NIGHTFALL

ASTRONOMICAL SOCIETY OF SOUTHERN AFRICA

Sky Candy

The wondrous muse of astrophysics as art

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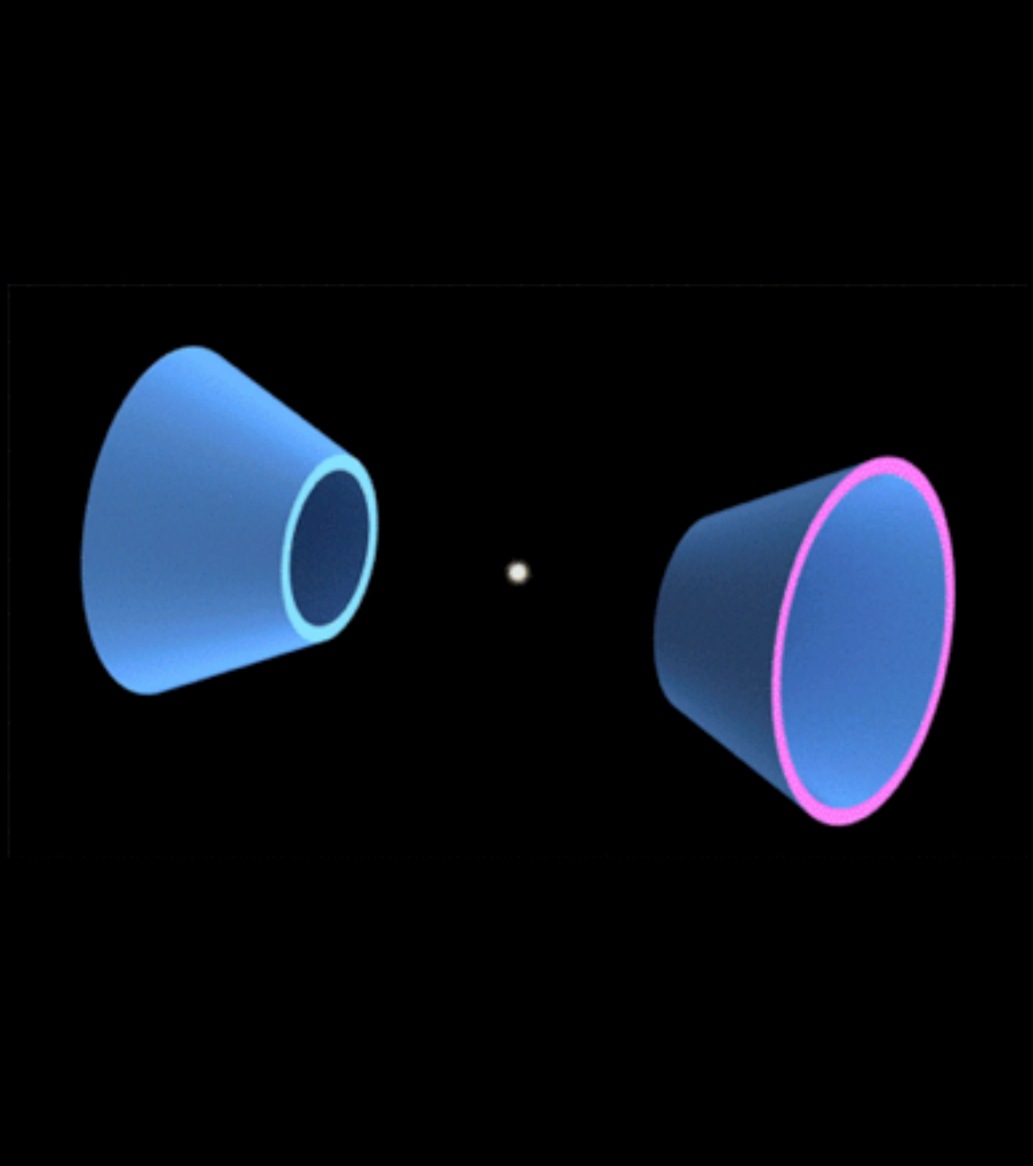
WHAT WOULD WE SEE IF WE TURNED ASTROPHYSICS INTO ART?



Run the full GIF here

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Published September 2021
by the Astronomical Society of Southern Africa
Observatory, Cape Town, South Africa
Editorial address: https://assa.saao.ac.za/
Website: http://assa.saao.ac.za/sections/deep-sky/nightfall/

Production services by Atelier Books LLC
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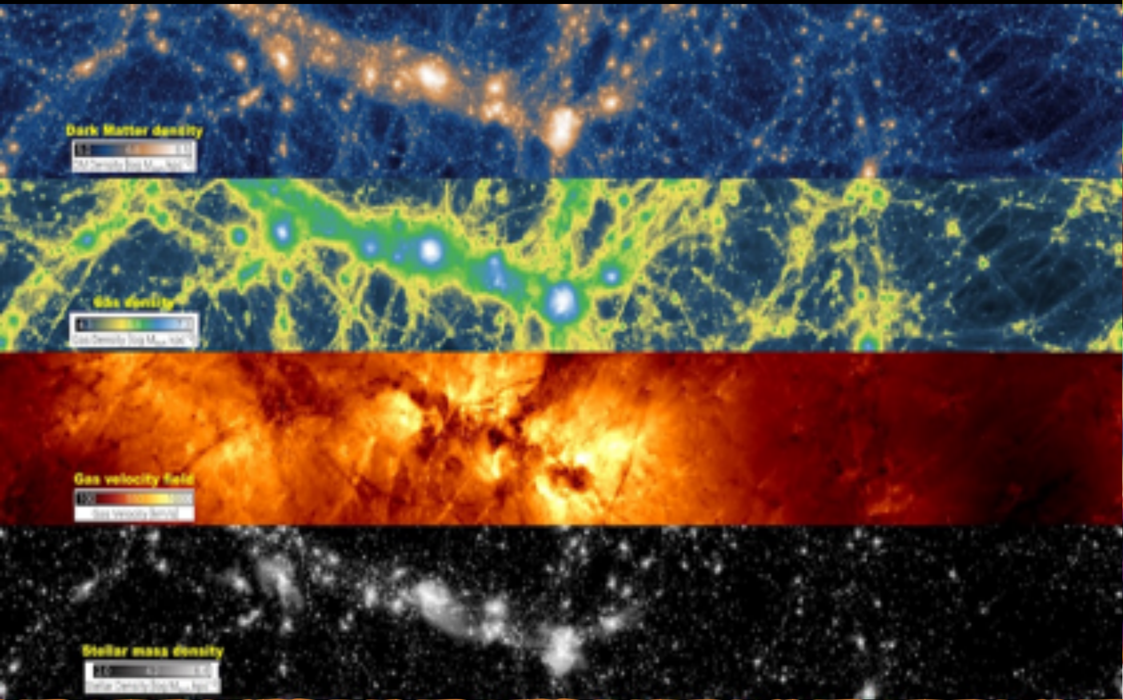
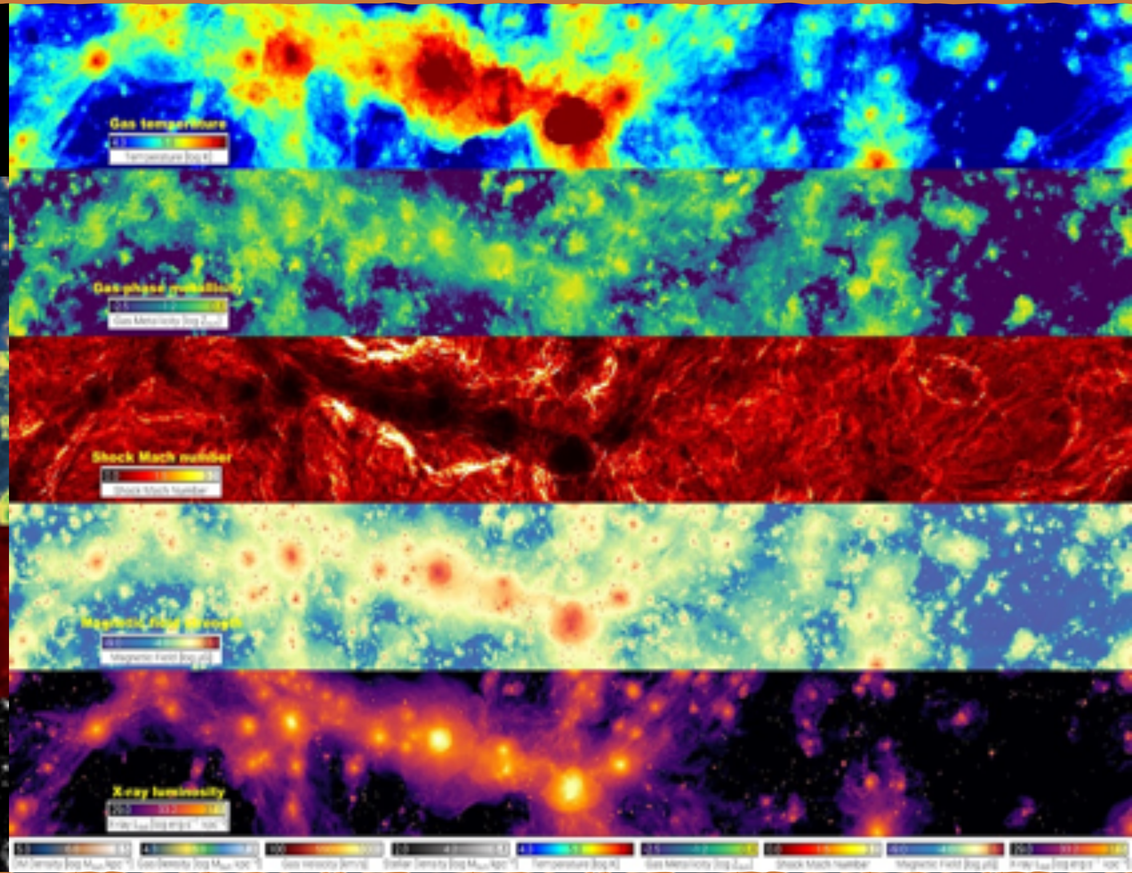
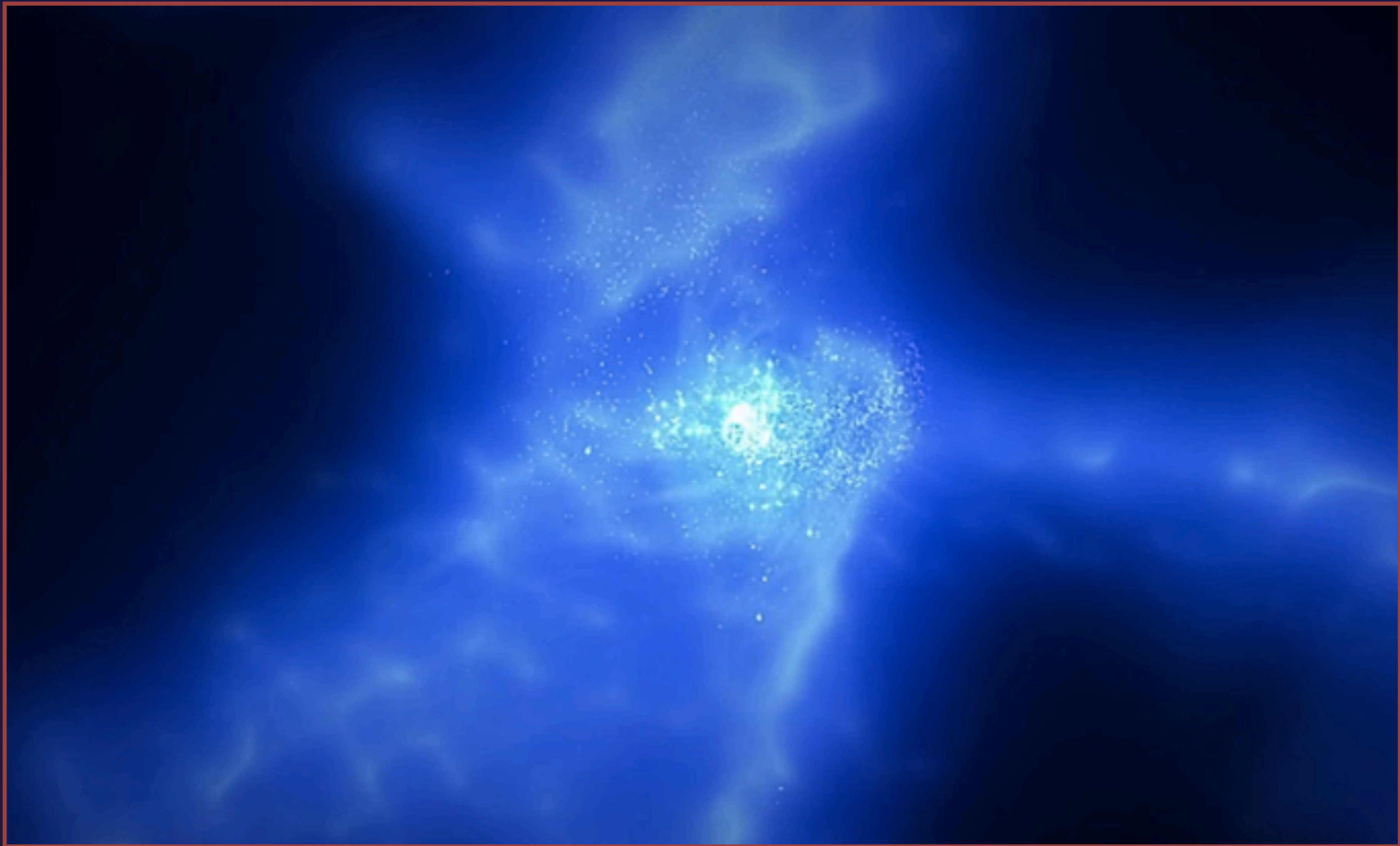
THE BEAUTY OF WHAT WE CANNOT SEE





The inconvenient truth of astronomy is that the universe we see with our eyes, our binoculars, and all our beloved telescopes with their mountings and go-to systems and eyepieces to see with, delivers to us only one percent of the electromagnetic spectrum. The ‘Stellar Mass Density’ image just above is what we see in our telescopes. Ninety-nine percent of the universe eludes us. Our eyes are not made to see in these wave bands. Yet that other ninety-nine percent contains more astronomical information—and more astonishing beauty that anything we can see with our eyes. The other 8 images in the above picture show what we cannot see. Infrared astronomy didn’t become a widely used imaging band until the late 1960s; the first infrared space telescope was IRAS in 1983. The first UV or ultraviolet image was acquired on the Apollo 16 lunar mission in April 1972. The first cosmic X-ray source beyond the solar system was Scorpius X-1 discovered by a sounding rocket in 1962; it later proved to be the optically visible star, V818 Scorpii, but 10,000 times brighter than in visual light. Radio astronomy had been used in astronomy since the 1950s, but the first radio map wasn’t produced until 1955 in The Second Cambridge Catalogue of Radio Sources (2C). Microwave astronomy really came into its own with the first map of the Cosmic Microwave Background by the COBE Explorer from 1989 to 1993. Assembling all these different observations into multiband images such as the above is done with computer modelling algorithms.

Long long ago and far far away, this is how we began



while far far away and long into the future, a lad named Hubble was watching us

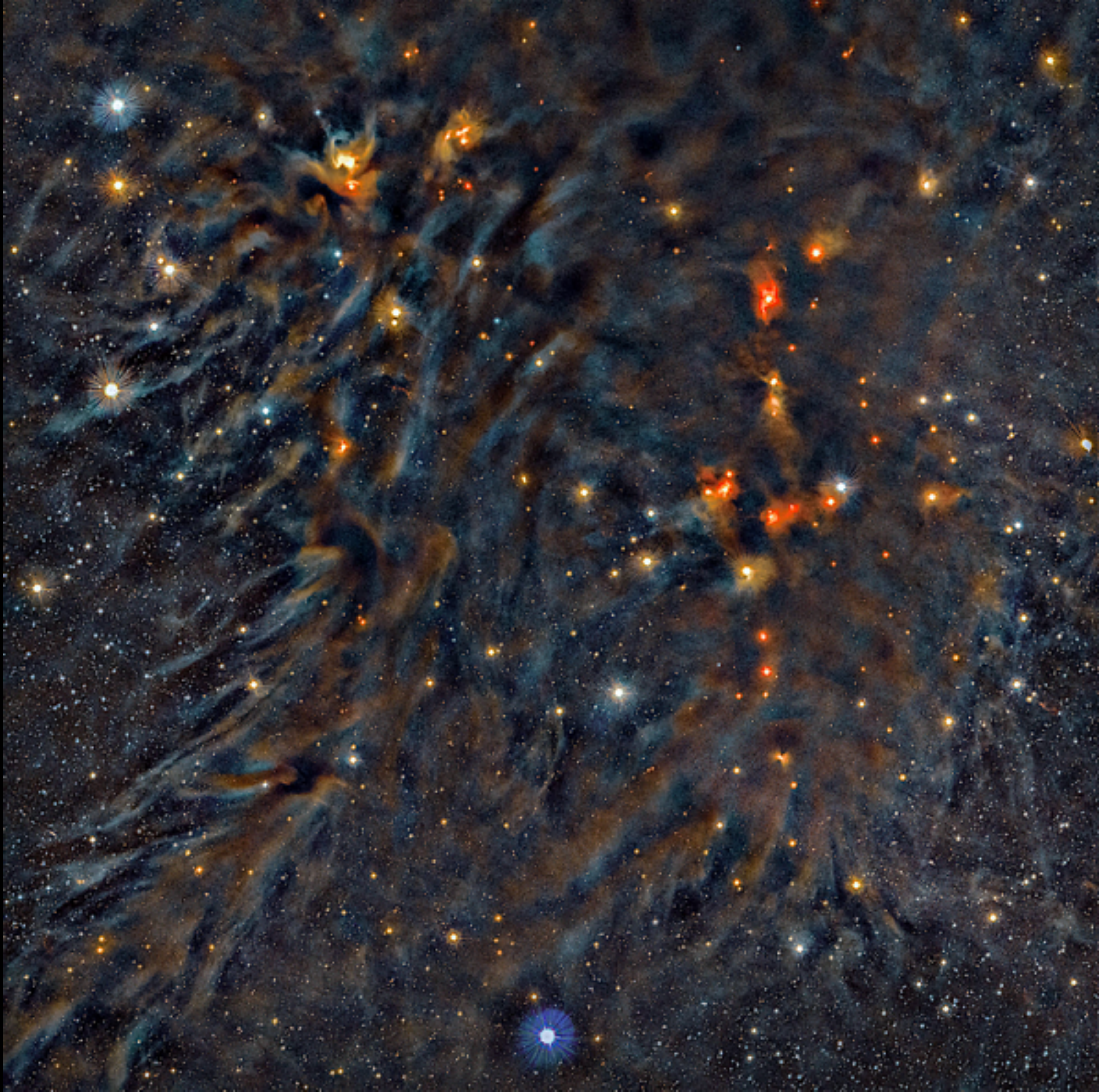
For the next few billion years, we lived like this

Click on the link in the arrow to watch a movie of the motion of cosmic gas in a small region of the universe about one billion years after the Big Bang. The colours signify velocity, from local rest (black) to 1000 km/s (bright red and white). In this era of the universe's expansion, accretion and infall from the intergalactic medium has already coalesced into the centres of a great many small pre-galactic dark matter halos. Stellar feedback from star surface winds and supernovae energised galactic winds which gradually pushed outwards until a number of black holes became massive enough to launch high-velocity outflows. The *TNG/Illustris* video that portrays this image shows the stellar distribution of the star-forming protocluster and the process of hierarchical assembly. The structure of the universe takes shape as stellar streams produce, shells, tidal tails, and merging galaxies.

When we were young we looked a fright

Have you ever wondered what our birthplace looked like before the Sun was a star? Bewonder no longer. The complex star-forming region to the right is part of the LI688 star-forming cloud in Ophiuchus. Like most star-forming clouds, it has a dense core of molecular hydrogen (a pair of hydrogen protons but only one electron orbiting them), plus 10% and 20% of cosmic dust particles by mass, all of which are surrounded by a thick shield of atomic hydrogen. The atomic hydrogen scatters many of the incoming high-energy cosmic rays which can weaken star formation.

In this image of LI688 the core has fragmented into numerous ultra-dense clumps. While the original giant core comprised perhaps 10 to 100 atoms per cubic centimetre, the dense clumps glowing in yellow-red here have upwards of one million atoms per cc. That density is the threshold at which gravitational collapse overcomes thermal pressure and the clump collapses into star clusters containing a few hundred to a few thousand stars. It is thought that the Sun's birth cluster contained around 4000 stars ranging from tiny dwarfs barely able to glow up a steeply rising scale of masses to a top level of a few blazing hot O supergiants between 25 and 60 times the sun's mass. Almost all large young star clusters are similarly composed. Today only a small handful of the Sun's siblings are known. One of them is *90 Hercules*, a 5th magnitude star near Vega in Lyra.



Scaling relationships in the Kennicutt–Schmidt (KS) relation tells us that there is a uniform scale between the mass of gas and its star formation rate (SFR). The KS relationship gave astronomers the tool they needed to trace star formation not just in star-forming clouds like LI688, but indeed all star clusters in all galaxies throughout the history of the universe. Using laws like these astronomers can explain how galaxies have grown and matured across time spans of billions of years.

In the LI688 image on the previous page the bright white objects with halo-like rays are nearby field stars that not part of the Ophiuchus molecular cloud complex, so disregard them as you consider what is going on in the image.

Molecular clouds range greatly in size and density, from small clouds less than a light-year across up to the giant molecular clouds (GMCs), which are over 100 light-years across and contain enough material to make several hundred thousand stars. LI688 has enough gas to make several hundred to a thousand stars of many different mass sizes from tyke to titan.

The most common component of these clouds is molecular hydrogen (H_2). Other molecules include carbon monoxide (CO, which astronomers often use to trace molecular cloud structure) and organic compounds such as methanol. While dust is present throughout the galaxy's gas/dust medium in between the stars, the dust density in molecular clouds becomes opaque enough to make the clouds appear like black splotches. The densest dark clouds in the above image also contain bright red-yellow patches. These are very young star-forming regions which in time will produce bright stars like we saw in NGC 2244 described earlier.

Yet many of the dark splotches in the image have no star-forming activity. Why not?

Up until the year 2005 there were two basic models of how stars form in molecular clouds. In the gravitational collapse model, star-forming molecular clumps hundreds to thousands of solar masses in size fragmented into dense cores (greater than 2 grams per cc) that then collapsed down to the extreme densities seen in the middle of stars. When the temperature of the dense gas reaches about 7 million degrees Kelvin, hydrogen begins to fuse to make deuterium and releases energy. That provides a considerable amount of outward pressure, but the cloud's gas and dust continue to fall into the young star until outward nuclear fusion pressure matches the gravitational pressure of the cloud and the star stops growing. The dark blobs with red-yellow patches in LI688 are what that model looks like in the real world of a galaxy spiral am.

The other model was called the competitive accretion theory. That view proposed that all stars were born smaller than about half the mass of the Sun, and that the vast range of stellar masses actually observed grew by the accretion of unbound gas from the original molecular and atomic clouds. The LI688 image gives some credence to that idea, too. The entire star-forming region, and particularly the left side, is marked by obvious streams of gas and dust streaming directly into the dark clumps where it appears no stars are being born.

If a single image can give visual credence to two completely contradictory theories of star cluster formation, how do we decide which theory is right?

One clue was the detection of X-rays in young star clusters. When X-ray astronomy began in the late 1960s, the only way to get above the Earth's X-ray blotting atmosphere was by sending detectors high above the stratosphere in helium balloons. The first satellites dedicated to X-ray astronomy were Uhuru, Ariel 5, SAS-3, OSO-8, and HEAO-1. Their resolution was good enough to detect individual stars, but not to map the delicate nuances of complex star-forming regions with legions of X-ray protostars. By the early 2000s sophisticated satellites like RXTE, ROSAT, ASCA, as well as BeppoSAX were good enough to suggest, but not prove, that competitive accretion could not amass enough gas onto a star to make stars more massive than about 10 solar masses—rather incongruously called mid-mass stars. Anything heavier had to be explained by the theory that mid-mass stars collided often enough to make the required number of observed 40 to 60 Msol high-mass stars.

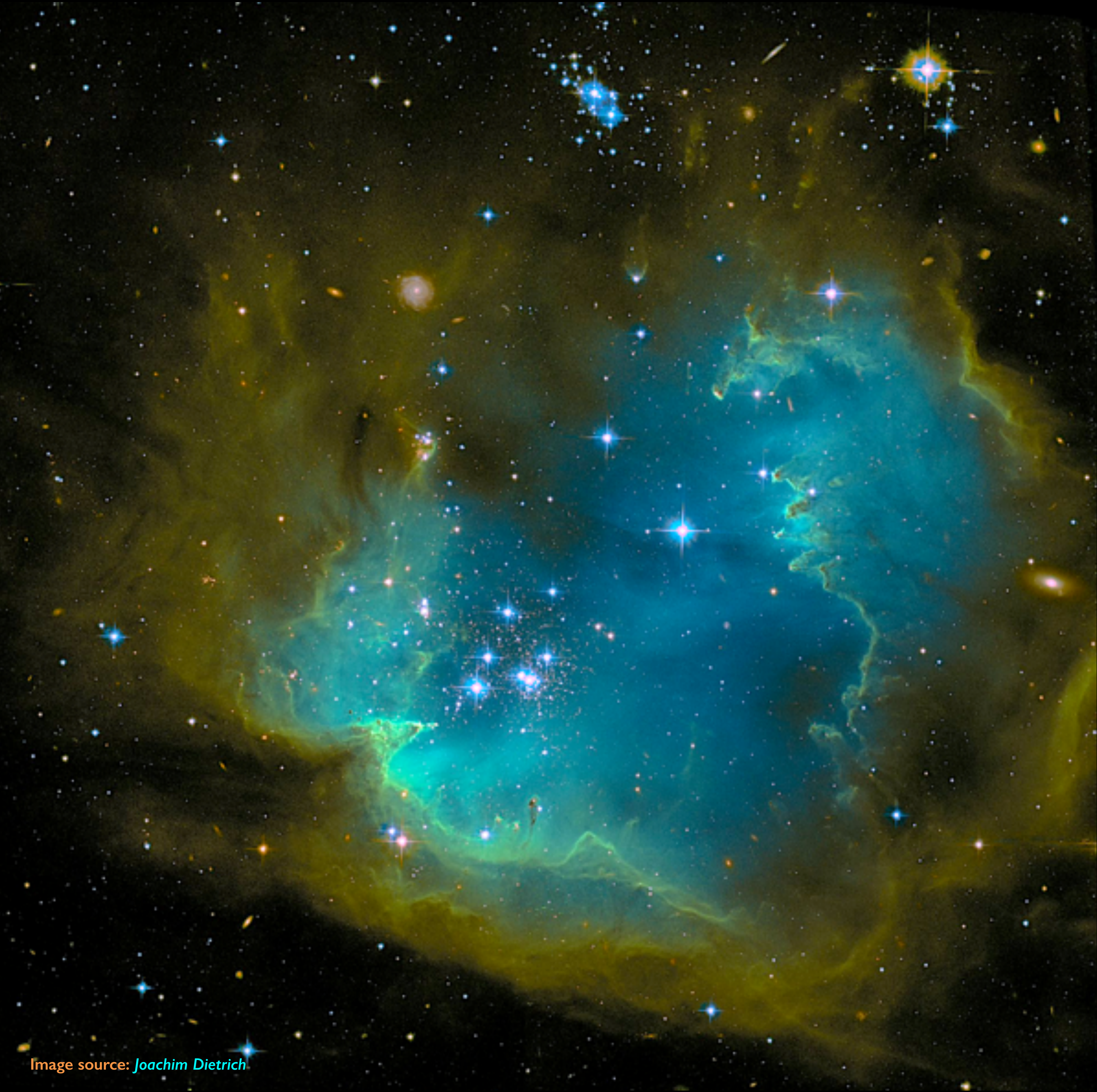
That, frankly, was a bit of a stretch, especially when the first observations of accretion discs around stars arrived in a series of papers (*1*,*2*,*3*) that confirmed through observations that gas could fall into stars via accretion disks rotating at high speed around the stars' equators. That's science for you: new observations throw old theories out the window.

The LI688 image does make sense if we consider that stars in a cluster form nearly all at the same time, but different clusters growing out of a single giant cloud can form at different times until the cloud is exhausted. We see the gas infall, the growing dark masses of dense clouds, and the first starburst in still-dark clouds, all in one picture. To see what it looks like in simulations, see *1*,*2*,*3*,*4*.

There is a reasonable case to be made that our Sun was born in a cloud that looked much like LI688 some 4.6 billion years ago.

Astronomy is a wondrous science. With it we can describe not only what out Sun's house looked like before it was built, but also what its suburb looked like when it was still empty space.

And stepping a bit further back in our perceptual apparatus, squint a bit and LI688 is a work of abstract art you wouldn't mind hanging above your desk.



A bit of age fixed that

NGC 602 in the Small Magellanic Cloud is a young star cluster only a few million years old clearing out the cluster's unused natal gas via UV radiation pressure and turbulent shock fronts. As the radiation pressure accelerates gas and dust particles away from the cluster, the shock fronts force the cluster gas into the surrounding gas that was in the area long before the cluster collapsed into stars. Now the cluster is forcing its excess gas into the local medium, creating broad, long supersonic shock waves. Since the pre-existing gas and dust was clumpy, the radiation pressure wraps itself around denser pockets of gas, creating turbulent shock surfaces. Pressure in shock fronts can become so high that secondary star formation occurs.

So-called 'pillars of creation' reveal very dense local pockets that look like mountain peaks in space. The combination of supersonic shock waves and a sudden rise in temperature induces secondary star formation that we see as brightly illuminated tips pushed into comet-like compression surfaces, at the tip of which infant stars are being born. The resemblance to the Hubble Space Telescope's famous 2012 'Pillars of Creation' photograph is not accidental—nearly all star clusters that formed out of a molecular cloud that collapsed into stars endure the gas clearance phase that we see here approx. mid-way through the cycle of expelling unused gas back into space.

The non-uniformity of gas/dust clouds which quietly reside in galaxies is clearly evident not just in the rugged shock fronts and pillar-like structure we see here, but also in the markedly non-uniform density of the cluster stars themselves. Few open clusters have the ball-of-stars look of ancient globular cluster. Instead they have the inchoate look of NGC 602.

Soon enough it was time to find a home of our own

The Pleiades and its southerly sibling IC 2602 are glitterbox gems that will shine for multi-millions of years. Yet on the way to today's splendour they left behind a dreadful amount of debris.

Only a few percent of a cold molecular cloud eventually becomes a star. The rest is eroded, dissipated, vaporised back into warm (5000 K) atoms and molecules to try again another day. In Beverly Lynds' dark cloud #122 we see the ferocious ultraviolet sear of nearby hot stars blowing dust back into the universe.

A hundred million or more years from now, the gas and dust seen here will return to much this same state, only to be blown away again. Again, again, again, till one day they can finally ignite. Patience is a job description in a star's resumé.

Source: Martin Heigan.

Watch this snapshot turn into a movie

For awhile this shady penthouse looked pretty good

The giant Eagle Nebula M16 is a huge bubble of gas and dust. Inside it these growing clouds are spectacular star bursts making an open star cluster. The dark sculptures seen here are evaporating as UV ultraviolet starlight abrades away their woolly cumulus shapes.

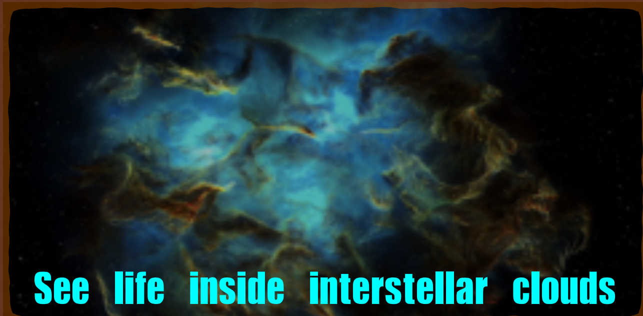
This Hubble Telescope IR image reveals striking dust pillars of the Eagle Nebula that might be described as a gigantic icebergs of gas and dust. These bergs, though, are ten light years tall. Their bluish radiation is much hotter than the gas, hence their glow. The pillars here are about 7,000 light years away. They will evaporate completely in about 100,000 years.

The image was released in 2005 as part of the fifteenth anniversary celebration of the launch of the Hubble Space Telescope.

More than you will ever want to know about dust pillars in molecular clouds

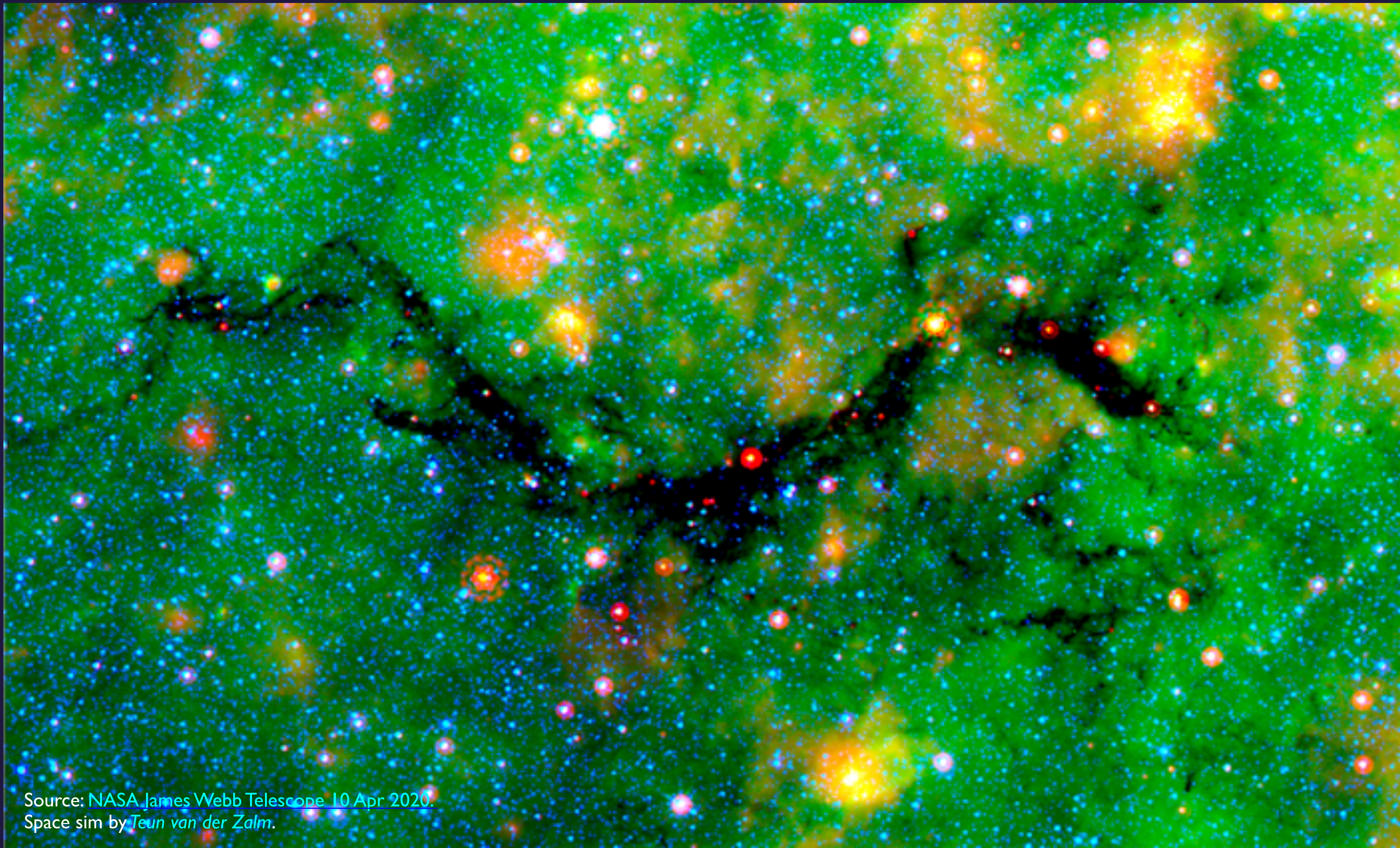
But we were warned of dangers of over-reaching

Even after so many years of gazing through our telescopes, looking at the starry sky still thrills us with the mystery of so much immensity. Why is it all there? We wouldn't see the stars and planets deep within these gravid clouds of dust and gas, but we would certainly feel their heat. So we make infrared receivers.



Infrared light travels little hindered by dense dust. Imagine this same area in IR . Dim glows are transformed into veils of silk and gauze streaming in the winds. By observing worlds very different from our own, we grasp the nature of our home in the universe. Why that home was built is the mystery we seldom ask.

But on the other hand, if you think small, small is what you get



Source: NASA James Webb Telescope 10 Apr 2020.
Space sim by *Teun van der Zalm*.

The Seahorse is a doppelgänger filamentary cloud being squeezed from both sides by turbulent dense gas clouds busily forming stars. Only the filament's solenoidal magnetic field is holding the pressures at bay, but its flux tube is being crumpled into disconnected clumps. When magnetic support is lost, gravitational collapse is inevitable. If the gas masses are sufficiently high, stars form. In this infrared image from the Spitzer Space Telescope, the blue dots are stars relatively undimmed by dust, while the red dots are gas embedded stars.

Click here to see why it looks like this.

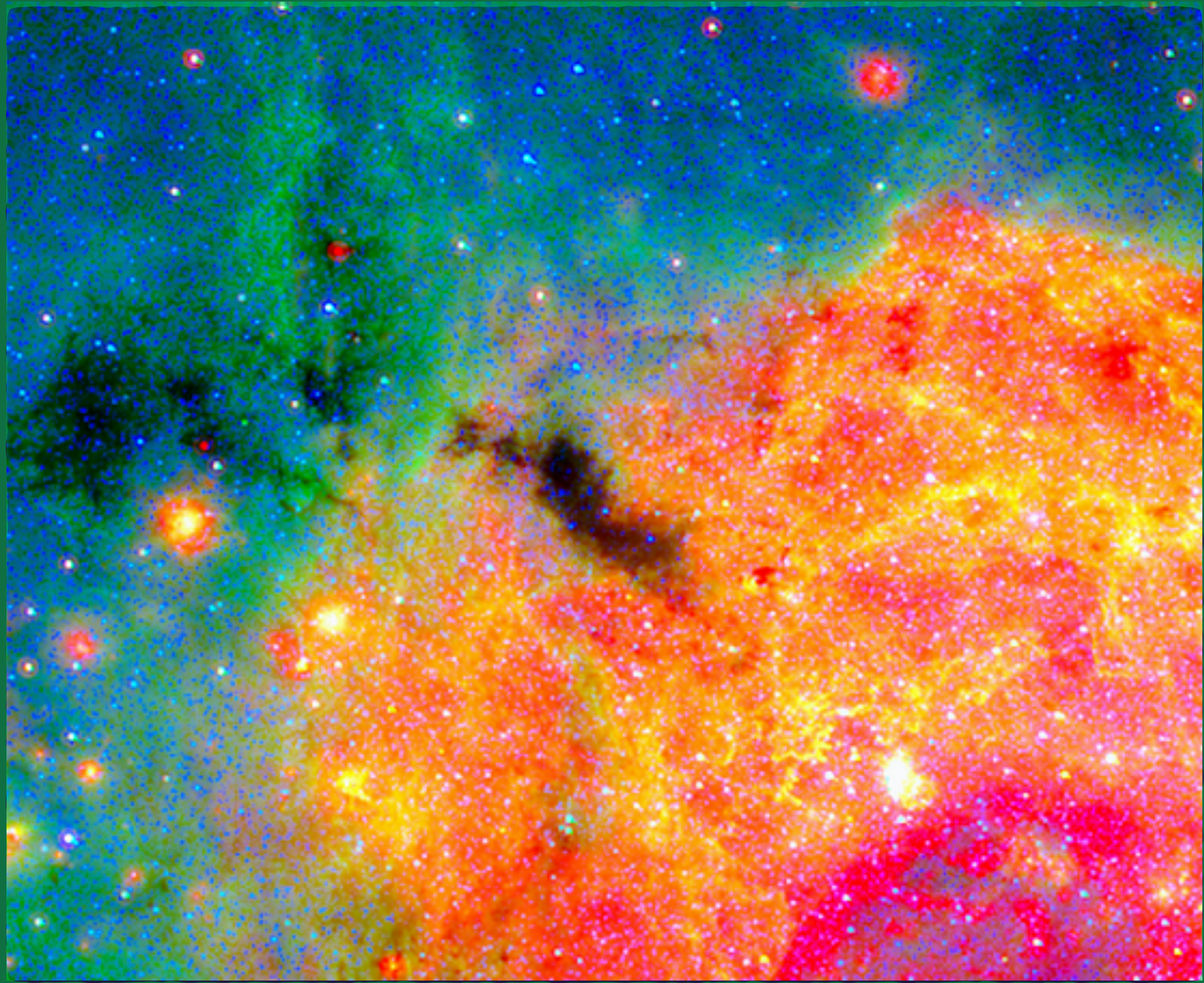
So we jumped in the water figuring we could learn how to swim

Galactic building blocks don't come in compact, tidy, Euclidean bundles. Yet put them all together and the end result is much the same—an awe-inspiring edifice that illumines as it beautifies.

High-mass stars might die as dazzling supernovae, but their births are mysteries garbed in murk. They form in very dense, cold clouds of gas and dust that can have up to 100,000 times the mass of the Sun. Little is known about these regions. They are so dense that they often seem like vacuous ink blobs in the sky. Initially devoid of stars, these molecular clouds obscure the light from background stars.

Made of gas with a dash of dust, molecular clouds are the baptismal fonts of baby stars. When their densities reach 1 million atoms per cubic centimetre ($n = 10^6$), they can even block out the infrared light which usually propagates through dusty environments—hence their name: IRDCs or infrared-dark clouds.

Given the moniker 'The Brick', the IRDC centred here weighs in at over 100,000 times the mass of the Sun. It isn't forming any stars yet, but based on its density and volume, when it does form stars it will become a YMC – Young Massive Cluster.



Source: NASA James Webb Telescope 10 Apr 2020.

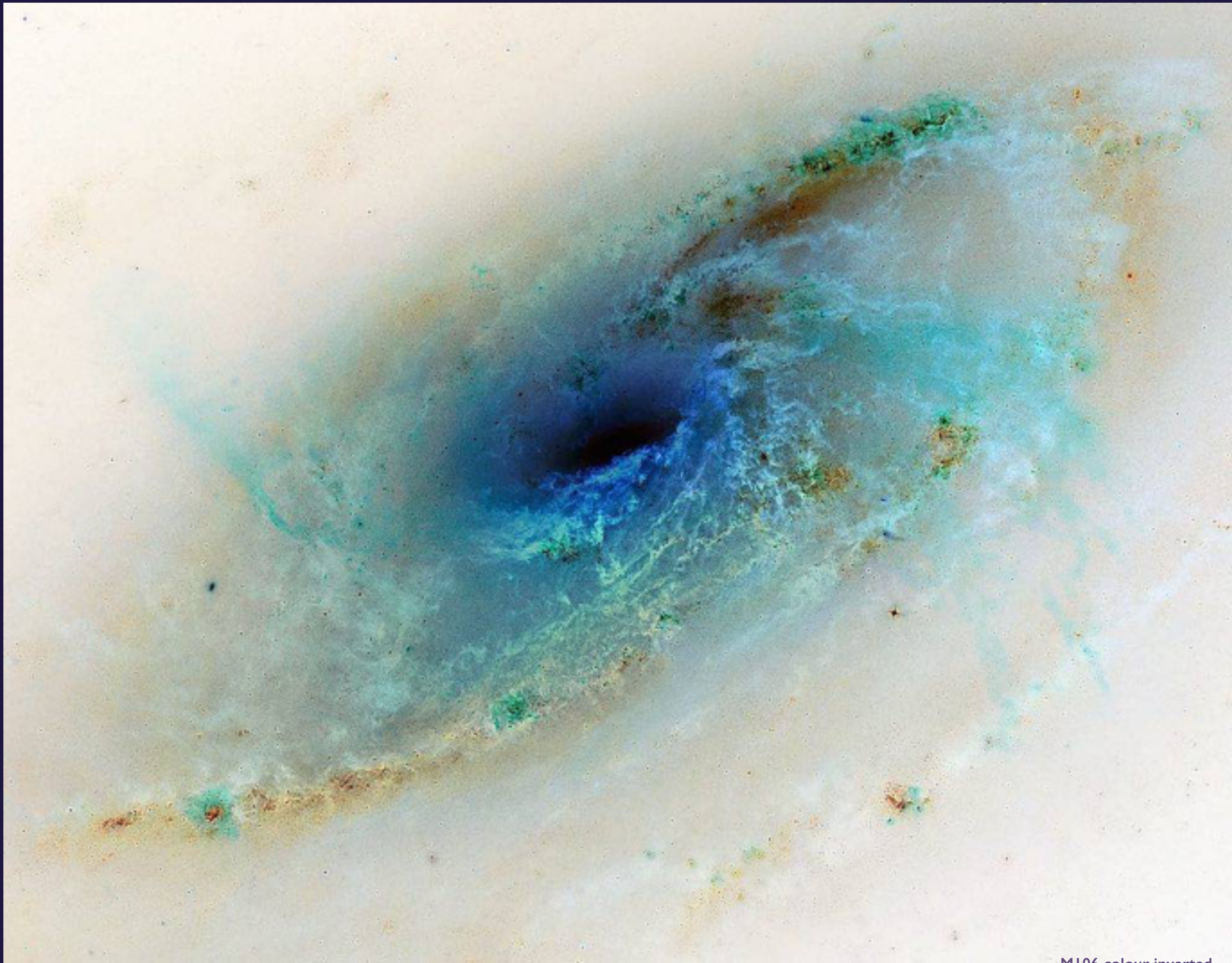
Here is the future that awaits the Brick.

There seemed to be no end of oceans we could swim in

More complicated than it looks.

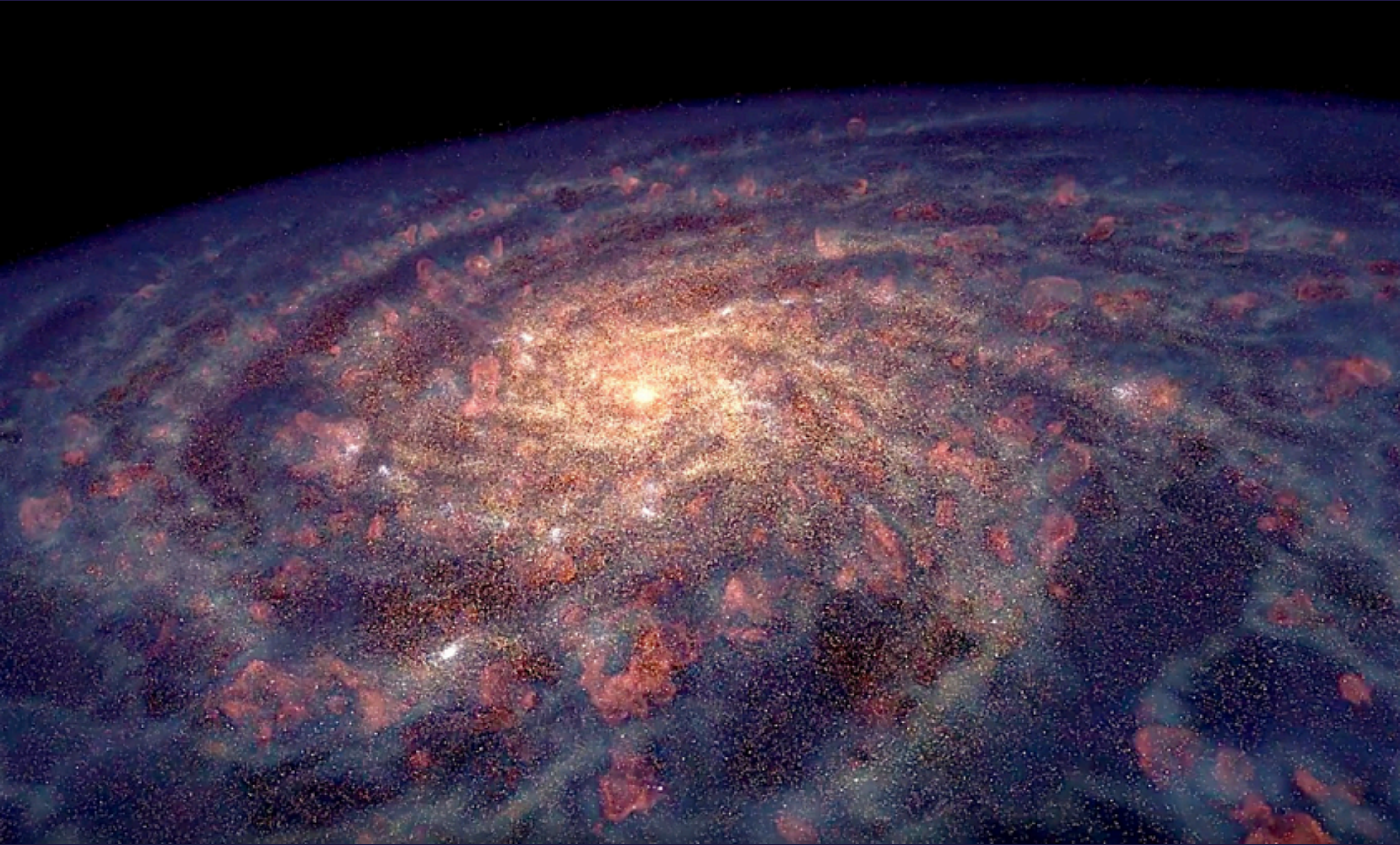
NGC 1512 in Horologium ('The Clock') is a graceful study in the dynamics of galactic bars. Several hundred million years ago this galaxy was a modest-sized flocculent spiral, with many short armlets and rotationally stretched star-forming clumps. The bulge was not very massive. At some point a tiny perturbation or bump occurred at the bulge's Inner Lindblad Resonance (ILR), a ring-like region where the gravitational pull between the bulge mass and the mass of the arms balanced. The bump grew over time into the giant, diffuse bar we see here. The pattern speed of a galaxy bar rotates faster than the pattern speed of the spiral arms, so N1512's bar has raced through the arms it connects to, attaching and detaching several times, like trying to find an acceptable bridge partner. During any given pile-up, a large portion of the spiral arm's gas, dust, and stars are diverted in a giant swerve to orbit in long ellipses around the bulge. A portion of the infalling matter is diverted when it reaches the bulge. There it bursts into hot, blue stars. This zone is the same ILR that started the process so very long ago.

One place looked like it had a terrible problem with the drains



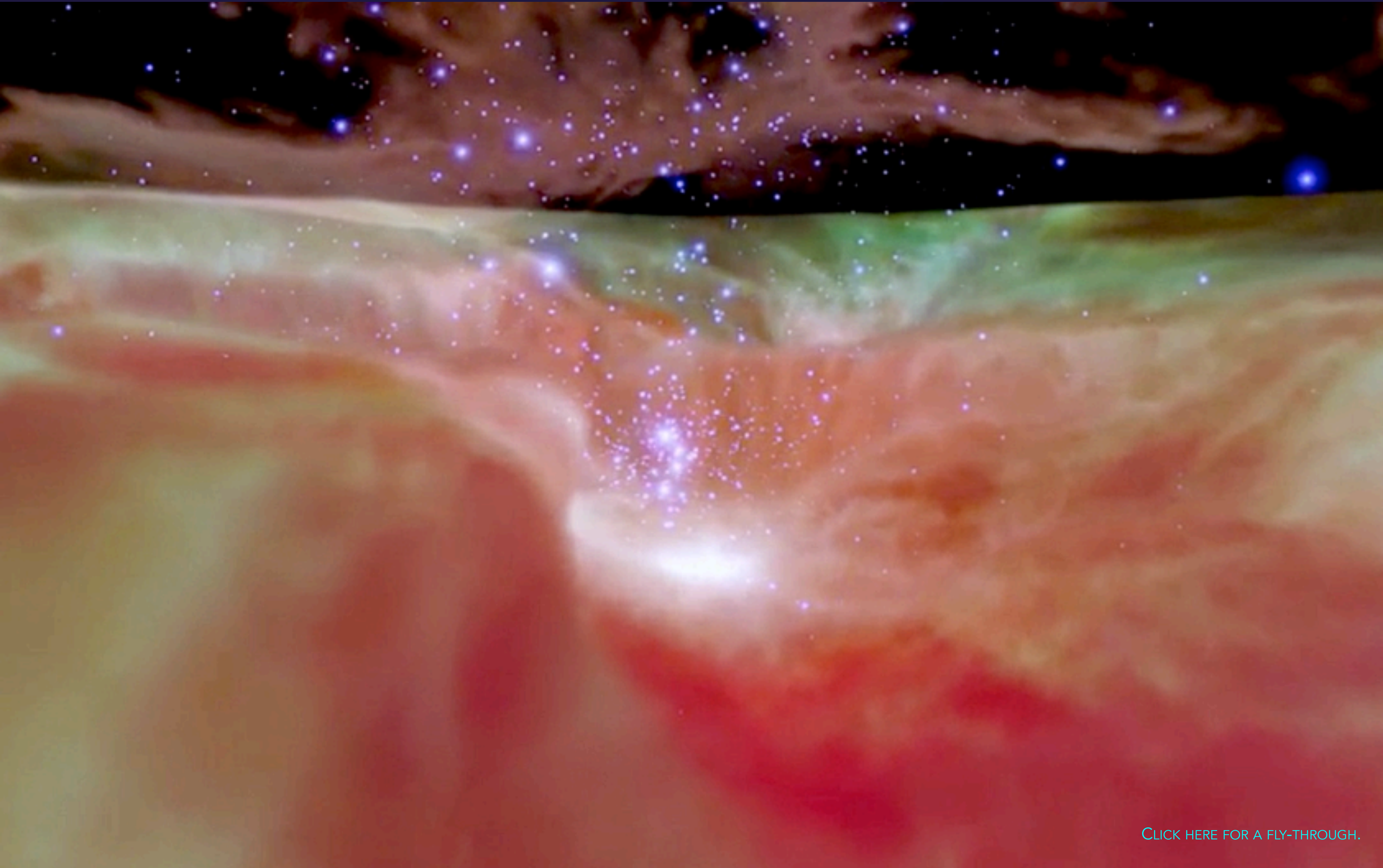
M106 colour inverted

But then we found a place that had the look of a proper home



Click here for a fly-to.

Hmmm, this neighbourhood had a promising look to it



Click here for a fly-through.

So we decided to call it home.

A painting depicting the Earth as a sphere, populated by all manner of living forms and surrounded by the ocean of the sky, all of which were threatened from beyond the sky by allegorical symbols of humankind's internal evils. Beyond all of these was the fiery radiance of a supernal being whose energy is at once infinitesimal and infinite. The artist who depicted this vision is shown in the lower left corner inscribing on wax tablets with a stylus. Those notes and drawings on wax were rendered into the image shown here by a scribe named Volmer and artists of the Monastery of Rupertsberg in what is now Germany. The image was painted onto vellum in a book titled *Liber Divinorum Operum* (Book of Divine Works). It was the last book to be written by its author, who considered it the pinnacle of her life's work. She was Hildegard of Bingen, born 1098 as the 10th child of a modest aristocratic family, and died 1179 the most famed and influential woman in medieval history.

It was so friendly we were welcomed by a comet.

And in case anyone ever asks, dark matter is not dark.

Here is the proof

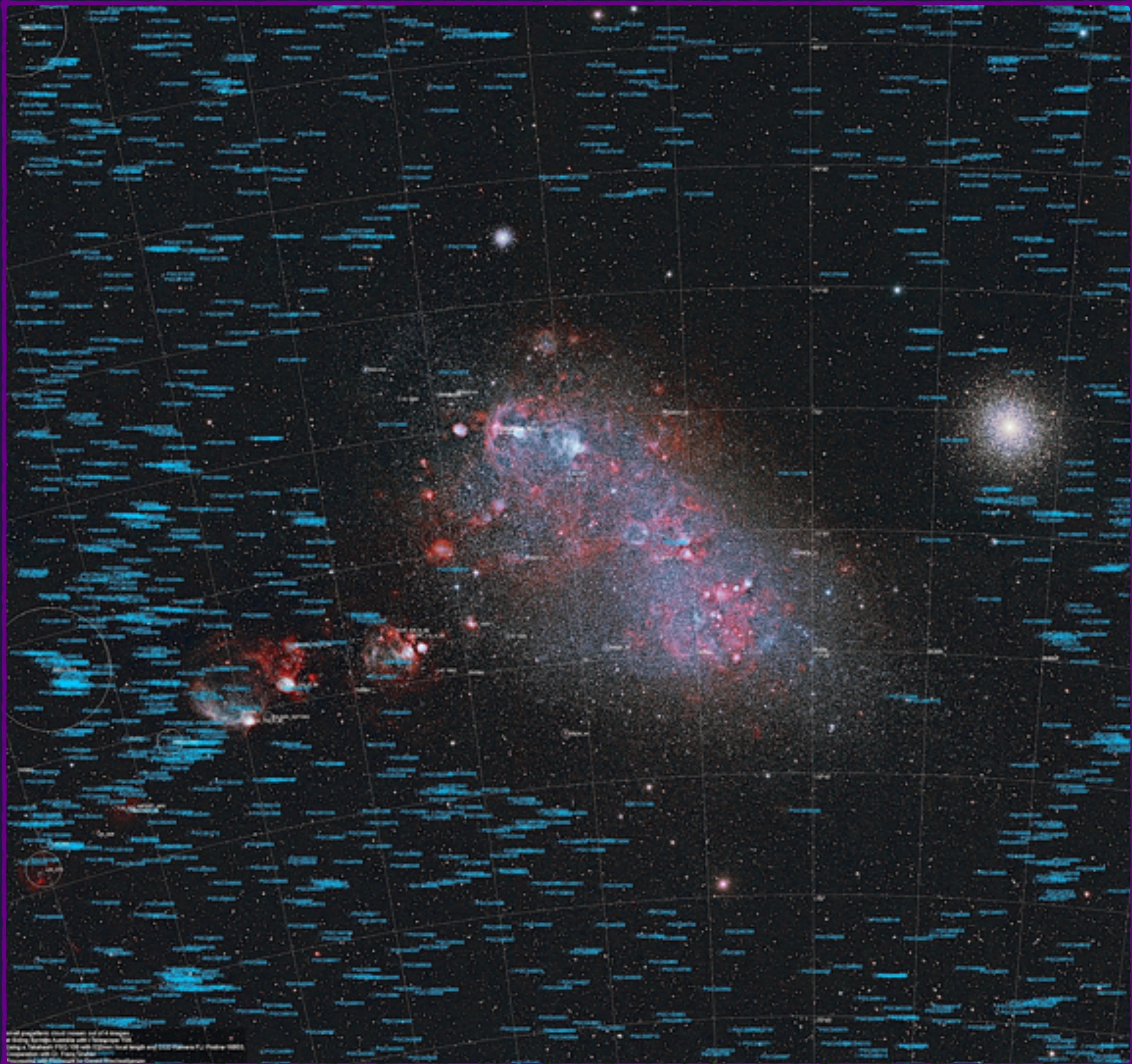
Every reader whose eyes are now glued to this page will recognise that big fuzzy thing in the middle as the Small Magellanic Cloud (SMC), the middle-sized speckly thing in the right centre as 47 Tucanae (NGC 104 for fussy types) the smaller speckly thing above the SMC as NGC 362, and the string of globby things leading left of the SMC as bright, dense, not-so-young star forming regions torn loose by the SMC's last argument with its big brother, the Large Magellanic Cloud. Their fraternal hissy-fit some 300,000 years ago ripped an entire arm off the LMC, popped the LMC's bar off the galaxy's bulge by some 1,000 light years, ram-pressure stripped away most of the SMC's gas and sprayed it across the sky as far away as Andromeda, and performed several other astrophysical deeds too unseemly to mention. What the LMC–SMC collision did NOT do was remove any of either galaxy's dark matter.

How do we know this? You see all those blue labels on this image? They are remote galaxies from the Uppsala General Catalogue (UGC) and Catalogue of Principle Galaxies (PGC), plus a few New General Catalogue (NGC) galaxies. These galaxies pepper this image fairly uniformly—except near the SMC. Do a bit of dreary diligence with the few blue objects close to the SMC disk and you find they are brighter than the 12th magnitude in the blue band. All the others occupy the luminosity range from M_B <12 down to M_B *19*.

Now, we know that galaxies are mostly dark matter we can't detect mixed with a small percentage of baryonic (atomic) matter that we detect with admiring eyes every time we look up at night. So then … the dark zone around the LMC means that dark matter is dark, right?

Alas, no cigar. The dark zone around the SMC that is so self-evident here is dark *DUST* that was once part of the gas-dust halo around the SMC. Every galaxy has a gas-dust halo, but dust is heavy (relatively speaking) compared with gas. When the LMC stripped off the LMC's gas-dust halo, the dust decoupled from the gas and stayed bound to the galaxy. There is j-u-s-t enough of it to absorb the light of all those evanescently faint UGC and PGC galaxies we don't see here.

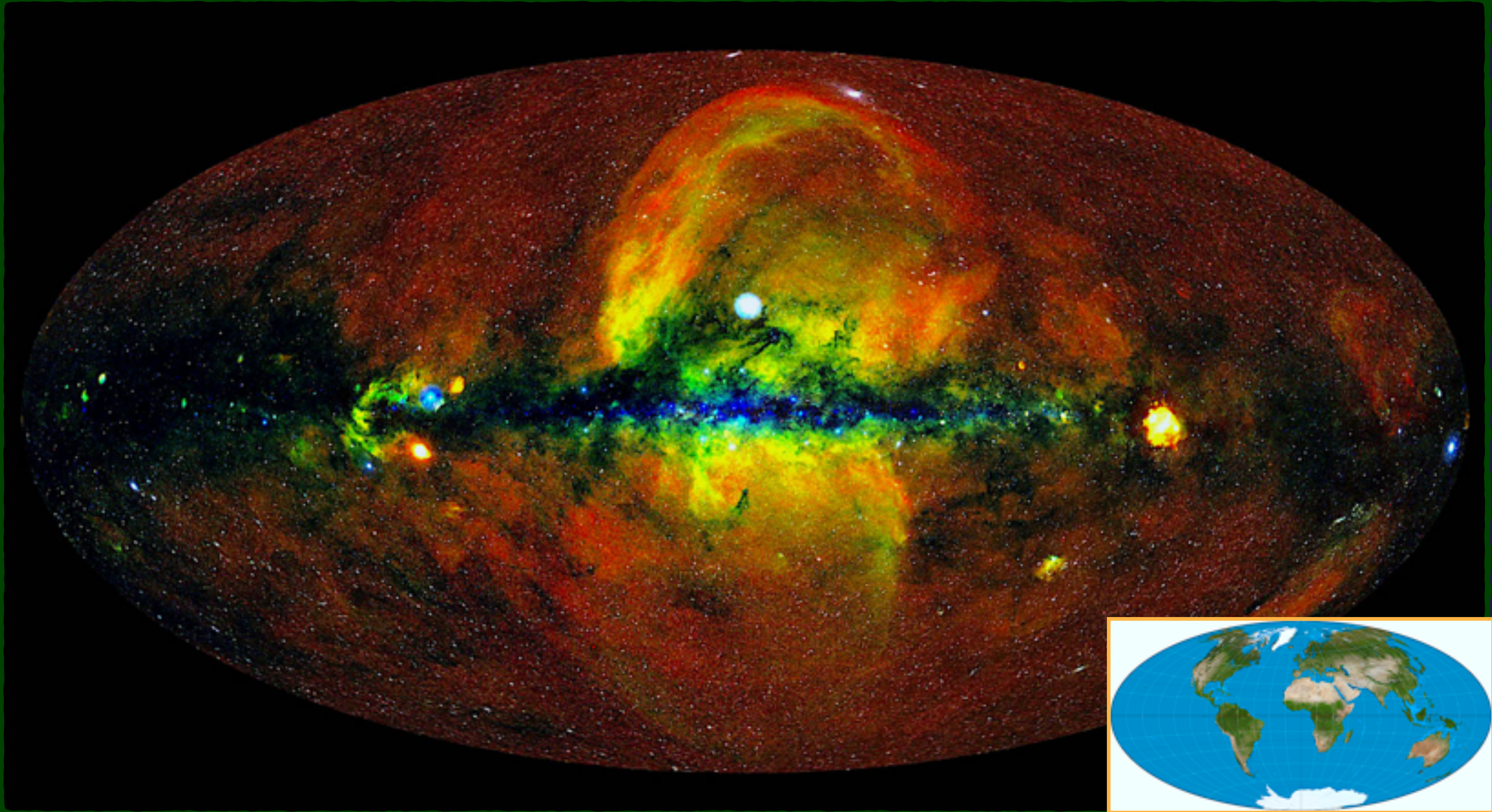
So, while it's true that dark matter is not dark (it is in fact invisible because it interacts only with gravity), this image proves quite nicely that dust sticks to galaxies a lot better than gas.



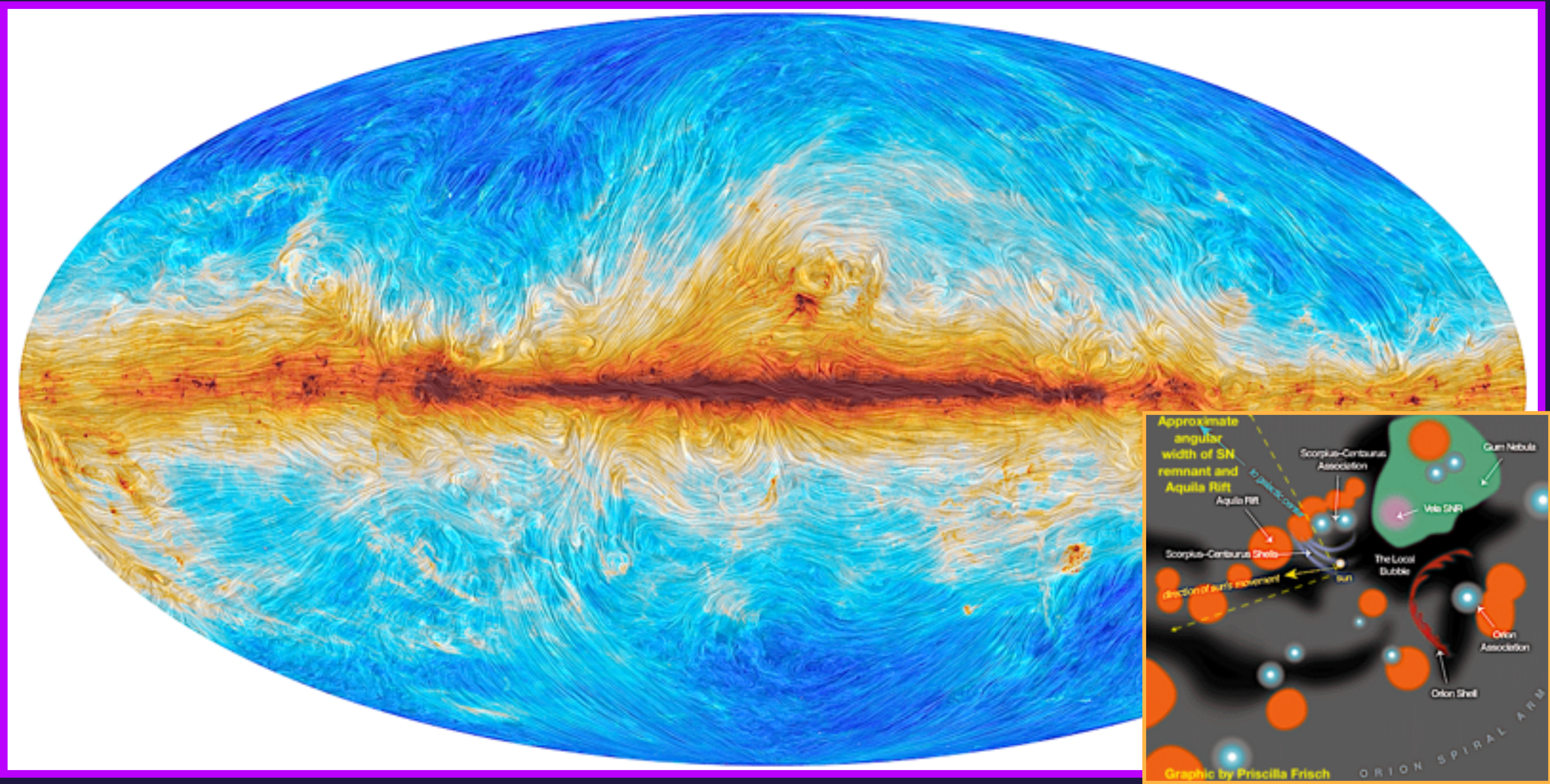
Let's visit the Palomar Hale Telescope as it was 30 years ago.

And while we're at it, stay overnight.

Don't laugh at the Flat Earth Society, there's a Flat-Sky Society, too



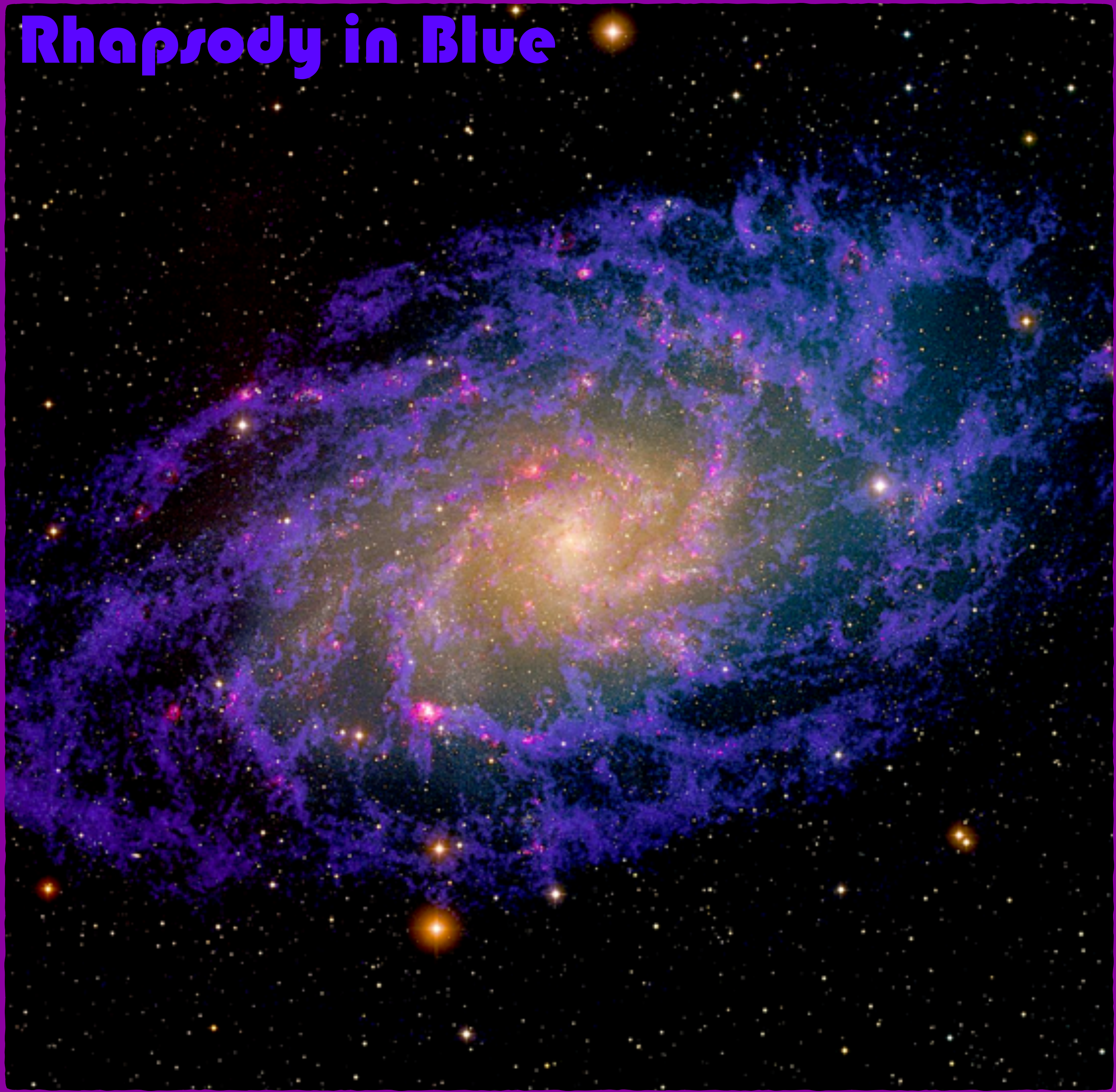
Aitoff projection of the Earth



The Aitoff projection in these images is often used to project a spherical view all around us onto a flat plane in such a way that all the data on the sphere are visible in one image that can be printed on a single page. Concessions have to be made when converting a sphere all around us to a flat page in front of us, and shape is one of them. To mentally turn the flat-sky Aitoff projection we see above back into a sphere, face the centre, reach out and grasp both side edges and pull them around till they meet in the middle of your back. Imagine the result as a cylinder like a Mercator projection. Then curl the top & bottom of the cylinder inward till they join directly above and below you. You are back in the middle of a sphere.

The other major concession is that Aitoff projections can't show anything in 3D. A 25th magnitude star 100 light years away or 25th magnitude quasar 10 billion light years away can occupy two adjacent pixels and we would have no idea one was near and the other one far. Like it or not, this is a Flat Sky version of a Flat Earth.

The image on the previous page is the X-ray sky as recorded by the Rosita X-ray satellite. The image on this page is the magnetic field structure visible in the 353 Ghz radio band extracted by the Planck telescope and processed to show magnetic fields without distracting stars, nebulae, and galaxies. The misleading quality of a 2-D surface is evident in the huge arcs above and below the Milky Way. Those are actually a nearby ancient supernova remnant in the Aquila Rift that occupies a modest volume of nearby space in 3D but looks utterly immense in the illusory 2D projection.



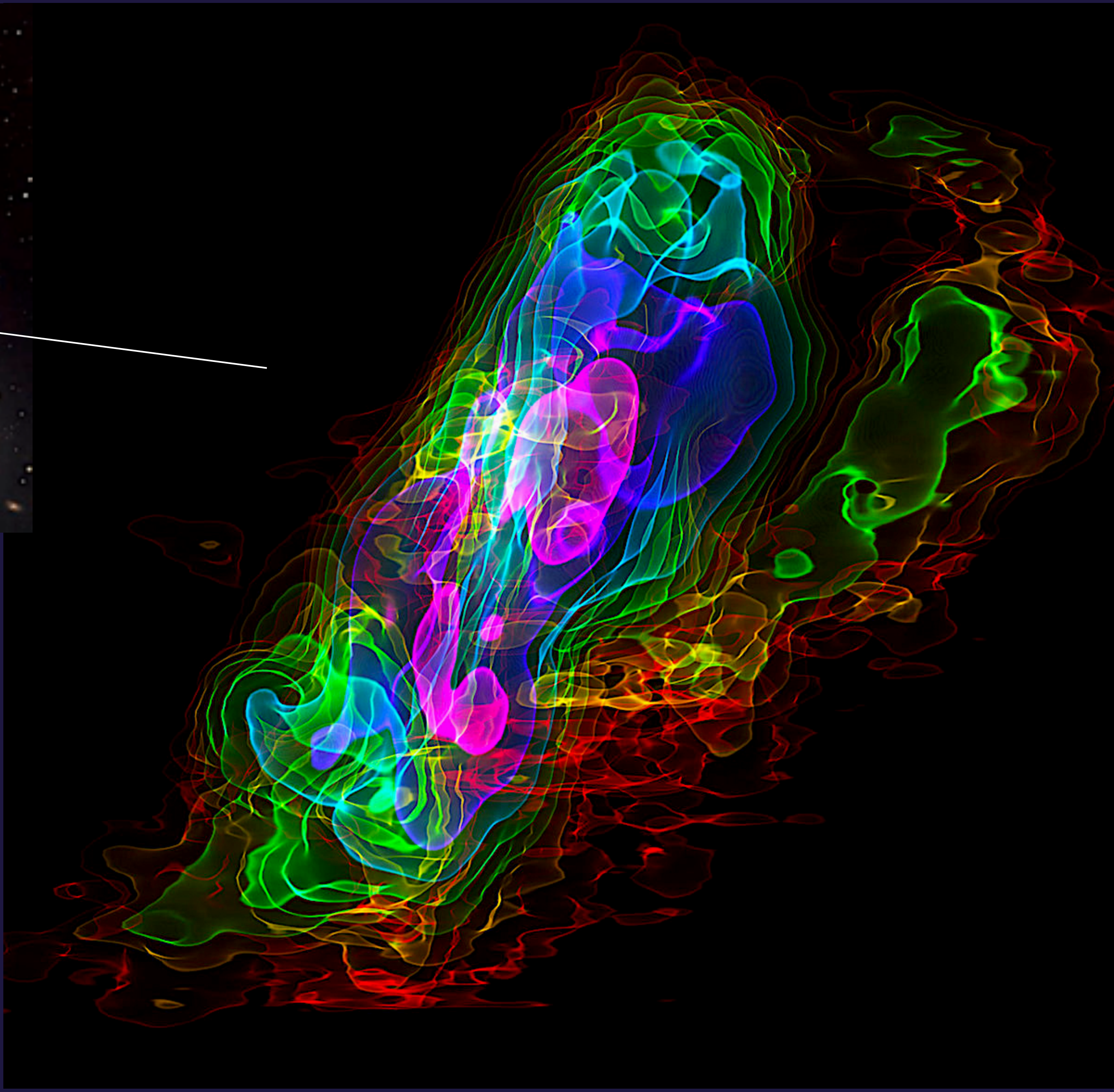
There is more to M33 than we see in the eyepiece

The Triangulum Galaxy M33 is the 3rd largest galaxy in the Local Group of galaxies, after the Andromeda Galaxy (M31) as most massive and the Milky Way in second place as slightly less massive. M33 is over thirty thousand light-years across, and more than two million light-years away. M33 is weakly bound to M31 gravitationally, and both are easing their way toward an eventual very messy interaction with the Milky Way. The end result will be an elliptical galaxy that retains the stellar mass of all three galaxies but loses nearly all the gas mass to explosive star formation and unused gas expulsion.

This image of the Triangulum Galaxy was created by combining optical data from the National Science Foundation's 0.9-meter telescope on Kitt Peak in Arizona (B, V, I, and Hα image in the centre) with radio data from the Karl Jansky Very Large Array (JVLA) telescope in New Mexico and the Westerbork Synthesis Radio Telescope (WSRT) in the Netherlands. The optical image shows the stars and reddish HII gas star-forming regions which are familiar items in the visual and imaging astronomers' repertoire.

The radio data, however, reveal a much larger galaxy whose outer environs are roughly twice the diameter of the optical disc. Portrayed here in vivid blue, the enormous primordial hydrogen reserves in M33's gravitational embrace will provide star fuel for billions of years to come—until it is all stripped away and hurled into the Cosmic Web.

The Secret Life of a Well-Known Friend



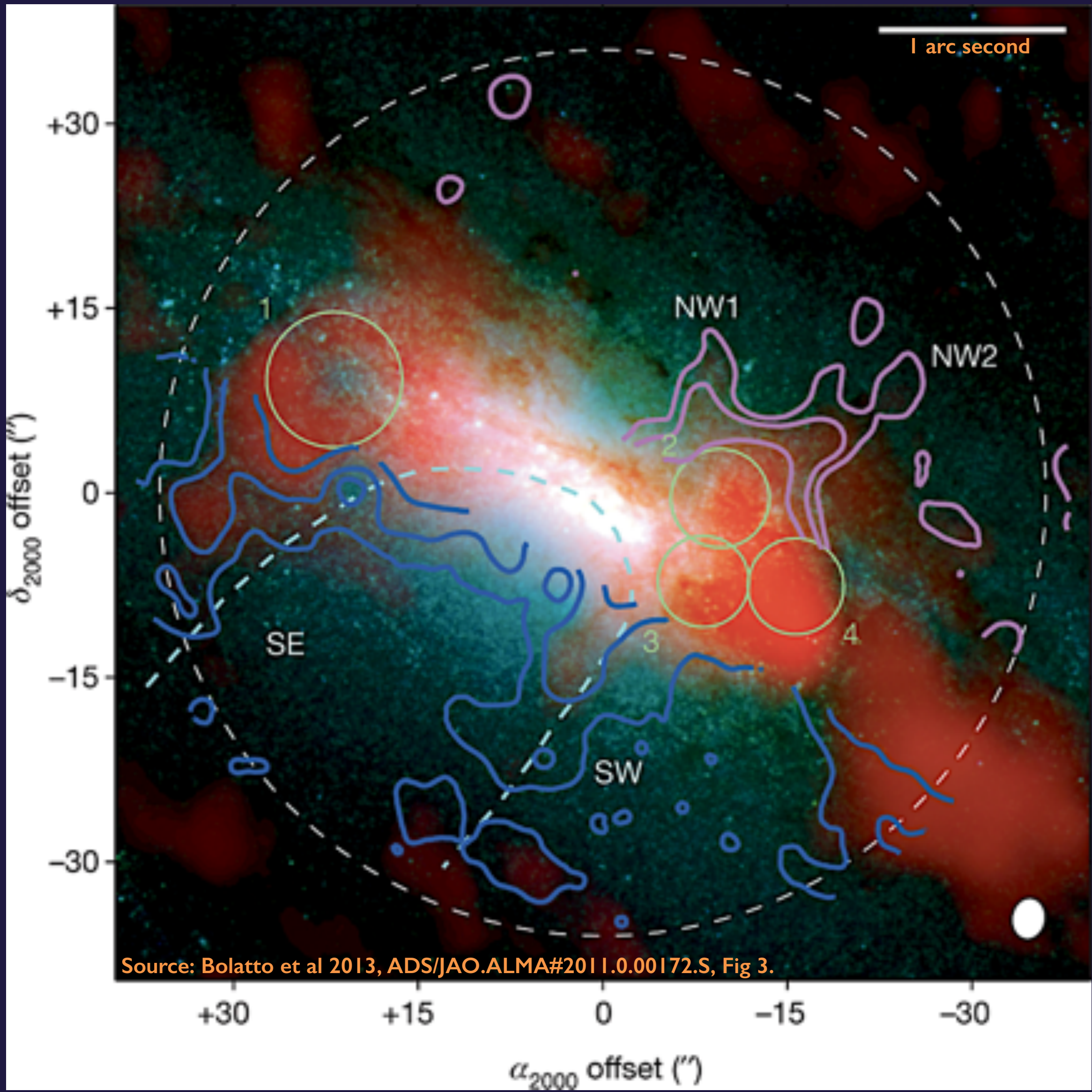
EVERYONE KNOWS NGC 253 IN SCULPTOR—OR AT LEAST WE THINK WE DO
But does it conceal secrets behind that mottled surface that we all see and image so well in our telescopes? What does NGC 253 look like if we examine a contour map of its carbon monoxide (CO) gas? CO is a well-known tracer of neutral hydrogen gas—the simplest of all atoms. Atomic hydrogen is the raw material of star formation, but radiates very little energy on its own and is therefore hard to quantify. However, simple H_I gas is often associated with CO gas clouds which radiate electromagnetic energy in the far infrared and microwave bands. The map to the right shows the contours of CO gas concentrations in NGC 253, and thus the reservoirs of hydrogen gas available for star formation there. Blue is low density (<1000 atoms per cc) and pink is high density (>10,000 atoms / cc). The box superimposed on the galaxy shows where the image is located in the galaxy. The densest hydrogen is in the middle of the galaxy, which should translate to abundant star formation there. But it doesn't. The star formation rate (SFR) or NGC 253 is roughly 3 new stars per year (the Milky Way SFR is between 1 and 2). Given the densities of hydrogen gas in NGC 253, it should be forming 3 to 5 times as many stars as it does. So what is stopping it ('quenching' in astro-speak)?

Source: Bolatto et al 2013, *Suppression of star formation in the galaxy NGC 253*. Nature 499(7459):450-3. Original image: *ALMA (ESO/NAOJ/NRAO)/Erik Rosolowsky.*

Galaxies tend to be their own worst friends. They self-regulate to the point where no matter how near or far we look, they tend to fall into fairly narrowly defined ranges of mass—we don't see very many eenie tiny spirals, nor do we see huge sprawling things a dozen times the size of the Milky Way or Andromeda. Conversely, we do see a significant size (and therefore mass) range in elliptical galaxies. That's because elliptical galaxies started off as multiple spiral galaxies that collided with each other so often that they have settled into a giant bee swarm bereft of any hydrogen to make new stars. Ellipticals range from tiny, ancient dwarf galaxies with a few million stars to behemoths such as M87 in Virgo at multi-trillions of solar masses. The one thing all have in common is they have no gas left to form stars—they are literally 'red and dead'.

So those beautiful swirly lines in the first image are a portrait of life in a rather tough, riot-prone neighbourhood. In fact, the mottled visual image of NGC 253 suggests that the galaxy has a good many dense dark dust clouds mixed in with bright clumps of star-forming clouds. This is a hallmark of galaxies forming large numbers of large star clusters. Those bright clouds are tempestuous places to live. They are chockablock with shock waves from young stars and supernovae, searing UV light that tears molecules to shreds, and gas so energetically hot that it tends to burst outwards in the form of low-velocity explosions known as massive gas flows. The placid regions of cold hydrogen and cool molecular gas get pushed in front of the expanding shock waves, to the point where they are ejected from the galaxy altogether at speeds of dozens to hundreds of kilometres per second. The depletion of so much hydrogen gas has a disastrous effect on the ability of the galaxy to form new stars. That is why NGC 253 is forming only one-third to one-ninth the number of stars that its gas reservoirs say it can.

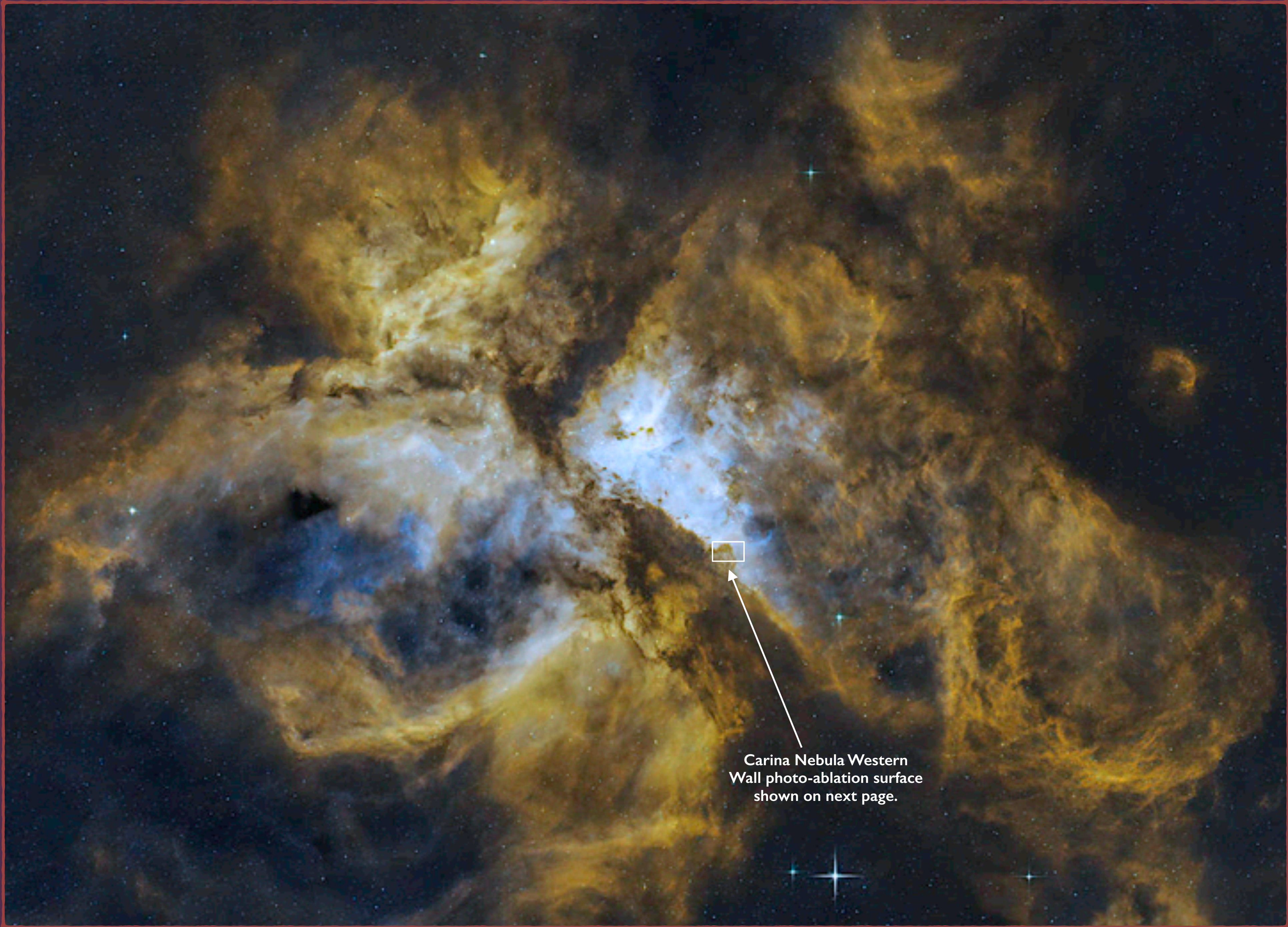
To the right we see the results of multiple starburst clusters hurling out gas at high velocities. The green circles are known starburst regions (largely hidden from our direct view by dense galactic dust). The pink contours above the galaxy show two outflow regions erupting from the starbursts near the galaxy's core; they are reddish to indicate that they are red-shifted away from the galaxy centre. The multiple blue contours show at least three massive gas outflows ejected in our direction, hence are blue-shifted. All that gas ejected at high velocities out of the galaxy depletes the available gas in the galaxy's central regions. The destructive effects are largely confined to the central regions because those are where the available gas pressures are high enough to form energetic supermassive young clusters.



Beyond the central region roughly within the white box above, star formation in the spiral arms approximates that which we find in run-of-the-mill spirals like our own Milky Way and Andromeda. Just how long NGC 253 can continue at this rate depends on the amount of ejected gas that eventually returns plus the inflow of pristine gas along the cosmic filament in which our Local Group and nearly all the galaxies in the 30 Mpc Local Sheet reside. Given what we know thus far, NGC 253 may end up as a gas depleted ageing-star spiral of the SO or lenticular type.

Further reading: *Levy et al 2020, Walter et al 2017, Leroy et al 2014.*

Clouds of creation



Clouds of Destruction

The relentlessly erosive effects of photo-ablation from high-energy UV radiation vividly reveal themselves in this five light-year (50 trillion km) section of the Western Wall in the Carina Nebula. The hillocky terrain of the Western Wall density occlusion comprises multiple pimple-like domes compressed by multiple turbulent shocks and searing stellar winds. The bright reddish surfaces on darker gas/dust pockets reveal high-energy photons sputtering atoms off dust particle surfaces and iHII and HI gas ionising into electrons and protons.

The smeary look to dusty gas that appears to be dripping off the right edge of the cloud suggests low-velocity wind shear. The crisp resolution in this image is due to the adaptive optics system on the Gemini South 8.1 metre telescope atop Cerro Pachón in Chile. The Gemini telescopes' adaptive optics design has resulted in a ten-fold improvement in the Gemini North and South detail resolution. (*Watch their video here*.)

There is a familiar face behind all this hair

Is this vibrantly hued mess the same Pleiades star cluster known to every school child as the 'Seven Sisters'?

Well, not exactly. The optical-band light from the several hundred stars that make up the famed asterism were intentionally suppressed in this image by Francesco Antonucci, the astronomer who recorded and processed this plate. (The stars we do see here are not part of the Pleiades cluster; they are field stars on the near and far sides.)

Suppressing only the Pleiades stars when processing this picture enabled Antonucci to concentrate on the intricate lacework of dusty filaments that lies behind the Pleiades. The Pleiades stars have relatively little dust of their own. The dust clouds that are moving behind the Pleiades are part of an enormous molecular cloud dozens of times as massive and many times larger than the Pleiades.

Dust-riddled molecular clouds delight astronomers no end. They are the birthplaces of stars. Without any dust in a molecular cloud there would be no stars in the sky at night, no sun (a star, after all), and of course, no us.

Molecular clouds contain vast amounts of the stuff—5% to 20% by mass, though only a few thousandths of a percent by volume. The tiny sooty carbon or flinty silicon/sulphur/iron dust particles contain all the atomic elements that appear here on Earth. Plain old H_2O water, for example, coats the surfaces of most sooty carbon dust particles so other atoms and molecules adhere to it.

But it is the silicon-rich particles that intrigued Francesco Antonucci. Many silicious particles are dipolar, they have magnetic poles. Hence they align with local magnetic fields, as we see so vividly here in all this stripey hair. The partly chaotic and partly coherent filaments here indicate the degree of shock turbulence in the dust behind the Pleiades. The colours are artificial, but use the same palette we associate with warm (red) and cool (blue). The yellow-green is in between. The magnetic field lines frozen into the gas/dust cloud behind the Pleiades cluster suggest that the far-off cloud is lumpily collecting itself together, in many *many* millions of years might infall into a new star cluster—just like the Pleiades did 106 million years ago.

The reason Frencesco Antonucci was so interested in the passing cloud's magnetic fields becomes more apparent in this wide view of the region between the Pleiades (blue cluster top) and the California Nebula (red vertical smear bottom centre). Magnetic fields tend to do two things in a complex gas/dust/stars region like this. First, they align silicious dust particles into linear filaments that trace the magnetic field lines. This is readily apparent in the linear streaks in the California Nebula and several other regions in this image.

The second function of magnetic fields is that they are part of the tripartite interaction between the divisive properties of turbulent shock waves, the aggregative property of gravitational fields, and magnetic fields as the tempering mechanism between the two. Star formation begins millions of years prior to the appearance of any stars. Brutally cold clouds of molecular hydrogen collapse out of originally diaphanous, pristine clouds of neutral hydrogen and dust very tenuously bound by their own gravity. A galaxy is occupied in part by veritable multitudes of atomic hydrogen clouds that rotate benignly around a galaxy's disc along with the stars. However, can be triggered into collapsing as they enter into the ponderous, elephantine, lumbering spiral arms of the galaxy, which are, after all, density waves.

As dust clouds collapse, the dust tends to gravitate toward the centre. Dust absorbs energetic starlight that would otherwise go into warming up the gas atoms, keeping them at energy levels that are brutally cold to us but warm by galaxy standards—50 to 100 degrees Kelvin (above absolute zero). With dust absorbing starlight, the atoms can cool, all the way down to a few degrees above absolute zero. Under these conditions, two atoms of hydrogen can couple, lose an electron, and become molecular hydrogen. Only molecular hydrogen can make stars because its binding energy can take extreme heat whereas atomic hydrogen ionises at 3000 to 6000 K.

The end result is a fairly rapid mass collapse into clumps which become dense enough to form star clusters. When a star cluster first forms, the inward pull of gravity is resisted by turbulent shock waves that are ubiquitous in spiral arms. Nearly all those lens-shaped structures in the picture are the compressed gas and dust on the front surface of a shock wave. Shock waves are hugely divisive—just as ocean waves come in many sizes and shapes. But now, all those electrons that were freed when molecular hydrogen was made can race throughout the region. They are harnessed by magnetic fields into powerful bands of electromagnetic strength that slowly weaken the shock waves until gravity can eventually take over to collapse molecular clouds into brilliant star clusters like the Pleiades.

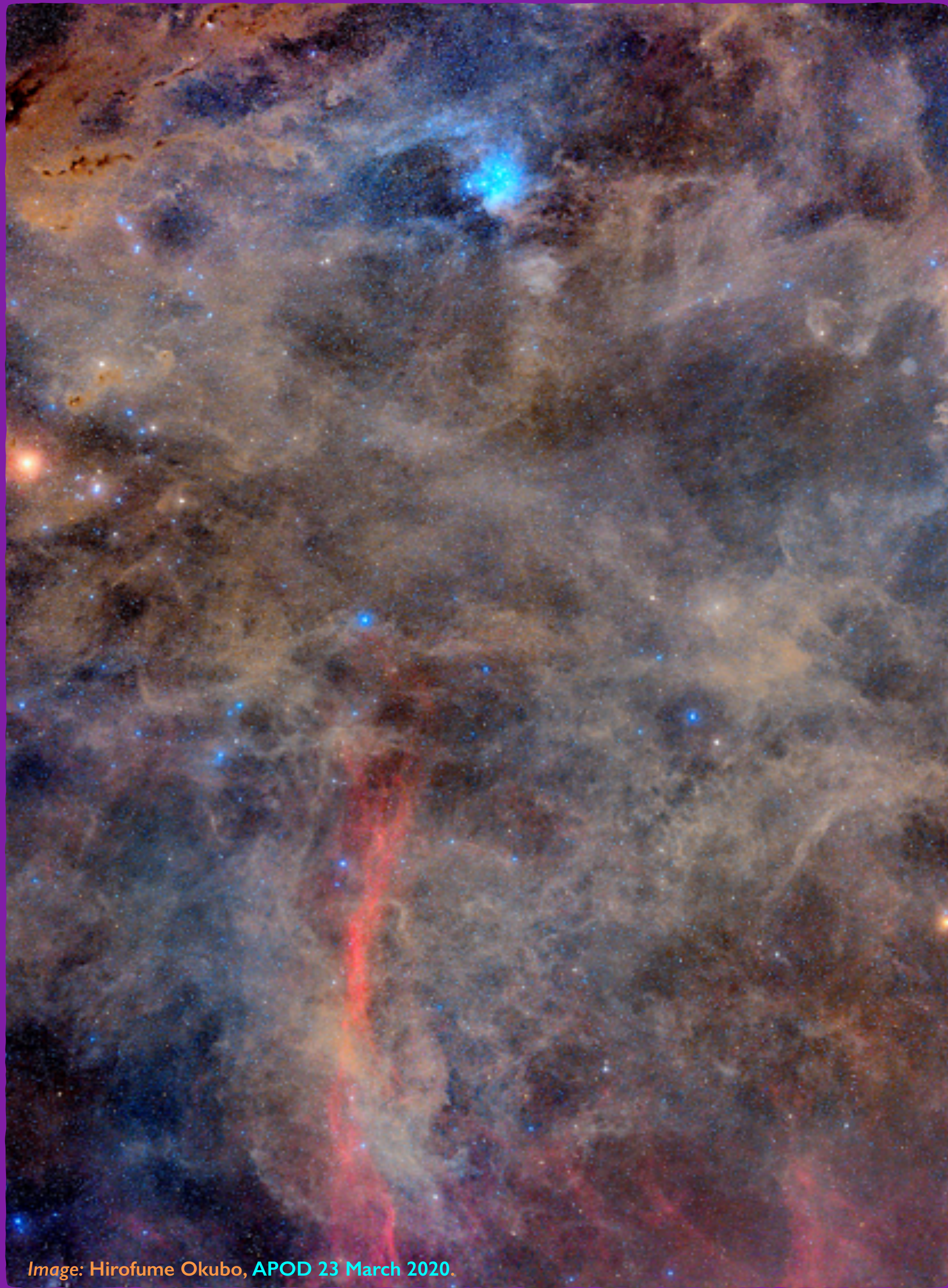


Image: Hirofume Okubo, APOD 23 March 2020.

The inside story of the Rosette Nebula

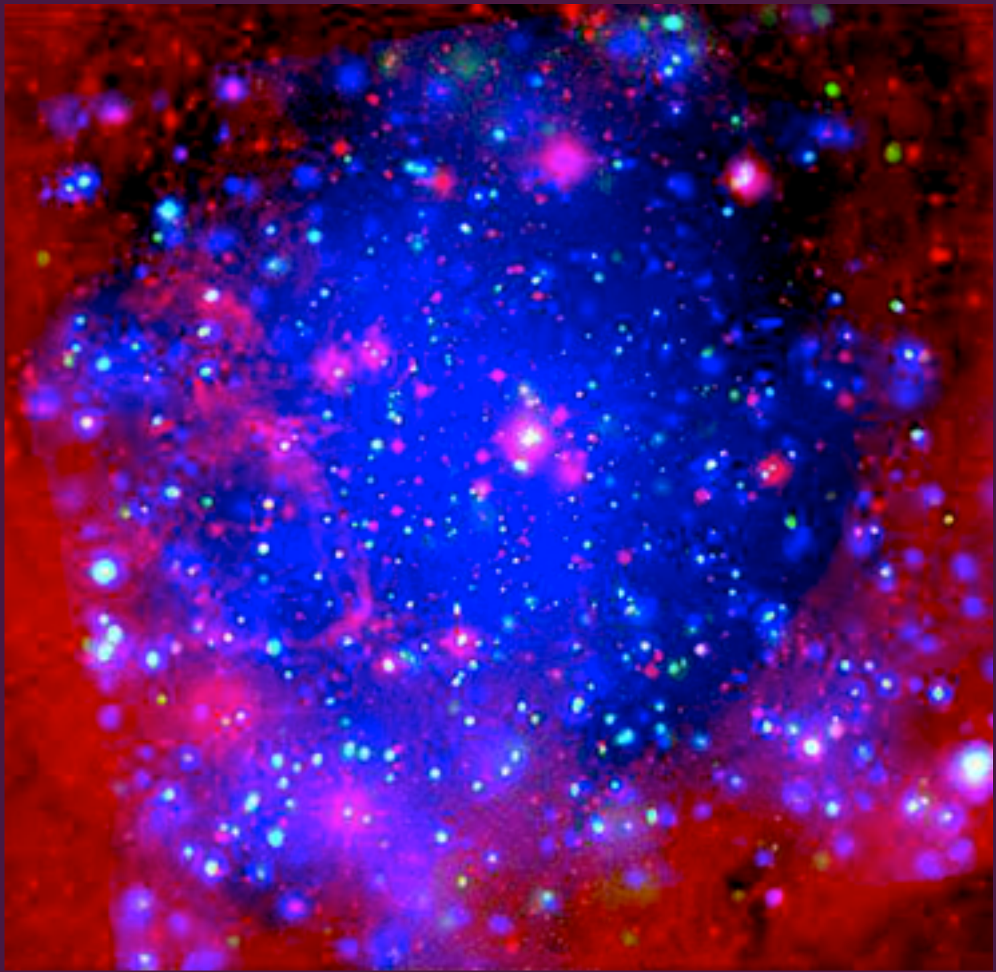
NGC 2244

How many times have we looked at the endless variations of the full-diameter Rosette Nebula in Monocerous and marvelled at the beauties of the gas shell and those twisty dark filaments, without paying all that much attention to the stars?

In this image by Don Goldman we see the rich variation in stars that create the energy that lights up the outskirts, clears the gas from the centre, and will eventually eject all this tracery into the 10,000 K warm chemistry lab of the Interstellar Medium. Many future generations of stars will be made from this gas. Star formation efficiency within giant molecular clouds is only about 1% to 5%. Each generation of stars will have more complex chemical mixes as the interstellar medium is enriched by the new elements forged in any given cluster. Expelling their birth gas in as necessary to a star cluster as shedding skin is to a snake.

The glittery stars in the centre of this image are a young cluster of around 2000 stars whose widely varying masses were ordained by the densities of gas, magnetic fields, and gravity that control the making of a star cluster across a typical cluster formation span of a million years.

Yet it is the stars we don't see that make NSG 2244 such an interesting study. What are they, where are they, and why are they invisible to our optical-band telescopes?



When we look at images of the the two million year old star cluster NGC 2244 in optical band light, we can spot perhaps 50 stars in the hollowed-out central hole of the cluster. The hole signifies that the cluster has initiated its gas-clearance cycle, which will hurl its unused gas back into the nearby spiral arm. What we do not see are more than 900 X-ray sources that are very young stars up to 100,000 times brighter in the X-ray band than in the visual. This Chandra satellite image reveals these stars for the first time. Of these, some 77% were also detected by the FLAMINGOS near-infrared (NIR) project that catalogues previously unknown young members of clusters like NGC 2244. If we are to fully understand the dynamics that make a star cluster and predict its future, we first have to know its SFR or Star Formation Rate—how many stars it actually has, what kind, and when they formed in relation to the rest. For every optically visible star there may be many other stars that emit only in X-ray and infrared bands. Very young stars go through a brief phase called the T Tauri stage in which they emit most of their light in X-rays. The X-rays are produced by magnetic reconnection of field lines broken by the chaotic turbulence of he star's interior and the high rate of gas infall onto its surface. A census of the X-ray population helps us calculate the cluster's age and its probable total mass. In this X-ray satellite image the overall blue colour comes from soft (0.5–2 keV) X-ray emission. The green intensity is scaled to the hard (2–7 keV) X-ray emission. The bright dots are T-Tauri stars that were previously unknown. *Source: Wang et al 2007*.

These beautiful filaments and clumps look cold and dark, but infrared observations reveal them to be the wombs of unborn stars. The filaments are leftovers after the star cluster's rapid initial collapse into the stars we see as NGC 2244. For over a million years they remained cold dark blobs in the outskirts, lightly bound by their own gravity but too low-mass to initiate collapse into stars on their own. The ignition of the hot young protostars in the left-side image has now supplied enough radiation energy to compress these clouds' surfaces, overcoming their feeble internal pressure to initiate collapse into stars. That this stage is now underway in these blobs has been confirmed by infrared photometry. Infrared observations, like the X-ray images opposite, require that the detectors must be beyond the earth's atmosphere, which absorbs radiation in the key window between 20µm to 850µm. Hence the high budgets allocated to designing and lofting the satellites like XMM Newton and Spitzer which were specifically designed to record X-ray and infrared radiation respectively. Not all of these blobs will achieve the critical density that initiates gravitational collapse. Most will become brown dwarfs only 13 to 80 times as massive as Jupiter, warm enough to fuse deuterium (^{2}H) or, in the more massive (> 65 M_J) lithium (^{7}Li) which is detected by the presence of a 670.8 nm emission line in a spectrogram. The study of brown dwarfs is a complex one, but well worth the read. *Image source:* ESO *potw1847a,* Nov 2018 acquired with the FORS 2 camera on the VLT in Chile's Atacama Desert.

This rather painterly abstraction depicts a very young star in its first squall of life after being born. Its three principle components were captured in this spectacular image by the Hubble Space Telescope. The blue wisps in the lower left of the image have been daubed onto the sky by the long paintbrush of an infant star cocooned within the dusty dull red of a clump of molecular hydrogen gas to the upper right. The star has collapsed only quite recently into a dense ball massive enough to ignite fusion in its core. The surrounding cloud glows from within in several other places, revealing other protostars hiding deeply within their billowing birth cauls of dust.

The intense spike punching its way out of the cloud is an extremely hot collimated jet hurled from the young star by fierce magnetic fields powered by the star's rapid rotation. As this jet spits outward at Mach 3 or 4 through space, it collides with cold, dense gas hidden within the dark blob of a second cloud that is difficult to trace here. The cloud's cold gas quenched the jet so rapidly that it no longer emits in the visual light of this image. As if to spite its surroundings, the jet still hurls a massive amount of gas at supersonic speeds into the cloud in front of it. So rapid is the compression shock that the gas in front of the jet cannot move out of the way fast enough. It compresses into a dense lens-shaped shock front that heats into an incandescent complex of shock waves called a Herbig-Haro or HH object (after the two French astronomers who first explained them).

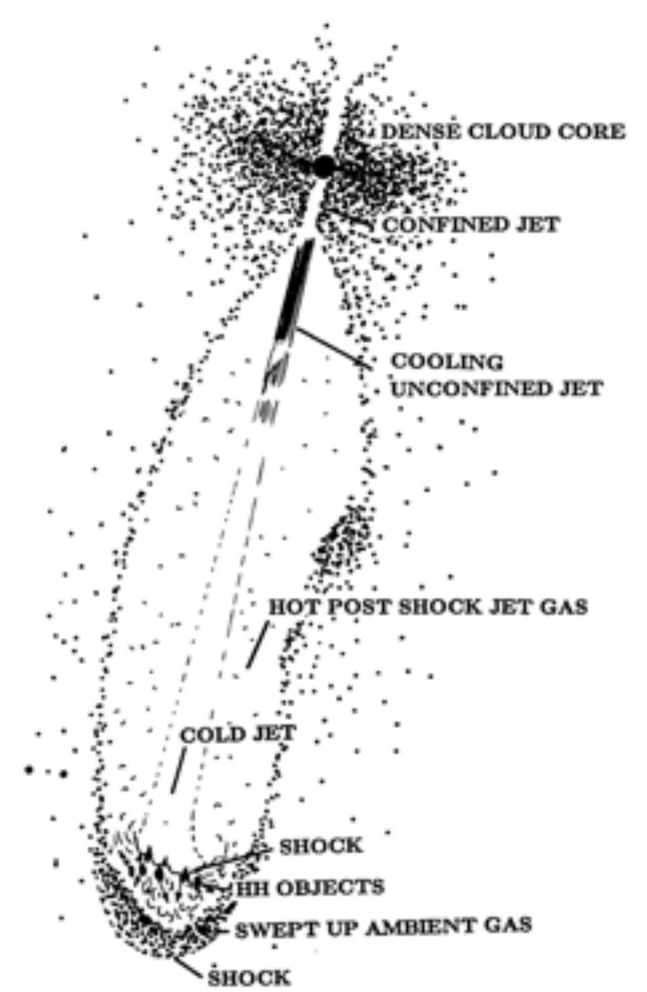
Although the jet extends the entire length between the infant star and HH34, only a fraction of it is visible in this image. The HH phase of a star's formation is relatively brief, only a few thousand years. Source: *NASA/ESA Hubble*.

HH 34

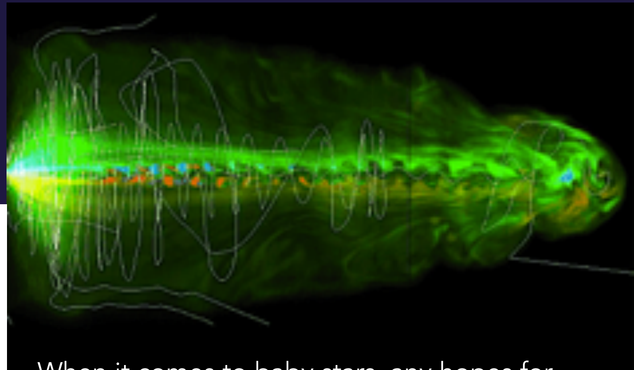
MYSTERY INSIDE AN ENIGMA UNVEILS A PARADOX

This image is an enlargement of a three-colour composite of the young object Herbig-Haro 34 (HH-34), now in the protostar stage of evolution. It is based on CCD frames obtained with the FORS2 instrument in imaging mode, on November 2 and 6, 1999. This object has a remarkable, very complicated appearance that includes two opposite jets that ram into the surrounding interstellar matter. This structure is produced by a machine-gun-like blast of "bullets" of dense gas ejected from the star at high velocities (approaching 250 km/sec). This seems to indicate that the star experiences episodic "outbursts" when large chunks of material fall onto it from a surrounding disc. HH-34 is located at a distance of approx. 1,500 light-years, near the famous Orion Nebula, one of the most productive star birth regions. Note also the enigmatic "waterfall" to the upper left, a feature that is still unexplained.

THE FIERY ART OF LOSING A LITTLE TO GAIN A LOT

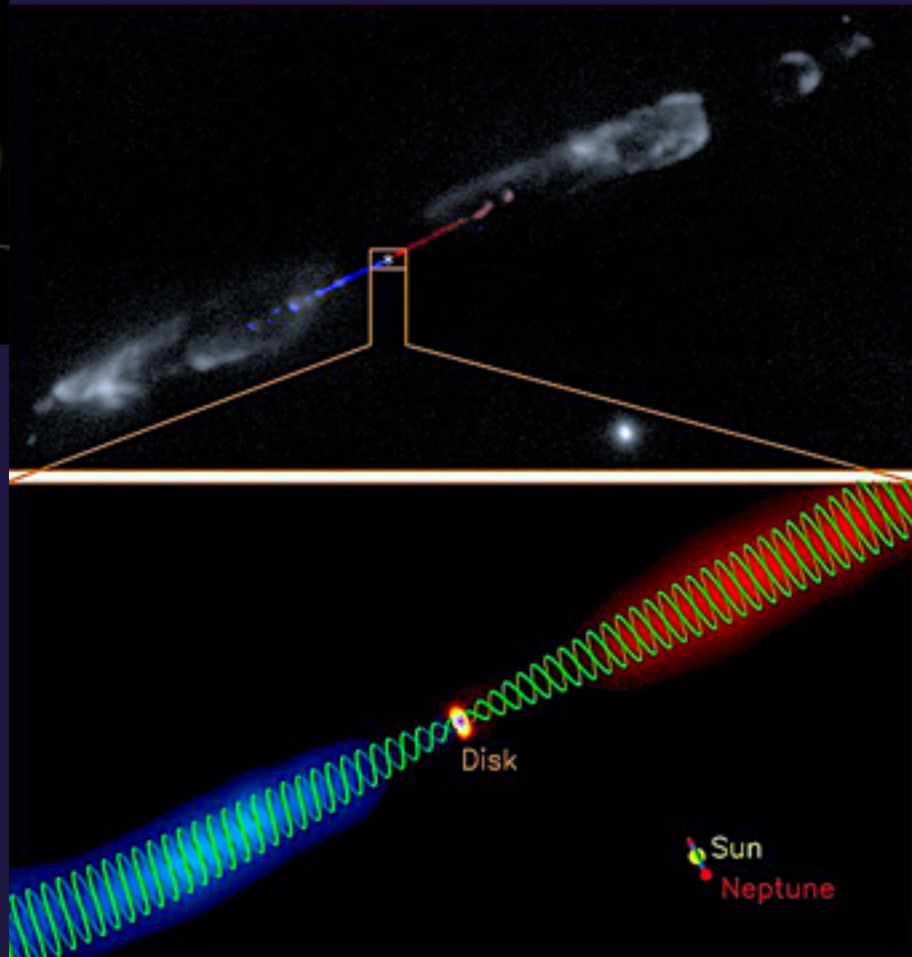


The supersonic outflow ejected from the magnetic north and south poles of an infant star produce a large oval-like cavity filled with hot ionised gas that shines brightly in visual and X-ray bands. Rapid cooling of a hot jet into a cold jet explains the inexplicably short spike jetting outward from the star. As the jet races outward it also cools, slows down (to 3.5 km/sec in this case), and no longer emits visual light. Cold or not, the jet's gases are still moving at a velocity high enough to compress a large, dense lens of matter which soon fragments into multiple shock fronts and dense clumps. Source: Reipurth et al, 1986, *Jet and energy source of HH34, Fig. 16*, A&A 164, 51-66.



When it comes to baby stars, any hopes for simple explanations are tossed out the window. Even the magnetic field that energise the protostellar jet model to the left is fiendishly complex—weeks of computer time go into a drawing like the one above. The thin lines represent magnetic field lines. Above, we see not one but four different sets of them, all emanating from one of the magnetic poles of the spinning star out of the field to the left. In the centre, a helicoid tube of field lines collimates the jet into a thin pencil as it speeds outward. Further outward, two other sets of field lines serve to confine the outward thrust into a gently flaring oval, and to mute the violence of turbulent shocks that result from such a forceful intrusion into the region's former tranquillity. The net result is clearly visible in the clumpy yet well constrained image to the right. It may look an unholy mess, but it is a very predictable one.

Ironically, protostellar jets serve to fatten up the underlying star. As angular momentum is removed via spin out the poles, it reduces gas pressure in the equatorial region of the star. The reduced gas pressure at the equator allows gas from the surrounding cloud to accrete onto the star's surface so rapidly that a tiny infant core grows into a massive hulking teen-ager within a few hundred thousand years. In star time, that is considered 'instantaneous'.



In 2018 an international research team led by Chin-Fei Lee in the Academia Sinica Institute of Astronomy and Astrophysics (ASIAA) made a breakthrough observation using the Atacama Large Millimeter/submillimeter Array (ALMA). Their study confirmed the presence of magnetic fields in a jet from a protostar. Such jets seem to play an important role in star formation. They help a protostar accrete mass from a disk of gas and dust by removing angular momentum from the disk and ejecting it out of the star's magnetic poles. The jets are highly supersonic (Mach 3 or 4) and collimated. Although jets have been long predicted to be powered and collimated by magnetic fields, no one was really sure about it. Now, thanks to the high-sensitivity of ALMA, Chin-Fei Lee and his colleagues finally confirmed the presence of magnetic fields in a protostellar jet by detecting molecular line polarization. The magnetic field in the jet is likely a helicoid stream. If so, the physics of the protostellar ejection process may be more than merely visual analogs to the vastly larger and more powerful jets that erupt from active galactic nuclei (AGN) that are typically energised by a supermassive black hole in the centre of a galaxy. If calculations and computer modelling demonstrate the two phenomenon are indeed related, it would be yet another example of how relatively simple physical laws determine the properties of a large range of sky objects that we study. *Watch the video here*. Source: Lee et al. *Unveiling a magnetized jet from a low-mass protostar*, *Nature Communications* (2018).

Fornax A radio lobes

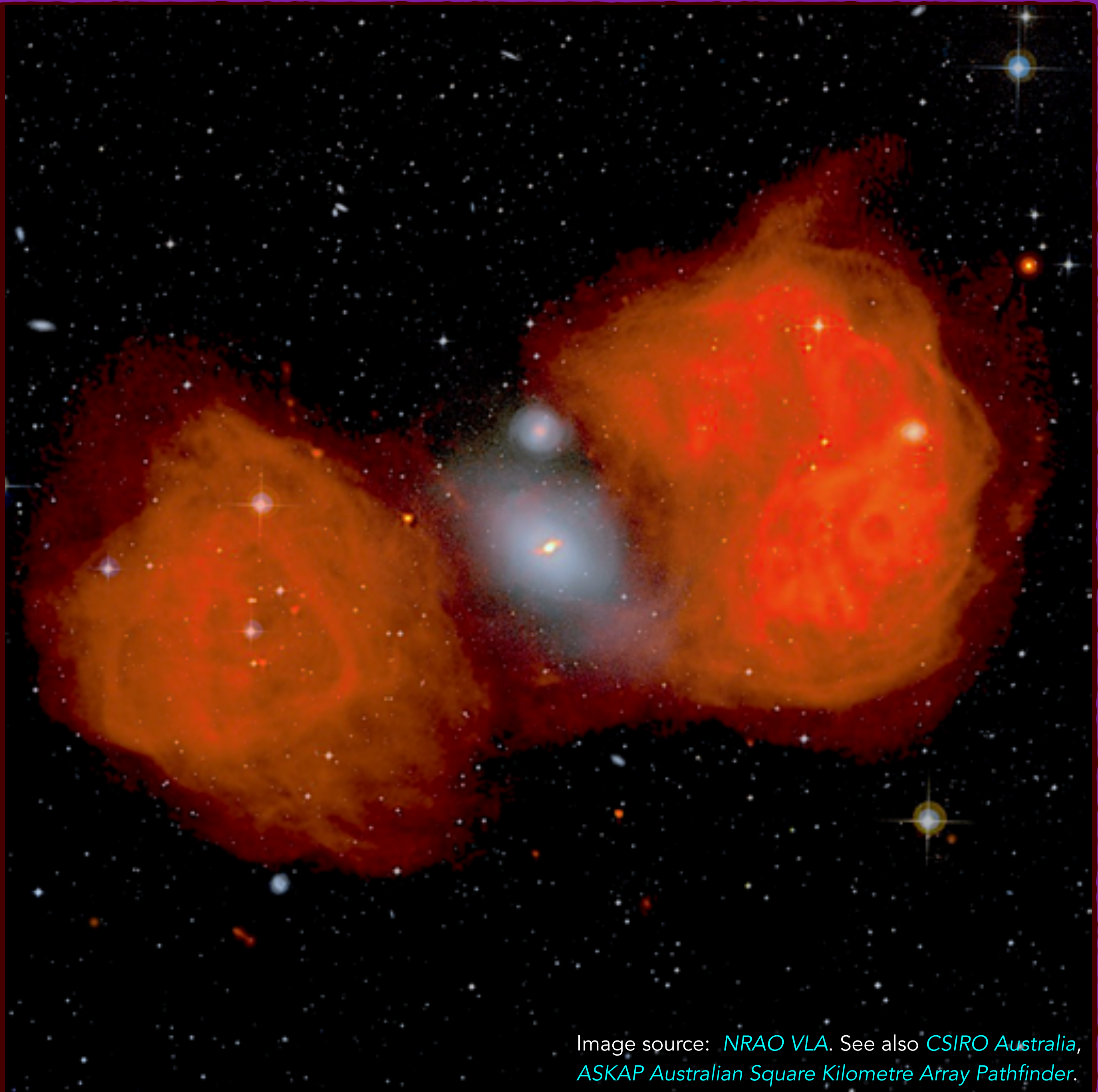


Image source: NRAO VLA. See also CSIRO Australia, ASKAP Australian Square Kilometre Array Pathfinder.

Gigantic radio lobes emanating from NGC 1316 in the Fornax galaxy cluster

Fornax A is a galaxy with an accreting-disc black hole in its core that is spraying near-relativistic jets out of its poles. The poles can be seen as tiny ansae extending a few mm beyond the core of the galaxy (bright dot) at an angle of ~70°–250° and bisecting the red radio lobes. The jets heat the thin gas in the surrounding intergalactic medium to kinetic temperatures above 100 million degrees K. The enormous volumes of space in between galaxies in a cluster is one of the hottest yet most rarefied environments in the Universe. On average there is only one atom per cubic meter in this medium (<10^{-27} kg/m^3), but they have so much stored kinetic energy that their kinetic temperature is equivalent to 10 million degrees K.

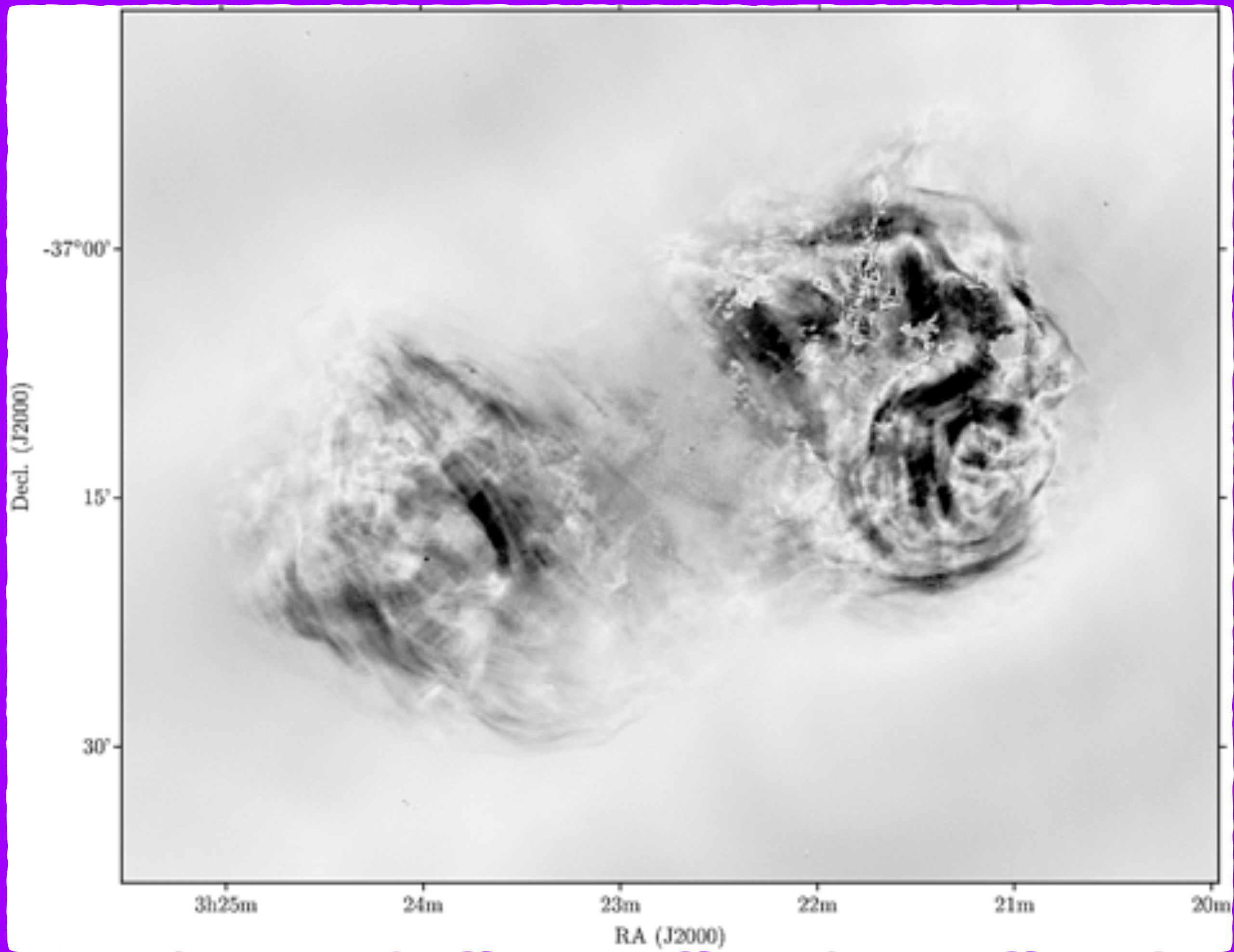
Temperature in space is not what your skin feels, it is the accumulated kinetic energy in a particle after billions of years of being bombarded by cosmic ray collisions, thermal and supersonic shock waves from supernovae, extremely hot O stars, and entire galaxies ejecting relativistic particles from their poles. NGC 1316 is one such galaxy. Its central black hole is accreting massive amounts of gas that swirls at such high velocities that its accretion disc temperatures are in the multi-millions of degrees. (Note that not all black holes are active; if there is no nearby gas to accrete, they are quiescent and undetectable.).

Here, the white glow in the center is the visible galaxy NGC 1316 that any amateur astronomer with an 8-inch telescope can see as a faint white fuzzy. But where is NGC 1316 getting all that gas?

Notice the small spiral galaxy above it? It is NGC 1317 and these two galaxies are merging. Gas and dust are being pulled out of the small galaxy into the center of NGC 1316. The black hole nestled in NGC 1316 spins the accreted gas into a razor-thin disc rotating around its equator at hypersonic velocities. The huge radio lobes to either side of this merger are the telltale signs that a black hole is being fed more than it can digest. The magnetic field lines generated by all those electrons rotating around the accretion disc spiral up the sides of the spherical black hole, and twist into a helically rotating jet that speeds straight as an arrow out of the polar axis into intergalactic space. Large numbers of electrons and protons are swept along with the magnetic field lines. When these particles expand and cool, they interact with the hydrogen and other atoms that populate intergalactic space. These atoms may be few in number, but over the vast distances involved here (roughly 1.5 million light years) that is a lot of magnetic field/ particle energy transfer from the jet to the intergalactic medium (IGM).

The end result is a huge reservoir of hot gas that emits radio waves, observed as the orange (false-color) blobs in the above image. The radio image is superposed on an optical survey image of the same part of the sky.

Strange patterns in the radio lobes (see right) suggest that slight changes in the directions of the jets acquire patterns of their own due to the differences in gas density and magnetic field strength of the huge volume of space surrounding a galaxy.

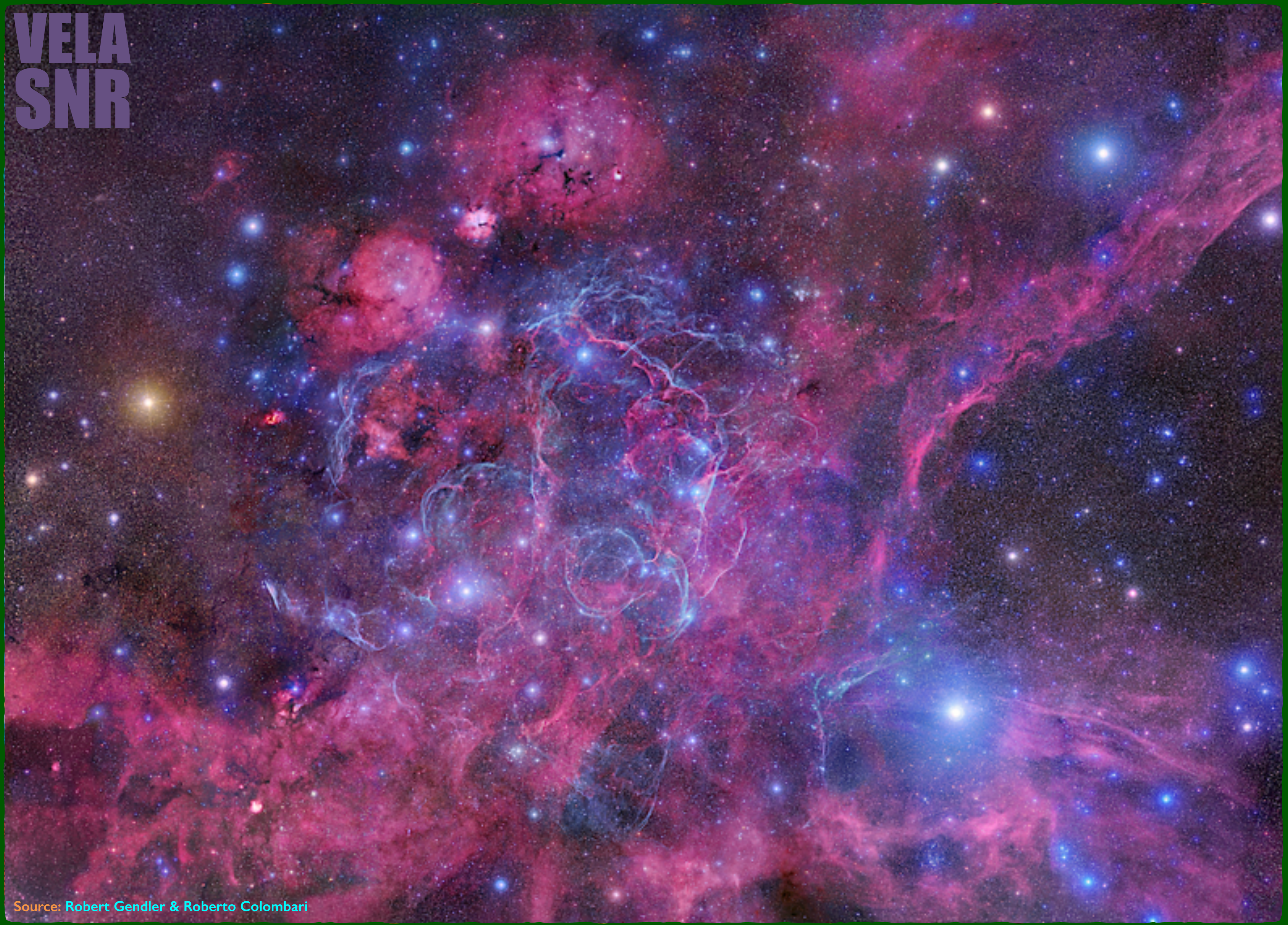


The fine structure of the energy transfer from jet to IGM is shown in the image above. These are the billowing ends of powerful jets shooting spun-up, escaped material far into space. The core of NGC 1316 is the tiny dot in between the two giant radio lobes. In this image, darker areas represent regions of strong linearly-polarised emission. The eastern (left-hand) lobe shows multiple layers of parallel filaments of polarised radio emission as dark streaks whose cause is thus far unexplained. Similar laminar patters are observed in other galactic radio lobes as well, and these too are inexplicable given current data.

The right-hand lobe presents fewer conundrums. The round multilayered region near the bottom of the lobe is actually a magnetic shadow cast by a spiral galaxy in front of the lobe that is so dim in visual light that we detect it only by its shadows as revealed by the NGC 1316 radio lobe.

Taken together, all these phenomenon boil down to the fact that the seemingly frail, thin medium we call intergalactic space is an extraordinarily elusive complex of mass and energy with many secrets still to be observed and explained.

For a more complete analysis of the structures in the above image, see '*Searching for magnetic fields in radio galaxy Fornax A (NGC 1316)*' from the CSIRO Australia Telescope National Facility.


VELA
SNR
Source: Robert Gendler & Roberto Colombari

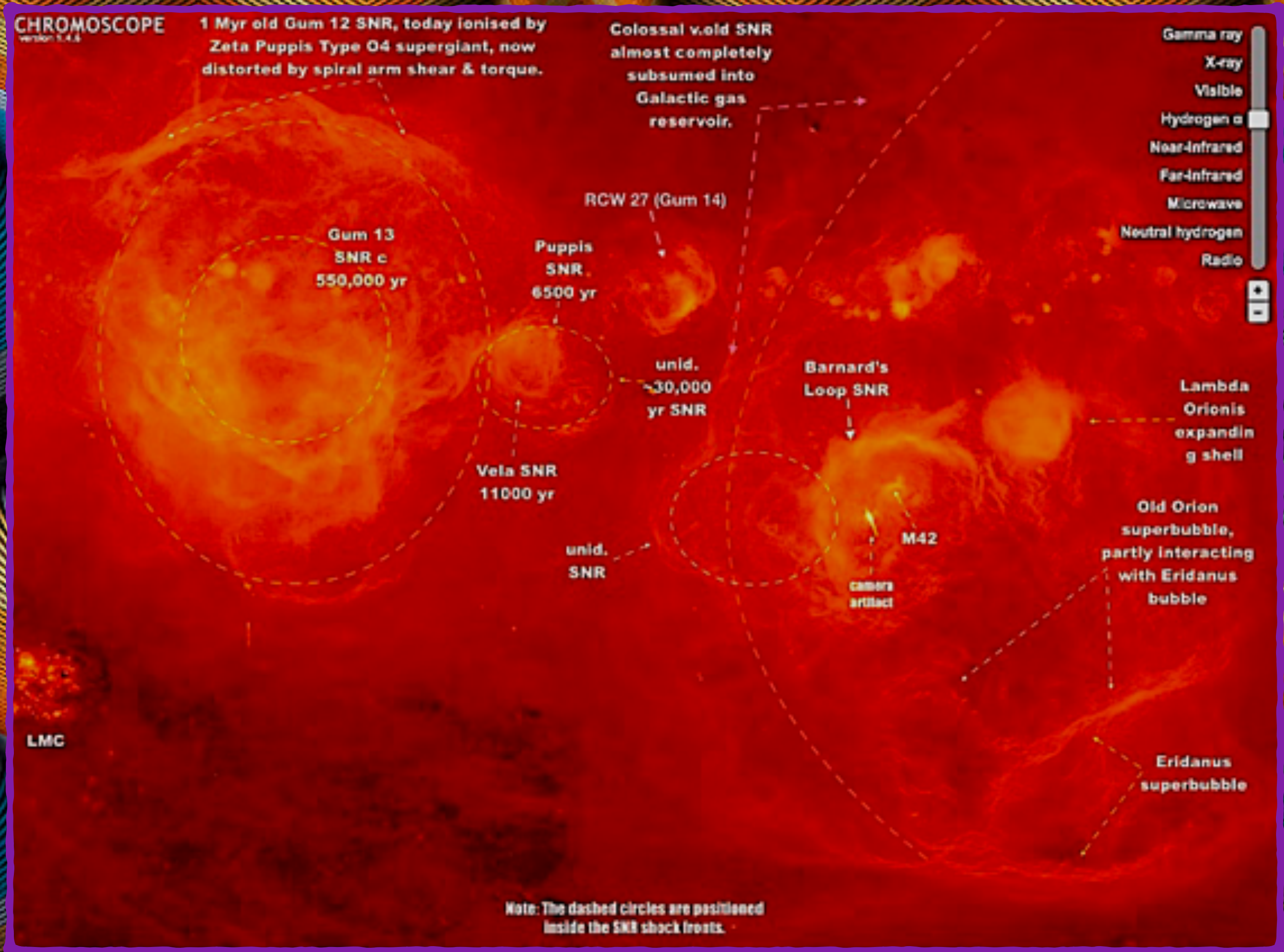
At 11,000 years old, the Vela supernova remnant is only the latest in a long history of supernova remnants (SNR) that have occurred in this small corner of the sky in the last 3 million years

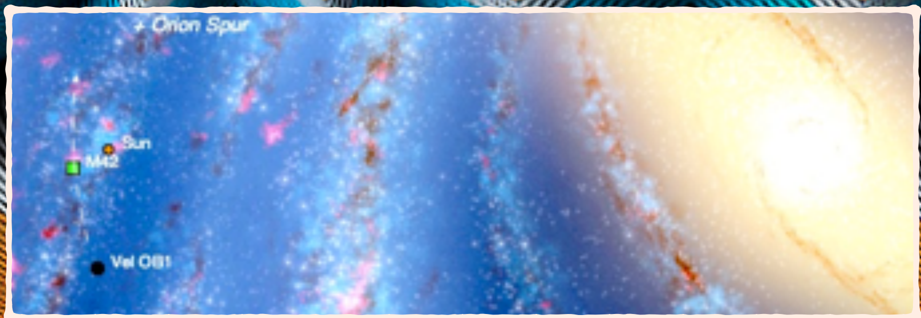
The constellation Vela sails above Carina, whose hull floats on the Milky Way. When we look toward those sails we see sparkling mattes of stars. Invisible to us are incandescent red gas and dust-laden densities that will one day be more stars to see. This image covers a huge area—from the LMC to well beyond the Orion Nebular Complex and Barnard's Loop mid-right. The complex intertwined layers of red hydrogen alpha emission record the fiery deaths of massive stars. The community elder is Vela's Gum 12 that ejected its great arcs of shells over a million years ago.

The Vela SNR is part of the Vela OB1 Association of stars much younger than the Vela SNR. It probably formed hundreds to thousands of stars 14,000 to 16,000 years ago as the final stage of a cluster-making process than began over four million years ago. In contrast, the M42 Orion Nebula star-formation history started only about 300,000 years ago and is a long way from witnessing its first supernova.

Molecular clouds, like stars and gas nebulae, rotate around the Galaxy in a circle (arrow in the drawing to the left). As the clouds enter into the dense spiral arms at an angle, they are subject to wrenching shear and torque forces that initiate star formation in very large numbers.

The portrait to the right shows a million years in the life of a spiral arm. To see what it looks like speeded-up, *watch this video*.

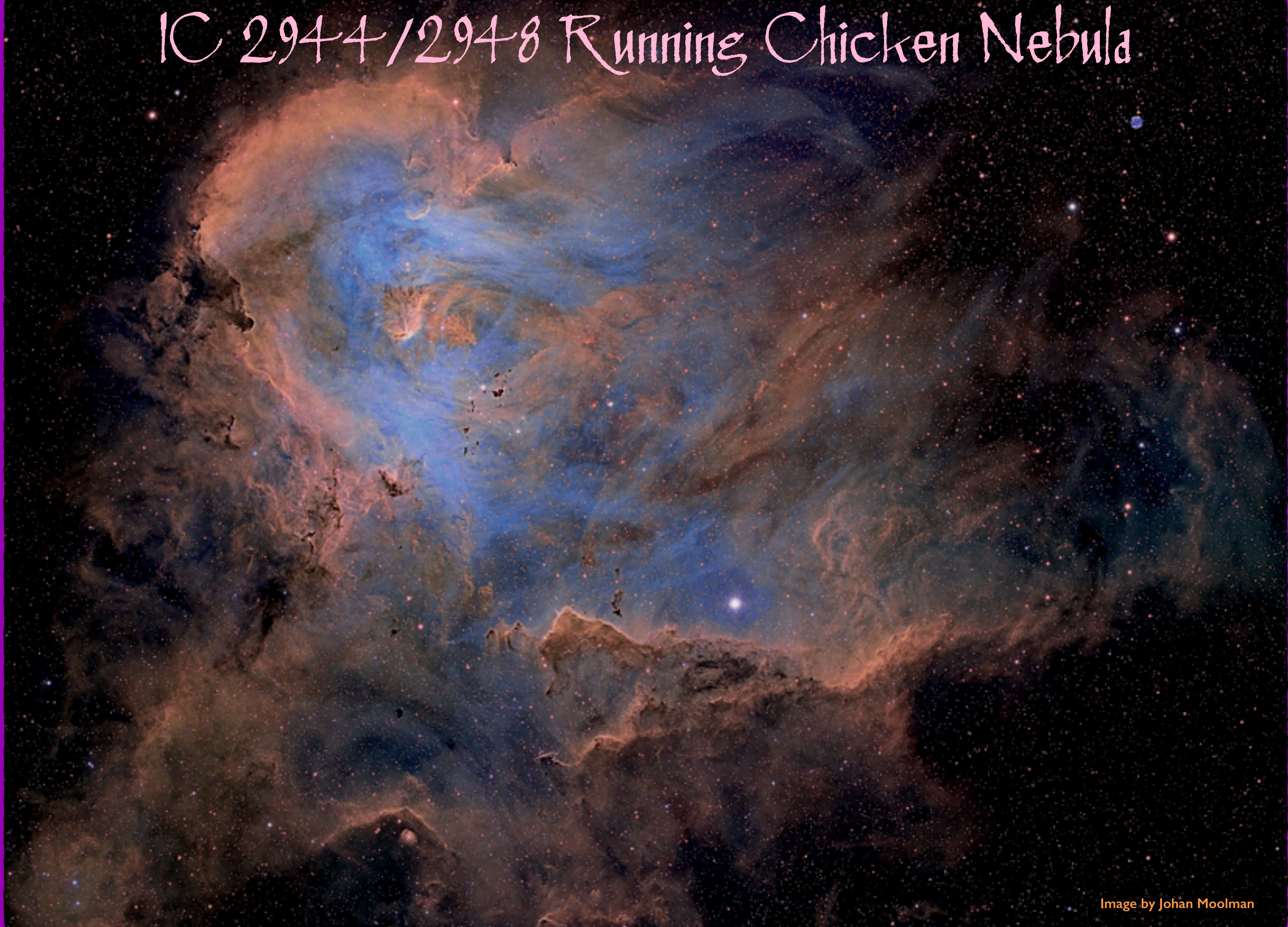




Above: Note how two colliding superbubbles such as the Orion and Eridanus bubbles tend to flatten at their contact interface. This occurs because the gas/dust that the expanding supernova shells have compressed in front on them as they expand now respond to their accumulated gravitational binding energy and the dynamics of interacting shock waves. *Source:* Chromoscope, University of Durham, U.K.

Left: Despite the seeming chaos of this image, it is simply astrophysics following the laws of electromagnetism, thermodynamics, Mach speed, and gas dynamics. Boringly predictable, but also spectacularly beautiful.

IC 2944/2948 Running Chicken Nebula

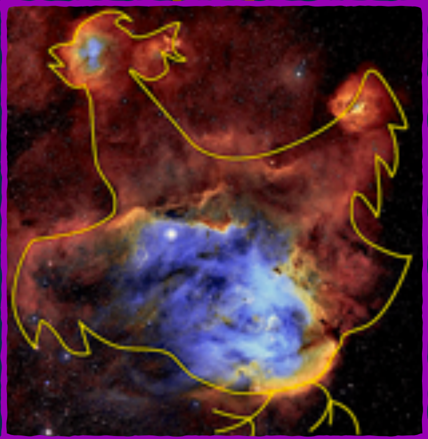


The imaginatively named Running Chicken Nebula in Centaurus is a difficult object to image successfully. It lies in a region dominated by the bright 3rd magnitude star Lambda Centauri, whose glare easily wipes out subtle, dim nebulosity nearby. Most imaging attempts that do not evade Lambda Cen end up showing indistinct, tepid patches of red as a result. Moreover, three nearby bright open clusters, NGC 3766, NGC 3355, and IC 2714 surround the region shown on the above page. Taken together, these usually translate into images of the Running Chicken Nebula more resembling the straw on the floor of the chicken hock (coop) than the chicken crossing the road.

ASSA astro-imager Johan Moolman faced two problems as he tried to capture the above highly detailed and subtly nuanced image of one of the southern hemisphere's most elusive patches of nebulosity. First he had to solve the bright-competition problem by adroitly framing the imaging field in the recording chip of his ZWO 1600 camera at the focal plane of his Skywatcher Esprit 100ED APO Triplet in such a way that the nebulosity would just fill the imaging chip while excluding the bright stars nearby. The fact that there is no uniform bath of white glow dimming the delicacy of the nebula's traceries and colours testifies to the success of Johan's careful pointing and tracking.

Avoiding the glare was the lesser of Johan's obstacles. The larger problem was the bright suburban skies he lives under. These are light-polluted to a level of glare known as Bortle 6 in astronomy jargon. That means the Milky Way is just barely visible when it is overhead and only the brightest stars can be seen below 35° above the horizon. Worse, the bath of light from urban LED street and parking lot lights turns the sky an insipid hue resembling curdled cream. An image as finely detailed and subtle as Johan's would be impossible without adroitly selective filtration and carefully calculated exposure times.

Luckily for legions of aspiring astrophotographers like Johan, the hobby has become so profitable that astronomical equipment makers have invested huge sums to satisfy the demands of imagers. The telescope that produced the image above has a diameter of only 100 mm (four inches), yet the image Johan produced with it would have been the envy of a large professional observatory just 25 years ago.



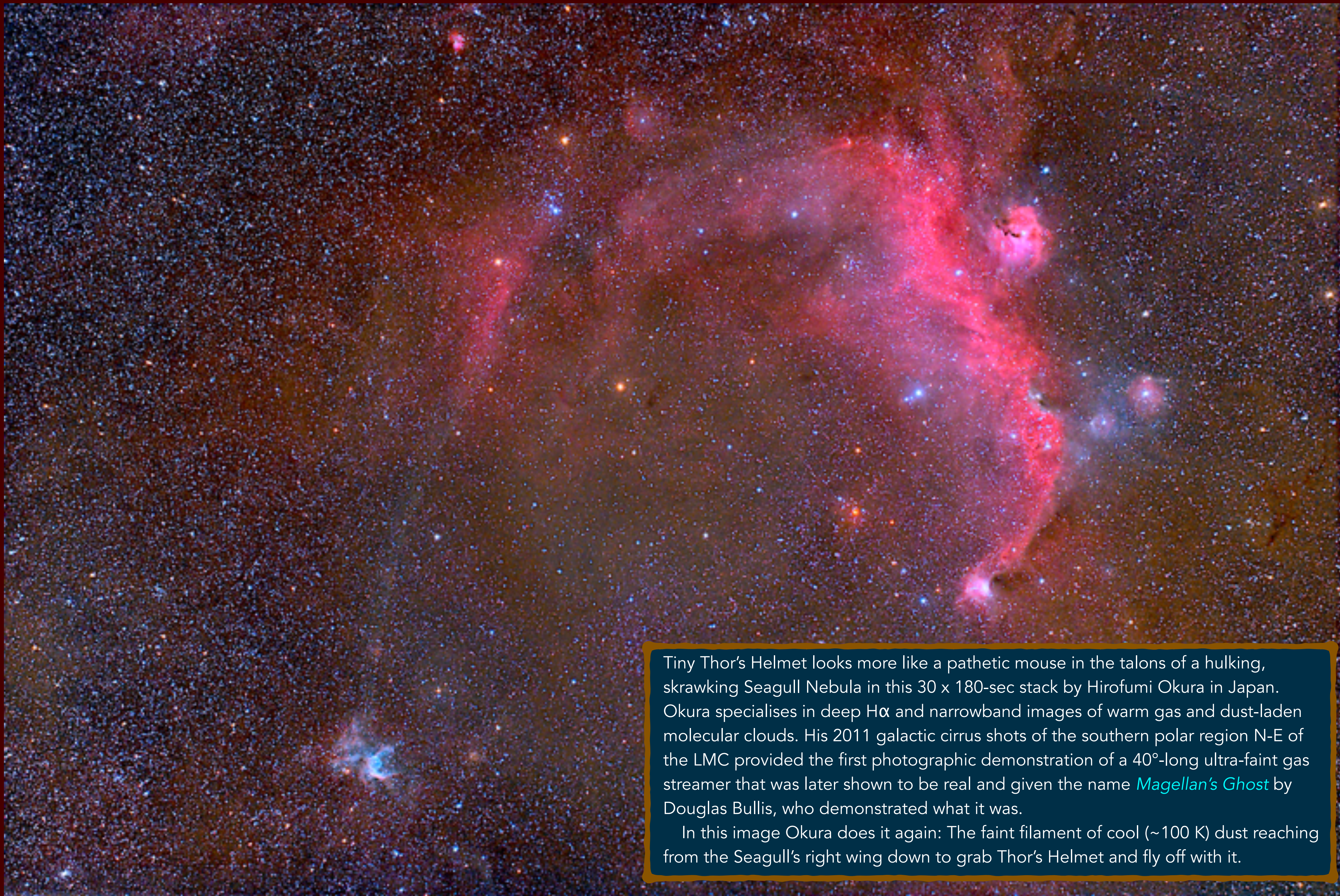
Now you know how I got my name!

Equipment investments have not gone into not just better and more finely resolving cameras, but also a wider choice of narrowband filters that imagers can choose to record light that reflects complex underlying physics we would not detect in broadband images. Nuclear, magnetic, and supersonic shocks produce spectral lines that reveal telltale signs of exactly what reactions are taking place inside and on the surfaces of stars, and in the thin gas and dust in between those stars and us. For this image Johan chose a Hα filter of 5 nm (nanometre = billionth of a metre) bandwidth, a doubly-ionised oxygen (or OIII) filter 3 nm wide; and a singly ionised sulphur (SII) filter of 3 nm bandwidth.

The reason for these choices is that Hα records the internal energy of a hydrogen atom as it cools from an earlier warm state; the intense red in the image is the telltale sign of large quantities of hydrogen in the nebula. OIII records the energy added to an oxygen atom when an electron collides with it in an environment warmer than about 10,000 K; the blue glow in this image comes from light emission at 500.7 and 495.9 nm. In the Running Chicken Nebula here, that emission is most likely coming from the hot star Lambda Centauri, which Johan carefully excluded from this image because its brightness would have overpowered everything else. The SII signal comes from warm sulphur, which indicates the presence of sulphur-based dust mixed in with the gas. Sulphur and silicon-based dusts are aliphatic (chain- instead of ring-like) which can act as tracers of local magnetic fields generated by dust grains that are dipolar, with positively charged atoms at one end and negatively charged atoms or molecules at the other. SII is not as good as silicious dust at revealing magnetic activity, but is a very good tracer of kinetic temperature.

The red-edged clumpy features in the image are shock surfaces where high-energy electrons and protons penetrate into a dense gas/dust layer and raise its temperature till it glows above 3000 K. The delicate striations in the blue patches can reveal either magnetic field lines and/or the streamlines of high-velocity winds. The dense, dark blobs and specks are dense pockets of gas molecules and dust called Thackeray or Bok globules depending on their smoothness and sphericity, some of which will collapse into infant stars.

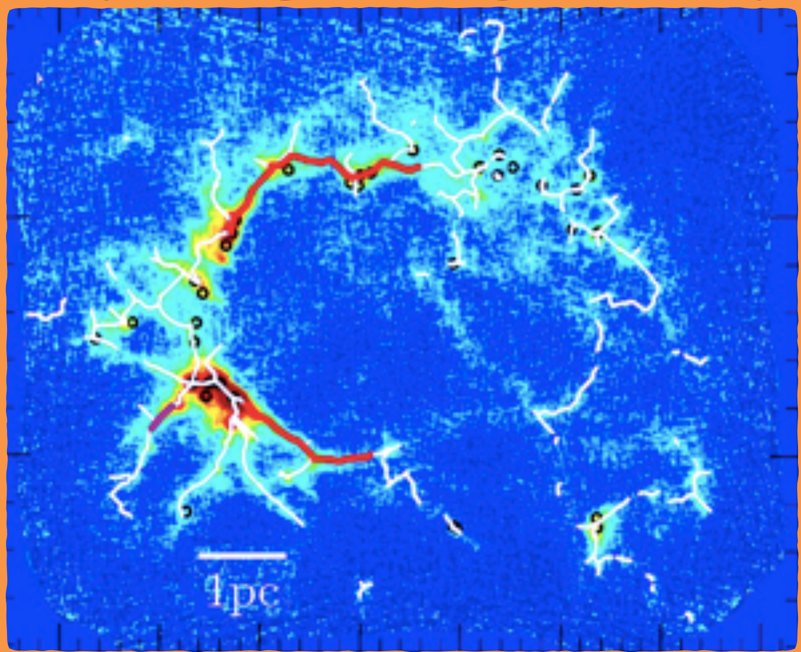
Scandal in the skies! Thor's Helmet snatched by a seagull



Tiny Thor's Helmet looks more like a pathetic mouse in the talons of a hulking, skrawking Seagull Nebula in this 30 x 180-sec stack by Hirofumi Okura in Japan. Okura specialises in deep Hα and narrowband images of warm gas and dust-laden molecular clouds. His 2011 galactic cirrus shots of the southern polar region N-E of the LMC provided the first photographic demonstration of a 40°-long ultra-faint gas streamer that was later shown to be real and given the name *Magellan's Ghost* by Douglas Bullis, who demonstrated what it was.

In this image Okura does it again: The faint filament of cool (~100 K) dust reaching from the Seagull's right wing down to grab Thor's Helmet and fly off with it.

Luckily for us, the real news in astronomy isn't quite so breathlessly extravagant as the above headline. However, there is real news here—the shock front exploding from the Wolf-Rayet star at the centre of Thor's Helmet appears to be inducing low-mass star formation—a rather unexpected phenomenon given that the ejected gas is only 20 to 30 solar masses itself, spread out over a large sphere. Here ASSA astro-imager Johan Moolman captures the very bright leading edges of shock fronts of gas being ejected by a super-hot ~35,000 K Wolf-Rayet star in the centre. The bright shock fronts mark the transition zone when gas compressed by a highly supersonic shock wave abruptly slows to subsonic speeds after the shock passes. In the image below we see red lines that mark the transsonic zone have a number of white dots that mark the positions of shock-compressed gas clouds dense enough to emit IR radiation—possible precursors to baby stars.



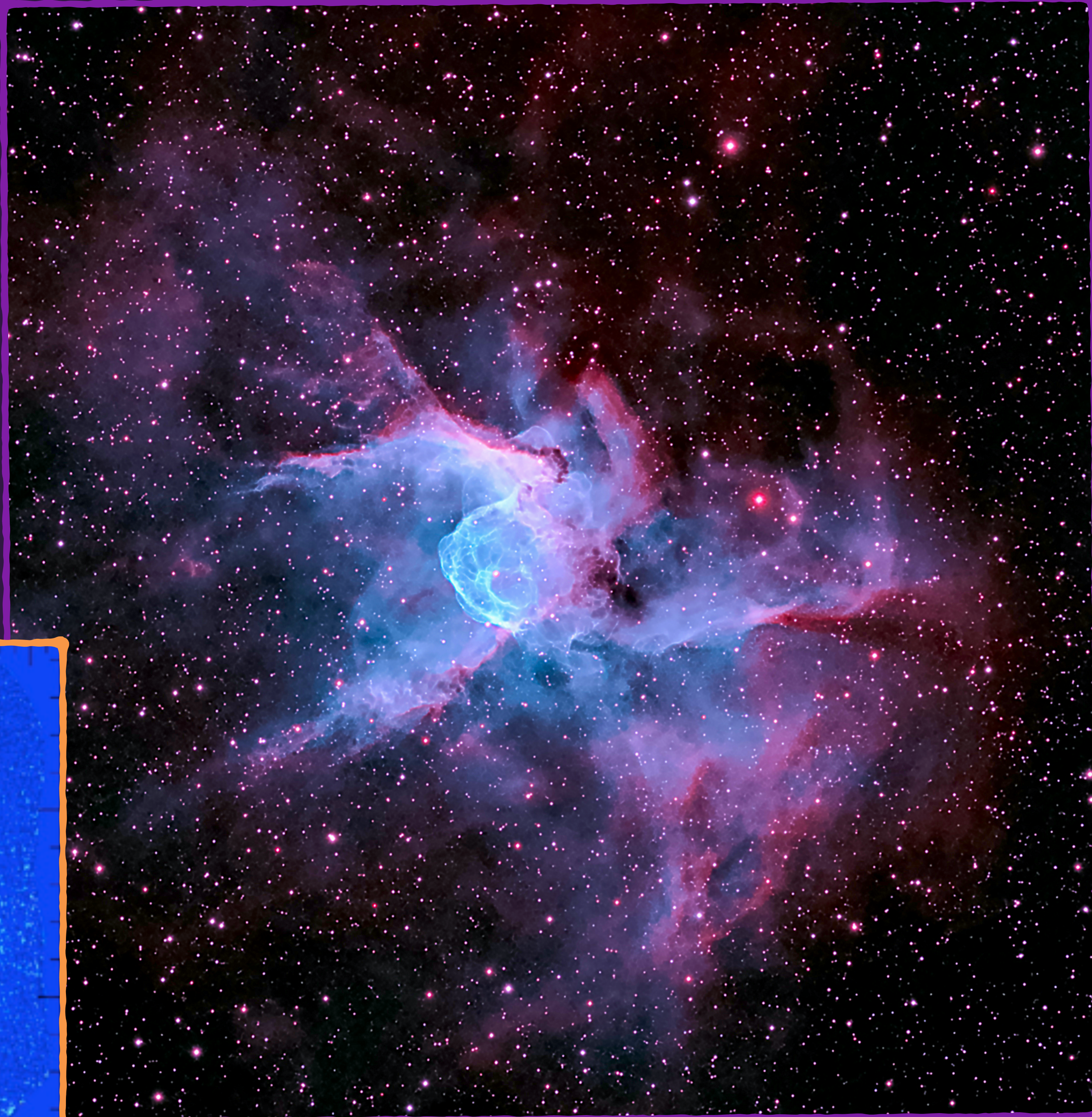


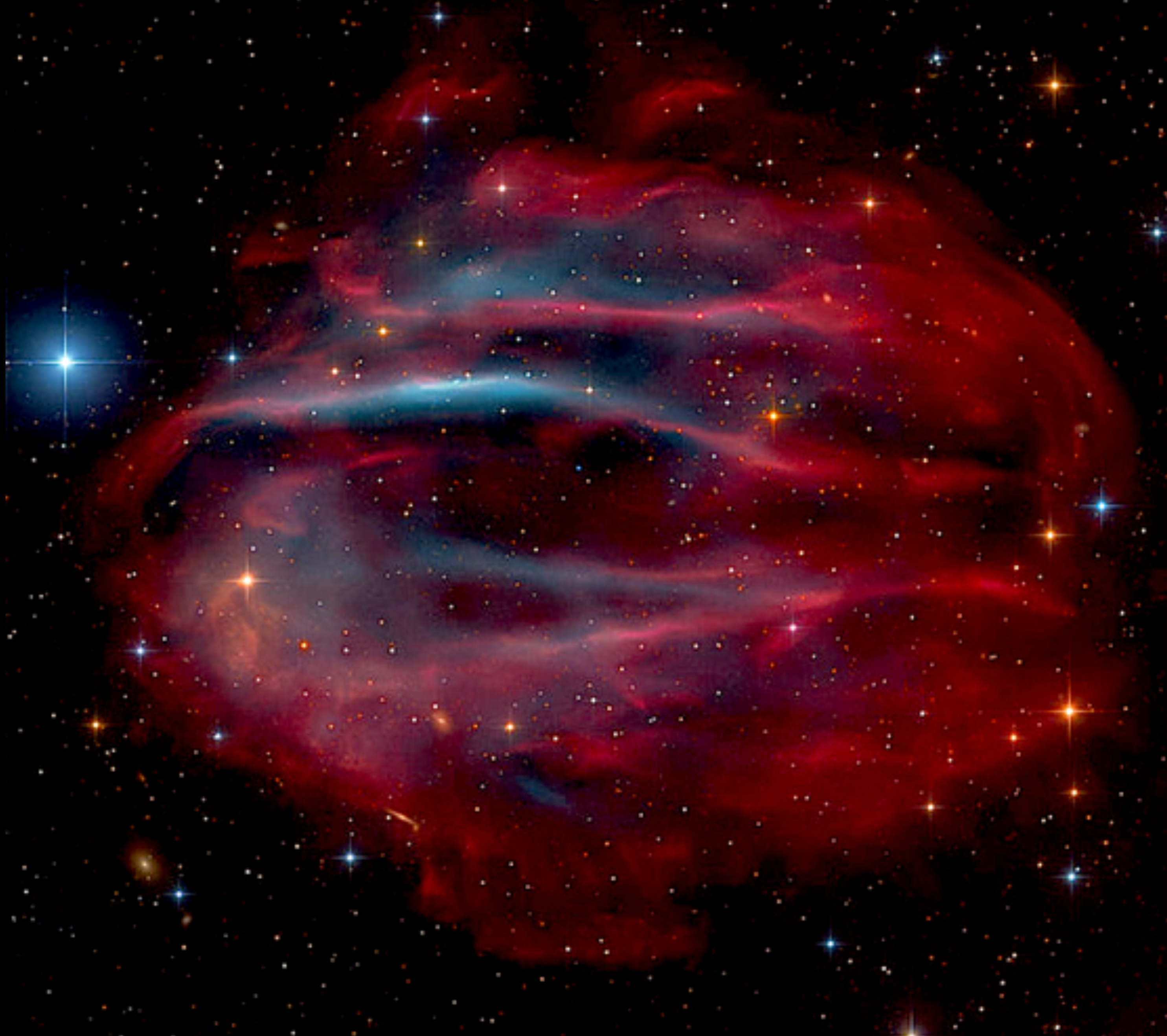
Image source: Johan Moolman, ASSA

Planetary Nebulae get age lines, too

What explains the unusual striations in Planetary Nebula StDt56 in Triangulum, near M33?

Planetary nebulae are the lasts gasps of dying AGB red giants. As the core of carbon and oxygen atoms squeeze into a tiny ultra-dense ball called a white dwarf, its gravitational energy can no longer retain the massive layers of gas in their envelopes. In response the envelopes expand rather rapidly into the vacuous interstellar medium around them. The 'Eye of God' annulus of M57 in Lyra and the Helix Nebula in Aquarius are an illusion of a hole in a ring is caused by our viewing them almost directly down their former polar axis. In reality, planetary nebula gases expand outward in an *impressive array of hard-to-explain shapes* whose causes include magnetic fields, how fast the original star was rotating, internal shock waves, and the unpredictable gas/dust medium surrounding them.

StDr 56 was discovered by amateur astronomers Marcel Drechsler and Xavier Strottner, who are members of a very small club of planetary enthusiasts who comb through surveys of the sky looking for undiscovered planetary nebulae. In this image, we do not gaze down the middle of the thing, we are looking at it almost equatorially. The slight protrusions at the north and south poles suggest the polar axis is perpendicular to us, as though we were looking at the Earth from above the



Strottner–Drechsler 56 (StDr56) Goblet of Fire nebula equator. Nor is the nebula rotating rapidly like Jupiter, causing distinct belts of streaming gas. In fact, the nebula is not rotating at all. Instead, its energy goes into expansion.

The first thing to note is those long thick filaments. Filaments this contiguous with respect to the overall size of the planetary are very unusual for a PN, and rather hard to explain. Such striping can occur when the gas flows along magnetic field lines. A white dwarf can indeed have a strong magnetic field, but it is doubtful that the original star's magnetic field was so powerful it could shape a gas structure of this size.

In the image, the red emission is hydrogen-alpha, signifying that the outer hydrogen envelope of the star was ejected first. The bluish colour comes from doubly ionised oxygen (perversely shortened to O-III) that originated deep inside the star near the old core, which is now a white dwarf. Both H-alpha and O-III glow strongly from the energetic ultraviolet (UV) light from the central star—whose surface may sear the sky with 100 million degrees K radiation at the surface. If the oxygen layers seem smaller and inside the structure of the hydrogen, that is because the oxygen originated very near the centre of the star and was likely dredged up from the star's surface by giant convection cells that are common in the last stages of an AGB star's life just before it becomes a full-fledged planetary.

StDr56's apparent size on the sky is nearly the same size as the full Moon. Drechsler and Strottner identified a star named Gaia DR2 300394067131824768 as a candidate for the nebula's central star. It is about 1,130 light years from Earth. That would make the nebula about 10 light years across. That is suspiciously large for a planetary and raises the question of what, exactly, could make it so big.

Can we answer that question by carefully measuring the properties of the nebula? Well, yes … and no. The layers we see are the shells of gas from inside the star before the star exploded. When the white dwarf compressed into a superheated ball, the thick layers of helium, traces of beryllium, boron, carbon, and nitrogen expanded unevenly, mixing the gases. These were shaped into distinctive patterns by the star's magnetic field. . Measurements of the Doppler velocity for the gas suggest that the outermost hydrogen gas layer must have been accelerated almost explosively for it to reach the diameter that it presently has. Further inward, each layer of progressively heavier elements wasn't accelerated as much due to their heavier mass. If the dying star was massive enough, say 5 to 7 times the Sun's mass, then it might have enough energy to generate such a rapid wind into space.

StDr 56 is in the constellation of Triangulum, which is 30° above the plane of the Milky Way. Space is a near vacuum that far from the dense environs of the Galactic disc. StDr 56 could expand with very little gas and virtually no dust to offer resistance. The nebula's distance of ~1130 light years puts it in the very upper reaches of the Galactic disc, a region in which few disc stars reside.

StDr56 is vexingly faint. The above image was acquired by astrophotographer Robert Pölz in Austria using a 25-centimetre telescope. The image required a boggling 60 hours of exposure time. That is two and a half full days—for a full-colour astro image. Taking a narrowband spectrum of the gases would mean a staggering amount of time if one was after the O-III line. Unfortunately, an accurate spectrum is the only way one can determine the nebula's actual expansion velocity. Planetary nebulae expand in the dozens of km/sec range. Acquiring a spectrum would take a large telescope of the size accessible only to professional astronomers. First, though, one must convince an astronomer that this object is so important it warrants big-telescope time—and cost. Good luck.

As co-discoverers, Drechsler and Strottner had the right to give it a name. They call it the Goblet of Fire Nebula.

HDW 2 is a similar hard-to-understand striated planetary disc.

Is NGC 474 a galaxy or an onion?

Elliptical galaxies are generally known for their smooth surface density profiles—especially when compared with spiral galaxies. One particular class of spirals are called flocculent spirals because of their multiple dust lanes and fragmentary spiral arms. NGC 470 on the left is such a galaxy. But this image shows structures around the elliptical galaxy NGC 474 on the right that look somewhat like the flocculent shell version of the beclotted spiral arms next door. Why has NGC 474 such a layered look instead of the traditional elliptical galaxy's smooth, featureless ball?

These features are due to smaller dwarf galaxies infalling into the once-smooth NGC 474 ellipsoid within the last billion years. The pre-infall ellipsoid had long ago been smoothed by the interaction of multiple spiral and irregular galaxies far back in the early history of the universe.

Despite how close they may seem in this image, these two galaxies have never interacted—if they had, NGC 470 would have been ripped to shreds and smeared all over this image like NGC 474's other low-mass victims.

This image was provided courtesy of the Dark Energy Survey acquired by the Dark Energy Camera on the Víctor M. Blanco 4-meter Telescope on Cerro Tololo in Chile. *Graçias, señores y señoritas!*

ngc 5291 has the worst table manners in the Centaurus Galaxy Cluster

Galaxies have never been known as dainty diners and this image from the *SMARTS 0.9-meter Telescope* at *Cerro Tololo Inter-American Observatory* shows the result of a truly spectacular galactic food fight. The bloated galaxy NGC 5291 (the oval cloud in the centre with its dusty belt sagging well below its belly) took a rather too libidinous look at a tasty morsel of spiral galaxy some 300 million years ago and left behind this unedifying mess of blue luminous X-ray bones splattered left and right. The clumps glow strongly in GALEX X-ray images but show no Hα signature, *which suggests gas starvation* after a blistering starbake heated the poor spiral's gas to over 100 million K. Don't even *think* what the napkin must look like.

And *STILL* NGC 5291's appetite was not sated. The galaxy is now sipping on a piña colada in the shape of PGC 48894, which looks more like a comma than its rather more prosaic moniker, the Seashell Galaxy. The uninvolved onlooker to the upper right is the spiral galaxy PGC 48877, and the complex barred galaxy below left is PGC 48911, which may have similar designs on the dwarf galaxy PGC 718090 just below it.

Source: The SMARTS 0.9-meter Telescope, constructed in 1965 by Boller & Chivens. *Membership in the four-telescope SMARTS open-access telescope network is open to individuals or institutions.* For more science & instrumentation information, *see this page*. Download the *Operating Manual here*.

Source: Wide-field Mosaic II camera on the Blanco 4-meter telescope at Cerro Tololo Interamerican Observatory, Chile.

THIS PAINTERLY INFRARED IMAGE PUSHES ASIDE OPAQUE CURTAINS OF DUST THAT BECLOUD THE MESSY ORIGINS OF HOT, YOUNG STAR CLUSTERS In this Blanco 4-Meter Telescope image, two infant clusters' first stars have burst into life in the centre and bottom centre. If we lived next door to these clusters—say about half the distance between the Sun and Alpha Centauri—we would see an intricately cloud-wreathed sky speckled with stars like the computer simulation creator Teun Van Der Zalm's works *Interstellar Clouds* and *Stellar Nurseries*. The intricate folds, loops, filaments, and bright clouds are actually fairly standard scenery in the theatrical playbook of molecular clouds collapsing into young clusters. The chaotic palette seen here portrays starry sculpture in the making—imagine Michelangelo chipping away at a large chunk of marble to reveal the beautiful young man named David hidden inside all along just waiting for the right man with the right chisel. The streaming laceworks in red to the left and right reveal large-scale magnetic fields aligning immense numbers of tiny silica-based dust specks into dipolar streams that have arrived at the party too late to join in the star-making. The two intensely white glows are hot young stars in the first one to three hundred thousand years of their long lifetimes ahead. Because the interstellar dust is opaque to visible light, infrared and radio observations are crucial in the understanding of the earliest stages of the stellar evolution—and unveiling this majestic scene for us to enjoy.

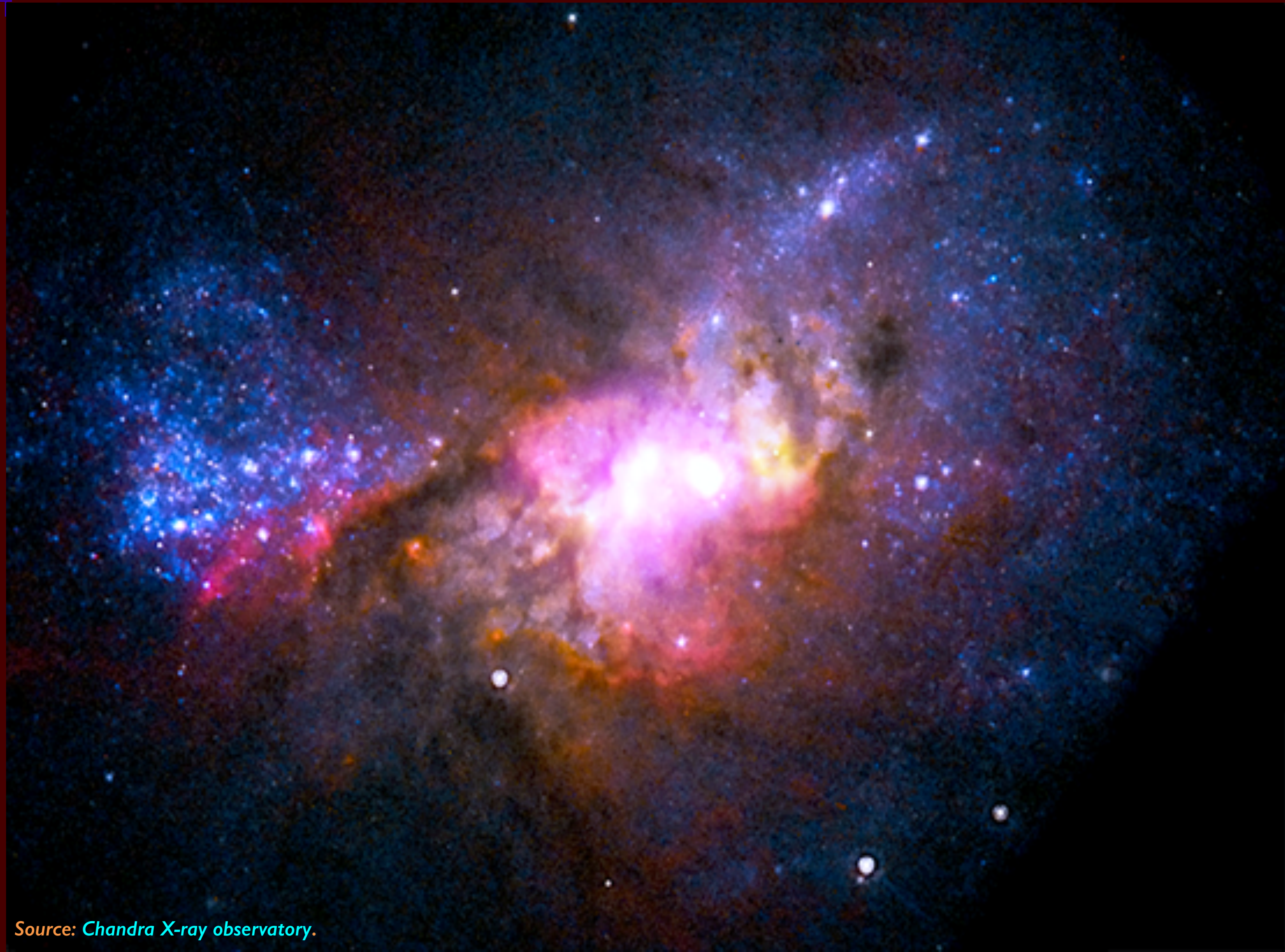
Henize 2-10 dwarf starburst galaxy in Pyxis

Henize 2-10 is a dwarf galaxy about 30 million light years from Earth. It has unusual properties similar to those in the early Universe.

Now, some new X-ray data from the Chandra X-ray Observatory in space and the Very Large Array in New Mexico suggest that black hole growth may precede the growth of bulges in some galaxies. This has long been suspected but proof was lacking. This X-ray and radio image from the Chandra/VLA collaboration indicate that the black hole at the center of Henize 2-10 has a mass about one million times that of the Sun.

Stars are forming at a prodigious rate in this galaxy. The star clusters in the outskirts of the galaxy glow in blue, the signature of hot young stars. Since Henize 2-10 does not contain a significant bulge of stars in its center, this suggests that supermassive black hole growth may precede the growth of the bulge in this particular galaxy. Henize 2-10 is only about 30 million light years from Earth, but most nearby galaxies have galaxy bulges and supermassive black holes growing in parallel.

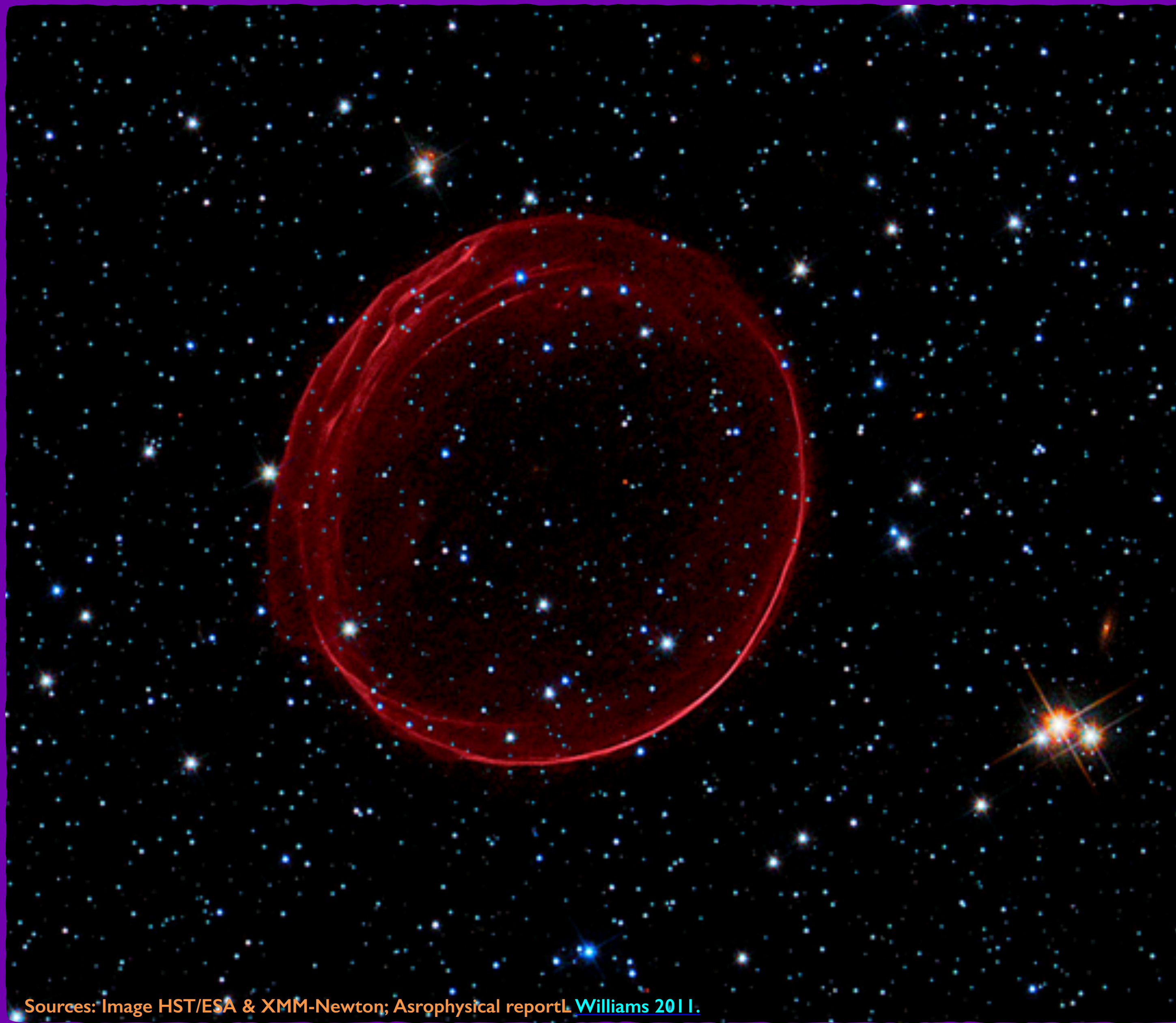
Hence this image provides astronomers with a detailed new look at how galaxy and black hole formation might have occurred in the early Universe. Optical data in this image from the Hubble Space Telescope shows in red, green, and blue. X-ray data from NASA's Chandra X-ray Observatory is in purple. Radio data from the National Radio Astronomy Observatory's Very Large Array is in yellow. A compact X-ray source at the center of the galaxy coincides with a radio source, giving evidence for an actively growing supermassive black hole with a mass of about one million times that of the Sun.



Source: Chandra X-ray observatory.

Nearly perfect: SNR B0509-67.5

The cumbrously named supernova bubble SNR B0509-67.5 is one of the most comely serenities in the sky. Yet in space, even serenity is not what it seems. Only about 400 years old, this delicate bubble is expanding at over 6000 km/sec into a thin mix of gas and silicate-based dust. The stratifications on the left are explained as density gradients of 2 to 4 times ambient densities. The delicate thinness of the shells suggests a low local gas-to-dust ratio and dust that is largely grainy (silicon-based) rather than porous (carbonaceous with water ices). There is scant evidence of blueish O-III emission in the 500.7 μm band but significant O-III, Fe, and Si emission in X-ray. The front edge of the shock compresses the local medium to 12 times its base density, a higher-than-normal ratio that implies that the shell efficiently accelerates proton-rich cosmic-rays generated in the initial SN 1a detonation. The wobbly segments suggest the dust density gradients were perturbed by pre-SN subsonic waves passing through. Strong Fe and Si emission lines may come from both the ejecta and the shocked ambient gas. The dust-to-gas mass ratio of the ambient medium is significantly lower than what is expected in the ISM. All these data reinforce the notion that in astronomy great beauty can result equally from the most subtle and most violent events.



Sources: Image HST/ESA & XMM-Newton; Asrophysical reportL Williams 2011.

Galactic Cirrus near Barnard's Galaxy

The infrared cirrus consists of moderately far-IR bright, widely extended, predominantly filamentary Galactic dust emission visible over most of the sky. With a mean temperature of 25 K (Low et al. 1984), it is best studied at λ = 100 − 200 µm, although it partially correlates with 21 cm neutral hydrogen emission and tracers of molecular hydrogen (Deul & Burton 1990; Weiland et al. 1986). The origin of the cirrus is not yet known, but in its present state it is perhaps a relatively simple laboratory for studying the interaction of dust, gas, magnetic fields, and interstellar radiation due to the low optical depth, distance from stellar formation and evolution processes, and frequency of shock signatures. =Source: *SOFIA Science Centre*.

The presence of Barnard's Galaxy NGC 6822 overexposed as the bright patch in the upper right centre of this image gives us a convenient yardstick to gauge the height of the Galactic cirrus that shrouds our night skies without us being aware of it. 'Galactic cirrus' is a convenient rubric for clumpy and filamentary patches of microscopic dust that lie in thin laminae only a hundred parsecs (326 light years) thick above and below the part of the disc in which the Solar System resides. Barnard's Galactic declination is –18.4°, so simple trigonometry places these clouds in the upper regions of the thin disc.

NGC 6822 Barnard's Galaxy in Sagittarius/Capricornus is the bright patch upper right centre. The dusky streaks and hillock-like mounds are made of Galactic disc dust whose only illumination is the combined light from the Milky Way itself. These dust clouds are only a few to a few dozen particles per cubic meter, hence their faint visual presence t Mag 25 to 28 magnitudes per arcsec^{-2}. Image © 2021 by George Vlazg, *originally published in IceInSpace 19 Aug 2021*.

How do we make sense out of this mess?

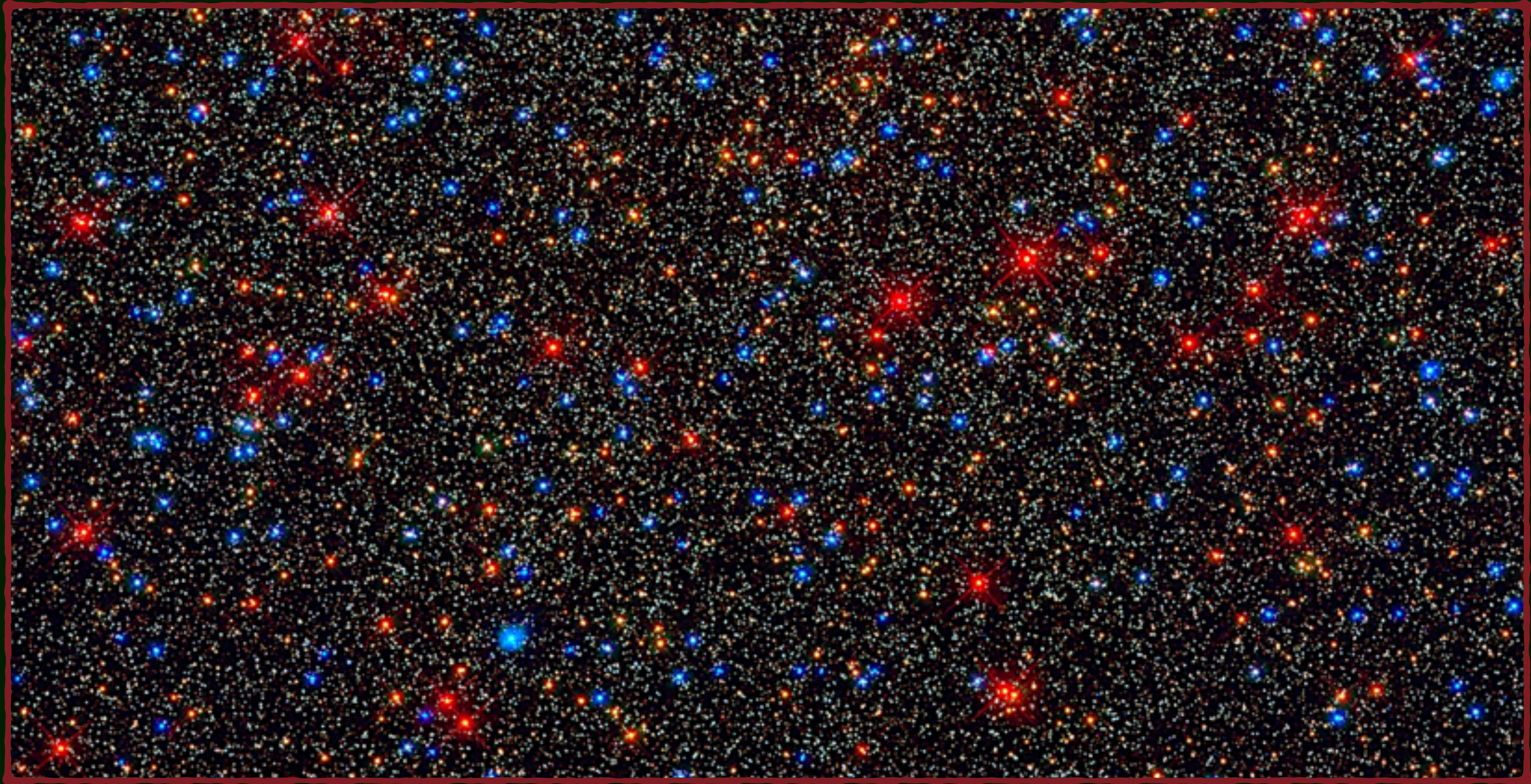
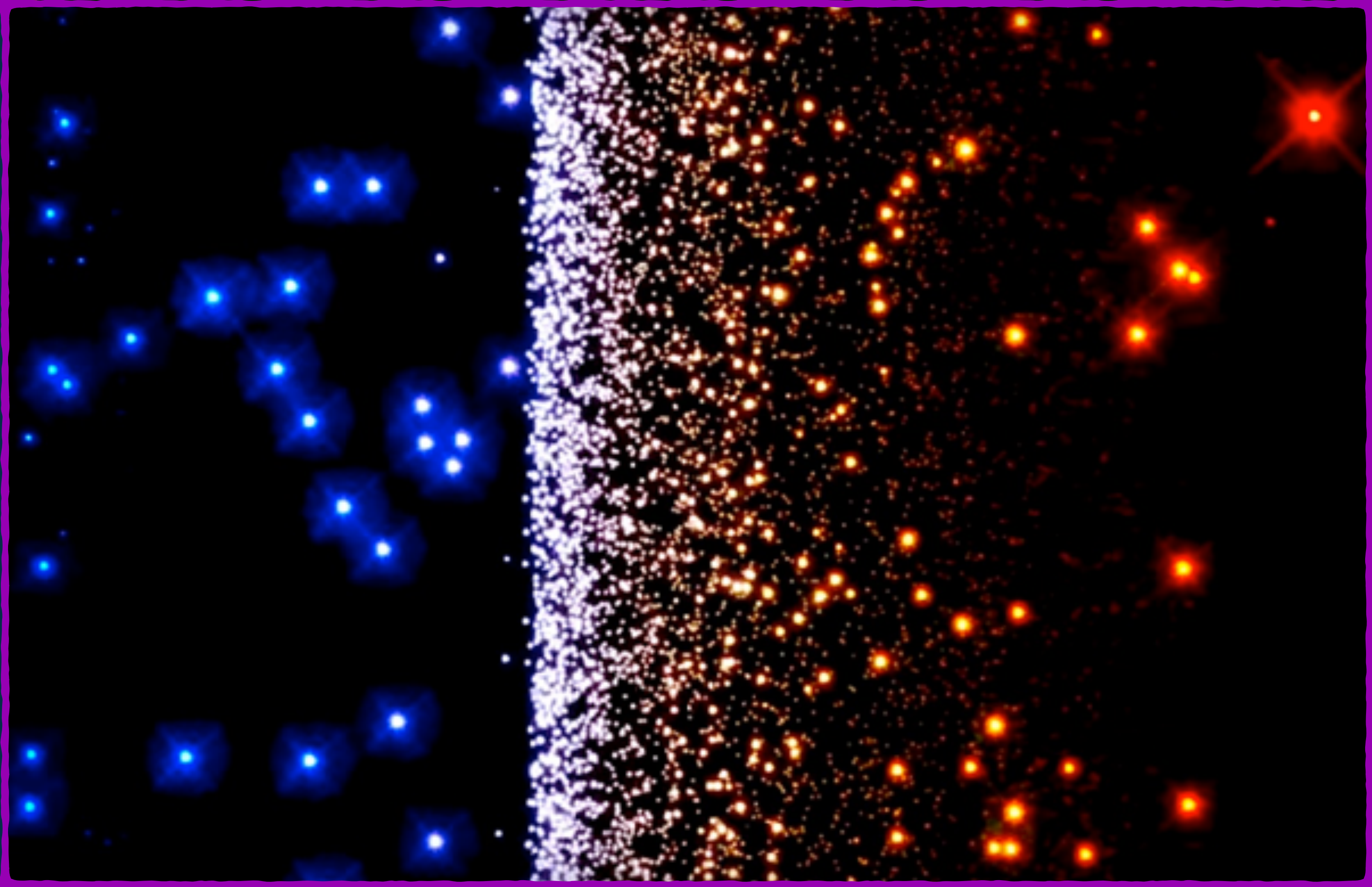


Image of the central region of the Omega Centauri dwarf galaxy core acquired by the Hubble Space telescope. The resolution of the Hubble is so good that we can see through the cluster to the vast emptiness of space beyond.

Watch how we can convert a picture of stars in the sky to information about the size, age, and life span of stars in their cluster.

The giant ball of stars in southern skies named Omega Centauri has long been called a globular cluster. But the presence of multiple populations of stars within it and its enormous mass of at least 10 million stars has long been suspected to be the core of an ancient dwarf galaxy that was accreted (the astronomer's polite way of saying shredded to bits) in a long-ago series of sideswipes that transferred the dwarf's disc stars to the Milky Way, mostly in its vast spherical halo. The ancient core was too dense to let that happen, and today soldiers on as Omega Centauri. Amateur astronomers consider it one of the great showcases of the sky because no matter what size telescope you have, it glitters with myriads of pinpoint stars, reminiscent of what a disco ball would look like if all its mirrors were half a millimetre square lit by a giant laser.

There are a number of ways to sort out the truth of this object's ancestry. One of them is its colour-magnitude diagram, aka CMD. As we look at the above image we see plenty of bright blue and red stars mixed in with the white specks. All those represent individual stars of specific mass, which largely determines their colour and age. Around 1910 a Dane named Ejnar Hertzsprung and an American named Henry Norris Russell thought of a way to move a field of of stars to a 2-D diagram that classified them by brightness and colour—blue for hot and red for cool. It turned out that the white stars did not line up vertically as in this image, but rather along a rising line sloping upward to the left. To see the full-motion transition between stars in the sky to CMD on a page, watch the video in the arrow.



Click here

What 50 years hath wrought

NGC 3432 is a feeble Magnitude 11.7 glimmer in Leo Minor

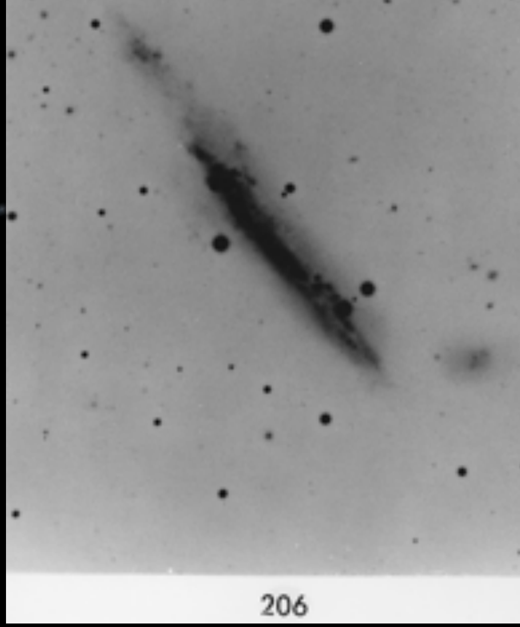
It is a difficult visual target when we search for it with a 6- or 8-inch backyard telescope because it is only 6.7 arcmin long and 1.5 arcmin wide.

But when imaged through the Hubble Telescope (right) the galaxy becomes a rich jumble of reddish regions overlying a rather subdued-looking blue glow in the background. Even so, this object is such a muddle that even with the Hubble's trademark visual precision it defies a ready explanation. The reddish HII regions seem to form a shallow, clumpy S on the upper left side but thickly overlie each other on the lower right. There appears to be a descending hook on the right, which suggests a vestigial spiral arm. Still, there seems to be a fiendish glee laughing at us from behind the facade of all this frenetic energy.

Back in 1966 when he was examining the now-legendary National Geographic Palomar Schmidt Telescope plates that became what we refer to as the POSS plates, Halton Arp thought this object was an elaborate deception, too. But he had a suspicion of what the deceiver was, even though no one had explored the force Arp intuitively guessed. Fifty years later, we know a great deal about what Arp did not know, and he was right. Magnetic fields pervade entire galaxies, and can have effects as momentous as starbirth.

But let's imagine ourselves looking over his shoulder as he was compiling his *Atlas of Peculiar Galaxies*. The very first paragraph of his Atlas is as true today as it was then: 'Forty years after the discovery that galaxies were independent stellar systems, we still have not penetrated very far into the mystery of how they maintain themselves or what physical forces are responsible for shaping their observed forms. The galaxies are the constituent units of mass and energy in the universe, and yet we are still challenged by such questions as: What causes the characteristic shape of spiral galaxies? How are elliptical galaxies related to spiral? How are galaxies formed, and how do they evolve?'

We will read the rest of Arp's words on the next page, but for now, let's cut to the chase with Arp 206: We are looking at a big galaxy eat a little galaxy. Beautiful as it may seem, you are looking at one gigantic galactic burp. Toothpicks, anyone?



Halton Arp's ***original Palomar Schmidt telescope image.***

Image: ***NASA/Goddard photo acquired by the Hubble Telescope 21 Feb 2020.***

Atlas of Peculiar Galaxies, by Halton Arp

Preface

It is difficult to resist an oversimplified impression of what a galaxy is because the Hubble classification divides the galaxies into the well-known categories of smooth, amorphous ellipticals and flattened spirals with star-studded arms. But not all galaxies fit the schematic idealization of the Hubble sequence of nebular forms. In fact, when looked at closely enough, every galaxy is peculiar. Appreciation of these peculiarities is important in order to build a realistic picture of what galaxies are really like.

But the peculiarities are also important for another reason. If we could analyze a galaxy in the laboratory, we would deform it, shock it, probe it in order to discover its properties. The peculiarities of the galaxies pictured in this Atlas represent perturbations, deformations, and interactions which should enable us to analyze the nature of the real galaxies which we observe and which are too remote to experiment on directly. In general, the more conspicuous the peculiarity, the more illustrative it is of special events and reactions that occur in galaxies. Therefore the greatest deviations from the normal are emphasized in this Atlas. In some cases small peculiarities are included to illustrate, in sequence, how a certain type of peculiarity develops in importance until it dominates the form of the object. But it is from this overall range of experiments that we must then select and study the ones which will give the most insight into the composition and structure of a galaxy and the forces that govern it.

The present Atlas specifically started from an attempt to better understand spiral galaxies. Many analyses, often complex mathematical treatments have been made over the years, starting from the assumption that spiral arms were the result of tracks of stellar orbits moving under the gravitational influence of a central force field. I believe that the forms of spiral arms, their bifurcations and convolutions cannot be explained by such theories. In 1962 I undertook to assemble a series of photographs that would demonstrate this point. In the investigation of these spiral properties, galaxies which showed unusual or perturbed arms or filamentary extensions were sampled with high-resolution photographs with the Palomar 200-inch telescope. Subjects were first drawn from the pioneering work on peculiar galaxies by Zwicky and Vorontsov-Velyaminov. So many important objects emerged under high-resolution, limiting-magnitude study, however, that the investigation into the nature of spiral arms was postponed in order to systematically organize these new phenomena into groups and to publish a representative sample of the most significant objects.

The Atlas as it has been realized in the following pages illustrates again that galaxies contain more than just stars, radiation, and gravitation. The pictures emphasize the importance of dust in some, they particularly imply a much more important role for the gas in general, and point to the existence of either new forces or forces which previously have been little considered. For example, if we consider galaxies to be merely an assemblage of mass particles, we should be able to treat them, in the limit, hydrodynamically as a frictionless fluid. But the twisted, distorted shapes and curious linkages pictured there suggest that viscosity-like forces are present. Dynamical friction does not seem sufficient because some of the filaments suggest a degree of viscosity approaching that of an elastic medium. Probably the only agency likely to account for this is that of magnetic fields that interconnect regions of wholly or partially ionized gas. Vorontsov-Velyaminov has stressed in the past the probable magnetic nature of some of the effects in peculiar galaxies.

Magnetic forces are very difficult to study optically, but are undoubtedly of great importance in our universe. Recent radio astronomy discoveries of violent events in galaxies reveal sources of energetic charged particles. These charged particles interact with magnetic fields and offer the hope of mapping, measuring, and understanding cosmic magnetic fields. The connection between the plasmas observed with the radio telescopes and the optical evidences of plasma effects pictured in the present Atlas is now open to us.

The overall aim of this Atlas is to present a number of examples of various kinds of peculiar galaxies. They are displayed in groupings that appear roughly similar, thereby furnishing also a rough, initial classification. Phenomena which each group represent may then be investigated by selecting the most favorable members in size or brightness, studying different members of the group in different orientations, and, finally, making some preliminary statistics of certain kinds of phenomena and their relationship to other observable parameters. It is hoped that this investigative procedure will not only clarify the workings of galaxies themselves, but reveal physical processes and how they operate in galaxies, and ultimately furnish a better understanding of the workings of the universe as a whole.

The source document is available in its entirety here.

Inertial Enigma reveals secret Crown Jewel

NGC 3628 is a large, edge-on spiral galaxy and one of three galaxies in the "Leo Triplet" so popular with visual and imaging astronomers alike

NGC 3628 is best known for its warped disc and the long tidal tail seen in the images in the montage on these pages. For professional astronomers, the intriguing feature of NGC 3628's disc is the extraordinarily thick and bulbous outer disc which extends much higher above and below the galaxy's plane than most spiral galaxy gas discs. Galaxy collisions usually strip away disc gas, but NGC 3628's 260,000 light year tidal tail seems not to have affected the disc gas at all.

The clumpy tail results from gravitational interaction with the nearby M66 member of the Leo Triplet (above this scene on the right side of NGC 3628).

Yet until five years ago, there was a celestial secret hiding within the profuse detail of this scene—a sphere of stars as numbrous as Omega Centauri in the Milky Way.

Look carefully—can you spot it? Don't feel bad is you don't pick it out it right away. Astronomers didn't notice it until 2016—and they used amateur telescopes to do it!

This is a story to savour with your buddies at your next star party. Who needs 5 metres of glass when 0.5 m discovers an Omega Cen?

Source: This image was acquired with the B (blue), V (green), I (orange) and Hydrogen-Alpha (red) filters using the Mayall 4-meter telescope at Kitt Peak National Observatory by T. A. Rector of the University of Alaska Anchorage and H. Schweiker of the NOIRLab.

Watch this *AURIGA Project simulation of stellar motions in a short-barred spiral galaxy* (as NGC 3628 is suspected to be, based on a red DECaLS DR3 image shown below. in which the bar is seen directly along our line of sight).

Why is the collisional stream of NGC 3628 flying the wrong way?

This superbly detailed image was captured by Mark Hanson at his Stellar Winds Observatory near Animas, New Mexico, USA. Mark was one of the imagers who participated in the *Dwarf Galaxy Survey with Amateur Telescopes* (DGSAT) 2016 study in which RCOS, PlaneWave, and Takahashi-class telescopes from 106mm (4 inches) to 0.8 m (30 inches) were used to discover ultra-faint (27.5 mags per sq arcsecond) stellar streams of dwarf galaxies accreted into the halos of larger, usually spiral, galaxies. Mark's telescope used in the DGSAT project was a 24-inch Planewave R-C. The above and next two NGC 3628 images came from Mark and his colleagues. Read a *profile of Mark and his imaging methods here.*

In astrophysical terminology, tidal streams like this beauty stripped from the Leo Triplet galaxy NGC 3628 are studied as diagnostics of galaxy formation. The serenely mature spiral galaxies we gaze upon so fondly today belie unedifyingly messy childhoods and adolescence. (See *1*, *2*, *3*.) It is hard to imagine why professional astronomers who write proposals for observing time on 8-metre telescopes would deign to look twice at the dream telescopes of the amateur community like the Takahashi super-wide super-sharp FSQ106 series (4 inch) up to the RCOS or Planewave 17 and 18.5 inch beauties. And yet the professionals get results from these that enable theoreticians to better constrain the conditions that shape galaxies.

NGC 3628's Tidal Tail

NGC 3628 is whimsically known as the Hamburger Galaxy. It is a barred spiral galaxy about 35 million light-years away in the constellation Leo discovered by William Herschel in 1784. Today the galaxy is known as part of the Leo Triplet. This trio is a perennial favourite among budding astro-imagers. The Leo Triplet's formal identities are NGC 3623 (M65), NGC 3627 (M66), and NGC 3628 (the 'Hamburger Galaxy' because it looks like one).

NGC 3628 has been the subject of much attention since Fritz Zwicky reported an 'optical plume' extending from NGC 3628 in a clumpy shallow arc extending 80 kpc (260,000 ly) which he calculated as comprising a total HI mass of 540 million solar masses (M_{sol}), or about 15% of the total HI mass in the main body of NGC 3628 itself. Moreover, the galaxy's gas and stars rotate in opposite directions to each other—a signature of galactic slide-by as distinct from pass-through interaction. Slide-by interactions pull off tidal streamers while pass-through interactions produce starbursts of young clusters. Photometric and spectroscopic studies reveal that the NGC 3628 plume underwent a remarkable epoch of star-forming activity about 540 million years ago.

The clumpy nature of the NGC 3628 plume is clearly seen in the following two images. The first image is partly inverted to show faint structures, and partly in traditional view to make it easier to identify stellar structures. This presentation style was developed by David Delgado-Martinez in collaboration with several amateur astro imagers with a long-standing interest in discovering ultra-faint accretion structures around galaxies.

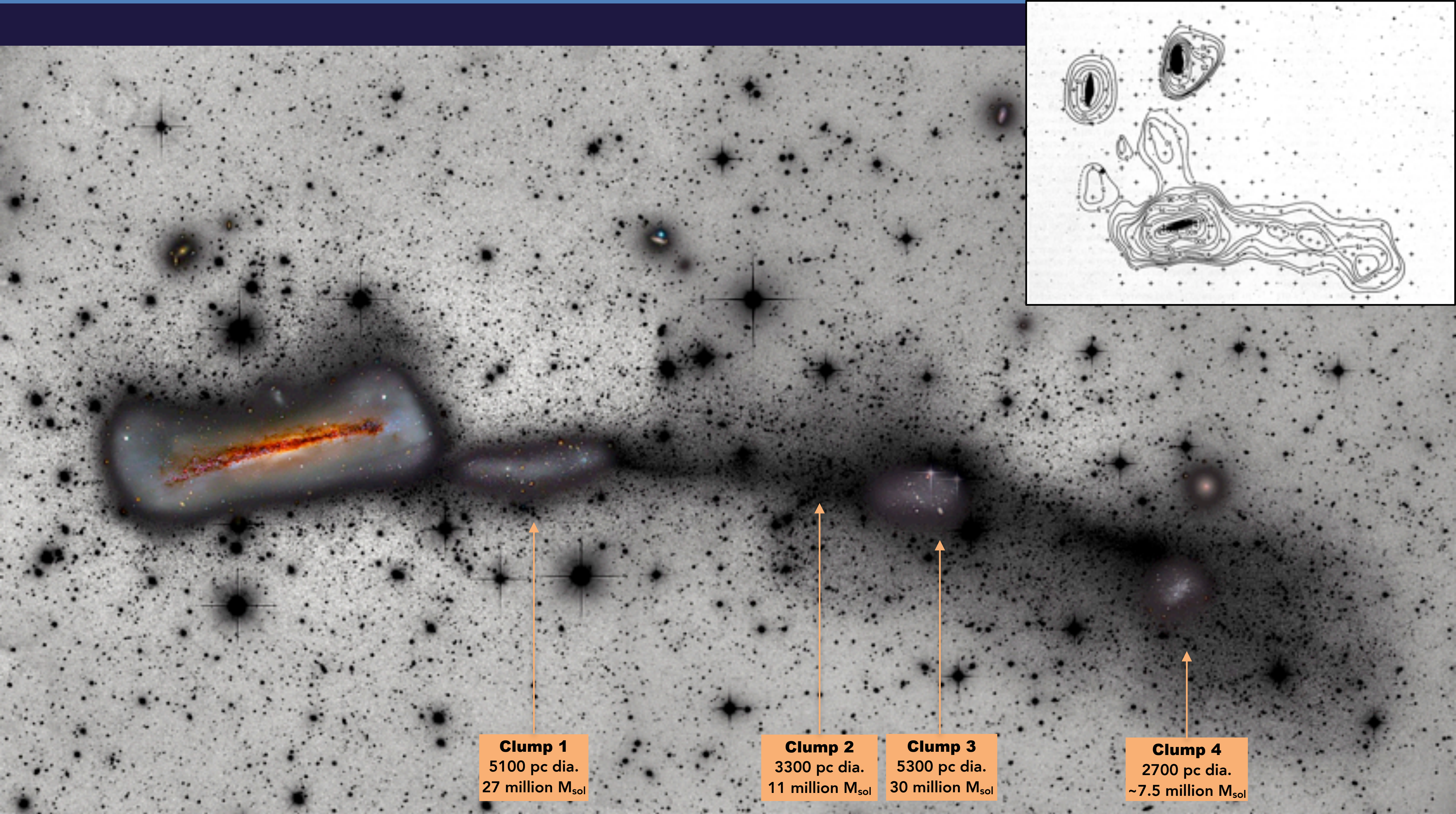
There are two major mysteries about NGC 3628 and the Leo Triplet in general. The first is how the apparent core of an accreted galaxy (NGC3628-UCD1 pointed out above) found its way to the largest clump next to the main galaxy—this object was, after all, discovered only in 2016. If this is indeed the core of a dwarf galaxy, where are the rest of the dwarf's stars? There is no hint of faint stellar streams wrapping around NGC 3628. All we can do based on current observations is to surmise those old dwarf stars are mixed in with NGC 3628's disc stars—they may in fact be a significant component in the galaxy's counter-rotating star versus gas discs.

The second problem with NGC 3628 is its Inertial Enigma—why its 80 kpc 'plume' lies along a curve whose shape and mass distribution cannot be plausibly visualised as resulting from an interaction with NGC 3627 (M66)? The only kinematic orbital projection based on computer calculations was made by *Arnold Rots way back in 1978*—an era when astronomical projections of stellar motions were very coarse-grained by the standards of N-body and moving-mesh calculations today.

In 1998 *Frederick Chromey et al* updated the three-body orbital models for the tidal interactions between NGC 3628 and its companion NGC 3627, which reproduce the formation of a long plume and give a lookback time of 800 million years since their closest approach or perigalacticon at 27 kpc (88,000 ly). Gas removal by ram pressure and stellar redistribution by tidal effects are two distinct processes, neither of which seem to suggest plausible orbital pathway that reproduces the distribution we see in the Leo Triplet today.

Section 2 of a *1993 paper by Xiaolei Zhang et al* parses out the complexities or galaxy rotation and interaction direction. In it, Fig. 2 reproduces the 1978 Rots kinematics more clearly than the original 1978 paper. Still, the enigma remains

Source file: ***Stellar Winds Observatory at DSNM, Animas, New Mexico***



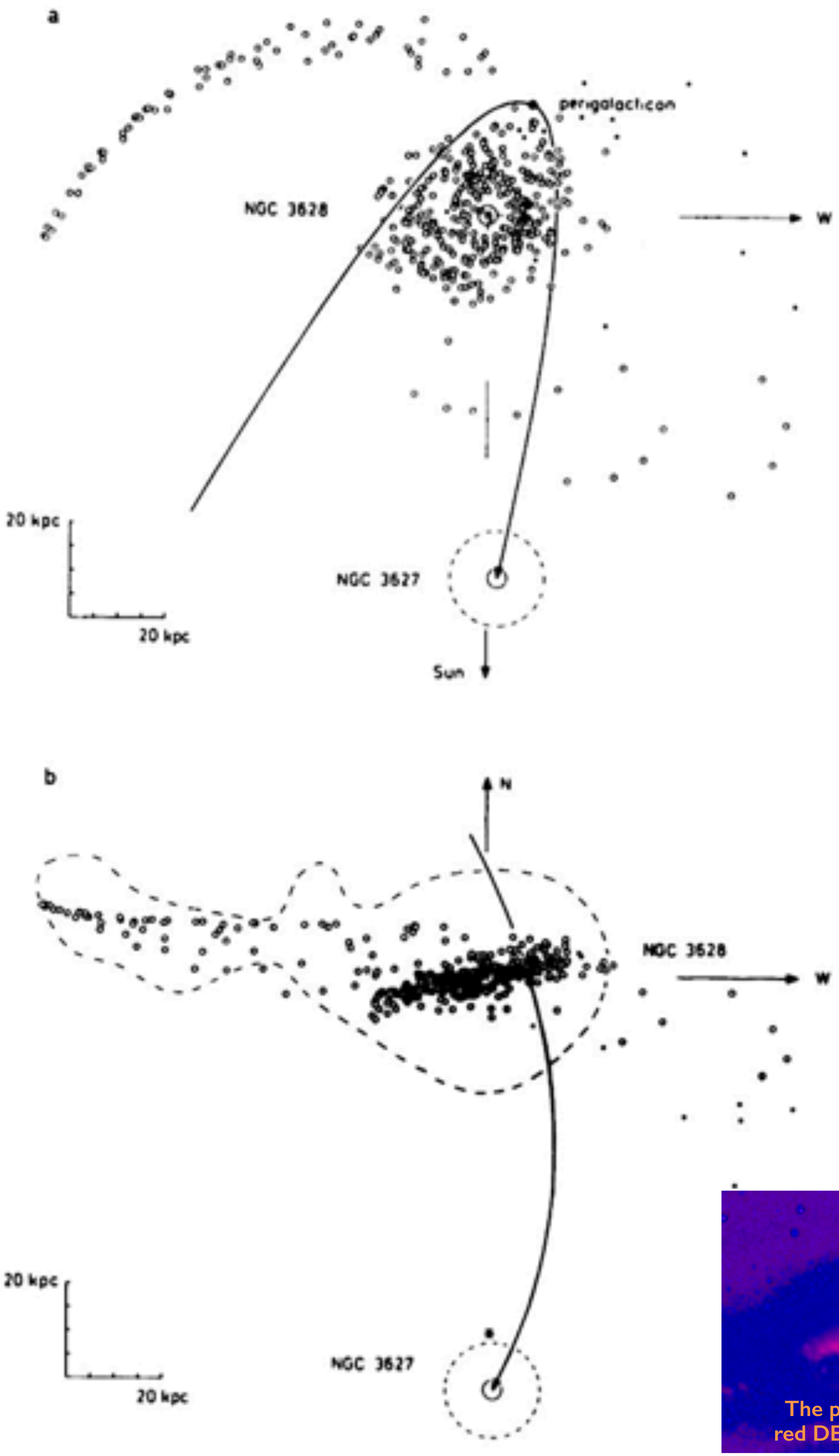
Mark Hanson's ultra-faint dust imaging

Mark Hanson has been an amateur astro-imager for over 25 years. He started out with a local group in Wisconsin, but realised that he needed to move to darker skies. He moved his equipment to Animas, New Mexico in the USA, where he could operate his equipment remotely. Mark is a member of the team of Pro-Am astronomers who search for galaxy merger remnants led by Dr. David Martínez-Delgado of the *Max-Planck Institute* for astronomy and *R. Jay GaBany* who oversaw the images acquired by Mark Hanson that have been reproduced here.
The David Martinez-Delgado & Jay GaBany 2008–2010 collaboration *Stellar Tidal Streams in Spiral Galaxies of the Local Volume: A Pilot Survey with Modest Aperture Telescopes* was conducted with three privately-owned observatories in Europe, USA, and Australia.

The members of the faint-stream imaging group acquire images reaching magnitude 27.5 MPSAS to reveal ultra-diffuse and faint stellar tidal streams. The debris streams originate in tiny dwarf galaxies that have been accreted and absorbed into larger galaxies over the last several billion years.

Due to the complex and often competing interactions of mixed star/dust/gas particle masses and the forces of turbulent shock waves, magnetic fields, and gravity, the tiny dwarfs are never completely absorbed but rather leave behind thin streamers of stars whose uniform chemical mix and age can be used to trace to their original parent galaxy. The *Milky Way presently has 23 tidal streams*, some of which are traced via a mere two hundred stars.

Mark Hanson acquired the data that went into these images using three telescope/imaging systems spread over five years of patient data collection. *See his website here*.



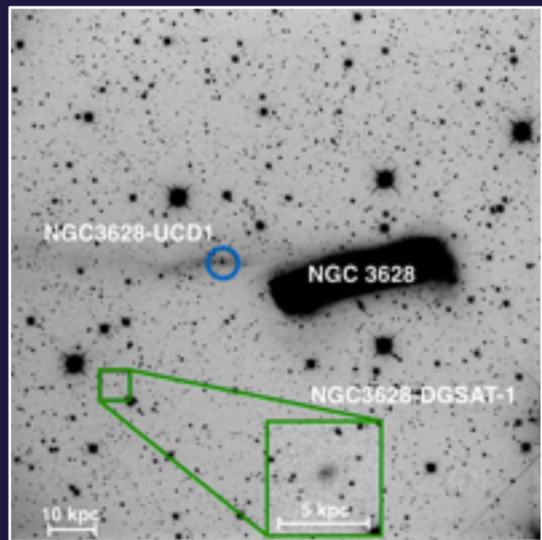
LEFT: The 1978 Arnold Rots 3-body interaction calculations for the orbital encounter between NGC 3628 and NGC 3627 (M66). Image (a) looks downward through the polar axis of NGC 3628. M66 moves inward from the left and above NGC 3628 in a parabolic arc that loops to the perigalacticon point 27 kpc from NGC 3628's polar axis at the disc plane, then sweeps beneath the galaxy to reach its present position. Perigalacticon occurred an estimated 800 million years ago, hence the total time span shown in the parabola in image (a) would be perhaps 1.6 billion years. That is a great deal of time for tidal gravitation to pull stars and gas from the parent galaxies into a long chubby filament better described as a plume. Many of the NGC 3628 plume's features today can be explained by the approx. two hundred million years the galaxies were close enough to each other for tidal stripping to take place. Imagine for a moment that you are standing by the side of a road just as a large truck passes. As it recedes into the distance, gusts of debris follow, riffling your hair and getting dust in your eyes. You have just experienced what NGC 3628 experienced in v—e—r—y slow motion.

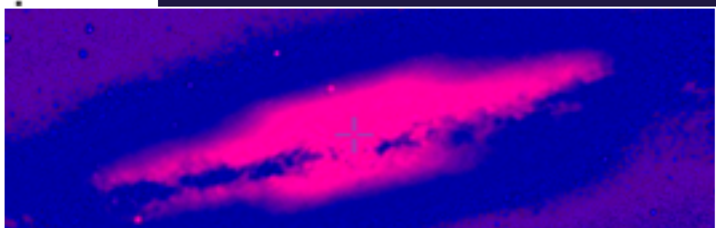
Image (b) shows the encounter as seen from NGC 3628's disc plane. M66 does not actually punch through NGC 3628; it was 27 kpc behind NGC 3628 when it crossed the disc plane. The mass exchange in this encounter was almost wholly tidal, since only the far outer discs of either galaxy would have experienced ram pressure stripping. The slow velocity of the encounter's prograde motion with respect to NGC 3628's rotation resulted in over 1 billion solar masses of HI gas being gravitationally extracted from NGC 3628 into the plume feature we see above. Much less gas was lost from M66 because the direction of the passage was retrograde with respect to its disc rotation. The route of the passage was in effect bucking a headwind. Even so, at least two large clumps of HI were removed from M66 and still reside near it today.

PREVIOUS PAGE: The four clumps identified on the previous image reveal that much of the HI gas that was removed from the galaxy was then turbulence-shocked into forming three well developed OB associations highlighted in the image above. Clump 2 probably did not have the critical mass necessary for HI clouds to collapse into molecular hydrogen clouds that contain large quantities of gas in the centre surrounded by a large sphere of hydrogen and dust debris swept up in the gas stripping maelstrom. The light profile of the plume is approximately constant, 26.5 mag arcsec^{-2}, which is the same surface brightness as the optical edges of the disk. These observations support the theory that the tidal plume was formed from material in the outer disc of NGC 3628. If we look back on the page titled 'Rhapsody in Blue' some 10 pages earlier, and consider the enormous mass of HI gas that exists in M33's outer disc that can be traced only by 21cm radio and CO emission studies, and add the fact that NGC 3628 may have undergone nearly a complete prograde revolution during the time it was being tidally stripped by M66, we can more easily understand why the plume had so much gas to make its stars with.

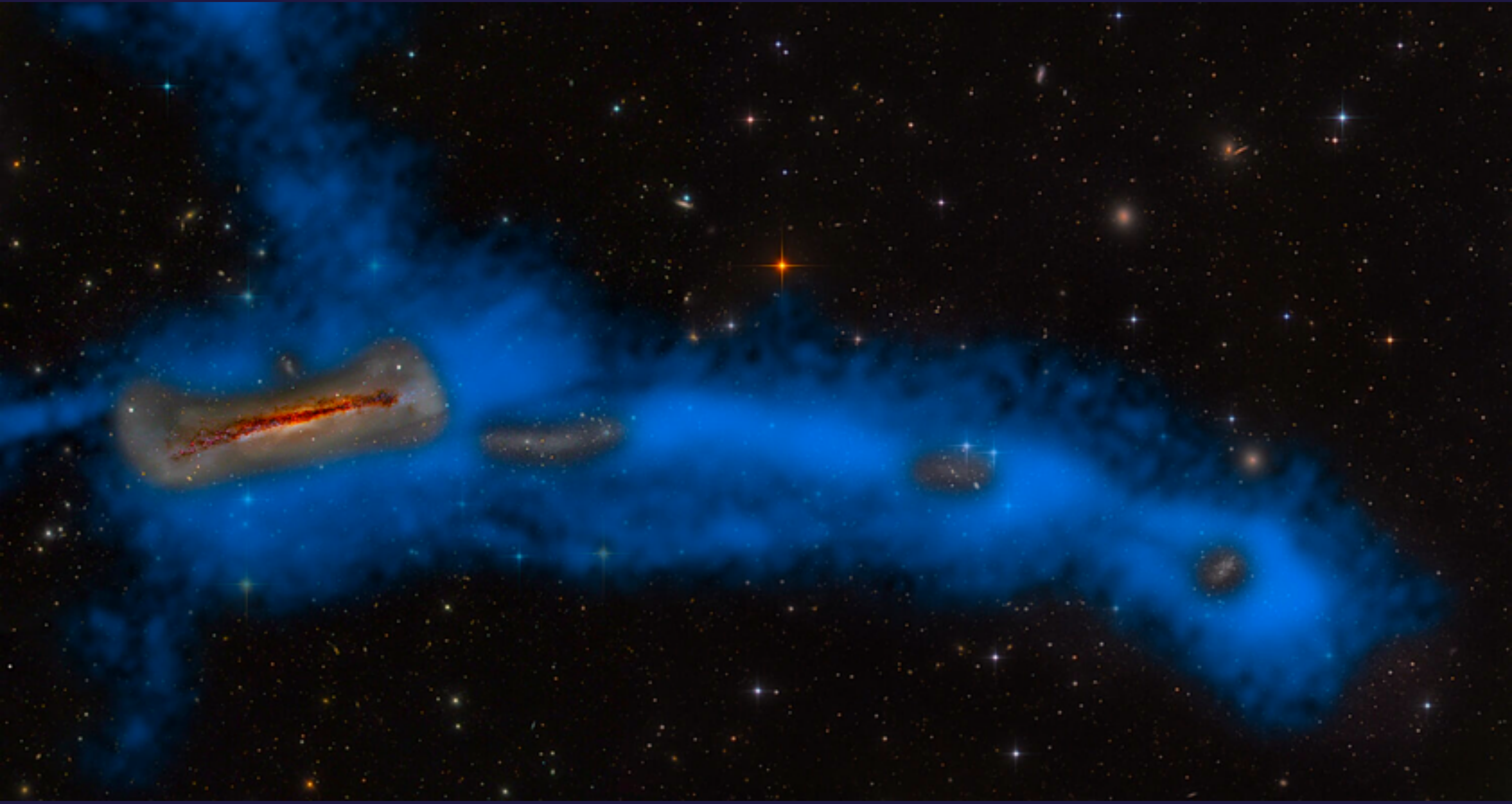
The HI gas density is nearly constant along the plume and about the same gas density as in the outer envelope of NGC 3628—consistent with the gas dynamics of tidal stripping. The three star-specked optical clumps in the plume are coincident with HI density peaks. The stellar population's average age of several hundred million years in the three clumps is consistent with star formation ensuing after the time of perigalacticon. The stellar masses of a few times 10 million solar masses are typical of massive star-forming complexes elsewhere in the universe. The proportion of stellar mass versus HI mass suggests a star formation efficiency in the plume of about 4% overall, which is also about average for the star-forming spirals in the nearby universe.

RIGHT: 2015 discovery image of ultra-compact dwarf galaxy NGC3628–UCD1 in DGSAT paper #1, 'Discovery of low surface brightness systems around nearby spiral galaxies', *Javanmardi et al 2016*.



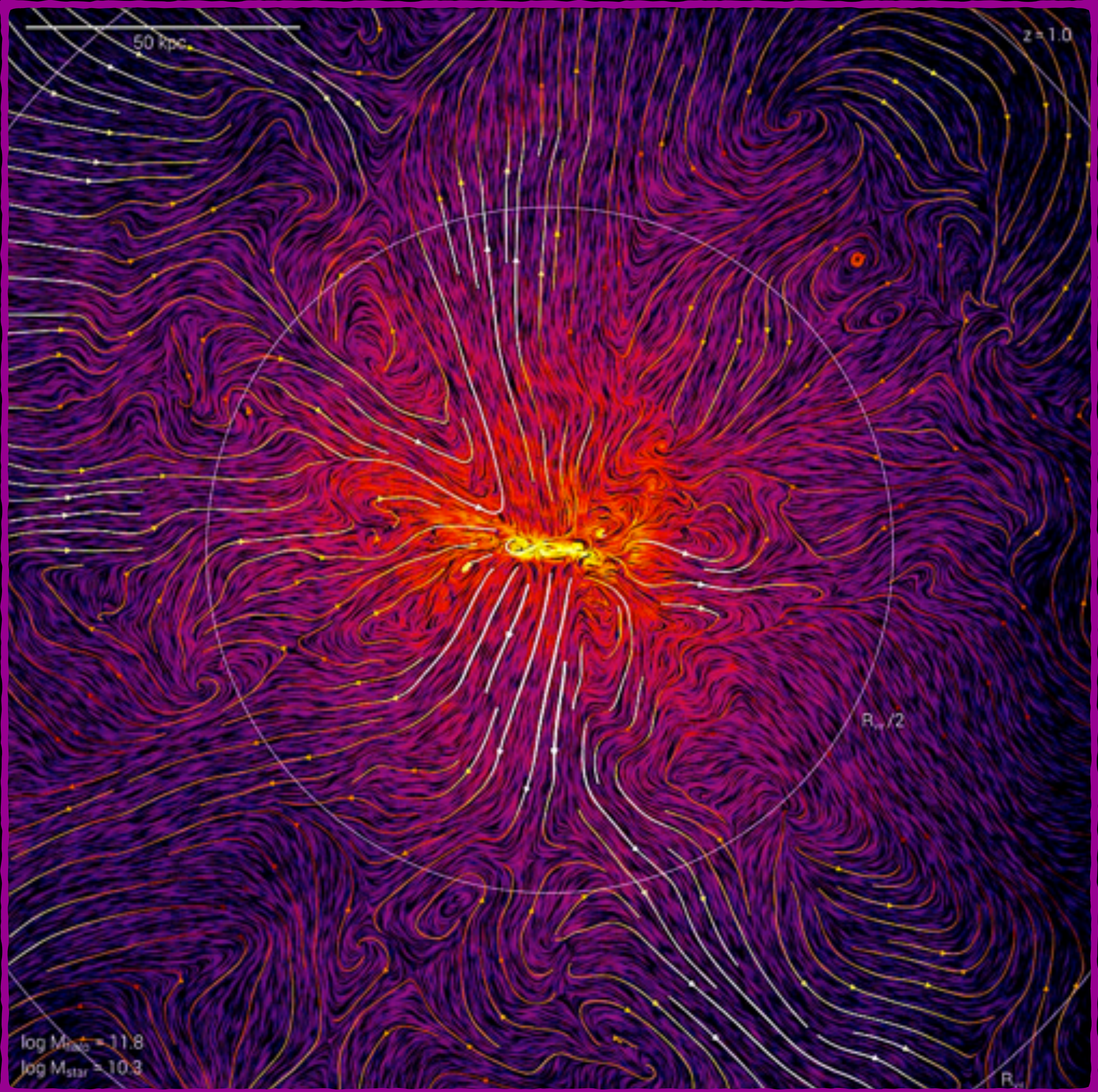

The presence of a bar viewed end on is revealed in this red DECaLS DR3 image extracted from the Aladin image

All that said, maybe we should just enjoy the beauty of the thing.



Source: *Stellar Winds Observatory at DSNM, Animas, New Mexico.*

How do galaxies breathe?



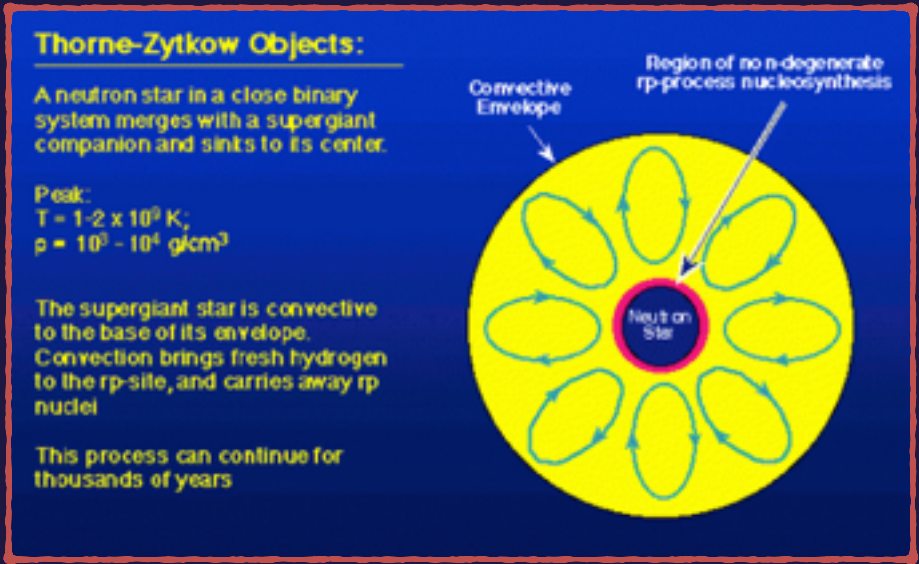
Where do galaxies get their gas, and how do they get rid of it?

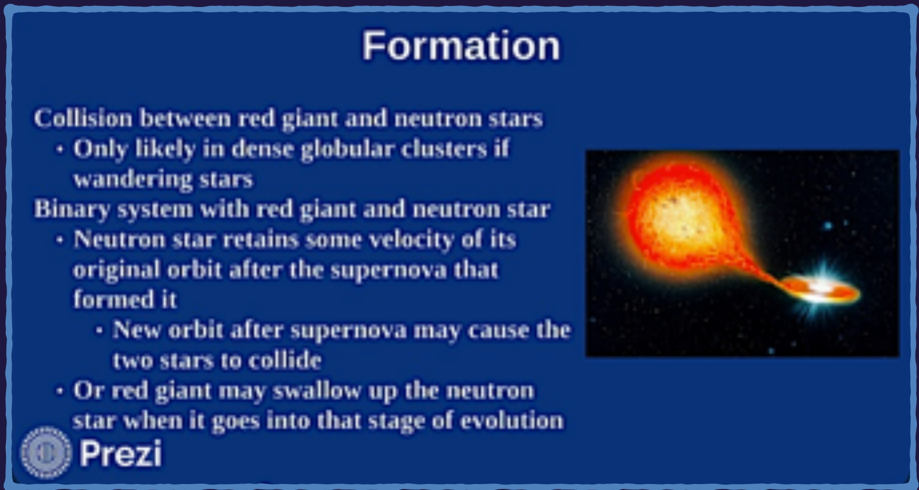
If a picture is worth a thousand words, the image to the left is a dictionary in a language with a few words and a lot of equations. The image caption reads, ‘The topology of halo-scale gas flows around a single TNG50 system, similar in mass to a Lyman-break galaxy. Streamlines of gas motion are overlaid on a line-integral convolution image of gas density modulated by its velocity field. Outflows emerge collimated from the central galaxy traverse half the virial radius (dotted circle), producing small-scale vortical motions as well as a large-scale, circulatory, galactic-fountain type flow confined within the halo virial radius.’ *Illustris TNG 50.*

Well, that’s one way of explaining it. Let’s see if we can break that down. The Cosmic Web comprises a great number of filamentary structures that flow into large cores (aka nodes). The nodes are filled with galactic superclusters of hundreds to thousands of galaxies; most of them are elliptical, meaning they have no starforming gas left. The filaments, on the other hand, are largely filled with spiral galaxies—a great many of them, in fact: our 30 megaparsec (98 million ly) in diameter Local Sheet being an example. Most of the spirals are aligned so their rotating discs line up with the filament flows. Enormous amounts of primordial hydrogen from the beginning of the universe flow down those filaments, and enter the spiral galaxies via their disc planes. (The video below shows how it works.) Once in the galaxy disc the gas naturally forms stars, many of which expire rather noisily as supernovae. On average a spiral galaxy can experience 25 to 45 supernovae every million years. The supernovae blow the gas upward and out of the galaxy back into deep space. Consider this whole exercise as a galaxy taking a deep breath, holding it, and finally exhaling a vast sigh. [That took 187 words, BTW.]

Watch the full-cycle video here.
Source: ARC Centre for All-Sky Astrophysics.

What is a Thorne-Żytkow object?
Can they actually exist?
Where would we look?





Of the all-too-many attempts to visually portray TZOs, a slide show by Megan Meraz produced in 2014 dos the best job of it. Source: *Formation and Properties of TZOs*.

A THORNE-ŻYTKOW OBJECT (TZO) is a so-far theoretical hybrid that consists of a neutron star that lies at the core of the red giant. One way a TZO could be created is from the evolution of a close binary of two stars of more than 8 solar masses which are tightly orbiting each other. (The supermassive RD20a binary in Westerlund 2 in Carina, weighing in at 81 and 82 solar masses, is a candidate for a TZO when one of the pair goes supernova—although stars that massive tend to implode directly into stellar-mass black holes, whereinafter they roam the galaxy and let's hope one doesn't lurk our way anytime soon.)

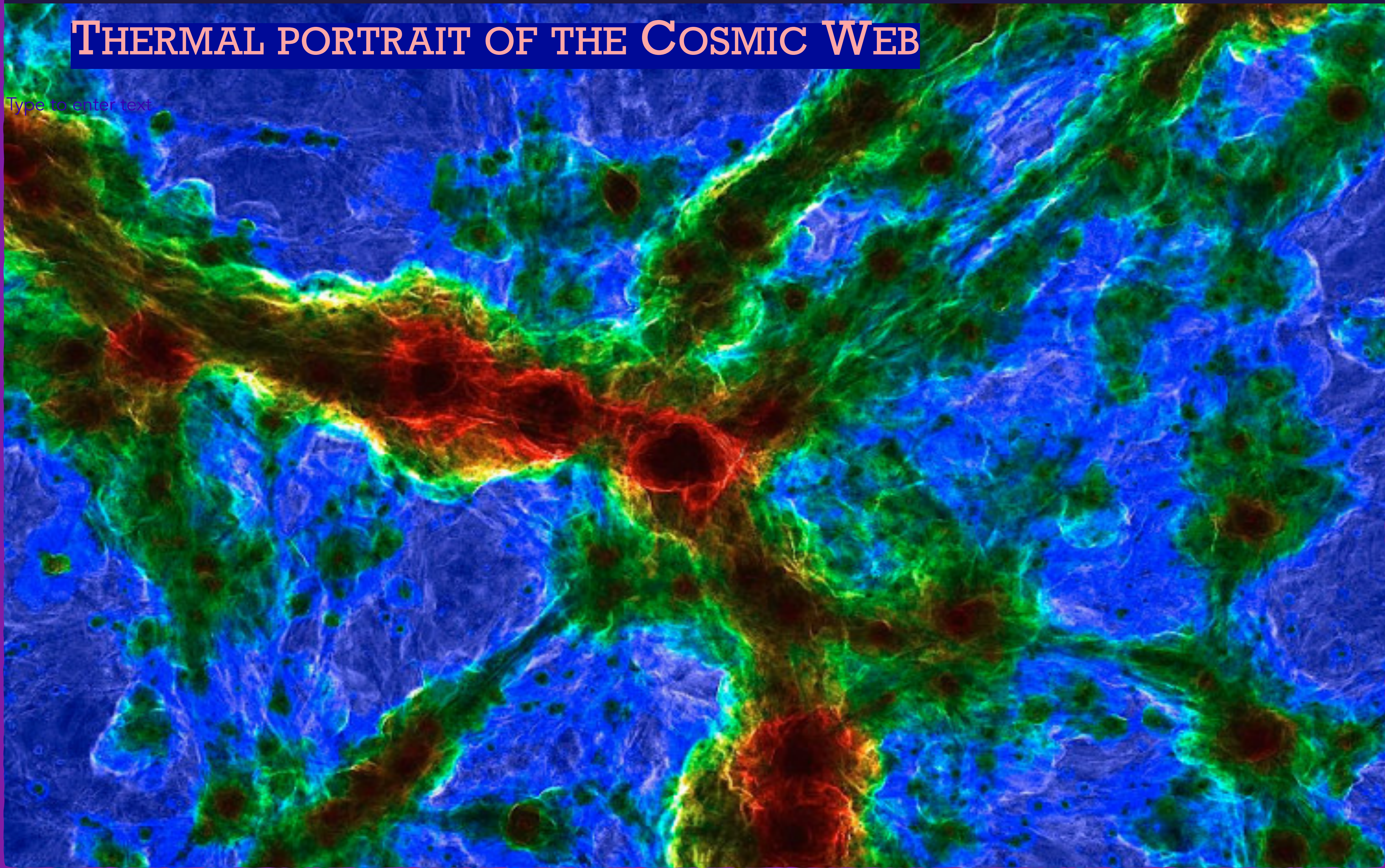
When the more massive star of a TZO pair explodes its core will likely be a dense neutron star. The blast wave and subsequent rebound shock wave tear huge chunks off the remaining star's hydrogen envelope, but do not disrupt the star's deeper layers so badly that it cannot recover its spherical shape in diminished form. Even so, it is still too massive to avoid going supernova; it just has to wait awhile.

As the neutron star gains mass from tidally stripping the red supergiant, it spirals inward and sinks into the hydrogen envelope of the red supergiant. Eventually the neutron star will sink to the core, but because its surface temperature at that stage of its life is around 1 billion K, it causes enormous havoc to the chemical mixes in the carbon-oxygen, nitrogen, neon, manganese, and silicon layers it spirals through on its way to the core. Since the neutron star is so tiny relative to the star it invades, the thermal and nuclear havoc it wreaks is local, but in the process such searing amounts of local thermal energy create elements that seldom appear in normal supernovae, e.g. rubidium, molybdenum, lithium, and calcium via *rapid proton nucleosynthesis*. Once the neutron star reaches the core of its hapless host galaxy, it is as hot or hotter than the core of the star it resides within.

All this messy nuclear aberrancy takes 100,000 to a million years yet observers on Earth would be blissfully unaware of anything amiss—until the neutron star reaches the core of the red supergiant. That core will be so dense it is nearly the same as the invader's. The two merge so violently that gravitational waves radiate at the speed of light into the universe. Our Ligo and Virgo detectors would spot the signal not as the usual neutron merger signal of a 0.2 second chirp but as a much weaker continuous wave until the star converts into its next brief stage, a WN8 nitrogen-rich Wolf-Rayet star. You can read Kip Thorne and Anna Zytkow's *original source paper here*, but be forewarned, it is very maths-dense.

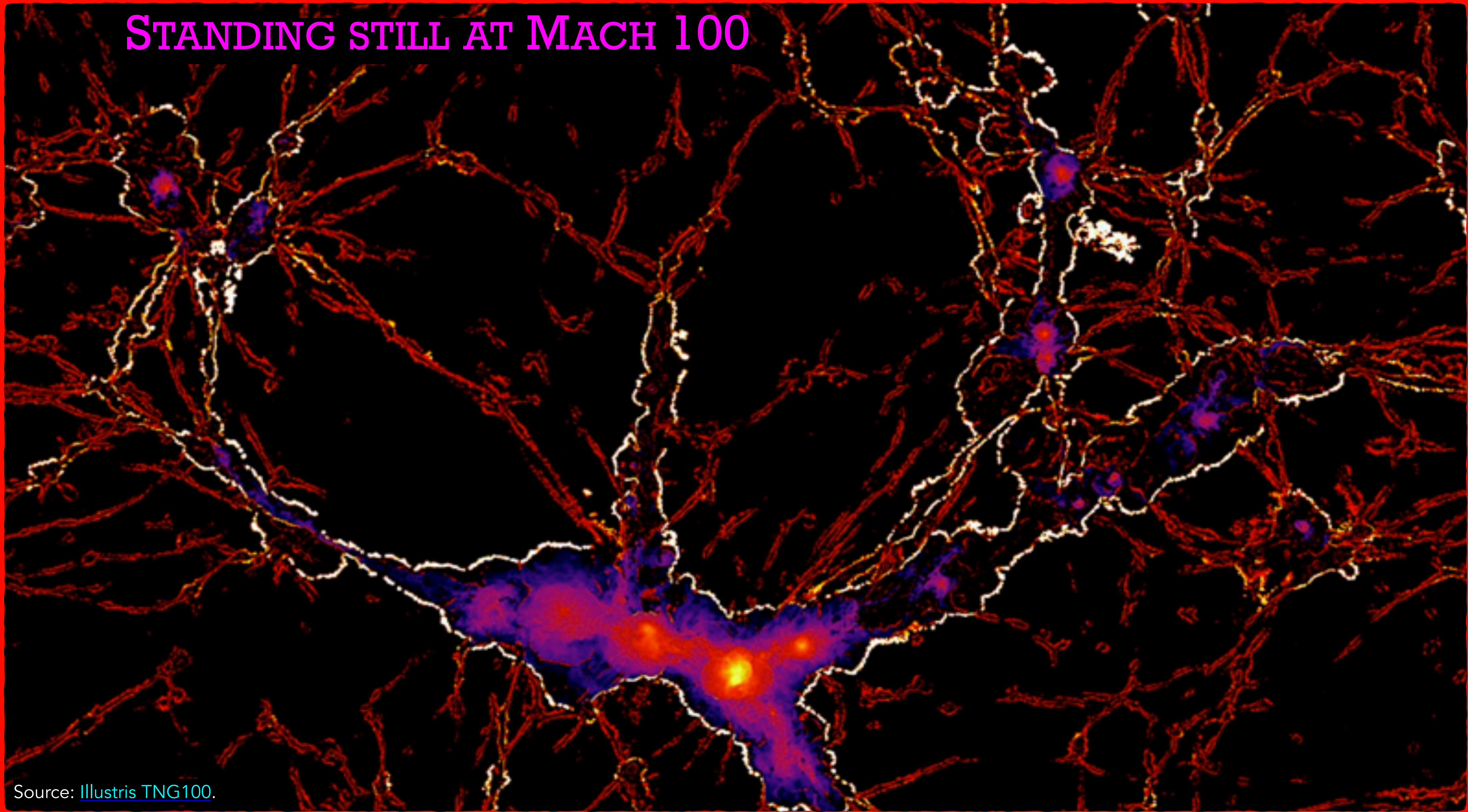
How would someone look for such a star? Well, in the words of the paper itself (p. 833), 'the only distinguishing external feature of our models with neutron cores is their extreme redness : because they sit precisely on the edge of the Hayashi forbidden region, they must be the reddest stars in the universe; but they will be redder than stars at the tip of the normal giant branch by only a very slight amount, $\Delta \log T_{ph} \ll 0.1$.' Source: *Astrophysical Journal*, 212 832-858 15 Mar 1977.

THERMAL PORTRAIT OF THE COSMIC WEB



You CAN hear a scream in space! You just need the right ears to do it. Twenty octaves below our hearing range just might do it. Conversely, we CANNOT feel temperature in space, even though intergalactic temperatures in scenes like the above range from 100 million degrees K and upward. But stick your finger out the spacecraft port and it will instantly freeze. *Illustris TNG 100 fullbox composite* which combines gas temperature (as the color) and shock mach number (as the brightness). Red indicates 10 million Kelvin gas at the centres of massive galaxy clusters, while bright structures show diffuse gas from the intergalactic medium shock heating at the boundary between cosmic voids and filaments. *Watch this Illustris video of the magnetic B-field shaping gas flows on 100 MPc intercluster scales.*

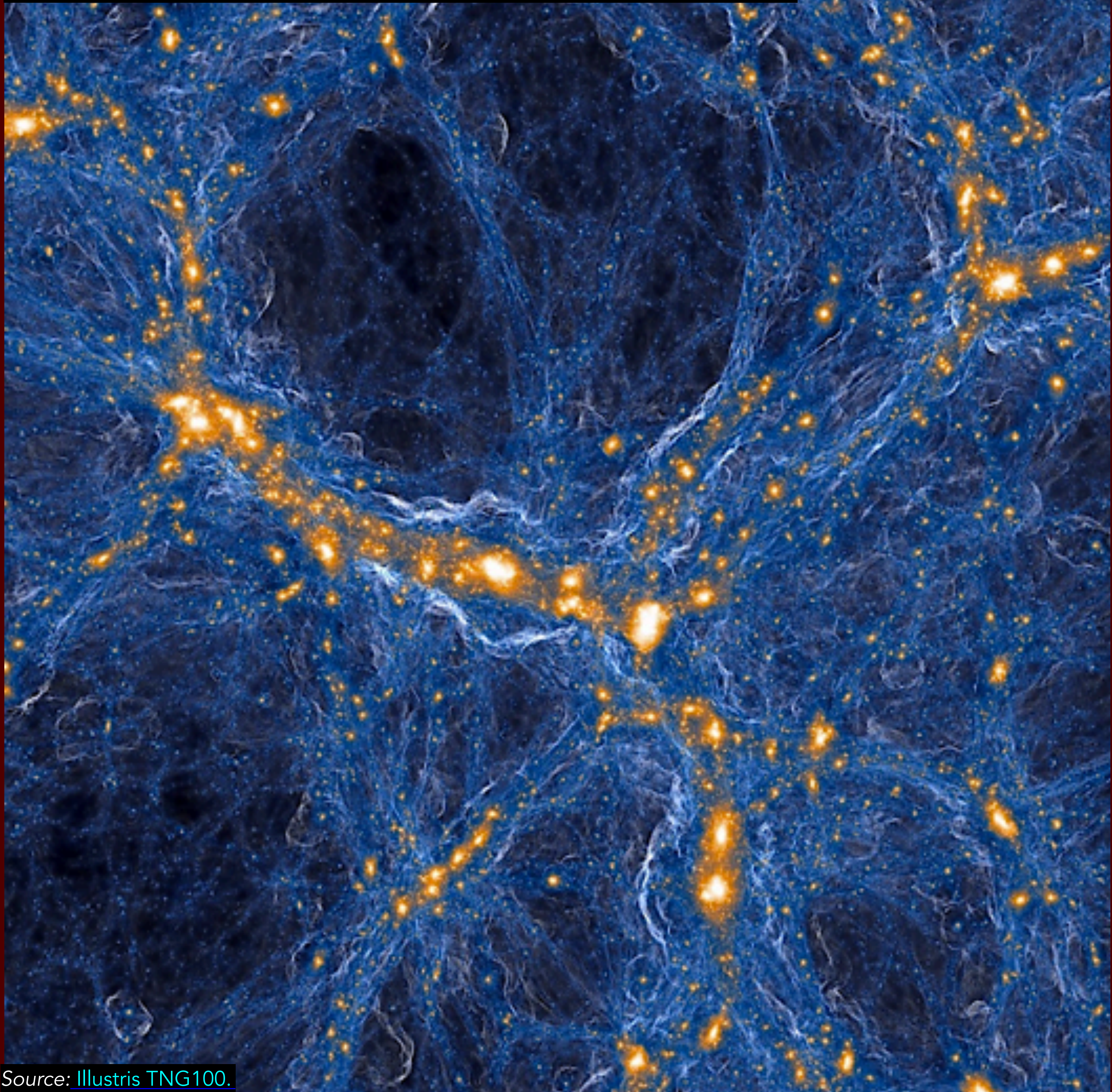
Standing still at Mach 100



Source: Illustris TNG100.

Mach speed propagates data across cosmological space just as it propagates data from the space between you and your hi-fi speakers across the room. Mach 1 is the speed at which compression and rarefaction waves move through the local medium. The medium can be as dense as lead or as thin as hydrogen atoms in a cosmic void — roughly 1 atom in a sphere the diameter of you standing tiptoe with your arms raised straight up. In this image the thin primordial hydrogen gas in the inky dark voids is pulled out of the voids by the gravitational attraction of ribbon-like cosmic filaments and clumpy galaxy superclusters like Virgo, Hercules, Perseus-Pisces, the Shapley Supercluster, Great Wall, and others even more remote. The outflowing void gas is supersonic compared with the dense gas in the filaments and clusters. As the gas enters the density gradient of the filament surfaces it slows down abruptly to the subsonic velocity that prevails inside filament. The atoms' supersonic energy is converted into thermal kinetic energy, or temperature. The glowing edges in this simulation are hydrodynamic shock zones – sonic booms millions of light-years long, which mark the boundaries between voids and gaseous halos.

The more we look the more we see



Source: Illustris TNG100.

Our awareness of the *Cosmic Web* began with four landmark papers by Yakov Zel'dovich in 1968–70 on the subjects of large-scale gravitational instability, magnetic inhomogeneity, shock waves at high temperatures, and adiabatic heating. These set forth the basic properties of the Cosmic Web as we know it today. The Web has become vastly more complicated as equipment and theory improved over the next five decades. Today out picture of the Cosmic Web looks like the image to the left. The supposedly empty voids are in fact interlaced with gas filaments and modestly sized galaxy clusters. Intercluster filaments are now seen to be complex highways of mainly spiral galaxies and gas funnelling fresh matter and energy into the beclotted nodes of galaxy superclusters. The filaments have now been found to be rotating in helicoid tubes, a phenomenon that has yet to be fully explained—but which was predicted in Zel'dovich's 1970 paper on magnetic inhomogeneity in the Cosmic Web. The image to the left is a portrait of the detail and complexity of the Web as we know it today. The Cosmic Web looks remarkably like a neural network, and the physics of mass, energy, and time give the impression that we are looking at a life form that exists on time and sizes scales we cannot imagine.

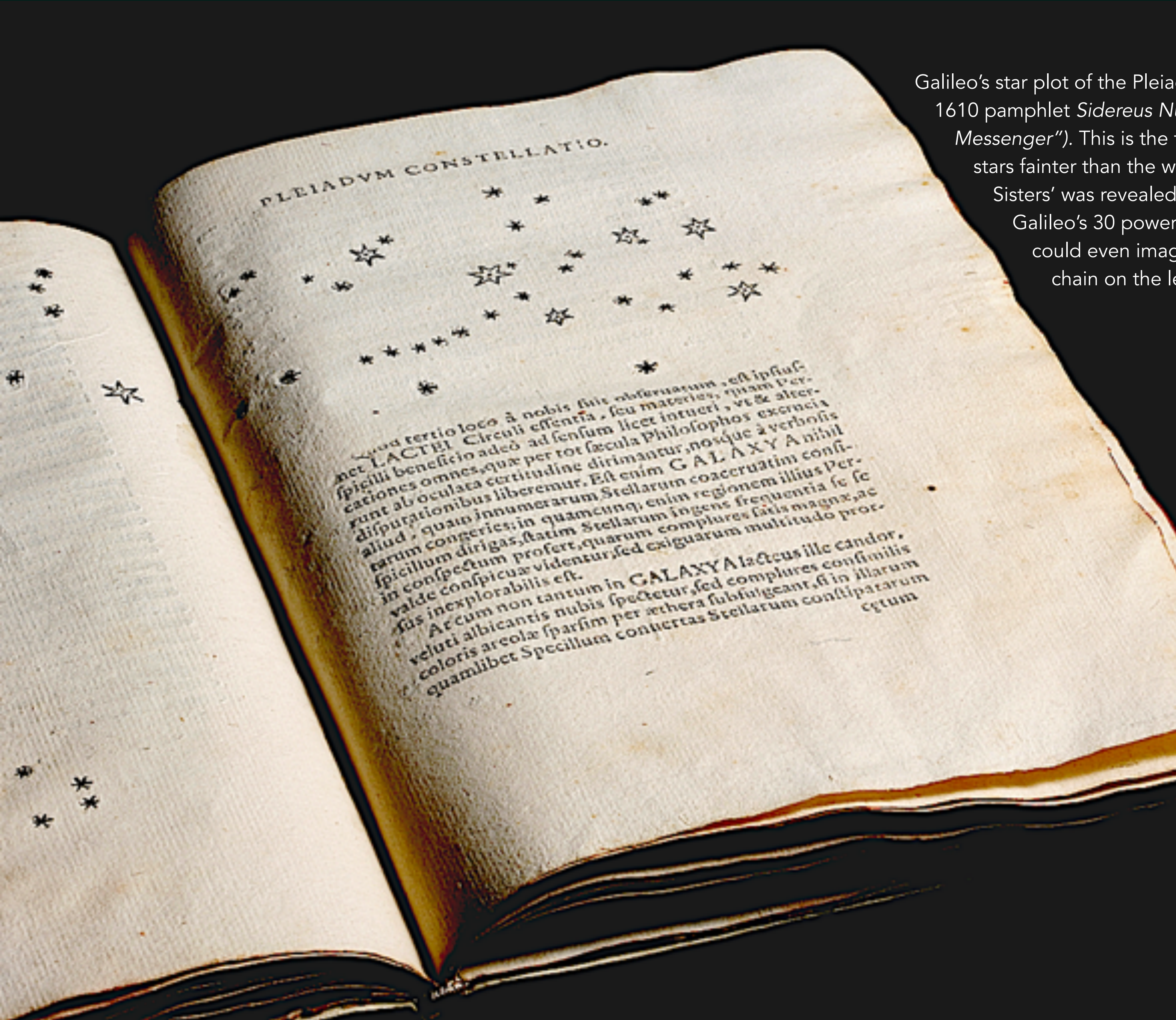
From the website:

Composite image of the full TNG100-1 box which overlays a projection of the dark matter density with the output of our on-the-fly cosmological shock finder, here used to derive the average mach number of shocks along each line of sight. All the gravitationally collapsed structures (in orange/white) are surrounded by successive shock surfaces (blue) which encode their formation histories

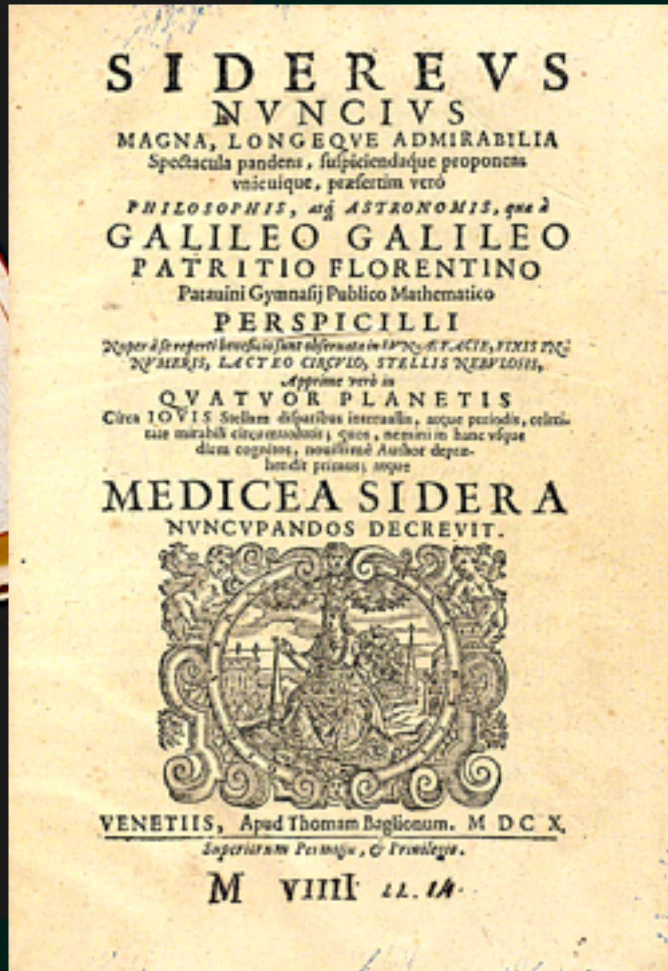
Sometimes it is good to dream about something besides stars

Fishing in spring the Pont de Clichy (Asnieres), Vincent Van Gogh, 1887

On the other hand, look what happens when you dream about stars



Galileo's star plot of the Pleiades from his March 1610 pamphlet *Sidereus Nuncius ('Sidereal Messenger")*. This is the first time the Pleiades stars fainter than the well-known 'Seven Sisters' was revealed to the world. Until Galileo's 30 power telescope, no one could even imagine the distinctive starry chain on the left side of the cluster.



SIDEREVS
NVNCIVS
MAGNA, LONGEQVE ADMIRABILIA
Spectacula pandens, suspiciendaque proponens
vnicuique, præsertim verò
PHILOSOPHIS, atq; ASTRONOMIS, quæ à
GALILEO GALILEO
PATRITIO FLORENTINO
Patauini Gymnasij Publico Mathematico
PERSPICILLI
Nuper à se reperti beneficio sunt obseruata in LVNÆ FACIE, FIXIS INNUMERIS, LACTEO CIRCVLO, STELLIS NEBVLOSIS,
Apprime verò in
QVATVOR PLANETIS
Circa IOVIS Stellam disparibus interuallis, atque periodis, celeritate mirabili circumuolutis; quos, nemini in hanc vsque diem cognitos, nouissimè Author deprehendit primus; atque
MEDICEA SIDERA
NVNCVPANDOS DECREVIT.
VENETIIS, Apud Thomam Baglionum. M DC X.
Superiorum Permissu, & Priuilegio.
M VIIII

Source: *Houghton Library, Harvard, Public Domain*.

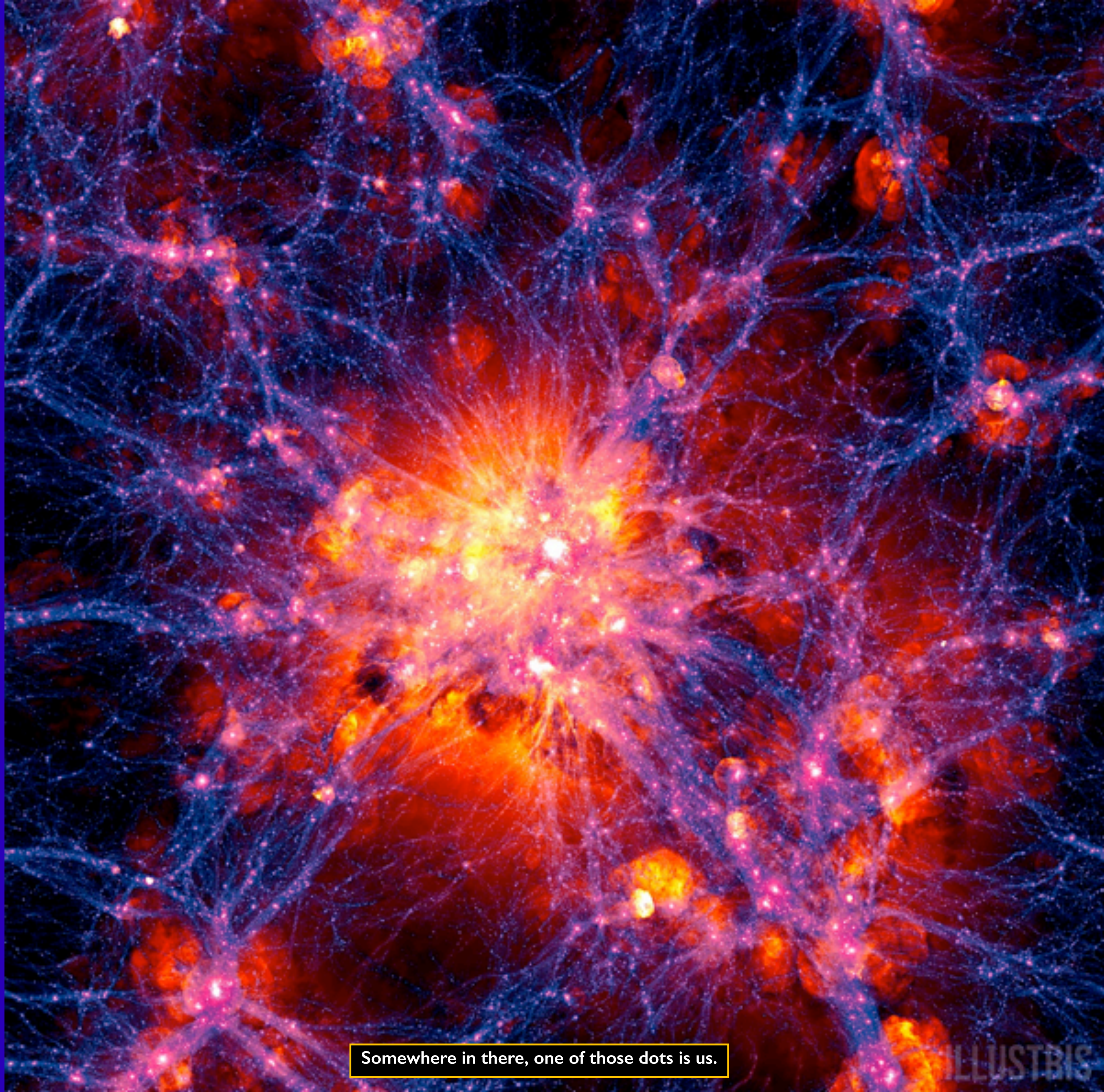
1611

Galileo's back-of-the-envelope drawings of Jupiter's moons

We still use the backs of envelopes

2021

They're just better



Somewhere in there, one of those dots is us.

Astronomical Society of Southern Africa

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ISSN 2617-7331