The First Stars

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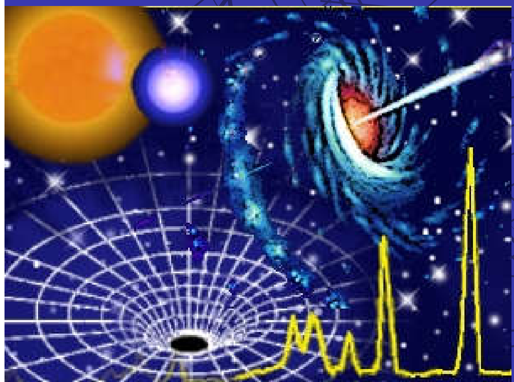

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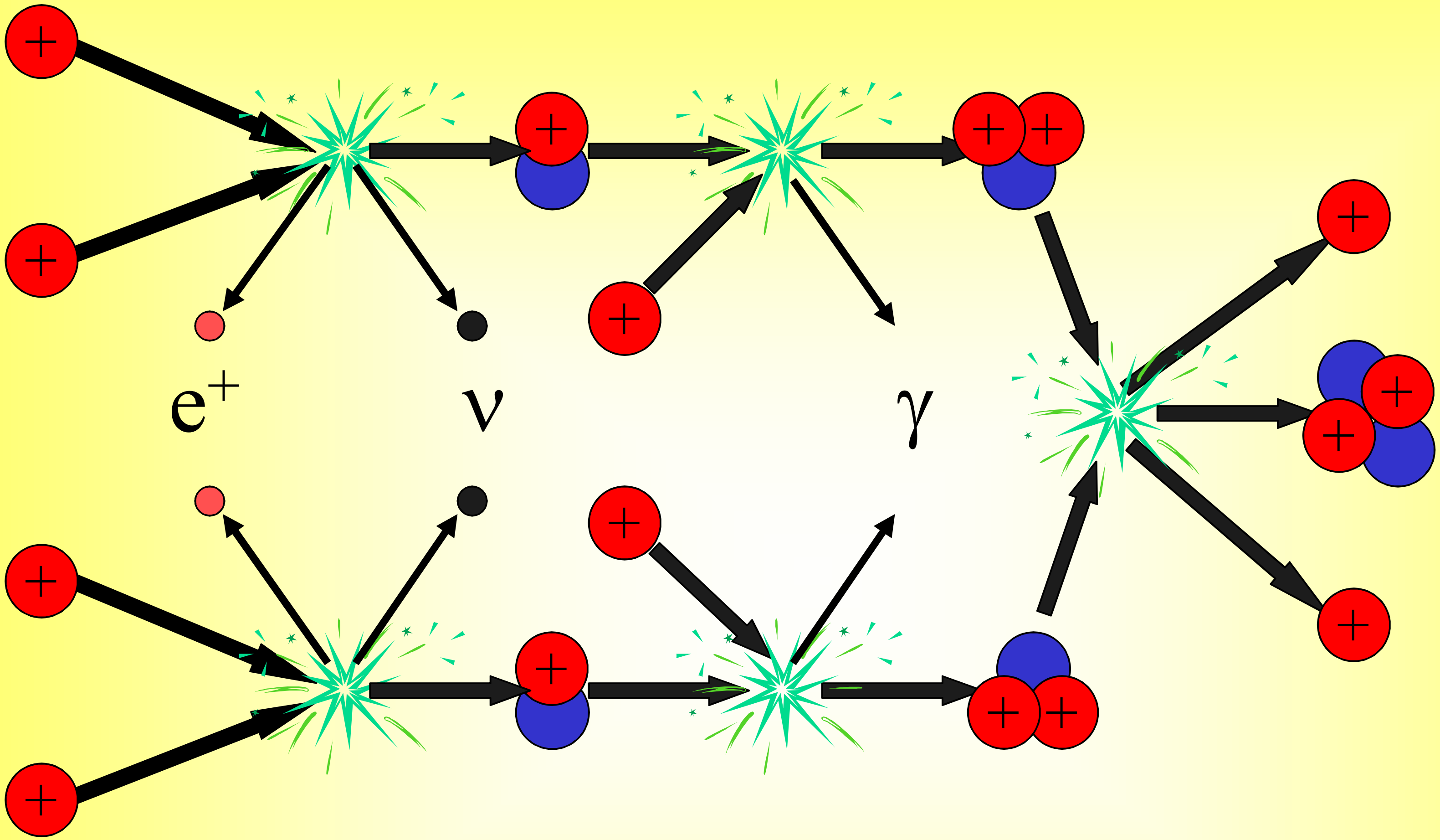
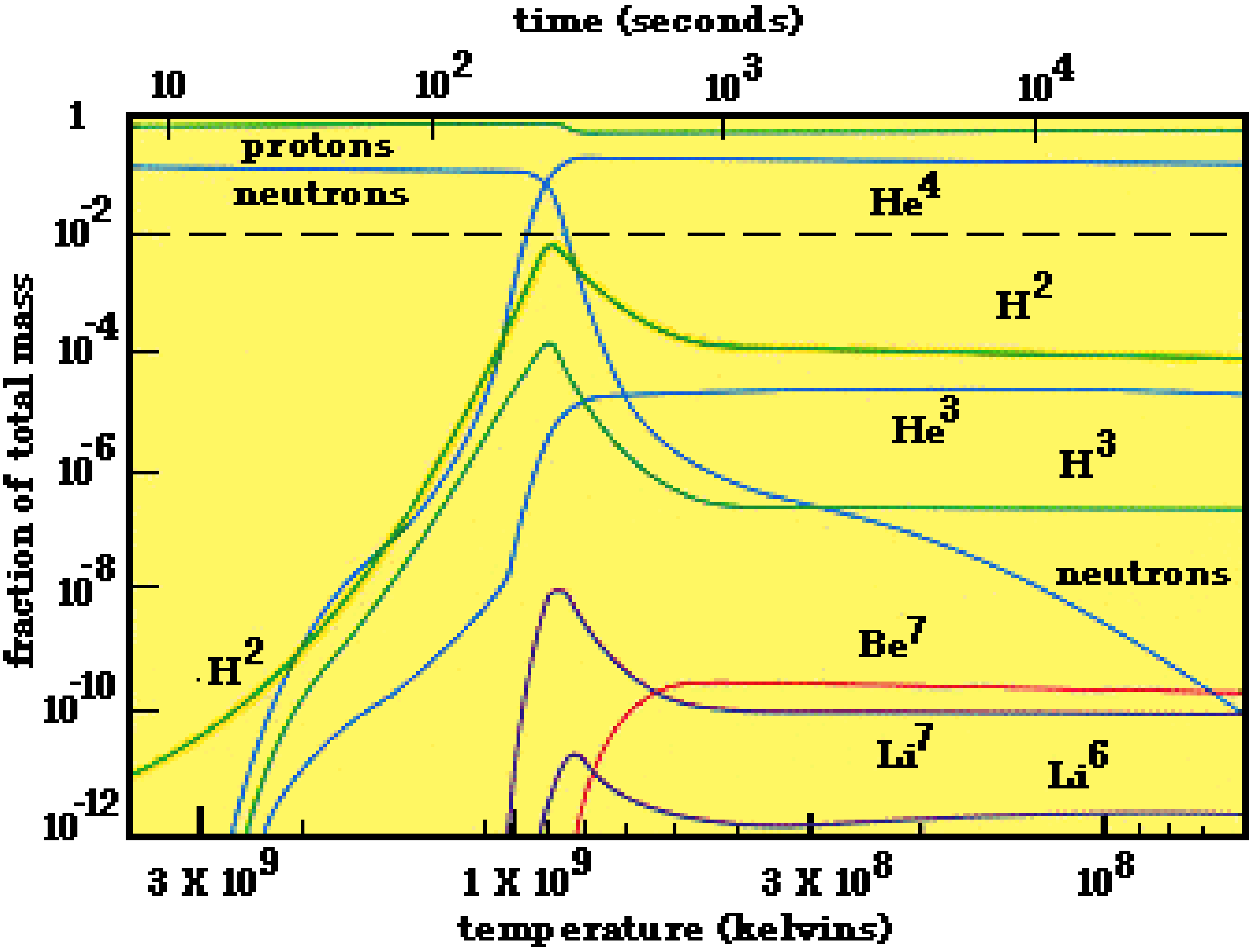
The Big Bang

- Universe created at t=0 in hot dense phase, immediately starts to expand and cool
- Cosmic Microwave Background Radiation with T = 2.7K that pervades all of space is remnant from this fireball phase.
- At t~1s protons and nucleons condense out of hot plasma
- In the first 3 mins nucleosynthesis creates H, D, ^{3}He, ^{4}He, ^{7}Li, ^{7}Be. No metals!
- Density perturbations led to formation of structure within which the first stars formed.

The PP I Chain

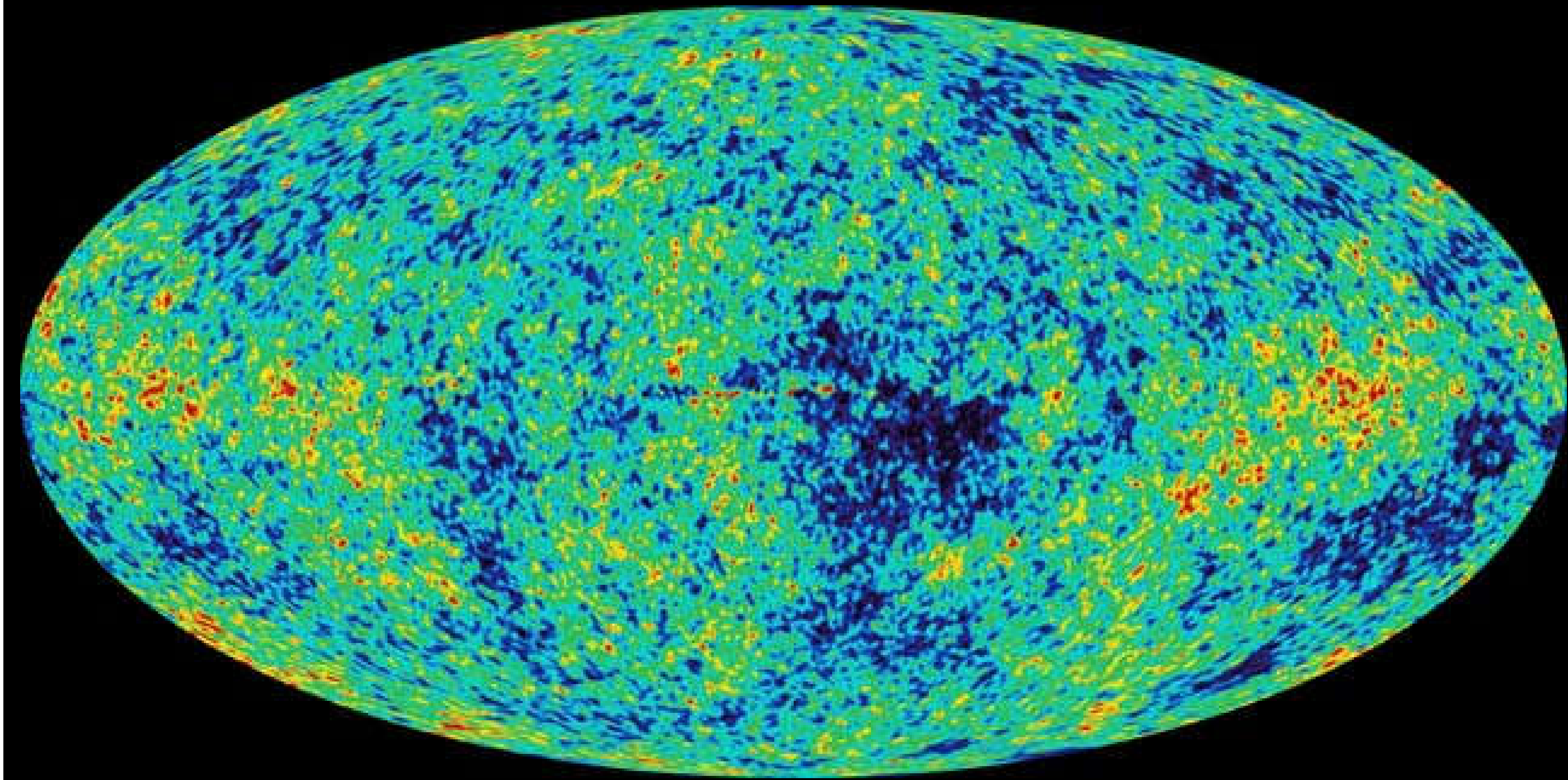


$4\ {}^{1}\mathrm{H}\ \square\ {}^{4}_{2}\mathrm{He} + 2e^{+} + 2\nu + 2\gamma$ 26.2 (0.52) MeV



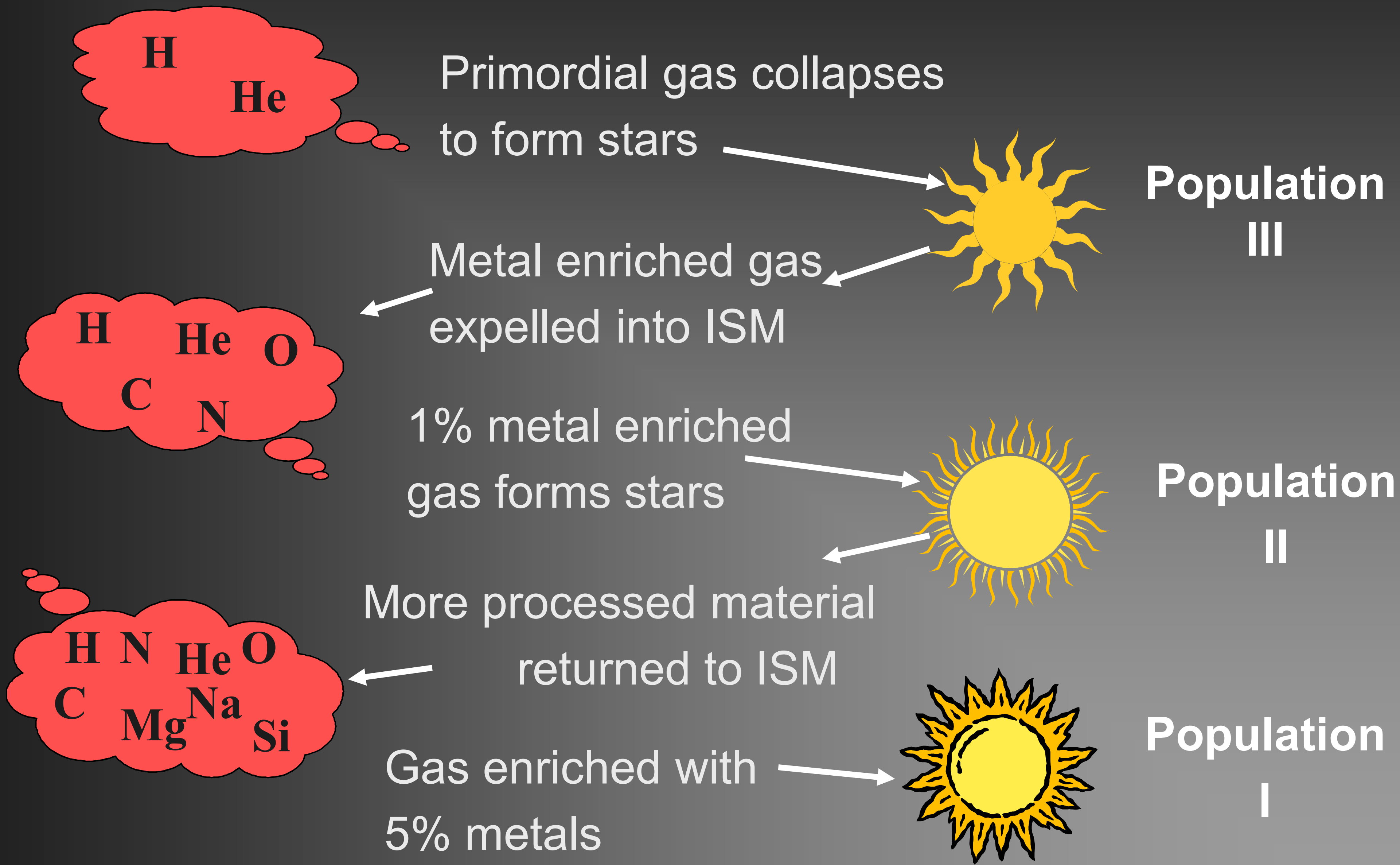
time (seconds)
10
10^2
10^3
10^4
1
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
fraction of total mass
protons
neutrons
He^4
H^2
He^3
H^3
neutrons
Be^7
H^2
Li^7
Li^6
3×10^9
1×10^9
3×10^8
10^8
temperature (kelvins)

WMAP Plot of Temperature Perturbations in CMBR



Red = Hot = High Density   Blue = Cold = Low Density

Cosmic Element Factory



First stars made entirely of primordial material i.e. only H & He

No such stars have been found; find old stars with low metallicity (Pop II stars)

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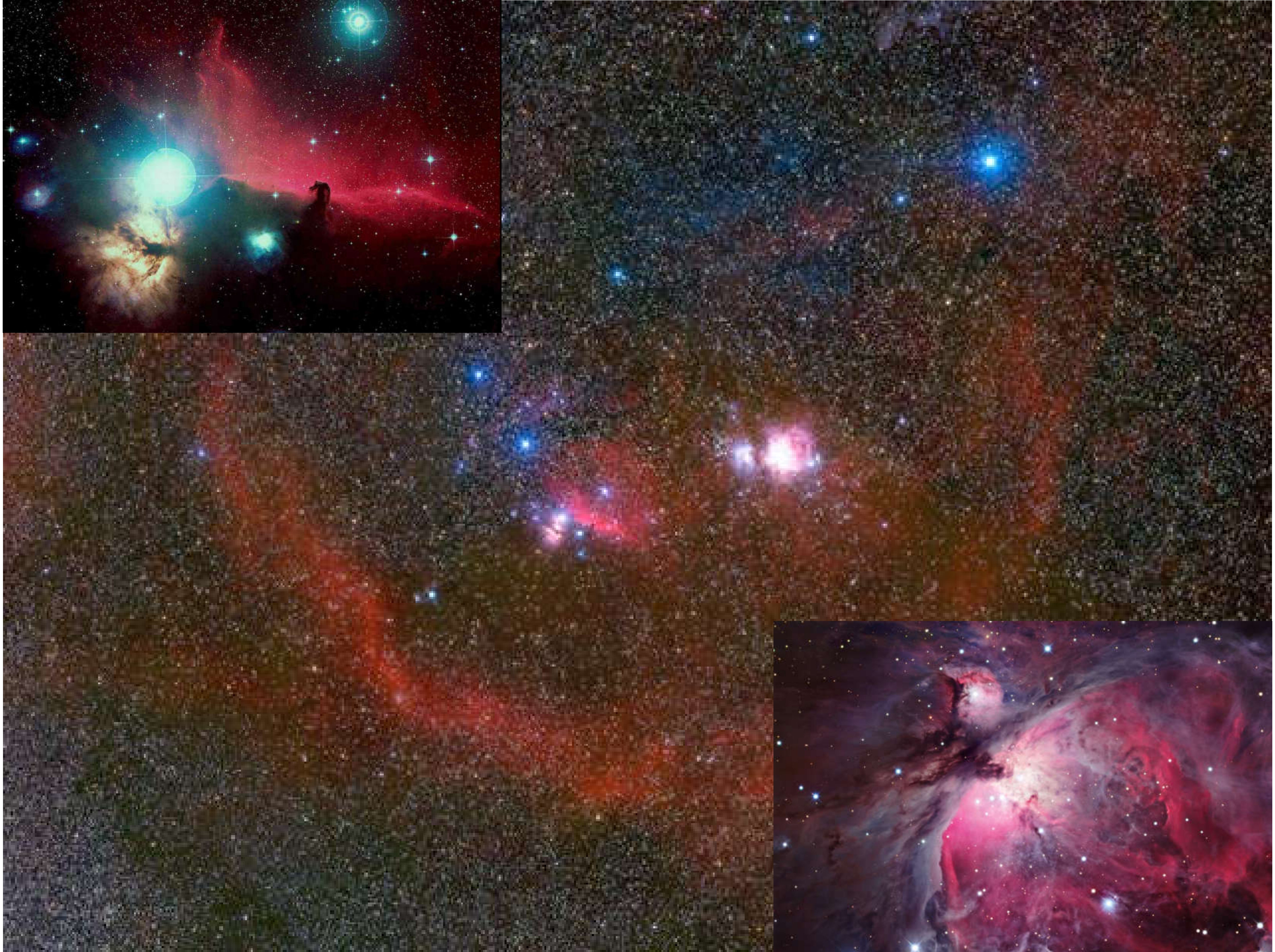
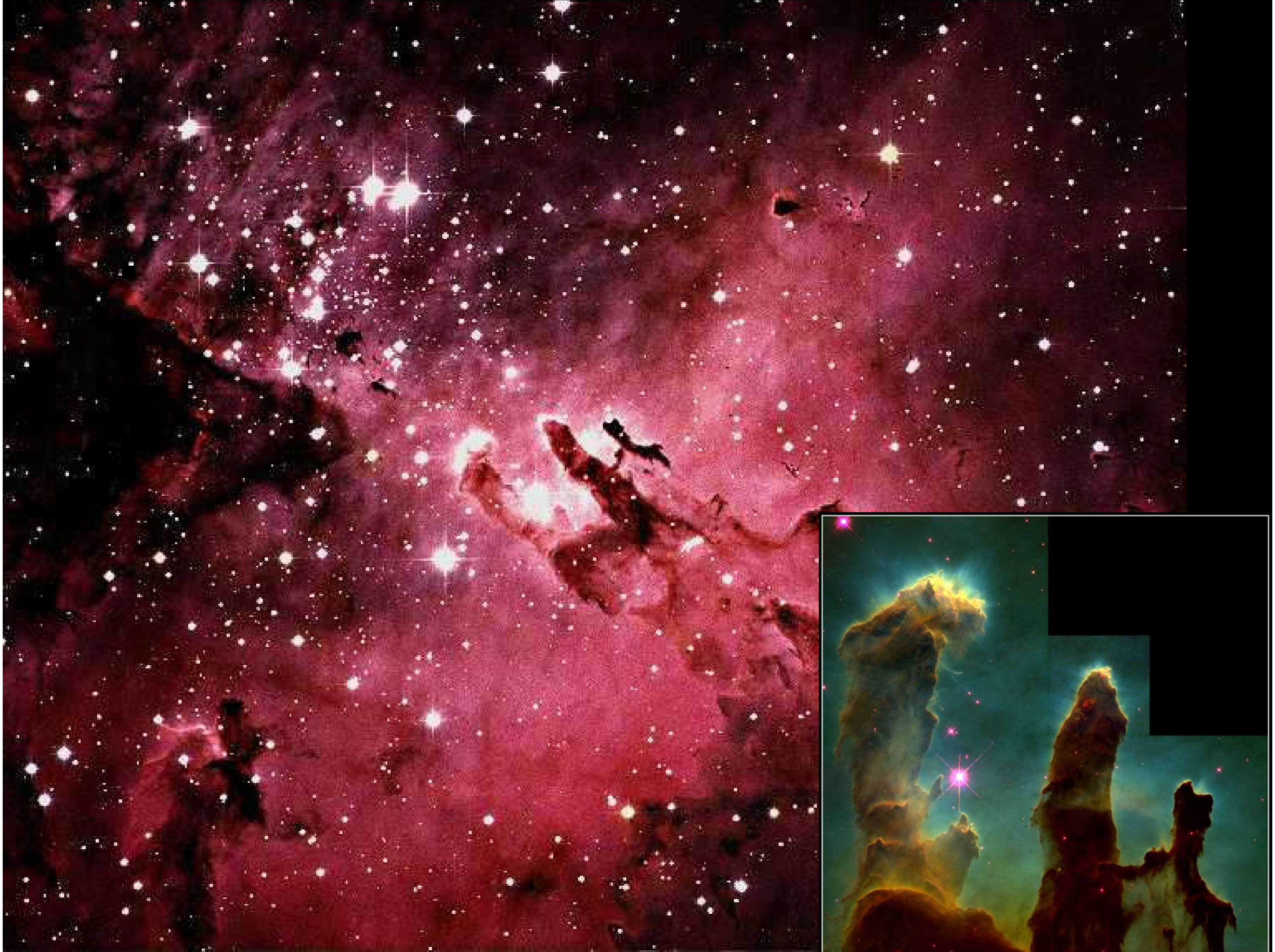
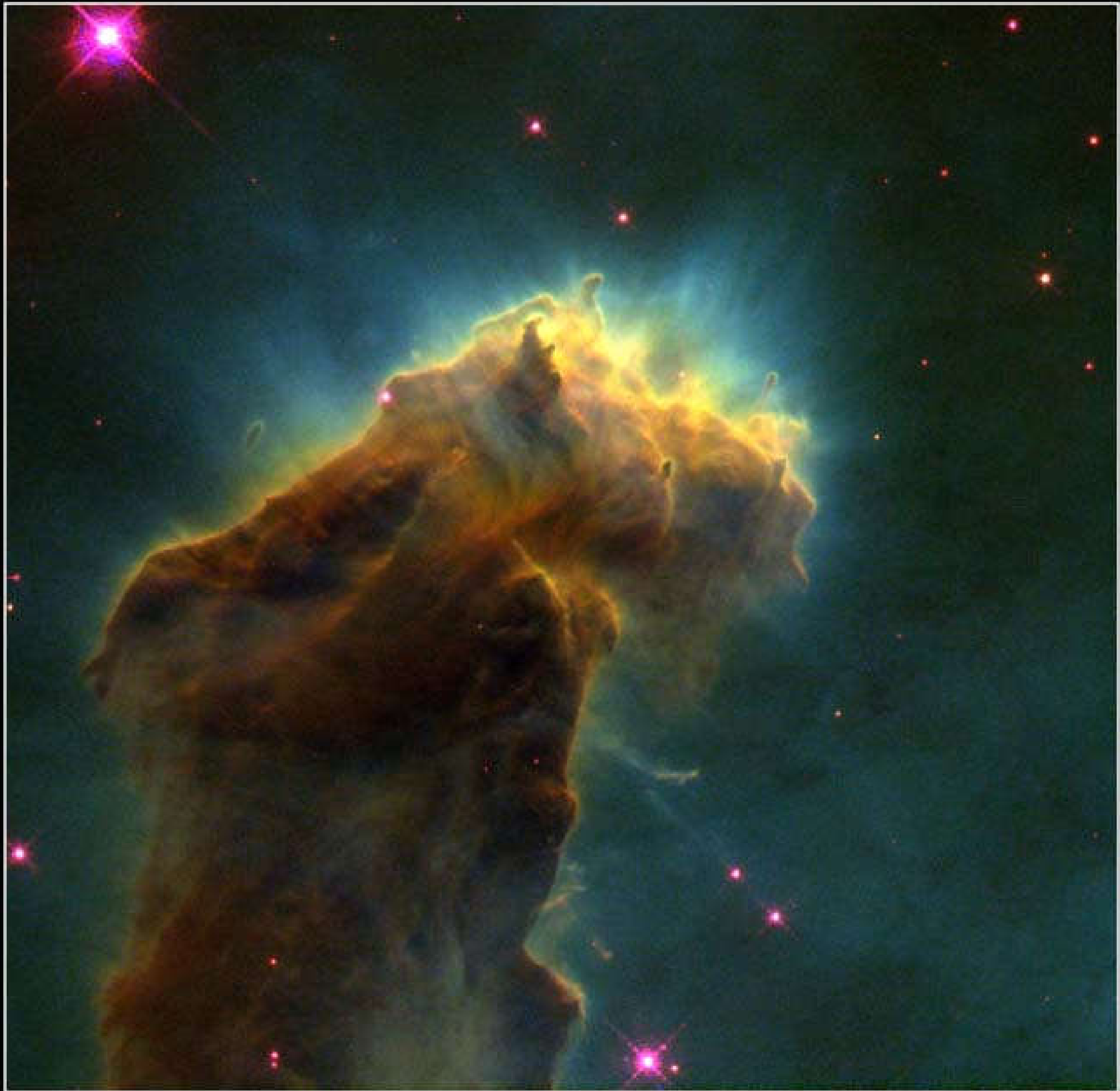
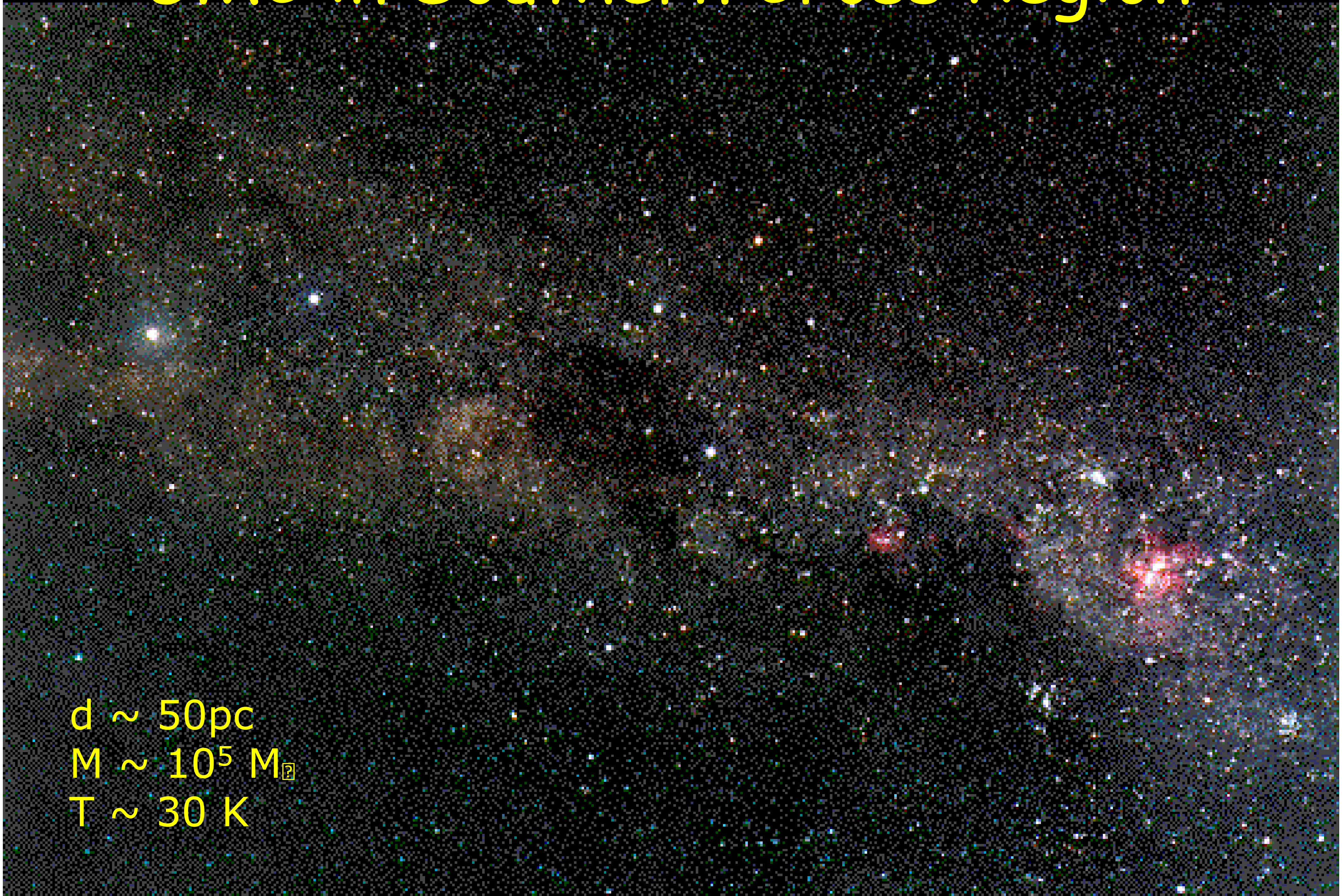






Star-Birth Clouds · M16 HST · WFPC2

GMC in Southern Cross Region



Bok
Globule

Dust

1. Smoke = product of combustion, hence often C based
   Dust = finely powdered material from abrasion of solids

2. In astronomy dust = heavy elements locked up in submicron sized particles containing ~ 10^9 particles

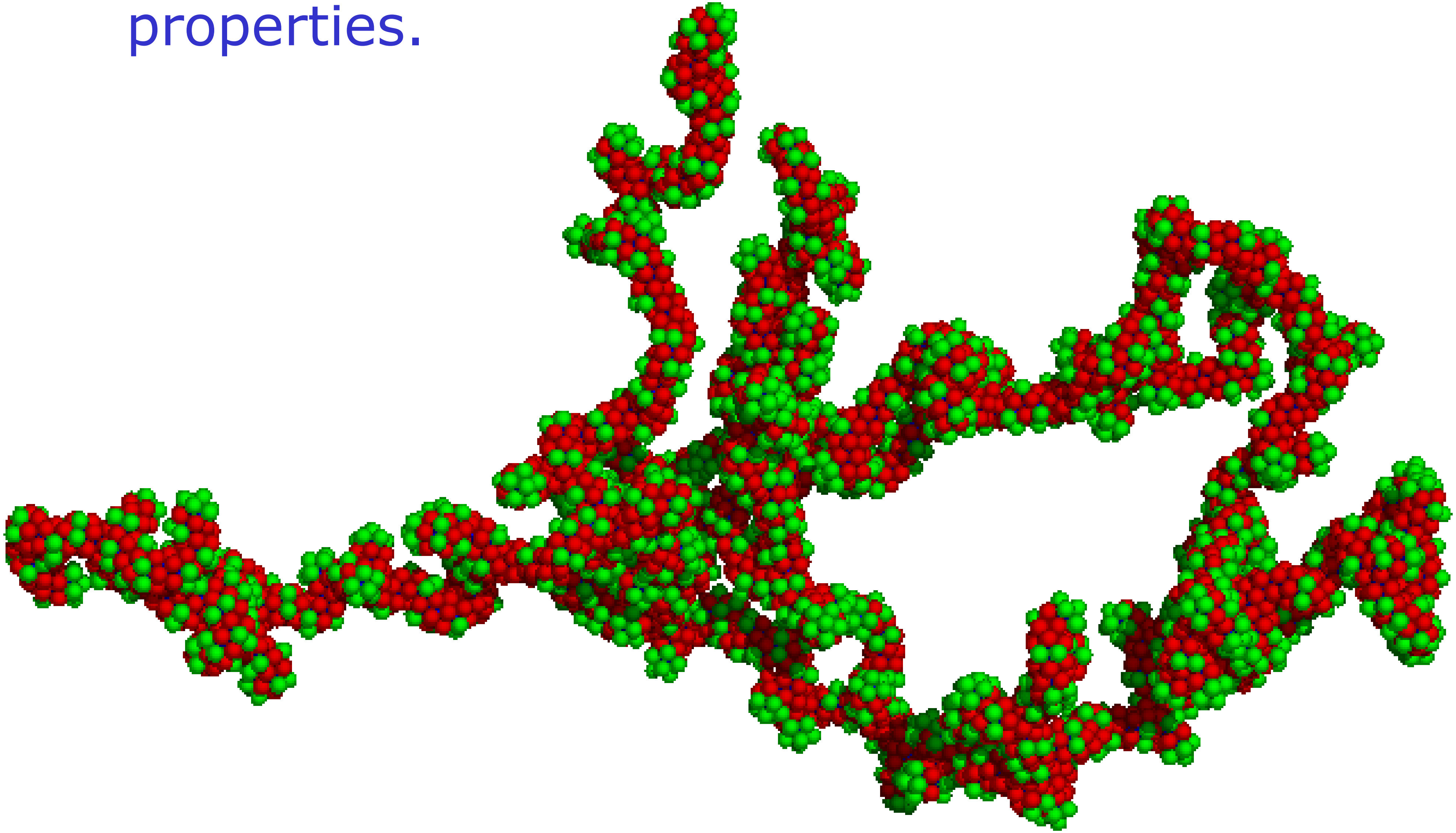
3. Makes up ~1% of mass of ISM

4. Grains play a catalytic role in interstellar chemistry; H atoms trapped in surface defects in grain structure combine to form H_2 then ejected from surface = main mechanism for H_2 production in Universe

5. Influence molecular abundances by reducing intensity of dissociating radiation

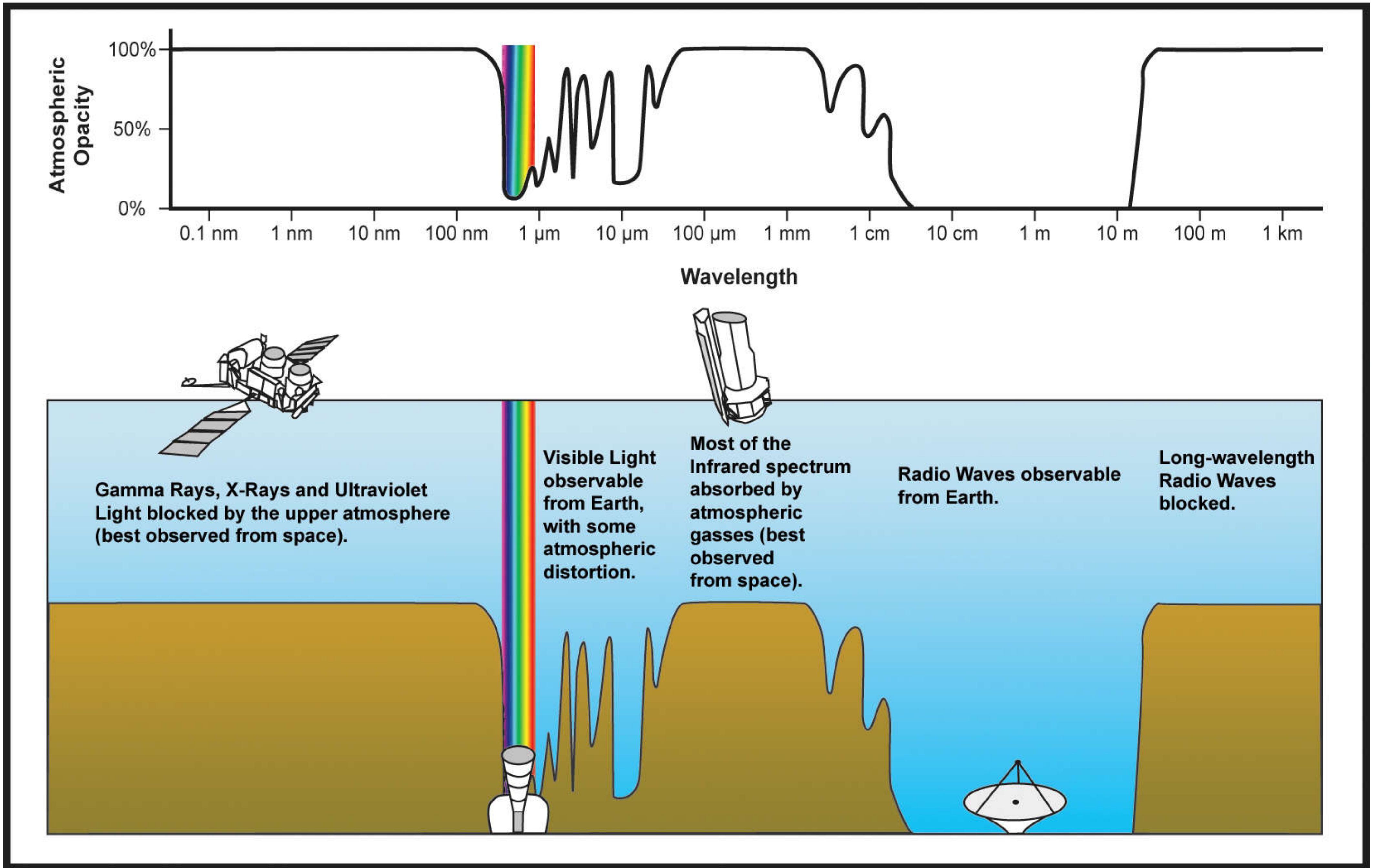
6. Opaque to optical light but transparent to longer wavelengths

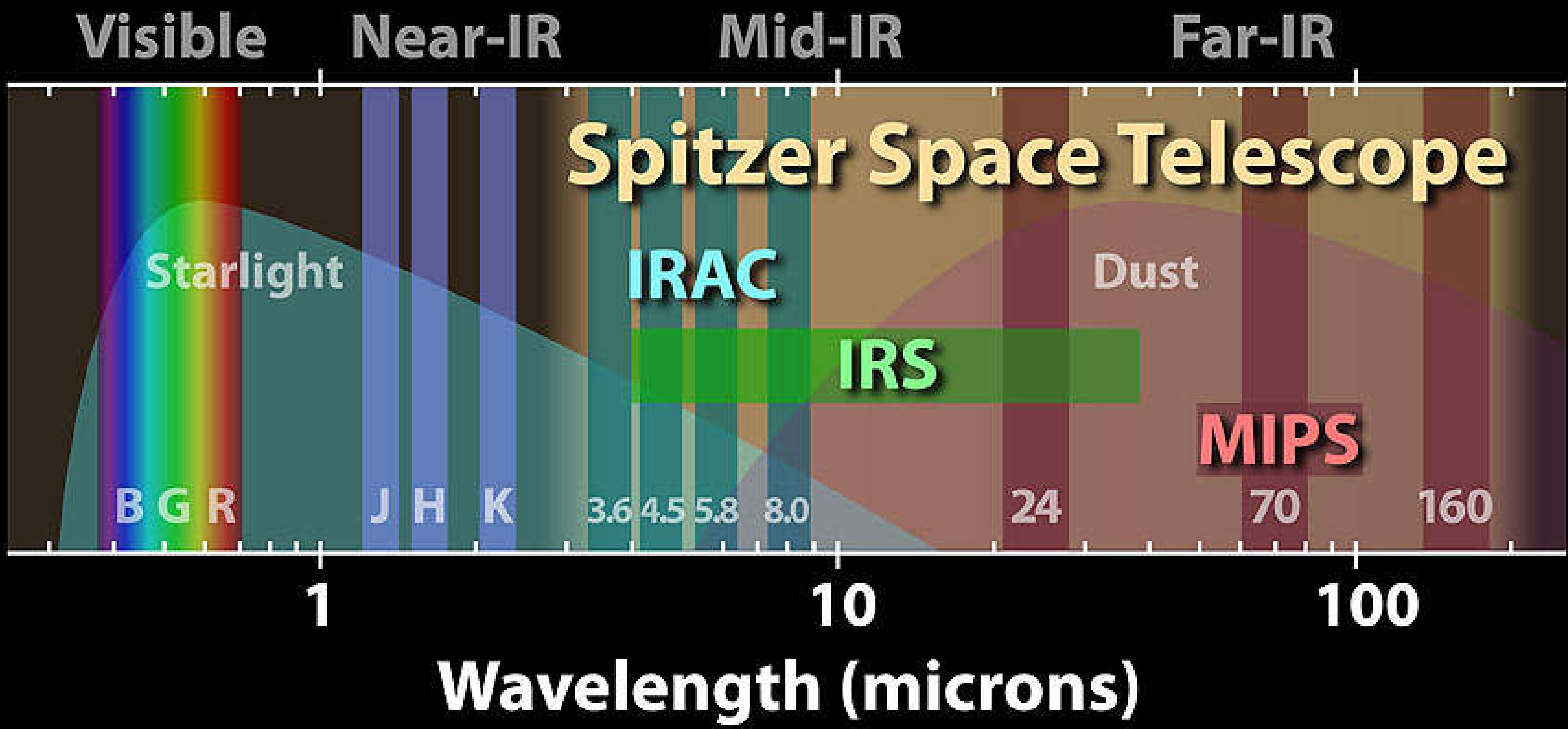
Fractal adhesion model for dust grains involving random conglomerates of spherical compounds of different properties.

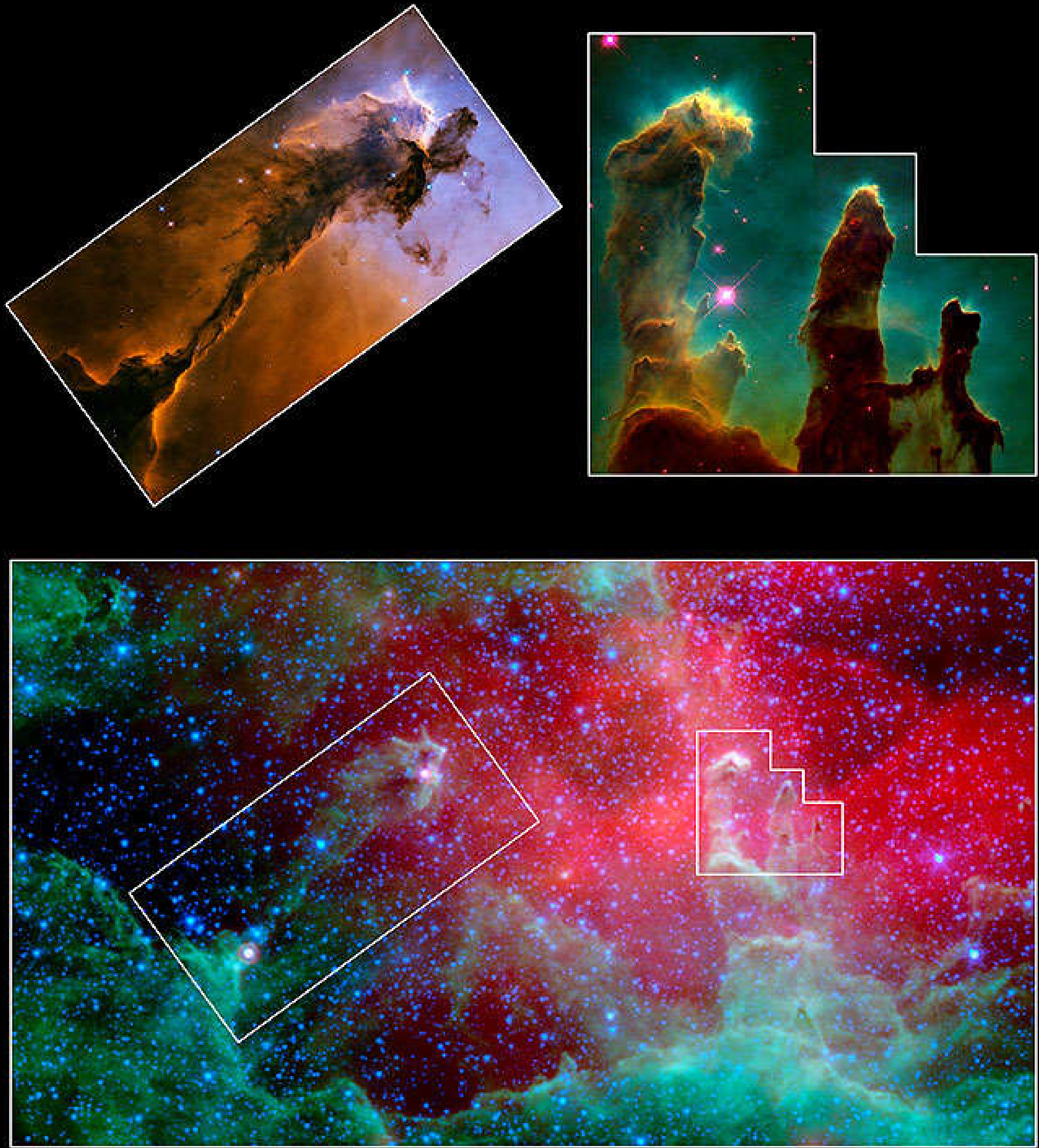


A piece of interplanetary dust, composed of glass, carbon and a conglomeration of silicate mineral grains. Size = 10 microns.

Atmospheric Opacity

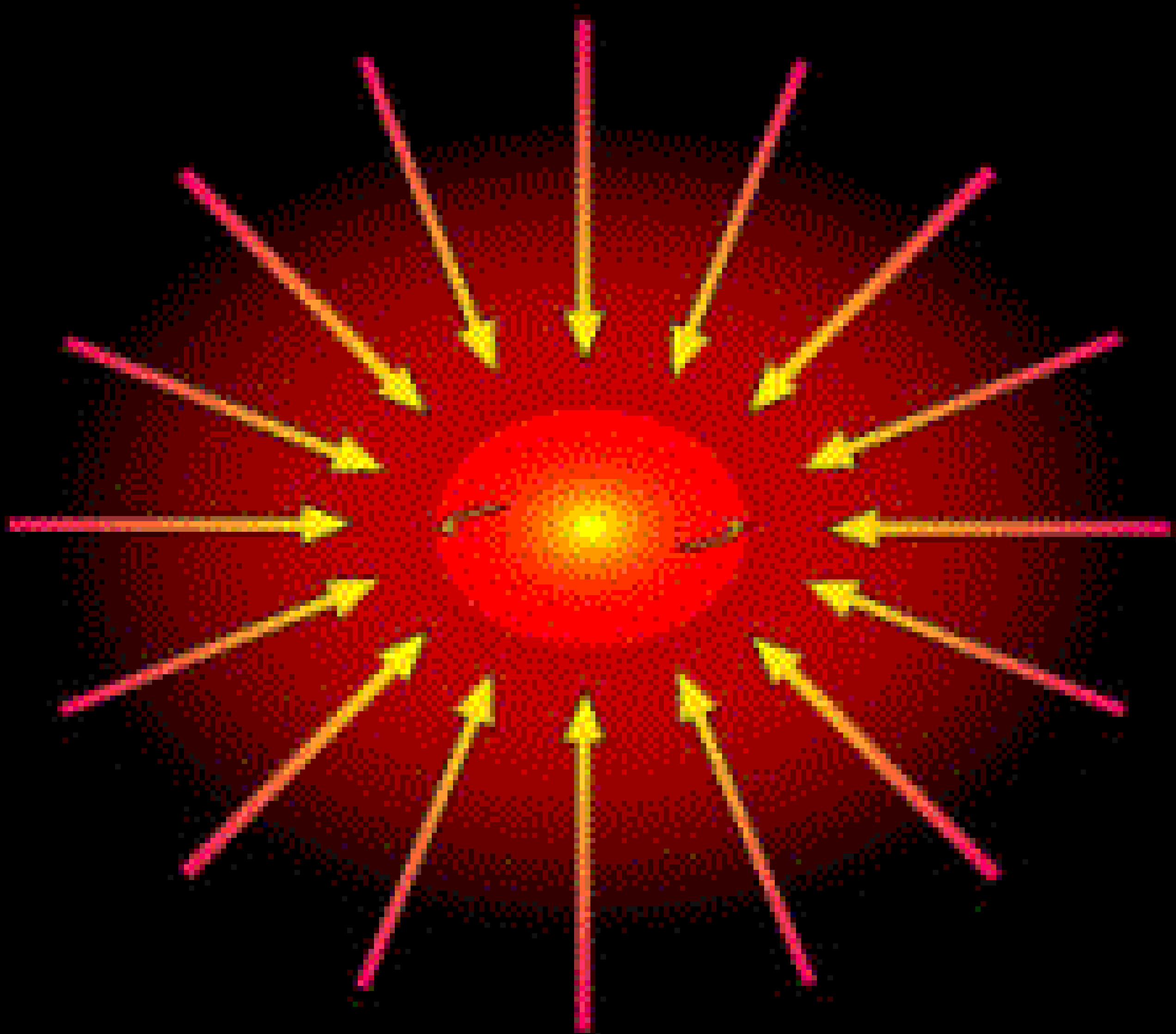



Visible
Near-IR
Mid-IR
Far-IR
Spitzer Space Telescope
Starlight
IRAC
Dust
IRS
MIPS
B G R
J H K
3.6 4.5 5.8 8.0
24
70
160
1
10
100
Wavelength (microns)



Eagle Nebula (M16) Pillars   Spitzer Space Telescope • IRAC • MIPS

Cloud Collapse



Heat generated by in-falling material must be efficiently removed to prevent disruption of the core by turbulence.

Radio – FIR radiation produced by blackbody radiation from dust and radiative transitions of vibrating and rotating molecules can escape from the gas and keep it cool

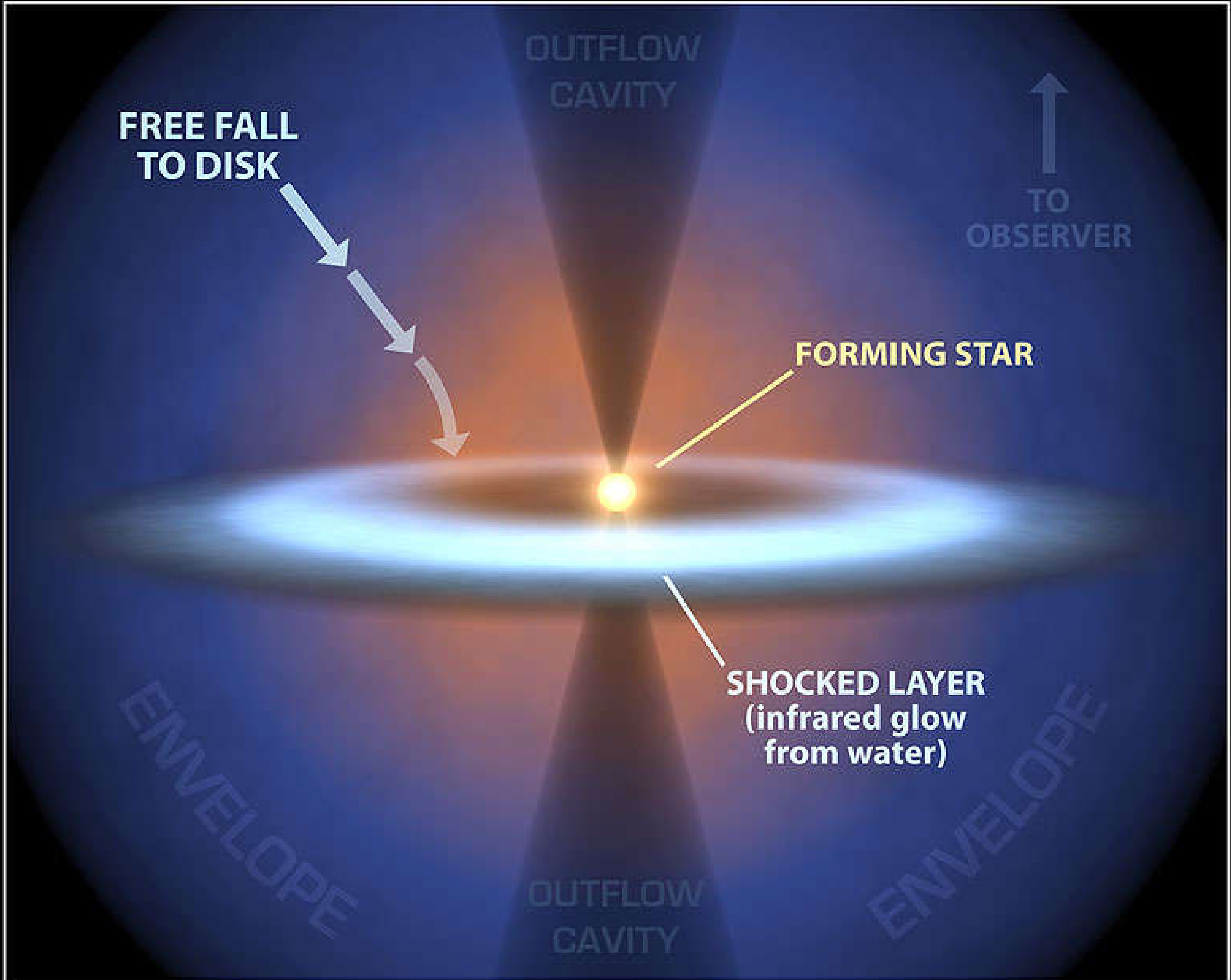
The Role of Dust

As in-falling material heats up, the warm dust radiates energy in IR.

IR escapes from the material, cooling gas

Adsorption of atoms onto the surface of grains leads to the formation of molecules, in particular H_2

Absorbs optical/UV photons from ISRF, thereby protecting the molecules in the gas from dissociation.

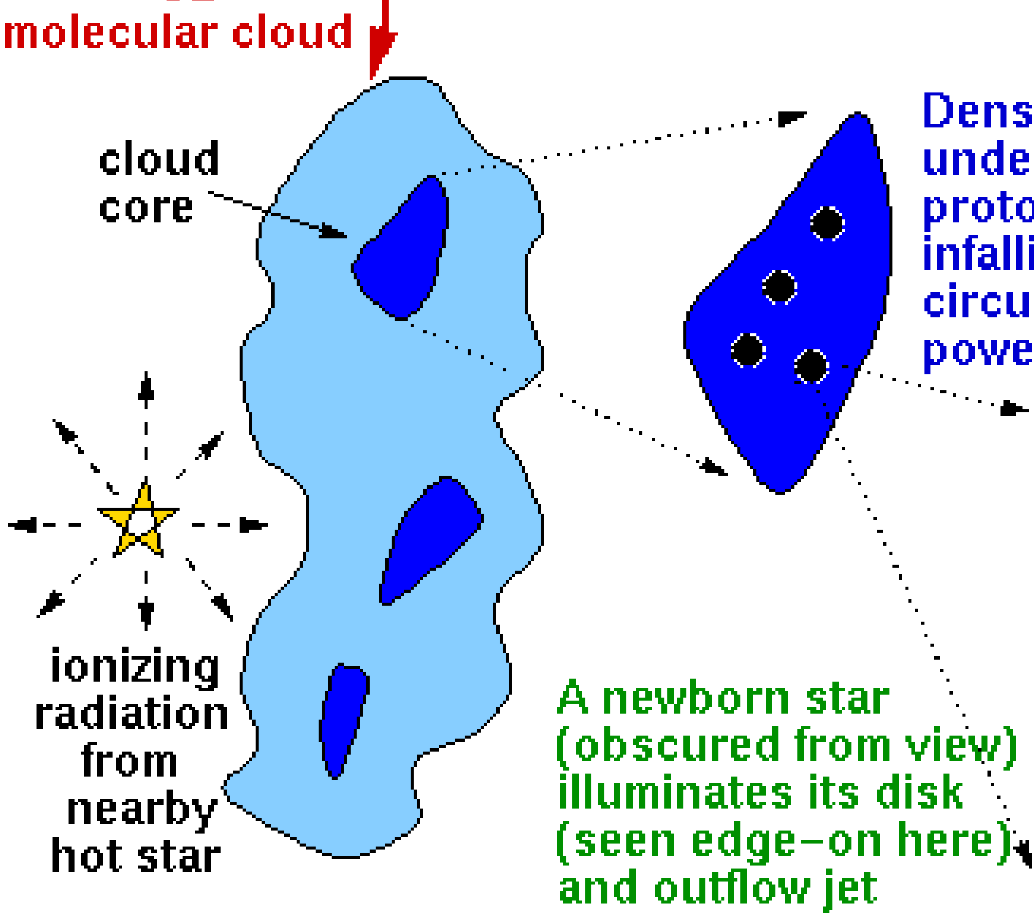


Infrared Water Emission From Protoplanetary Disk Spitzer Space Telescope • IRS

Molecular clouds are cold, dark, giant condensations of dust and molecular gas which serve as "stellar nurseries".

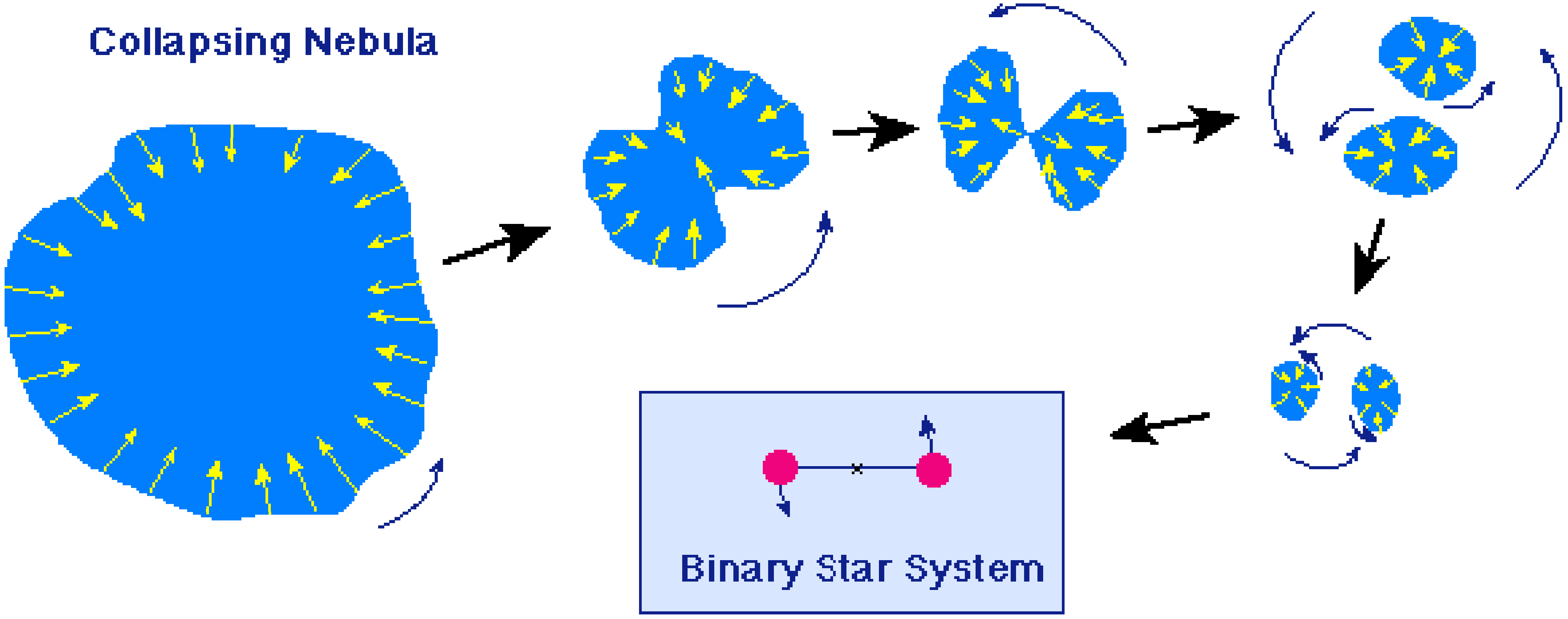
All stars are born in molecular clouds, including our Sun. Molecular clouds are the "stuff" we're made of!

Because of their dusty content, visible light cannot penetrate into a molecular cloud. Thus, infrared and submillimeter observations are needed to "see" the star-forming process.



Dense fragments collapse under gravity, making protostars. These accumulate infalling matter and form circumstellar disks and powerful outflows and jets.

Fragmentation



The Problem

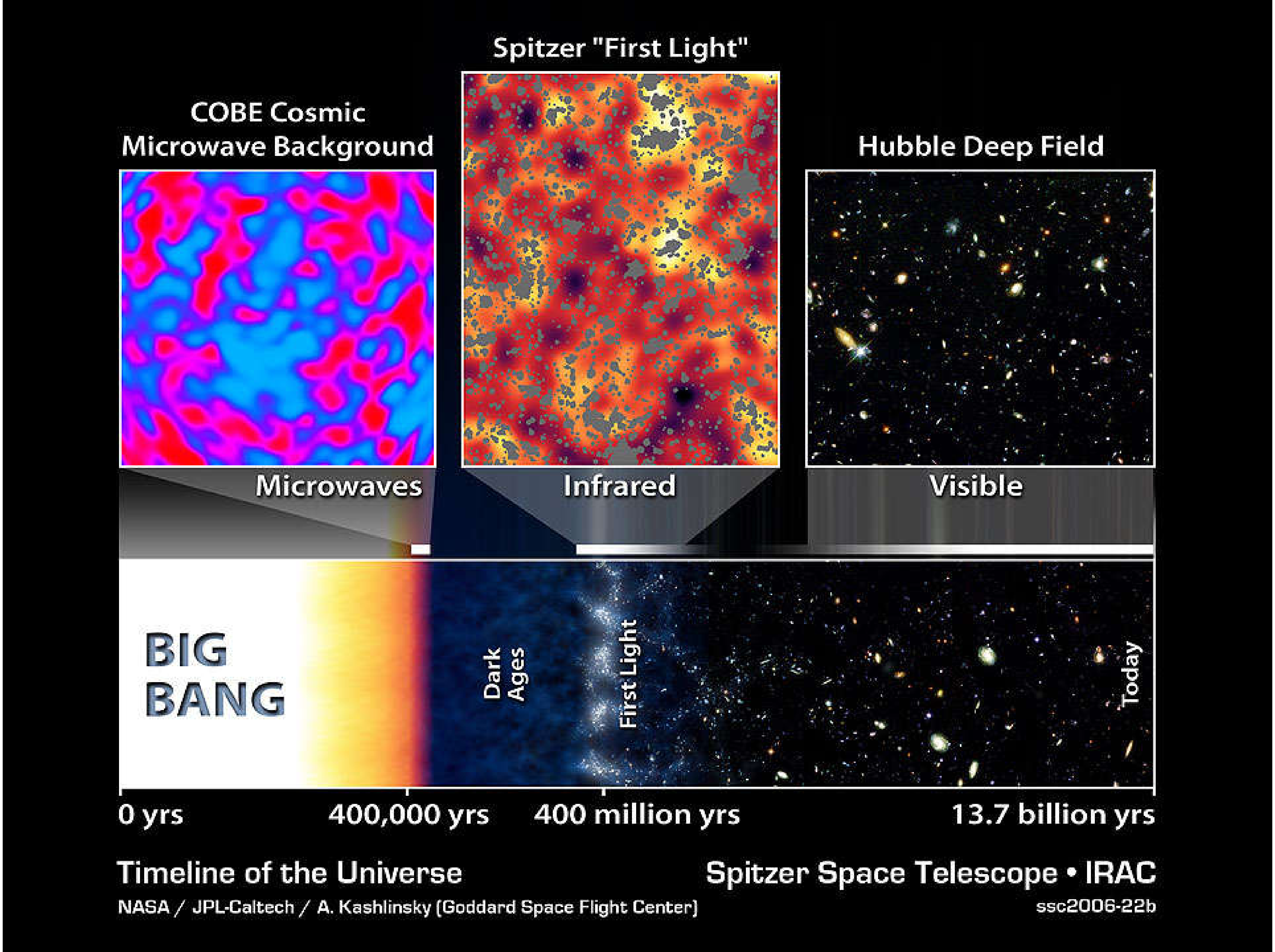
No metals (C, O, Si, Mg, Fe) → no dust

No dust → no site for formation of H_2

No H_2 → no cooling

No cooling → in-falling material heats up and core is disrupted by turbulence

No dust → molecular environment not protected from background radiation that dissociates molecules


COBE Cosmic Microwave Background
Spitzer "First Light"
Hubble Deep Field
Microwaves
Infrared
Visible
BIG BANG
Dark Ages
First Light
Today
0 yrs
400,000 yrs
400 million yrs
13.7 billion yrs
Timeline of the Universe
Spitzer Space Telescope • IRAC
NASA / JPL-Caltech / A. Kashlinsky (Goddard Space Flight Center)
ssc2006-22b

Molecular Hydrogen

At low densities H_2 produced by

- $e^- + H \rightarrow H^- + h\nu$
- $H^- + H \rightarrow H_2 + e^-$

At densities $n > 10^8\ cm^{-3}$ H_2 produced by 3 body reactions

- $H + H + H \rightarrow H_2 + H$
- $H + H + H_2 \rightarrow H_2 + H_2$

- H_2 radiatively dissociated if $T_B > 300$ K
- Requires $z < 100$ for temp to drop low enough for H_2 to survive.

The First Stars

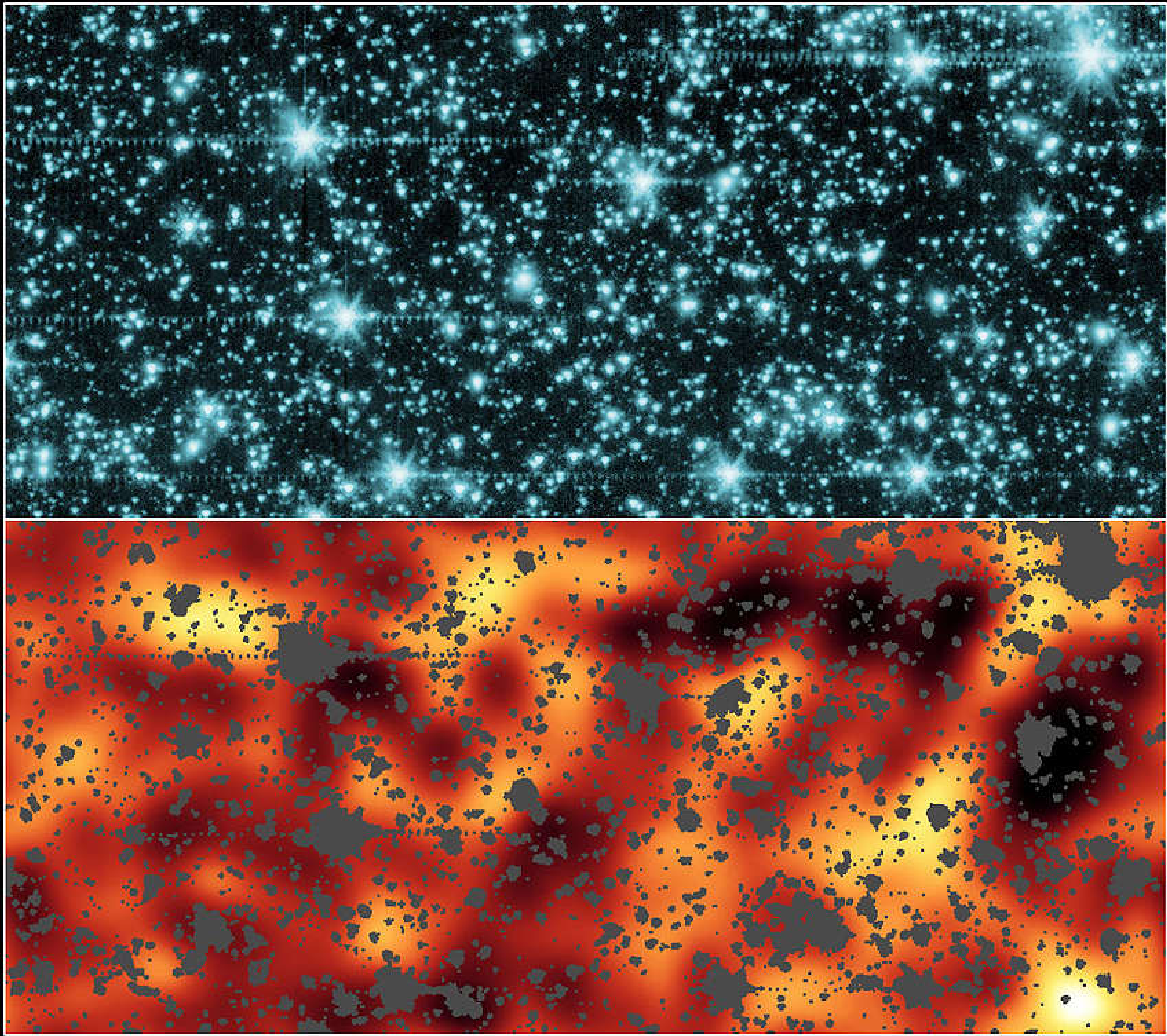
150 – 200 million years after the BB temperature of CMBR had dropped below 300K → H_2 not radiatively dissociated

$N(H_2)/N(H) \sim 1/1000$

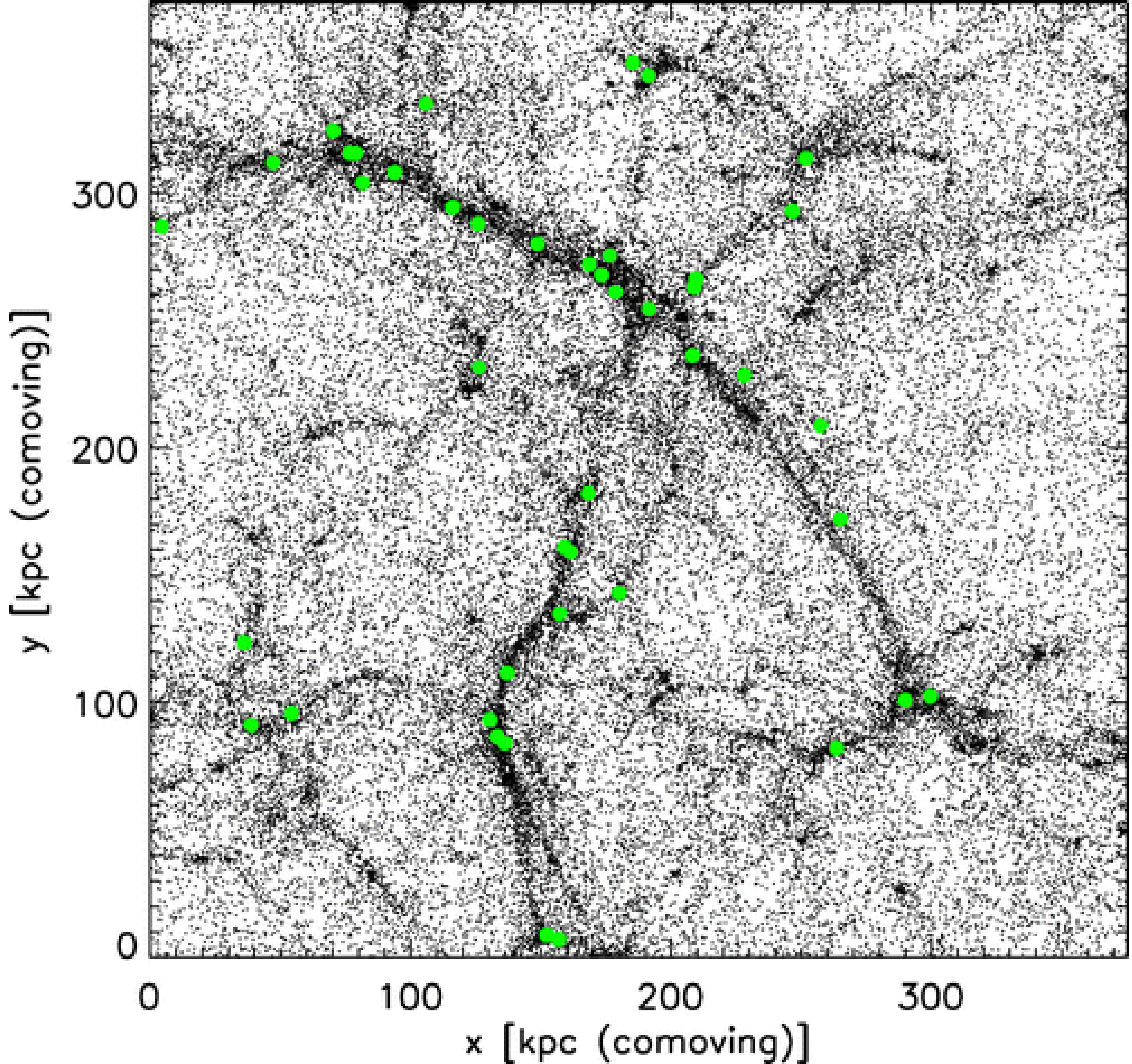
In clouds with $M \sim 10^5\ M_\odot$ gravitationally held together by dark matter, mini-halos formed with $T \sim 1000$ K regulated by H_2

Hotter than in today's star-forming clouds

To overcome pressure and collapse into dense clumps stars of mass 30 – 500 $M_\odot$ formed



Infrared Background Light from First Stars Spitzer Space Telescope • IRAC



300
200
100
0
y [kpc (comoving)]
0
100
200
300
x [kpc (comoving)]

Thank you

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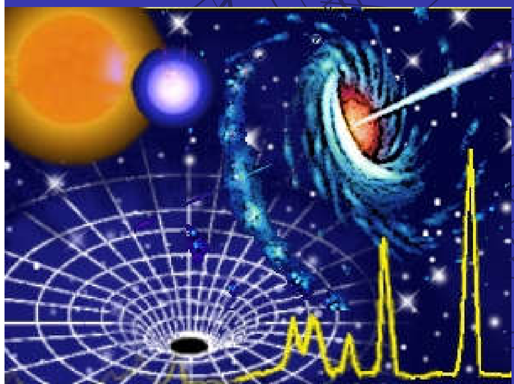

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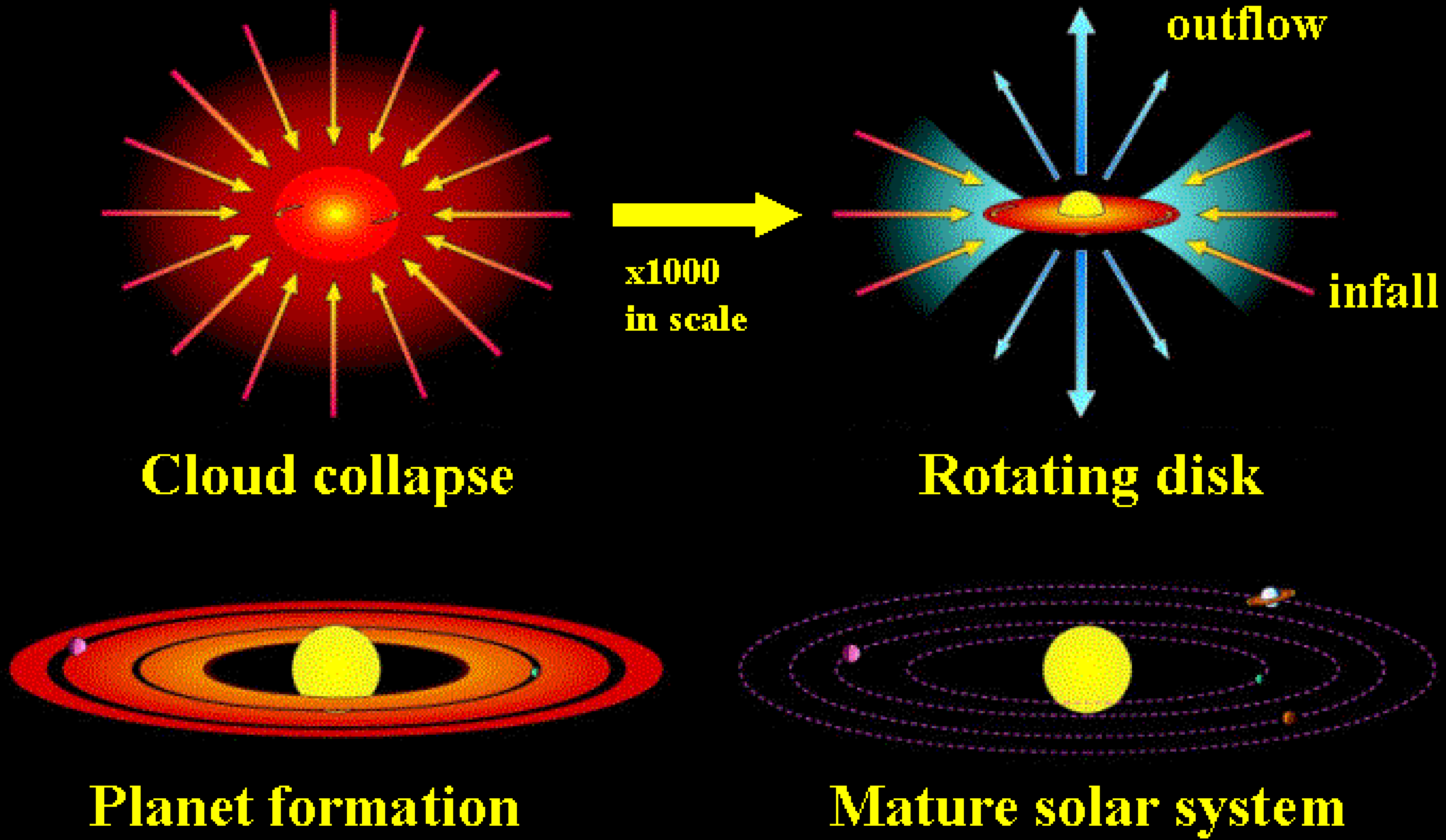
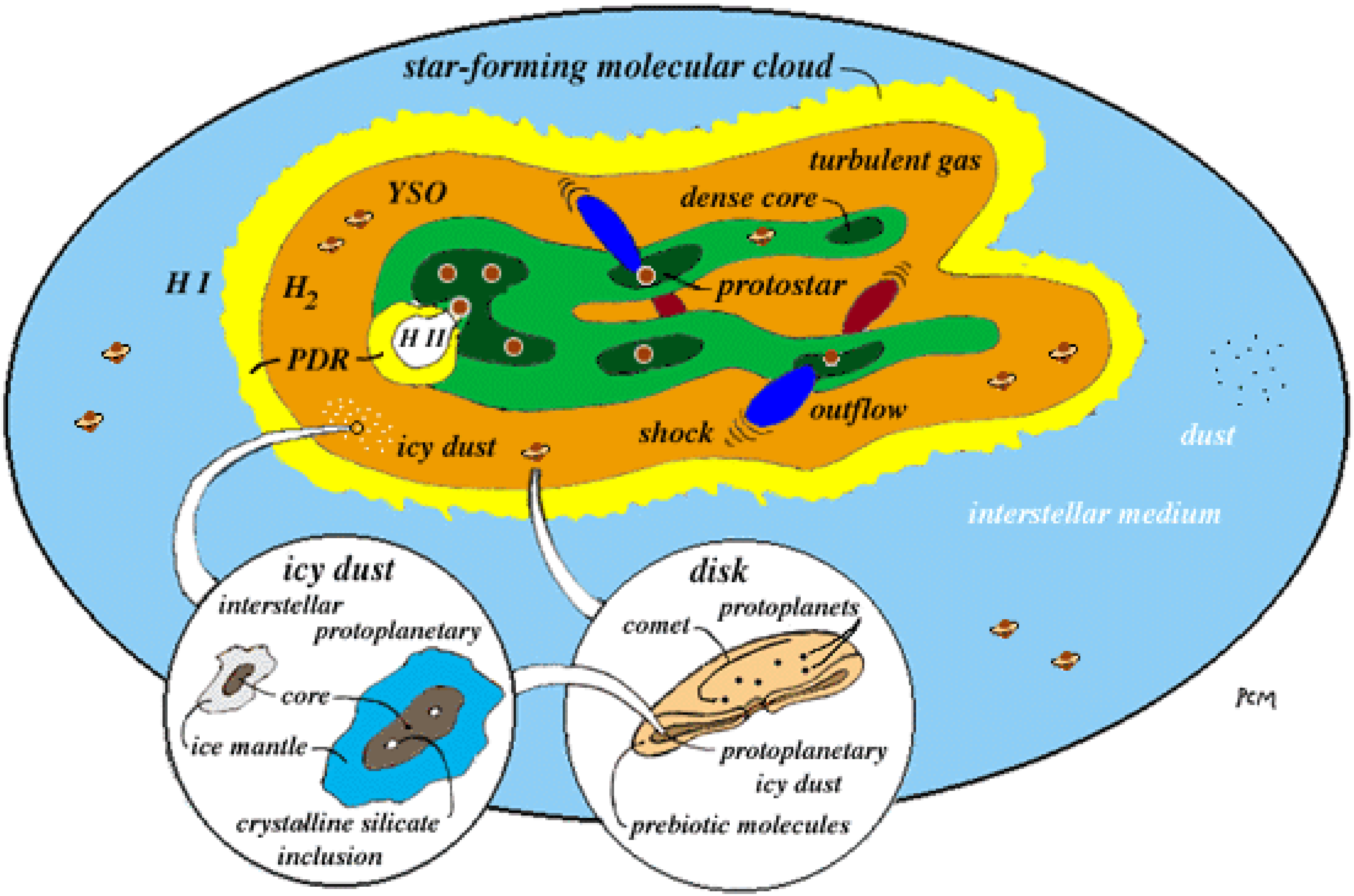
How are single stars born?



Scenario largely from indirect tracers.

Fig. by McCaughrean



star-forming molecular cloud
turbulent gas
YSO
dense core
H I
H_2
protostar
H II
PDR
outflow
shock
icy dust
dust
interstellar medium
icy dust
interstellar
protoplanetary
core
ice mantle
crystalline silicate
inclusion
disk
protoplanets
comet
protoplanetary
icy dust
prebiotic molecules
PCM

1. Density perturbation creates core that attracts atoms to its centre.
2. As atoms fall in, gain speed converting gravitational energy into kinetic energy.
3. Collisions distribute energy randomly, heating the gas.
4. Molecules in the gas excited to higher energies, decay back to lower levels by radiative transitions.
5. Radiation in FIR, submm, radio can escape from the gas, keeping material cool.

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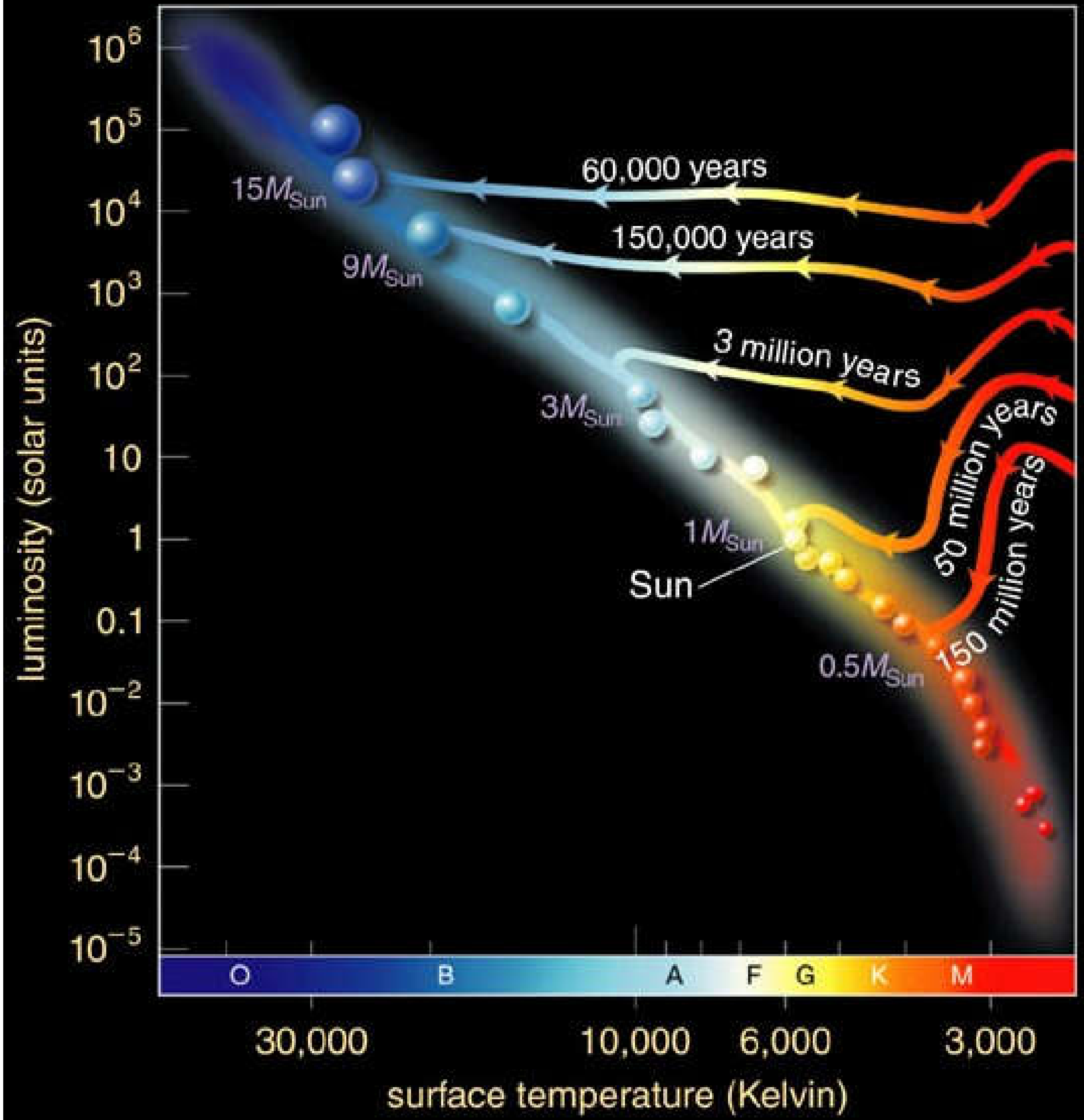

Time scales for stars to form