Composite Supernova Remnants: Multiwavelength Observations and Theoretical Modelling

Okkie de Jager & Stefan Ferreira (NWU, South Africa)

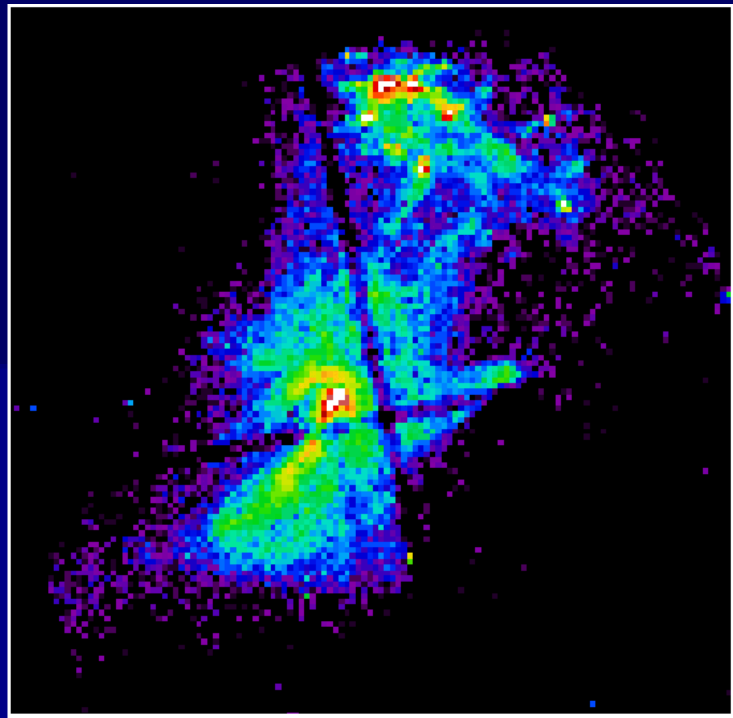
Regis Terrier & Arache Djannati-Ataï (Univ. of Paris VII, France)

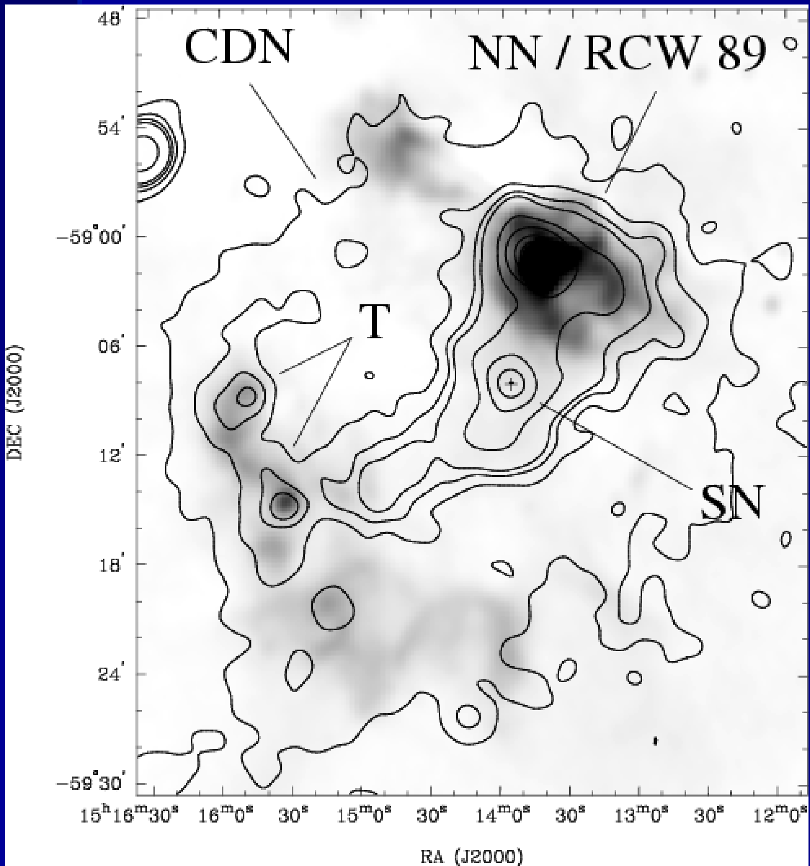
ASSA Symposium, Durban
7 July 2008

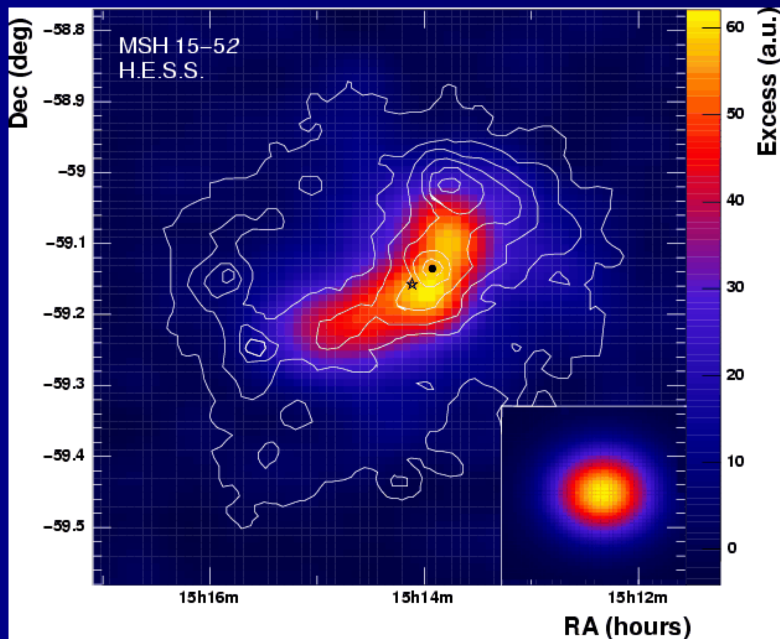
Composite Supernova Remnants – a concise review

- Stars with masses > 8 solar mass burn their nuclear fuel to iron.
- Iron at center cannot burn further and collapses to form either a neutron star or black hole.
- Outward moving shock drives envelope to form supernova blast wave with kinetic energy 10^{51} erg (10^{44} J)
- Conservation of magnetic flux gives the neutron star a large magnetic moment (fields of 10^{12} G).
- Conservation of angular momentum results in birth periods of 300 ms ± 150 ms. Minimum birth period 11 ms (N157B in LMC).
- Rapid rotation of neutron star results in dynamo process. Particle acceleration => gamma-ray production => electron-positron pair production. Ejected into pulsar wind.
- Pulsar (rotating neutron star) drives a relativistic wind of particles (electrons and positrons) and magnetic fields => Pulsar Wind
- Pulsar wind nebula (PWN) expands inside the supernova shell.
- PWN radiates synchrotron (radio, infrared, optical, X-rays) and inverse Compton scattered gamma-rays.

MSH 15-52
1,700 years
P=0.15 s



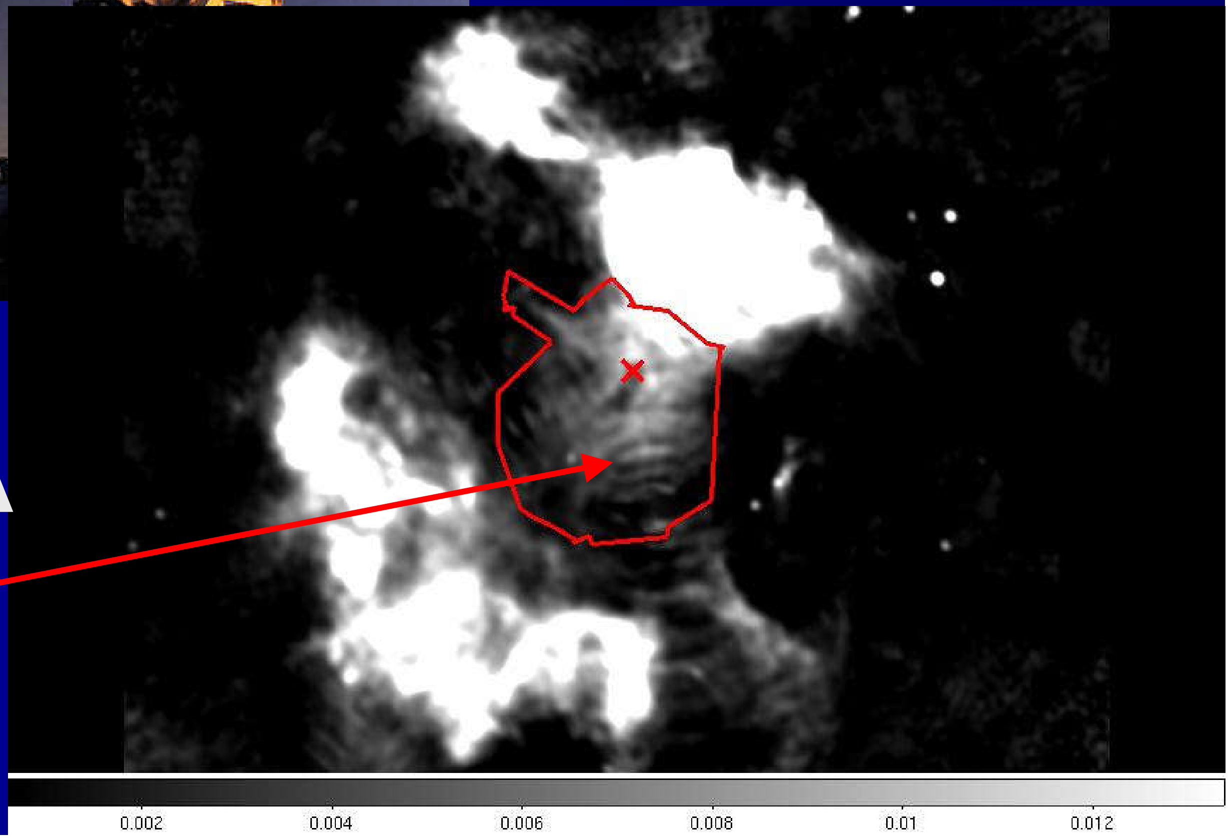




RADIO
(Very Large Array & Parkes)

Australian Compact Telescope Array GHz range

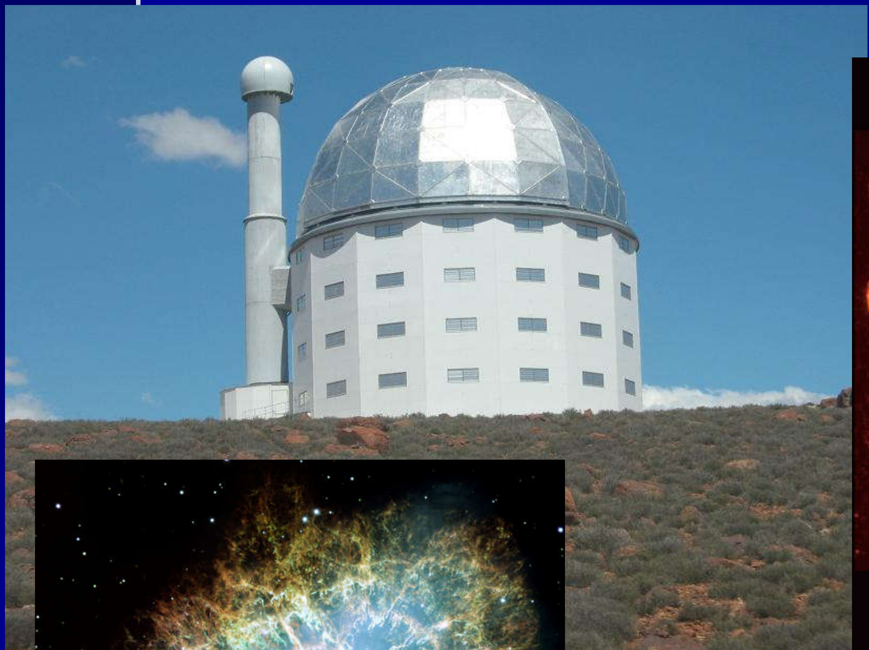
MSH 15-52
Problem for SA
SKA also?

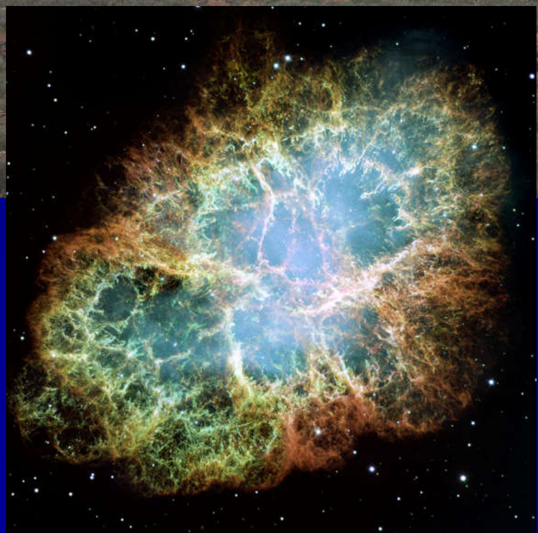


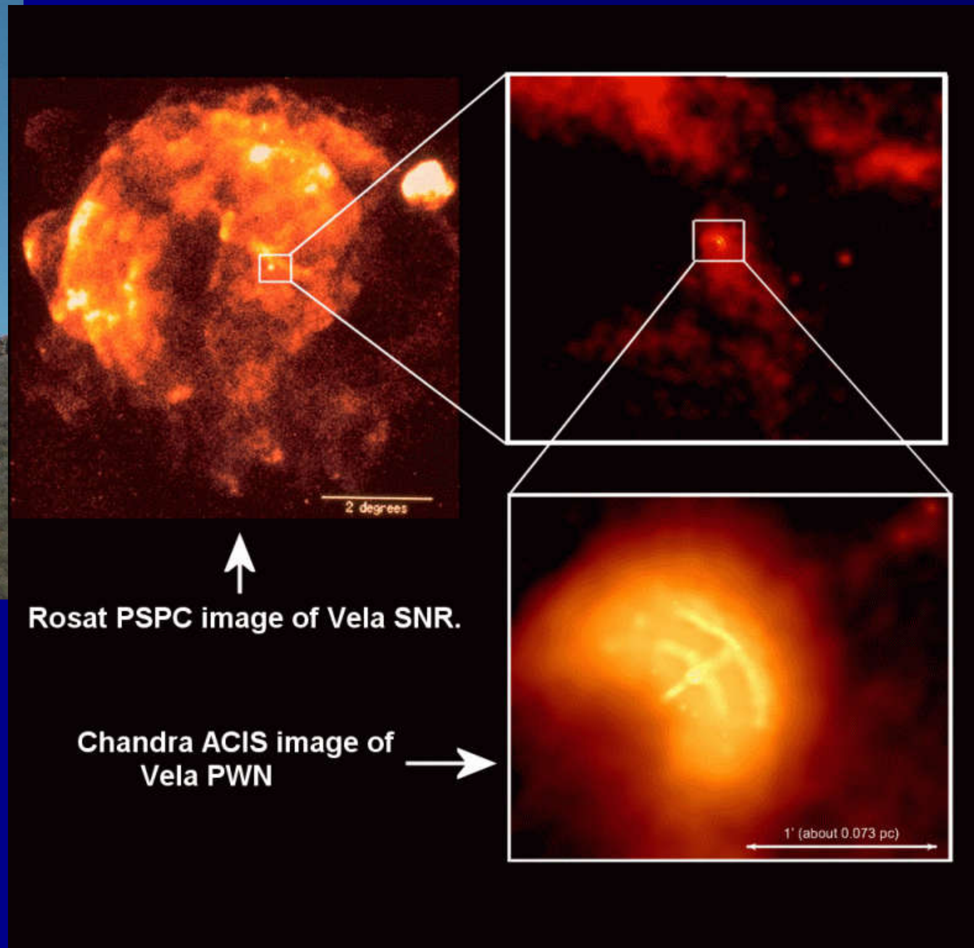
BIMA Array: 100 - 300 GHz

ISO & SPITZER infrared telescopes
Sensitivity limited by huge background

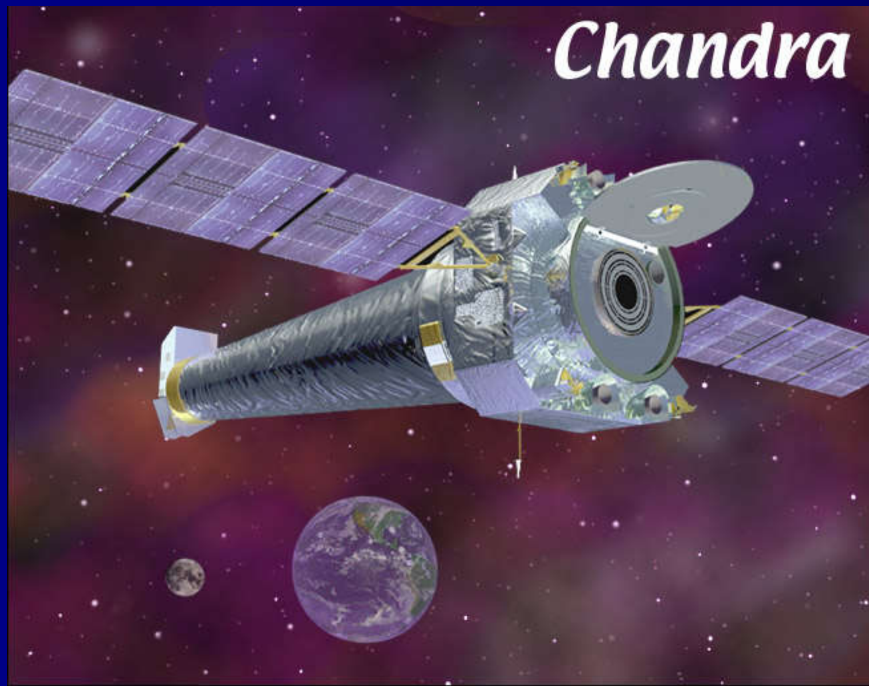
SALT and other optical telescopes. Sensitivity for PWN limited by extinction and large background when attempting to image a PWN. Only Crab PWN properly imaged.





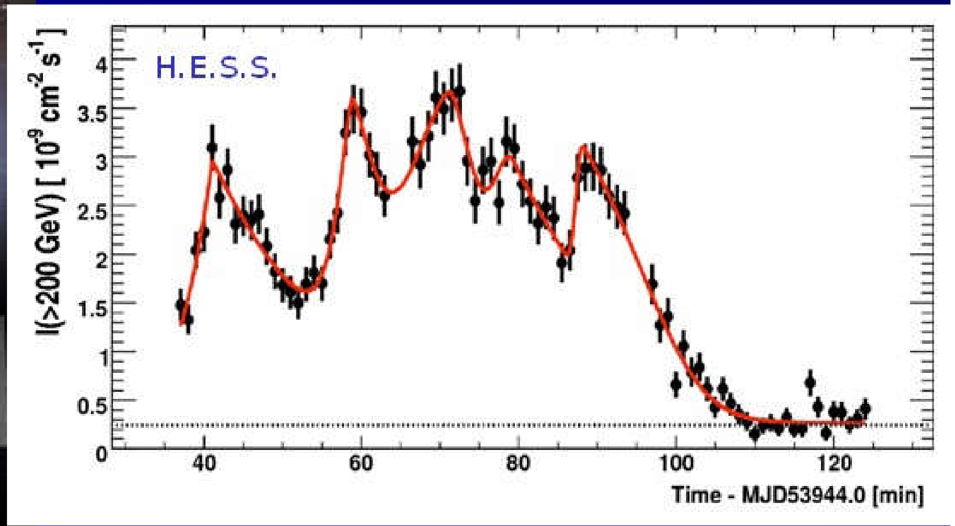


X-Rays:
0.1 to 10 keV

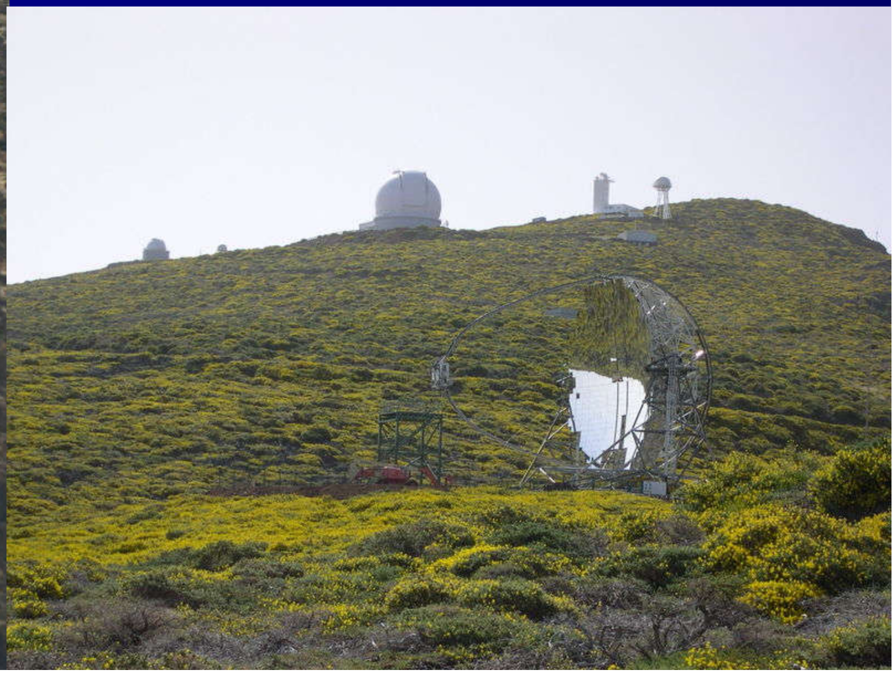


INTEGRAL – Hard X-rays
20 – 300 keV

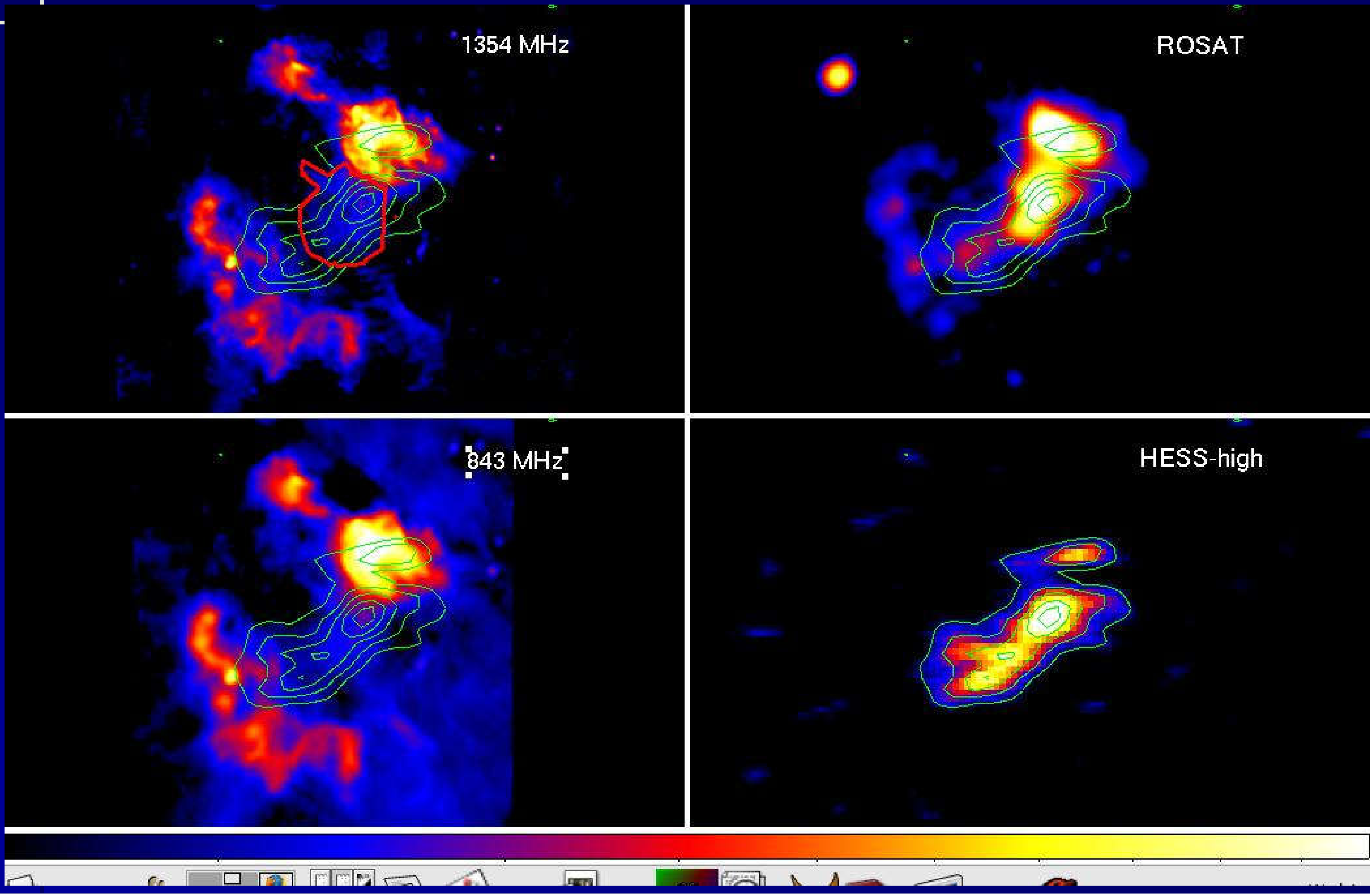
GLAST – Gamma-ray Large Area Telescope
50 MeV to 100 Ge – Launched June 2008
An opportunity for Amateur Astronomers on optical variability of AGN/Blazars



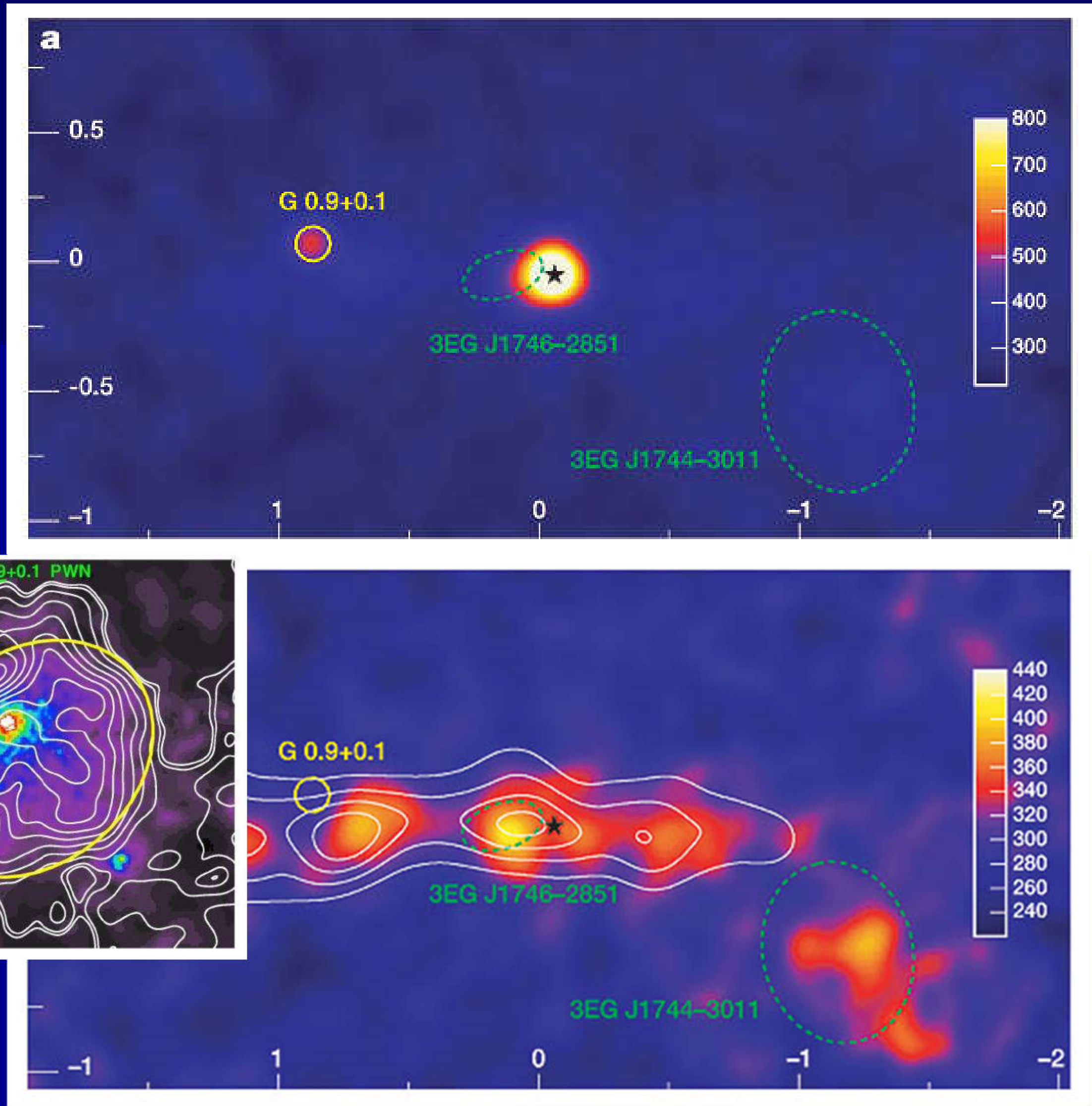
H.E.S.S., VERITAS, MAGIC
30 GeV to 30 TeV

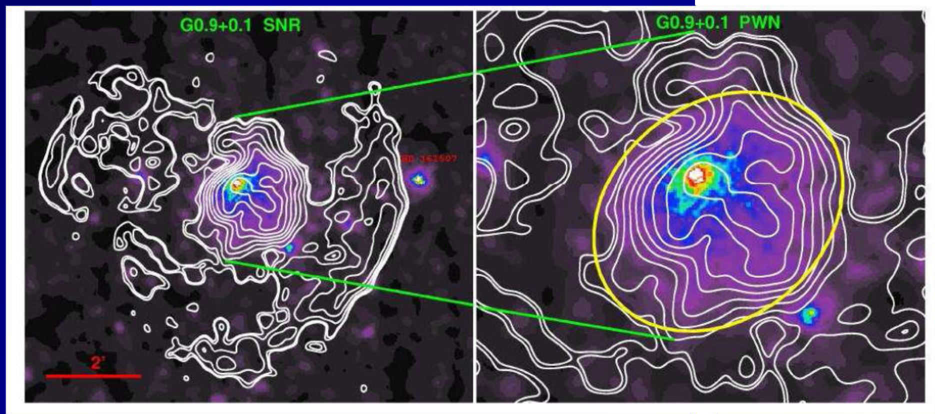


MSH 15-52;1,700 years, P=0.15 s Collaboration between SA, Argentina & Germany



G0.9+0.1
Period ?





Numerical Scheme for SNR and PWN
(see Chevalier (2005) for analytical approach)

Euler equations

$$\frac{\partial}{\partial t}\rho + \nabla \cdot (\rho \mathbf{v}) = 0,$$

$$\frac{\partial}{\partial t}(\rho \mathbf{v}) + \nabla \cdot (\rho \mathbf{v}\mathbf{v} + P\mathbf{I}) = 0,$$

$$\frac{\partial}{\partial t}(\frac{\rho}{2}\mathbf{v}^2 + \frac{P}{\gamma - 1}) + \nabla \cdot (\frac{\rho}{2}\mathbf{v}^2\mathbf{v} + \frac{\gamma \mathbf{v} P}{\gamma - 1}) = 0$$

For the initial and boundary conditions of the SNR

$$v = \frac{r}{t} = v_{ej} r / r_{ej}.$$

$$v_{ej} = \sqrt{\frac{10}{3}\frac{E_{ej}}{M_{ej}}}.$$

$$\rho_{ej} = \frac{3M_{ej}}{4\pi r_{ej}^3}$$

$r_{ej} = 0.1$ pc

adiabatic index of 5/3

For the PWN we allow input power to decrease as a dipole spinning down. Magnetic field generation in PWN according to Faraday induction. Not fully MHD since field is calculated kinematically from flow (Scherer & Ferreira 2005).

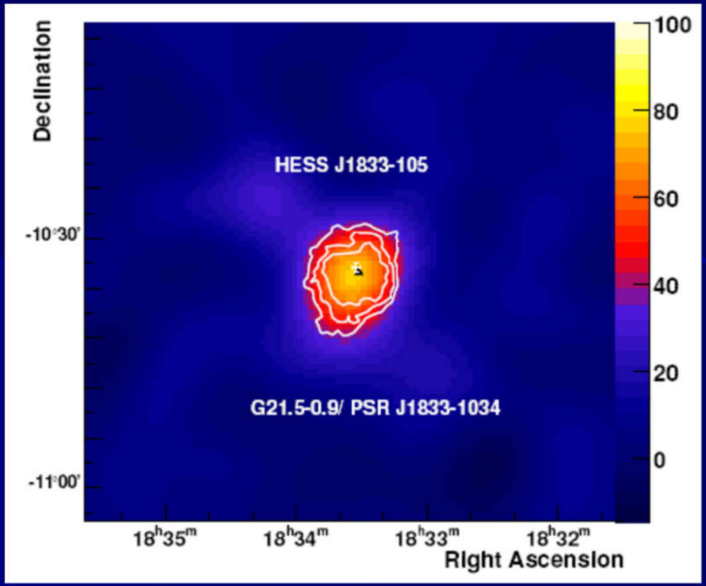
$$L(t) = \frac{L_0}{\left(1 + \frac{t}{\tau}\right)^2}$$

$$\frac{\partial \mathbf{B}}{\partial t} + \nabla \times (\mathbf{v} \times \mathbf{B}) = 0$$

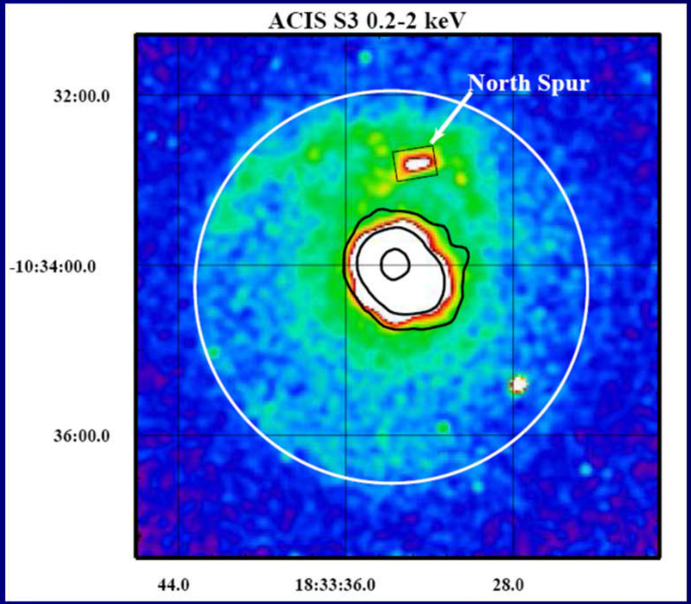
Numerical scheme of LeVeque (2002), Ferreira & de Jager (2008), using wave propagation approach to solve hyperbolic differential equations. See also van der Swaluw et al. (2001), Bucciantini et al. (2003). One fluid approach since post shocked flow downstream is non-relativistic $v<c/3$ (van der Swaluw et al. (2001).

G21.5-0.9

- R_{PWN}=1.2 pc; R_{SNR}=3.3 pc
- Requires n≈10 cm^{-3} to reproduce R_{SNR}=3.3 pc after a kyr.
- Age: 500 – 1000 yr => P_0=55 ms given P=61.8 ms
- $\dot{E}t \approx 1 - 2 \times 10^{48}$ erg for $L_0 = 5 \times 10^{37}$ erg/s.
- Equipartition argument gives $E_{min} \approx 3 \times 10^{47}$ erg
- H.E.S.S. observations give lower field strength B≈25 μG
- => Total particle energy of 2×10^{48} erg ≈ $\dot{E}t$
- => Very efficient accelerator! Puts an upper limit on birth period (< 55 s).



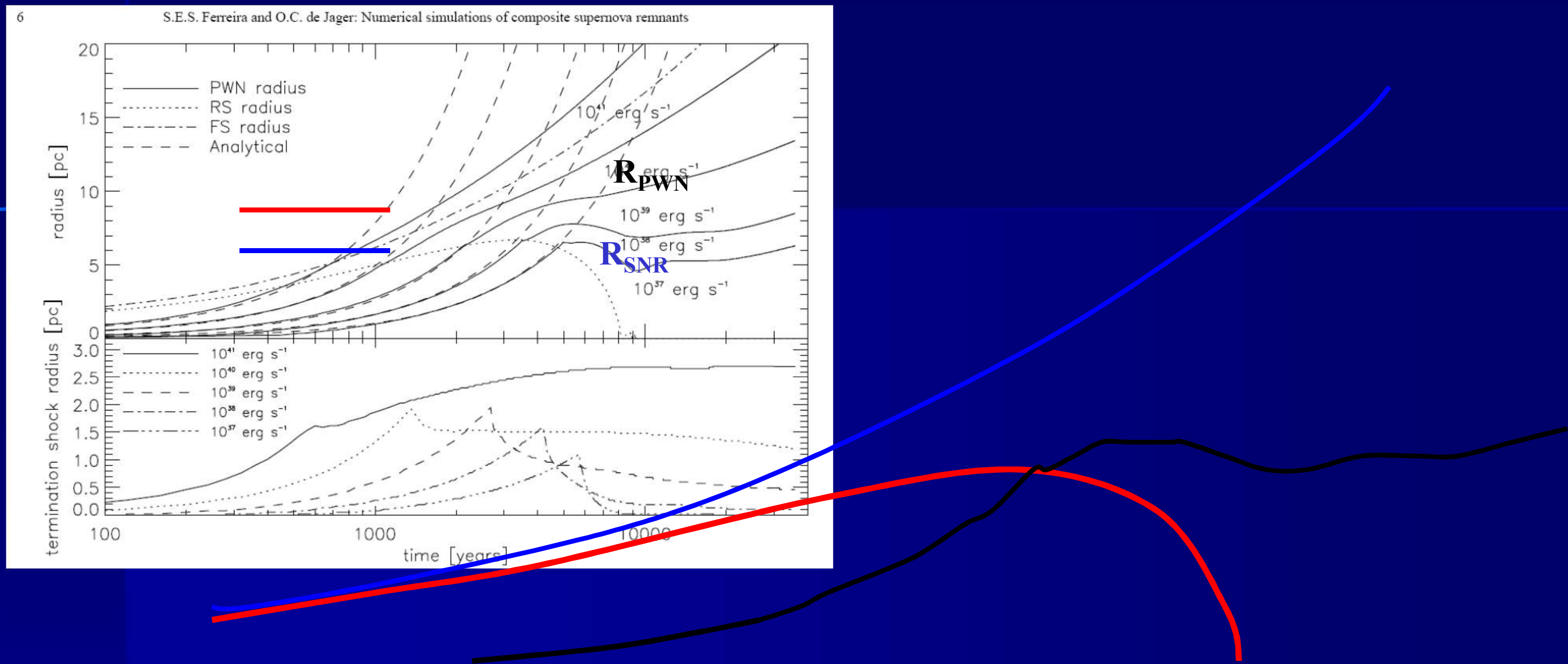
H.E.S.S.: Djannati-Ataï et al. (2007)



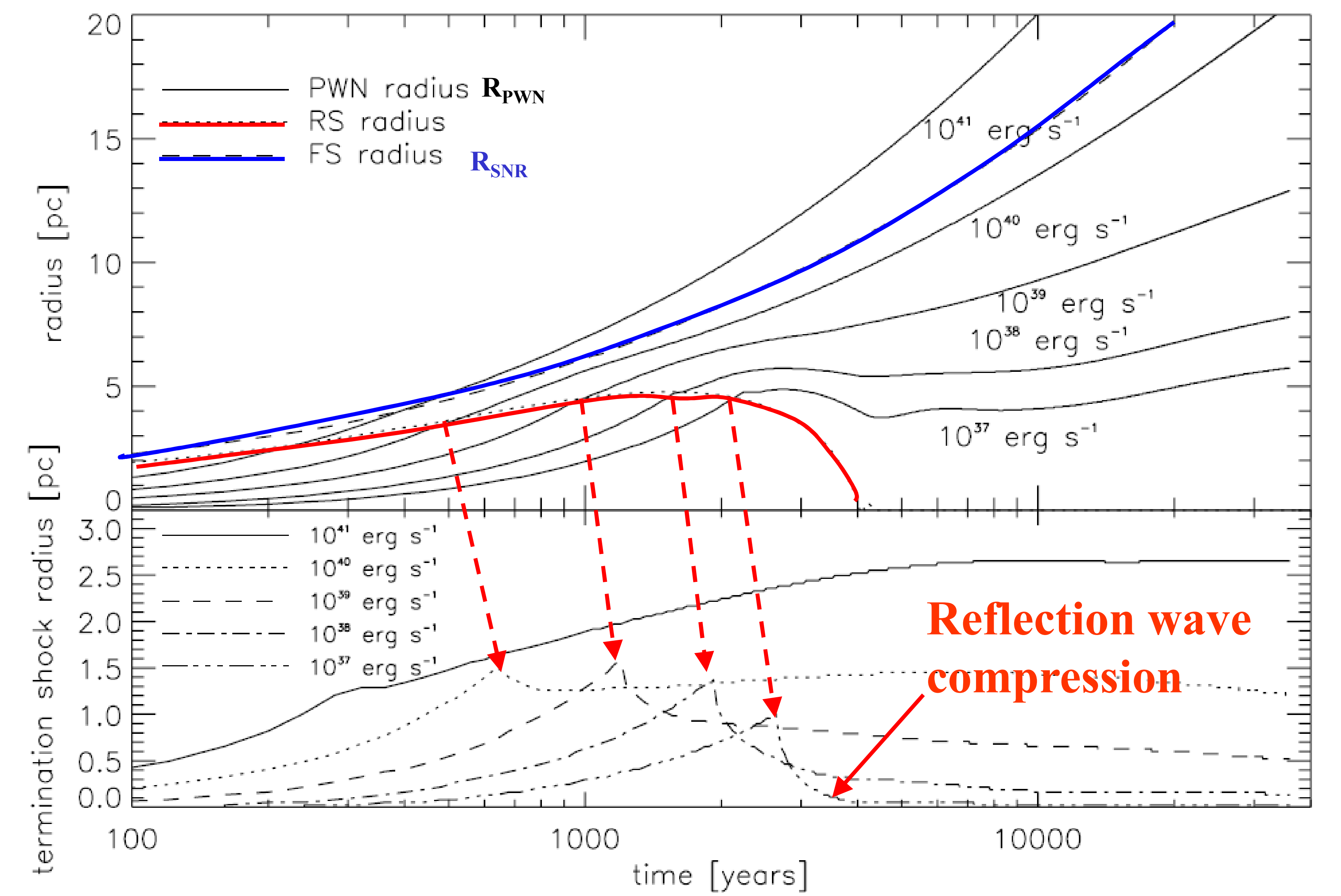
XMM-Newton: Bocchino et al. (2005)

τ=3000 yr; $E_{SNR}=10^{51}$ erg; $n_{ISM}=0.6\ cm^{-3}$; Ejecta Mass: 8 M_o

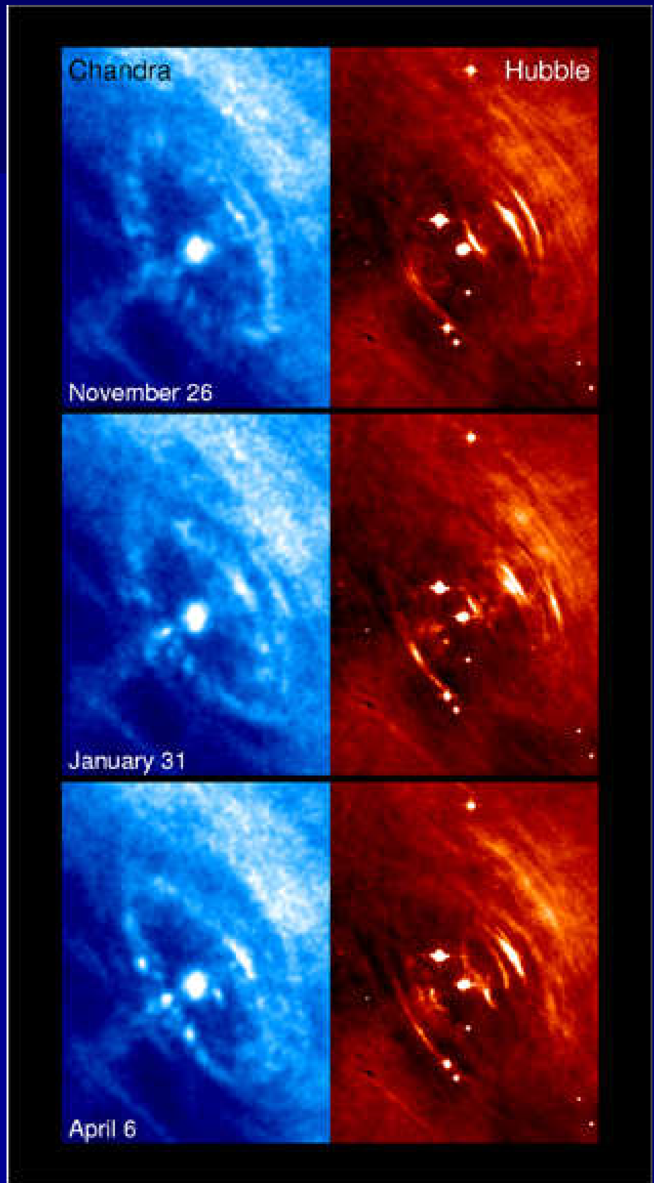
RS encounters shift to later times.



τ=3000 yr; $E_{SNR}=10^{51}$ erg; Ejecta Mass: $3M_o$

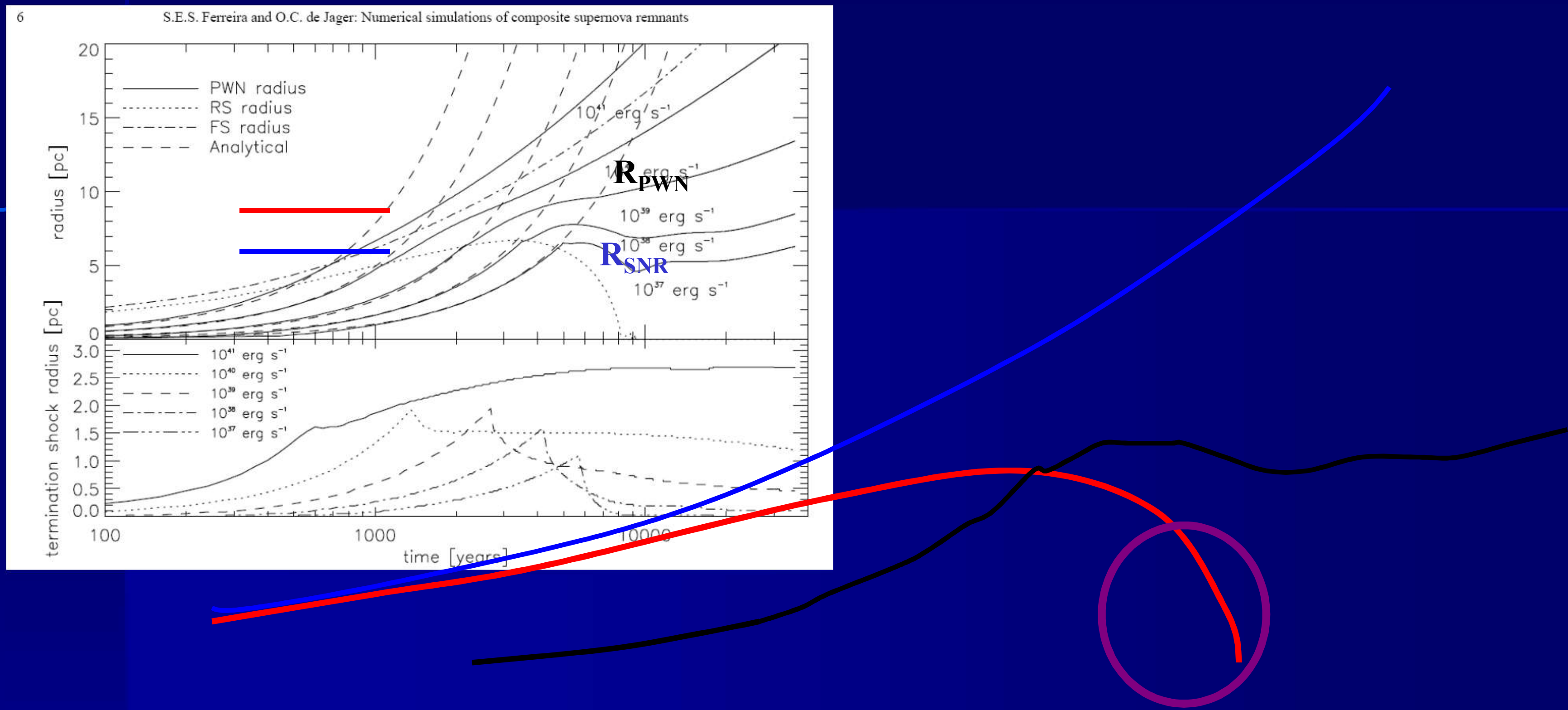


Crab Nebula Pulsar Wind Termination Shock



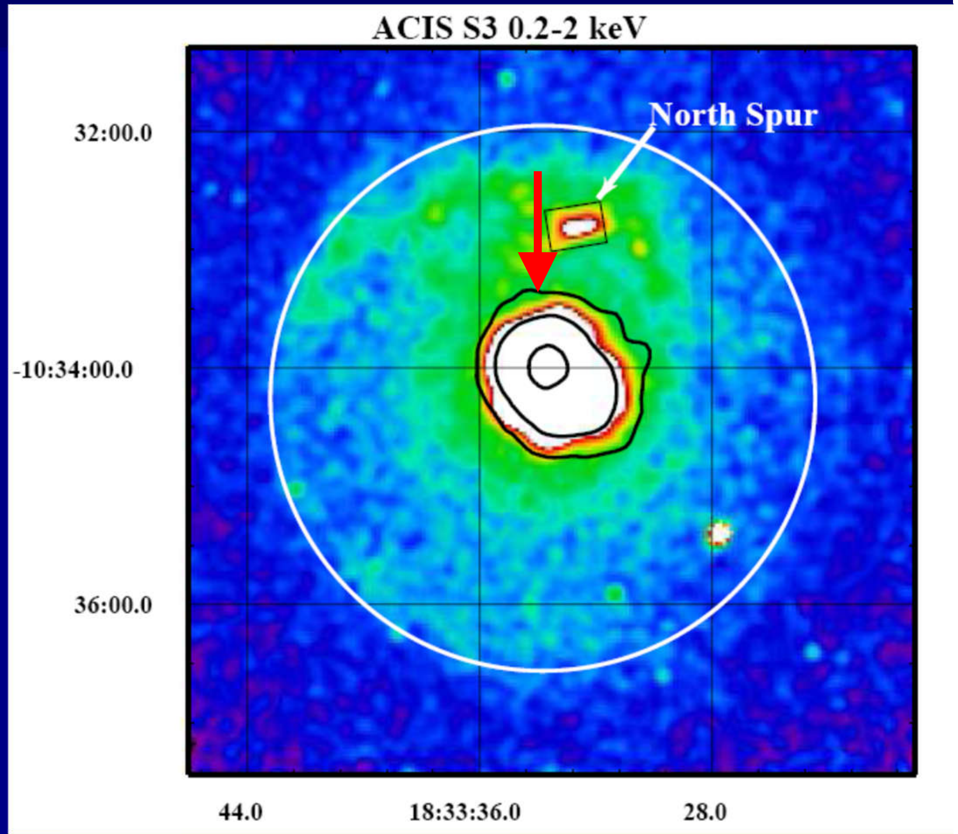
τ=3000 yr; $E_{SNR}=10^{51}$ erg; $n_{ISM}=0.6\ cm^{-3}$; Ejecta Mass: 8 M_o

RS encounters shift to later times.



G21.5-0.9 (Start of Reverse Shock)

- L_X/L_γ decreases with time in a low density medium.
- MHD simulations show that North Polar Spur is probably start of reflection wave dragging field into SNR => enhanced synchrotron emission (Ferreira & de Jager 2008).
- Future is expected to produce an offset PWN, shifted to south.
- More realistic prediction of future SED should treat 2-zone field evolution (compressed towards north and uncompressed towards south), as observed from middle aged VHE PWNe.

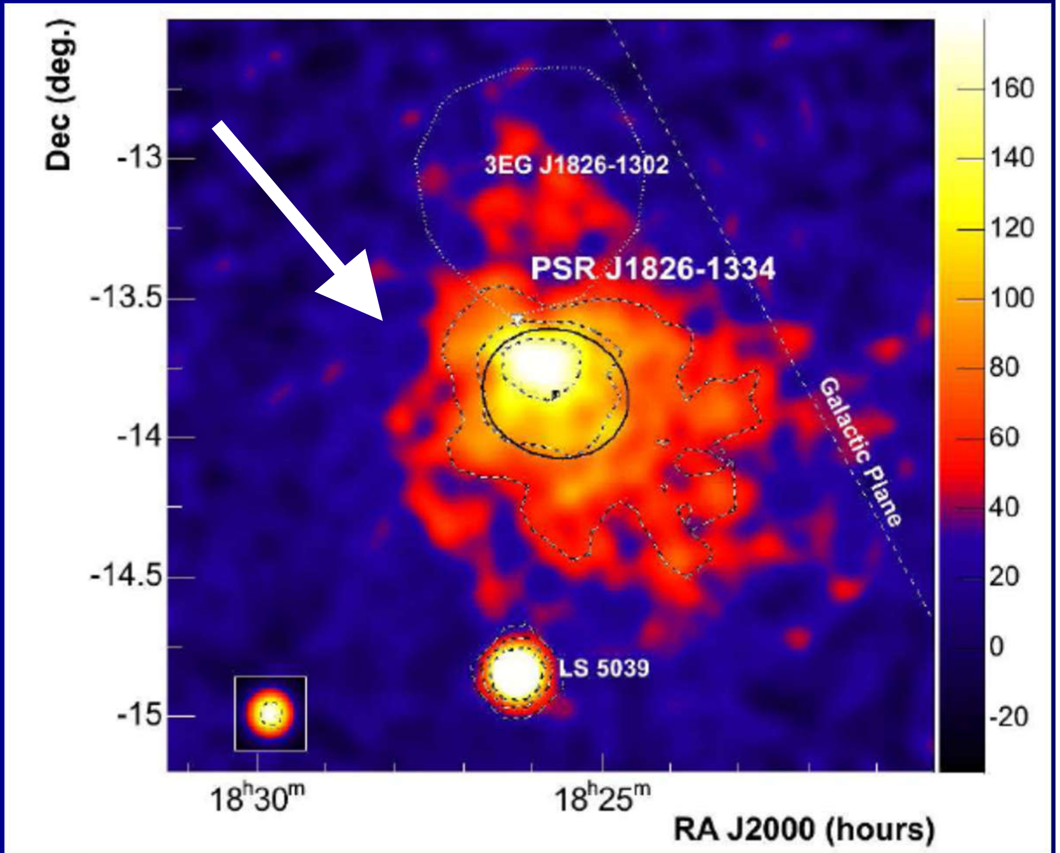


XMM-Newton: Bocchino et al. (2005)

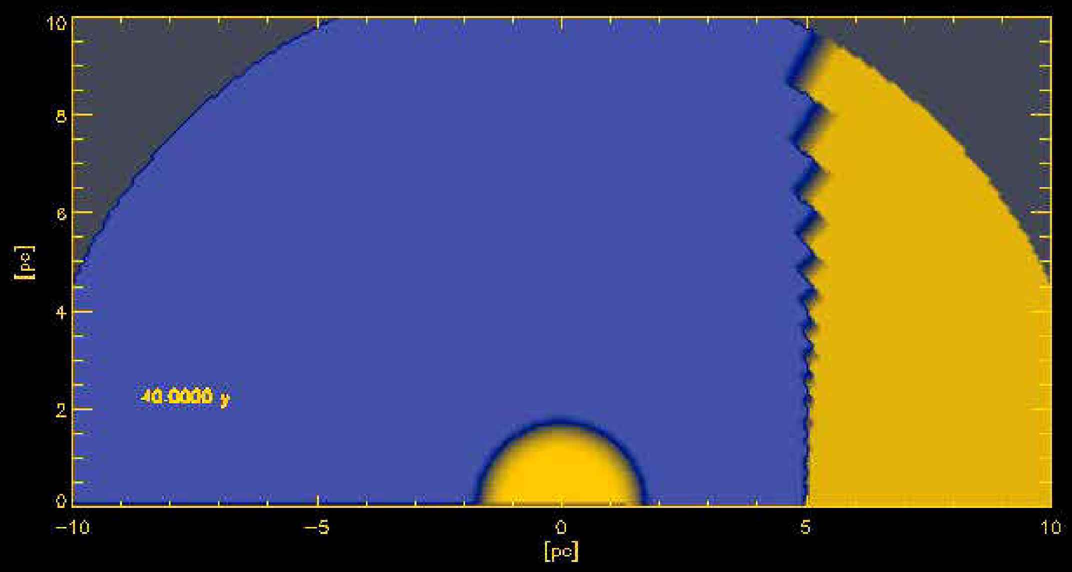
HESS J1825-137 – an offset PWN, also the largest PWN in the galaxy?

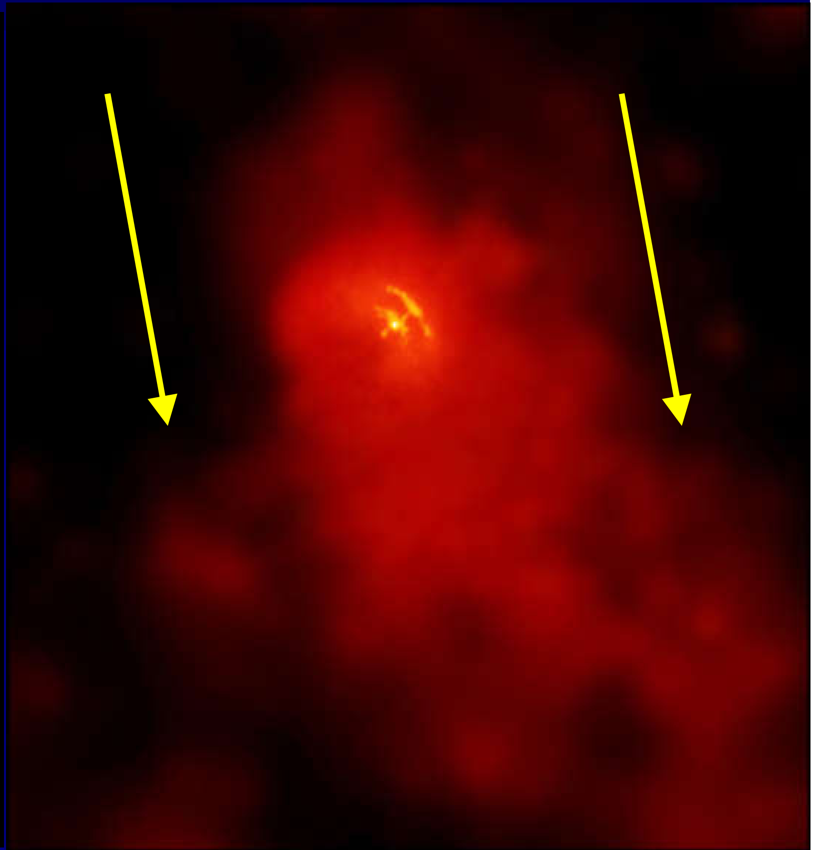
- R_{PWN}=35 pc (R/0.5°)(d/4 kpc)
- Bright source!
- Totally off the scale of R_{PWN} calculations
- Requires lower ISM density for larger FS and PWN shock radii.
- For this enormous size the relic wind since birth must have survived.
- Use HESS IC observations to measure the total energy in electrons
- Set a minimum limit on $\dot{E}t$ and hence birth period
- Compare then with simulations using lower ISM density.
- Must have struck a high density wall to give offset PWN from PSR.

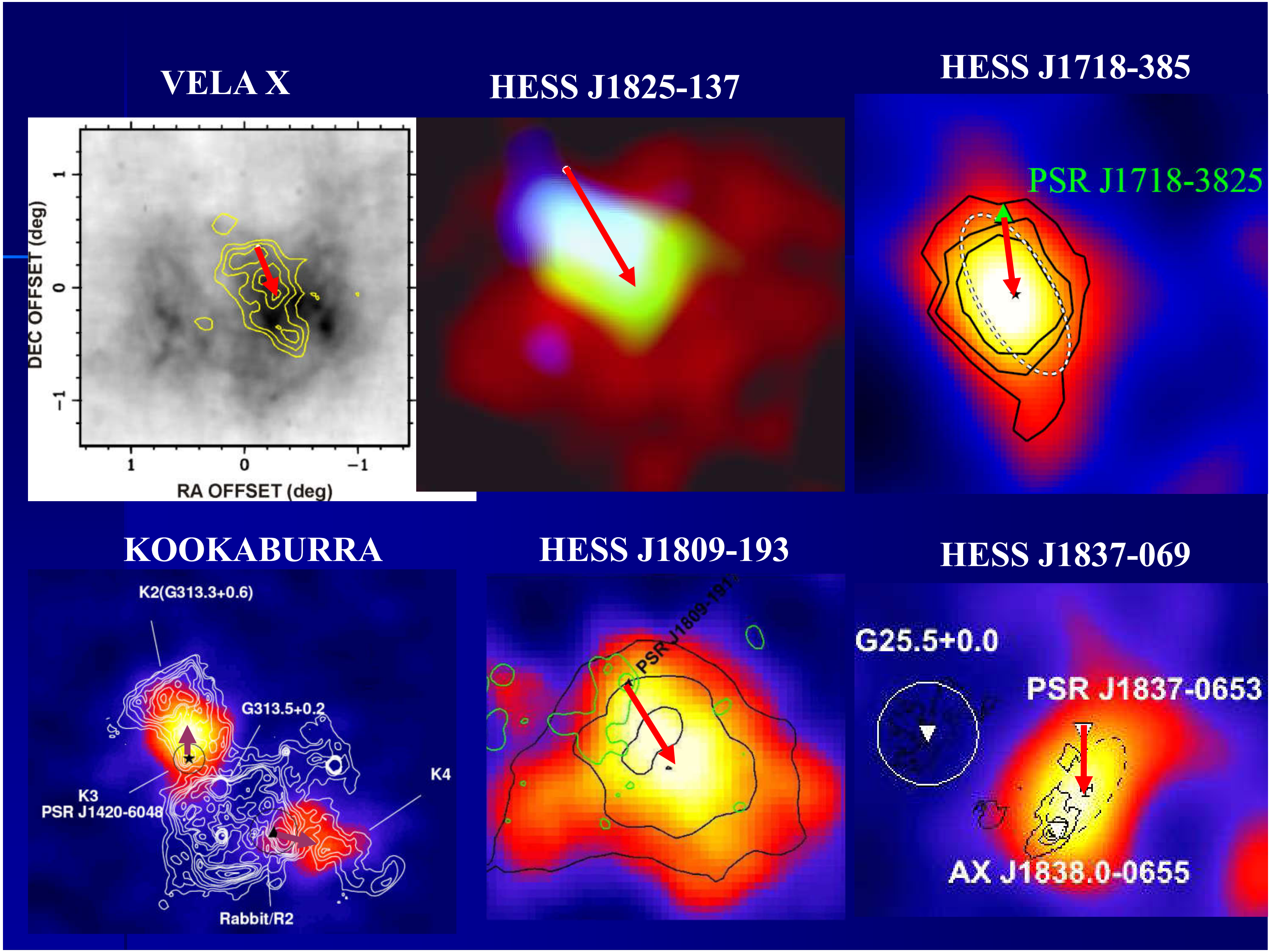
Aharonian et al. (2006)



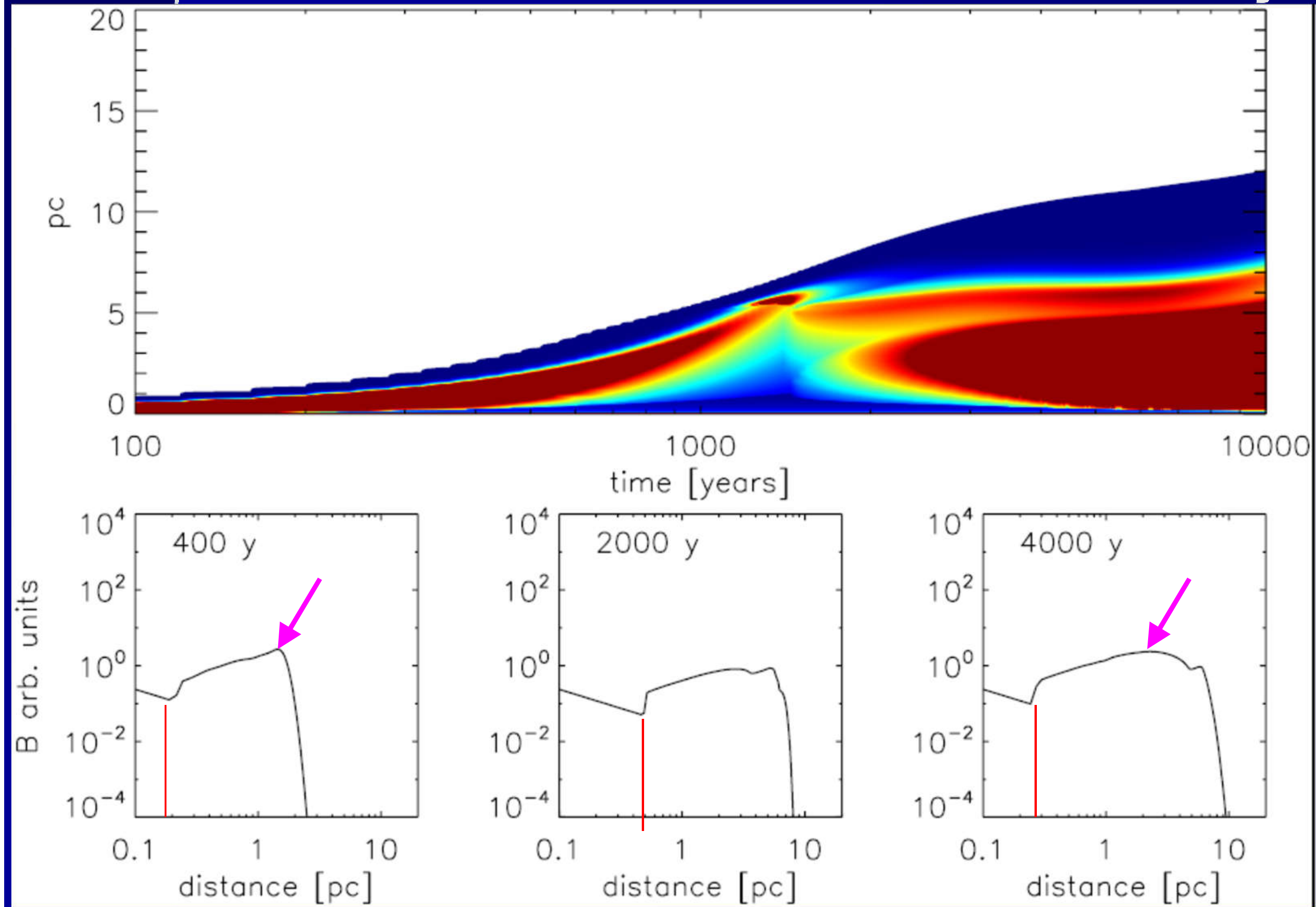
Movie of composite remnant with SNR shock hitting a high density wall. Reverse shock acts like a continuous wind, sweeping even freshly injected particles back. See Vela PWN freshly injected electrons swept back, long after crushing phase started.






VELA X
DEC OFFSET (deg)
RA OFFSET (deg)
1
0
−1
HESS J1825-137
HESS J1718-385
PSR J1718-3825
KOOKABURRA
K2(G313.3+0.6)
G313.5+0.2
K3
PSR J1420-6048
K4
Rabbit/R2
HESS J1809-193
PSR J1809-191
HESS J1837-069
G25.5+0.0
PSR J1837-0653
AX J1838.0-0655

FIELD STRENGTH EVOLUTION:
Early: B amplification at edge (pressing on ejecta); Later: B amplification deeper into PWN due to reverse shock crushing the PWN
$L_0=10^{40}$ erg/s; $\tau=300$ yr; $M_{ej}=8M_o$



Evolutionary radiation model, constrained by MHD results.

Two-component (radio/X-ray) injection (Venter & de Jager 2006)

$$Q(\gamma,t) = \begin{pmatrix} Q_0(t)(\gamma/\gamma_b)^{-p_1} \text{ for } \gamma < \gamma_b \\ Q_0(t)(\gamma/\gamma_b)^{-p_2} \text{ for } \gamma_b < \gamma < \gamma_{\max} \end{pmatrix}$$

$$\int Q(\gamma,t)\gamma d\gamma = \eta L(t).$$

$L(0)$ (or P_0) constrained by R_{PWN}/R_{SNR} from MHD

Particle spectrum from Leaky Box approach:
see e.g. Zhang et al. (2008)

$$\frac{dN(E_e,\ T_{\rm age})}{dE_e} = \int_0^{T_{\rm age}} Q(E_e,t)\exp\left(-\frac{T_{\rm age}-t}{\tau_{\rm eff}}\right)dt$$

Effective loss timescales constrained by MHD

Pair production multiplicity from continuity equation (Sefako & de Jager 2003)

The electron continuity equation is given by

$$\int_0^\infty Q(E)\,dE = \eta_p\frac{I_{\rm GJ}M}{e}\,, \qquad (3)$$

where η_p is the fraction of all pairs escaping through the light cylinder, which contributes to the compact nebular emission. The expression for the Goldreich-Julian current (converted to a rate) from the pulsar polar caps is $I_{\rm GJ}/e \sim (6\dot{E}c)^{1/2}/e$. The pair-creation multiplicity is M, as defined earlier.

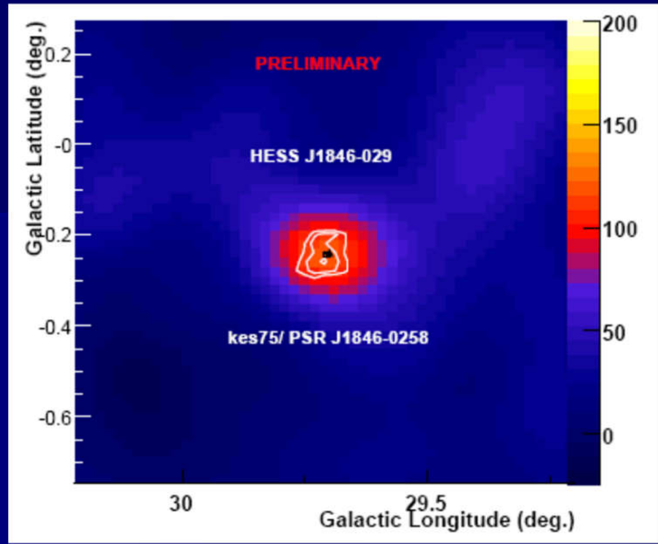
Maximum particle energy constrained by gyroradius limit ($\varepsilon = r_g/R_s$). PWN termination shock radius cancels out (Venter & de Jager 2006; de Jager & Djannati-Atai 2008)

$$E_{\max}(t) \approx \frac{e}{2}\sqrt{\frac{\sigma L(t)}{(1+\sigma)c}}$$

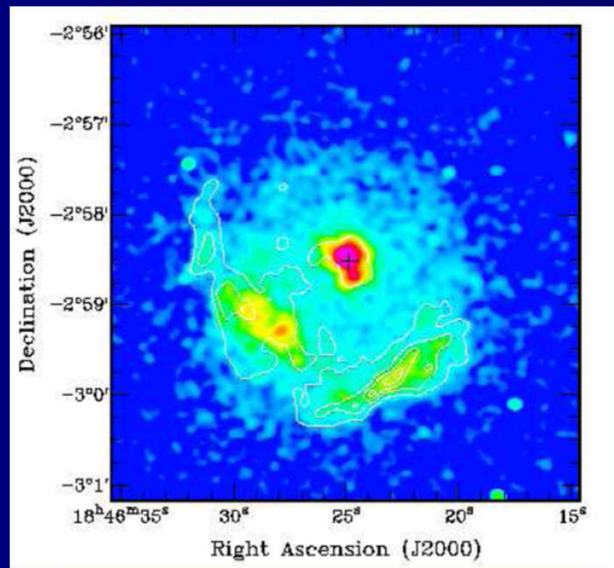
$$= (110\,{\rm TeV})\kappa\left(\frac{\epsilon}{0.2}\right)\left(\frac{\sigma}{0.1}\dot{E}_{36}\right)^{1/2}$$

KES 75 (Nearly a ``Magnetar")

- R_{PWN}=0.6d_6 pc; R_{SNR}=2.8d_6 pc
- Requires n≈20 cm^{-3} (Leahy & Tan 2007)
- R_{PWN}/R_{SNR} => P_0=80 ms (van der Swaluw & Wu 2001)
- T_{age}≈800 yr.
- $\int(-\dot{E})dt \approx 2 \times 10^{48}$ erg for $L_0=8\times10^{38}$ erg/s.
- H.E.S.S. observations give field strength below equipartition B≈15 μG or $W_B=2\times10^{44}$ erg (Djannati-Atai et al. 2007; Ng et al. 2008).

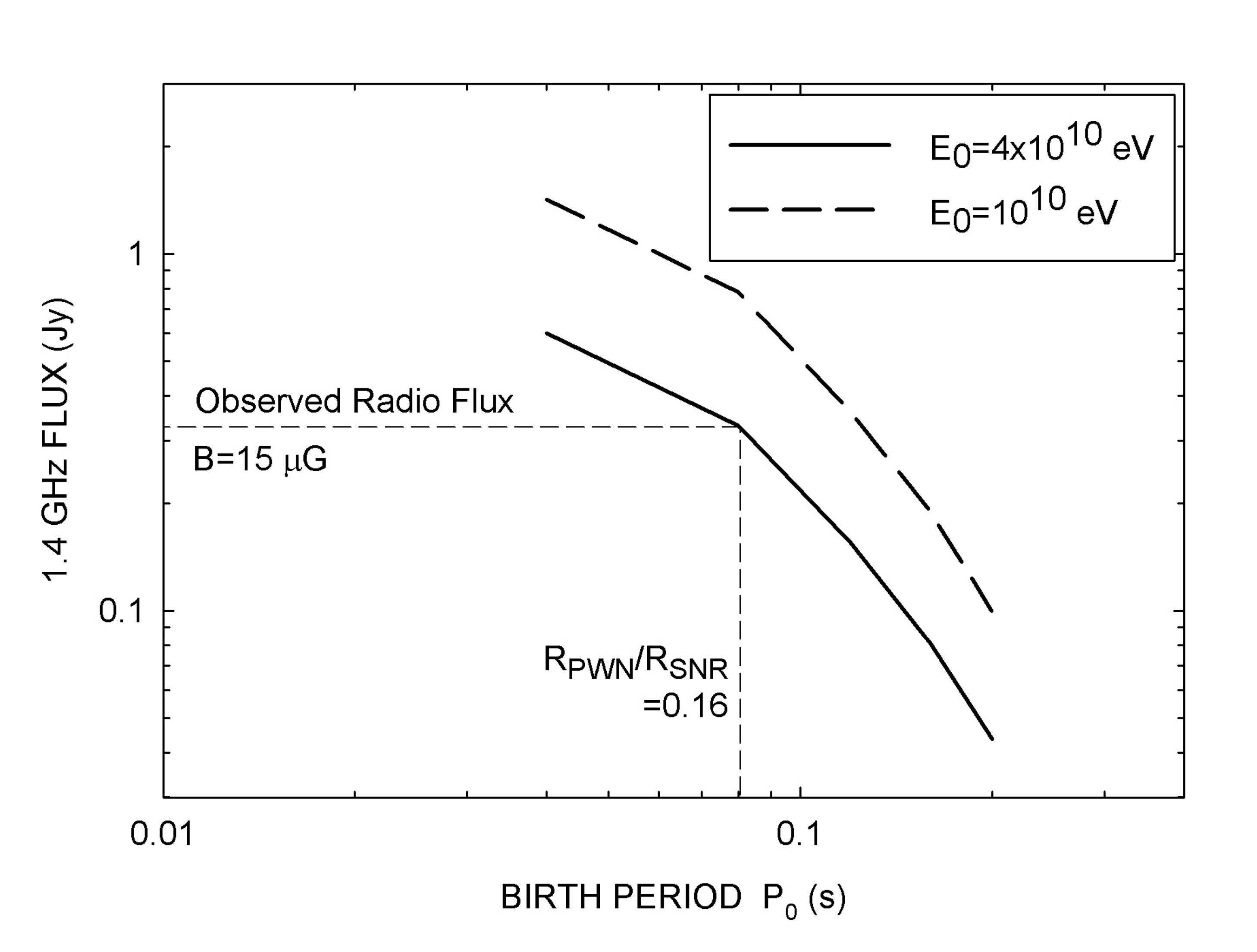


H.E.S.S.: Djannati-Ataï et al. (2007)

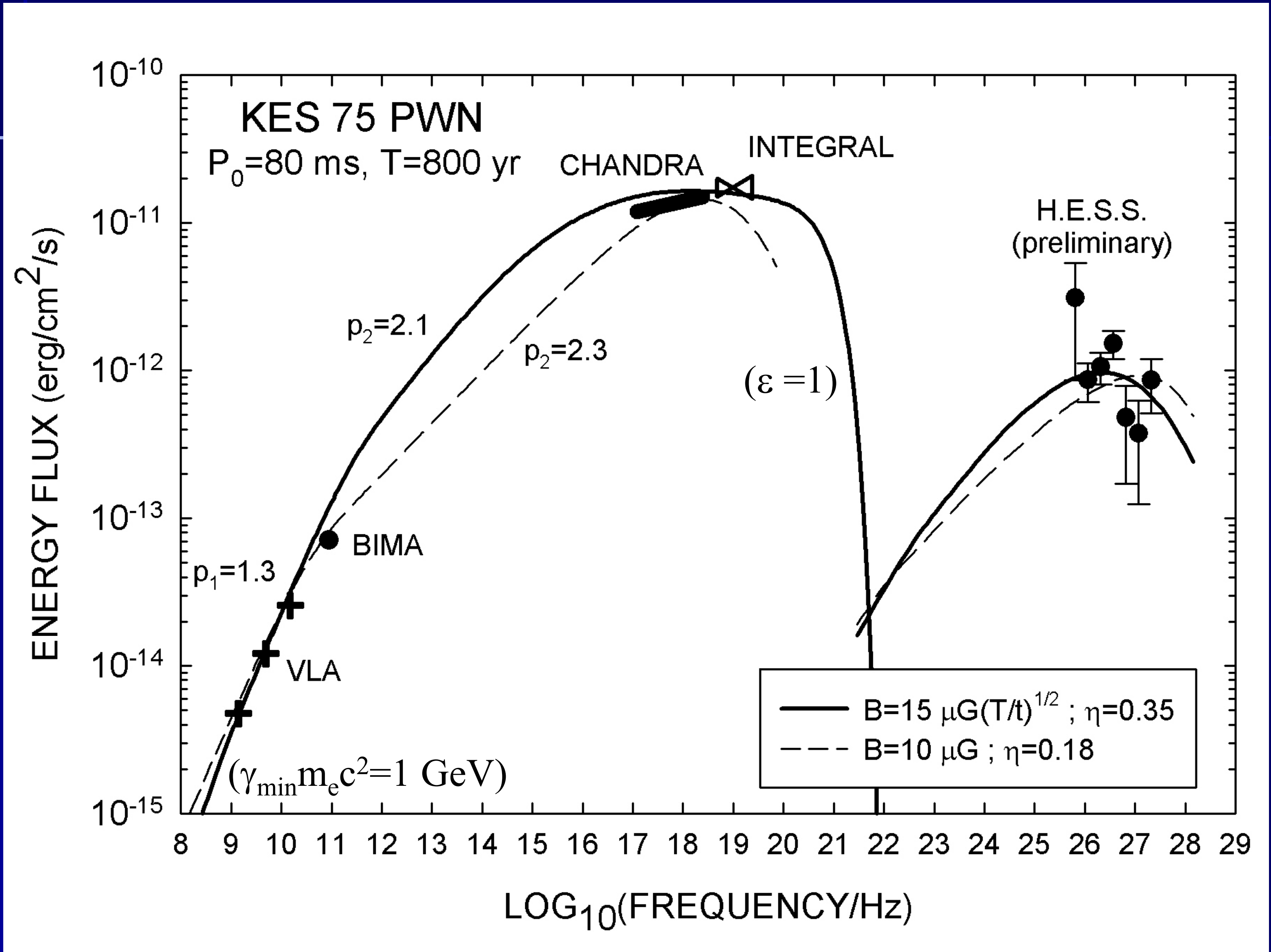


CHANDRA: Helfand et al. (2002)

Time dependent injection model for MWL spectrum of KES 75 – Observed radio flux consistent with P_0 = 80 ms and H.E.S.S. determined field strength. Intrinsic break energy 40 GeV – consistent with X-ray and VHE gamma-ray observations.



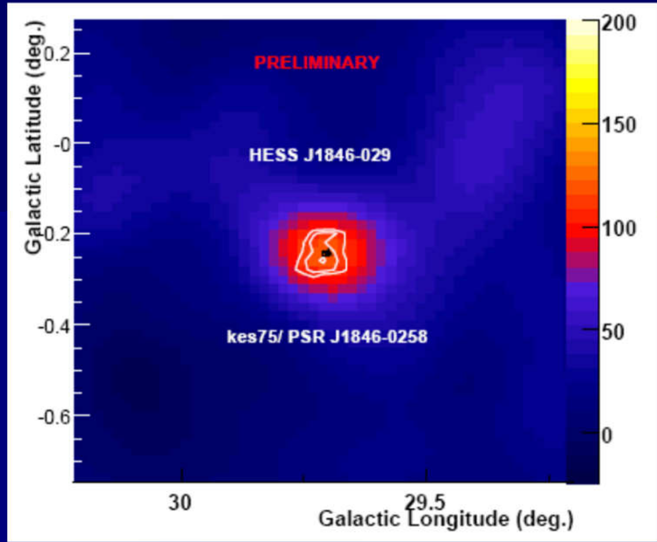
Time dependent model for MWL spectrum of KES 75. Radiation break energy smeared by variable field strength.



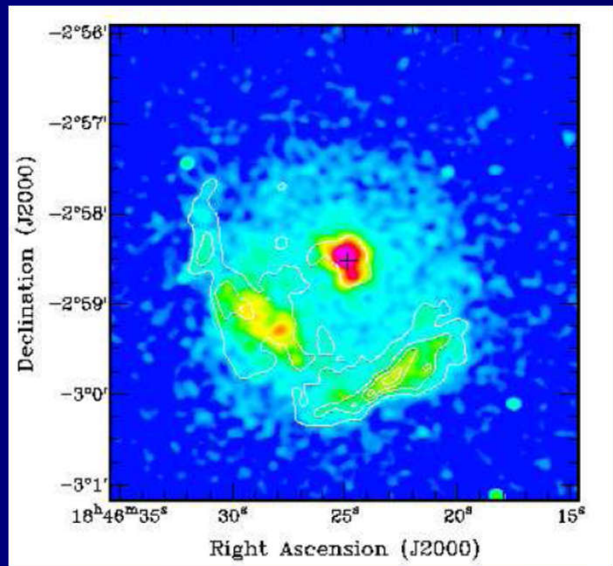
KES 75 Results

- Energy in field: W_B=2x10^{44} erg (same as Ng et al. 2008)
- Total particle energy of W_E=3.4x10^{47} erg ≈ 0.17 $\int(-\dot{E})dt$ (some fraction lost to radiation). Clearly particle dominated, unlike Crab Nebula!
- Total number of leptons: N_e>8x10^{48} (1 GHz radio frequency lower limit from 1 GeV $e^{\pm}$)
- Integrated number of Goldreich Julian pairs: N_{GJ}=1.6x10^{44}
- Pair production multiplicity (upper limit from electron energy lower limit of 1 MeV):

$$2.5\times10^5 > M > 2.4\times10^4$$



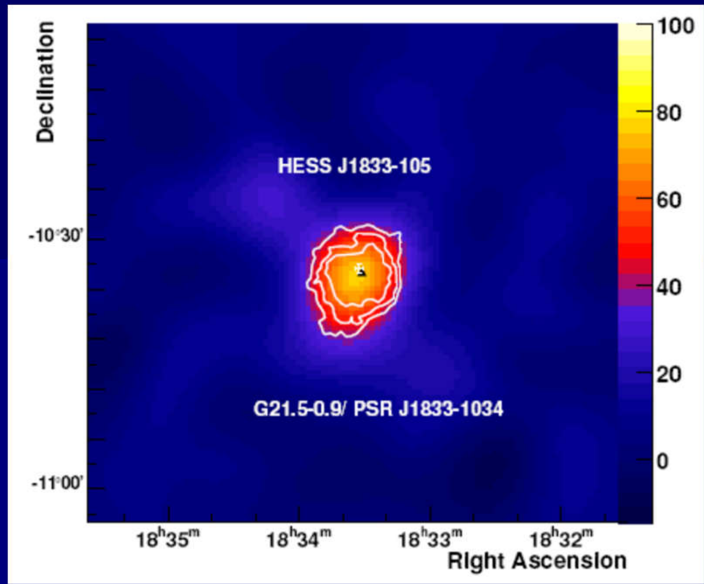
H.E.S.S.: Djannati-Ataï et al. (2007)



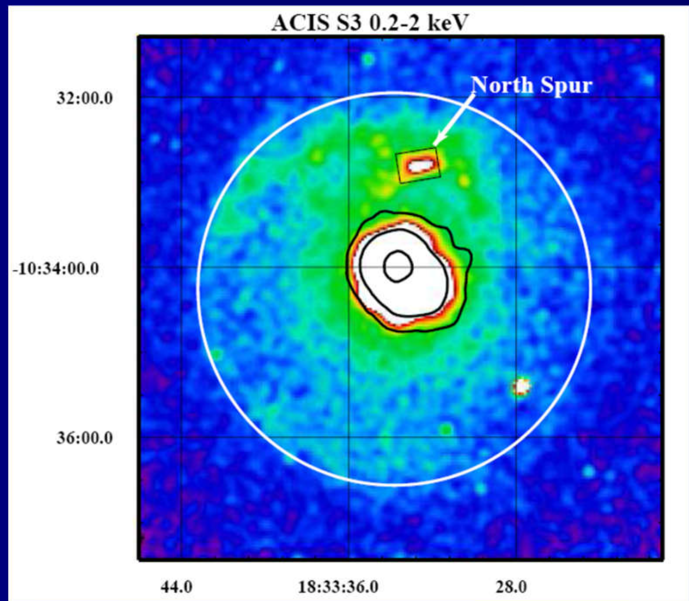
CHANDRA: Helfand et al. (2002)

G21.5-0.9

- $L = 4.7 \times 10^{48}$ erg/s
- R_{PWN}=1.2 pc; R_{SNR}=3.3 pc
- Expansion age 870 ± 200 yr => P_0=55 ms given P=61.8 ms.
- $\int(-\dot{E})dt \approx 3.8 \times 10^{48}$ erg for $L_0 = 1.1 \times 10^{38}$ erg/s.
- Requires $n \approx 0.6$ cm^{-3} to reproduce R_{SNR}=3.3 pc after a kyr.
- Requires $8M_o$ ejecta mass to reproduce R_{PWN} radius.
- Equipartition argument gives $E_{min} \approx 3.2 \times 10^{47}$ erg (Bocchino et al. 2005) and B_{eq}=0.2 mG.
- H.E.S.S. observations give lower field strength (Djannati-Atai et al. 2007) $B \approx 25\ \mu G$ => ten times lower than equiparition.

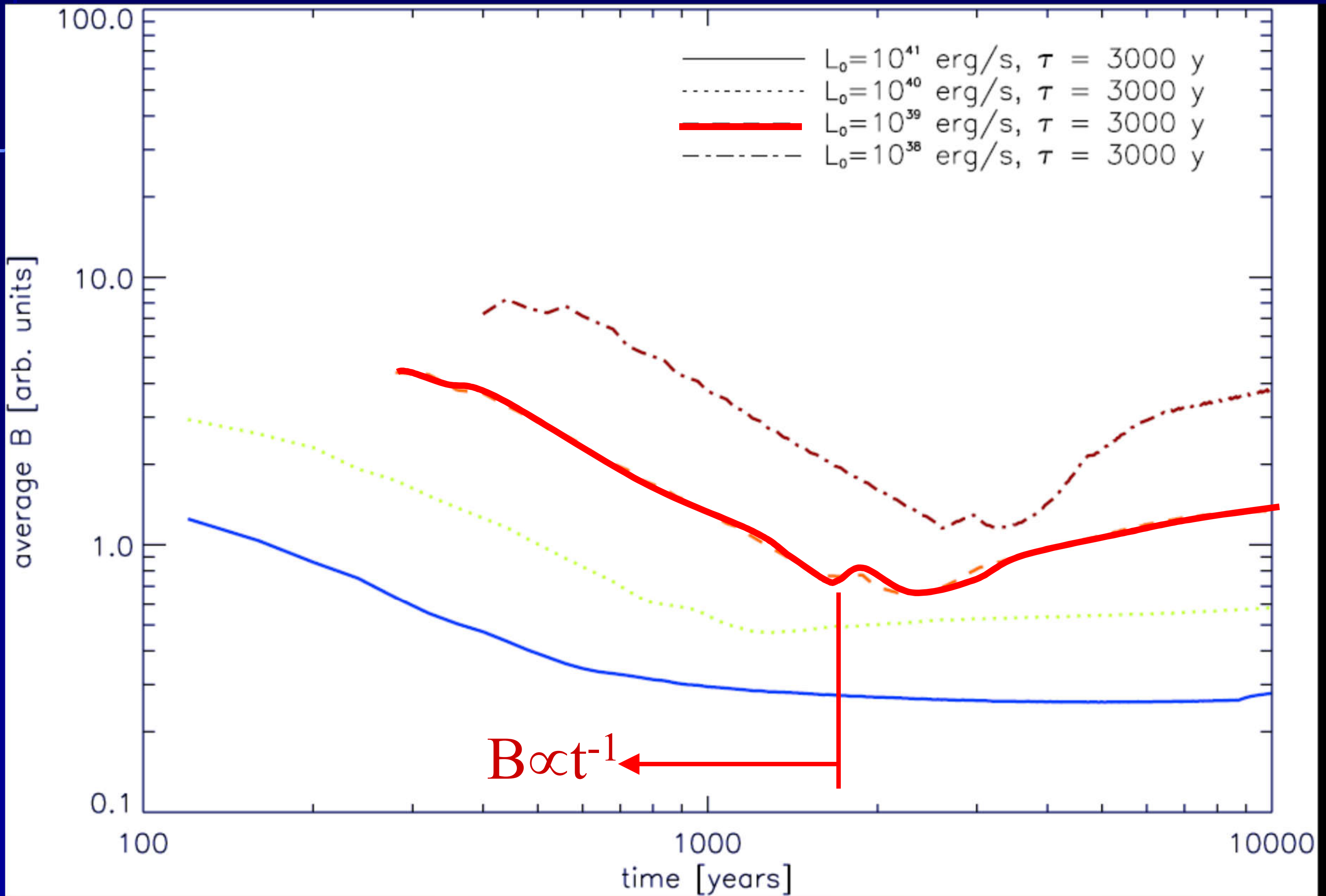


H.E.S.S.: Djannati-Ataï et al. (2007)

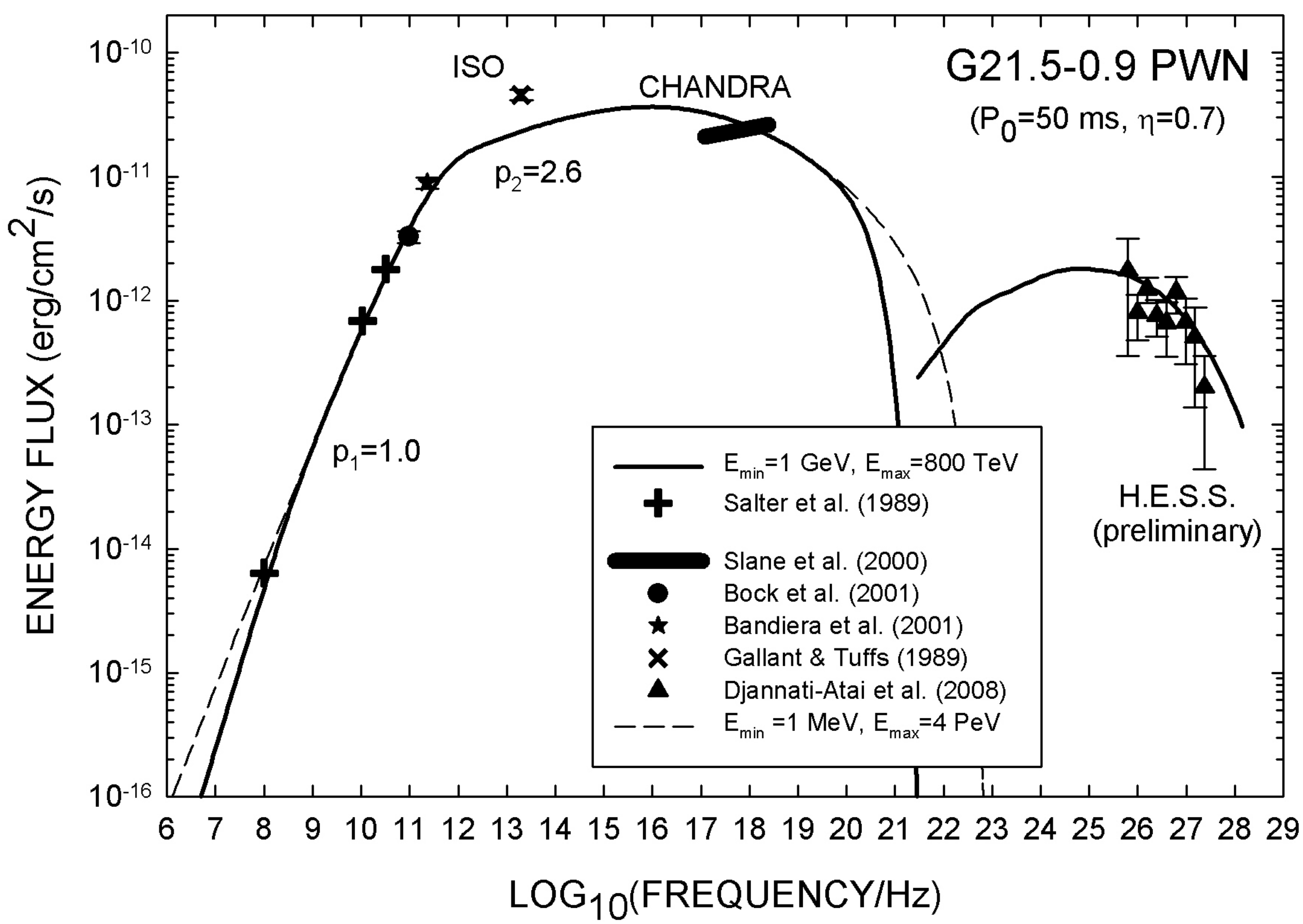


XMM-Newton: Bocchino et al. (2005)

EVOLUTION MEAN FIELD STRENGTH IN PWN of G21.5-0.9
($L_0 = 10^{38}$ erg/s; τ = 3000 yr; $M_{ej} = 8M_o$; $n_{ISM} = 0.6\ cm^{-3}$)



RADIATION SPECTRUM OF G21.5-0.9
B=25 μG (T/t)

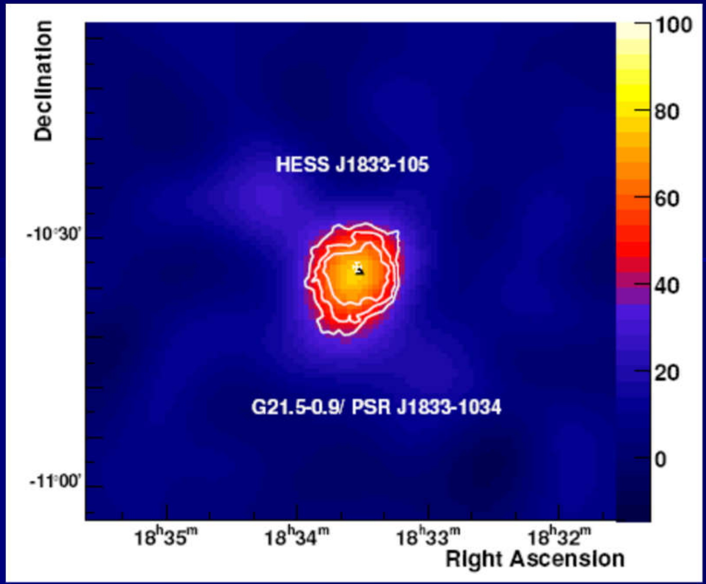


G21.5-0.9

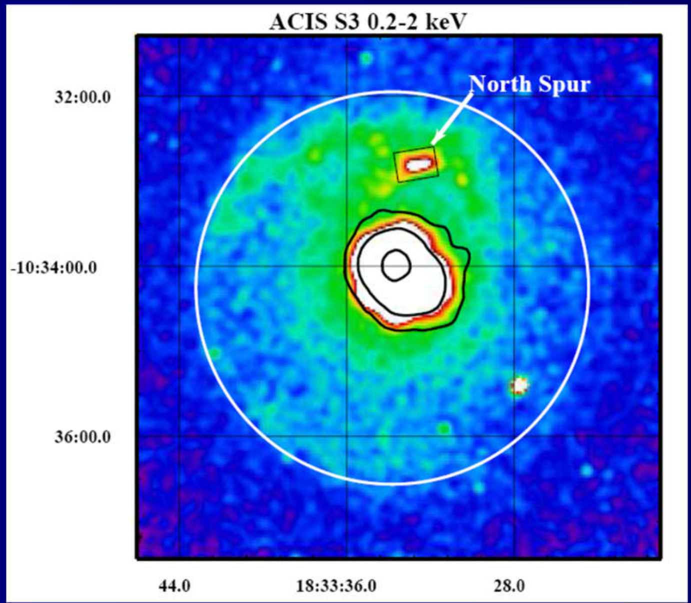
- Pair production multiplicity:

  $2.2x10^5 > M > 0.9x10^5$

- Challenge for standard models?

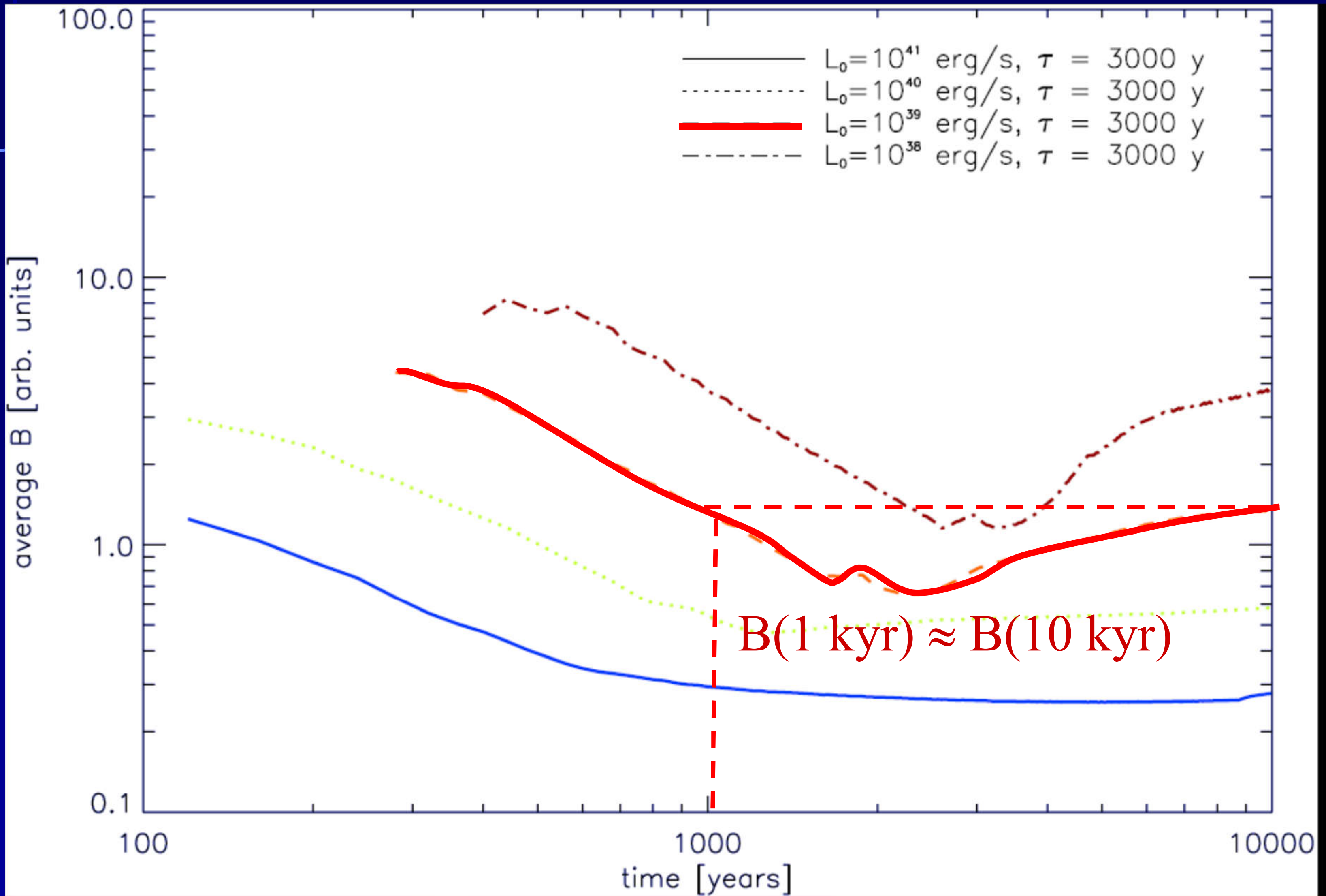


H.E.S.S.: Djannati-Ataï et al. (2007)



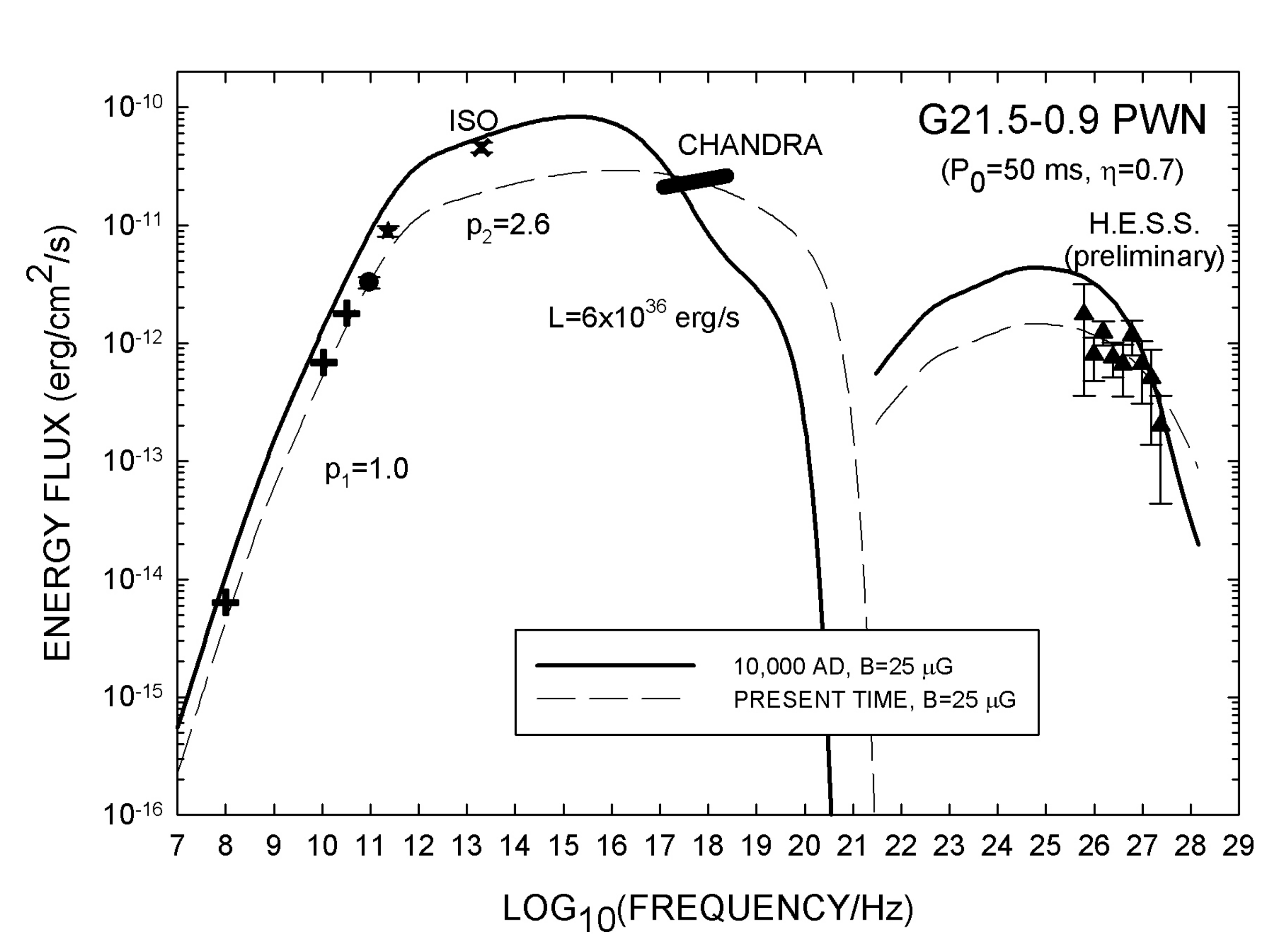
XMM-Newton: Bocchino et al. (2005)

EVOLUTION MEAN FIELD STRENGTH IN PWN of G21.5-0.9
($L_0 = 10^{38}$ erg/s; τ = 3000 yr; $M_{ej} = 8M_o$; $n_{ISM} = 0.6\ cm^{-3}$)



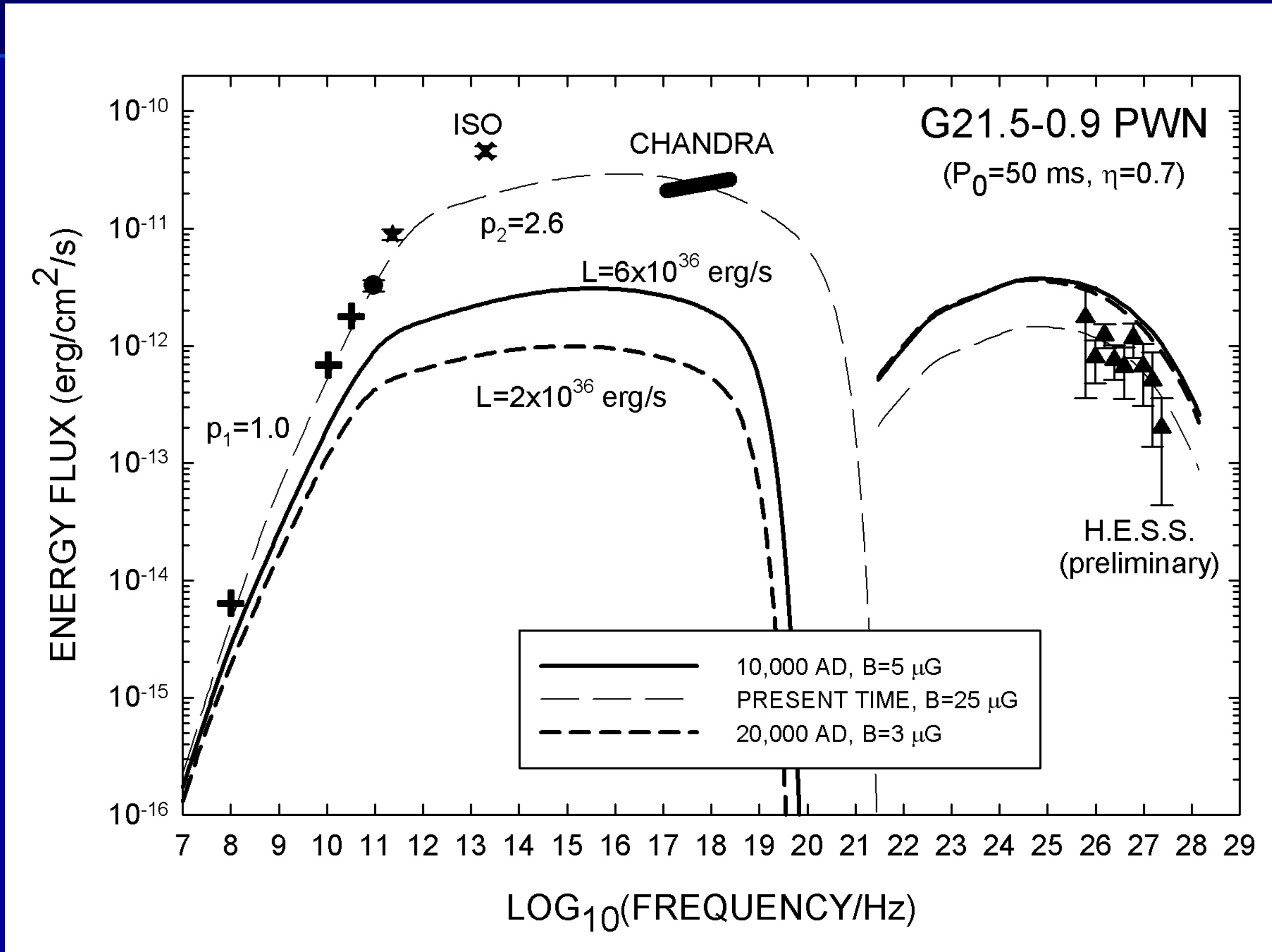
G21.5-0.9: 10,000 AD

Field strength restored to 25 μG after 10 kyr in oscillatory motion (due to reverse shock). End spindown power 6×10^{36} erg/s



G21.5-0.9: 10,000 AD & 20,000 AD

Explosion in low density ISM. Field strength drops significantly before reverse shock compresses PWN. Assuming H.E.S.S. type B-values.



Conclusions

- SNR explosion near high density wall gives reverse shock in the form of a "wind" lasting more than 10,000 yr, rather than just a crushing effect of short duration. Explains continuous sweeping of freshly injected X-ray electrons in Vela X.
- Two-component radiation model with boundary conditions predicts radio, X-ray and VHE gamma-ray SEDs of KES 75 and G21.5-0.9 satisfactorily.
- Pair production multiplicities are $2.5\text{x}10^5 > M > 2.4\text{x}10^4$ for KES 75 and $2.2\text{x}10^5 > M > 0.9\text{x}10^5$ for G21.5-0.9.
- Density of ISM has an impact on the evolution of X-ray to VHE gamma-ray luminosity. Middle aged VHE PWNe most likely due to expansion in low density ISM.