Understanding PWN through observations

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Dublin Summer School on High Energy Astrophysics 4th - 15th July 2011

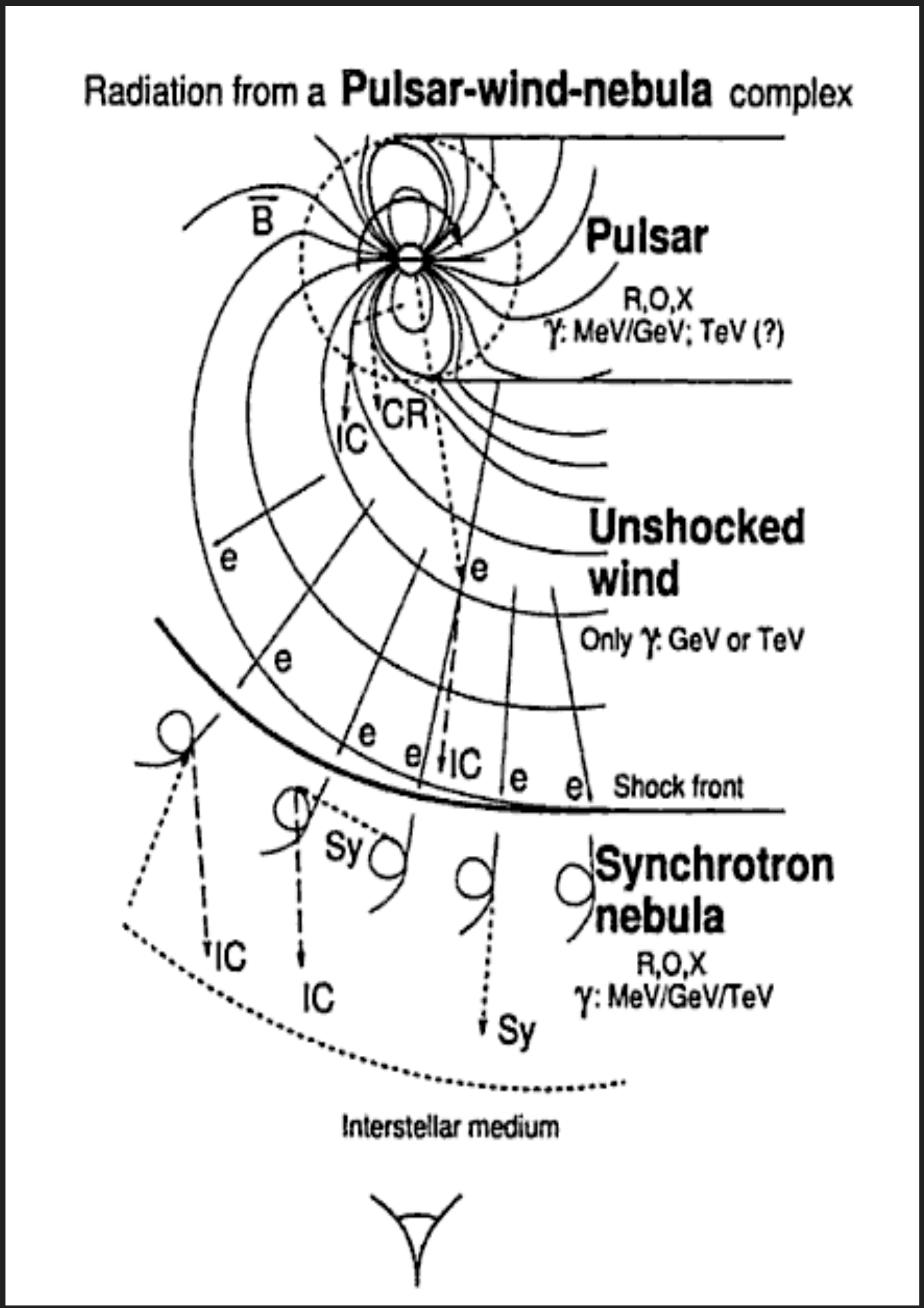
Outlook

- Review of main features related to observational parameters (for a theoretical review see lecture by J. Arons - Thursday 7th 9:00h): From the neutron star to the nebula
- Dynamical and spectral evolution of PWNe
- The Crab Nebula and a few observational examples
- PWN at Very high energy: what can we learn from them?

Some slides borrowed from:
- P. Slane
- F. Aharonian
- E. Amato

http://chandra.harvard.edu/photo/2002/0052/animations.html

Pulsar Wind Nebulae (PWN or plerions)



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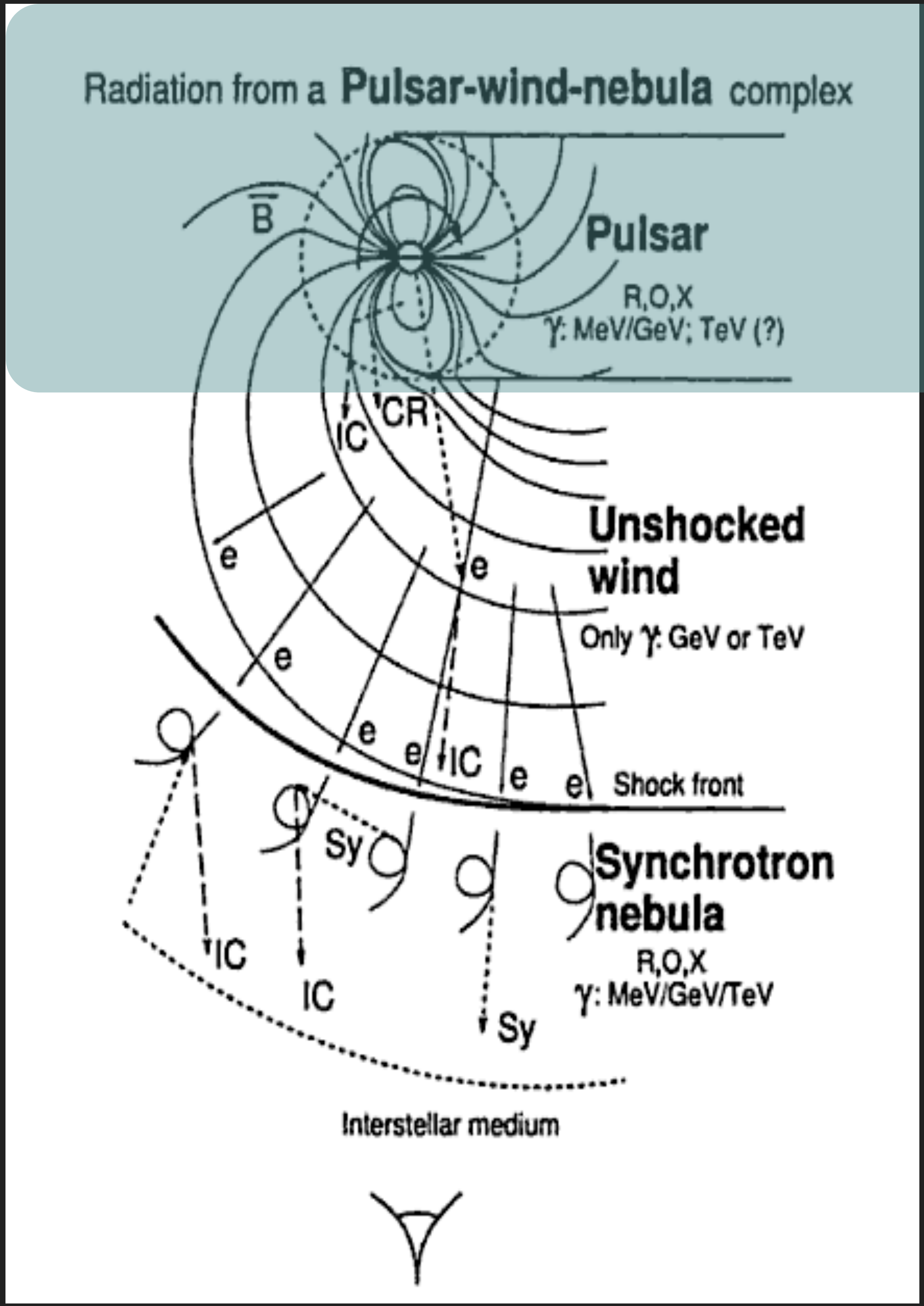

- Pulsed emission
  - Polar cap
  - Outer gap
  - Slot gap

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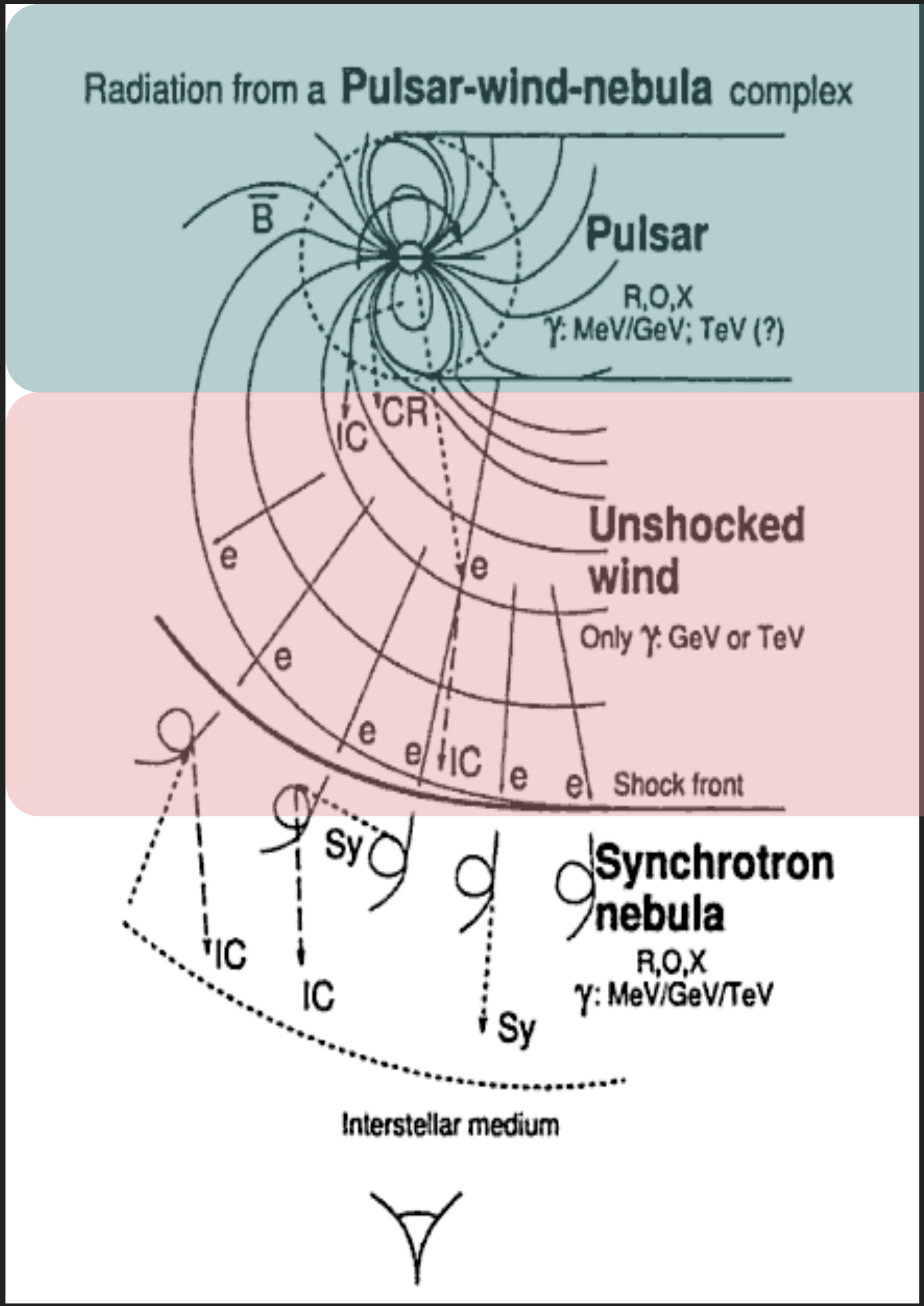

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- Non-thermal pulsed soft photons target -> Pulsed IC emission
- Thermal isotropic radiation target ->Steady GeV emission

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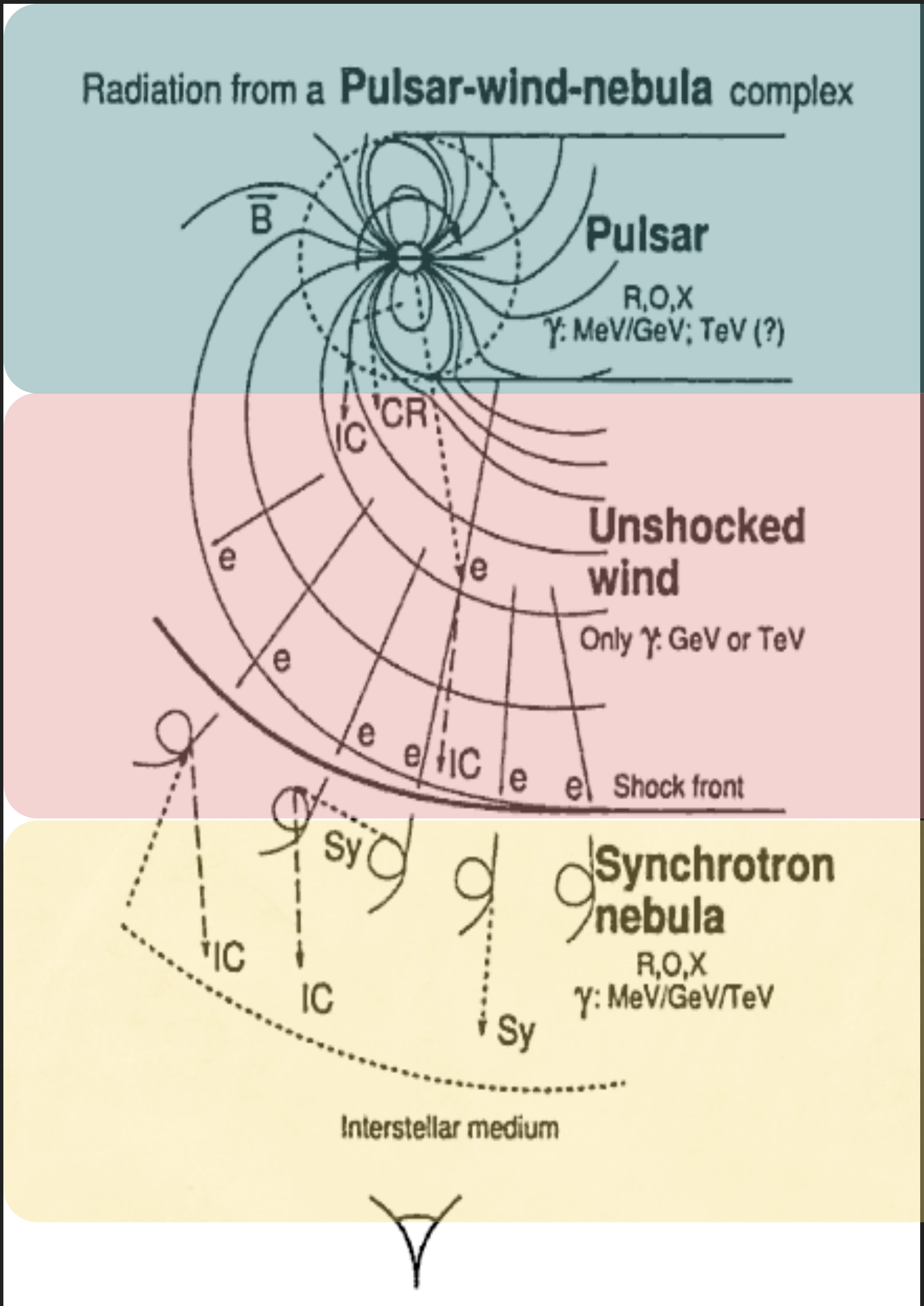

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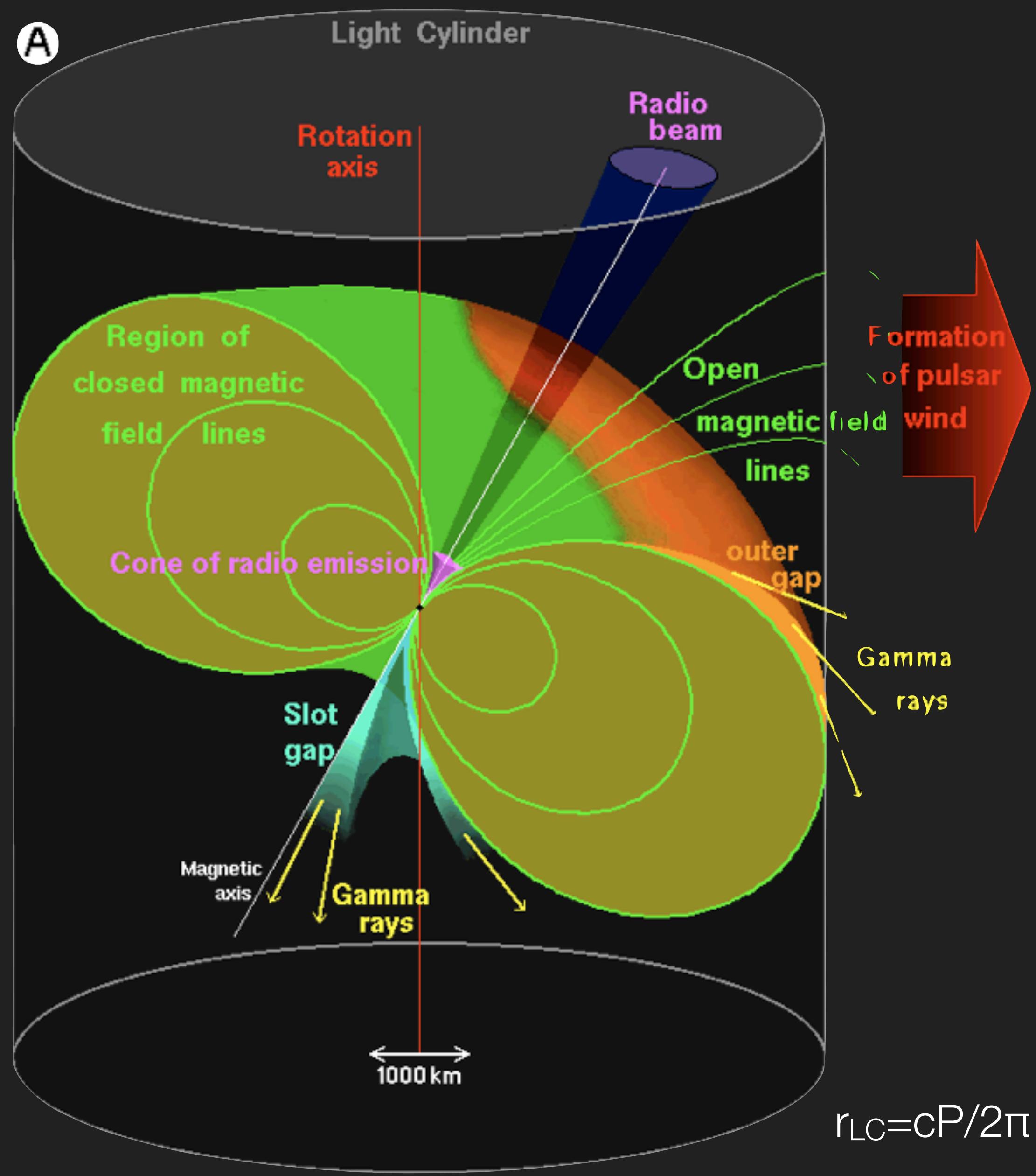
- Synctrotron Nebula
- IC
  - Unpulsed emission
  - Seeding on photons from the CMB, IR, UV and synchrotron

Pulsar Wind Nebulae (PWN or plerions)

Calorimeters that collect the rotation energy lost by fast-spinning magnetised neutron stars



$r_{LC}=cP/2\pi$

- Electric and magnetic fields dominate this region
- Rotating **B** produces an enormous **E**
- Tears particles from the stellar surface and accelerate up to high energies.
- e± cascada filling the magnetosphere and co-rotating with it
- At the LC the particles escape, carrying away magnetic flux and energy as an ultrarelativistic, magnetised wind.

Chandra (X-ray; 0.1 keV<E<50 keV)

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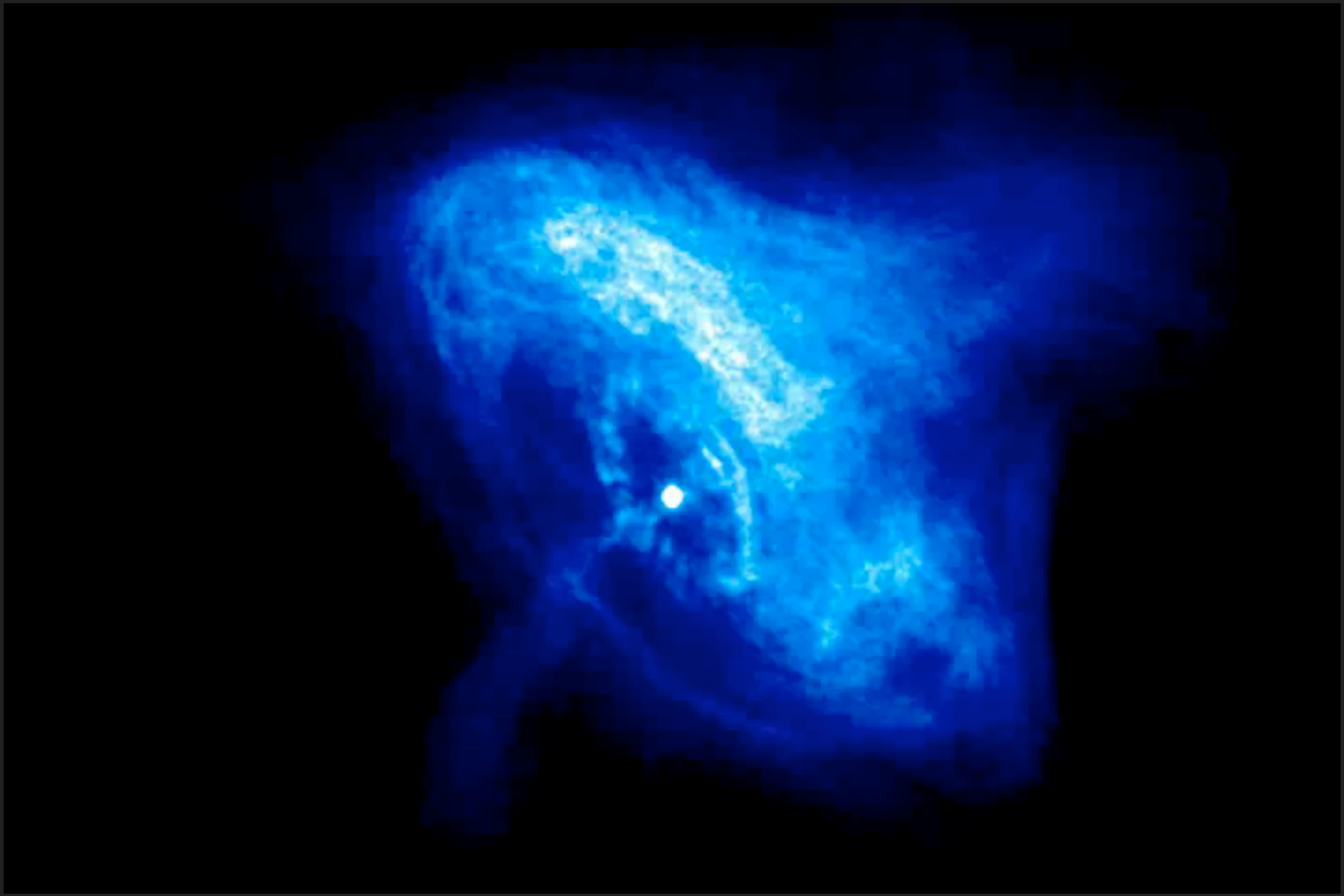
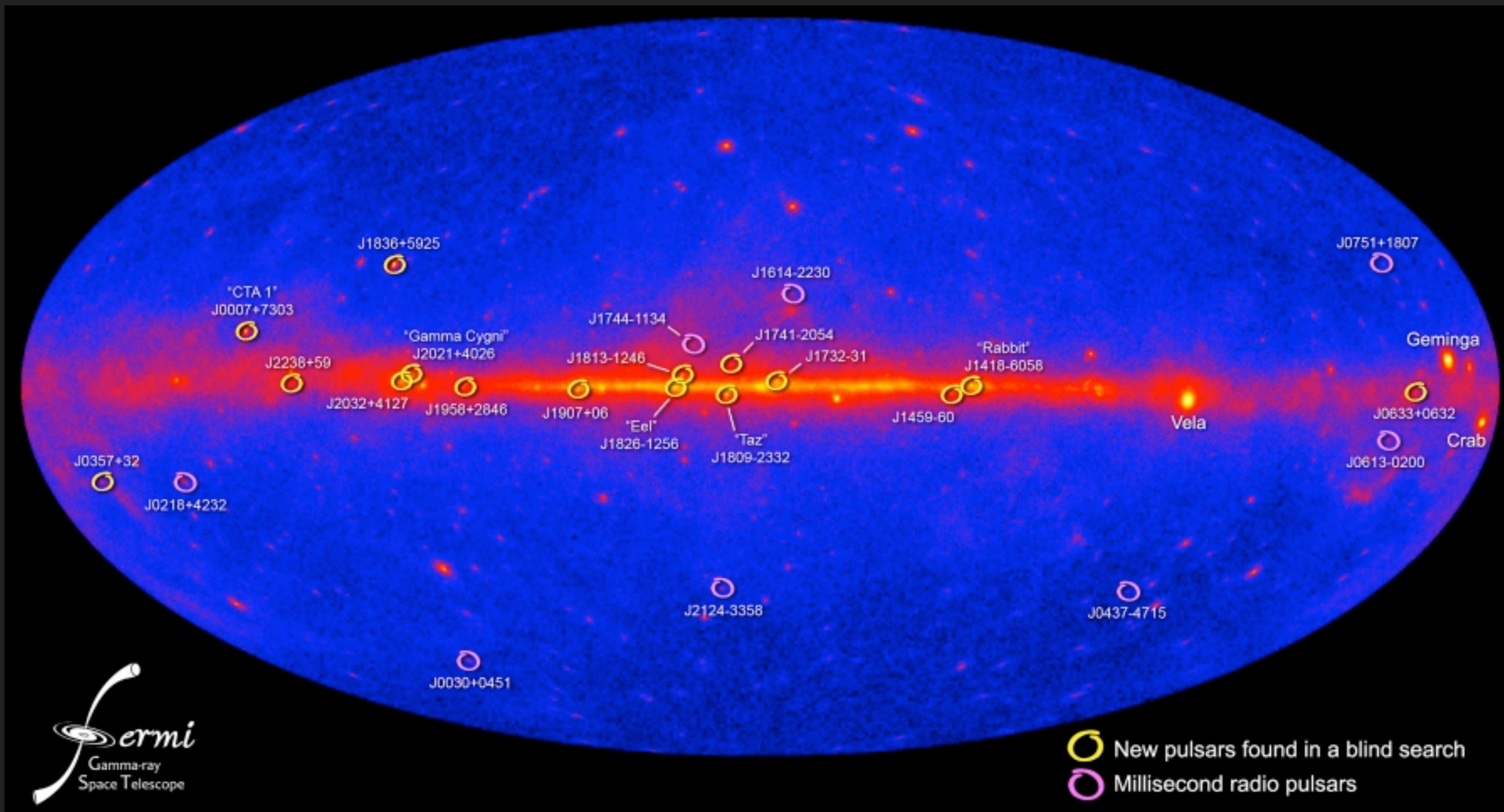


Fermi-LAT (HE; 100 MeV<E<100 GeV)

Abdo et al, ApJ.708, 1254,2010



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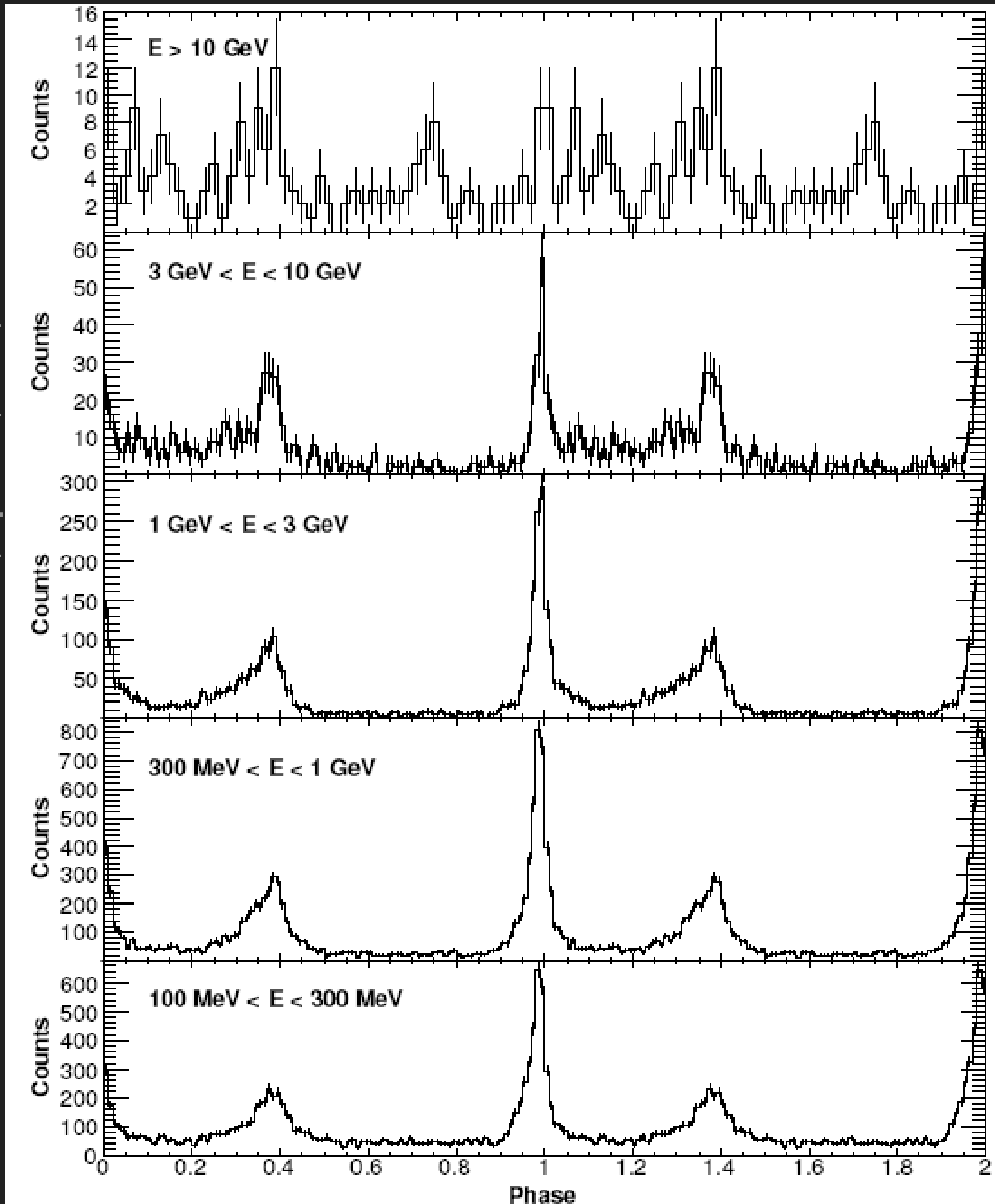

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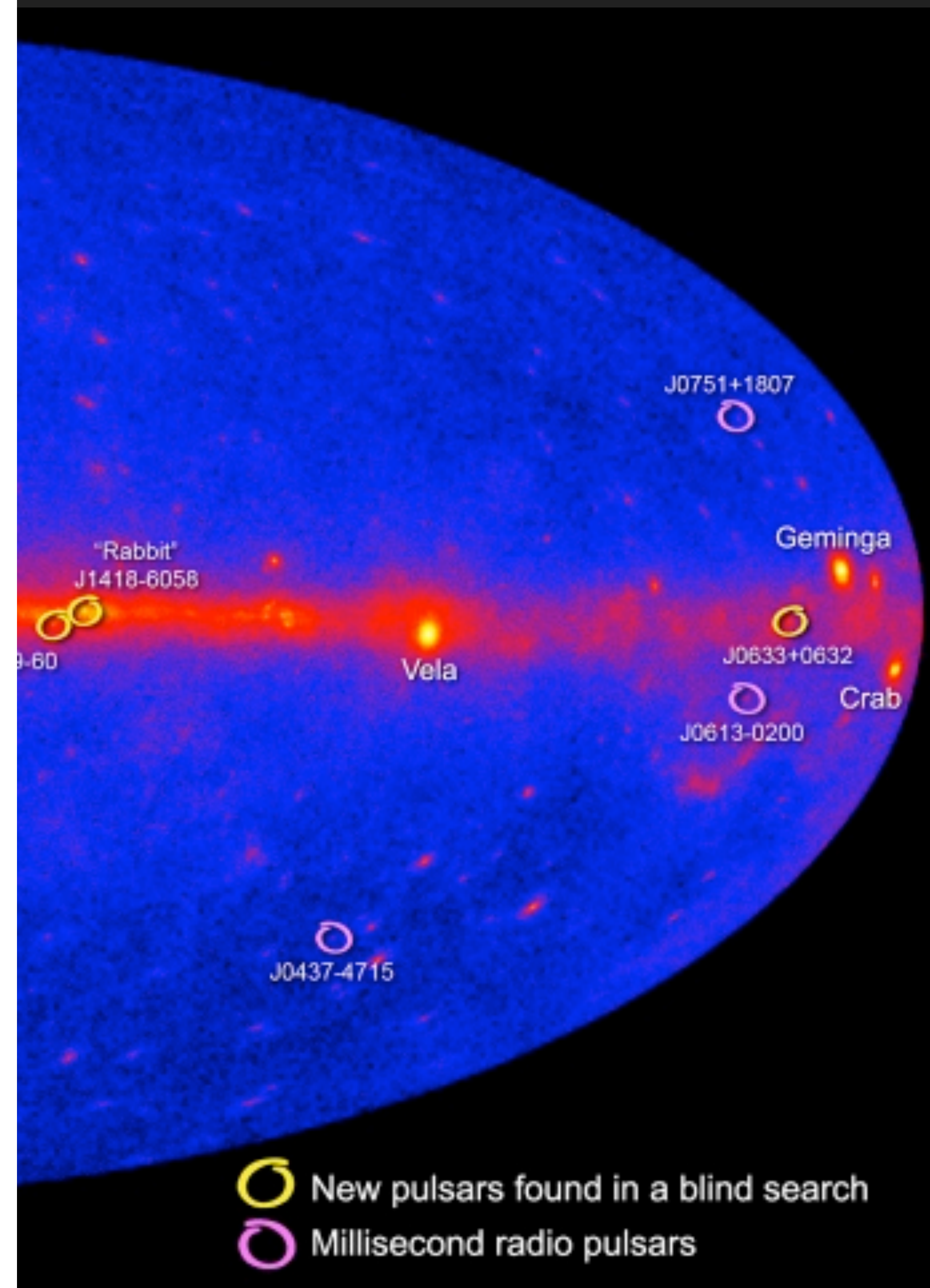

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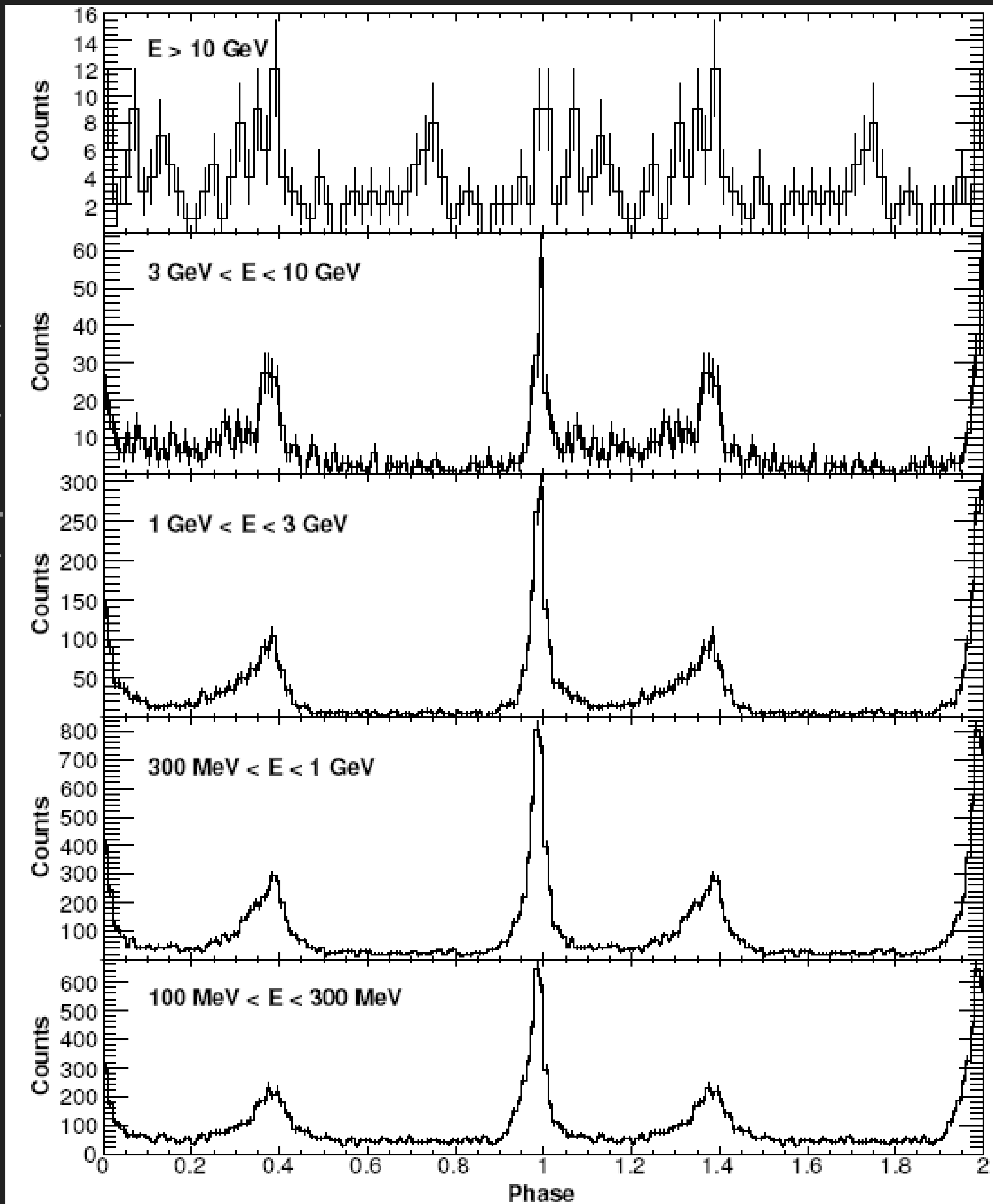

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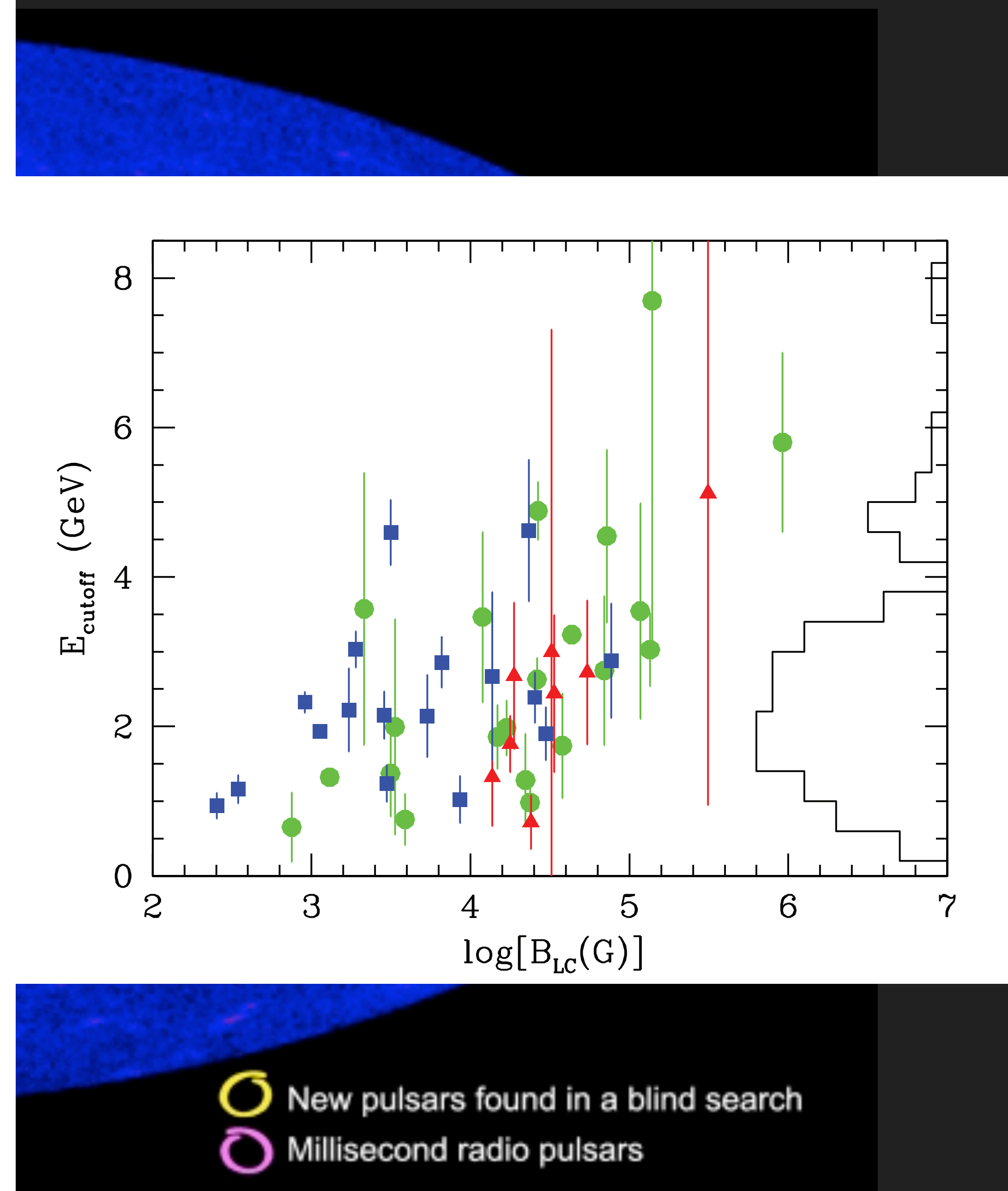
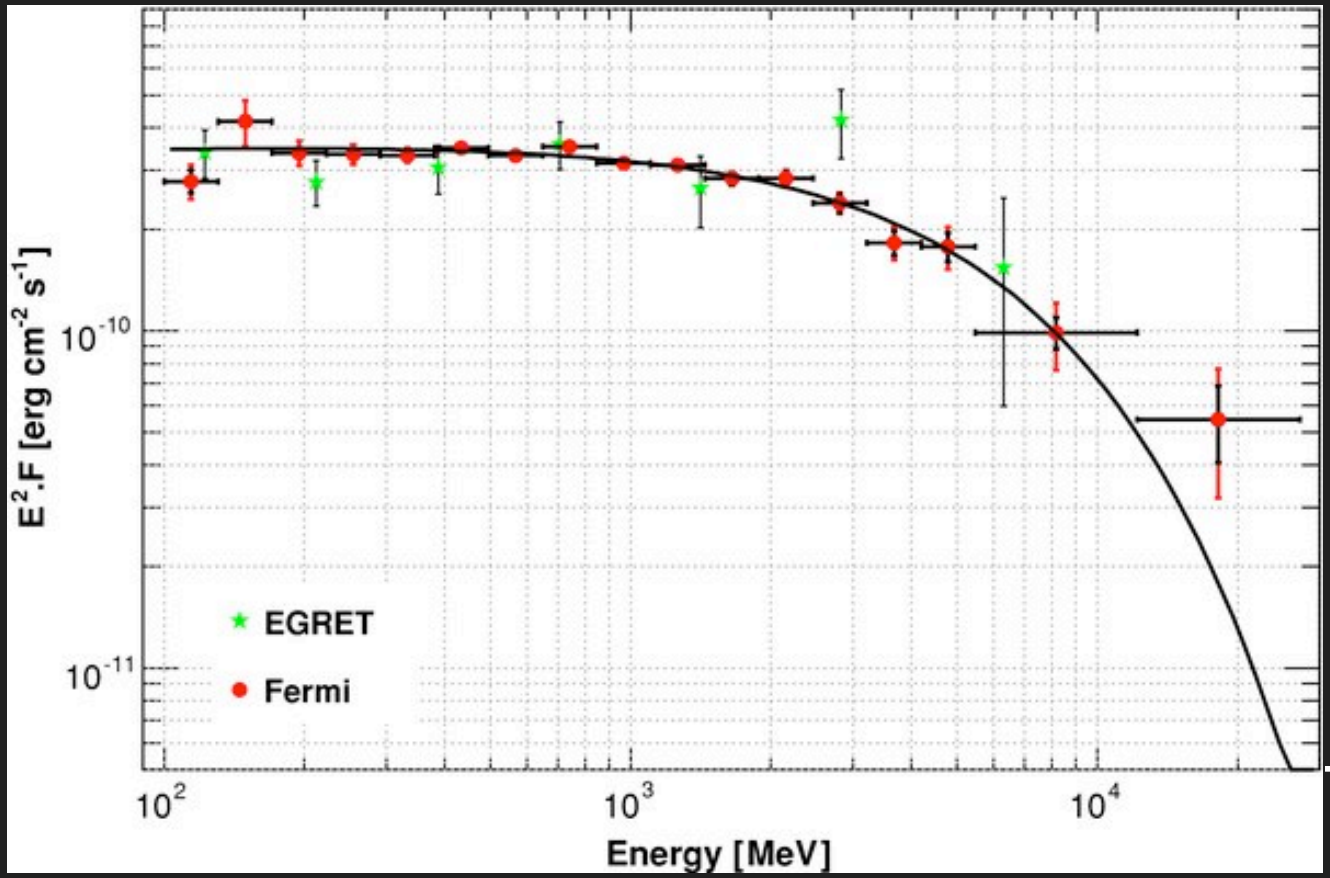


Pulsed emission from Crab at 300 GeV!

- Reported recently by VERITAS at VHE, 0.1 TeV<E<100 TeV (Otte, Fermi Symp, 2011) : 1% Crab Nebula, very soft spectrum



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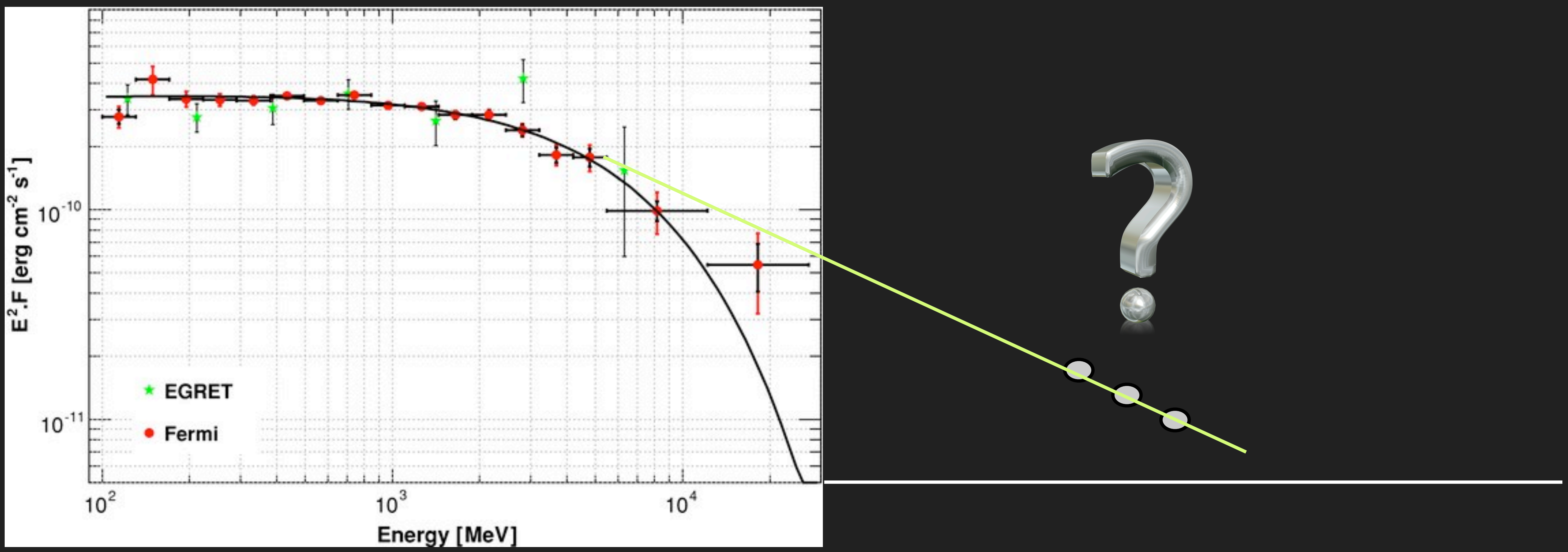

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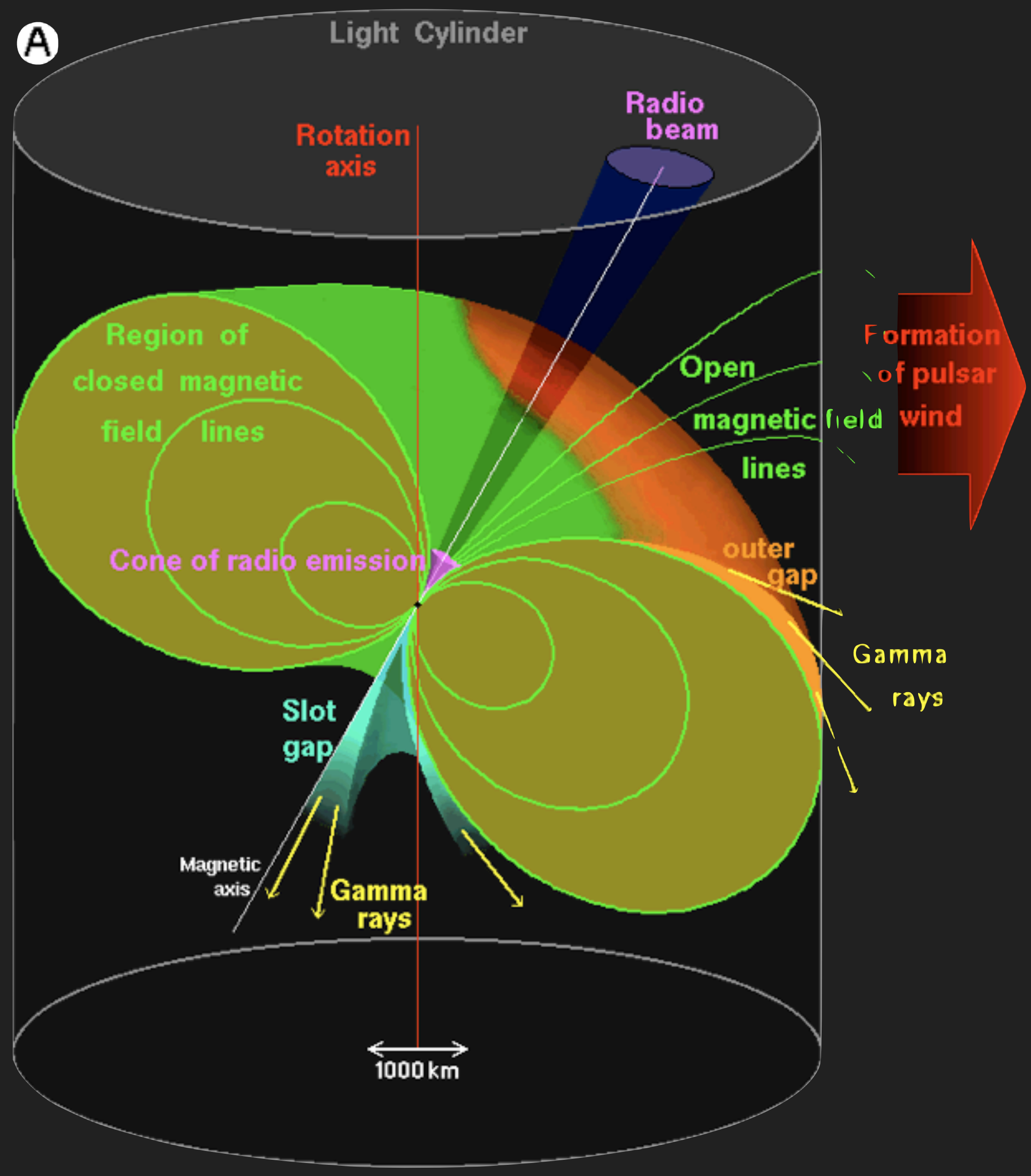

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- Energy is contained in the fields while the plasma total energy density remains small

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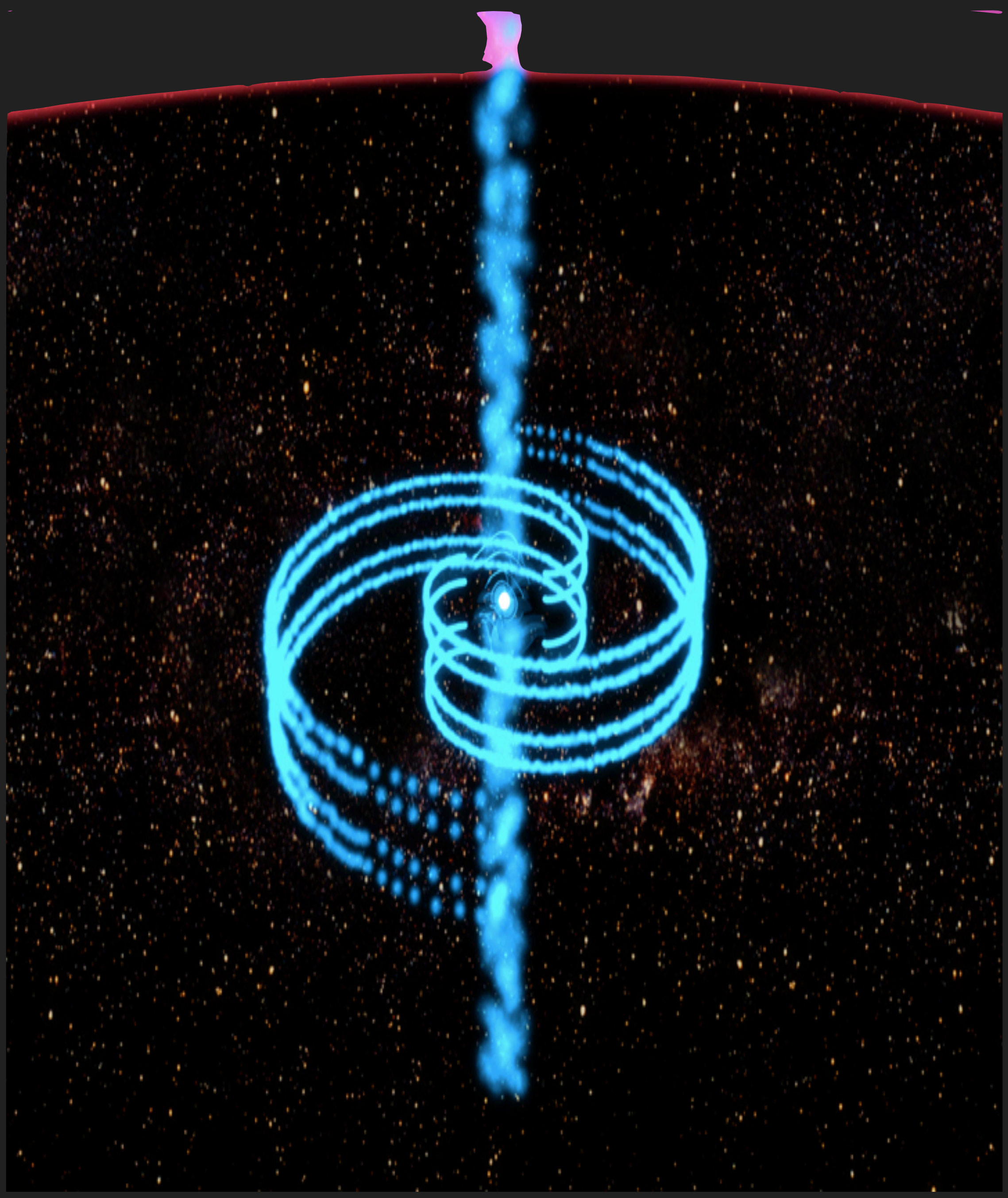

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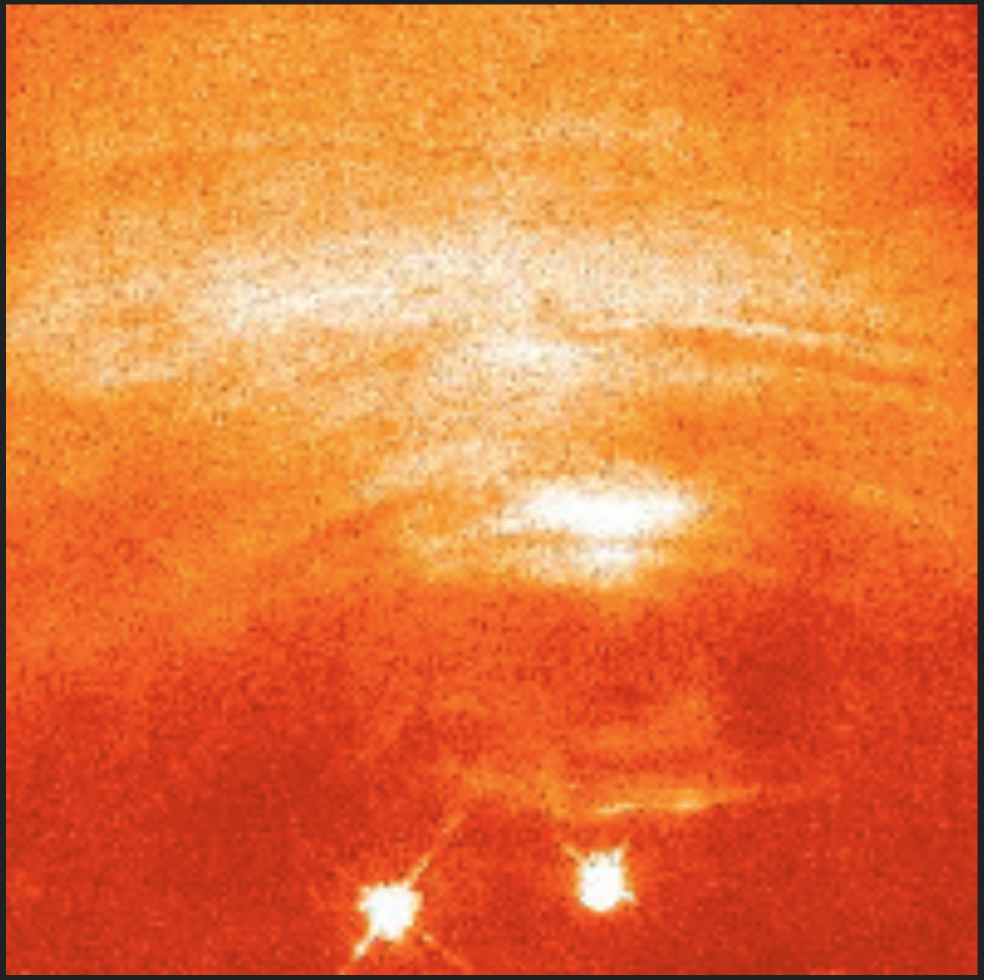

- From the LC to termination shock
- Energy is contained in the fields while the plasma total energy density remains small
- Termination shock (TS) is formed when the wind finds the slowly expanding nebula

$P_{ram} = P_{nebula}$

- Lorenz factor before the TS: $10^4 < \Gamma < 10^7$
- Relativistic wind is described by the magnetization parameter

$\sigma \equiv$ Poynting flux/kinetic energy flux
$= B^2/4\pi\rho\Gamma c^2$

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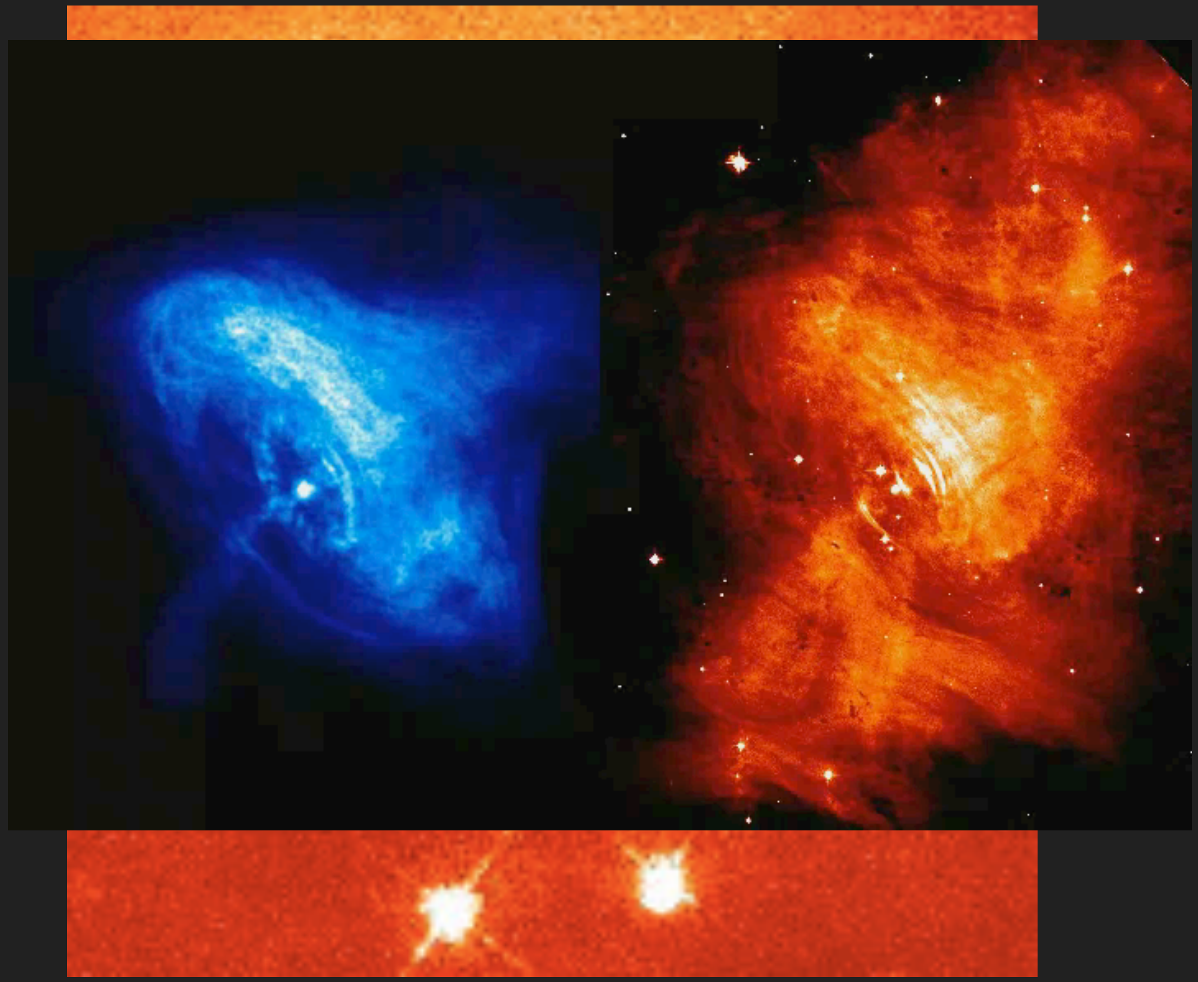

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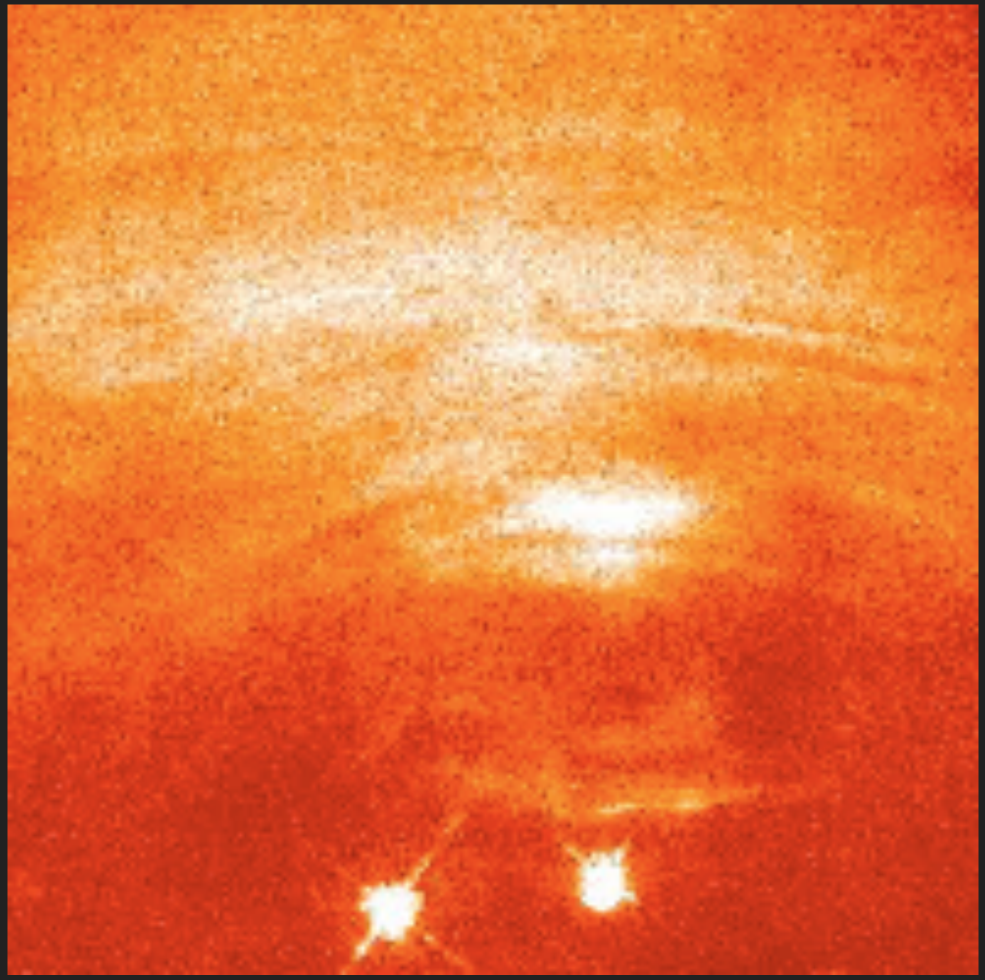

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The σ-paradox and spectrum "problems"

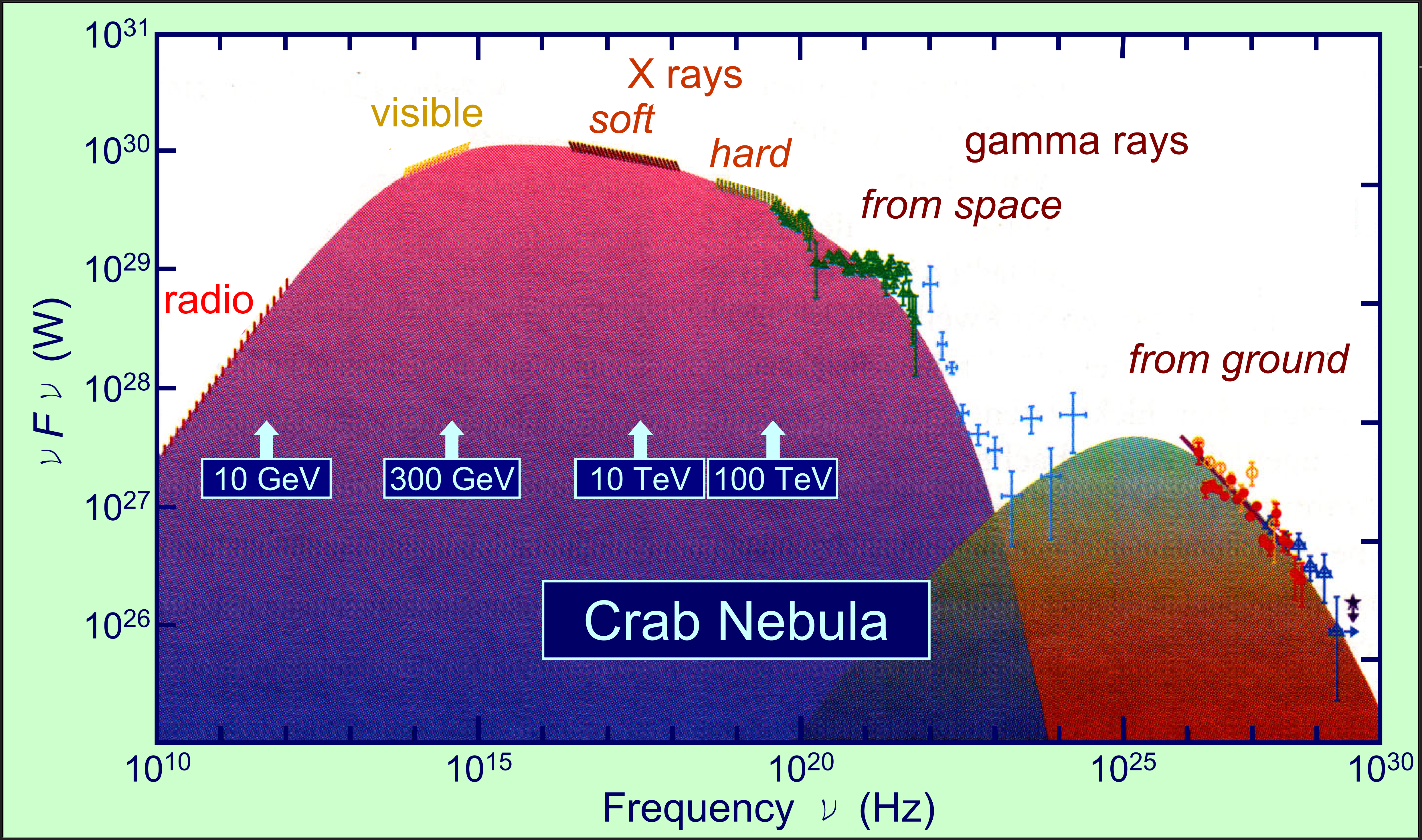
- Near the LC: $\sigma >> 1$ - strong electromagnetic fields at the origin of pulsar behaviour (for Crab $\sim 10^4$)
- Crab spectrum of the nebula was modelled by Kennel & Coroniti 1984 (K&C) : Best fit σ is 10^{-3}
- Value confirmed by MHD-simulations
- How to convert a magnetic-dominant wind in a particle dominated one?
  - Magnetic reconnection (Coroniti 1990; Michael 1994; Kirk et al. 2003...)
  - Non-ideal MHD effect (Melatos et al 1996...)
  - Linear acceleration mechanisms (Contopoulos et al 2002...)
  - ...

Modeling the Crab observations

- K&C reproduced the surface profile at optical and X-ray
- A cold MHD wind propagating up to the TS at a speed corresponding to a bulk Lorenz factor of $\Gamma \sim 3\ 10^6$ ($E \sim m_e c^2 \Gamma \sim 1$ TeV, $dN/dt \sim 10^{38} s^{-1}$)
- These $e^{\pm}$ emit from UV to gamma-ray
- Where do the IR & radio-emitting particles come from?
  - The large number requires $dN/dt \sim 10^{40}$ to $10^{41}\ s^{-1}$ -> $\kappa \sim 10^6$
  - $\Gamma \sim 10^4$ -> Upstream Wind $\Gamma \sim \Gamma_{radio} \sim 10^{-2}\ \Gamma_{ox}$
  - Relic Population of electrons?

$$\dot{N} = 2.7 \times 10^{30} \kappa (\frac{B_*}{10^{12} G})(\frac{P}{1s})^{-2} \mathrm{s}^{-1}$$

$$\frac{L_{sd}}{mc^2 \Gamma} \sim \dot{N}$$



X rays
visible
soft
hard
gamma rays
from space
radio
from ground
10 GeV
300 GeV
10 TeV
100 TeV
Crab Nebula
10^{31}
10^{30}
10^{29}
10^{28}
10^{27}
10^{26}
$\nu F \nu$ (W)
10^{10}
10^{15}
10^{20}
10^{25}
10^{30}
Frequency ν (Hz)

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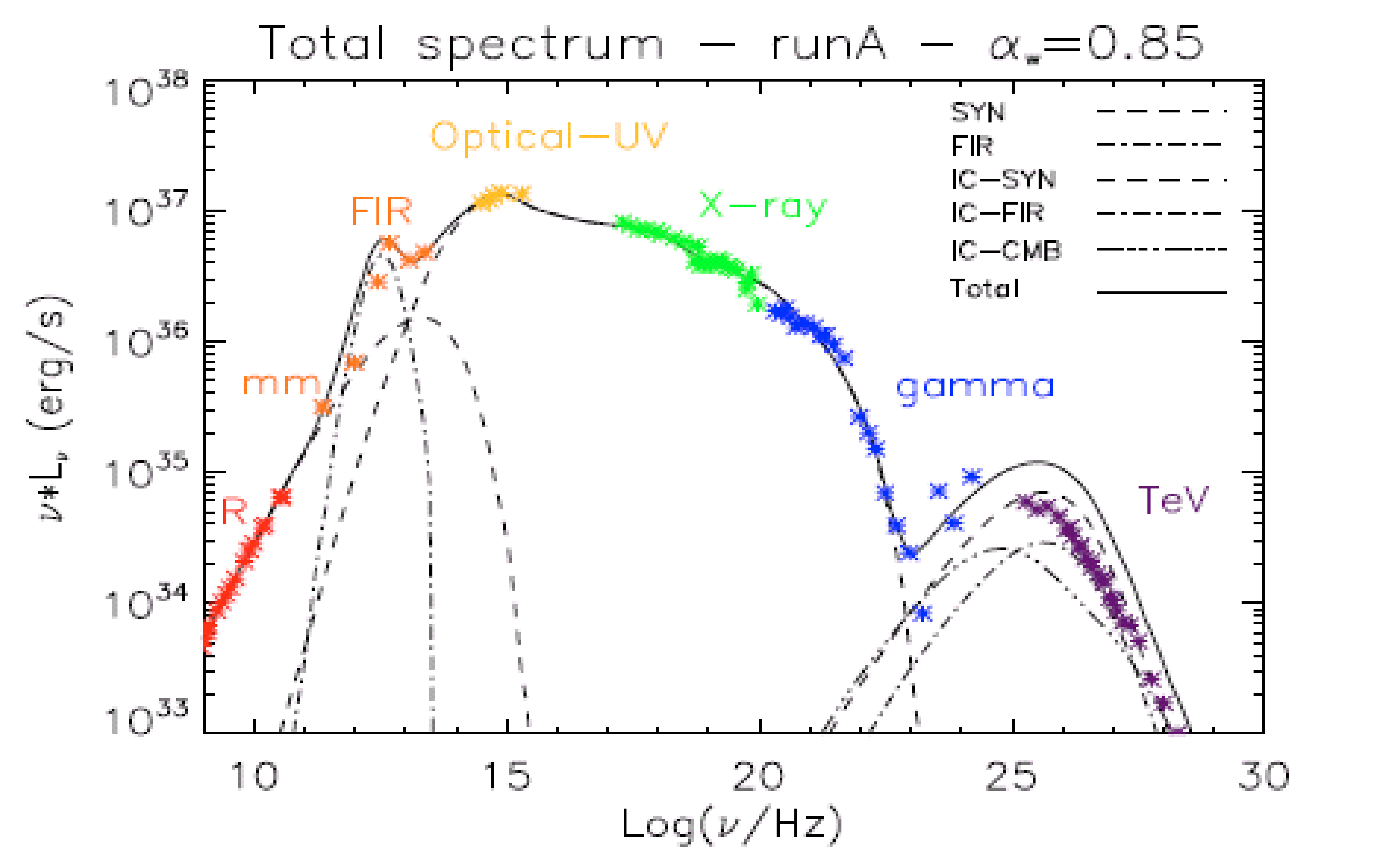

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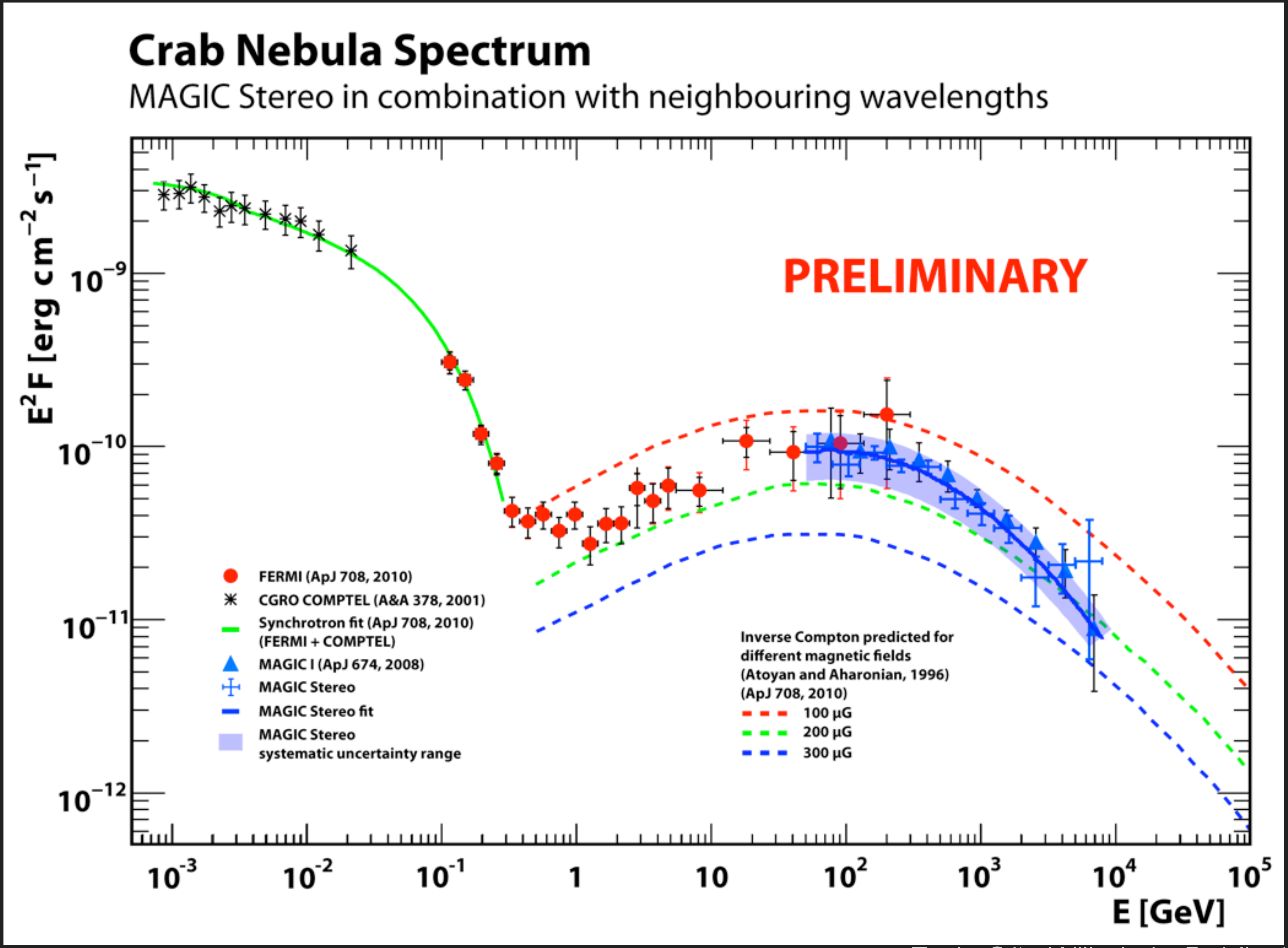


Crab Nebula Spectrum
MAGIC Stereo in combination with neighbouring wavelengths
PRELIMINARY
E^2F [erg cm^{-2} s^{-1}]
10^{-9}
10^{-10}
10^{-11}
10^{-12}
FERMI (ApJ 708, 2010)
CGRO COMPTEL (A&A 378, 2001)
Synchrotron fit (ApJ 708, 2010) (FERMI + COMPTEL)
MAGIC I (ApJ 674, 2008)
MAGIC Stereo
MAGIC Stereo fit
MAGIC Stereo systematic uncertainty range
Inverse Compton predicted for different magnetic fields (Atoyan and Aharonian, 1996) (ApJ 708, 2010)
100 μG
200 μG
300 μG
10^{-3}
10^{-2}
10^{-1}
1
10
10^{2}
10^{3}
10^{4}
10^{5}
E [GeV]

What's with the pwn observations?

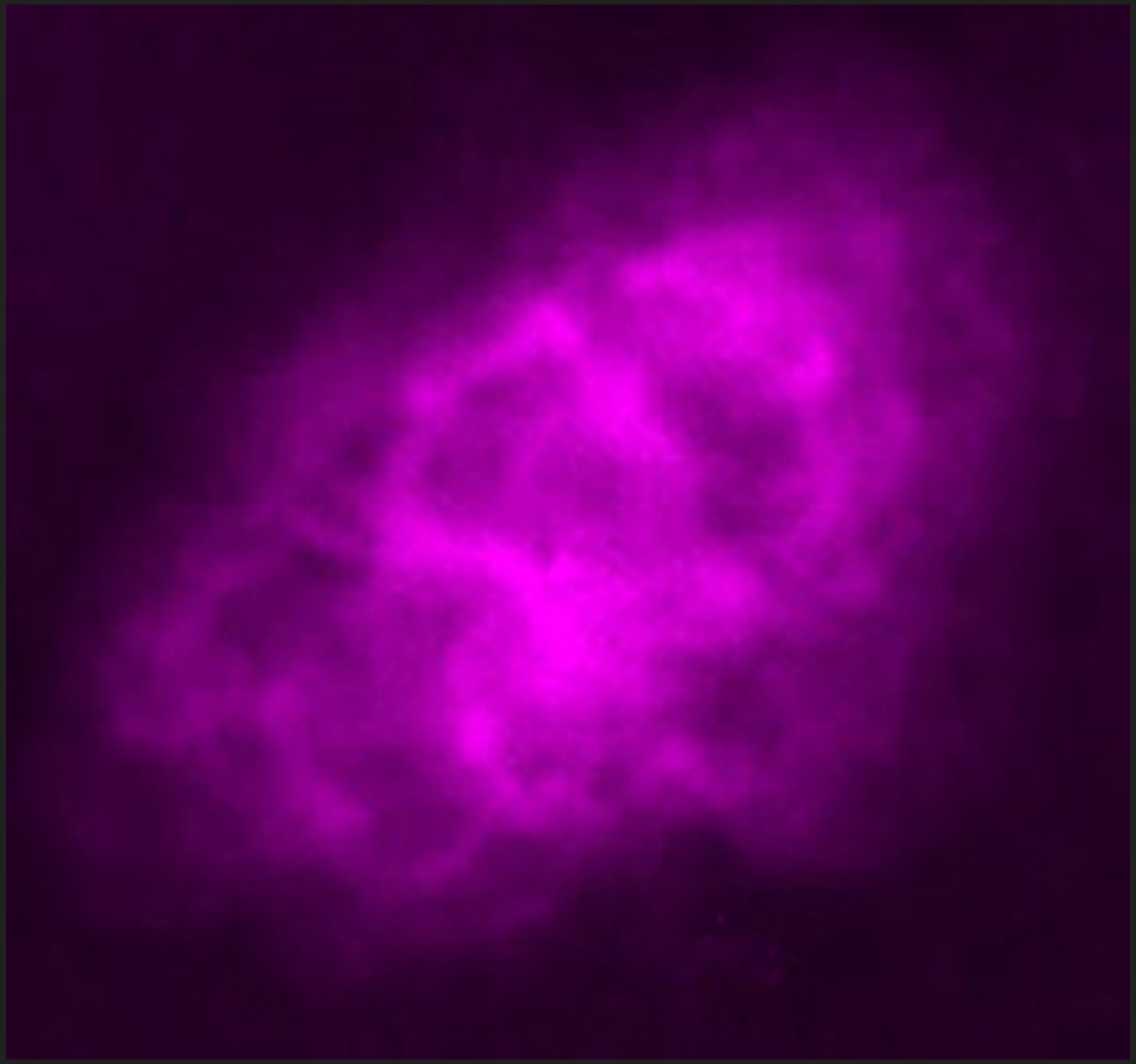
- Observed in radio (~25)

  $S_\nu \sim \nu^\alpha$, $N_E \sim E^{-\Gamma}$ ($\Gamma \equiv 1-\alpha$) -> $-0.3<\alpha<0$

- Optical & IR (~10 highly absorbed)

- X-rays (~25 Γ~2 -> spectral break!)

- Gamma-rays (~30 in 4 years! Γ~ 2.5)



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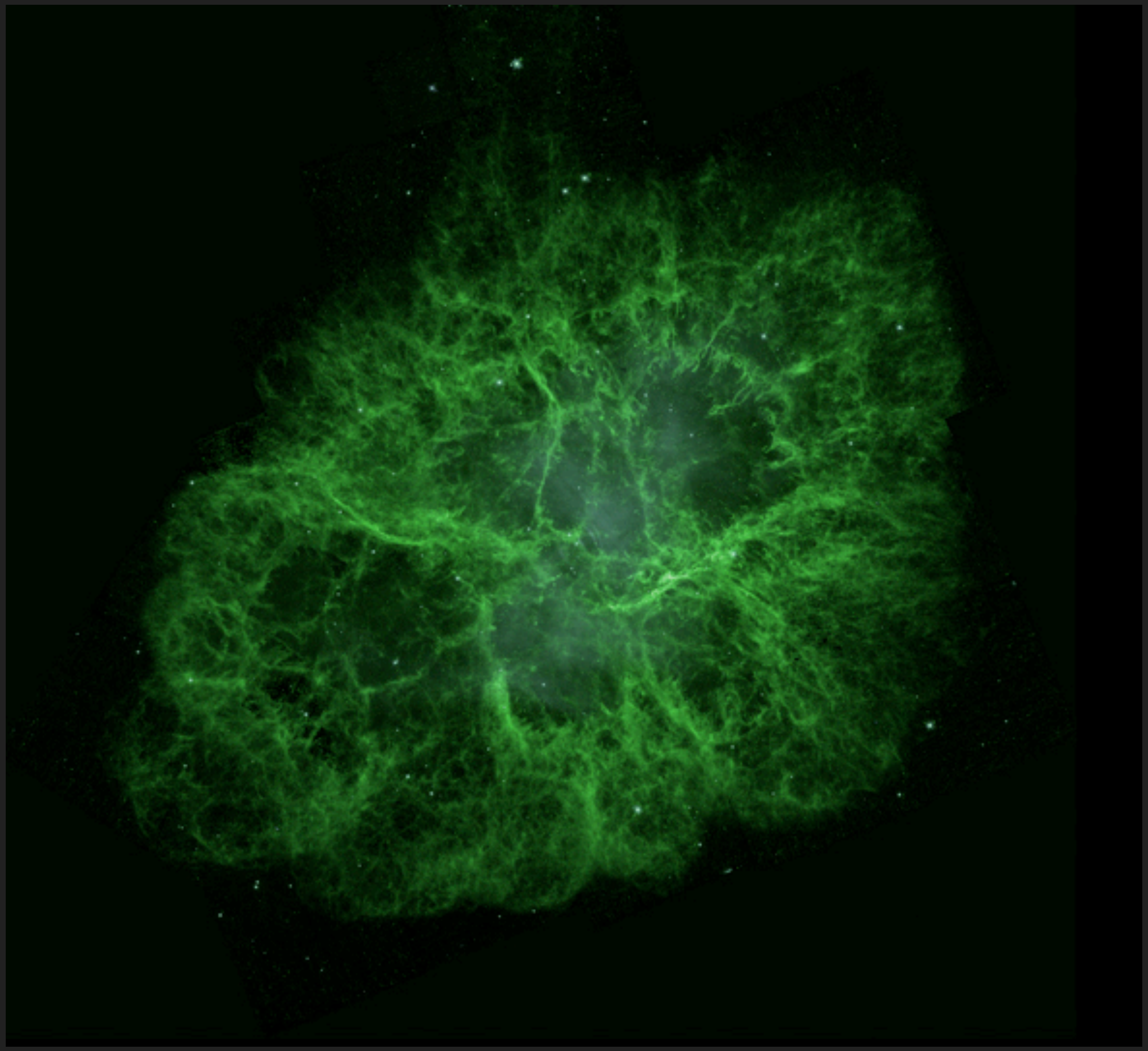

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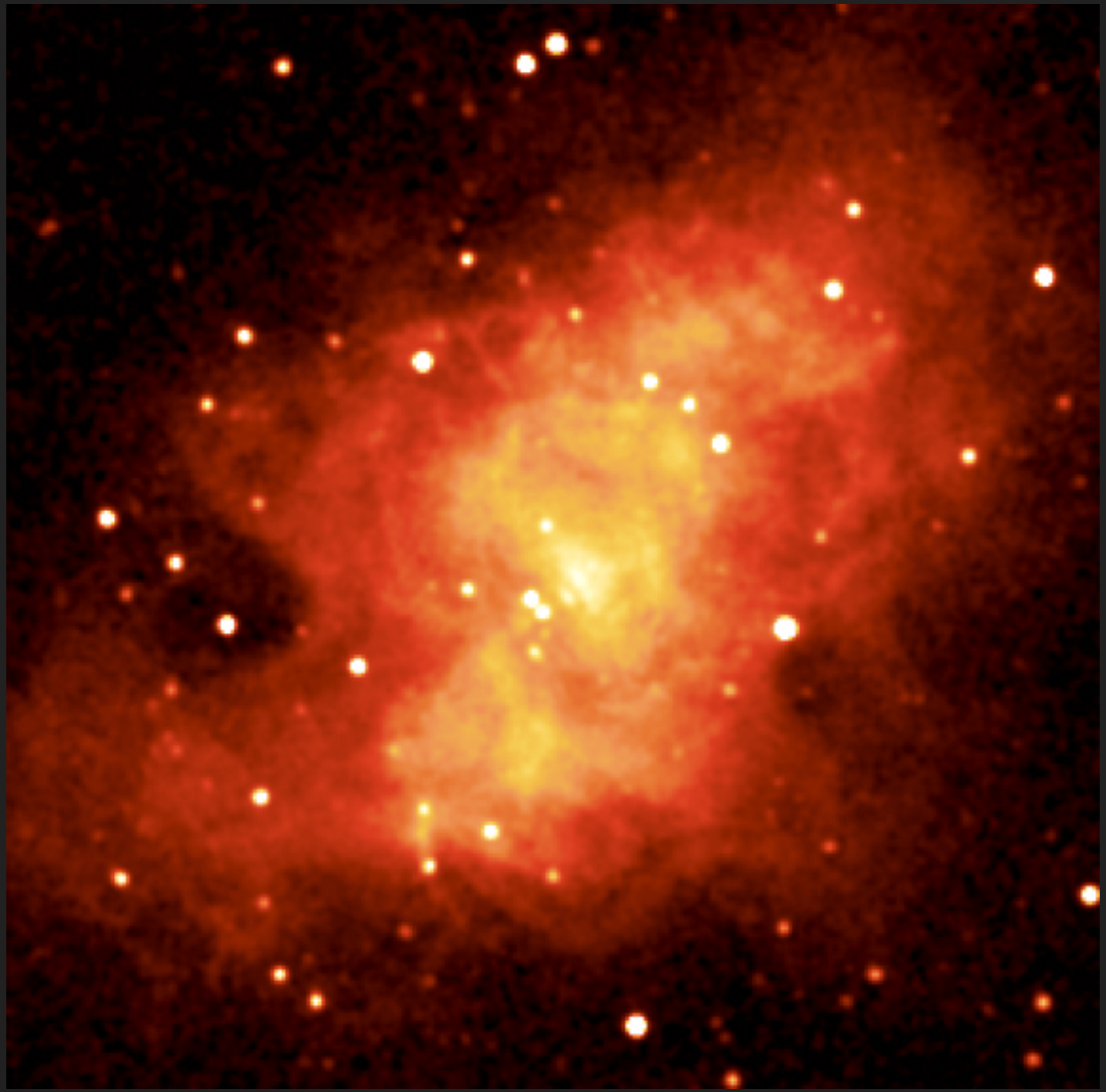

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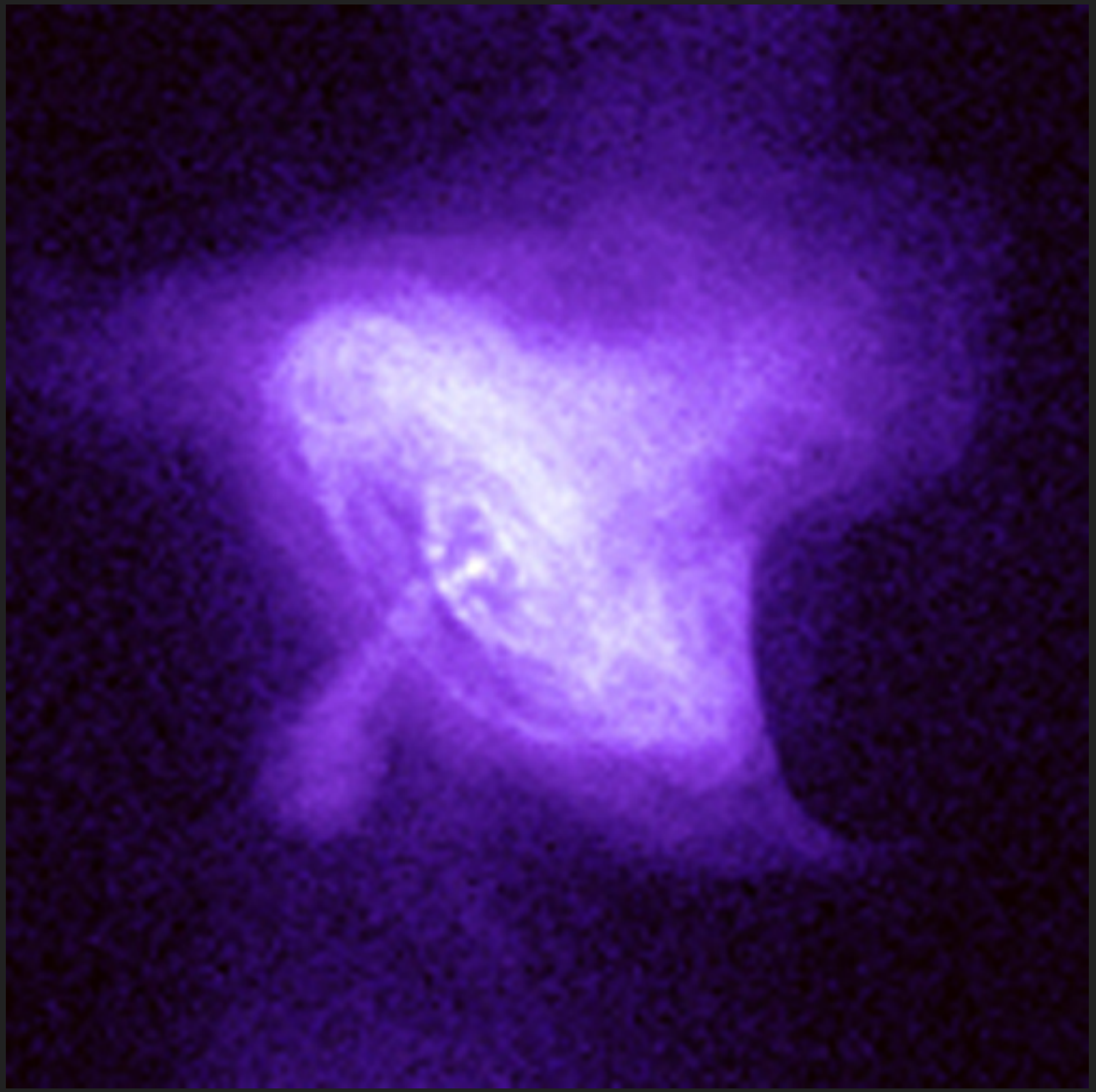

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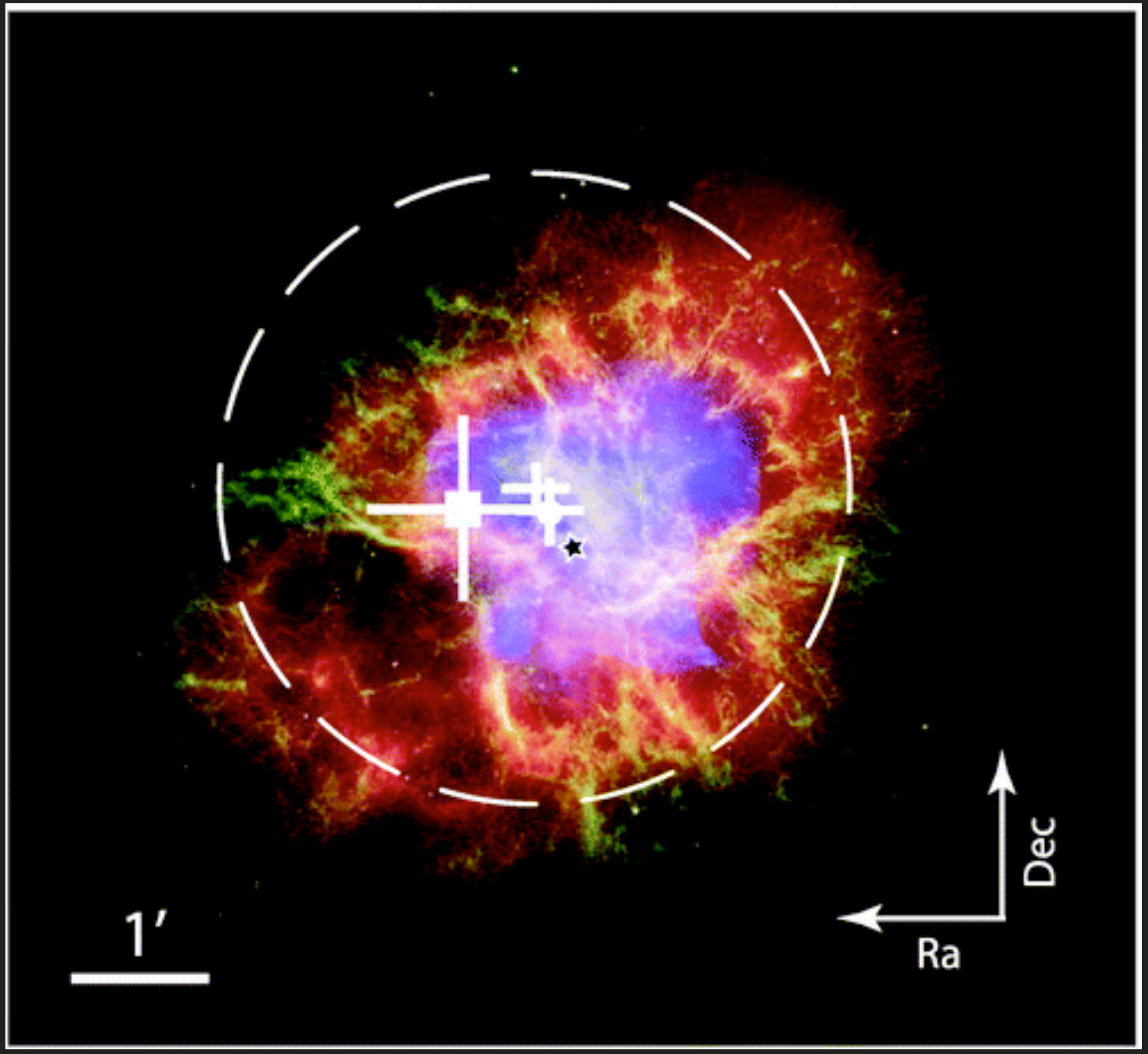


Dynamical Evolution

✓ Injection rate

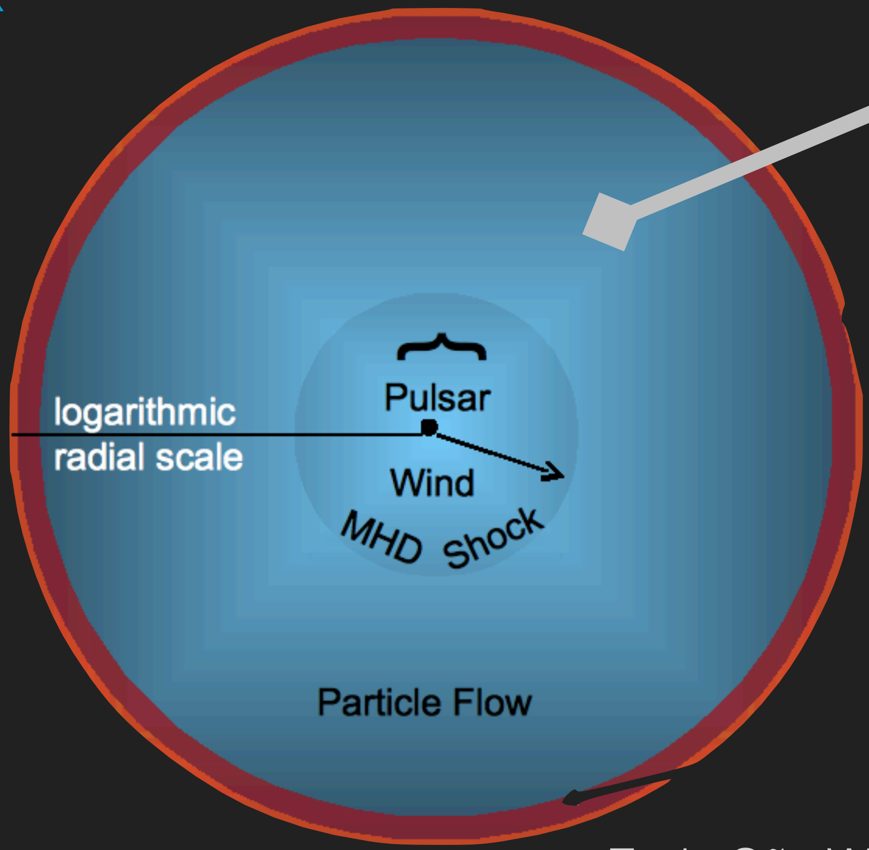
✓ Density of the material in which the nebula expands

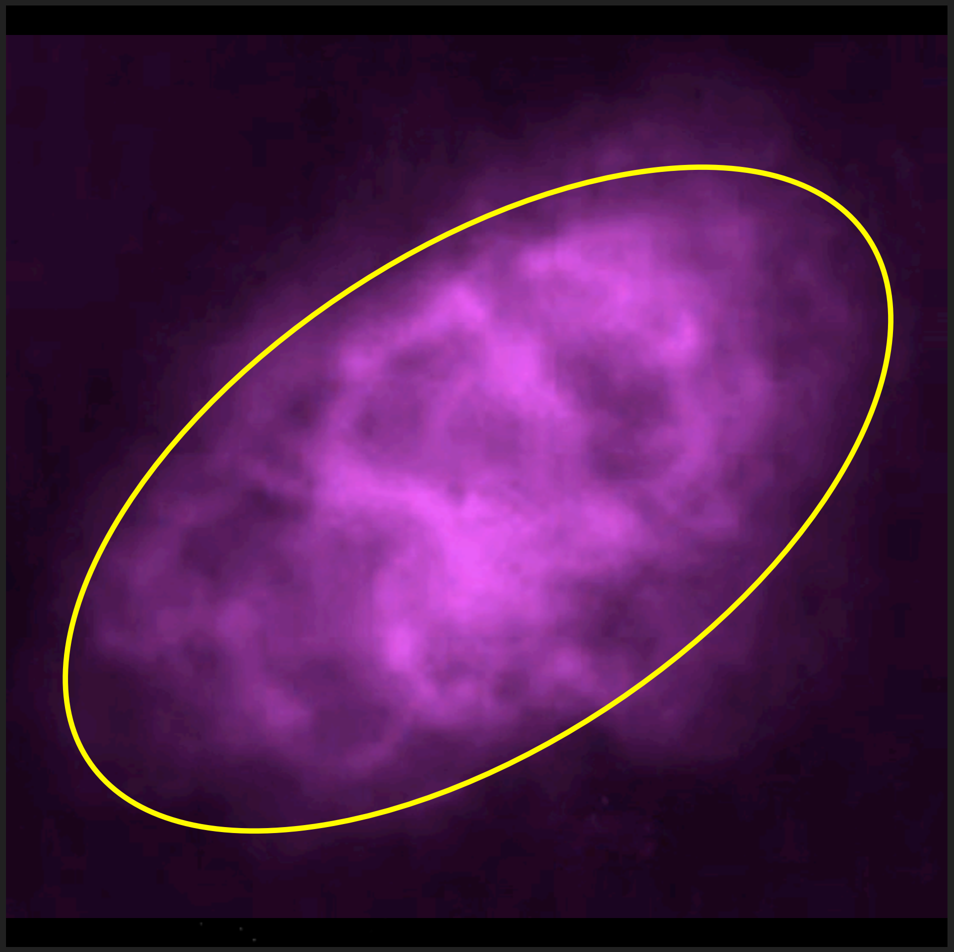
$$\dot{E} \equiv 4\pi^2 I \frac{\dot{P}}{P^3} = 3 \times 10^{28} - 5 \times 10^{38} \mathrm{erg} \cdot \mathrm{s}^{-1}$$

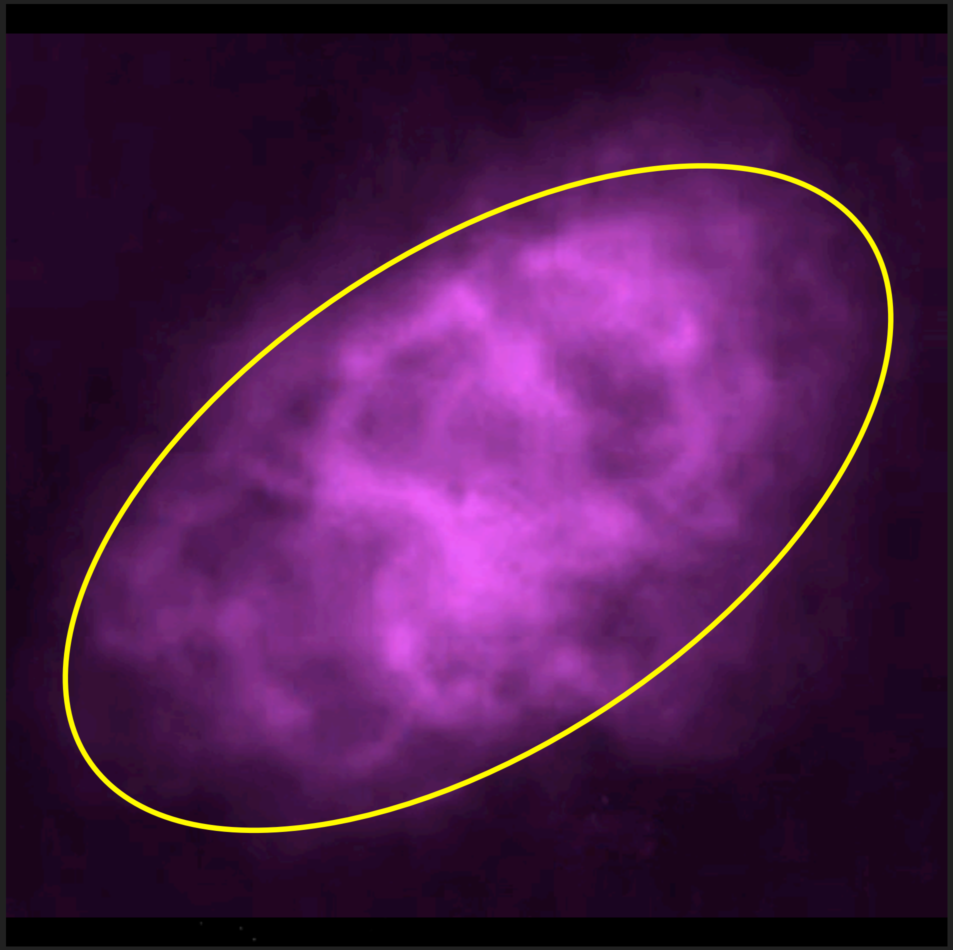
$$\dot{E} = \dot{E}_0 \left(1 + \frac{t}{\tau_0}\right)^{-\frac{(n+1)}{(n-1)}}$$

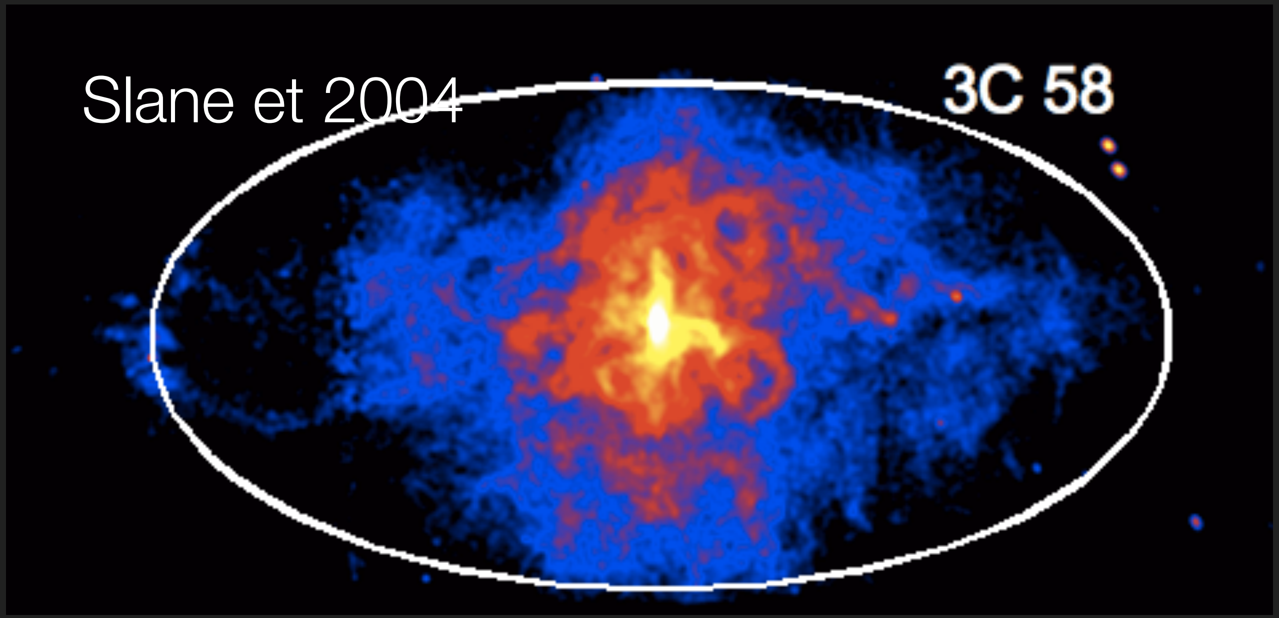
$$\tau \equiv \frac{P_0}{(n-1)\dot{P}_0}$$

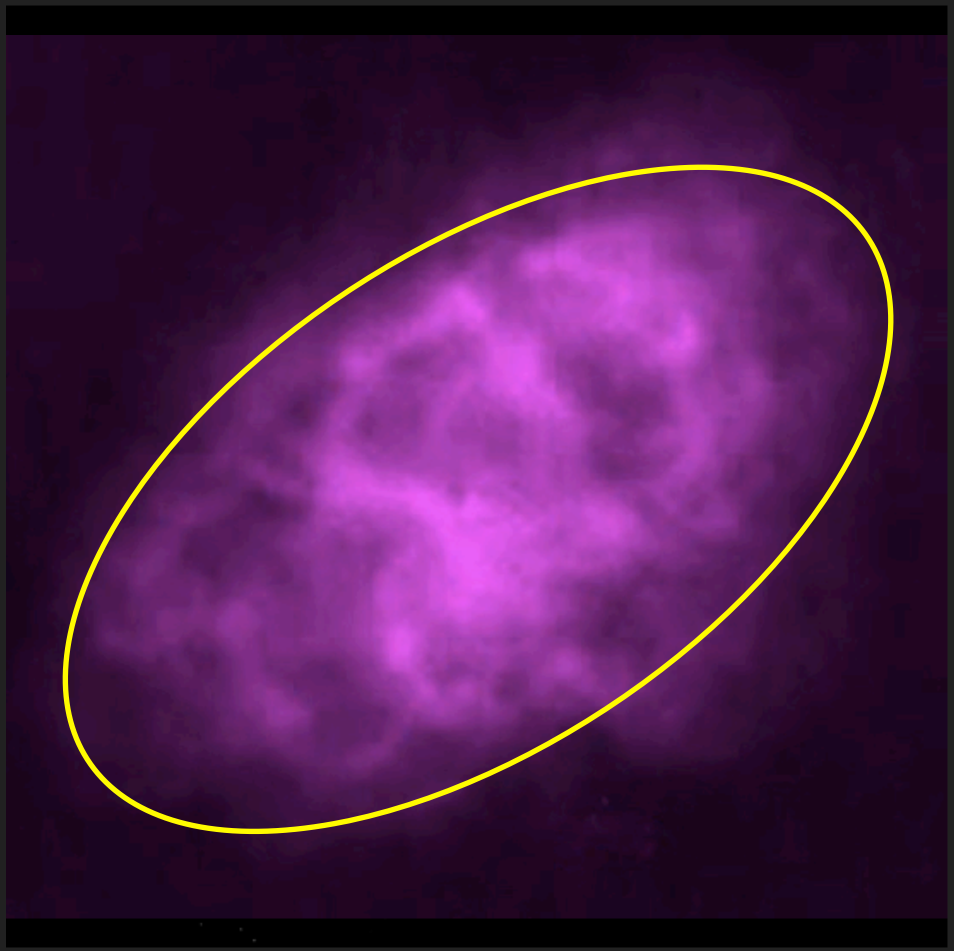
- As SNR/PWN ages, reverse shock modify PWN
- Toroidal field results in an elongation of the nebula

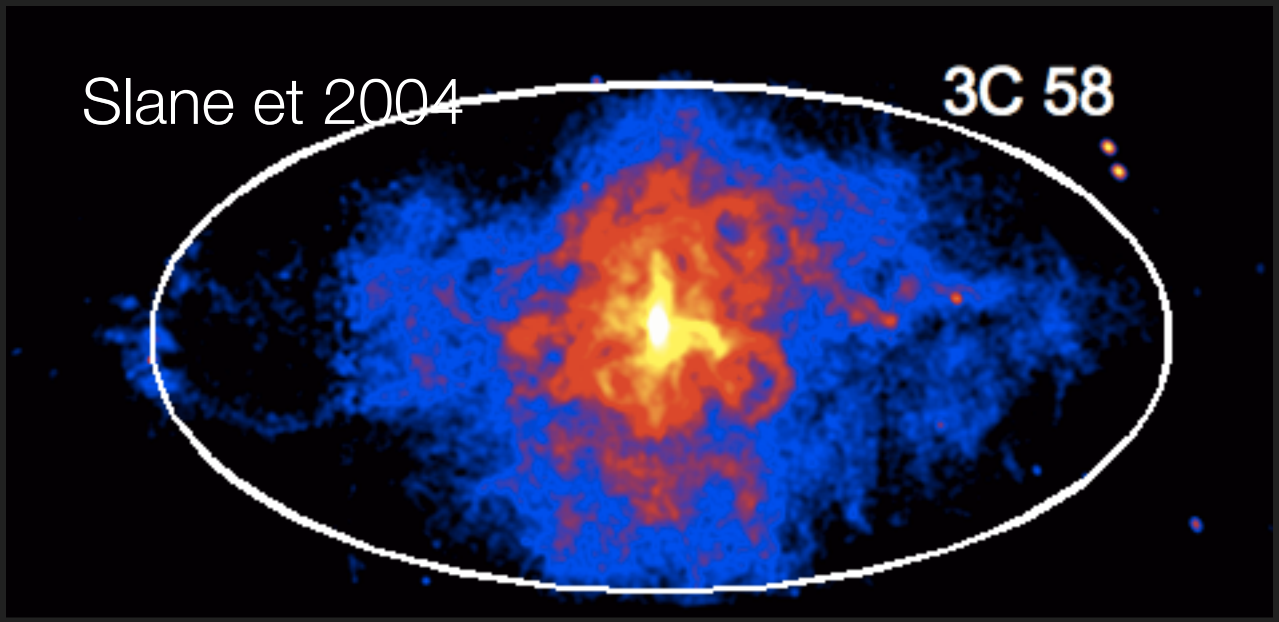







Slane et 2004
3C 58

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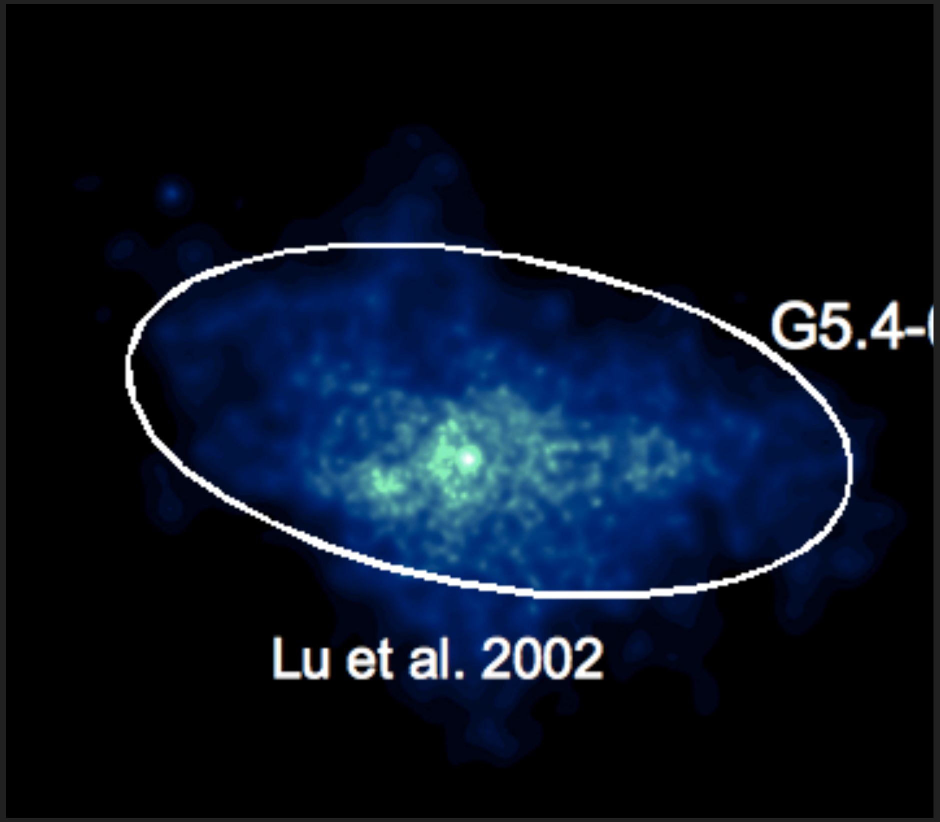
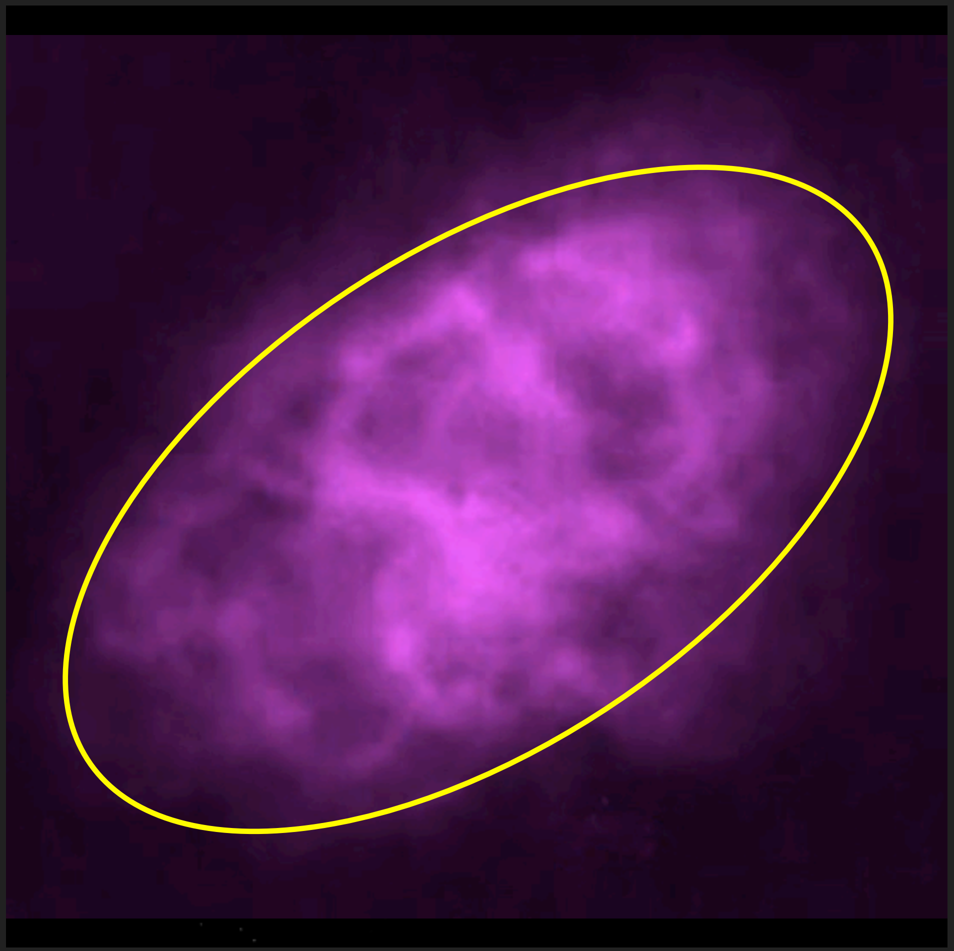
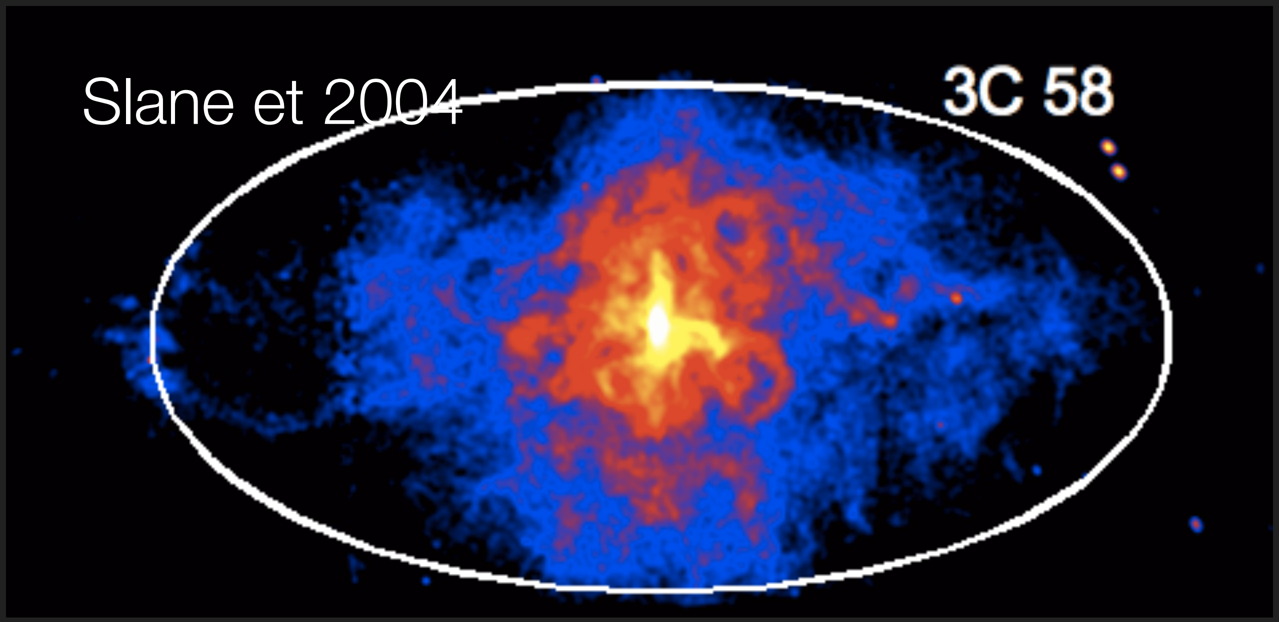

G5.4-
Lu et al. 2002

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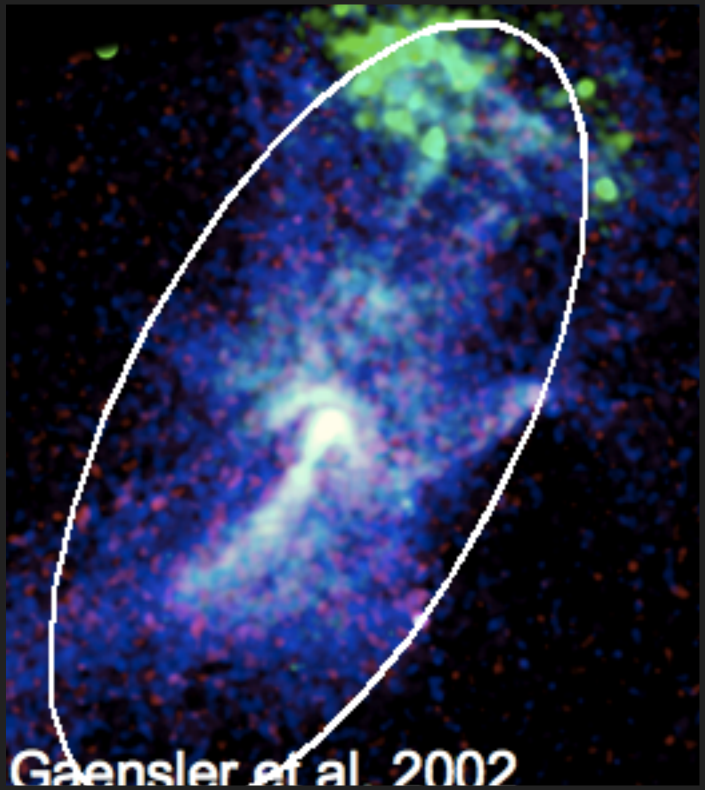
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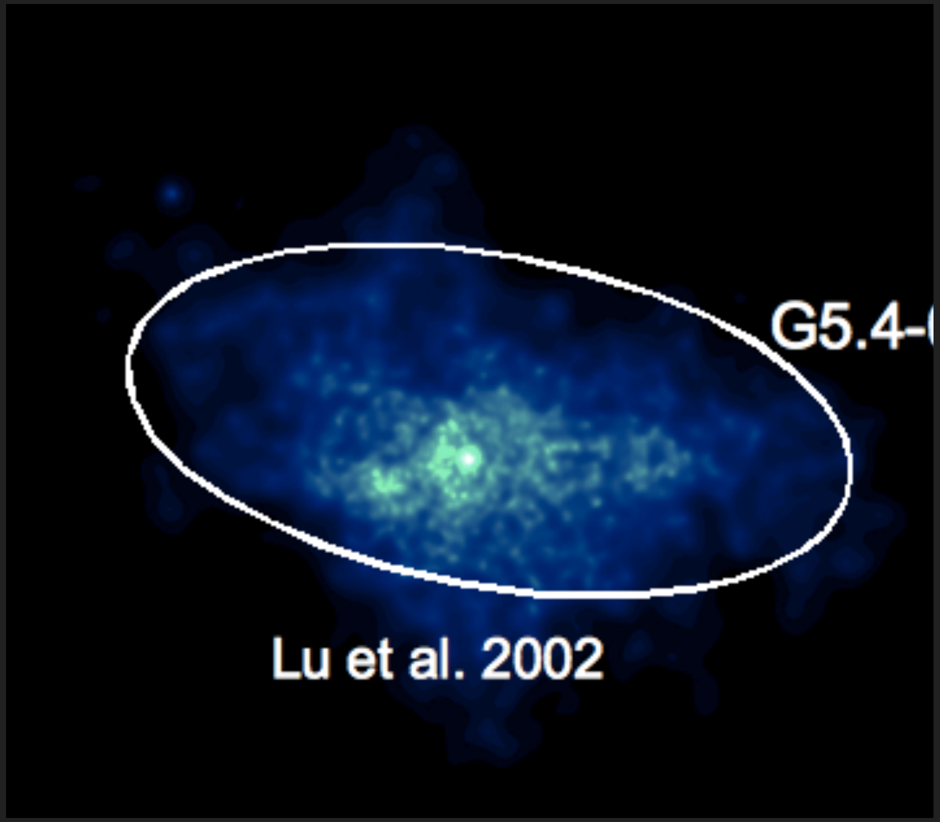
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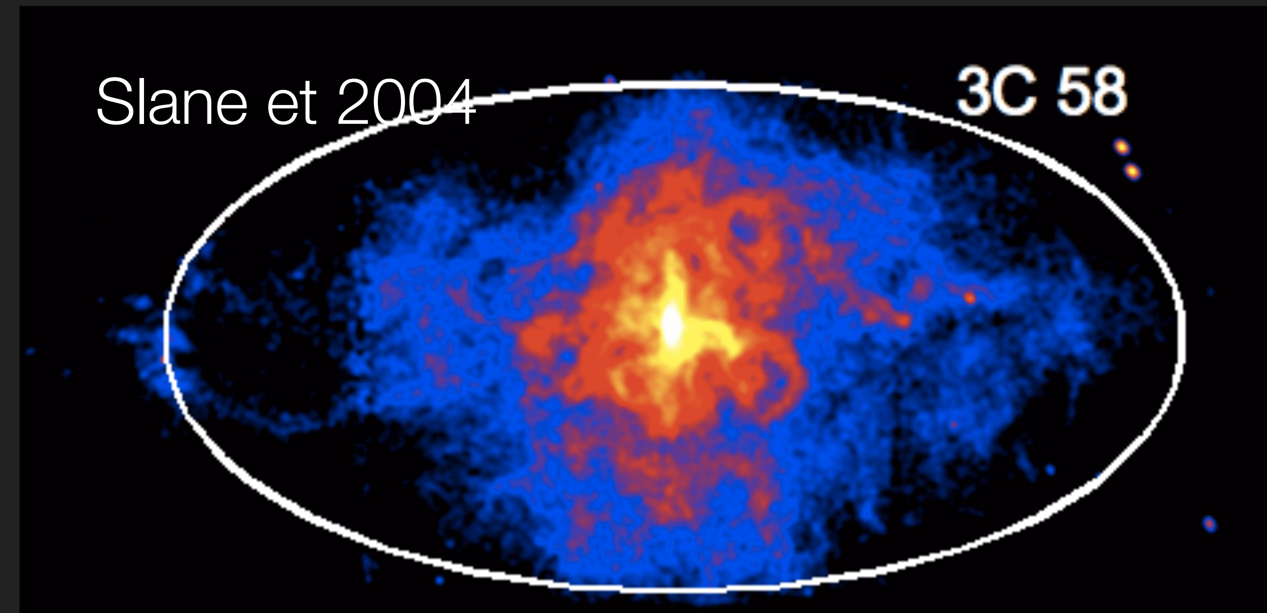
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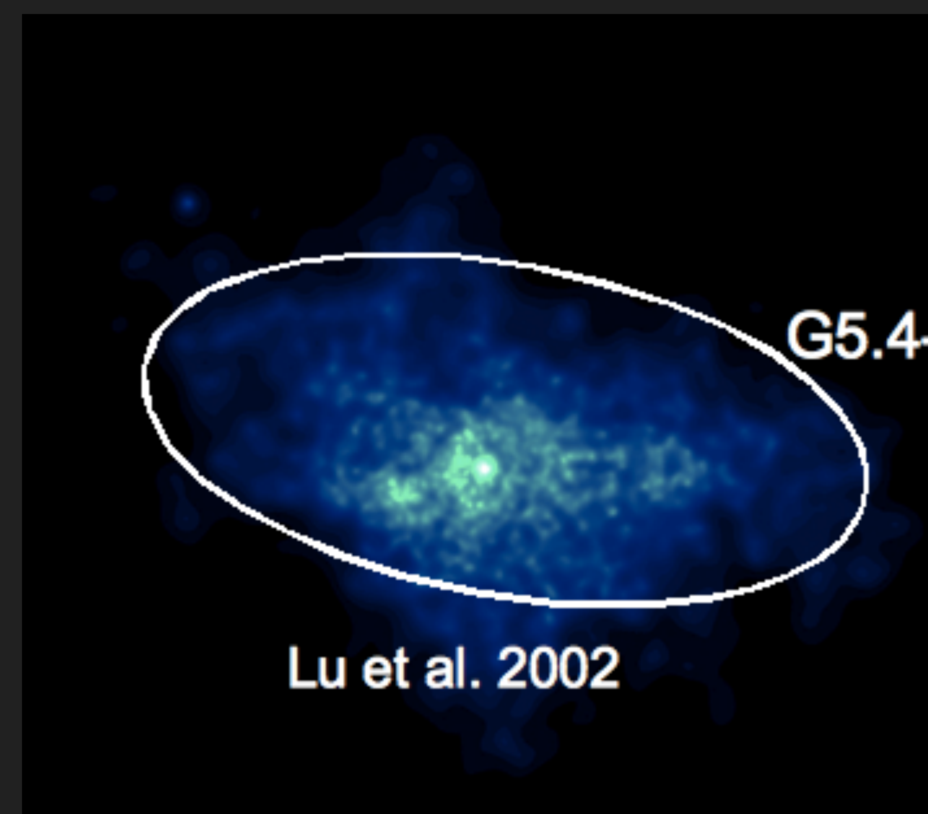
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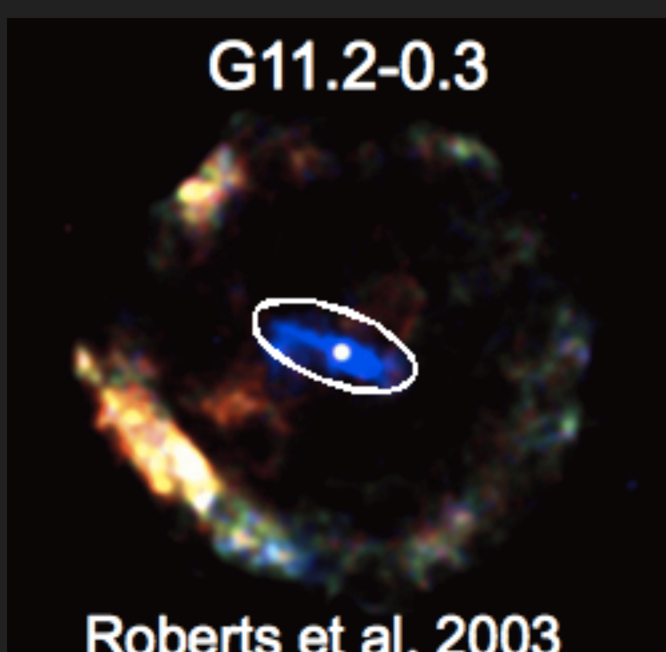
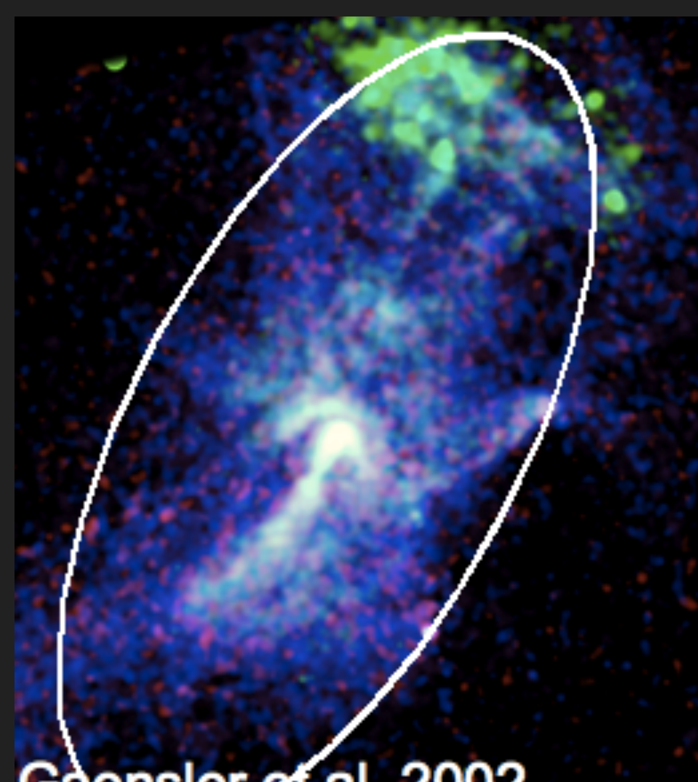

G11.2-0.3
Roberts et al. 2003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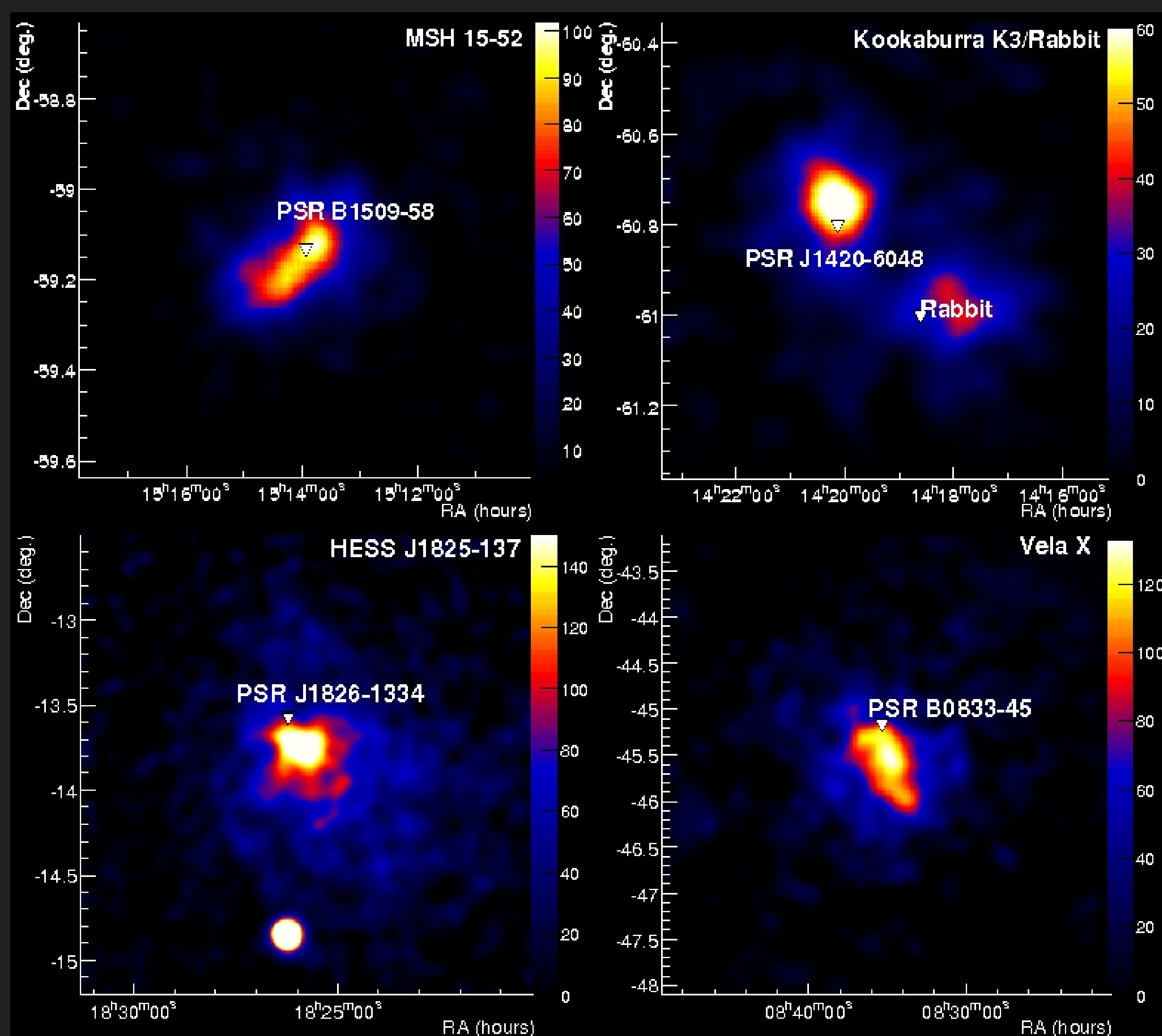
Dynamical Evolution

- ✓ Evolution of the SNR in an inhomogeneous medium
- ✓ Run-away pulsar (large proper motion)

H.E.S.S. (VHE ; E>0.1 TeV)



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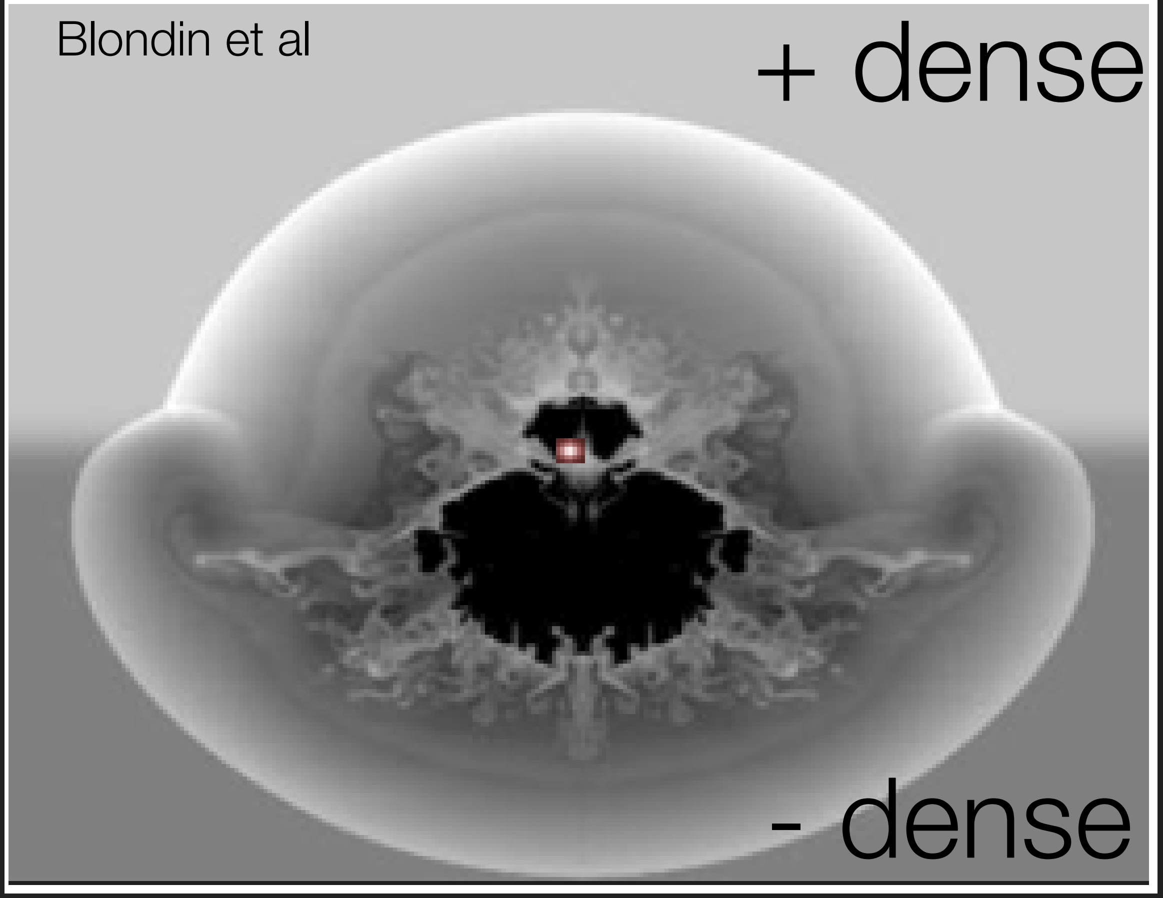

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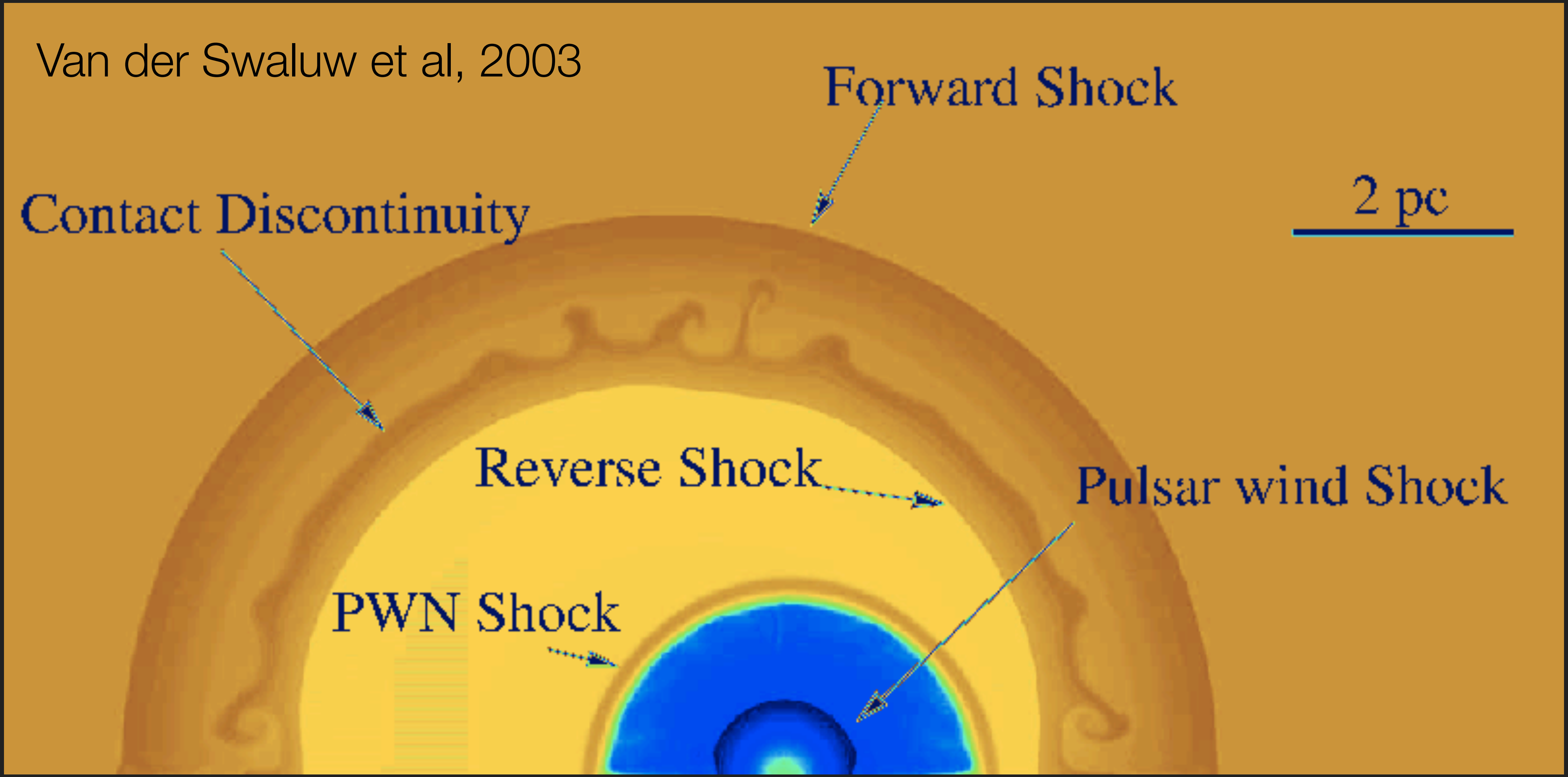

Dynamical Evolution

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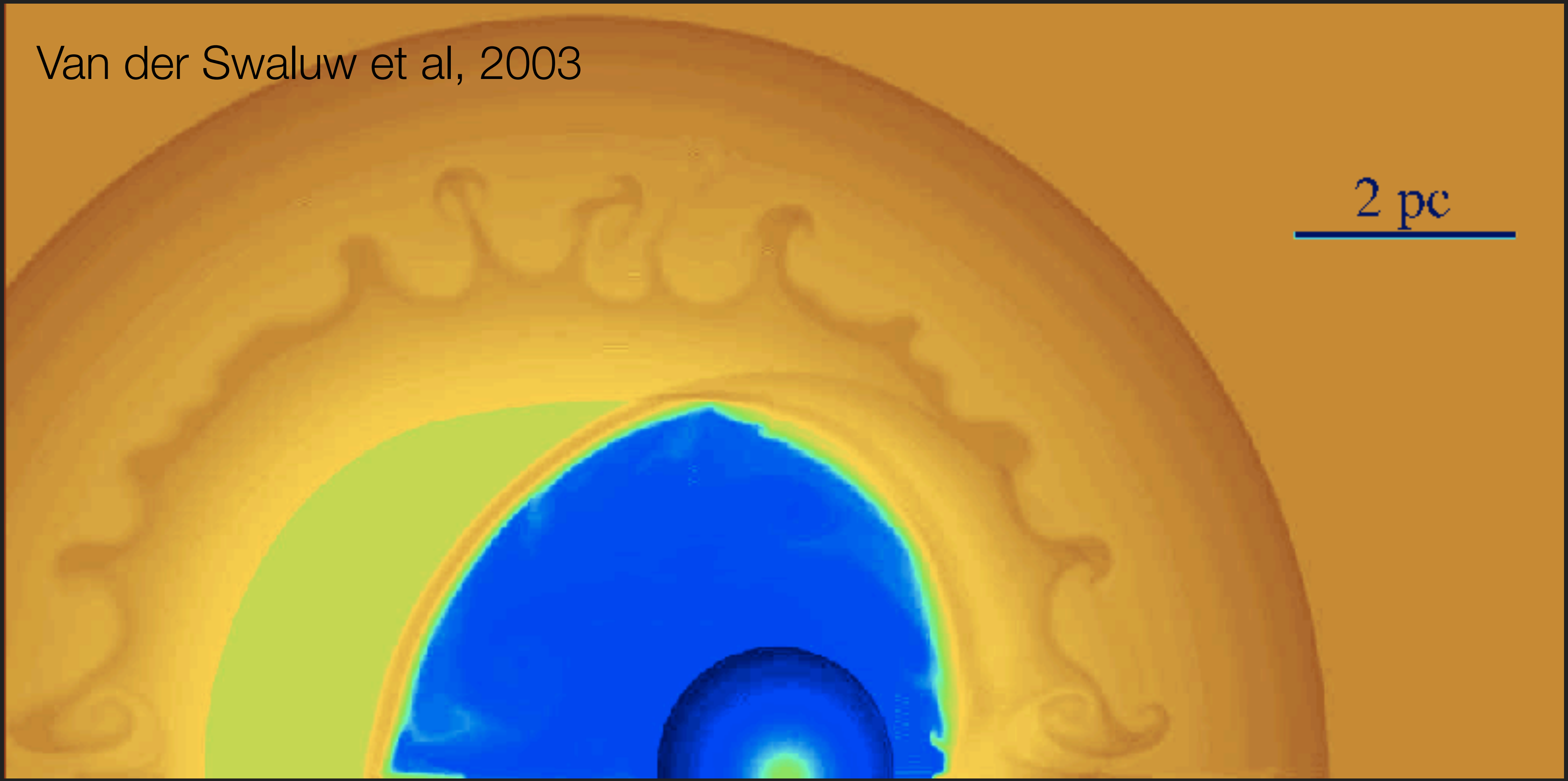
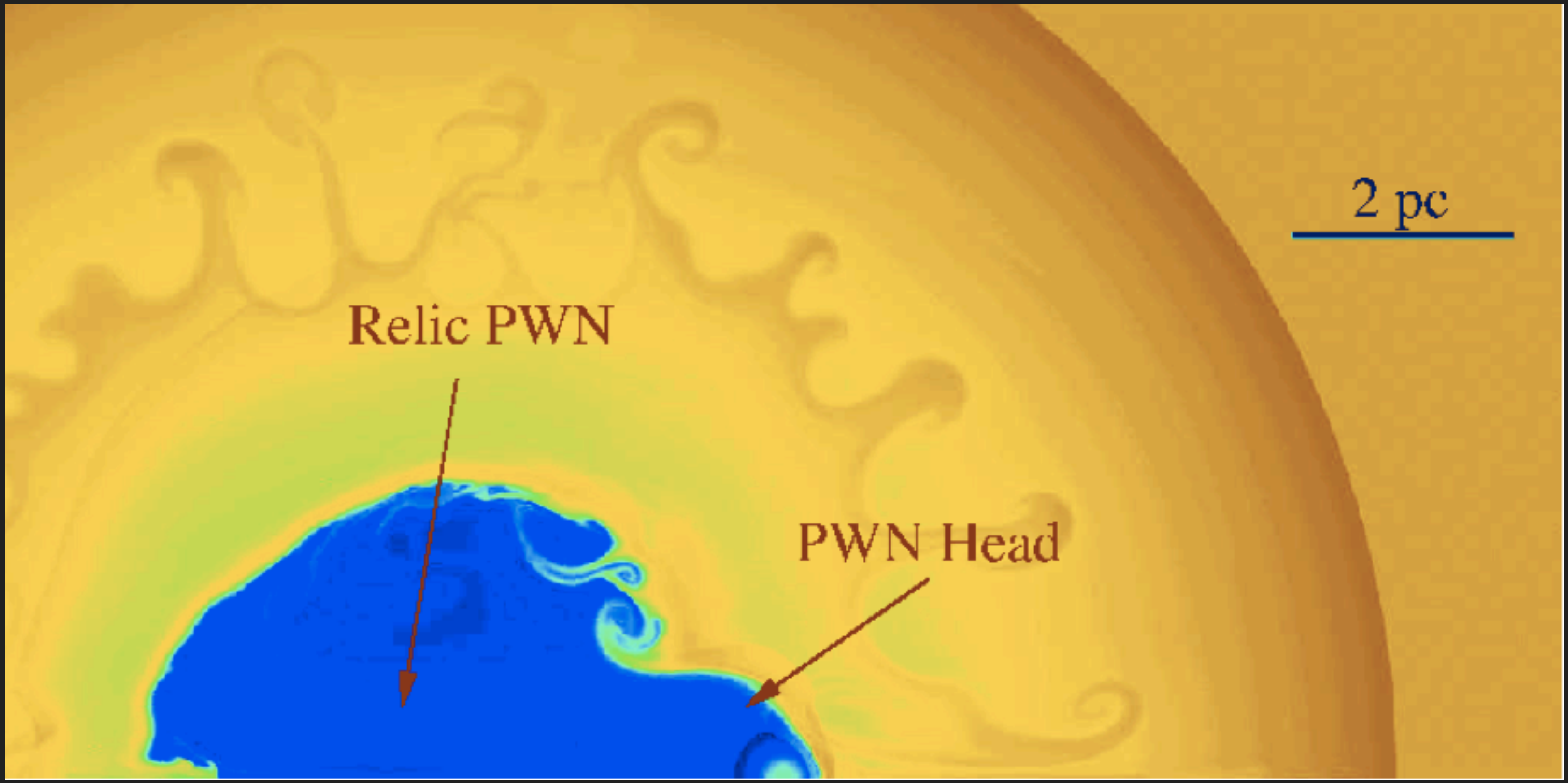


Dynamical Evolution

✓ Evolution of the SNR in an inhomogeneous medium



Dynamical Evolution

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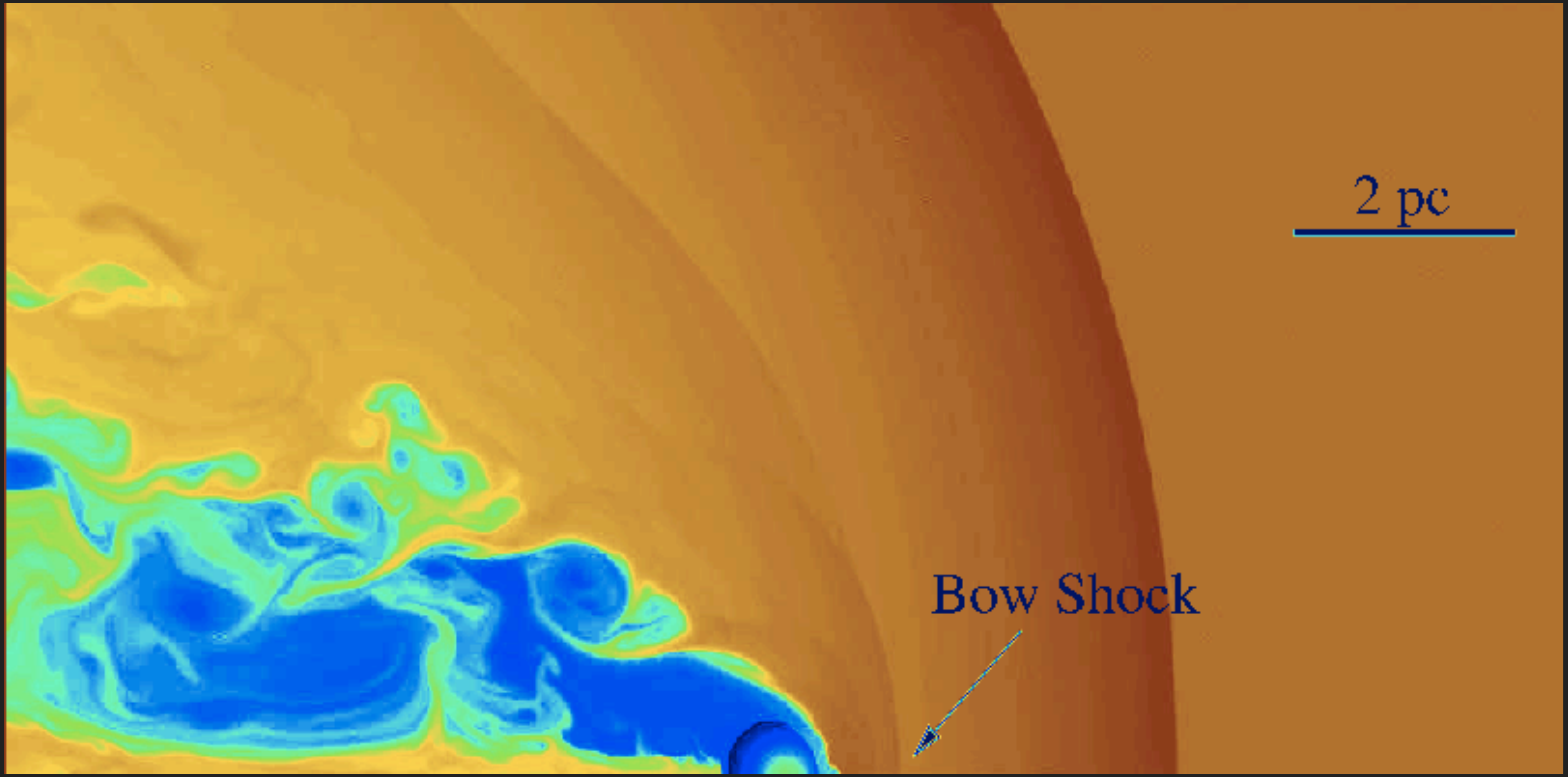
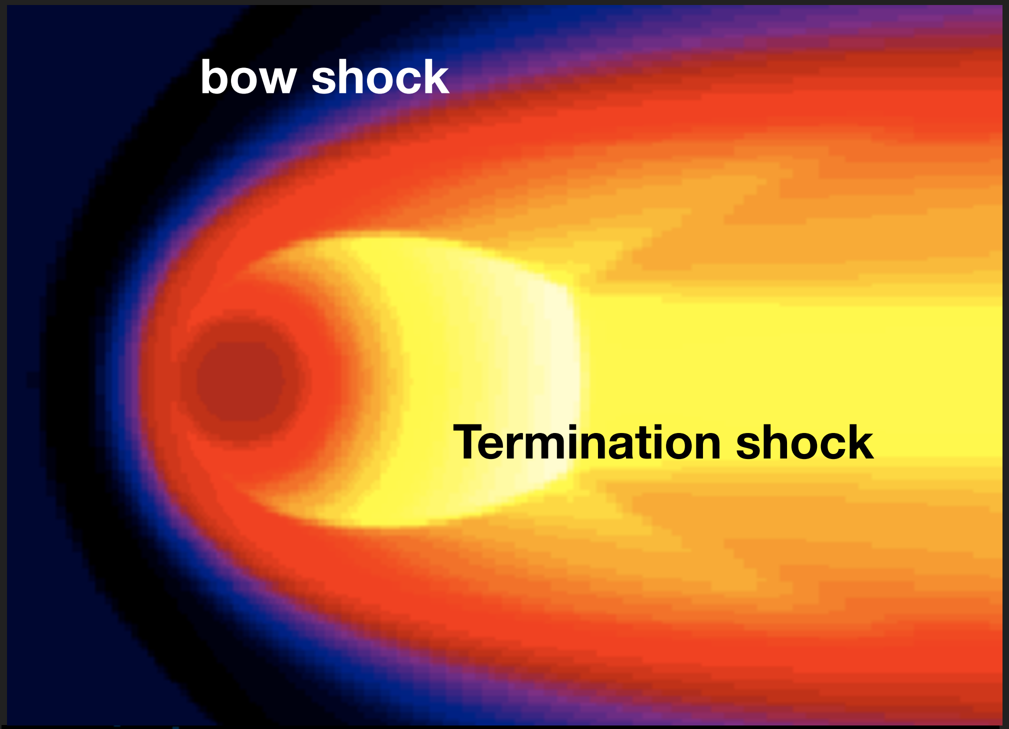
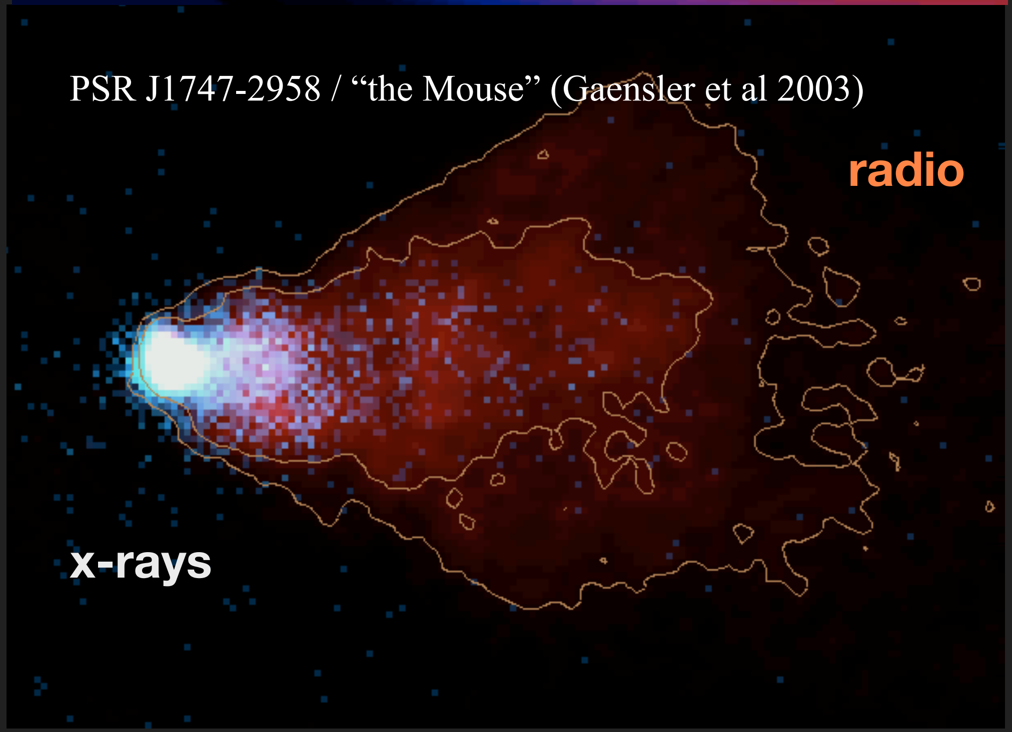


Dynamical Evolution

✓ Run-away pulsar (large proper motion)

- Bow-shock
- Subsonic movement in the hot gas
- Sound speed drops
- Supersonic movement of the pulsar
- ISM (1, 10 and 100 km s^{-1} for cold, warm and hot)





Spectral Evolution

- Electron spectrum: $Q(E_e,t)=Q_0(t)\ (E_e/E_0)^{-\alpha}$
- Photon spectrum consists:
  - ✳Synchrotron radiation in the nebular magnetic field
  - ✳Inverse Compton (IC) emission by scattering photons from
    - ✓ Cosmic-ray Microwave background
    - ✓ Ambient starlight & dust
    - ✓ Self-Synchroton of the nebula
    - ✓ If binary: photon field of the companion

Spectral Evolution

In a simple approximation

Required electron energy to radiate synchrotron keV photons:

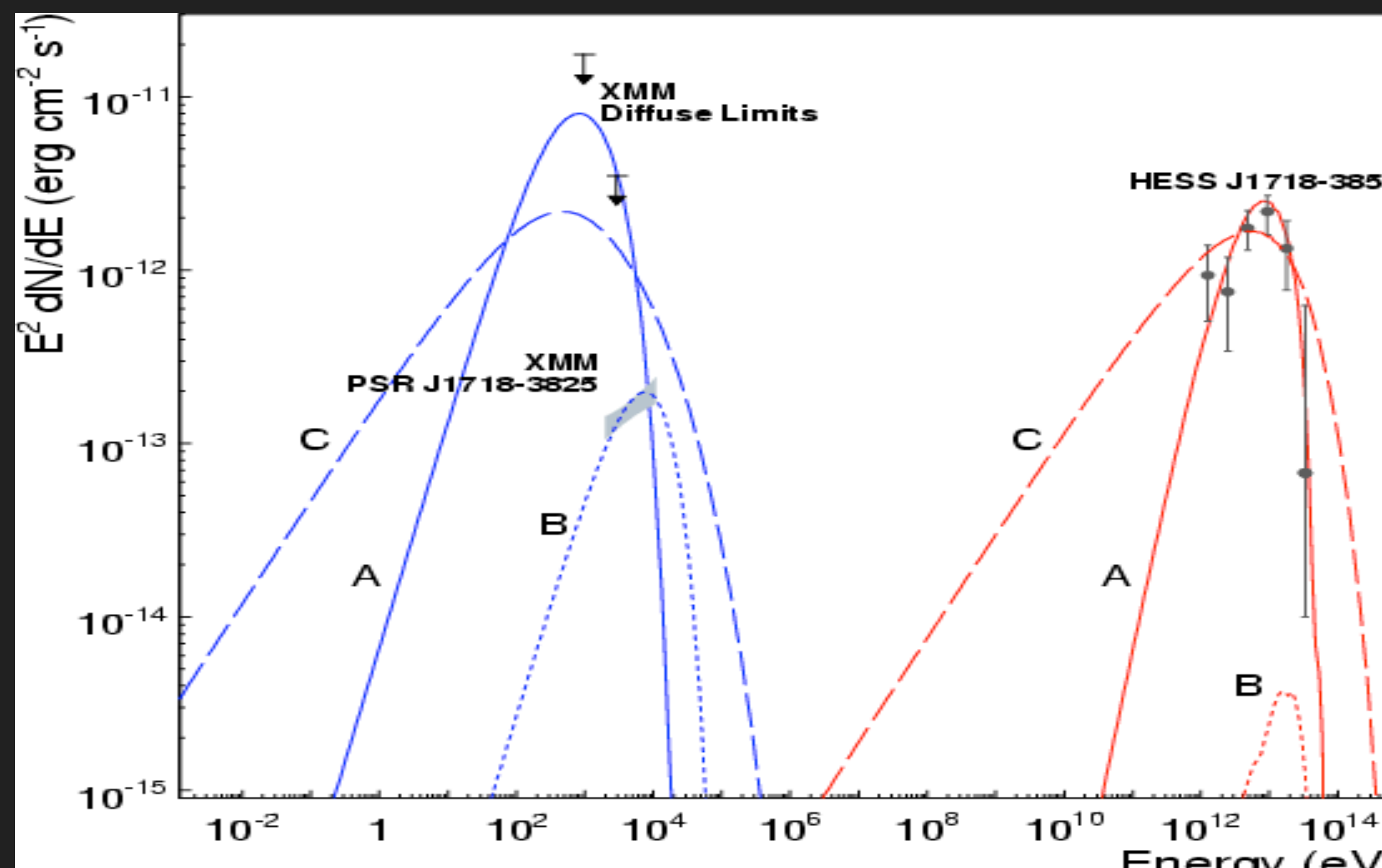
$E_e = (70\ \mathrm{TeV})\ B^{-1/2}_{-5}\ E^{1/2}_{keV}$

Mean electron energy to IC scatter CMB to TeV photons:

$E_e = (18\ \mathrm{TeV})\ E^{1/2}_{TeV}$

$(E_{keV}=0.06\ B_{-5} E_{TeV})$

$f_{IC}(\varepsilon_{IC})/f_s(\varepsilon_s) \approx 0.1\ B^{-2}_{-5}$



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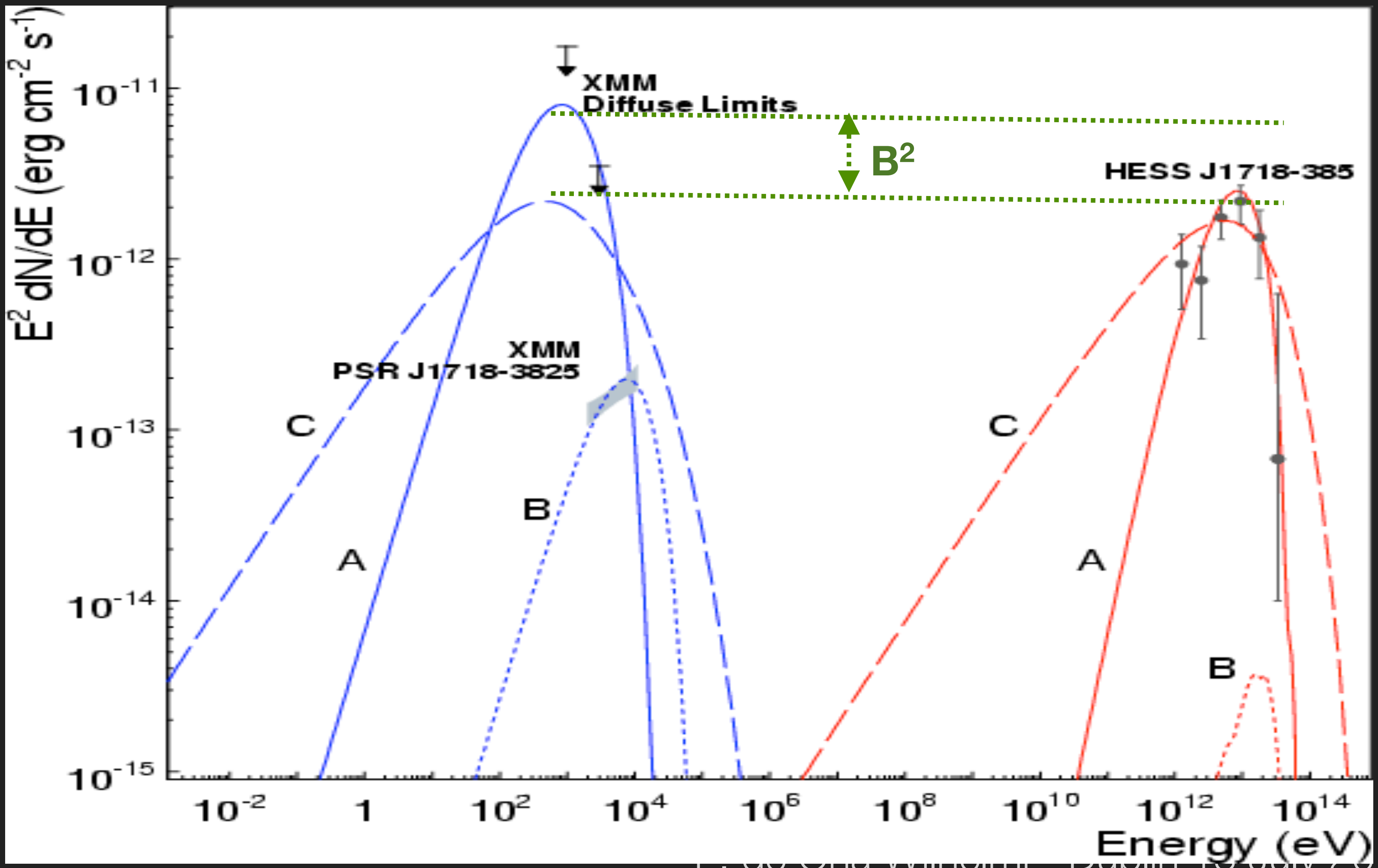

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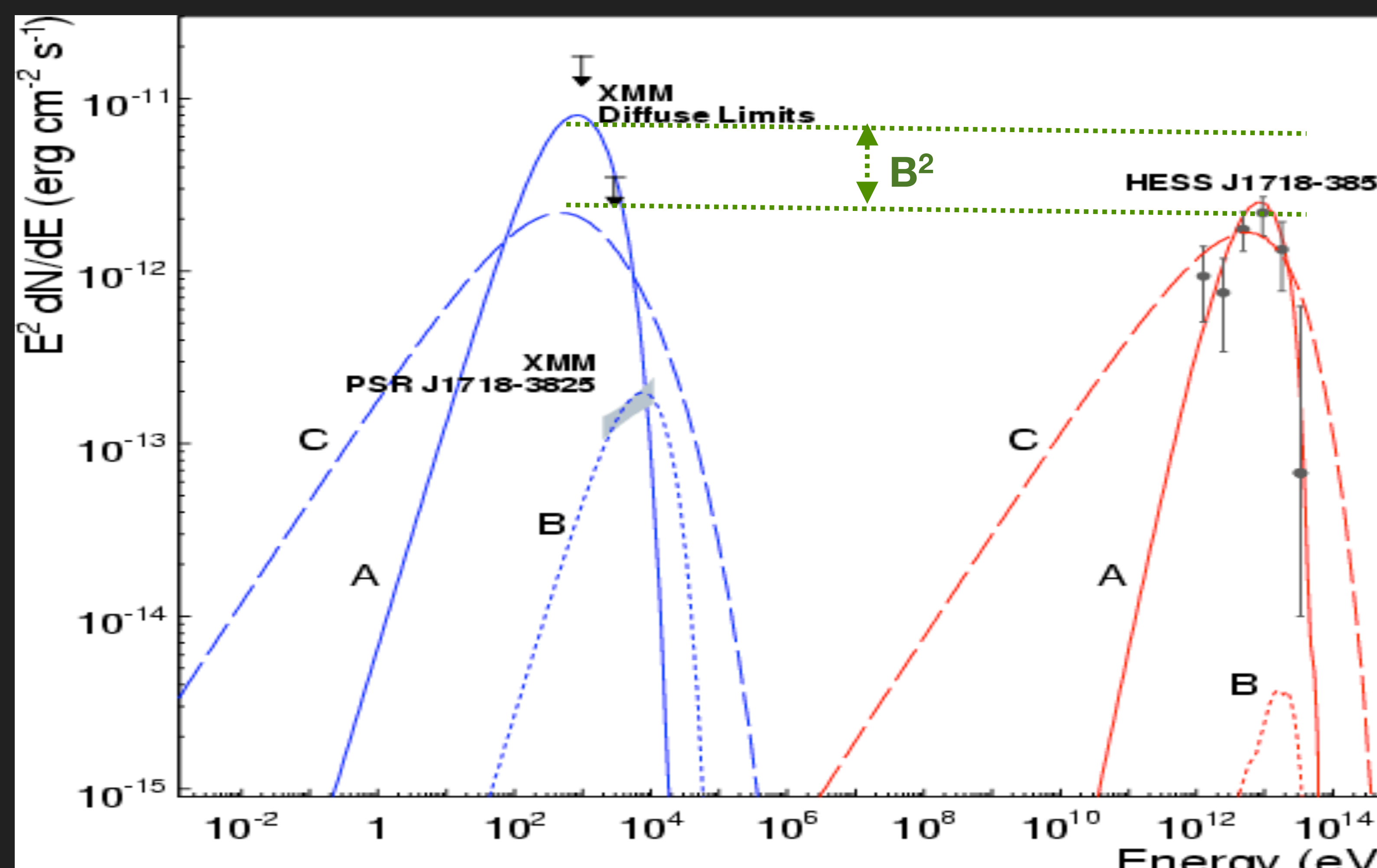
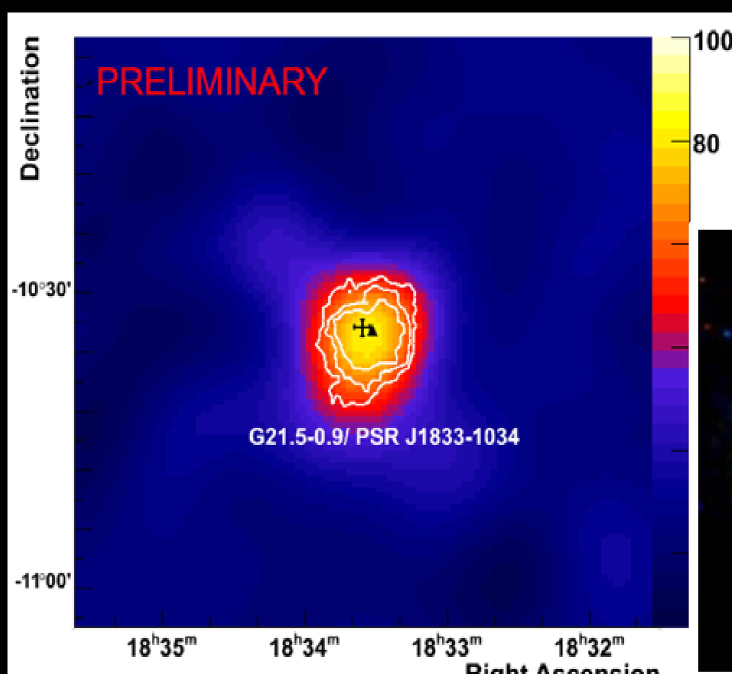
If B~150 uG:
electron producing 1 TeV photons IC will produce 1 keV synchrotron photons

If B<150 uG:
X-ray emitting electrons are more energetic than the gamma-ray emitting ones.

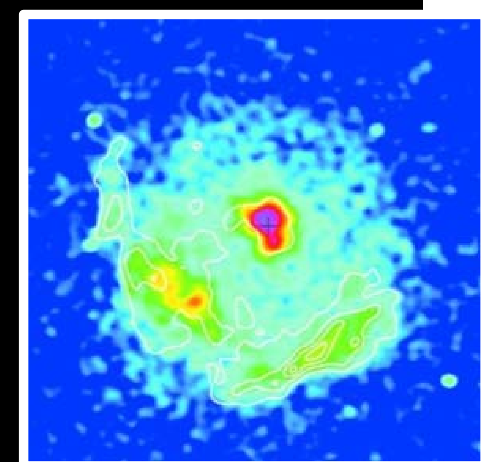


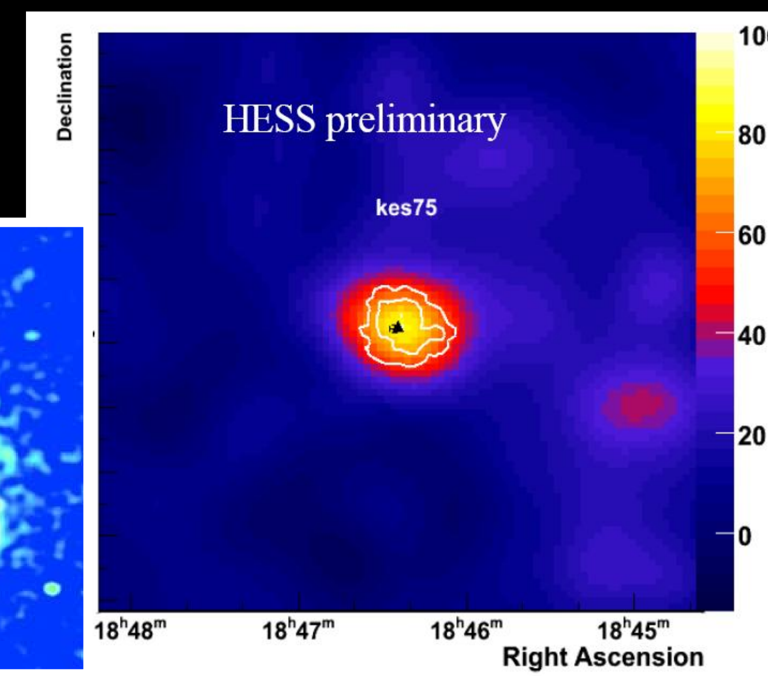
Particle dominated nebulae?

Young PWNe: Crab nebula, N157B, MSH 15-52, G0.9+0.1, *G21.5-0.9, Kes 75*



Djannati-Ataï et al. HESS (2008)
Terrier et al. HESS (2008)





G21.5/PSR J1833-1034 (Camilo et al. 2006)

τ_c = 4.7 kyr, $\dot{E}_{36}$ = 33, d ~ 5 kpc

age < 1 kyr (Biethenholtz et al. 2008)

$L_{(1\text{-}10\ keV)} = 1.8\ 10^{35}$ erg/s & $\Gamma_{(1\text{-}10\ keV)} = 1.5\text{-}2$

$L_{(1\text{-}10\ TeV)} = 3.7\ 10^{33}$ erg/s & $\Gamma_{(1\text{-}10\ TeV)} = 2.20$

Shell contribution unlikely ($R_{2\sigma}$ <1.8', low ρ_{gas})

Kes 75/PSR J1848-0258 (Gotthelf 2000)

τ_c = 723 yr, $\dot{E}_{36}$ = 8.3, d ~ 6 kpc

age ~ τ_c (Leahy & Tian 2008)

$L_{(1\text{-}10\ keV)} = 1.4\ 10^{35}$ erg/s & $\Gamma_{(1\text{-}10\ keV)} = 1.6\text{-}1.9$

$L_{(1\text{-}10\ TeV)} = 6.0\ 10^{33}$ erg/s & $\Gamma_{(1\text{-}10\ TeV)} = 2.29$

Shell contribution possible (high ρ_{gas})

Particle-dominated PWNe ($B < B_{eq}$)

Spectral Evolution

TeV Source

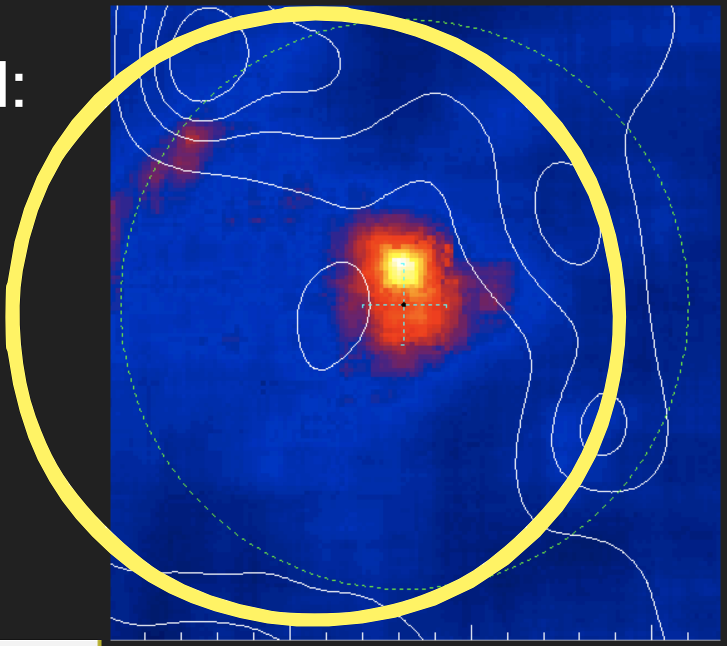
But we need to consider the time evolution of the PWN:

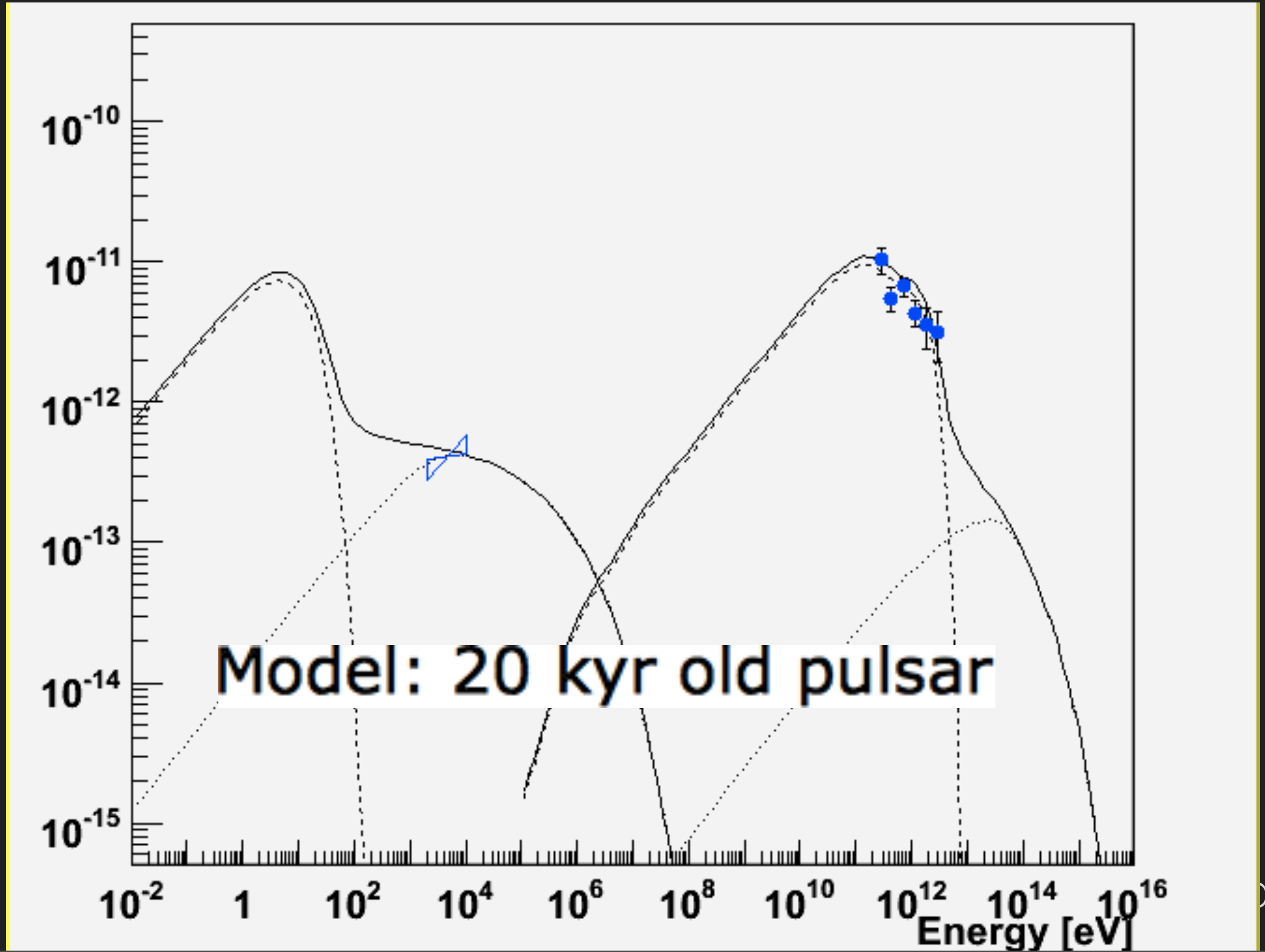
Synchrotron live-time of electron, scattering CMB to energies $E_\gamma = 10^{12}\, E_{TeV}$ eV

$\tau(E_\gamma) \sim (4.8\ \mathrm{kyr})\, B^{-2}_{-5}\, E_{TeV}^{-1/2}$

Live-time of keV-emitting electrons

$\tau(E_x) = (1.2\ \mathrm{kyr})\, B^{-3/2}_{-5}\, E_{keV}^{-1/2}$





Why are the TeV/X-ray sources sizes different?

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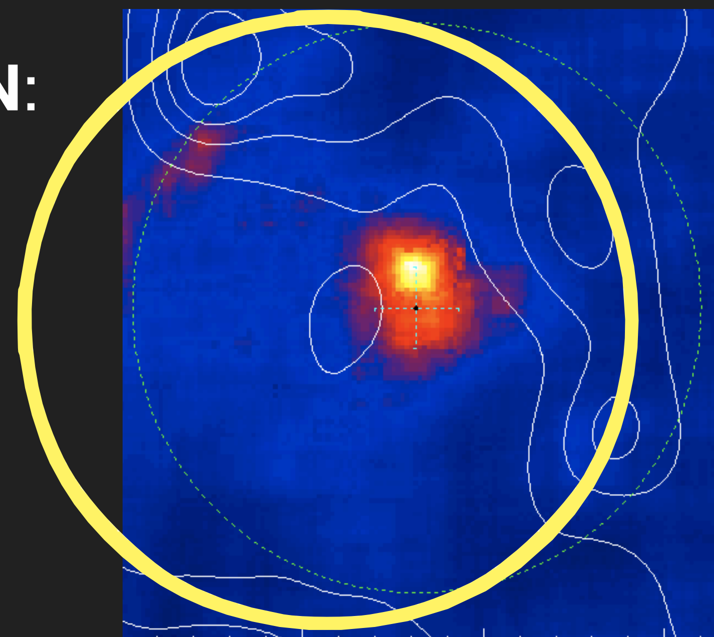

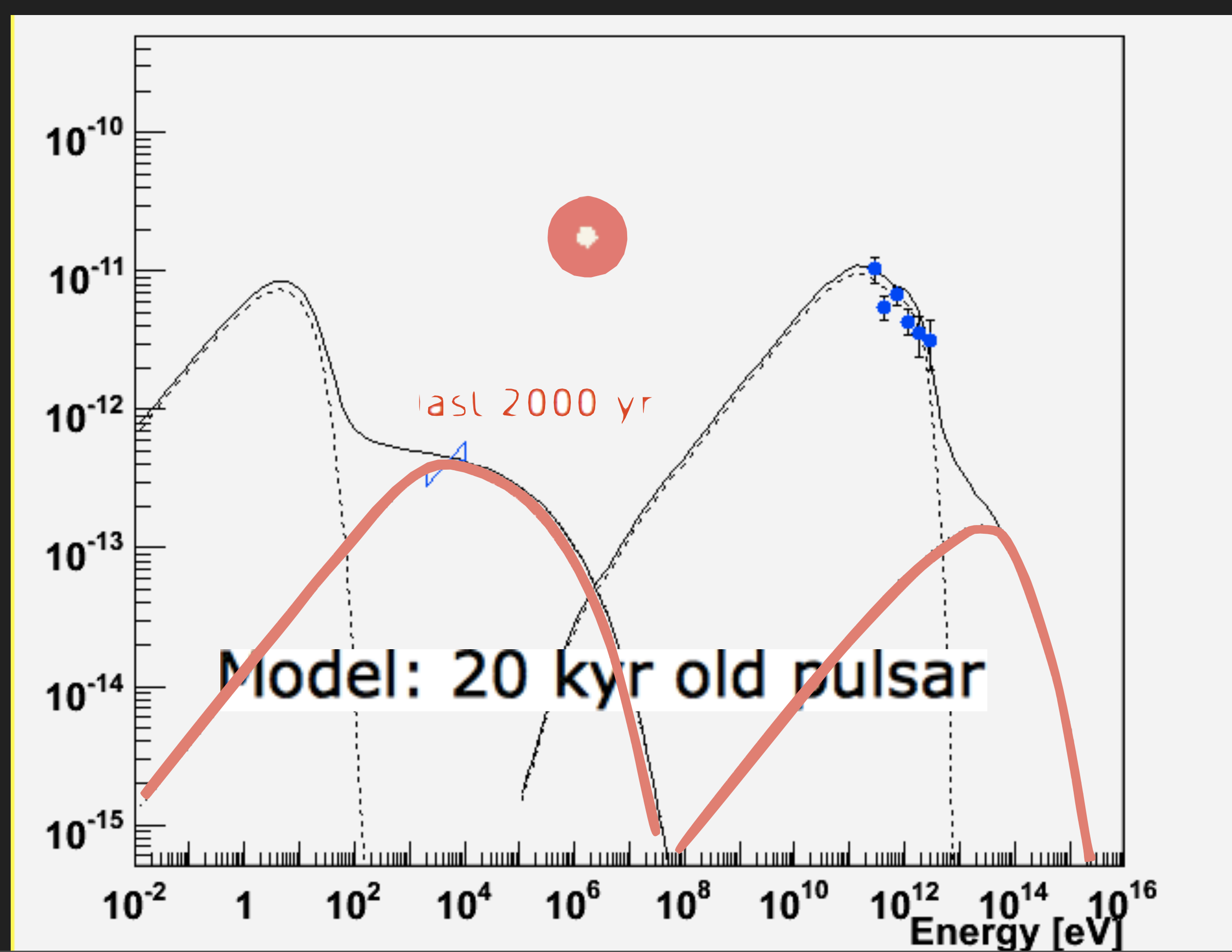

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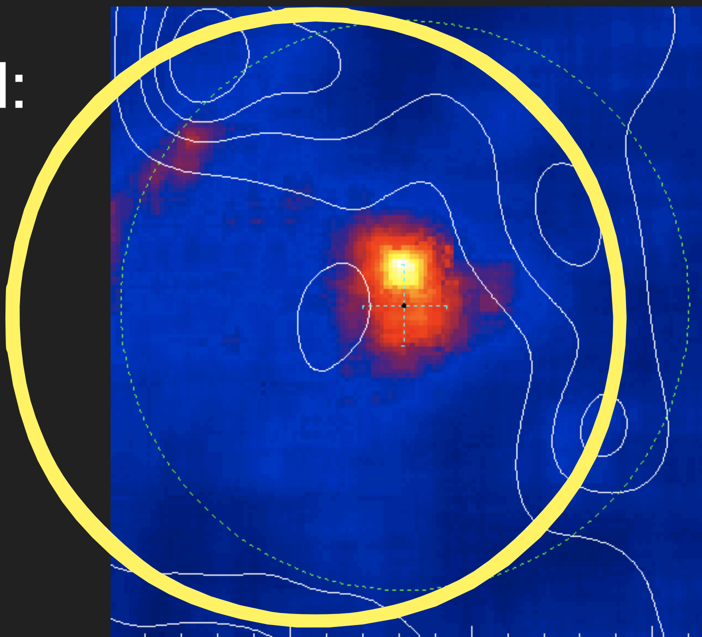

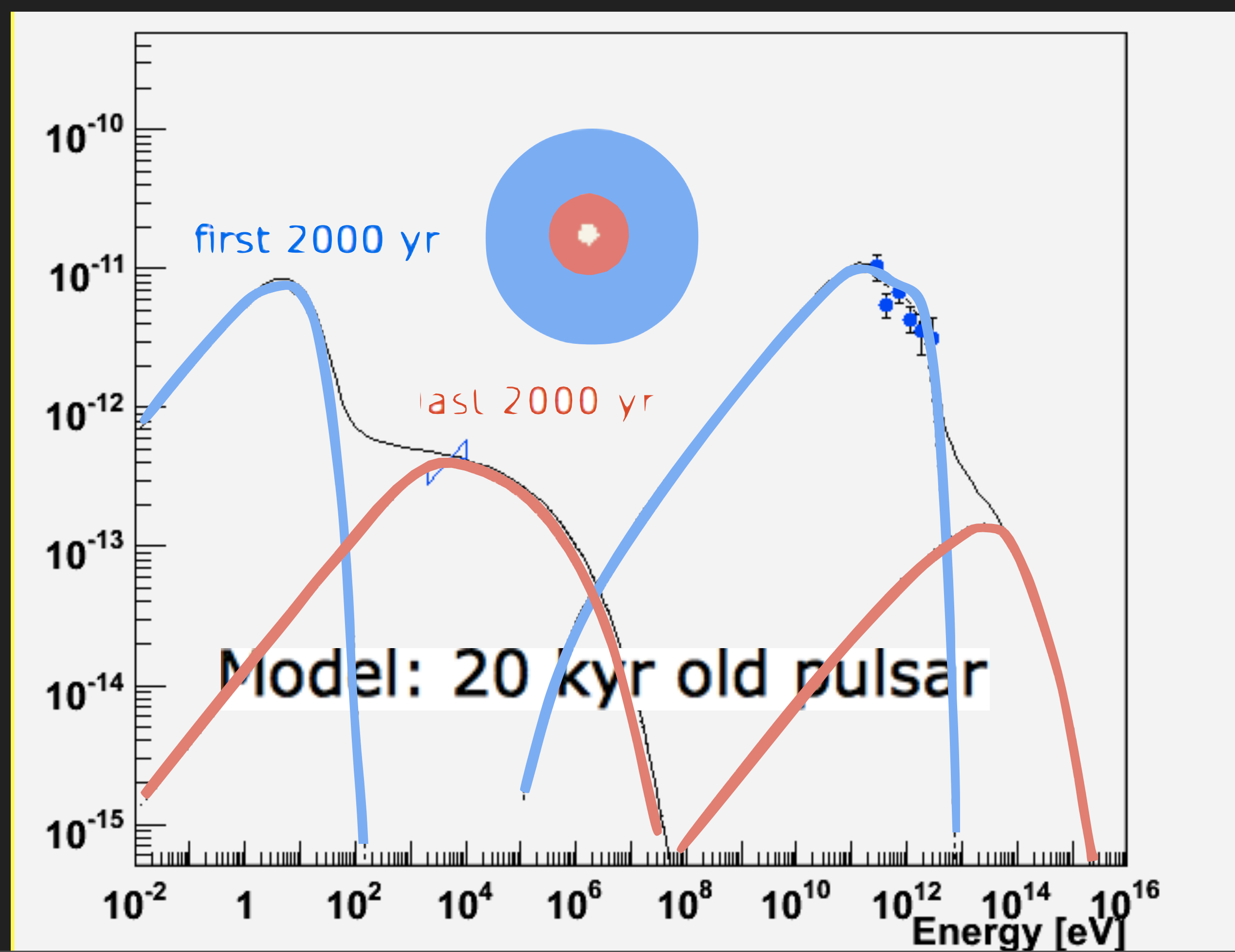

Why are the TeV/X-ray sources sizes different?

Spectral Evolution: Cooling Processes (IC)

HESS - VHE

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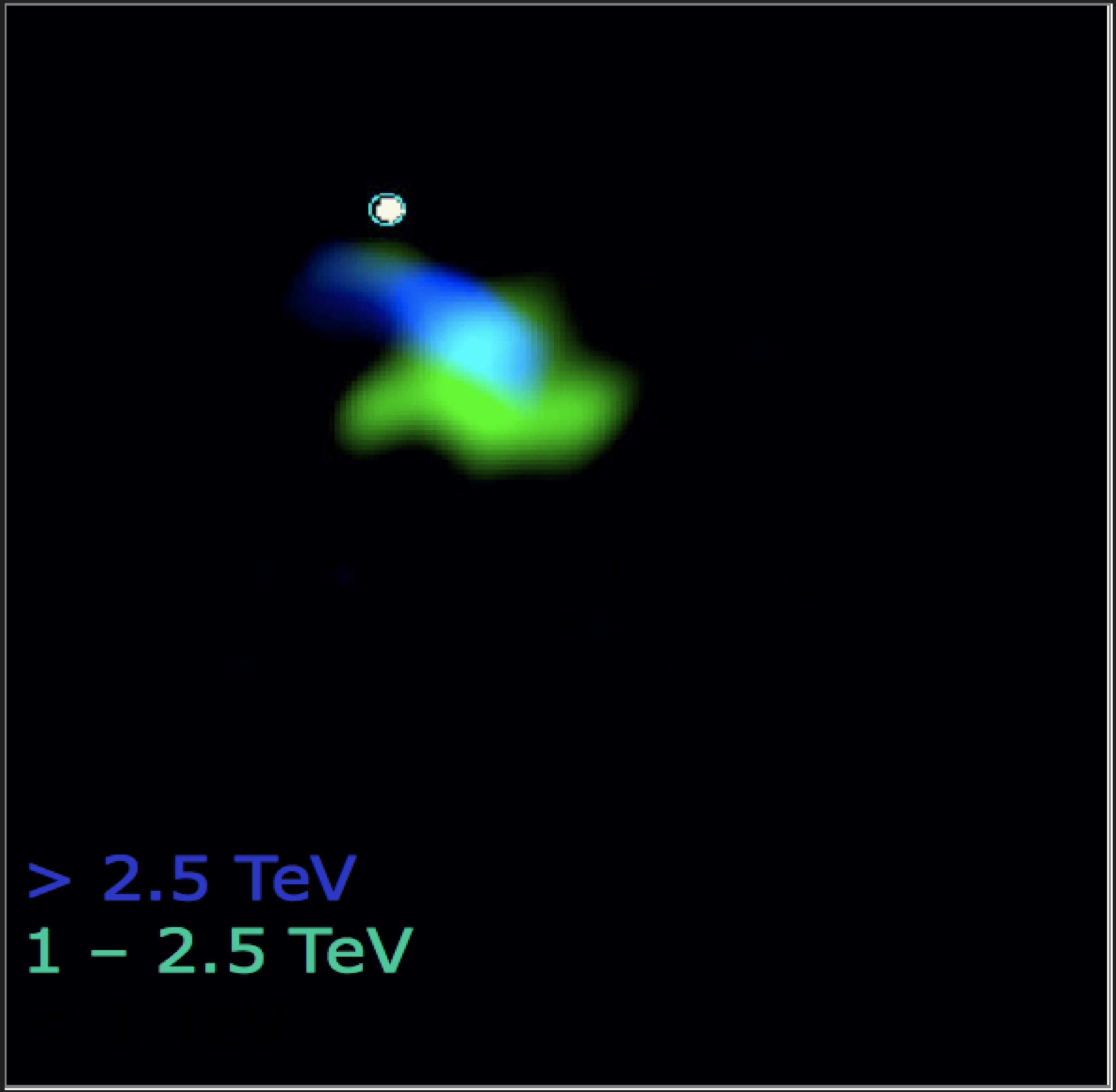
HESS - VHE



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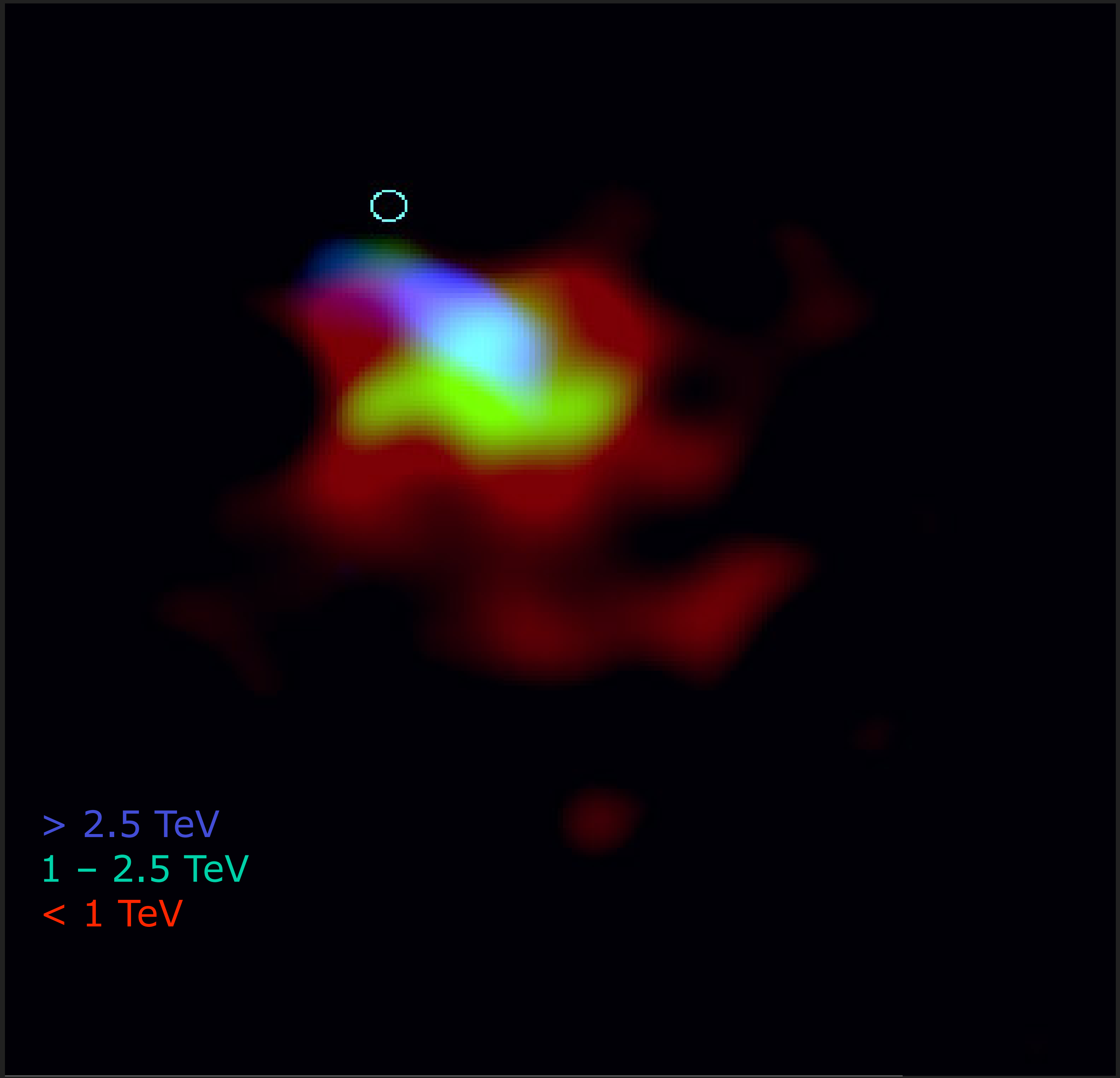
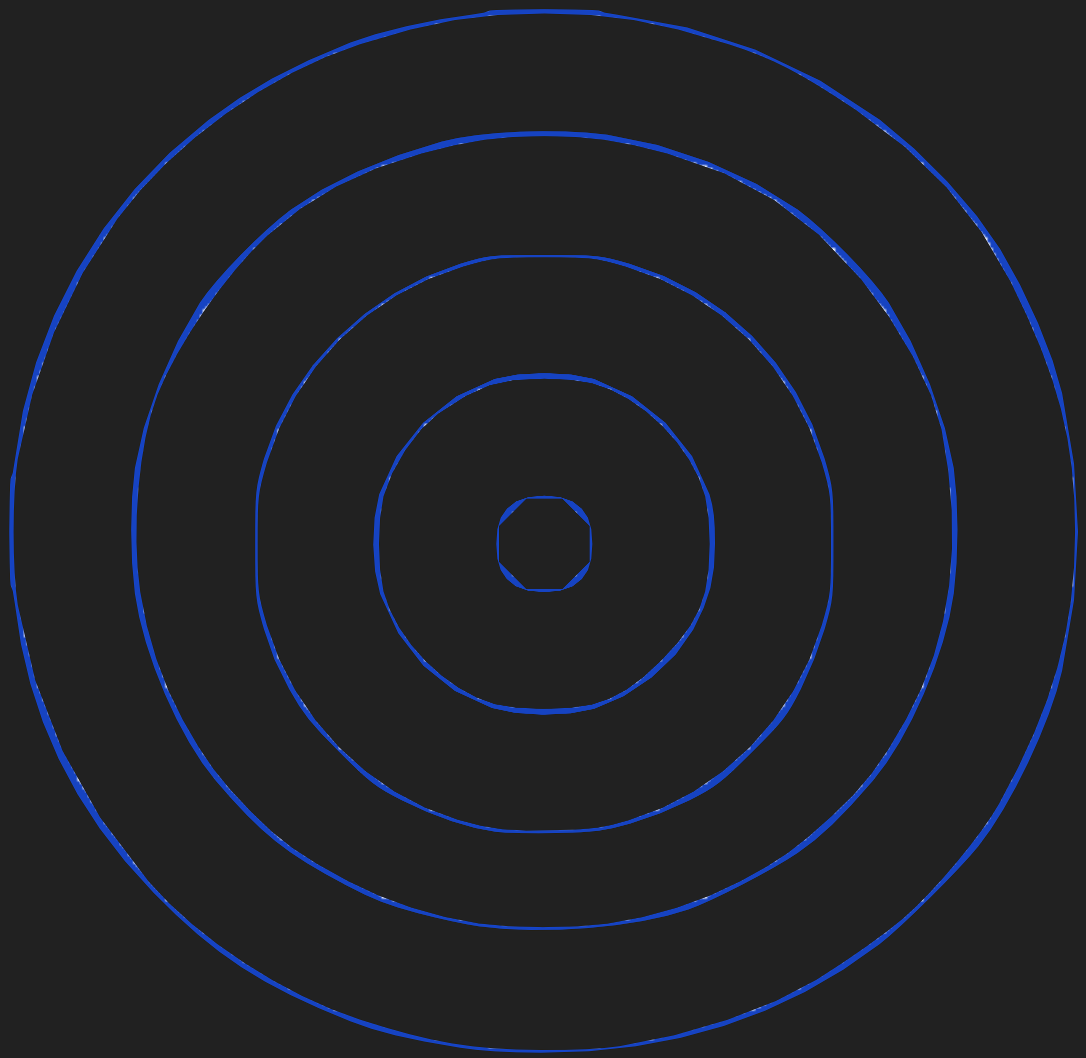
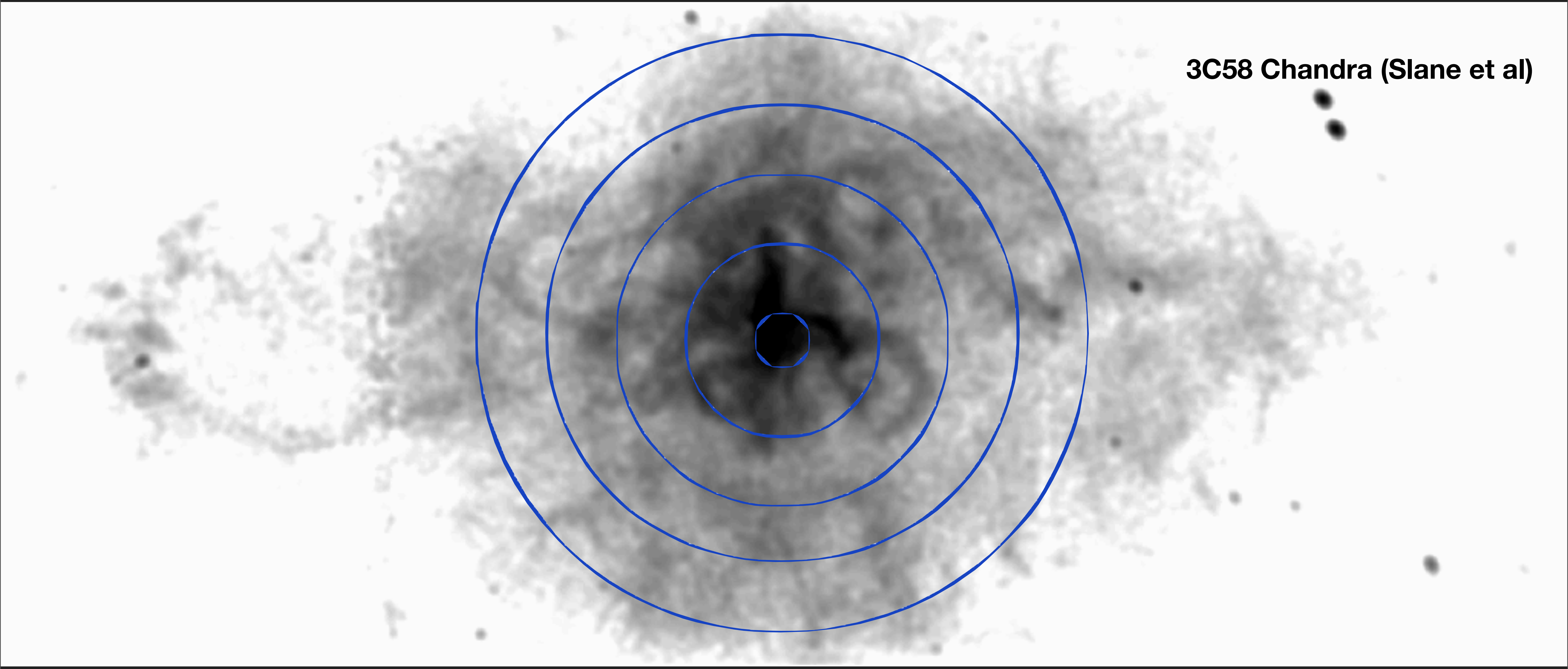


Spectral Evolution: Cooling Processes (Syn)



3C58 Chandra (Slane et al)

Spectral Evolution: Cooling Processes (Syn)



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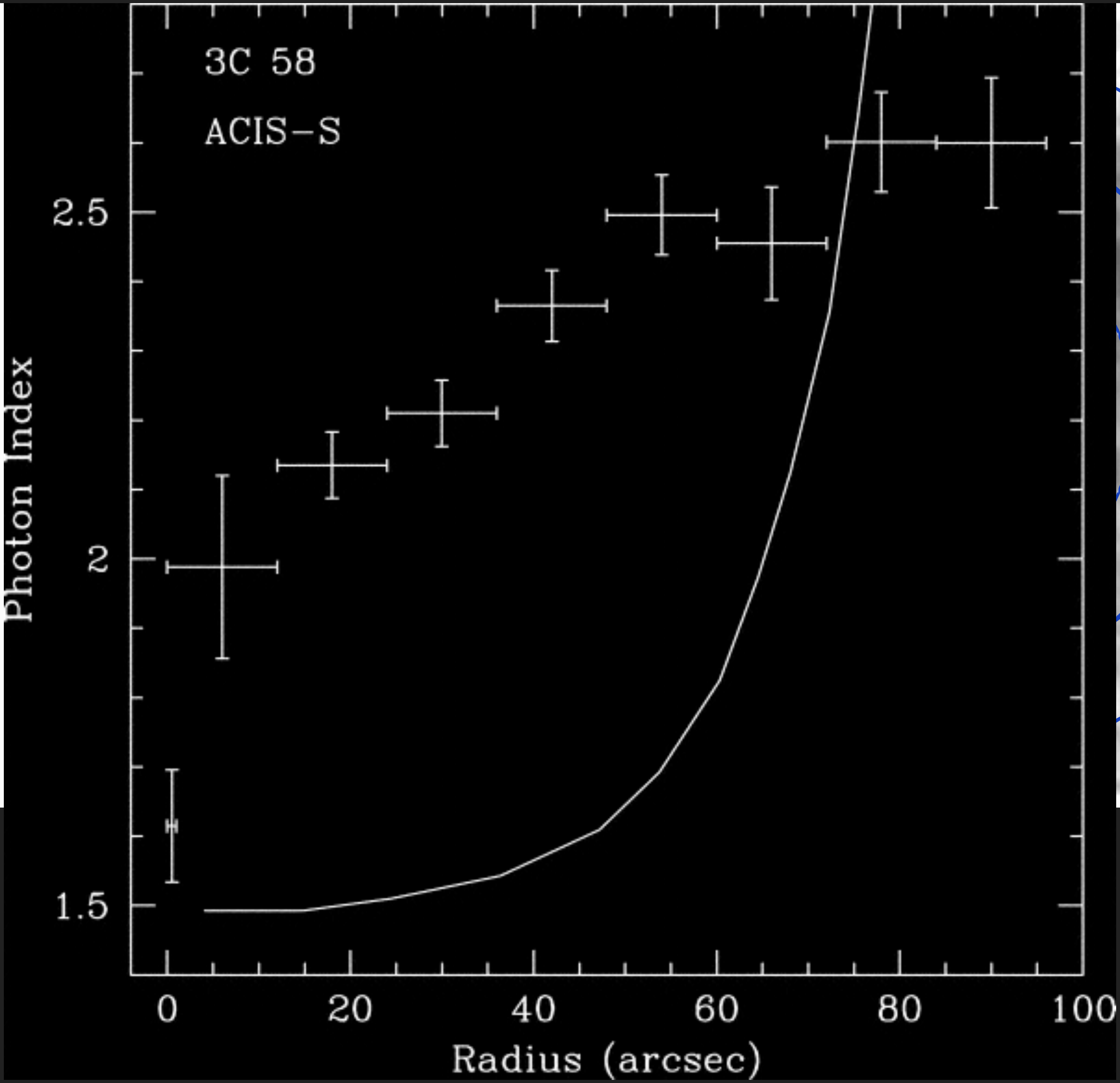
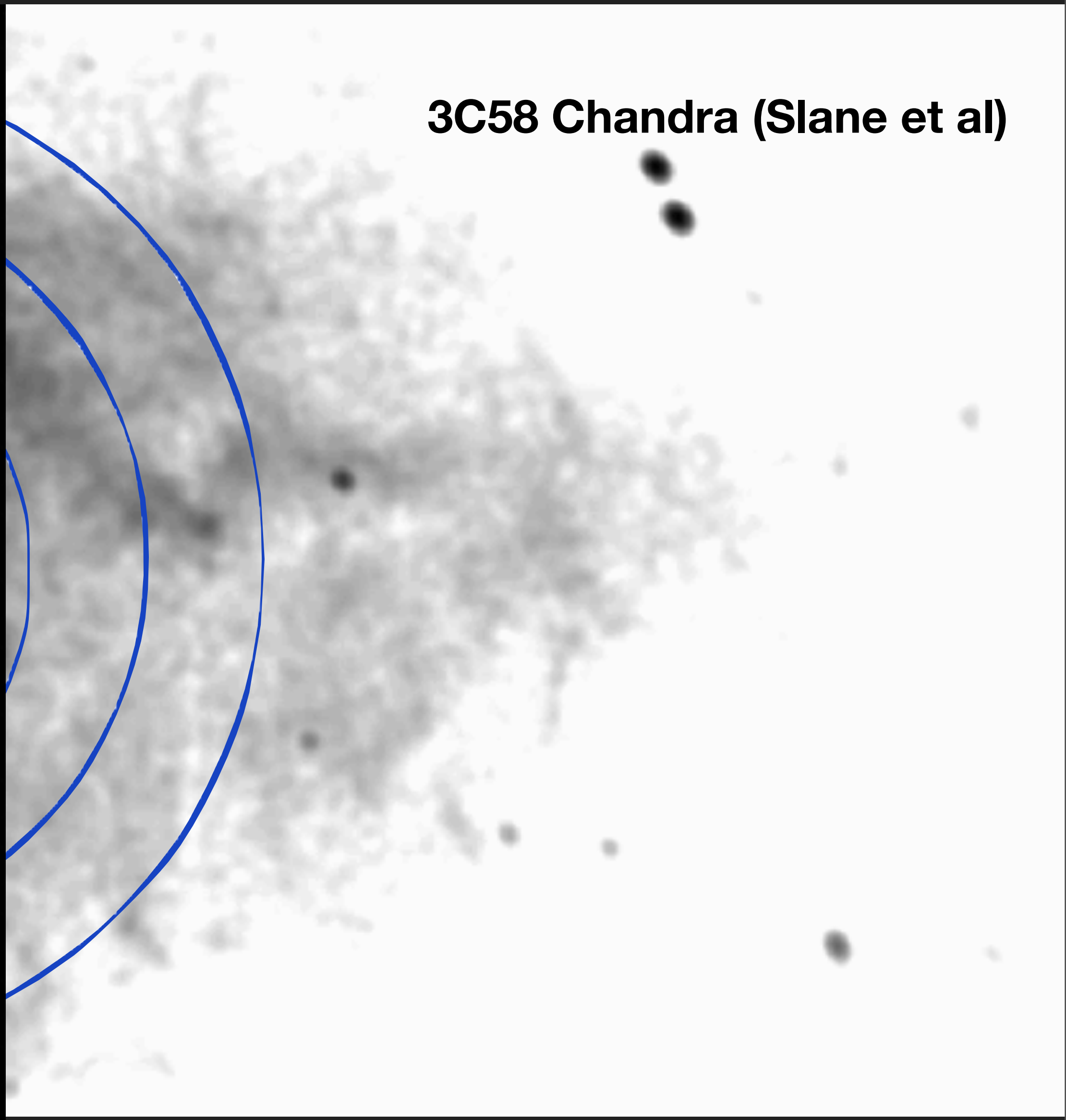
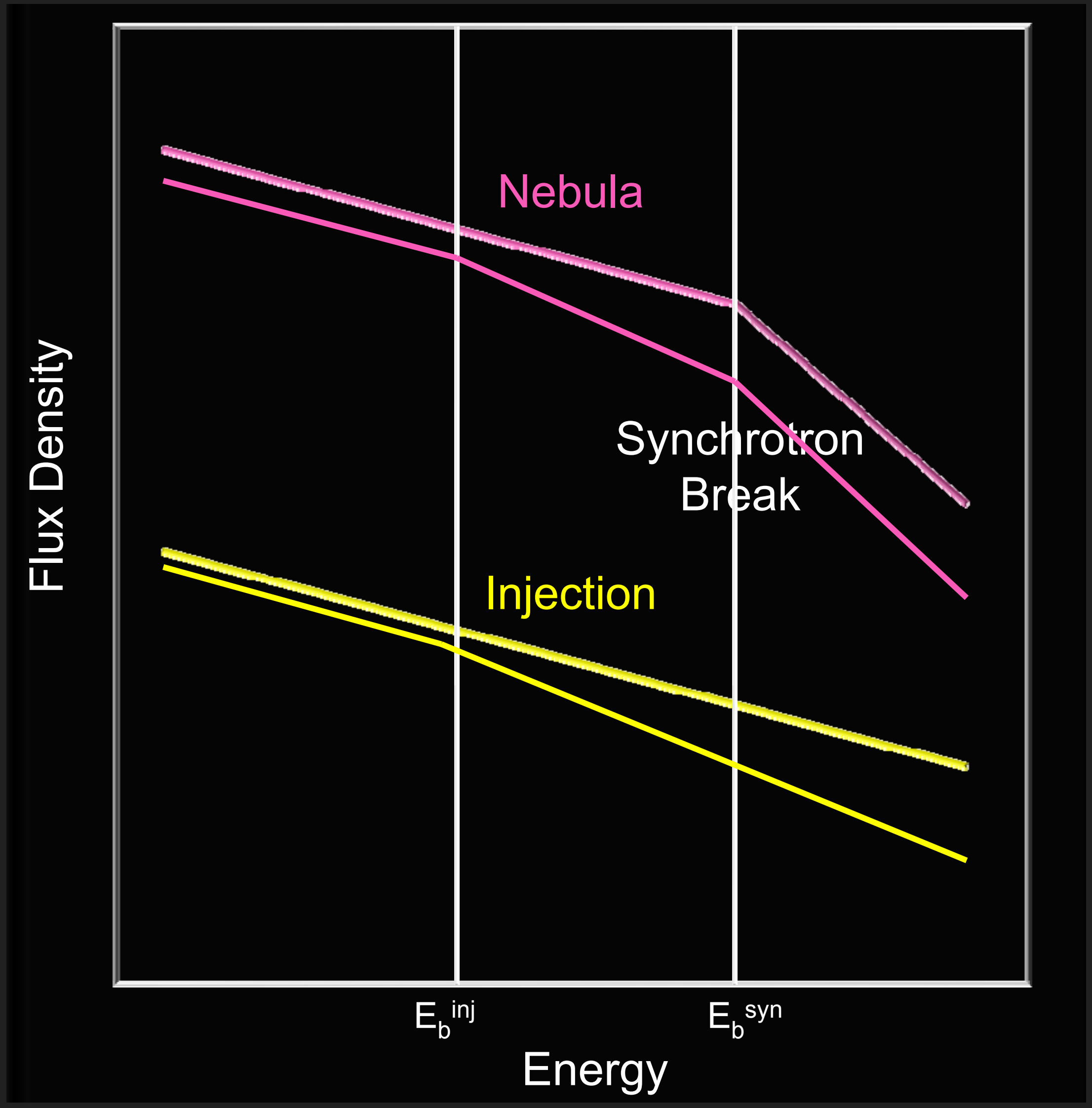


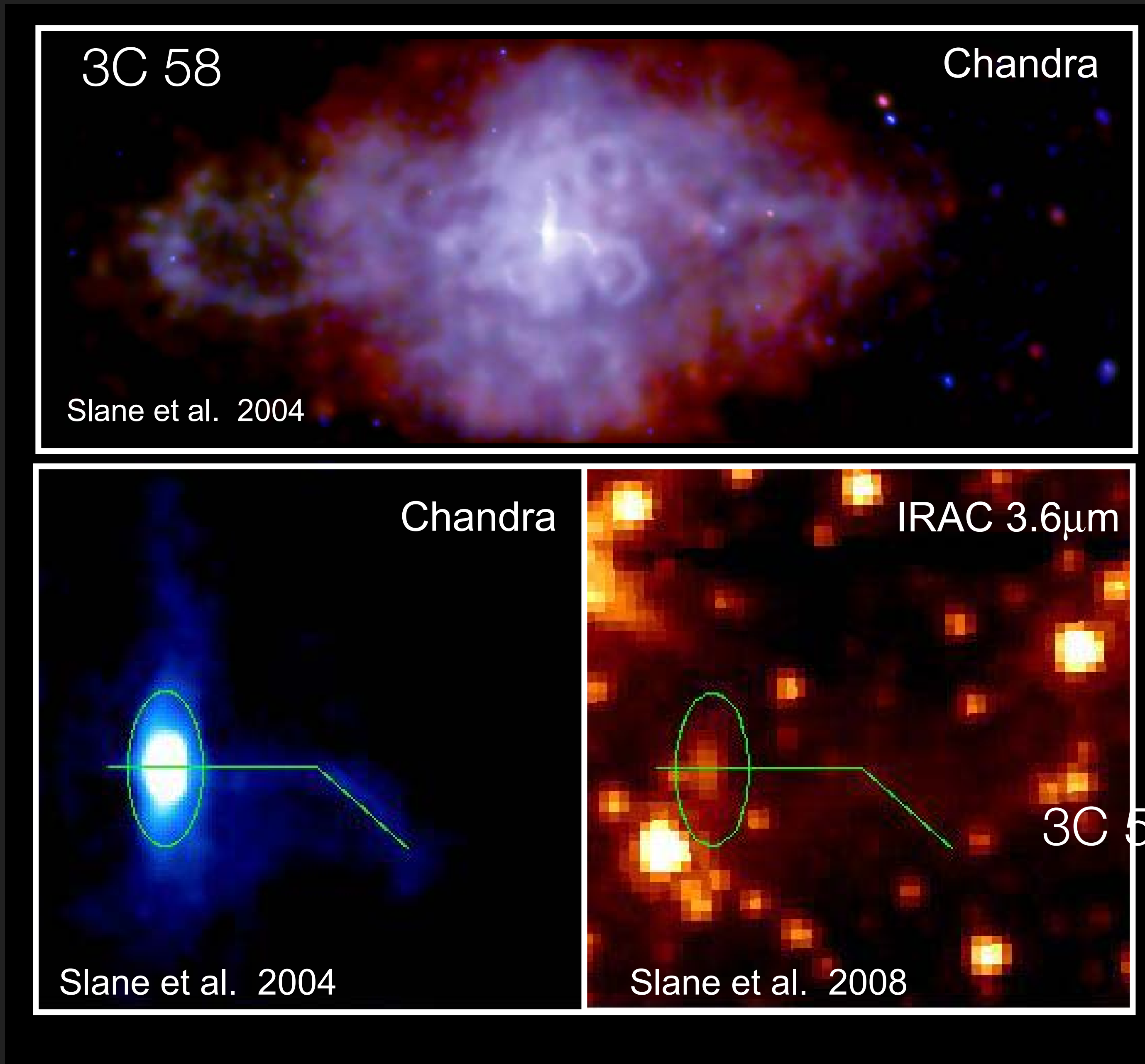


Spectral Evolution

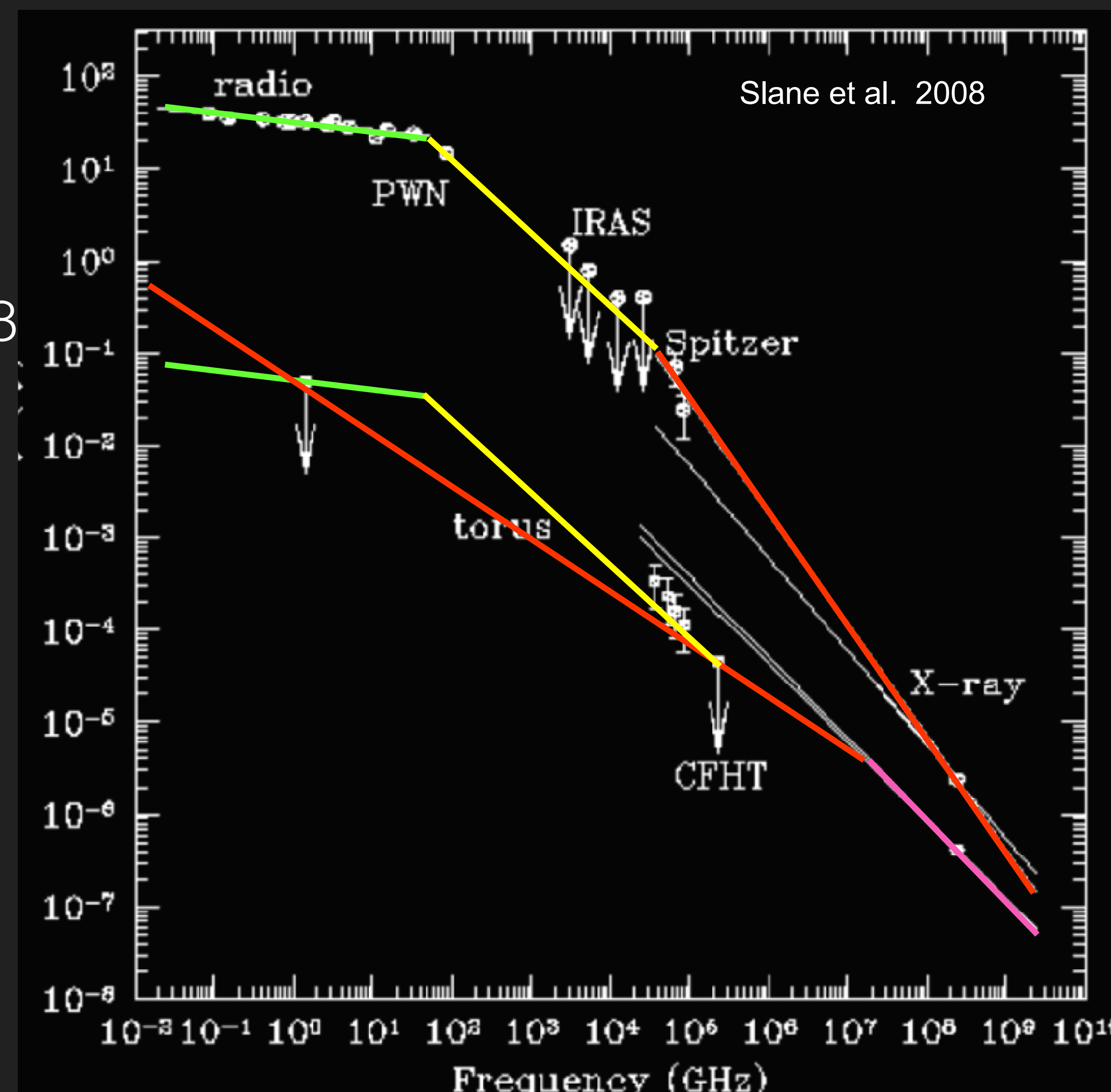
- But not as simple as a power-law injection with a spectral break

$$\nu_b = 10^{21} B_{-6}^{-3} t_{-3}^{-2} \quad \text{Hz}$$

- 

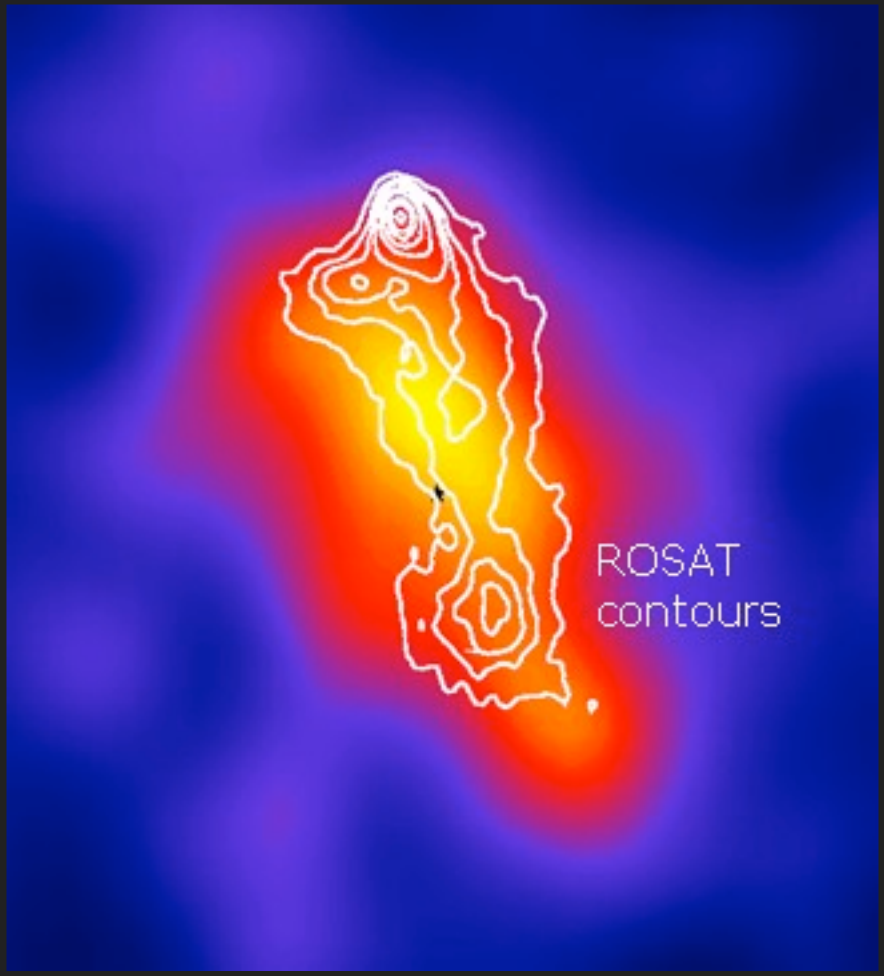

3C 58
Chandra
Slane et al. 2004
Chandra
IRAC 3.6μm
Slane et al. 2004
Slane et al. 2008

3C 58

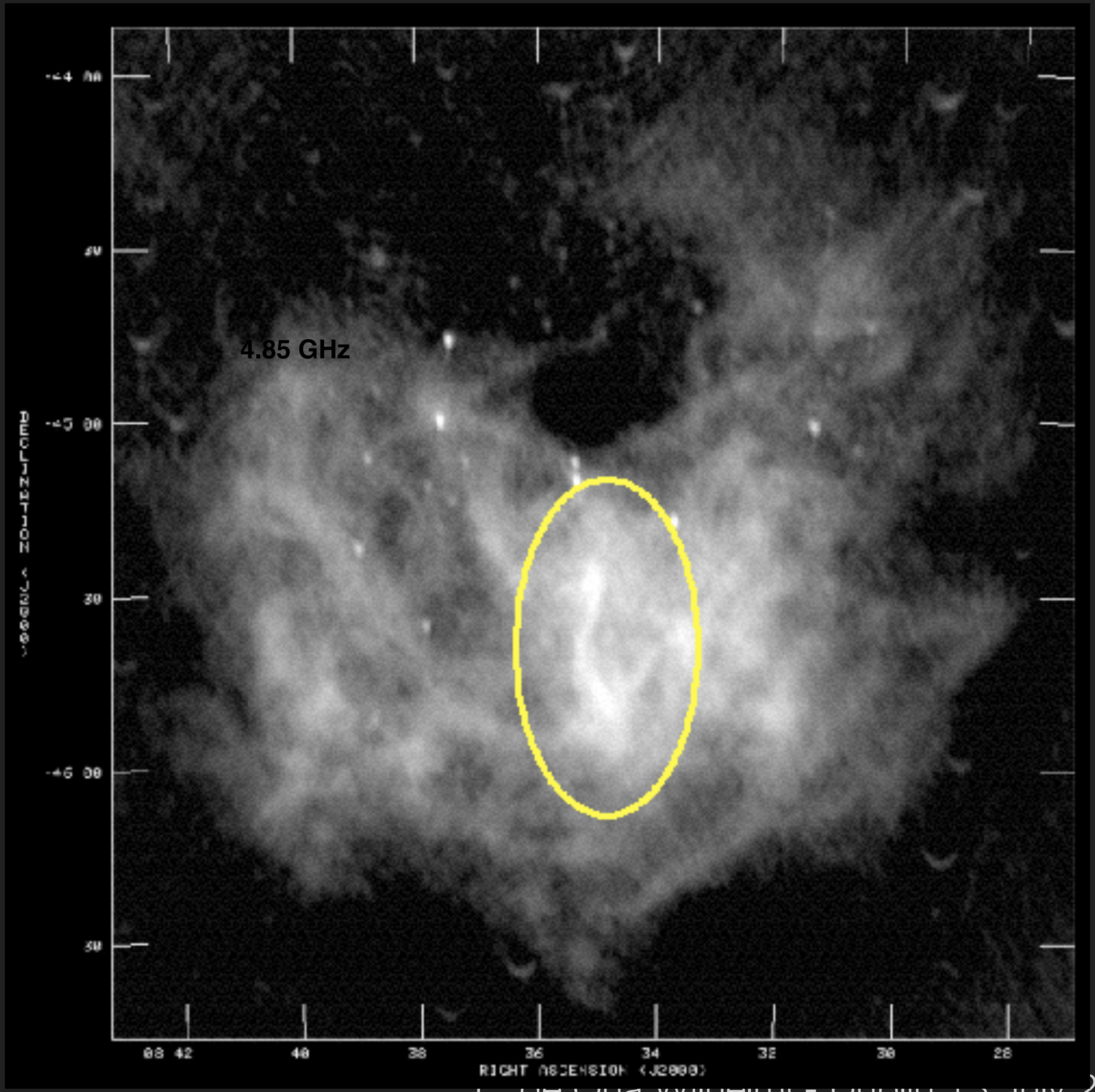

Slane et al. 2008
radio
PWN
IRAS
Spitzer
torus
CFHT
X-ray
Frequency (GHz)
10^2 10^1 10^0 10^-1 10^-2 10^-3 10^-4 10^-5 10^-6 10^-7 10^-8
10^-2 10^-1 10^0 10^1 10^2 10^3 10^4 10^5 10^6 10^7 10^8 10^9 10^10

Spectral Evolution

- Vela-X two population of electrons or mixed populations?



HESS: 10h



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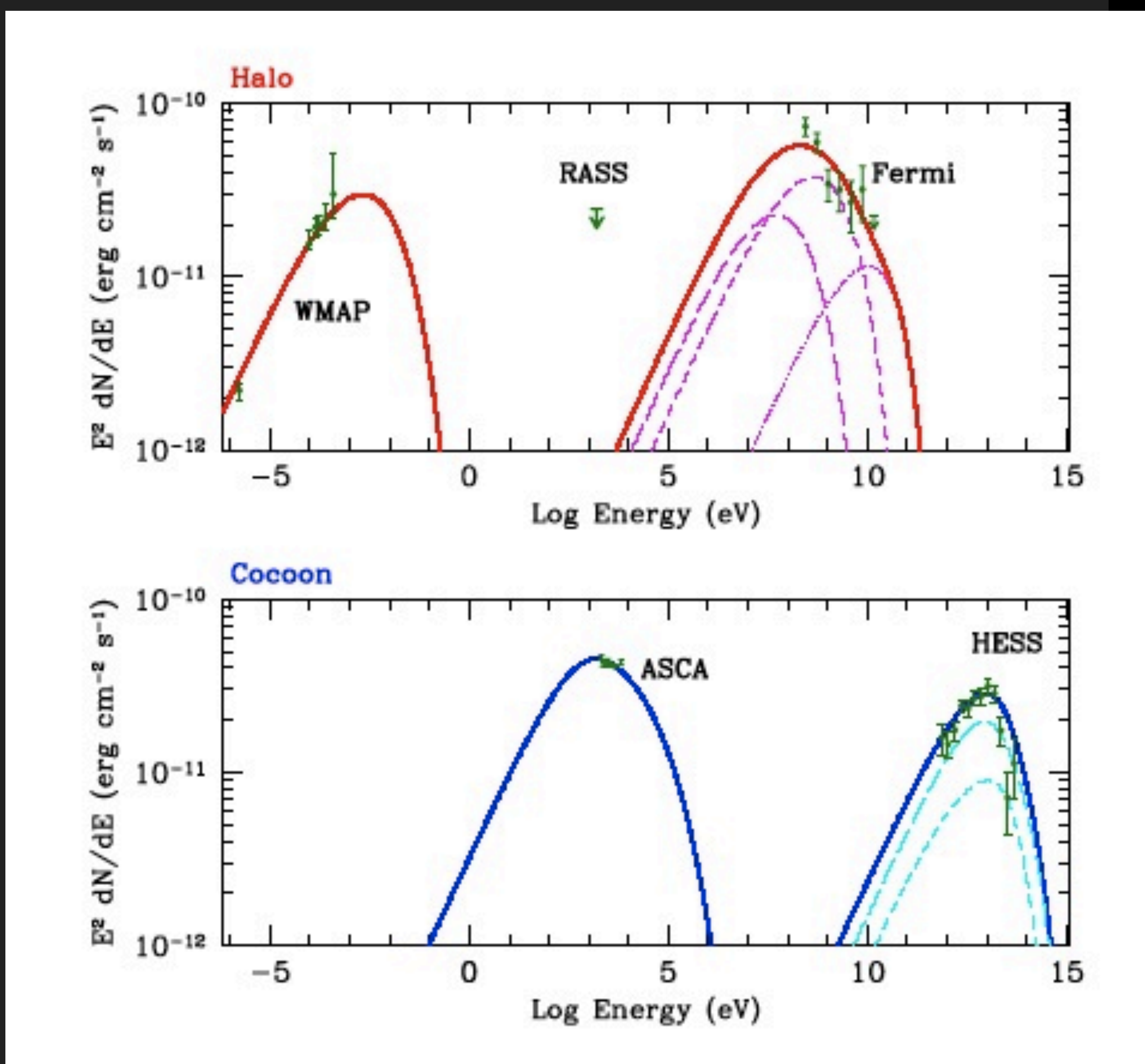

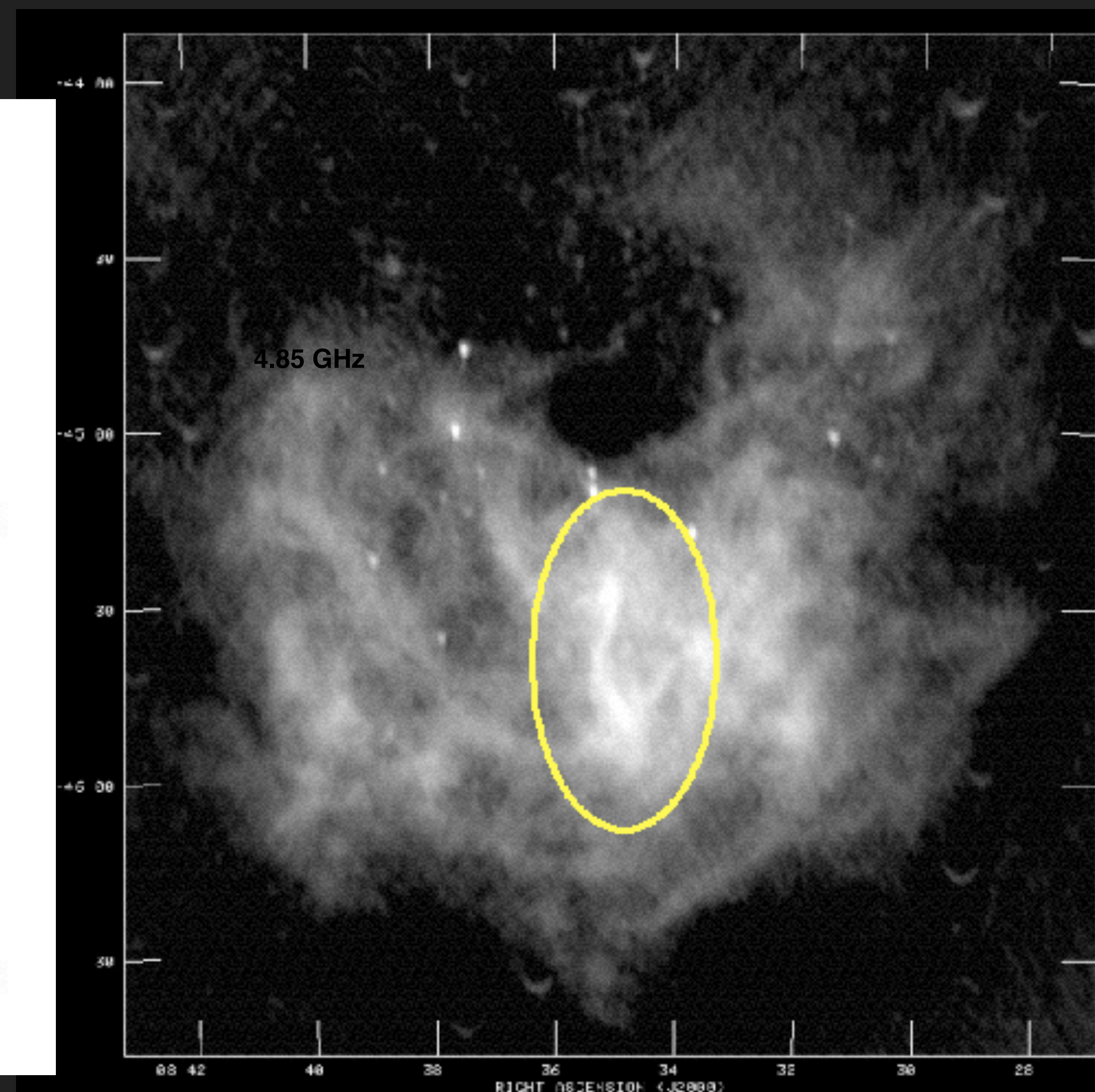

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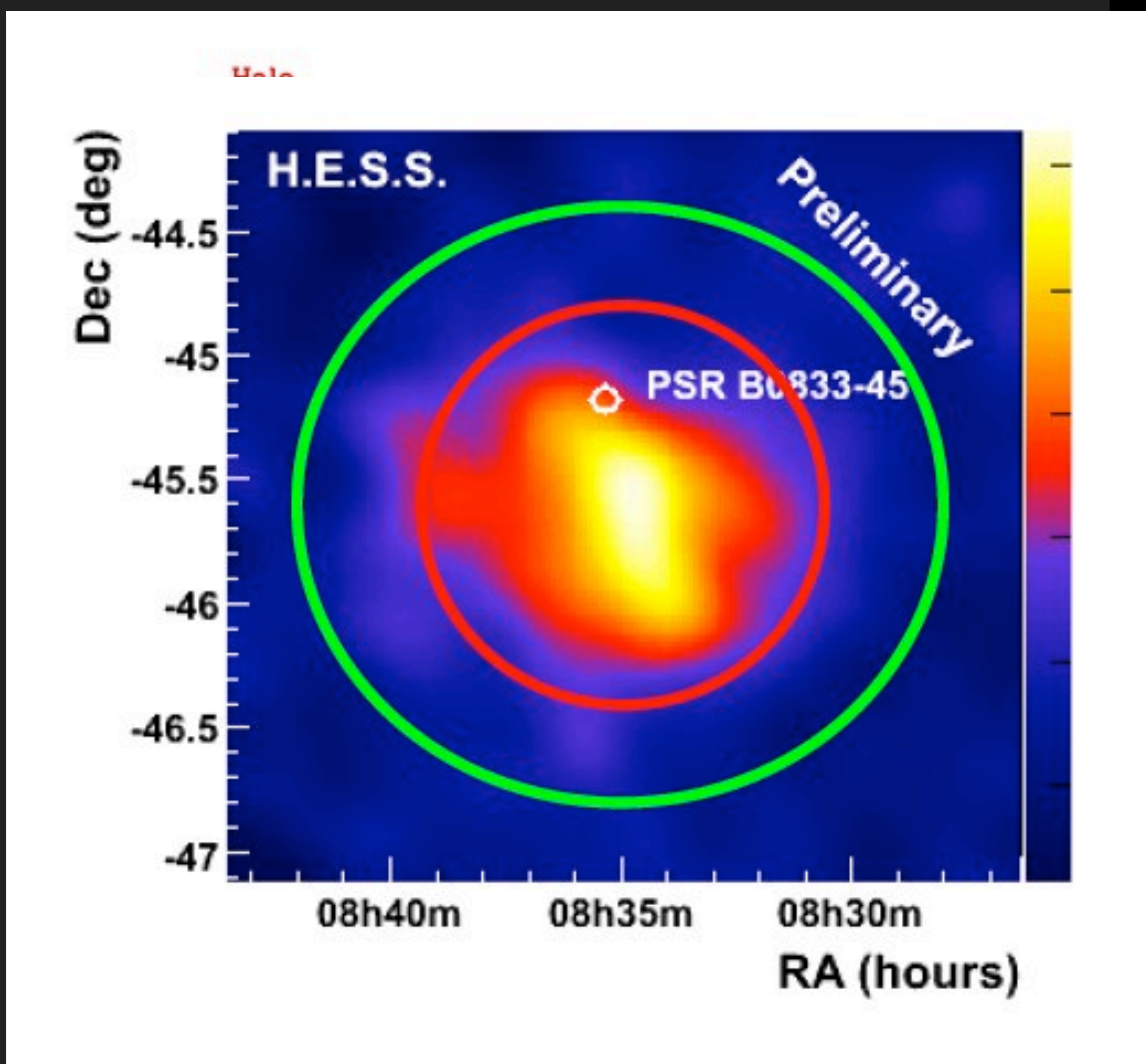

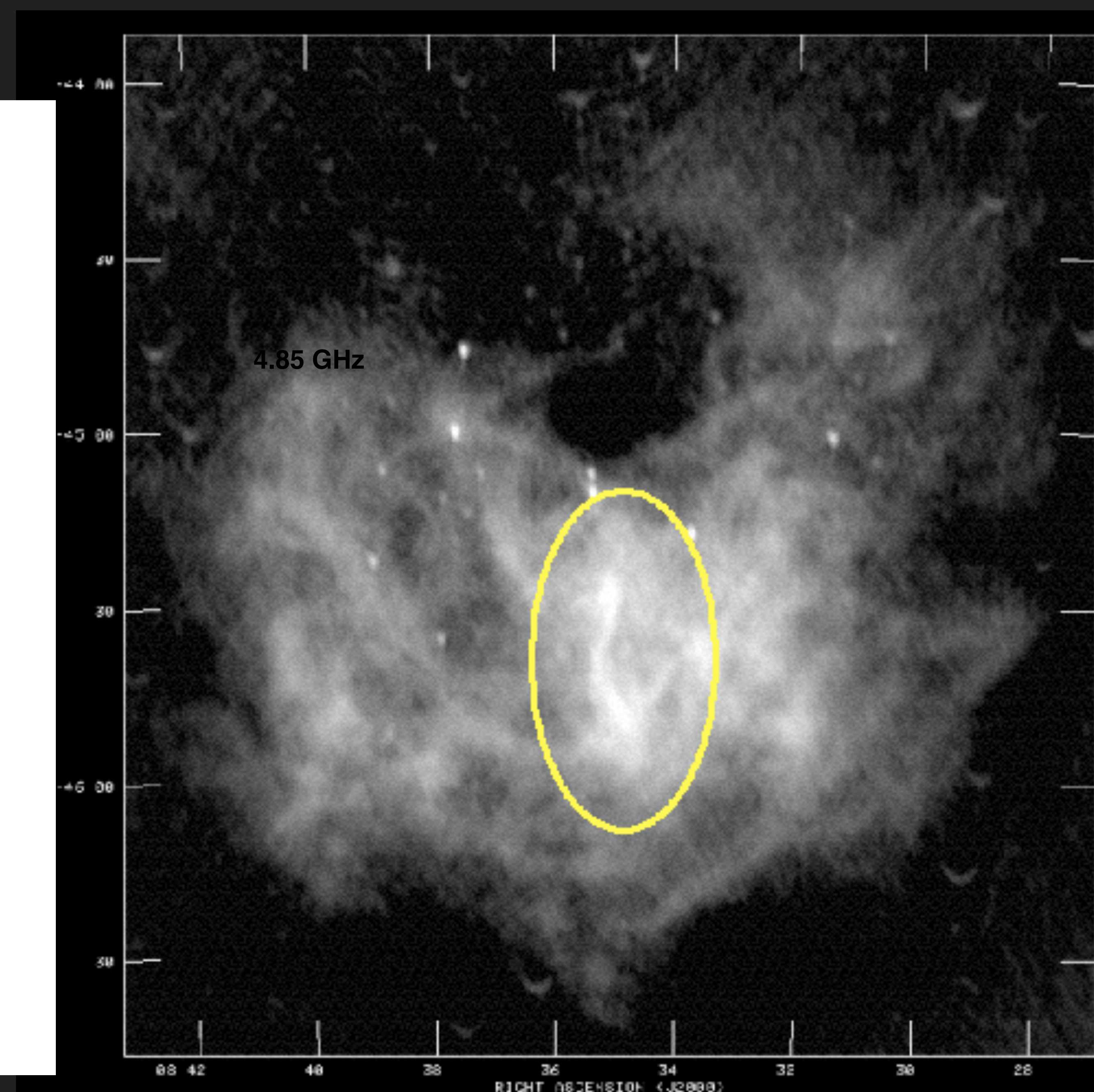

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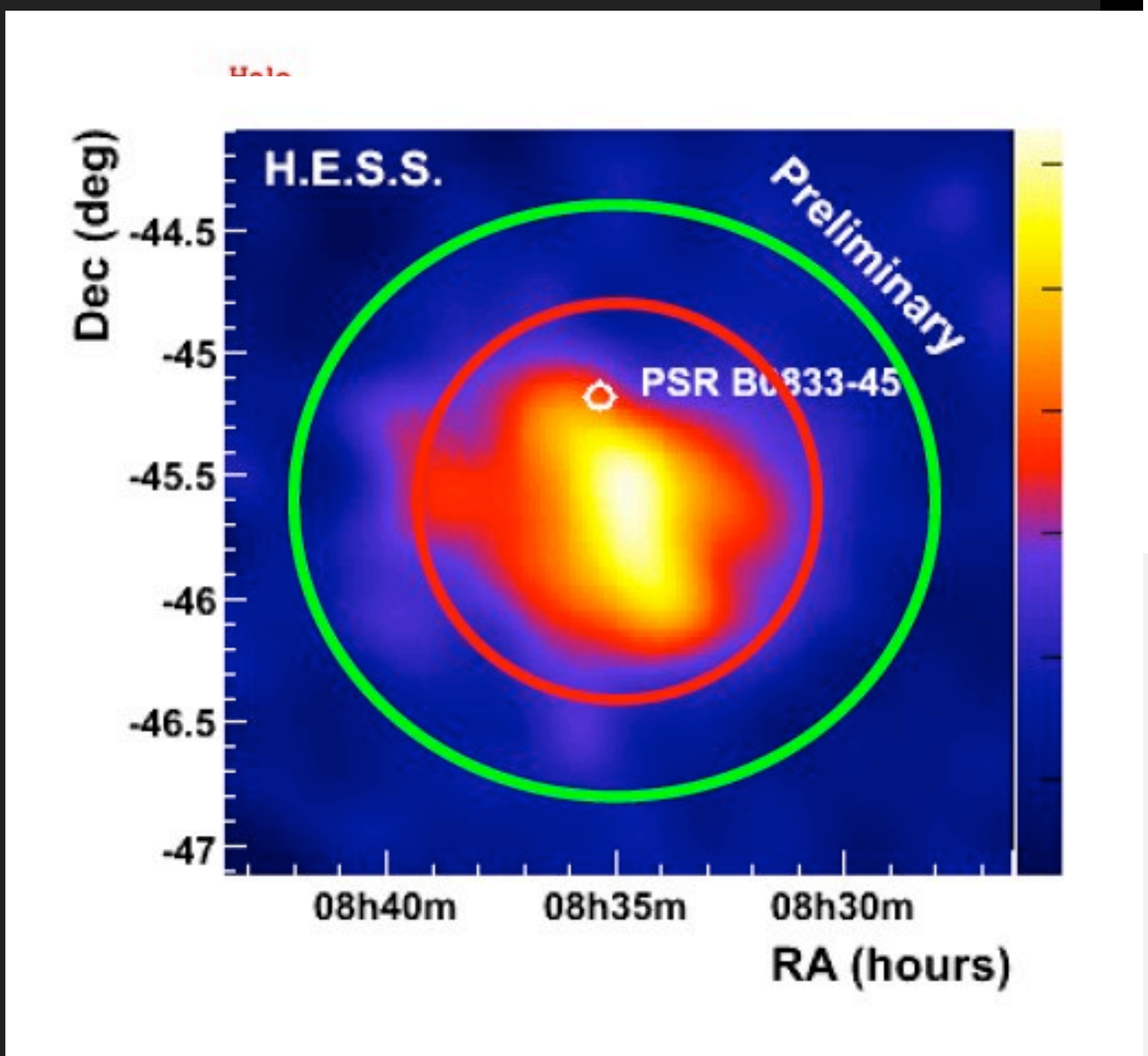
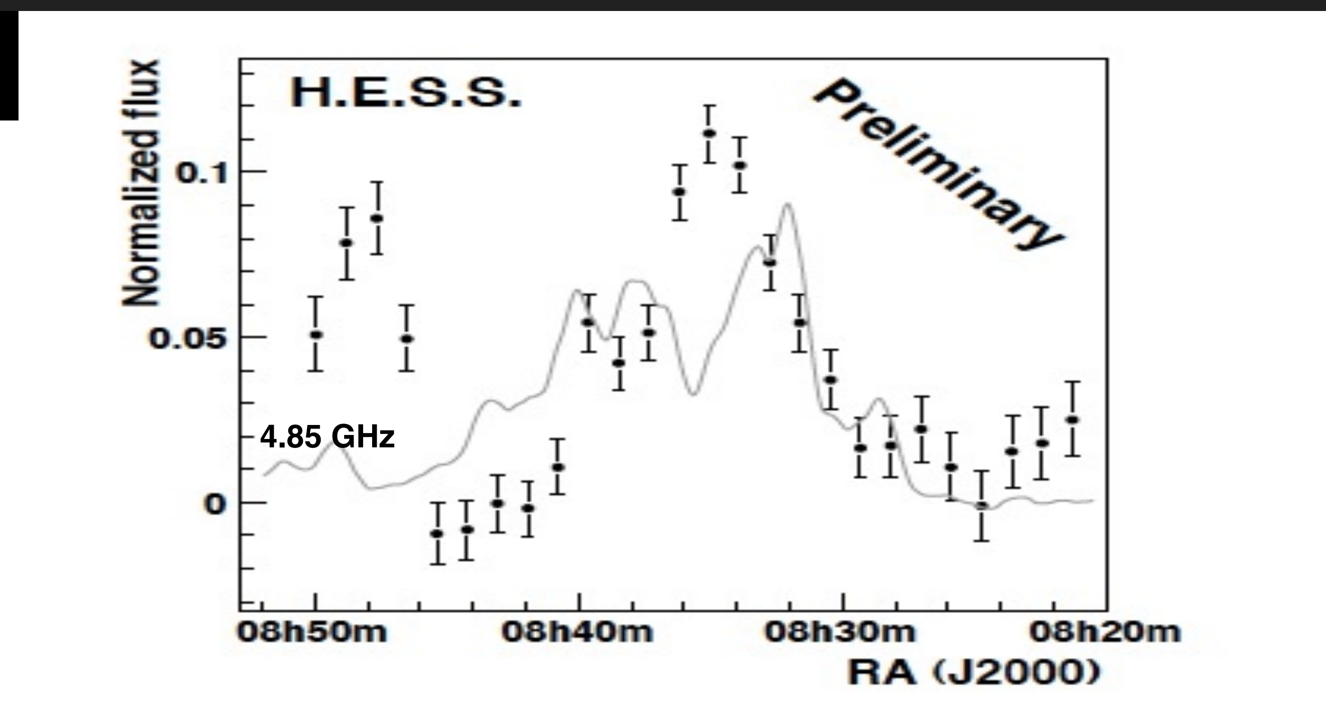
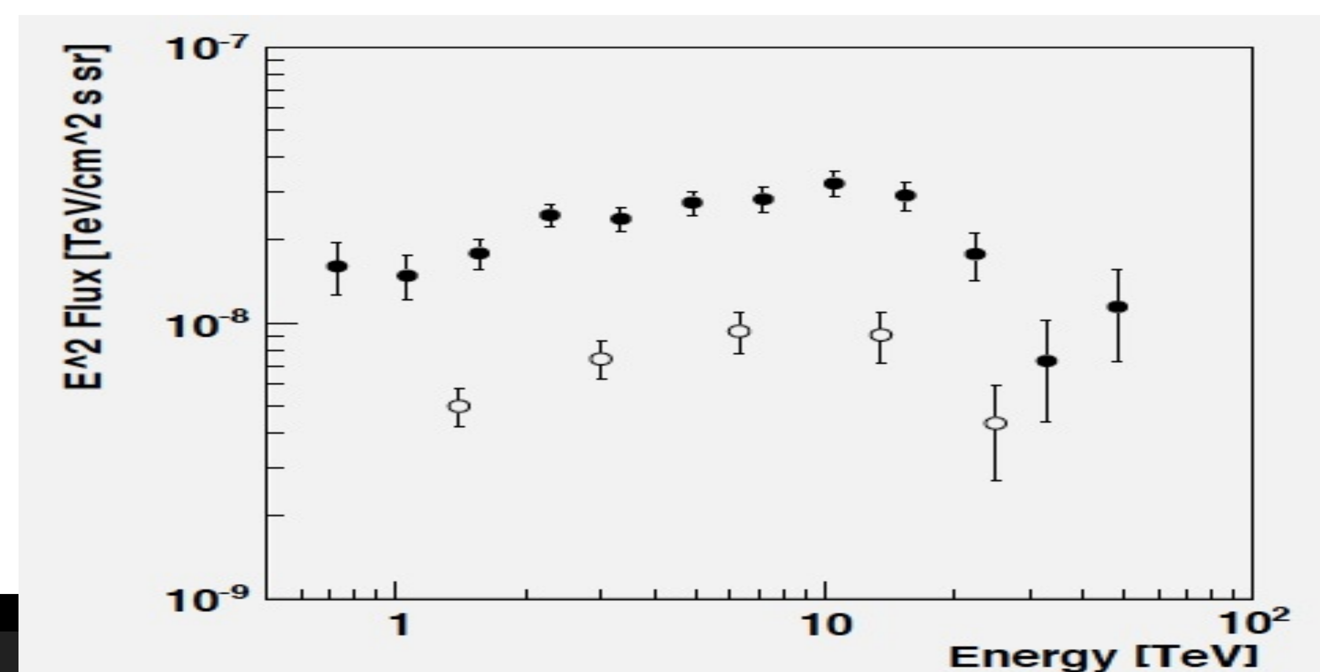
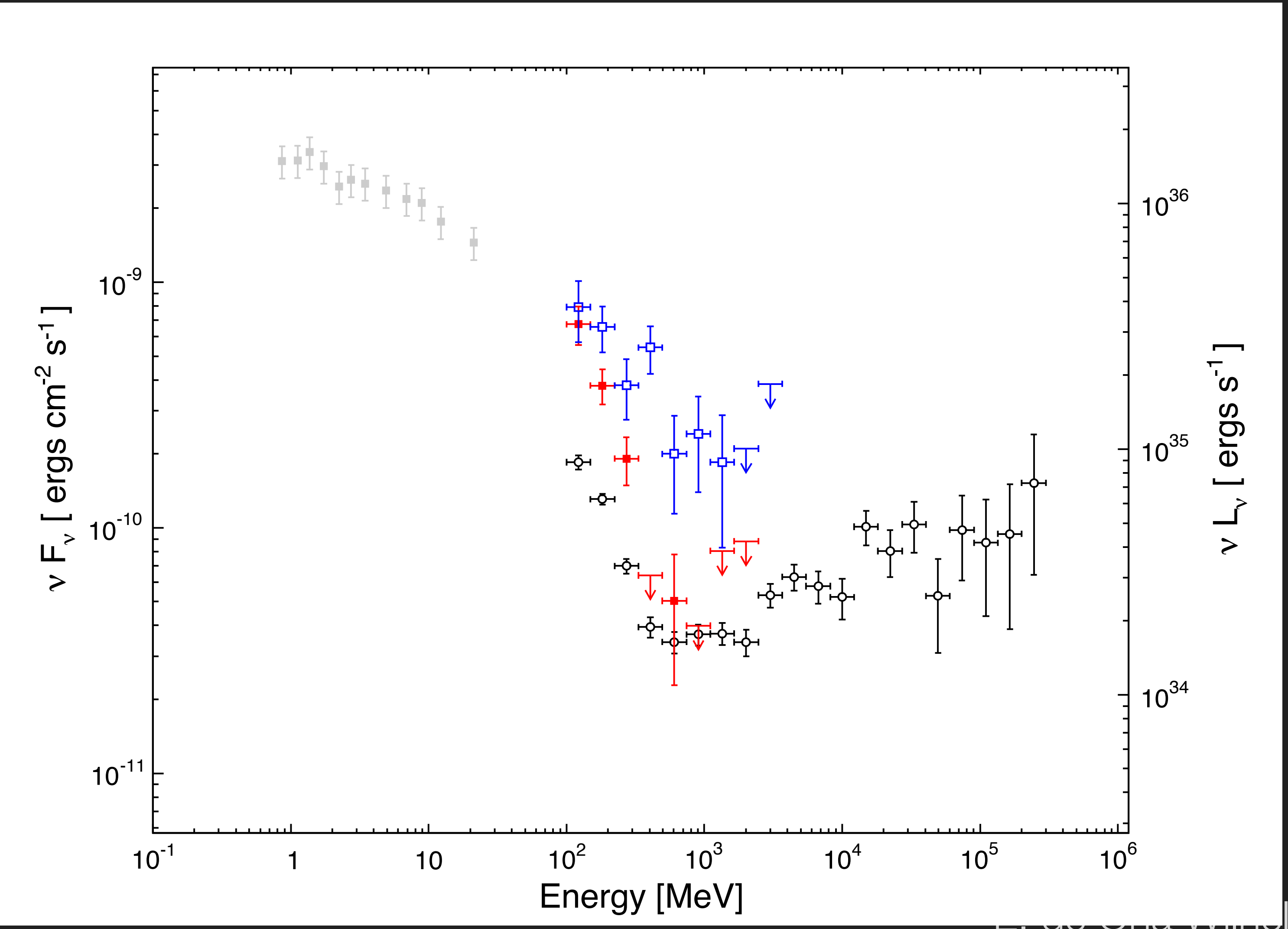






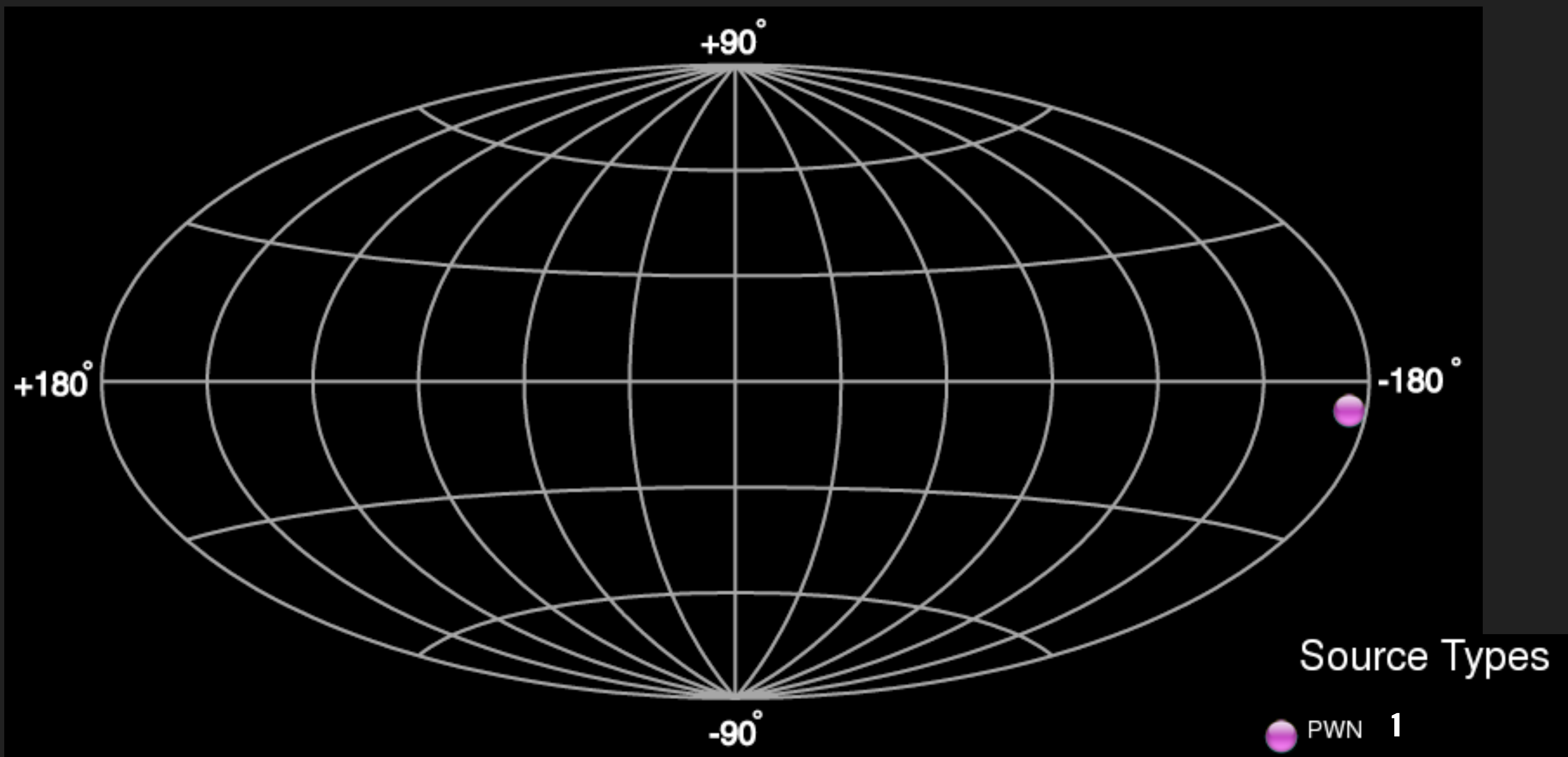
Spectral Evolution

- And even more puzzling! The Crab Nebula in flare
- AGILE & Fermi detected flares lasting ~days with 4-6 times larger flux
- $R<1.4\times10^{-2}$ pc
- Synchrotron PeV (10^{15} eV) electrons



PWN powering VHE sources

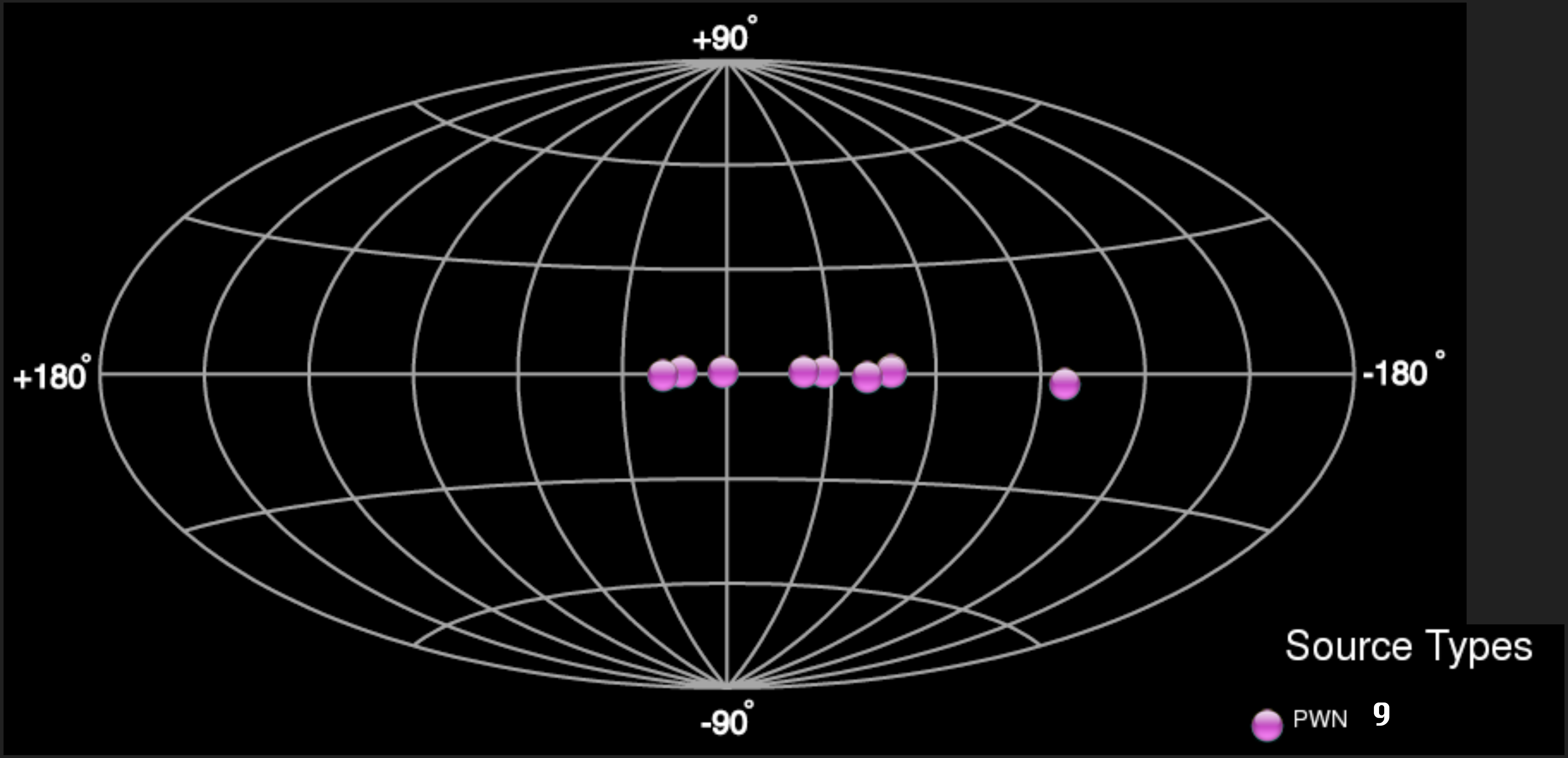
http://tevcat.uchicago.edu/



1989-2004

PWN powering VHE sources

http://tevcat.uchicago.edu/



2005-2006

PWN powering VHE sources

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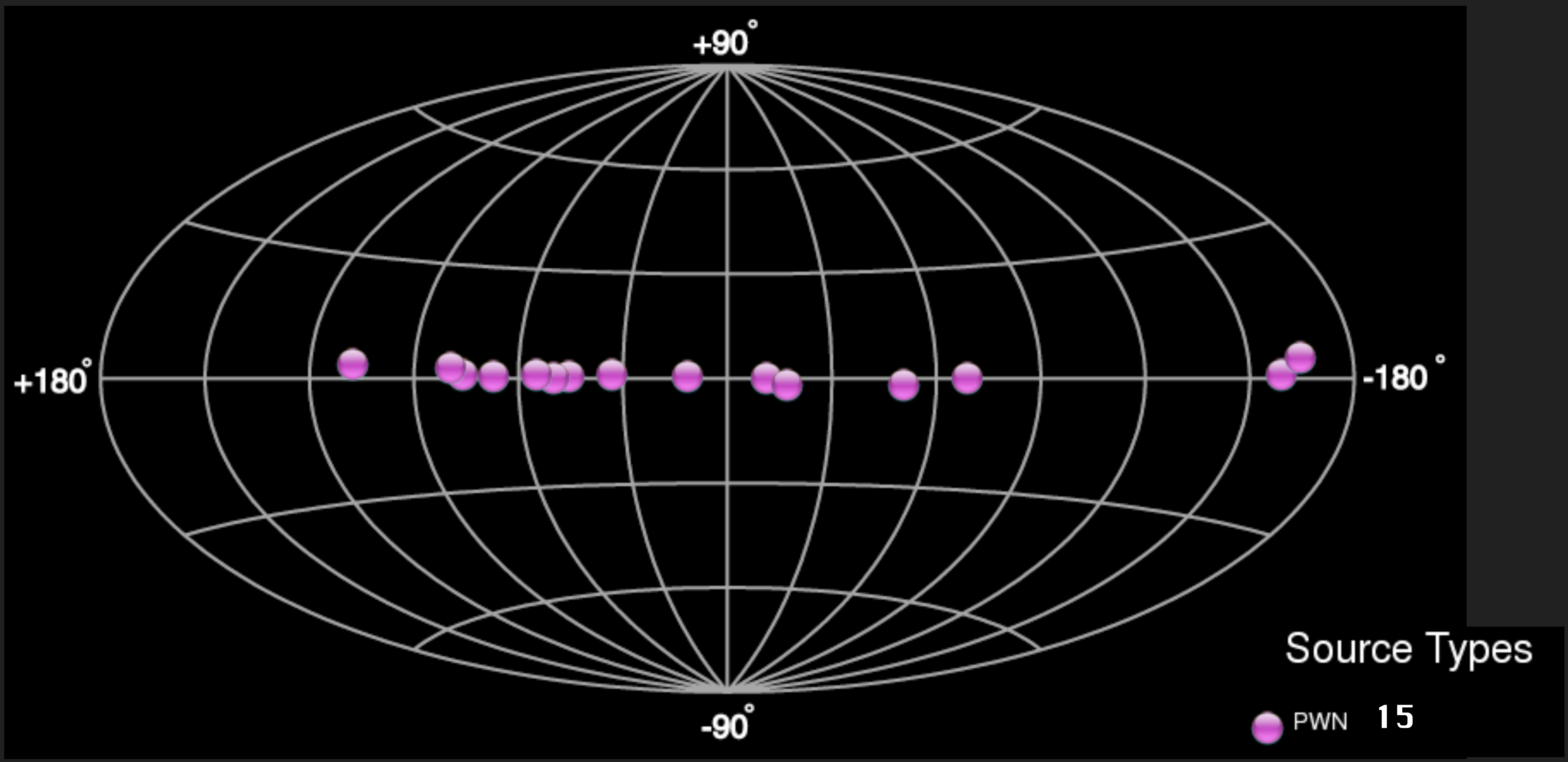
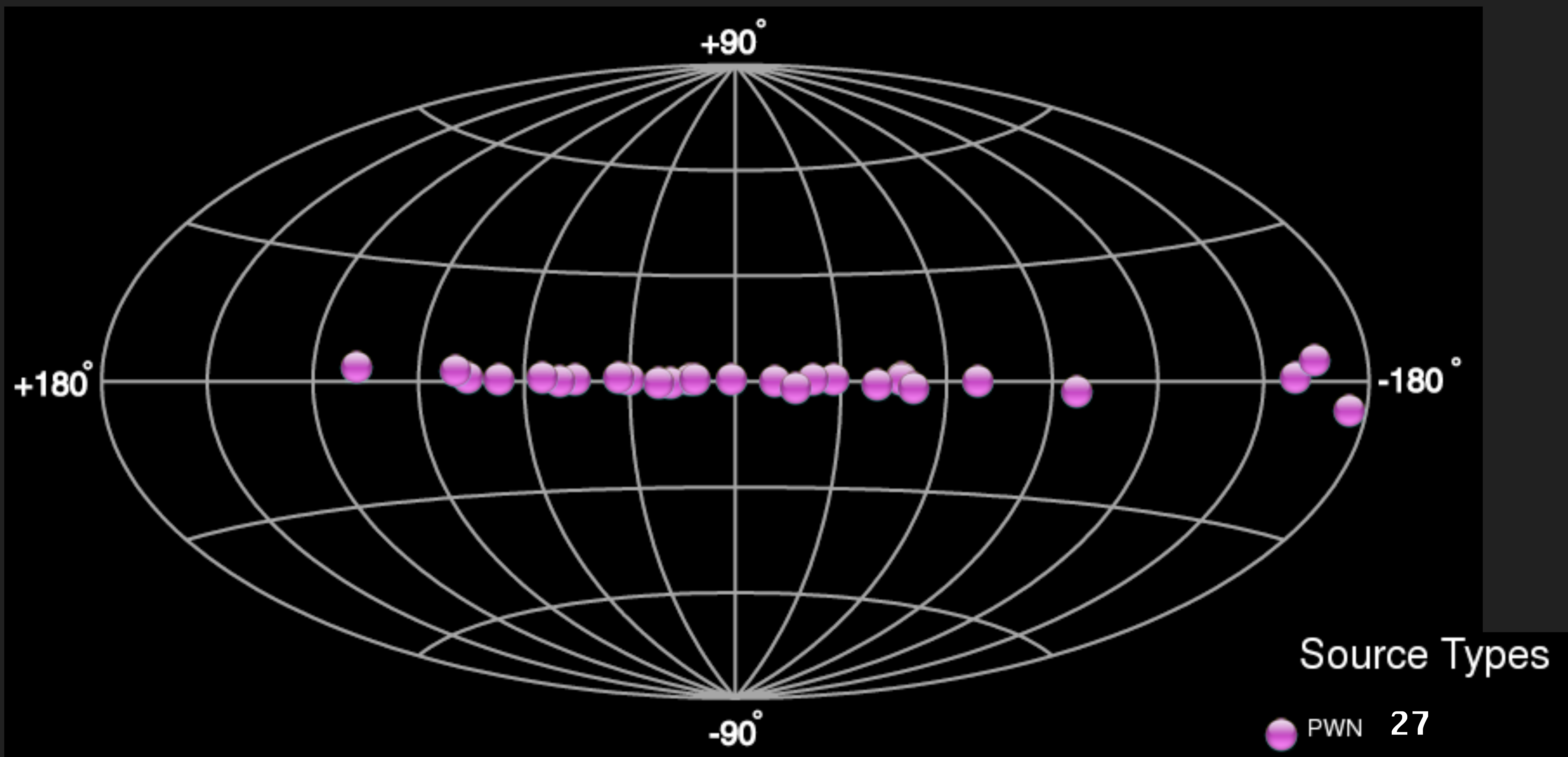


2007-2010

PWN powering VHE sources

http://tevcat.uchicago.edu/



1989-2010

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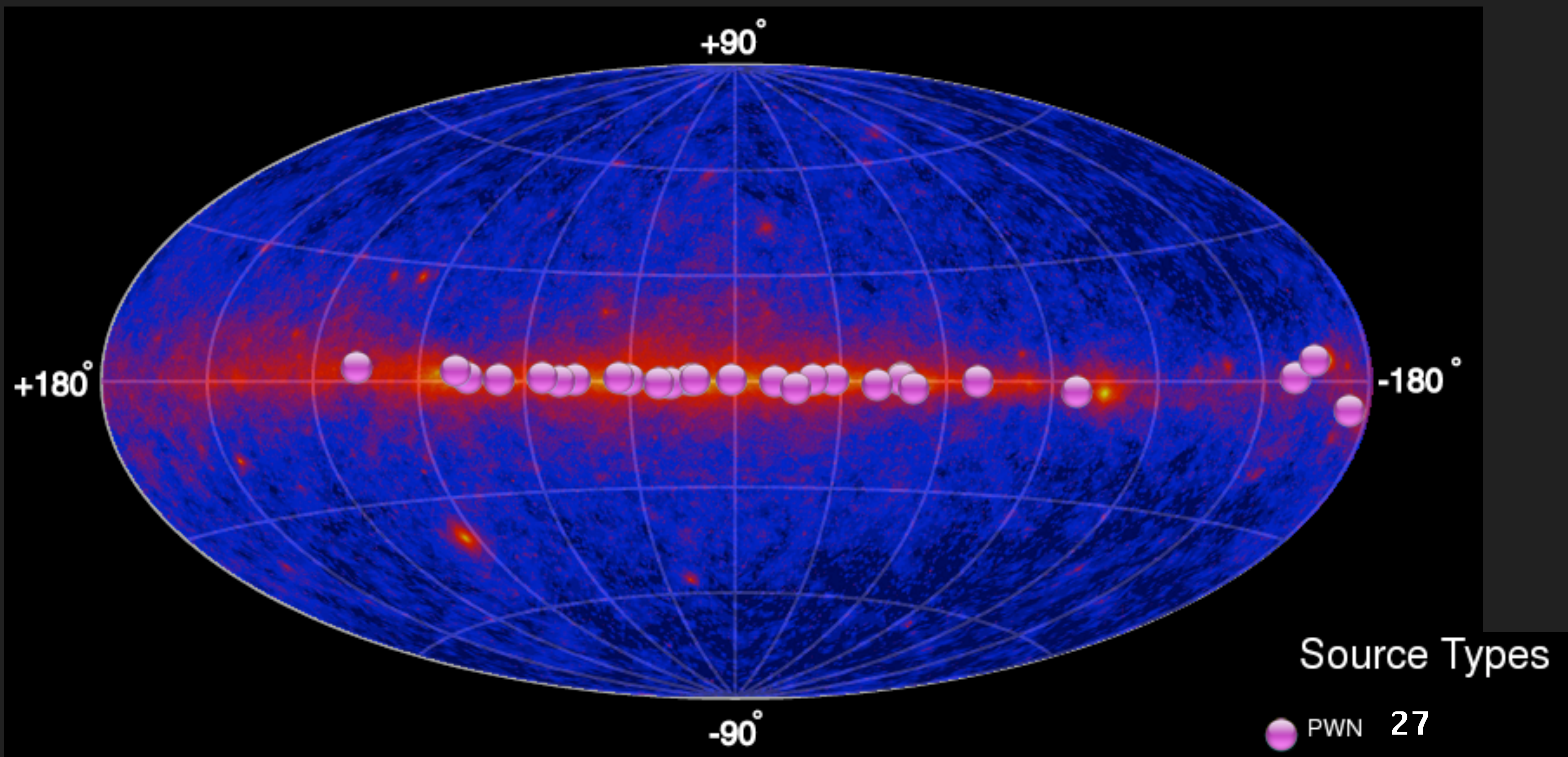
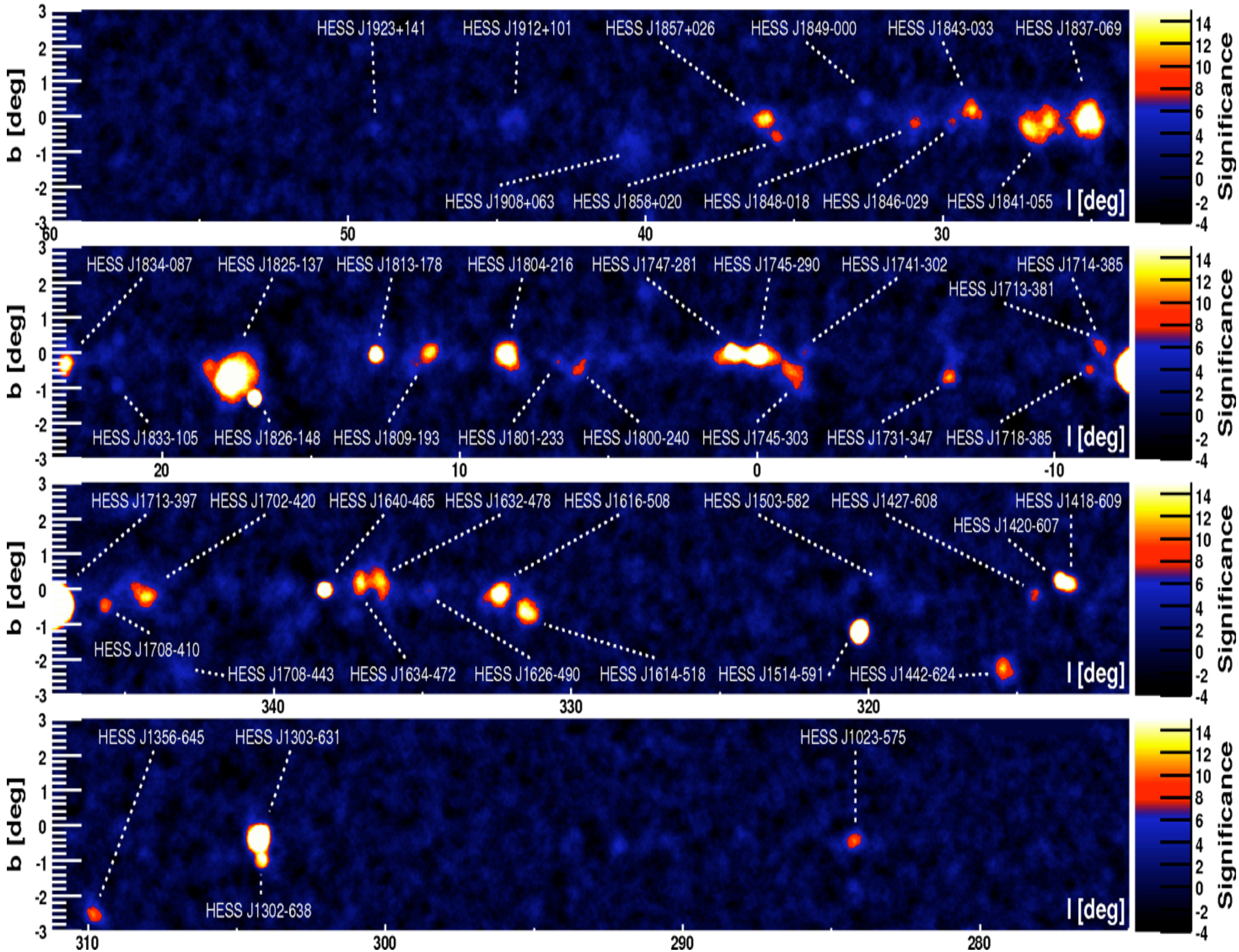
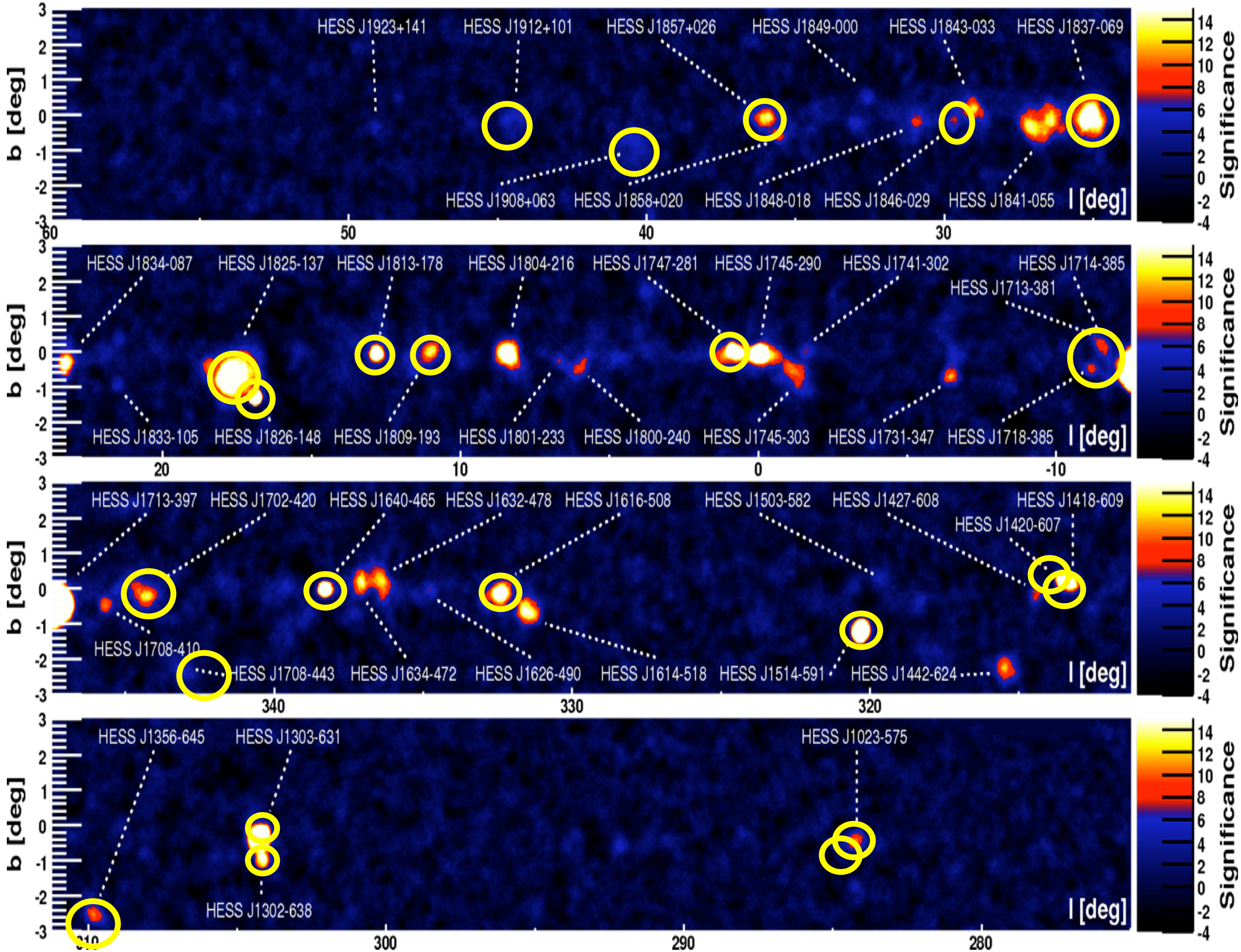


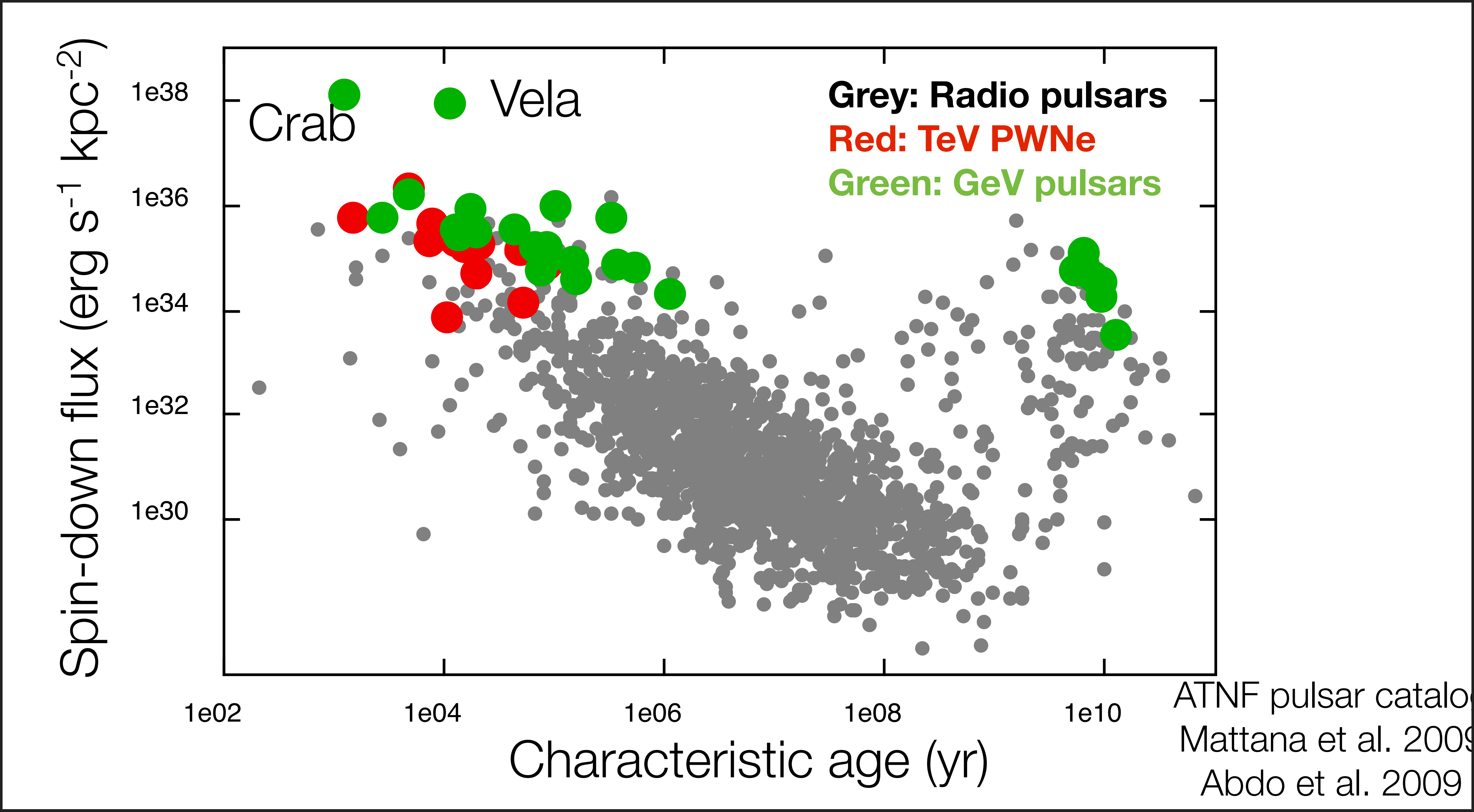
1989-2010



E. de Oña Wilhelmi - Dublin 13 July 2011


HESS J1923+141
HESS J1912+101
HESS J1857+026
HESS J1849-000
HESS J1843-033
HESS J1837-069
HESS J1908+063
HESS J1858+020
HESS J1848-018
HESS J1846-029
HESS J1841-055
HESS J1834-087
HESS J1825-137
HESS J1813-178
HESS J1804-216
HESS J1747-281
HESS J1745-290
HESS J1741-302
HESS J1714-385
HESS J1713-381
HESS J1833-105
HESS J1826-148
HESS J1809-193
HESS J1801-233
HESS J1800-240
HESS J1745-303
HESS J1731-347
HESS J1718-385
HESS J1713-397
HESS J1702-420
HESS J1640-465
HESS J1632-478
HESS J1616-508
HESS J1503-582
HESS J1427-608
HESS J1418-609
HESS J1420-607
HESS J1708-410
HESS J1708-443
HESS J1634-472
HESS J1626-490
HESS J1614-518
HESS J1514-591
HESS J1442-624
HESS J1356-645
HESS J1303-631
HESS J1023-575
HESS J1302-638
b [deg]
l [deg]
Significance

very young: age< 10^5 yrs
energetic: Edot > 10^{35} erg/s



C. Deil 2009

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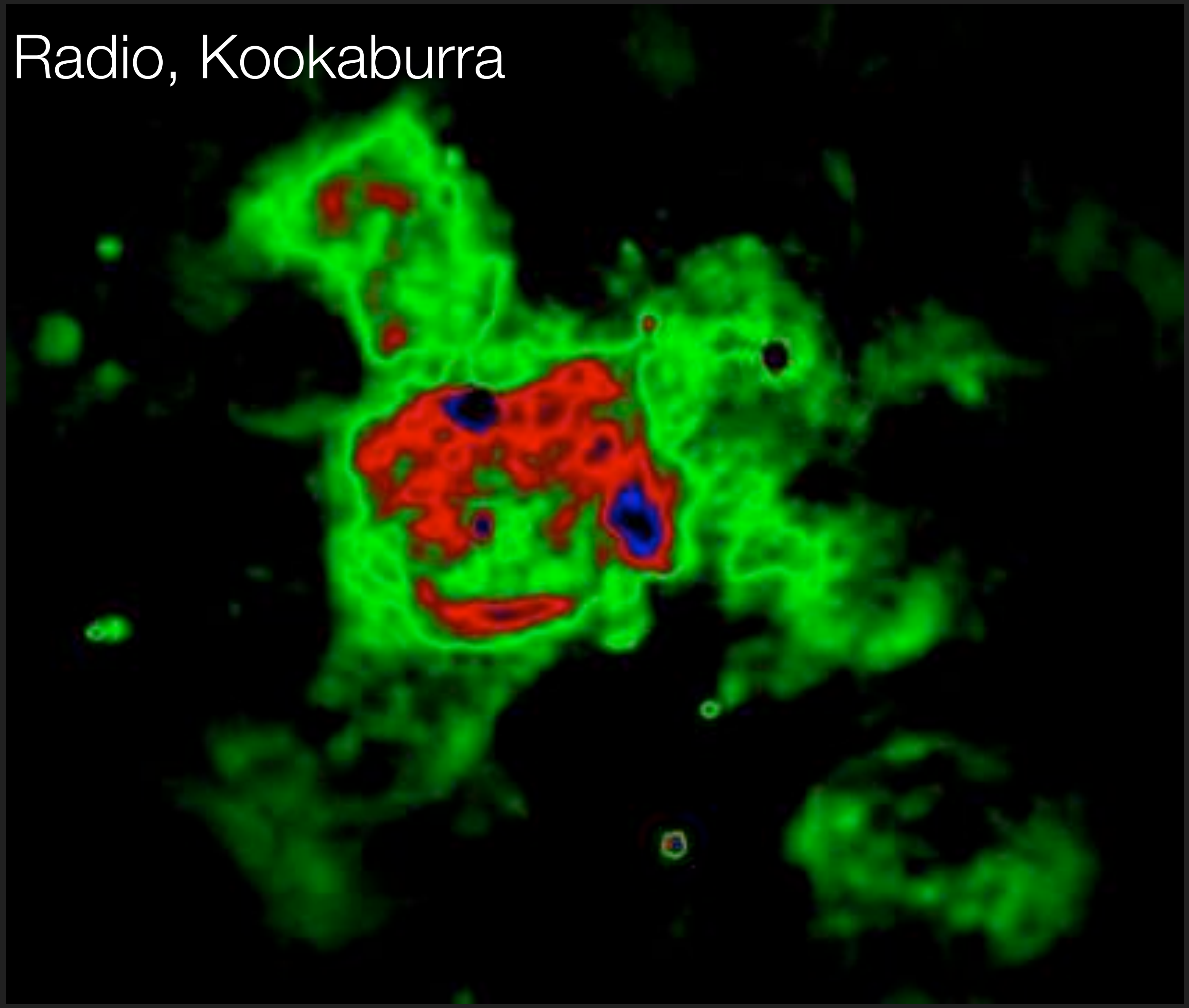
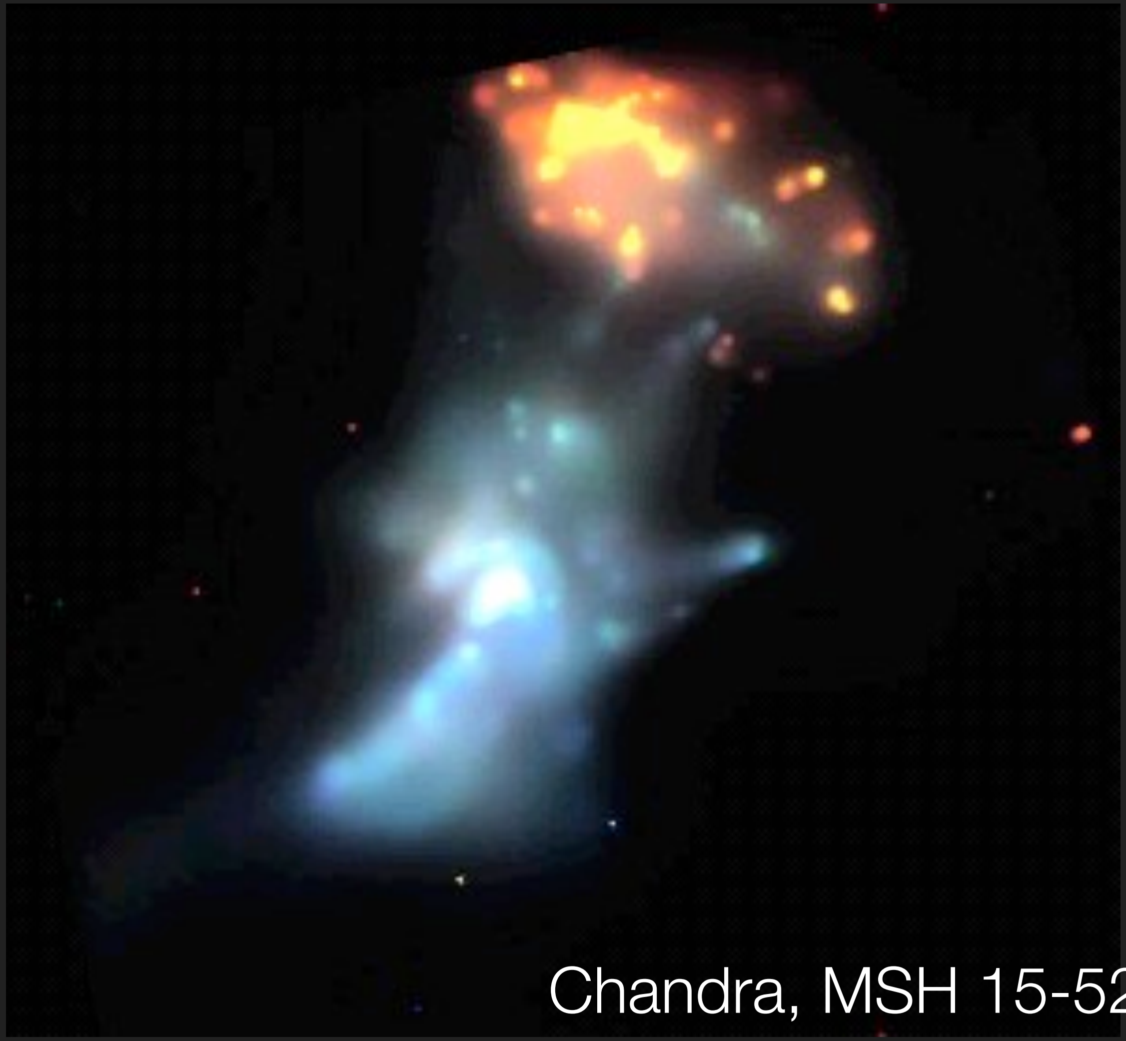
- Angular resolution is may not be yet as good as X-ray or radio observation (~0.1º) but given the huge size of the IC PWN (~tens of pc):





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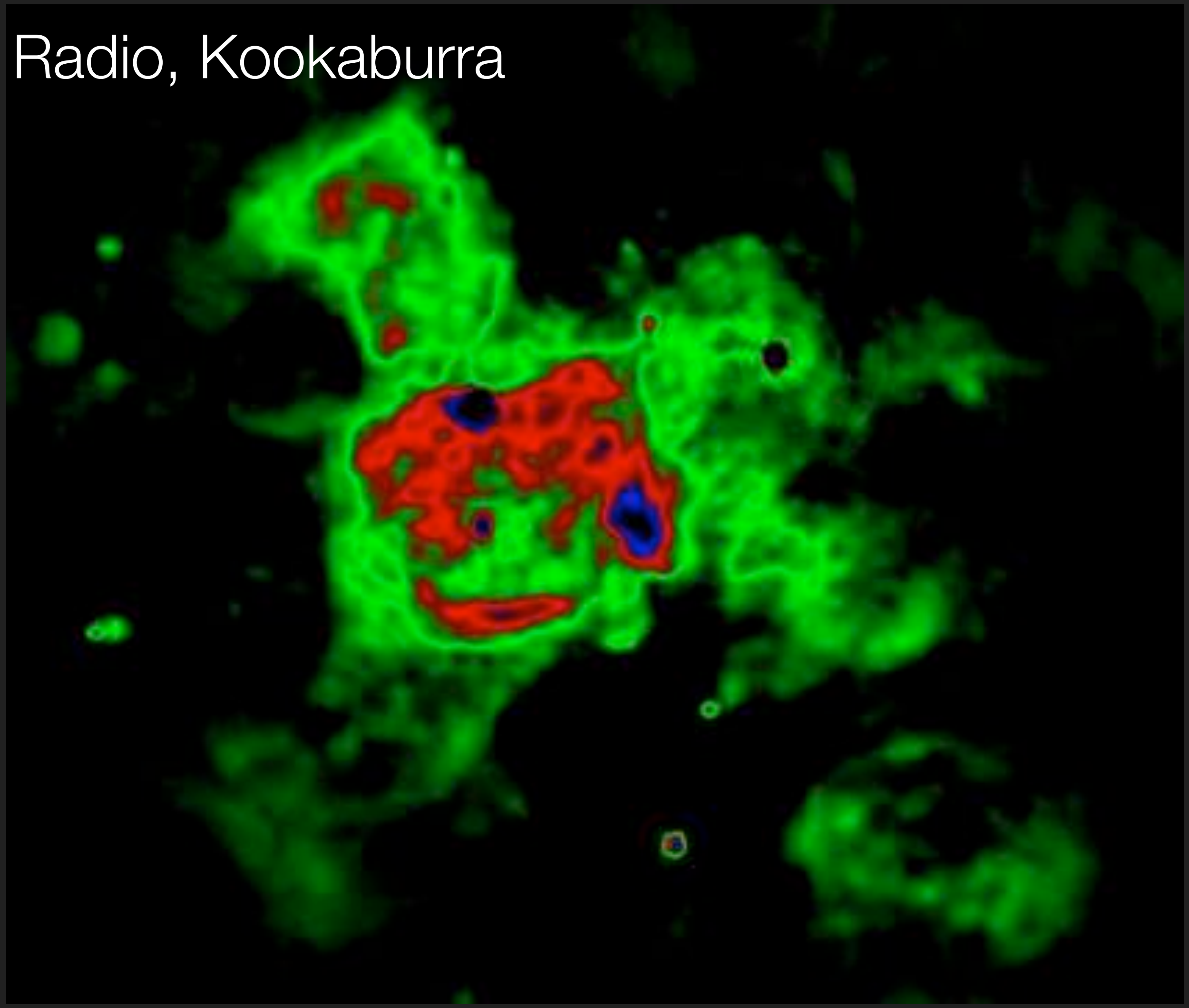

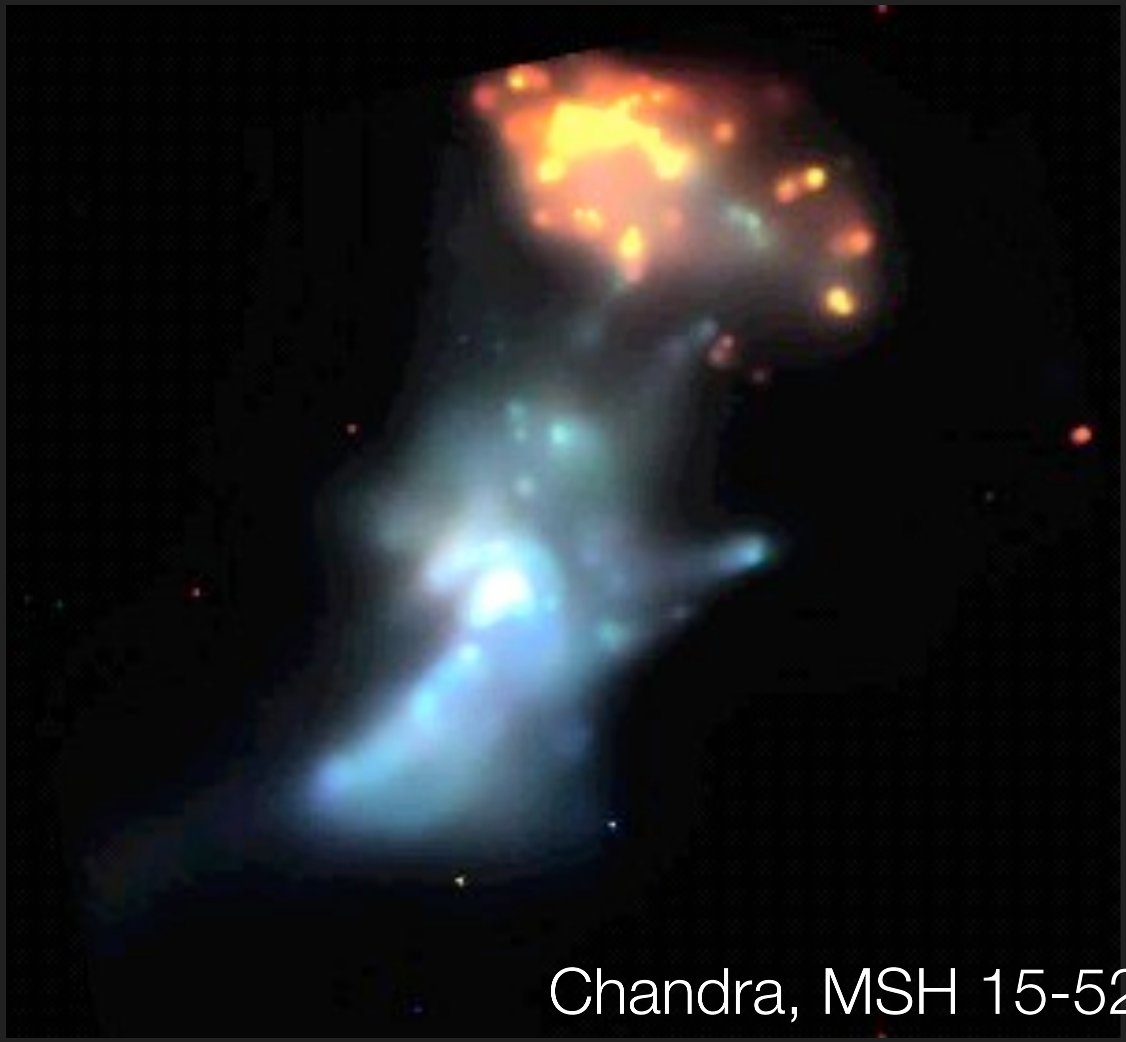

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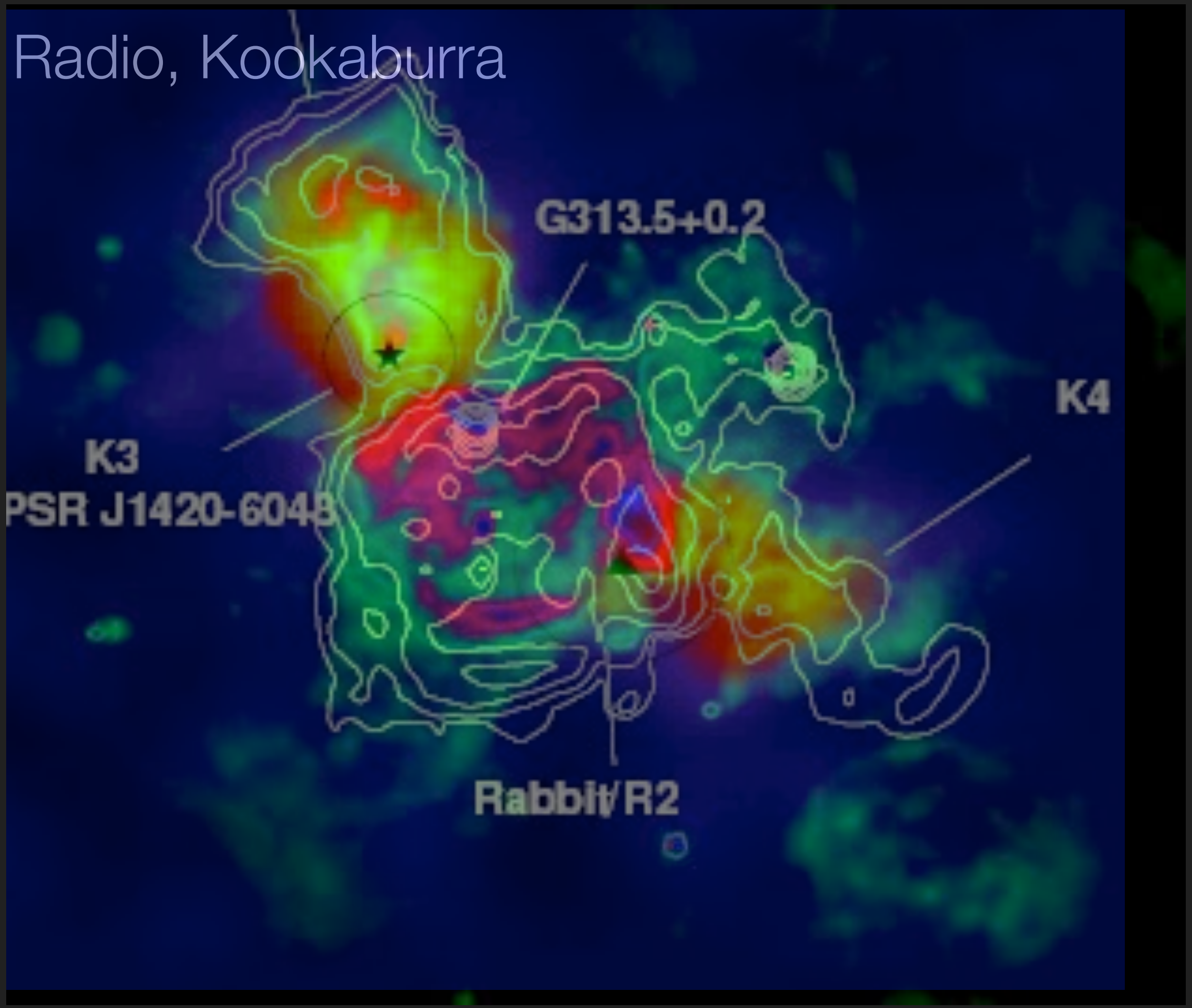
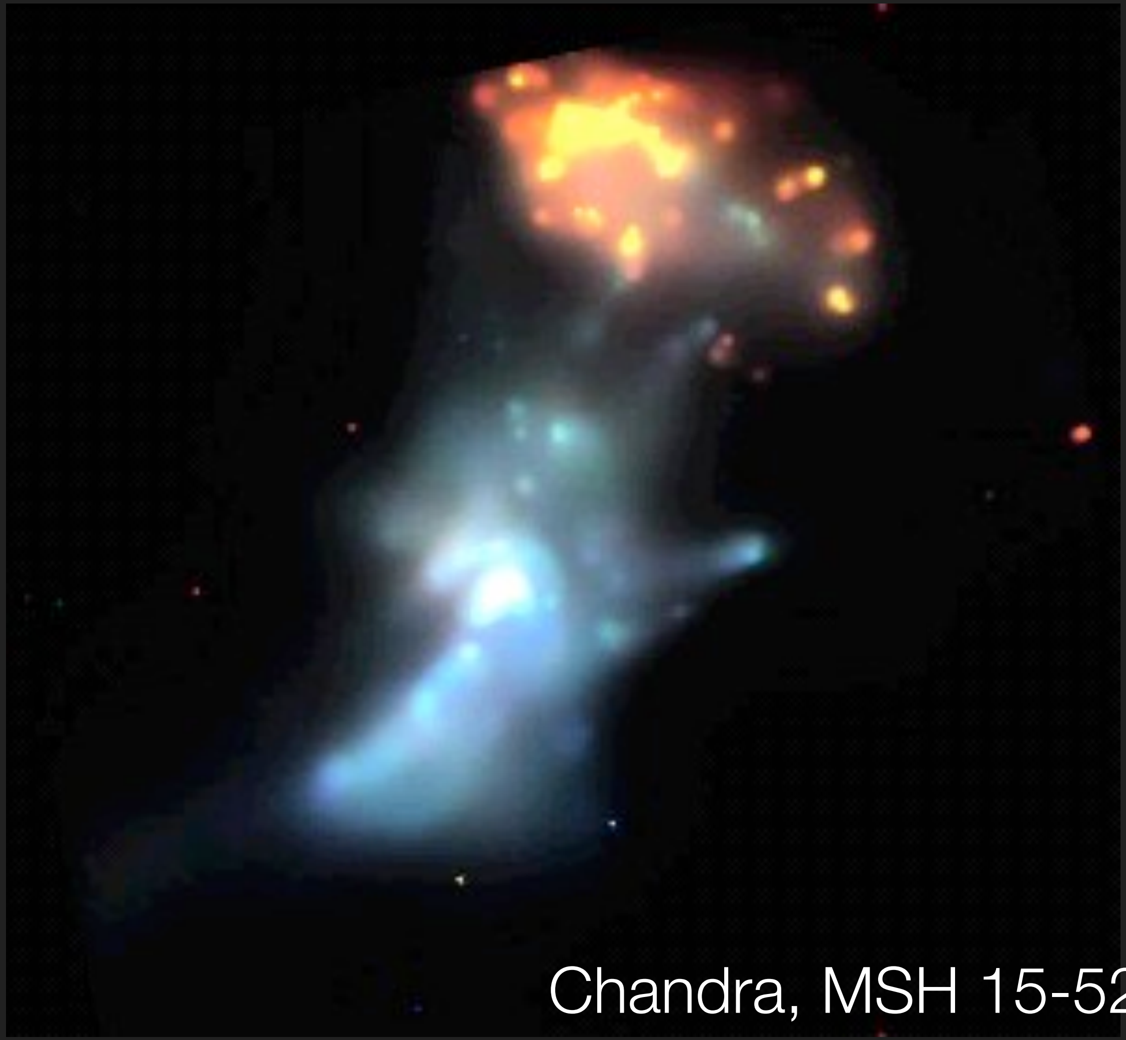
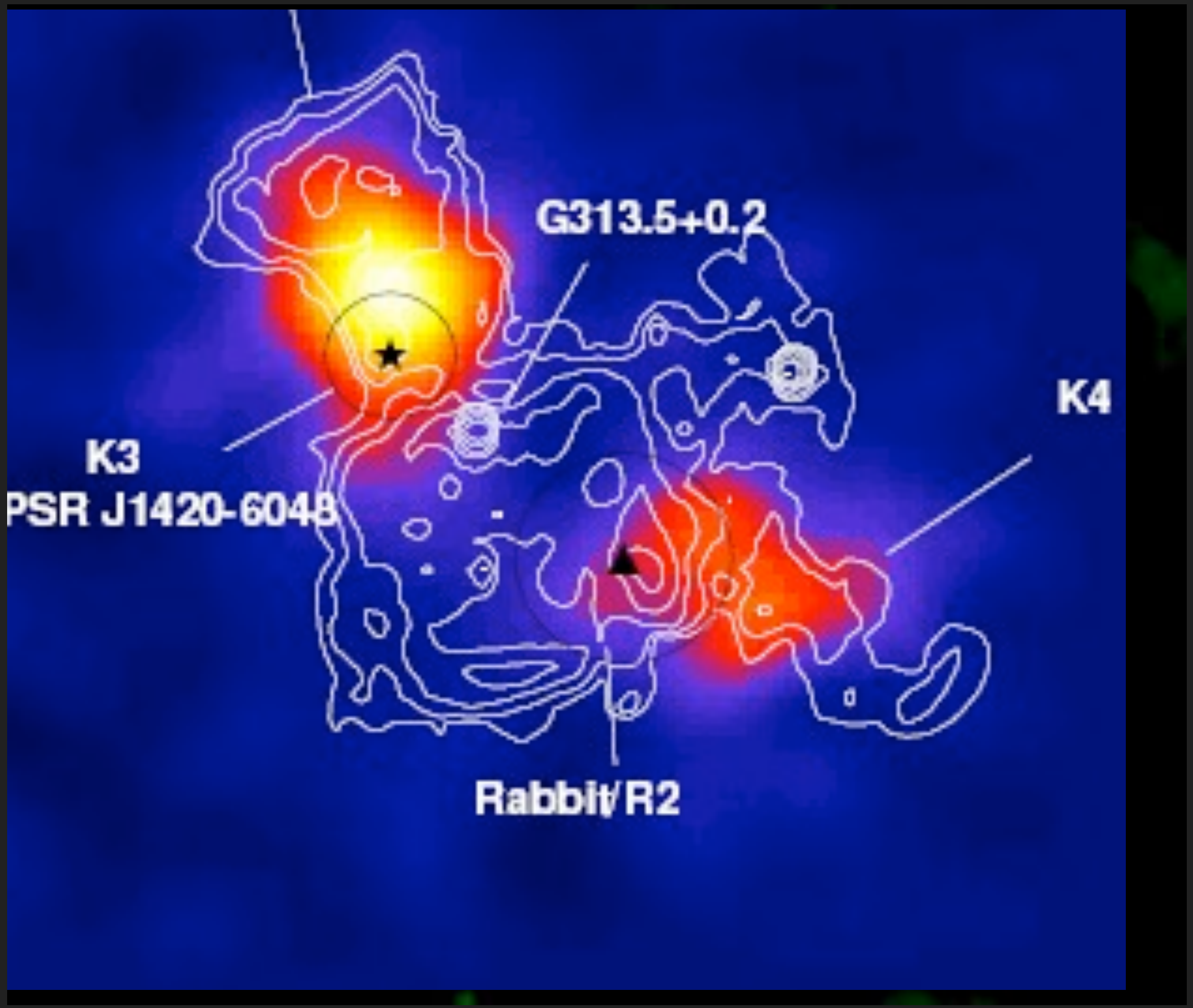
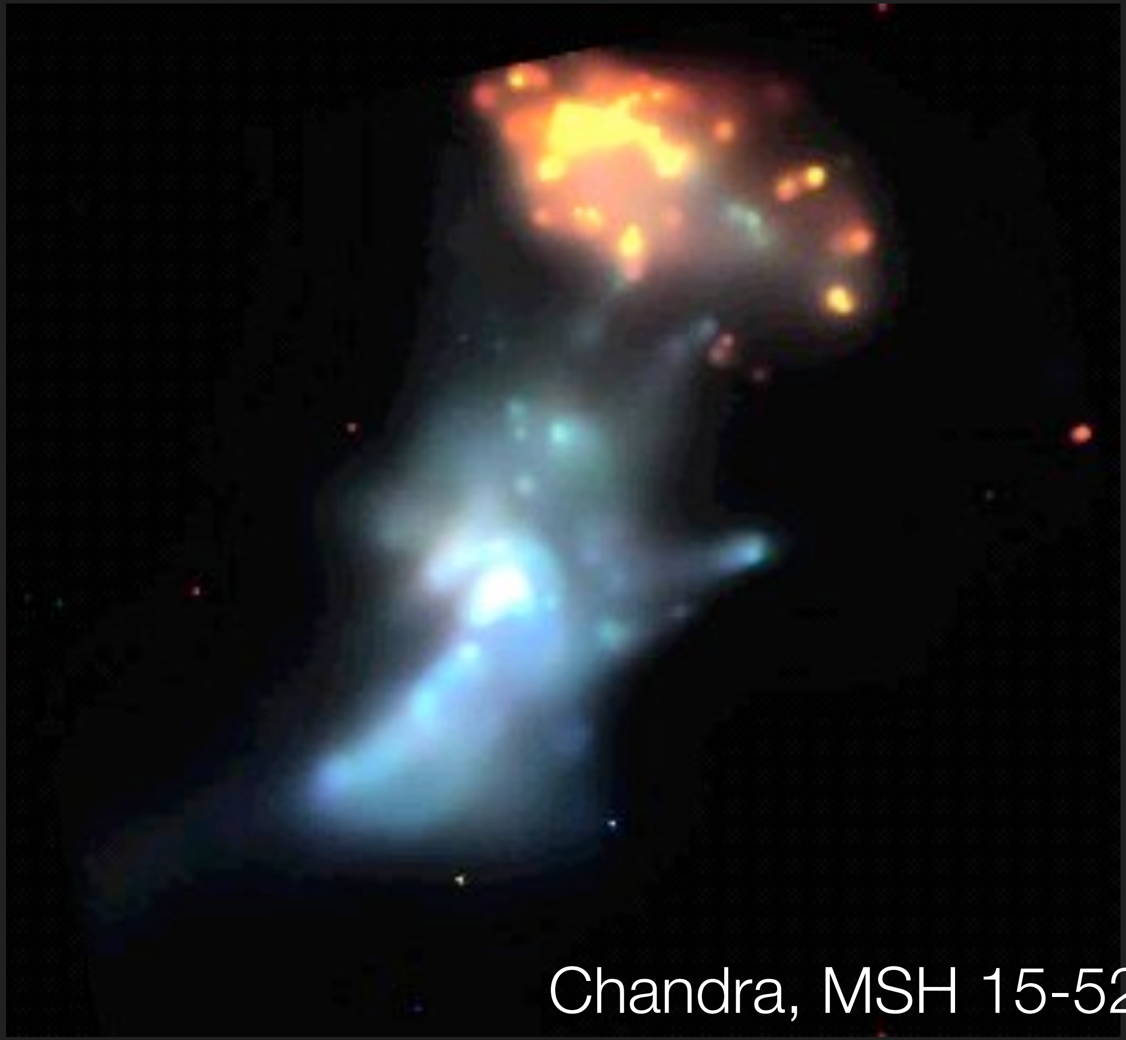




PWN powering VHE sources

- Angular resolution is may not be yet as good as X-ray or radio observation (~0.1º) but given the huge size of the IC PWN (~tens of pc):





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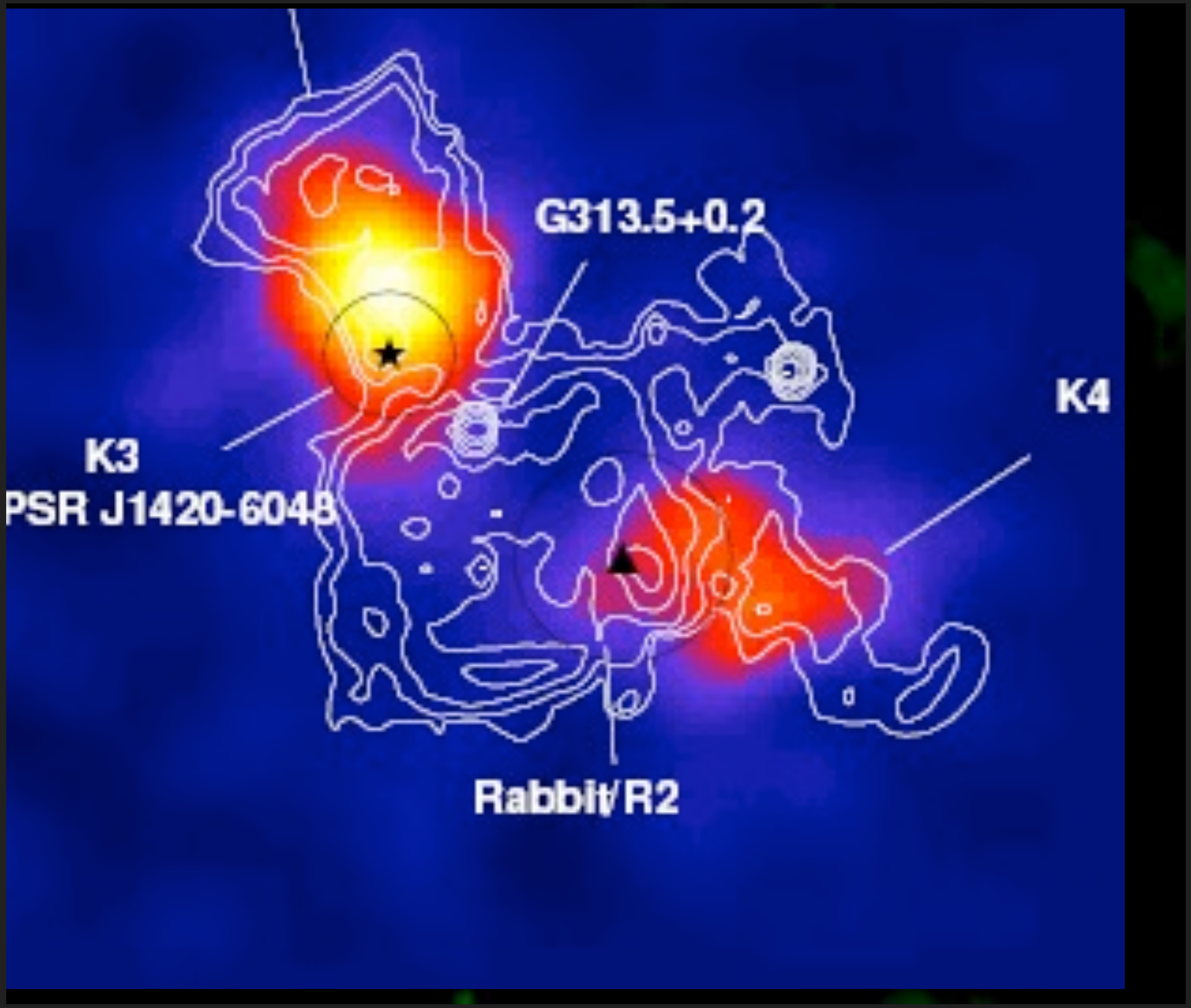

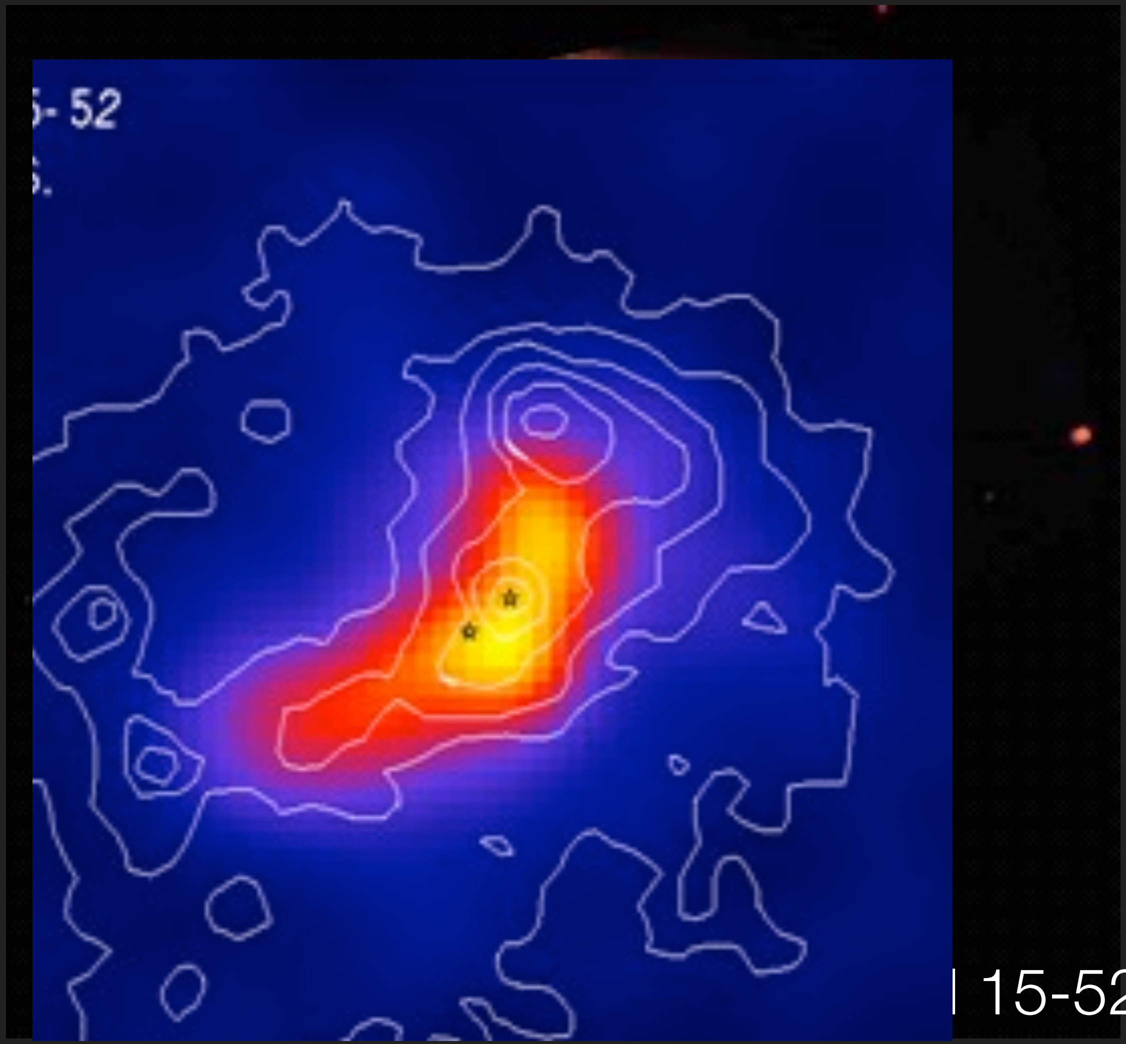

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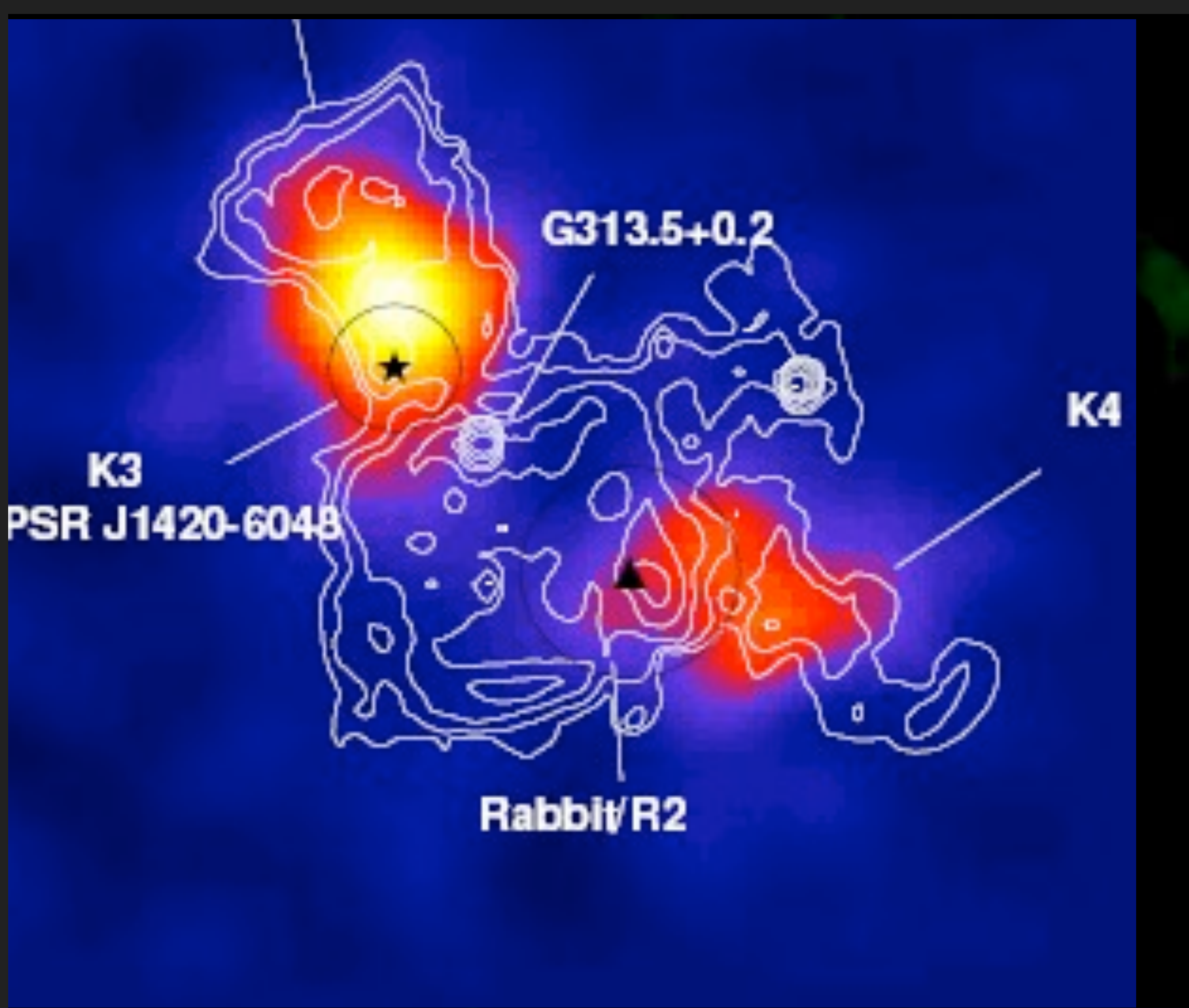

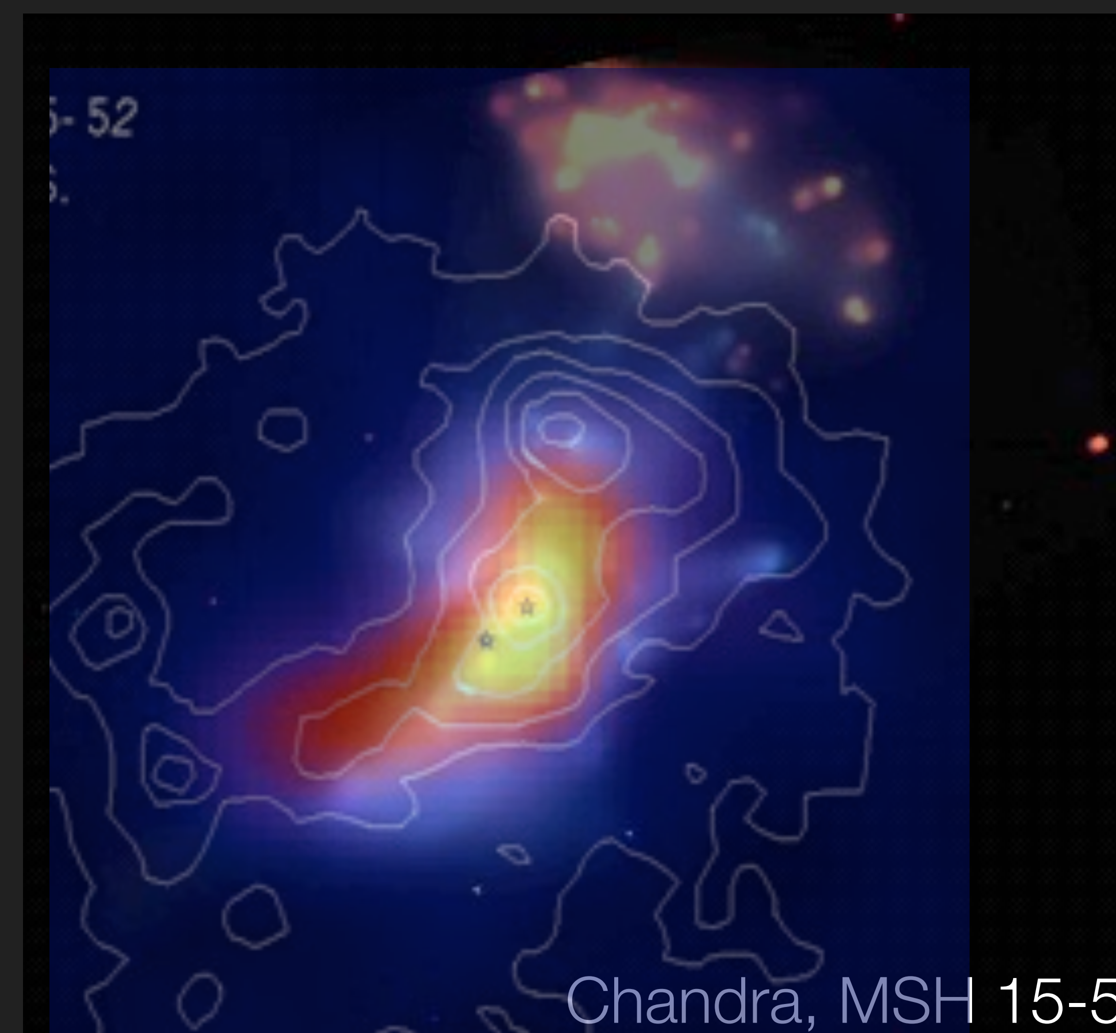

Chandra, MSH 15-52

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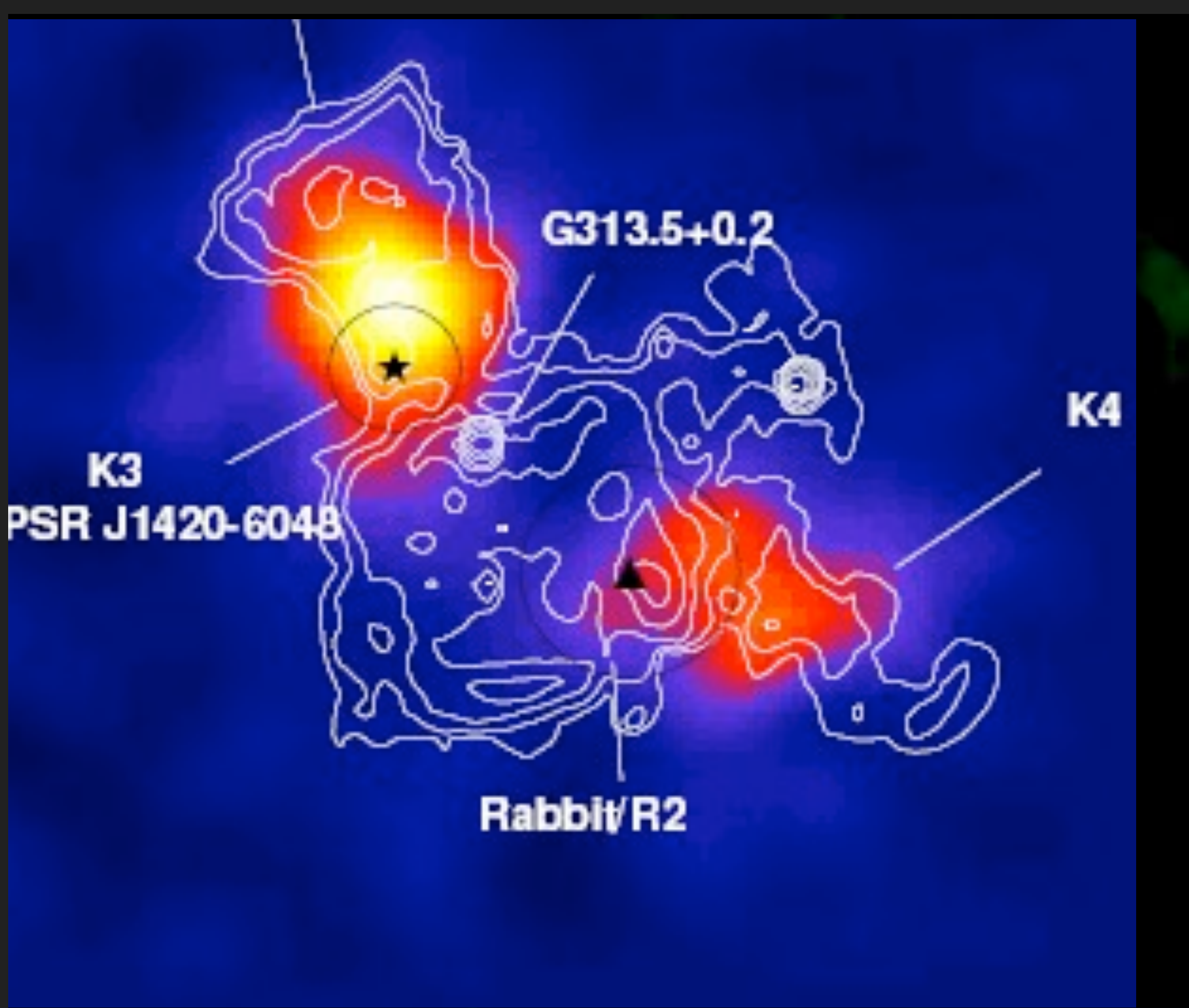
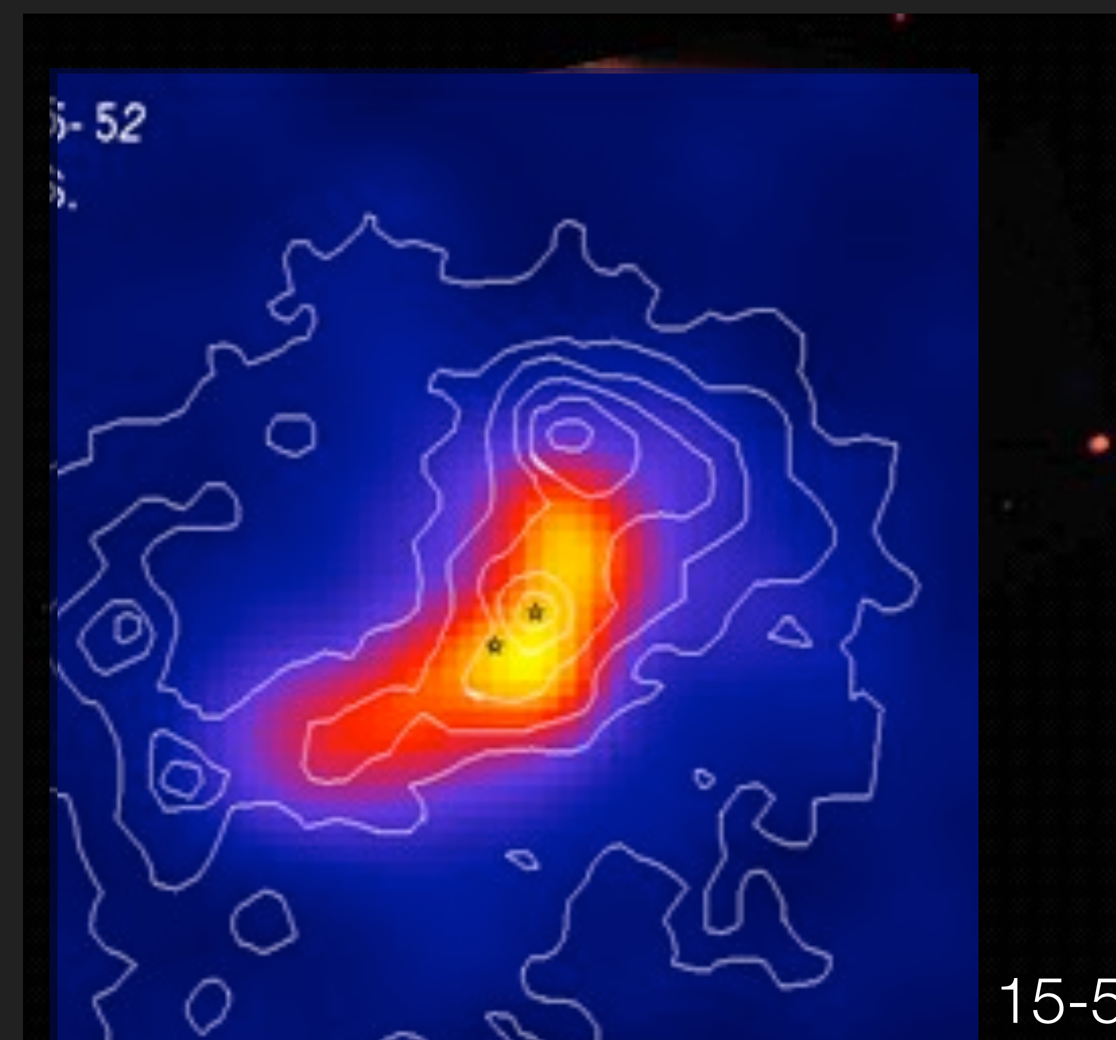
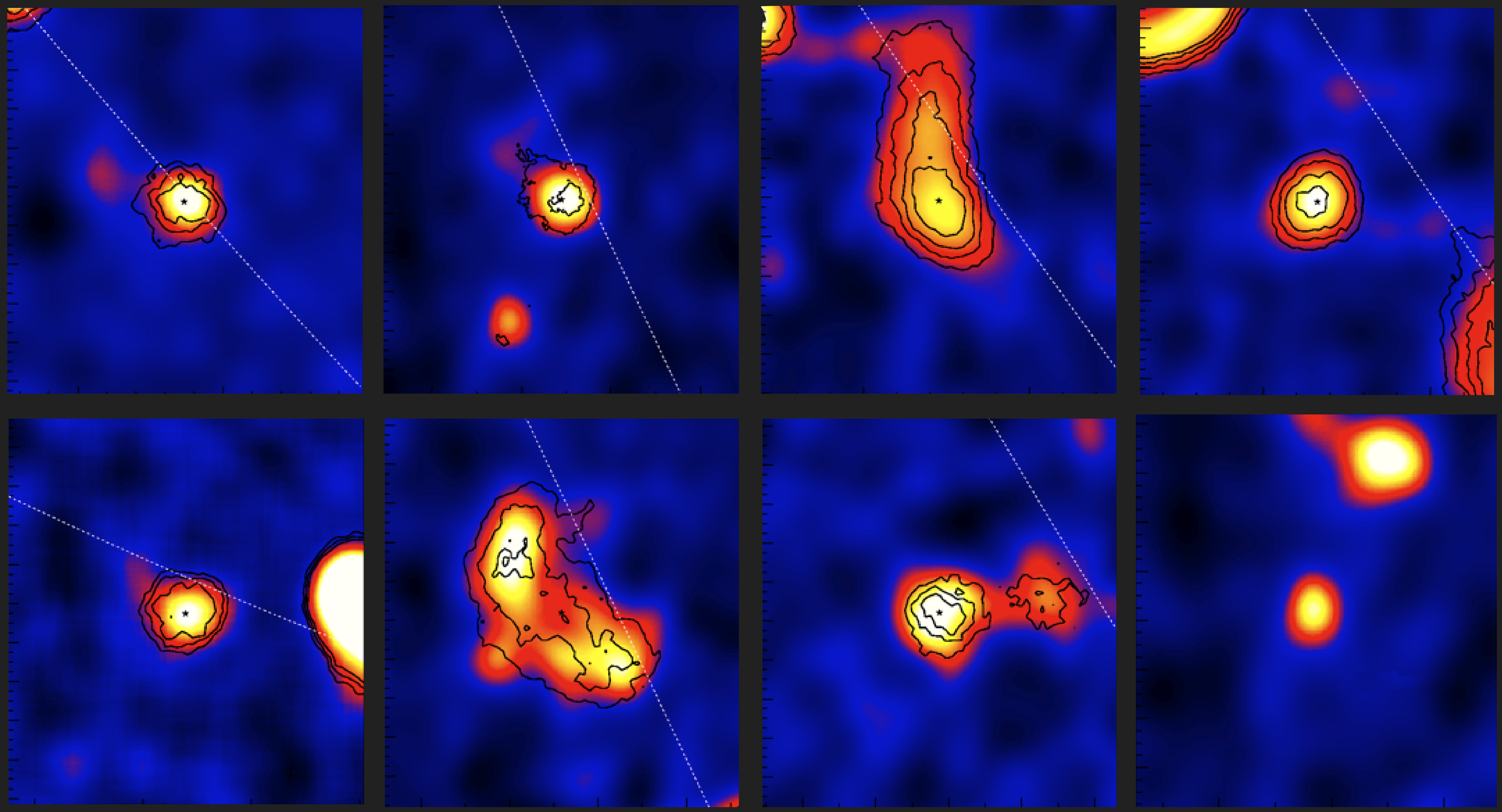




15-52

Unidentified or Dark Sources

Seem to shine only in g-rays
No plausible counterparts in radio, x-rays (yet!)



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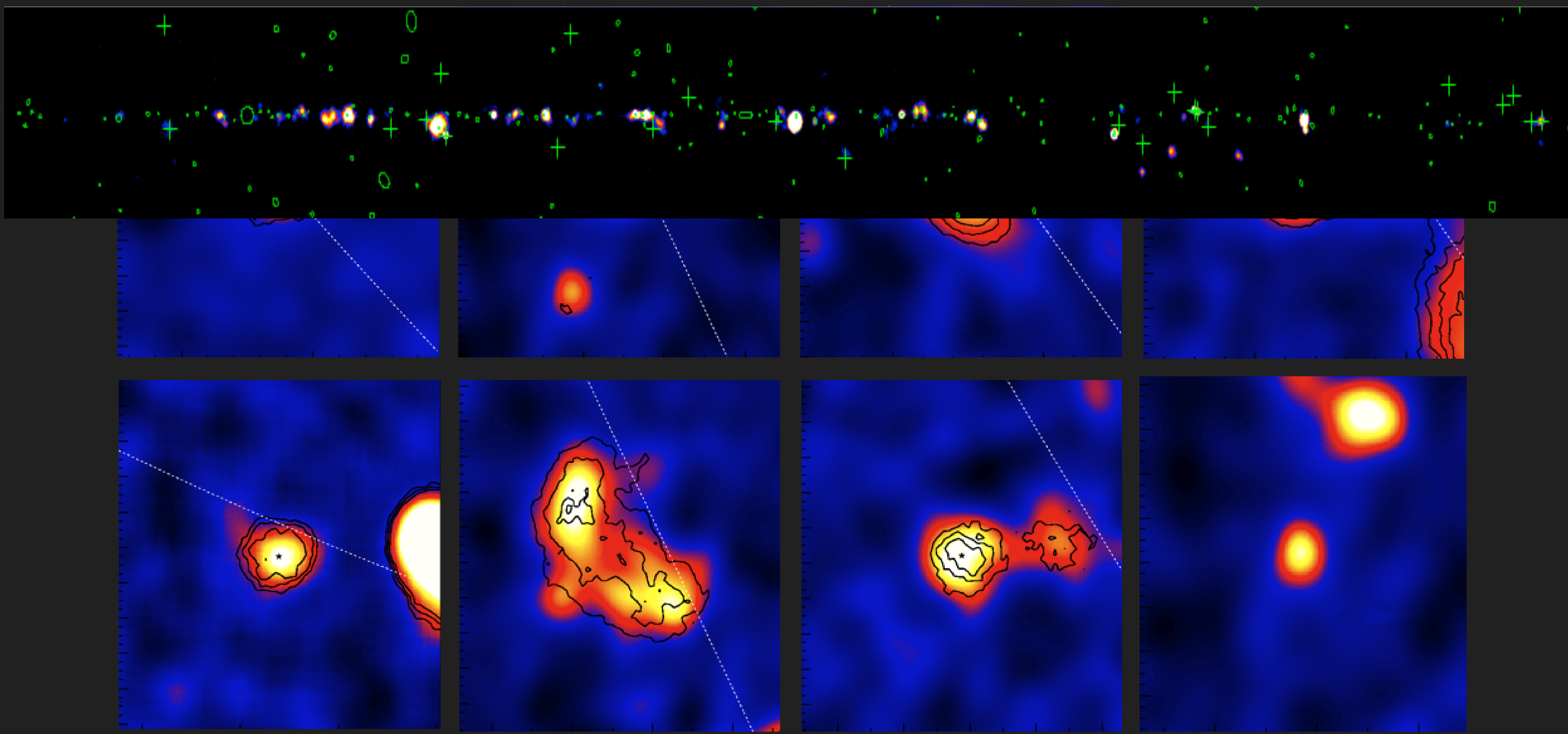

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- Relic PWN?

Unidentified or Dark Sources

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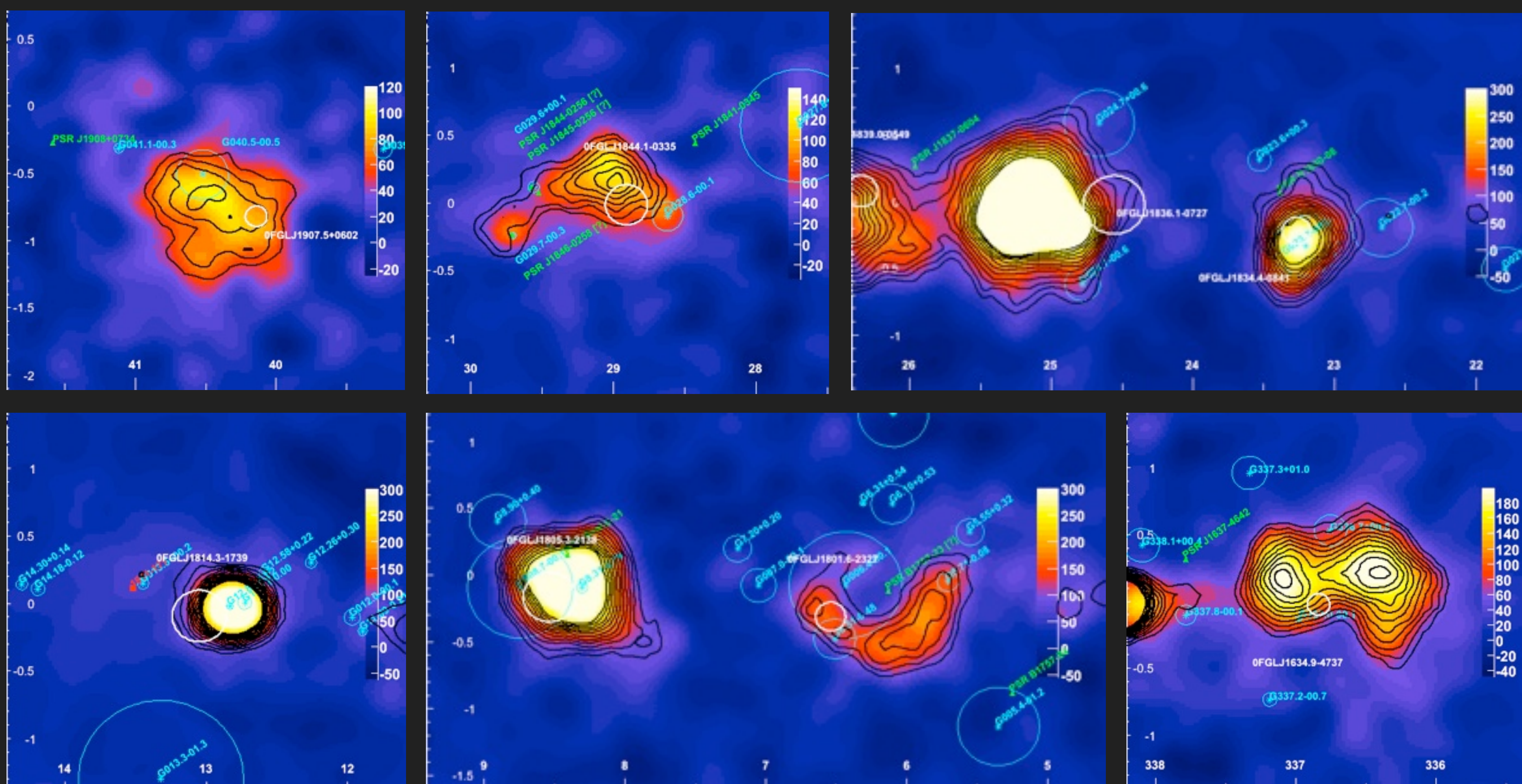
Relic PWN?



PWN @ VHE

- Provide an estimation of the magnetic field
- Good calorimeter (slower cooling time - relic emission from the PWNe)
- Very efficient VHE emitters -> Hunting for X-ray nebulae in the VHE sources

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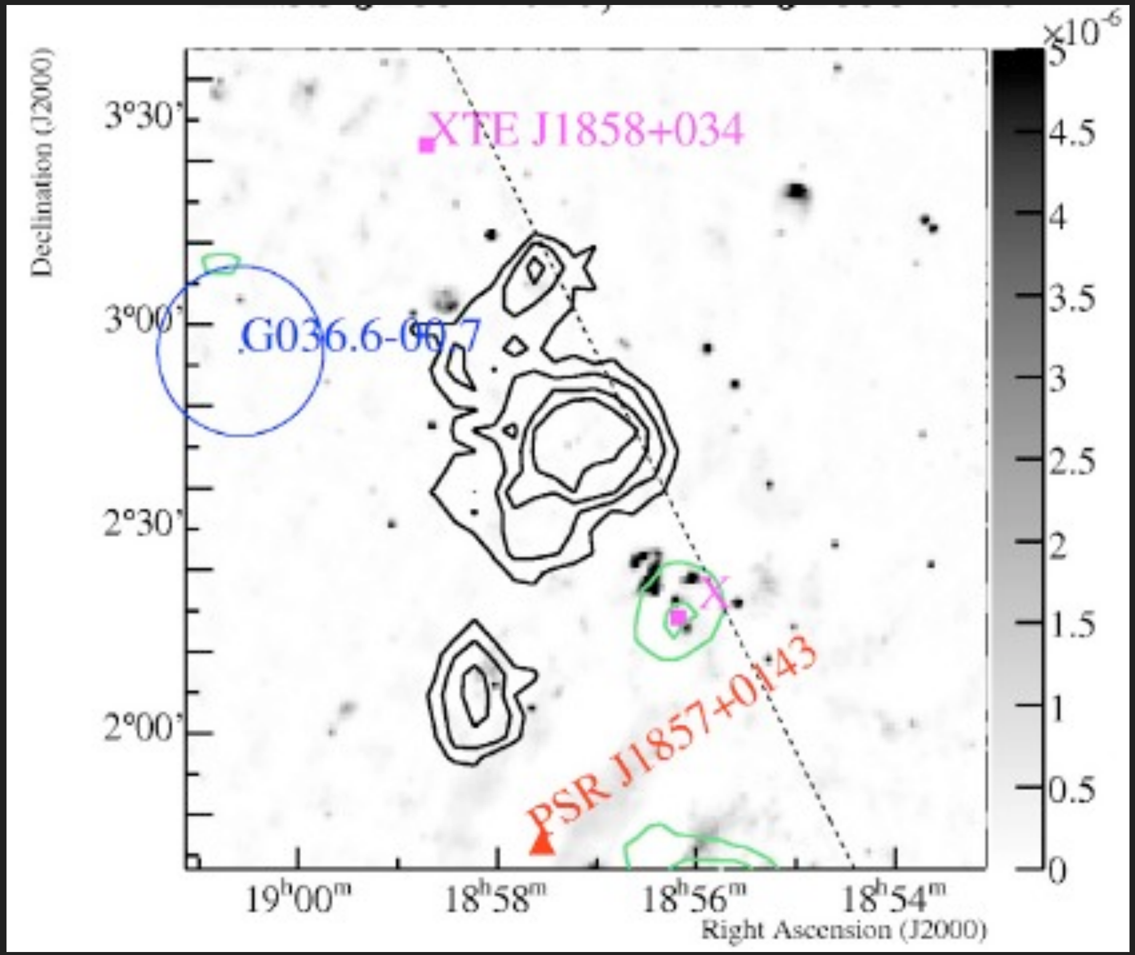
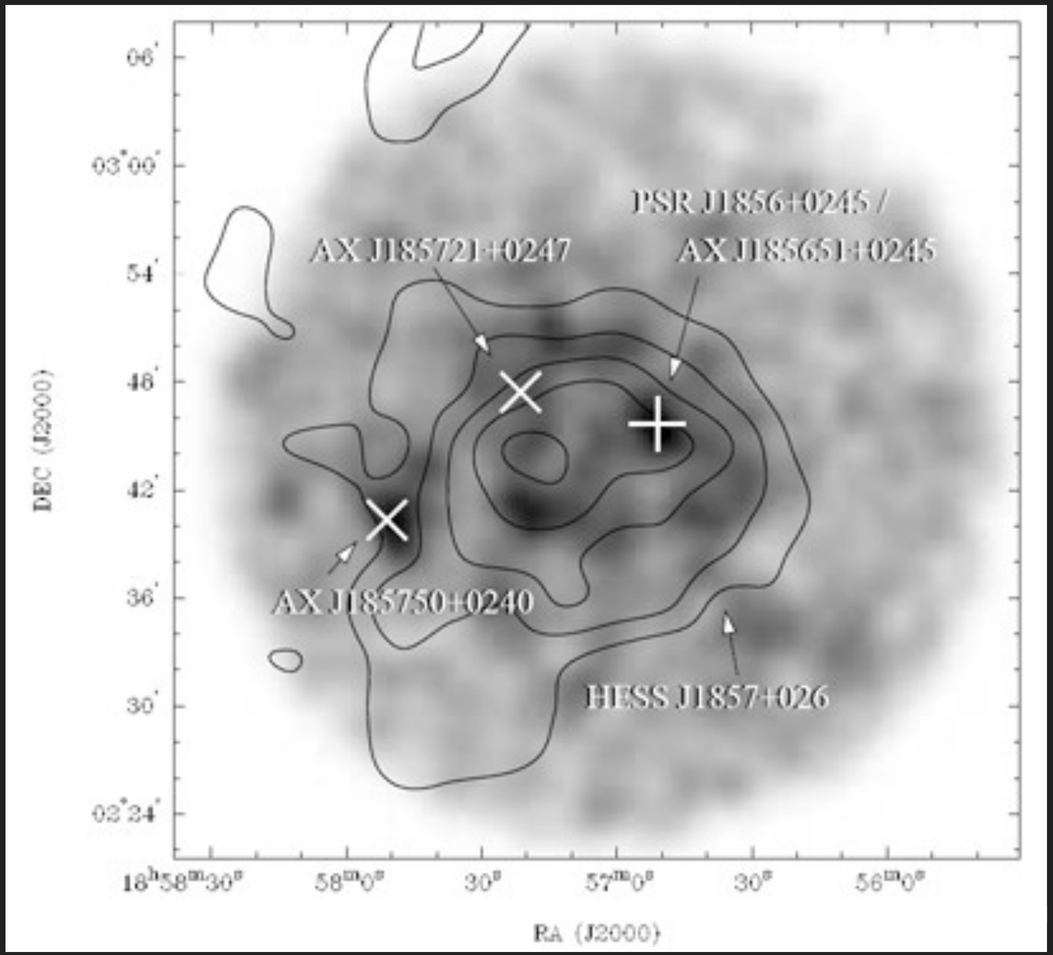
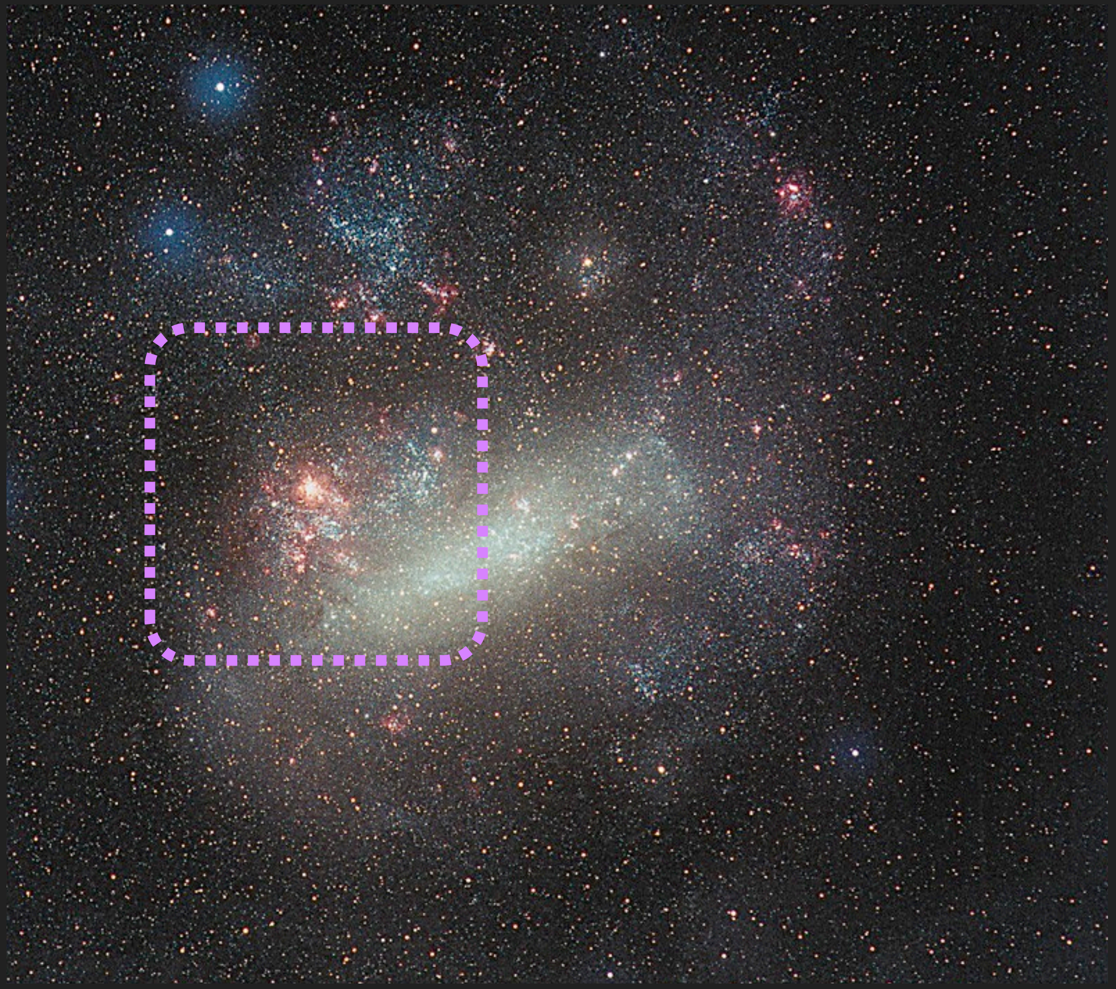




- Satellite spiral galaxy ~10° extension d~48 kpc
- Site of the recent and closest supernova SN1987A
- 44 h observation with HESS with Eth ~ 500 GeV

New γ-ray coincident with SNR N 157 B/PSR J0537-6910
4 kyr, 16 ms
IC from PWN
flux $_{(1\text{-}10\ \mathrm{TeV})}$ ~10^{-12} erg cm^{-2} s^{-1}
Most powerful pulsar known
Edot =4.9 10^{38} erg s^{-1}
Apparent efficiency 0.01% Edot



Most distant γ-ray PWN
First extra-galactic non-AGN TeV source

Summary

- X-ray and radio observations allow us to constrain the injection spectrum and to performed detailed morphological studies
- VHE observations allow an estimation of the magnetic field and due to the long cooling time of IC process a better understanding of the PWN evolution in time (but angular resolution!)
- The broad-bandwidth emission of PWN supplies the perfect scenario to study acceleration mechanisms (in the magnetosphere, in the wind & surrounding nebula)
- But still many questions to be answer:
  - Where is the pulsed emission originated? Up to 300 GeV for Crab!
  - What is the origin of the Crab Nebula flares?
  - Is the Crab nebula a prototype?
  - What is the injection spectrum and origin of the radio emission?
  - How the highly magnetised wind becomes particle dominated?
  - ...

Thank you for your attention!

Bibliography

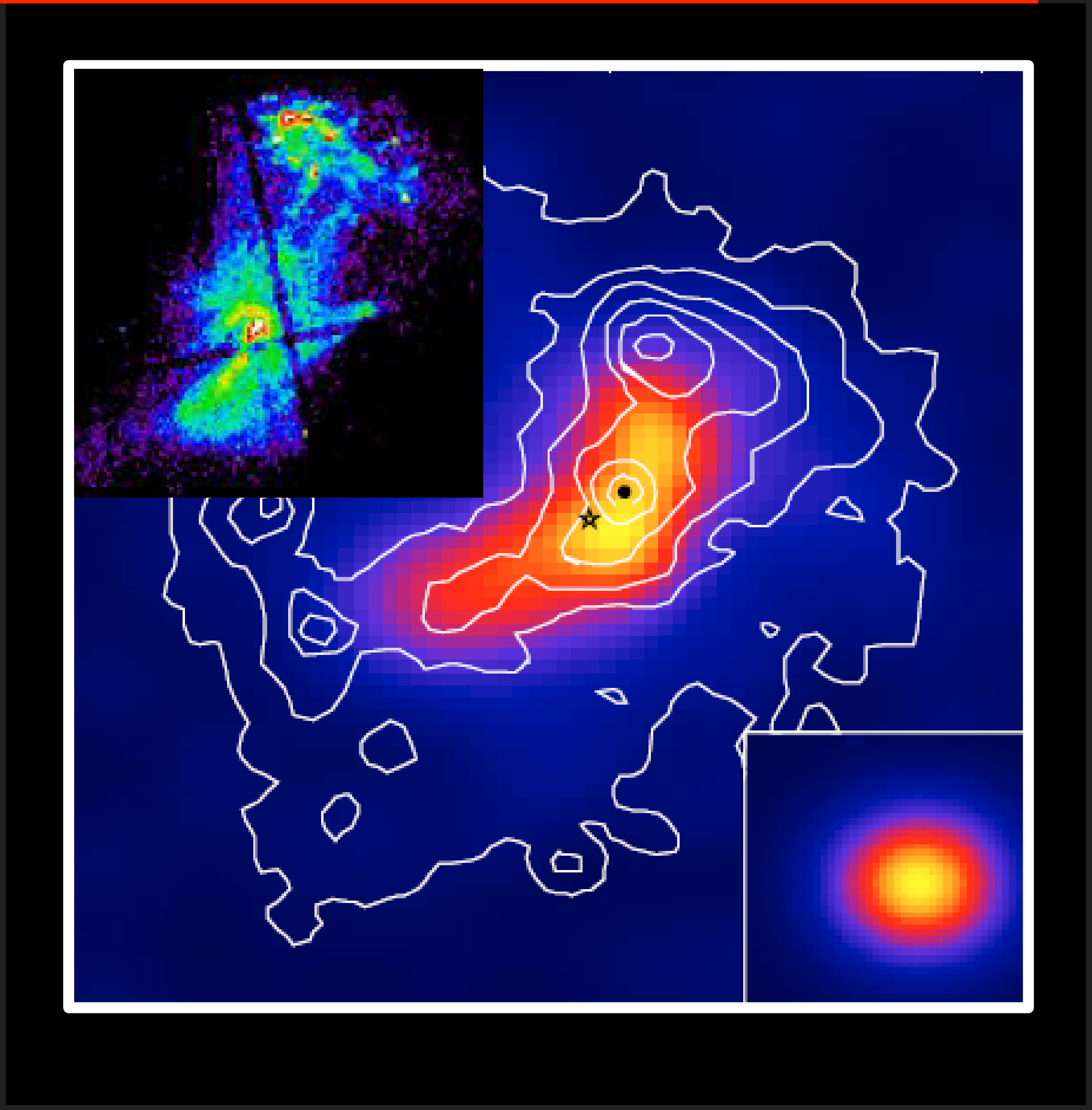
- E. Amato, Chin. J. Astron. Astrophys. Vol.3 (2003) Suppl. 316.
- J. Kirk, ...
- P. Slane, ...

very young: age<10^5 yrs

energetic: Edot >10^{35} erg/s

- <u>Category I:</u> unresolved sources or TeV-X-ray/radio matching

Crab Nebula, N157B, MSH 15-52, G0.9+0.1,HESS J1813-178, G21.5-0.9, Kes 75



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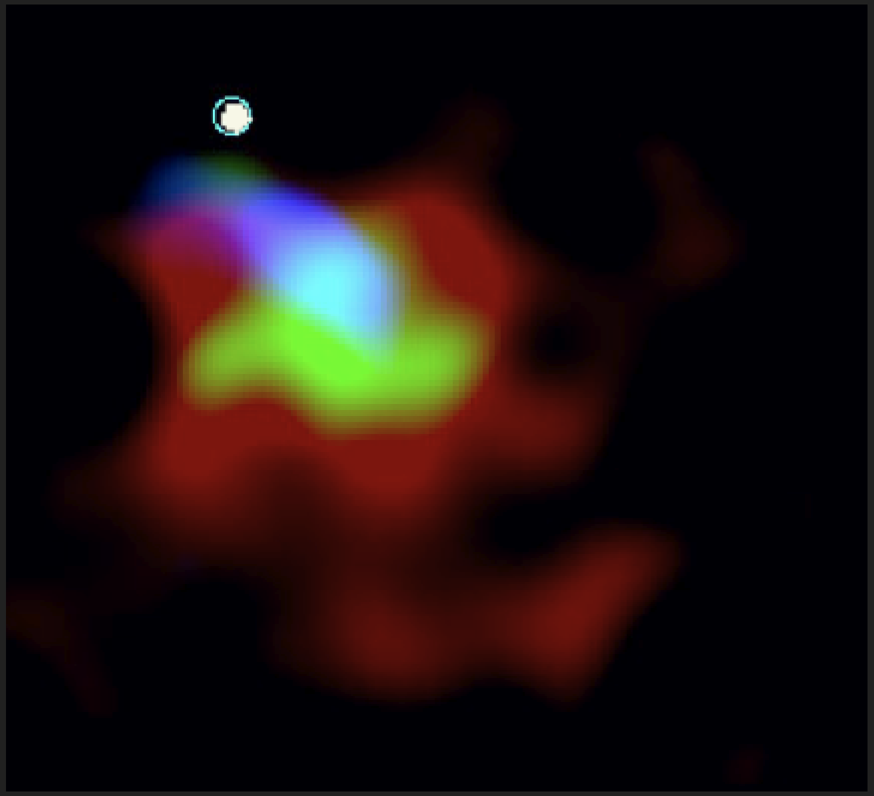
HESS J1825-137, Vela X, HESS J1356-645, HESS J1303-631



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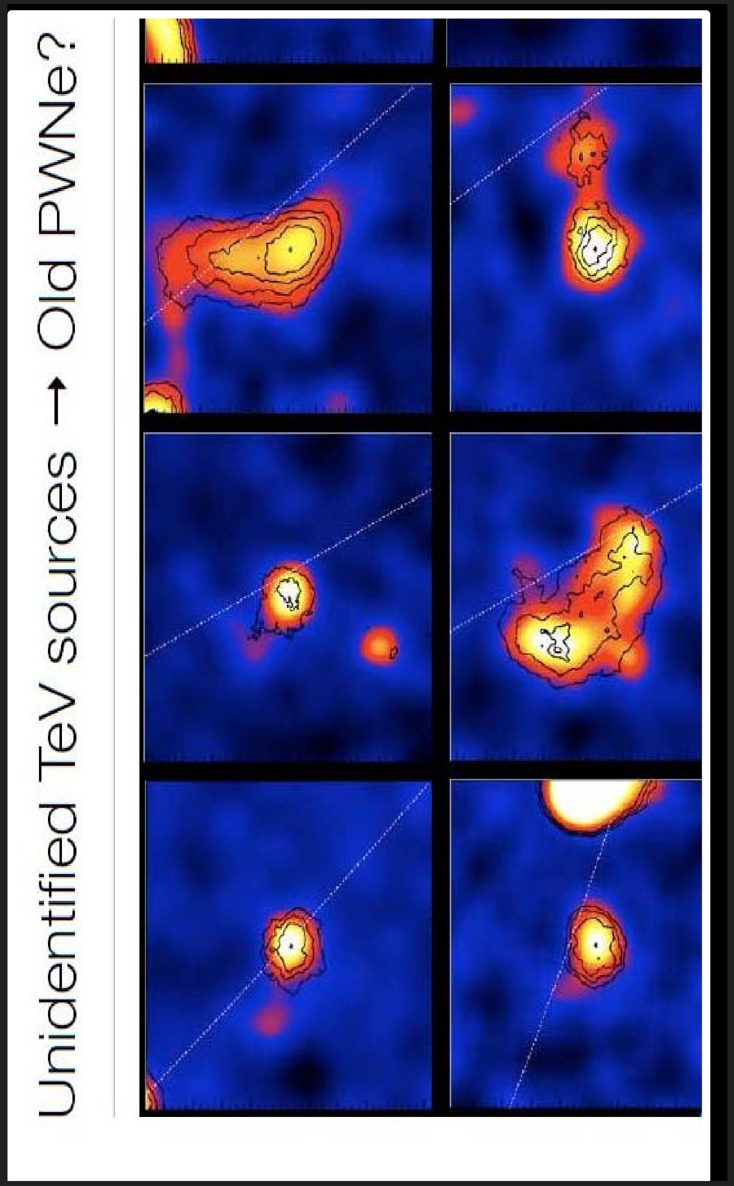

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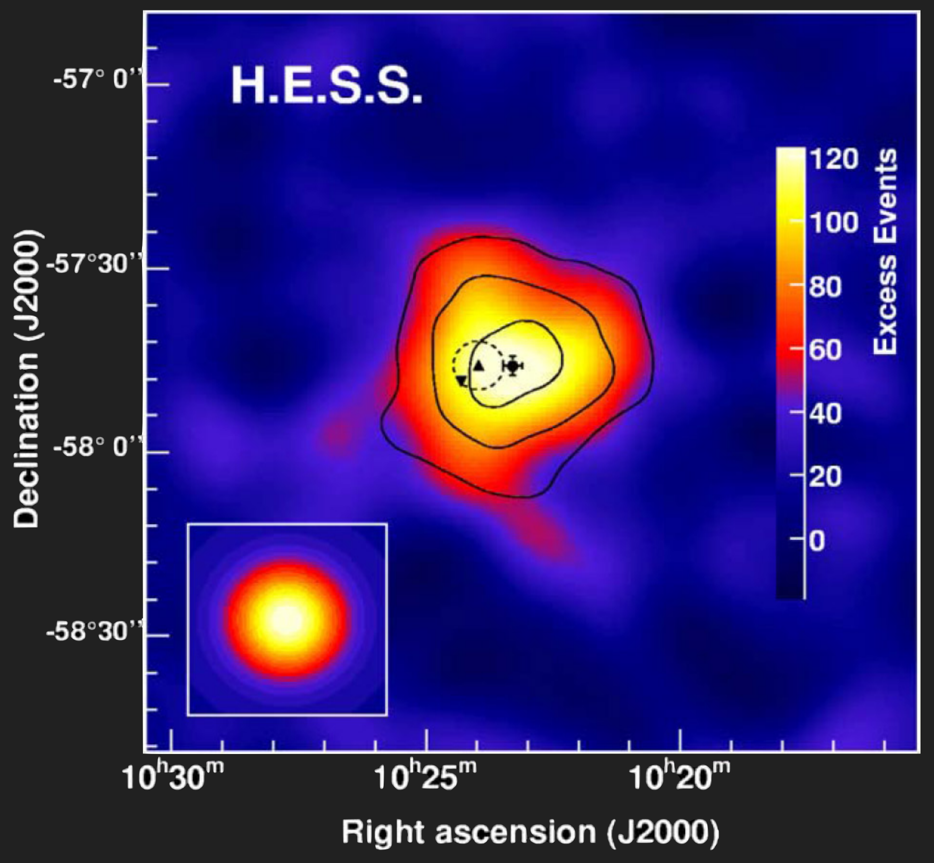
- Category 4: Other TeV src

CTB 37B complex, Westerlund 2? ...



- **Fast development of the field since 2005 -**
- **MAGIC II (working!) and HESS II (next year) will improve the sample, decreasing the Eth -> Pulsars!**

  VERITAS fully operative
- **MAGIC & HESS (maybe VERITAS?) -> CTA**
- **Population studies -> Better understanding of acceleration mechanisms**
- **Good multi-wavelength coverage: from radio/X-rays to Fermi would allow firm identifications**