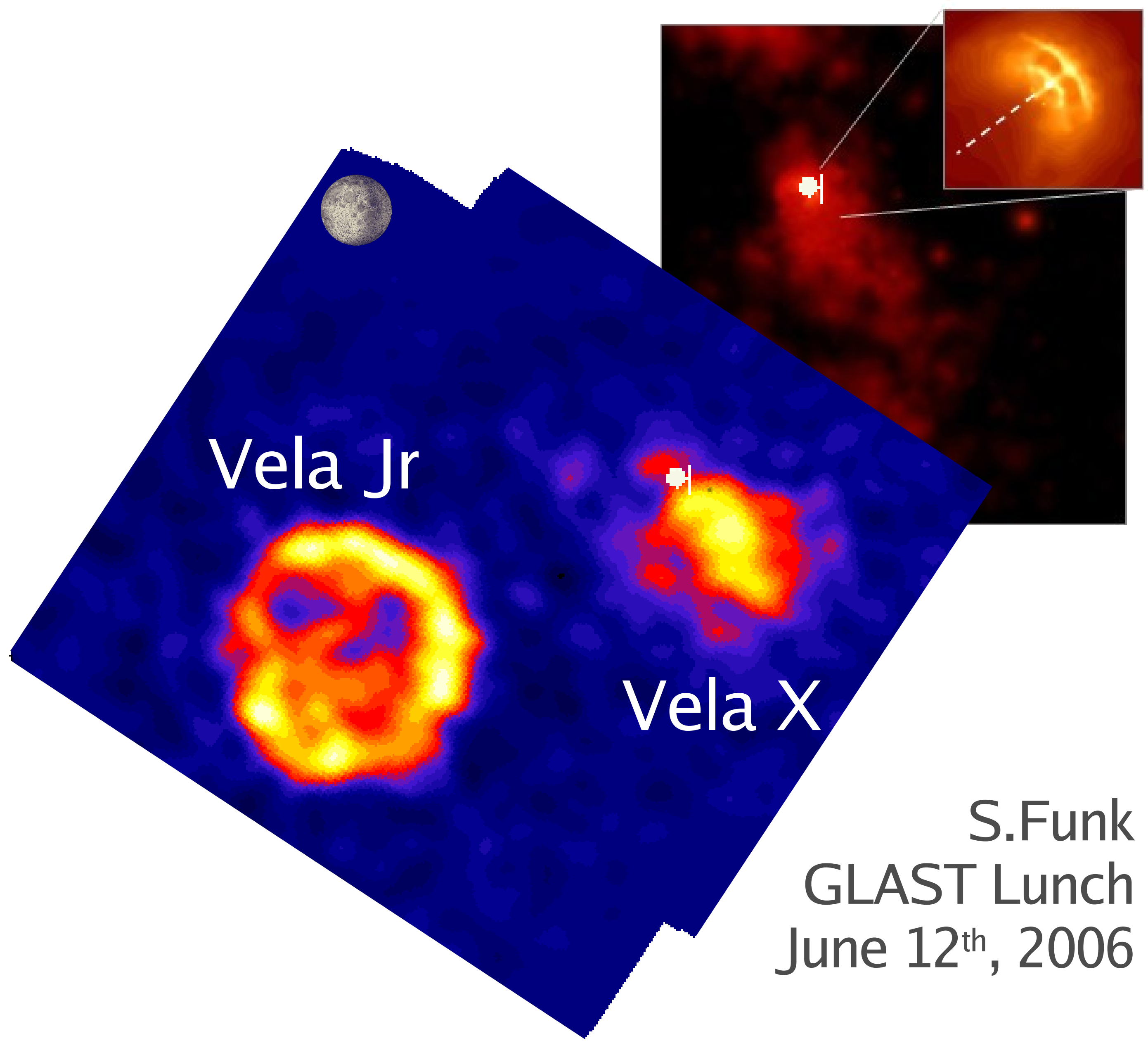
Gamma-ray Supernova remnants

Shell-type SNRs and Pulsar Wind Nebulae

Outline:

- Introduction
- Shell-type SNRs
- Energetic PWN



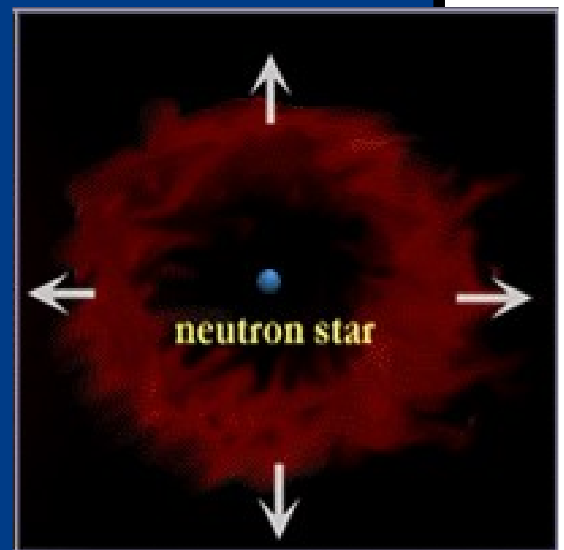
S.Funk

GLAST Lunch
June 12th, 2006

Introduction

History

Walter Baade



Fritz Zwicky

- "With all reserve, we advance the view that a ***supernova*** represents the transition of an ordinary star into a ***neutron star*** consisting mainly of neutrons...

  Baade & Zwicky (1934)

ON SUPER-NOVAE

By W. Baade and F. Zwicky

Mount Wilson Observatory, Carnegie Institution of Washington and California Institute of Technology, Pasadena

Communicated March 19, 1934

A. Common Novae.—The extensive investigations of extragalactic systems during recent years have brought to light the remarkable fact that there exist two well-defined types of new stars or novae which might be distinguished as *common novae* and *super-novae*. No intermediate objects have so far been observed.

History

COSMIC RAYS FROM SUPER-NOVAE

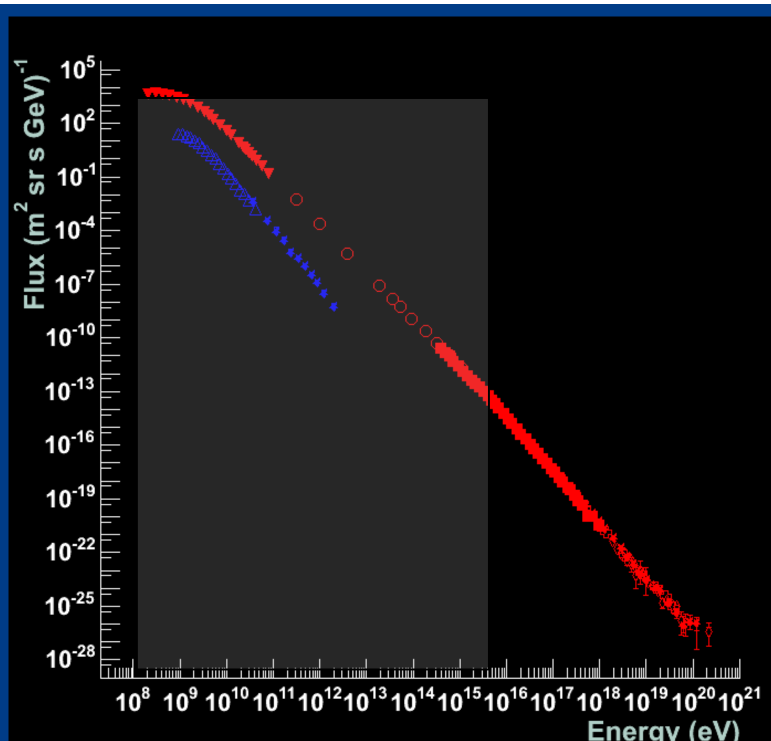
By W. Baade and F. Zwicky

Mount Wilson Observatory, Carnegie Institution of Washington and California Institute of Technology, Pasadena

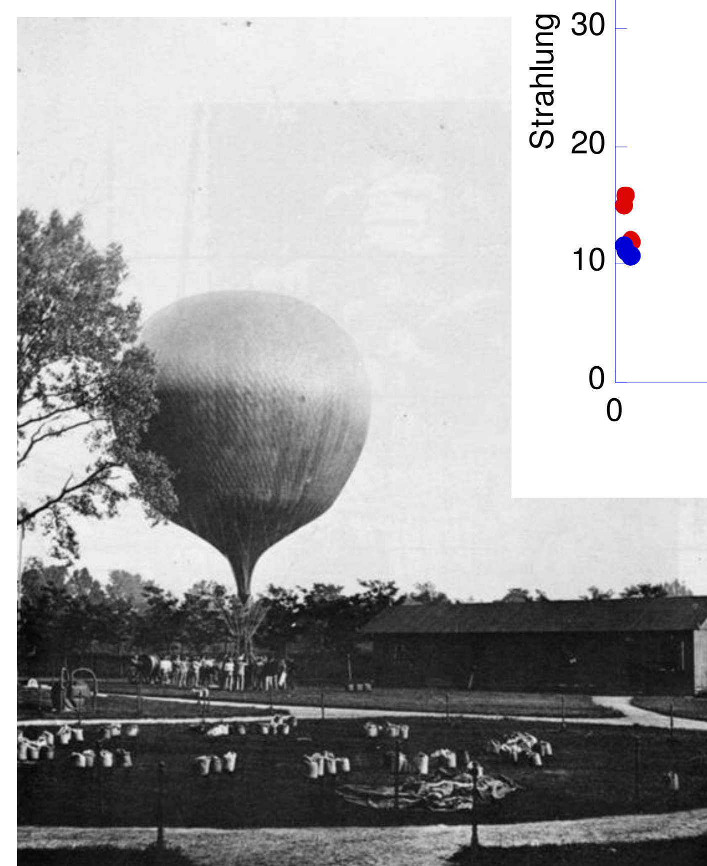
Communicated March 19, 1934

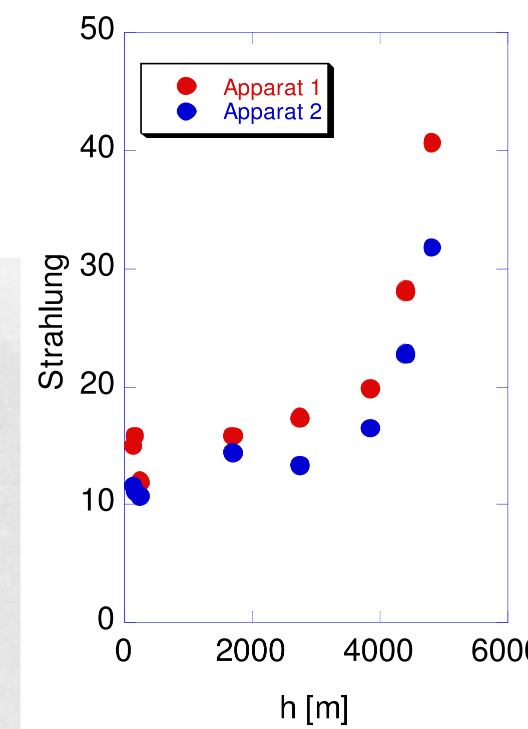
nebulae are in most respects similar to our own Milky Way. One arrives therefore at one of two hypotheses, either that cosmic rays originate in intergalactic space or that they are survivors from a time when physical conditions in the universe were entirely different from what they are now (Lemaître). On closer scrutiny both hypotheses prove to be very unsatisfactory. On both views one is forced to assume entirely fantastic processes as regards the mode of creation of the rays. Furthermore, on

galaxy. If, however, the production of cosmic rays is related to some sporadic process, such as the flare-up of a super-nova, the above-mentioned difficulties disappear. We shall try to show that this hypothesis enables us to derive the intensity of the cosmic rays which arrive on the earth, and that direct observations of intensity are in fair agreement with the value thus computed.

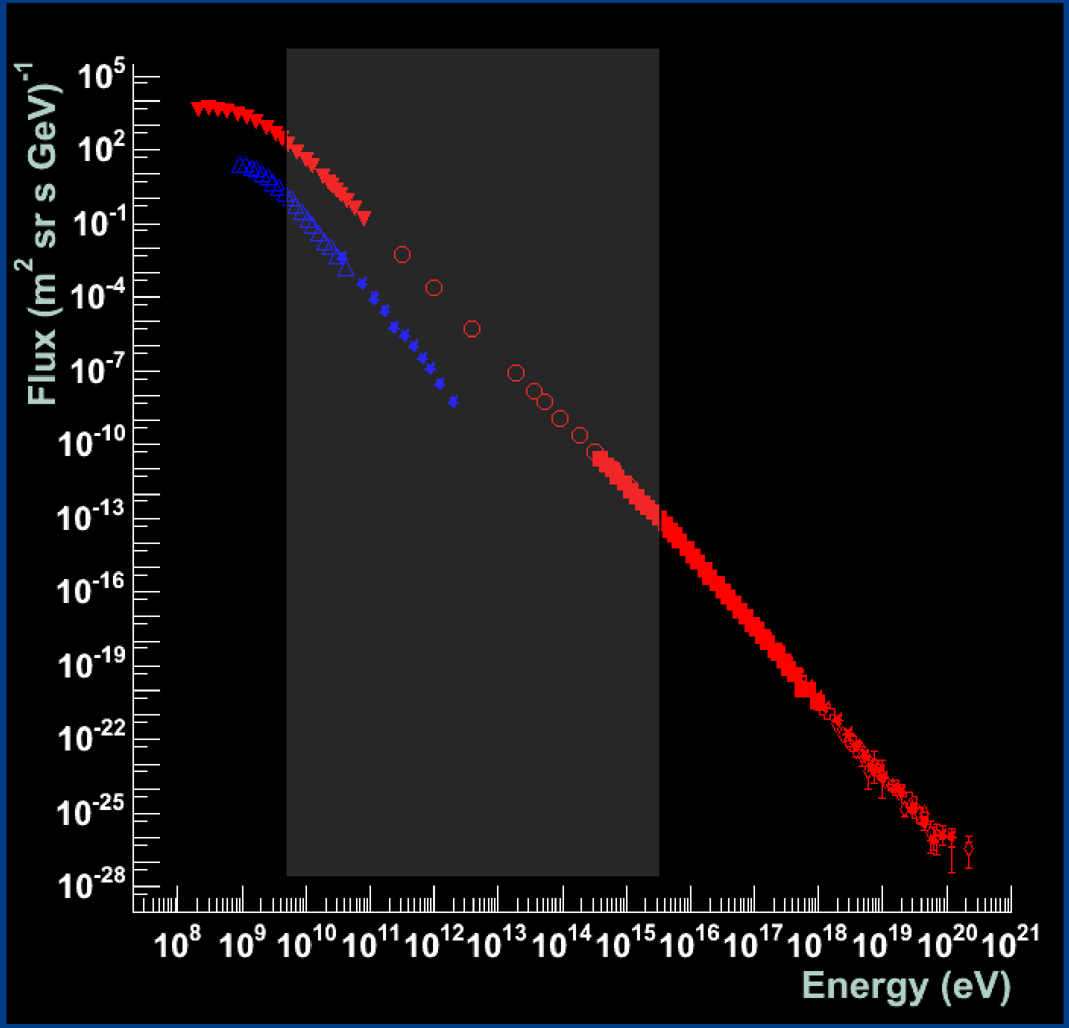


- **“Original motivation of VHE gamma-ray astronomy: the origin of the (hadronic) cosmic rays”**
- **Discovered in 1912 by Victor Hess in balloon flights**





The sources of cosmic rays

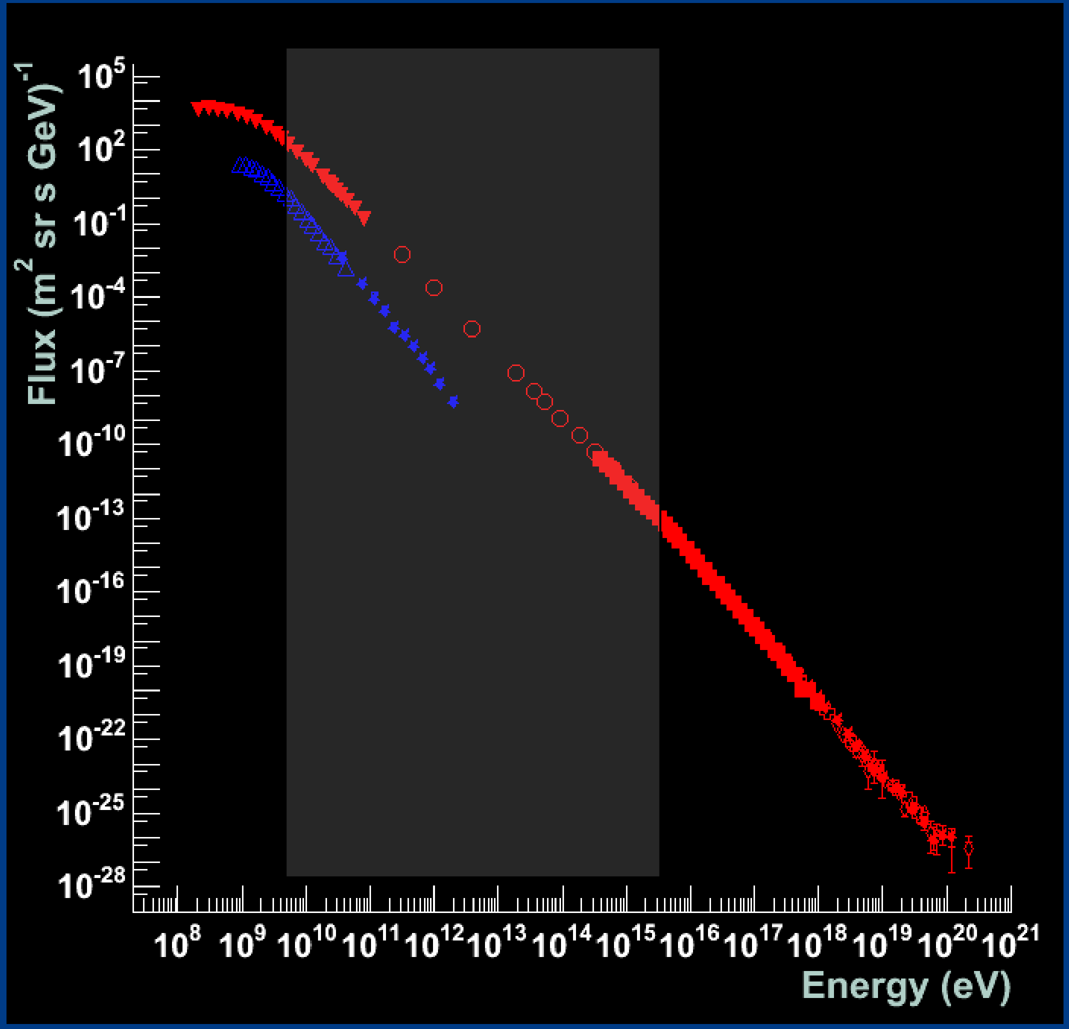


- **What do we know:**
  - Energy spectrum: $dN/dE = kE^{-2.6-2.7}$ up to the “knee” (10^{15} eV)
  - Chemical composition

Little doubt that Cosmic rays up to 10^{15} eV have Galactic Origin

  - Source spectrum close to $E^{-2.0-2.1}$
  - Production Rate 3x 10^{40} ergs/s

The sources of cosmic rays



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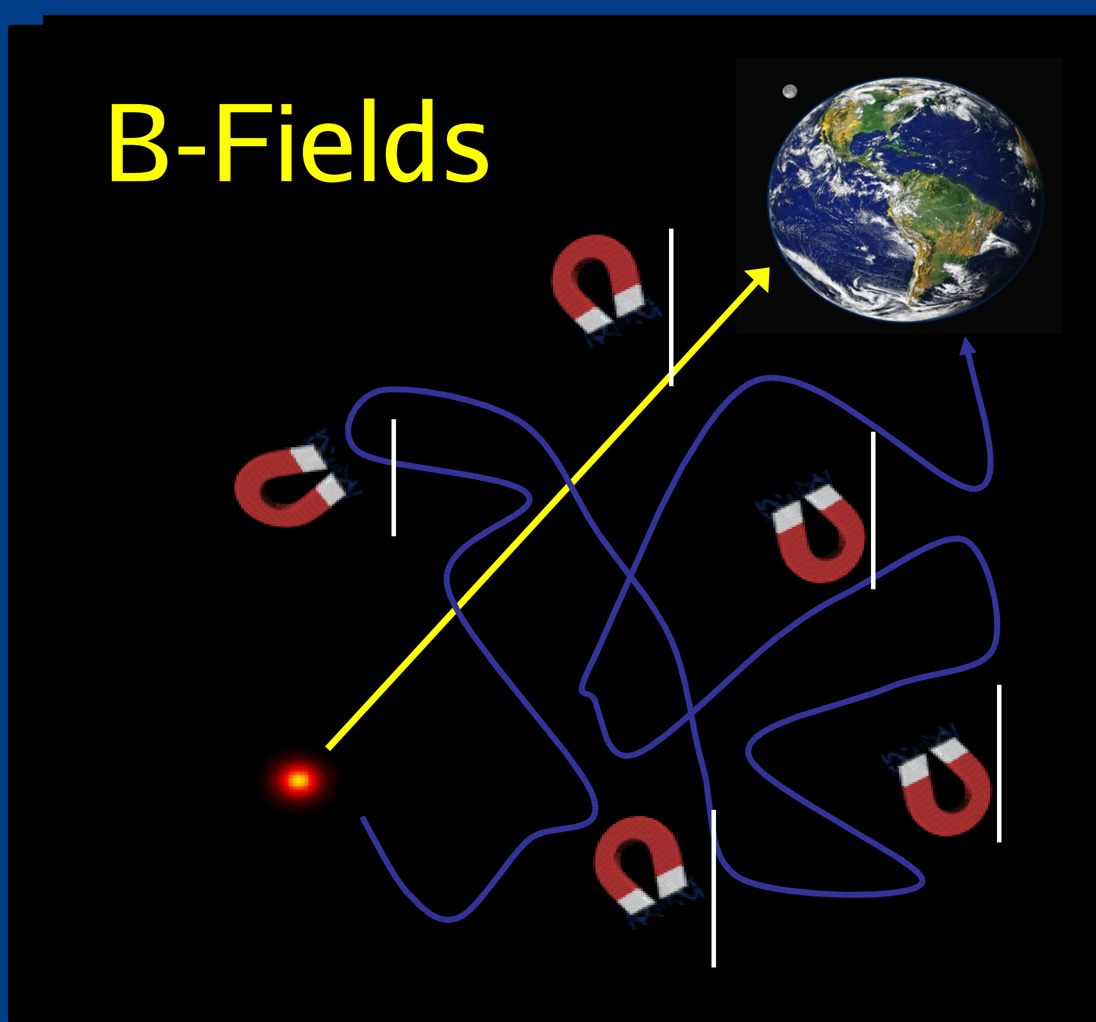
- **What do we not know:**
  - Acceleration site
  - Population of sources
  - Acceleration mechanism

The sources of cosmic rays



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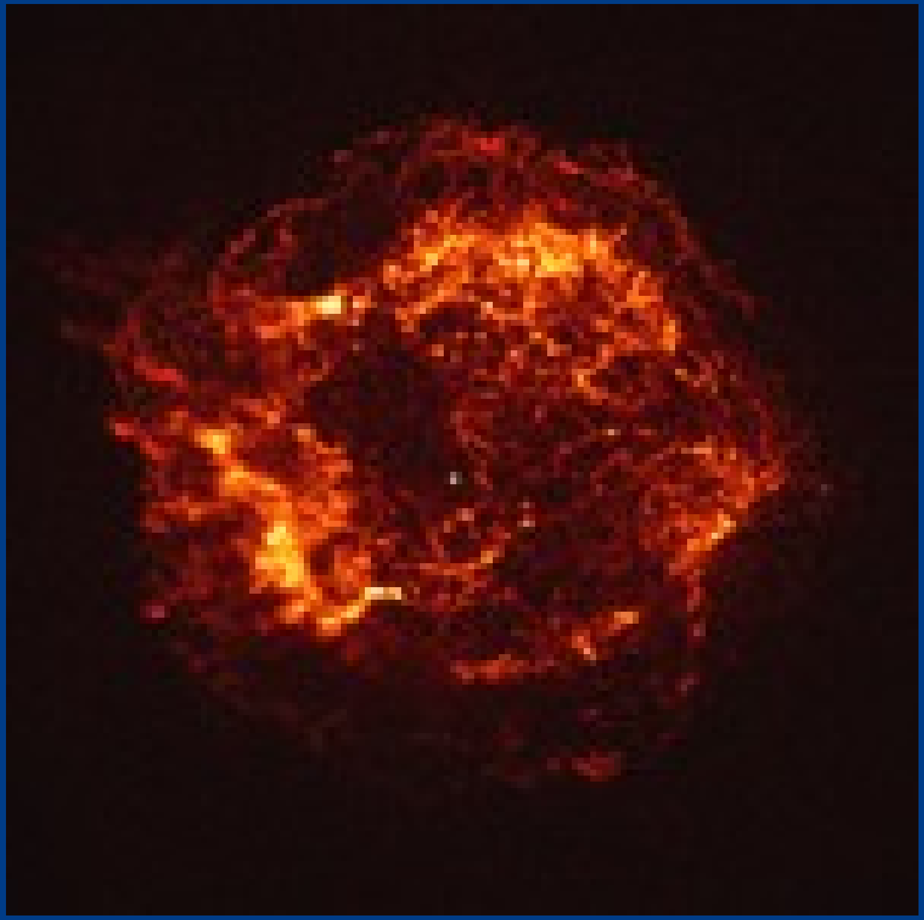
→Gamma-rays/Neutrinos

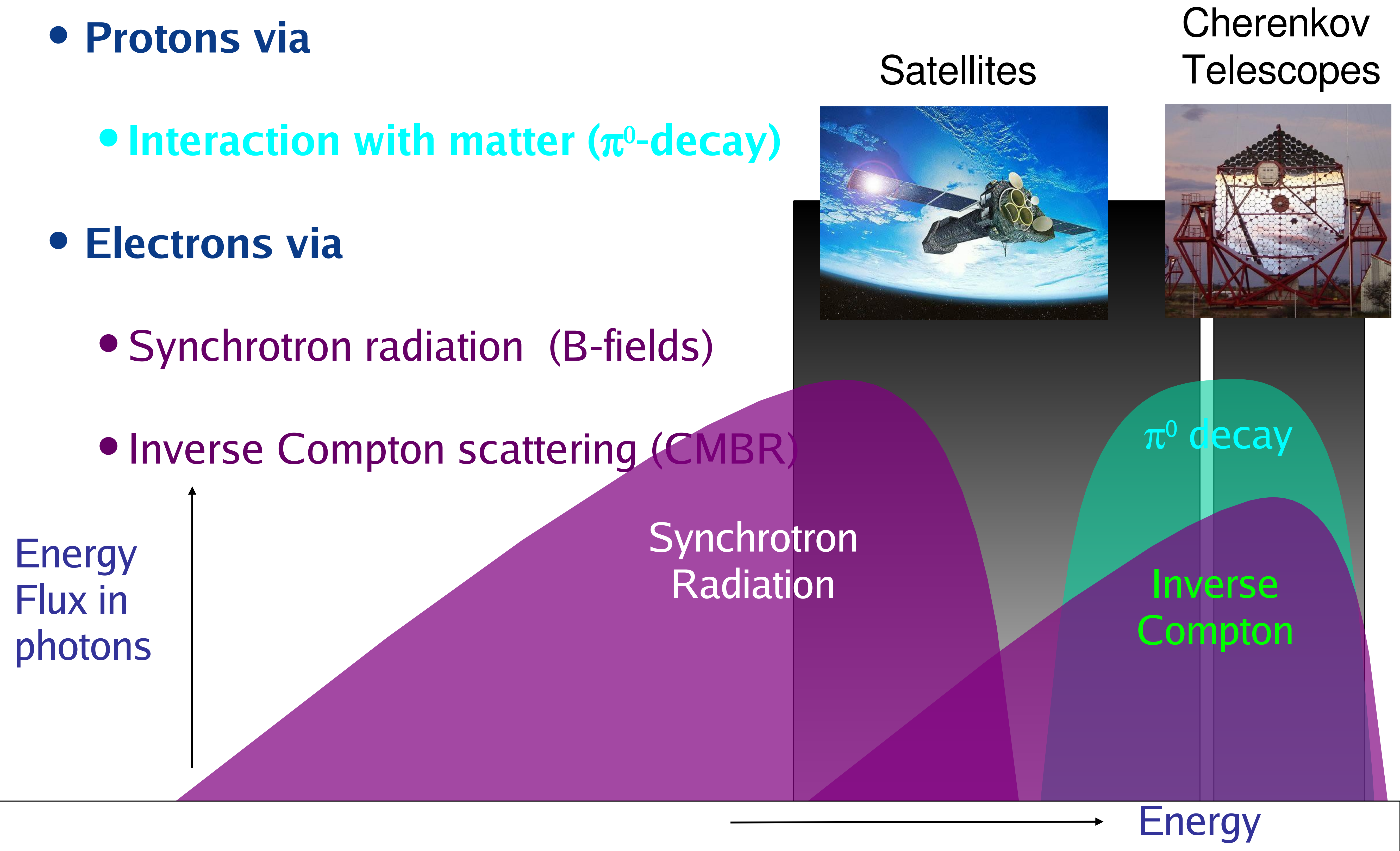
The most plausible source: SNRs?



- **(Almost) common belief for two main reasons:**
  - Energetics: 10% of the energy of SNRs would suffice
    - $E_{CR} \sim \rho V / \tau_{escape} \sim 10^{41}$ erg/s
    - $E_{SN} \sim 10^{51}$ erg/30y $\sim 10^{42}$ erg/s
  - Theoretical argument :
    - Diffusive shock acceleration
    - together with magnetic field amplification can accelerate charged particles to 10^{15} eV
    - Spectrum: $E^{-2.1-2.2}$
- **Final Proof: Detect Gamma-rays (or neutrinos) from hadronic interactions around SNRs**

Production mechanisms

- **Protons via**
  - **Interaction with matter (π^0-decay)**
- **Electrons via**
  - Synchrotron radiation (B-fields)
  - Inverse Compton scattering (CMBR)



Visibility ?

- **Gamma-ray flux from SNR arising from hadronic interactions (Drury 1994):**

- **Using:**
  $F\ \gamma\ (>E) \sim 10^{-11}\ A\ (E/1TeV)^{-1.1}\ cm^{-2}s^{-1}$

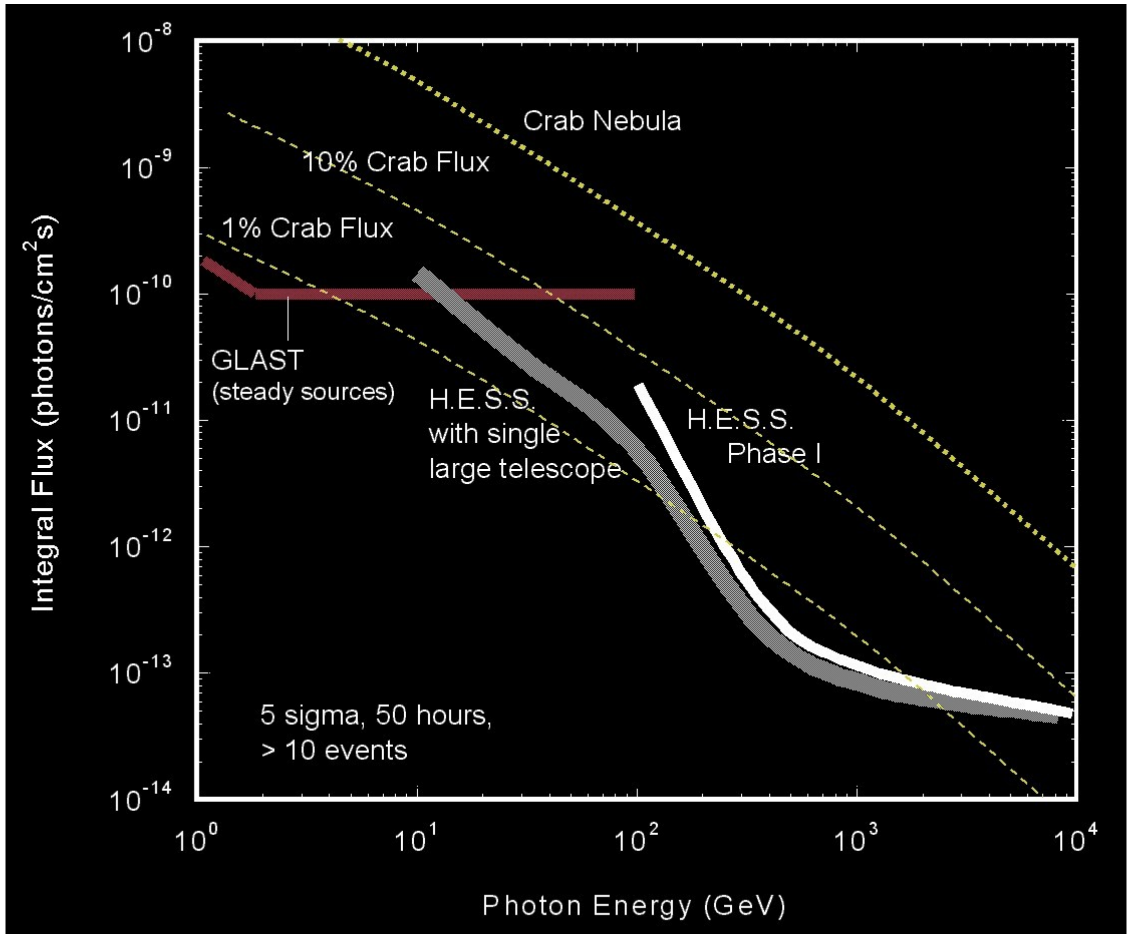
  - $A = (E_{SN}/10^{51}erg)\ (d/1kpc)^{-2}\ (n/1cm^{-3})$

- **E.g. H.E.S.S. Sensitivity: 1% Crab in 25 hour ($2x10^{-13}\ cm^{-2}s^{-1}$) for point source**

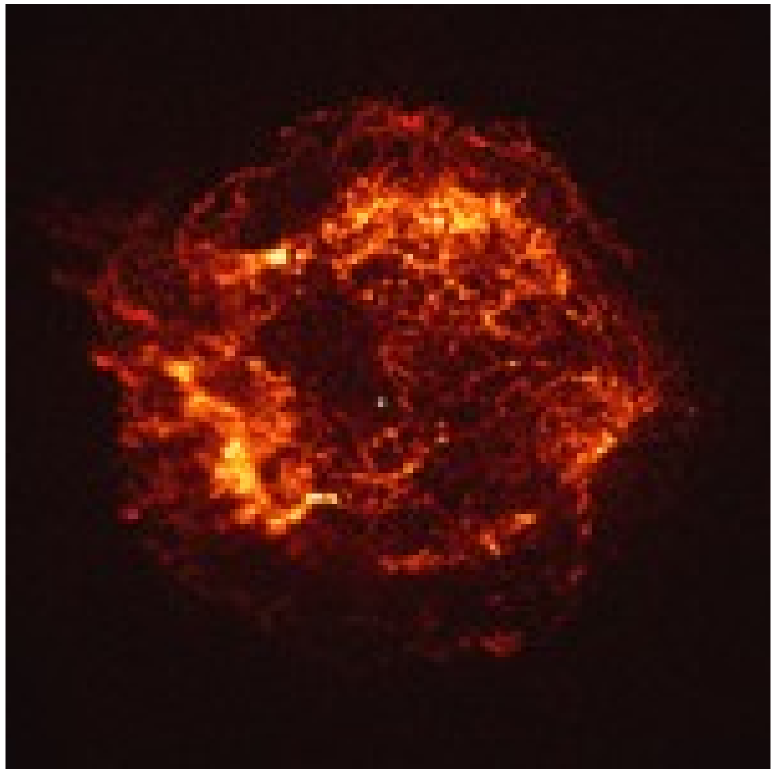
- **SNRs Detectable for A = 0.02**

- **For typical point-SNRs in interstellar medium ($n=1\ cm^{-3}$) out to d ~ 3 kpc**

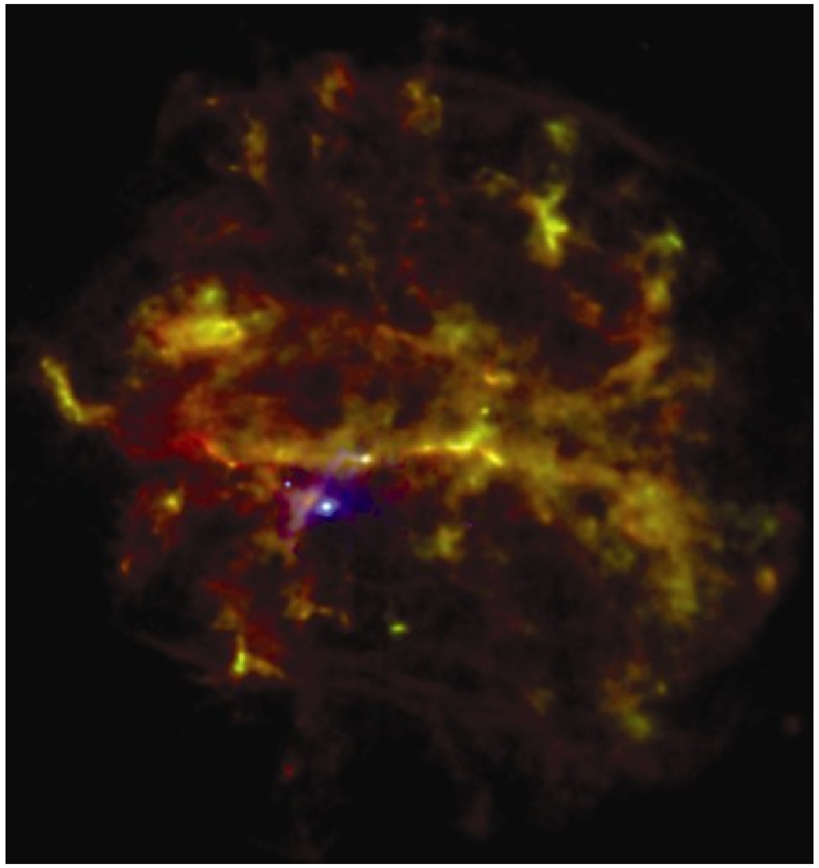
- **For extended sources, sensitivity scales roughly like square of size**



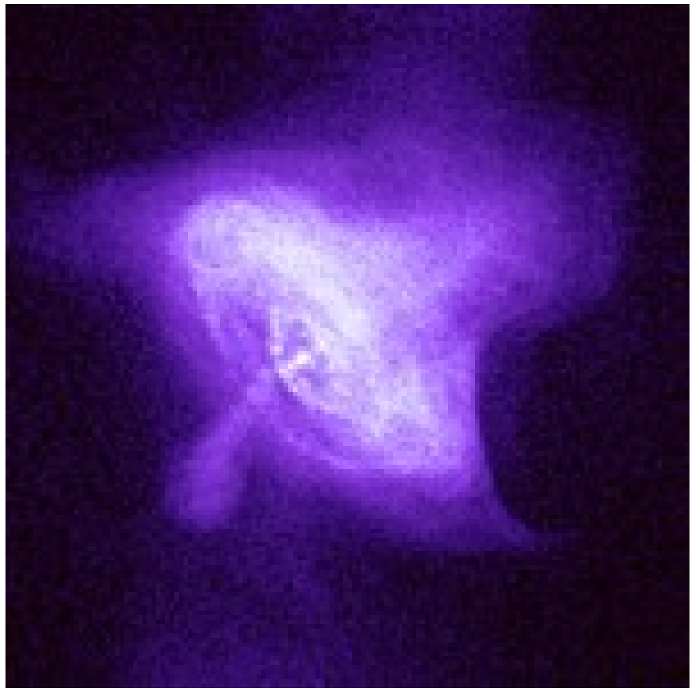
Classification of SNR



Shell

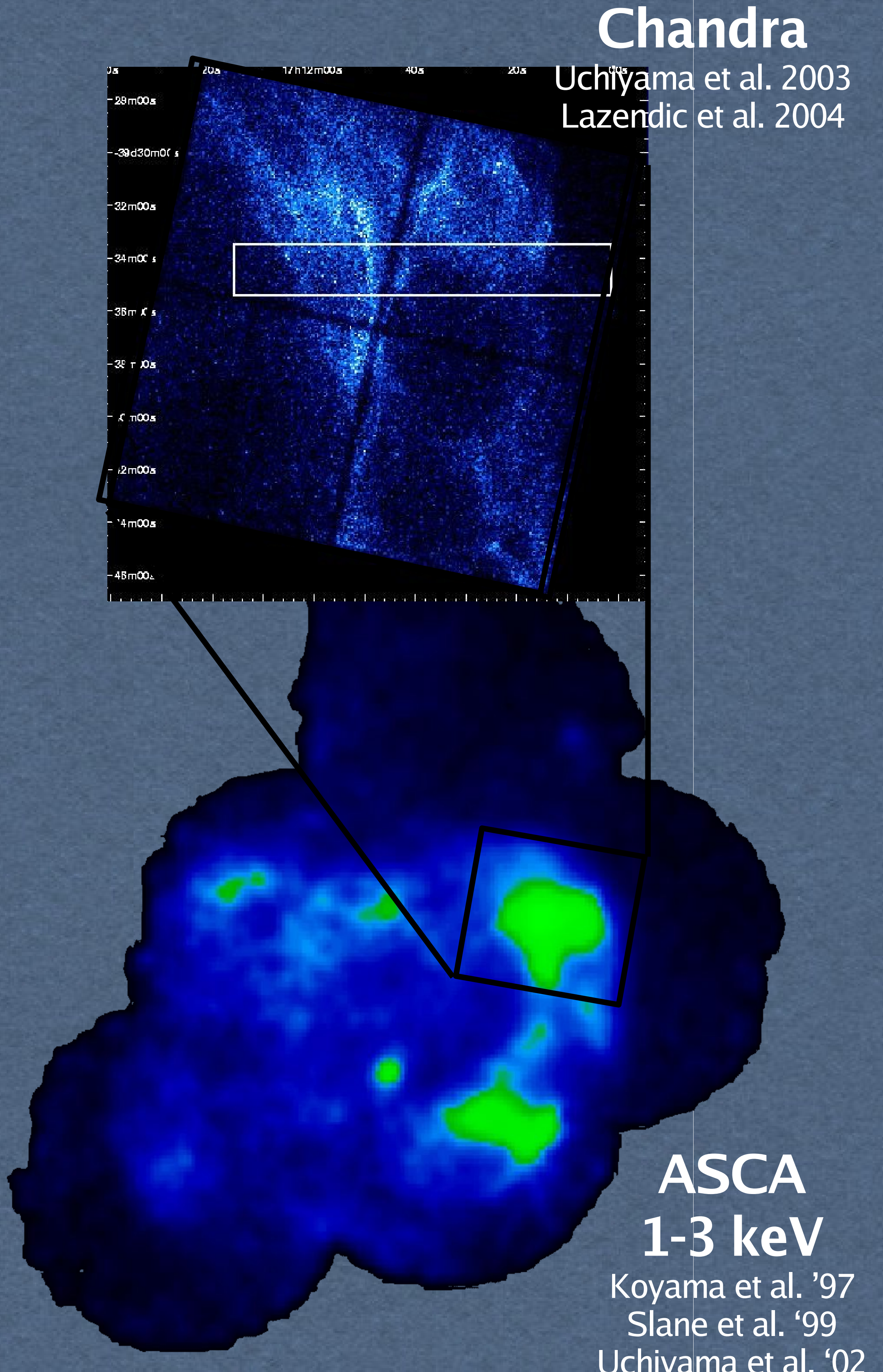


Composite



Plerion= πληρης= 'full'

Shell type SNR

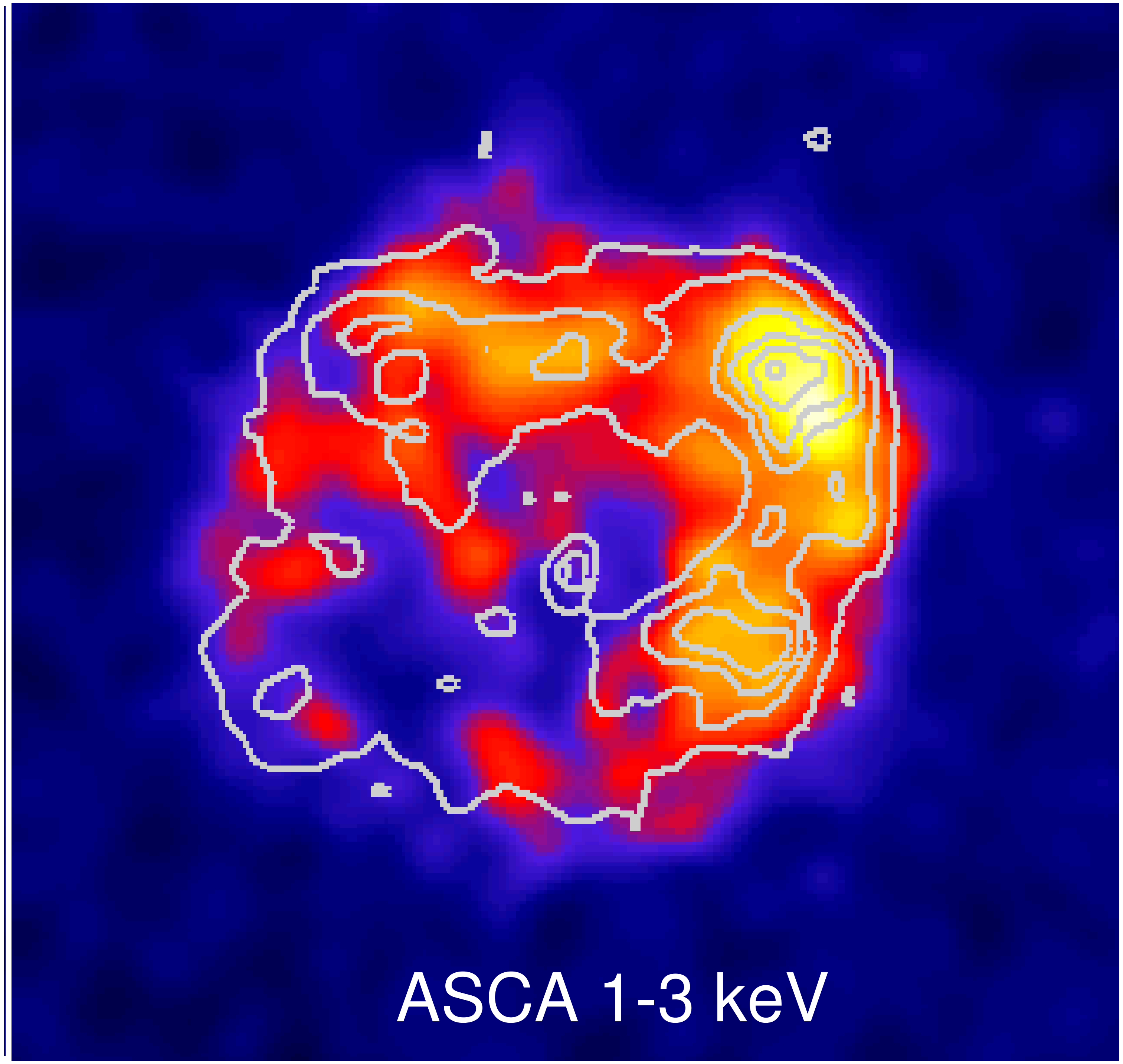


Shell type SNR

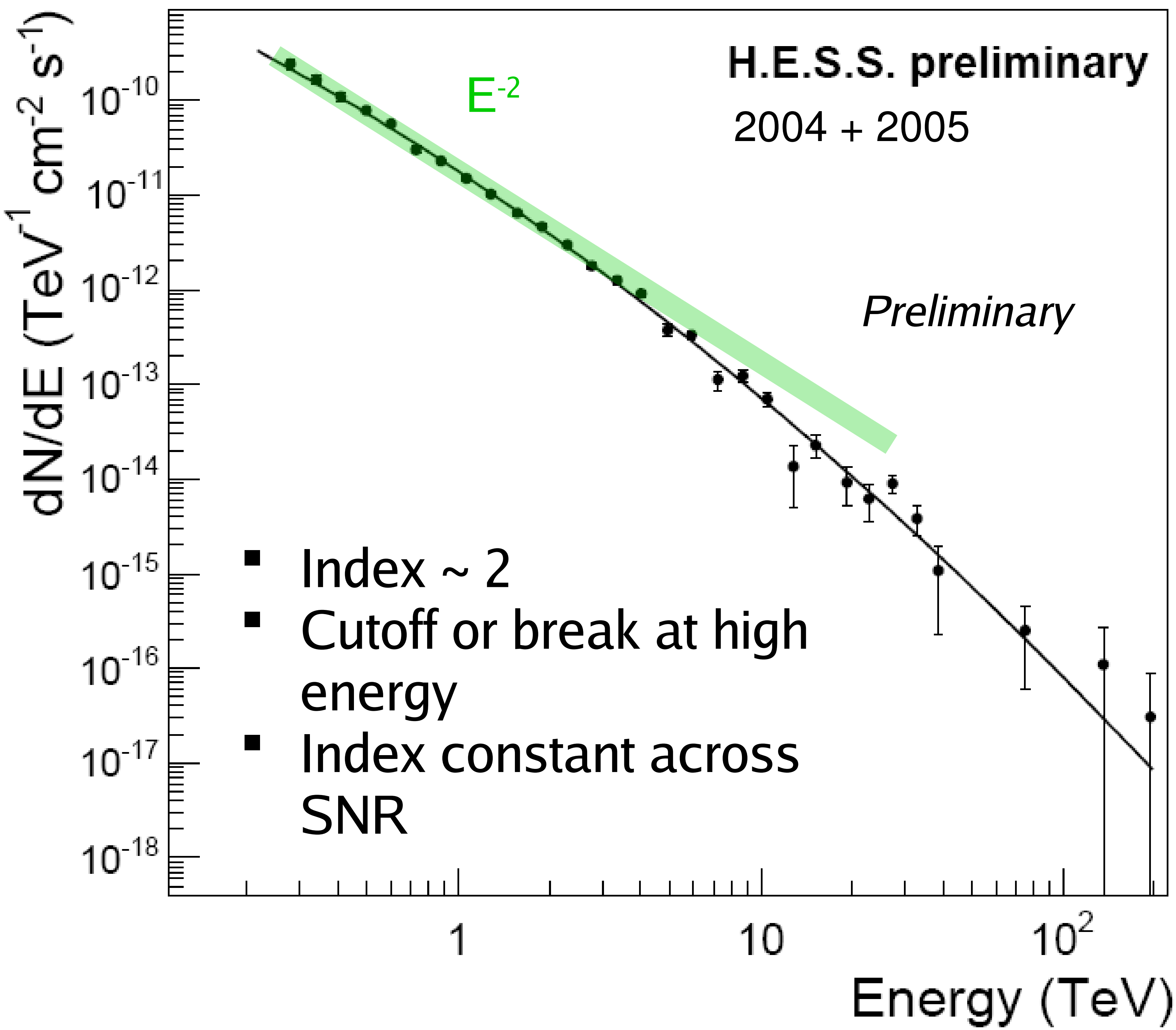
- Best case: dominant non-thermal X-ray emission (like RXJ 1713.7-3946)
- Small filaments in the shell point to high magnetic fields (field amplification?)
- Established existence of ~100TeV Electrons
- Also high-energy protons?

The prime object

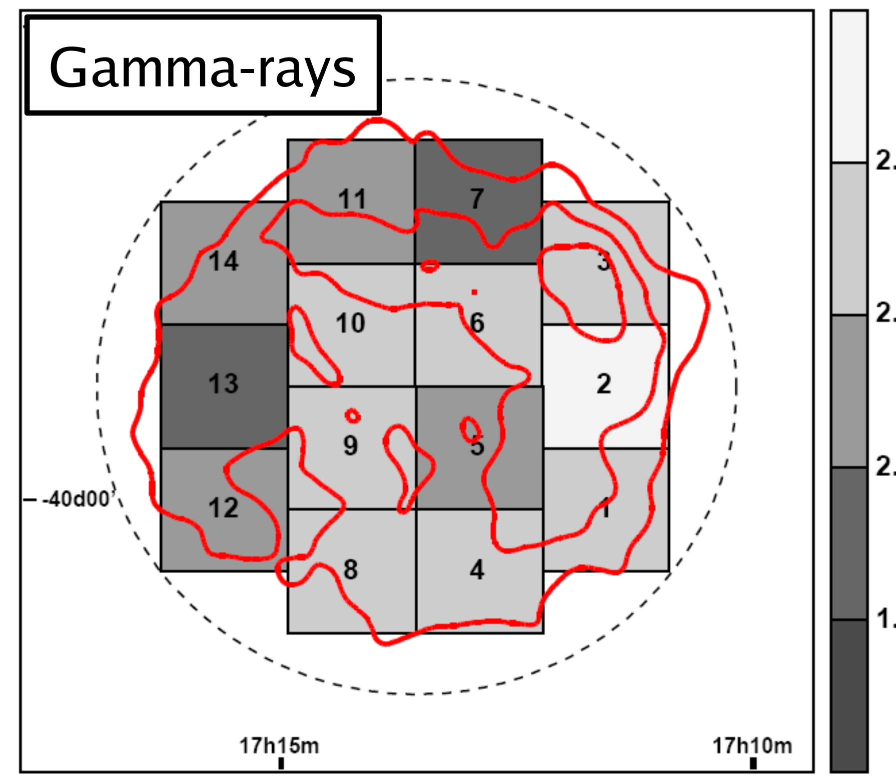
- **RXJ 1713.7-3946 is a VHE gamma-ray source**
- **Particle accelerator**
- **Key question: what is the particle population/ emission mechanism?**
- **Agreement with X-rays points to common origin**

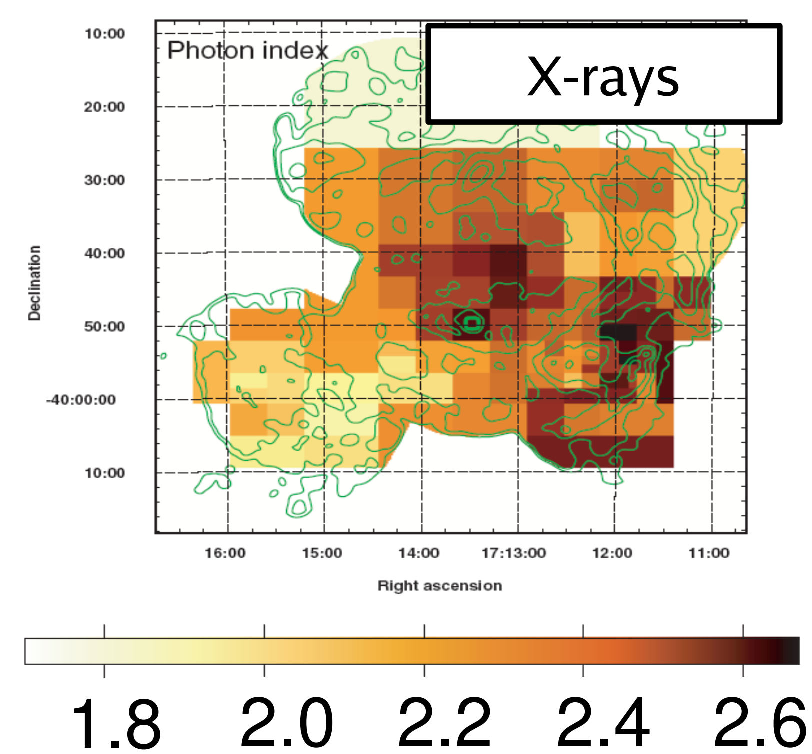


Hadronic or Leptonic?



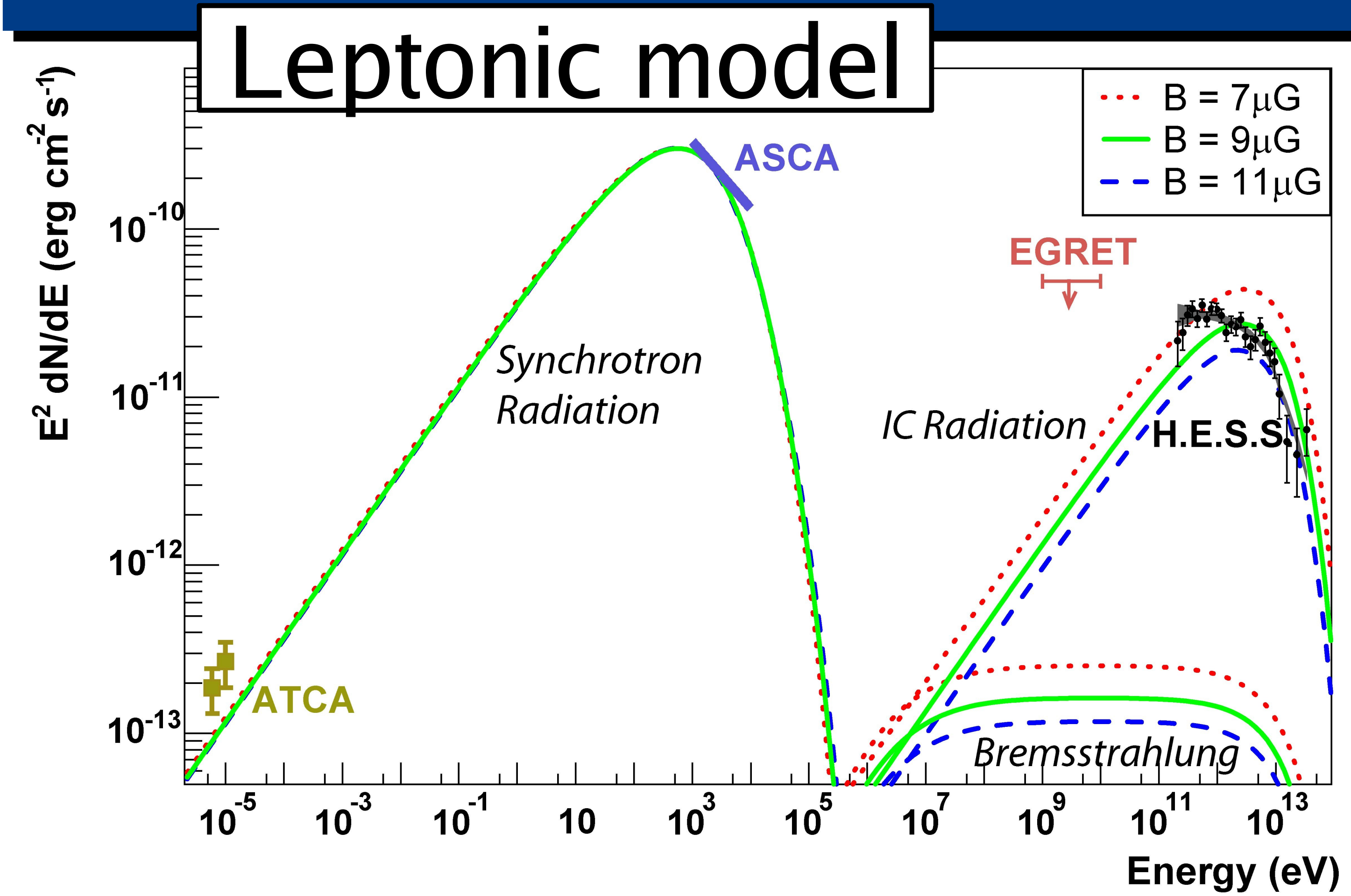
- Index ~ 2
- Cutoff or break at high energy
- Index constant across SNR

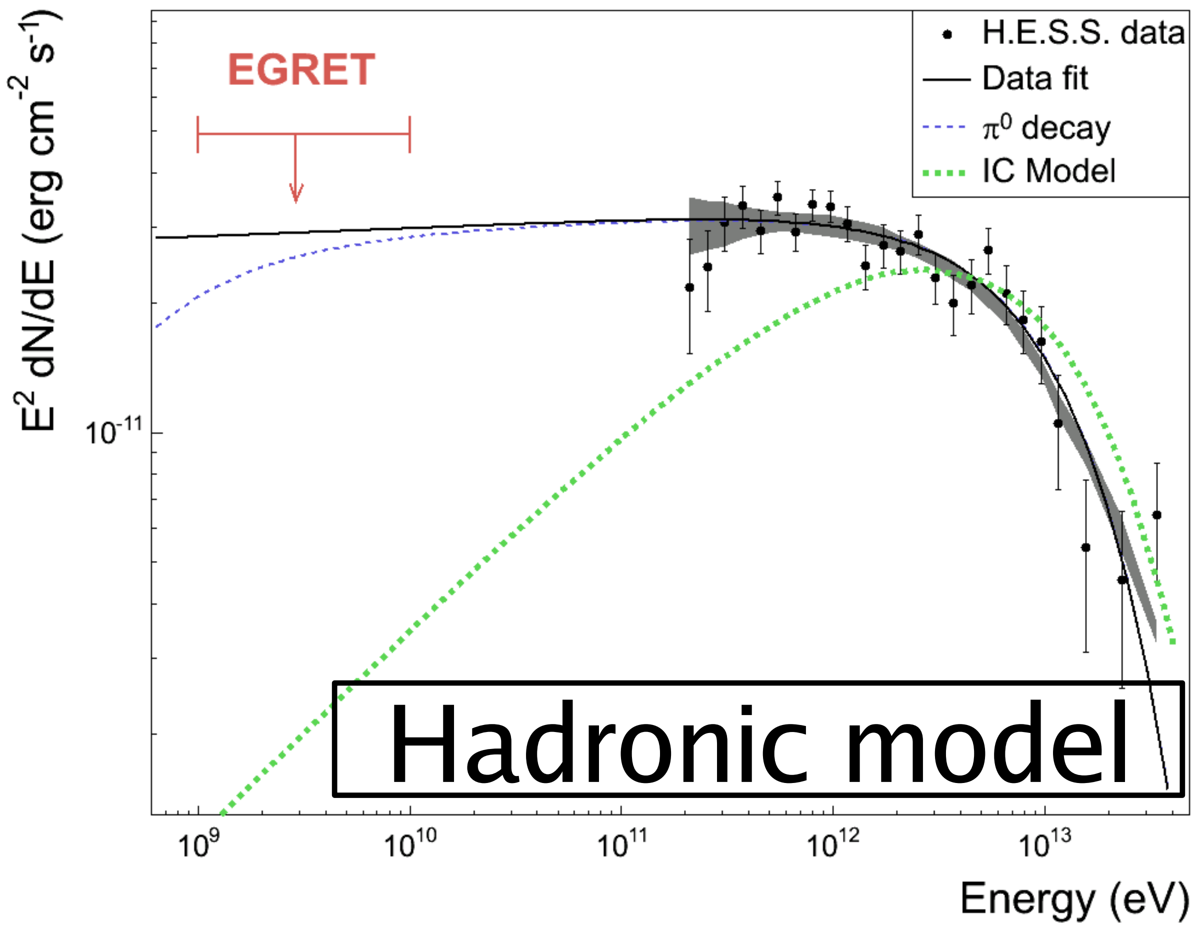




G. Cassam-Chenaï A&A 427, 199 (2004)

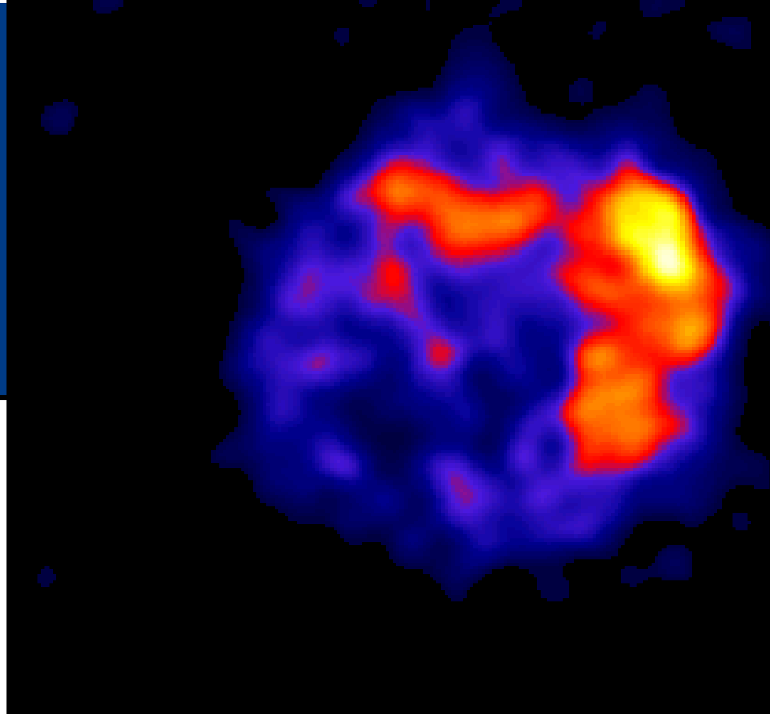
Modelling the emission



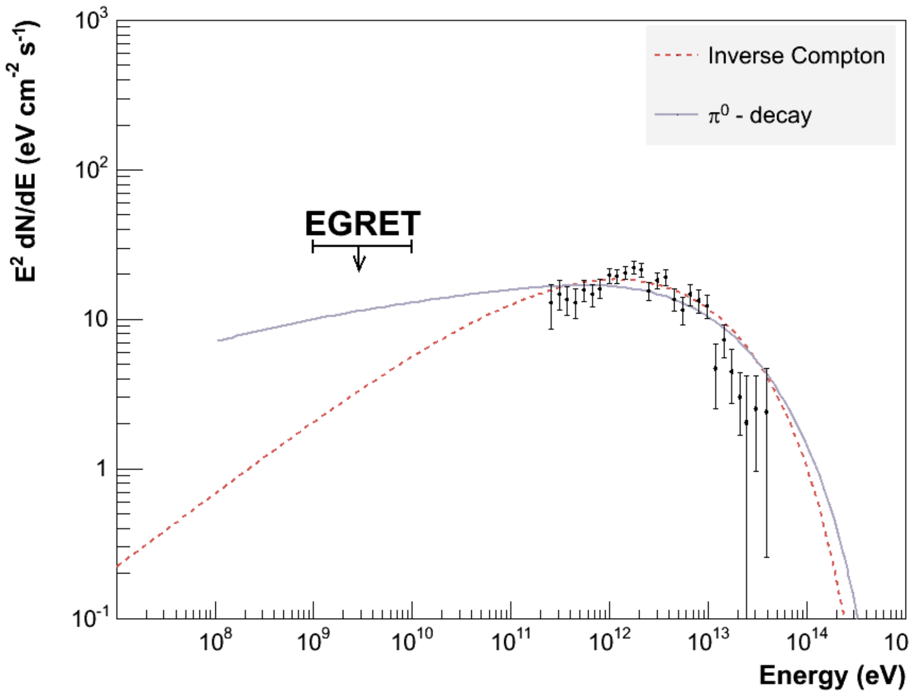


- Leptonic model suggests low B-Field (but what about filaments?)
- Generally H.E.S.S. spectrum not “peaky” enough
- Hadronic model seems to fit better
- Easier to fit since it decouples gamma-rays from X-rays

So what is it now?

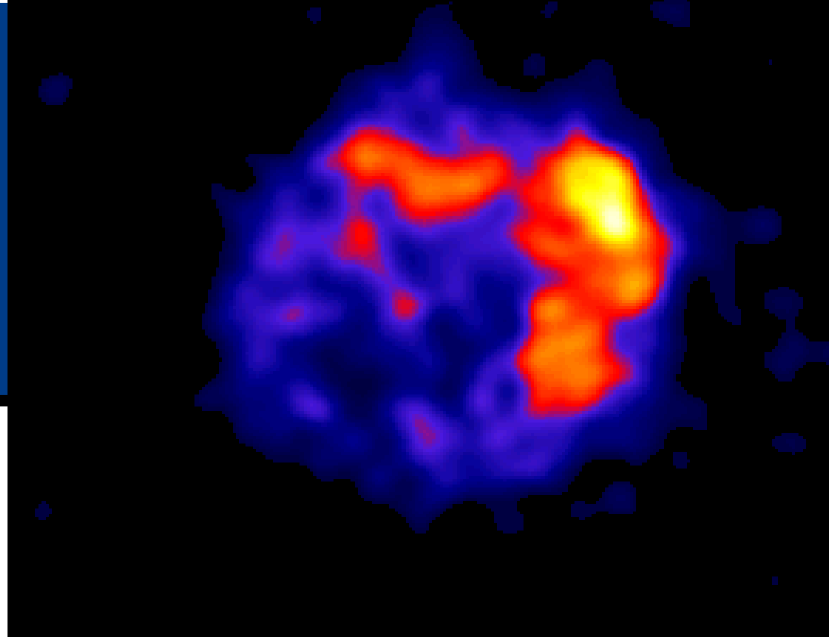


- **Hadrons:**
  - Spectral shape
  - Gamma-ray – X-ray correlation: common acceleration mechanism?
  - No apparent correlation with CO

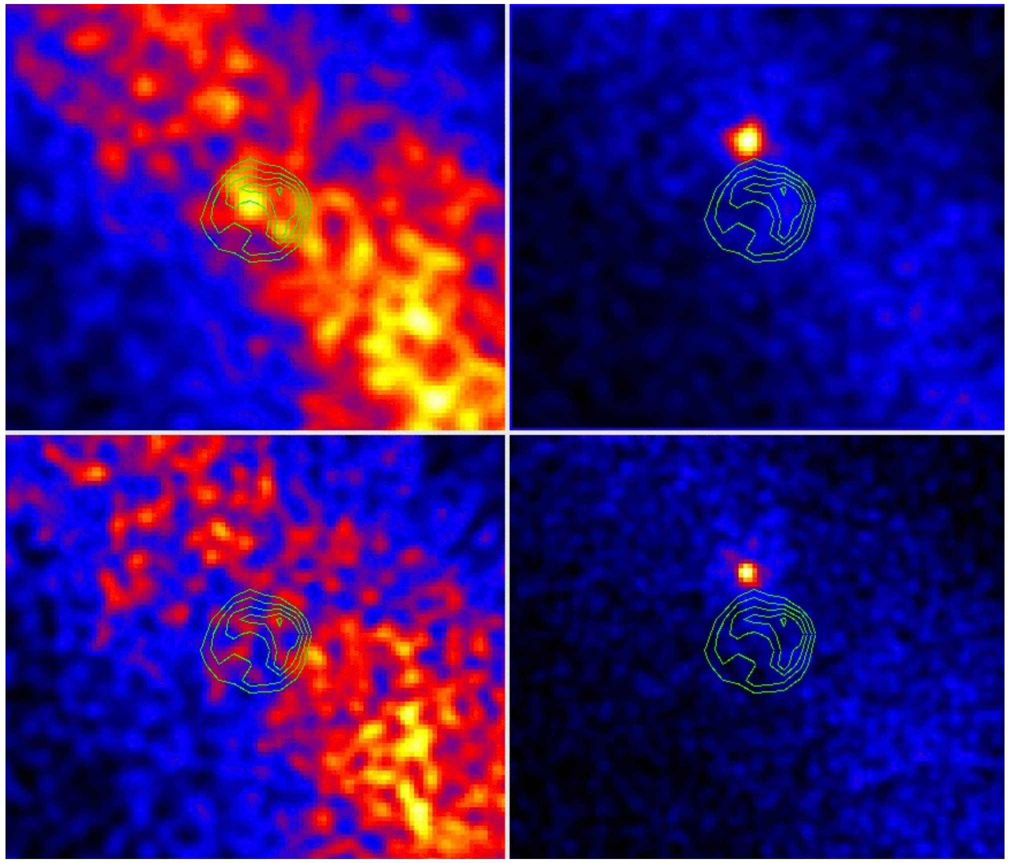


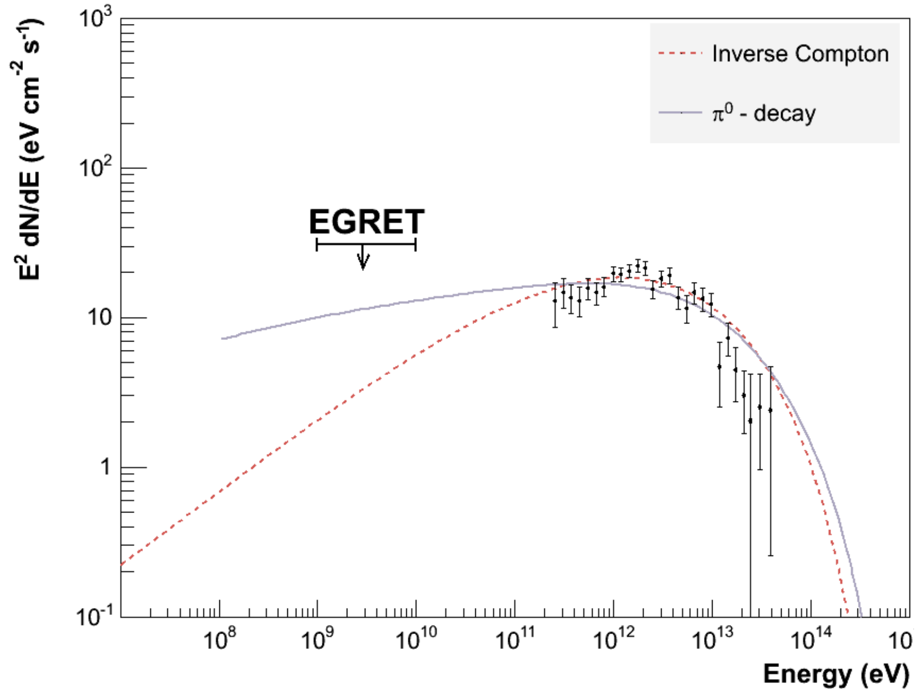
- **Electrons:**
  - Gamma-ray – X-ray correlation
  - B-field must be very low
  - keV/TeV ratio implies small B-Field (10 μG)
    (does not match 60-200 μG implied by Chandra/XMM)
  - Variation of spectral shape in X-rays, NOT in gamma rays

Prospects for GLAST



- Even in the most optimistic model, the gamma-flux above 100 MeV is $\sim 10e^{-8}\ cm^{-2}s^{-1}$
- This has to be compared to $50e^{-8}\ cm^{-2}\ s^{-1}$ for the (probably) unrelated EGRET source which will dominate the field
- Started modelling to see, what we can do

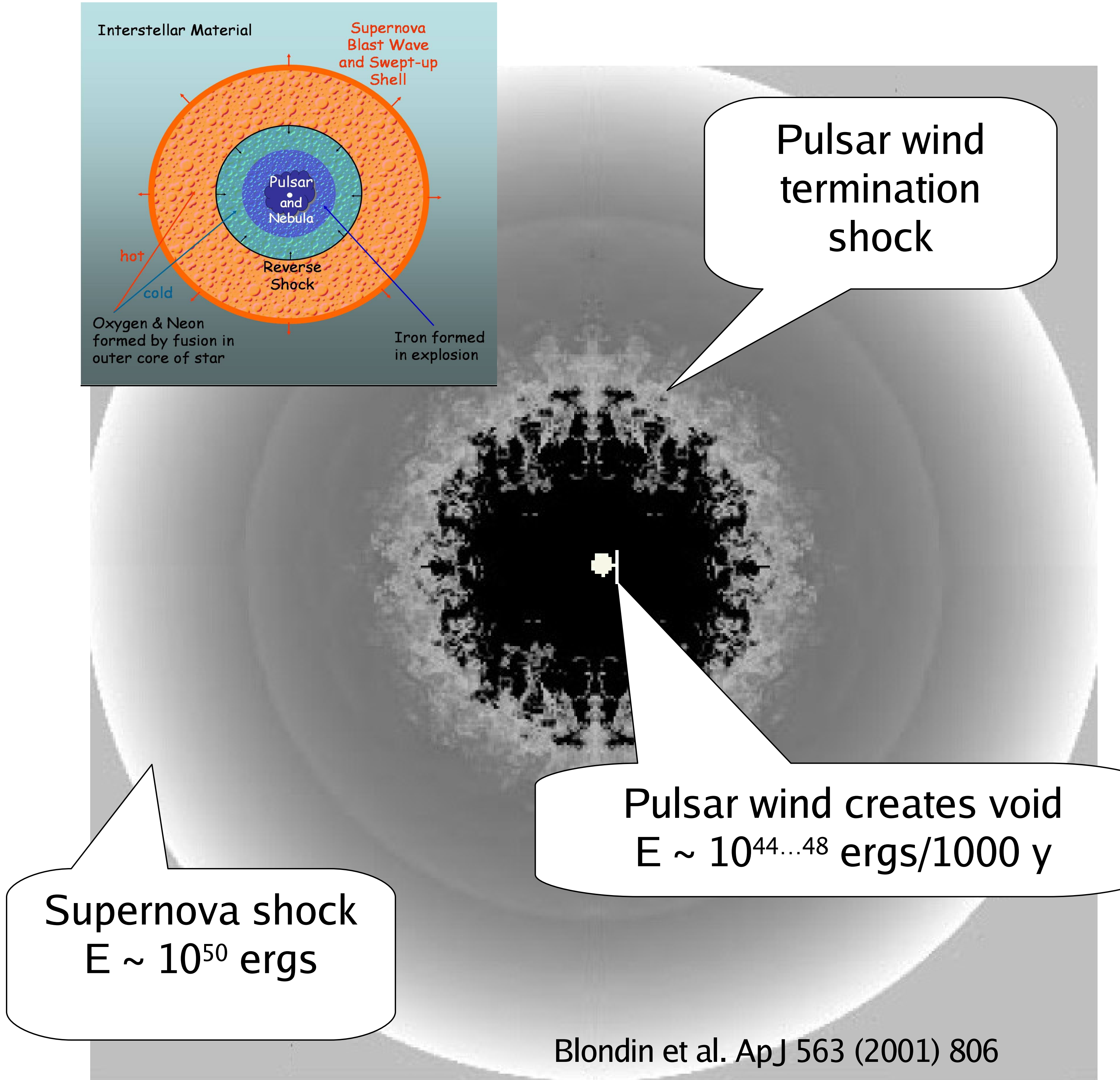




Pulsar Wind Nebulae

Pulsar wind nebulae

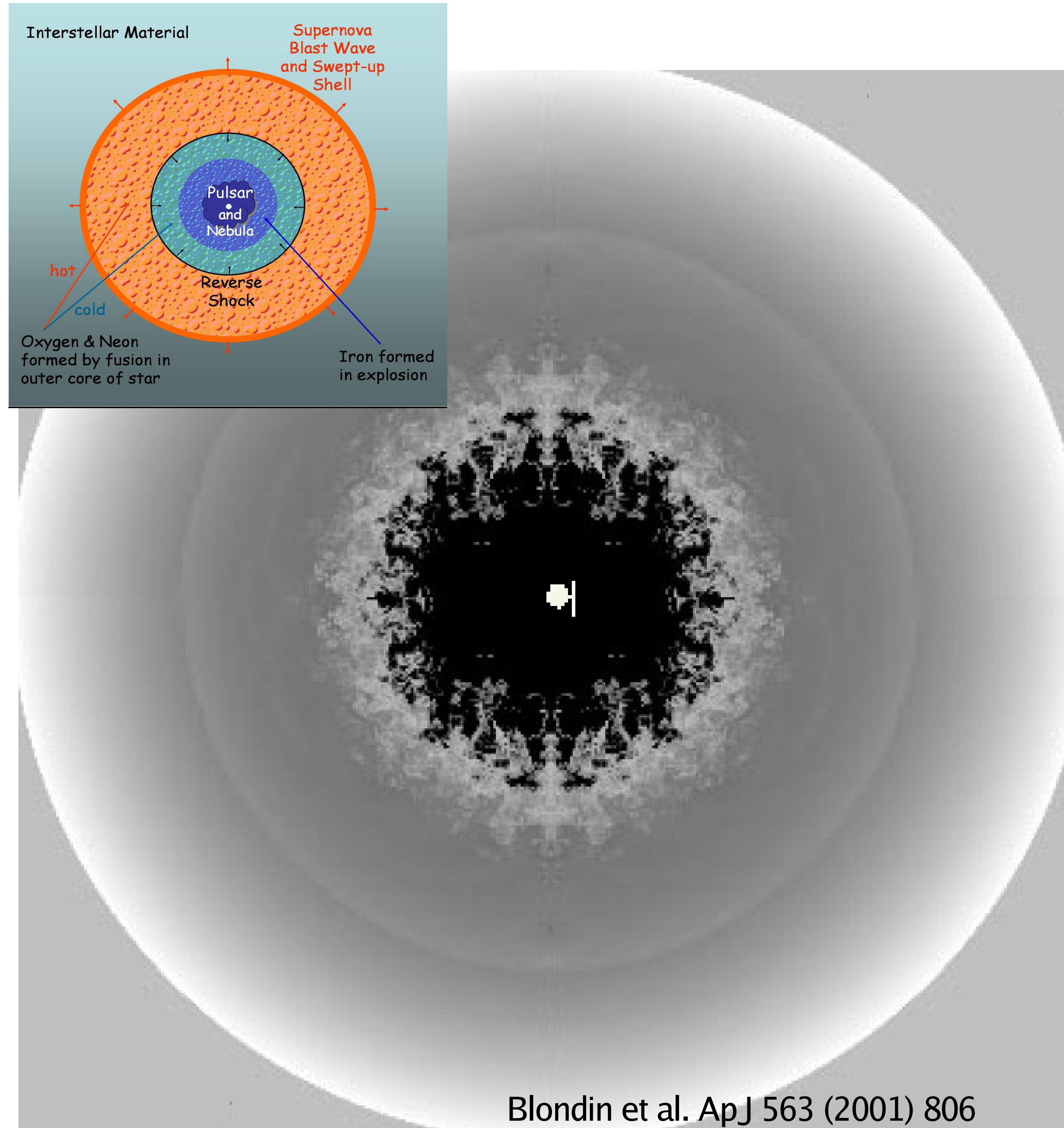
- Pulsar wind sweeps up ejecta; termination shock decelerates flow, PWN forms
- SNR sweeps up ISM; reverse shock heats ejecta; compresses PWN



Blondin et al. ApJ 563 (2001) 806

Pulsar wind nebulae

- Pulsar winds have modest energies compared to SN, but:
  - Most of the energy is in the electrons
  - Radiative IC loss time scales for **e**$^{\pm}$ are O(10^5) years, versus few 10^7 years for protons



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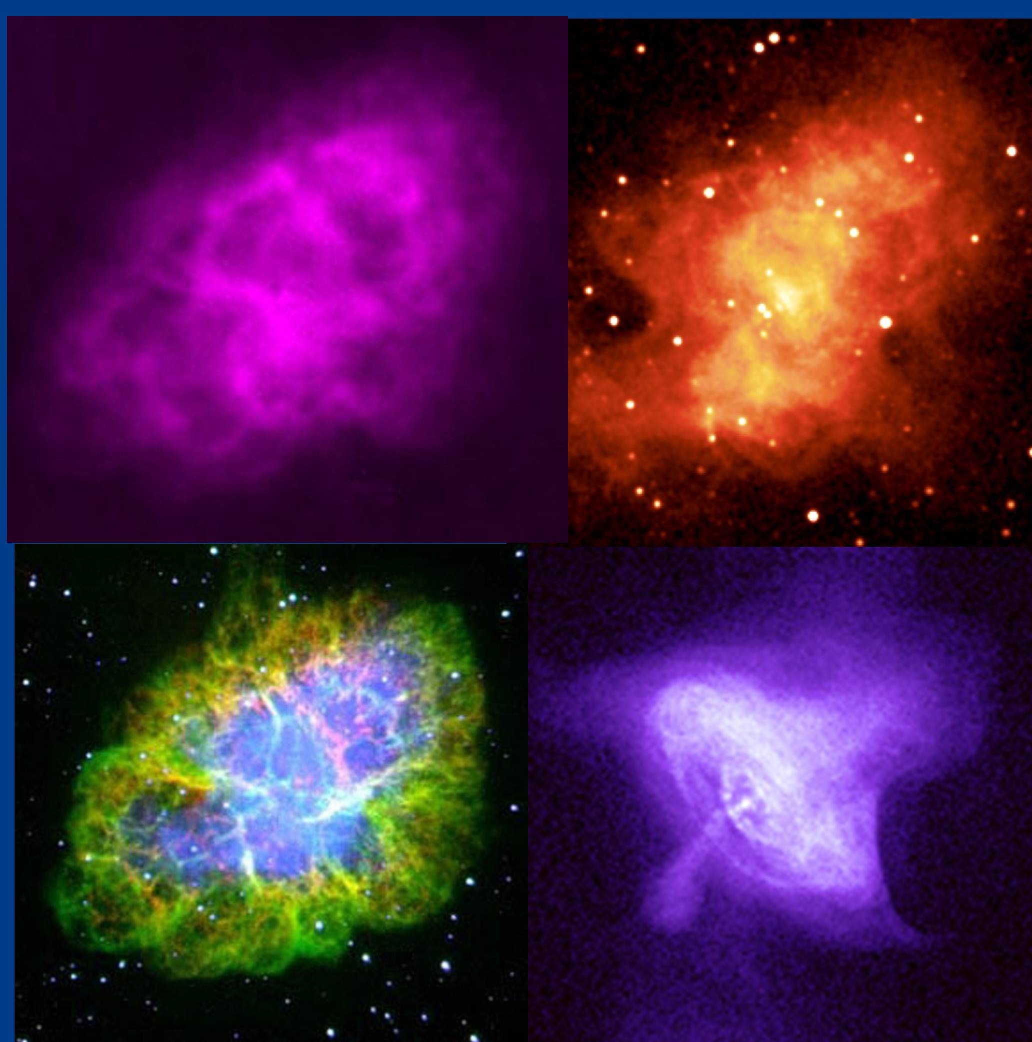
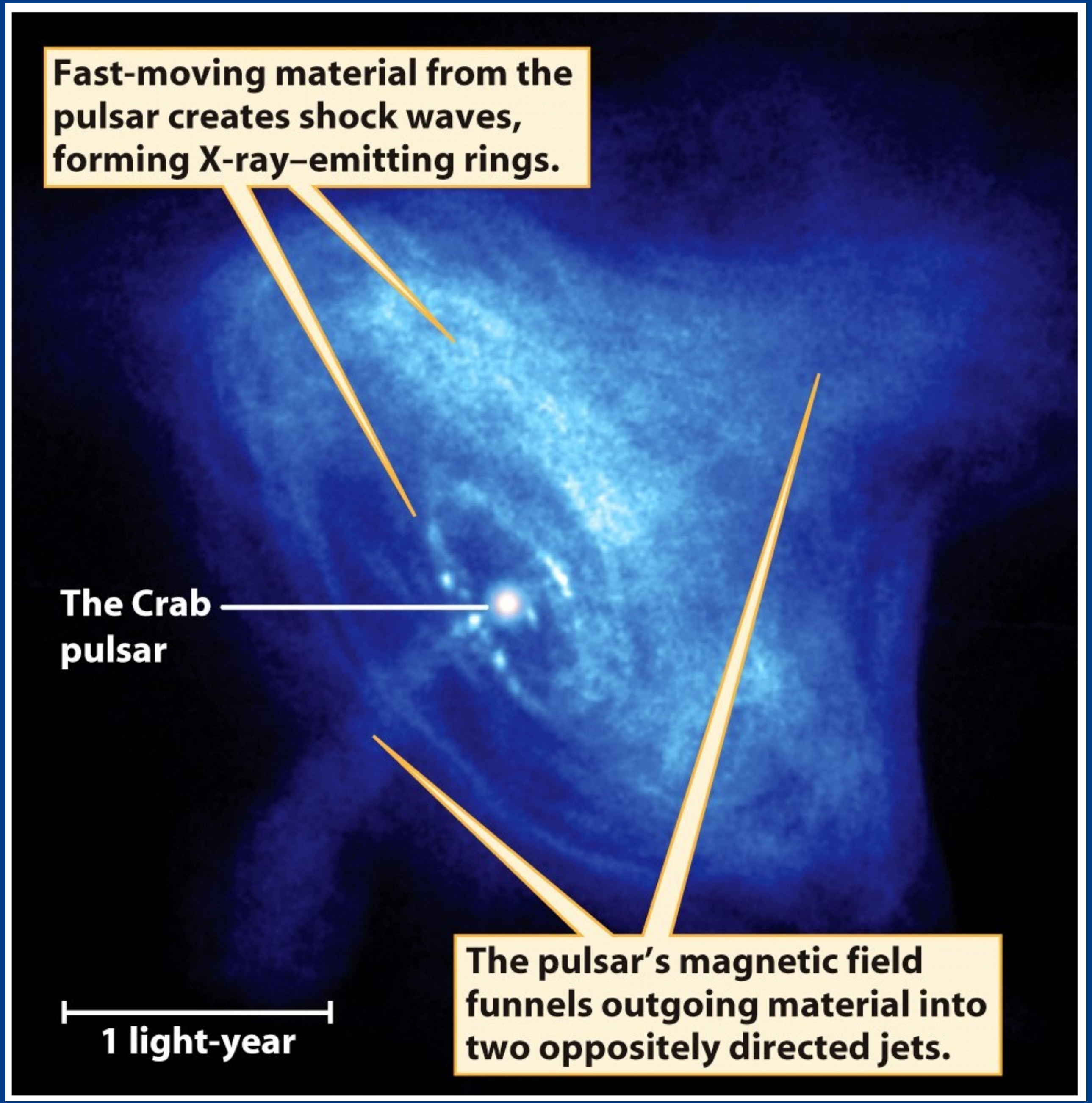
The Crab Nebula



- **Associated with 1054 CE Supernova**
- **Anomalous morphology:**
  - "filled" center which emits at all wavelengths
  - Typically, SNR = shell
- **1960: First obs of optical/radio pulsations from central star**
  - P = 53 ms
  - dP/dt = 36 ns/day
    - dK.E./dt = 5e38 erg/s

Theory of emission

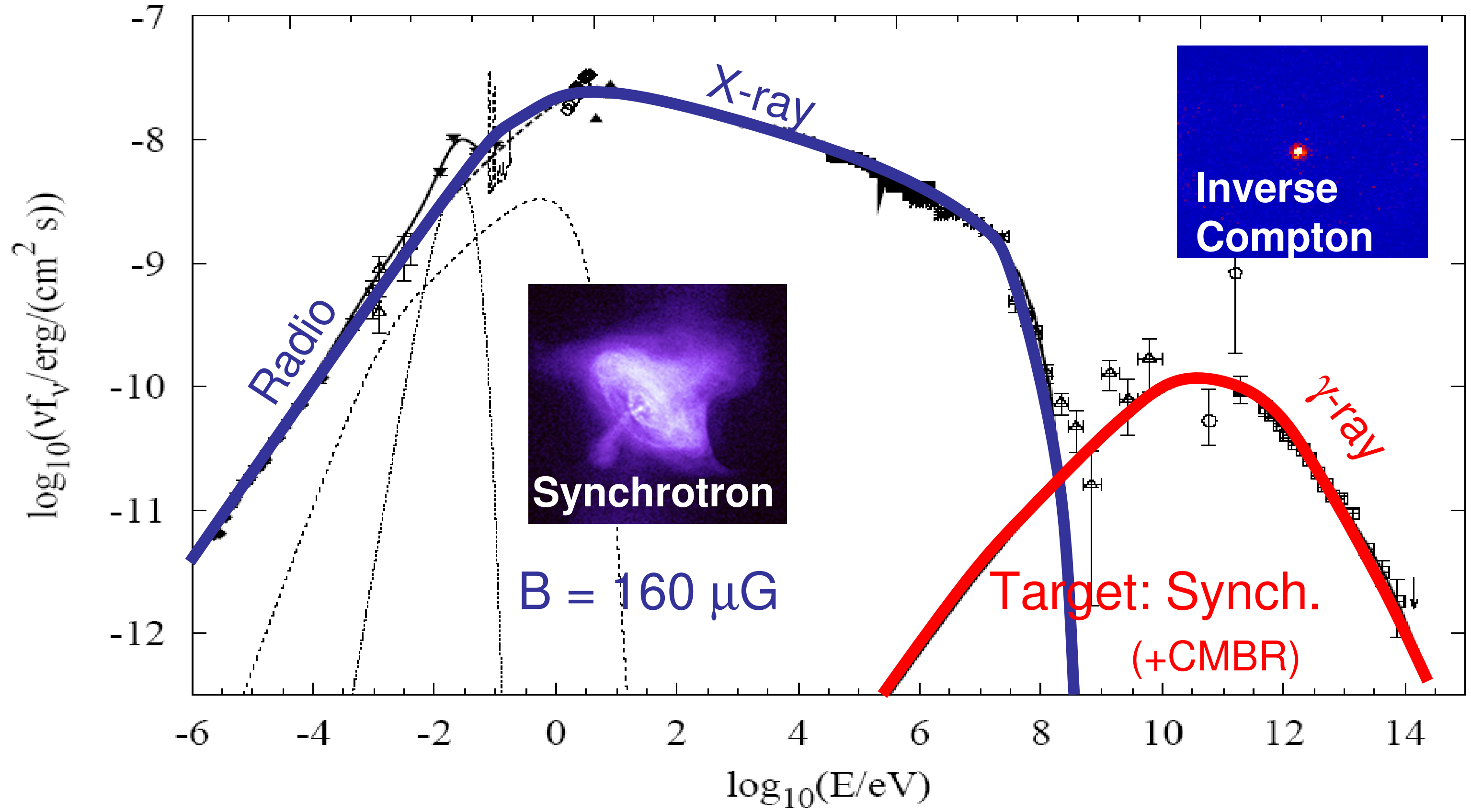
- **Central Pulsar generates magnitized wind outflow**
    - ultra-relativistic e+ and e-
- **Synchrotron photons from wind particles is responsible for observed emission**
- **$E_{tot} = 5x10^{49}$ ergs**
    - 1/3 of which released over 950 yr
    - versus 10^{50} erg released during explosion in typical SNR



Radio + X-Rays from PWN

Rotation ➡ Wind (e+/e-) ➡ Synchrotron emission in **B** field

- **Radio Waves:** $S_\nu \propto \nu^\alpha$
  - $-0.3 < \alpha < 0$
- **X-Rays:**
  - $\Gamma \approx 2$ (steeper than Radi

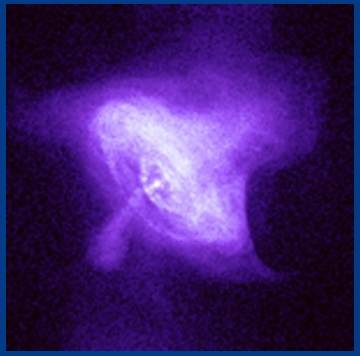


- **if know D, can calculate Luminosity (L_{radio}, L_X)**
  - $L_{radio} \approx 10^{34}$ erg/s $\qquad$ $L_X \approx 10^{35}$ erg/s
  - Conversion efficiency (to photons): $$\eta \equiv \frac{L}{\dot{E}} \simeq \begin{cases} 10^{-4} & \text{(radio)} \\ 10^{-3} & \text{(X-Ray)} \end{cases}$$

Highest energy pulsars

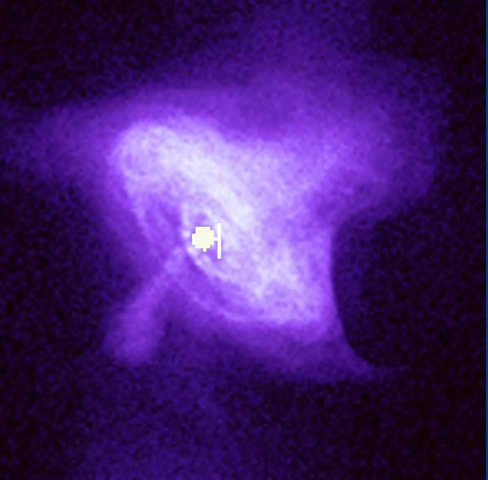
In terms of spin down flux, i.e.

Spin down energy loss rate / Distance^2



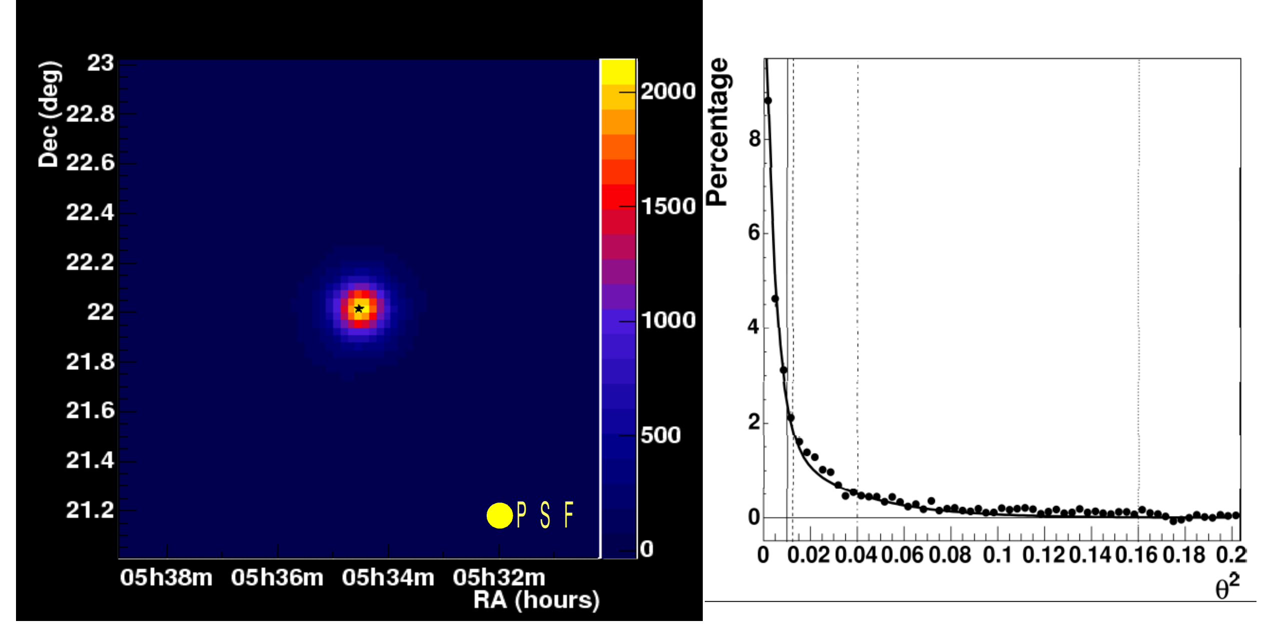
Taken from the ATNF Catalogue

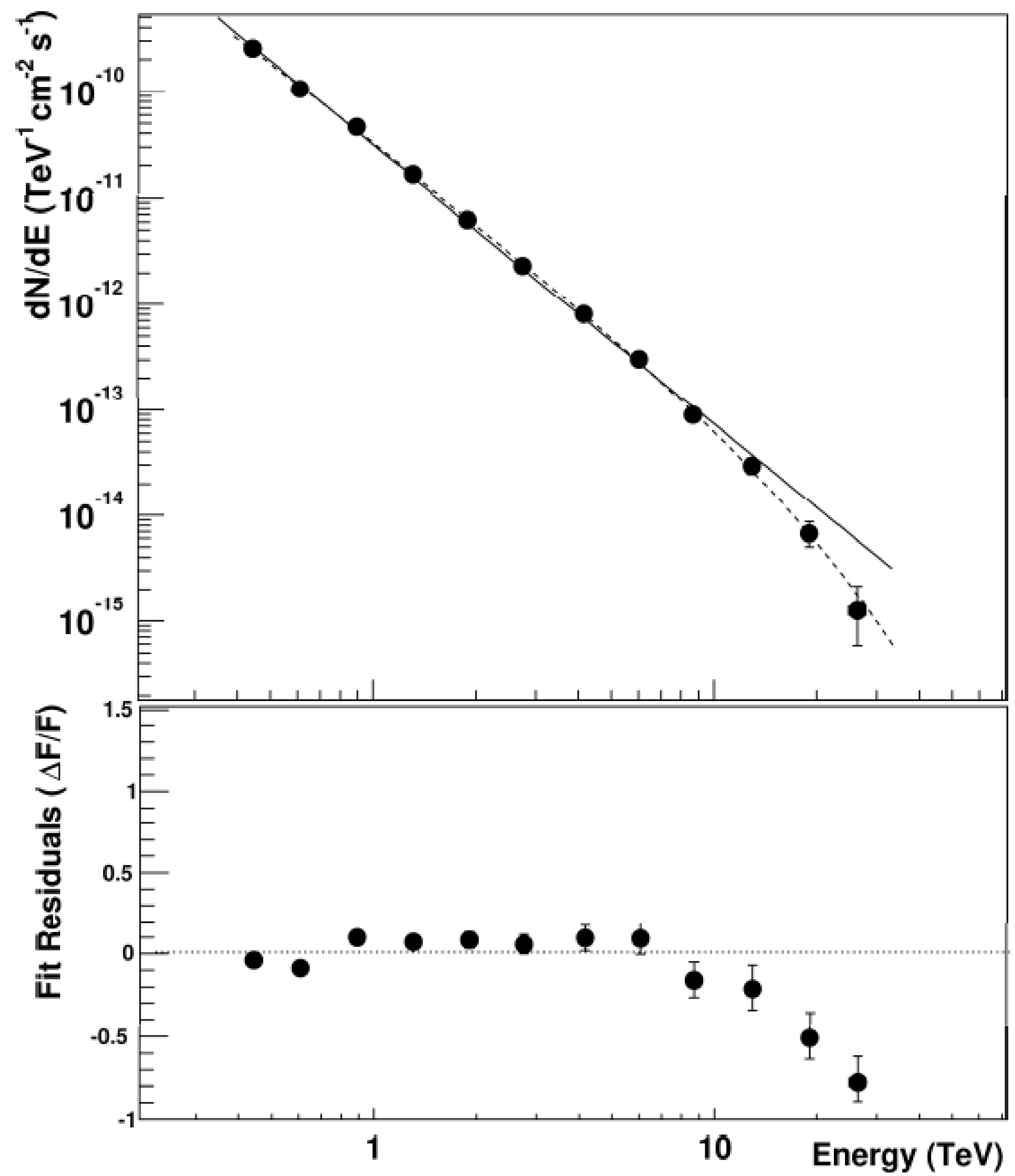
Name	Distance	Spin down Flux (E35 ergs/kpc^2/s)
Crab (B0531+21)	2.0	1200
Vela (B0833-45)	0.3	850
3C58 (J0205+6449)	3.2	26
Geminga (J0633+1746)	0.2	13
B1706-44	1.8	10
MSH 15-52 (B1509-58)	4.4	9.2
J0437-4715	0.14	6.1
CTB 80 (B1951+32)	2.5	6.0
G54.1 (J1930+1852)	5.0	4.6
B0656+14	0.3	4.6
G292.0 (J1124-5916)	5.4	4.1
Mouse (J1747-2958)	2.5	4.0
J1617-5055	6.5	3.8
B1046-58	3.0	2.3
J1524-5625	3.8	2.2
J0537-6910	49.4	2.0
J1357-6429	4.0	1.9
J1420-6048	7.7	1.8
B1823-13	4.1	1.7

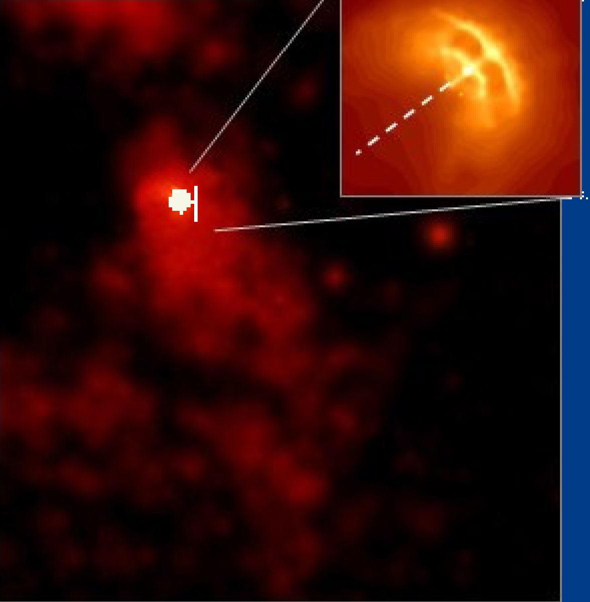


Crab

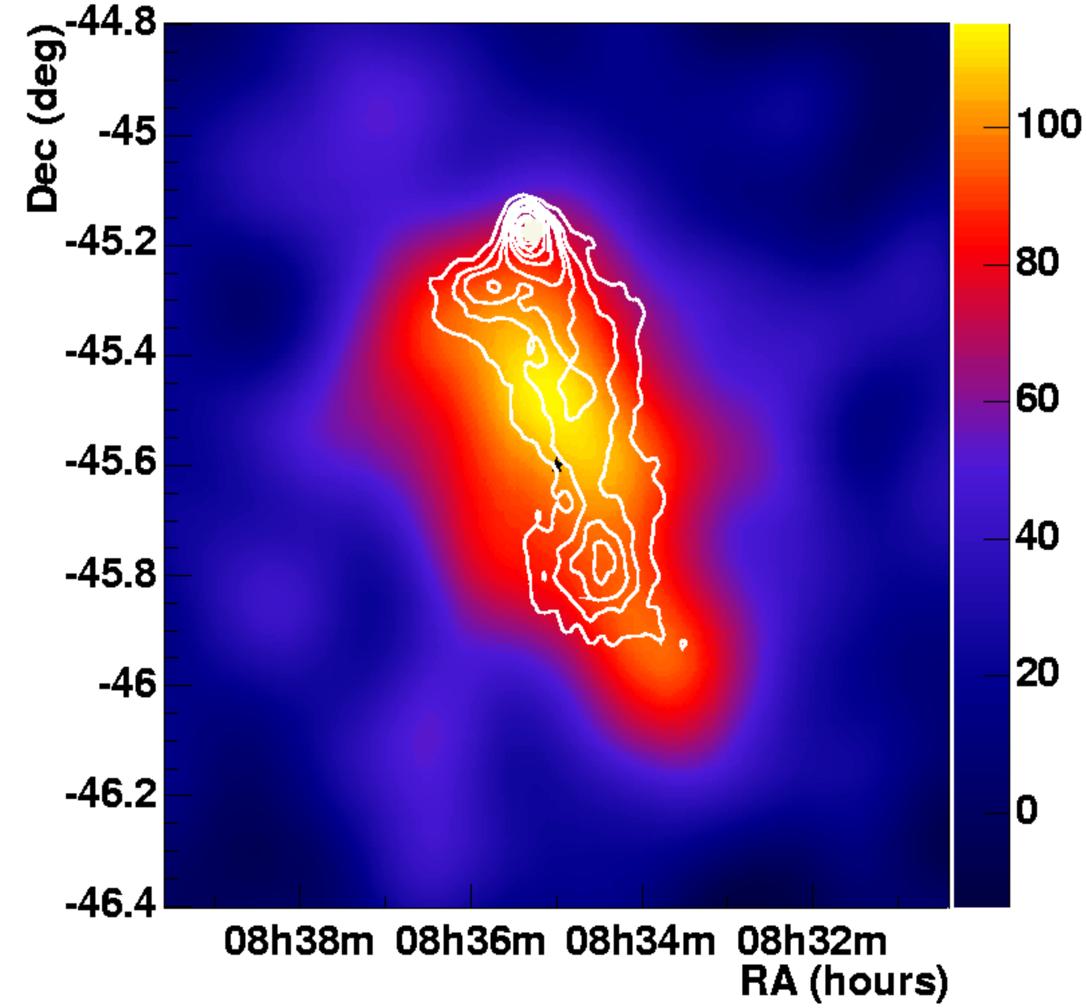
- Brightest steady VHE gamma-ray source
- Large zenith angles for HESS, energy threshold 400 GeV spectrum up to 30 TeV
- Point source for HESS, position consistent with X-ray PWN AND with Pulsar
- Indication for curvature in spectrum
- MWL data → leptonic origin



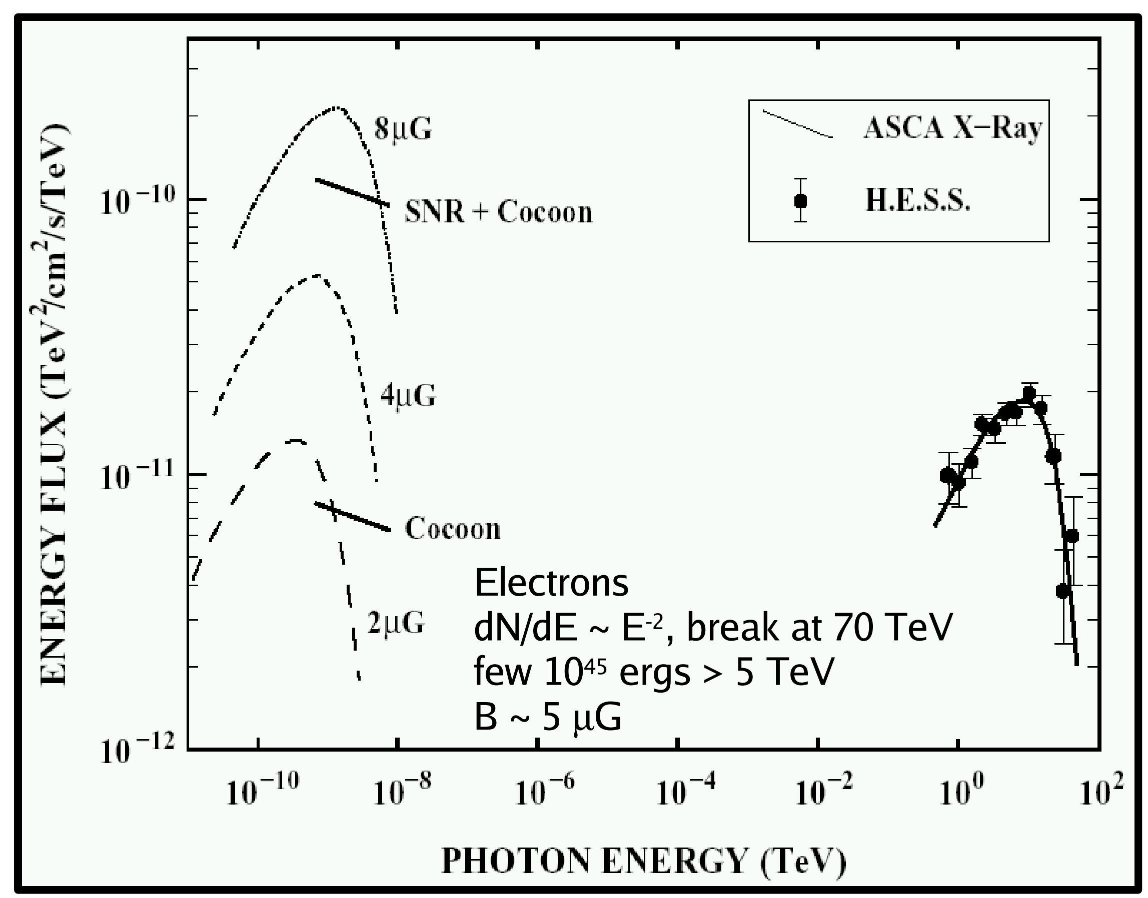


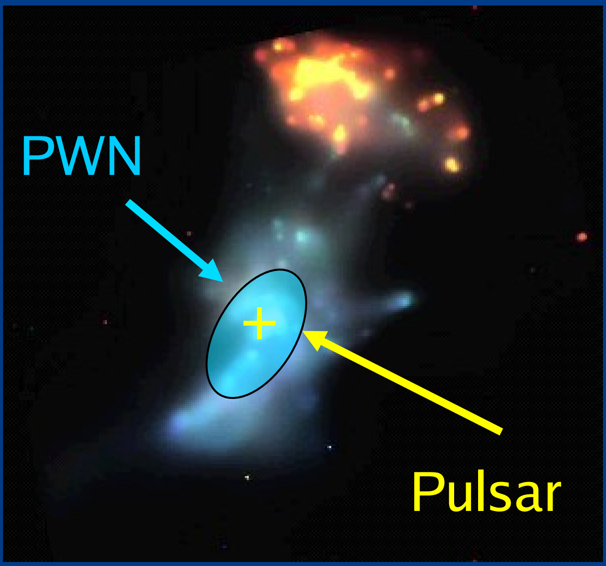


Vela X



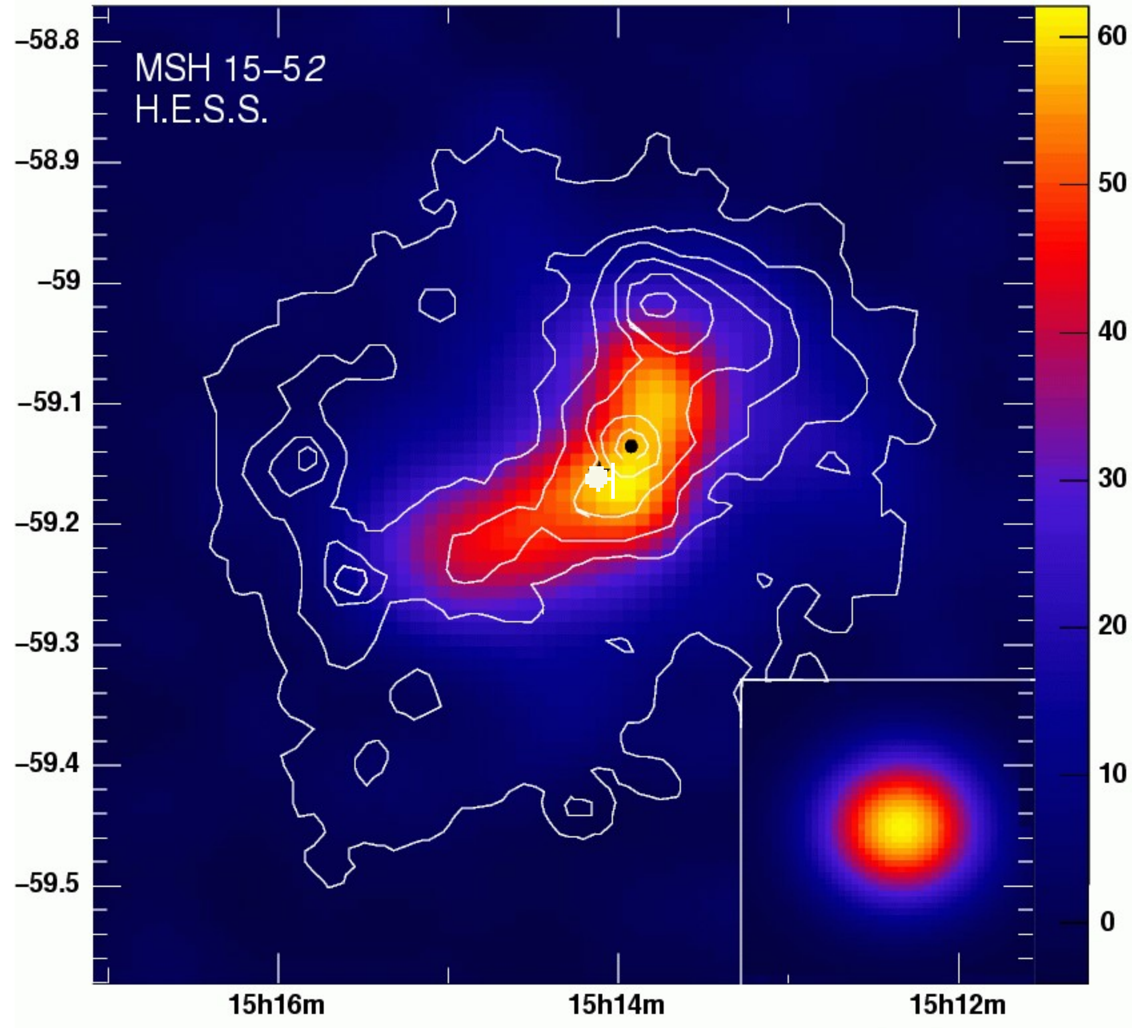
- Elongated structure, extending to the south of the pulsar, follows ROSAT X-ray emission
- Correlation to X-rays and spectrum clearly favours leptonic origin
- Clearly peaked spectral energy distribution suggests IC bump (normally at lower energies)
- No excess at the Vela Pulsar
- Interesting GLAST target



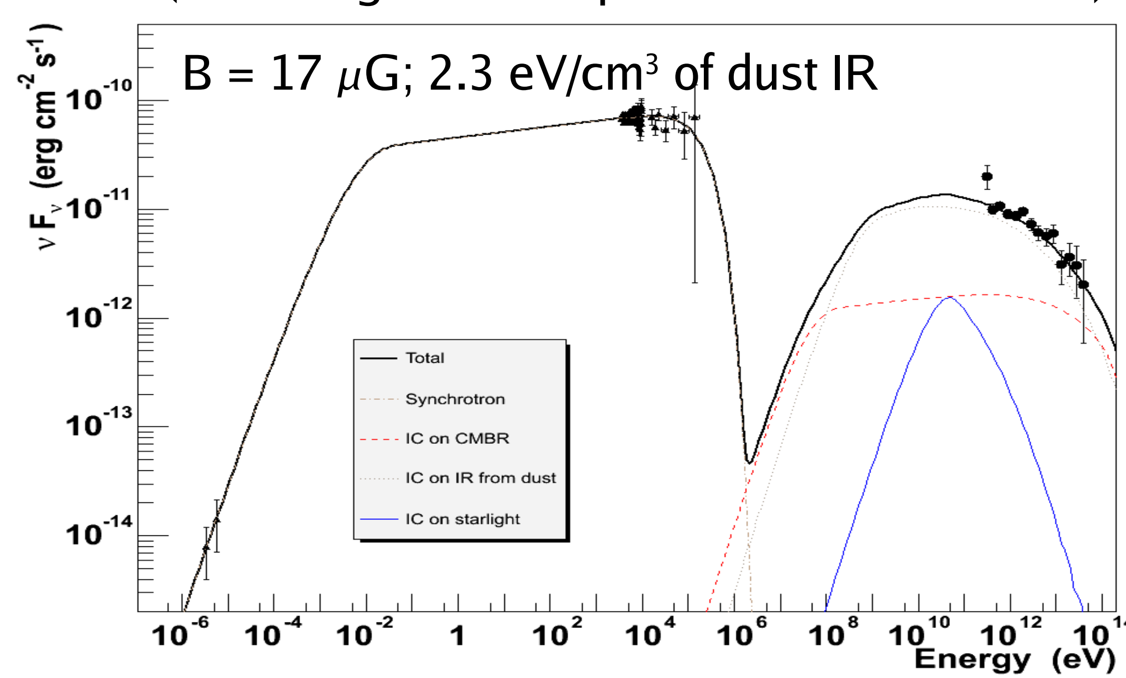


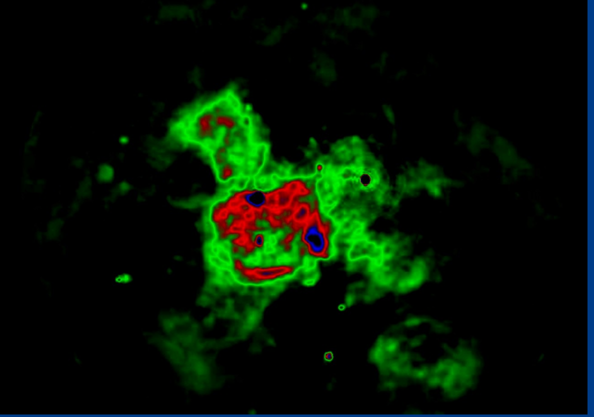
MSH 15-52

- Elongated structure, follows ROSAT X-ray emission
- X-ray and gamma-ray collimated emission along the pulsar axis
- Photon index of 2.3, again can be modelled with a Leptonic model
- Nothing seen by EGRET!



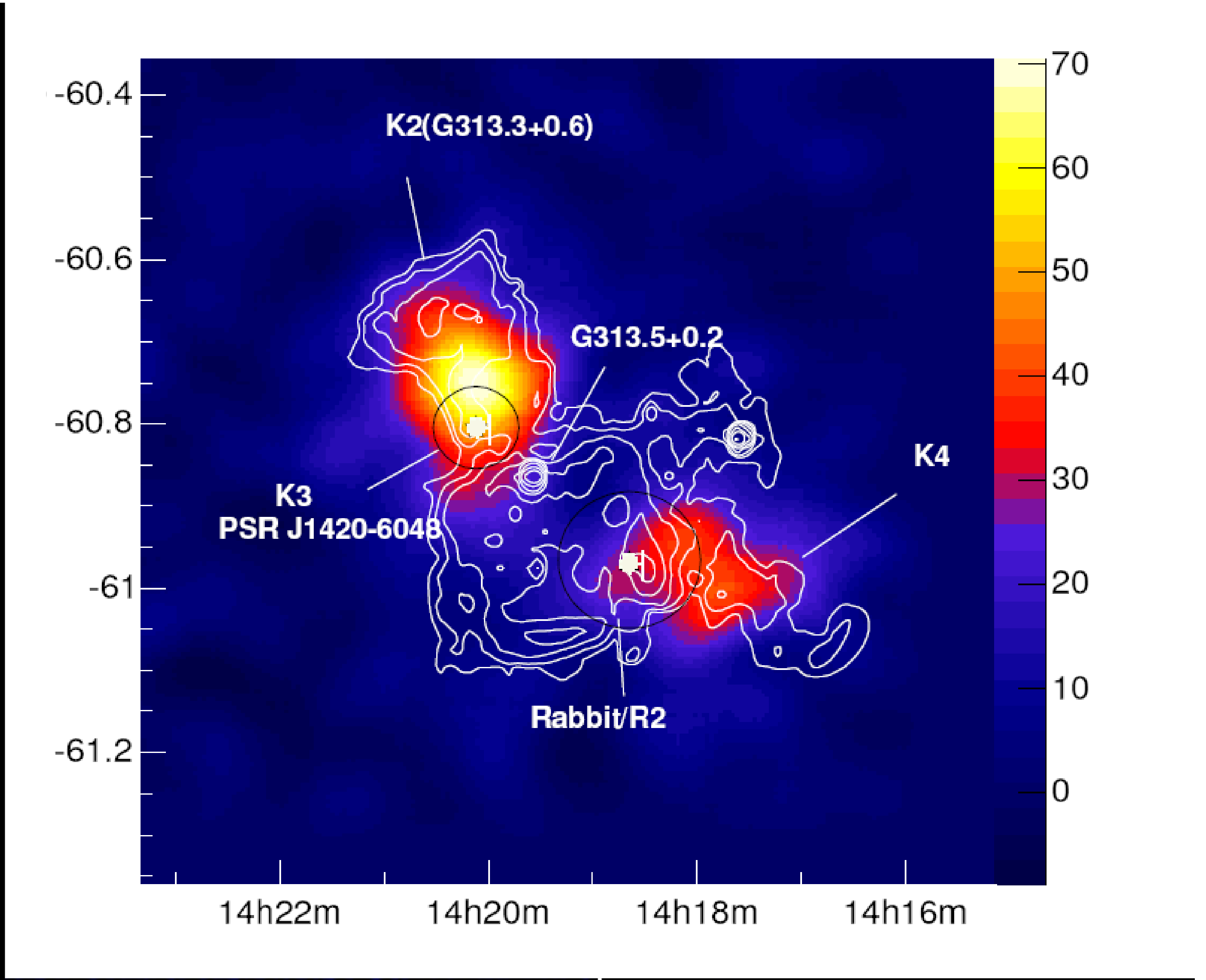
One-zone emission model
(assuming a broken power-law for electrons)

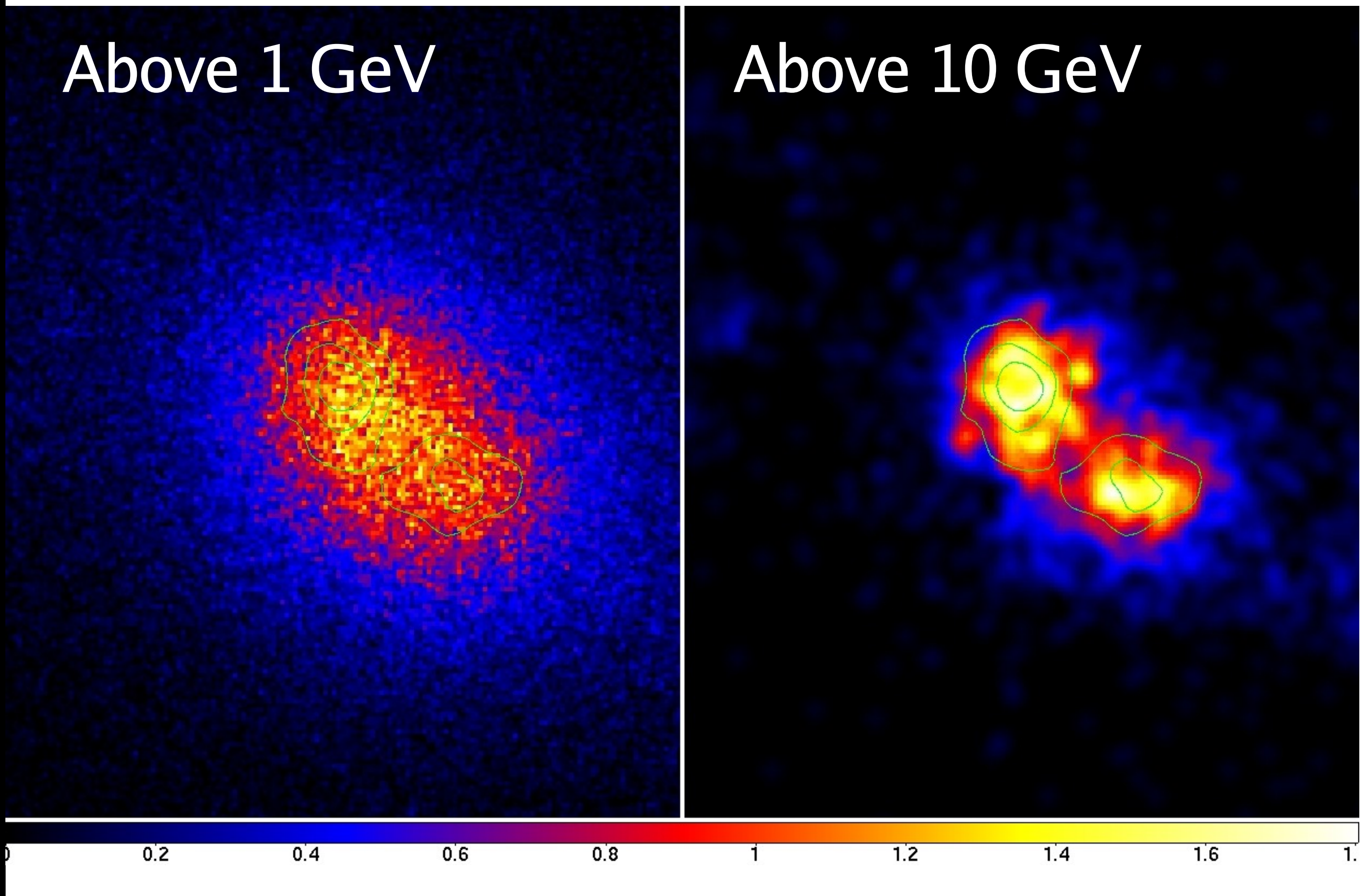


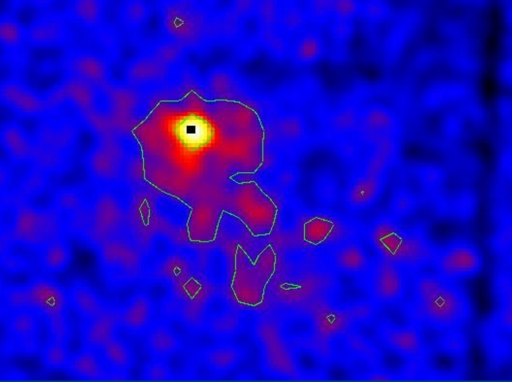


Kookaburra

- VHE gamma-ray emission coincident with the two non-thermal wings
- Again extending asymmetrically
- Photon index: 2.3, consistent leptonic model possible (requires high B-Field)
- Very interesting EGRET and GeV source (composite) – no pulsation
- Interesting GLAST target



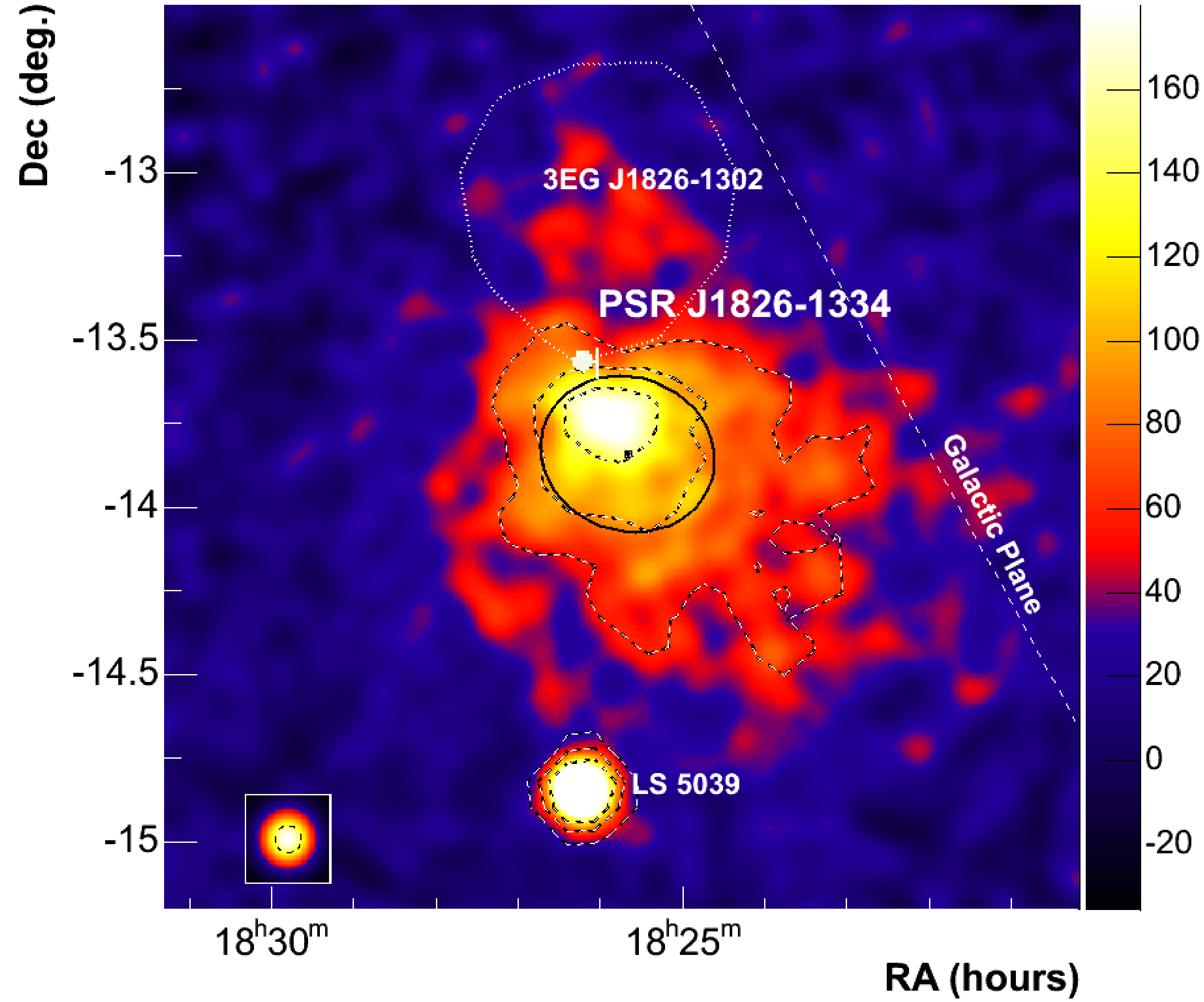


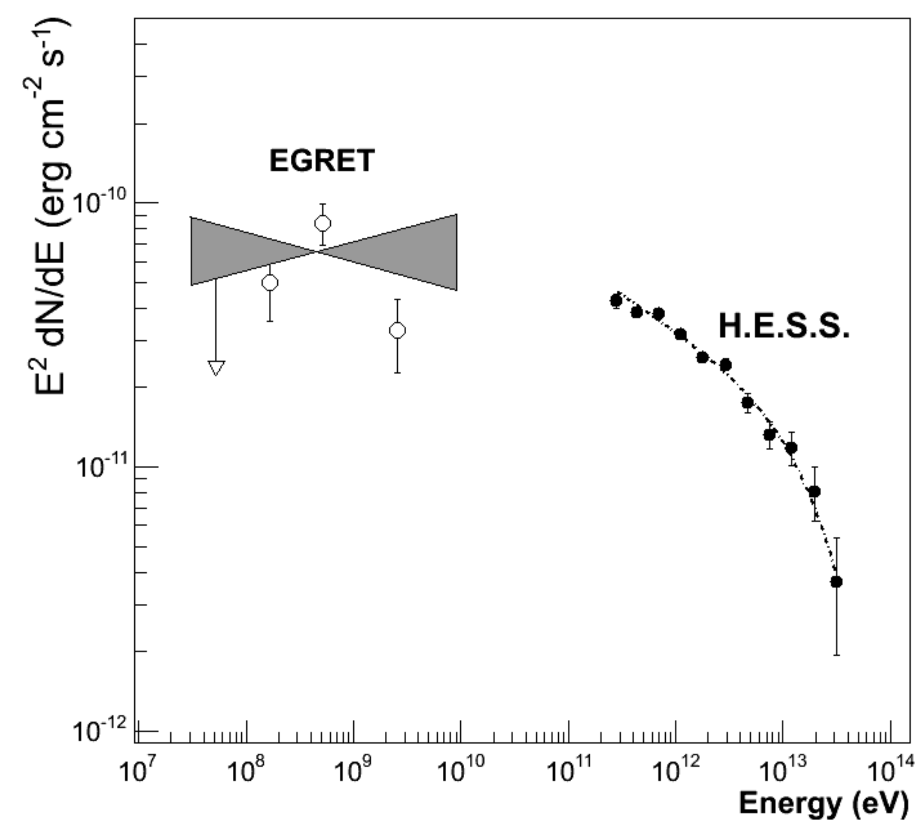


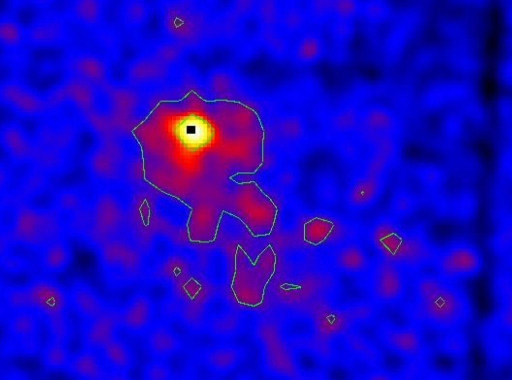
PSR B1823

- Vela-like pulsar, distance 4kpc
- Asymmetric X-ray PWN extending 5' to the south of the pulsar.
- CO cloud to the north at 4 kpc
- VHE gamma-ray scale factor 10 bigger than X-ray scale
  - Difference in energy of X-ray- and gamma-ray-emitting electrons
  - 1 keV Synch photons from 50 TeV electrons
  - 100 GeV IC photons from 1 TeV electrons

$$E_e \sim 20\,(E_g/\mathrm{TeV})^{-1/2}\ \mathrm{TeV}$$







PSR B1823

- Vela-like pulsar, distance 4kpc
- Asymmetric X-ray PWN extending 5’ to the south of the pulsar.
- CO cloud to the north at 4 kpc
- VHE gamma-ray scale factor 10 bigger than X-ray scale
  - Difference in energy of X-ray- and gamma-ray-emitting electrons
  - 1 keV Synch photons from 50 TeV electrons
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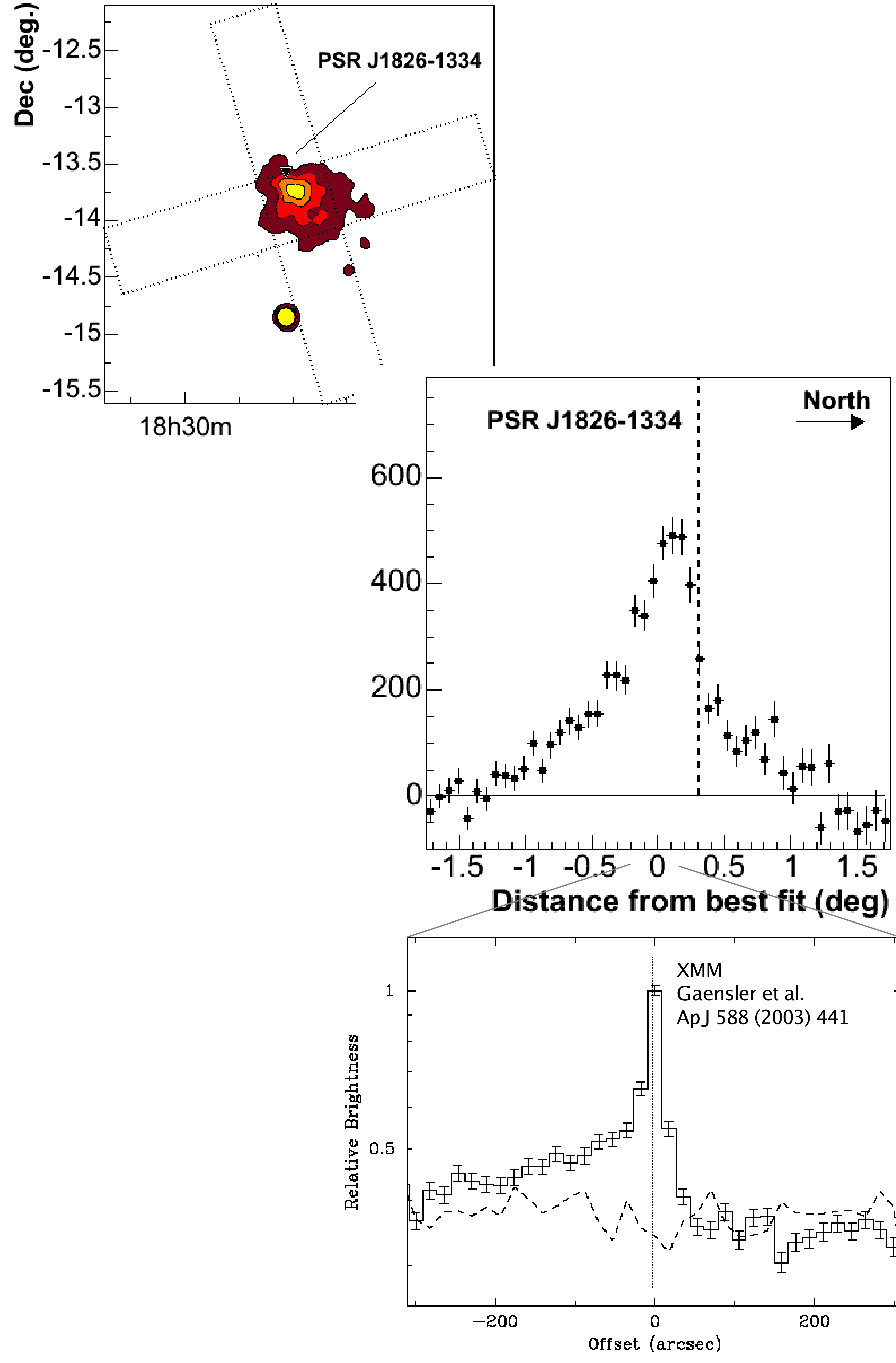

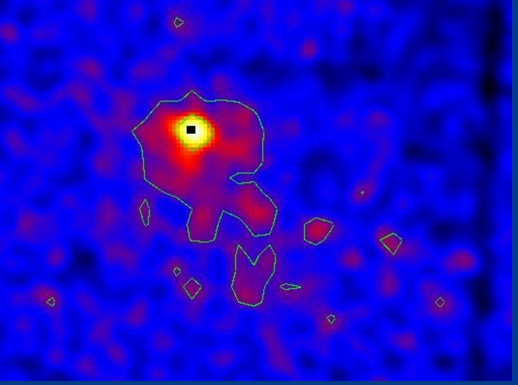

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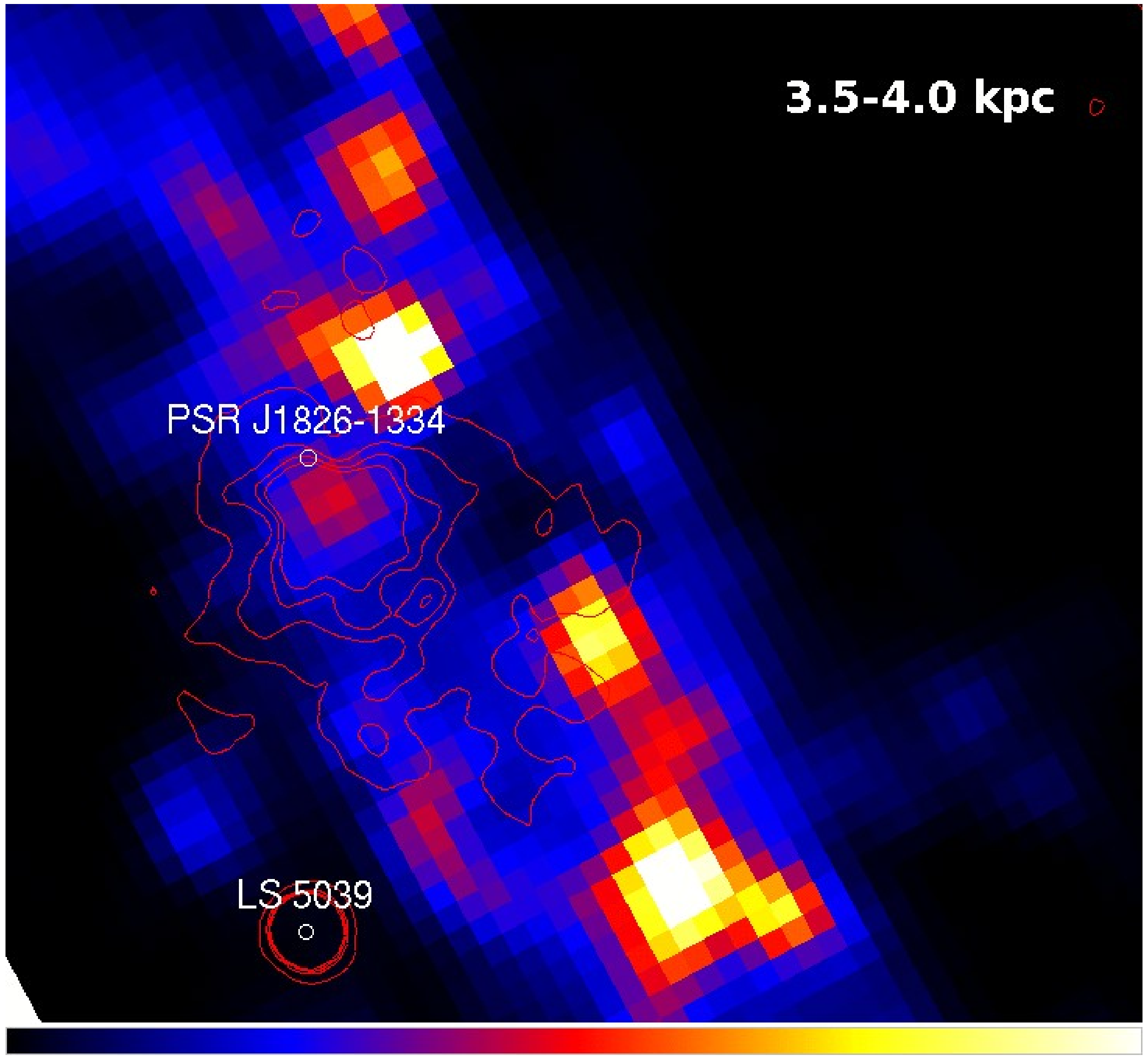

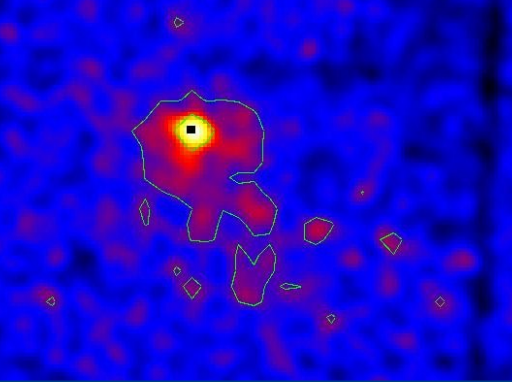

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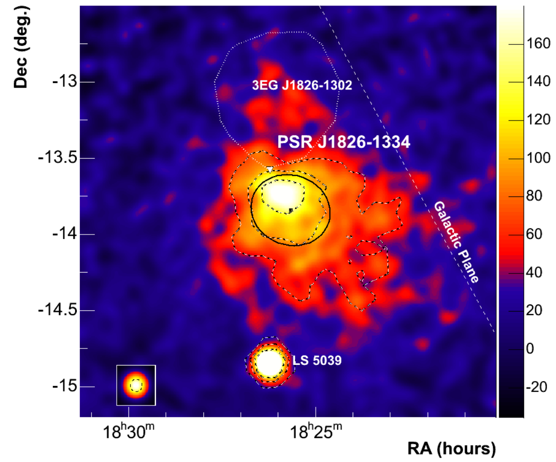
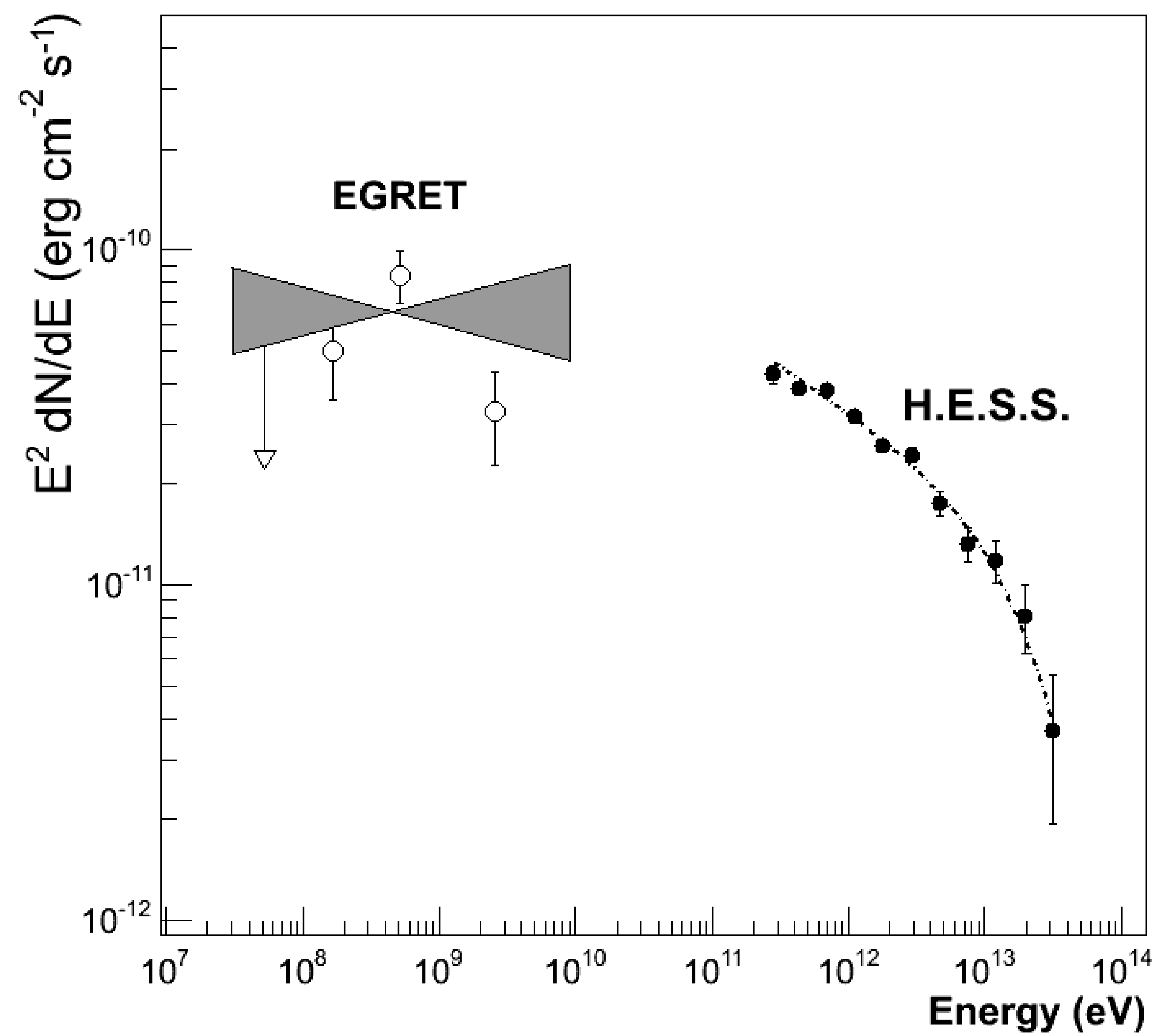


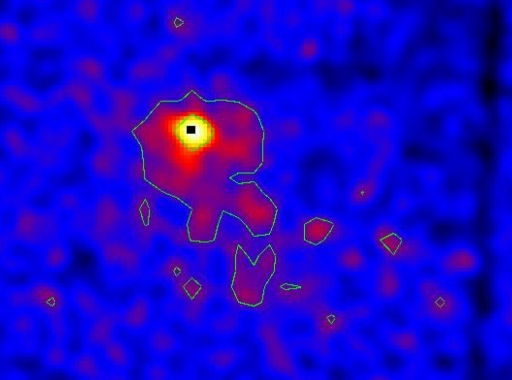
- Energy budget: gamma-flux comparable to Crab, but at 4 kpc (compared to 1 kpc) and spin down luminosity factor 100 lower.

- Must be very efficient

  $L_g \sim 10\%\ E_{pulsar}$

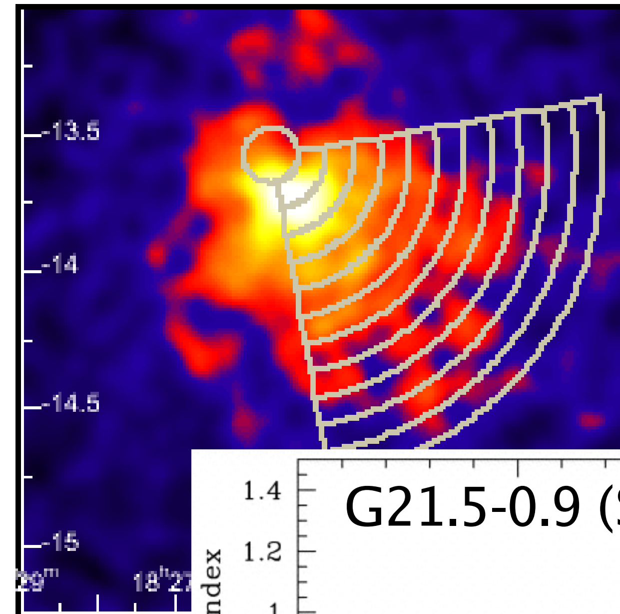
- Electrons from earlier epochs need to have survived till now to explain the sub-TeV flux

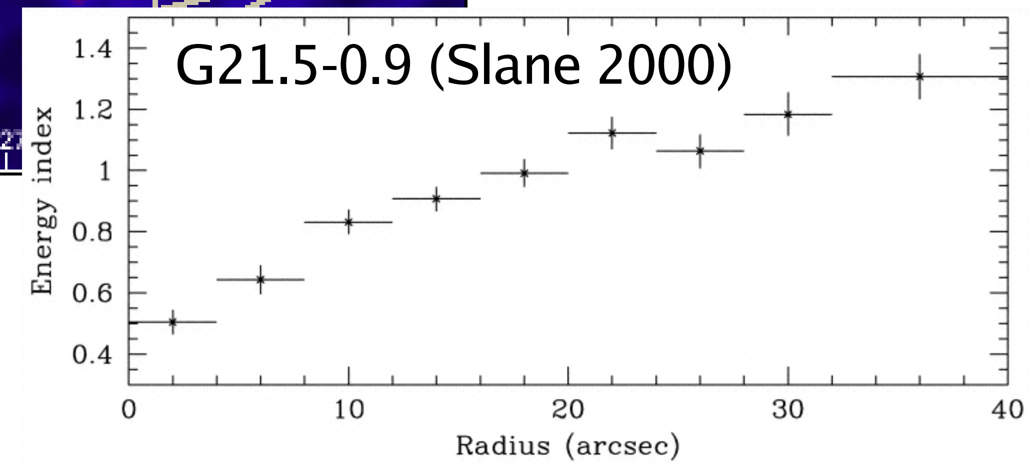


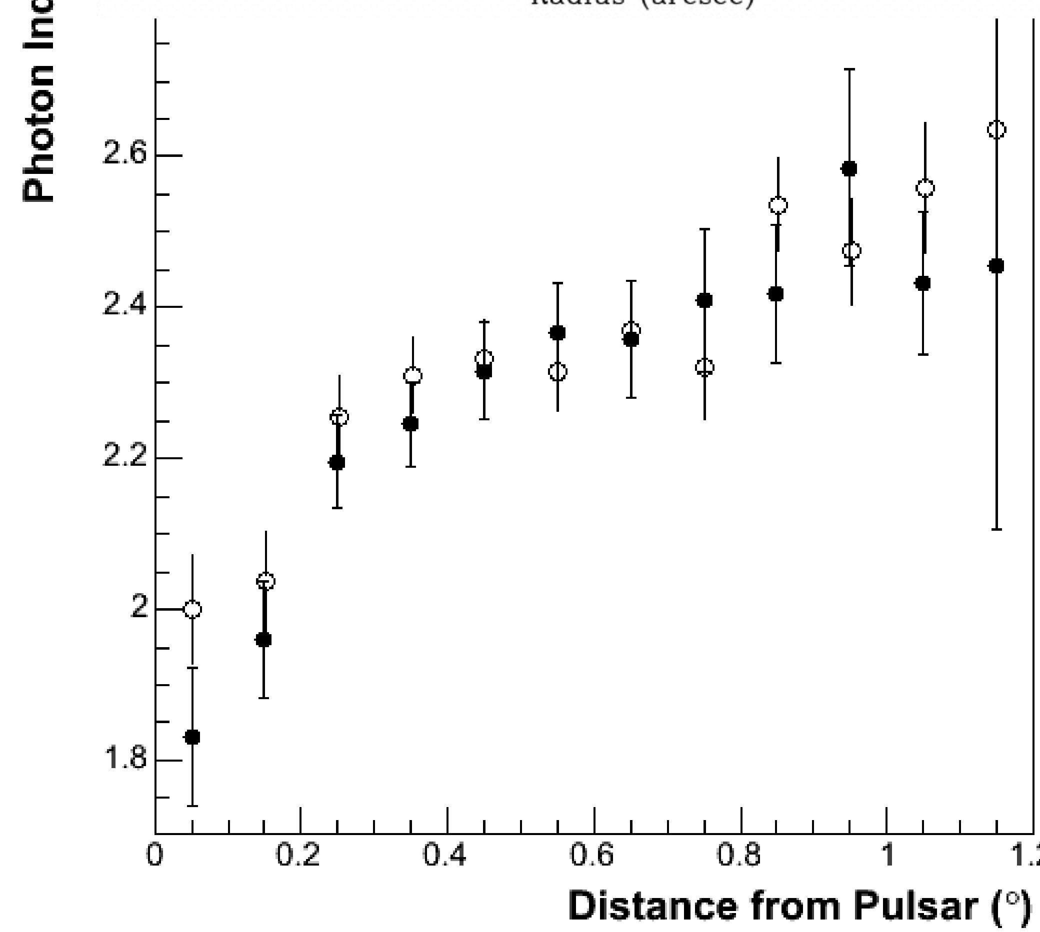


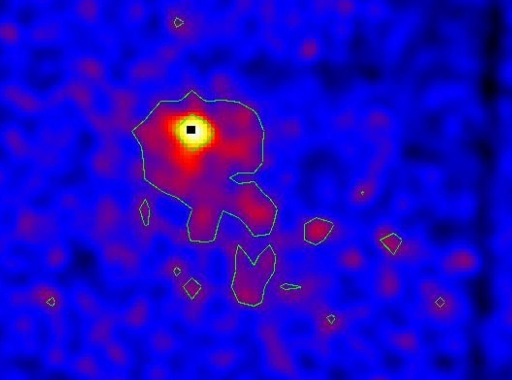
PSR B1823

- Energy dependent morphology as clear indication for e$^-$ cooling, i.e. energy loss of particles during propagation
  - Cooling time $\tau = E/(dE/dt)$, sync/IC: $dE/dt \sim E^2$
  - Other options: energy dependent diffusion speeds or variation of shape of injection spectrum in time
- Cooling timescales for 10 to 100 TeV electrons is below 20 kyears already for magnetic fields ~ 6 μG
  →Cooling expected!









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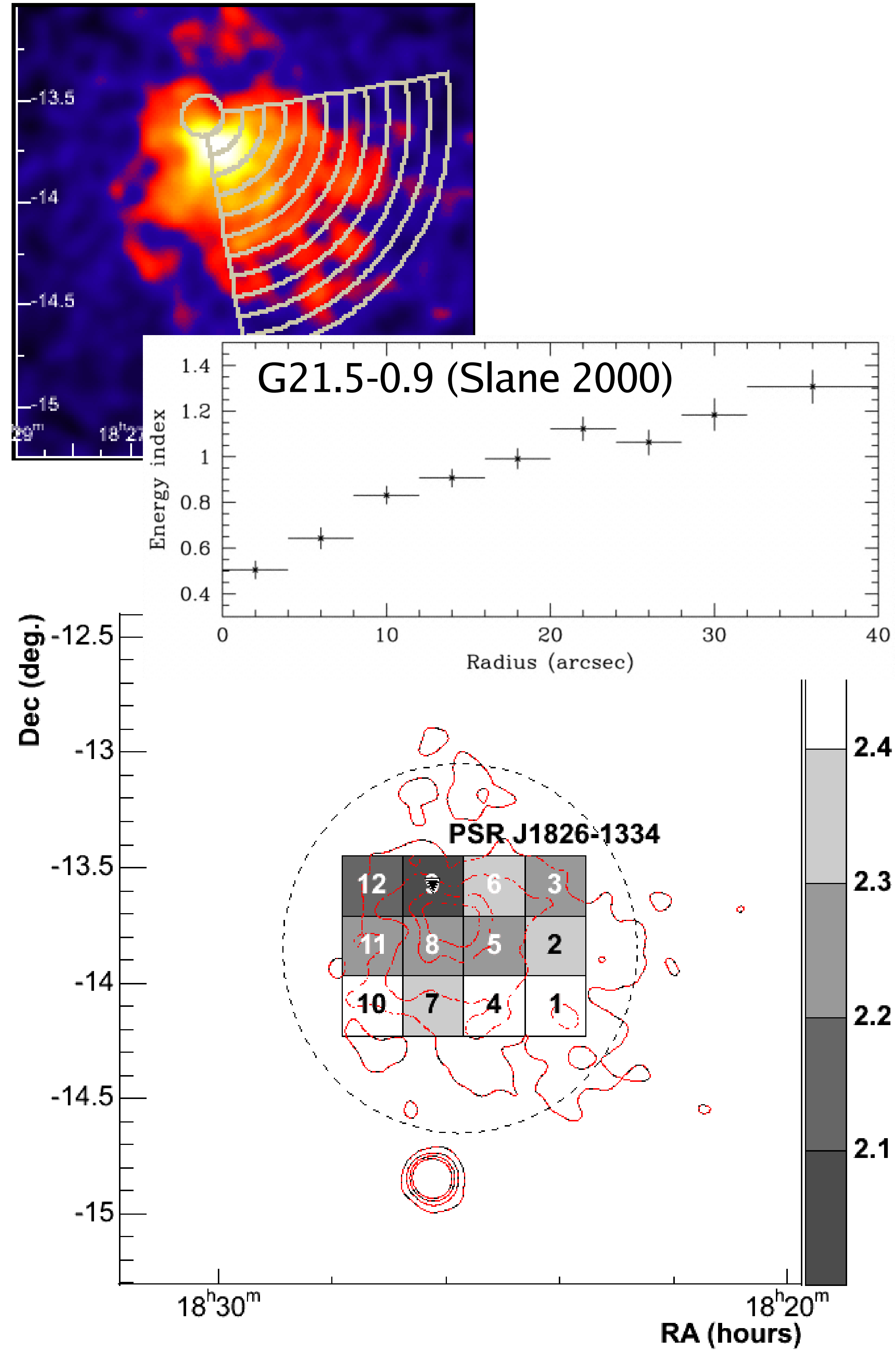
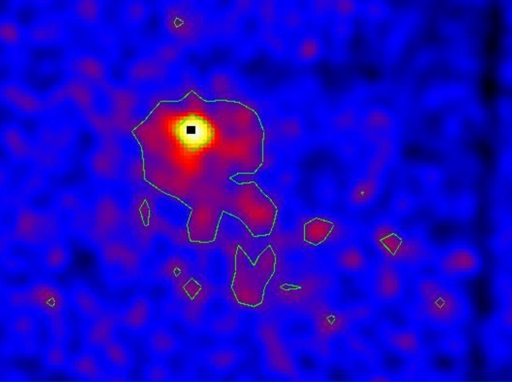
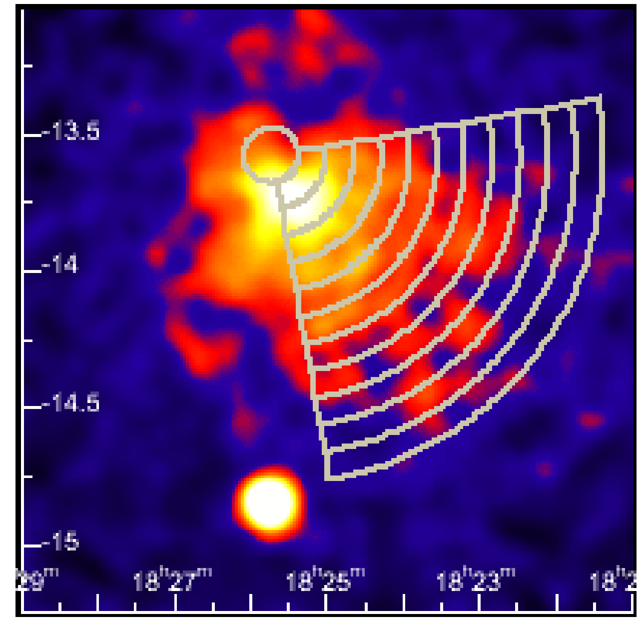
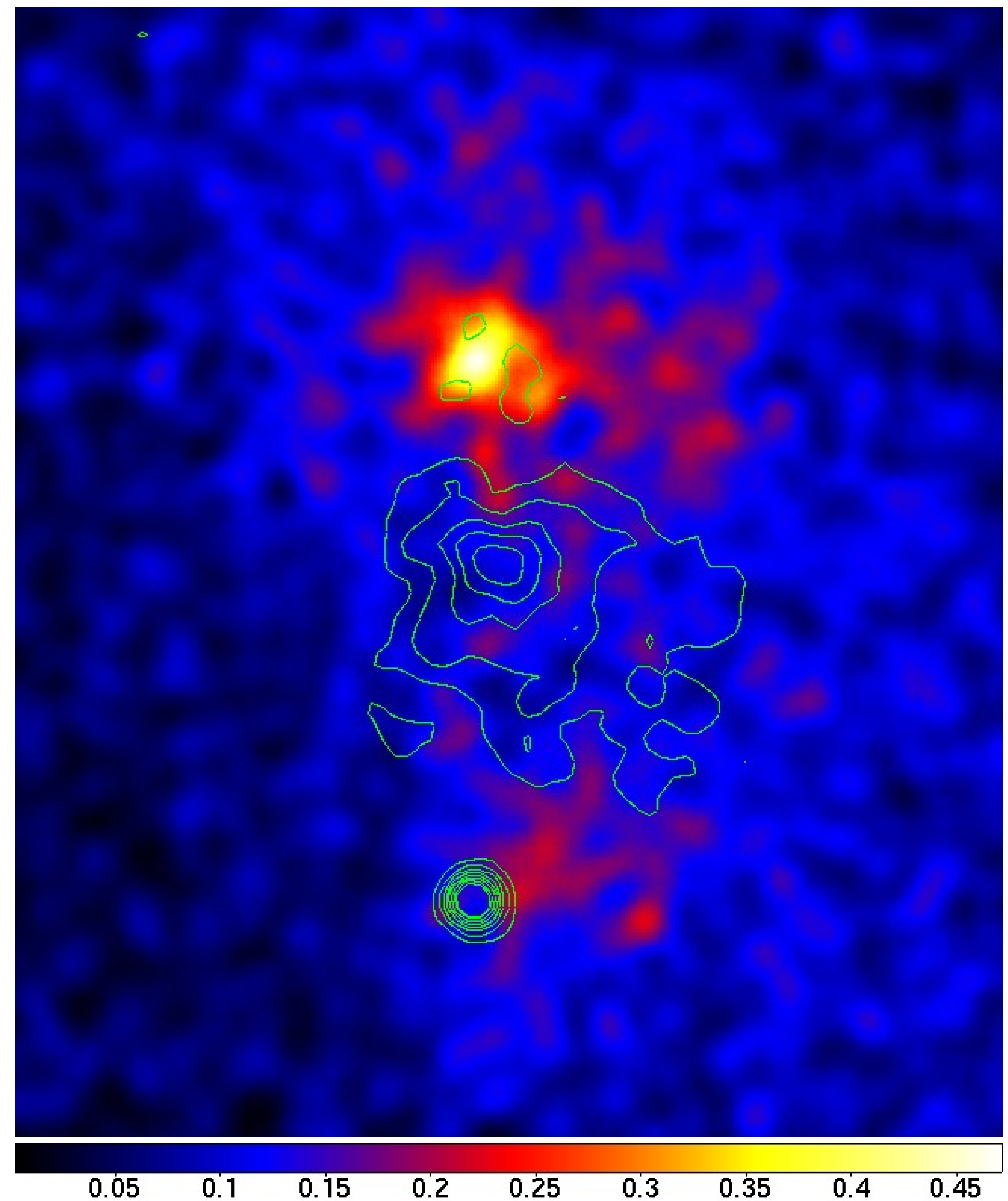




PSR B1823

- Prospects for GLAST:
  - Again difficult, since bright EGRET source in the vicinity
  - Quick check in DC2 data …





Highest energy pulsars

- High energy pulsars with X-ray synchrotron nebulae seem to be a really good case for Gamma-ray PWN (not surprising).
- Need to understand them individually in terms of MWL data to understand the population
- Started on predictions for GLAST in terms of different models
  - RXJ 1713.7
  - The VHE pulsar wind nebulae

Name	Spin down Flux	HESS
Crab (B0531+21)	1200	HESS J0534+220
Vela (B0833-45)	850	HESS J0835-455
3C58 (J0205+6449)	26	
Geminga	13	
B1706-44	10	
MSH 15-52 (B1509-58)	9.2	HESS J1514-591
J0437-4715	6.1	
CTB 80 (B1951+32)	6.0	
G54.1 (J1930+1852)	4.6	
B0656+14	4.6	
G292.0 (J1124-5916)	4.1	
Mouse (J1747-2958)	4.0	
J1617-5055	3.8	HESS J1616-508
B1046-58	2.3	
J1524-5625	2.2	
J0537-6910	2.0	
J1357-6429	1.9	
J1420-6048	1.8	HESS J1420-607
B1823-13	1.7	HESS J1825-137

Summary

- We are getting closer in the search for the origin of cosmic rays. It would be very nice if GLAST could finally solve the problem before the 100^{th} anniversary of their discovery
- PWN around energetic pulsars present the first “real” population of VHE gamma-ray sources. Their study will be fruitful with GLAST
- More to come …