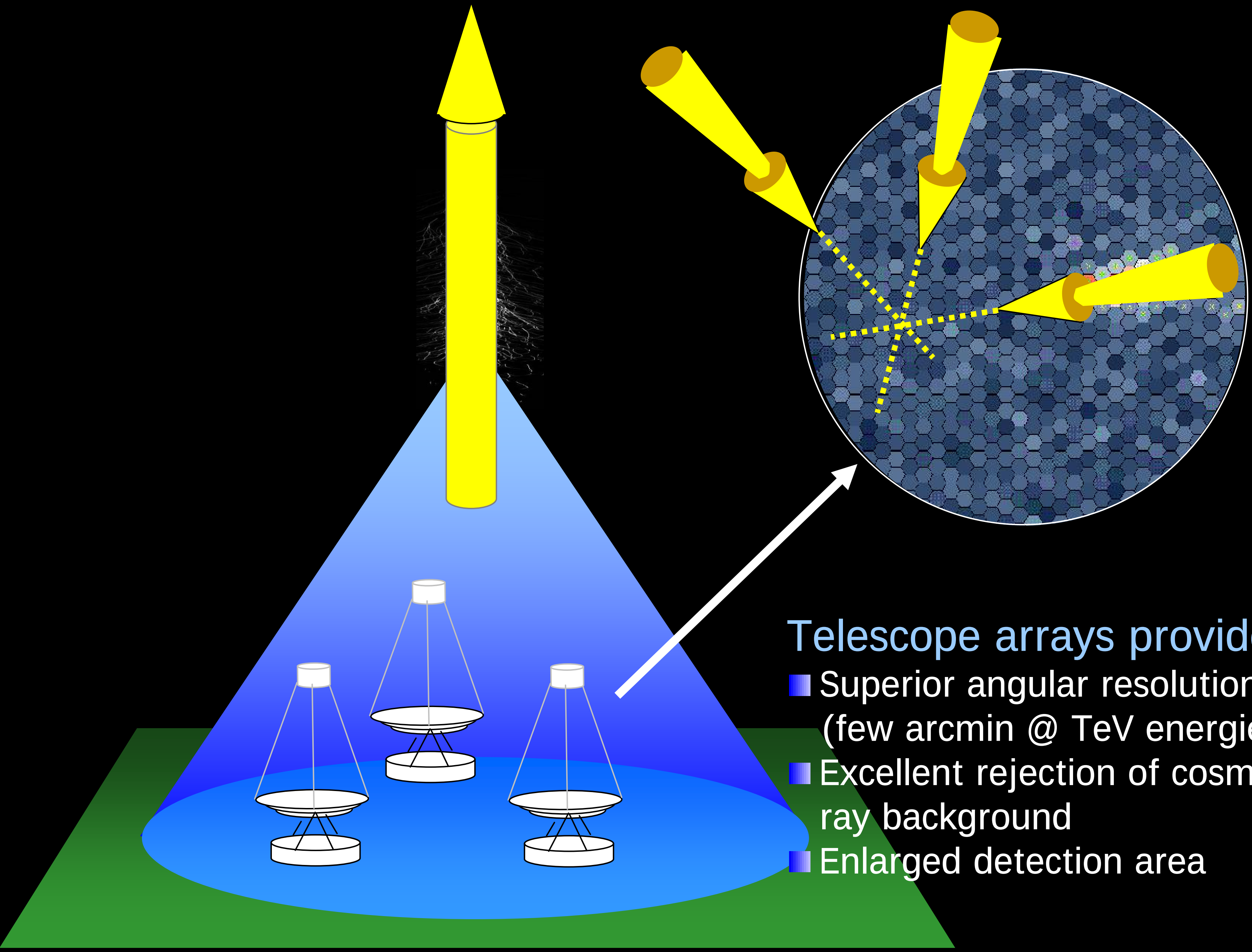
Gamma-Rays from Pulsars and Pulsar Wind Nebulae: Observations and Theory

O. de Jager, for the H.E.S.S. Collaboration

IAU JD02 – Prague – 16 Aug. 2006

H.E.S.S.



Telescope arrays provide

- Superior angular resolution (few arcmin @ TeV energies)
- Excellent rejection of cosmic-ray background
- Enlarged detection area

Contents

- PULSARS
  - Model independent background
  - Constraints on gamma-ray detections
  - KAT-GLAST-HESS II solution
- PULSAR WIND NEBULAE
  - New discoveries
  - Offset PWN
  - Models
  - A new window on pulsar/PWN evolution

Background

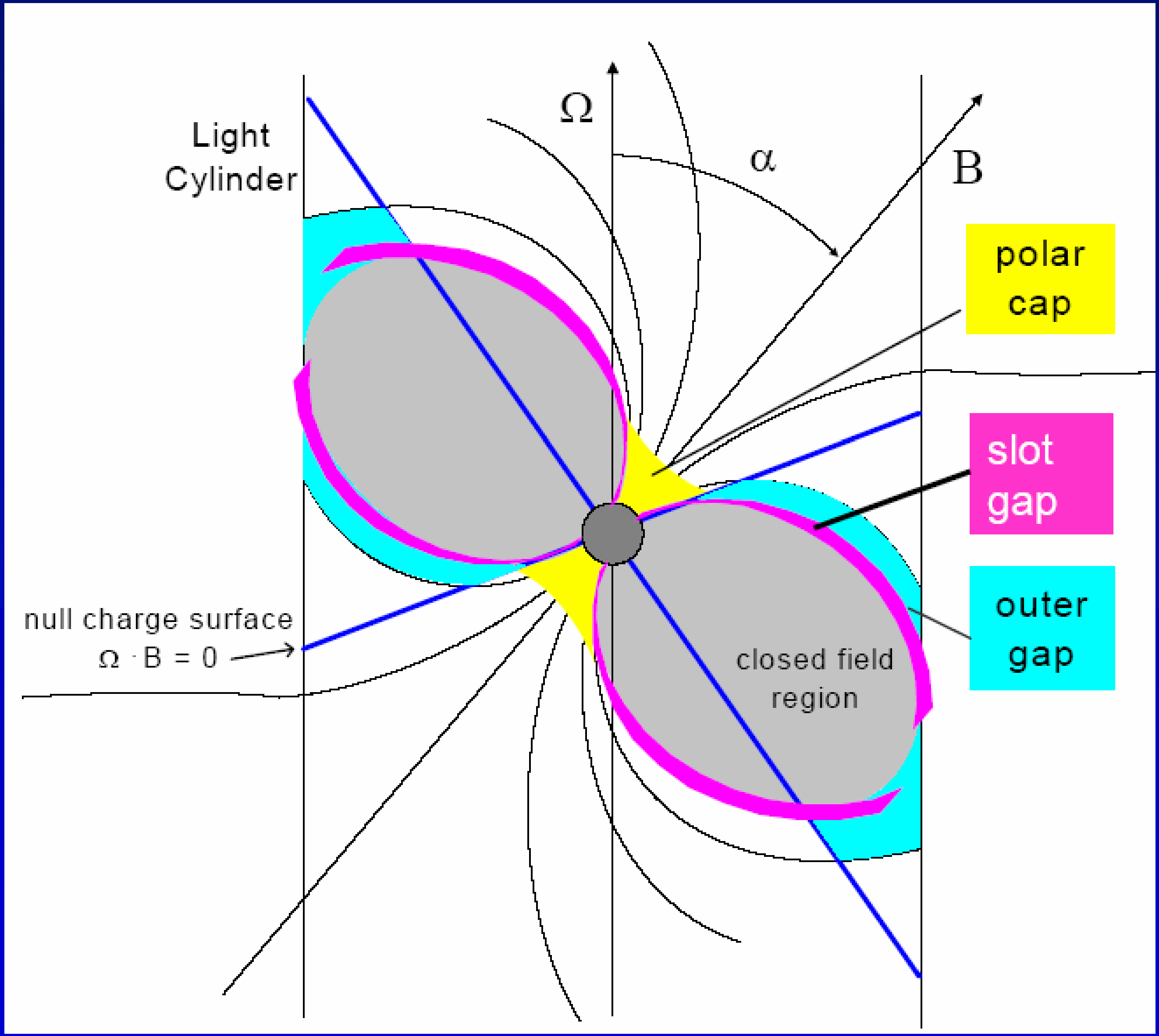
- Strong Magnetic Field & Fast Rotation implies dynamo driven electric field =>
  - Potential Drop and GJ Current $\propto B\Omega^2 \propto L^{1/2}$
  - Particle acceleration (polar cap/slot gap/outer gap) => Gamma-Ray Production.
  - Gamma-ray models predict spectral cutoffs due to various reasons.
  - Significant Pair Production => Radio Emission
- => Gamma-Ray production stands central to all pulsar models.
- Problems with gamma-ray visibility – result of instrument sensitivity problems

Pulsar high-energy emission models

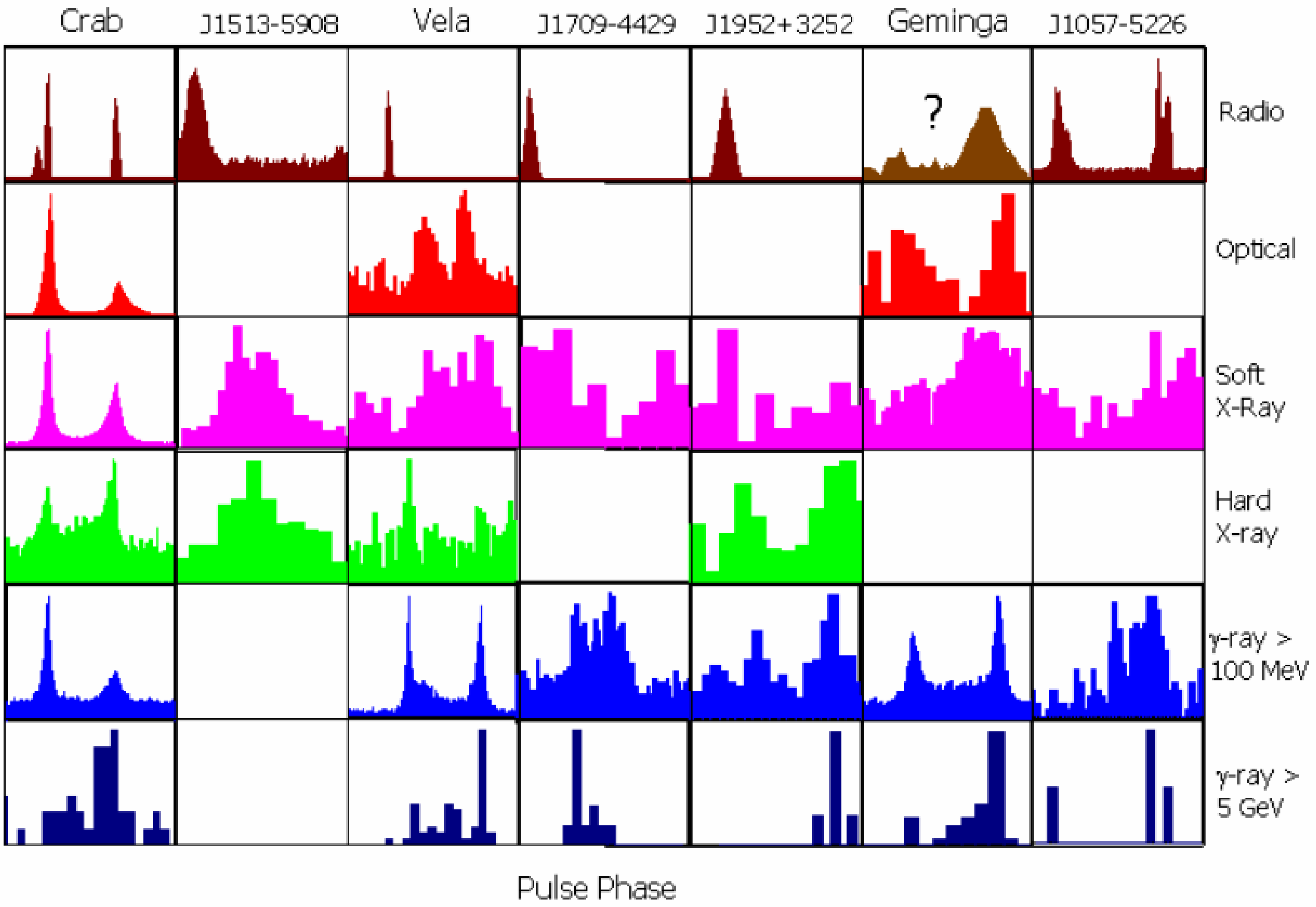
A.K. Harding,

Heraeus

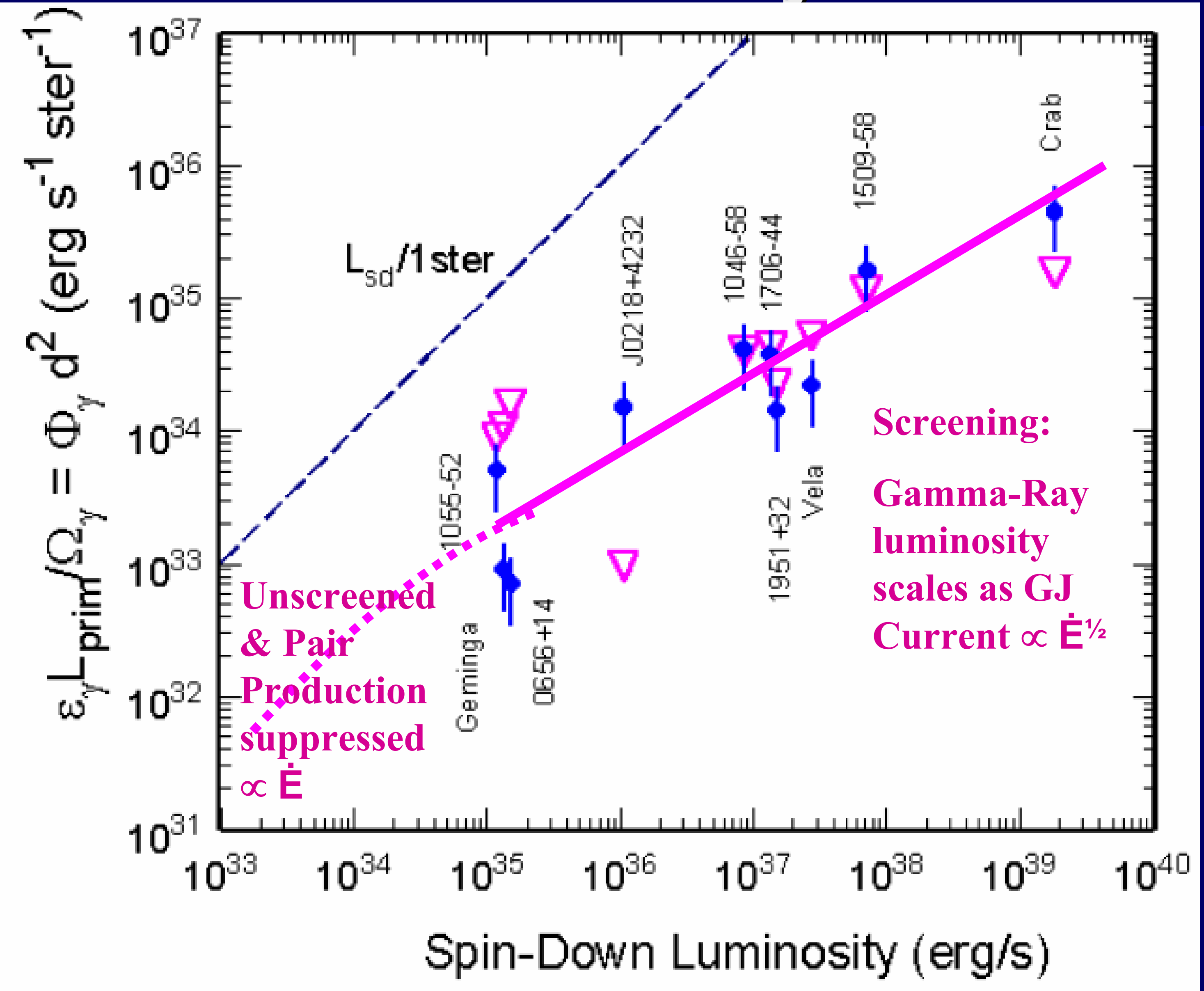
Bad Honef, 2006



The Gamma-Ray Pulsar Landscape



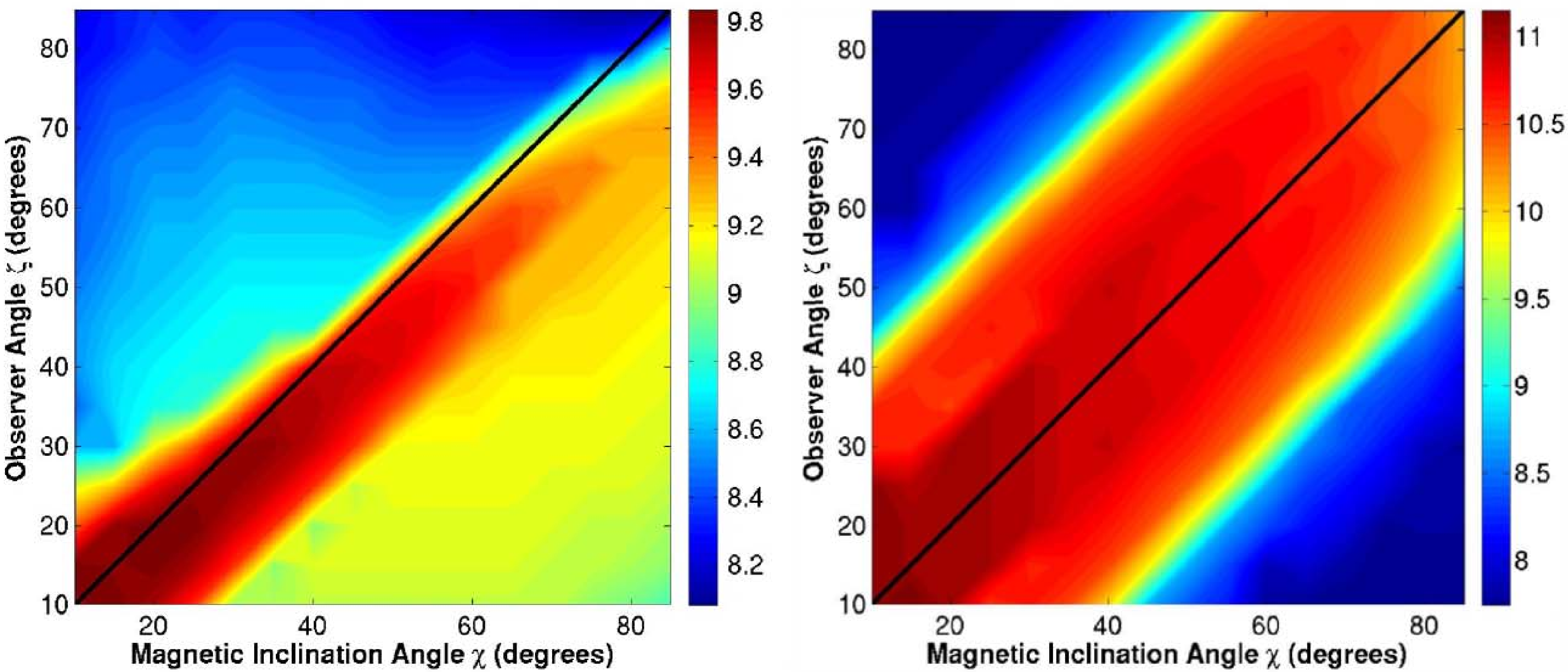
Conversion Efficiency of Spindown Power to Gamma-Rays



Low Spindown Power Pulsars - Unscreened – e.g. Millisecond Pulsars

For direct Polar Cap acceleration (e.g. GR Frame Dragging E-field as in the formalism of Muslimov & Harding)

= > Maximum gamma-ray energy depends sensitively on observer line-of-sight – 3D simulation of Venter & de Jager 2005.



Gamma-ray telescopes and the detection of pulsar pulsed gamma-ray emission.
See talk of David Smith for more details

- Ground-based telescopes: HESS I, MAGIC, VERITAS, CANGAROO have good sensitivity above 0.1 TeV, but models mostly predict spectral turnovers below this energy – wait for HESS II and GREAT (Gamma-Ray European African Telescope)
- EGRET had the proper energy coverage, but lacked collection area for sufficient statistics. Scratched the surface of the pulsar population.
- It is well known that GLAST will be the best instrument to search for PULSED emission from new gamma-ray pulsars. HESS II can also make a contribution above 10 GeV.

Gamma-Ray Pulsar Search strategies

- REQUIREMENT: High count rate relative to pulsar spin frequency allows for independent period searches
  - => Radio quiet pulsars. New information on pulsar beaming.
  - => GLAST (>0.1 GeV) & HESS II (>10 GeV)
- Fainter gamma-ray pulsars require multiwavelength input from radio or X-ray observations.

Limits on independent searches for new γ-ray pulsars :

COPE WITH THE FOLLOWING

SEARCH TIMESCALES:

- Spindown timescale as short as: $T_S < 12$ hours
- Within the timing noise timescale: $T_{TN} < 20$ days
- Within binary Doppler timescales: T_D (short)
- Timing errors due to positional uncertainties (months)

Accumulation of Trial Periods when searching for new gamma-ray pulsars

- T = Observation time – also the sensitivity timescale (i.e. to make a detection)
- T=few hours for HESS II, but up to 1 yr for GLAST
- f_0, df/dt, d^2f/dt^2 = frequency & derivatives
- Frequency after time T due to e.g. spindown & timing noise:

$$f = f_0 + (df/dt)T + \frac{1}{2}(d^2f/dt^2)T^2 + \ldots$$

- Sensitivity timescale T determines the order of the polinomial to be searched:

e.g. Number of Trials (N) for Isolated Canonical Pulsars.

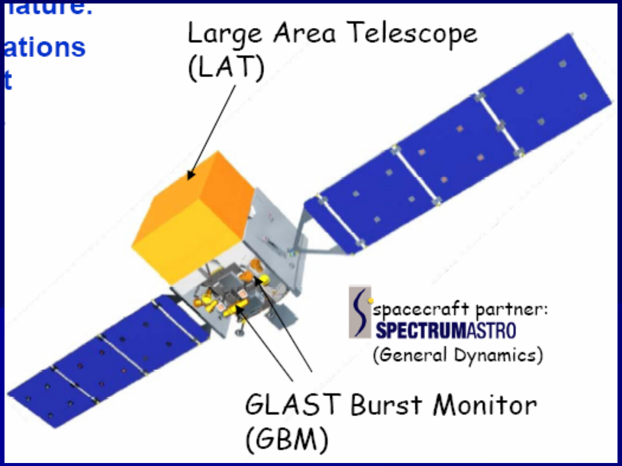
- Assume maximal values for canonical pulsars and assuming
- $\Delta f = (f_{max} - f_{min}) \sim 50$ Hz:
- $|df/dt|_m = 5E\text{-}10\ (s^{-2})$; $|d^2f/dt^2|_m = 2E\text{-}19\ (s^{-3})$
- Three timescales: T_1=12 hr, T_2=20 d, T_3=365 d
- $N_1 = \Delta f\, T_1 \quad = 2\times10^6\ (T_{12\ hr})$
- $N_2 = \Delta f\, |df/dt|_m T_2^3 \quad = 10^{11}\ (T_{20\ d})^3$
- $N_3 = ½\, \Delta f\, |df/dt|_m\, |d^2f/dt^2|_m\, T_3^6 \quad = 3\times10^{18}\ (T_{365\ d})^6$
- => Situation becomes unbearable for long integration times – GLAST quotes sensitivity for 1 year integration.

⇒ Need radio or X-Ray backup for GLAST – multiwavelength support!!!

⇒ Situation less dramatic for HESS II since sensitivity timescale is short if the maximum gamma-ray energy is above 30 GeV – compare 1 square meter for GLAST against 10^8 square meter for HESS II – statistics.

Planned Solution for GLAST

- The top part of the list of high Edot/d^2 pulsars will be covered by a number of existing radio telescopes for GLAST. This has been organised.
- However, limited FoV and limited number of beams per radio telescope makes coverage of ALL candidates impossible.
- Many GLAST sources may remain unidentified.



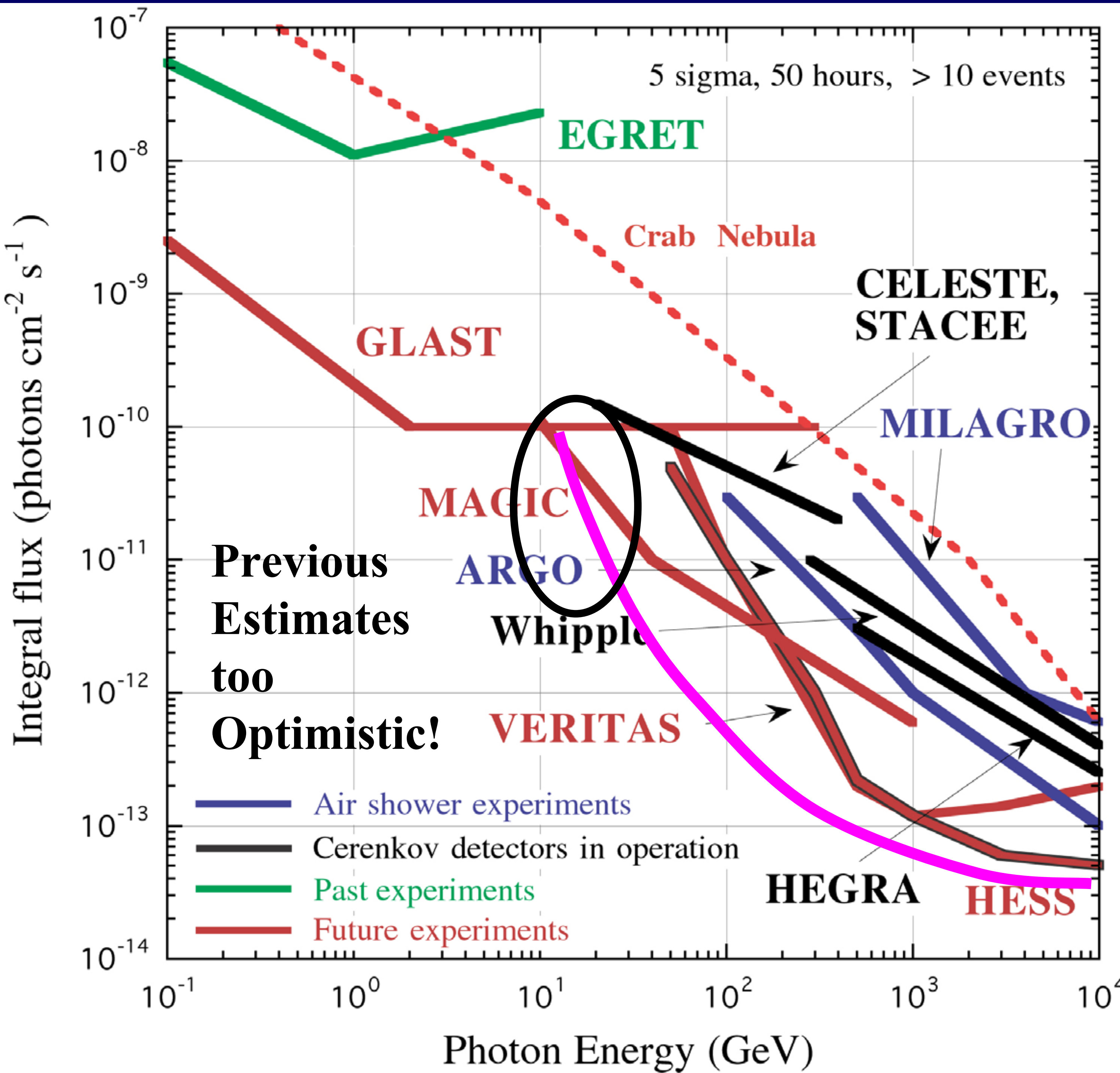
GLAST:

Good statistics in the range 0.1 to 30 GeV

Construction started: H.E.S.S. II 28 m dish

- HESS II

  Pulsed detection possible > 10 GeV

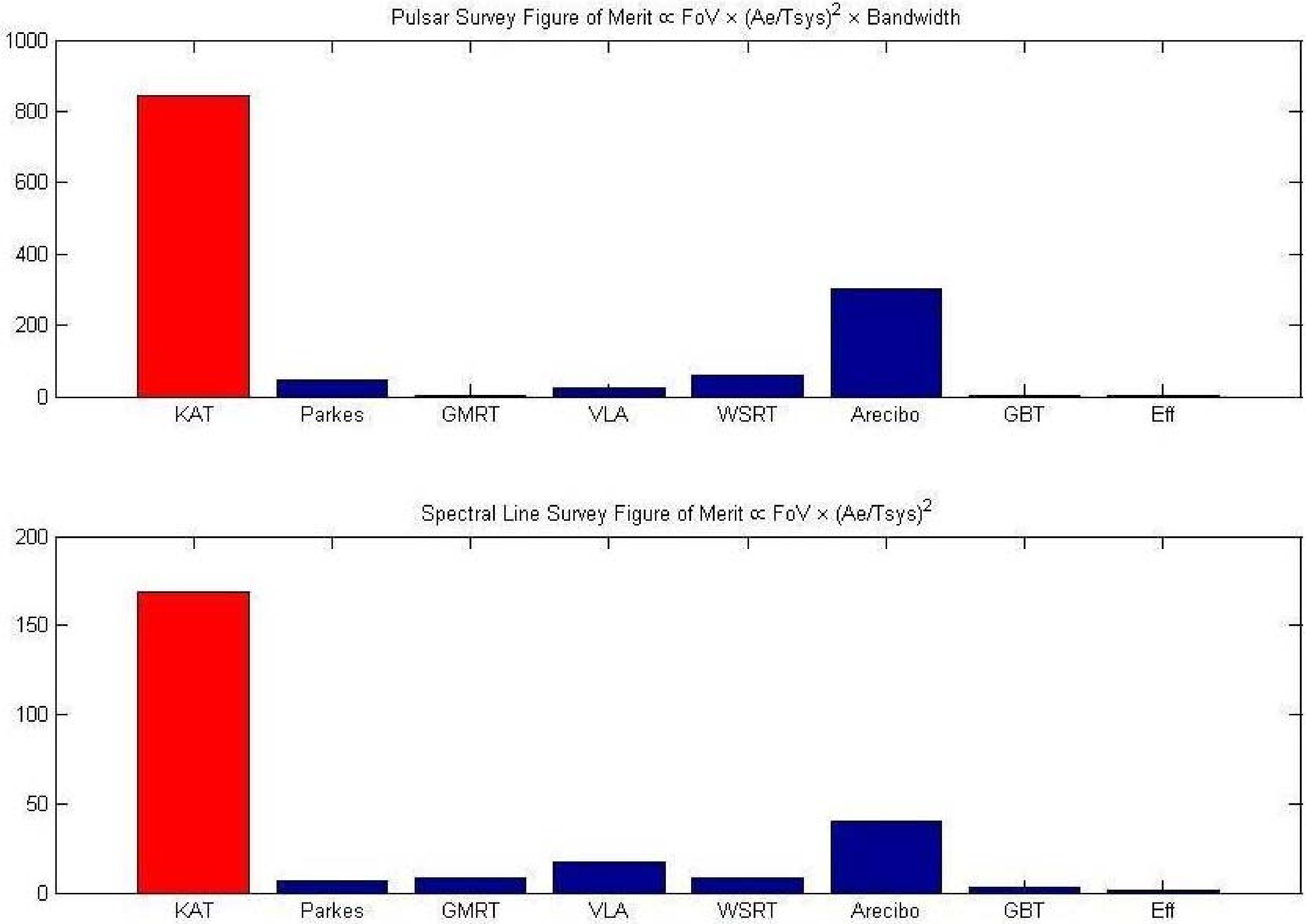

5 sigma, 50 hours, > 10 events
EGRET
Crab Nebula
CELESTE, STACEE
GLAST
MILAGRO
MAGIC
ARGO
Previous Estimates too Optimistic!
Whipple
VERITAS
Air shower experiments
Cerenkov detectors in operation
Past experiments
Future experiments
HEGRA
HESS
Integral flux (photons cm^{-2} s^{-1})
Photon Energy (GeV)
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}

HESS I & II

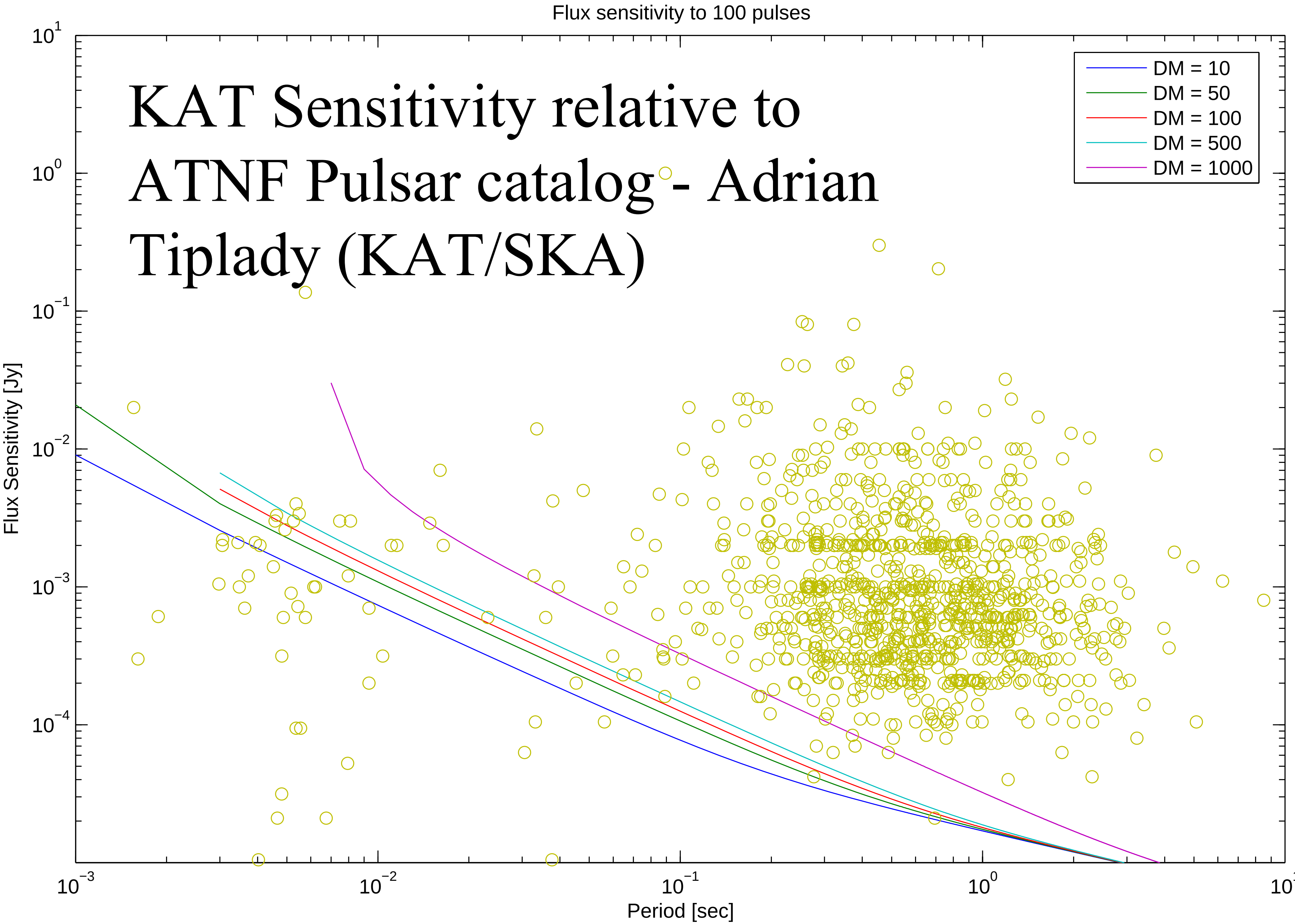
The Karoo Array Telescope (SKA prototype) as a solution for X-ray and Gamma-Ray Pulsar Searches

Why KAT?

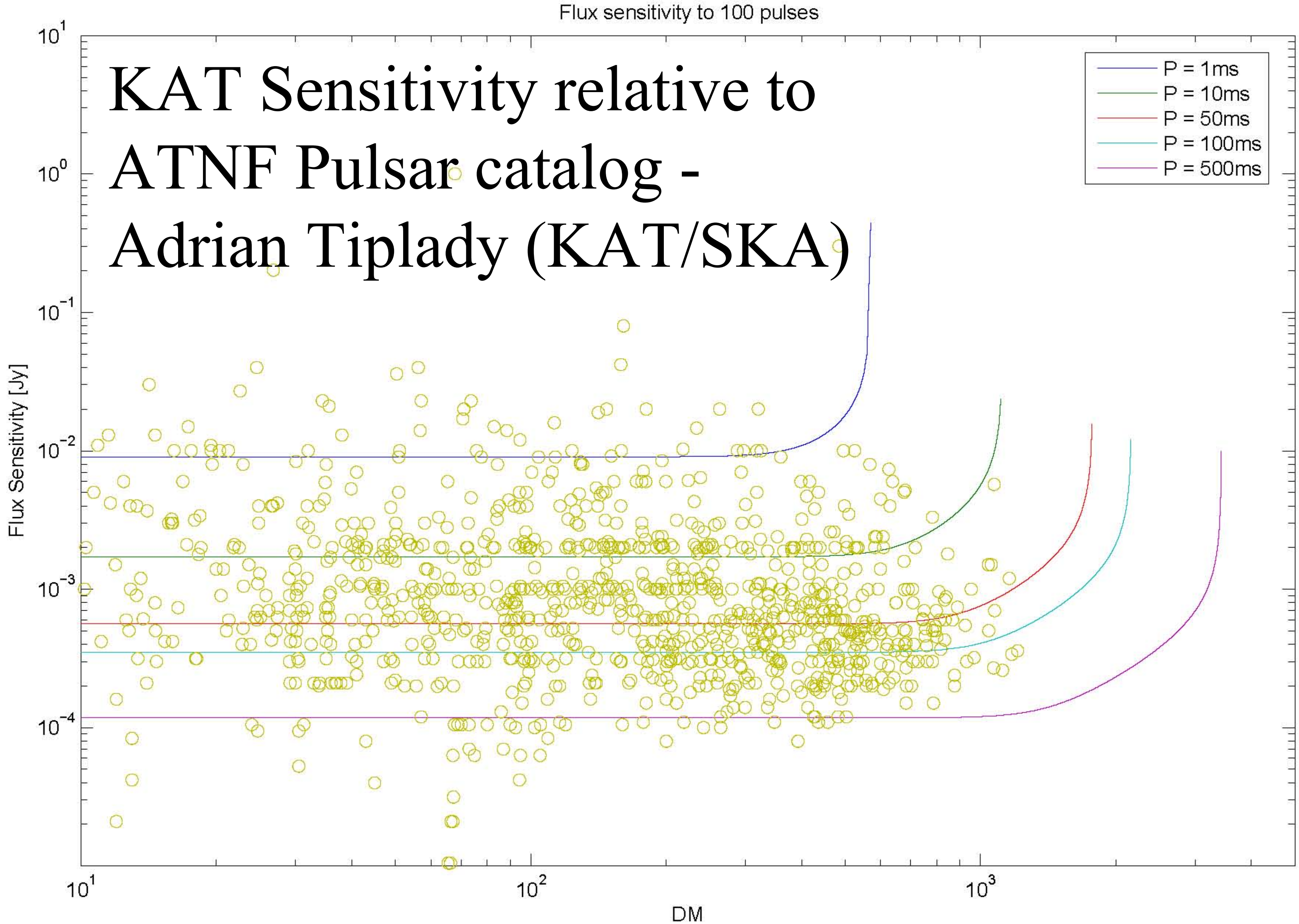
- Wide FoV (approx. 7x7 deg^2) from South Africa (Galactic Center at zenith).
- Multiple Beam (40) switching for simultaneous and intelligent pulsar search strategies inside FoV.
- Wide FoV allows coverage of most of the Galactic Plane in one Day.
- Provide contemporary radio parameters for pulsar searches, detect new pulsars.
- All details based on Stage II development: (FPA) Discuss details with Adrian Tiplady – Assist. Project Scientist.


Pulsar Survey Figure of Merit ∝ FoV × (Ae/Tsys)^2 × Bandwidth
1000
800
600
400
200
0
KAT
Parkes
GMRT
VLA
WSRT
Arecibo
GBT
Eff
Spectral Line Survey Figure of Merit ∝ FoV × (Ae/Tsys)^2
200
150
100
50
0
KAT
Parkes
GMRT
VLA
WSRT
Arecibo
GBT
Eff

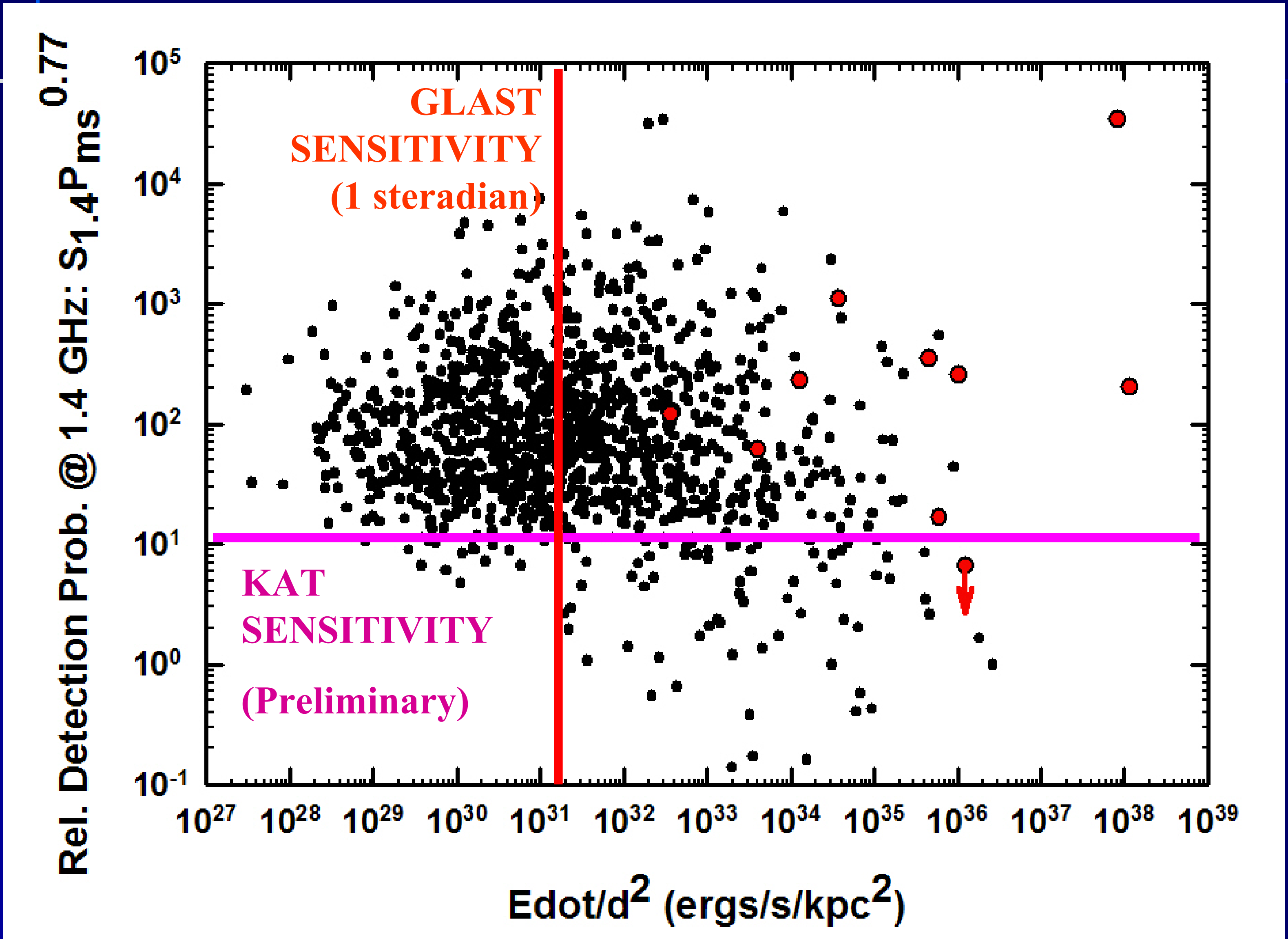
KAT Sensitivity relative to ATNF Pulsar catalog - Adrian Tiplady (KAT/SKA)



KAT Sensitivity relative to ATNF Pulsar catalog - Adrian Tiplady (KAT/SKA)



Radio Detection Sensitivity vs Relative Gamma-Ray Flux



Conclusions:
New Gamma-Ray Pulsar Detections:

- Present generation of VHE Ground-Based Gamma-Ray Telescopes:
  - Very good sensitivity above given threshold, but this
  - threshold energy is just too high at present for pulsed emission from pulsars.
  - 30 meter class HESS II & possibly new MAGIC initiatives under construction should capture >10 GeV pulsars with good statitics.
- Well planned strategy to cover top of Edot/d^2 pulsar list with current radio telescopes within the "GLAST Multiwavelength Programme." (e.g. Parkes etc.) – see David Smith's talk.
- No contingency plan for the bulk of the lower Edot/d^2 list and new radio pulsars to be discovered, where most of the faint GLAST pulsars will be.
- => Volume driven KAT-type support will be required (2009+).

PART II:
PULSAR WIND NEBULAE (PWN)

- Current ground-based VHE gamma-ray telescopes operating above 0.1 TeV very successful with PWN – most notably current HESS I.
- This is because a significant number of accumulated VHE electrons (>10 TeV) in weak field (<10 μG) parsec scale environment IC scatter CMBR to give bright VHE gamma-ray nebulae.
- => We directly map the distribution of relic VHE electrons.
- => We probe elecron energies which are larger than radio emitting electron energies, but lower than X-ray emitting energies.

Importance of VHE imaging of PWN

- X-Ray images of PWN are strongly convolved with field gradients within PWN

$$I_X \propto NB^2$$

$$\Delta I_X \propto (\Delta N)B^2 + N(2B\Delta B)$$

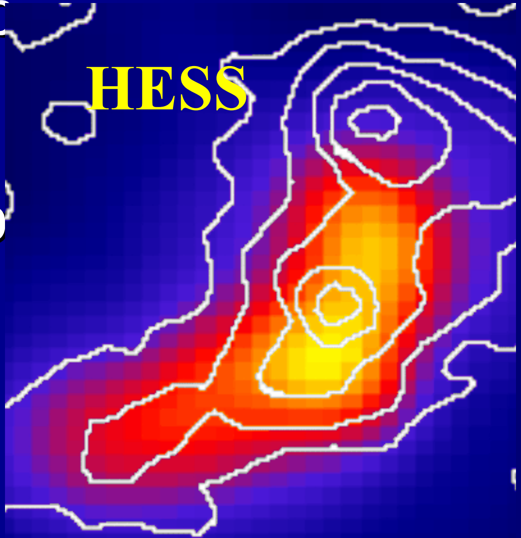
- However, VHE γ-rays map large scale CMBR (and possibly large scale galactic photon fields) into VHE domain

$$I_\gamma \propto NU_{rad}$$

$$\Delta I_\gamma \propto (\Delta N)\, U_{rad}$$

PSR B1509-58 in

MSH 15-52



IC on CMBR is like relief work on marble slab of uniform thickness and infinite size. Depth ∝ N

Ages of X-ray and VHE Images of PWN:

- Lifetime of VHE emitting electrons making γ-rays above 0.1 TeV:

$$\tau(E_\gamma) = 4.8 B_{-5}^{-2} E_{\mathrm{TeV}}^{-1/2} \text{ kyr}$$

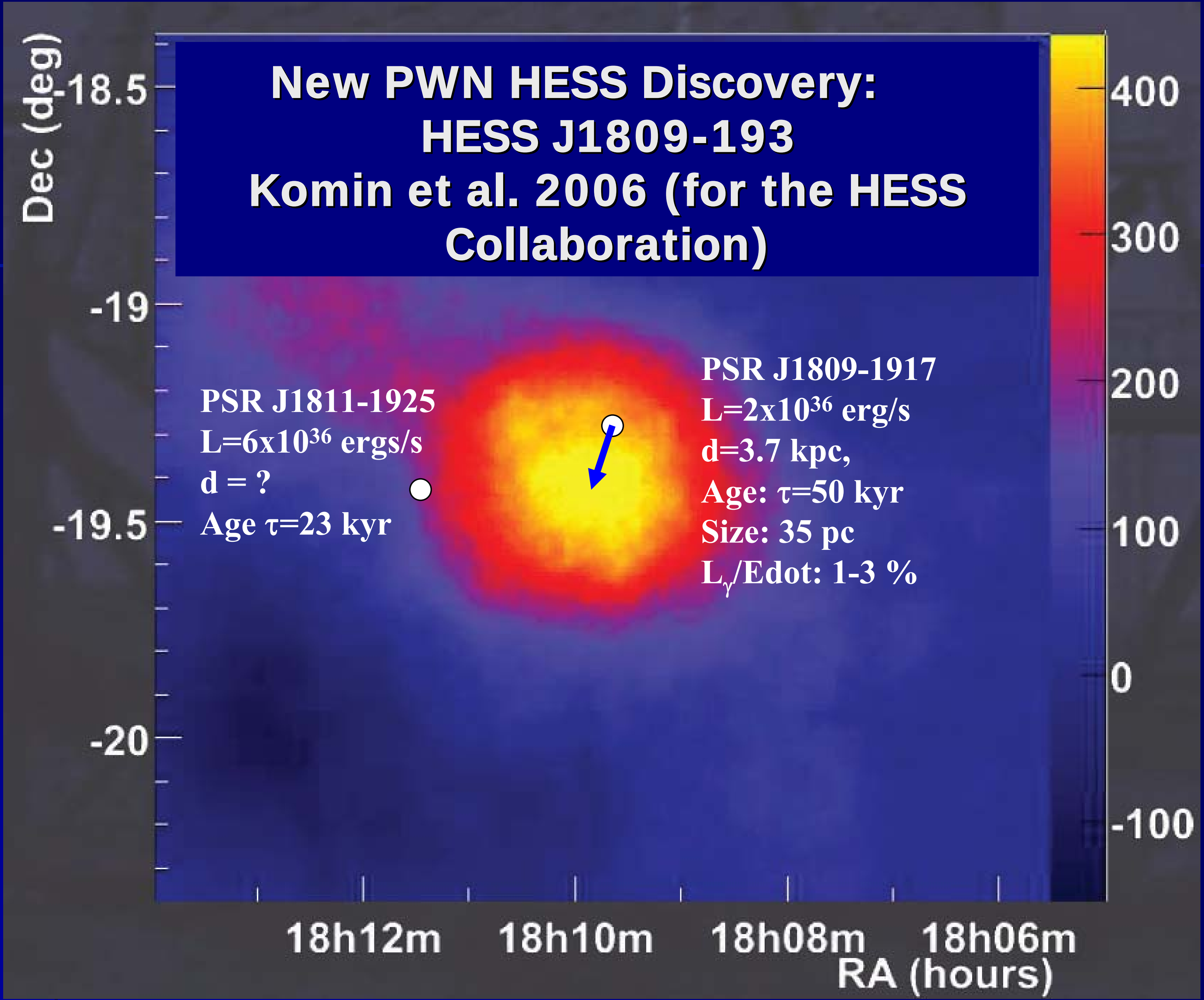
$$< 60 \, (\mathrm{B}/5\mu\mathrm{G})^{-2} \text{ kyr}$$

Probe early epochs of pulsar injection

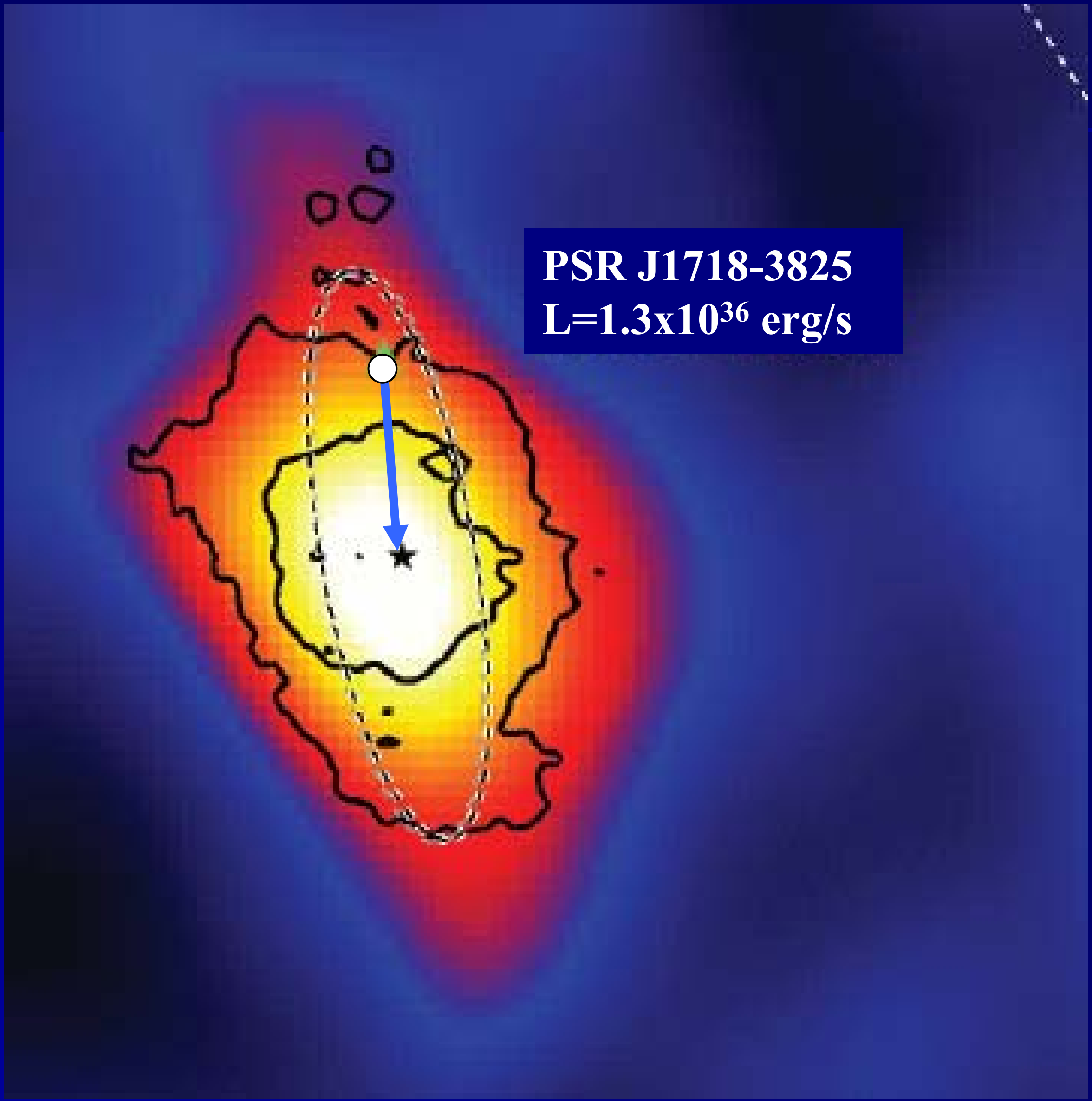
- Lifetime of X-ray emitting electrons:

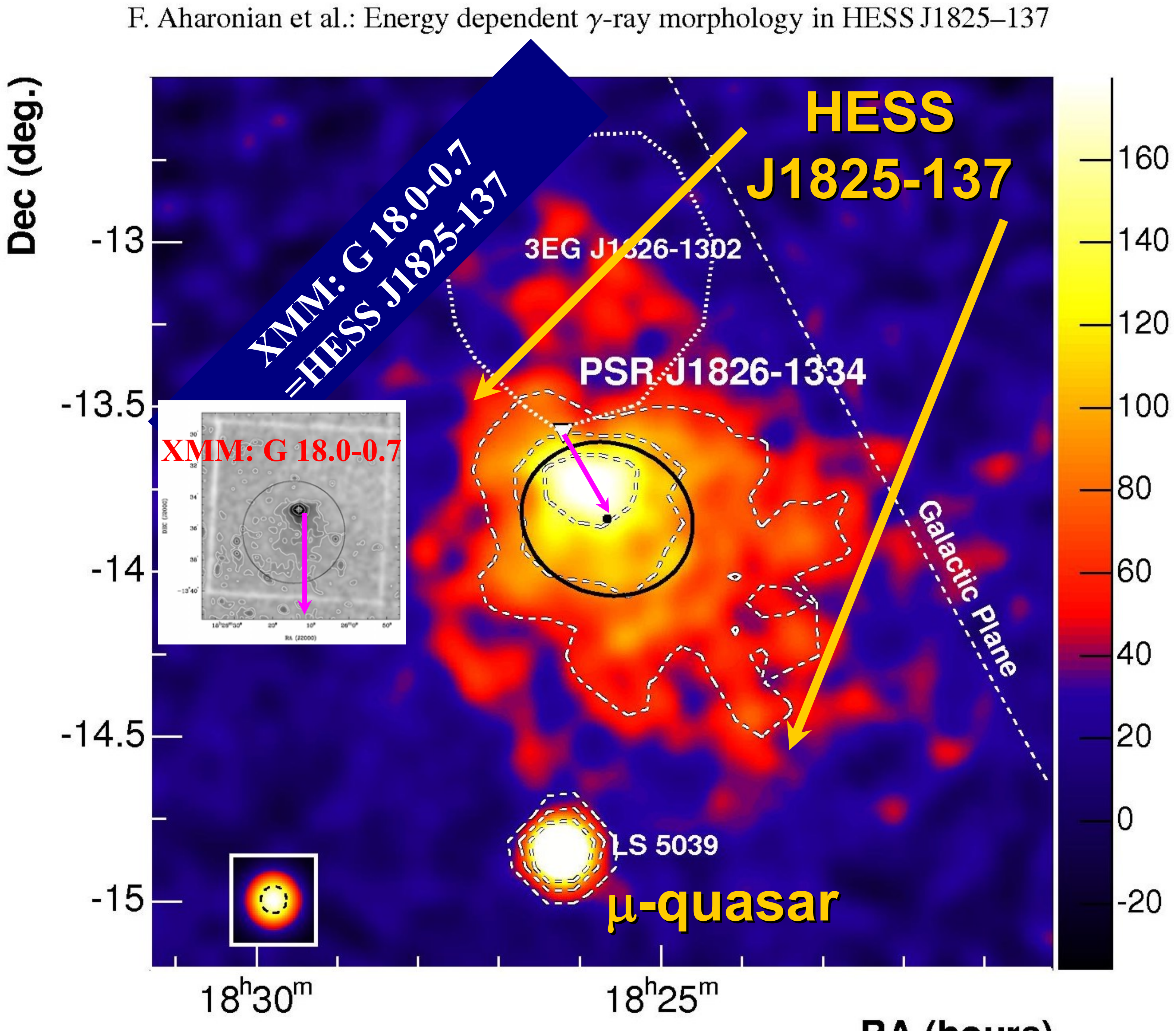
$$\tau(E_X) = 1.2 B_{-5}^{-3/2} E_{\mathrm{keV}}^{-1/2} \text{ kyr}$$

Probe freshly injected $e^{\pm}$


New PWN HESS Discovery:
HESS J1809-193
Komin et al. 2006 (for the HESS Collaboration)
PSR J1811-1925
L=6x10^36 ergs/s
d = ?
Age τ=23 kyr
PSR J1809-1917
L=2x10^36 erg/s
d=3.7 kpc,
Age: τ=50 kyr
Size: 35 pc
Lγ/Edot: 1-3 %
Dec (deg)
-18.5
-19
-19.5
-20
18h12m
18h10m
18h08m
18h06m
RA (hours)
400
300
200
100
0
-100

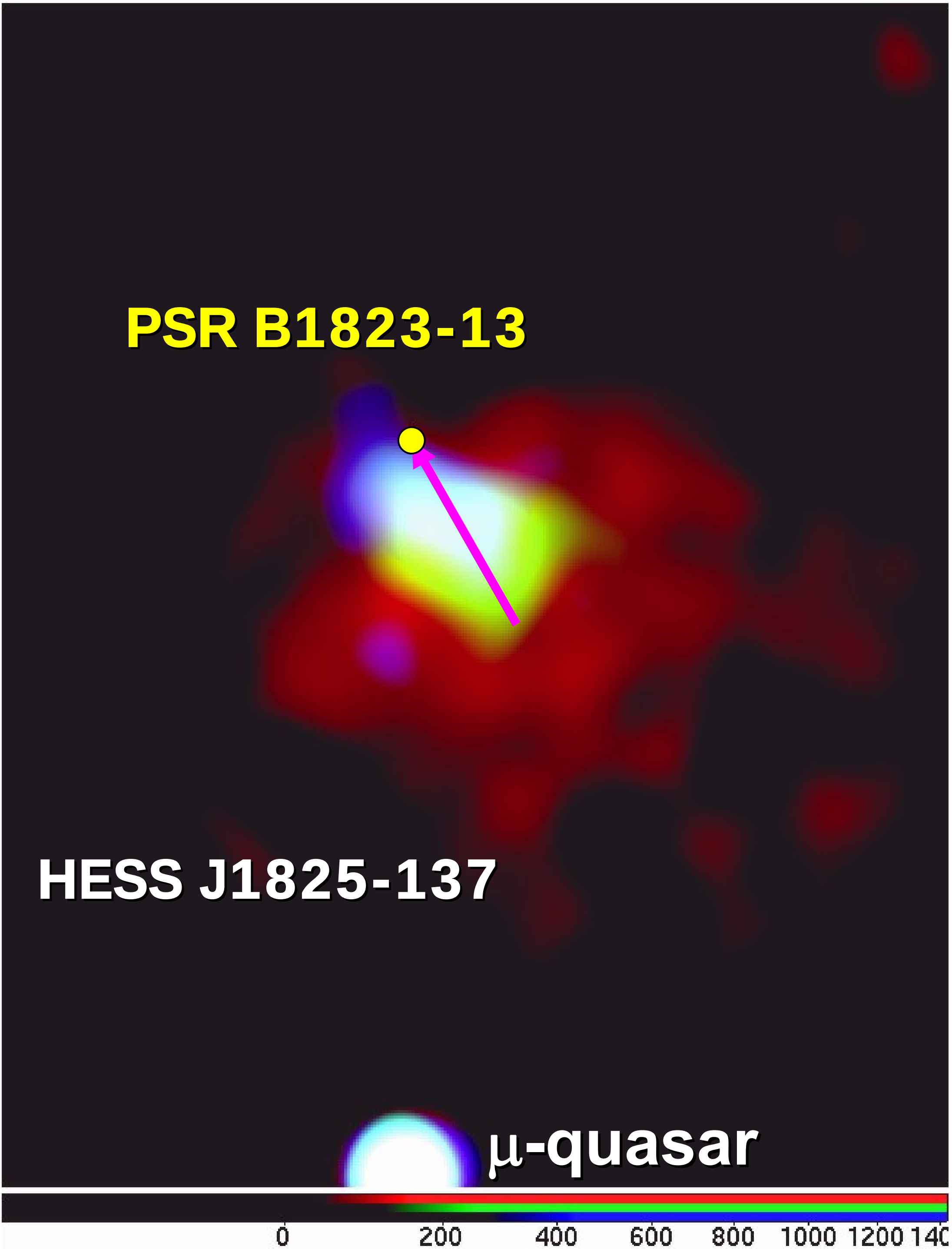
New PWN HESS Discovery: HESS J1718-3825
Hinton et al. 2006 (for the HESS Collaboration)





HESS: Aharonian et al. 2006, To appear in A&A

HESSJ1825-137 The First Colour (spectral) Image in the History of Gamma-Ray Astronomy



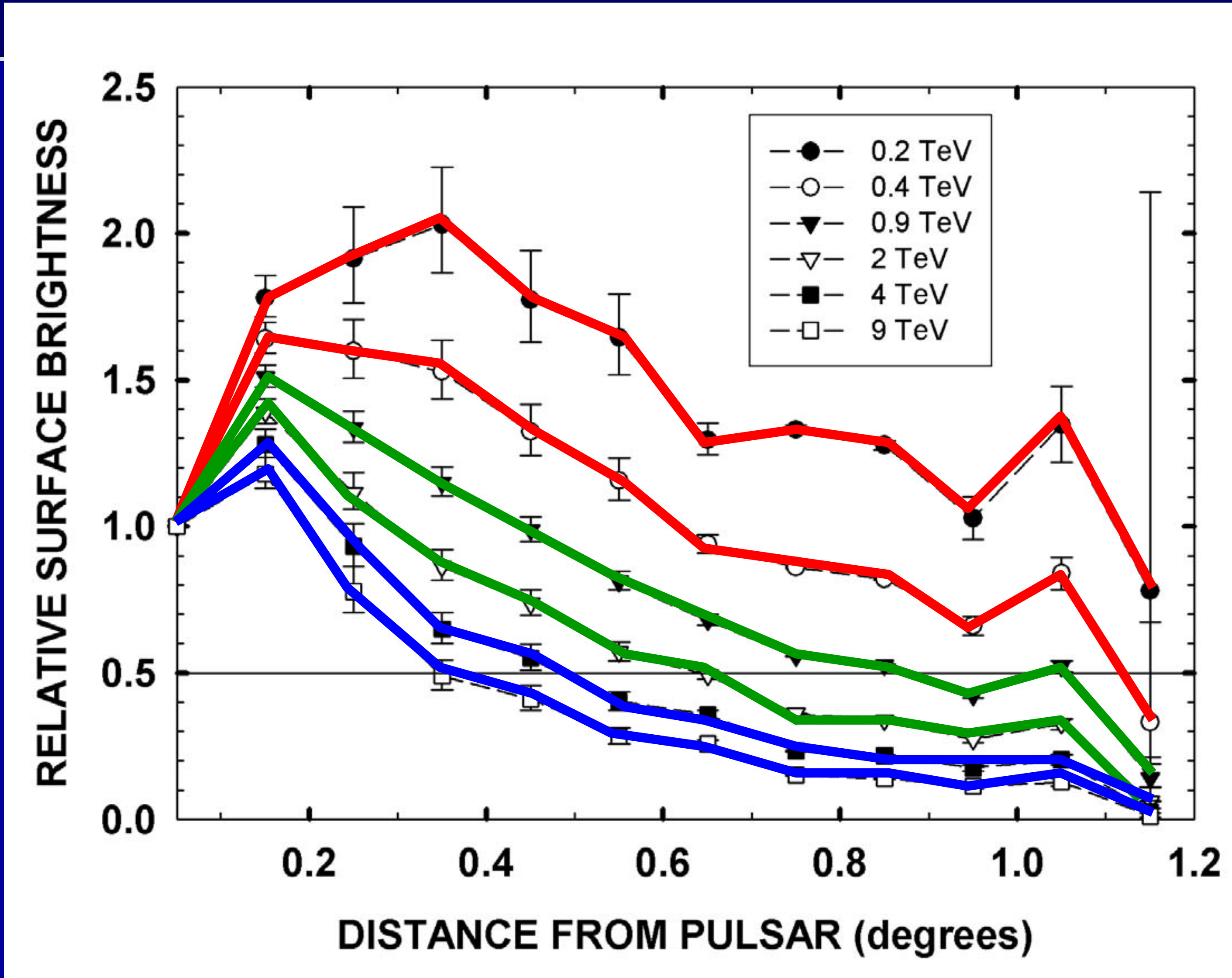
BLUE: $E_\gamma > 2.5$ TeV
Youngest & highest energy electrons

GREEN: 0.8 – 2.5 TeV
Medium energies

RED: <0.8 TeV
Low energies

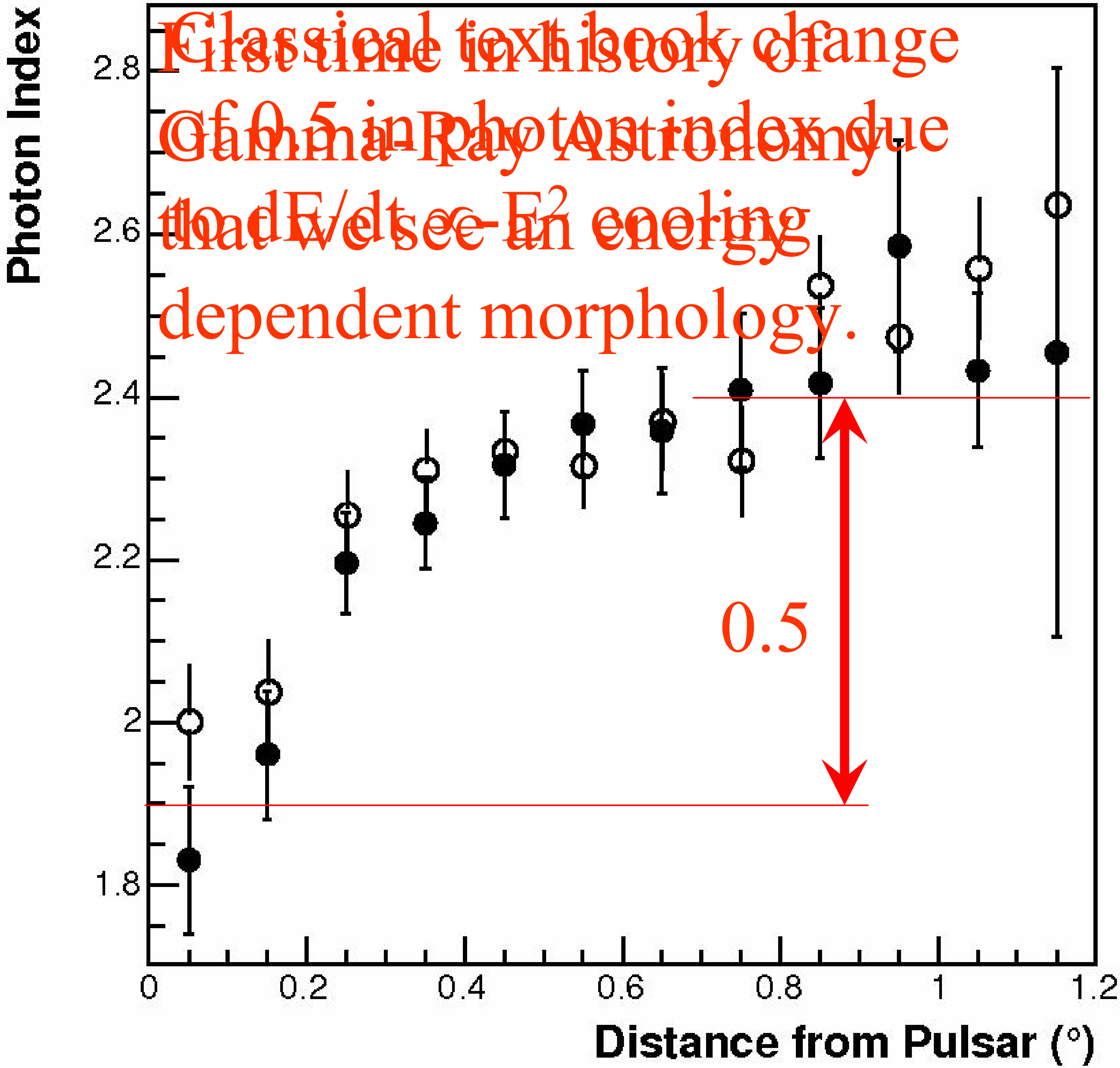
Aharonian et al. (HESS Collaboratioin) 2006, to appear in A&A.

HESS J1825-137 Energy Dependent Morphology

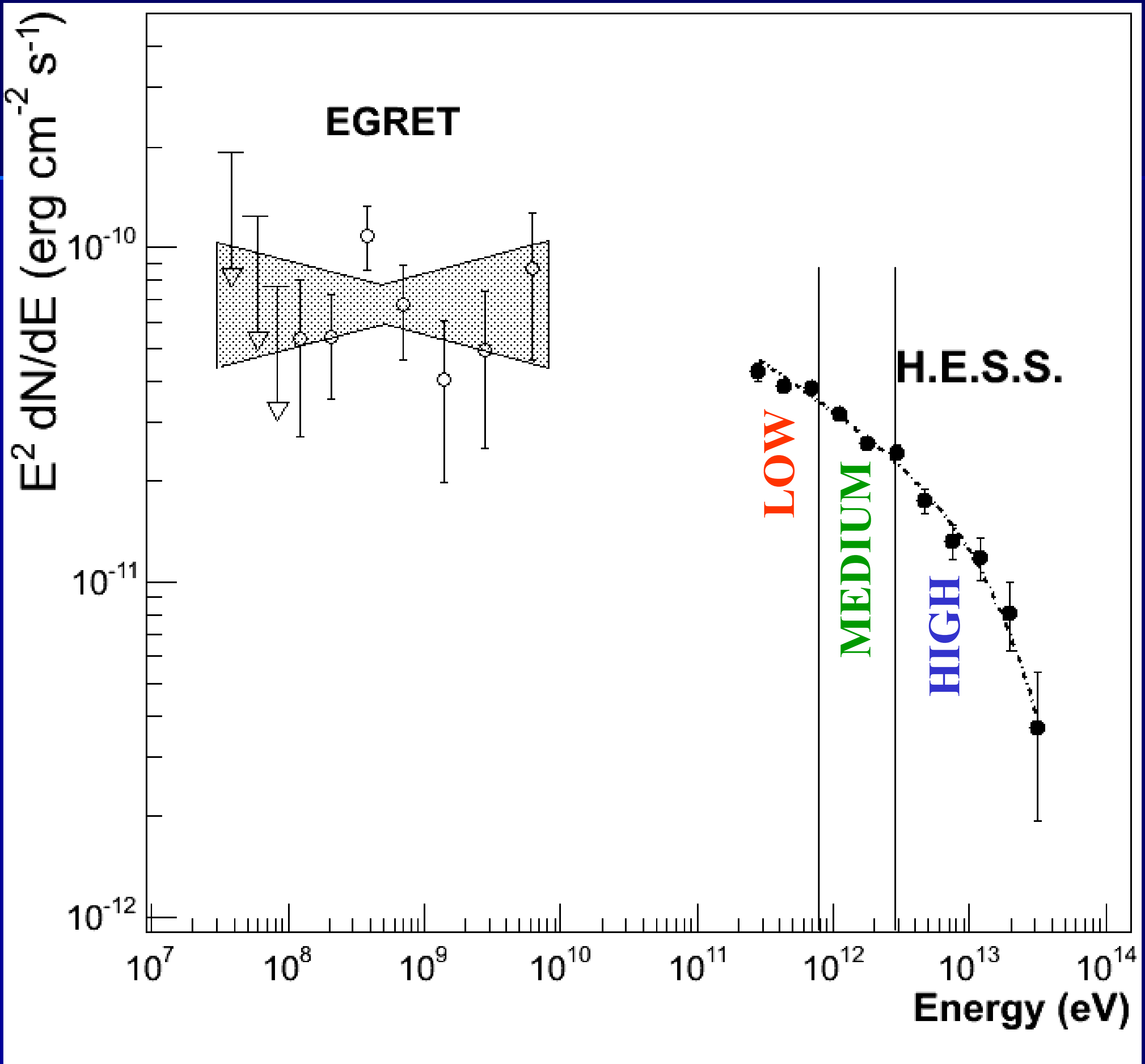


Classical text book change of 0.5 in photon index due to $dE/dt \propto -E^2$ cooling

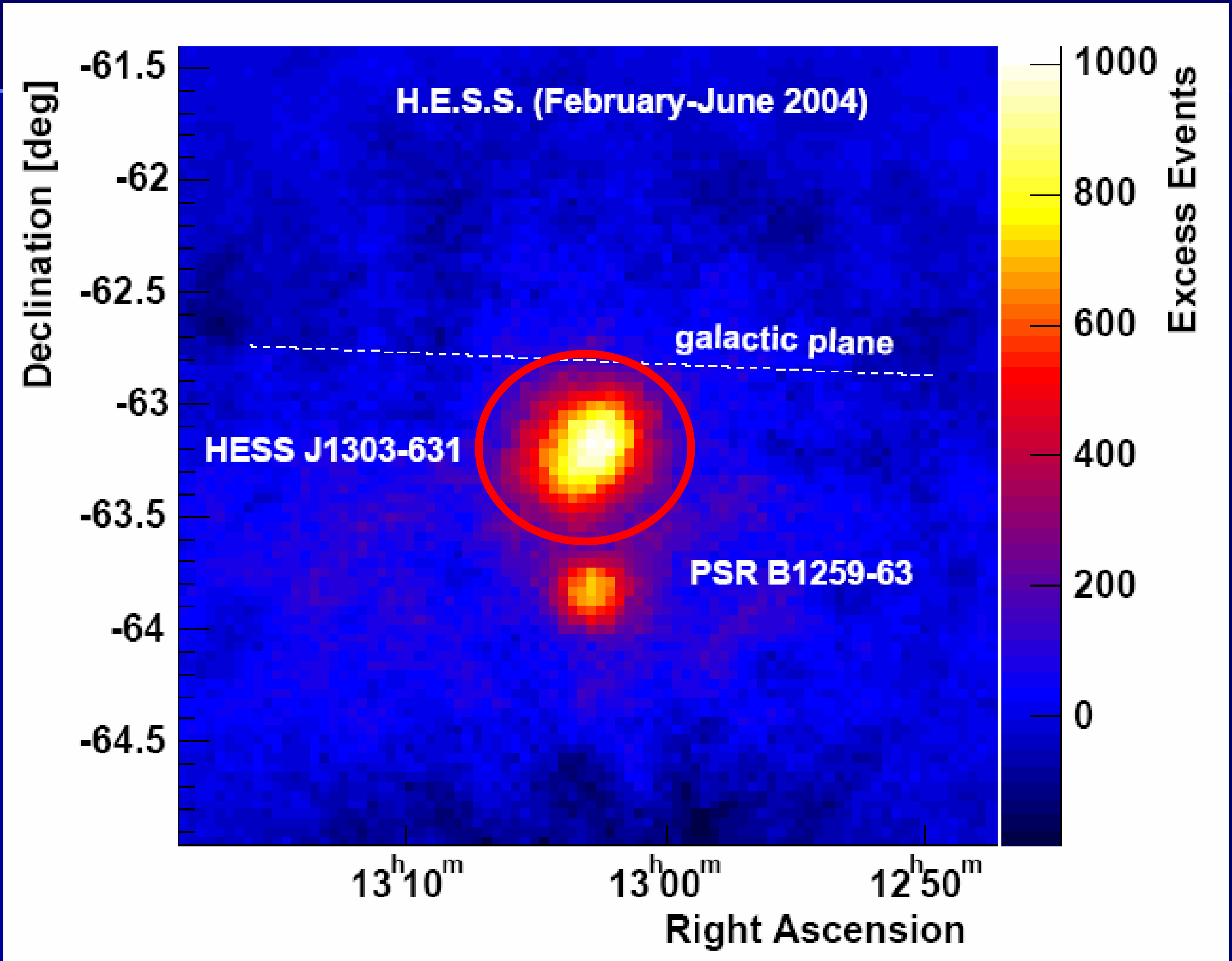
First time in history of Gamma-Ray Astronomy that we see an energy dependent morphology.



EGRET / HESS Spatially Averaged Spectrum of HESS J1825-137



The Unidentified Gamma-Ray Source HESS J1303-631



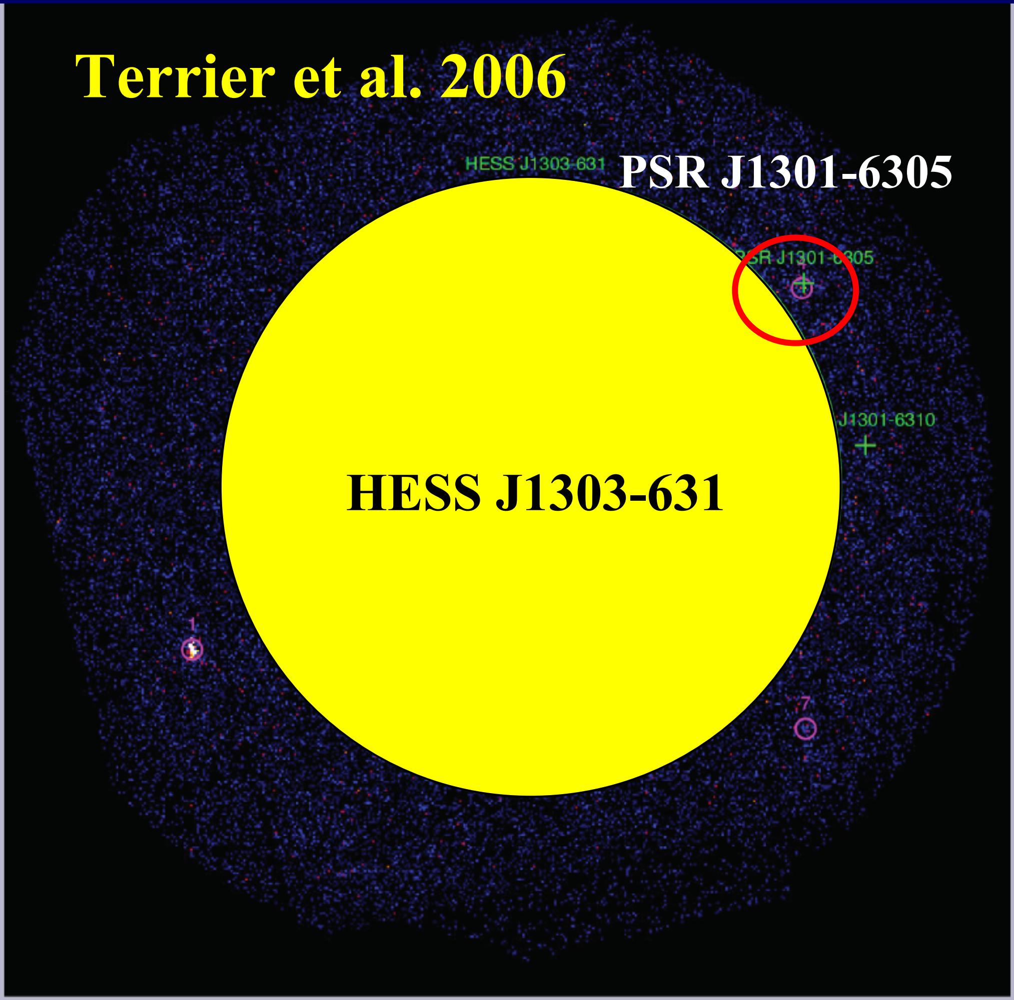
XMM observations

2-10 keV EPIC mosaic image of the HESS J1303-631 field. The circle is the 1s extension of the VHE source.

Source 4 is coincident with the pulsar PSR J1301-6305. It is detected as slightly extended (using symetrical models). It is the only pulsar detected in the field.

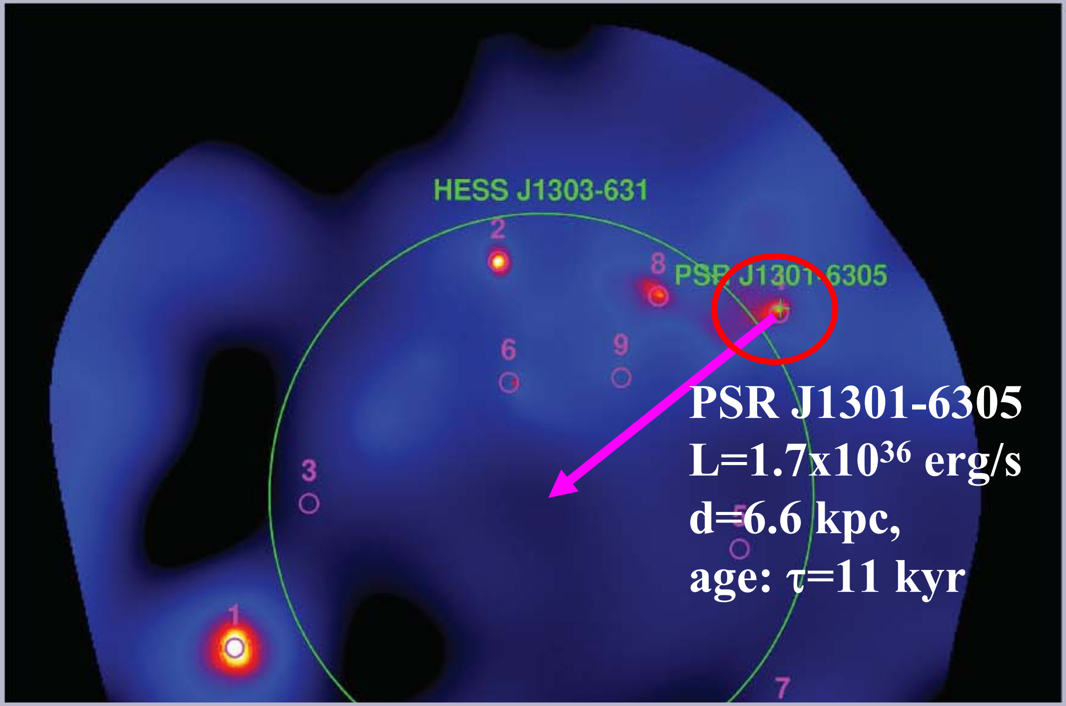
None of the 5 chandra sources are detected in this energy band

Except for PSR J1301-6305, no significant symetric extension of the sources were found by SAS task *emldetect*.

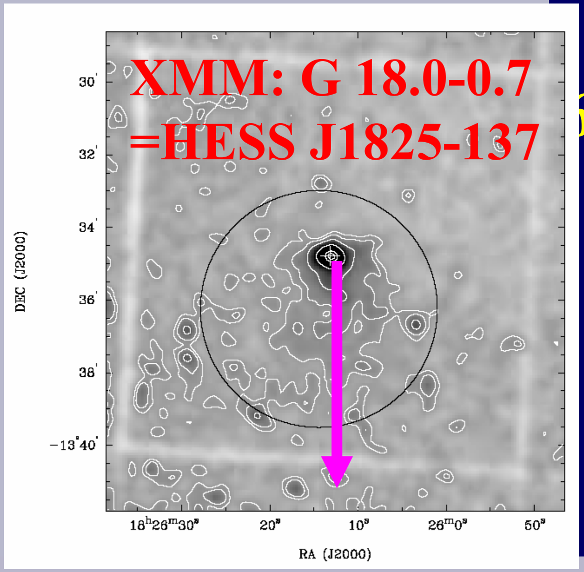


Searching for diffuse emission

To search for extended emission in the image, smoothed flux mosaic image have been produced. After background subtraction, the mosaicked count images were adaptively smoothed with the SAS task asmooth (threshold of 6 sigma) and the resulting template was applied to smooth both the mosaicked background-subtracted count images and their associated exposure maps. They were then divided to get a smoothed flux image, shown on the following figure.



2 - 4.5 keV mosaicked background subtracted flux image



Evidence for an extended emission of PSR J1301-6305

The emission from PSR J1301-6305 shows an asymmetric extension trailing towards the center of the VHE source. A quantitative study of the significance of the extension is underway. Nevertheless, this is a good evidence for the presence of an asymmetric pulsar wind nebula associated with PSR J1301-6305.

Distance to PSR J1301-6305

Using the NE2001 model, described by Cordes and Lazio (2002), the dispersion measure indicates a distance of about **6.6 kpc**, alleviating most of the problems raised before. The size of the nebula is indeed reduced to 36pc, and the ratio γ luminosity over Edot is about 6.5%.

Energetics

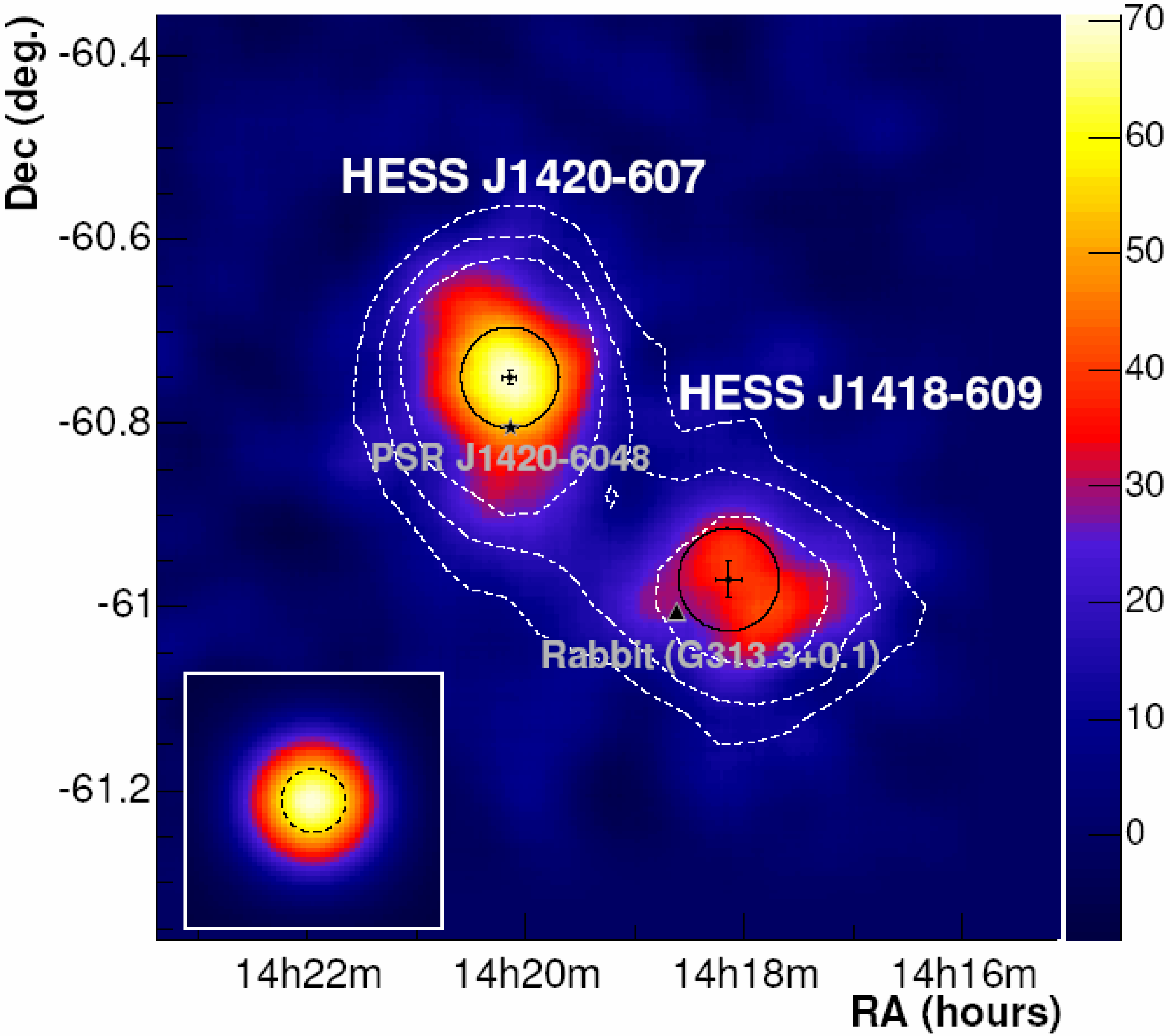
At a distance of 6.6 kpc, the luminosity of the source is 1.1 10^{35} erg/s (E>380 GeV). If we assume the signal is due to IC electrons on CMB, the total energy of the underlying TeV electrons is E ~ 1.5 10^{47} erg/s which is significantly less than the total energy released by a pulsar assuming initial spin down power of a few 10^{38} erg/s and a characteristic spin down time of 500-1000 years.

	Edot erg/s	age kyr	distance kpc	size pc	L_γ erg/s
HESS J1825-137	2.8 10^{36}	21.4	4.1	83	3 10^{35}
HESS J1303-631	1.7 10^{36}	11	6.6	36	1.2 10^{35}

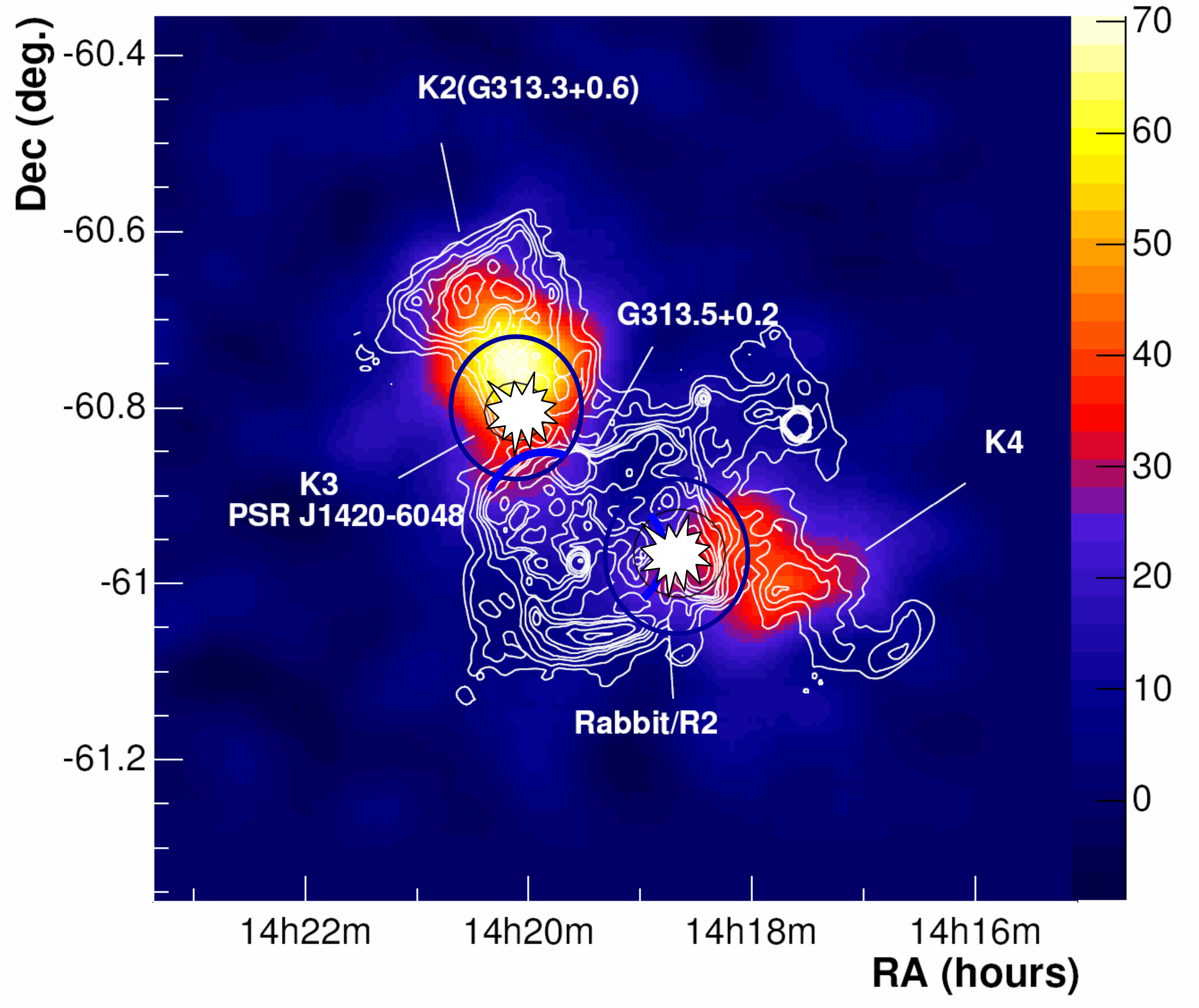
We should therefore expect an energy dependent morphology with a steepening of the spectrum at large distances from the pulsar due to electron cooling. Further TeV observations are required to confirm this possible link between HESS J303-631 and the energetic pulsar PSR J1301-6305 and its associated nebula.

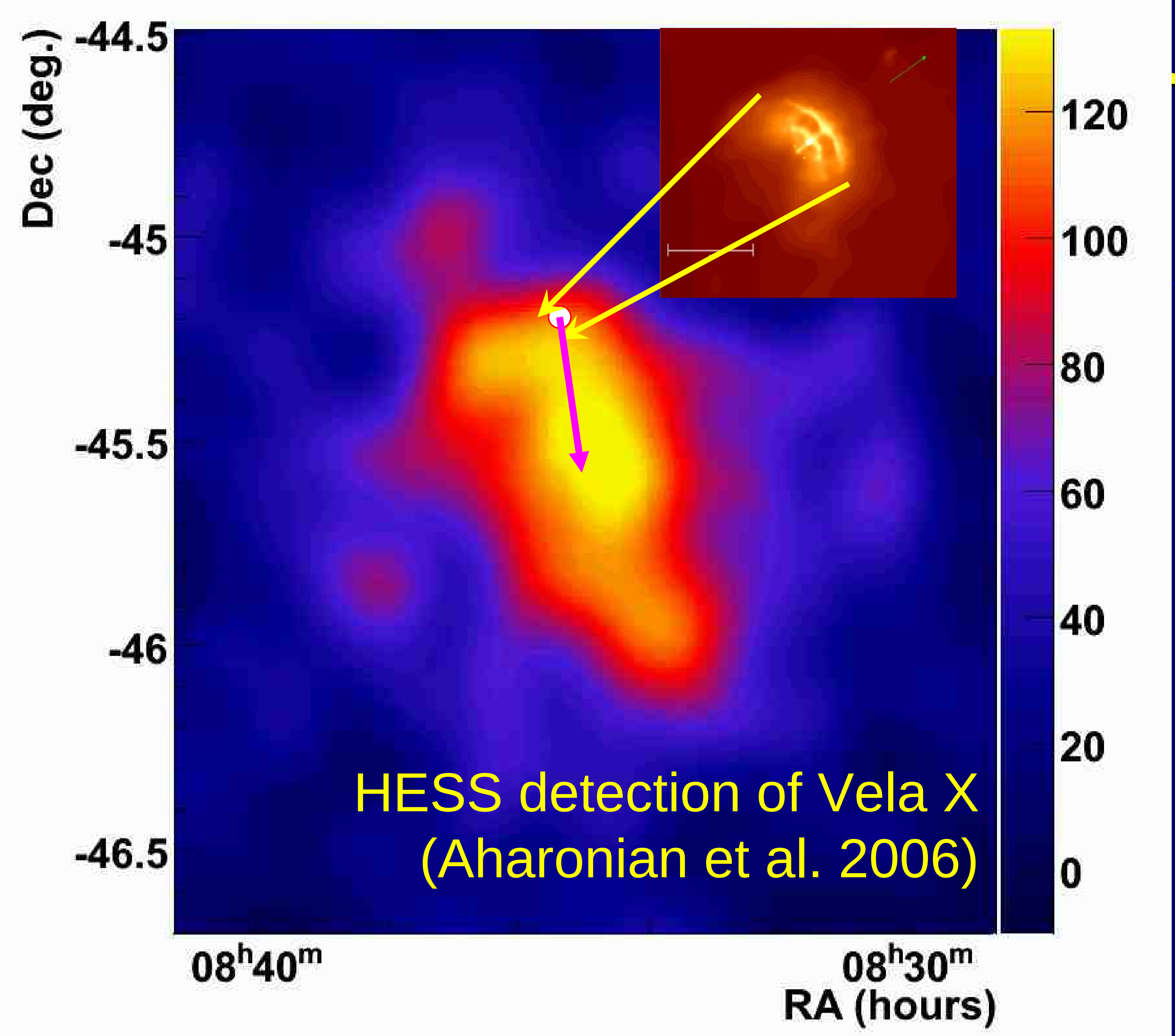
F. Aharonian et al.: Discovery of two sources in the Kookaburra region with H.E.S.S.

To Appear in A&A, see announcement in Official HESS website

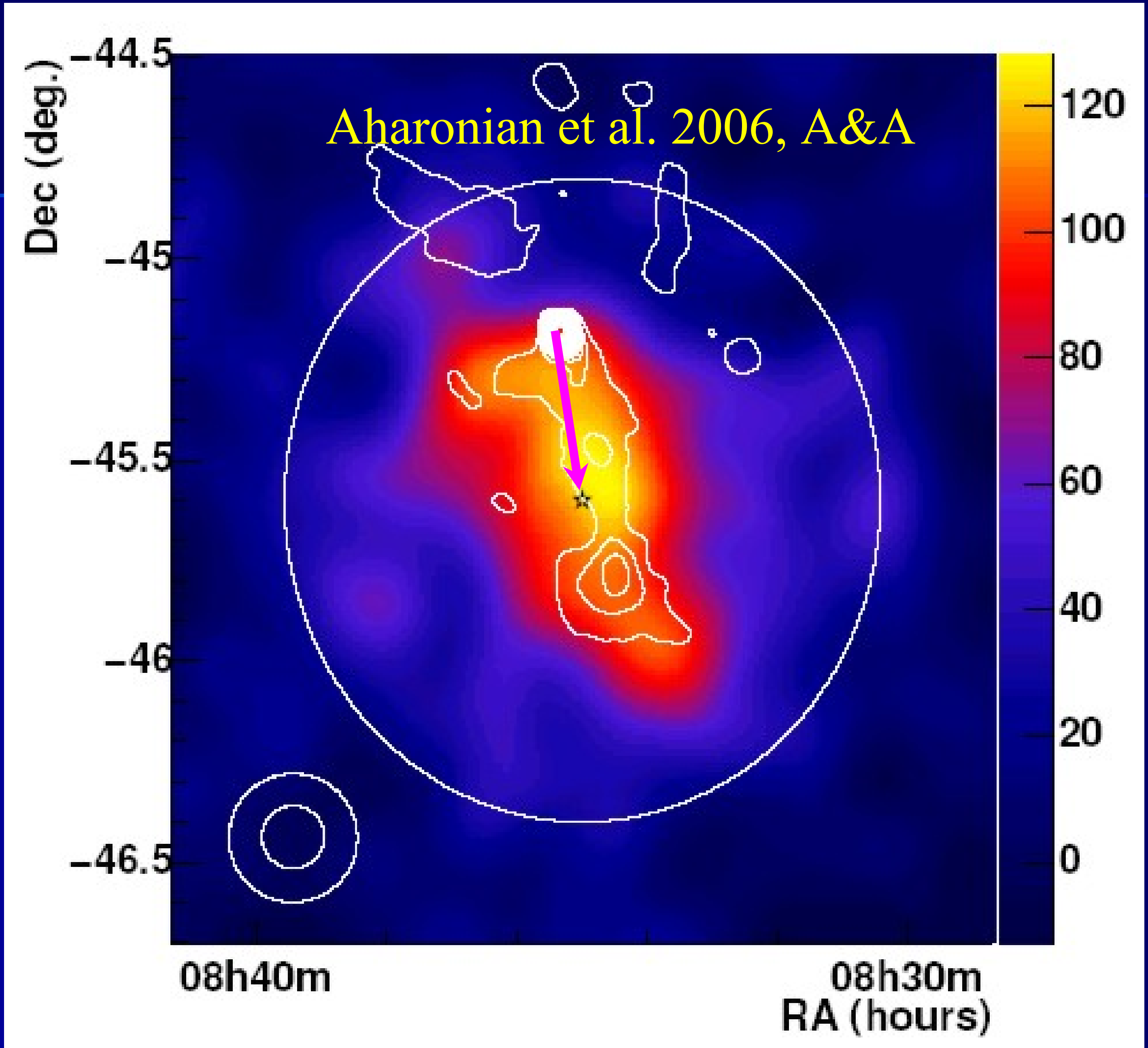


KOOKABURRA RADIO/VHE COMPARISON

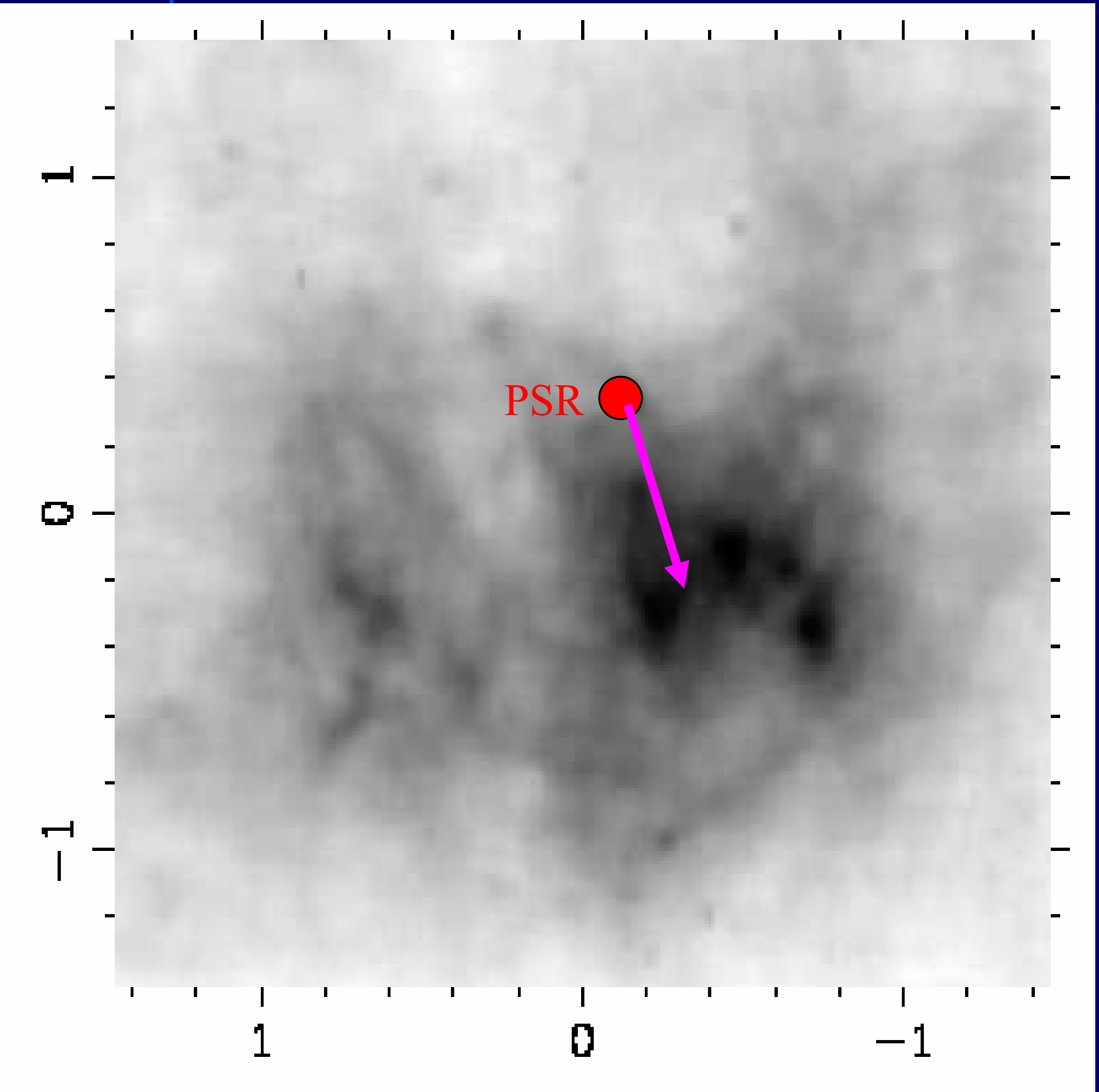



Dec (deg.)
-44.5
-45
-45.5
-46
-46.5
120
100
80
60
40
20
0
HESS detection of Vela X
(Aharonian et al. 2006)
08^h40^m
08^h30^m
RA (hours)

Offset VELA PWN as seen by HESS => Vela X



Vela X - 1-Degree Radio PWN



Vela X Radio Nebula is also offset to the South.

This sparked new Hydrodynamic studies about the reverse shock arriving at different times at the PWN (Blondin et al. 2001 with references)

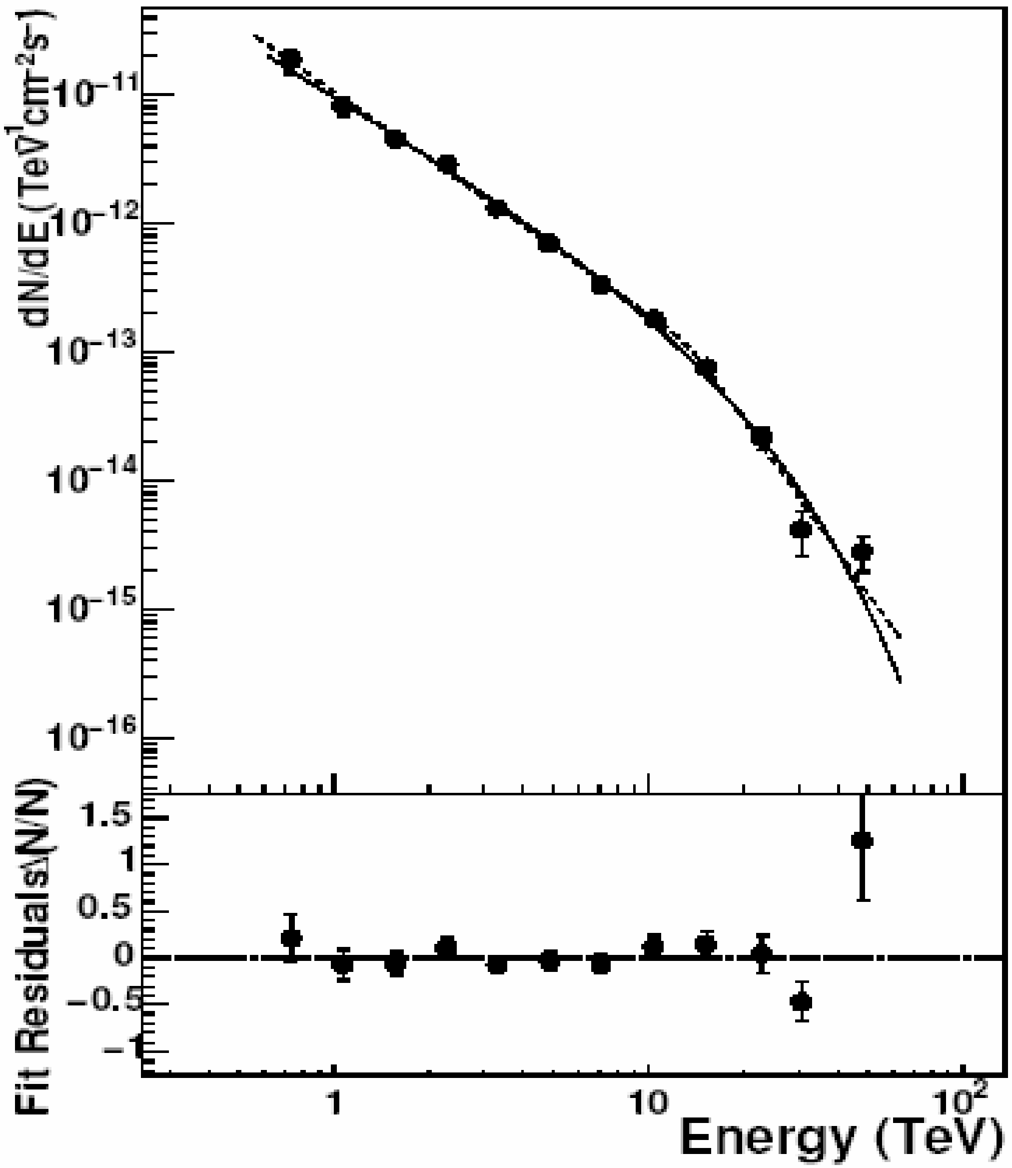


Fig. 3. Energy spectrum of γ-ray emission from the Vela X region. The solid line denotes the best fit of a power law with an exponential cutoff. The dashed line represents the best fit broken power law spectrum. The bottom panel shows the residuals to the exponential cutoff fit.

Vela X VHE γ-ray spectrum.

Brighther than Crab in the 3 to 30 TeV range!

~17σ sigificance

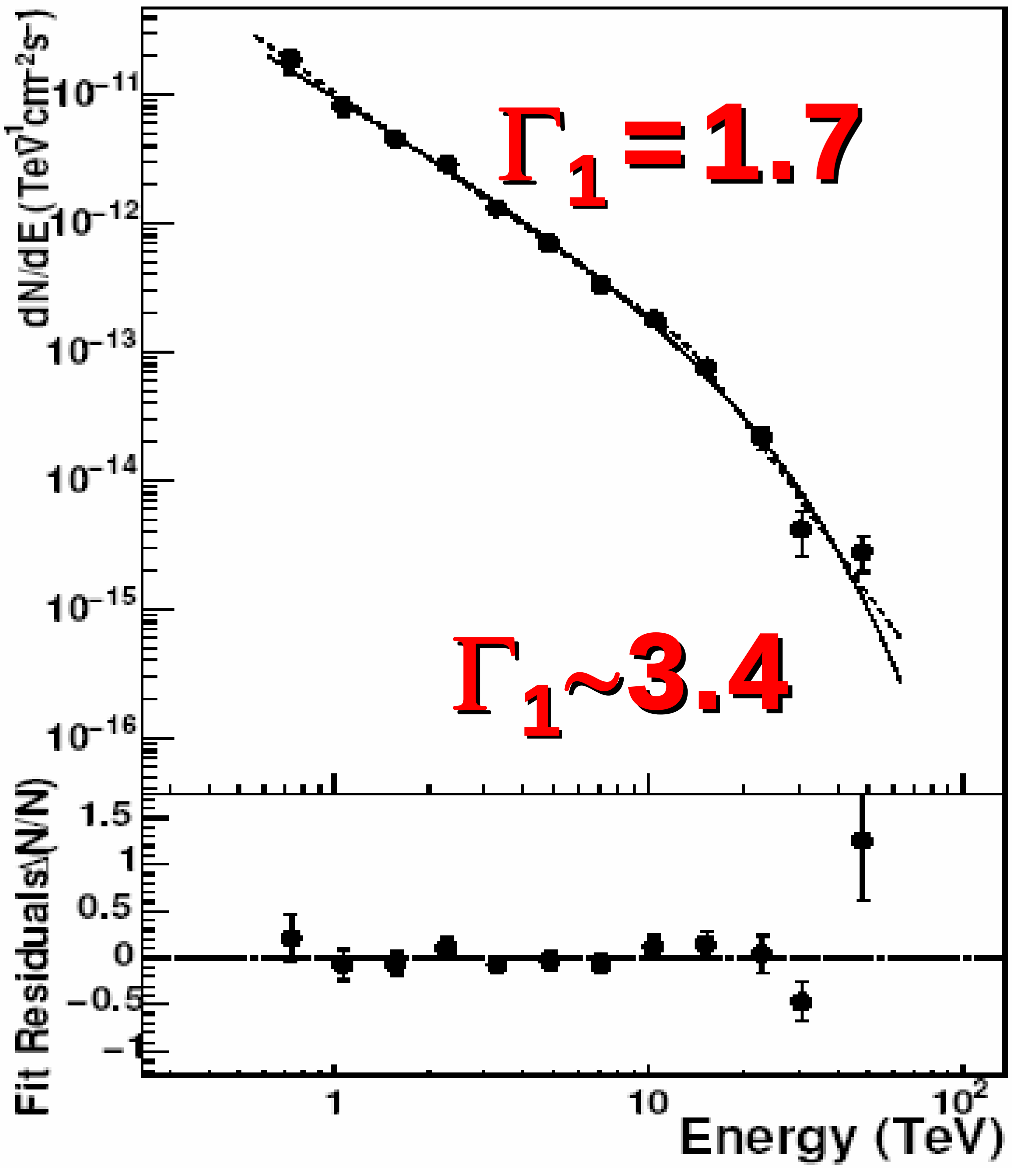


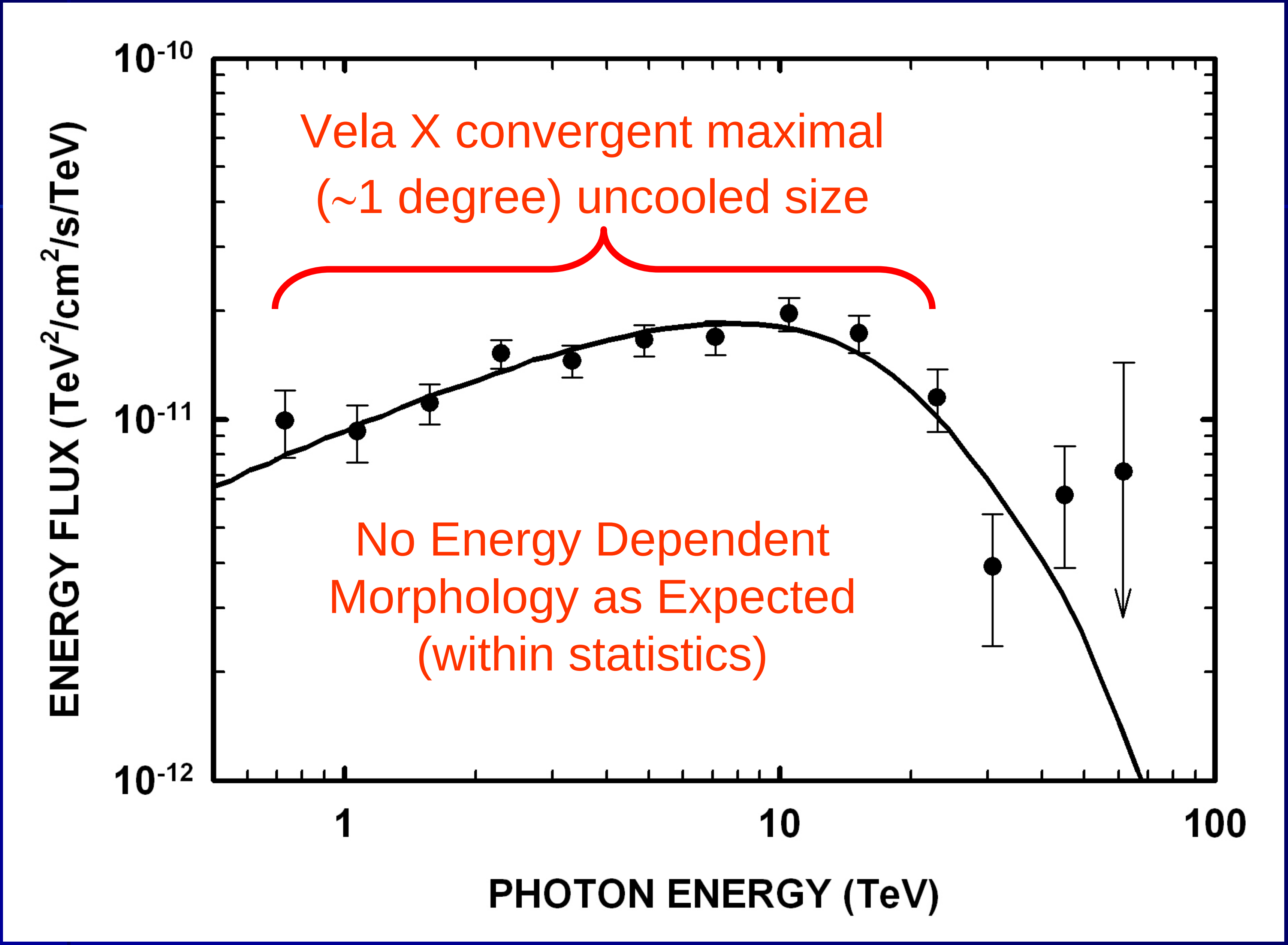
Fig. 3. Energy spectrum of γ-ray emission from the Vela X region. The solid line denotes the best fit of a power law with an exponential cutoff. The dashed line represents the best fit broken power law spectrum. The bottom panel shows the residuals to the exponential cutoff fit.

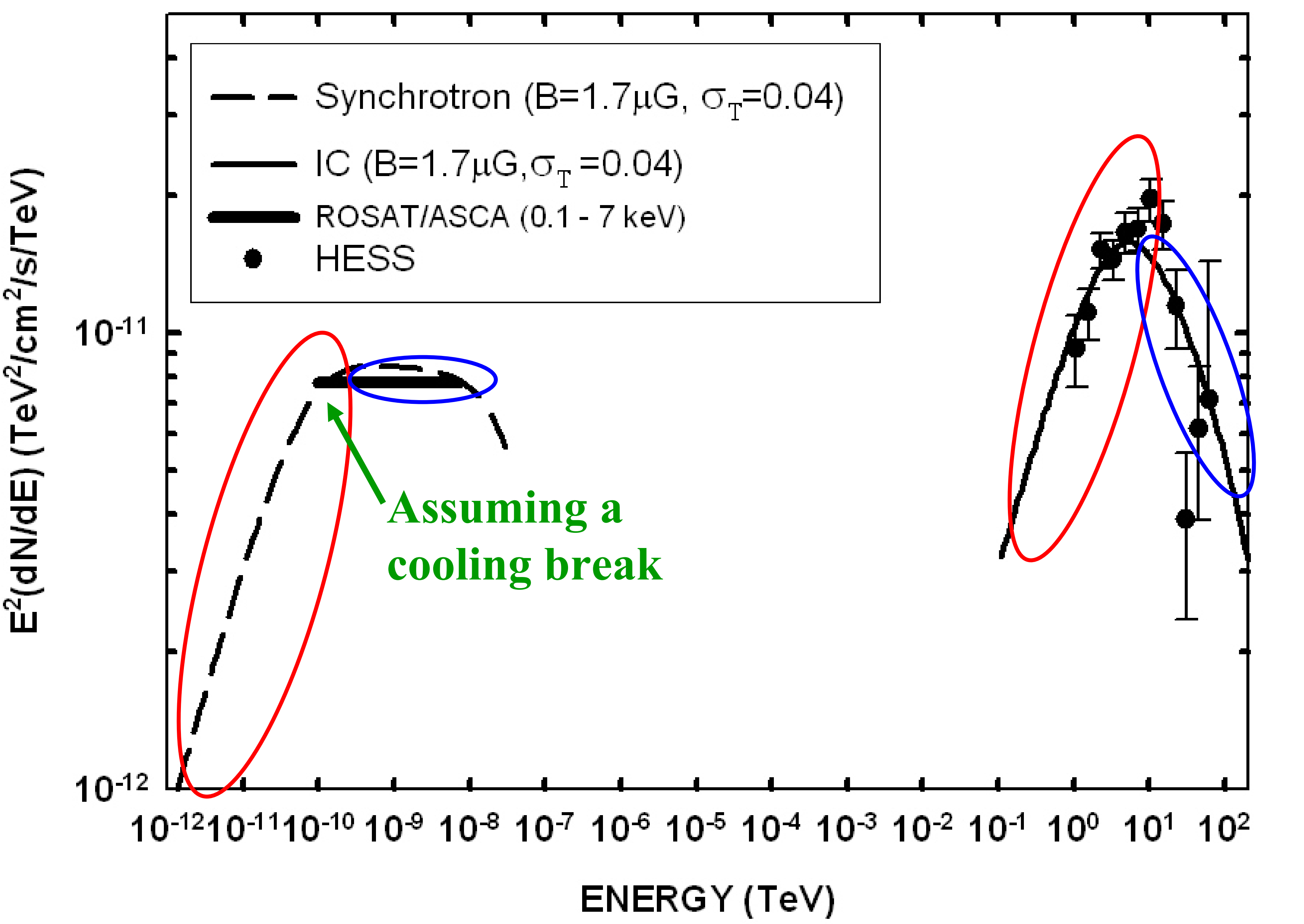
Vela X VHE spectrum:

$\Gamma_1 = 1.7 \pm 0.2$
$\Gamma_2 = 3.4 \pm 0.4$
or

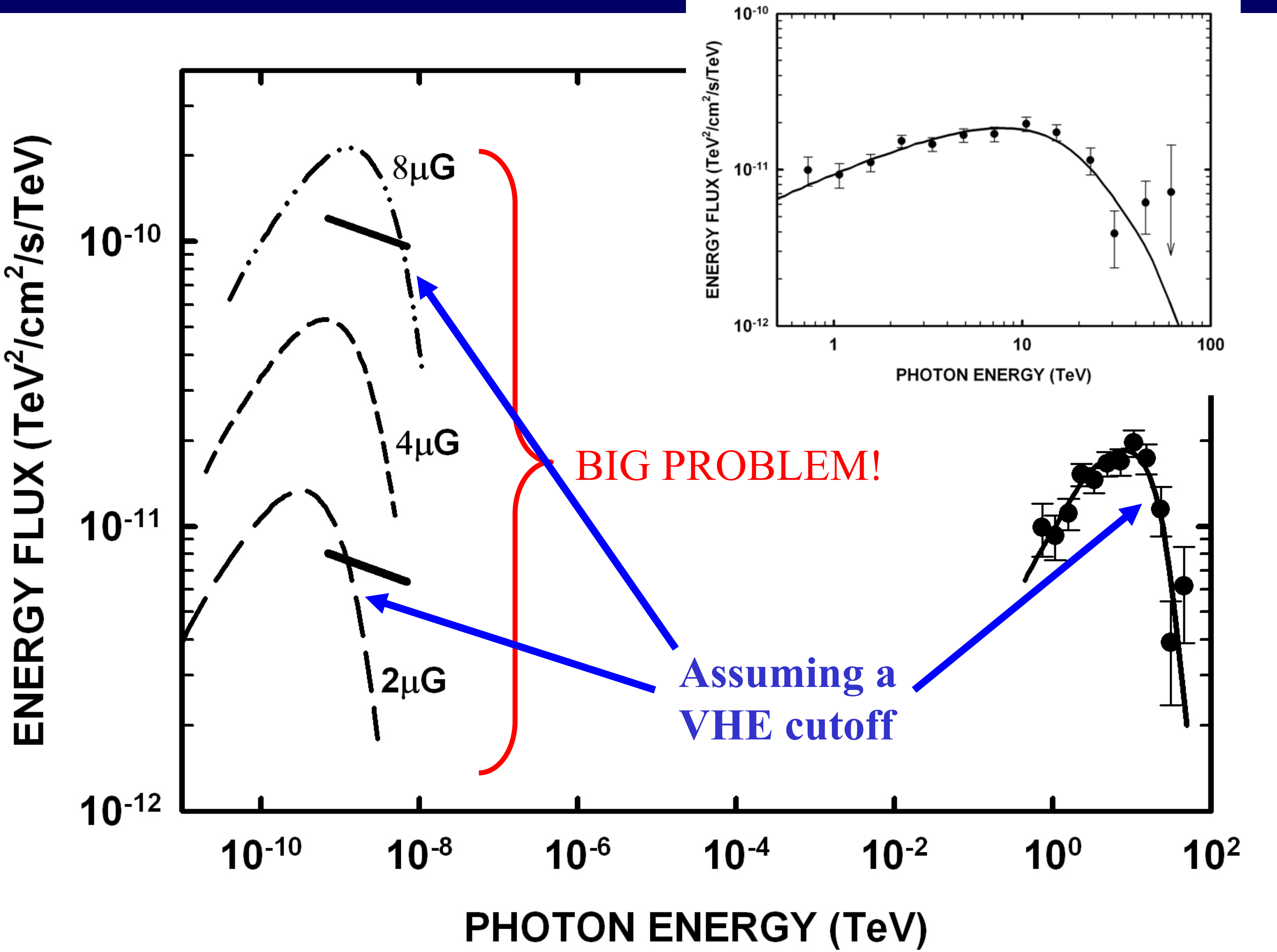
exp. Cutoff

$\Gamma_1 = 1.5 \pm 0.2$
$E_0 = 13.8 \pm 4.1$ TeV


Vela X convergent maximal
(~1 degree) uncooled size
No Energy Dependent
Morphology as Expected
(within statistics)
ENERGY FLUX (TeV²/cm²/s/TeV)
10⁻¹⁰
10⁻¹¹
10⁻¹²
1
10
100
PHOTON ENERGY (TeV)

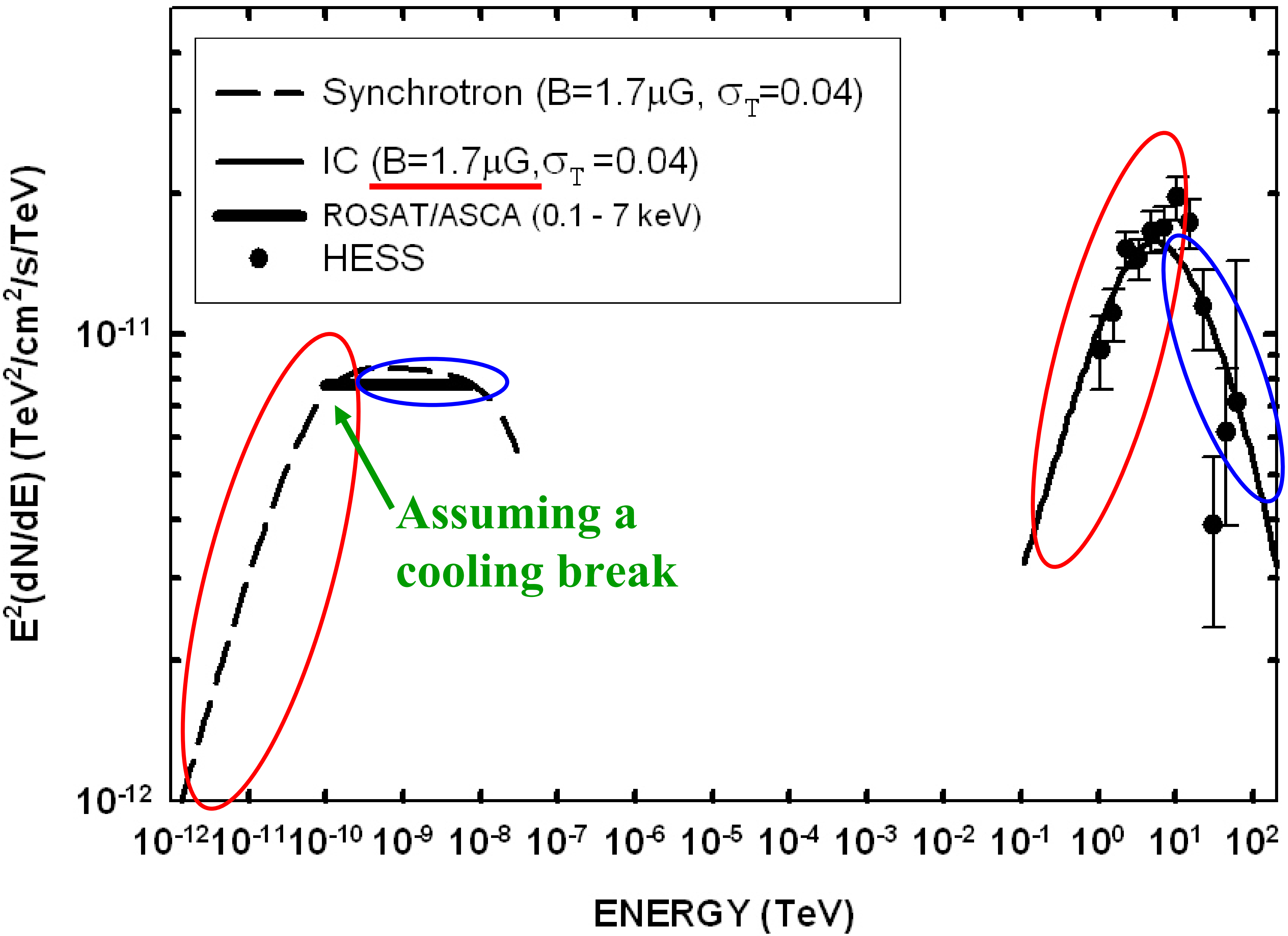


Synchrotron (B=1.7μG, σT=0.04)
IC (B=1.7μG,σT =0.04)
ROSAT/ASCA (0.1 - 7 keV)
HESS
Assuming a cooling break
E2(dN/dE) (TeV2/cm2/s/TeV)
10-11
10-12
10-12 10-11 10-10 10-9 10-8 10-7 10-6 10-5 10-4 10-3 10-2 10-1 100 101 102
ENERGY (TeV)



ENERGY FLUX (TeV2/cm2/s/TeV)
PHOTON ENERGY (TeV)
8μG
4μG
2μG
BIG PROBLEM!
Assuming a
VHE cutoff
10-10
10-11
10-12
10-10
10-8
10-6
10-4
10-2
100
102
ENERGY FLUX (TeV2/cm2/s/TeV)
PHOTON ENERGY (TeV)
1
10
100

MORE LIKELY



Synchrotron (B=1.7μG, σT=0.04)
IC (B=1.7μG,σT =0.04)
ROSAT/ASCA (0.1 - 7 keV)
HESS
Assuming a cooling break
E2(dN/dE) (TeV2/cm2/s/TeV)
ENERGY (TeV)
10-11
10-12
10-12 10-11 10-10 10-9 10-8 10-7 10-6 10-5 10-4 10-3 10-2 10-1 100 101 102

Implications for X-rays

- 1 keV emitting X-ray electron lifetime for a 1.7 μG field (IC losses on CMBR dominate) is then 7 kyr.
- Also comparable to T_{crush}, so that X-ray emitting electrons could have survived the crush.
- X-ray emitting electron energies are higher than VHE emitting electrons, so we see the effects on cooling (steeper photon index of 2.1).
- Test this: Is the non-thermal X-ray morphology of Vela X also energy dependent?

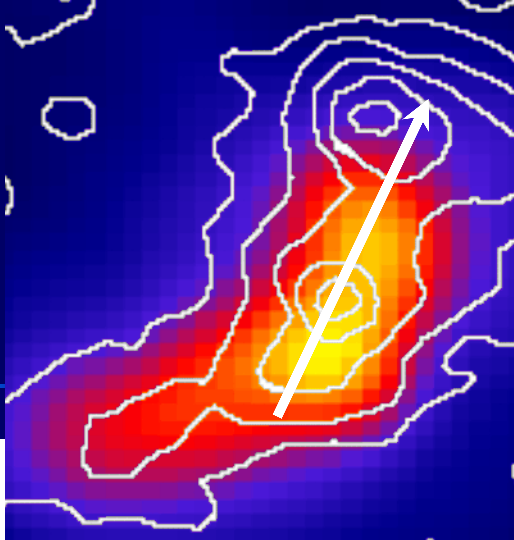
Why so many offset PWNe in VHE γ-Rays?

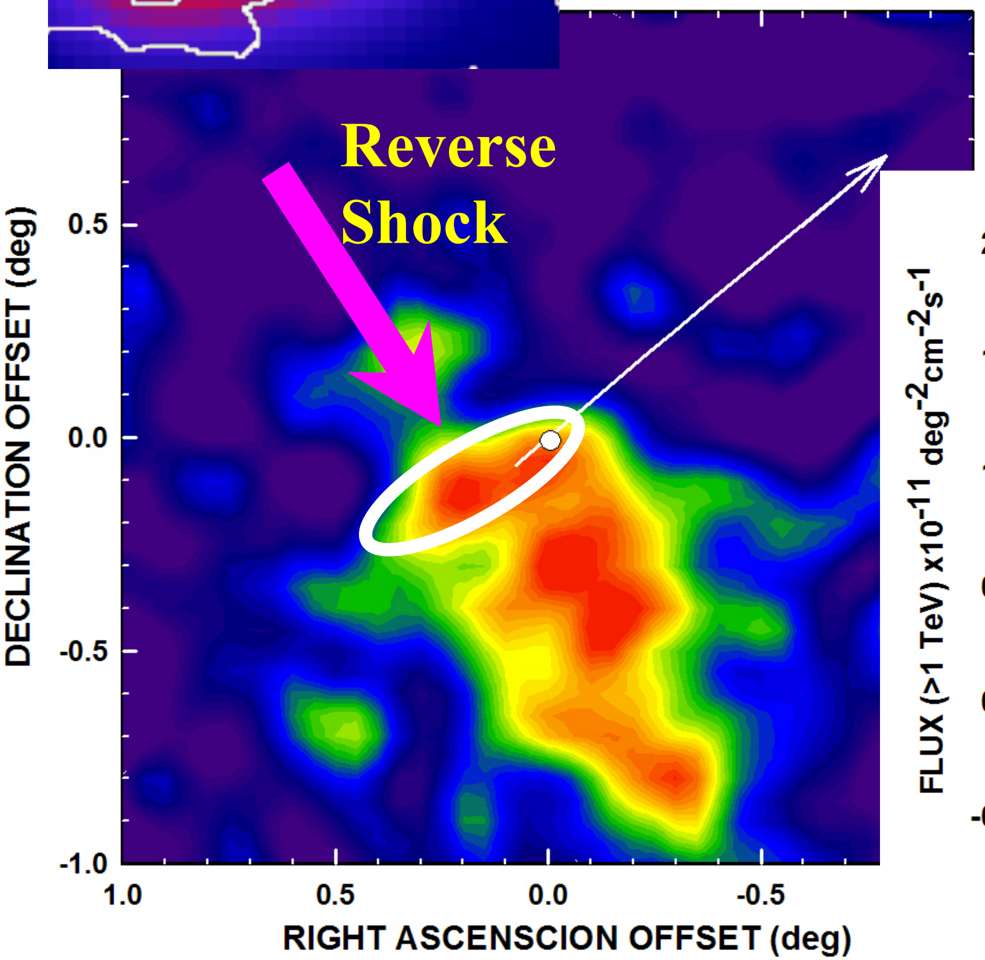
- Reverse shock from SNR return within T_{crush} ~5 to 10 kyr.
- Anisotropic ISM result in reverse shock returning at different times at the PWN, resulting in a crush in a preferred direction.
- Electron lifetime $\tau(E_\gamma)$ of VHE emitting electrons can be comparable to, or longer than the crush timescale:

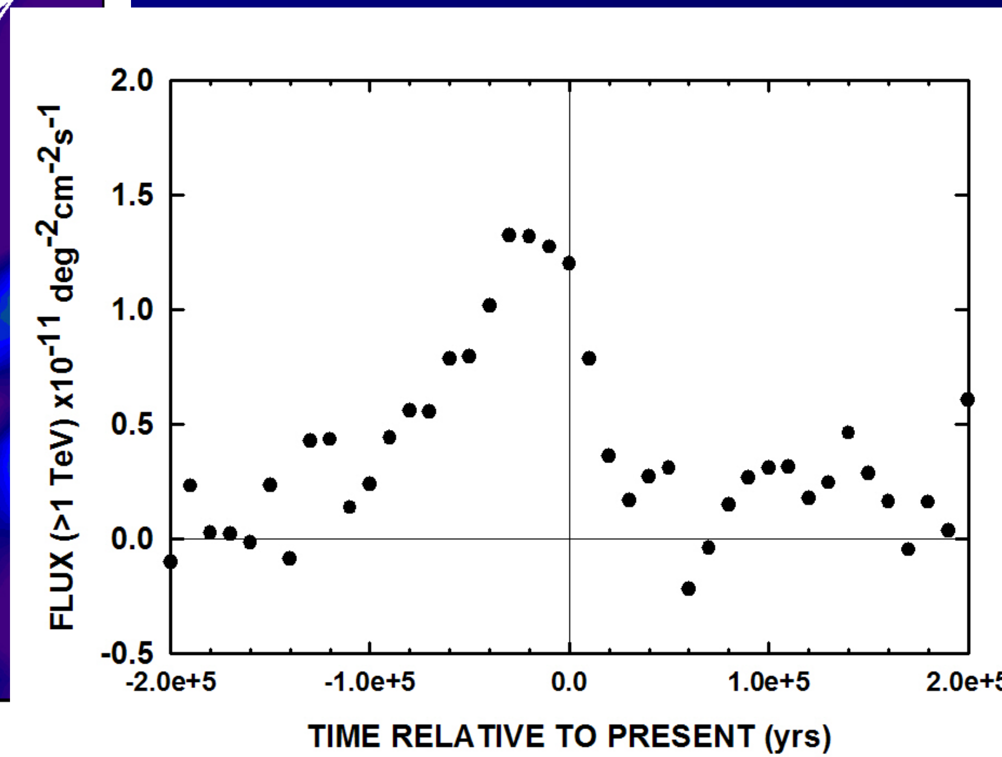
$$\tau(E_\gamma) = 4.8 B_{-5}^{-2} E_{\mathrm{TeV}}^{-1/2}\ \mathrm{kyr}$$ **> T_{crush} is possible**

- => Relic VHE emitting electrons pushed offset.
- $\tau(E_X)$ is usually much less, so we see the effect barely in X-rays, but mostly in VHE gamma-rays.

- PSR B1509-58 shows X-ray & VHE polar jet.
- HESS shows excess along expected jet direction near Vela pulsar

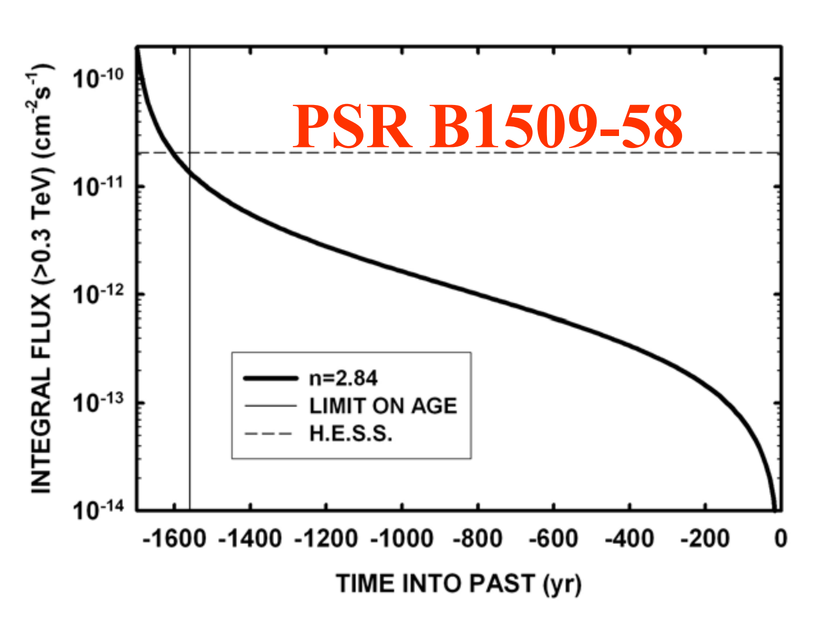


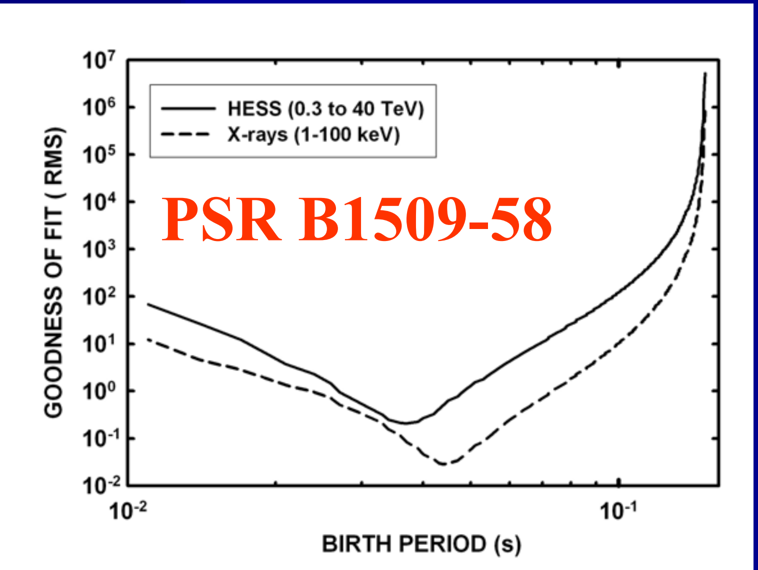


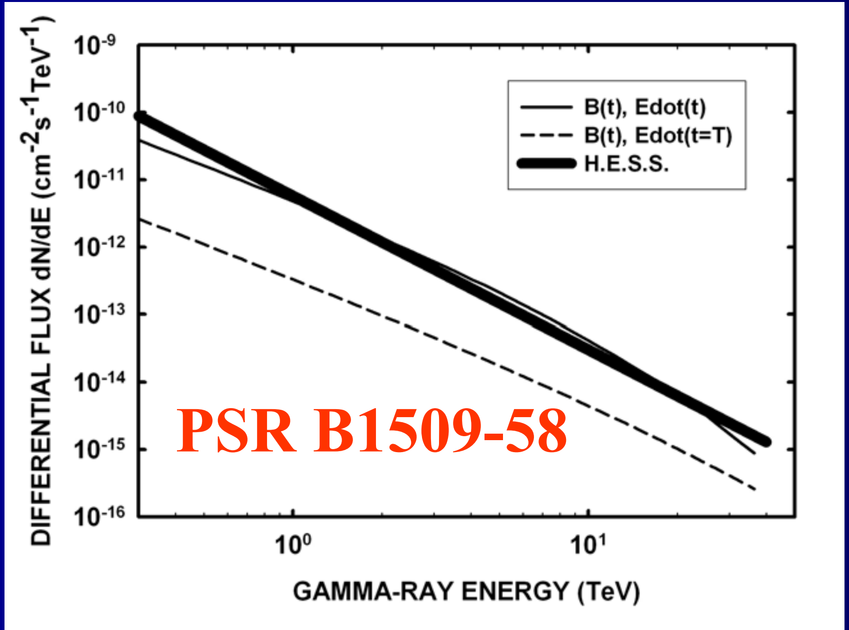


Time dependent modeling.

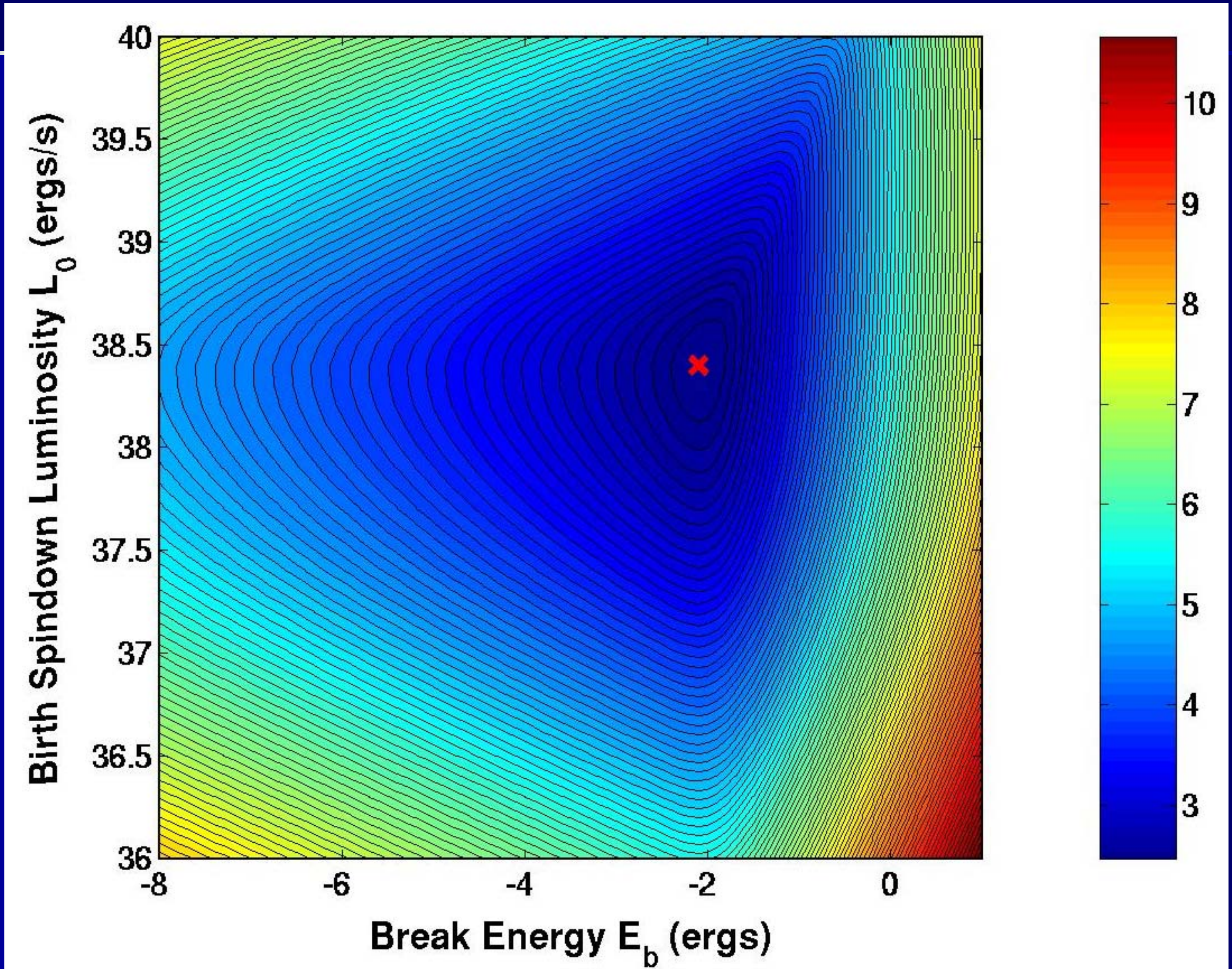
- Time dependent injection (braking index)
- PWN Magnetic field evolution.
- Normalisation to present torii/jet fluxes, spectra.
- Maximum acceleration energy constraint at PWN shock
- Survival of electrons to edge of PWN







Model of G0.9+0.1
Venter & de Jager 2006

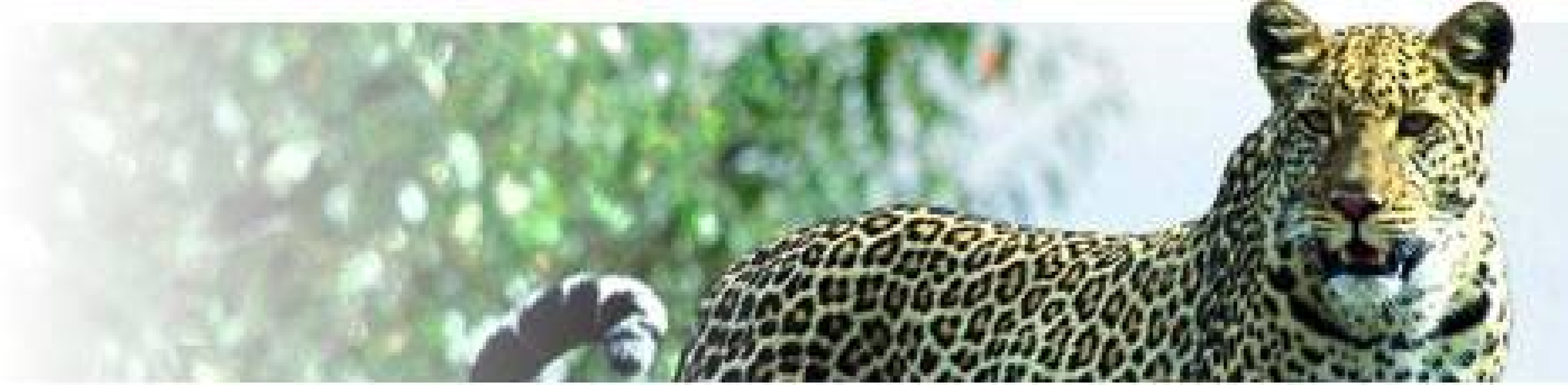


CONCLUSIONS - PWNe

- Up to know radio and X-rays probed the extreme ends of the electron spectral tail. Sometimes unrelated?
- HESS (VHE gamma-rays) made a ground braking contribution by adding spectral information on electron energies between radio and X-rays.
- VHE γ-ray emitting electron lifetimes are comparable to or just shorter than pulsar age.
- VHE γ-rays probe the lower energy tail of X-ray spectrum – in some cases we see the cooled component and in other cases the hard uncooled component as seen in torii and jets. We even see the important cooling break in some cases.
- We see the history of SNR reverse shock evolution on PWN older than 10 kyr. Those younger than 10 kyr are unshifted. PSR 1509-58 may become Vela X like.

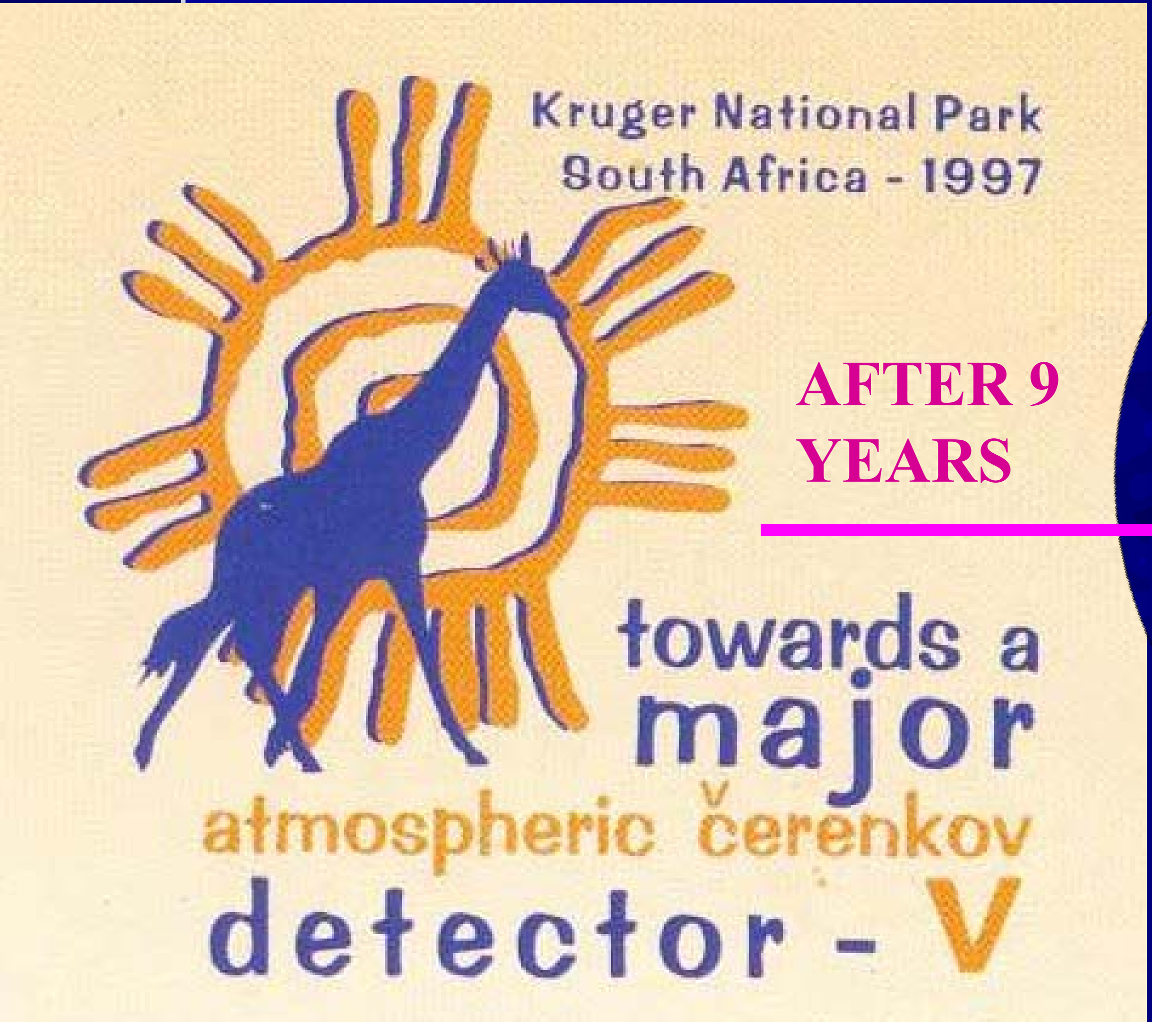
KRUGER NATIONAL PARK MEETING ON PULSARS AND SNRs – towards end of August 2007

The Multiwavelength Landscape of Pulsars and Supernova Remnants

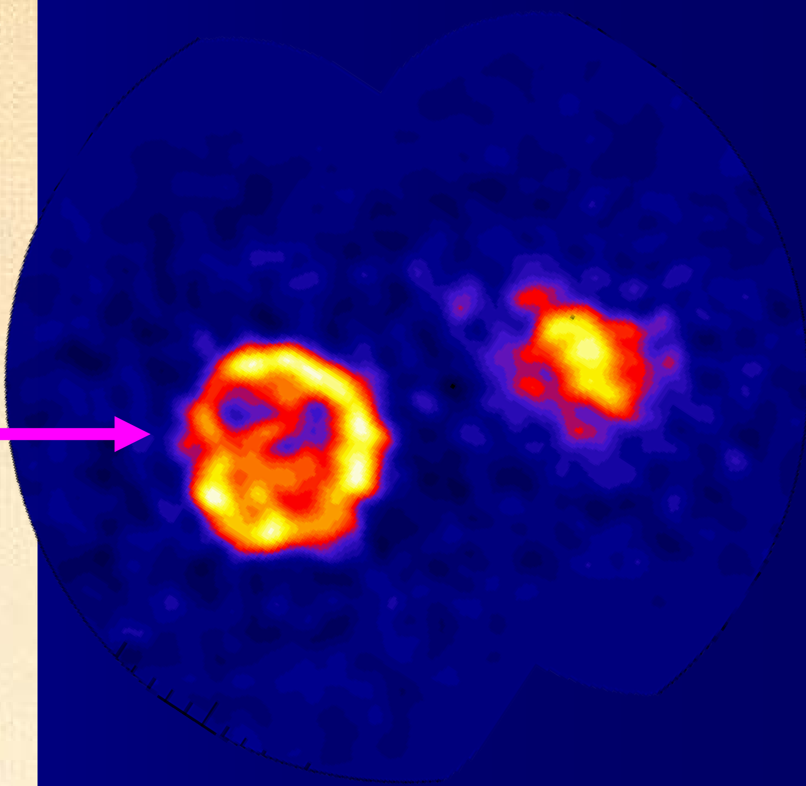


DESTINATION KRUGER PARK

Idea of HESS in Southern Africa was born 10 years ago in Kruger National Park meeting.



AFTER 9 YEARS



Thank You