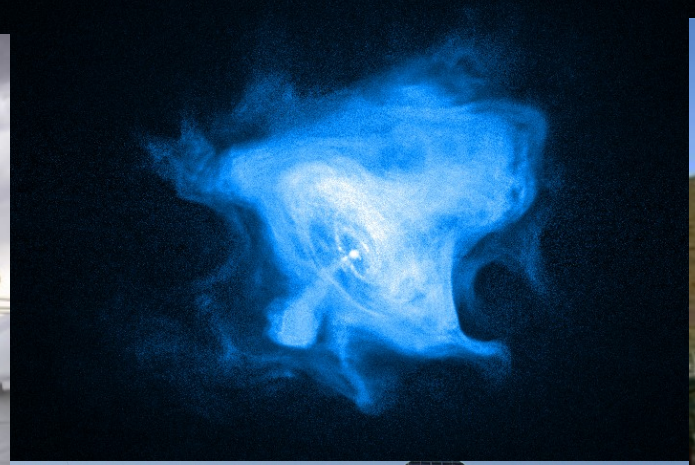
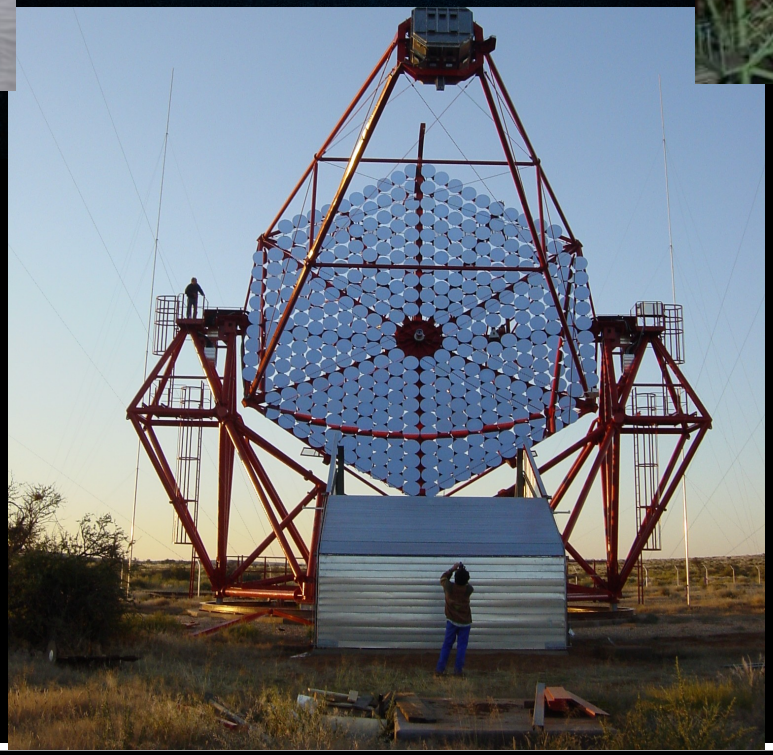
Pulsar Wind Nebulae:
Recent advances in the TeV range





Outline

I The Galaxy at TeV energies as seen by H.E.S.S :

PWN everywhere ?

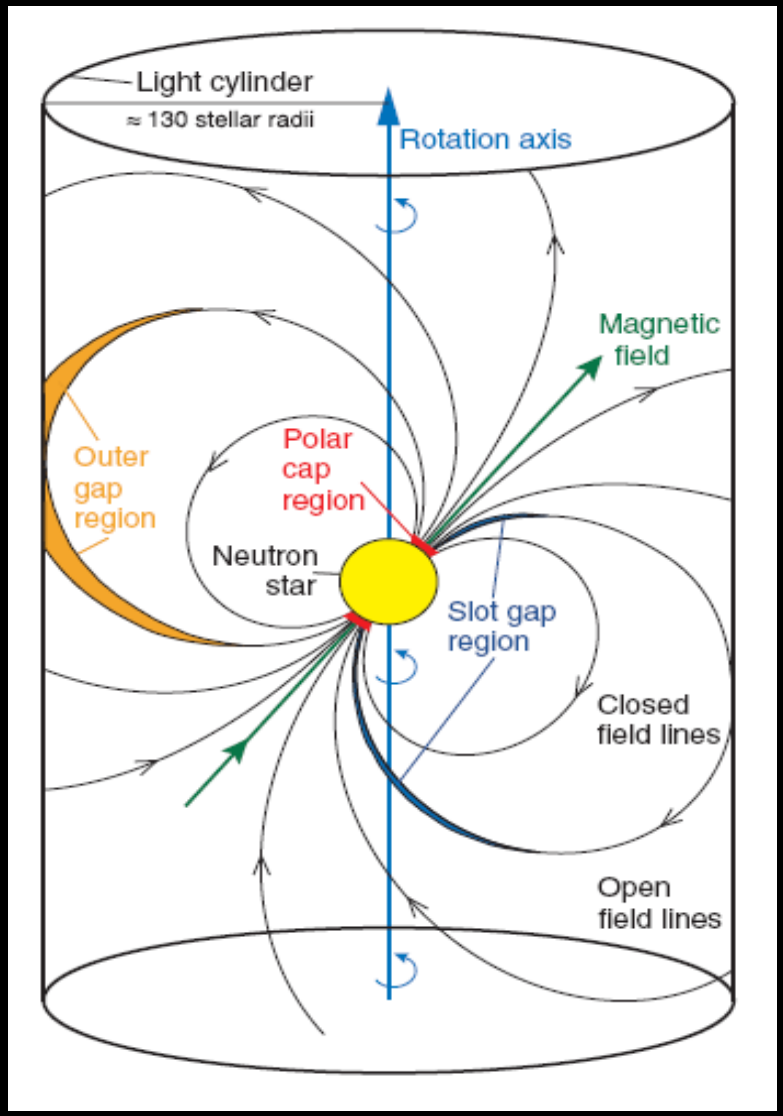
II Looking for firm association with pulsar wind nebulae :

A large variety of source !

III The population of the TeV PWN :

What have we learned ?

Pulsars Wind Nebulae



The period decreases with time
→ Pulsars emit energy :

$$\dot{E} = 4\pi I \frac{\dot{P}}{P^3}$$

$$\dot{E}(t) = \frac{\dot{E}_0}{\left(1 + \frac{t}{\tau_0}\right)^2}$$

2 regimes :

$t \ll \tau_0 \quad \dot{E} \approx \dot{E}_0$

$t \gg \tau_0 \quad \dot{E} \propto t^{-2}$

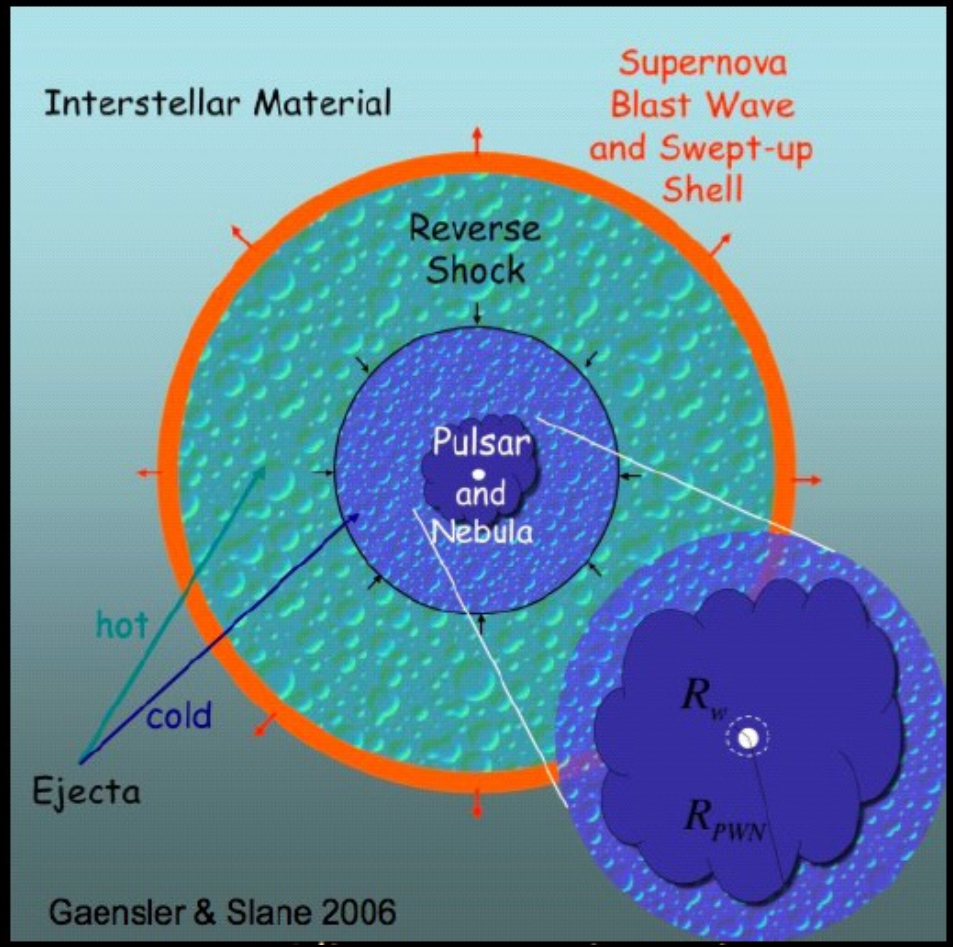
$$T = \tau_c - \tau_0 \qquad \tau_c = \frac{P}{2\dot{P}}$$

Particle escape from the pulsar magnetosphere
→ Relativistic wind

Relativistic wind interact with outer medium
→ Shock (+Acceleration)

Description of pulsar wind nebulae

Young system : PWN expend freely in supernova ejectas.



$$R_{PWN} = 1.1\,\mathrm{pc}\left(\frac{\dot{E}_0}{10^{38}\,\mathrm{erg.s^{-1}}}\right)^{1/5}\left(\frac{E_{SN}}{10^{51}\,\mathrm{erg}}\right)^{3/10}\left(\frac{M_{ej}}{10\,M_0}\right)^{-1/10}\left(\frac{t}{10^3\,\mathrm{yrs}}\right)^{6/5}$$

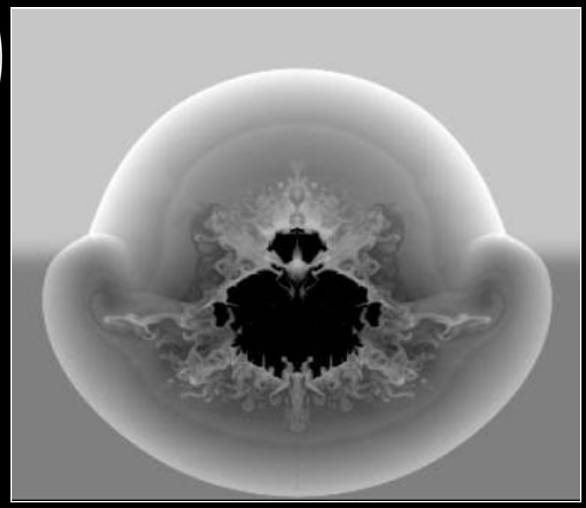
Chevalier (1977)

Description of evolved pulsar wind nebulae

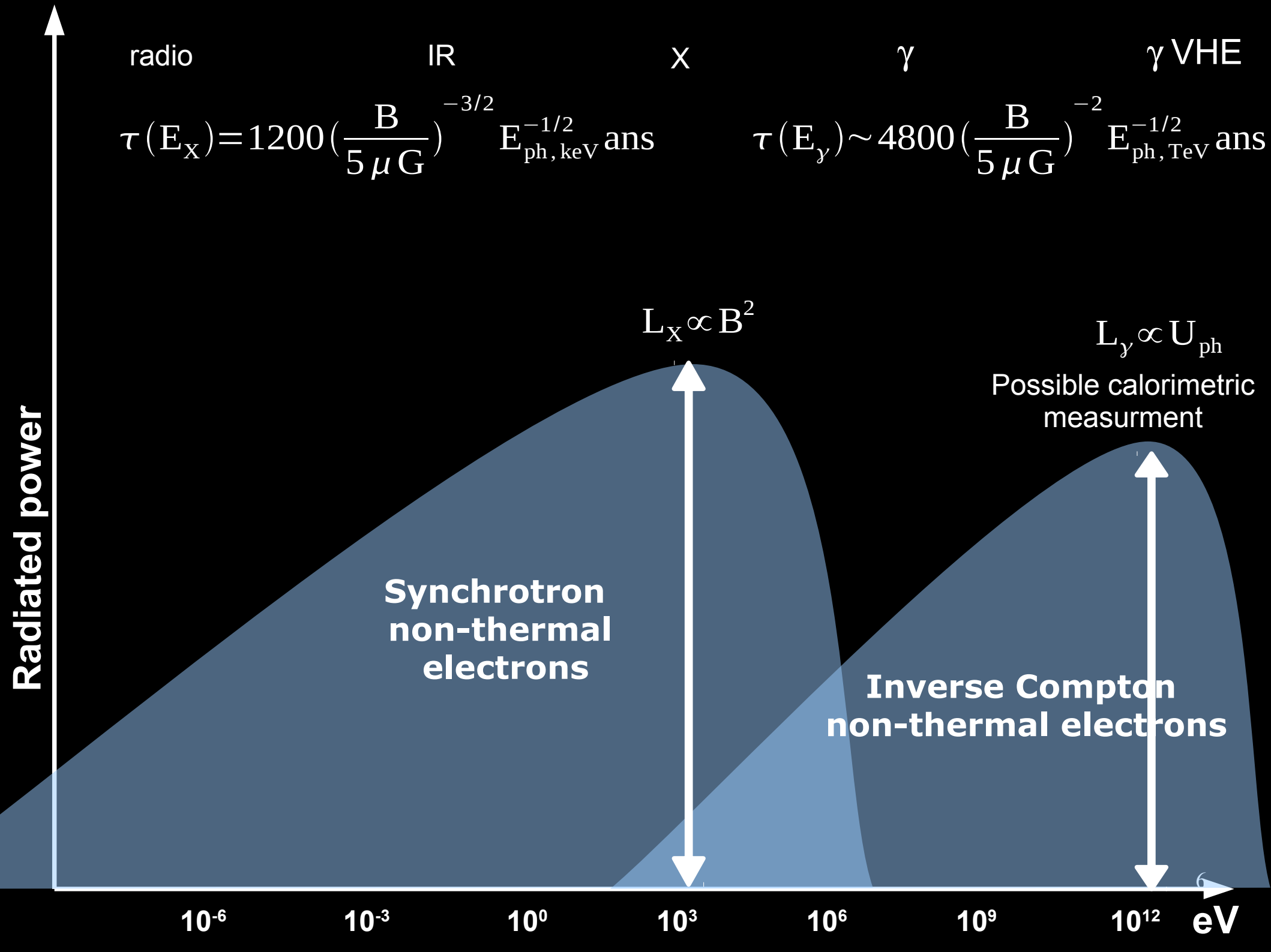
Evolved system :
(Interaction with the reverse shock)

Few thousand years after SN explosion

inhomogenous ISM → asymetric evolution



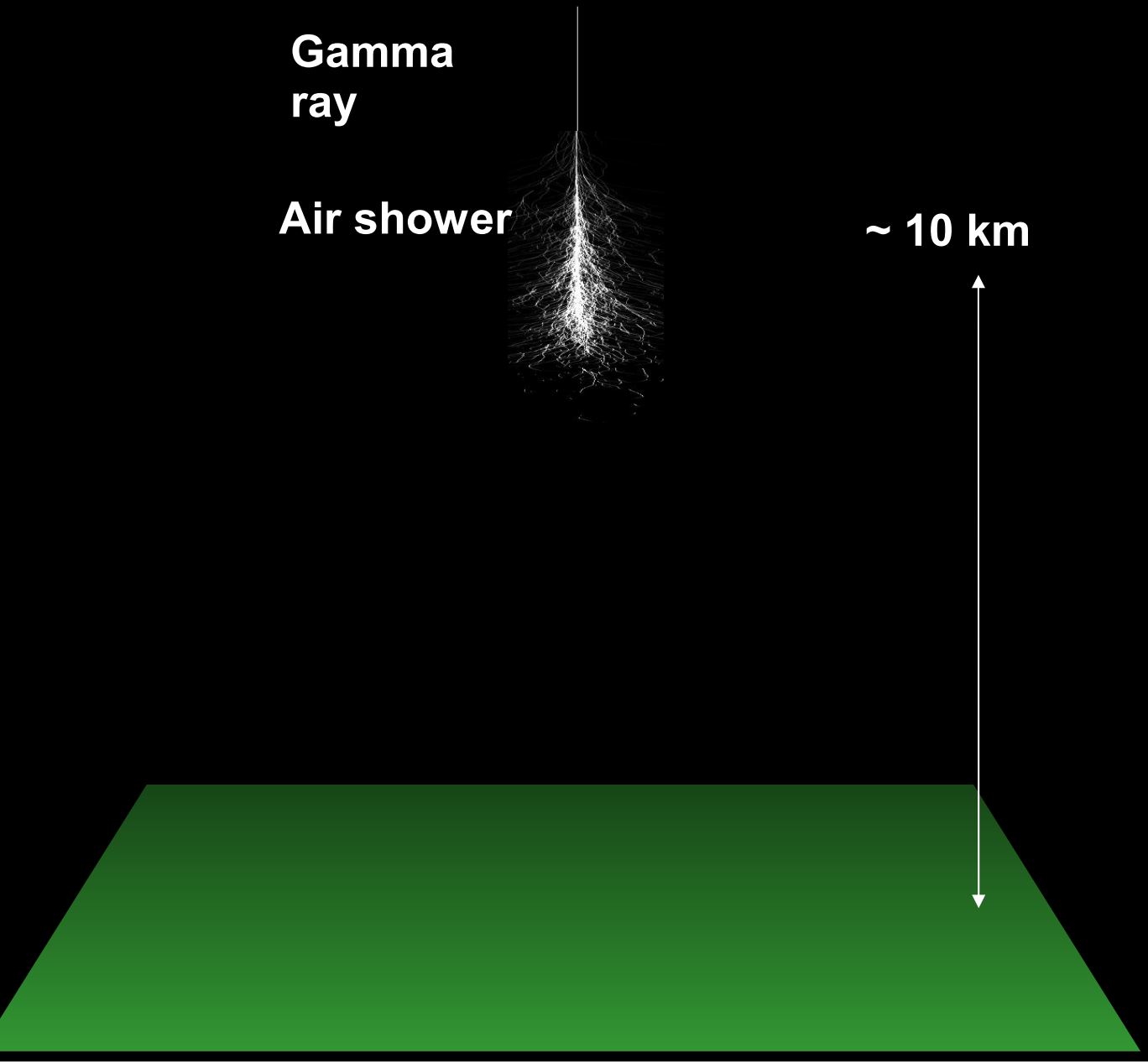
Blondin et al. 2001


radio
IR
X
γ
γ VHE
$\tau(E_X) = 1200 \left(\frac{B}{5\,\mu G}\right)^{-3/2} E_{ph,keV}^{-1/2}$ ans
$\tau(E_\gamma) \sim 4800 \left(\frac{B}{5\,\mu G}\right)^{-2} E_{ph,TeV}^{-1/2}$ ans
$L_X \propto B^2$
$L_\gamma \propto U_{ph}$
Possible calorimetric measurment
Radiated power
Synchrotron non-thermal electrons
Inverse Compton non-thermal electrons
10^{-6}
10^{-3}
10^{0}
10^{3}
10^{6}
10^{9}
10^{12}
eV
6

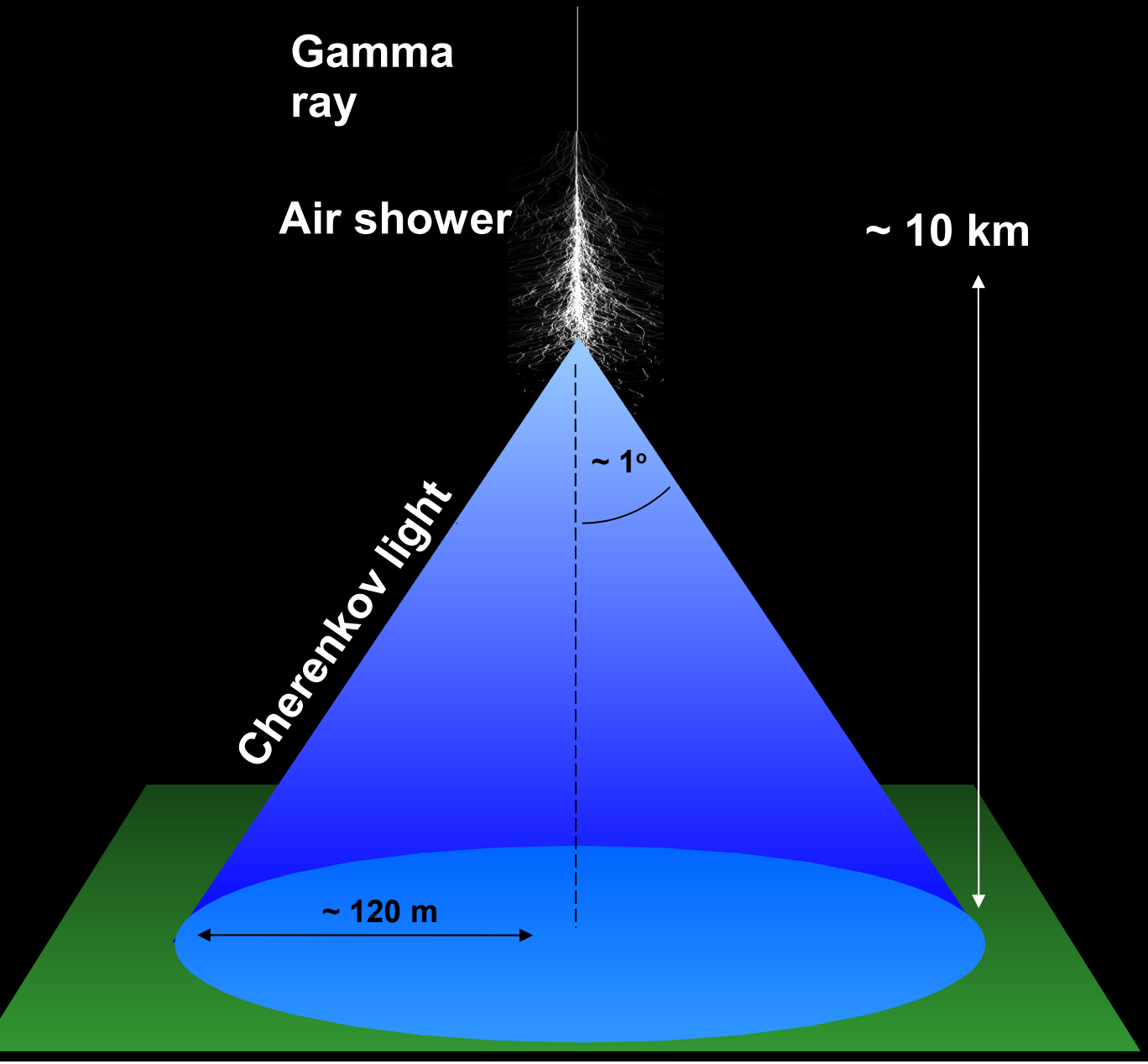
Čerenkov imager : Detection principle

Gamma ray

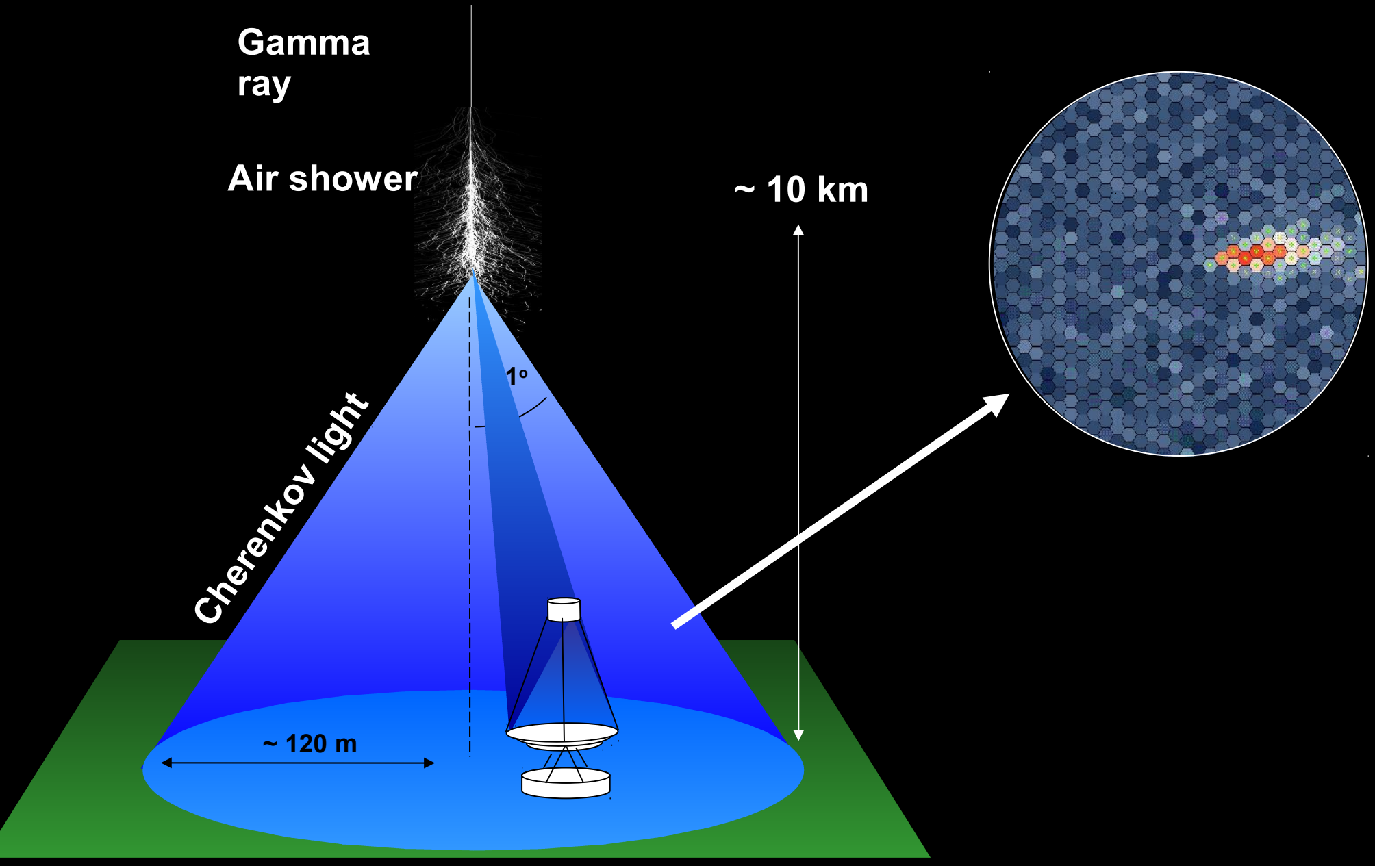
Čerenkov imager : Detection principle



Čerenkov imager : Detection principle



Čerenkov imager : Reconstruction principle



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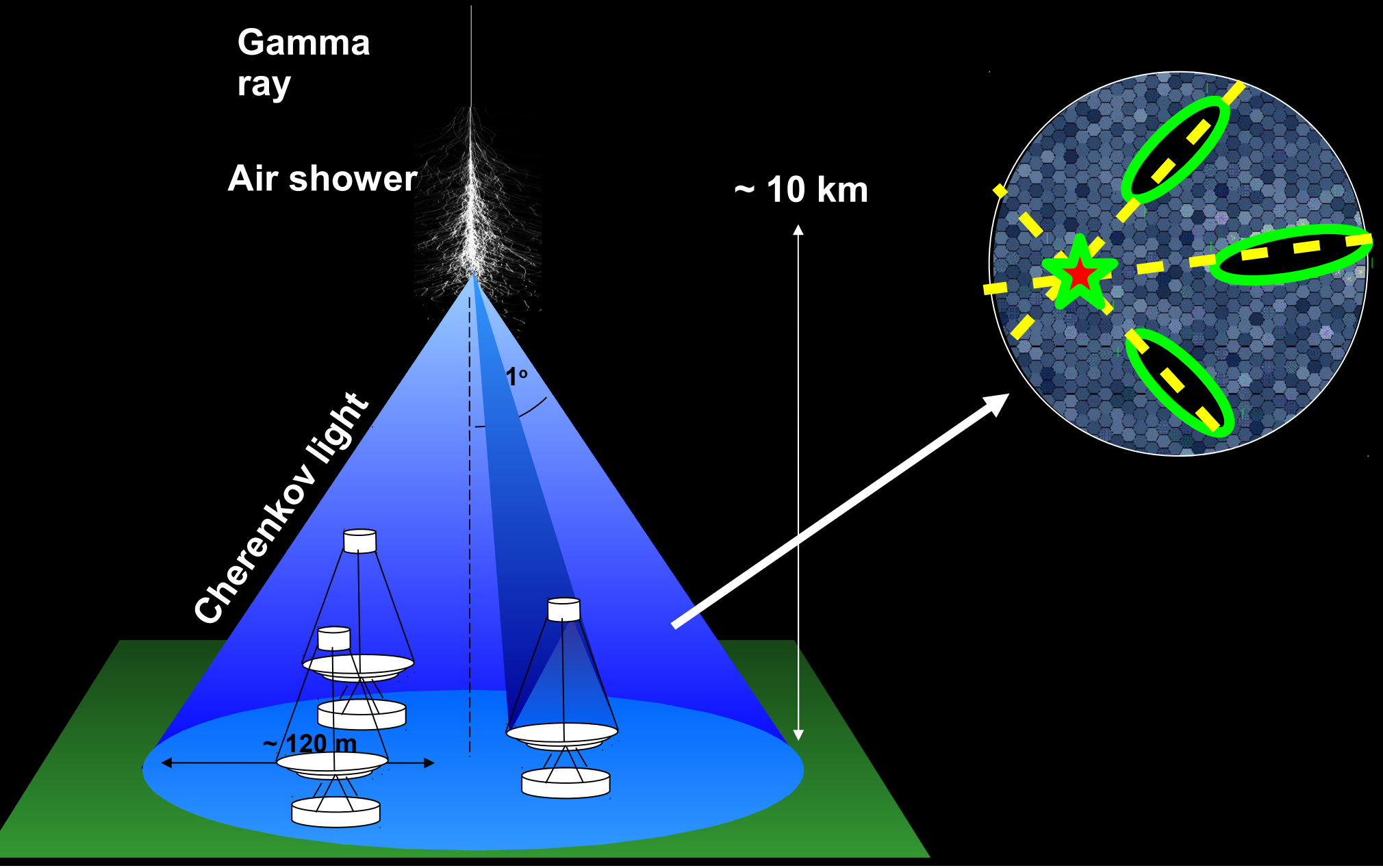
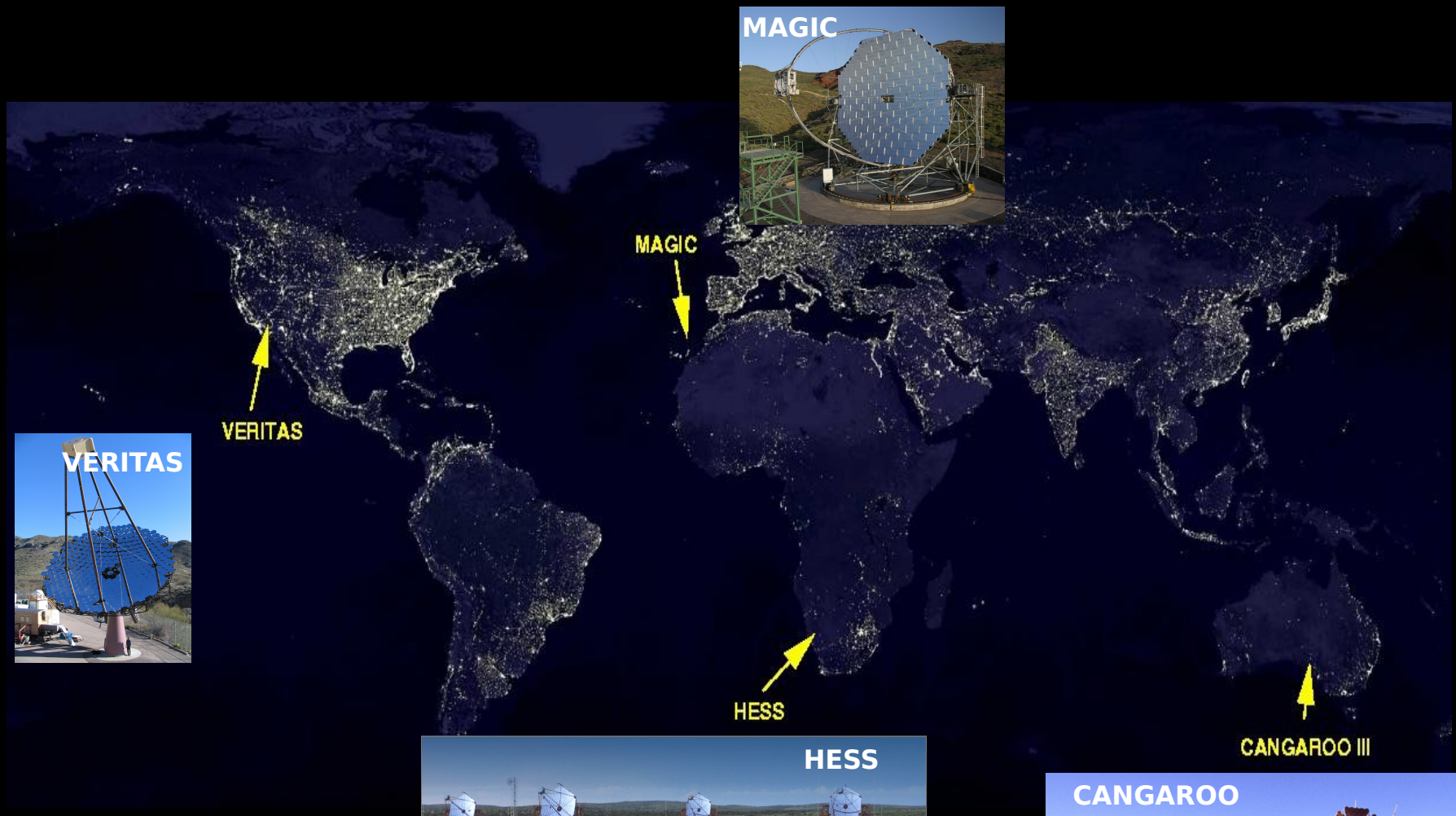


VHE gamma-rays detector around the world



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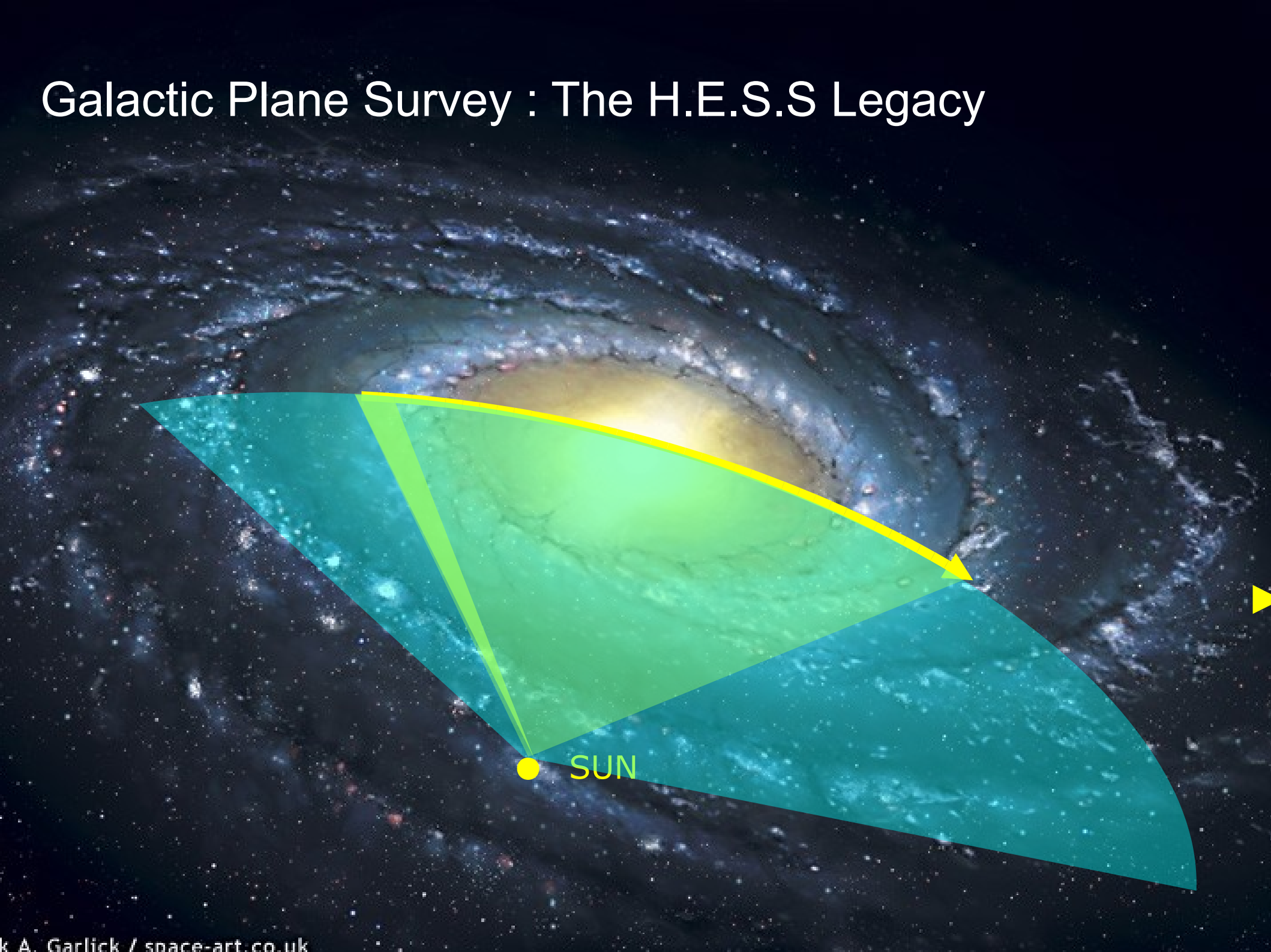
Galactic Plane Survey : The H.E.S.S Legacy



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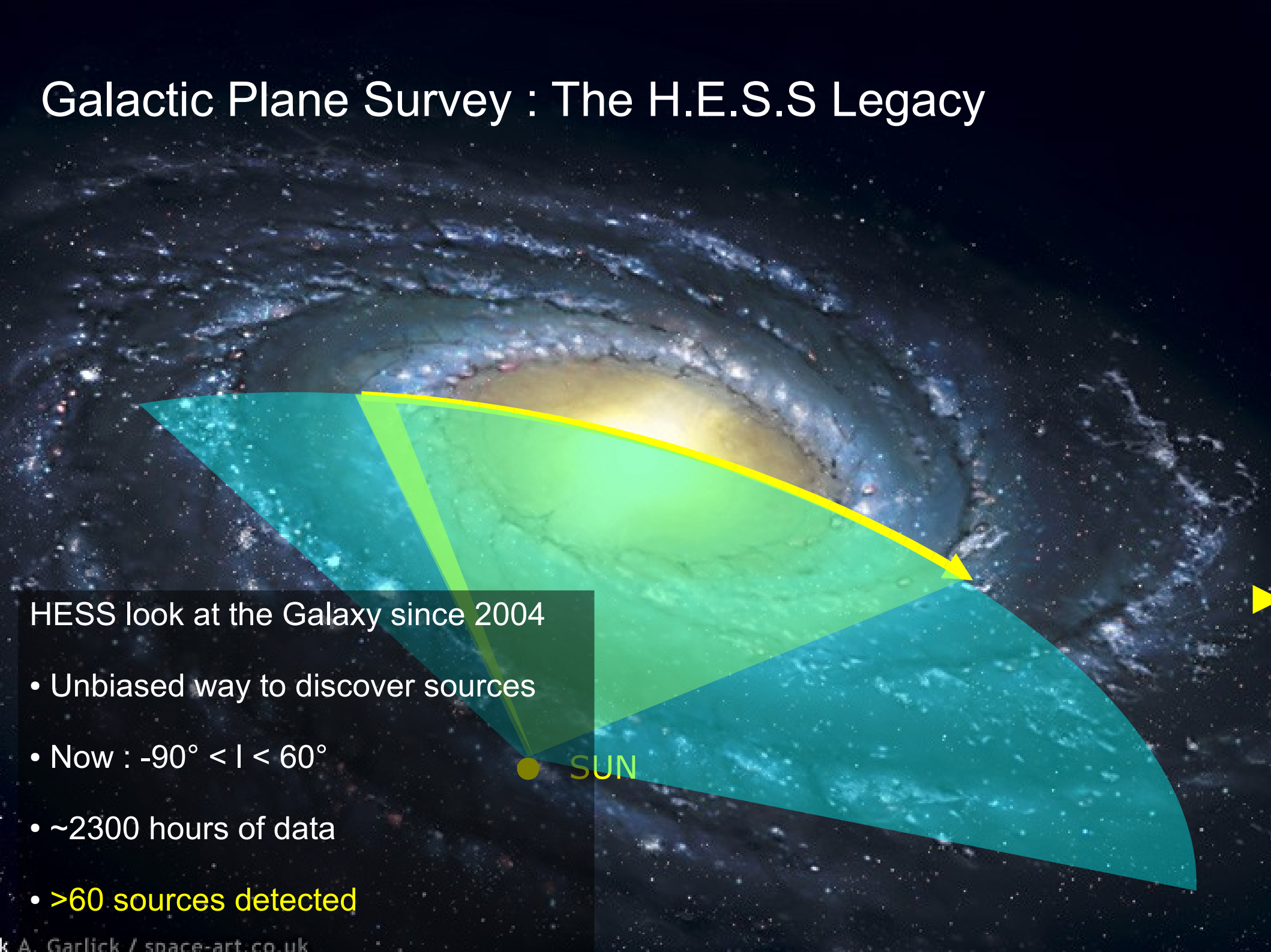
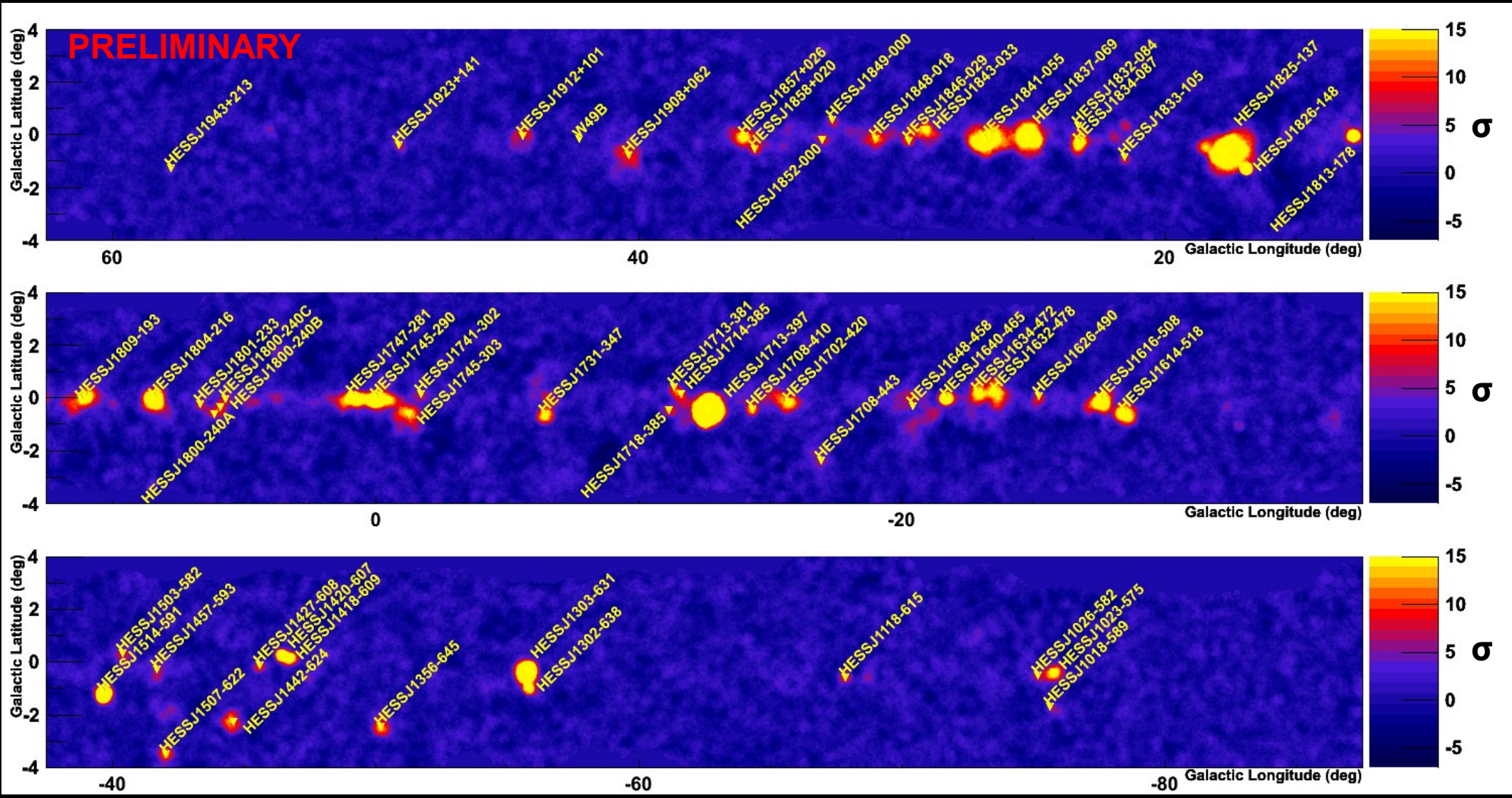


HESS look at the Galaxy since 2004

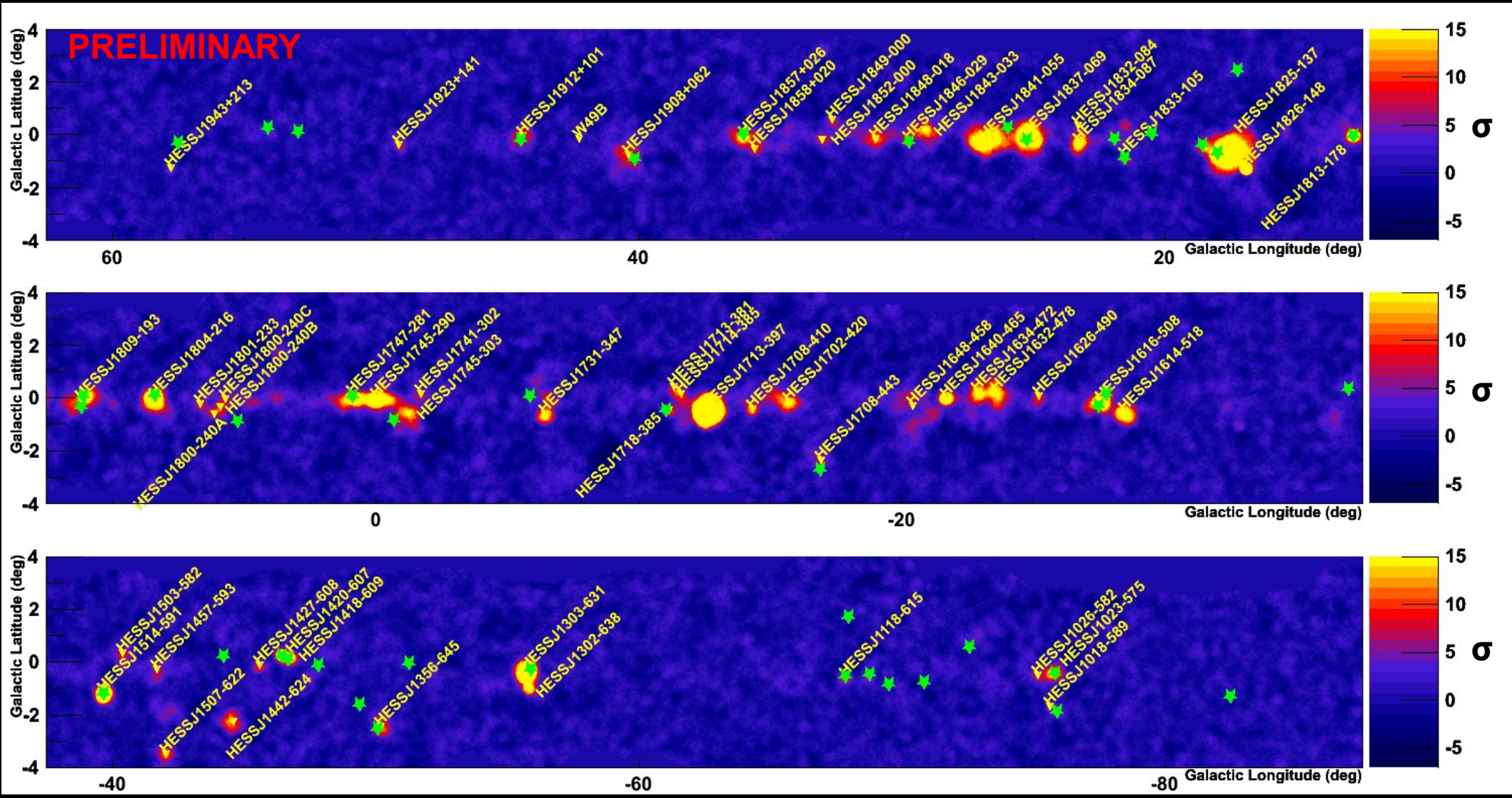
- Unbiased way to discover sources
- Now : -90° < l < 60°
- ~2300 hours of data
- >60 sources detected

H.E.S.S. Legacy : The Galactic Plane Survey



Significance Map, Integration radius = 0.22°

PWN : The most important population in the Galaxy !



~ 40% of the galactic source are PWN
Many unidentified sources are close to energetic pulsar

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Pulsar Wind Nebulae

- Major galactic source population
  Revealed by HESS galactic scan

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

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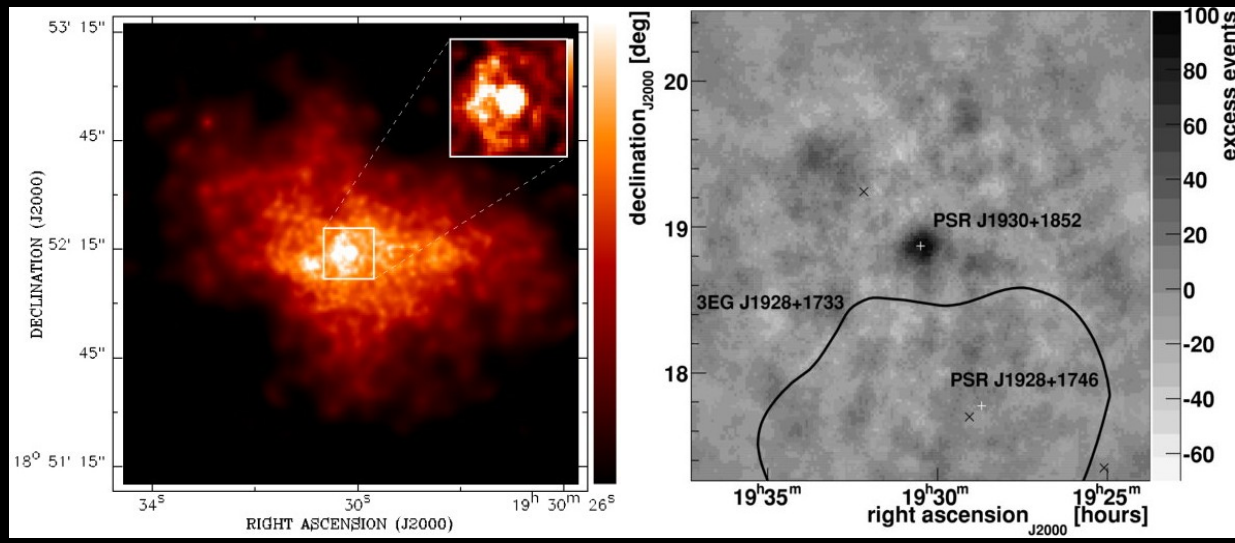
  pulsars
- **Two classes :**
  Young plerions (~few 10^3 yrs)
  - **Point-like, centered in the pulsar candidate**
  - **Nearly straight forward identification**

SNR G54.1+0.3
PSR J1930+1852,
$\dot{E}_{37} = 1.2$, $\tau_c = 2.9$ kyr,
P = 136 ms



Chandra 0.5-10keV
(Lu et al. 2002)

Veritas Acciari et al. 2010

Other Examples :
Crab, Kes 75, SNR G21.5-0.9, SNR G0.9+0.1, etc...

→ Disambiguation SNR/PWN :
- Energetic arguments
- PWN Resolution (SNR G0.9+0.1)

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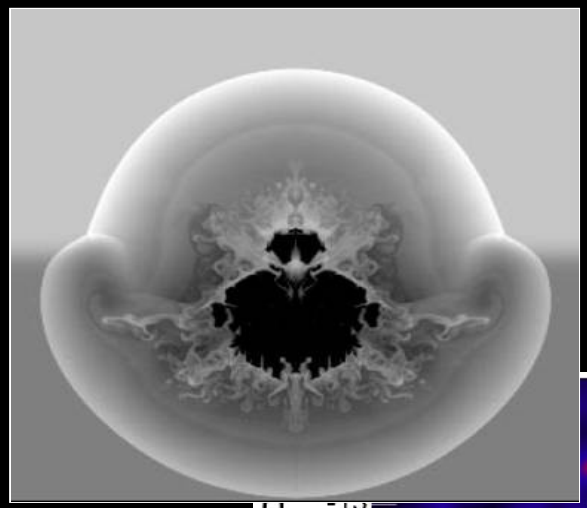
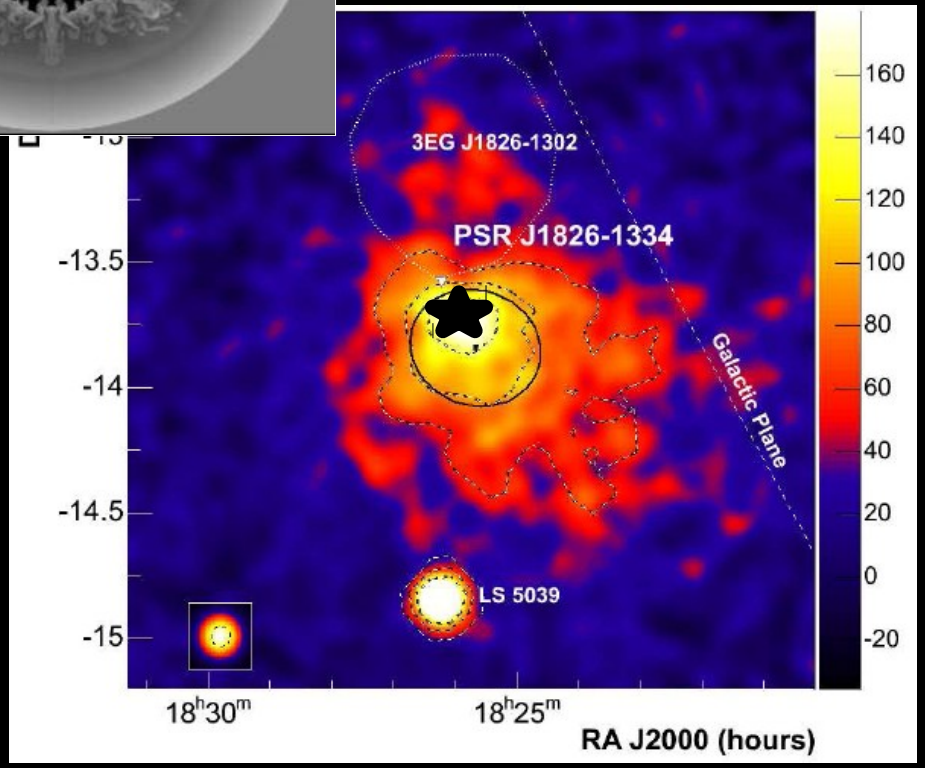
  Evolved PWN (> 10^4 yrs)
  - Nebulae with huge caracteristic sizes ~ few tens of pc
  - Mostly displaced TeV emission wrt pulsar position: "Crushed nebulae"
  - Difficult to unveil the association



Blondin et al. 2001



Aharonian et al. 2005

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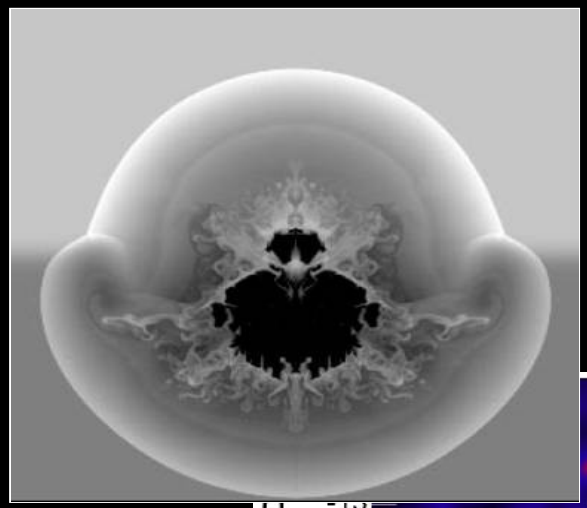

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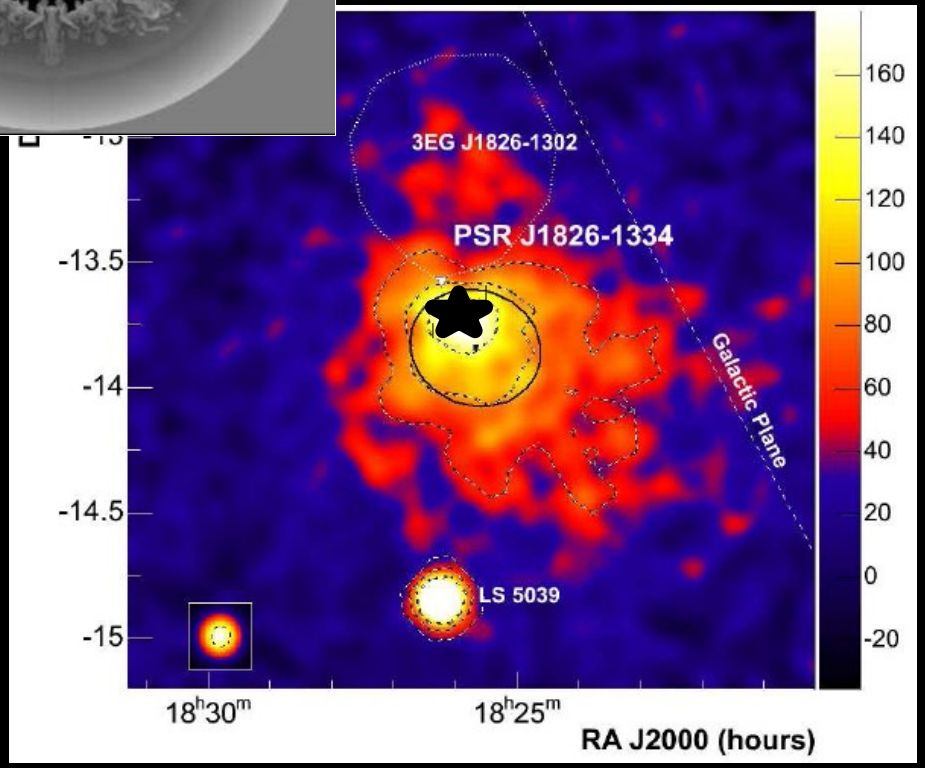

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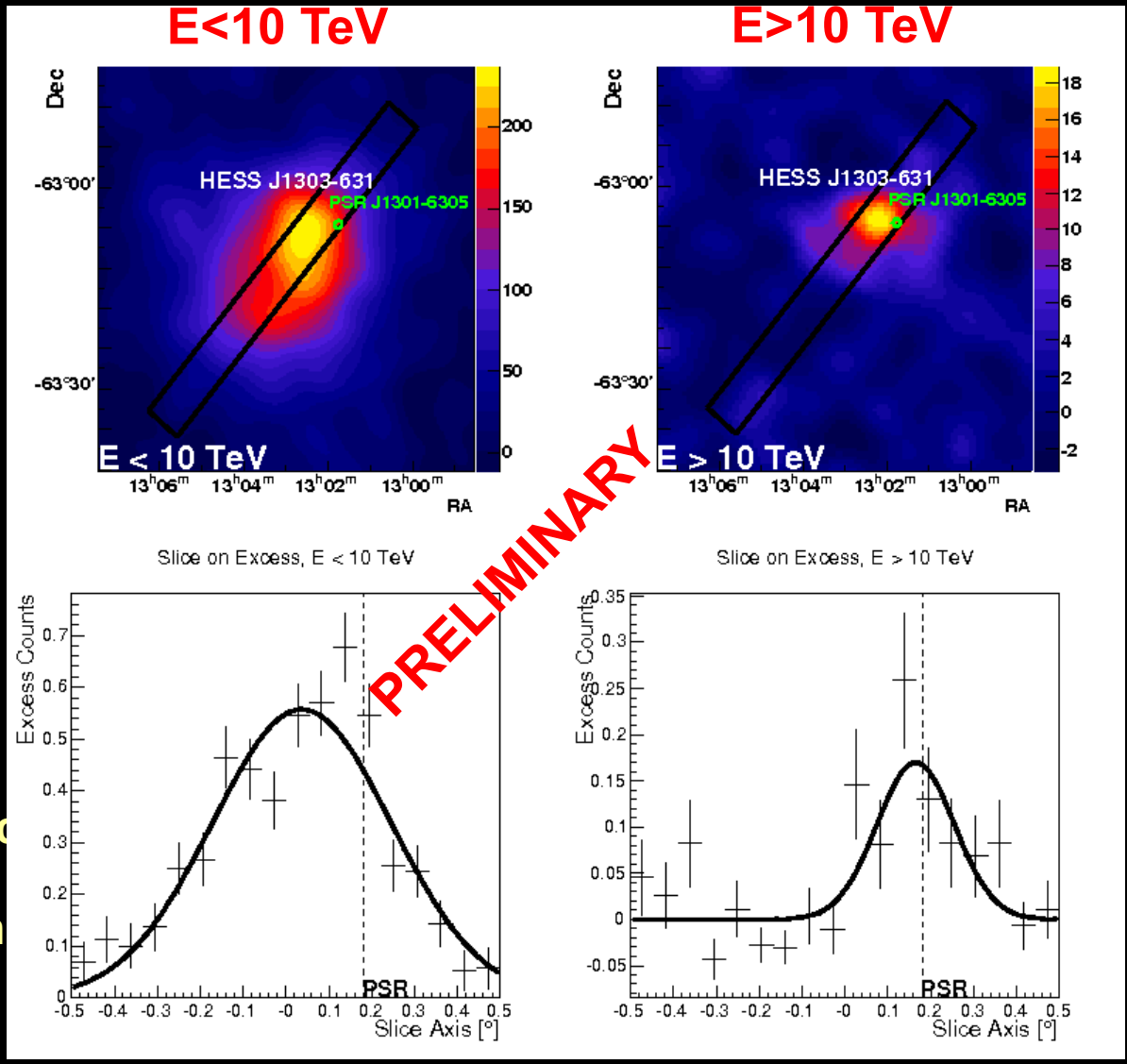
    (energetic and spectromorphologic aspects)

Spectro-morphology variations



(Dalton TeVPA 2010)

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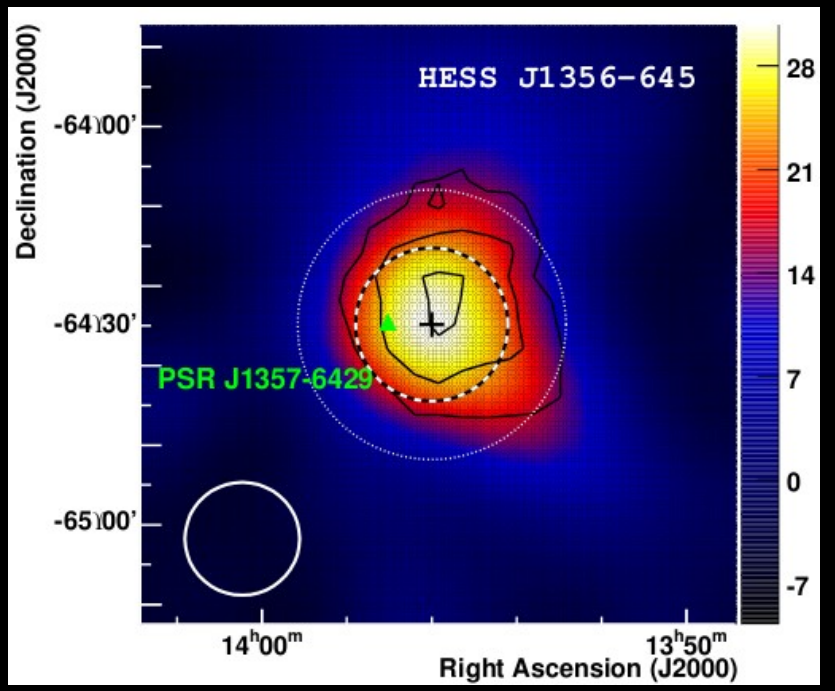
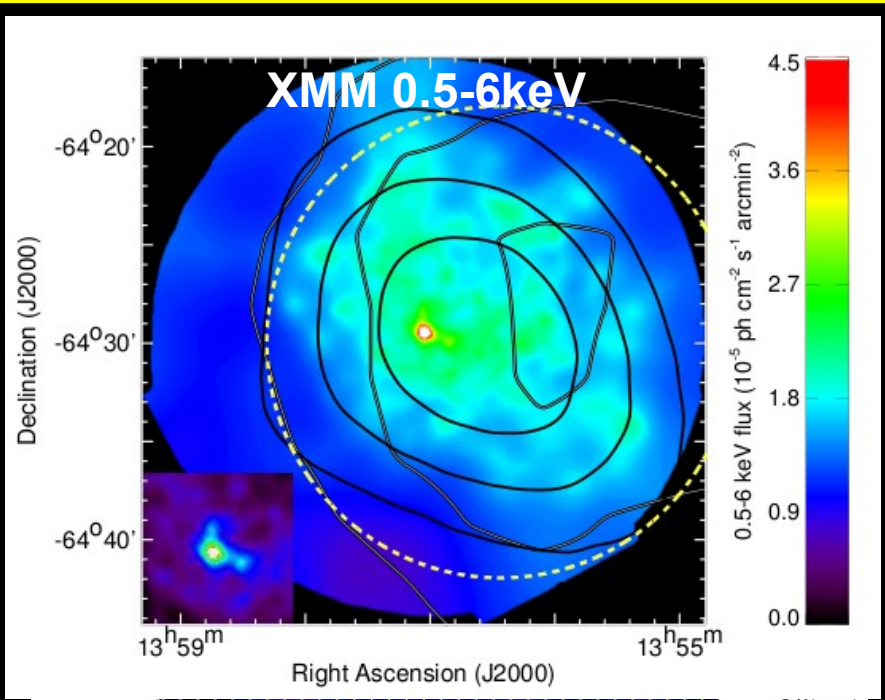
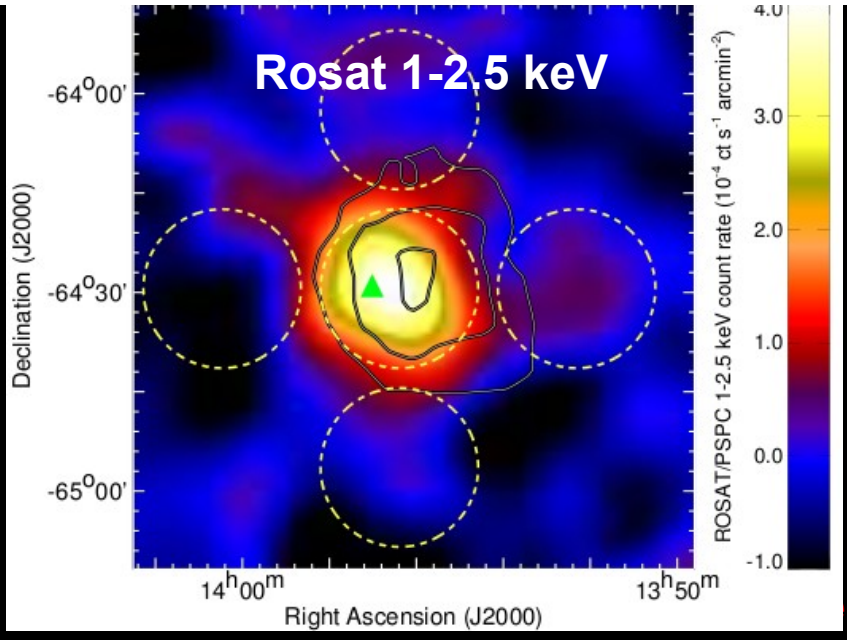


H.E.S.S. Collaboration 2011

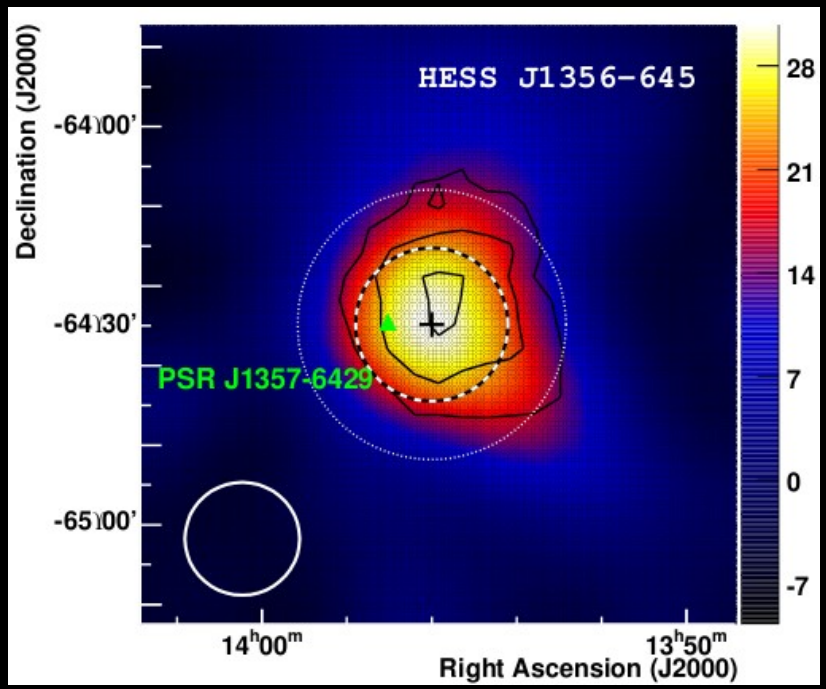
PSR J1357-6429
$\dot{E}_{36}$ = 3.1, τ_c = 7.3 kyr,
P = 166 ms
TeV caracteristics :
Γ = 2.2
F = 8 10^{-12} erg.cm^{-2}.s^{-1} (~11% Crab Flux)
Lg/$\dot{E}$ = 0.9-2.8 10^{-3} $d^2_{2.4kpc}$

Pulsar Wind Nebulae





Spatial correlation between X and TeV



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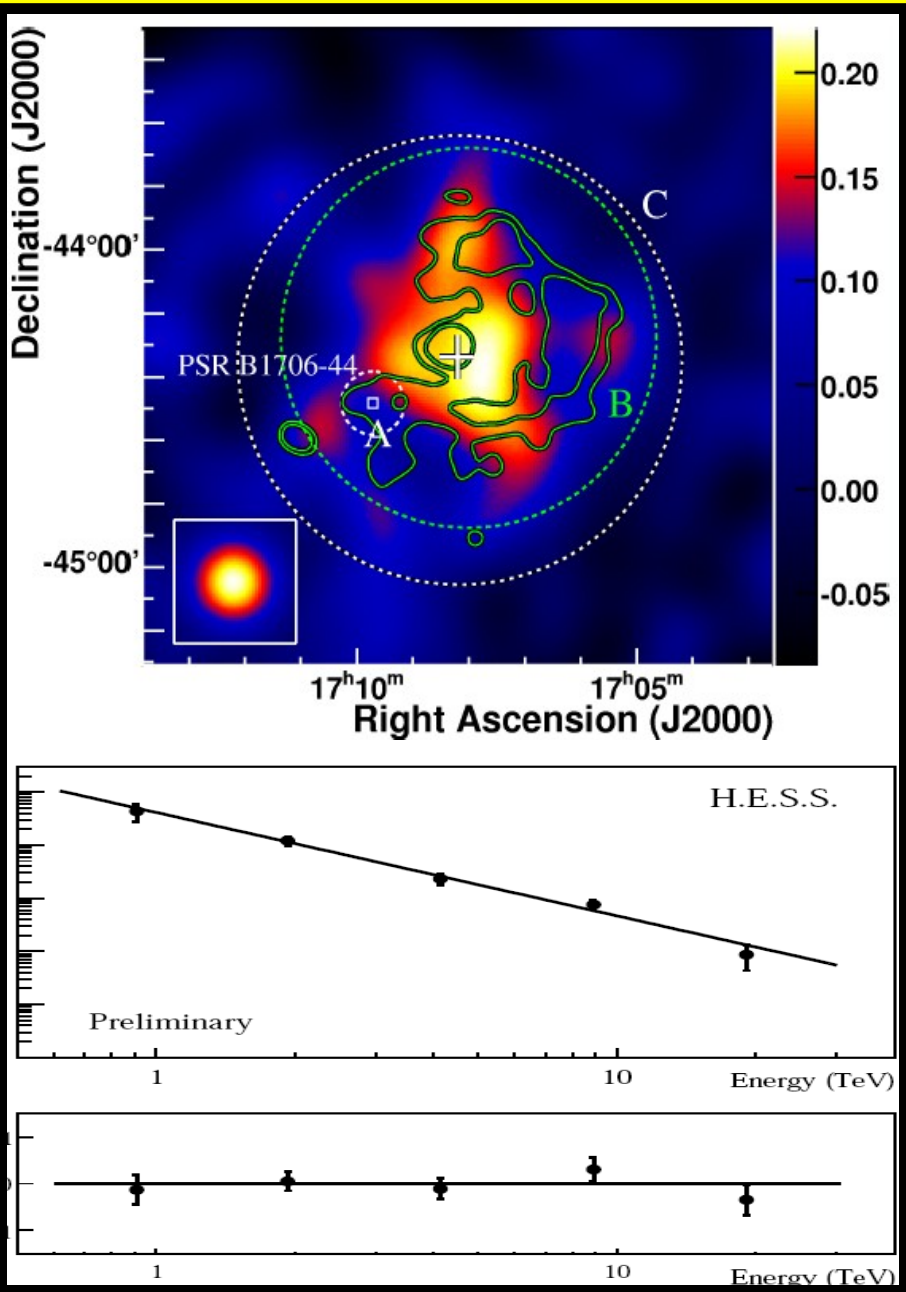
Bfield ~ 3µG

Pulsar Wind Nebulae



H.E.S.S. Collaboration 2011

PSR B1706-44 :

τ = 17.5 kyrs

$\dot{E} = 3.4\ 10^{36}$ erg/s *(Johnston et al 1992)*

1.8kpc < d < 3.5 kpc

Associated to SNR G343.1-2.3 ?

TeV Results :

Gaussian Extension $\sigma \sim 0.3°$

Offset ~ 0.3° → 12pc

Hard spectrum :

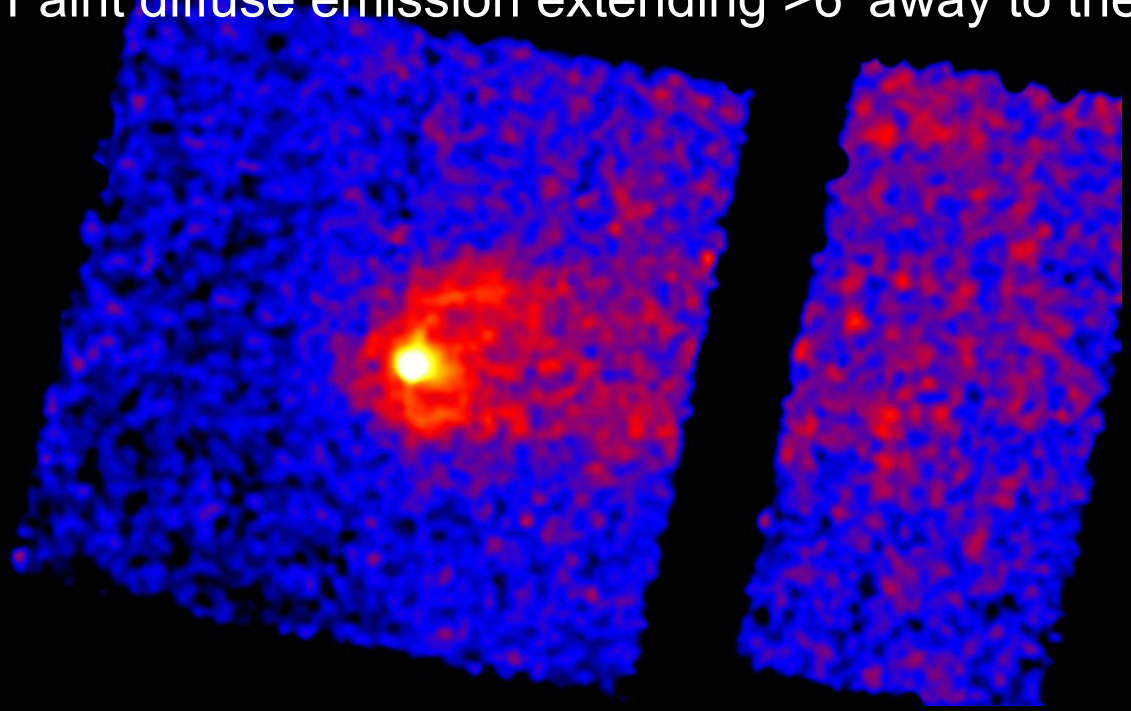
$\Gamma = 2.0 \pm 0.2$

$F(1\text{-}10\ \text{TeV}) \sim 1.5\ 10^{-11}$ erg.cm^{-2}.s^{-1}

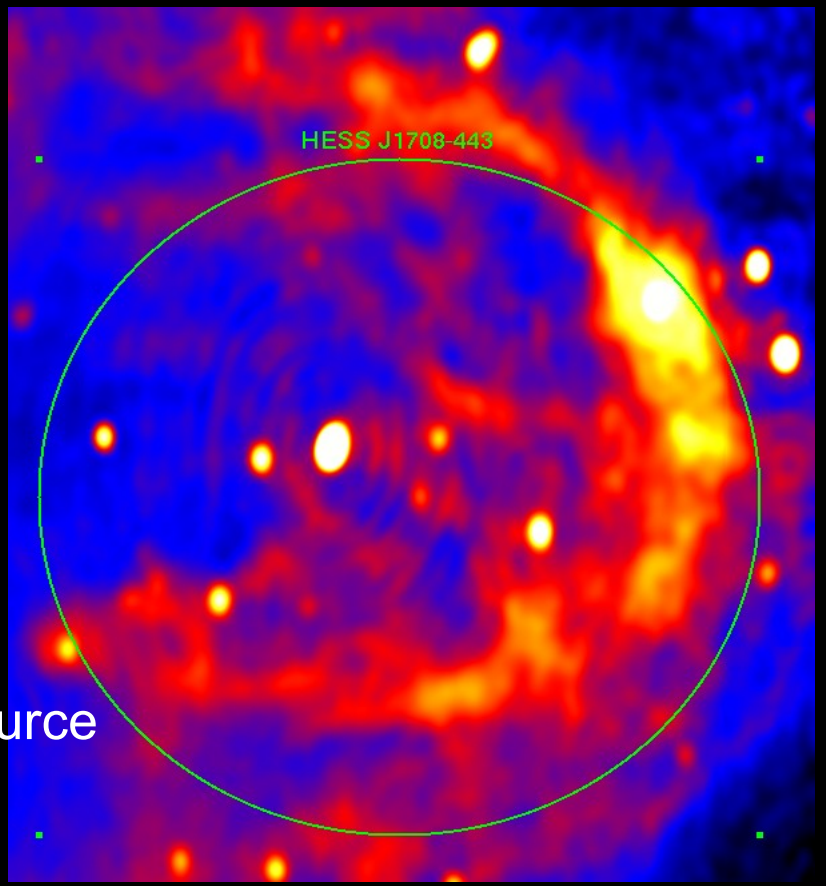
No point like emission from the pulsar.

Pulsar Wind Nebulae

Chandra 1-7 keV smoothed @ 8"
Faint diffuse emission extending >6' away to the west



From Terrier et al. HEEPS meeting 2010, Barcelona



X-rays nebula extend in the direction of the HESS source
→ Association with the pulsar is likely.

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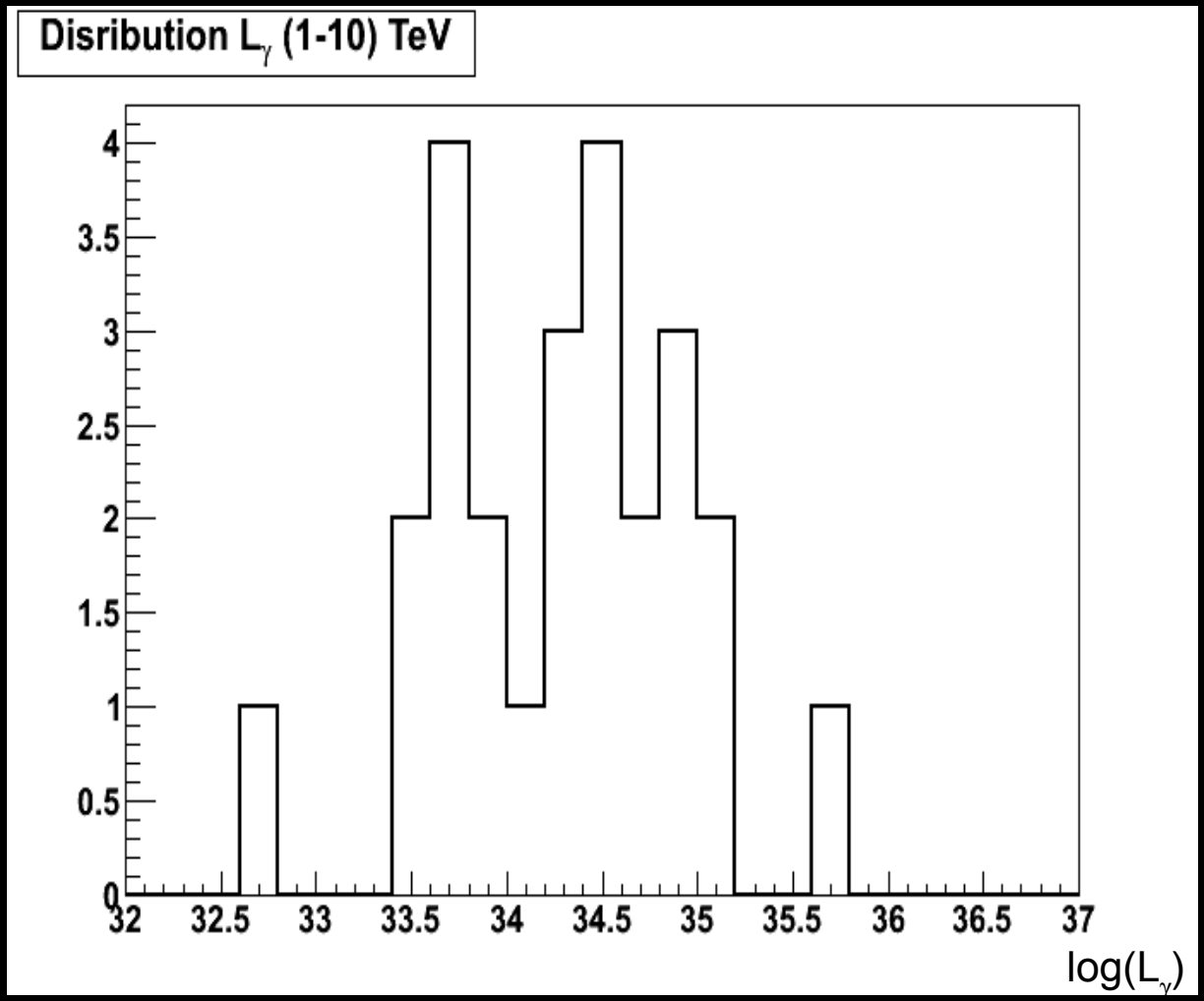
The TeV PWN Population



21 VHE sources « confidently » associated with a pulsar (with some a priori)

5 associations really questionable

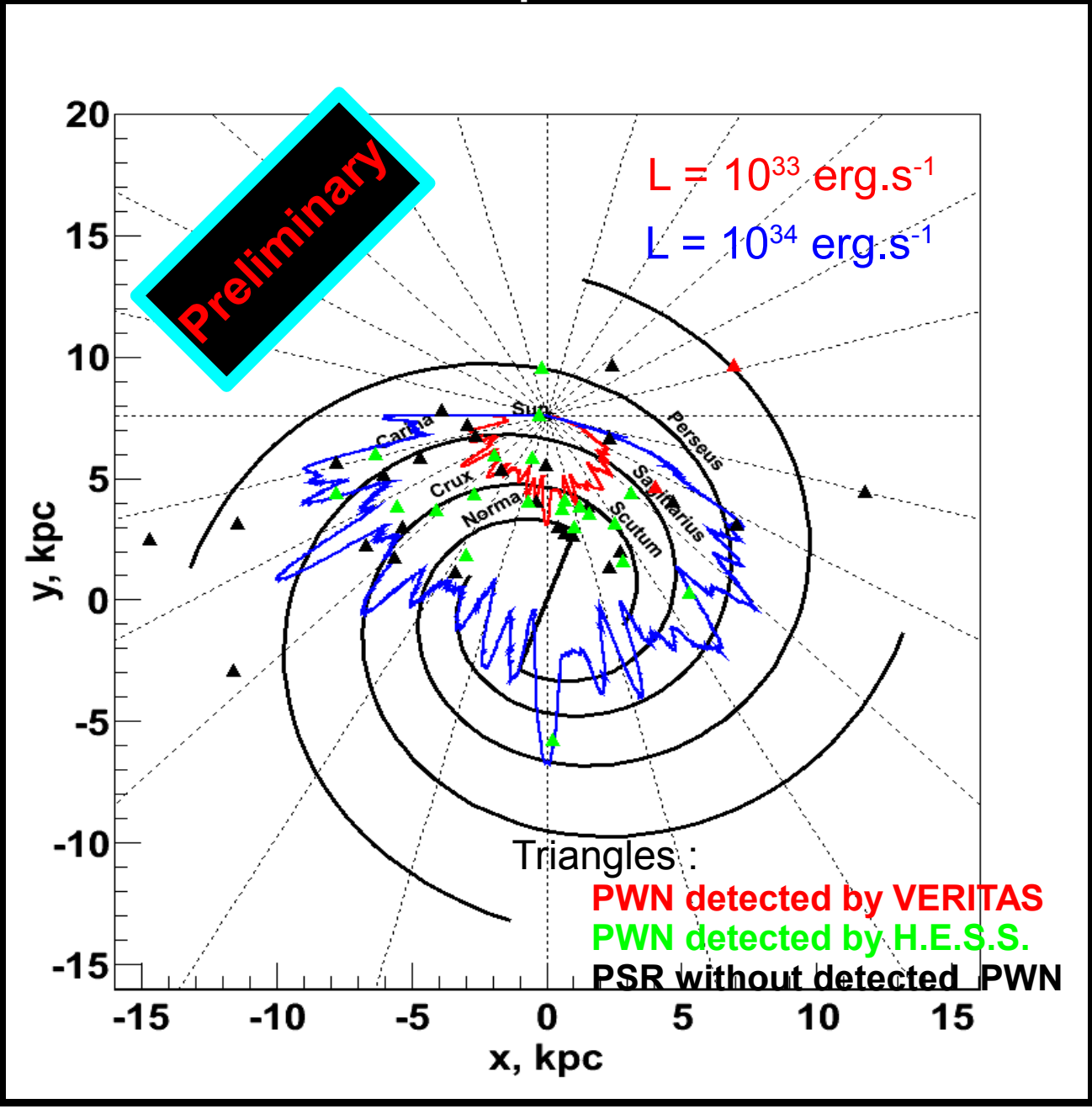
2/3 of pulsars with $\dot{E} > 10^{37}$ erg.s^{-1} have a detected TeV pwn (11 of 16)

~ 50% of pulsars $\dot{E} > 10^{36}$ erg.s^{-1} have a detected pwn.

Distribution of observed γ luminosities

→ Complete Sample ?

The completeness of the survey : horizon



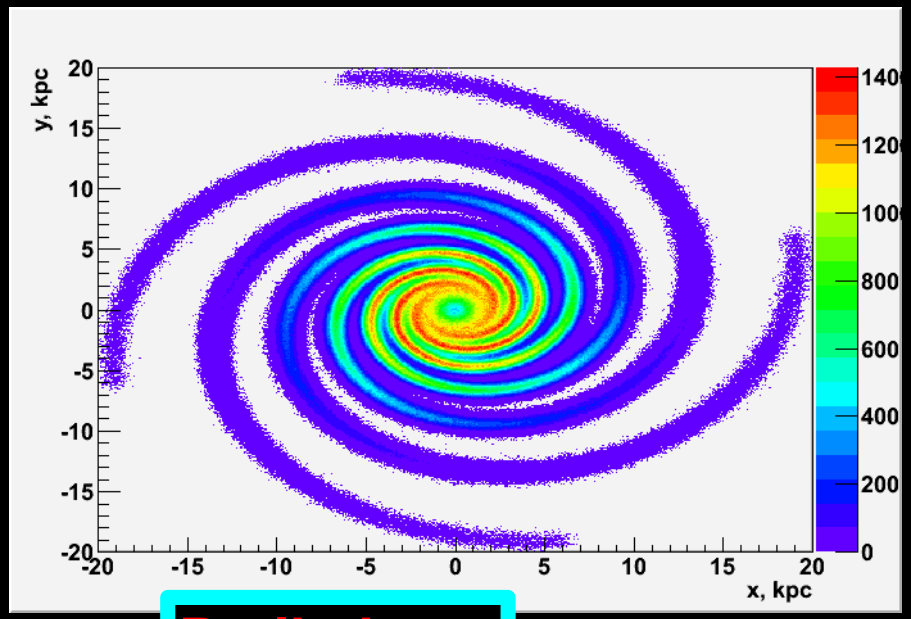
Use the 6.3σ H.E.S.S. sensitivity for Γ=2.3

Pulsar Undetected :

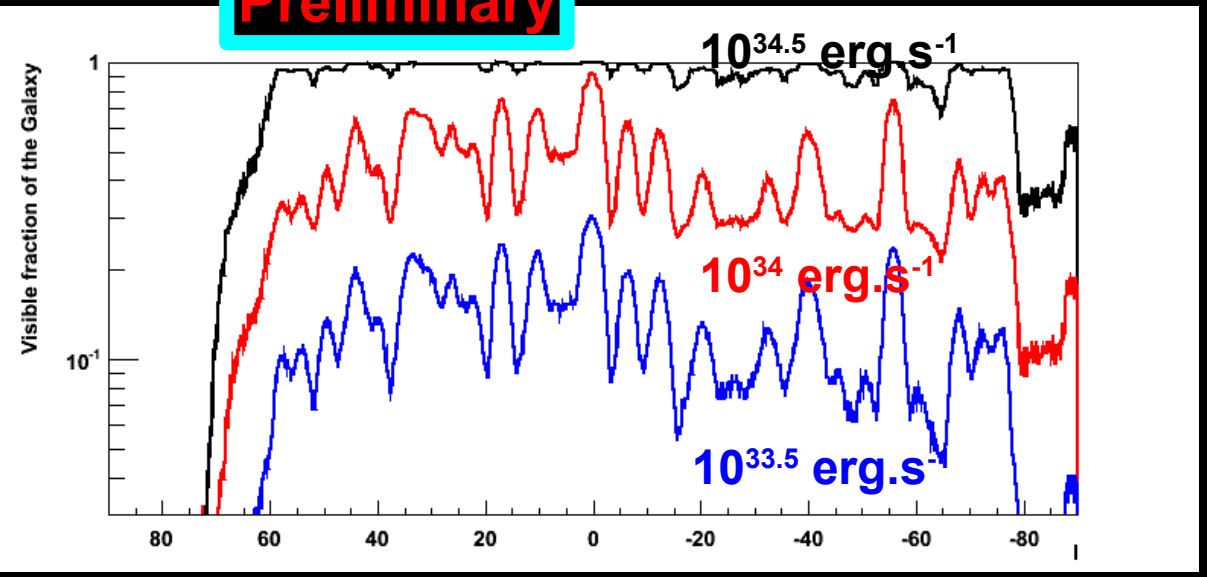
→ Large Distance

→ Low Luminosity

The completeness of the survey : horizon



Preliminary



- Arm Geometry : Vallée 2008
- Arm width : Gaussian of 450pc
  (300 in Cordez & Lazio 2002)
- Radial density : Lorimer 2004

$$\rho(r) = A\, r^{n} e^{-r/\sigma}$$

with A = 64.6
N = 2.35 and
σ = 1.528

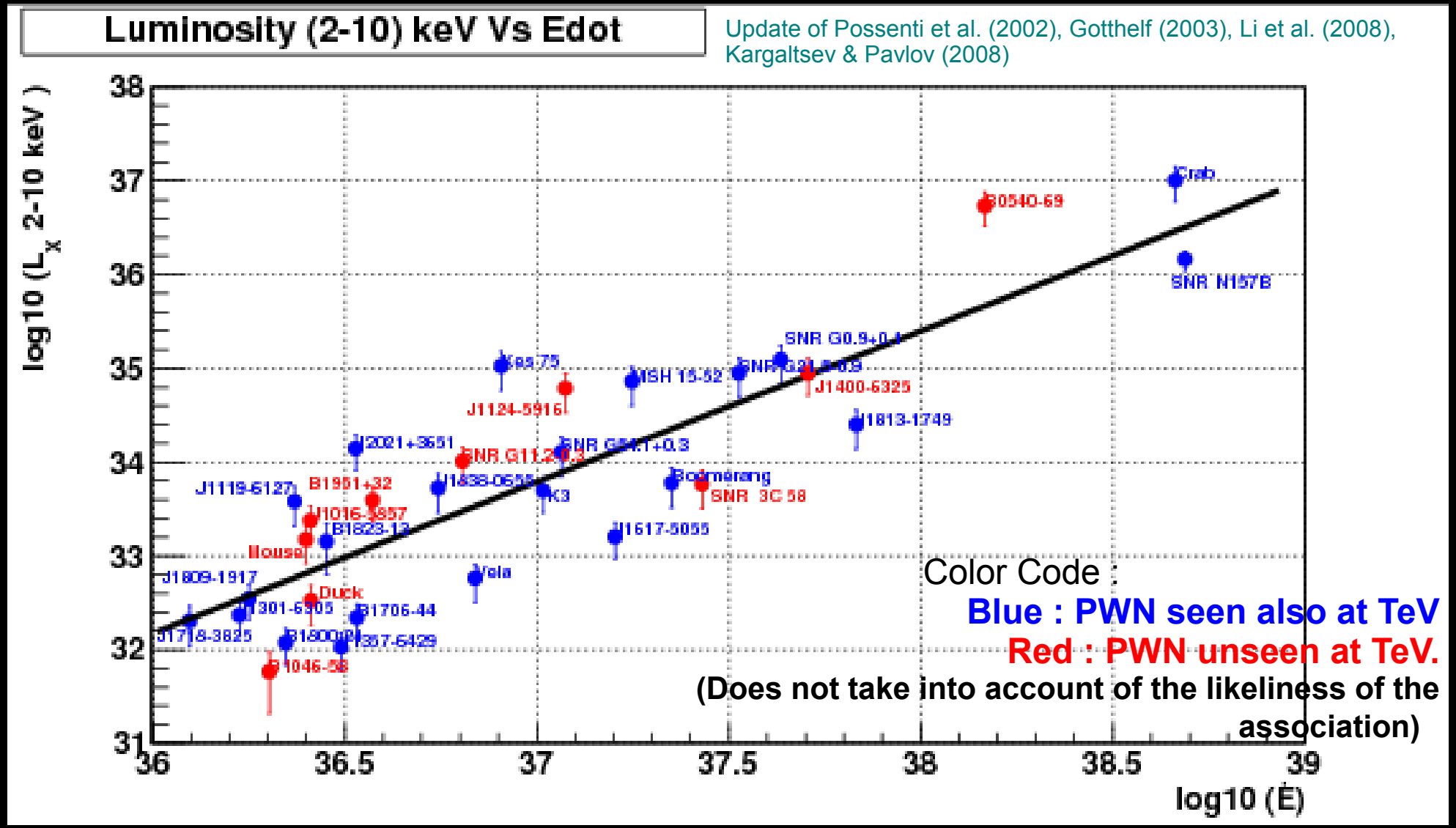
- Z axis distribution : Gonthier 2002
  Paczynski 1990

$$\rho(z) = e^{-z/z_0}$$

with z_0 = 75pc

Completeness reached only for
$L\gamma$ (1-10 TeV) ≥ 5 10^{34} erg.s^{-1}

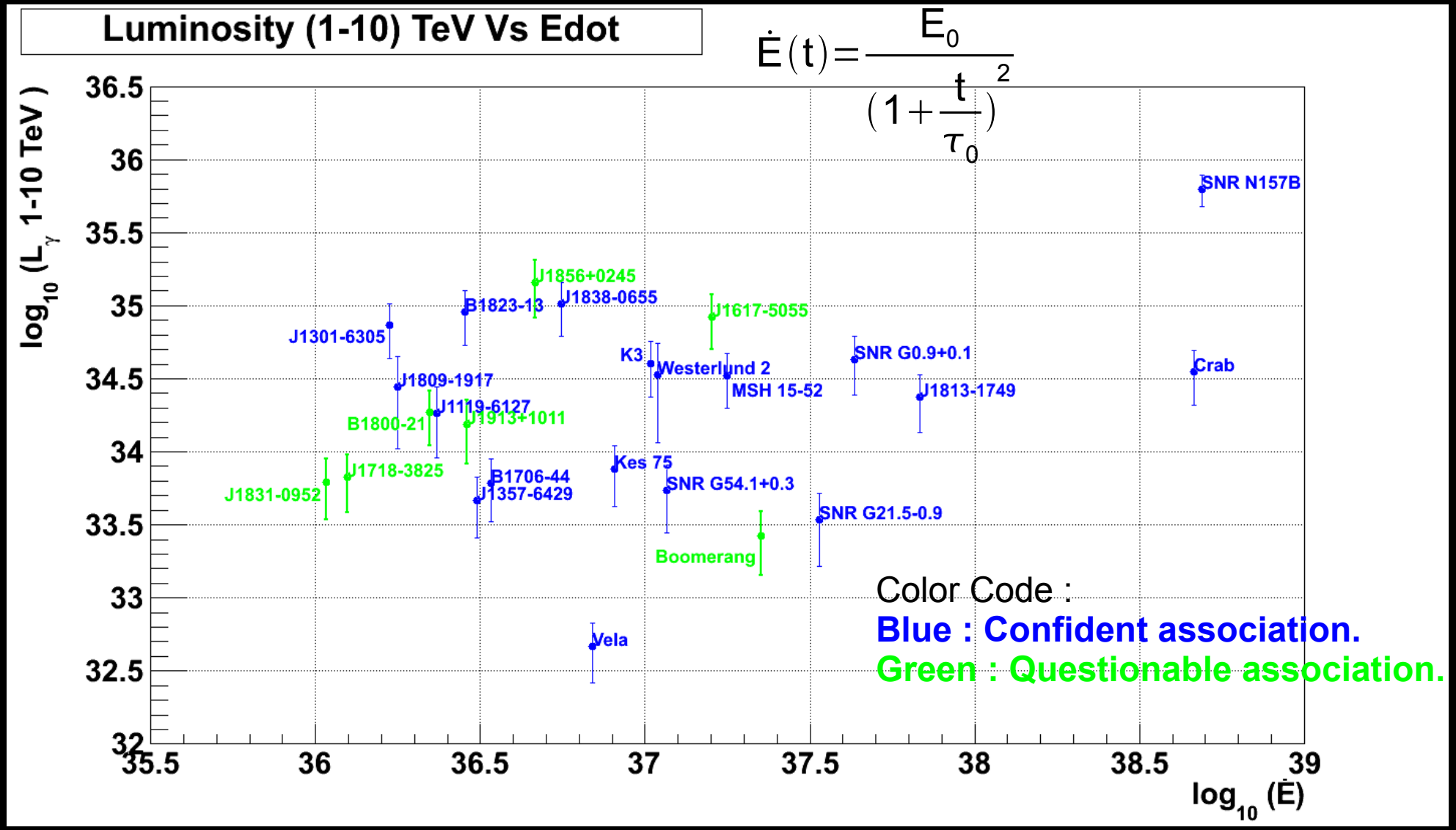
L_x strongly dependent of $\dot{E}$ (and age)



→ The life time of x-ray particles is short :

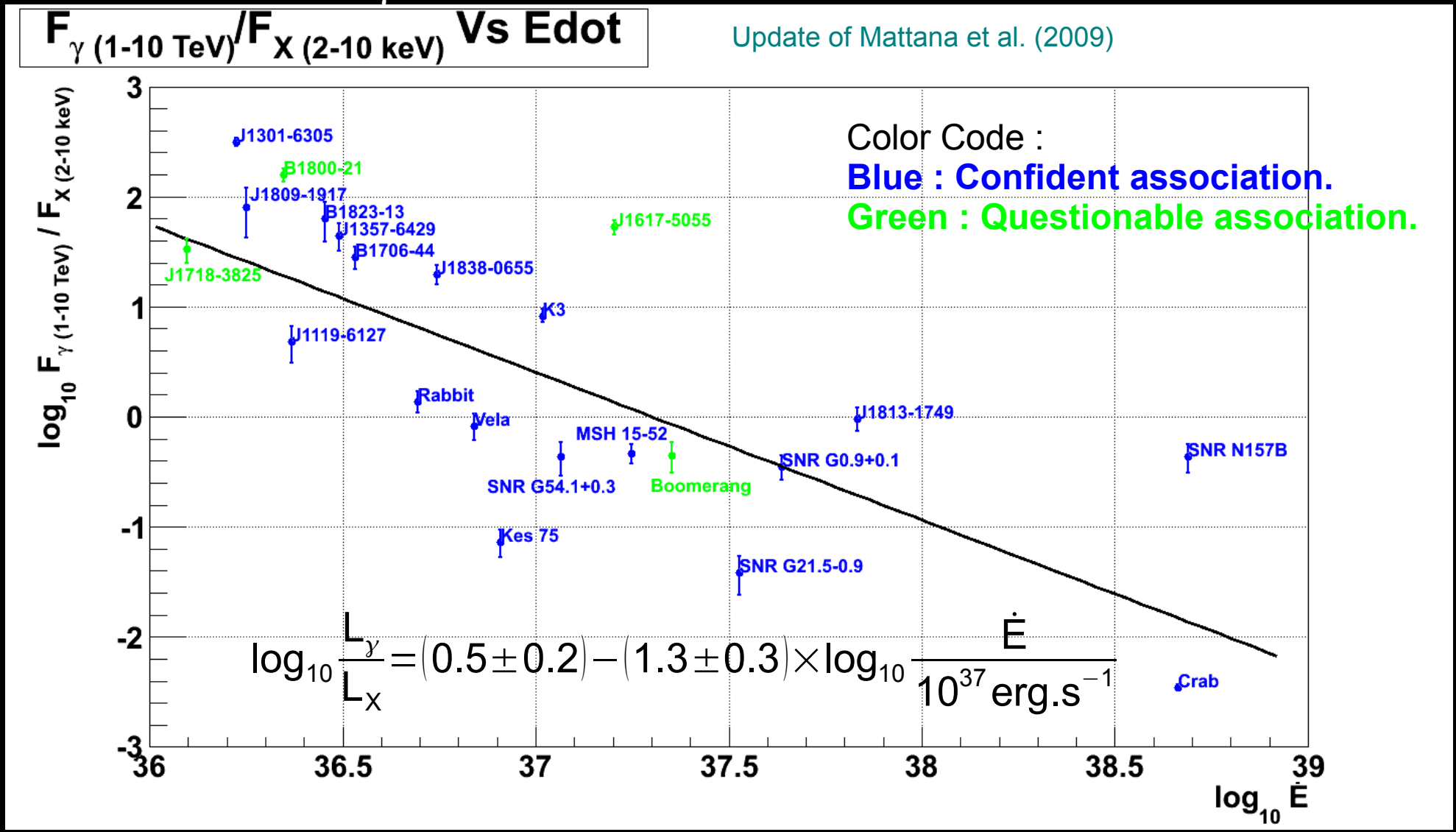
Strong correlation with the instantaneous parameters of the pulsar

L_γ independent on $\dot{E}$ (or age)

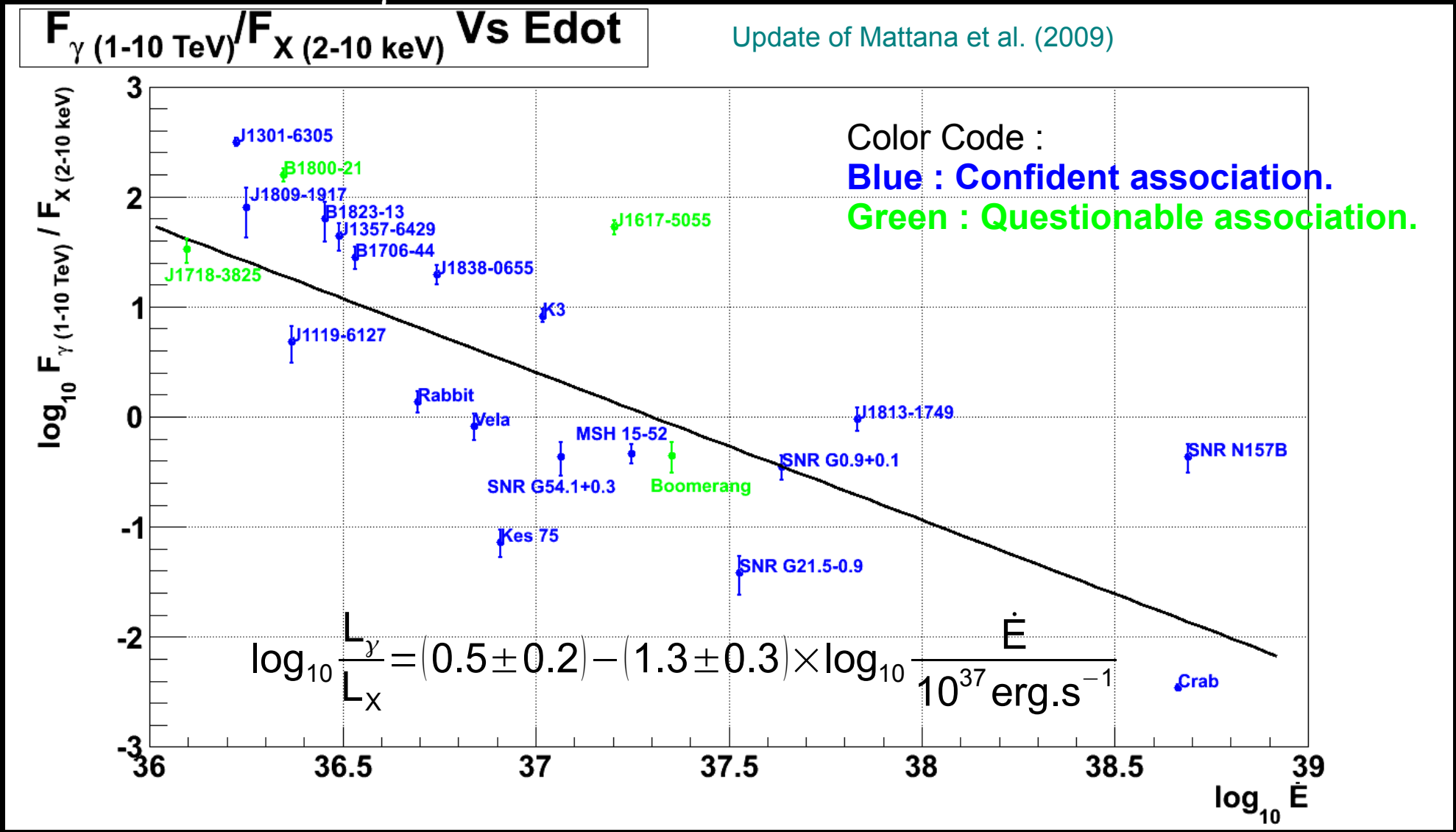


→ **The pulsar with detected TeV nebula have lost quickly their energy**

L_γ/L_x dependent on $\dot{E}$ (and age)

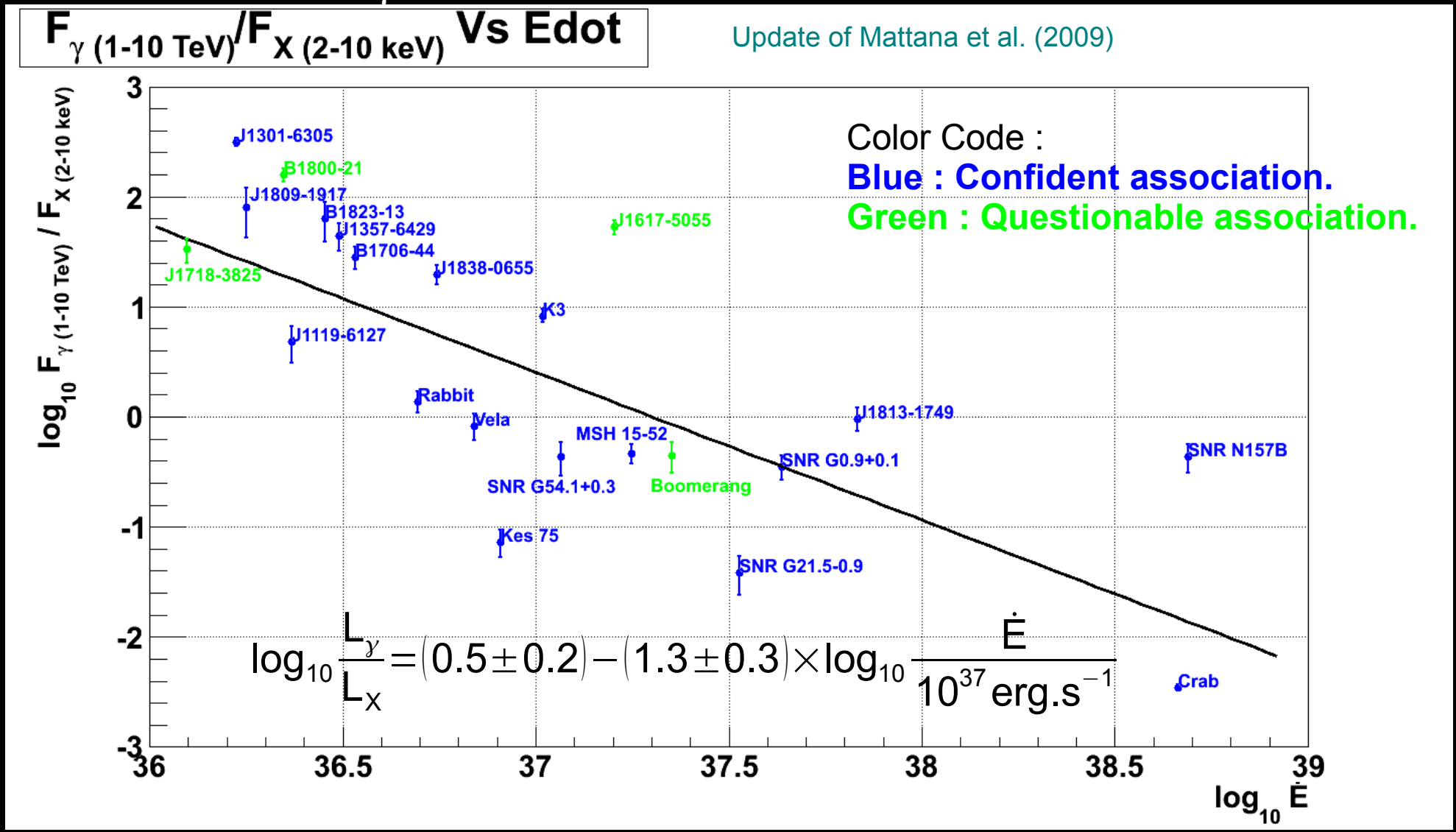


L_γ/L_x dependent on $\dot{E}$ (and age)



	L_X^{-1} Vs $\dot{E}$	L_γ/L_X Vs $\dot{E}$	L_X^{-1} Vs T	L_γ/L_X Vs T
Dispersion	0.32	0.5	0.4	0.3
Indice	-1.6 ± 0.3	-1.3 ± 0.3	1.8 ± 0.4	2.0 ± 0.4

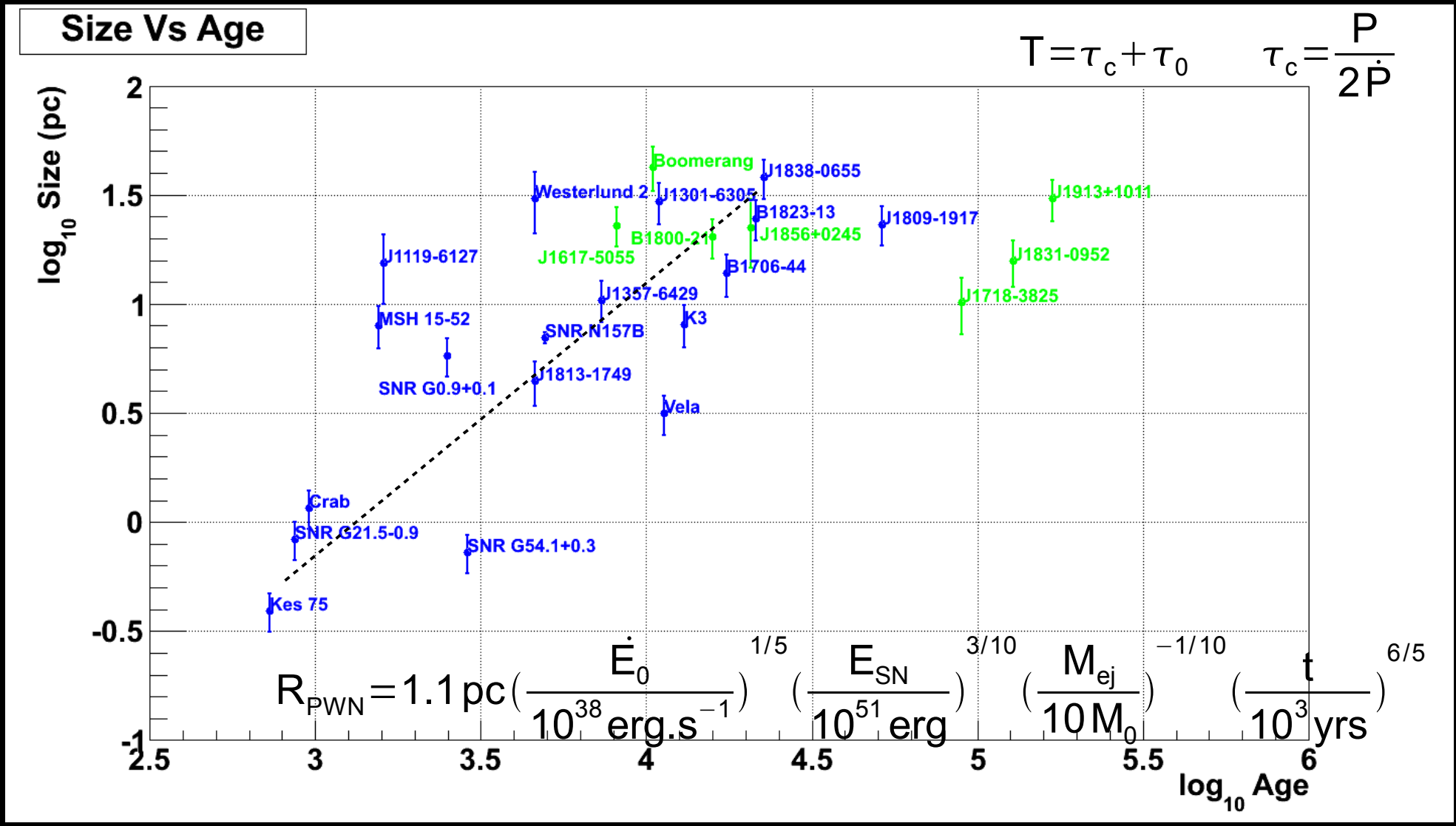
L_γ/L_x dependent on $\dot{E}$ (and age)



The correlation is due to X-rays!

Useful relation for prediction (independent on distance)

PWN Radius vs Age



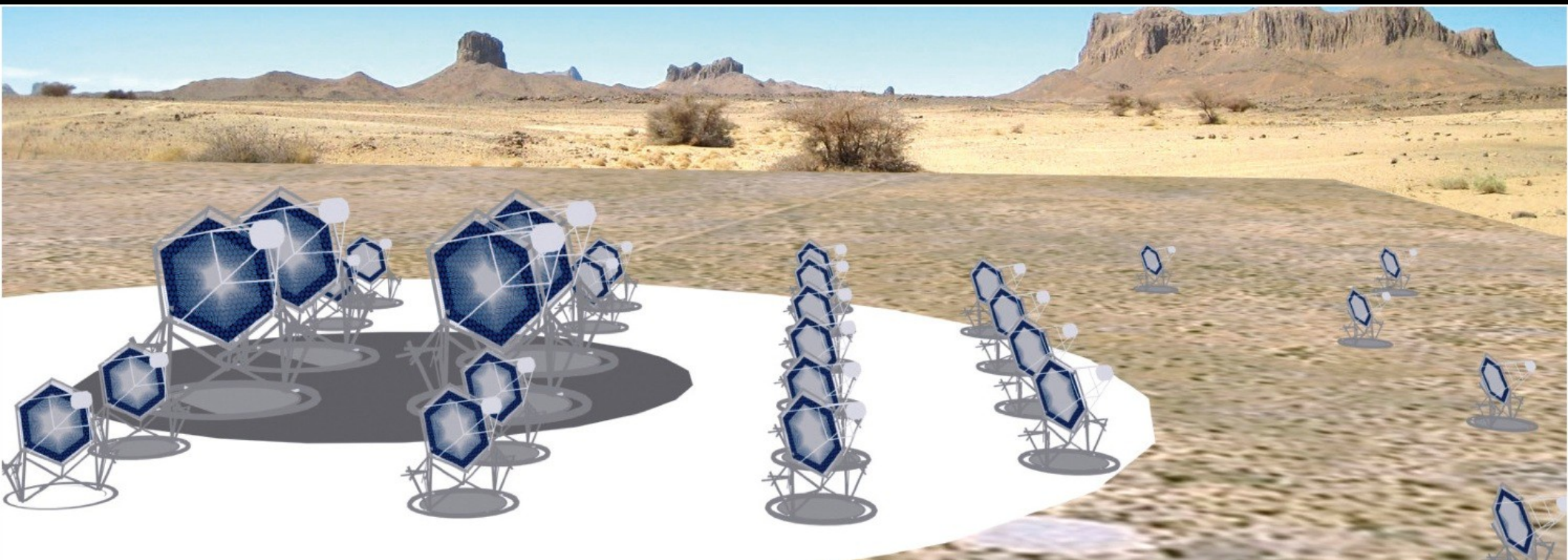
Global dependency is close to linear

Possibility of 2 regimes (young and old), but not enough statistics to conclude

The Future : HESS II and CTA

- H.E.S.S. II
  Improve the spectrum at low energies :
  → Caracterise the spectrum, cooling break, IC peak (Total Energy).

- CTA :
  x10 in sensitivity → x3 in horizon.
  → Increase source number (low luminosity)
  → Better spectro-morphology studies.



Conclusions

- 6 years of Galactic survey with HESS confirm the picture of a TeV Galaxy dominated by pulsar wind nebulae
  - Dedicated search for emission associated to known young pulsars
  - Association between extended TeV sources and evolved pulsars established for several systems
    → 50% of $\dot{E}>10^{36}$ erg/s pulsars have associated TeV nebula
  - A significant fraction of unID systems are likely to be evolved nebulae
- TeV nebulae sample is still incomplete
  - Many low luminosity systems are undetected
- TeV luminosity does not depend on pulsar parameters
  - Systems observed by HESS release most of their energy quickly
- Huge increase in statistics expected for CTA
  - Larger complete statistical sample