Recent results on Galactic cosmic ray's origin with TeV γ-ray astronomy

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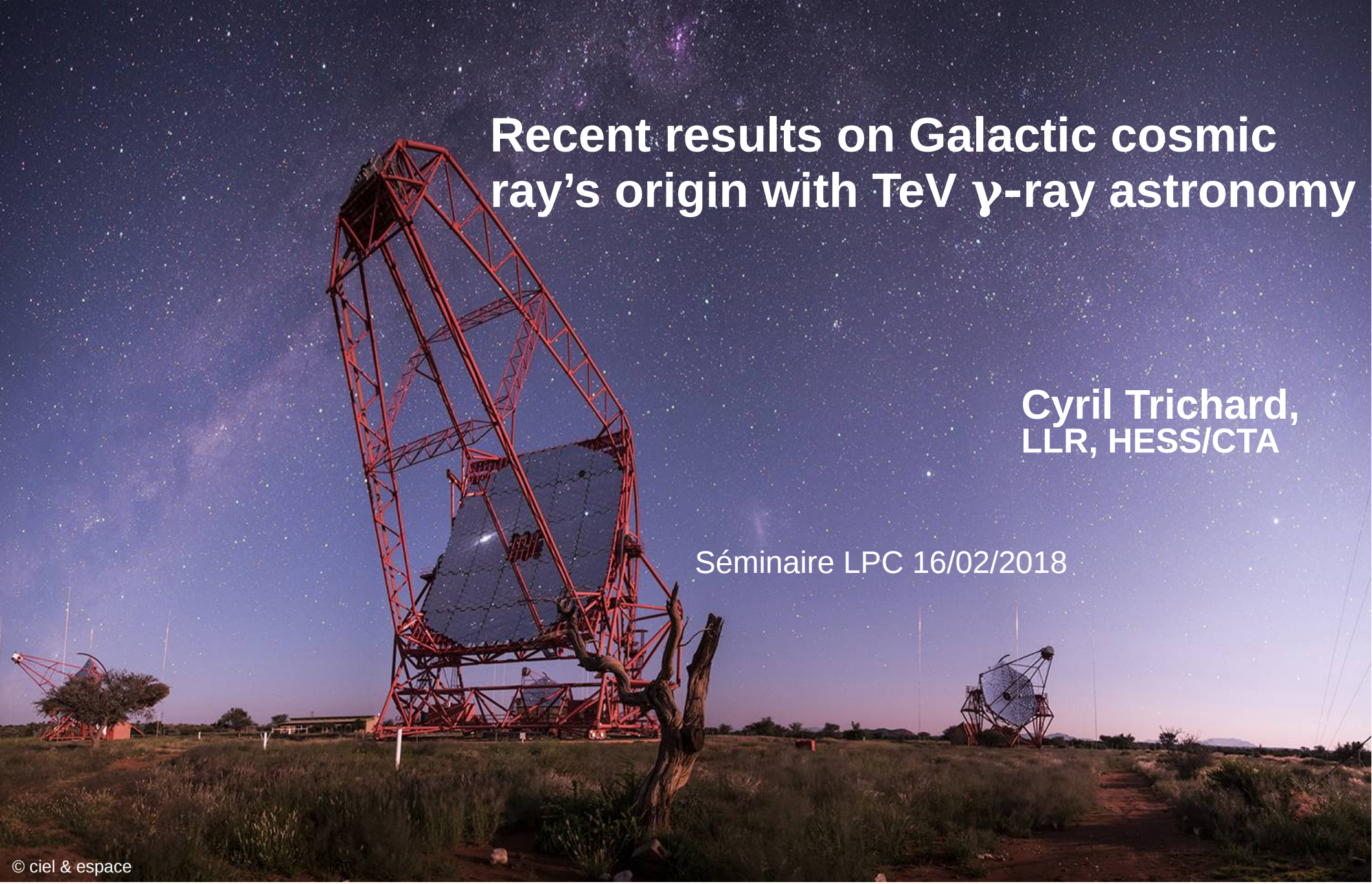
Séminaire LPC 16/02/2018



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The cosmic ray origin and the SNR paradigm

Gamma ray astronomy recent results

Higher energies

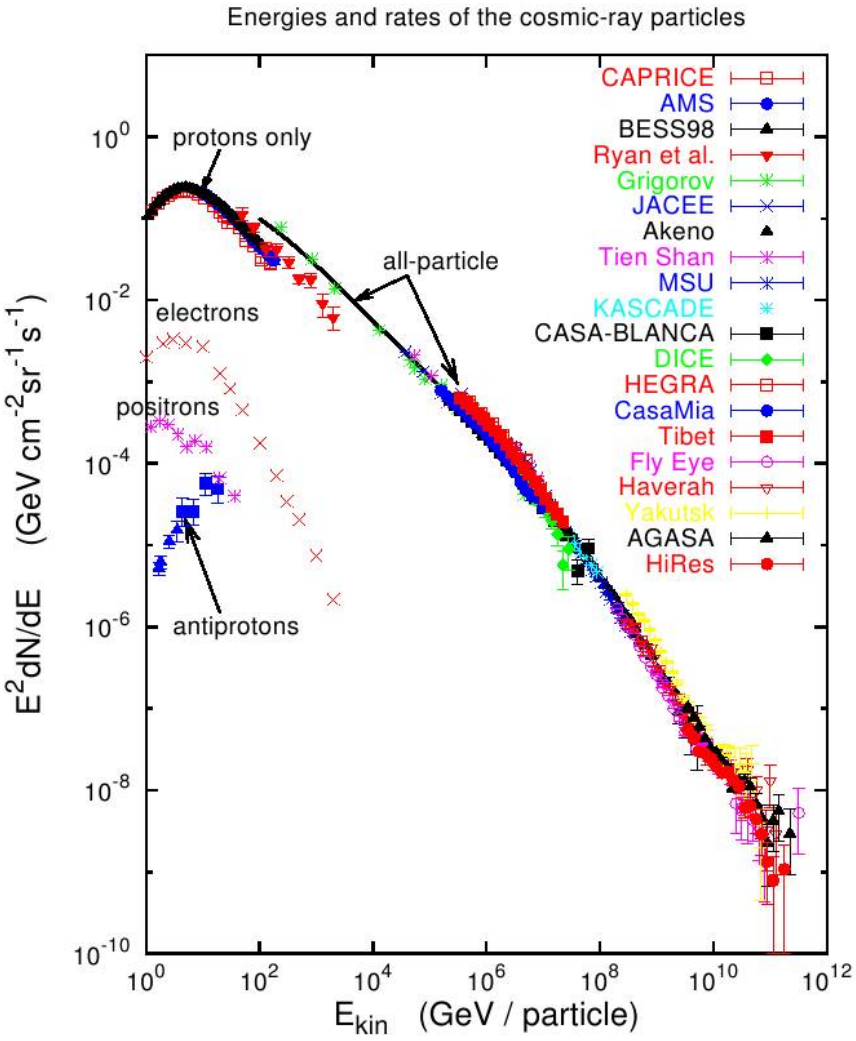
The cosmic ray origin and the SNR paradigm

Gamma ray astronomy recent results

Higher energies

Cosmic rays

- Largely dominated by protons
- Power law spectrum

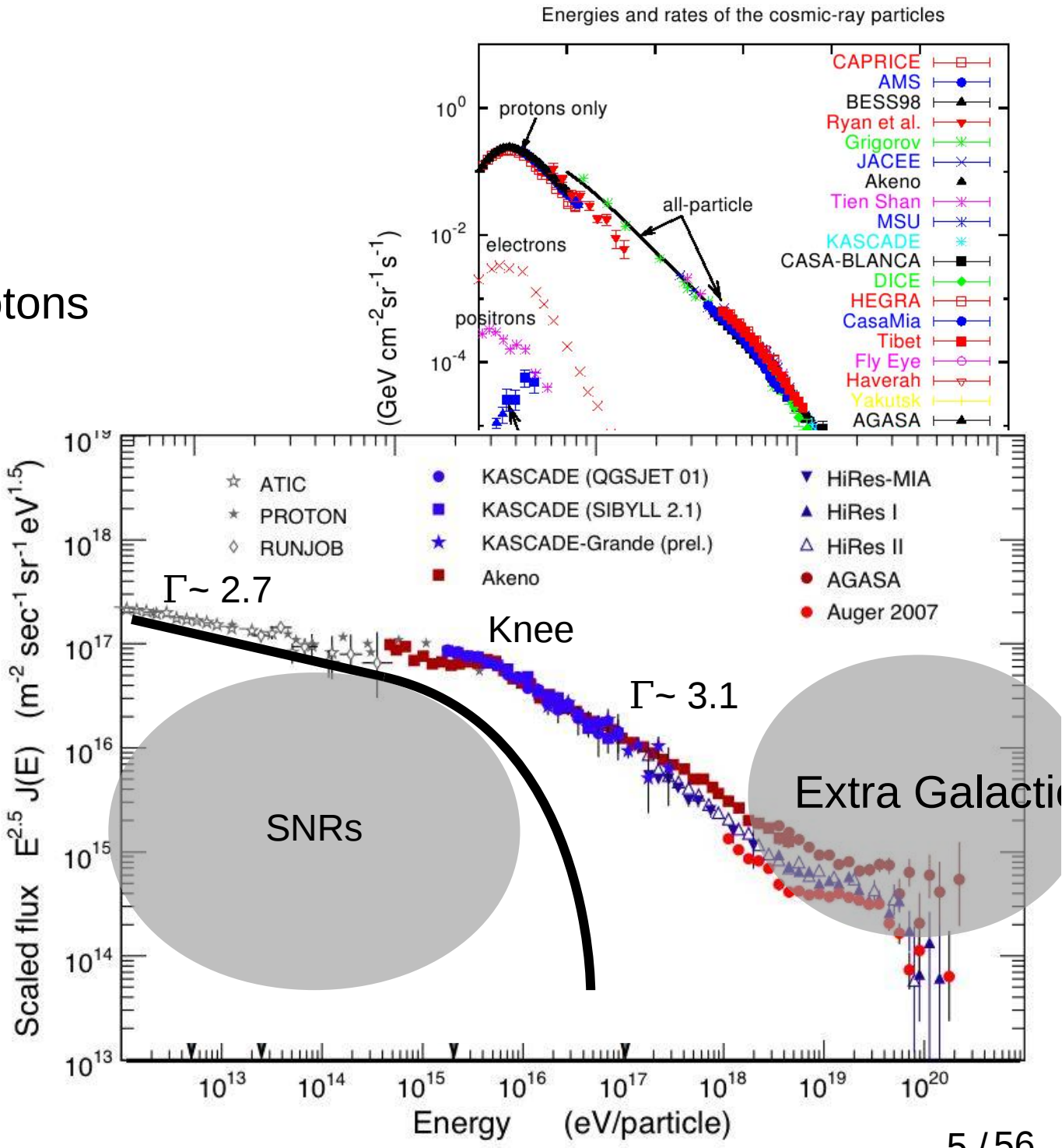


Cosmic rays

- Largely dominated by protons
- Power law spectrum
- Galactic origin <10^{15} eV

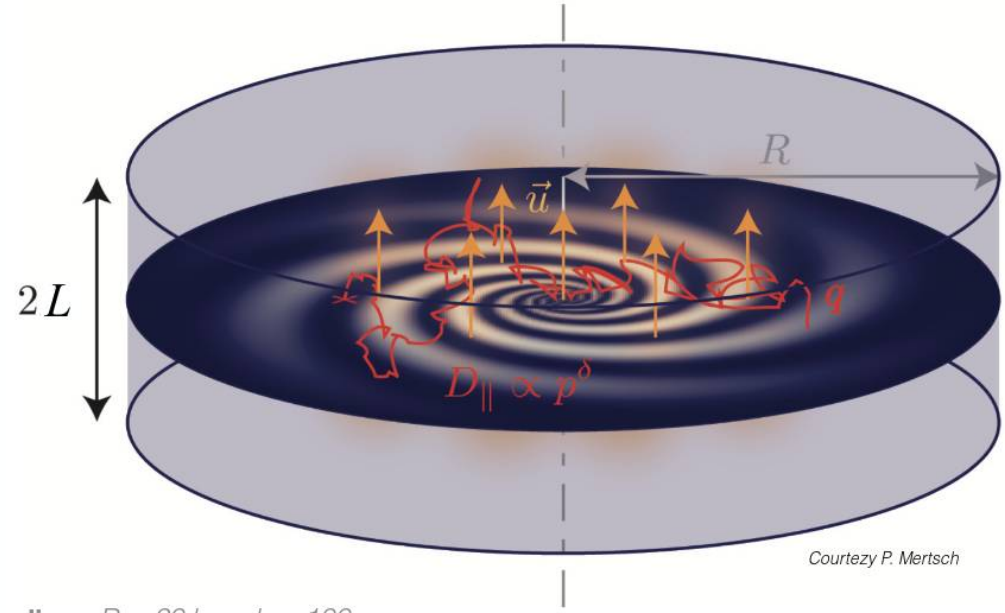
  Extra-Galactic >10^{19}eV

  -> Transition ?



Cosmic ray transport

The two-zone diffusion model



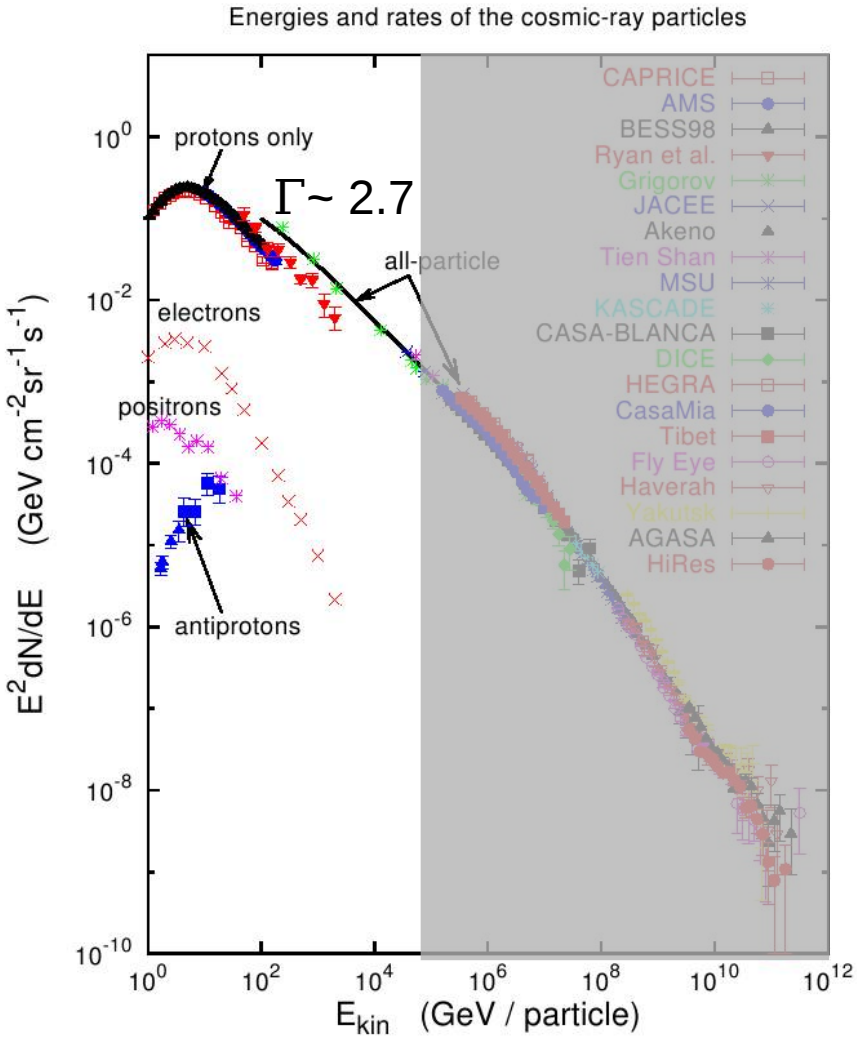
Courtezy P. Mertsch

The galactic disc - *R ~ 20 kpc, h ~ 100 pc*

Contains the gaz, the stars and the dust of the Galaxy. Distributed in the spiral arms. Cosmic rays are accelerated in the galactic disc.

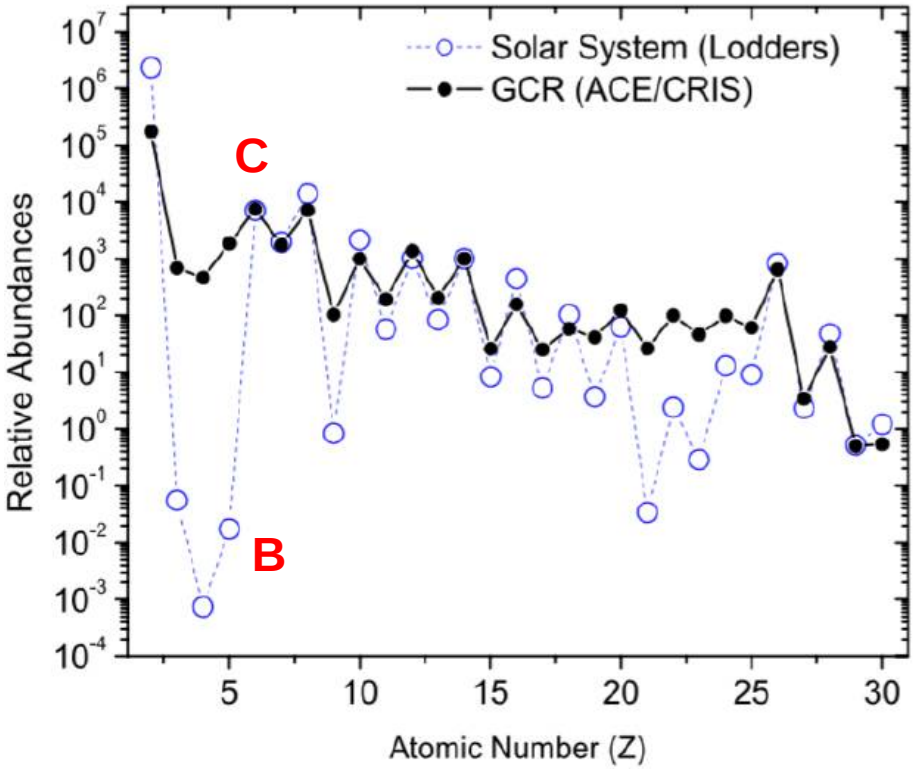
The magnetic halo - *R ~ 20 kpc, 1 ≲ L ≲ 20 kpc*

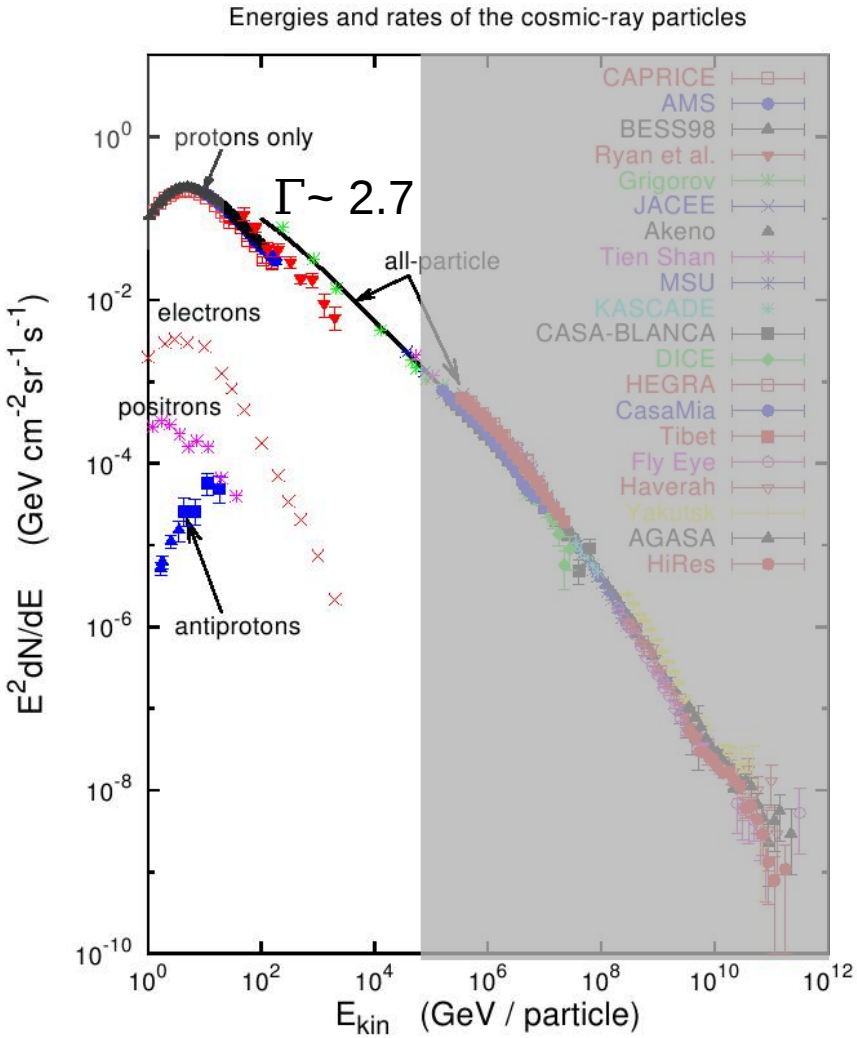
The diffusion zone of the model. Cosmic rays that escape the magnetic halo cannot go back.



- Semi-analytical / Numerical approches
- Assume SNRs as injection sources
- On earth = Average of all acceleration sites over time

CR transport constrains



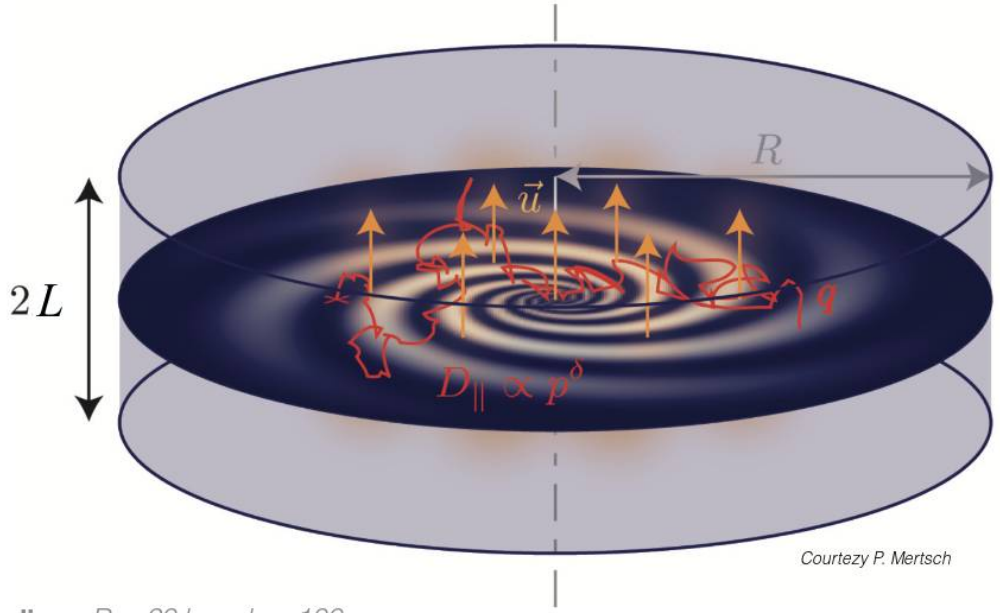


- No B at acceleration sites
  -> produced during transport : spallation
- Flux Ratio Primaries/Secondaries (B/C) : transport information
- Models favor spectral index change ~ 0.5 ... ~0.7 between injection and on earth

  -> Spectral index at acceleration site ~2.0

Cosmic ray transport

The two-zone diffusion model



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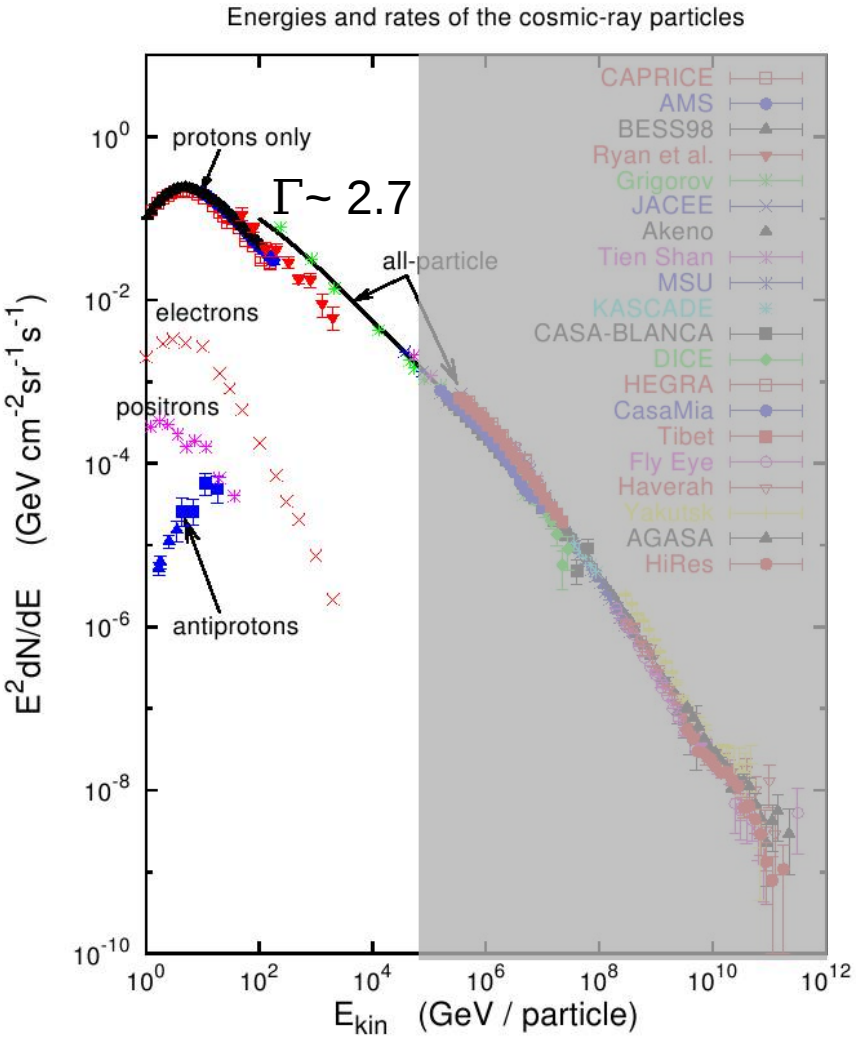

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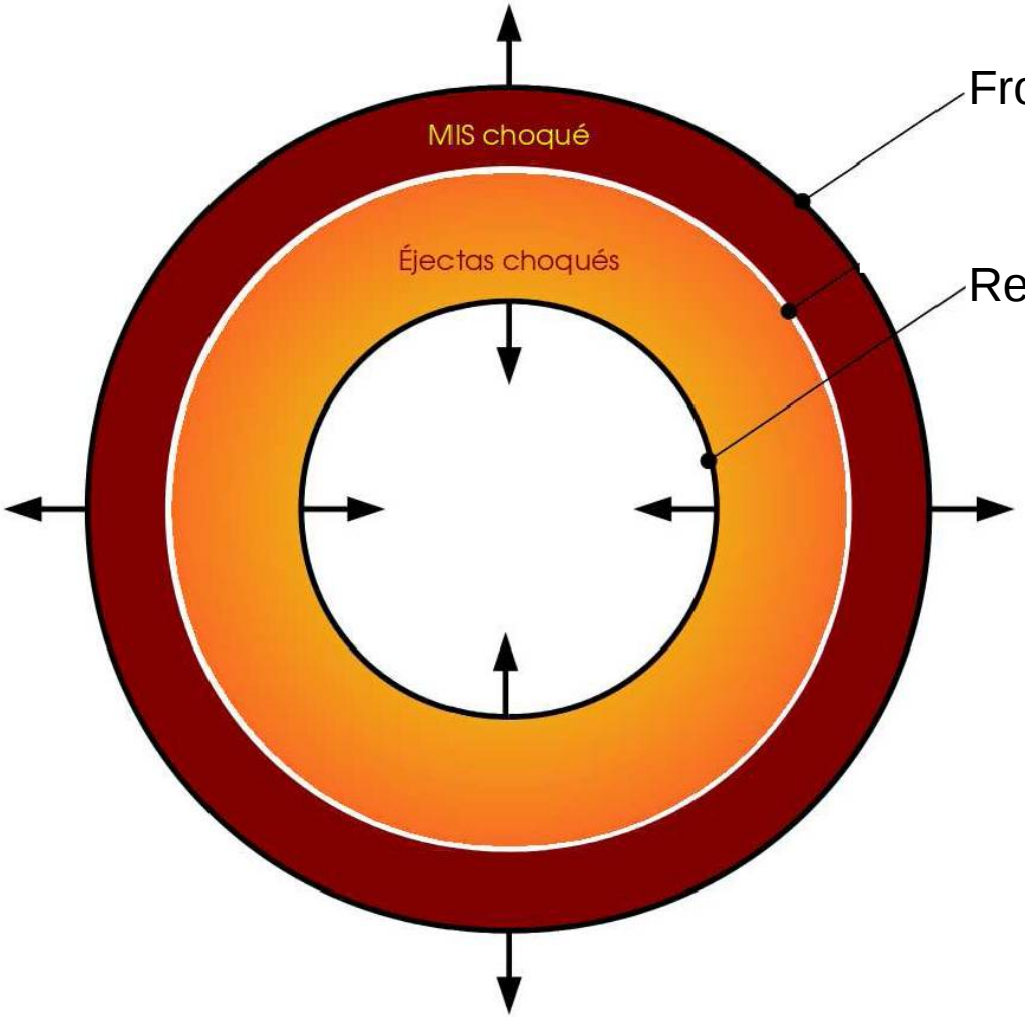
SNR paradigm

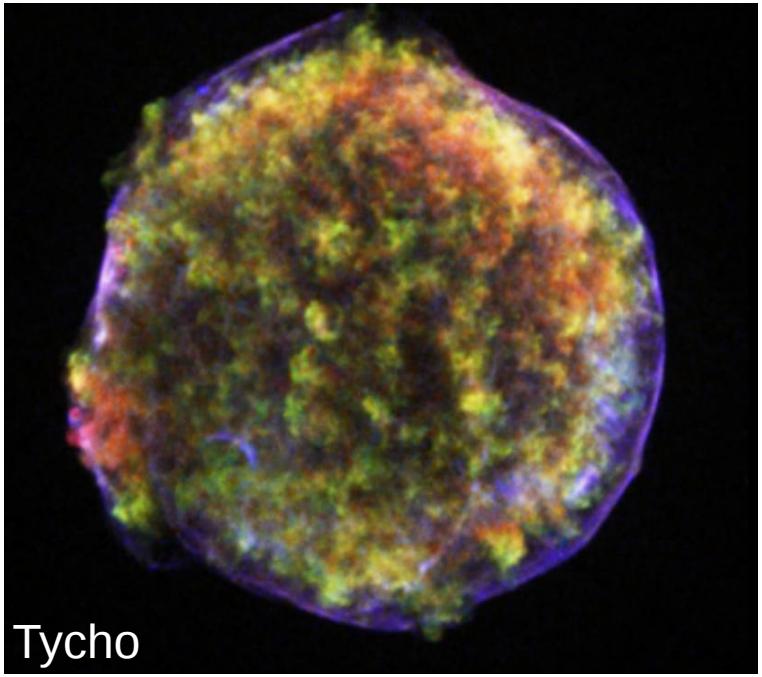
Mathieu Boudaud

SNR in a nutshell



- V shock ~ 10 000 km/s
- Time evolution depend on swept up material

  -> Environmental effects



SNR paradigm : CR energetics

Supernova remnants (SNRs) as primary source of CR energy

Blaade and Zwicky 1934
Ginzburg and Syrovatskii 1964

$$L_{\rm CR} \sim 10^{41} {\rm erg/s}$$

$$E_{\rm SN} \sim 10^{51} {\rm erg}$$ at a rate of a few per century

⟶ **Efficiency < 10 % is enough**

SNR paradigm : Fermi acceleration

in a nutshell

Acceleration at astro shock

$r =$ shock compression factor

$$\Delta E = \frac{4}{3}\frac{v}{c}\left(1 - \frac{1}{r}\right) E$$

Accelerated particle spectrum

$$N(\geqslant E) = N_0 \left(\frac{E}{E_0}\right)^{\frac{\log(1-P_{\rm esc})}{\log(k+1)}}$$

$$P_{\rm esc} = \frac{4v}{rc}$$

does not depend on energy !

$$N(E) \propto \left(\frac{E}{E_0}\right)^{-\alpha} \quad \alpha = \frac{r+2}{r-1}$$

$r = 4$ for strong shock

$\longrightarrow \quad \alpha = 2$

SNR paradigm : Maximum Energy ?

Maximum energy limited by age, energy losses, escape

Depends on

$$E_{\max} \propto Z\,B$$

For typical cases

young SNR, standard B -> $E_{\max}$ ~ tens TeV

=> Need B amplification to reach the knee !

Seen in several SNRs through synchrotron radiation from freshly accelerated electrons

Few active PeV accelerators expected in the galaxy

How to confirm SNR paradigm ?

1) Determine CR acceleration efficiency in (all) SNRs

2) Confirm that CR spectrum at acceleration site is $\propto E^{-2}$

3) Up to at least 10^{15} eV

→ **Not so easy !**

The cosmic ray origin and the SNR paradigm

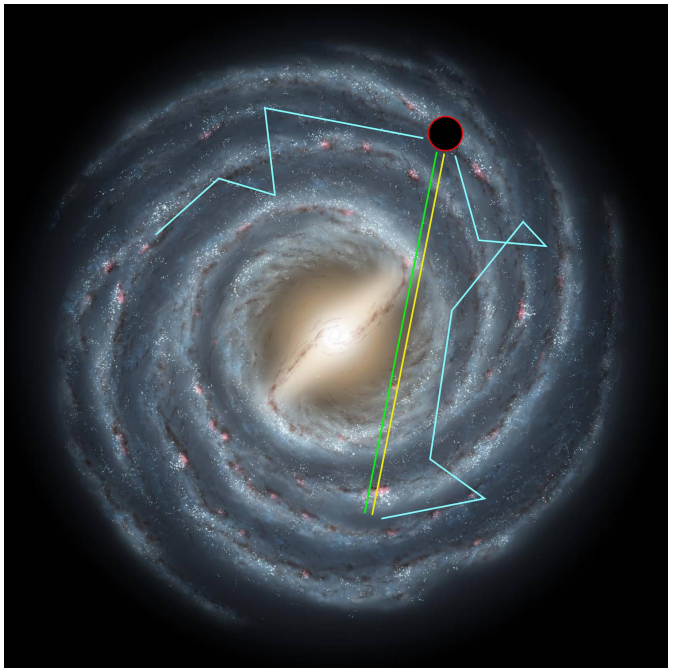
Gamma ray astronomy recent results

Higher energies

Why γ-ray astronomy ?

CR anisotropy very small : ~10^{-3} 10^{-4}

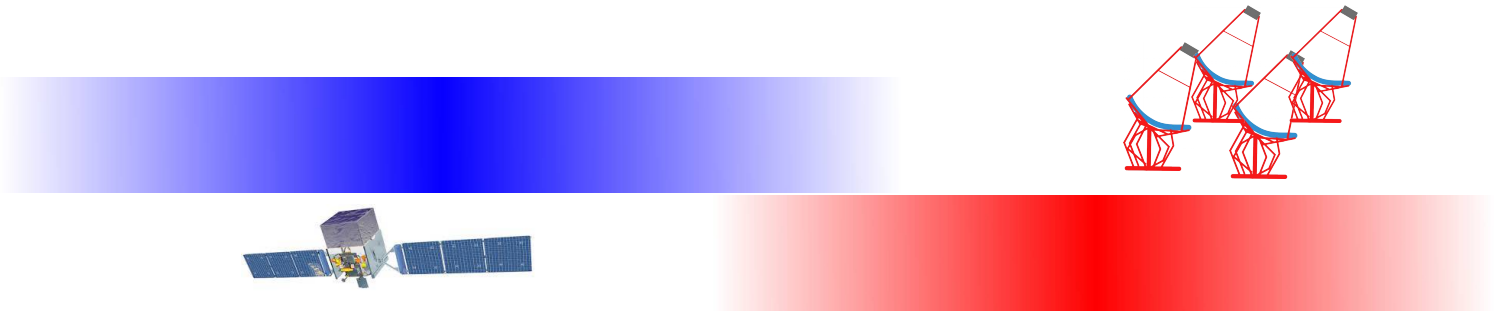
Need neutral messengers produced at acceleration sites



2 main γ-ray production mecanisms :

Leptonic
- Inverse compton scattering
- Bremsstrahlung

Hadronic
- Neutral pion decay

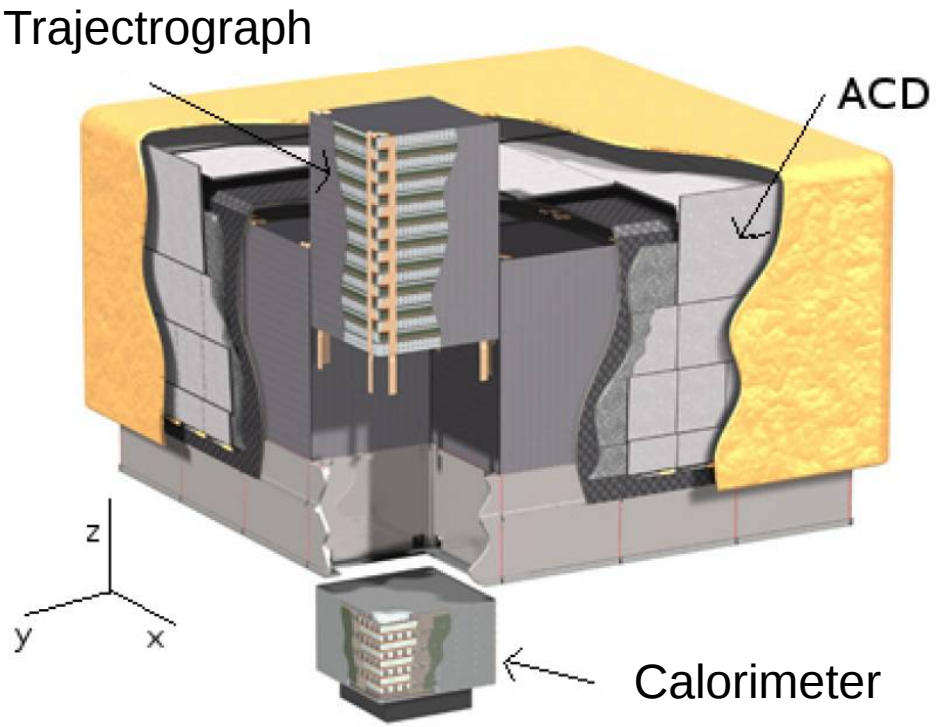


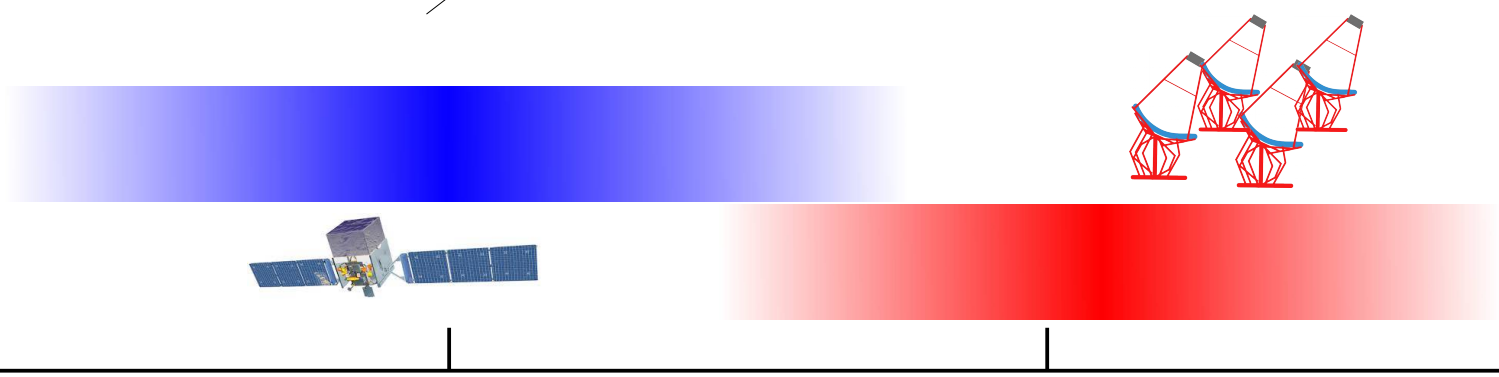
MeV **GeV** **TeV**

How γ-ray astronomy ?

Satellite fermi-LAT :

- Pair creation process
- Anti coincidence shield (against CR)
- Launched 2008
- ~100 MeV – 300 GeV
- Full sky coverage ~ 3h

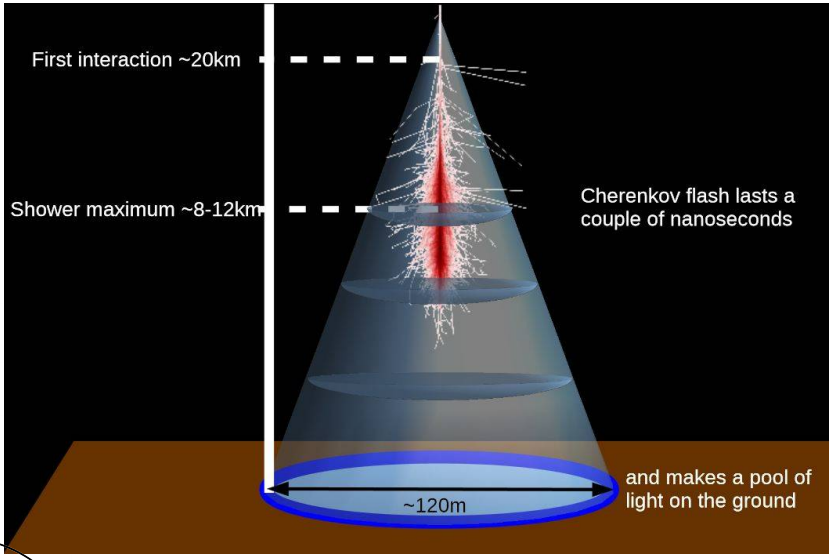


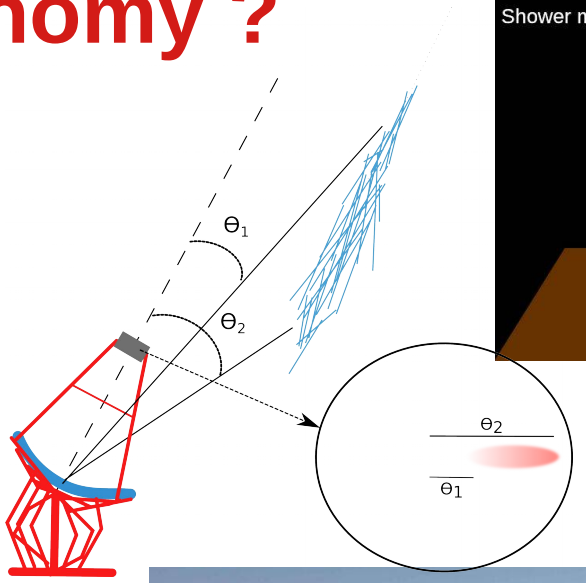


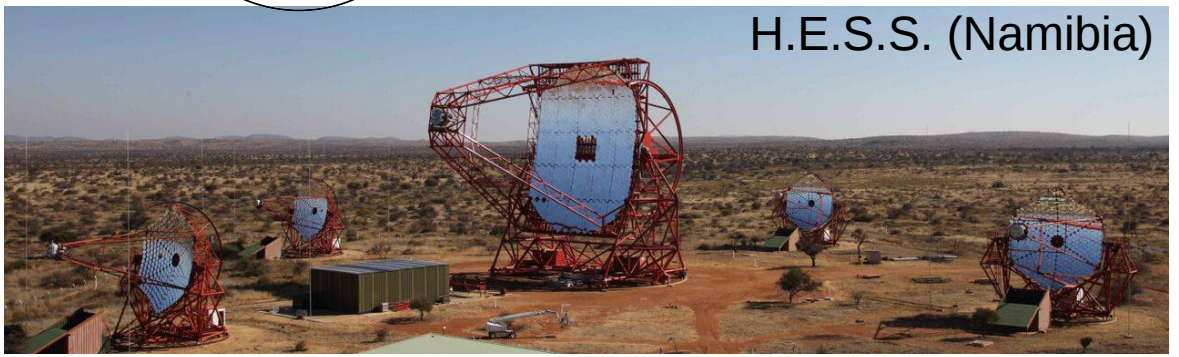
How γ-ray astronomy ?

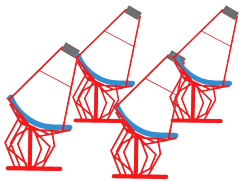
Cherenkov telescopes :

- Imaging air shower
- High background (CR)
- Started ~2004
- FoV ~ 5°
- ~100 GeV – 100 TeV
- 3 main collaborations
  - VERITAS (USA)
  - MAGIC (Spain)
  - H.E.S.S. (Namibia)









MeV GeV TeV

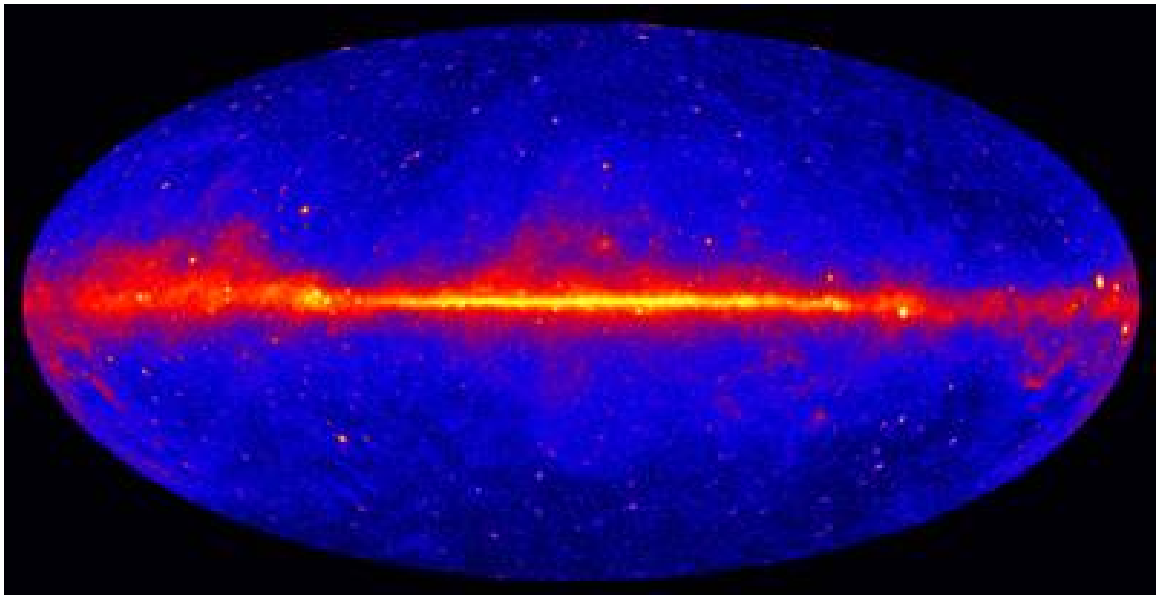
Galactic survey - GeV

Fermi-LAT

100 MeV - 300 GeV
All Sky survey

- Diffuse γ-ray from Galactic disk

  -> CR interaction with ISM



Galactic survey - GeV

Fermi-LAT

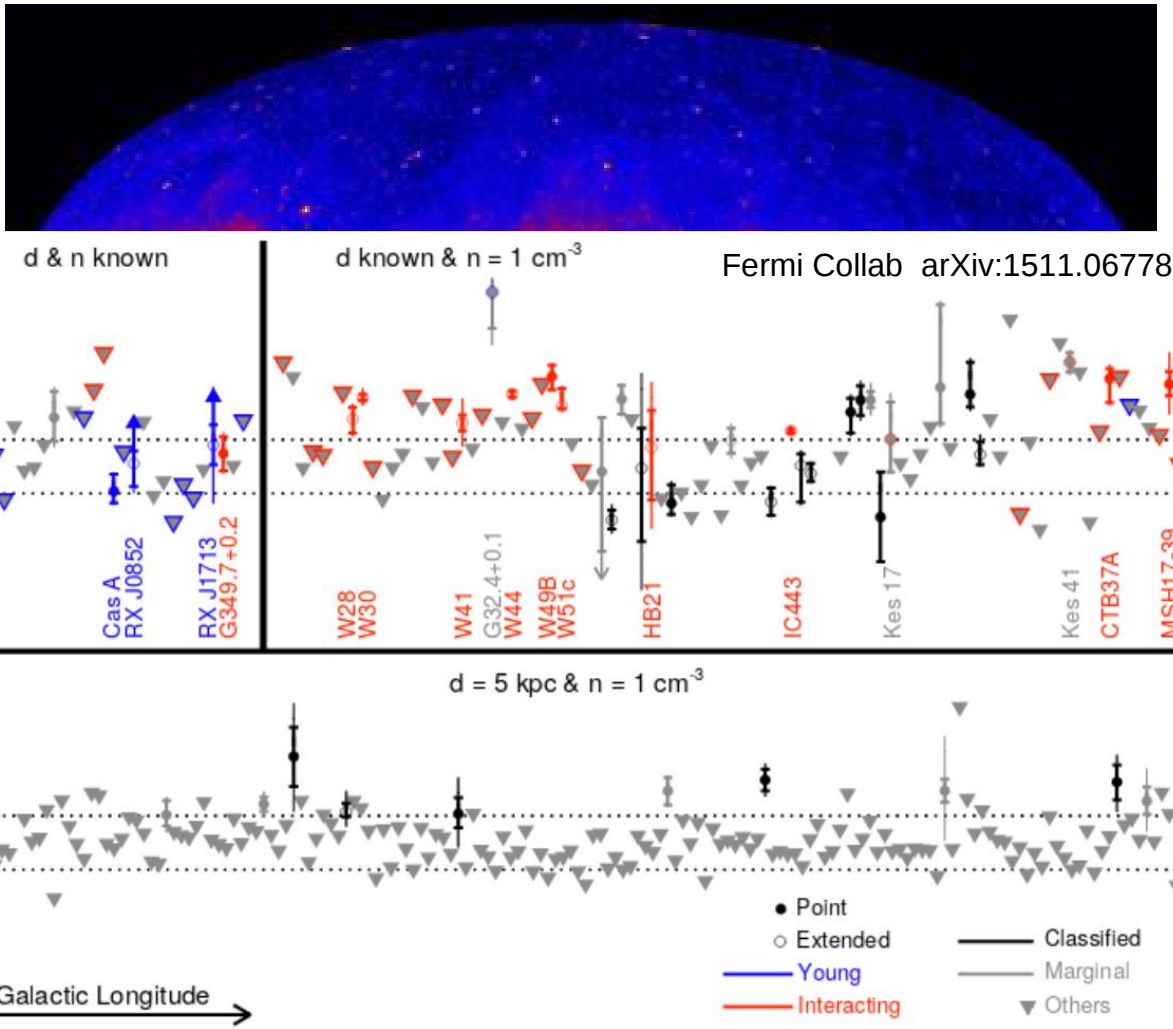
100 MeV - 300 GeV
All Sky survey

- Diffuse ɣ-ray from Galactic d

  -> CR interaction with ISM

- Acceleration in SNRs

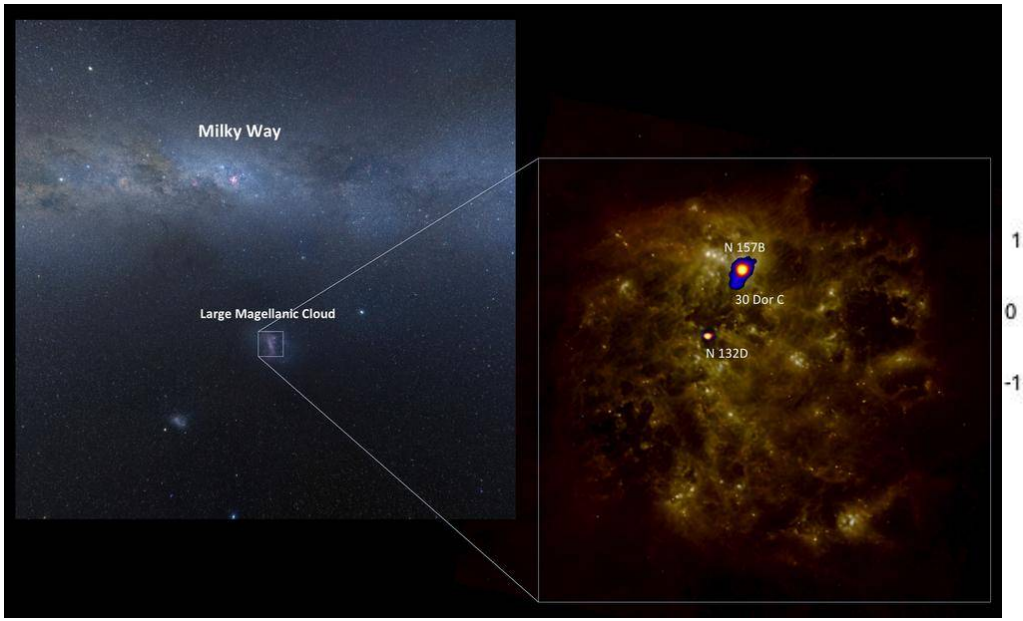
  -> Upper limits compatible with 10 % CR acceleration efficiency



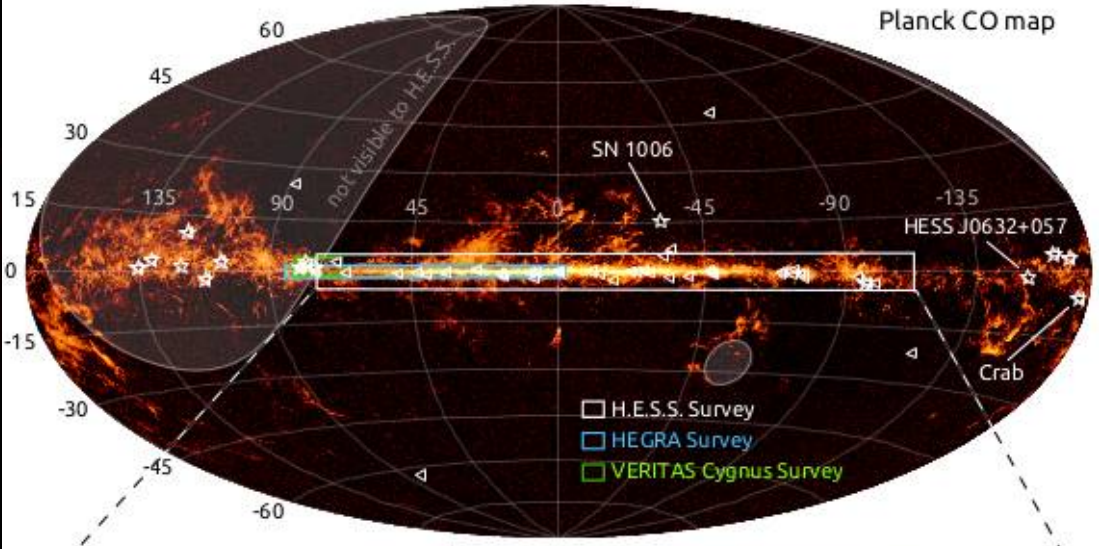
arXiv:1511.06778

2 « Galactic » surveys - TeV

Large Magellanic Cloud (LMC) Survey



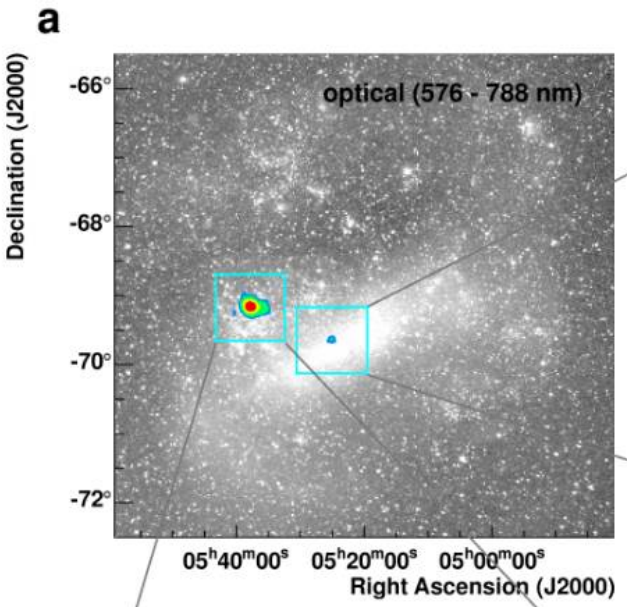
HESS Galactic Plane Survey (HGPS)



LMC survey - TeV

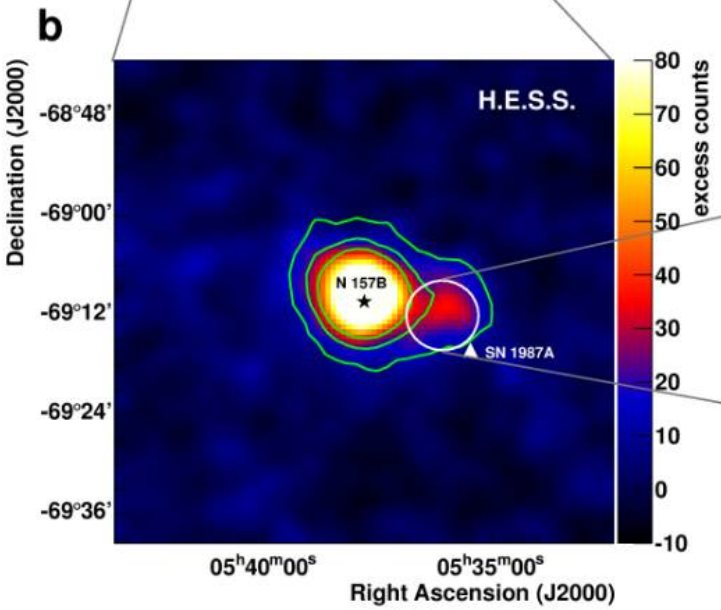
HESS Collab Science, arXiv:1501.06578

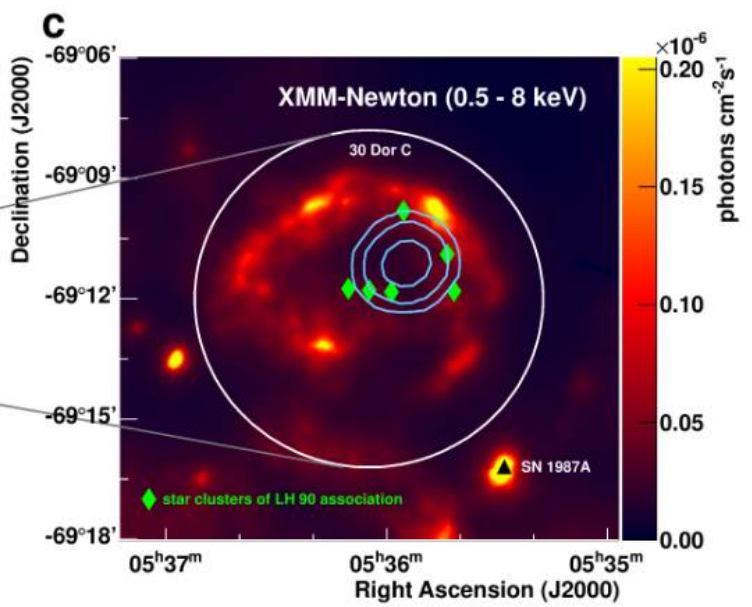
HESS Collab, arXiv:1801.06322



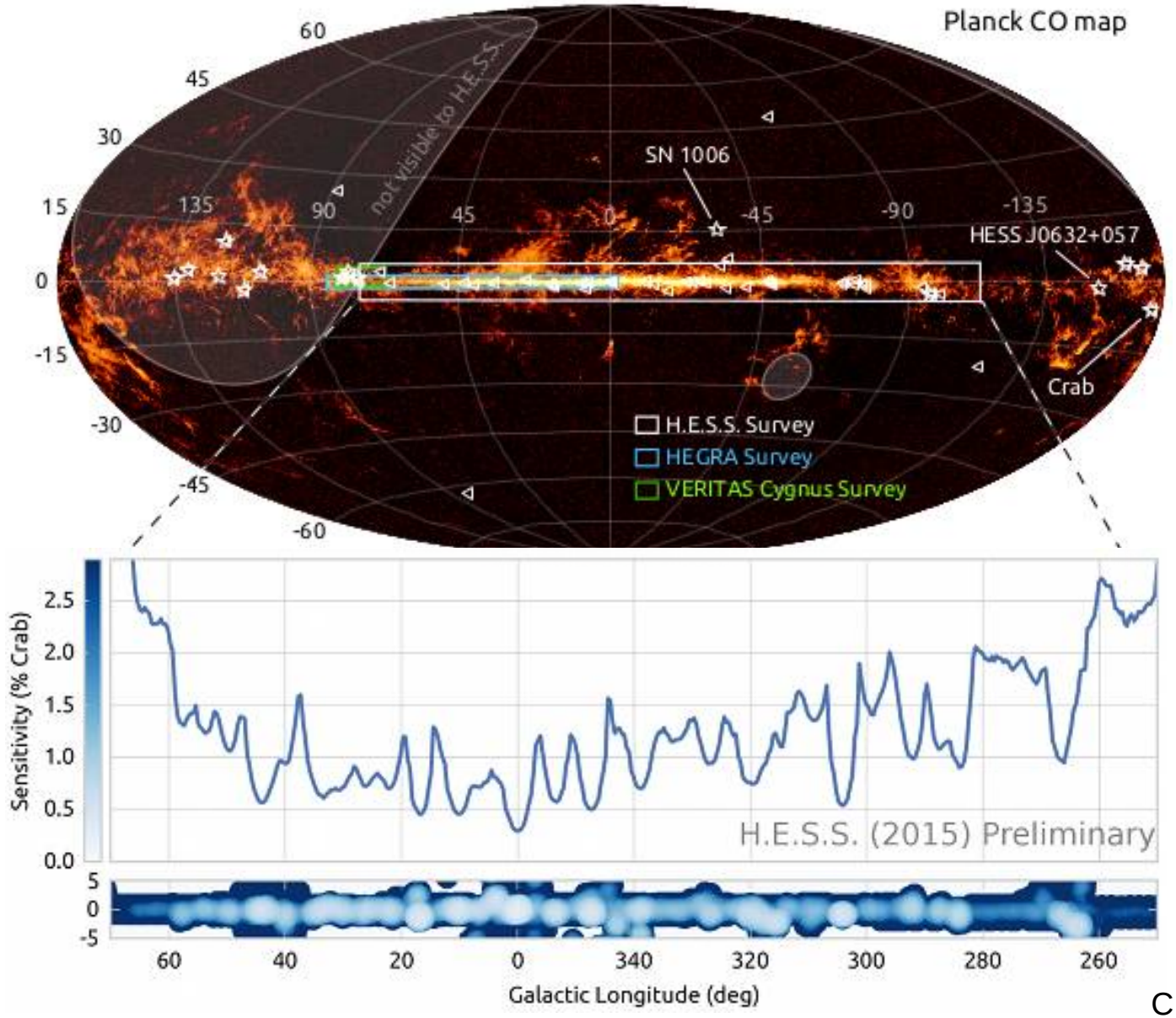
Remarkable sources !

- Very bright PWN
- New Binary in TeV
- First superbuble !
  Spectral index ~ 2.6
- SN1987A
  Upper limits by H.E.S.S.
  => CR acceleration efficiency <1% - <15 %





Galactic survey - TeV

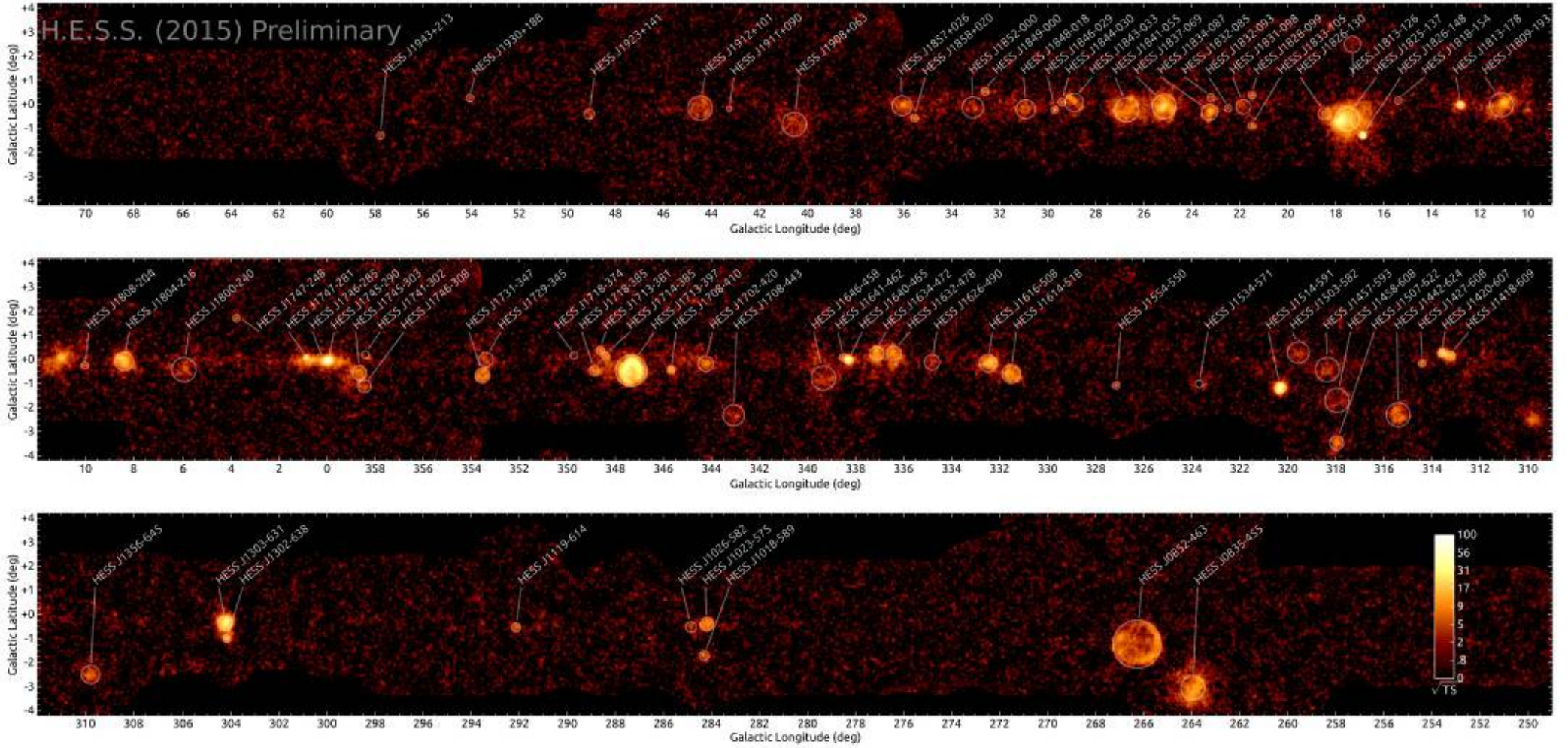


HESS Galactic Plane Survey (HGPS)

- Exposure follow pointing strategy
- ~ 2700 hours
- Better than 1.5 % Crab sensitivity
- Cover inner part of the Galaxy (incl Center)

Galactic surveys - TeV

HESS Collab accepted A&A



Galactic surveys - TeV

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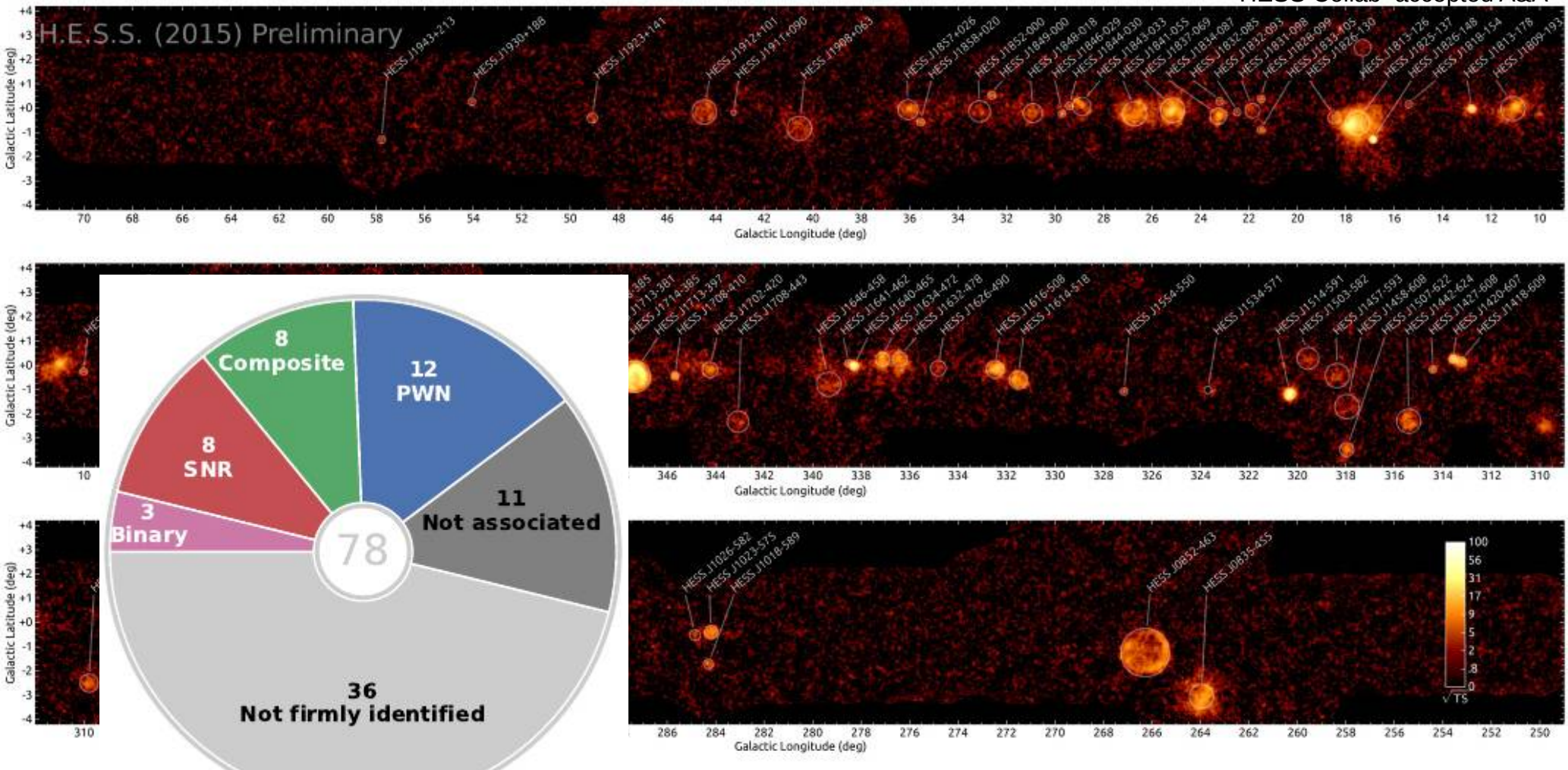
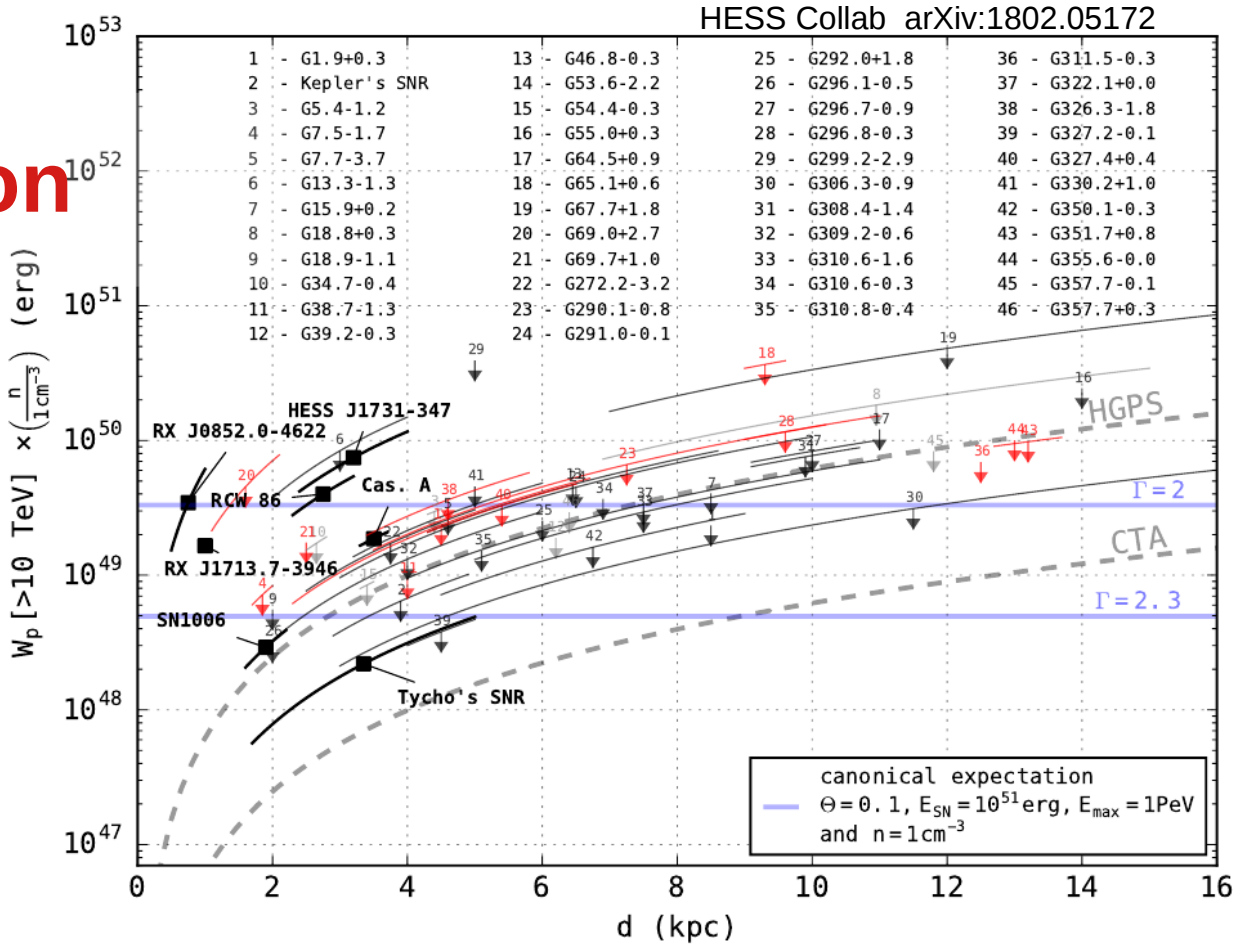


TeV SNR population

Acceleration efficiency in SNR

HESS Collab arXiv:1802.05172



- Start to probe the 10 % efficiency
- Still compatible

TeV SNR population

Acceleration efficiency in SNR

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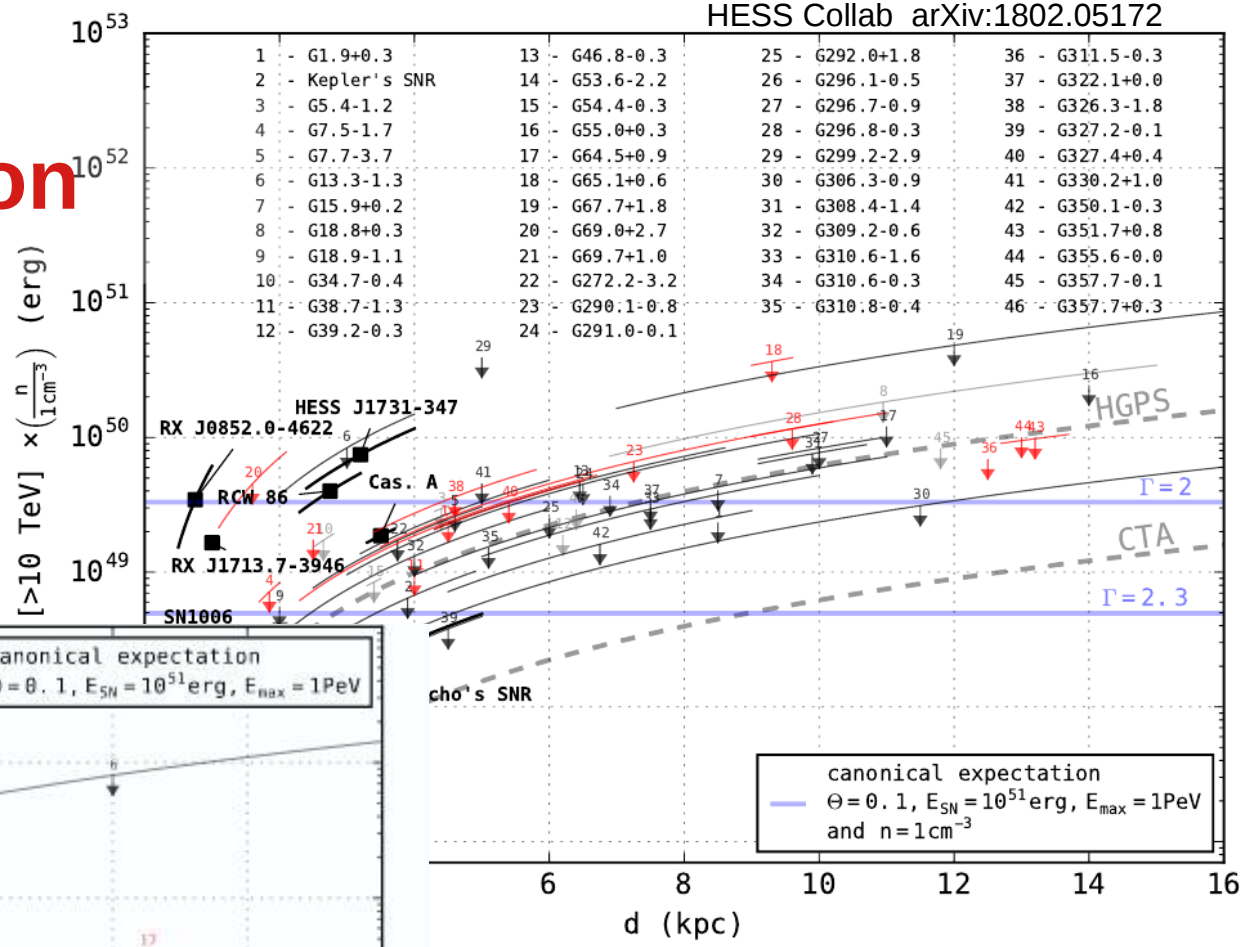
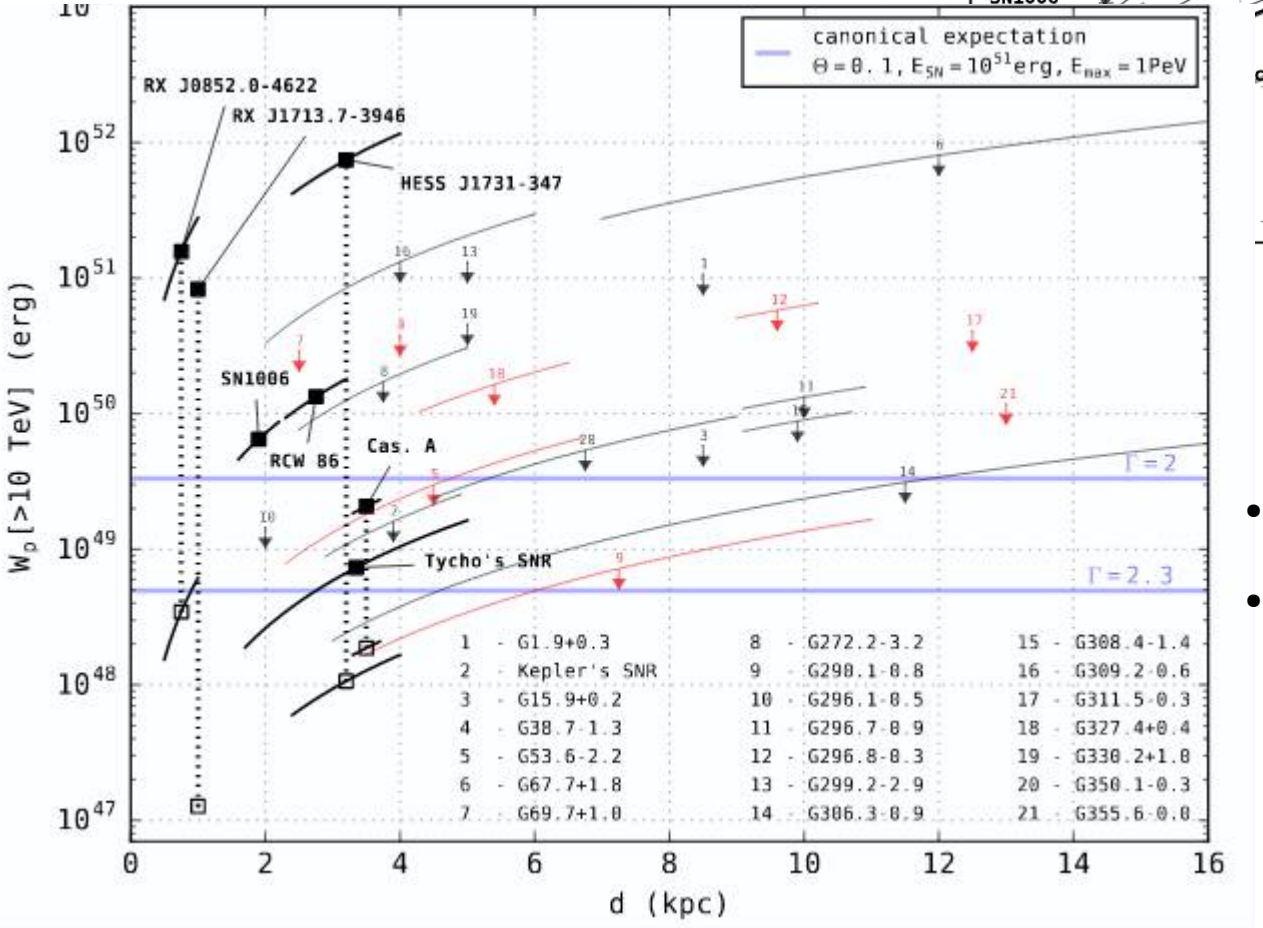




- Start to probe the 10 % efficiency
- Still compatible

How to confirm SNR paradigm ?

1) Determine CR acceleration efficiency in (all) SNRs

- **Not Detected SNRs :** 10% efficiency is not really probed by current experiments
- **Detected SNRs :** 10 % efficiency is reasonnable

2) Confirm that CR spectrum at acceleration site is $\propto E^{-2}$

3) Up to at least 10^{15} eV

⟶ **Not so easy !**

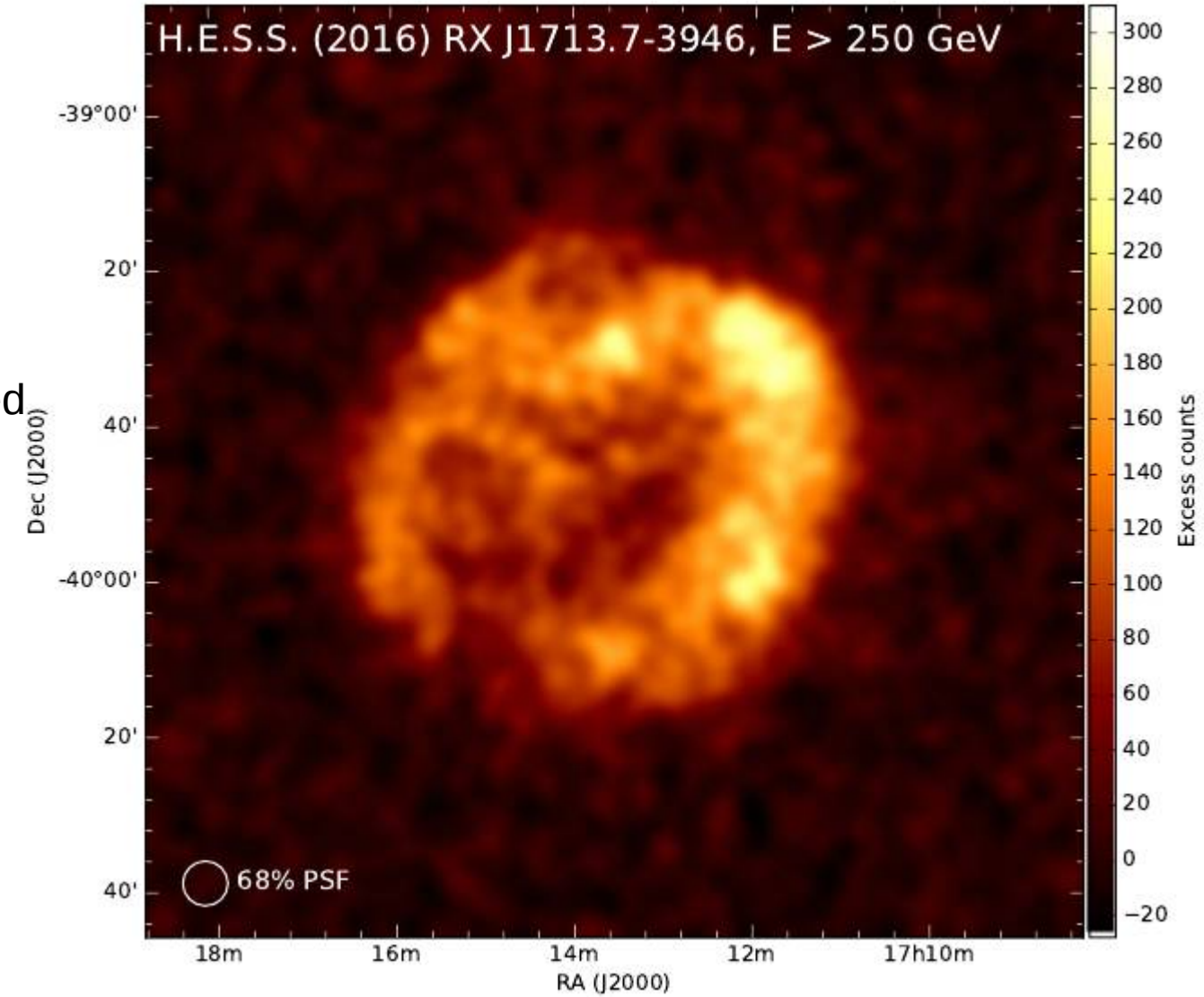
RX J1713-3946 in TeV

HESS Collab arXiv:1609.08671

Very well studied at all MWL

Typical case of ɣ-ray shell

- ~ 1 kpc
- Non thermal X rays dominated
- ~ 164 h HESS total exposure



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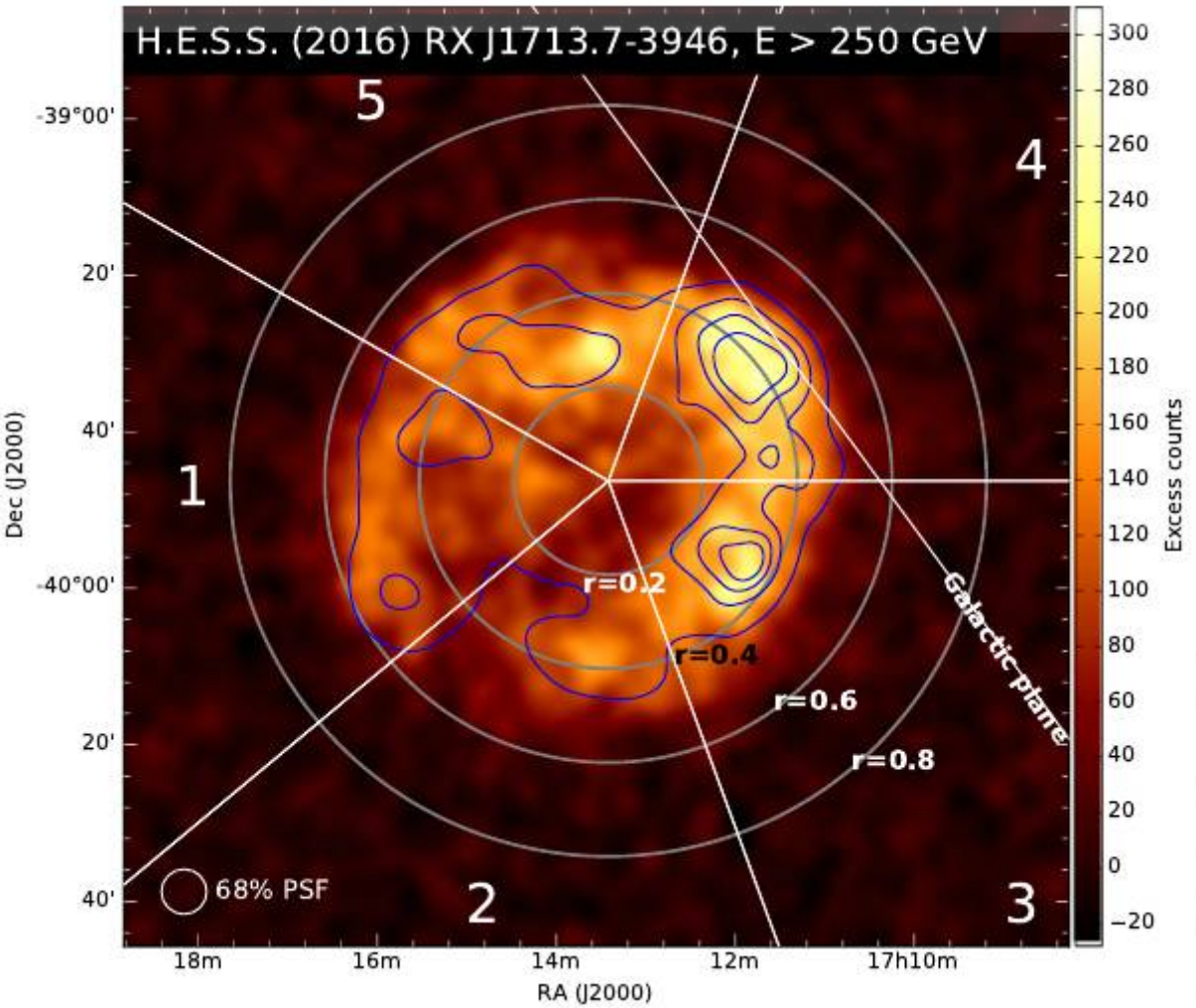
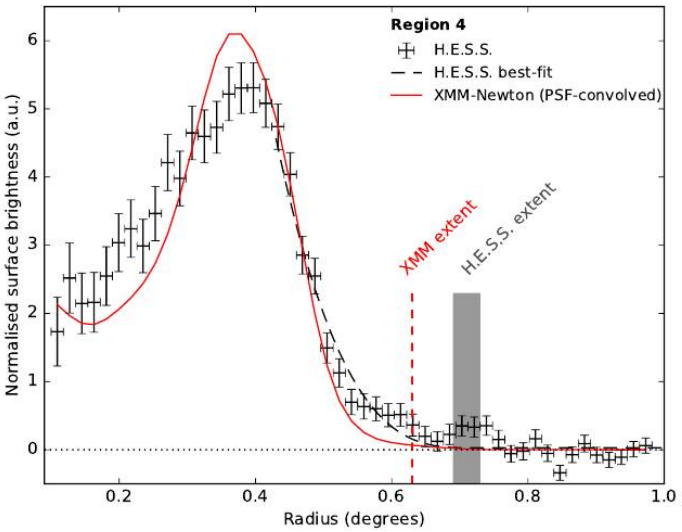
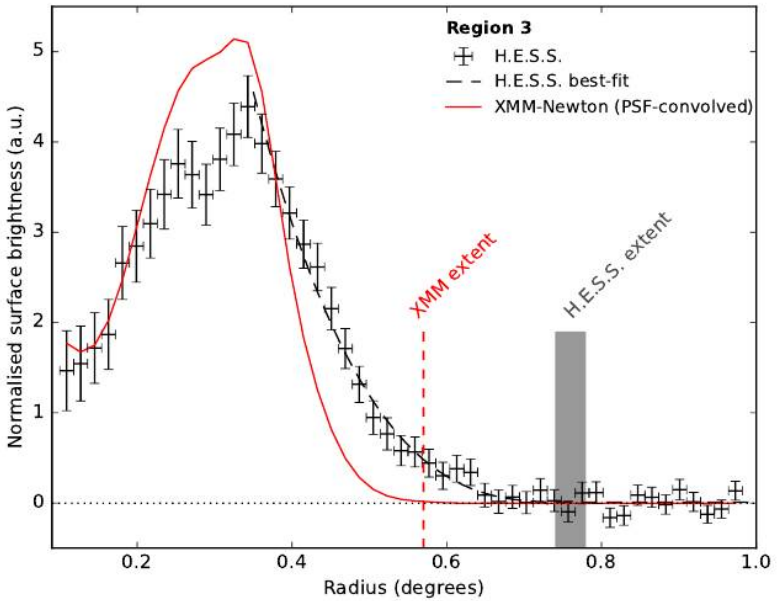






First evidence of particles ahead of the SNR shock !

CR escape ?
Acceleration in shock precursor ?

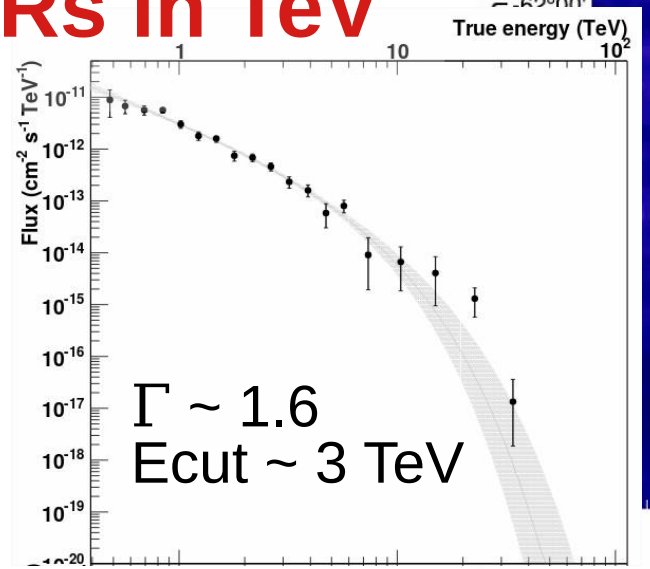
Other Shell SNRs in TeV

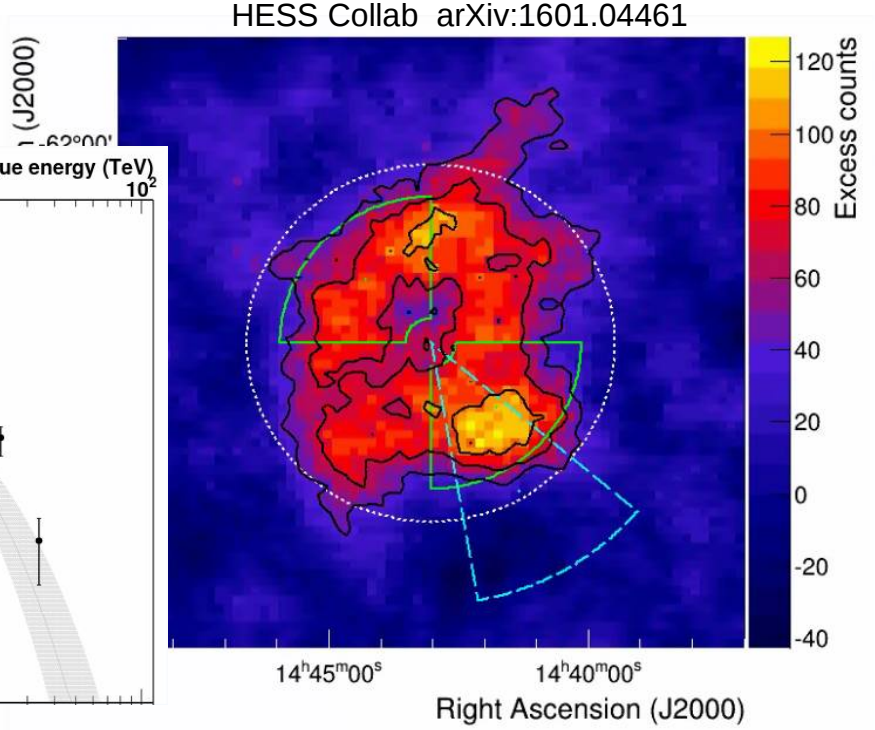
All shell SNRs show similar spectra

- Hard index (<2)
- Cutoff at low energy (~<10 TeV)

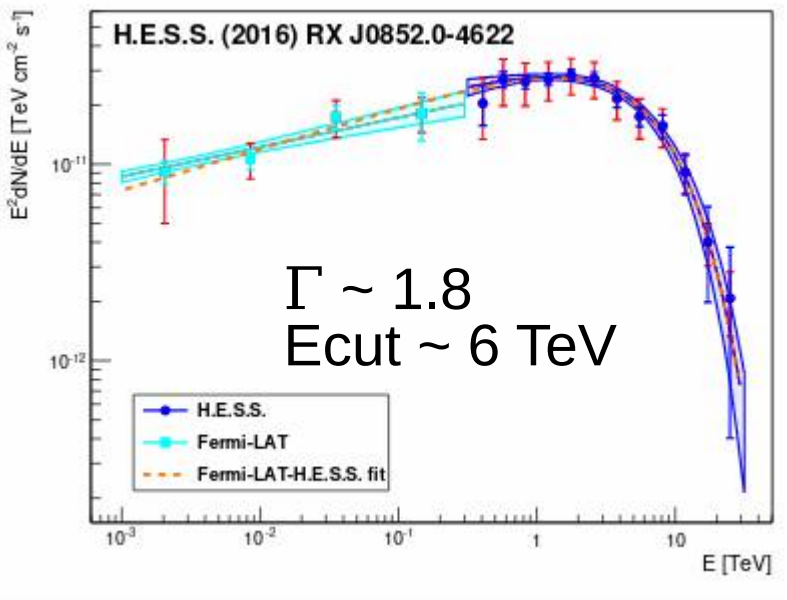
=> Generally better descibed by IC from electrons

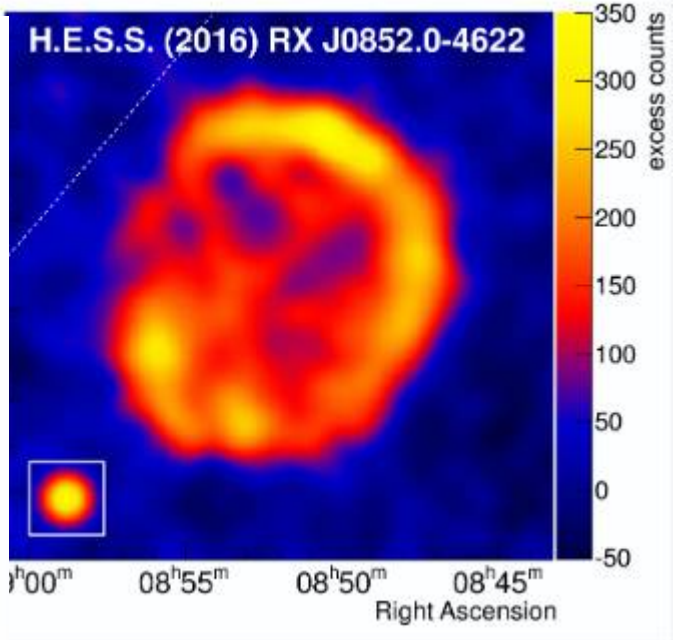
HESS Collab arXiv:1601.04461





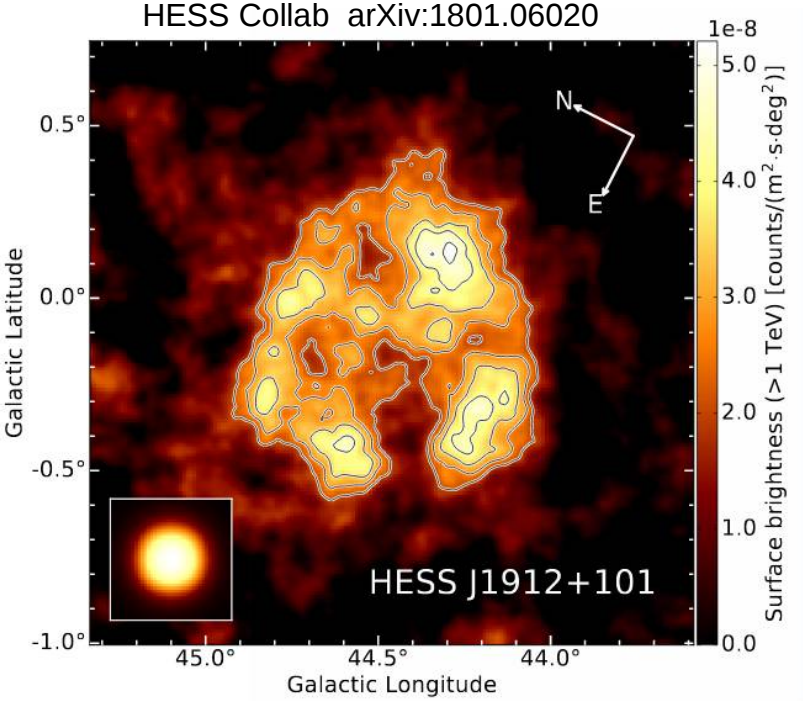
HESS Collab arXiv:1611.01863





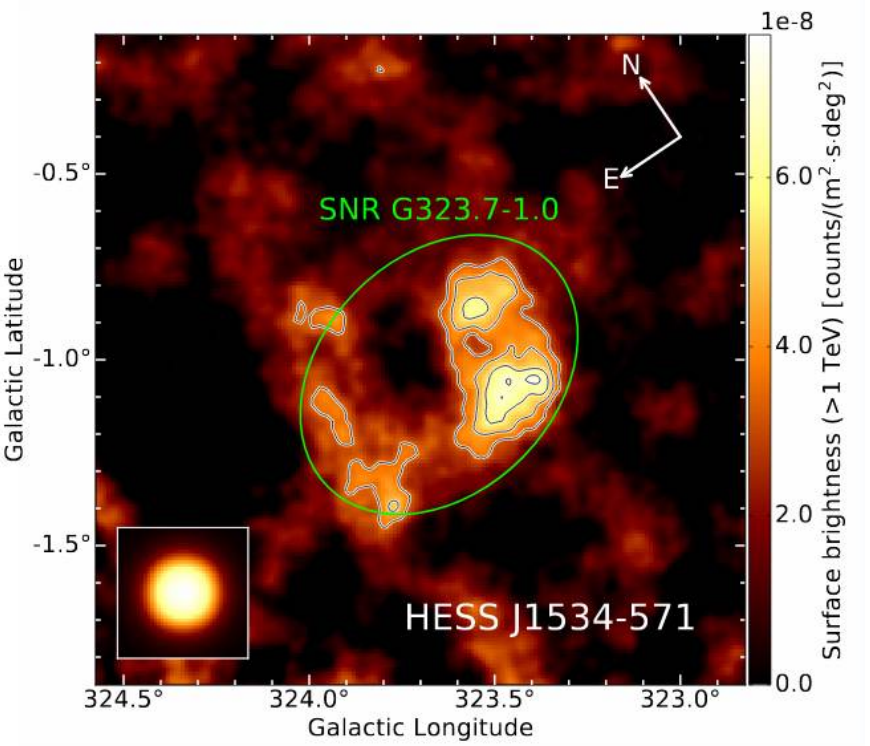
New Shell SNRs in TeV !

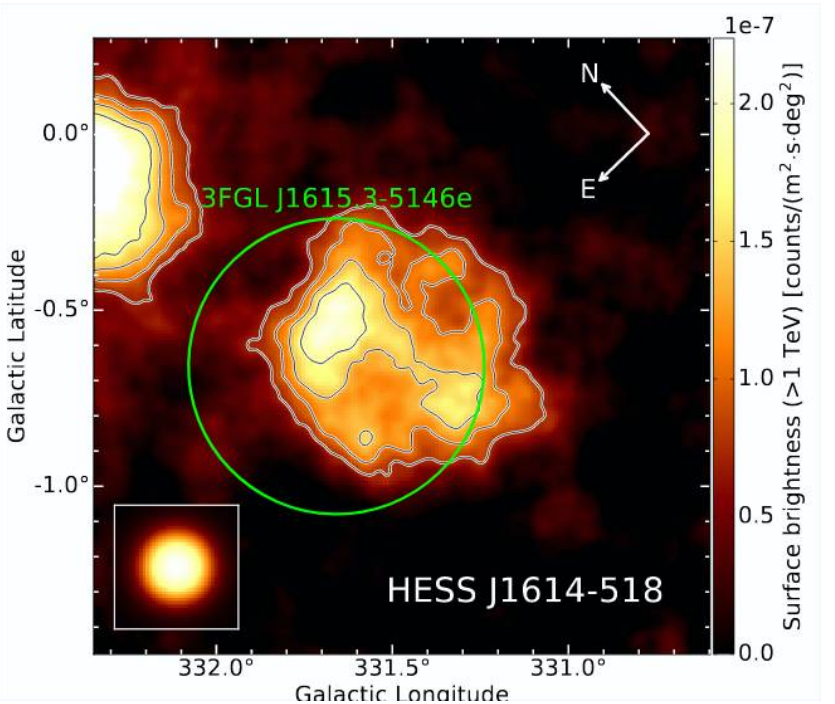
HESS Collab arXiv:1801.06020



Systematic search for Shell SNRs in HGPS

Comparison Shell like morpho to 2D gaussian





New Shell SNRs

S Collab arXiv:1801.06020

Systematic search for Shel

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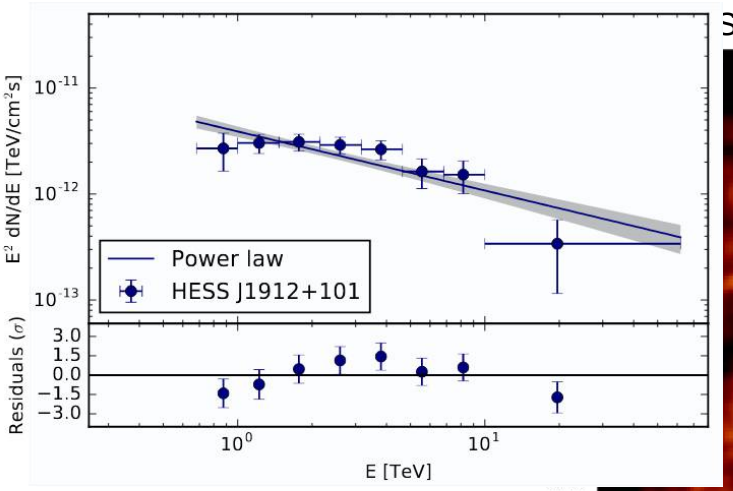
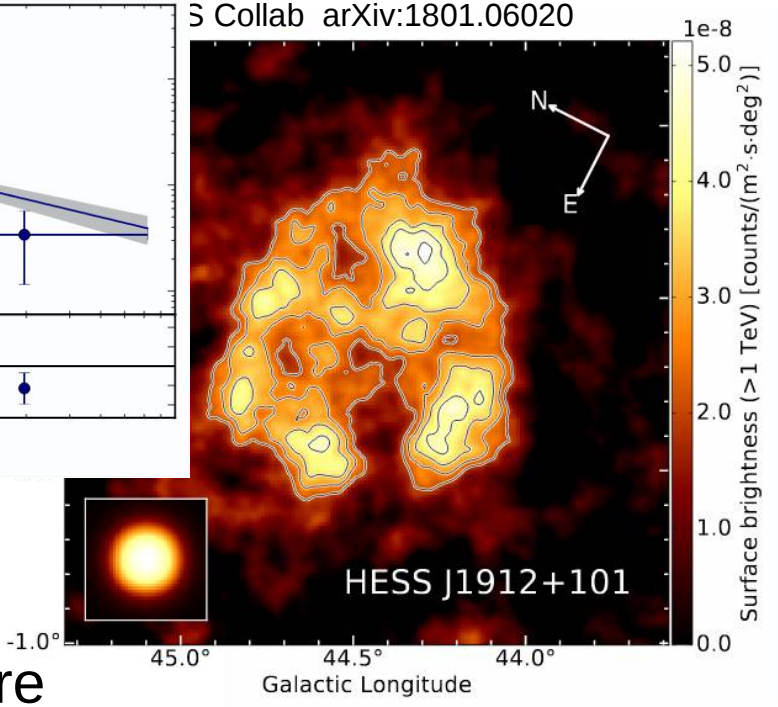
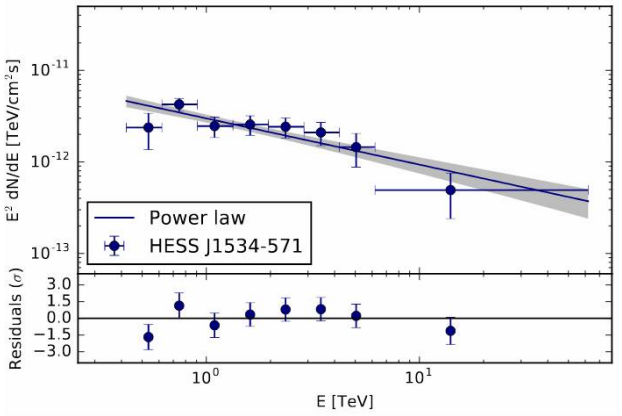
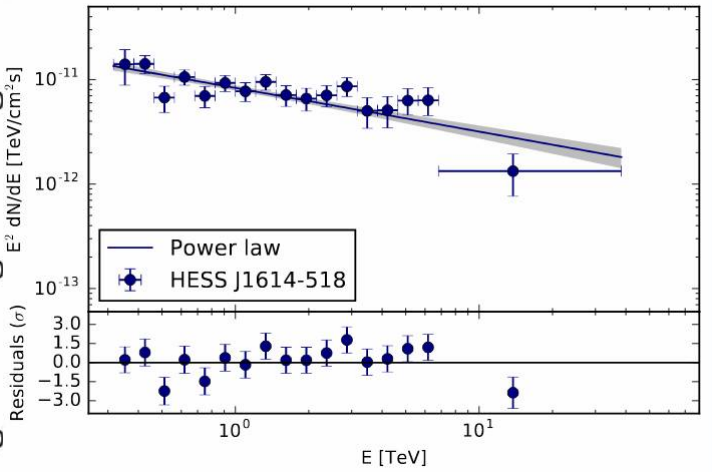


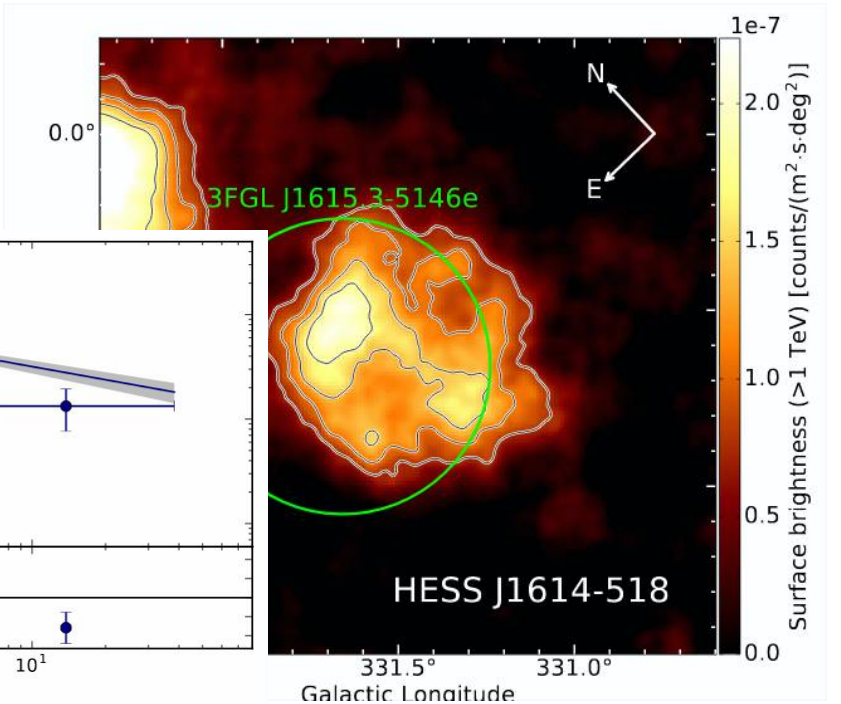




$\Gamma \sim 2.5$

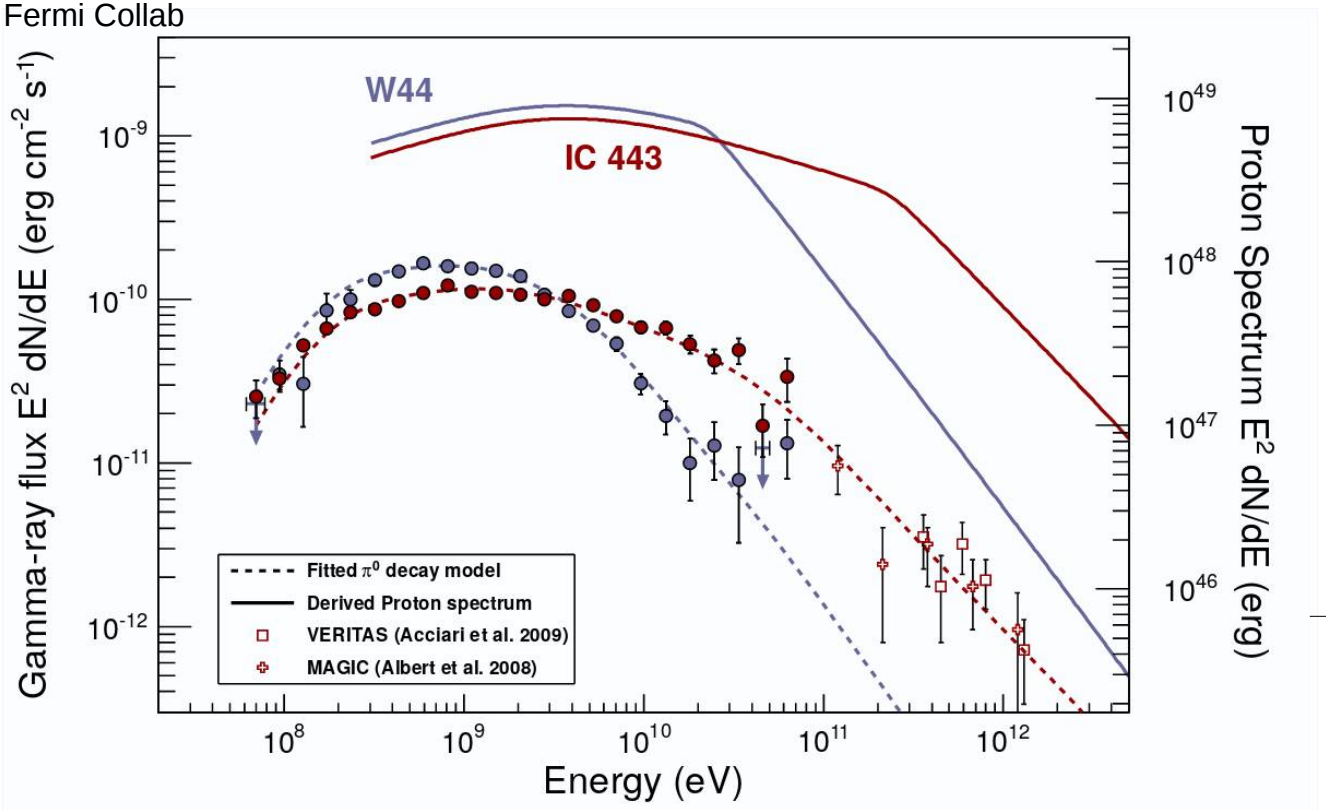
Hint of spectral curvature

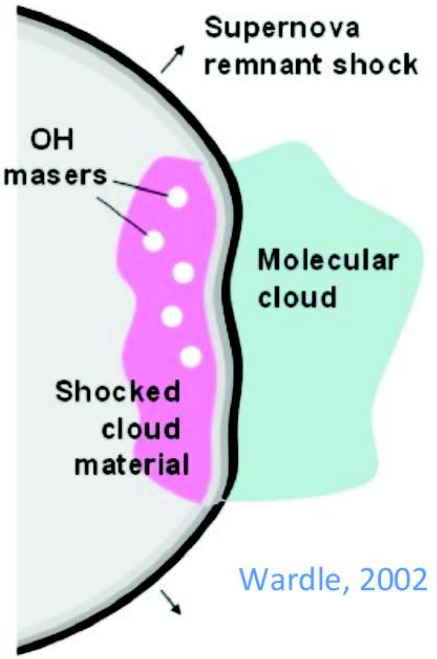




Interacting SNRs

Fermi Collab





→ First evidence of accelerated protons in SNRs !

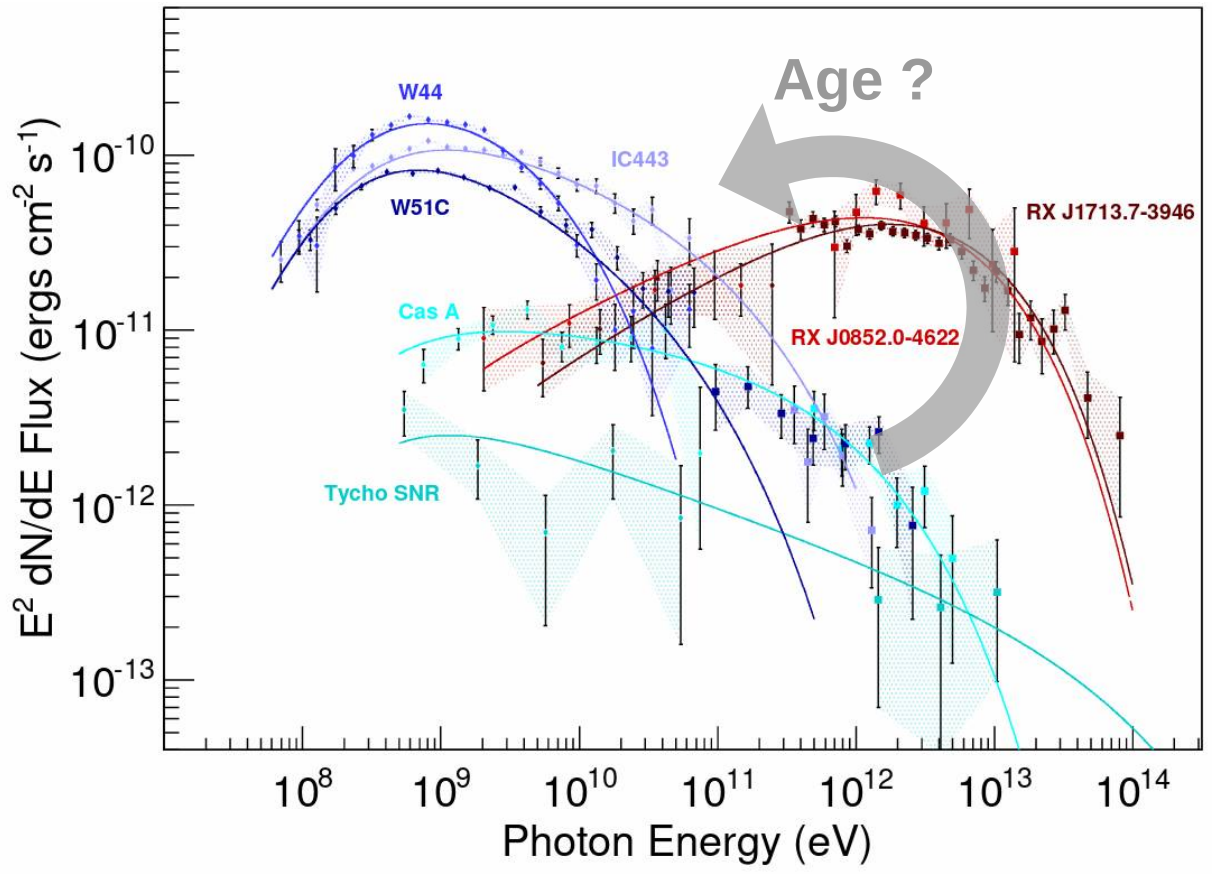
All interacting SNRs show similar spectra

Generally well explained by hadronic emission

Hard index (~2.2) before break
Soft index (~2.8) after break → Problem for Fermi acceleration ?

SNR spectra evolution

Funk (2015) arXiv:1508.05190

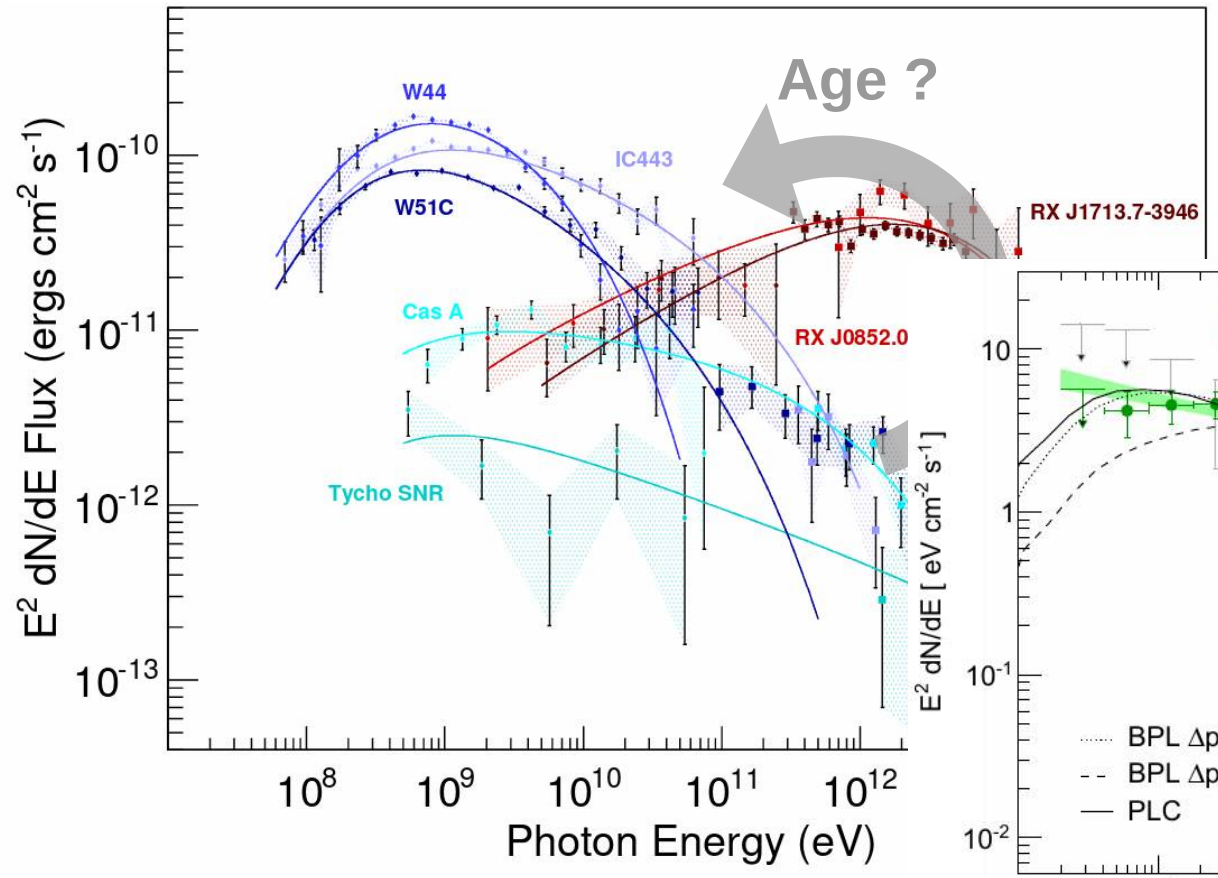


γ-ray spectral evolution ?

- Low flux hard spectra (very young <1000 yr)
- IC peak (?) for shell SNRs (young ~2000yr)
- GeV dominated with break before TeV (>10 000yr)

SNR spectra evolution

Funk (2015) arXiv:1508.05190



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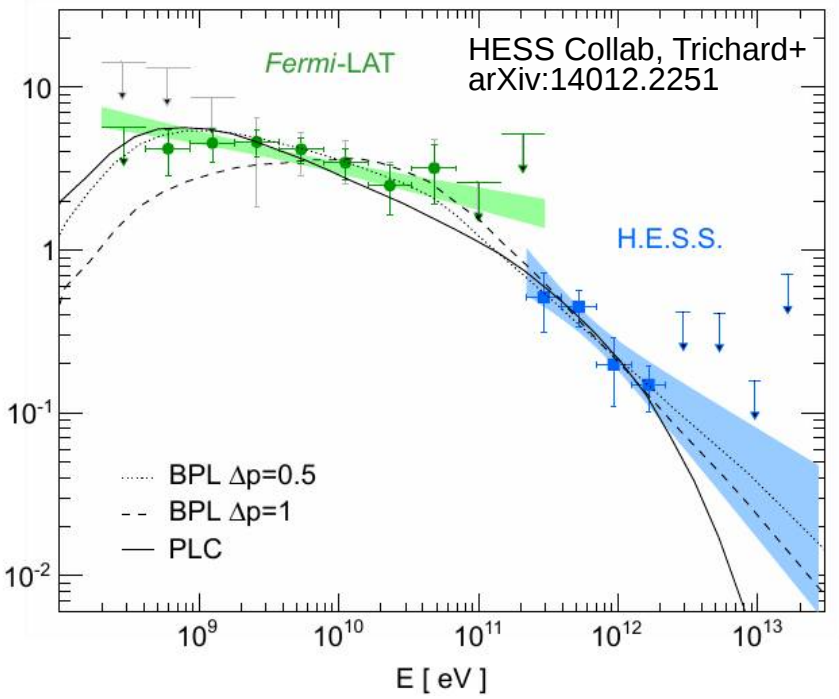

eak

SNR spectra evolution ?

γ-ray spectral evolution ?

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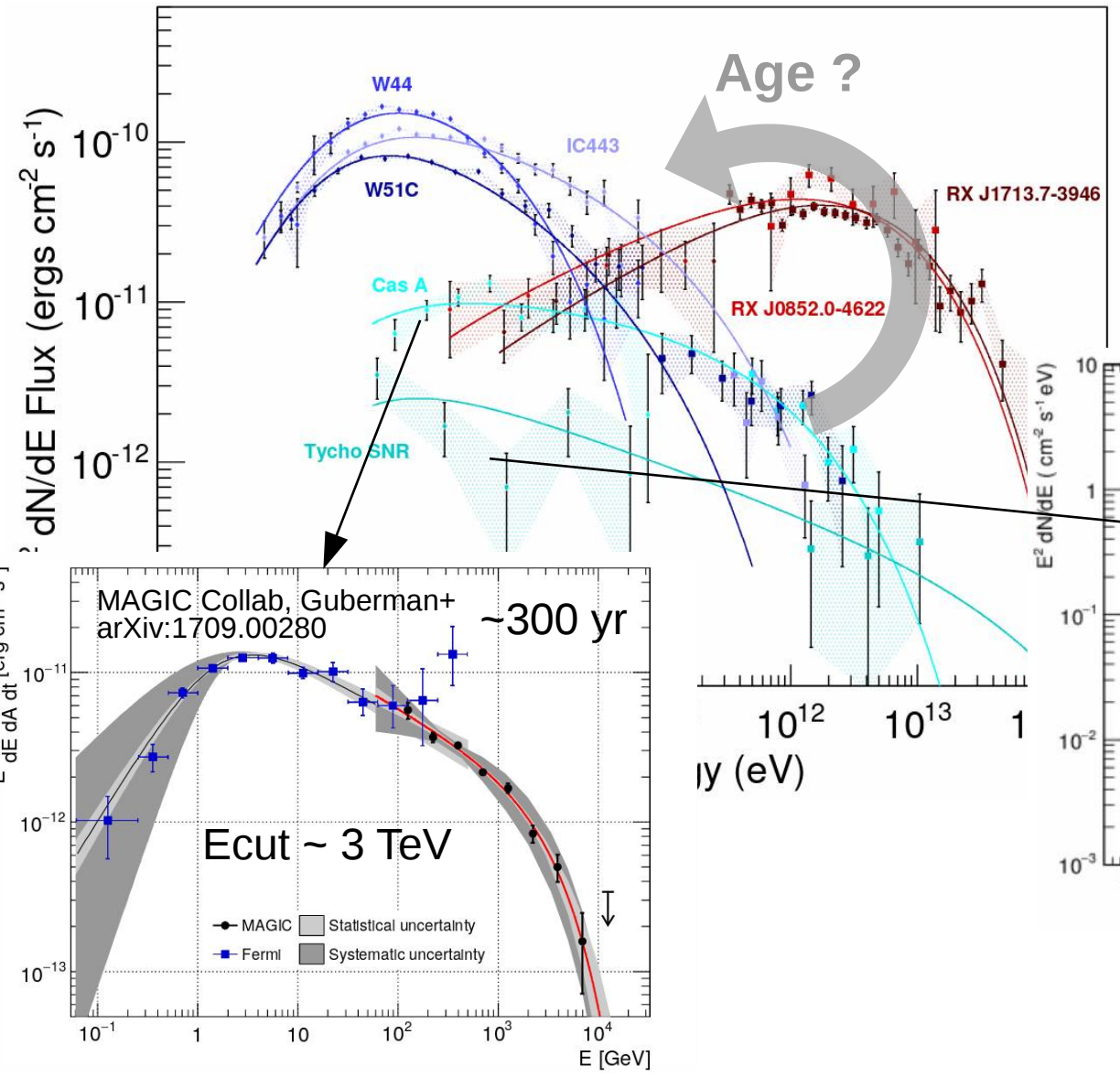

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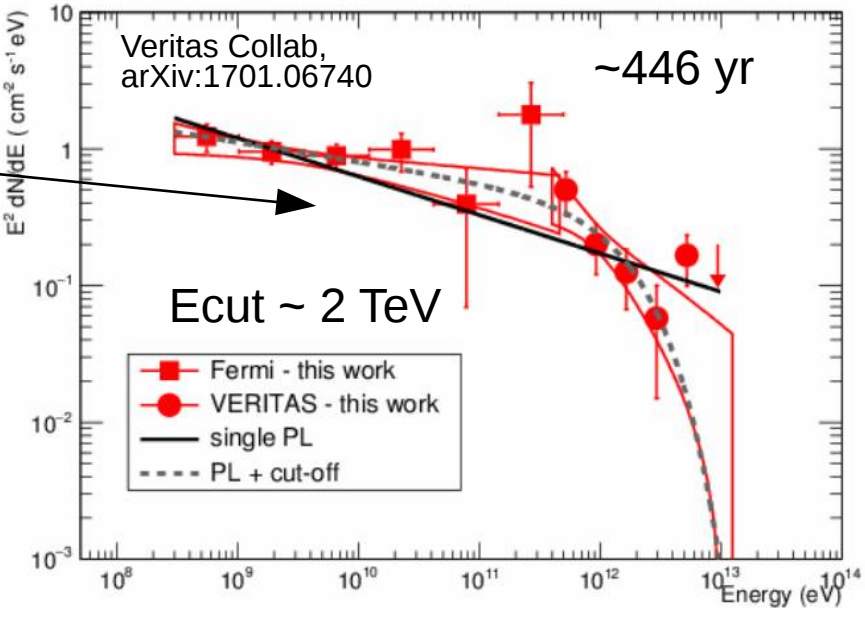

How to confirm SNR paradigm ?

1) Determine CR acceleration efficiency in (all) SNRs

- **Not Detected SNRs :** 10% efficiency is not really probed by current experiments
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2) Confirm that CR spectrum at acceleration site is $\propto E^{-2}$

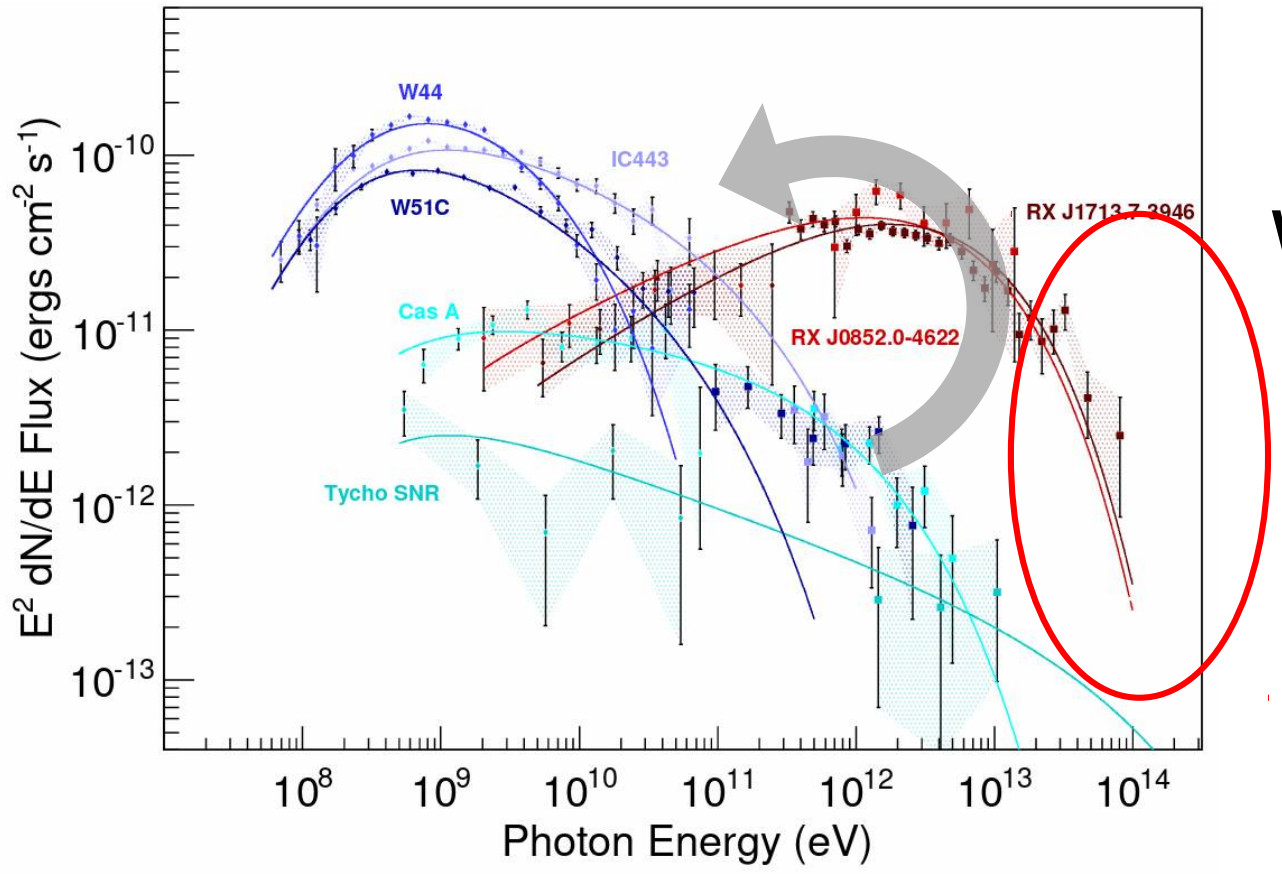
- **In GeV band :** $\propto E^{-2.1 \ldots -2.2}$
- **In TeV band :** $\propto E^{-2.5 \ldots -2.8}$ or even spectral cutoff

3) Up to at least 10^{15} eV

⟶ Not so easy !

Other Shell SNRs

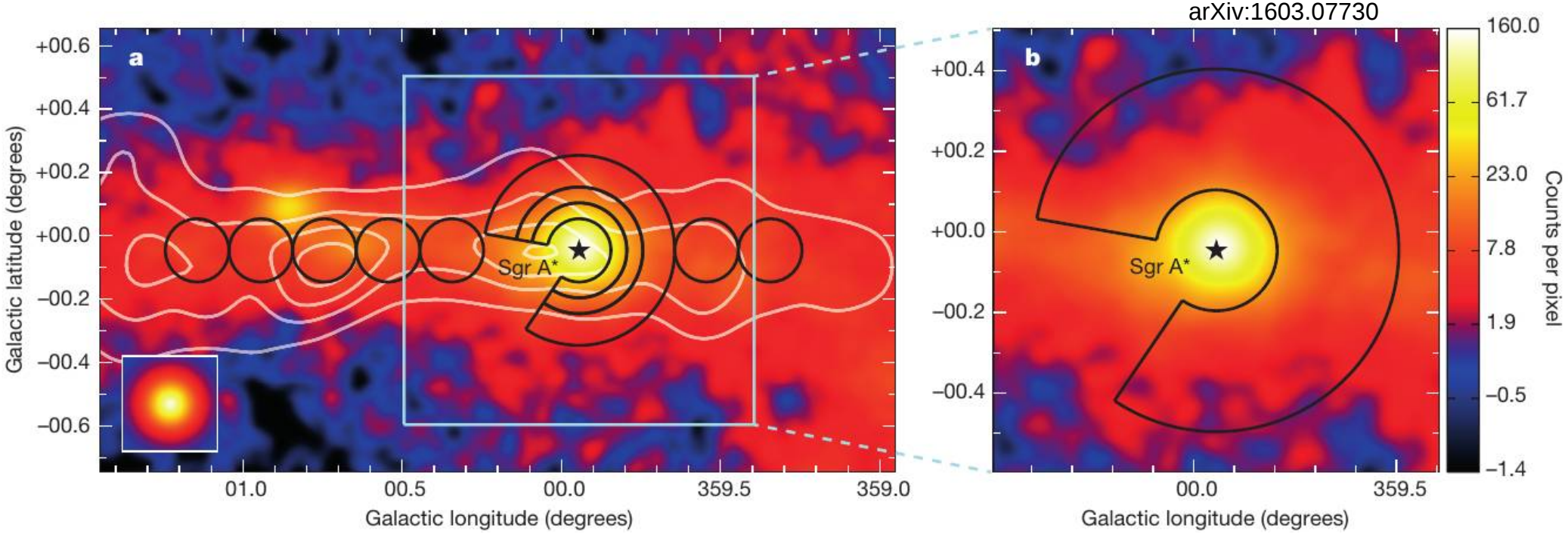
Funk (2015) arXiv:1508.05190



Where are the PeVatrons ?

PeVatron in the Galactic center

HESS Collab, Nature
arXiv:1603.07730



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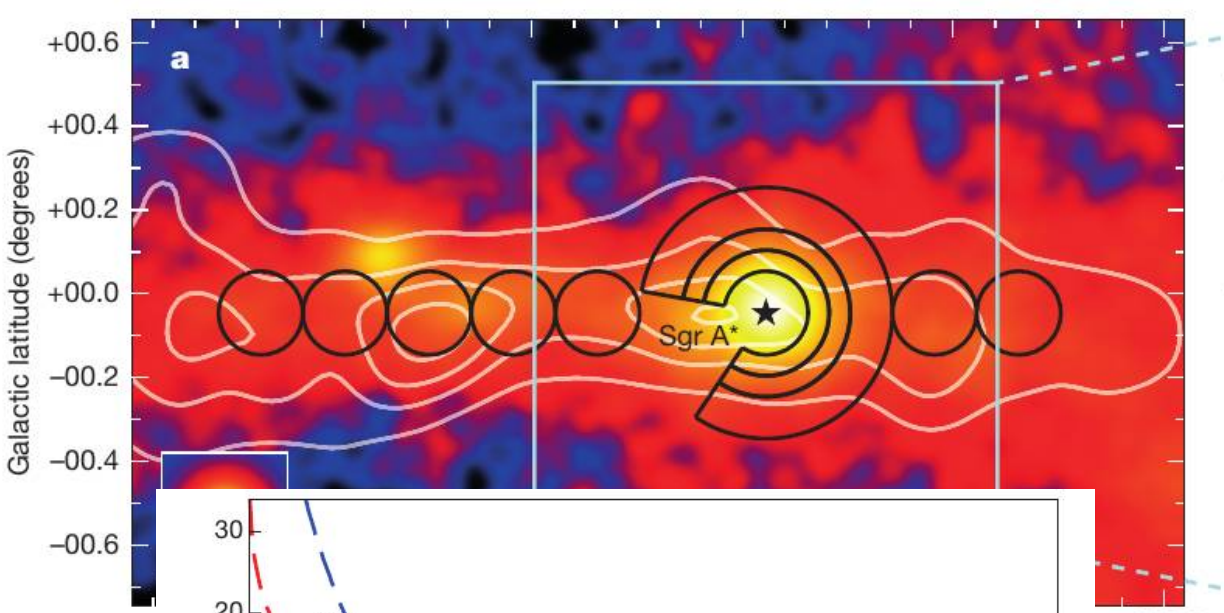
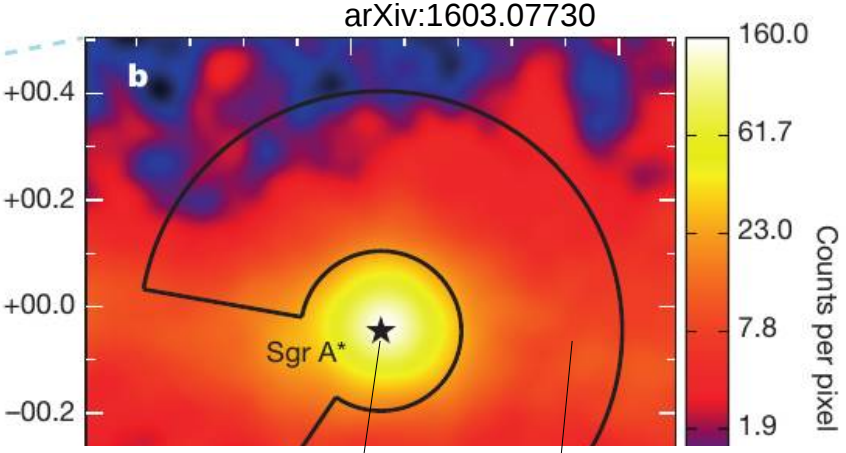
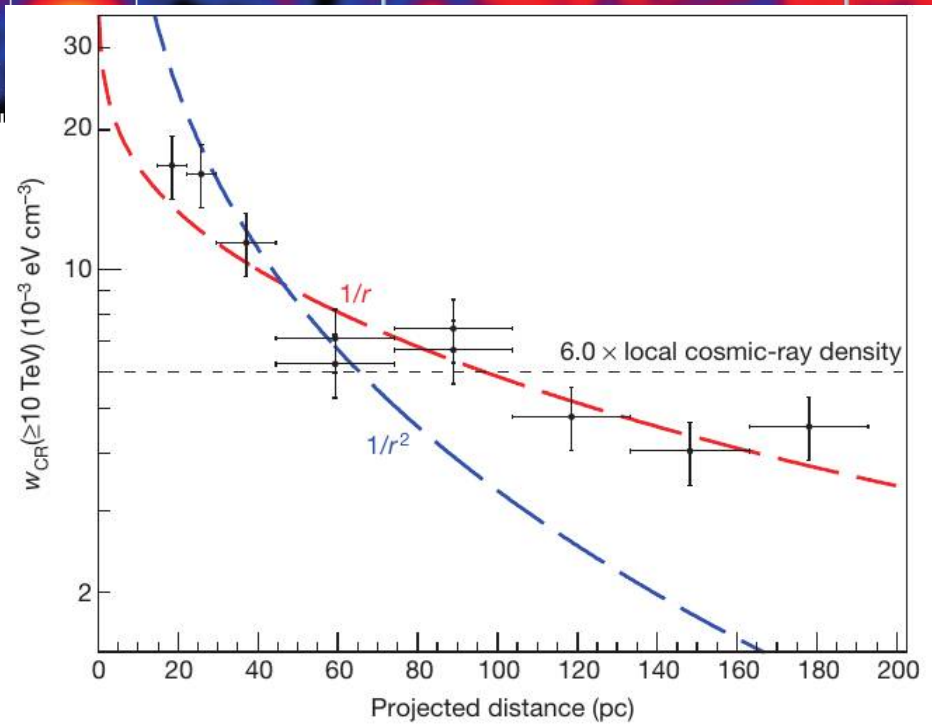
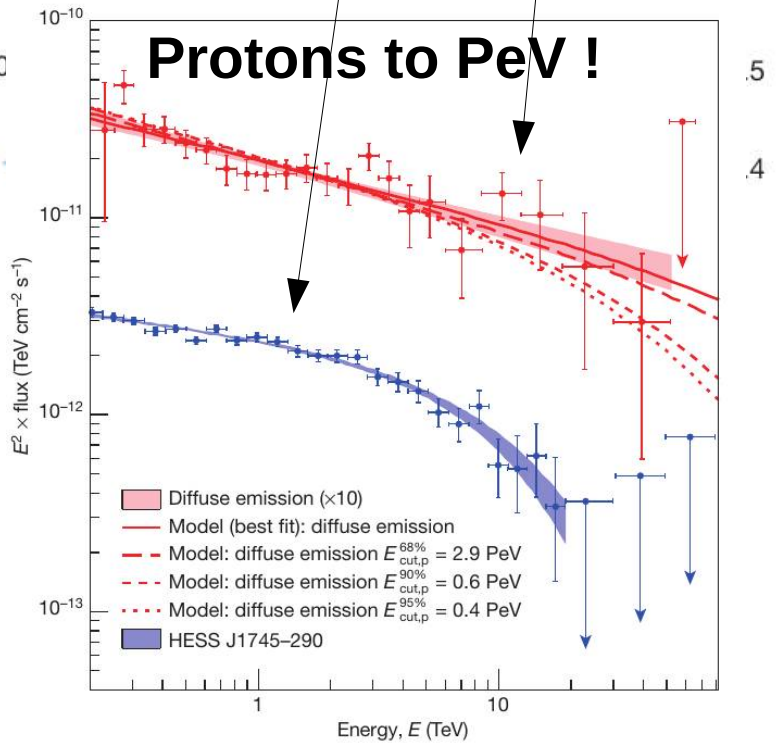




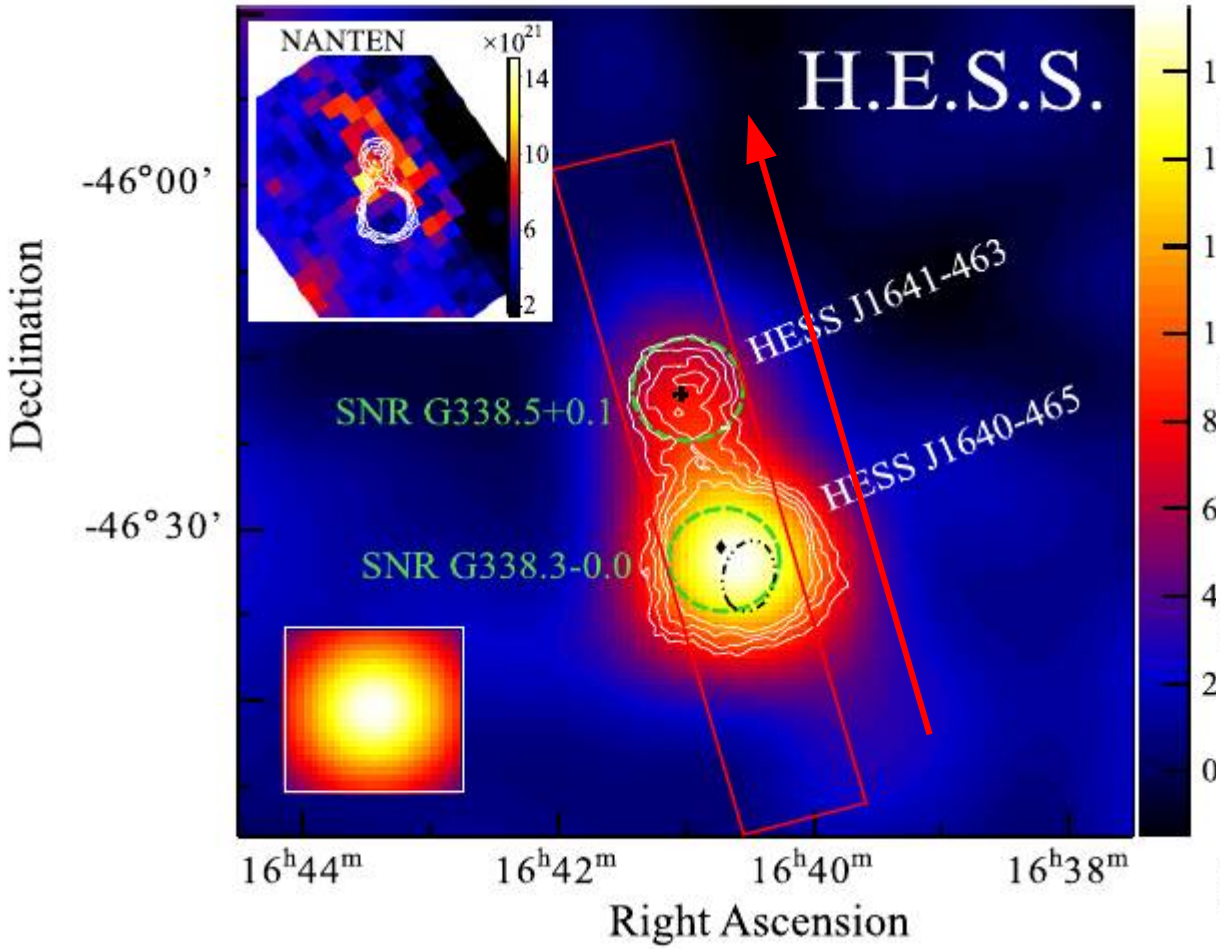


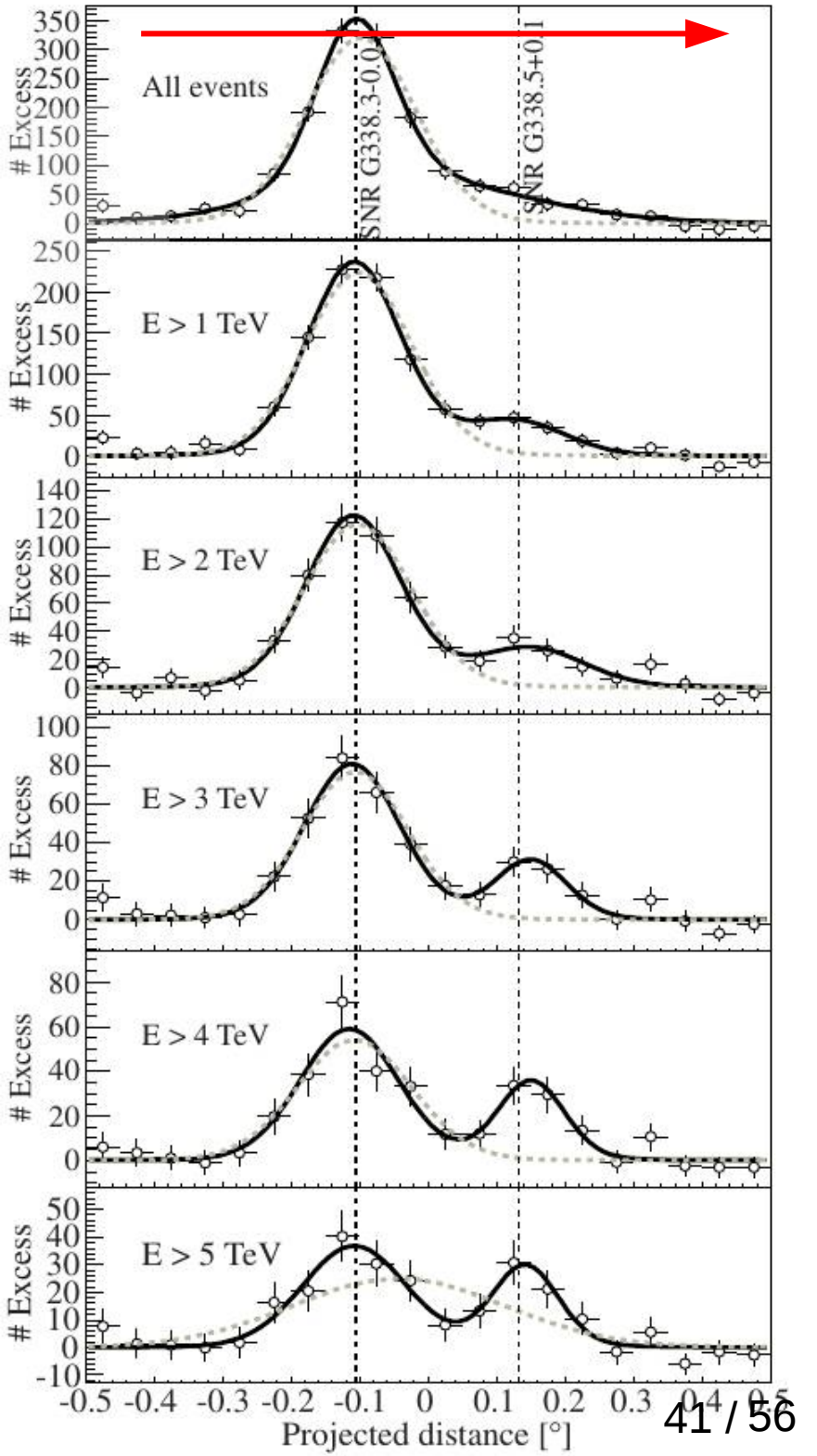
Protons to PeV !



Other PeVatrons ?

HESS Collab,
arXiv:1408.5280



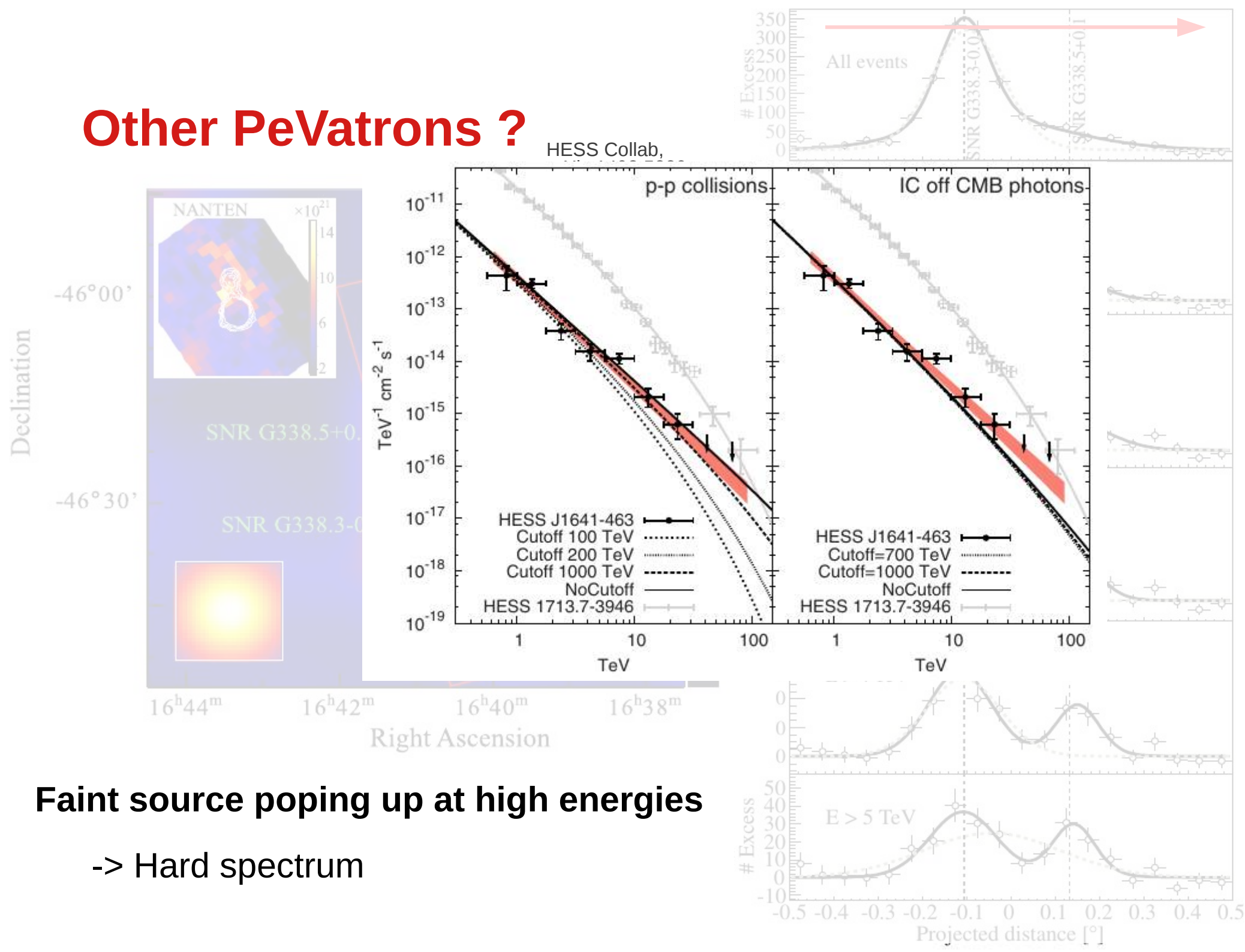


Faint source poping up at high energies

-> Hard spectrum

Other PeVatrons ?

HESS Collab,



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3) Up to at least 10^{15} eV

- No detection yet
- Some good canidates
  - Interesting candidate in Galactic center

The cosmic ray origin and the SNR paradigm

Gamma ray astronomy recent results

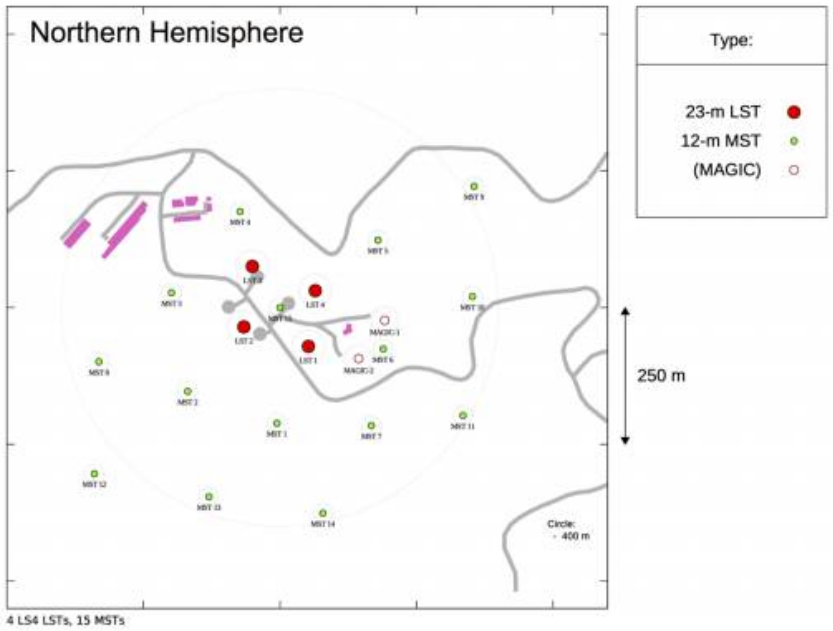
Higher energies

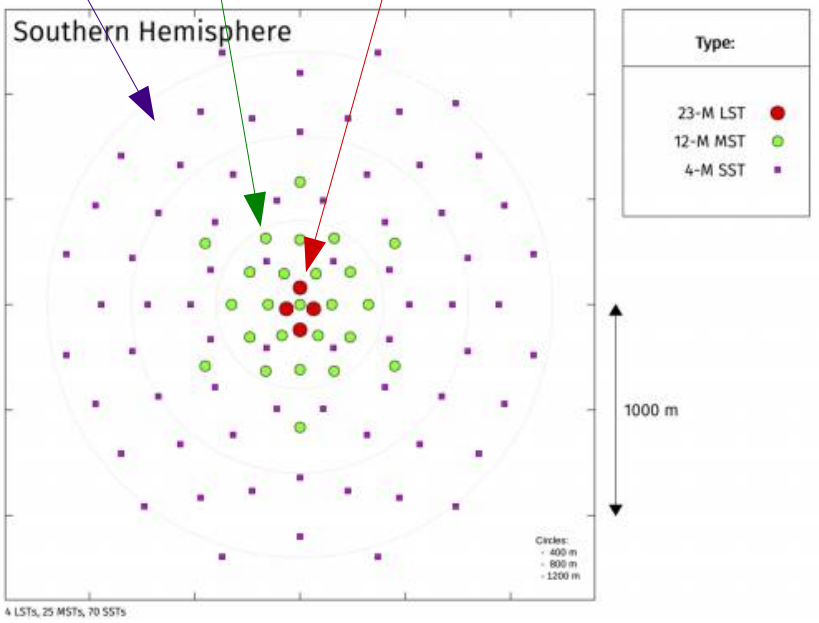
CTA

La Palma (North)
Chili (South)

N	S	
4	4	LST
25	15	MSTs
70	0	SSTs

Start construction in 2018 - 2019





CTA Collab arXiv:1709.07997

CTA - KSPs

Extra Galactic Survey

Galactic Center

AGNs

PeVatrons

Dark Matter

Galactic Plane Survey

Cluster of Galaxies

LMC

Star forming systems

Transients

CTA Collab arXiv:1709.07997

CTA - KSPs

Extra Galactic Survey

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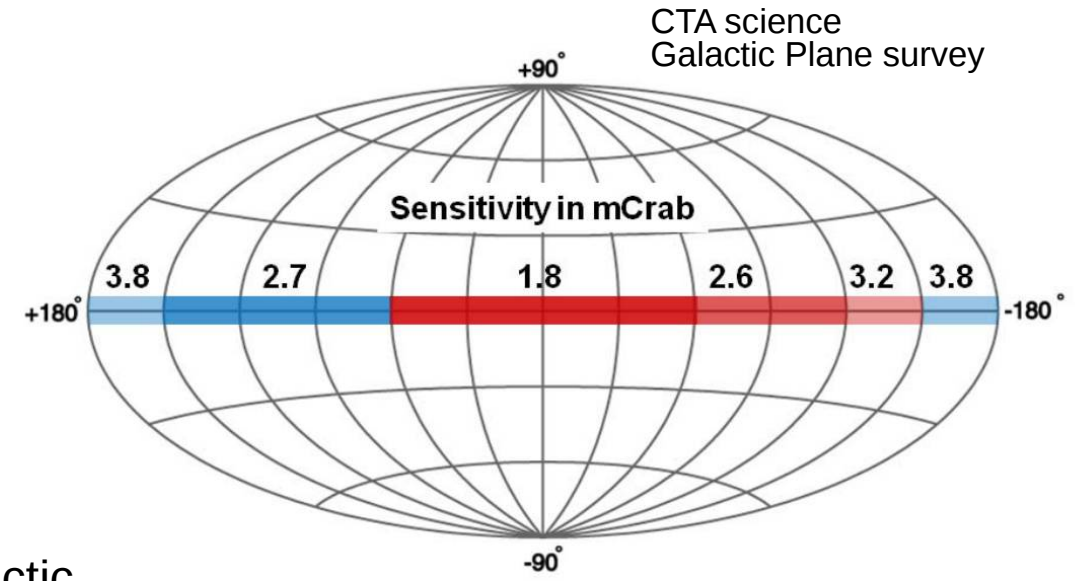
CTA GPS



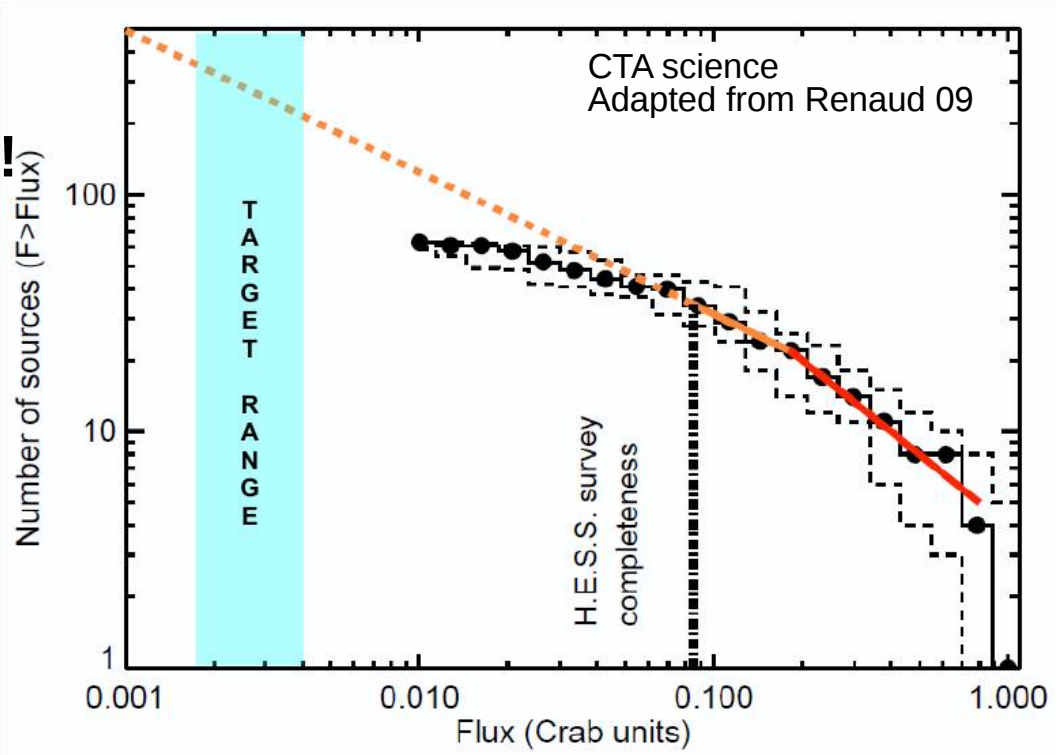
Total of ~ 1600 hours

Sensitivity of a few mCrab with focus on Galactic Center

Huge increase of number of sources !

+ very detailed studies of detected sources

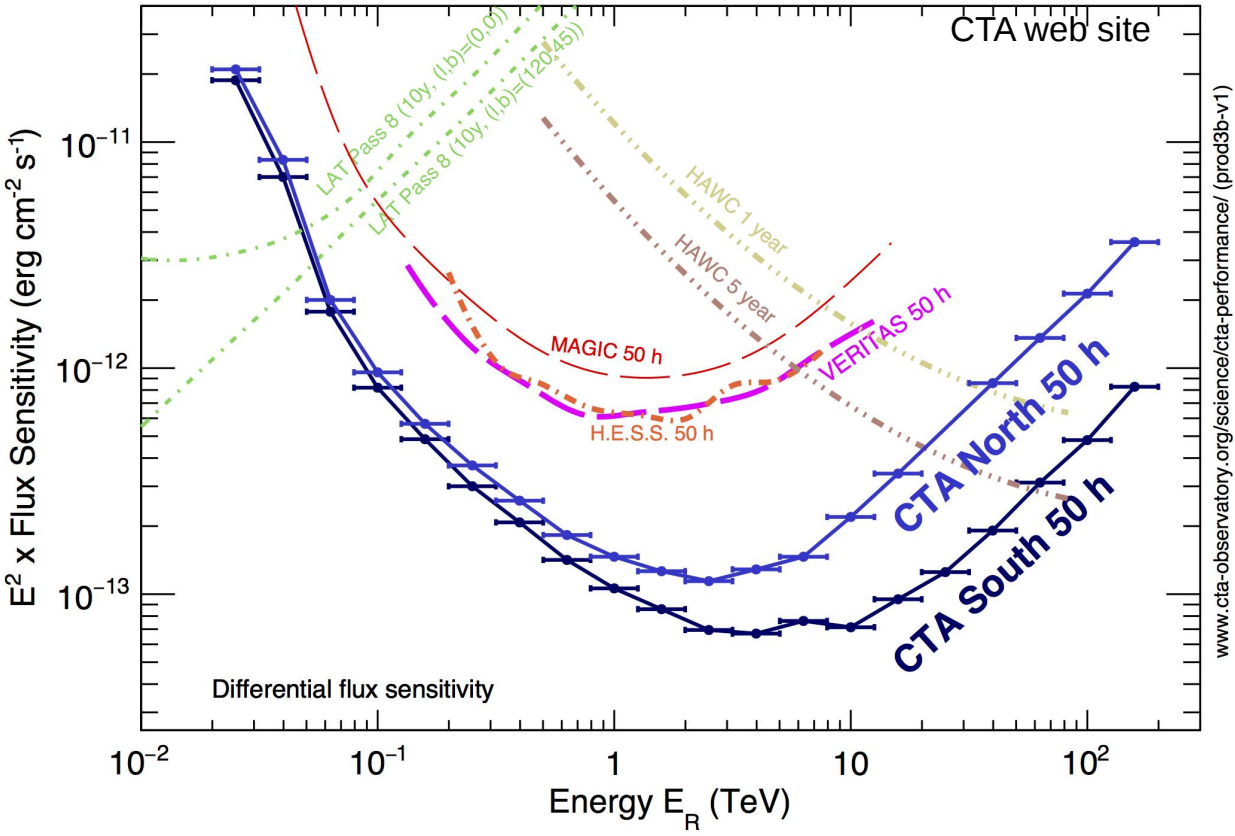
Dataset use to trigger deeper observation on PeVatrons



CTA PeVatrons

Very well designed instrument for PeVatron discovery

Unexplored energy range



PeVatron KSP strategy :

- Find 5 PeVatron candidates in CTA GPS
- Deep observations (50h each)

CTA PeVatrons

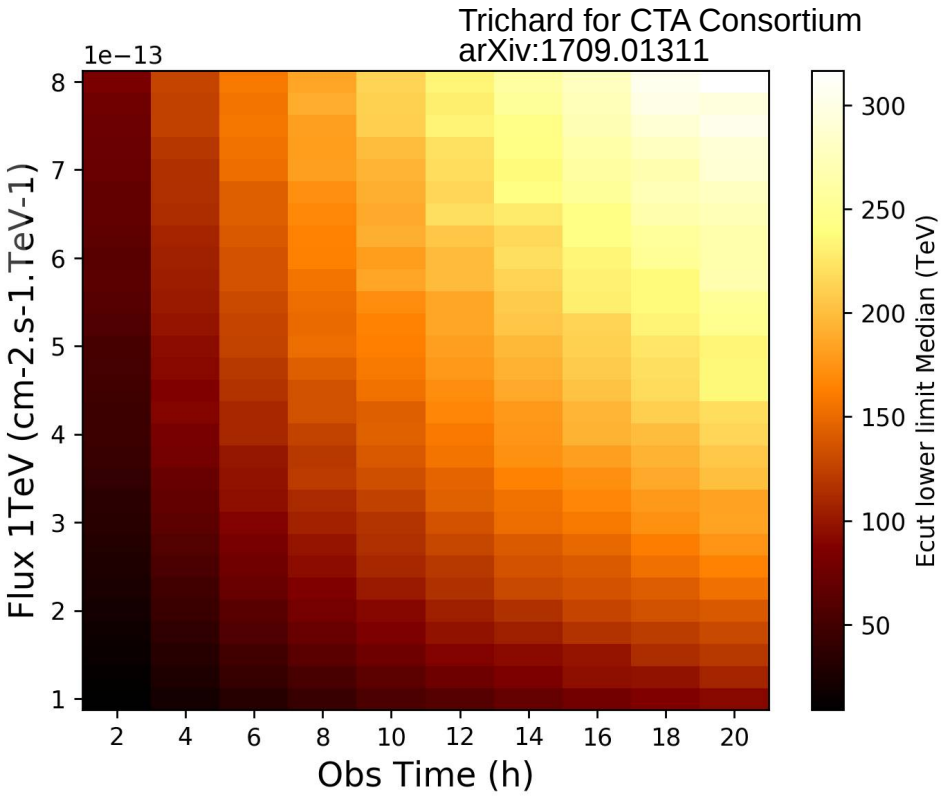
Determining CTA sensitivty to PeVatrons

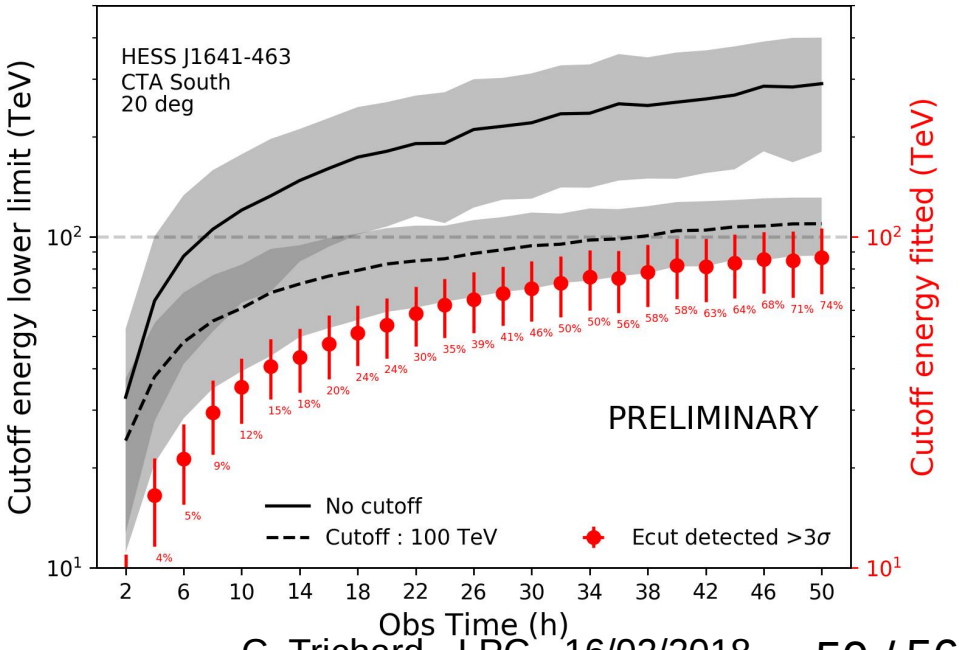
- Simulate non cutoff spectra
- Determine cutoff lower limits derived on reconstructed spectra

  -> 100 TeV in 15h for 0.5 % Crab source

- Determine probability of detecting a cutoff at 100 TeV in PeVatron candidates

Goal is to determine strategy to trigger observation on PeVatrons



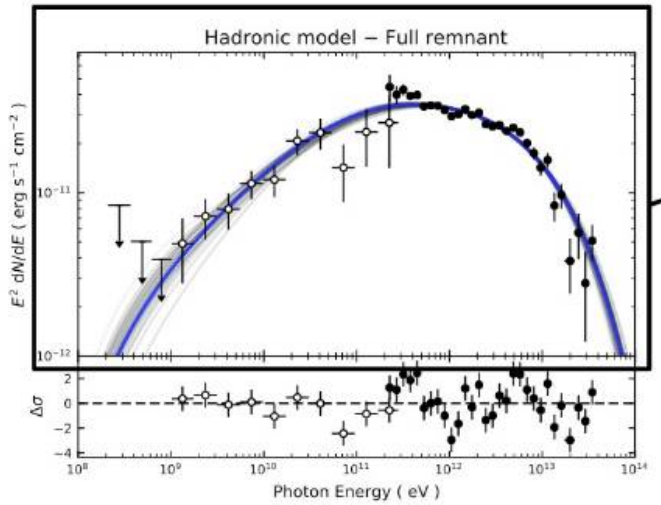


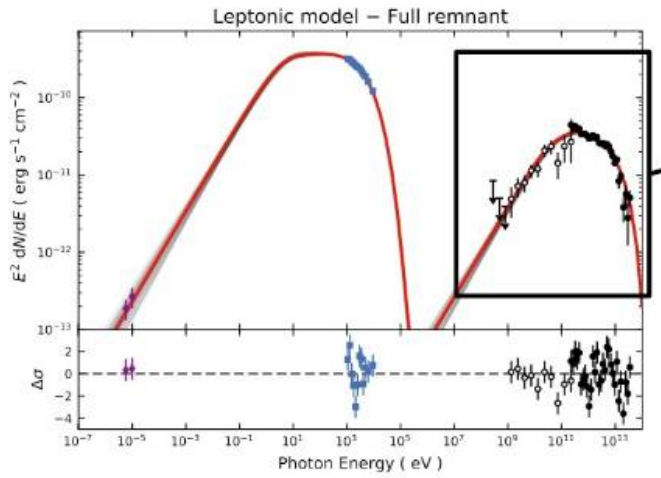
Conclusion

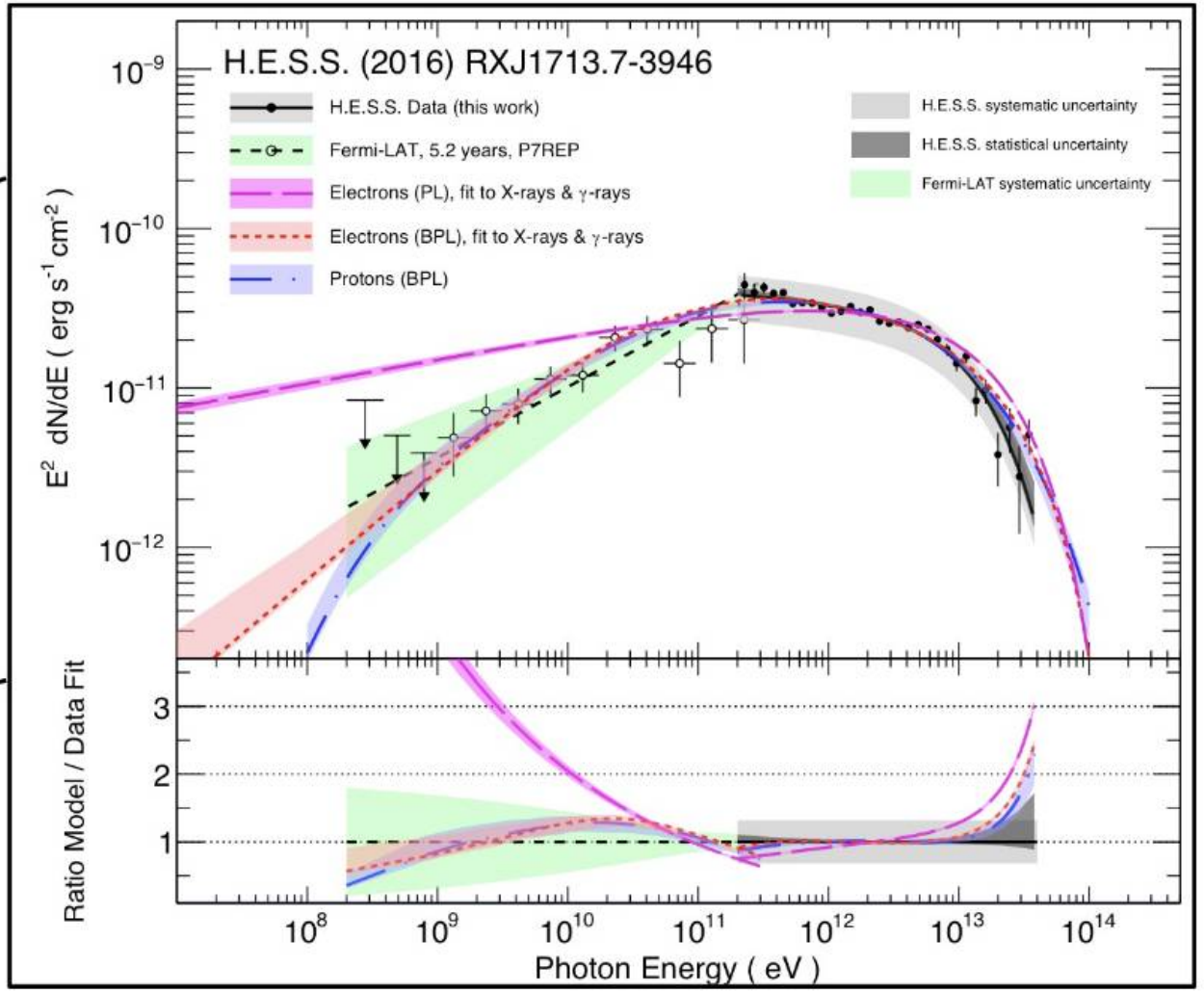
- **SNR paradigm is remarquably strong (> 80 yr old)**
- **TeV current experiments (mainly HESS) :**
  - **SNR γ-ray spectra > ~100 GeV in tension with Fermi mecanism**
  - **Strong indication of ~ 10^{15}eV accelerators :**
    - Galactic center
    - Few candidates in Galactic plane
- **CTA very well design to push toward higher energies**
  - **PeVatron detection ?**
  - **Sensitivity to deeply probe the 10 % CR acceleration efficiency**

HESS Collab arXiv:1609.08671

RX J1713-3946 in TeV

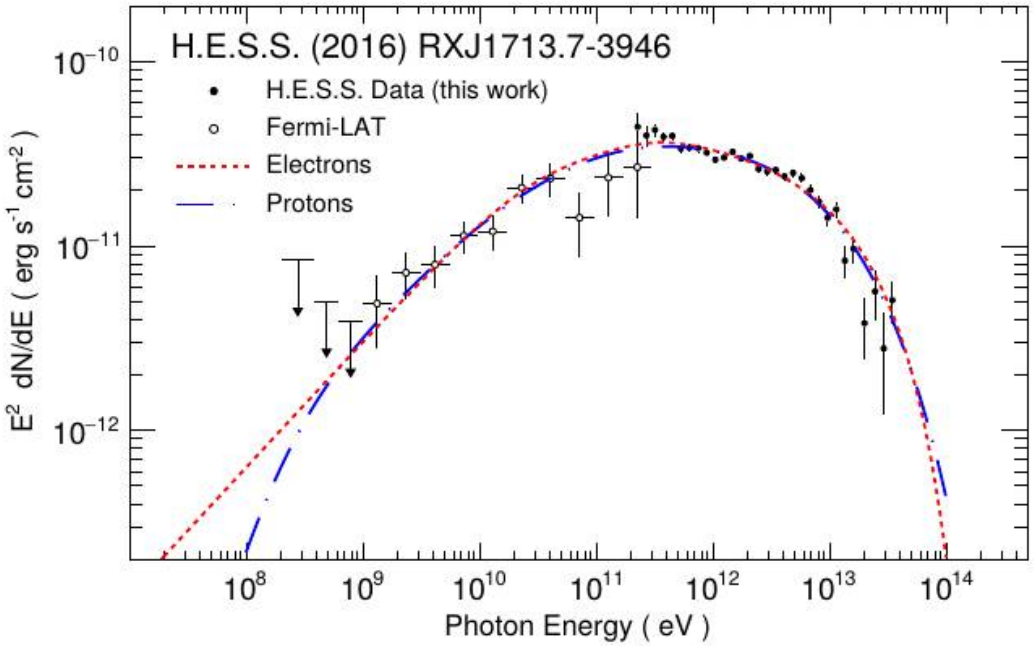


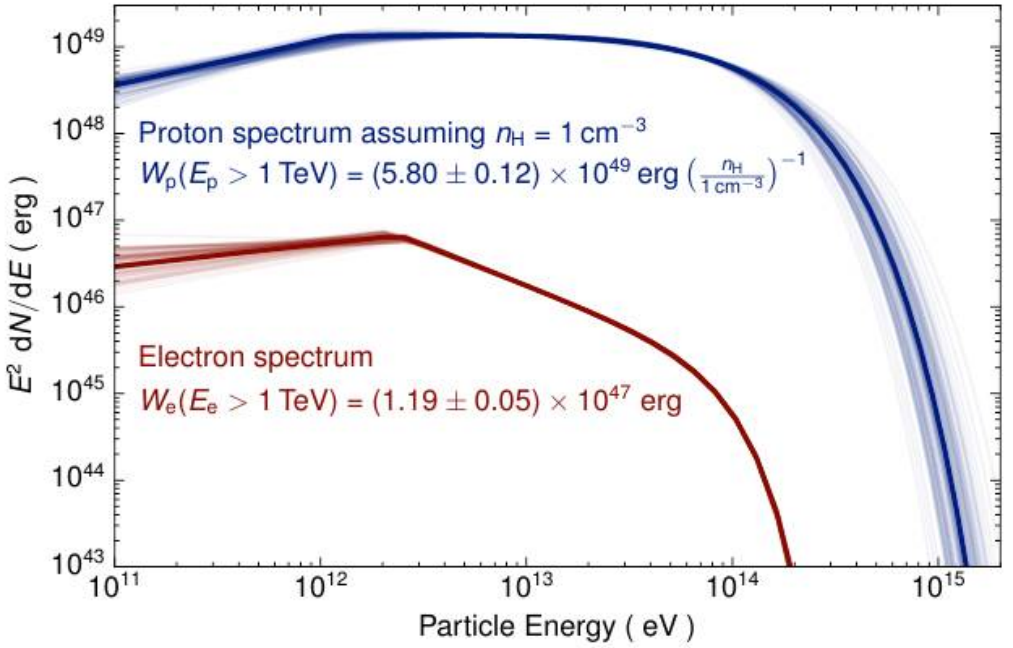




RX J1713-3946 in TeV

HESS Collab arXiv:1609.08671

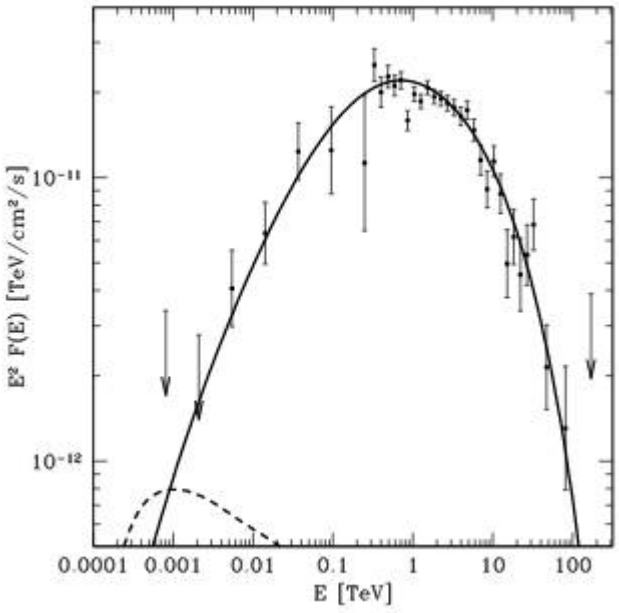


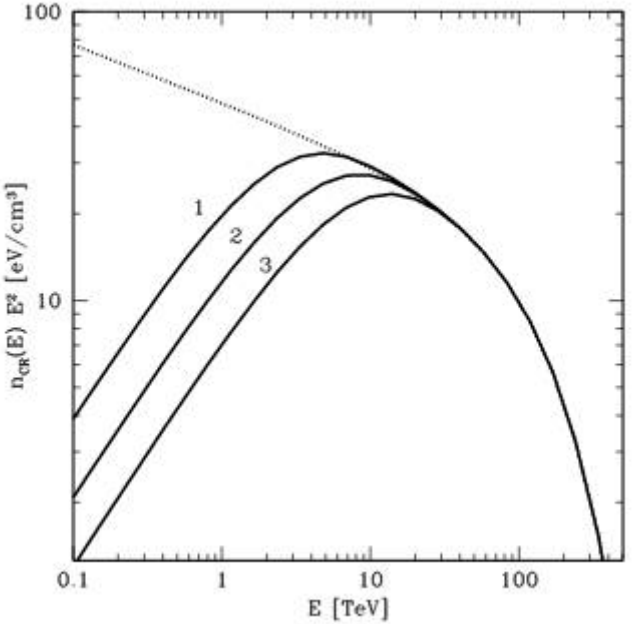


Gabici & Aharonian 2014

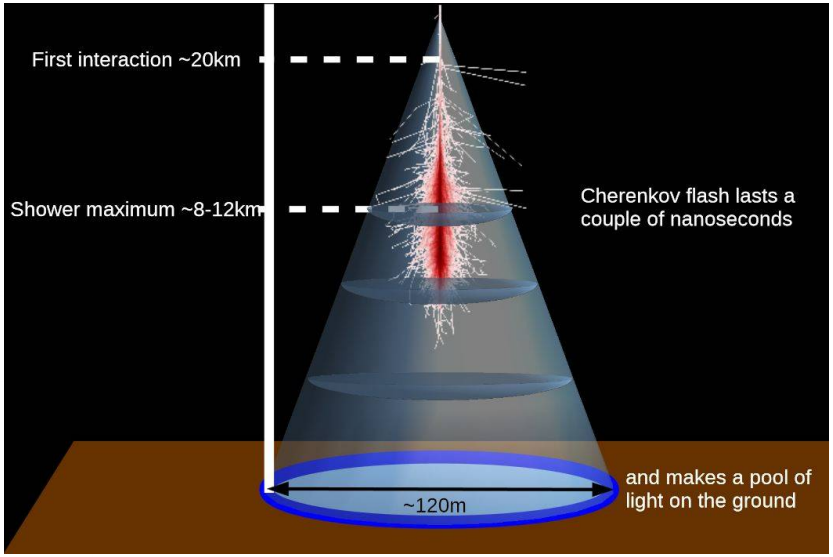
Alternative scenario :

Clumpy medium





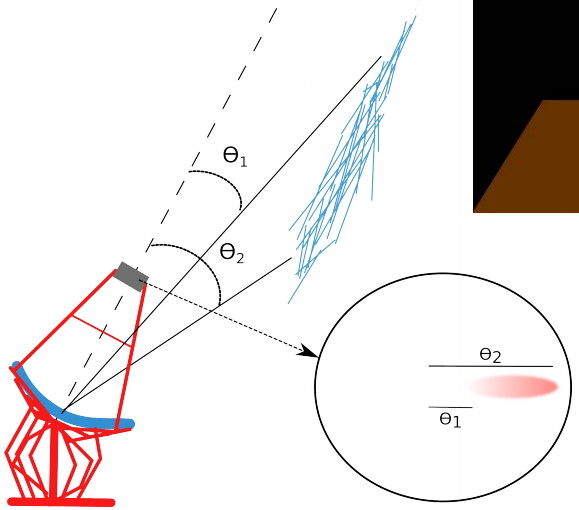
H.E.S.S.

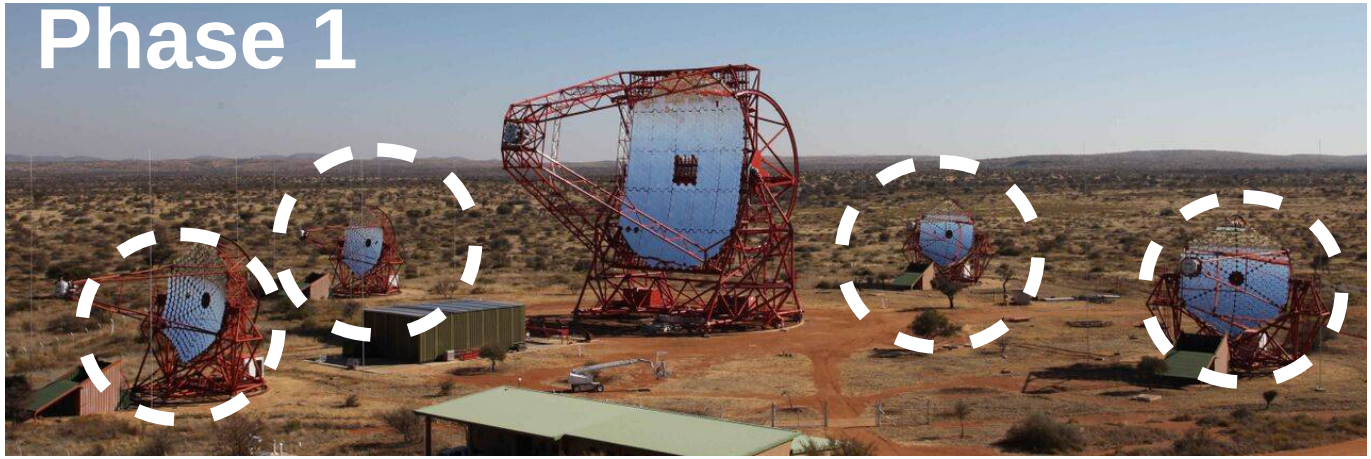


Opérationnel depuis 2004

- 100 GeV – 100 TeV
- Imagerie Tcherenkov

- Surface effective ~10^5 m^2





Analyse H.E.S.S.

Reconstruction :

- Energie
- Direction