Introduction to Gamma-Ray Astronomy

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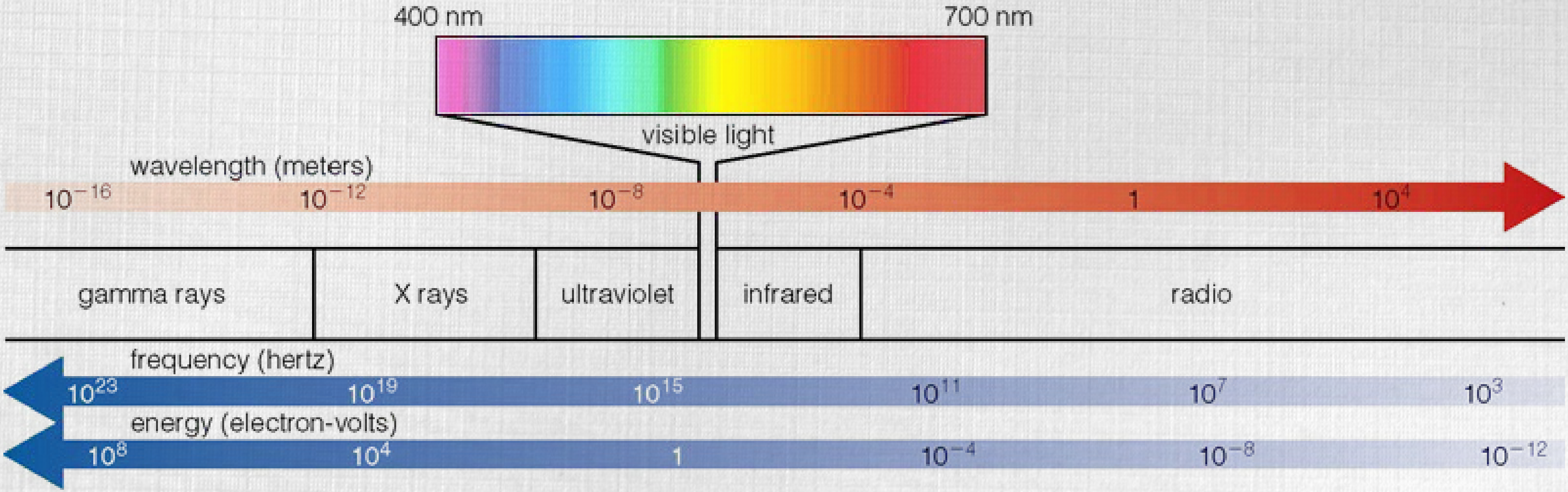
Outline

- ✪ What are gamma rays?
- ✪ How are they emitted?
- ✪ How can we detect them?
- ✪ What are the major results?

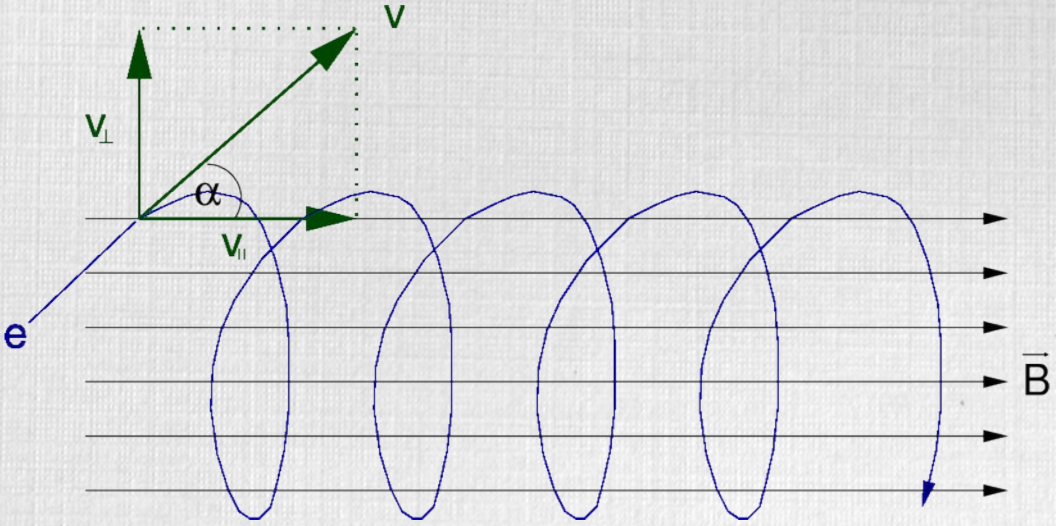
Gamma Rays



- gamma rays:
  - E > 100 keV
  - high energy (HE) gamma rays: 100 MeV ... 100 GeV
  - very-high-energy (VHE) gamma rays 100 GeV ... 100 TeV
- emission mechanisms
  - inverse Compton scattering
  - pion production and decay

Synchrotron Radiation

- charged particles spiral around magnetic field lines
- energy loss
  → photon emission
- energy E_{sy} of photon depends on
  - magnetic field B
  - electron energy E_e
- $$E_{sy} = 2\left(\frac{B}{100\,\mu\mathrm{G}}\right)\left(\frac{E}{1\,\mathrm{TeV}}\right)^2 \mathrm{eV}$$



- TeV electrons produce synchrotron radiation in keV
  - X-ray observations

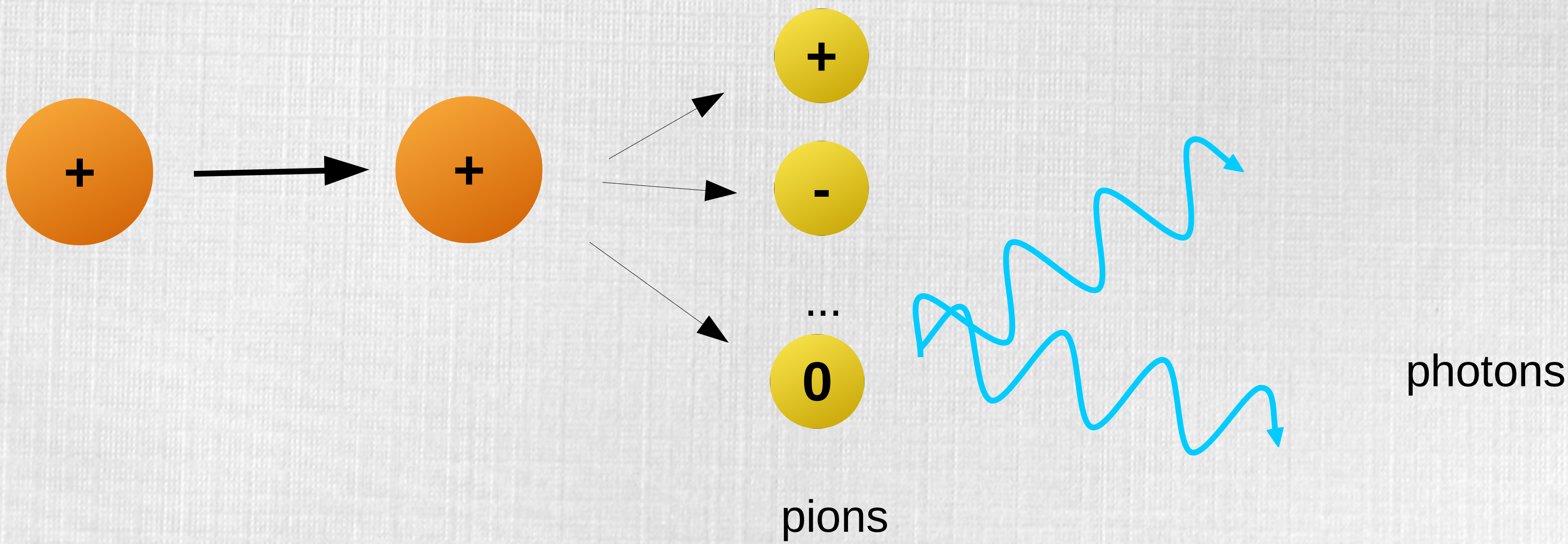
Inverse Compton Scattering

- relativistic electron hits low-energy photon
  - blue-shifting of photon
- energy of IC photon depends on
  - energy of electron
  - energy of photon
    - typically: Cosmic Microwave Background
    - but also: star light, infra-red, ...
- simple case, only CMB:

$$E_{\mathrm{IC,CMB}} = 6 \left(\frac{E}{1\,\mathrm{TeV}} \right)^2 \mathrm{GeV}$$

- TeV electron emits GeV photon → γ-ray observations

Hadronic Emission



- inelastic proton-proton scattering → pion production
  - target density!
- pion decay → photon production
  - $E_{\text{min, photon}} = ½\, m_\pi c^2 = 67.5$ MeV
  - $E_{\text{max, photon}} \approx 0.1\, E_{\text{proton}}$, up to 100 TeV

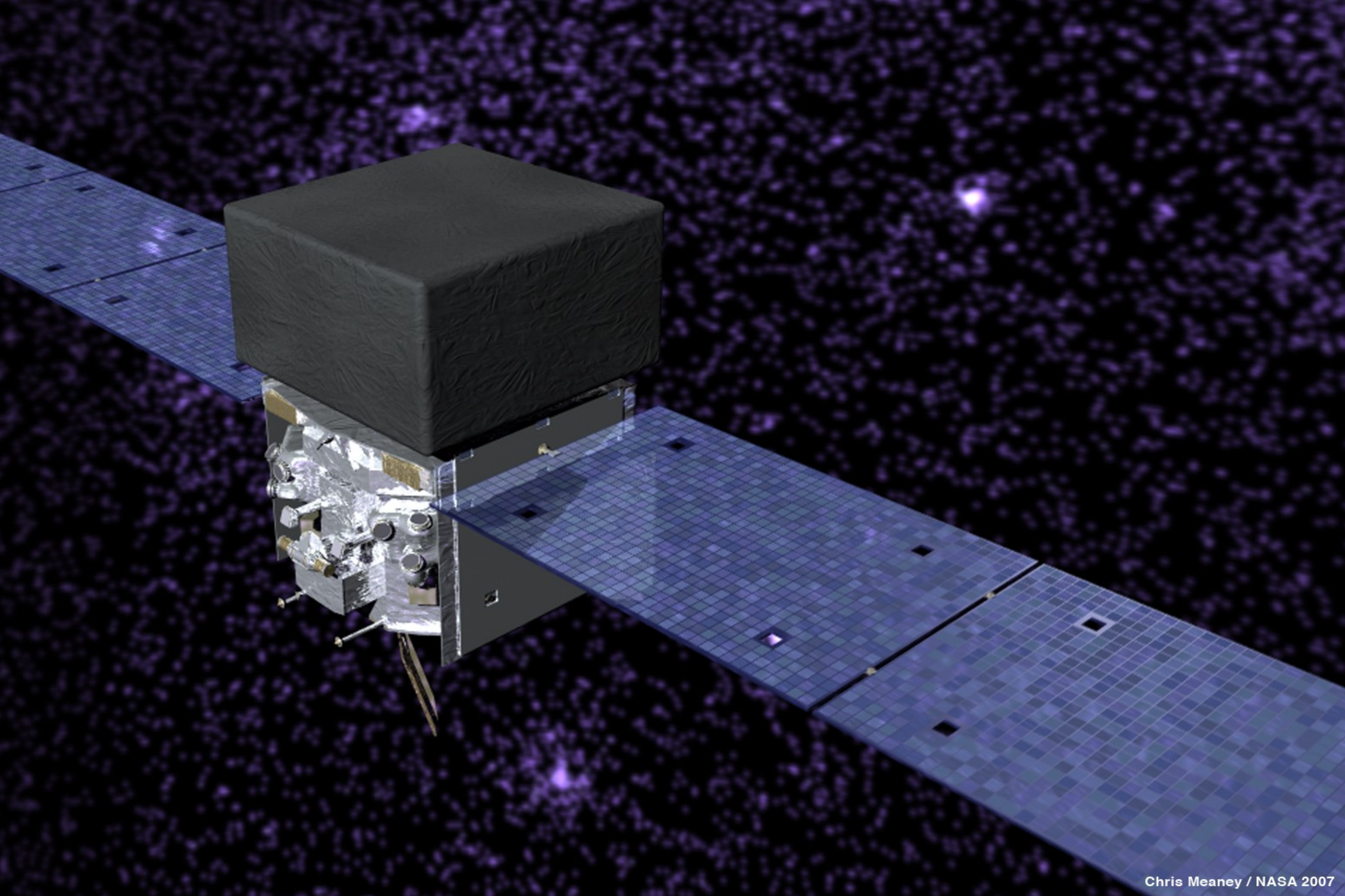
Gamma Ray Detection

- ✪ space based
  - direct detection
  - small effective area
  - high duty cycle
  - full-sky coverage
  - *Fermi*/LAT

- ✪ ground based
  - indirect detection (air showers and Cherenkov light)
  - large effective area
  - small field of view
  - H.E.S.S., Veritas, MAGIC

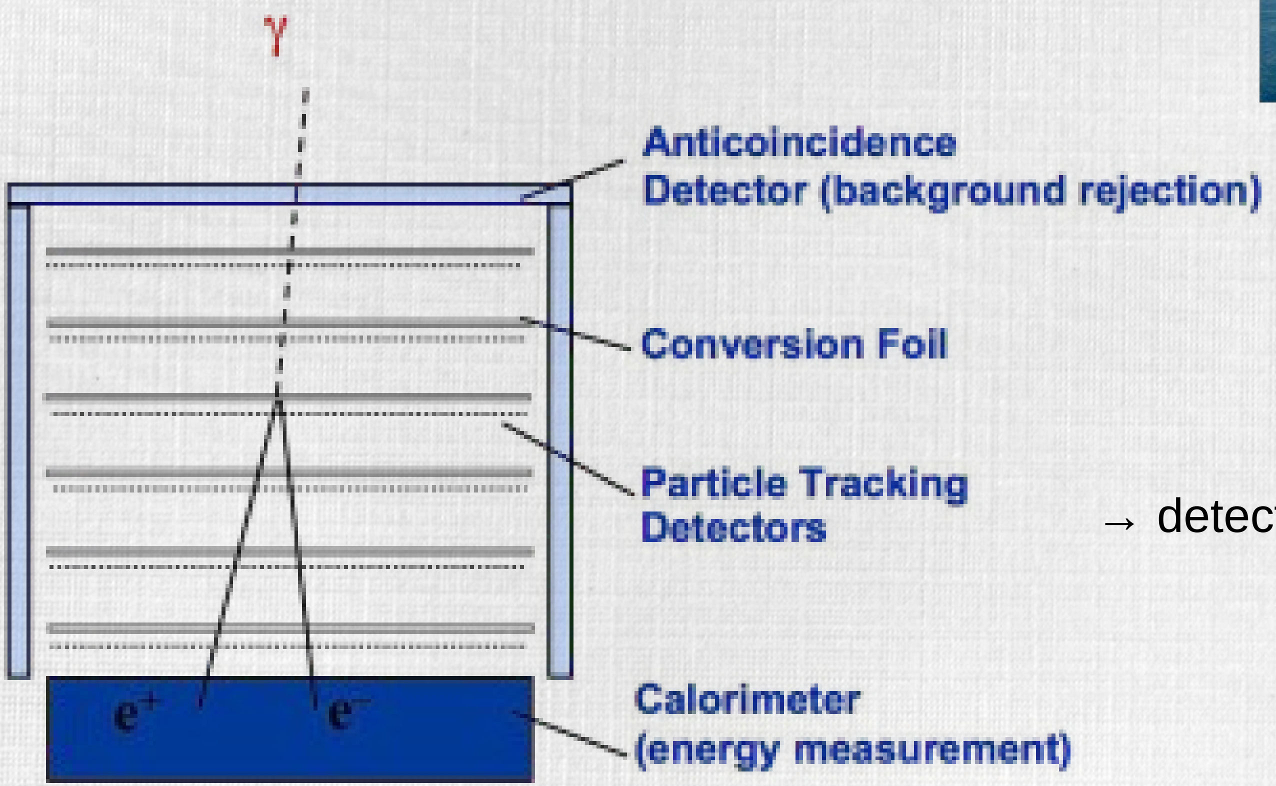
- ✪ ground based
  - indirect detection (air showers)
  - large field of view
  - high duty cycle
  - HAWC

Space Based: Fermi Satellite



The Fermi Large Area Telescope

- ✪ NASA satellite (launched 11/06/2008)
- ✪ Large Area Telescope
  - pair conversion: $\gamma \rightarrow e^- + e^+$
  - silicon strip detector for direction
  - caesium iodide calorimeter for energy



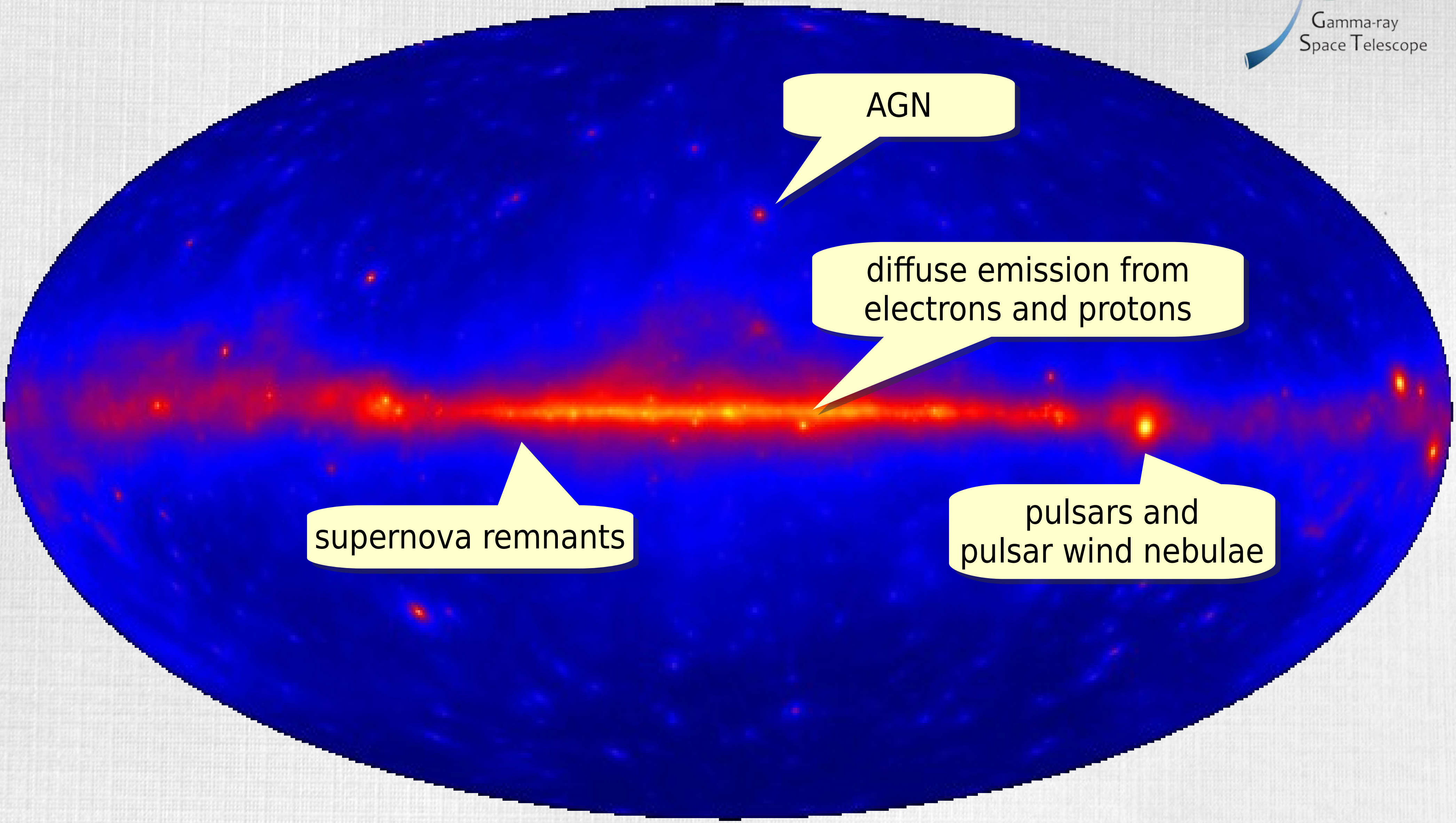
→ detects individual photons!

The Fermi Large Area Telescope

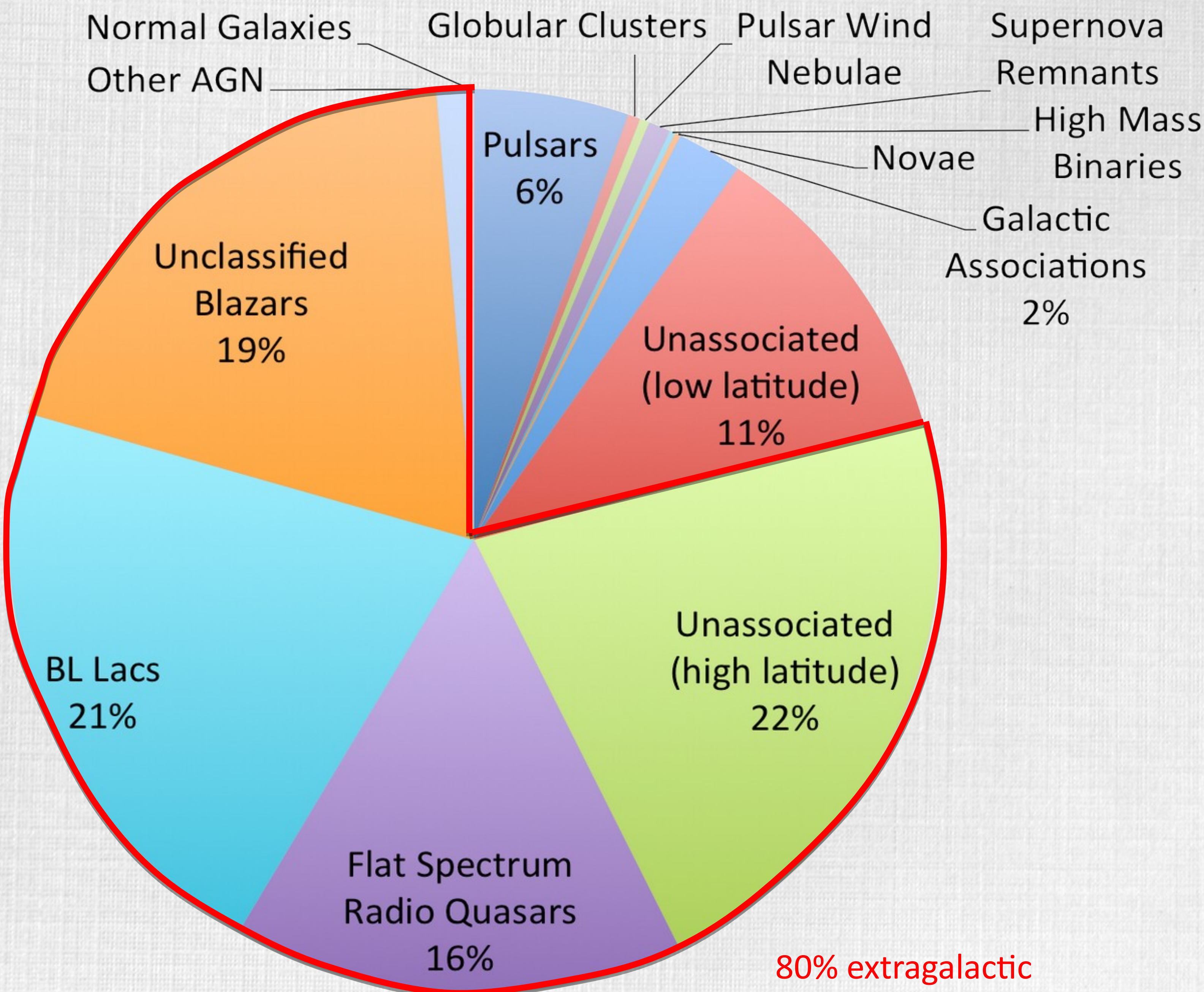
- energy range: 100 MeV ... 500 GeV
- surface ~1 m^2 → sensitivity (4 years) 10^{-9} $cm^{-2}s^{-1}$
- field of view: ~40°
- angular resolution: 0.2° ... 10°
- observation mode: sky survey
  - satellite is orbiting Earth
  - satellite changes orientation
- high duty cycle: 24/7
- operated as observatory
  - data publicly available: http://fermi.gsfc.nasa.gov/cgi-bin/ssc/LAT/LATDataQuery.cgi
- advantages:
  - large FoV + scanning mode = full-sky coverage
  - high duty cycle

The Fermi Large Area Telescope

nearly 7 years of data



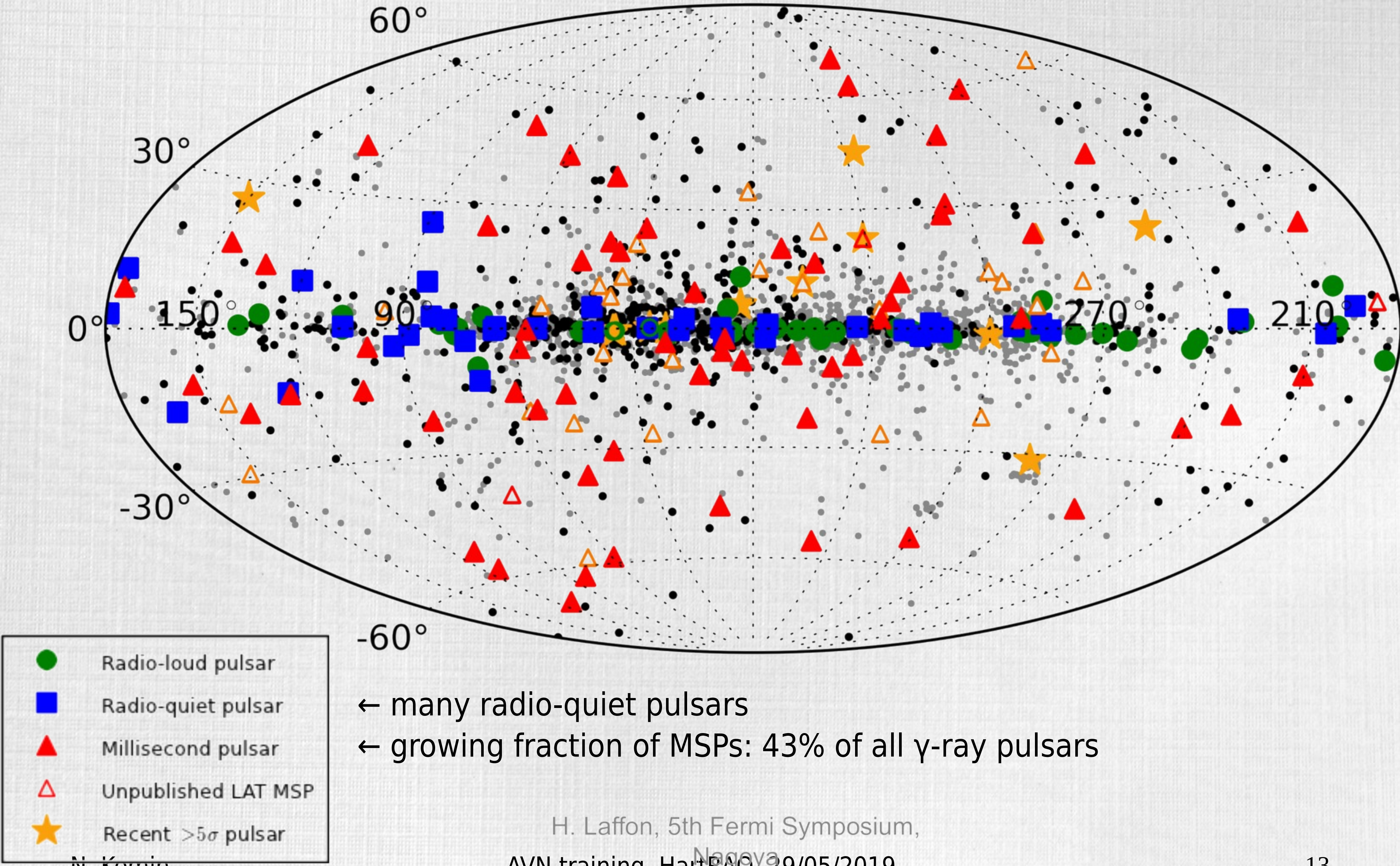
The Fermi Large Area Telescope



>3033 sources
>100 MeV
Based on 3FGL
[E. Hays, ICRC 2015]

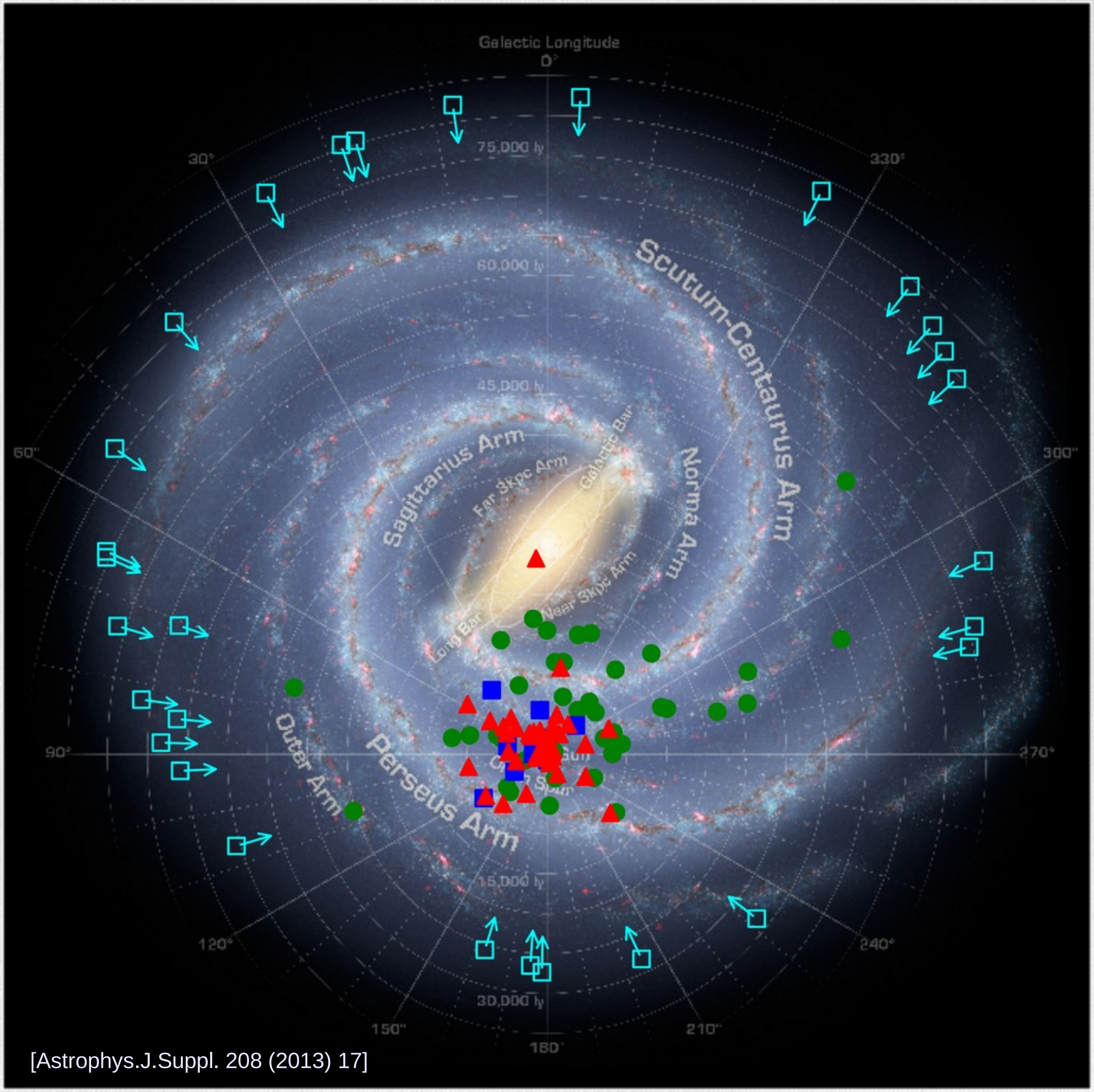
80% extragalactic

Fermi/LAT: Pulsars



← many radio-quiet pulsars
← growing fraction of MSPs: 43% of all γ-ray pulsars

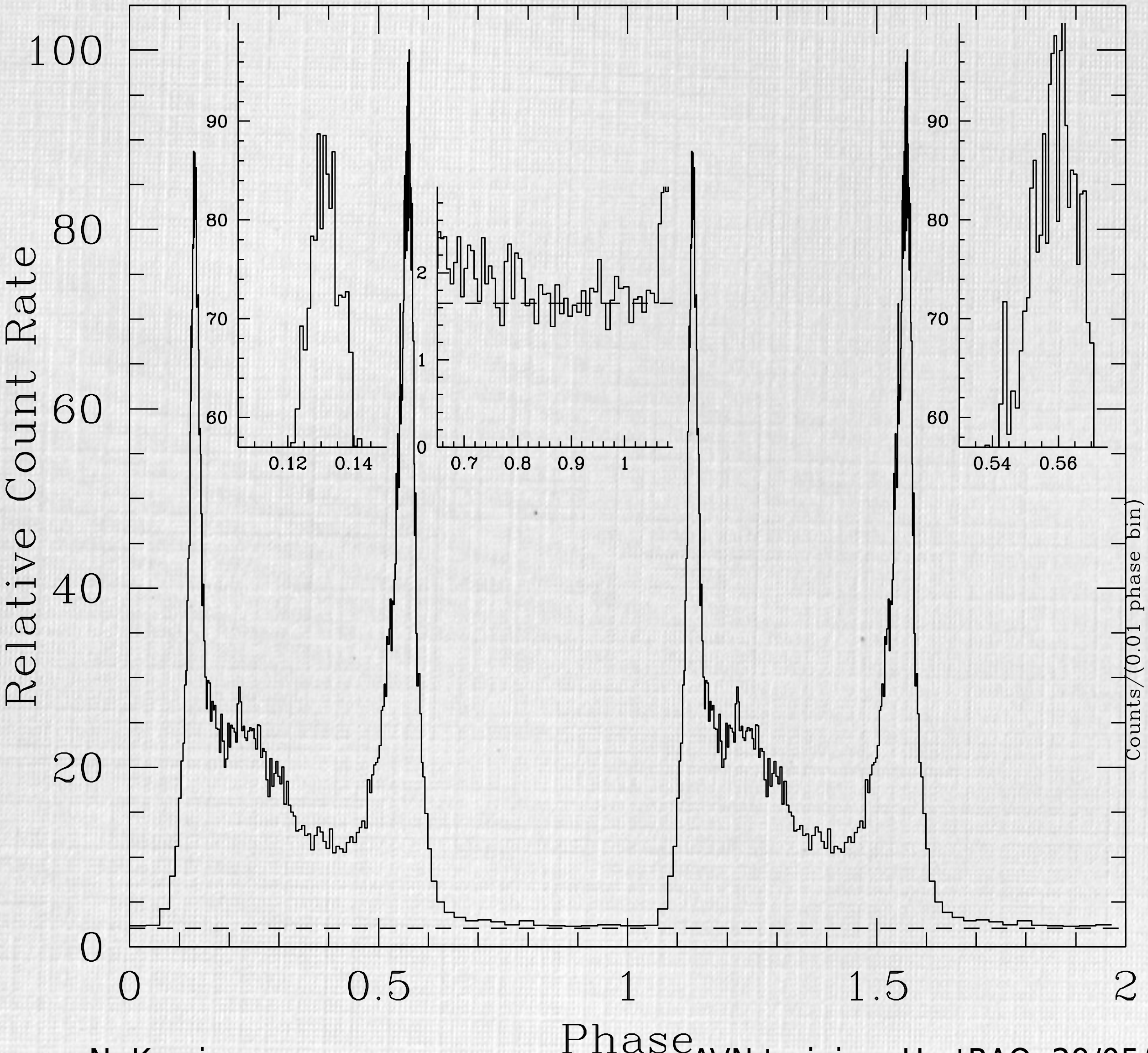
Fermi/LAT: Pulsars

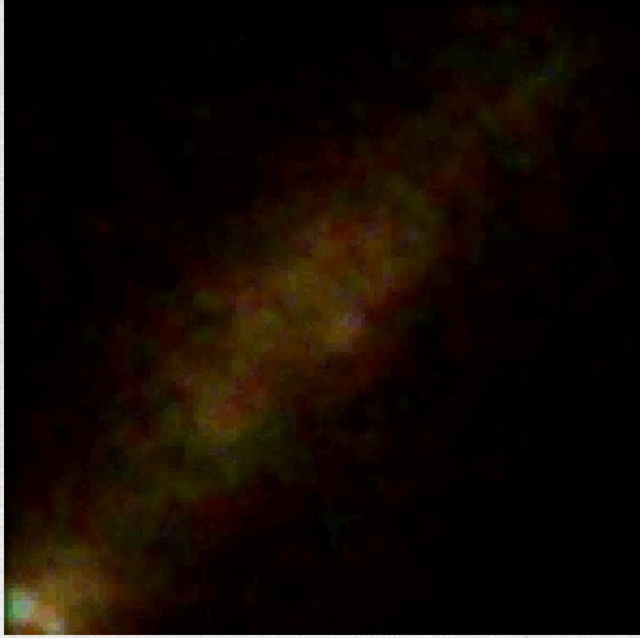


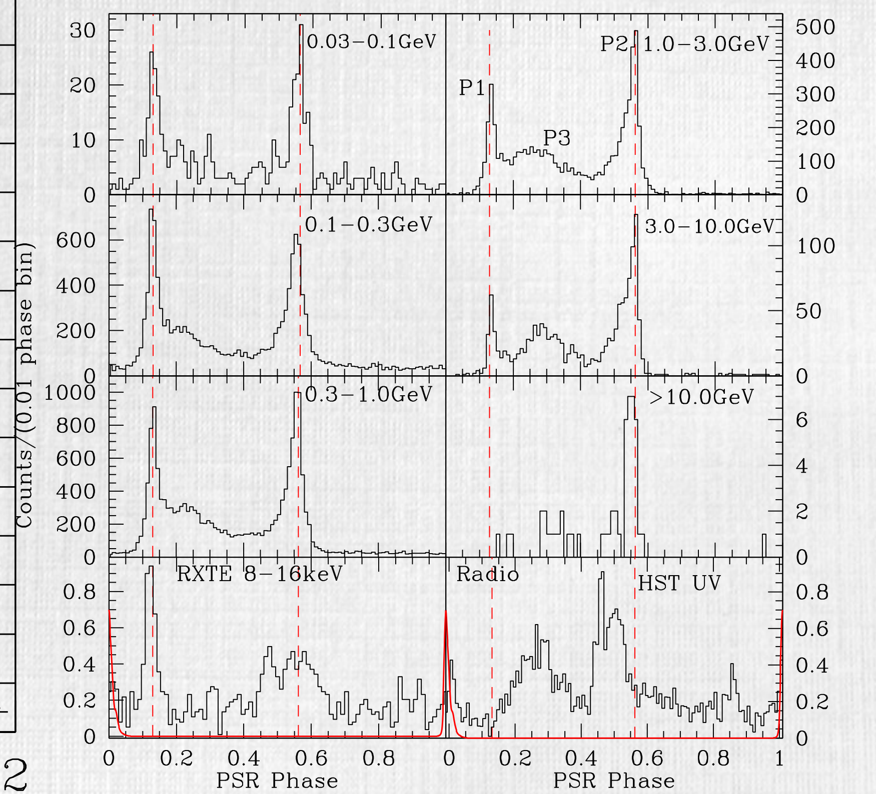
Note:
"Galactic Centre pulsar"
lies above the Galactic plane!

Fermi/LAT: Vela Pulsar

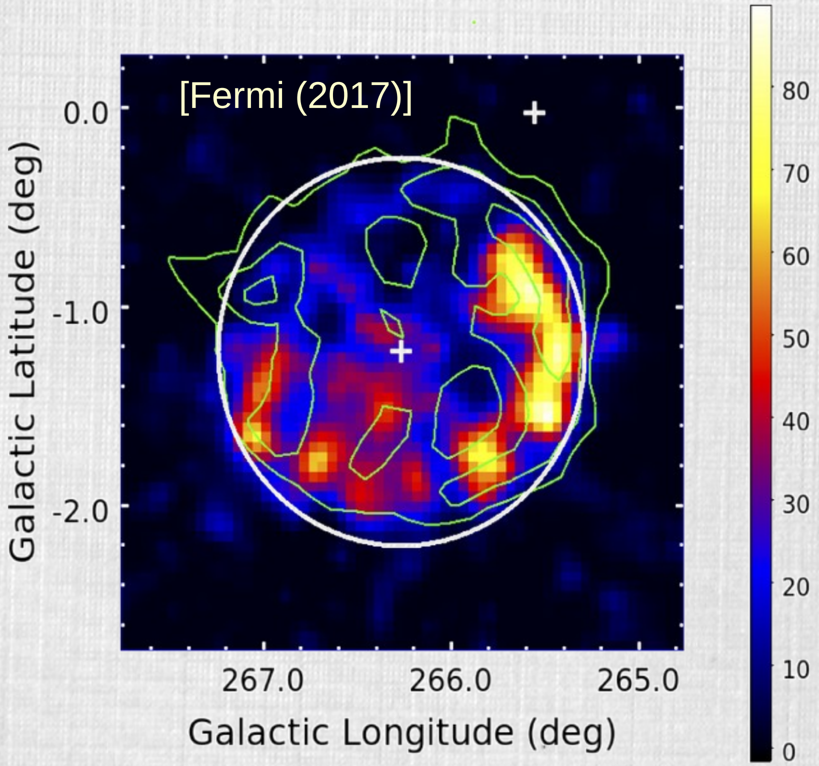
[*ApJ* 696:**1084** (2009)]





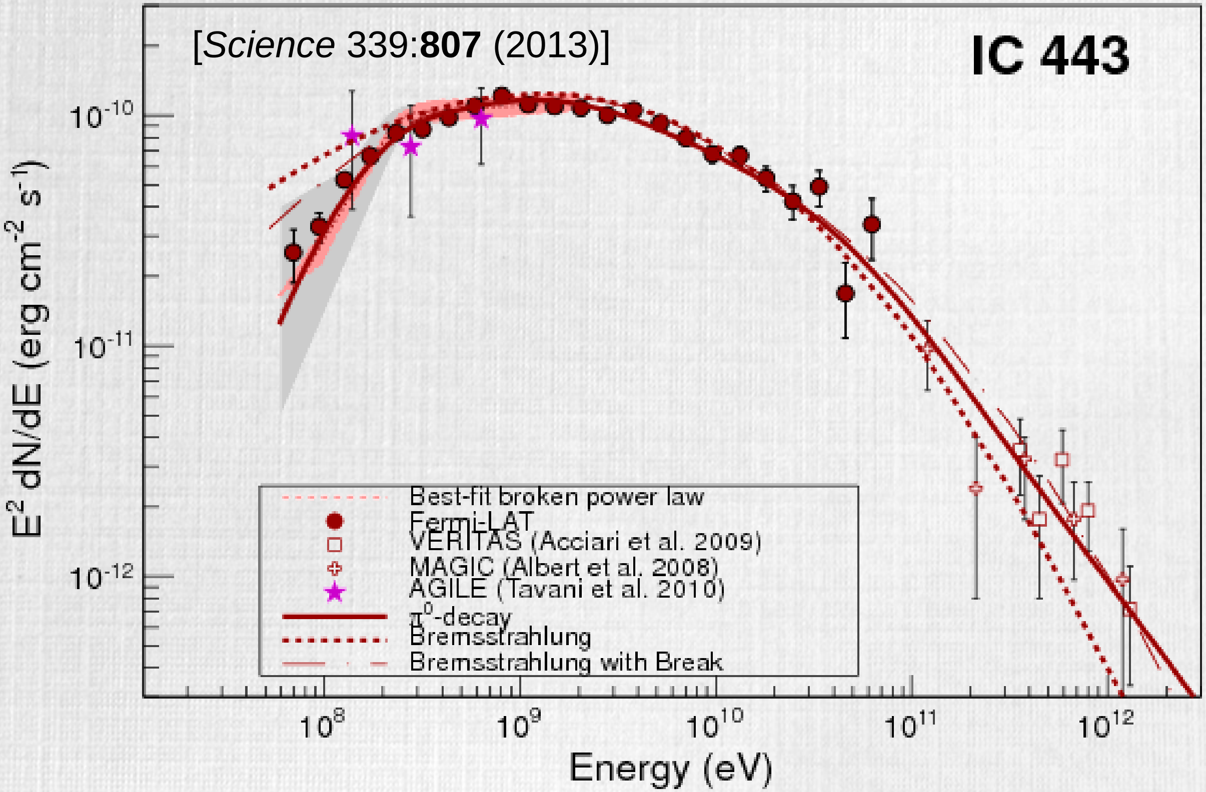


Fermi/LAT: Supernova Remnants

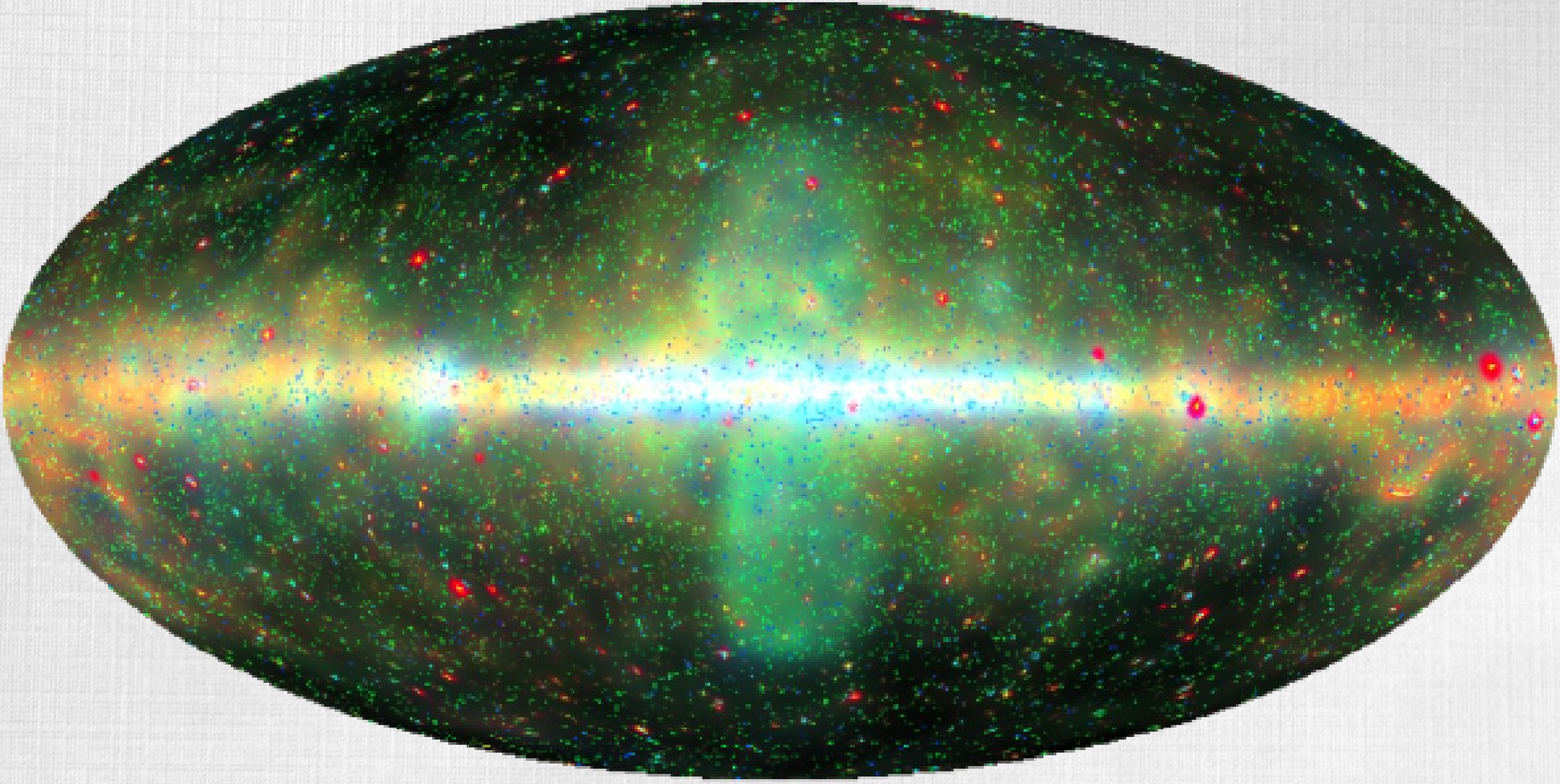


resolve the shells of SNRs

“pion bump”
→ clear indication for proton acceleration

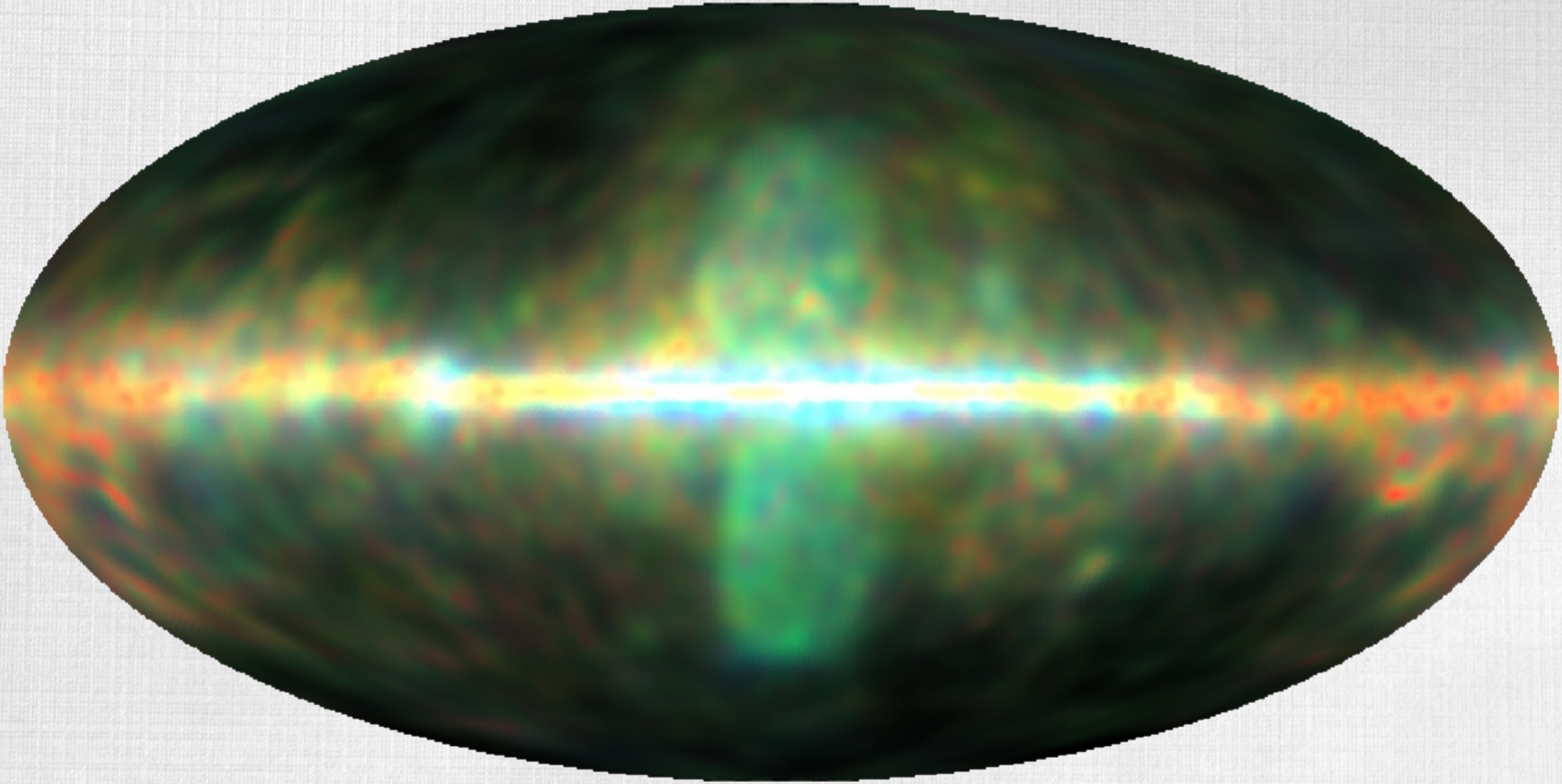


Fermi/LAT: Diffuse Emission



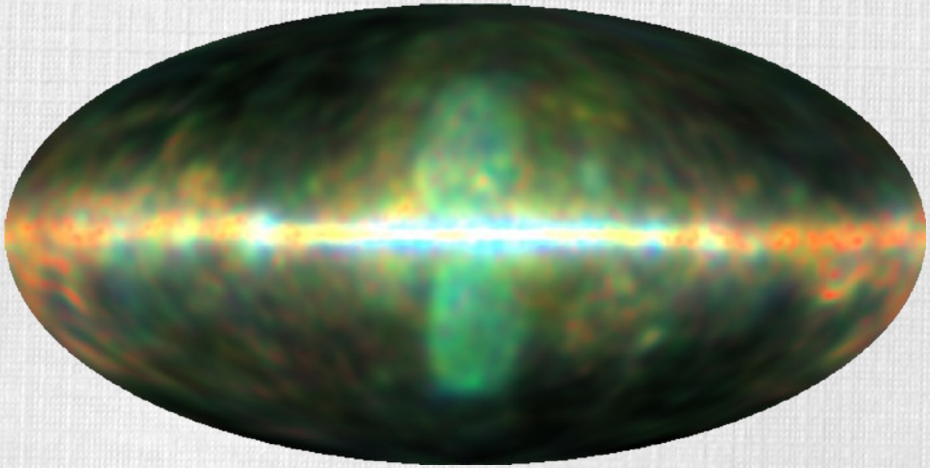
D[3]PO: denoised, deconvolved, decomposed Fermi sky [Selig et *al*. A&A **581:**A126 (2015)]

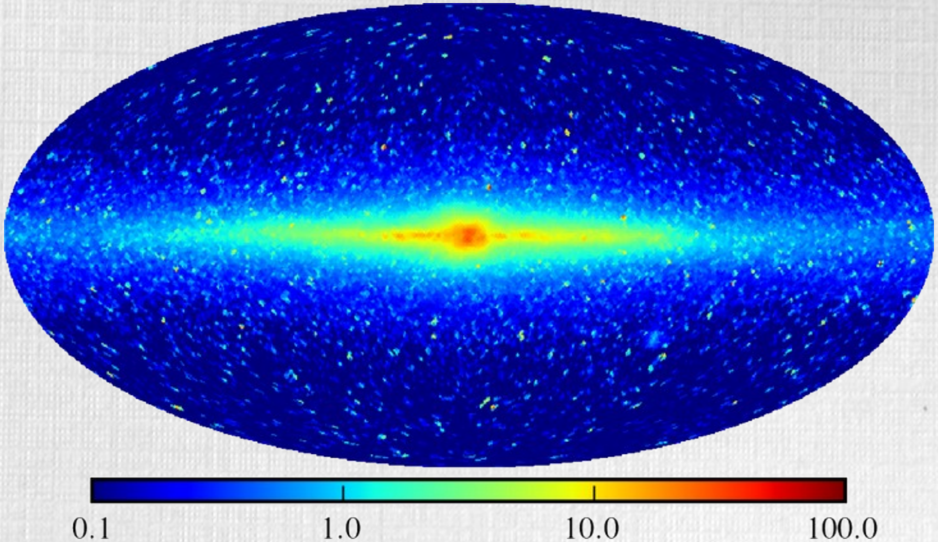
Fermi/LAT: Diffuse Emission



point sources removed → diffuse emission
colour coding: ~1 GeV, ~100 GeV

Fermi/LAT: Diffuse Emission

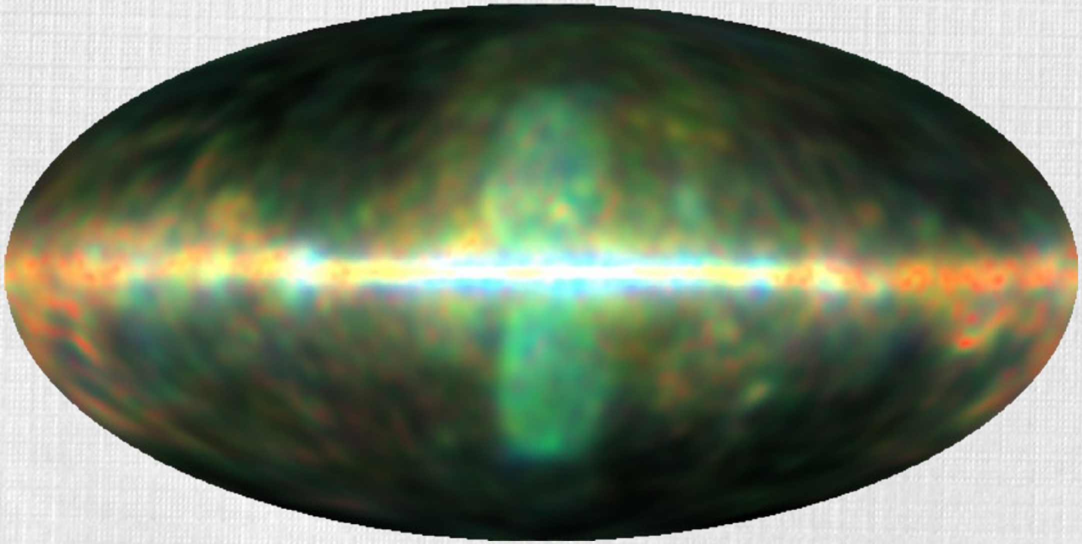


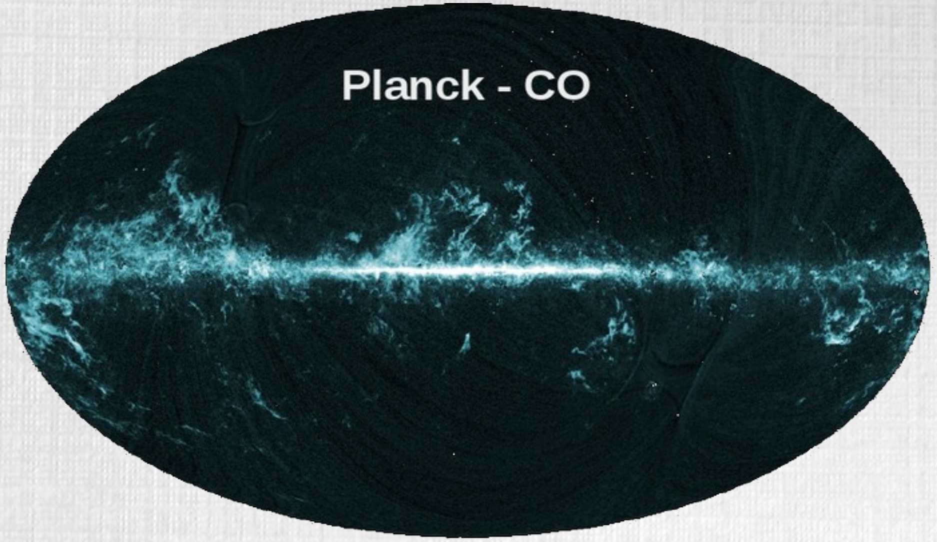


IR emission, 2.2 µm, from Porter (ICRC 2015)

- inverse Compton emission
- traces
  - electron distribution
  - photon distribution

Fermi/LAT: Diffuse Emission

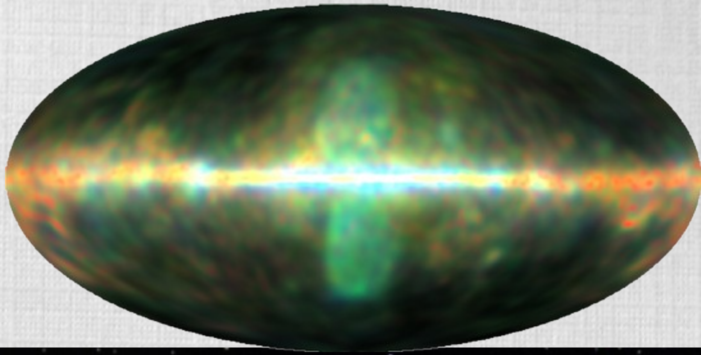


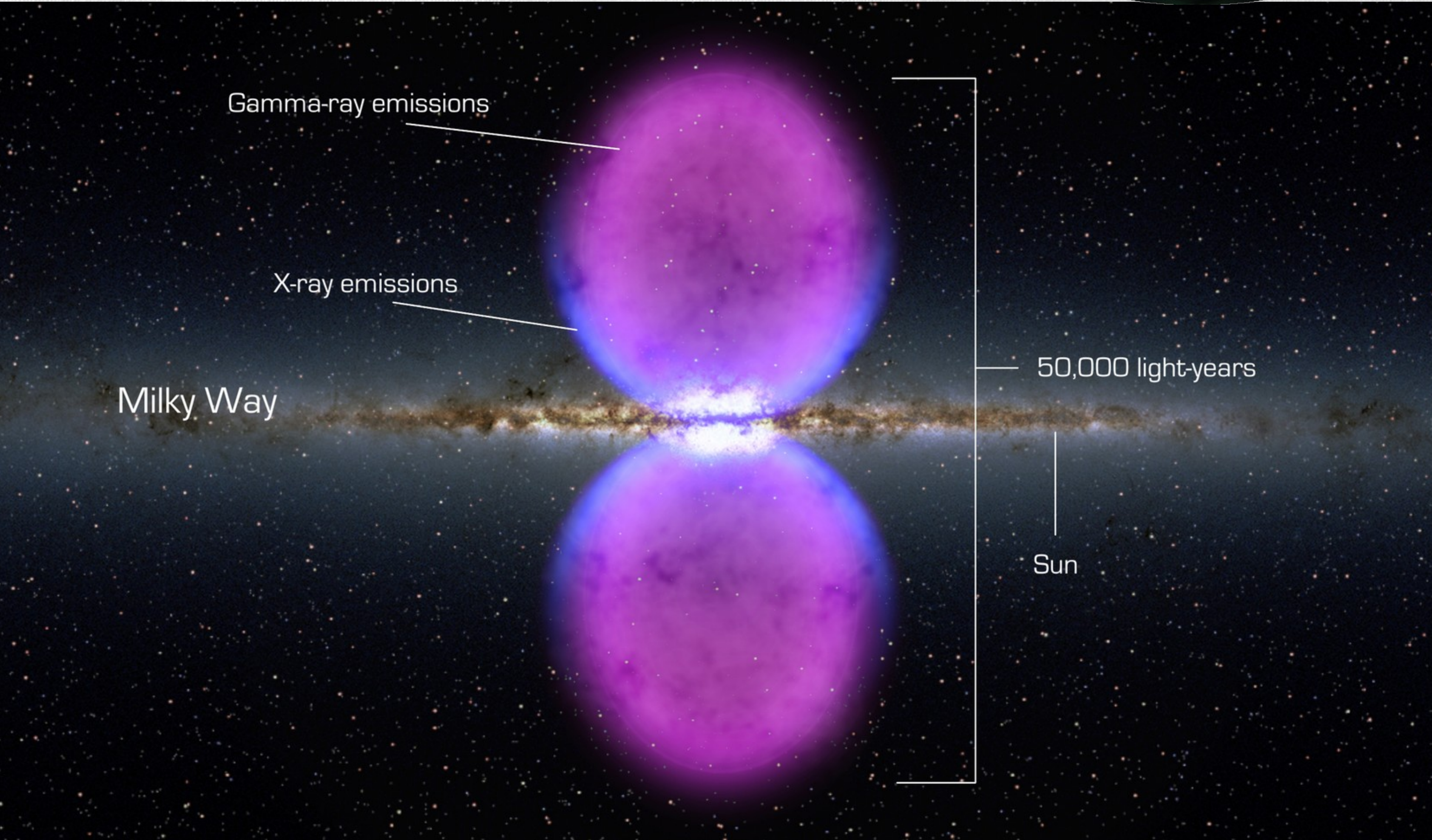


- ✪ bremsstrahlung and pion production
- ✪ traces
  - cosmic-ray protons
  - matter distribution in Milky Way

The Fermi Bubbles

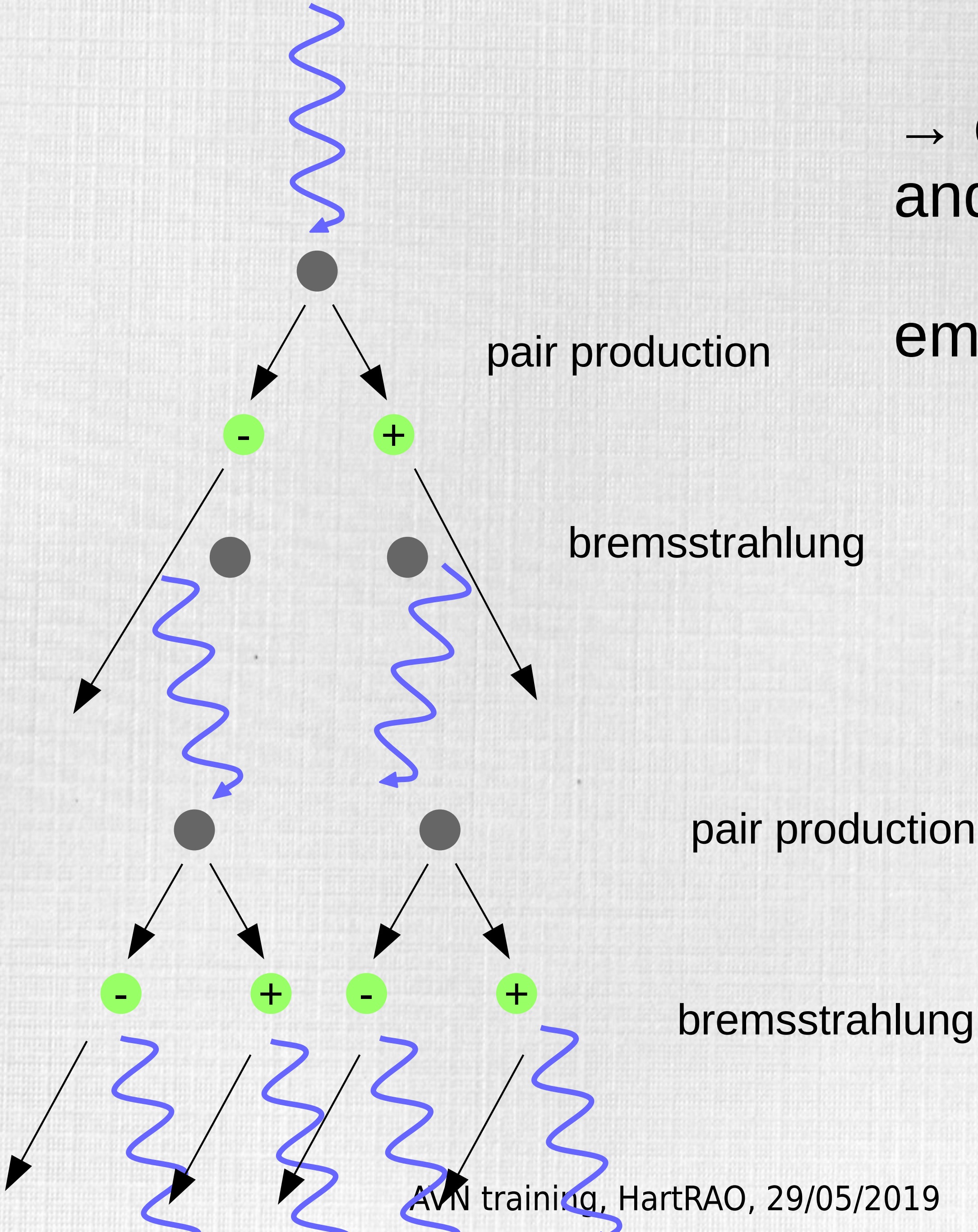
outflow from Milky Way
electrons? protons? source is still unknown





Imaging Air Cherenkov Telescopes

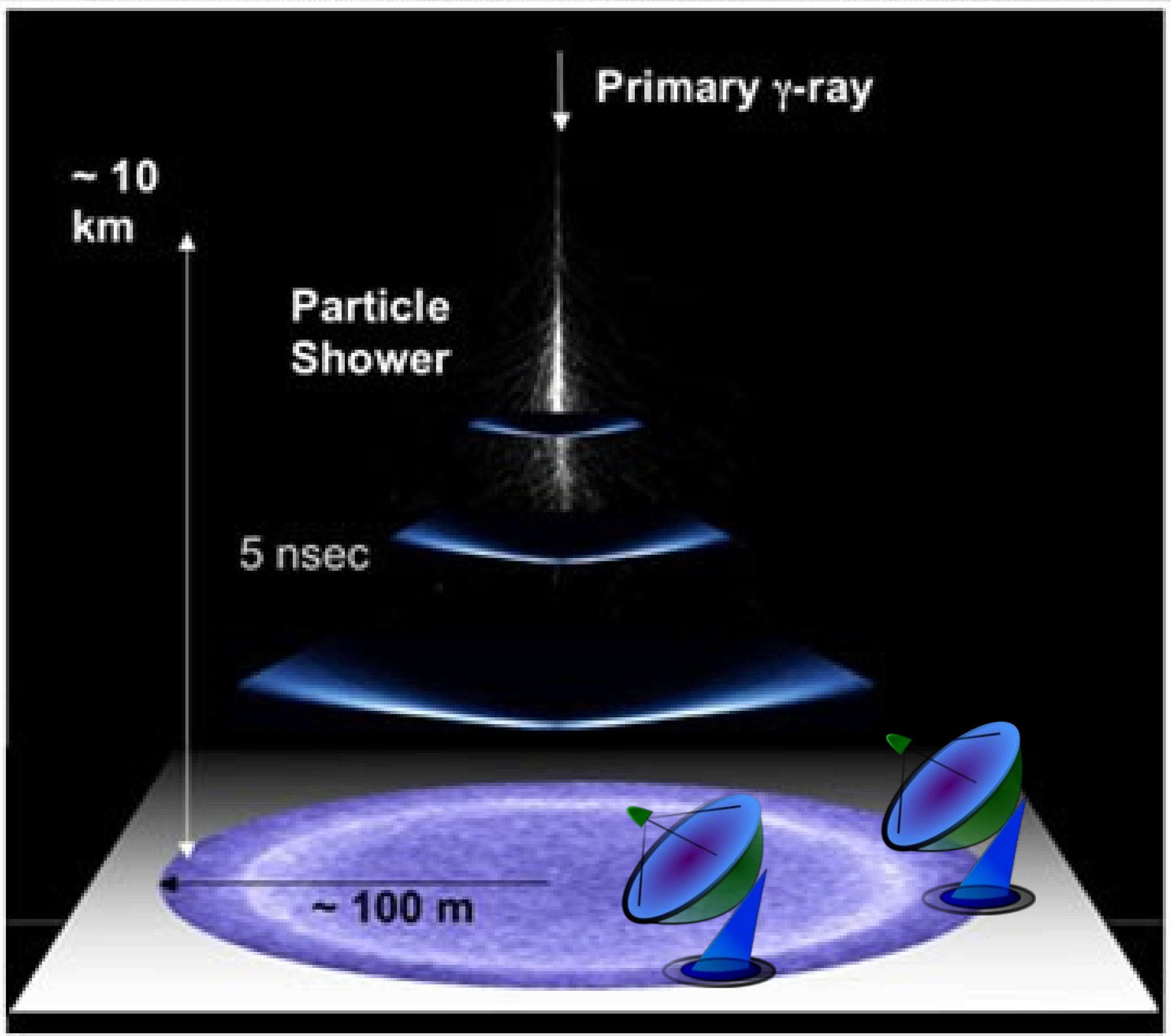
Electromagnetic Air Shower



→ cascade of photons and electrons/positrons

emit Cherenkov light

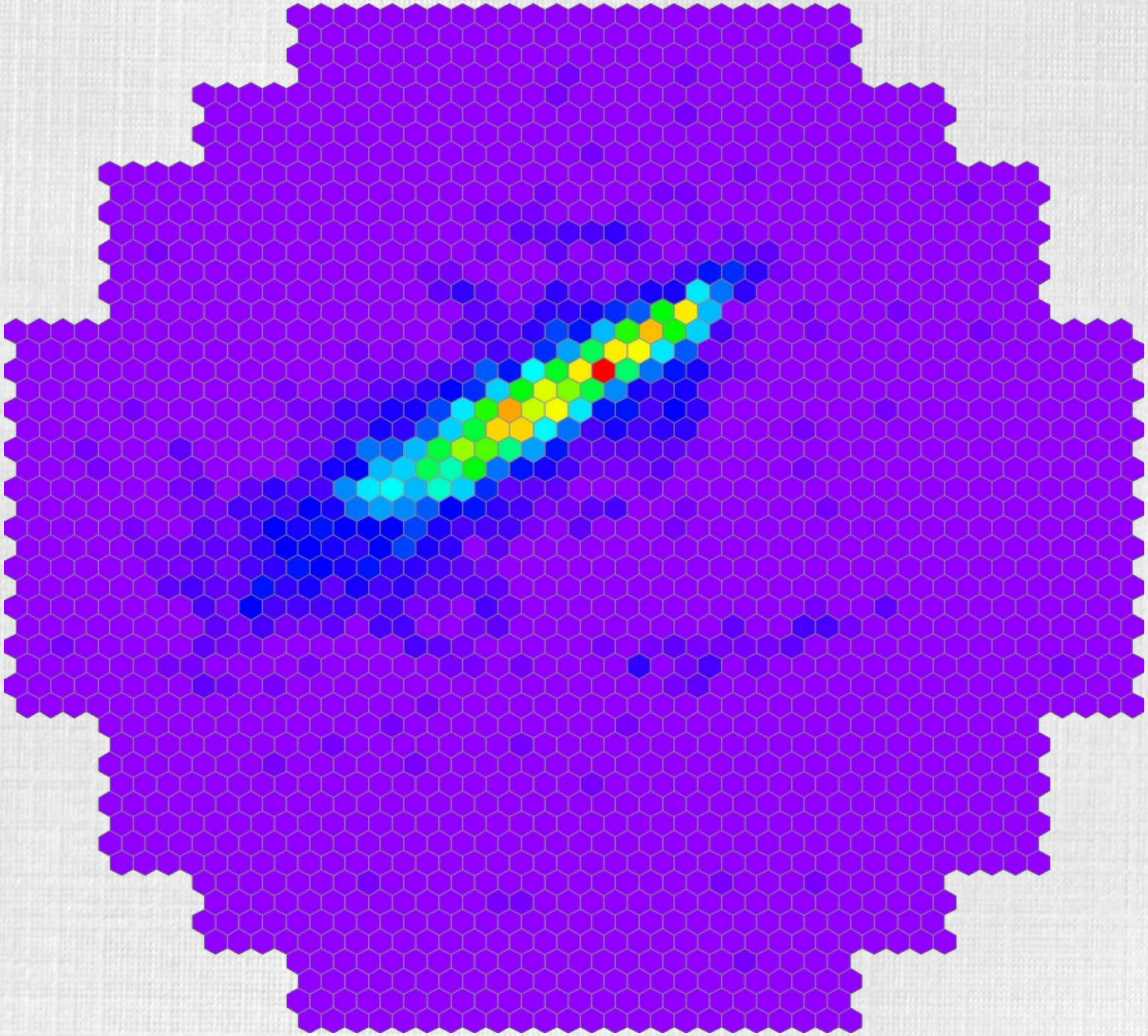
Cherenkov Emission of Air Shower

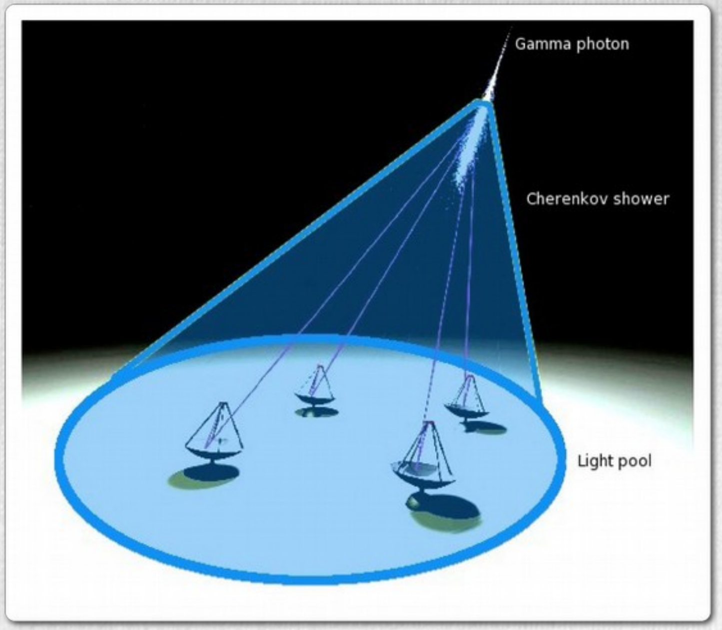


→ detects individual photons!

Imaging Air Cherenkov Technique

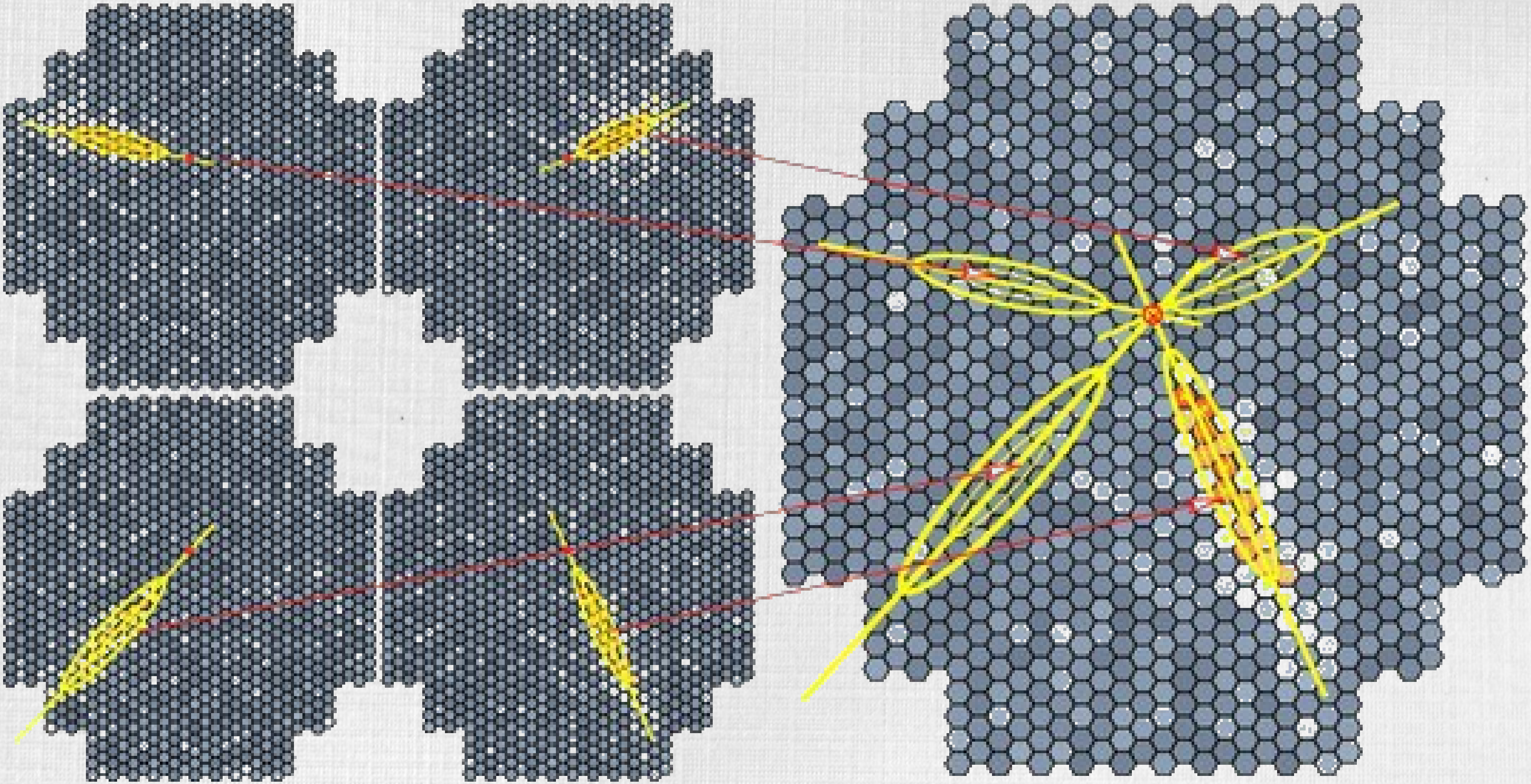
- ✪ short light flashes in camera





Imaging Air Cherenkov Technique

stereoscopic reconstruction of shower axis



Imaging Air Cherenkov Telescopes

H.E.S.S.

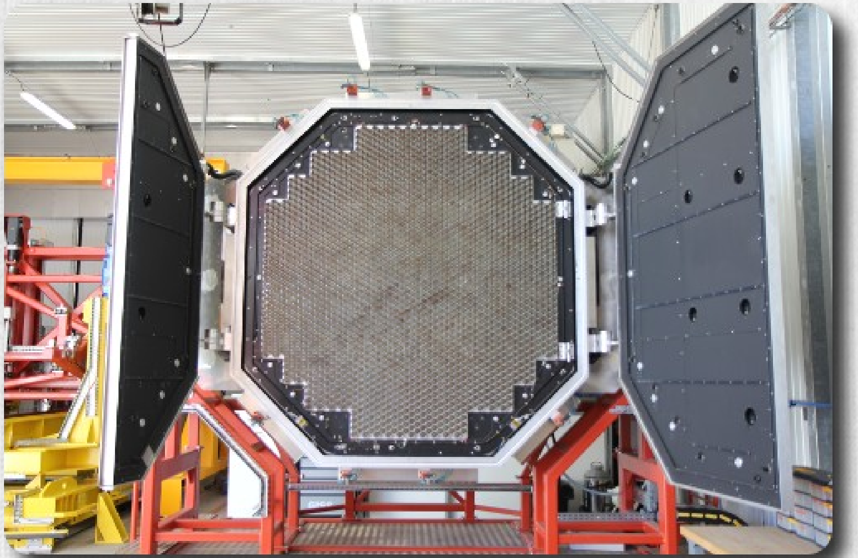
- **H**igh **E**nergy **S**tereoscopic **S**ystem
- location Nambia
  - Khomas highland, 100 km from Windhoek
- operational since
  - 2004 (4 telescopes)
  - 2013 (5 telescopes)

H.E.S.S. CT1 – 4

- 12 m diameter
- mirror
  - 382 mirror facets
  - focal length 15 m
  - 108 m^2
- camera:
  - field of view 5°
  - 960 photo multipliers

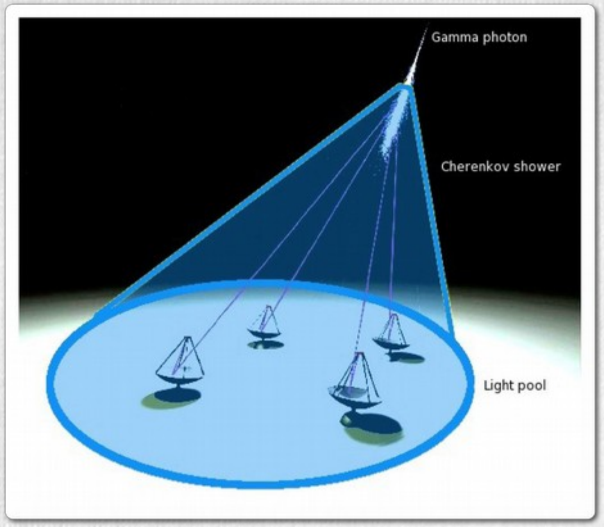
H.E.S.S. CT5

- ✪ 28 m diameter
- ✪ mirror
  - 875 mirror facets
  - focal length 36 m
  - 614 m^2 area
- ✪ camera
  - field of view 3.2°
  - 2048 photo-multipliers



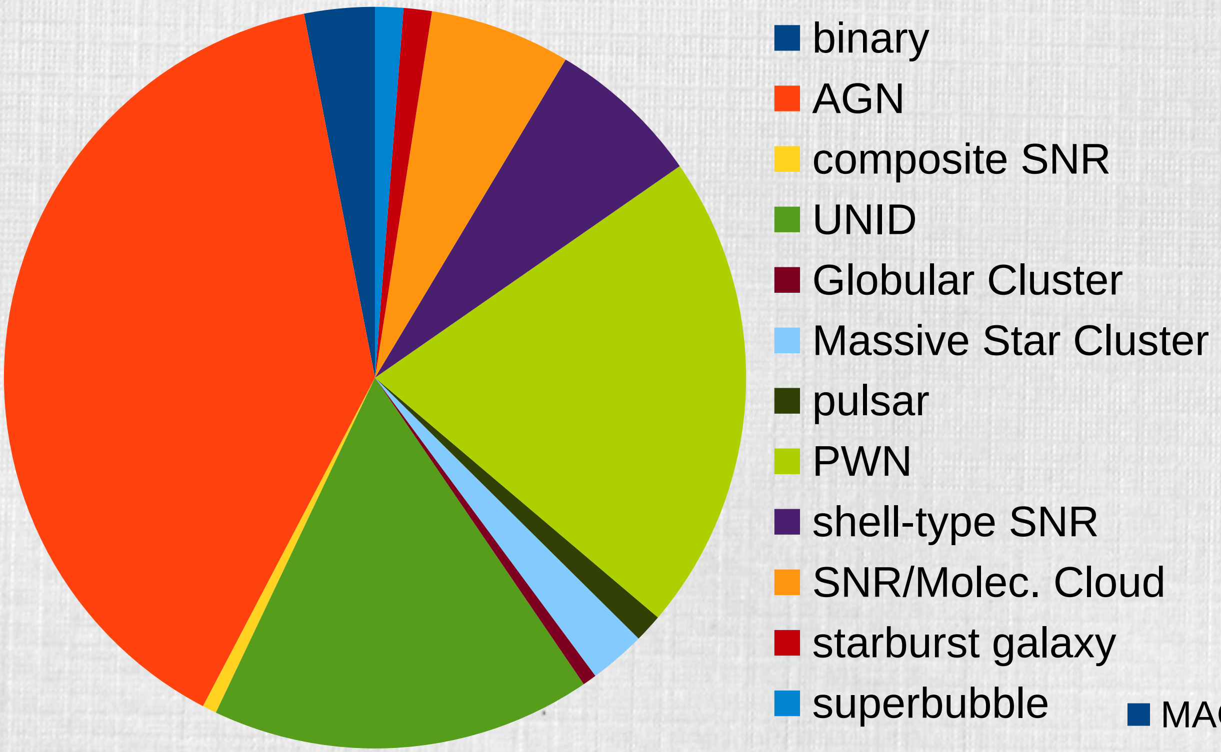
Imaging Air Cherenkov Technique

- observation of Cherenkov light of air showers
- energy range: 50 GeV ... several 10 TeV
- sensitive area: ~10 000 m^2
  → sensitivity 10^{-13} $cm^{-2}s^{-1}$ in 25 h
- small field of view: several degrees
- low duty cycle
  - clear, moonless nights
  - ~1000 h per year
- good angular resolution: 0.05° ... 0.1°
- advantages:
  - large effective area, good angular resolution



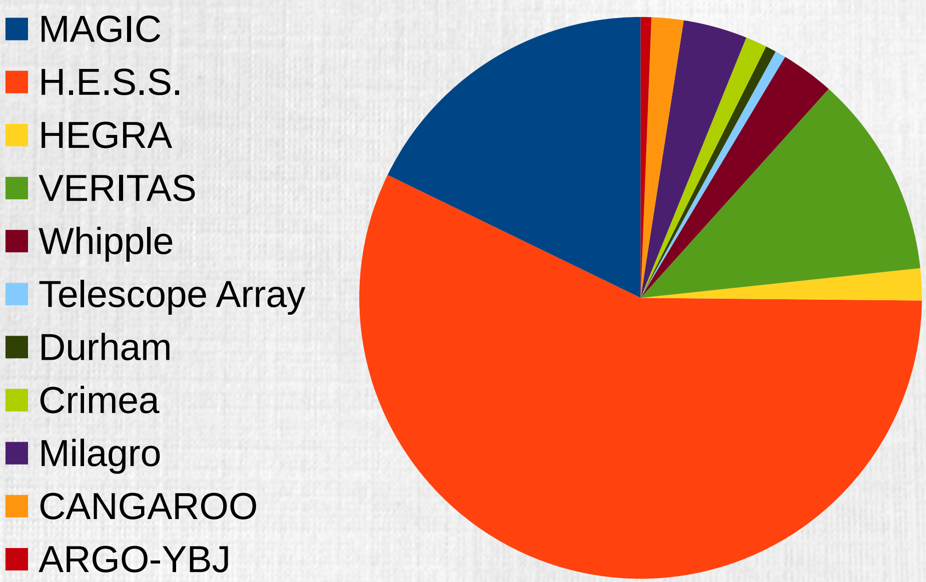
tevcat.uchicago.edu

TeV Catalogue

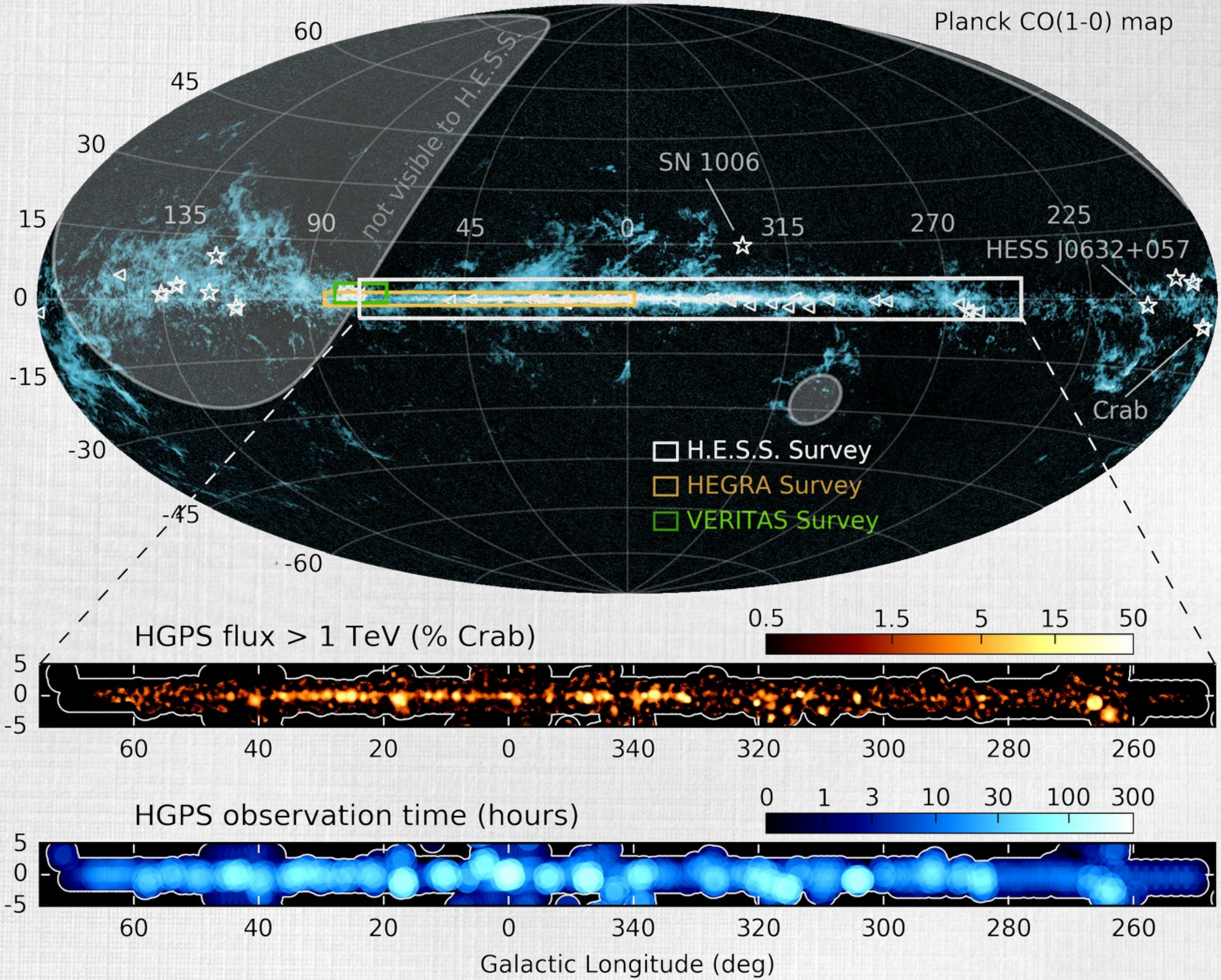


163 sources

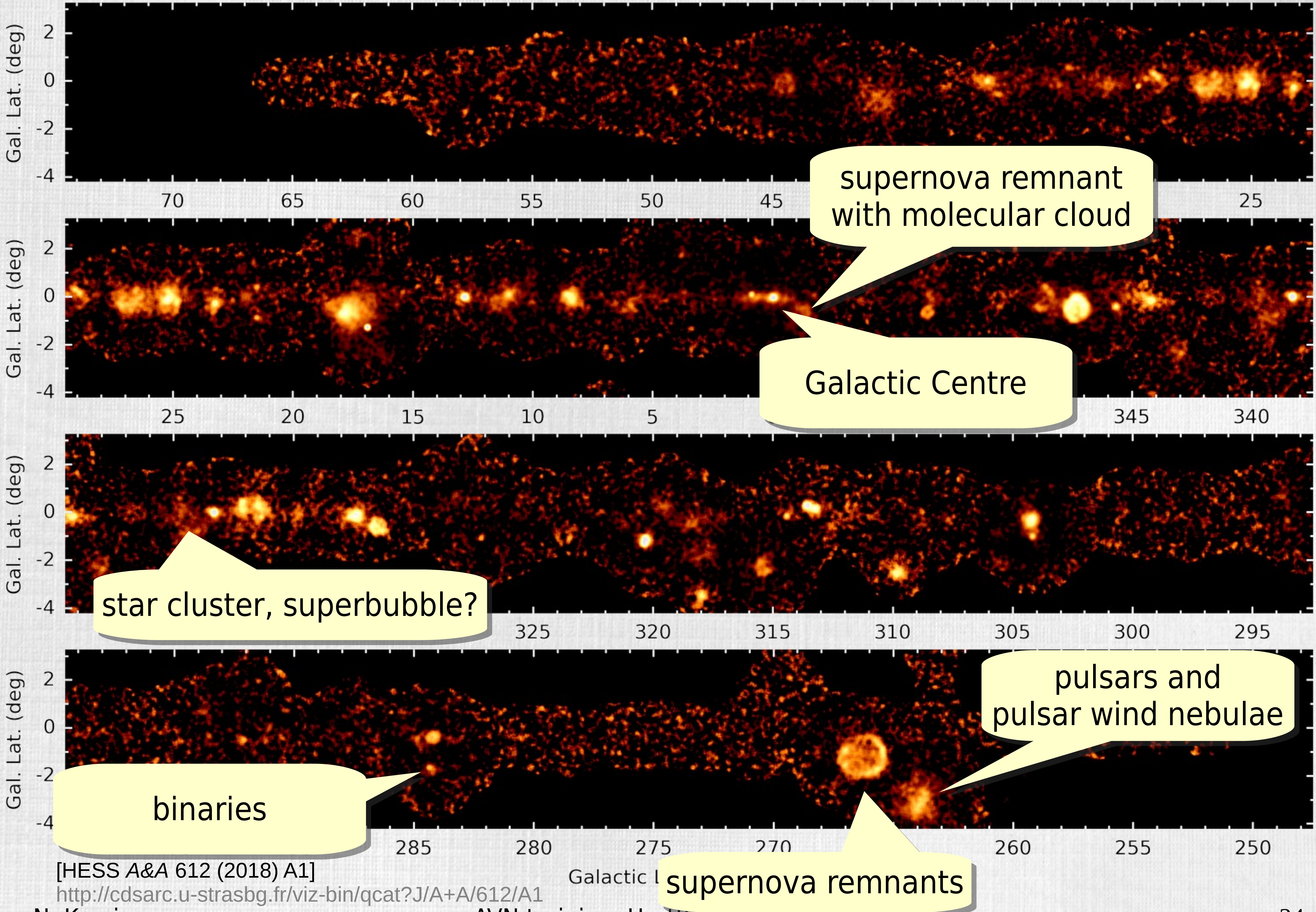
mainly galactic sources!



H.E.S.S. Results: Galactic Plane

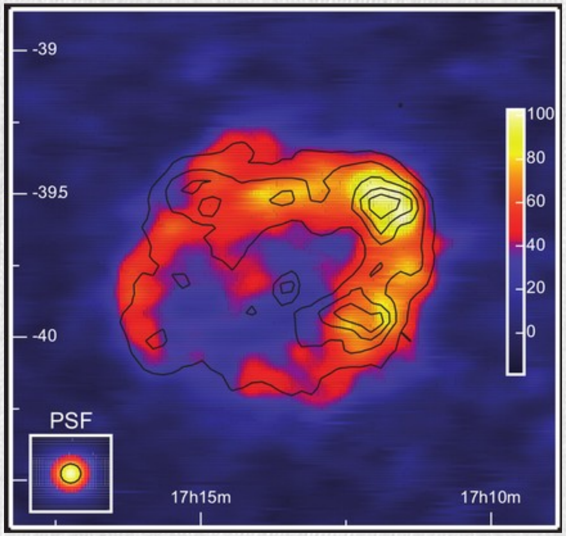


H.E.S.S. Results: Galactic Plane

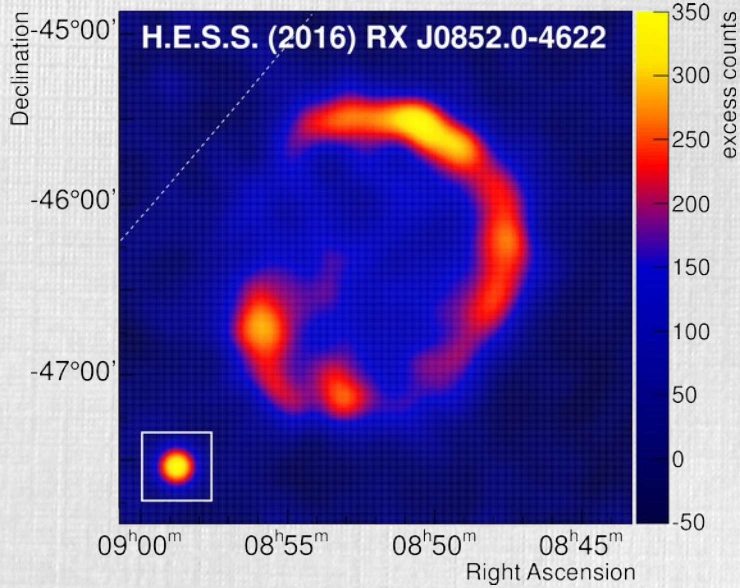


[HESS *A&A* 612 (2018) A1]
http://cdsarc.u-strasbg.fr/viz-bin/qcat?J/A+A/612/A1

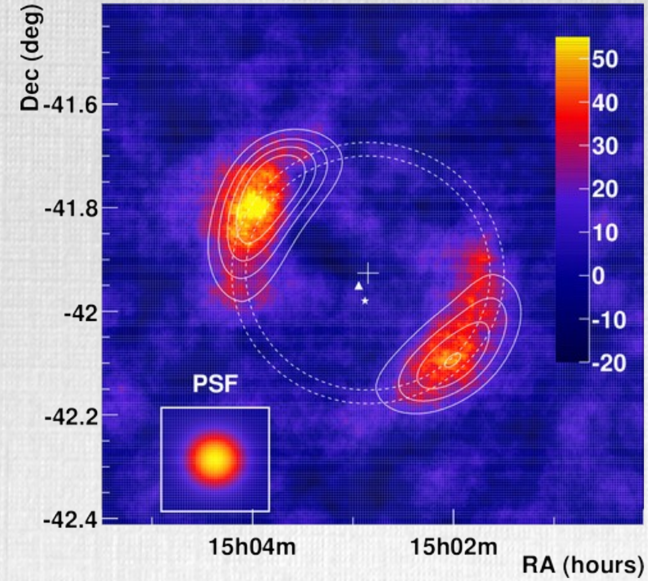
Gamma-Ray Shells seen with H.E.S.S.



RX J1713.7–3964 (Ø 1.2°)

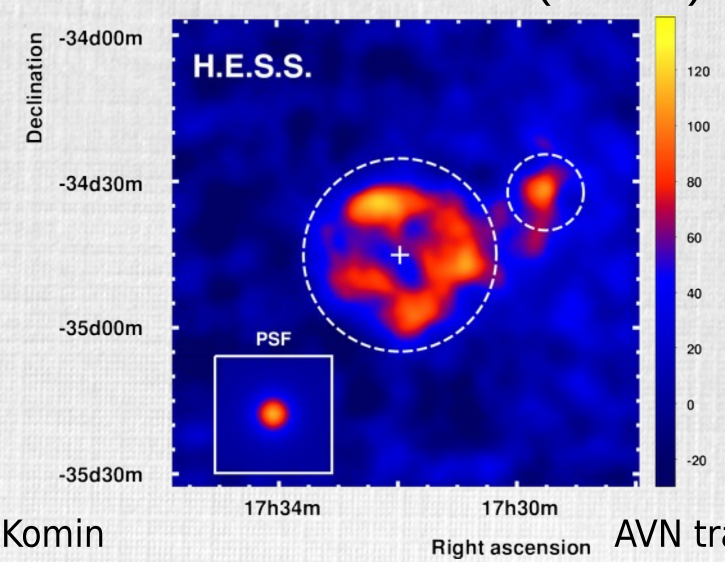


Vela Junior (Ø 2°)

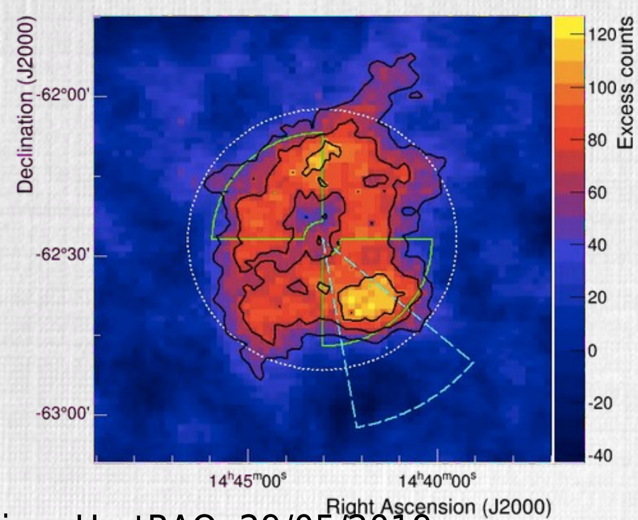


SN 1006 (Ø 0.5°)

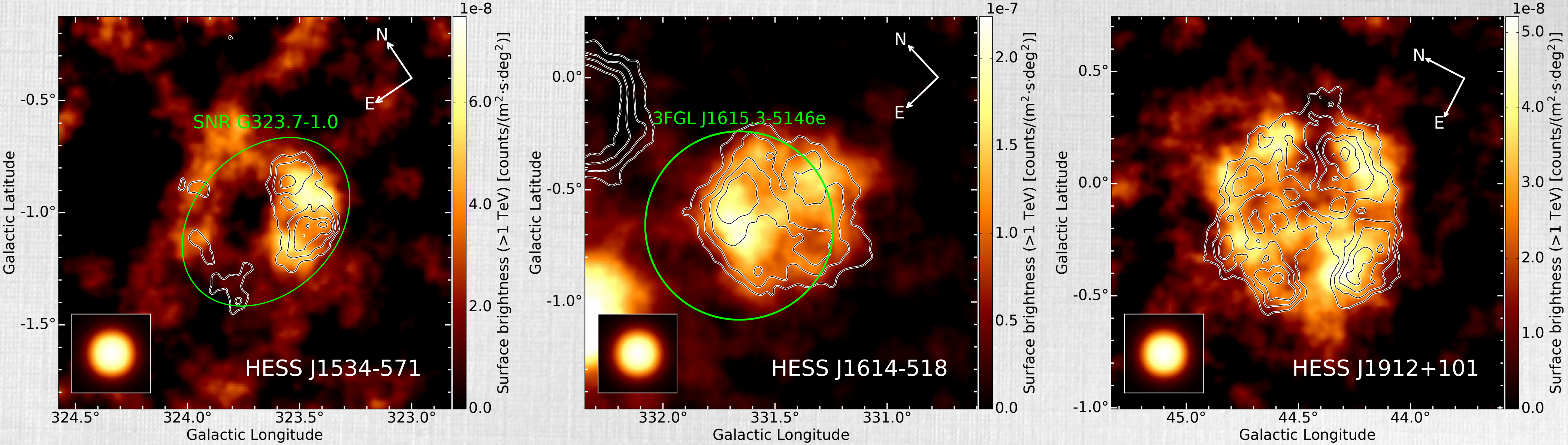
HESS J1731–347 (Ø 0.5°)



RCW 86 (Ø 0.9°)



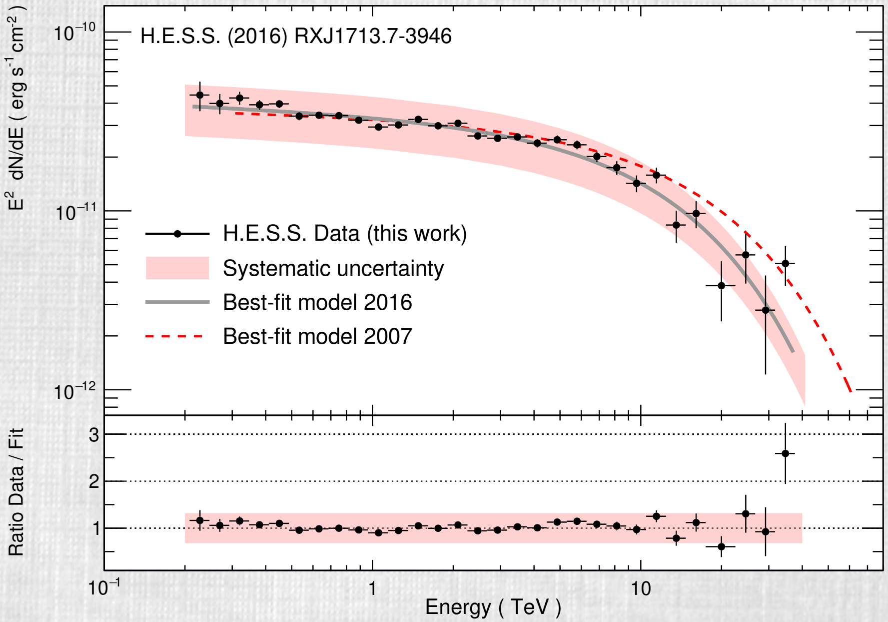
Three New TeV Shells

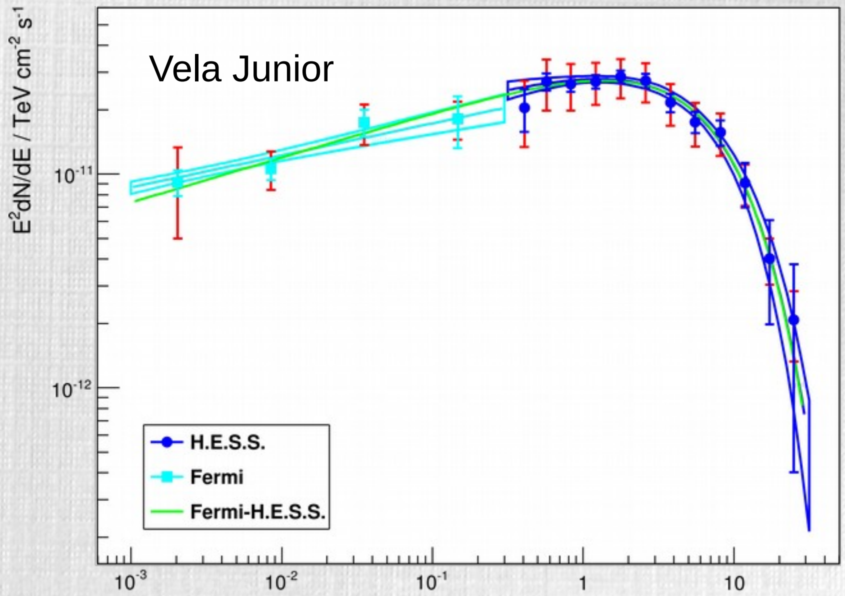


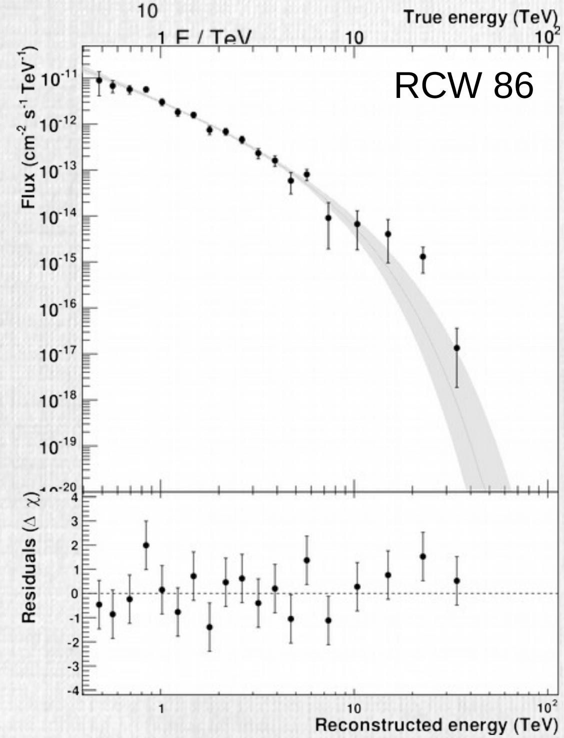
[HESS *A&A* 612 (2108) A8]

- systematic search for shells in H.E.S.S. Galactic Plane Survey
  - test for shell-like morphology
- HESS J1534-571: clear association with radio SNR
- two additional candidates
  - one with Fermi counter-part

High-Energy Cut-Off



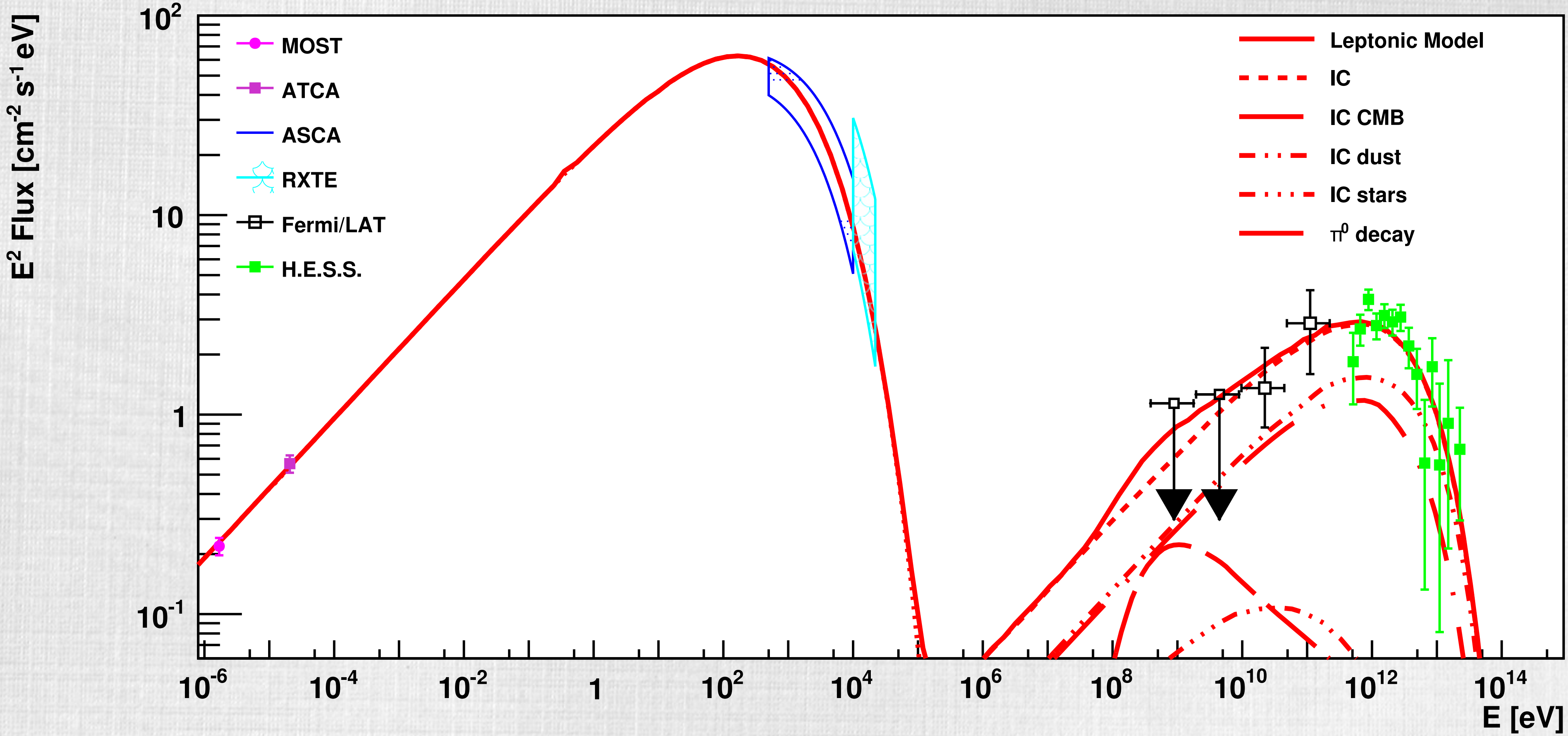




- ✪ clear detection of cut-offs (spectral indices 1.6 … 1.8)
  - RX J1713.7–3964
    - 12.9 ± 1.1 TeV
    - [HESS *A&A* 612 (2018) A6]
  - Vela Junior
    - 6.7 ± 1.2 TeV
    - [HESS *A&A* 612 (2018) A7]
  - RCW 86
    - 3.5 ± 1.2 TeV
    - [HESS *A&A* 612 (2018) A4]

Implications

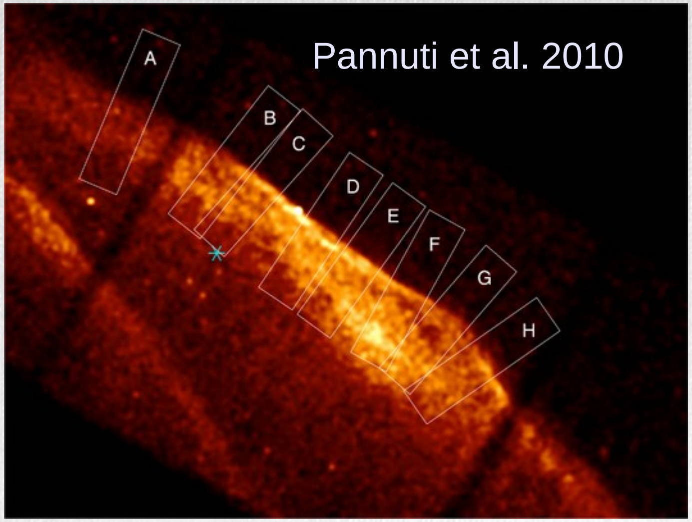
example: RCW 86 [HESS *A&A* 612 (2018) A4]

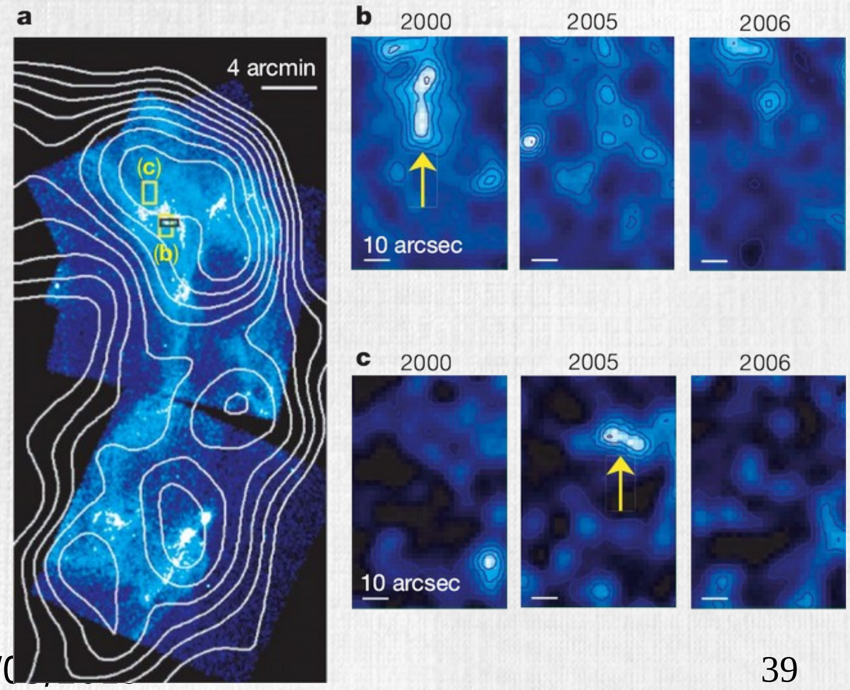


magnetic field: B = 22 μG

Magnetic Field Amplification

- ✪ magnetic field amplification up to mG
  - [Bell&Lucek 2001]
- ✪ X-ray filaments
  - [Bamba et al. 2005]
  - gyro-radius of electrons
  - Vela Junior: several 100 μG
  - or thin sheet of magnetic field
- ✪ X-ray variability
  - [Uchiyama et al. 2007]
  - fast variability
    → short life-time
  - → *B* up to 1000 μG

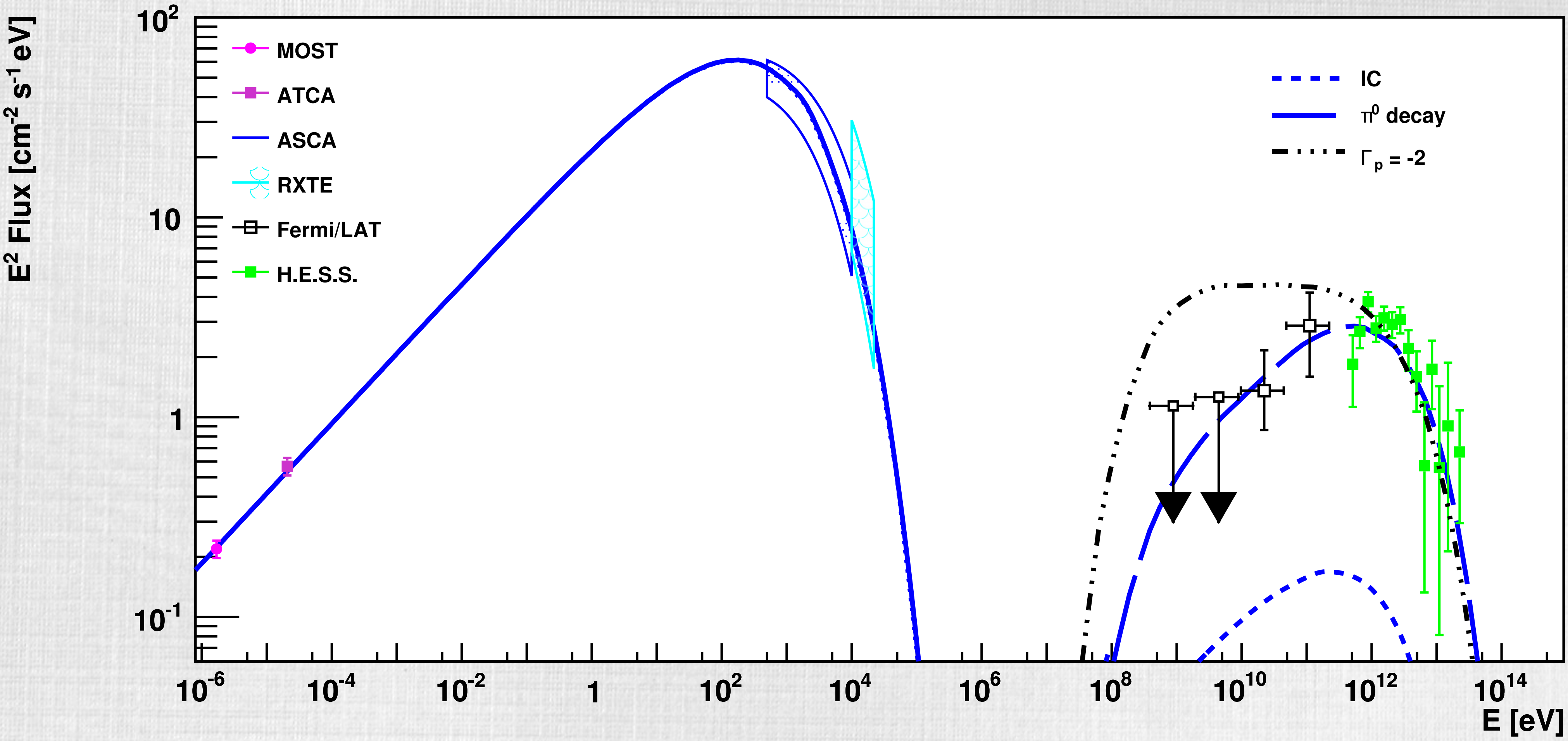




Implications II

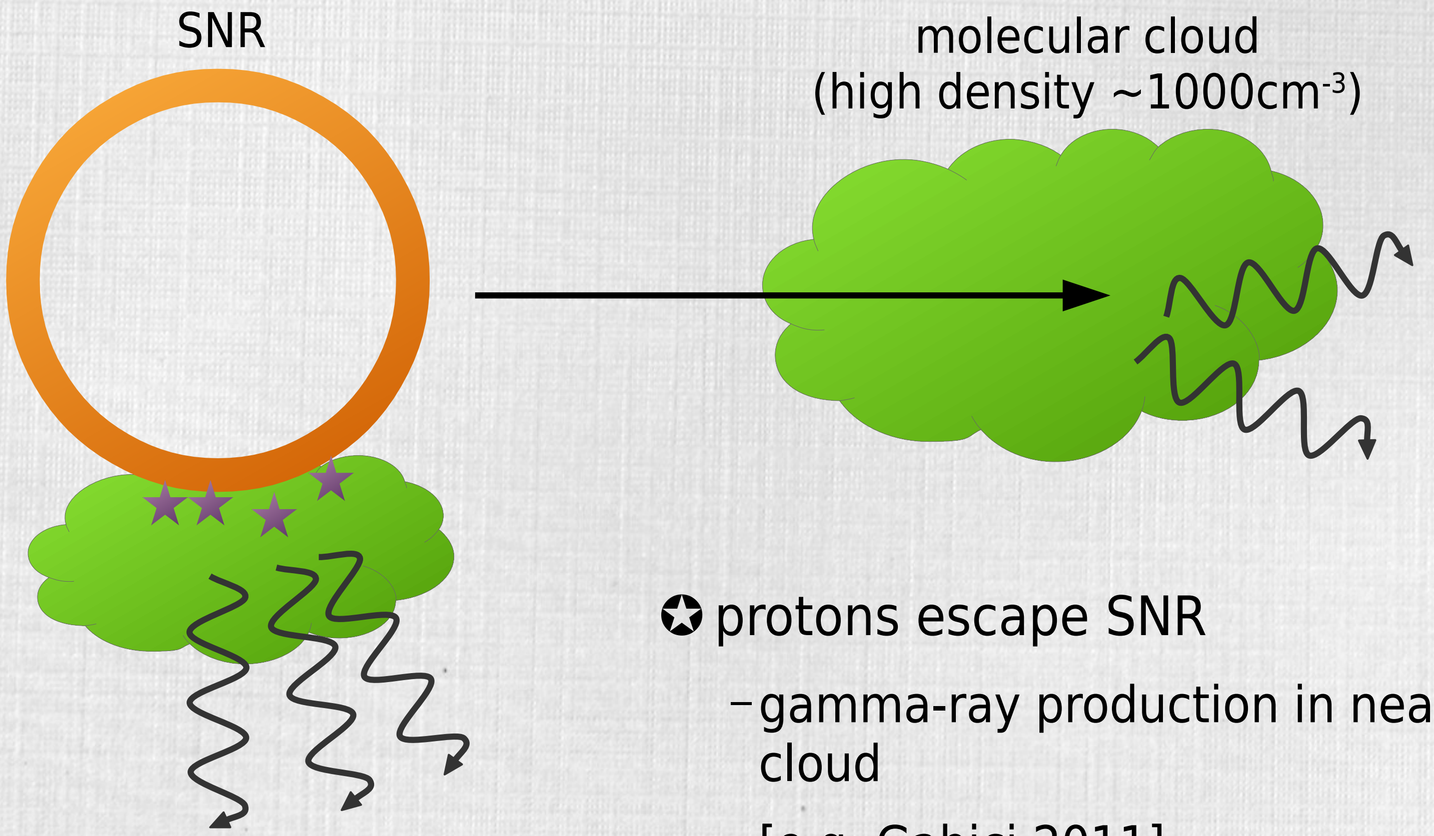
magnetic field: B = 100 μG

example: RCW 86 [HESS *A&A* 612 (2018) A4]



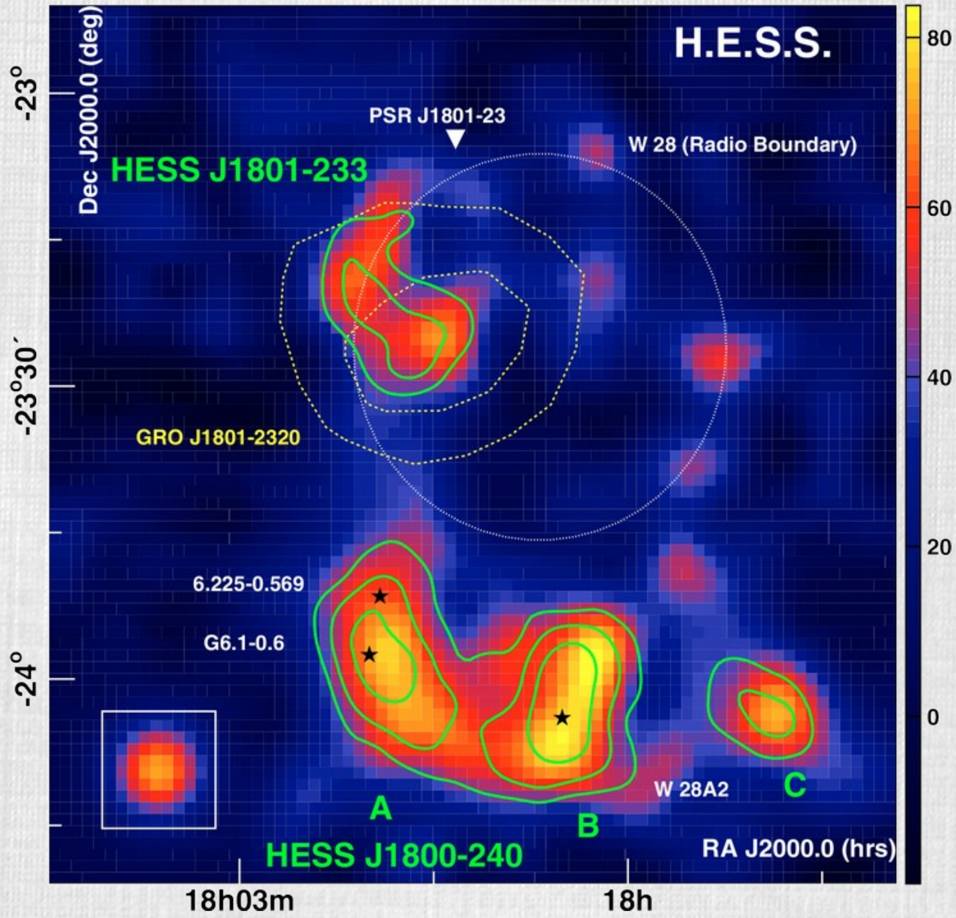
- emission from protons possible
- proton spectral index different than expected -2

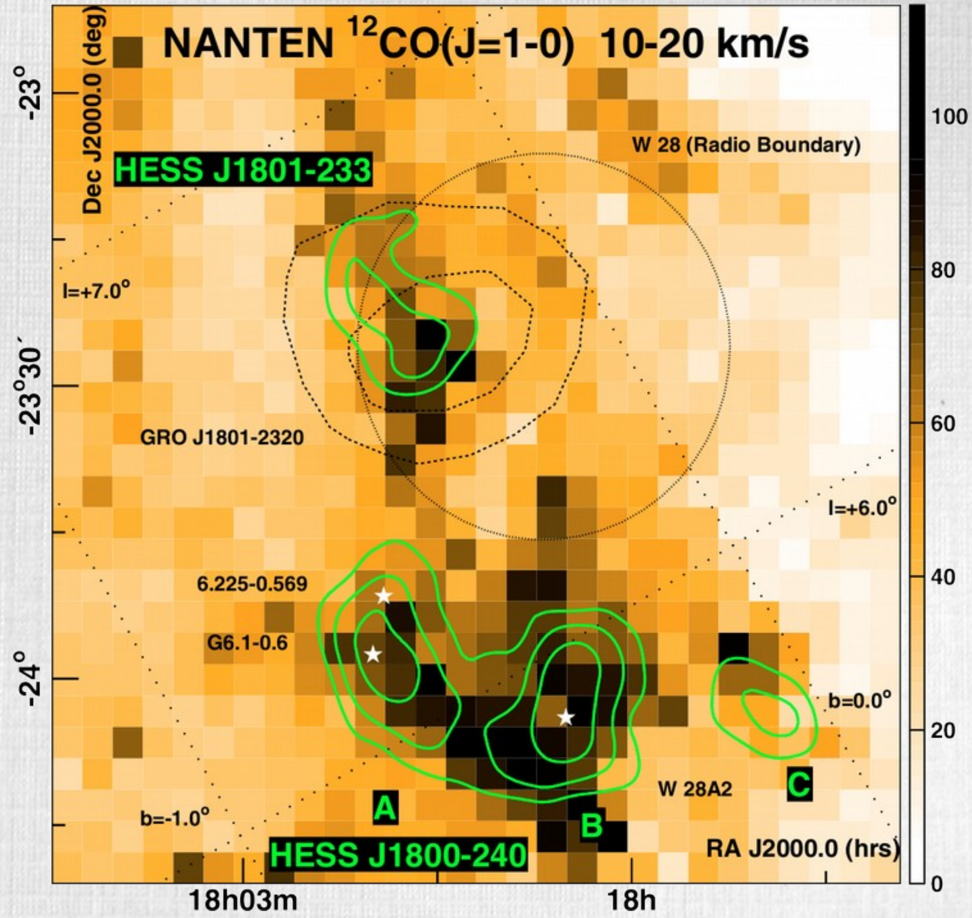
SNRs and Target Material



- protons escape SNR
  - gamma-ray production in nearby molecular cloud
  - [e.g. Gabici 2011]
- shock front crushes cloud
  - OH masers tracer for shock/cloud interaction
  - 1720 MHz
  - [Frail et al. 1996]

Cosmic Ray Escape: W 28



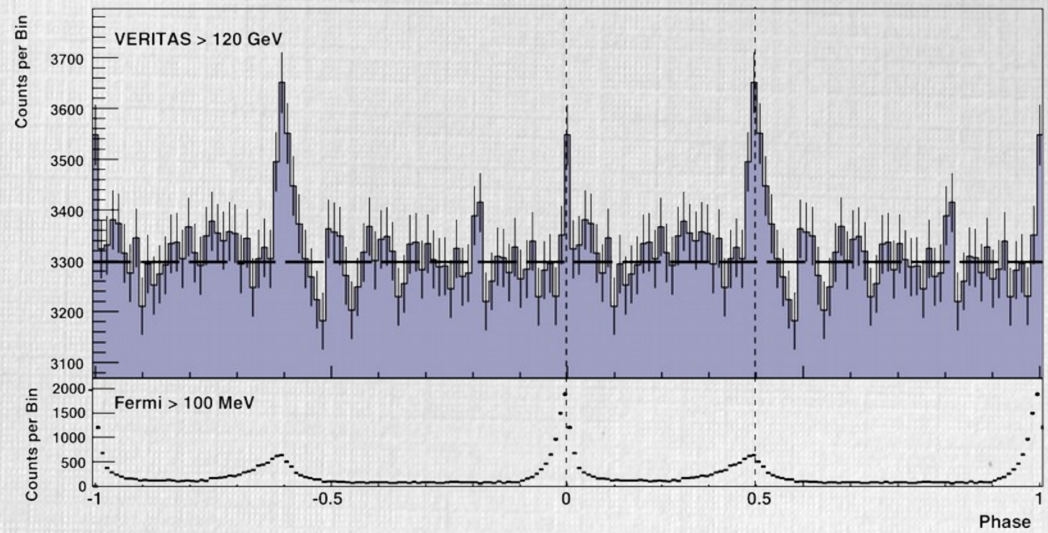


- ✪ gamma-ray emission correlated with molecular clouds [HESS 2008]
  - ^{12}CO emission as tracer for molecular clouds

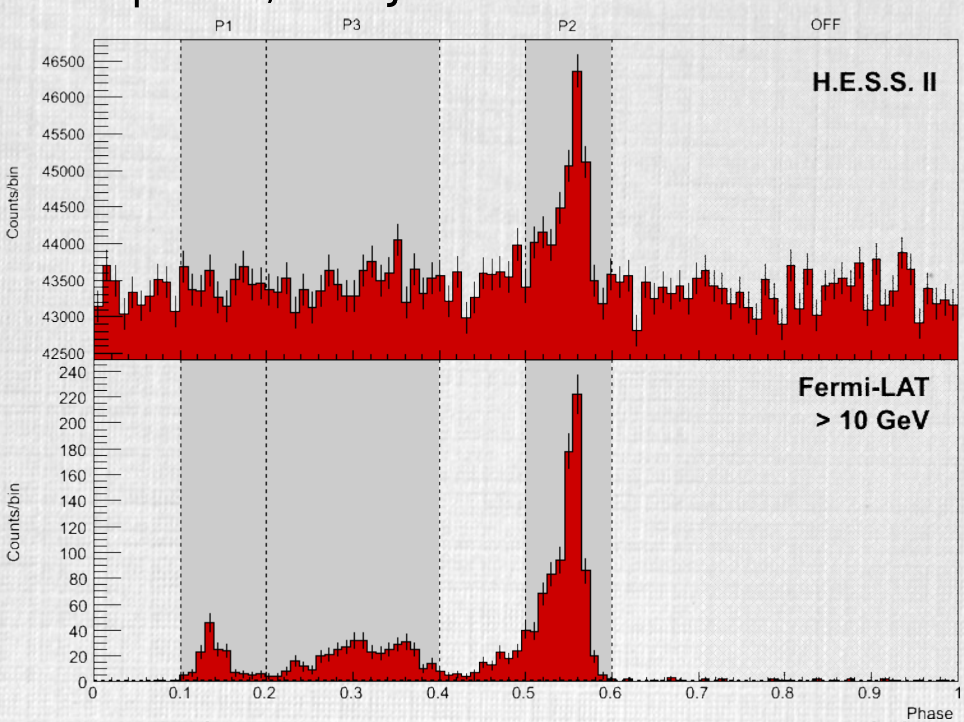
TeV Pulsars

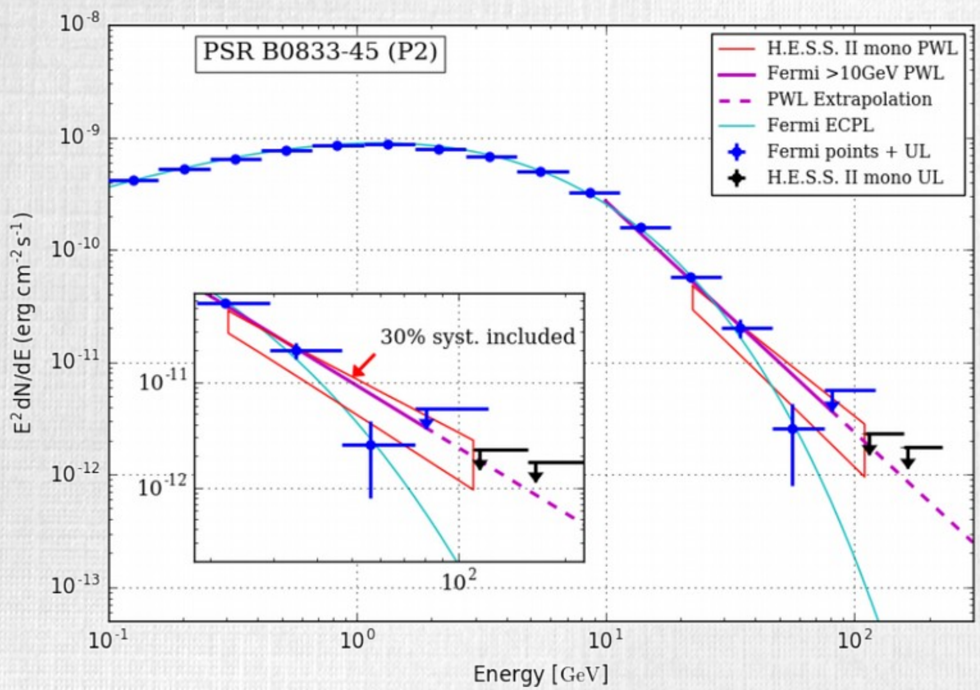
Crab pulsar
PSR B0531+21

(also detected by MAGIC)



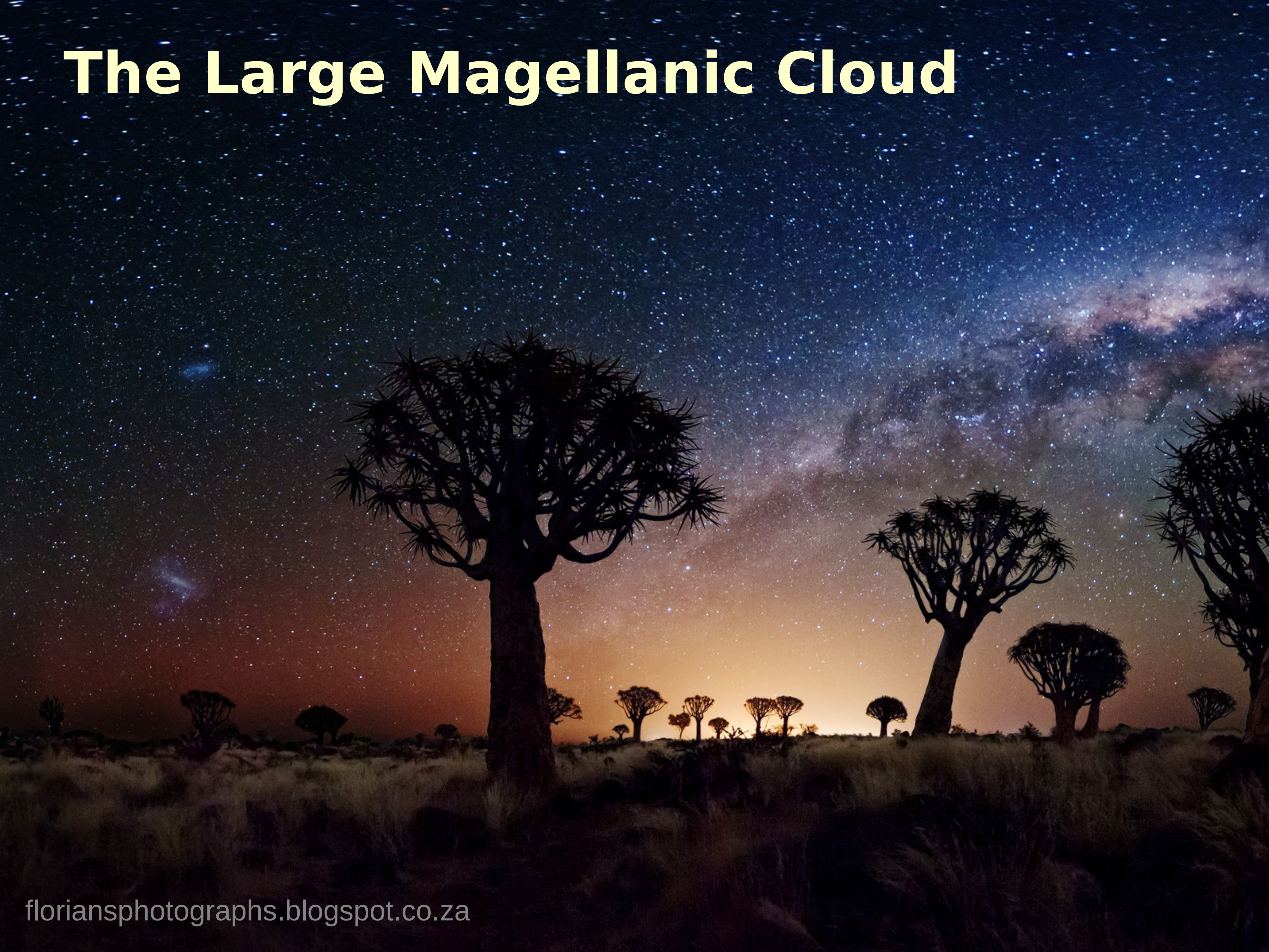
Vela pulsar, PSR J0835-4510



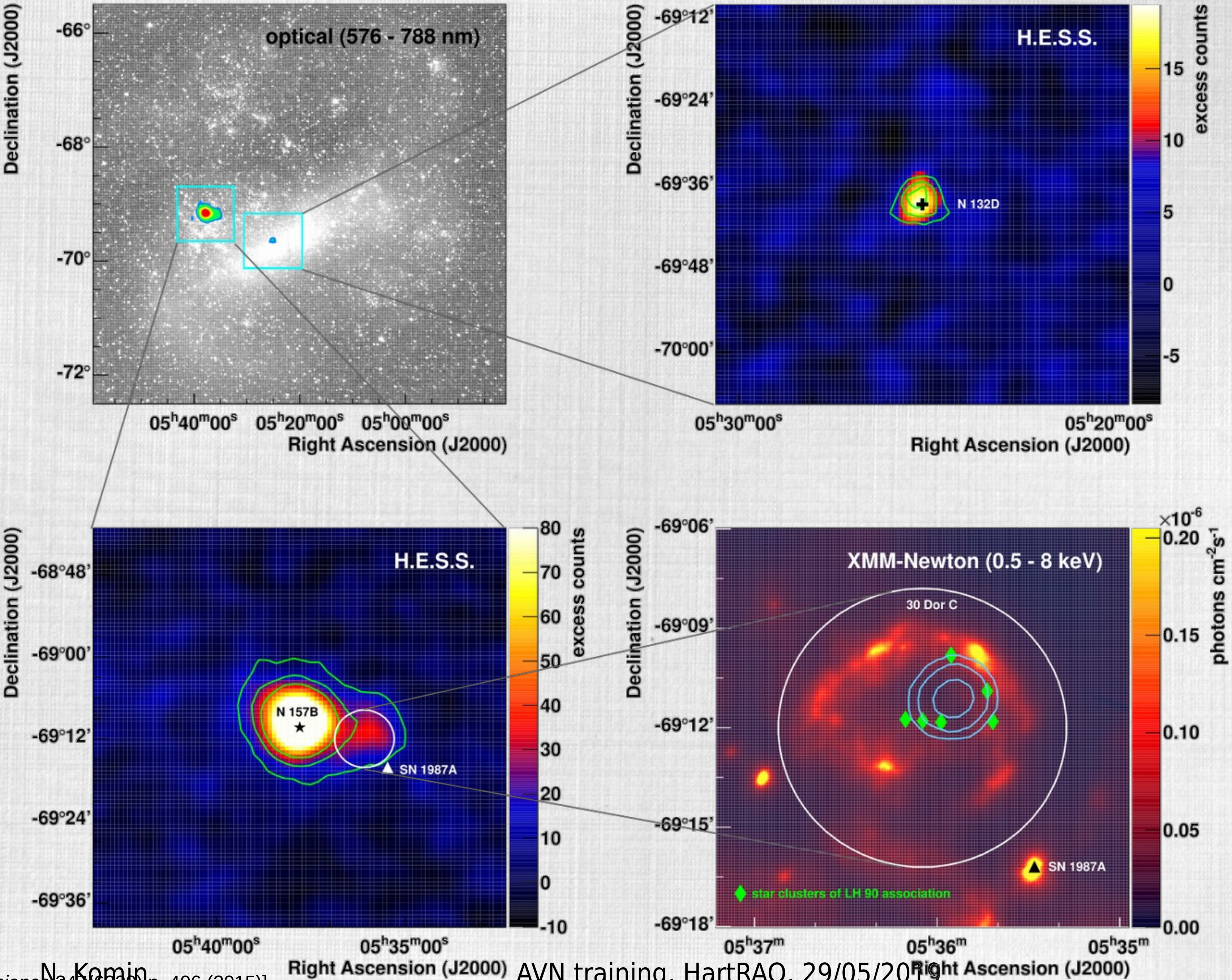


[HESS 2017, AIP 1792, 040028]

The Large Magellanic Cloud



The Large Magellanic Cloud

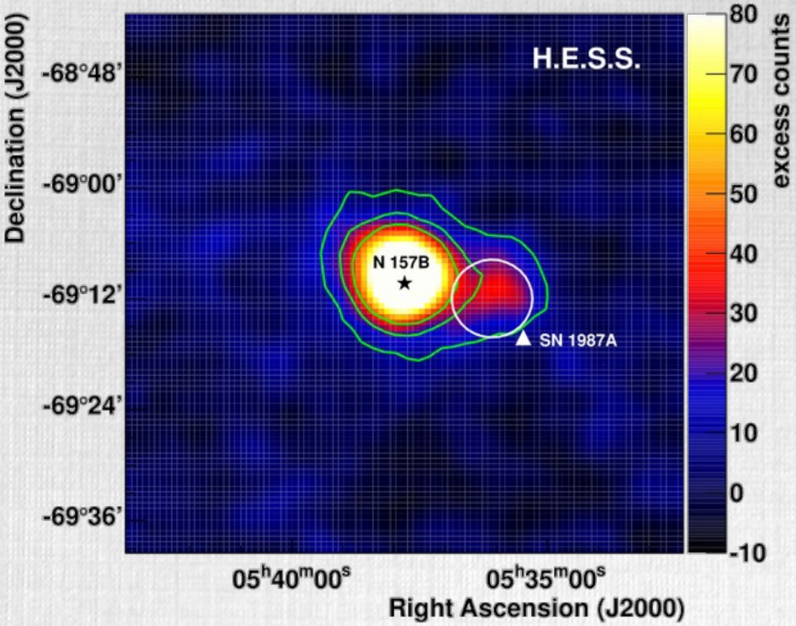


[*Science* 347(6220) p. 406 (2015)]

The Pulsar Wind Nebula N 157B

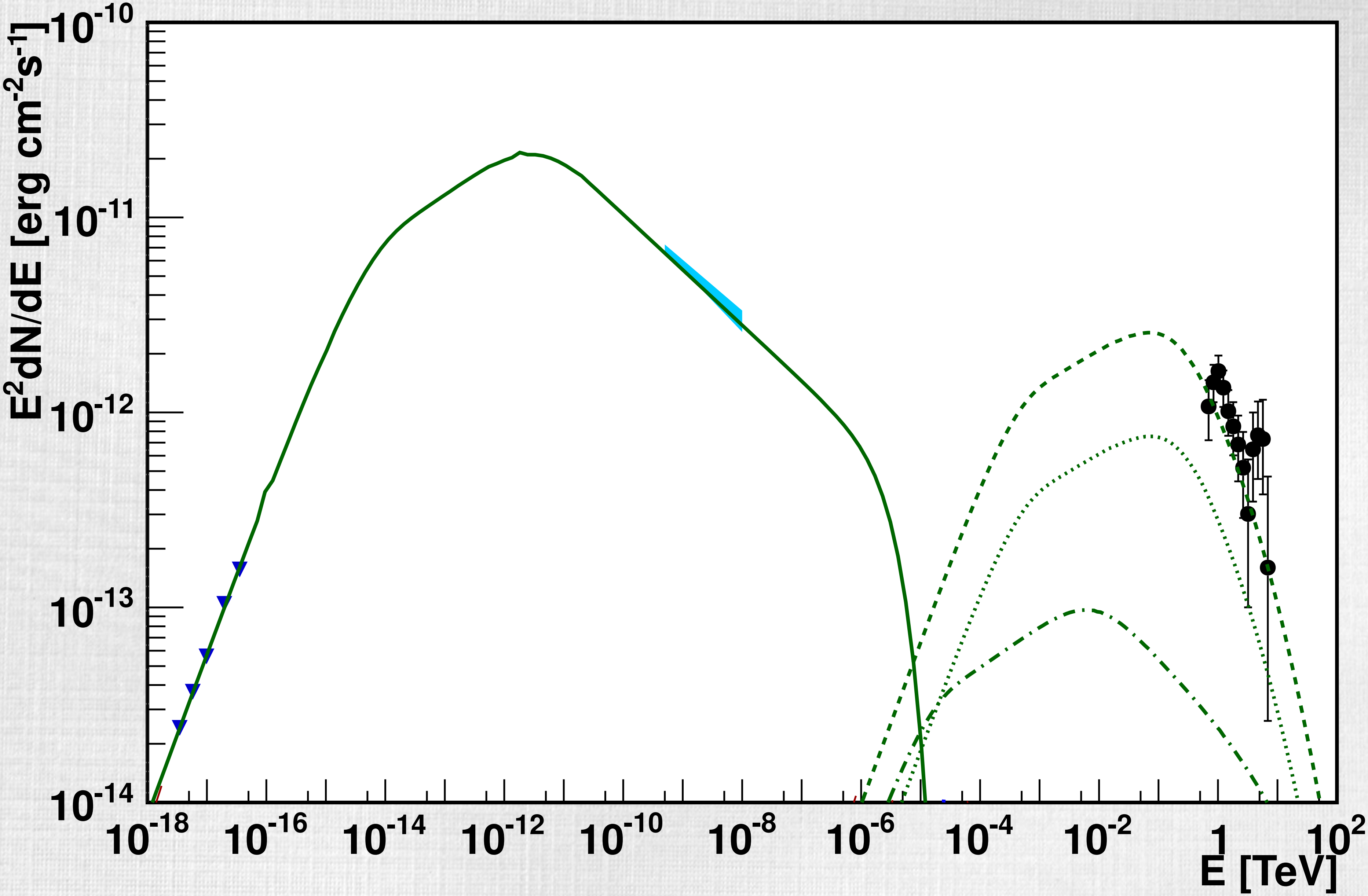
- PWN
  - energy flux in gamma rays:
    $F = 1.97 \times 10^{-12}$ erg cm^{-2} s^{-1}
  - total gamma-ray power:

    $P = F \times A_{\mathrm{sphere}} = F \times 4\,\pi\,(50\ \mathrm{kpc})^2$
    $= 5.9 \times 10^{35}$ erg/s



- powered by PSR J0537-6910
  - $\dot{E} = 4.9\ 10^{38}$ erg/s
- pulsar efficiency: $P / \dot{E} = 0.12\%$

The Pulsar Wind Nebula N 157B



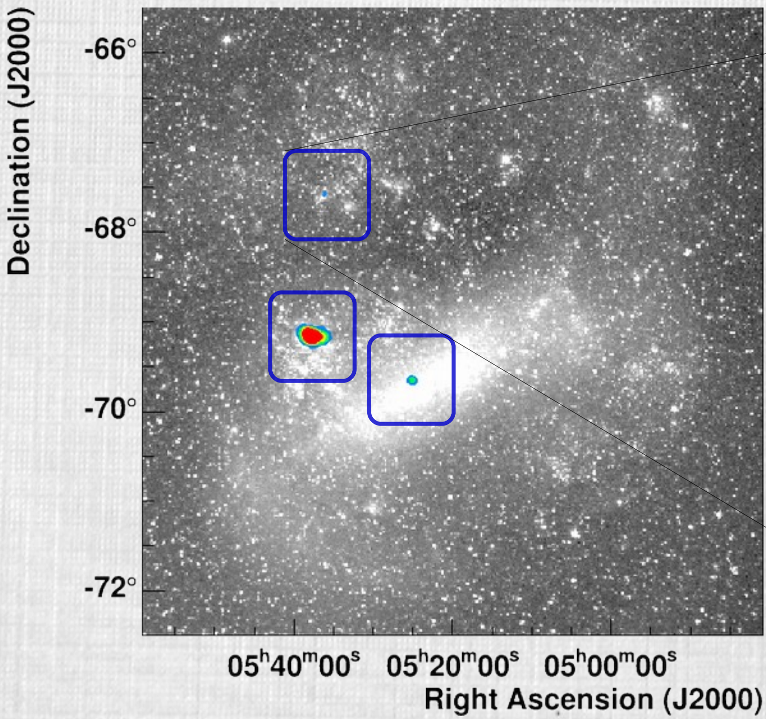
The Pulsar Wind Nebula N 157B

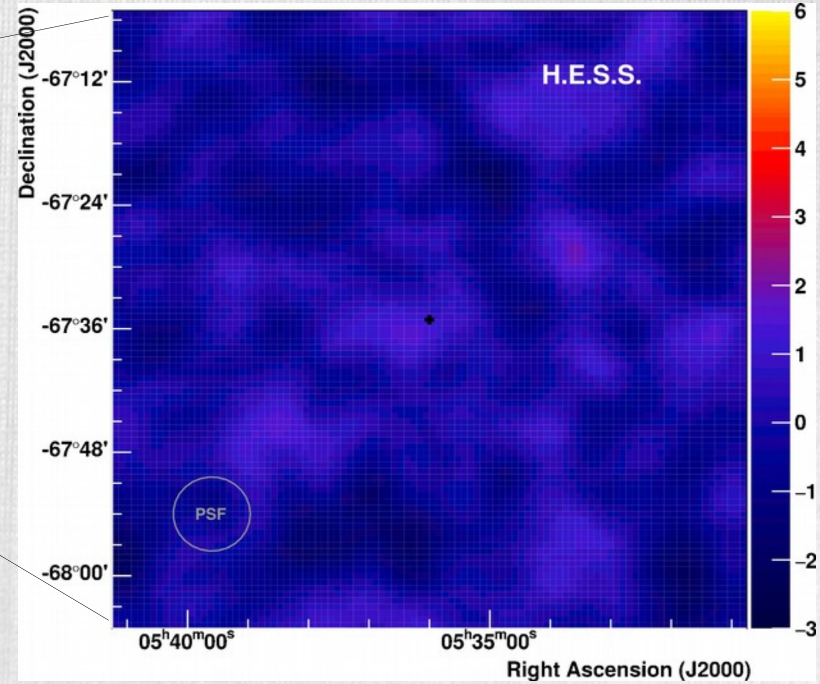
- ratio of synchrotron and IC emission
  - magnetic field of 41 µG
- integration of electron spectrum
  - total energy in electrons 4×10^{49} erg
- all energy from pulsar spin-down → birth period of 10 ms

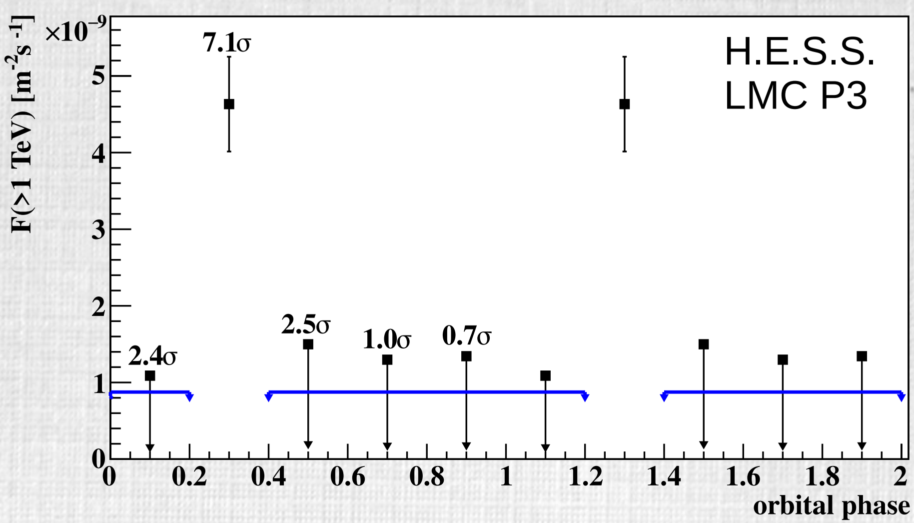
$$
\begin{aligned}
W_{\mathrm{tot}} &= \epsilon\eta\,(E_{\mathrm{rot},0} - E_{\mathrm{rot}}) \\
&= \epsilon\eta\frac{1}{2}I\left(\left(\frac{2\pi}{P_0}\right)^2 - \left(\frac{2\pi}{P}\right)^2\right) \\
&= 2\times 10^{49}\epsilon\eta\frac{I}{10^{45}\,\mathrm{g\,cm^2}}\left(\left(\frac{10\,\mathrm{ms}}{P_0}\right)^2 - \left(\frac{10\,\mathrm{ms}}{P}\right)^2\right)\mathrm{erg}
\end{aligned}
$$

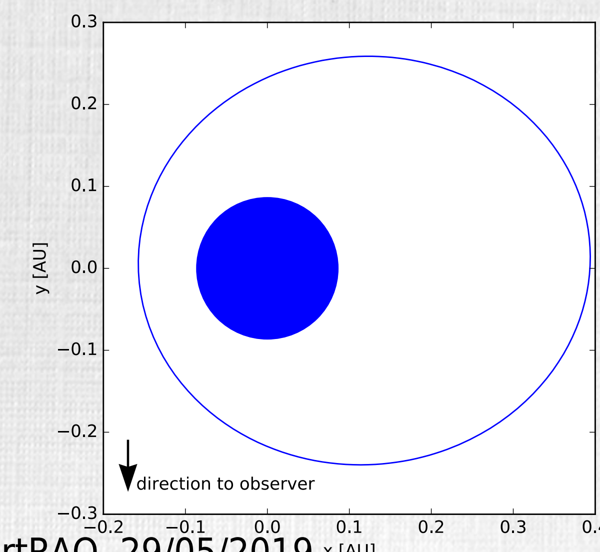
[*A&A* 545, L2 (2012)]

Gamma-Ray Binary LMC P3









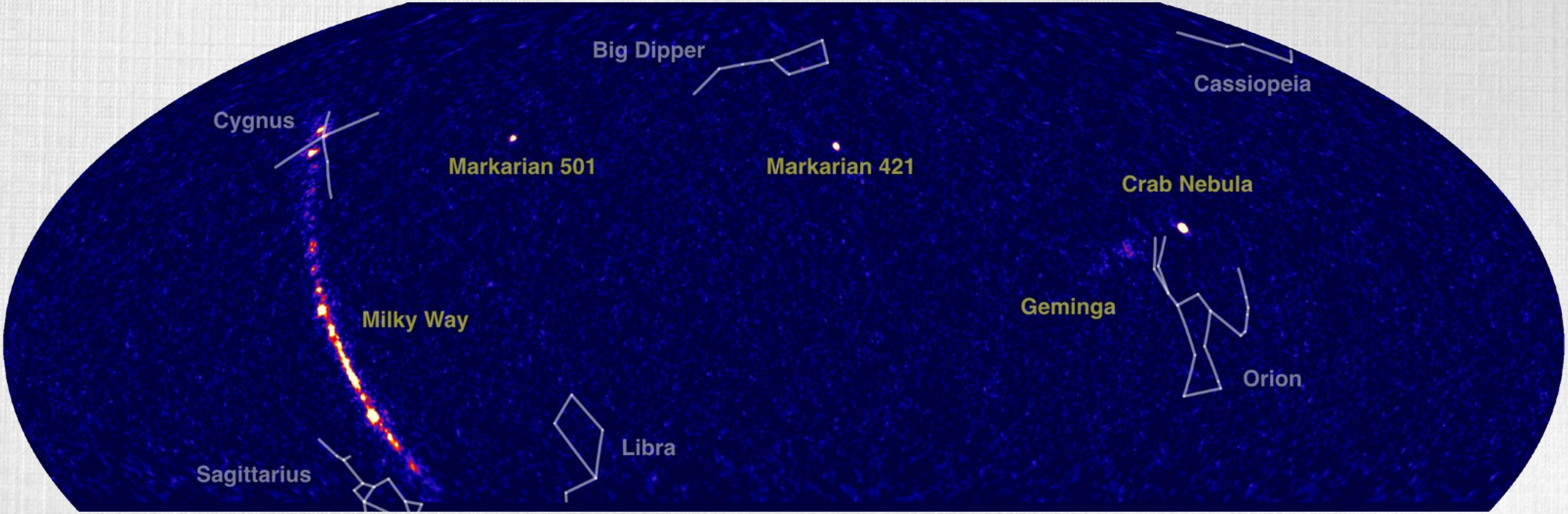
10.3-day period

[HESS A&A, 610 (2018) L17]

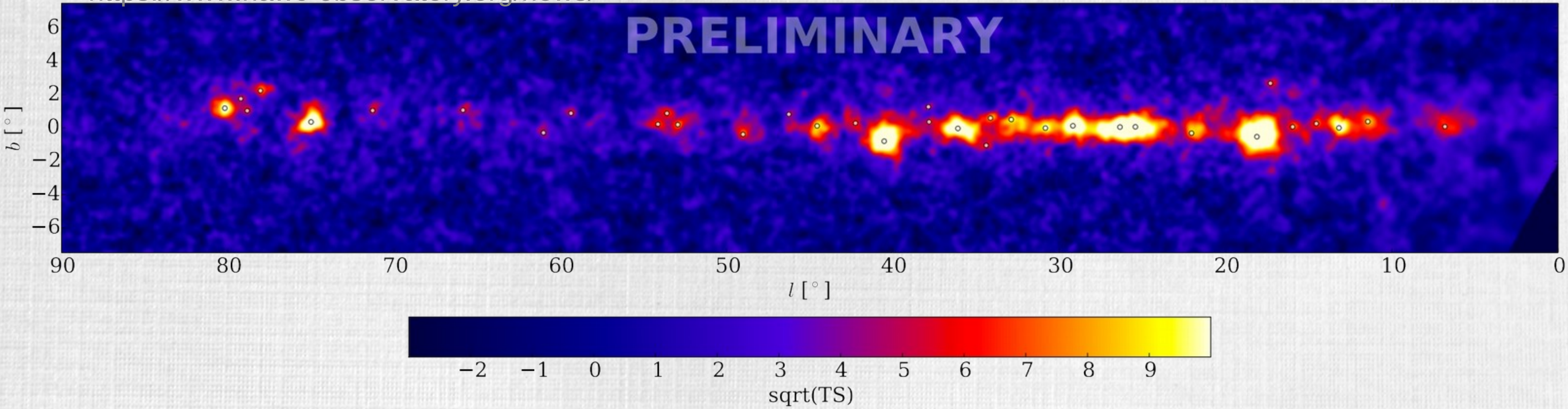
HAWC

- ✪ **H**igh **A**ltitude **W**ater **C**herenkov Observatory
- ✪ direct detection of air showers
  - –→ detects individual photons
- ✪ water Cherenkov tanks
- ✪ altitude 4100 m
- ✪ energies: 100 GeV ... 100 TeV
- ✪ large field of view: 15% of sky
- ✪ large duty-cycle: 24/7
- ✪ 2/3 of sky covered in 24 h
- ✪ angular resolution 0.2°...2°
- ✪ advantages: large field of view, large duty cycle

HAWC Results

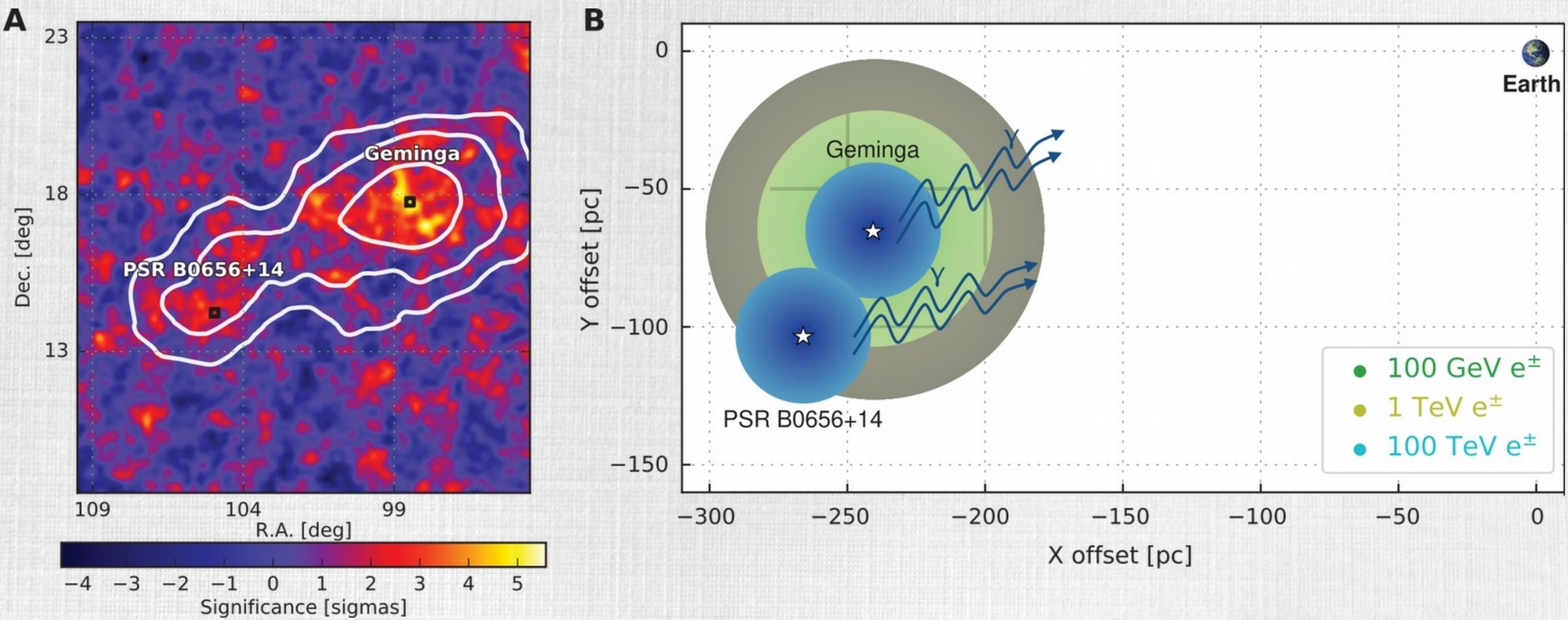


https://www.hawc-observatory.org/news/



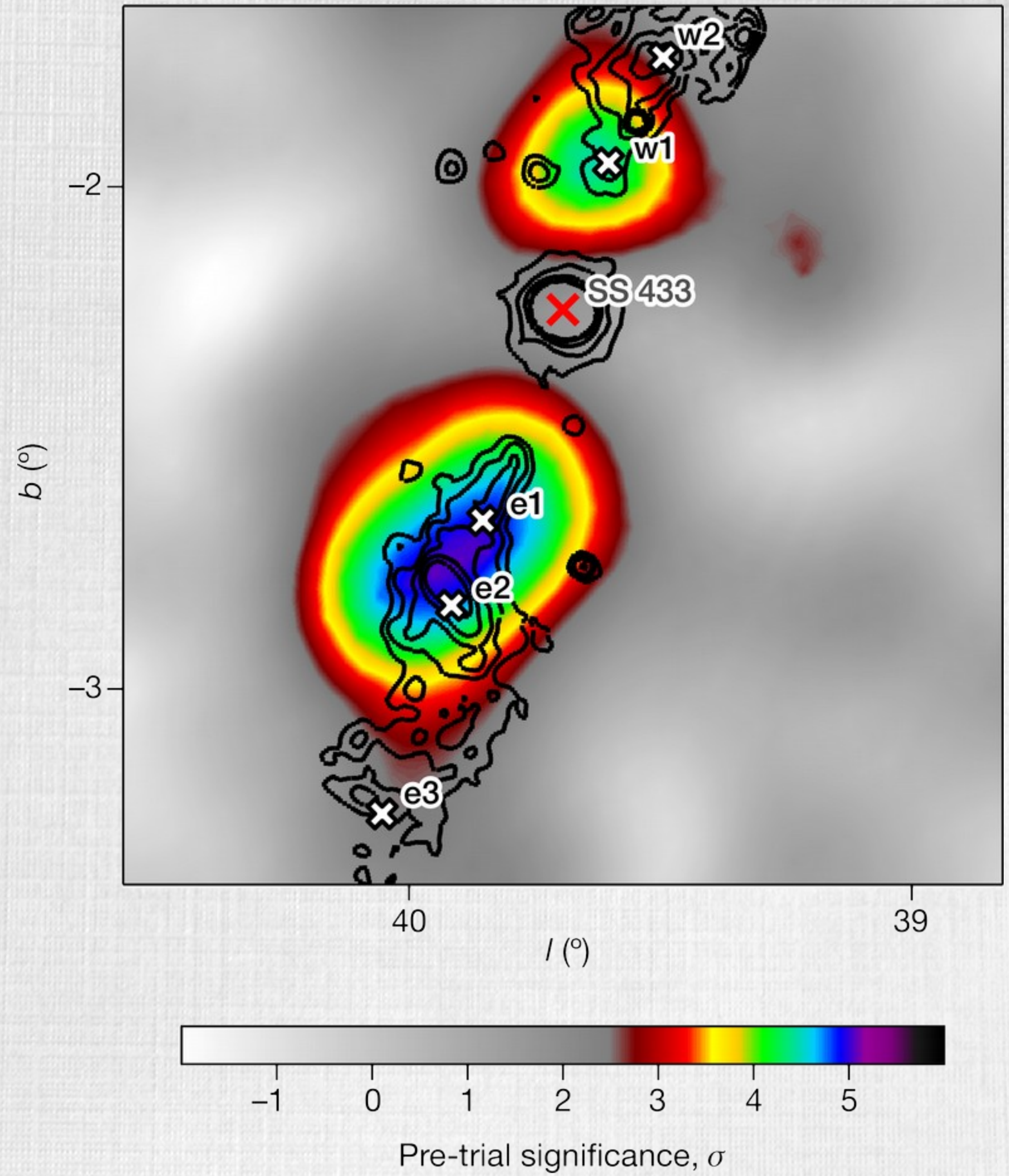
HAWC Results

- ✪ “Extended gamma-ray sources around pulsars constrain the origin of the positron flux at Earth”
  - [HAWC Collaboration (2017), Science 358, 6365, pp. 911-914]
- ✪ large extended gamma-ray emission around two pulsars
- ✪ measurement of diffusion coefficient of electrons and positrons
  - → lower then expected, sources are not origin of positron flux on Earth



HAWC Results

- ✪ "Very-high-energy particle acceleration powered by the jets of the microquasar SS 433"
  - [HAWC Collaboration (2018), Nature 562, 82–85]
- ✪ binary system, microquasar
  - A7I star, compact object
  - accretion of stellar material onto compact object
  - mildly relativistic jets, perpendicular to line-of-sight
- ✪ gamma-ray emission from jet
  - acceleration in the jet, not the central engine
  - most likely electrons

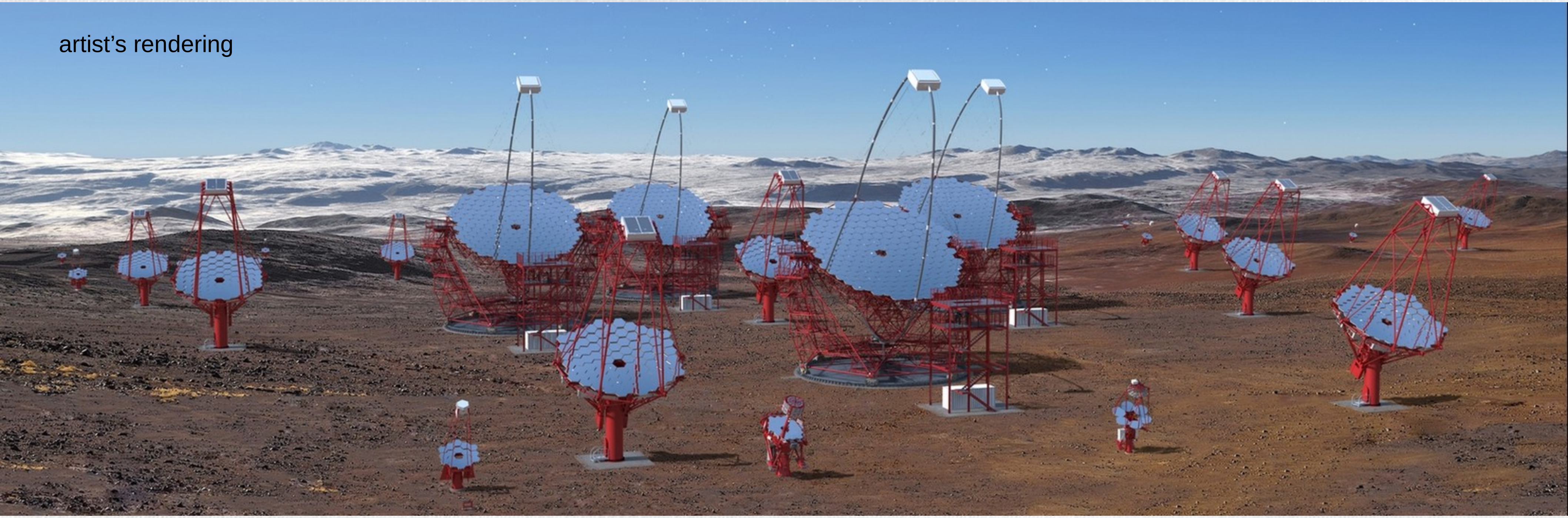


Gamma-Ray Instruments

	space based	imaging air Cherenkov Telescopes	ground based
	Fermi/LAT	H.E.S.S., VERITAS, MAGIC	HAWC
energy range	100 MeV ... 100 GeV	50 GeV ... 10 TeV	100 GeV ... 100 TeV
effective size	1 m^2	~10000 m^2	22500 m^2
angular resolution	0.2°...10°	0.05°...0.1°	0.2°...2°
duty cycle	24/7	1000 h per year	24/7
field of view	40°	3°...5°	
sky coverage	full	-	2/3

Future: Cherenkov Telesope Array

- ✪ 100 telescopes on 2 sites
  - north: Canary Islands
  - south: Chile
- ✪ prototypes done, first light observed
- ✪ construction to begin in 2019
- ✪ aim for 10 times better sensitivity than H.E.S.S.



Summary

- ✪ gamma rays:
  - E > 100 keV
  - high energy (HE) gamma rays: 100 MeV ... 100 GeV
  - very-high-energy (VHE) gamma rays 100 GeV ... 100 TeV
- ✪ emission:
  - inverse Compton scattering (electrons)
  - inelastic proton scattering
  - → probes non-thermal universe!
- ✪ detection:
  - space: Fermi/LAT
  - ground/atmosphere: H.E.S.S. and others
  - ground: HAWC
  - → detect individual photons
- ✪ some major results:
  - pulsars, pulsar wind nebulae, supernova remnants, binaries
  - plus many more...