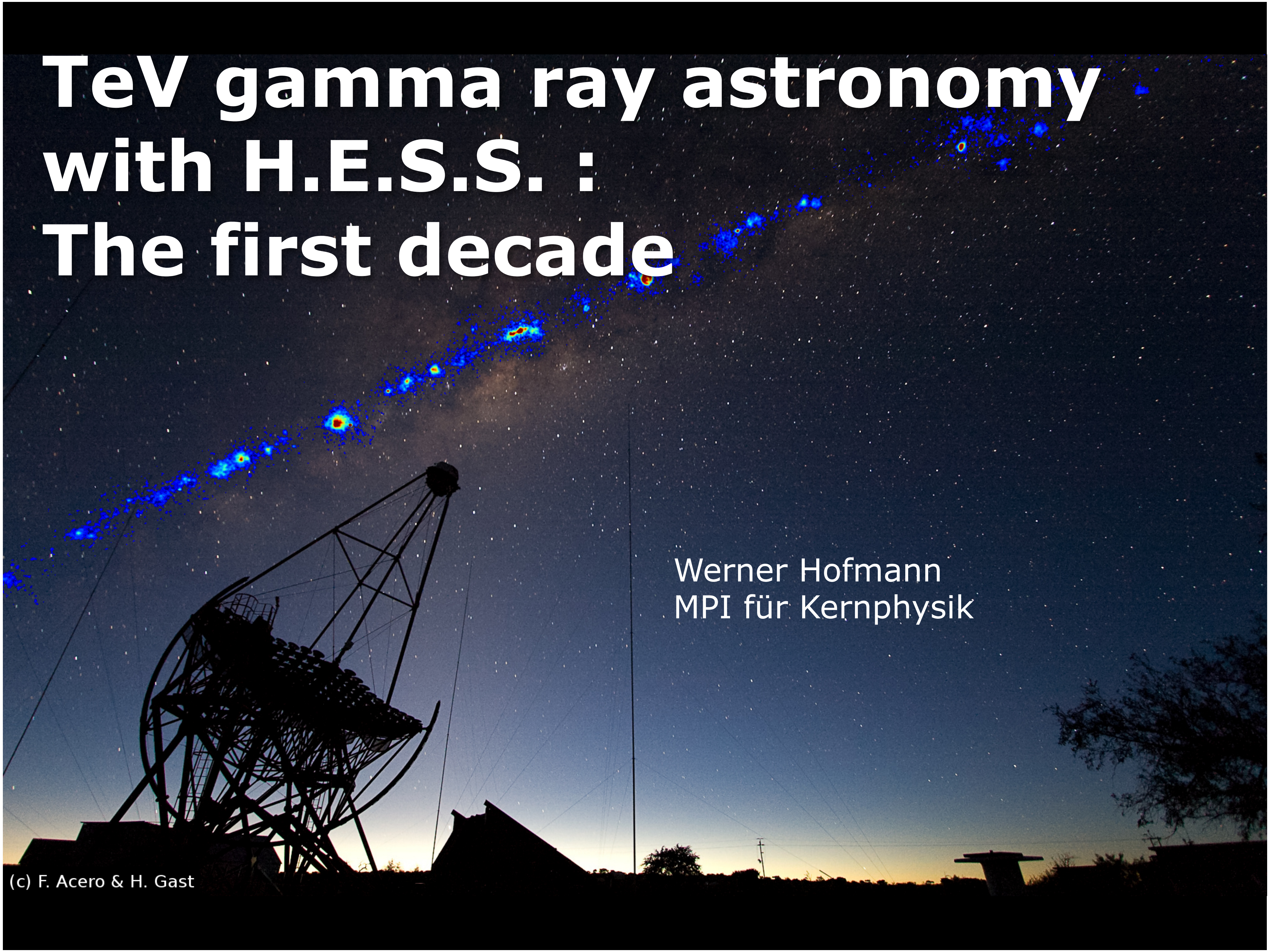
TeV gamma ray astronomy with H.E.S.S. : The first decade

Werner Hofmann
MPI für Kernphysik

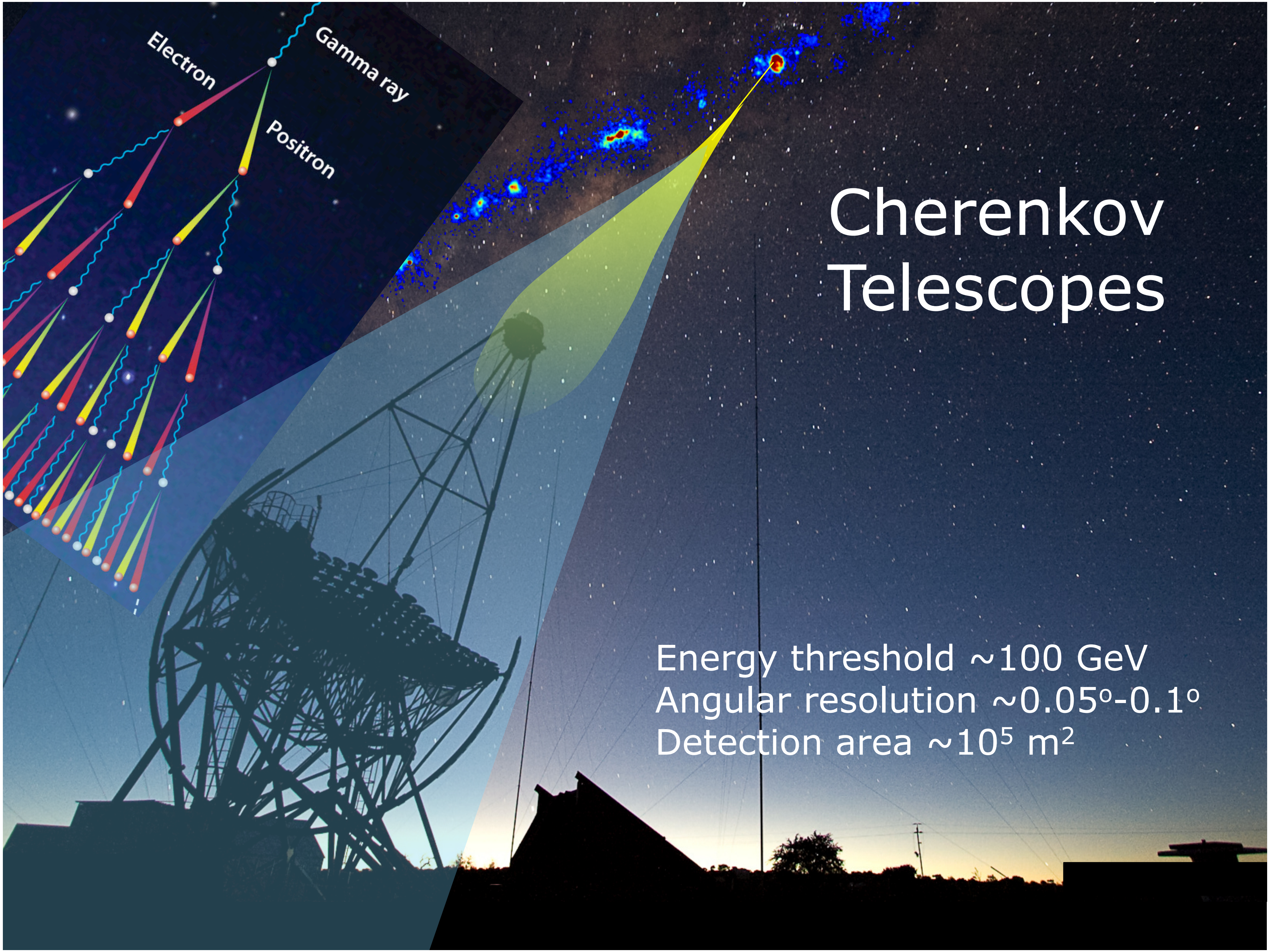



2012
(c) F. Acero & H. Gast

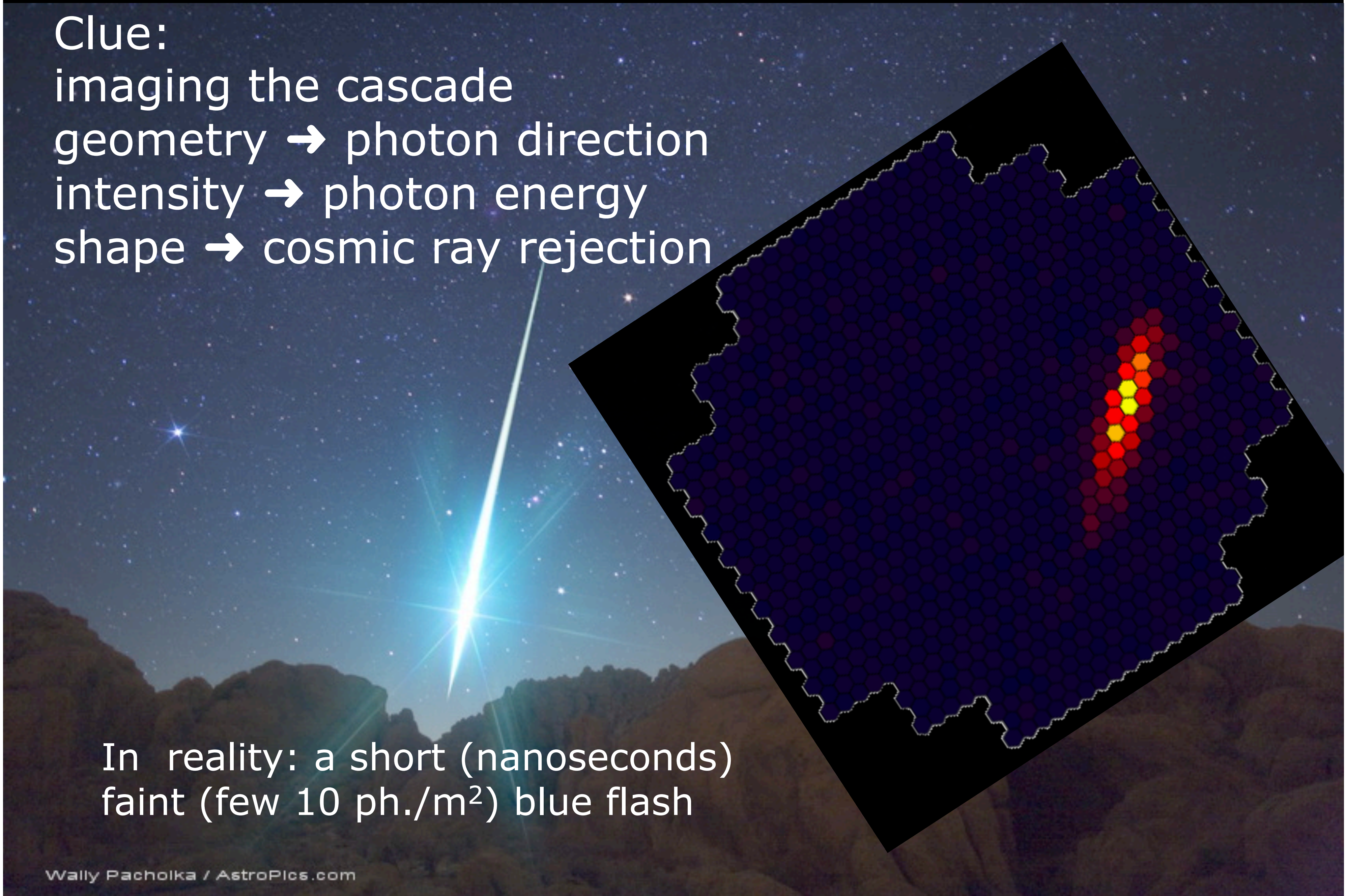

10 years of H.E.S.S operation
2002: Inauguration of the
first H.E.S.S. telescope


Inauguration of the
H.E.S.S. II telescope
H.E.S.S.

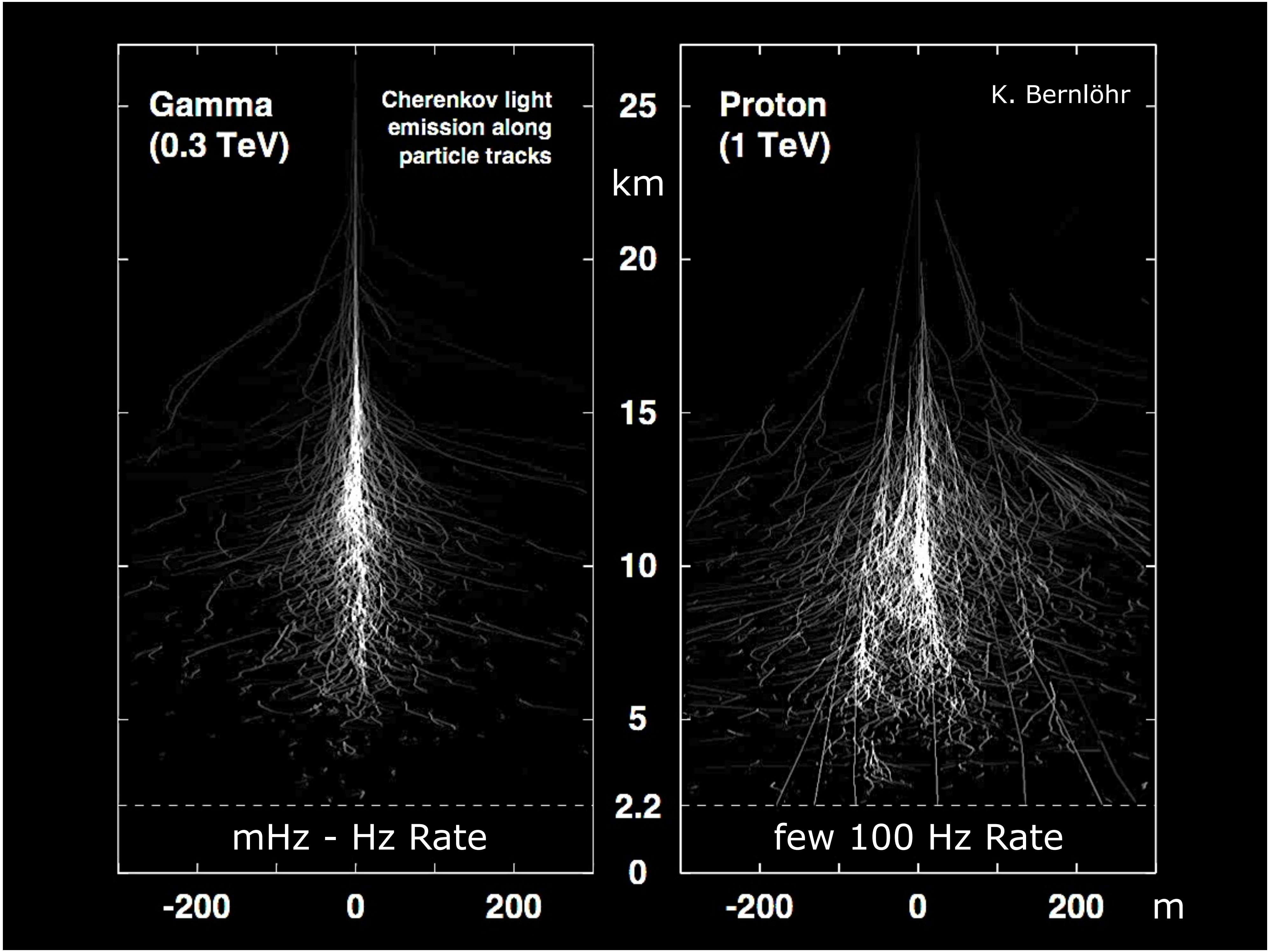

H.E.S.S.


Electron
Gamma ray
Positron
Cherenkov Telescopes
Energy threshold ~100 GeV
Angular resolution ~0.05°-0.1°
Detection area ~10⁵ m²

Clue:
imaging the cascade
geometry ➜ photon direction
intensity ➜ photon energy
shape ➜ cosmic ray rejection



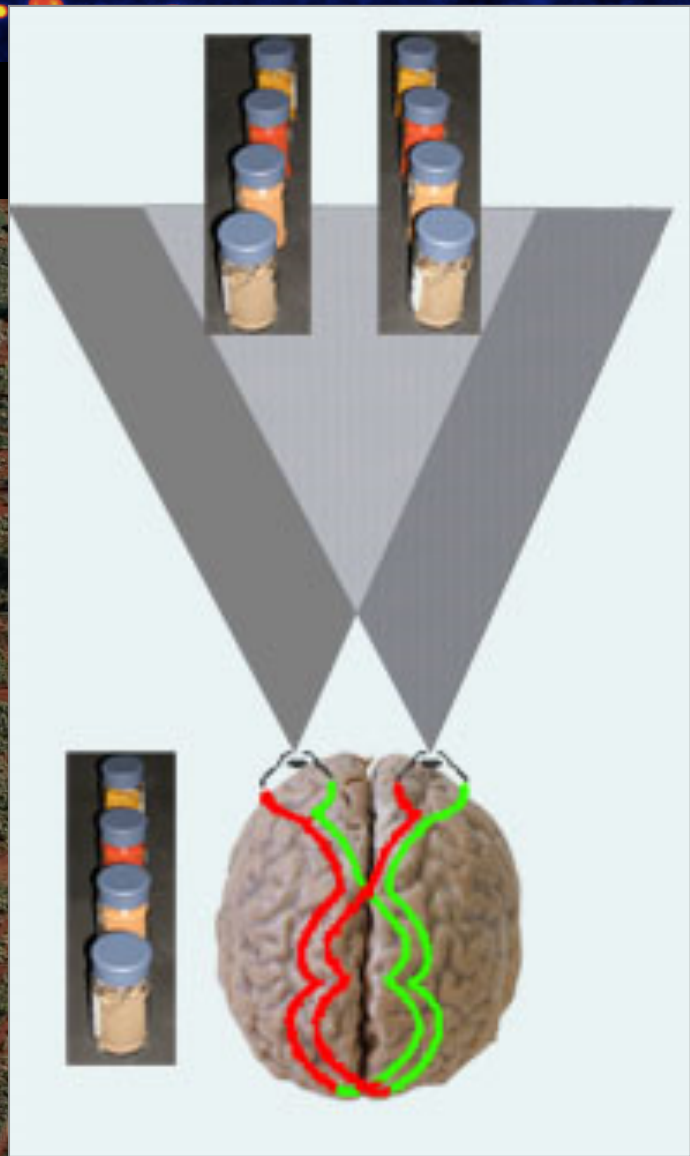
In reality: a short (nanoseconds) faint (few 10 ph./m^2) blue flash



Gamma
(0.3 TeV)
Cherenkov light
emission along
particle tracks
Proton
(1 TeV)
K. Bernlöhr
25
km
20
15
10
5
2.2
0
mHz - Hz Rate
few 100 Hz Rate
-200
0
200
m

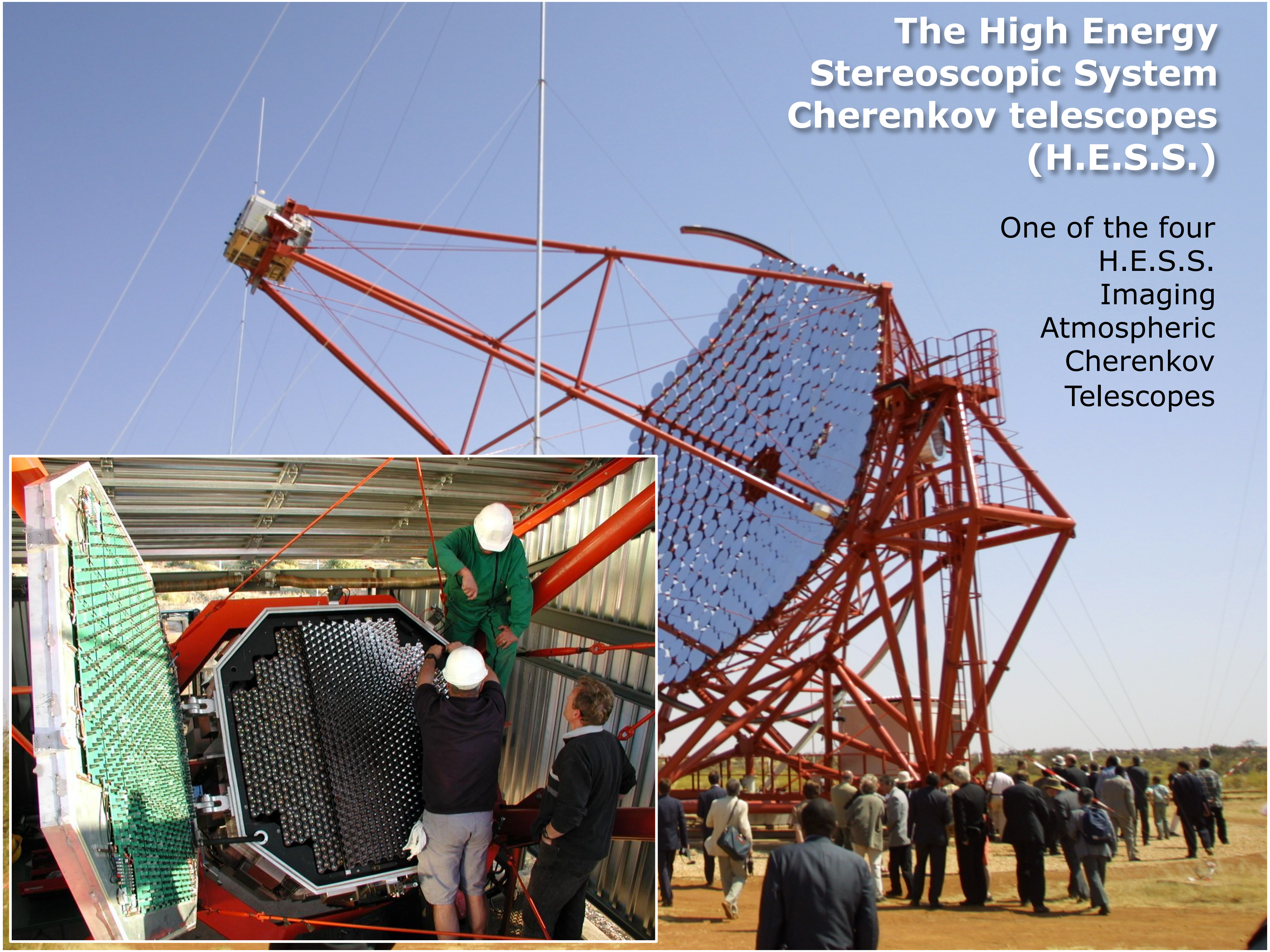
Stereoscopic multi-telescope systems

provide 3D view of cascade

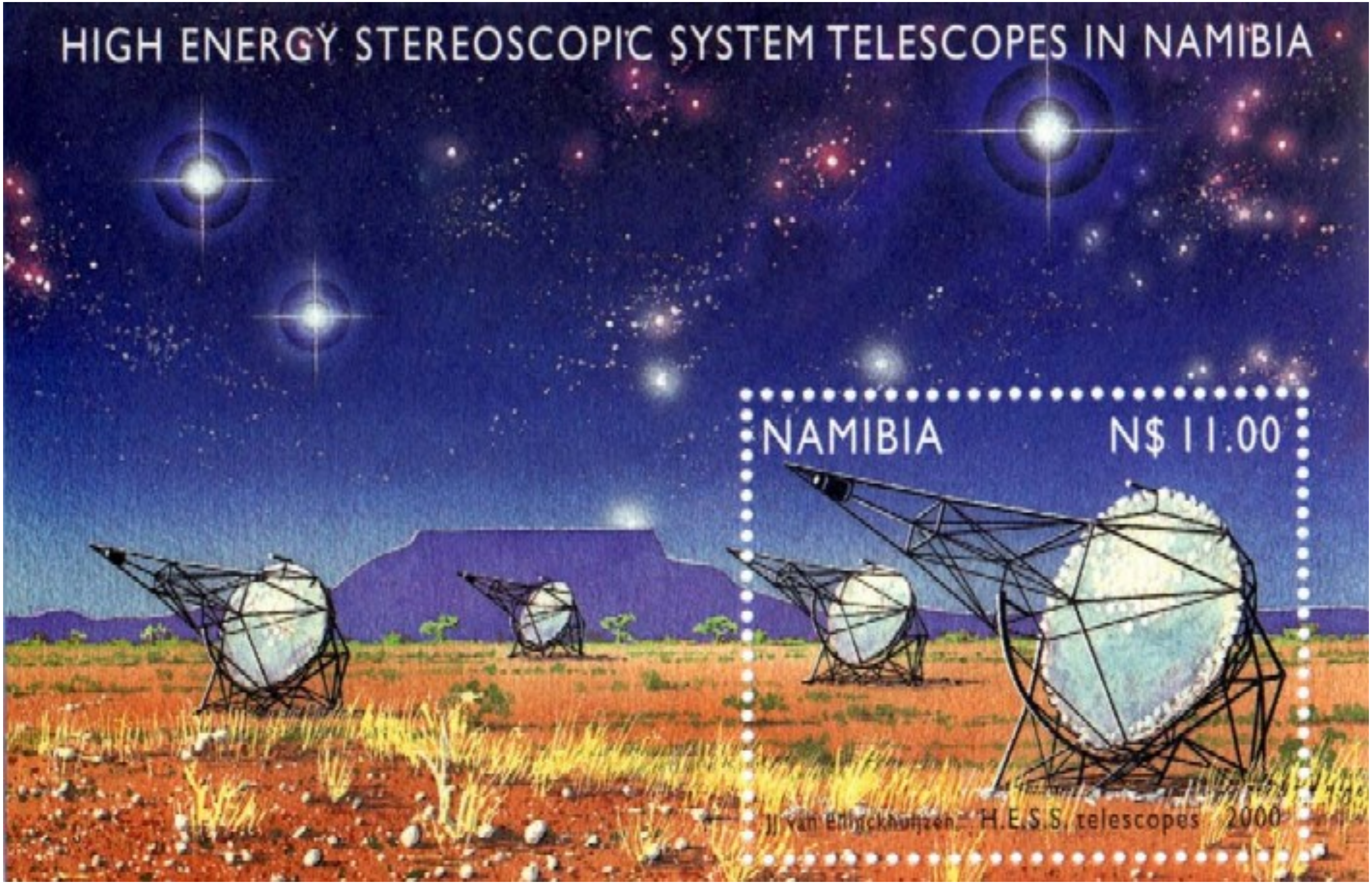


The High Energy Stereoscopic System Cherenkov telescopes (H.E.S.S.)

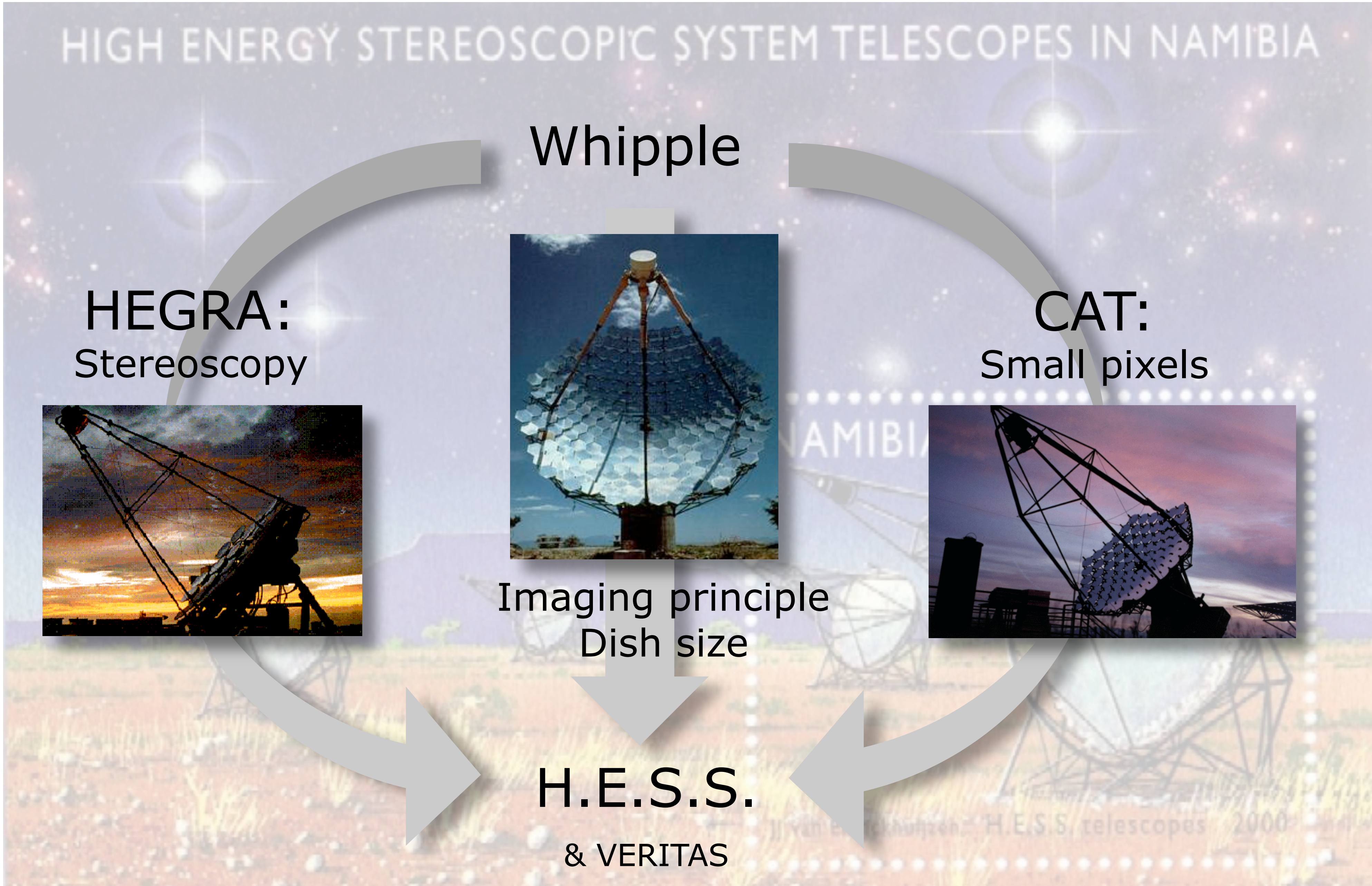
One of the four H.E.S.S. Imaging Atmospheric Cherenkov Telescopes



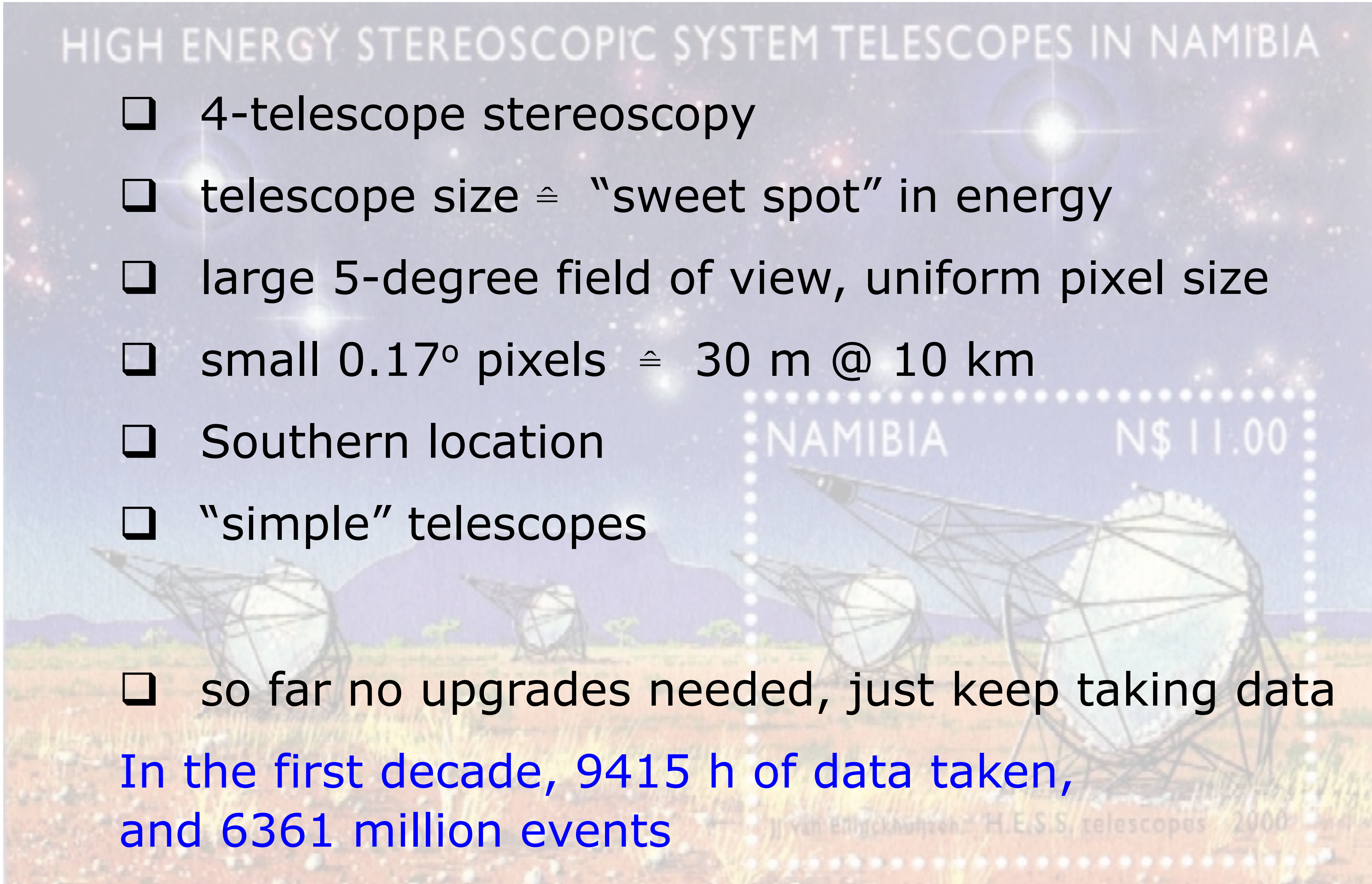
H.E.S.S. Heritage & Design



H.E.S.S. Heritage & Design



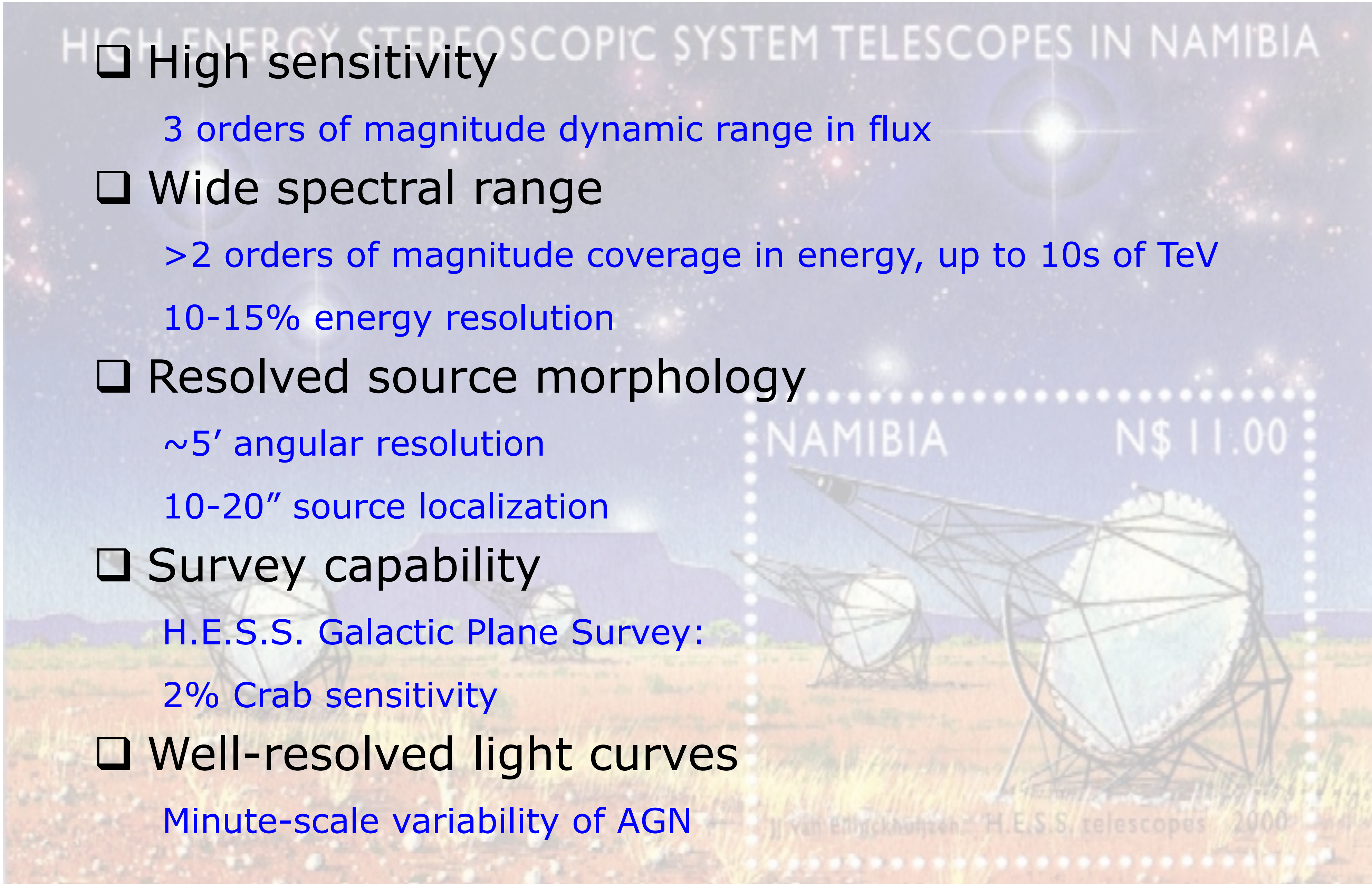
Key design choices of H.E.S.S.



- 4-telescope stereoscopy
- telescope size ≙ "sweet spot" in energy
- large 5-degree field of view, uniform pixel size
- small 0.17° pixels ≙ 30 m @ 10 km
- Southern location
- "simple" telescopes
- so far no upgrades needed, just keep taking data

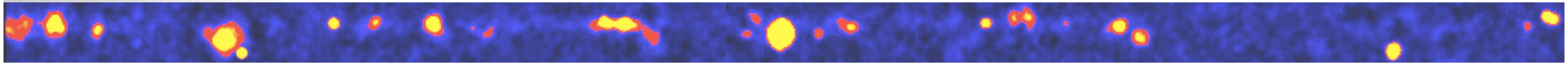
In the first decade, 9415 h of data taken,
and 6361 million events

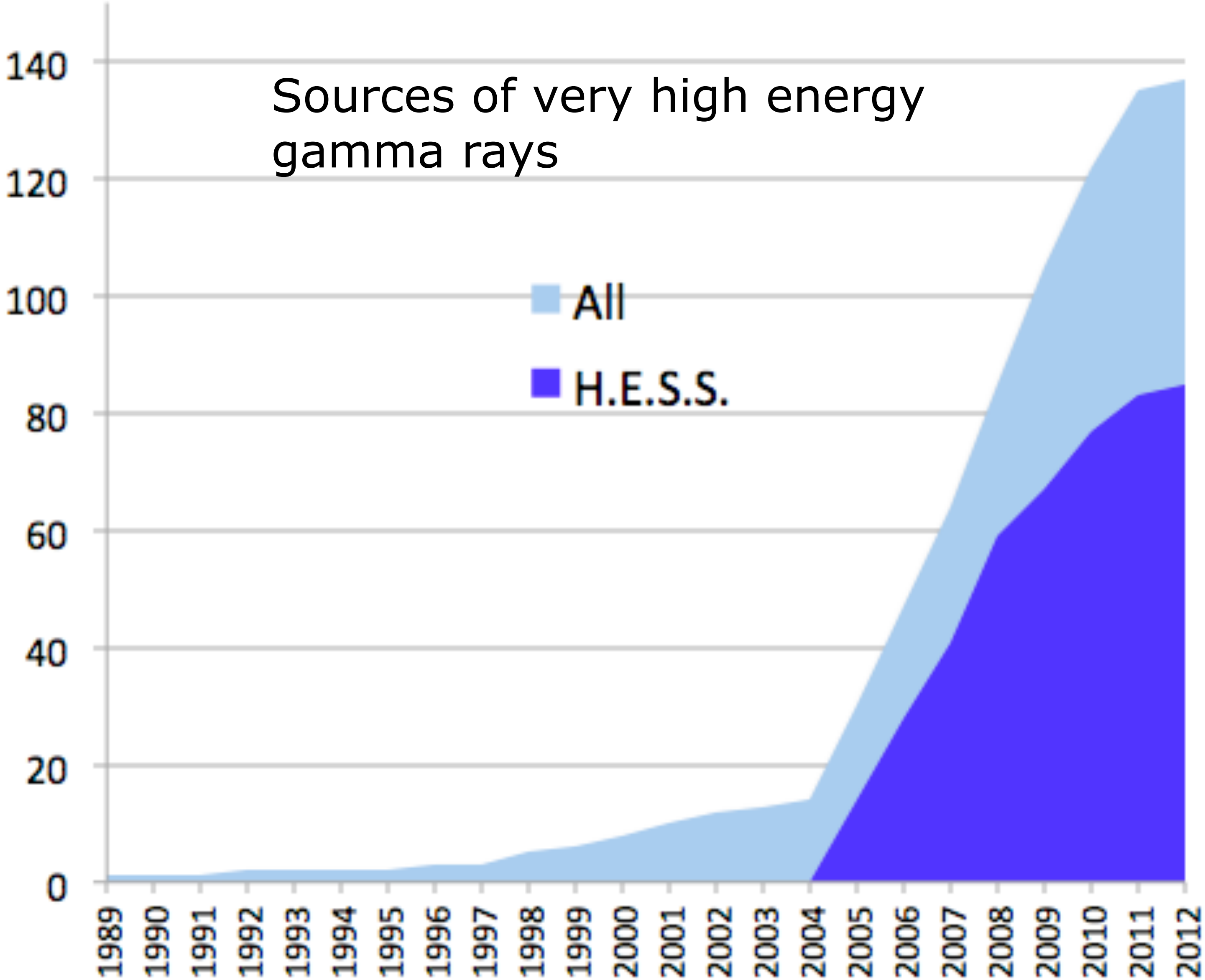
“Real astronomy” in a new energy band



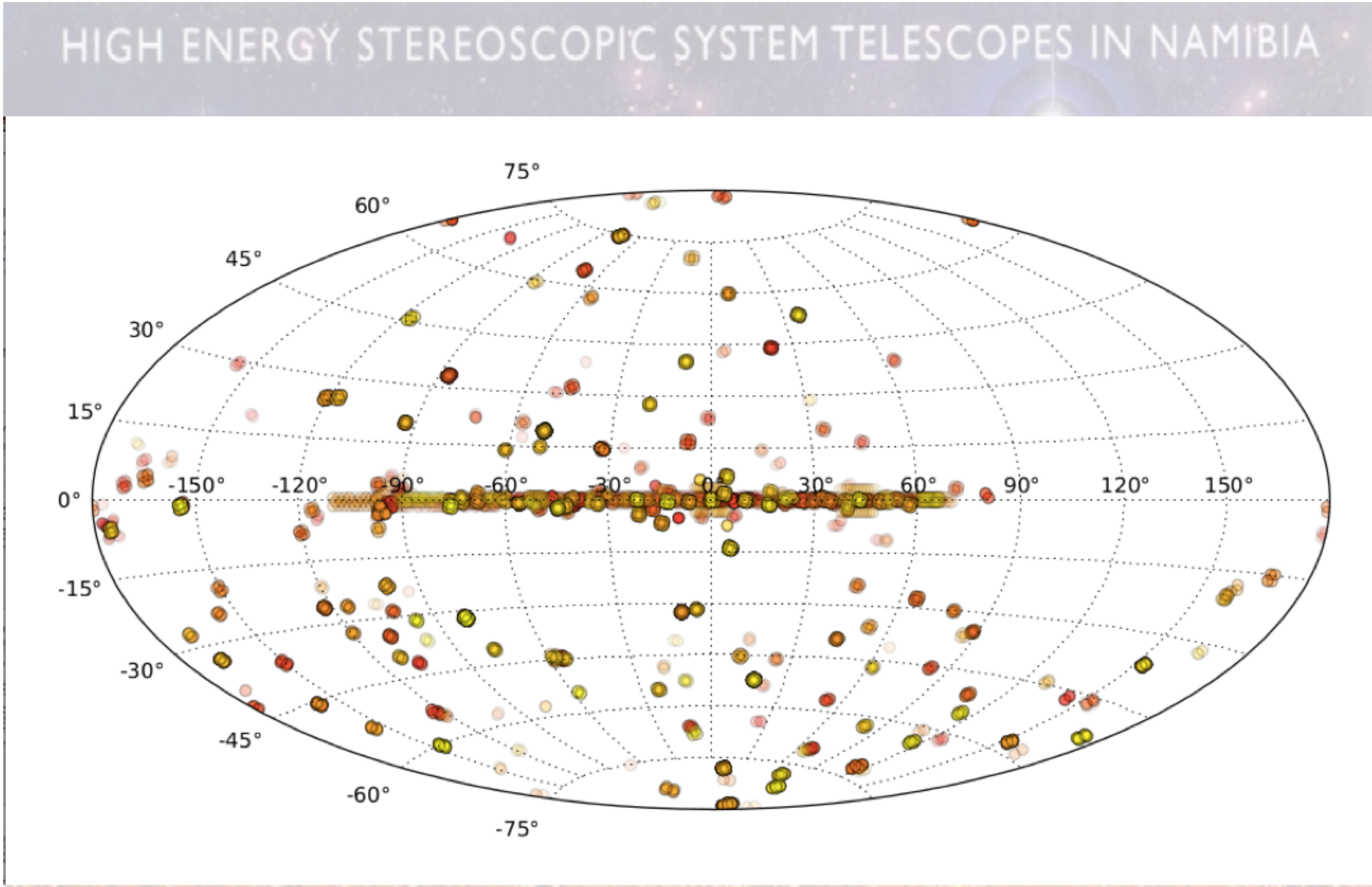
- ❑ High sensitivity
  - 3 orders of magnitude dynamic range in flux
- ❑ Wide spectral range
  - >2 orders of magnitude coverage in energy, up to 10s of TeV
  - 10-15% energy resolution
- ❑ Resolved source morphology
  - ~5′ angular resolution
  - 10-20″ source localization
- ❑ Survey capability
  - H.E.S.S. Galactic Plane Survey:
  - 2% Crab sensitivity
- ❑ Well-resolved light curves
  - Minute-scale variability of AGN

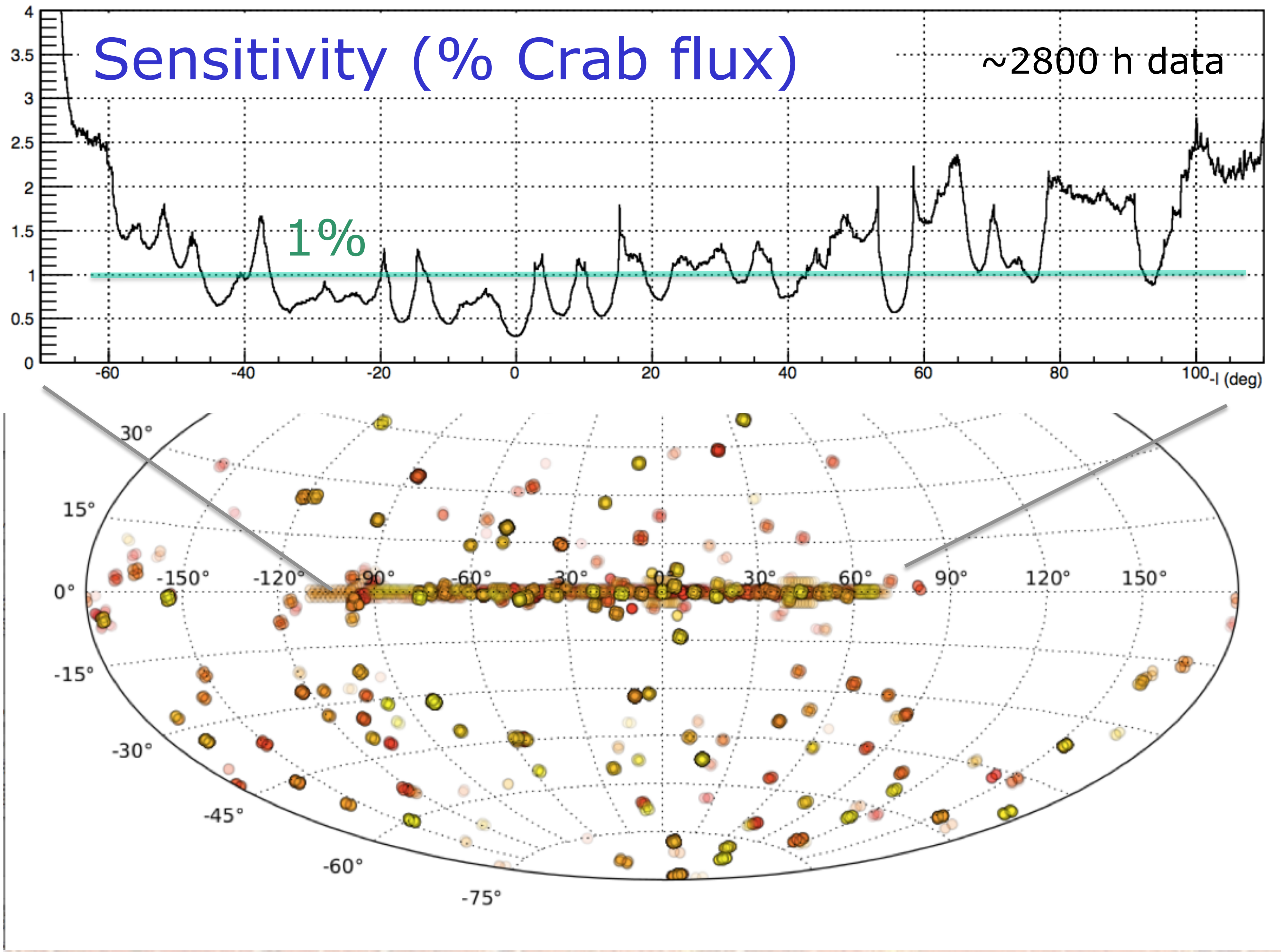
H.E.S.S. Discoveries



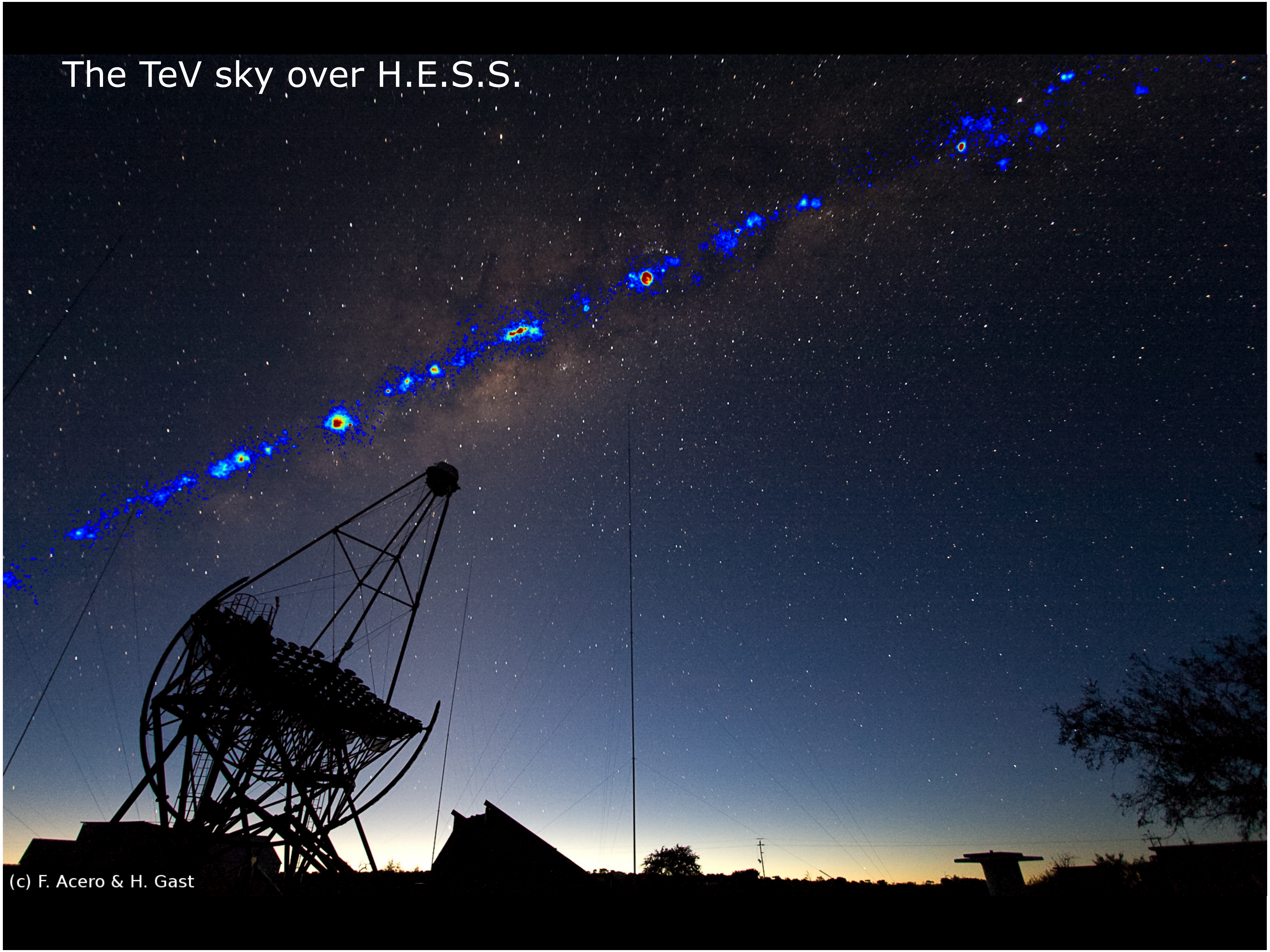


Sky coverage





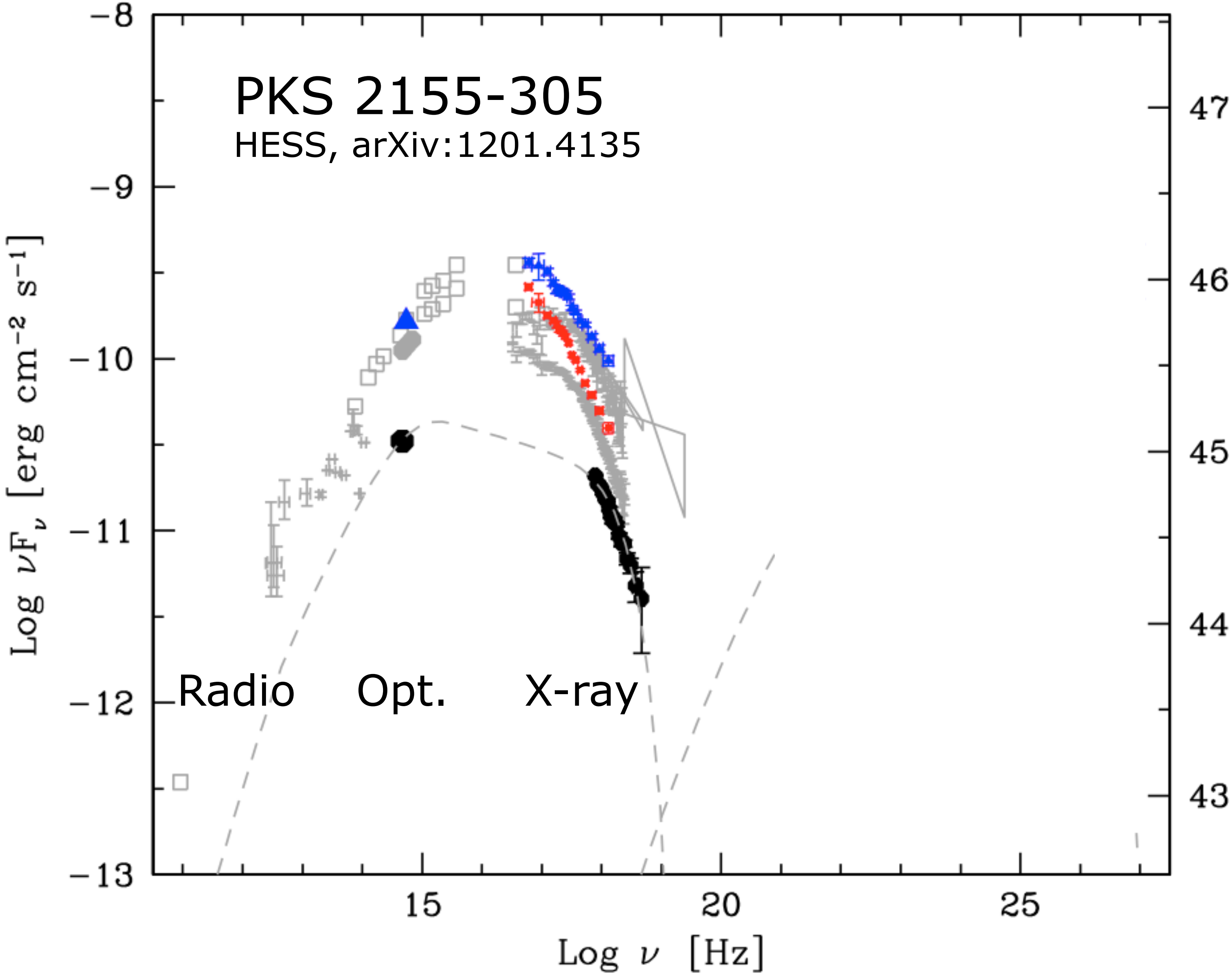
Sensitivity (% Crab flux)
~2800 h data
1%
l (deg)


The TeV sky over H.E.S.S.
(c) F. Acero & H. Gast


Cherenkov telescopes & H.E.S.S.
Why very high energy gamma-ray astronomy?
Cosmic rays, gamma rays, & the Universe
10 years H.E.S.S.: The TeV sky
Beyond 2012
(c) F. Acero & H. Gast


Roberta Weir

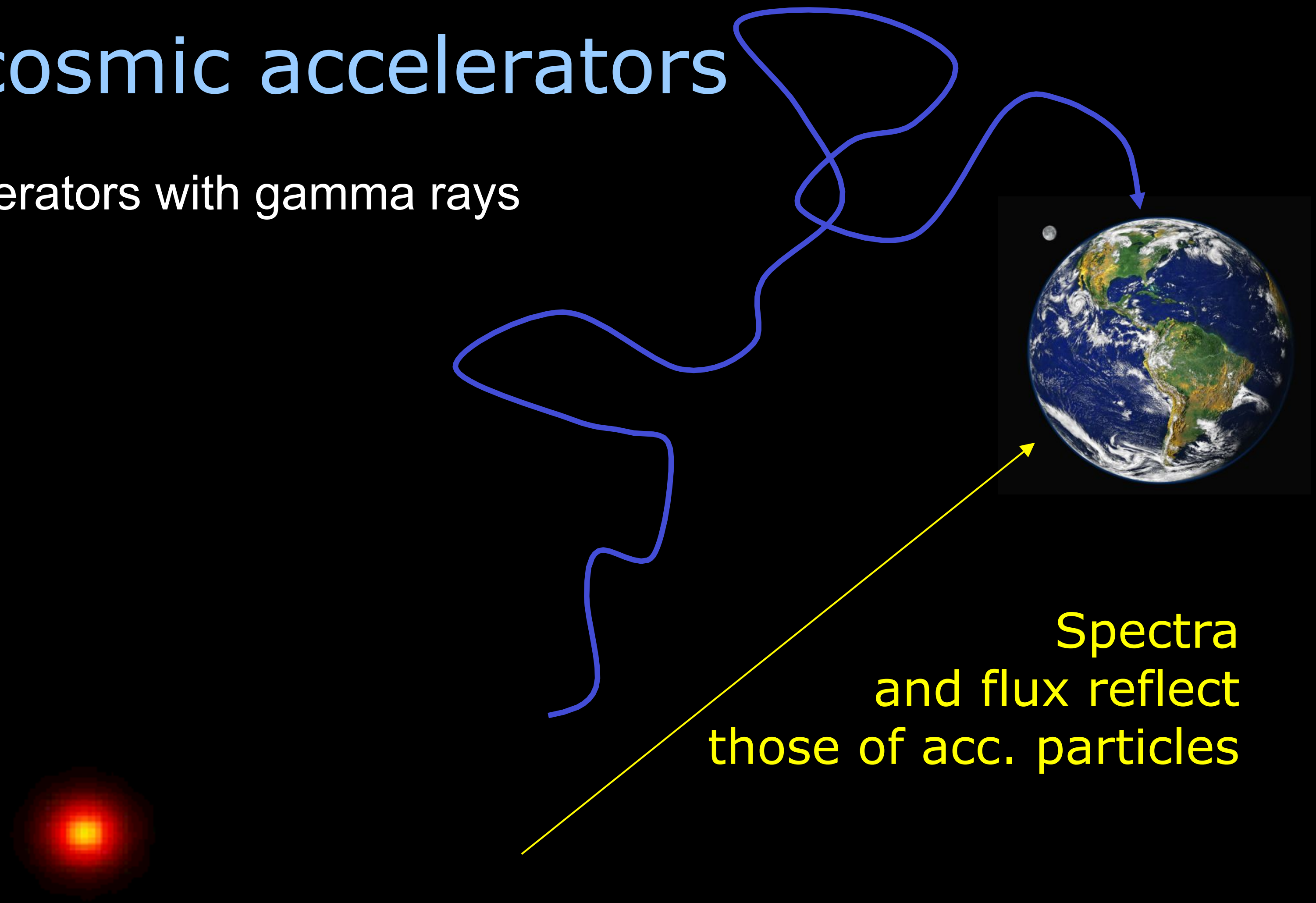
Energy output across EM spectrum



Motivation II:
Seeing cosmic particle accelerators

Seeing cosmic accelerators

➔ Image accelerators with gamma rays



Spectra
and flux reflect
those of acc. particles

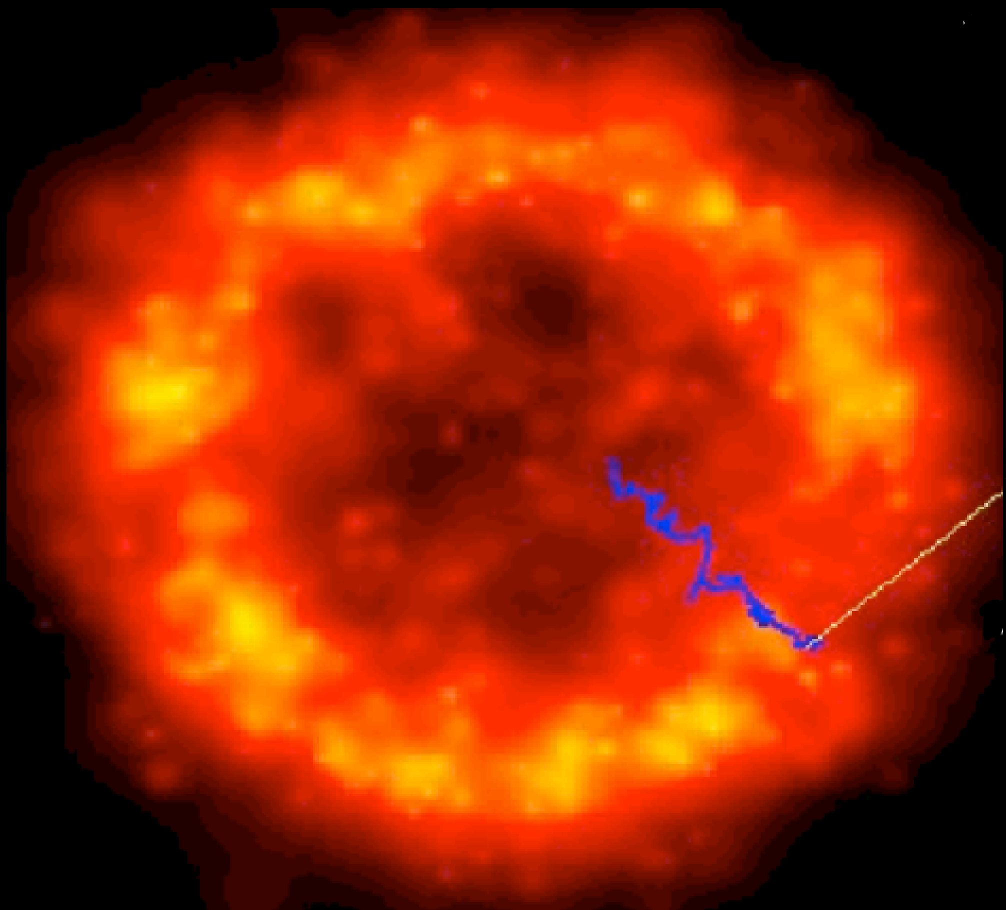
p + nucleus ➔ π +X

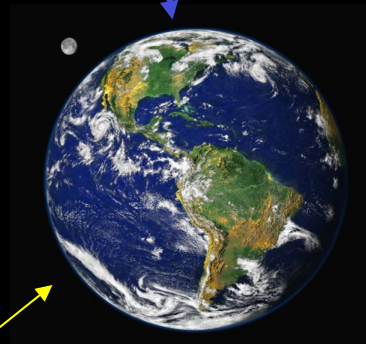
π^{o} ➔ $\gamma\gamma$

$\pi^{\pm}$ ➔ $\mu^{\pm}$ ν

Seeing cosmic accelerators

➔ Image accelerators with gamma rays





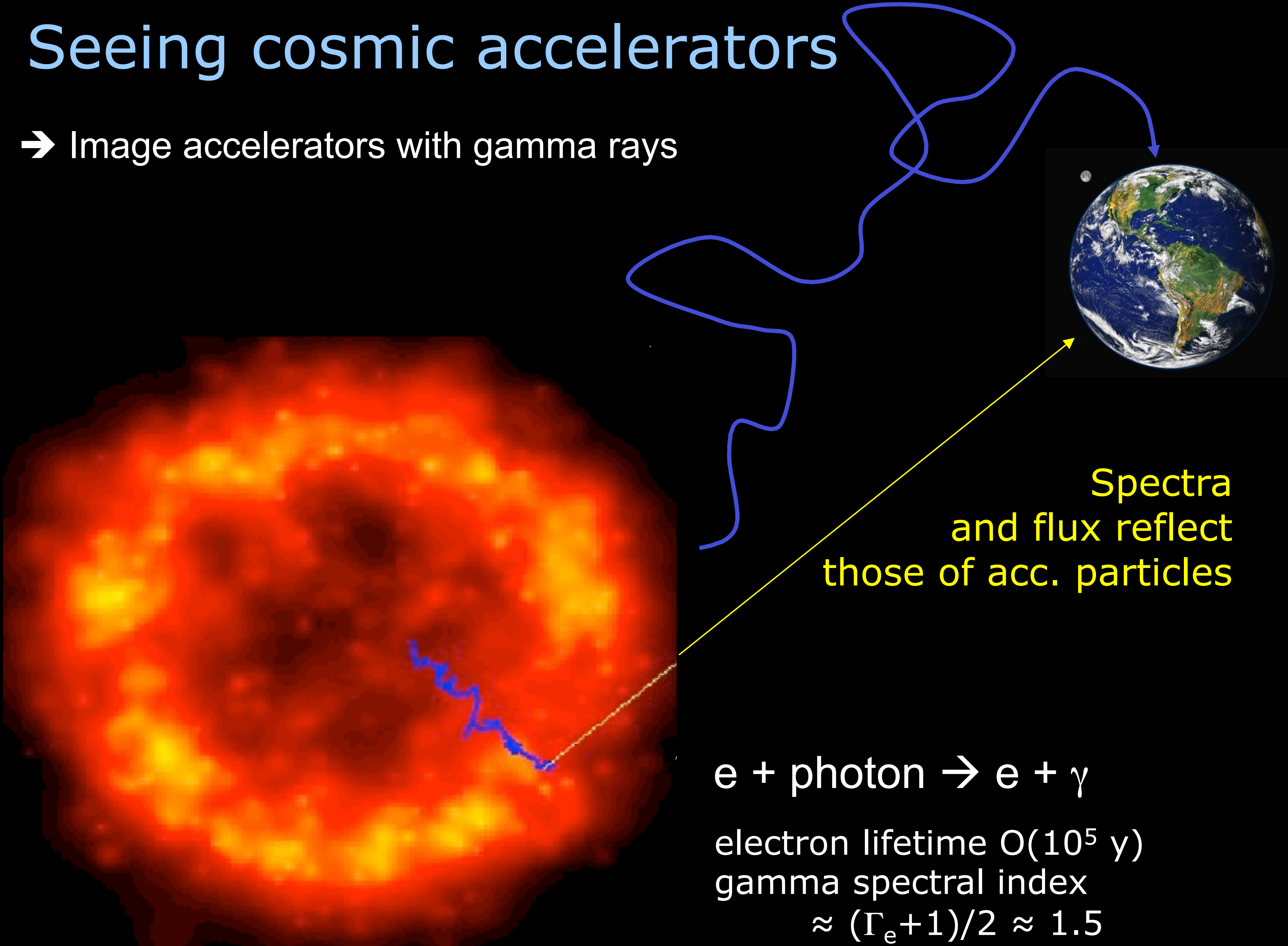
Spectra
and flux reflect
those of acc. particles

p + nucleus ➔ π +X

proton lifetime O(10^7 y)
gamma spectral index
≈ proton index ≈ 2

Seeing cosmic accelerators

➔ Image accelerators with gamma rays

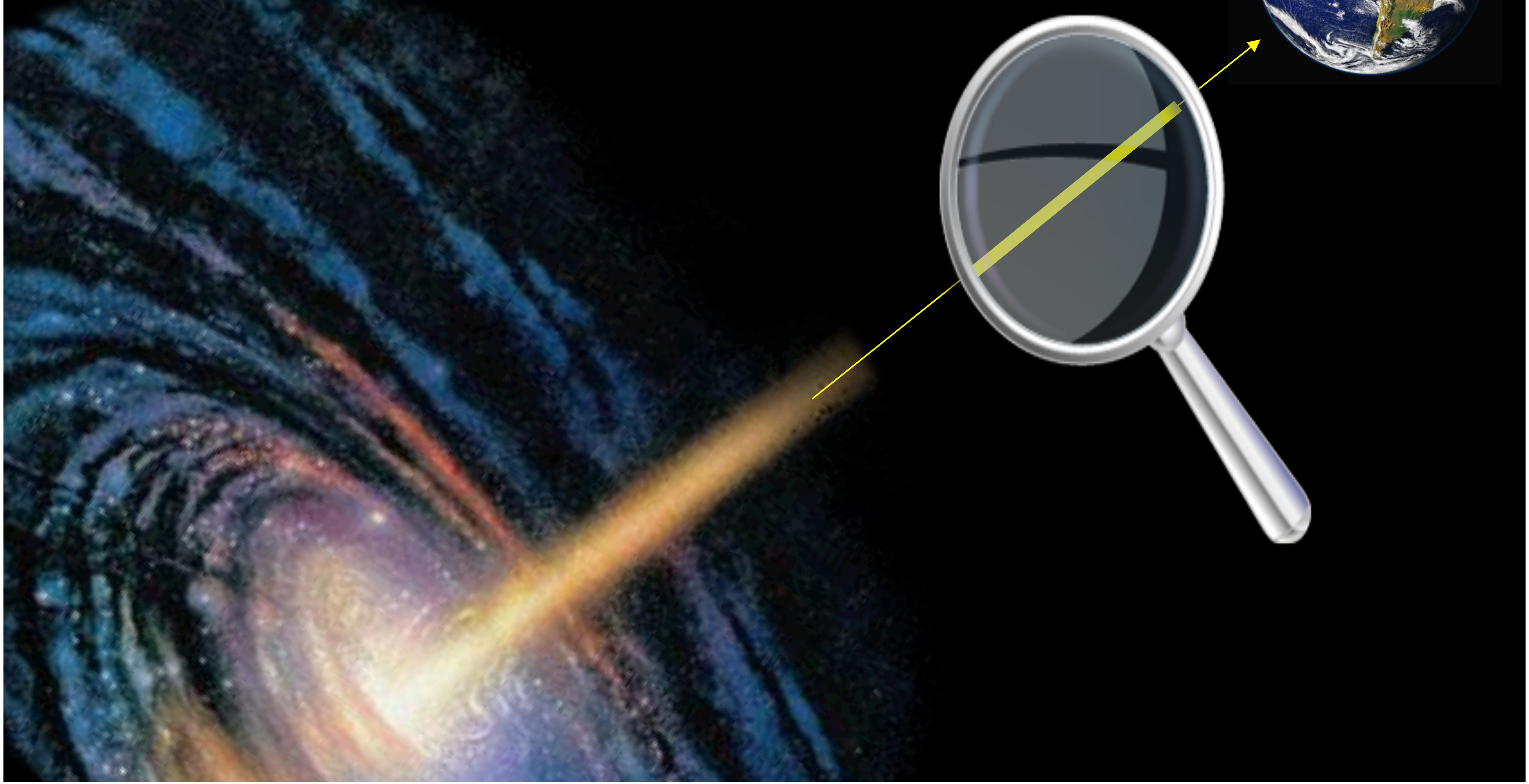


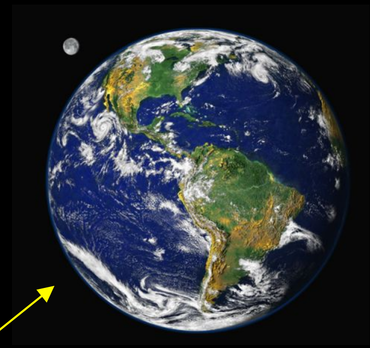
Spectra
and flux reflect
those of acc. particles

e + photon ➔ e + γ

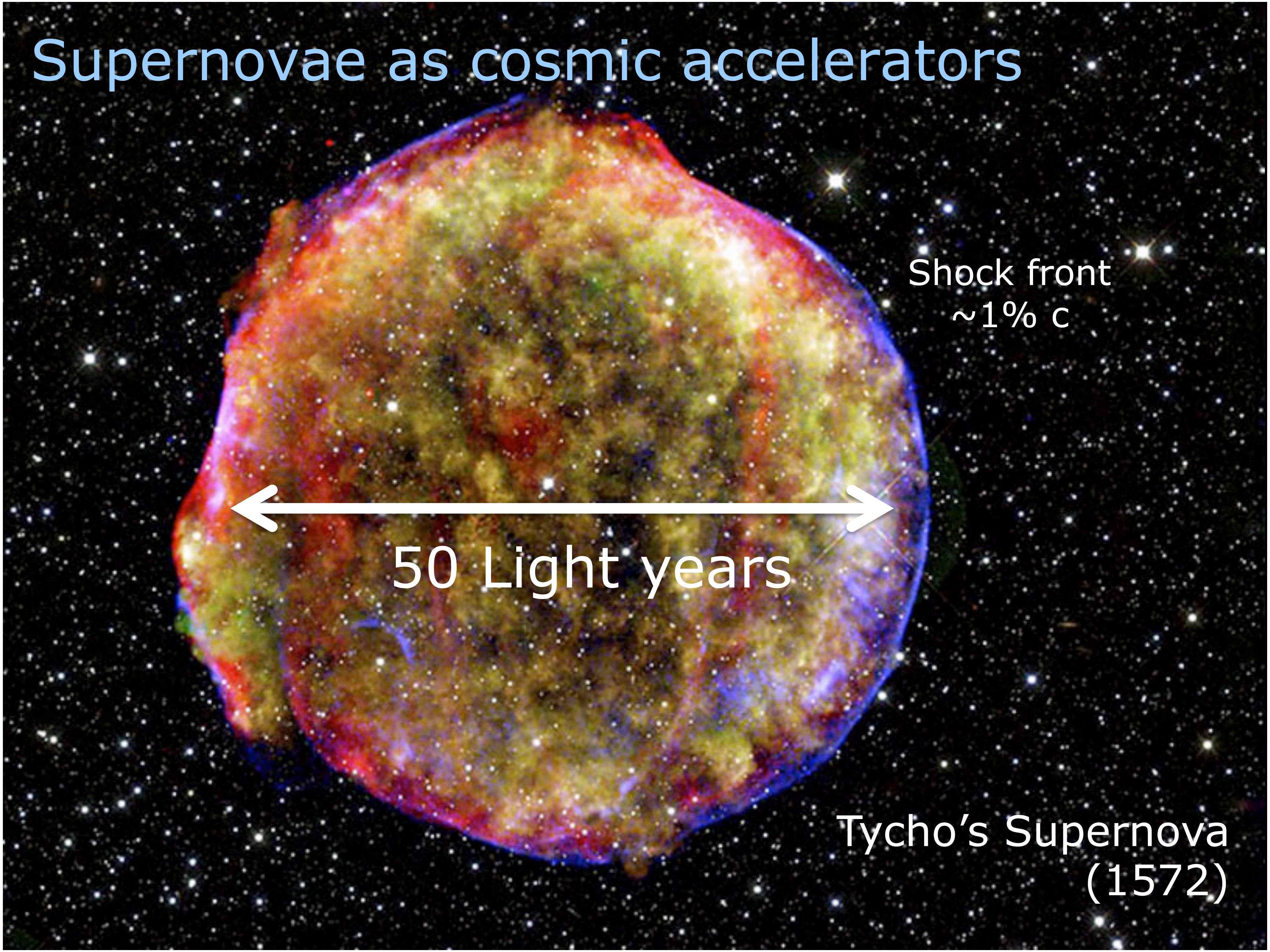
electron lifetime O(10^5 y)
gamma spectral index
$\approx (\Gamma_e+1)/2 \approx 1.5$

Motivation III:
Fundamental Physics –
Photon propagation,
Dark Matter annihilation

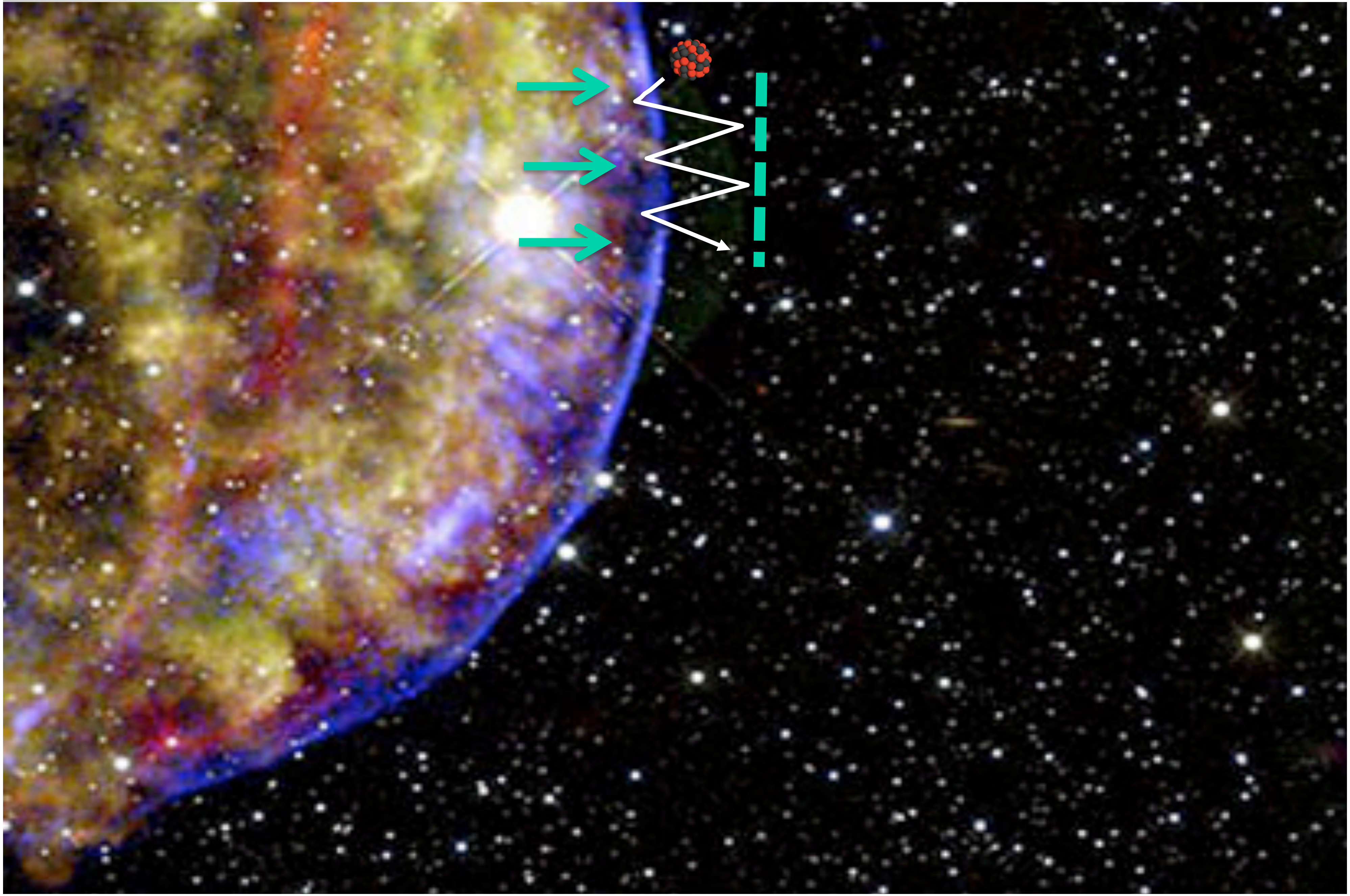




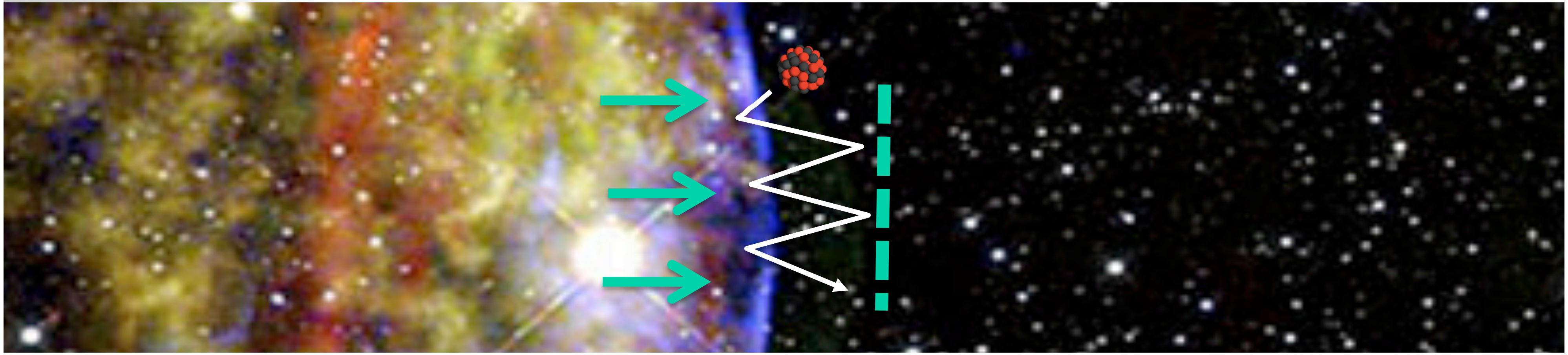
Cherenkov telescopes & H.E.S.S.
Why very high energy gamma-ray astronomy?
Cosmic rays, gamma rays, & the Universe
10 years H.E.S.S.: The TeV sky
Beyond 2012


Supernovae as cosmic accelerators
Shock front
~1% c
50 Light years
Tycho's Supernova
(1572)

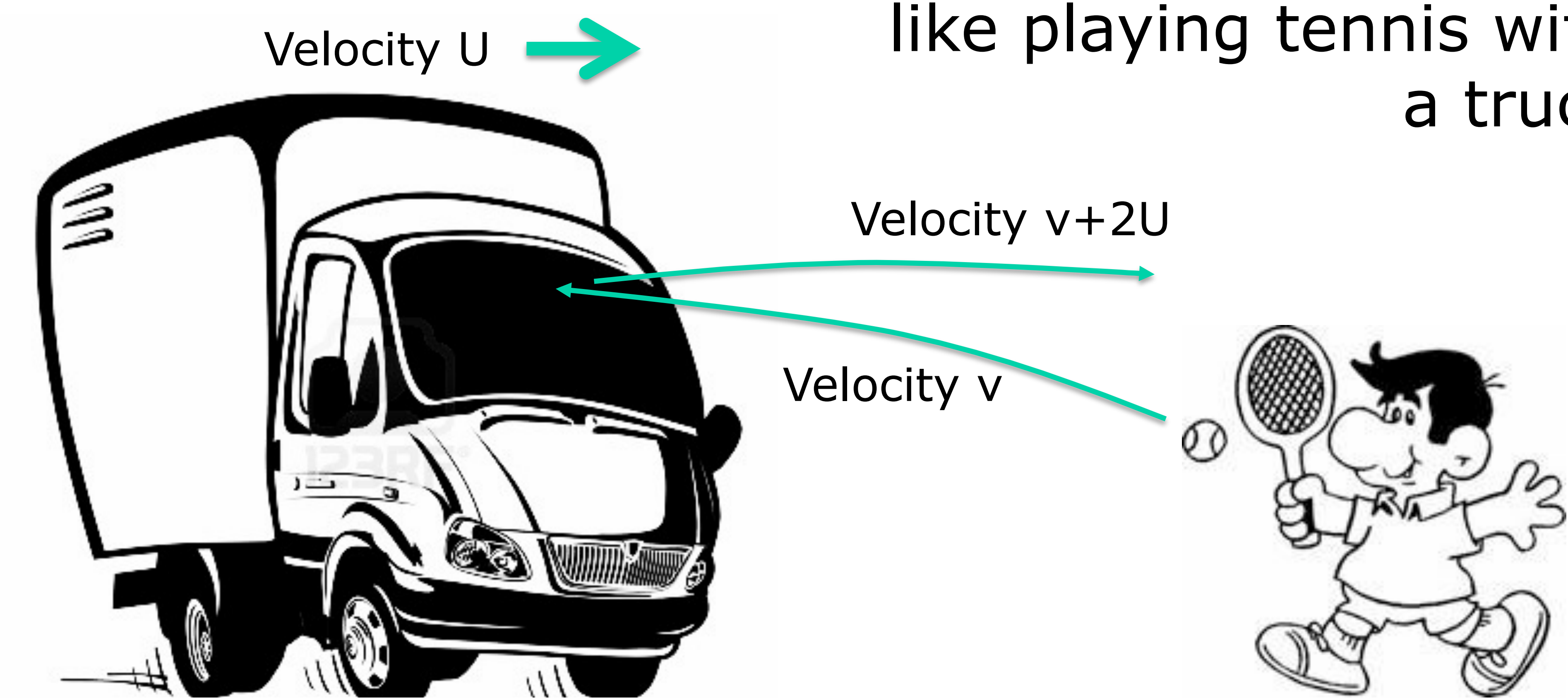
Fermi Acceleration



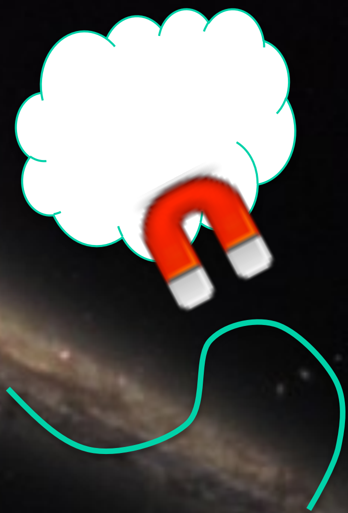
Fermi Acceleration



like playing tennis with a truck



Cosmic rays and our Galaxy



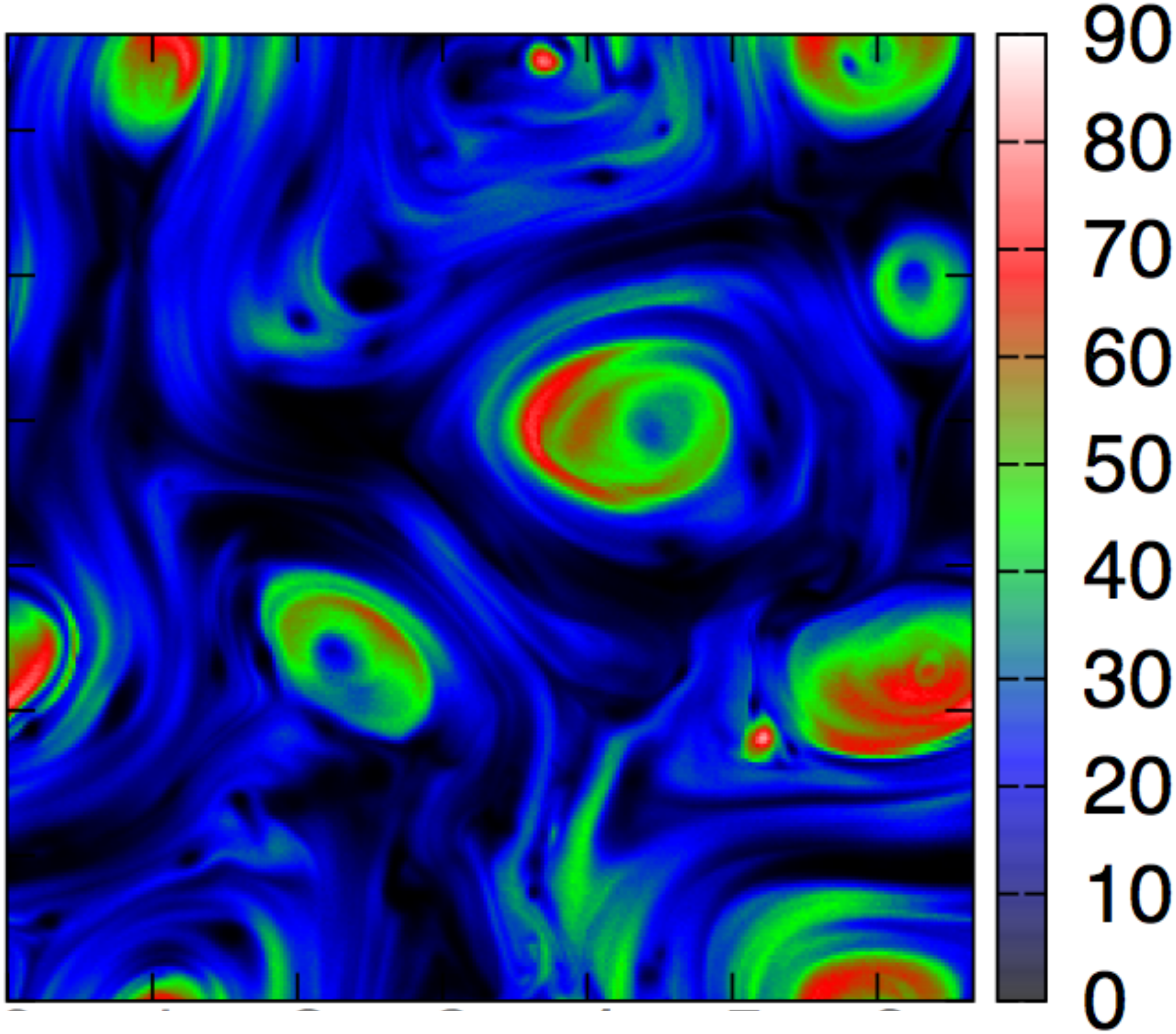
Energy density in CR

≅ Energy density in magnetic fields

≅ Energy density in gas kinetic energy

➜ "beam bends accelerator"

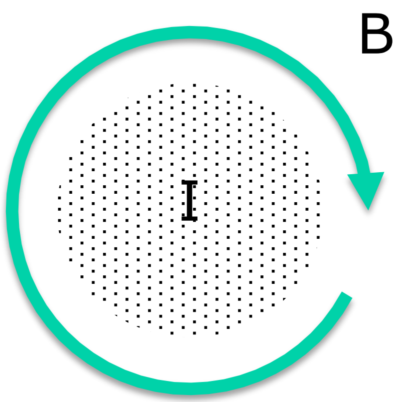
Field amplification by streaming CRs



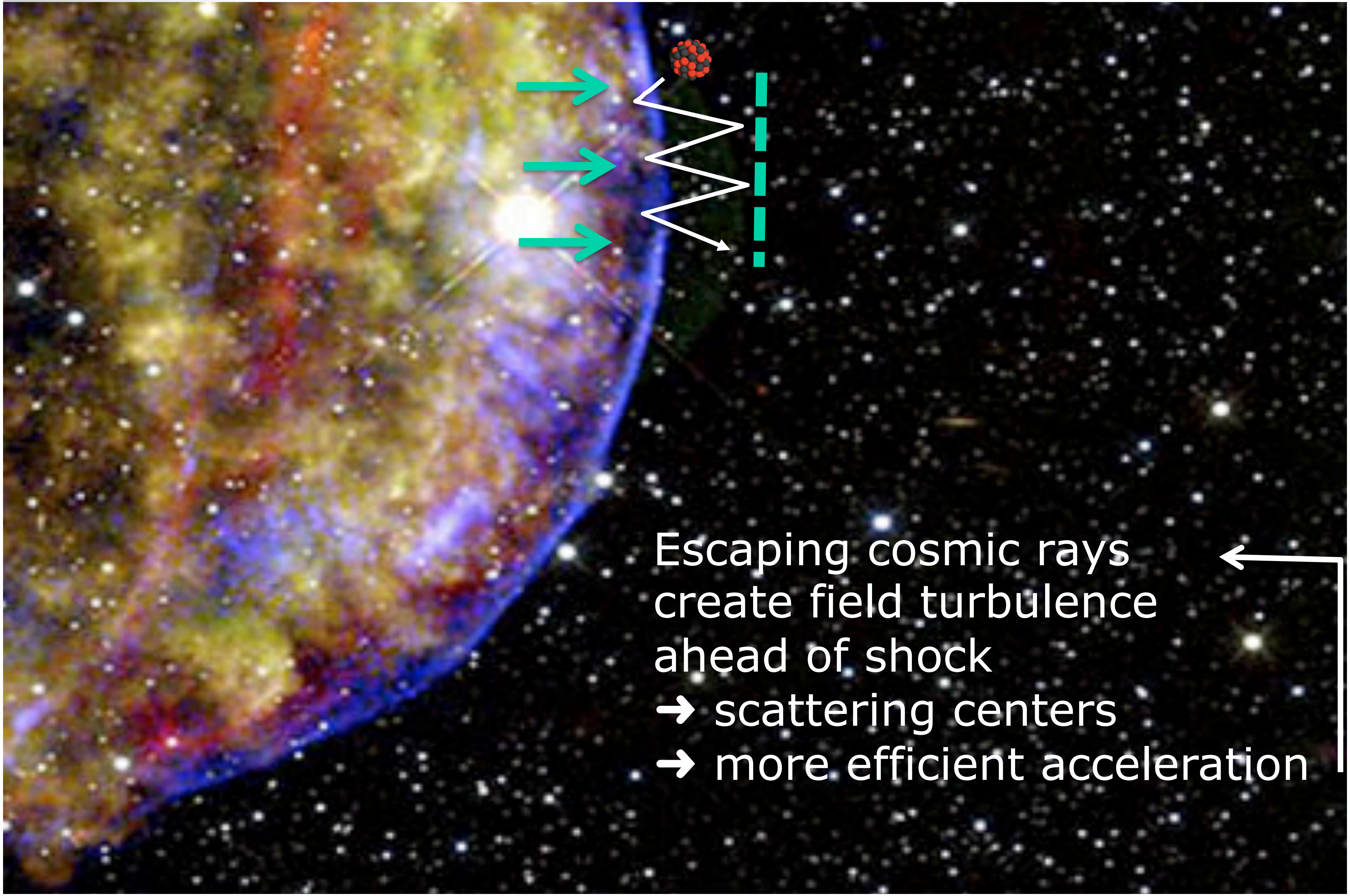
Front view:

Magnetic field

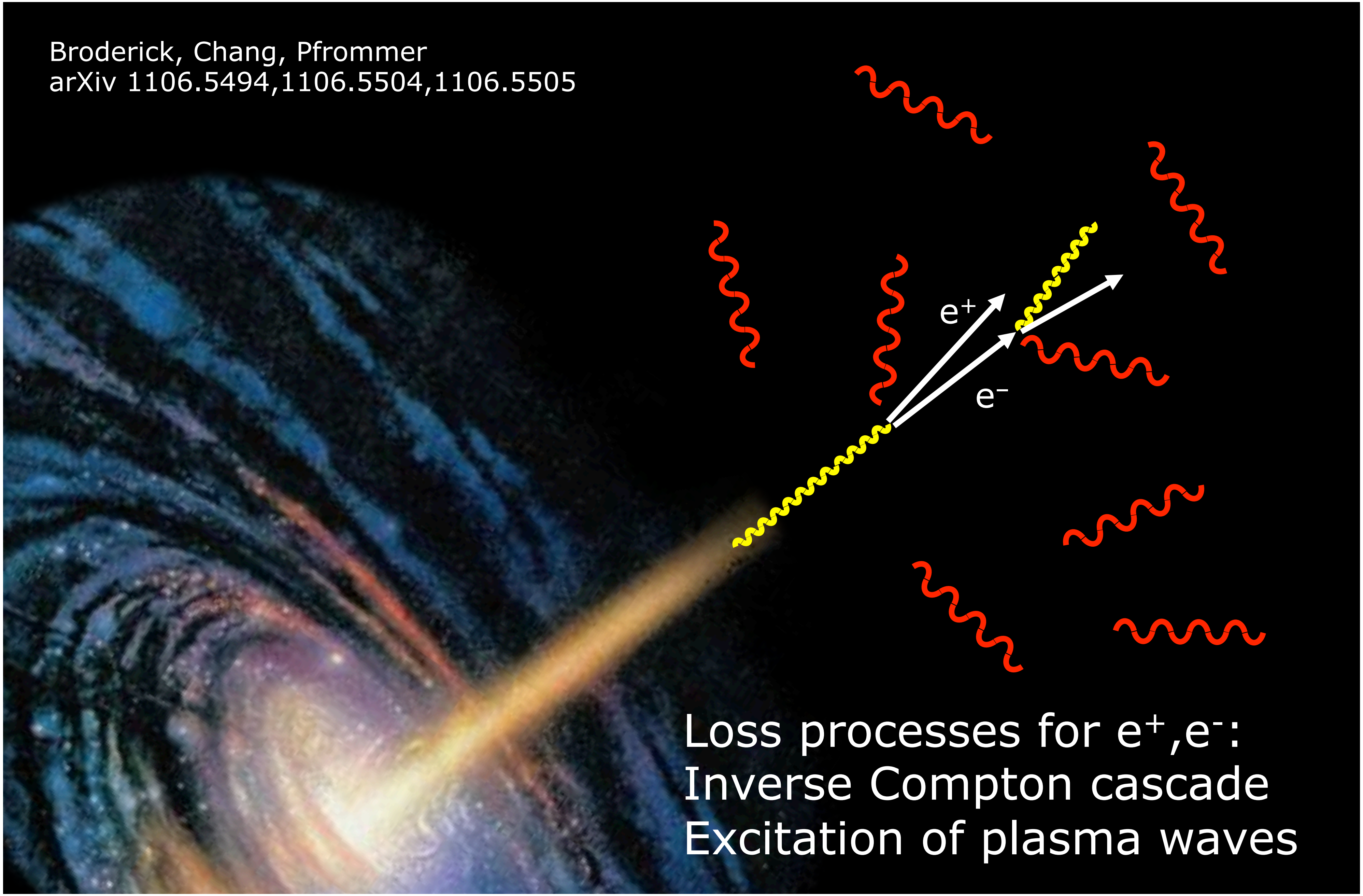
Ohira et al.
arXiv:0812.0901



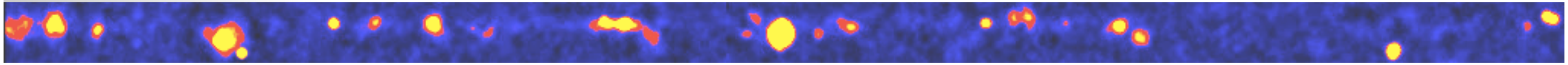
Fermi Acceleration



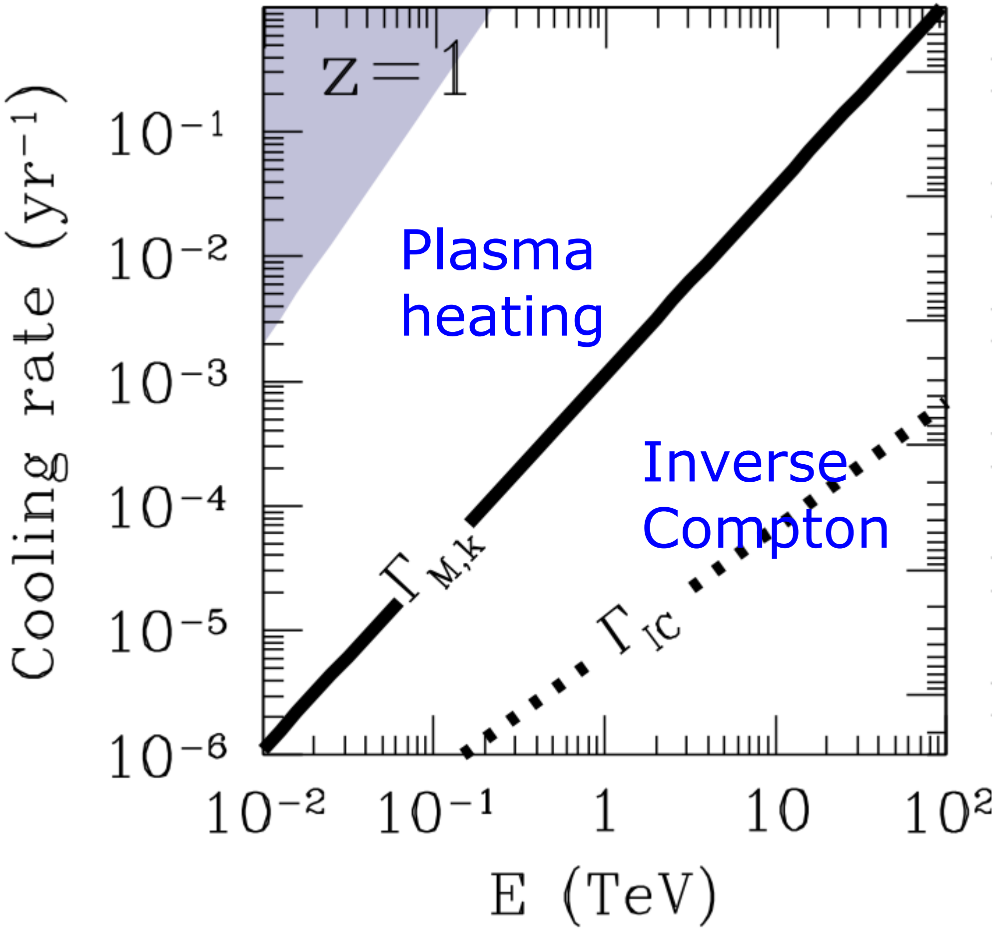
Latest twist: Blazar heating



Latest twist: Blazar heating



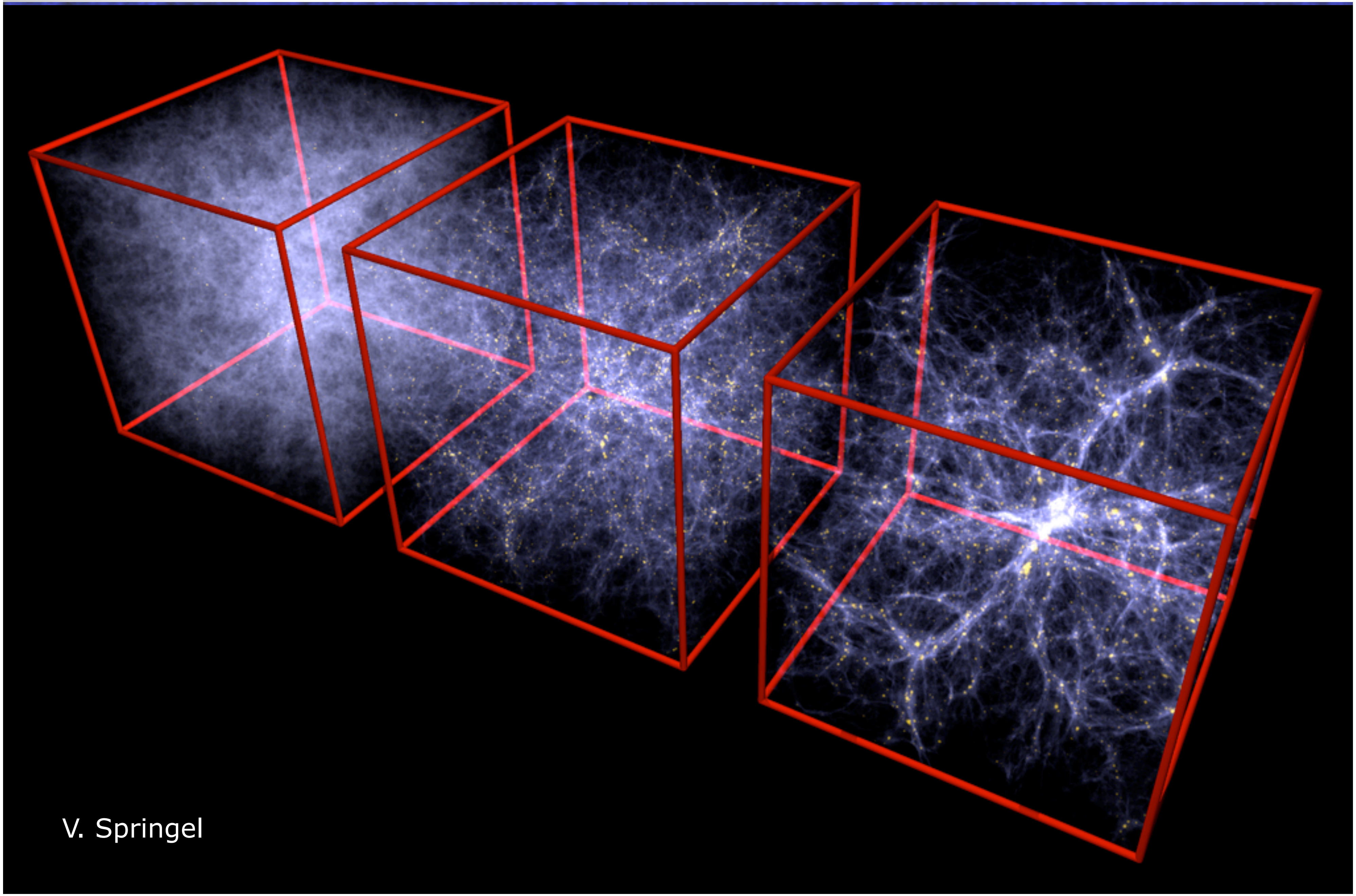
Broderick, Chang, Pfrommer
arXiv 1106.5494,1106.5504,1106.5505



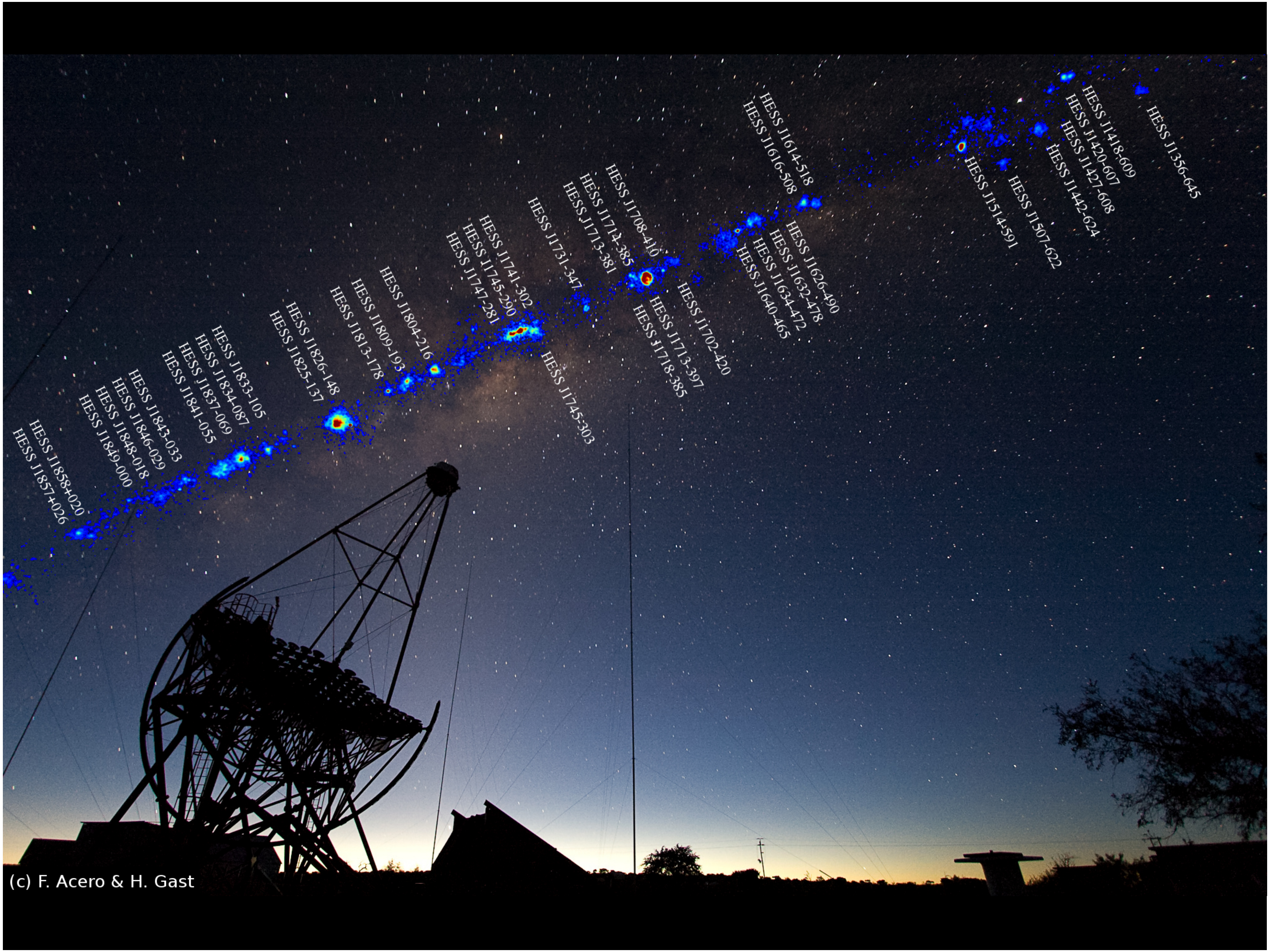
Plasma waves heat extragalactic gas:

10^4 K ➜ 10^5 K @ z = 2

Bad news for dwarf galaxies




10 years
H.E.S.S.:
The TeV Sky
(c) F. Acero & H. Gast

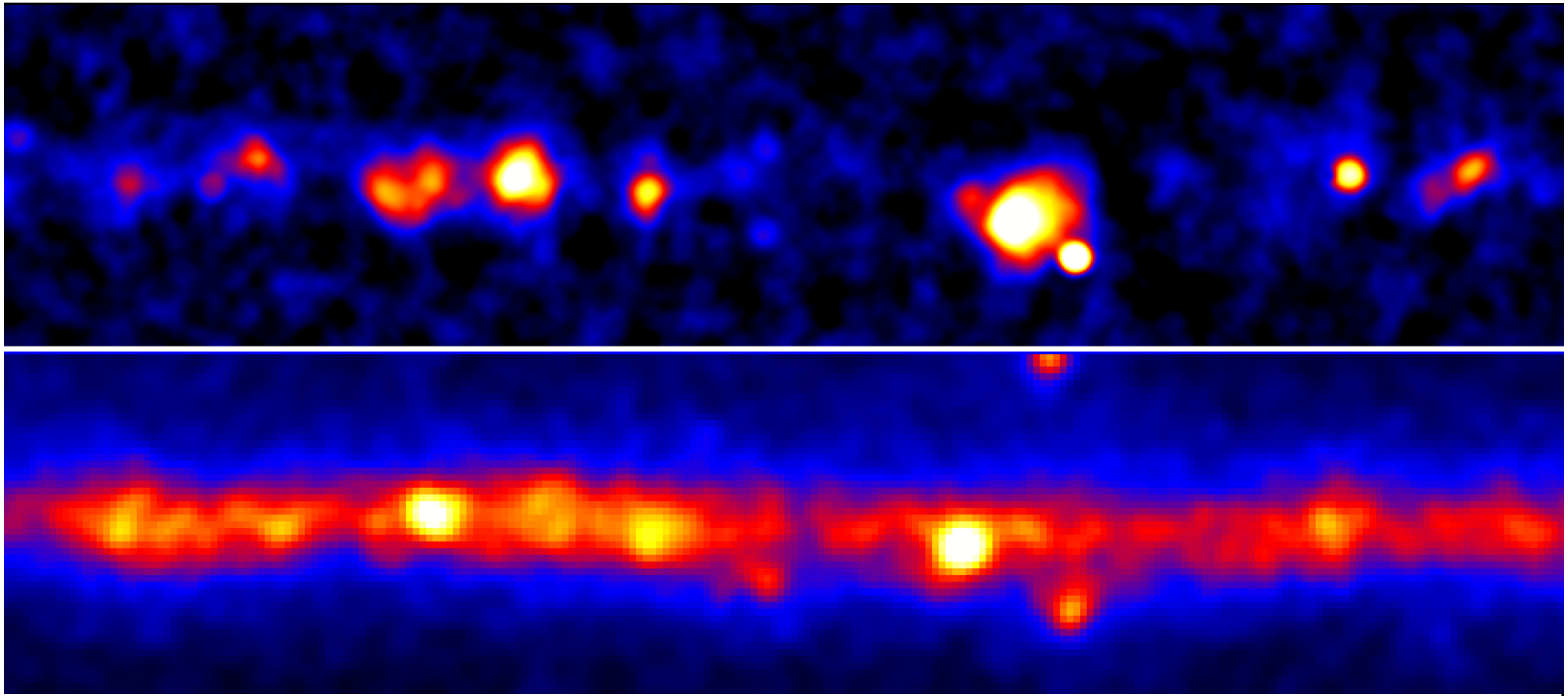


HESS J1858+020
HESS J1857+026
HESS J1849-000
HESS J1848-018
HESS J1846-029
HESS J1843-033
HESS J1841-055
HESS J1837-069
HESS J1834-087
HESS J1833-105
HESS J1826-148
HESS J1825-137
HESS J1813-178
HESS J1809-193
HESS J1804-216
HESS J1747-281
HESS J1745-290
HESS J1741-302
HESS J1745-303
HESS J1731-347
HESS J1713-381
HESS J1714-385
HESS J1708-410
HESS J1718-385
HESS J1713-397
HESS J1702-420
HESS J1640-465
HESS J1634-472
HESS J1632-478
HESS J1626-490
HESS J1616-508
HESS J1614-518
HESS J1514-591
HESS J1507-622
HESS J1442-624
HESS J1427-608
HESS J1420-607
HESS J1418-609
HESS J1356-645
(c) F. Acero & H. Gast

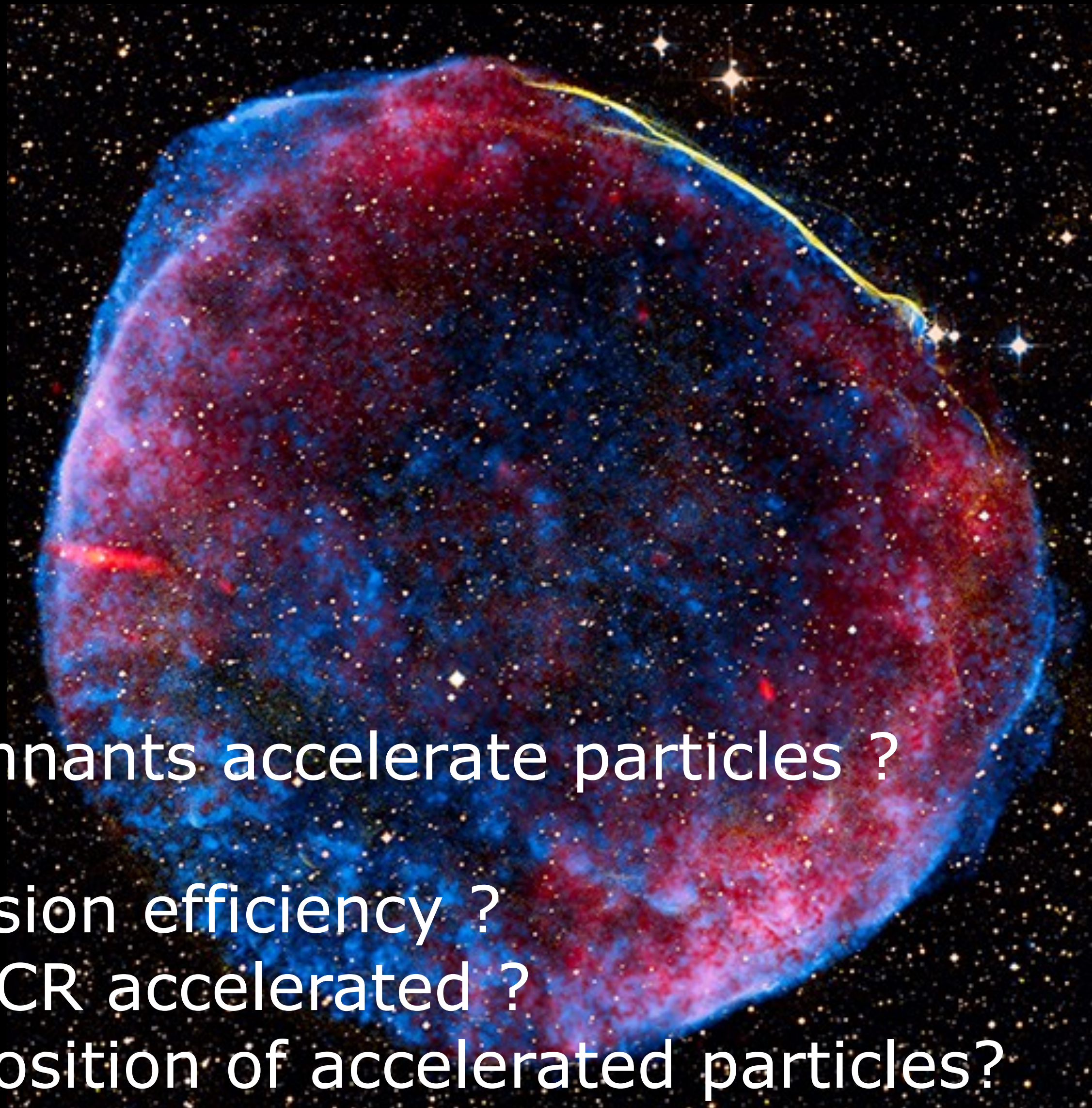
Surveys: The High Energy Milky Way

Extended sources, size typically few 0.1°
few 10 pc

H.E.S.S. (TeV)

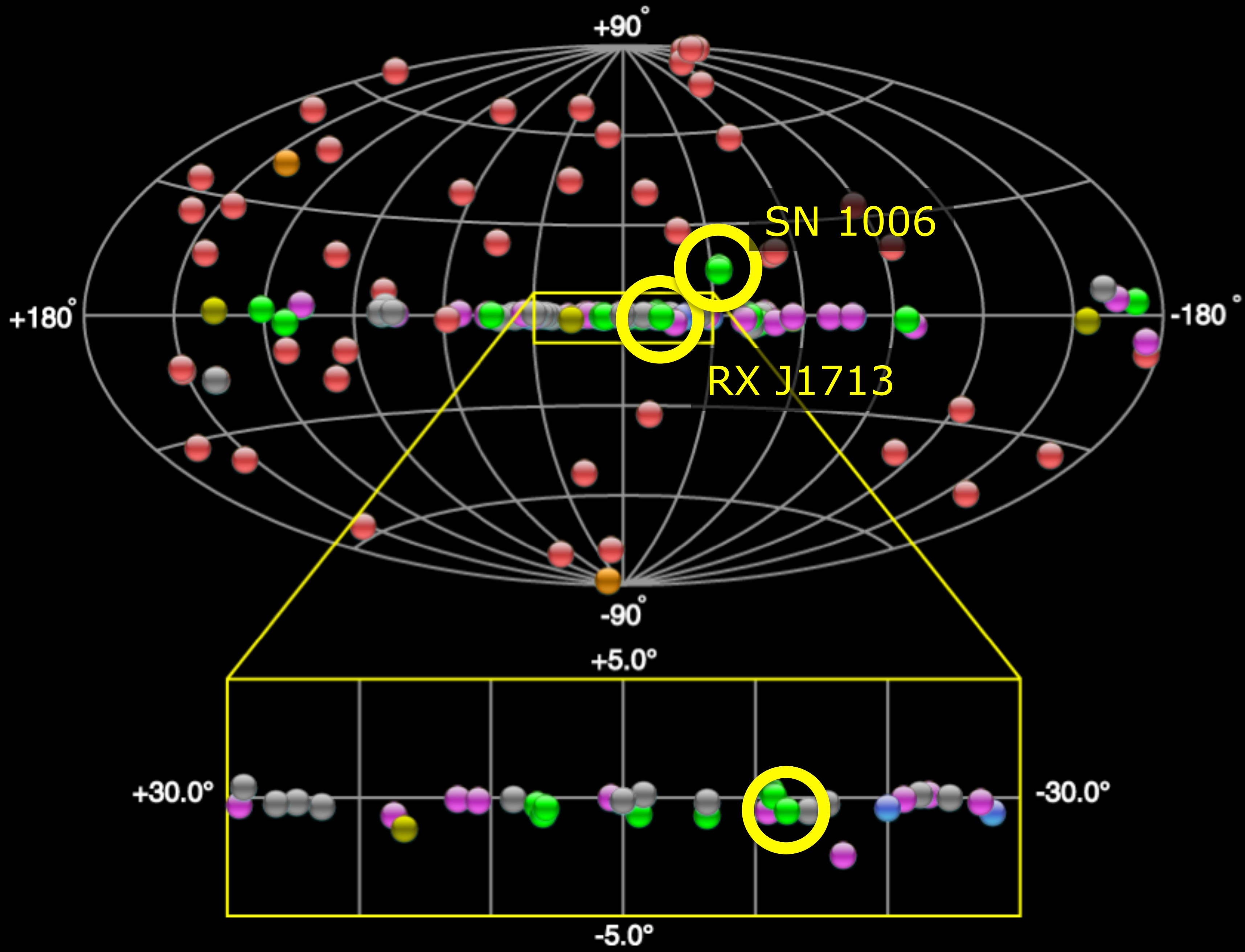


Fermi-LAT (GeV)



Do supernova remnants accelerate particles ?
To PeV energies ?
With what conversion efficiency ?
How in detail are CR accelerated ?
What is the composition of accelerated particles?
How are they released from the remnant?
Can SNR account for flux and spectrum of galactic CR?

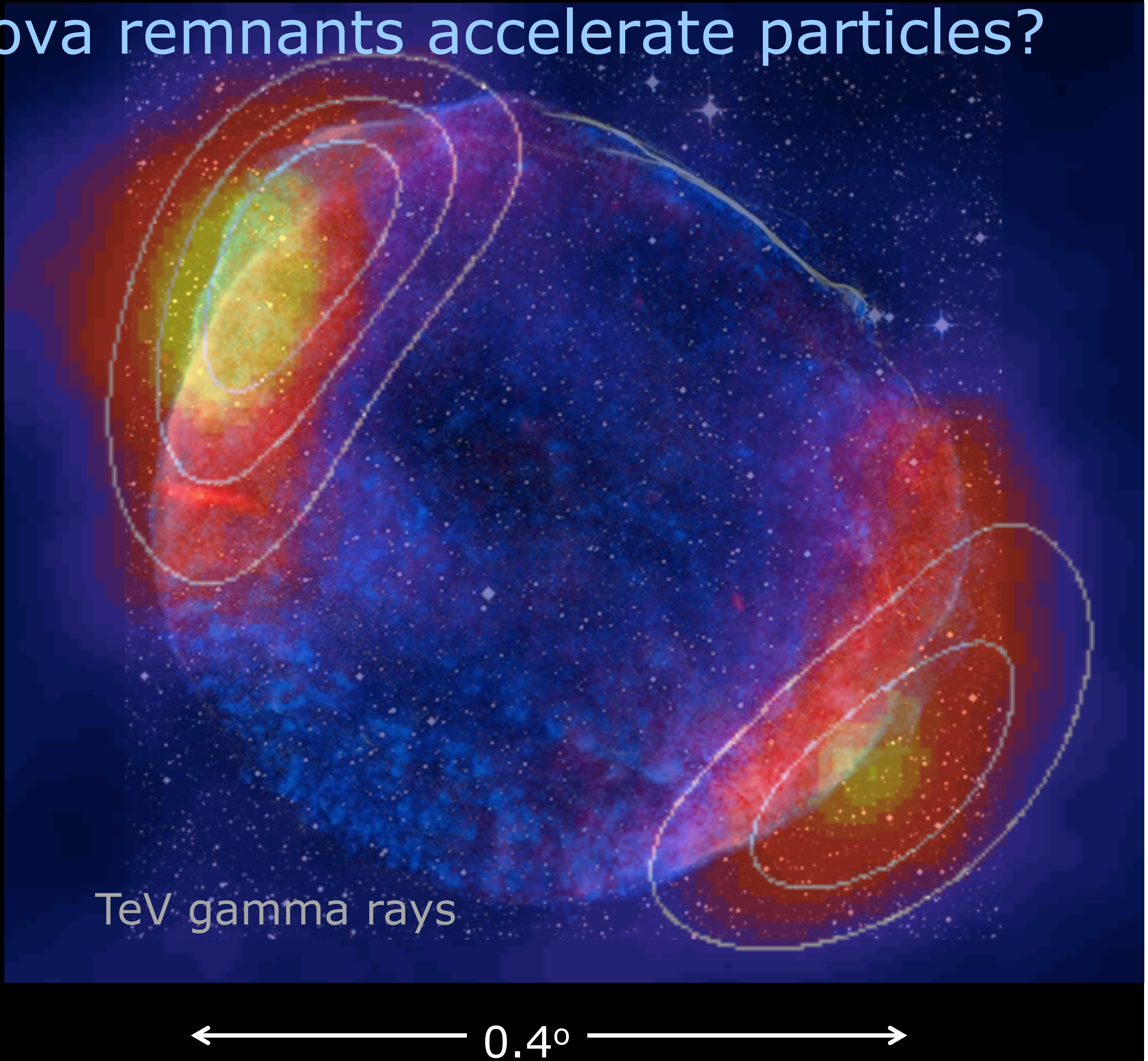
Supernova remnants



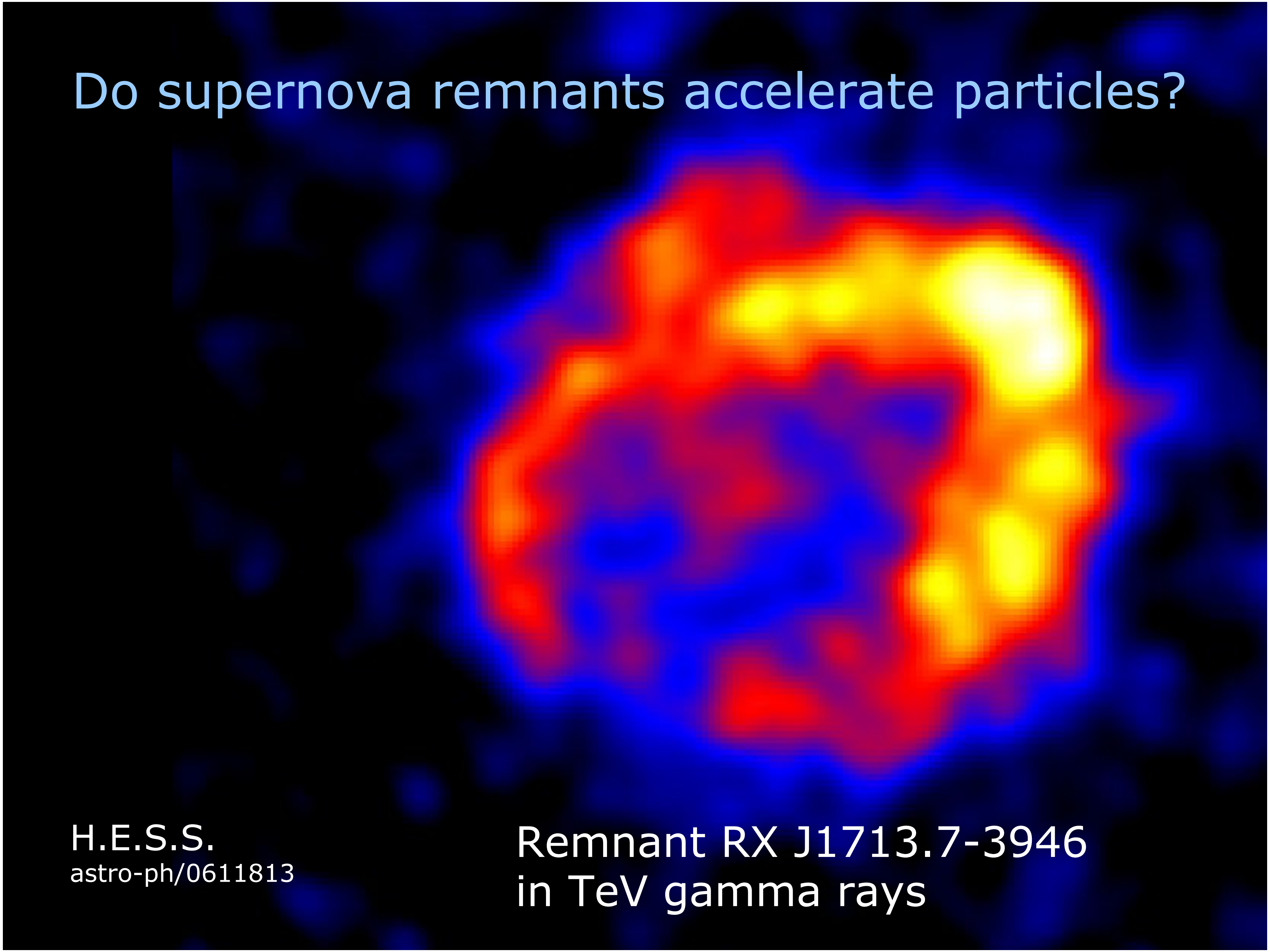
Do supernova remnants accelerate particles?

SN 1006

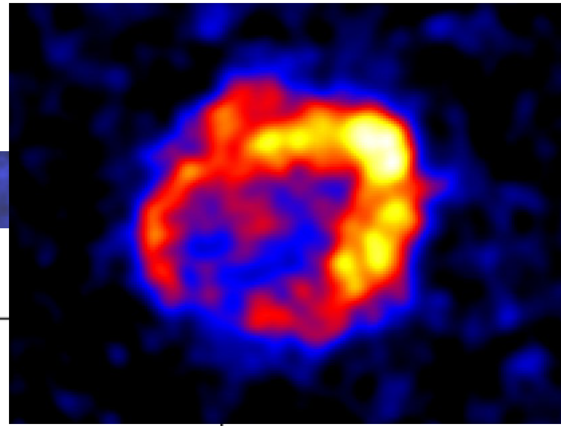
H.E.S.S.
arXiv:1004.2124



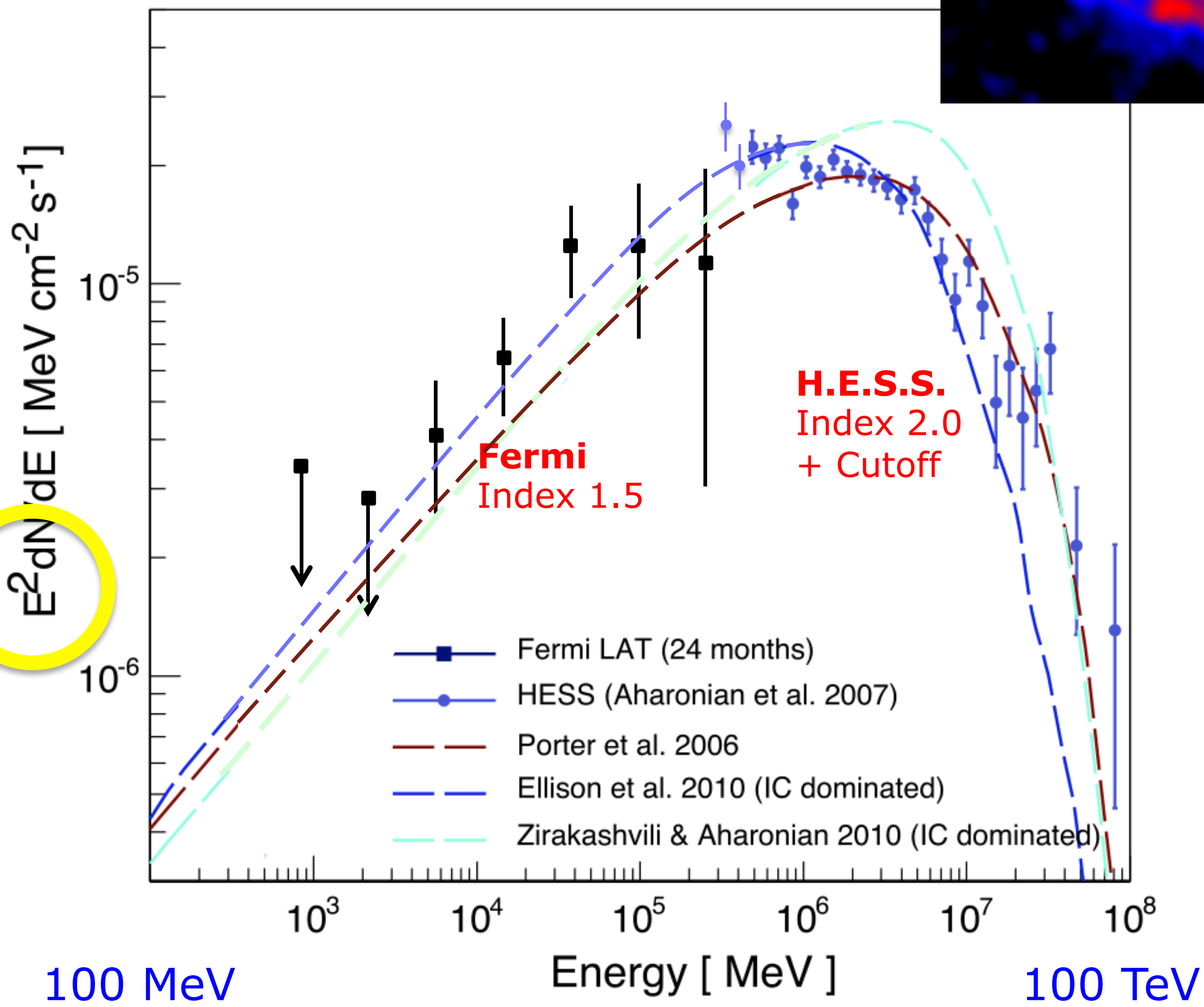
(Credit:X-ray: NASA/CXC/ Rutgers/G.Cassam-Chenai, J.Hughes et al.; Radio: NRAO/ AUI/NSF/GBT/VLA/Dyer, Maddalena & Cornwell; Optical: Middlebury College/ F.Winkler, NOAO/AURA/NSF/ CTIO Schmidt & DSS)

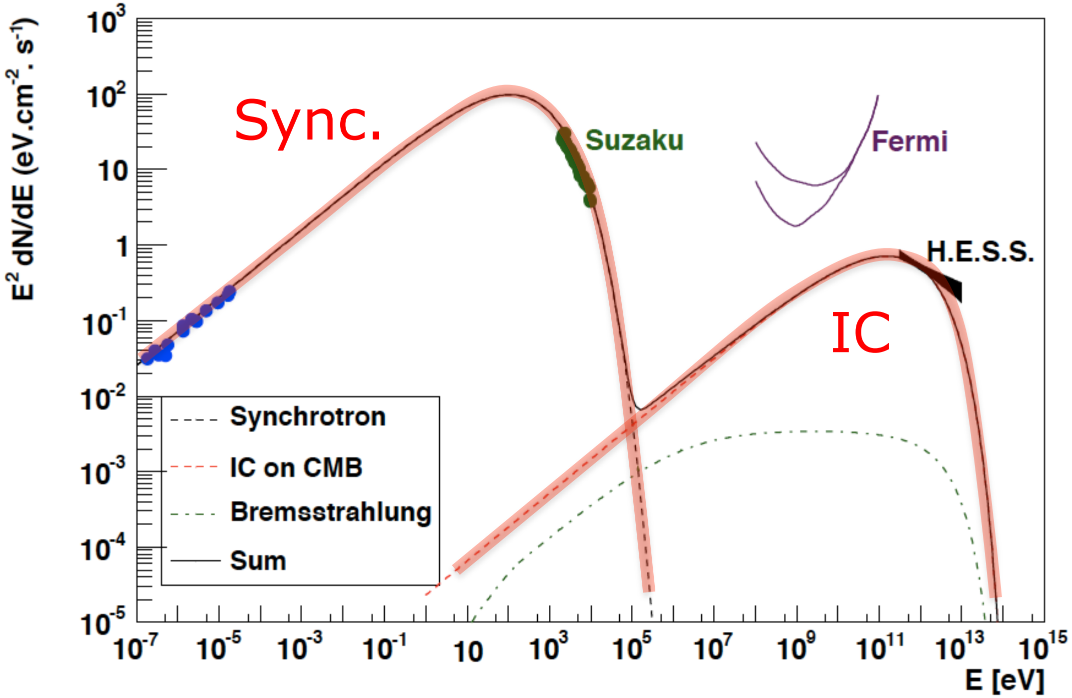

Do supernova remnants accelerate particles?
H.E.S.S.
astro-ph/0611813
Remnant RX J1713.7-3946
in TeV gamma rays

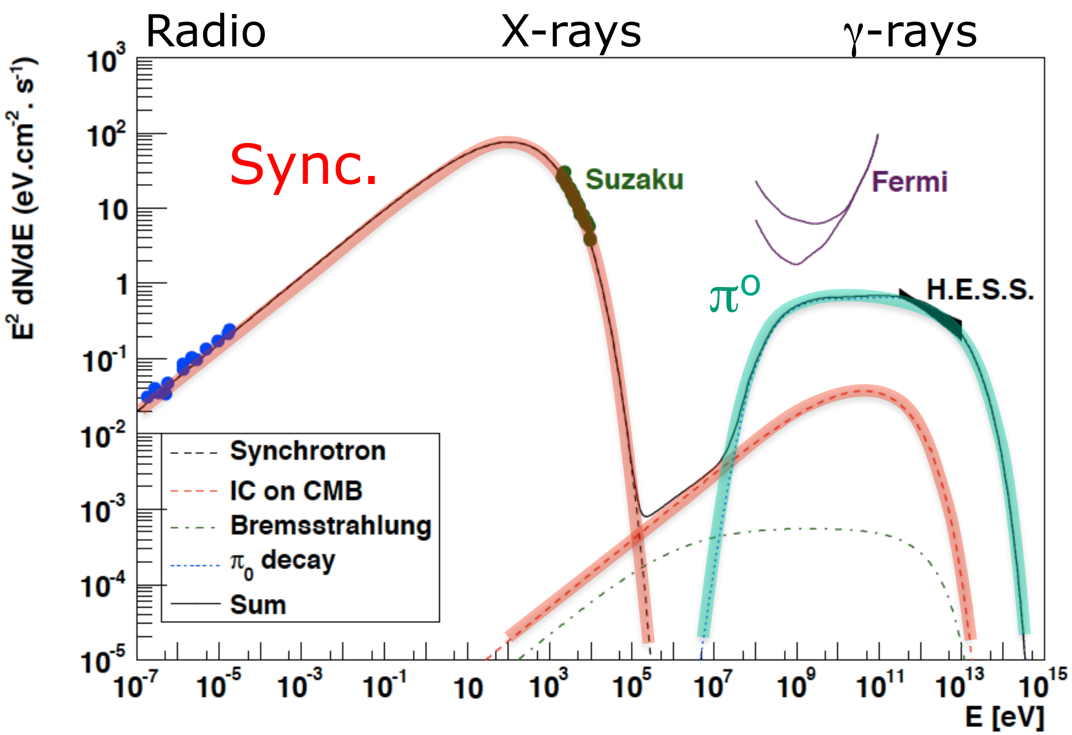
To PeV energies?



Fermi-LAT Collab.
arXiv:1103.5727







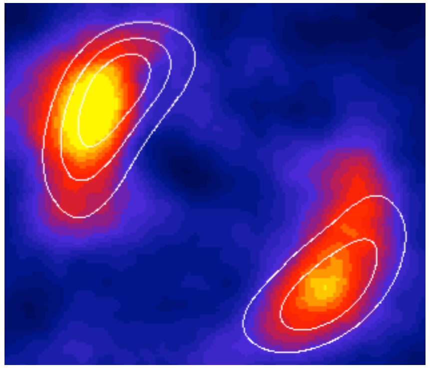
With what conversion efficiency ?

Gamma rays from electrons

W_e = 3.3 x 10^{47} ergs

ε= 0.03%

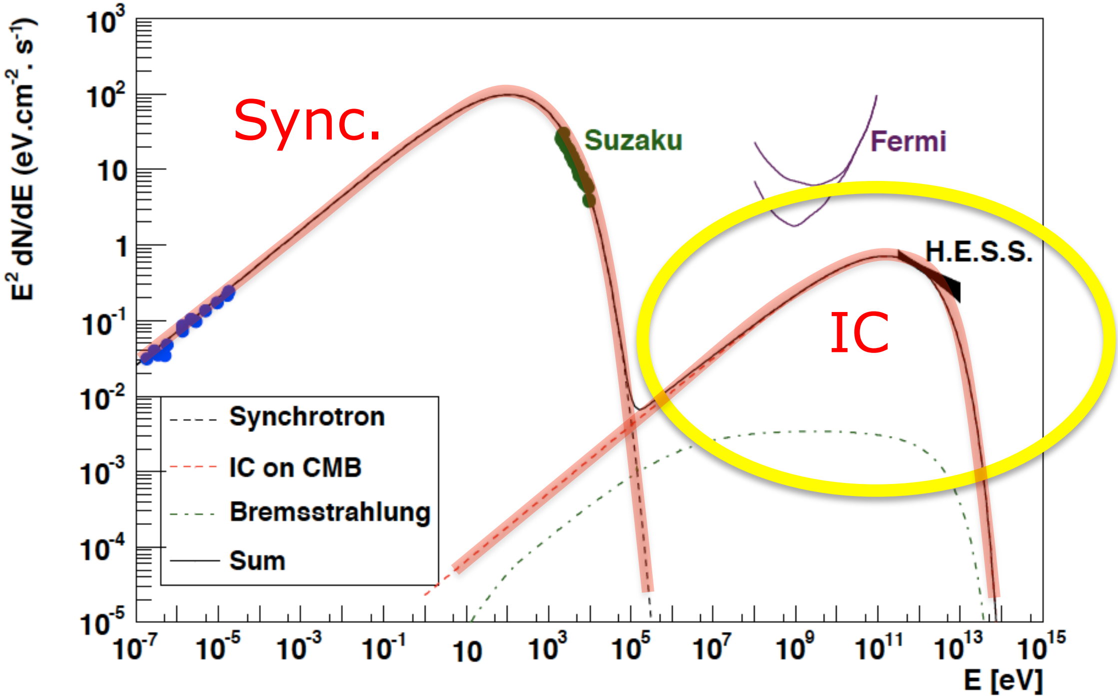
SN 1006



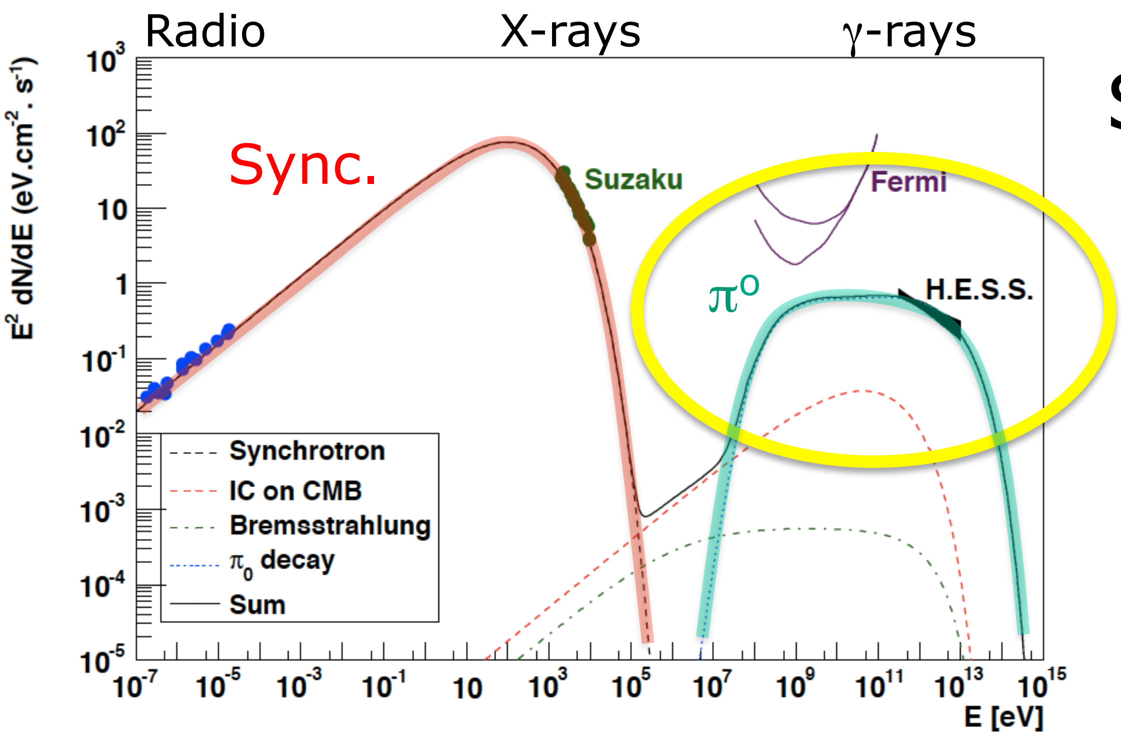
Gamma rays from protons

W_P = 3 X 10^{50} ergs

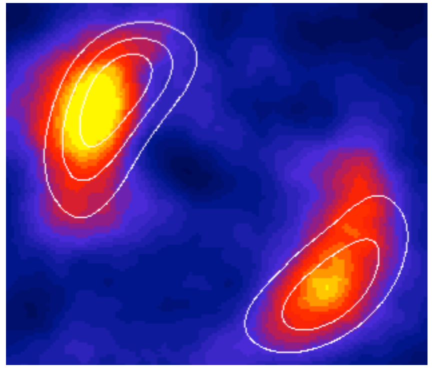
ε = 30%



Gamma rays from electrons
Spectral index ~1.5
Rising SED

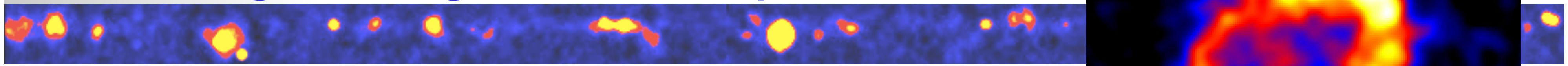


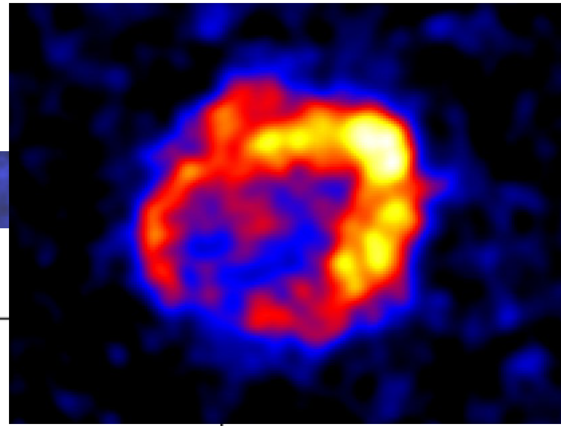
SN 1006



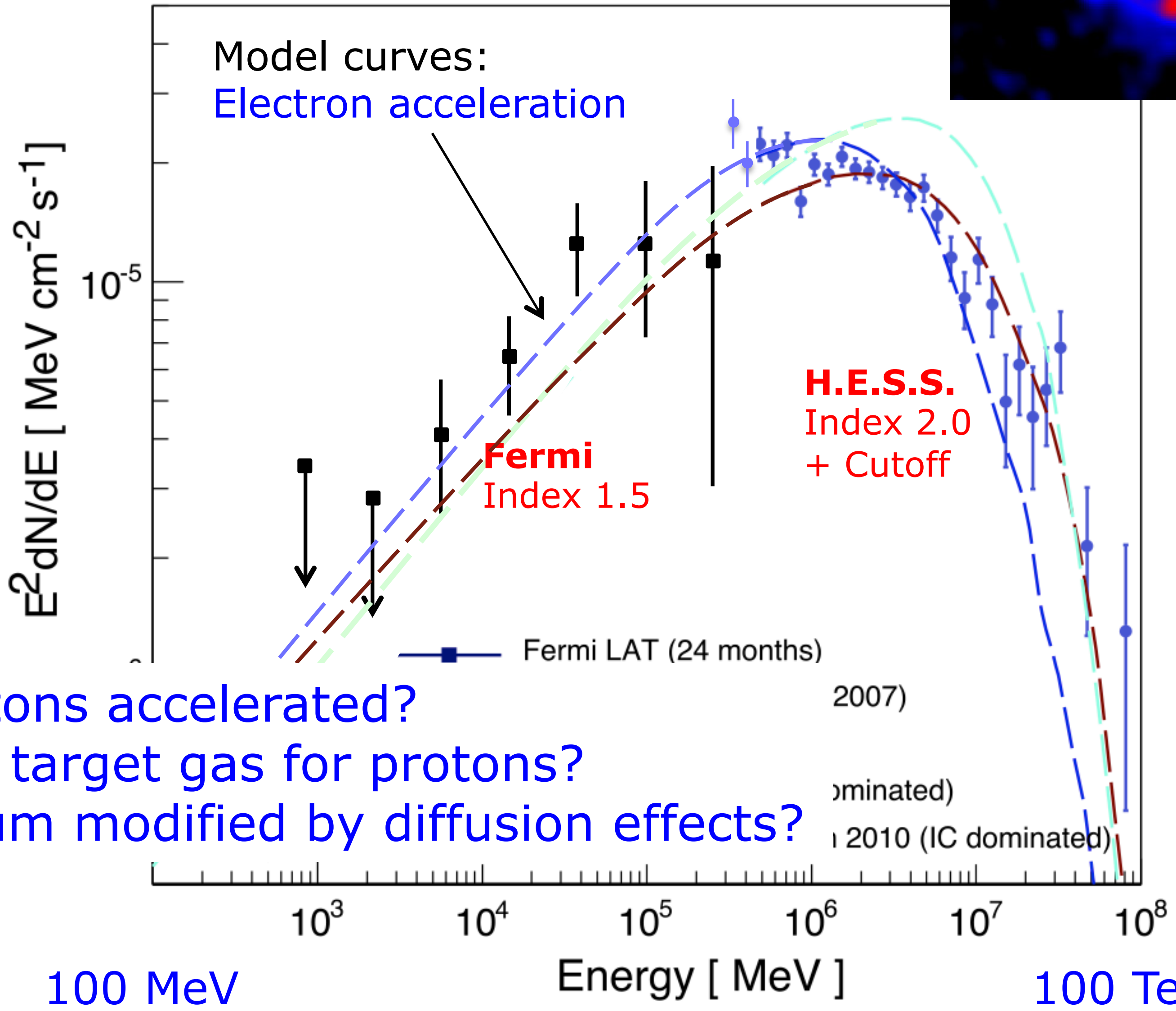
Gamma rays from protons
Spectral index ~2.0
Flat SED
Lower cutoff at ~$m_\pi/2$

Electrons or protons as origin of gamma rays?



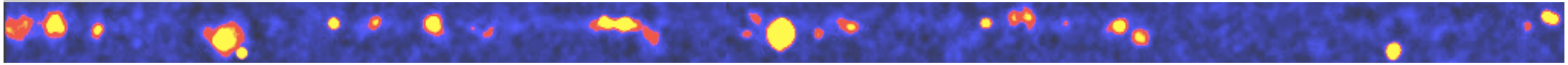


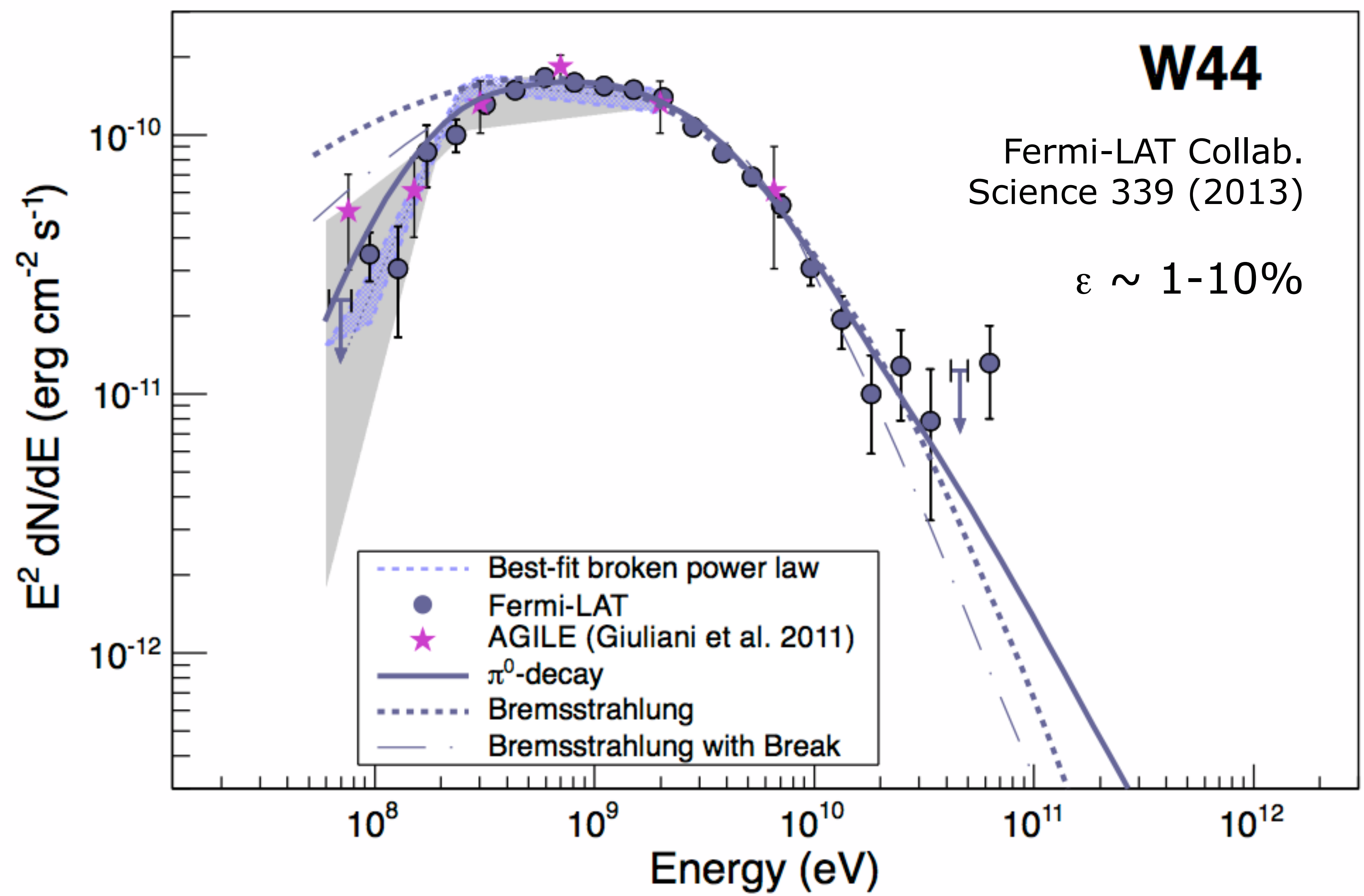
Fermi-LAT Collab.
arXiv:1103.5727



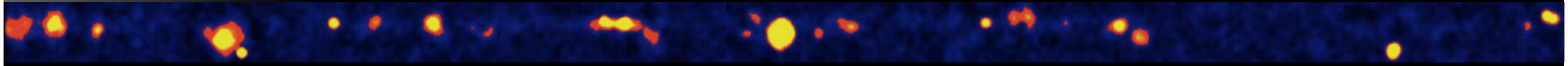
No protons accelerated?
Lack of target gas for protons?
Spectrum modified by diffusion effects?

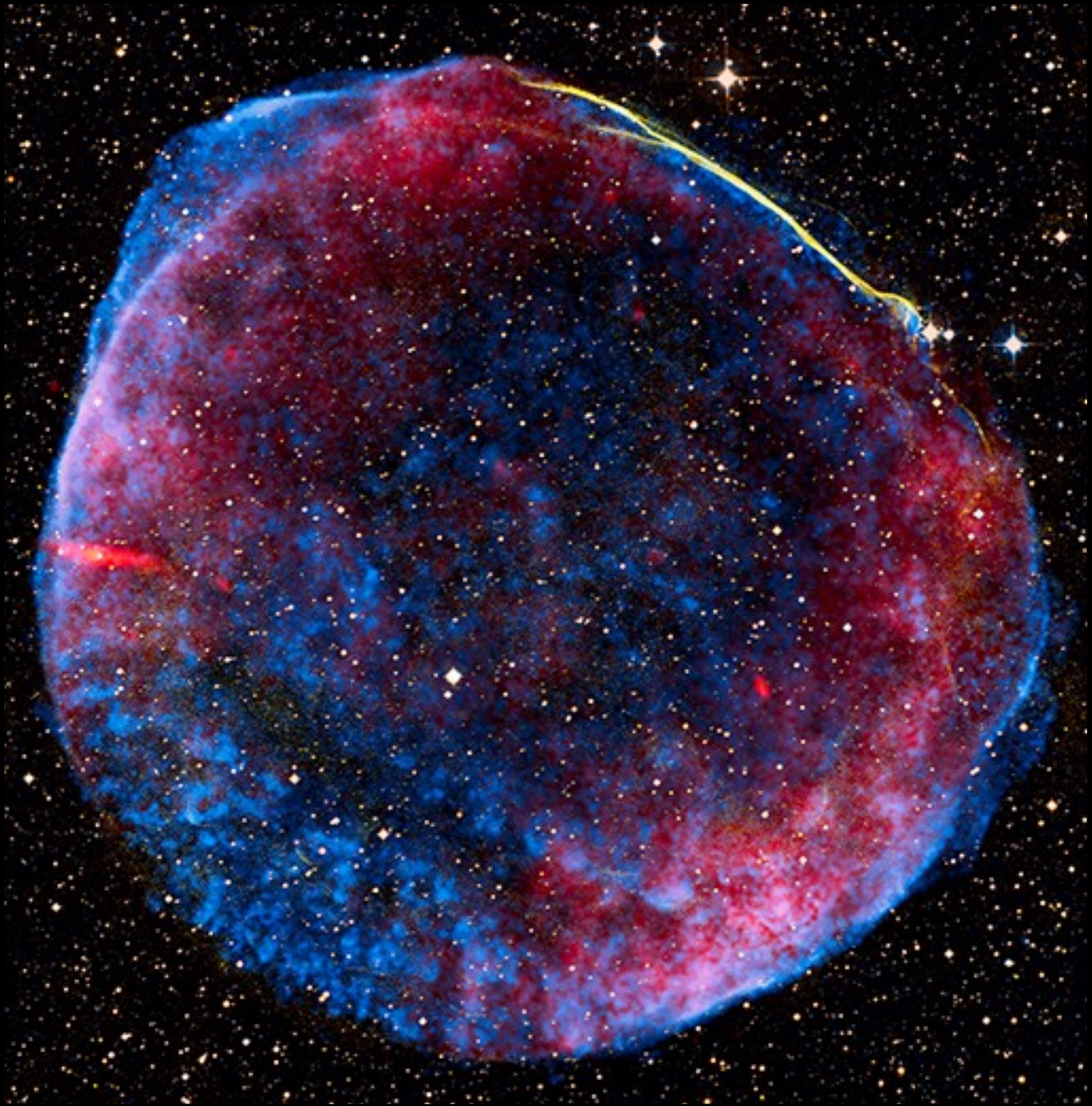
Pion-decay signature in Fermi data





Conversion efficiency: indirect means



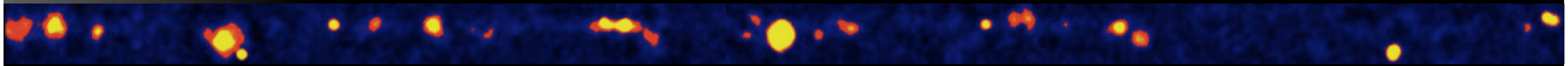


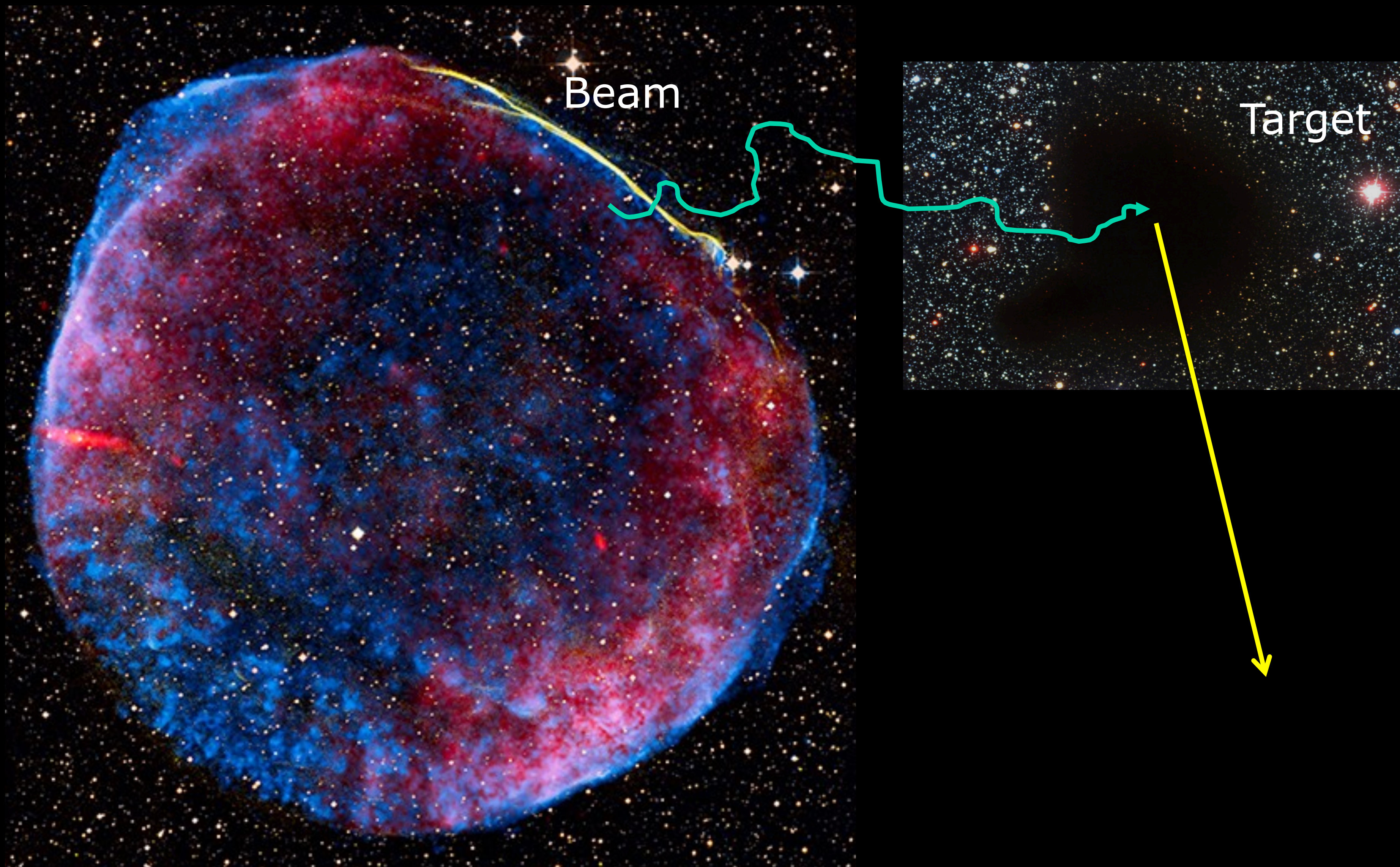
Gas temperature behind the shock

RCW 86:
Helder et al., Science 2009

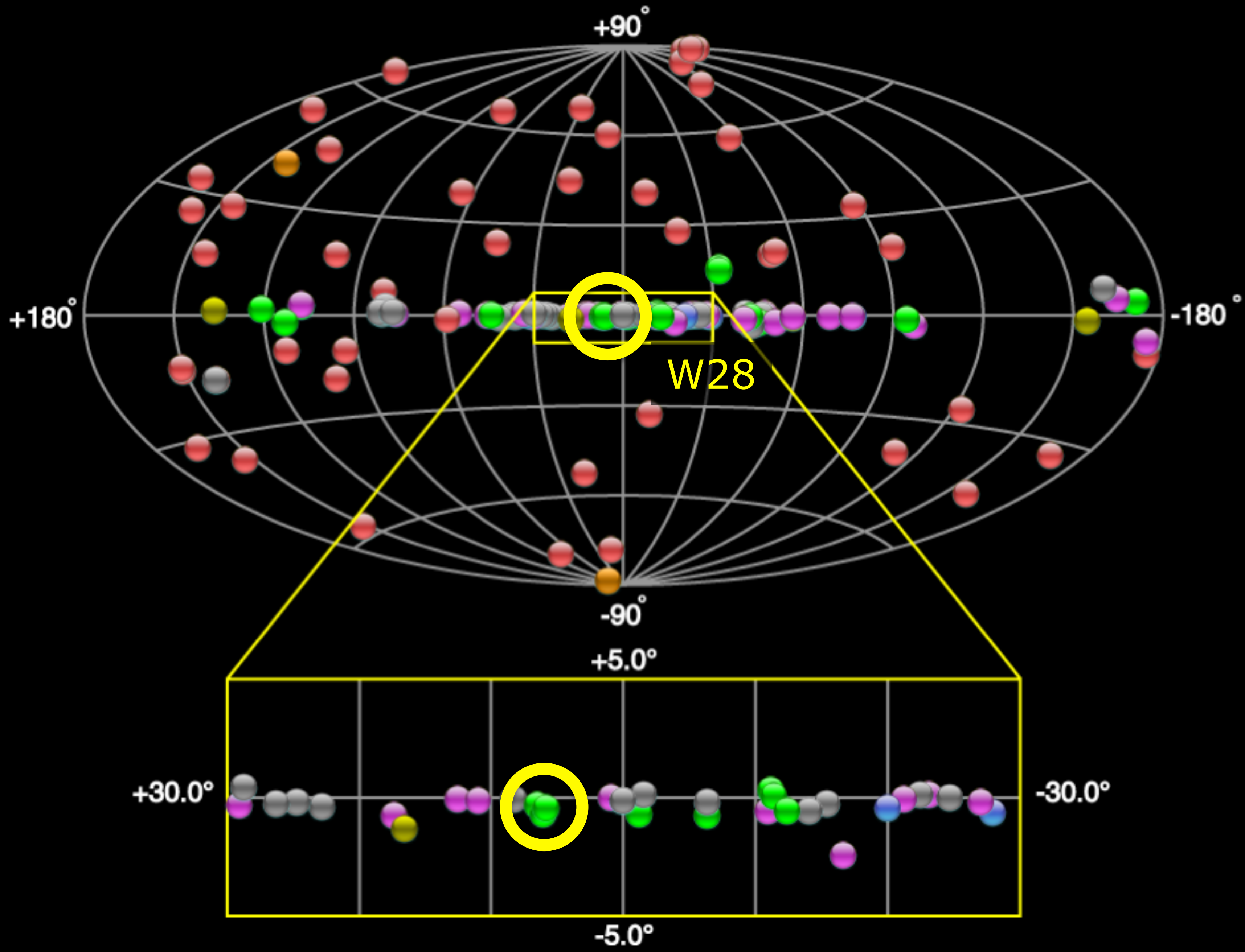
SN 1006:
Nikolić et al., Science Express Feb. 2013

How are CR released from the remnant?

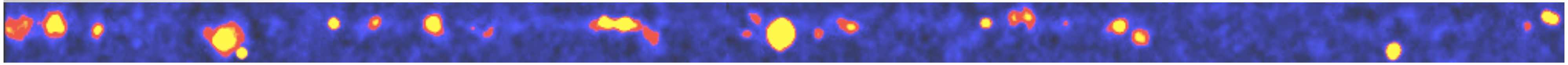


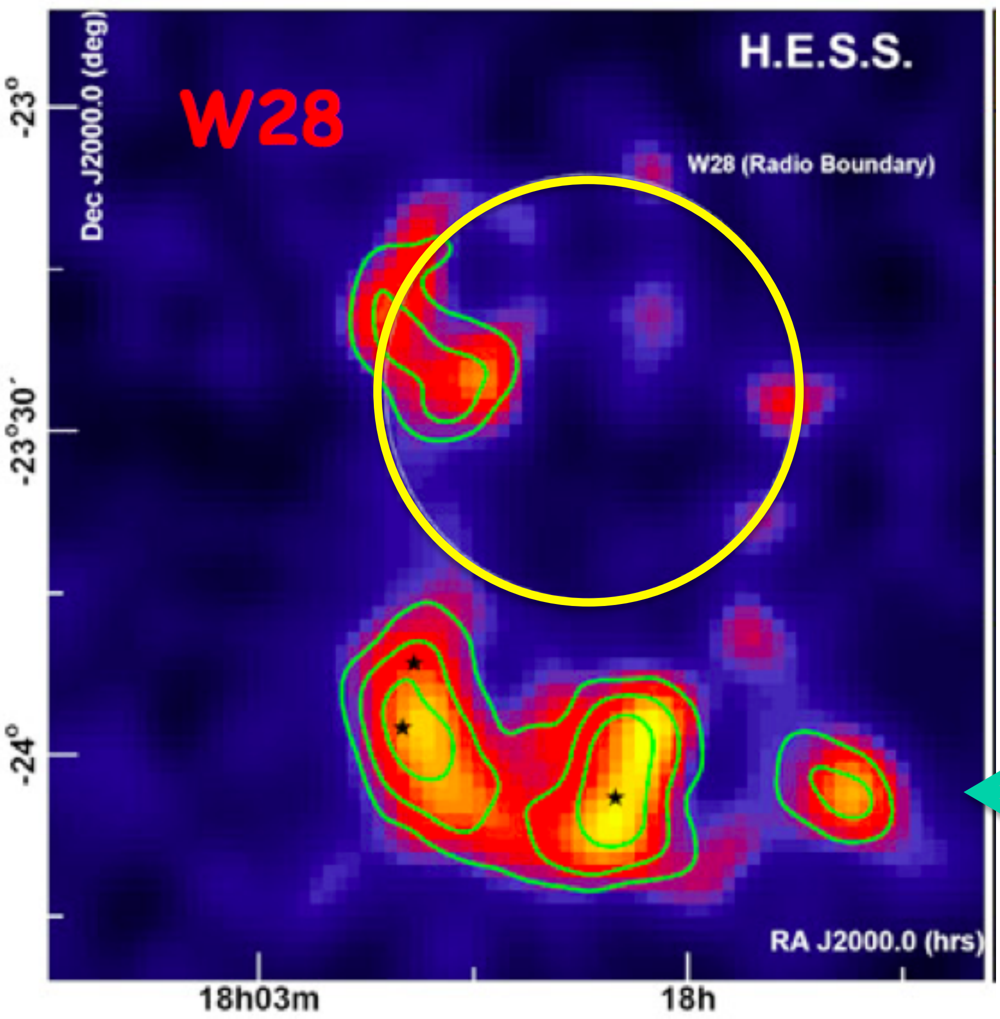


Cosmic-ray release



SNR W28





HESS:
Aharonian et al., arXiv:0801.3555

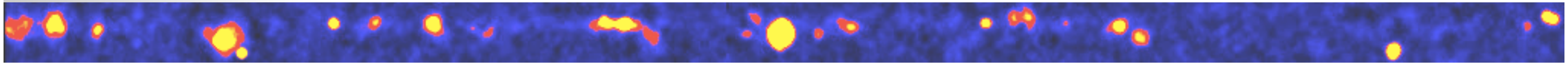
Fermi:
Abdo et al., ApJ 718 (2010) 348

AGILE
Giuliani et al., arXiv:1005.0784

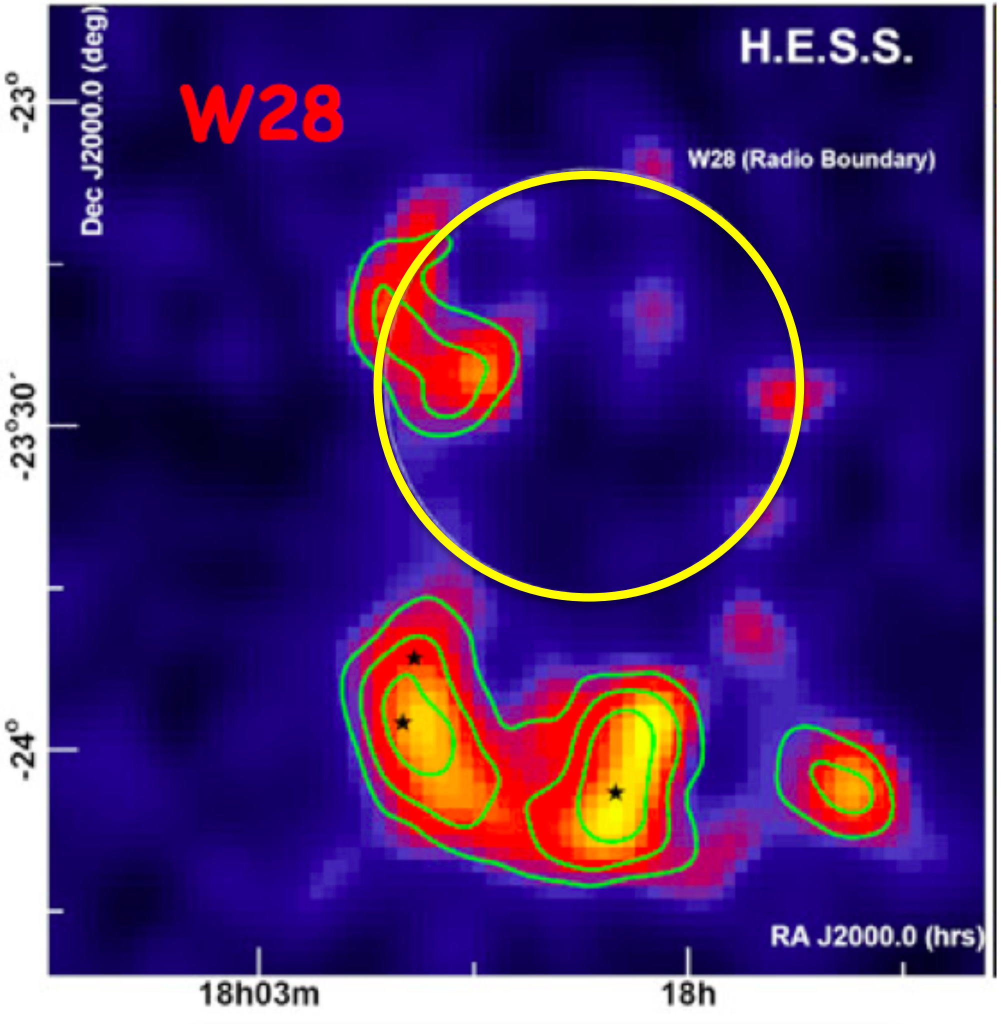
Models:
Gabici et al., arXiv:1009.5291
Li & Chen, arXiv:1009.0894
Ohira et al., arXiv:1007.4869

CRs escaping from 35-150 kyr old SNR interacting with clouds?

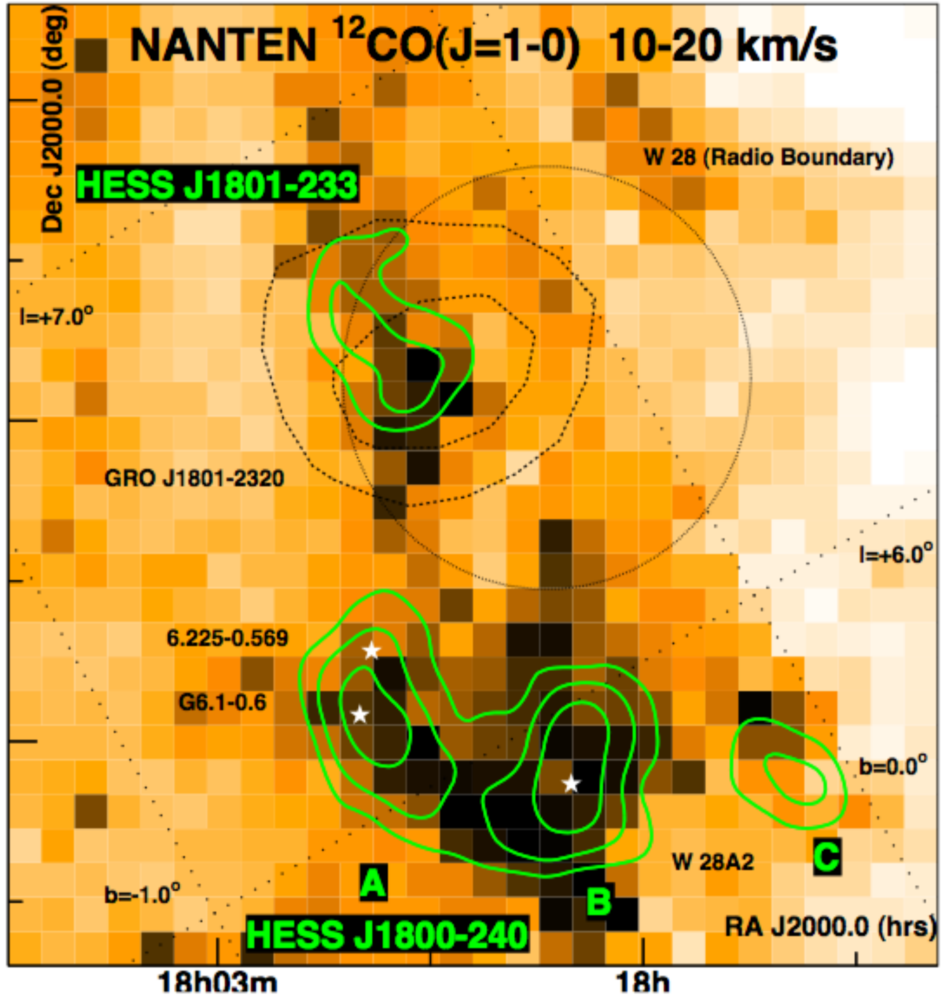
SNR W28

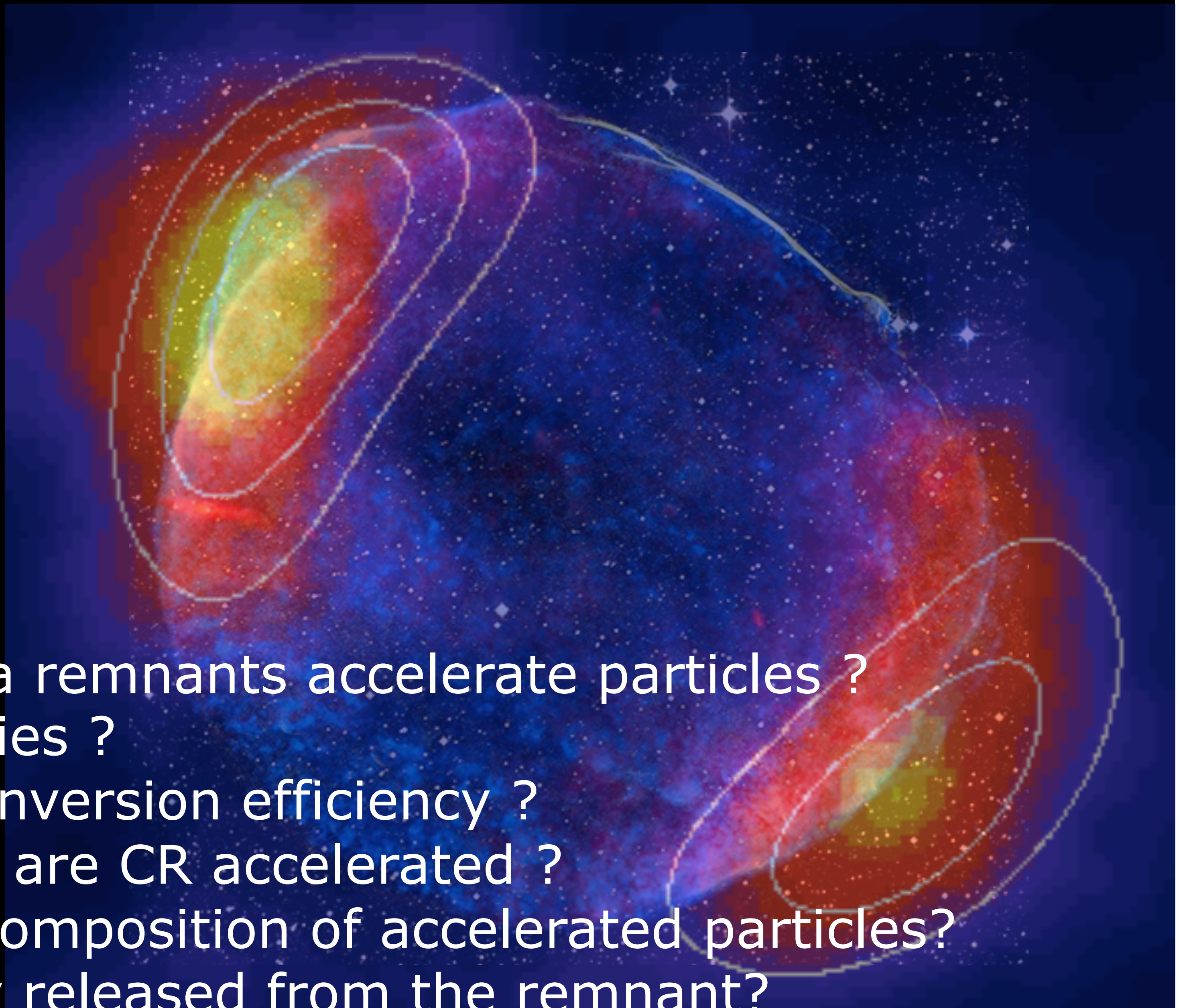


VHE gamma rays

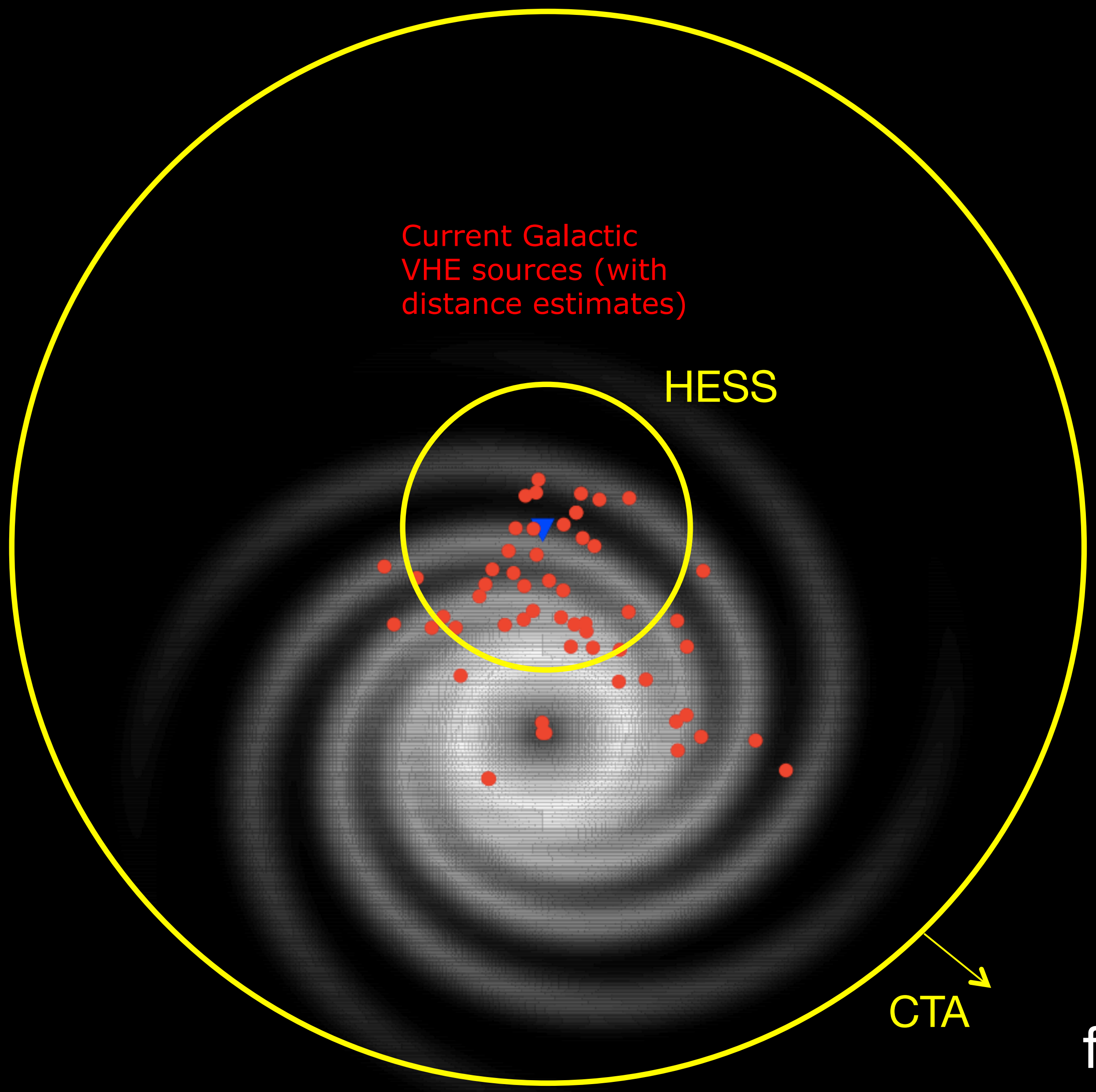


Molecular clouds





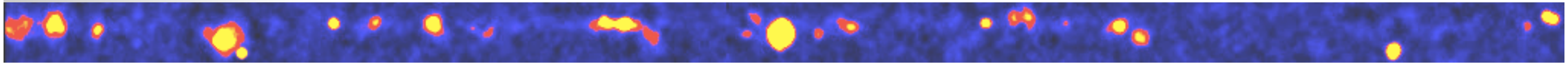
Do supernova remnants accelerate particles ?
To PeV energies ?
With what conversion efficiency ?
How in detail are CR accelerated ?
What is the composition of accelerated particles?
How are they released from the remnant?
Can SNR account for flux and spectrum of galactic CR?



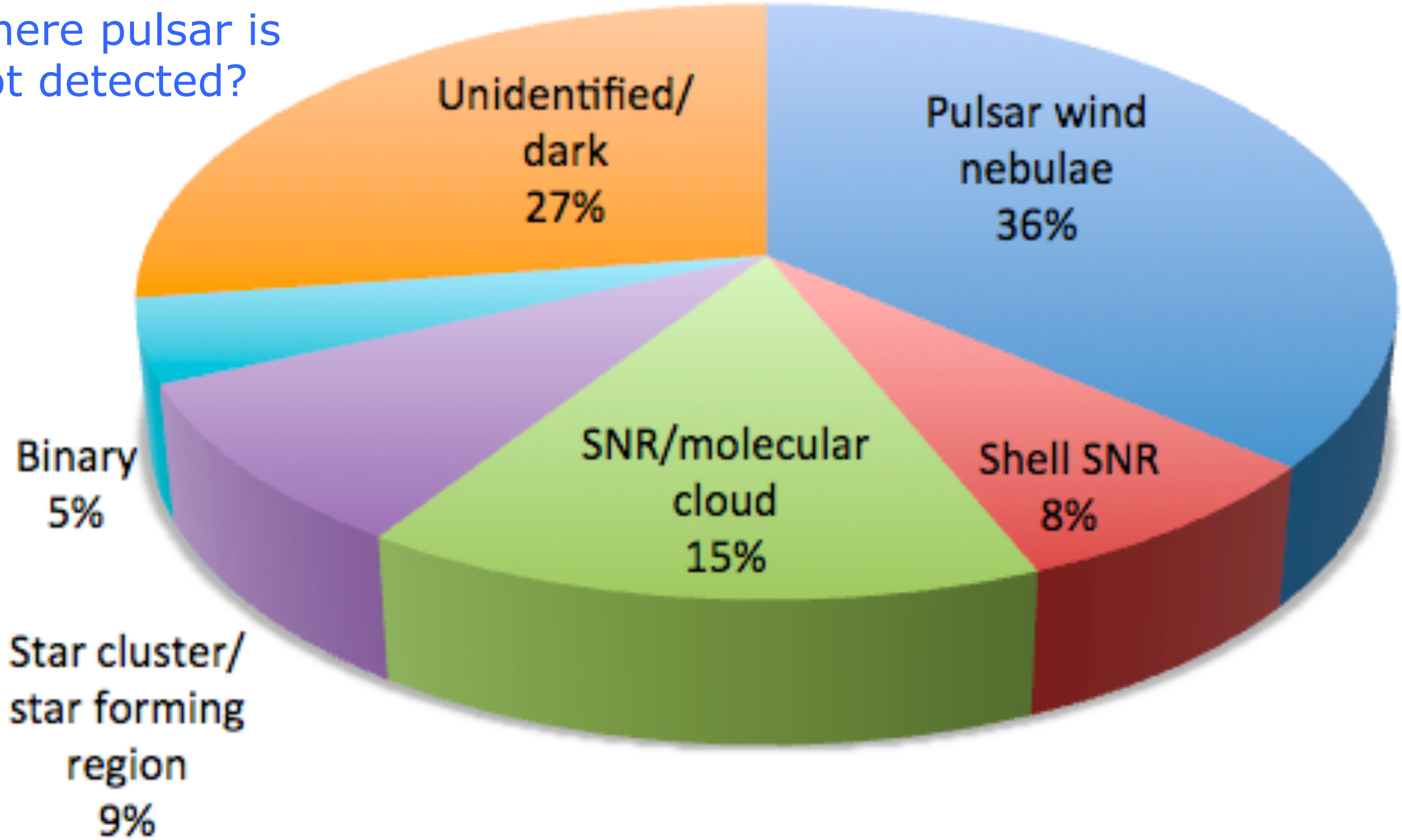
Current vision:
PeV acceleration
last only few 100
years, when shock
speed is high

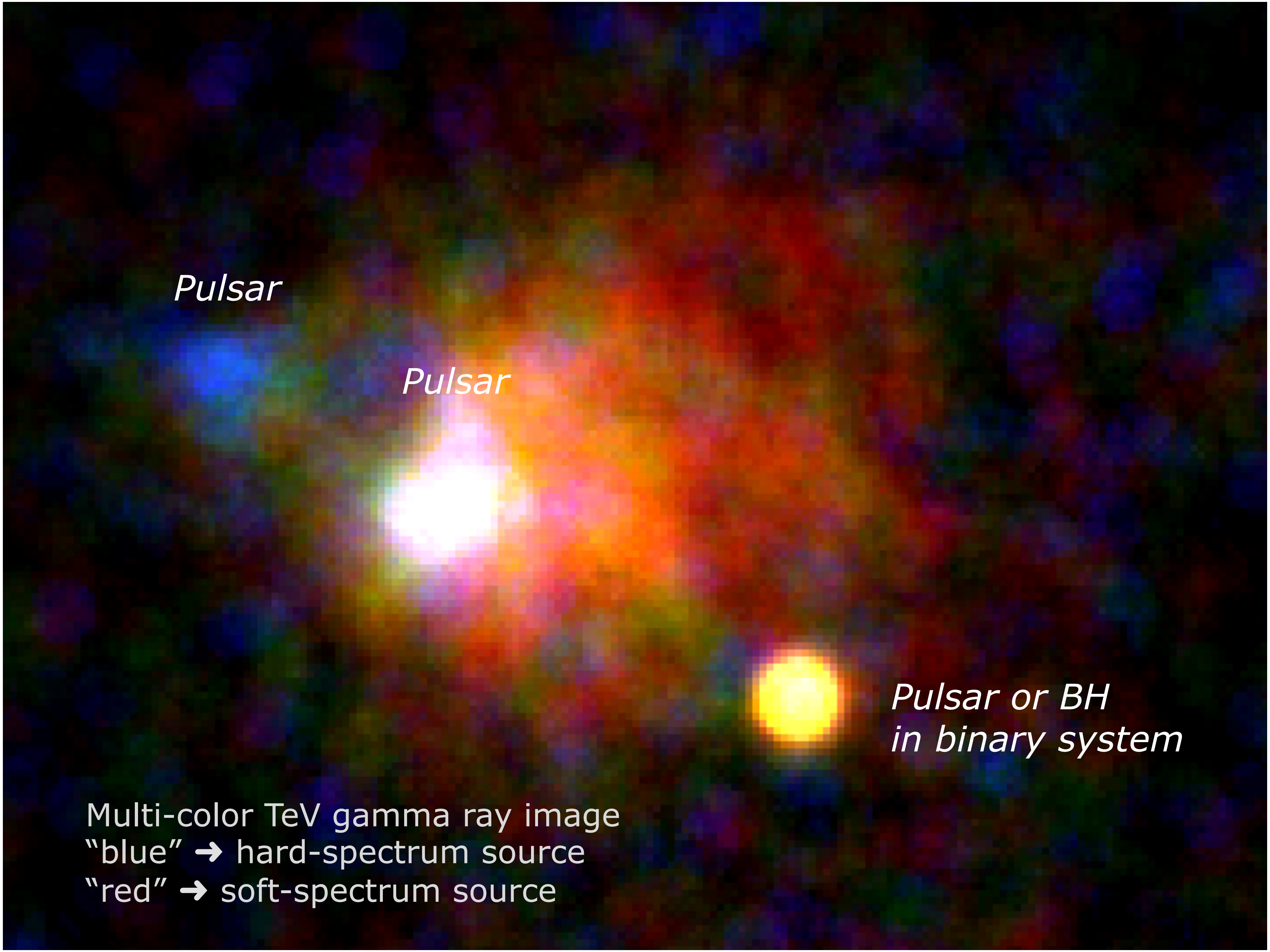
At a rate of one SN
per 30-100 y, very
few active Pevatrons
in Galaxy

Source classes

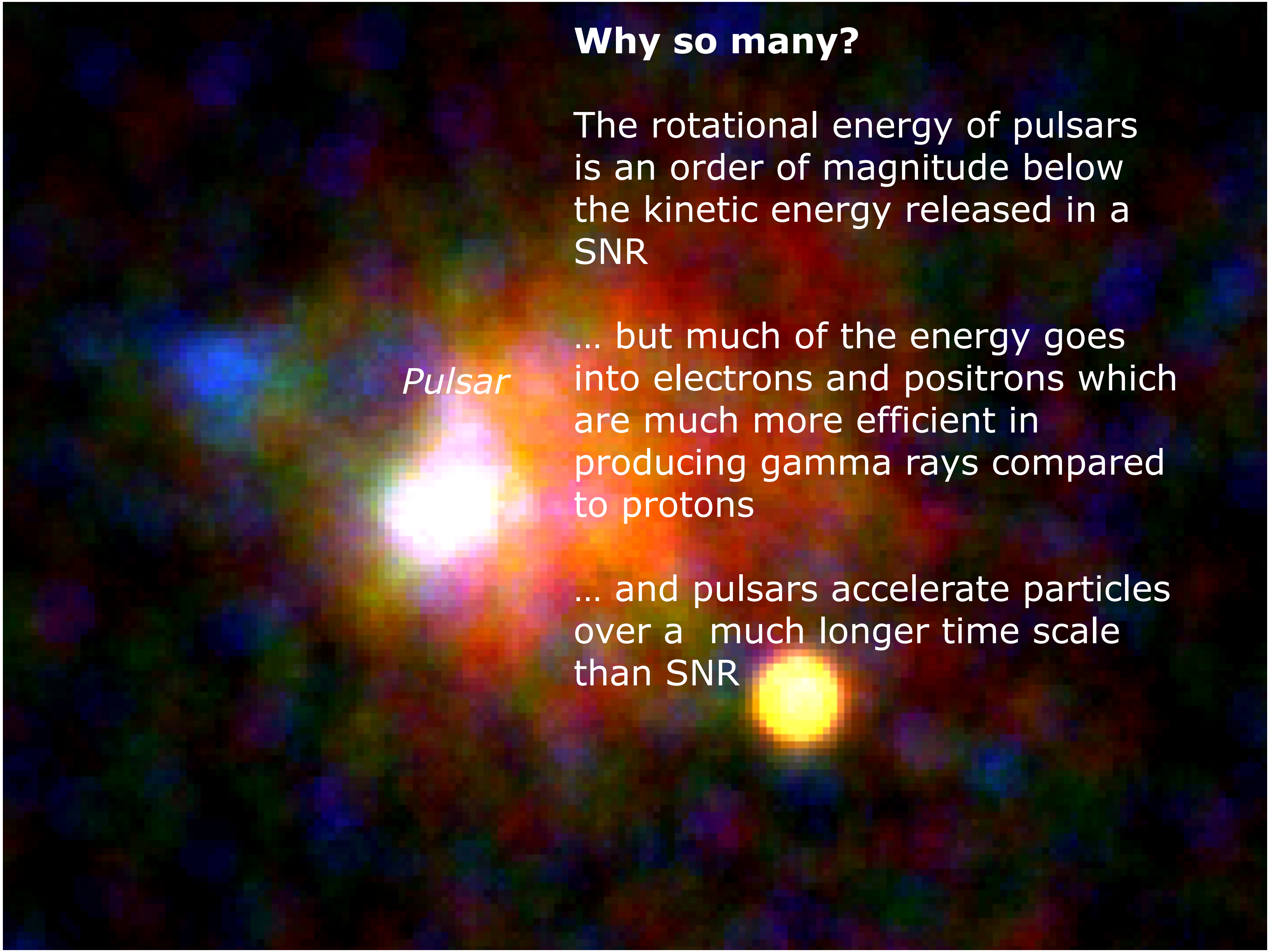


Pulsar wind nebulae
where pulsar is
not detected?




Pulsar
Pulsar
Pulsar or BH
in binary system
Multi-color TeV gamma ray image
"blue" ➜ hard-spectrum source
"red" ➜ soft-spectrum source

Why so many?

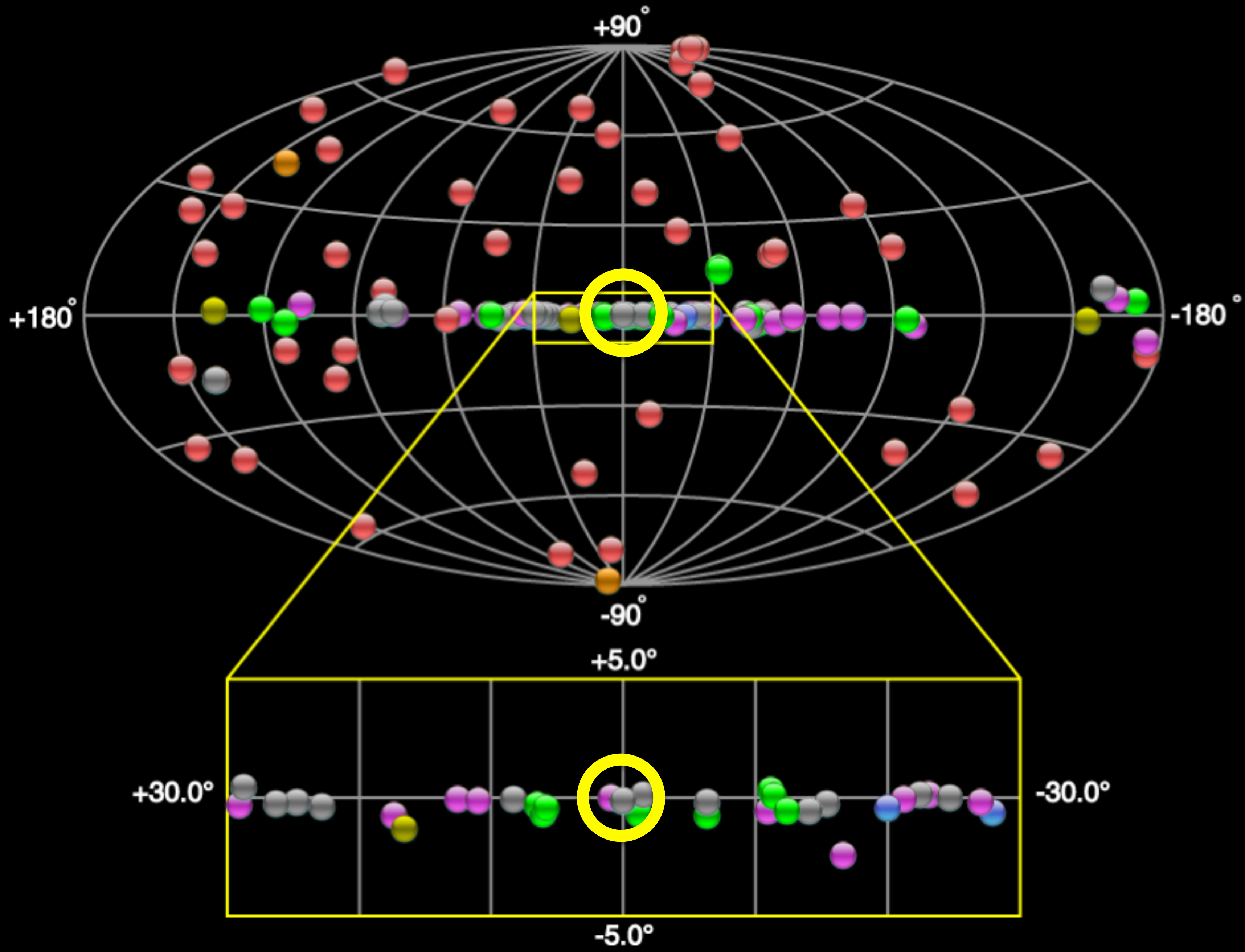


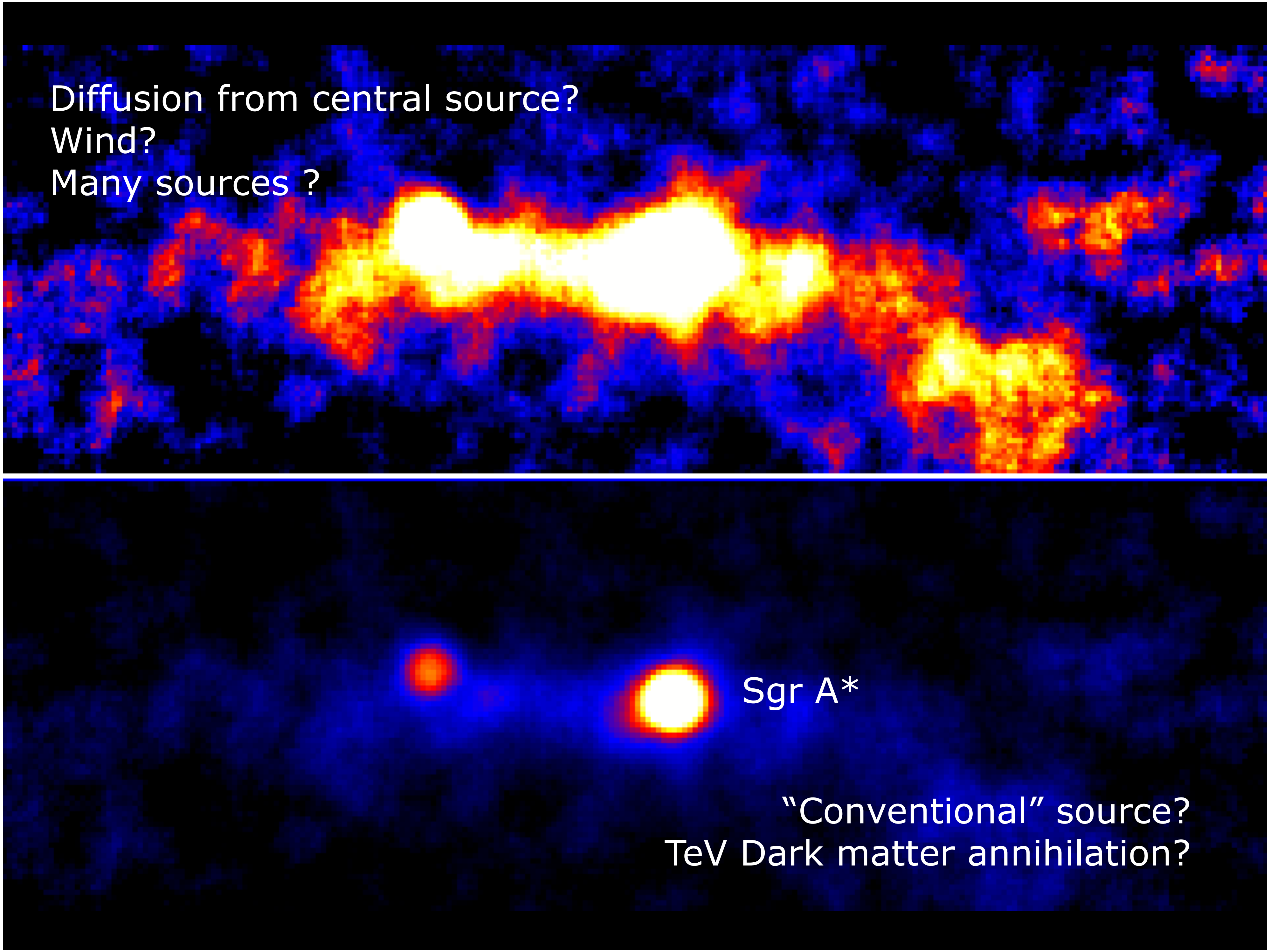
The rotational energy of pulsars is an order of magnitude below the kinetic energy released in a SNR

… but much of the energy goes into electrons and positrons which are much more efficient in producing gamma rays compared to protons

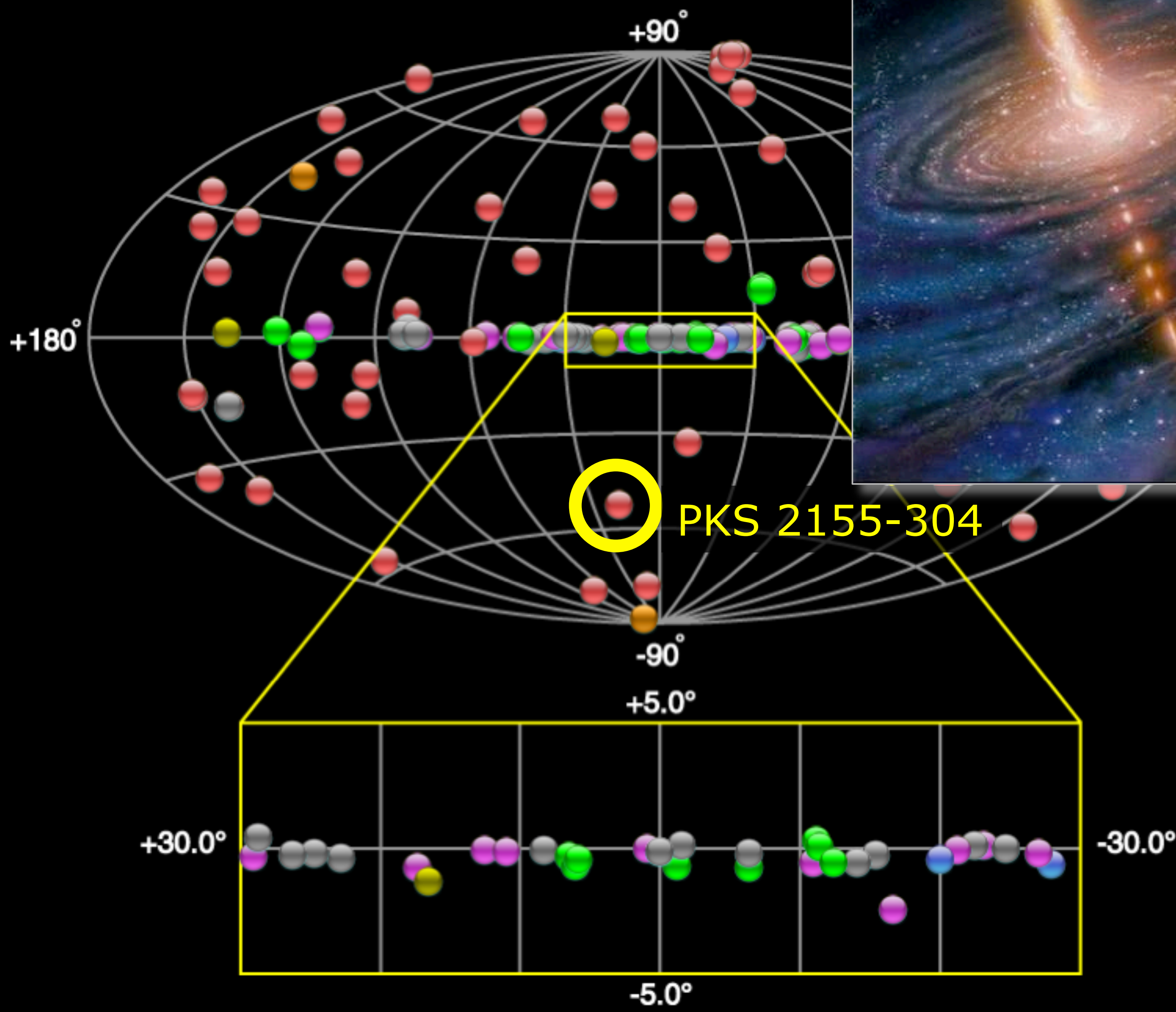
… and pulsars accelerate particles over a much longer time scale than SNR

Galactic Center

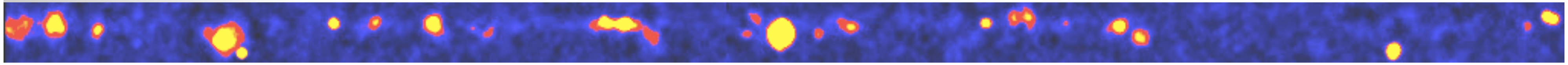



Diffusion from central source?
Wind?
Many sources ?
Sgr A*
“Conventional” source?
TeV Dark matter annihilation?

Active galactic nuclei

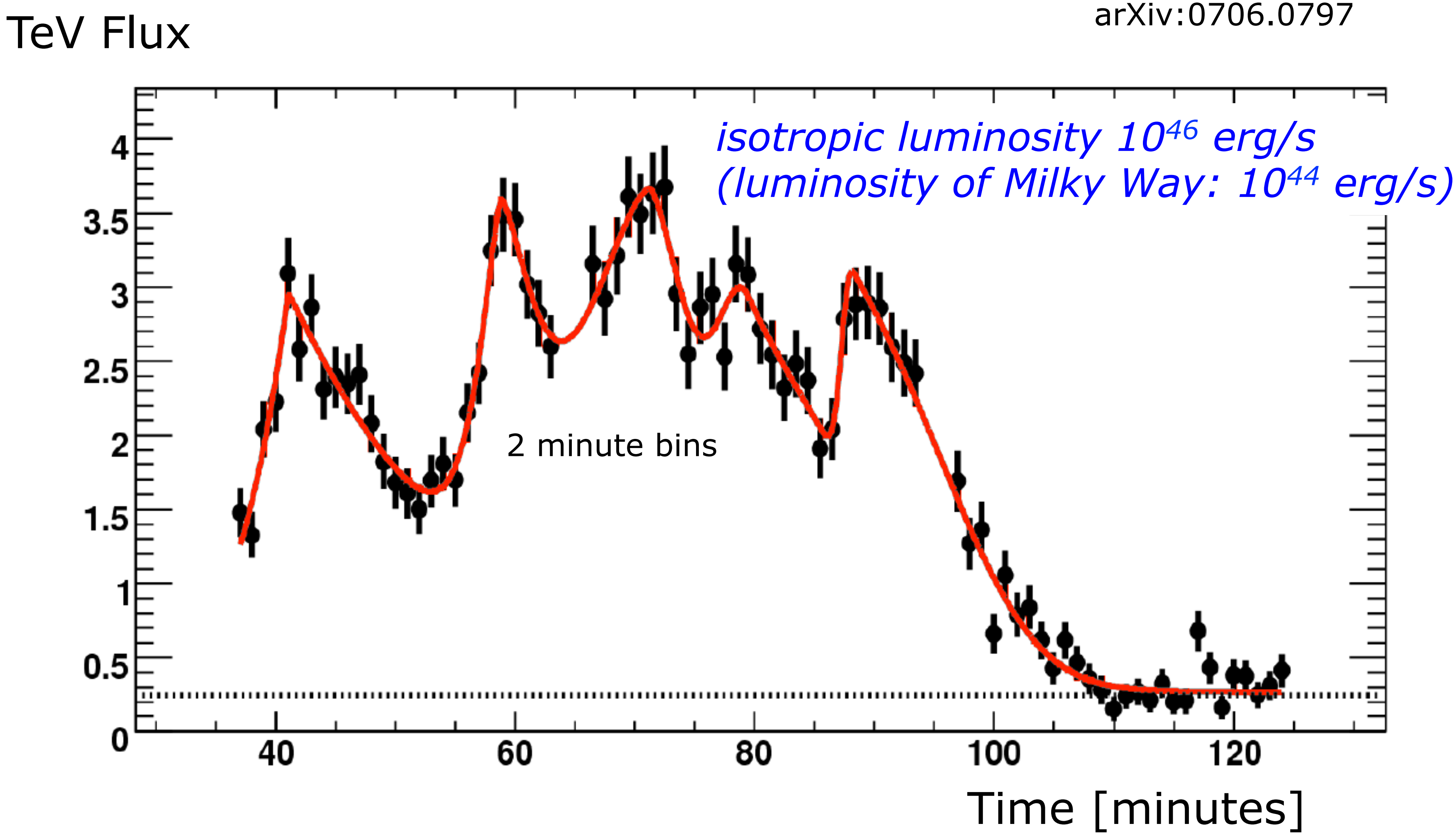


One of the most violent blazars: PKS 2155-304



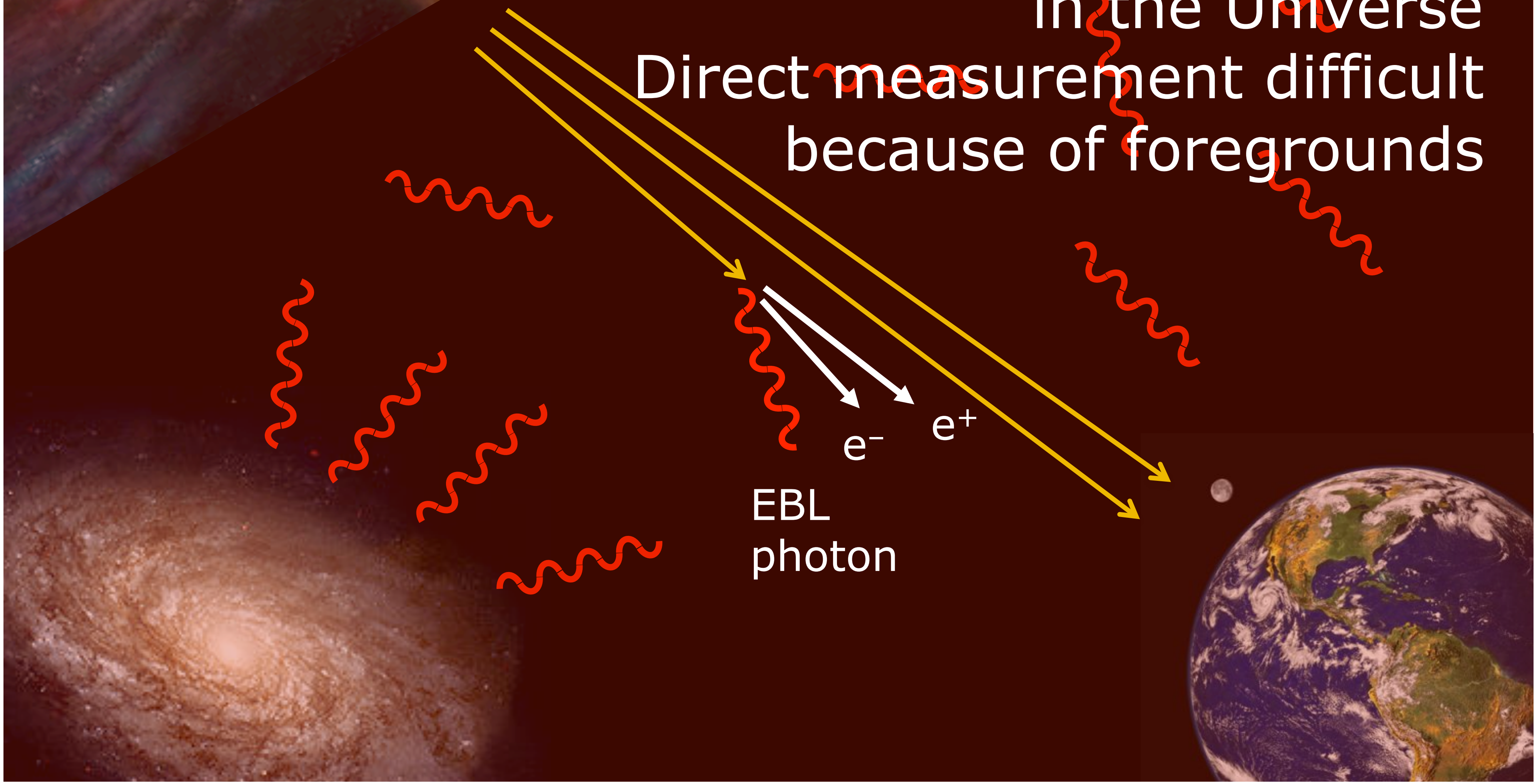
PKS 2155-304 flare

arXiv:0706.0797

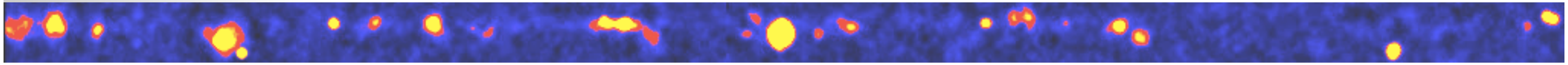


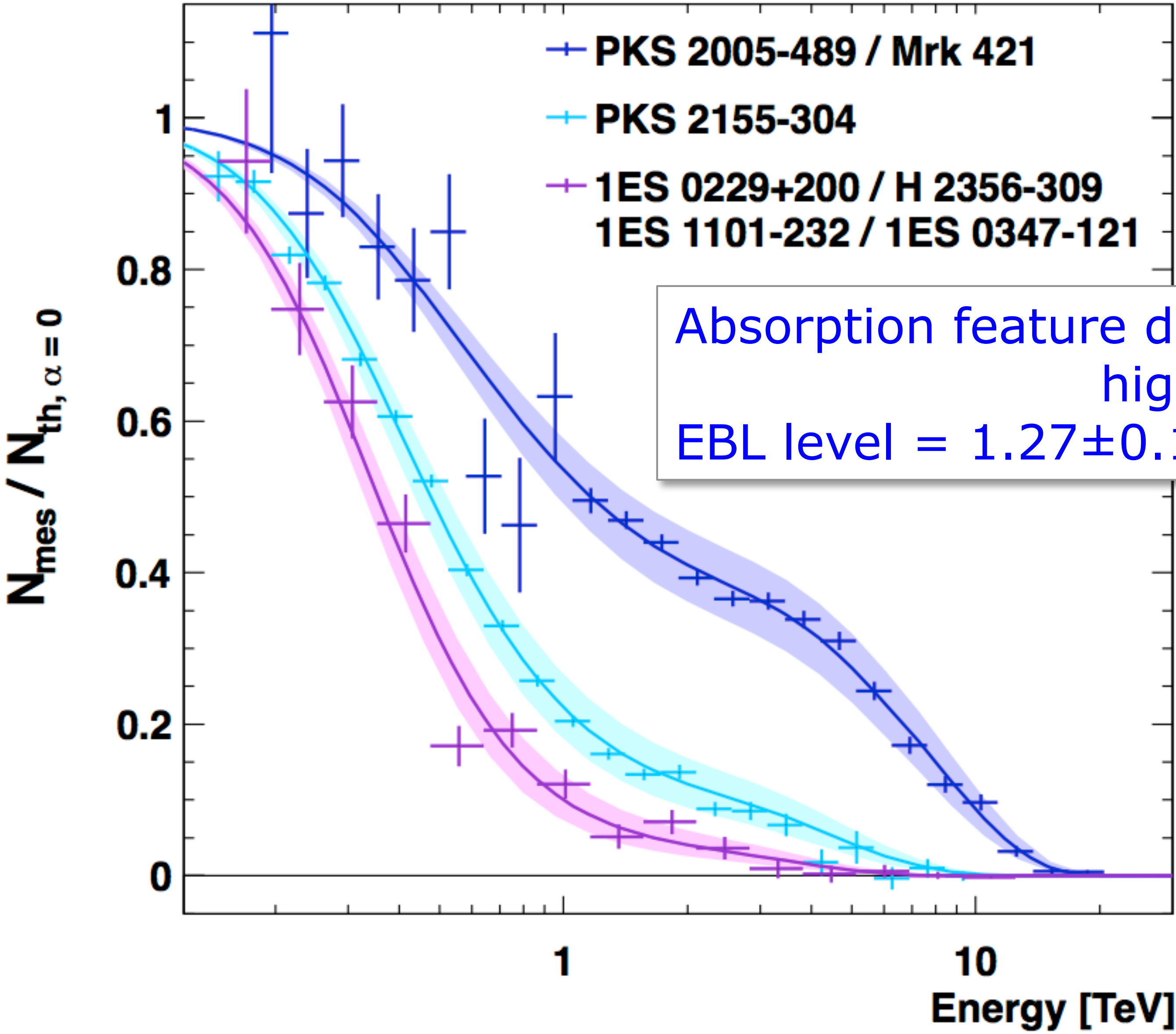
EBL absorption

EBL measures integrated
star formation history
in the Universe
Direct measurement difficult
because of foregrounds



EBL absorption



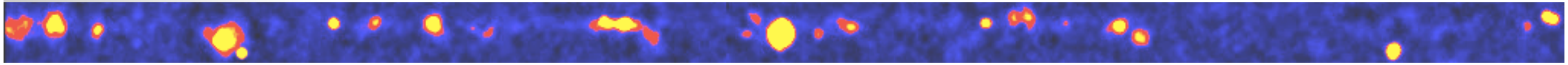


Absorption feature detected at high significance
EBL level = 1.27±0.18±0.25 x model

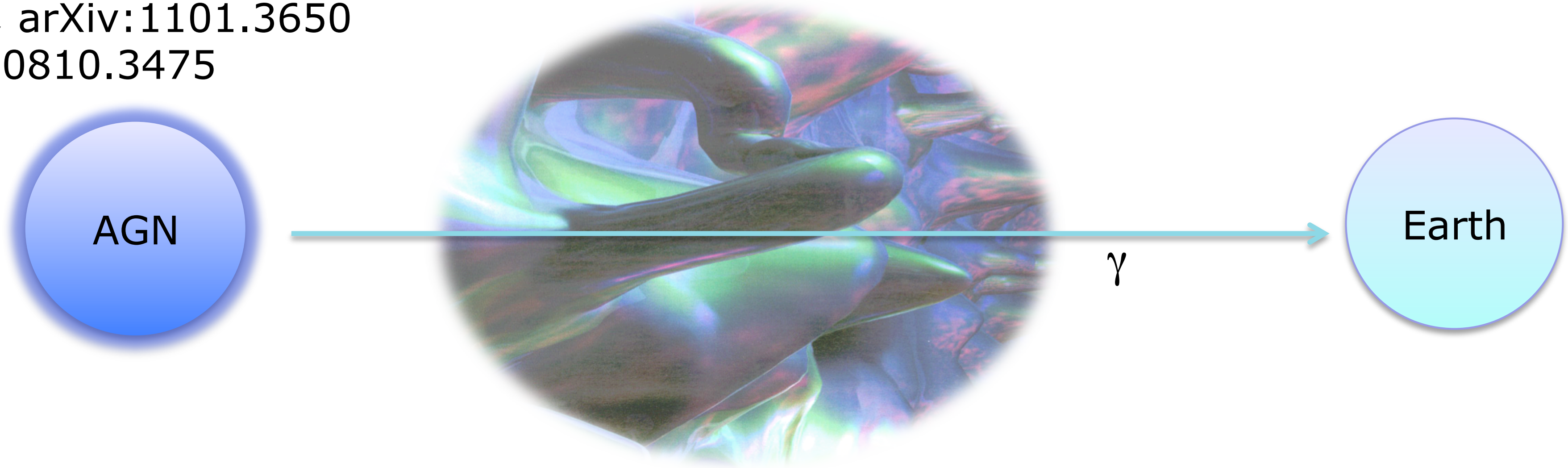
H.E.S.S.
arXiv:1212.3409

see also: Fermi Science (2012)

Photon propagation: LI violation



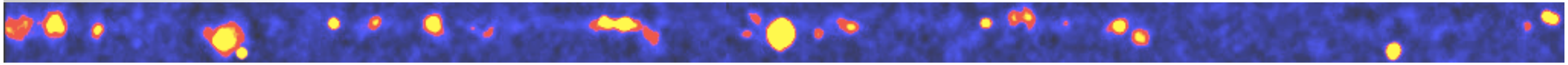
HESS, arXiv:1101.3650
arXiv:0810.3475

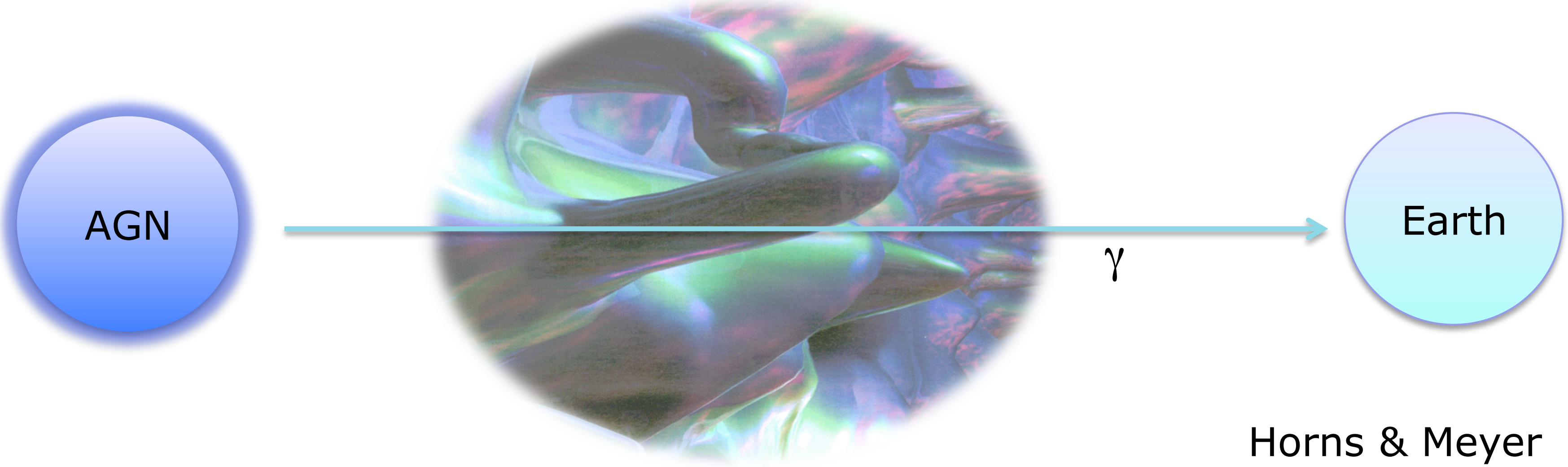


Velocity dispersion across HESS energy range less than ~20 s for ~10^9 y travel $\simeq 10^{-15}$

➜ LIV mass scale > $2 \cdot 10^{18}$ GeV (~E), $6 \cdot 10^{10}$ GeV (~E^2)

Photon propagation: Axion limits

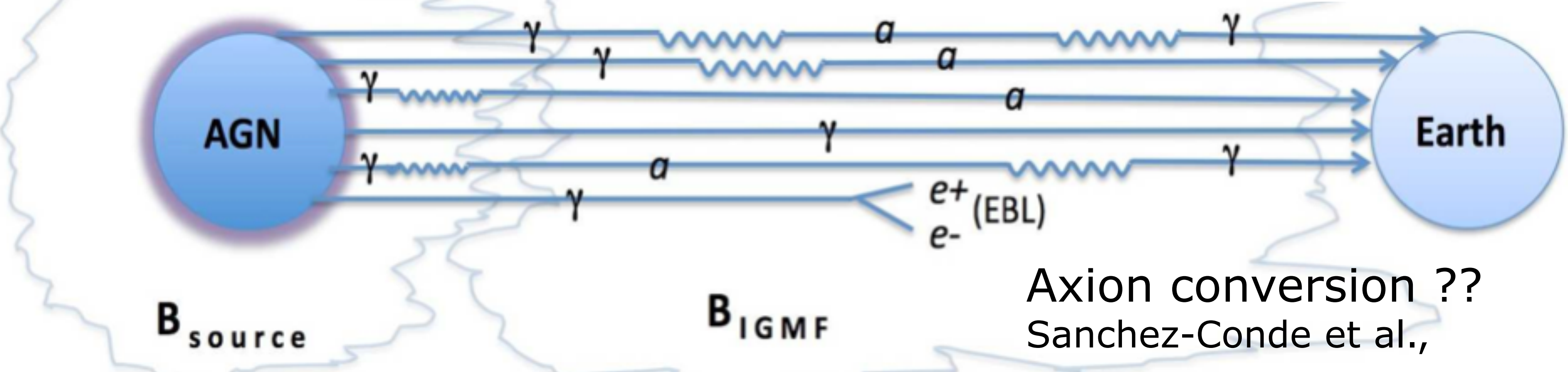




Horns & Meyer
arXiv:1201.471

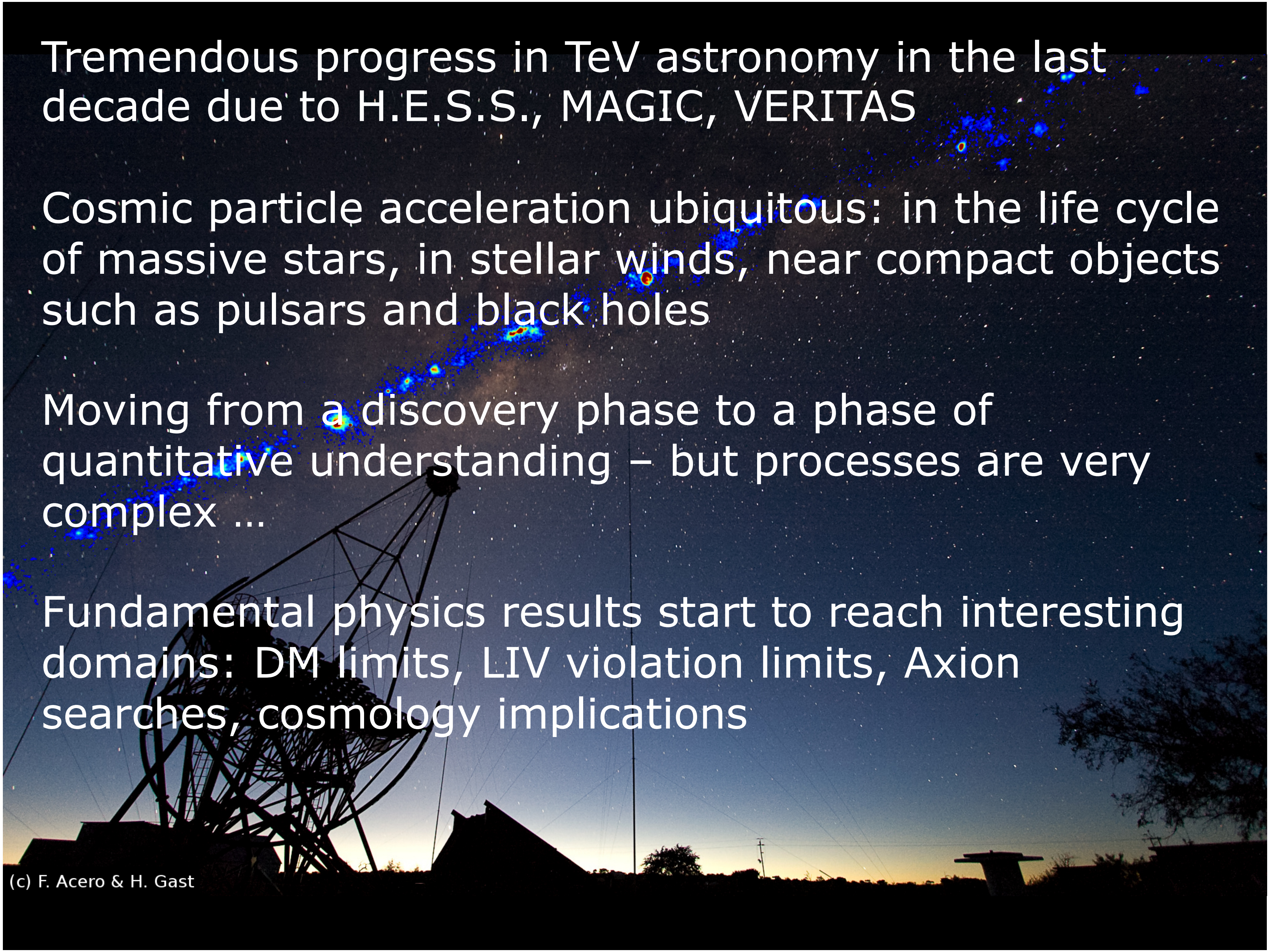
M. Meyer et al.
arXiv:1302.1208

Best results on axion coupling in the 10^{-7-9} eV range



Axion conversion ??

Sanchez-Conde et al.,
arXiv:0905.3270



Tremendous progress in TeV astronomy in the last decade due to H.E.S.S., MAGIC, VERITAS

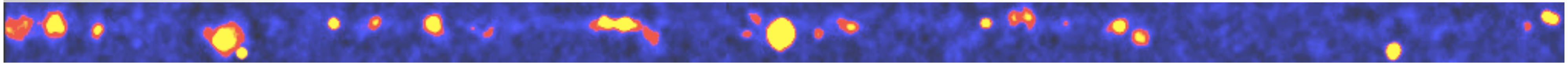
Cosmic particle acceleration ubiquitous: in the life cycle of massive stars, in stellar winds, near compact objects such as pulsars and black holes

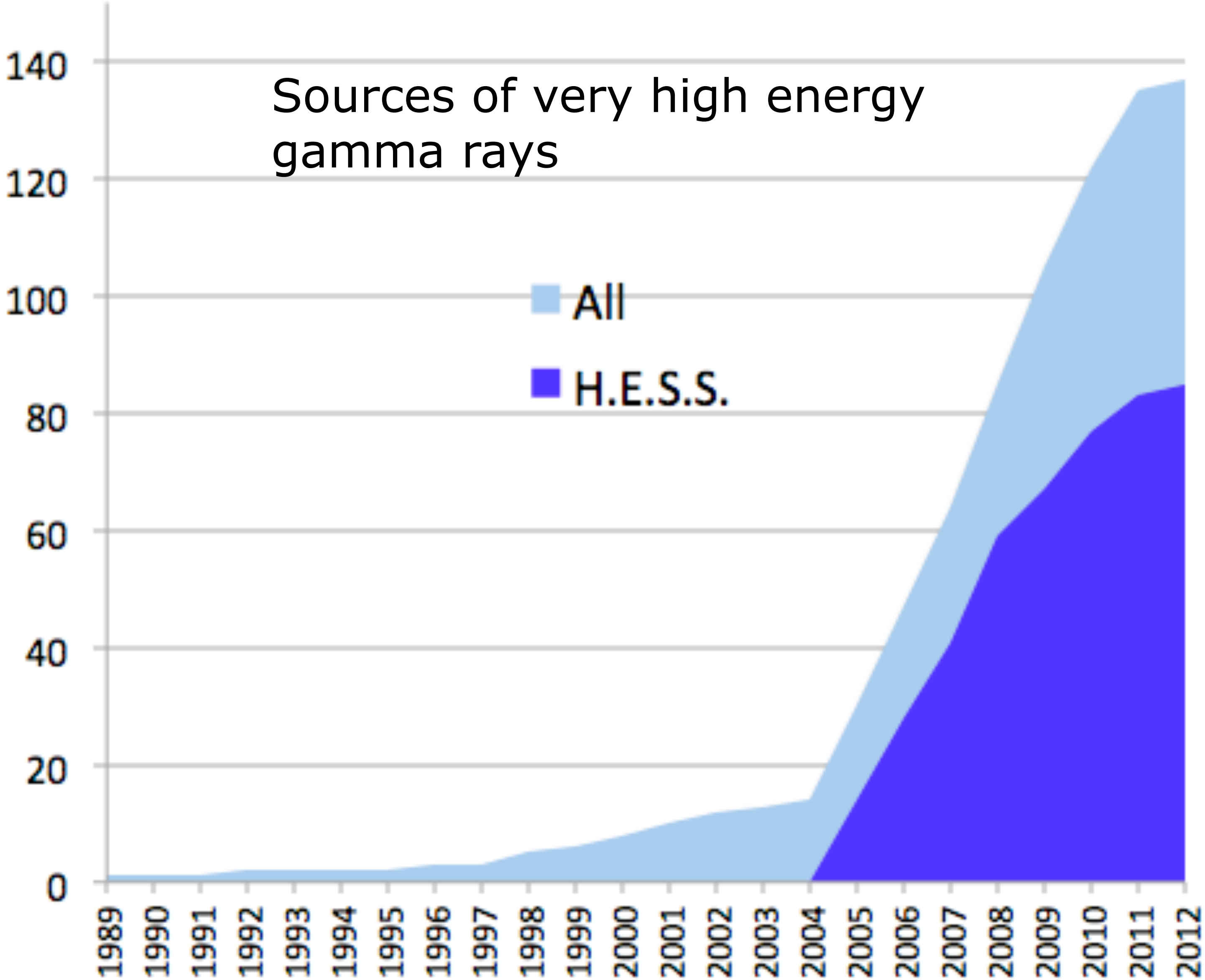
Moving from a discovery phase to a phase of quantitative understanding – but processes are very complex …

Fundamental physics results start to reach interesting domains: DM limits, LIV violation limits, Axion searches, cosmology implications


Beyond
2012
(c) F. Acero & H. Gast

Discoveries





H.E.S.S.

The Next Phase

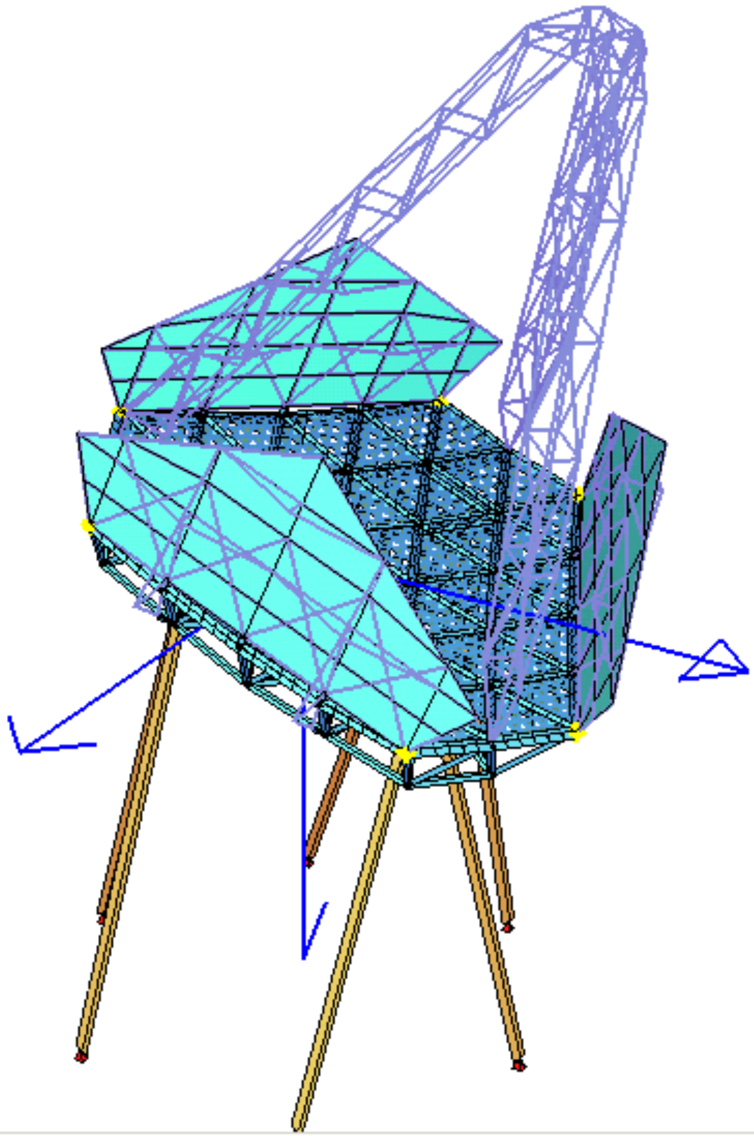
More telescopes

or

larger telescope(s) ?

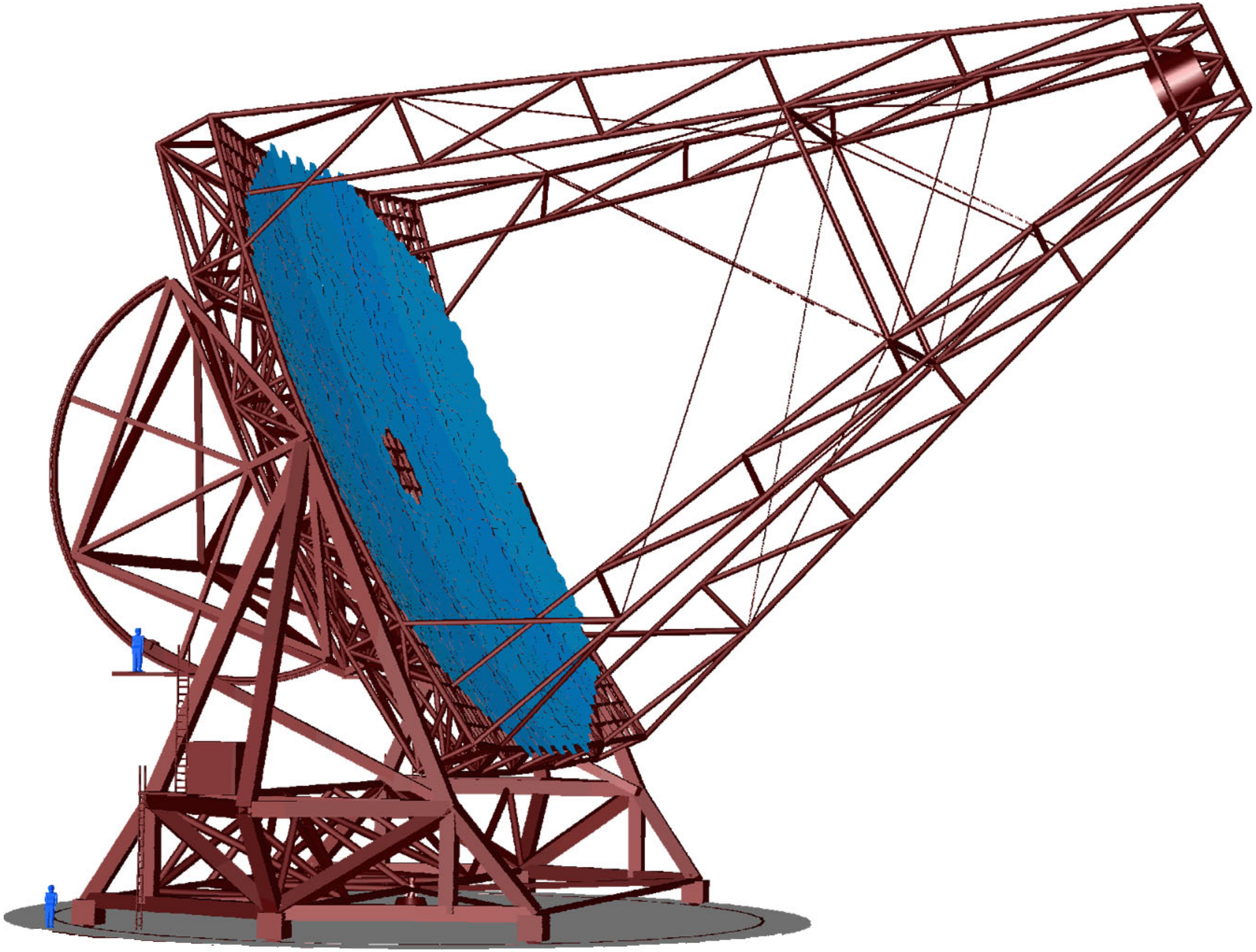
2001 Ringberg presentation, W. Hofmann

Design study: Hexapod mount



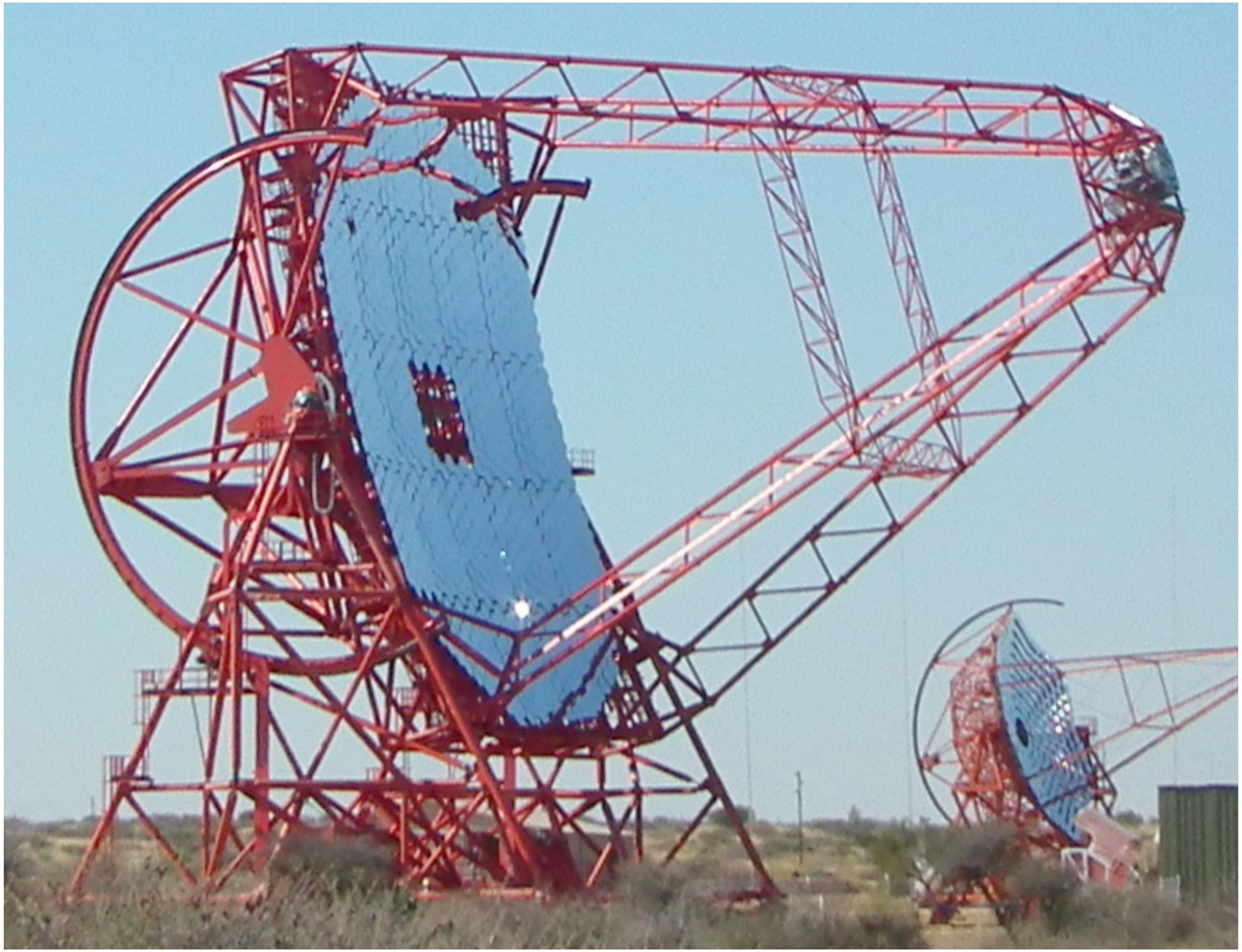
2003 Ringberg presentation, W. Hofmann

MAN Design: conventional alt-az mount



2003 Ringberg presentation, W. Hofmann

2012



Next step: H.E.S.S. I camera upgrade (DESY)

Next:

The Cherenkov Telescope Array CTA