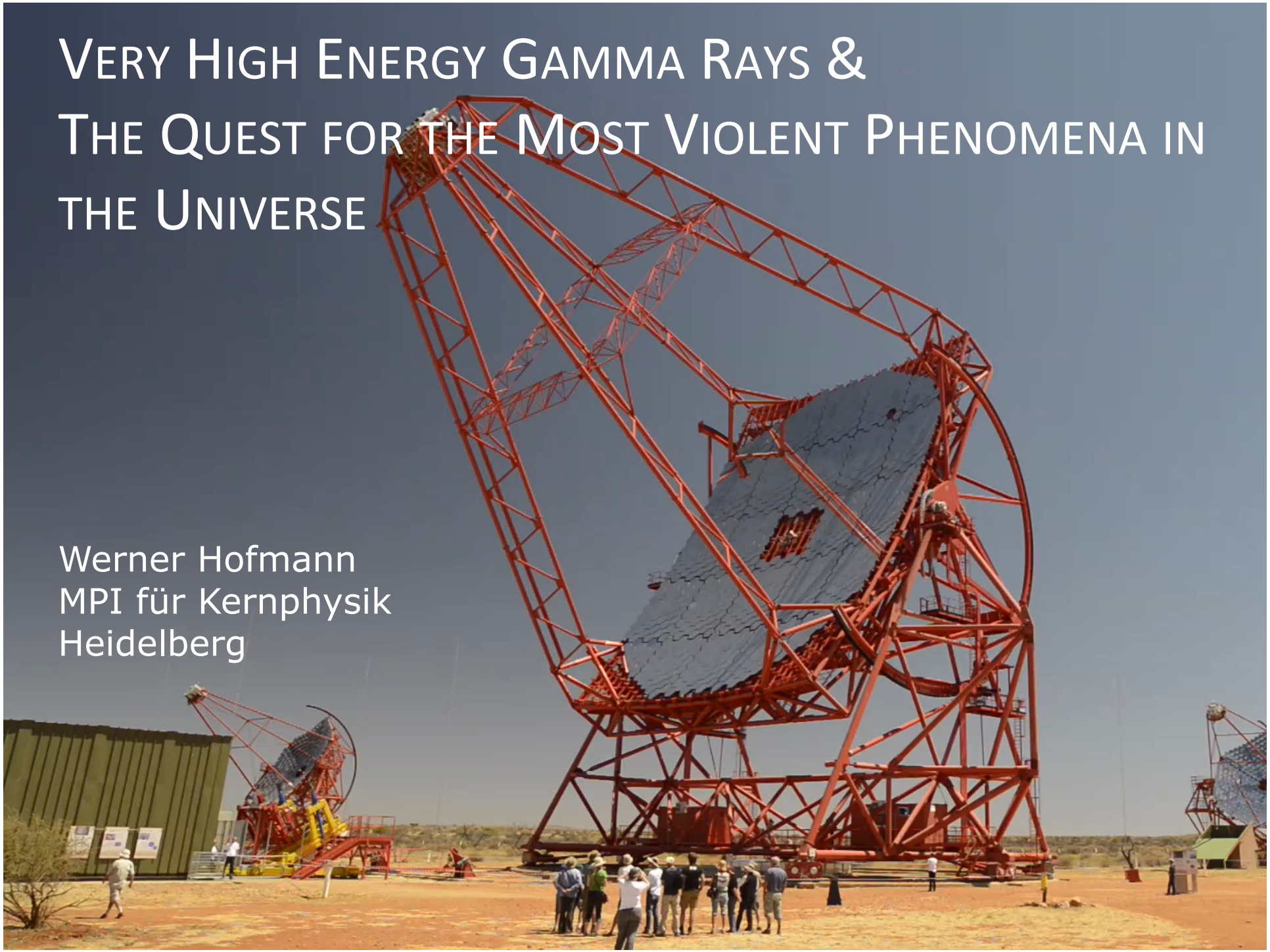
Very High Energy Gamma Rays & The Quest for the Most Violent Phenomena in the Universe

Very High Energy Gamma Rays & The Quest for the Most Violent Phenomena in the Universe



Werner Hofmann
MPI für Kernphysik
Heidelberg

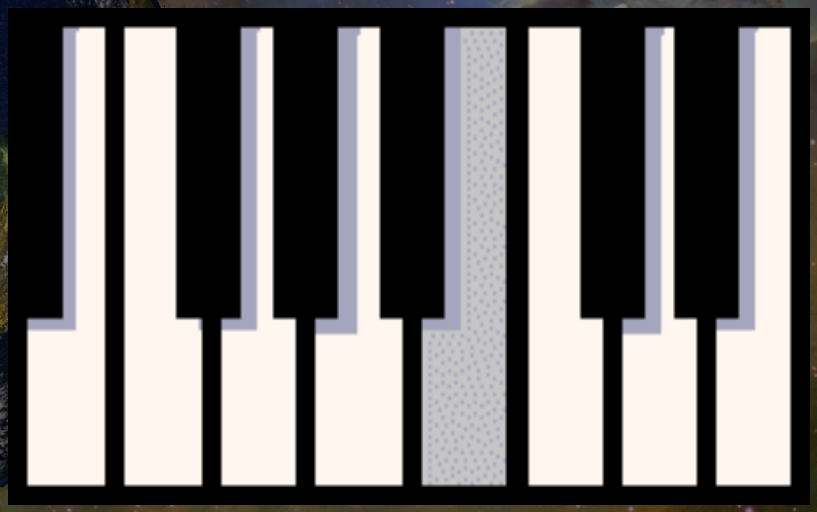

Light

Radiation from the Cosmos: a 15 m long piano!

Light

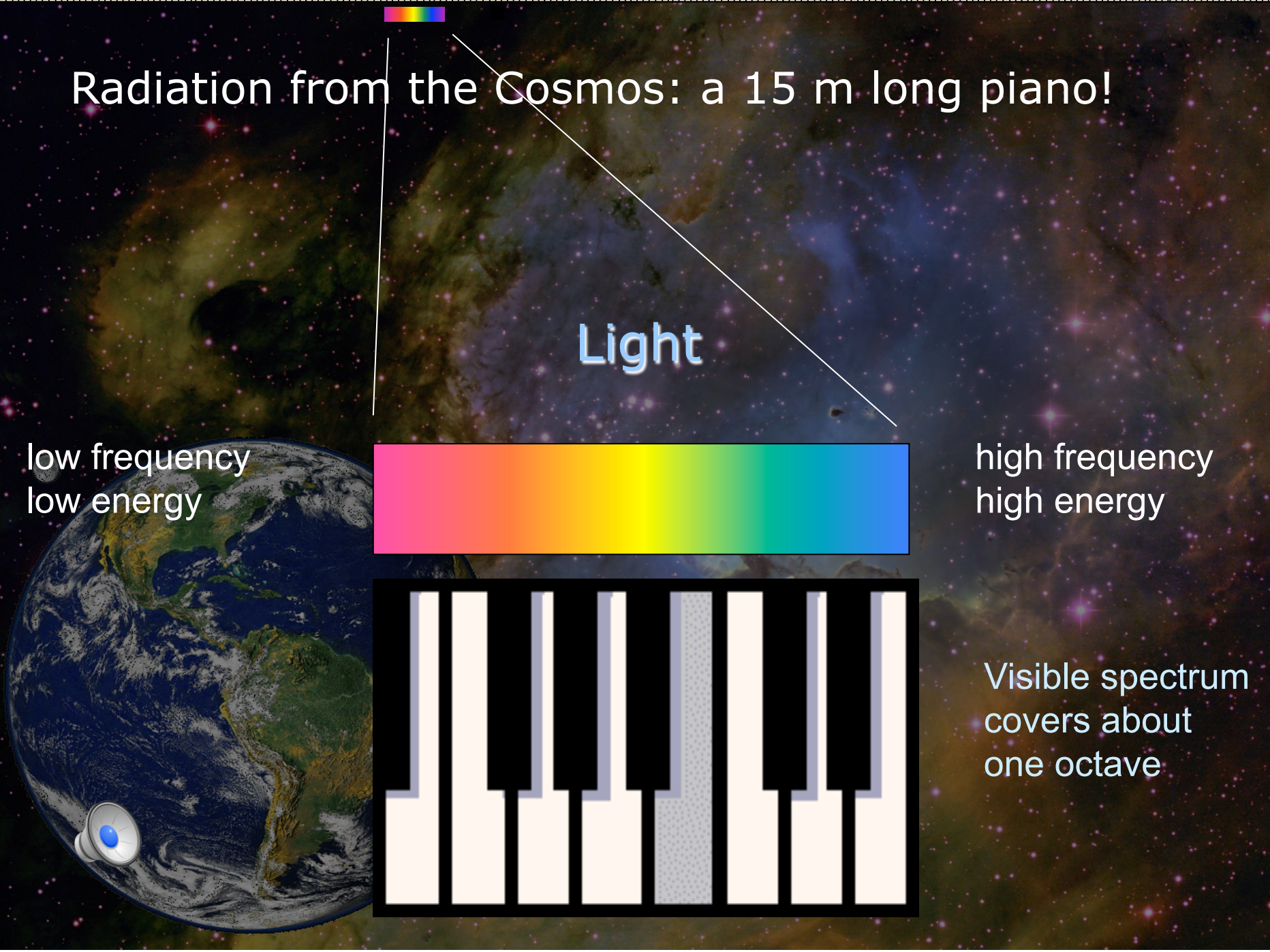
low frequency
low energy

high frequency
high energy

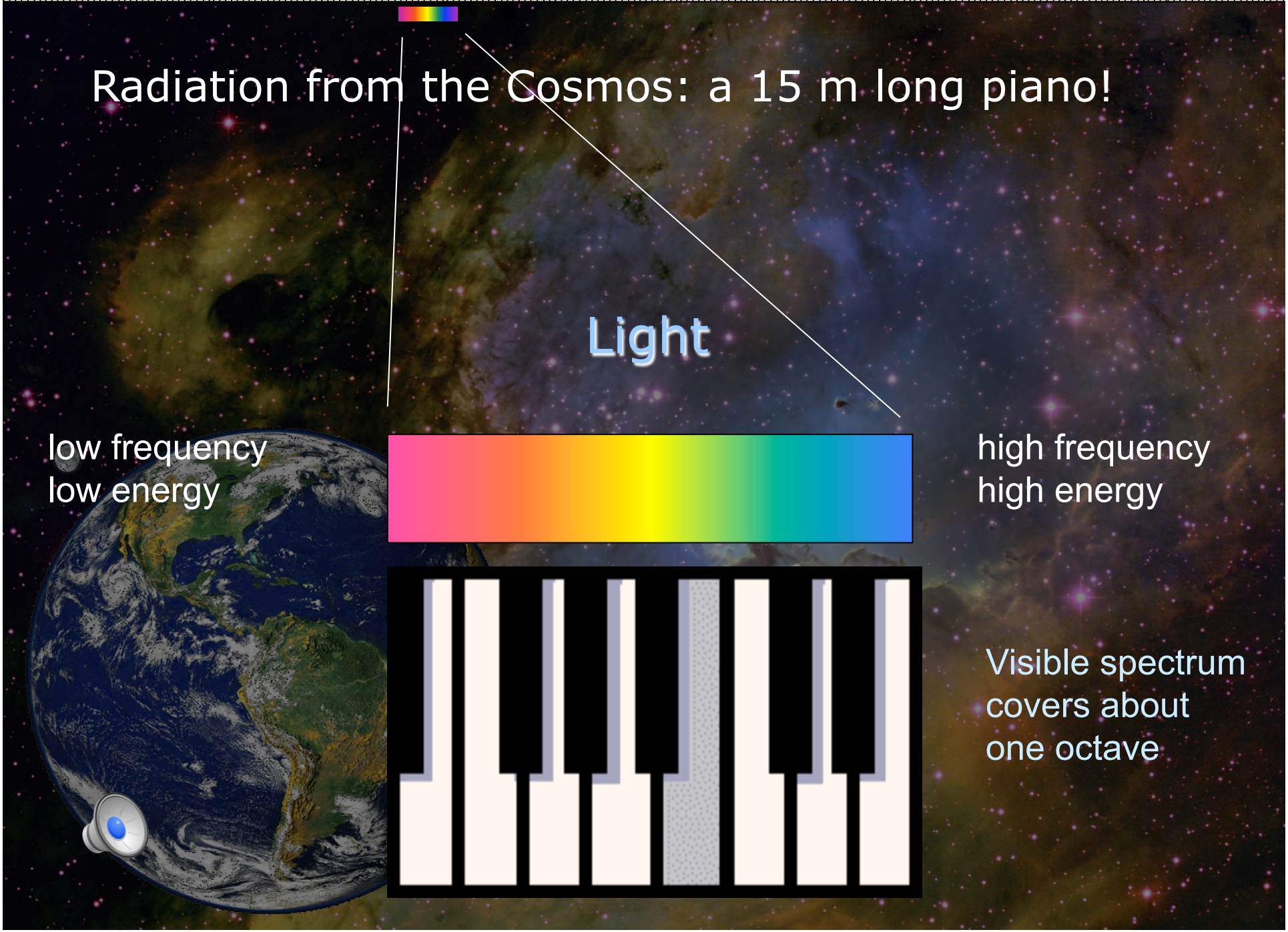


Visible spectrum
covers about
one octave

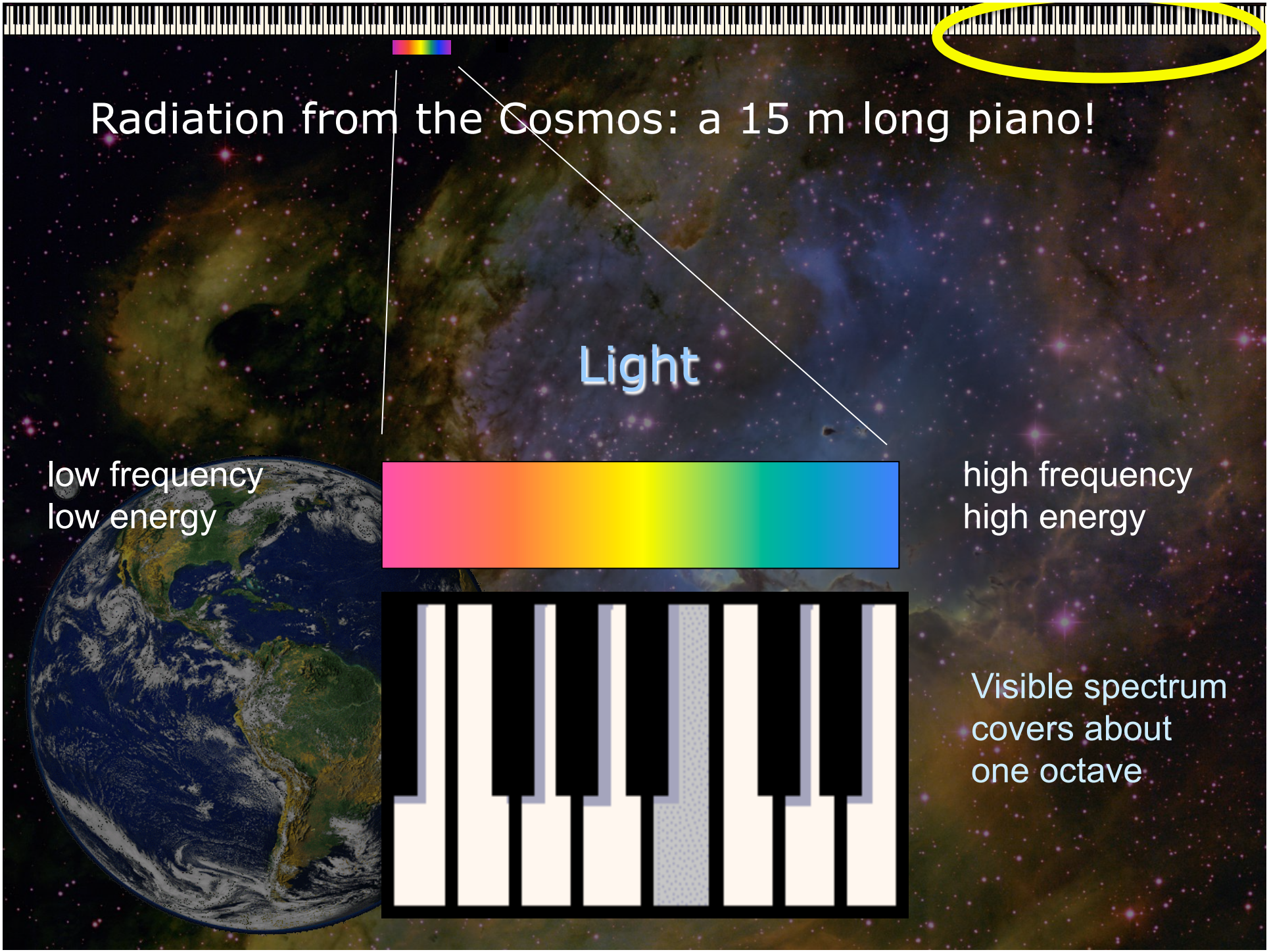
Radiation from the Cosmos: a 15 m long piano!

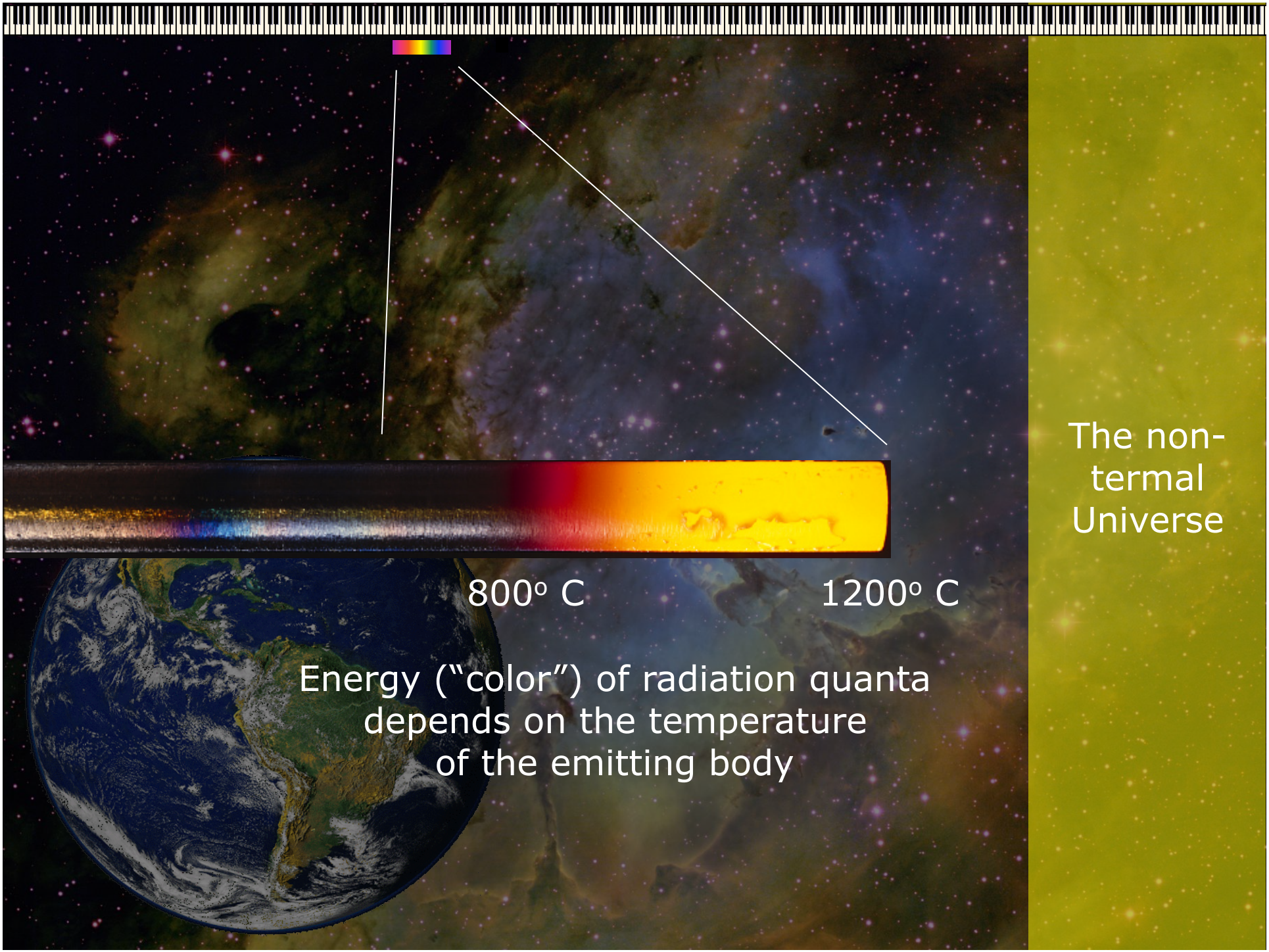


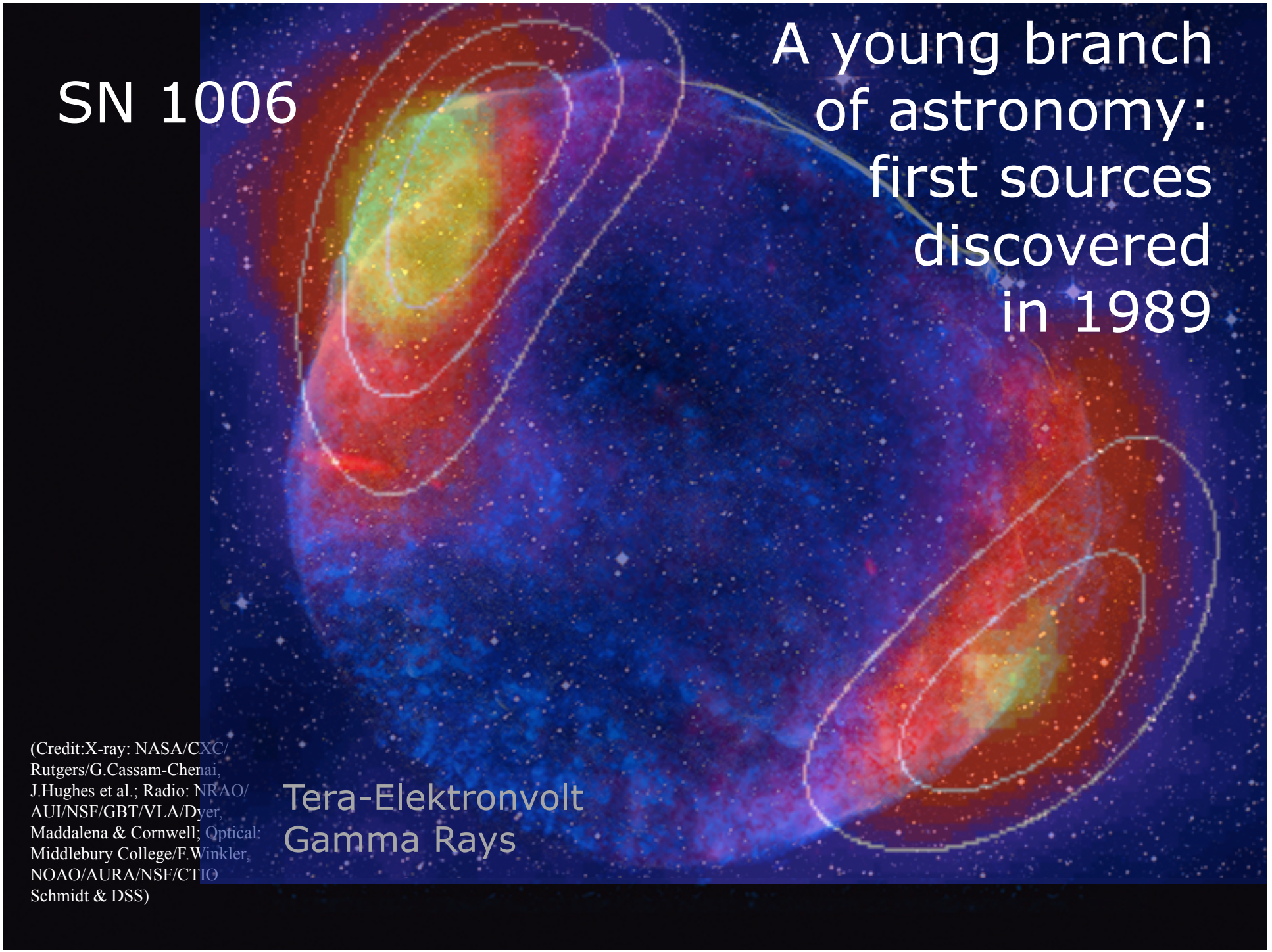
Radiation from the Cosmos: a 15 m long piano!



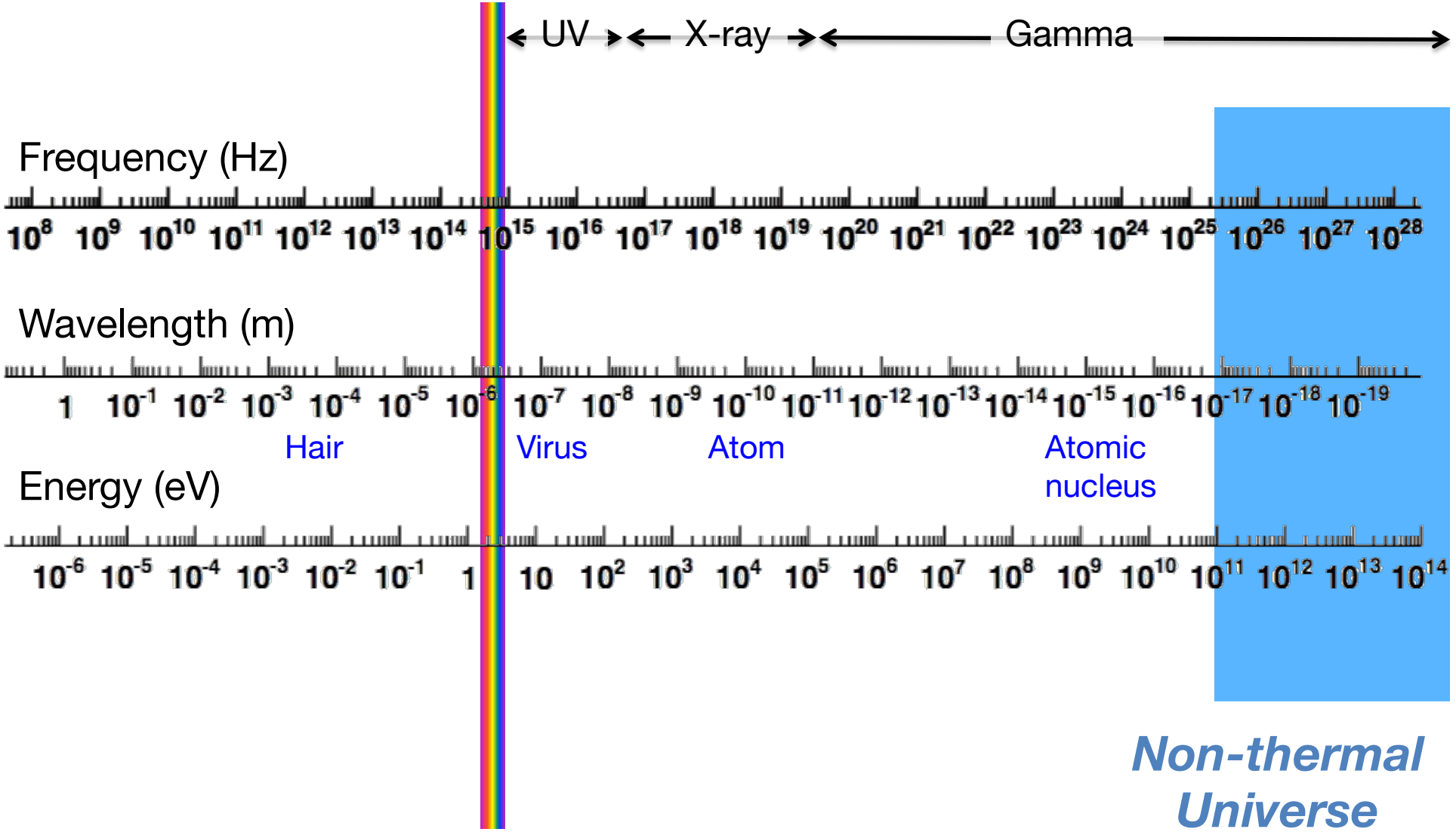
Radiation from the Cosmos: a 15 m long piano!



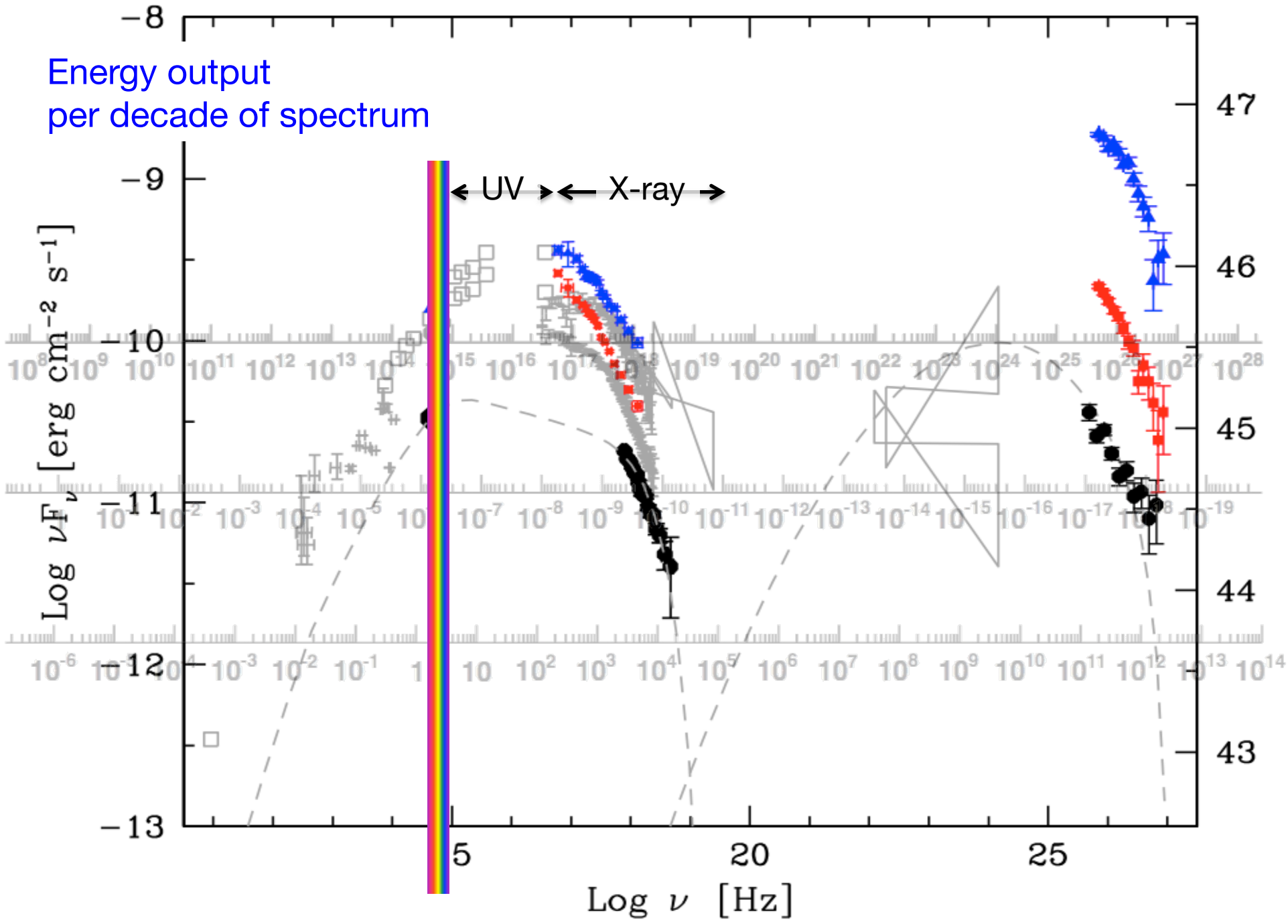

800° C
1200° C
Energy (“color”) of radiation quanta
depends on the temperature
of the emitting body
The non-
termal
Universe


SN 1006
A young branch of astronomy: first sources discovered in 1989
Tera-Elektronvolt Gamma Rays
(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)

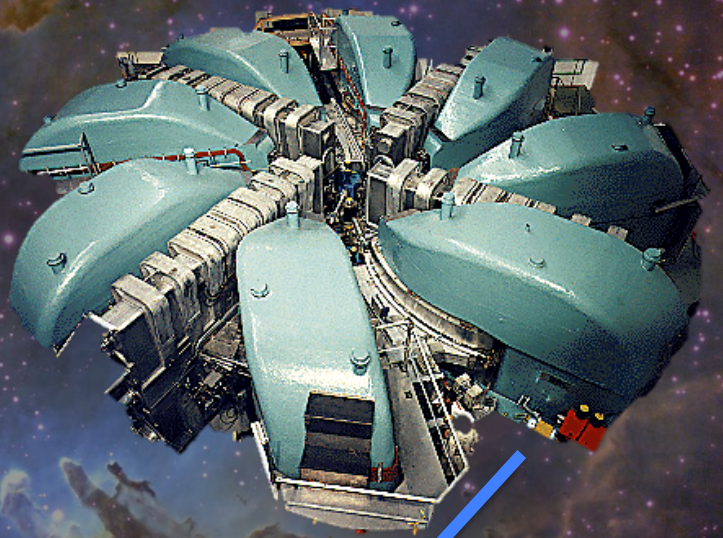
FREQUENCY, WAVELENGTH, ENERGY

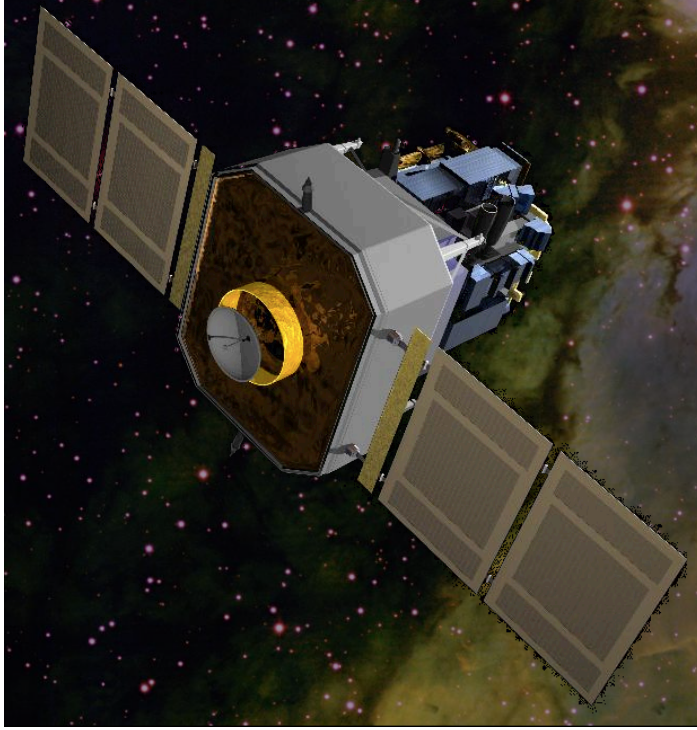


Non-thermal Universe


Energy output
per decade of spectrum
UV
X-ray
Log νF_ν [erg cm⁻² s⁻¹]
Log ν [Hz]
−8
−9
−10
−11
−12
−13
47
46
45
44
43
5
20
25

Cosmic particle accelerators

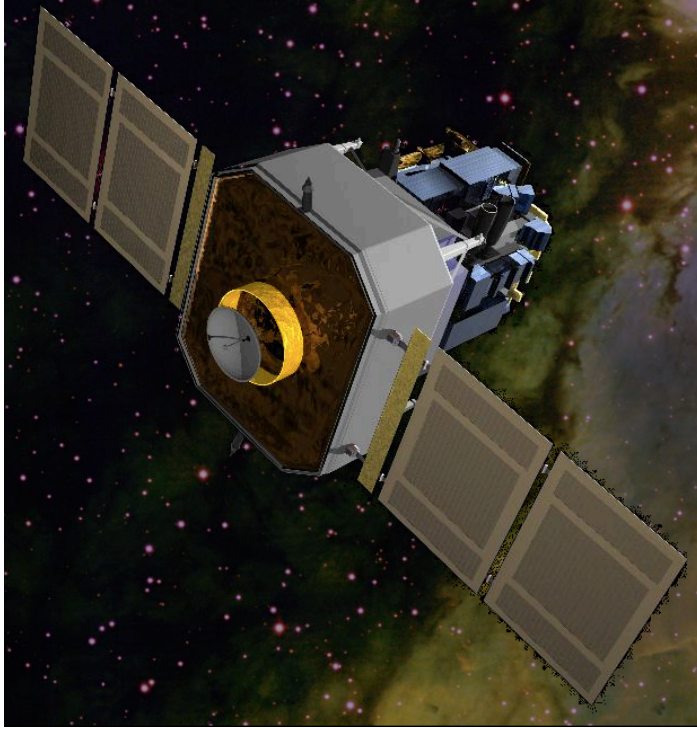


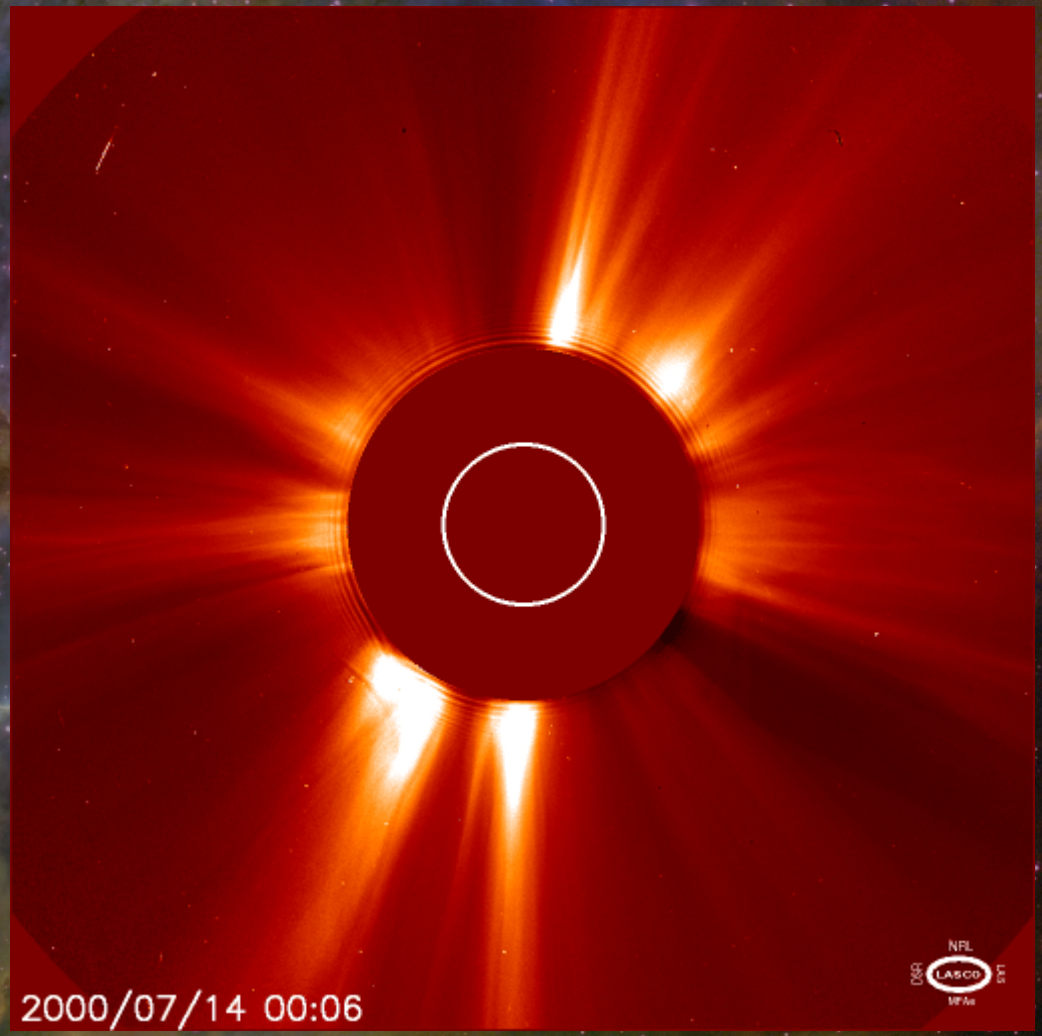


"Beam" of cosmic rays

Gamma rays

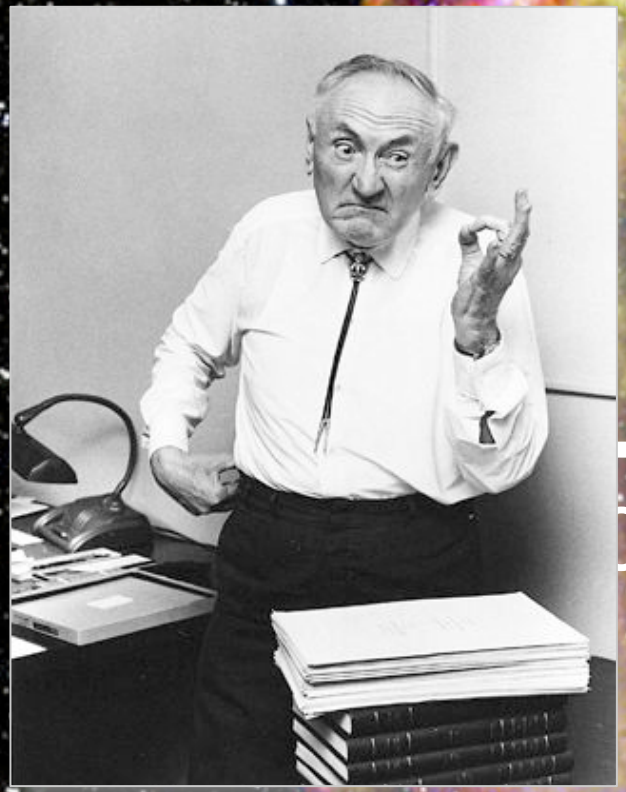
Cosmic particle accelerators: The sun



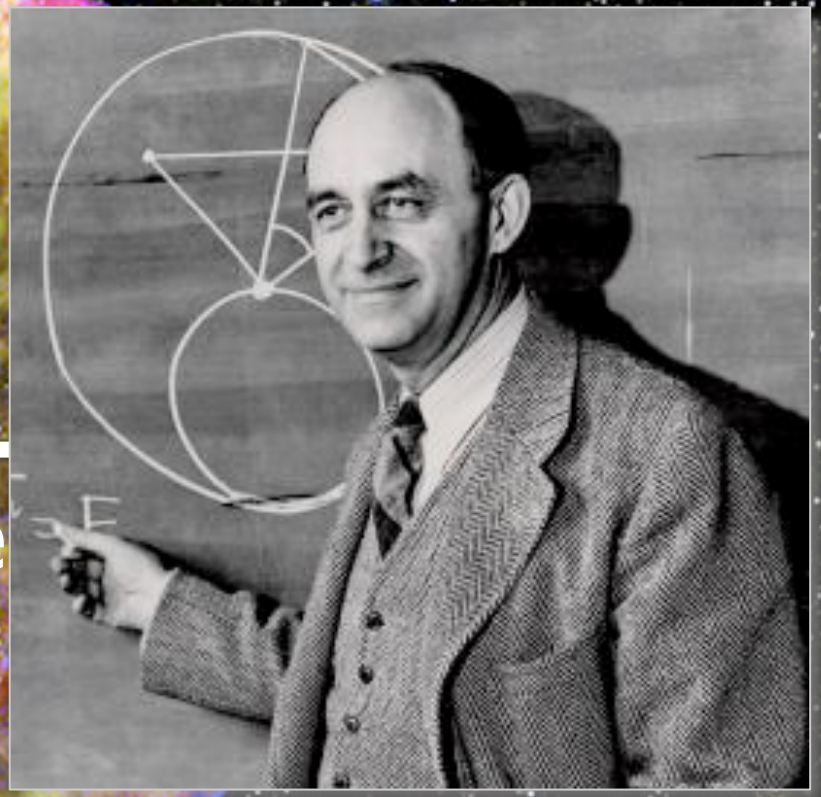


Supernovae as cosmic accelerators

Zwicky 1933



Fermi 1949



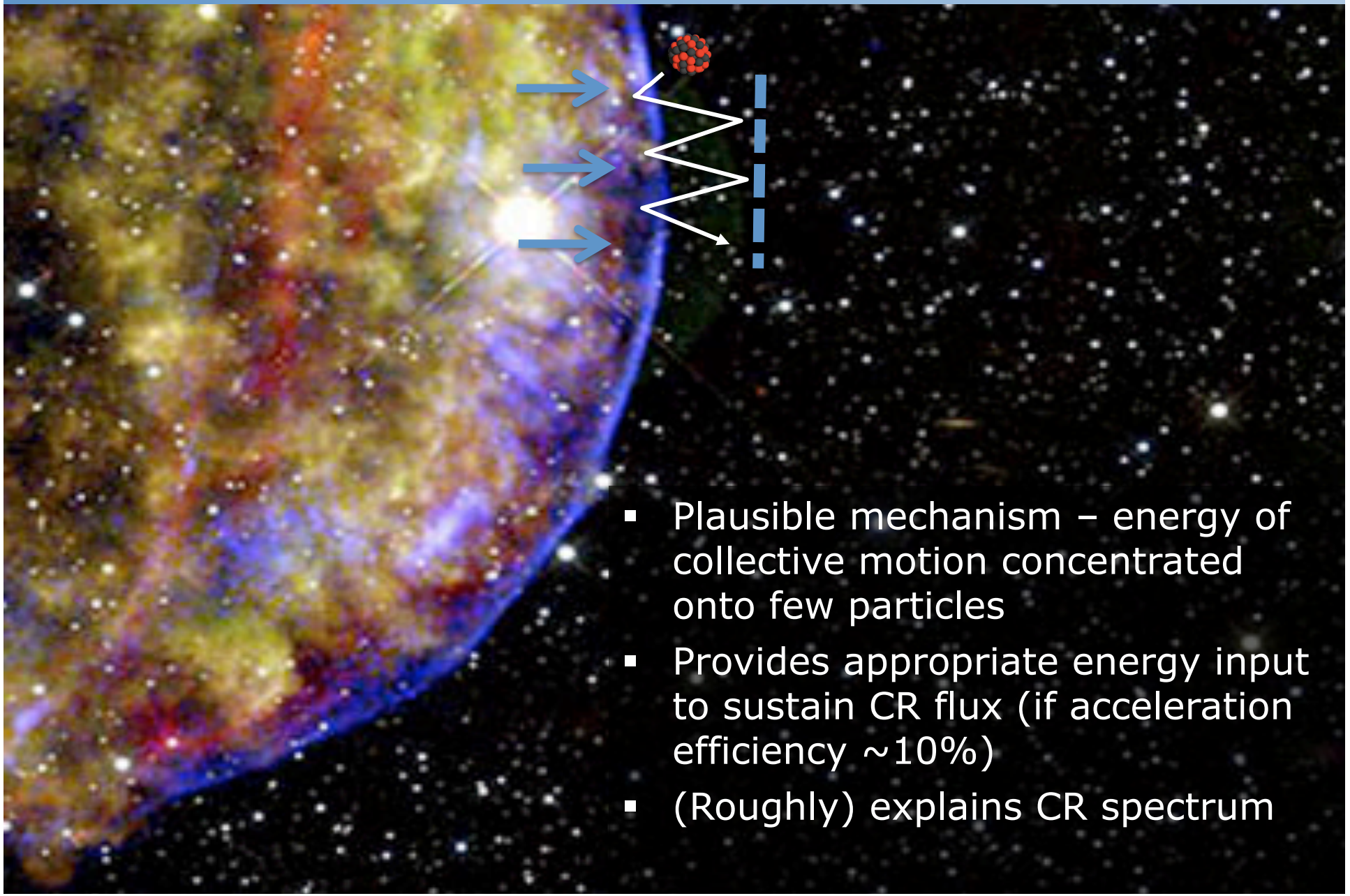
0 Light ye

Sufficient power source

Acceleration mechanism

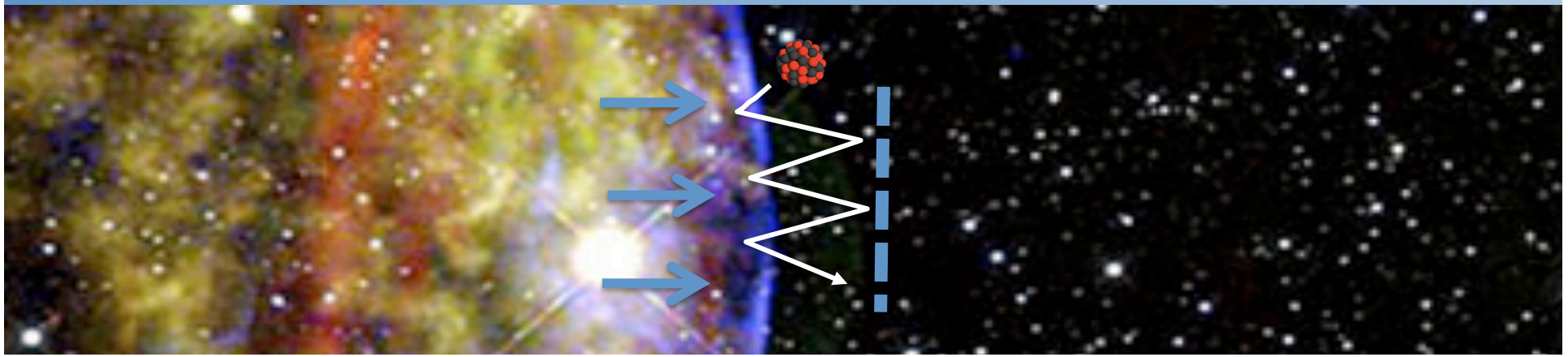
Tychos Supernova of 1572

FERMI ACCELERATION IN SNR



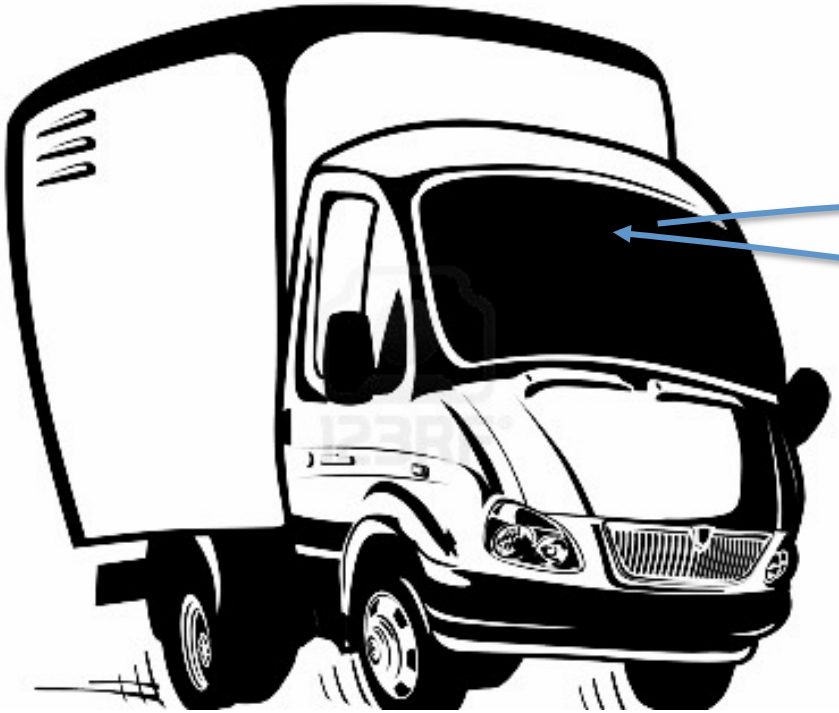
- Plausible mechanism – energy of collective motion concentrated onto few particles
- Provides appropriate energy input to sustain CR flux (if acceleration efficiency ~10%)
- (Roughly) explains CR spectrum

FERMI ACCELERATION



Velocity U

like playing tennis with a truck

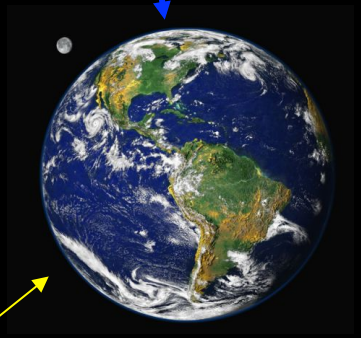


Velocity v+2U

Velocity v

SEEING COSMIC ACCELERATORS

➔ Image accelerators with gamma rays



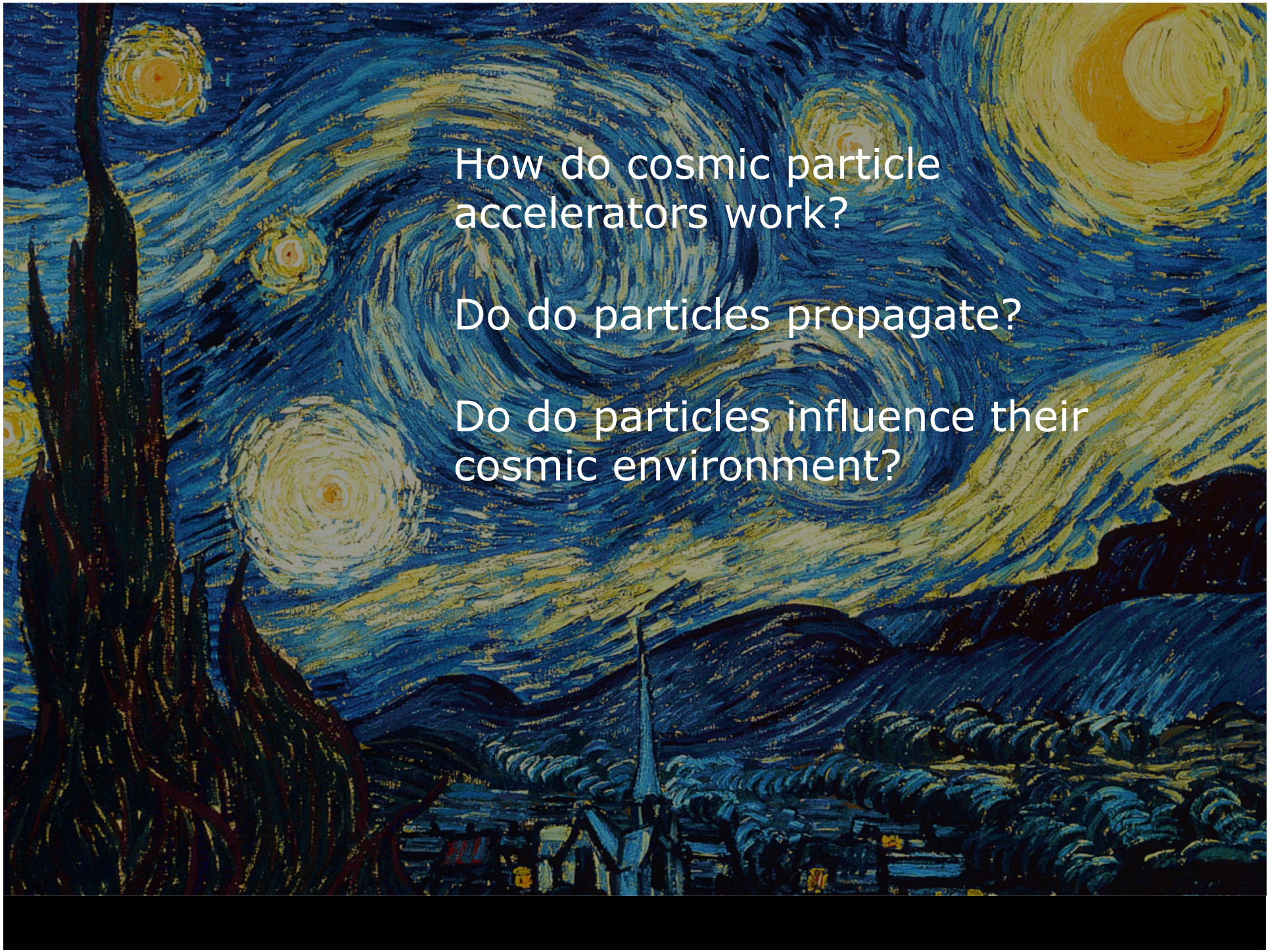
Spectra
and flux reflect
those of acc. particles

p + nucleus → π +X

$\pi^o \rightarrow \gamma\gamma$

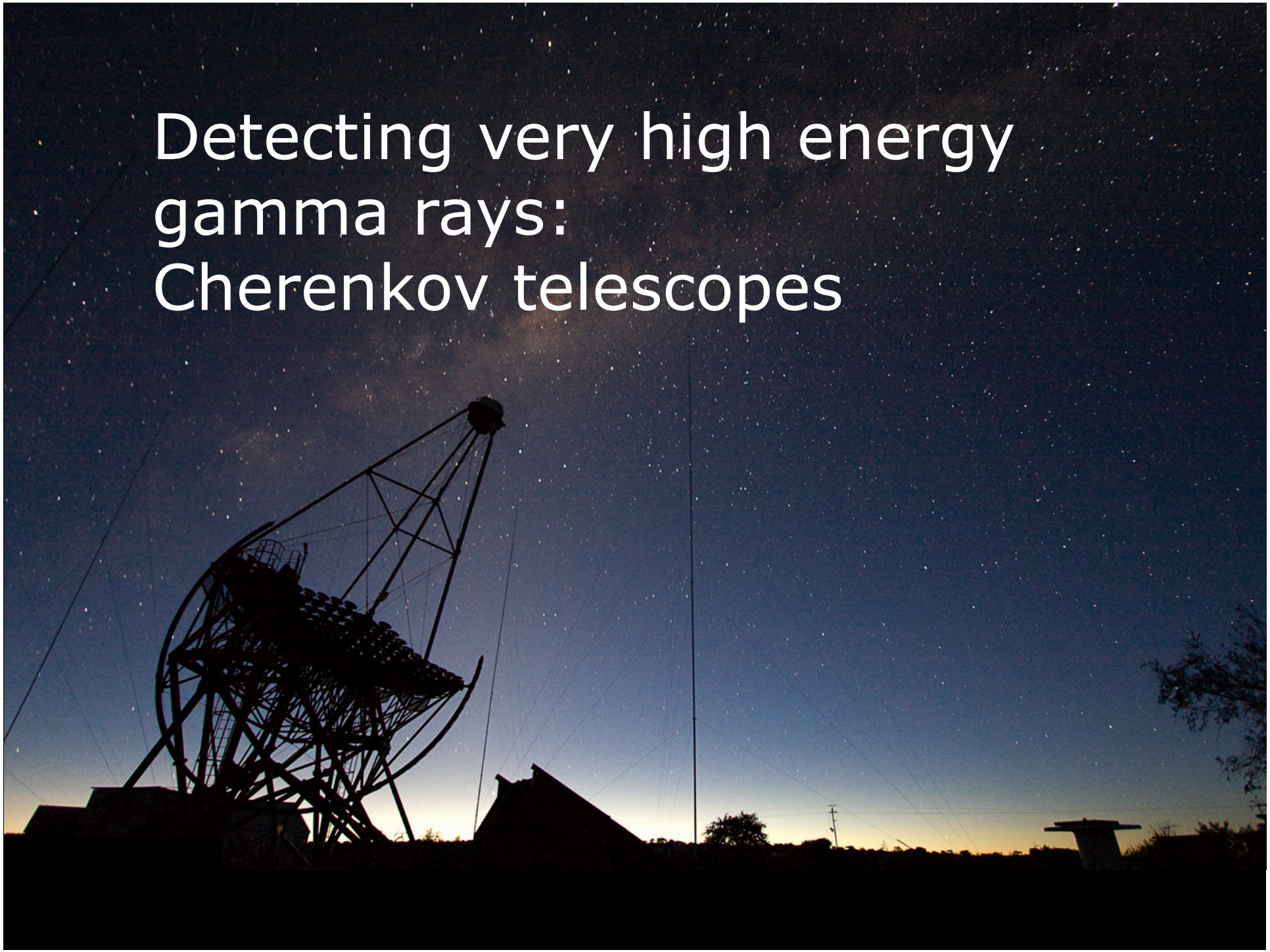
$\pi^{\pm} \rightarrow \mu^{\pm} \nu$

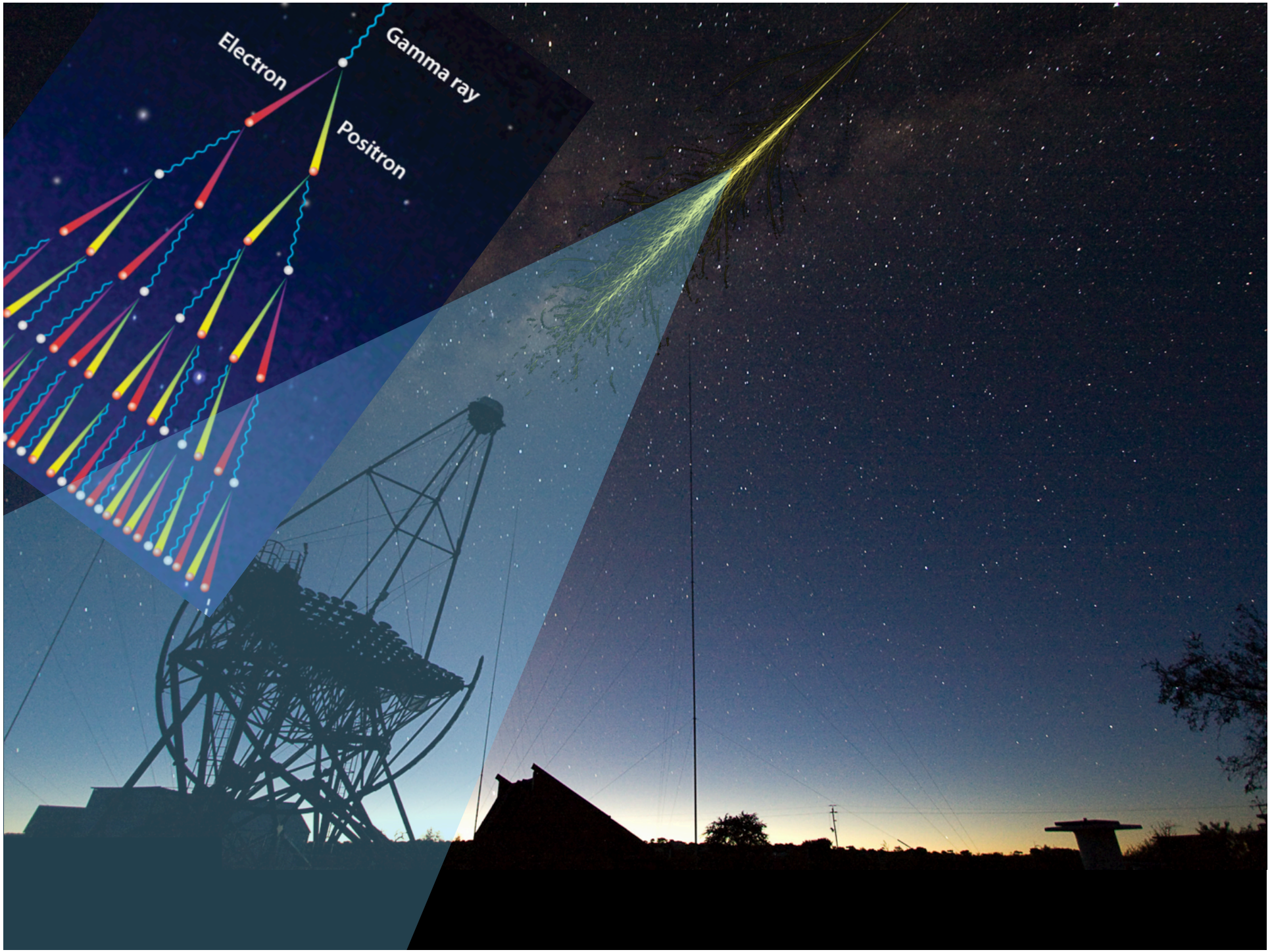

"Gamma ray astronomy traces the
energy skeleton of the Universe"

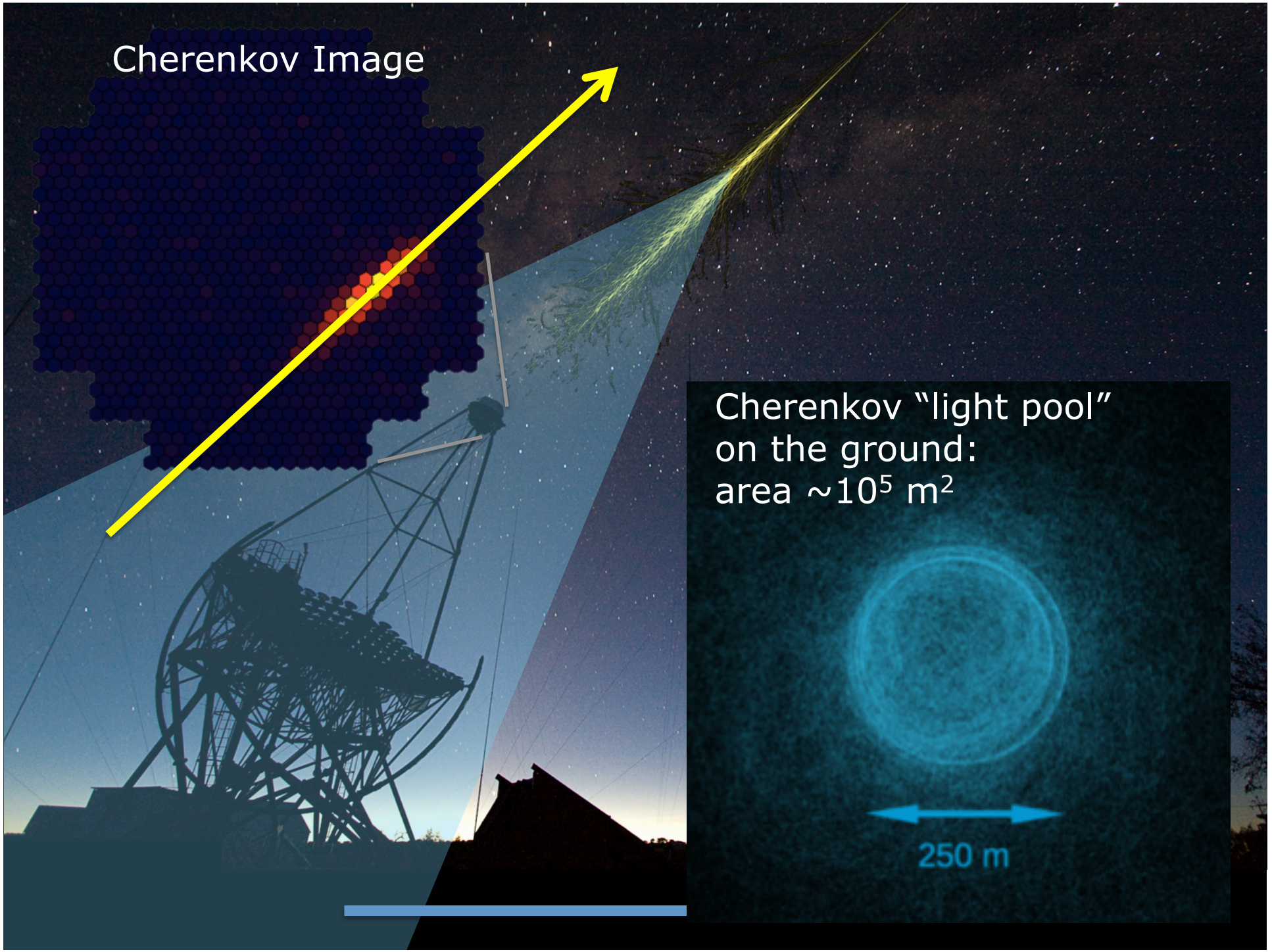

How do cosmic particle accelerators work?
Do do particles propagate?
Do do particles influence their cosmic environment?

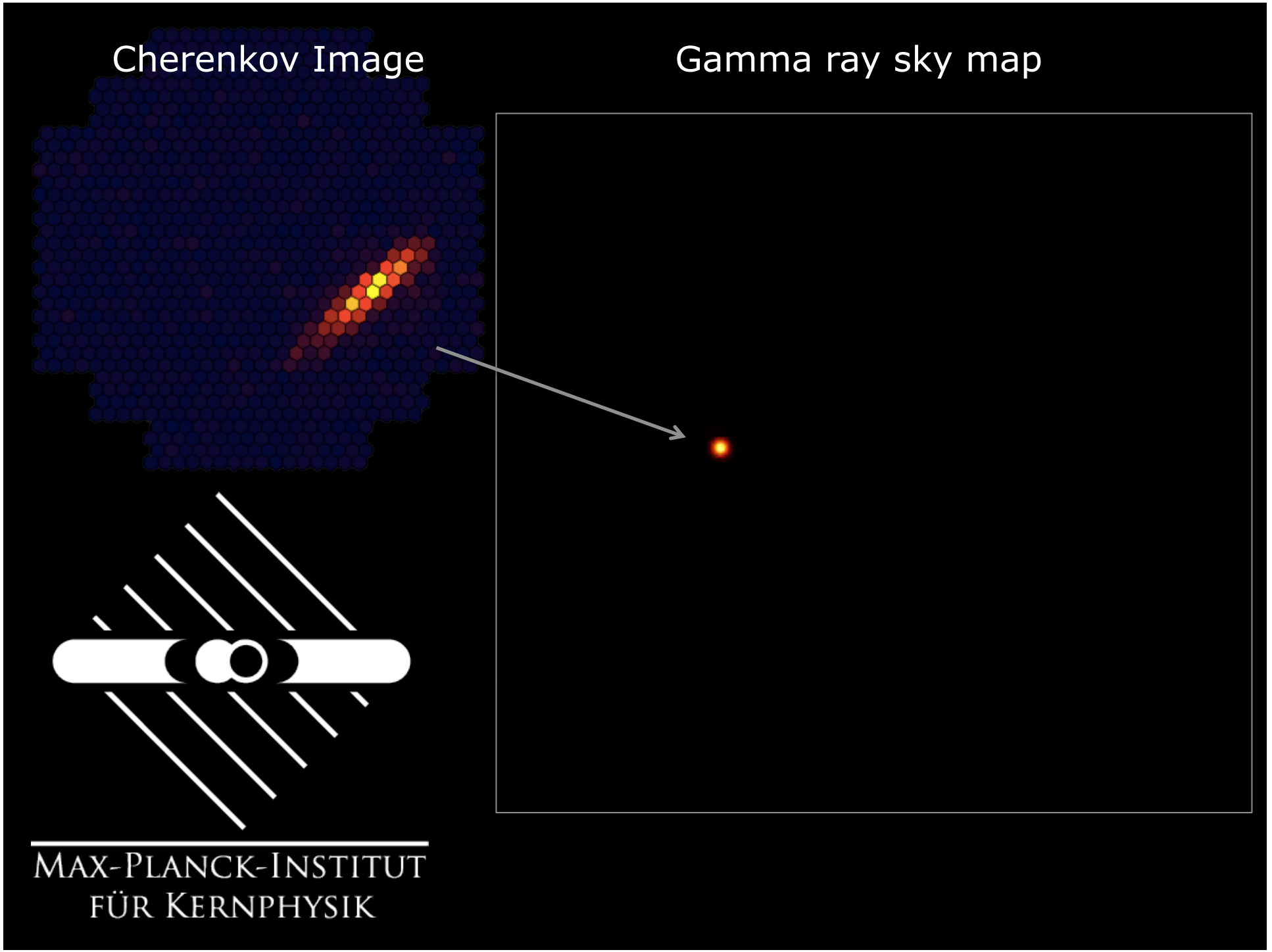

Gamma rays trace annihilating / decaying relics ➜ Dark Matter
Gamma rays propagate over 10^9+ years ➜ LIV, Axions, …

Detecting very high energy gamma rays: Cherenkov telescopes

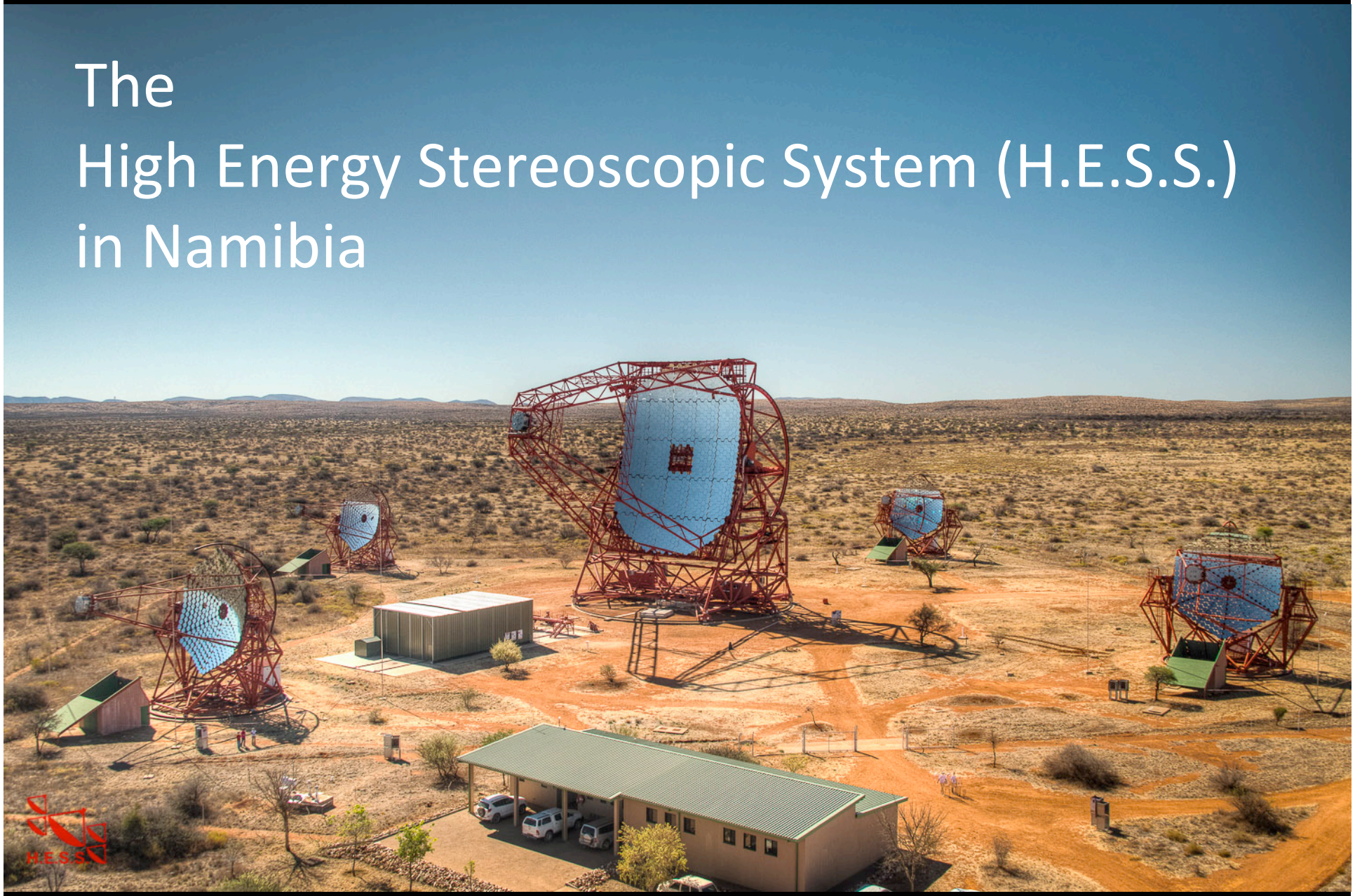



Electron
Gamma ray
Positron

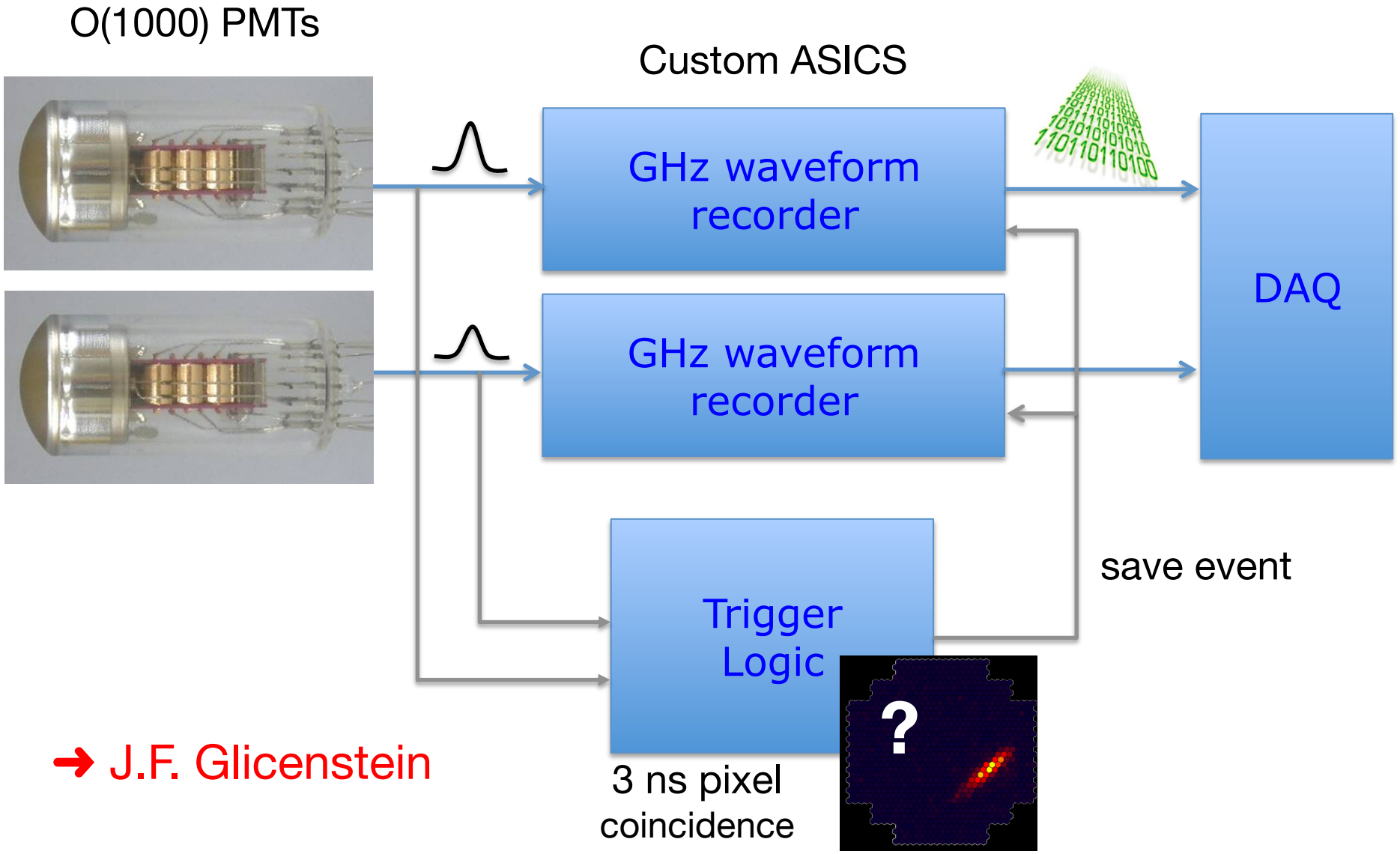

Cherenkov Image
Cherenkov "light pool"
on the ground:
area ~10^5 m^2
250 m


Cherenkov Image
Gamma ray sky map
MAX-PLANCK-INSTITUT
FÜR KERNPHYSIK

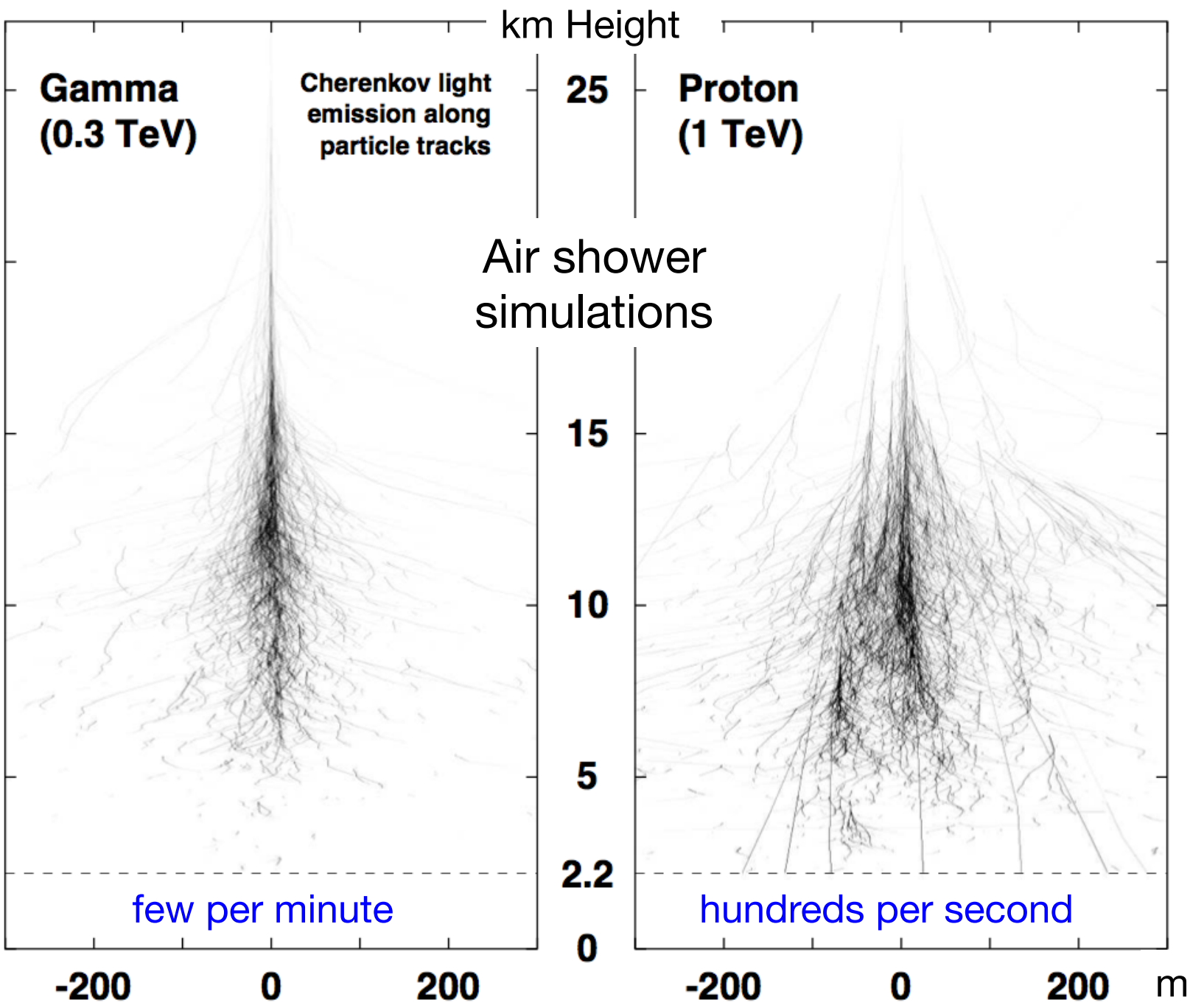
The
High Energy Stereoscopic System (H.E.S.S.)
in Namibia



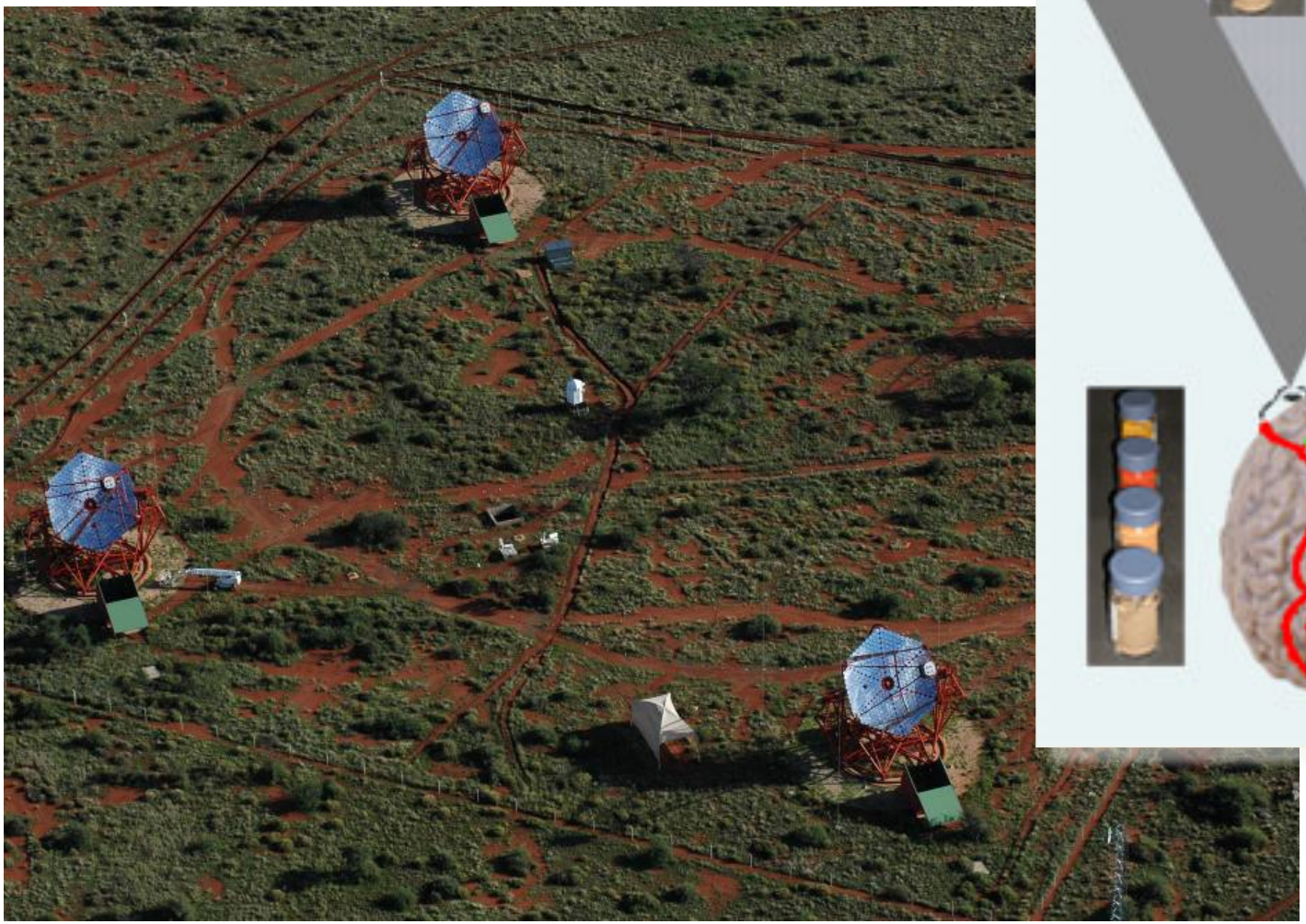
SENSORS AND READOUT

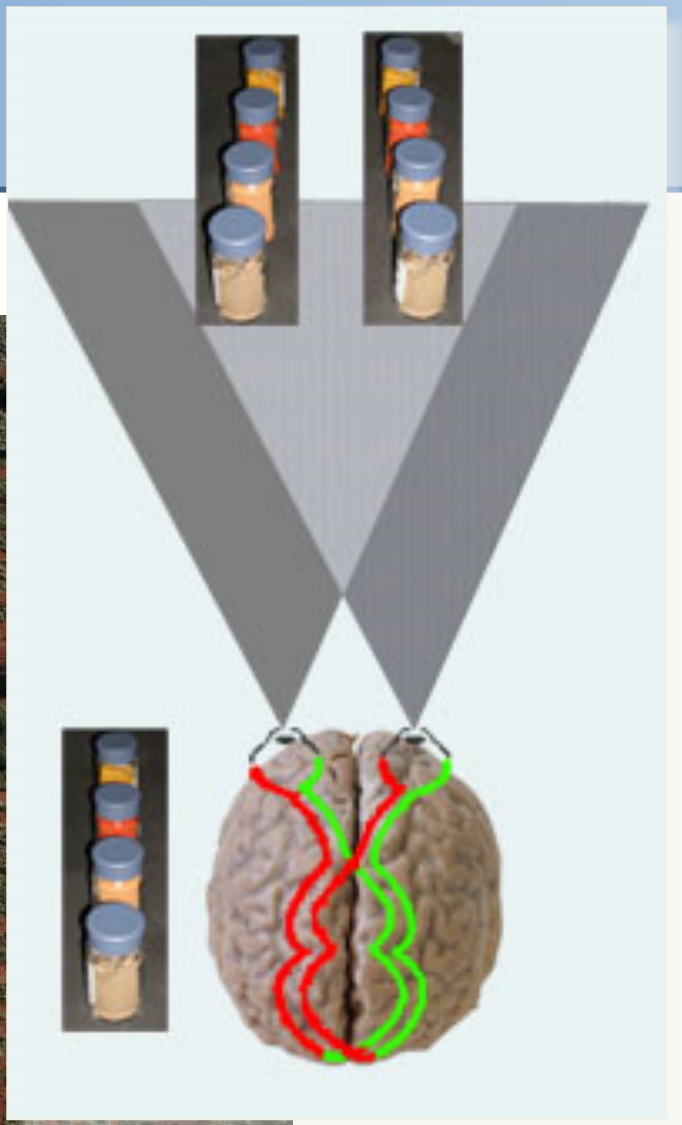


➜ J.F. Glicenstein


km Height
Gamma
(0.3 TeV)
Cherenkov light
emission along
particle tracks
25
Proton
(1 TeV)
Air shower
simulations
15
10
5
2.2
0
few per minute
hundreds per second
-200
0
200
-200
0
200
m

FOUR EYES





A decade of H.E.S.S operation

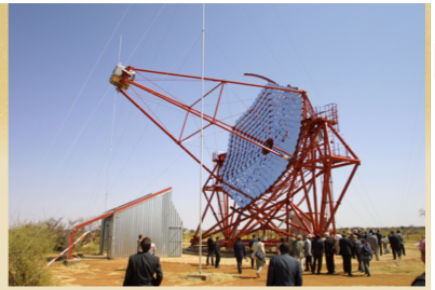
2002: Inauguration of the first H.E.S.S. telescope

2004: Four-telescope system complete

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

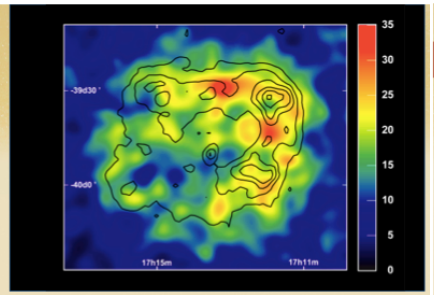
2000

Start of H.E.S.S. Construction



2002

Inauguration of the First Telescope

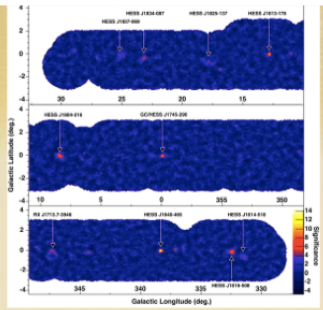


2004

First Images of a Supernova Remnant

2004

Inauguration of the Four-Telescope H.E.S.S. I System



2005

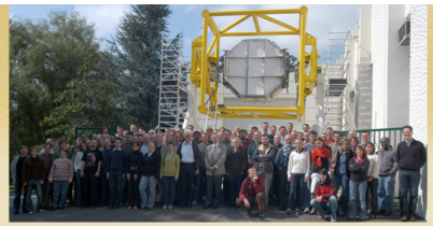
The First Images of the Milky Way

2006

Descartes Prize of the European Commisson

2009

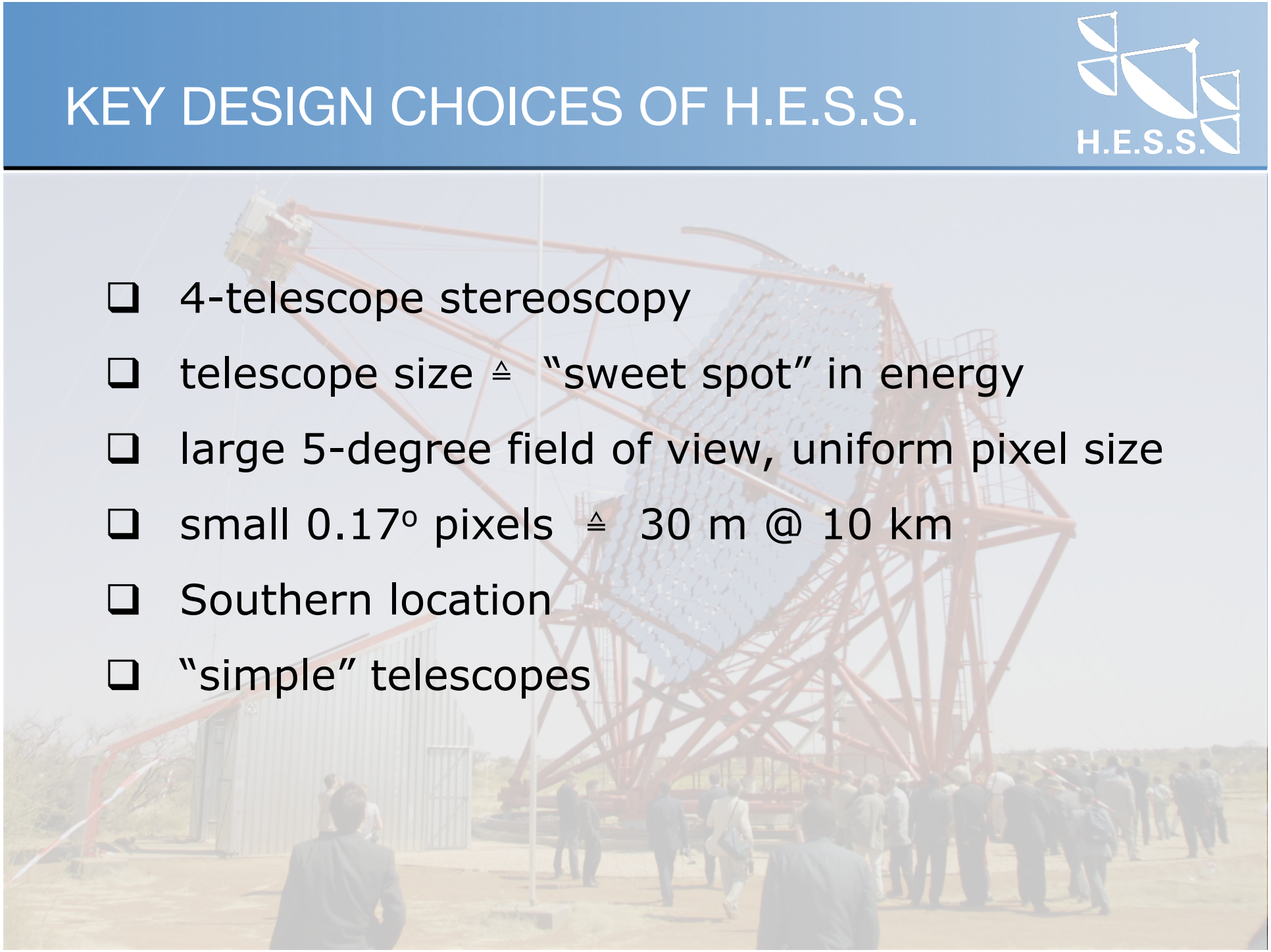
H.E.S.S. Listed Among the Top 10 Observatories Worldwide



2010

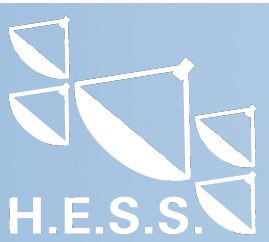
Rossi Prize of the American Astronomical Society

KEY DESIGN CHOICES OF H.E.S.S.



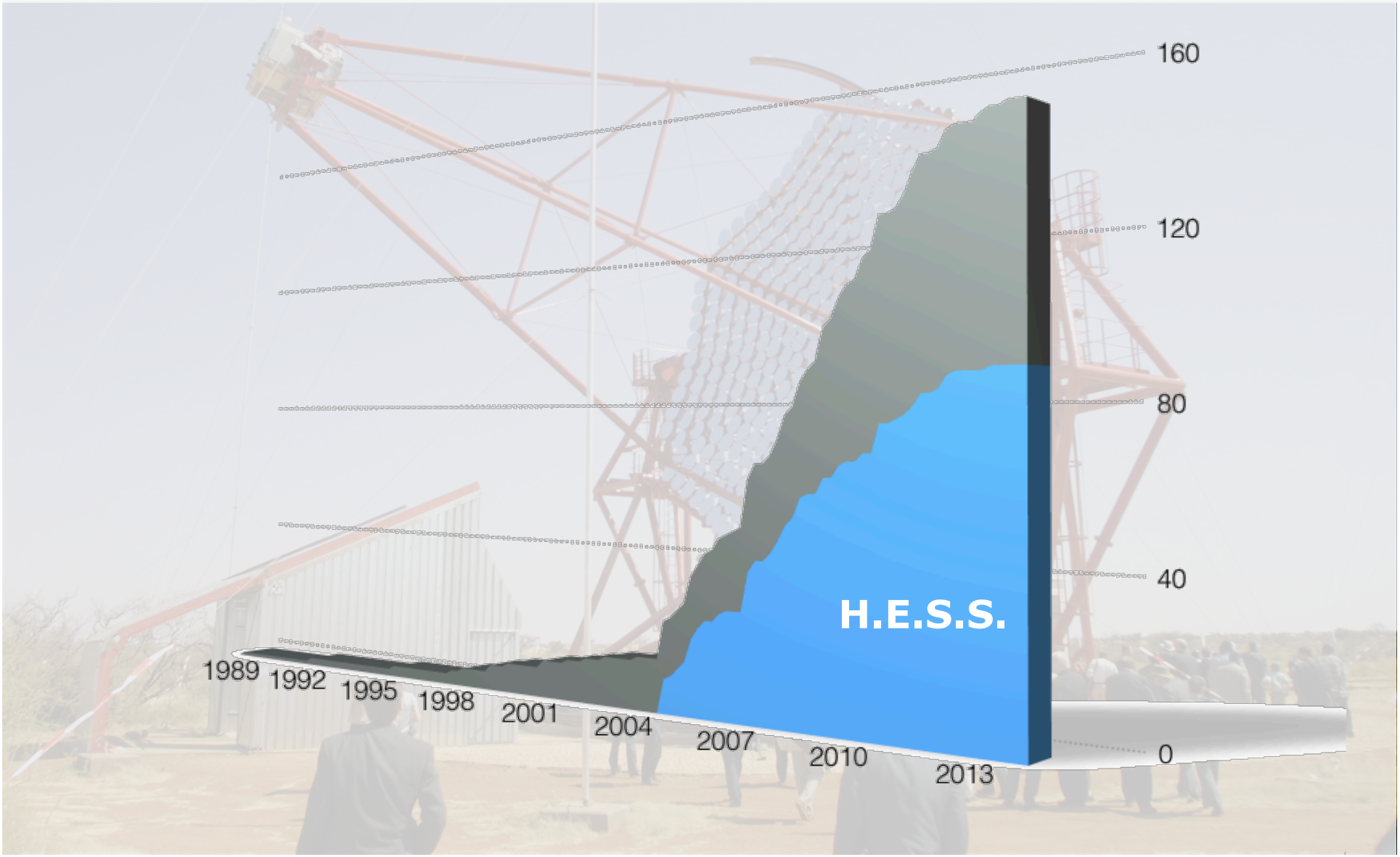
- 4-telescope stereoscopy
- telescope size ≙ "sweet spot" in energy
- large 5-degree field of view, uniform pixel size
- small 0.17° pixels ≙ 30 m @ 10 km
- Southern location
- "simple" telescopes

“REAL ASTRONOMY” IN A NEW ENERGY BAND



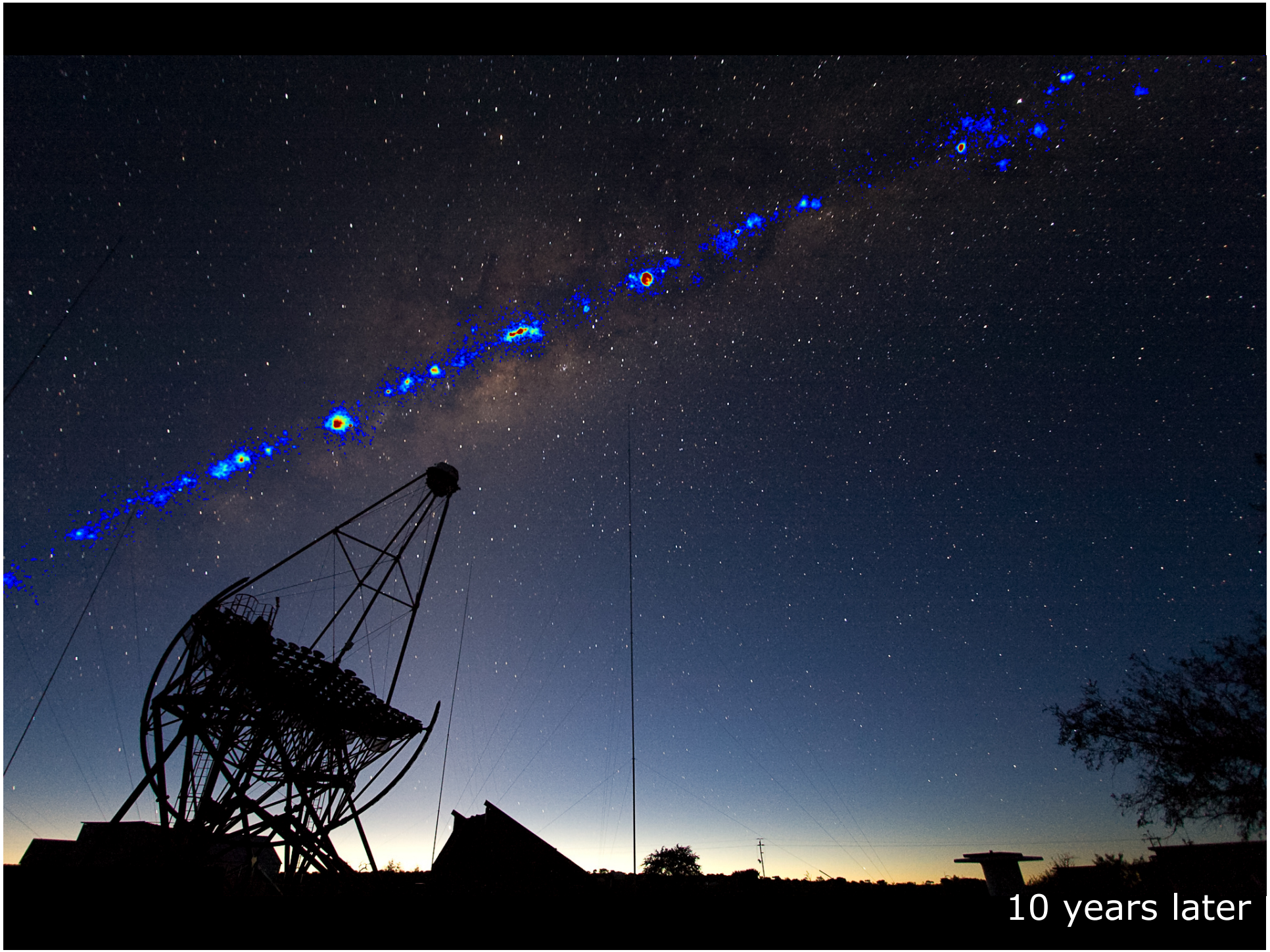
- High sensitivity
  - 3 orders of magnitude dynamic range in flux, down to 0.01 “Crab”
- Wide spectral range
  - >2 orders of magnitude coverage in energy, up to 10s of TeV
  - 10-15% energy resolution
- Resolved source morphology
  - ~5’ angular resolution
  - 10-20” source localization
- Survey capability
  - H.E.S.S. Galactic Plane Survey:
  - better than 2% Crab sensitivity
- Well-resolved light curves
  - Minute-scale variability of AGN

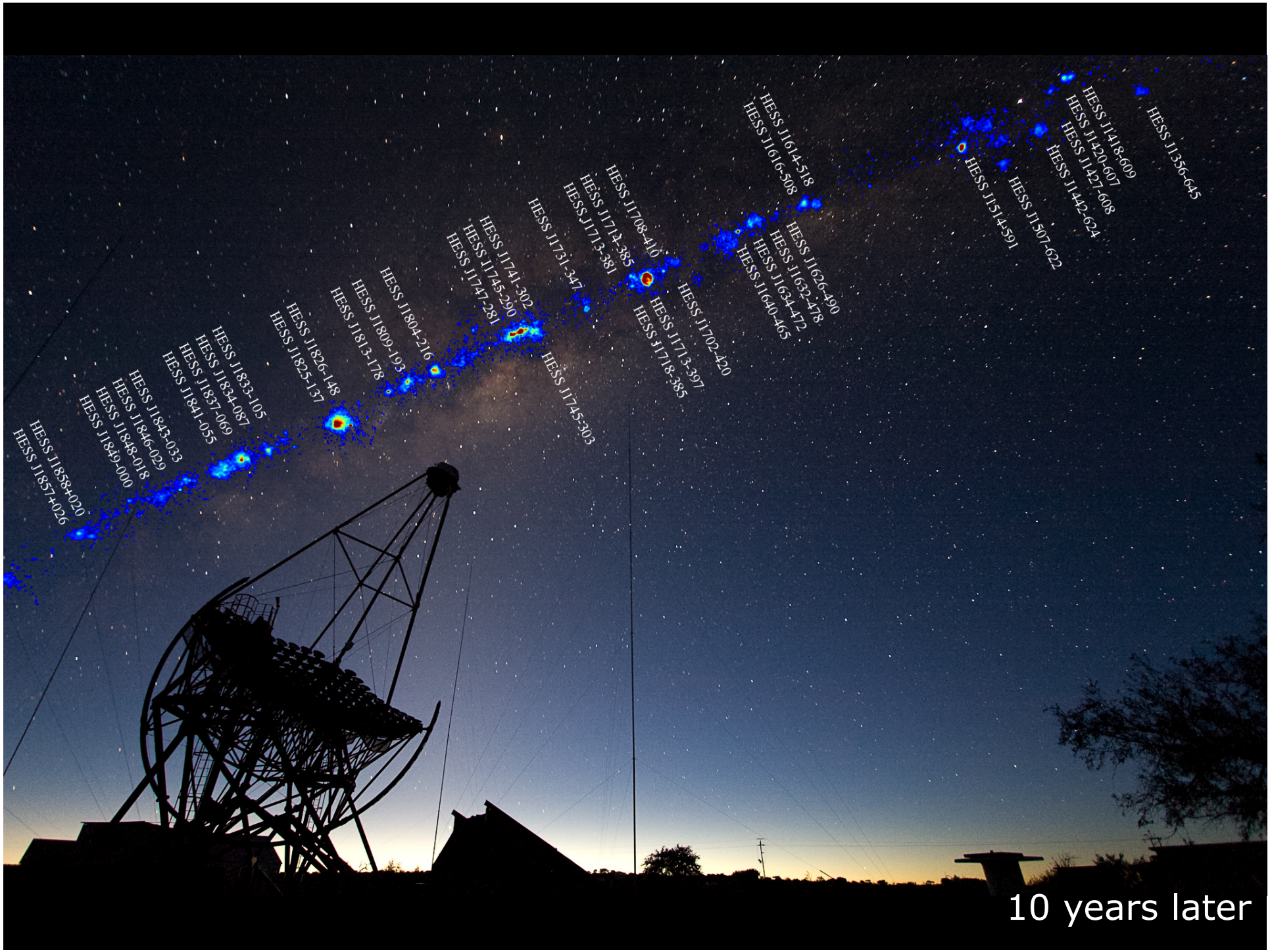
VHE GAMMA RAY SOURCE DISCOVERIES



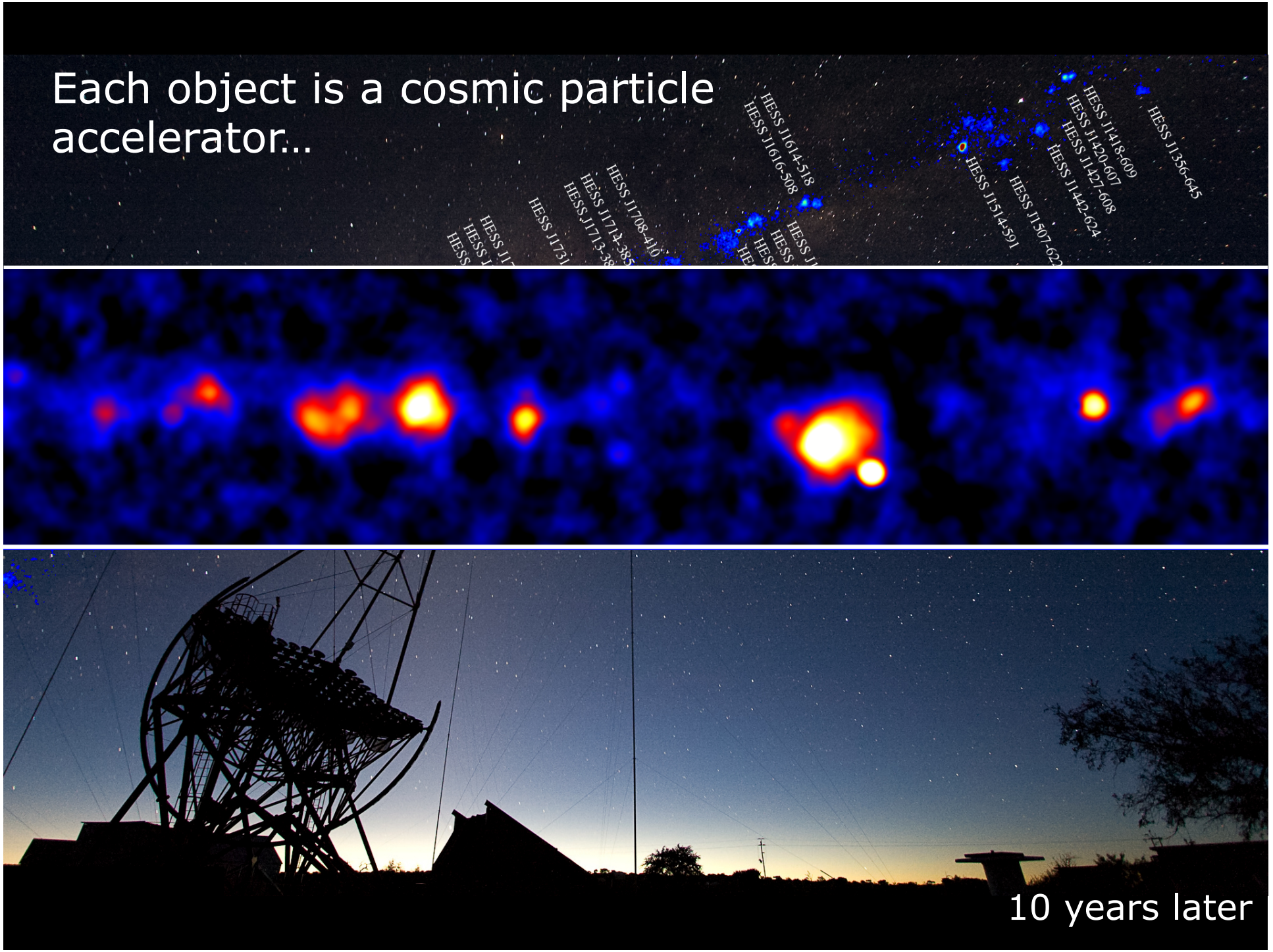
The sky at TeV energies

10 years later

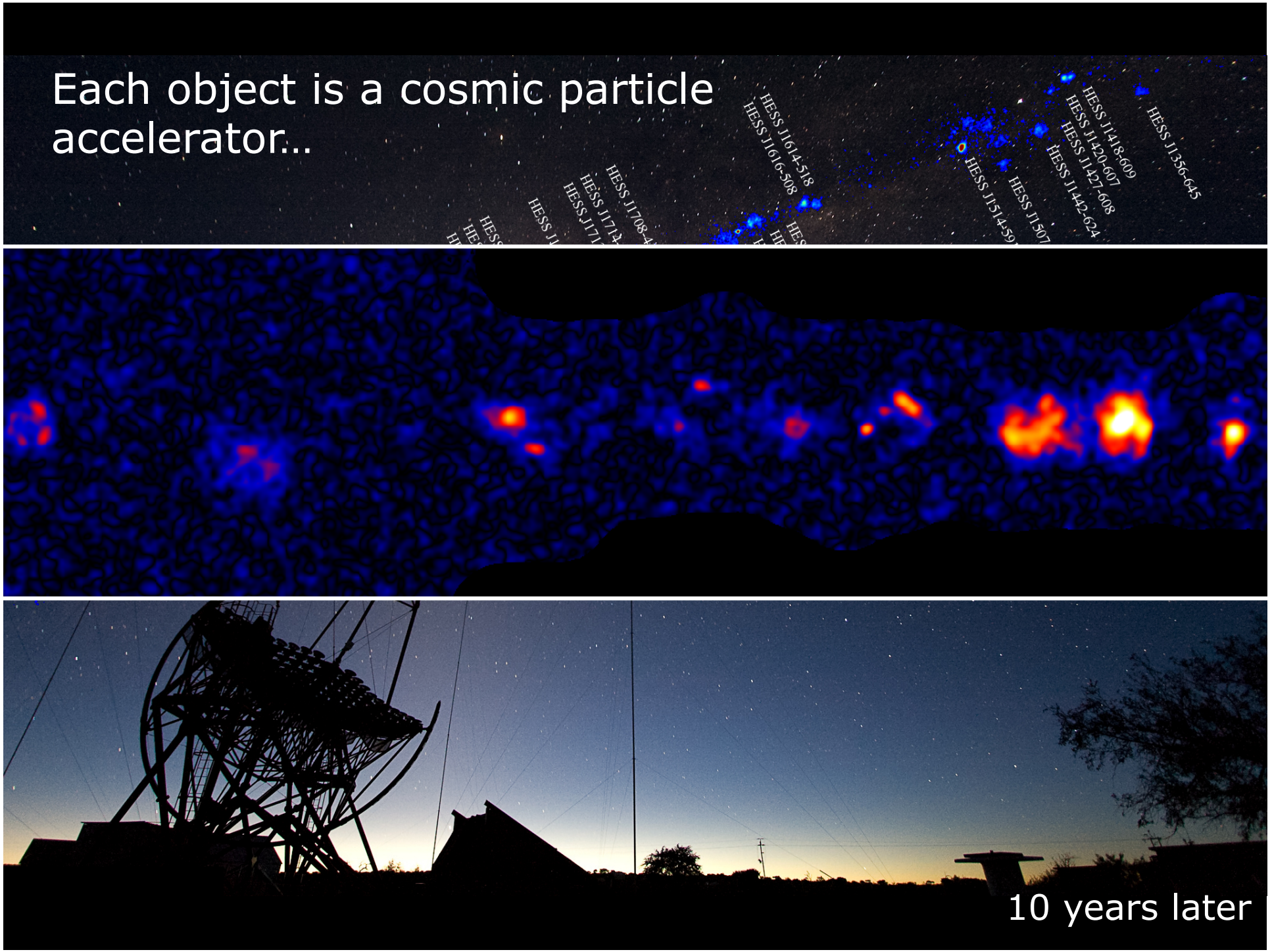

10 years later


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

Each object is a cosmic particle accelerator…



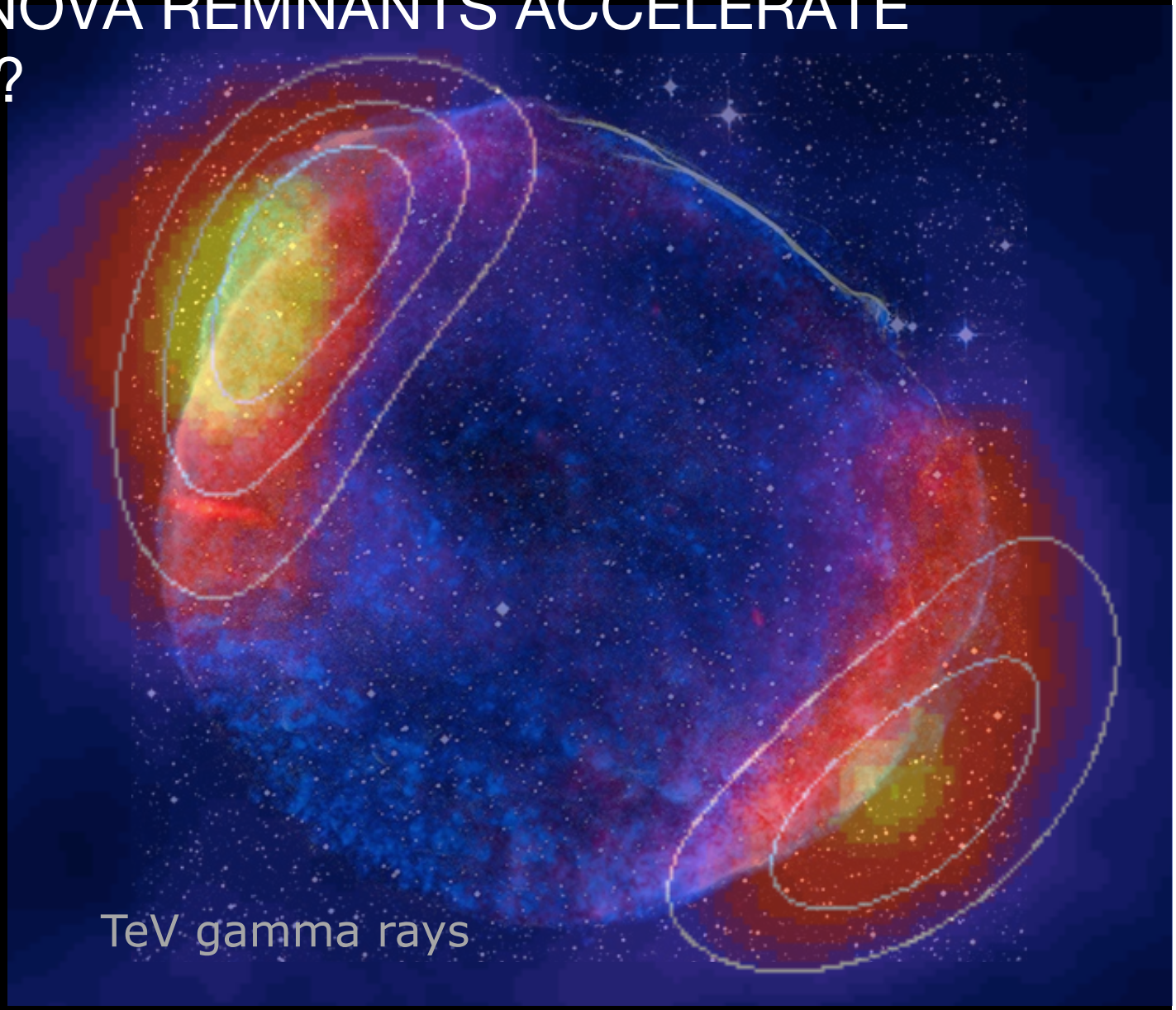
Each object is a cosmic particle accelerator…



DO SUPERNOVA REMNANTS ACCELERATE PARTICLES?

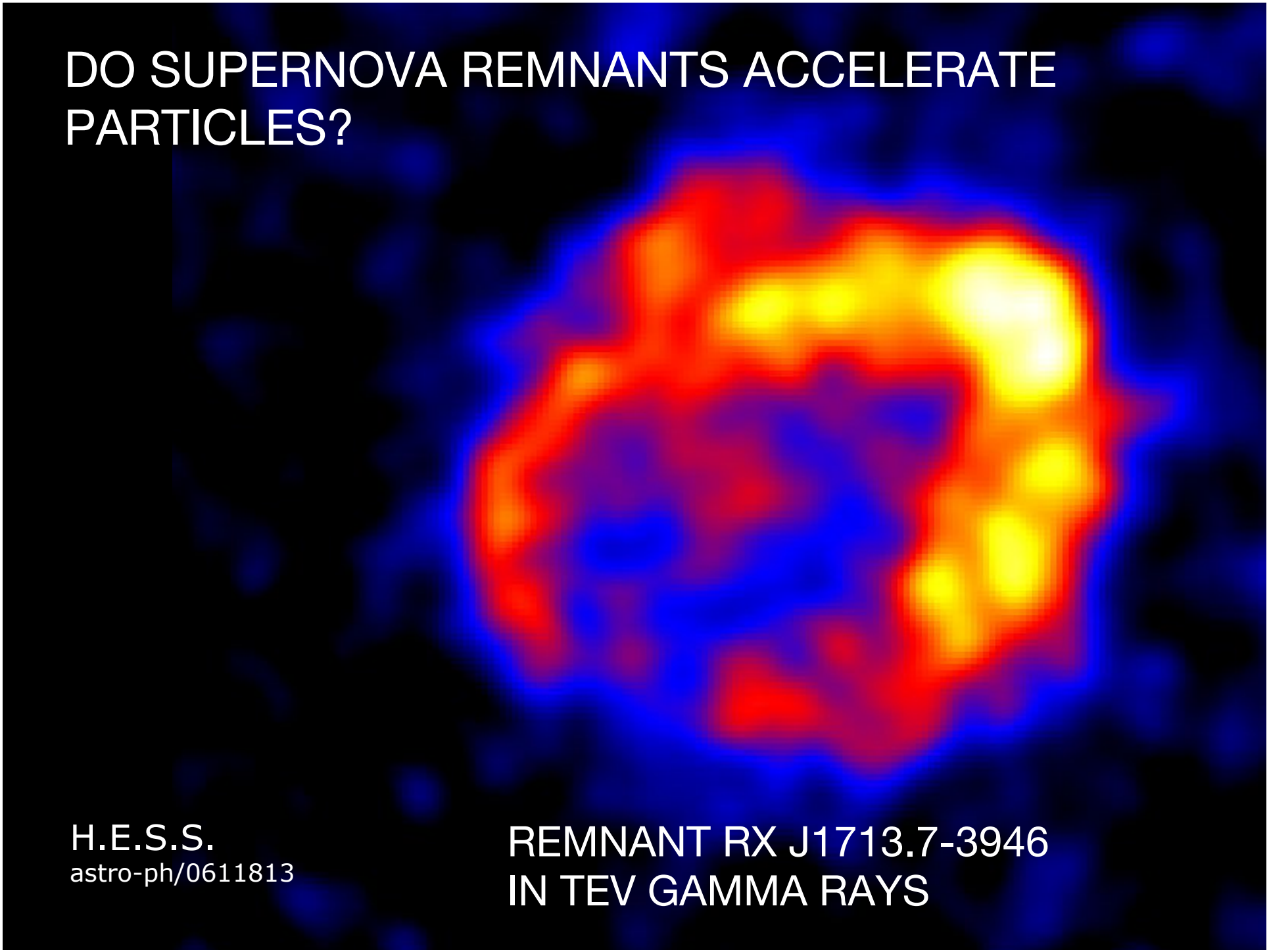
SN 1006

H.E.S.S.
arXiv:1004.2124



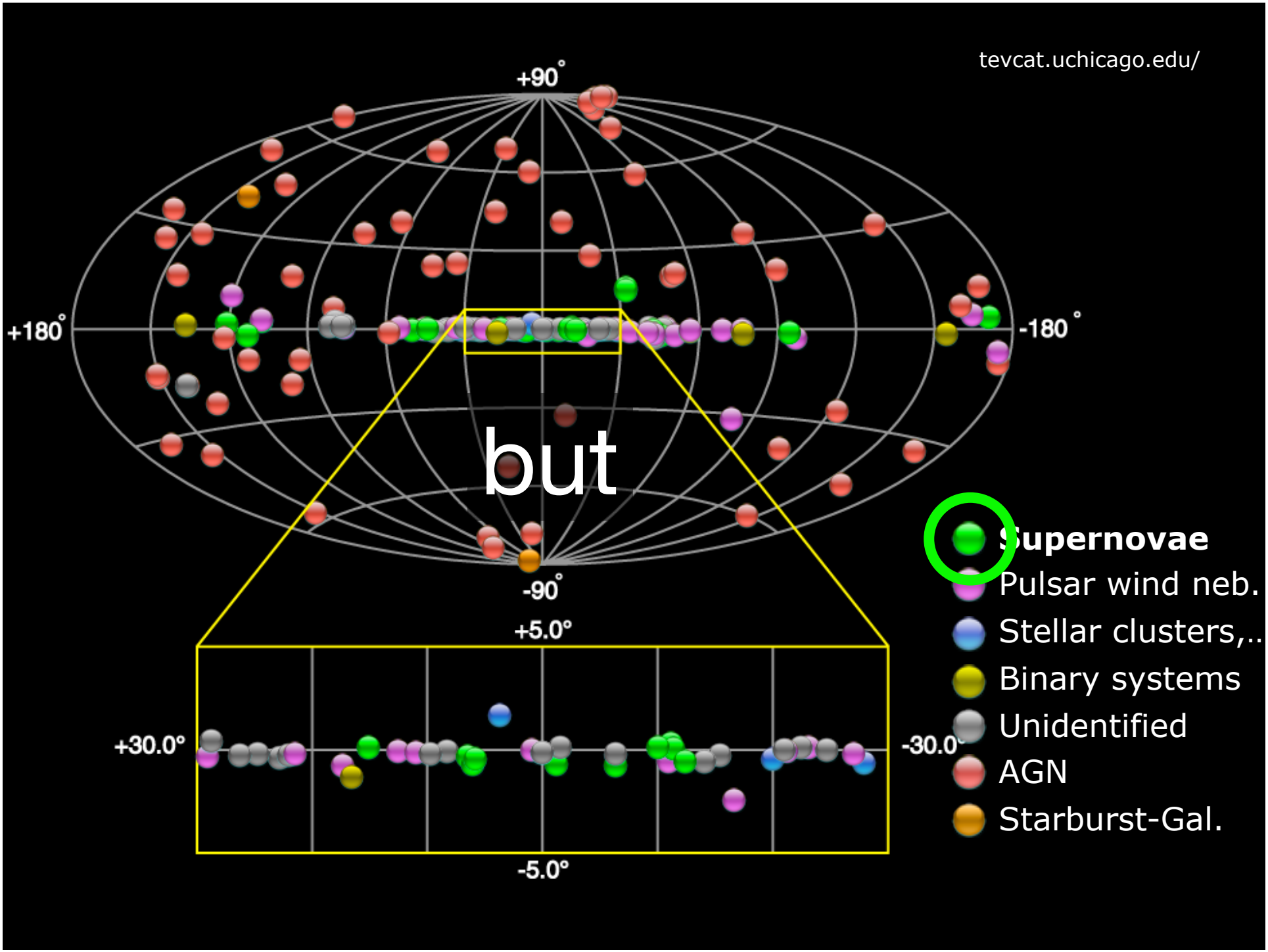
(Credit:X-ray: NASA/CXC/ Rutgers/G.Cassam-Chenai, J.Hughes et al.; Radio: NRAO/ AUI/NSF/GBT/VLA/Dyer, Maddalena & Cornwell; Optical: Middlebury College/ F.Winkler, NOAO/AURA/NSF/ CTIO Schmidt & DSS)

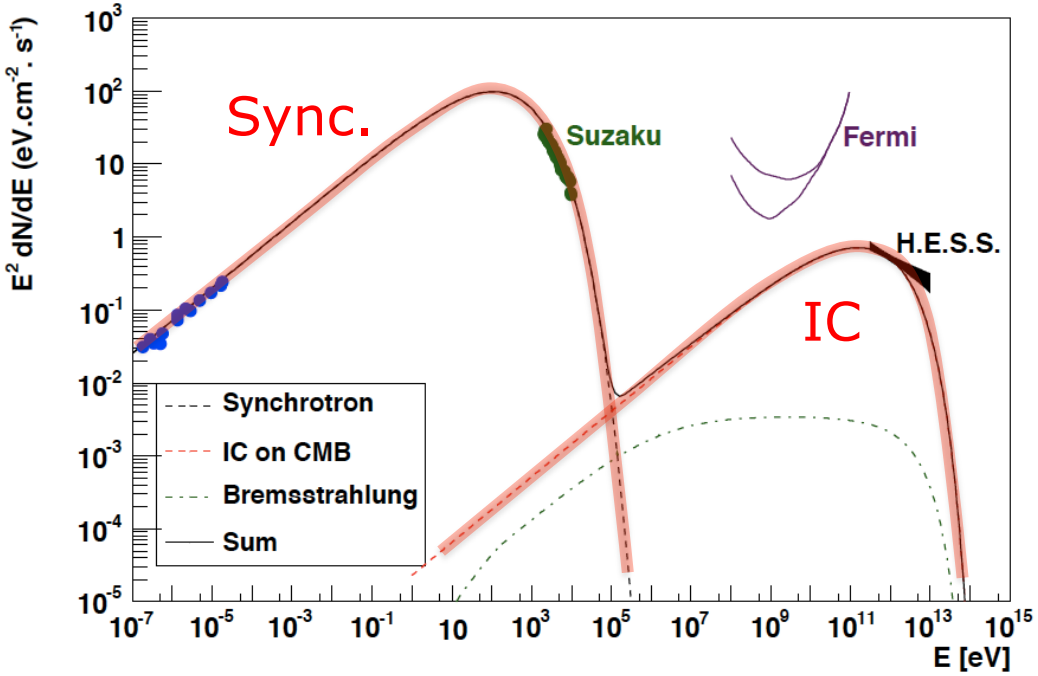
DO SUPERNOVA REMNANTS ACCELERATE PARTICLES?

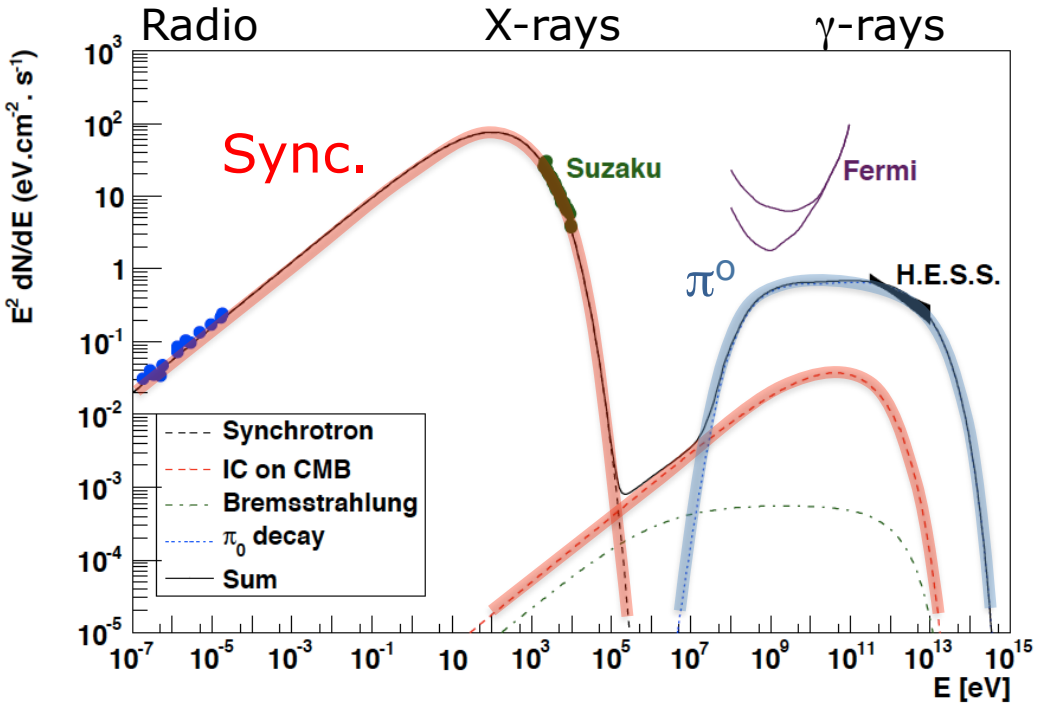


H.E.S.S.
astro-ph/0611813

REMNANT RX J1713.7-3946
IN TEV GAMMA RAYS


tevcat.uchicago.edu/
+90°
+180°
-180°
-90°
but
+5.0°
+30.0°
-30.0°
-5.0°
Supernovae
Pulsar wind neb.
Stellar clusters,..
Binary systems
Unidentified
AGN
Starburst-Gal.





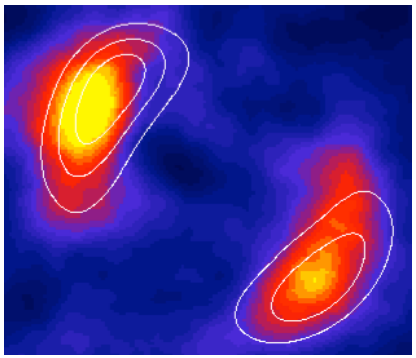
Supernova spectra extend to 10s of TeV, but not to PeV energies

Gamma rays from electrons

$W_e = 3.3 \times 10^{47}$ ergs

$\varepsilon = 0.03\%$

SN 1006



Gamma rays from protons

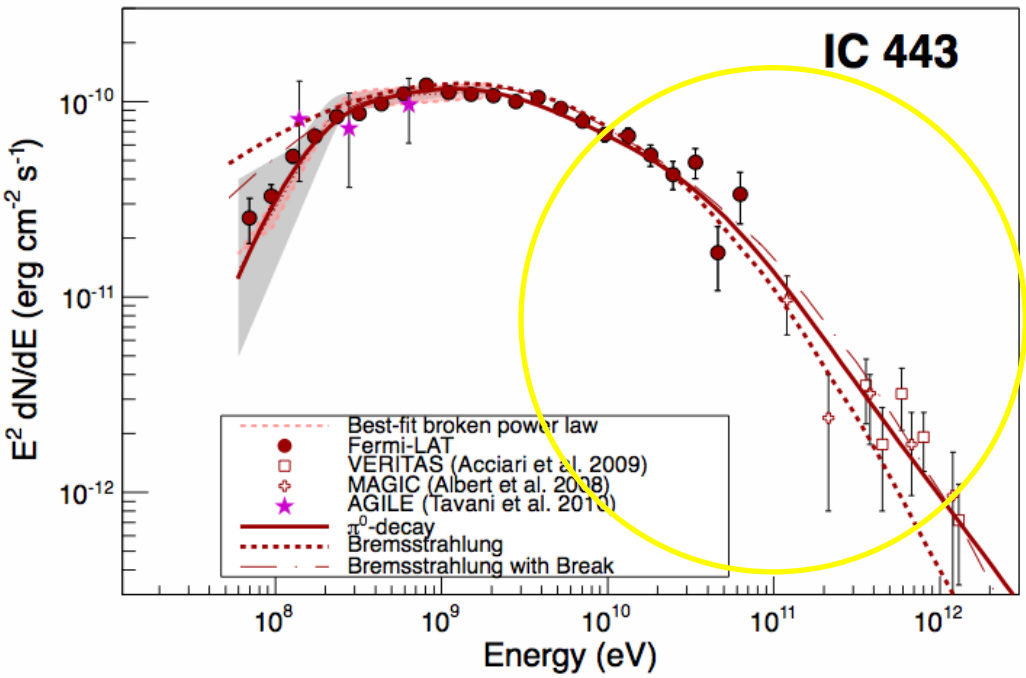
$W_P = 3 \times 10^{50}$ ergs

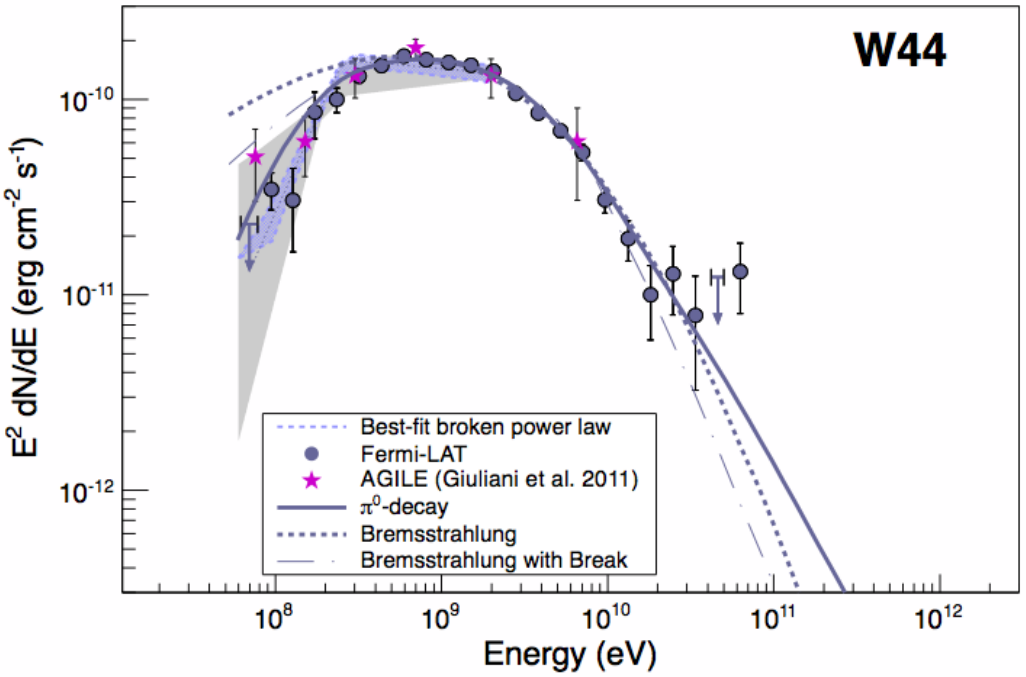
$\varepsilon = 30\%$

PION DECAY SIGNATURES

Fermi-LAT
Ackermann et al.
arXiv:1302.3307

➜ Proton acceleration in (soft-spectrum) SNR





SUPERNOVA
AS SOURCES

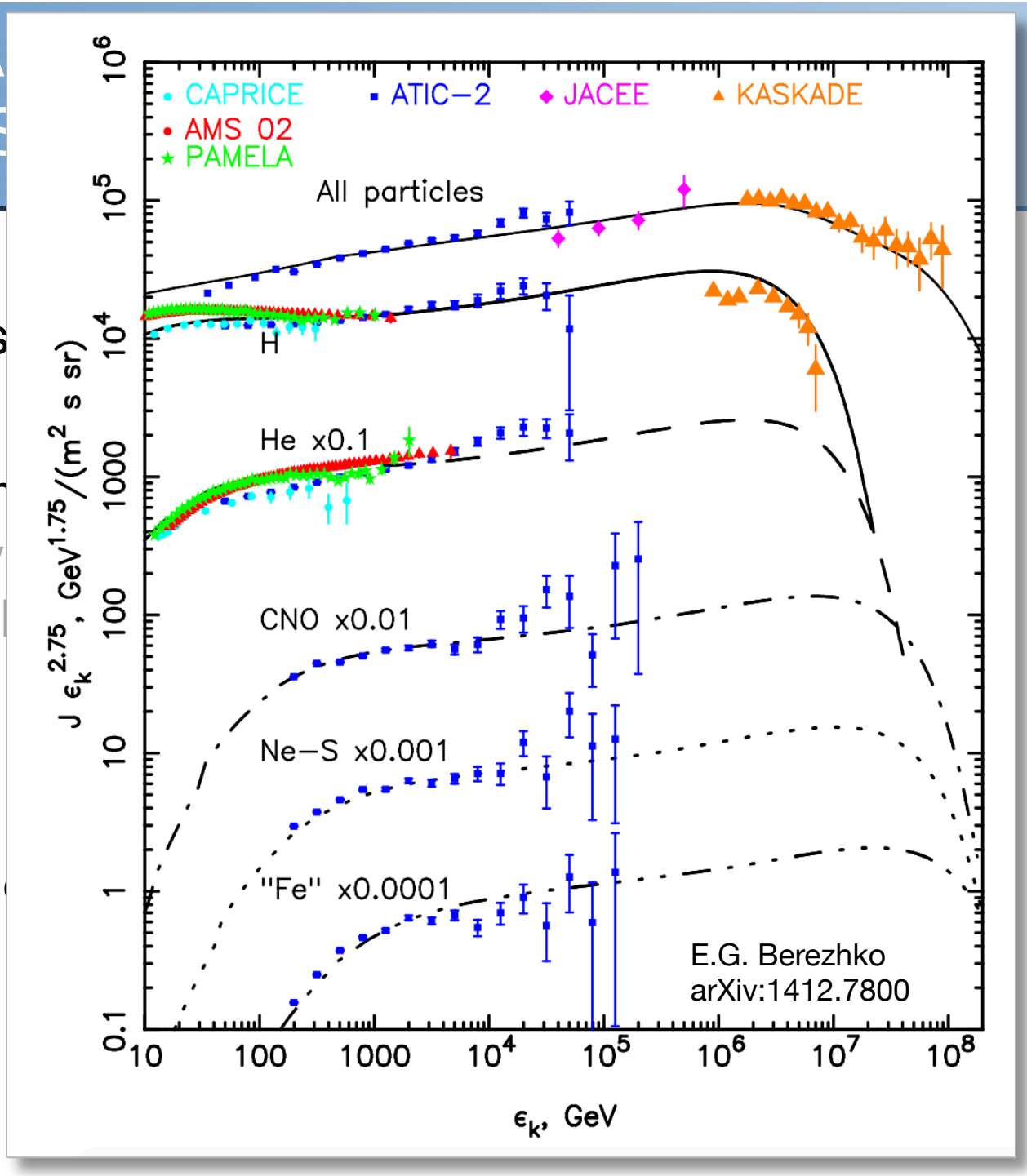
Are SNR sources

Are SNR the (dor
which quantitativ
Are they cosmic

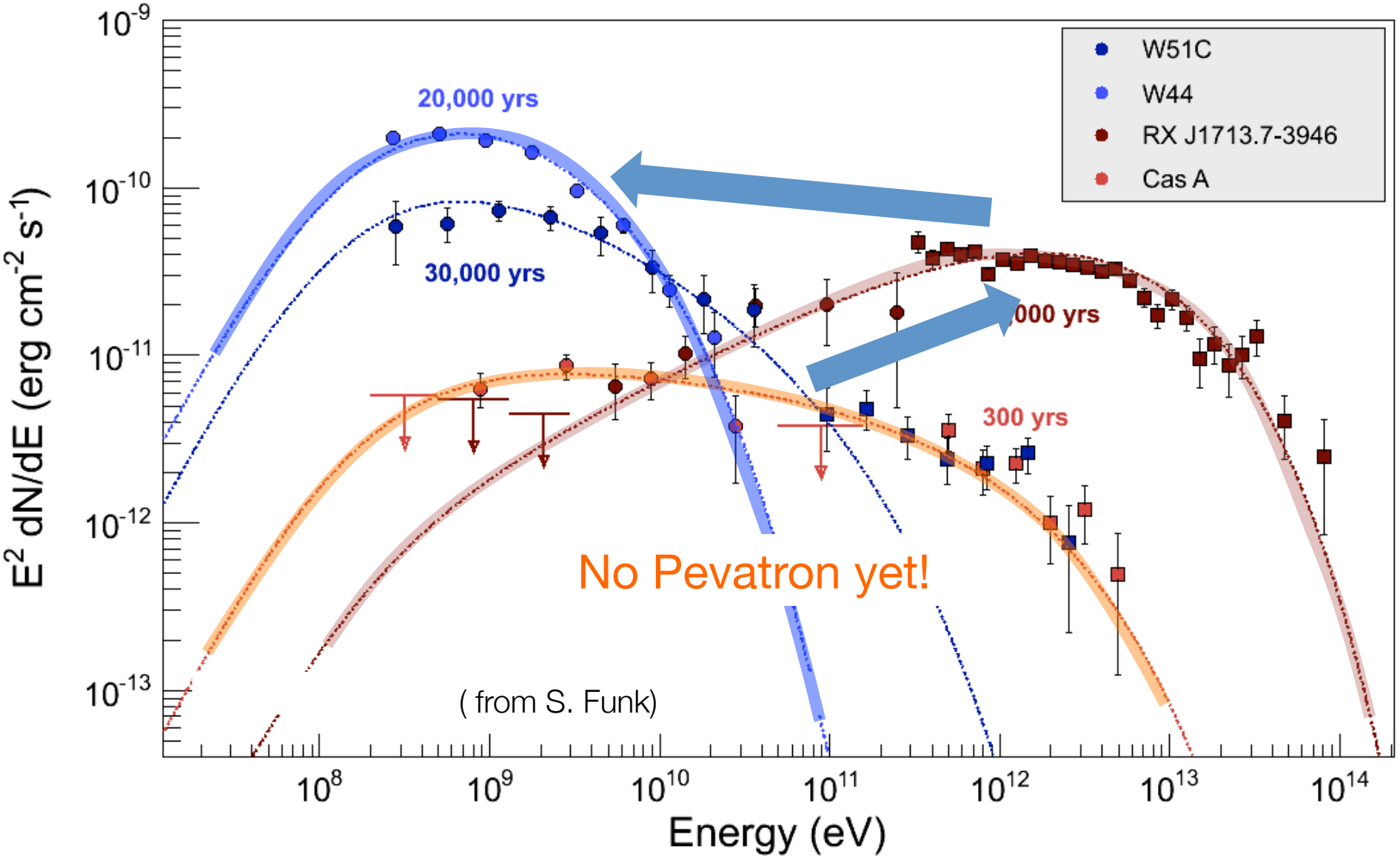
➜ Measure CR fl

or

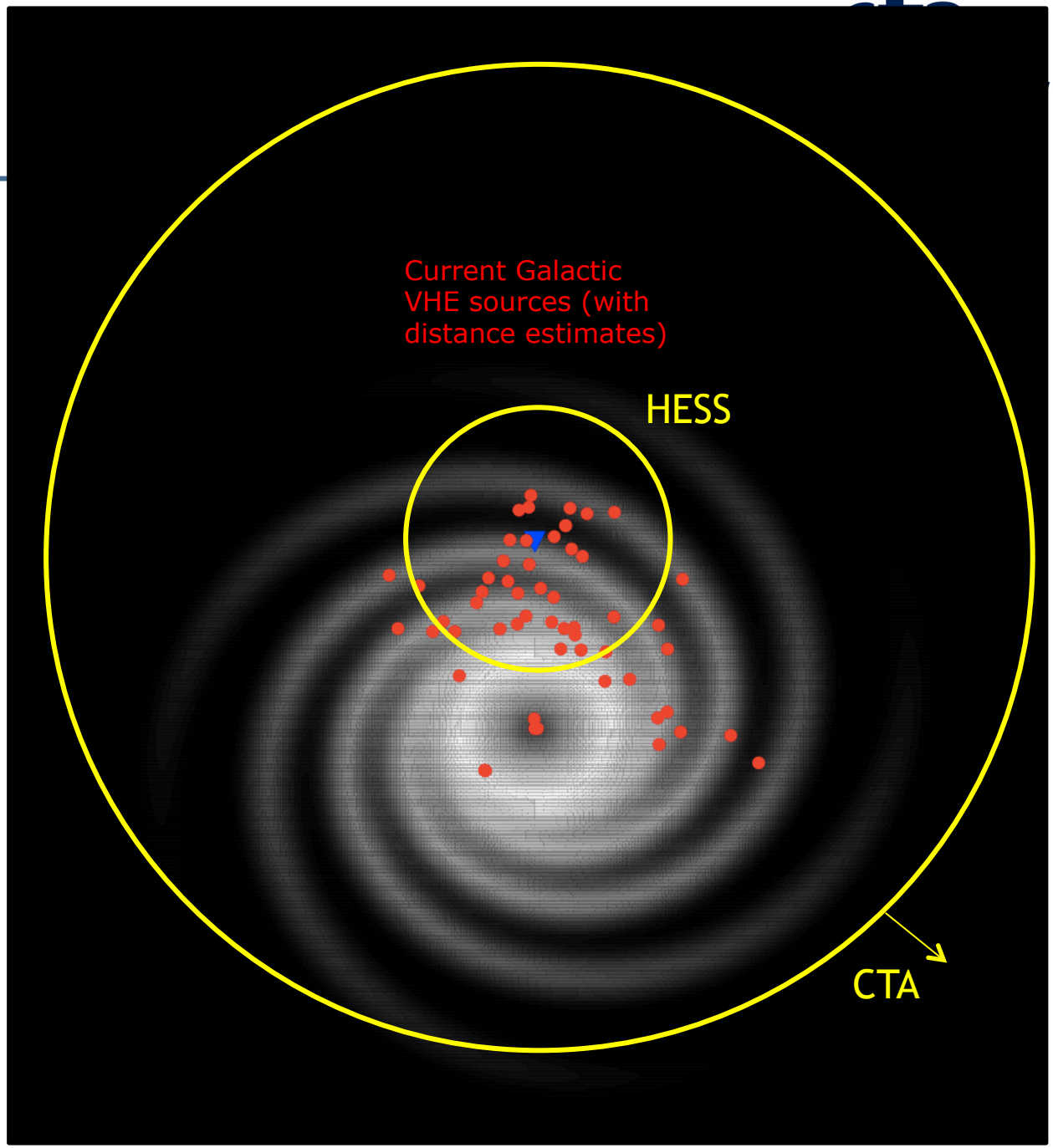
➜ Verify models

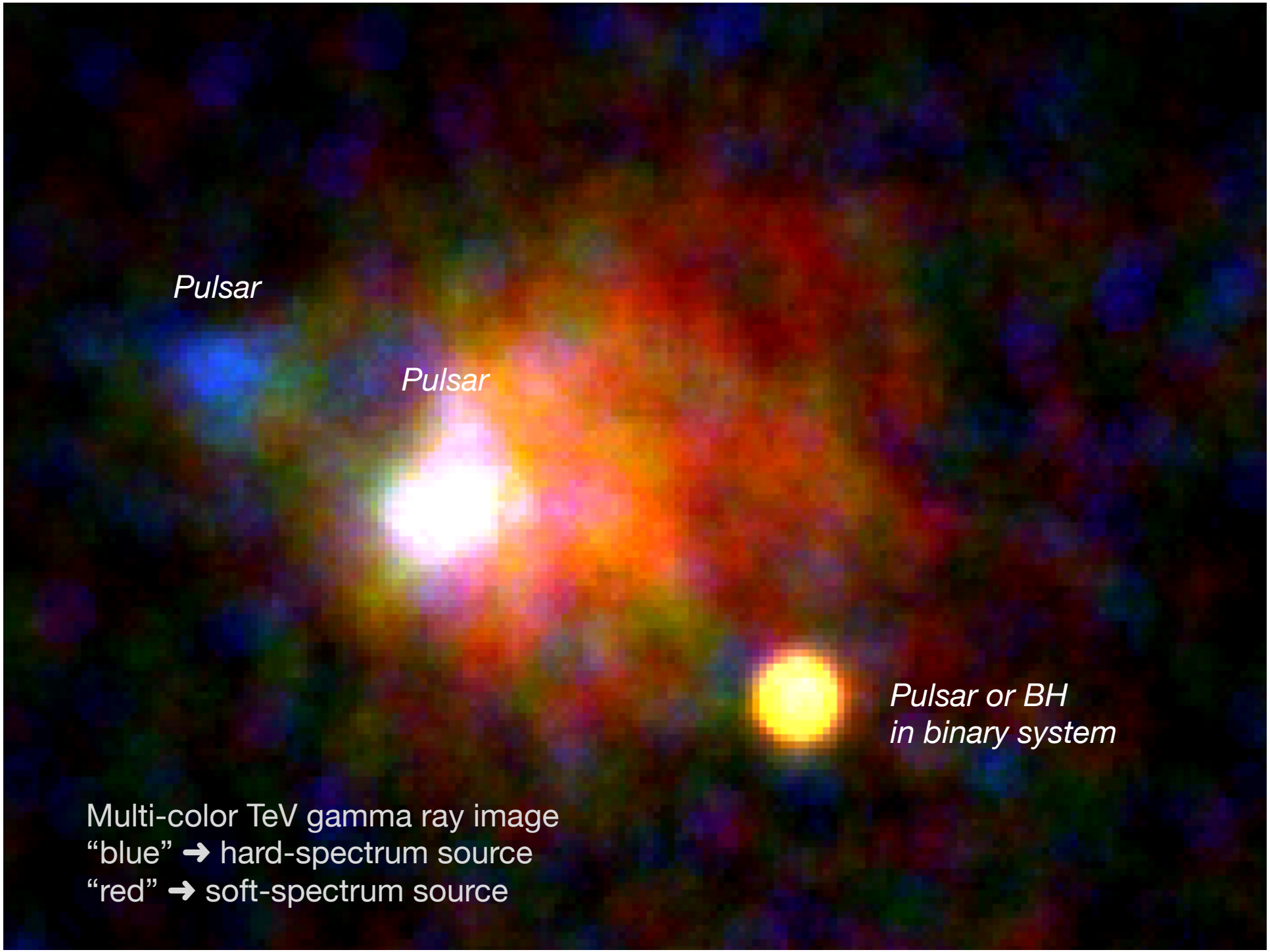


SPECTRA OF SUPERNOVA REMNANTS

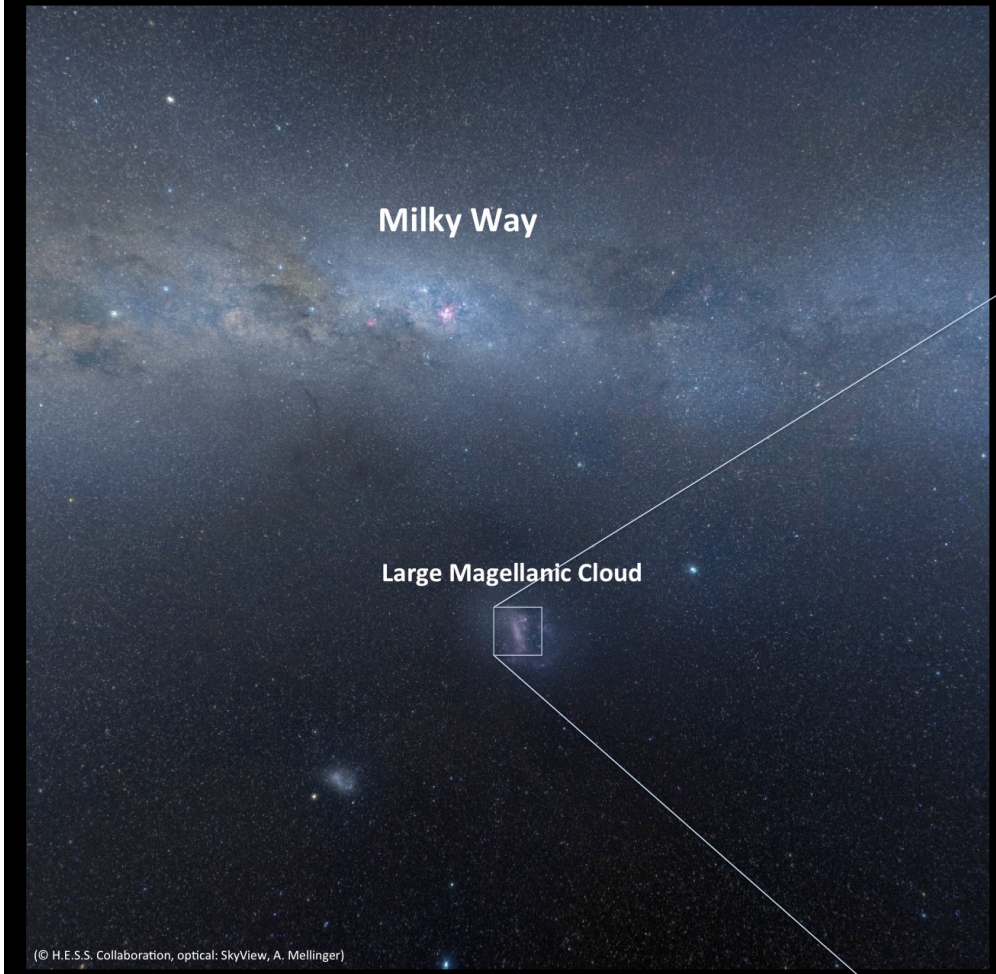


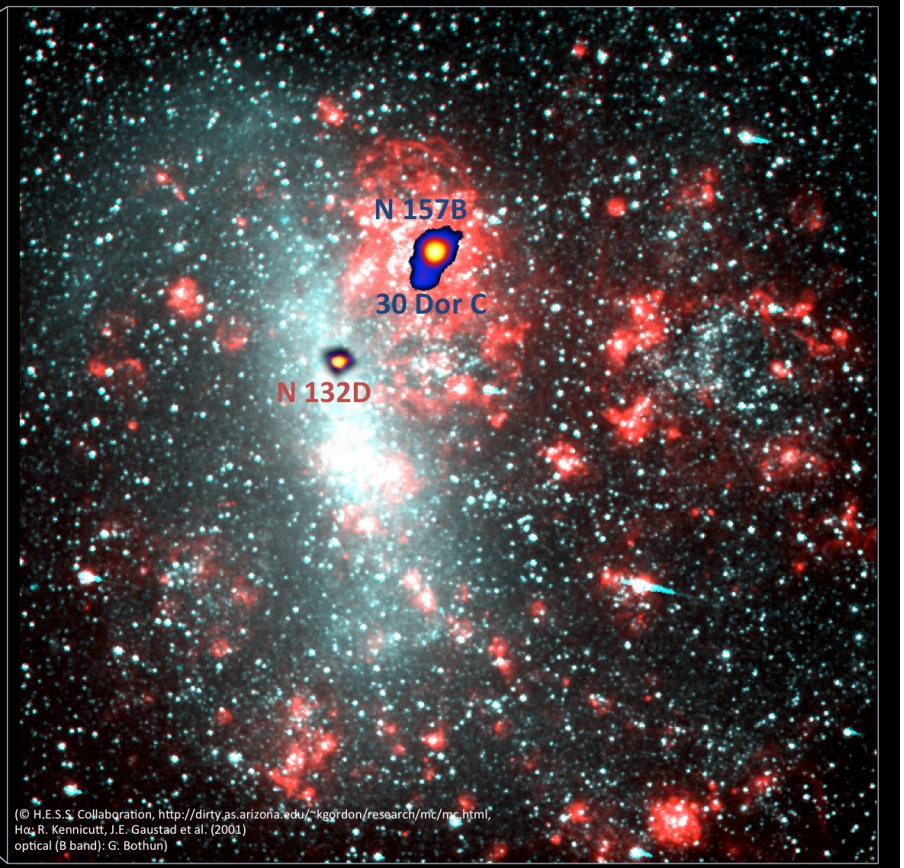
CTA REACH


Current Galactic
VHE sources (with
distance estimates)
HESS
CTA


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

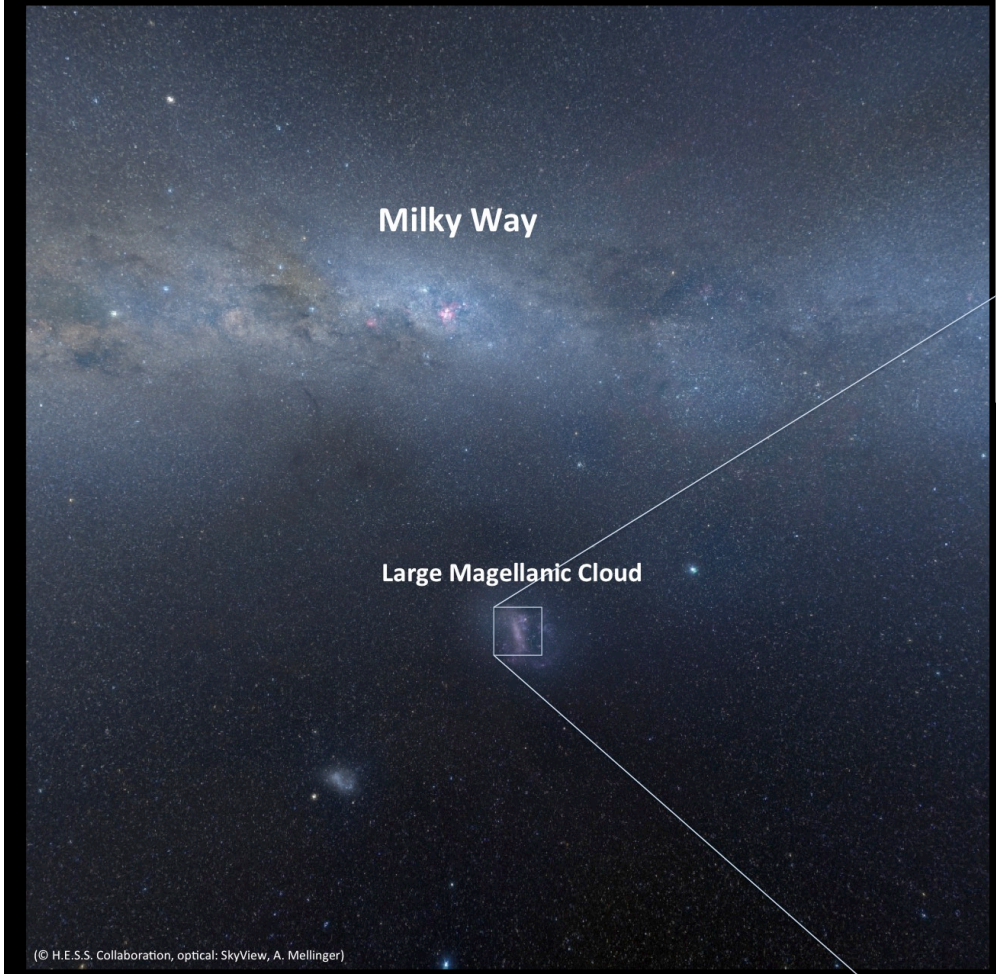
EXTREME ACCELERATORS IN THE LMC

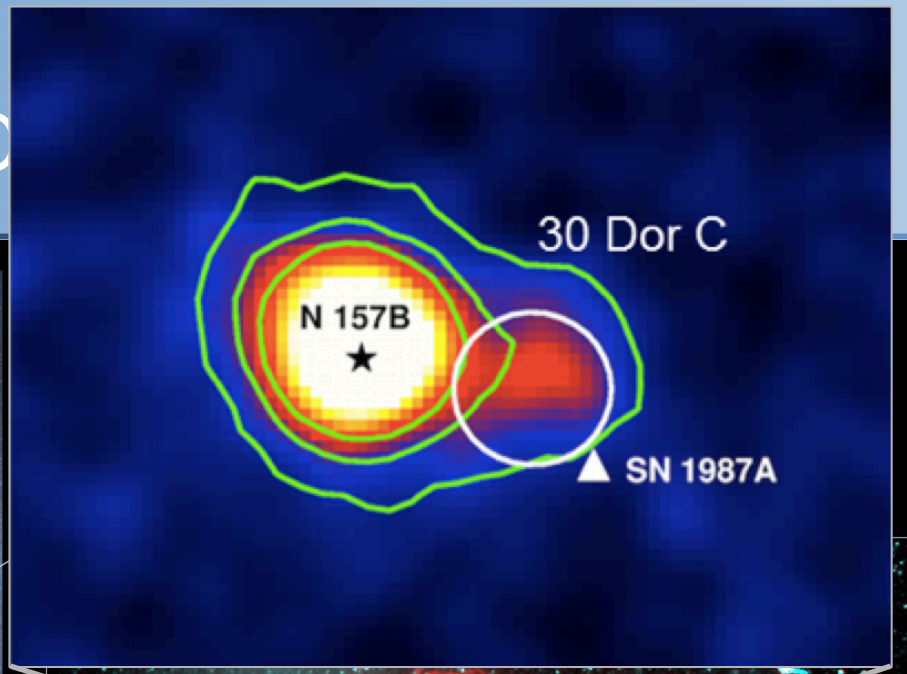


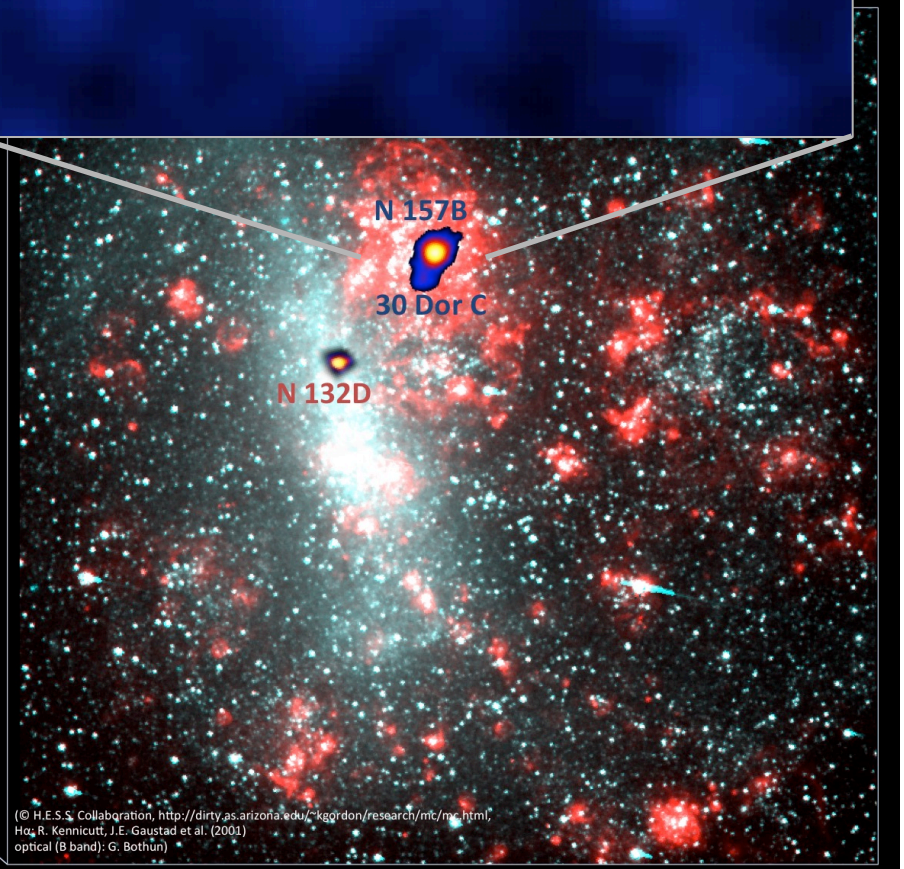


Science 347 (2015) 406

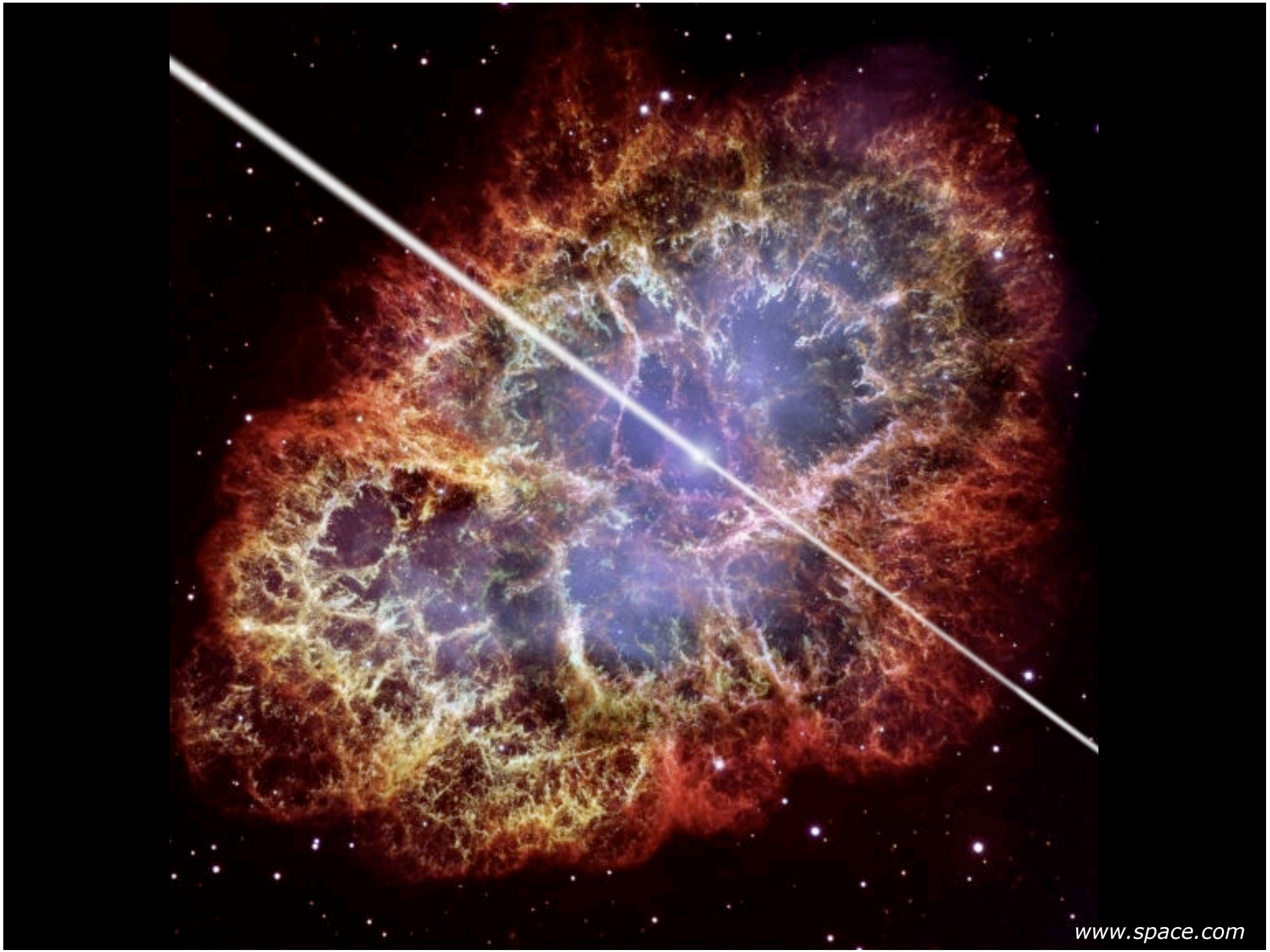
EXTREME ACCELERATO

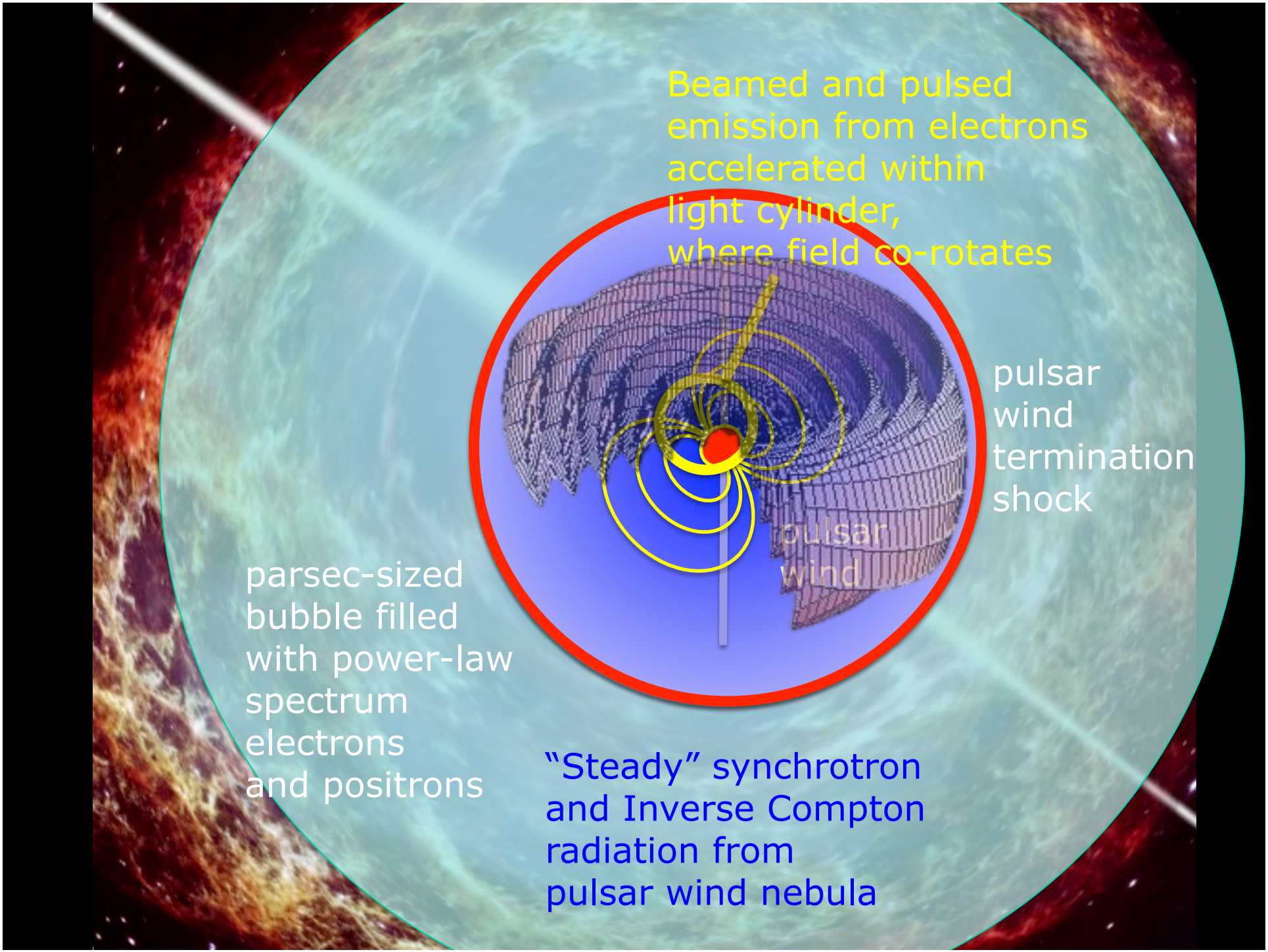




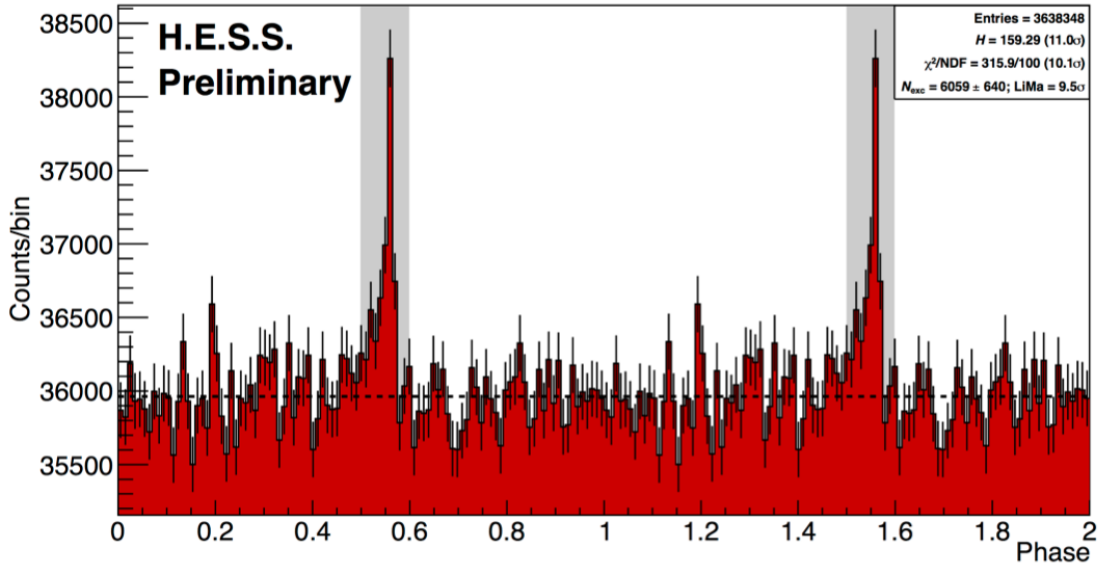


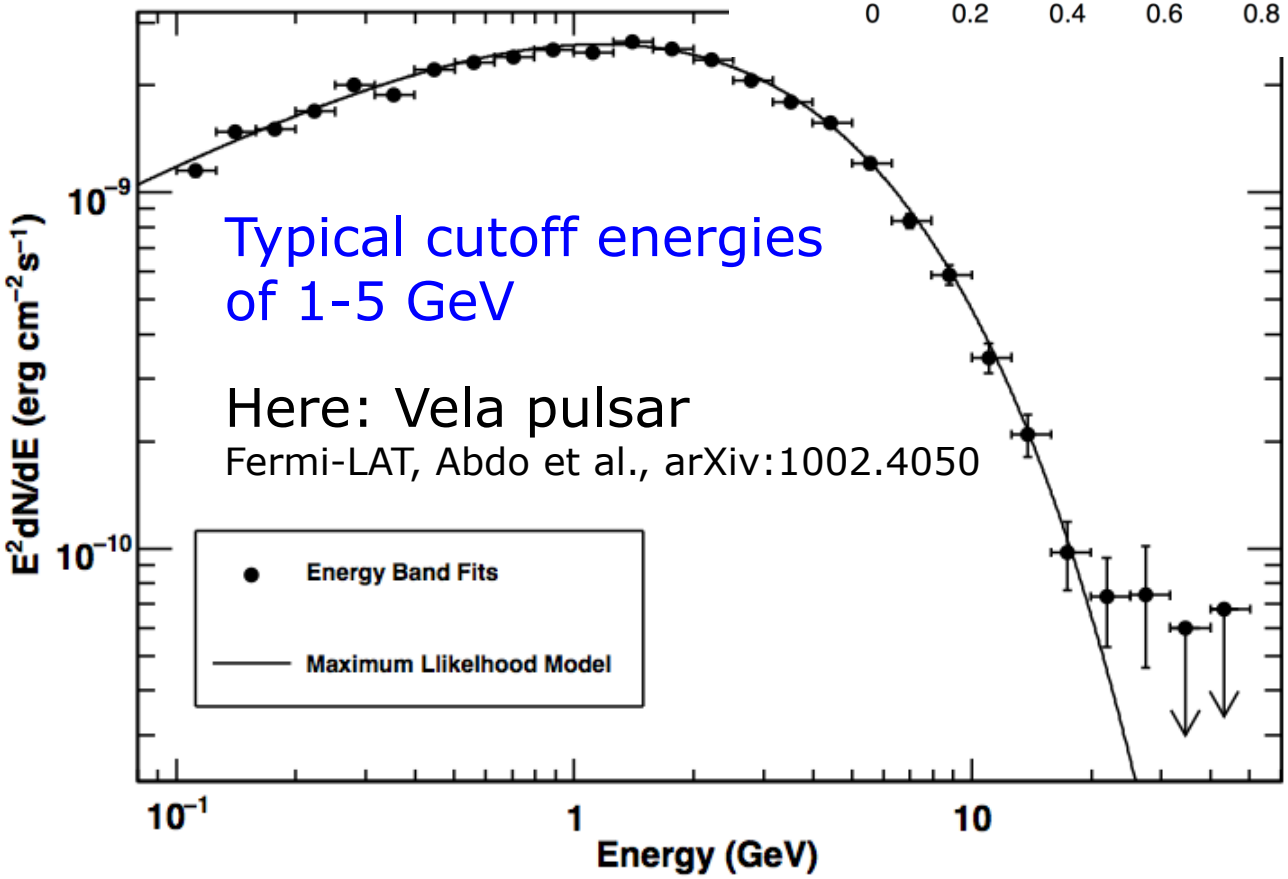
Science 347 (2015) 406


www.space.com


Beamed and pulsed emission from electrons accelerated within light cylinder, where field co-rotates
pulsar wind termination shock
pulsar wind
parsec-sized bubble filled with power-law spectrum electrons and positrons
"Steady" synchrotron and Inverse Compton radiation from pulsar wind nebula

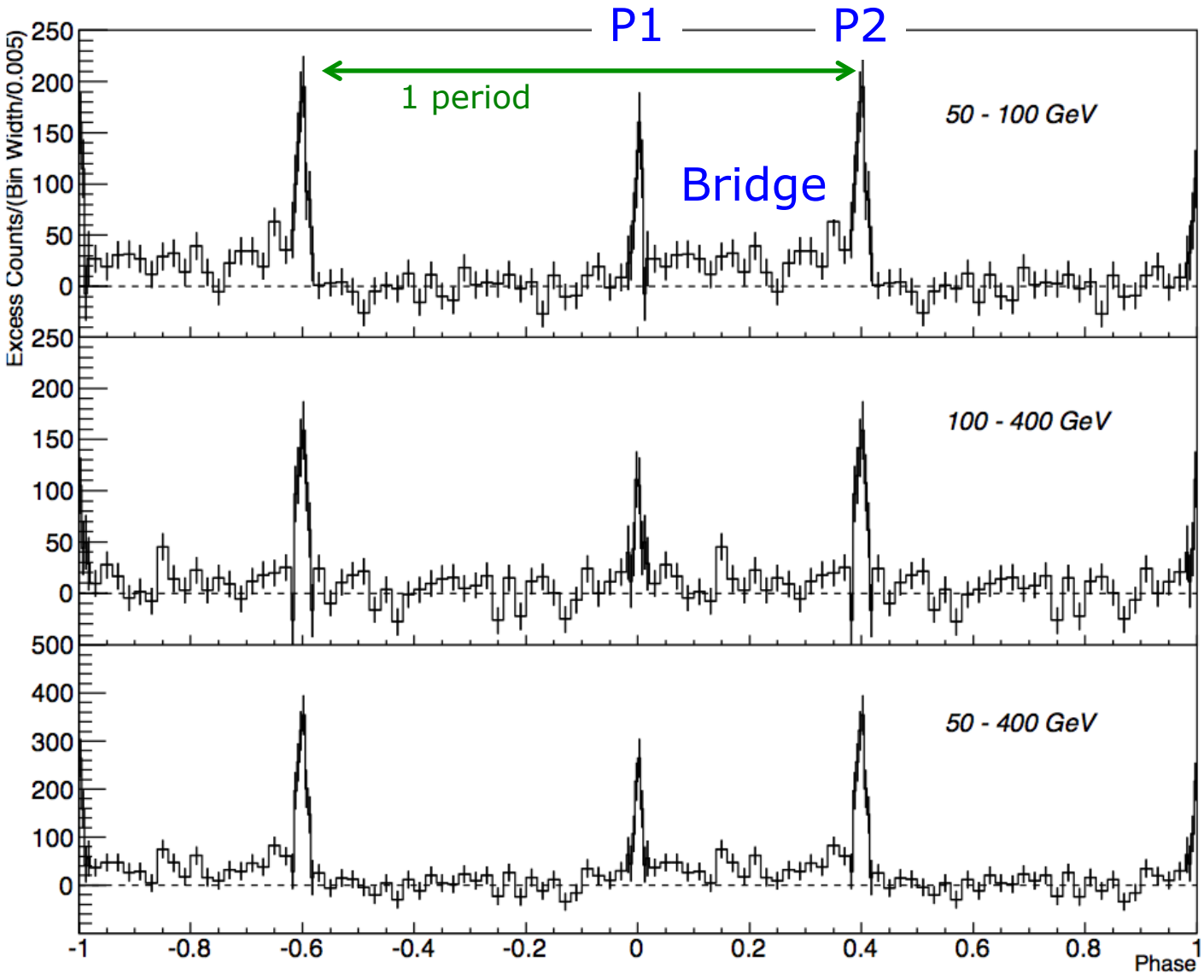
CUTOFFS IN PULS





Vela:
Pulsed signal
in 20-50 GeV
energy range

PULSED GAMMA-RAYS FROM THE CRAB NEBULA TO BEYOND 100 GEV

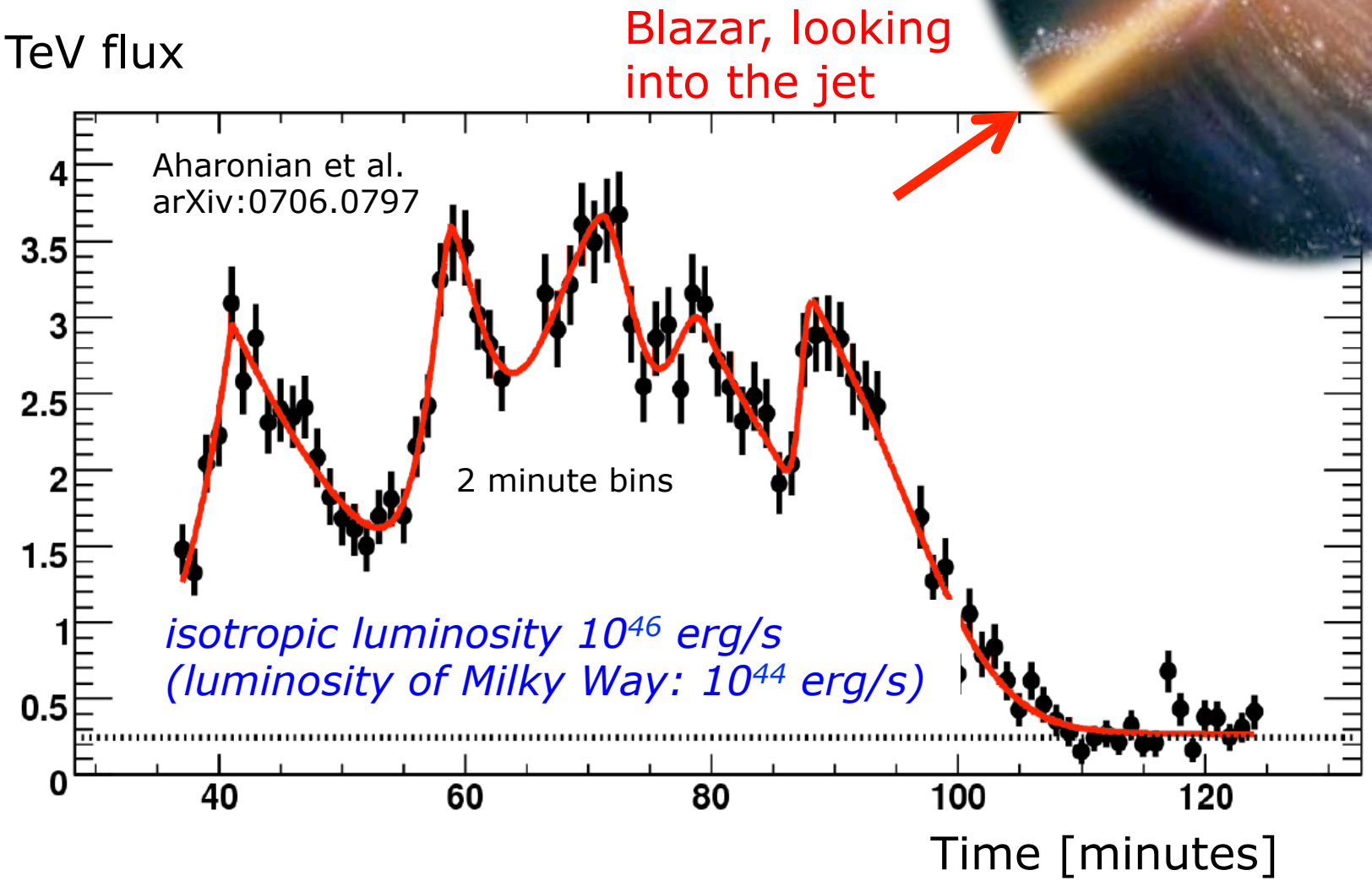


VERITAS & MAGIC

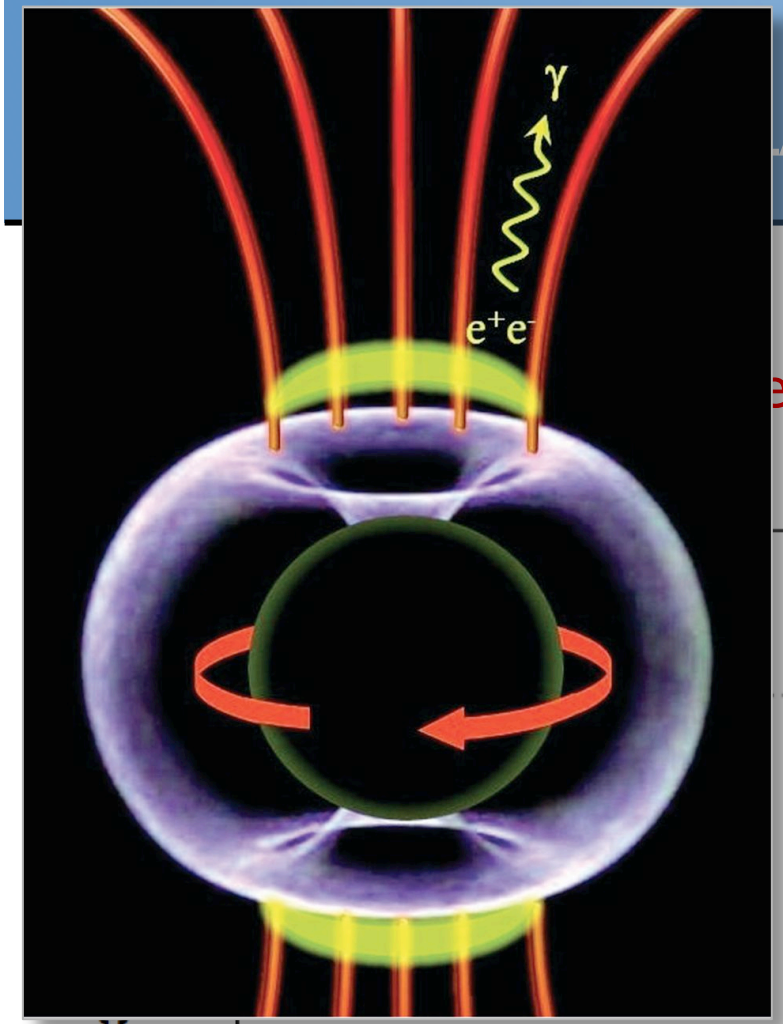
Aleksic et al. arXiv:1042.4219


Beyond our
Galaxy:
mostly AGN
(c) F. Acero & H. Gast

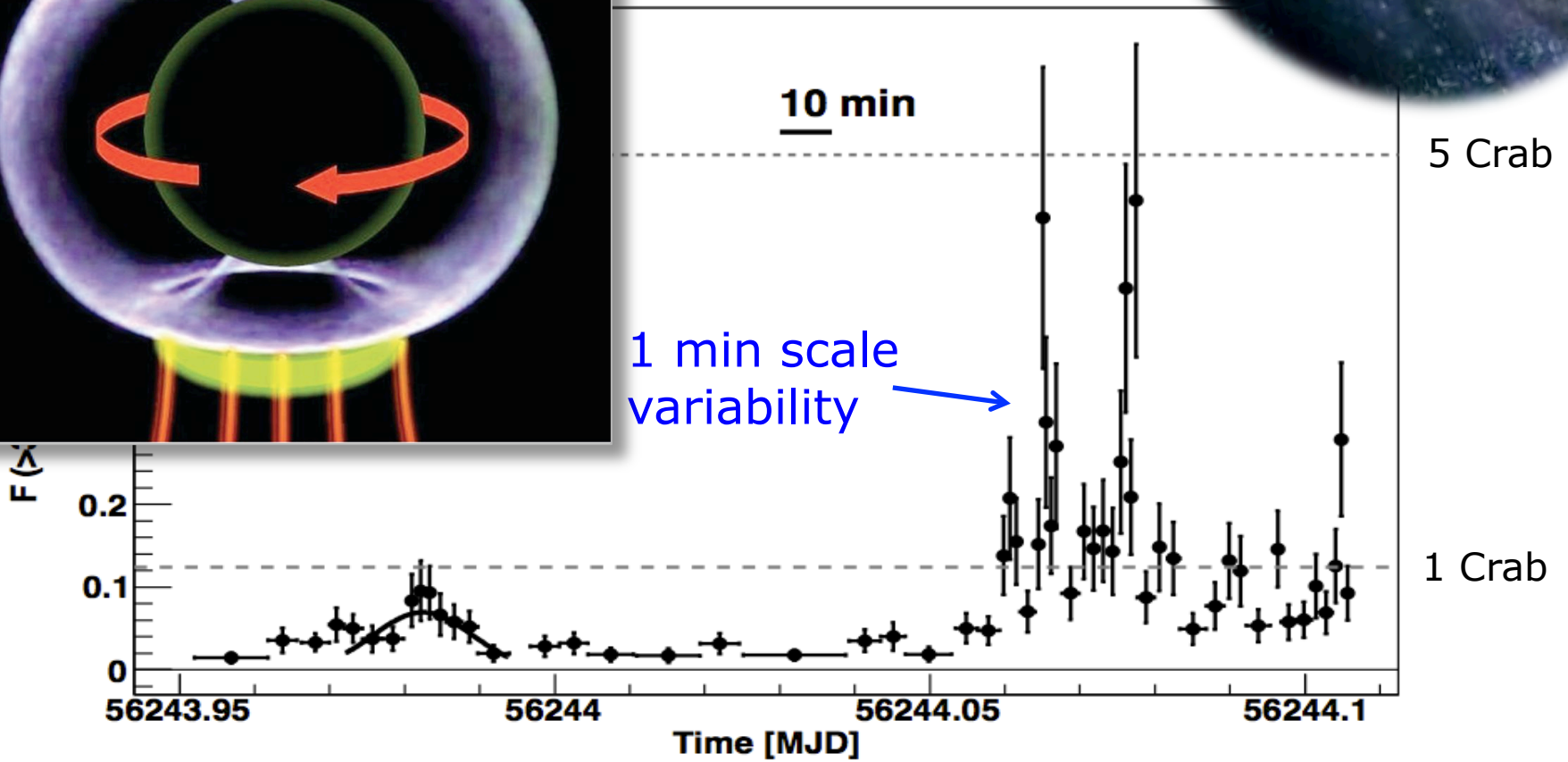
AMAZING TEV FLARES: PKS 2155-305



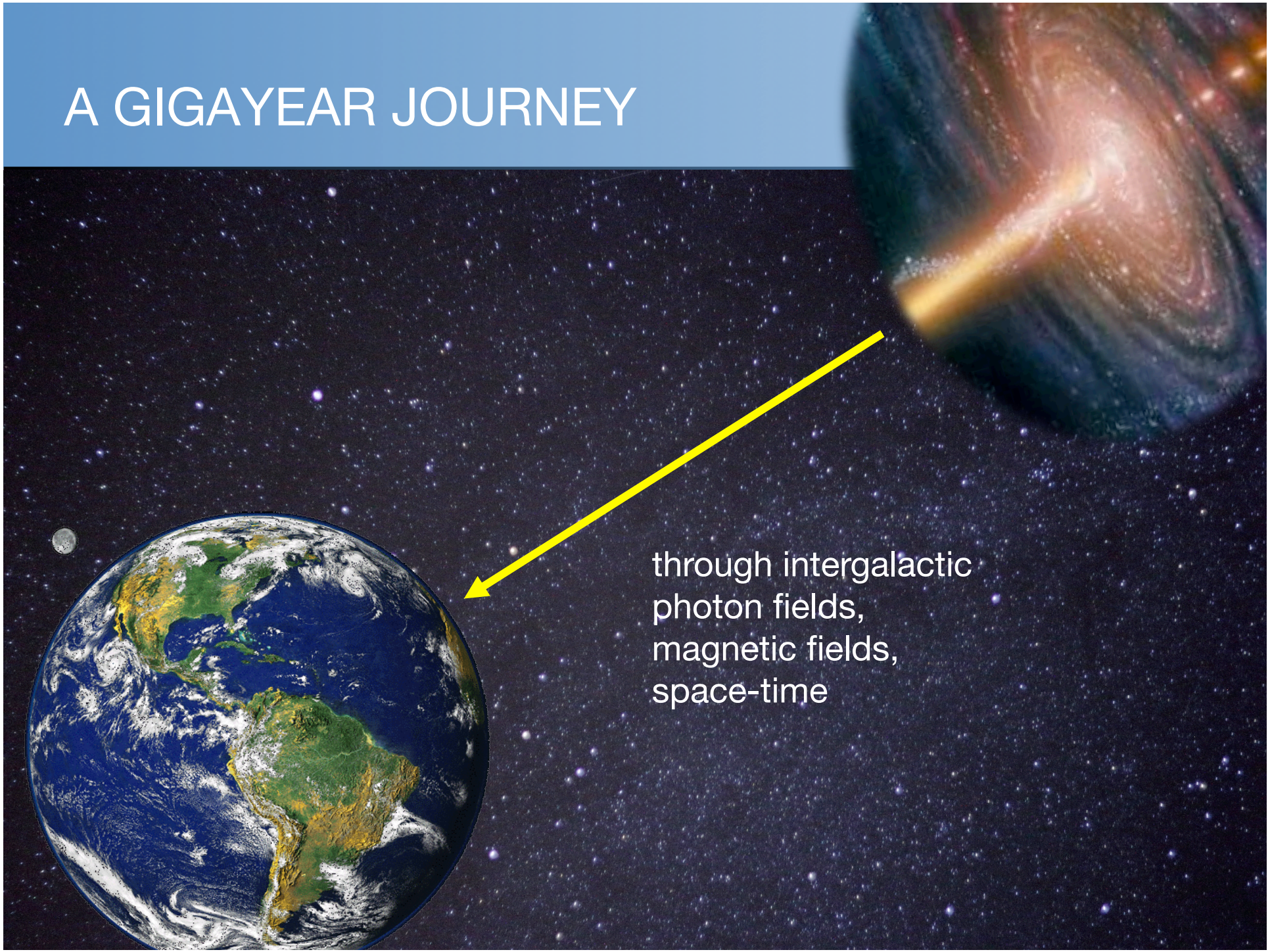
ARES: IC 310



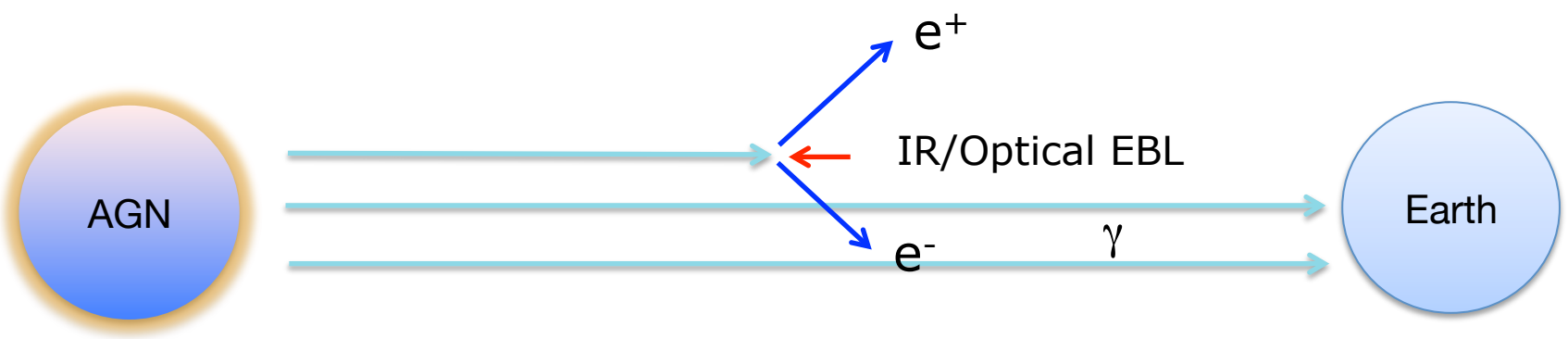
galaxy, jets
ed to line of sight



A GIGAYEAR JOURNEY



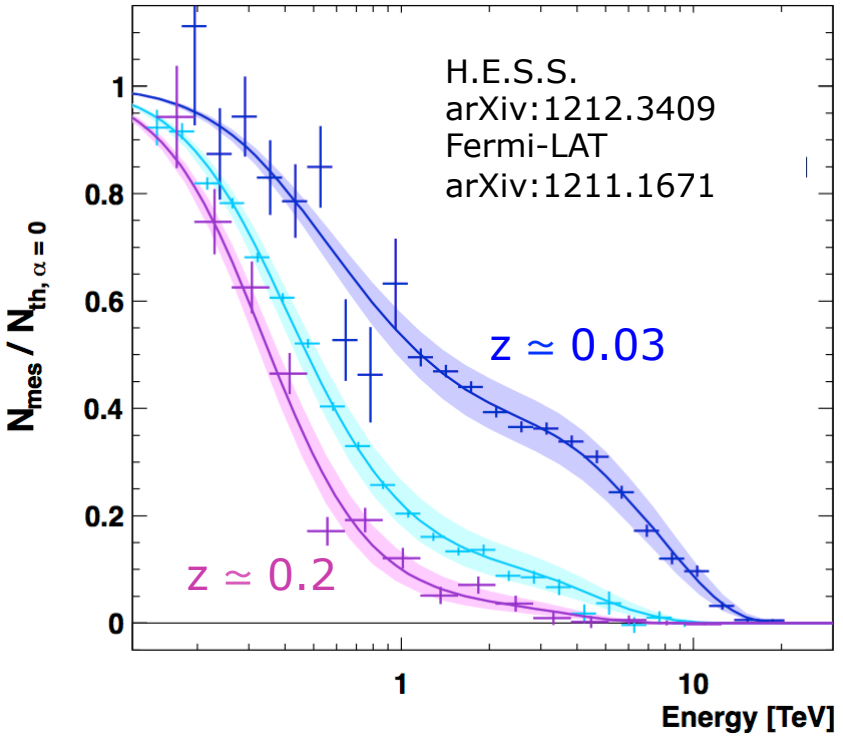
PHOTON PROPAGATION: OPTICAL DEPTH



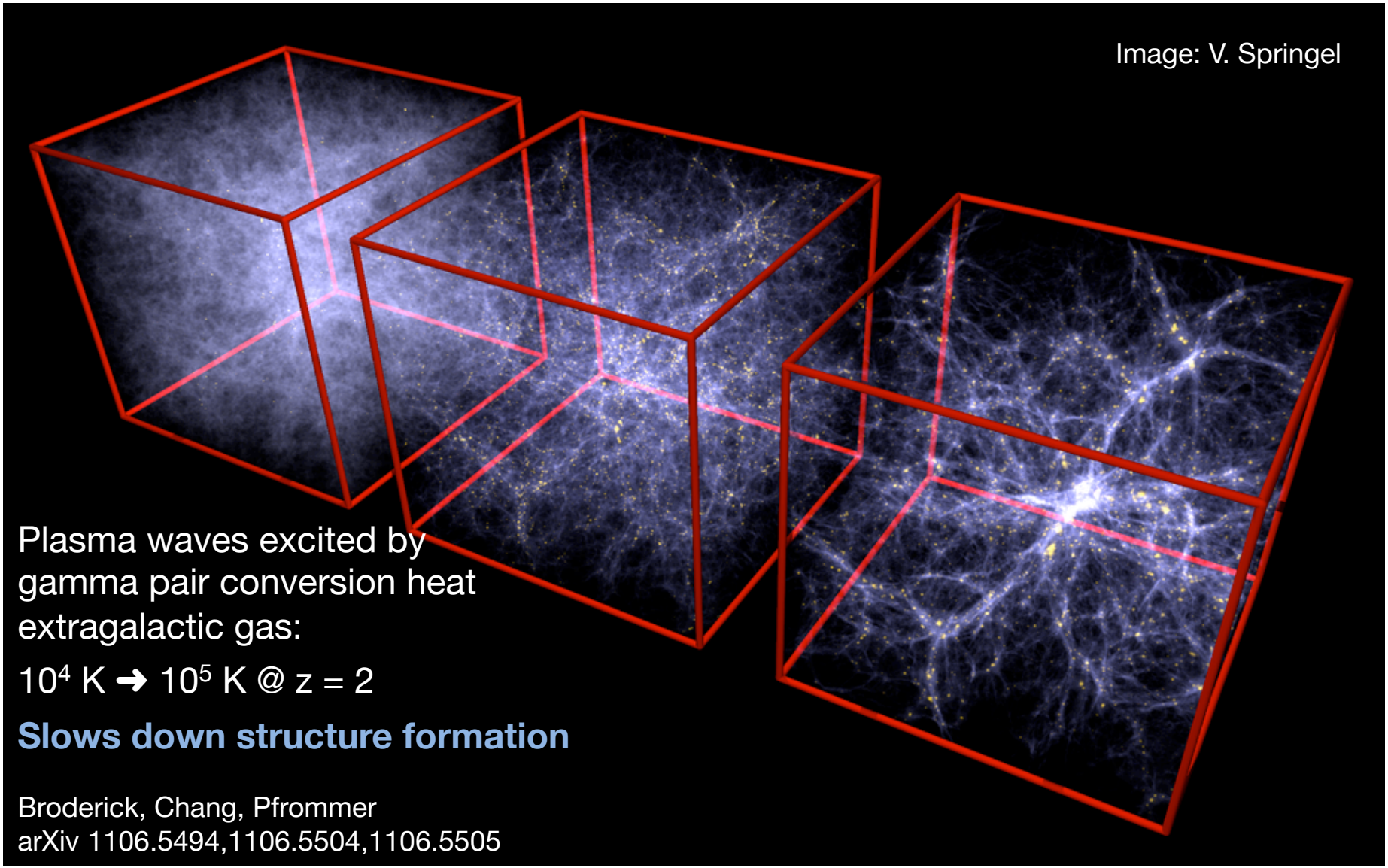
Extragalactic background light (EBL) measures integrated star formation history in the Universe

Direct measurement difficult because of foregrounds

State-of-the-art star formation models describe data within ~30% error



BLAZAR HEATING OF IGM



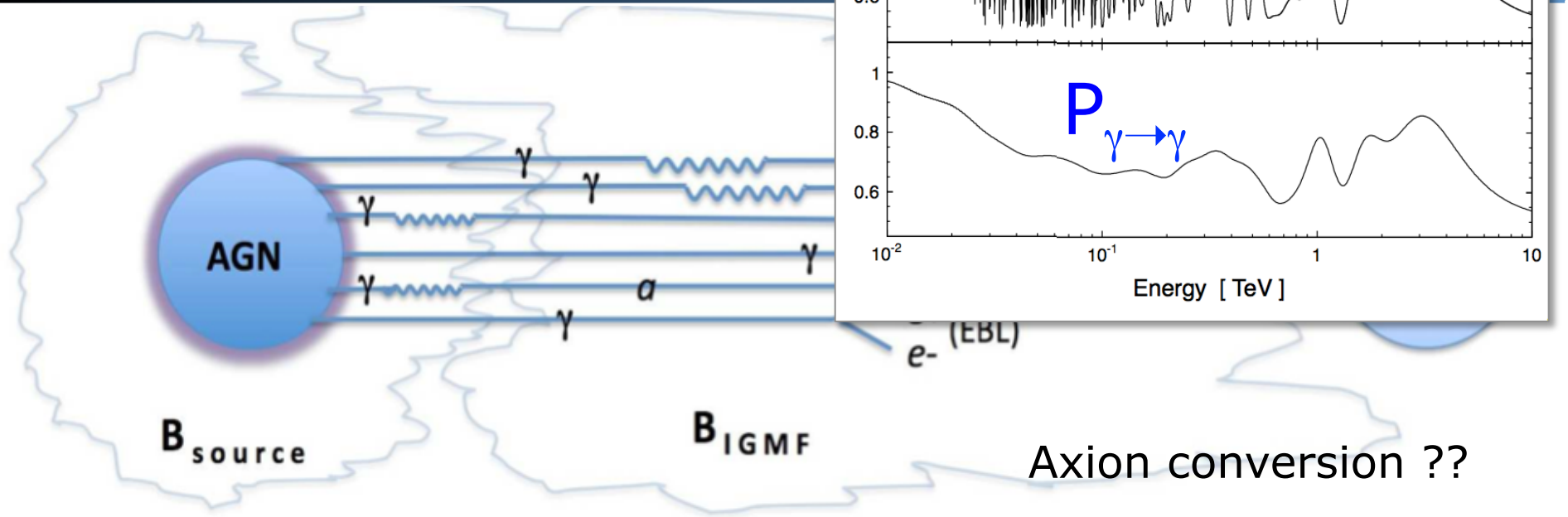
Plasma waves excited by gamma pair conversion heat extragalactic gas:

10^4 K ➜ 10^5 K @ z = 2

Slows down structure formation

Broderick, Chang, Pfrommer
arXiv 1106.5494,1106.5504,1106.5505

PHOTON PROPAGATION:



Axion conversion ??

Sanchez-Conde et al., arXiv:0905.3270

Horns & Meyer arXiv:1201.471

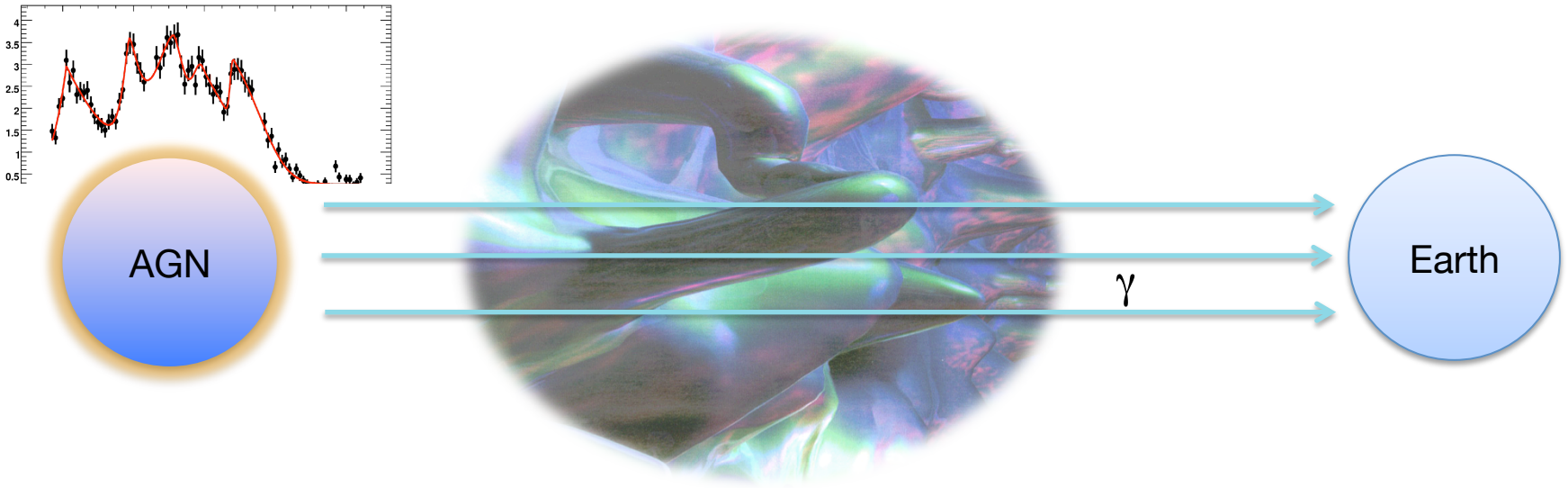
M. Meyer et al. arXiv:1302.1208

- Increased transparency of Universe
- Modulation of spectra

In neV Axion mass range comparable to or better than dedicated experiments

e.g. H.E.S.S. arXiv:1311.3148

PHOTON PROPAGATION: LI VIOLATION



Velocity dispersion across TeV energy range
less than ~20 s for ~10^9 y travel ≃ 10^{-15}

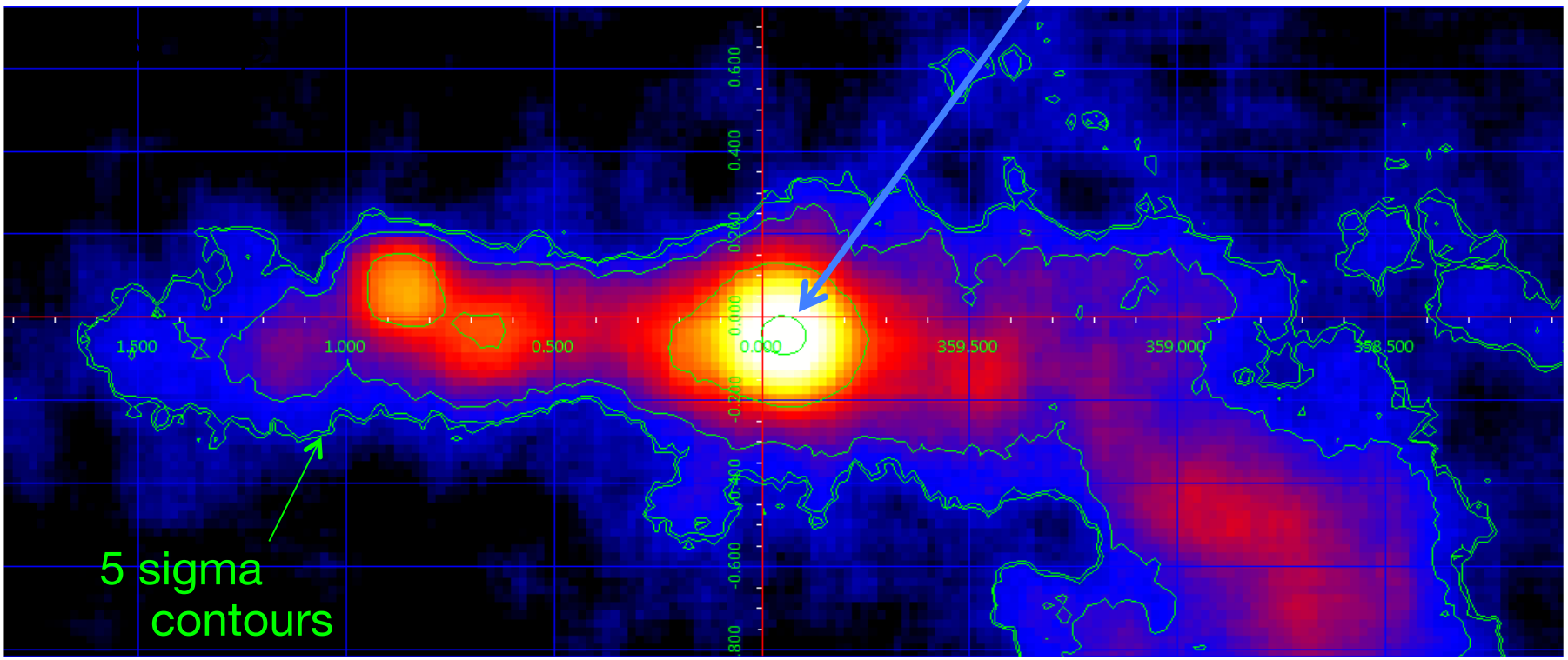
➜ LIV mass scale > $2 \cdot 10^{18}$ GeV (~E), $6 \cdot 10^{10}$ GeV (~E^2)

HESS, arXiv:1101.3650
arXiv:0810.3475


Galactic Center
mysteries
(c) F. Acero & H. Gast

GALACTIC CENTER REGION @ TEV ENERGY

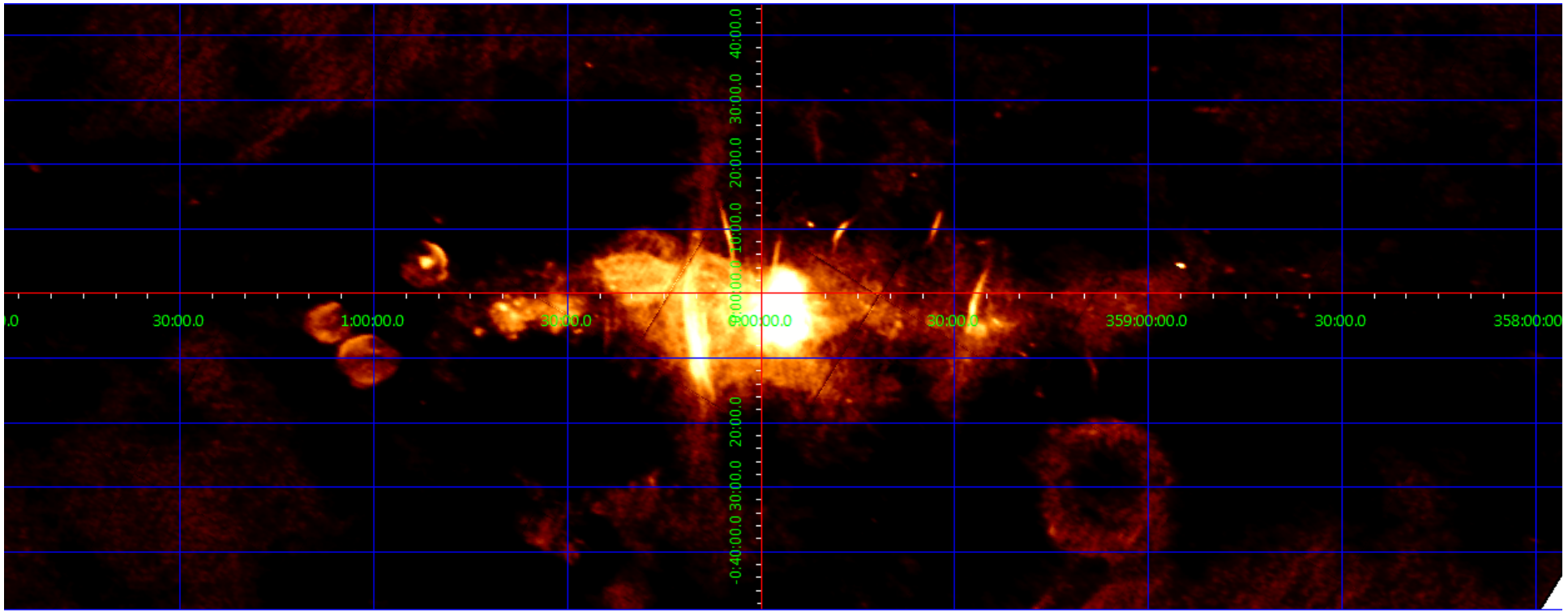
Source consistent with BH
within 13” error



5 sigma
contours

2°
300 pc

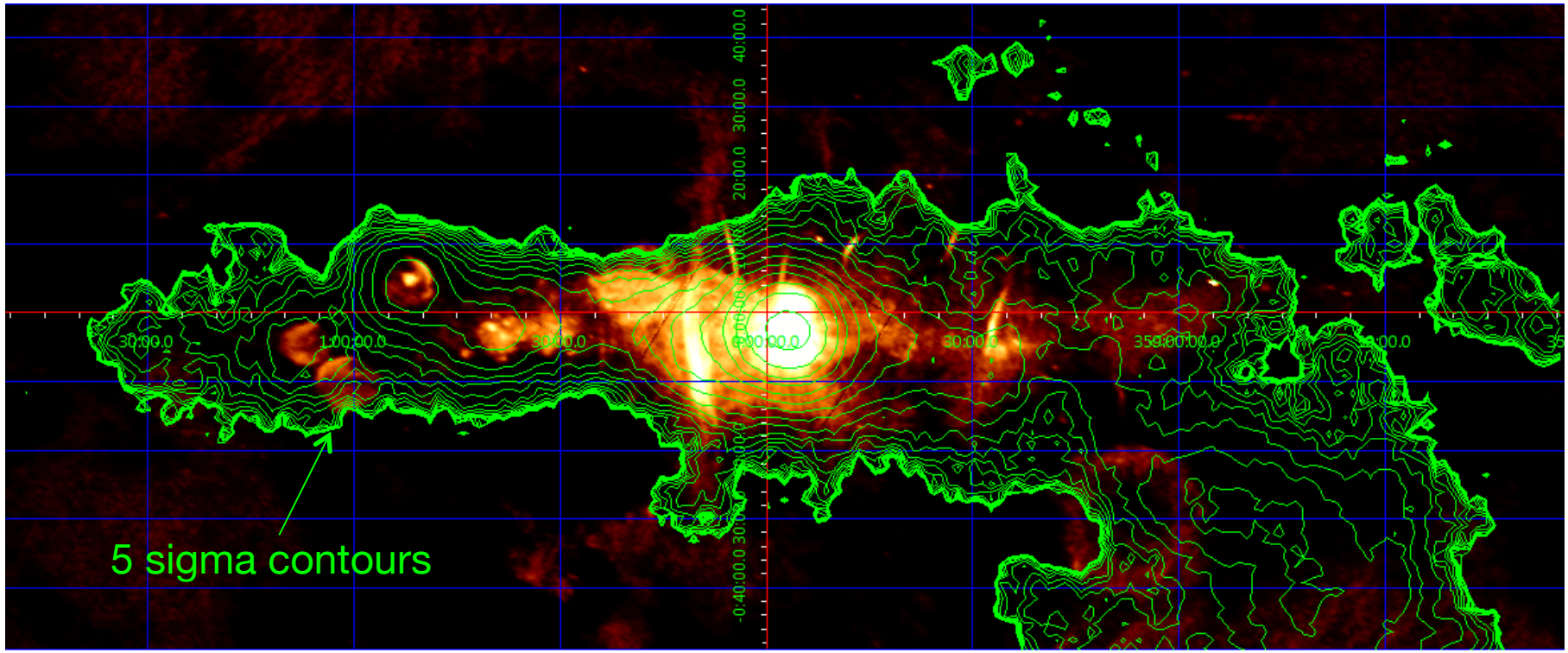
GALACTIC CENTER REGION



GALACTIC CENTER REGION

Complex, structured VHE source
Gas clouds illuminated by Pevatron?

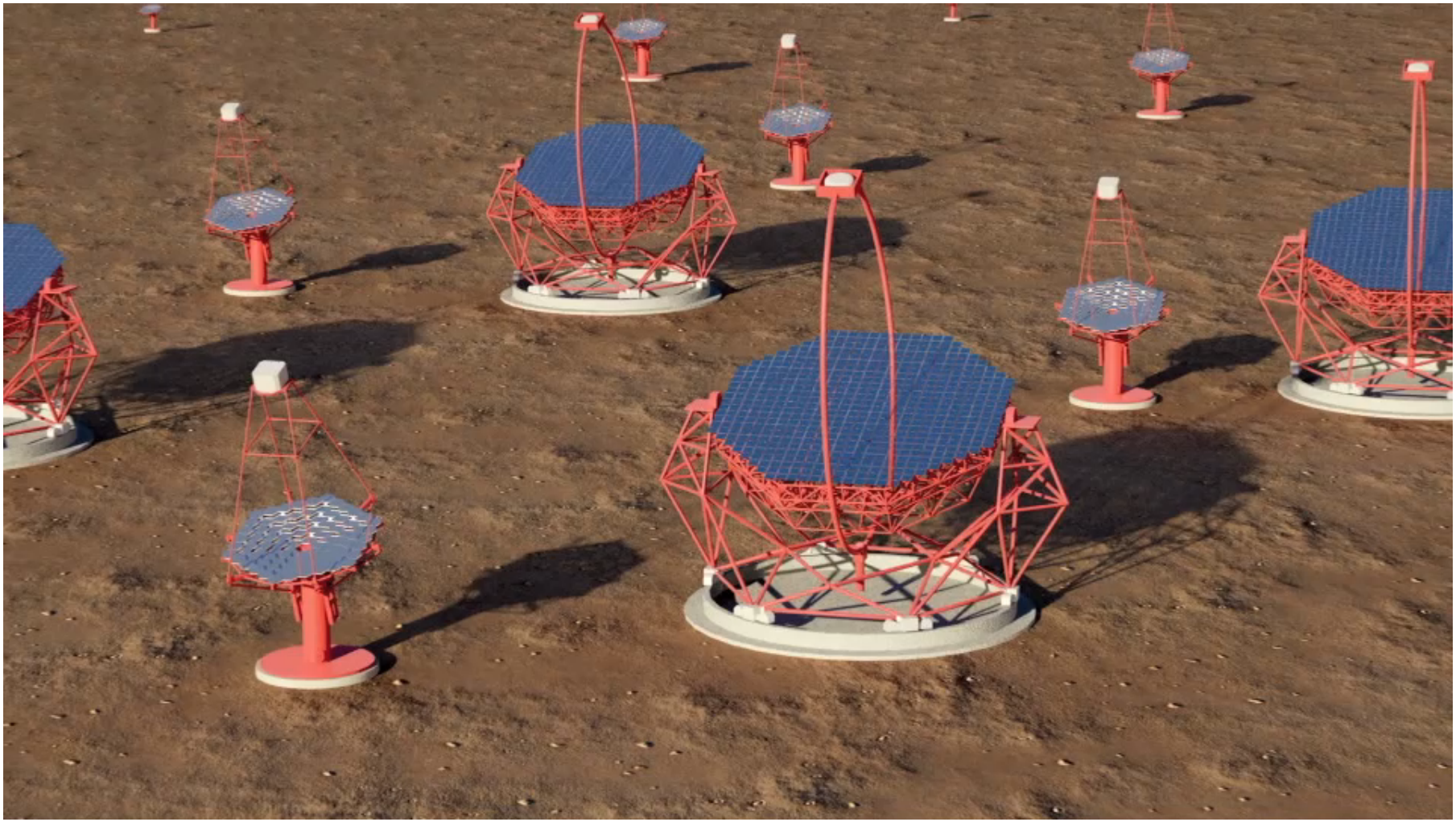
Dark matter halo emission?
Launch of Fermi bubbles?



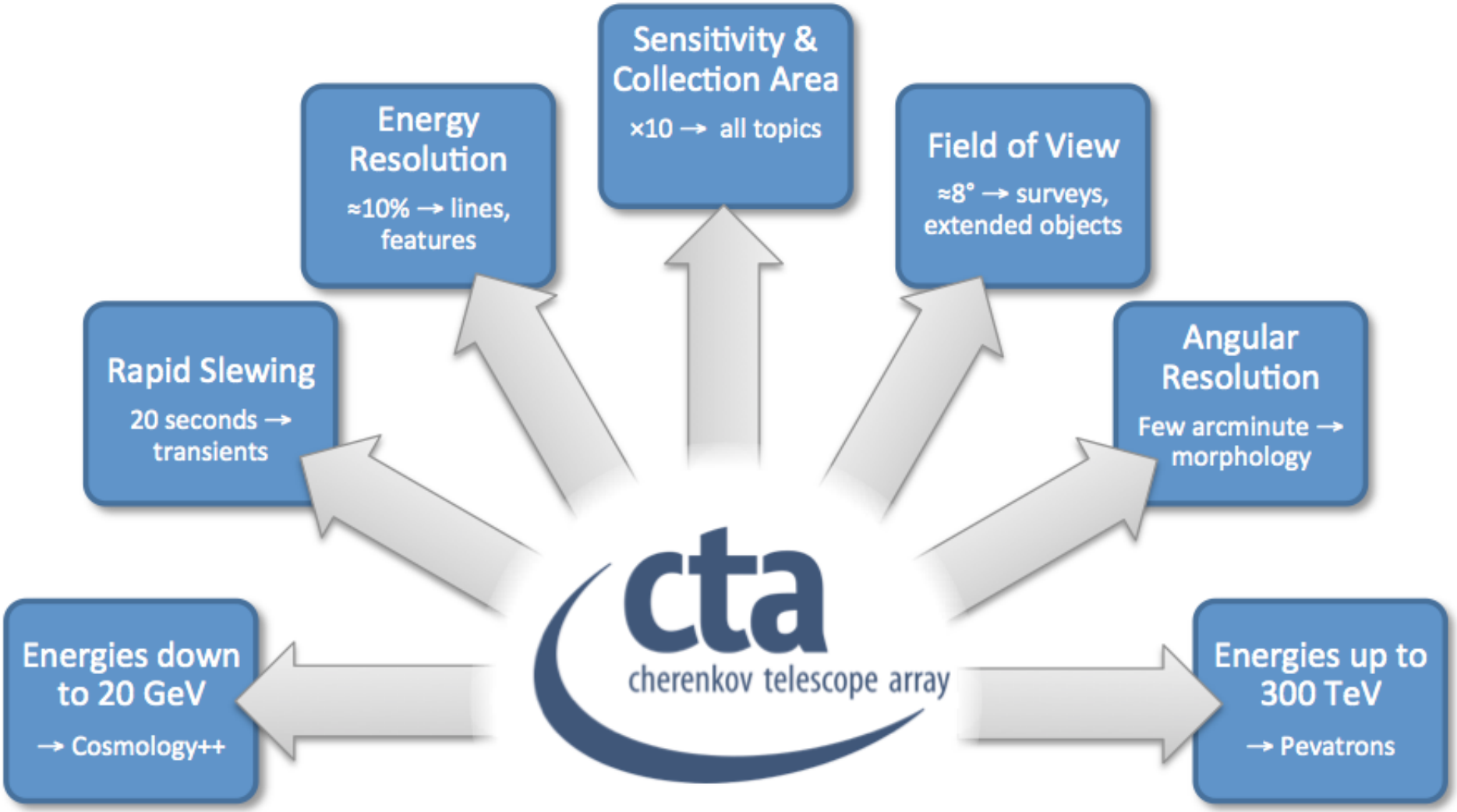
SUMMARY

- Gamma rays trace violent cosmic events
- Gamma ray sources = cosmic particle accelerators, are ubiquitous in the Cosmos
- In the last decade, 10-fold increase in number of GeV, TeV sources
- Instruments now produce sky maps, resolve complex sources and follow light curves
- Variety of acceleration mechanisms, often related to life cycle of massive stars (wind, SN explosion, pulsar / BH)
- Qualitative understanding of (some) mechanisms, but many issues open (are SNR the dominant source of CR?)
- Now also at the verge of addressing fundamental issues in cosmology, DM, axion searches, Lorentz inv. violation

THE CHERENKOV TELESCOPE ARRAY CTA

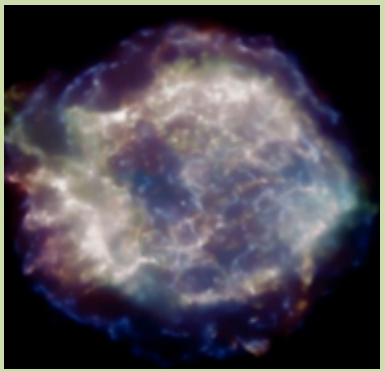


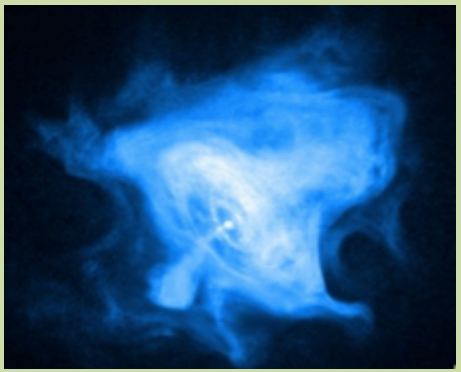
REQUIREMENTS & DRIVERS



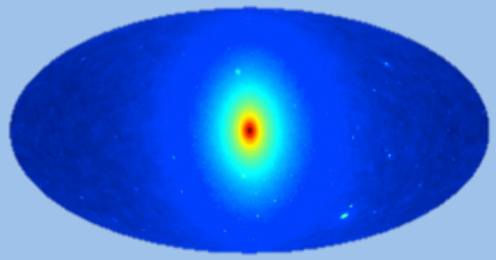
CTA SCIENCE

In-depth understanding of known objects and their mechanisms





Expected discoveries of new object classes



The fun part:
Things we haven't thought of

?