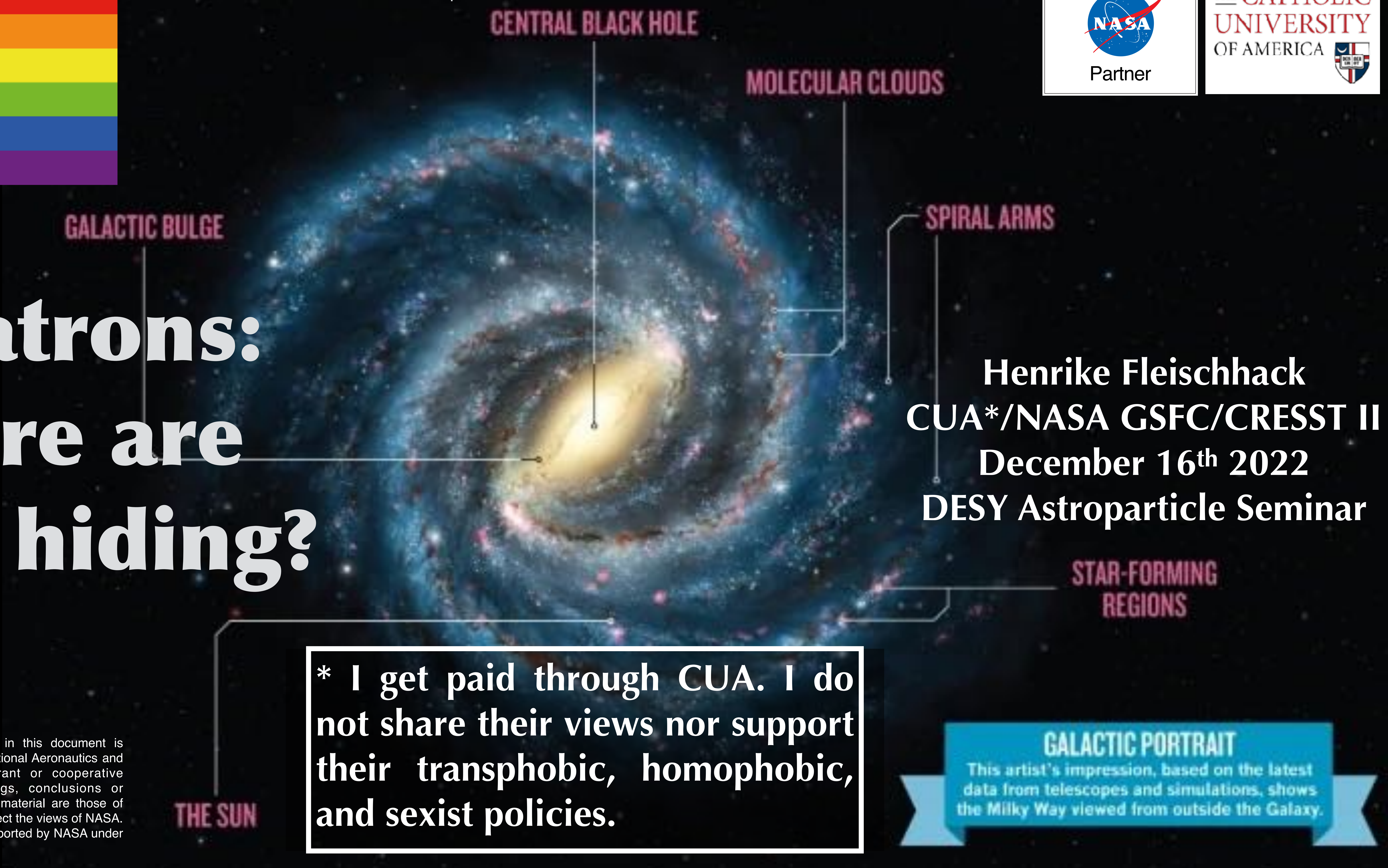
https://www.nature.com/articles/490024a



NASA Partner

THE CATHOLIC UNIVERSITY OF AMERICA

PeVatrons: Where are they hiding?

Henrike Fleischhack
CUA*/NASA GSFC/CRESST II
December 16th 2022
DESY Astroparticle Seminar

* I get paid through CUA. I do not share their views nor support their transphobic, homophobic, and sexist policies.

Disclaimer: The material contained in this document is based upon work supported by a National Aeronautics and Space Administration (NASA) grant or cooperative agreement. Any opinions, findings, conclusions or recommendations expressed in this material are those of the author and do not necessarily reflect the views of NASA. The material is based upon work supported by NASA under award number 80GSFC21M0002.

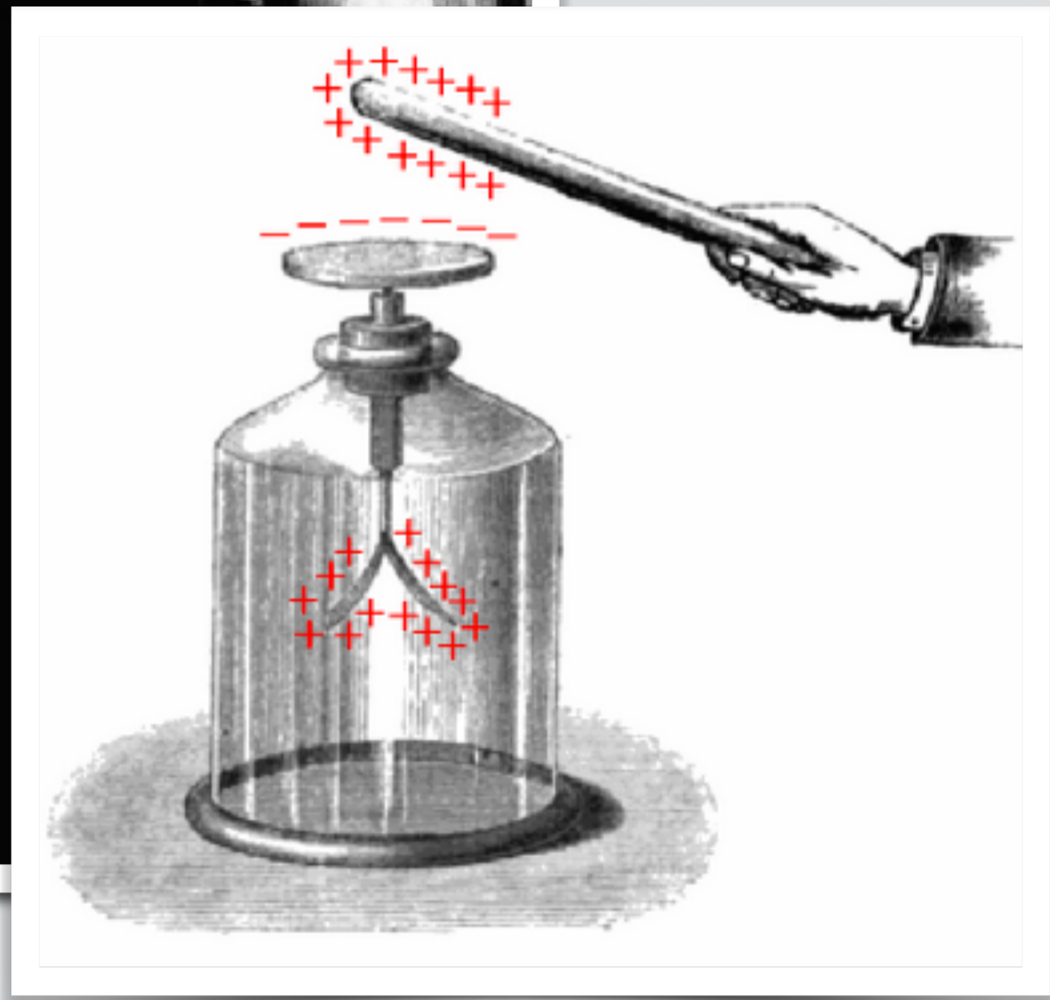
Content

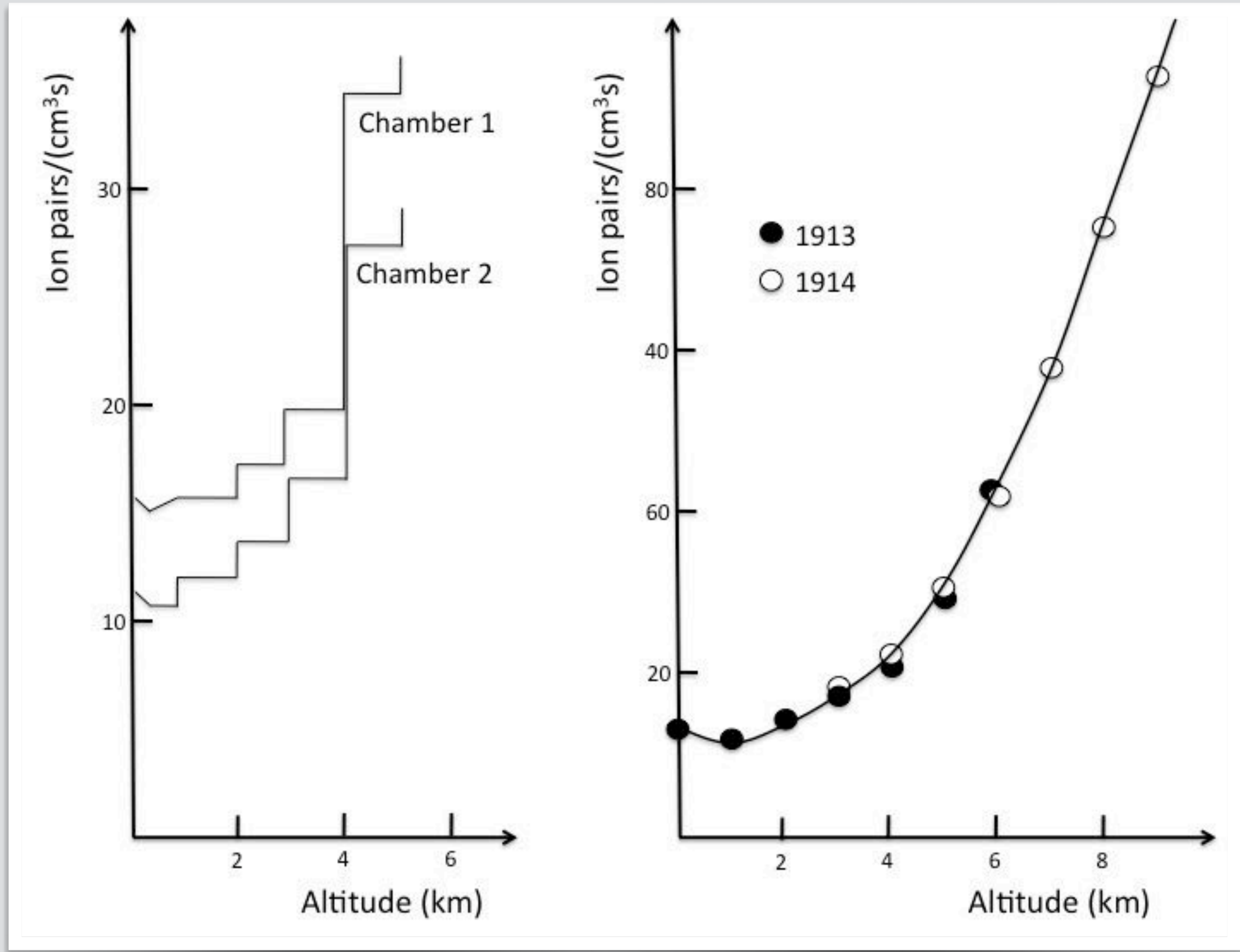
1. Introduction: What are PeVatrons?
2. Messager 1: Protons
3. Messager 2: Neutrinos
4. Messager 3: Photons
    a. Gamma-ray astronomy with HAWC
    b. Multi-Wavelength analysis of SNR G106.3+2.7
5. Future prospects

What are PeVatrons?

Altitude Radiation

Hess & Kohlhörster 1912:
Rate of ionizing radiation increases with altitude





https://commons.wikimedia.org/wiki/File:HessKol.jpg

Cosmic Rays

Cosmic rays are charged particles impinging upon the Earth's atmosphere from all directions.

https://www.vox.com/the-highlight/2019/7/16/17690740/cosmic-rays-universe-theory-science

Cosmic Rays and the Galaxy

Cosmic rays interact with:

- Star formation,
- Magnetic fields,

and

- Structure formation

In the Galaxy

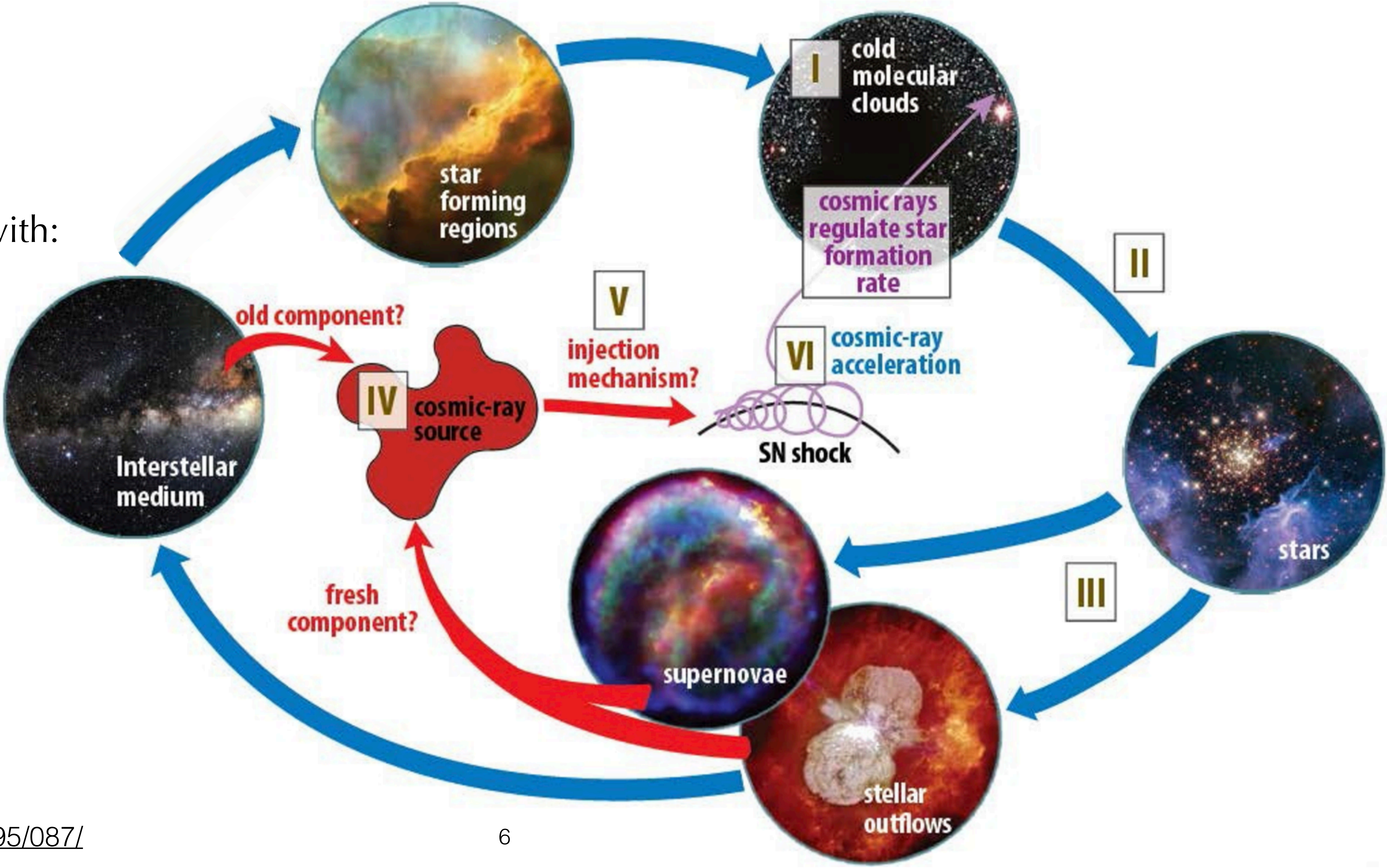


Image: https://pos.sissa.it/395/087/

Cosmic-Ray Energies

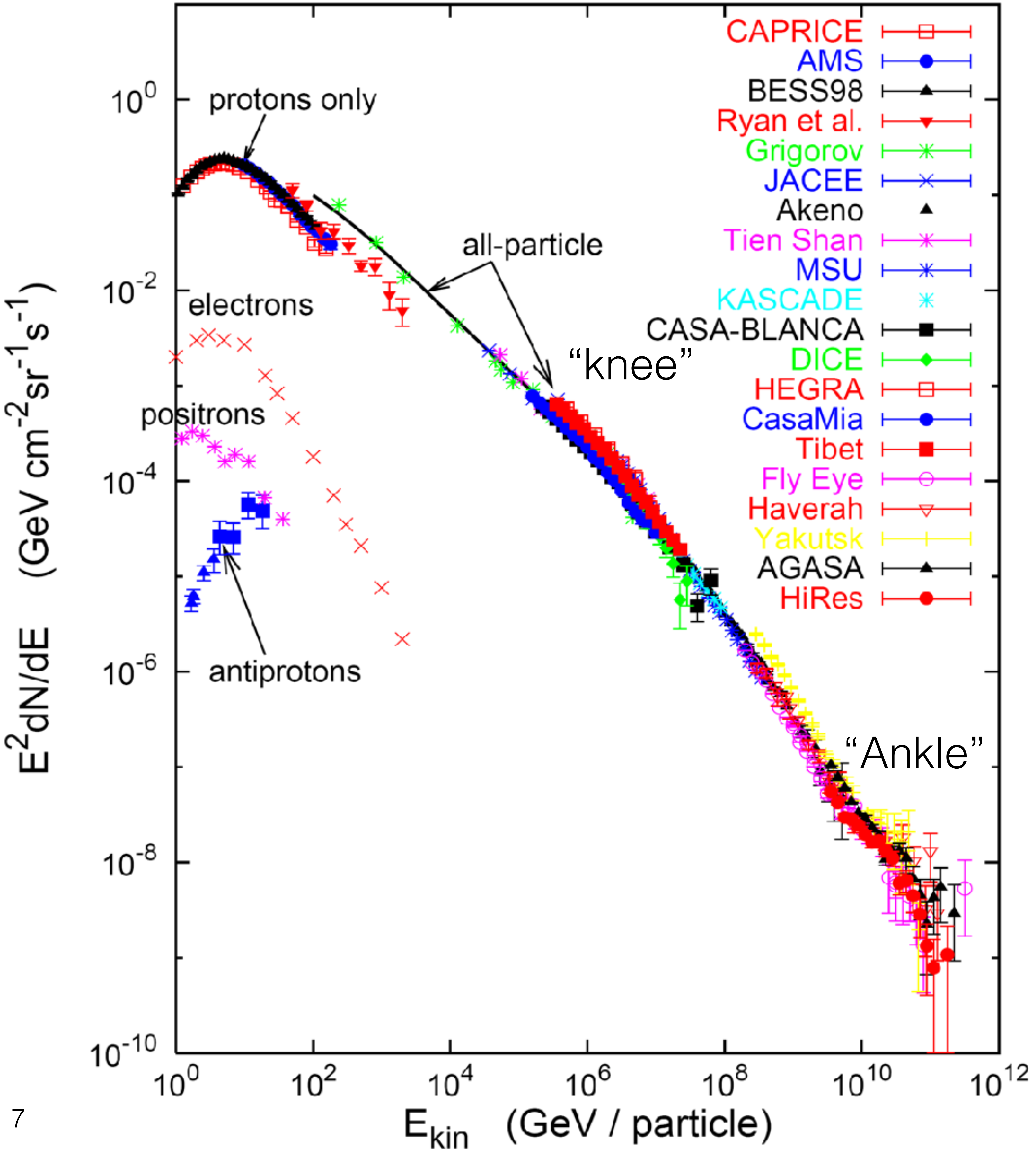


Image: http://w3.iihe.ac.be/~aguilar/PHYS-467/PA3.html

Cosmic-Ray Energies

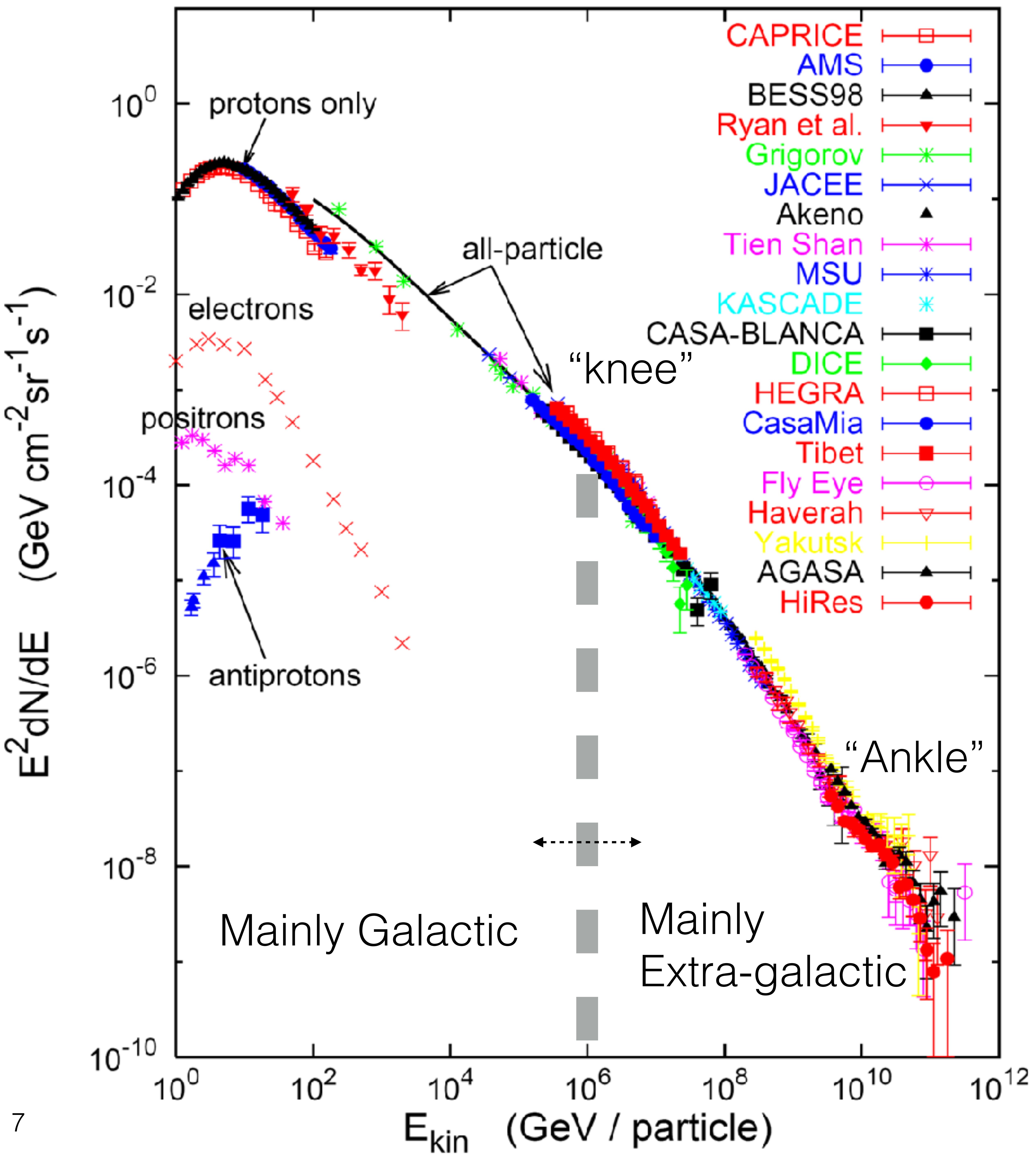


Image: http://w3.iihe.ac.be/~aguilar/PHYS-467/PA3.html

Cosmic-Ray Energies

PeVatrons are:

- **Galactic** CR sources
- accelerating **protons**
- to **PeV** energies (10^{15} eV = 10^{6} GeV)

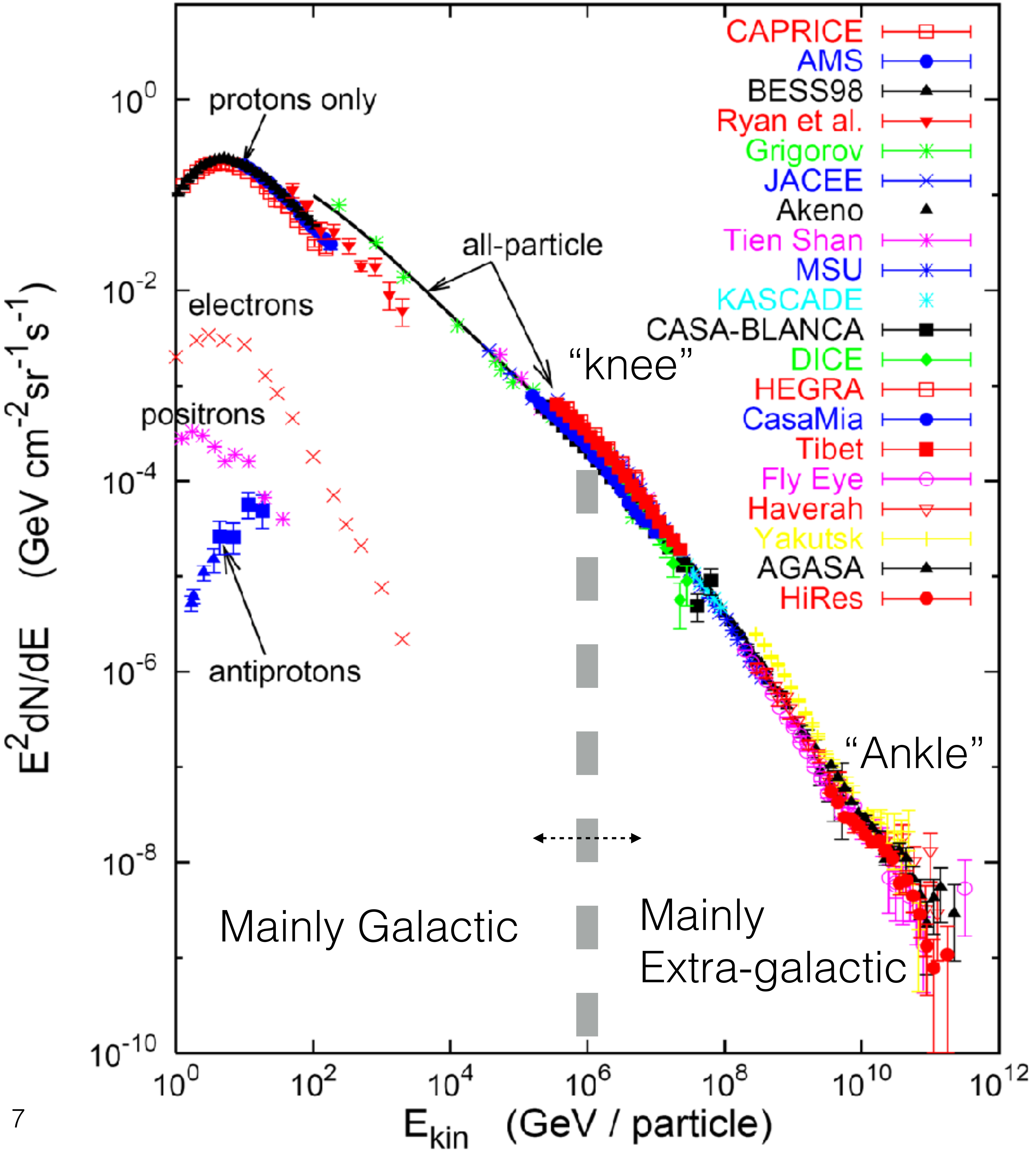


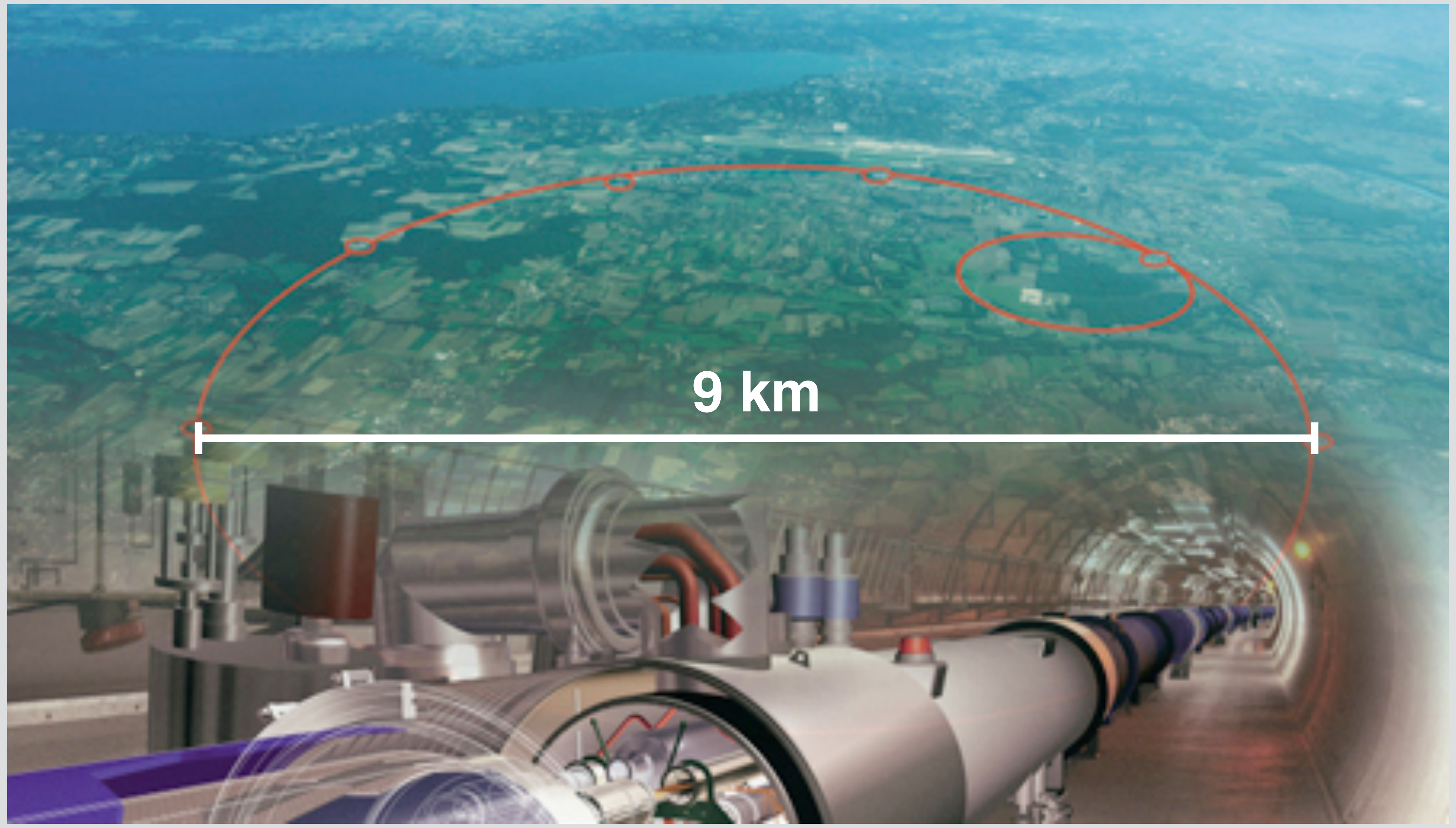
Image: http://w3.iihe.ac.be/~aguilar/PHYS-467/PA3.html

Particle Accelerators

10^6: **Mega**
10^9: **Giga**
10^{12}: **Tera**
10^{15}: **Peta**

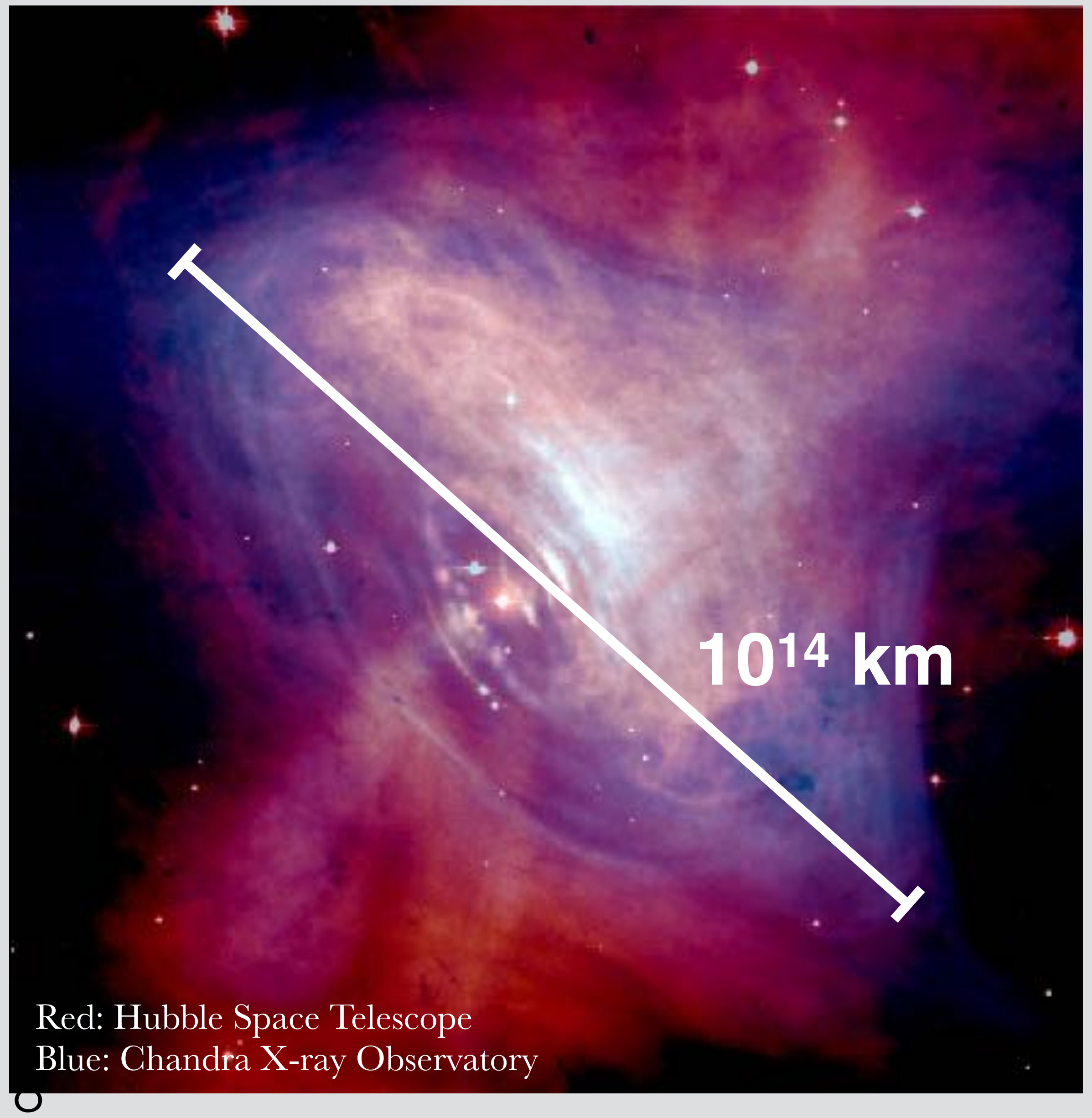
Terrestrial accelerators:

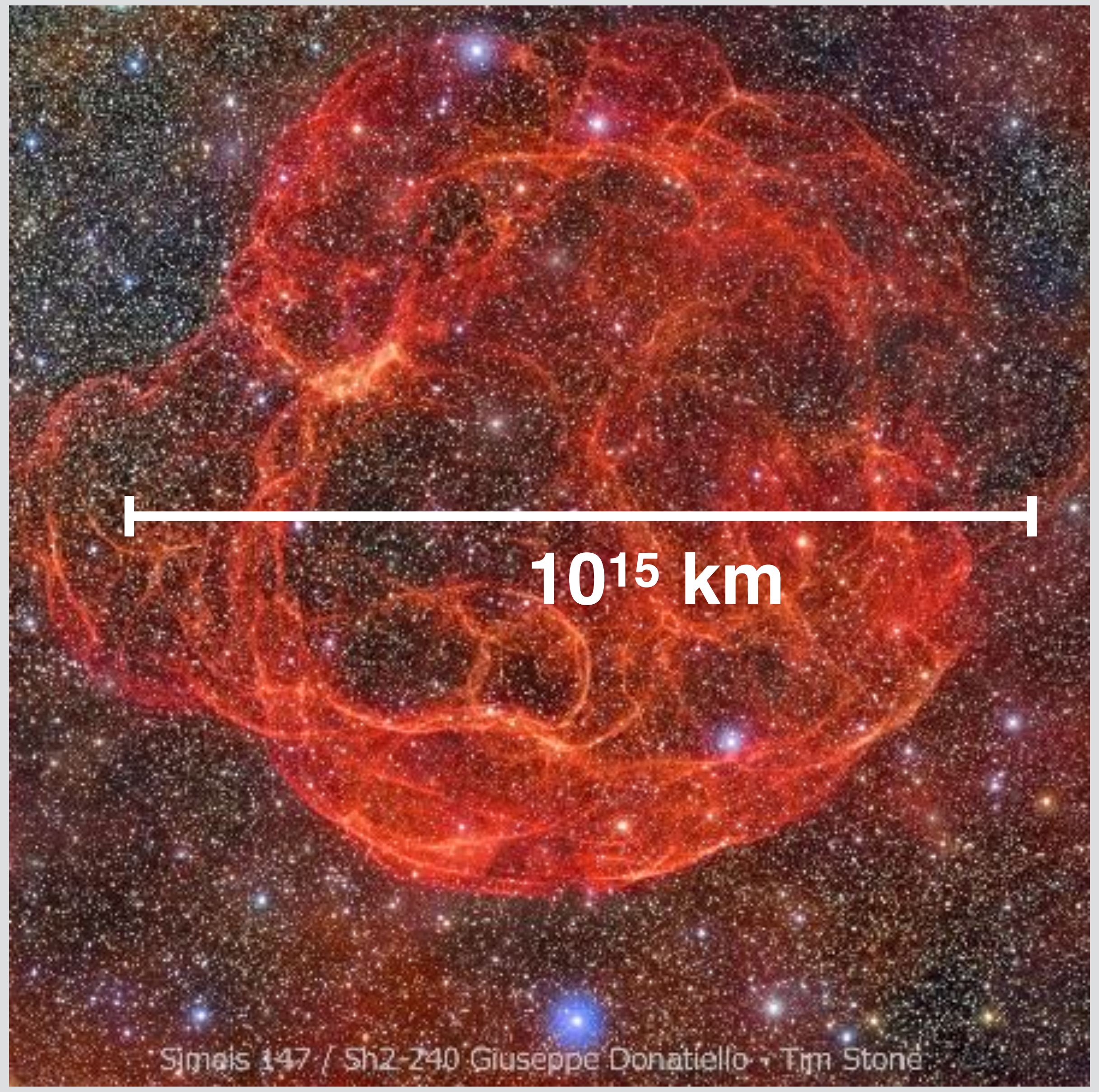
- LHC: protons ~ $6.5*10^{12}$ eV
- TeVatron: protons ~ 10^{12} eV
- Decades of planning.
- Thousands of engineers and scientists.
- Active for a few decades.



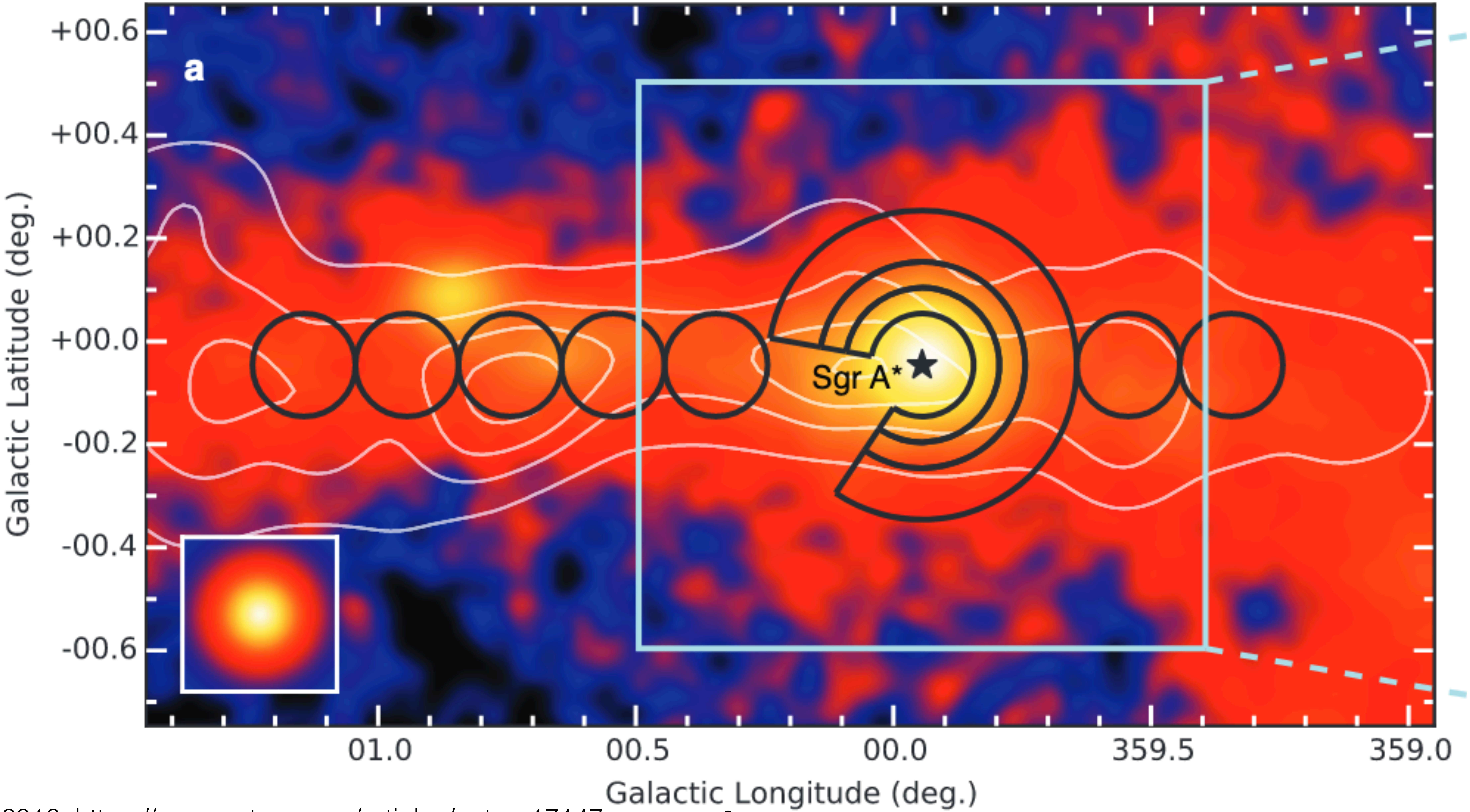
Cosmic accelerators:

- Galactic: protons ~10^{15} eV
- Extragalactic: protons ~ 10^{20} eV
- No engineers and scientists involved.
- Can be active for seconds to millions of years.





Diffuse PeV protons near the GC

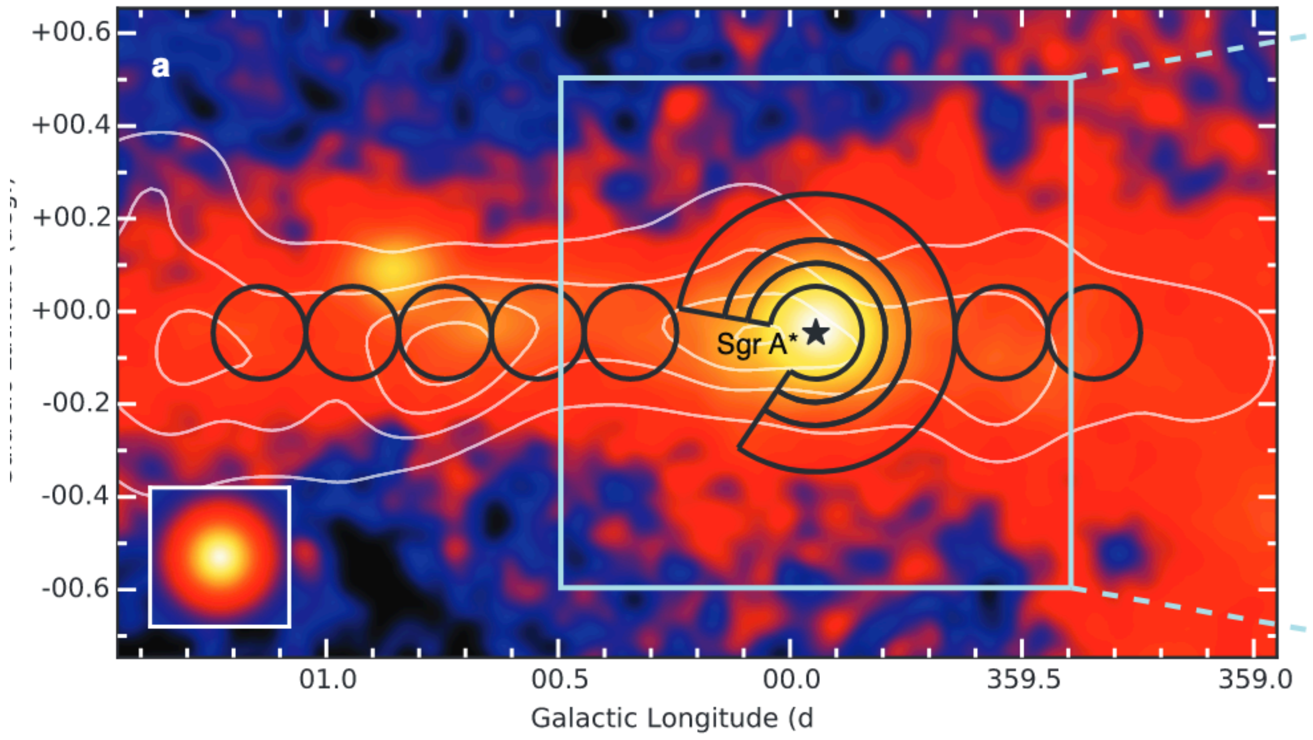


H.E.S.S. 2016: https://www.nature.com/articles/nature17147

Diffuse PeV protons near the GC

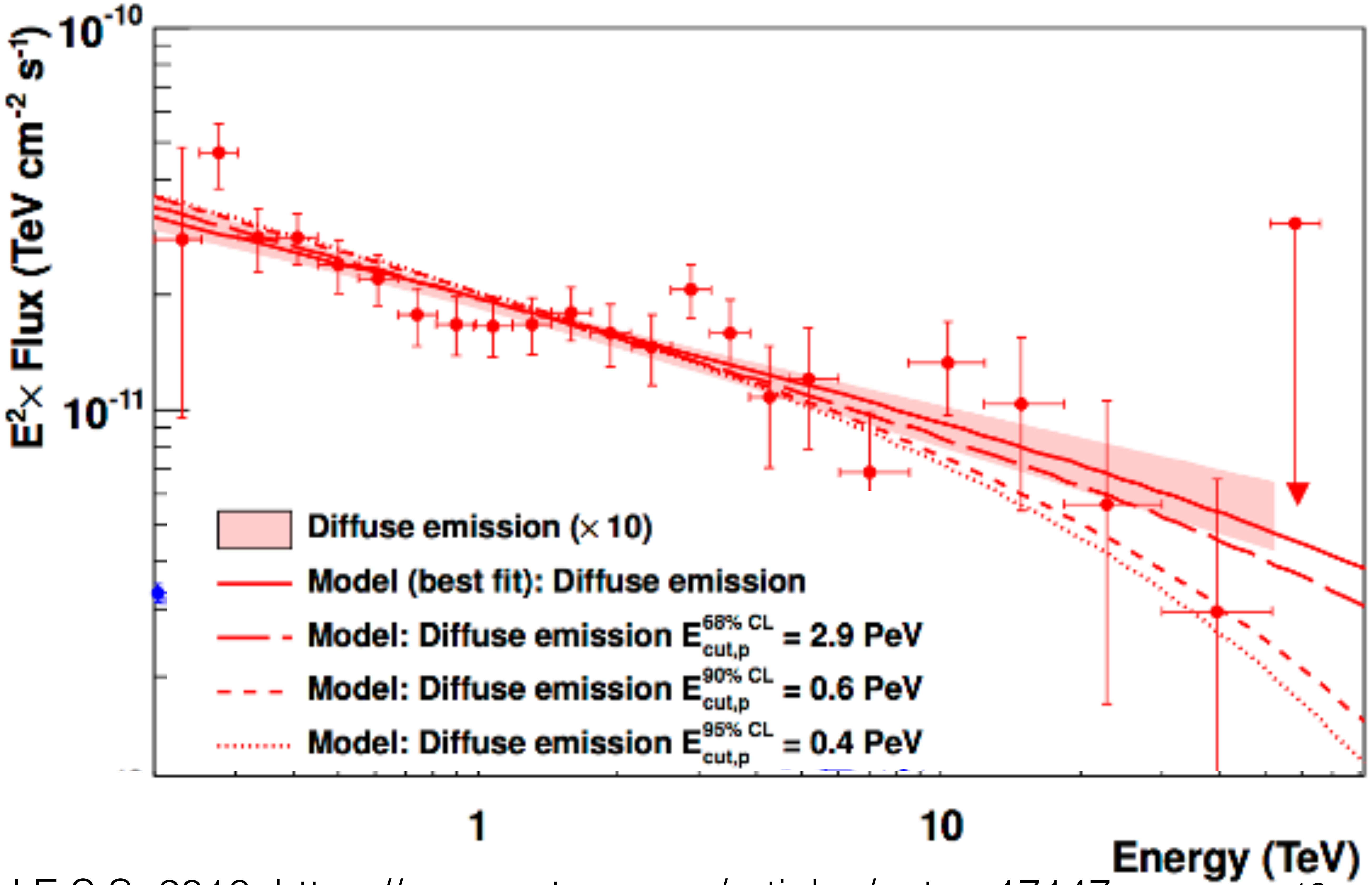
Gamma-rays >50 TeV:

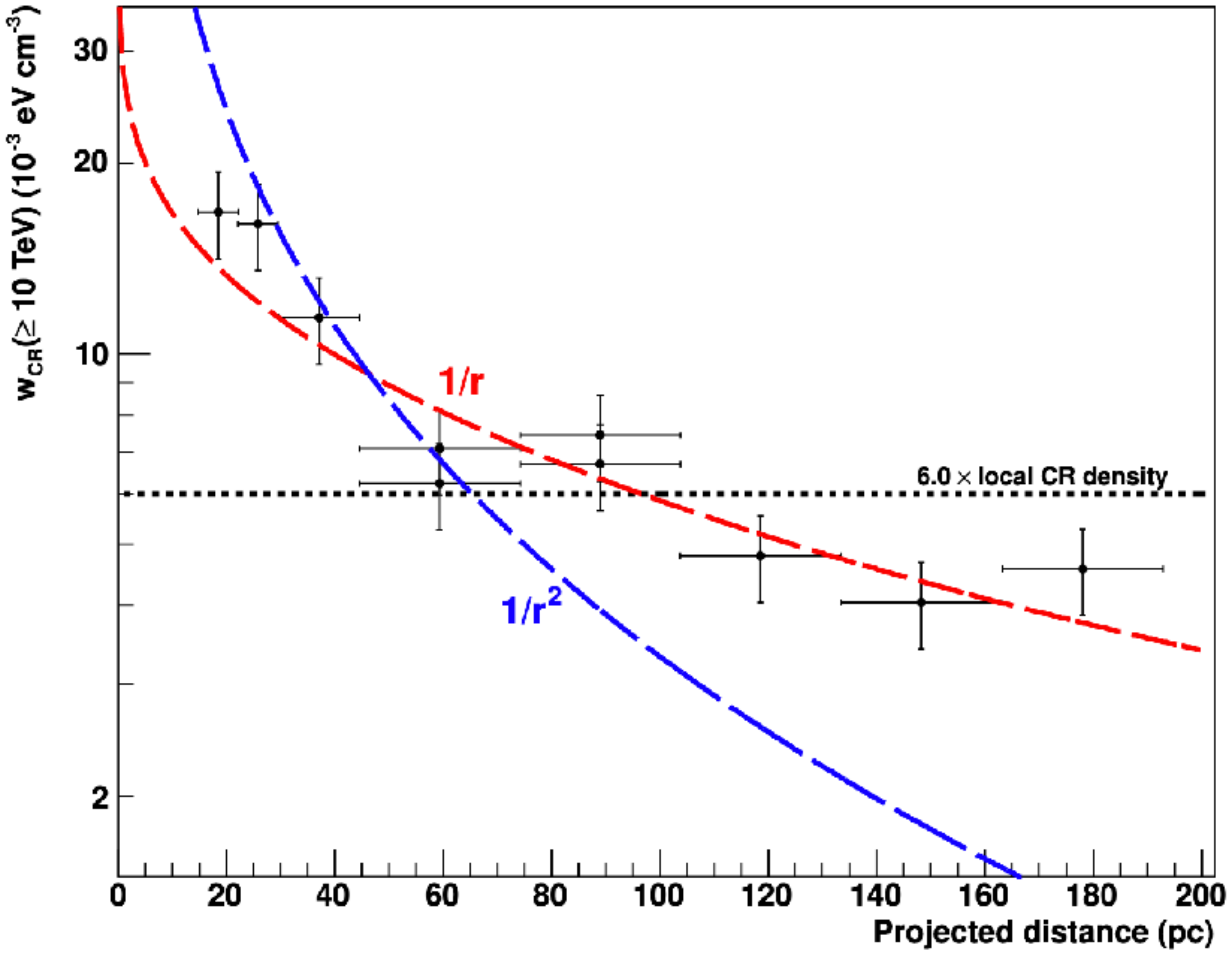
PeV protons



Gamma-ray **morphology**:

Proton **diffusion** from Sgr A*





H.E.S.S. 2016: https://www.nature.com/articles/nature17147

Cosmic Accelerators

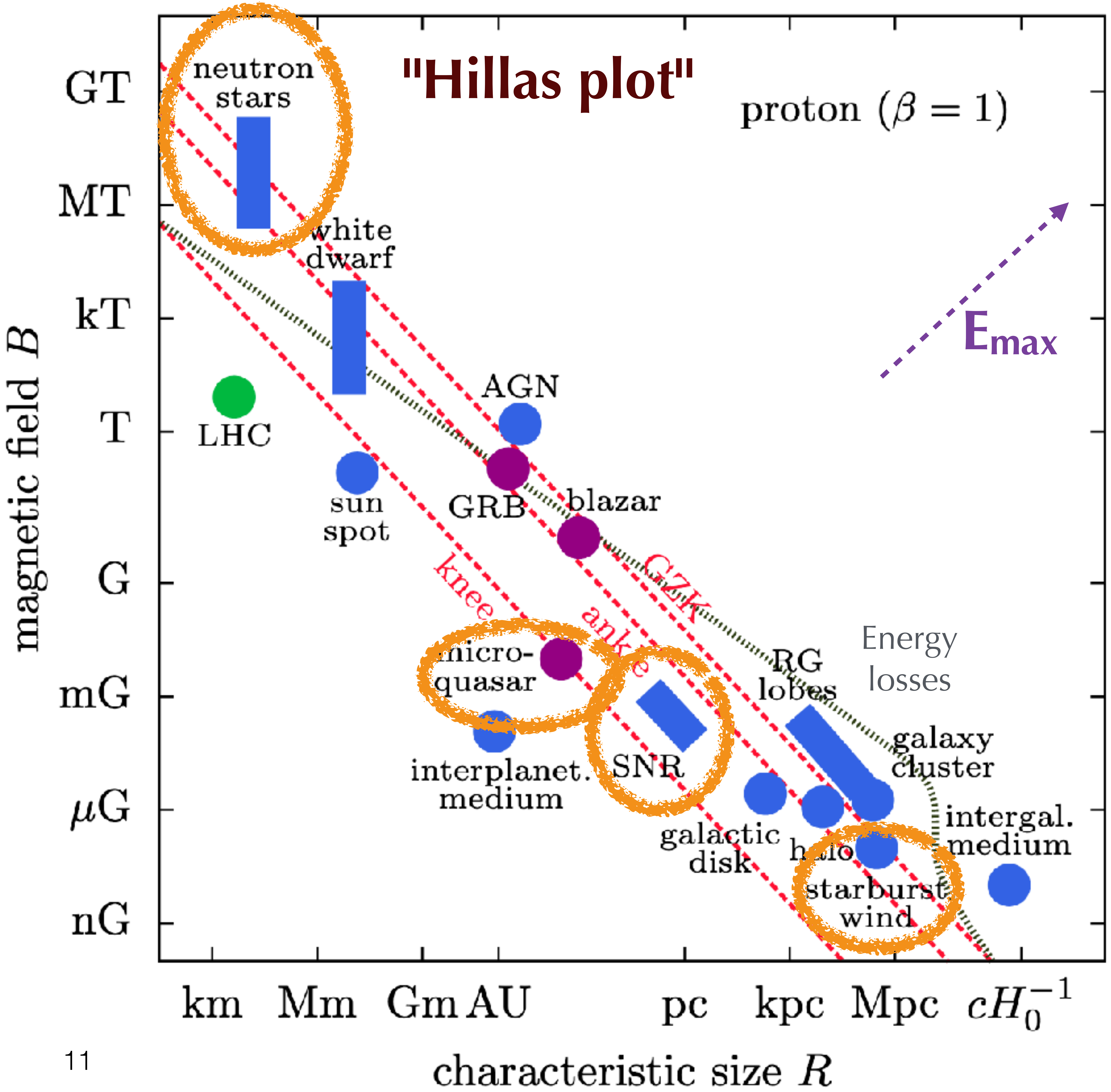
Image: https://www.sciencedirect.com/science/article/pii/S0273117717303757

Requirements:

- **Engine**: Shocks or magnetic reconnection
- **Fuel**: Charged particles
- **Container**: magnetic field (confinement)
- Energy budget
- Lifetime

Candidates source classes:

- Supernova remnants
- Pulsars and pulsar wind nebulae
- Starforming regions



PeVatrons as multi-messenger sources

- **1 PeV protons plus gas/dust** produce
- **~100 TeV photons** and
- **~50 TeV Neutrinos**

Images: https://legacy.ifa.hawaii.edu/info/press-releases/ASASSN_IceCube/
https://solarsystem.nasa.gov/resources/822/cassiopeia-a-supernova-remnant/
https://science.nasa.gov/get-involved/toolkits/spacecraft-icons

Messager 1: Protons

Cosmic-ray acceleration in SNRs

SNRs as Particle Accelerators

SNRs likely produce the **bulk of Galactic CR**:

- Sufficient energy budget to maintain GCR population.
- Strong shocks → diffusive shock acceleration.

Isolated SNRs accelerate CR **up to TeV** energies.

Higher E_{max} achieved via:

- Young SNRs with fast shocks.
- CR-induced magnetic field amplification.
- Superbubbles and collective effects in massive stellar clusters.

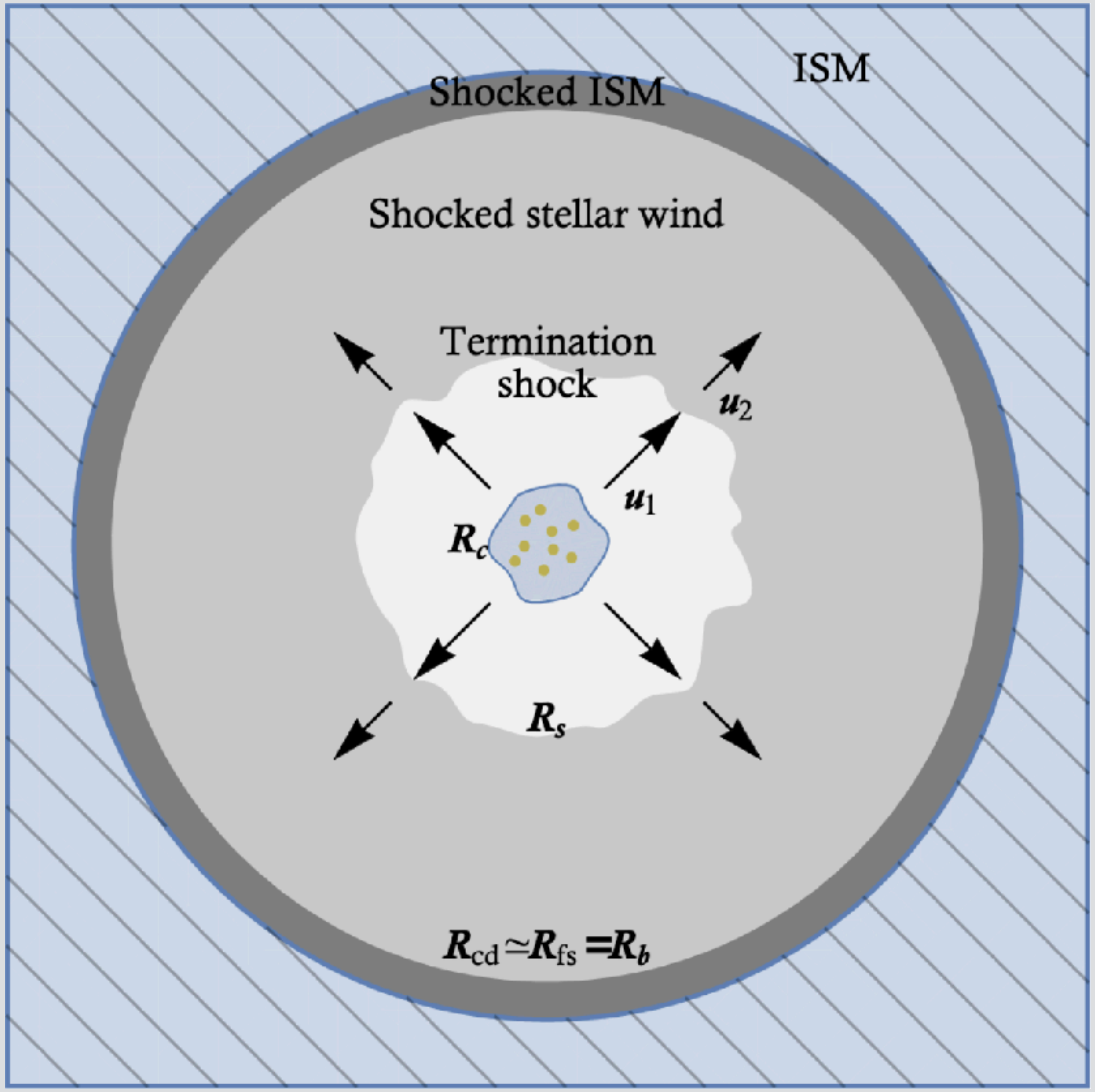
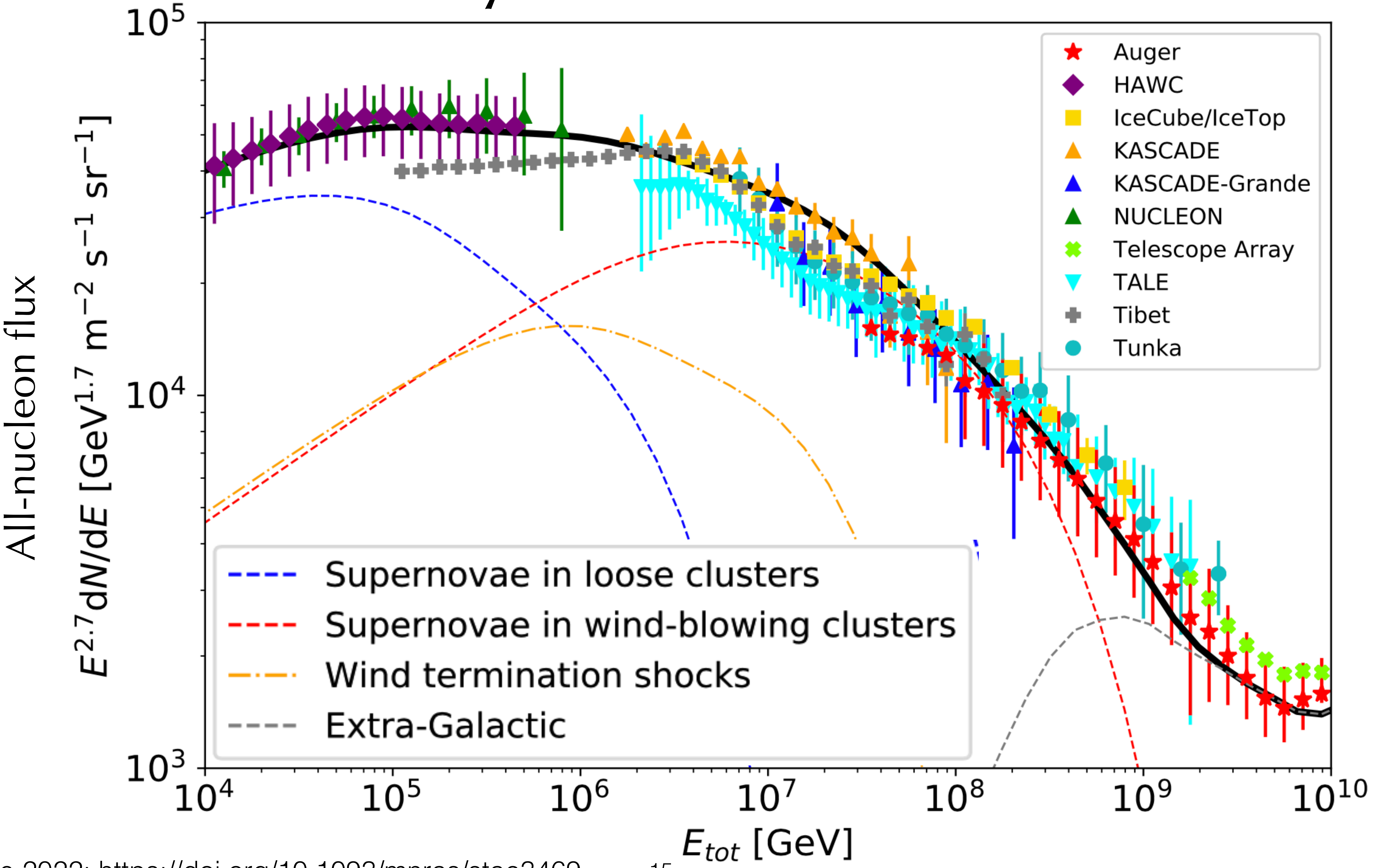


Image: Morlino 2021, https://doi.org/10.22323/1.395.0444

PeV Cosmic Rays massive stellar clusters?

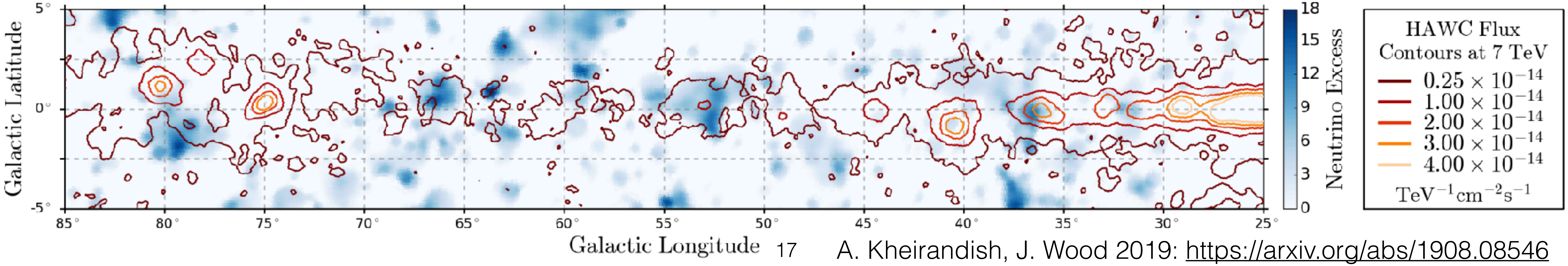


T. Vieu, B. Reville 2022: https://doi.org/10.1093/mnras/stac3469

Messager 2: Neutrinos

Neutrinos as smoking guns

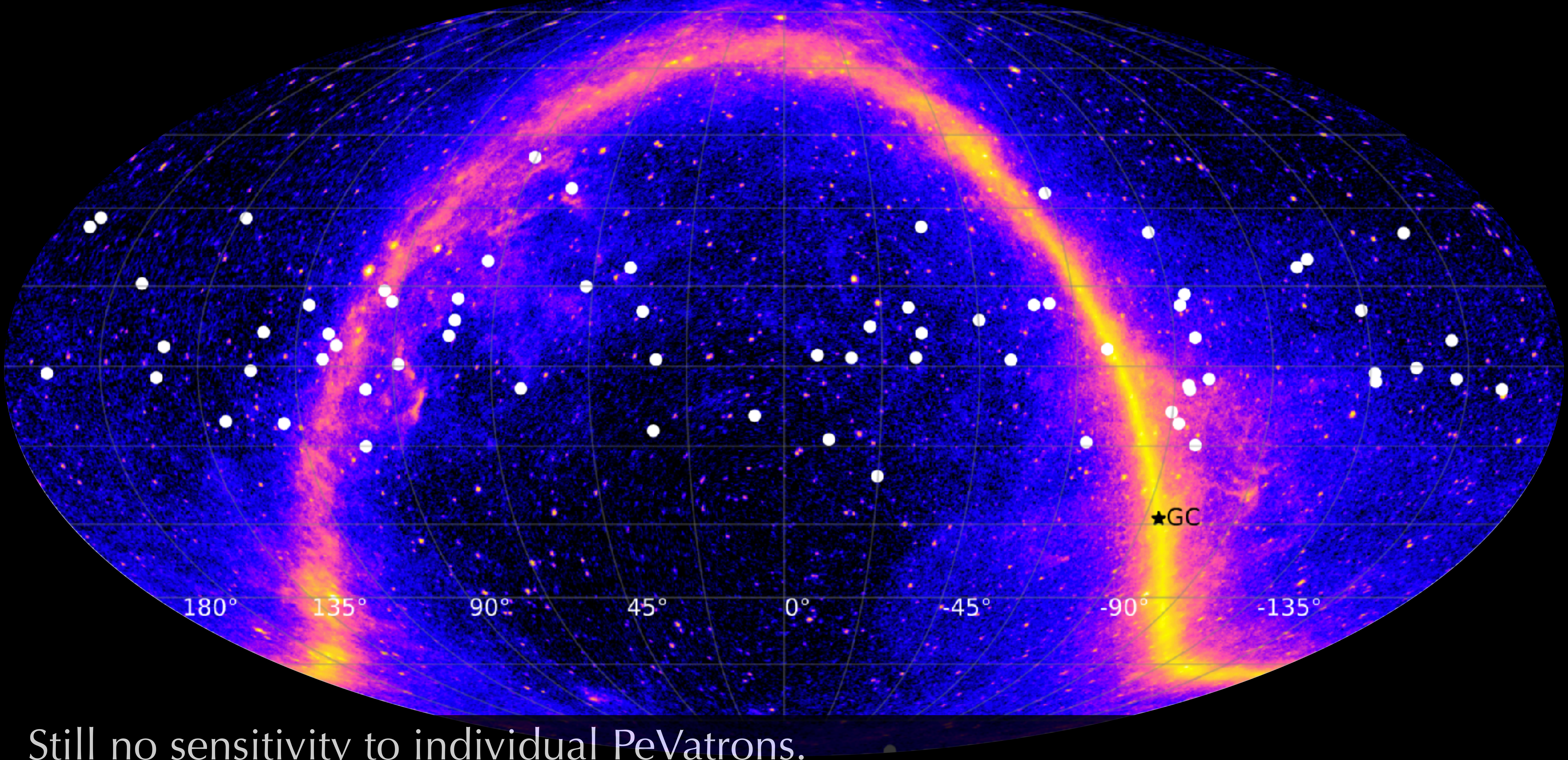
- ~50 TeV neutrinos guaranteed to accompany gamma rays from PeVatrons.
- Neutrinos can be traced back to their sources.
- So far, no* significant neutrino signal from the Galaxy.
- Current neutrino observatories **not sensitive enough** to detect PeVatrons.



A. Kheirandish, J. Wood 2019: https://arxiv.org/abs/1908.08546

Galactic neutrinos?

Kovalev et al 2022: https://arxiv.org/abs/2208.08423



- Still no sensitivity to individual PeVatrons.
- Possible evidence (4.1σ) for diffuse neutrino signal >200 TeV from galactic plane.

Messager 3: Photons
Gamma-Ray Astronomy with HAWC

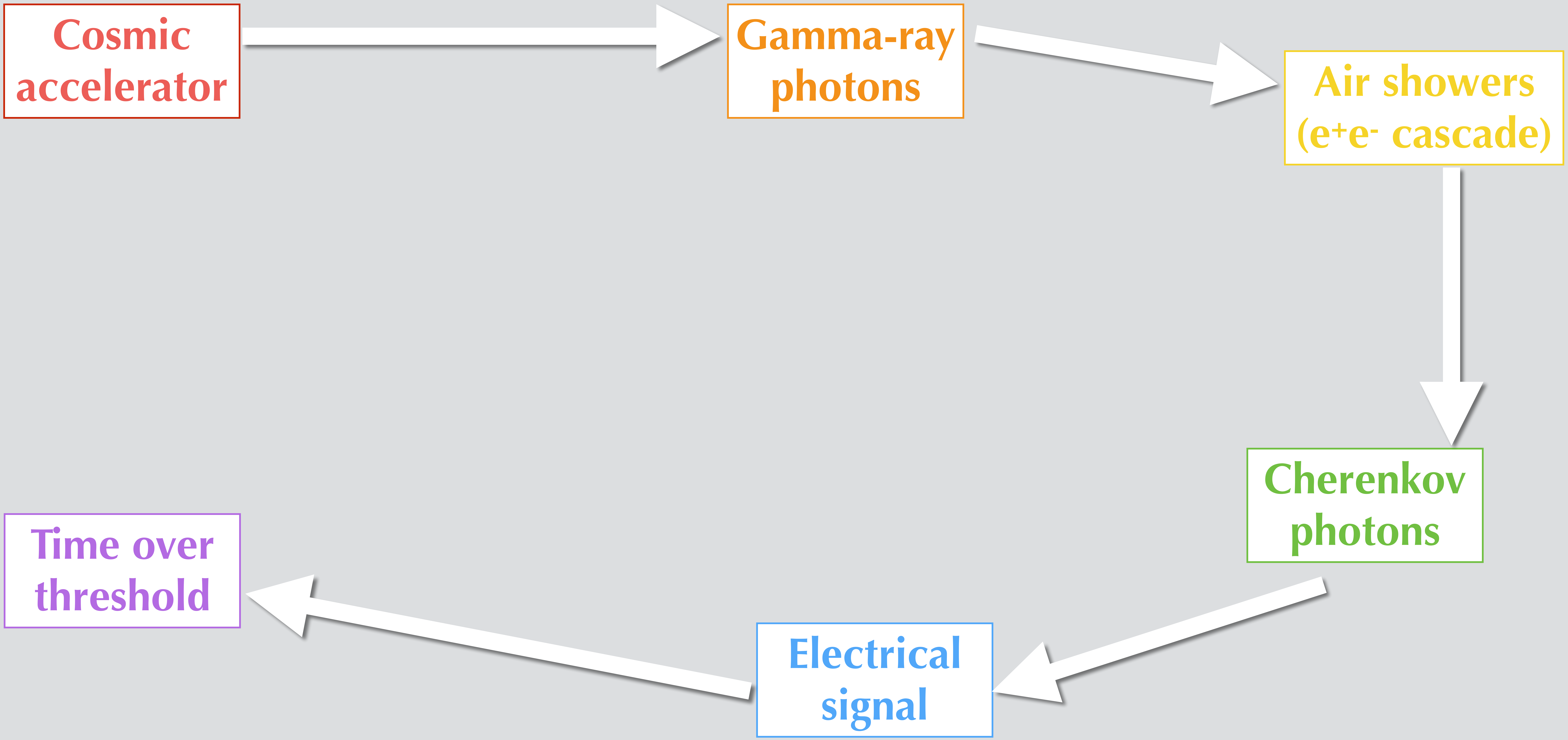
High Altitude Water Cherenkov Observatory

10^6: **M**ega
10^9: **G**iga
10^{12}: **T**era
10^{15}: **P**eta

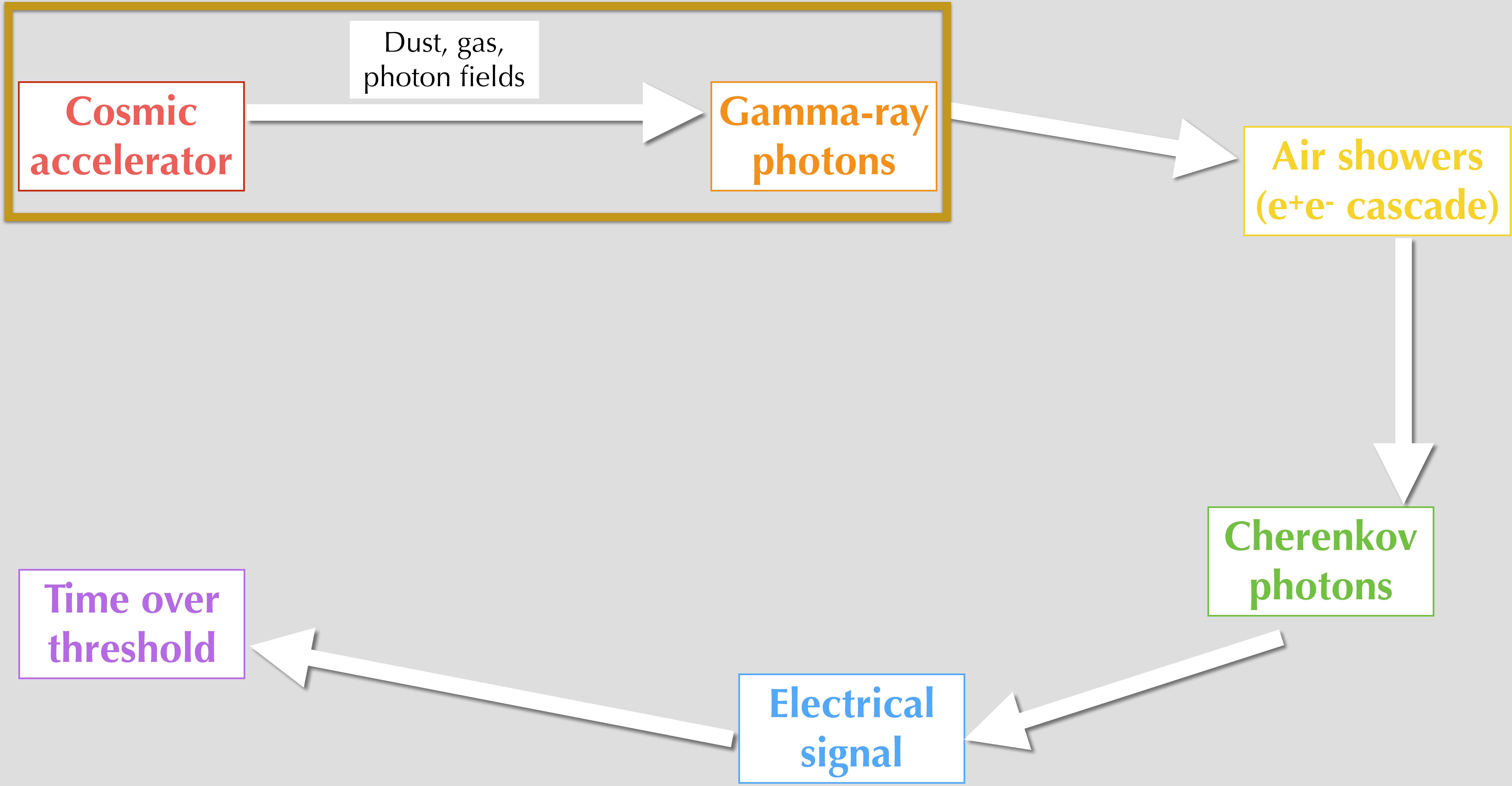
Energy range: ~300 GeV — 100 TeV
Angular resolution: ~0.1°
Field of View: ~2 sr
>95% Uptime

Main array completed March 2015
Outriggers deployed 2018

Gamma-Ray Astronomy with HAWC



Gamma-Ray Astronomy with HAWC



Cosmic Rays and Gamma Rays

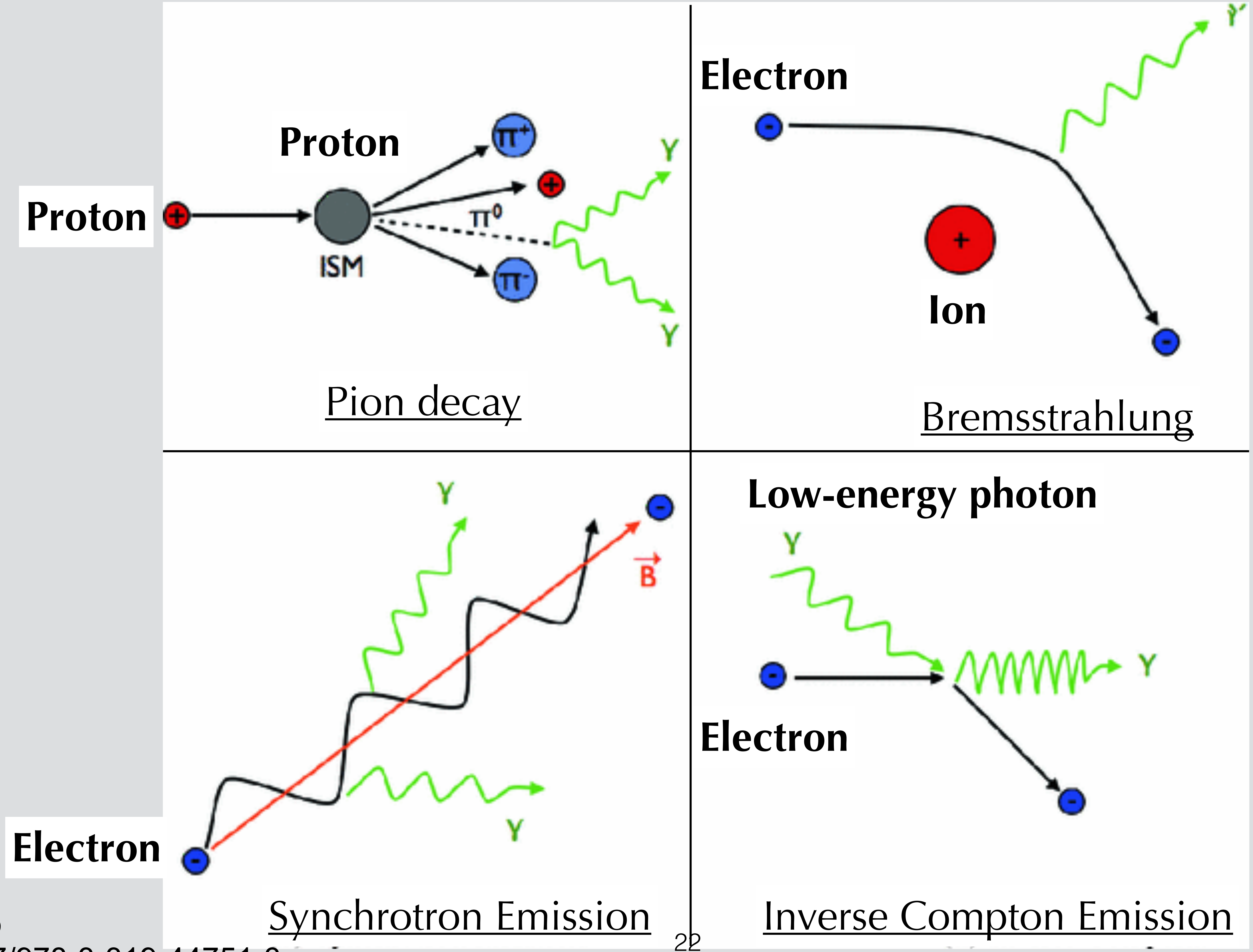
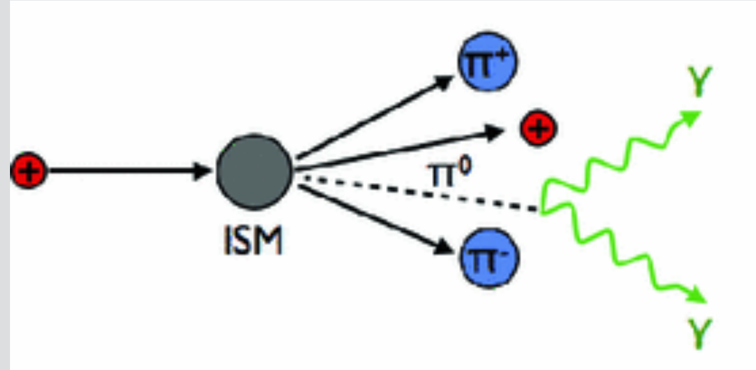


Image: R. Lopez-Coto
https://doi.org/10.1007/978-3-319-44751-3

Gamma-Ray Astronomy with HAWC

Cosmic accelerator

Dust, gas, photon fields



Gamma-ray photons

Air showers (e^+e^- cascade)

Cherenkov photons

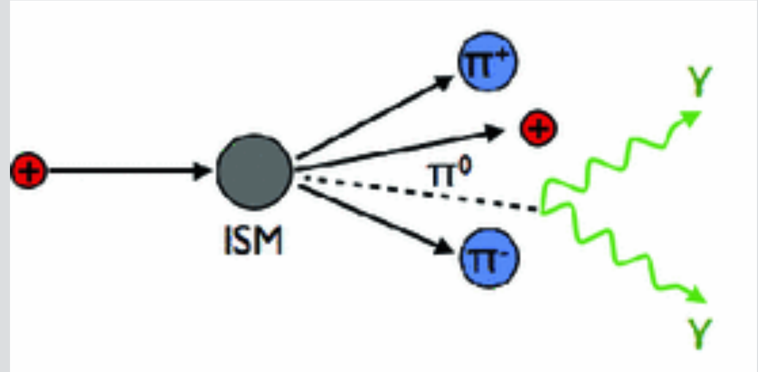
Electrical signal

Time over threshold

Gamma-Ray Astronomy with HAWC

Cosmic accelerator

Dust, gas, photon fields



Gamma-ray photons

Atmosphere

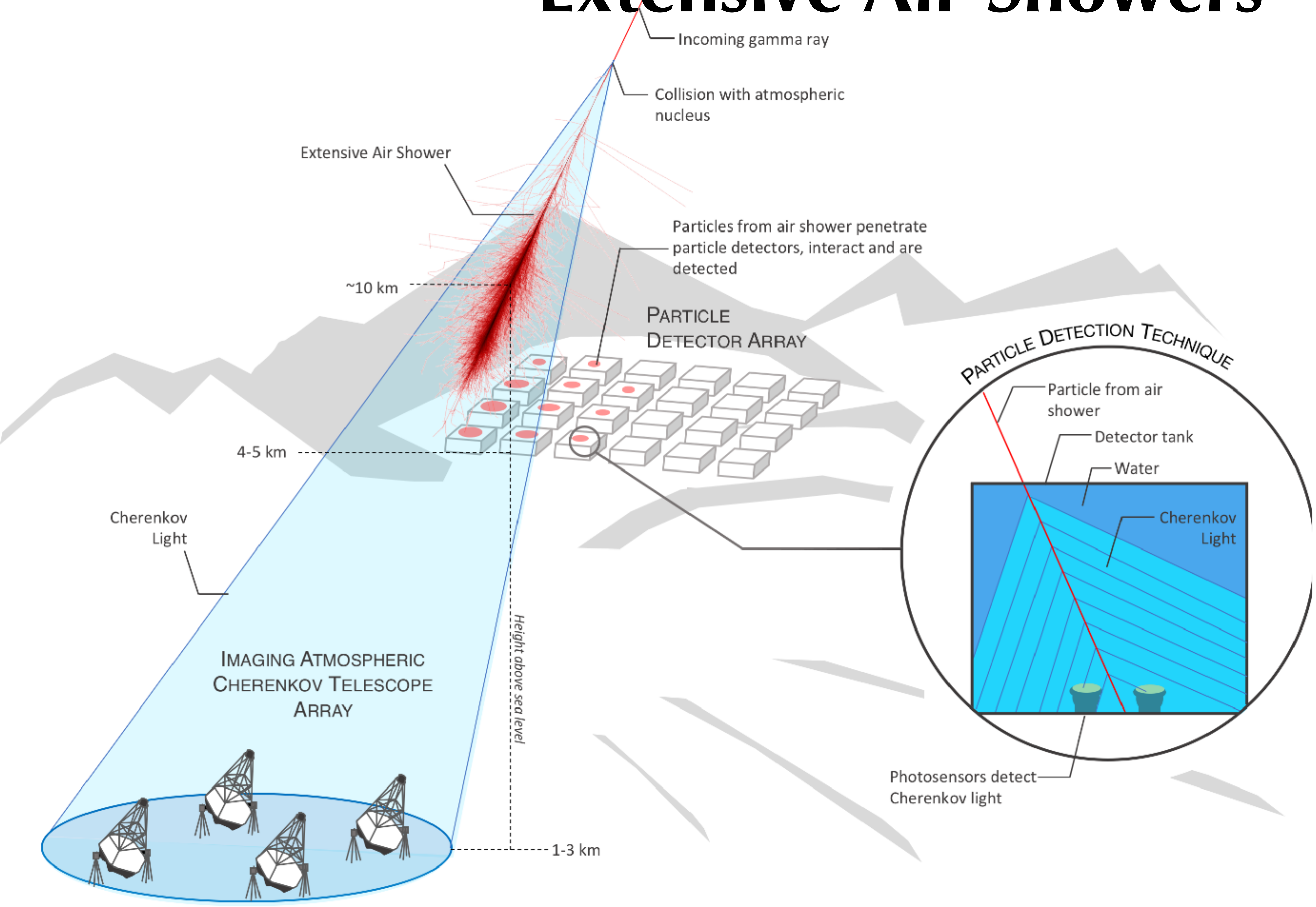
Air showers (e^+e^- cascade)

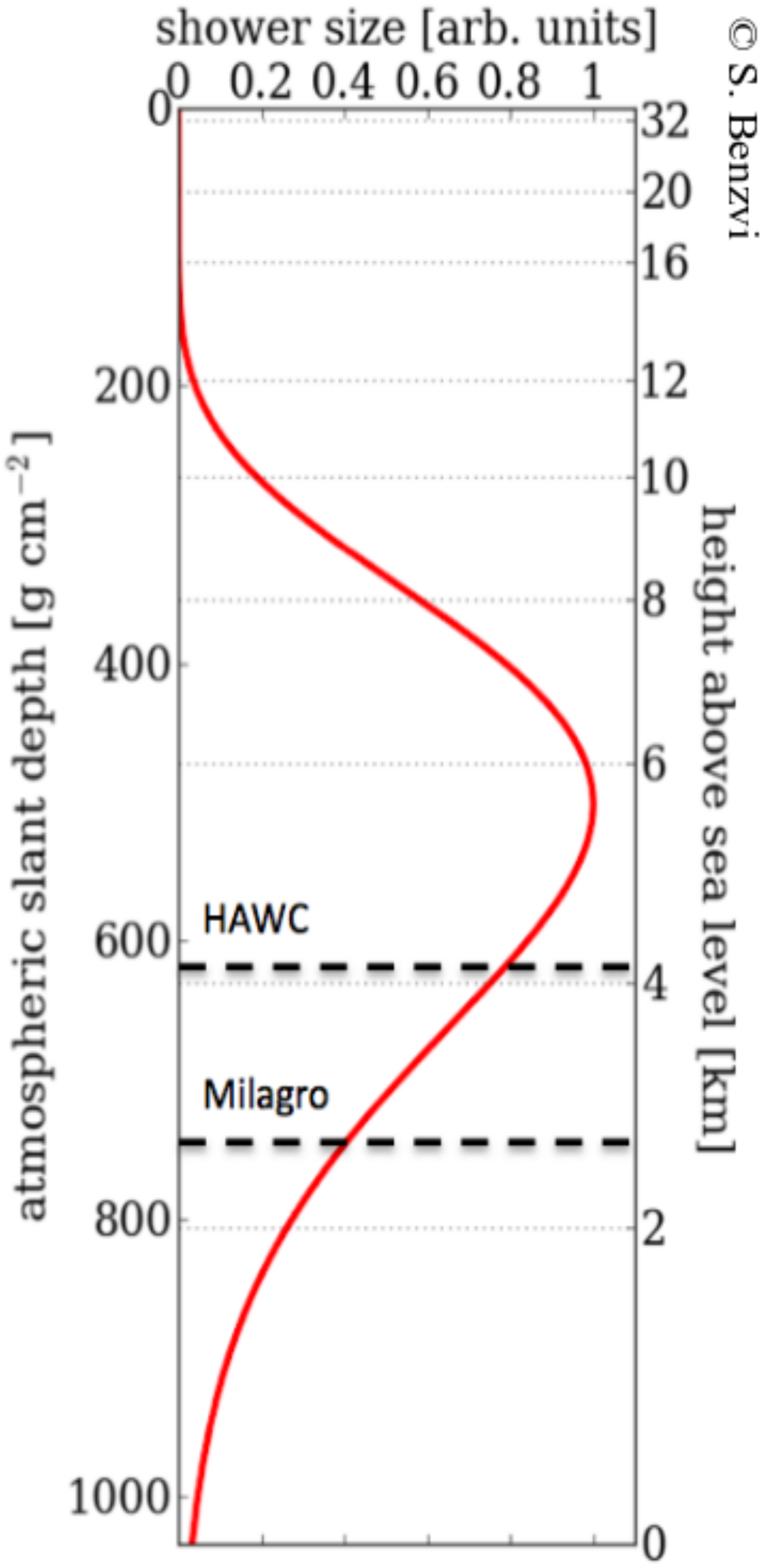
Cherenkov photons

Electrical signal

Time over threshold

Extensive Air Showers





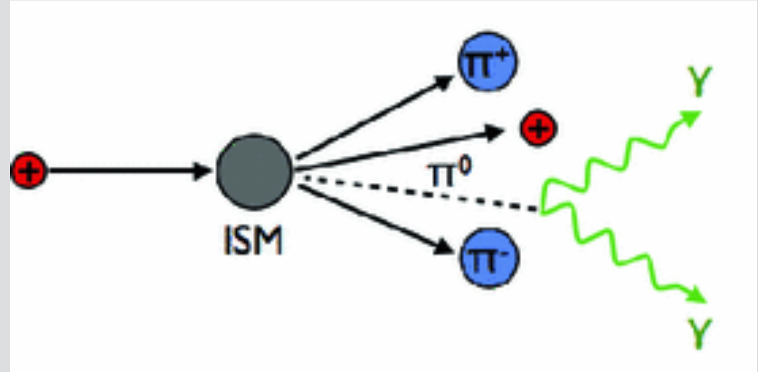
Shower image, 100 GeV γ-ray adapted from: F. Schmidt, J. Knapp, "CORSIKA Shower Images", 2005, https://www-zeuthen.desy.de/~jknapp/fs/showerimages.html

Not to scale

Gamma-Ray Astronomy with HAWC

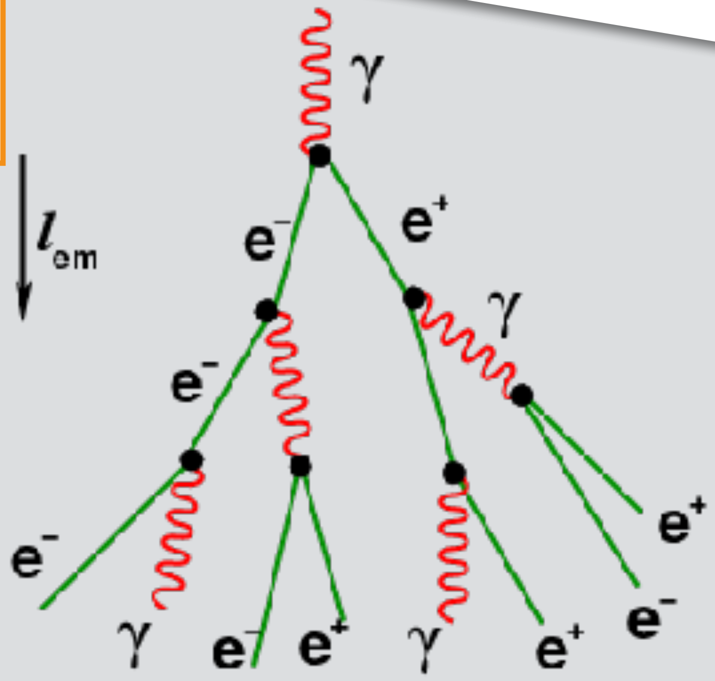
Cosmic accelerator

Dust, gas, photon fields



Gamma-ray photons

Atmosphere



Air showers (e^+e^- cascade)

Cherenkov photons

PMT

Electrical signal

DAQ electronics

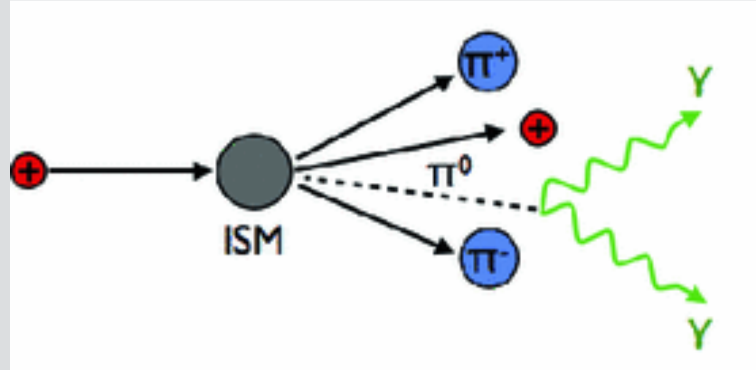
Time over threshold

Gamma-Ray Astronomy with HAWC

Gamma-Ray Astronomy with HAWC

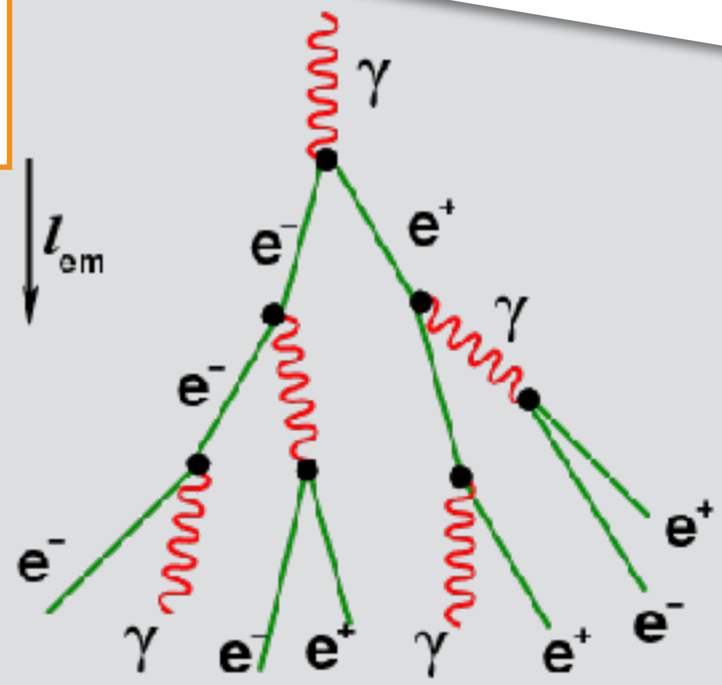
Cosmic accelerator

Dust, gas, photon fields

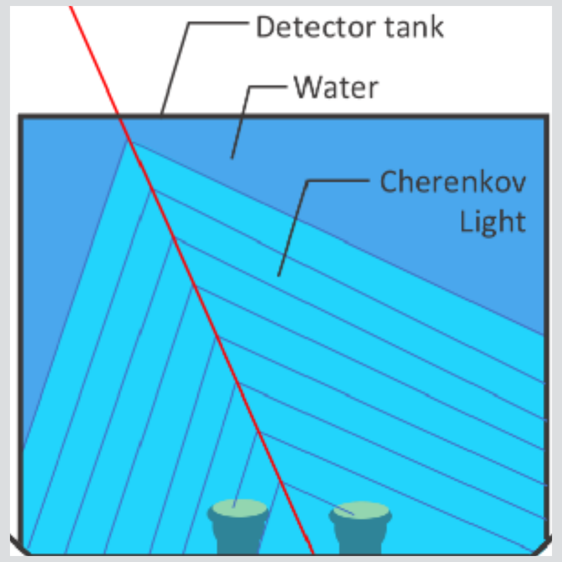


Gamma-ray photons

Atmosphere



Air showers (e^+e^- cascade)



Water tank

Cherenkov photons

PMT

Electrical signal

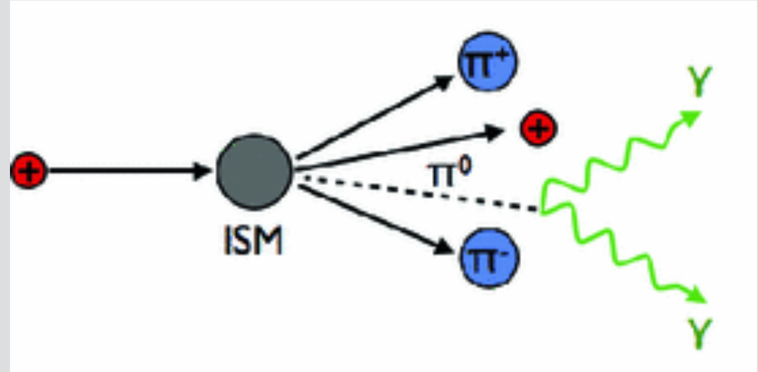
DAQ electronics

Time over threshold

Gamma-Ray Astronomy with HAWC

Cosmic accelerator

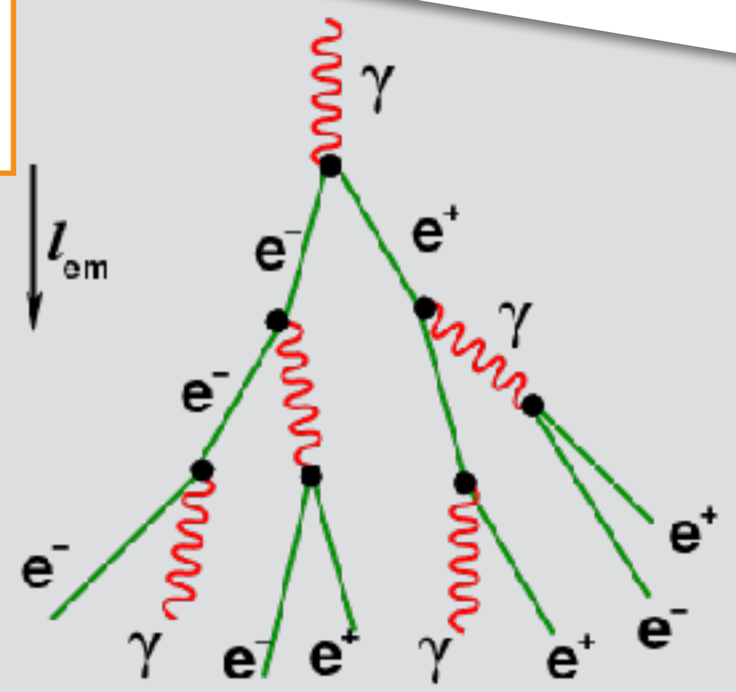
Dust, gas, photon fields

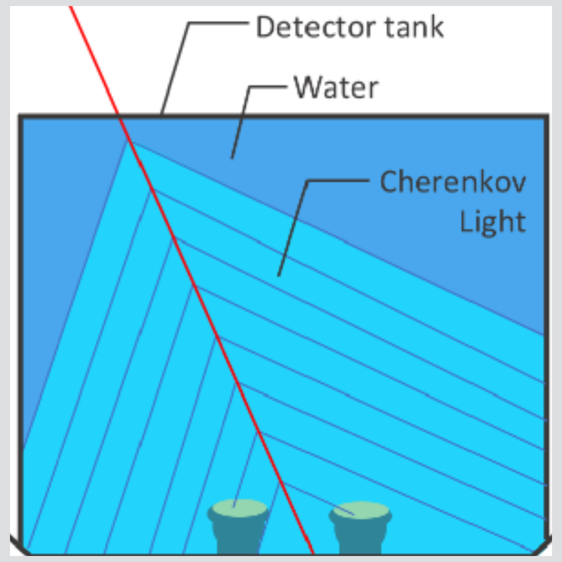


Gamma-ray photons

Atmosphere

Air showers (e^+e^- cascade)

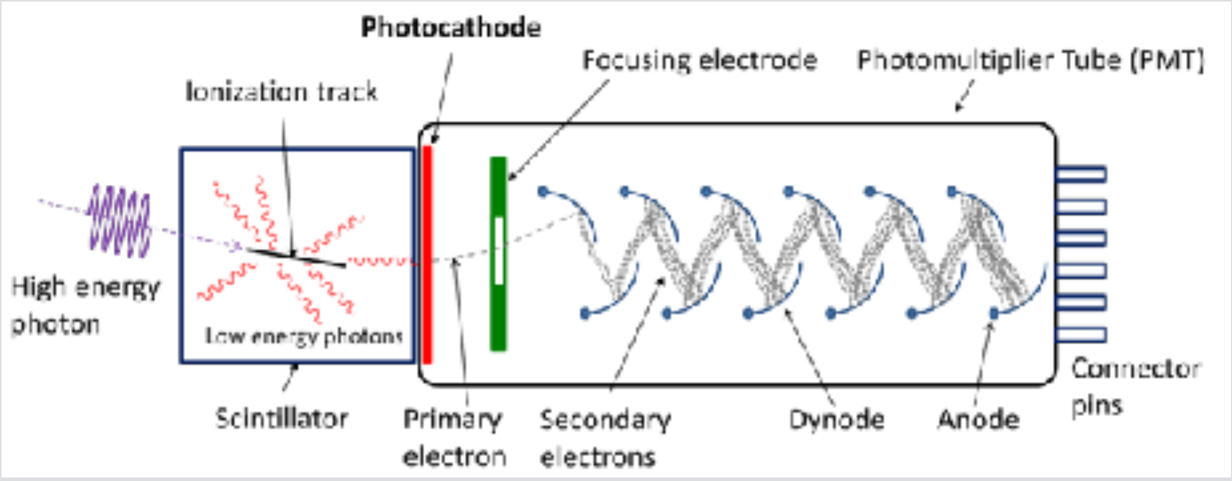




Water tank

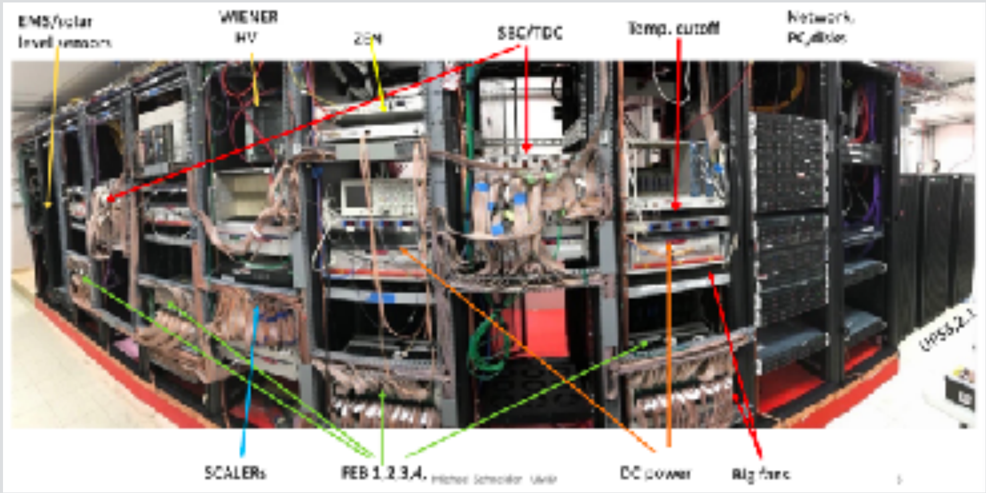
Cherenkov photons

PMT



Electrical signal

DAQ electronics



Time over threshold

Gamma-Ray Astronomy with HAWC

Cosmic accelerator

Gamma-ray photons

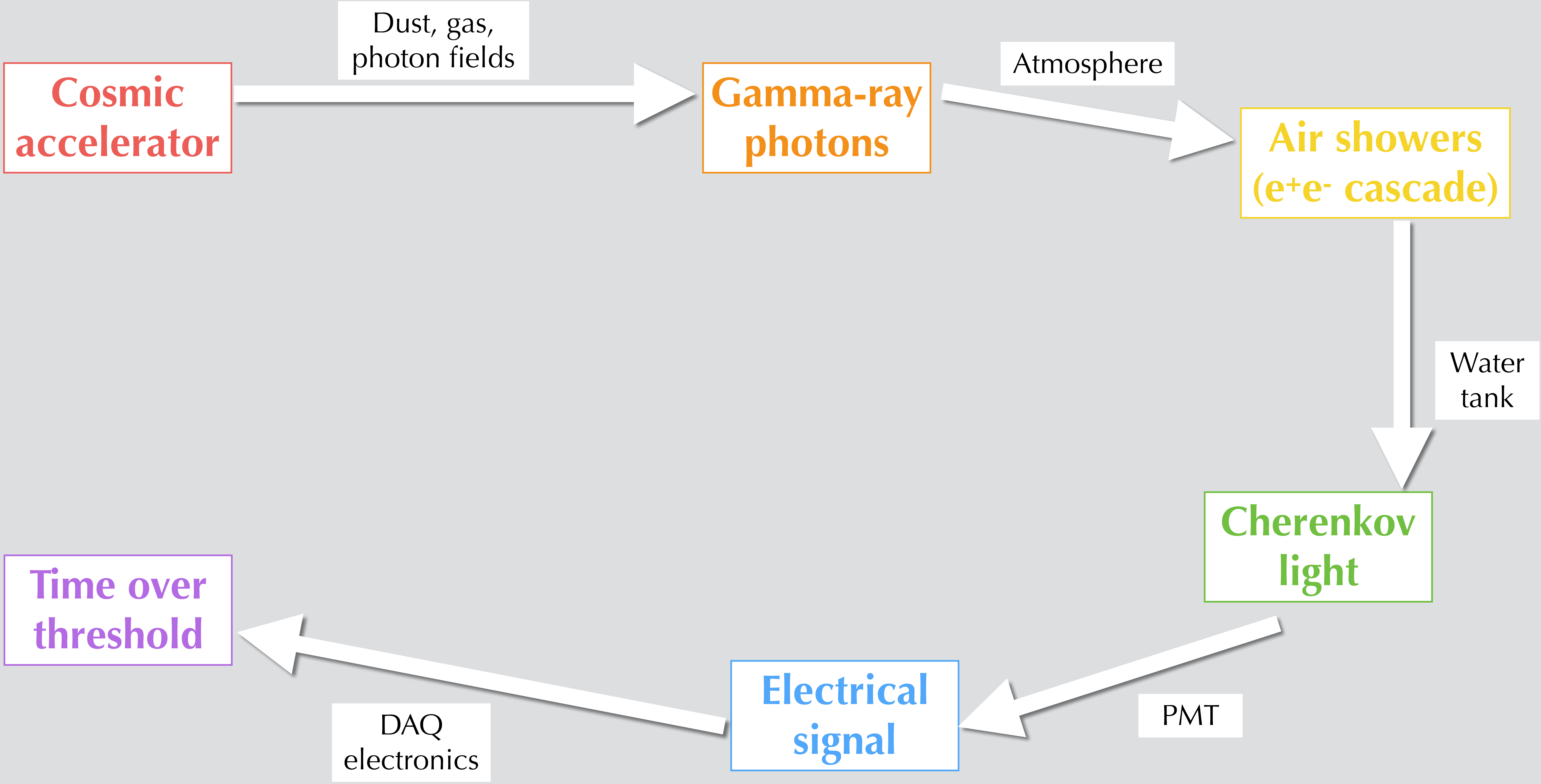
Air showers (e^+e^- cascade)

Cherenkov light

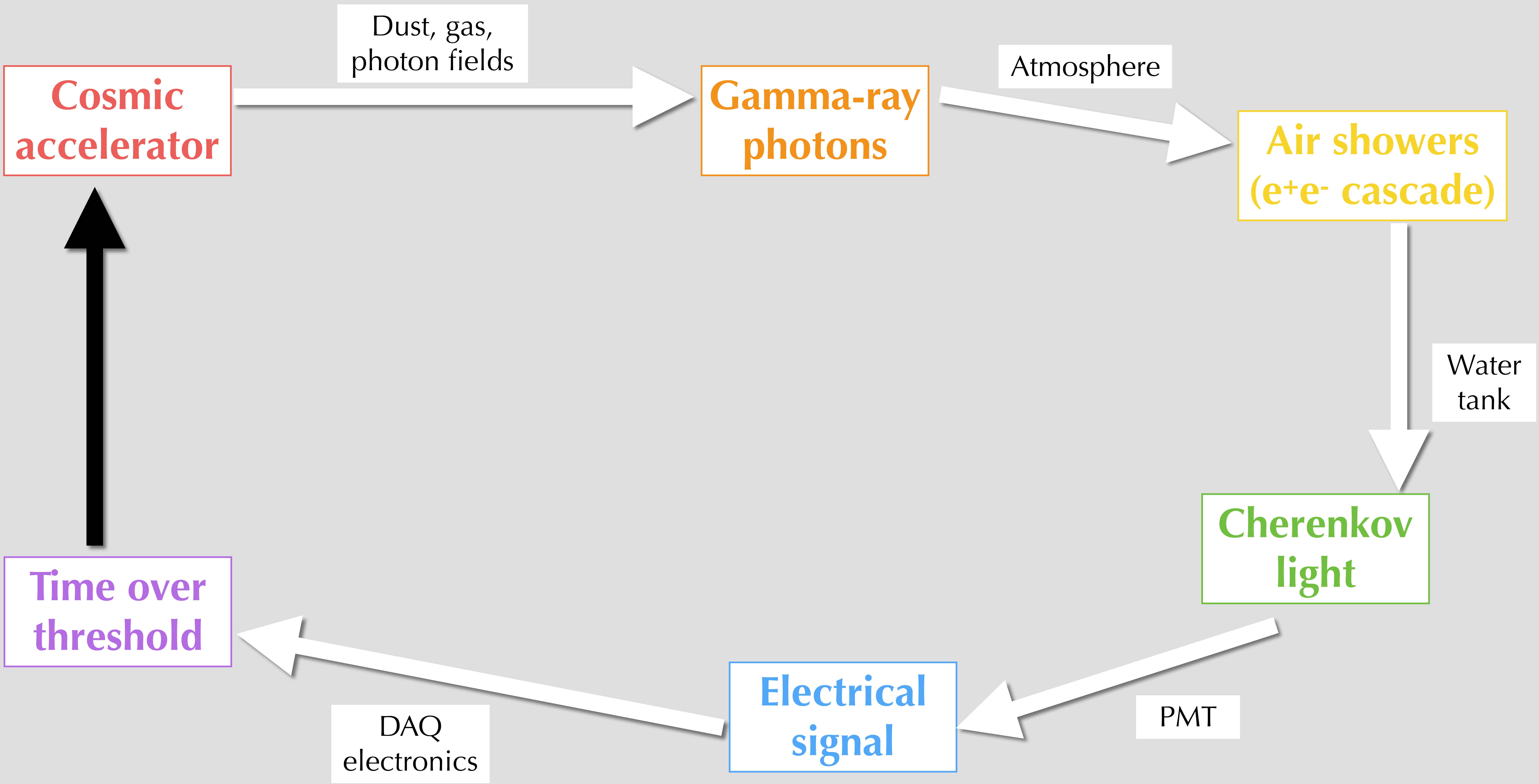
Electrical signal

Time over threshold

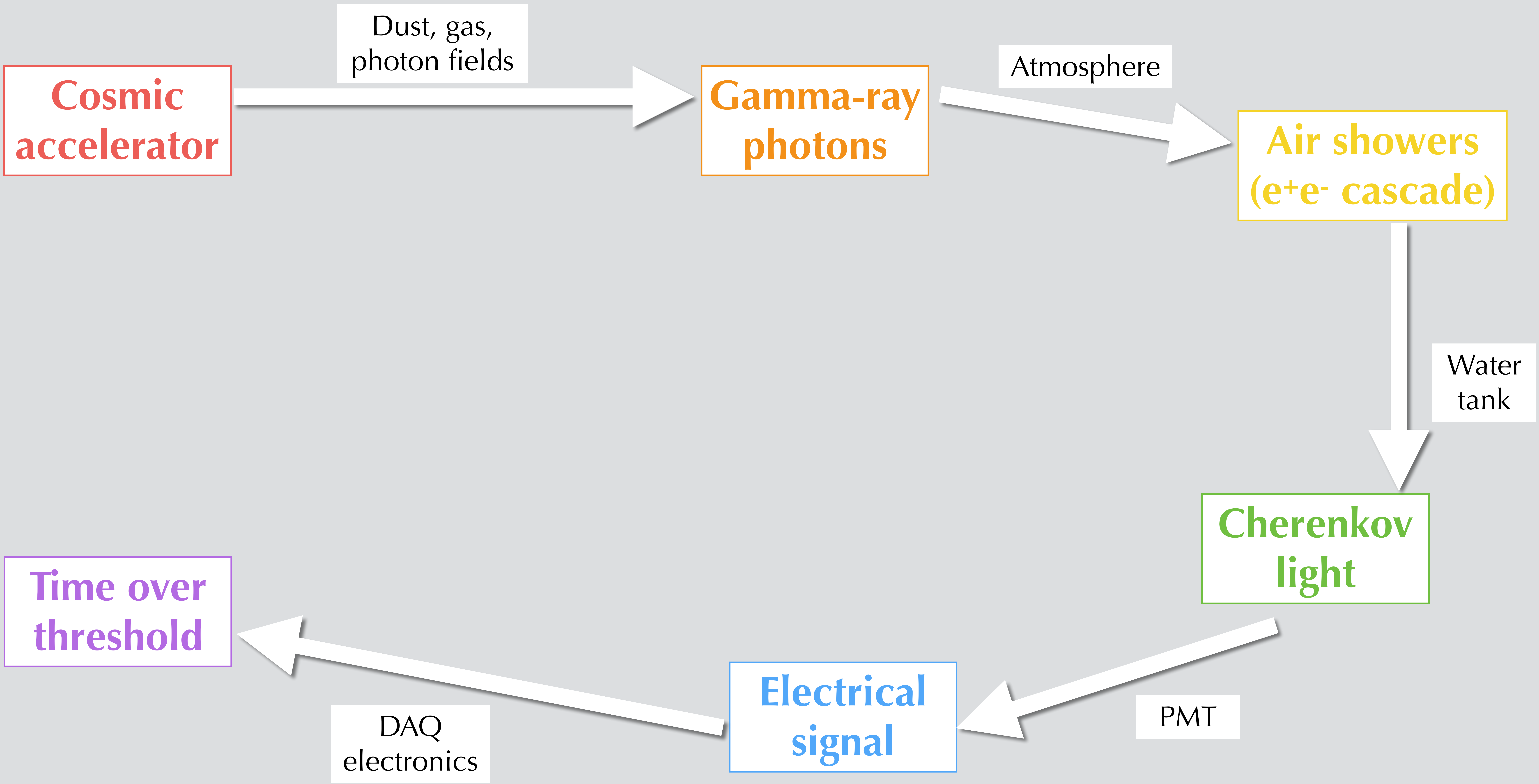
Gamma-Ray Astronomy with HAWC



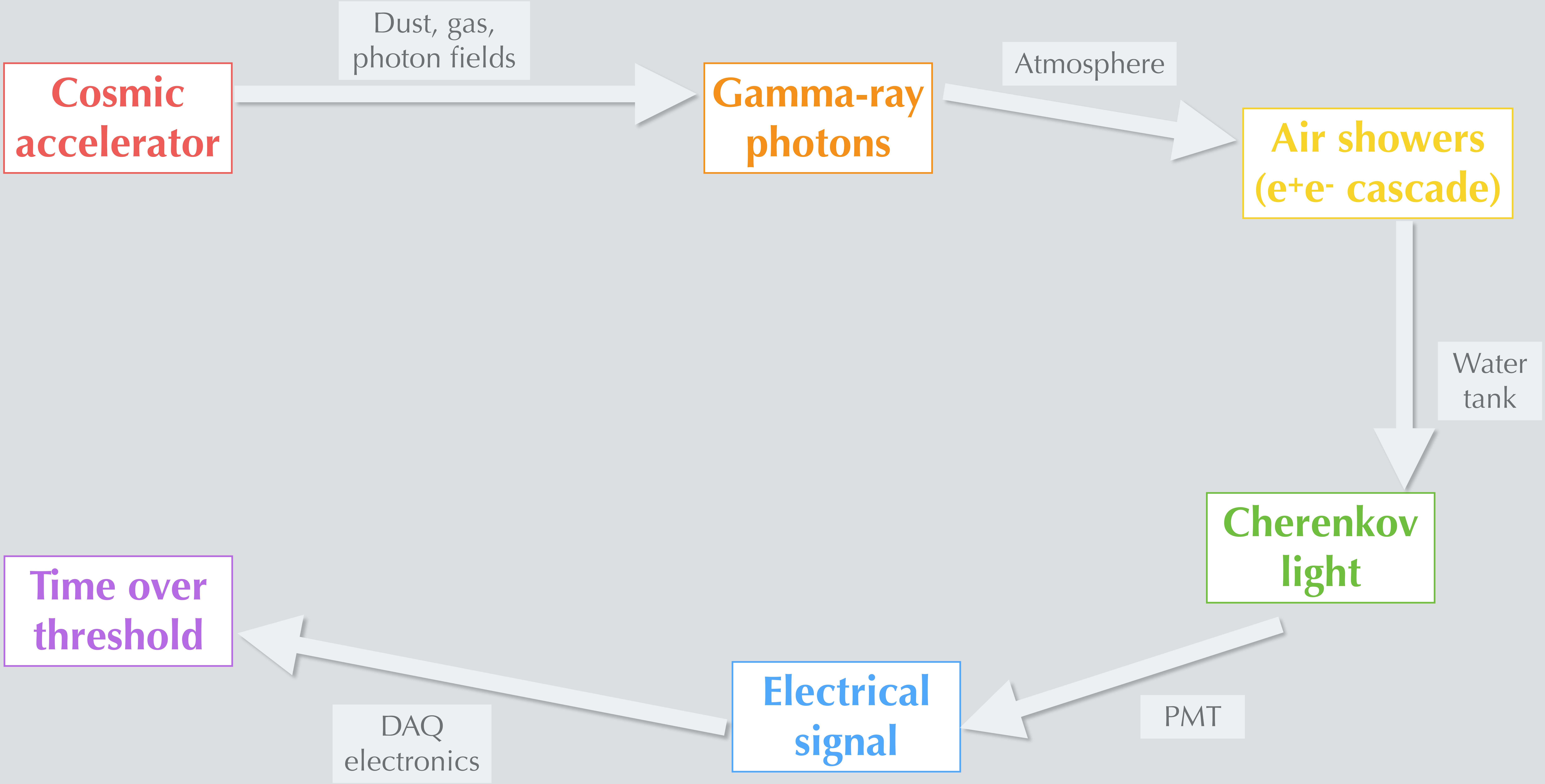
Gamma-Ray Astronomy with HAWC



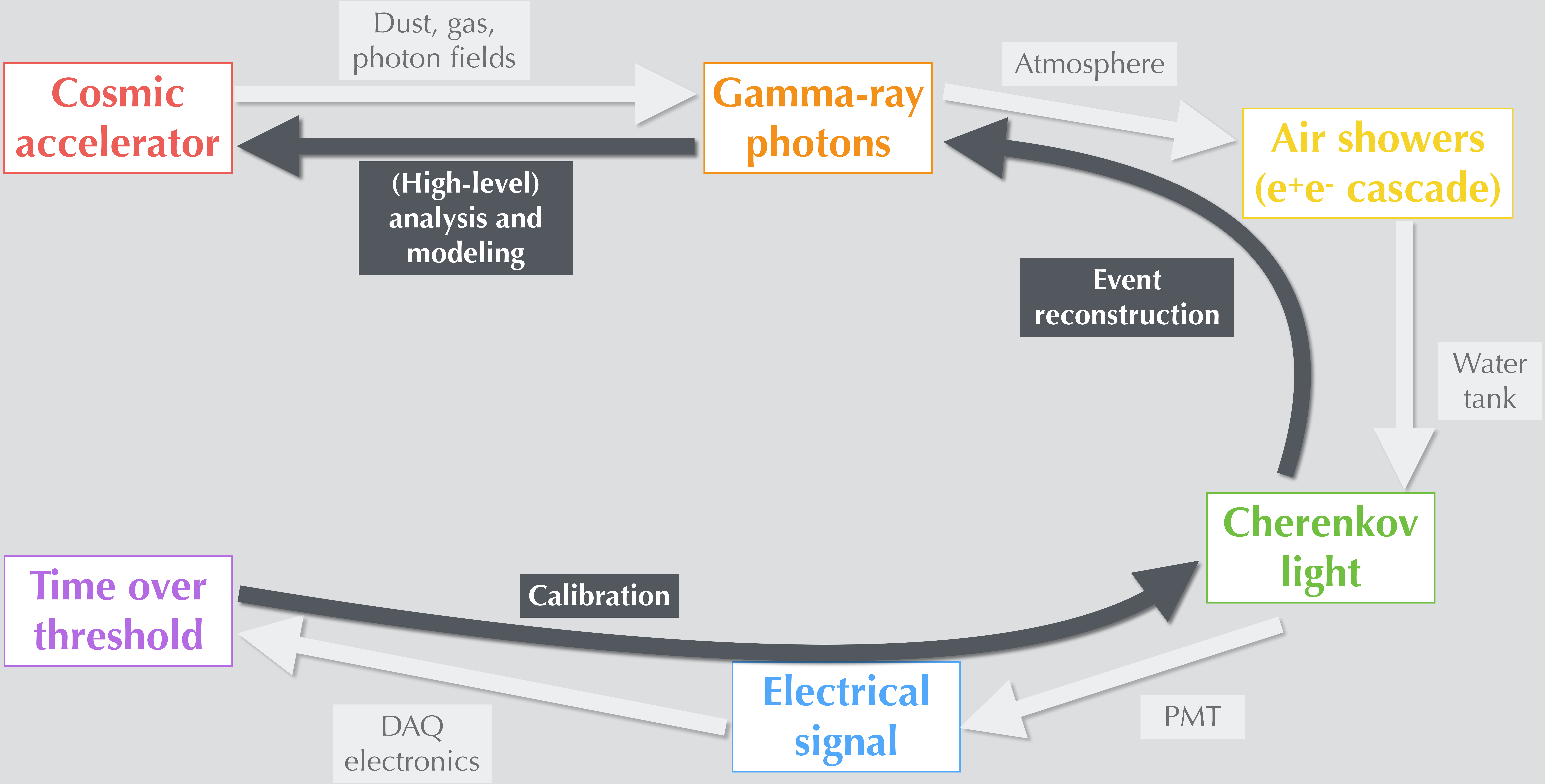
Gamma-Ray Astronomy with HAWC



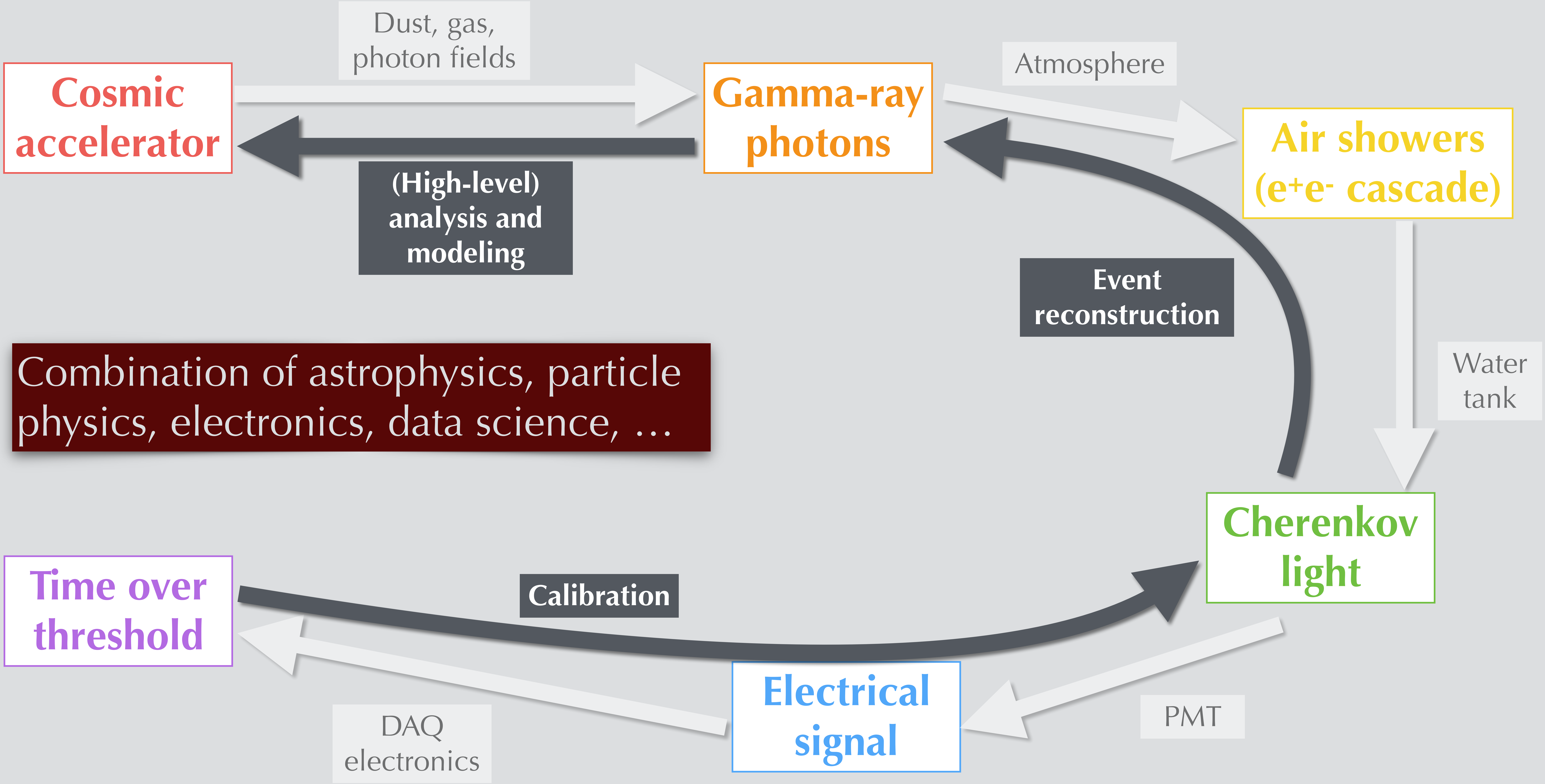
Gamma-Ray Astronomy with HAWC



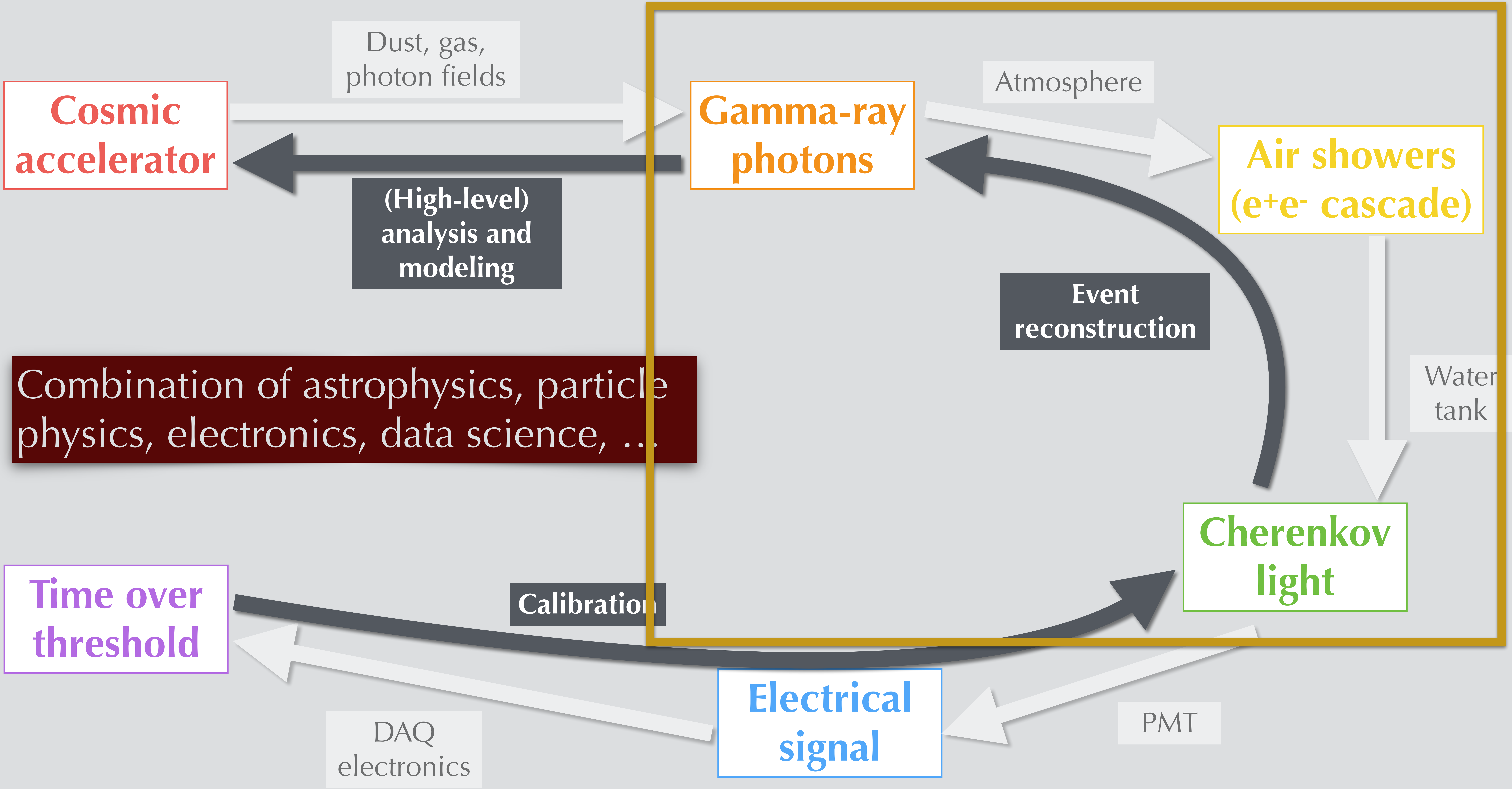
Gamma-Ray Astronomy with HAWC



Gamma-Ray Astronomy with HAWC

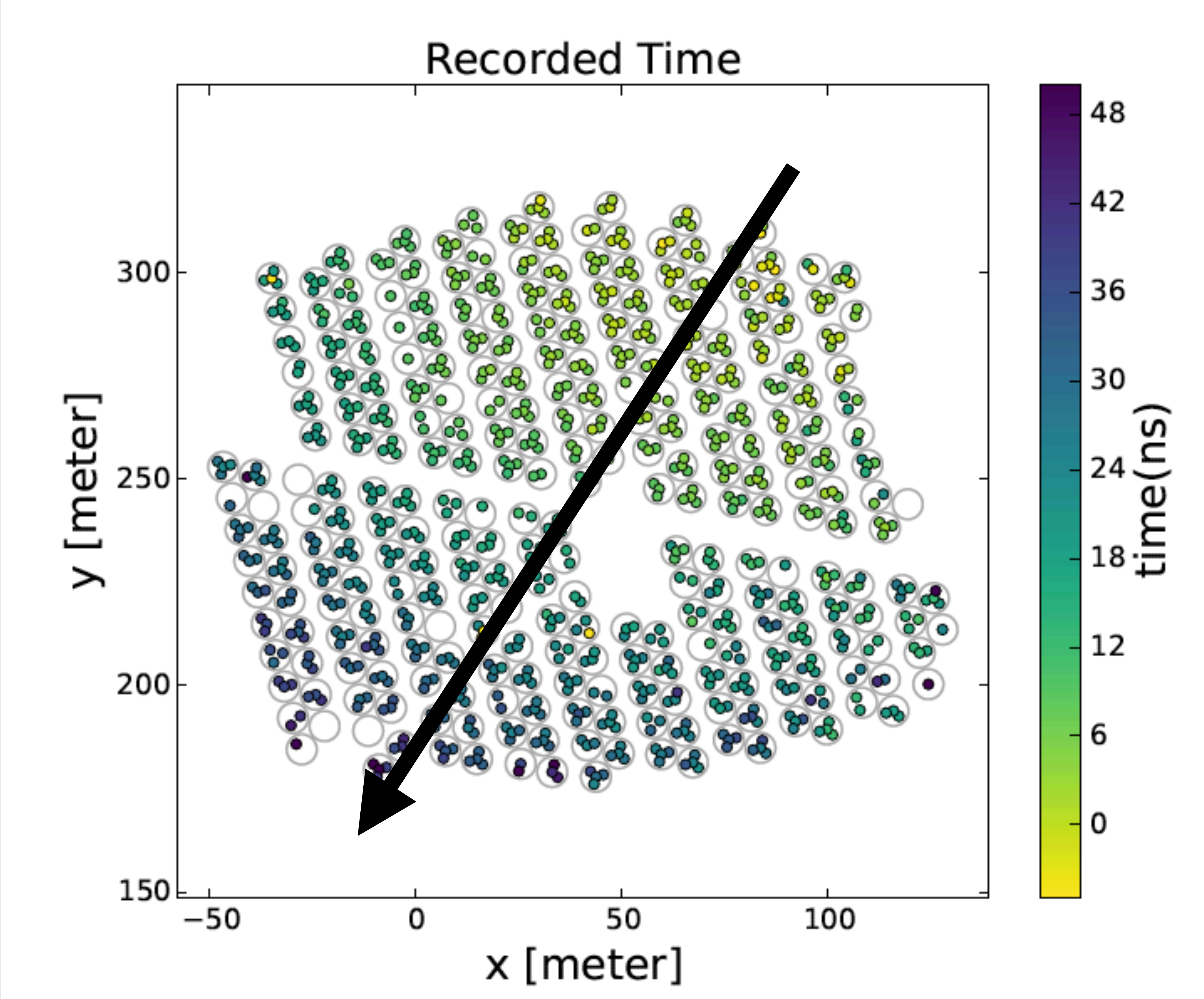


Gamma-Ray Astronomy with HAWC

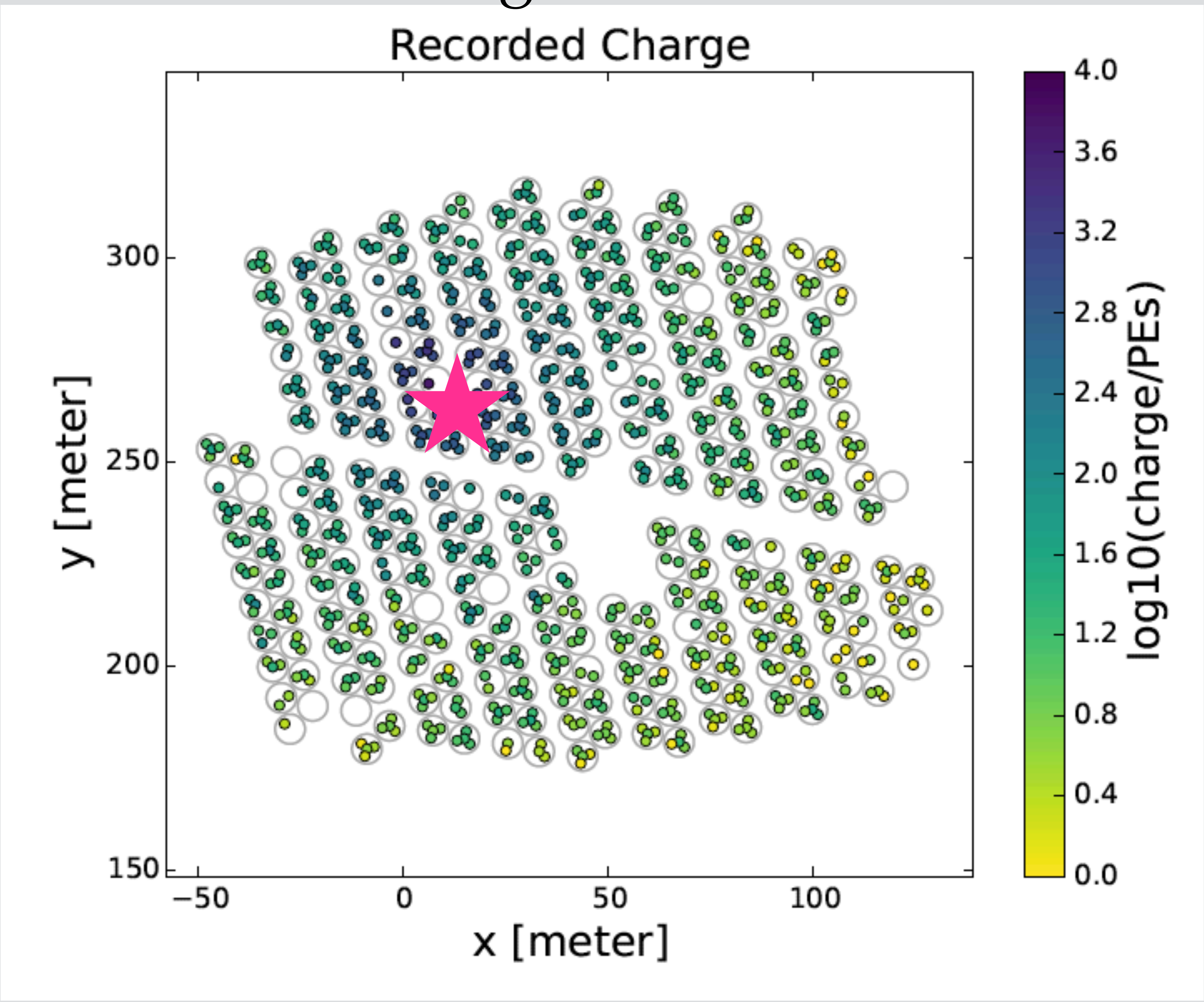


Event Reconstruction

Incident Direction
(Time Gradient)



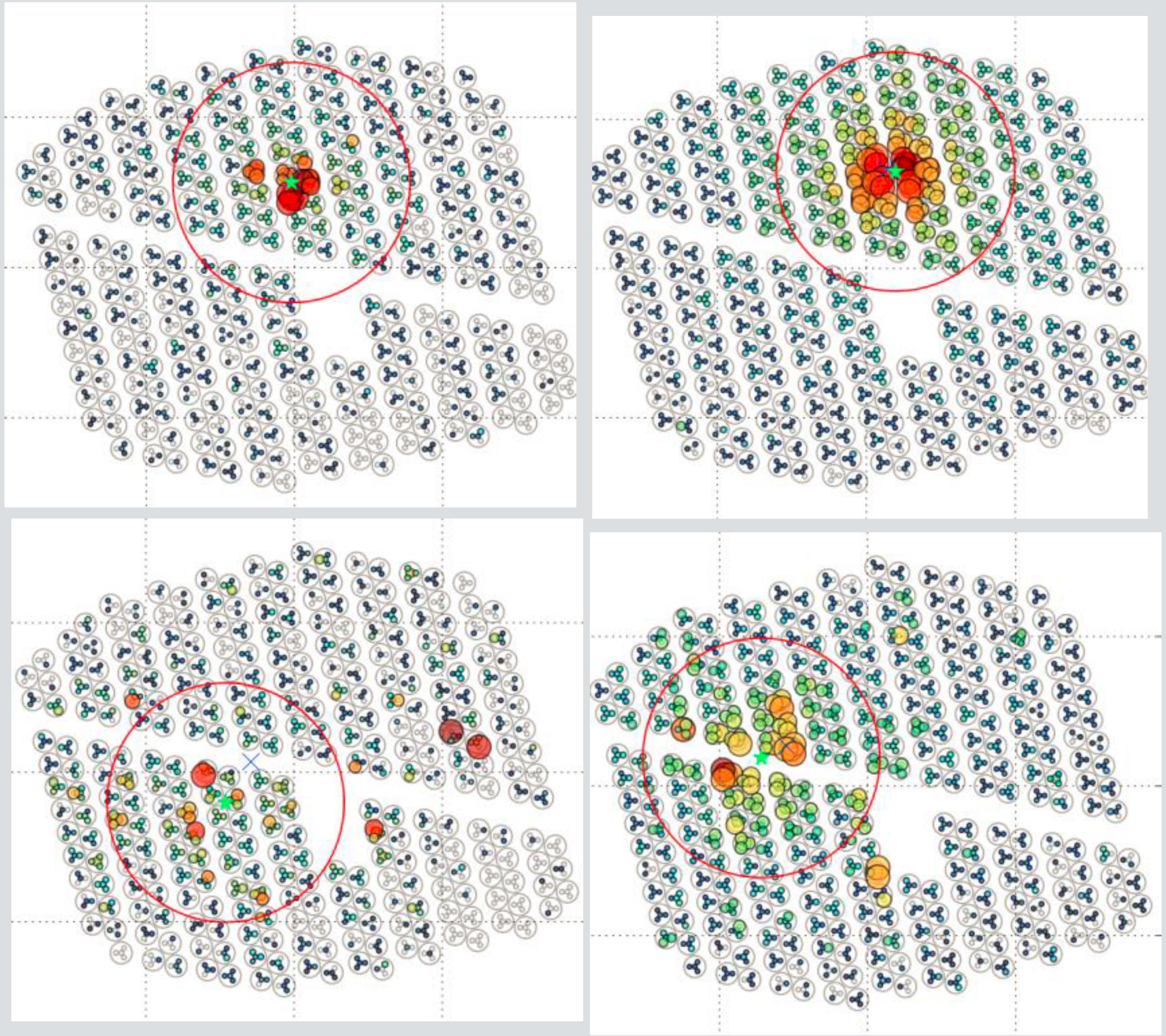
Core Location
(Light level)



Gamma/Hadron Separation

Gamma-ray events

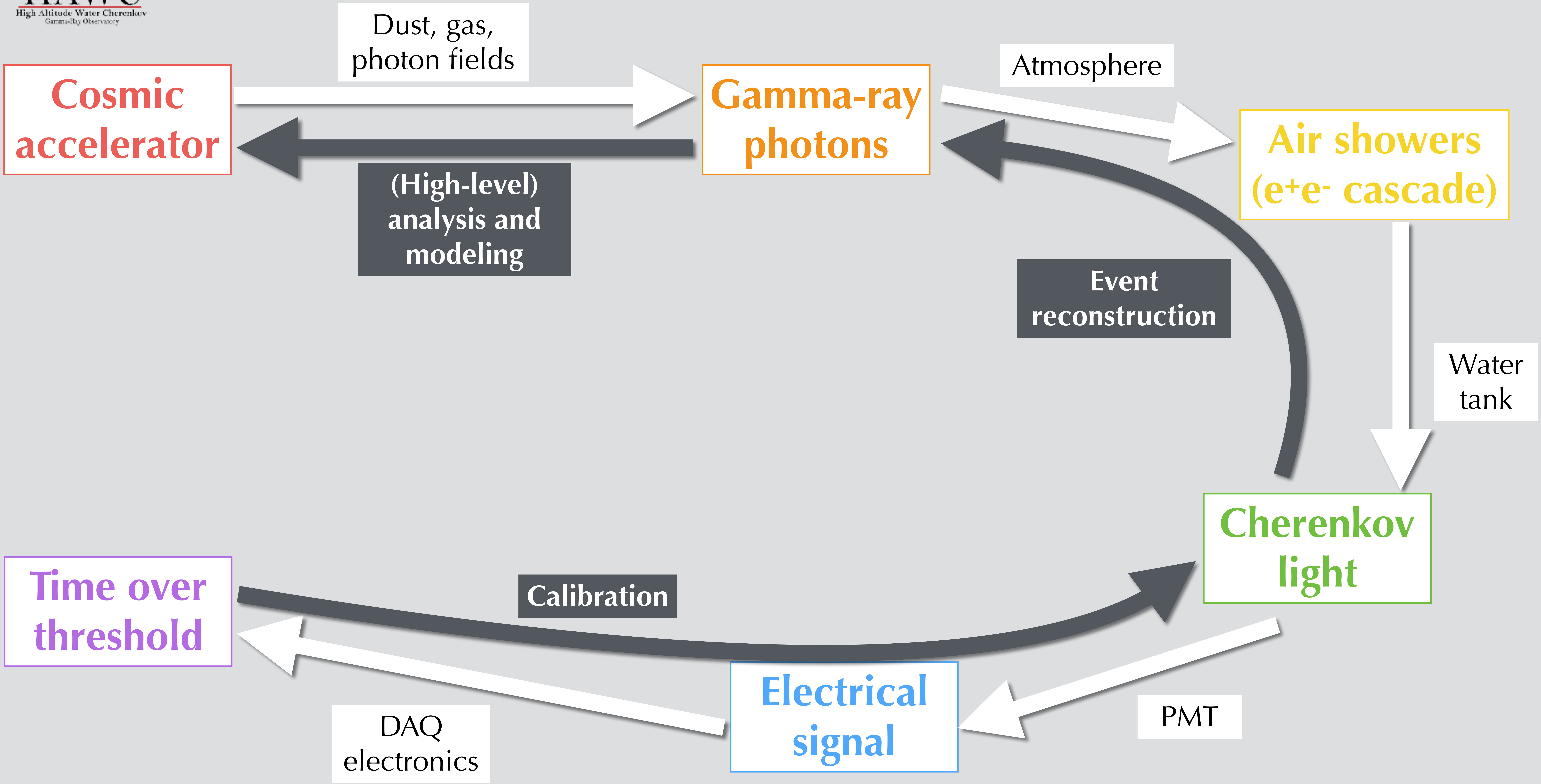
Cosmic-ray events



Axial symmetry

Asymmetric, high charge hits far from core

Gamma-Ray Astronomy with HAWC



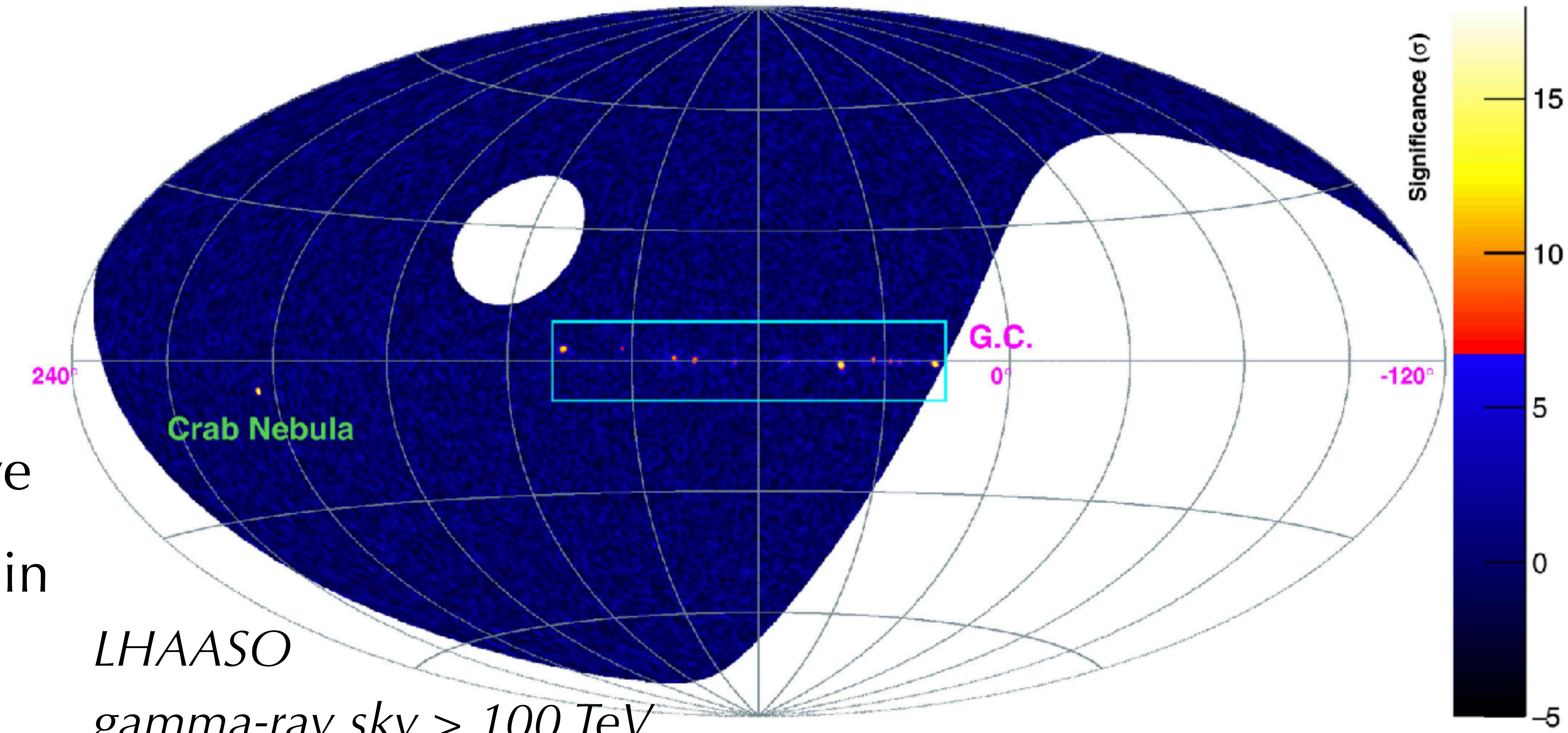
Gamma-Ray Astronomy with HAWC

Caveat

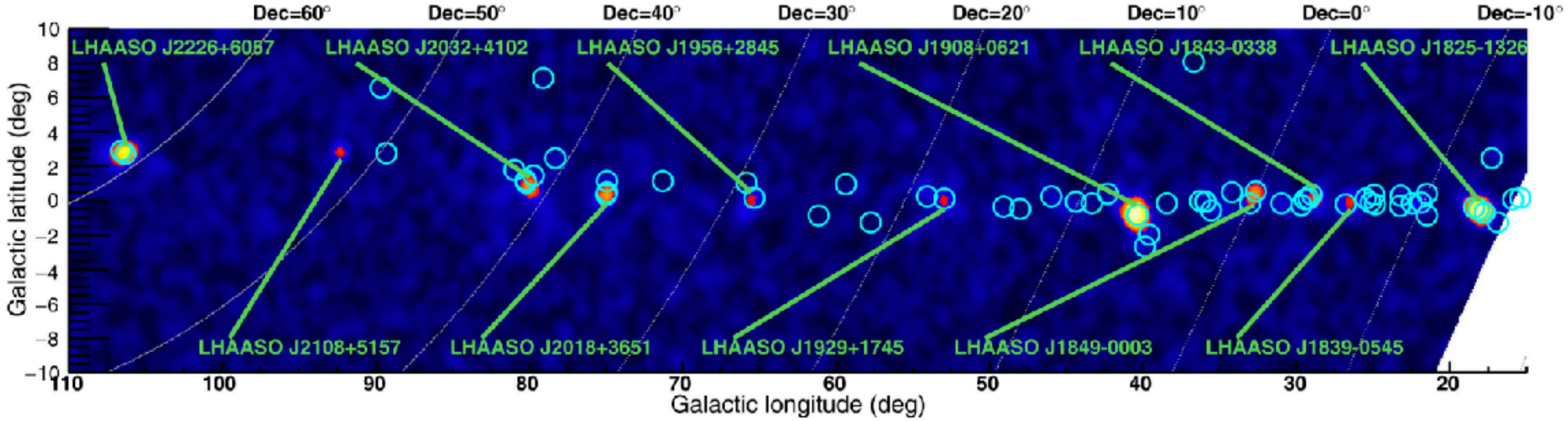
Myth: Emission > 100 TeV makes a PeVatron

- >10 known sources >100 TeV.
- Many show entirely leptonic emission (**leptonic PeVatrons**)
- Most UHE LHAASO sources have at least one **bright young pulsar** in the vicinity. (Correlation ≠ causation!)

(E. de Oña Wilhelmi et al 2022)



LHAASO
gamma-ray sky > 100 TeV



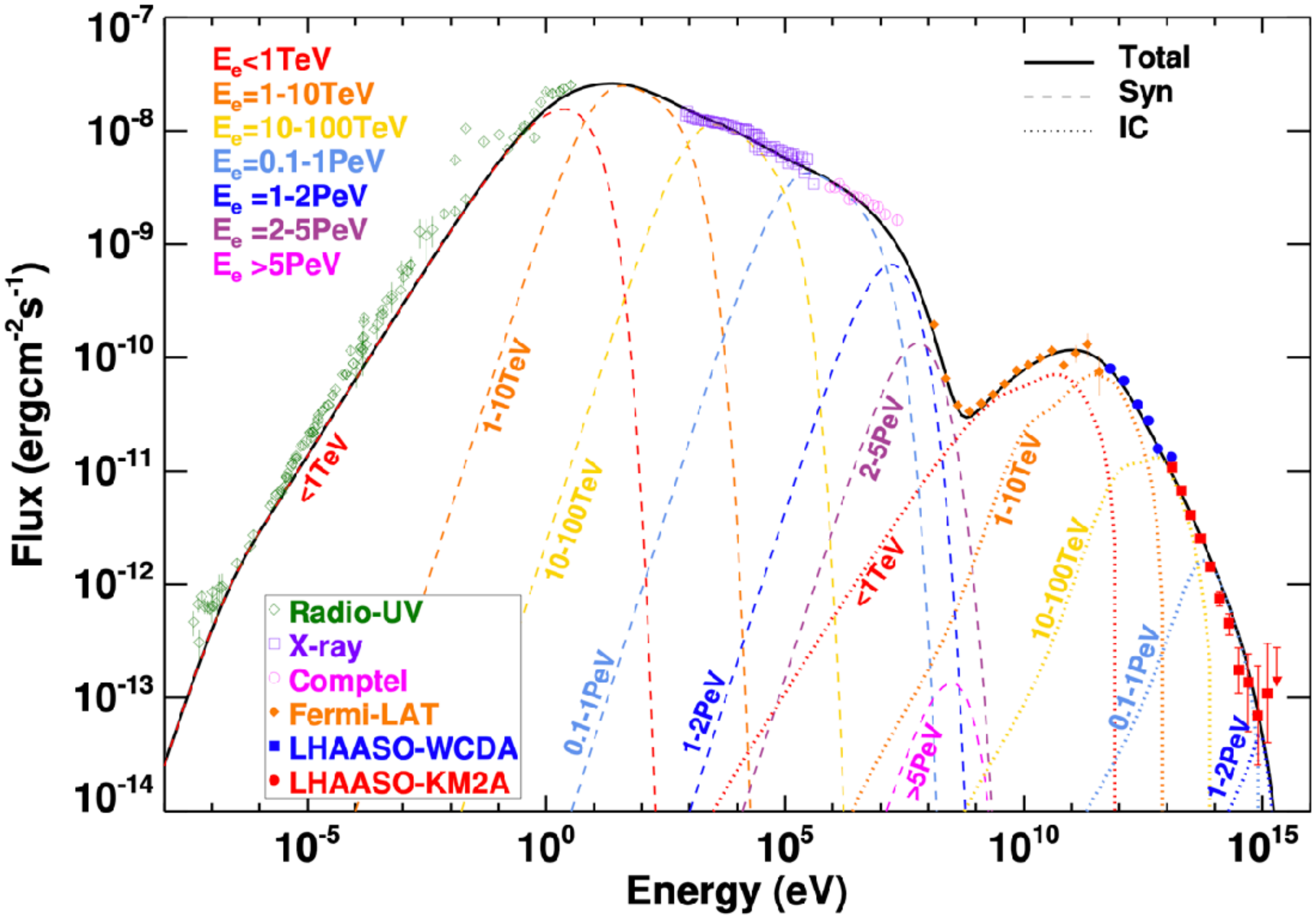
LHAASO 2021: https://www.nature.com/articles/s41586-021-03498-z

Myth: Emission > 100 TeV makes a PeVatron

- >10 known sources >100 TeV.
- Many show entirely leptonic emission (**leptonic PeVatrons**)
- Most UHE LHAASO sources have at least one **bright young pulsar** in the vicinity. (Correlation ≠ causation!)

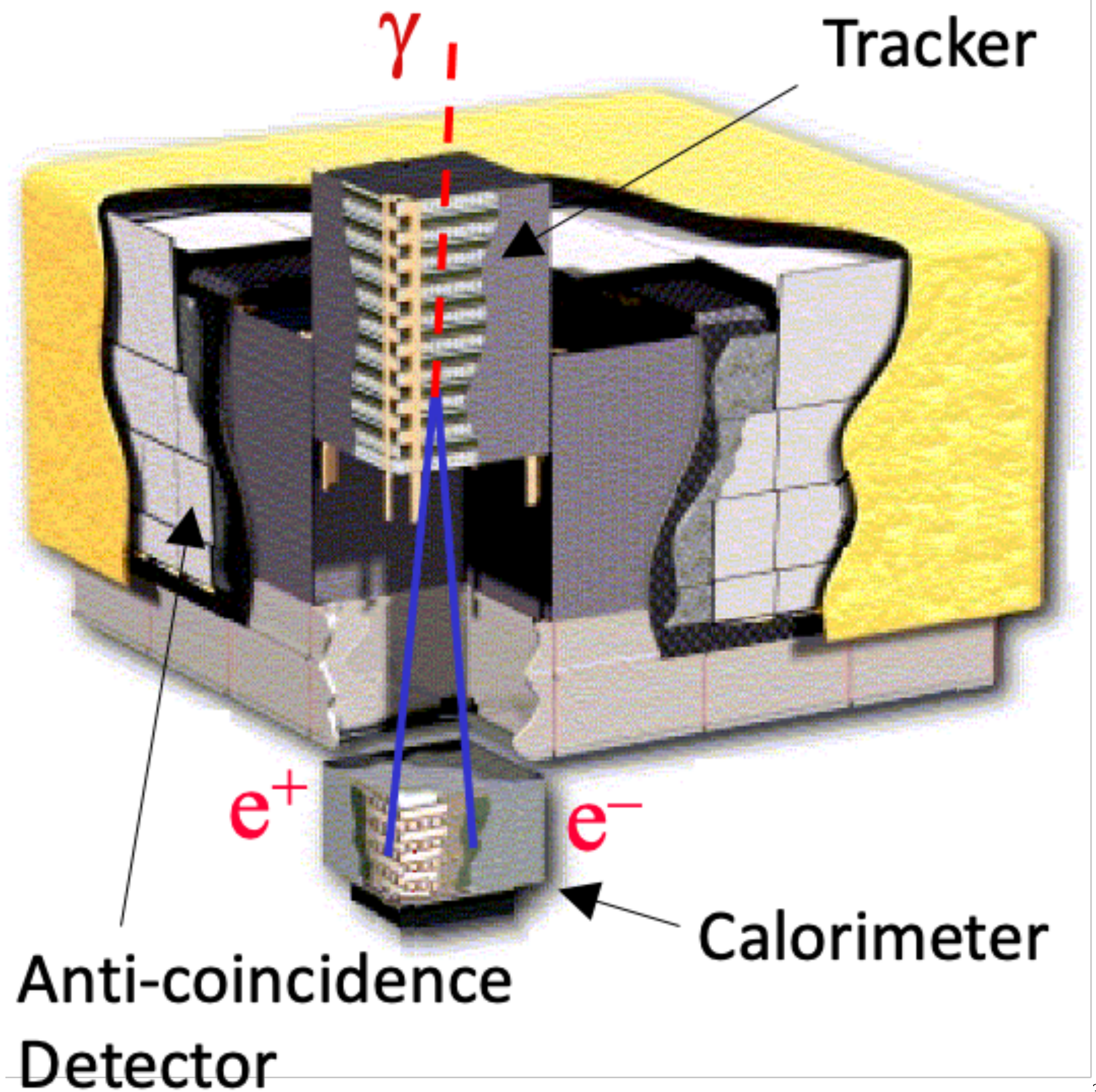
  (E. de Oña Wilhelmi et al 2022)
- **Need in-depth MW spectral and spatial studies.**
- Example: Crab pulsar wind nebula

Crab nebula energy spectrum and leptonic model



LHAASO 2021: https://www.science.org/doi/10.1126/science.abg5137

Gamma-ray Astronomy with Fermi-LAT



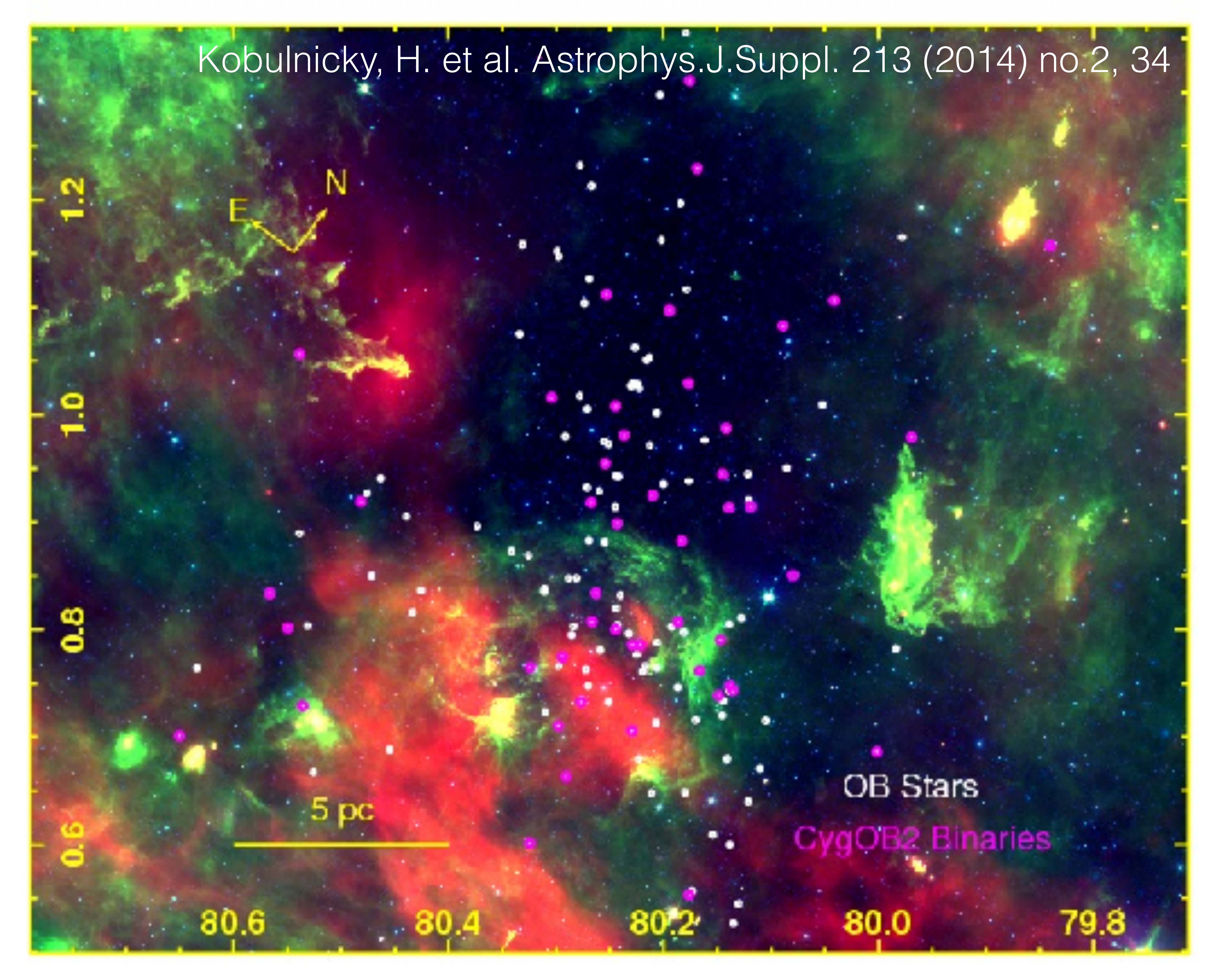
	LAT	HAWC
Size	$(1.8m)^2$ * 1.5m	$(150m)^2$
Sensor	Si strips	Water + PMTs
Direction reconstruction	Tracking	Timing
Energy range	30 MeV - 2 TeV	100 GeV - PeV
Angular resolution	~10˚ (100 MeV) ~0.05˚ (1 TeV)	~1˚ (1 TeV) ~0.1˚ (100 TeV)

Image: https://www-glast.stanford.edu/instrument.html

Star-forming regions as PeVatrons?

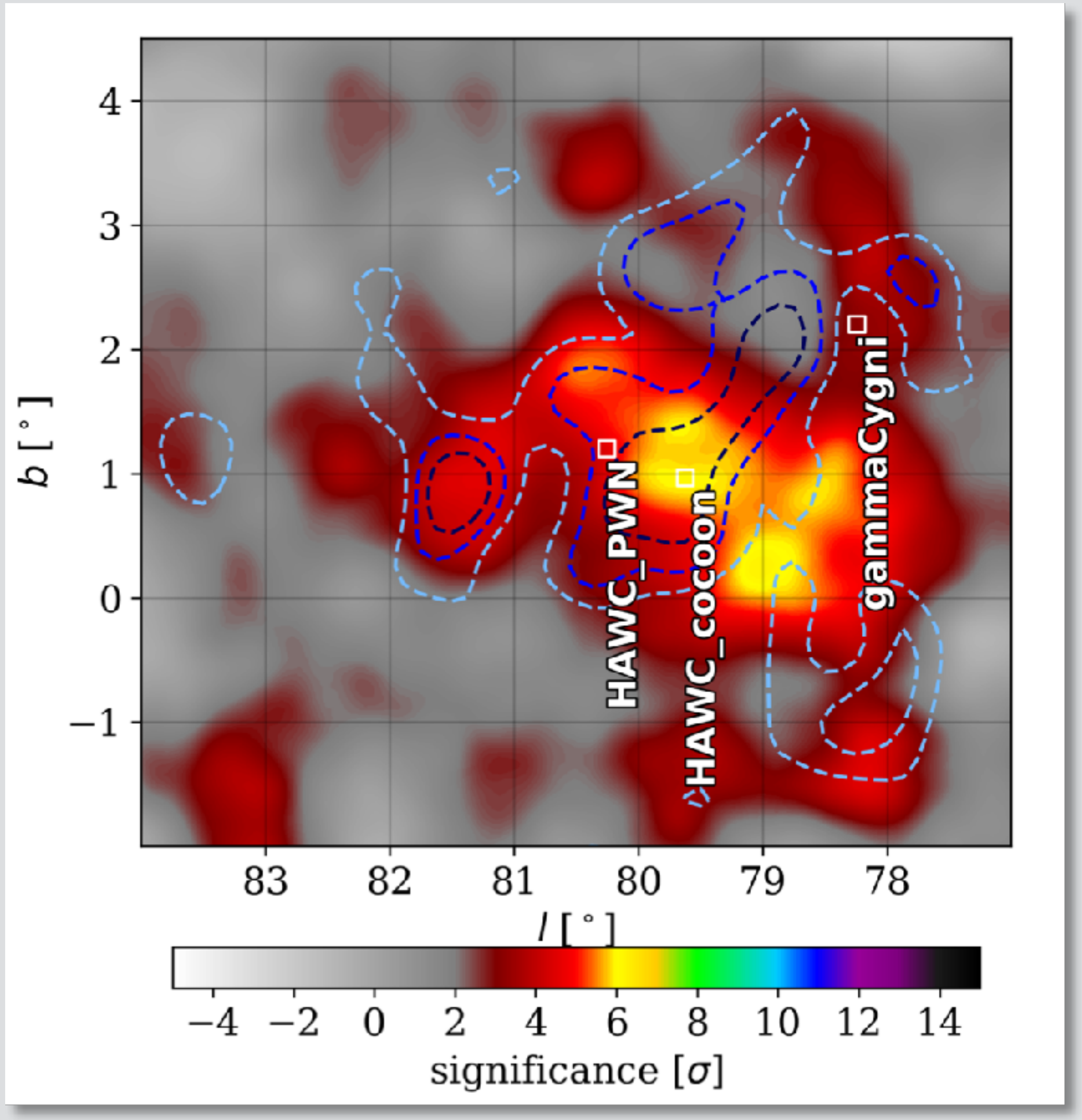
Cygnus OB2 Association

- OB association in the Cygnus region.
- 1400 pc from Earth.
- Few 10^6 years old.
- 50-100 O-type stars.
- ~50 binary systems.
- Large-scale (3°) GeV-TeV gamma-ray emission



Cygnus OB2 Association

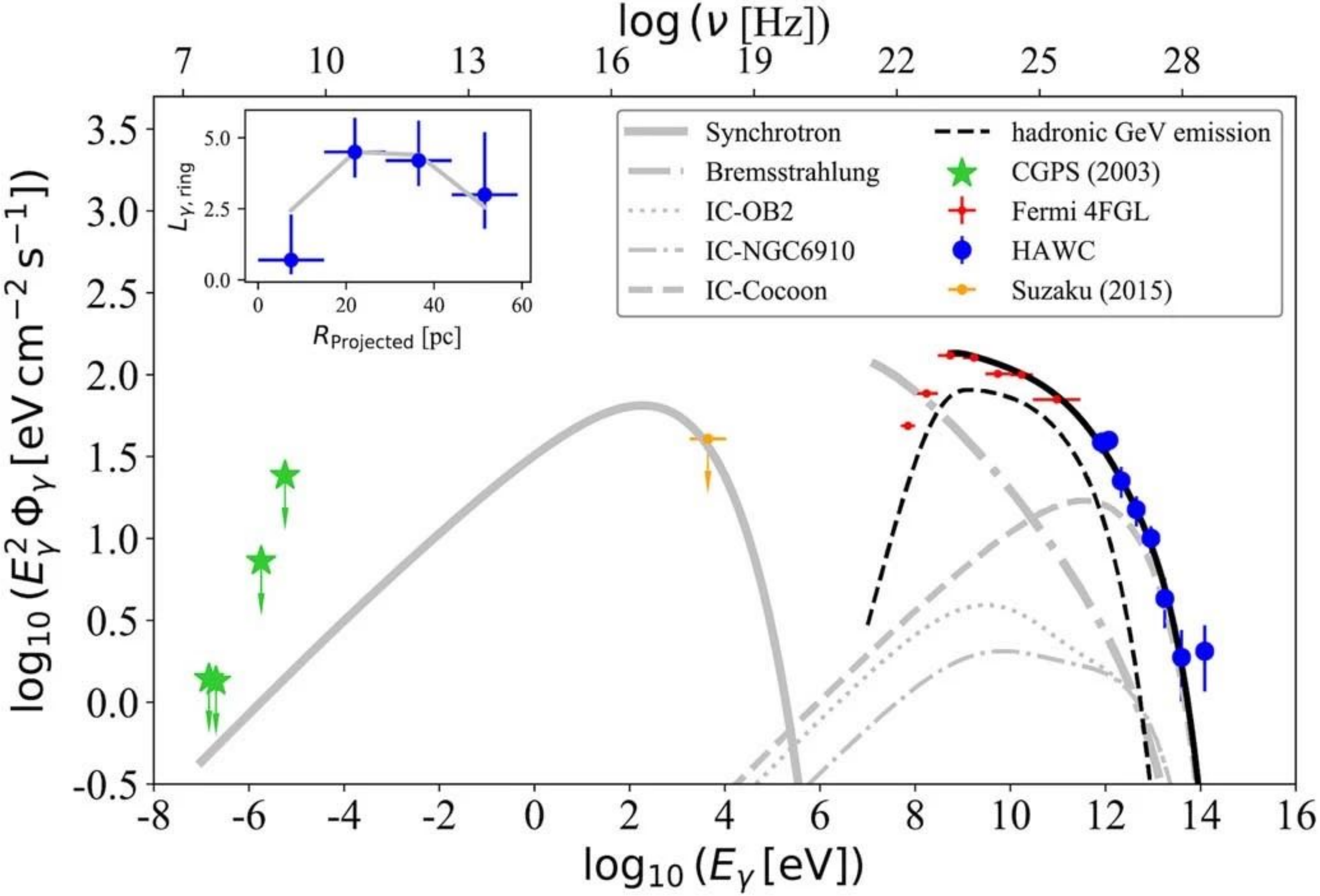
- OB association in the Cygnus region.
- 1400 pc from Earth.
- Few 10^6 years old.
- 50-100 O-type stars.
- ~50 binary systems.
- Large-scale (3°) GeV-TeV gamma-ray emission



HAWC (incl. HF) 2021: https://www.nature.com/articles/s41550-021-01318-y

>100 TeV Protons in Cygnus OB2 association

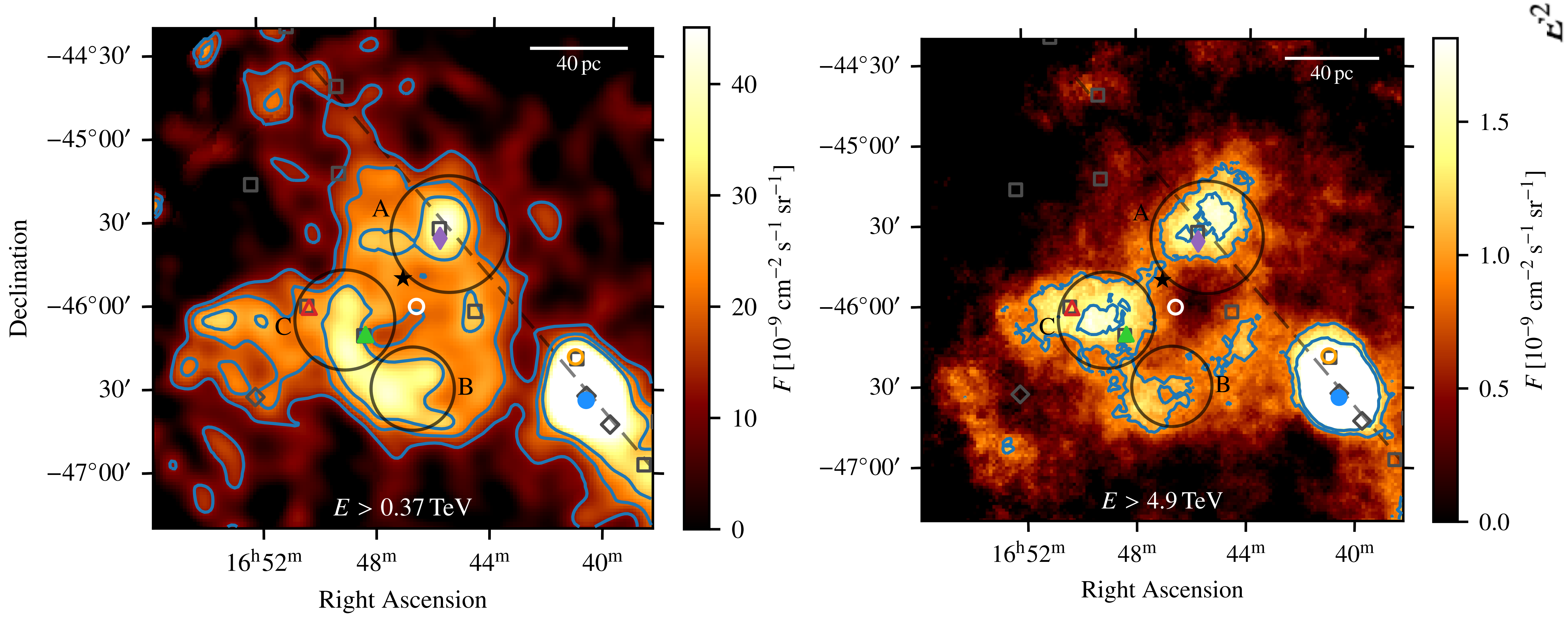
- **Protons >100 TeV** explain gamma-ray emission**.**
- X-ray/radio observations disfavor leptonic origin.
- Continuous acceleration or "recent" starburst activity.
- **~1% of the kinetic energy in stellar winds** is converted to relativistic protons.

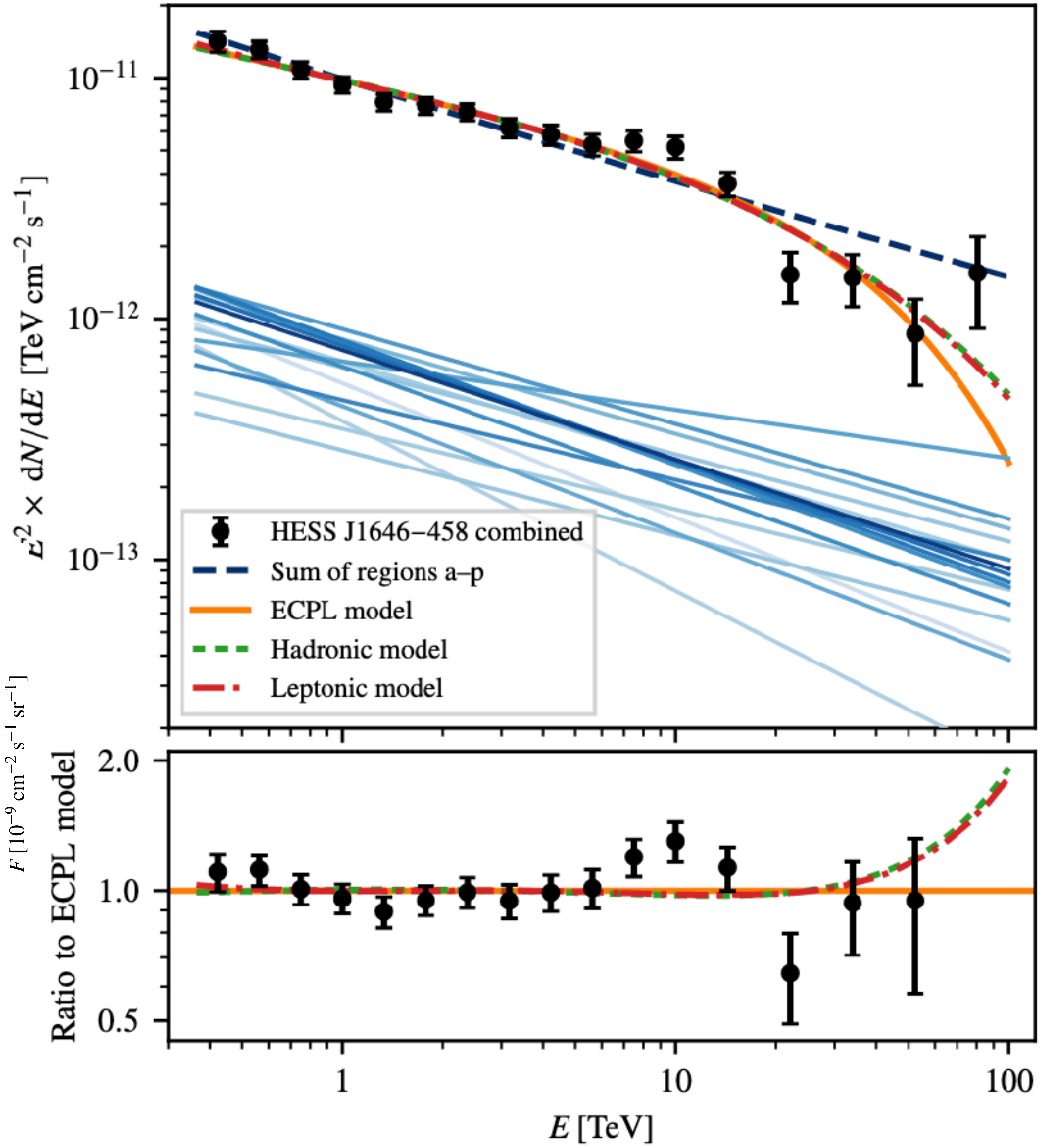


HAWC (incl. HF) 2021: https://www.nature.com/articles/s41550-021-01318-y

PeV Protons from Westerlund I?

- Young star-forming region with complex TeV morphology.
- Emission up to 100 TeV -> PeVatron candidate.
- Leptonic models not excluded by spectral analysis but disfavored by morphology.

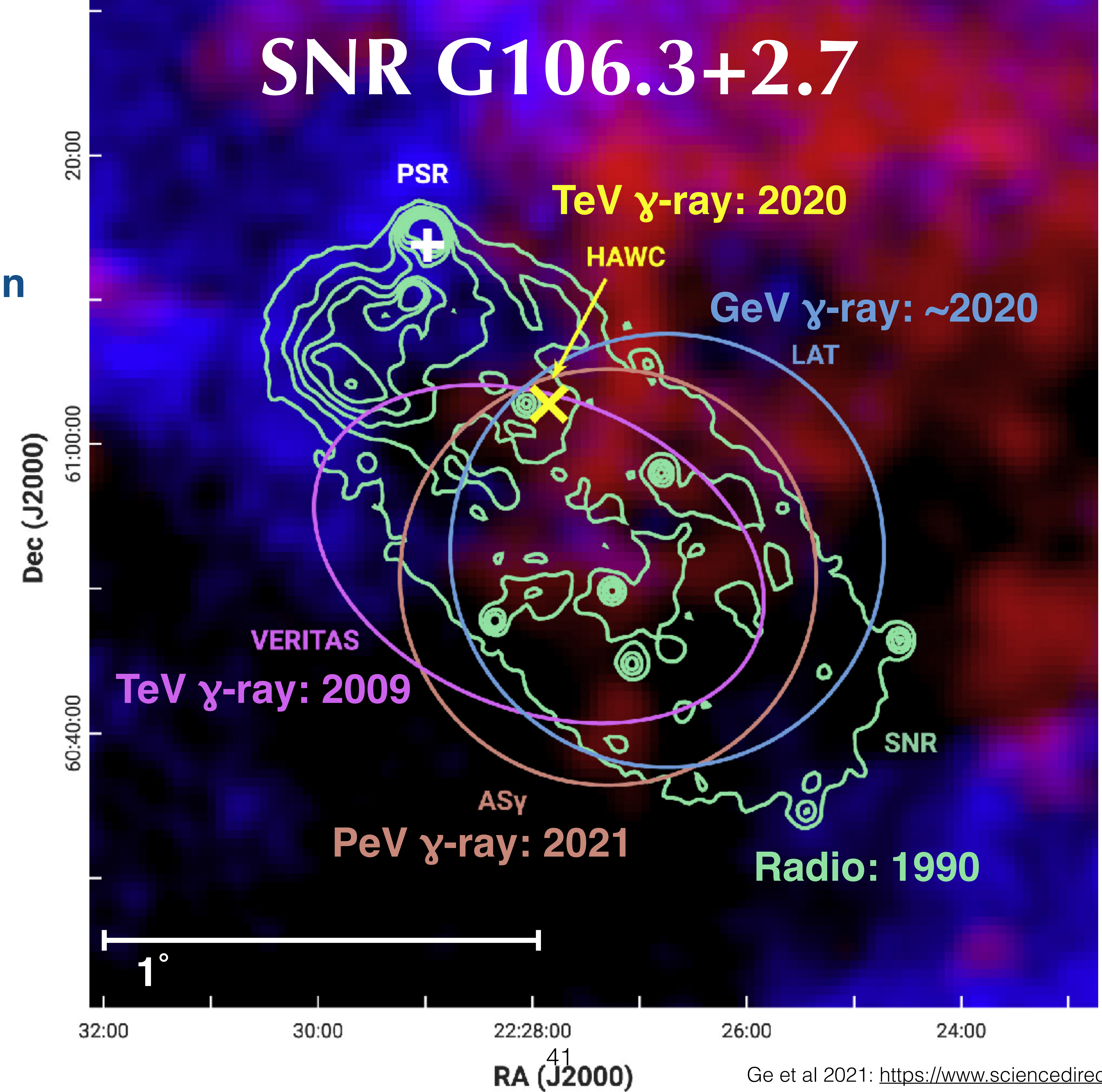




H.E.S.S. 2022: https://doi.org/10.1051/0004-6361/202244323

The case of SNR G106.3+2.7

Blue: Neutral atomic Hydrogen



Moon to scale

Red: Molecular Hydrogen

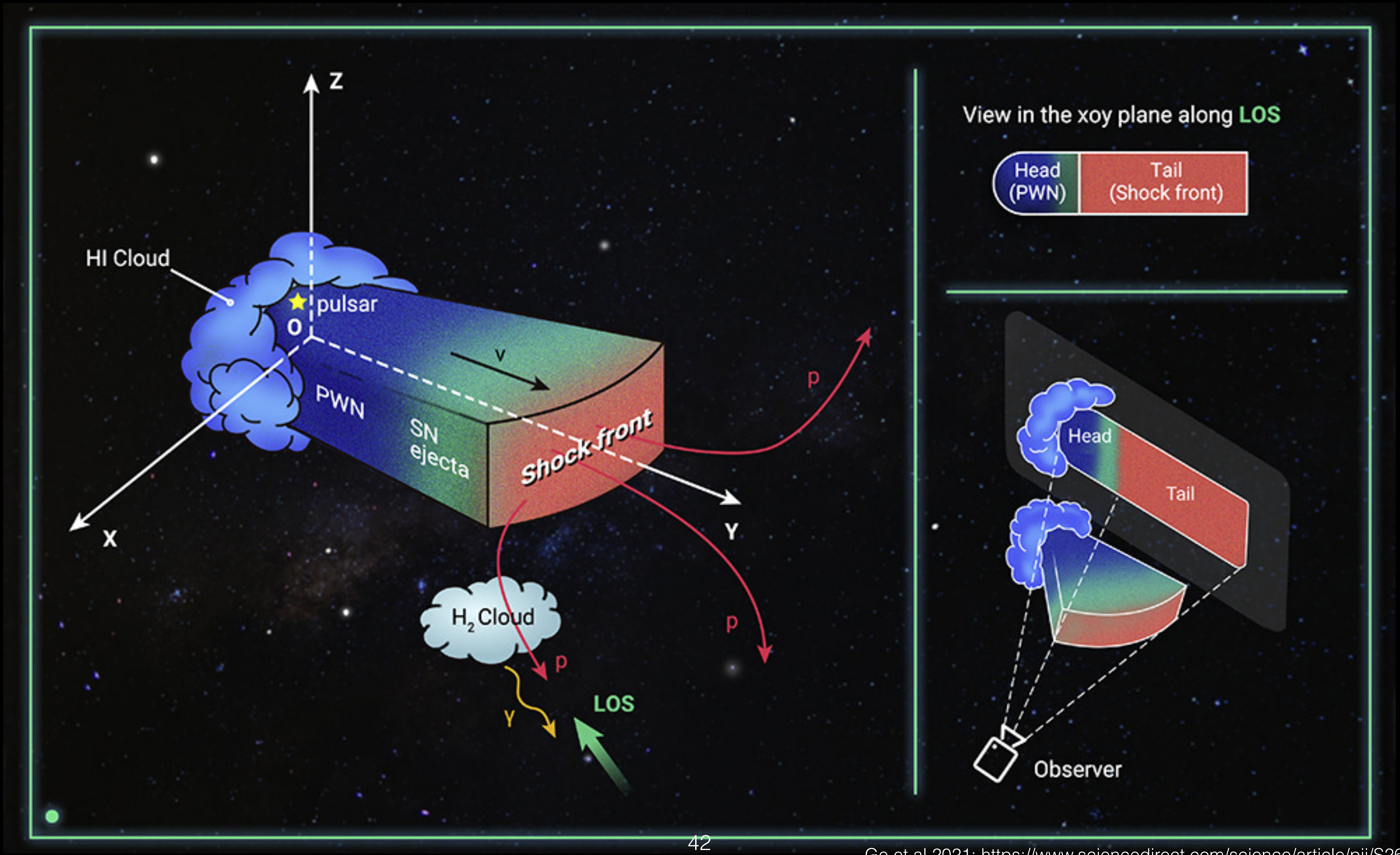
Age: ~10 000 yr (or younger)

Distance: 800 pc

Also seen by MAGIC and LHAASO

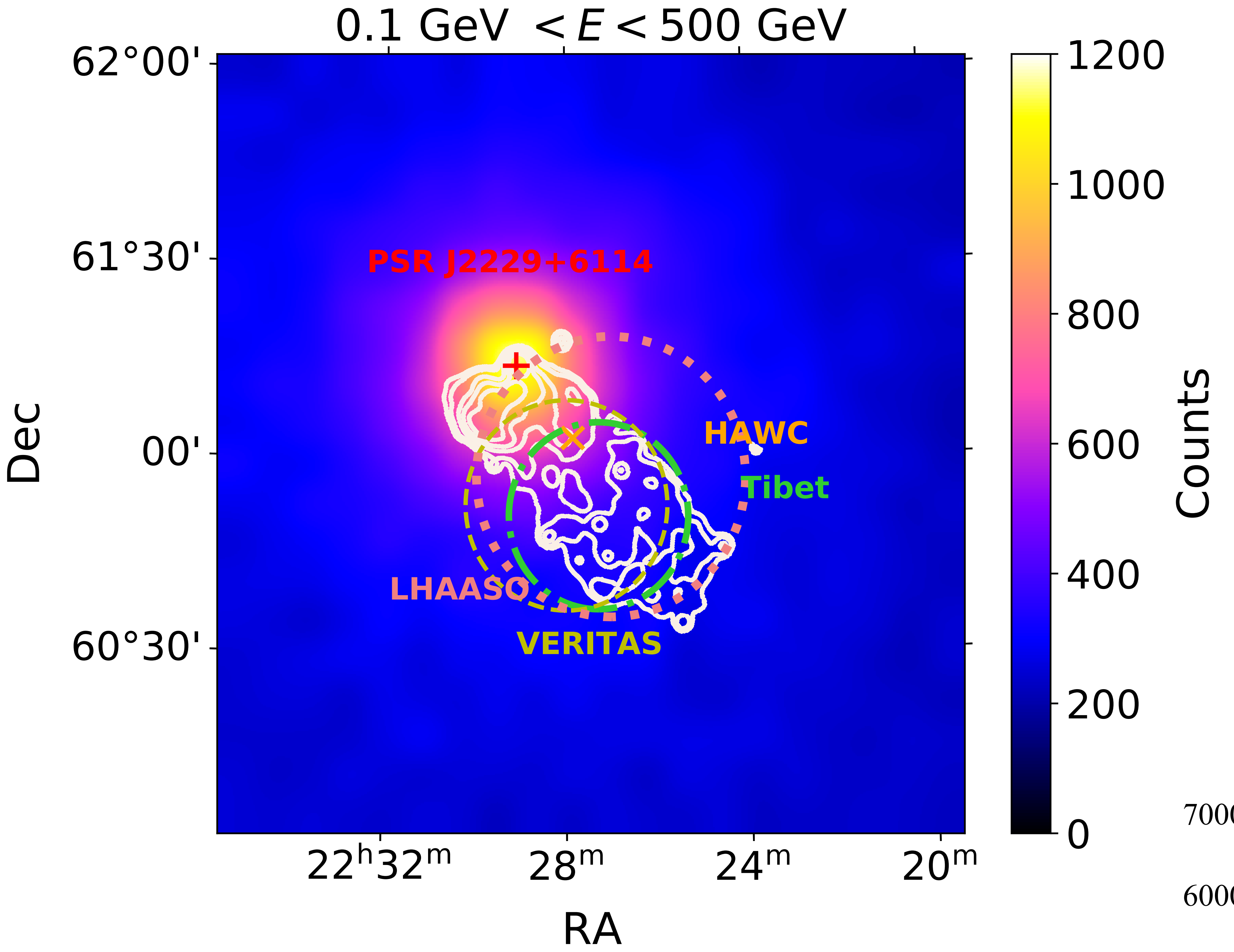
Ge et al 2021: https://www.sciencedirect.com/science/article/pii/S2666675821000436

SNR G106.3+2.7 schematic

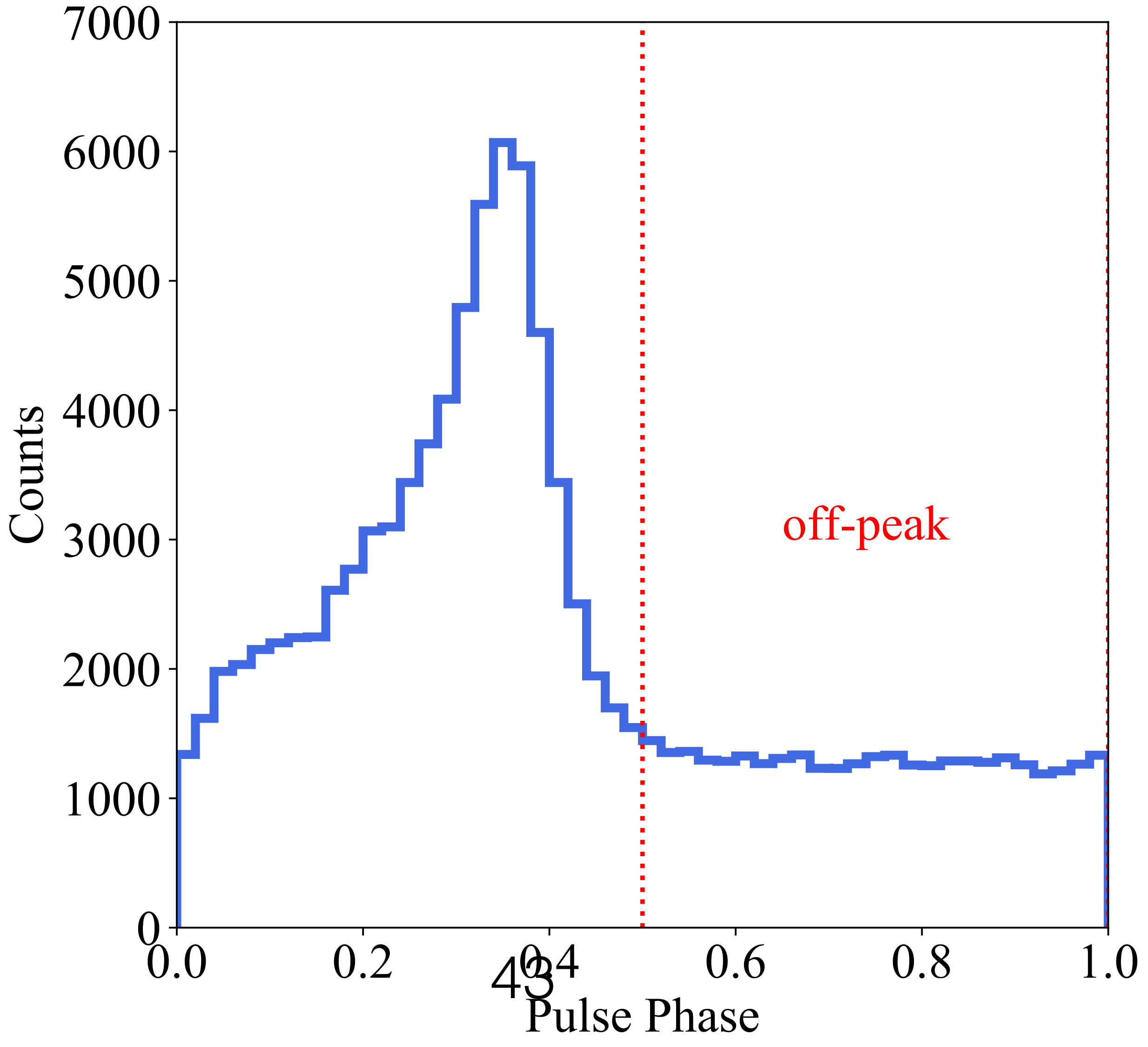


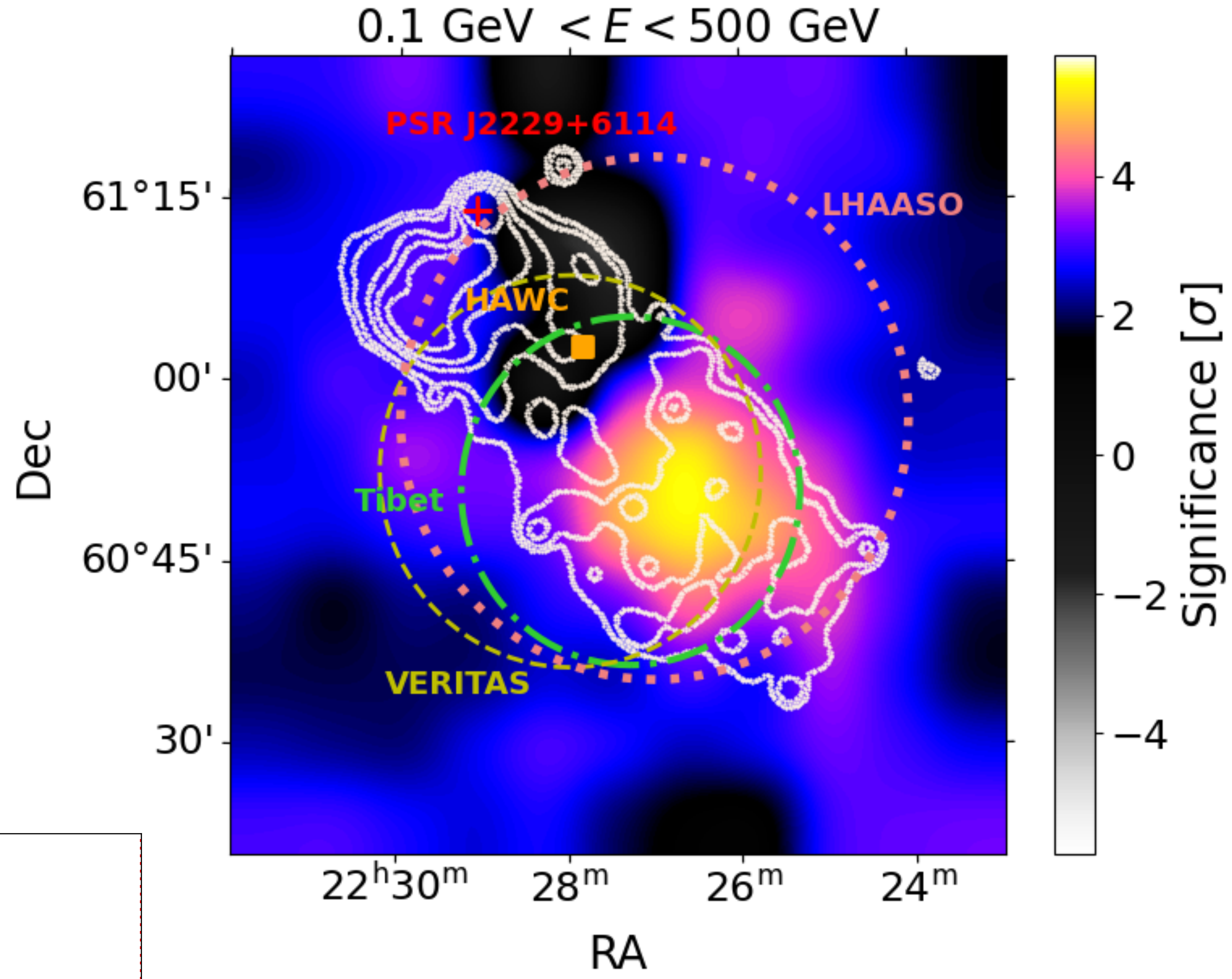
Ge et al 2021: https://www.sciencedirect.com/science/article/pii/S2666675821000436

Phased analysis of GeV data



Bright gamma-ray pulsar dominates the GeV band

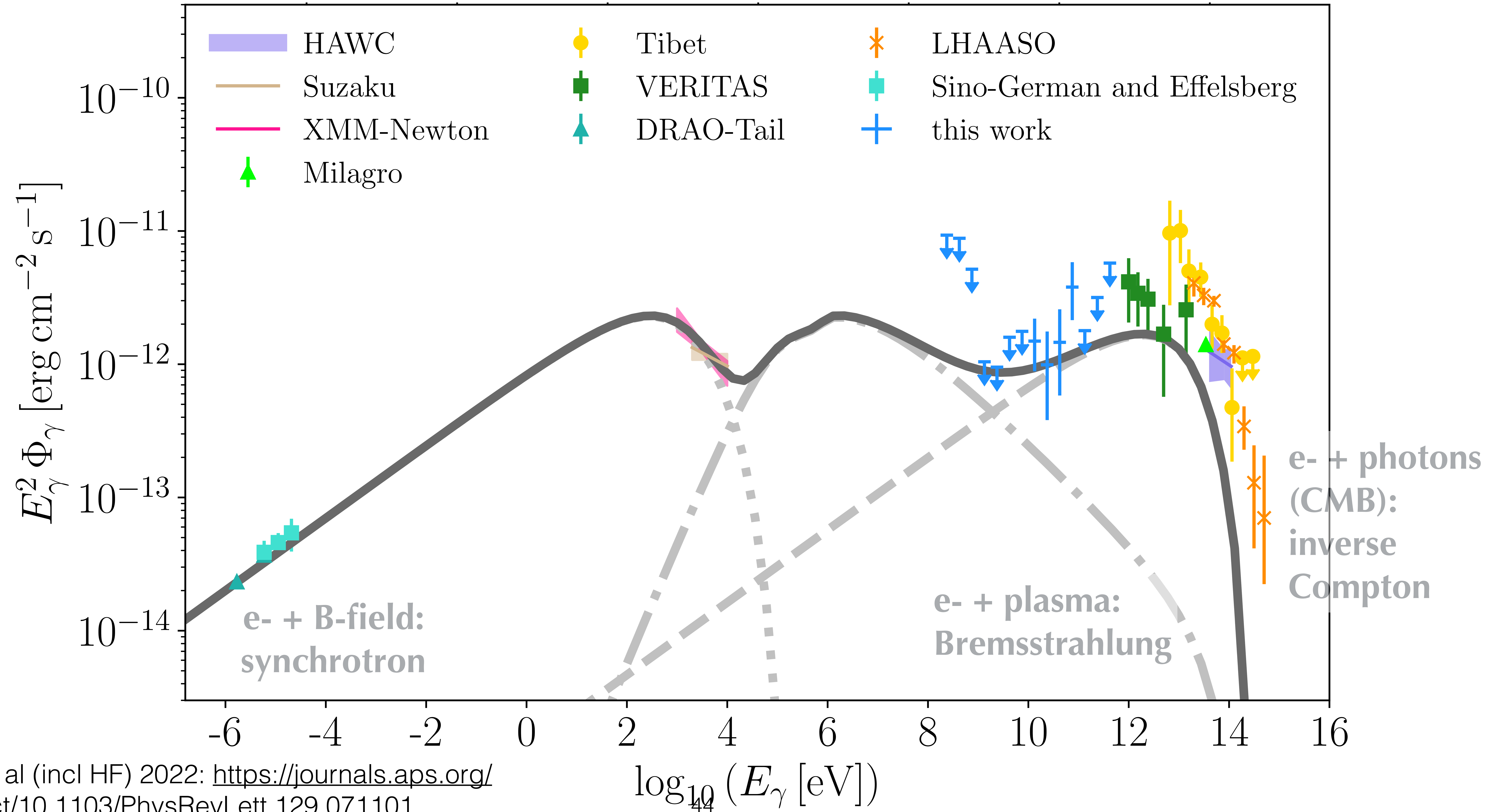




Selecting off-peak data (pulsar beam facing away) removes pulsar contamination

K. Fang et al (incl HF) 2022: https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.129.071101

Model 1: Electrons only



K. Fang et al (incl HF) 2022: https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.129.071101

Model 1: Electrons only

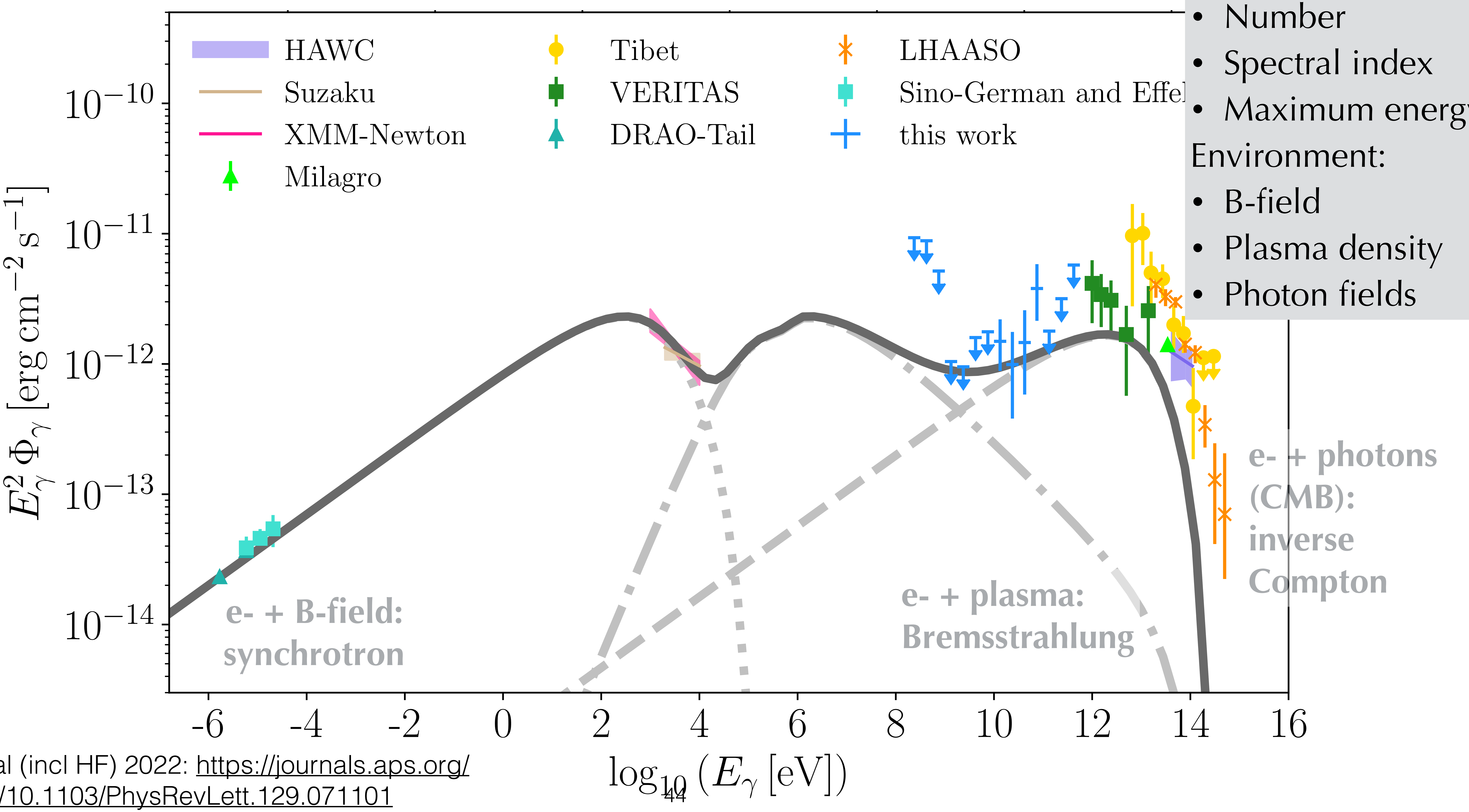
Model parameters

Electrons:

- Number
- Spectral index
- Maximum energy

Environment:

- B-field
- Plasma density
- Photon fields



K. Fang et al (incl HF) 2022: https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.129.071101

Model 1: Electrons only

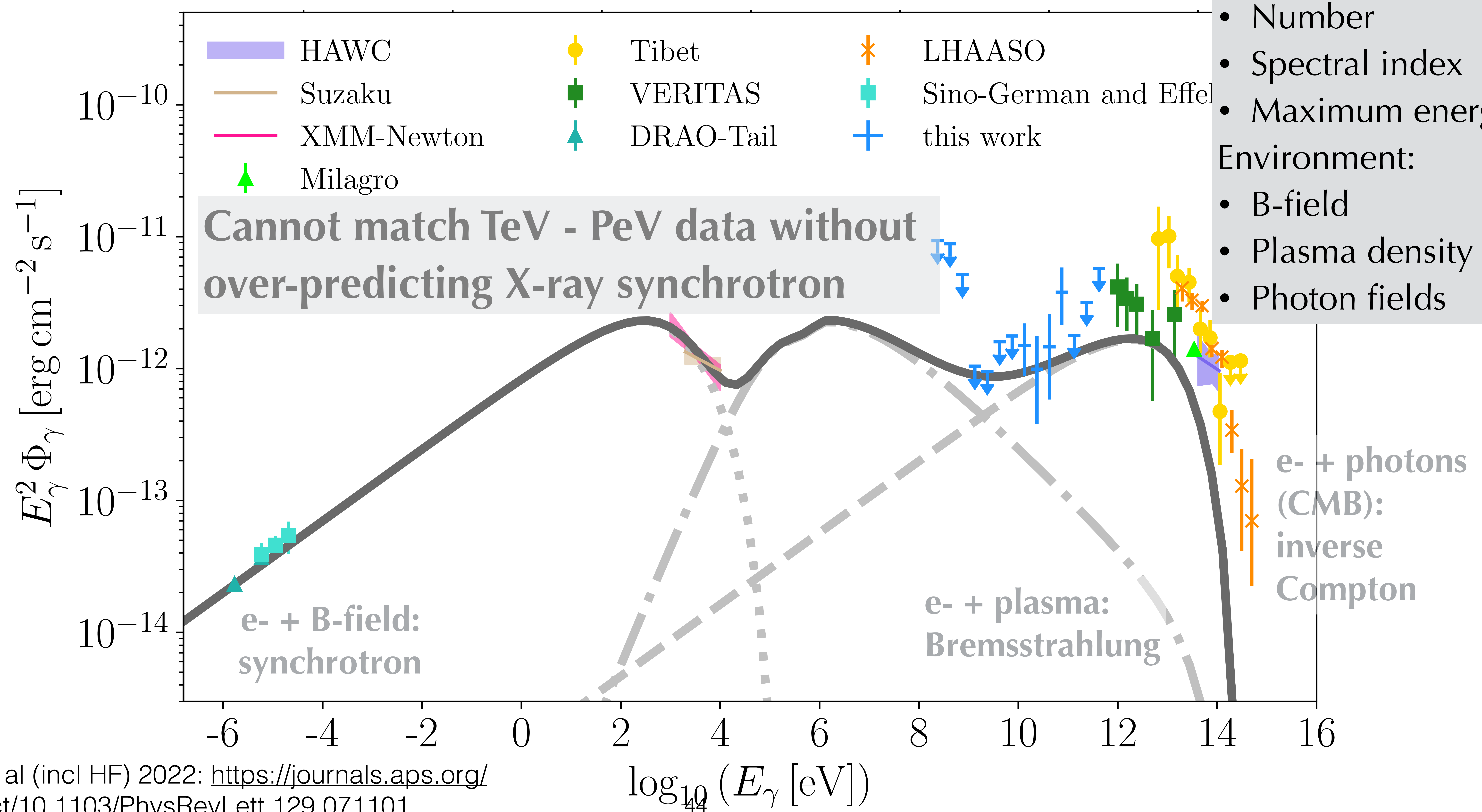
Model parameters

Electrons:

- Number
- Spectral index
- Maximum energy

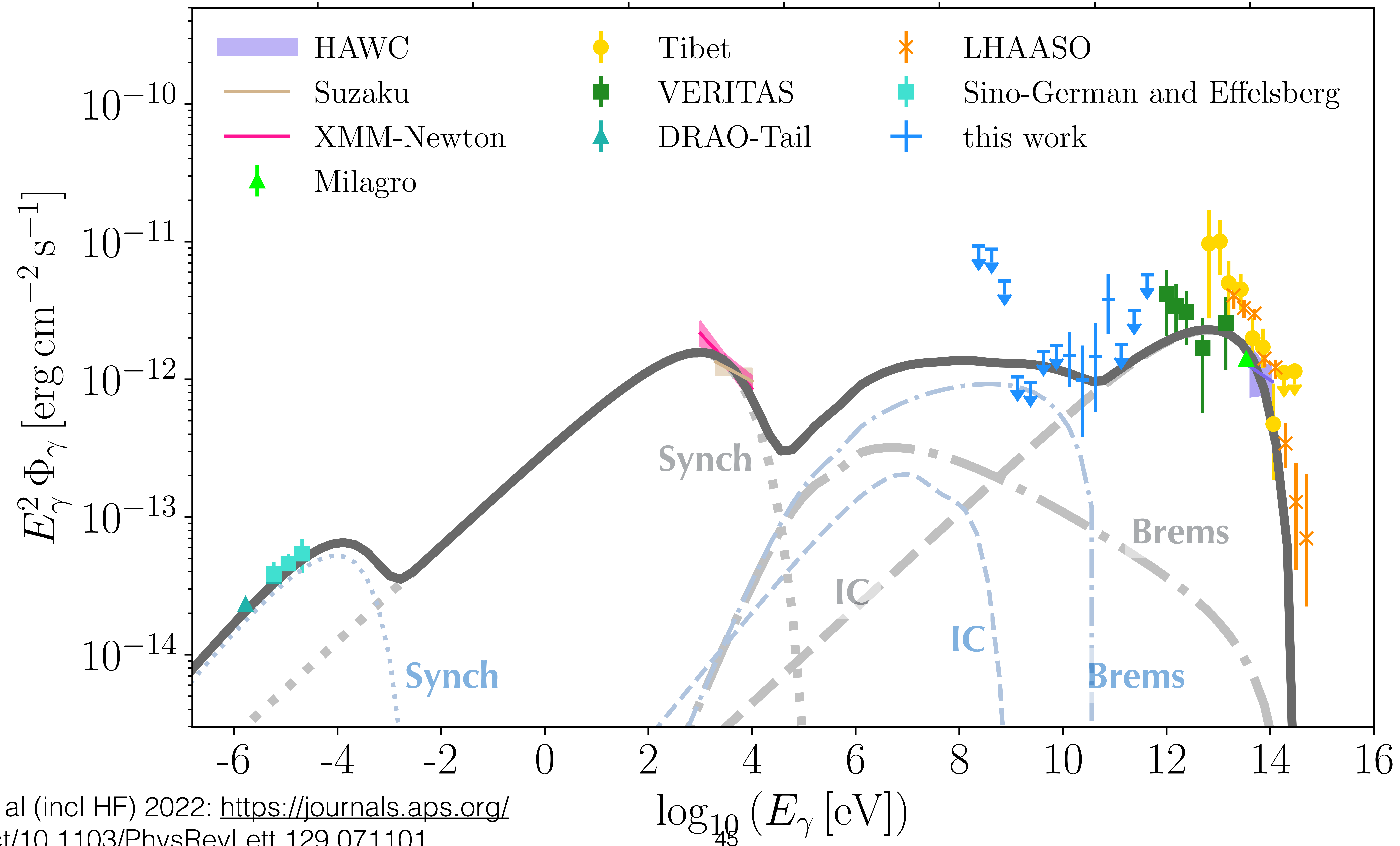
Environment:

- B-field
- Plasma density
- Photon fields



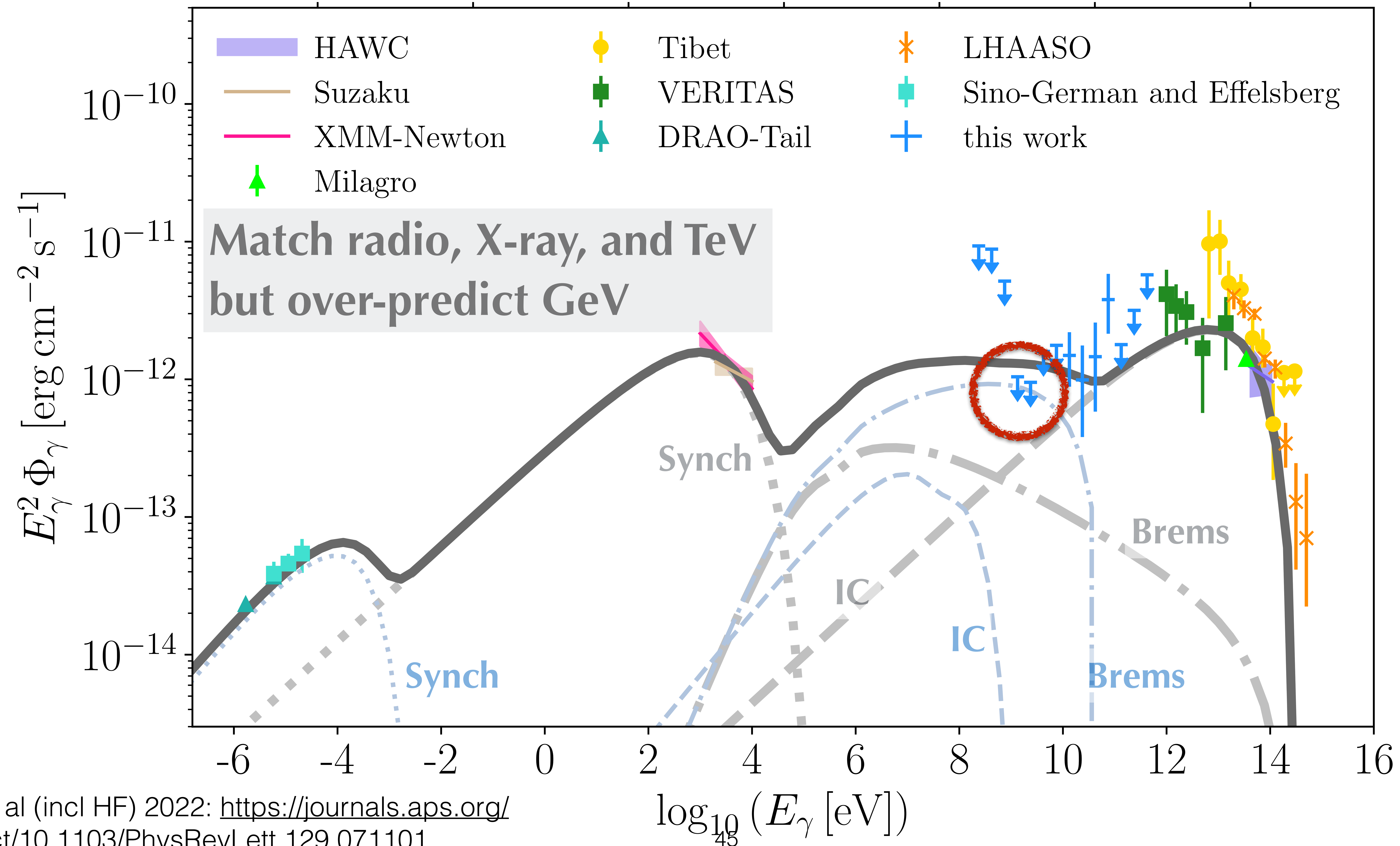
K. Fang et al (incl HF) 2022: https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.129.071101

Model 2: Two Electron components



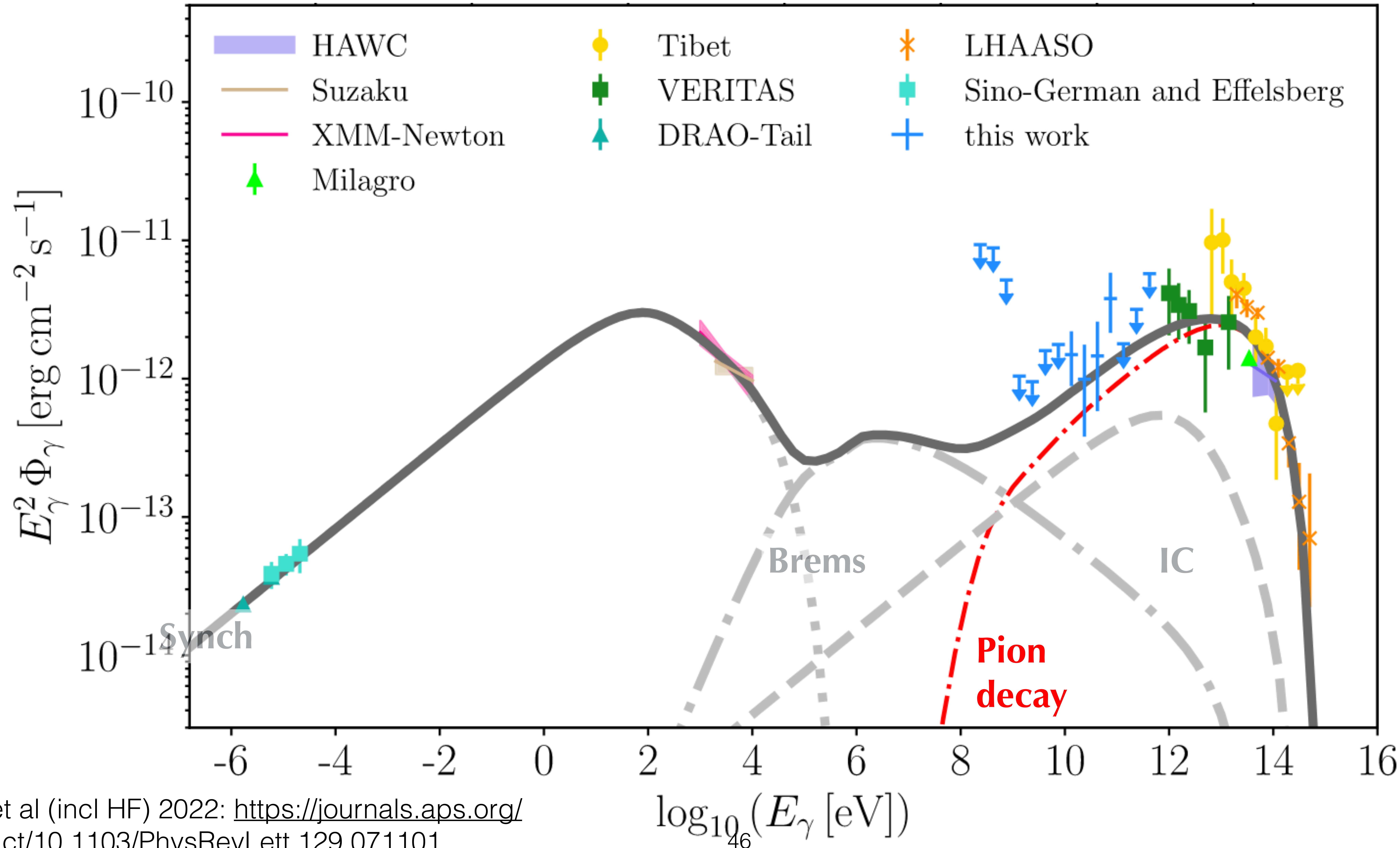
K. Fang et al (incl HF) 2022: https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.129.071101

Model 2: Two Electron components



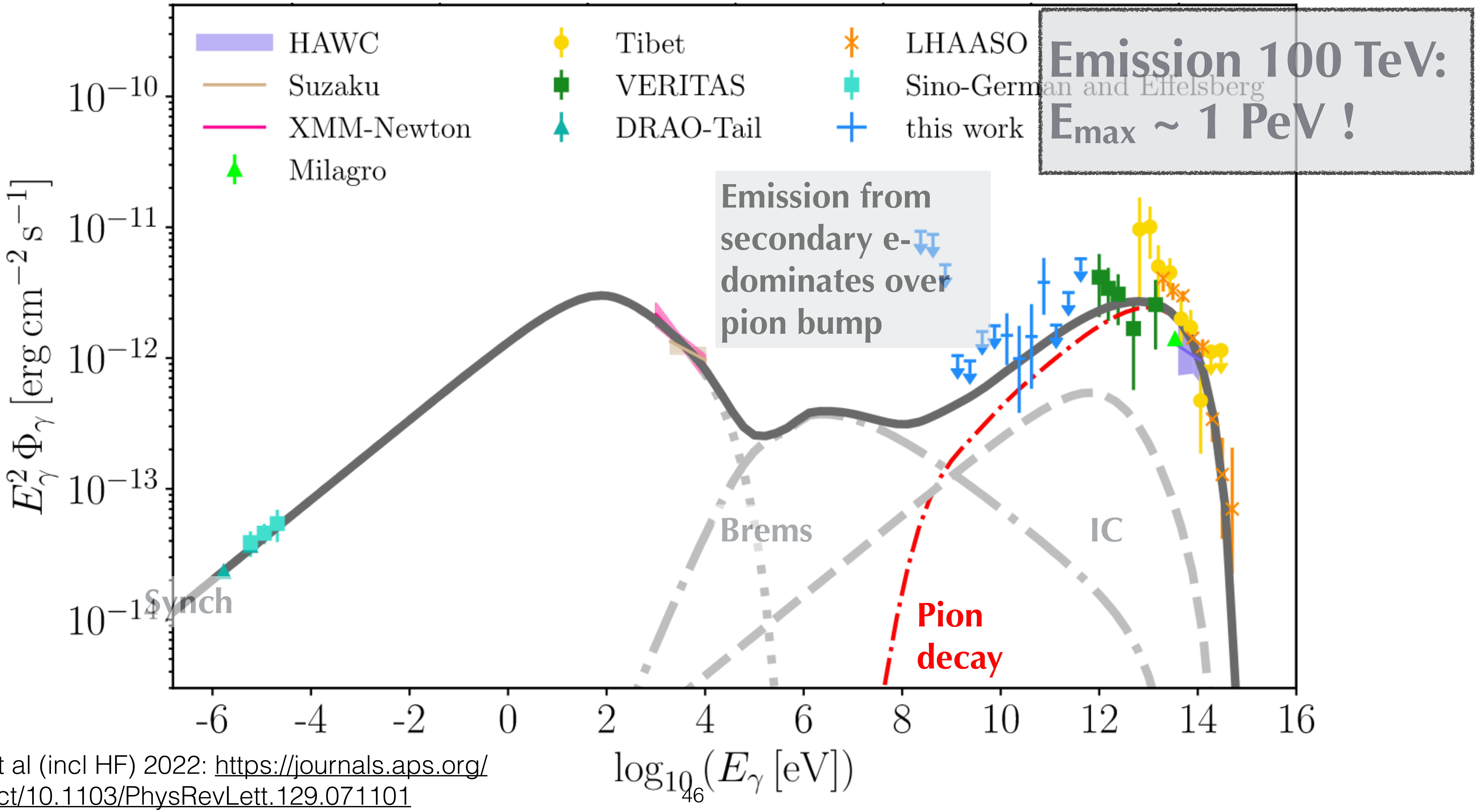
K. Fang et al (incl HF) 2022: https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.129.071101

Model 3: Protons and electrons



K. Fang et al (incl HF) 2022: https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.129.071101

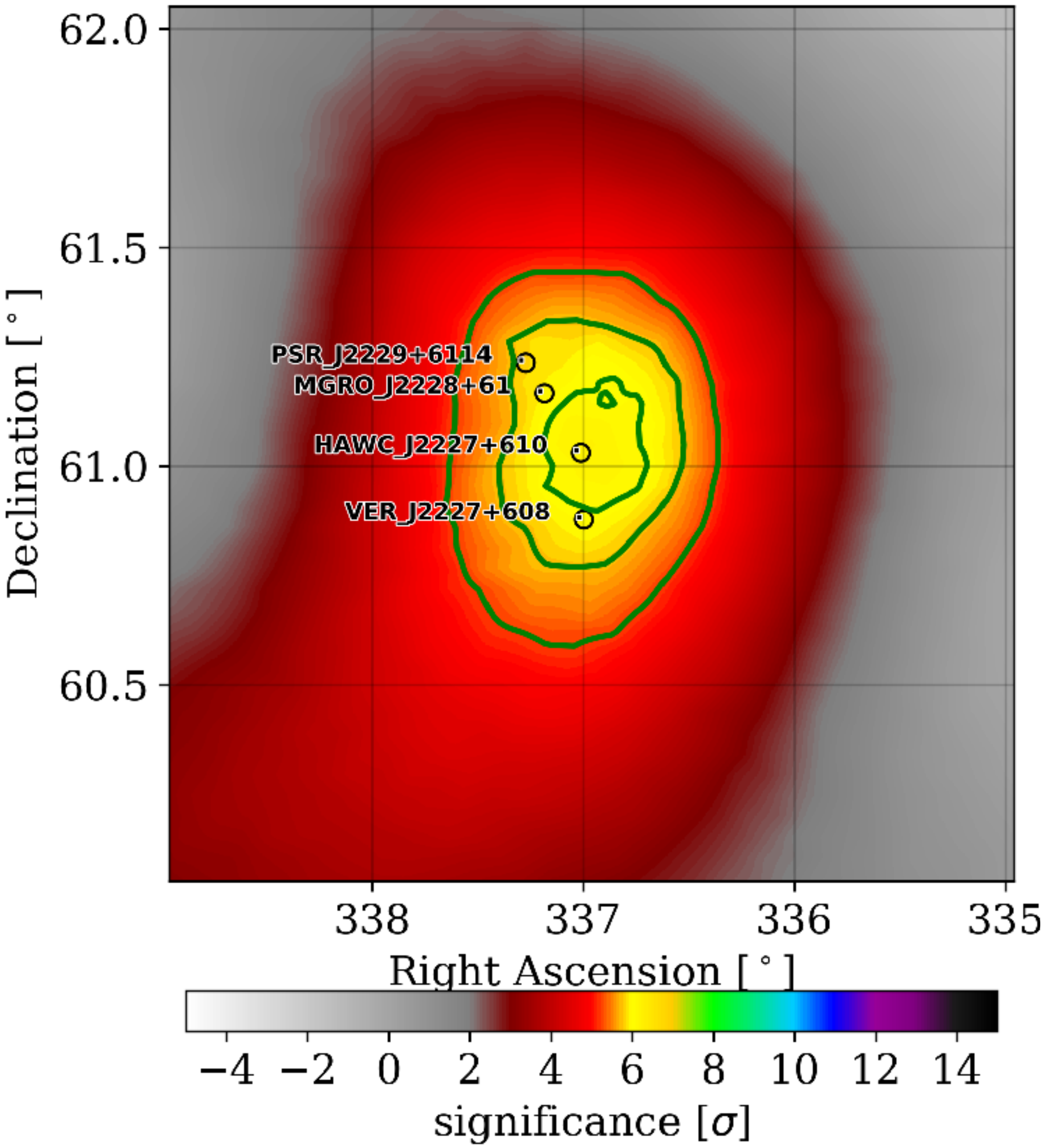
Model 3: Protons and electrons

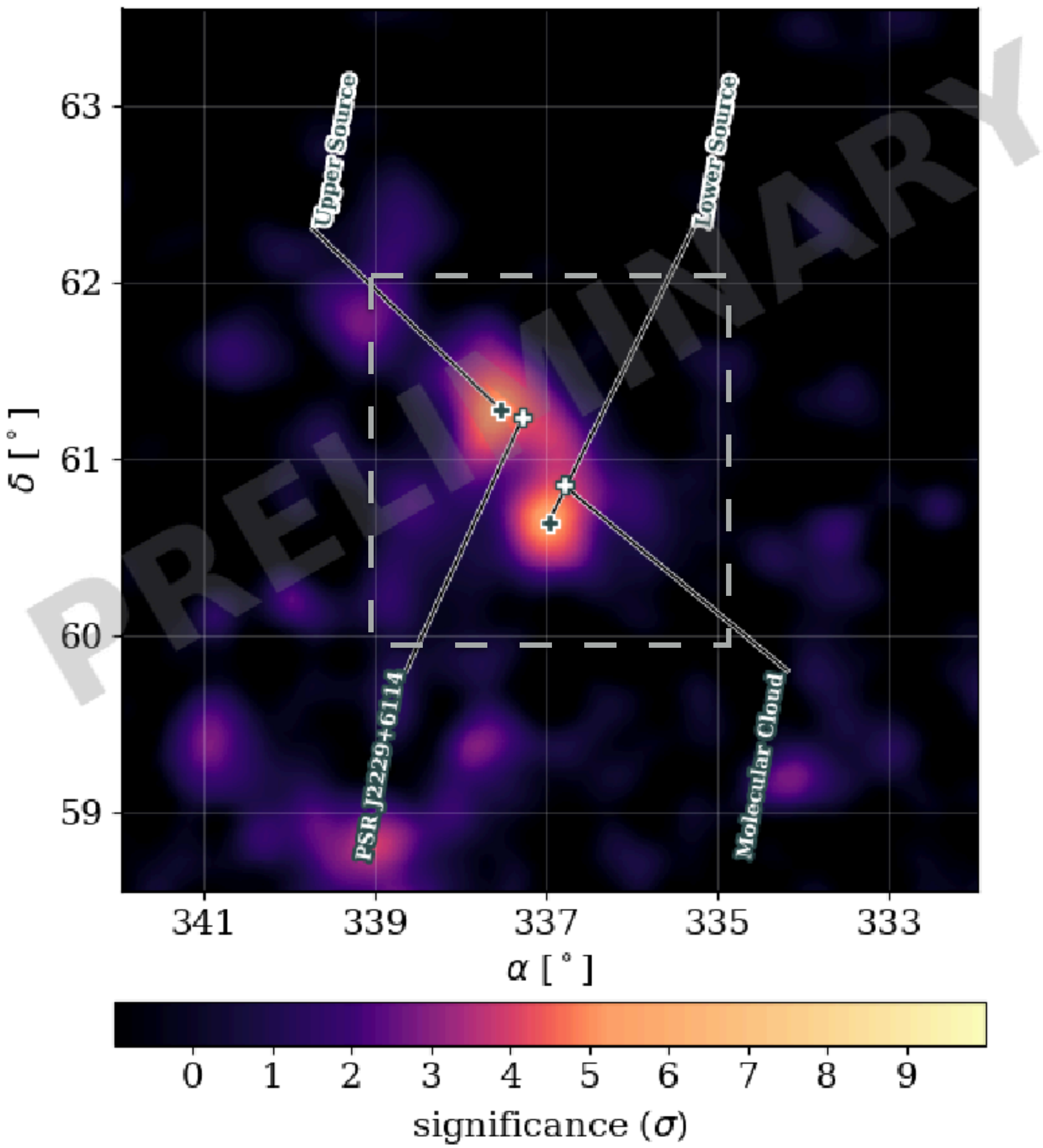


K. Fang et al (incl HF) 2022: https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.129.071101

What's Next?

News from G106.3+2.7

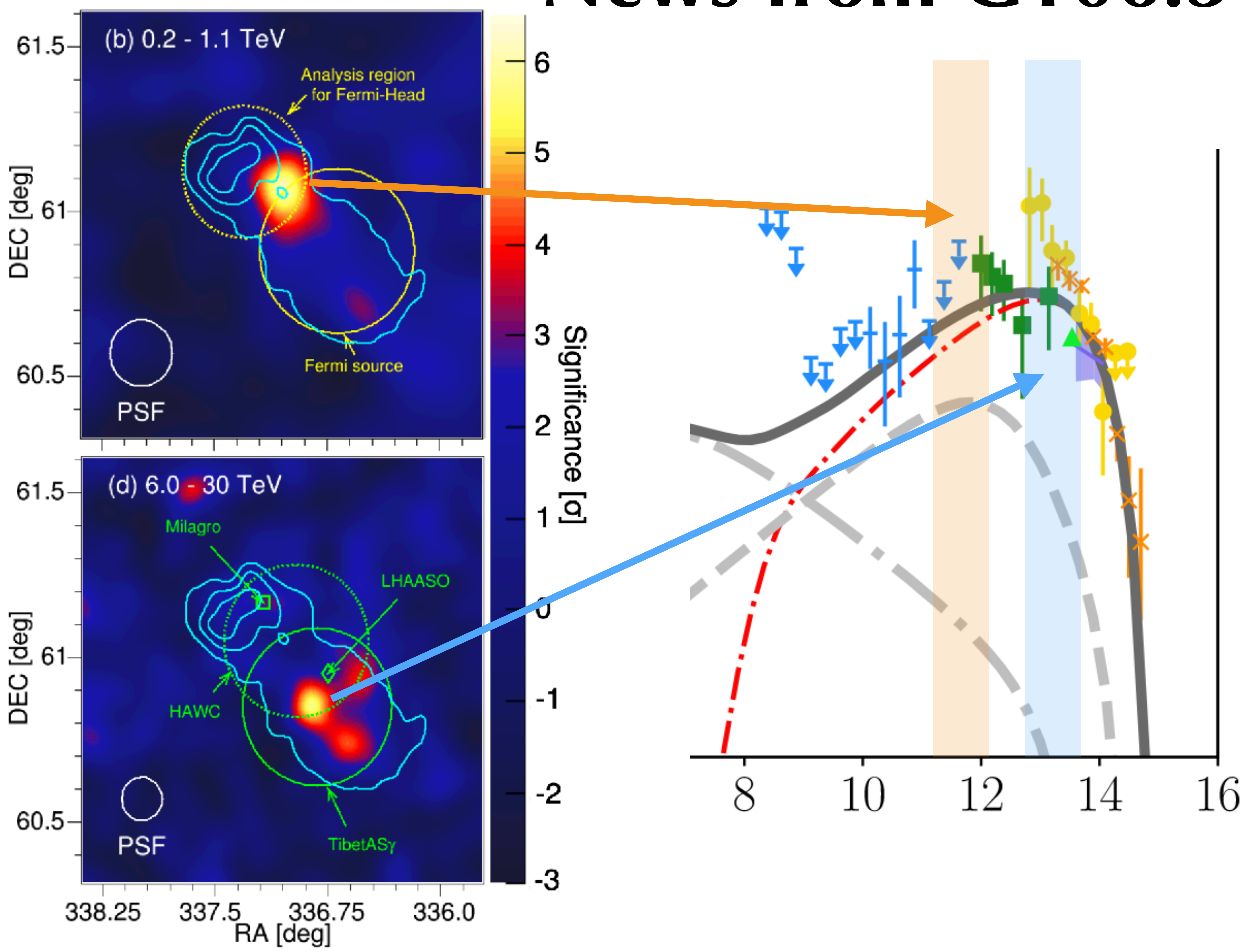




HAWC (incl HF) 2020: https://iopscience.iop.org/article/10.3847/2041-8213/ab96cc

HAWC (X. Wang): TeVPA 2022

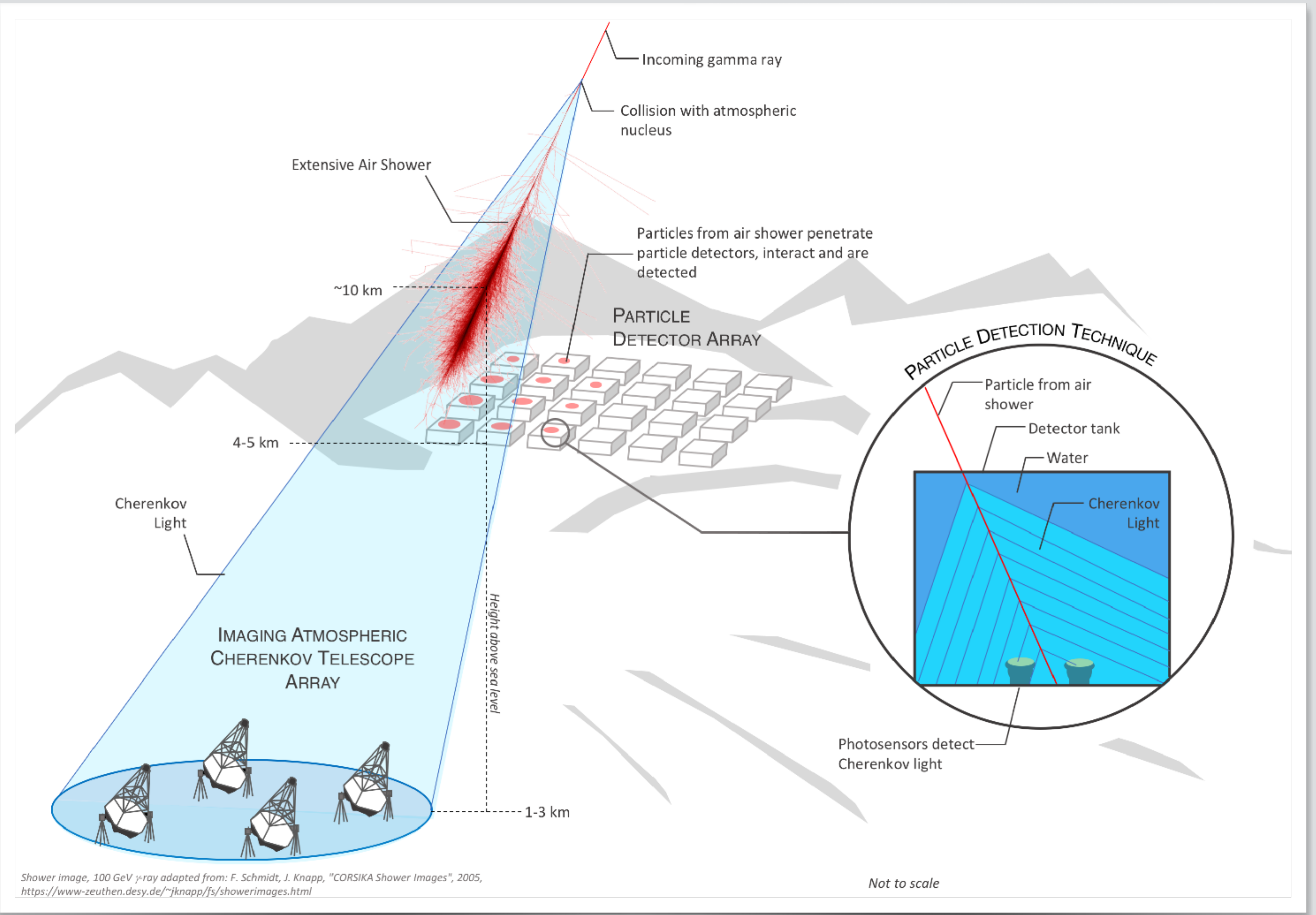
News from G106.3+2.7

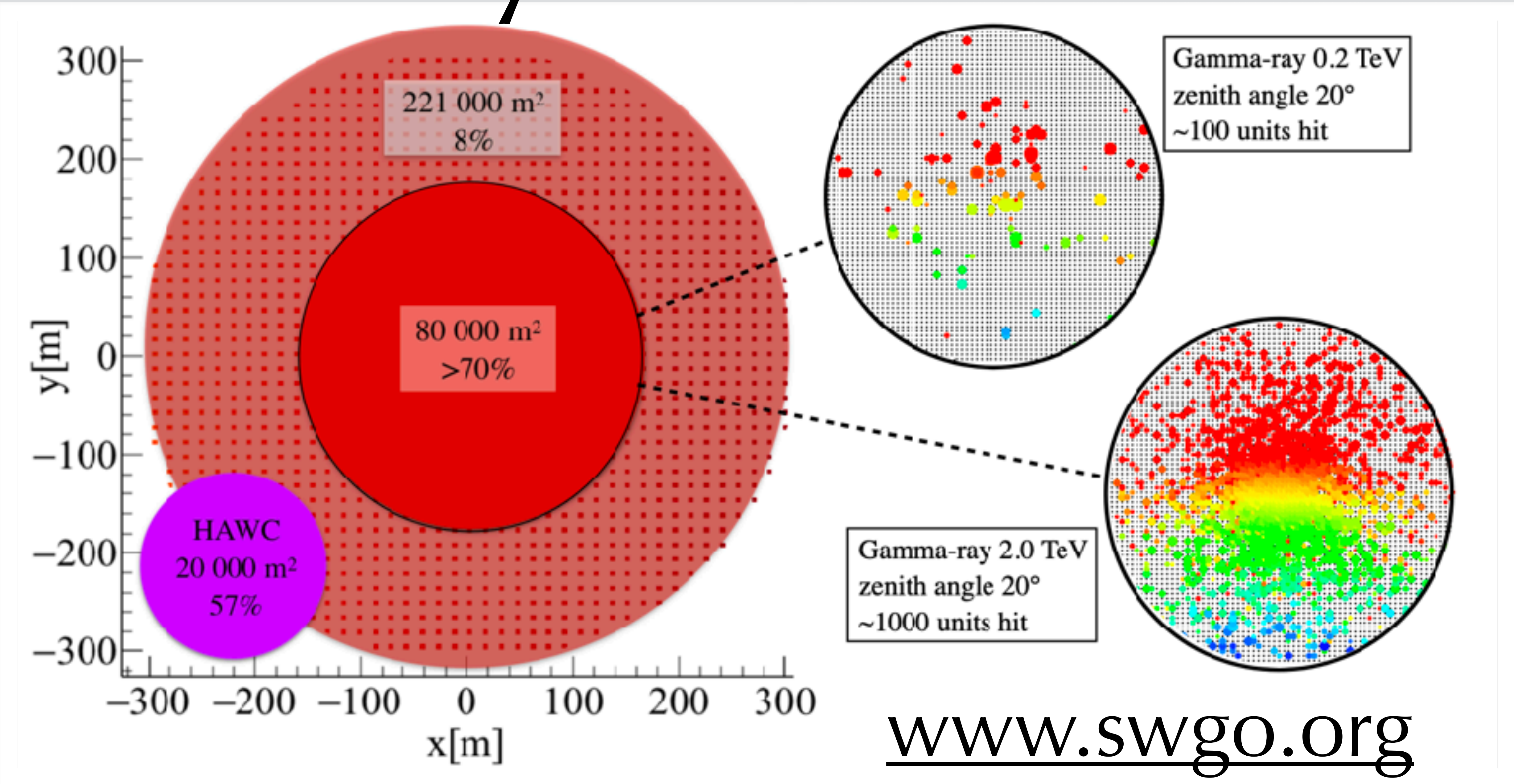


- PeV acceleration in G106.3+2.7 is unexpected.
- Newest results (MAGIC, HAWC) indicate two emission sites with energy-dependent morphology.
- Stay tuned for updated modeling!

MAGIC 2022: https://arxiv.org/abs/2211.15321

Next Generation VHE Gamma-ray observatories

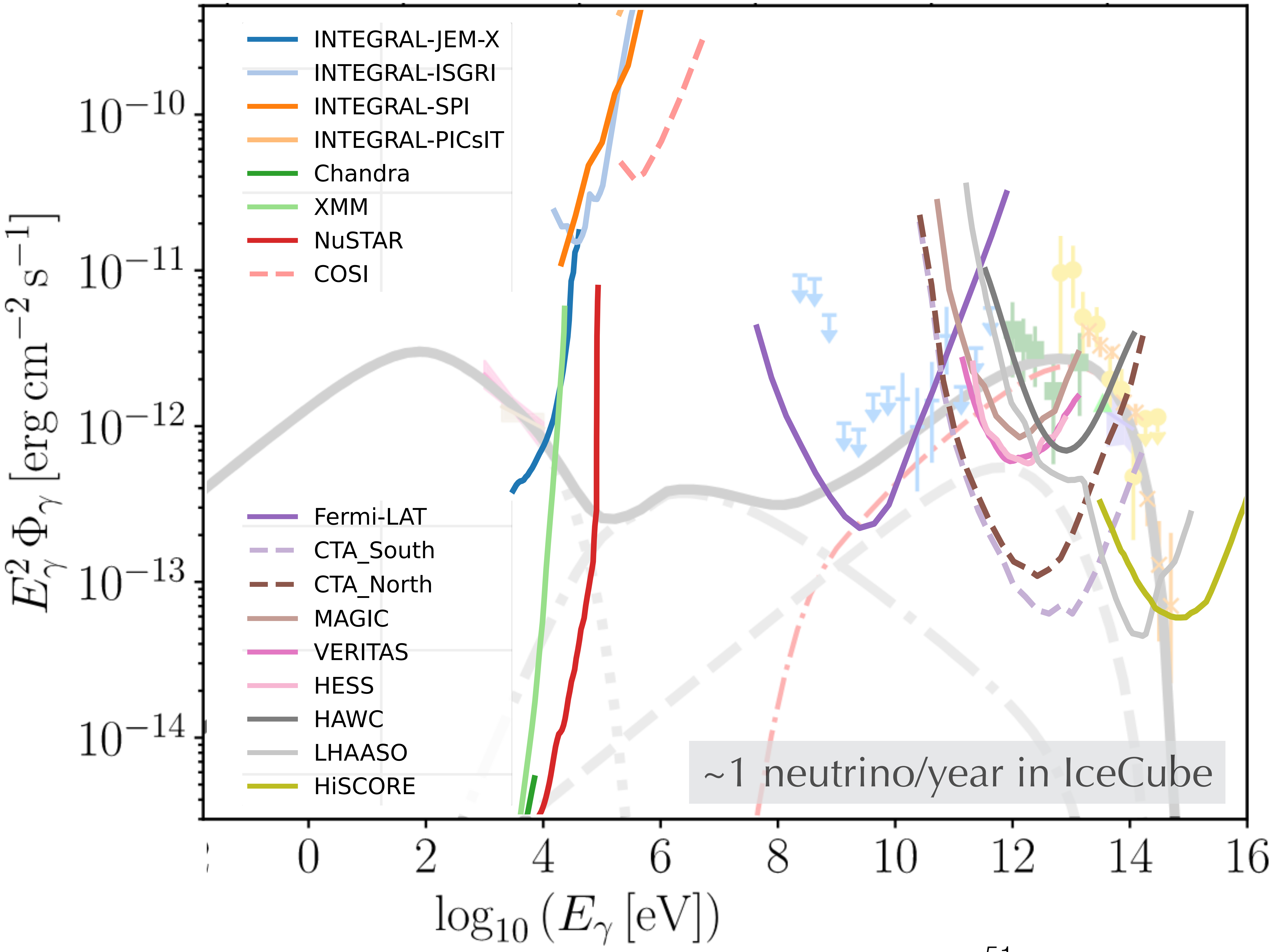




www.swgo.org

www.cta-observatory.org

Future instrumentation



- **Gamma rays (and neutrinos) generic features of shock acceleration.**
- Excellent GeV-TeV coverage by near-future instruments.
- Contamination from Galactic diffuse gamma-ray background and other sources.
- X-ray limited by source confusion and source size.
- **MeV band (Bremsstrahlung) challenging**.
- Neutrino detection requires larger instrumented volume.

Sensitivities: Luccheta et al 2022: https://arxiv.org/abs/2204.01325

Conclusions

- PeVatrons are galactic proton accelerators capable of accelerating protons to PeV energies.
- PeVatrons are expected to emit >100 TeV gamma rays.
- 100 TeV gamma rays alone are not sufficient to claim PeVatron detection.
- Multi-wavelength data and physics modeling can help shed light on the emission mechanism and particle acceleration in gamma-ray sources.
- SNR G106.3+2.7 was identified as a galactic PeVatron through multi-wavelength data analysis.