

PeVatrons - The Most Extreme Particle Accelerators in our Galaxy

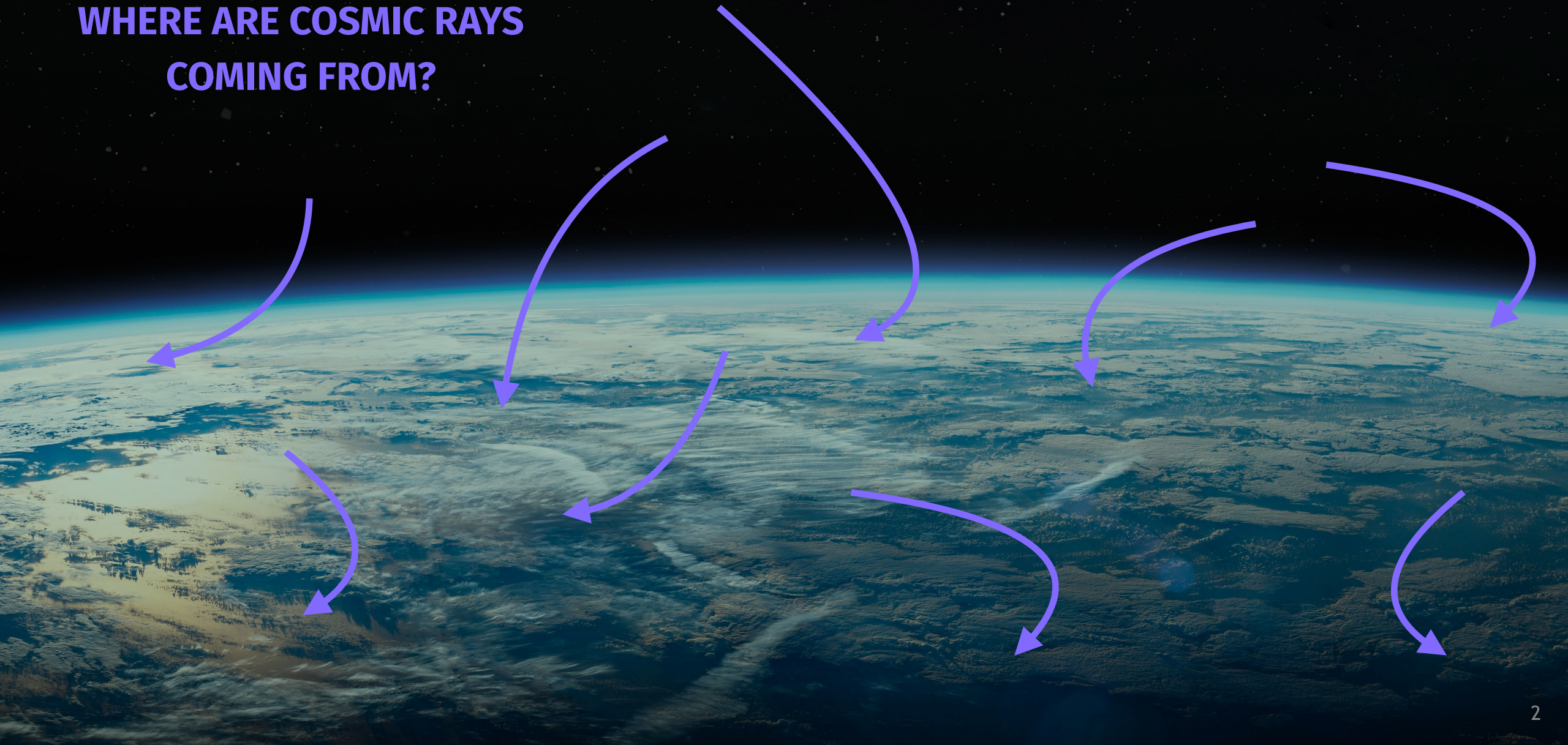
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International Symposium on Cosmology & Particle Astrophysics
July 8th, 2026



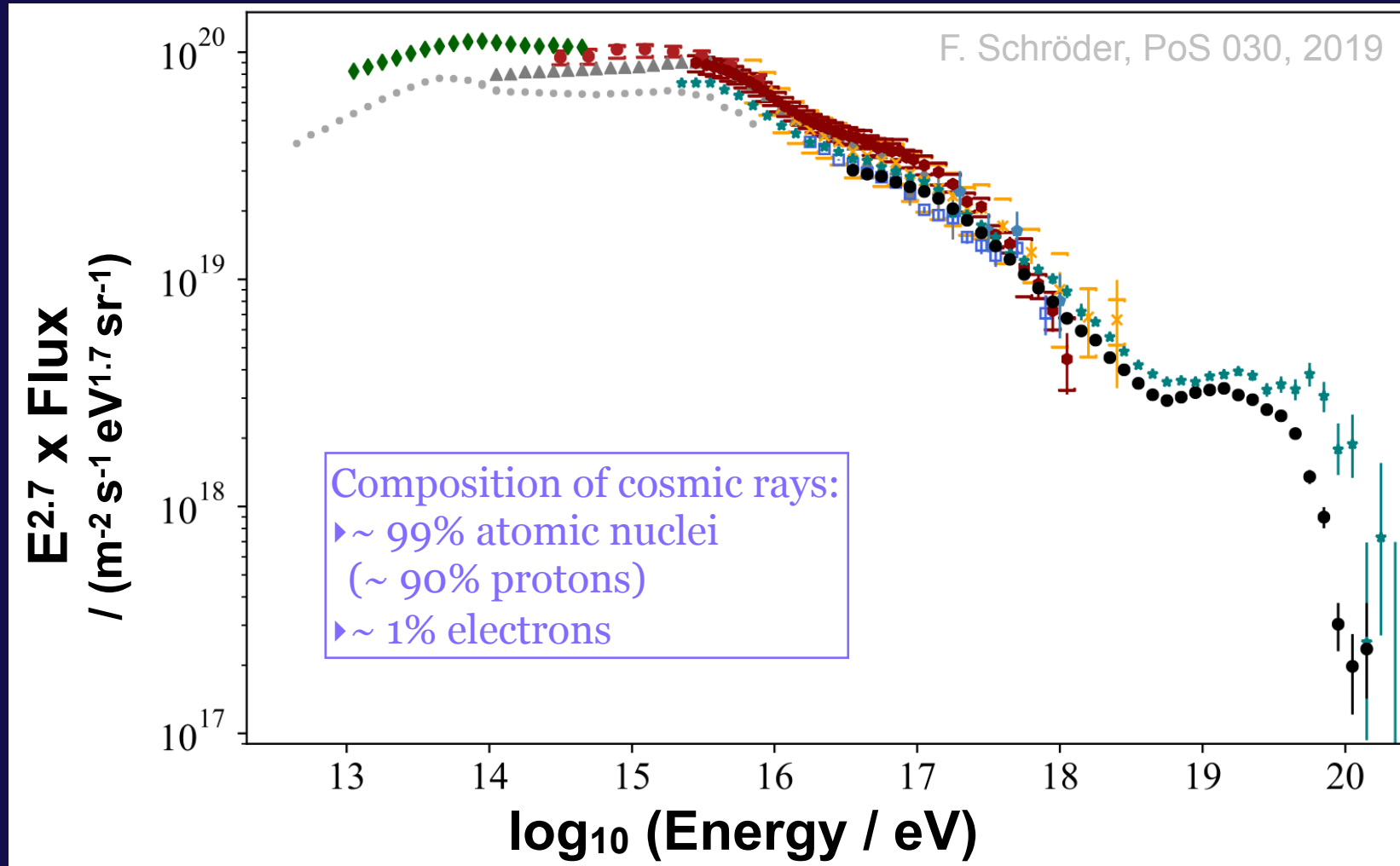
A 114-Year-Old Mystery

**WHERE ARE COSMIC RAYS
COMING FROM?**

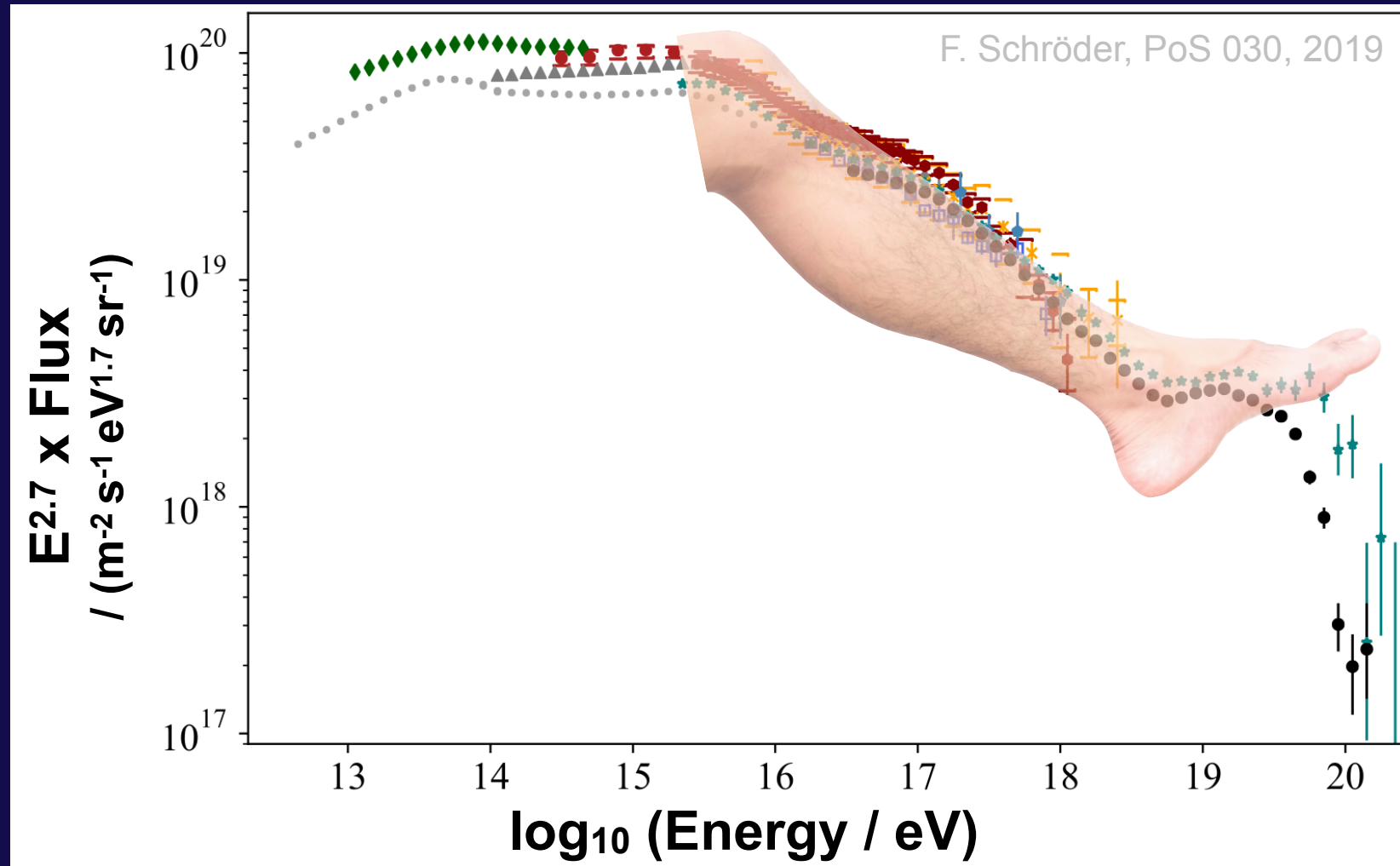


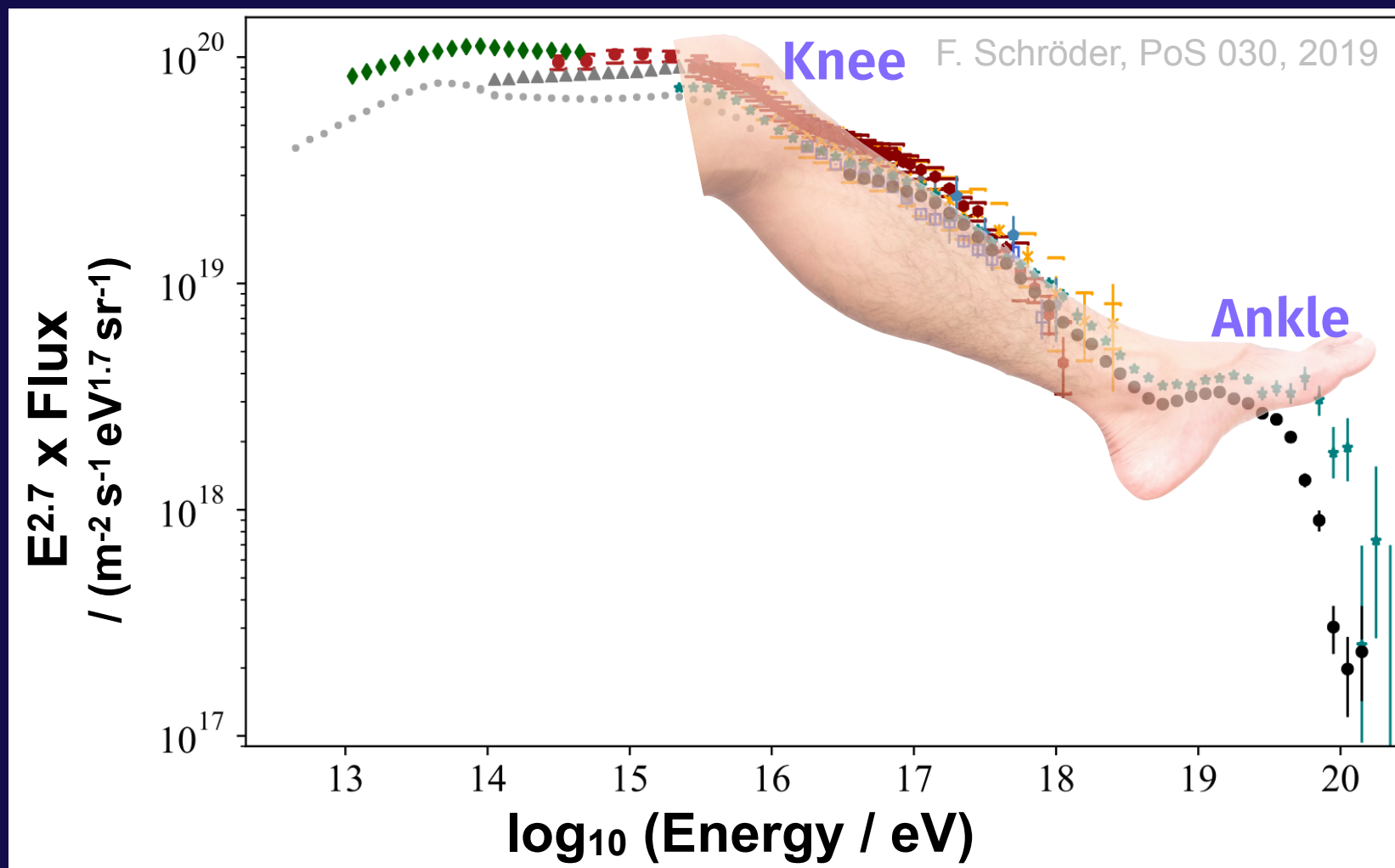
Spectrum of Cosmic Rays

(Radiation measurements from all sky directions combined)

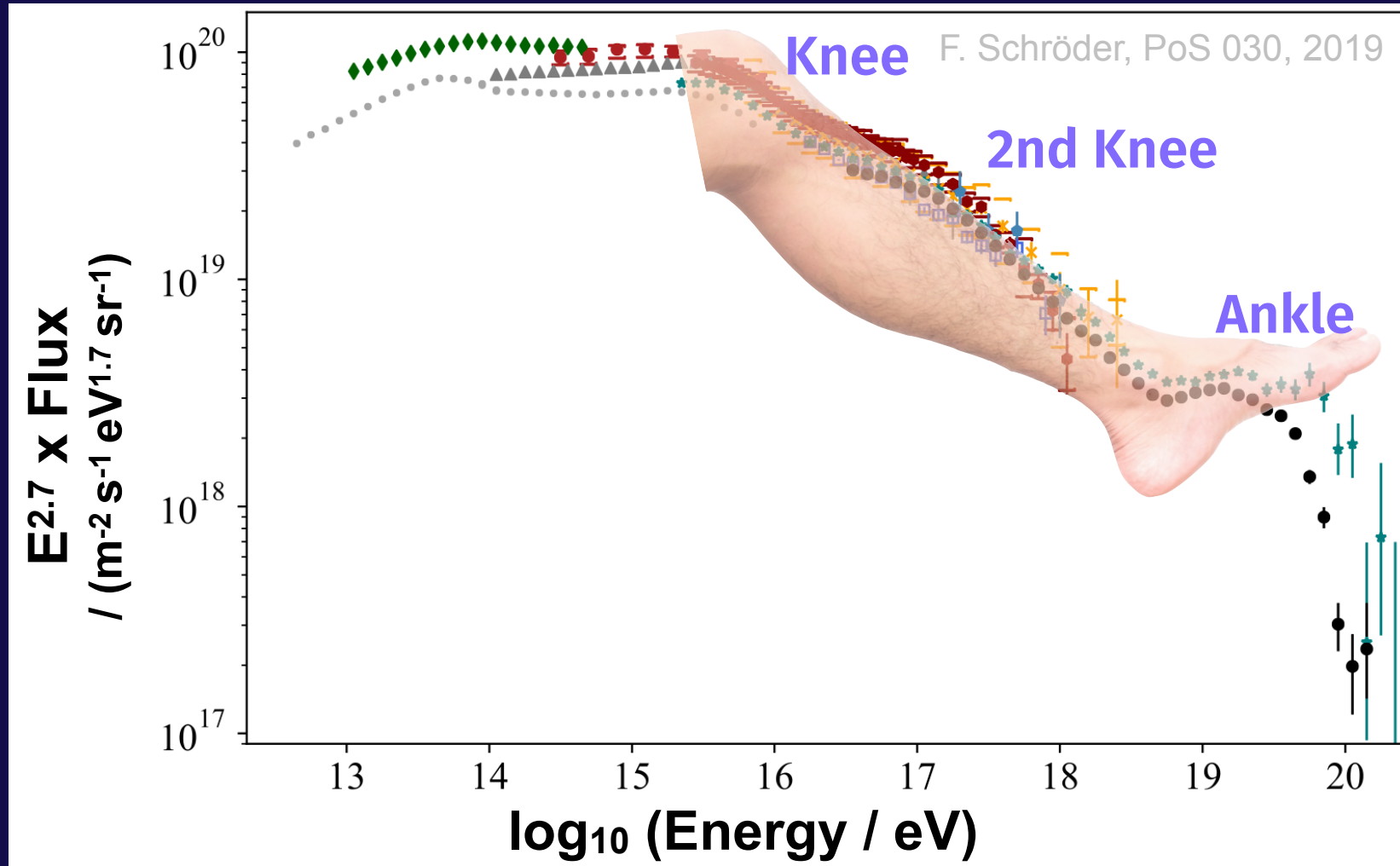


Spectrum of Cosmic Rays

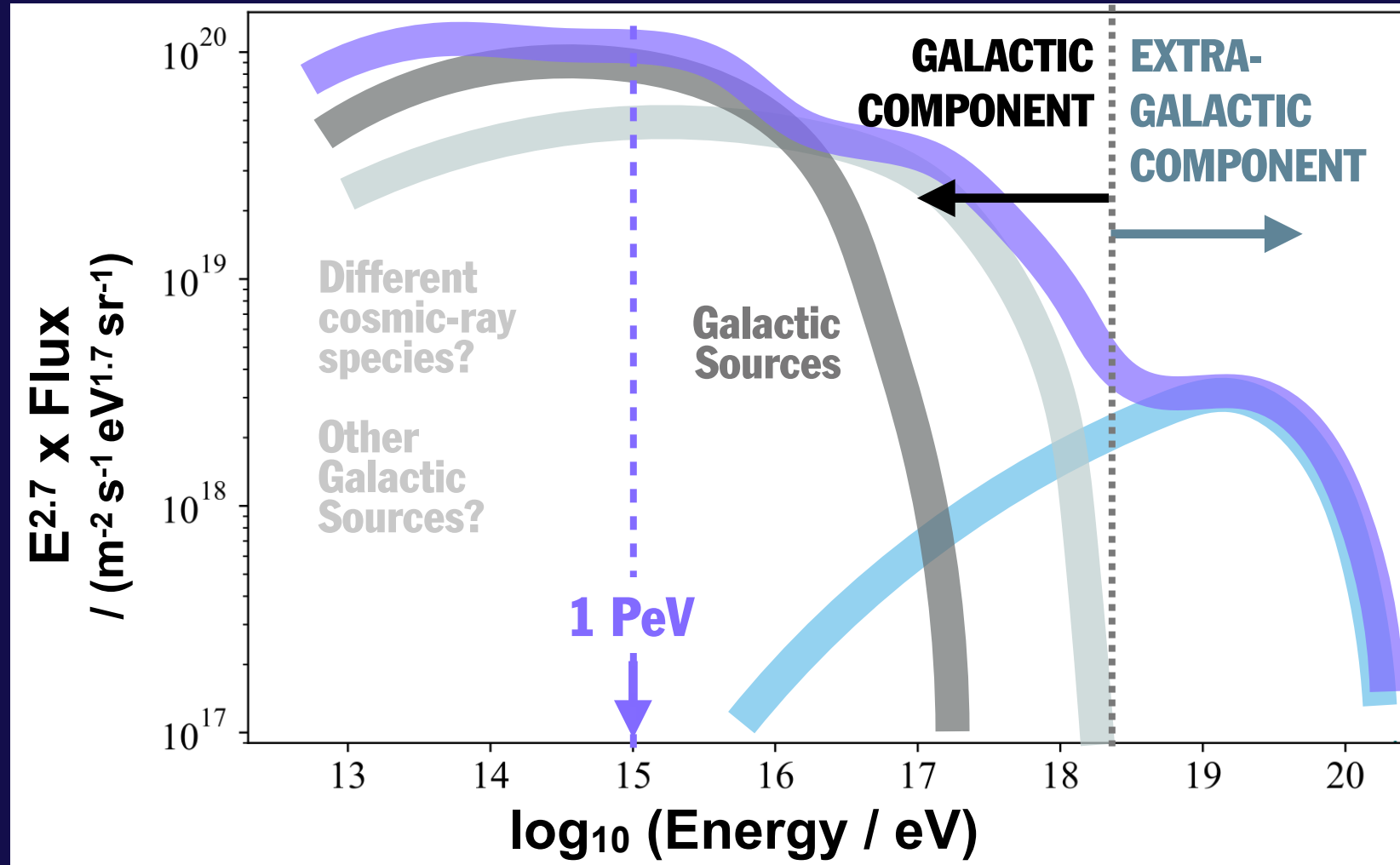




Spectrum of Cosmic Rays



Spectrum of Cosmic Rays



- Which astrophysical objects are behind the cosmic-ray emission from our Galaxy?

 - Supernova remnants? Pulsar wind nebulae? Massive stellar clusters?

- Which mechanism accelerated cosmic rays to PeV energies?

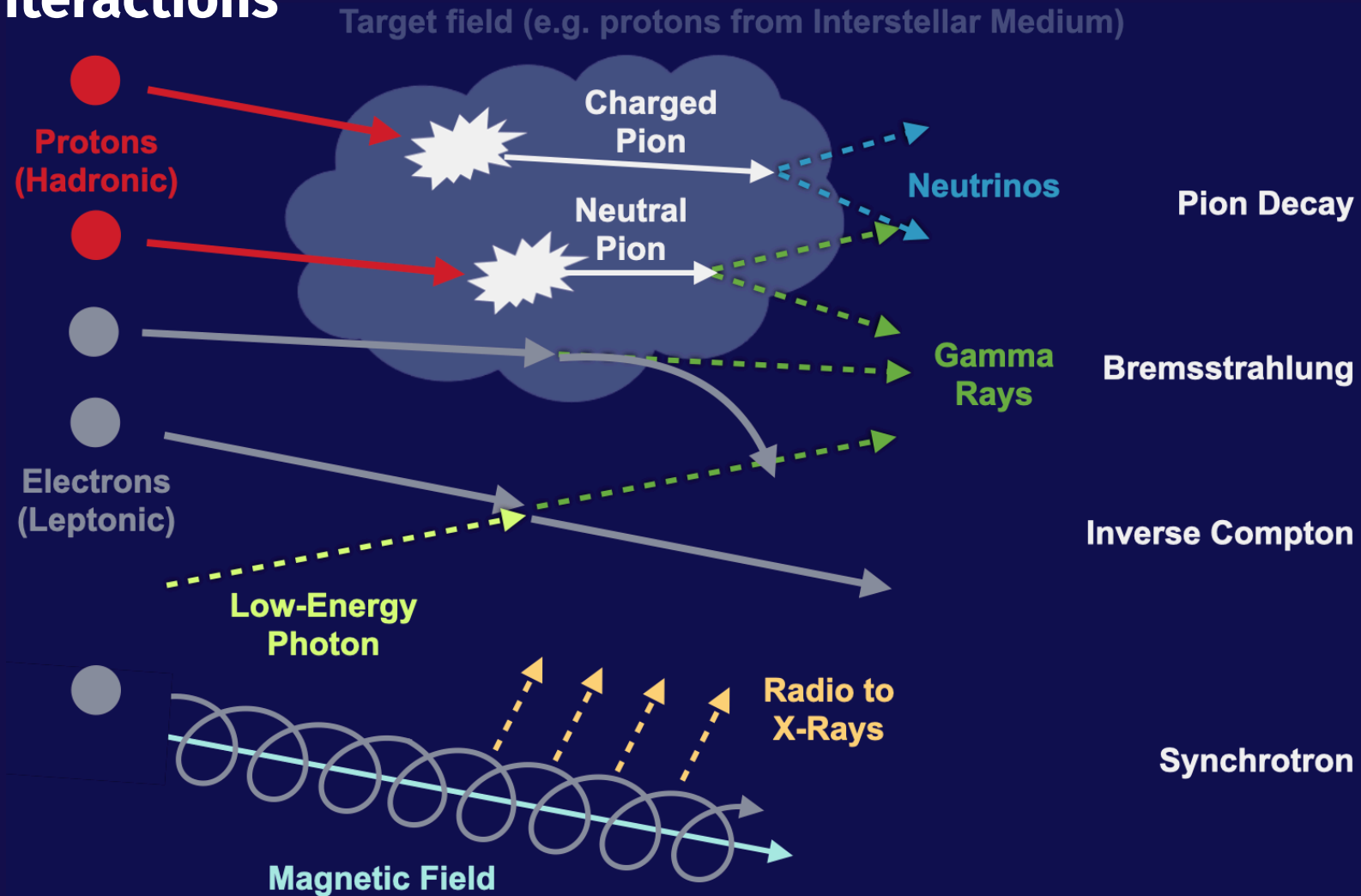
 - Where are these extreme accelerators?

 - How can we find them?

How can we find them?

- ✦ Charged cosmic rays ✖
(due to deflection by magnetic fields)

Cosmic-ray Interactions

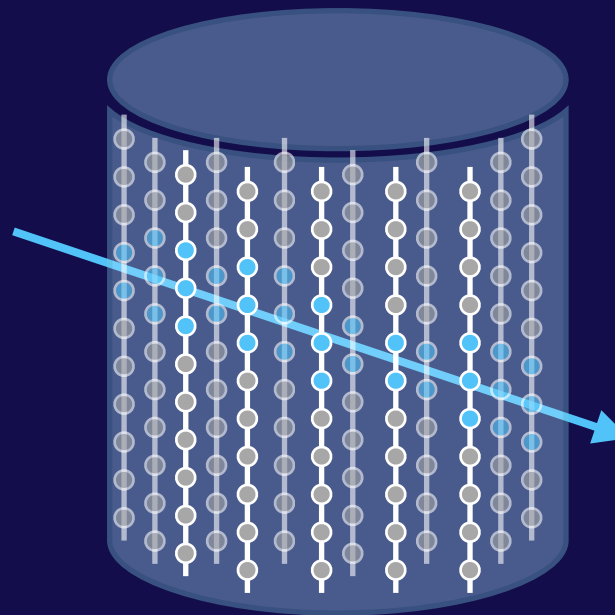


All these processes involve **relativistic particles** interacting with **matter, magnetic fields** or **radiation**!

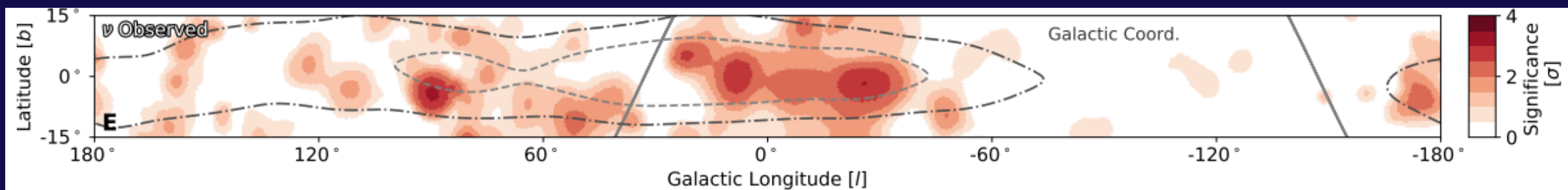
Those ingredients are around in the Universe!

How can we find them?

- ♦ Charged cosmic rays ✗
(due to deflection by magnetic fields)
- ♦ Neutrinos ✗
(due to low statistics and poor angular resolution of current instruments)



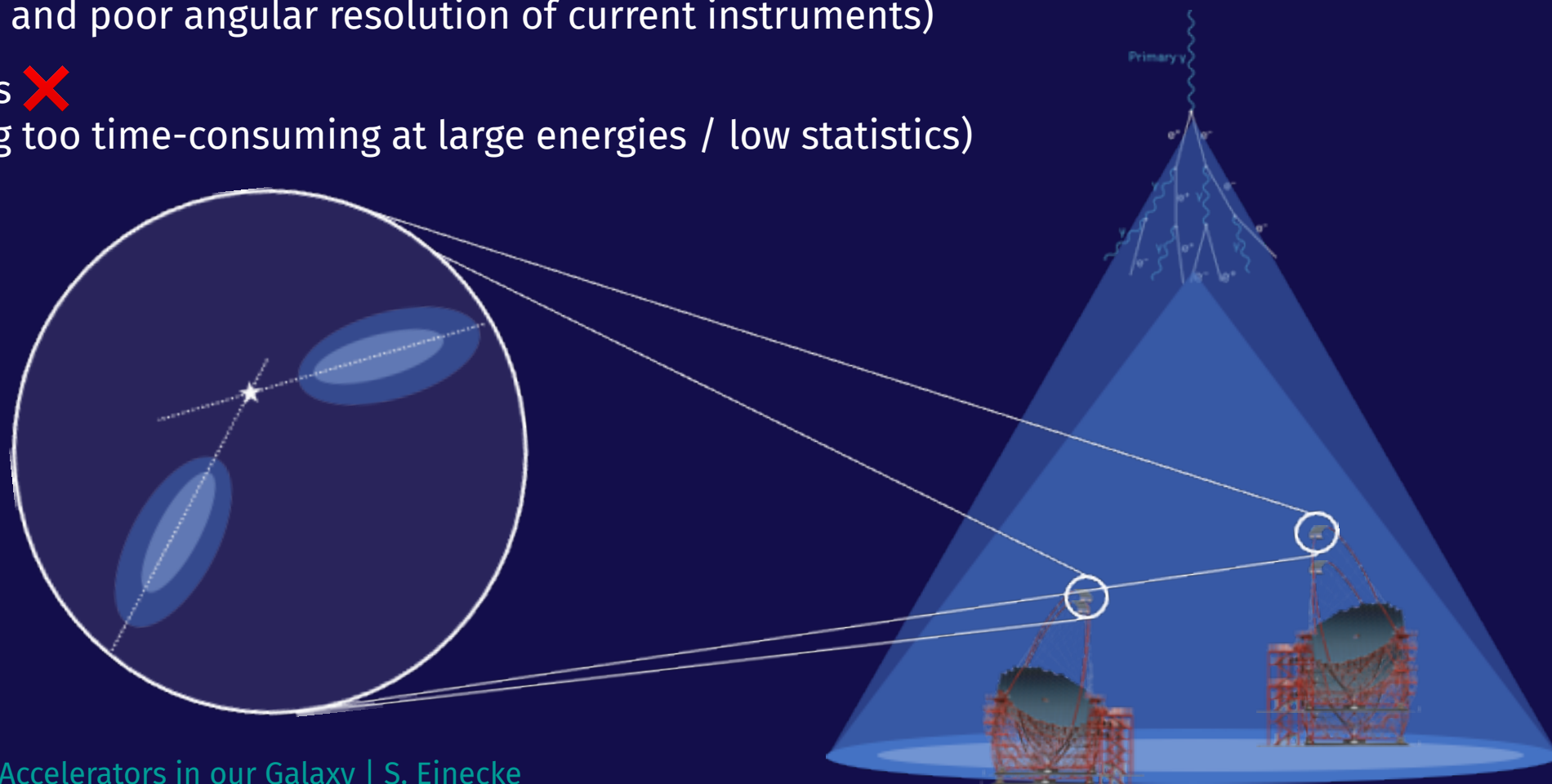
IceCube Measurement *Science* 380, 6652 (2023)



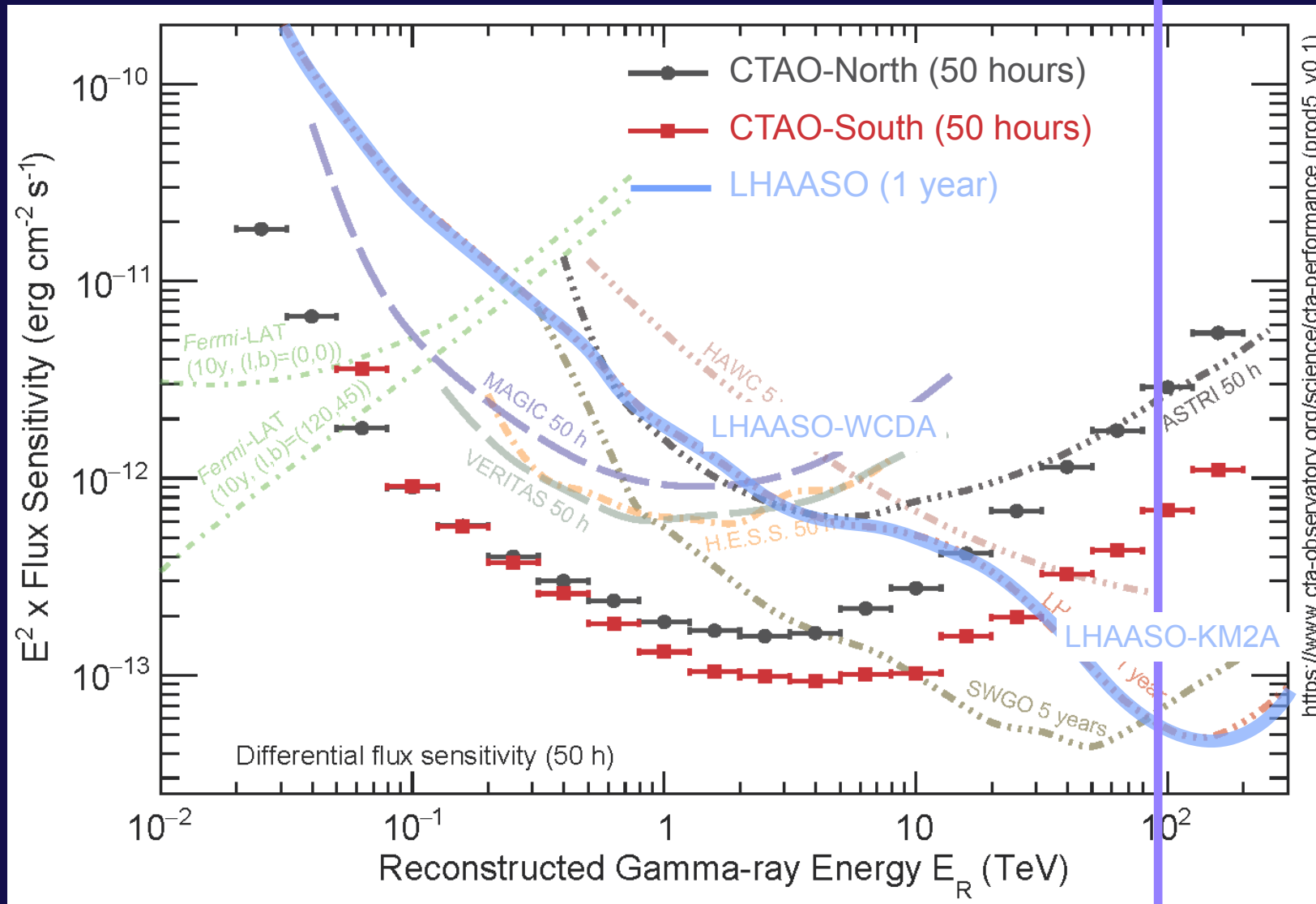
~4,200 astrophysical neutrinos; measured with angular resolution of ~10deg

How can we find them?

- ♦ Charged cosmic rays ✗
(due to deflection by magnetic fields)
- ♦ Neutrinos ✗
(due to low statistics and poor angular resolution of current instruments)
- ♦ Gamma rays via IACTs ✗
(due to surveys being too time-consuming at large energies / low statistics)



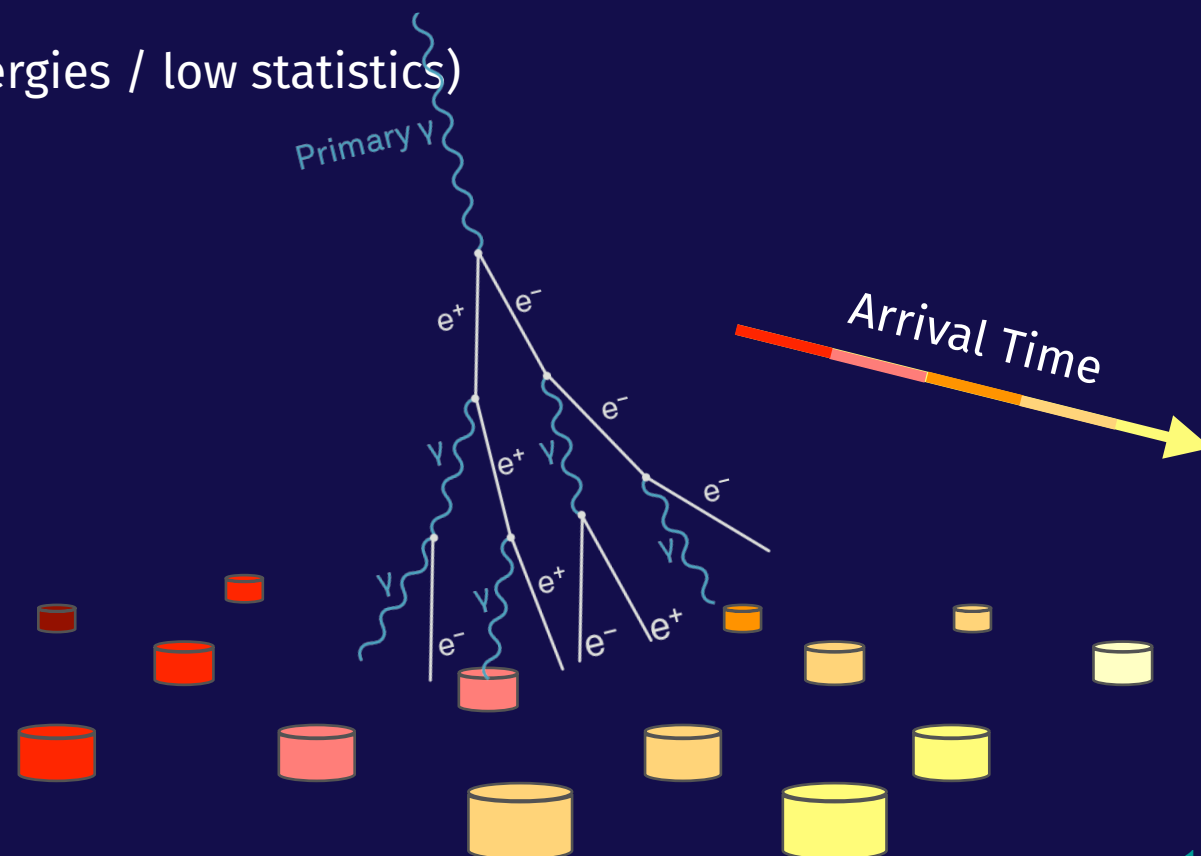
Gamma-Ray Detectors: Sensitivity



Critical energy range for FINDING PeVatrons!

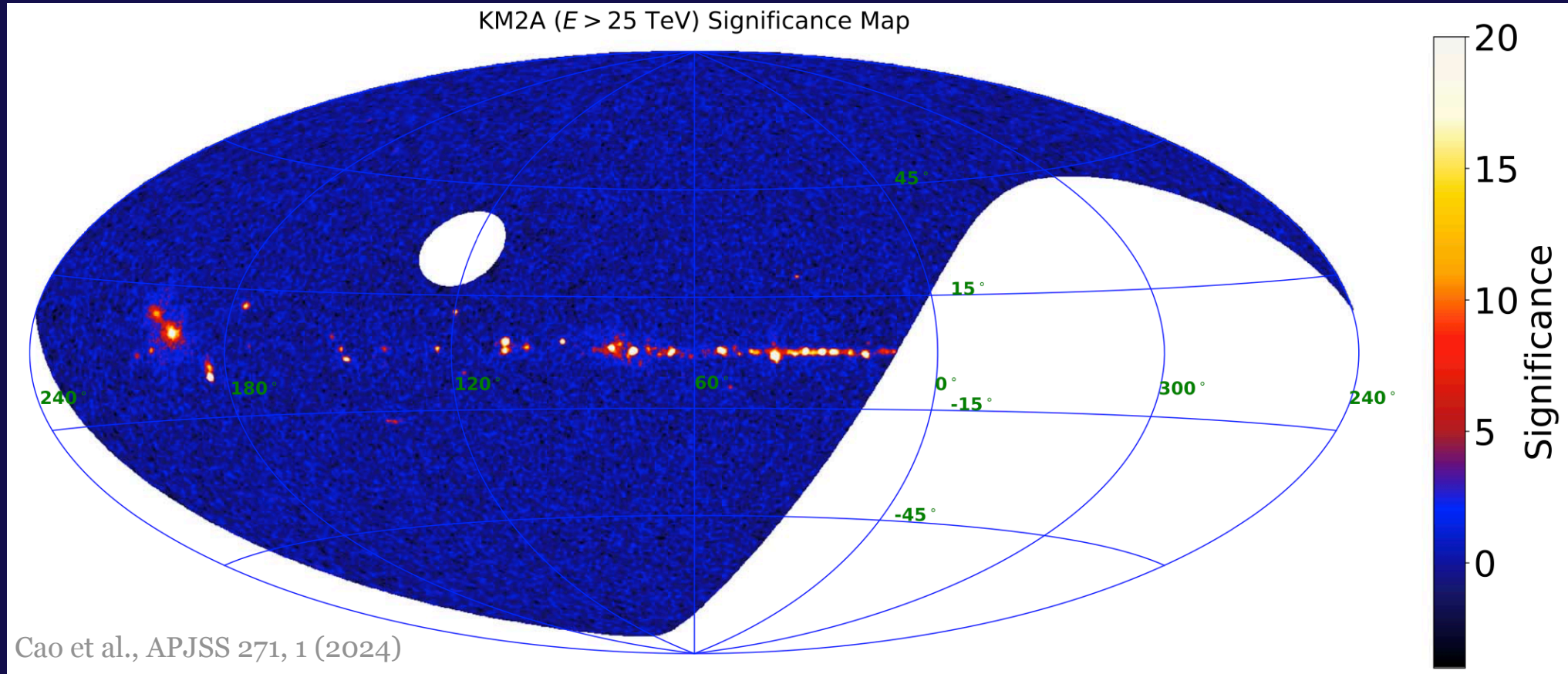
How can we find them?

- ♦ Charged cosmic rays ✗
(due to deflection by magnetic fields)
- ♦ Neutrinos ✗
(due to low statistics and poor angular resolution of current instruments)
- ♦ Gamma rays via IACTs ✗
(due to surveys being too time-consuming at large energies / low statistics)
- ♦ Gamma rays via air shower arrays ✓
(due to 24/7 observations and large field of view)



Where are these extreme accelerators?

- ◆ First LHAASO Catalog: Detection of 43 gamma-ray sources > 100 TeV (equivalent to cosmic rays > 1 PeV)



Only the beginning...

Which astrophysical objects are behind these accelerators?

Some ideas...



“Best candidates” for a long time

- ✦ Energetics: Converting ~10% of energy supernova explosion into cosmic rays can account for observed energy density at Earth
- ✦ SNR shocks can provide efficient acceleration mechanism (→ *Diffusive Shock Acceleration*)
- ✦ Magnetic fields in SNR shocks can be amplified by accelerated particles, allowing acceleration beyond PeV energies
- ✦ Locally observed energy spectra follow power law with specific spectral index, consistent with theoretical predictions

But...

- ✦ So far, SNR observations revealed cutoffs below PeV energies
- ✦ Duration of “PeVatron phase” might be limited
- ✦ No SNR might be in this phase

Which astrophysical objects are behind these accelerators?

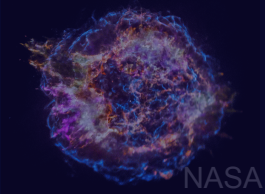
Some ideas...



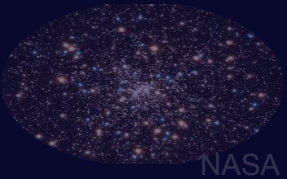
- ◆ Several possible acceleration sites, as they host hundreds of massive stars with fast winds, have turbulent interior, many potential SNRs inside them
- ◆ Active acceleration mechanism lasts up to a million years

Which astrophysical objects are behind these accelerators?

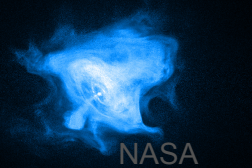
Some ideas...



Supernova Remnants



Stellar Clusters

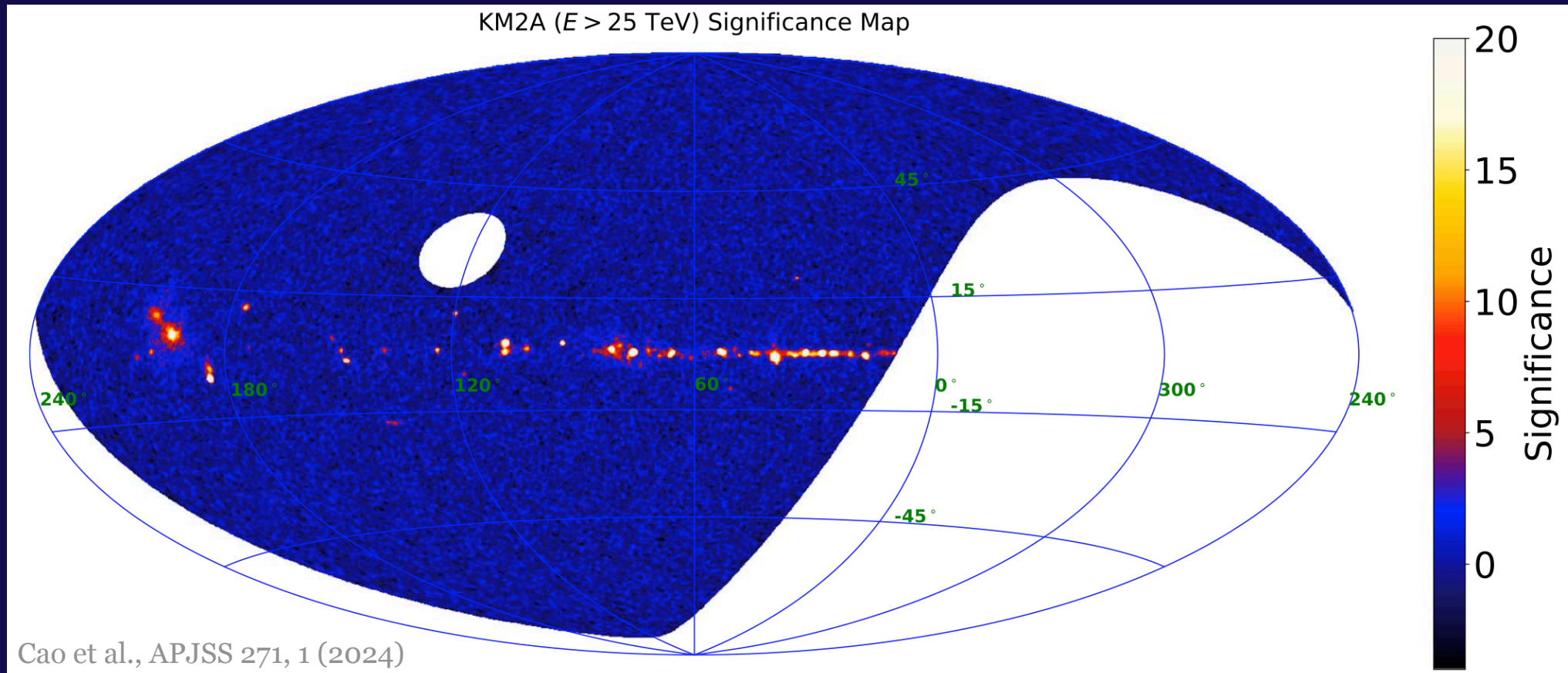


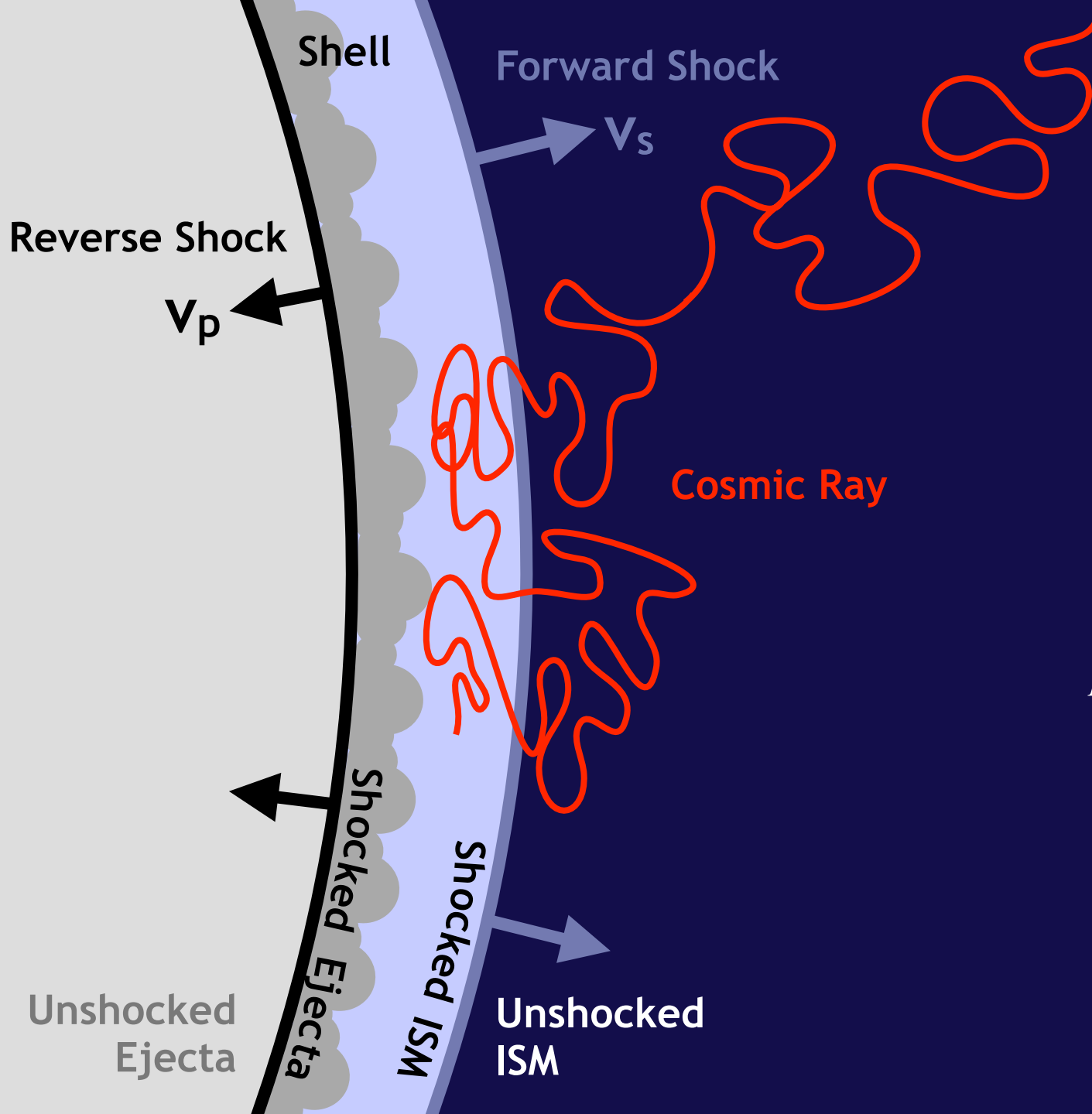
Pulsar Wind Nebulae

- ◆ Efficient acceleration, likely at termination shock of young PWN generated by pulsar wind and parent SNR
- ◆ Active acceleration for long time
- ◆ Numerous, but typically leptonic

Which astrophysical objects are behind these accelerators?

Search for objects in vicinity (< 0.5 deg) of LHAASO sources:
Only 7 out of 43 overlap with known SNRs





Cosmic-ray Escape

- ◆ Confinement condition (*Hillas criterion*): Diffusion length of particles ahead of shock cannot exceed the size of the system

$$l_{\text{dif}} = \frac{D(E)}{v_s} \lesssim R_s$$

$$R_s(t) = R_{\text{ST}} (t / t_{\text{ST}})^{2/5} \quad v_s(t) = R_{\text{ST}} / t_{\text{ST}} (t / t_{\text{ST}})^{-3/5}$$

- ◆ Time-dependent shock radius and shock velocity → **Escape is dependent on energy and time**

Particle Transport

Ginzburg, Ptuskin (1964), Skilling (1975)

$$\frac{\partial f}{\partial t} = \underbrace{Q}_{\text{Injection ("accelerated spectrum")}} + \underbrace{\nabla \cdot (D_{rr} \nabla f)}_{\text{Spatial Diffusion}} - \underbrace{\frac{\partial}{\partial p} \left(\dot{p} f \right)}_{\text{Momentum Gain / Loss}}$$

$$- \nabla \cdot (\mathbf{v} f) + \underbrace{\frac{1}{3} \frac{\partial}{\partial p} \left(p (\nabla \cdot \mathbf{v}) f \right)}_{\text{Adiabatic Momentum Gain / Loss}} + \underbrace{\frac{\partial}{\partial p} \left(p^2 D_{pp} \frac{\partial}{\partial p} \left(\frac{1}{p^2} f \right) \right)}_{\text{Diffusive Re-acceleration}} - \underbrace{\frac{1}{\tau_f} f - \frac{1}{\tau_r} f}_{\text{Losses by radioactive decay and fragmentation}}$$

Protons and electrons feature vastly different cooling times
(time taken for a particle to lose all of its energy)

- Protons: ~60 Myr in conventional ISM density ($n \sim 1 / \text{cm}^3$) and ~ 6 kyr in molecular clouds ($n \sim 10^4 / \text{cm}^3$)

$$t_{\text{cool,p}}(t) \approx 6 \times 10^7 \left(\frac{n}{\text{cm}^{-3}} \right)^{-1} \text{ yr}$$

- Electrons: Cooling typically dominated by synchrotron emission
→ electron of 1 TeV in magnetic field of 100 μG has cooling time of ~ 1 kyr

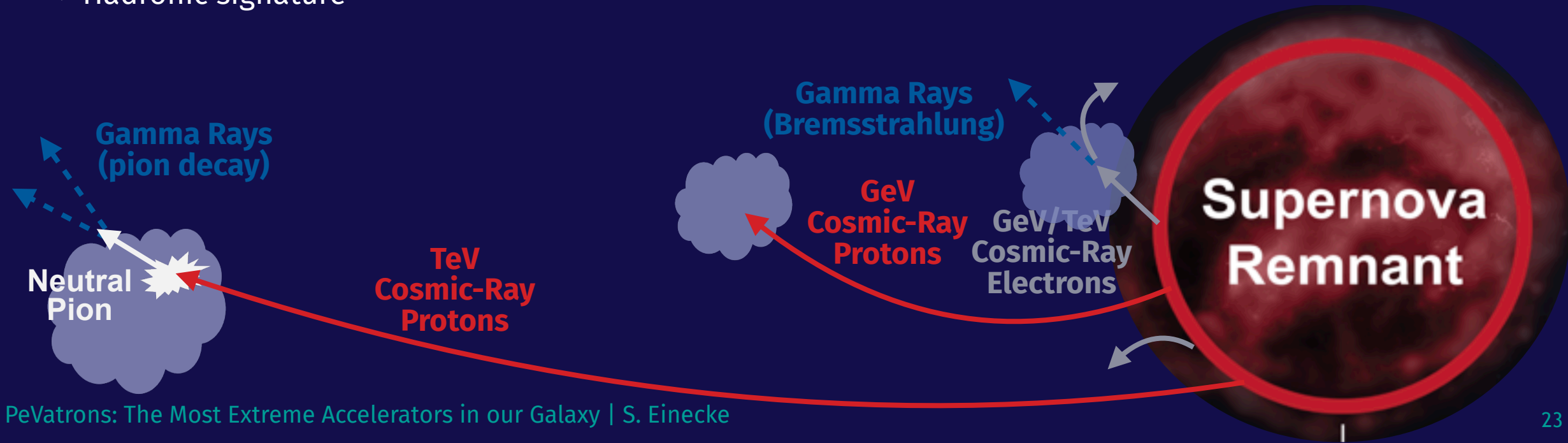
$$t_{\text{cool,e}}(E, t) \approx 12 \times 10^6 \left(\frac{B}{\mu\text{G}} \right)^{-2} \left(\frac{E}{\text{TeV}} \right)^{-1} \text{ yr}$$

Which astrophysical objects and which mechanisms are behind these accelerators?

♦ Leptonic vs hadronic scenarios

- ▶ TeV CR protons escaped during early phase have diffused substantial distance
- ▶ GeV CR protons escaped later and have diffused smaller distances
- ▶ GeV/TeV CR electrons lose their energy rapidly and diffuse only small distances

♦ Cosmic rays can escape from SNRs, propagate through the ISM and produce gamma-rays further away → Hadronic signature



- ♦ Challenge: Few astrophysical neutrinos (signal), many atmospheric neutrinos (background)
- ♦ Status: So far only 2 neutrino point sources detected
- ♦ Strategy: Stacking of multiple potential sources

Point source likelihood:

$$\log \mathcal{L} = \sum_i^{N_{evts}} \log \left(\frac{n_s}{N_{evts}} S_i + \left(1 - \frac{n_s}{N_{evts}} \right) B_i \right)$$



Stacking likelihood:

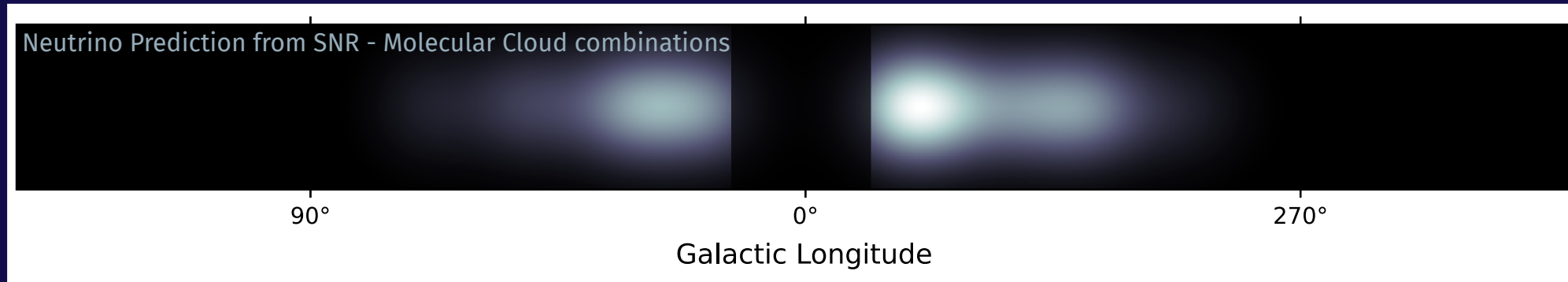
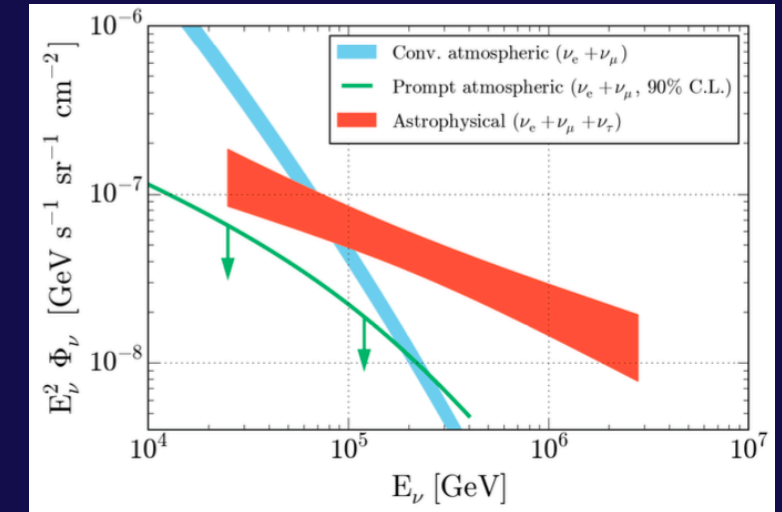
$$\sum_k n_k = n_s$$

$$\log \mathcal{L} = \sum_i^{N_{evts}} \log \left\{ \sum_k^{N_{srcs}} \left[\frac{n_k}{N_{evts}} S_{i,k} + \left(1 - \frac{n_k}{N_{evts}} \right) B_{i,k} \right] \right\}$$

- Which sources to stack?
- How many neutrinos from each source?
- What is the neutrino spectrum?

Stacking of Supernova Remnants & Gal. Plane Emission

- Strategy: Model each combination of supernova remnants and molecular clouds (from catalogues) in 3D. Vary a range of model assumptions (e.g. cloud distance, diffusion).
- Task I: Predict the most promising targets and stack them
- Task II: Can the most optimistic assumptions explain the Galactic Plane Emission?



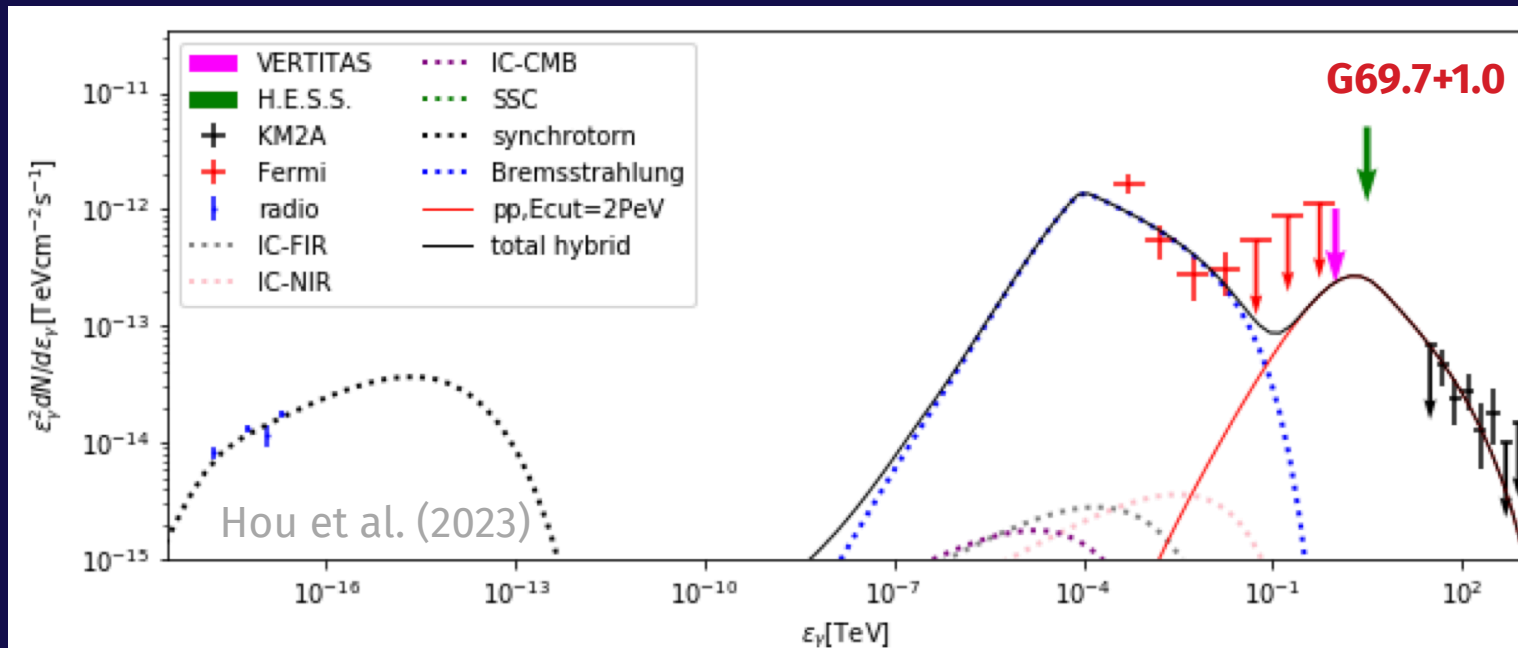
SE+ (2023): Hunting Neutrino Sources in our Galaxy: The Most Promising Targets associated with Supernova Remnants. PoS (ICRC2023) 1176.

SE+ (2023): Modelling the Transport of Particles in the Interstellar Medium. PoS (ICRC2023) 925.

Which astrophysical objects and which mechanisms are behind these accelerators?

Typical Approaches

- ◆ Power law, broken power law or similar distribution of CRs at adjacent ISM gas cloud
 - ◆ Good for comparing different SNRs and ISM gas clouds at different distances from SNR
 - ◆ Resulting parameters not directly related to mechanisms and environment
 - ◆ Physical motivation: Simplified assumptions about time evolution and particle diffusion can lead to power law Gabici (2009) or broken power law Ohira (2011)

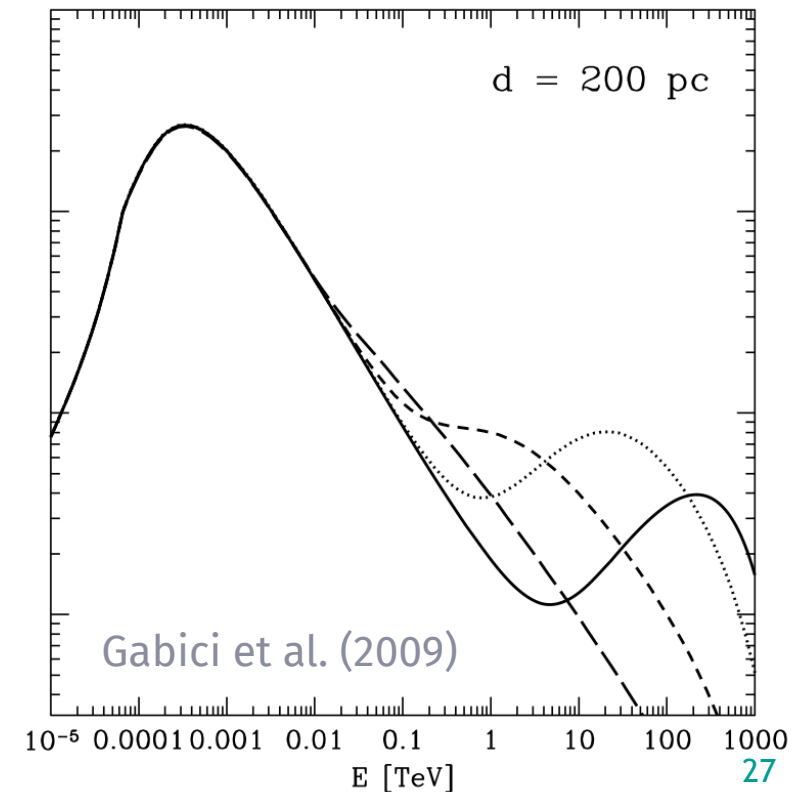
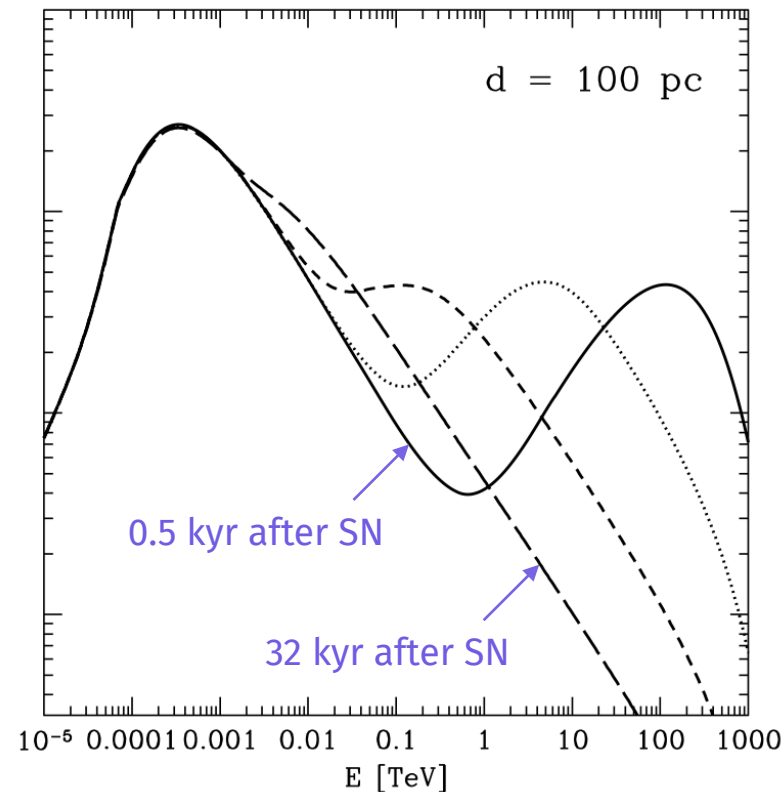
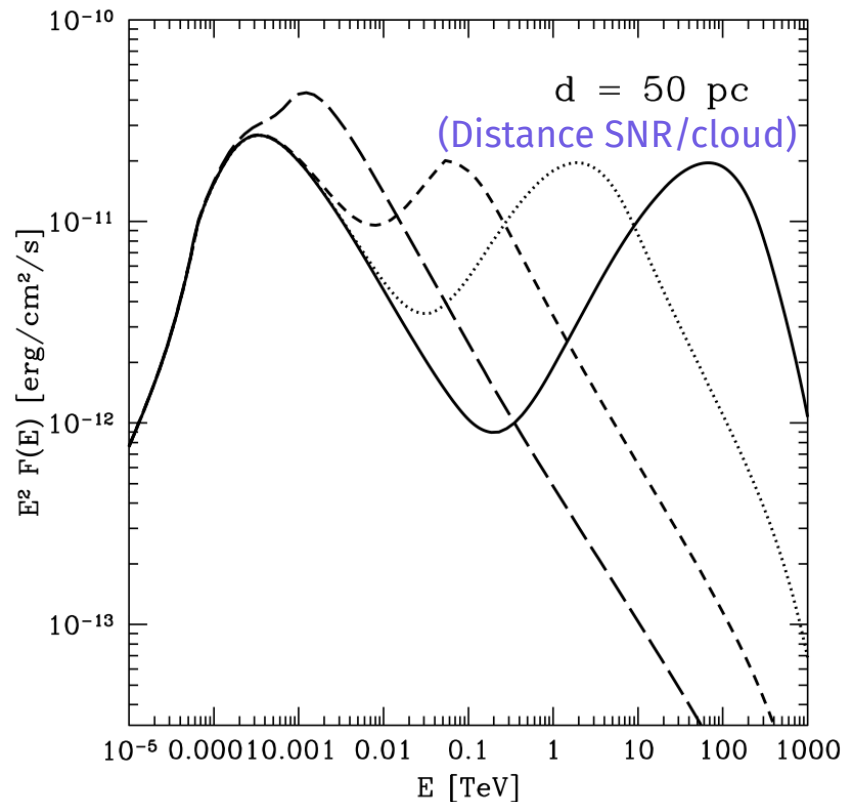


$$\frac{dN_p}{d\varepsilon_p} \propto \varepsilon_p^{-2.6} \exp[-(\varepsilon_p/2\text{PeV})]$$
$$\frac{dN_e}{d\varepsilon_e} \propto \varepsilon_e^{-2.4} \exp[-(\varepsilon_e/0.1\text{TeV})]$$

Which astrophysical objects and which mechanisms are behind these accelerators?

Typical Approaches

- ♦ CR distribution at fixed distance by analytically solving transport equation
 - ♦ Immediate conclusions about SNR and environment
 - ♦ Requires simple assumptions
(only spatial diffusion and radiative losses, spherical symmetry, isotropic and homogeneous external fields, ...)
 - ♦ Extension of ISM gas cloud (and anisotropic CR distribution over cloud) not taken into account

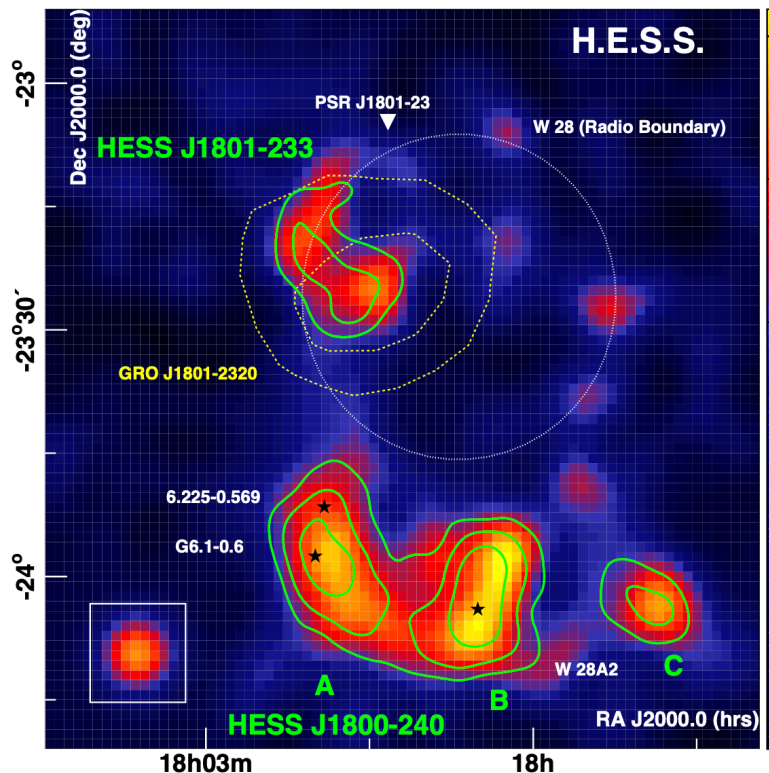


Which astrophysical objects and which mechanisms are behind these accelerators?

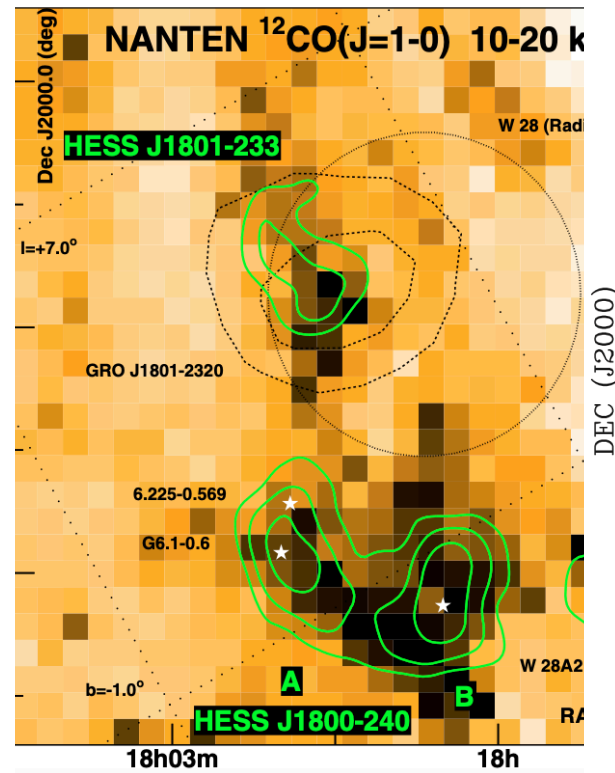
Typical Approaches

- ♦ Search for spatial correlation between ISM and gamma-ray observations
 - ♦ Good indicator for interaction of CRs and ISM gas
 - ♦ Conclusions about mechanisms and environment limited

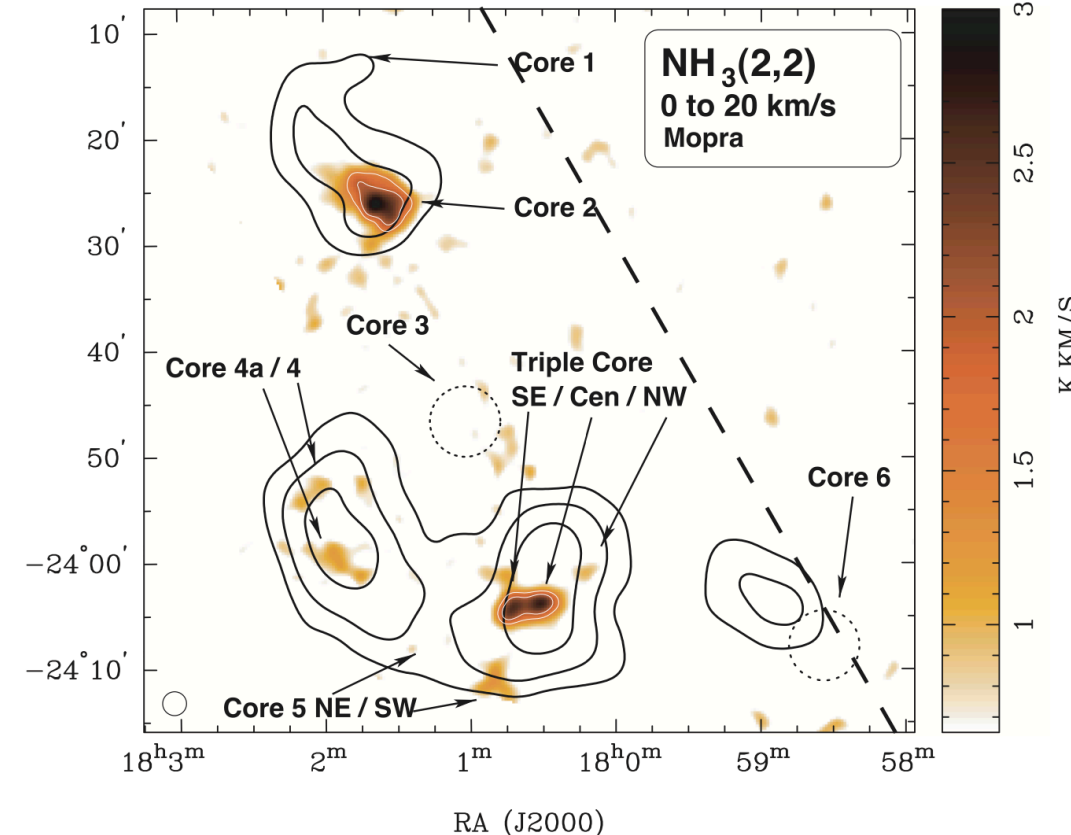
Aharonian et al. (2008)



Aharonian et al. (2008)



Nicholas et al. (2011)

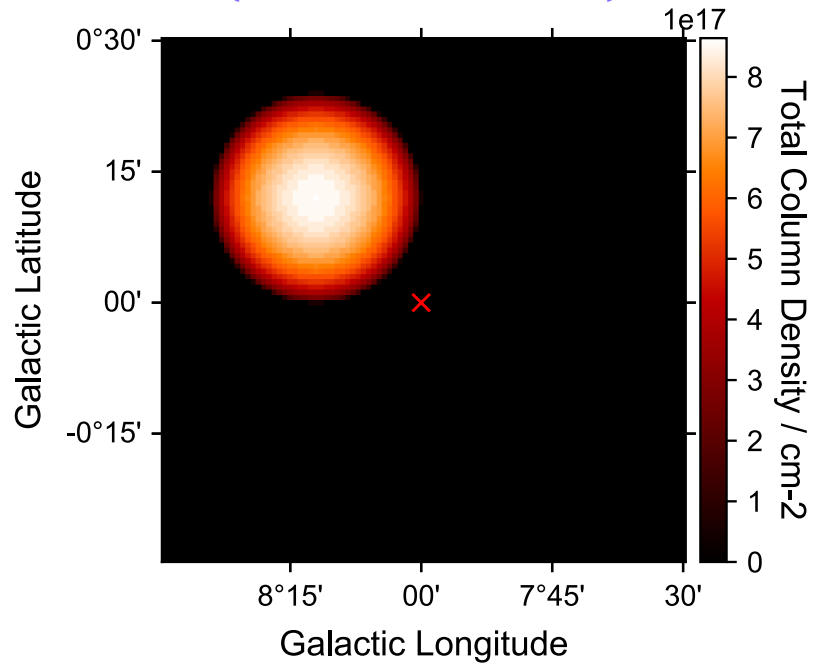


3D Modelling

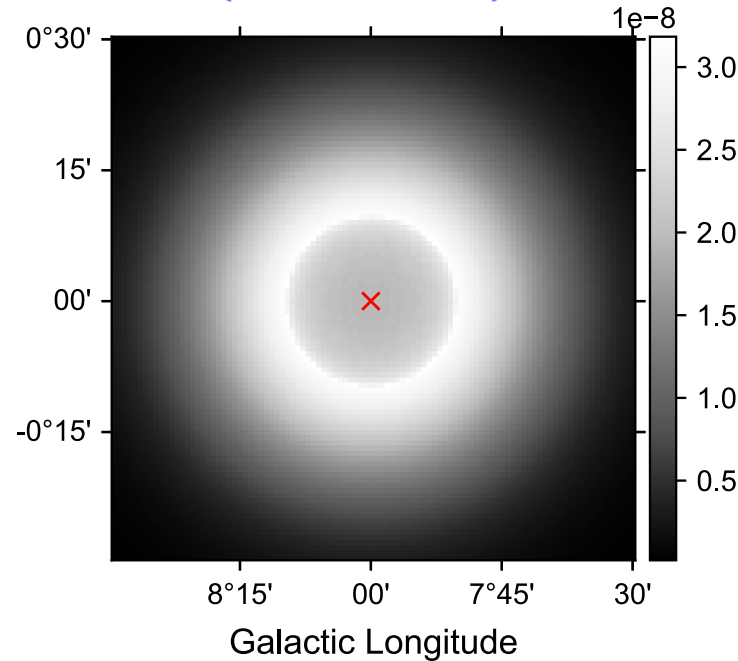
Strategy: Derive cosmic-ray, ISM & gamma-ray densities for small regions (= pixels)

- ◆ Use 3D pixels (= voxels)
- ◆ Include model for cosmic rays that have not escaped yet

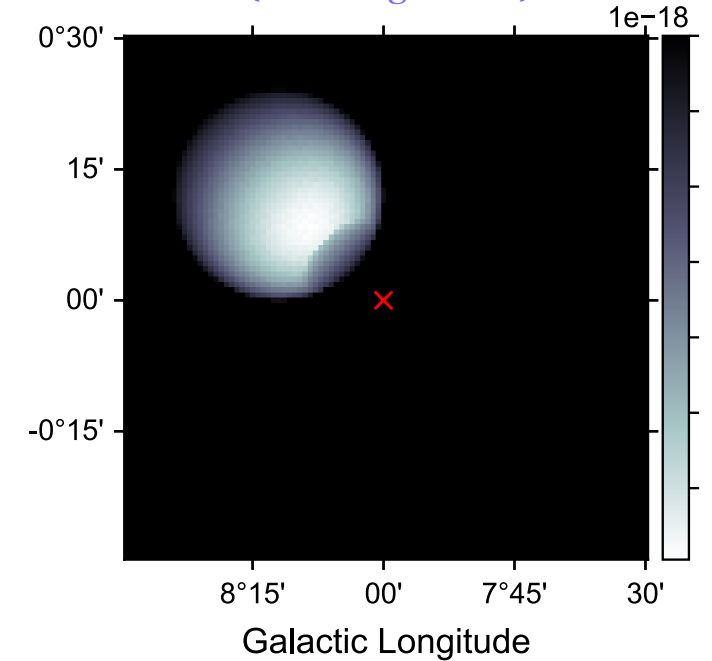
Interstellar Gas
(based on observations)



Cosmic-ray Flux
(based on model)



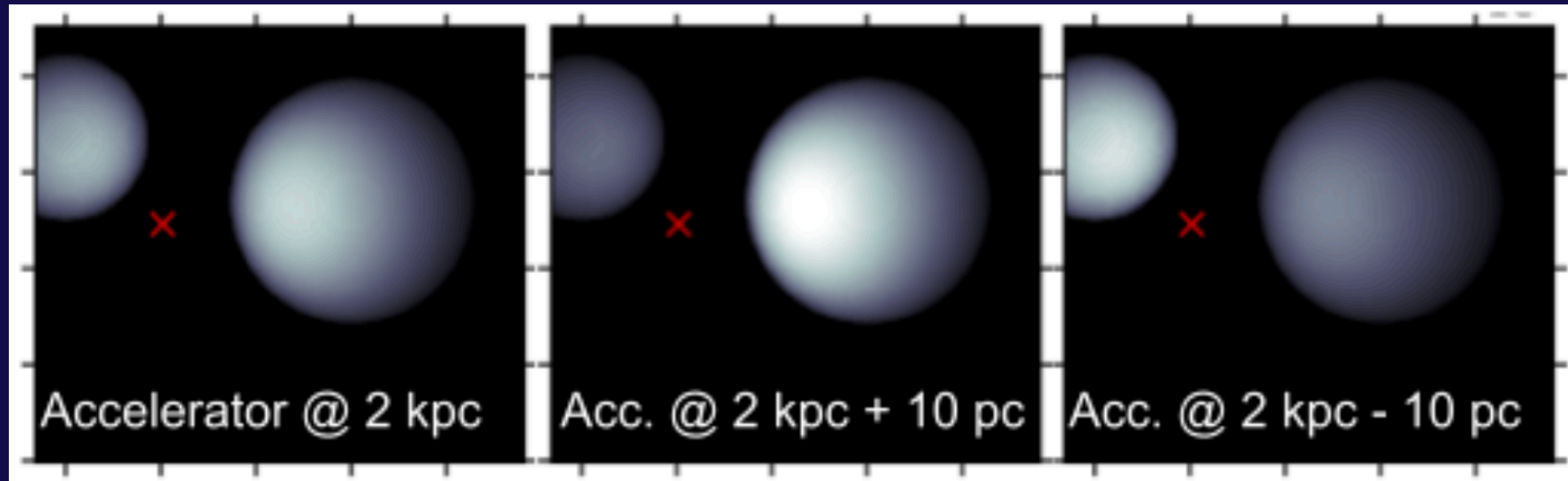
Gamma-ray Flux
(resulting model)



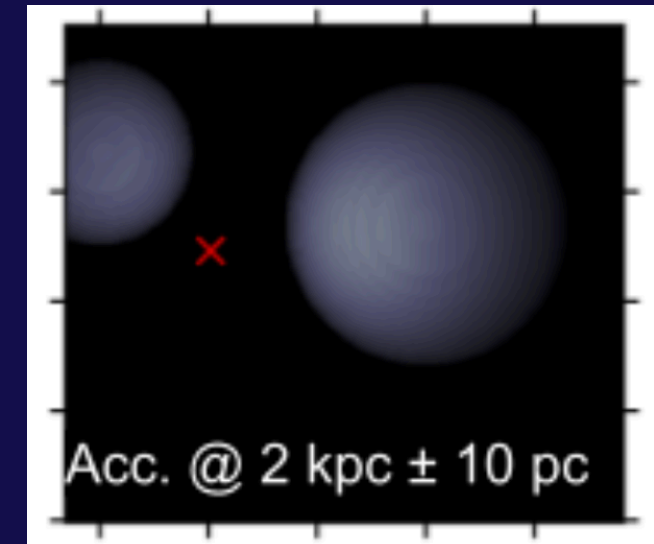
3D Modelling: Importance

Example: Clouds @ (2 kpc - 15 pc) and (2 kpc + 15 pc)

3D

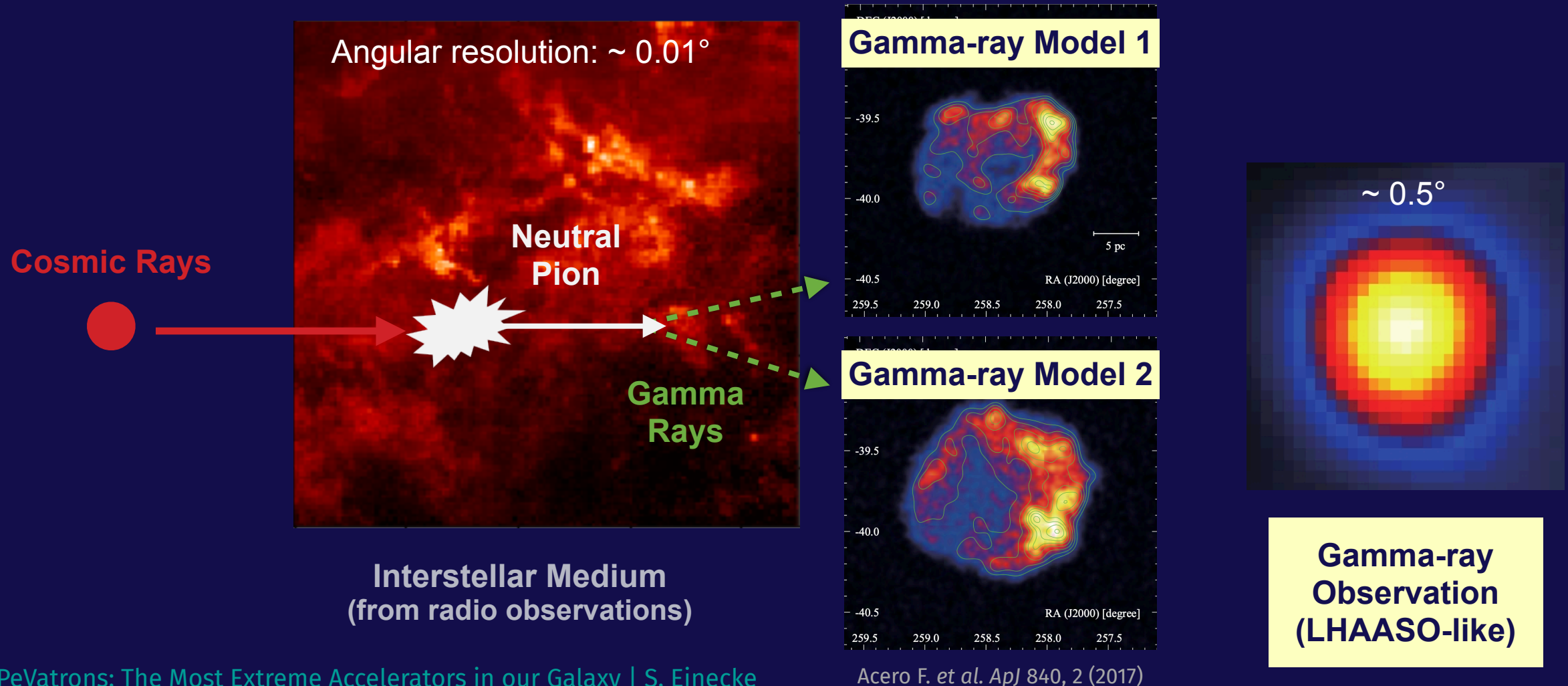


2D

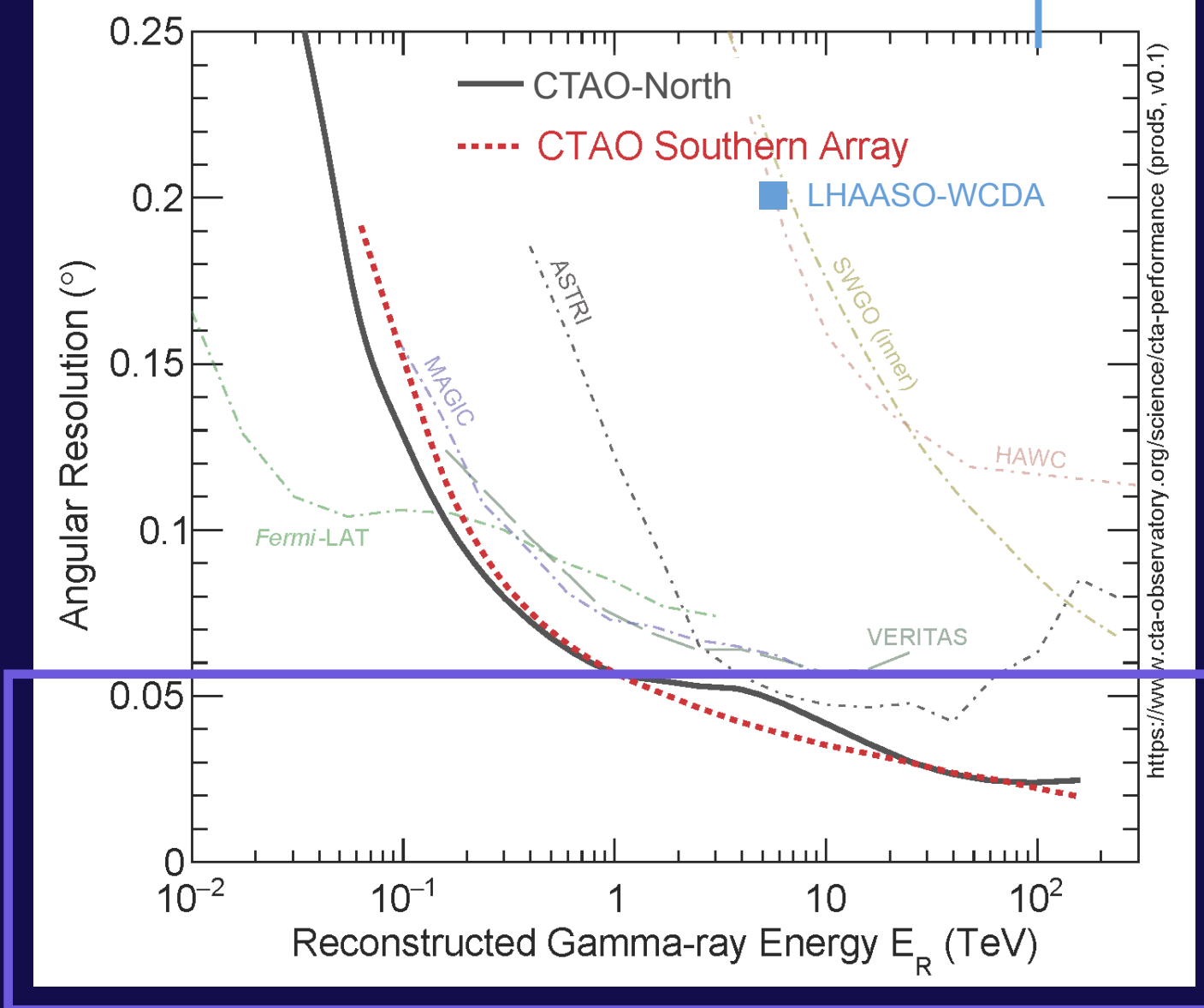


Which astrophysical objects and which mechanisms are behind these accelerators?

Strategy: Model acceleration and emission of potential objects and compare with observations



Critical angular resolution
for IDENTIFYING and UNDERSTANDING
accelerators!



Cherenkov Telescope Array Observatory

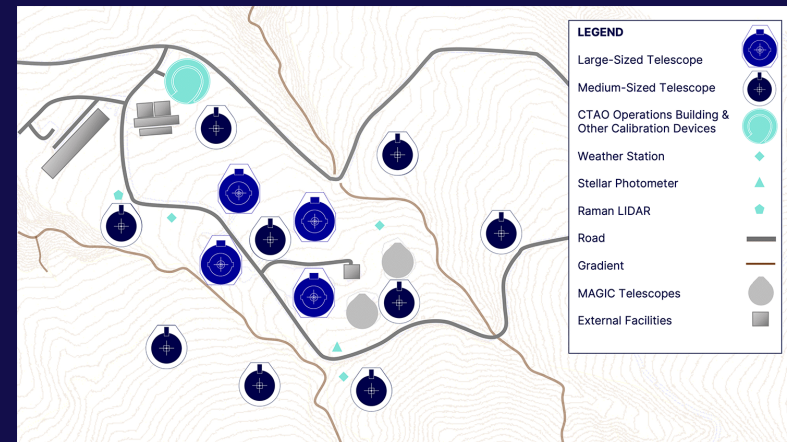
CTAO

- ◆ Next-generation High-Energy Discovery Machine
- ◆ EUR 330M project, >1,500 scientists from 25 countries

CTAO-South
@ Paranal, Chile:
14 medium-sized
telescopes,
37 small-sized
telescopes

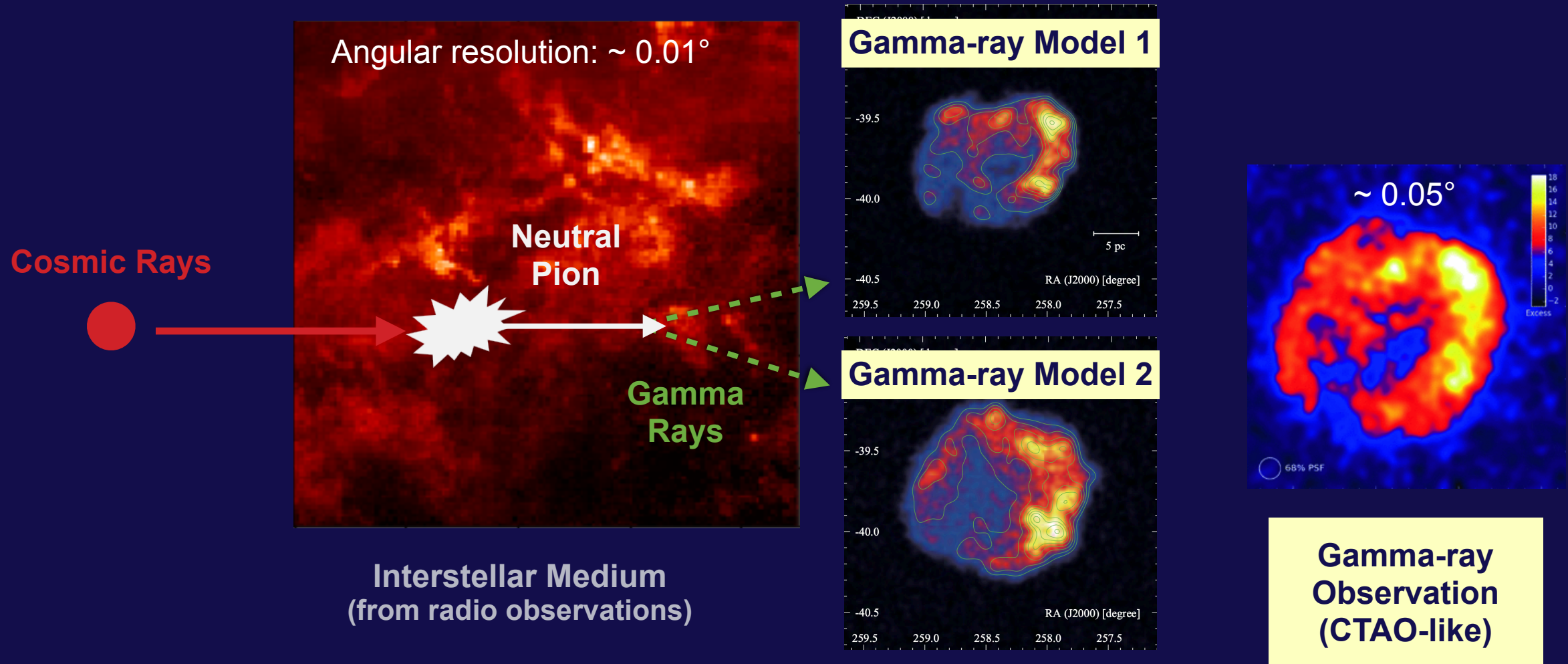


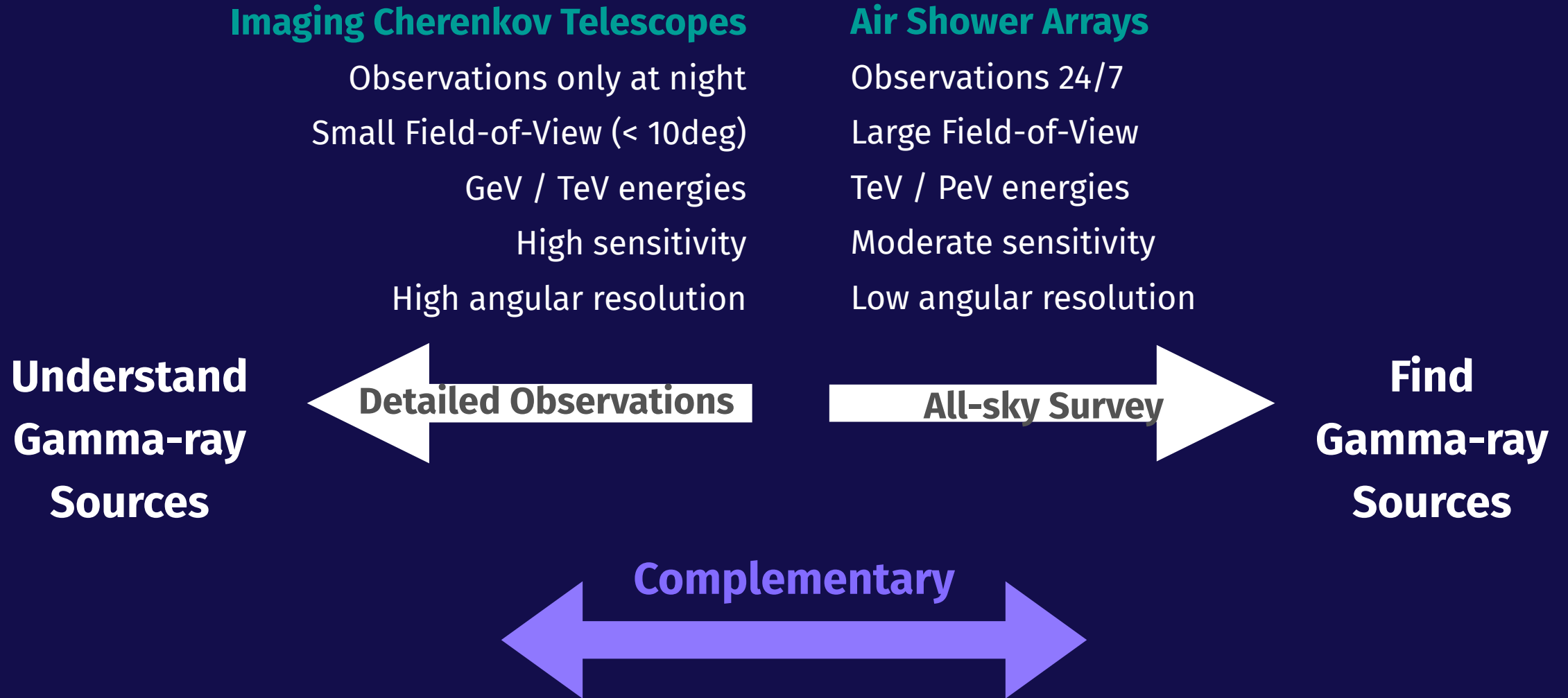
CTAO-North
@ La Palma, Spain:
4 large-sized
telescopes,
9 medium-sized
telescopes



Which astrophysical objects and which mechanisms are behind these accelerators?

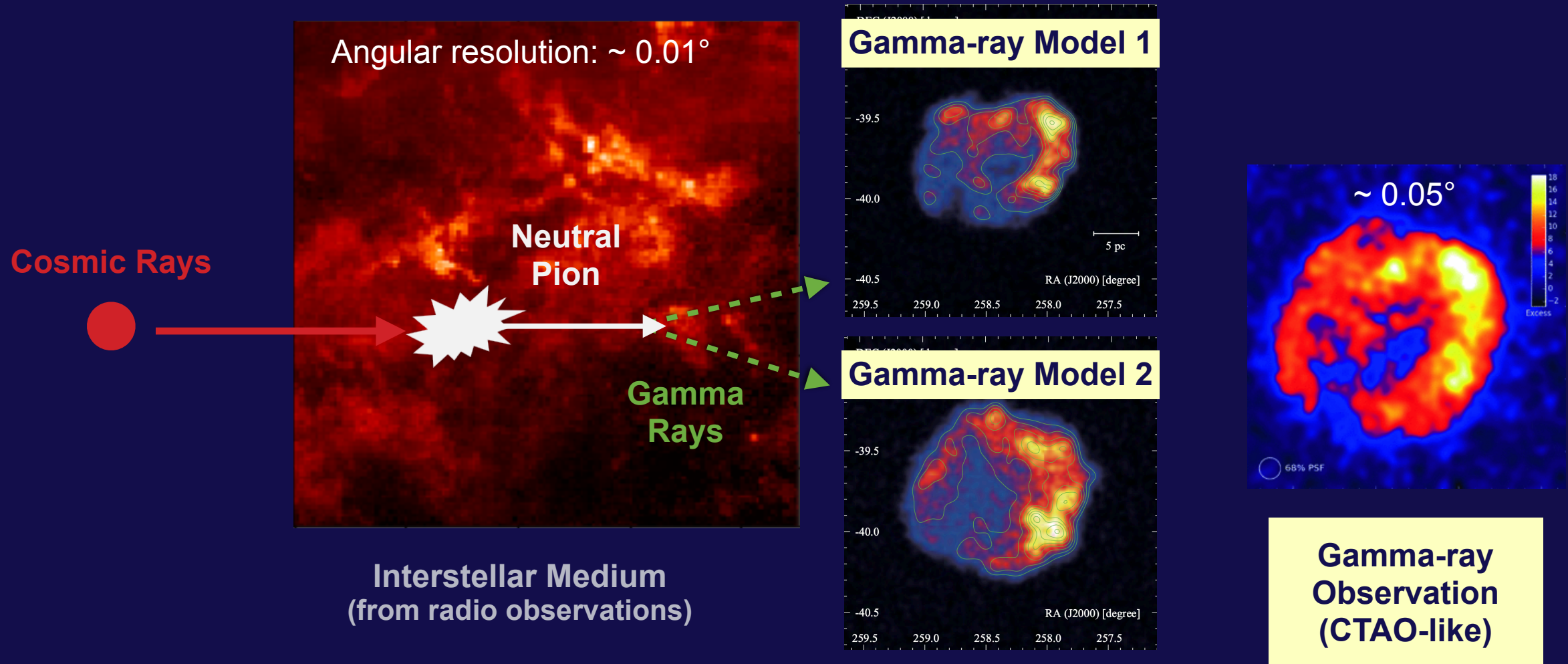
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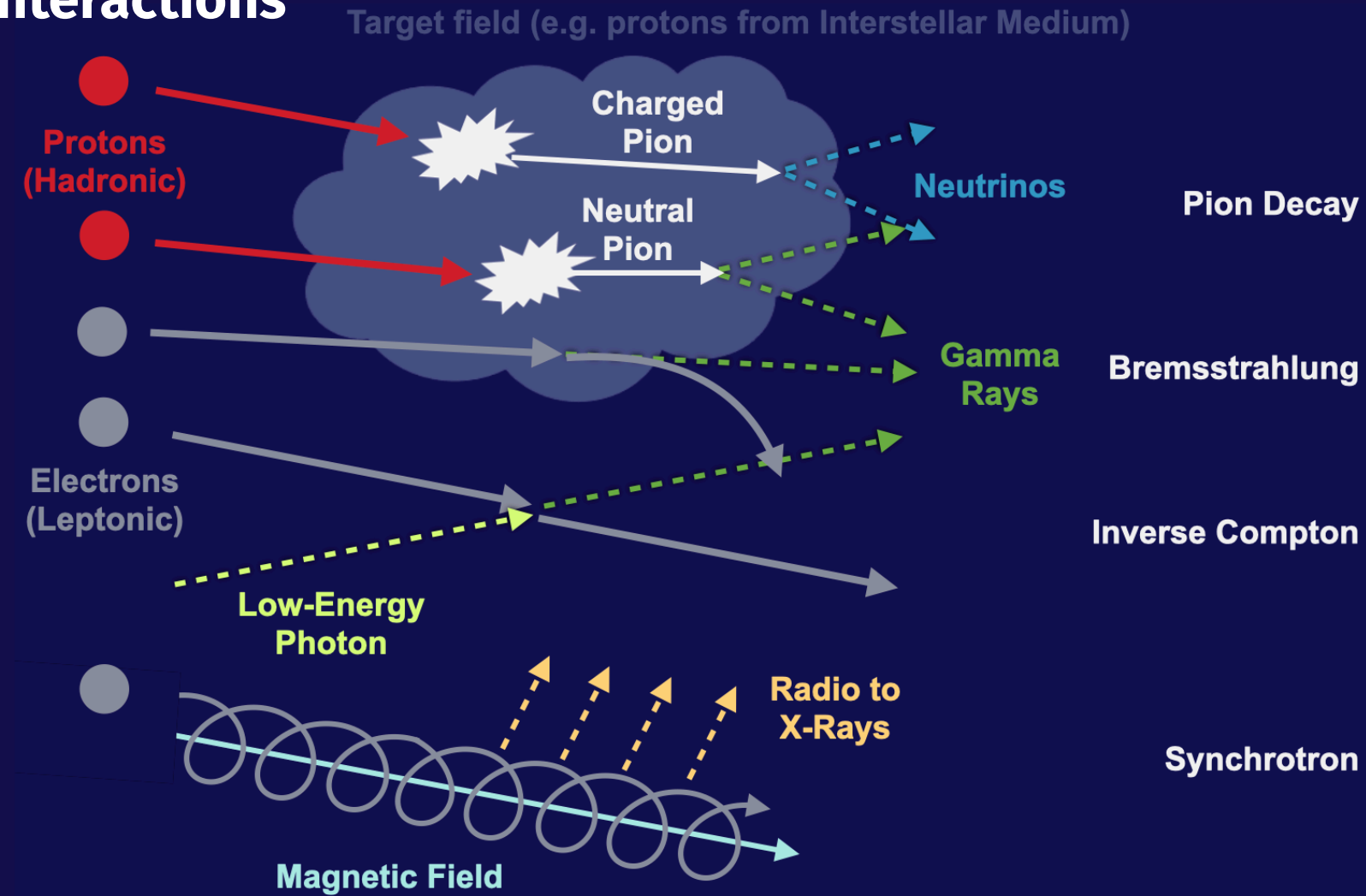


Which astrophysical objects and which mechanisms are behind these accelerators?

Strategy: Model acceleration and emission of potential objects and compare with observations



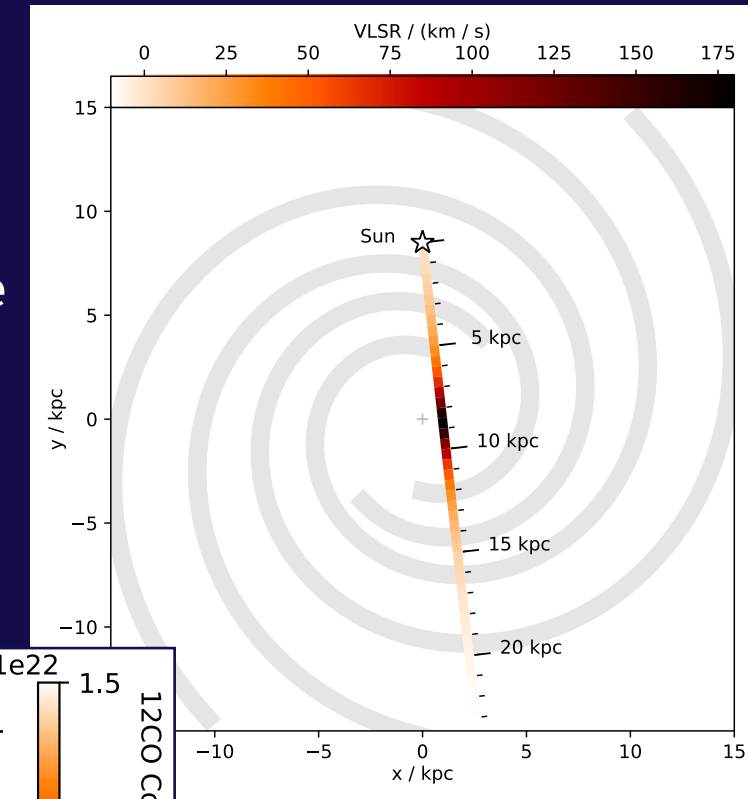
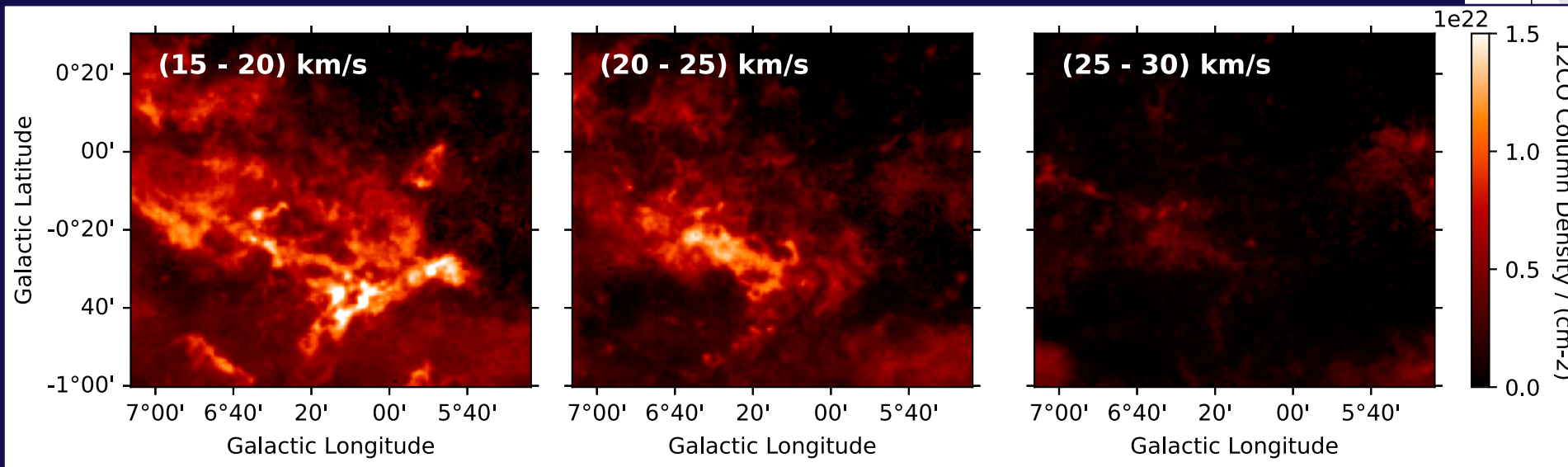
Cosmic-ray Interactions



Modelling: Interstellar Medium

Challenges

- ✦ Measurement of line-of-sight Doppler velocities instead of physical distance
- ✦ Model of Galaxy's rotation translates these velocities to distances, but ...
 - ... often it has two solutions ('near' and 'far' distance)
 - ... it does not consider local motions of the ISM
 - ... it produces rather large uncertainties (for our application)

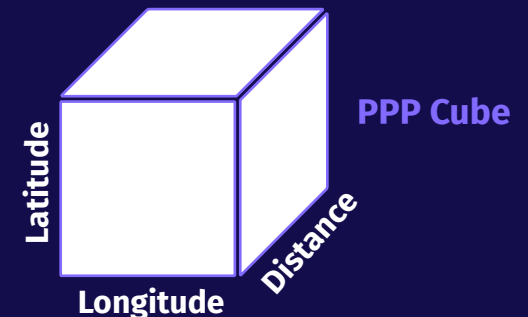
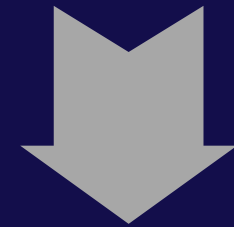
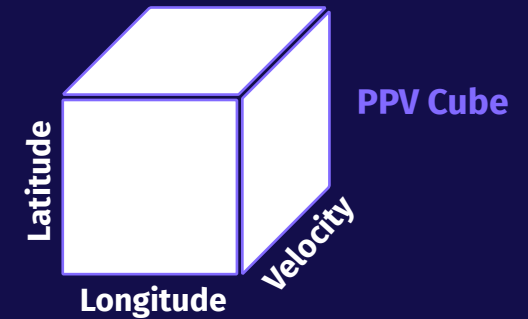


Optimisation Approach

- Location of individual clouds
- Selection of individual clouds
 - Need to know which voxel (=3D pixel) belongs to which cloud

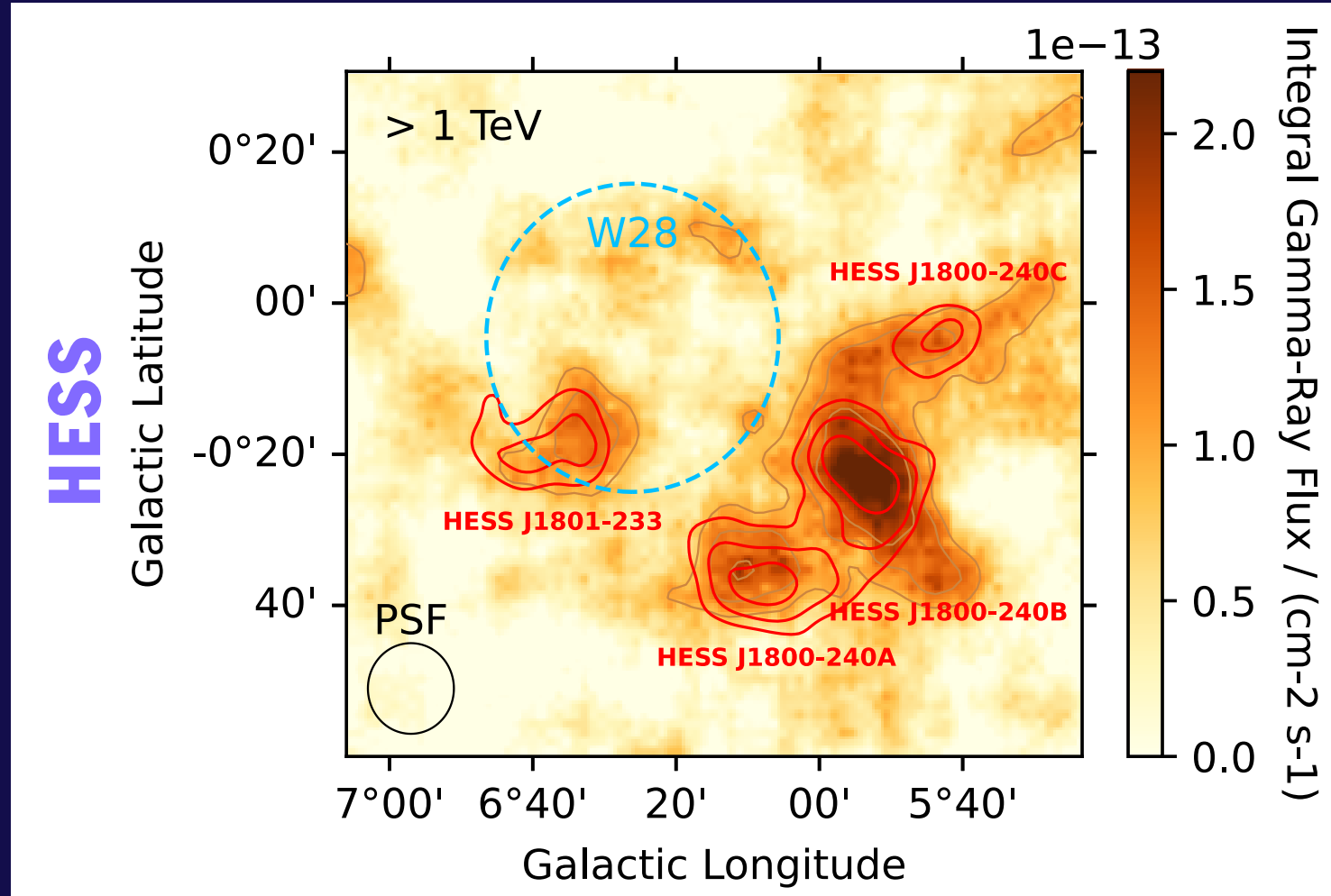
Identification of Individual Clouds

- Gaussian decomposition** with GaussPy+ (Riener et al., A&A 628 (2019) A78),
- Hierarchical clustering** with astrodendro:
 - Determines label for each component, specifying which molecular cloud it belongs to
- Selection of clouds to be included in final cube
- Selection of each cloud's location in final cube
 - Capable of separating overlapping clouds
 - Capable of moving clouds along distance axis separately



Proof of Concept: Supernova Remnant W28

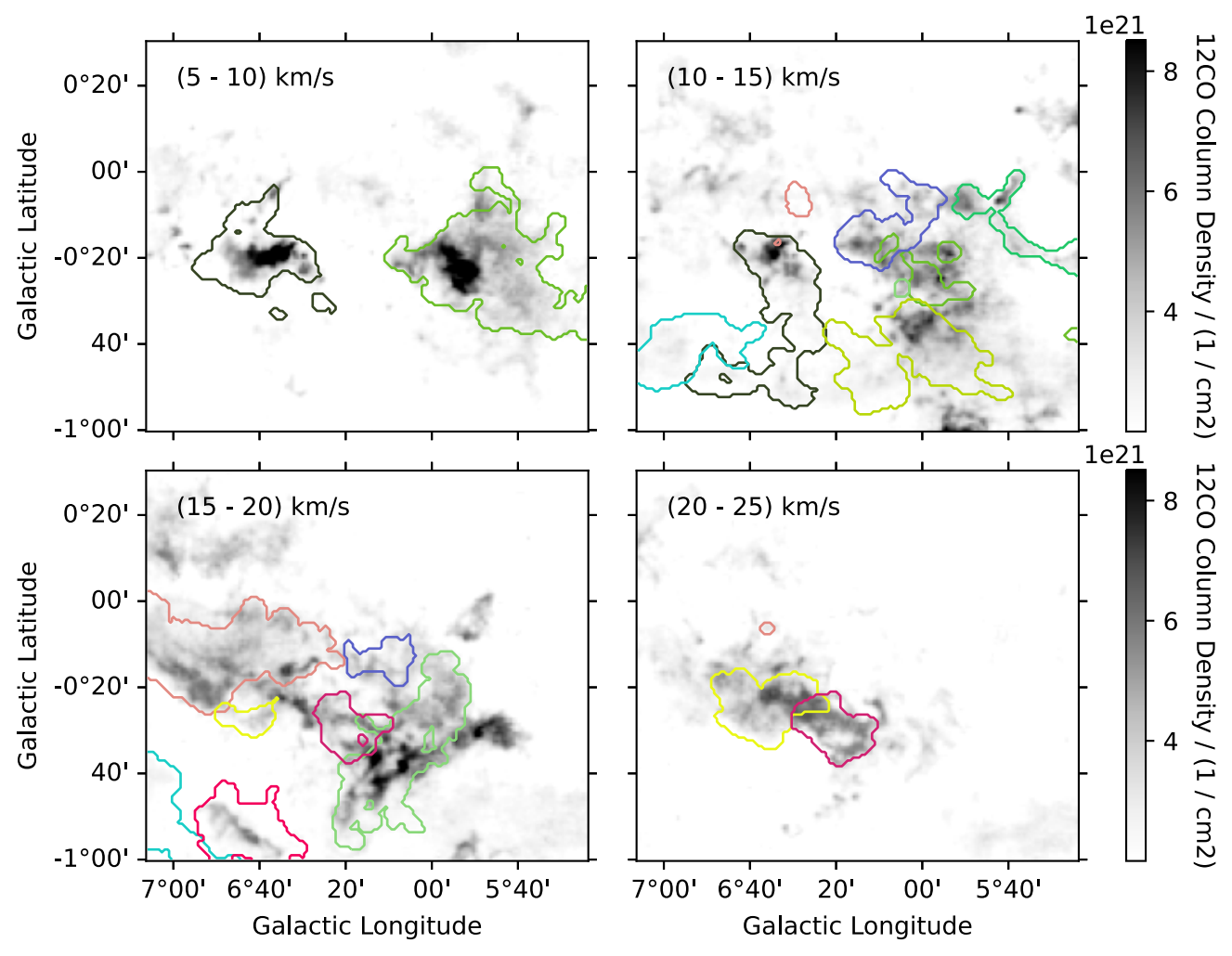
TeV Gamma-ray Observations



HESS Collab., A&A 612 (2018) A1
Aharonian et al., A&A 481 (2010) 401

Proof of Concept: Supernova Remnant W28

Results: ISM Cloud Clustering

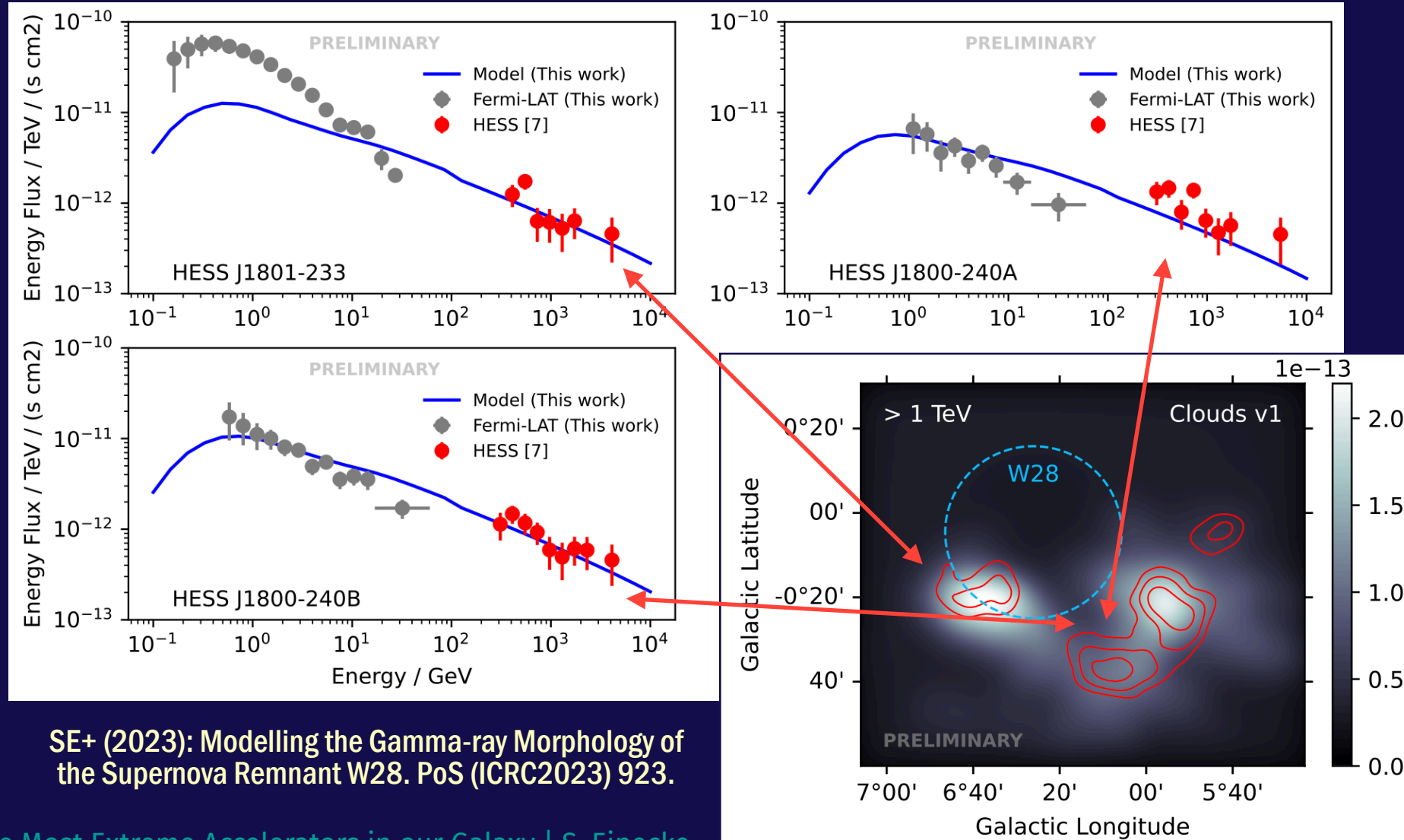


GLON / deg	GLAT / deg	Velocity / (km/s)	Components	Mass / (1e ³ M _⊙)	Y/N
5.8 ± 0.4	-0.4 ± 0.3	8.7 ± 2.0	1510	19.9	Y
6.6 ± 0.3	-0.4 ± 0.5	10.2 ± 5.3	1239	16.3	Y
6.0 ± 0.3	-0.7 ± 0.2	11.4 ± 1.4	794	8.7	Y
5.7 ± 0.3	-0.2 ± 0.2	12.6 ± 1.0	234	2.8	Y
6.1 ± 0.2	-0.2 ± 0.2	14.3 ± 2.3	434	6.7	Y
7.0 ± 0.2	-0.7 ± 0.3	14.4 ± 4.1	641	7.3	N
6.1 ± 0.3	-0.6 ± 0.4	17.9 ± 2.0	946	13.1	Y
6.8 ± 0.4	-0.2 ± 0.2	18.1 ± 1.9	1297	20.1	N
6.7 ± 0.2	-0.9 ± 0.1	18.6 ± 0.8	537	3.5	N
6.3 ± 0.2	-0.5 ± 0.1	20.5 ± 1.1	319	5.6	Y
6.6 ± 0.2	-0.4 ± 0.1	21.8 ± 3.0	577	6.4	Y

SE+ (2023): Modelling the Gamma-ray Morphology of the Supernova Remnant W28. PoS (ICRC2023) 923.

Proof of Concept: Supernova Remnant W28

Results: Modelled Gamma-ray Spectrum und Morphology



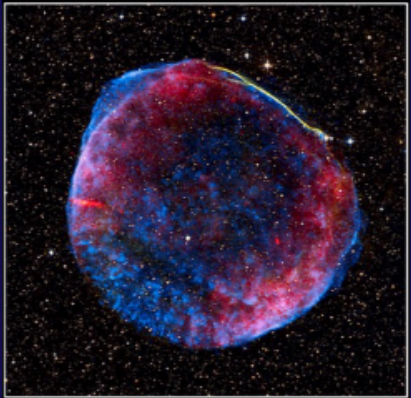
SE+ (2023): Modelling the Gamma-ray Morphology of the Supernova Remnant W28. PoS (ICRC2023) 923.

Legacy tool for complex arcminute-scale 3D modelling

- ◆ Framework for implementing scenarios with varying complexity
- ◆ Focus on modularity, user-friendliness, adaptability
- ◆ Particle transport of hadronic & leptonic cosmic rays, including numerical solutions for diffusion, advection, and energy loss in anisotropic and inhomogeneous environments  
- ◆ Production of photons, gamma rays and neutrinos, including neutrino oscillation and gamma-ray absorption 
- ◆ Configuration for supernova remnants, massive stellar clusters, and pulsar wind nebulae, e.g. magnetic field distributions and particle escape specific to these objects    
- ◆ Cloud clustering using different gas tracers, including combination of results 
- ◆ Access to ISM cloud catalogues 
- ◆ Access to diffuse gamma-ray emission models (from GALPROP) 

- ◆ PeVatrons: The most extreme accelerators in our Galaxy!
 - ◆ Where are these objects? - Close to gamma-ray sources > 100 TeV
 - ◆ How can we find them? - LHAASO
 - ◆ How can we identify and characterise the accelerator? - CTAO
 - ◆ Related to solving the century-long mystery of the origin of Galactic Cosmic Rays
- ◆ Multi-messenger astronomy: Cosmic rays, gamma rays and neutrinos
- ◆ Multi-wavelength astronomy: Required for modelling and measuring the interstellar medium
- ◆ CTAO and LHAASO complementary - we require both!
- ◆ Gamma and neutrino observations complementary - we require both!





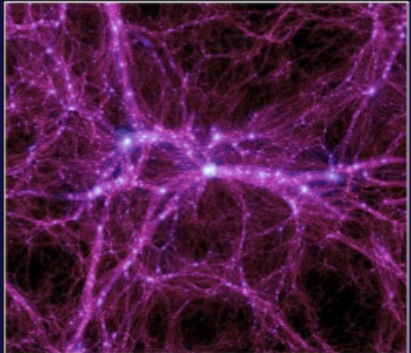
Understanding the Origin and Role of Relativistic Cosmic Particles

- ✦ What are the sites of high-energy particle acceleration in the Universe?
- ✦ What are the mechanisms for cosmic particle acceleration?
- ✦ What role do accelerated particles play in feedback on star formation and galaxy evolution?



Probing Extreme Environments

- ✦ What physical processes are at work close to neutron stars and black holes?
- ✦ What are the characteristics of relativistic jets, winds and explosions?
- ✦ How intense are radiation fields and magnetic fields in cosmic voids?



Physics Frontiers

- ✦ What is the nature of dark matter?
- ✦ Are there quantum gravitational effect on photon propagation?
- ✦ Do axion-like particles exist?

Key Science Projects / Programmes

- ◆ Dark Matter Programme
- ◆ Galactic Centre
- ◆ Galactic Plane Survey
- ◆ Large Magellanic Cloud Survey
- ◆ Extragalactic Survey
- ◆ Transients
- ◆ Cosmic-Ray PeVatrons
- ◆ Star-forming Systems
- ◆ Active Galactic Nuclei
- ◆ Cluster of Galaxies
- ◆ Beyond Gamma Rays

Observation Types

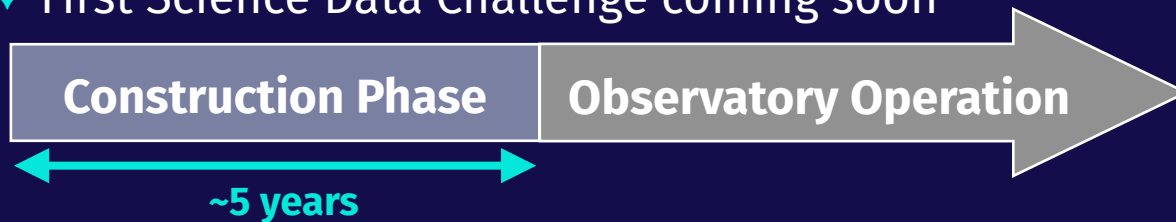
- Sky surveys
- Deep targeted observations
- Follow-up of transient and multi-messenger events
- Monitoring of variability



- ✦ CTAO is more than only a *[insert your physics here]* experiment!
- ✦ CTAO will be the first ground-based gamma-ray observatory with open access (proprietary period ~1 year)
- ✦ Major performance improvements compared to current instruments
- ✦ Funding (~330MEuro) for first construction phase secured (4 LSTs, 23 MSTs, 37 SSTs)

Get ready for early science NOW!

- ✦ CTAO will perform sky surveys, deep observations, follow ups, monitoring
- ✦ Extensive science programme to answer key questions and unveil the VHE gamma-ray sky
- ✦ Important multi-wavelength and multi-messenger synergies
- ✦ First Science Data Challenge coming soon



**from emission
to discovery**

More information at www.cta-observatory.org

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www.cta-observatory.org/consortium_acknowledgments/