MULTIWAVELENGTH STUDY OF GALACTIC COSMIC-RAYS

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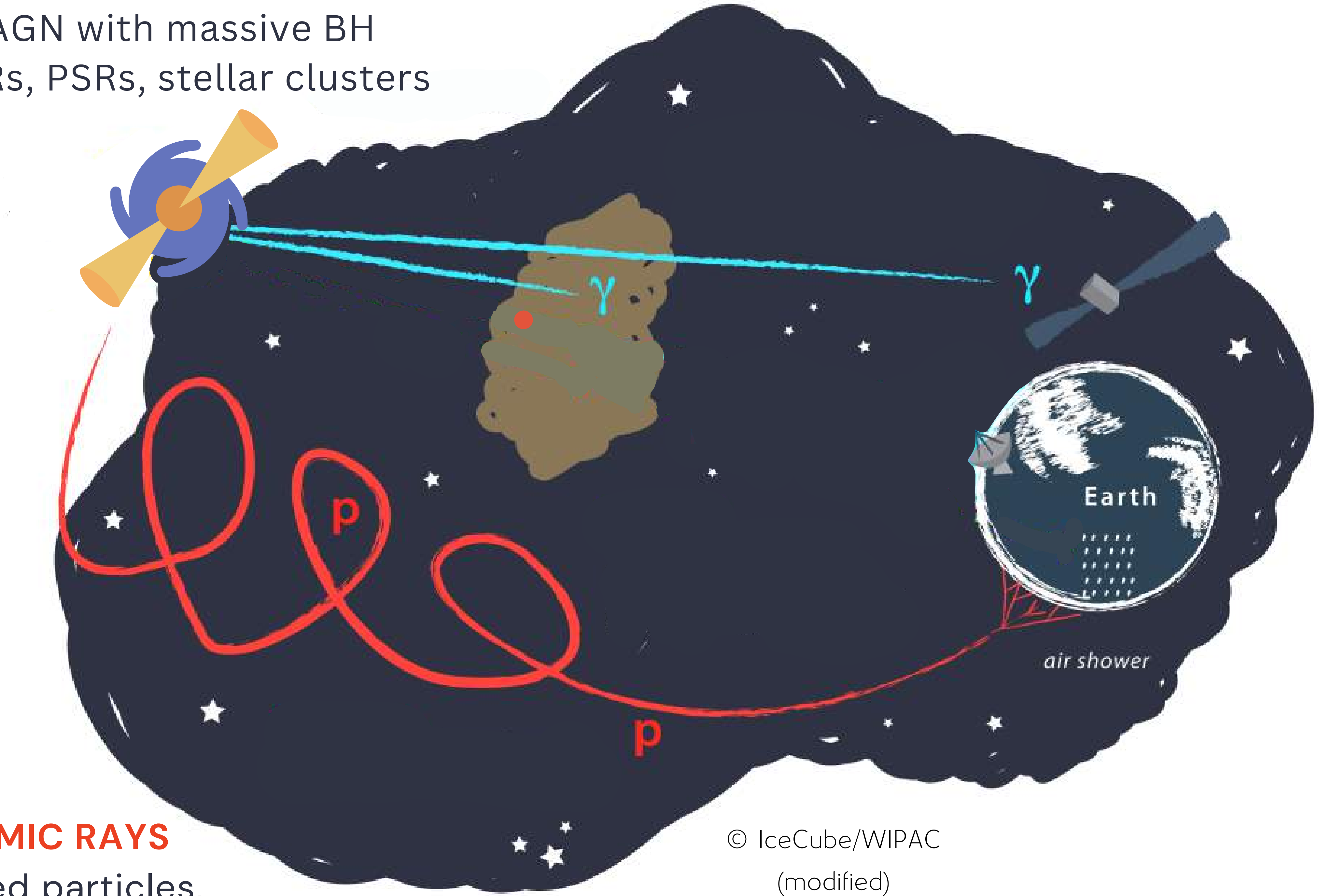
INTRODUCTION: what is the origin of galactic cosmic-rays?

VIOLENT PHENOMENA → POWERFUL ACCELERATORS
AGN with massive BH
SNRs, PSRs, stellar clusters



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COSMIC RAYS
Charged particles, deflected by magnetic fields

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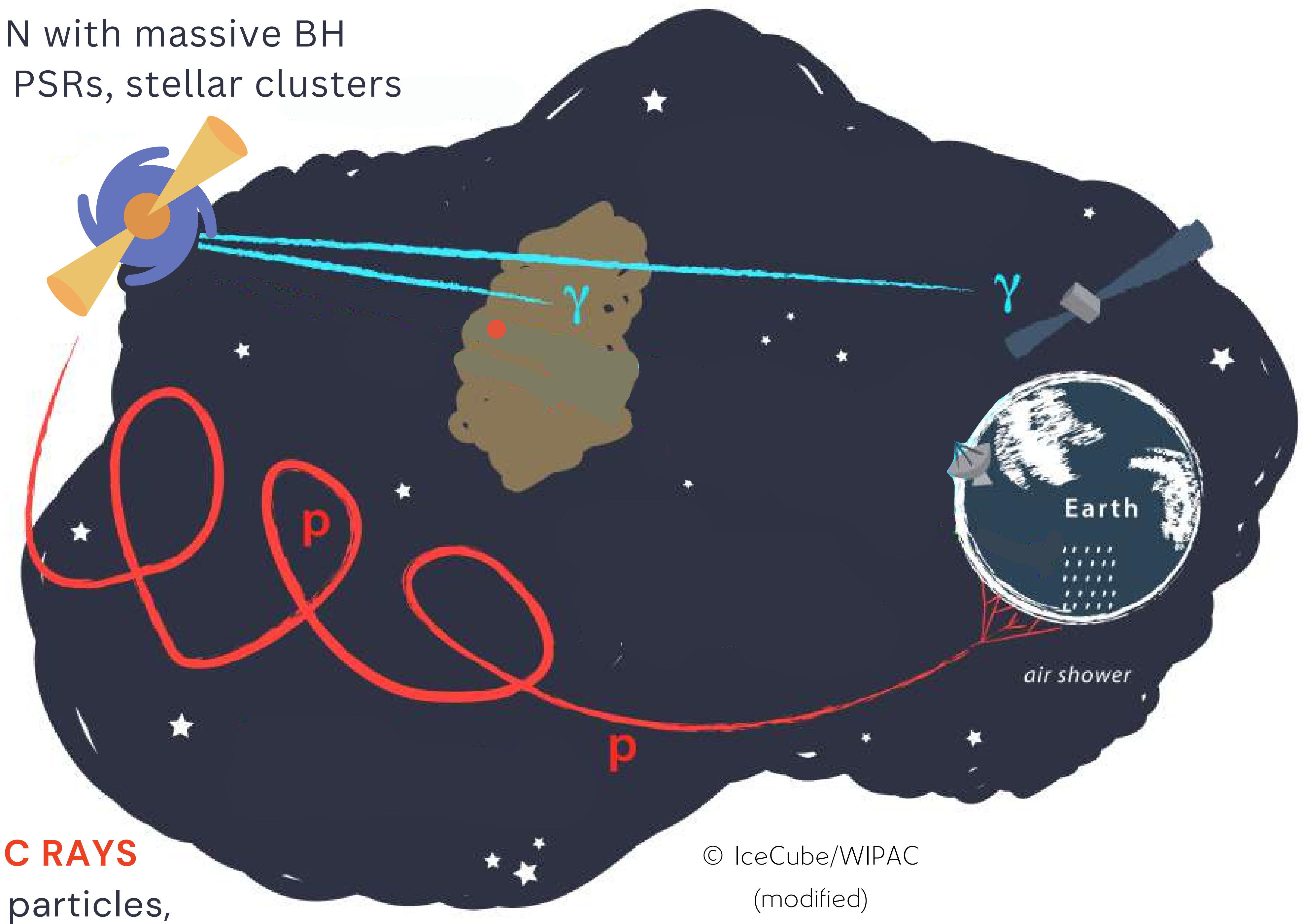

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How to point back to the violent phenomena in our Galaxy?

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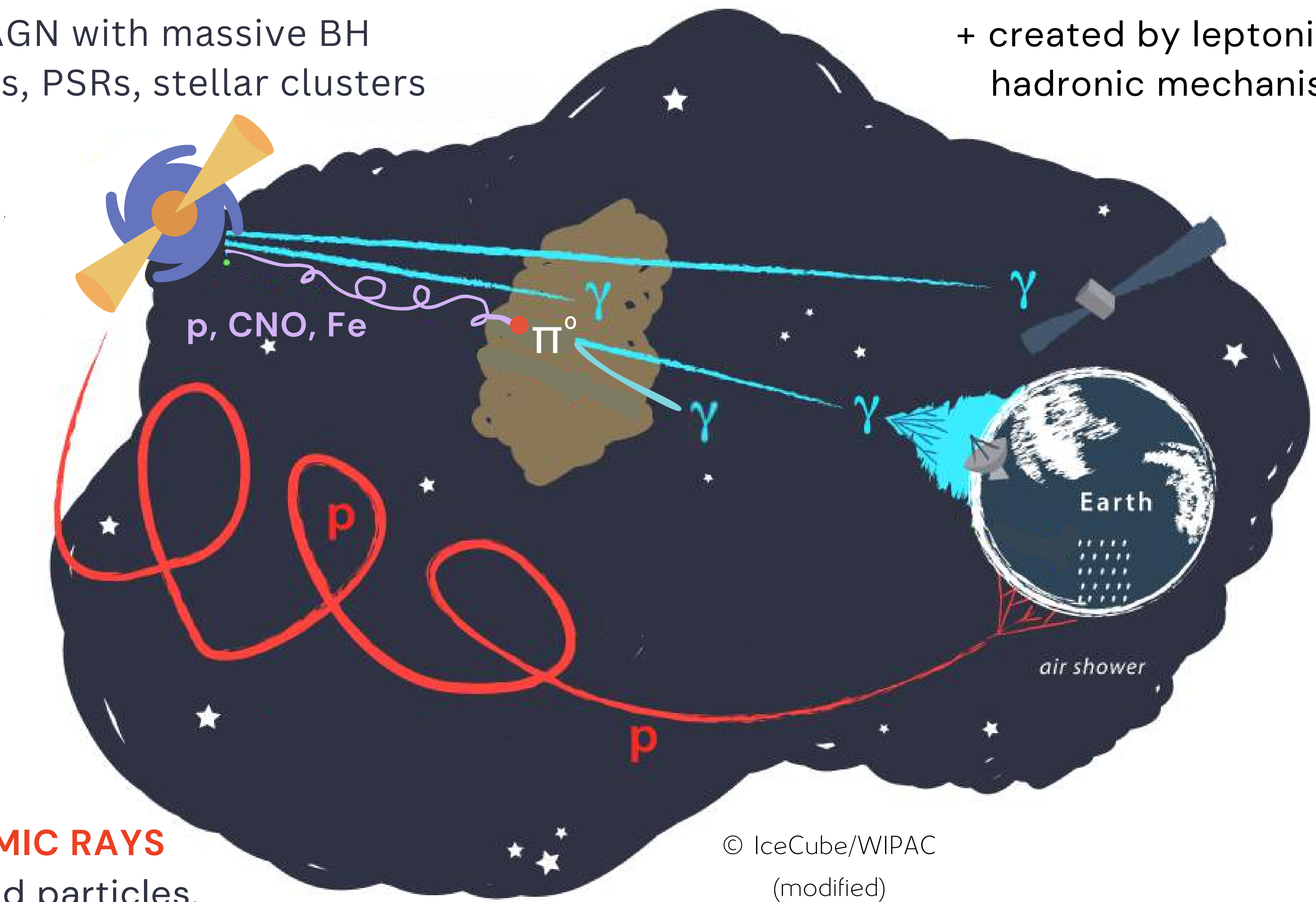
GAMMA RAYS
Point to their sources
+ not absorbed in our Galaxy
+ created by leptonic and hadronic mechanisms

HADRONIC PROCESS
Interaction of CRs with matter
Neutral pion decay process



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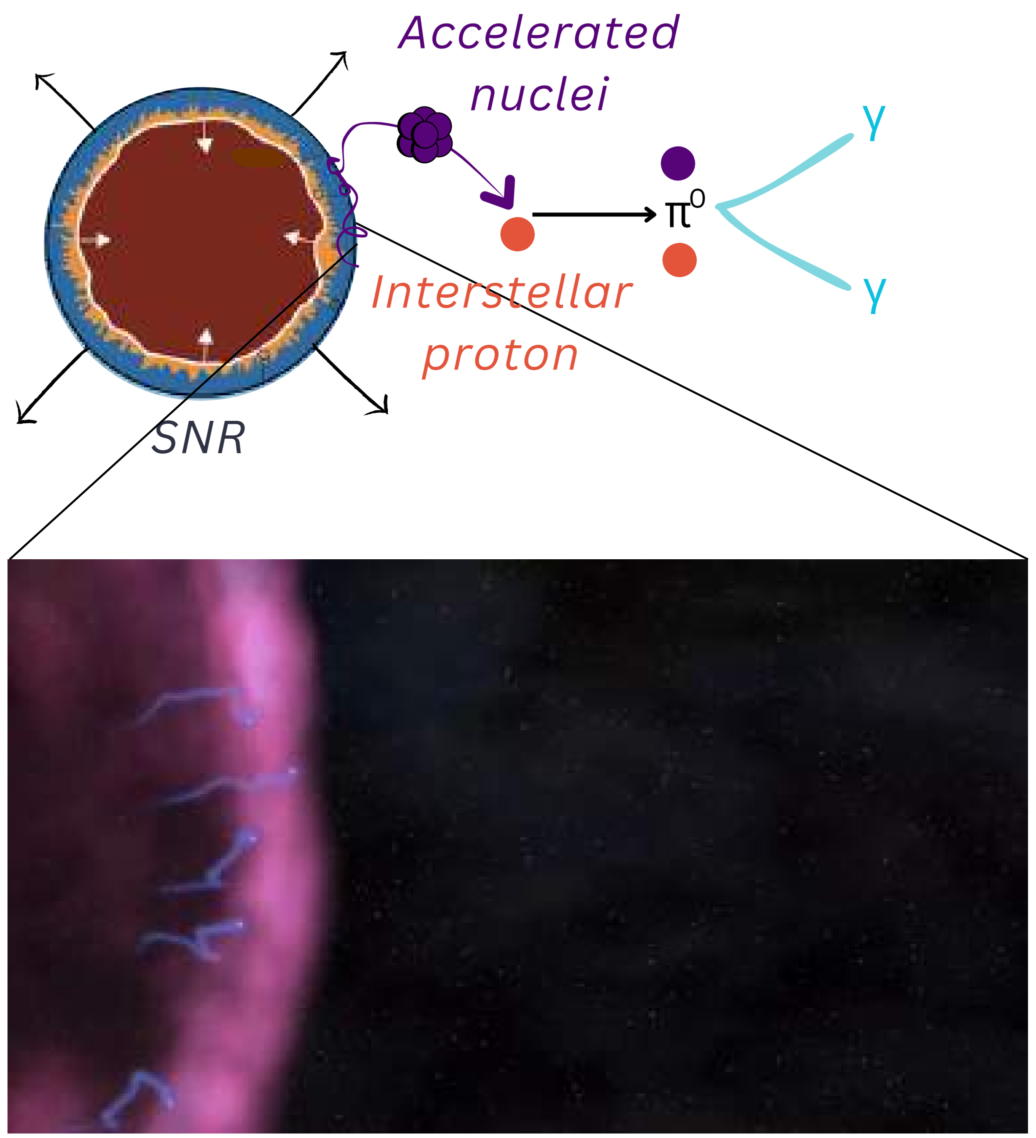

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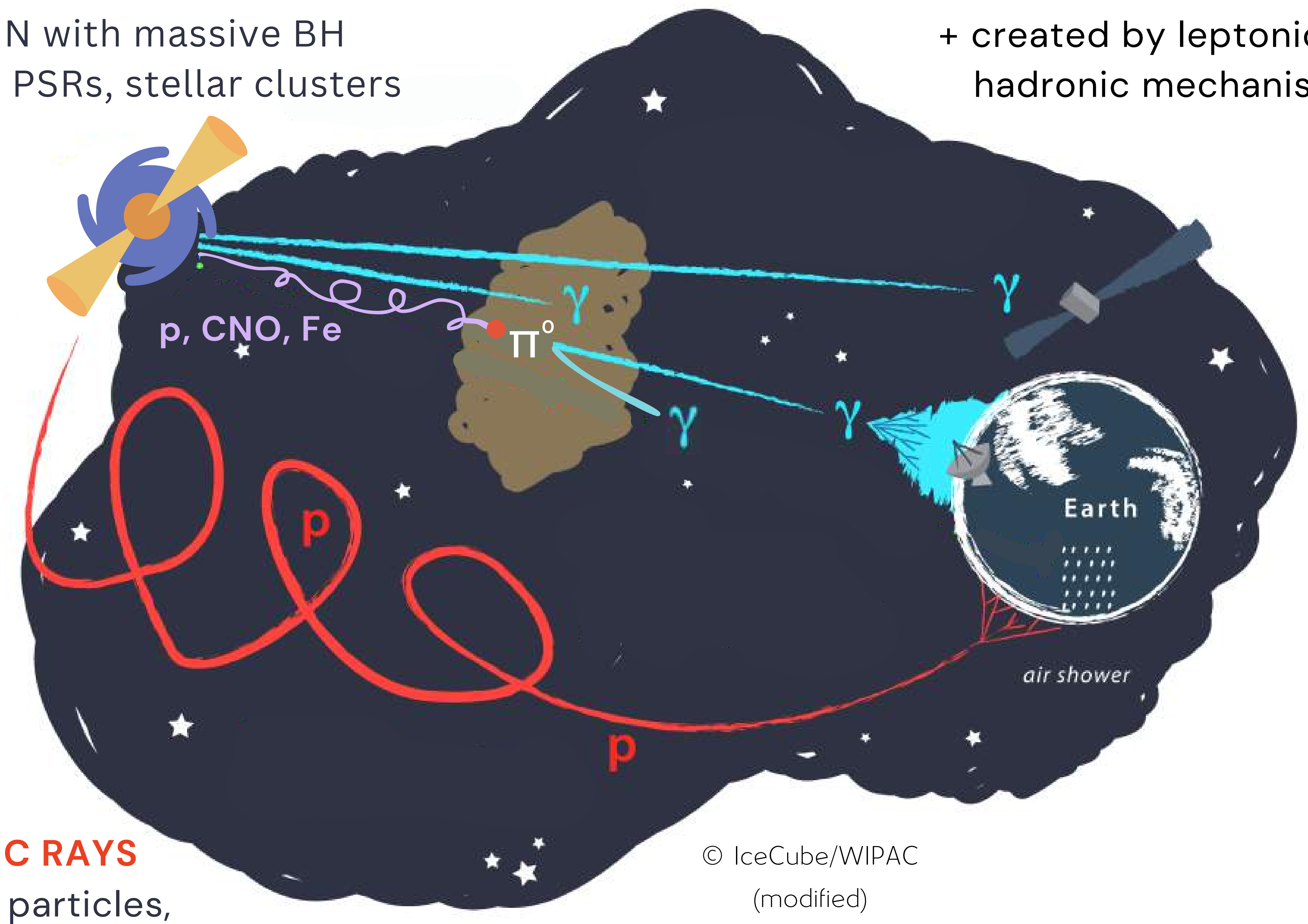

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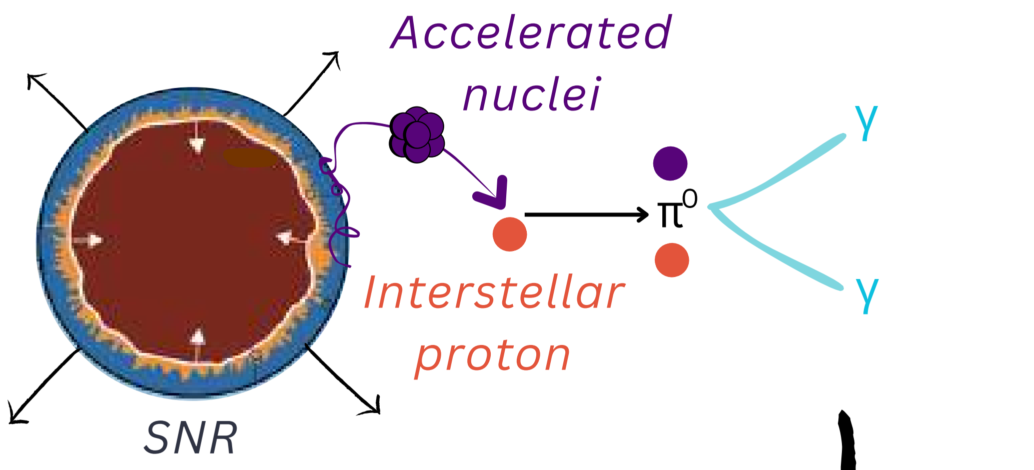
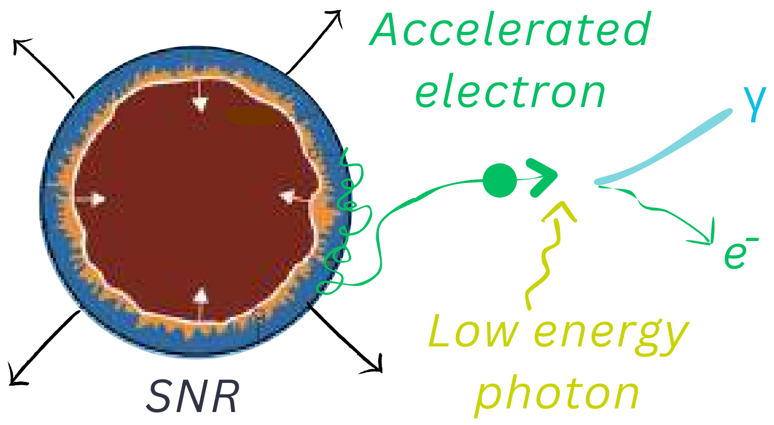


Energy

LEPTONIC PROCESS
Synchrotron
Bremsstrahlung
Inverse Compton
processes



CONTEXT

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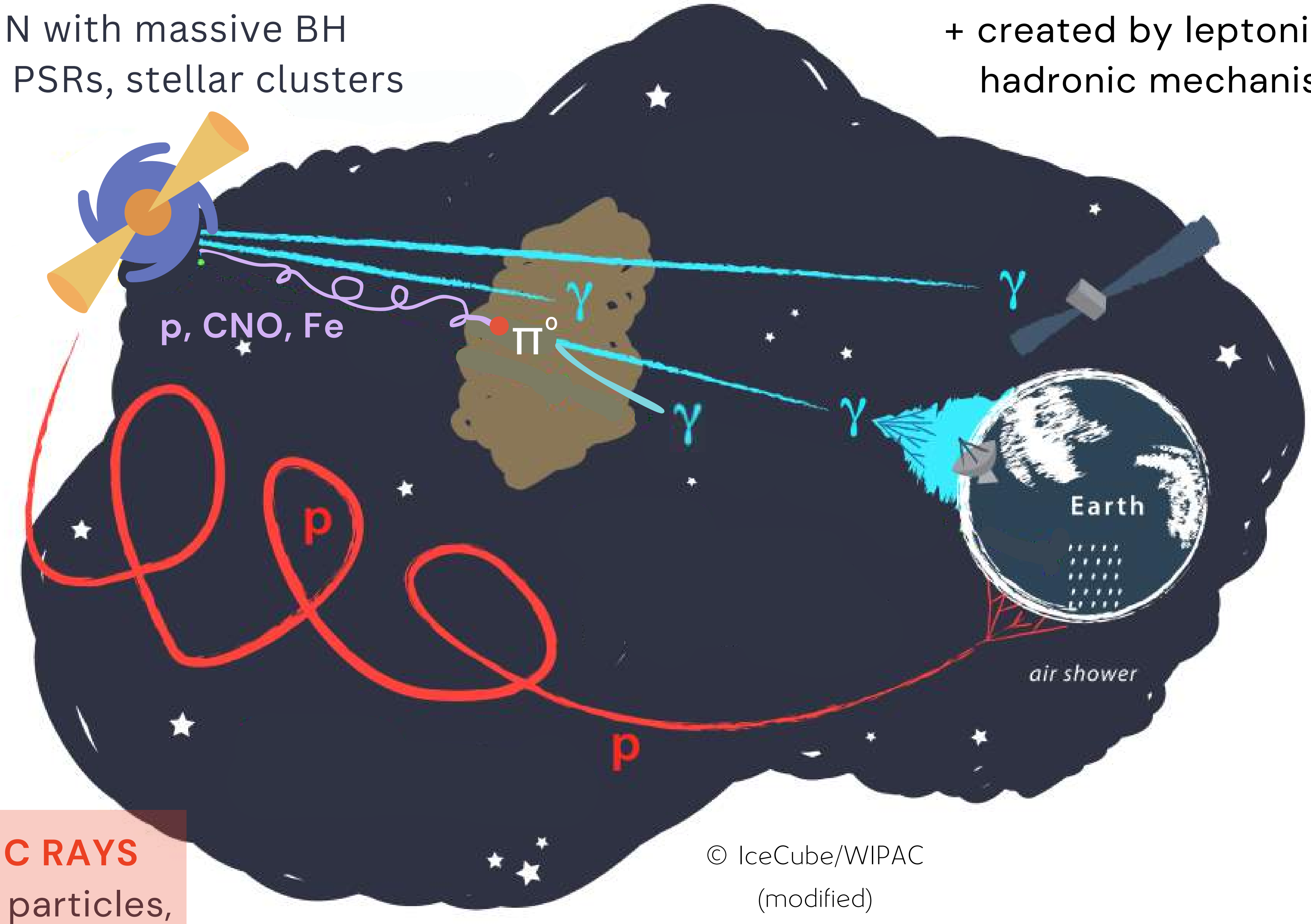

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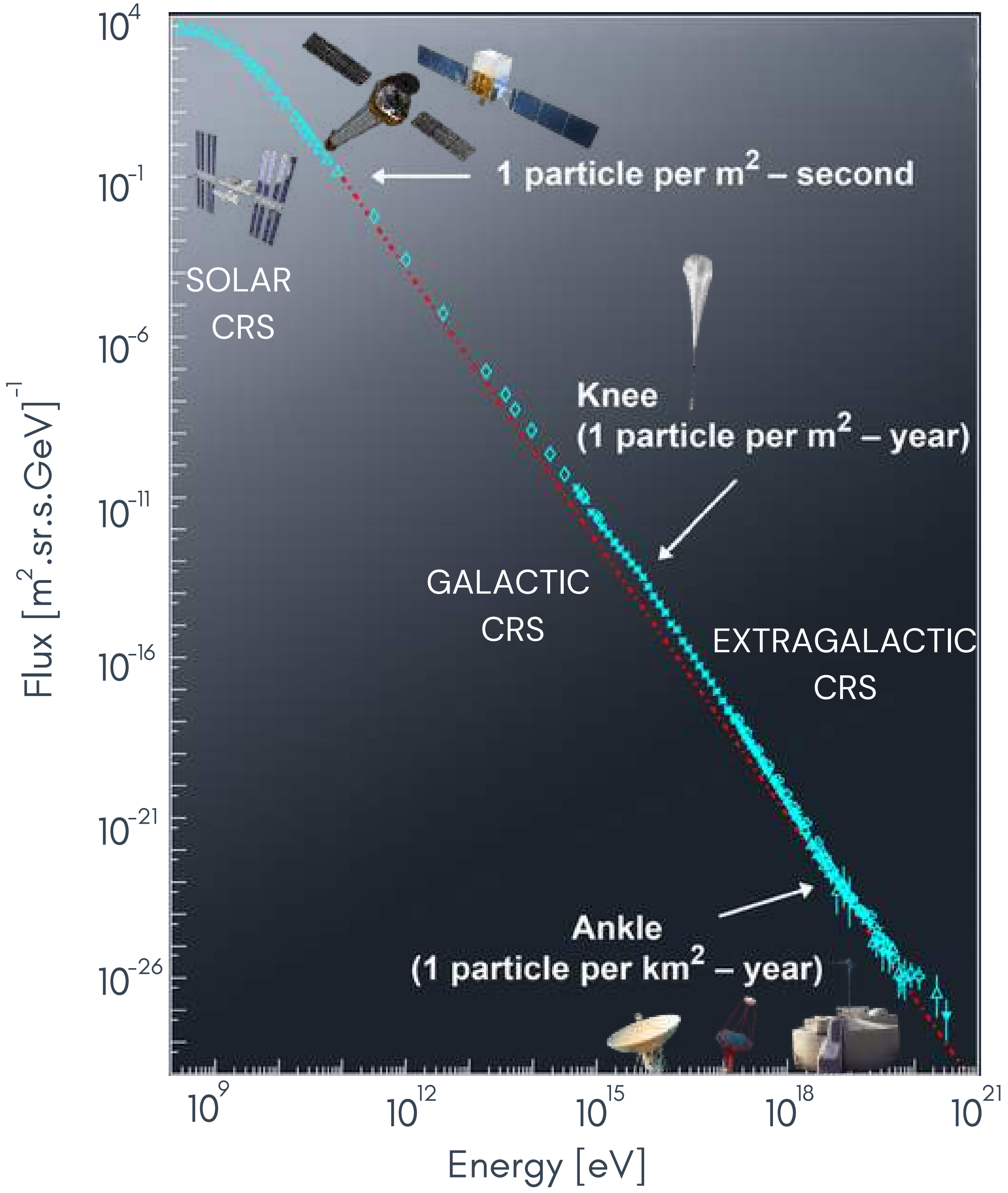
COSMIC RAYS
Charged particles,
deflected by
magnetic fields

CONTEXT

COSMIC RAY SPECTRUM

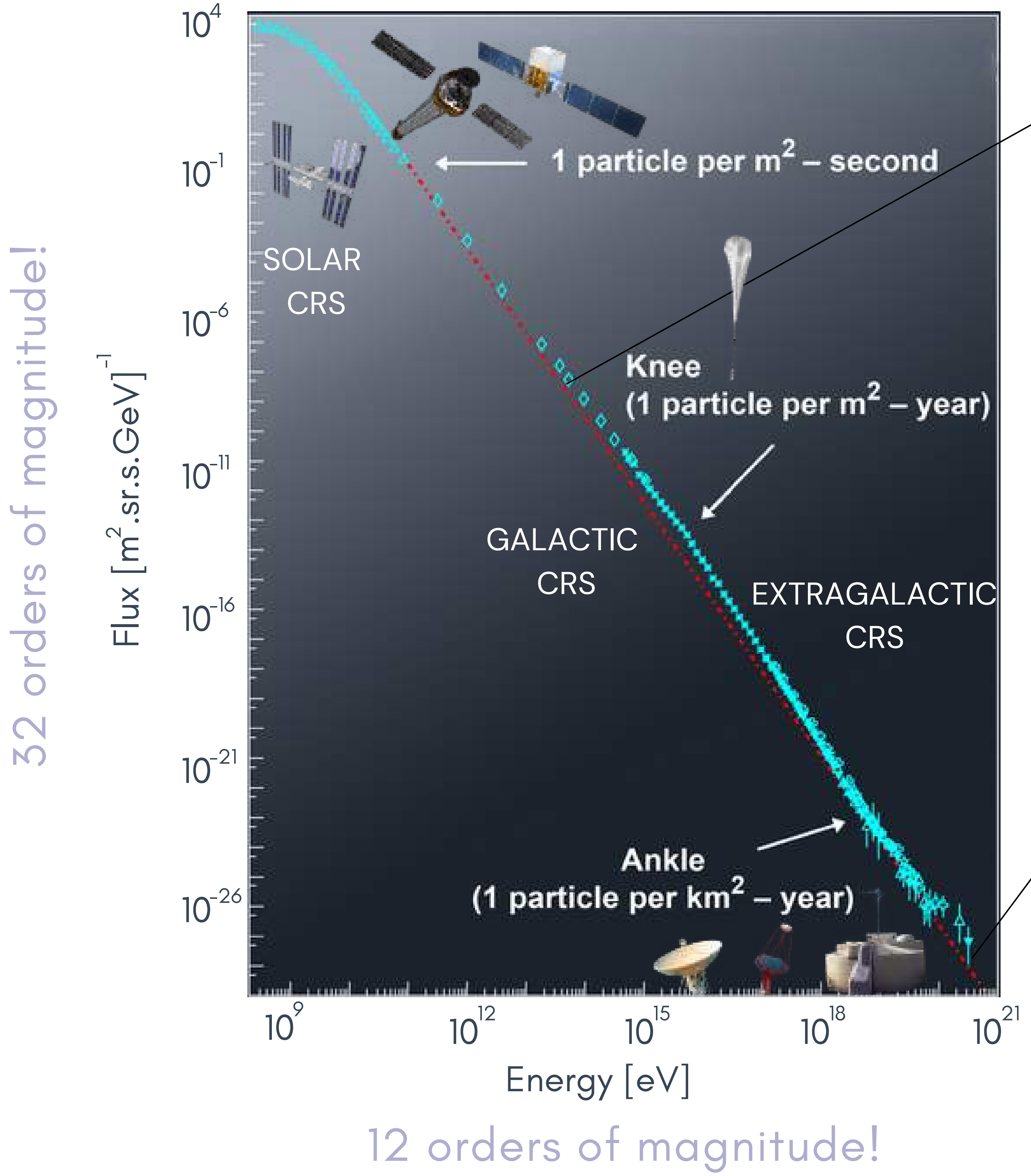


32 orders of magnitude!

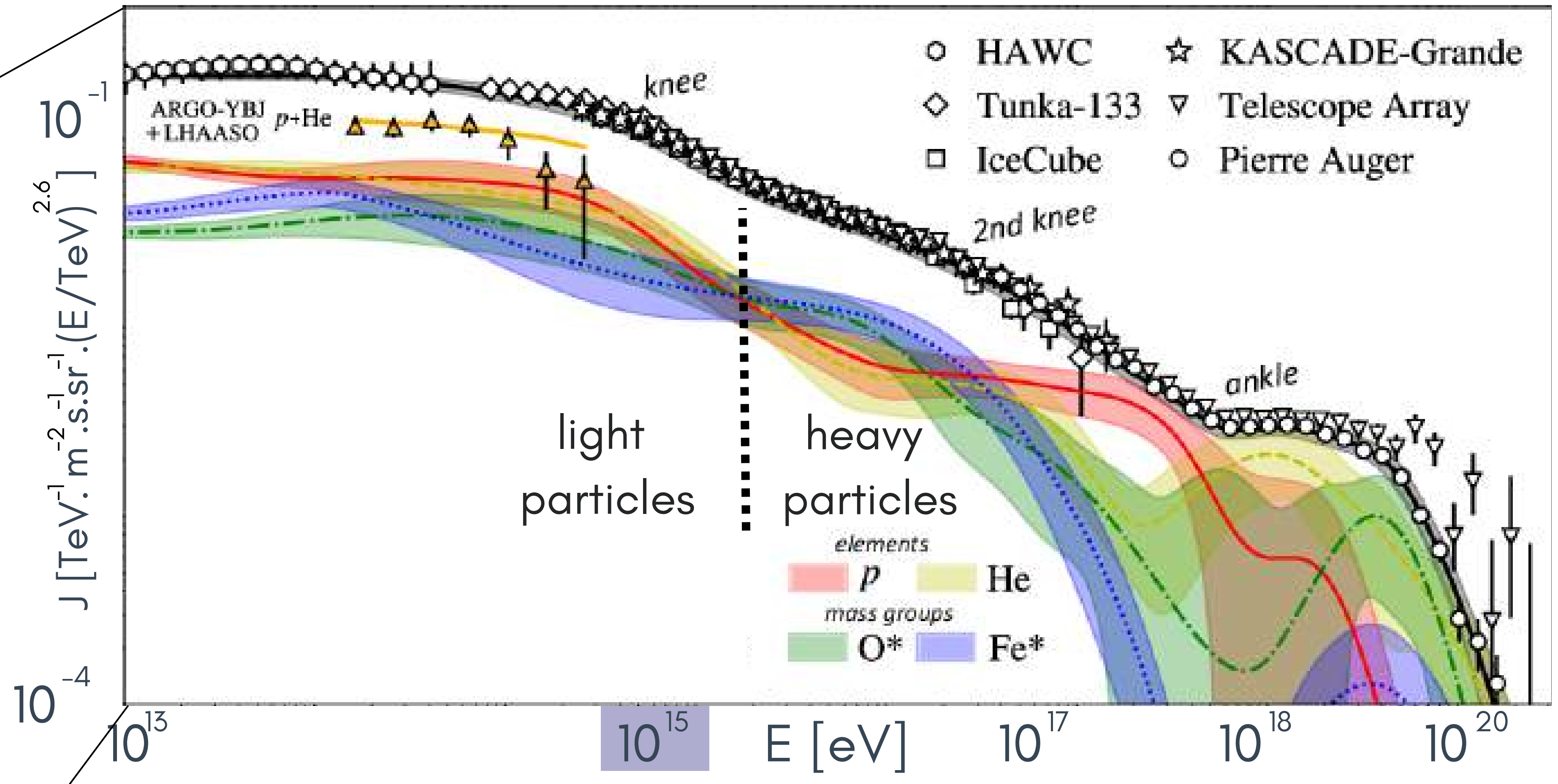
12 orders of magnitude!

CONTEXT

COSMIC RAY SPECTRUM



ALL-PARTICLE SPECTRUM



© Spectrum of cosmic-ray nucleons, kaon production, and the atmospheric muon charge ratio
Gaisser et al. 2012

CRs accelerated by Galactic sources? PeVatrons

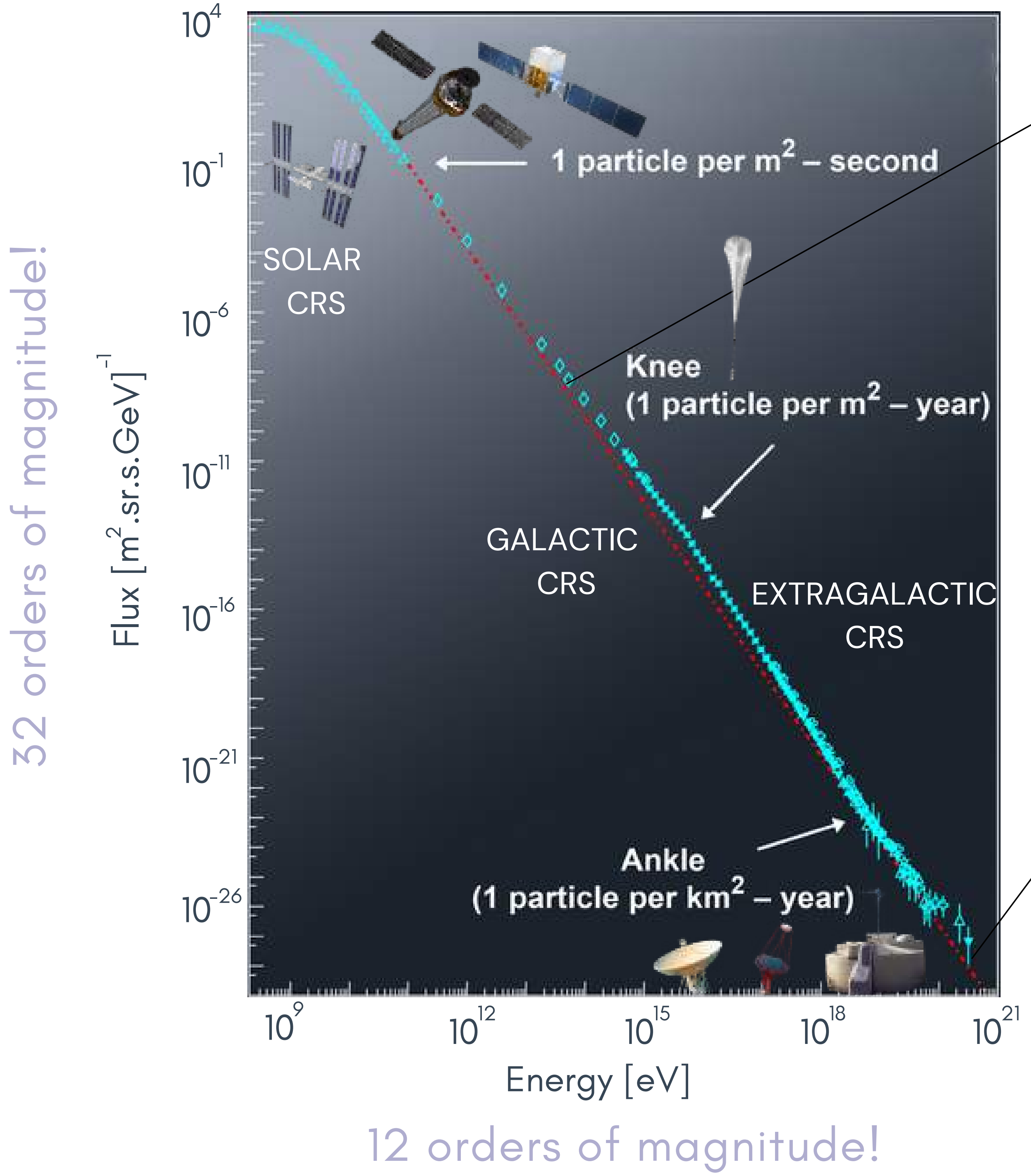
<u>PeVatron candidates</u>:

Supernova Remnant

Stellar Cluster

CONTEXT

COSMIC RAY SPECTRUM



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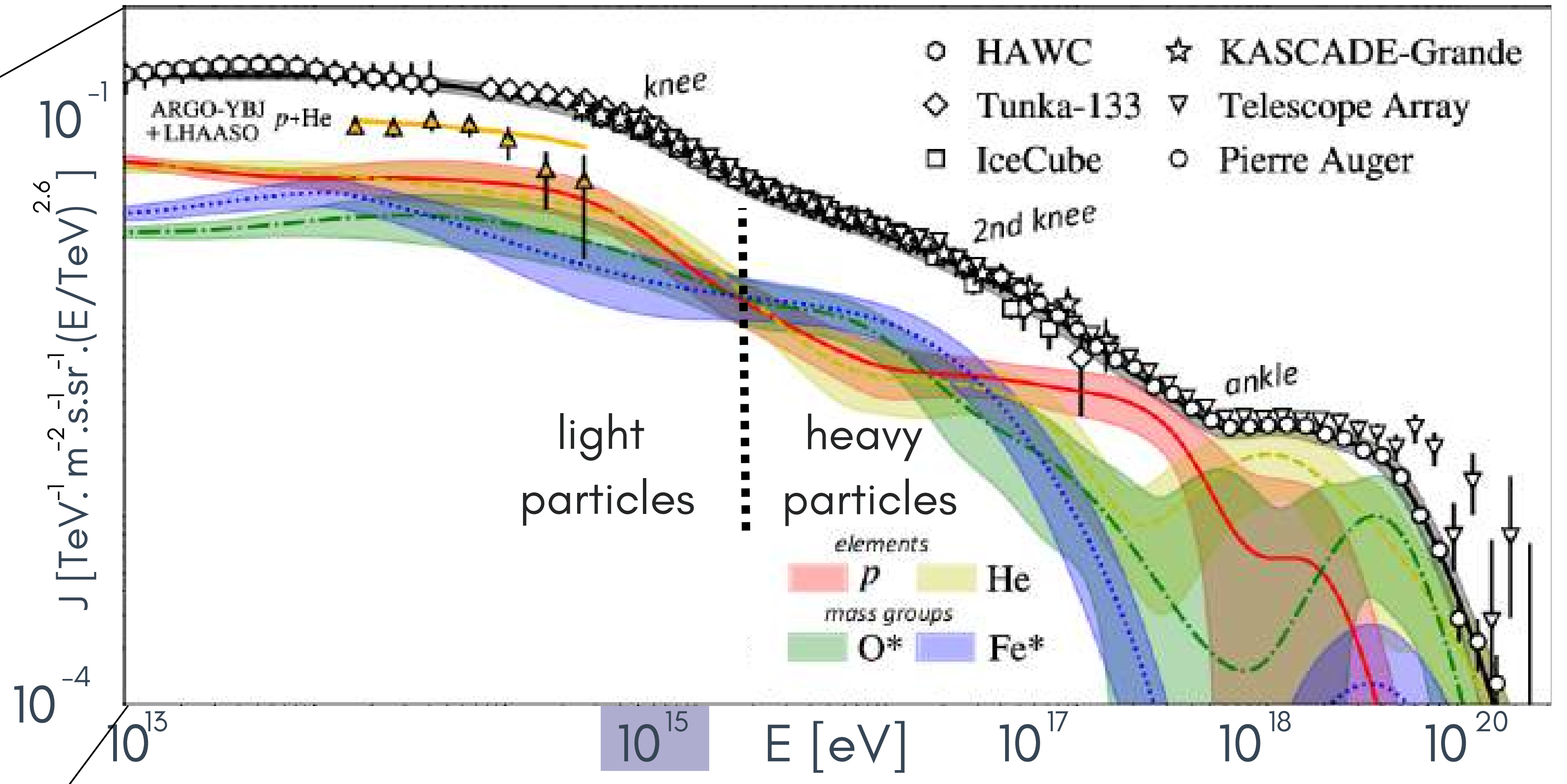

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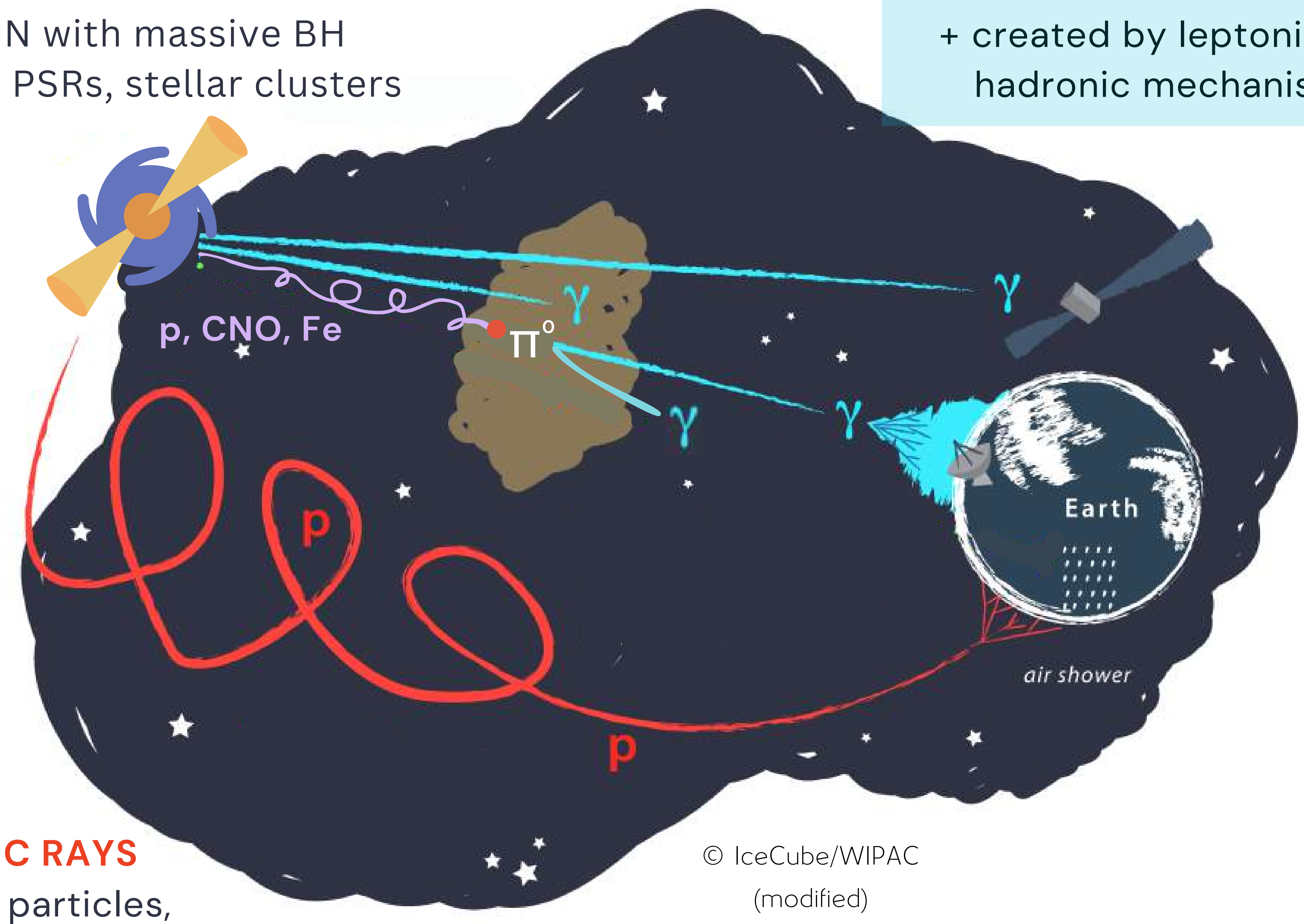

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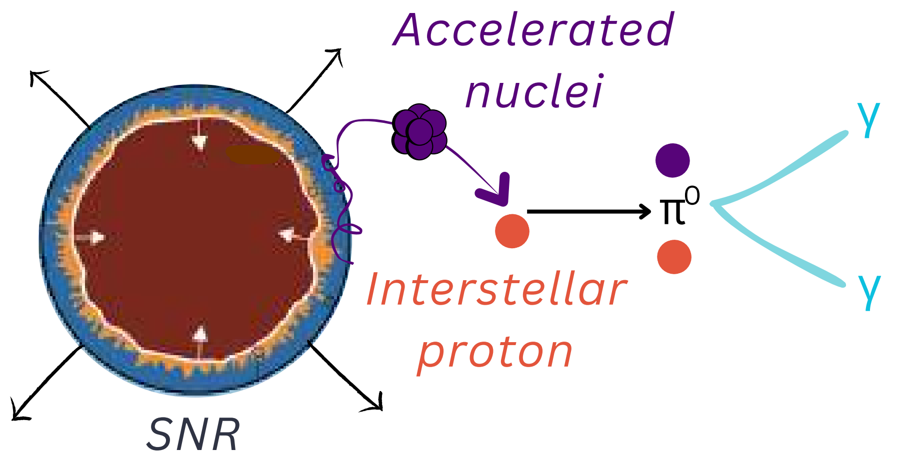
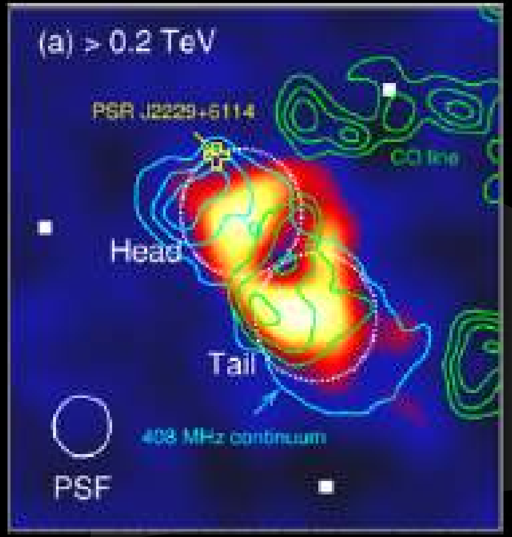


I - How to model heavy CRs?

MWL ANALYSIS OF THE SPECTRUM OF 2 SNRS

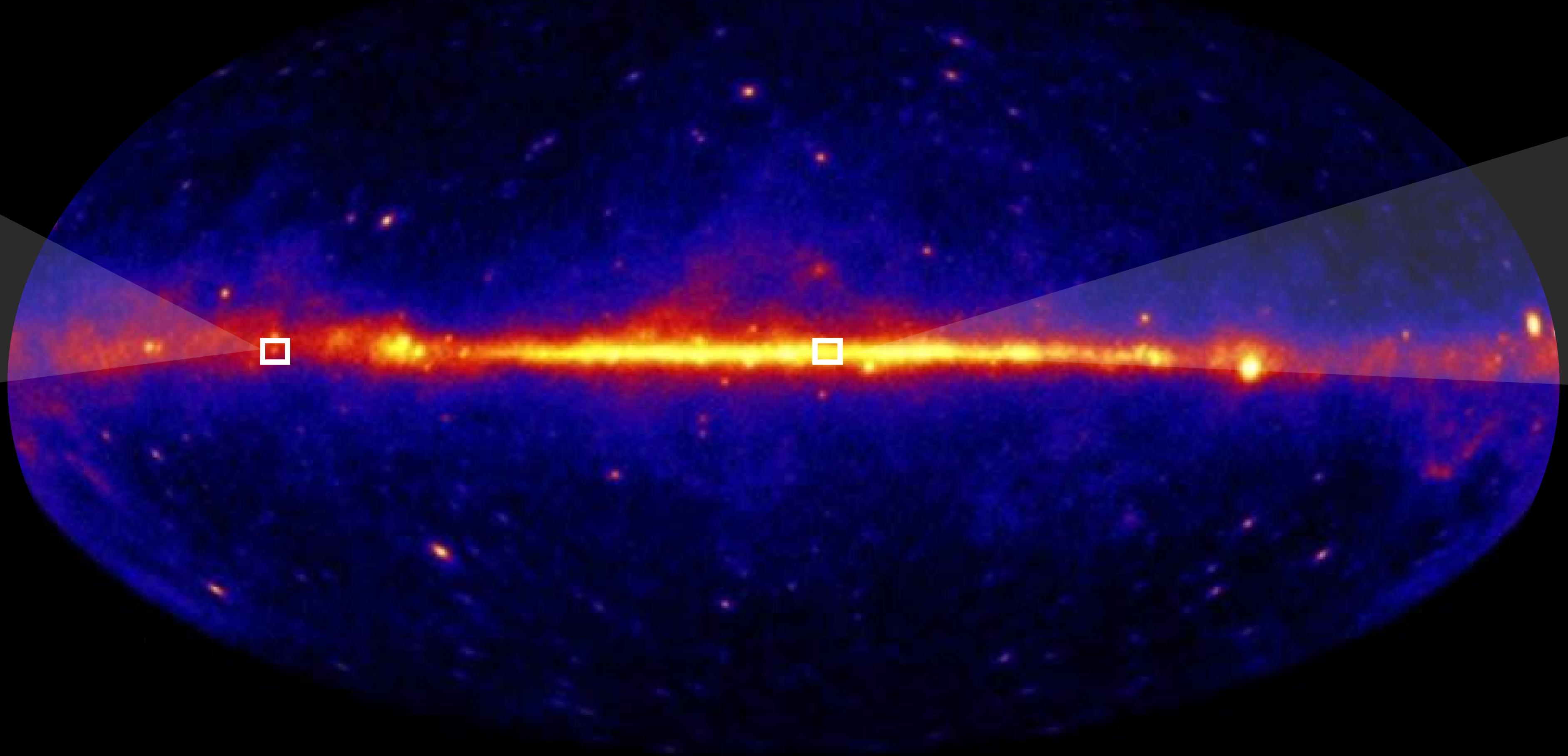
FERMI-LAT / VERITAS / LHAASO / HAWC TELESCOPES

SNR | **HAWC J2227+610**



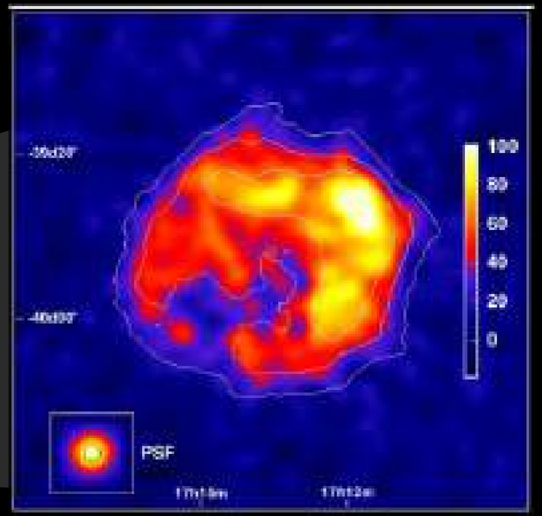
The γ-ray supernova G106.3+2.7
MAGIC collaboration 2022

GAMMA-RAY SKY



FERMI / H.E.S.S. TELESCOPES

RX J1713.7-3946 | SNR



A detailed spectral and morphological study of the gamma-ray supernova remnant RX J1713.7-3946 with H.E.S.S
HESS Collaboration 2005

I - How to model heavy CRs?

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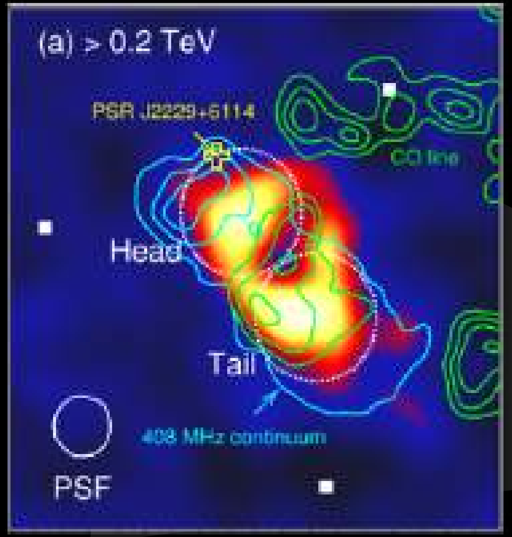

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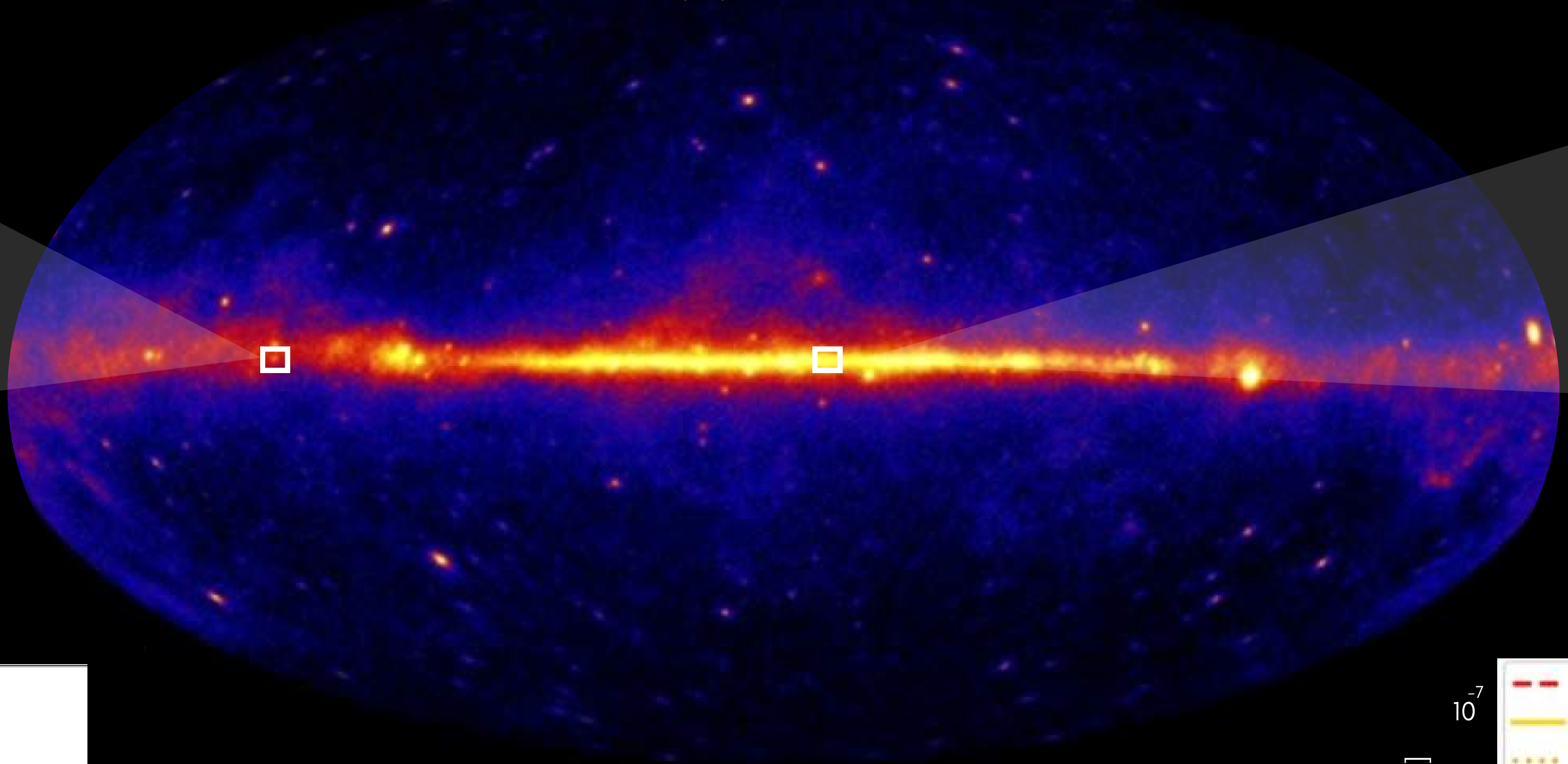

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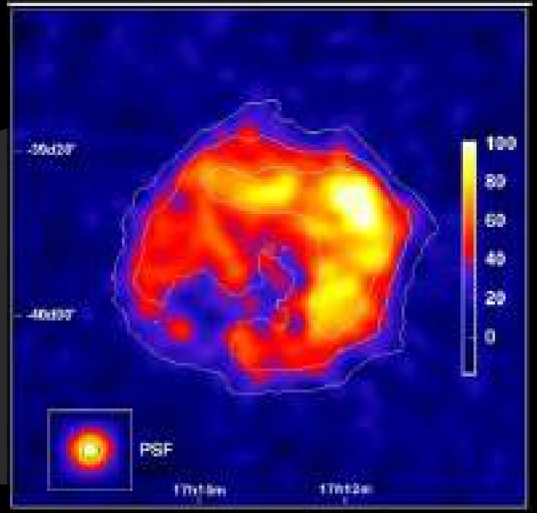
RX J1713.7-3946 | SNR



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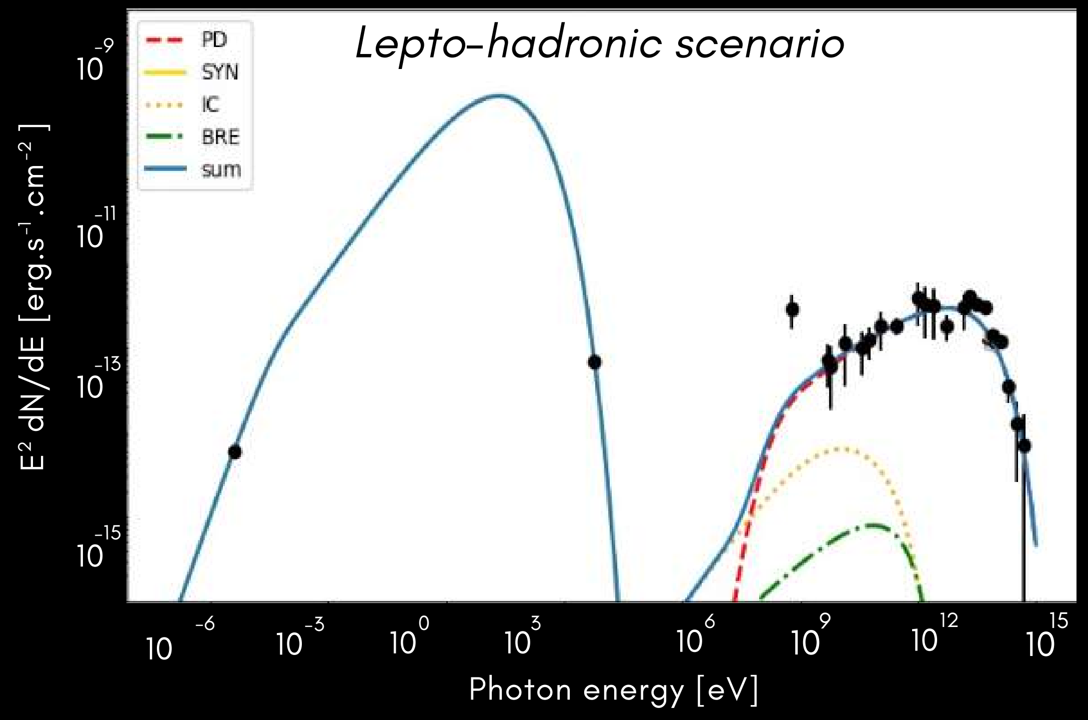
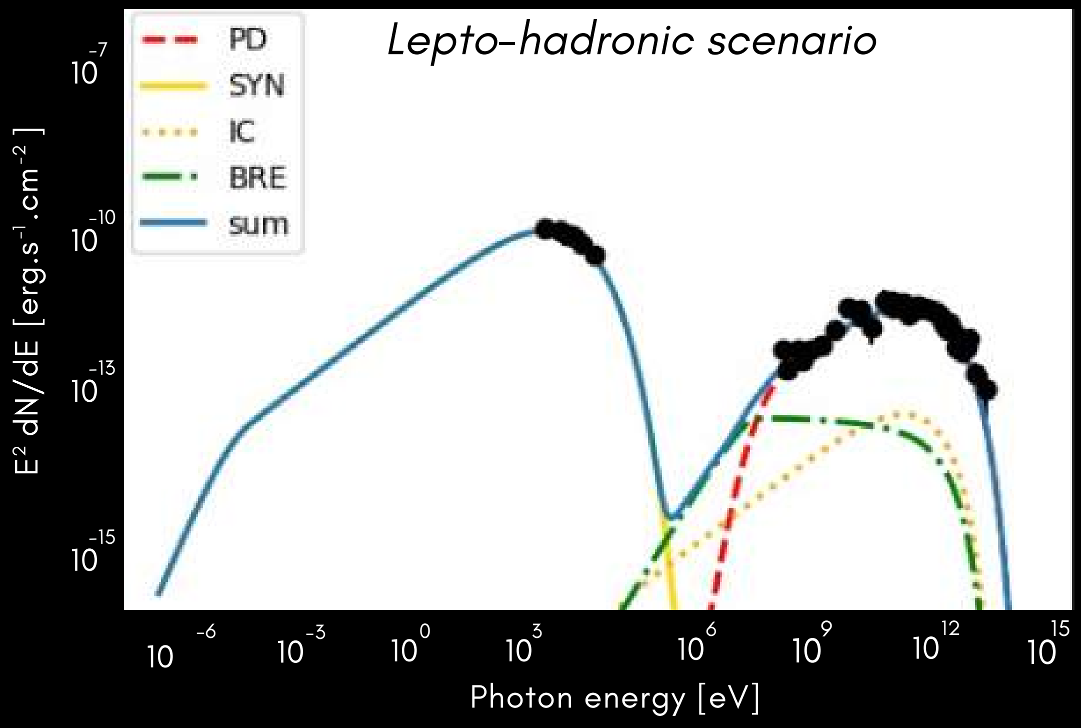


Multiwavelength analysis of Galactic Supernova Remnants

P. Sharma, Z. Ou, C. Henry-Cadrot, C. Dubos and T. Suomijärvi (JCAP 2023)

SCAN ME



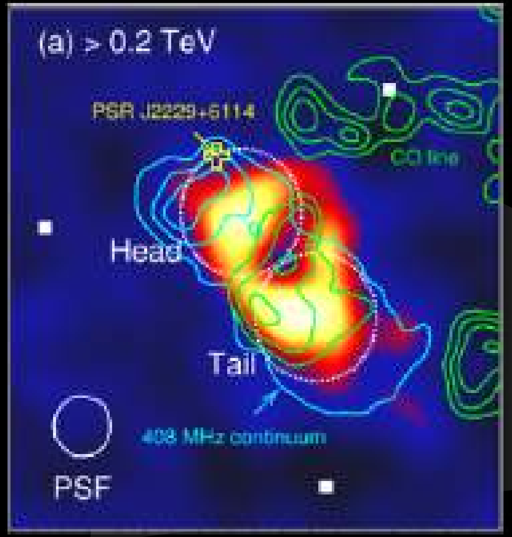
I - How to model heavy CRs?

MWL ANALYSIS OF THE SPECTRUM OF 2 SNRS

Dominant hadronic contribution at high energies

FERMI-LAT / VERITAS / LHAASO / HAWC TELESCOPES

SNR | HAWC J2227+610



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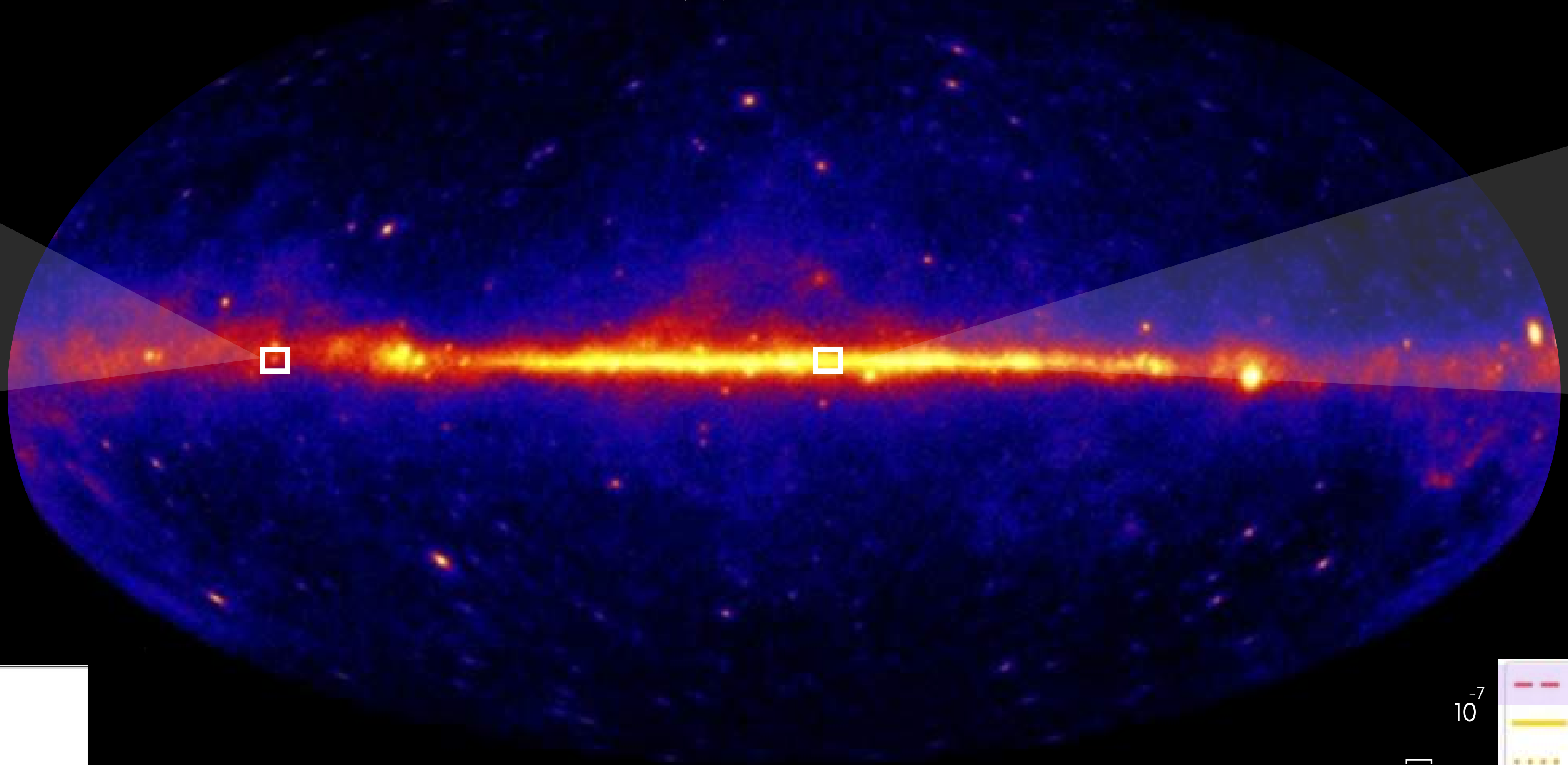
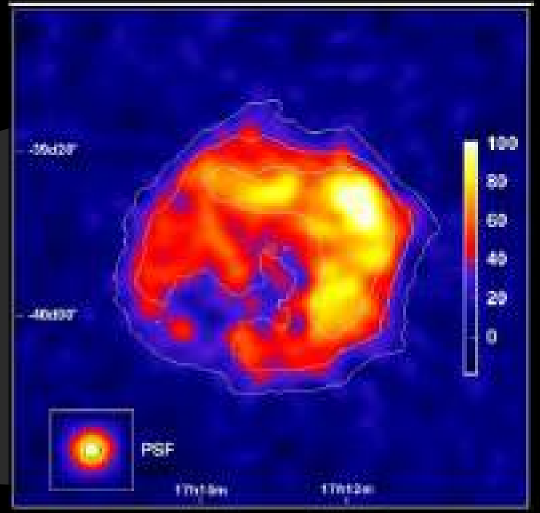
GAMMA-RAY SKY



FERMI / H.E.S.S. TELESCOPES

RX J1713.7-3946 | SNR



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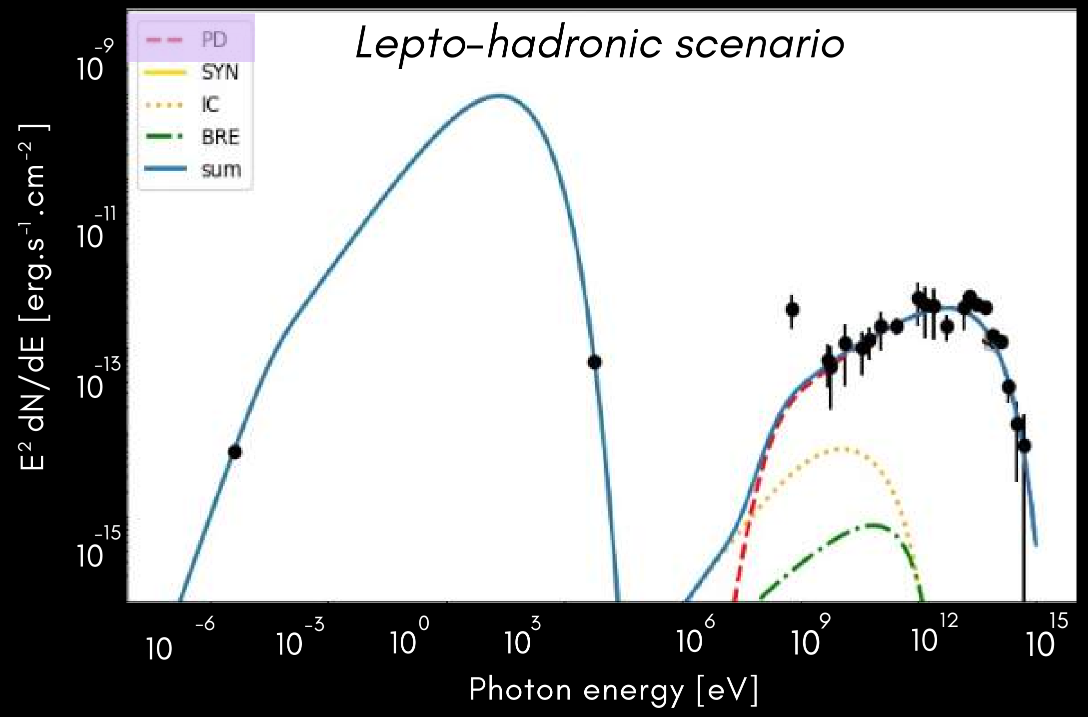

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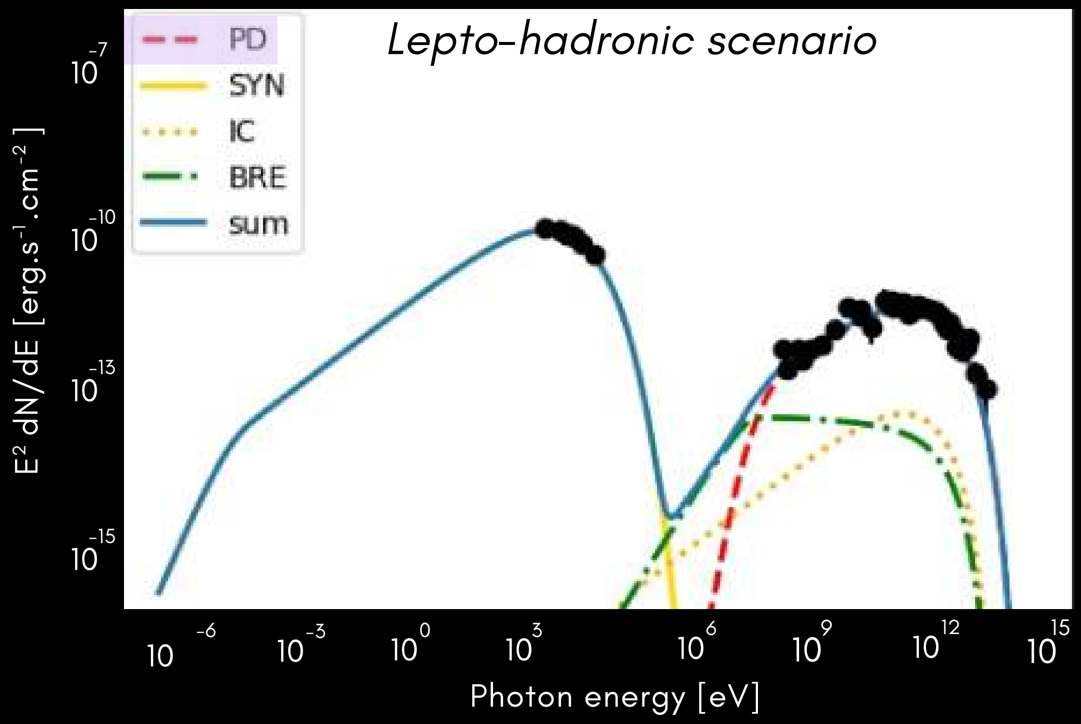


I - How to model heavy CRs?

Heavy CR pion decay decay modelling

GAMMAPY NAIMA

Photon flux emitted from CR distribution

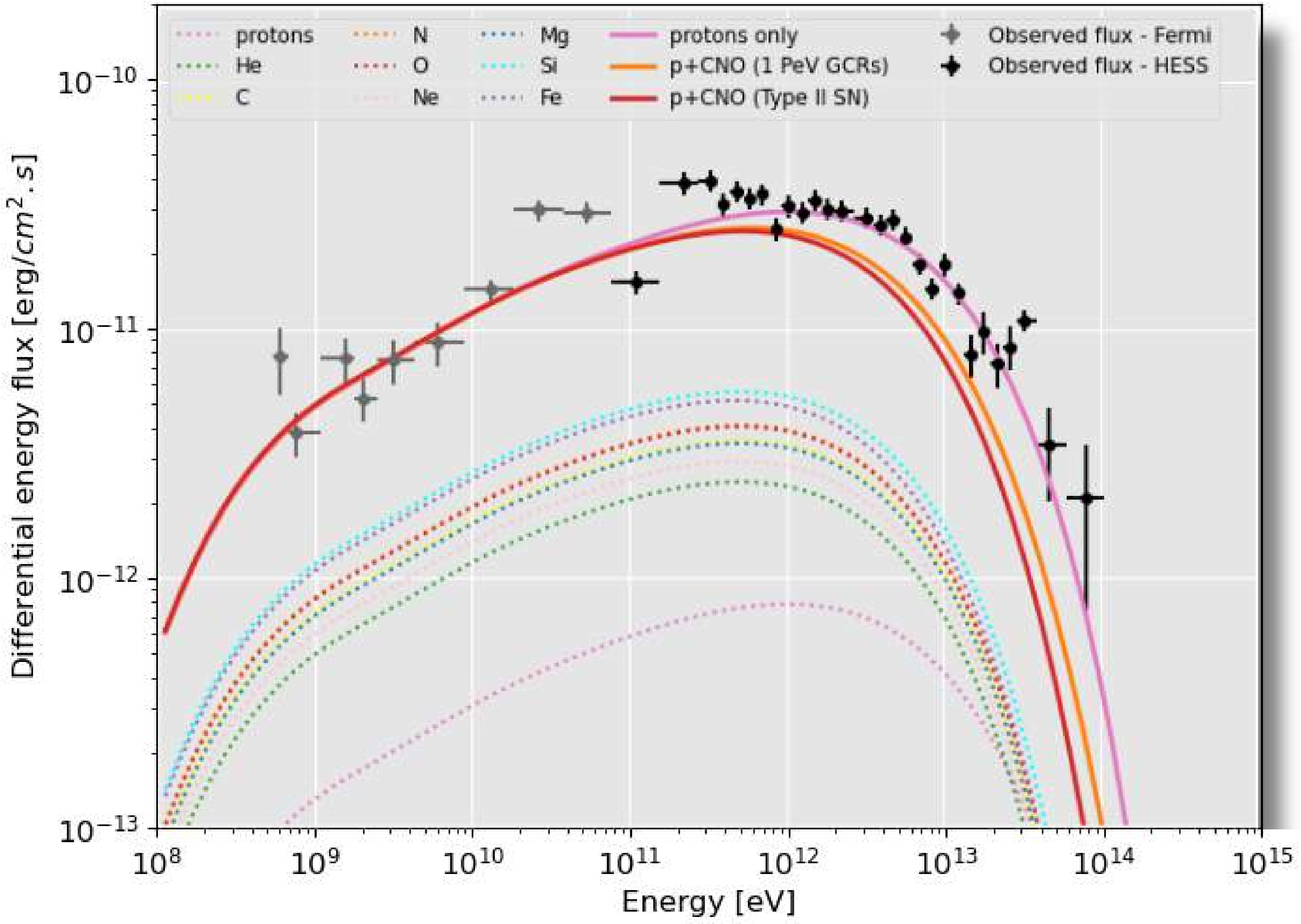
$$F(E) = f.\sigma.\mathbf{N_H}.\mathbf{A_m}.(E/\mathbf{E_0})^{-\boldsymbol{\alpha}}.e^{-(E/Z.\mathbf{E_c}/A)^{\boldsymbol{\beta}}}$$

N_H: number density of the target protons
A_m: amplitude of the proton distribution
E_0 : reference energy

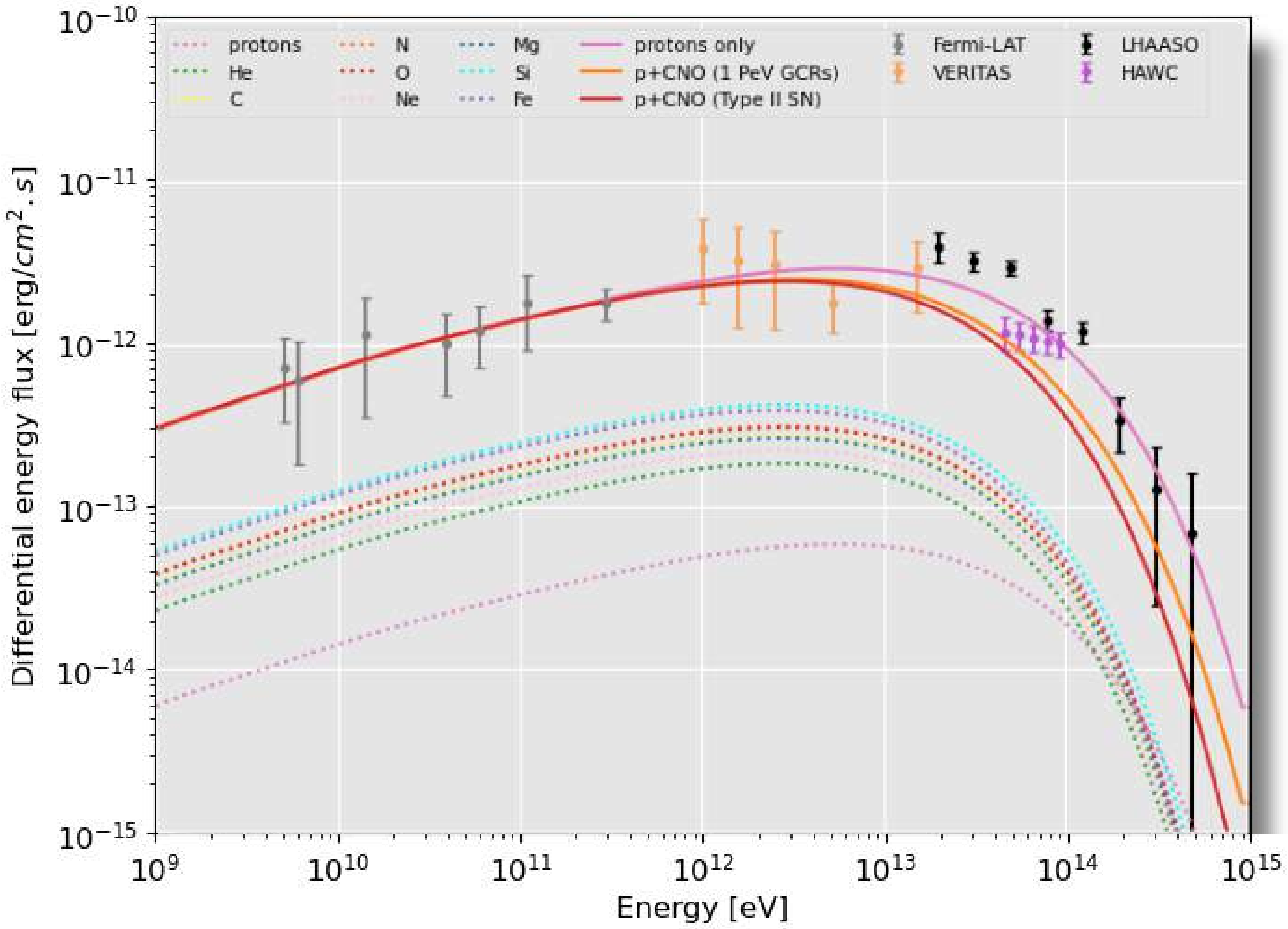
α: proton spectral index
E_c : proton cut-off energy
β: cut-off exponent

Spectral parameters fixed by the MWL analysis

γ spectrum of **RX J1713.7-3946**



γ spectrum **HAWC J2227+610**



I - How to model heavy CRs?

Heavy CR pion decay decay modelling

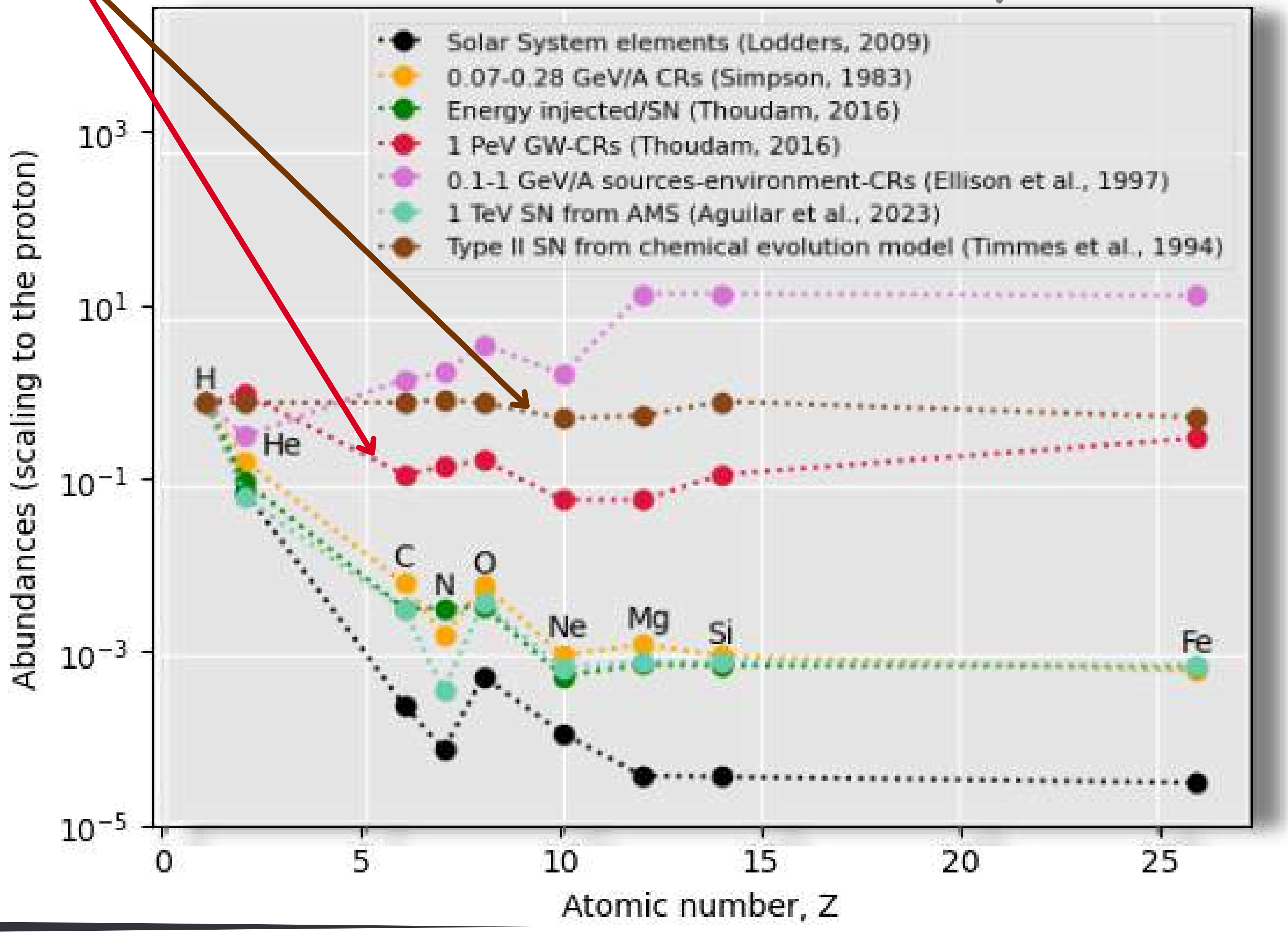
<u>Photon flux emitted from CR distribution</u>

$$F(E) = \mathbf{f}.\boldsymbol{\sigma}.N_H.A_m.(E/E_0)^{-\alpha}.e^{-(E/\mathbf{Z}.E_c/\mathbf{A})^{\beta}}$$

2 different CR composition used for this study, linked to:
- the source: **Type II Supernova (SN)**
- or the acceleration of the GCRs: **1 PeV CRs**

f: fraction of the CRs abundances
σ: inelastic cross-section
Z: CR charge
A: CR mass number

CR abundance curves



I - How to model heavy CRs?

Heavy CR pion decay decay modelling

γπ GAMMAPY - NAIMA

Pion decay model considering CRs of:
- protons only
- protons + CNO with a 1 PeV CRs
- protons + CNO with a type II SN composition

Photon flux emitted from CR distribution

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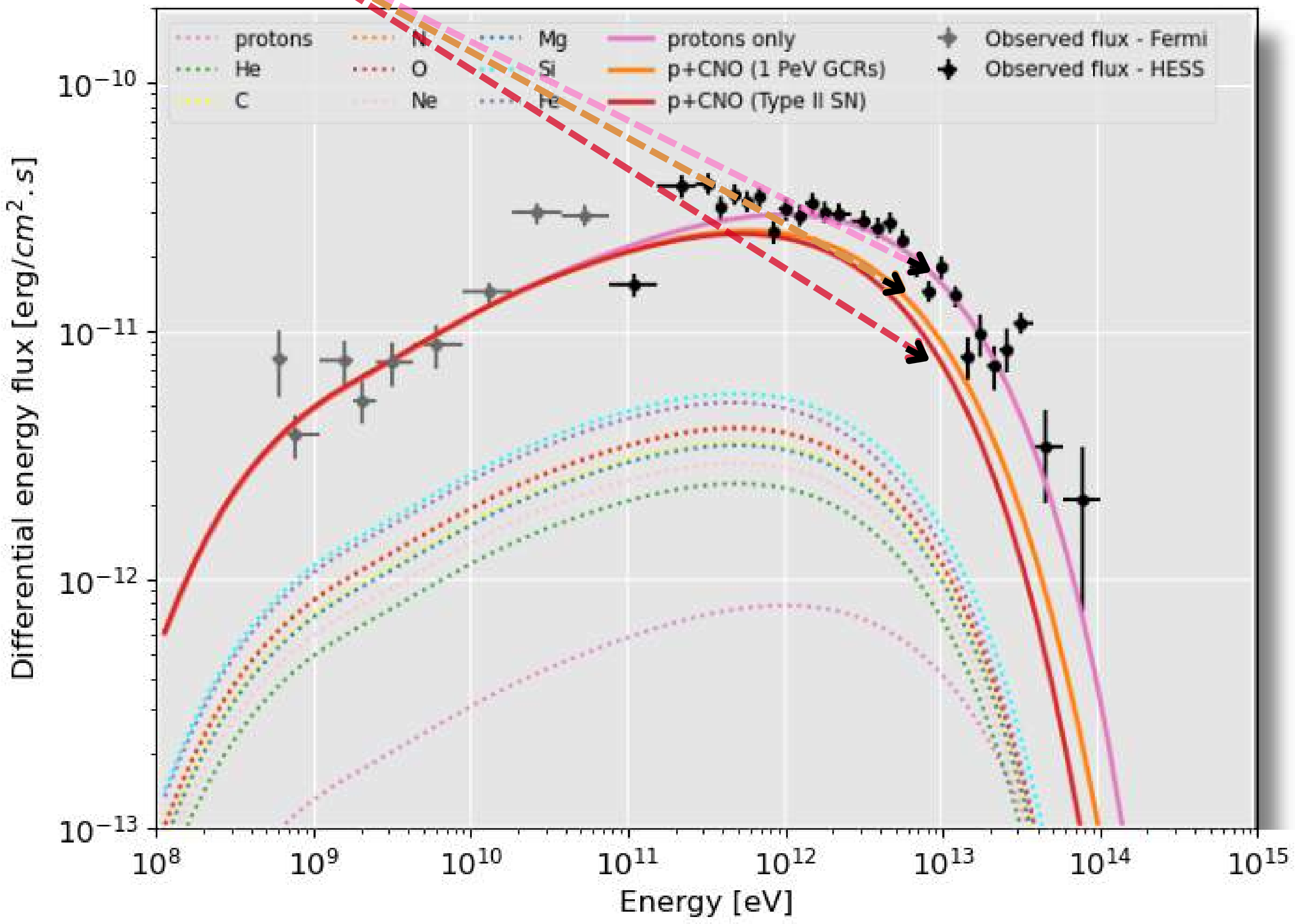

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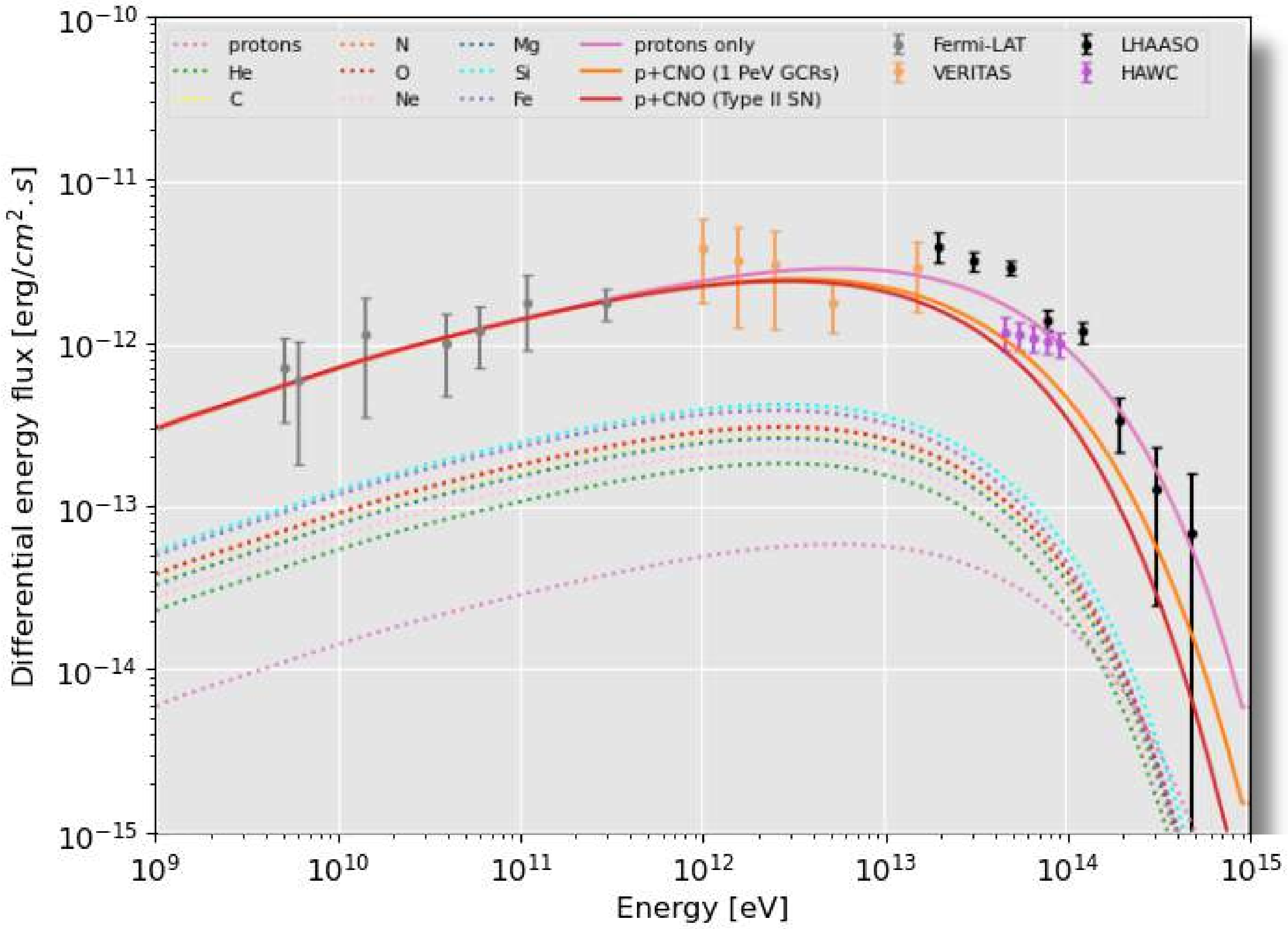
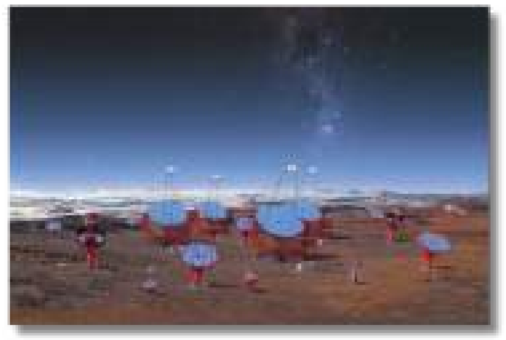


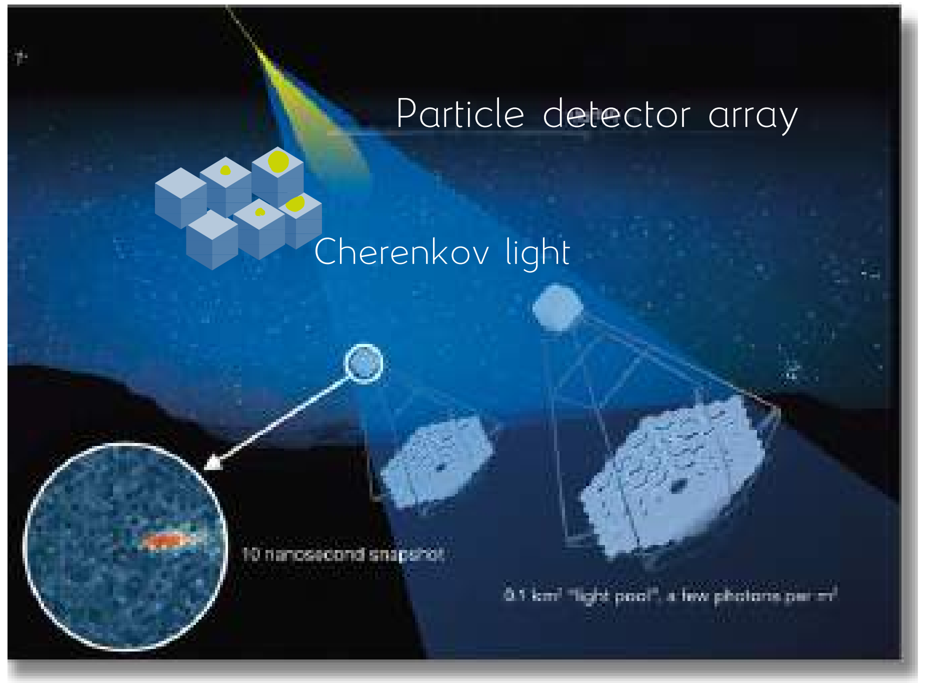
II - How to simulate the flux of a source with CTAO?

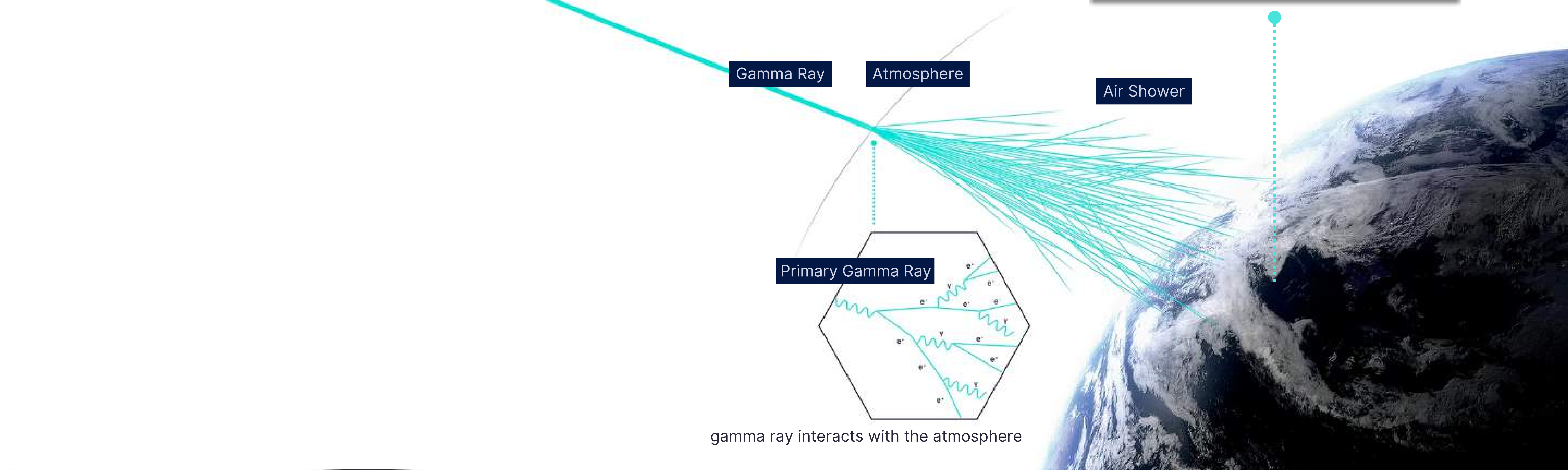
Gammapy - Naima

South site
Atacama Desert, Chile



North site
La Palma, Canary Island





gamma ray interacts with the atmosphere

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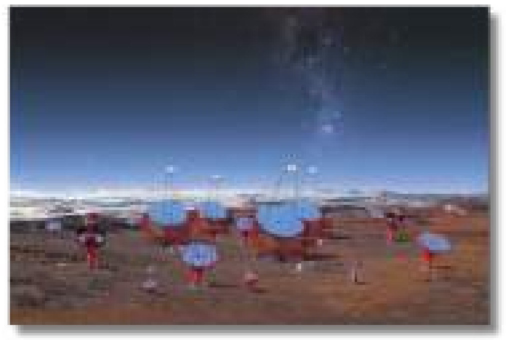

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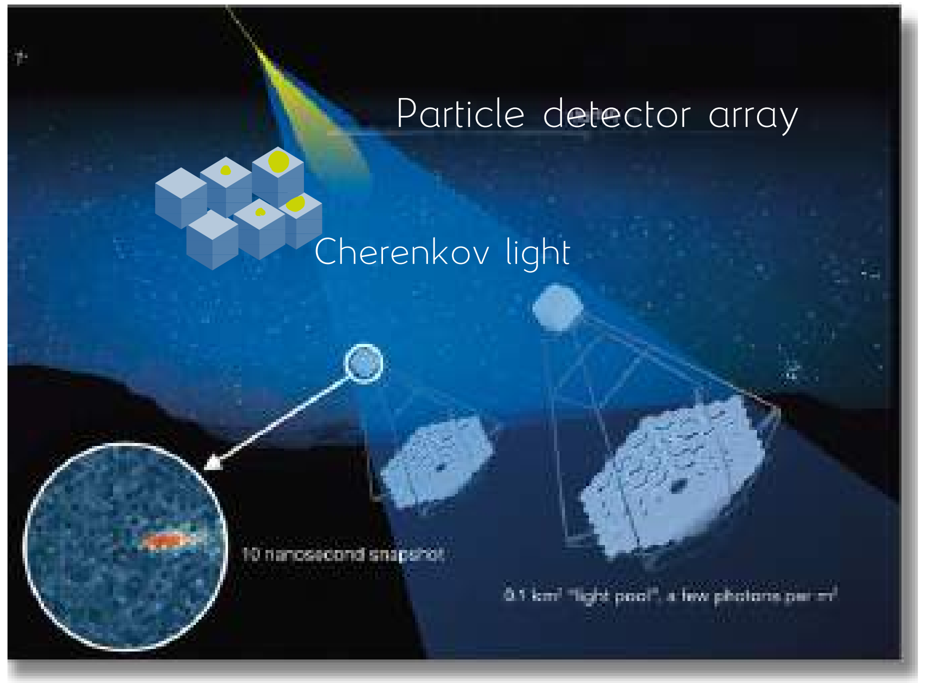
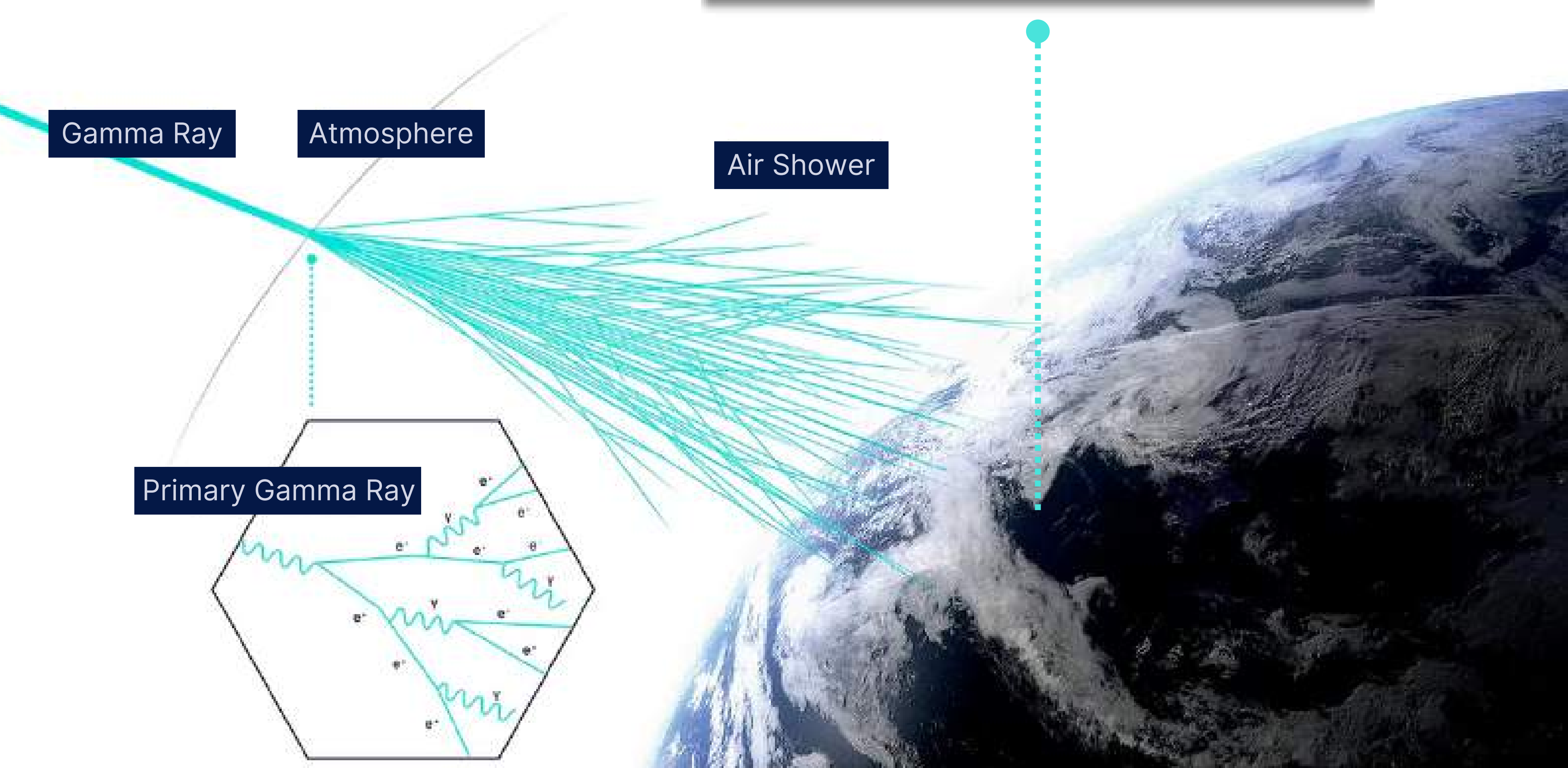


How to perform CTAO simulations of γ spectrum with Gammapy?

- Instrument Response Function (IRF): **prod5 v0.1**
  Monte Carlo simulations of the γ-ray shower
  ⟶ zenith angle / observation time: **50h** / South site (14 MSTs + 37 SSTs)

- Consideration of the background: **1D On-Off analysis**

- Input radiative models: pion decay considering CRs of:
  ⟶ protons only
  ⟶ **CNO with 1 PeV CR** composition
  ⟶ **CNO with a type II SN** composition
  ⟶ **Fe with a type II SN** composition



gamma ray interacts with the atmosphere

III - Can CTAO detect CRs from SNRs?

<u>Can we separate the studied models</u>?

Data fitting: if Log-Likelihood test **ΔTS > 29 (5σ)** (2 free parameters) => the models are distinguished

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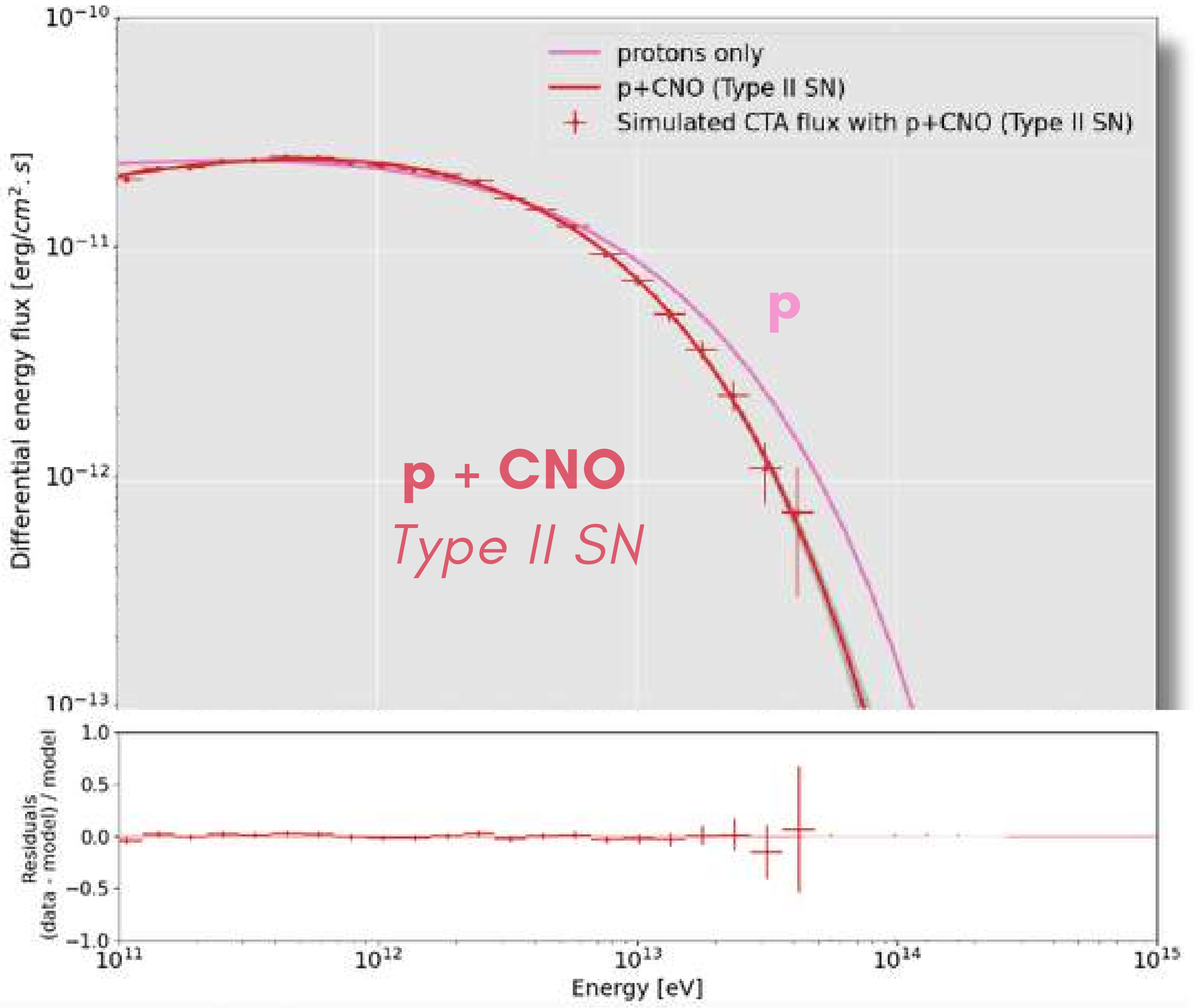
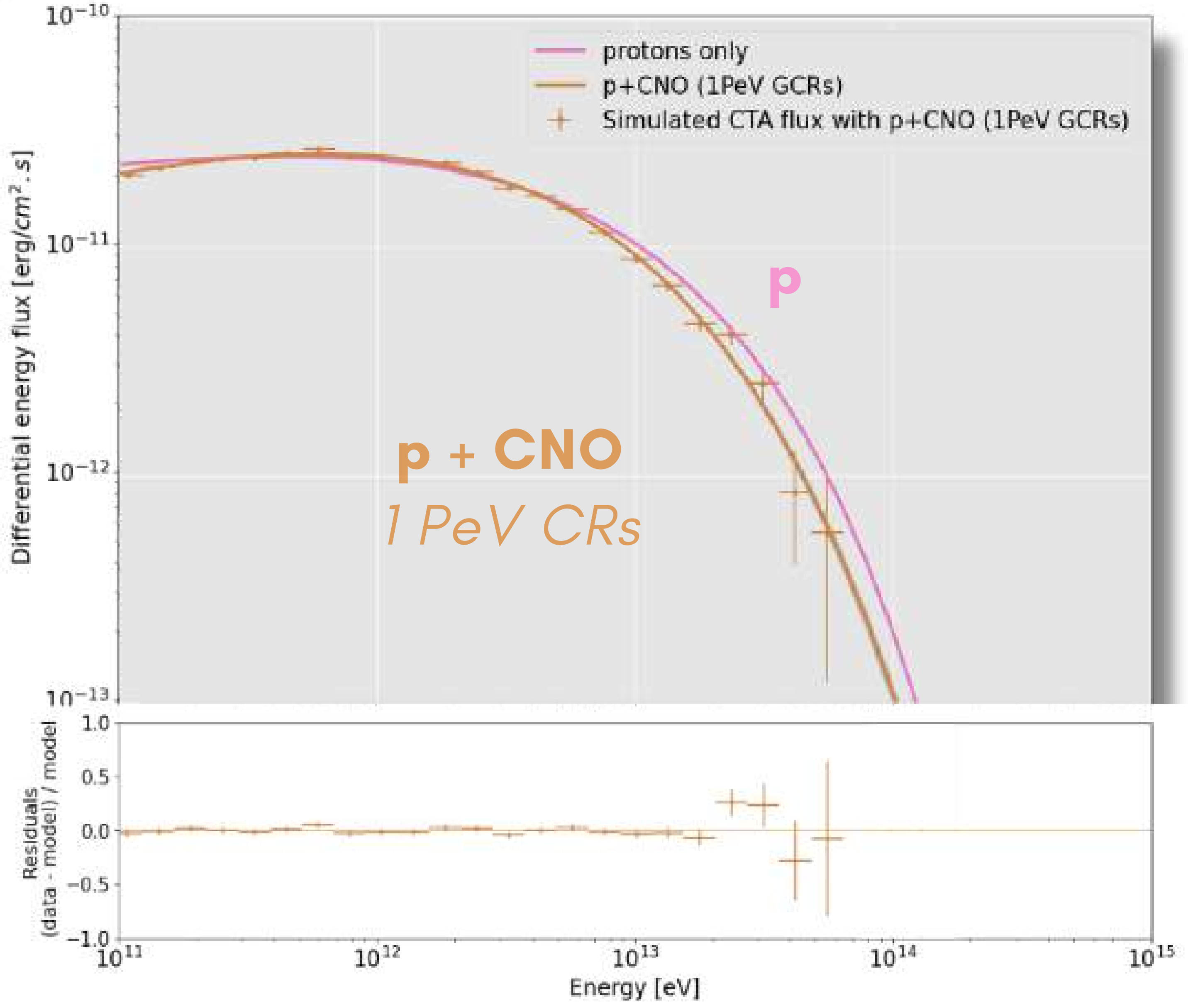
CTAO simulations of **RX J1713.7-3946** (A_m and α are free during the fit)



ΔTS = 202 ✓



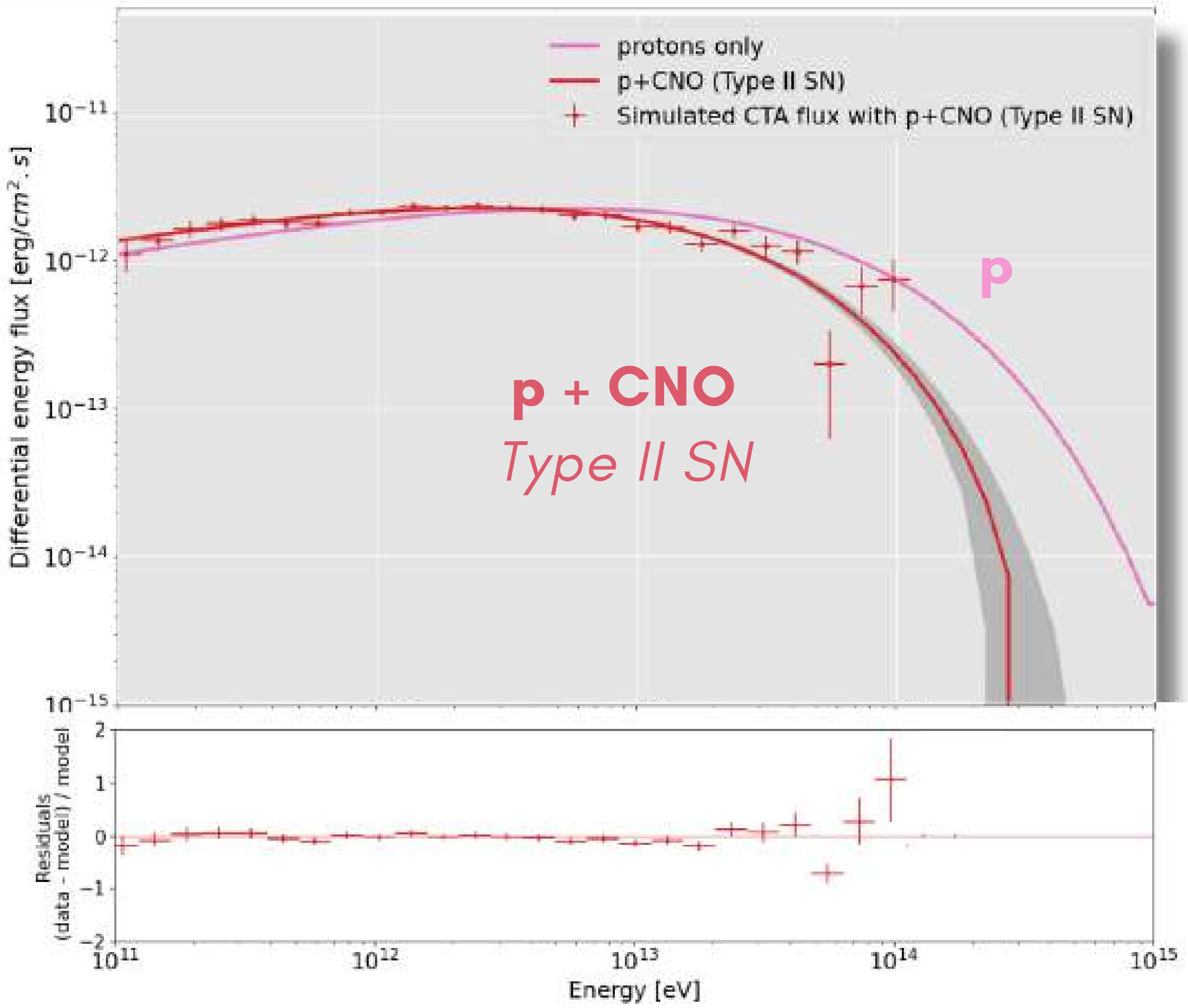
ΔTS = 102 ✓

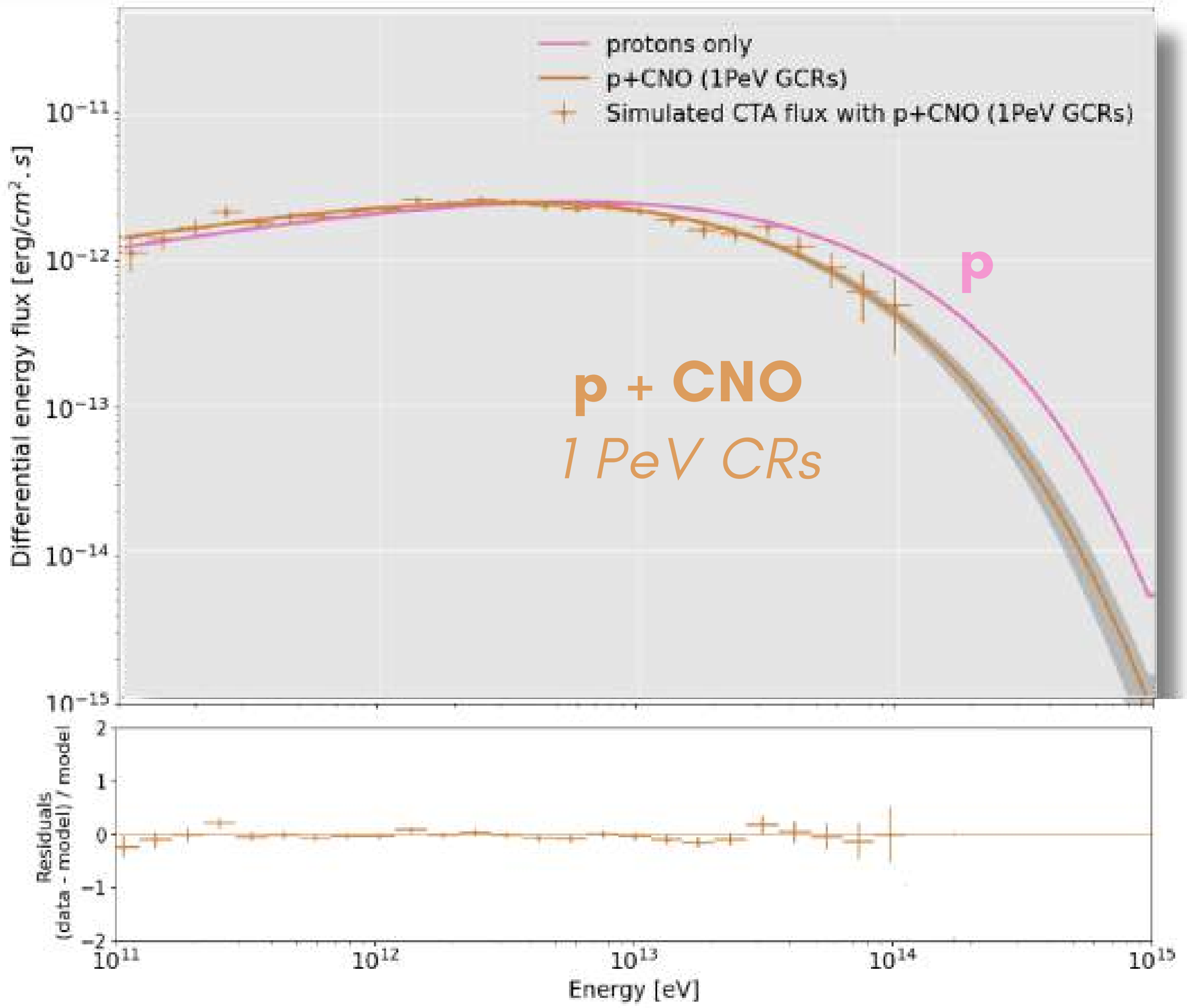
III - Can CTAO detect CRs from SNRs?

<u>Can we separate the studied models</u>?

Data fitting: if Log-Likelihood test **ΔTS > 25 (5σ)** (1 free parameter) => the models are distinguished

CTAO simulations of **HAWC J2227+610** (A_m is free during the fit)



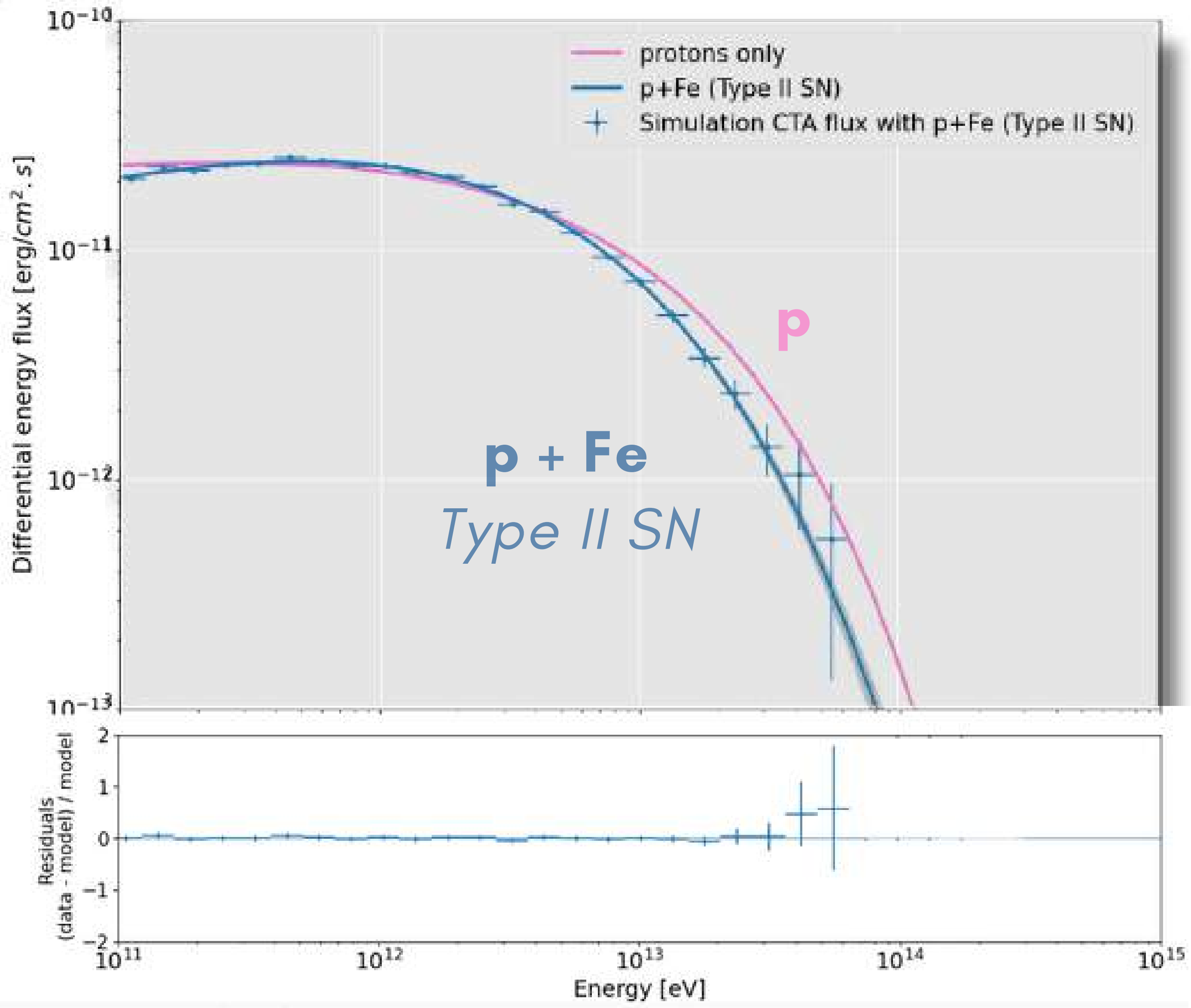


ΔTS = 113 ✓

ΔTS = 53 ✓

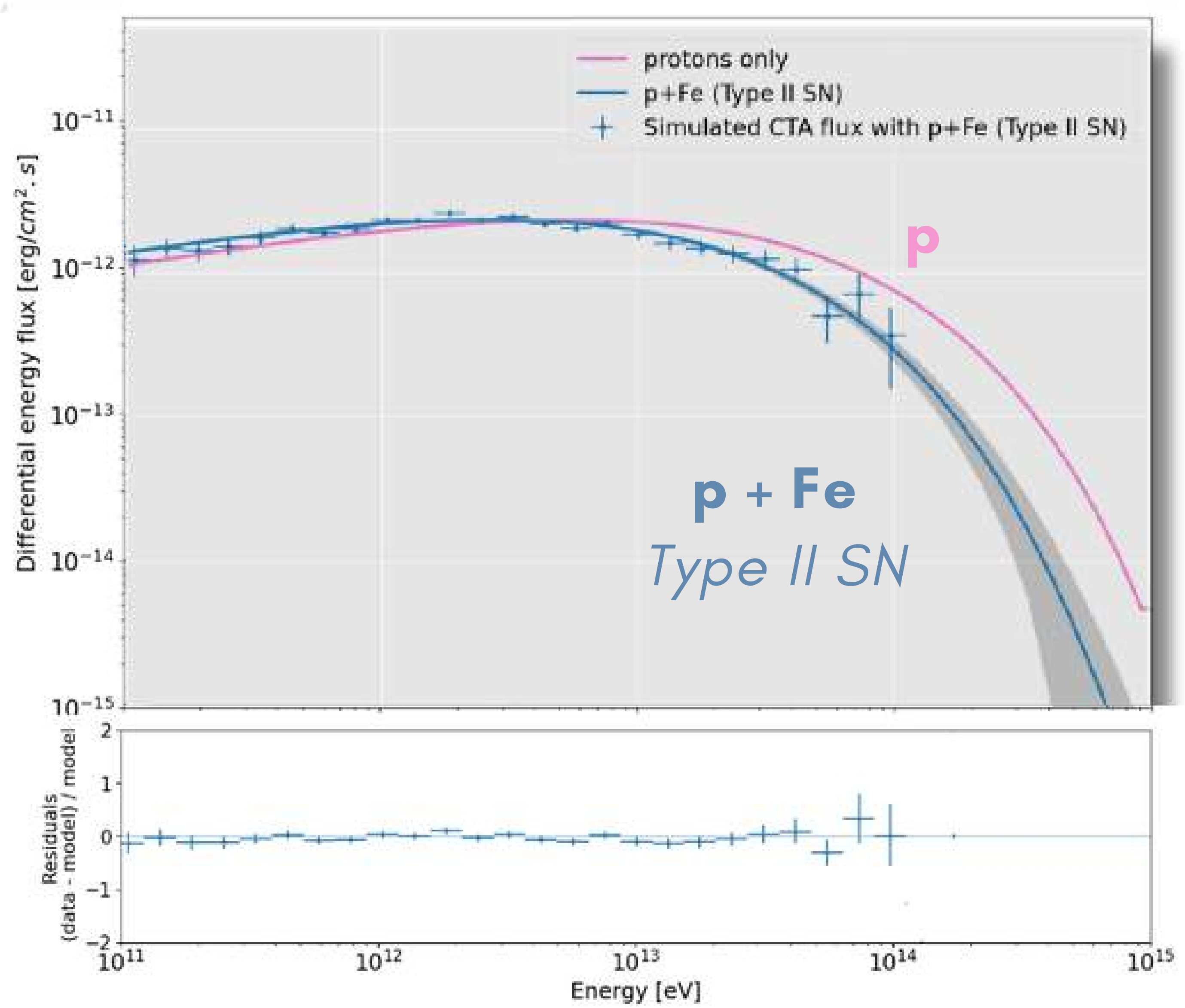
III - Can CTAO detect CRs from SNRs?

CTAO simulations of **RX J1713.7-3946**



ΔTS = 188 ✓

CTAO simulations of **HAWC J2227+610**



ΔTS = 88 ✓

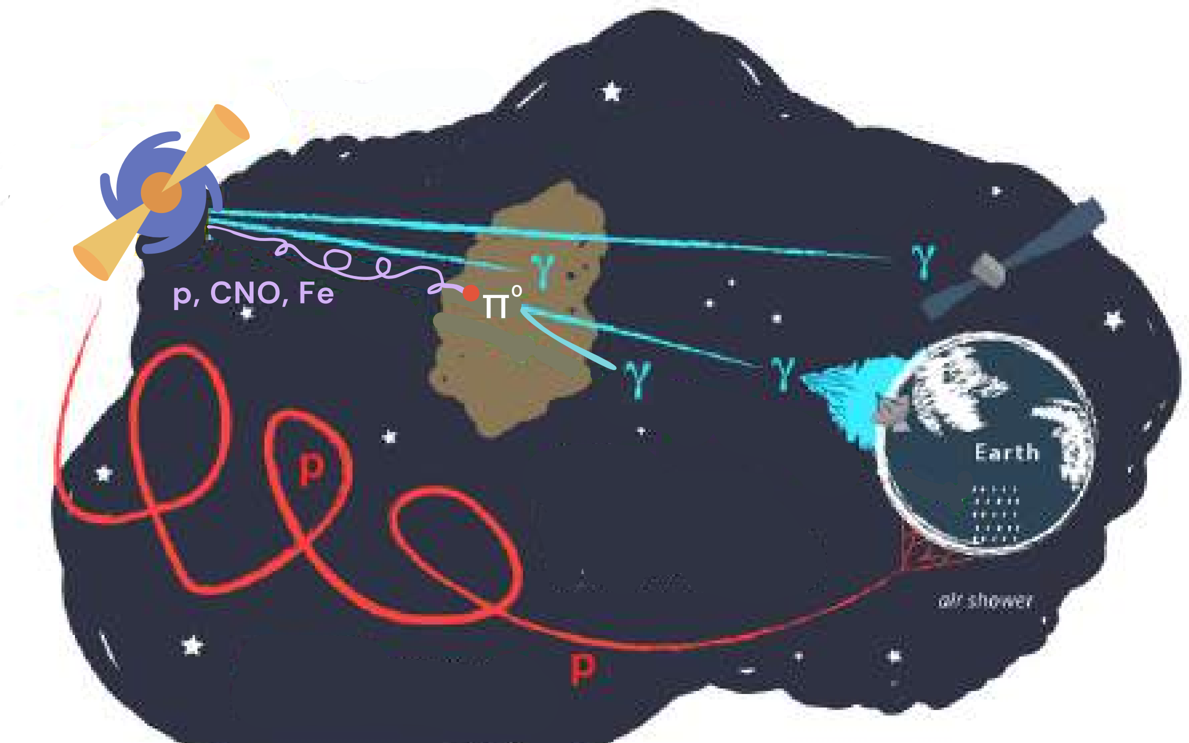
CONCLUSION

<u>Why study CRs with CTAO</u>?

CTAO offers indirect means of **pinpointing the CR source** using gamma-rays. Actually, charged CRs are deviated by Galactic magnetic fields and lose the knowledge of their original direction.

<u>What will CTAO bring to the knowledge of CRs?</u>

CTAO will increase the sensitivity to the spectral shape of γ-rays. In addition to a MWL analysis, this will allow us to **distinguish protons from heavy CRs, providing clues about their origin.**



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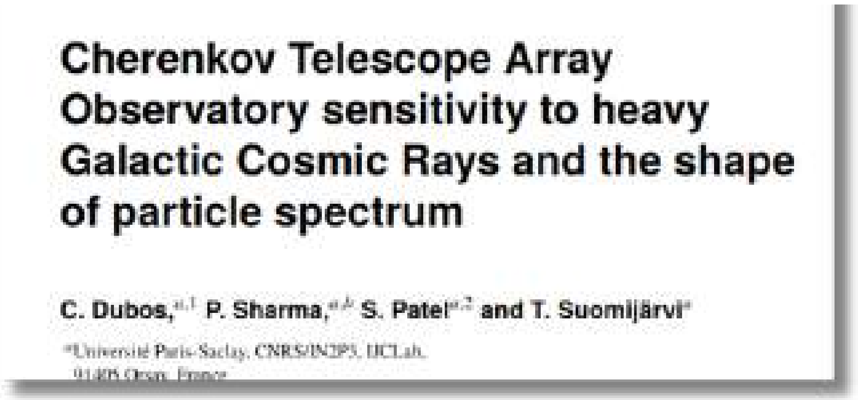
<u>Where can we find this work</u>?

JCAP, Dubos, Sharma, Patel, and Suomijärvi, February 2025 (DOI: 10.1088/1475-7516/2025/02/078)

SCAN ME


Cherenkov Telescope Array Observatory sensitivity to heavy Galactic Cosmic Rays and the shape of particle spectrum

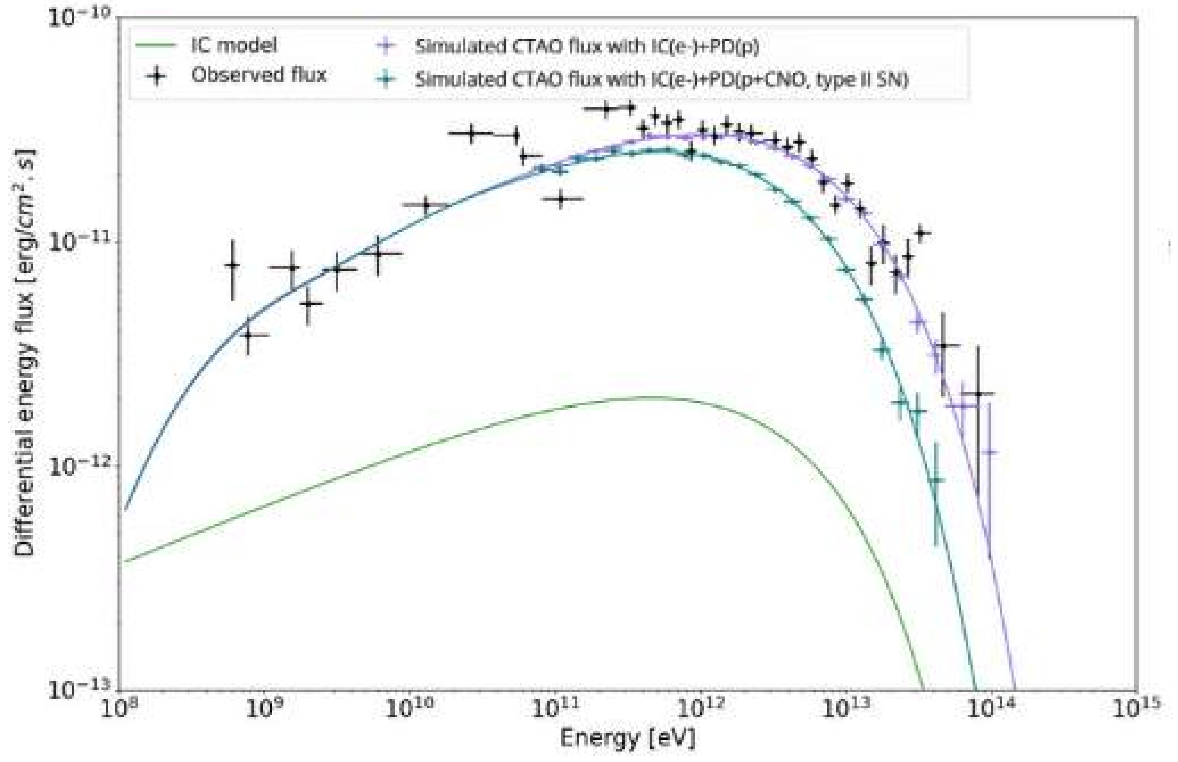
C. Dubos, P. Sharma, S. Patel and T. Suomijärvi

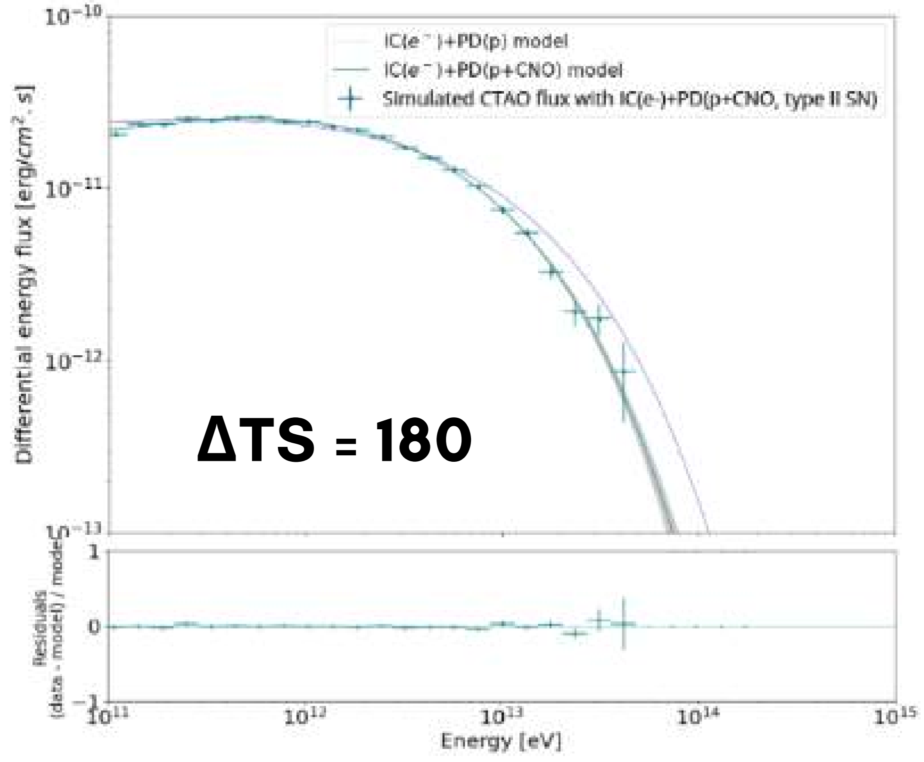
Université Paris-Saclay, CNRS/IN2P3, IJCLab,

CTAO could investigate the **origin of the particle distribution shape**, which may result from **heavy nuclei** or various **acceleration scenarios**.

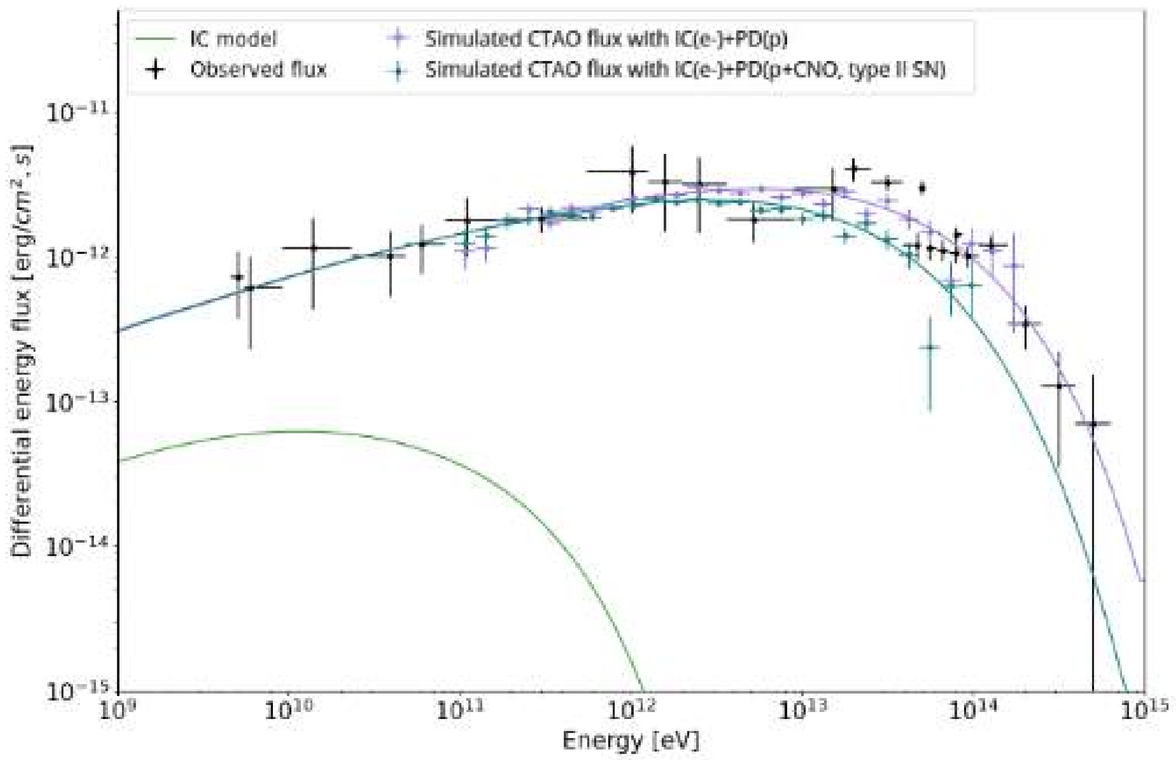
Contribution of electrons through the Inverse Compton process

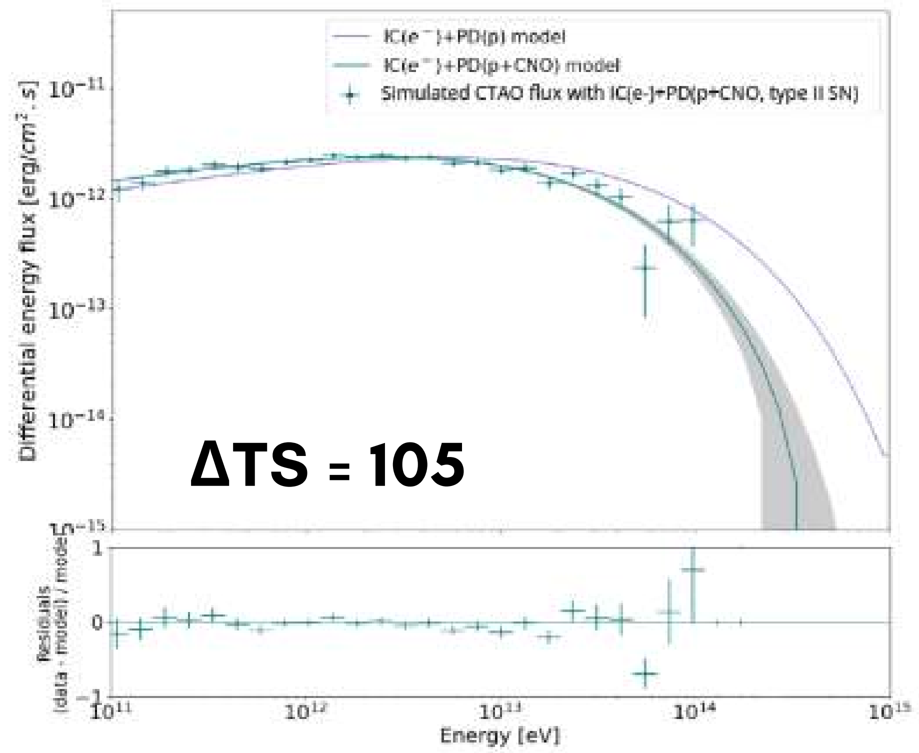
RX J1713.7-3946





HAWC J2227+610

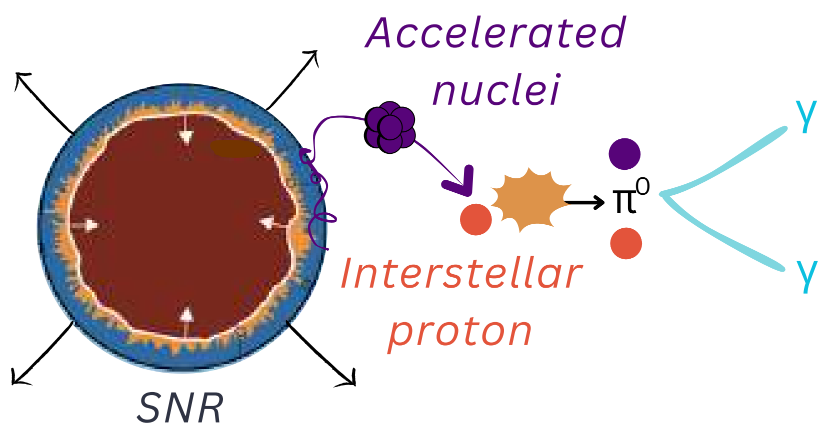




HADRONIC PROCESS FOR GAMMA-RAYS

proton-proton interaction -

Neutral pion decay process



LEPTONIC PROCESS FOR GAMMA-RAYS

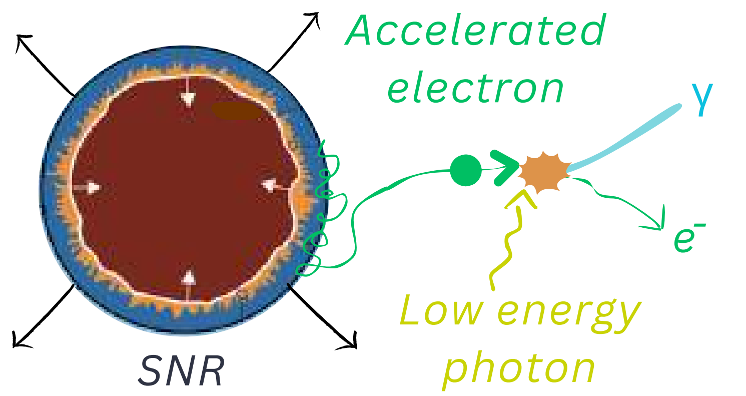
Synchrotron

Bremsstrahlung

Inverse Compton

processes

Energy



APPENDIX

<u>Photon flux emitted from CR distribution</u>

$$F(E) = \mathbf{f}.\sigma.N_H.A_m.(E/E_0)^{-\alpha}.e^{-(E/Z.E_c/A)^{\beta}}$$

free in the fits for **RX J1713.7-3946**

	Theoretical proportion [%]	Fitted proportion [%]	Relative dispersion [%]
p+CNO (1 PeV GCRs)	fp = 66	fp = 65 ± 5	1
p+CNO (Type II SN)	fp = 24	fp = 16 ± 9	35
p+Fe (Type II SN)	fp = 60	fp = 53 ± 11	11

CTAO could reconstruct the composition of the very-high energy CRs, specifically for CRs accelerated up to PeV energies.

What about the other PeVatron candidates?

CRs accelerated by Galactic sources? **PeVatrons**

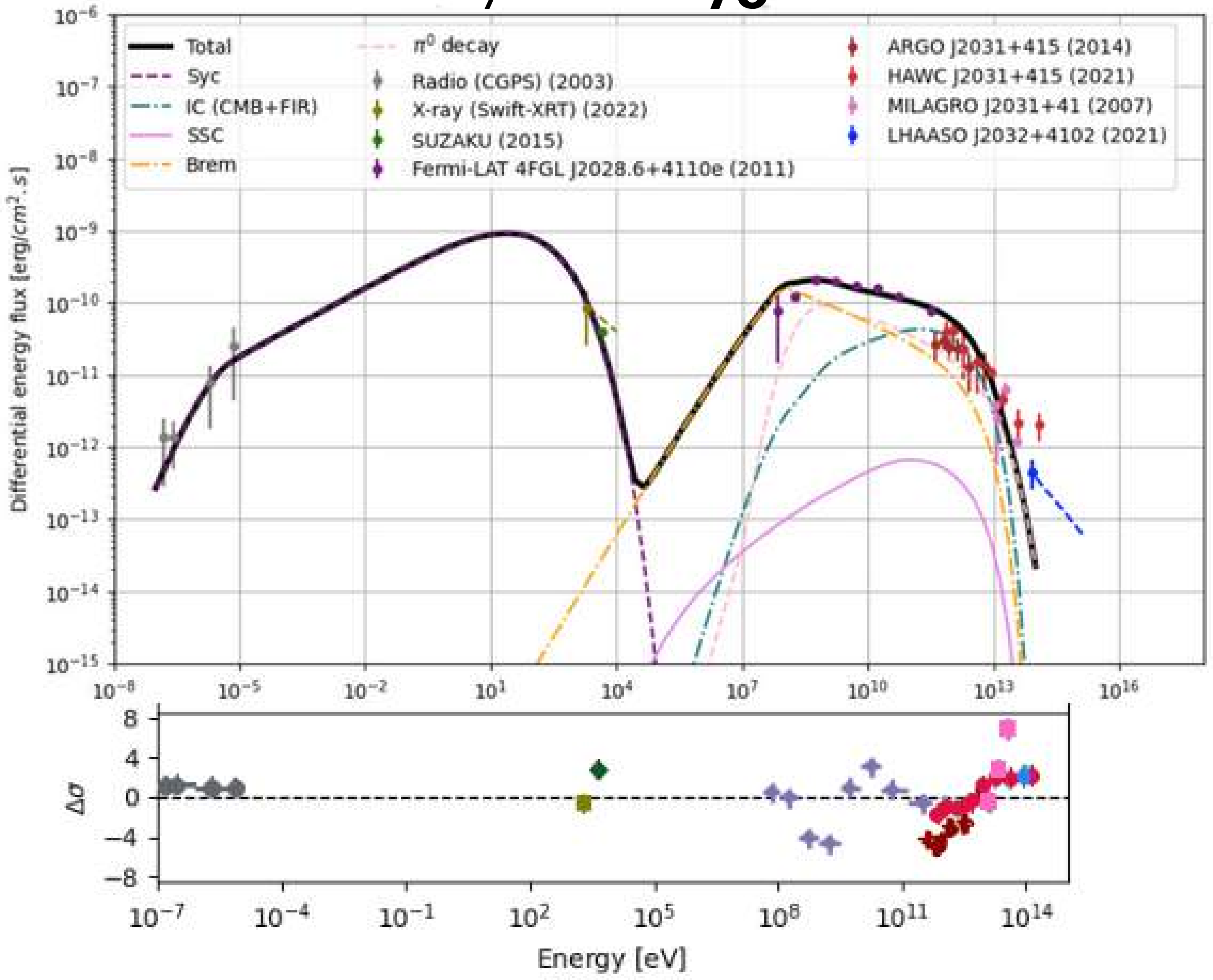
<u>PeVatron candidates</u>:

Supernova Remnant

Stellar Cluster

TS (obs)	TS (obs+CTAO)
212.24	118.80

MWL analysis of **Cygnus Cocoon**



Inclusion of CTAO simulations