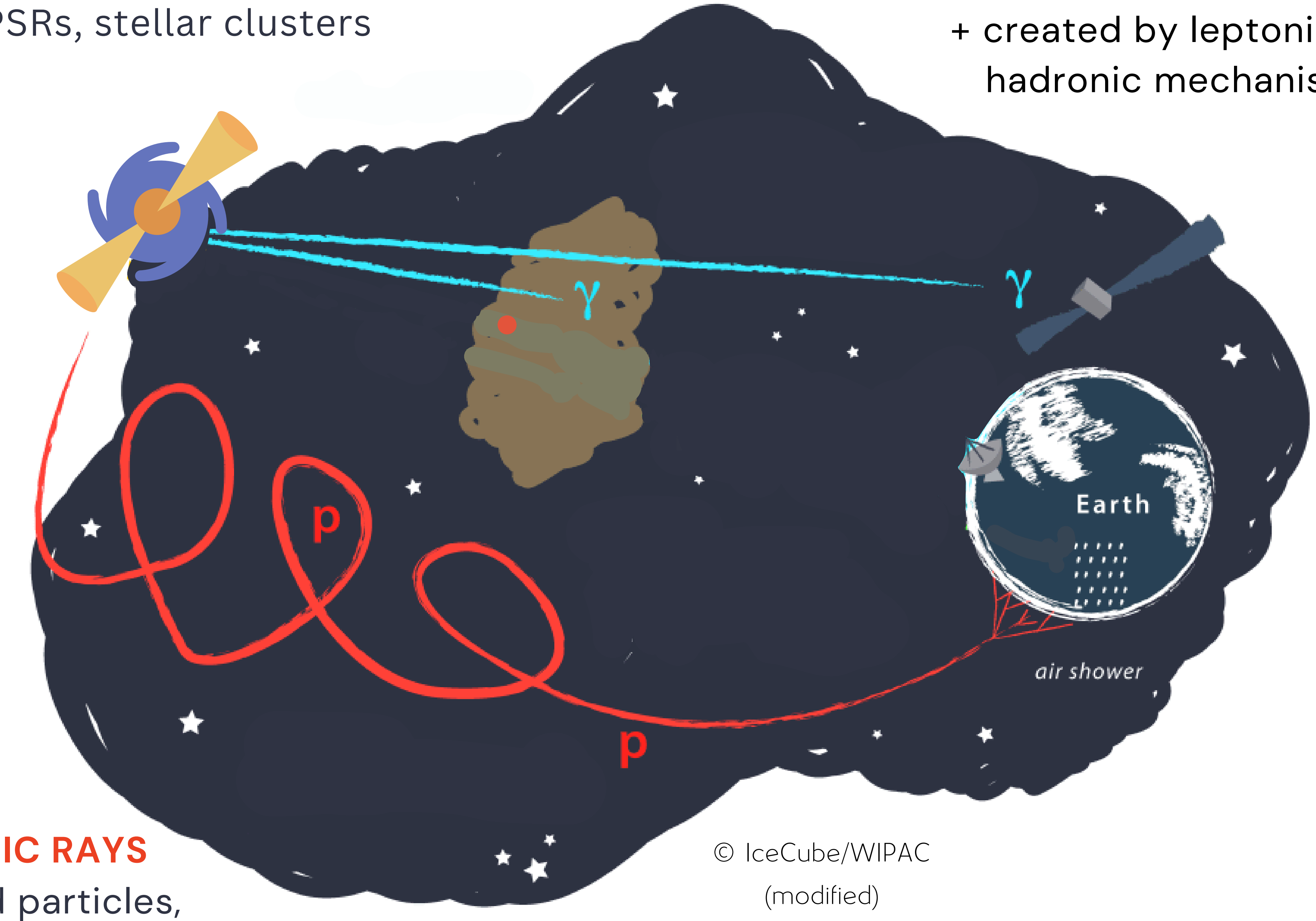
CTAO SENSITIVITY TO HEAVY GALACTIC COSMIC RAYS

Coline Dubos,
Tiina Suomijärvi
IJCLab
3rd year, mail : coline.dubos@ijclab.in2p3.fr

INTRODUCTION

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

GALACTIC SOURCES
SNRs, PSRs, stellar clusters



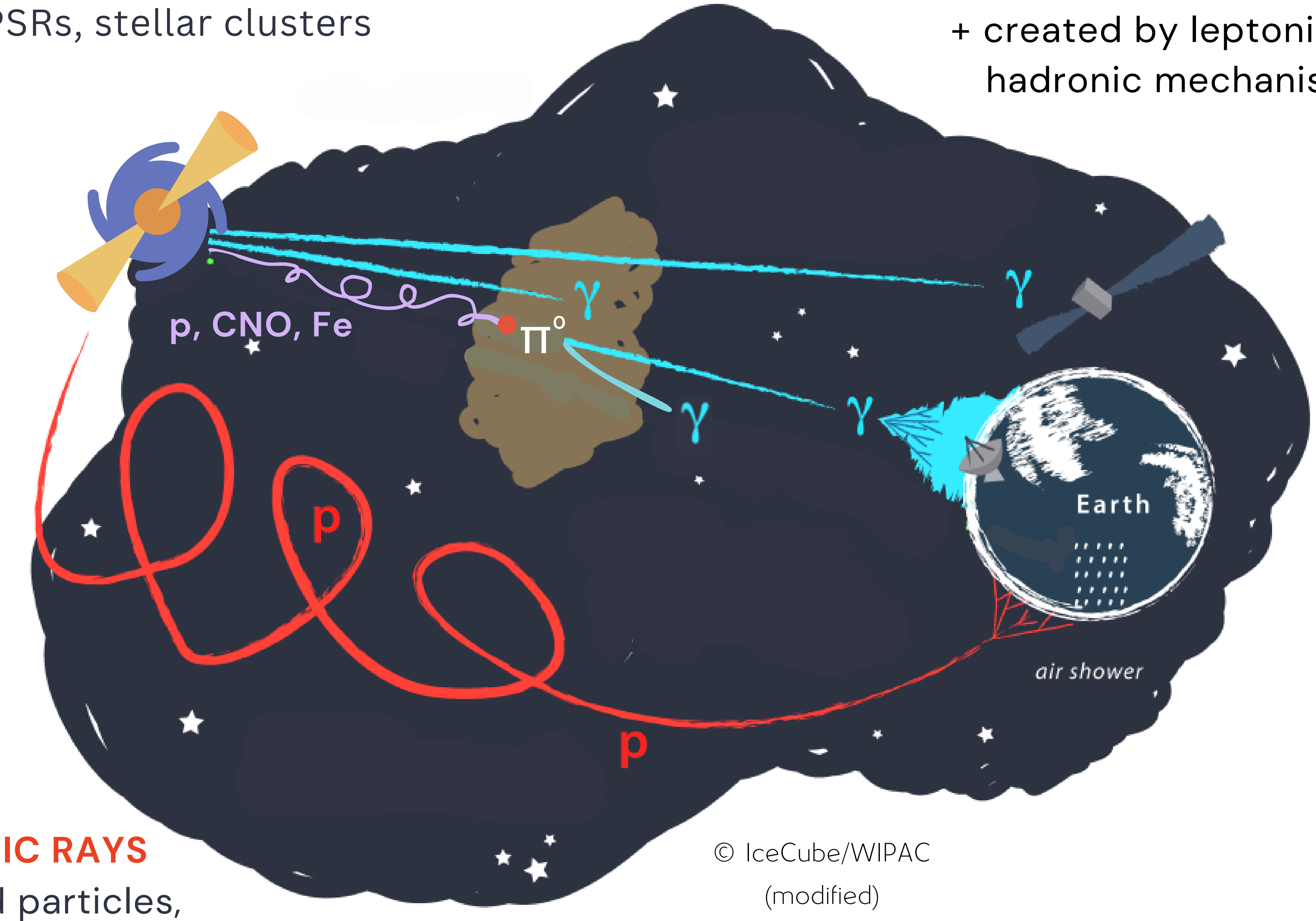
© IceCube/WIPAC
(modified)

COSMIC RAYS
Charged particles,
deflected by
magnetic fields

INTRODUCTION

GALACTIC SOURCES
SNRs, PSRs, stellar clusters

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



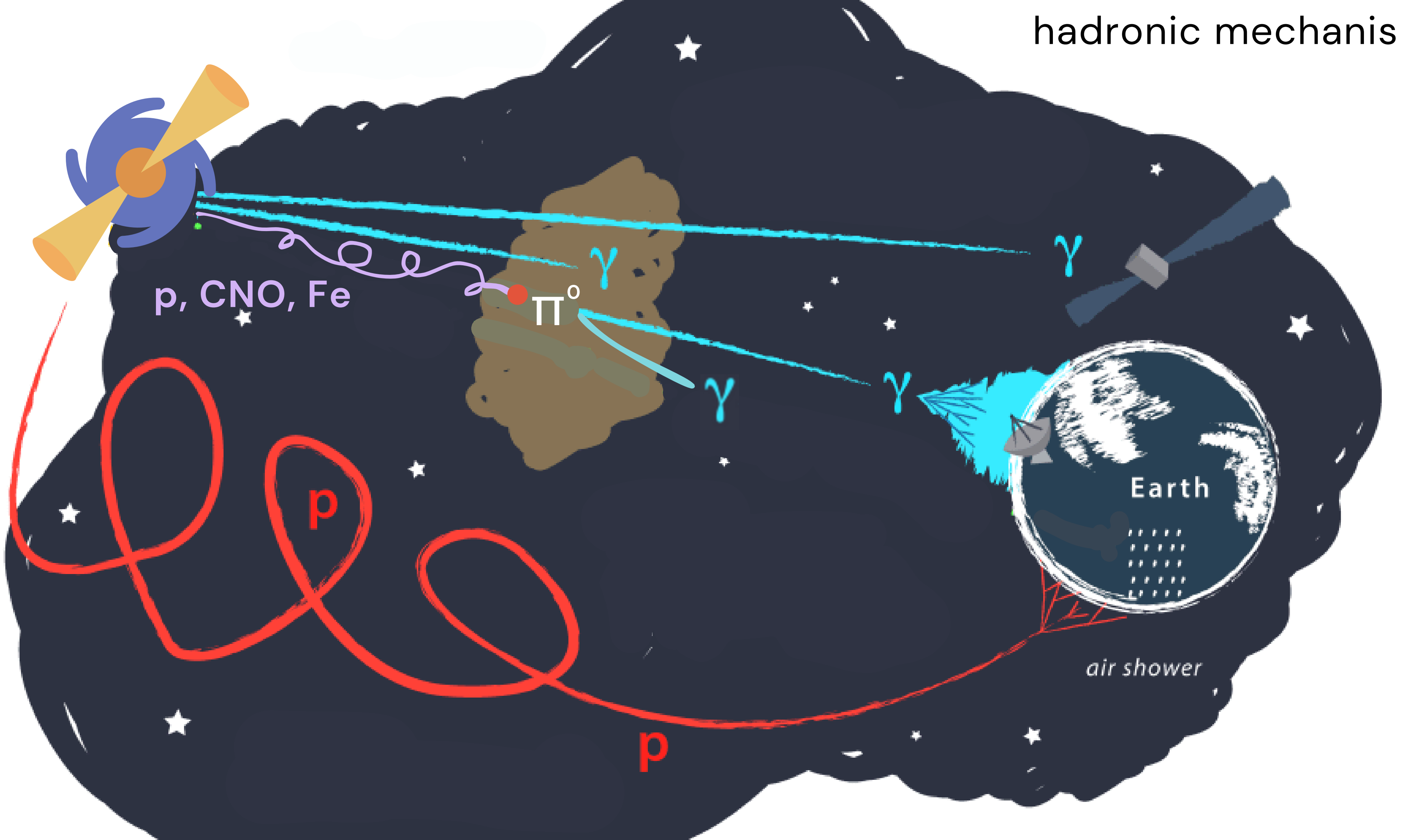
© IceCube/WIPAC
(modified)

COSMIC RAYS
Charged particles,
deflected by
magnetic fields

INTRODUCTION

GALACTIC SOURCES
SNRs, PSRs, stellar clusters

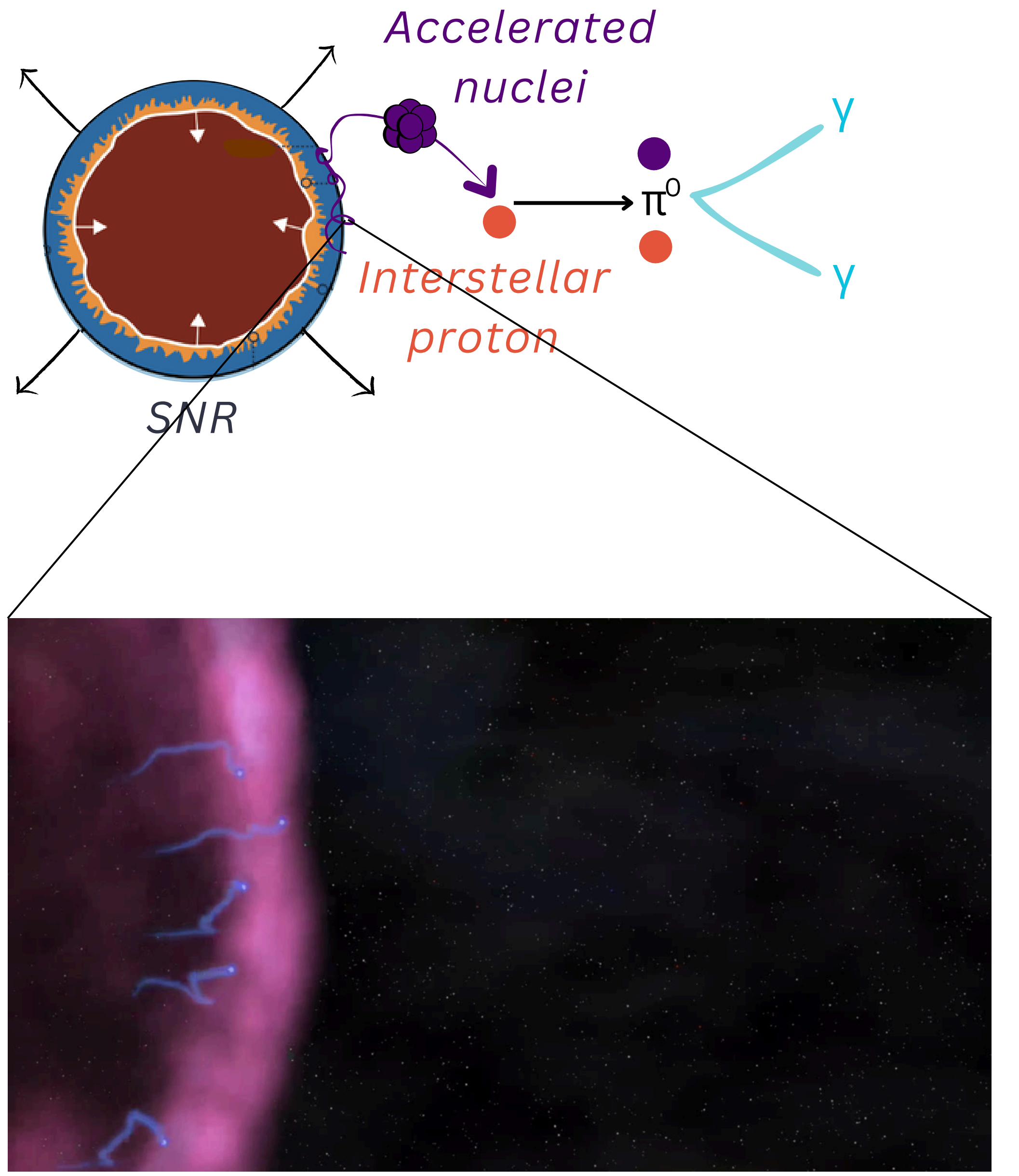
GAMMA RAYS
Point to their sources
+ not absorbed in our Galaxy
+ created by leptonic and hadronic mechanisms



© IceCube/WIPAC (modified)

COSMIC RAYS
Charged particles, deflected by magnetic fields

HADRONIC PROCESS FOR GAMMA-RAYS
CRs-proton interaction - Neutral pion decay process

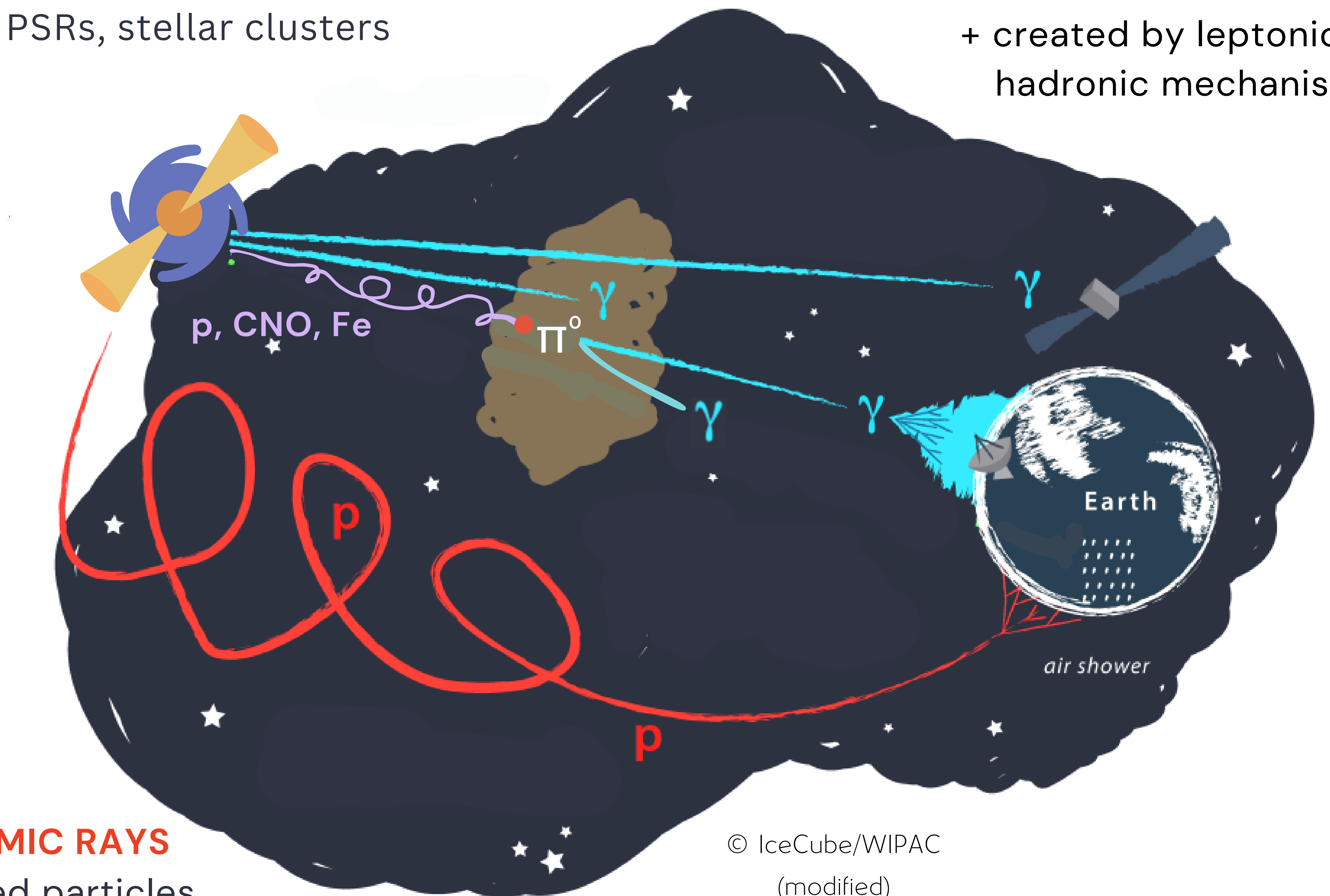


© NASA's Goddard Space Flight Center

INTRODUCTION

GALACTIC SOURCES
SNRs, PSRs, stellar clusters

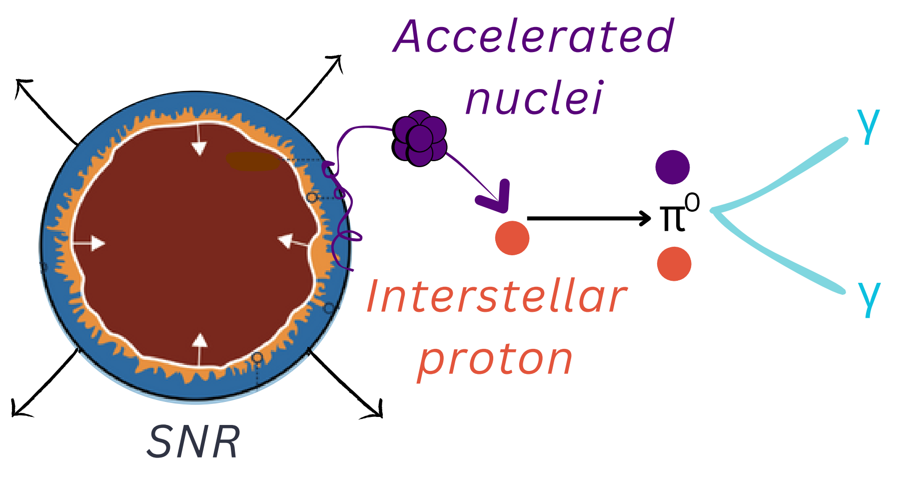
GAMMA RAYS
Point to their sources
+ not absorbed in our Galaxy
+ created by leptonic and hadronic mechanisms



© IceCube/WIPAC (modified)

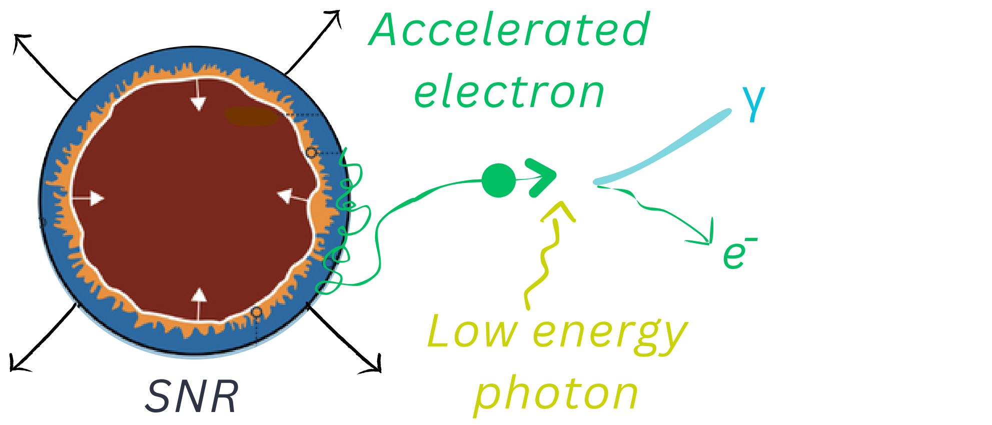
COSMIC RAYS
Charged particles, deflected by magnetic fields

HADRONIC PROCESS FOR GAMMA-RAYS
CRs-proton interaction - Neutral pion decay process



LEPTONIC PROCESS FOR GAMMA-RAYS
Synchrotron
Bremsstrahlung
Inverse Compton
processes

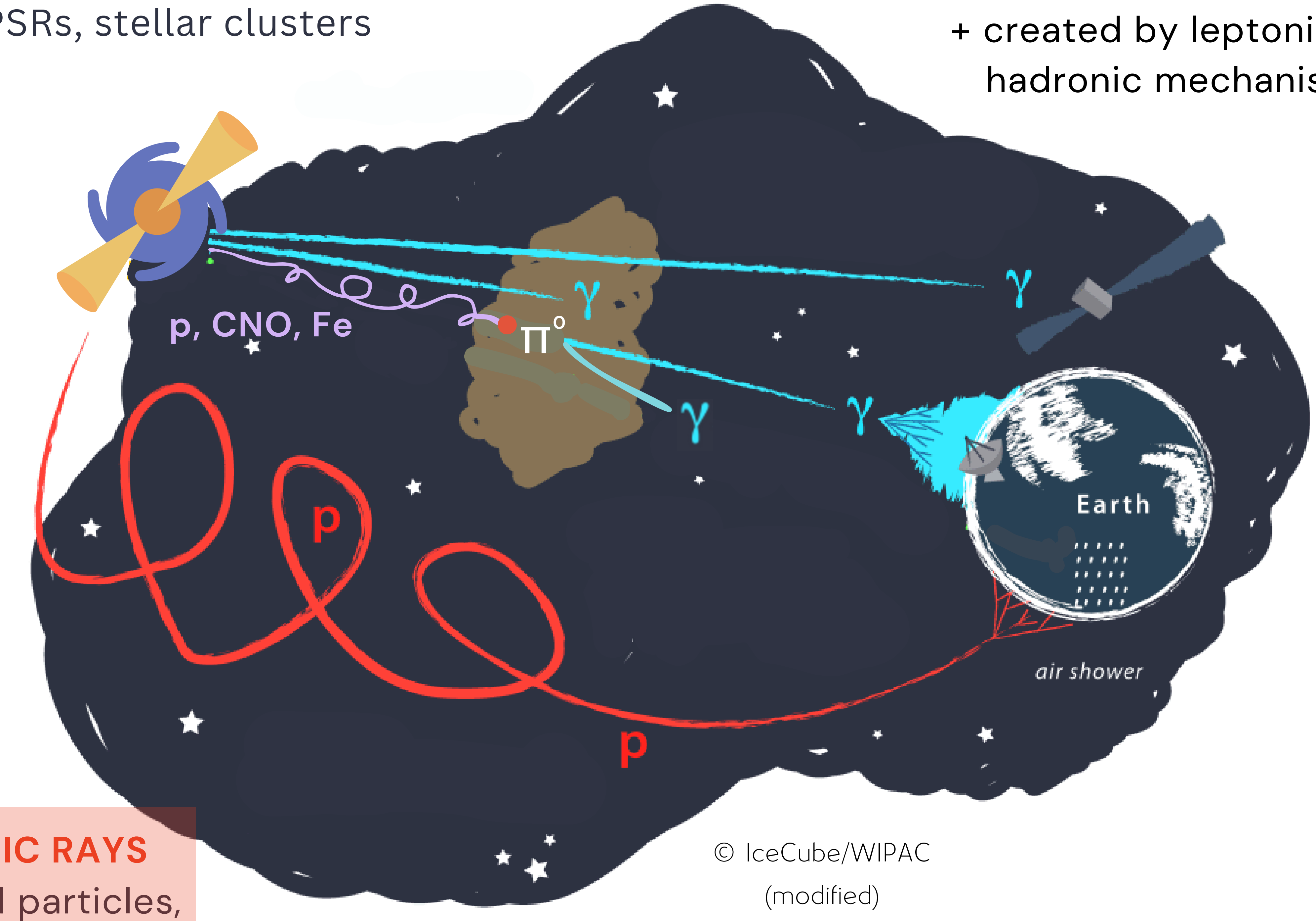
Energy ↓



INTRODUCTION

GALACTIC SOURCES
SNRs, PSRs, stellar clusters

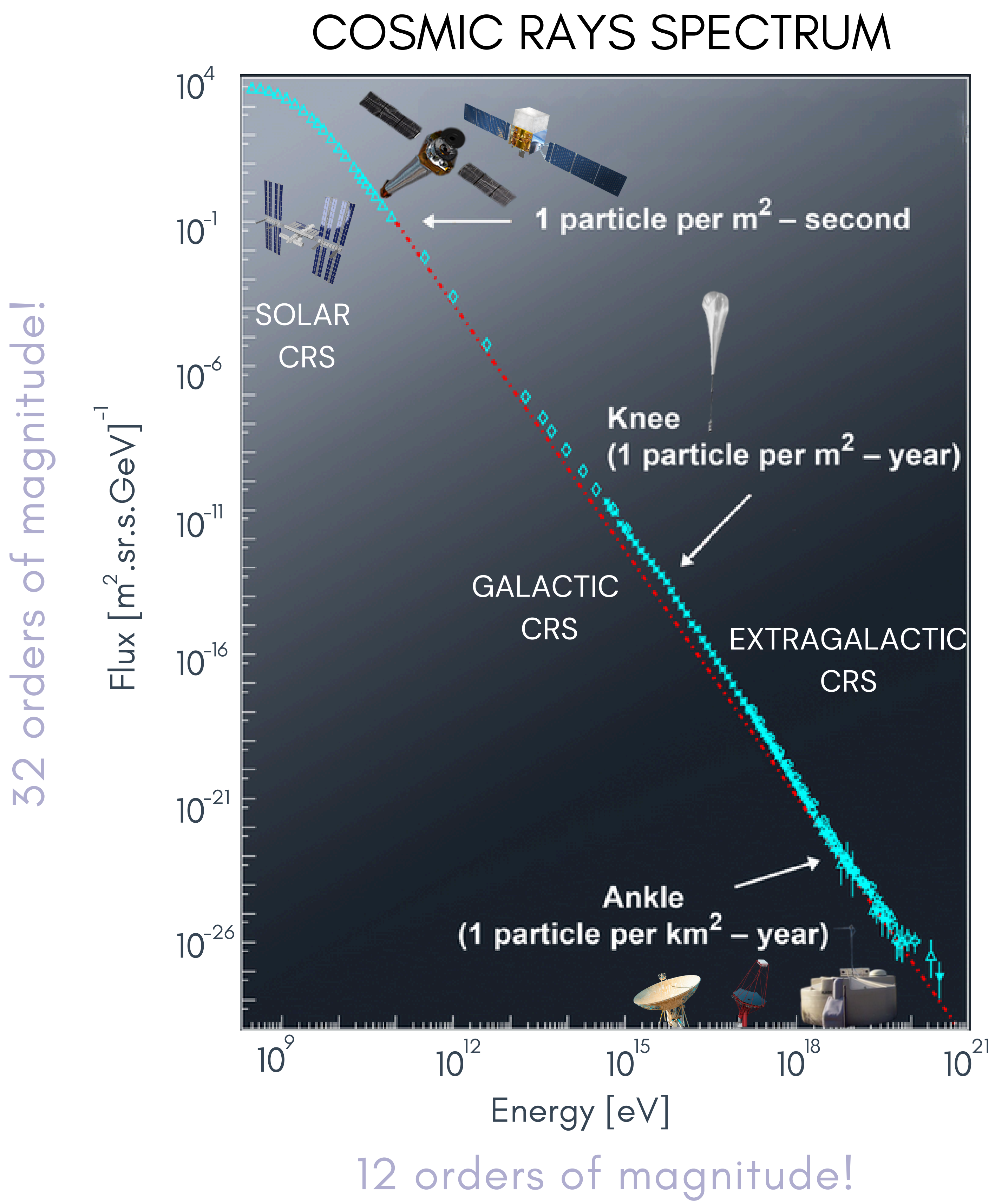
GAMMA RAYS
Point to their sources
+ not absorbed in our Galaxy
+ created by leptonic and
hadronic mechanisms



© IceCube/WIPAC
(modified)

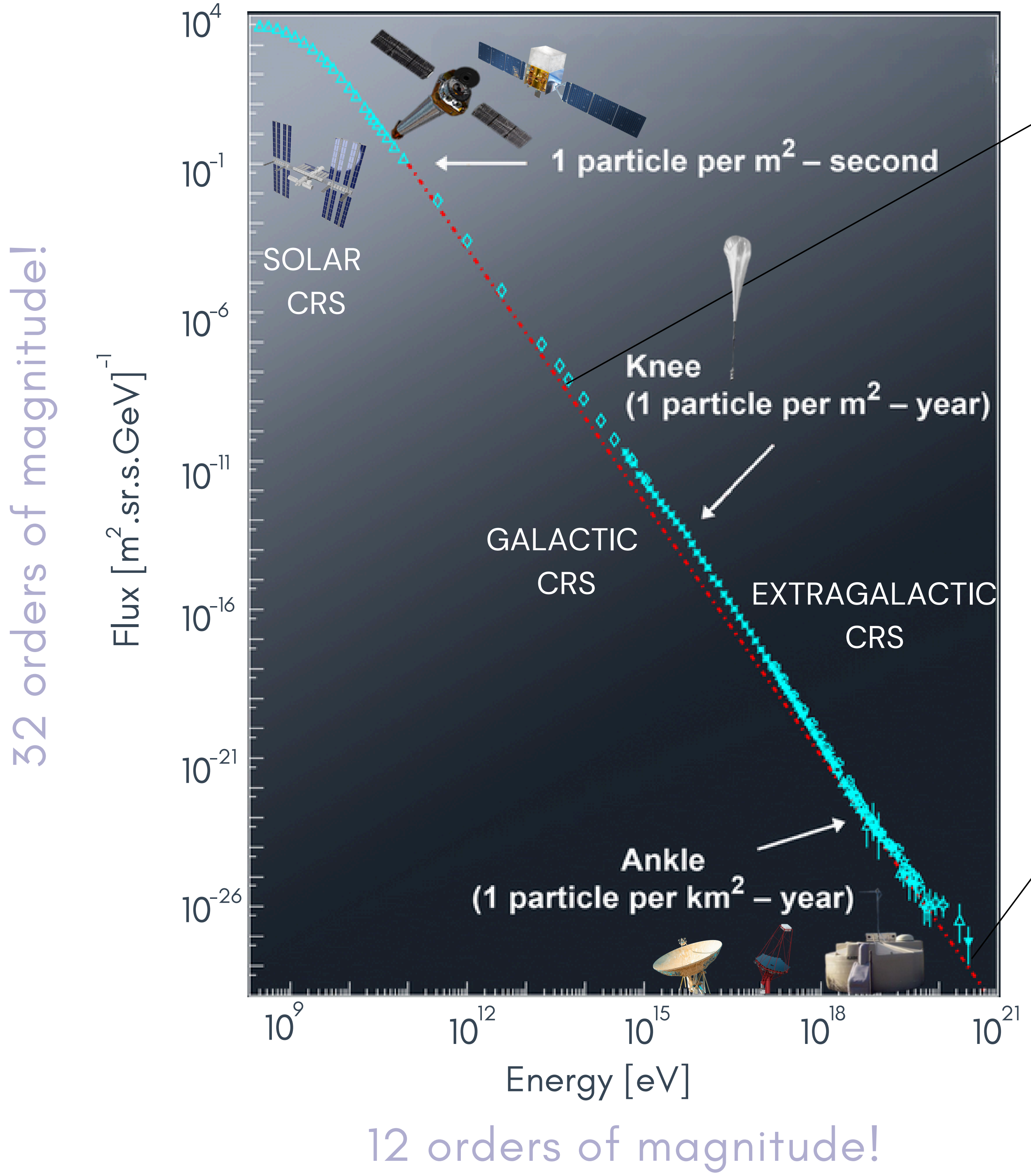
COSMIC RAYS
Charged particles,
deflected by
magnetic fields

CONTEXT

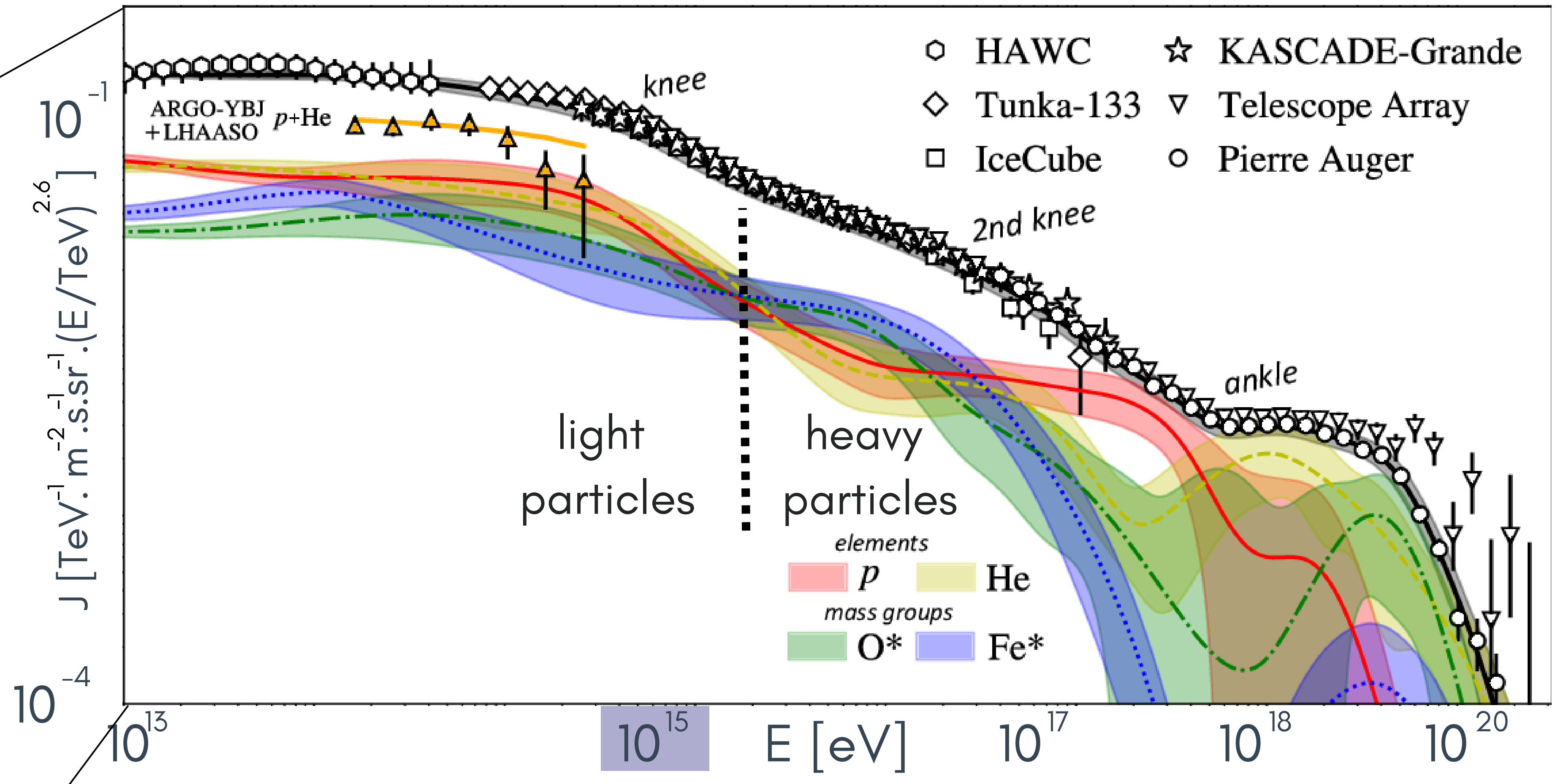

COSMIC RAYS SPECTRUM
10^{4}
10^{-1}
10^{-6}
10^{-11}
10^{-16}
10^{-21}
10^{-26}
Flux [m^2.sr.s.GeV]$^{-1}$
1 particle per m^2 – second
SOLAR CRS
Knee
(1 particle per m^2 – year)
GALACTIC CRS
EXTRAGALACTIC CRS
Ankle
(1 particle per km^2 – year)
10^{9}
10^{12}
10^{15}
10^{18}
10^{21}
Energy [eV]
32 orders of magnitude!
12 orders of magnitude!

CONTEXT

COSMIC RAYS 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>:

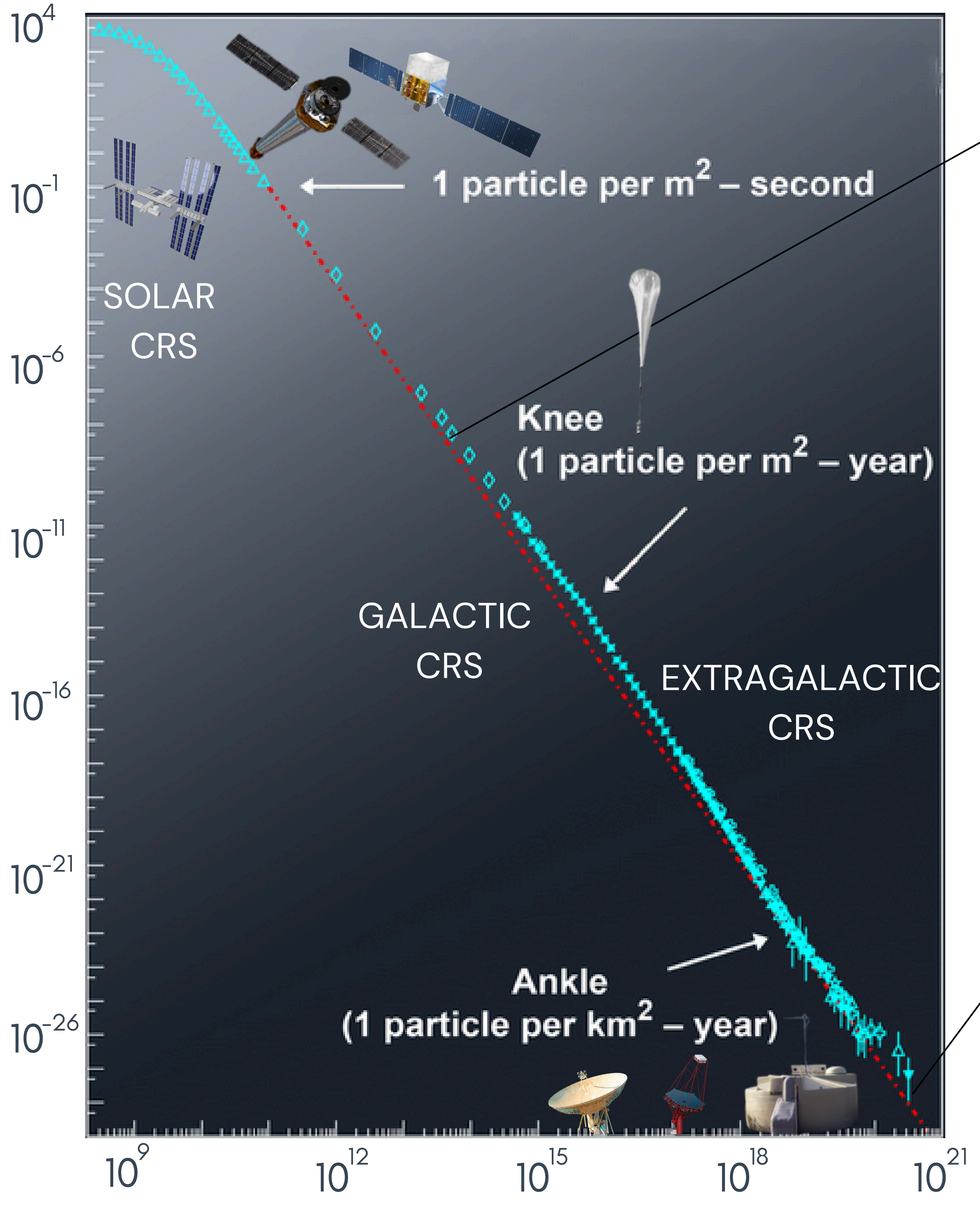
Supernova Remnant

Stellar Cluster

CONTEXT

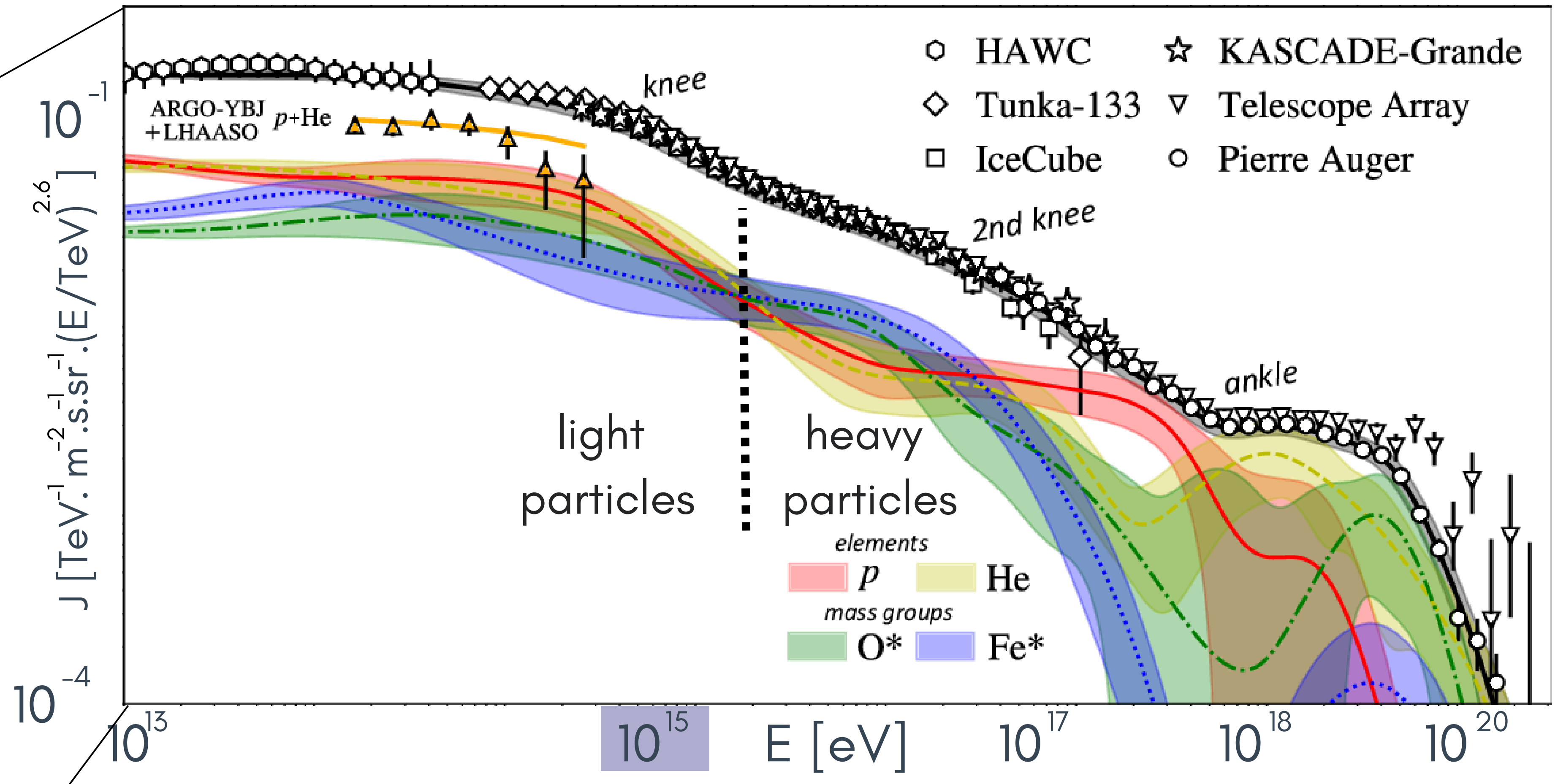
COSMIC RAYS SPECTRUM

32 orders of magnitude!



12 orders of magnitude!

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

PeVatron candidates:

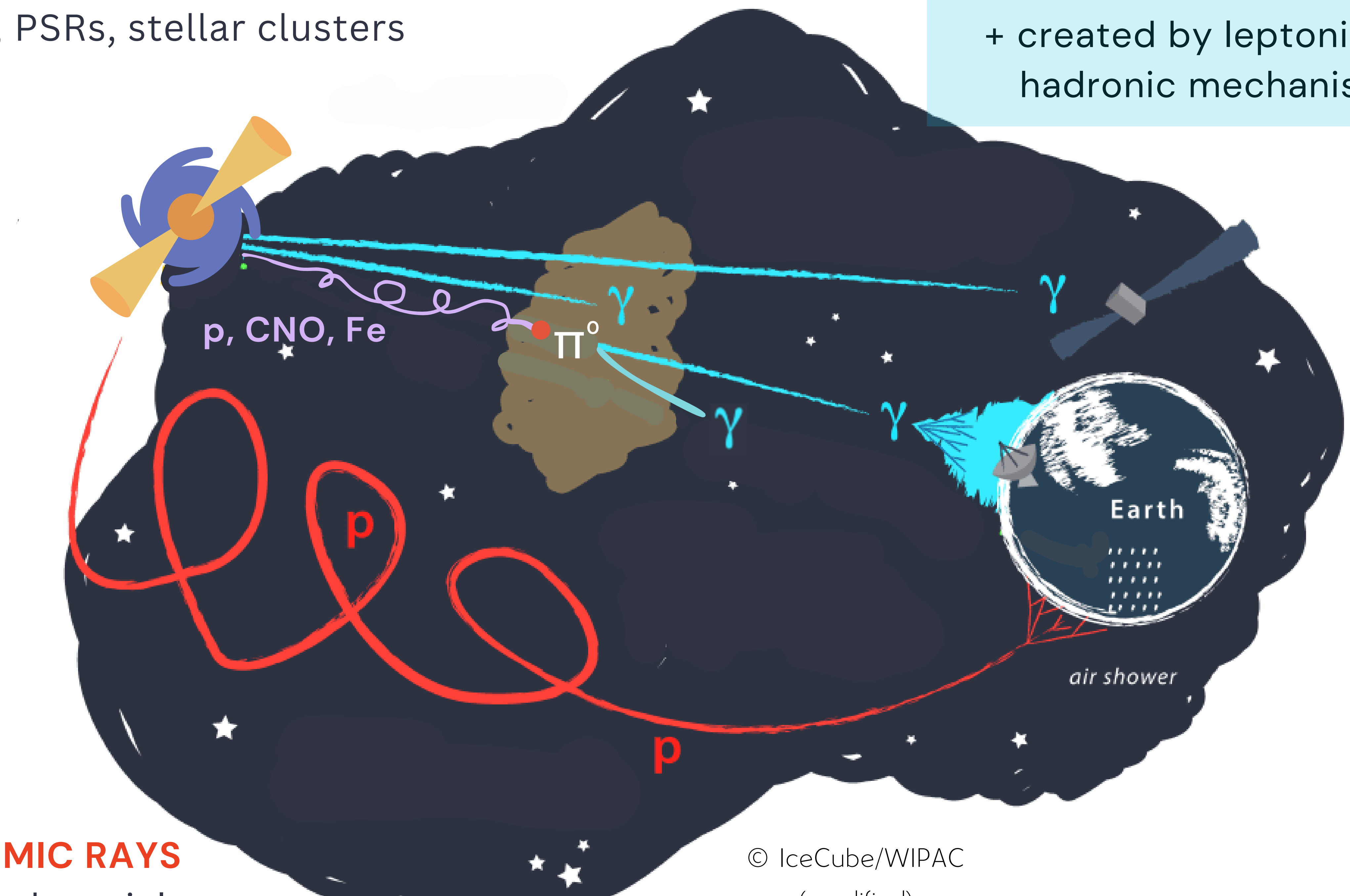
Supernova Remnant

Stellar Cluster

I - WHEN MODELS MEET DATA

GALACTIC SOURCES
SNRs, PSRs, stellar clusters

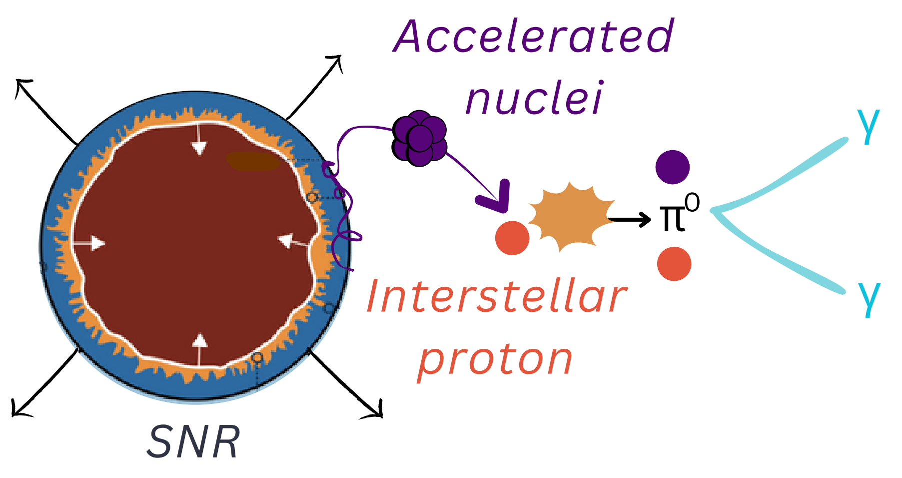
GAMMA RAYS
Point to their sources
+ not absorbed in our Galaxy
+ created by leptonic and hadronic mechanisms



© IceCube/WIPAC (modified)

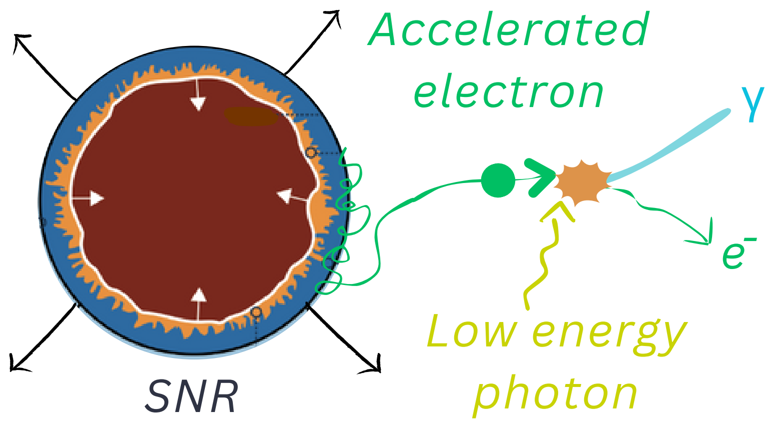
COSMIC RAYS
Charged particles, deflected by magnetic fields

HADRONIC PROCESS FOR GAMMA-RAYS
proton-proton interaction -
Neutral pion decay process



LEPTONIC PROCESS FOR GAMMA-RAYS
Synchrotron
Bremsstrahlung
Inverse Compton
processes

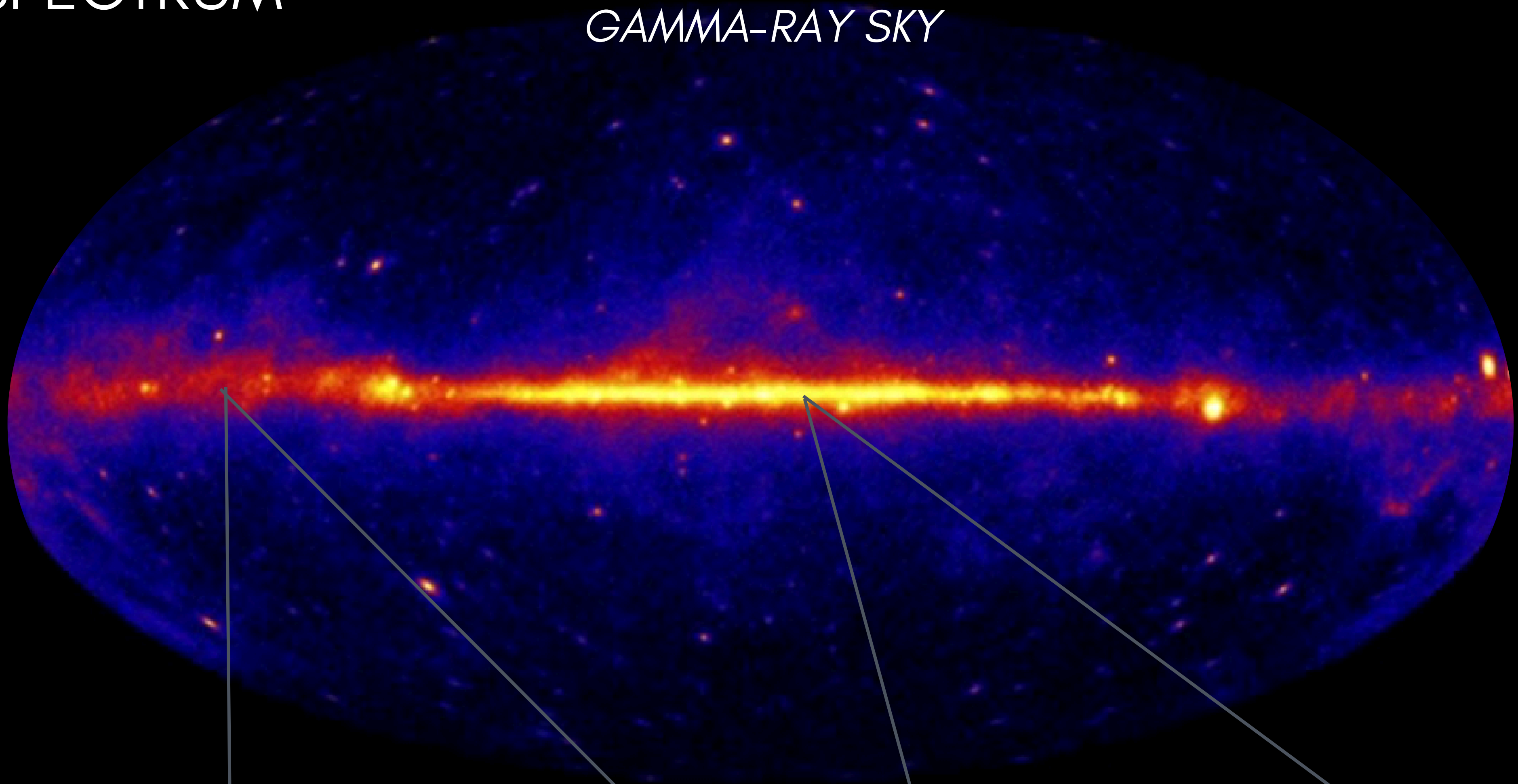
Energy



I - WHEN MODELS MEET DATA

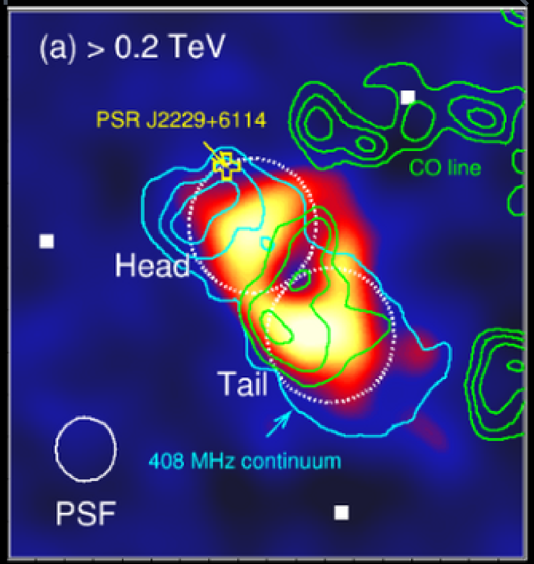
MWL ANALYSIS OF THE γ SPECTRUM OF 2 SNRS

GAMMA-RAY SKY

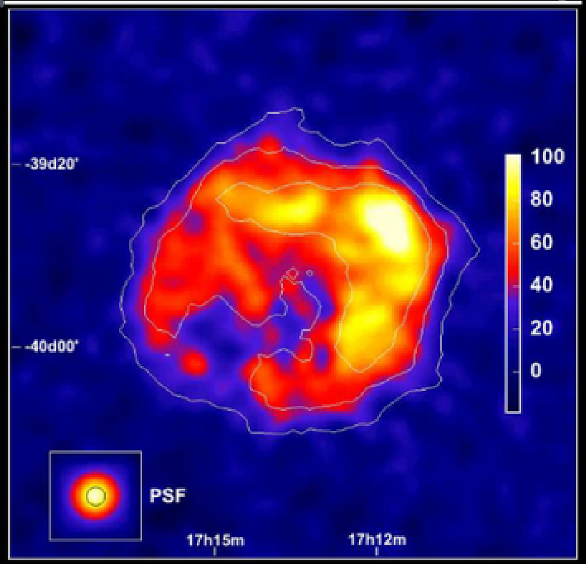


SNR | **HAWC J2227+610**

RX J1713.7-3946 | SNR



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



The γ-ray supernova remnant
RX J1713.7-3946
F. Aharonian et al. 2018

I - WHEN MODELS MEET DATA

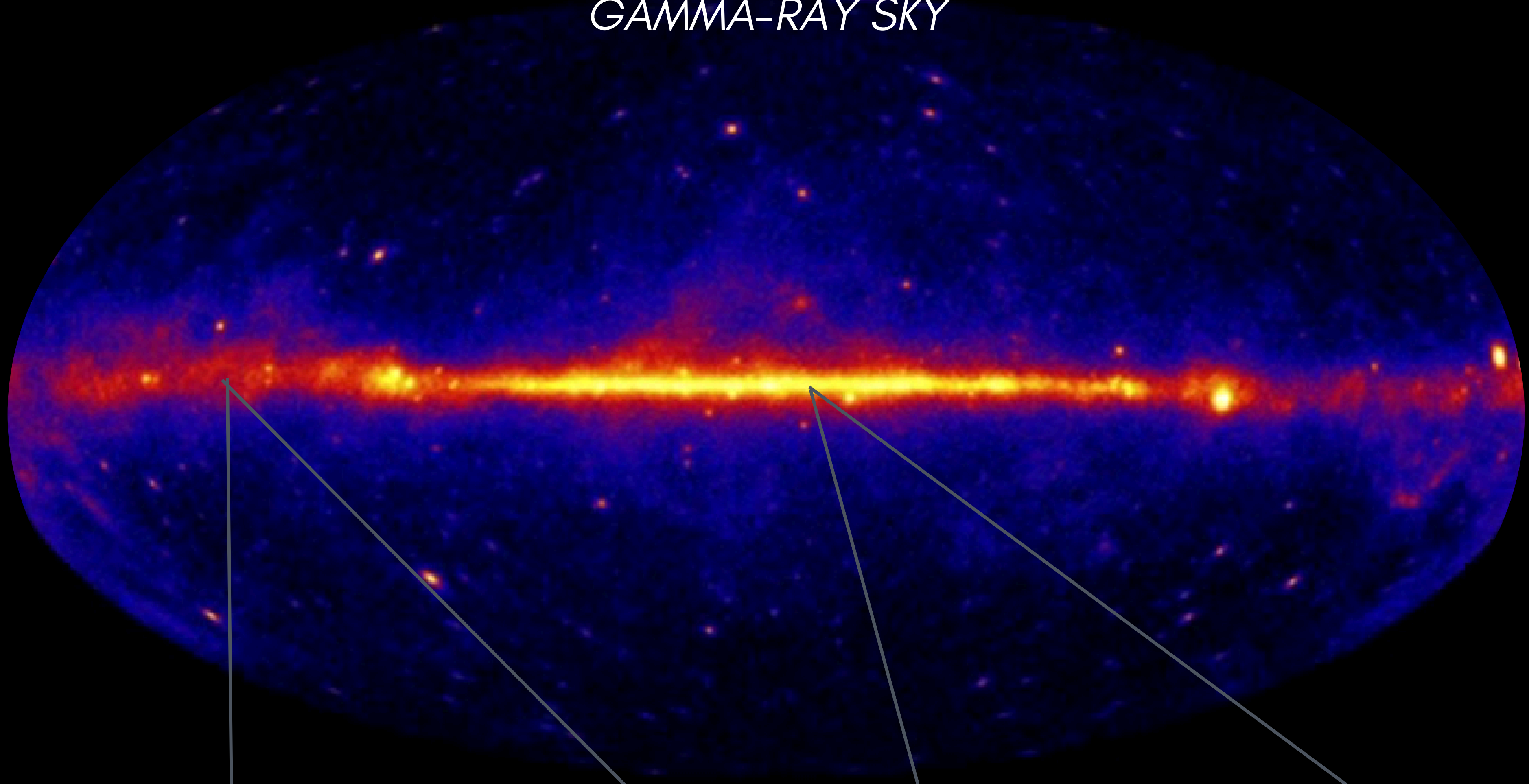
MWL ANALYSIS OF THE γ SPECTRUM OF 2 SNRS

Multiwavelength analysis of Galactic Supernova Remnants

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

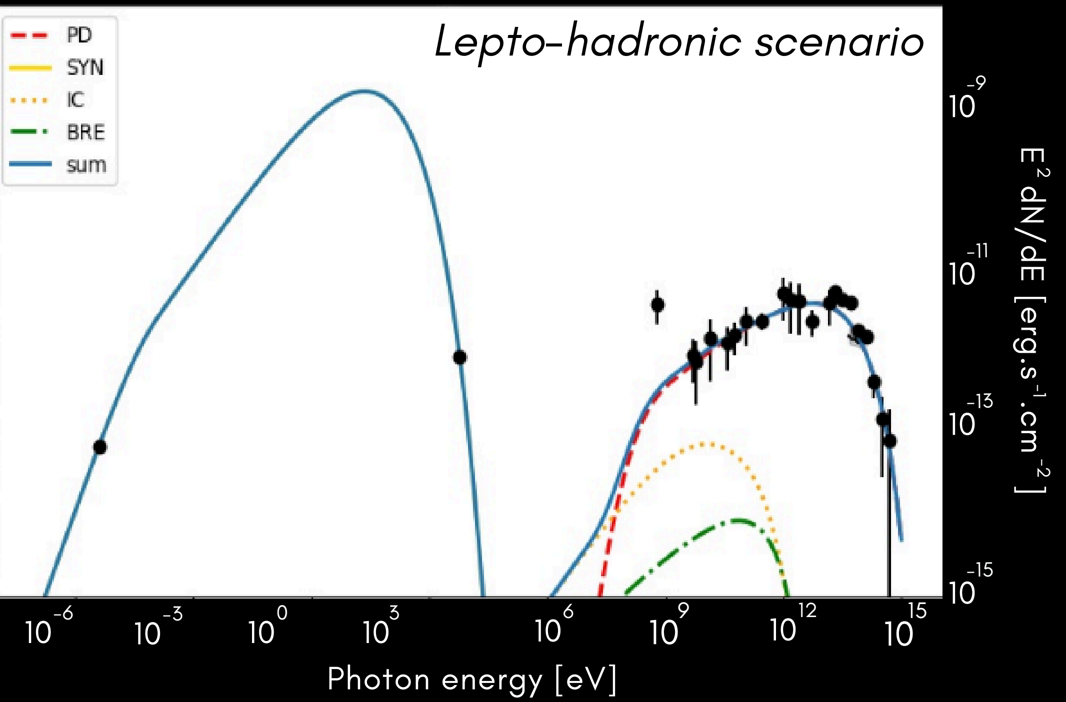
SCAN ME

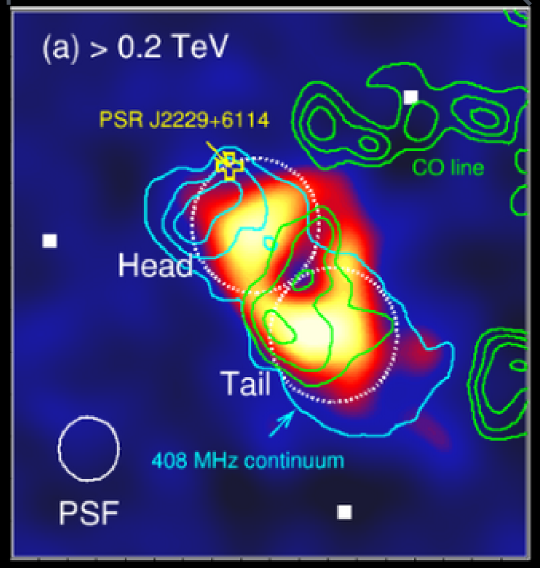
GAMMA-RAY SKY



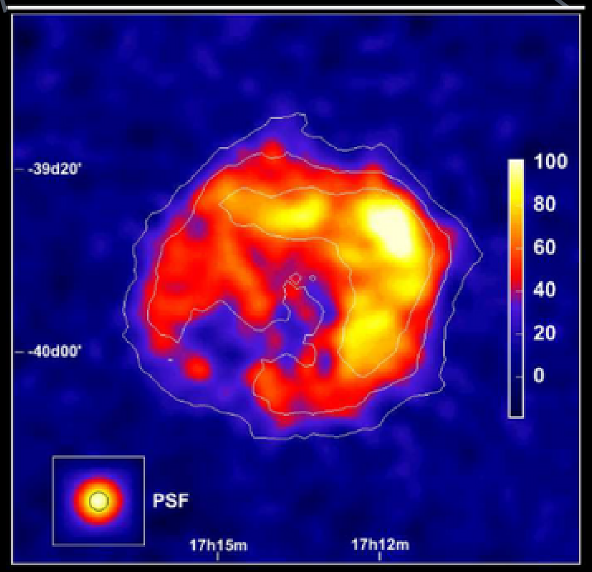
FERMI-LAT / VERITAS / LHAASO / HAWC TELESCOPE

SNR | HAWC J2227+610





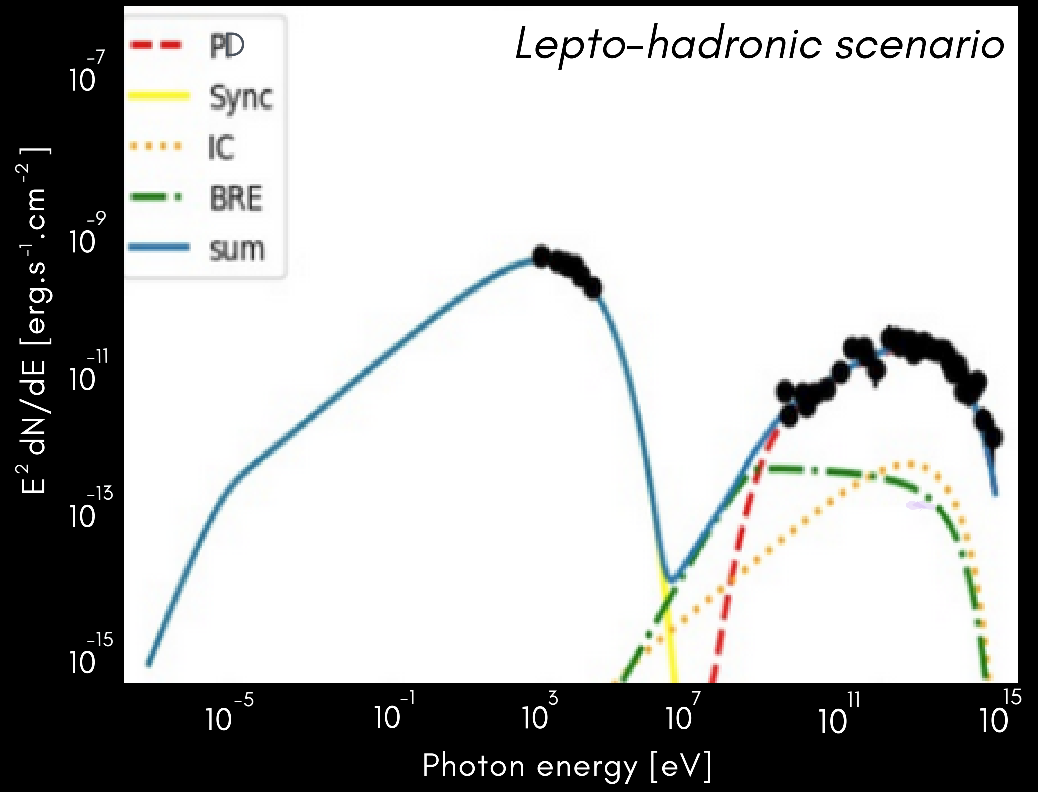
The γ-ray supernova G106.3+2.7
MAGIC collaboration 2022



The γ-ray supernova remnant RX J1713.7-3946
F. Aharonian et al. 2018

FERMI / H.E.S.S. TELESCOPE

RX J1713.7-3946 | SNR



I - WHEN MODELS MEET DATA

HEAVY CR PION DECAY MODELLING

GAMMAPY - NAIMA

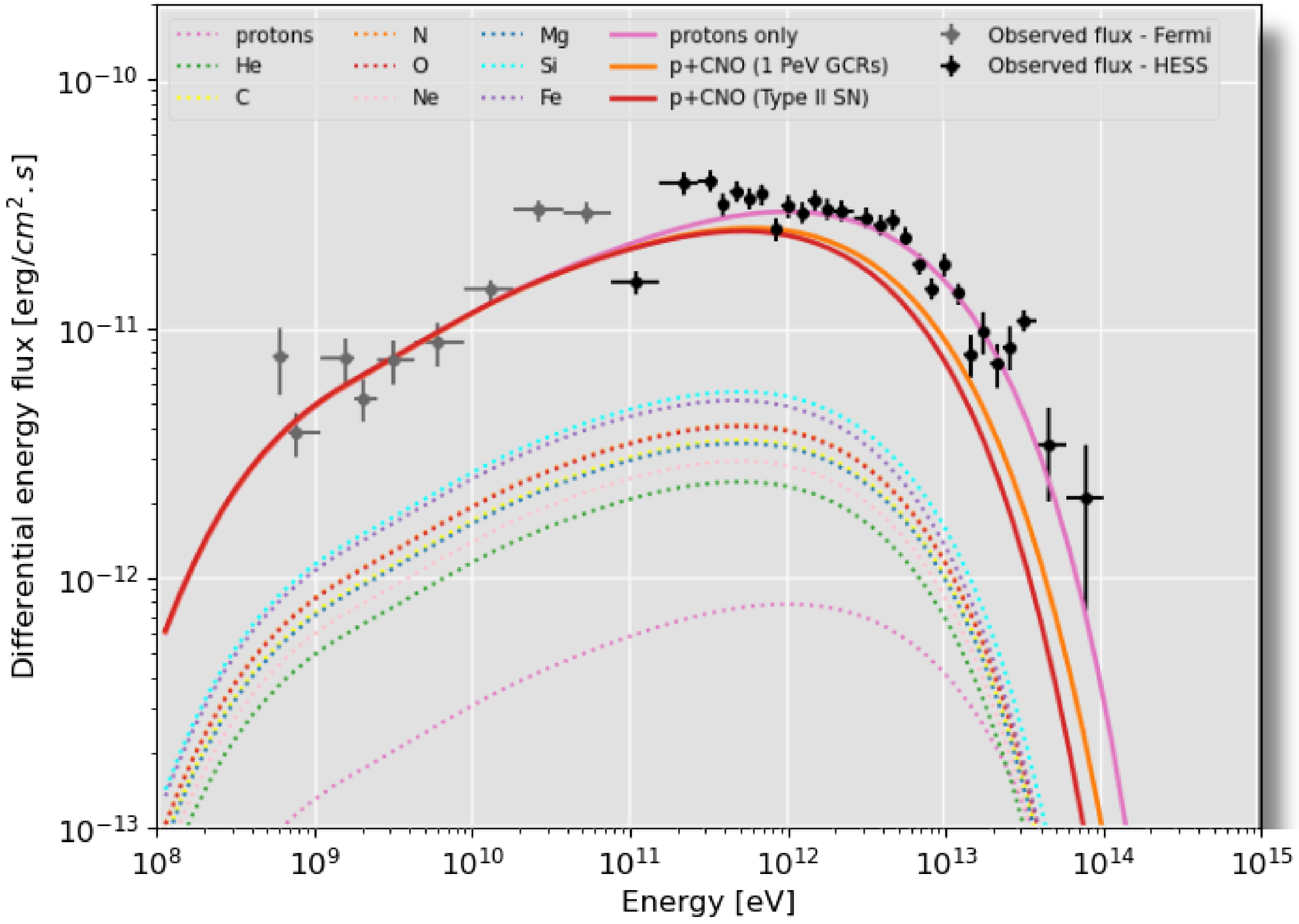
Photon flux emitted from CR distribution

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

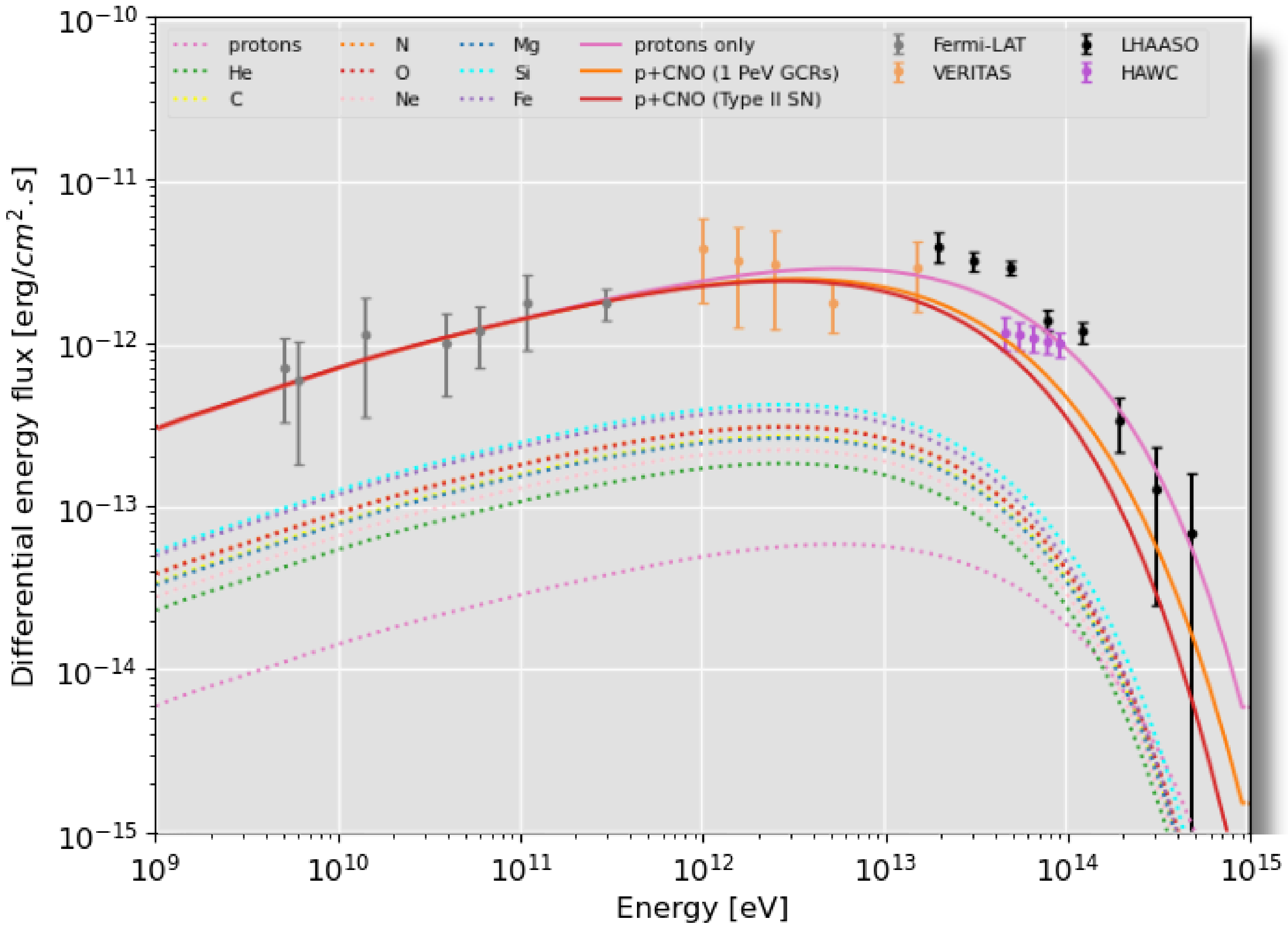
$\mathbf{N_H}$: number density of the target protons
$\mathbf{A_m}$: amplitude of the proton distribution
$\mathbf{E_0}$: reference energy
$\boldsymbol{\alpha}$: proton spectral index
$\mathbf{E_c}$: proton cut-off energy
$\boldsymbol{\beta}$: cut-off exponent

Spectral parameters fixed by the MWL analysis

γ spectrum of **RX J1713.7-3946**



γ spectrum **HAWC J2227+610**



I - WHEN MODELS MEET DATA

HEAVY CR PION DECAY MODELLING

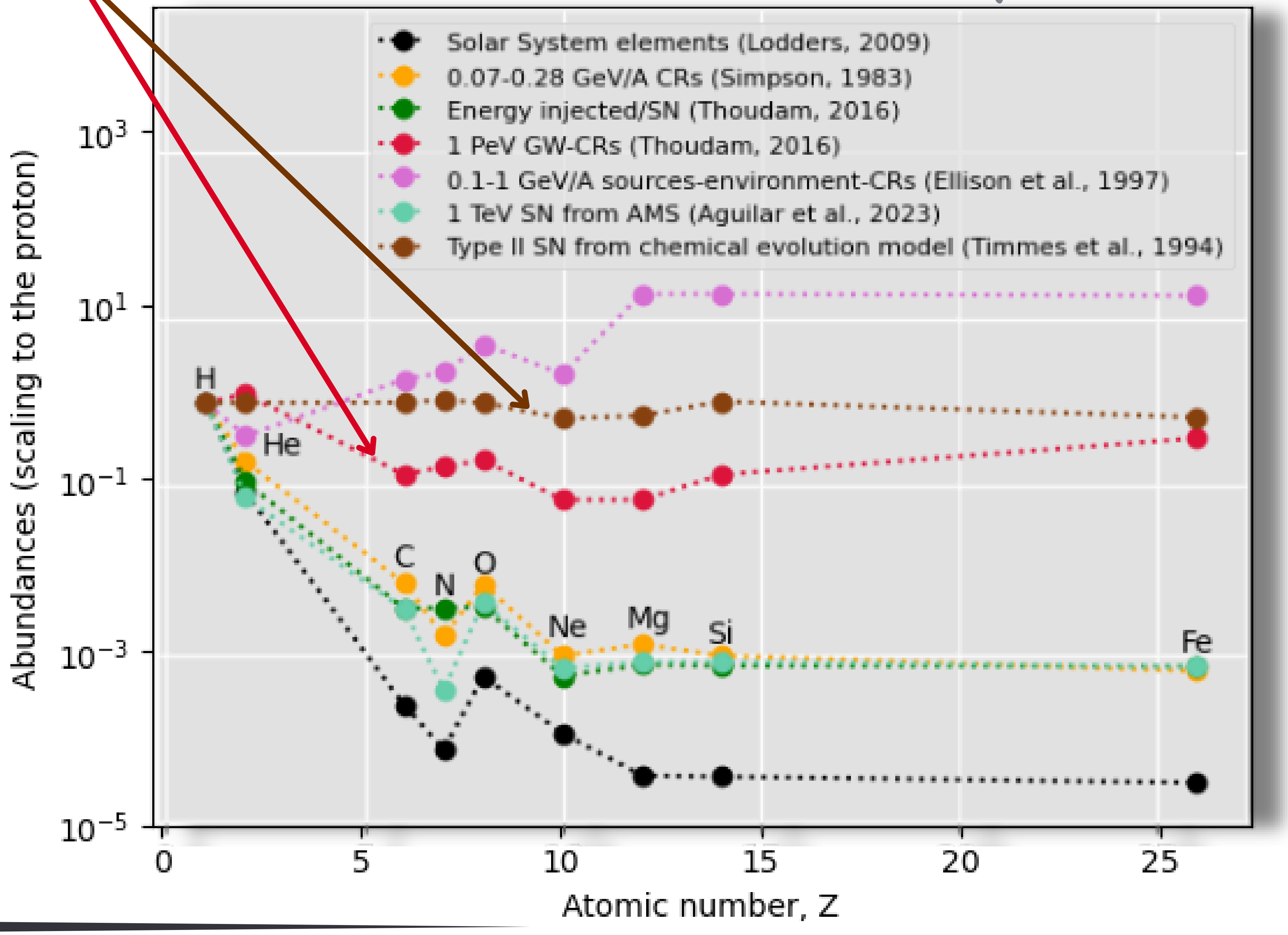
Photon flux emitted from CR distribution

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

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 - WHEN MODELS MEET DATA

HEAVY CR PION 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

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

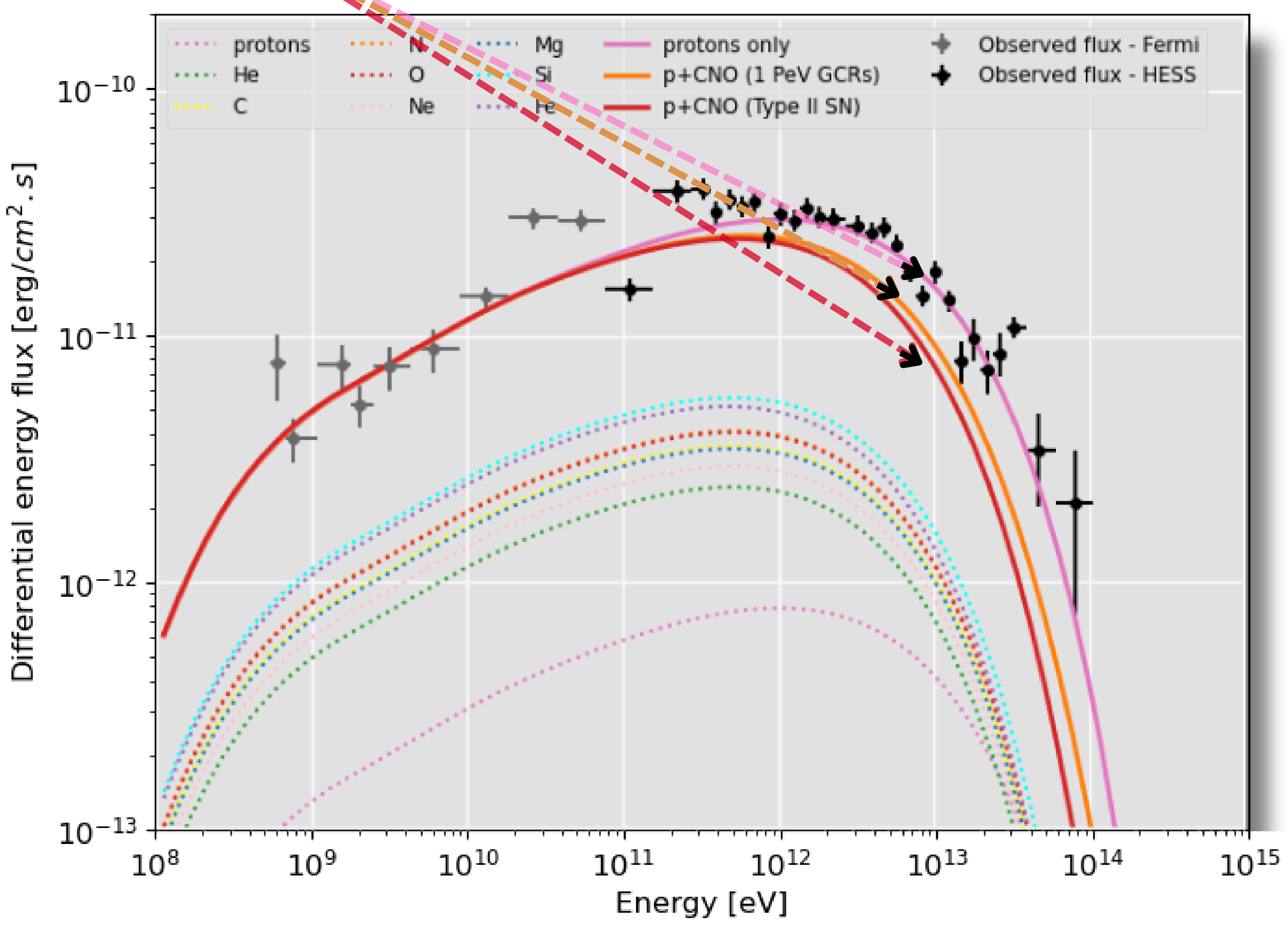
N_H: number density of the target protons
A_m: amplitude of the proton distribution
E_0 : reference energy

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

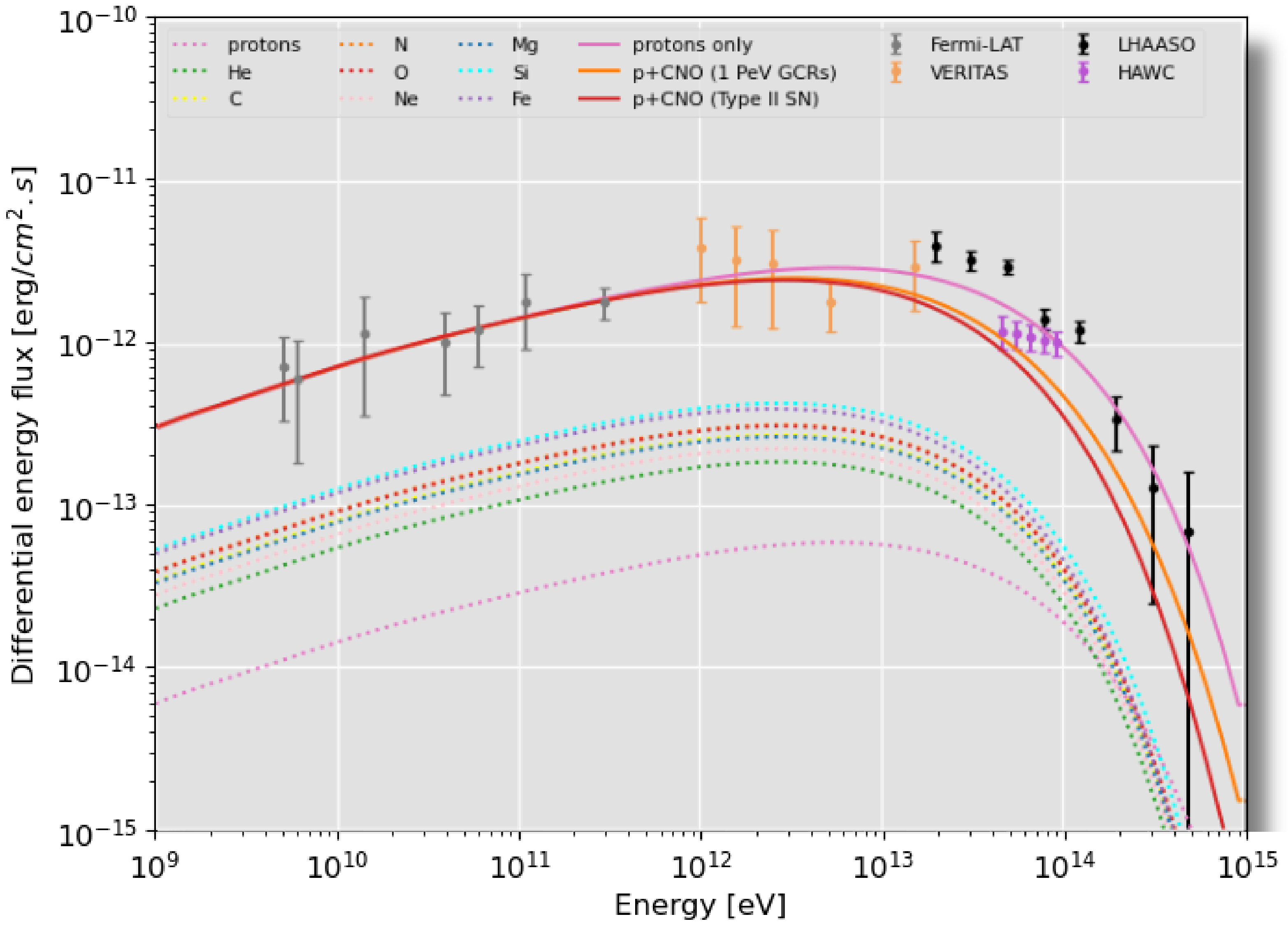
Spectral parameters fixed by the MWL analysis

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

γ spectrum of **RX J1713.7-3946**



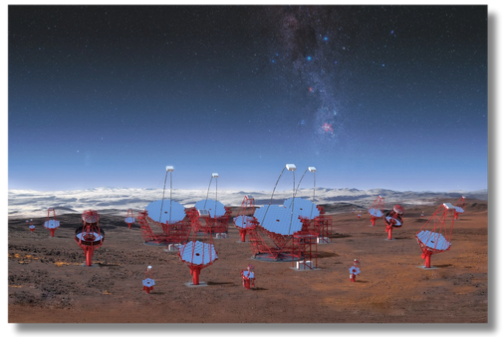
γ spectrum of **HAWC J2227+610**



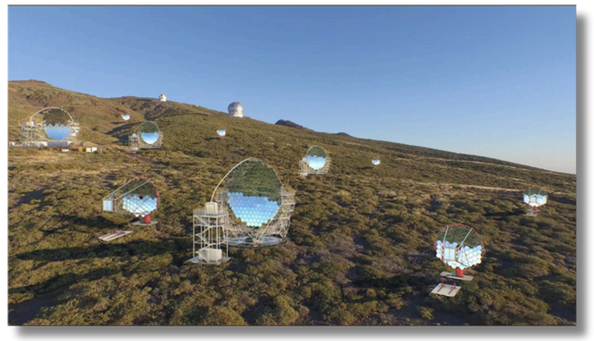
II - WHEN CTAO SIMULATIONS MEET MODELS

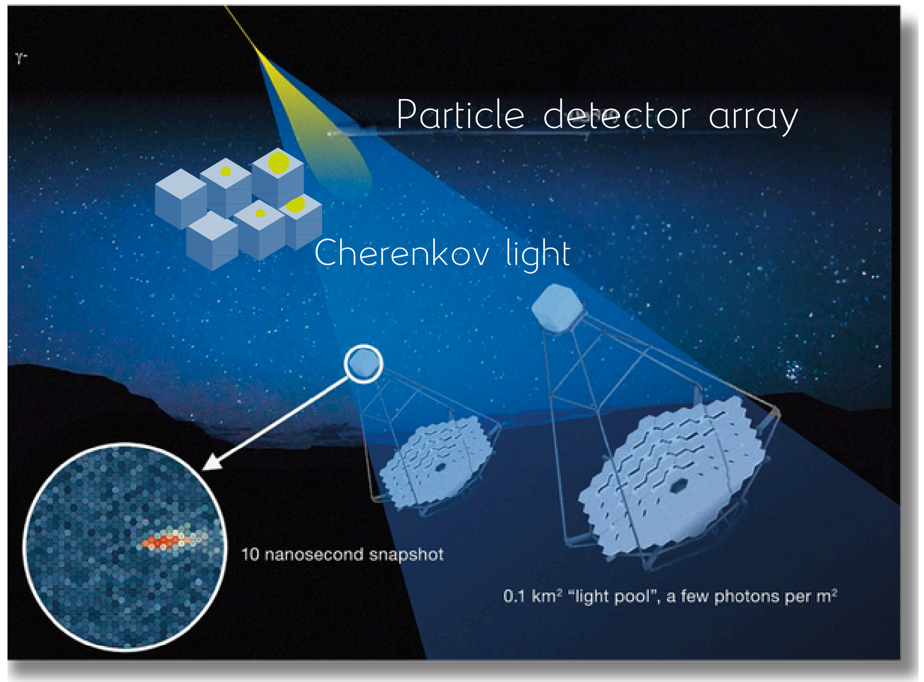
Gammapy - Naima

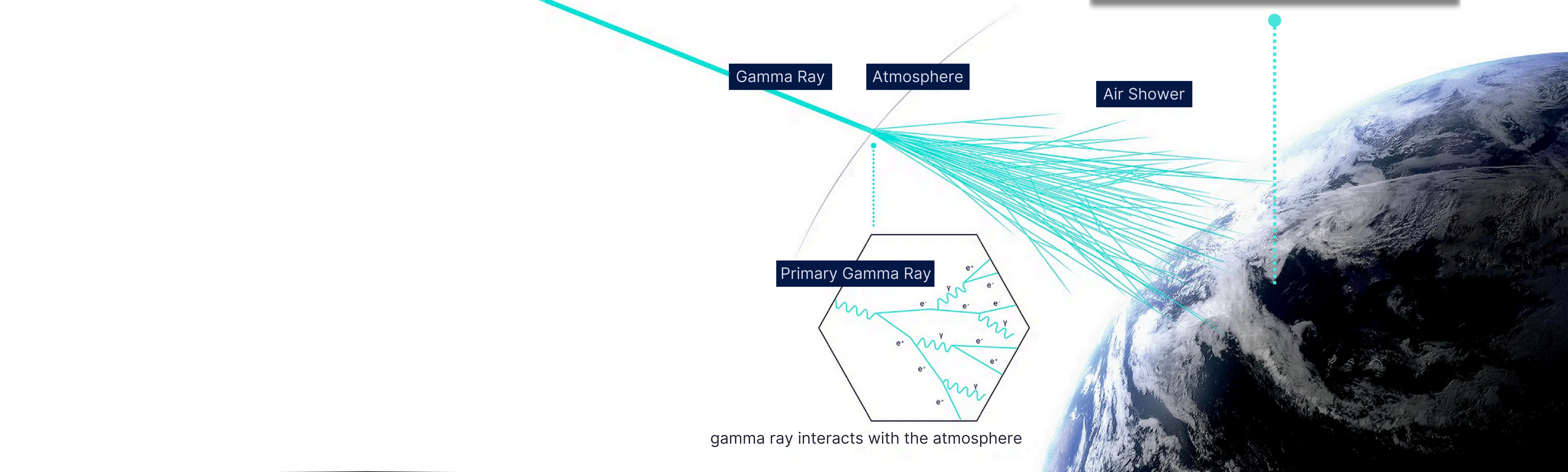
South site
Chile



North site
Canary Island





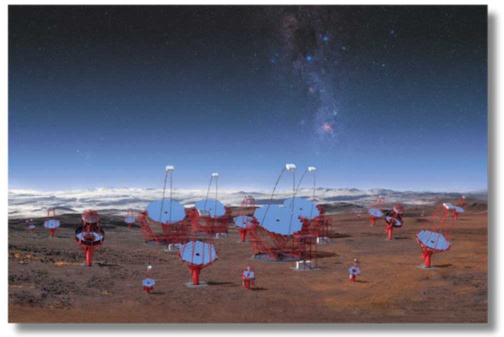


gamma ray interacts with the atmosphere

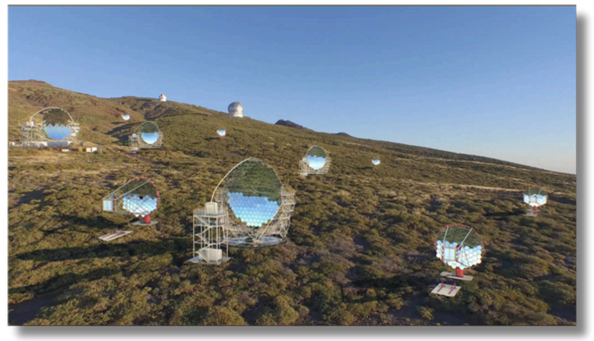
II - WHEN CTAO SIMULATIONS MEET MODELS

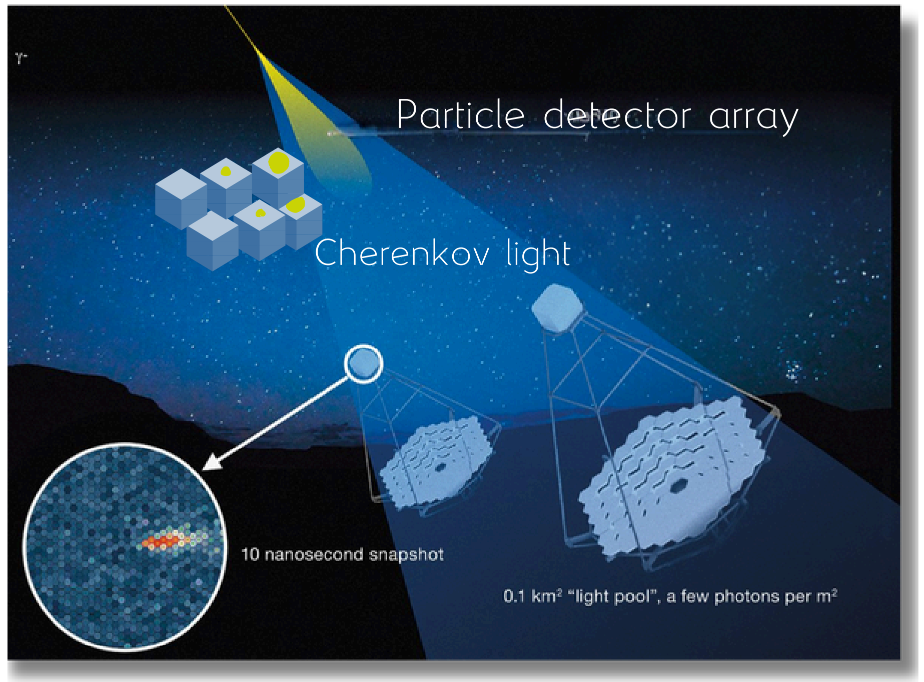
Gammapy - Naima

South site
Chile



North site
Canary Island



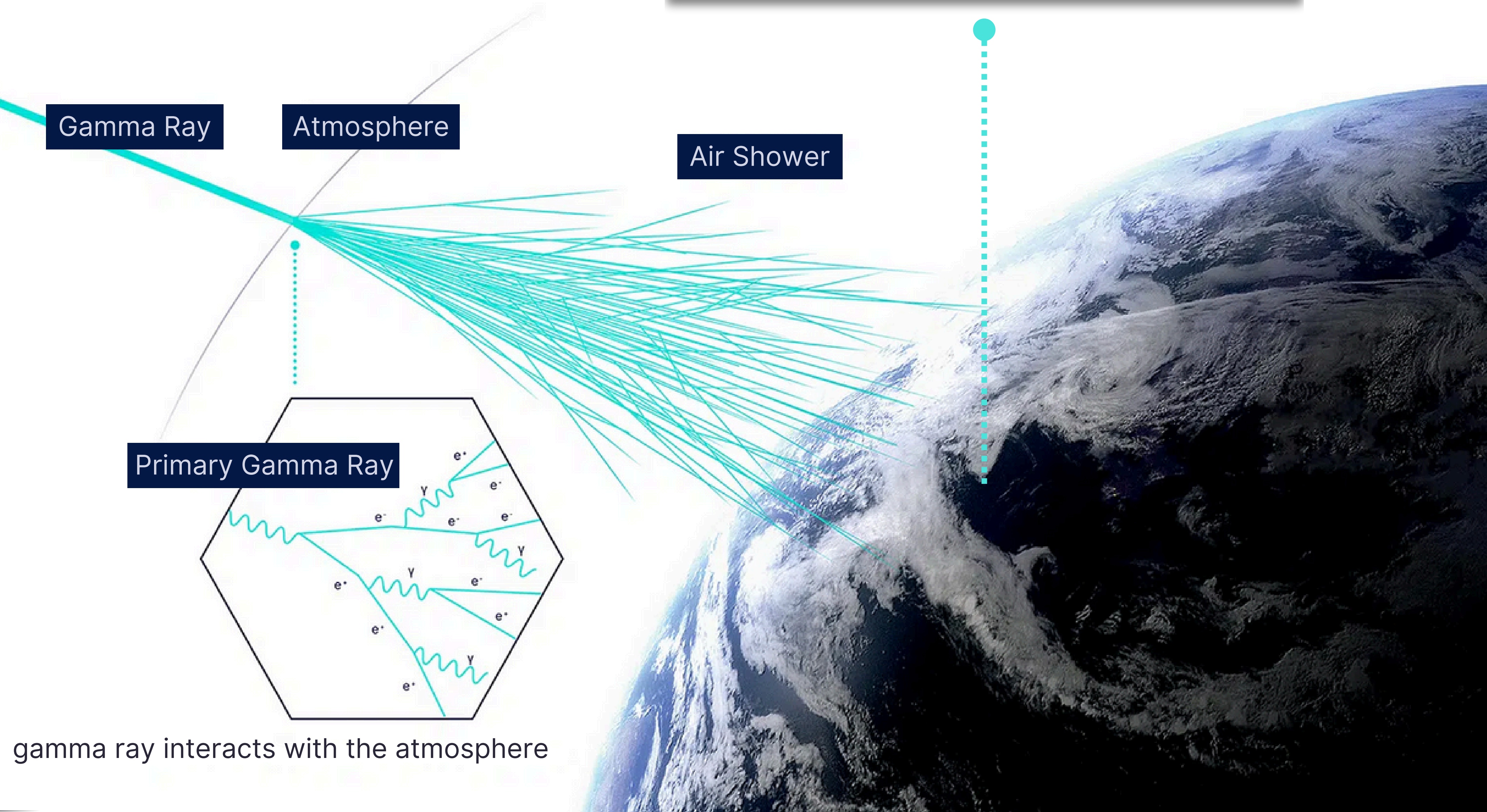


How to perform CTAO simulations of γ spectrum with Gammapy?

- 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)

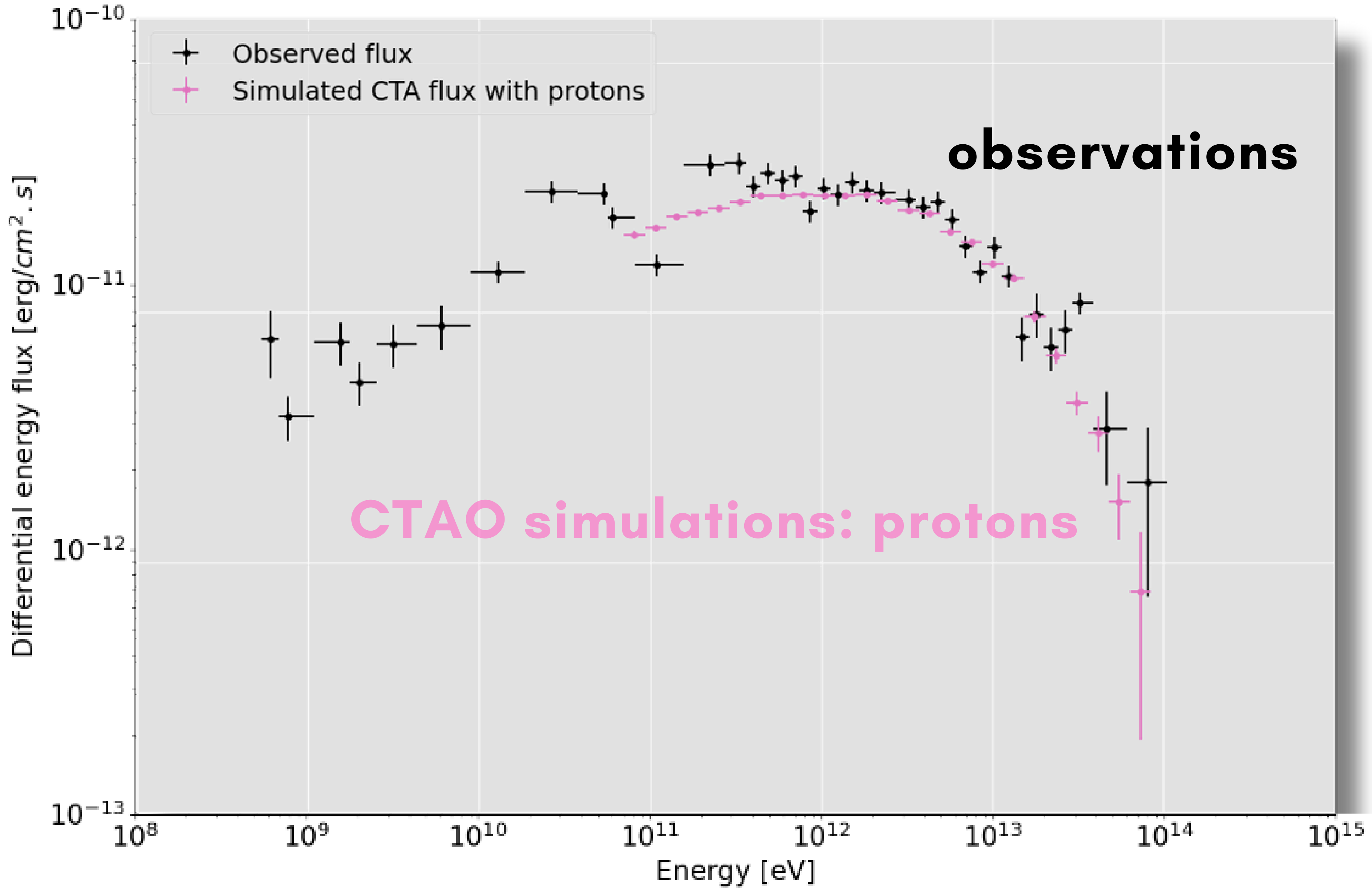
- Consideration of the background: **1D On-Off analysis**

- 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

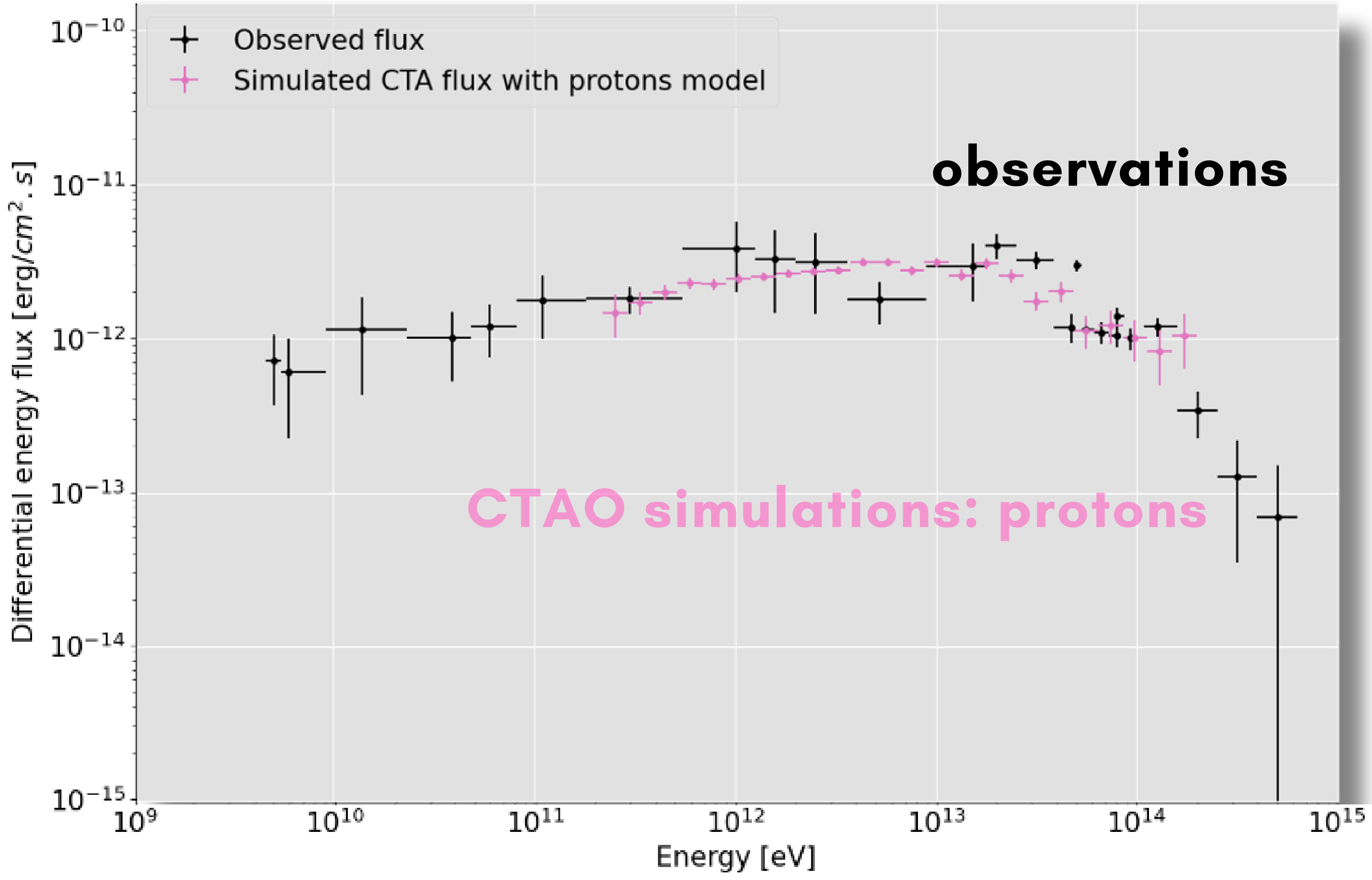


II - WHEN CTAO SIMULATIONS MEET MODELS

RX J1713.7-3946



HAWC J2227+610



III - CAN CTAO detect CRs from SNRs?

Can we separate the studied models?

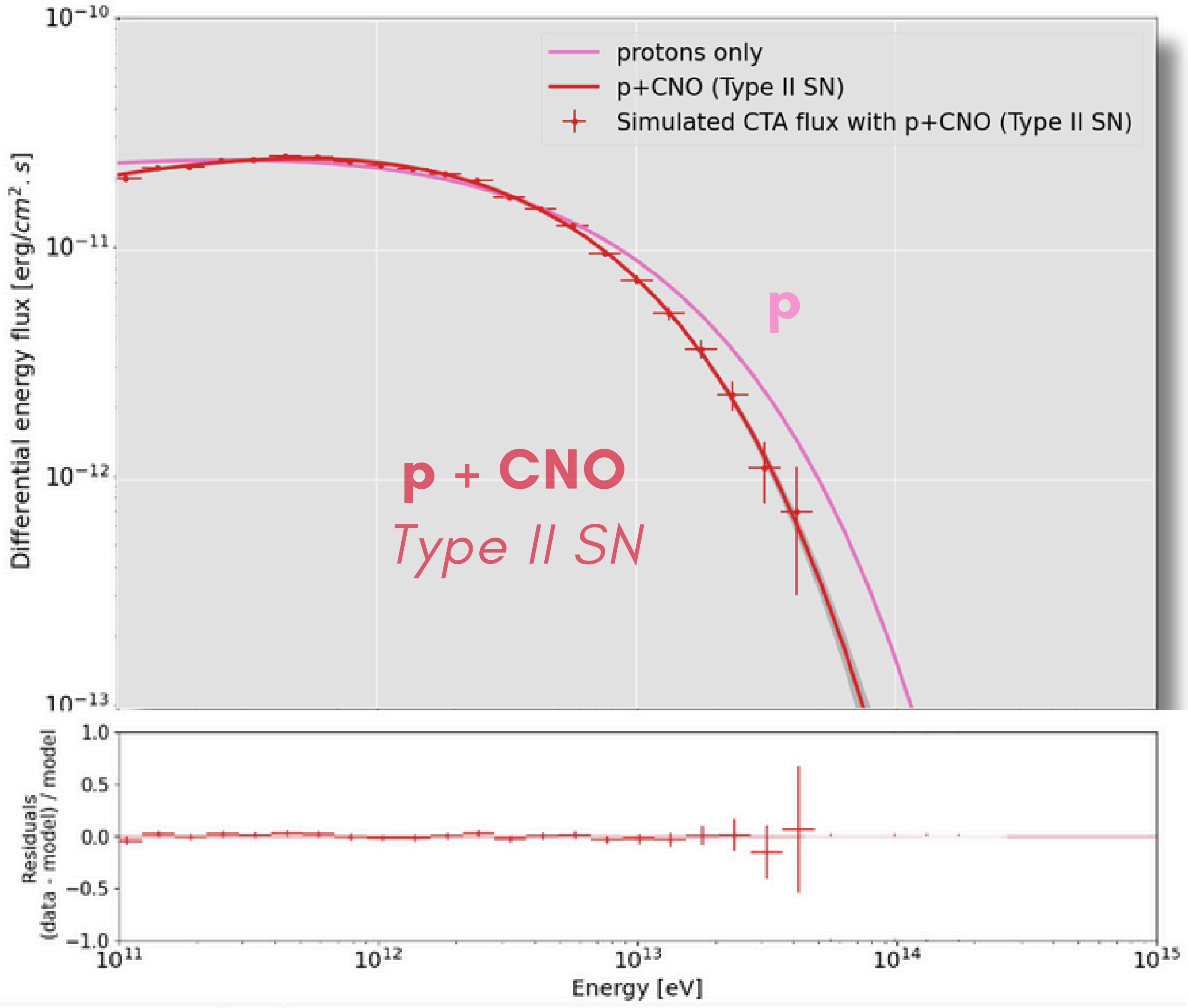
Data fitting: if Log-Likelihood test **$\Delta TS > 29$ (5σ)** (2 free parameters) => the models are distinguished

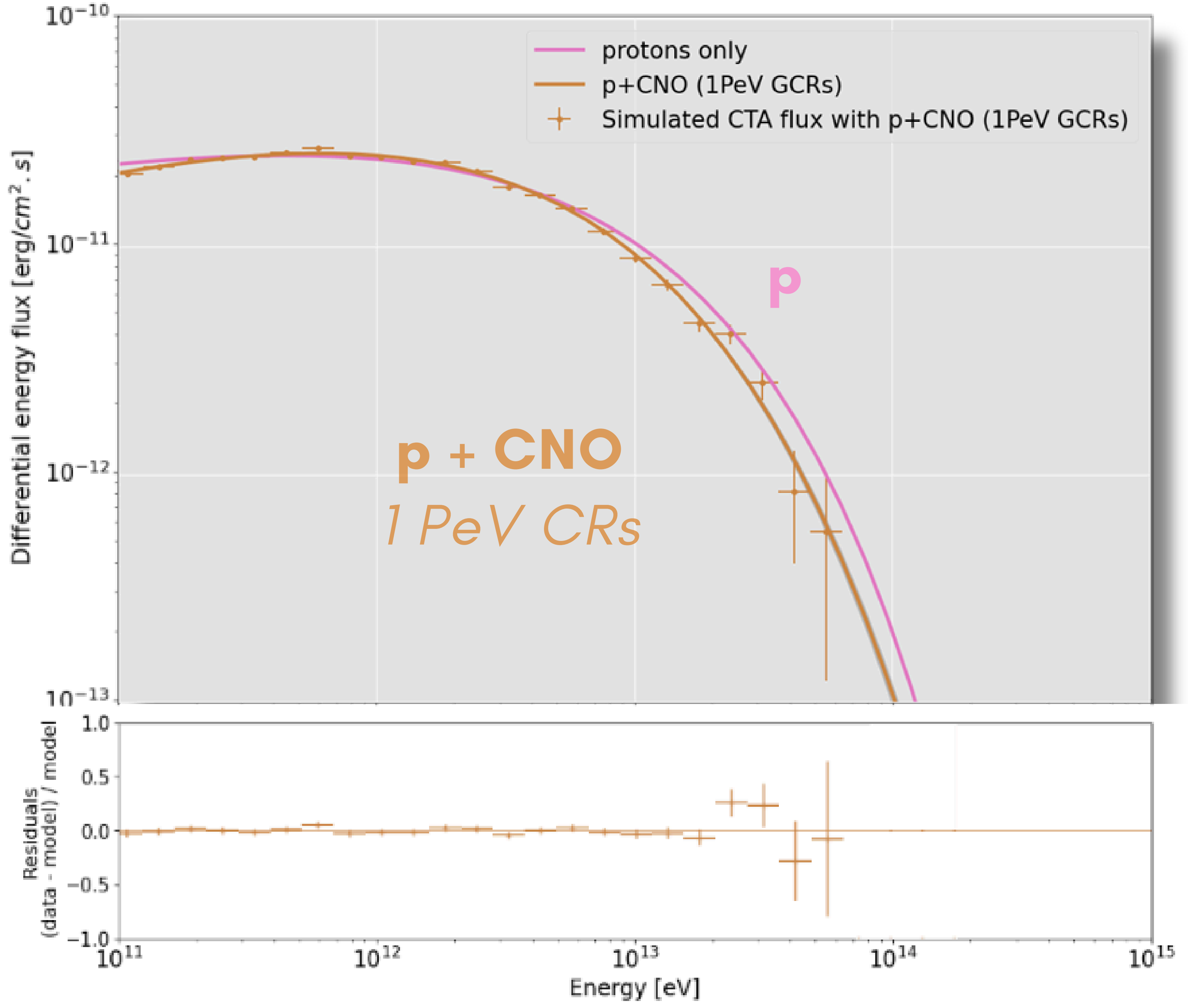
III - CAN CTAO detect CRs from SNRs?

Can we separate the studied models?

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

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





ΔTS = 202 ✓

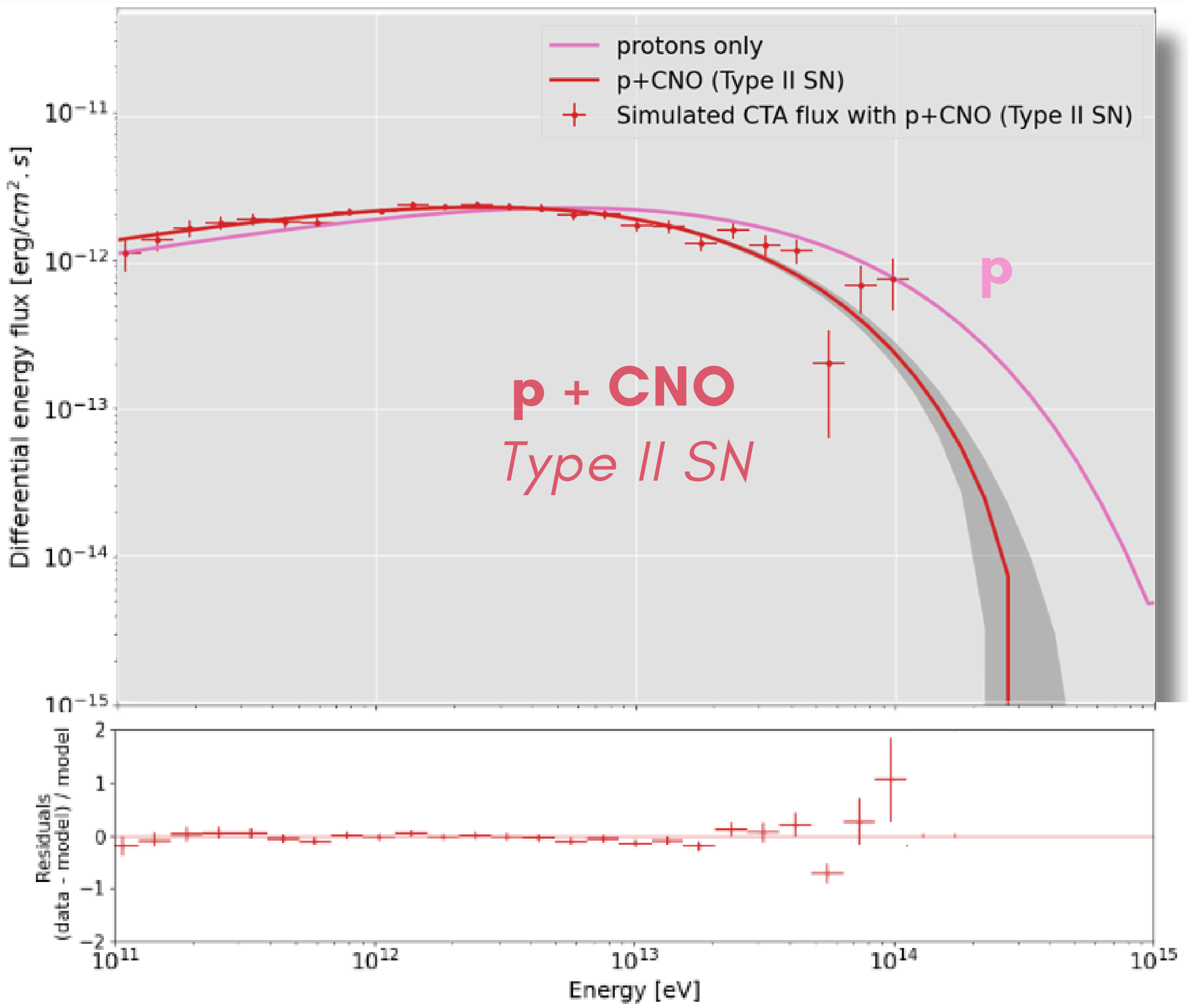
ΔTS = 102 ✓

III - CAN CTAO detect CRs from SNRs?

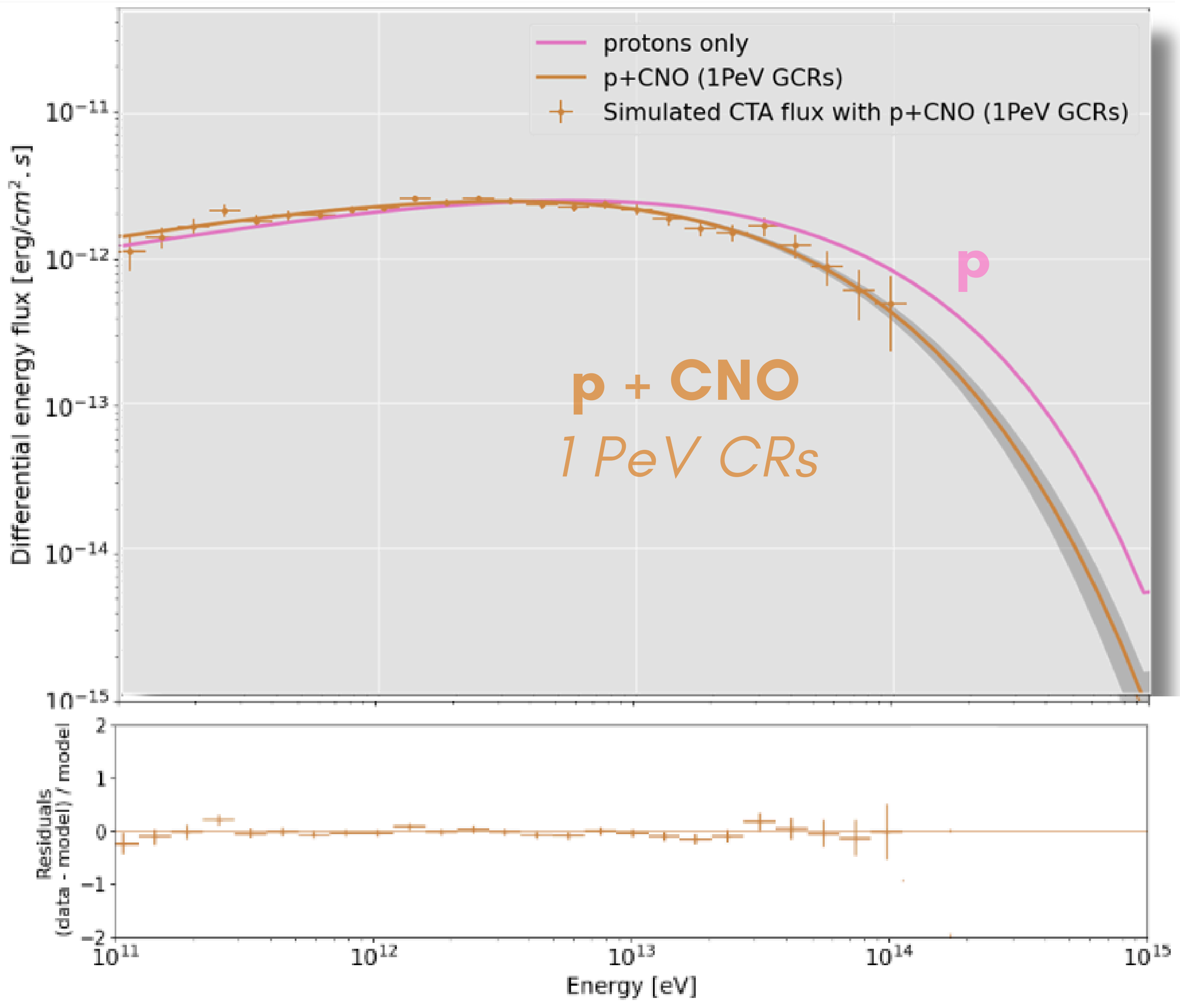
<u>Can we separate the studied models</u>?

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)



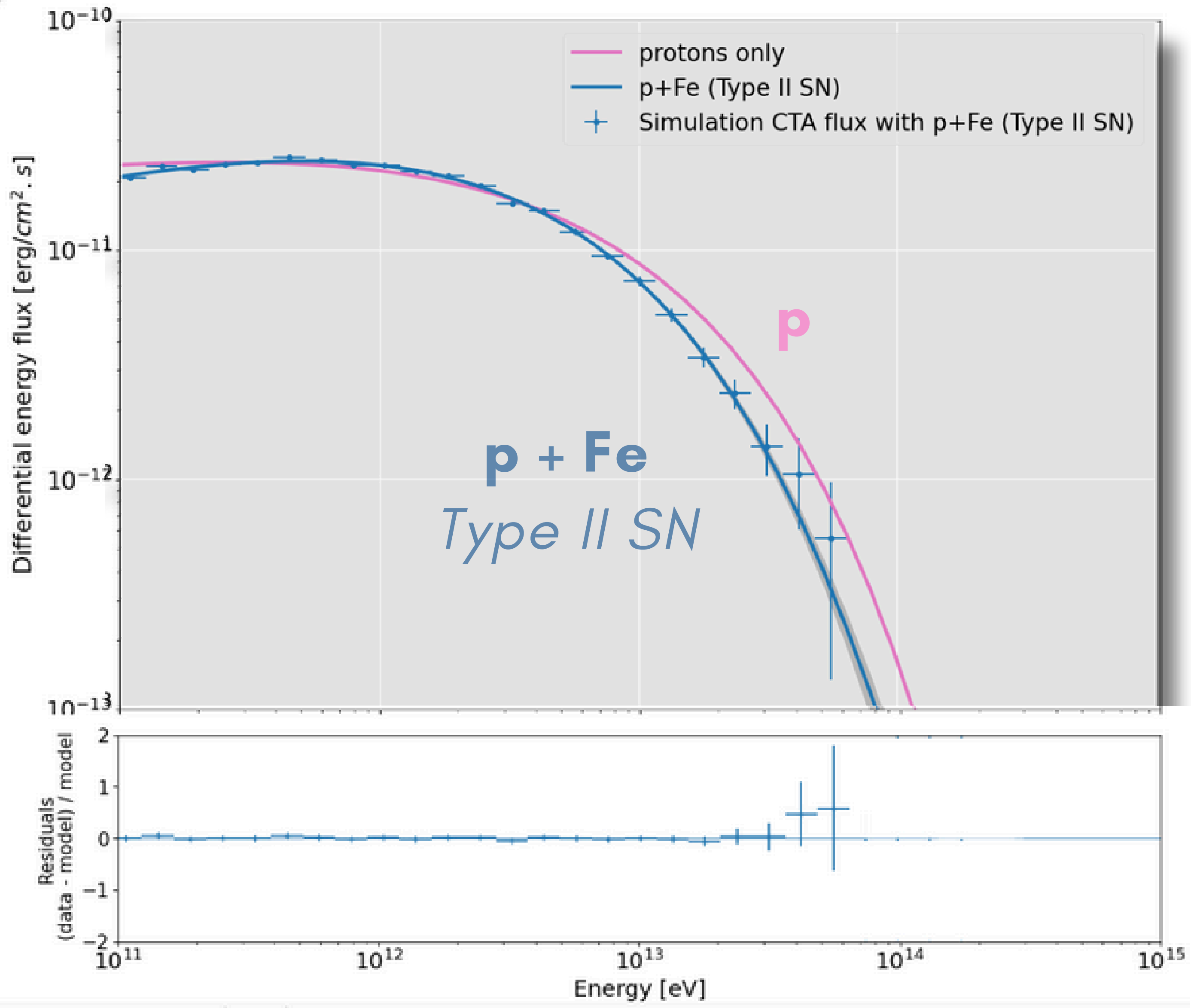
ΔTS = 113 ✓



ΔTS = 53 ✓

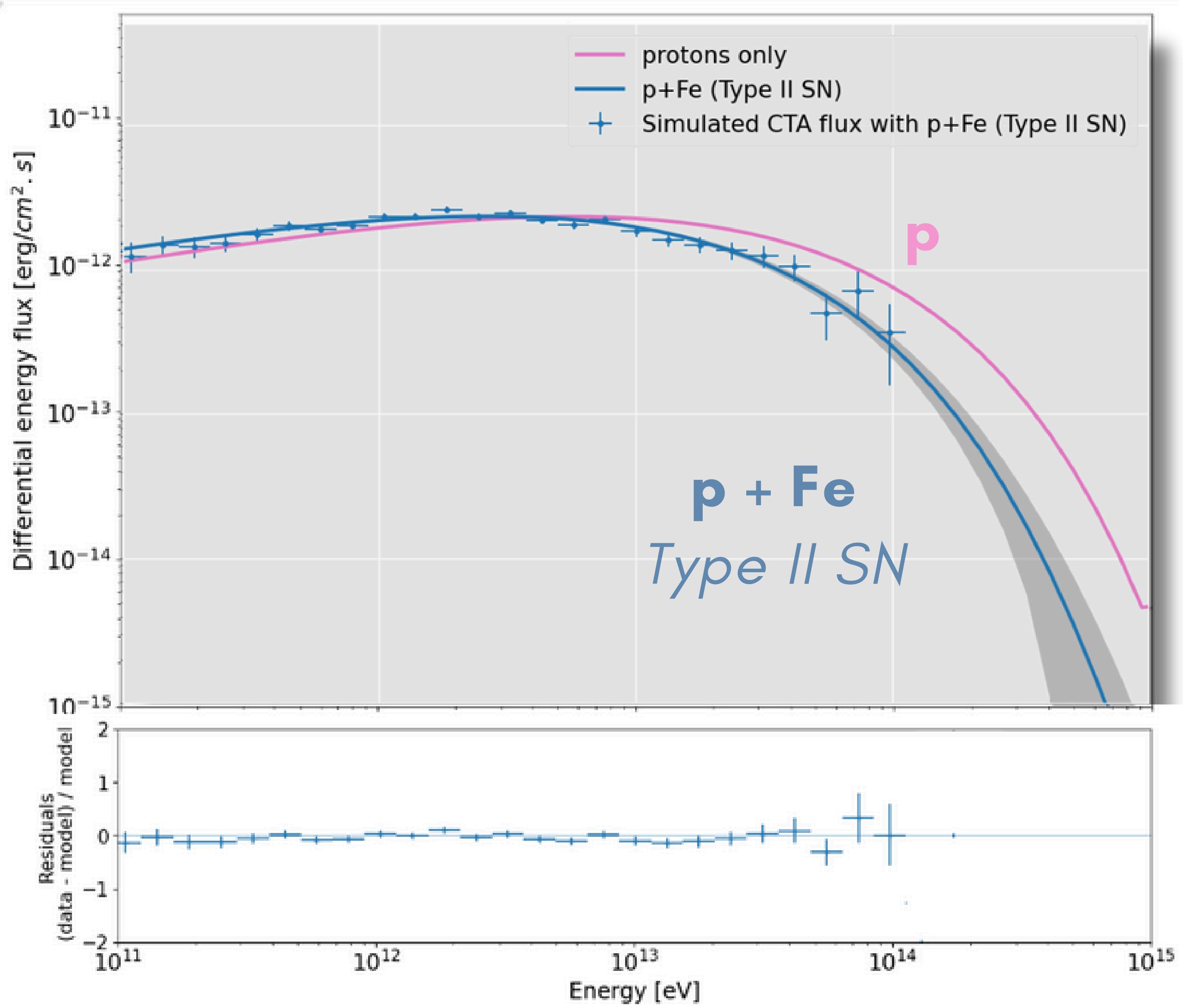
III - CAN CTAO detect CRs from SNRs?

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



ΔTS = 188 ✓

CTAO simulations of **HAWC J2227+610**

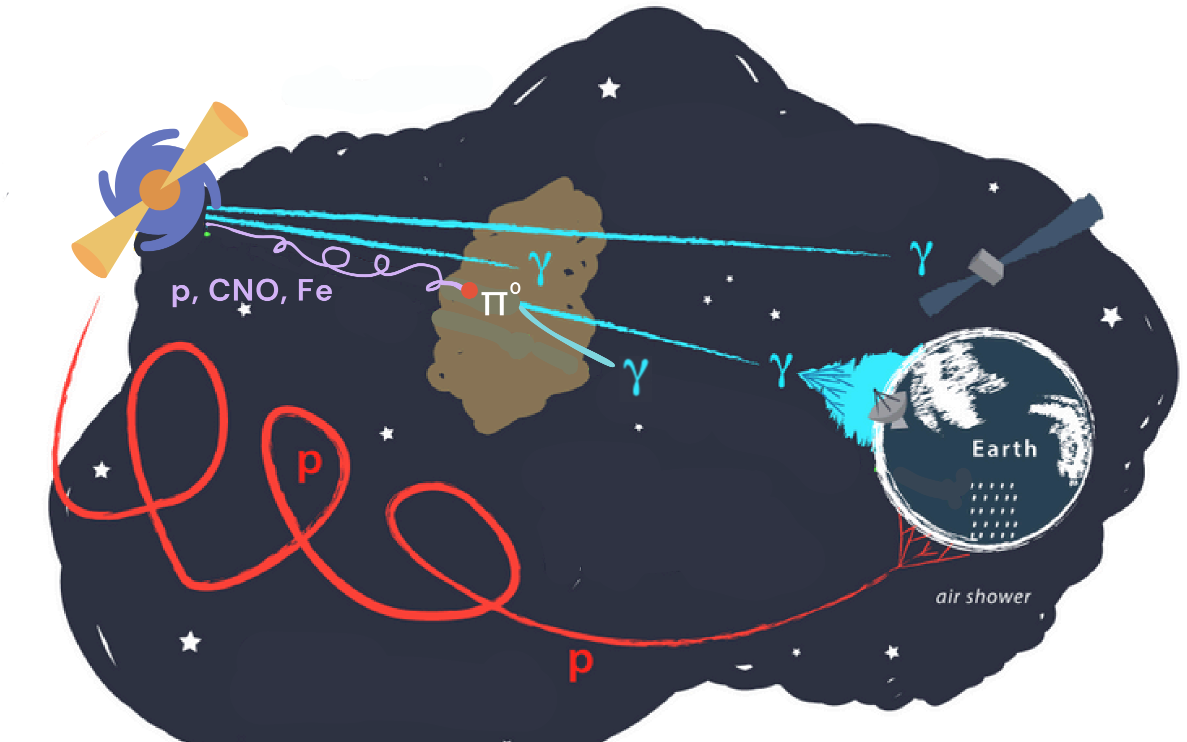


ΔTS = 88 ✓

CONCLUSION

Why study CRs with CTAO?

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.



© IceCube/WIPAC (modified)

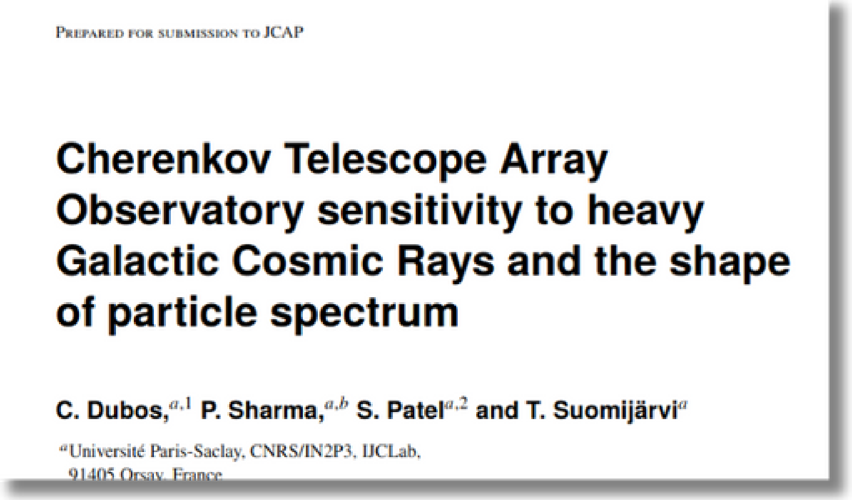
What will CTAO bring to the knowledge of CRs?

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 and thus investigate the origin of very high energy CRs**.

Where can we find this work?

ArXiv, **submitted to JCAP:**

SCAN ME


PREPARED FOR SUBMISSION TO JCAP

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

C. Dubos,[a,1] P. Sharma,[a,b] S. Patel[a,2] and T. Suomijärvi[a]

[a]Université Paris-Saclay, CNRS/IN2P3, IJCLab, 91405 Orsay, France

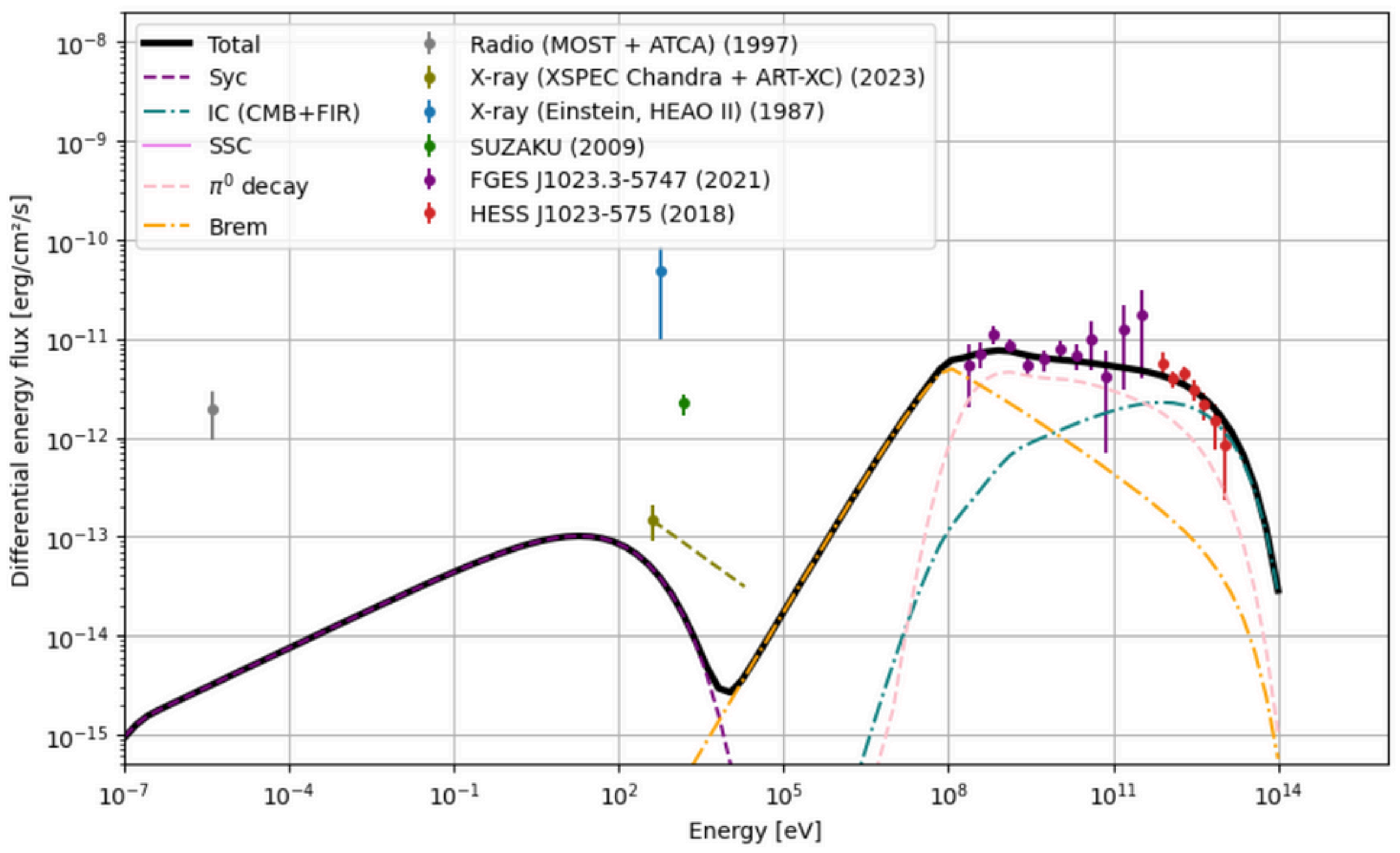
CTAO could investigate the **origin of the particle distribution shape**, which may result from **heavy nuclei** or various **acceleration scenarios**.

CONCLUSION

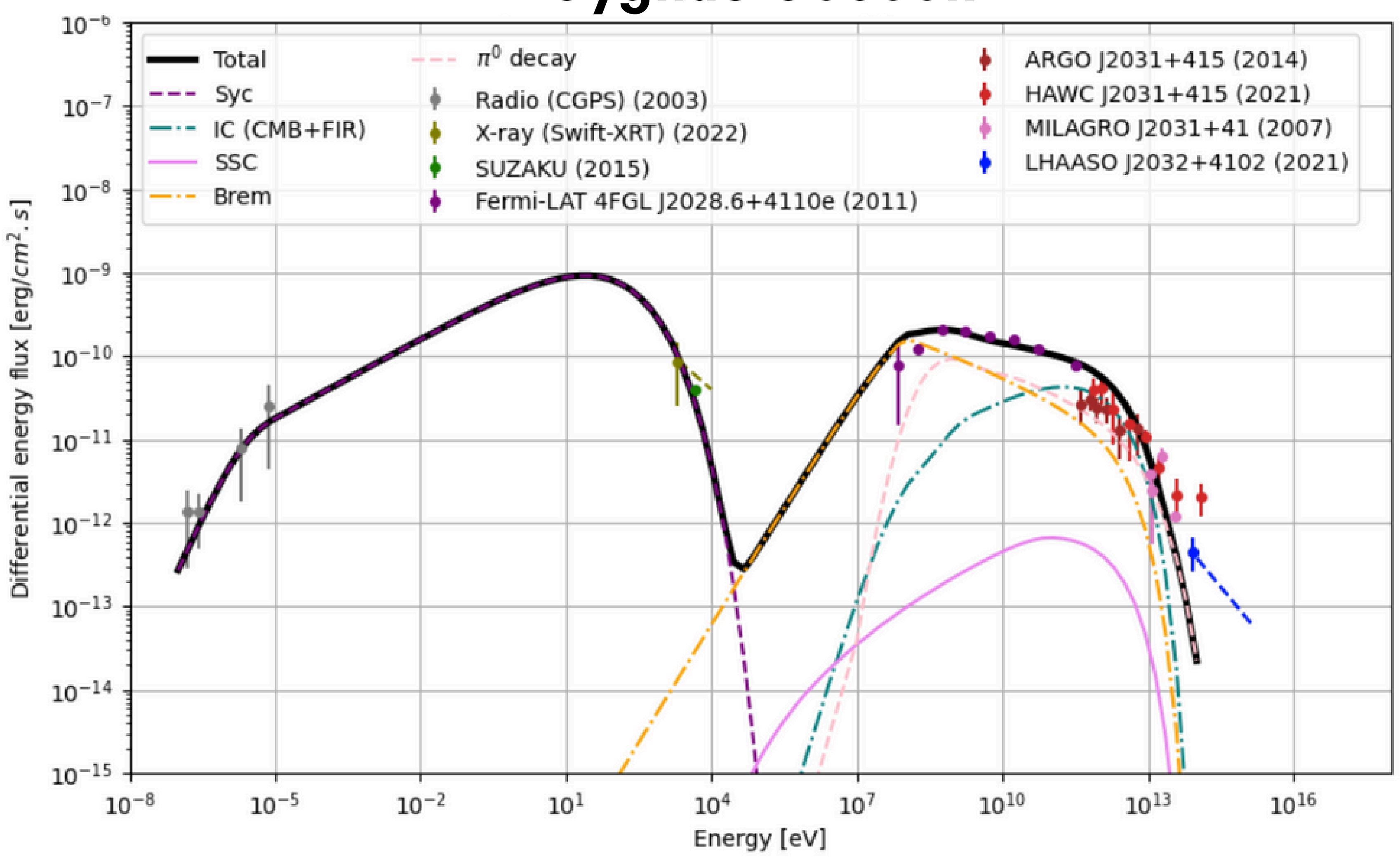
<u>And the other sources</u>?

Stellar clusters are also candidates for the origin of very high energy CRs.
We are performing **MWL analysis** on these sources as well.

Westerlund II

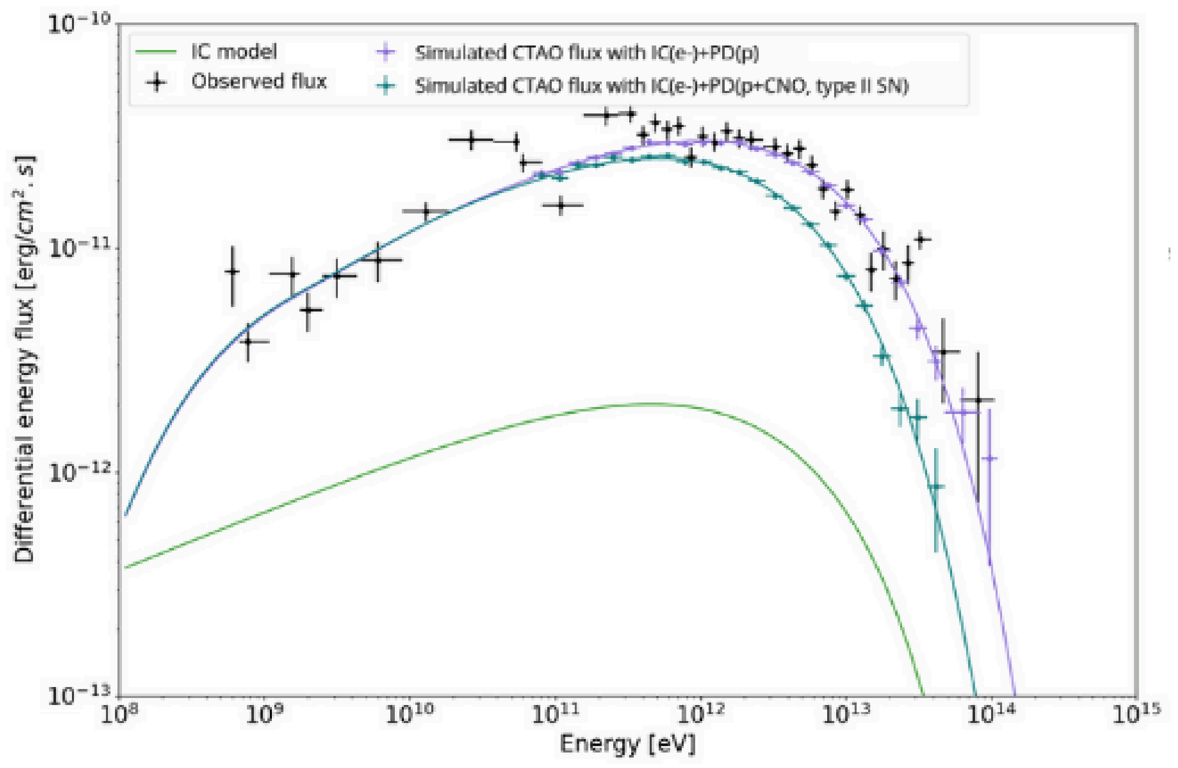


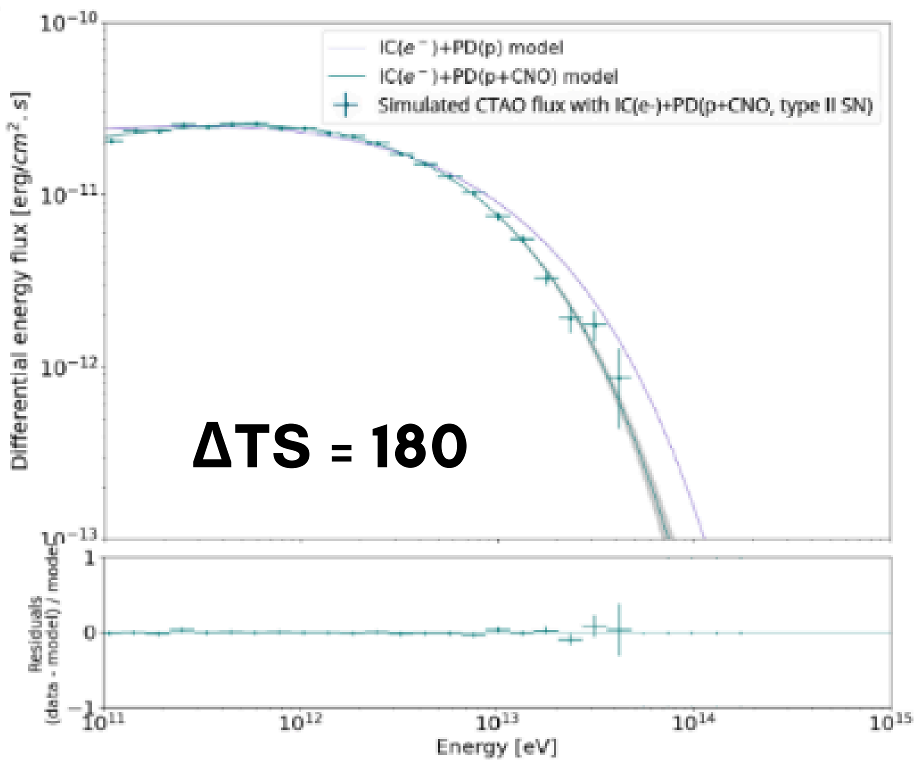
Cygnus Cocoon



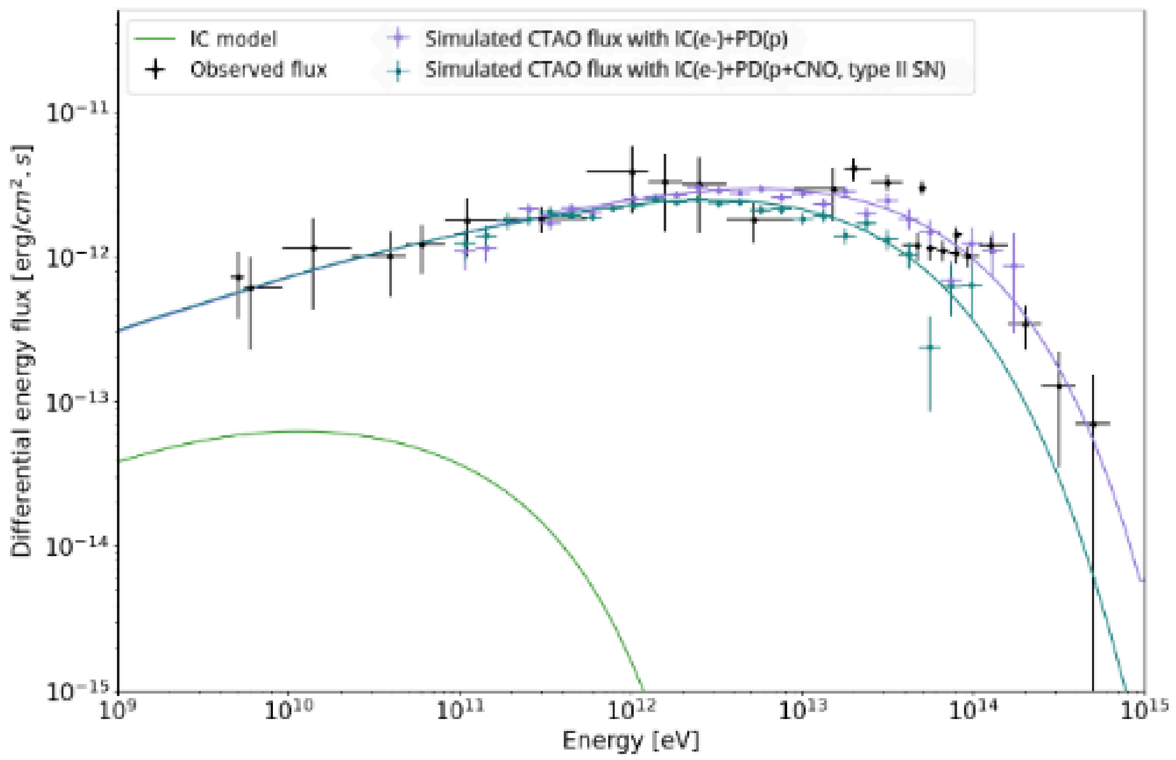
APPENDIX CONTRIBUTION OF ELECTRONS THROUGH THE INVERSE COMPTON PROCESS

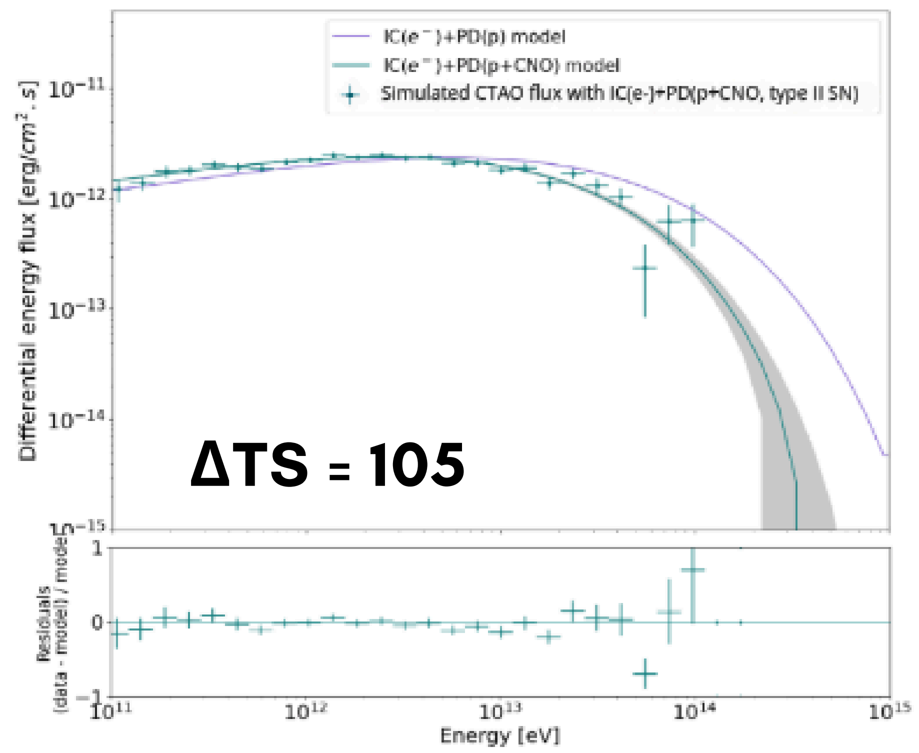
RX J1713.7-3946





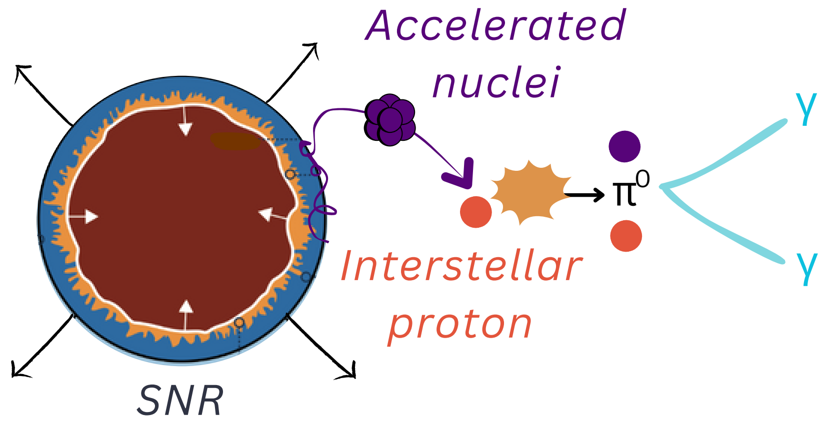
HAWC J2227+610





HADRONIC PROCESS FOR GAMMA-RAYS

proton-proton interaction -
Neutral pion decay process



LEPTONIC PROCESS FOR GAMMA-RAYS

Synchrotron
Bremsstrahlung
Inverse Compton
processes

Energy