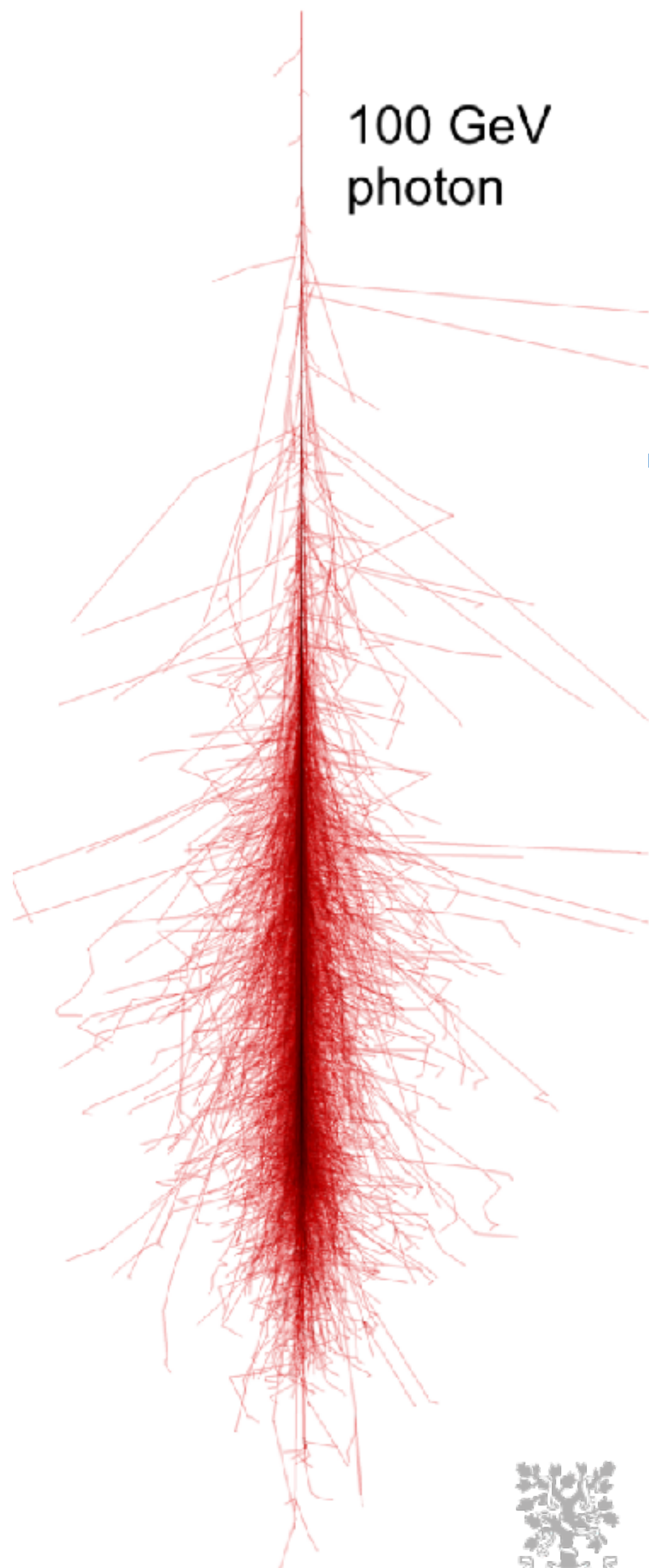


(An introduction to) Astroparticle Physics

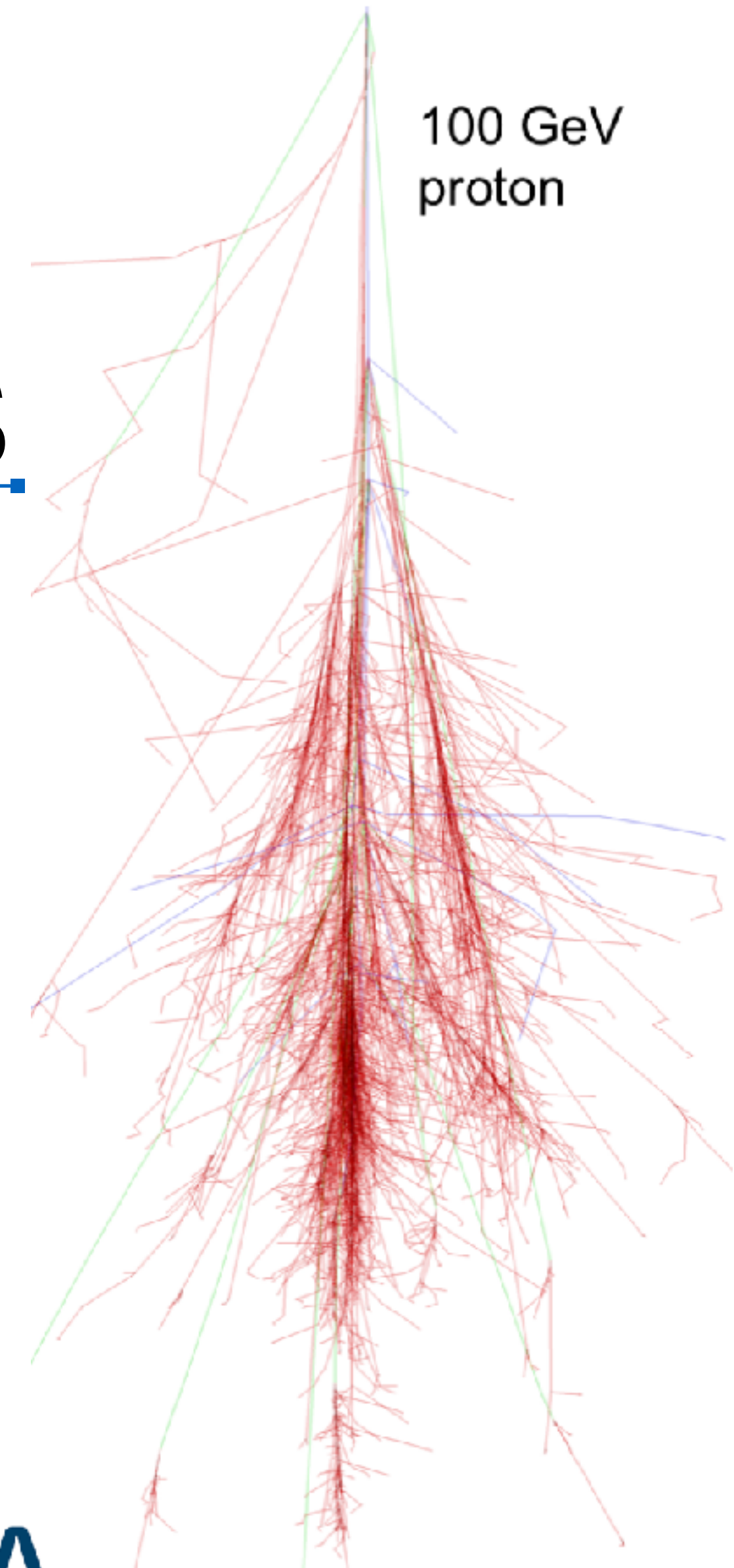
Lecture 1/2

Bradley J Kavanagh [he/him]
Instituto de Física de Cantabria (CSIC-UC)
kavanagh@ifca.es

CERN Summer Student Lecture Programme:
Monday 27th July 2026



100 GeV
photon



100 GeV
proton



CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

CSIC

UC

Universidad
de Cantabria



i F (A

Instituto de Física de Cantabria

Timeline

1912: Hess discovers cosmic rays

1933: Anderson discovers the positron in Cosmic Ray tracks

1939: Auger and collaborators demonstrate the existence of Cosmic Ray *air showers*

1960s: Homestake Experiment detects Solar Neutrinos (and the Solar Neutrino Problem)

1970s: The “Dark Matter” paradigm coalesces

2010: Discovery of the Fermi gamma-ray bubbles and Galactic centre excess

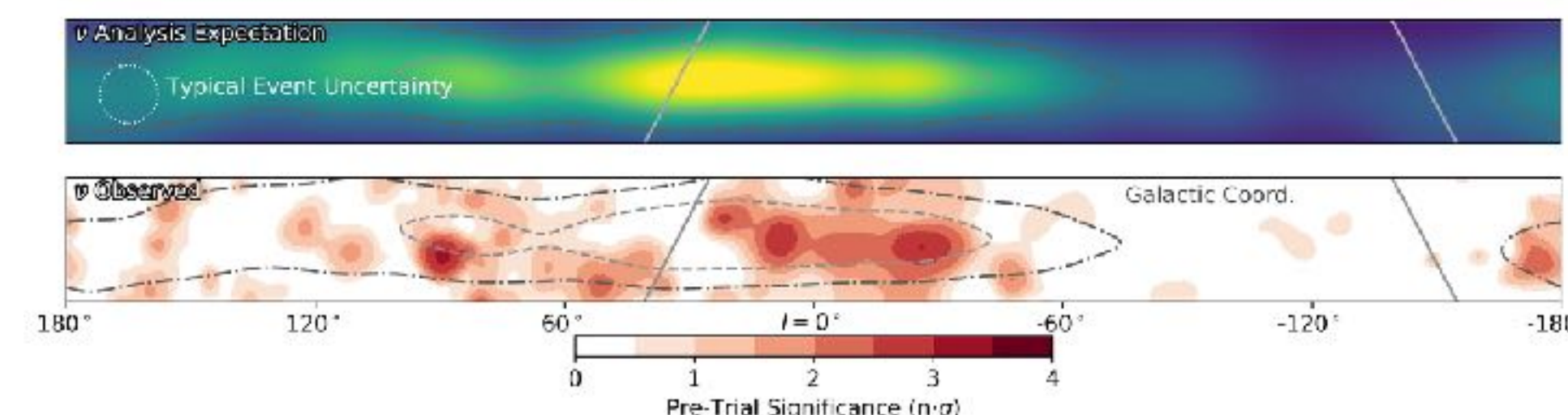
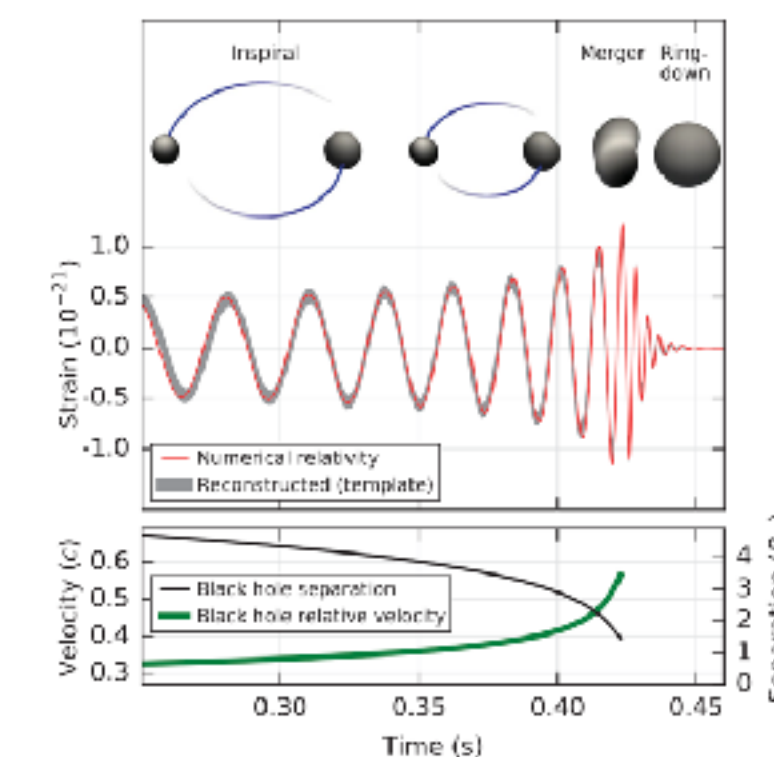
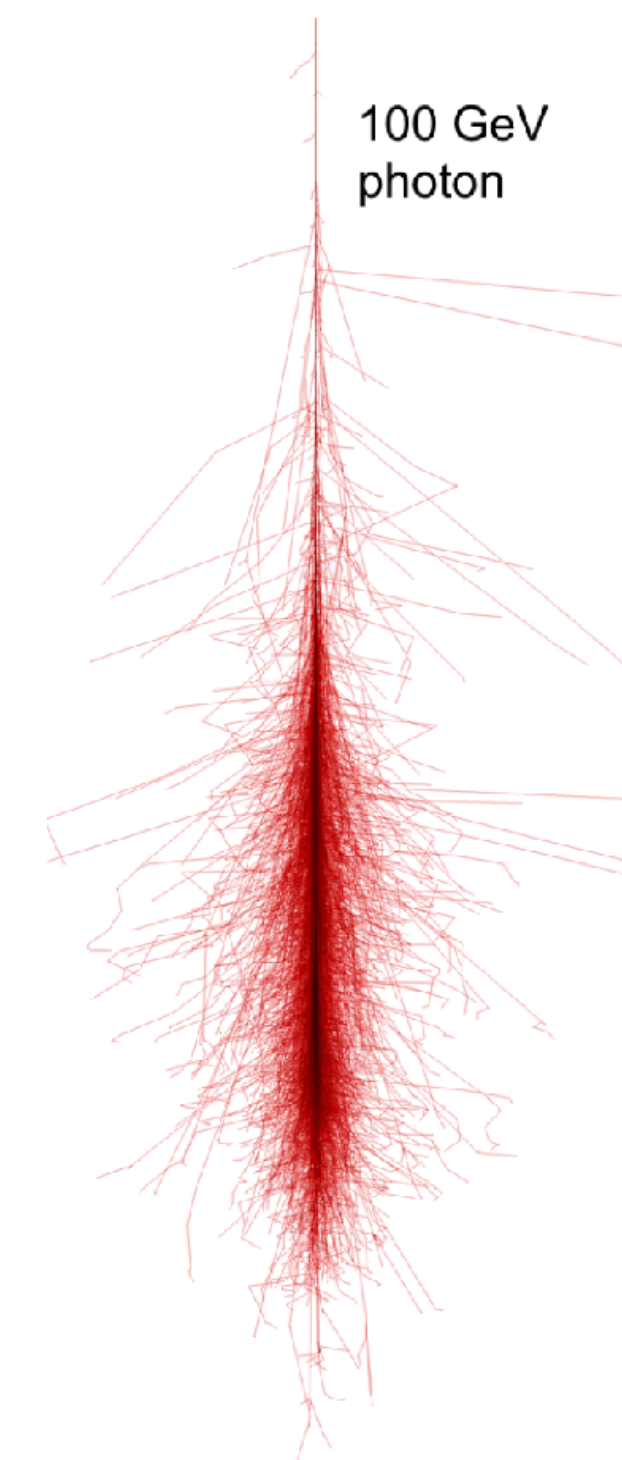
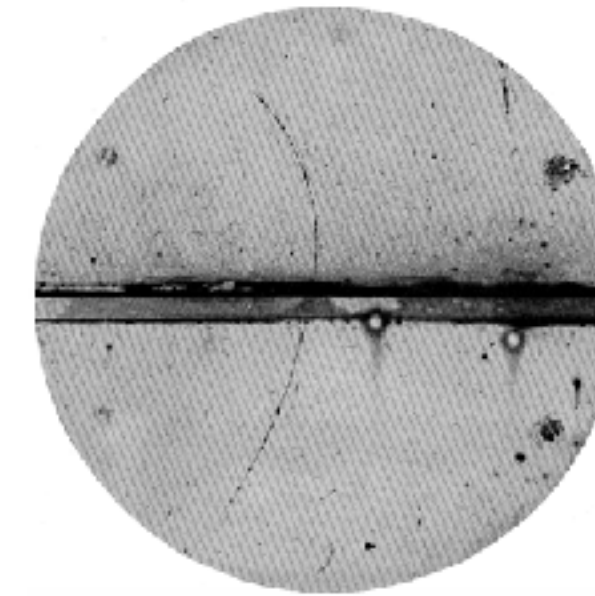
2015: GW150914 - First direct observation of GWs from Black Hole Binary Mergers

2017: TXS 0506+056 - First multimessenger detection of a blazar (neutrinos + gamma rays)

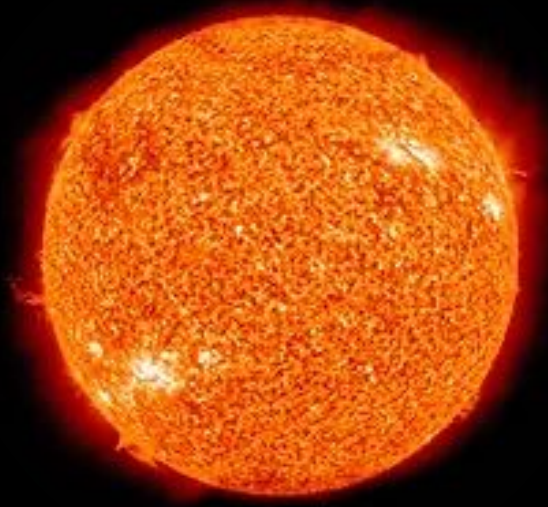
2017: GW170817 - First direct observation of GWs from Neutron Star Mergers by LVK

2023: Detection of Milky Way in Neutrinos by IceCube

2023: NANOgrav & IPTA detect nHz Gravitational Waves



The Sun



Supernovae

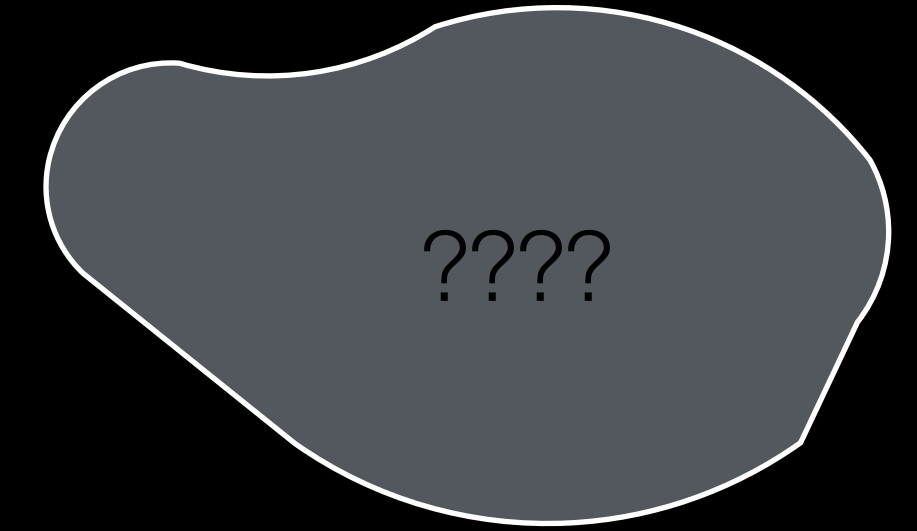
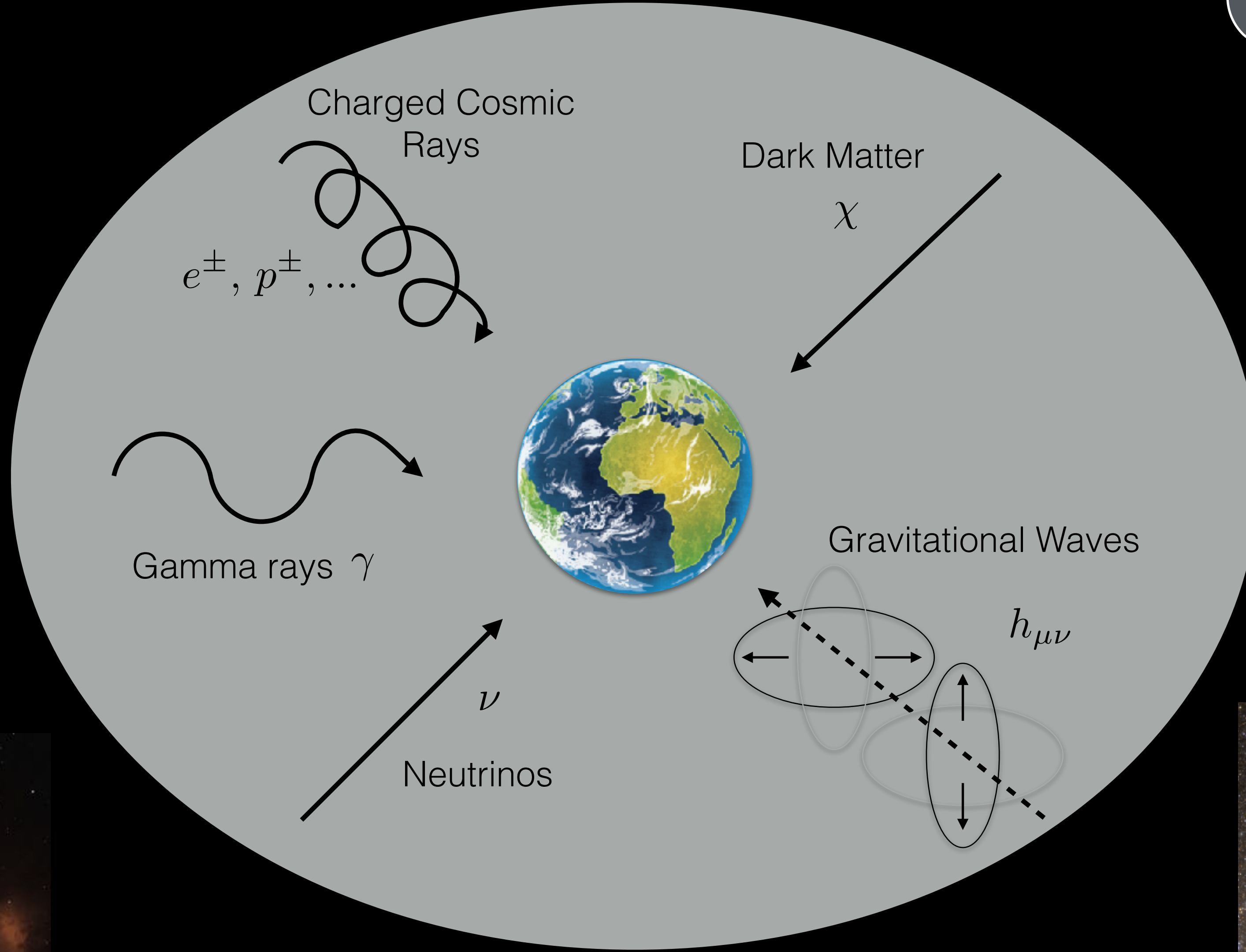


Quasars/AGN

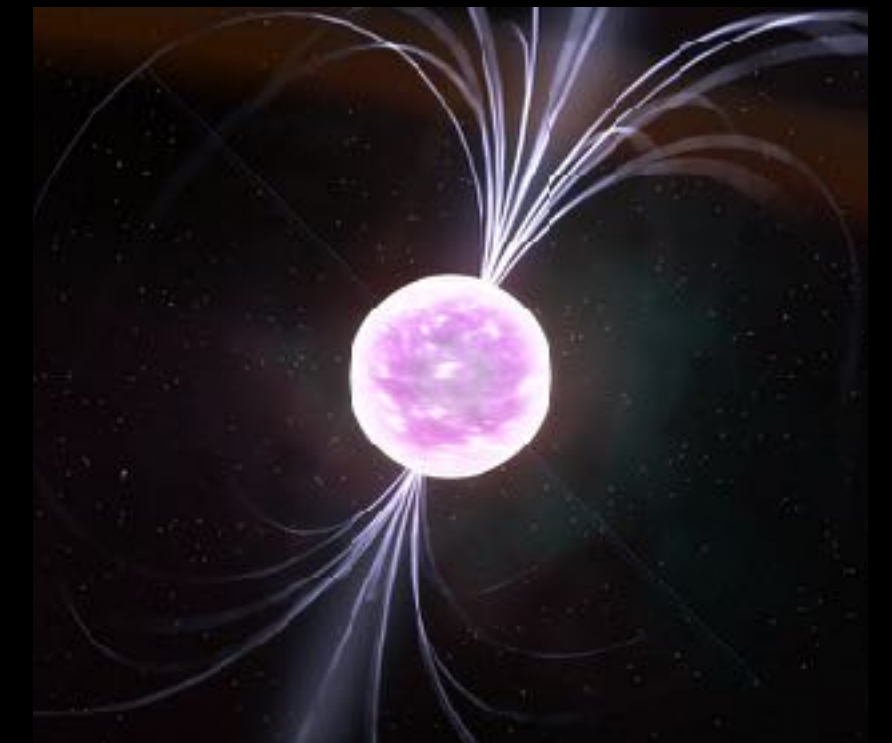


Credit: NASA/CXC/SAO

Credit: ESO/M. Kornmesser

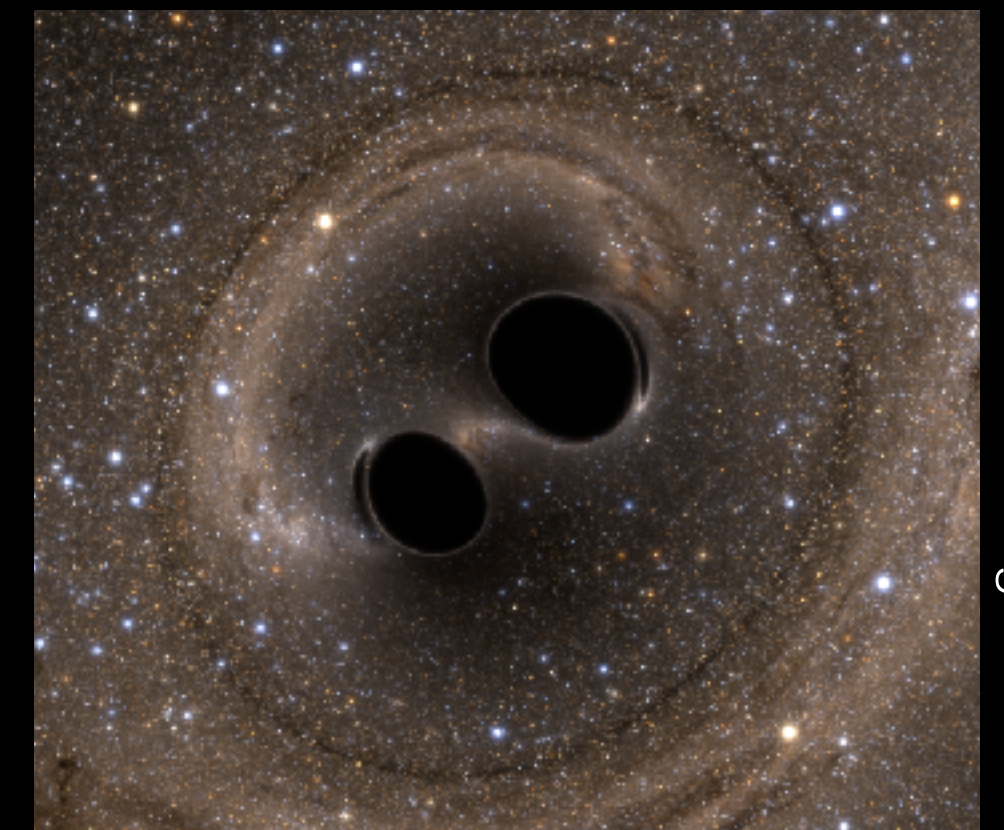


Pulsars



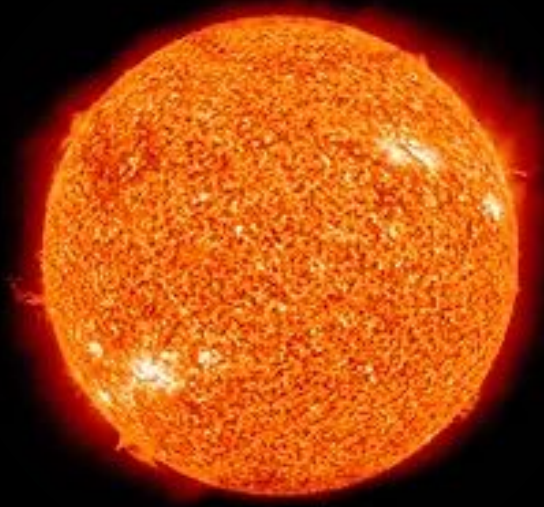
Credit: Kevin Gill / Flickr

BH/NS Mergers



Credit: SXS Lensing

The Sun



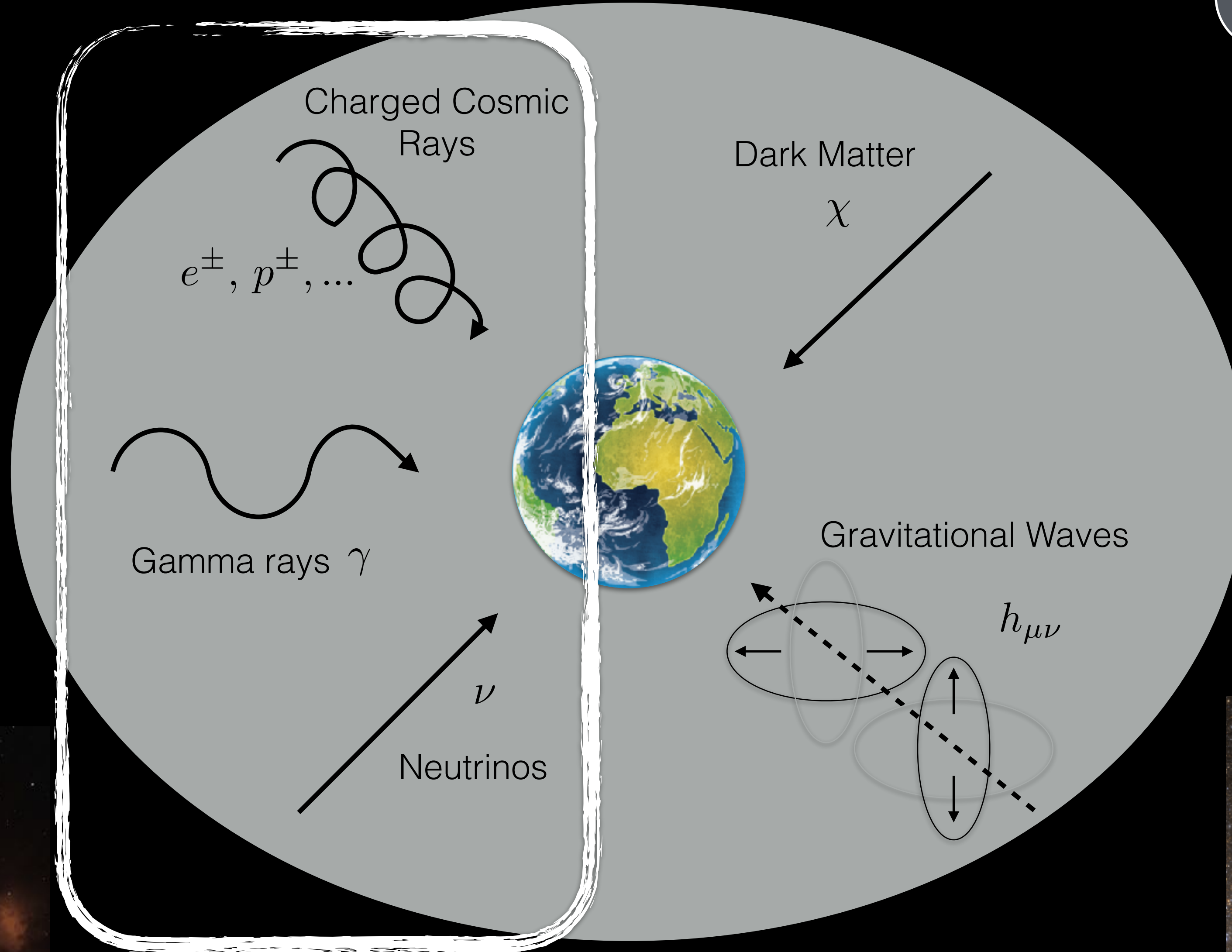
Supernovae



Quasars/AGN

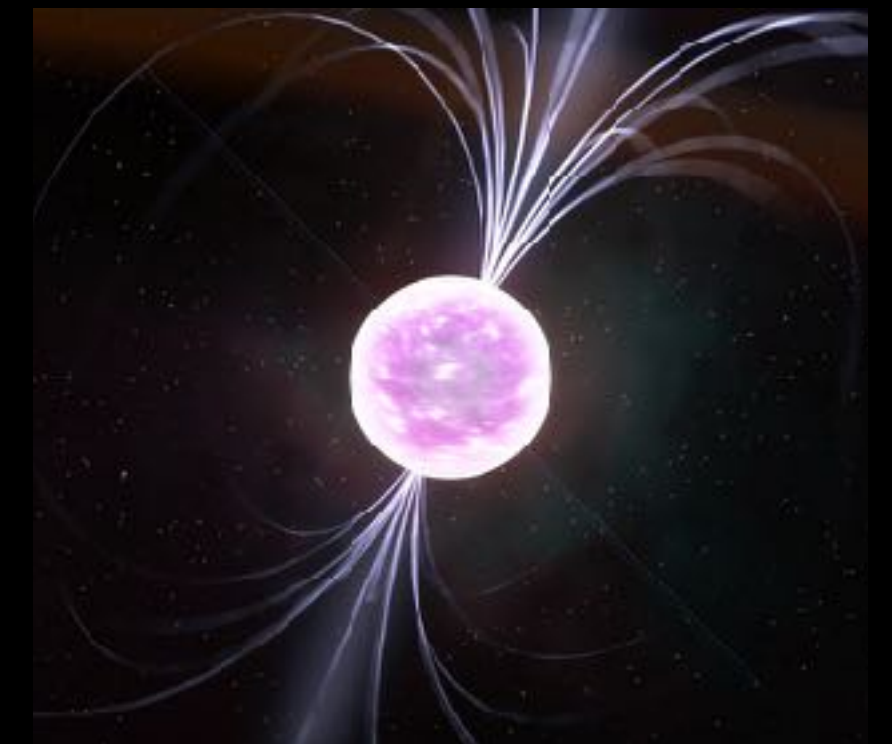


Lecture 1

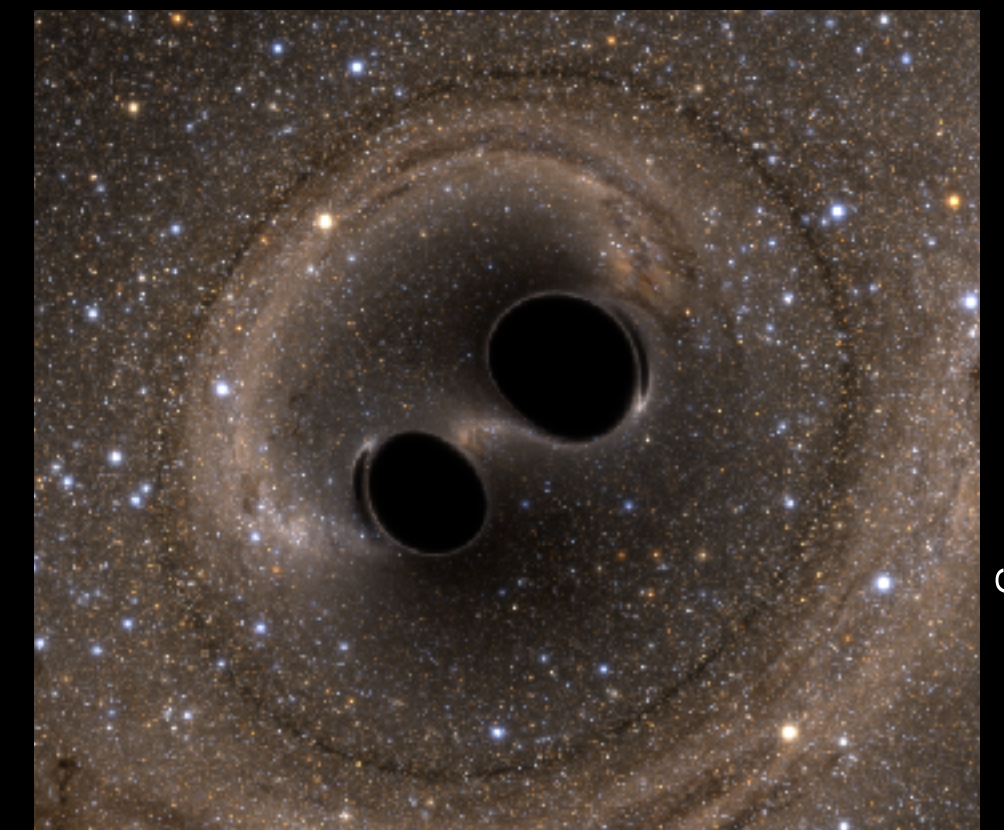


????

Pulsars



BH/NS Mergers



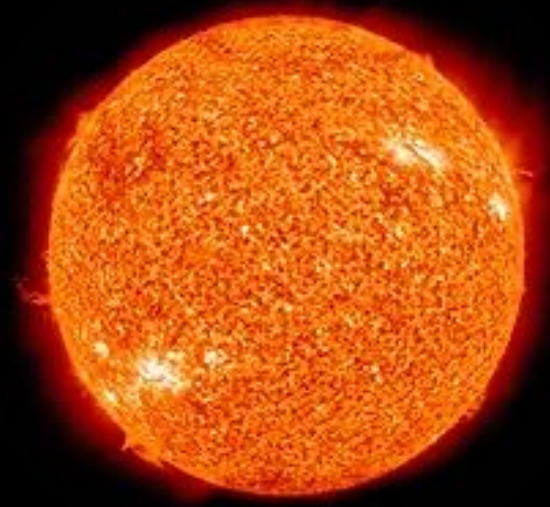
Credit: NASA/CXC/SAO

Credit: ESO/M. Kornmesser

Credit: Kevin Gill / Flickr

Credit: SXS Lensing

The Sun



Supernovae

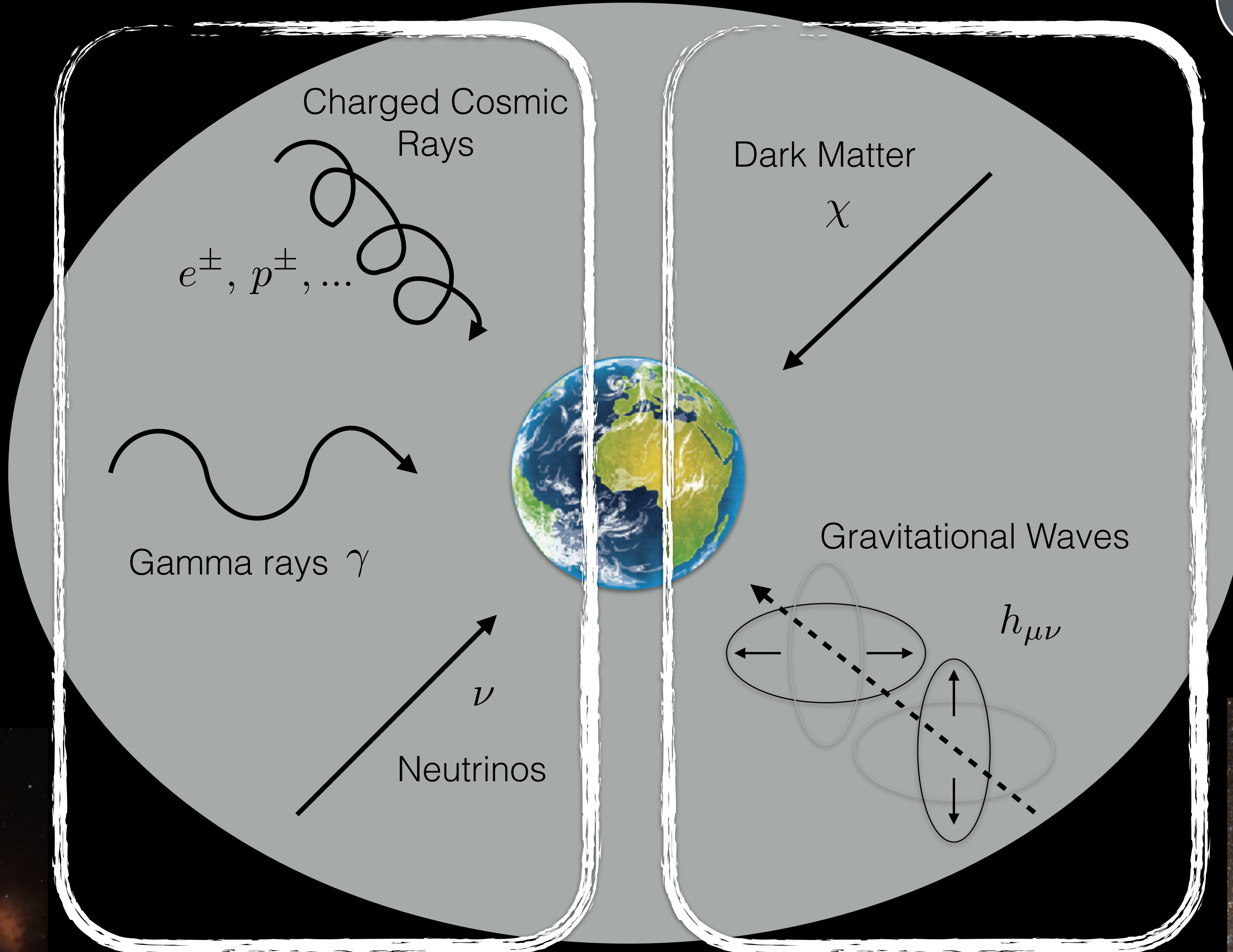


Quasars/AGN



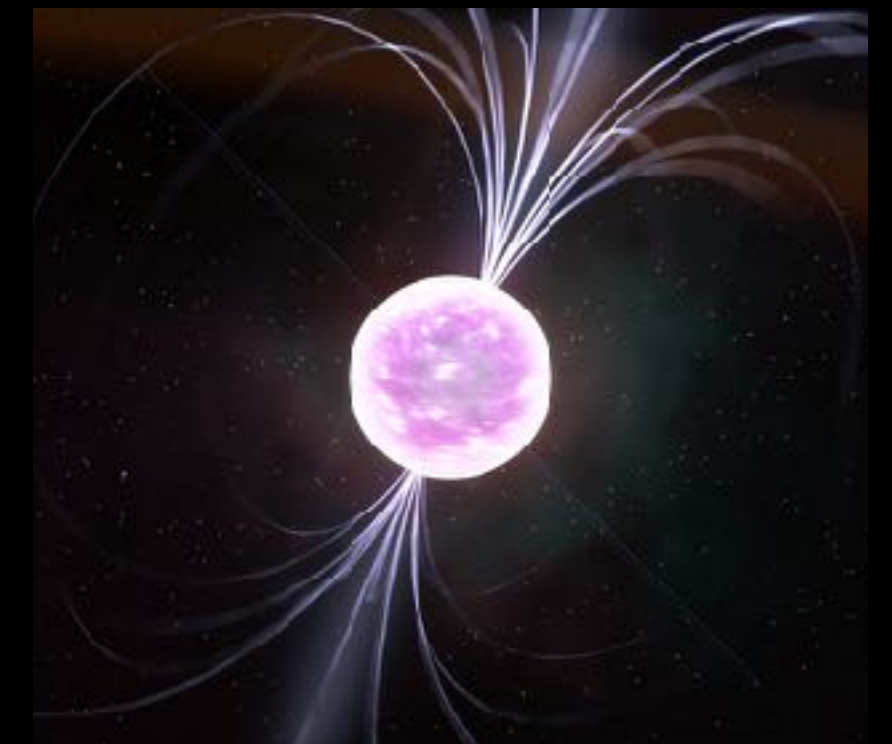
Lecture 1

Lecture 2



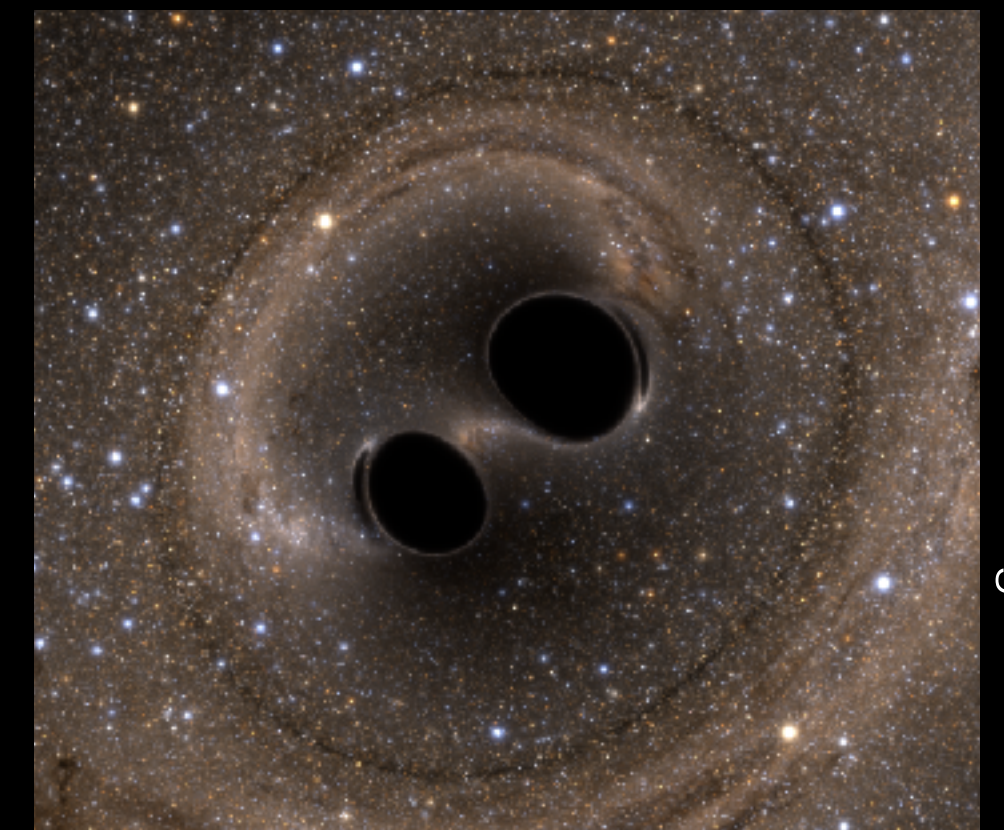
????

Pulsars



Credit: Kevin Gill / Flickr

BH/NS Mergers



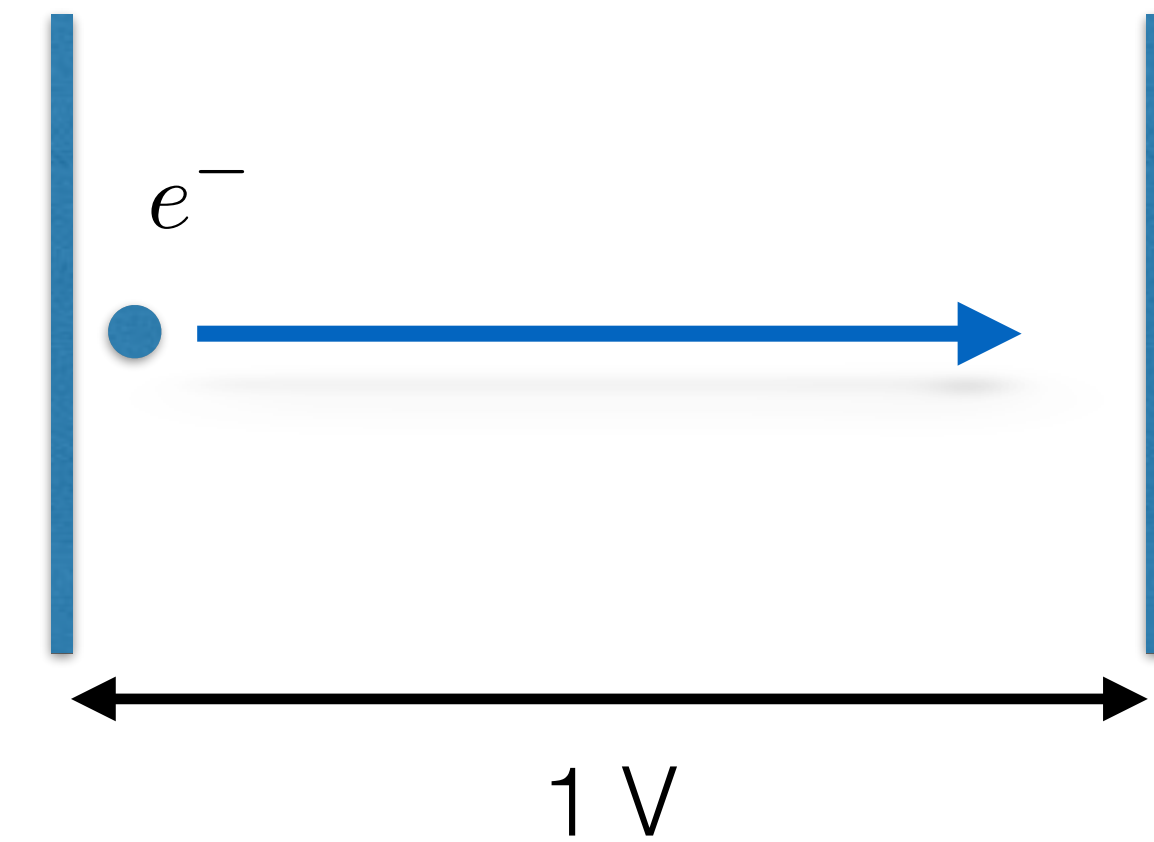
Credit: SXS Lensing

Credit: NASA/CXC/SAO

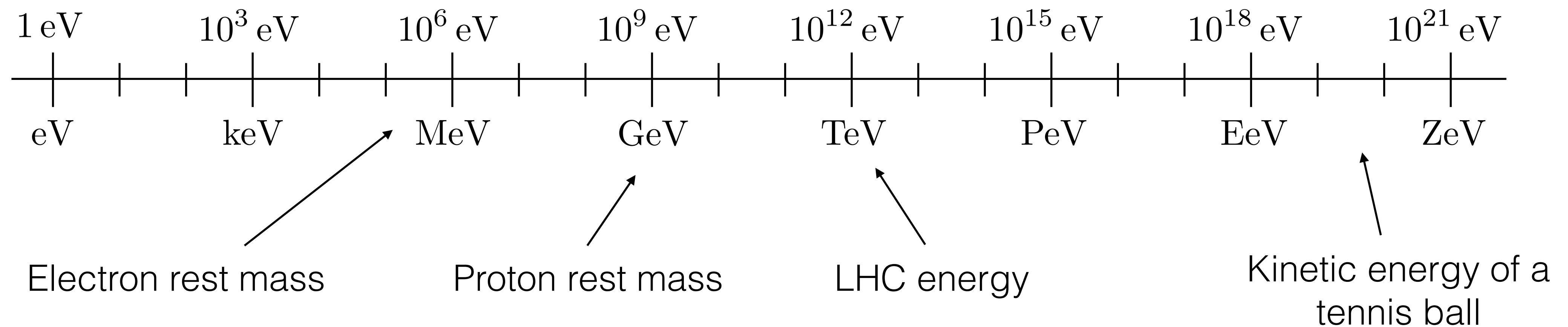
Credit: ESO/M. Kornmesser

A huge range of energy scales...

1 eV is the kinetic energy an electron gains from being accelerated across a potential of 1 V



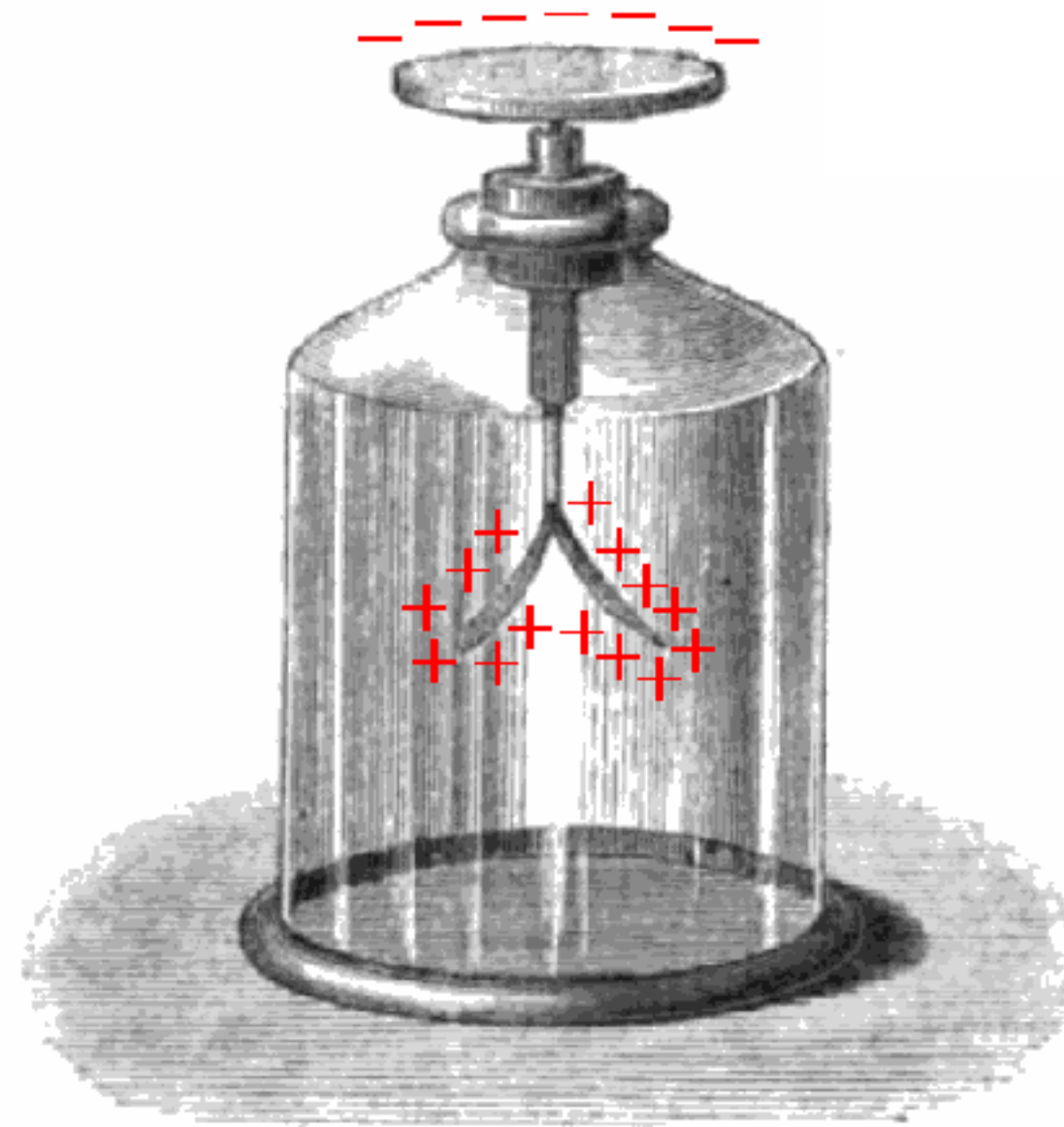
$$\begin{aligned}1 \text{ eV} &\approx 1.6 \times 10^{-19} \text{ J} \\ &\approx 1.8 \times 10^{-36} \text{ kg} \\ &\approx 1.2 \times 10^4 \text{ K}\end{aligned}$$



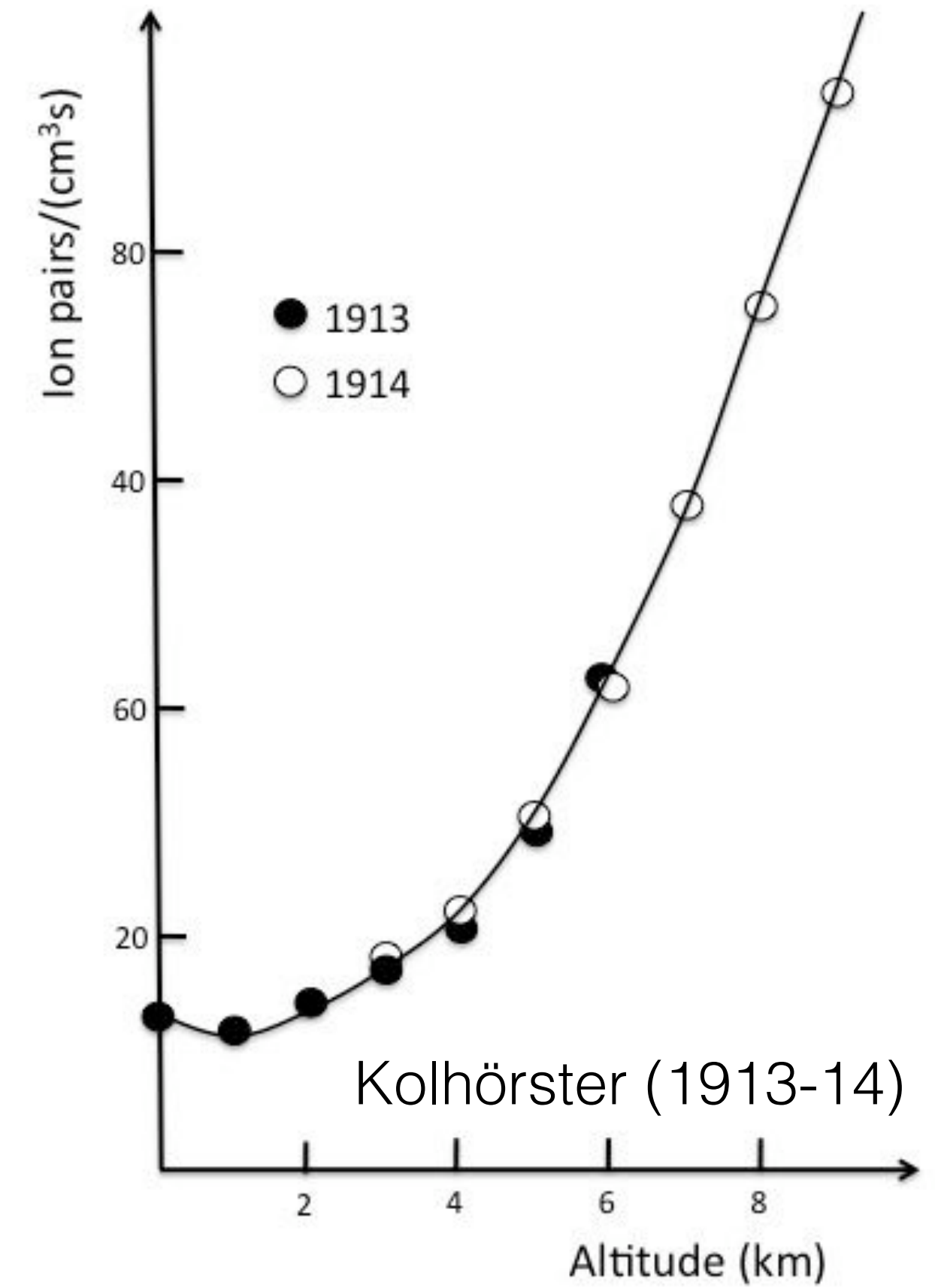
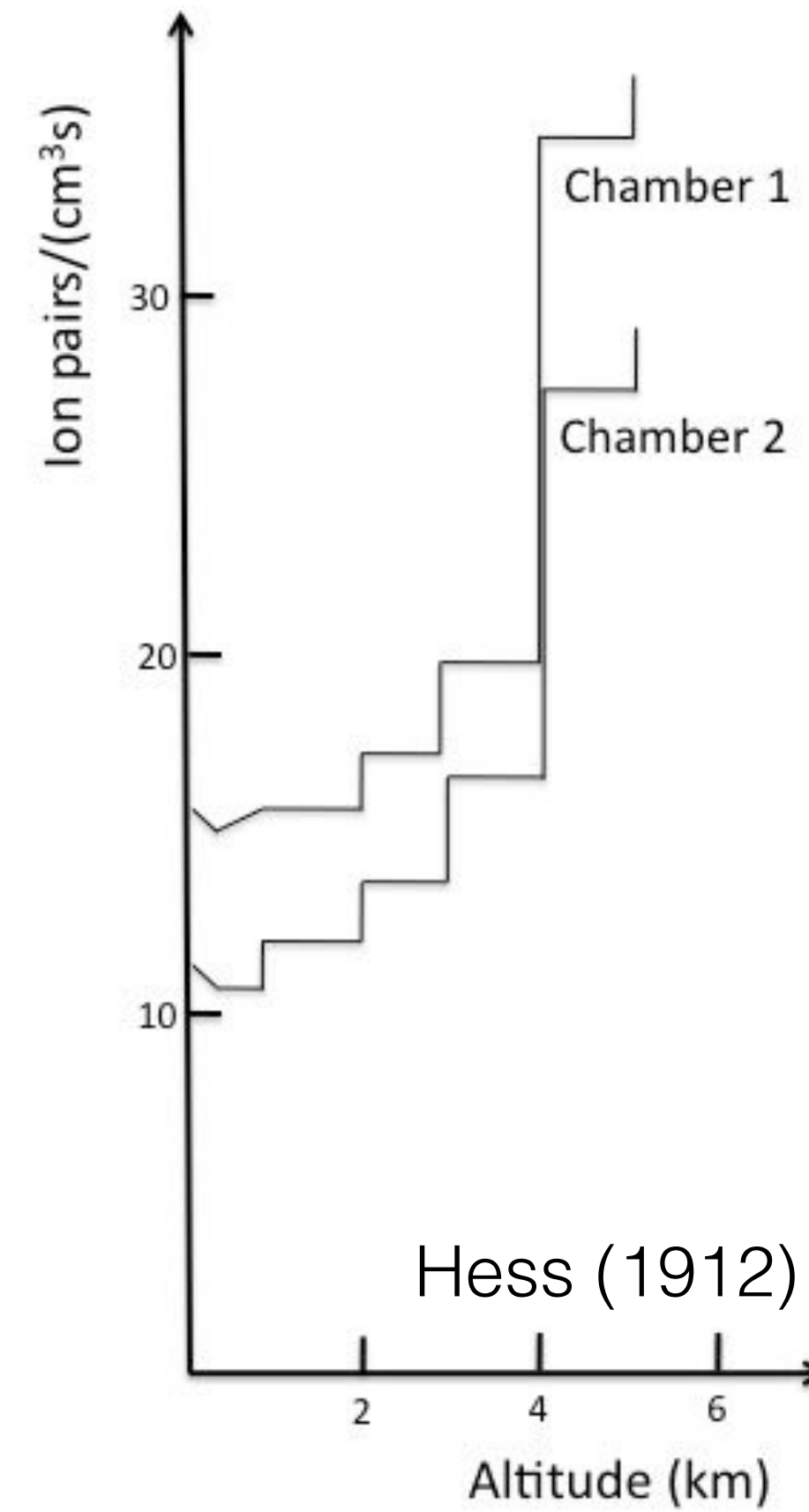
History of astroparticles



Victor Hess
(1883 - 1964)



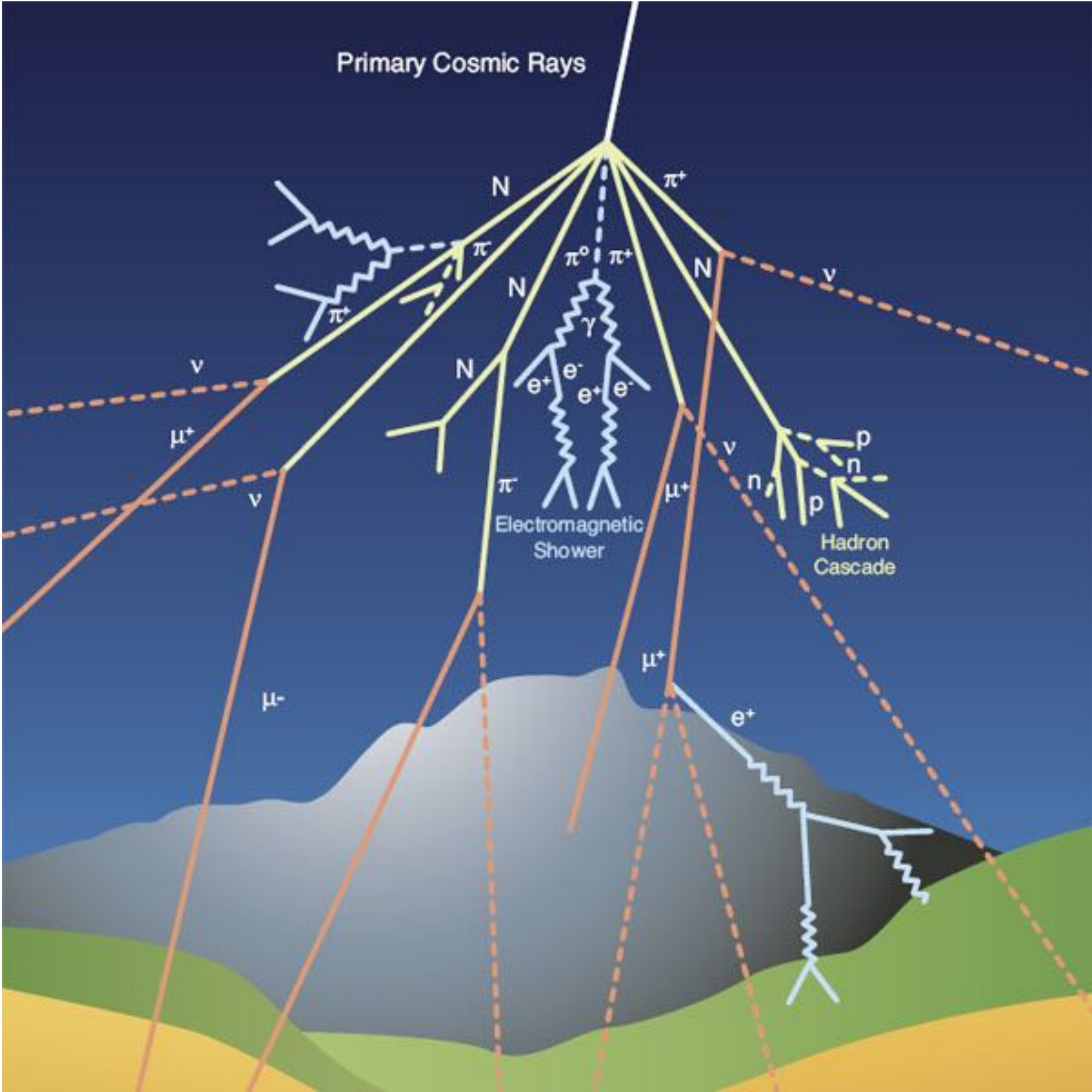
Credit: Sylvanus P. Thompson (1881),
Chetvorno (2008)



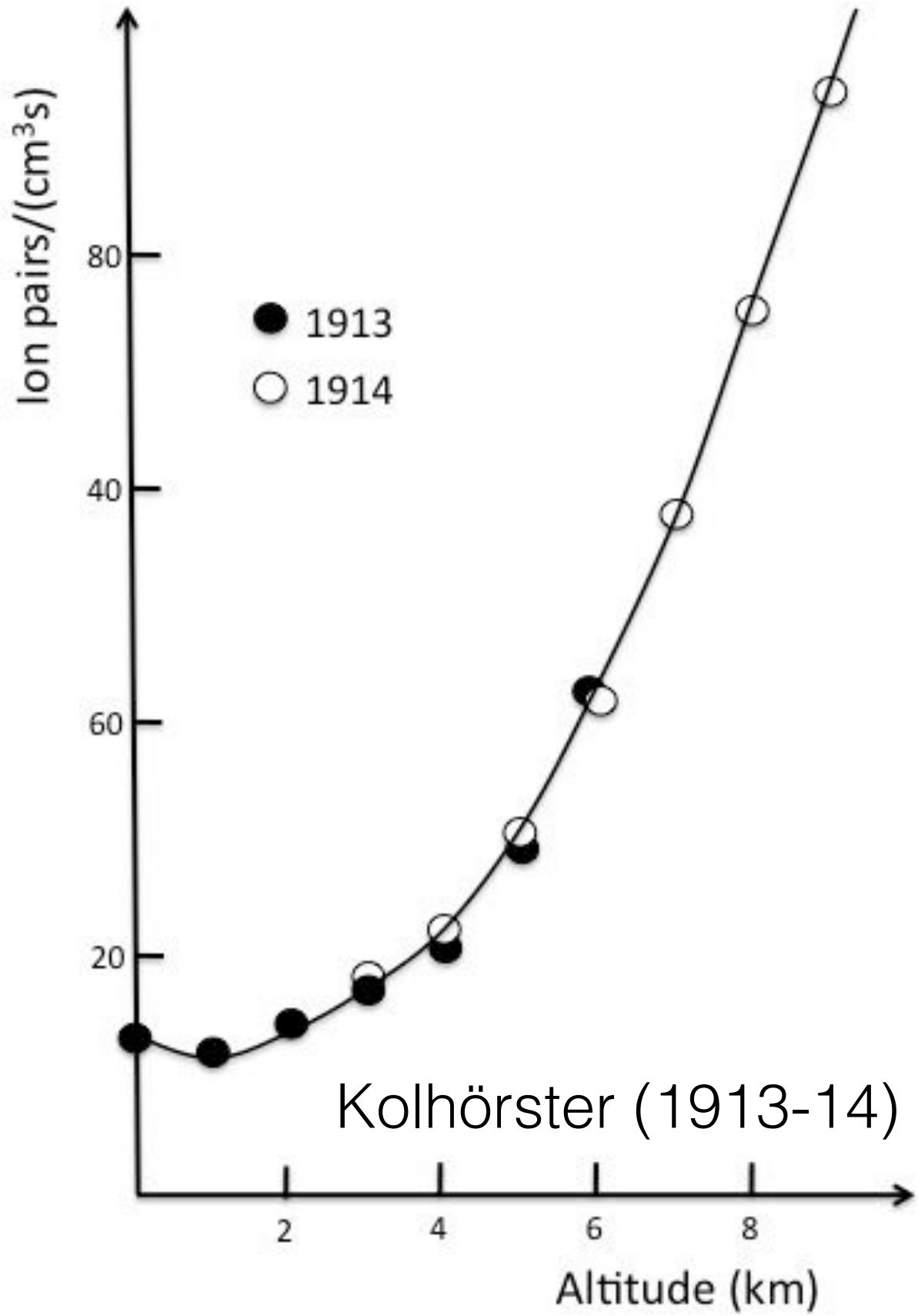
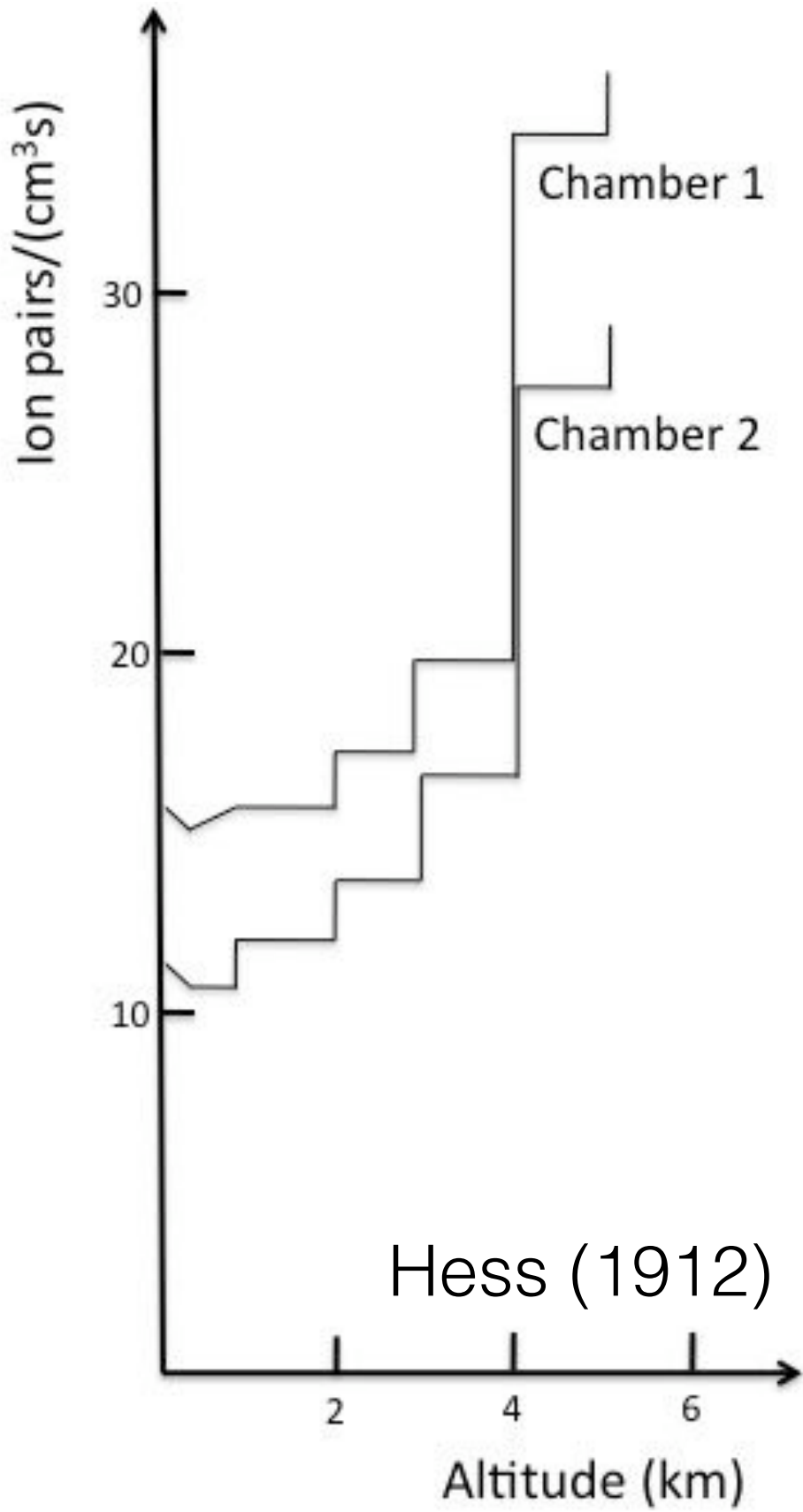
Credit: Alessandro De Angelis

History of astroparticles

Cosmic Ray “Showers” first understood by Auger et al. (1939)



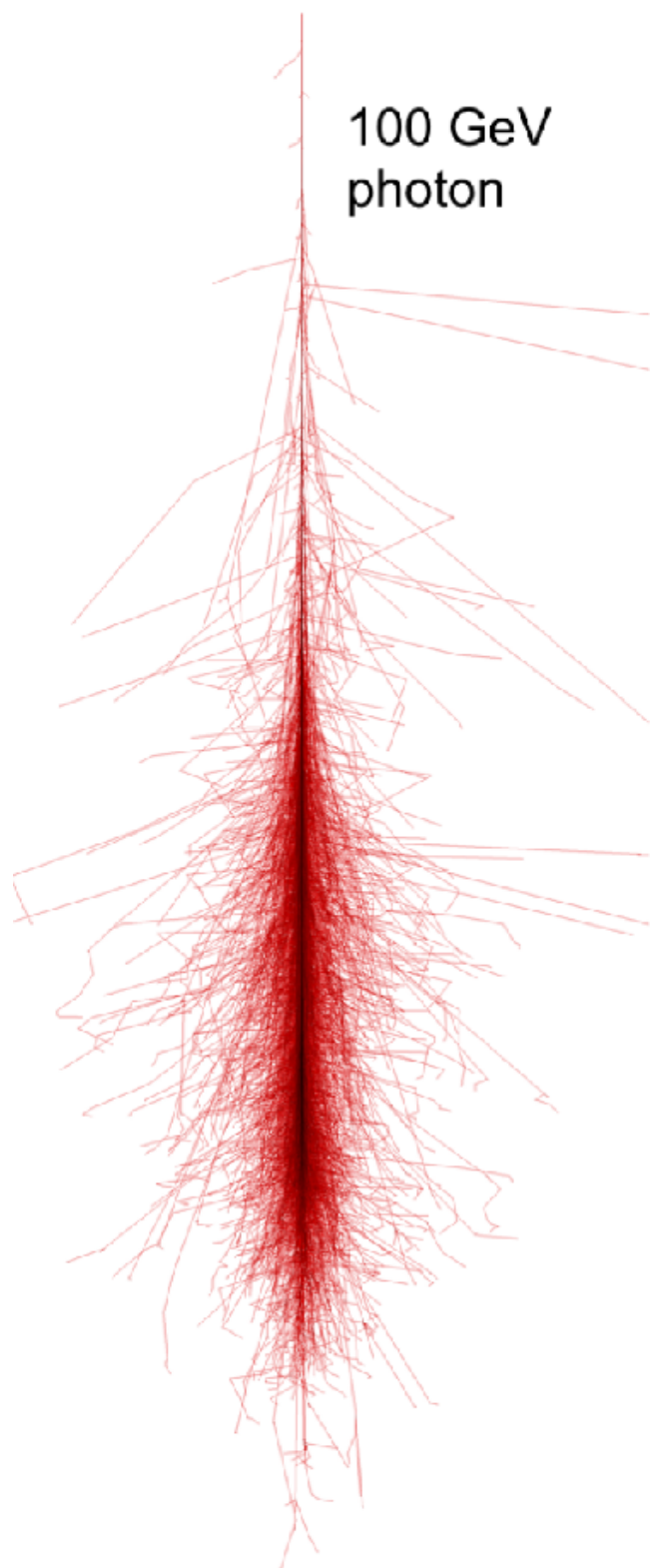
Credit: CERN



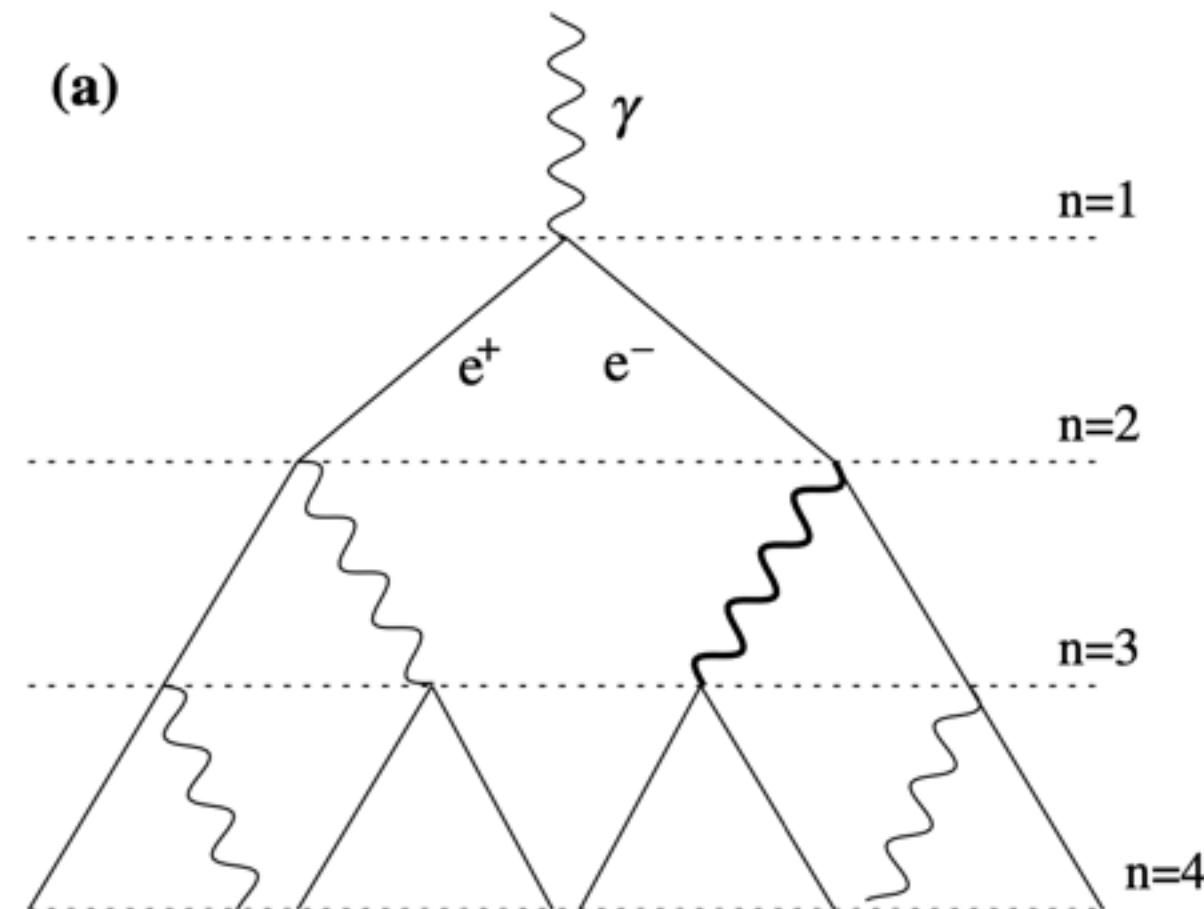
Credit: Alessandro De Angelis

Gamma rays vs Charged Cosmic rays

Gamma Rays



$$E_n = \left(\frac{1}{2}\right)^n E_0^\gamma$$



Protons/nuclei

$$E_{\text{had}} = \left(\frac{2}{3}\right)^n E_0^p$$
$$E_{\text{em}} = \left[1 - \left(\frac{2}{3}\right)^n\right] E_0^p$$

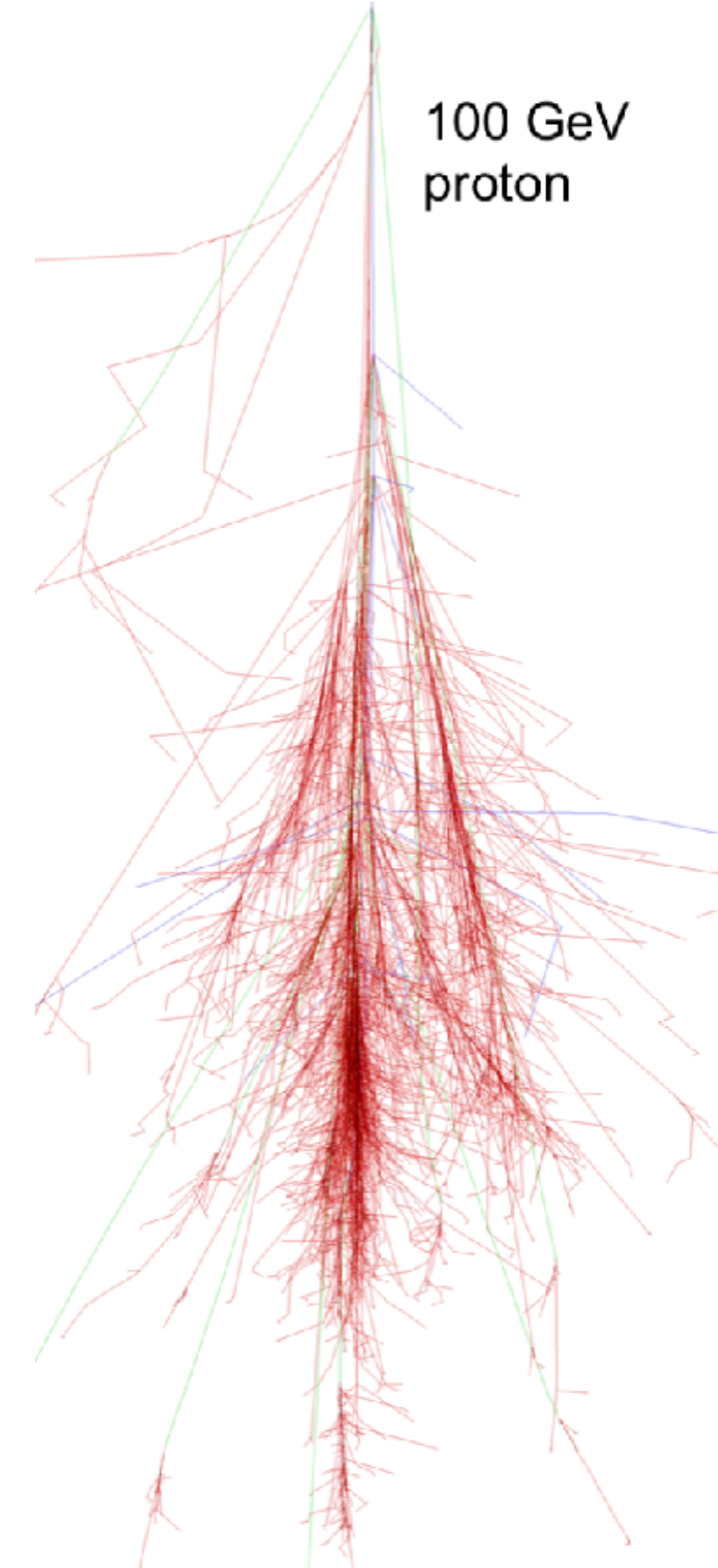
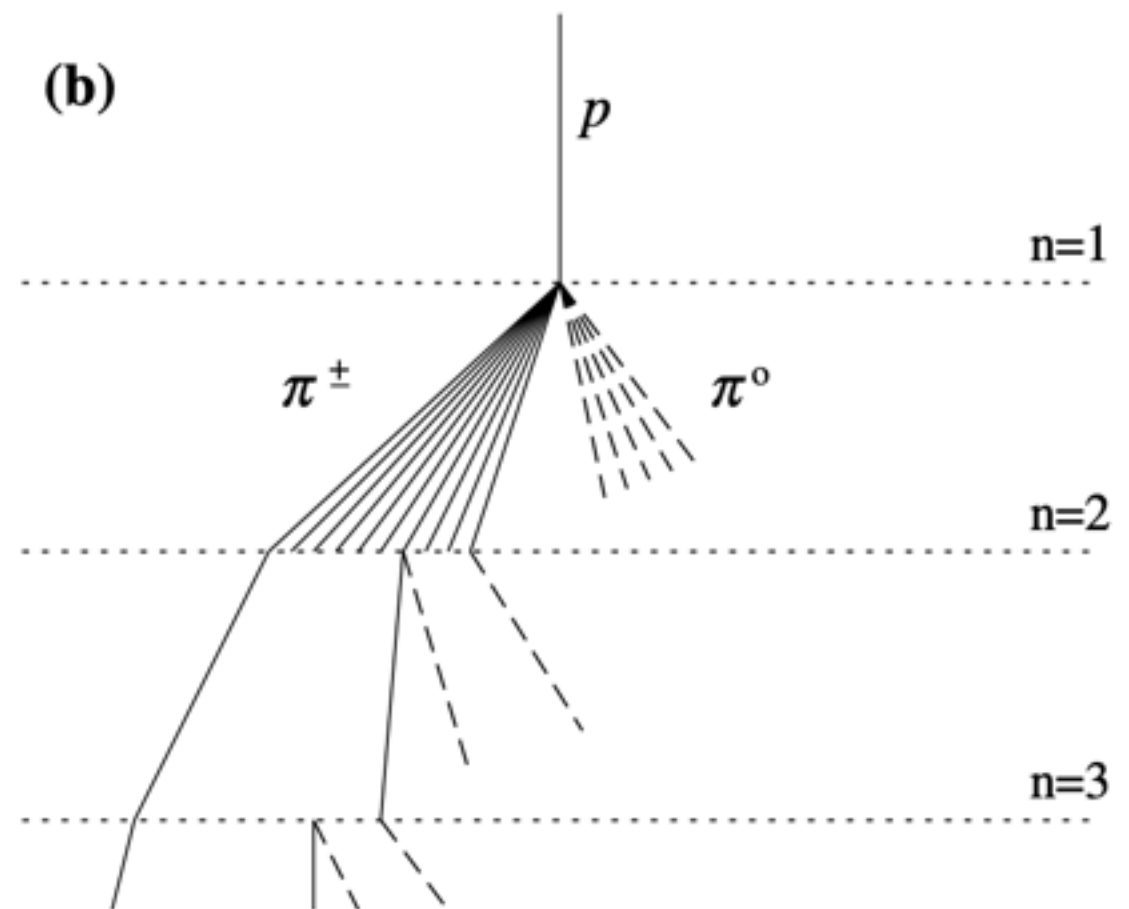
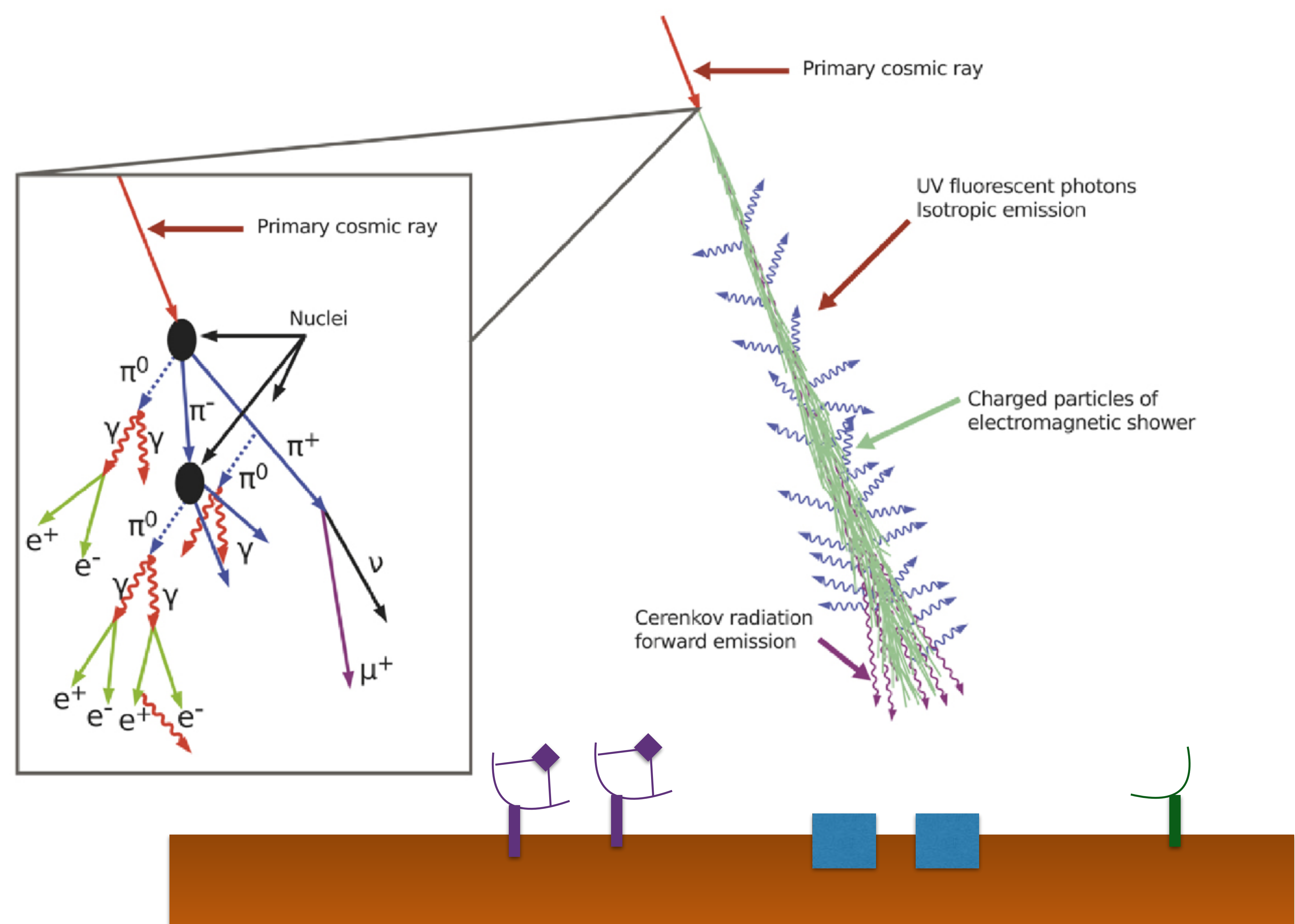


Fig. 1. Schematic views of (a) an electromagnetic cascade and (b) a hadronic shower. In the hadron shower, dashed lines indicate neutral pions which do not re-interact, but quickly decay, yielding electromagnetic subshowers (not shown). Not all pion lines are shown after the $n = 2$ level. Neither diagram is to scale.

[1510.05675](#)

Credit: [Matthews \(2005\)](#)

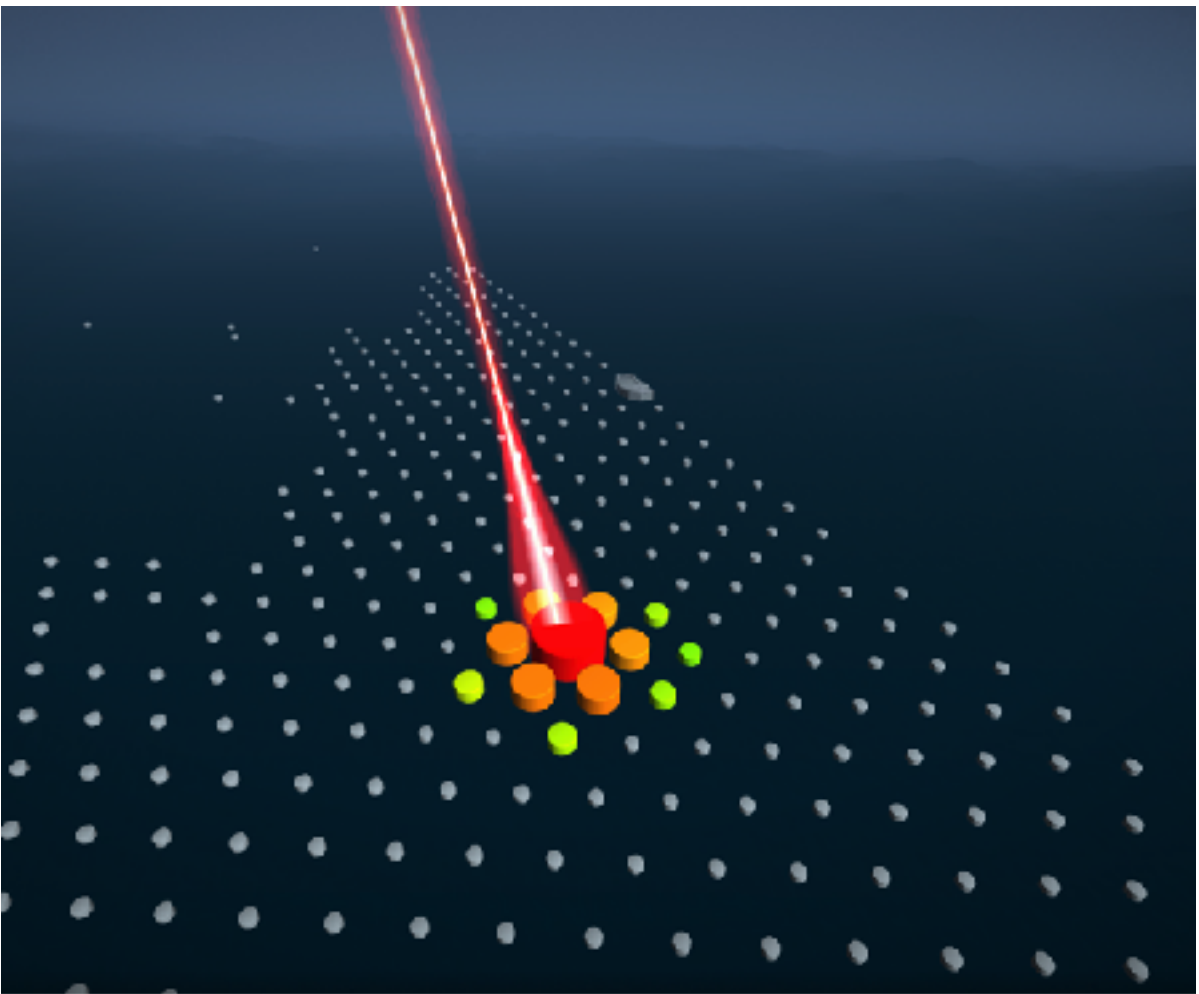
Detection of cosmic rays (Earth)



Fluorescence
(e.g. Fly's Eye, Auger observatory)

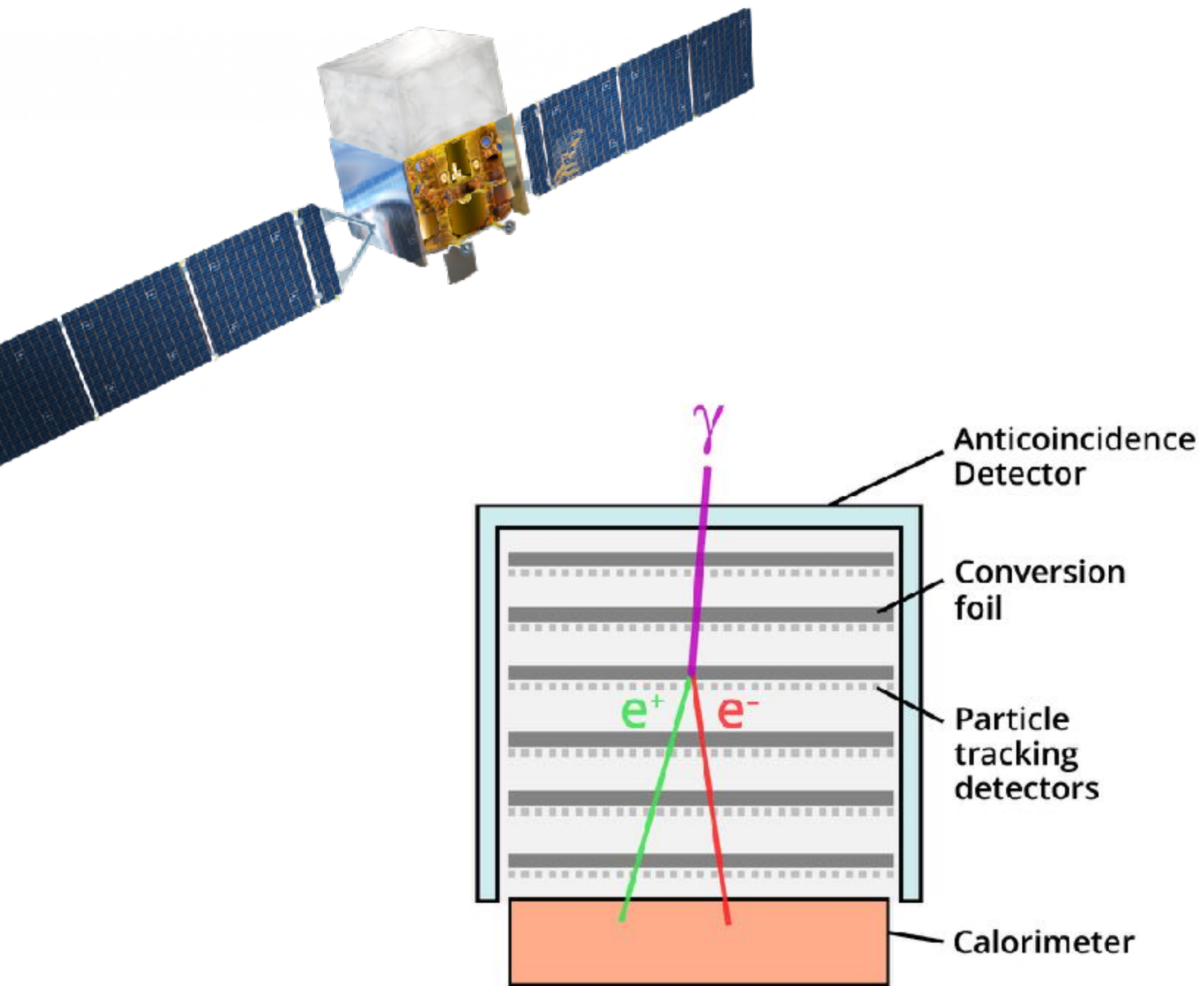
Imaging Air Cherenkov Telescope (IACT)
(e.g. MAGIC, VERITAS, HESS, planned CTA)

Ground array and Water Cherenkov detectors
(e.g. KASCADE-GRANDE, MILAGRO, HAWC)



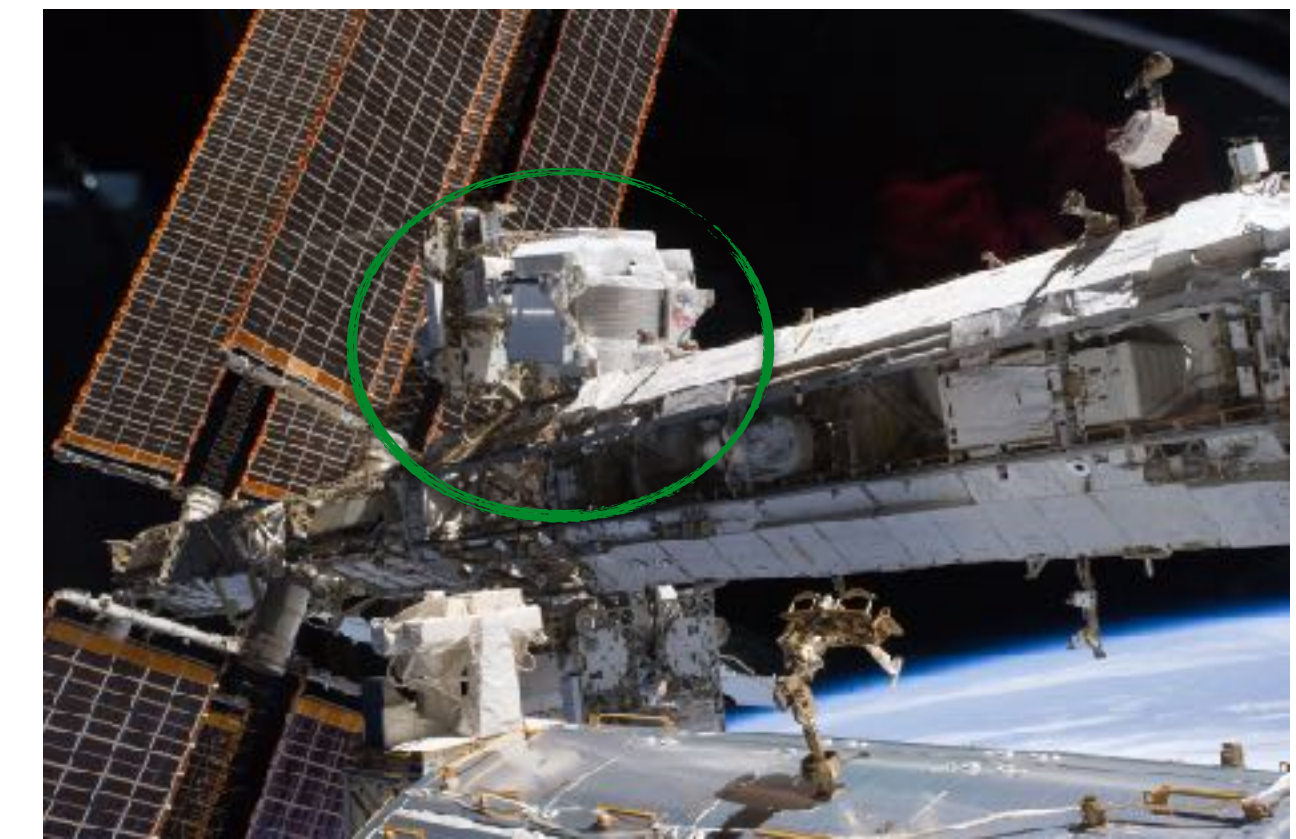
Detection of cosmic rays (Space)

Fermi-LAT (2008-)

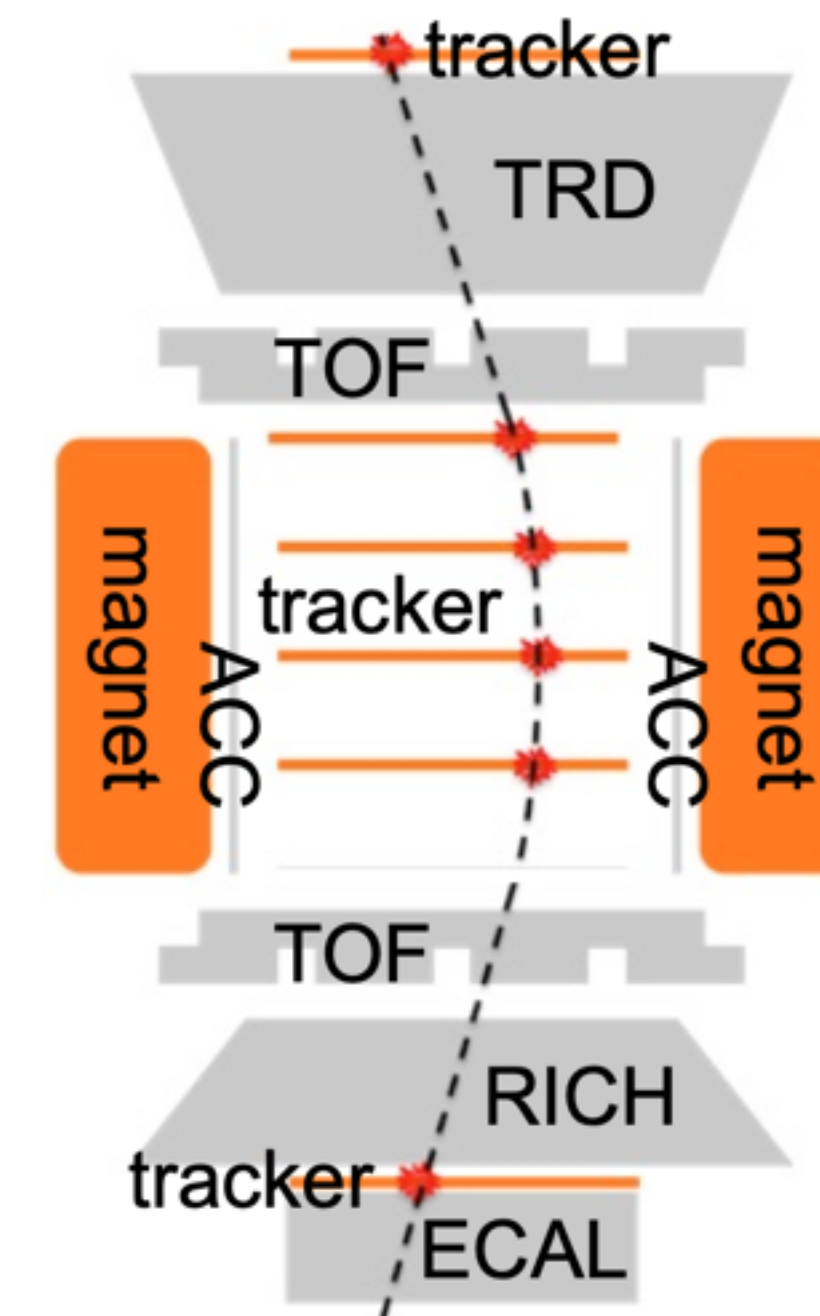


Credit: NASA's Goddard Space Flight Center

Detection of gamma-rays
in the range 20 MeV - 300 GeV



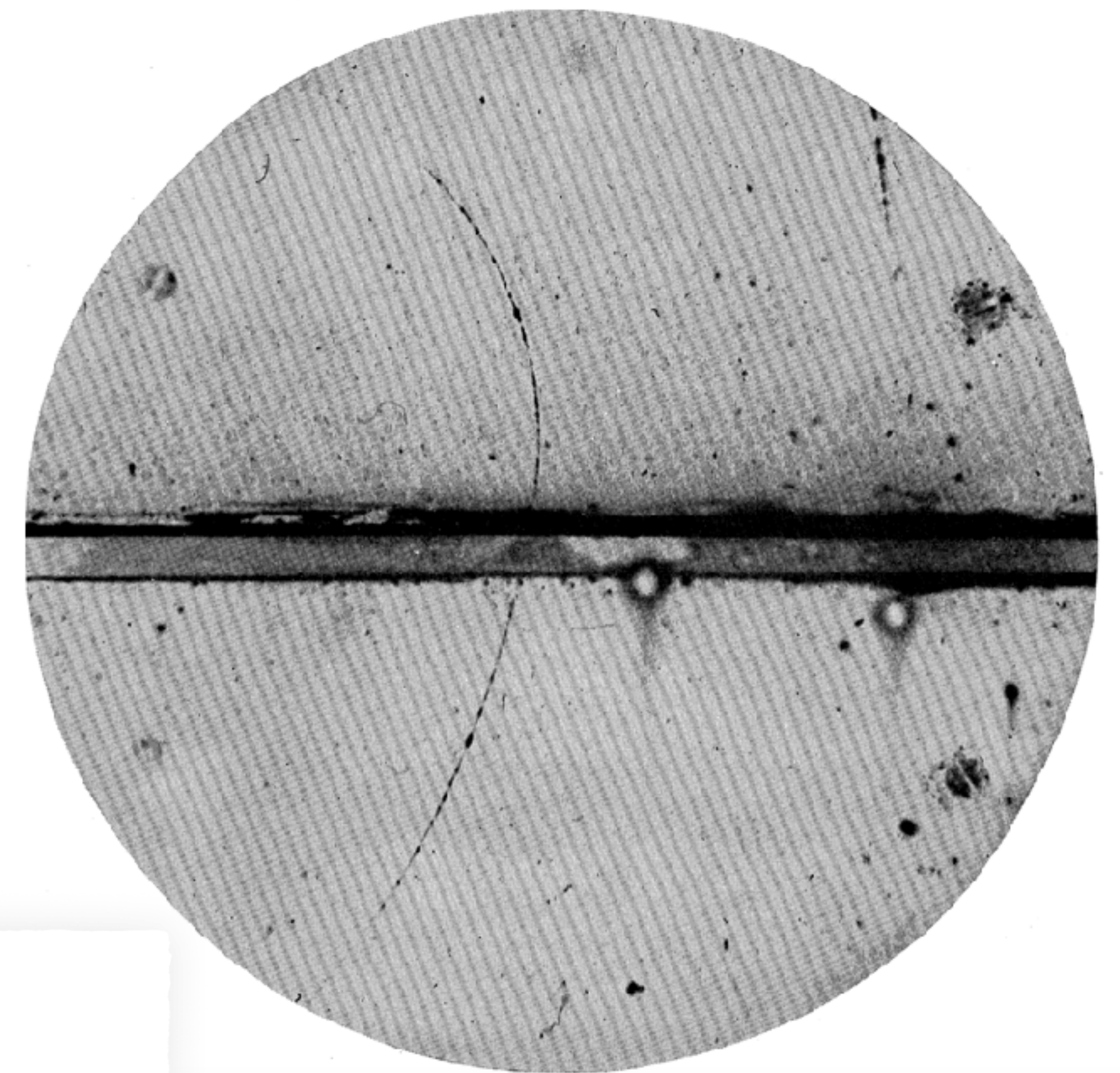
AMS (2011-)



[1507.02712](#)

Detection of $e^\pm$, $p^\pm$ and heavier nuclei
in the range 1 GeV - 2 TeV

The Positive Electron



The Positive Electron

CARL D. ANDERSON, *California Institute of Technology, Pasadena, California*
(Received February 28, 1933)

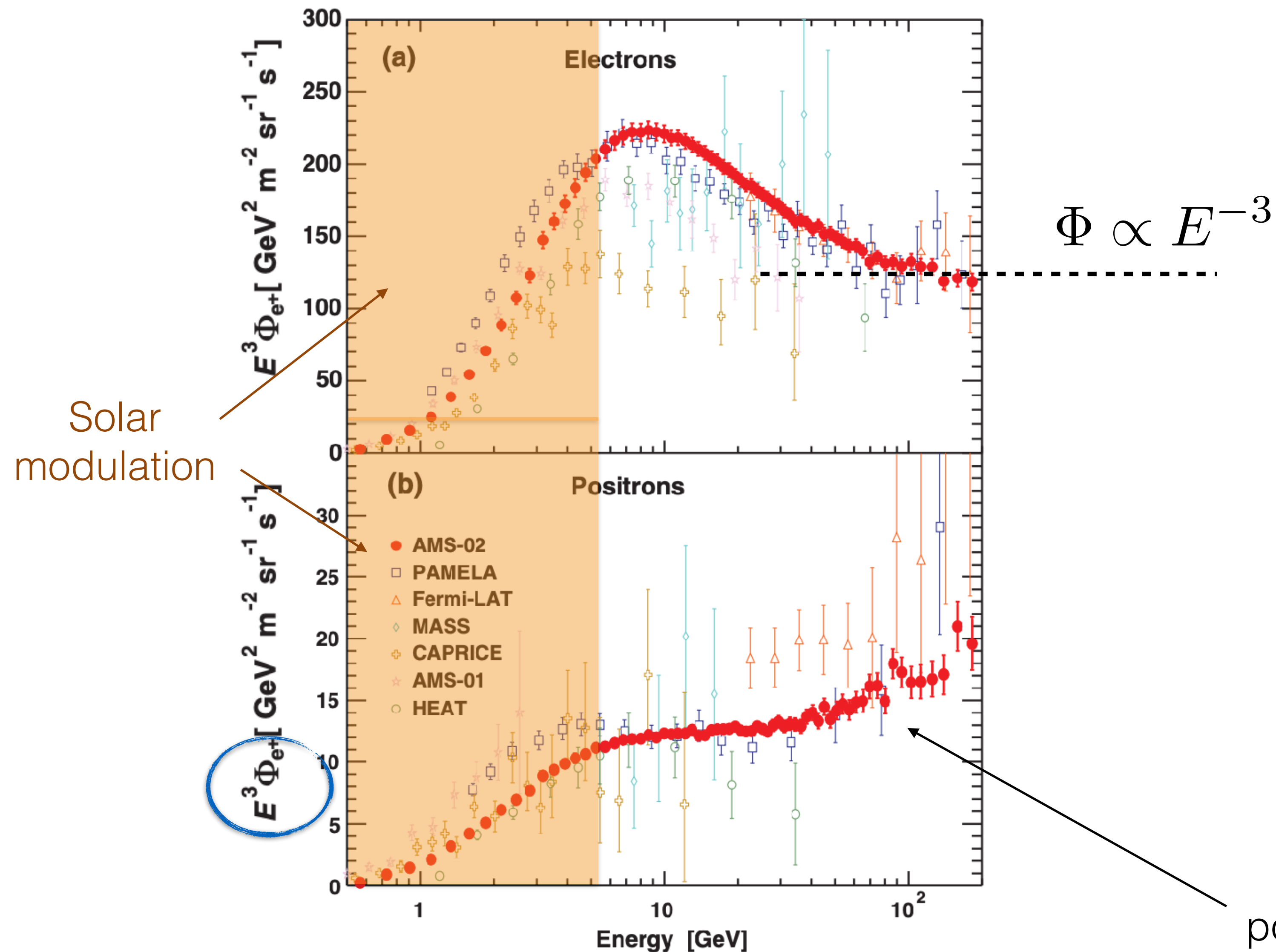
Out of a group of 1300 photographs of cosmic-ray tracks in a vertical Wilson chamber 15 tracks were of positive particles which could not have a mass as great as that of the proton. From an examination of the energy-loss and ionization produced it is concluded that the charge is less than twice, and is probably exactly equal to, that of the proton. If these particles carry unit positive charge the

curvatures and ionizations produced require the mass to be less than twenty times the electron mass. These particles will be called positrons. Because they occur in groups associated with other tracks it is concluded that they must be secondary particles ejected from atomic nuclei.

Editor

[[Phys. Rev. 43, 491 \(1933\)](#)]

Electrons vs Positrons



Electrons can be directly accelerated
(i.e. **primary cosmic rays**)

Positrons are only produced by the
collisions of other cosmic rays
(i.e. **secondary cosmic rays**)

Expect different spectra. But, rise in
positron flux at high energy is still not yet
understood (“positron excess”)!

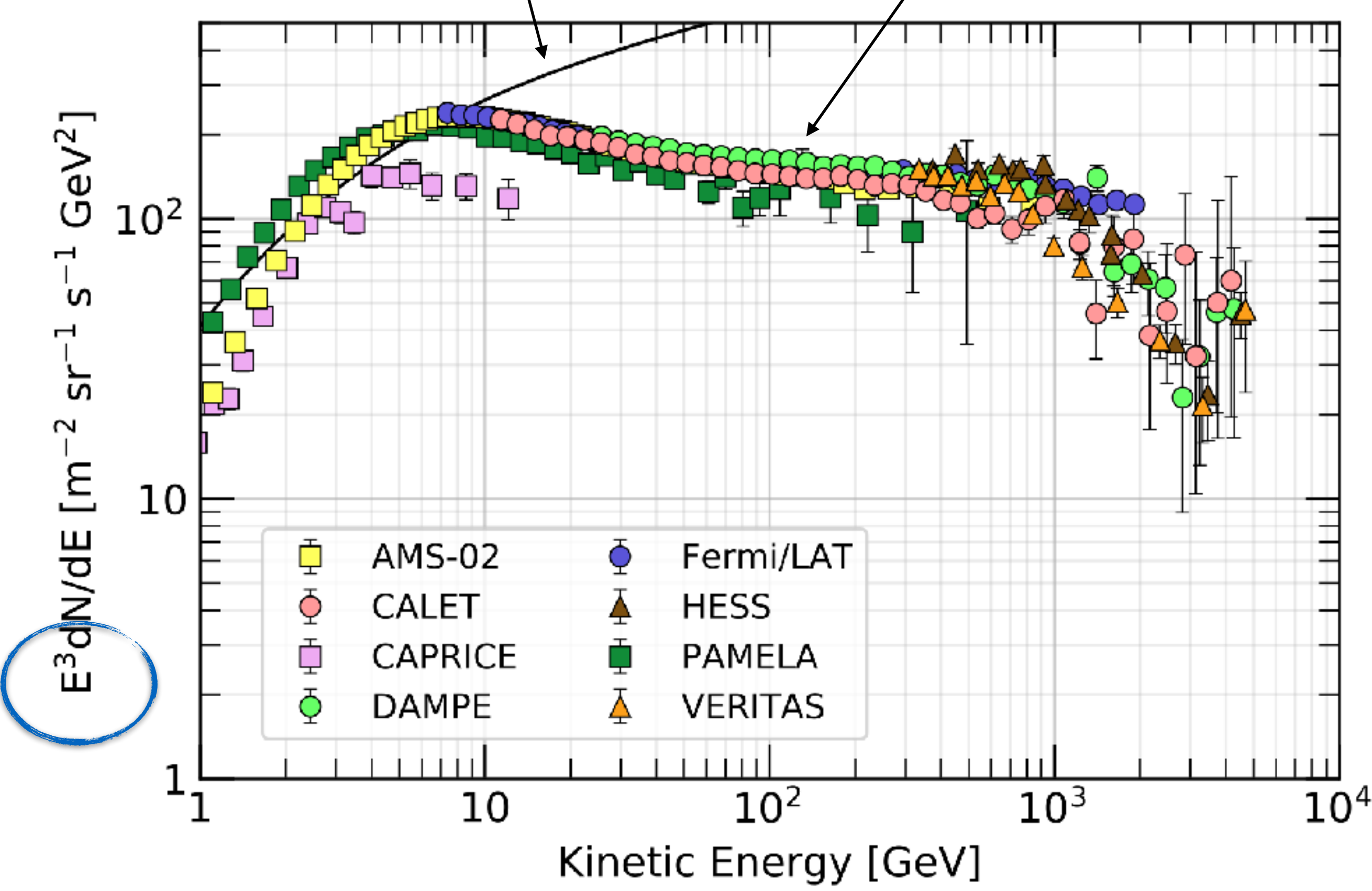
Credit: [M. Aguilar et al. \(AMS Collaboration\), 2014](#)

E.g. [1303.0530](#)

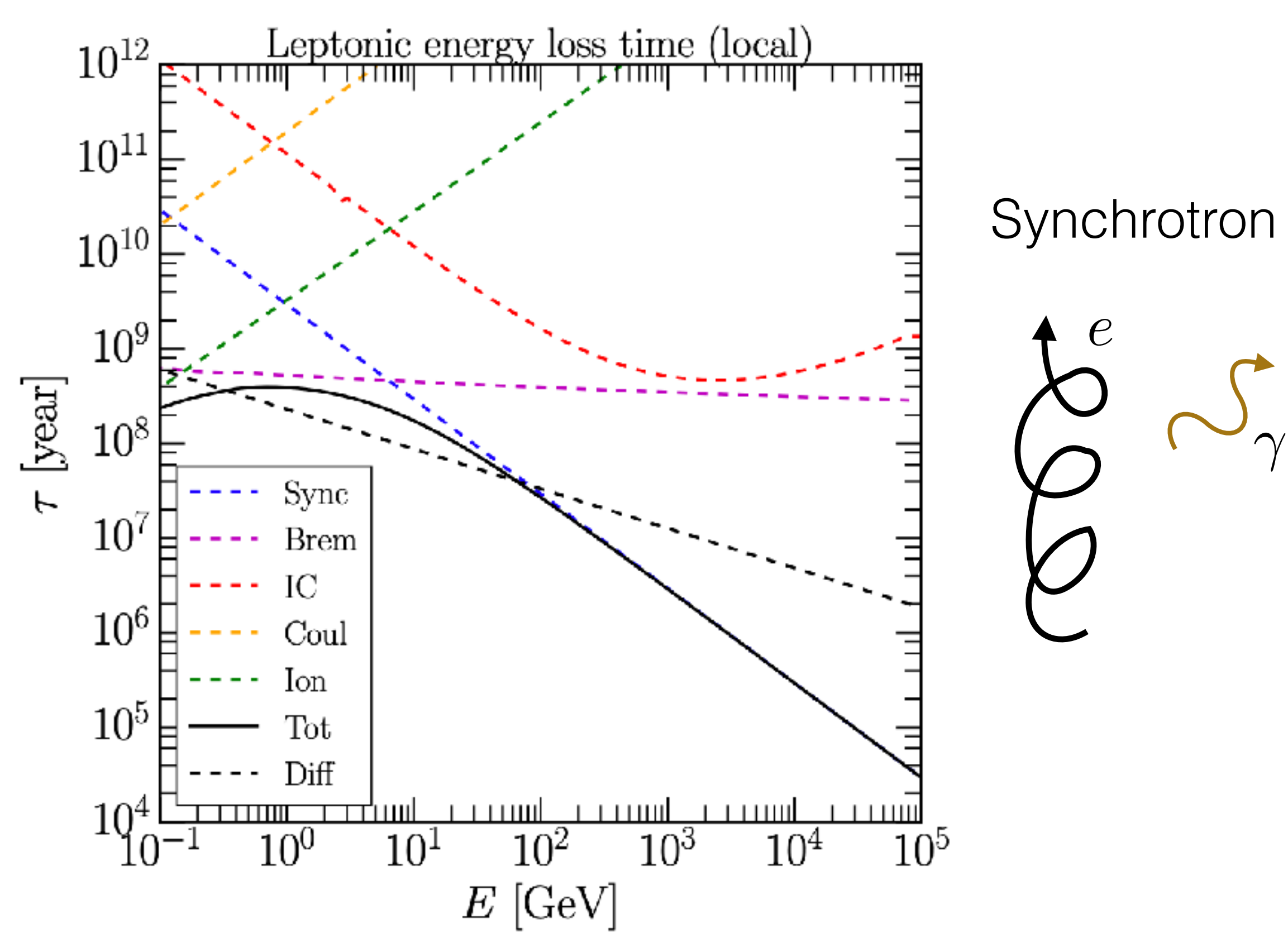
Electrons vs Protons

Proton Spectrum (x0.01)

Electron + Positron Spectrum



Electrons and positrons lose energy much more rapidly (than nuclei) as they move through the Galaxy

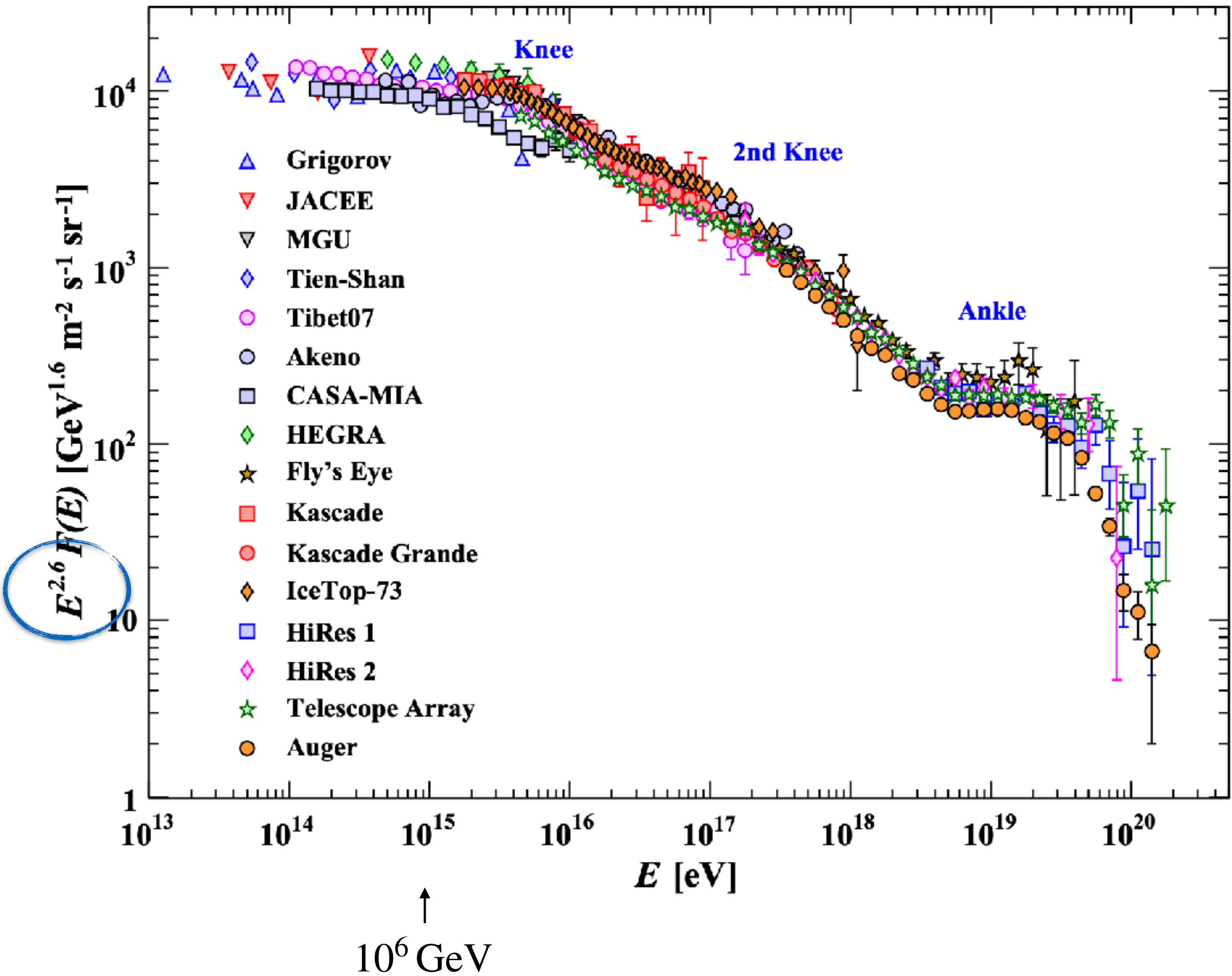


See e.g. Appendix C of [1607.07886](#)

Credit: [Particle Data Group \(2020\)](#)

Ultra high-energy cosmic rays

All particle cosmic ray spectrum

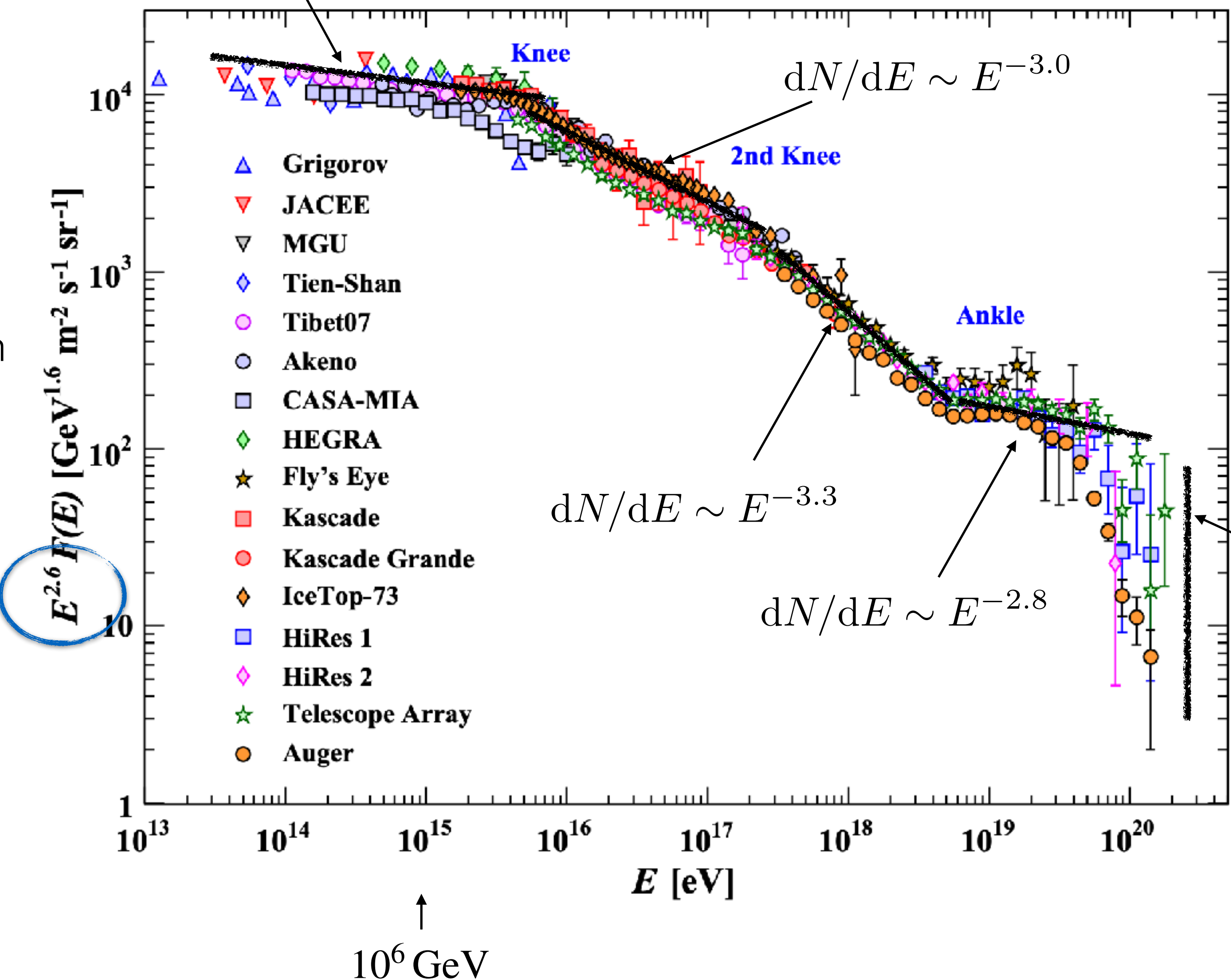


Credit: Particle Data Group (2020)

Ultra high-energy cosmic rays

Extragalactic CRs begin to dominate above the ankle.

$dN/dE \sim E^{-2.7}$ All particle cosmic ray spectrum

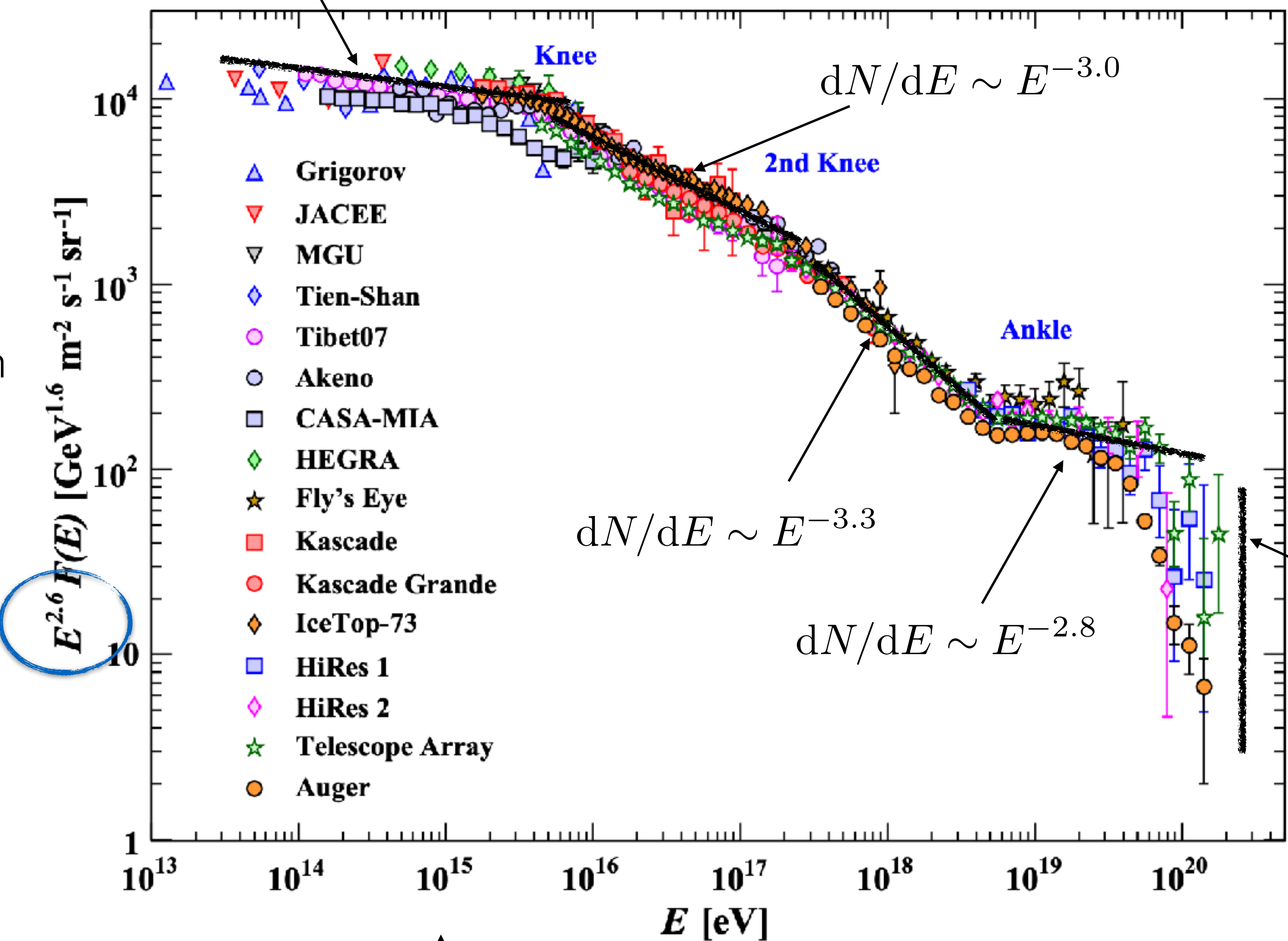


Credit: Particle Data Group (2020)

Ultra high-energy cosmic rays

Extragalactic CRs begin to dominate above the ankle.

$dN/dE \sim E^{-2.7}$ All particle cosmic ray spectrum



Heavier nuclei begin to dominate above the 2nd knee.

Possible cut-off?

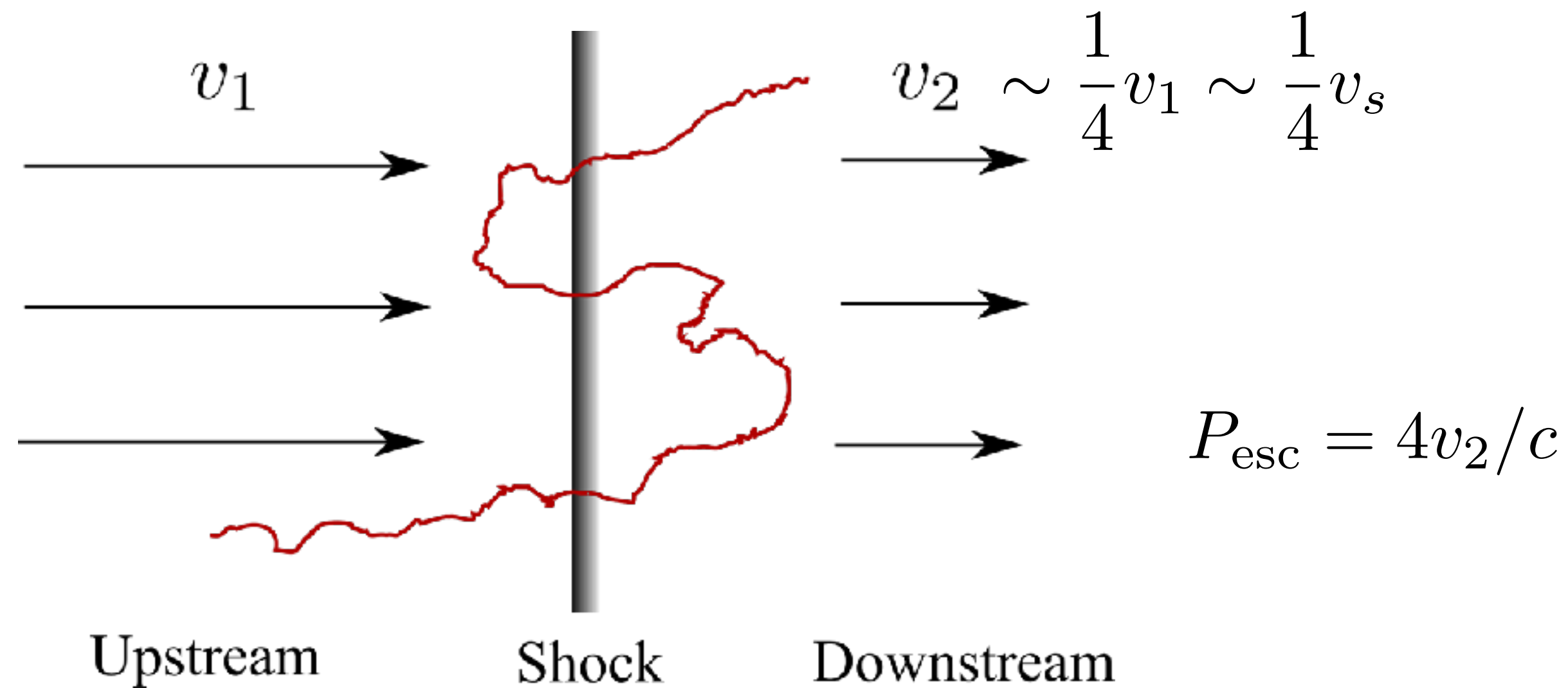
Can we understand this structure?

Credit: Particle Data Group (2020)

Production of cosmic rays

Tycho Supernova remnant

Diffusive shock acceleration (or **Fermi Acceleration**)



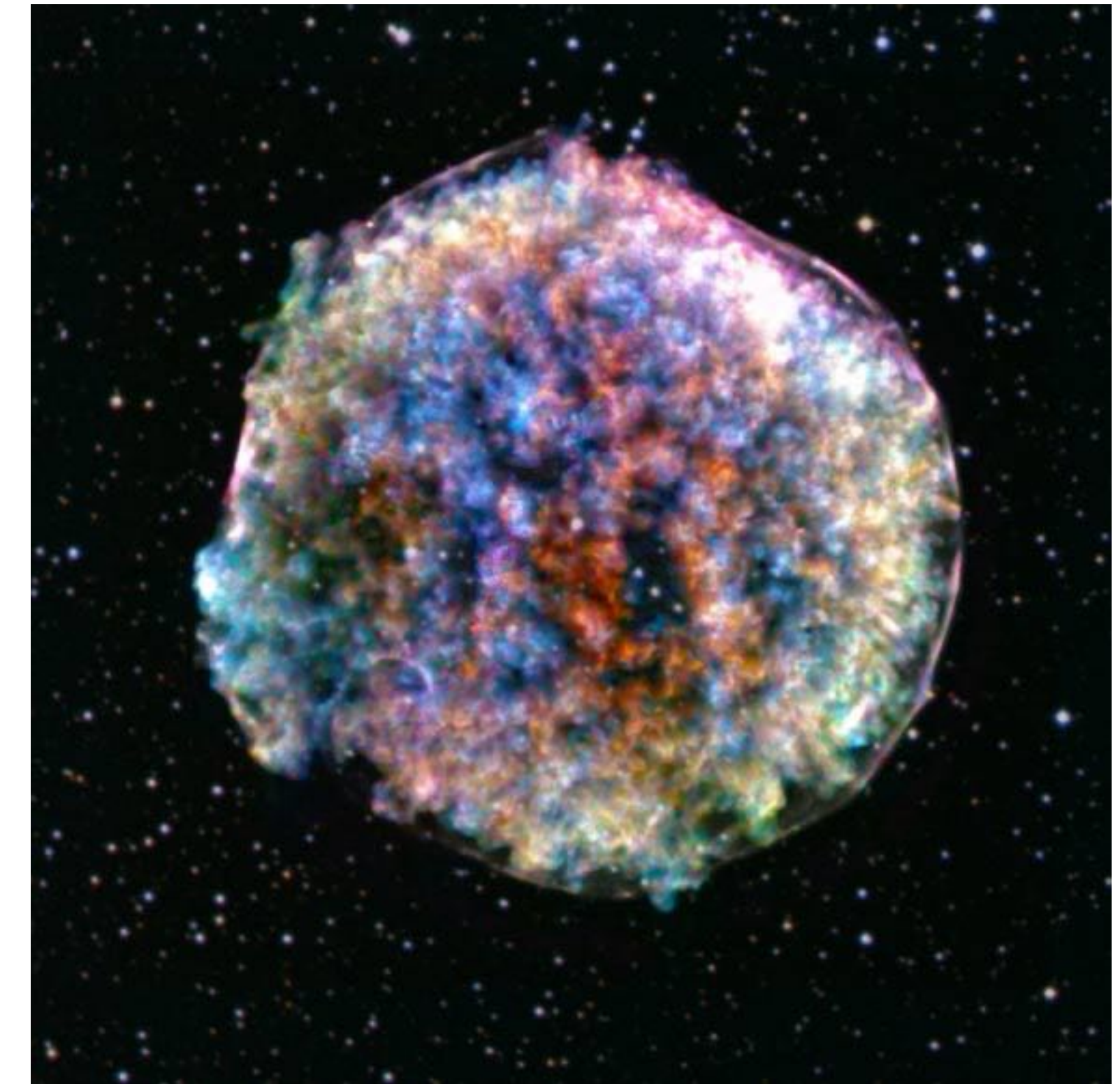
With each crossing: $\xi = \left\langle \frac{\Delta E}{E} \right\rangle = \frac{4}{3} \frac{v_1 - v_2}{c}$

After n crossings: $E_n = (1 + \xi)^n E_0$

Fraction of particles above a given energy: $f(E > E_n) = \sum_{m=n}^{\infty} (1 - P_{\text{esc}})^m = \left(\frac{E_n}{E_0} \right)^{P_{\text{esc}}/\xi}$

→ Injected flux of particles: $\frac{dN_{\text{inj}}}{dE} \propto \frac{df}{dE} = \left(\frac{E}{E_0} \right)^{-2}$

E.g. [1910.06006](#)

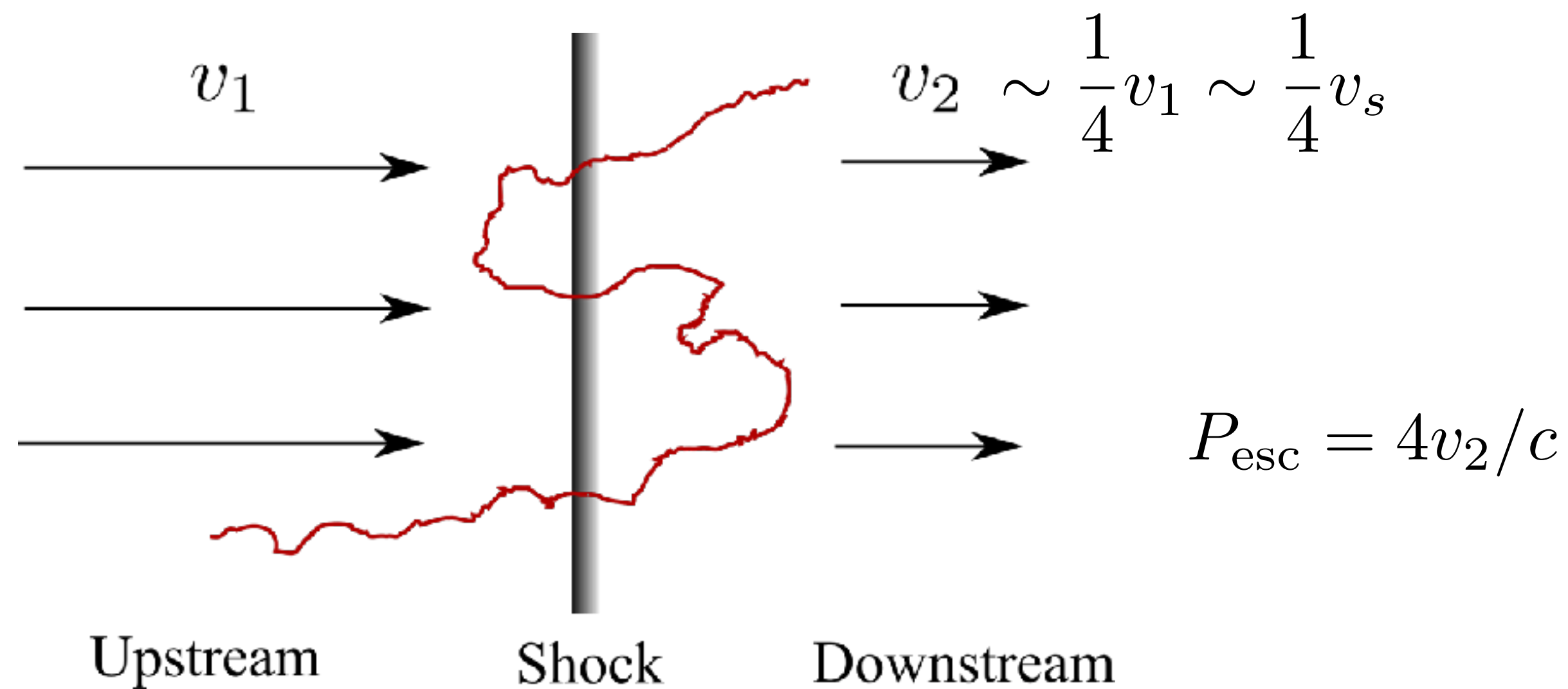


Credit: NASA / CXC / RIKEN / NASA's Goddard Space Flight Center / T. Sato et al / DSS

Production of cosmic rays

Tycho Supernova remnant

Diffusive shock acceleration (or **Fermi Acceleration**)



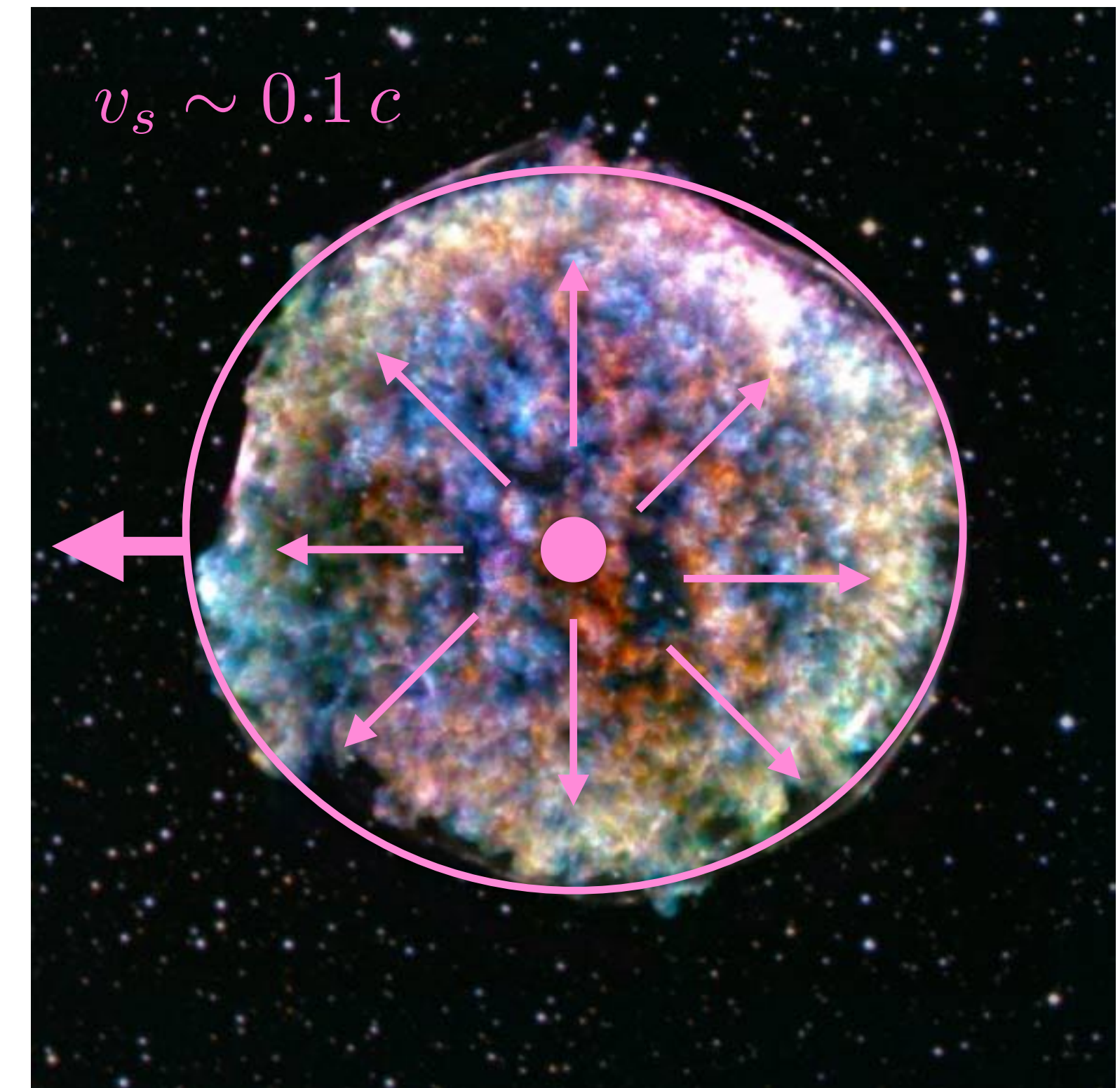
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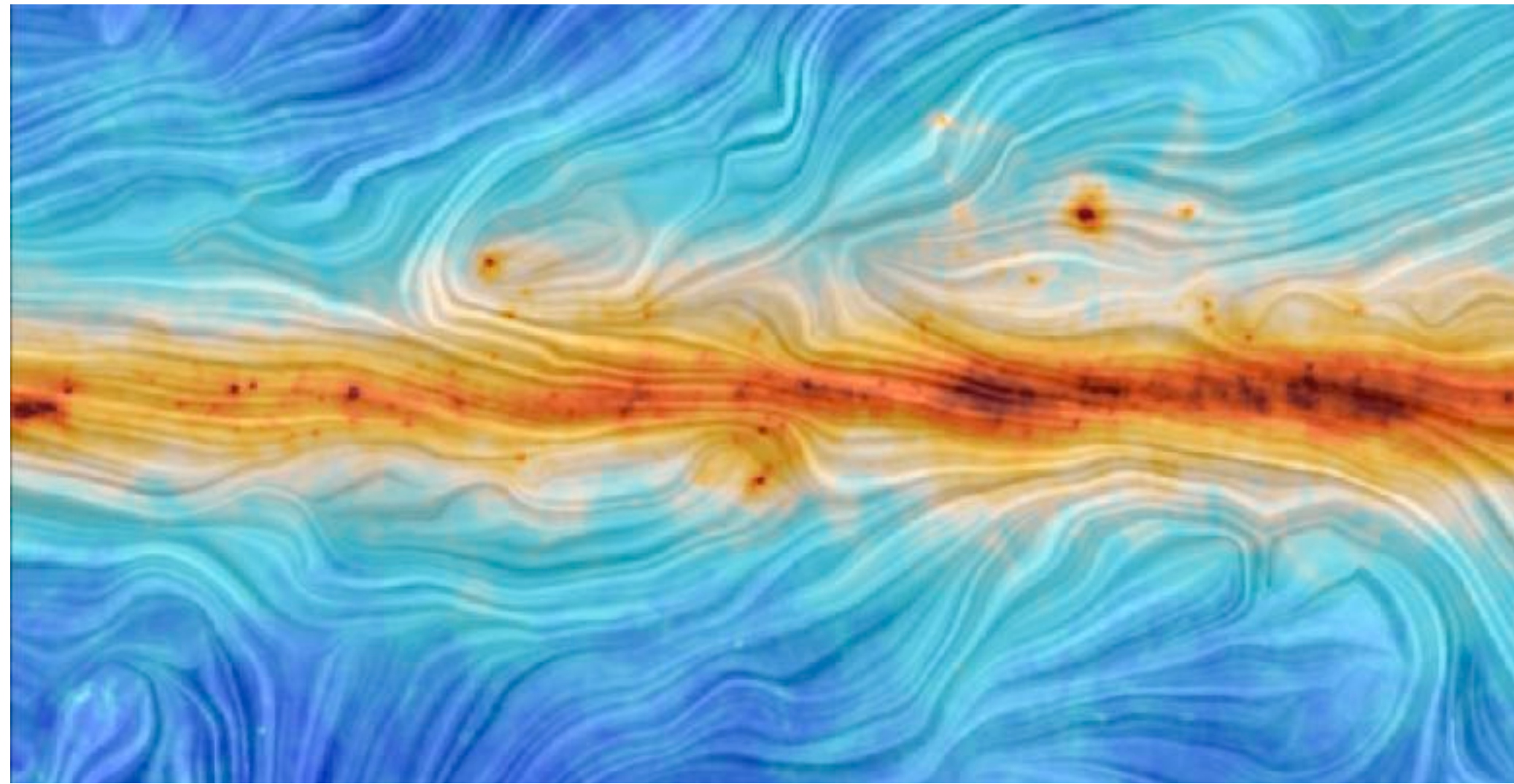
E.g. [1910.06006](#)



Credit: NASA / CXC / RIKEN / NASA's Goddard Space Flight Center / T. Sato et al / DSS

Propagation of CCRs

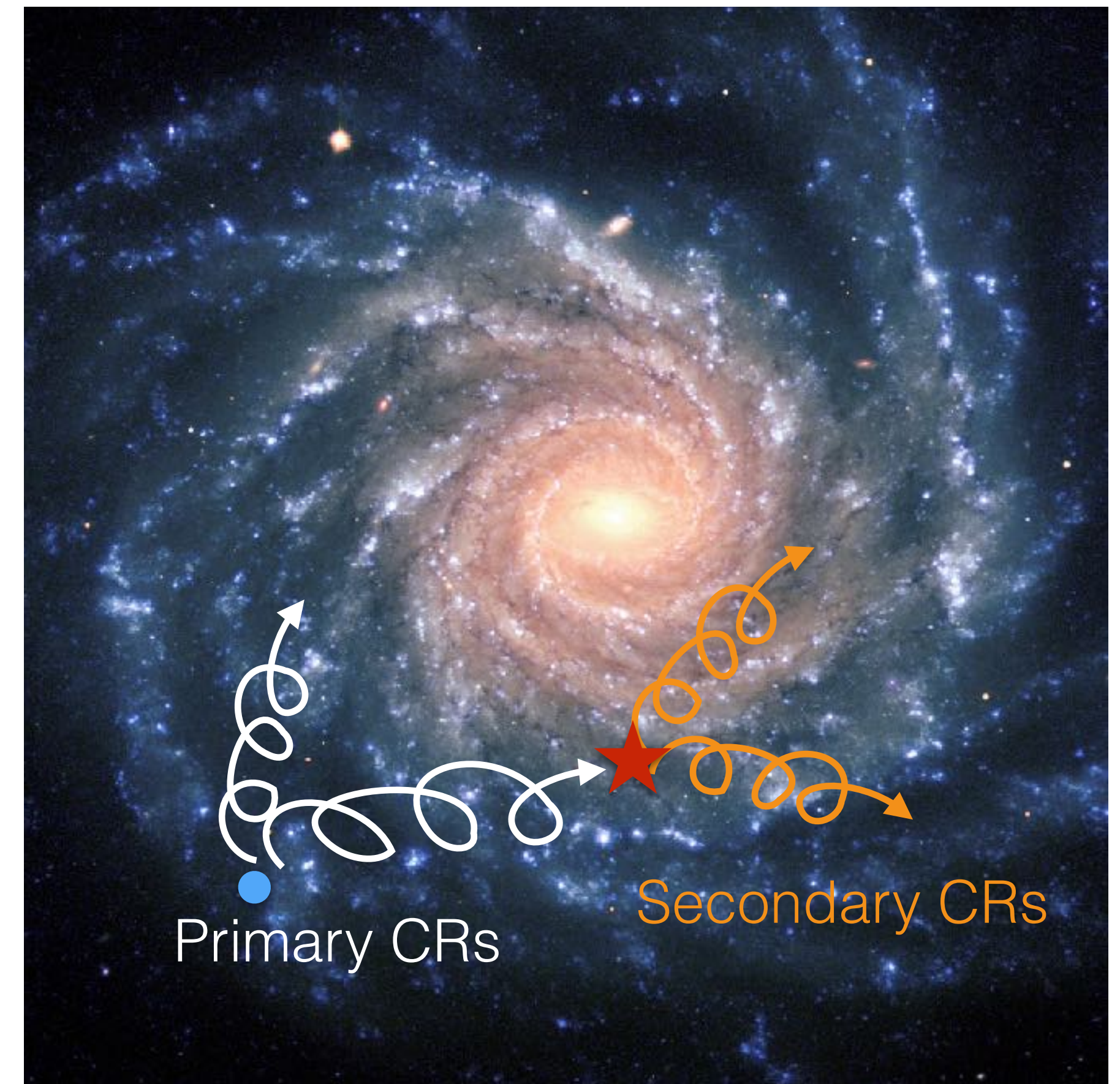
Credit: ESA/Planck Collaboration



Evolution of number density
of cosmic ray species i :

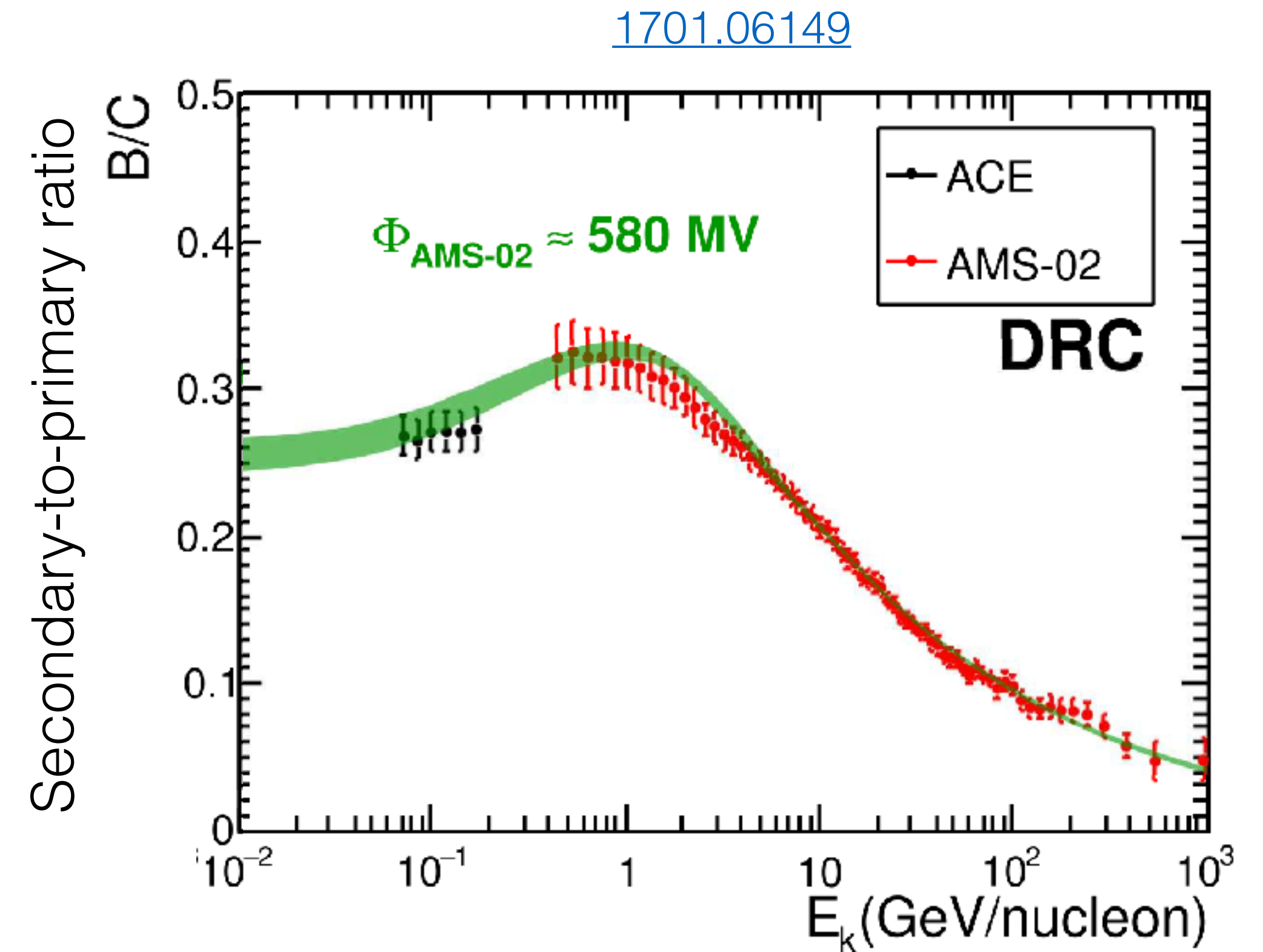
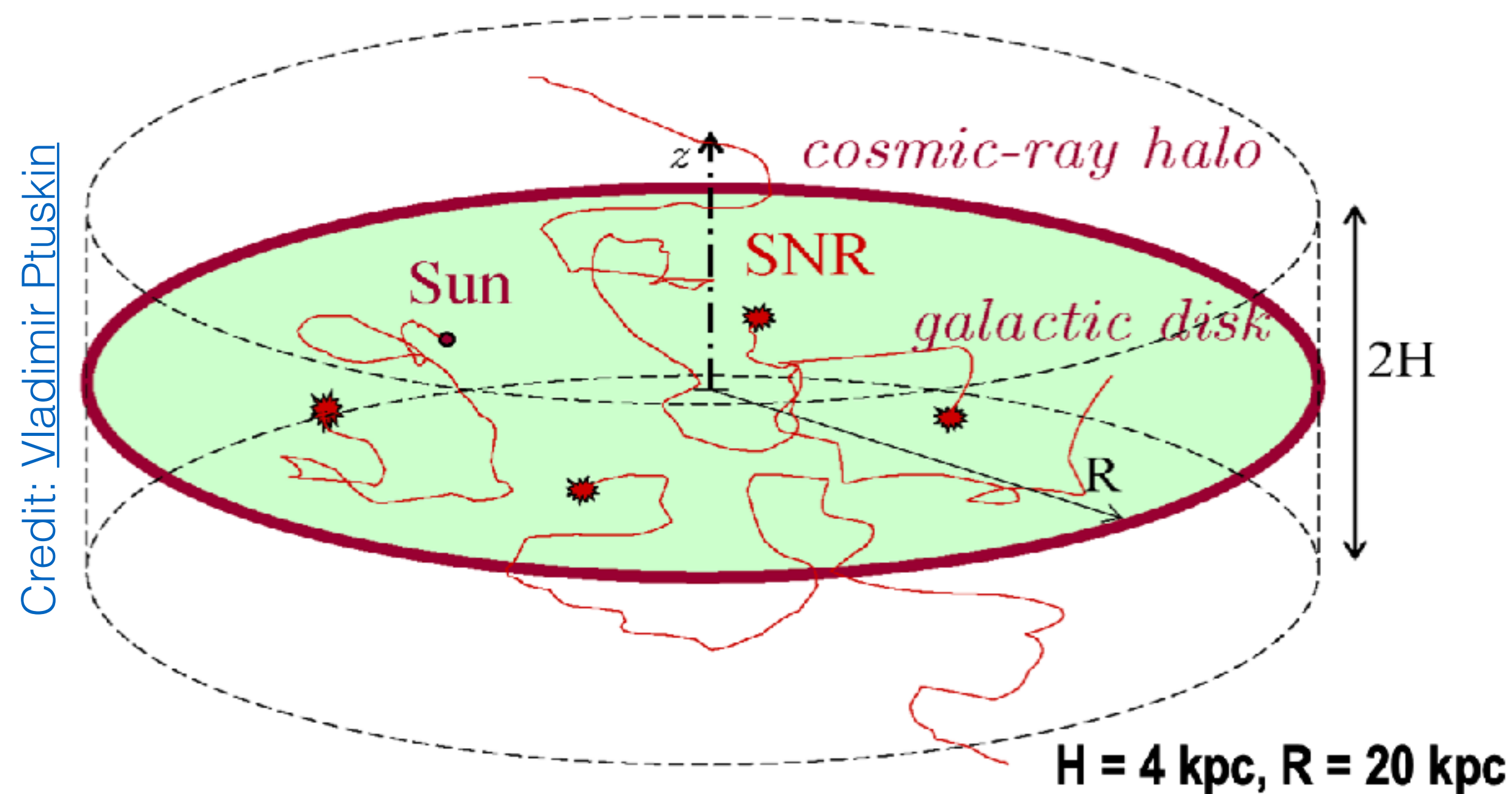
$$N_i = N_i(\vec{r}, E)$$

$$\frac{\partial N_i}{\partial t} = \underbrace{Q}_{\text{Sources}} + \underbrace{D(E)\nabla^2 N_i}_{\text{Diffusion}} + \underbrace{\frac{\partial}{\partial E}[b(E)N_i]}_{\text{Energy losses}} - \underbrace{\frac{N_i}{\tau_i}}_{\text{Escape and attenuation}} + \underbrace{\sum_{j>i} \frac{P_{ji}}{\tau_j} N_j}_{\text{Secondary production}}$$



Modelling CR propagation

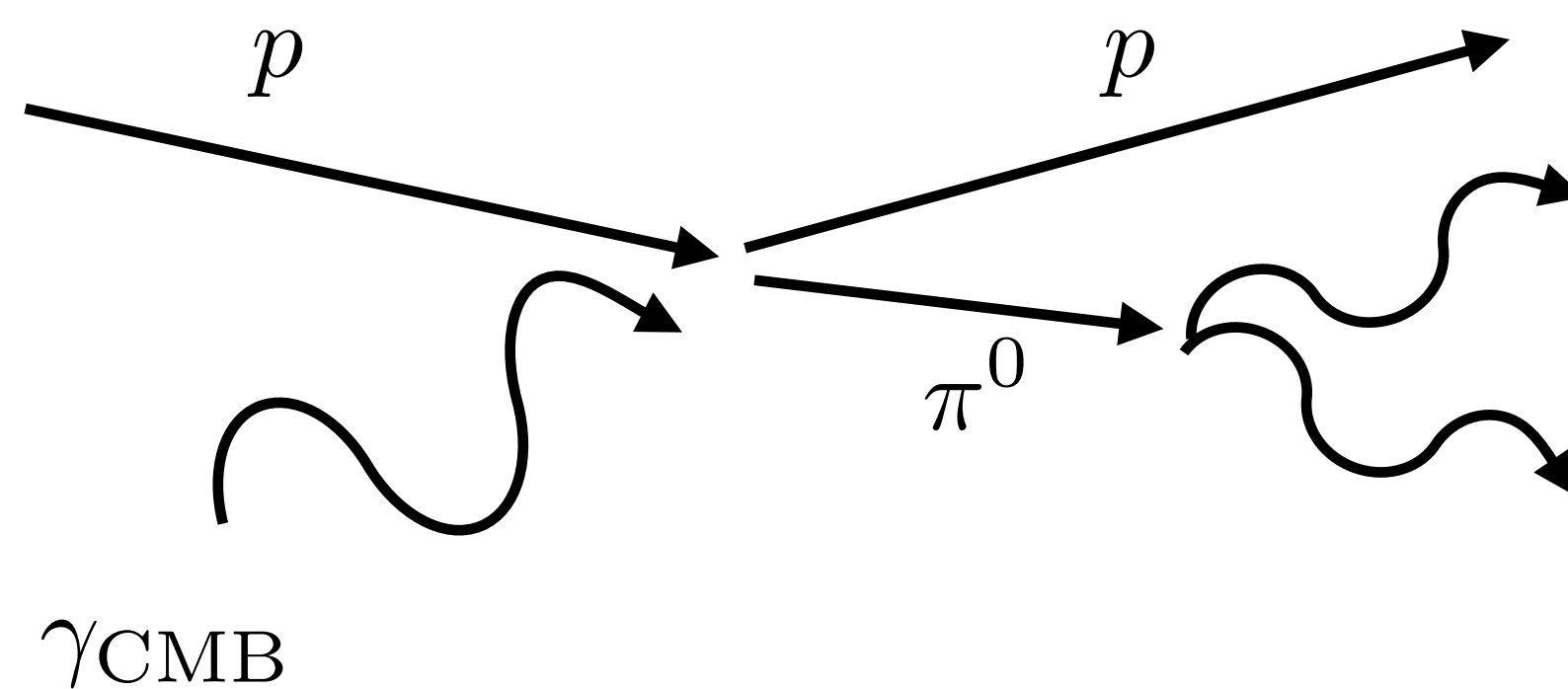
Parametrize properties of the diffusive halo and solve for CR density
(e.g. GALPROP, DRAGON, USINE, ...)



Typical diffusion distance $\langle R^2 \rangle \sim D(E)t$. Coefficient $D(E)$ grows with E , steepening the observed CR spectrum...

GZK cut-off

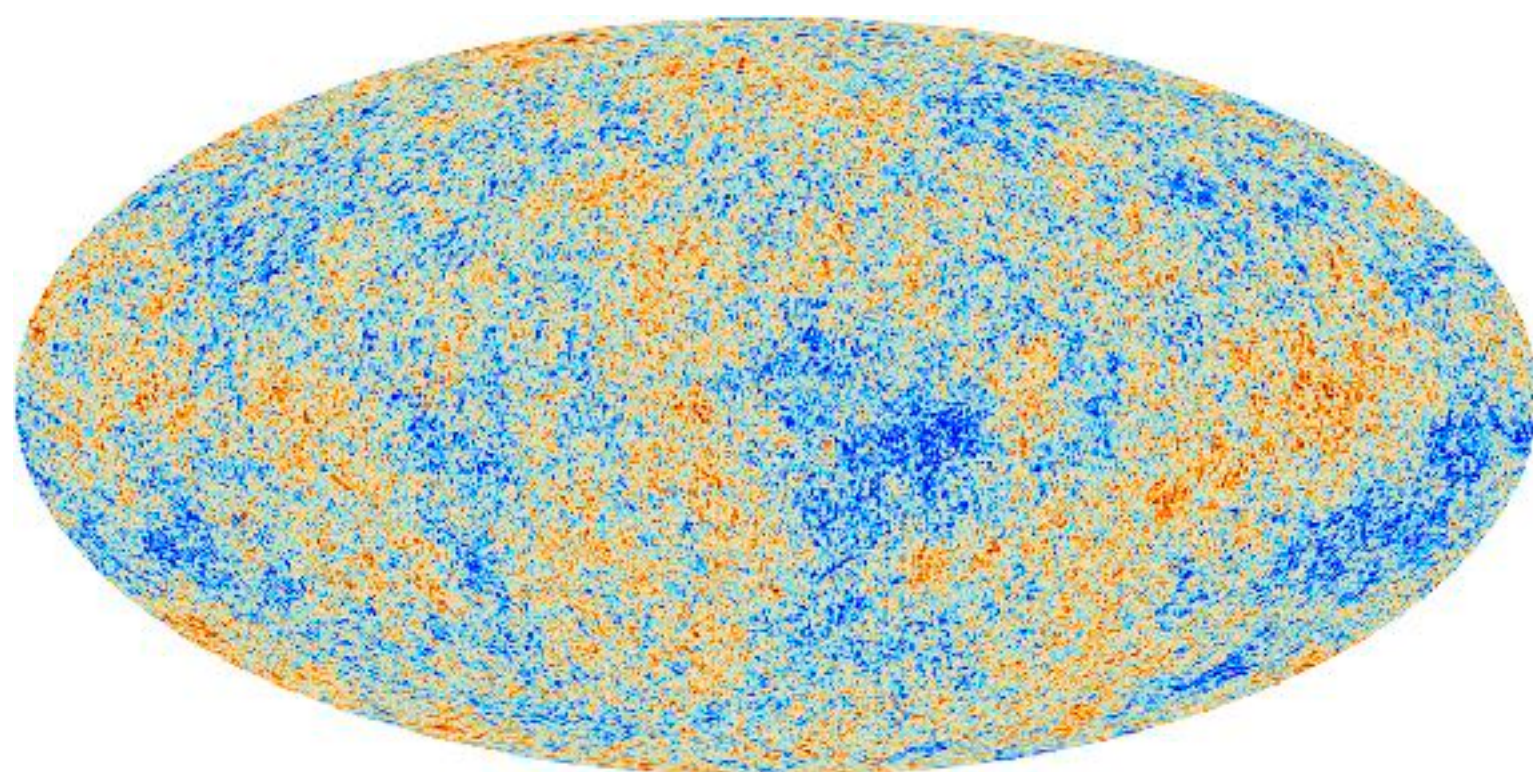
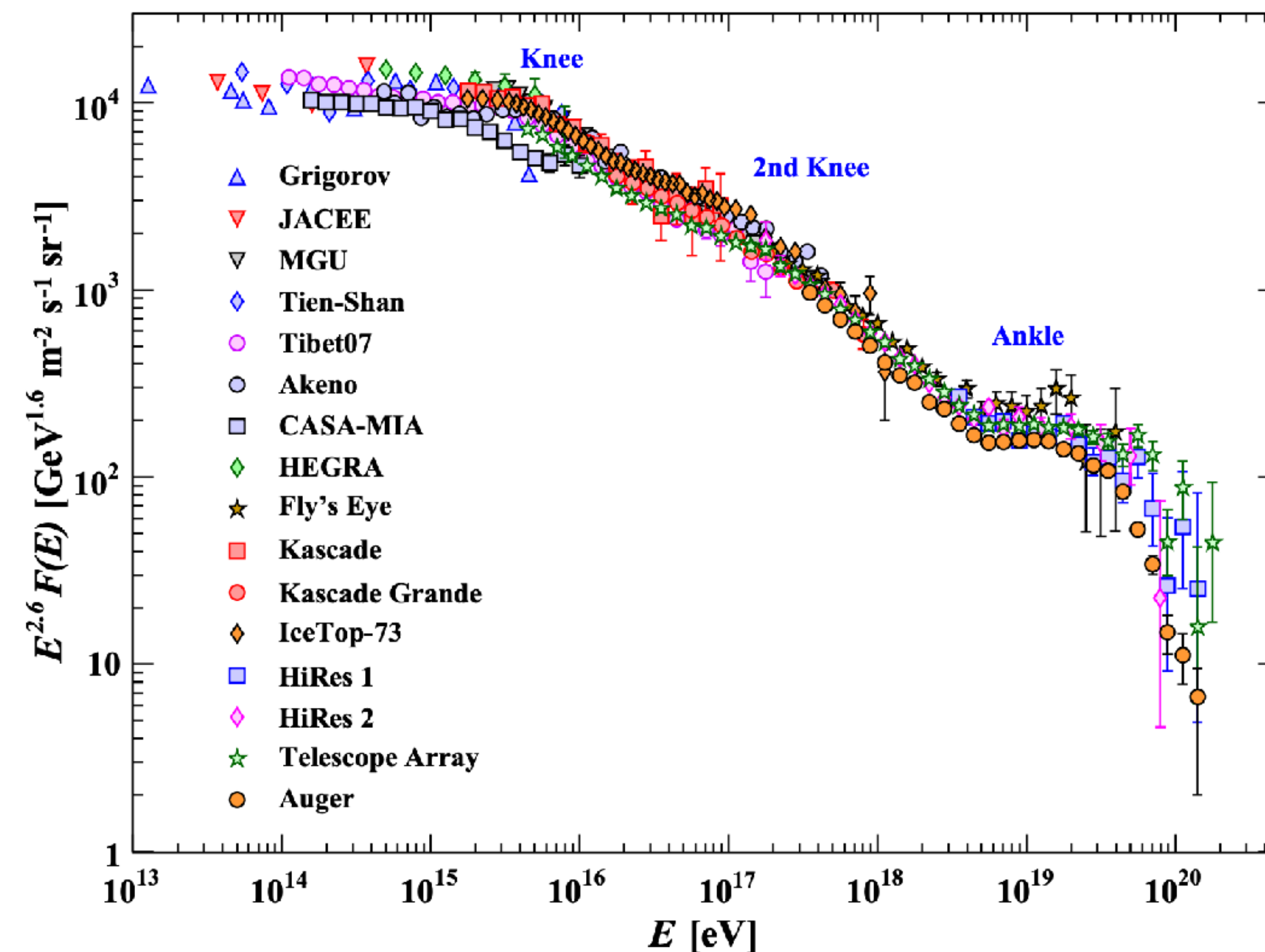
Very high energy cosmic rays will be destroyed by interactions with background photons:



Threshold energy for this process gives rise to the Greisen–Zatsepin–Kuzmin (GZK) cut-off:

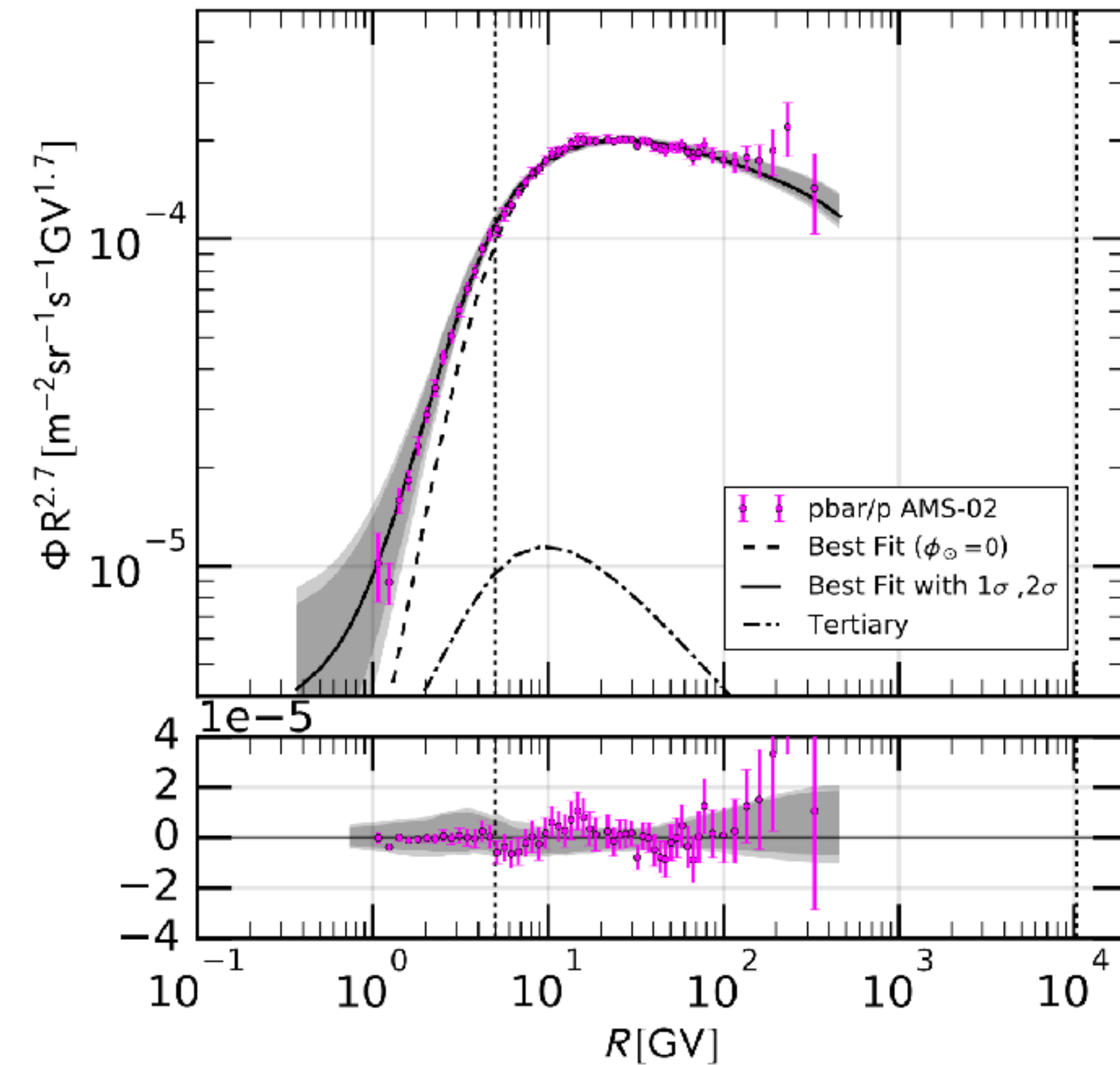
$$E_{p\gamma} \approx 3.4 \times 10^{19} \left(\frac{\epsilon}{10^{-3} \text{ eV}} \right)^{-1} \text{ eV}$$

Ultra high energy CRs cannot propagate more than around $\ell_{\text{GZK}} \sim 50 \text{ Mpc}$ before being destroyed.



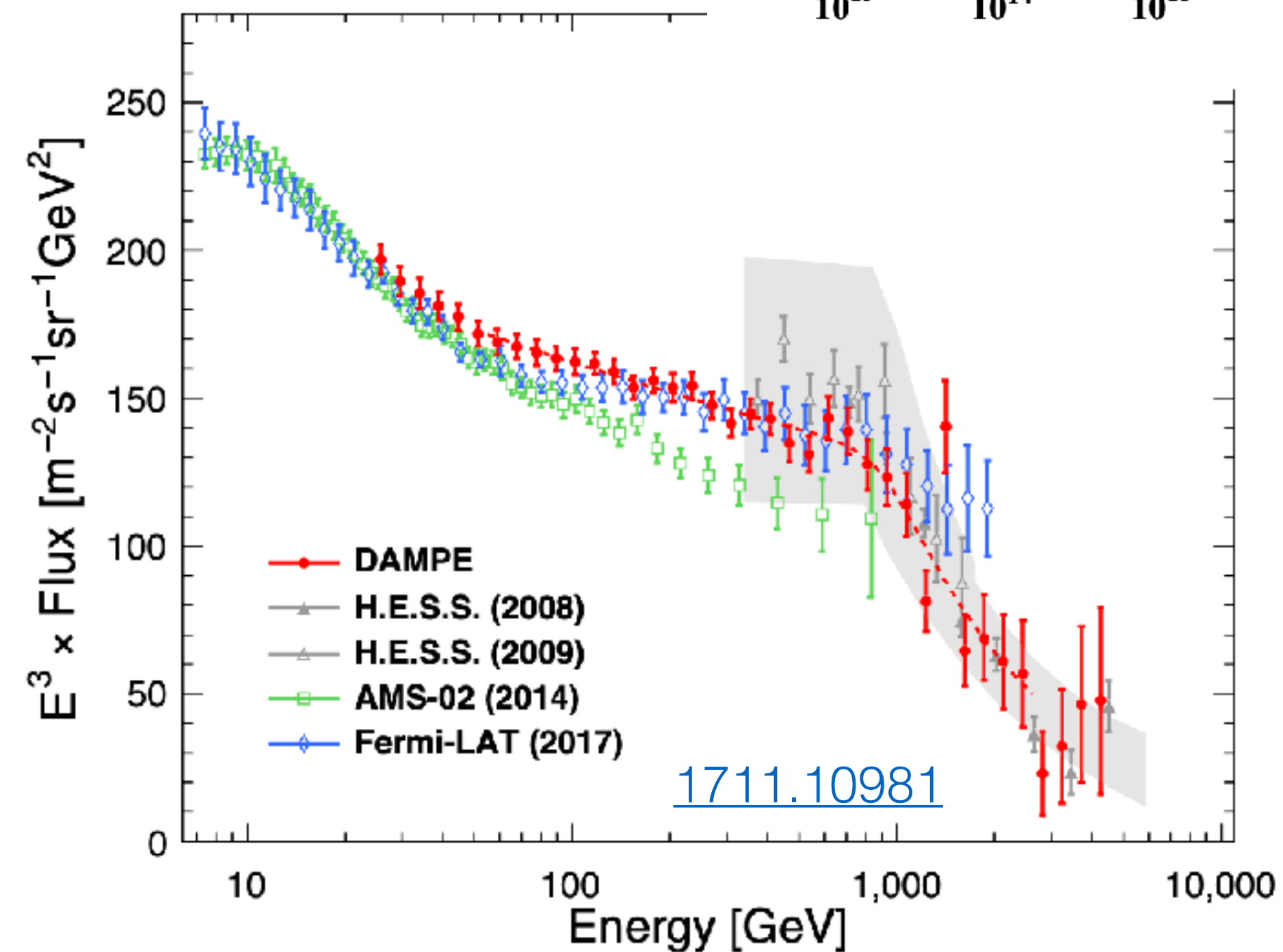
CCR anomalies, questions, challenges

Excess in anti-protons?

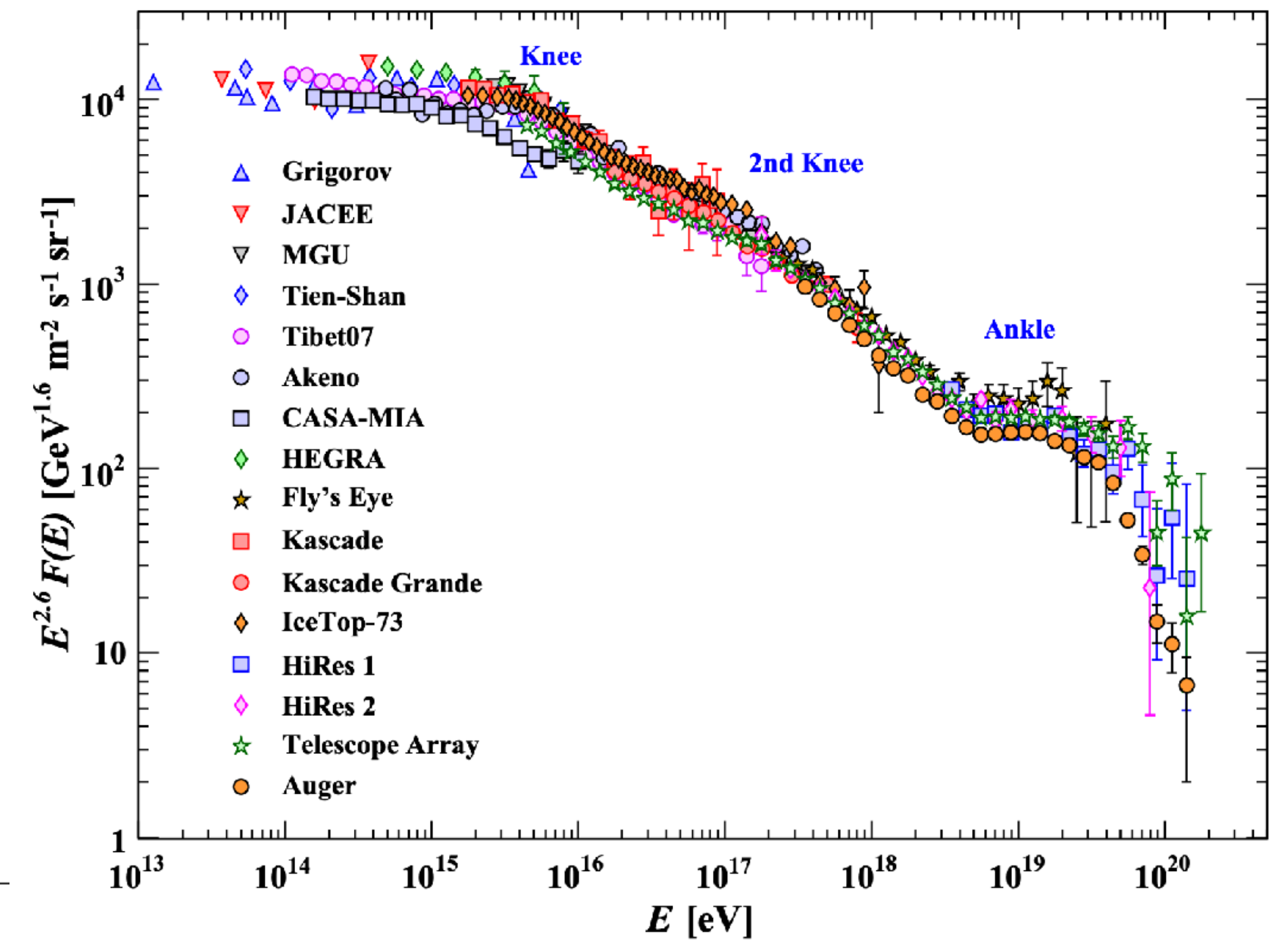


[1610.03071](#)

Excess in electrons?



[1711.10981](#)

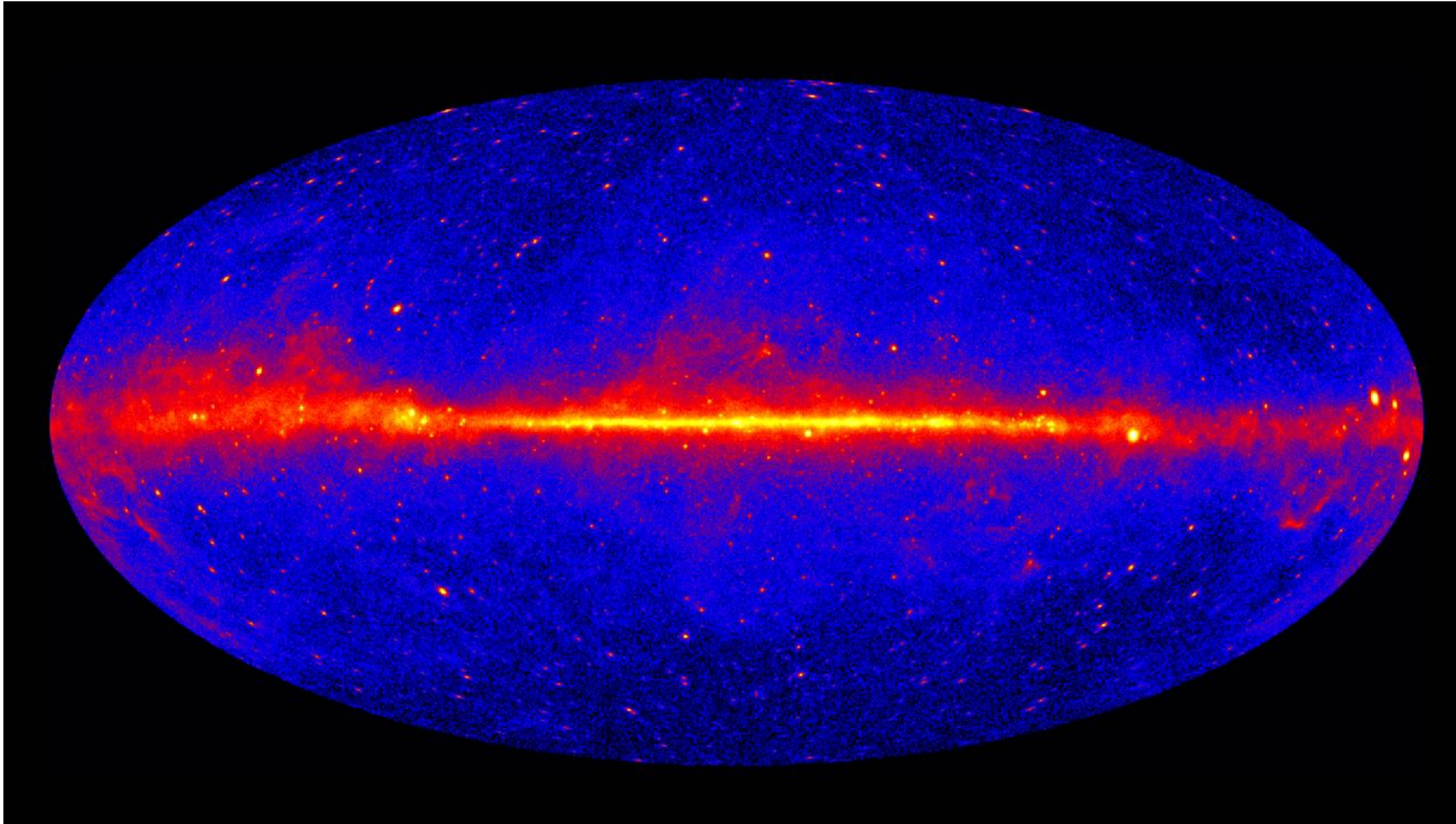


What are the sources?

Where do the CRs
come from?

The Gamma-ray Sky

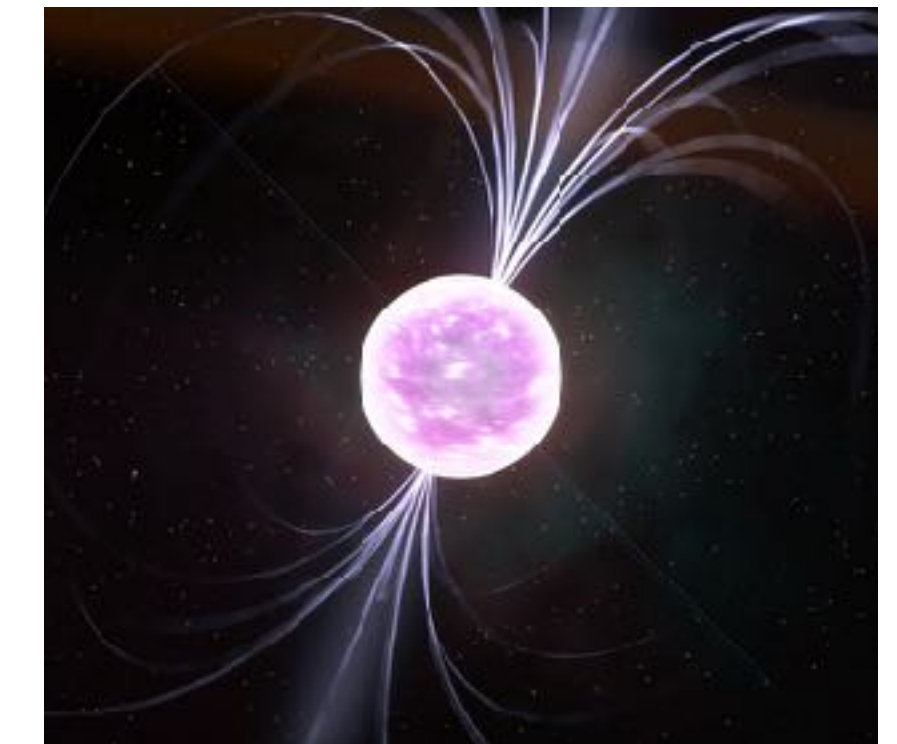
Gamma-ray Sky above 1 GeV, according to Fermi:



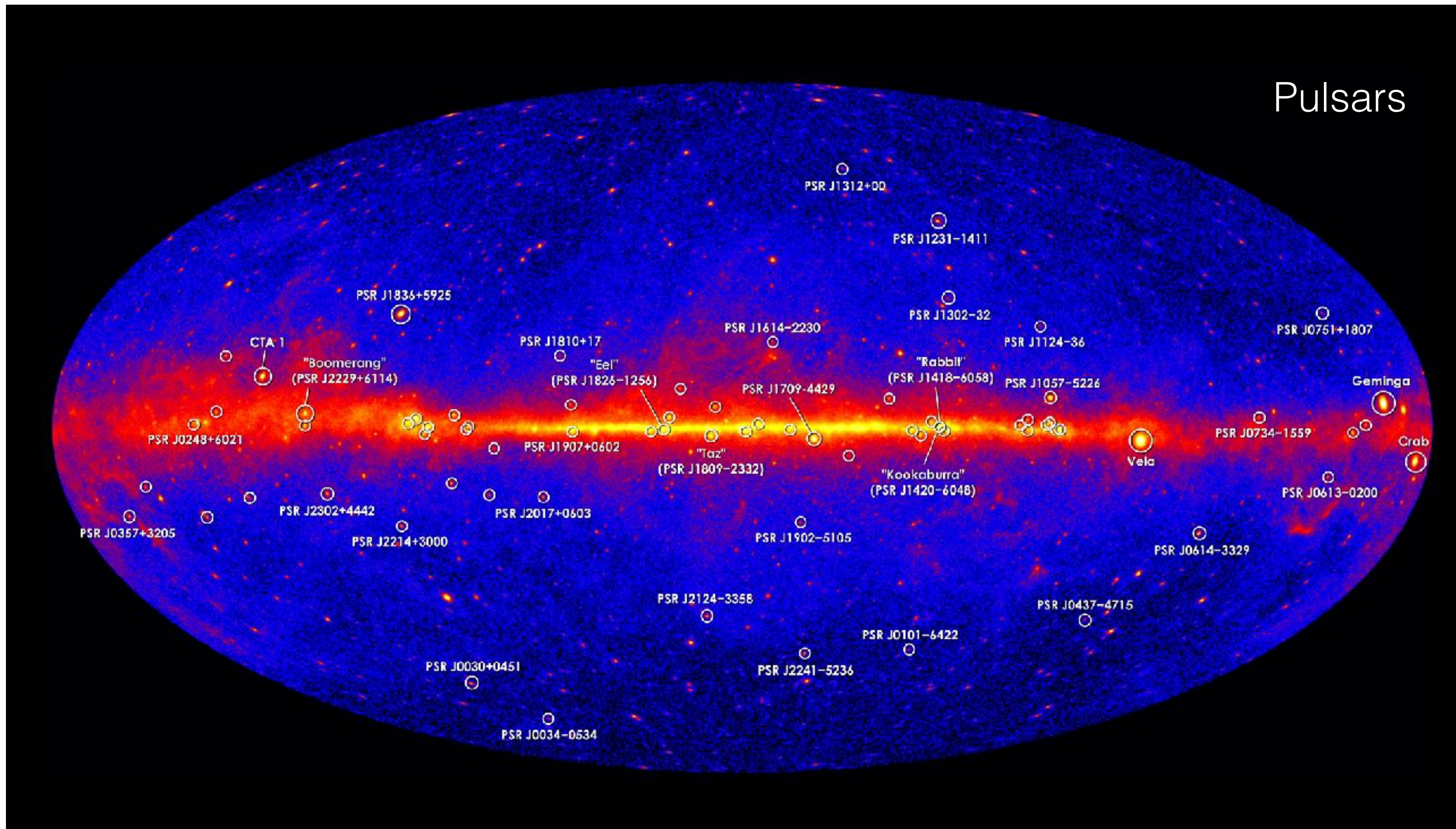
Credit: [NASA/DOE/Fermi LAT Collaboration](#)

The Gamma-ray Sky

Gamma-ray Sky above 1 GeV, according to Fermi:



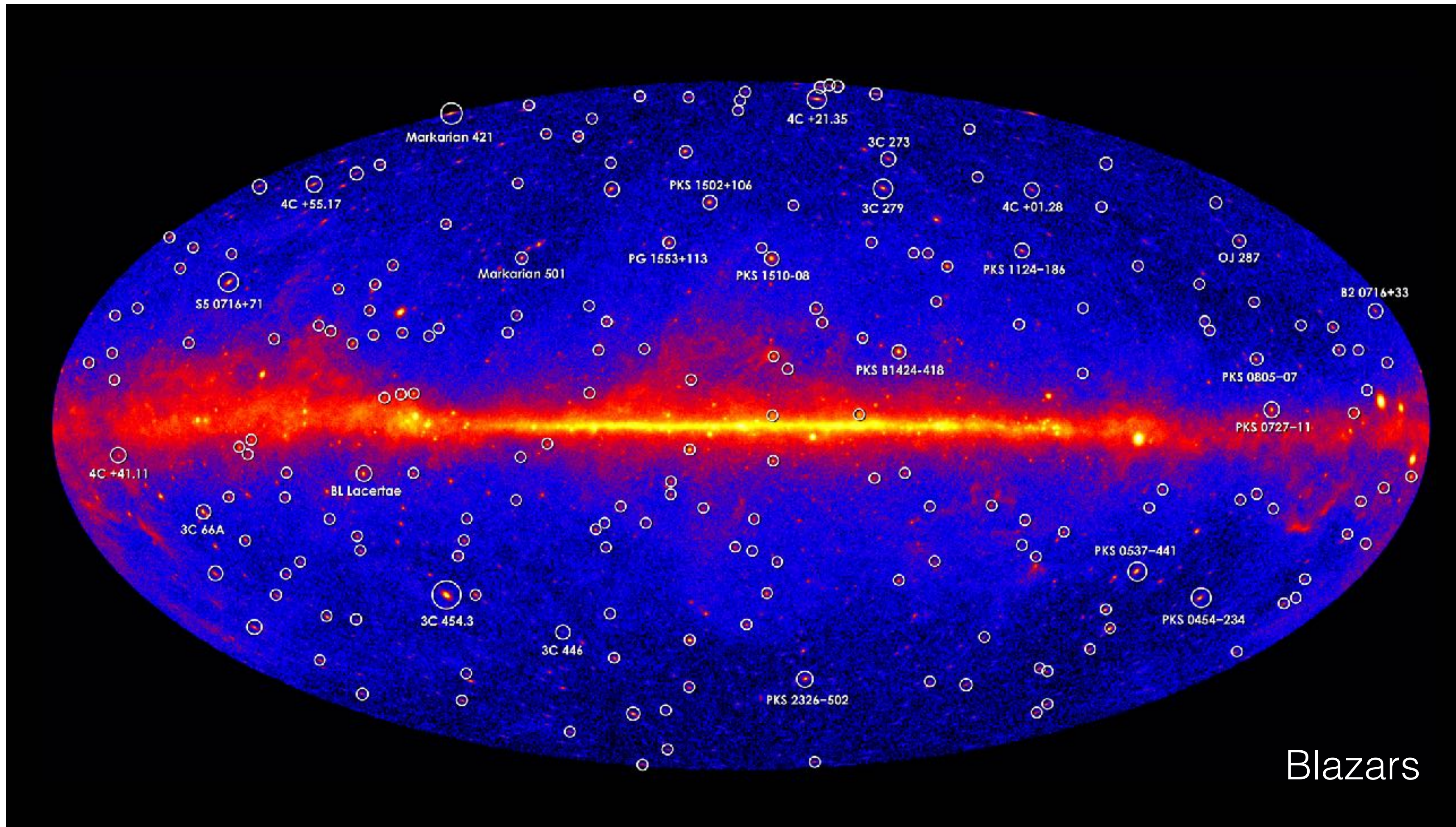
Credit: Kevin Gill / Flickr



Credit: [NASA/DOE/Fermi LAT Collaboration](#)

The Gamma-ray Sky

Gamma-ray Sky above 1 GeV, according to Fermi:

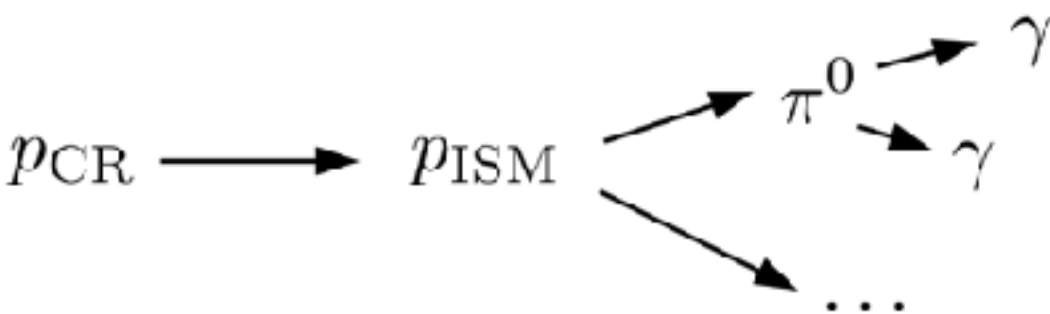


Credit: [NASA/DOE/Fermi LAT Collaboration](#)

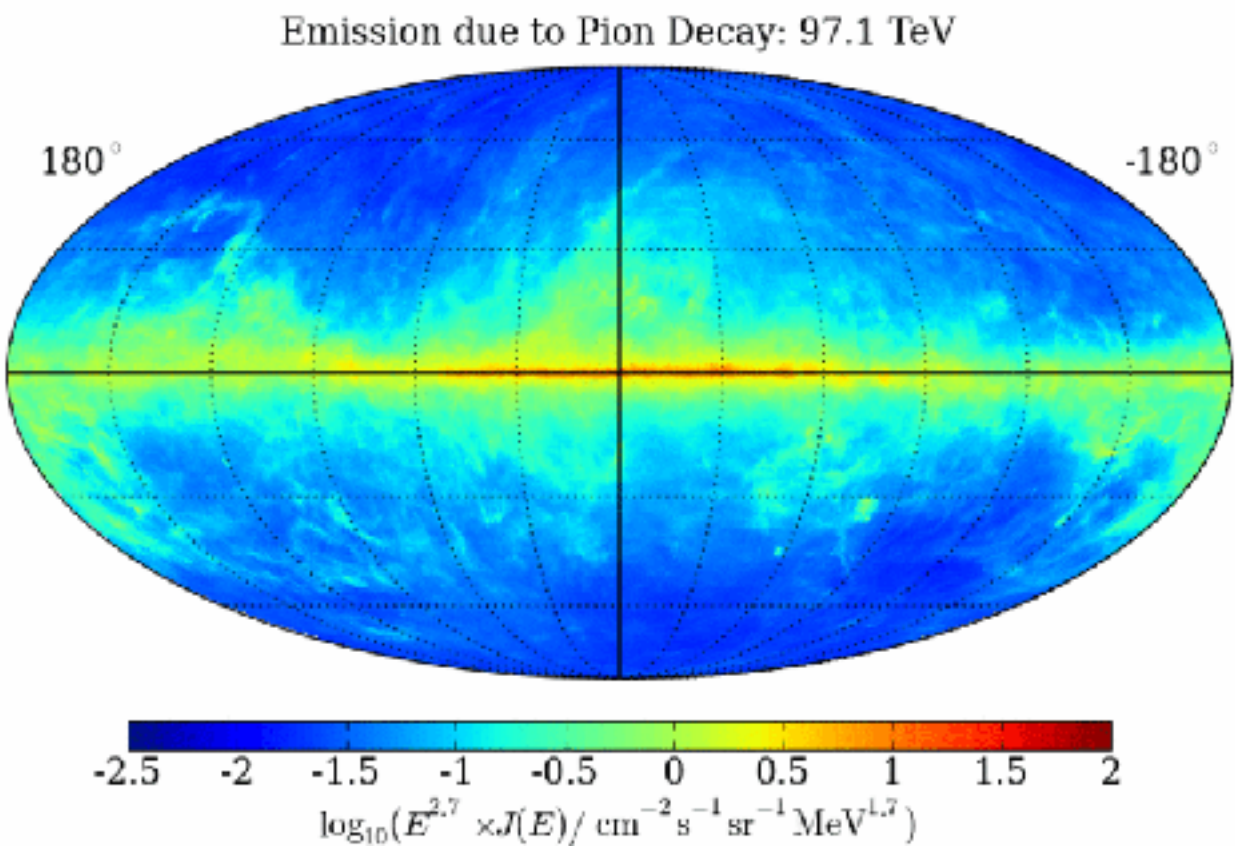
Credit: ESO/M. Kornmesser

Cosmic Ray Connection

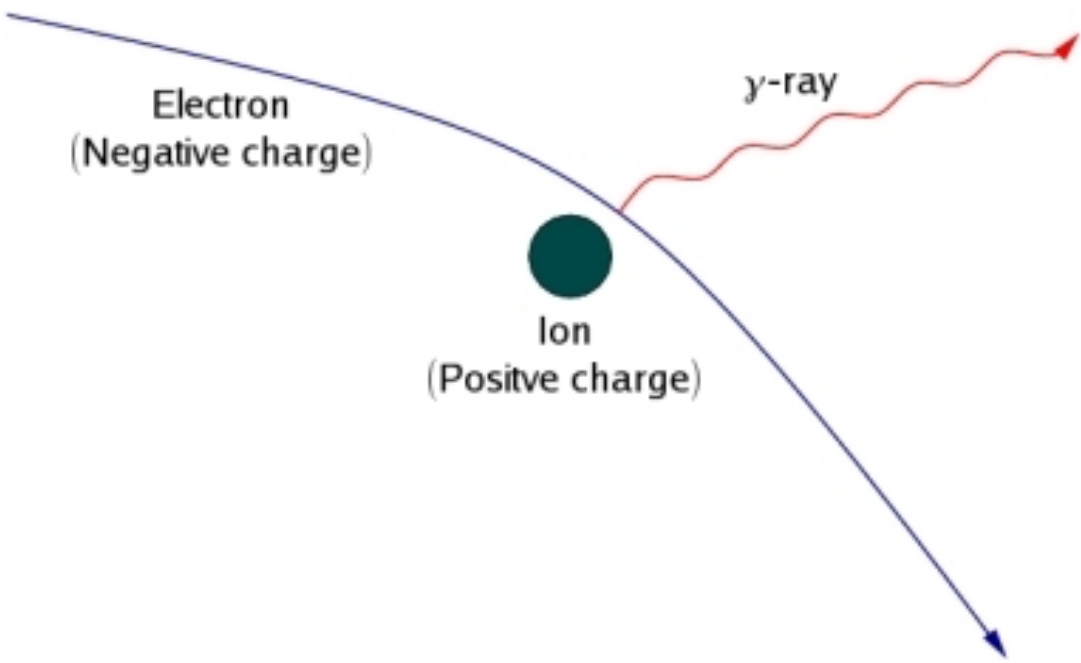
Pion Decay



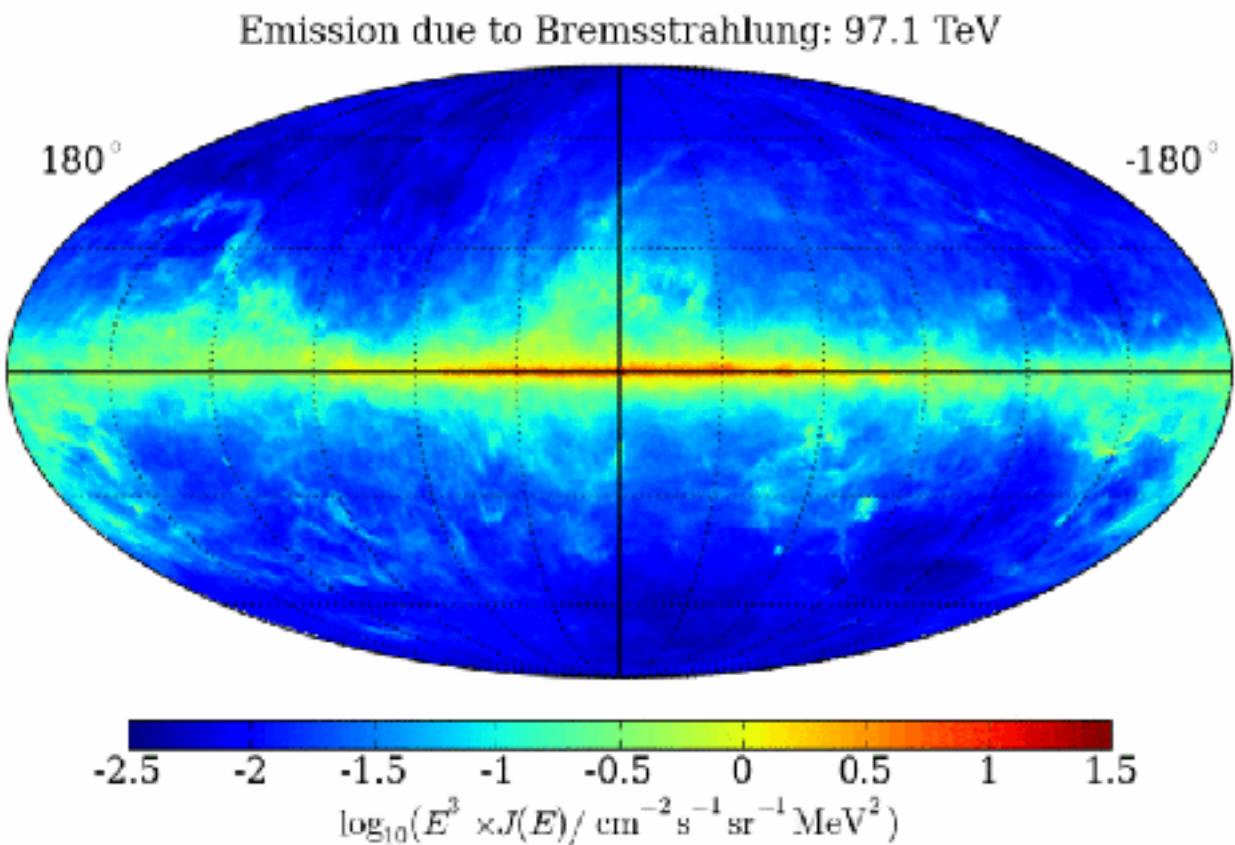
CR protons + gas



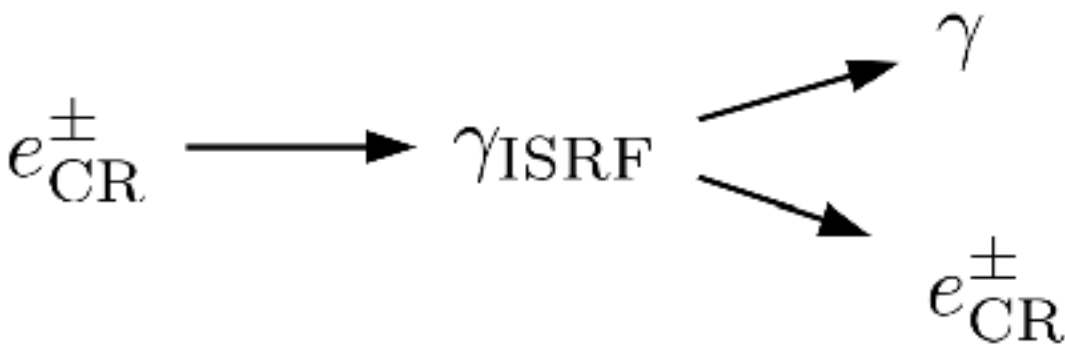
Bremsstrahlung



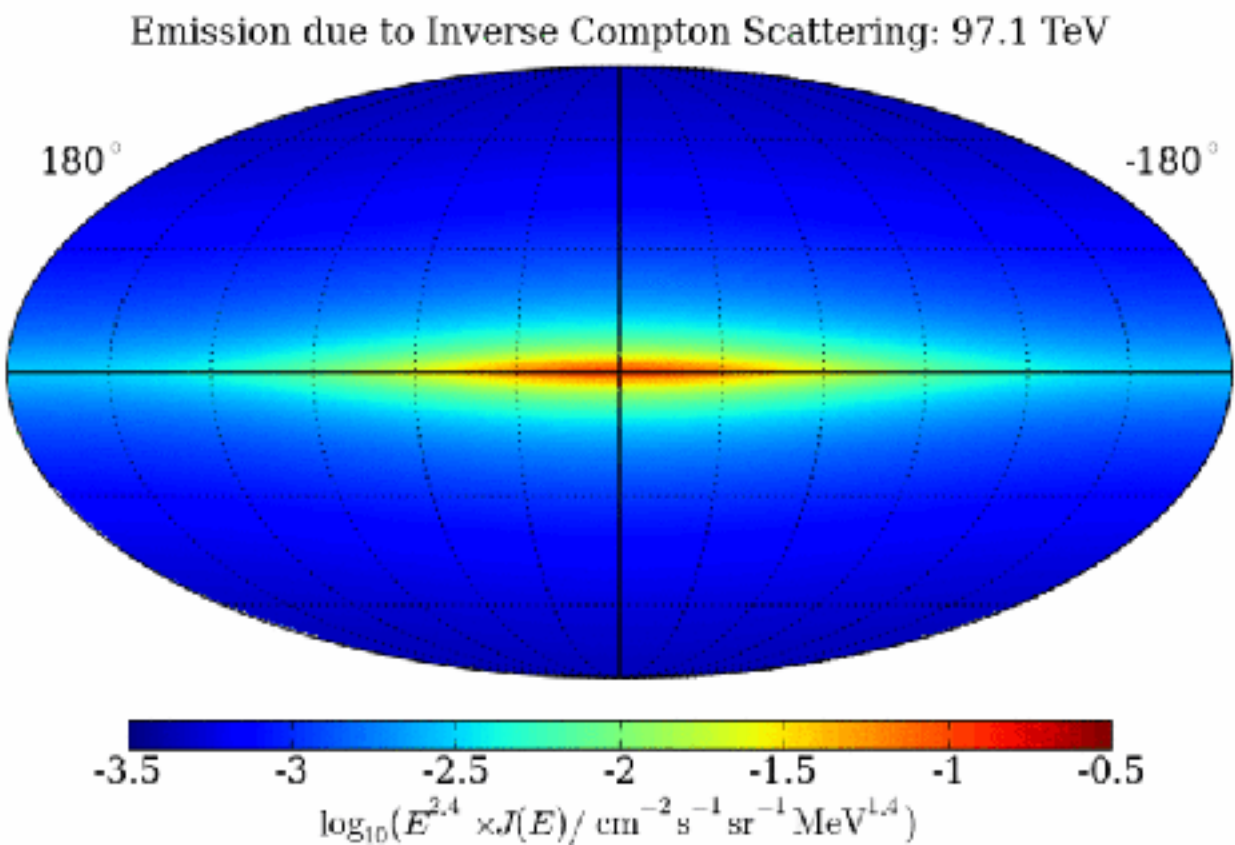
CR electrons + gas



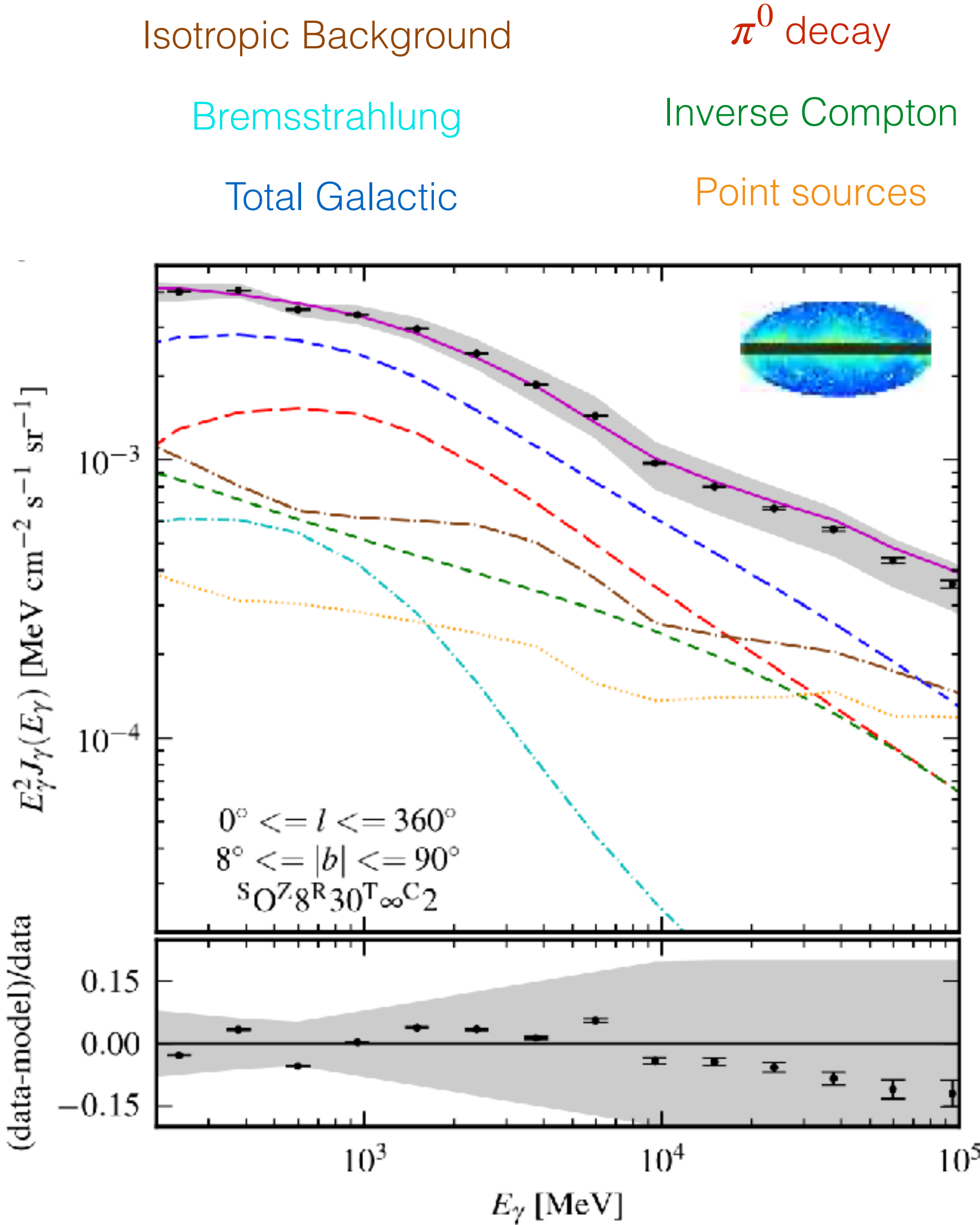
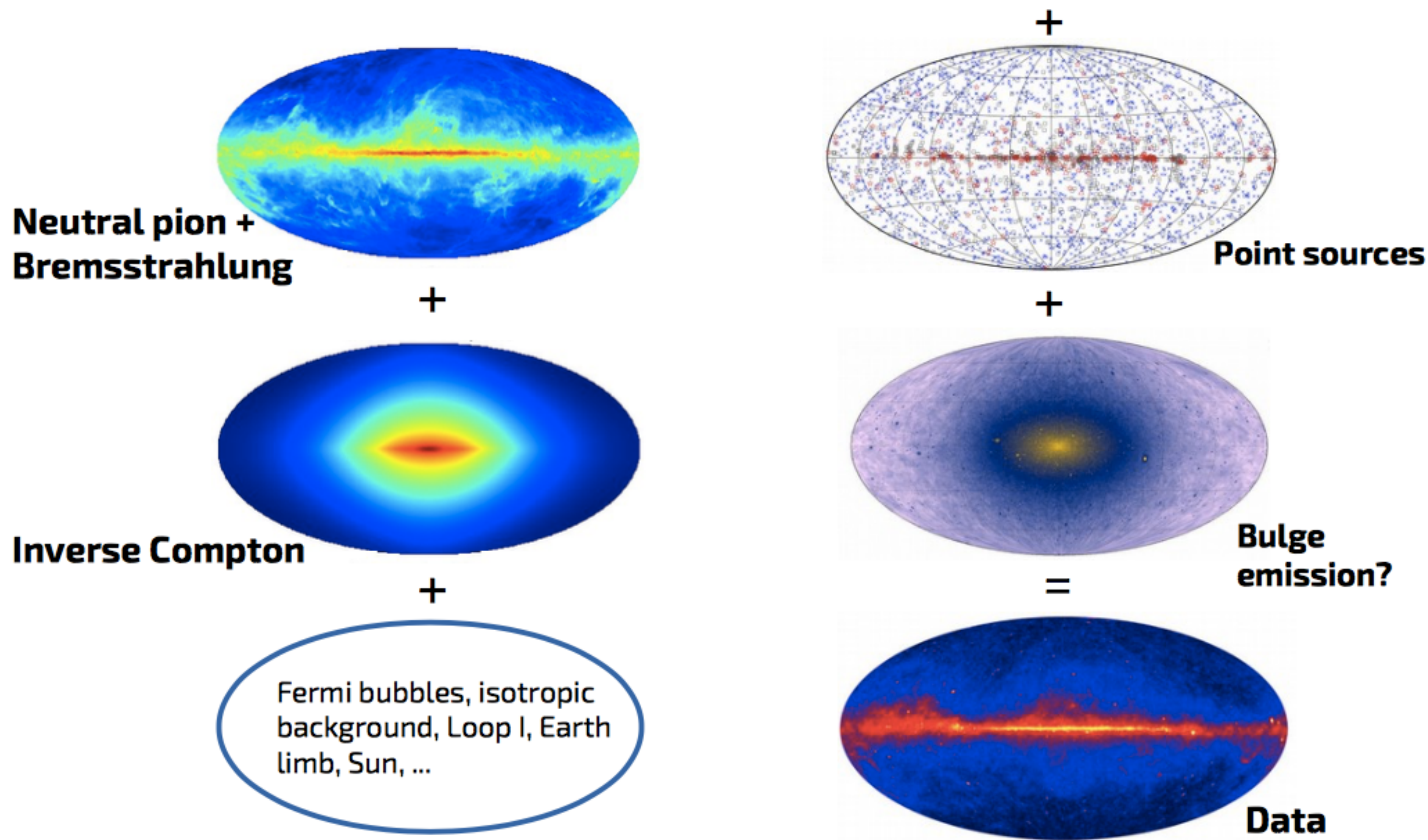
Inverse Compton



CR electrons + light

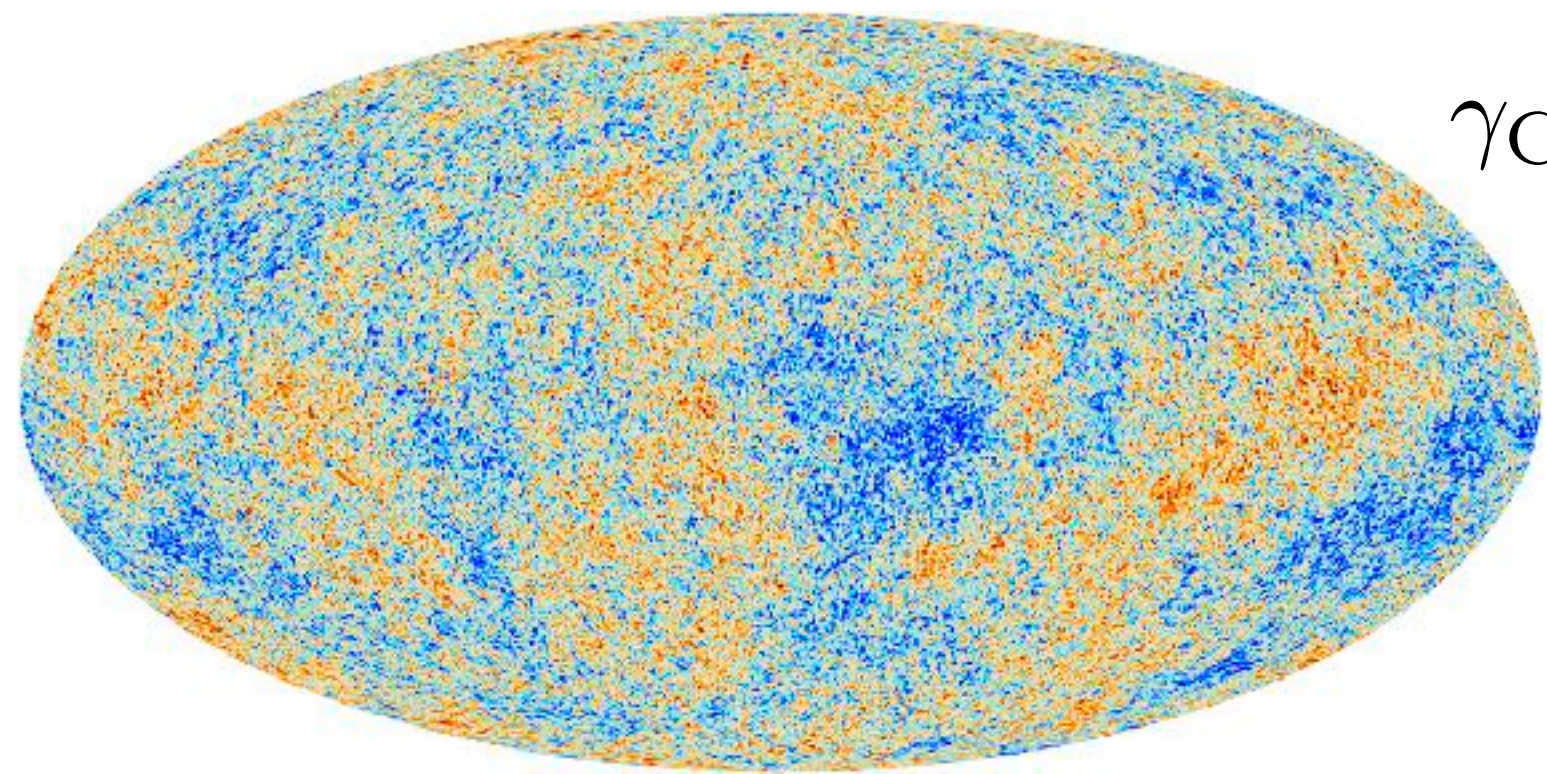
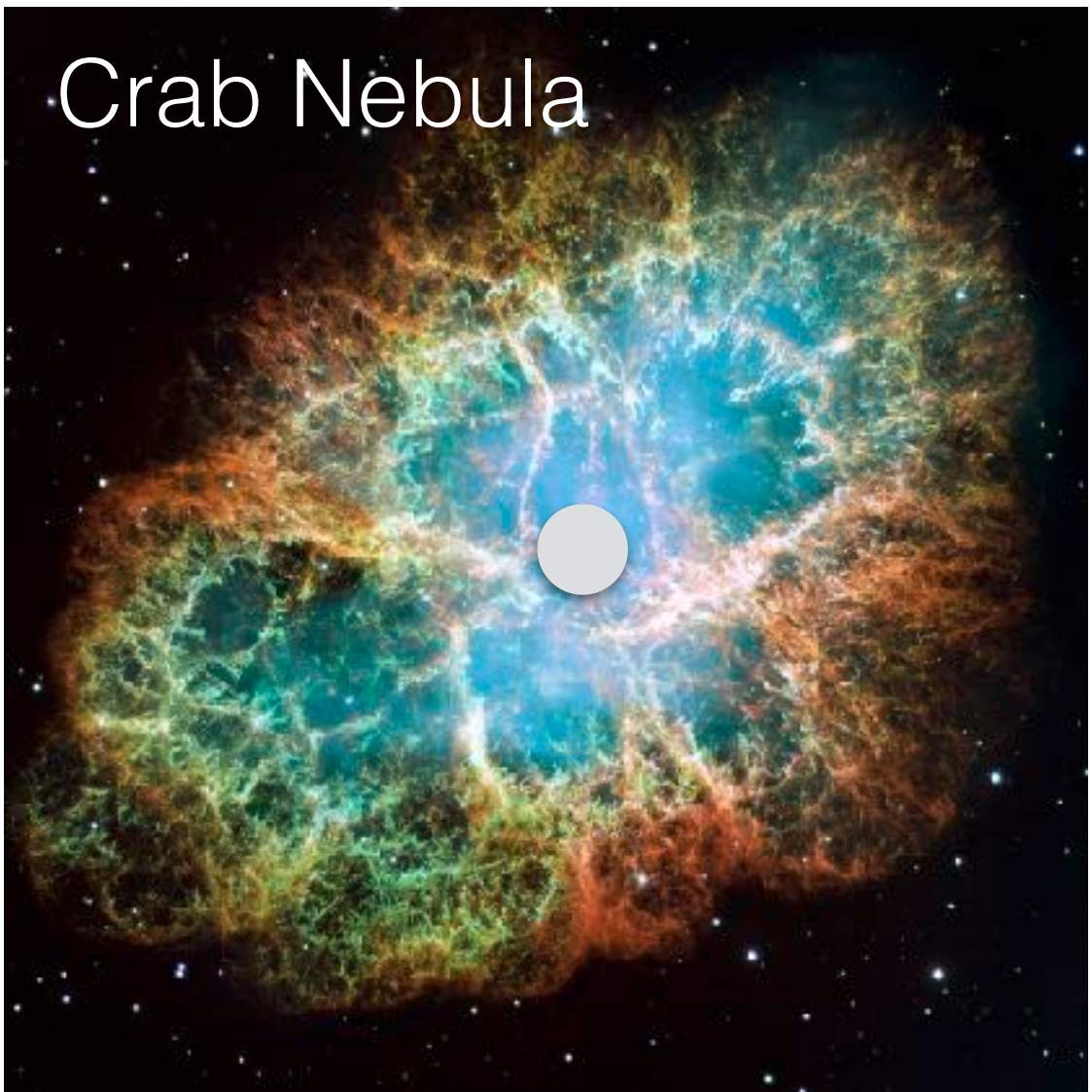


Modelling Gamma-ray emission

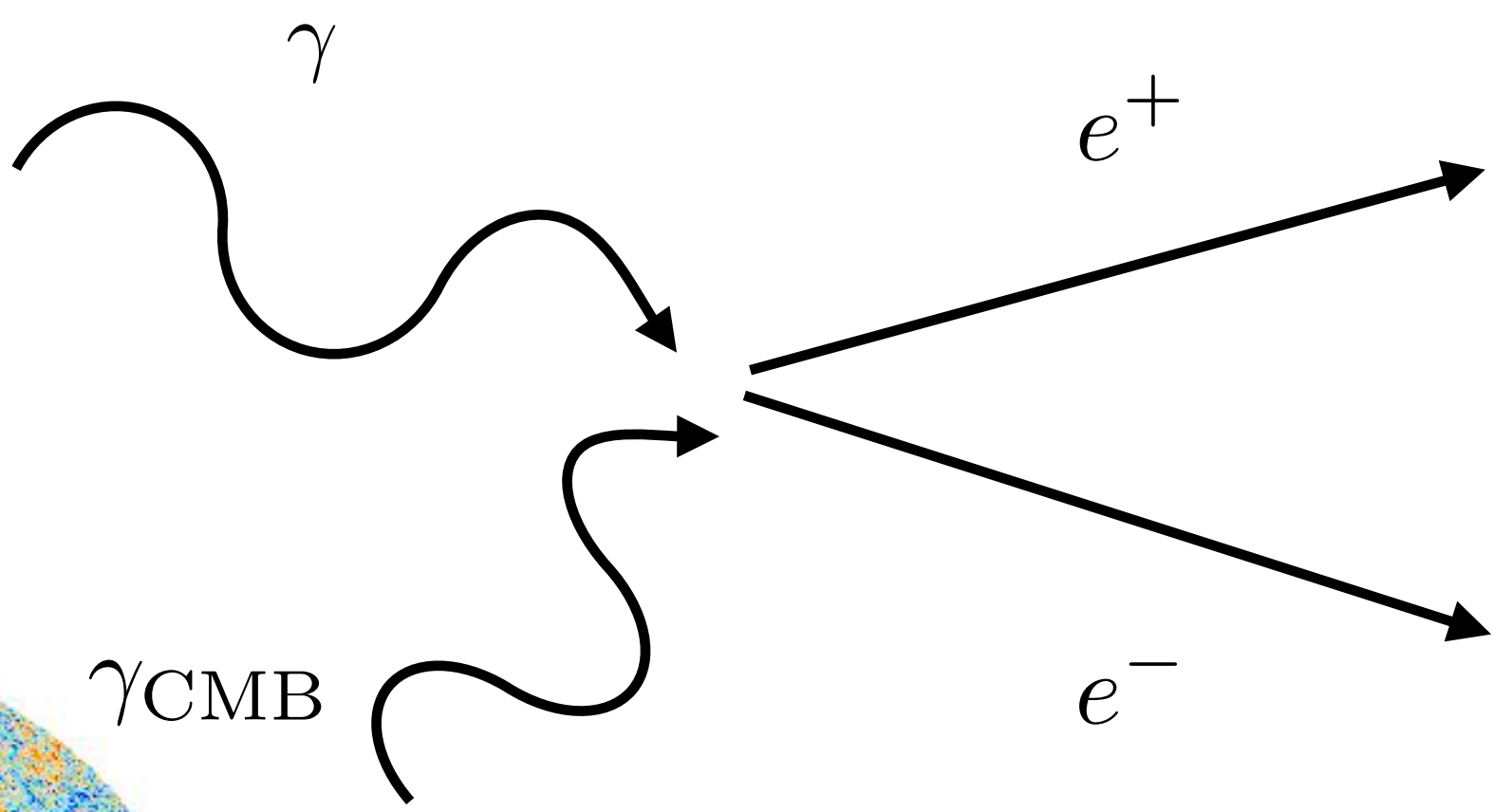


[1202.4039](#)

Crab Nebula

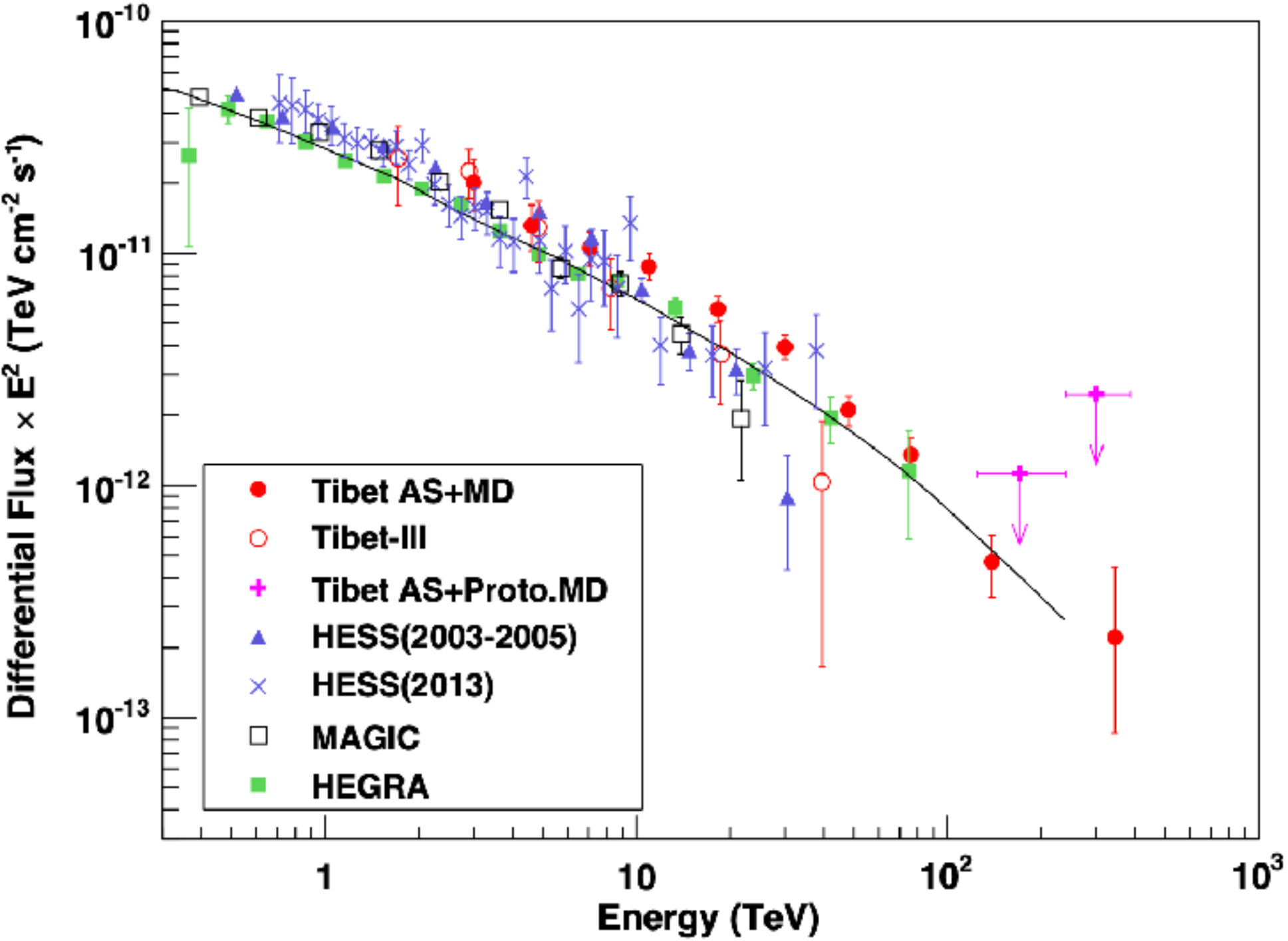


Similar to the GZK cut-off...



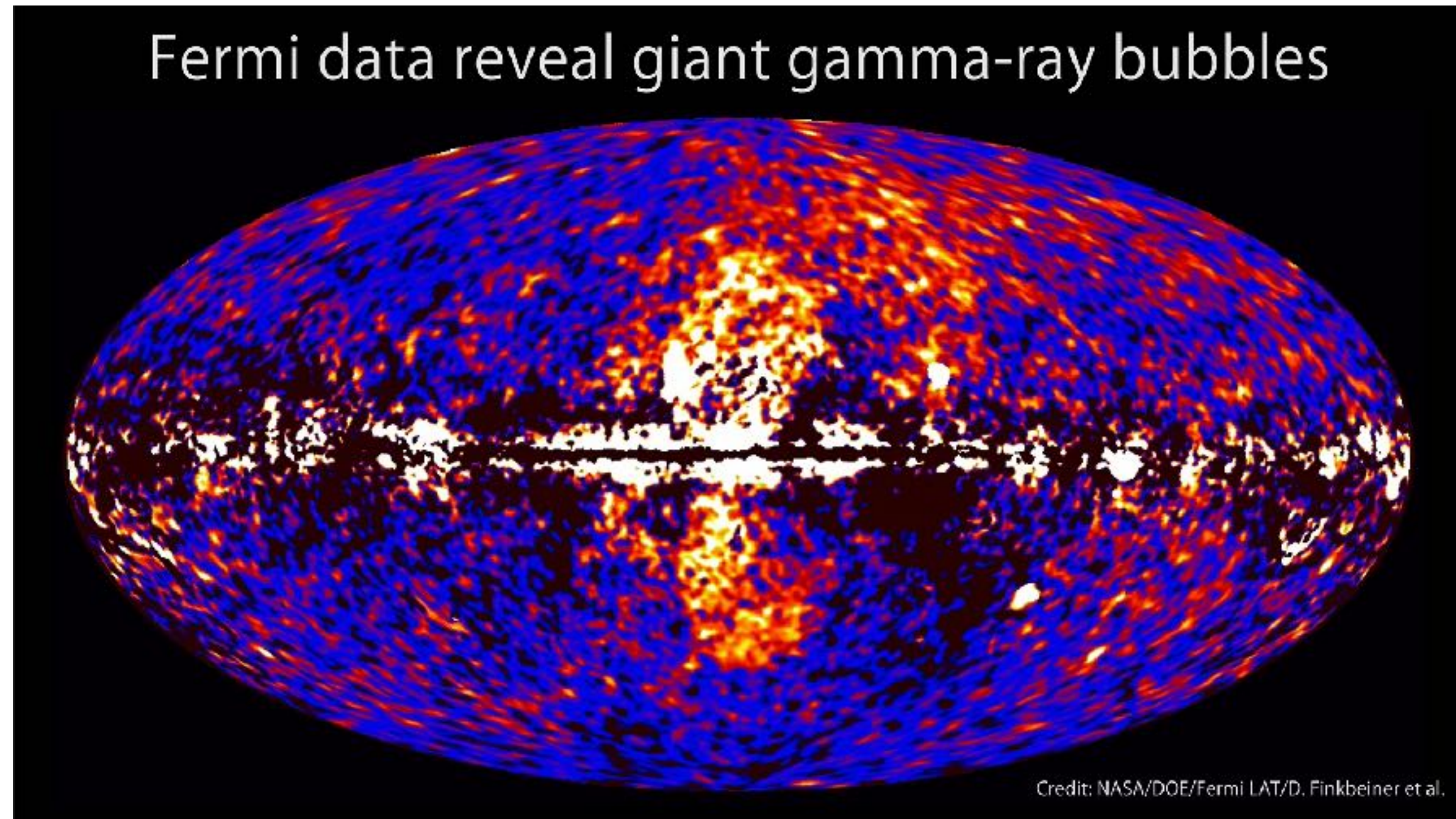
To produce an electron-positron pair, need a gamma-ray with energy greater than:

$$E_{\gamma} > \frac{2m_e^2}{E_{bg}} \sim \begin{cases} 1 \text{ TeV} & \text{for scattering of IR background} \\ 800 \text{ TeV} & \text{for scattering of CMB} \end{cases}$$

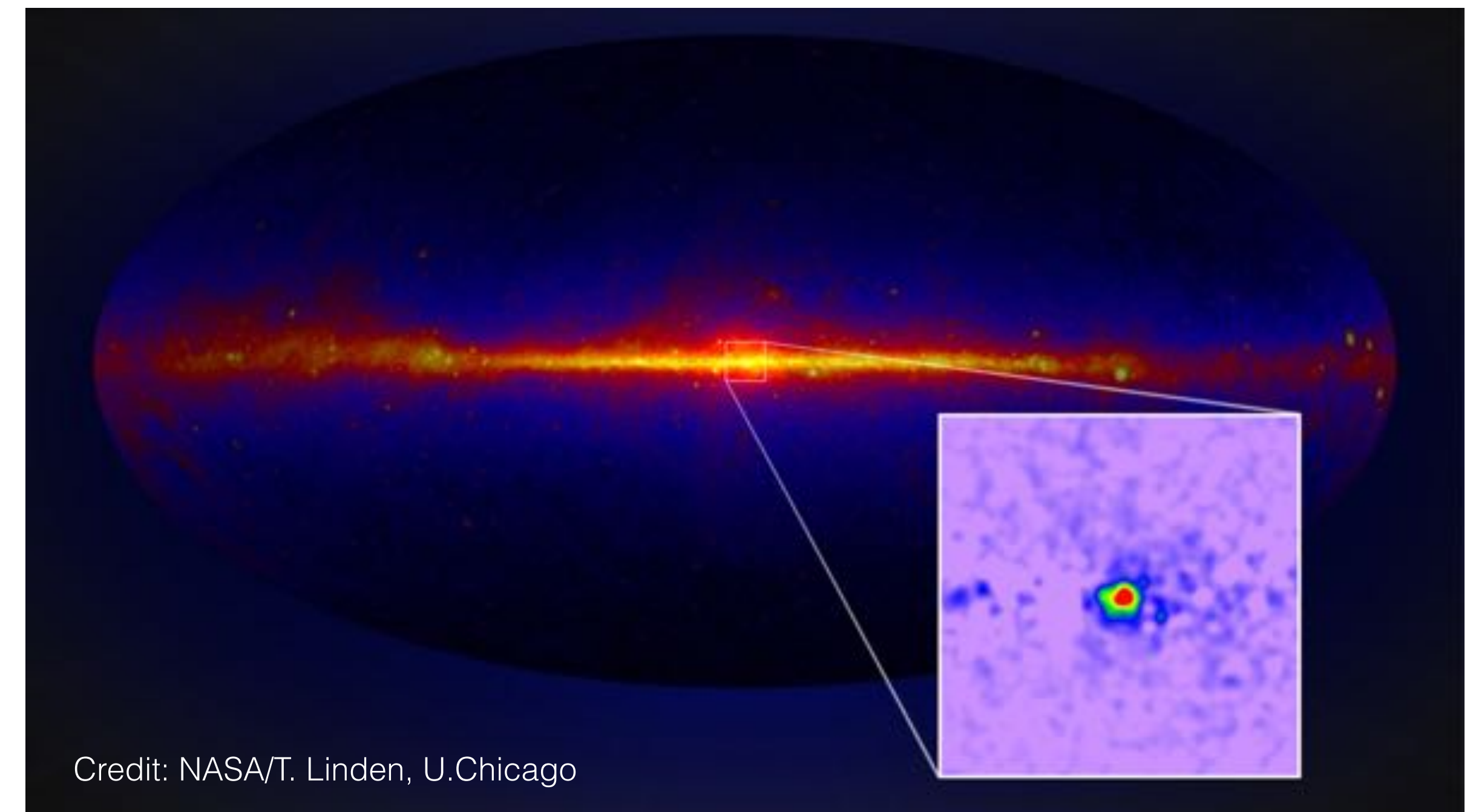


Gamma-ray anomalies

Fermi Bubbles



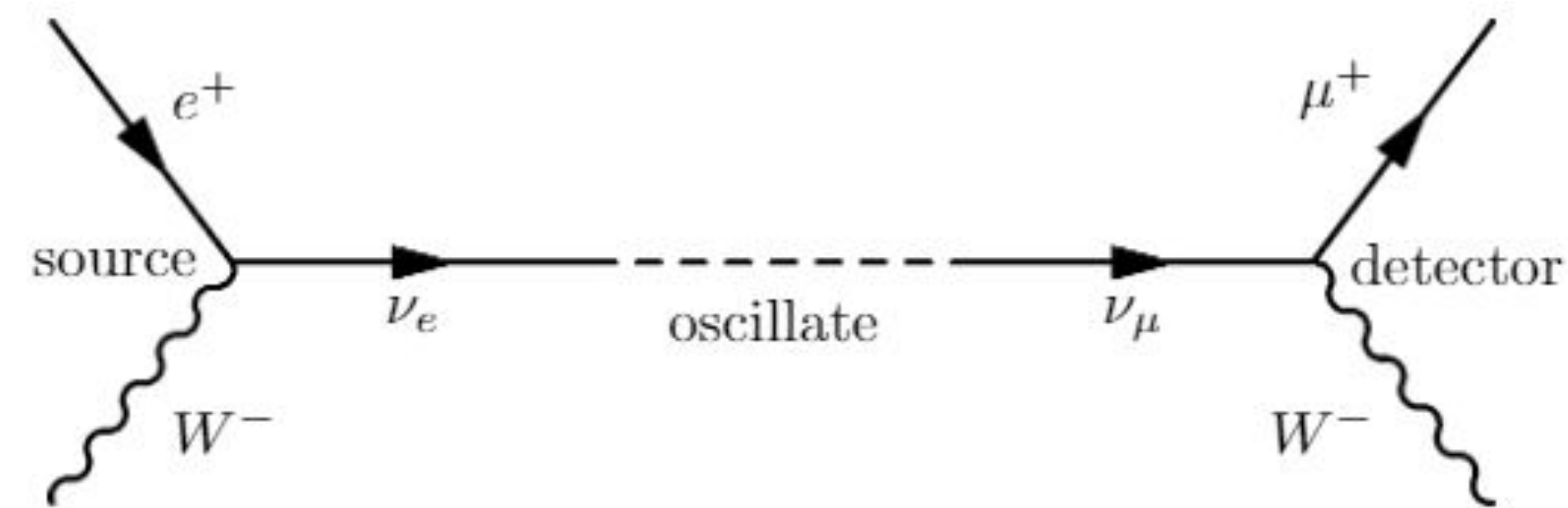
Galactic Centre Excess



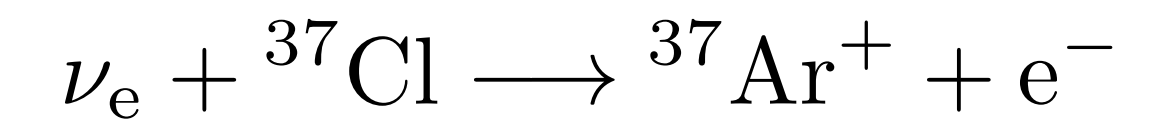
and others...

Neutrinos

Our story begins with *solar* neutrinos...



Homestake experiment (1960s)
~600 tons of C₂Cl₄



Credit: Brookhaven National Laboratory

Detected rate of ~ MeV neutrinos was
~1/3 of that expected from nuclear processes in the Sun

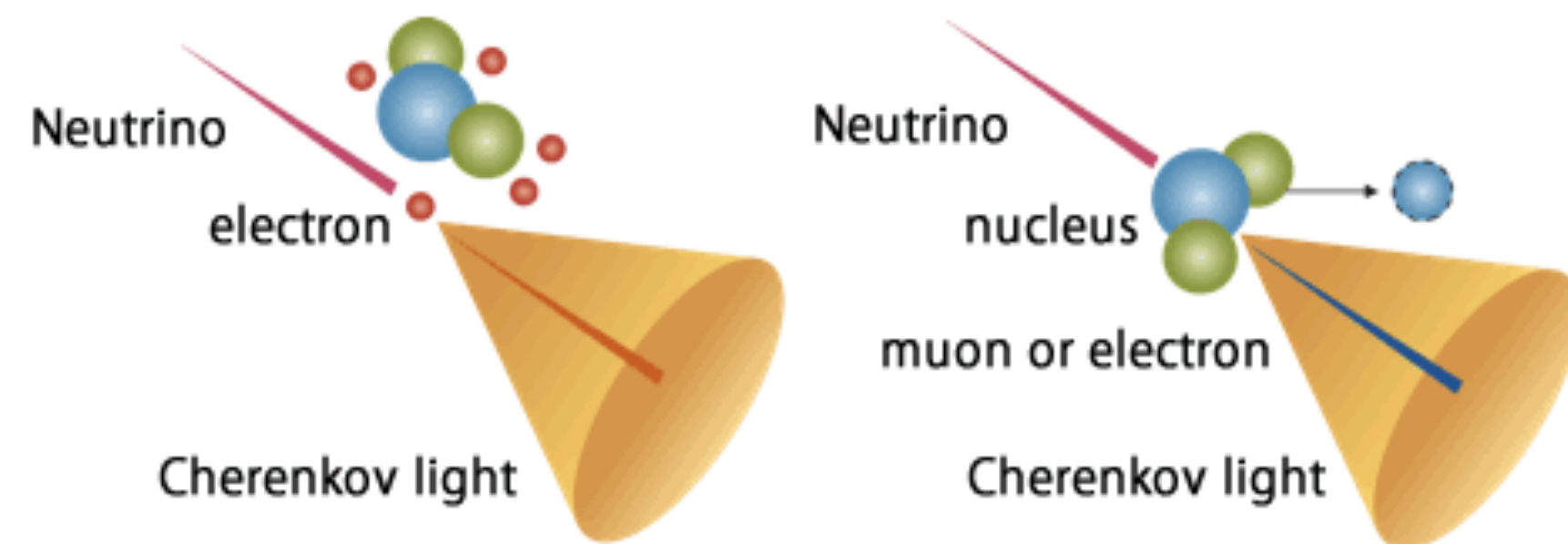
Neutrinos are produced with a definite flavor (e, μ, τ)
but they **oscillate** between the different flavors as they propagate.

Need an even bigger detector if you want to search for rarer, high-energy neutrinos...

IceCube

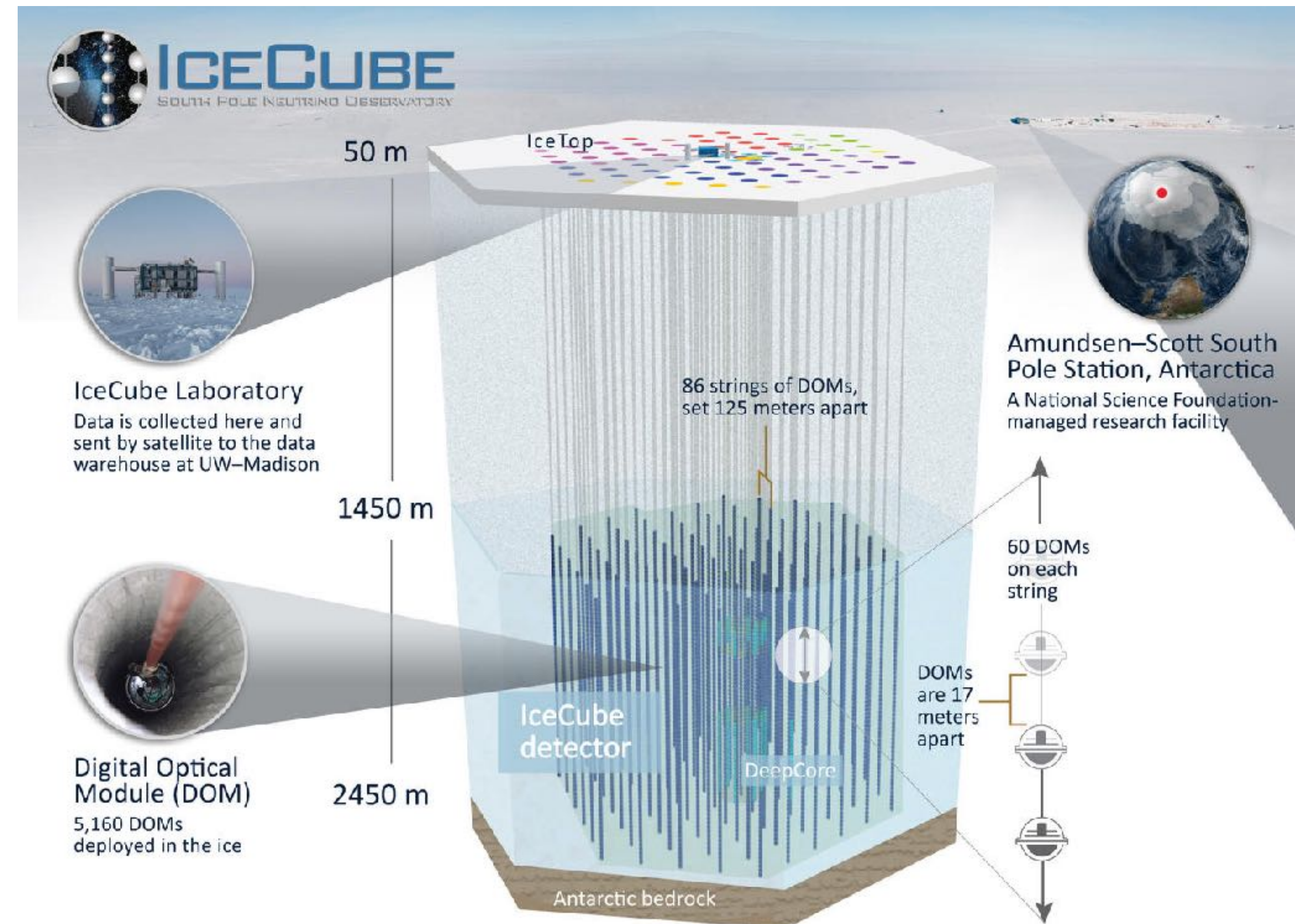
1701.03731

Look for the energetic particles produced by high-energy neutrino interactions over a huge volume:



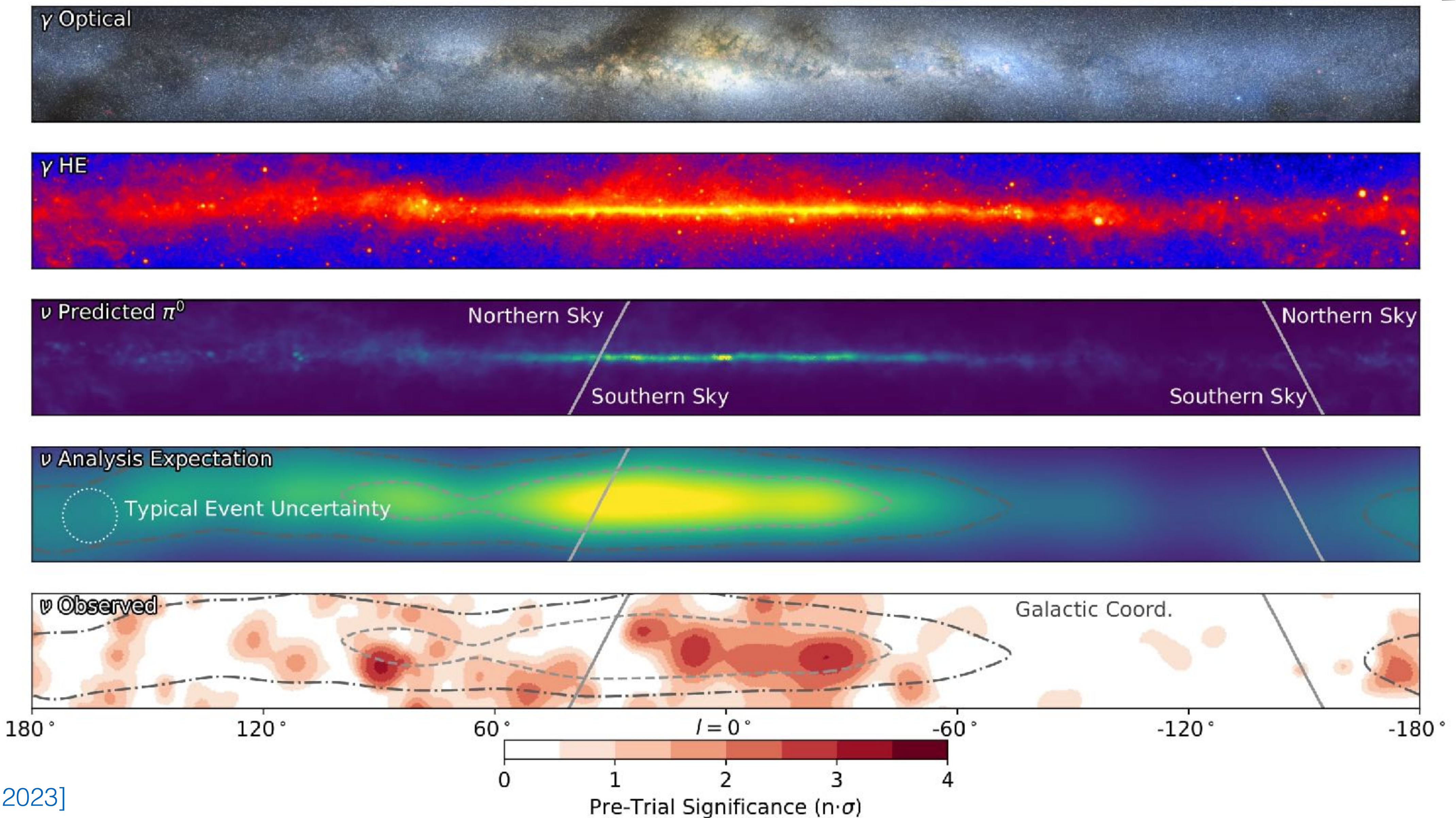
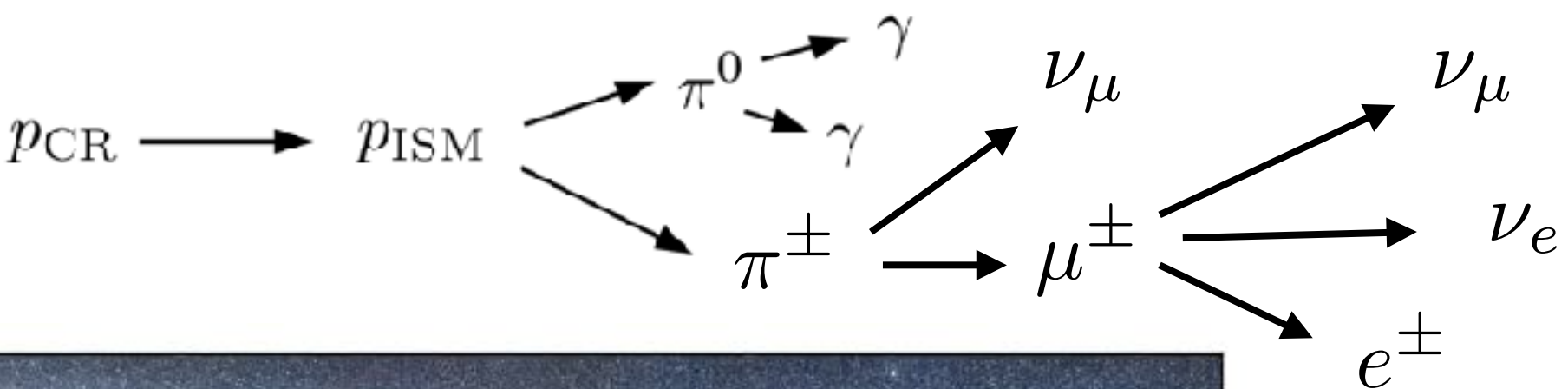
Credit: Hyper-Kamiokande

IceCube: a giant ice detector!
~1 km³ of instrumented volume

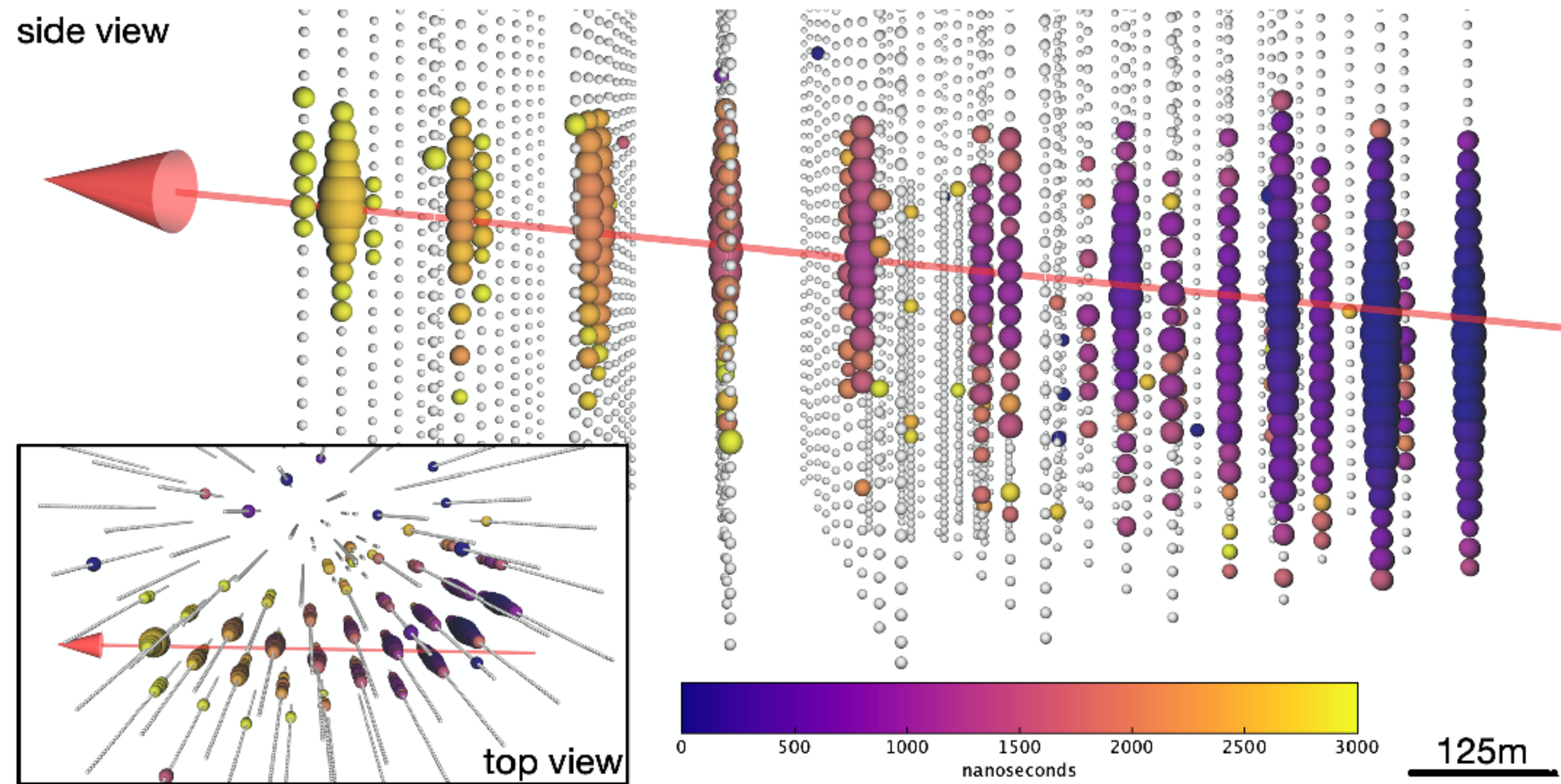


See also SuperKamiokande, ANTARES, KM3NET

Milky Way shines bright in Neutrinos!

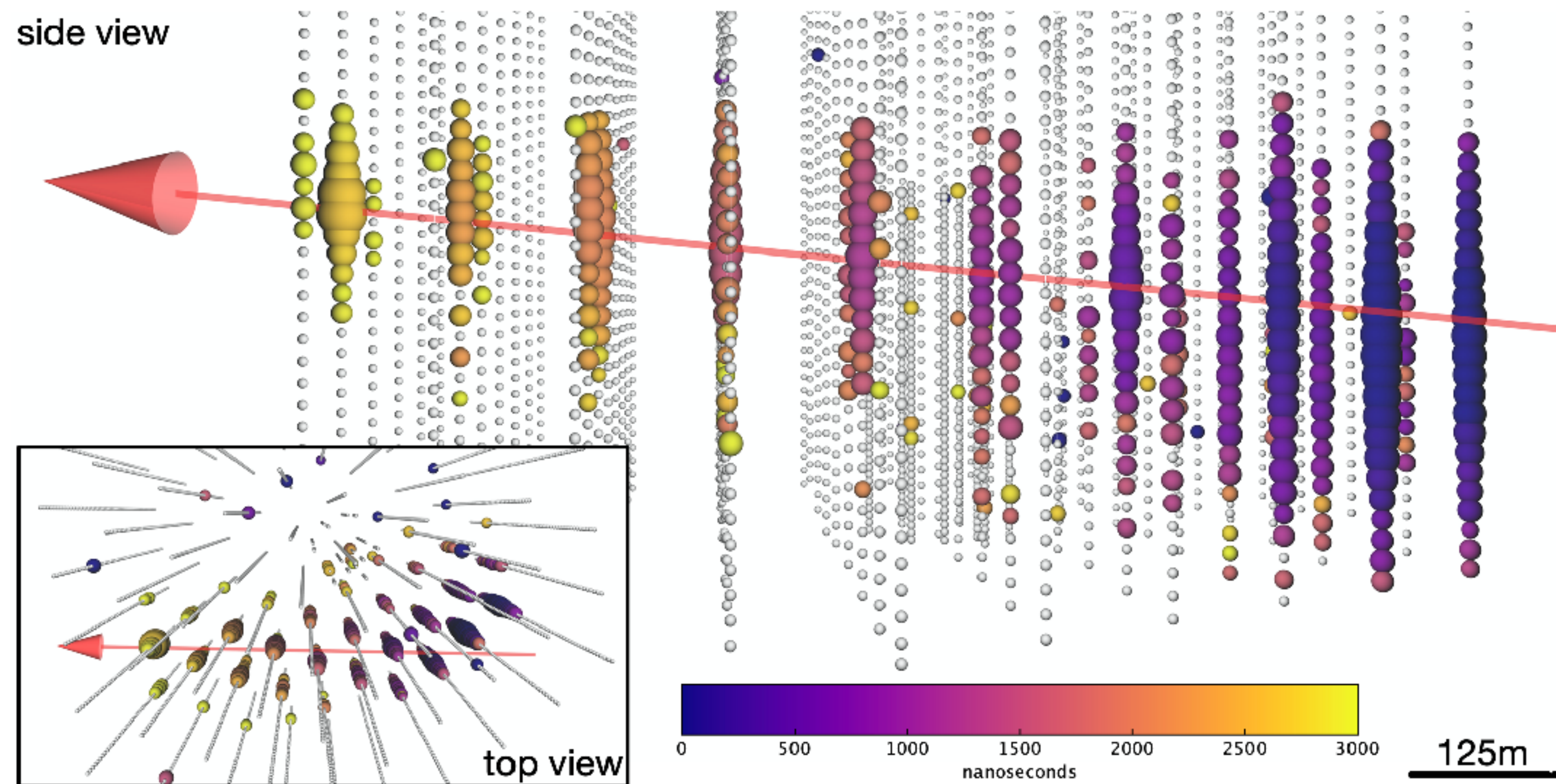


22 September 2017

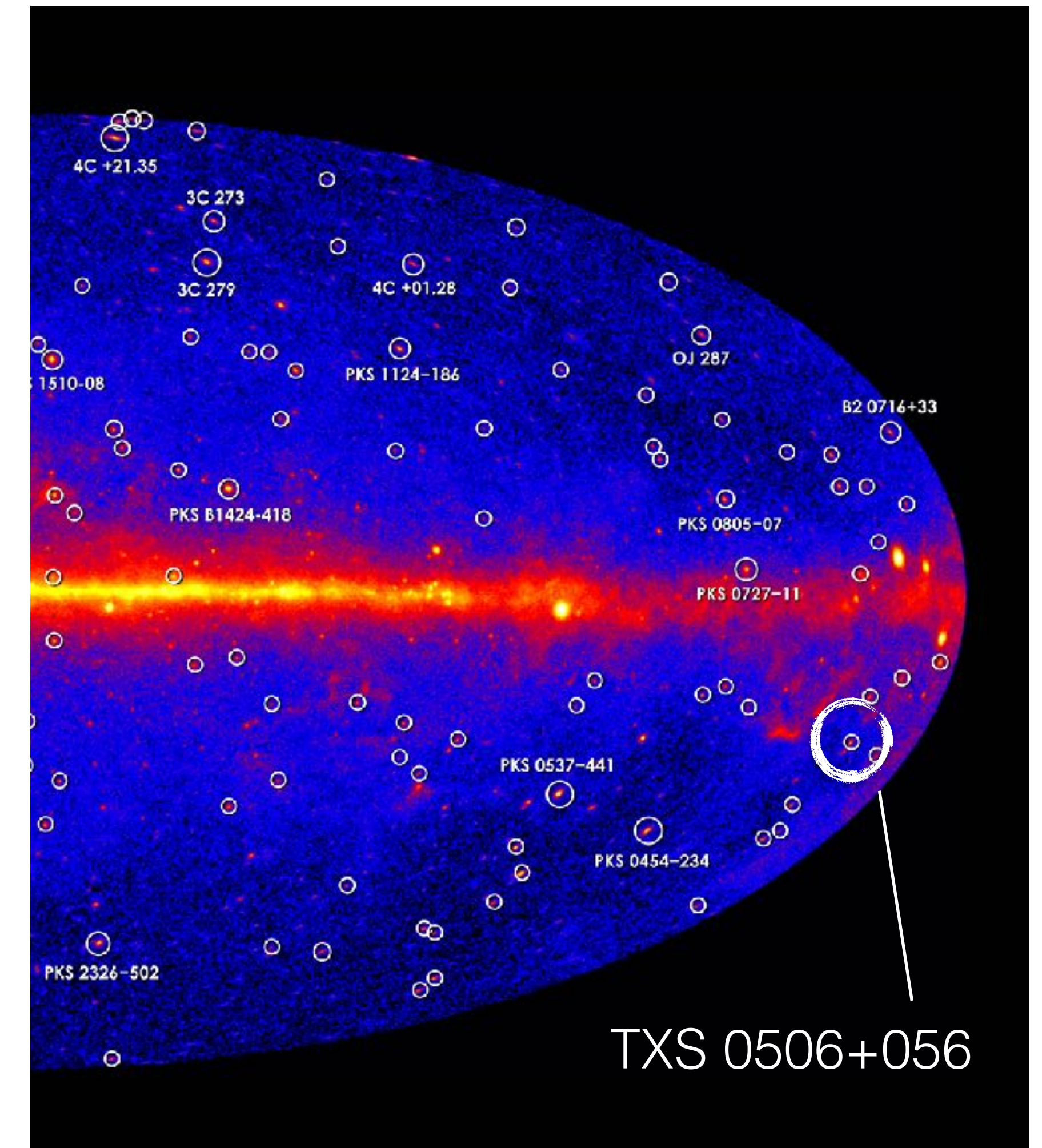


$$E_\nu \sim 290 \text{ TeV}$$

22 September 2017



$$E_\nu \sim 290 \text{ TeV}$$

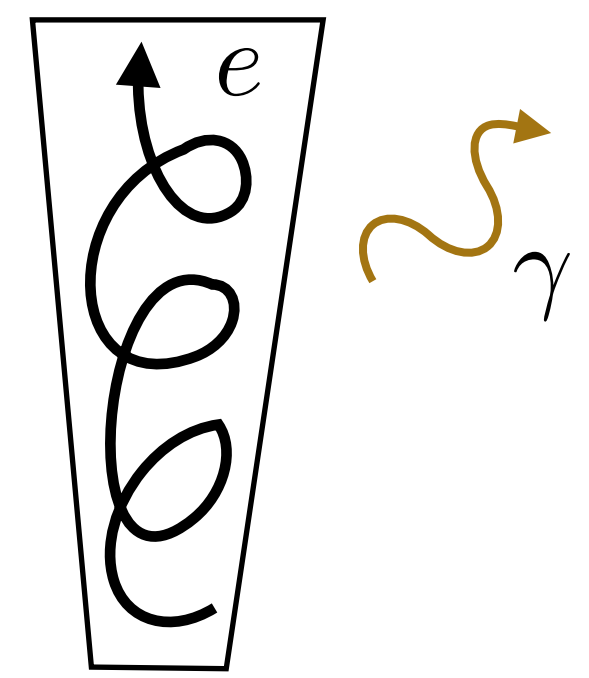


TXS 0506+056 is a known blazar!

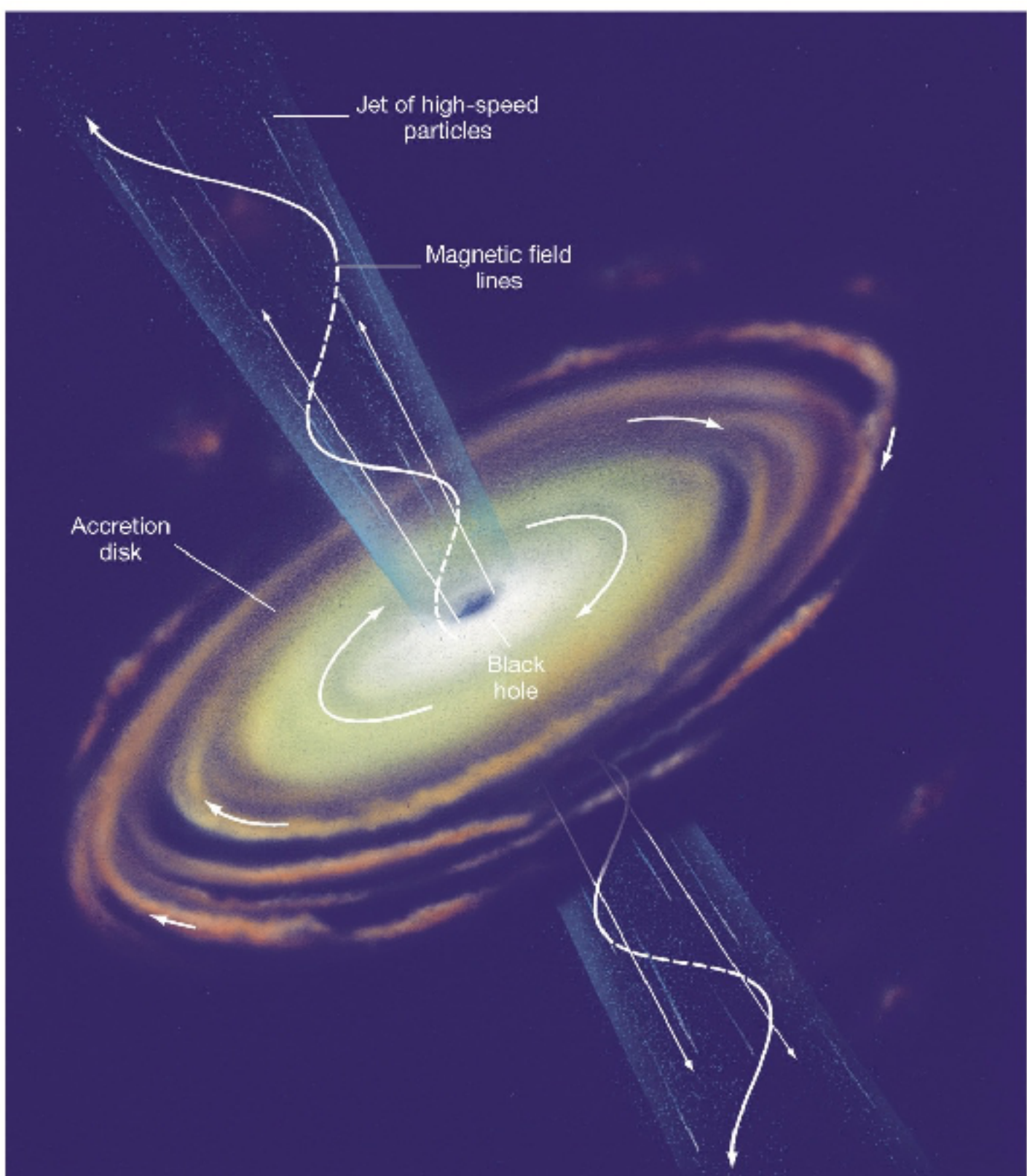
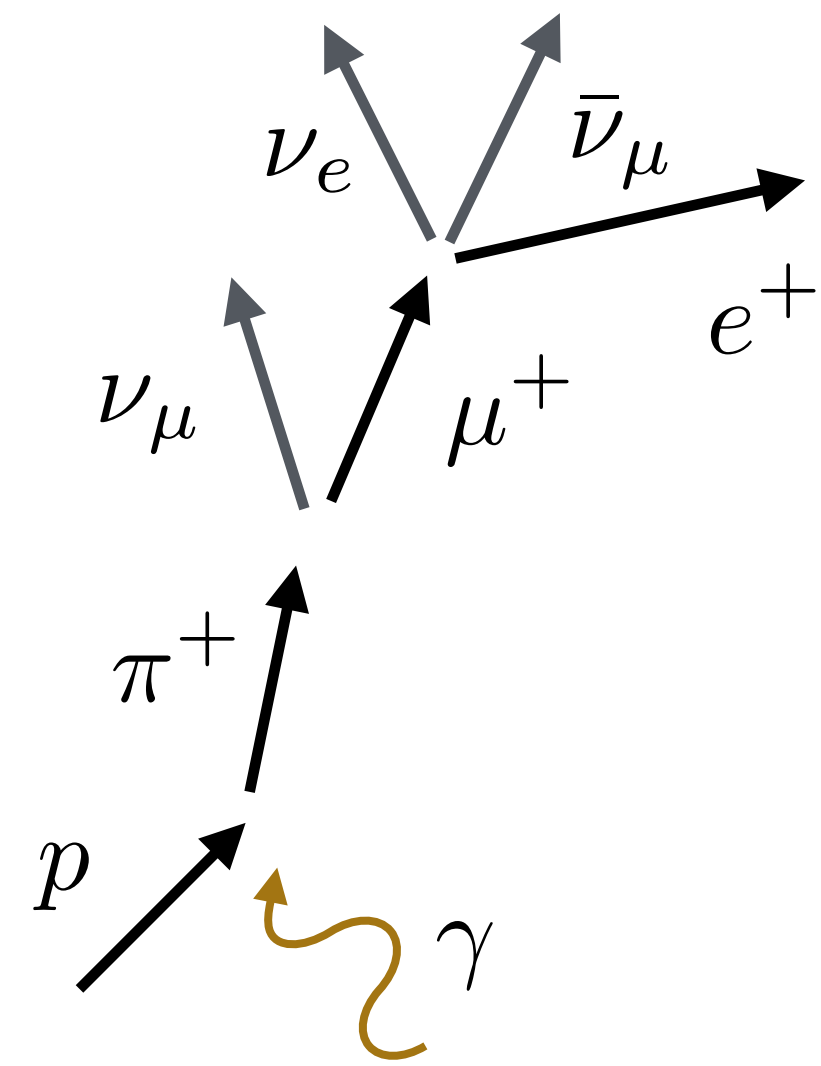
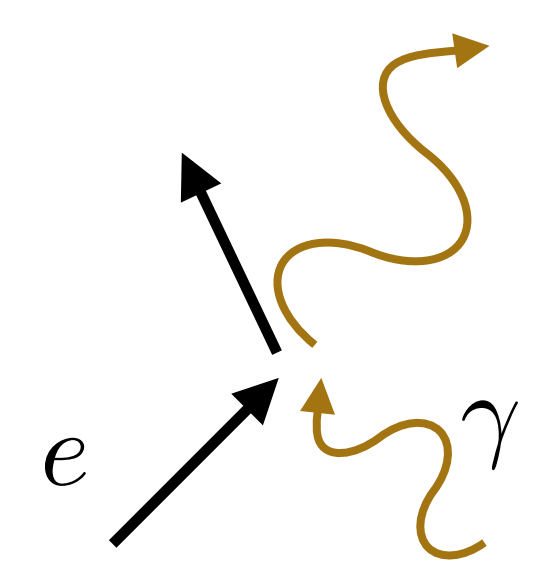
It was flaring in gamma rays
at the time of IceCube-170922A!

Blazar emission

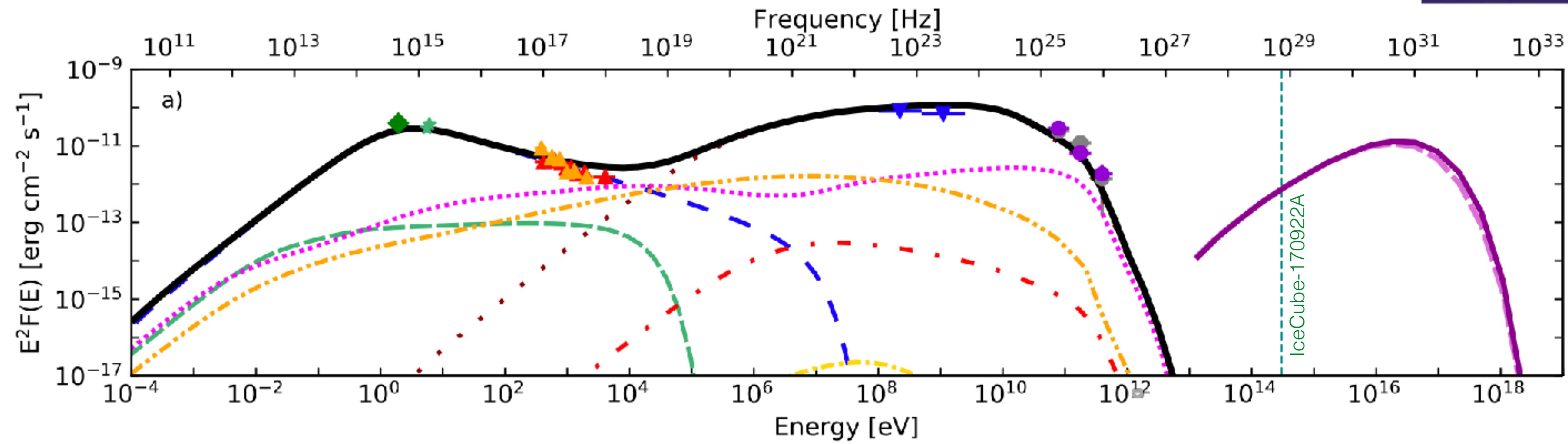
Electron synchrotron



Inverse Compton



Credit: Pearson Education, Inc., Upper Saddle River, New Jersey



- MAGIC 58057
 - MAGIC 58029-30
 - MAGIC LS
 - Fermi-LAT
 - NuSTAR 58025
 - NuSTAR 58045
 - Swift/XRT 58029
 - Swift/XRT 58030
 - Swift/XRT LS
 - KVA
 - UVOT
- $E_{p,max} = 10^{16}$
- e- sync. jet
 - e- sync. sheath
 - SSC
 - EC
 - $\gamma\pi$ cascade
 - μ sync.
 - BH cascade
 - total EM
 - $\bar{\nu}_\mu$
 - ν_μ

Optical

X-ray

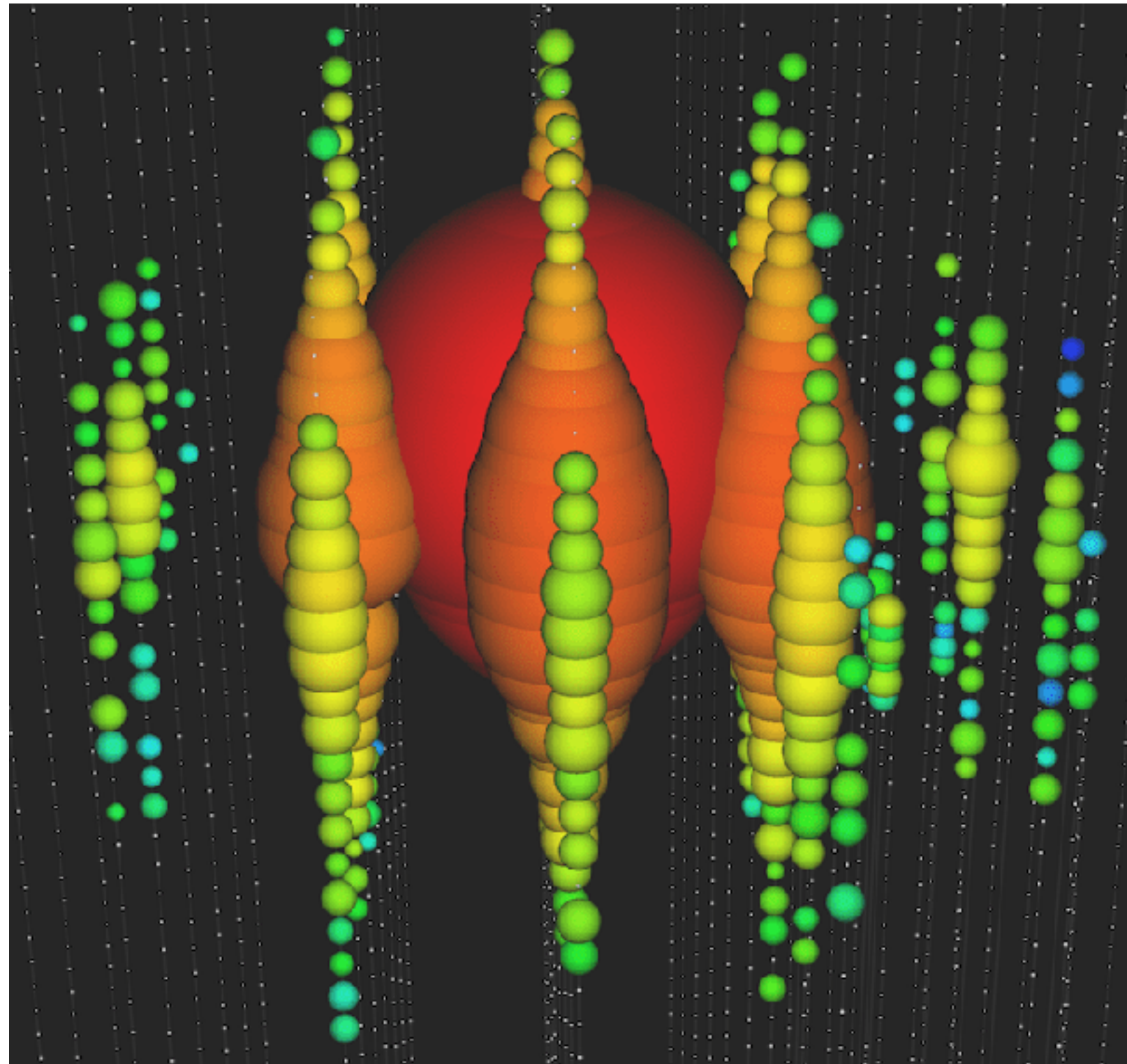
Gamma-ray

Neutrinos!

[1807.04300](https://arxiv.org/abs/1807.04300)

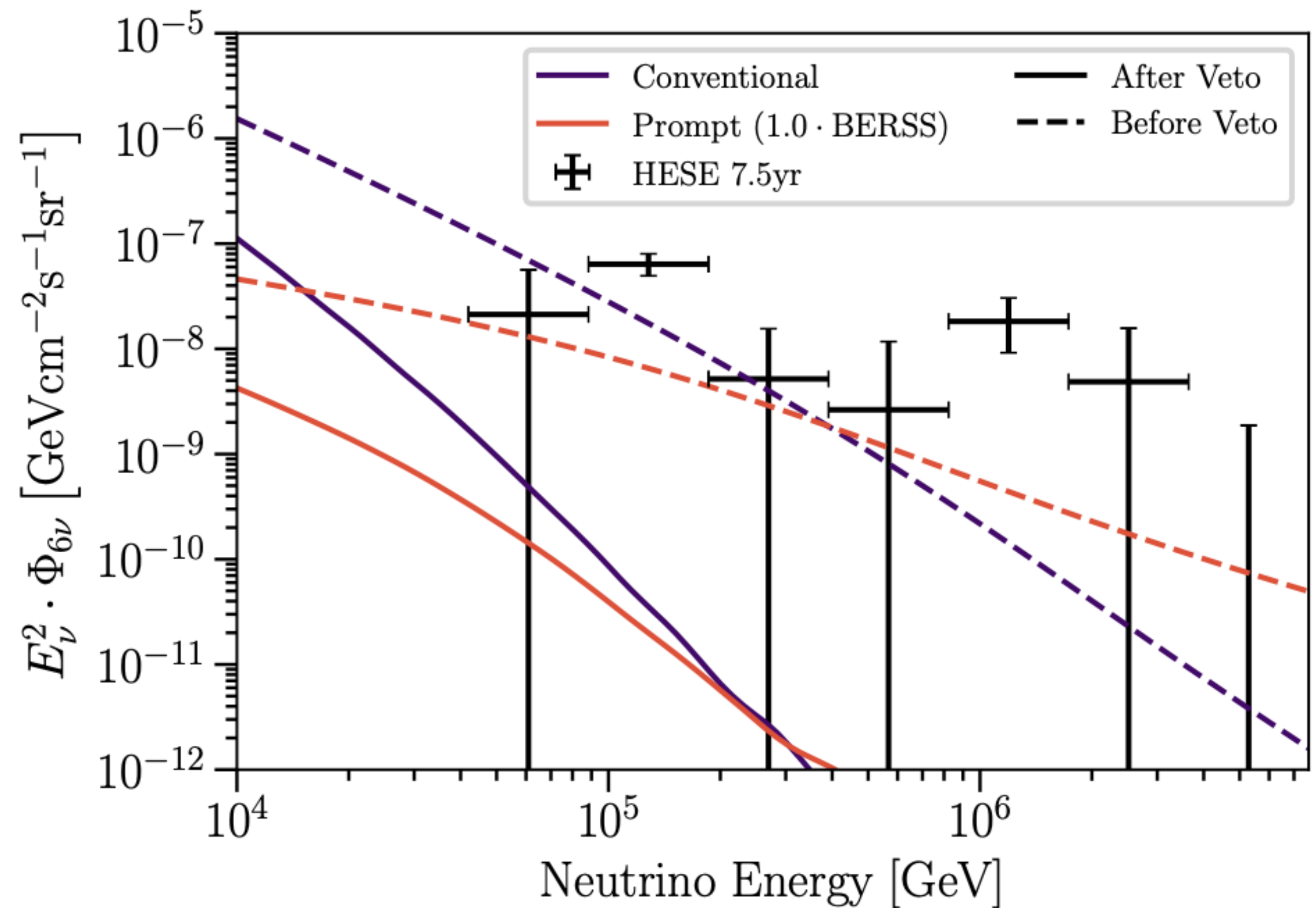
Ultra-high energy neutrinos

“Big Bird” - a 2 PeV neutrino, detected by IceCube on 4 December, 2012



Credit: IceCube Collaboration

IceCube ‘high energy starting events’ (HESE)

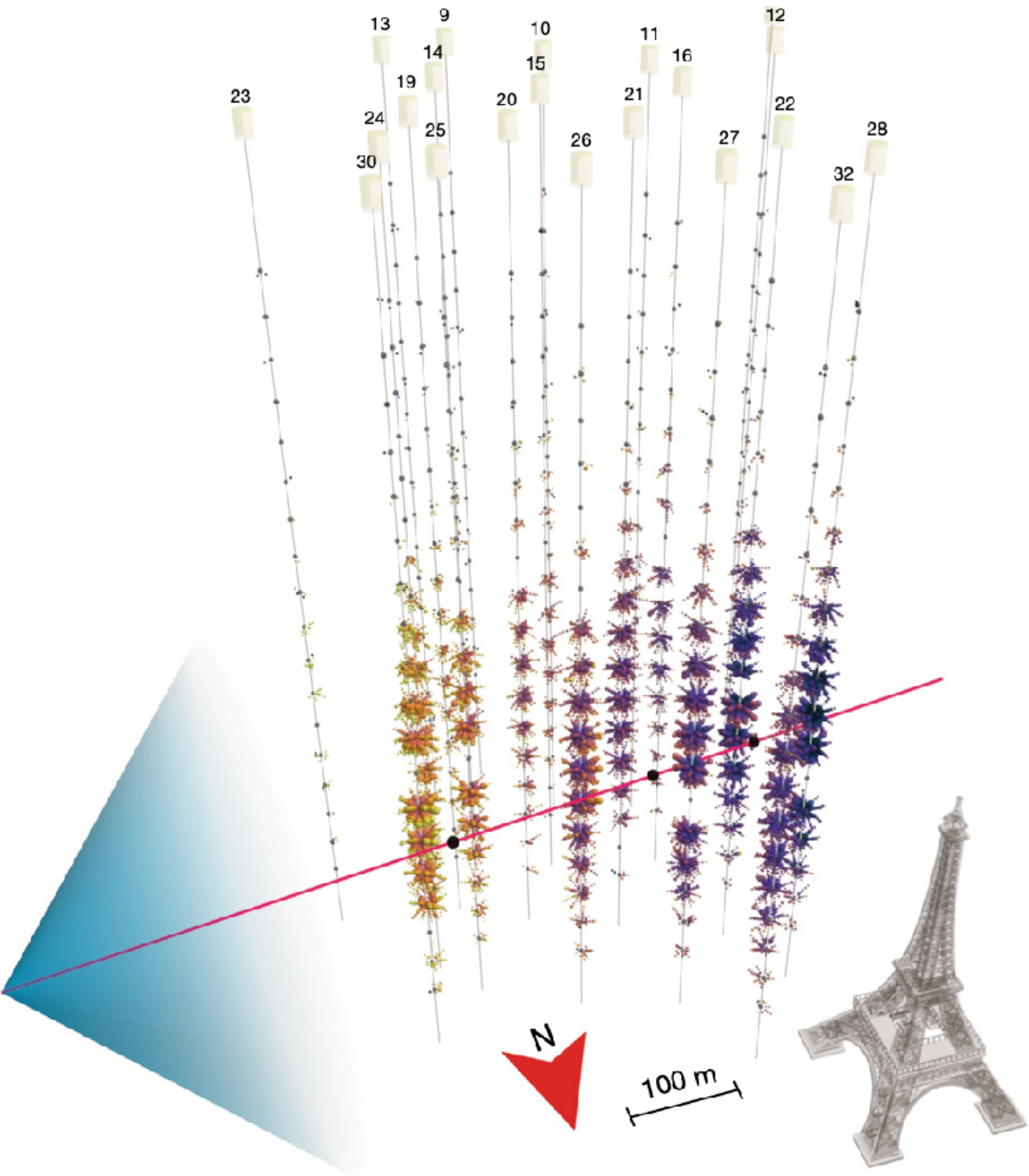
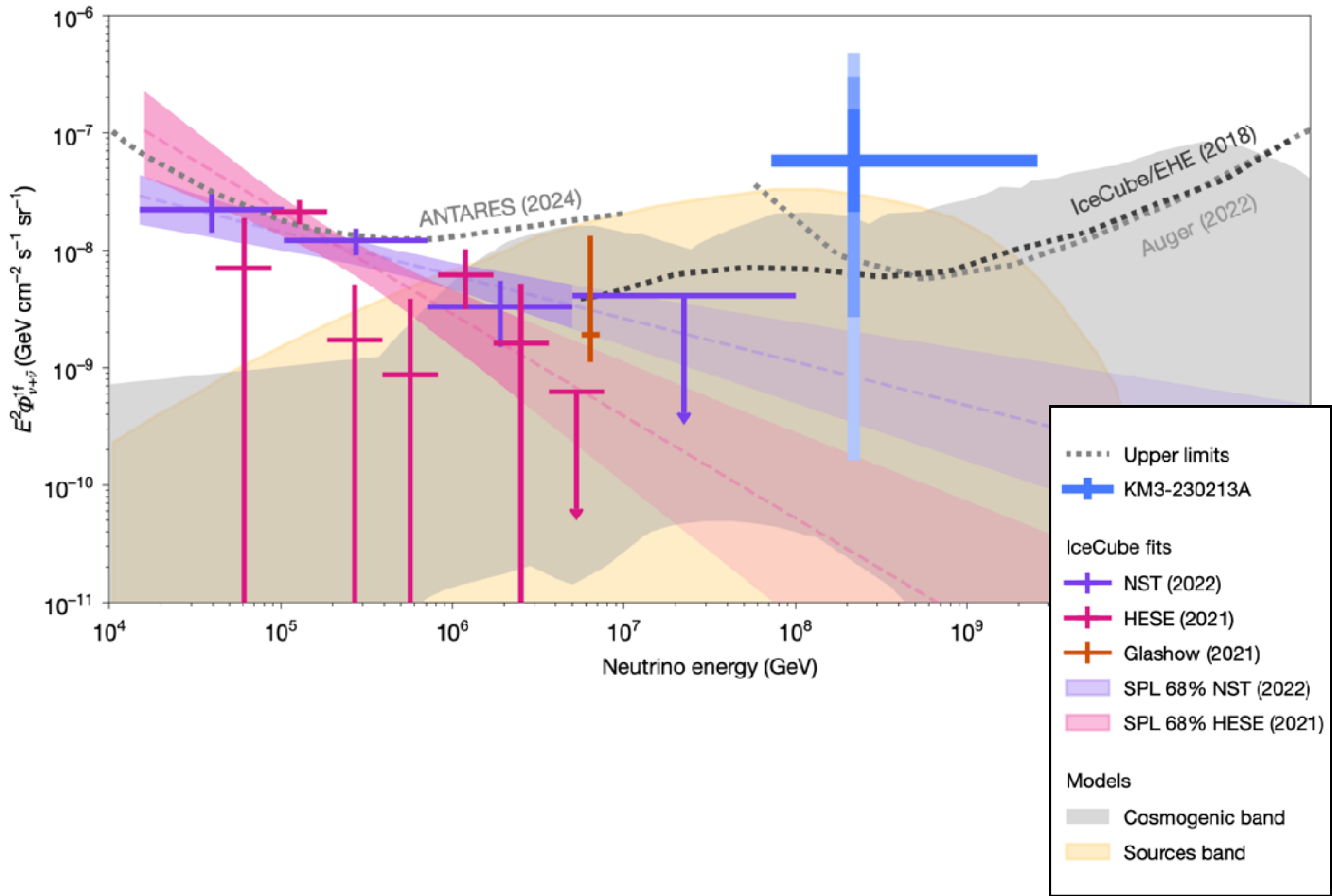


[2011.03545](#)

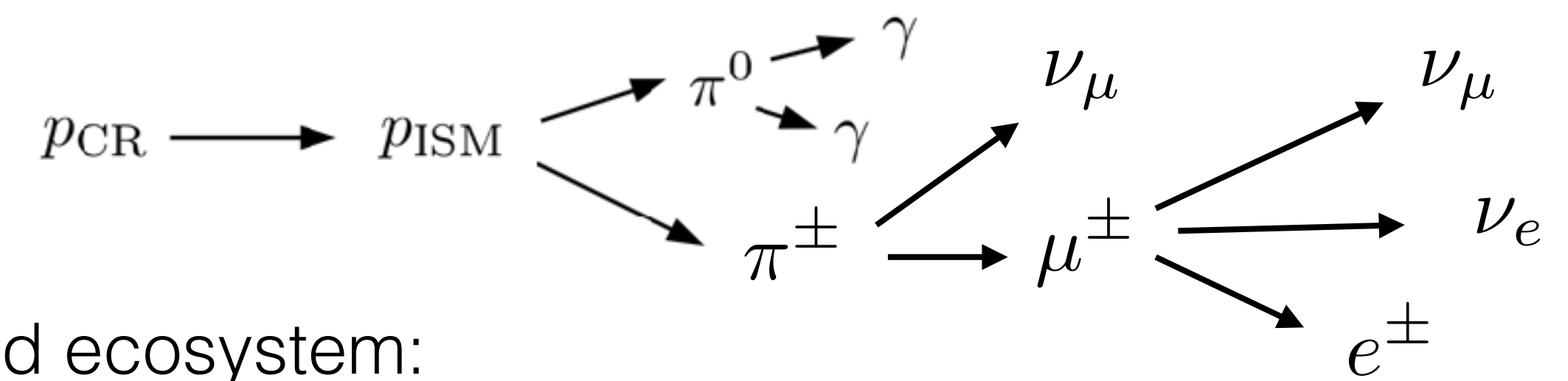
Unknown Territory

KM3NeT - A neutrino detector under development in the Mediterranean Sea

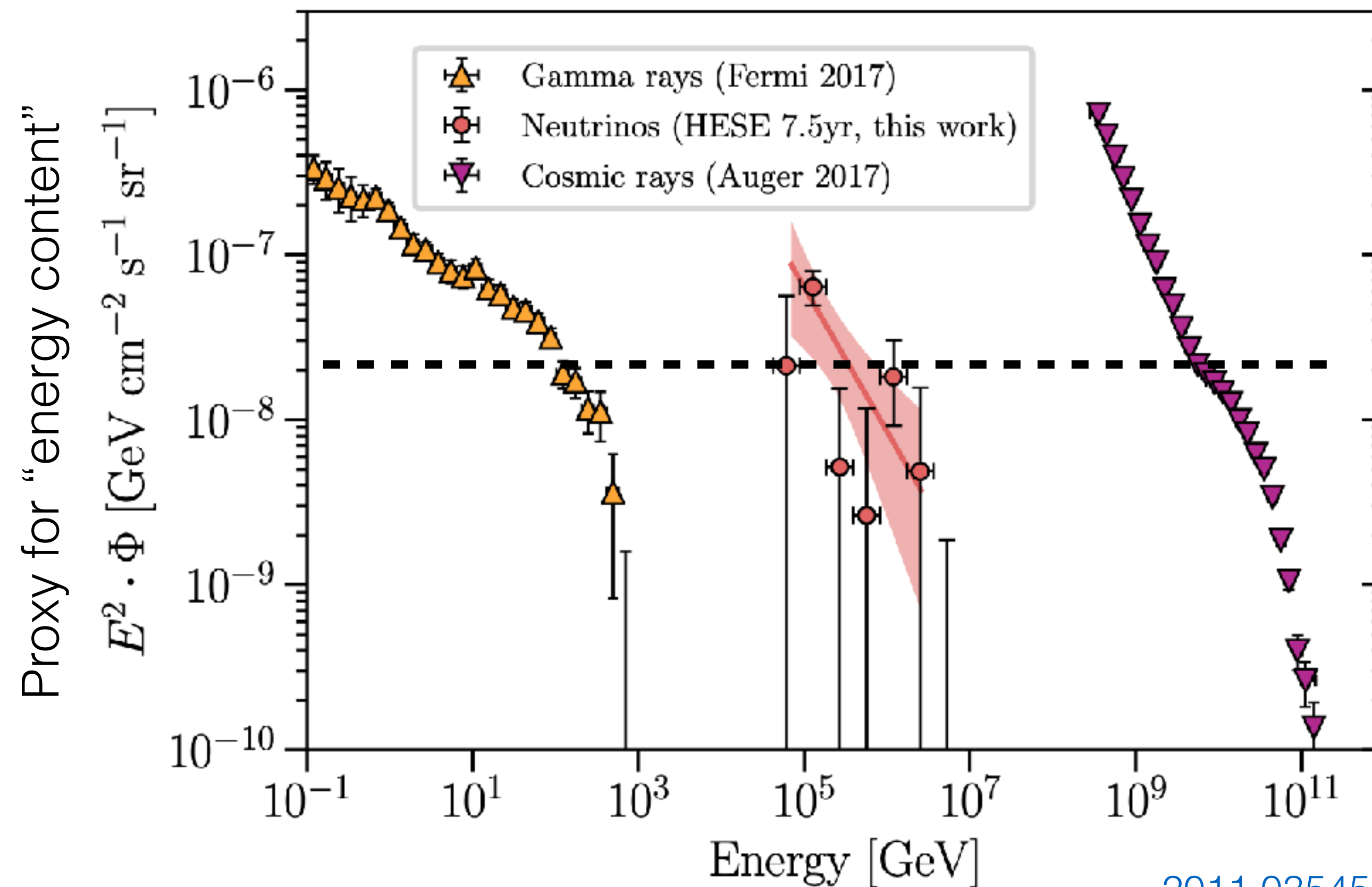
[Recently reported](#) a neutrino event with energy $E_\nu \sim 120 \text{ PeV}$



Violent and Energetic Universe



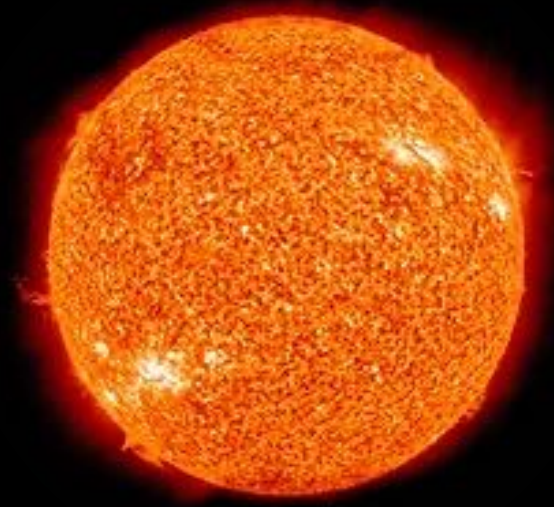
A complex and interconnected ecosystem:



[2011.03545](#)

Understanding it could shed light on the most violent processes in the Universe,
and on New Physics yet to be discovered...

The Sun



Supernovae

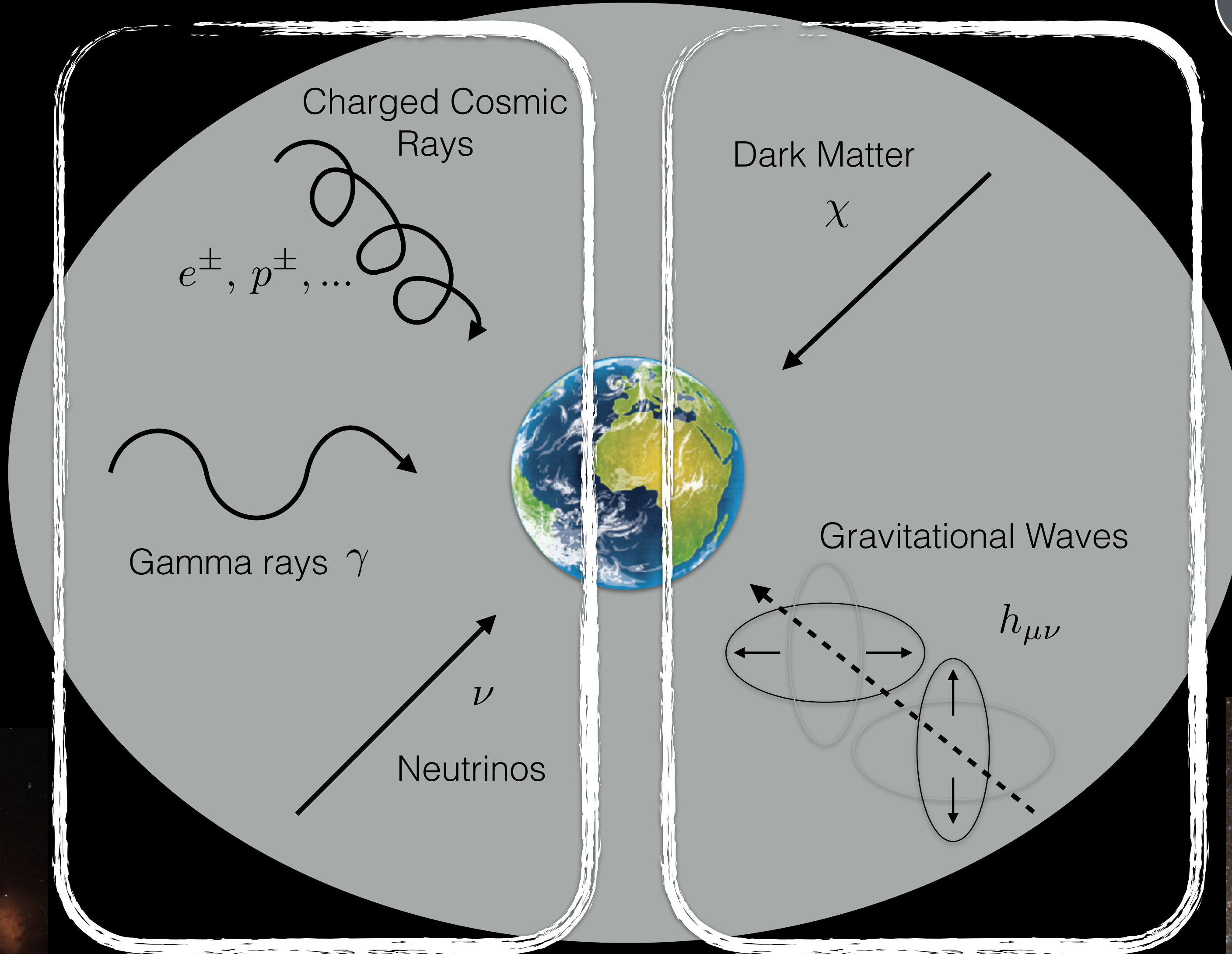


Quasars/AGN



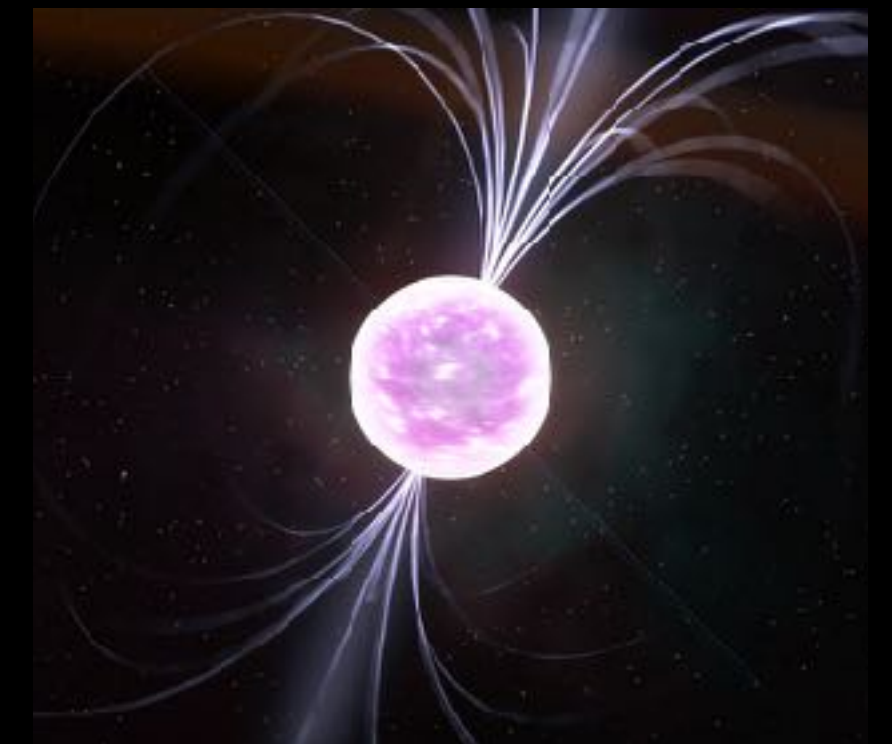
Lecture 1

Lecture 2



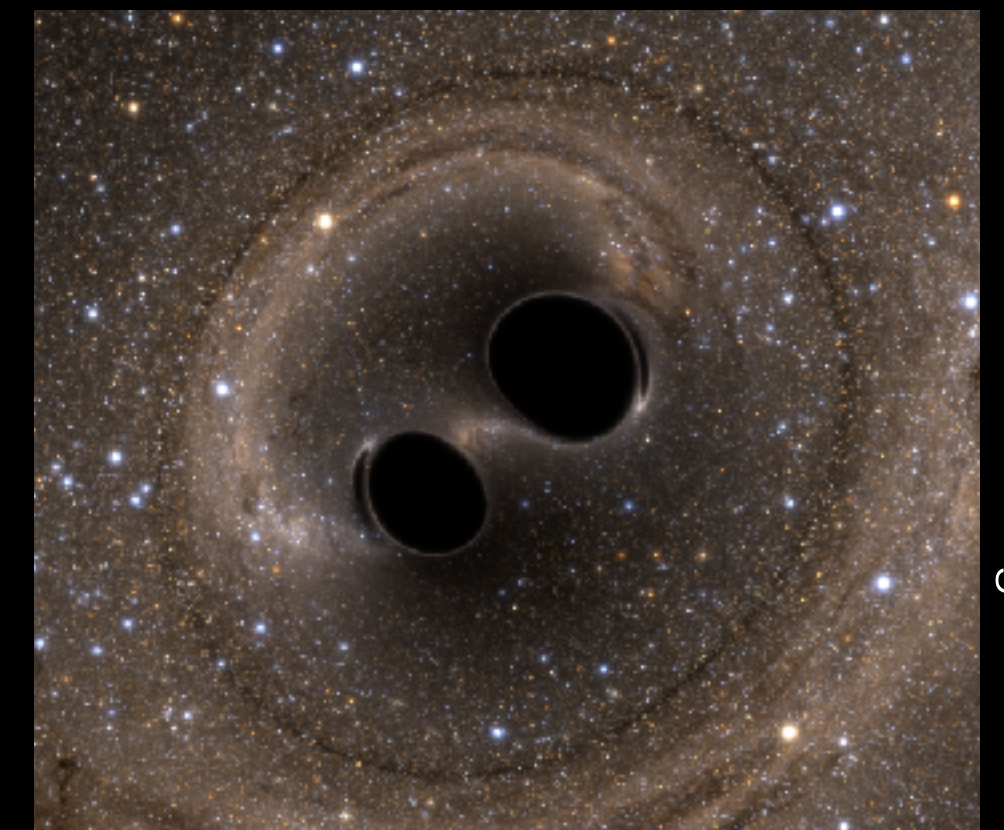
????

Pulsars



Credit: Kevin Gill / Flickr

BH/NS Mergers



Credit: SXS Lensing

Credit: NASA/CXC/SAO

Credit: ESO/M. Kornmesser

Astroparticle Physics: Theory and Phenomenology, Günter Sigl, [Atlantis Press Paris](http://atlantispress.com) (2017)

Lectures on Astroparticle Physics, Günter Sigl, hep-ph/0408165 (2004)

Introduction to Cosmic Rays, Peter Biermann & Günter Sigl, astro-ph/0202425 (2002)

An Introduction to Particle Dark Matter, Stefano Profumo, Leonardo Giani & Oliver F. Piattella, [arXiv:1910.05610](http://arxiv.org/abs/1910.05610) (2019)

The basic physics of the binary black hole merger GW150914, LIGO & Virgo Collaborations, [arXiv:1608.01940](http://arxiv.org/abs/1608.01940) (2016)

Check [arXiv](http://arxiv.org), and summaries on popular blogs like Sunny Vagnozzi's [HisDarkCMB](http://hisdarkcmb.com) or Mauricio Bustamante's [Daily arXiv Picks](http://dailyarxivpicks.com)!

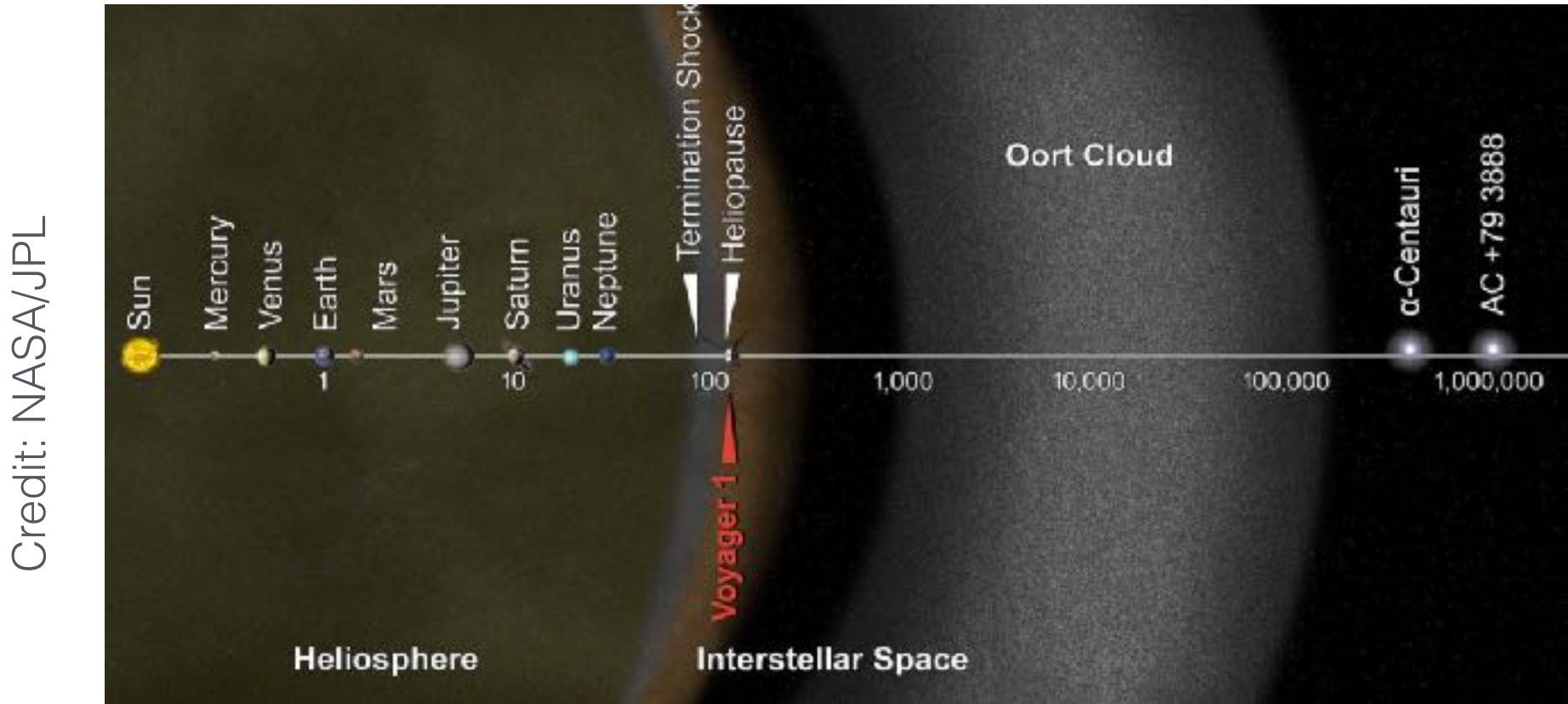
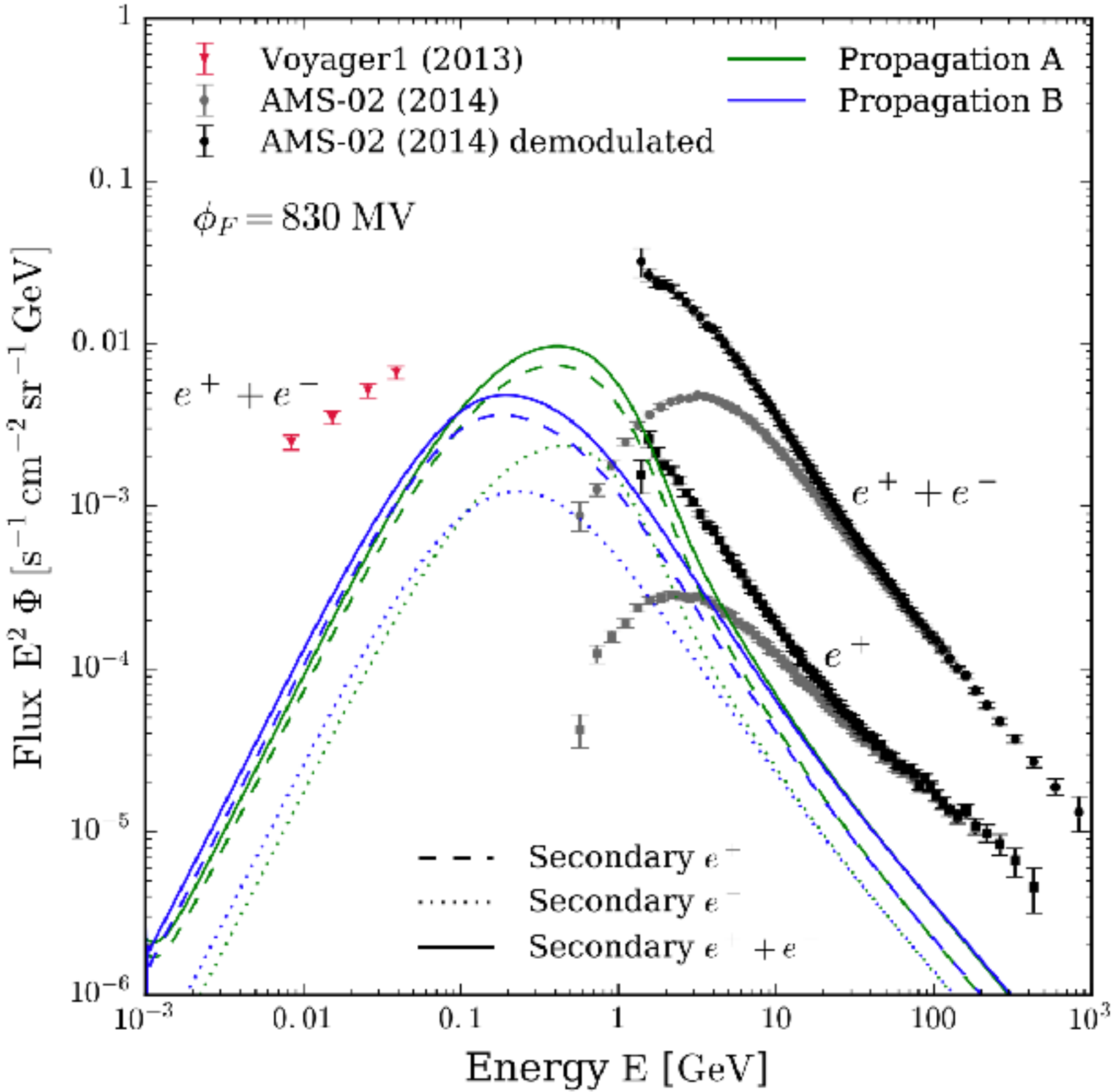
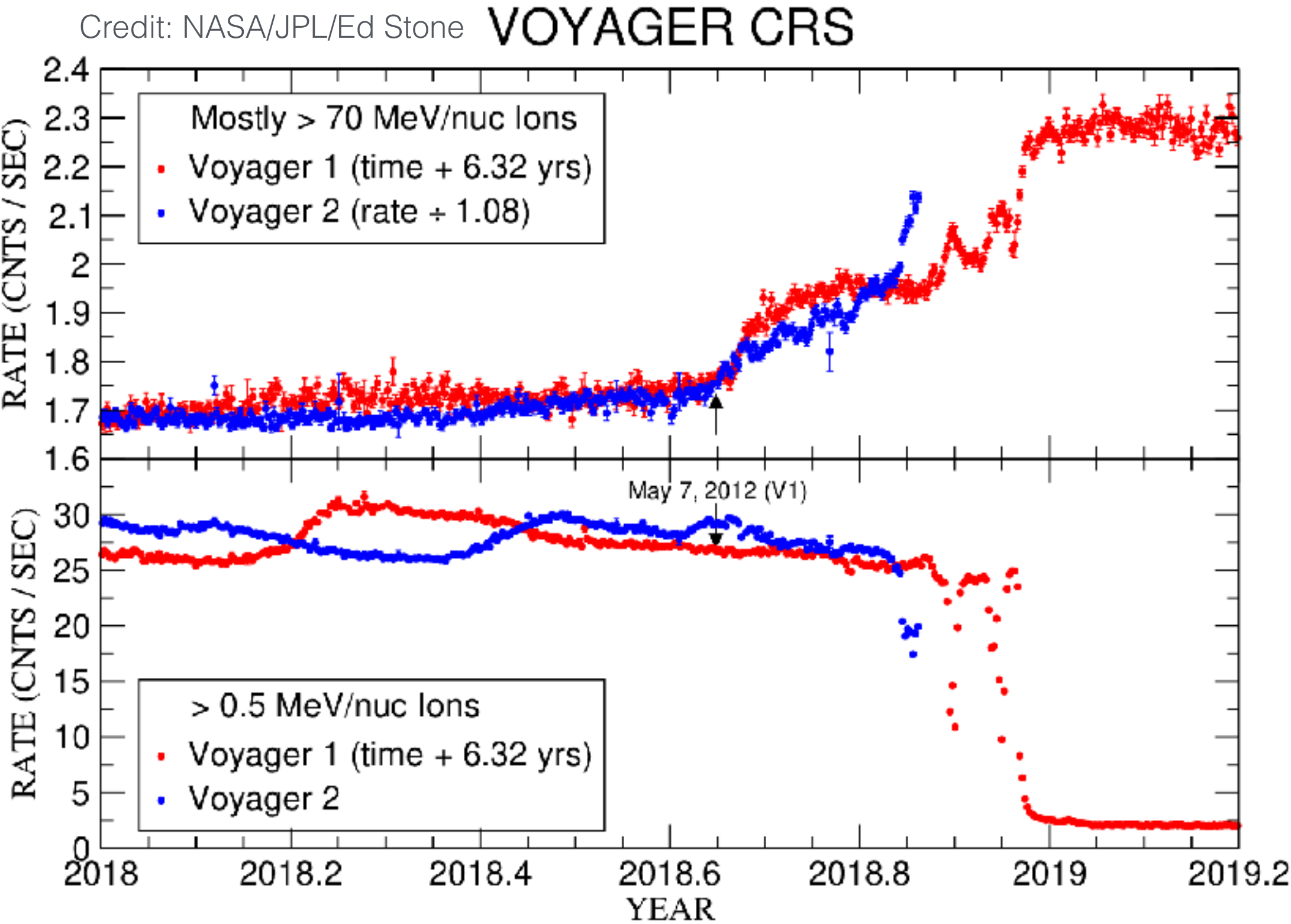
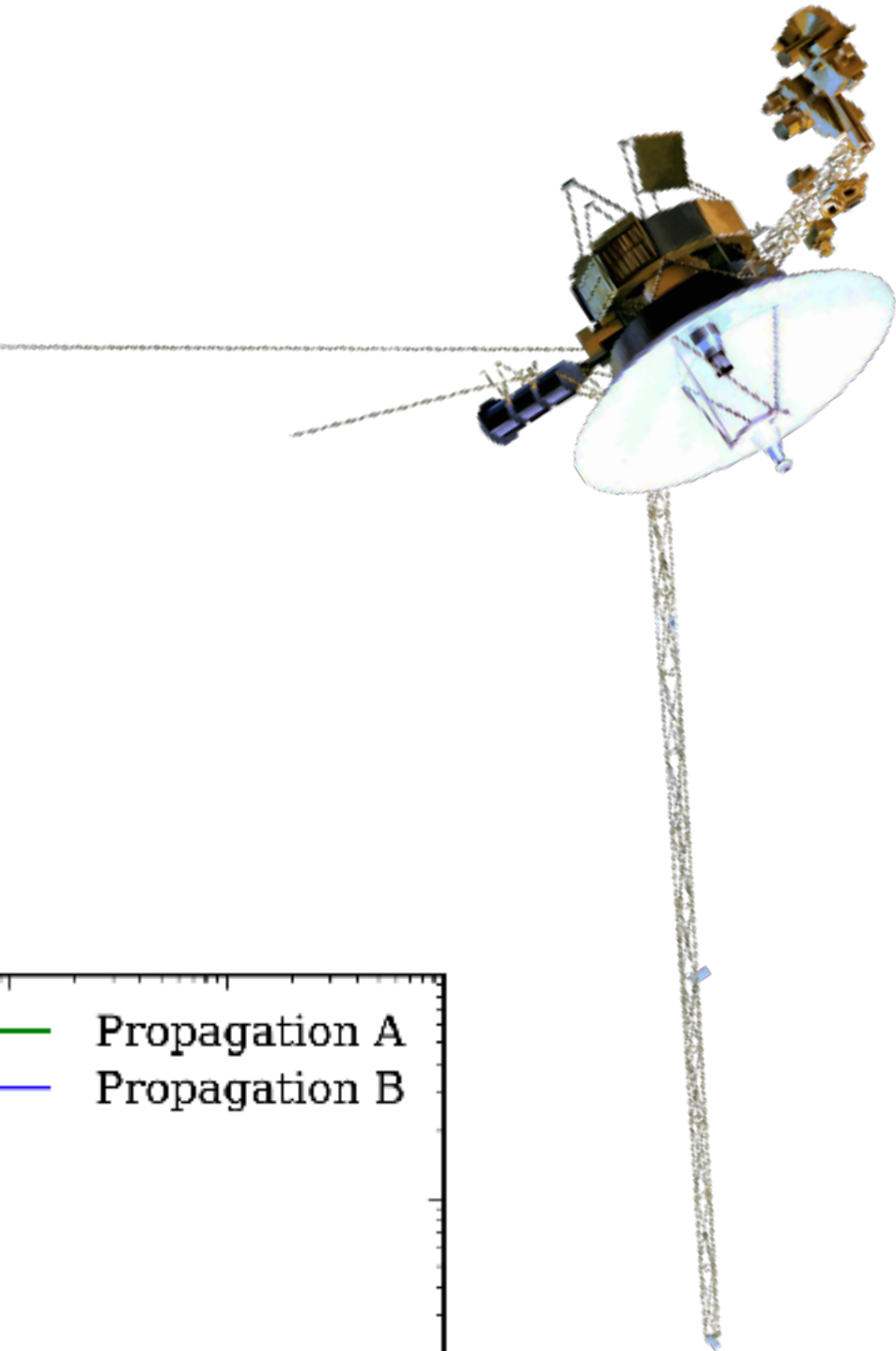
Feel free to email me at kavanagh@ifca.unican.es!

Additional Slides

Voyager (and solar modulation)

Voyager 1 - launched 1977,
crossed heliopause 2012

Voyager 2 - launched 1977,
crossed heliopause 2018

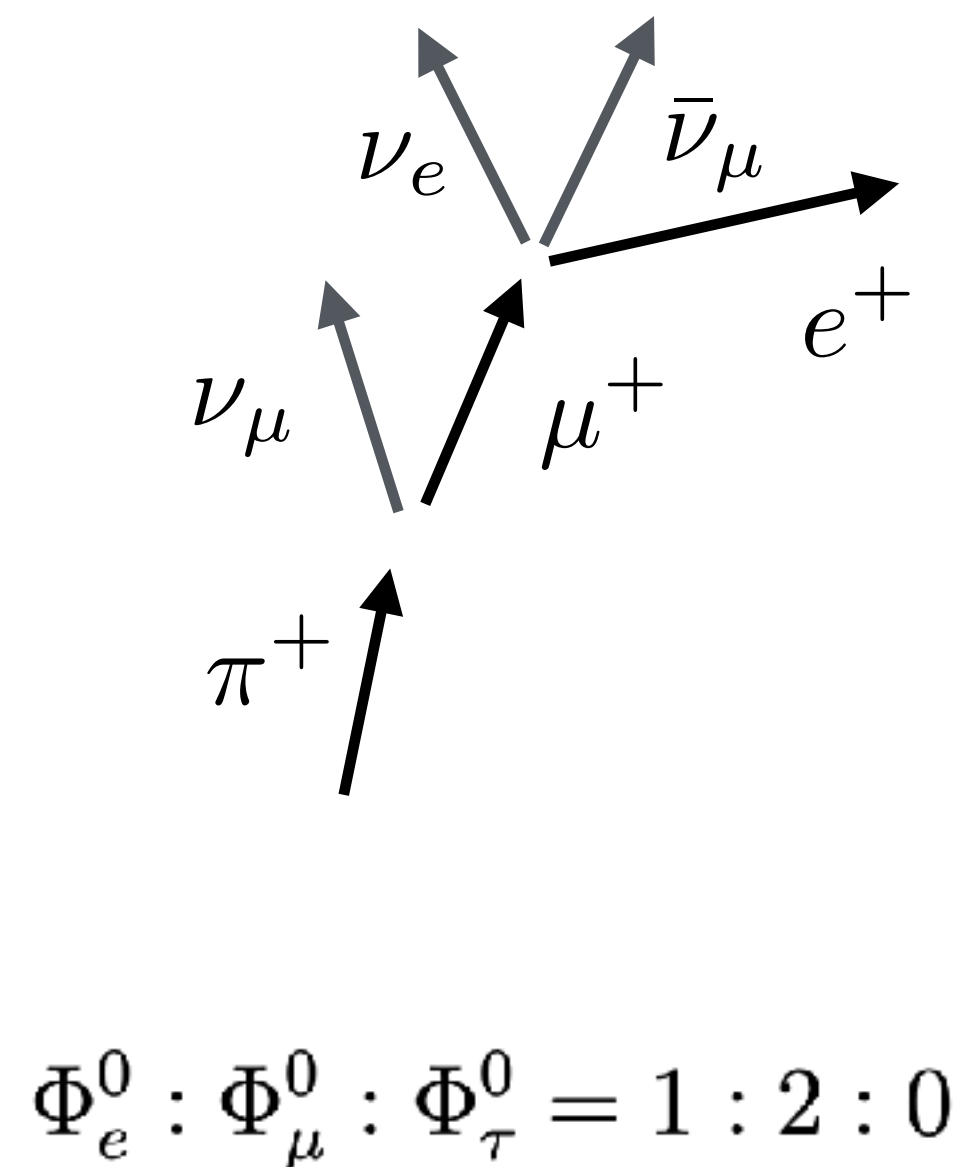


[arXiv:1612.07698](https://arxiv.org/abs/1612.07698)

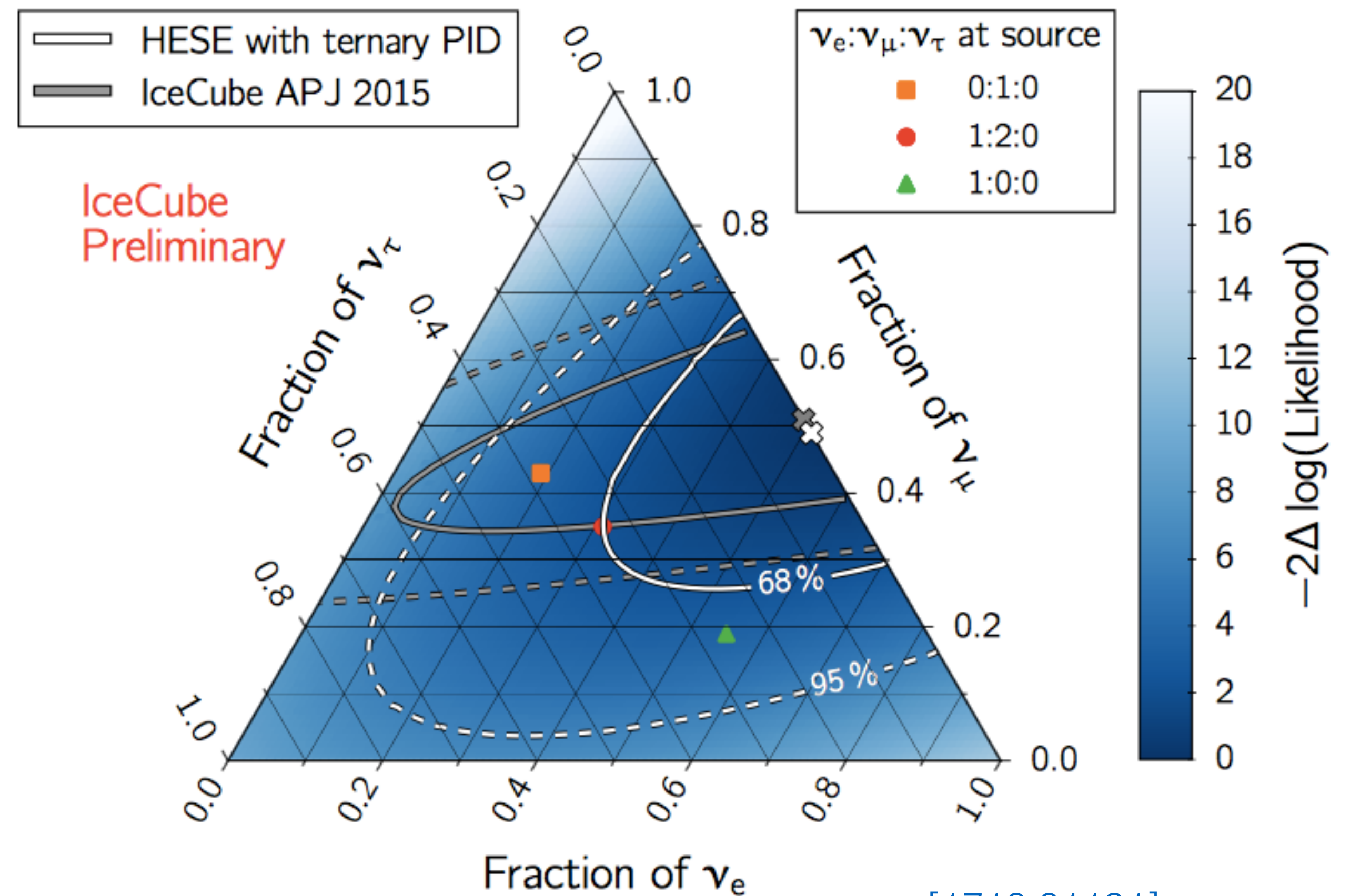
Origin of ultra high energy neutrinos?

Flavour composition can hint at how astrophysical neutrinos are produced:

E.g. decay of energetic pions:



Oscillation should lead to a 1:1:1 ratio at IceCube...



[1710.01191]

Q: First interaction in the atmosphere?

Quantify amount of atmosphere tranverse by the CR using the column depth:

$$X = \int_h^\infty \rho(h') dh'$$

Column depth of first interaction for gamma rays:

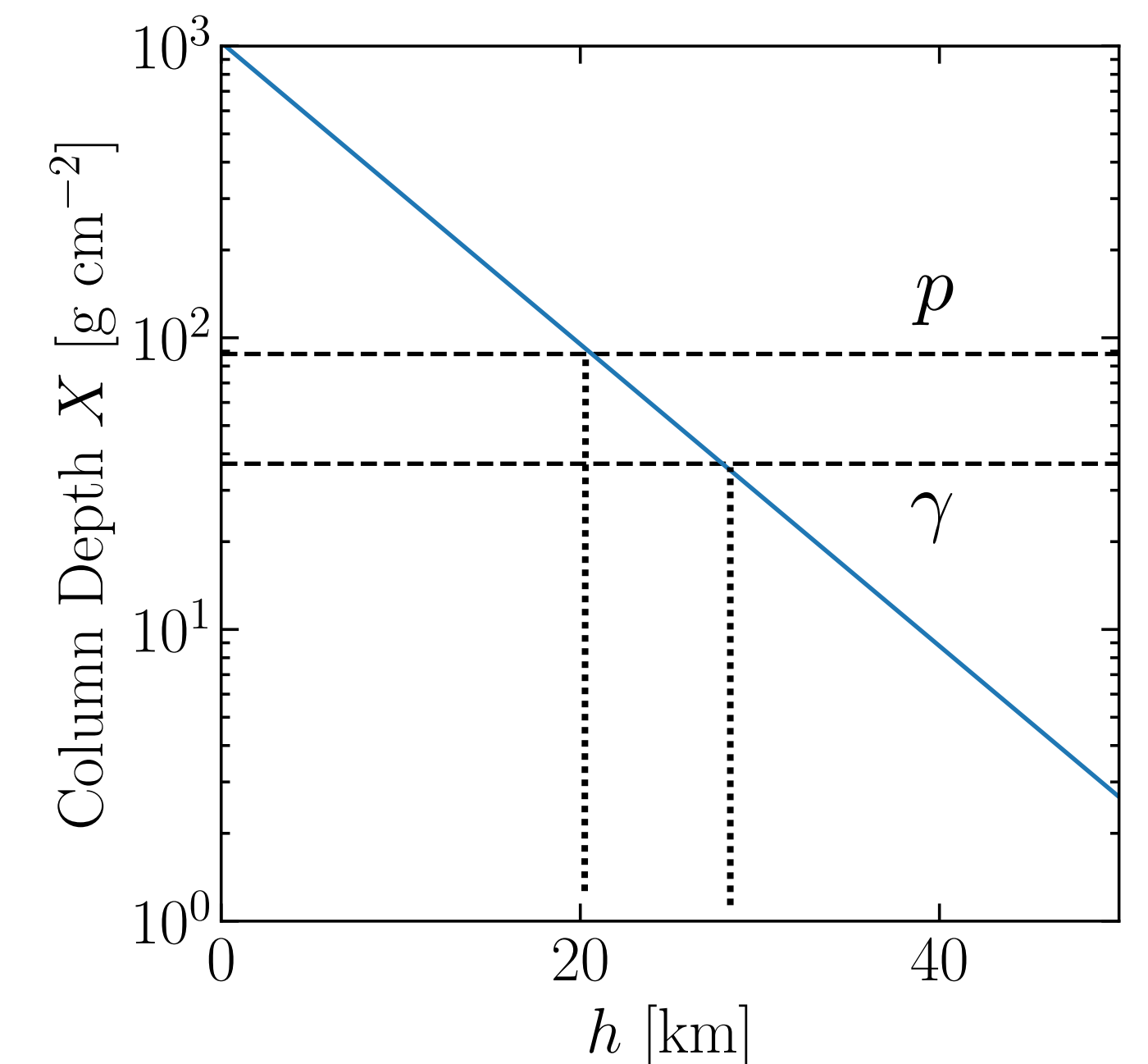
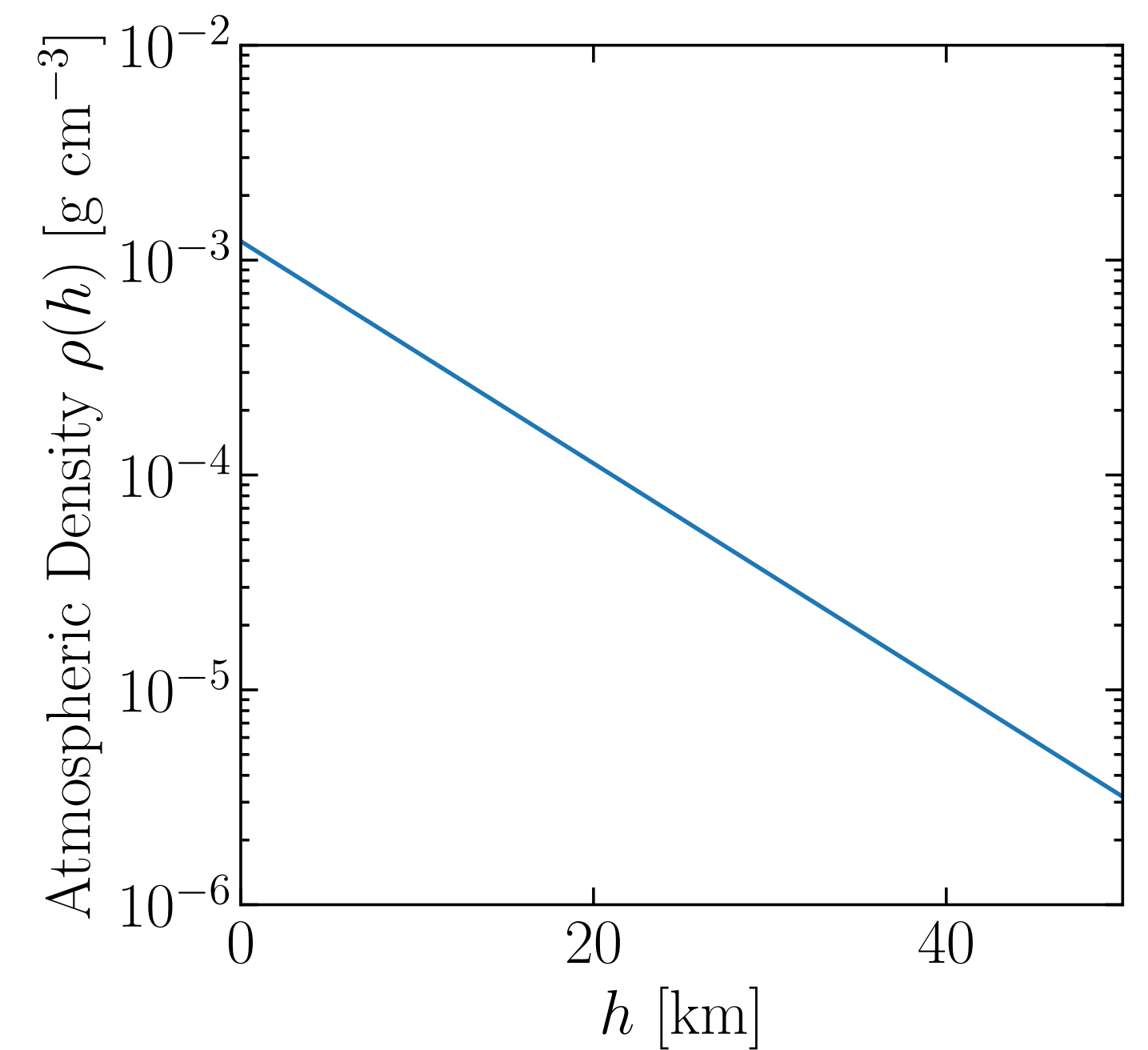
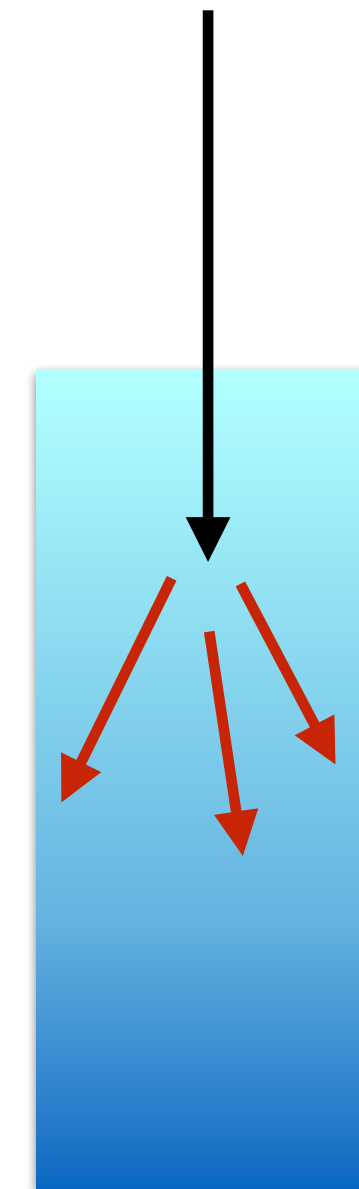
$$X_0^r \approx 37 \text{ g cm}^{-2}$$

Column depth of first interaction for protons:

$$X_0^p \approx \left[88 - 9 \log_{10} \left(\frac{E}{\text{EeV}} \right) \right] \text{ g cm}^{-2}$$

Interaction probability approaches 1 as $X \rightarrow X_0$

[\[arXiv:2401.04460\]](https://arxiv.org/abs/2401.04460)

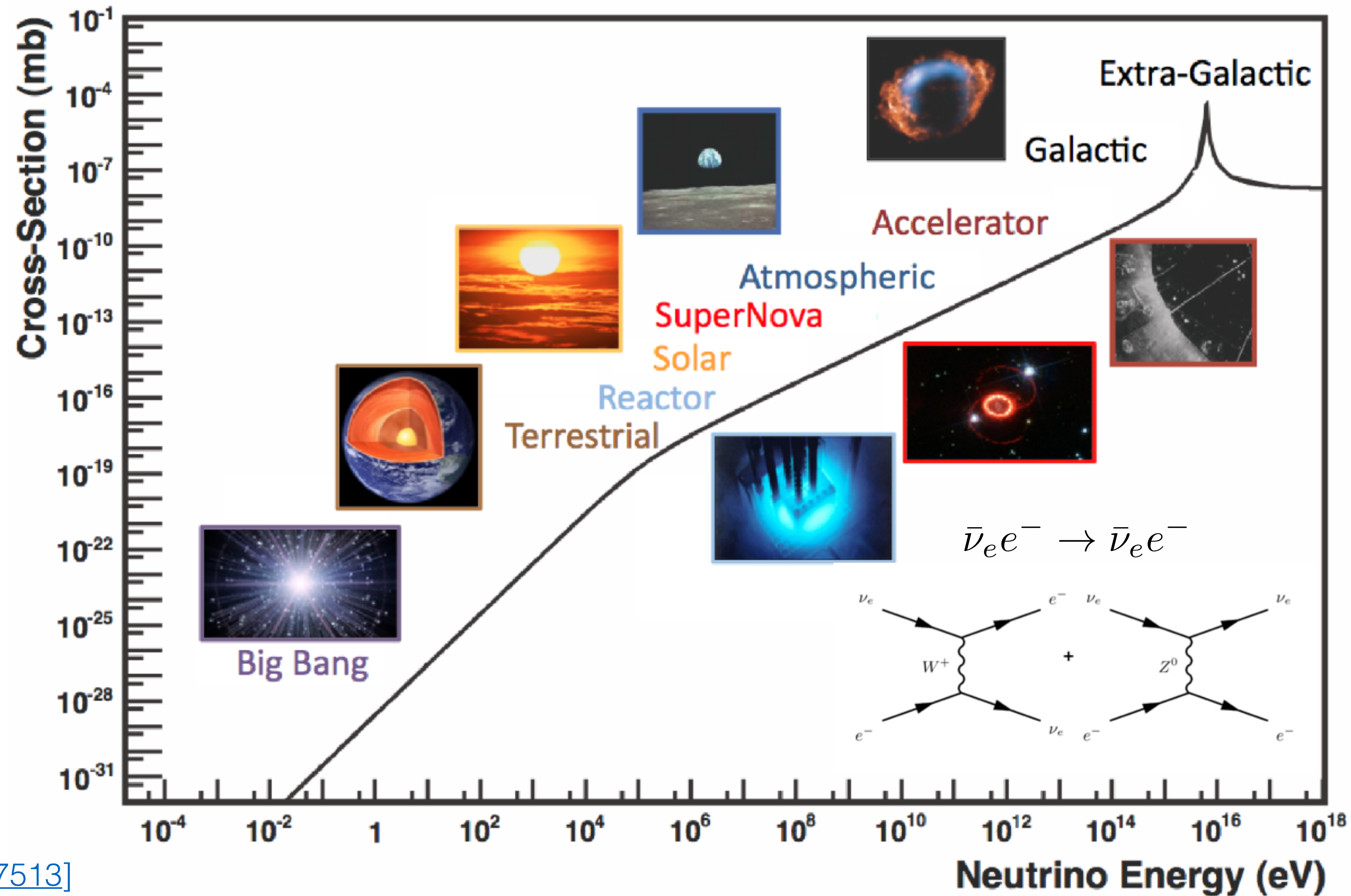


Q: Neutrino Cross-section?

Interaction length in water (at ultra-high energies):

$$\lambda = (n_e \sigma)^{-1} \sim 10^8 \text{ m}$$

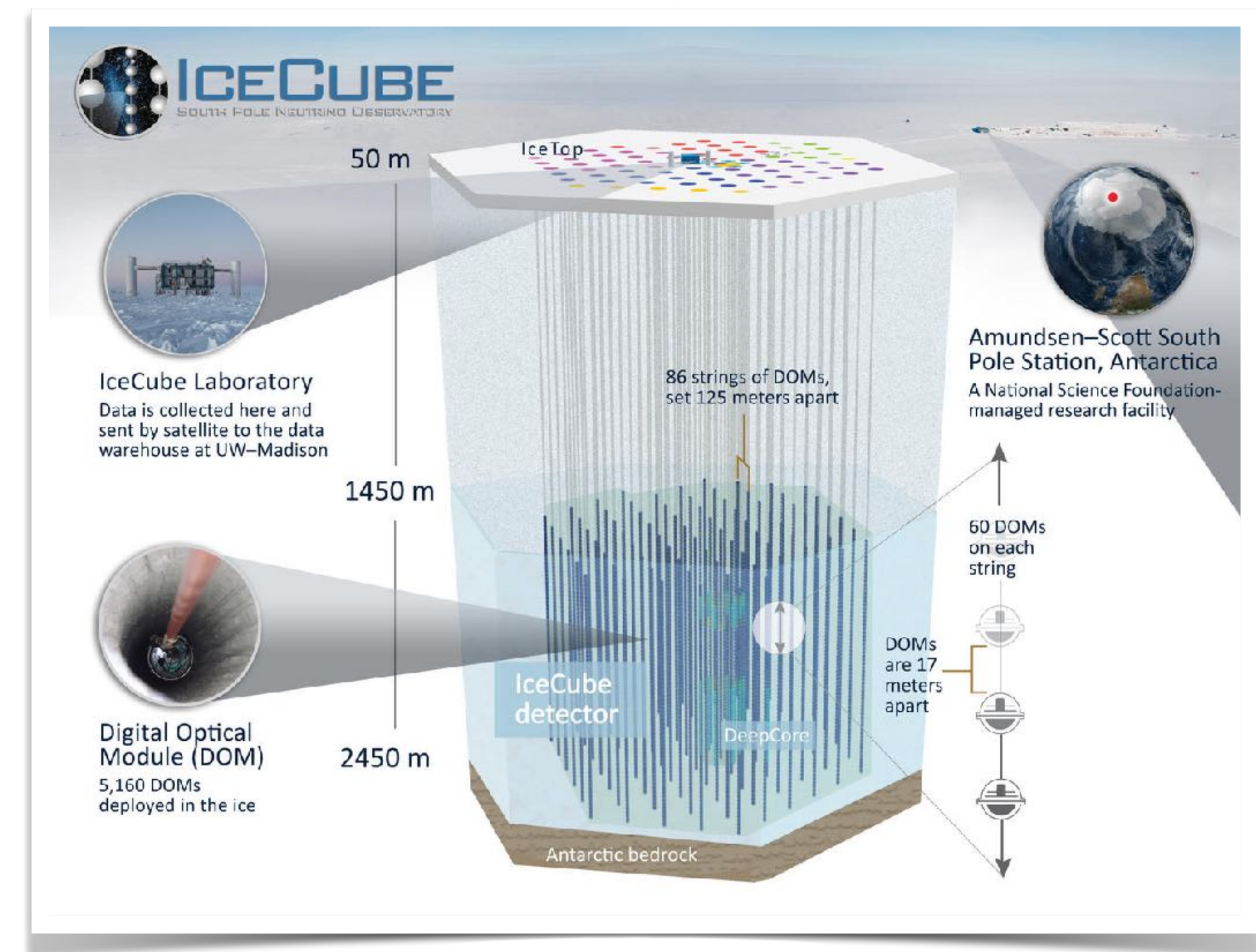
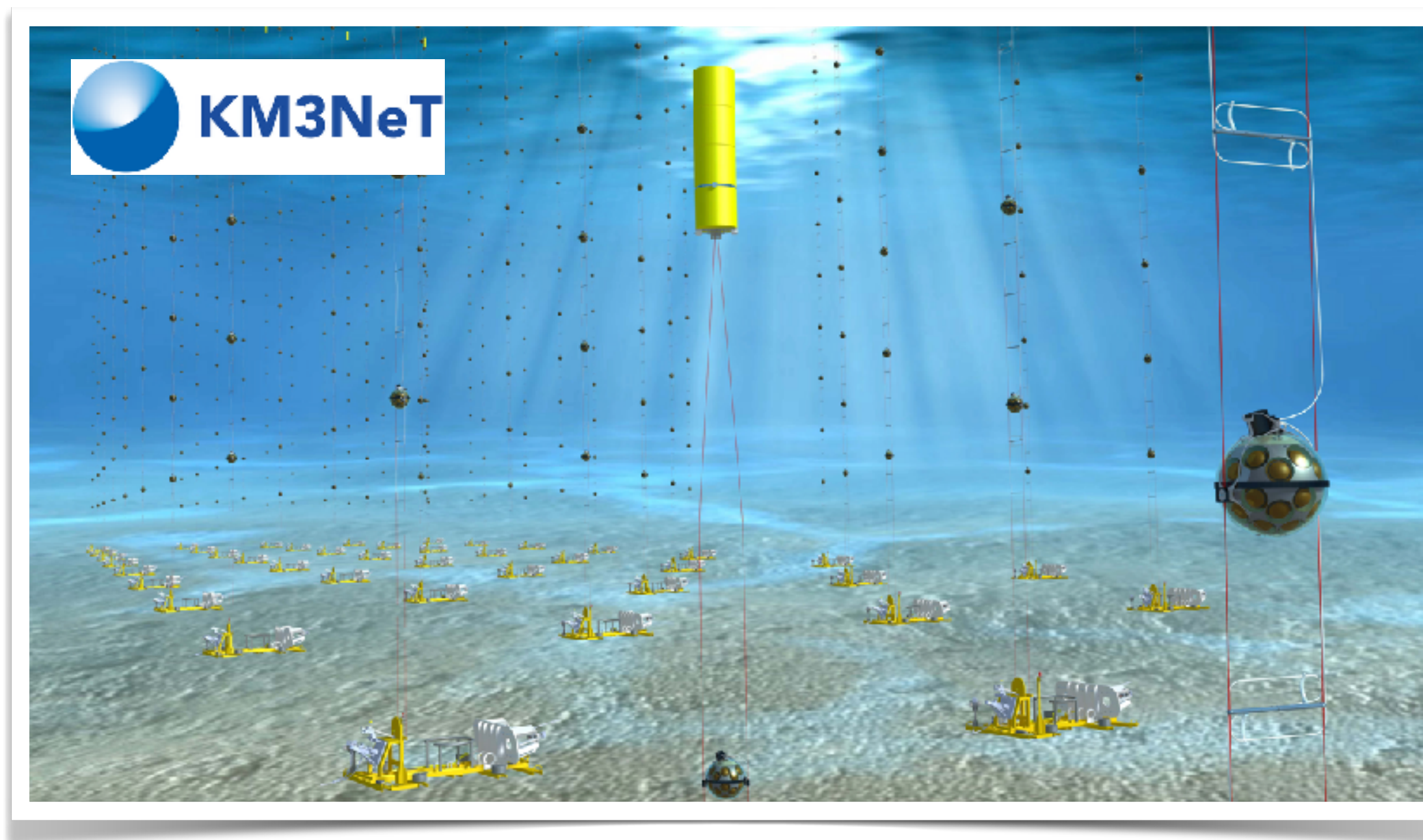
$$1 \text{ mb} = 10^{-27} \text{ cm}^2$$



[[arXiv:1305.7513](https://arxiv.org/abs/1305.7513)]

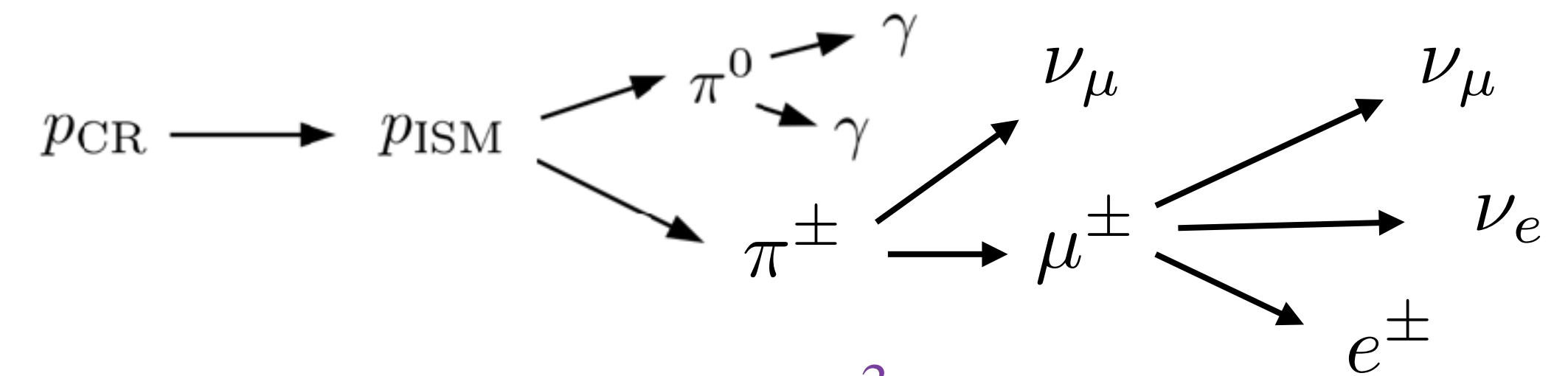
Q: Water vs Ice for neutrino detection

Light is scattered less in water, providing a better light collection and better angular resolution...



But ice has lower levels of background light (no bioluminescence, and radioactive decays)

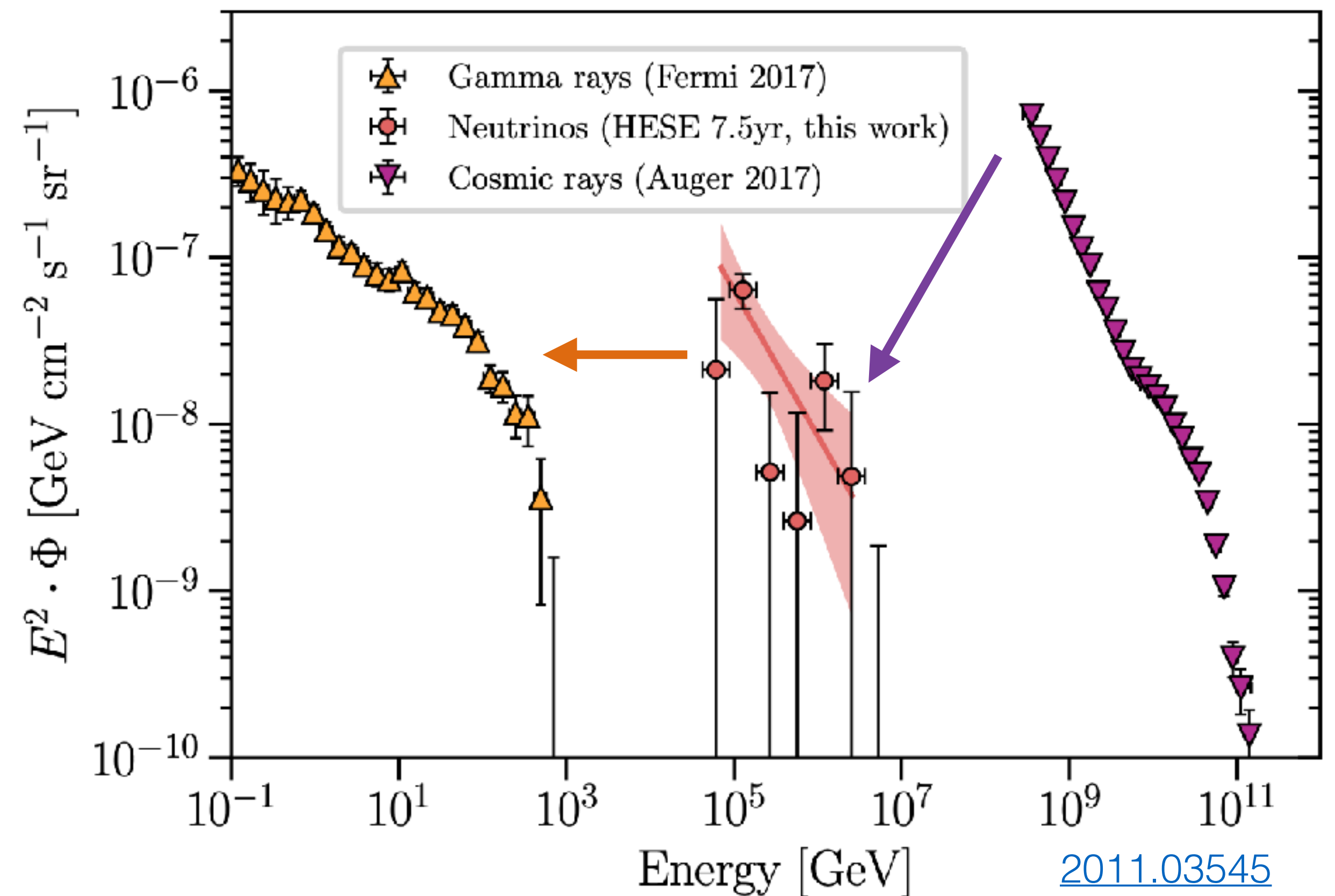
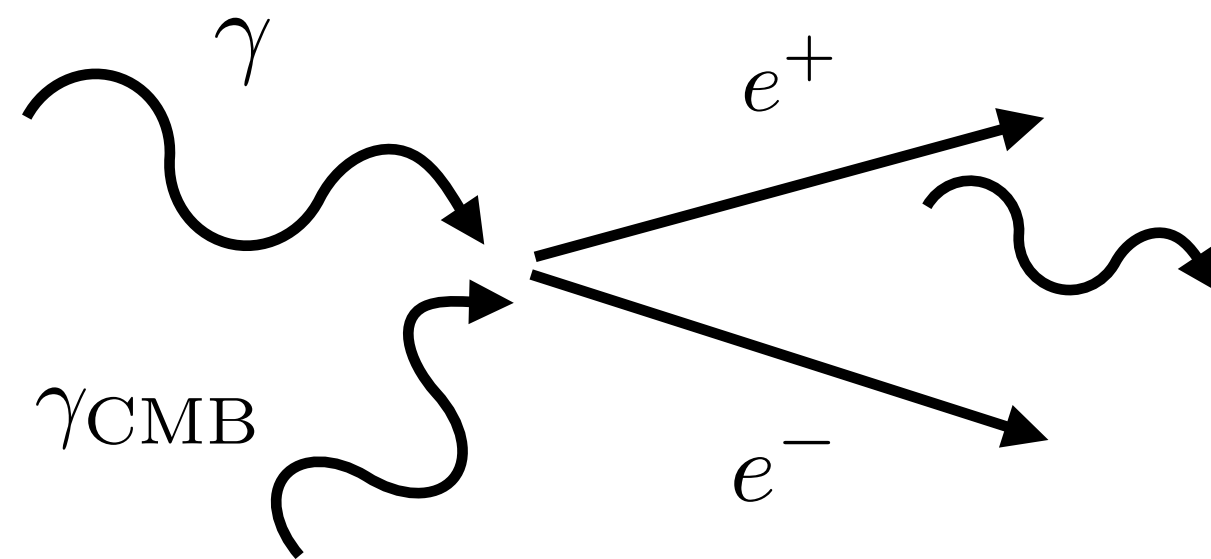
Q: CR, neutrino and γ -ray energies?



For CR interactions with interstellar medium, **interaction probability is small (say $\lesssim 10^{-3}$)** and **only some fraction of the initial CR energy** goes into any given pion

This pp process dumps comparable energy into gamma-rays and neutrinos. [astro-ph/0606058](https://arxiv.org/abs/astro-ph/0606058)

But, PeV gamma rays are above the threshold for pair-production, so they **cascade down** to the TeV energy scale



*Note that not all processes lead to substantial neutrino production (e.g. inverse compton)