

(An introduction to) Astroparticle Physics

Lecture 1/2

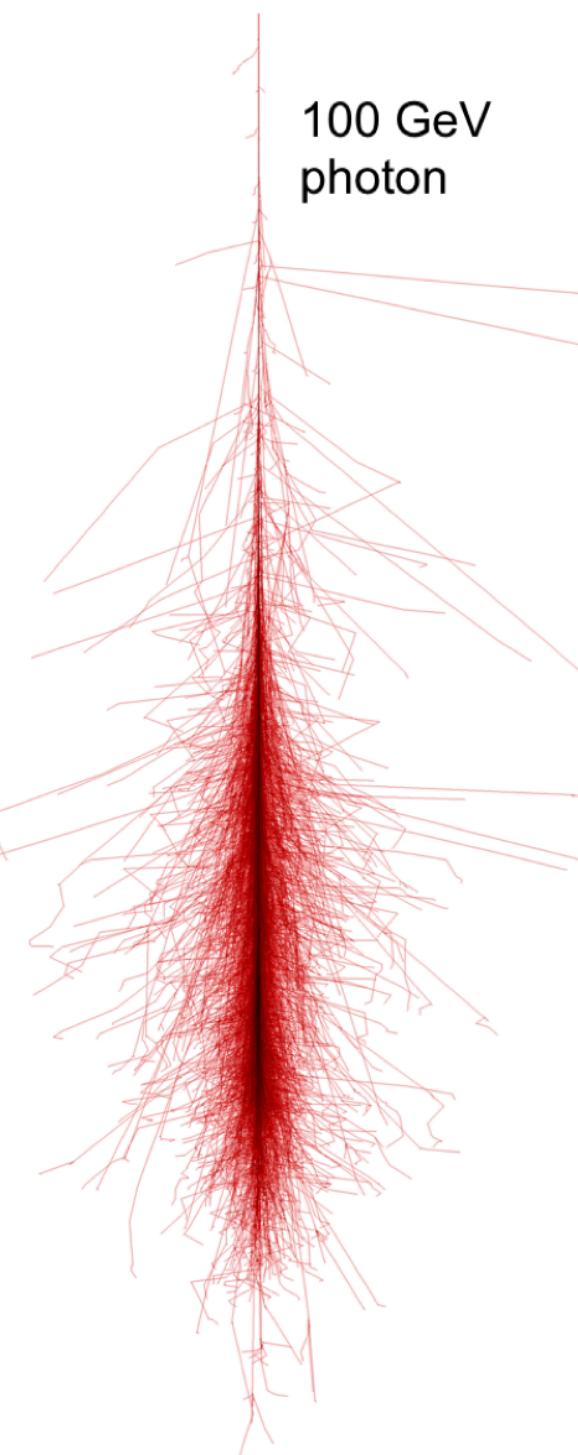
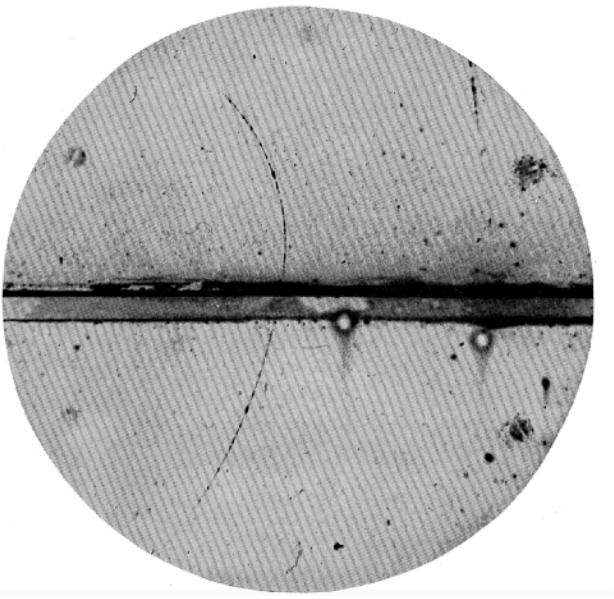
Bradley J Kavanagh [he/him]
Instituto de Fisica de Cantabria (CSIC-UC)
kavanagh@ifca.unican.es

CERN Summer Student Lecture Programme:
Wednesday 19th July 2023

Slides here: bradkav.net/talks

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*

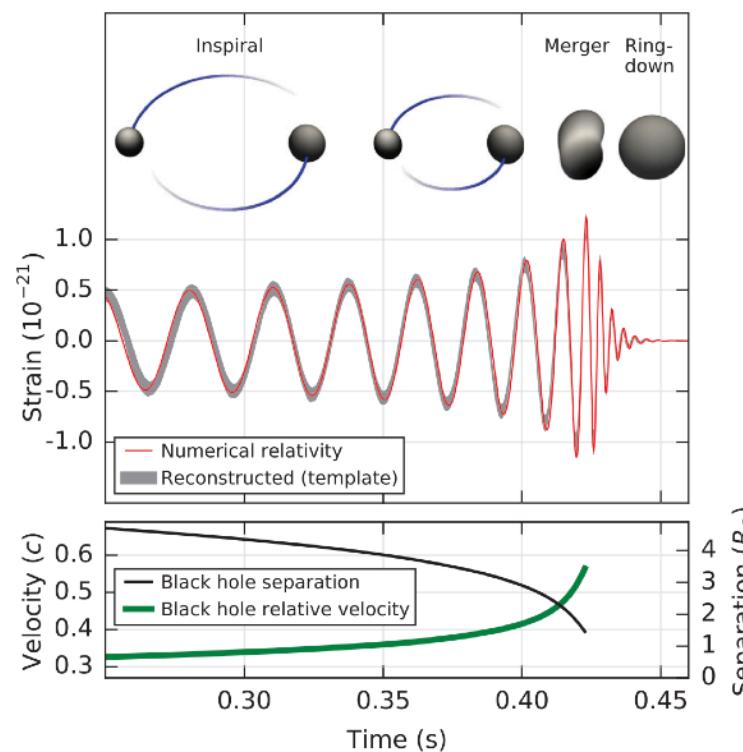
1960s: Homestake Experiment detects Solar Neutrinos (and the Solar Neutrino Problem)

1970s: The “Dark Matter” paradigm coalesces

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



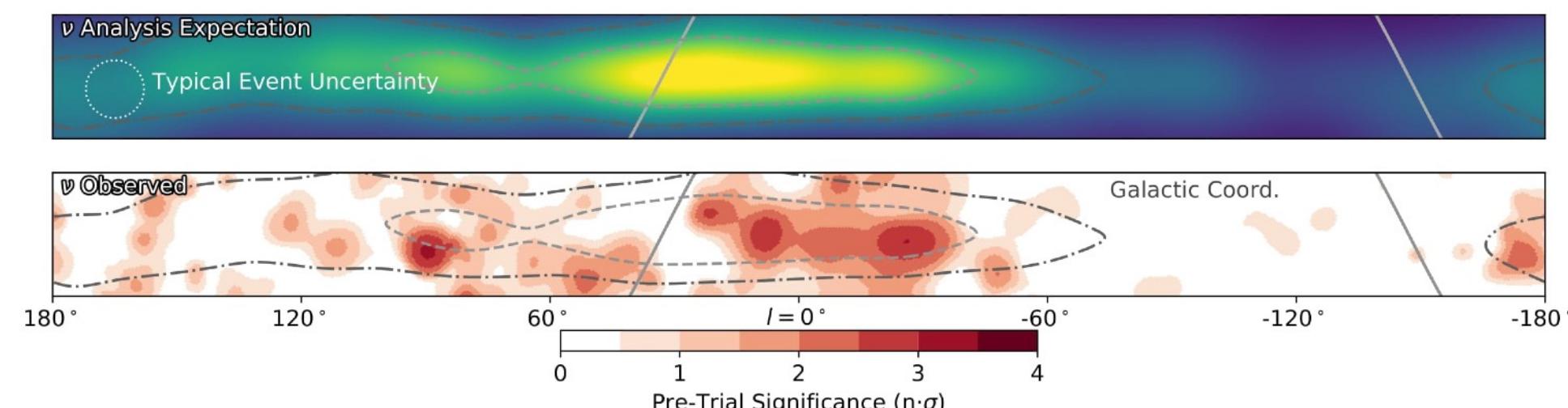
2015: GW150914 - First direct observation of GWs from Black Hole Binary Mergers



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

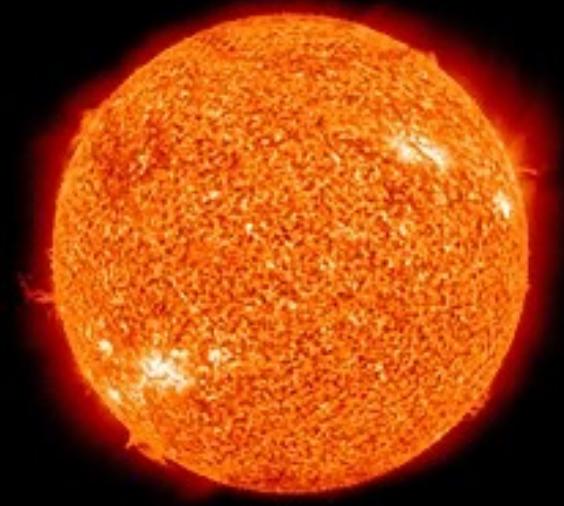
2017: GW170817 - First direct observation of GWs from Neutron Star Mergers by LVK

2023: Detection of Milky Way in Neutrinos by IceCube



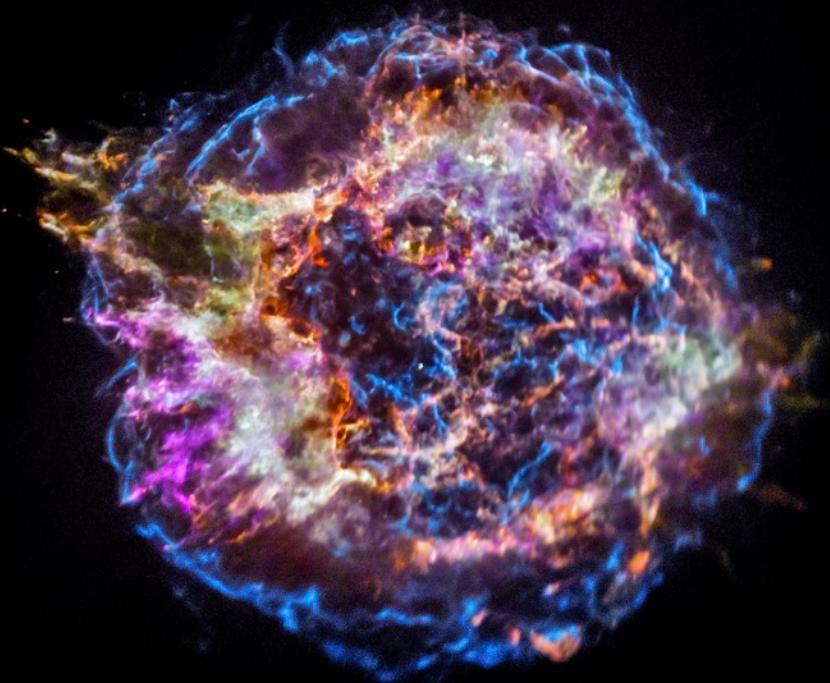
2023: NANOgrav & IPTA detect nHz Gravitational Waves

The Sun



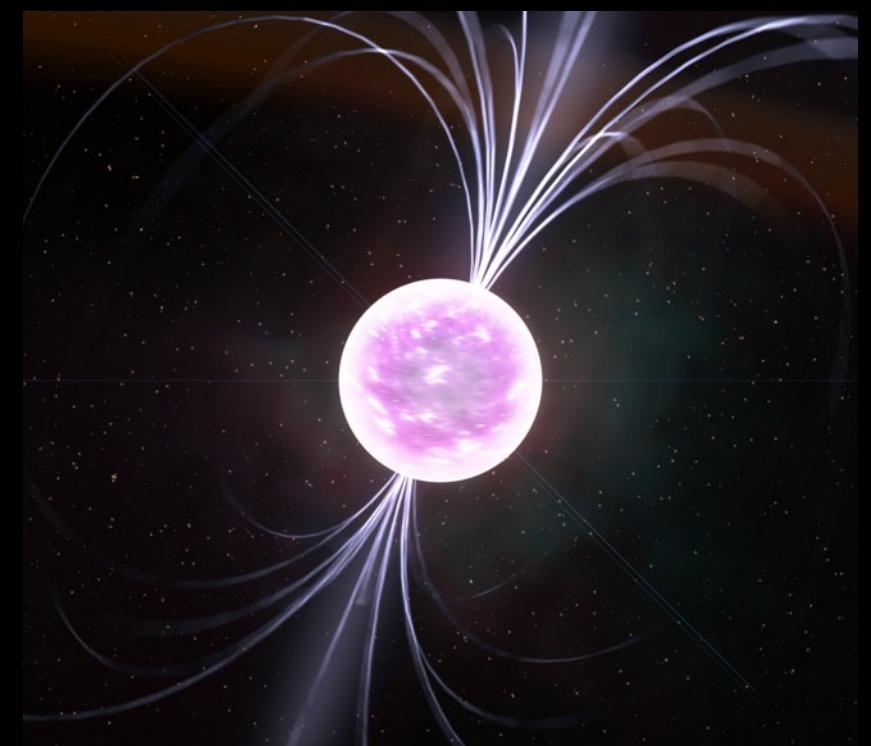
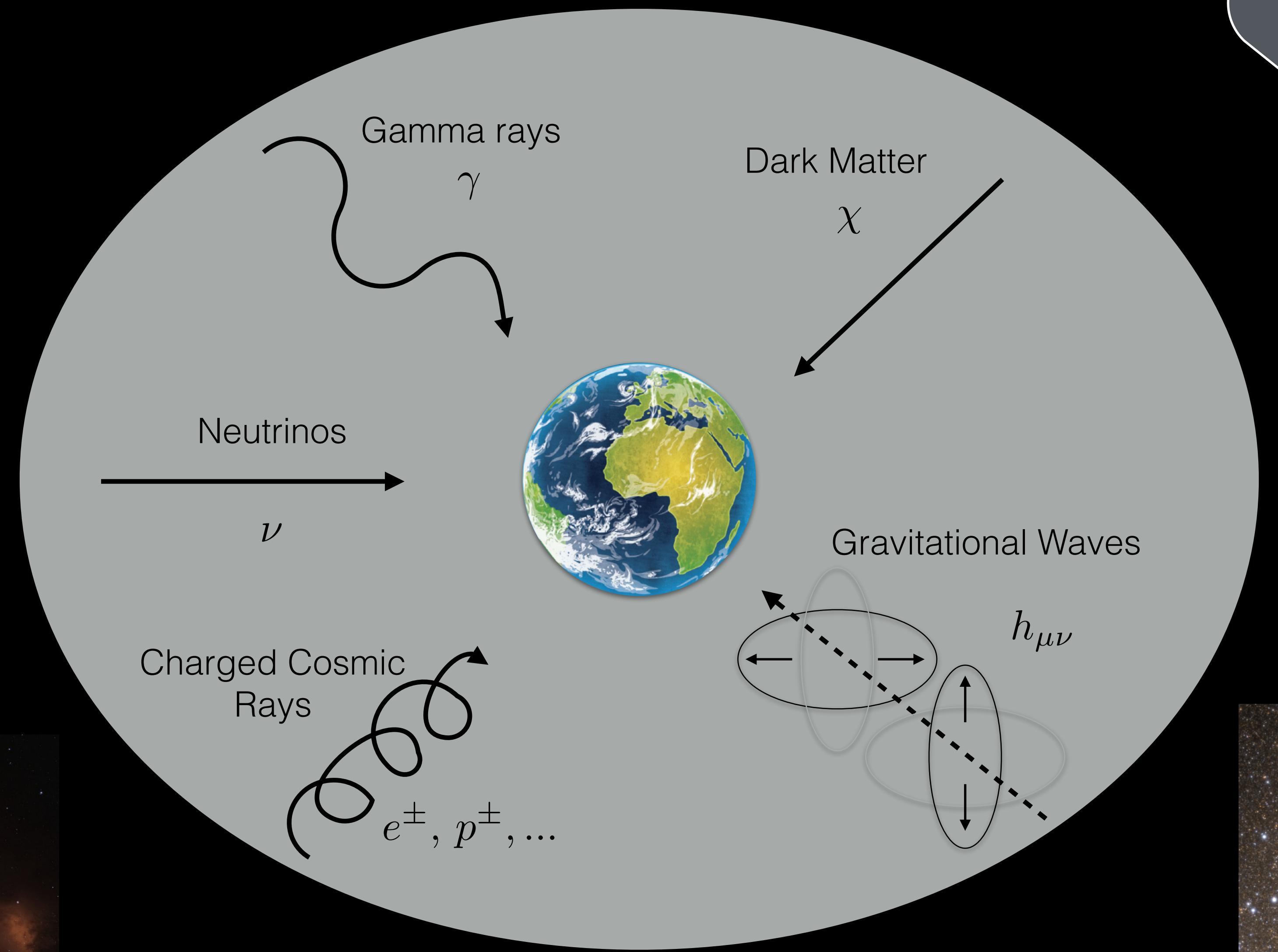
Credit: NASA/CXC/SAO

Supernovae

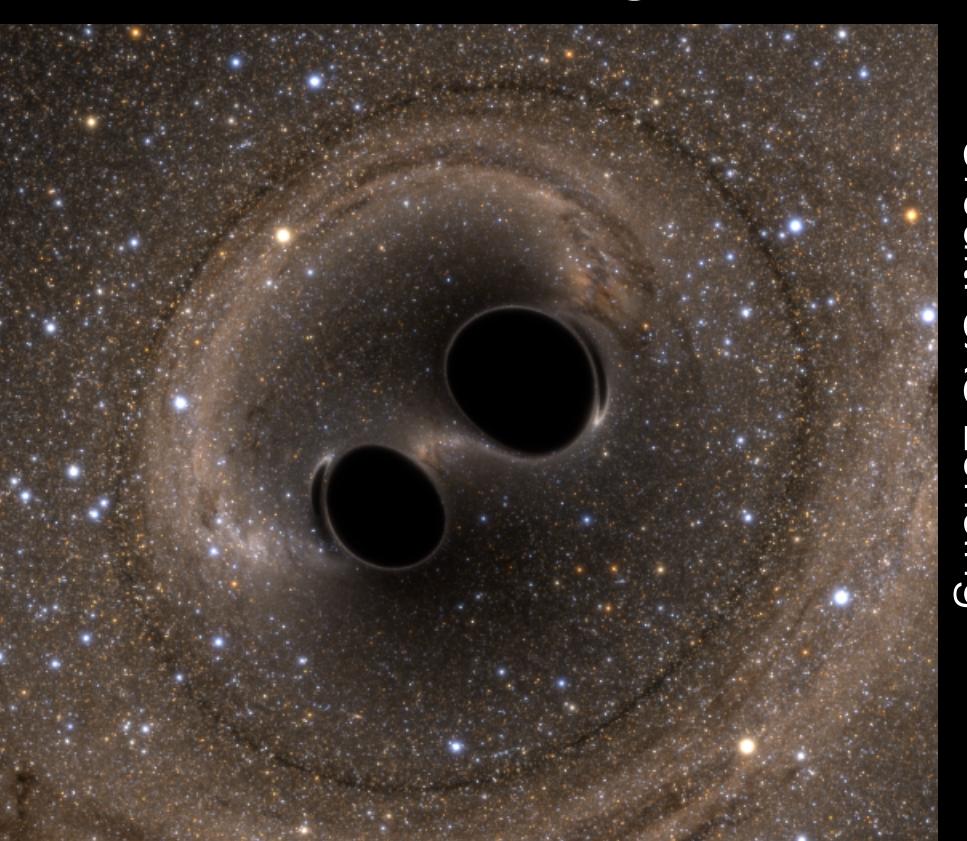


Credit: ESO/M. Kornmesser

Quasars/AGN

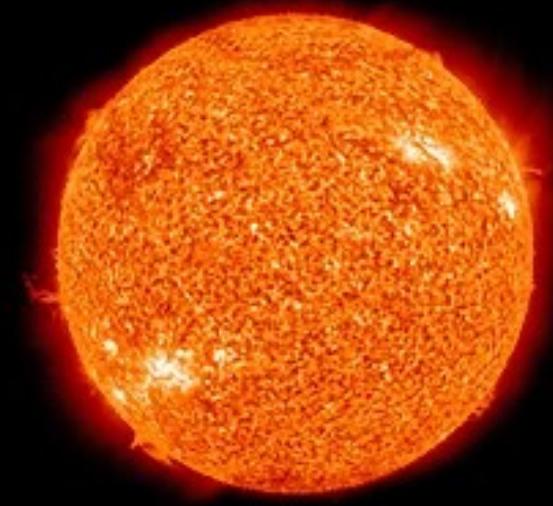


Credit: Kevin Gill / Flickr



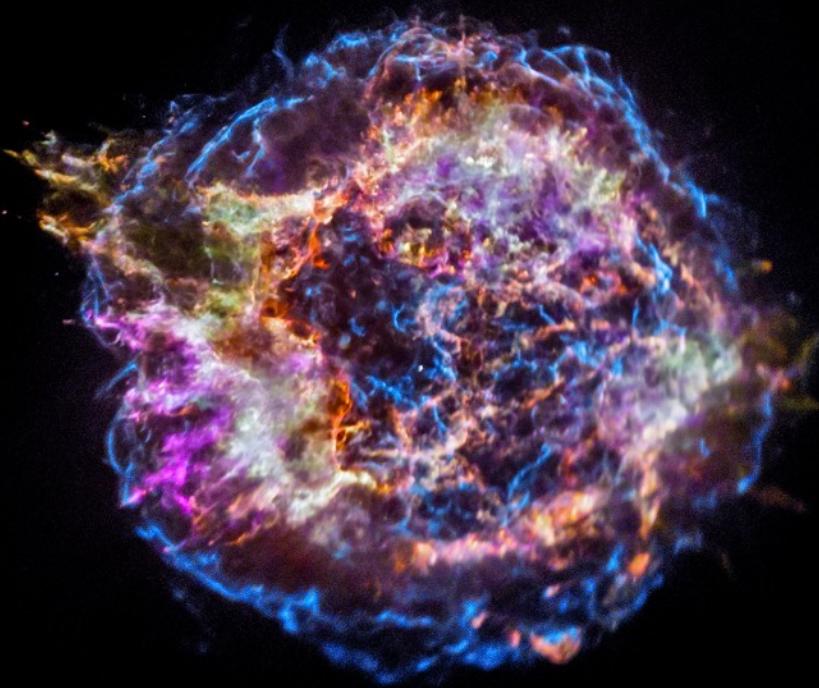
Credit: SXS Lensing

The Sun



Credit: NASA/CXC/SAO

Supernovae

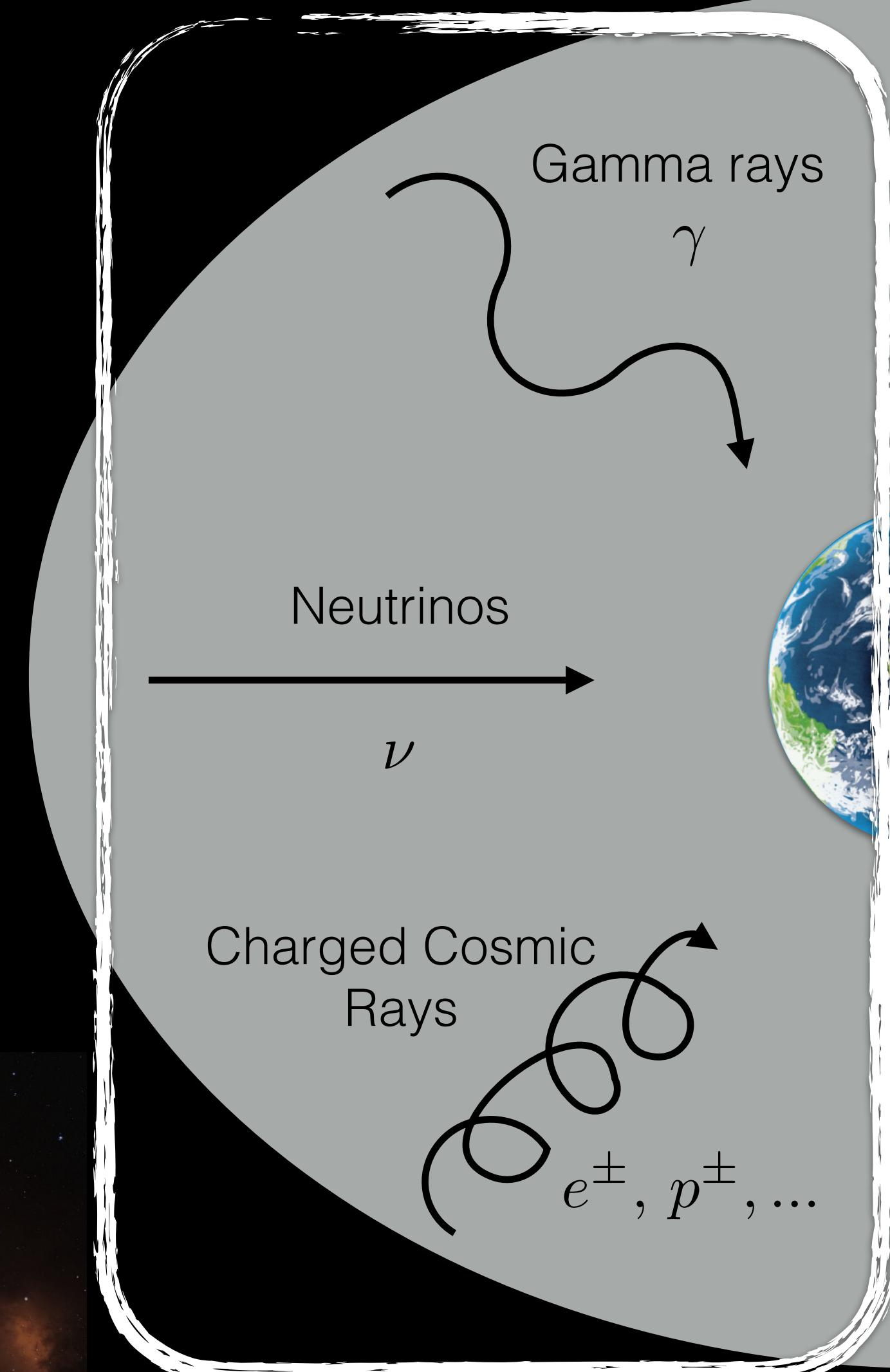


Credit: ESO/M. Kornmesser

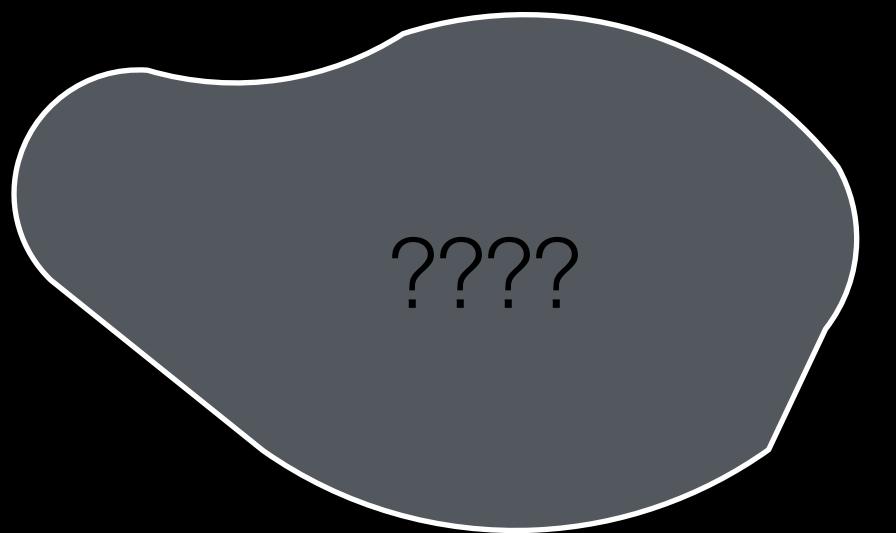
Quasars/AGN



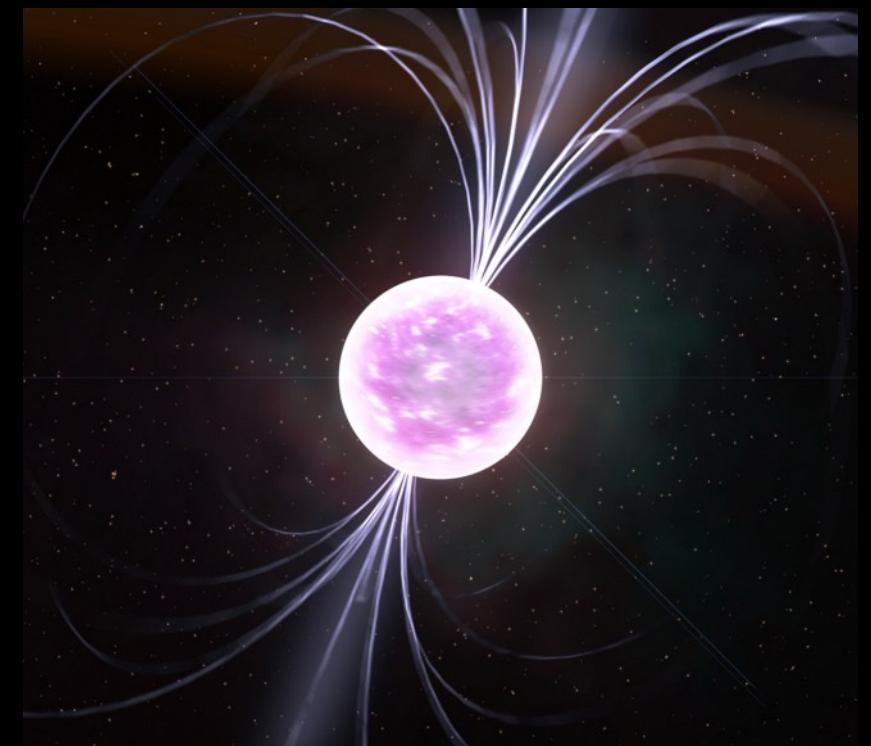
Lecture 1



Lecture 2

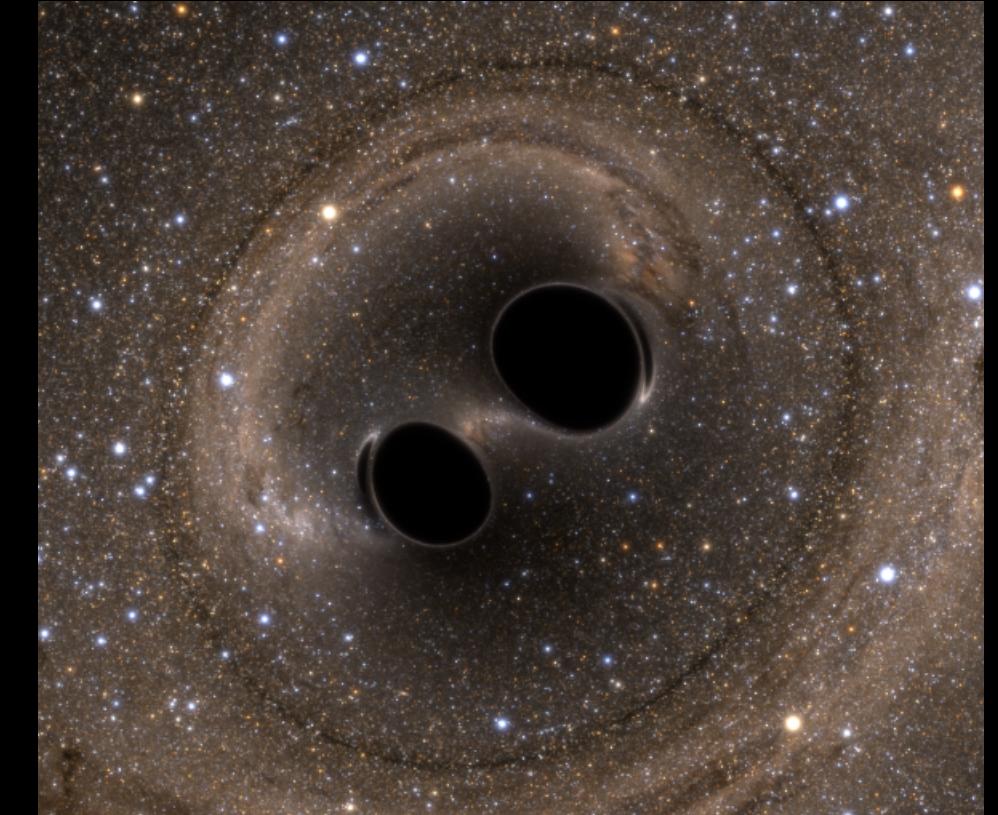


Pulsars



Credit: Kevin Gill / Flickr

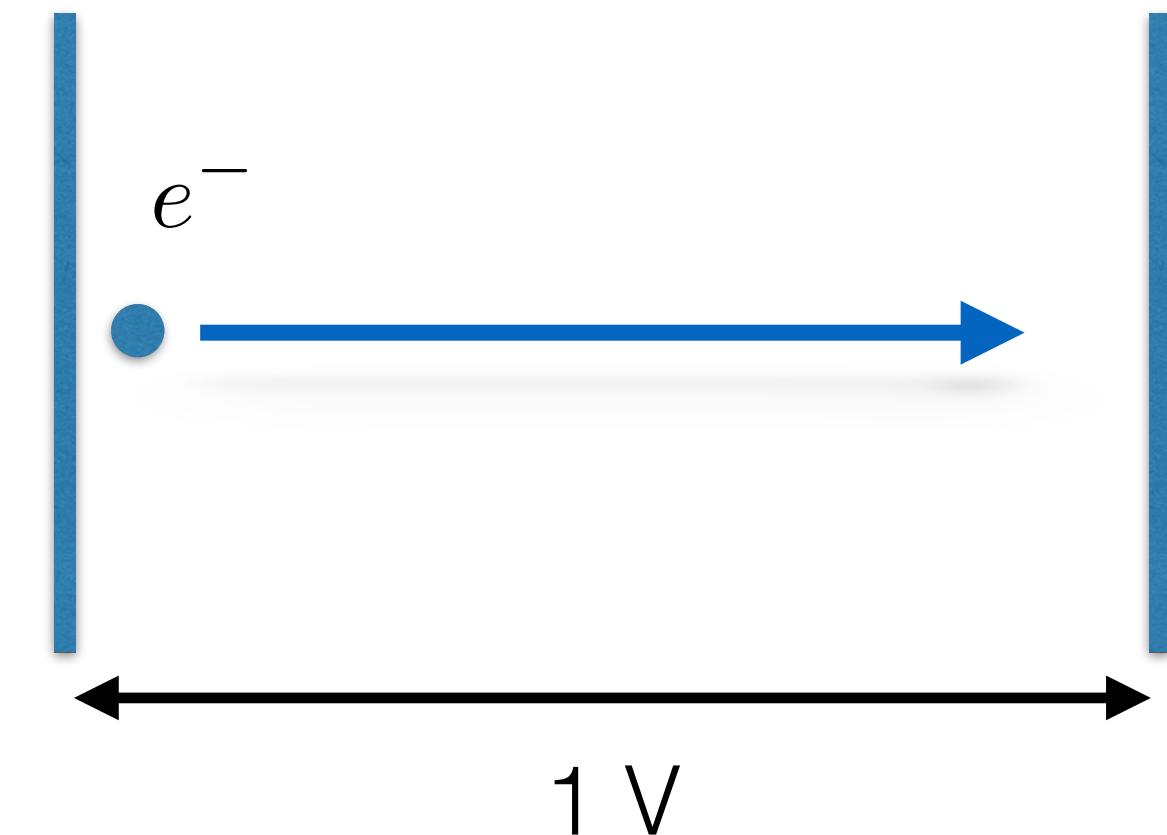
BH/NS Mergers



Credit: SXS Lensing

A huge range of energy scales...

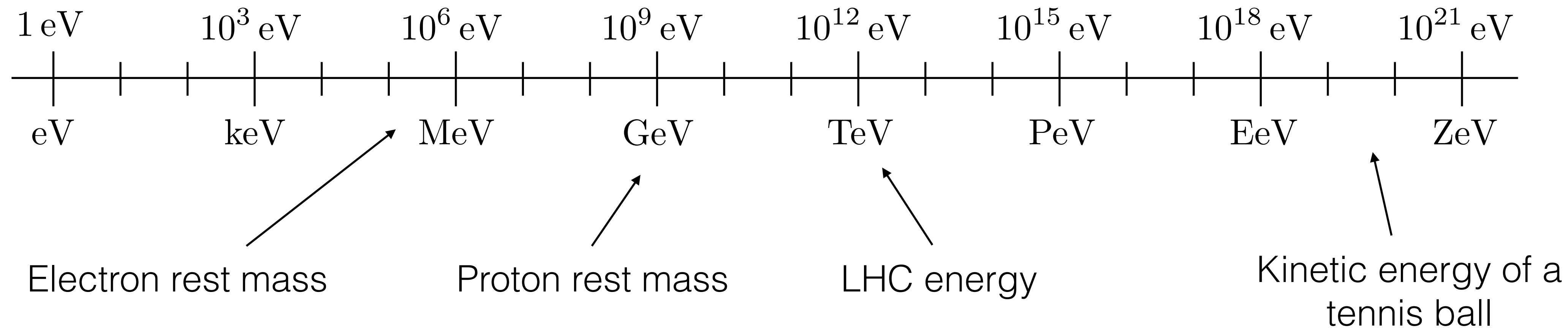
1 eV is the kinetic energy an electron gains from being accelerated across a potential of 1 V



$$1 \text{ eV} \approx 1.6 \times 10^{-19} \text{ J}$$

$$\approx 1.8 \times 10^{-36} \text{ kg}$$

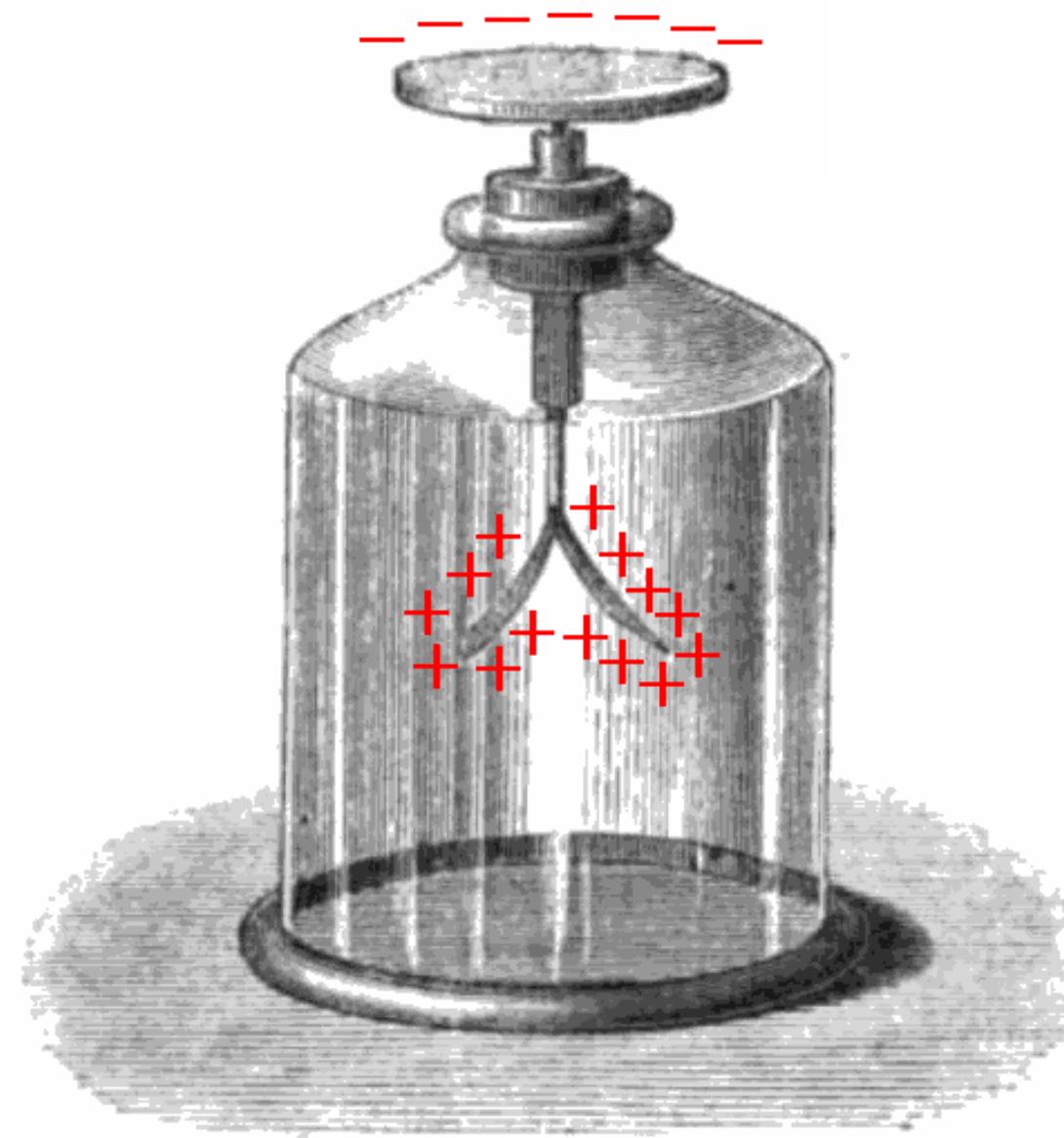
$$\approx 1.2 \times 10^4 \text{ K}$$



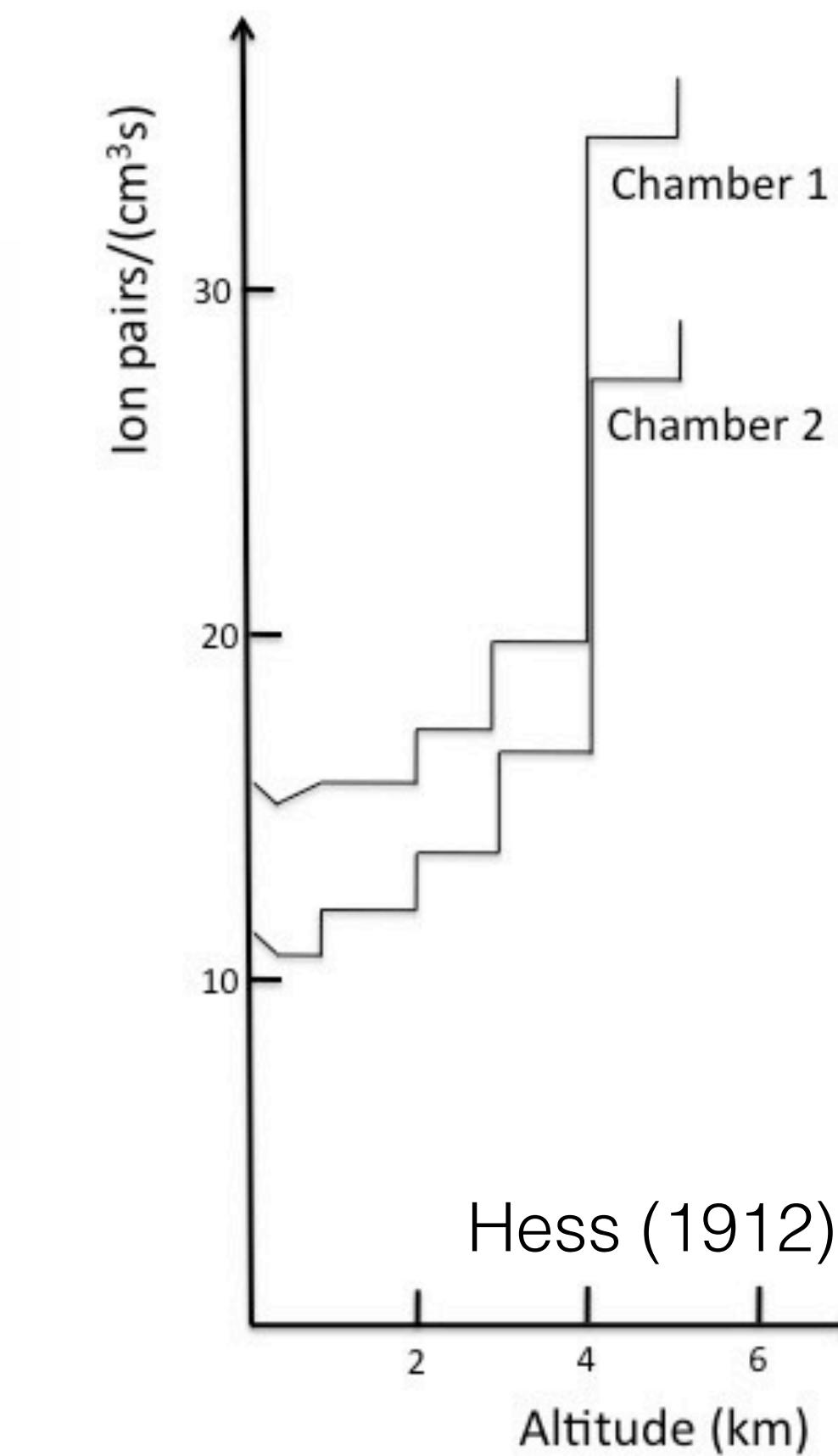
History of astroparticles



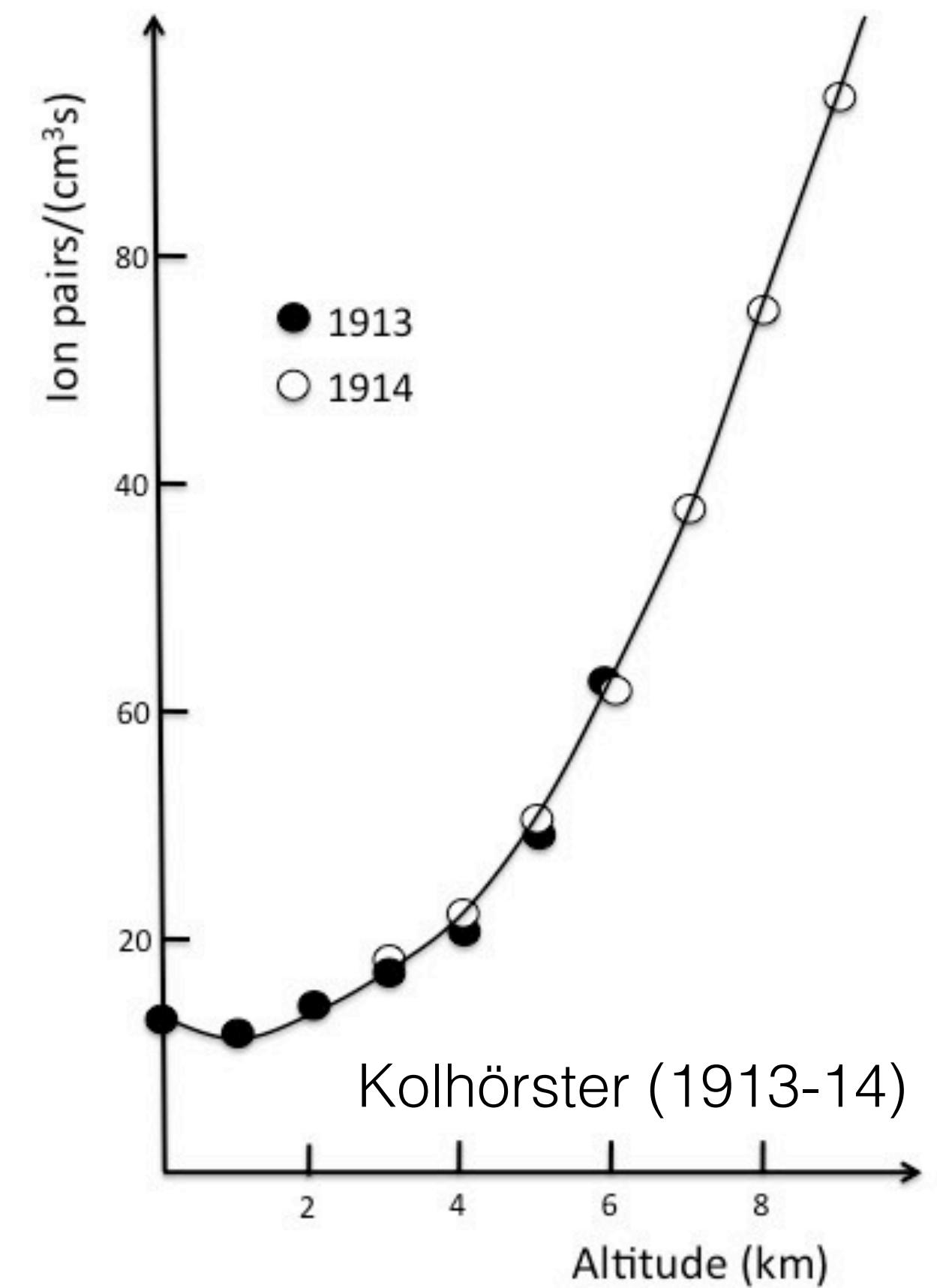
Victor Hess
(1883 - 1964)



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



Hess (1912)



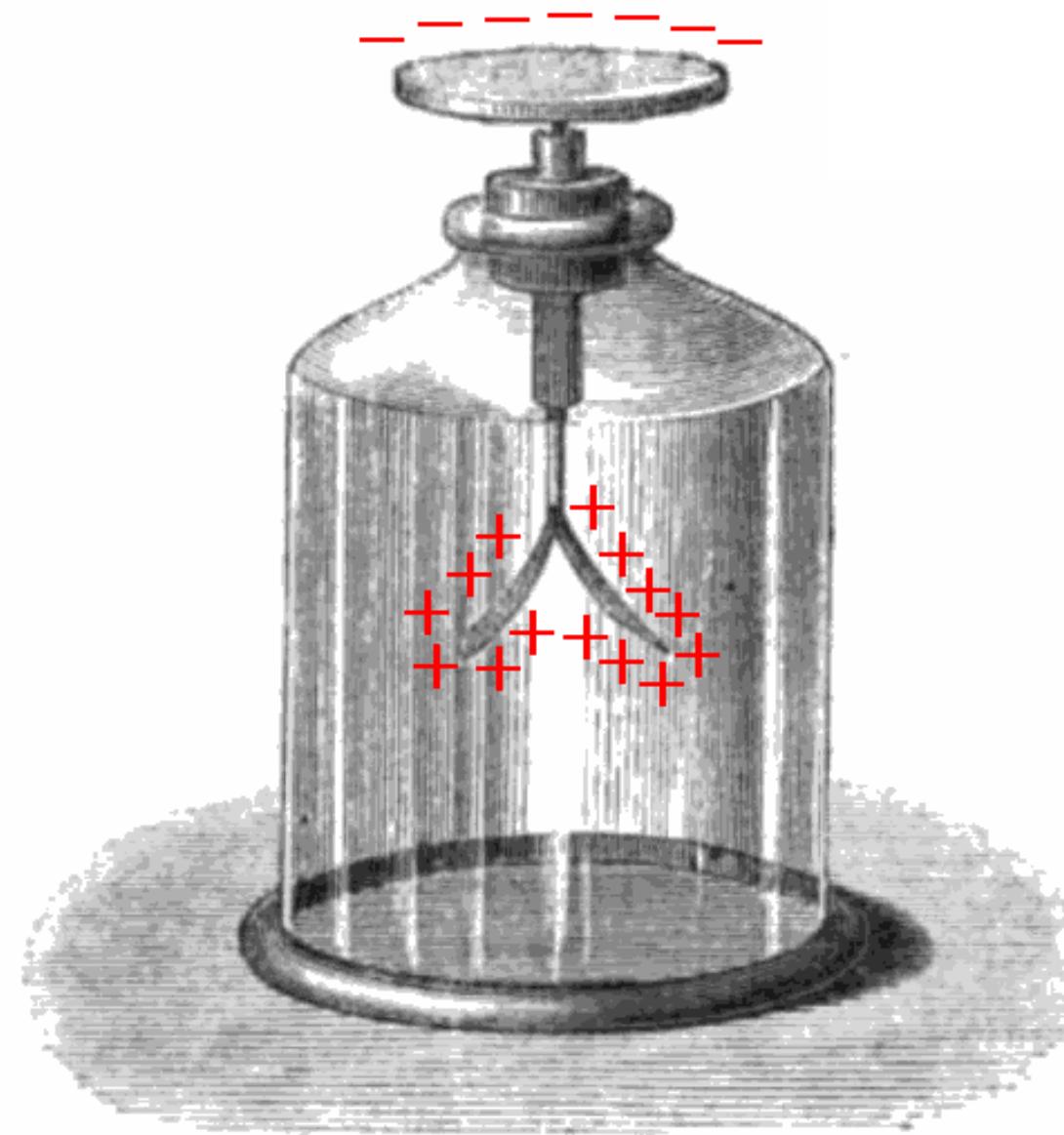
Kolhörster (1913-14)

Credit: Alessandro De Angelis

History of astroparticles

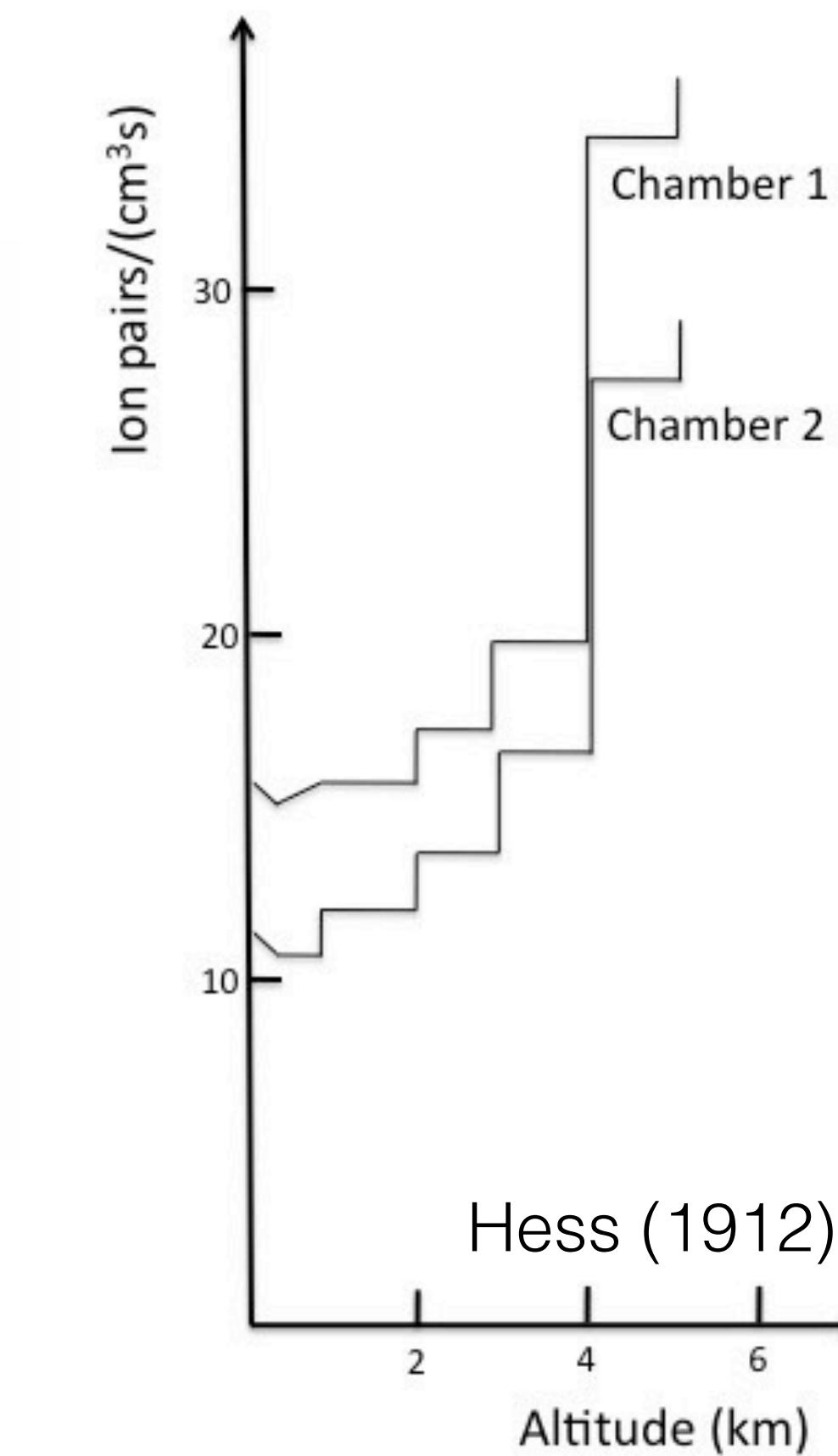


Victor Hess
(1883 - 1964)

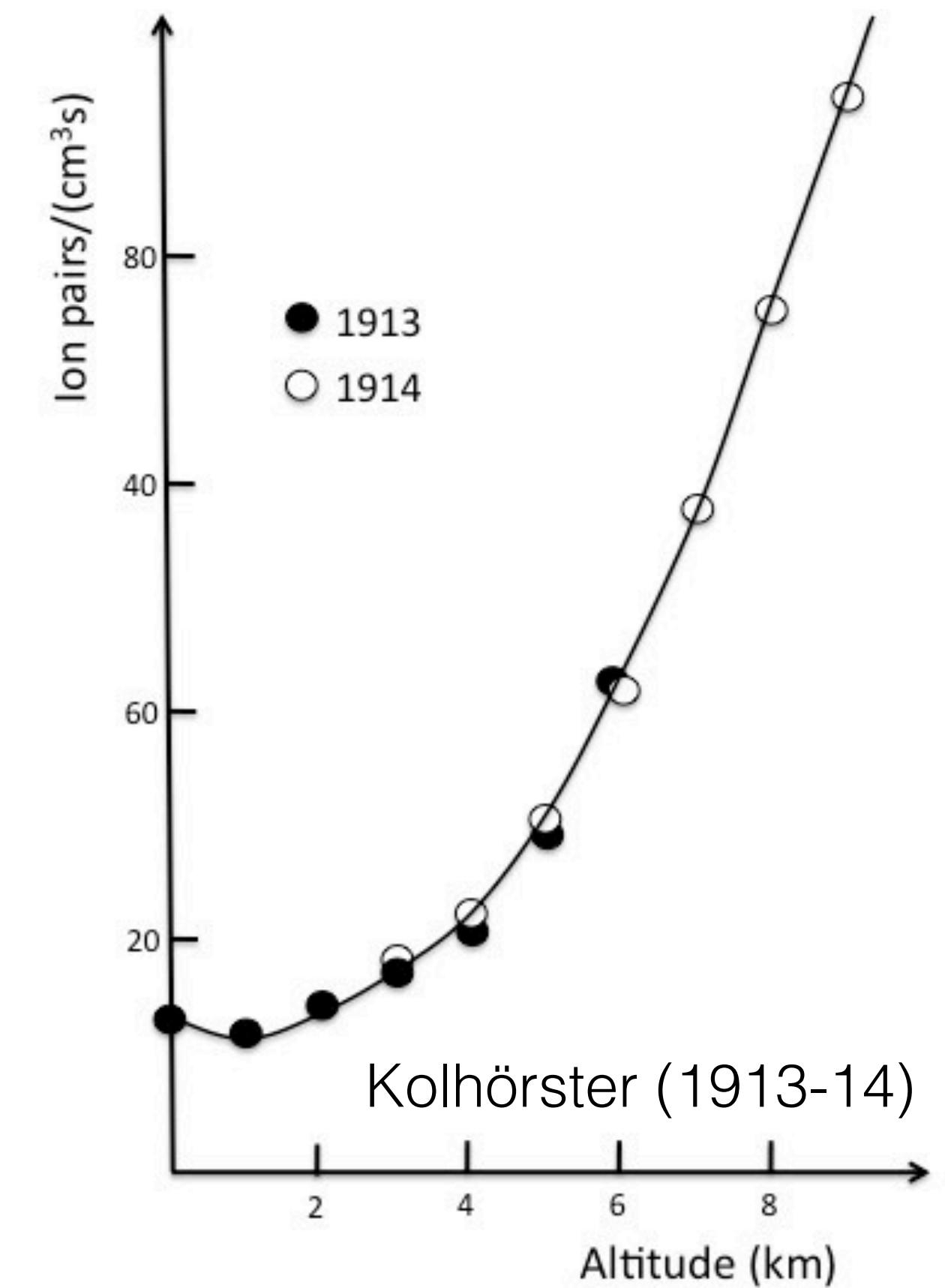


Credit: Sylvanus P. Thompson (1881),
Chetvorno (2008)

Credit: CERN



Hess (1912)

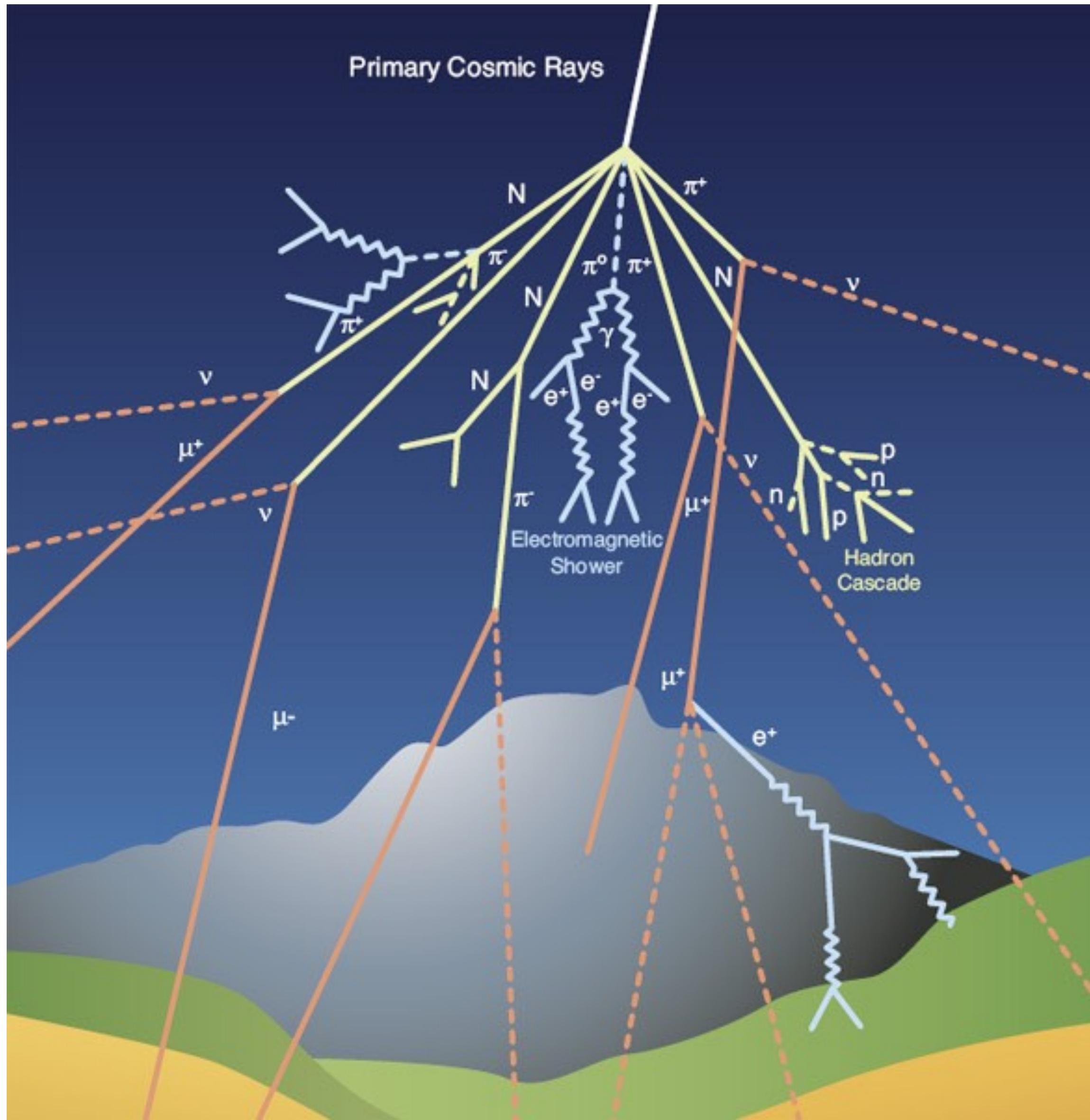


Kolhörster (1913-14)

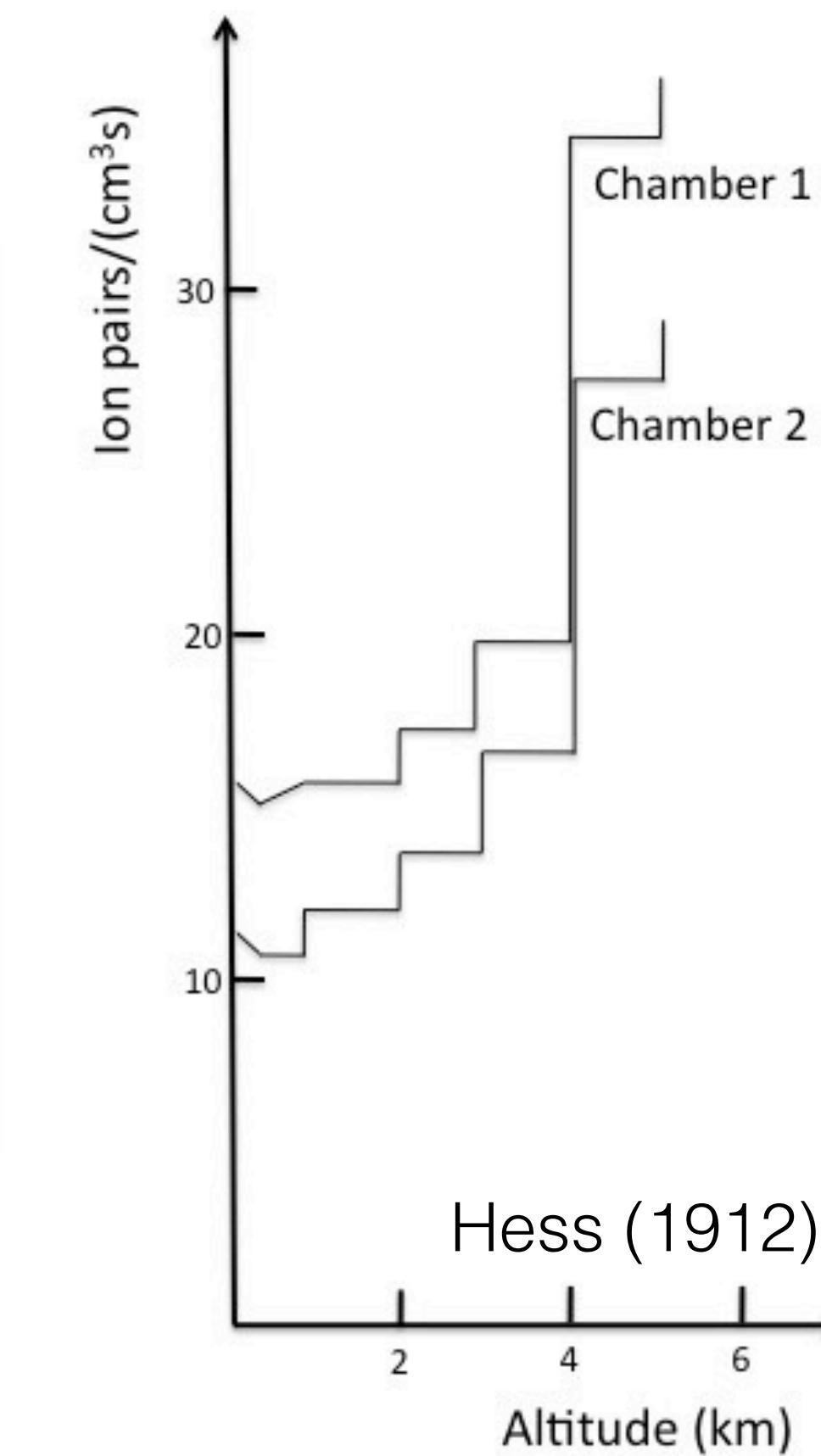
Credit: Alessandro De Angelis

History of astroparticles

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

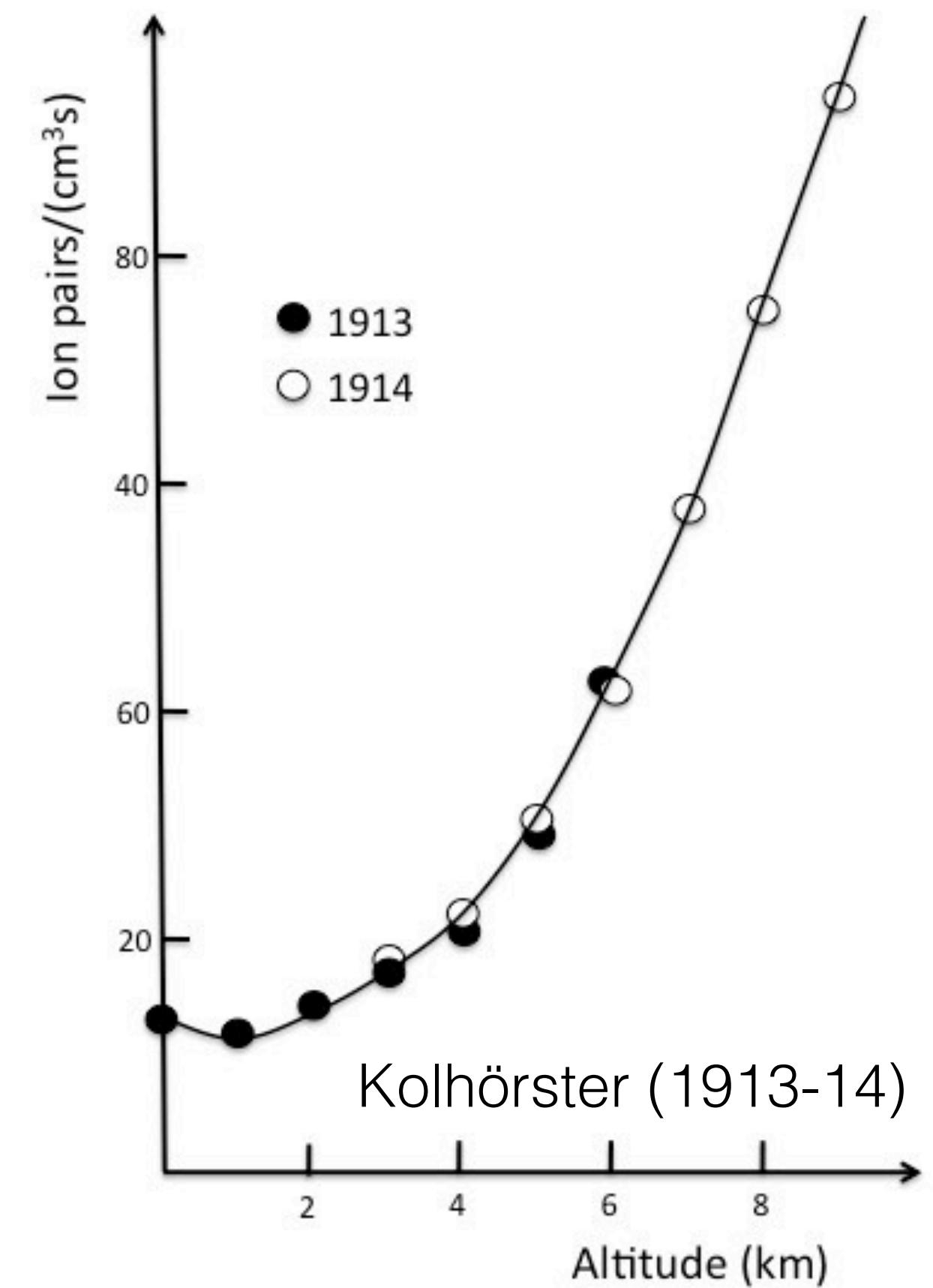


Credit: CERN



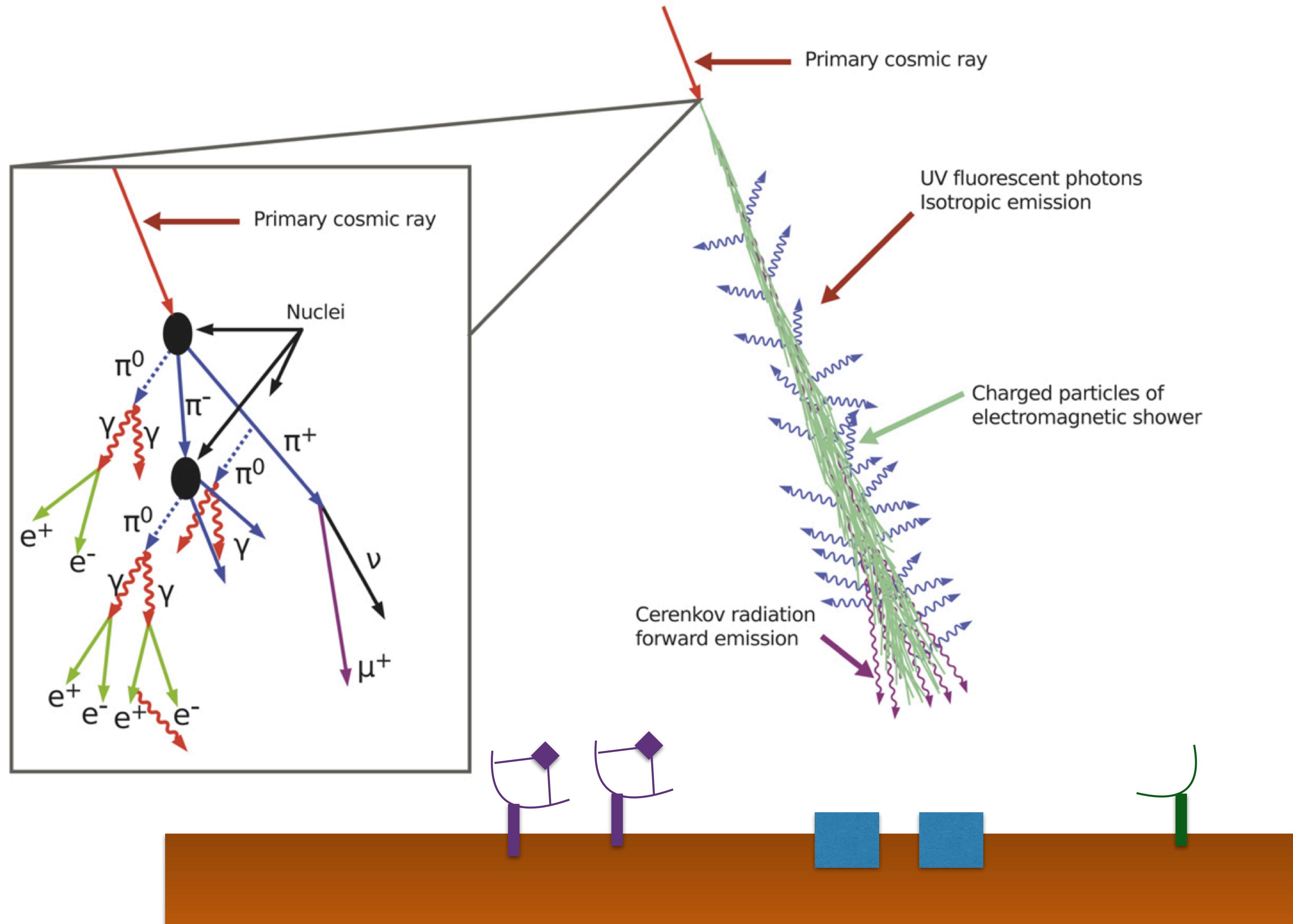
Hess (1912)

Credit: Alessandro De Angelis



Kolhörster (1913-14)

Detection of cosmic rays (Earth)



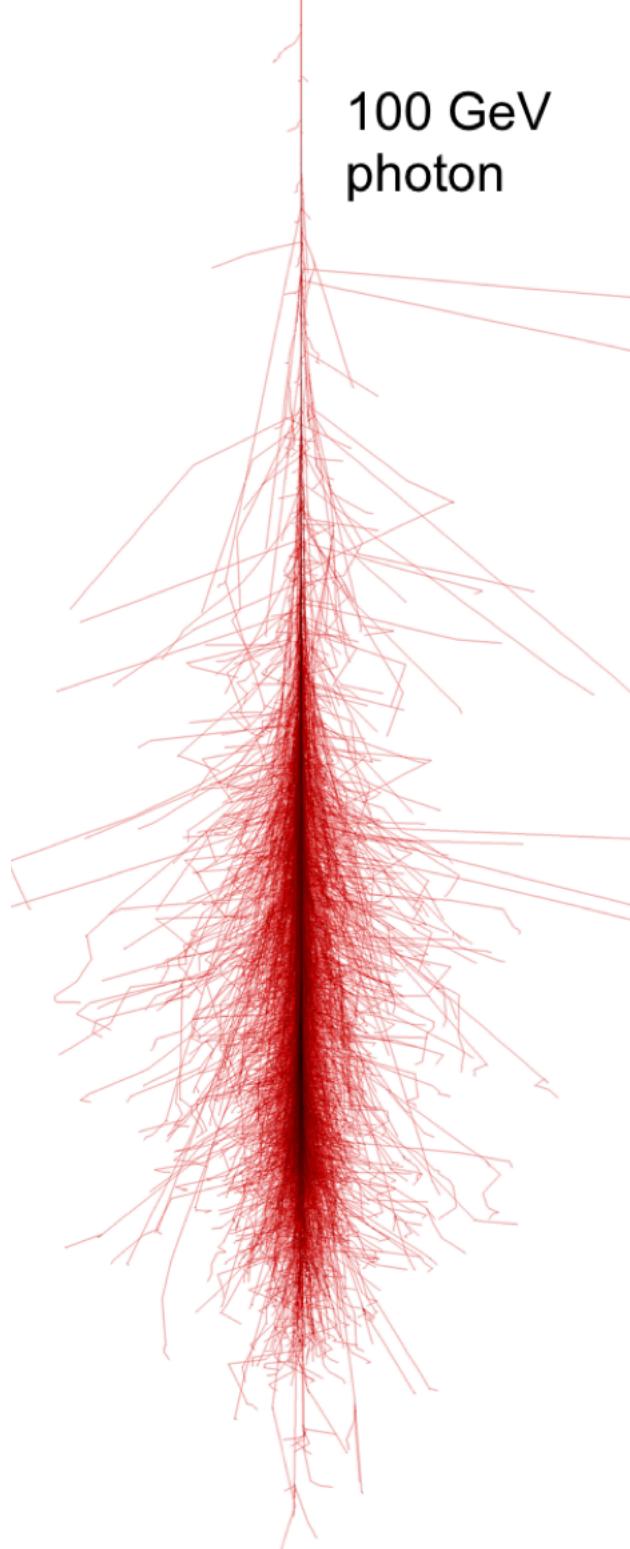
Fluorescence
(e.g. Fly's Eye, Auger observatory)

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

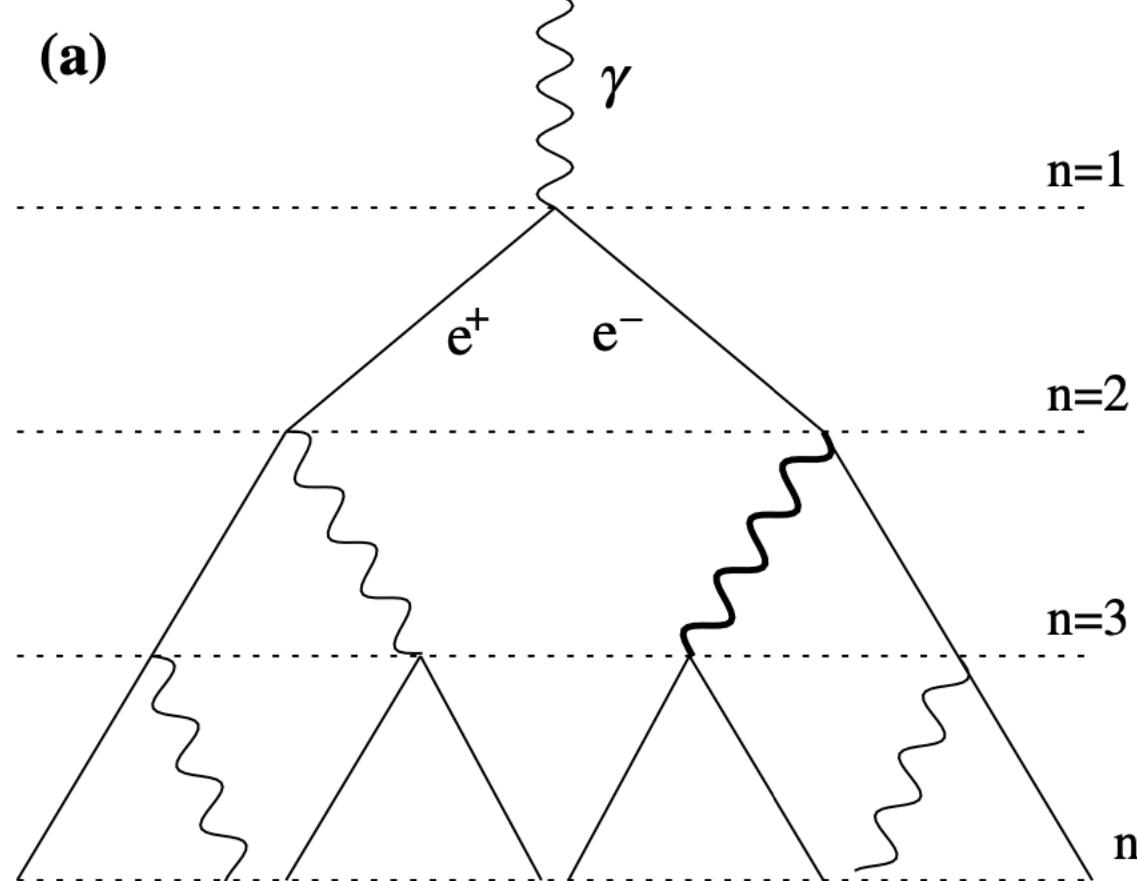
Ground array and Water Cherenkov detectors
(e.g. KASCADE-GRANDE, MILAGRO, HAWC)

Gamma rays vs Charged Cosmic rays

Gamma Rays



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



Protons/nuclei

$$E_{\text{had}} = \left(\frac{2}{3}\right)^n E_0^p$$

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

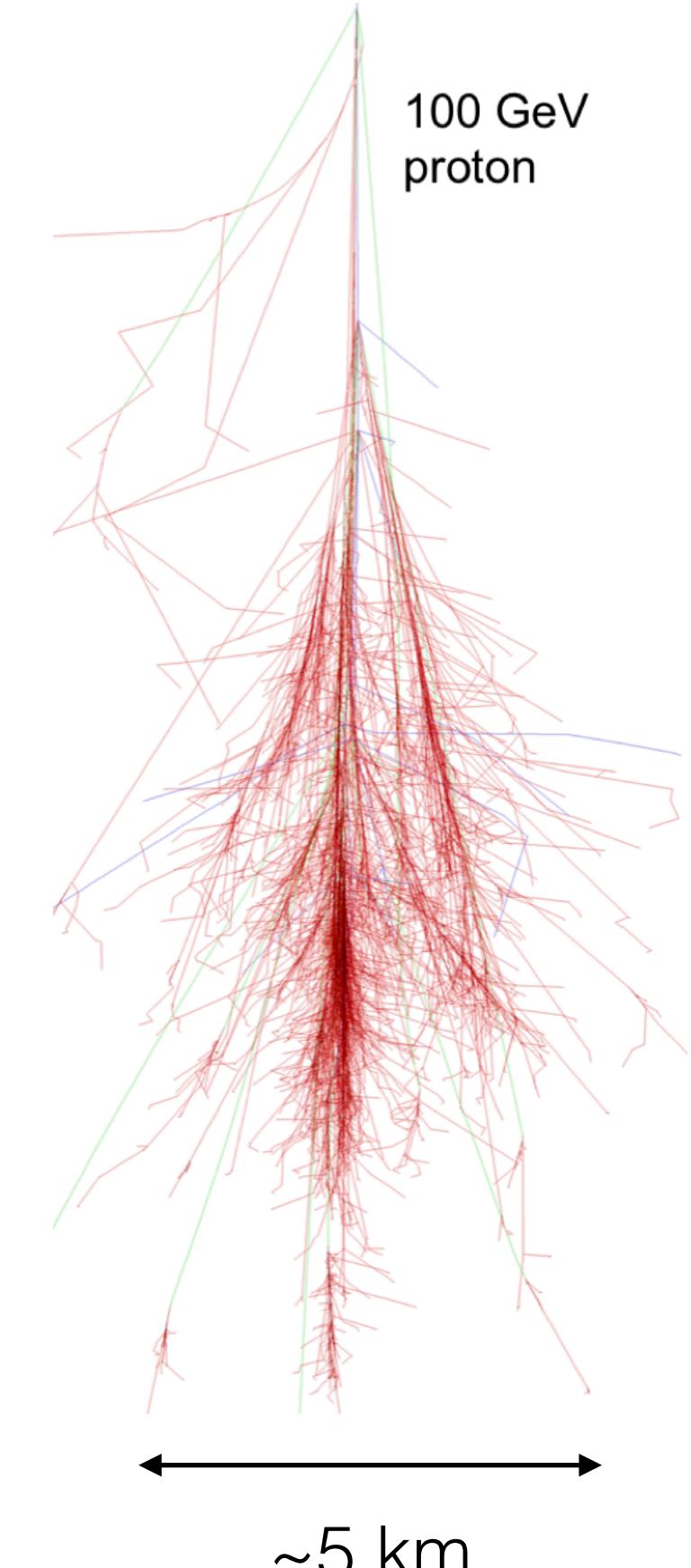
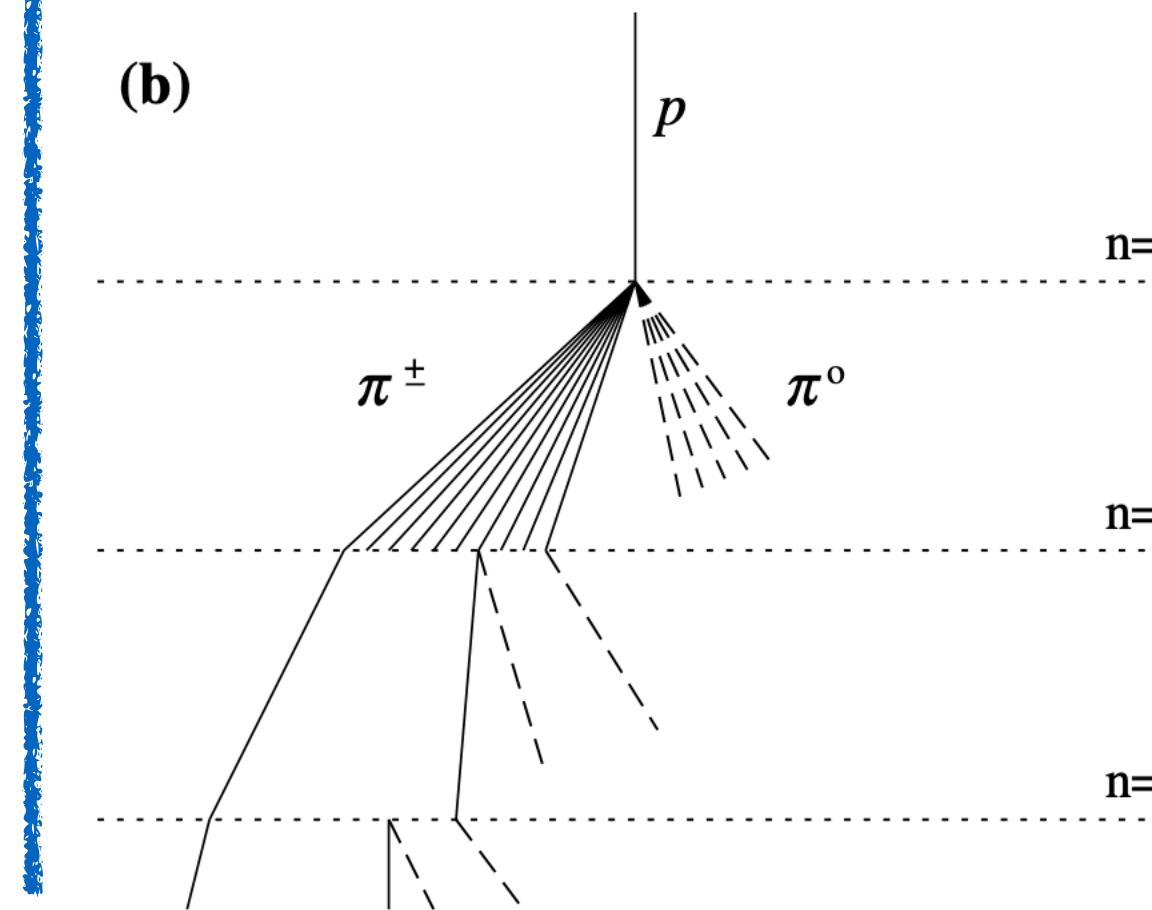


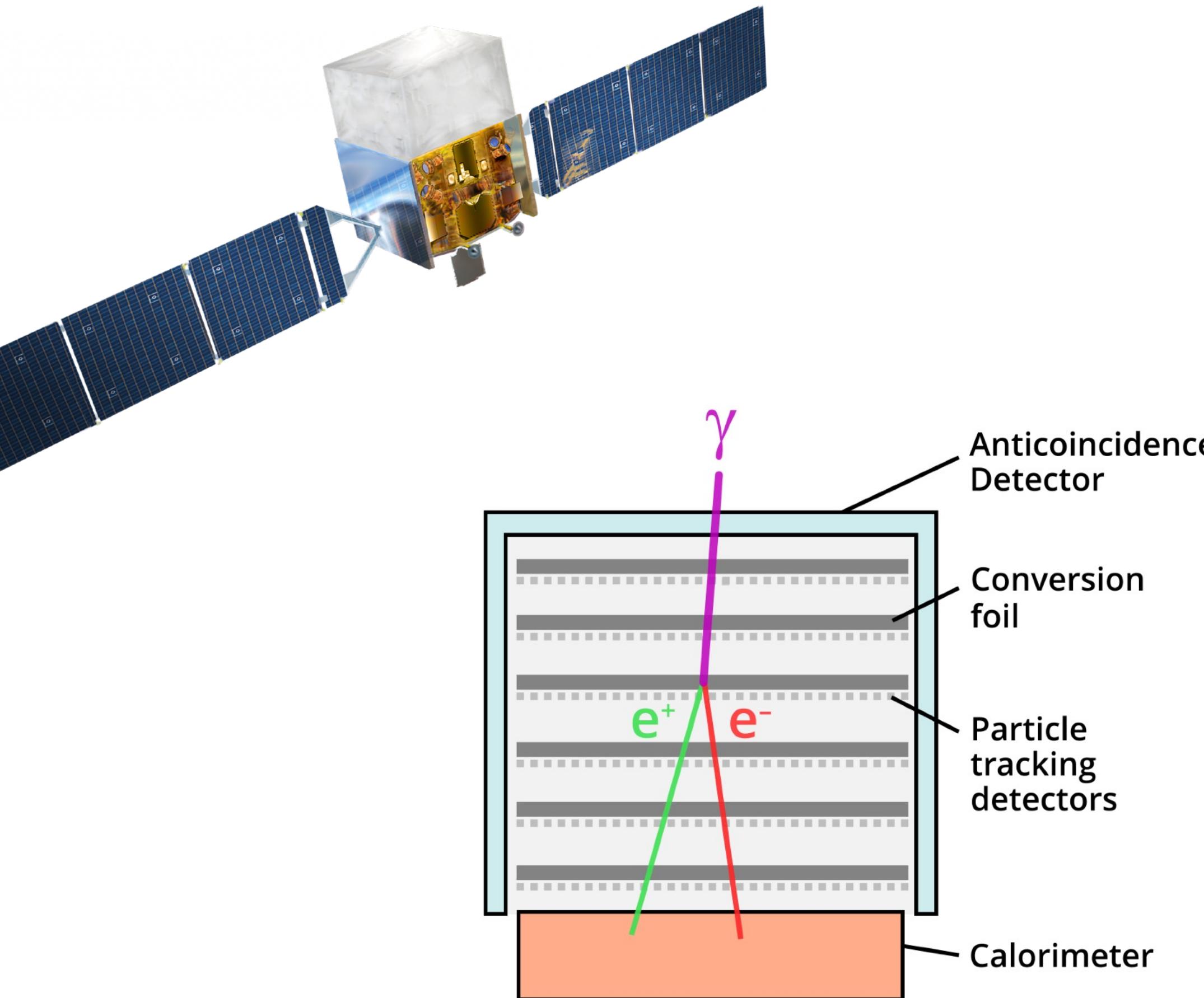
Fig. 1. Schematic views of (a) an electromagnetic cascade and (b) a hadronic shower. In the hadron shower, dashed lines indicate neutral pions which do not re-interact, but quickly decay, yielding electromagnetic subshowers (not shown). Not all pion lines are shown after the $n = 2$ level. Neither diagram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

[1510.05675](#)

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

Detection of cosmic rays (Space)

Fermi-LAT (2008-)

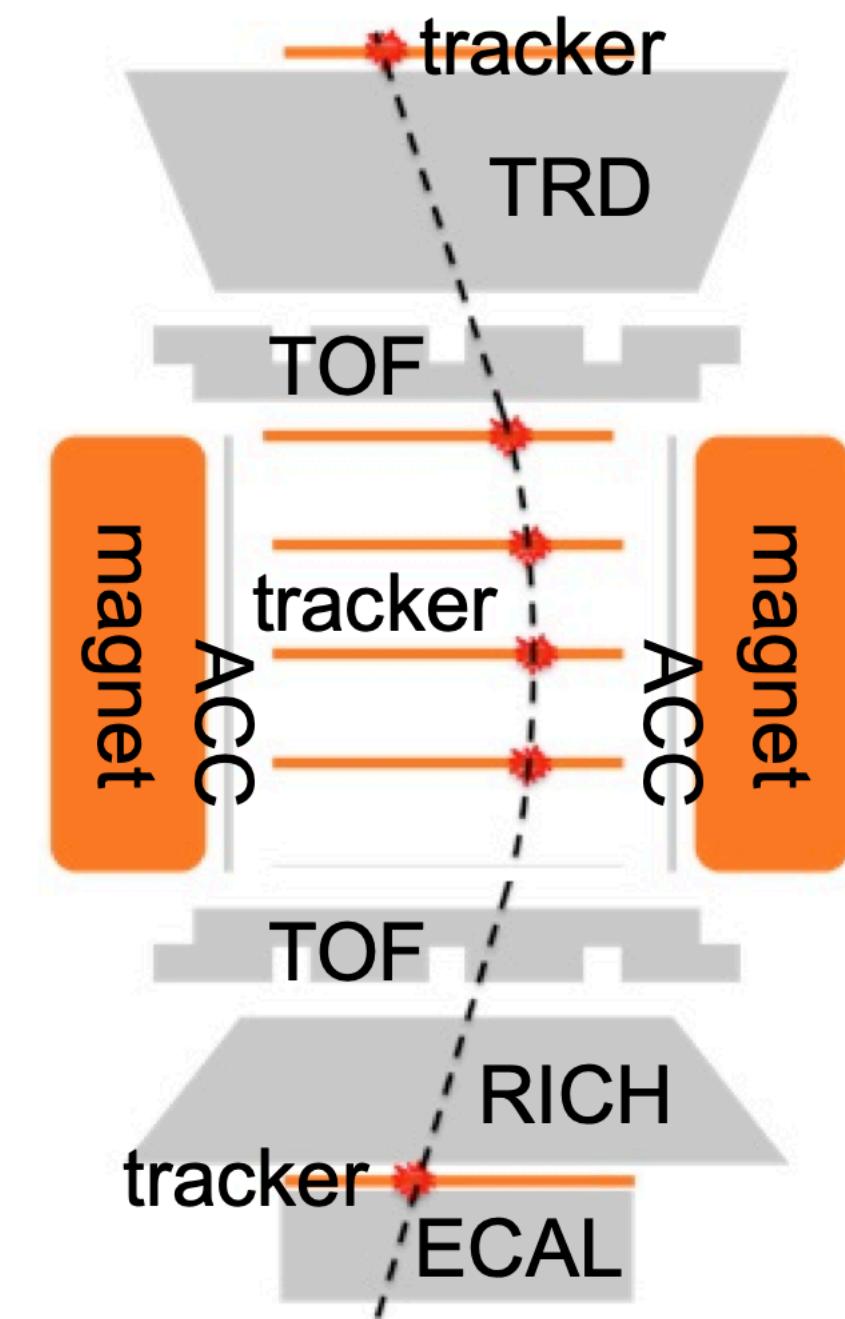


Credit: NASA's Goddard Space Flight Center

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



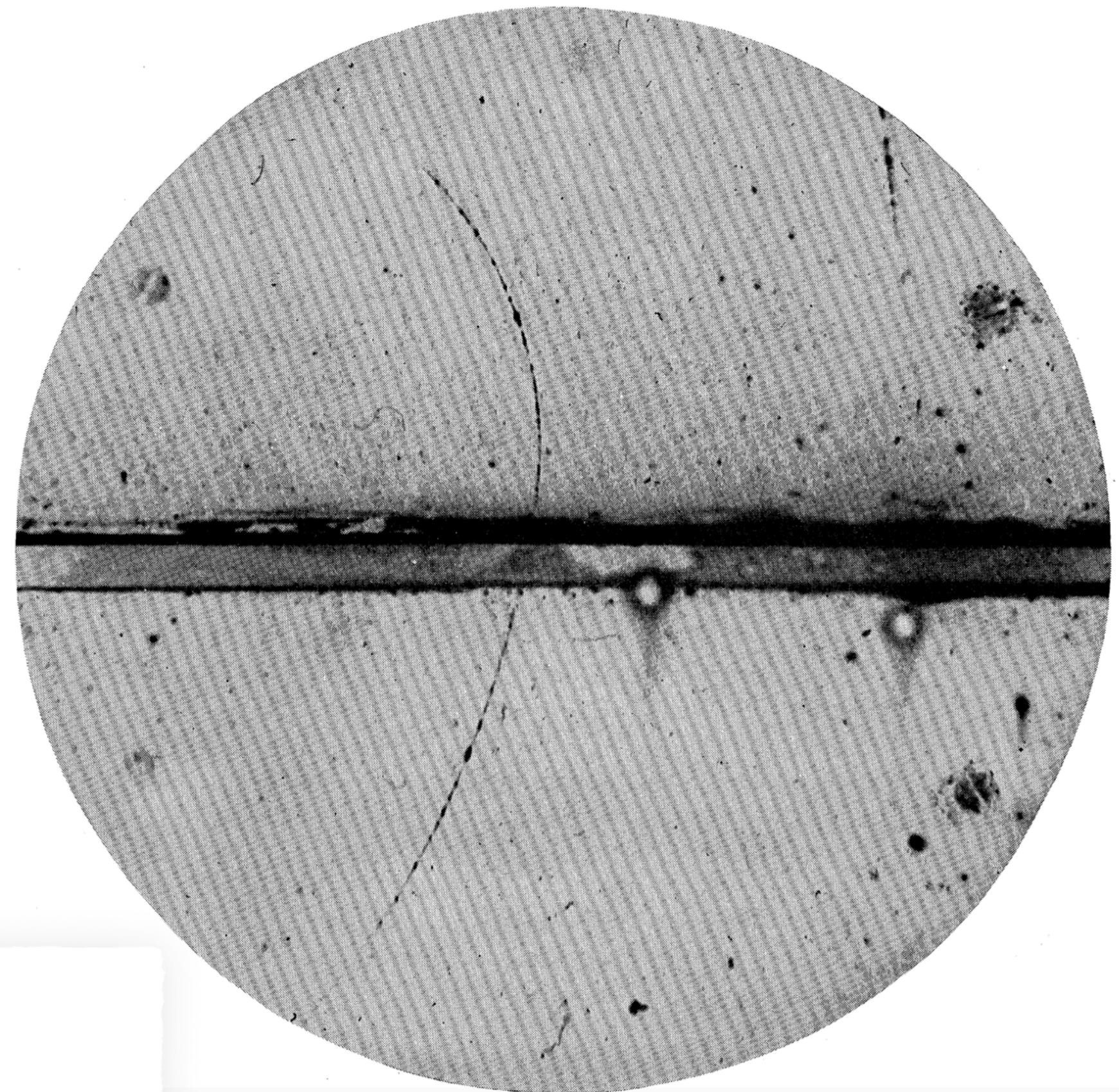
AMS (2011-)



[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*

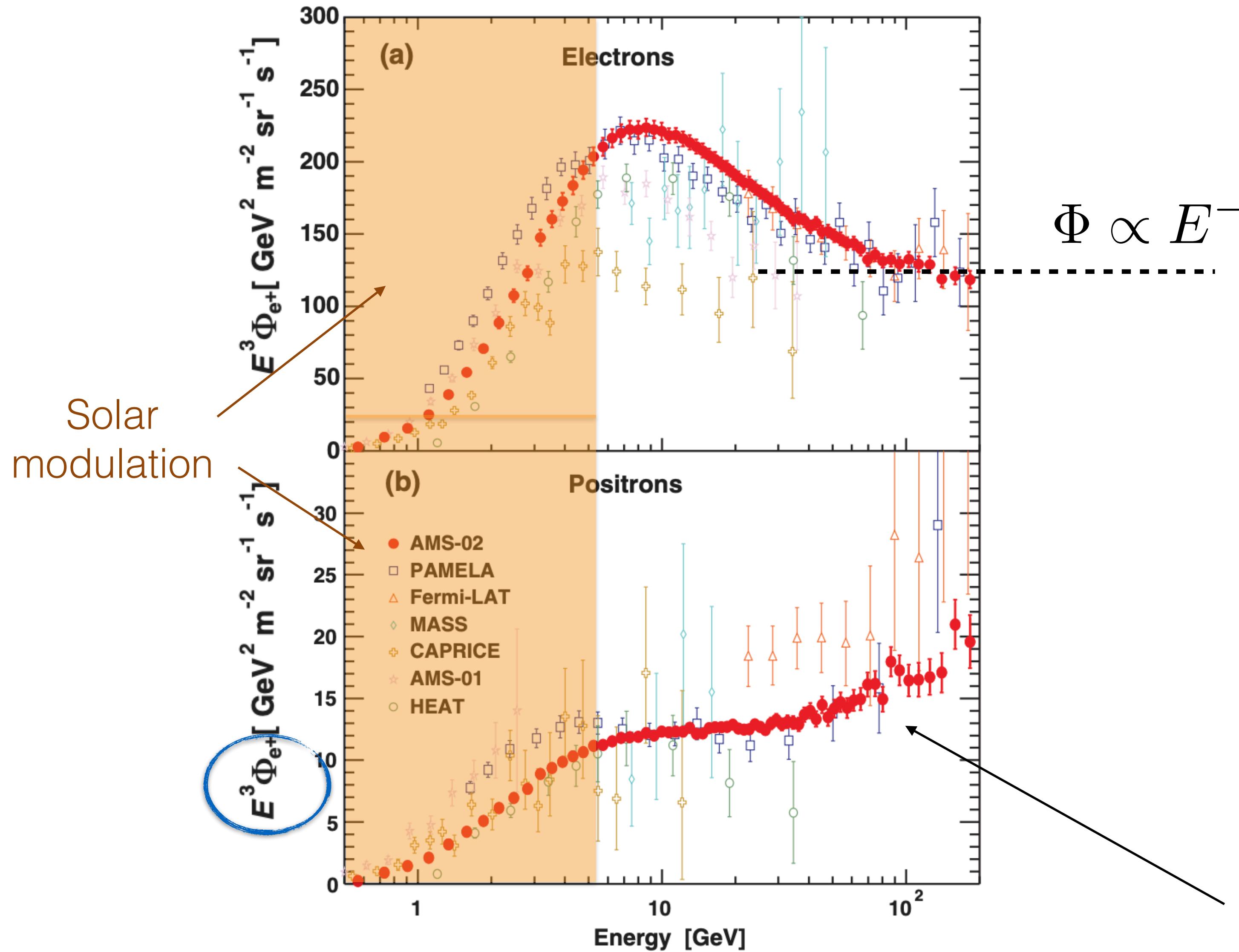
(Received February 28, 1933)

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

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**)

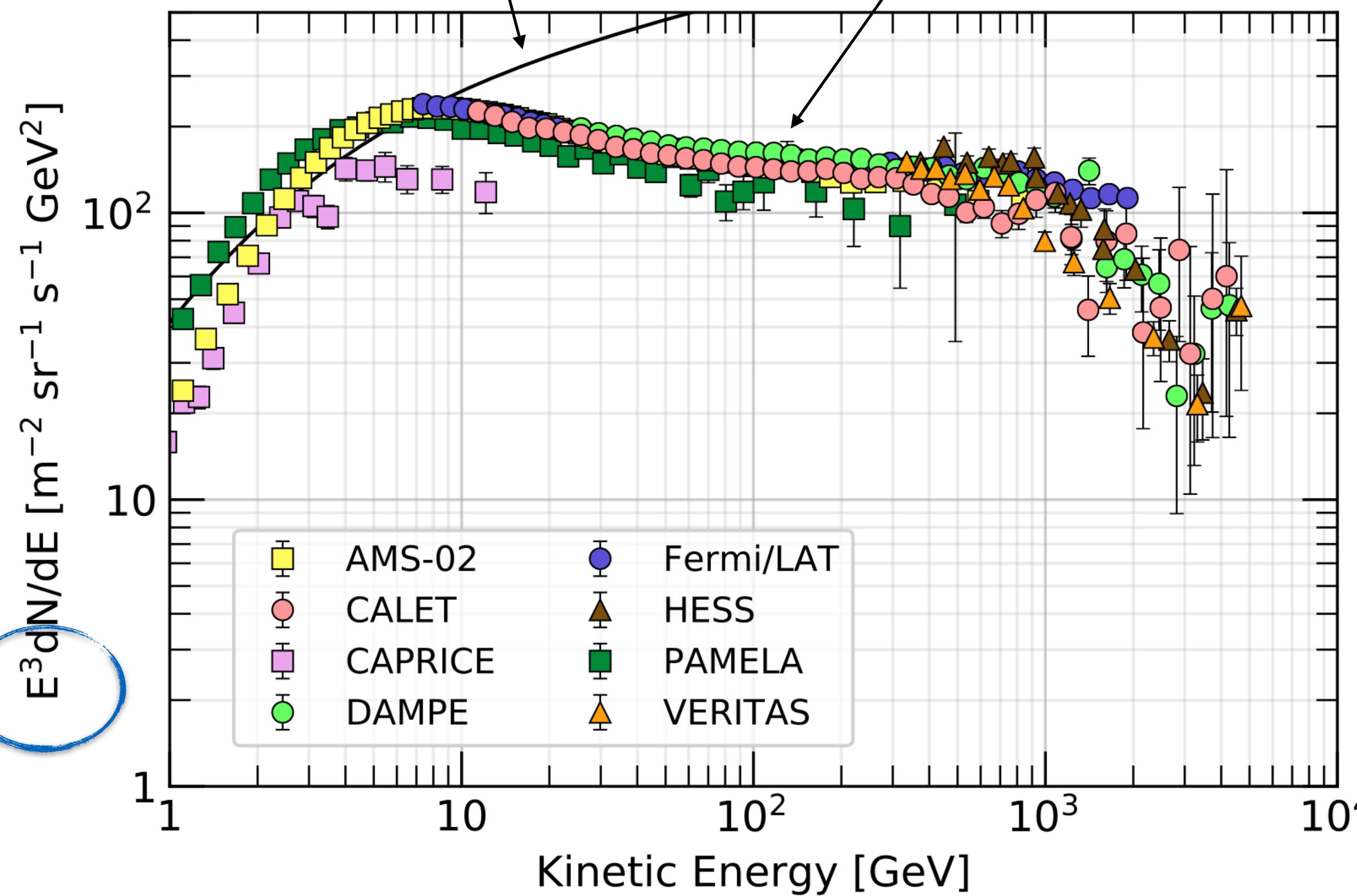
Expect different spectra. But, rise in
positron flux at high energy is still not yet
understood (“positron excess”)!
E.g. [1303.0530](#)

Credit: M. Aguilar et al. (AMS Collaboration), 2014

Electrons vs Protons

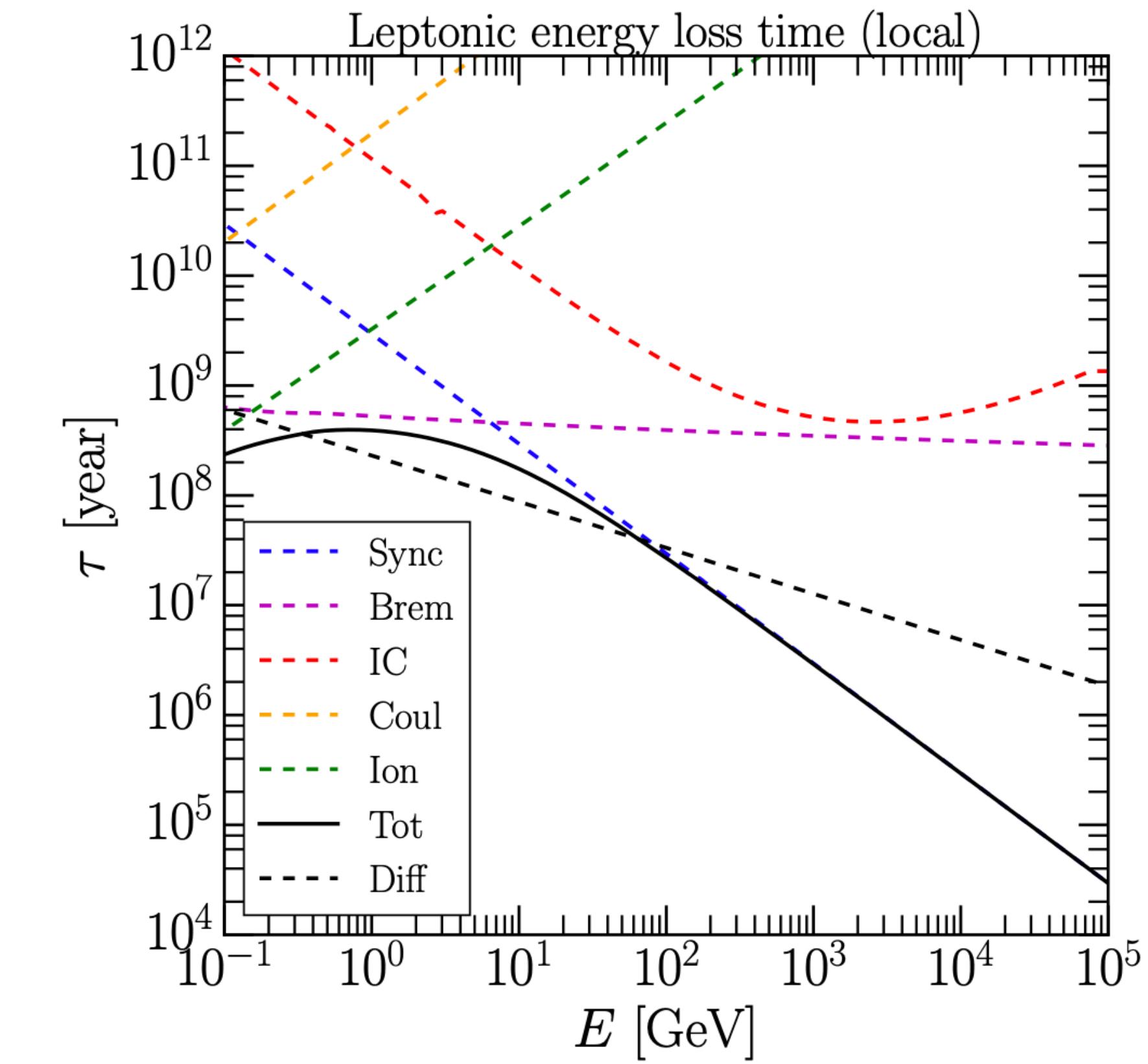
Proton Spectrum (x0.01)

Electron + Positron Spectrum

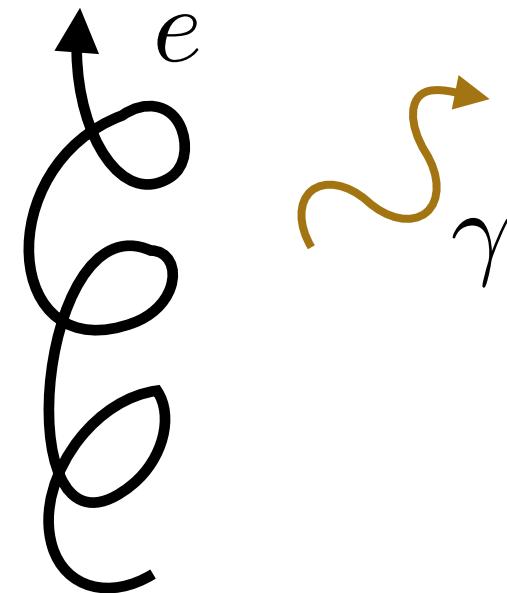


Credit: [Particle Data Group \(2020\)](#)

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



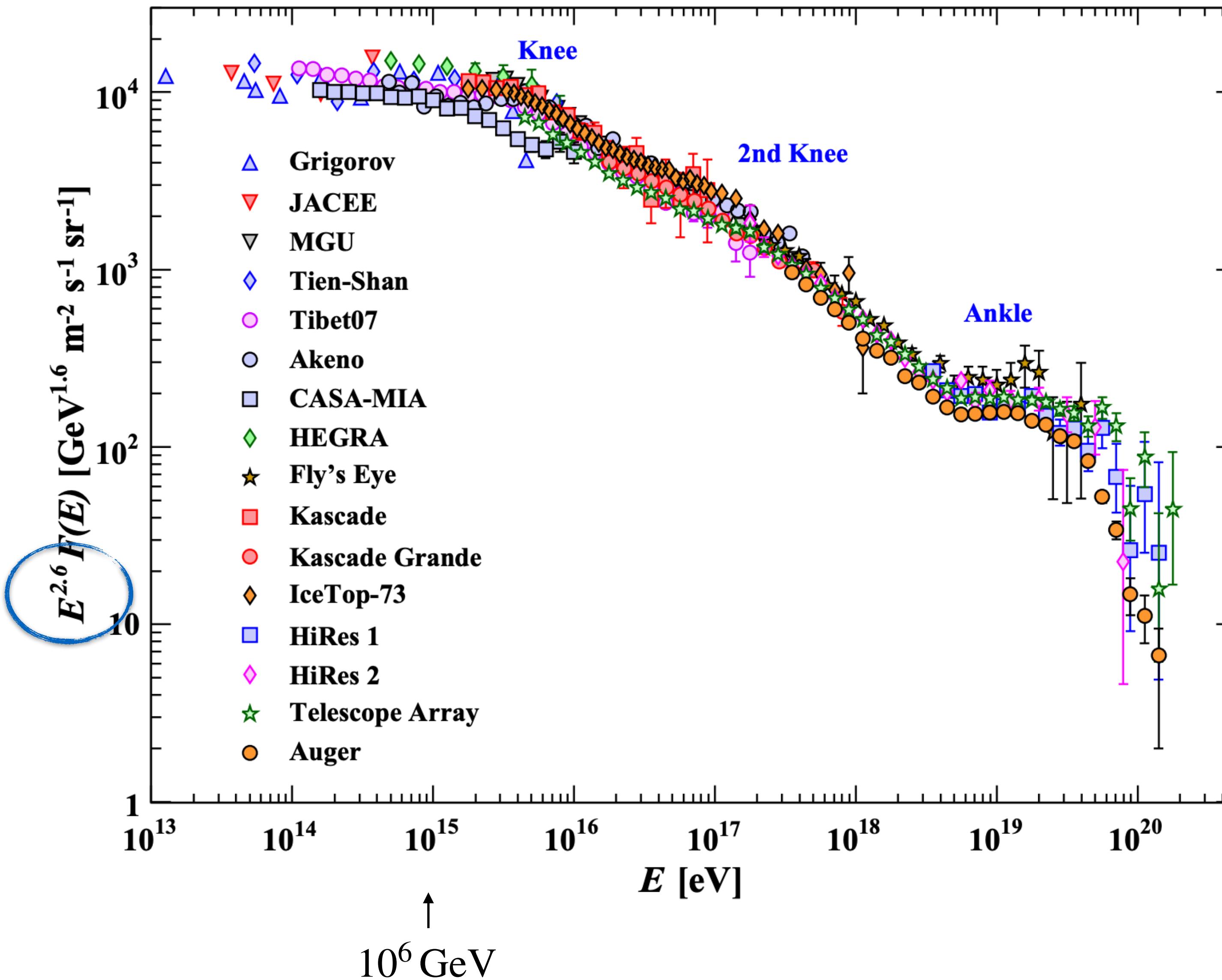
Synchrotron



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

Ultra high-energy cosmic rays

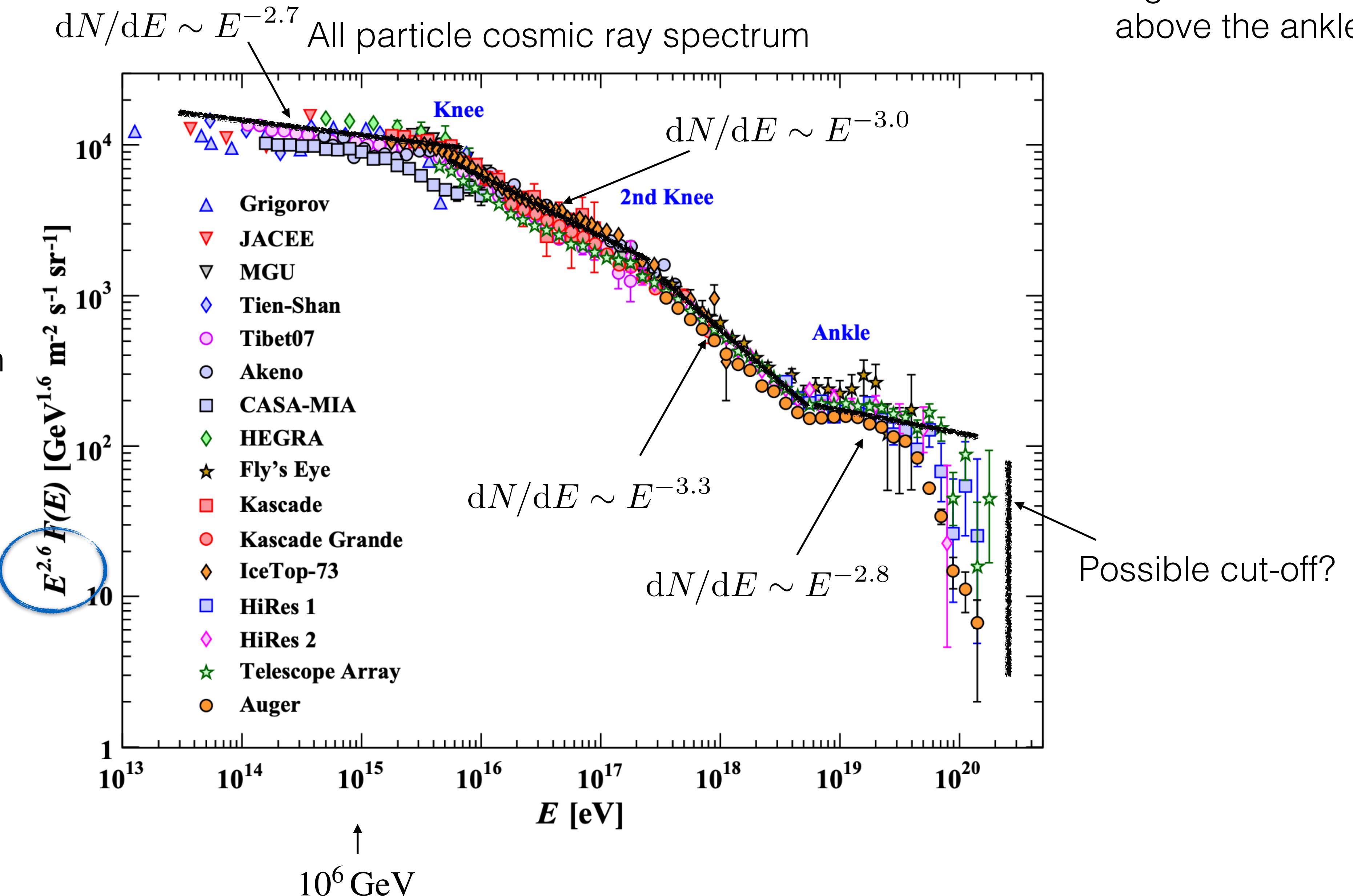
All particle cosmic ray spectrum



Credit: Particle Data Group (2020)

Ultra high-energy cosmic rays

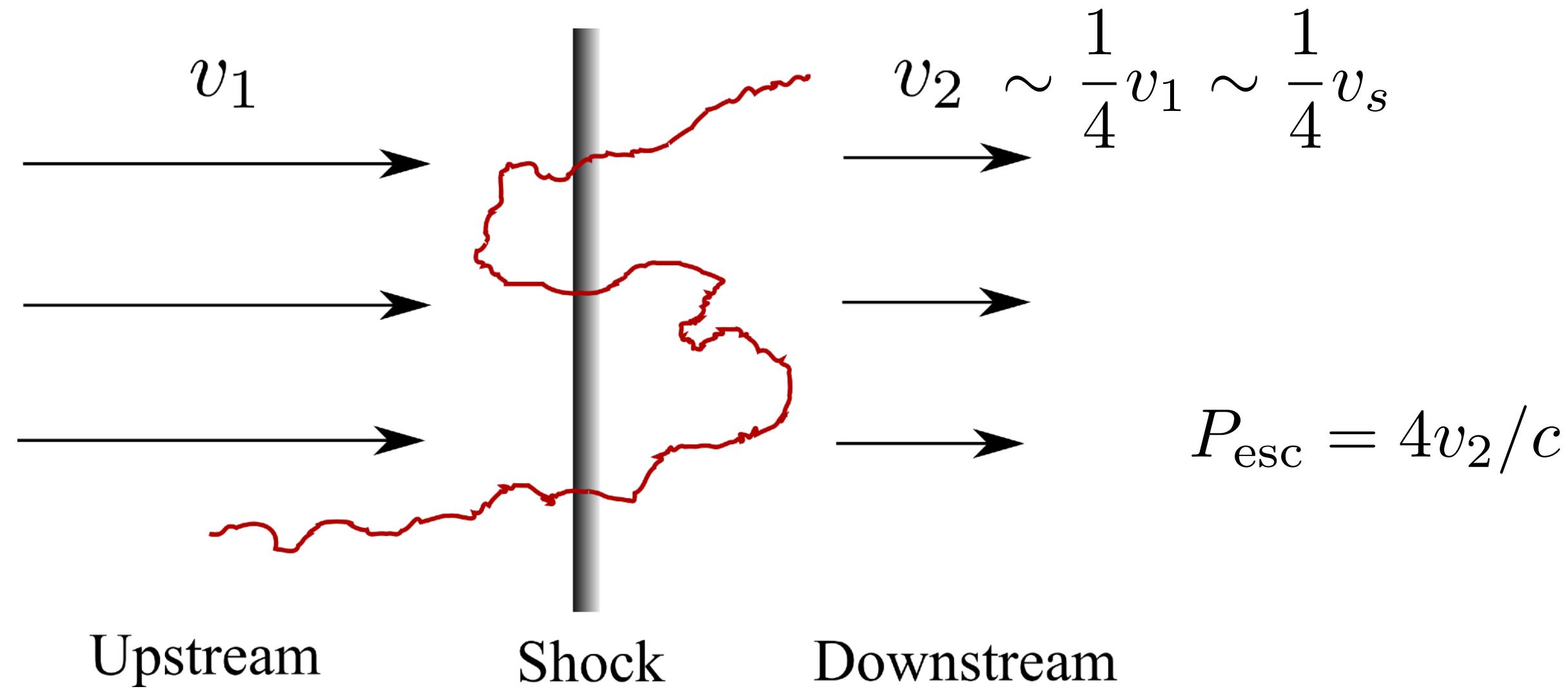
Heavier nuclei begin to dominate above the 2nd knee.



Production of cosmic rays

Tycho Supernova remnant

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



$$P_{\text{esc}} = 4v_2/c$$

With each crossing:

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

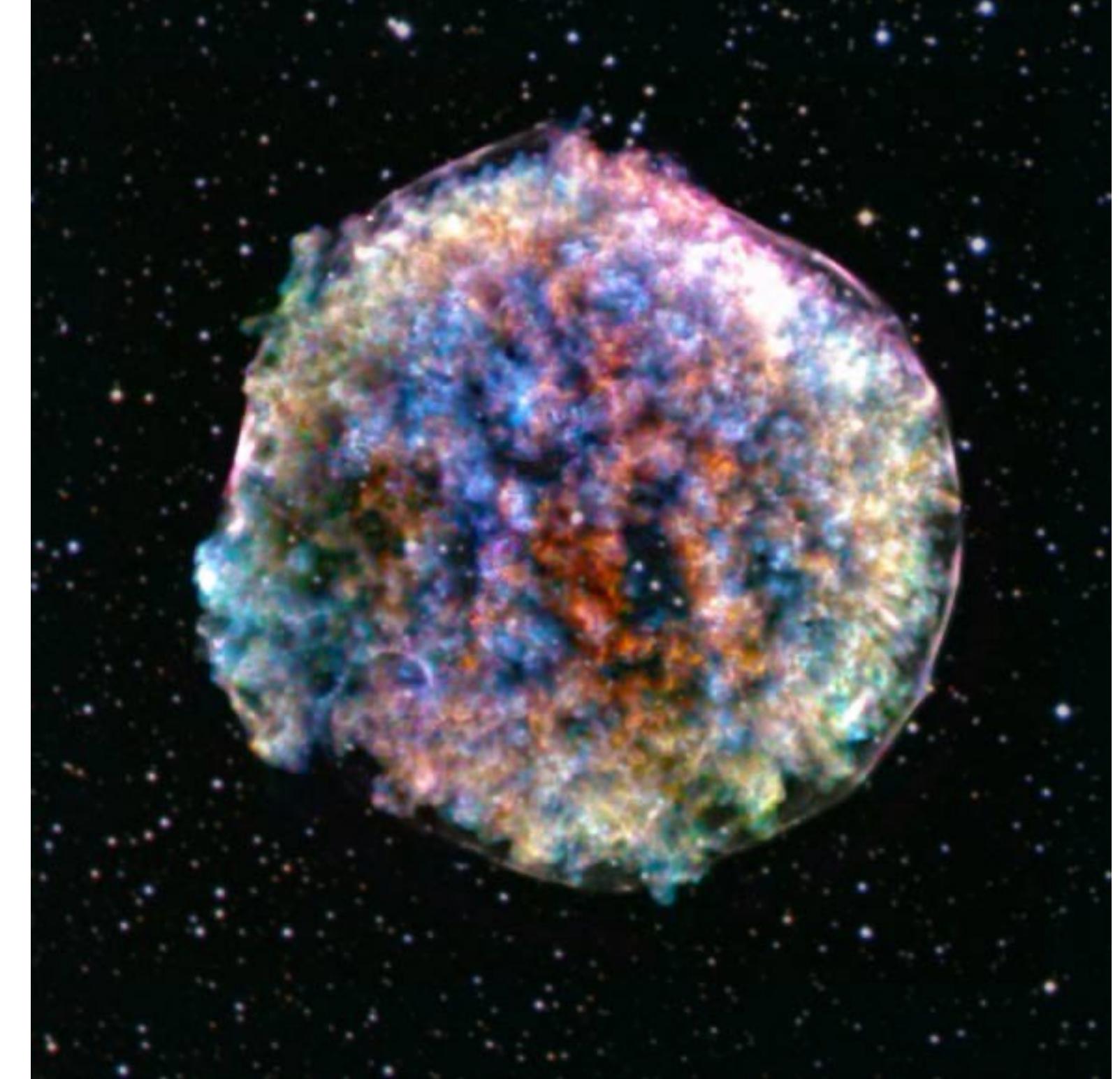
After n crossings: $E_n = (1 + \xi)^n E_0$

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](#)

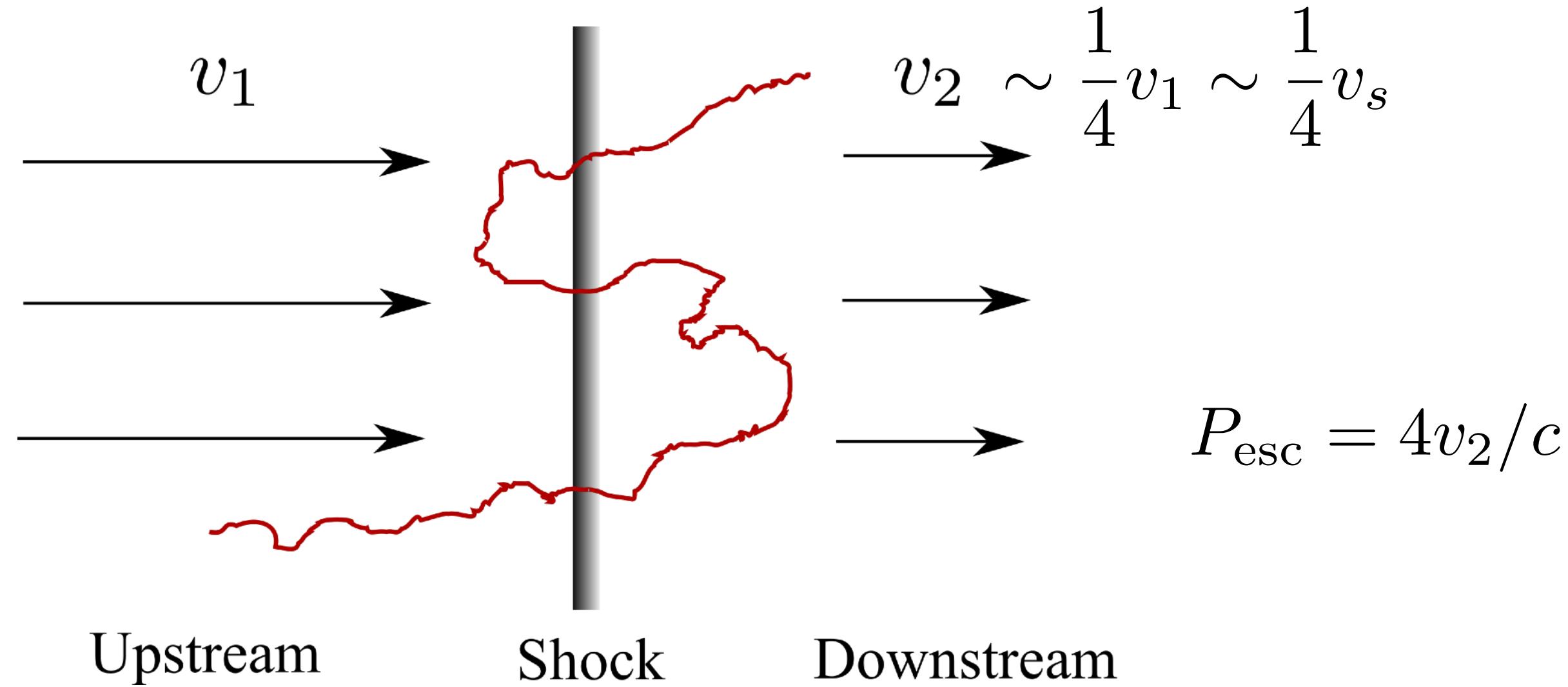


Credit: NASA / CXC / RIKEN / NASA's Goddard Space Flight Center / T. Sato et al / DSS

Production of cosmic rays

Tycho Supernova remnant

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



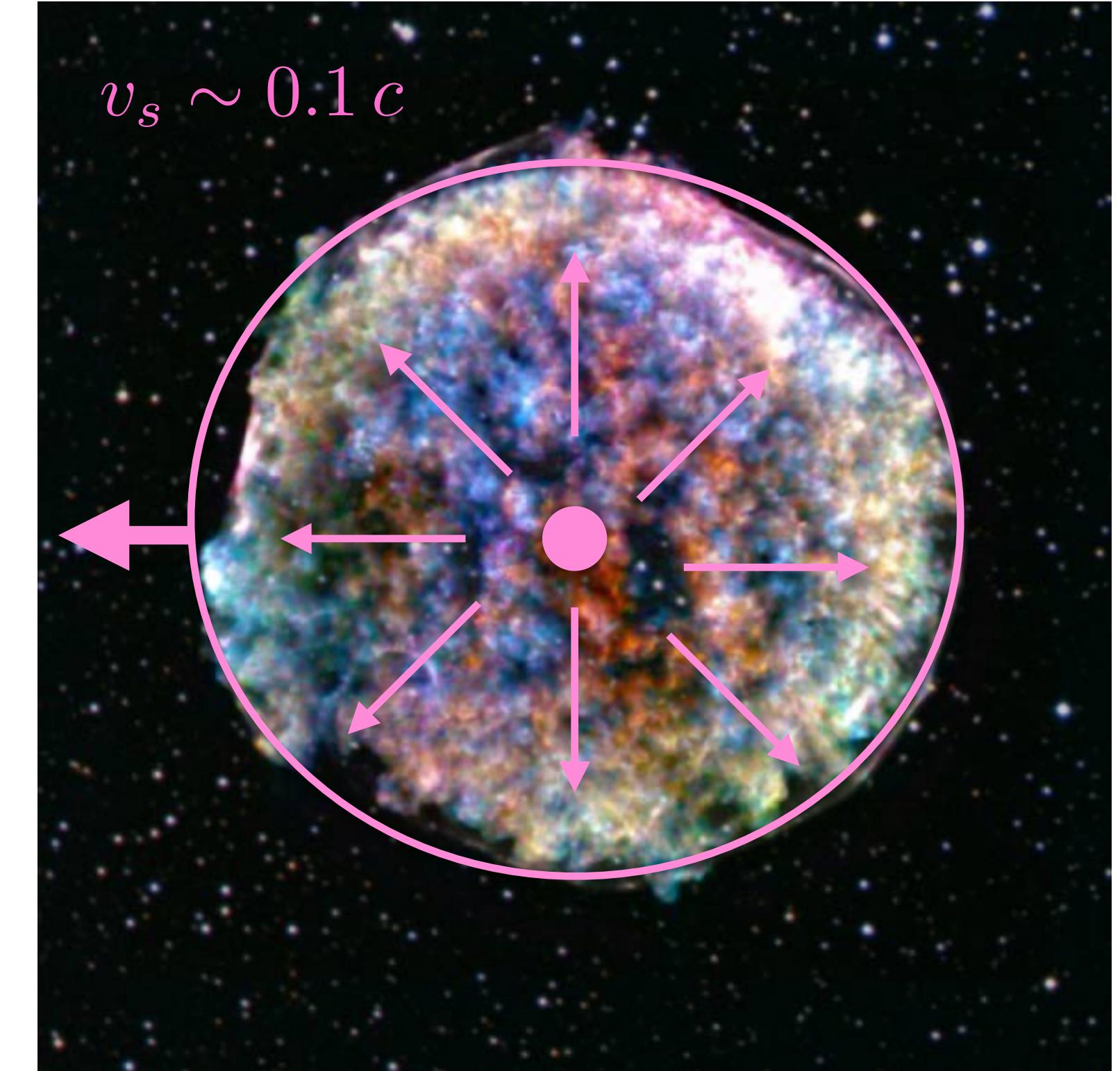
With each crossing: $\xi = \left\langle \frac{\Delta E}{E} \right\rangle = \frac{4}{3} \frac{v_1 - v_2}{c}$

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E.g. [1910.06006](#)

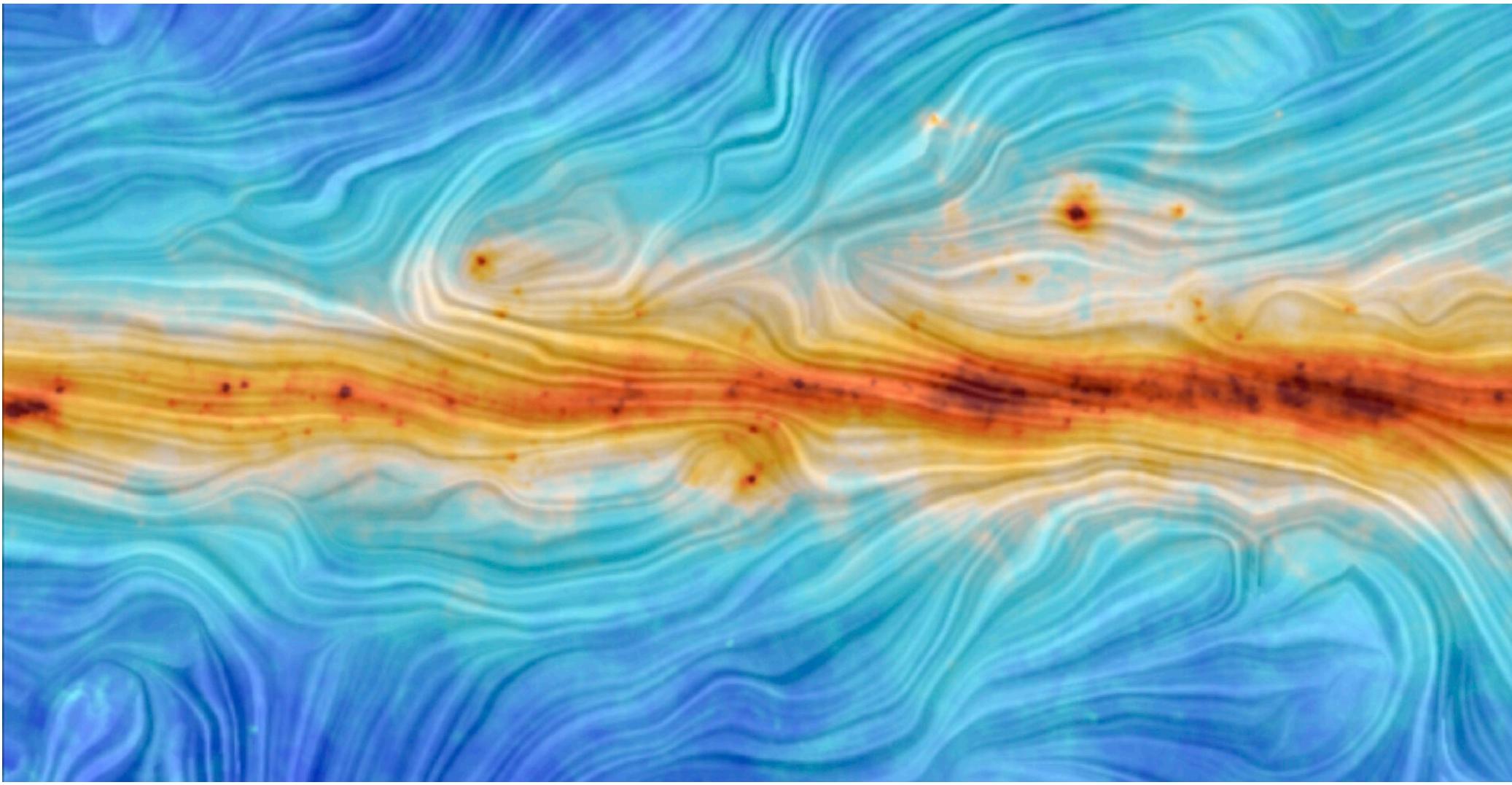
→ Injected flux of particles: $\frac{dN_{\text{inj}}}{dE} \propto \frac{df}{dE} = \left(\frac{E}{E_0} \right)^{-2}$



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

Propagation of CCRs

Credit: ESA/Planck Collaboration



Diffusion

$$\frac{\partial N_i}{\partial t} = D(E) \nabla^2 N_i + \frac{\partial}{\partial E} [b(E) N_i] - \frac{N_i}{\tau_i} + \sum_{j>i} \frac{P_{ji}}{\tau_j} N_j + Q$$

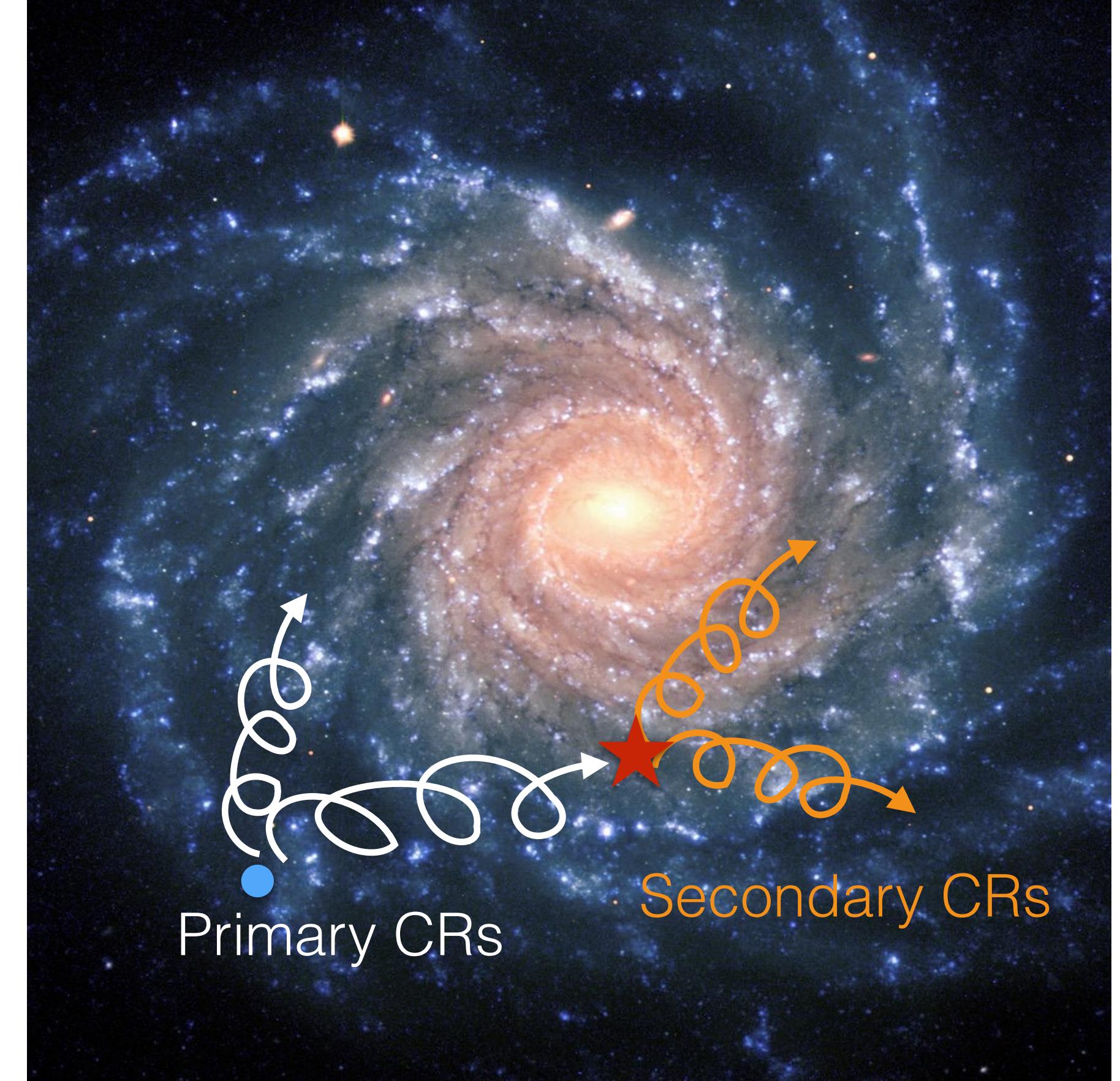
Energy losses

Escape and attenuation

Production
(by spallation)

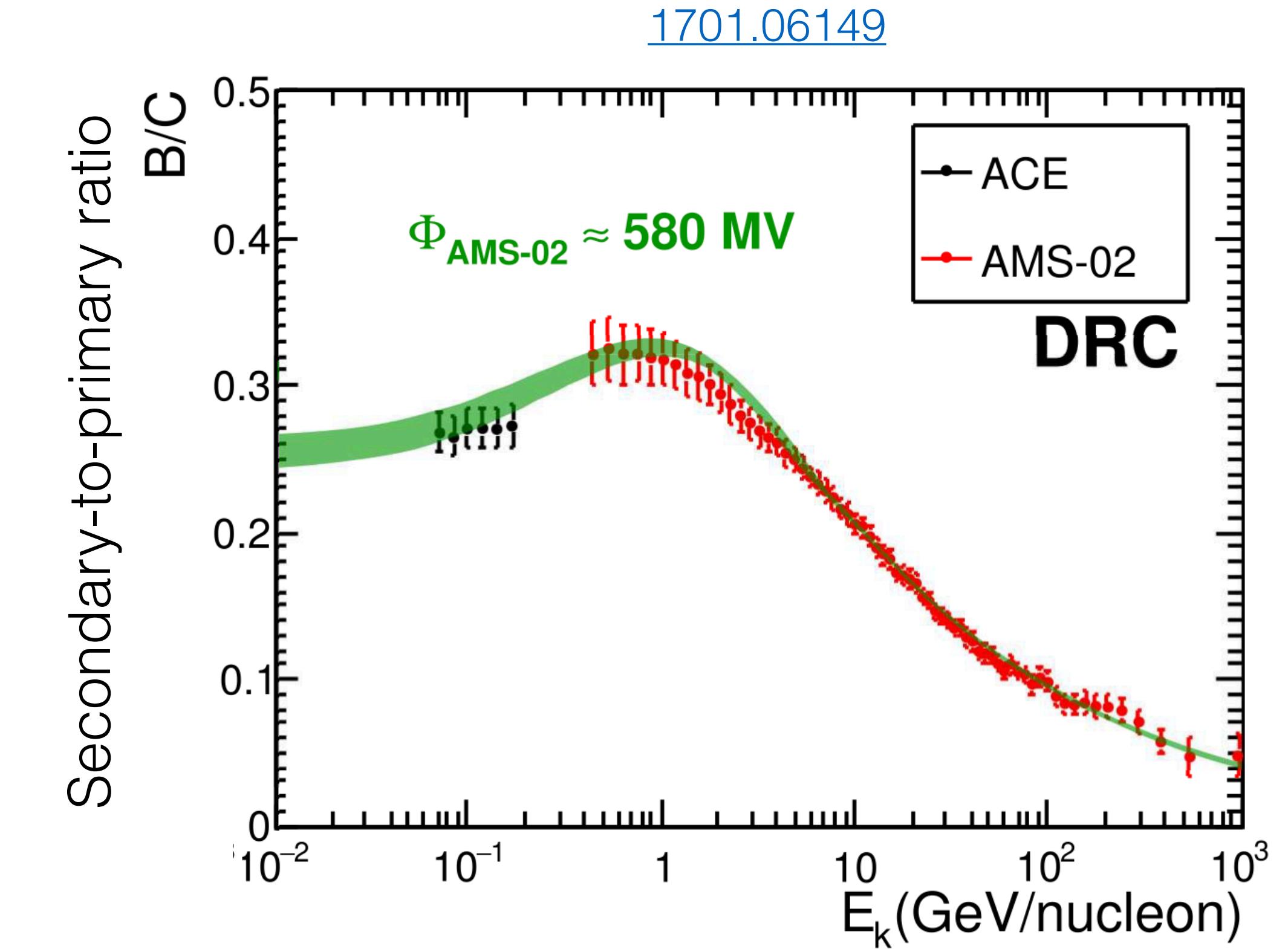
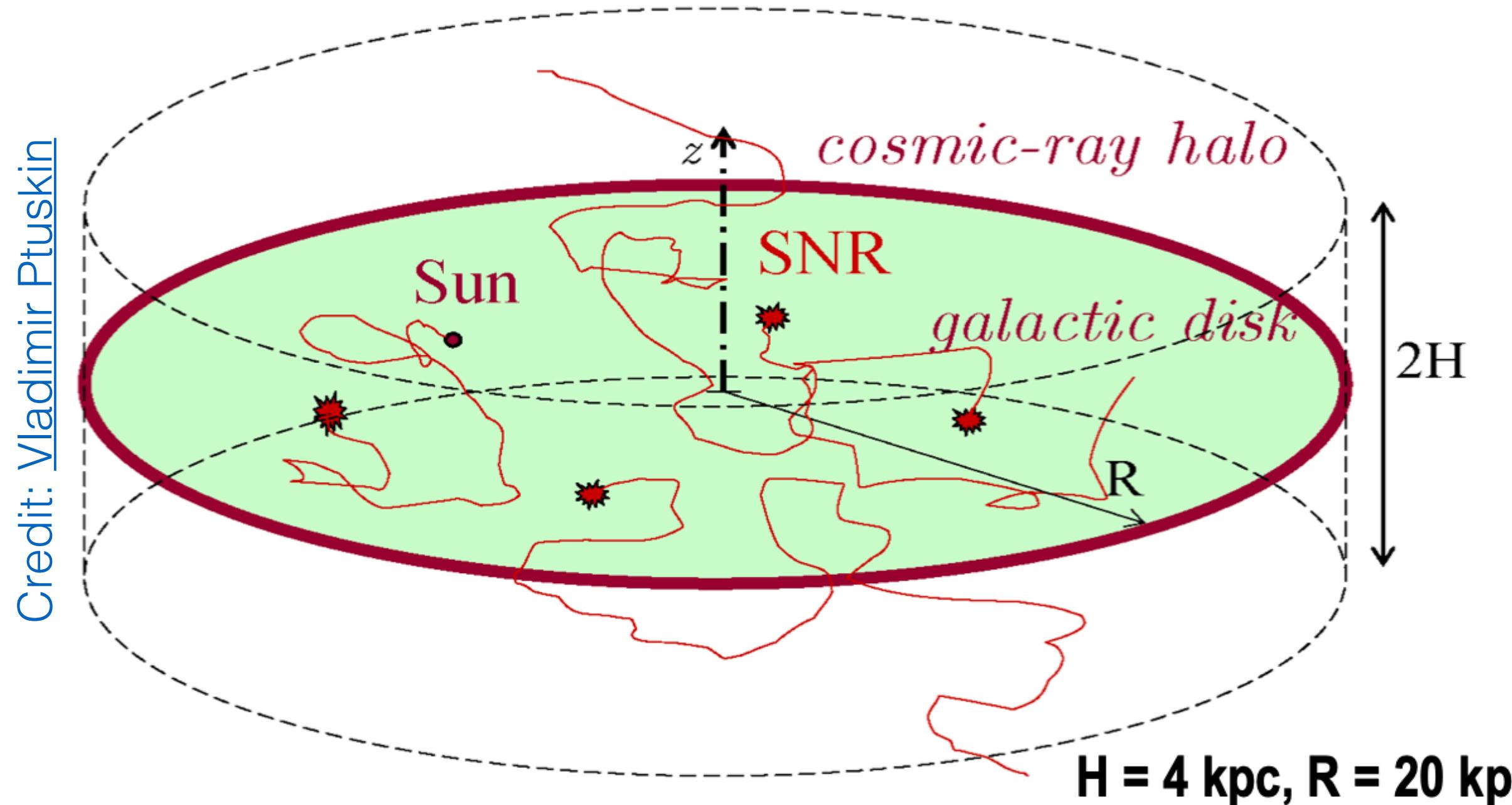
Sources

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



Modelling CR propagation

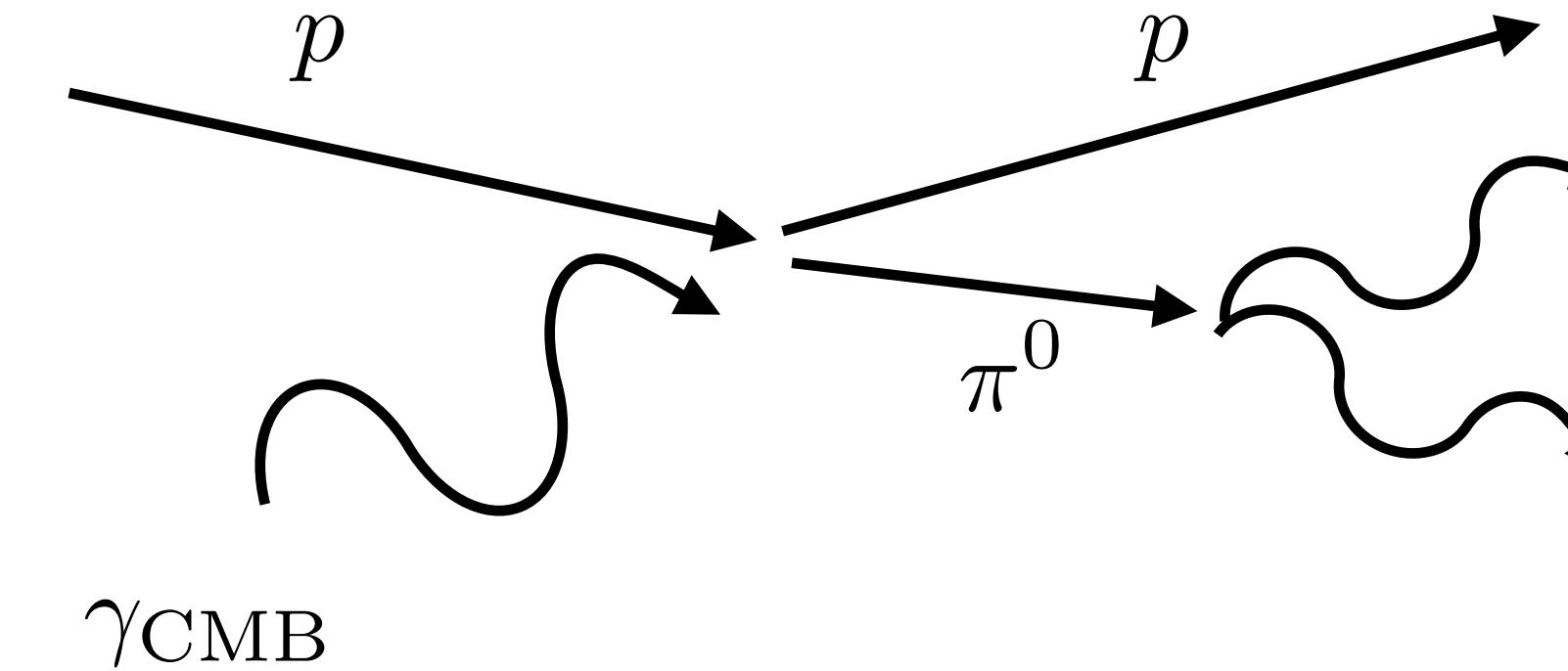
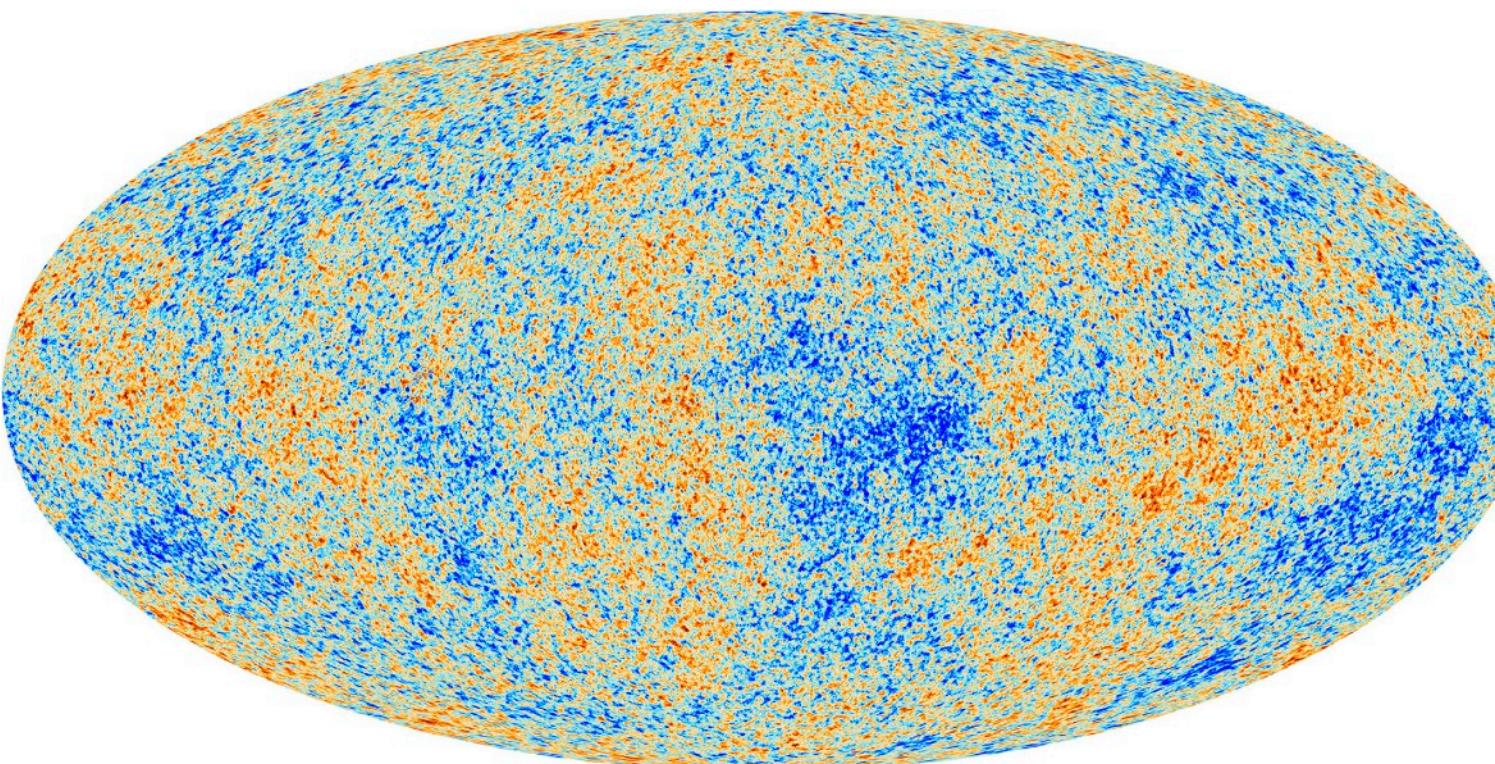
Parametrize properties of the diffusive halo and solve for CR density
(e.g. [GALPROP](#), [DRAGON](#), [USINE](#), ...)



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

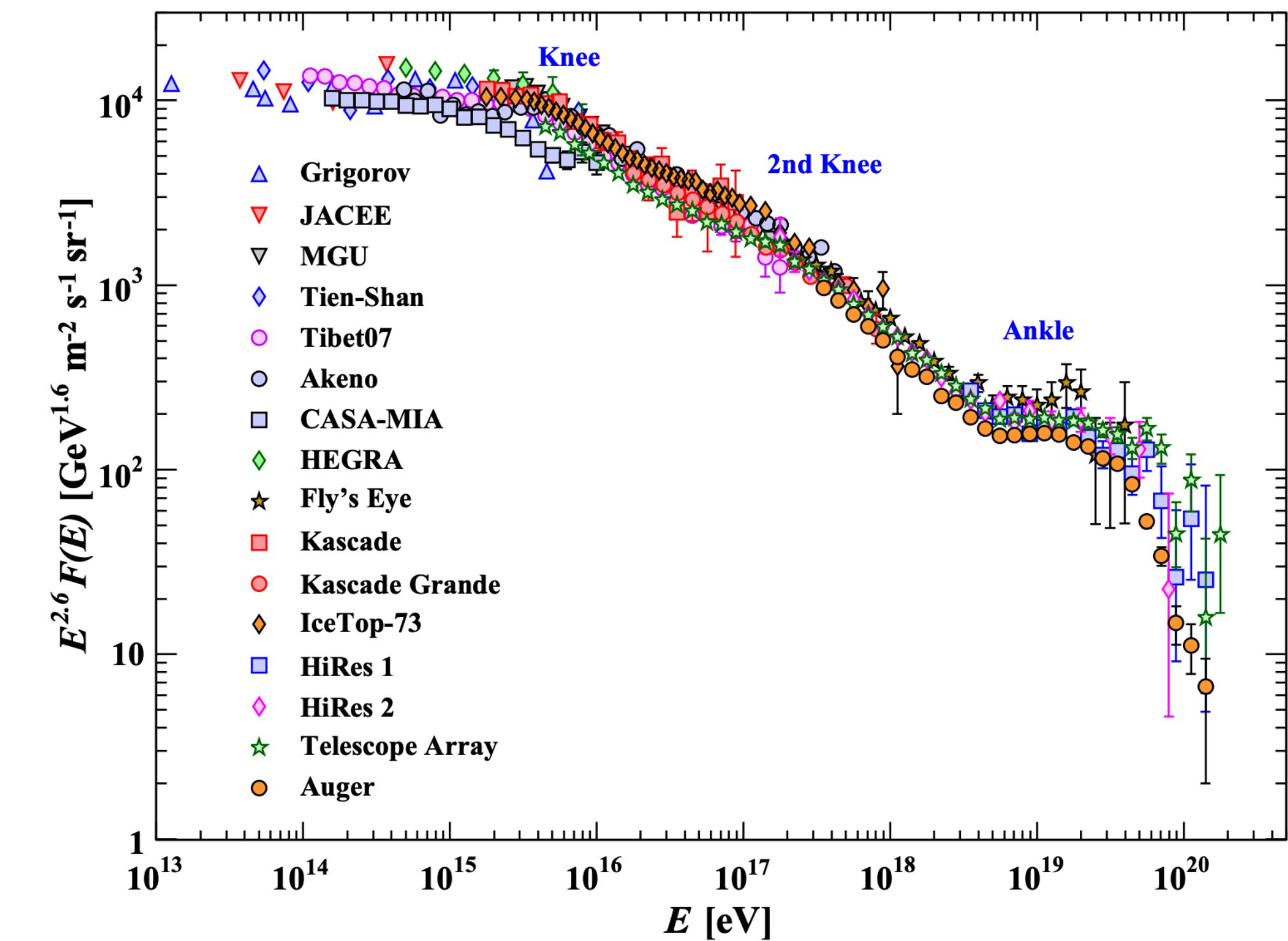
Very high energy cosmic rays will be destroyed by interactions with background photons:



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

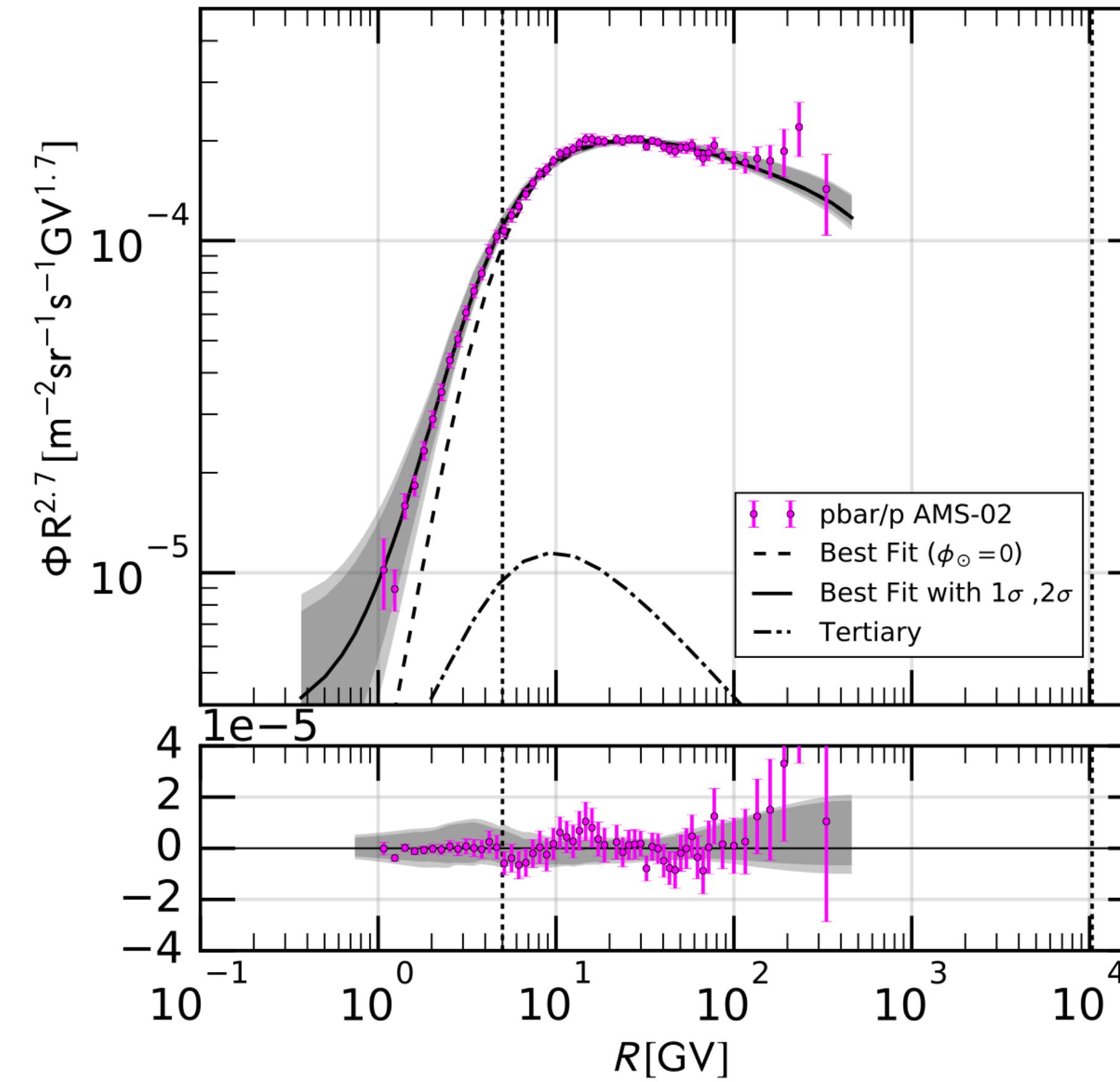
$$E_{p\gamma} \approx 3.4 \times 10^{19} \left(\frac{\epsilon}{10^{-3} \text{eV}} \right)^{-1} \text{eV}$$

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



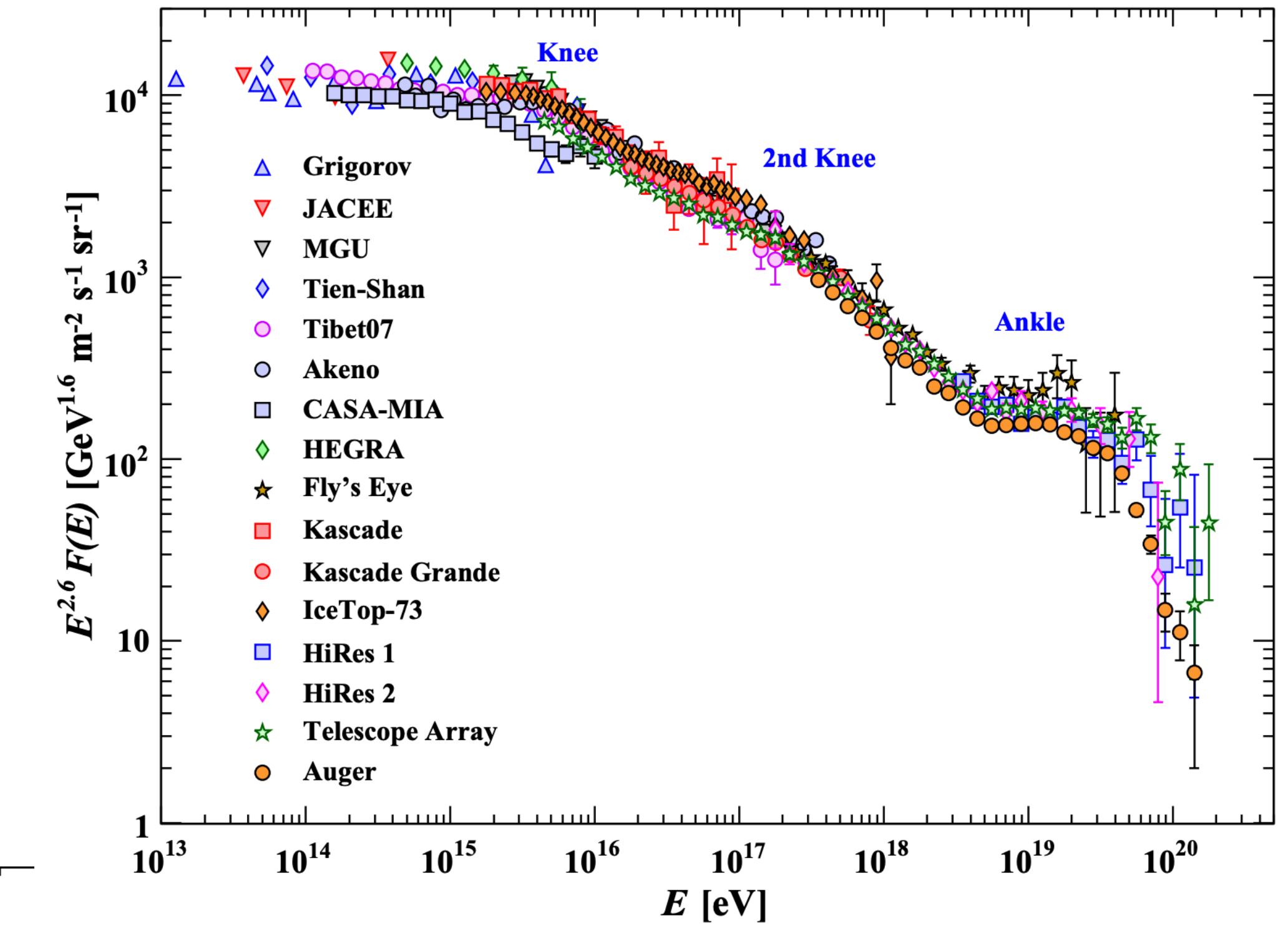
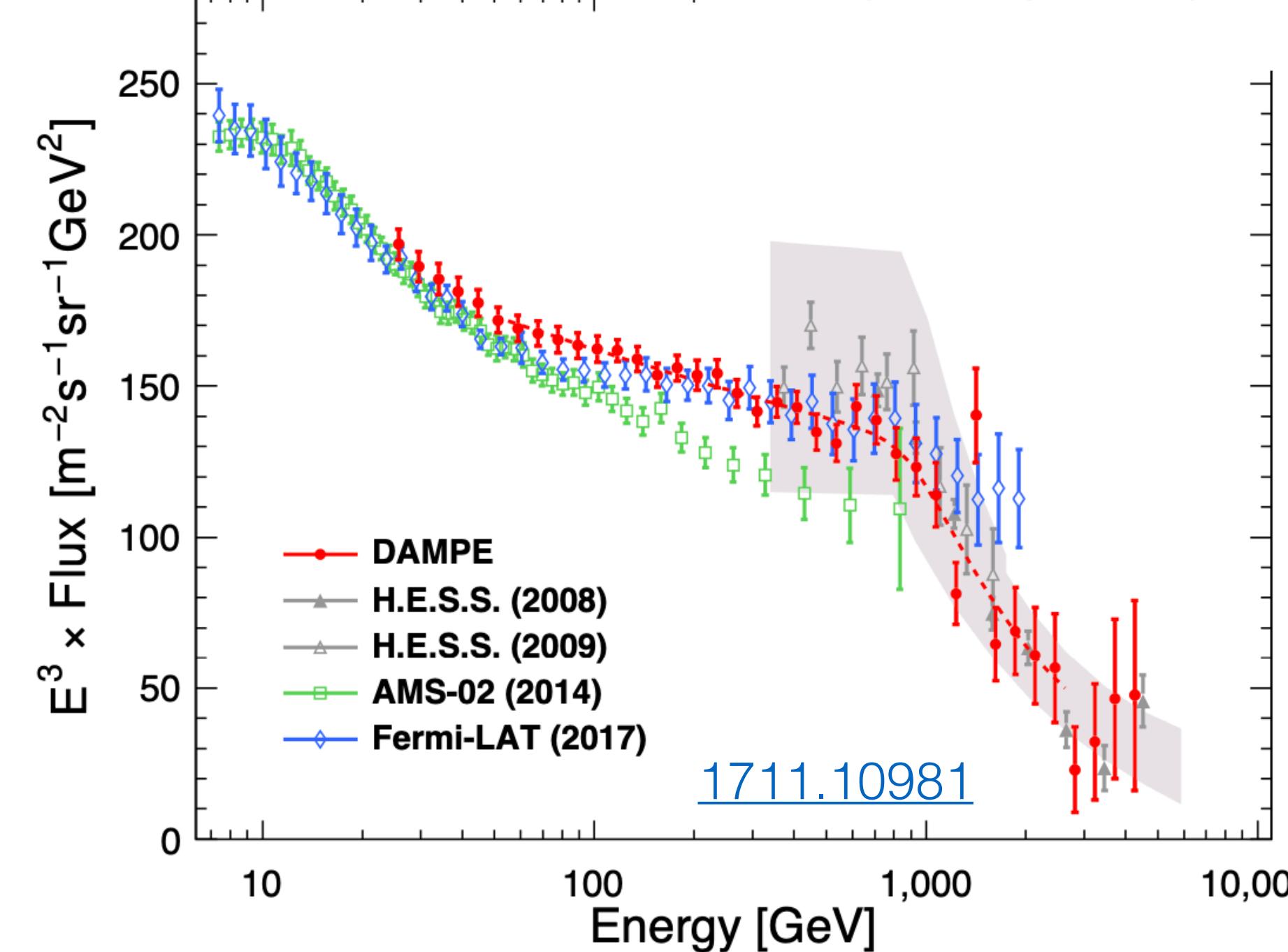
CCR anomalies and questions

Excess in anti-protons?



[1610.03071](#)

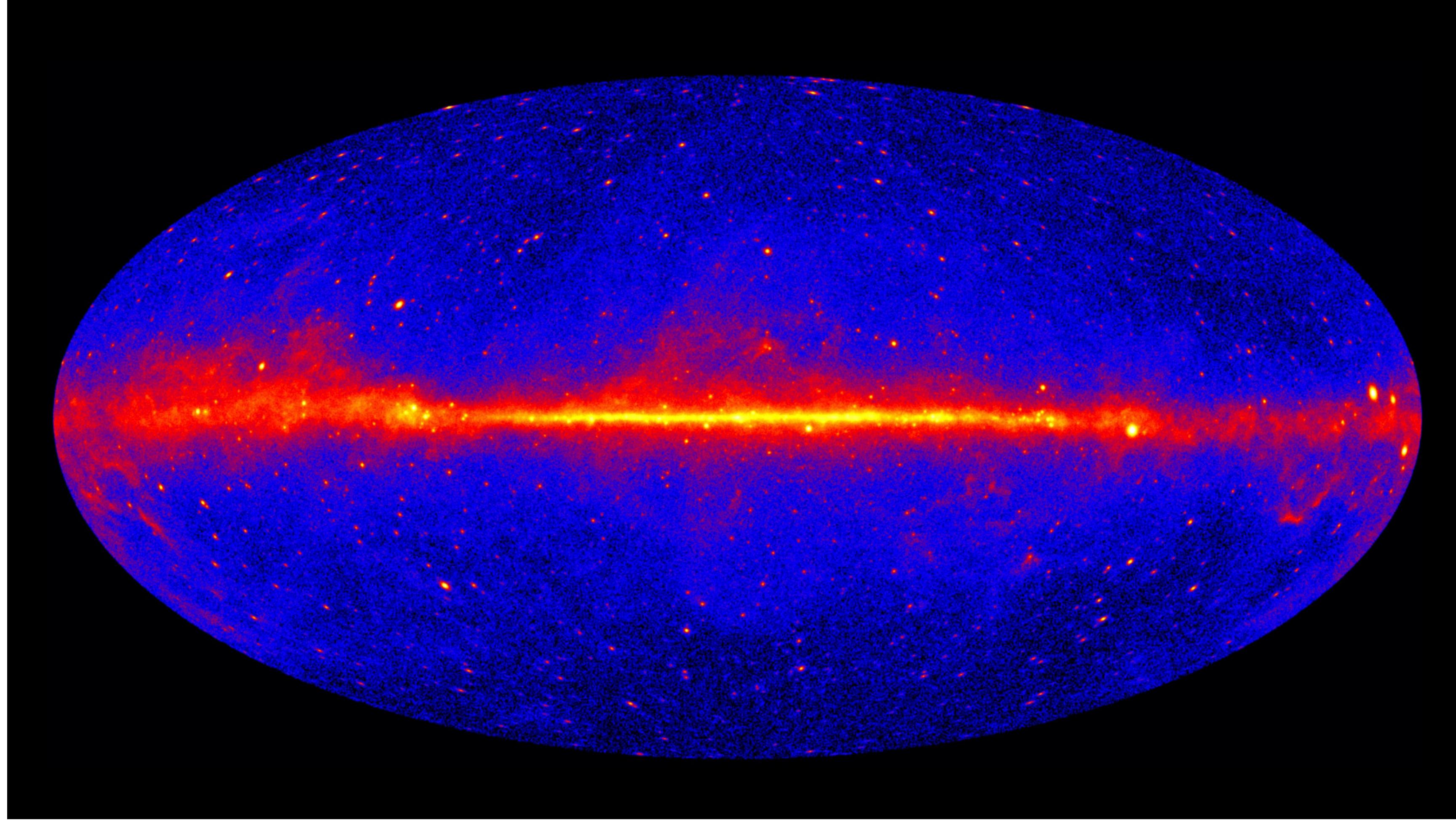
Excess in electrons?



and others...

The Gamma-ray Sky

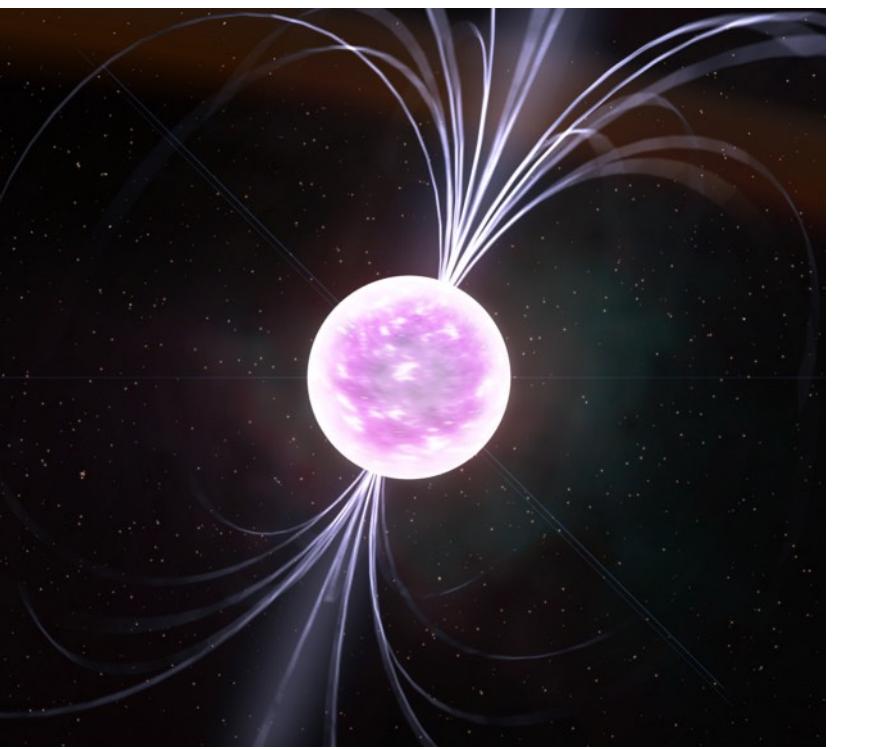
Gamma-ray Sky above 1 GeV, according to Fermi:



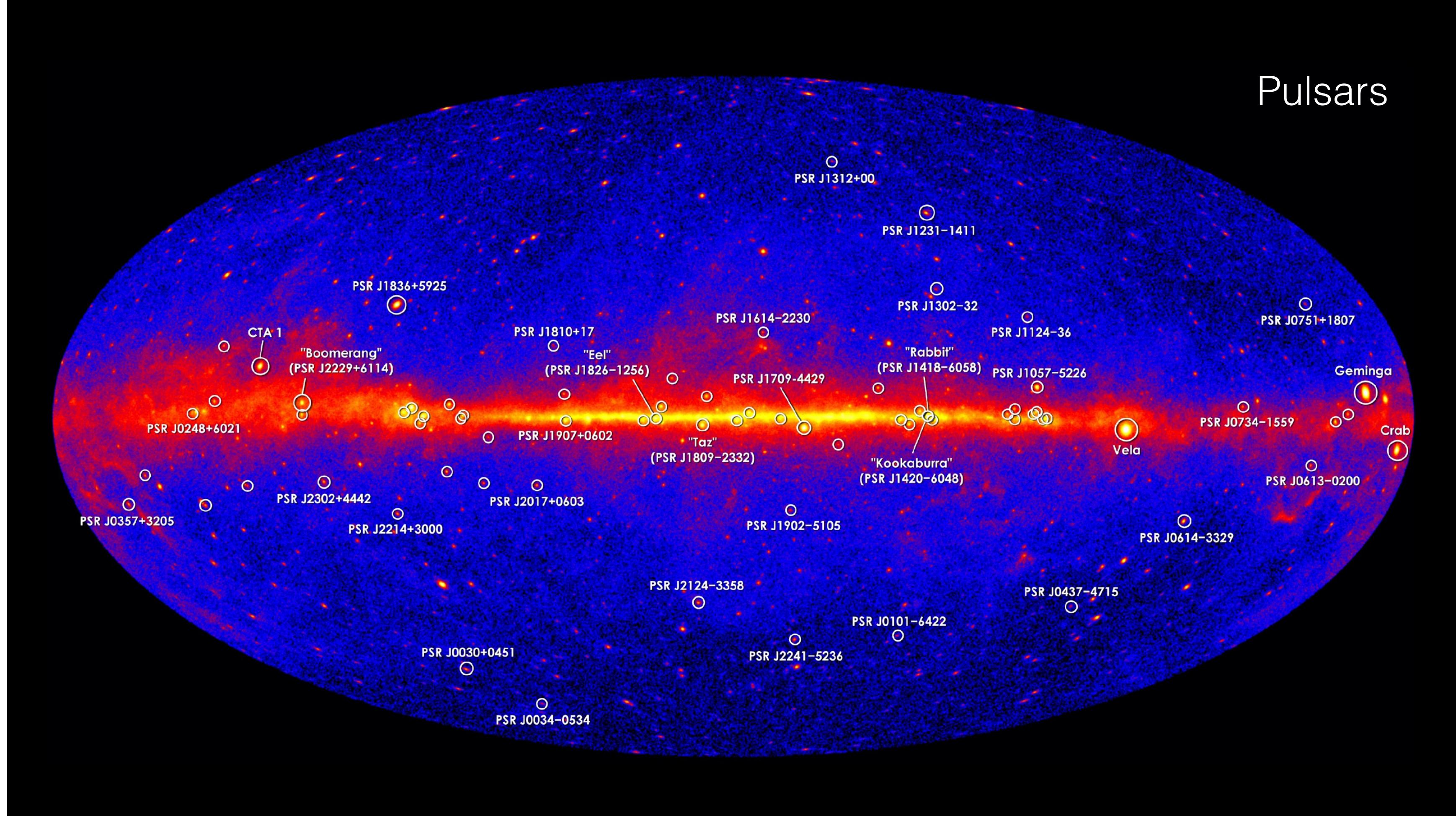
Credit: [NASA/DOE/Fermi LAT Collaboration](#)

The Gamma-ray Sky

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



Credit: Kevin Gill / Flickr

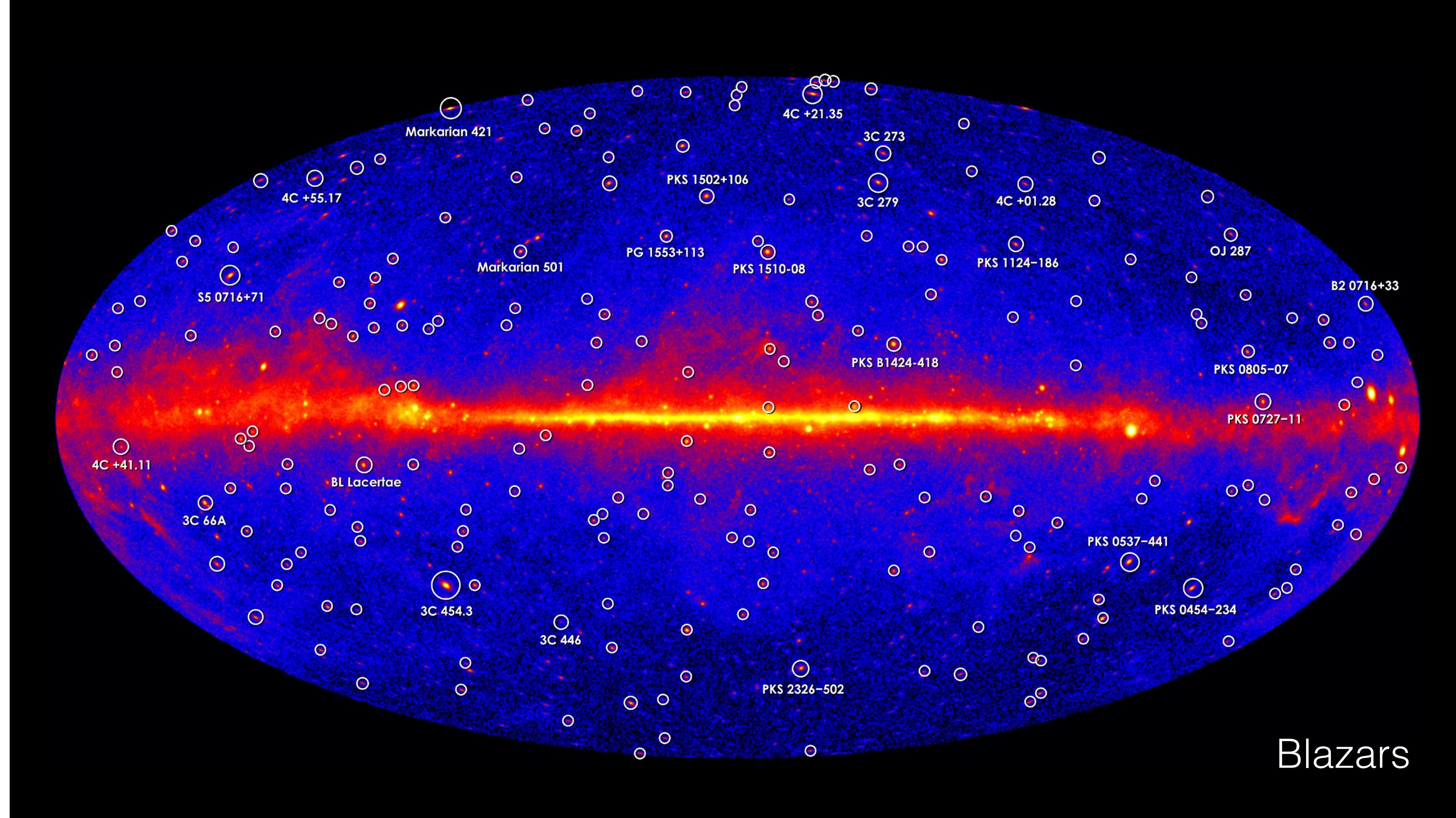


Credit: [NASA/DOE/Fermi LAT Collaboration](#)

The Gamma-ray Sky

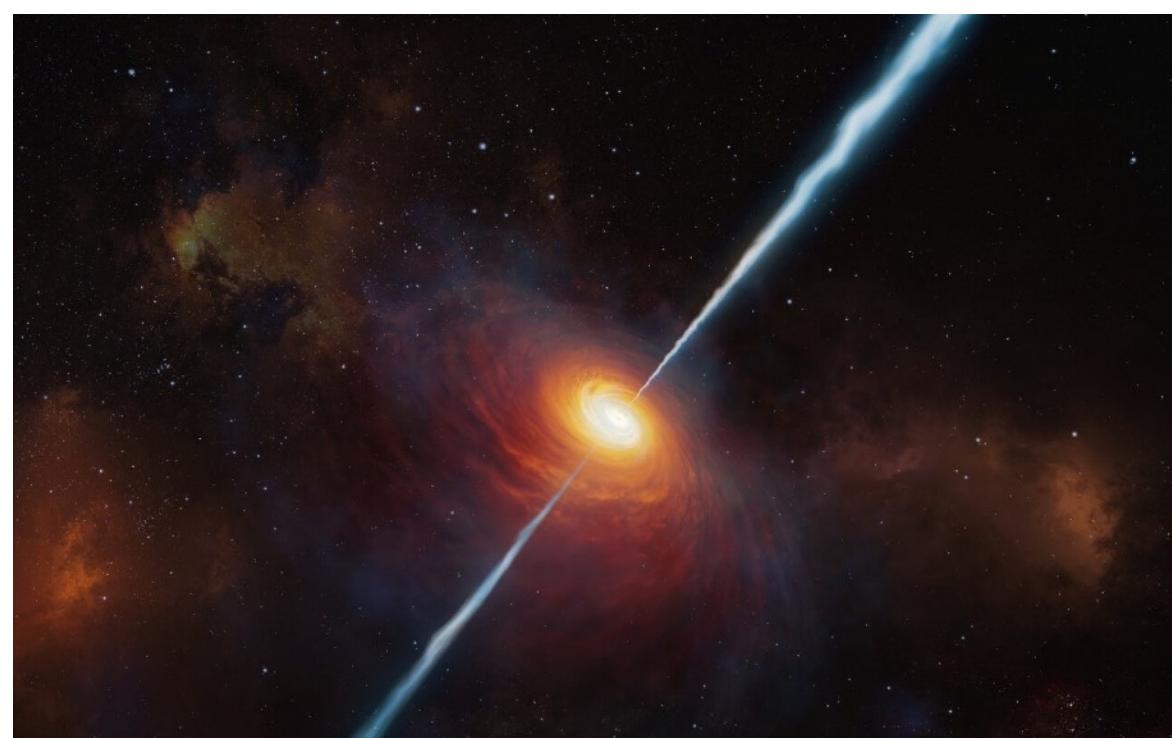


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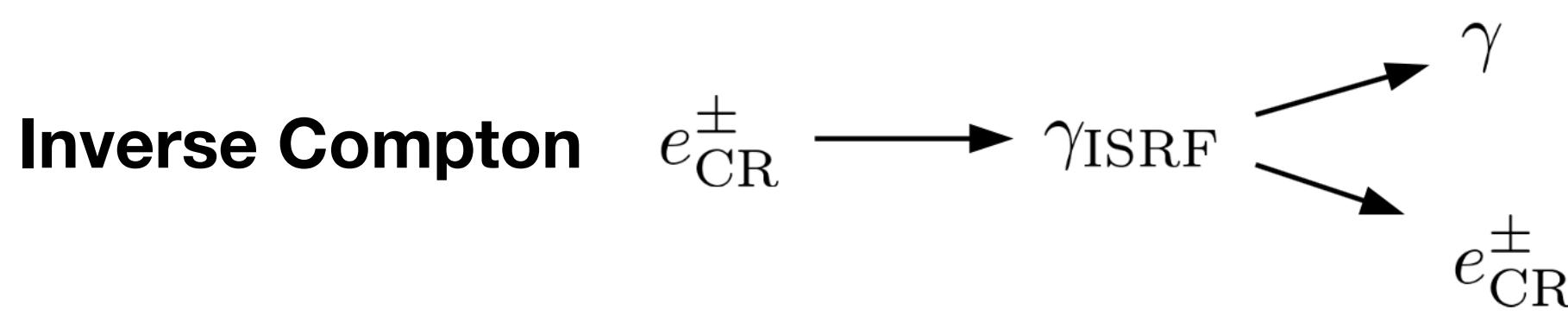
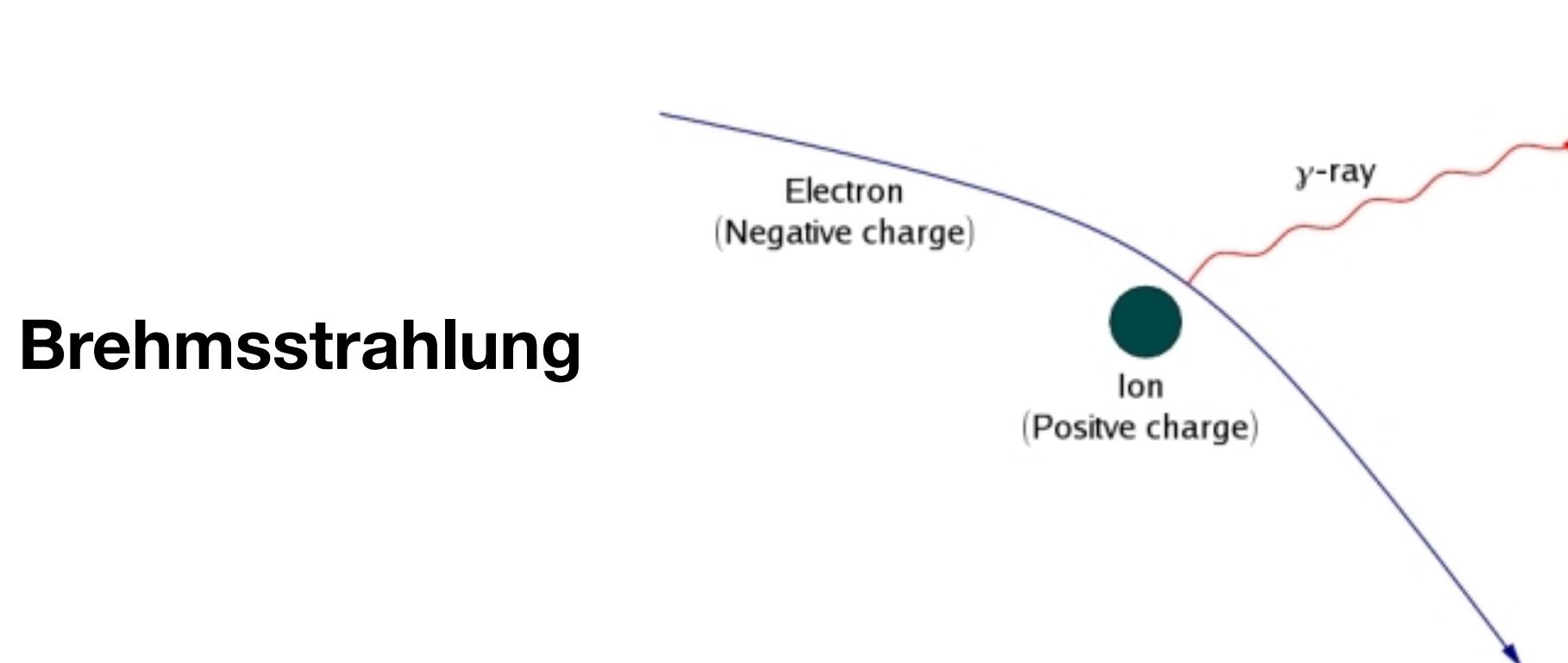
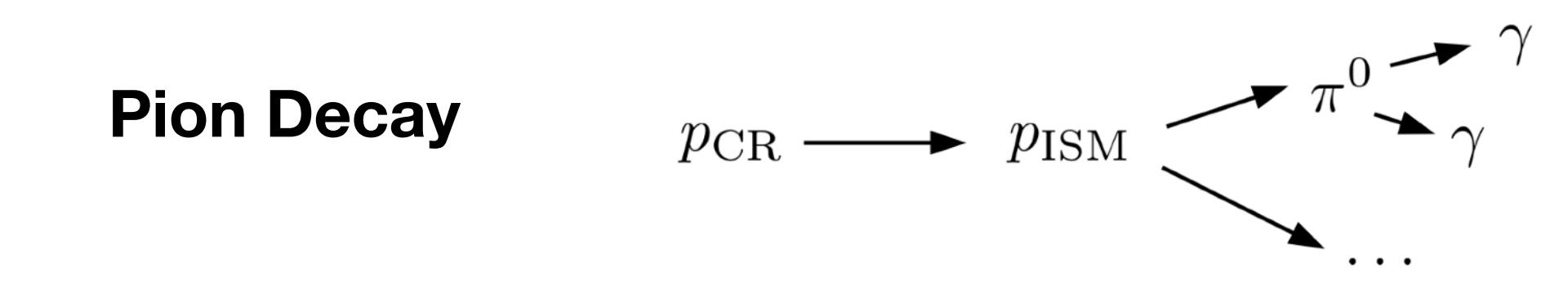
Blazars

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



Credit: ESO/M. Kornmesser

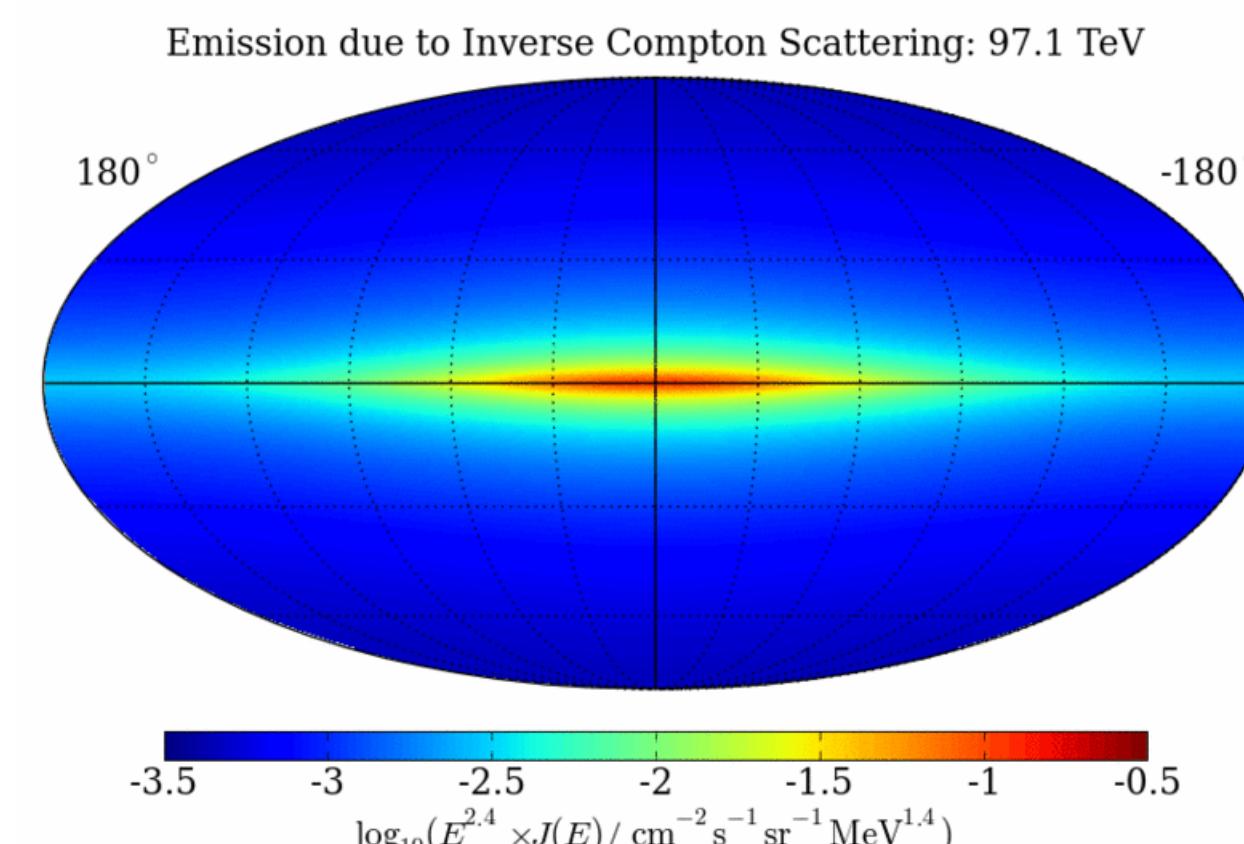
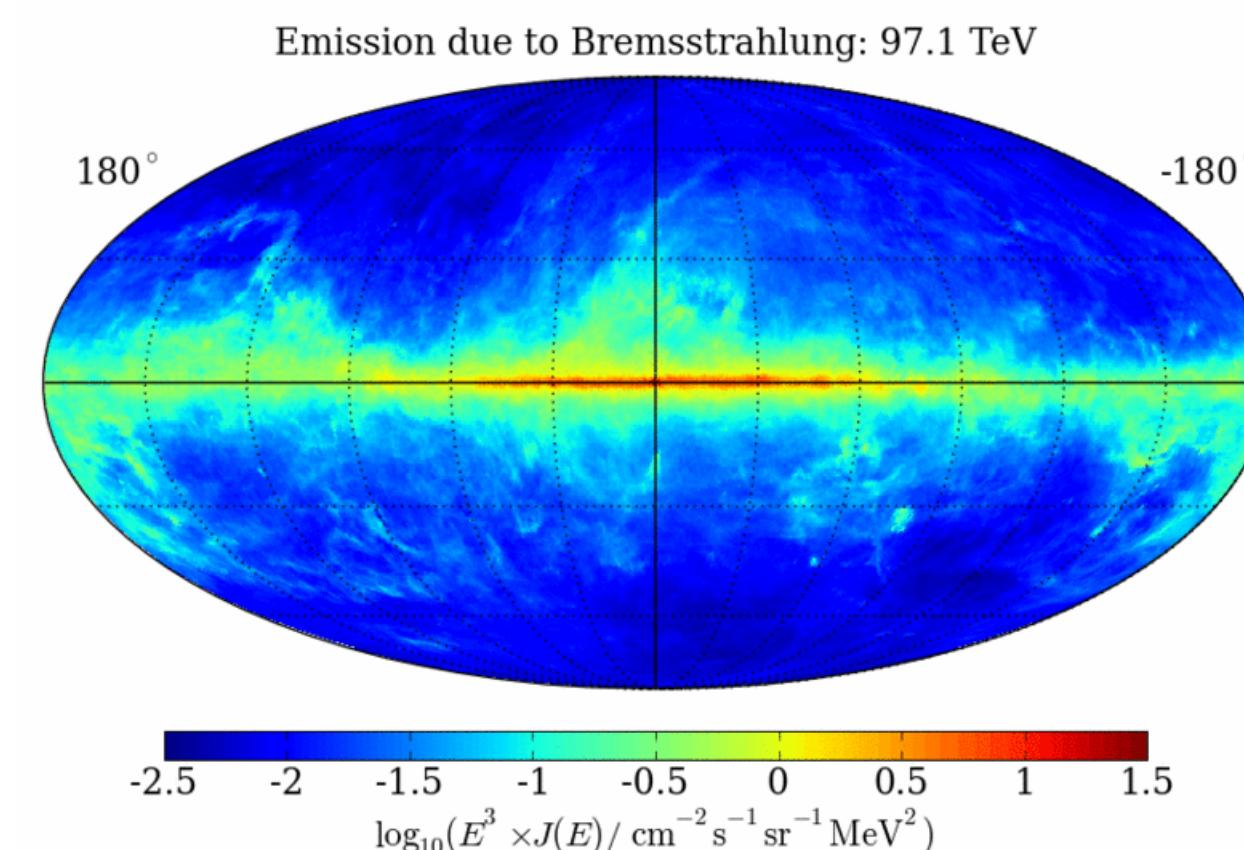
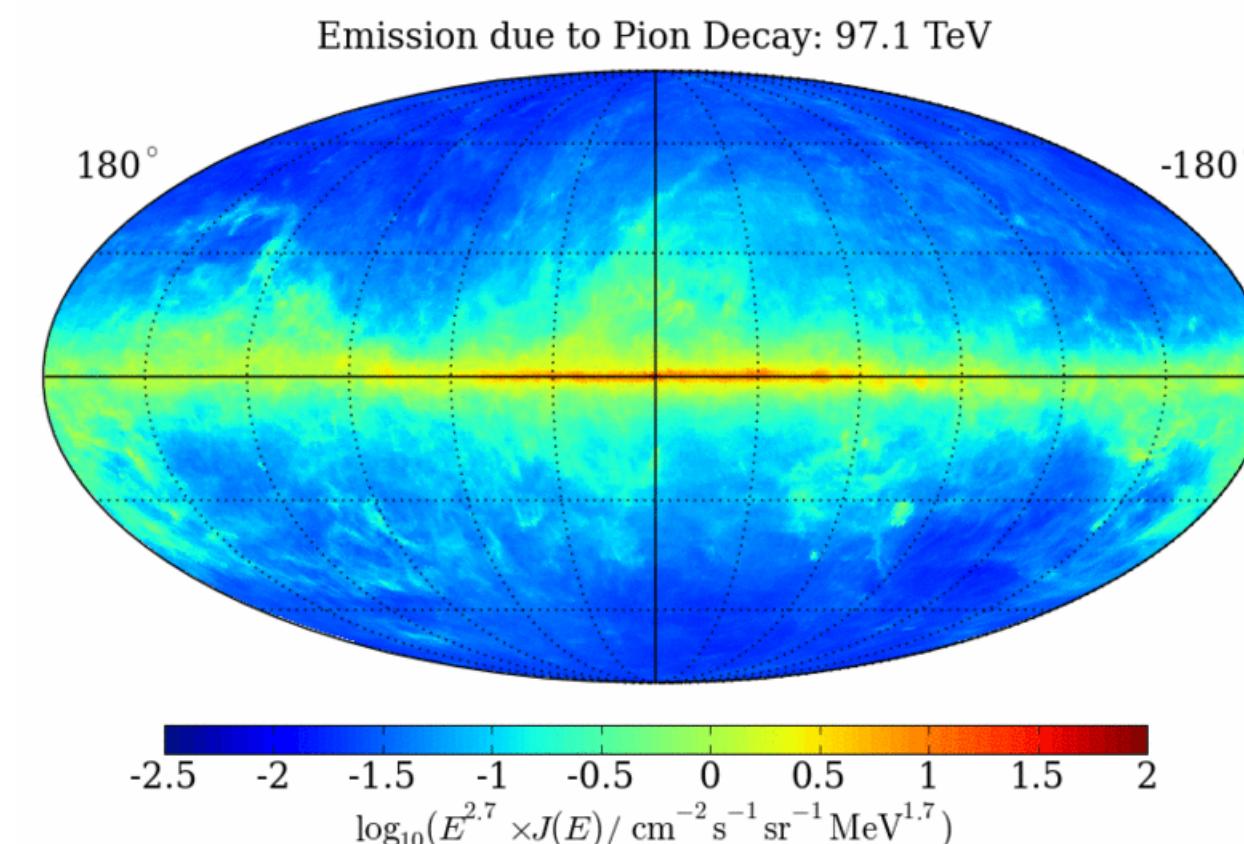
Cosmic Ray Connection



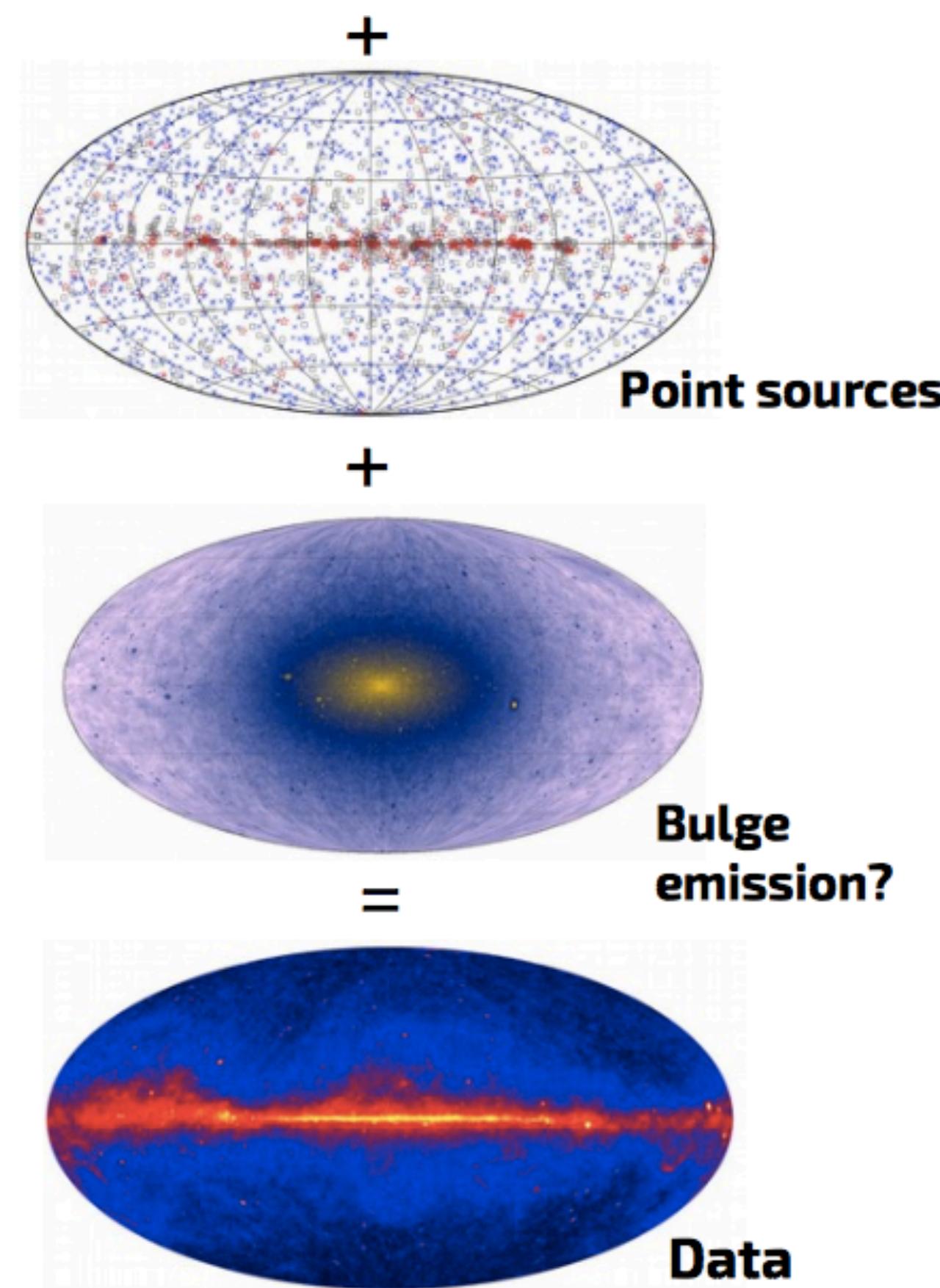
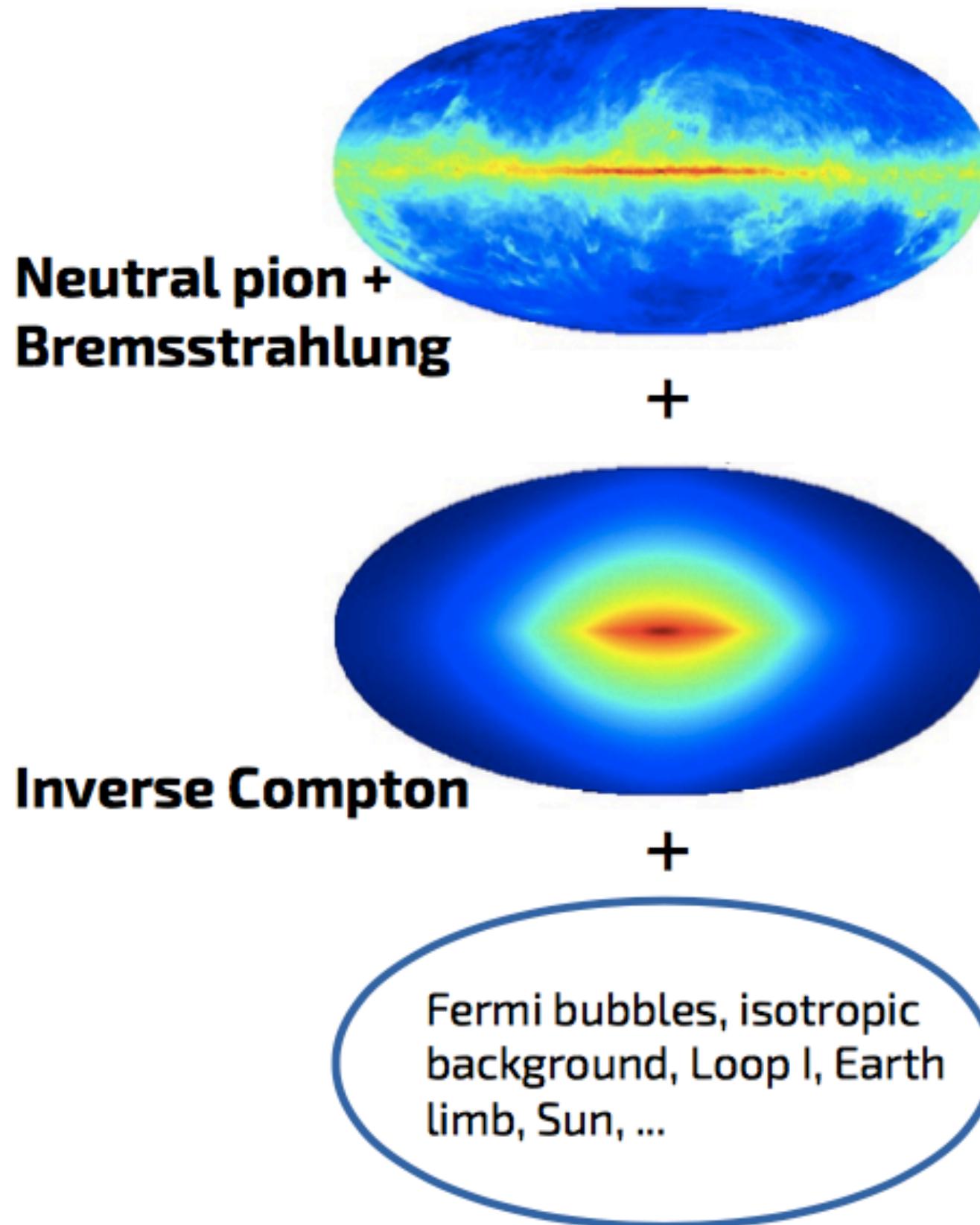
CR protons + gas

CR electrons + gas

CR electrons + light



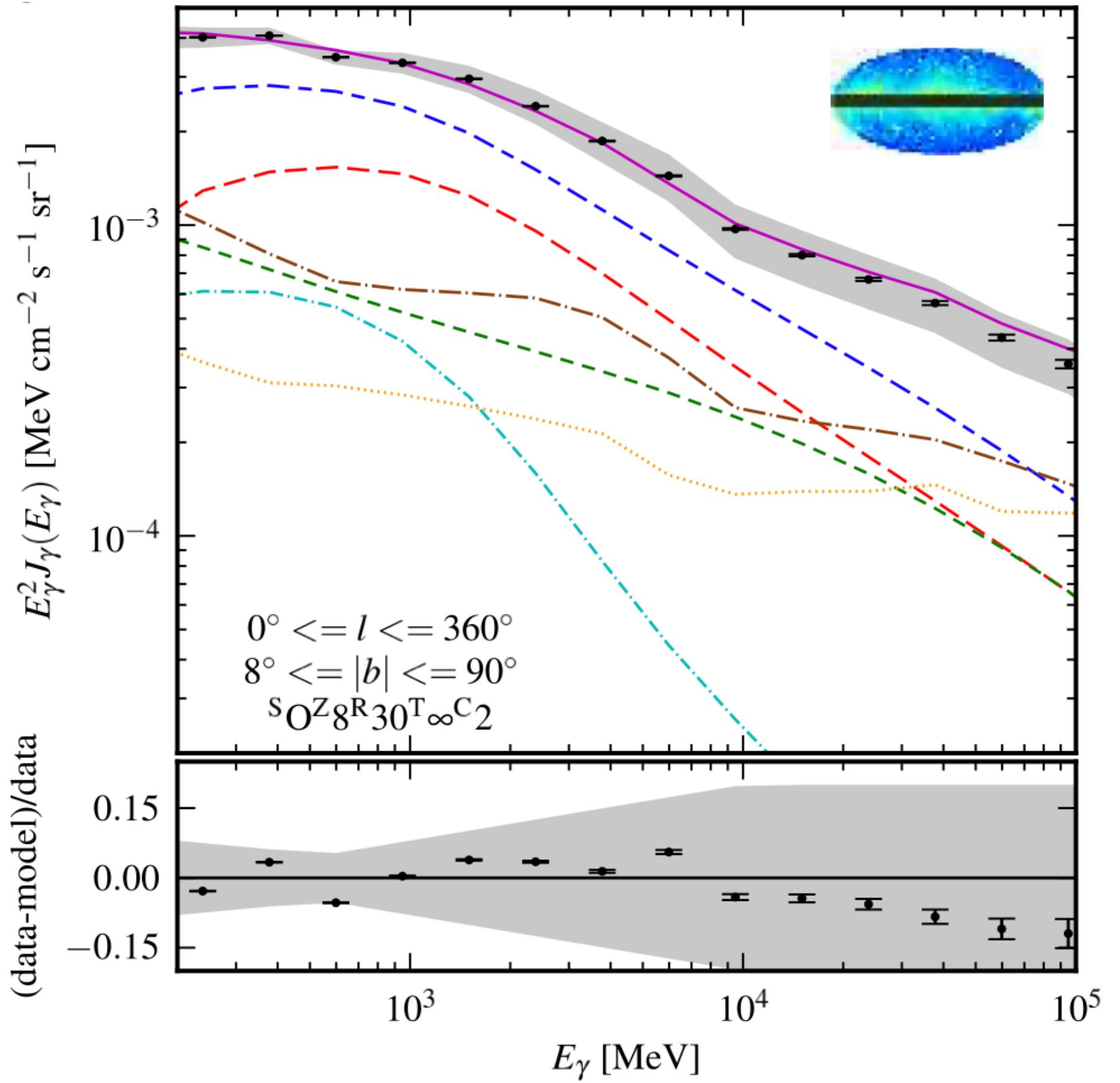
Modelling Gamma-ray emission



Isotropic Background
Bremsstrahlung
Inverse Compton

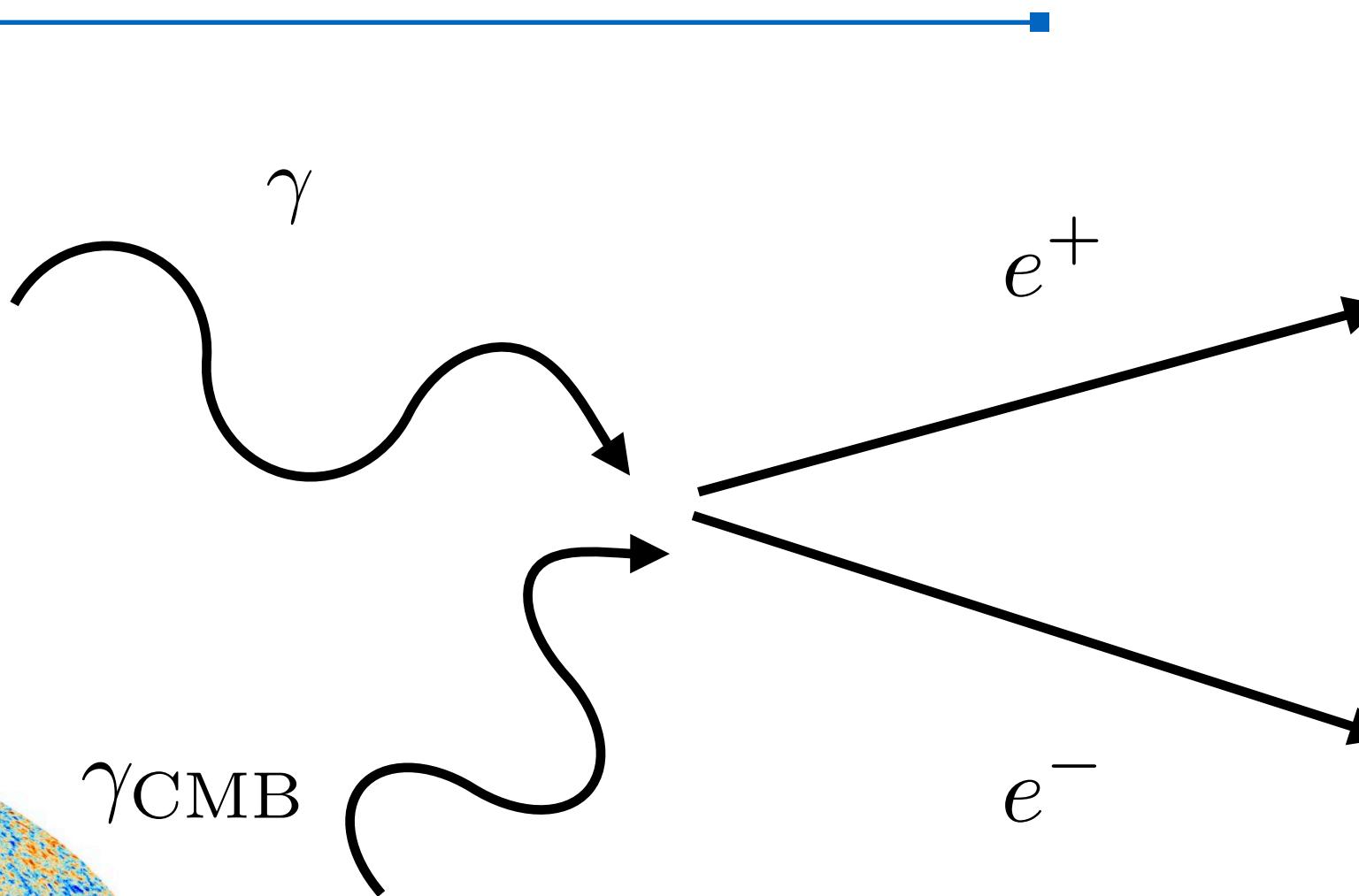
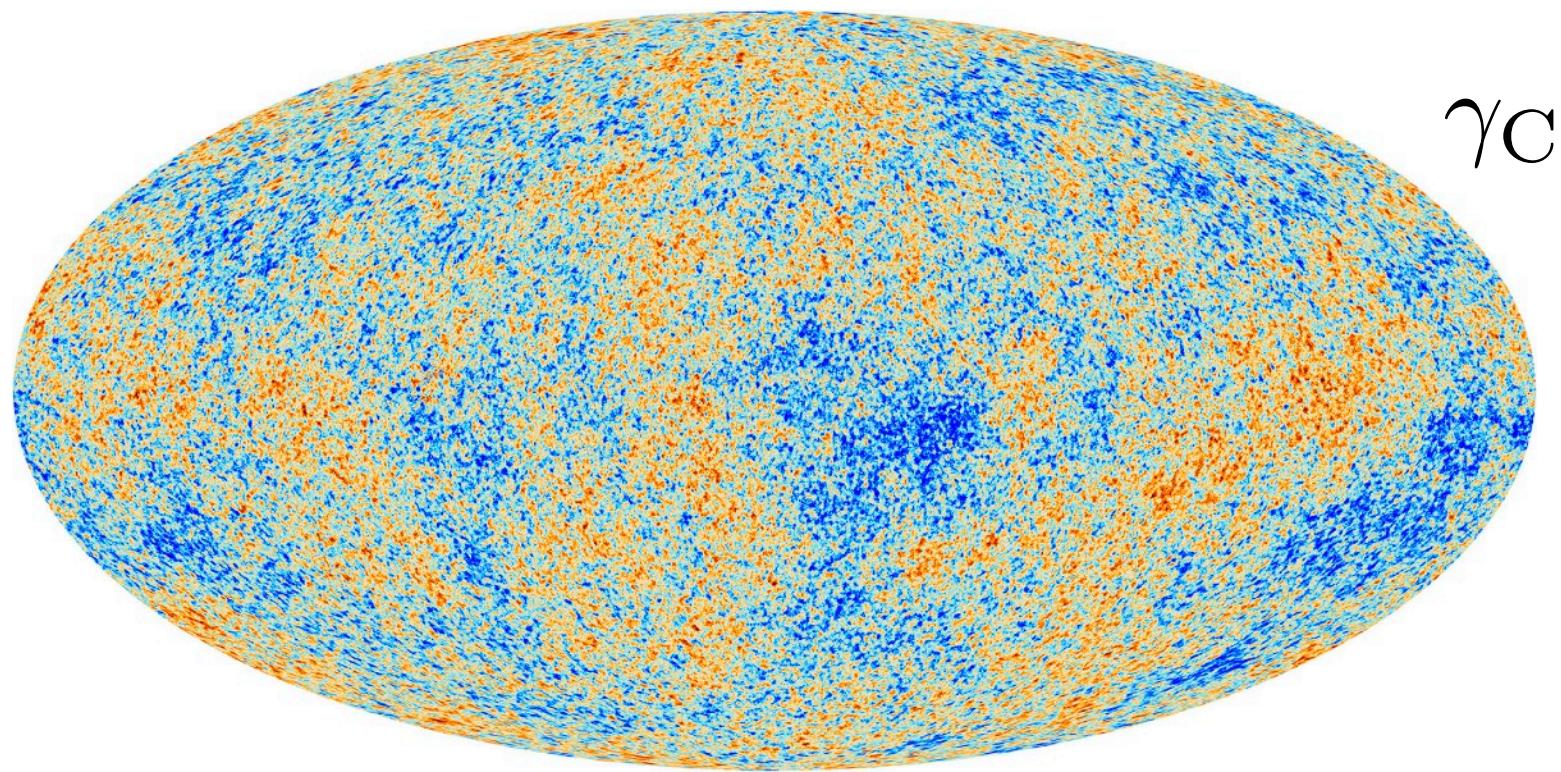
Total Galactic

π^0 decay
Point sources



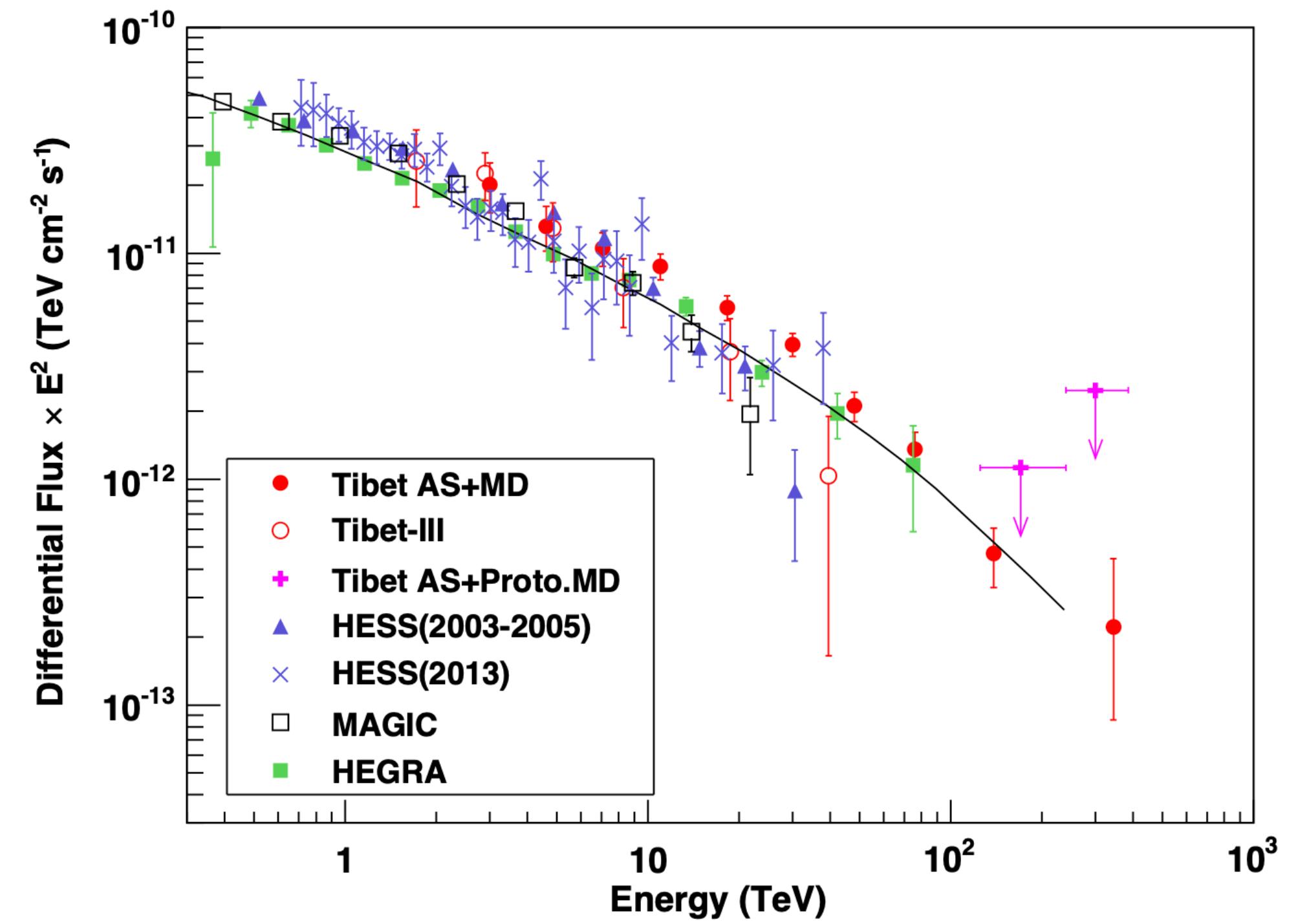
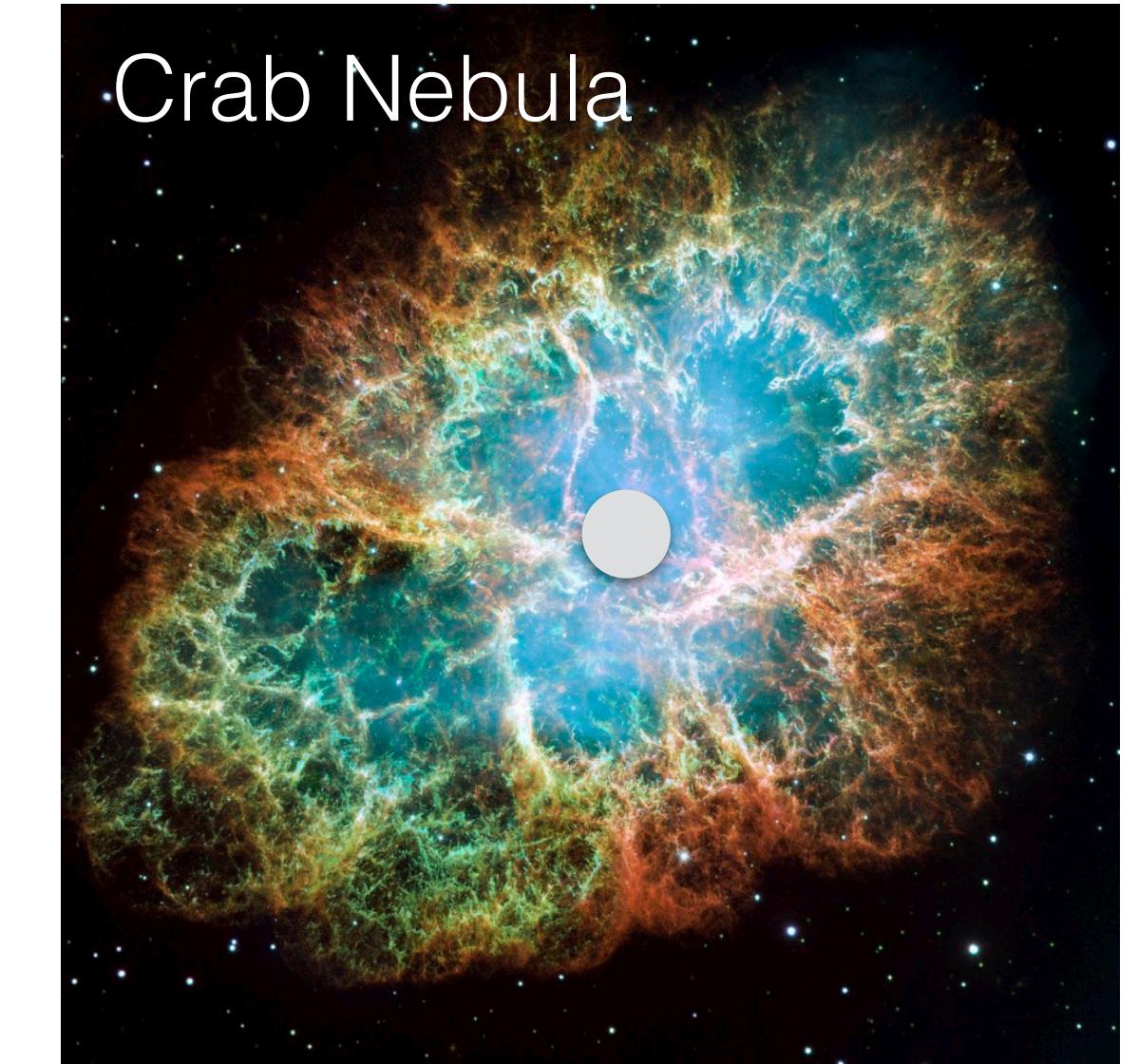
Gamma-ray horizon

Similar to the GZK cut-off...



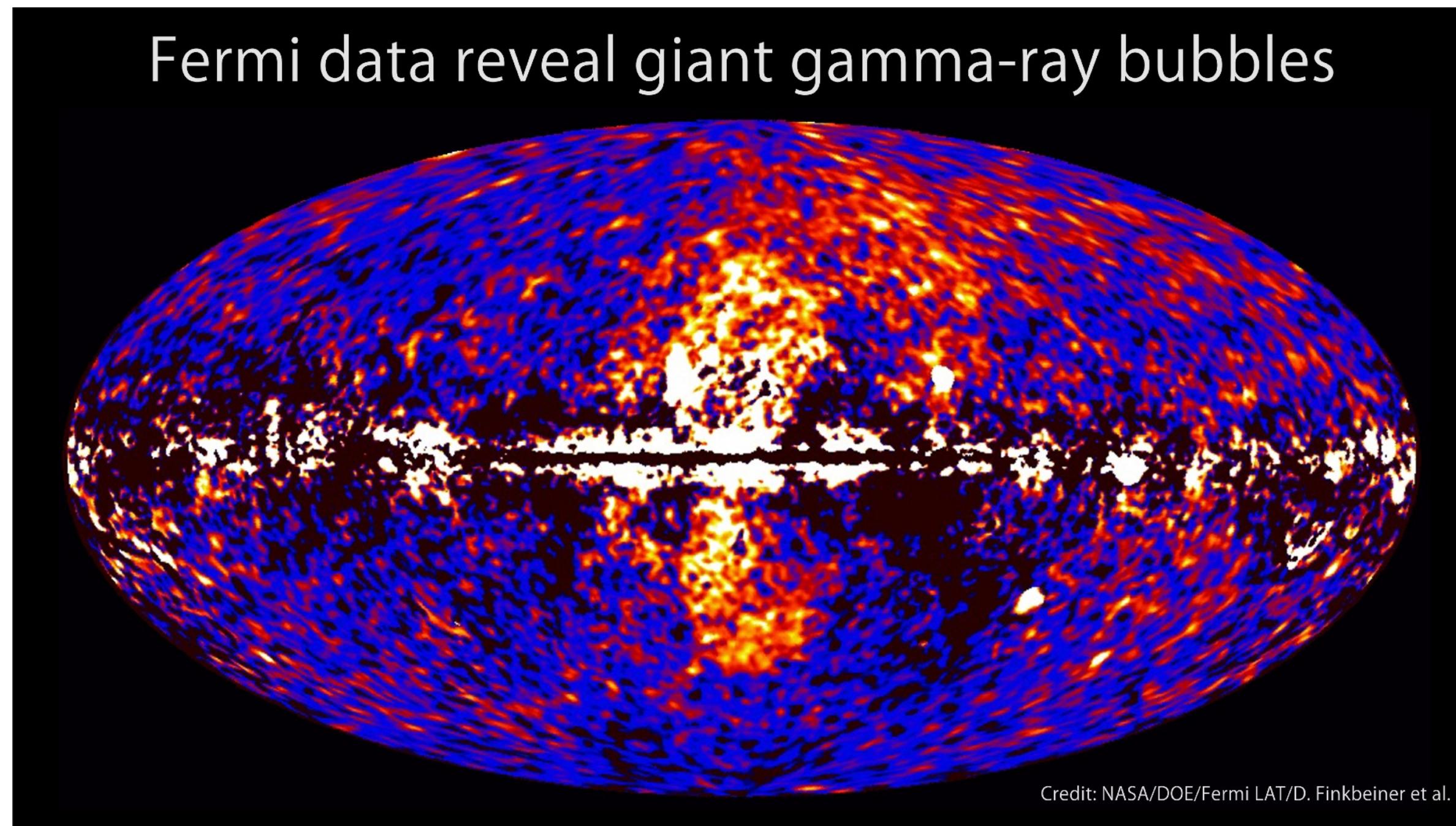
To produce an electron-positron pair, need a gamma-ray with energy greater than:

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

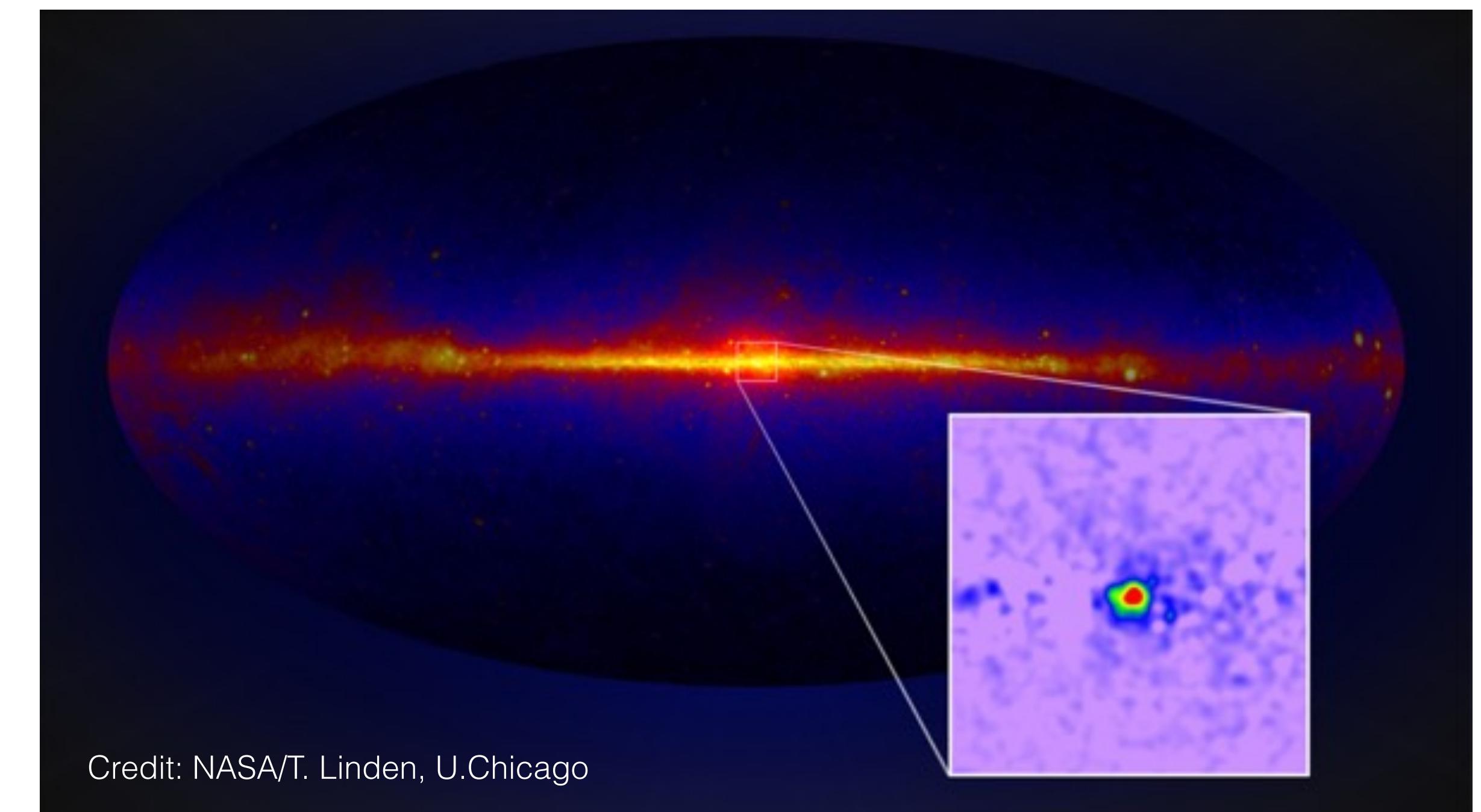


Gamma-ray anomalies

Fermi Bubbles



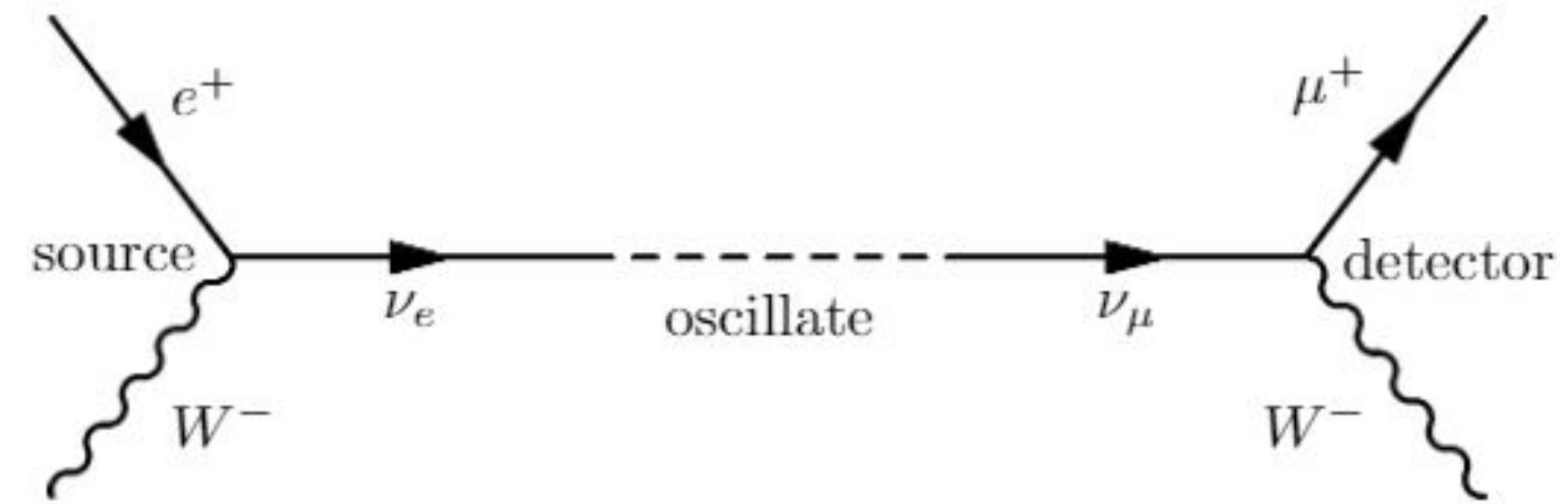
Galactic Centre Excess



and others...

Neutrinos

Our story begins with *solar* neutrinos...



Homestake experiment (1960s)
~600 tons of C_2Cl_4



Credit: Brookhaven National Laboratory

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

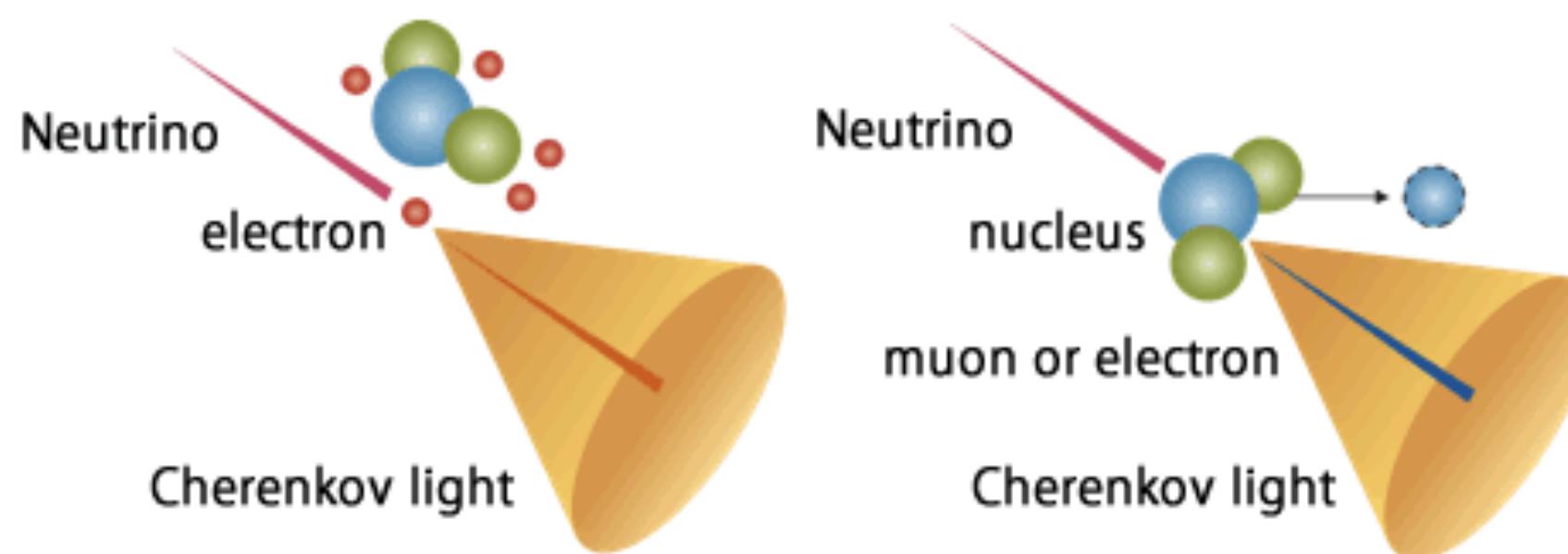
Neutrinos are produced with a definite flavor (e, μ, τ)
but they **oscillate** between the different flavors as they propagate.

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

IceCube

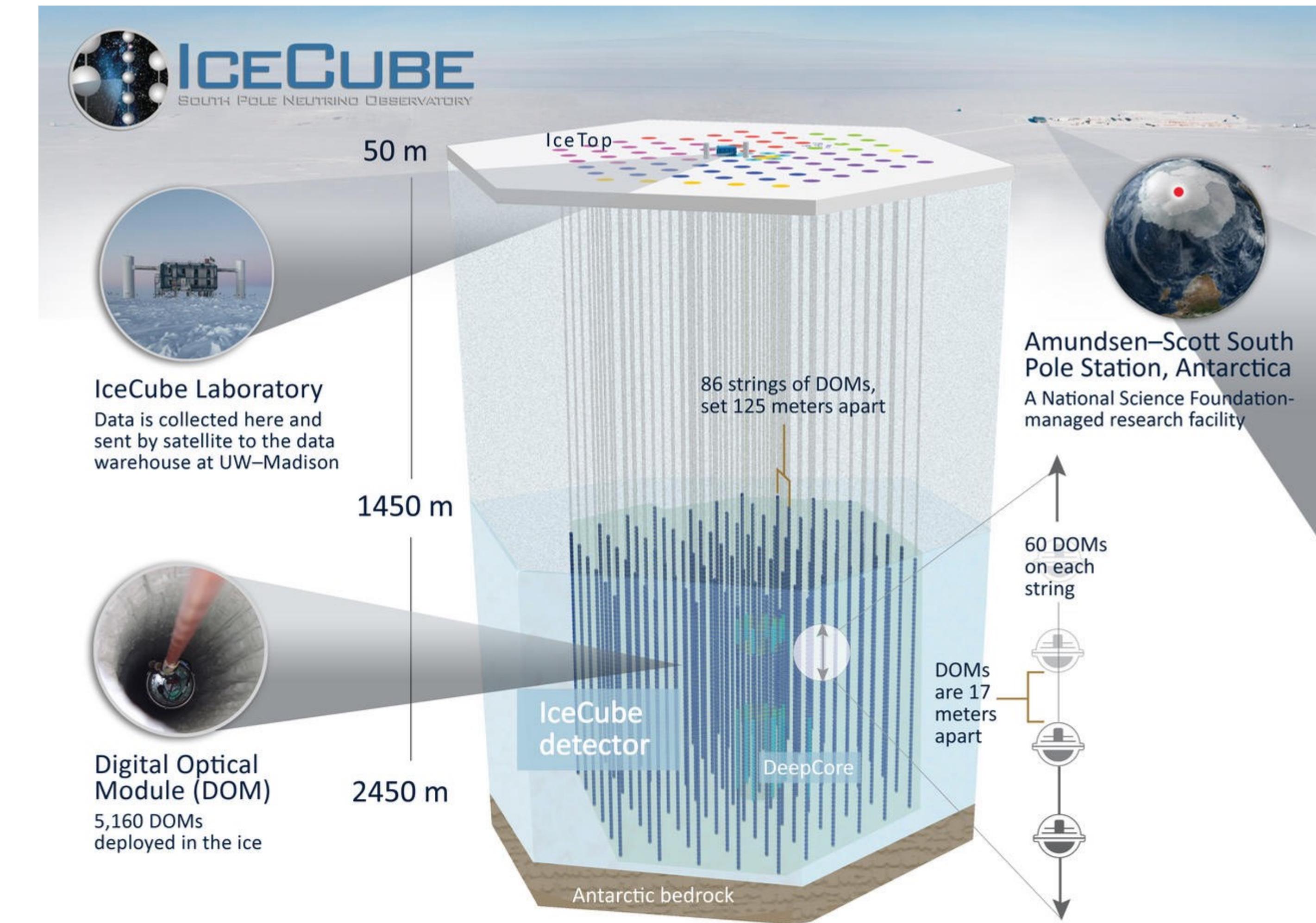
1701.03731

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



Credit: Hyper-Kamiokande

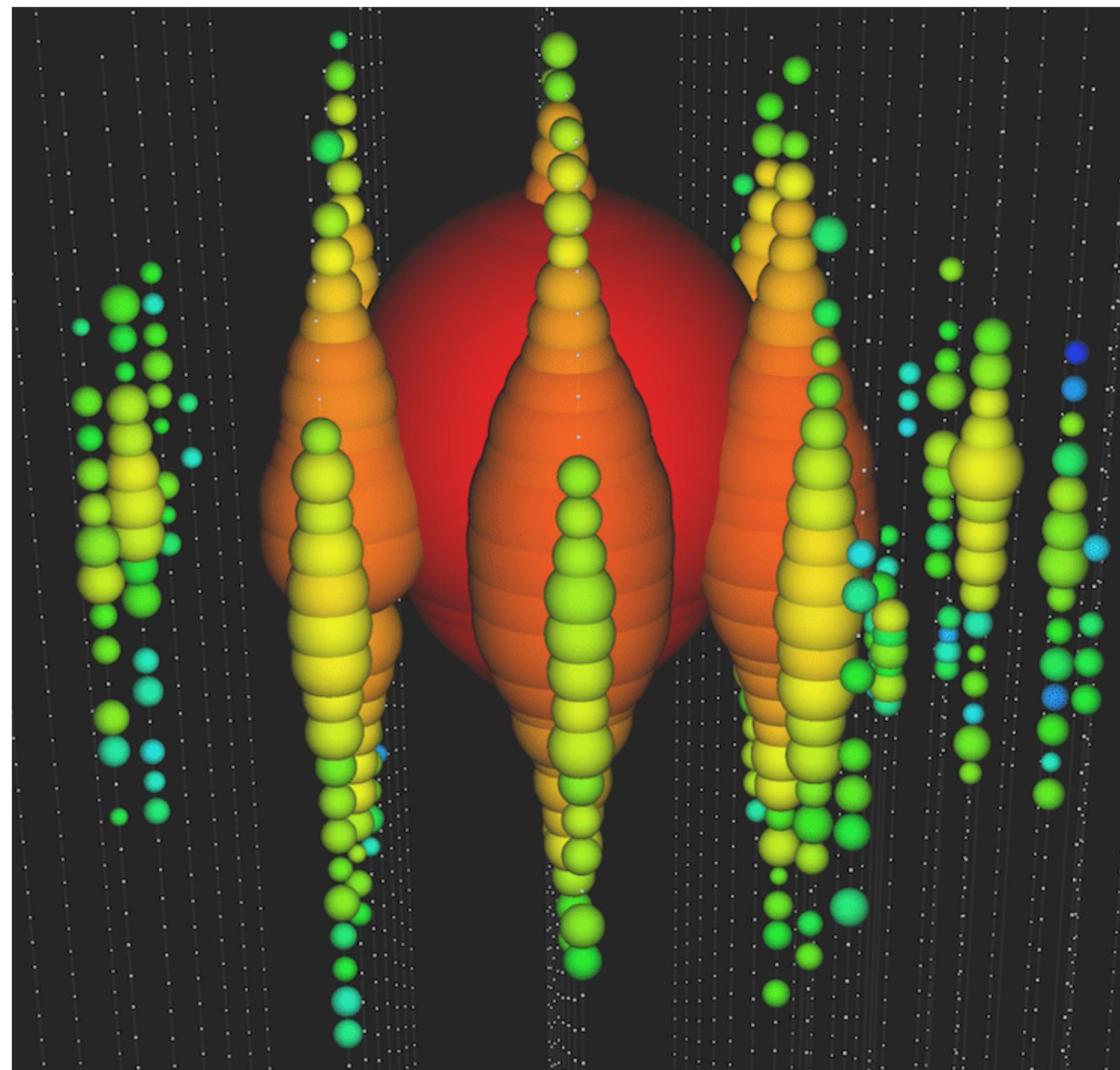
IceCube: a giant ice detector!
~1 km³ of instrumented volume



See also [SuperKamiokande](#), [ANTARES](#), planned [KM3NET](#)

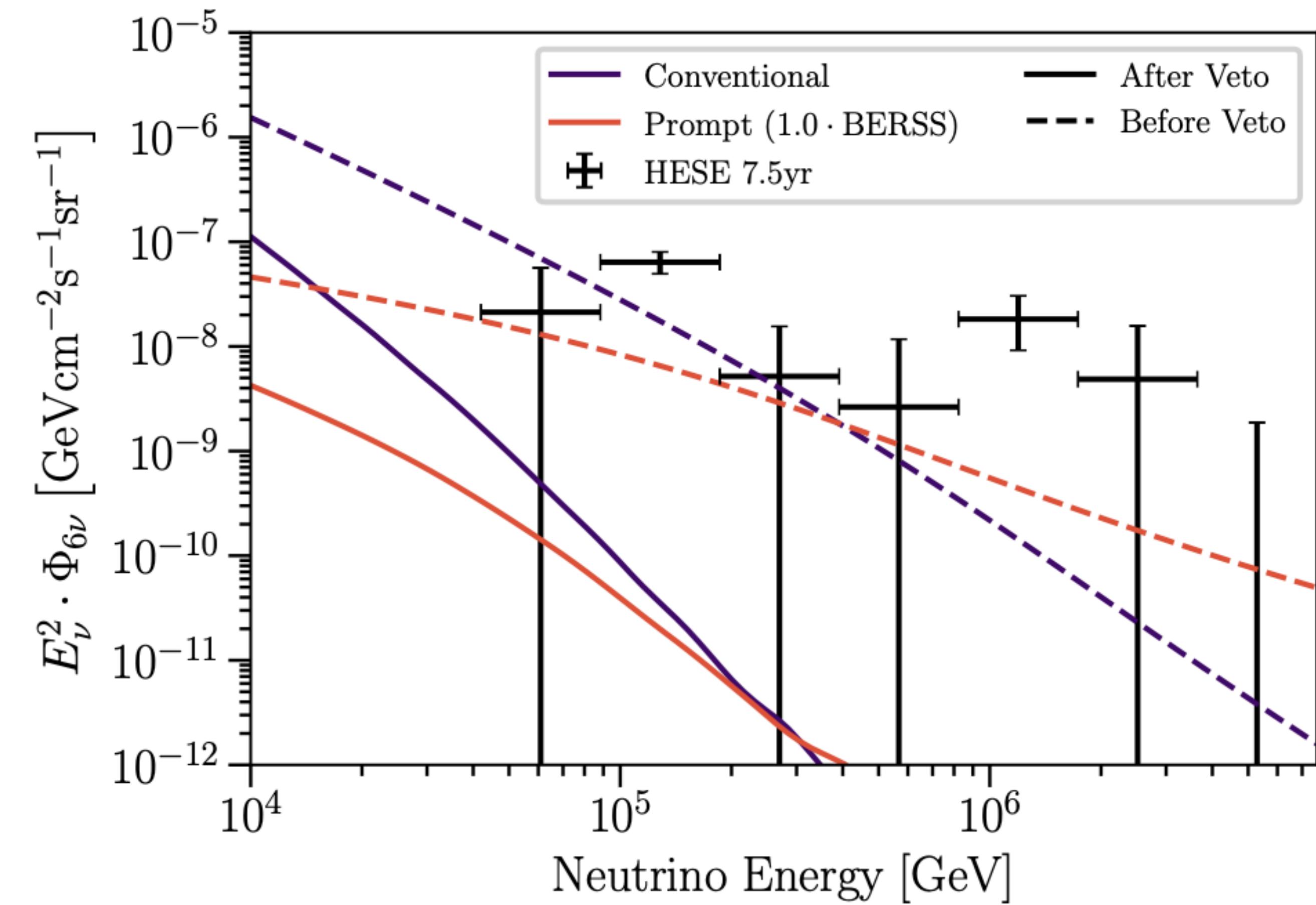
Ultra-high energy neutrinos

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



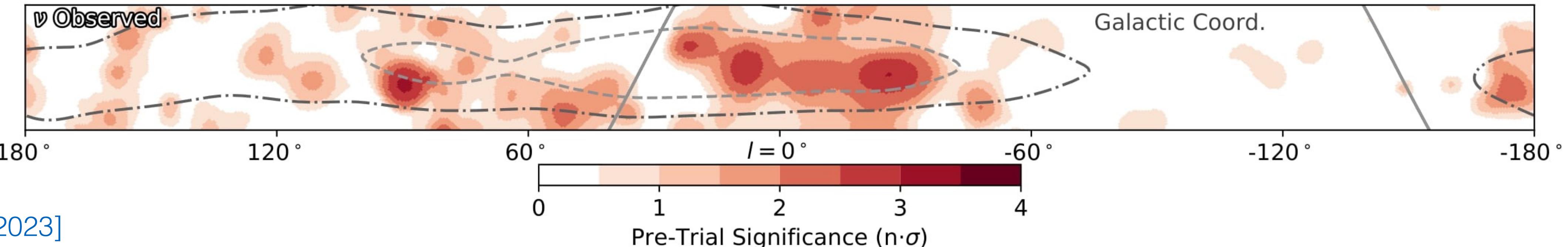
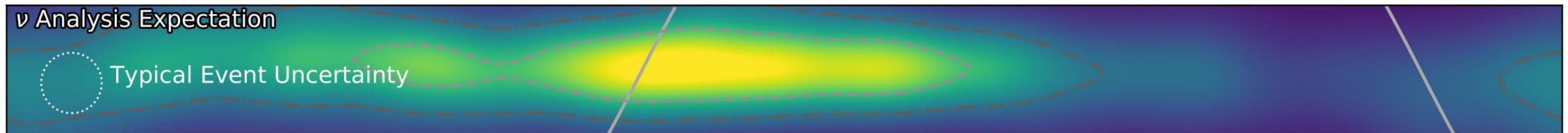
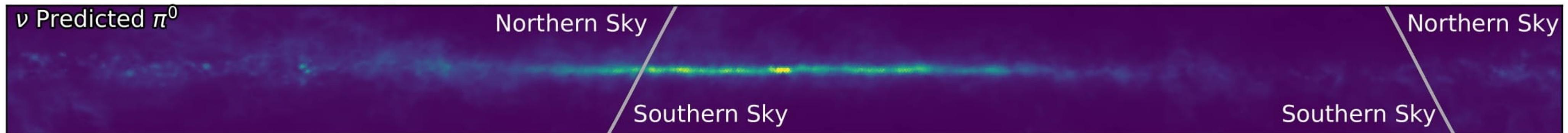
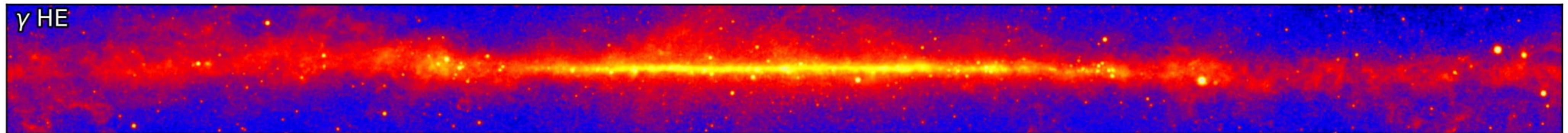
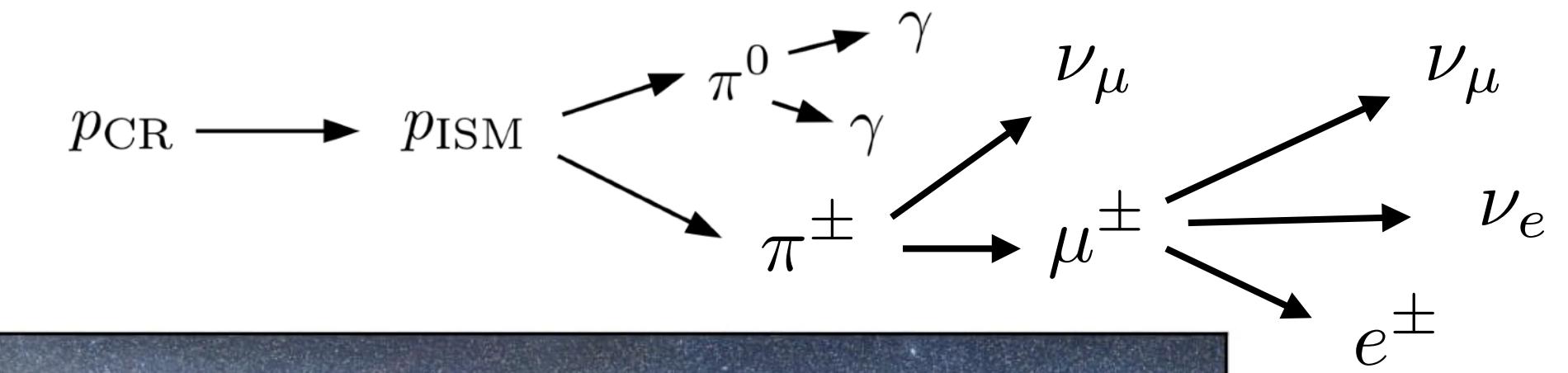
Credit: IceCube Collaboration

IceCube ‘high energy starting events’ (HESE)

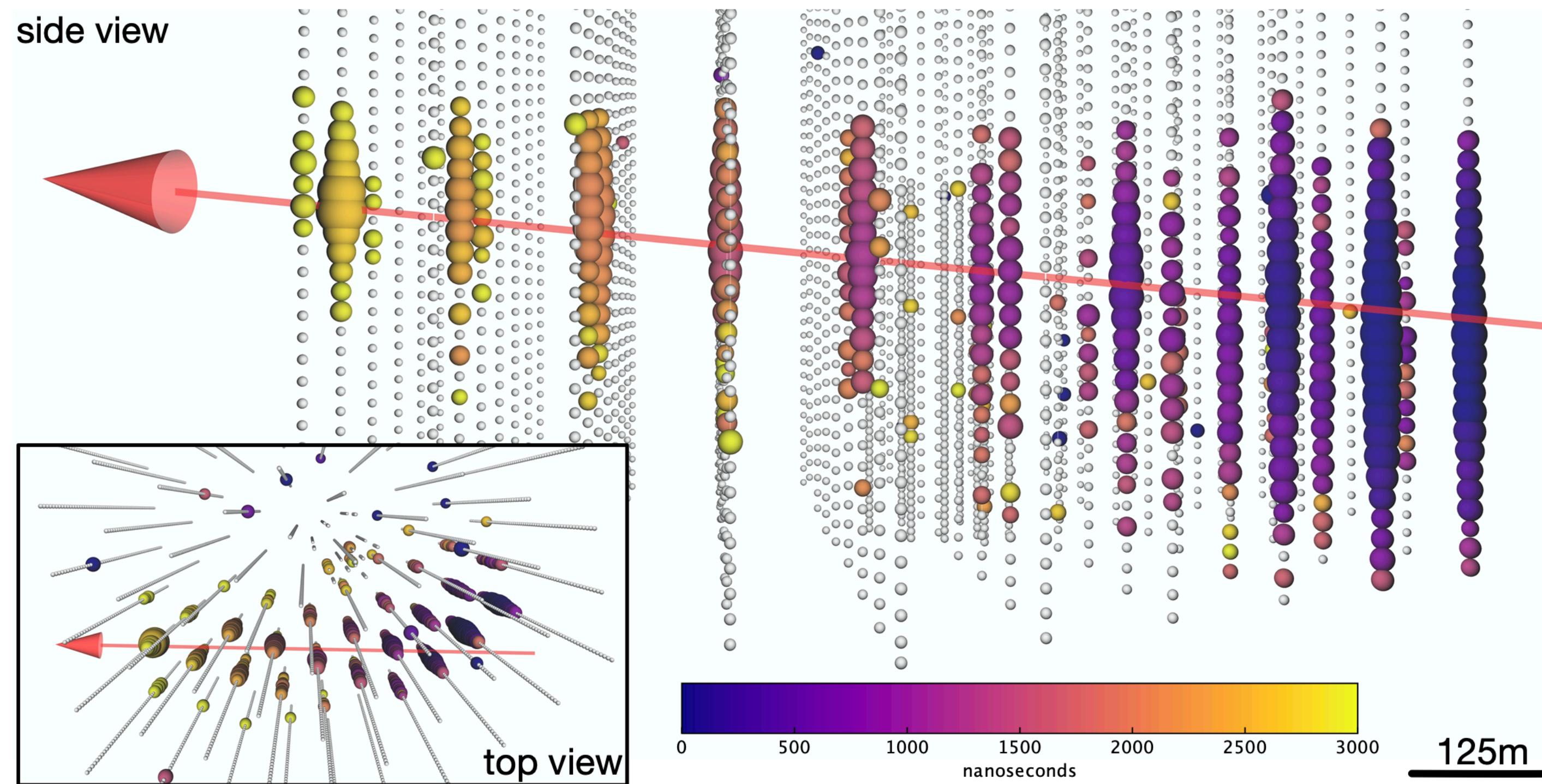


[2011.03545](#)

Milky Way shines bright in Neutrinos!



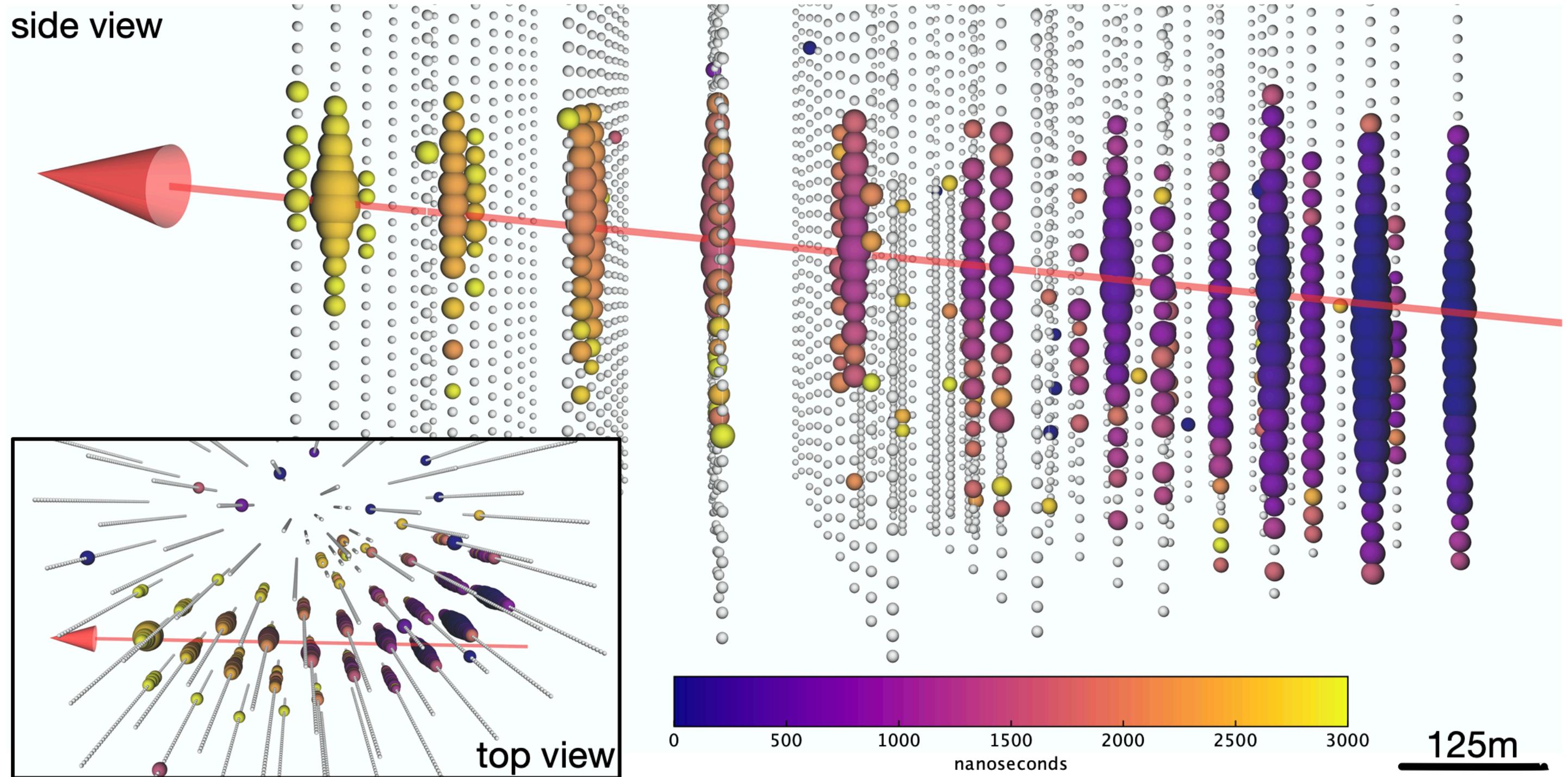
22 September 2017



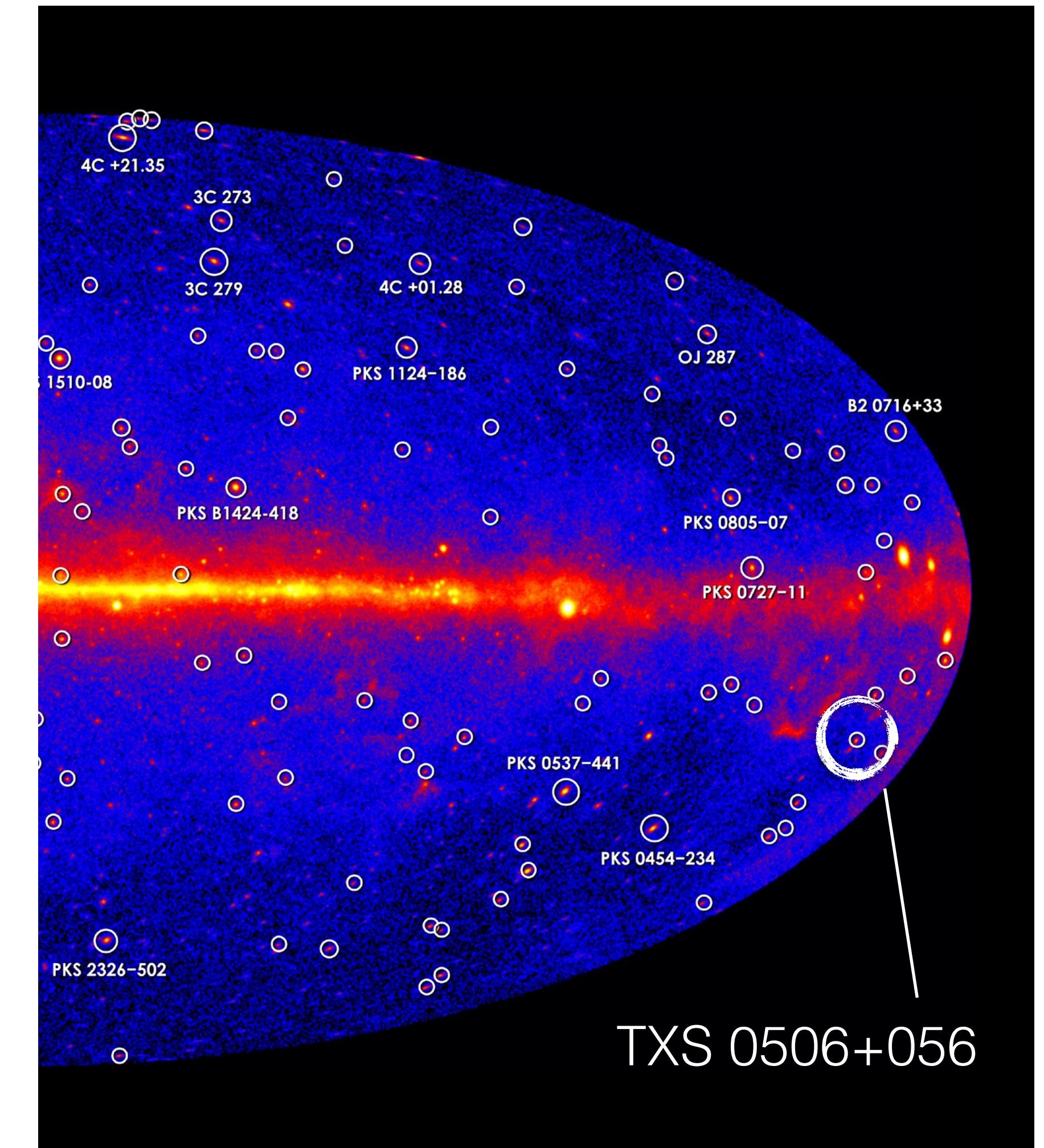
$$E_\nu \sim 290 \text{ TeV}$$

IceCube-170922A

[1807.08816]



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

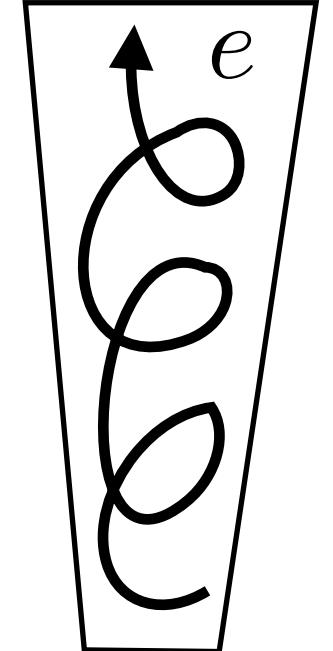


TXS 0506+056 is a known blazar!

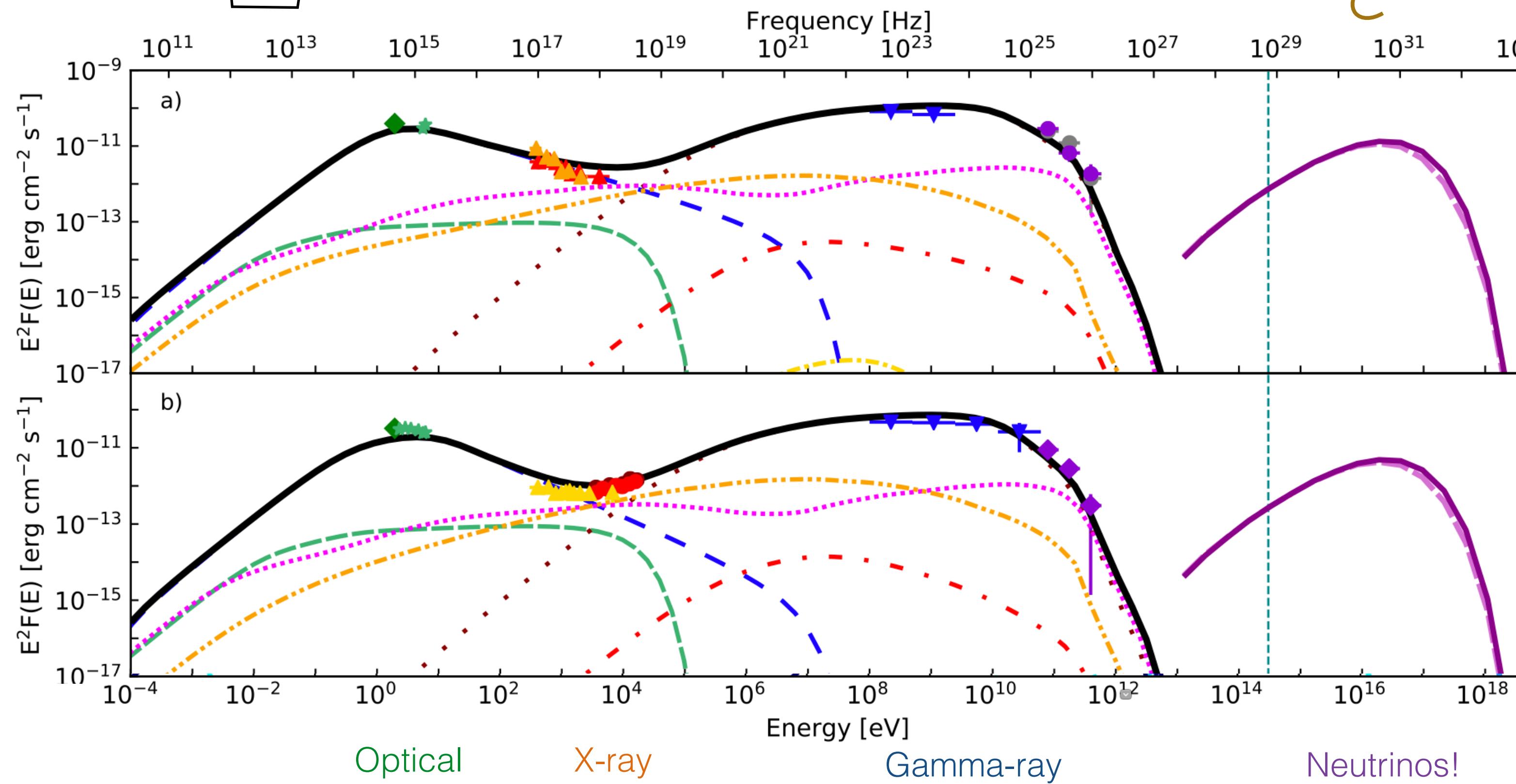
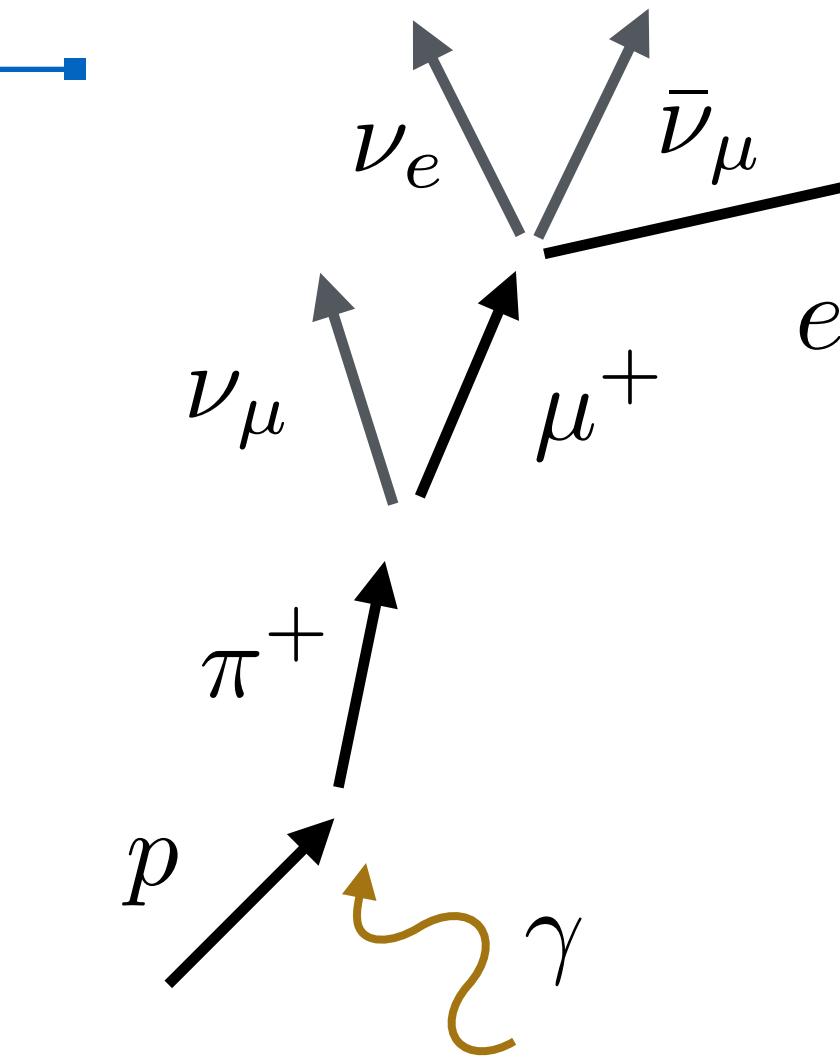
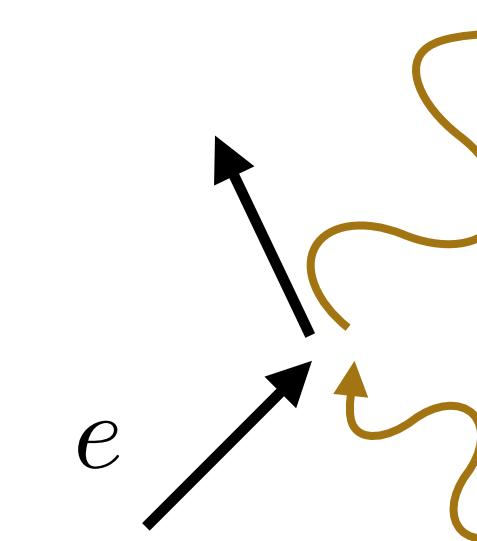
It was flaring at the time of
IceCube-170922A!

Blazar emission

Electron synchrotron



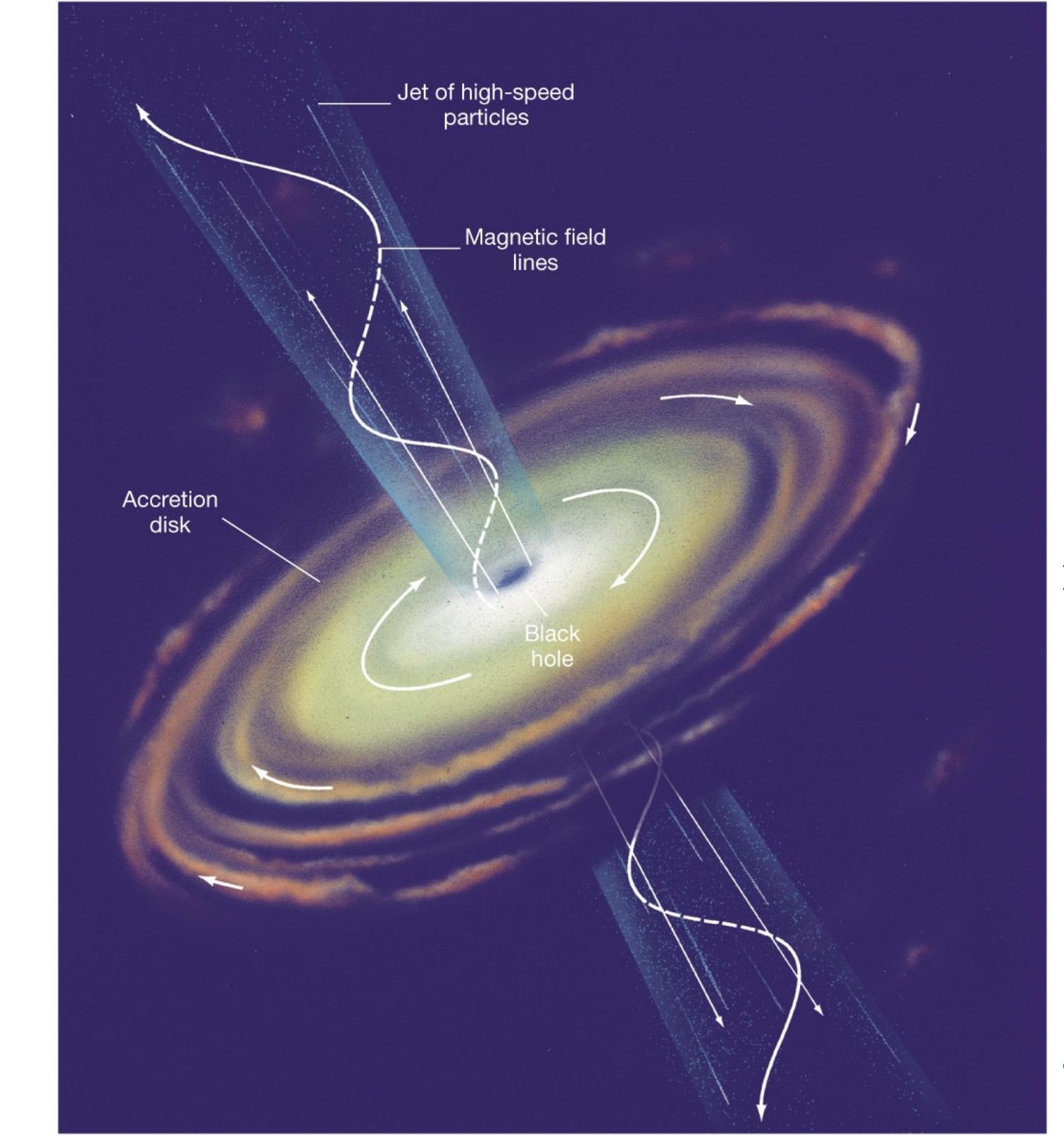
Inverse Compton



- MAGIC 58057
- MAGIC 58029-30
- MAGIC LS
- ▼ Fermi-LAT
- NuSTAR 58025
- NuSTAR 58045
- ▲ Swift/XRT 58029
- ▲ Swift/XRT 58030
- ▲ Swift/XRT LS
- ◆ KVA
- ★ UVOT

- $E_{p, \text{max}} = 10^{16}$
- e- sync. jet
- - e- sync. sheath
- . SSC
- . - EC
- $\gamma\pi$ cascade
- ... μ sync.
- . BH cascade
- total EM
- $\bar{\nu}_\mu$
- ν_μ

1807.04300

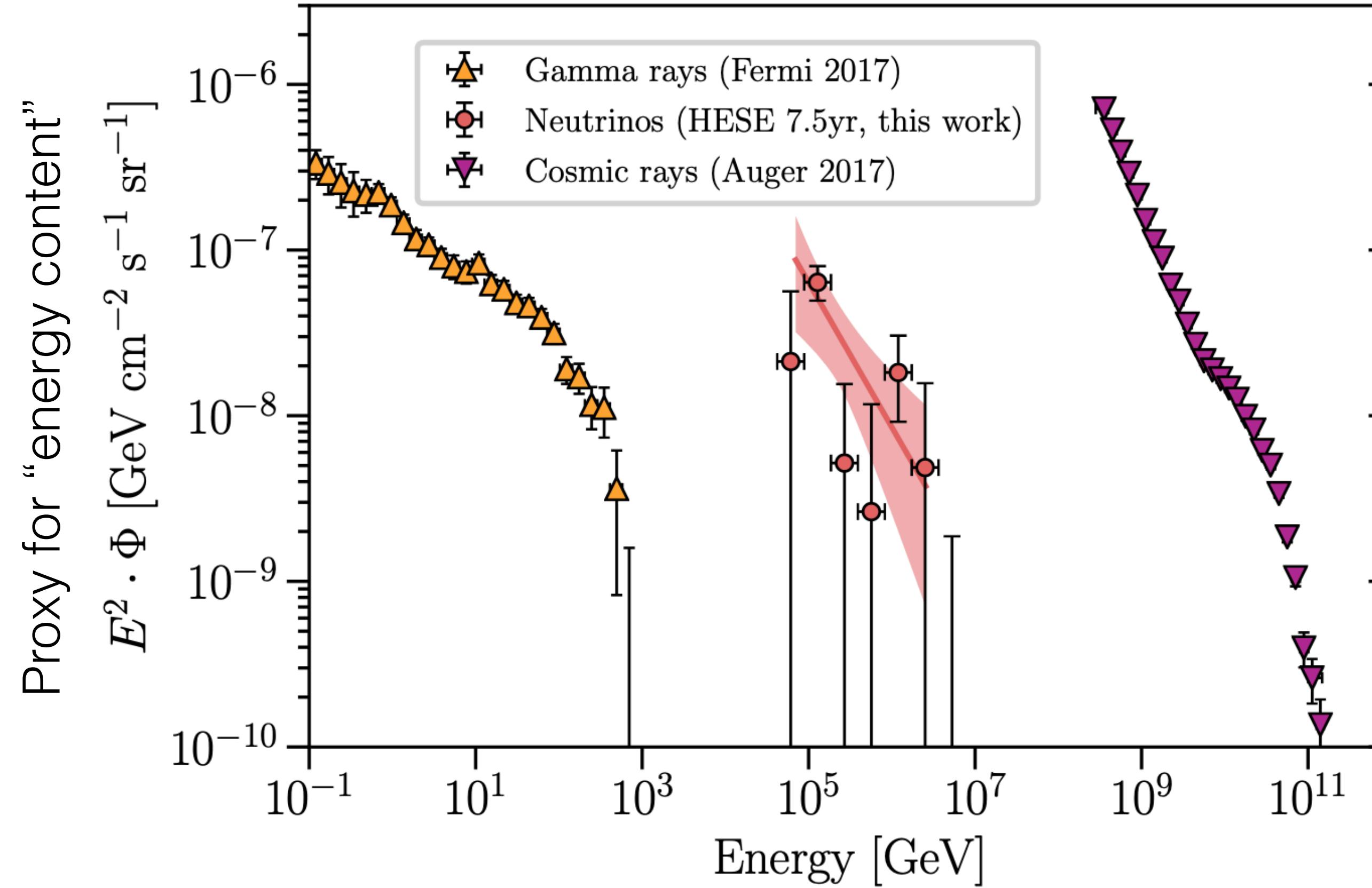


Violent and Energetic Universe

29

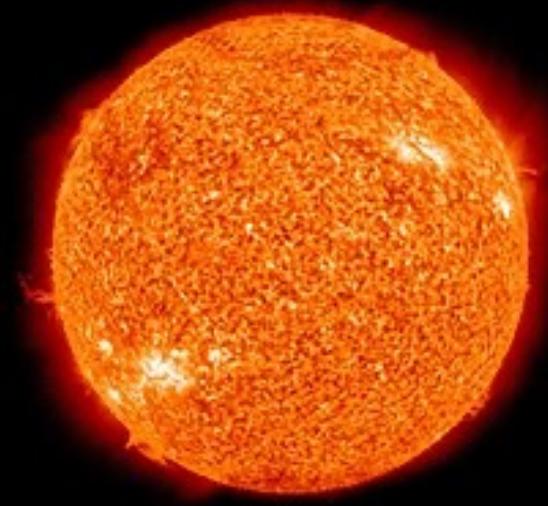
A complex and interconnected ecosystem:

[2011.03545](#)



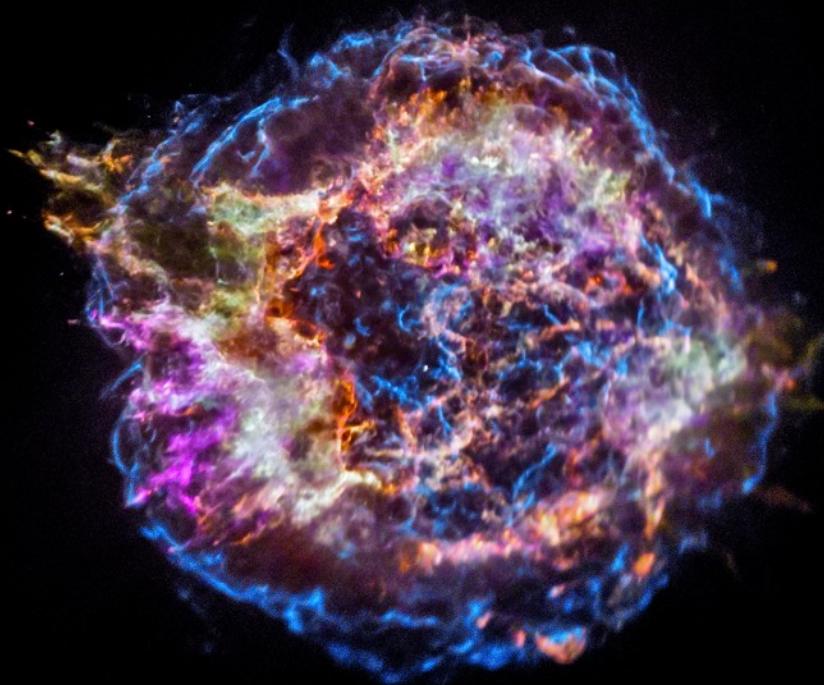
Understanding it could shed light on the most violent processes in the Universe,
and on New Physics yet to be discovered...

The Sun



Credit: NASA/CXC/SAO

Supernovae

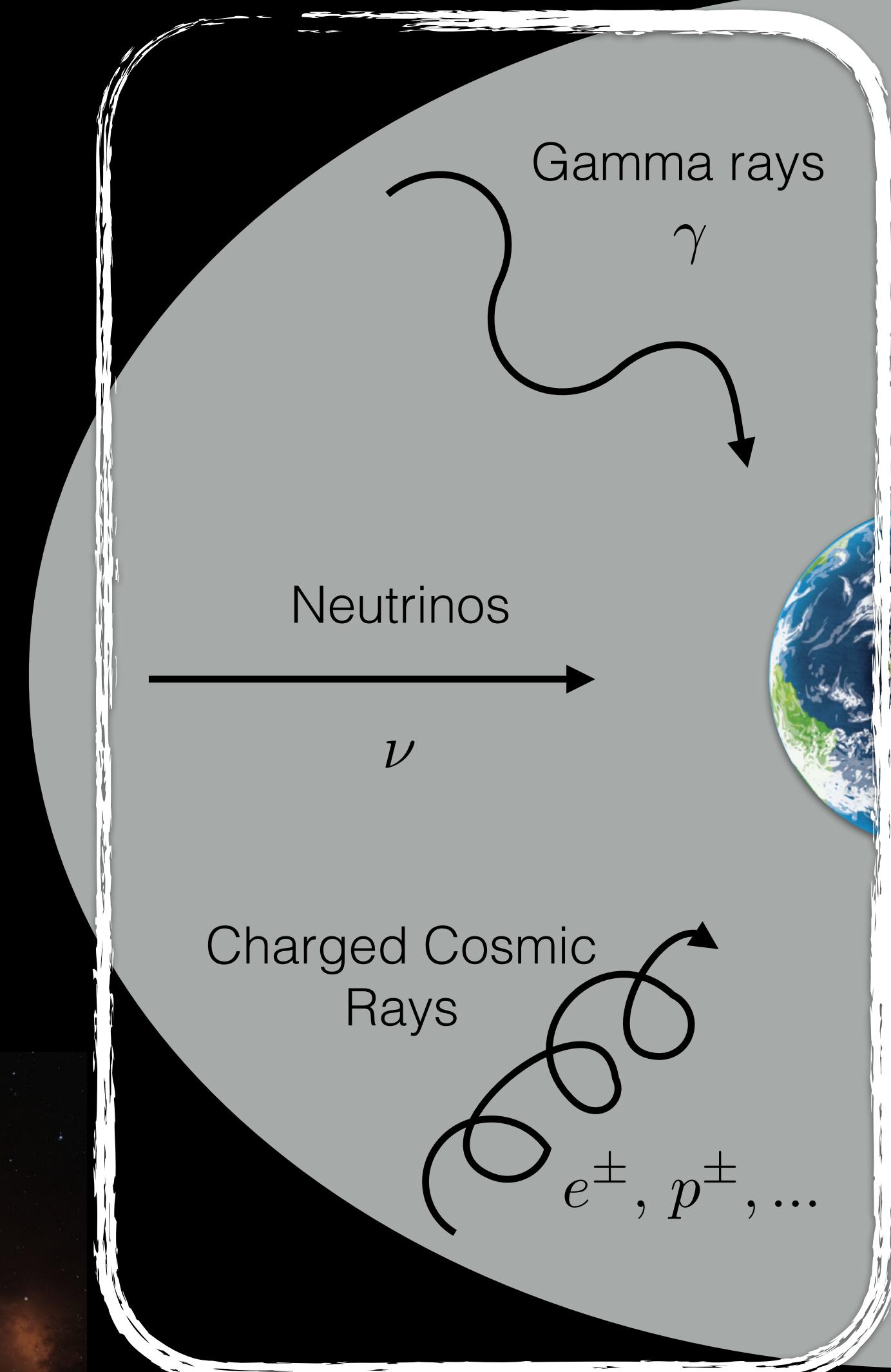


Credit: ESO/M. Kornmesser

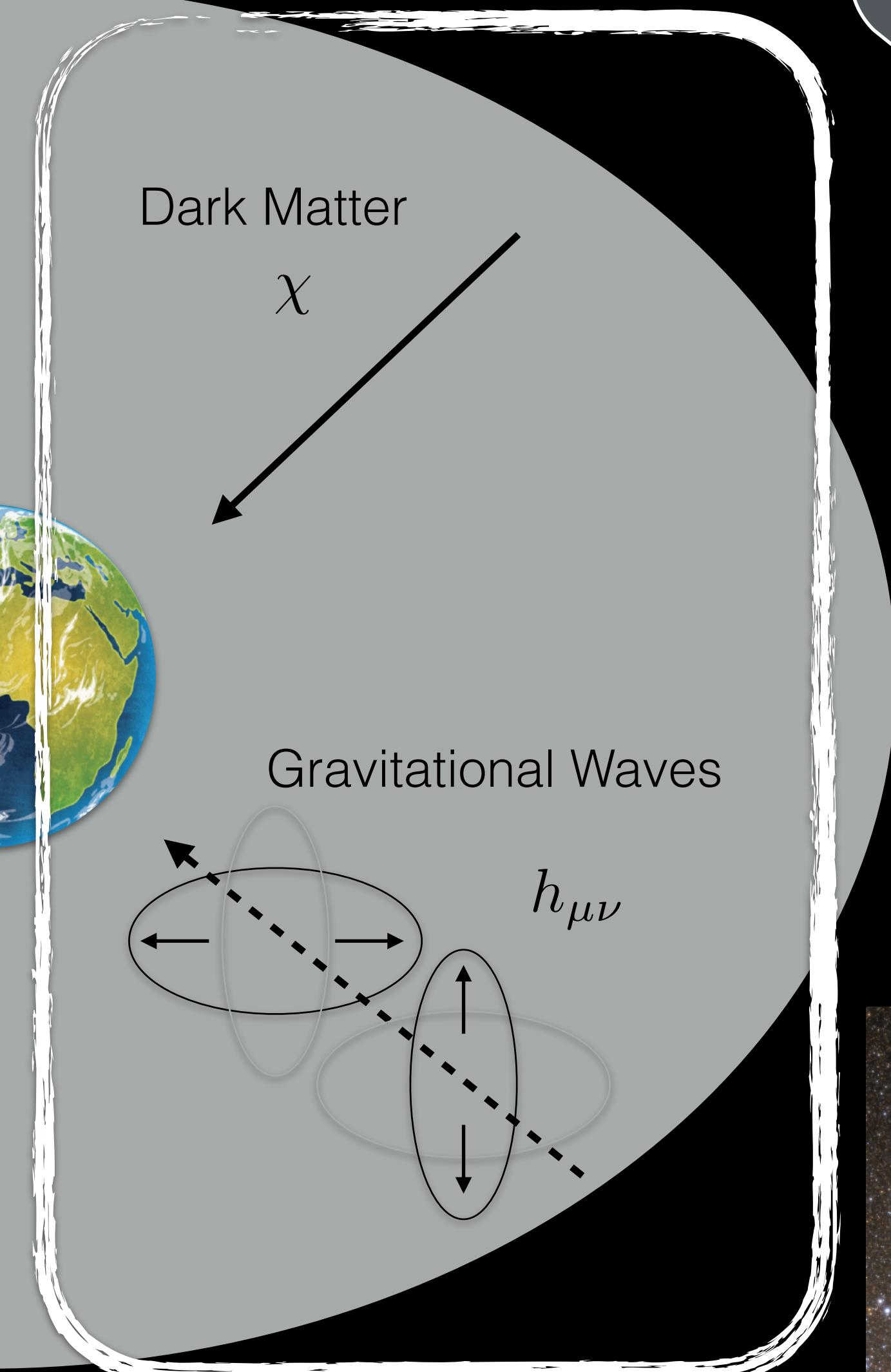
Quasars/AGN



Lecture 1

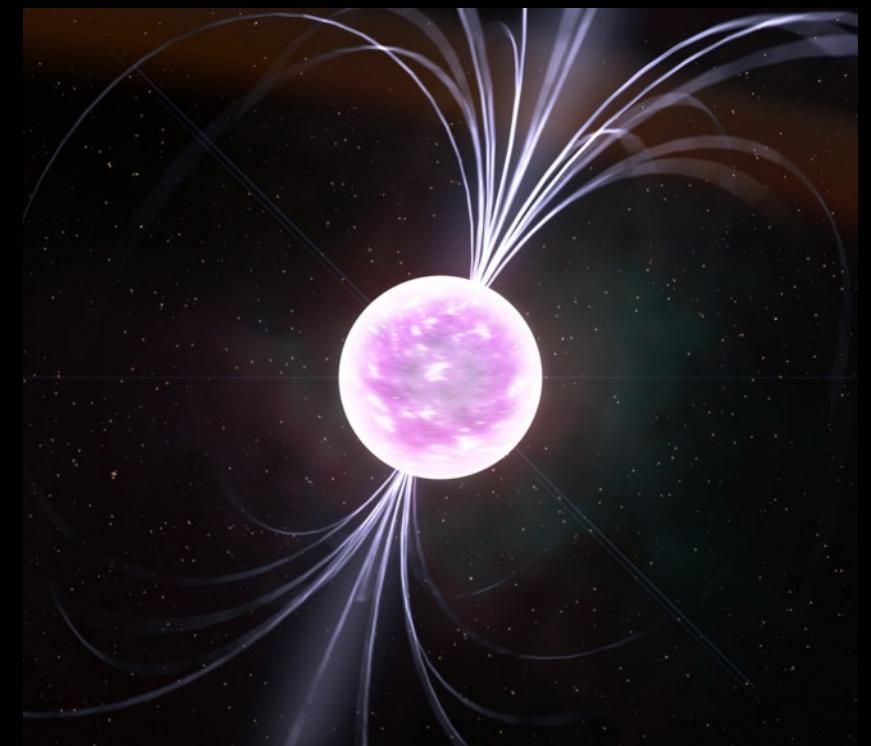


Lecture 2



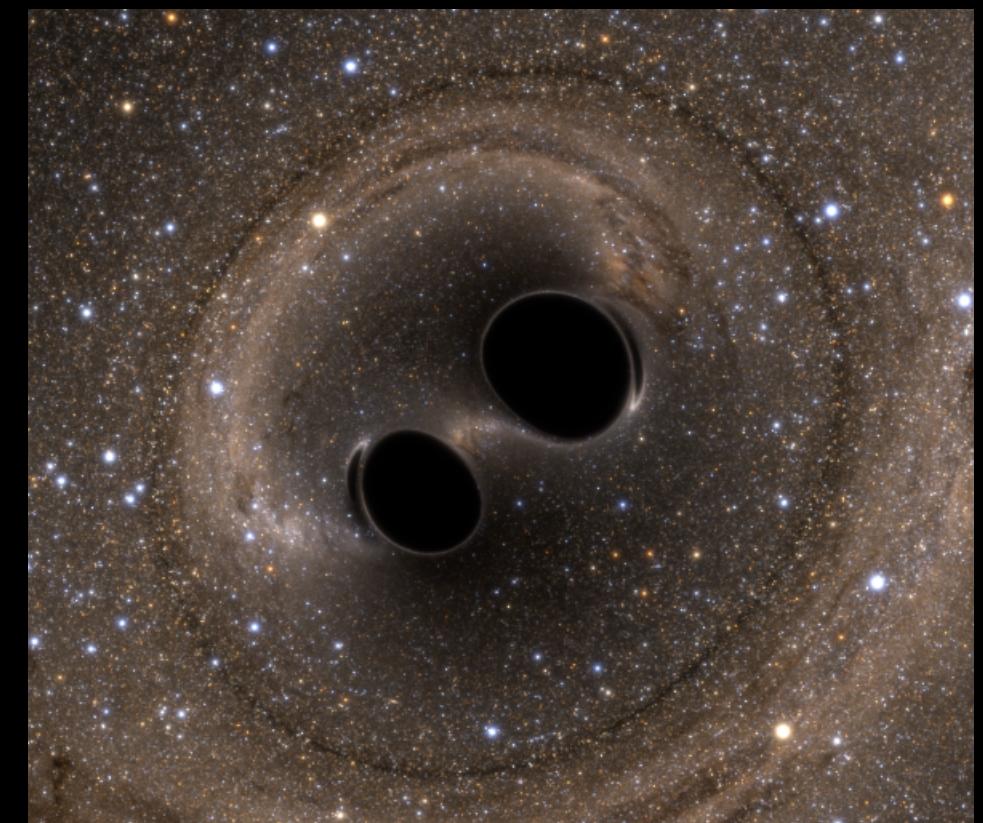
????

Pulsars



Credit: Kevin Gill / Flickr

BH/NS Mergers



Credit: SXS Lensing

Reading Suggestions

Slides here: bradkav.net/talks

Astroparticle Physics: Theory and Phenomenology, Günter Sigl, [Atlantis Press Paris](#) (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. Piatella, [arXiv:1910.05610](#) (2019)

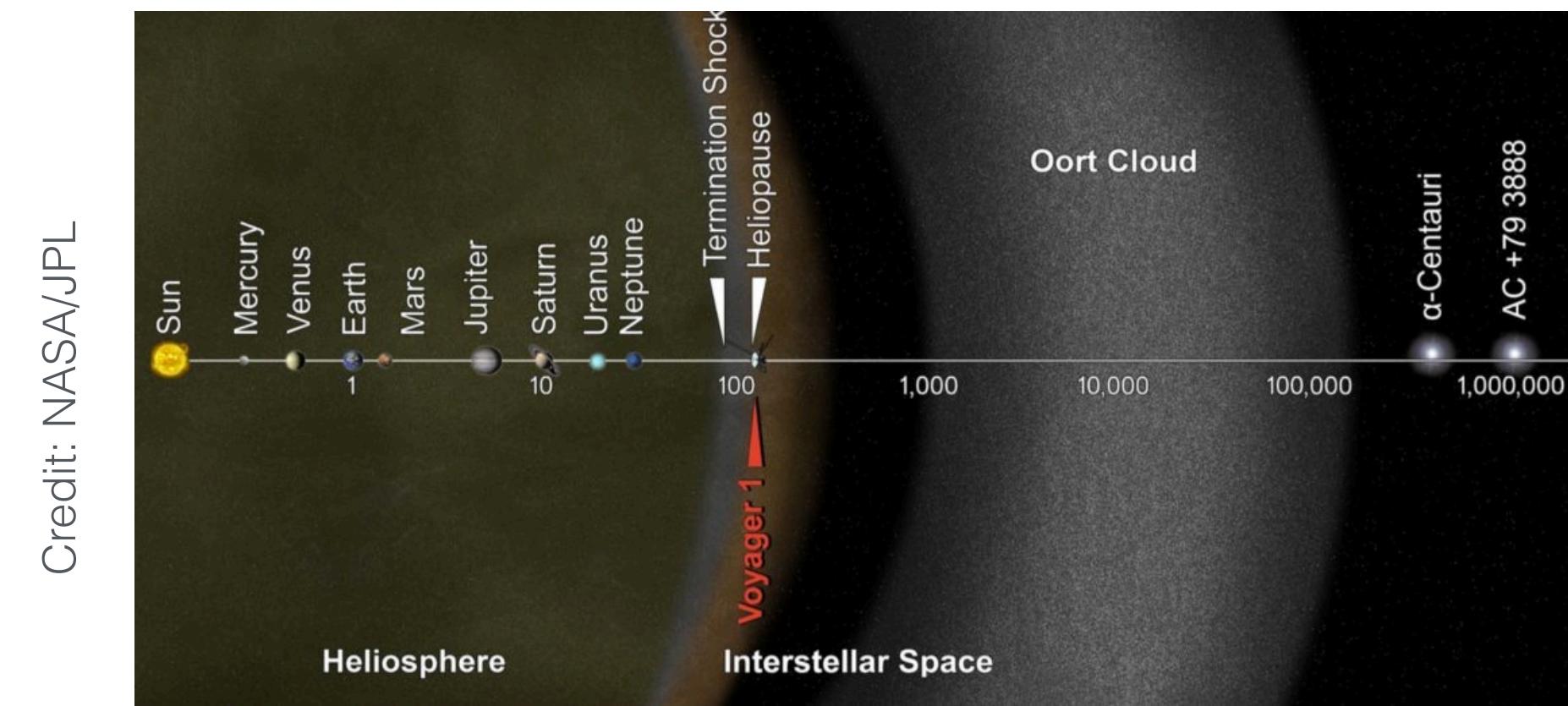
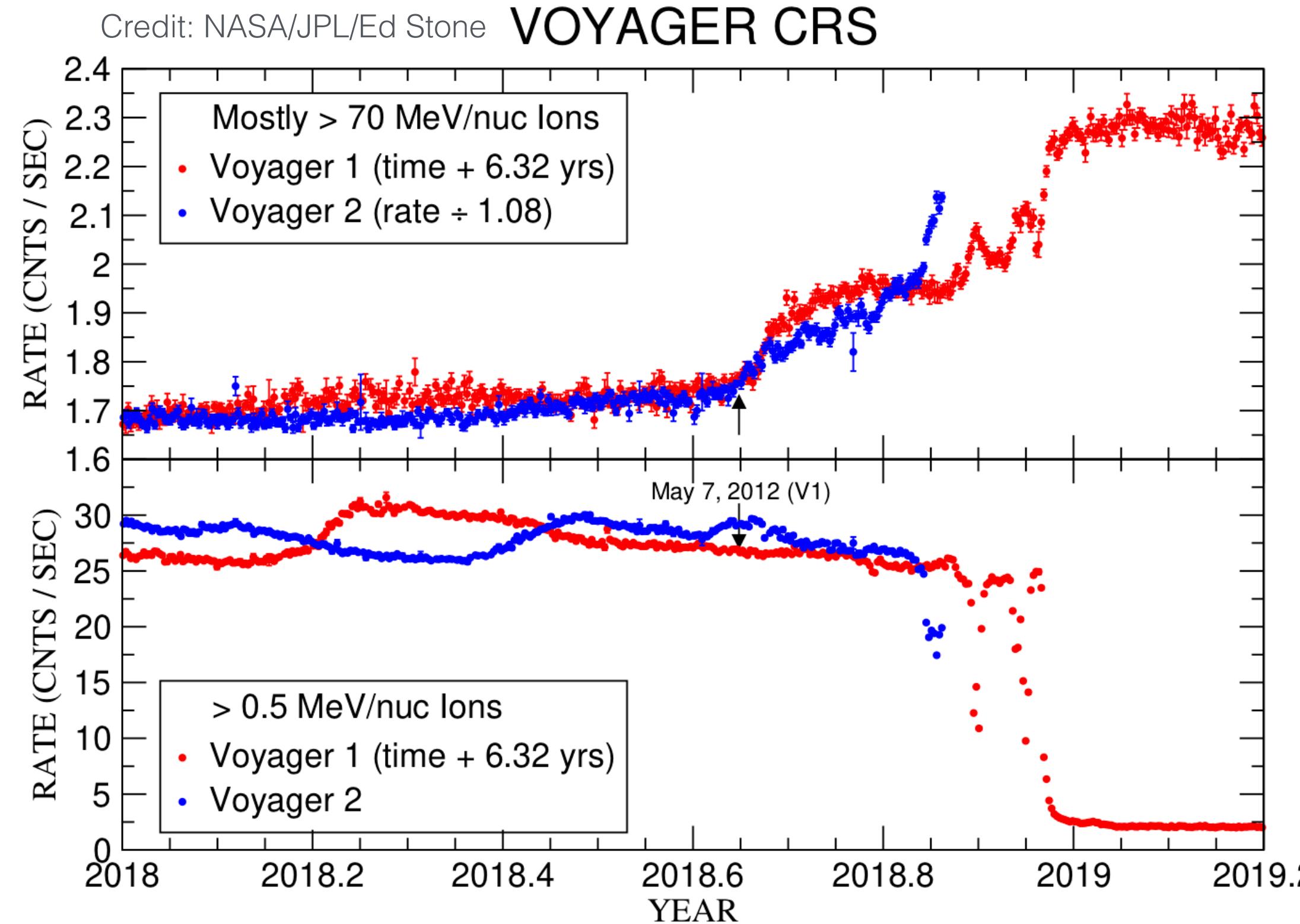
The basic physics of the binary black hole merger GW150914, LIGO & Virgo Collaborations, [arXiv:1608.01940](#) (2016)

Check [arXiv](#), and summaries on popular blogs like Sunny Vagnozzi's [HisDarkCMB](#) or Mauricio Bustamante's [Daily arXiv Picks!](#)

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

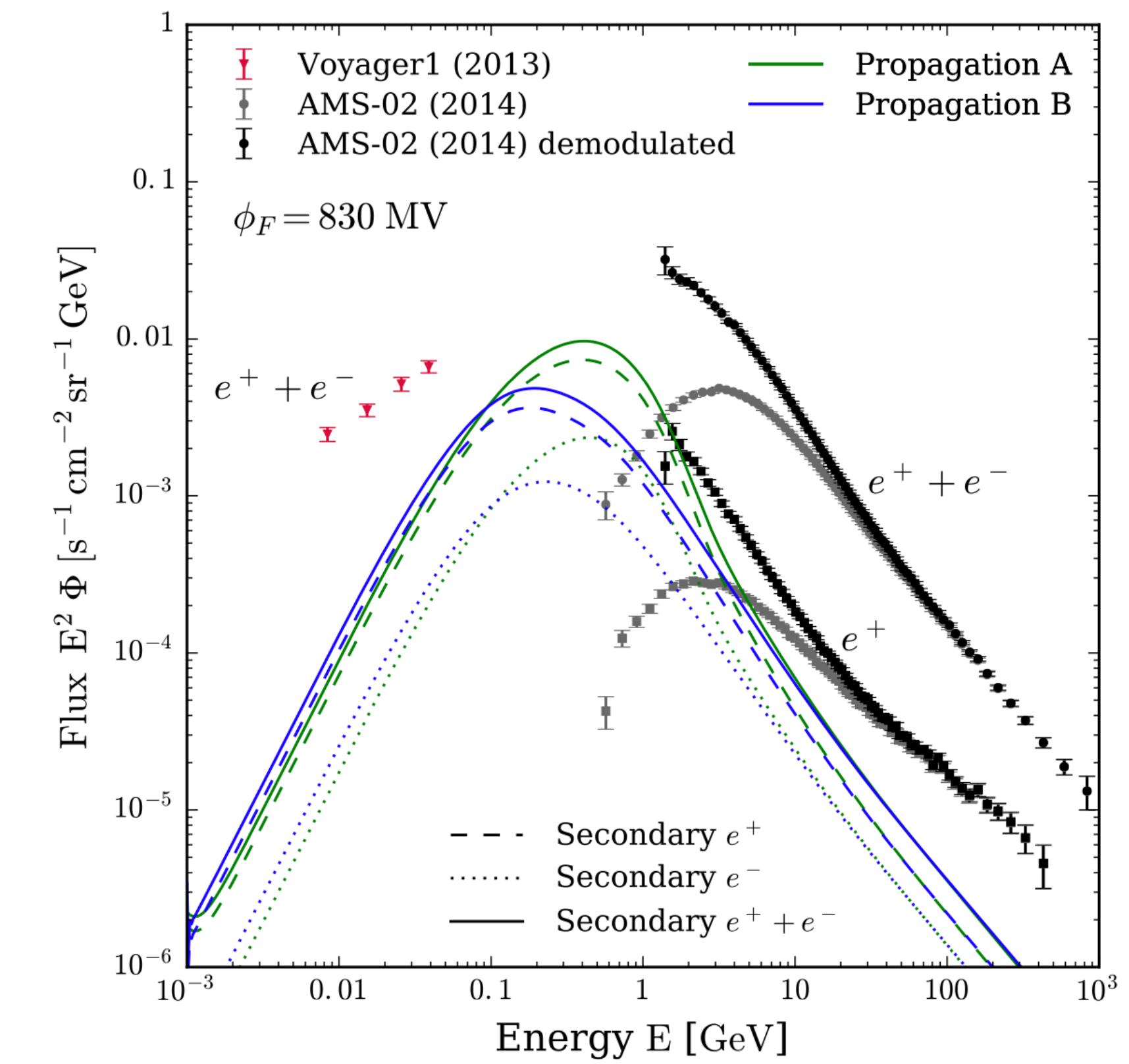
Additional Slides

Voyager (and solar modulation)



Voyager 1 - launched 1977,
crossed heliopause 2012

Voyager 2 - launched 1977,
crossed heliopause 2018



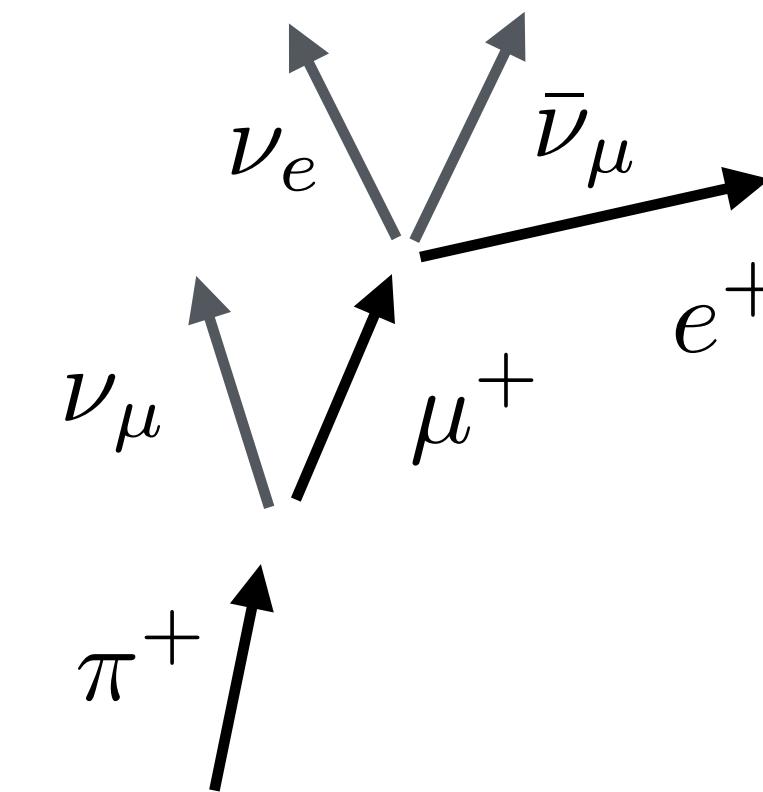
[arXiv:1612.07698](https://arxiv.org/abs/1612.07698)



Origin of ultra high energy neutrinos?

Flavour composition can hint at how astrophysical neutrinos are produced:

E.g. decay of energetic pions:



$$\Phi_e^0 : \Phi_\mu^0 : \Phi_\tau^0 = 1 : 2 : 0$$

