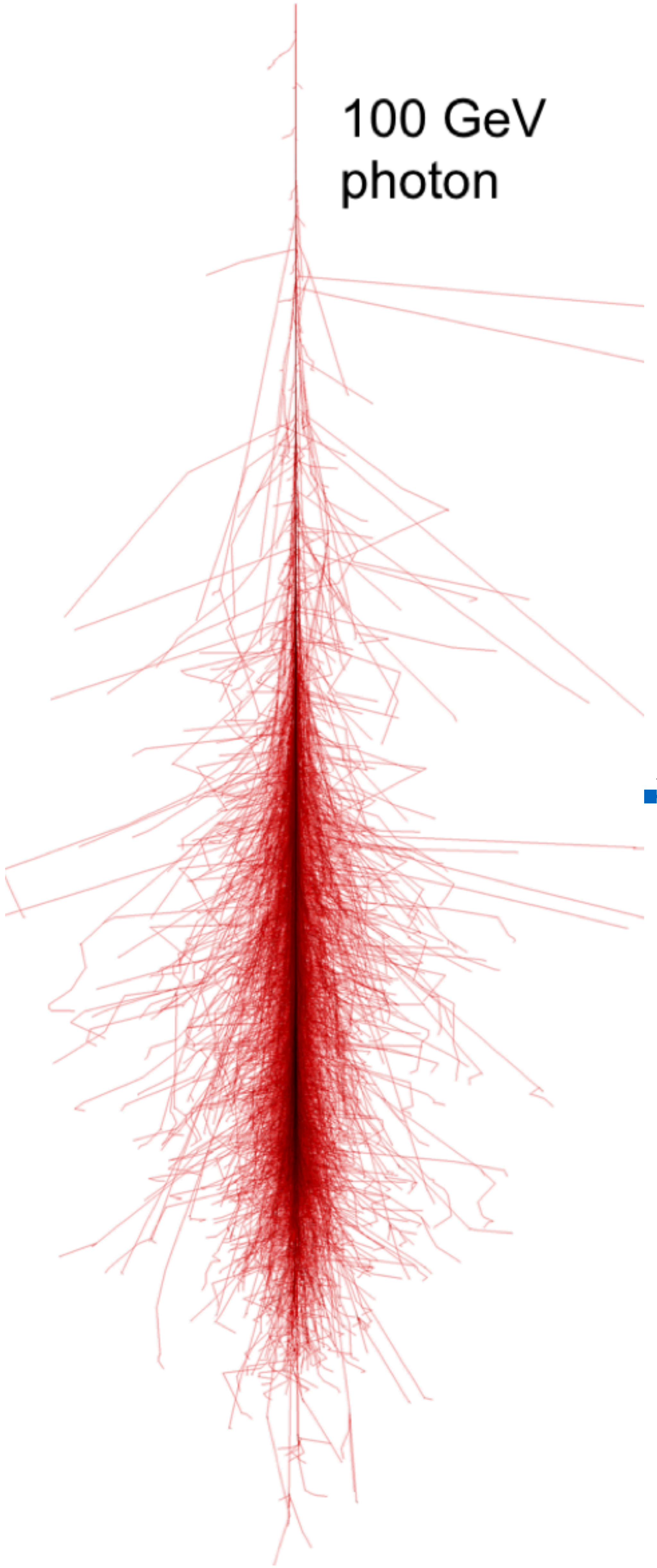
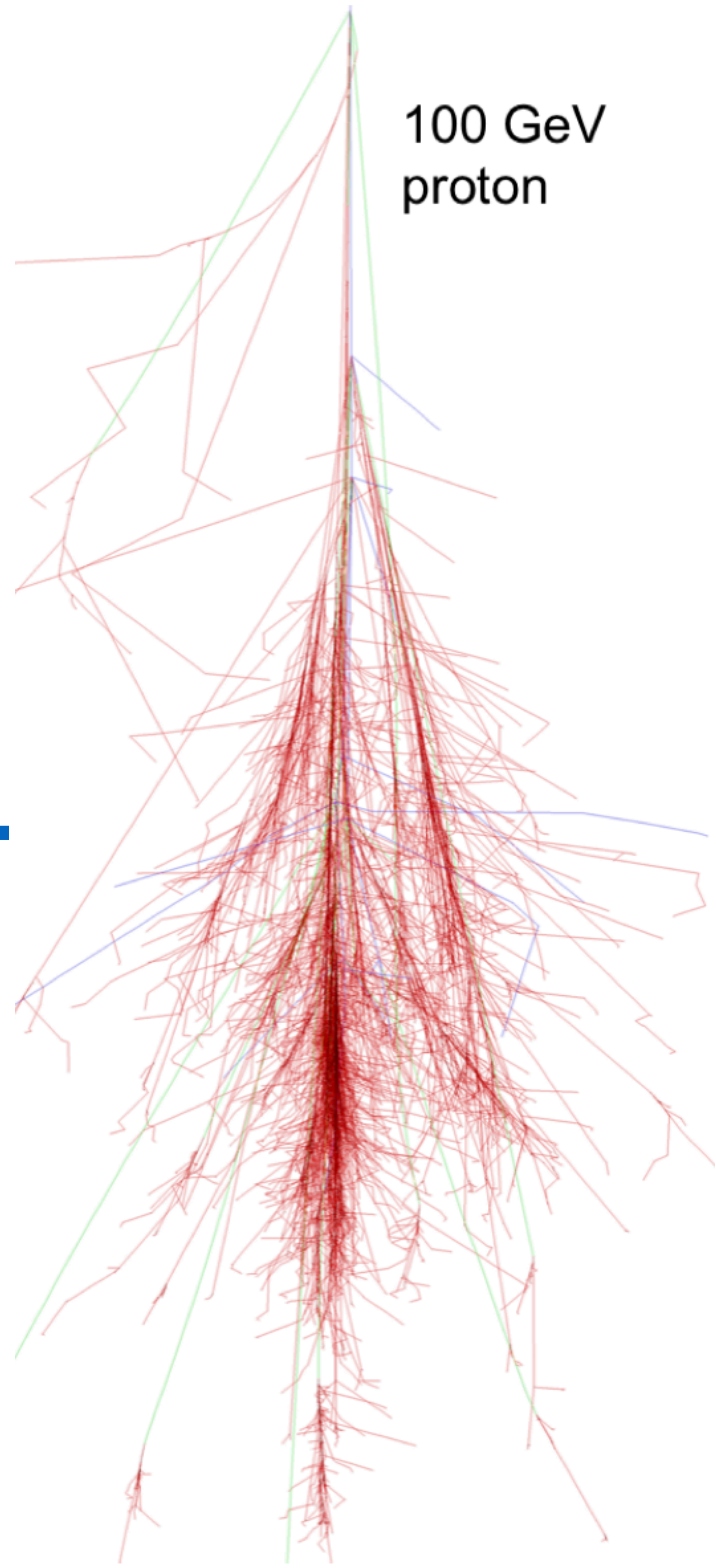


Astroparticle Physics

Lecture 1/2

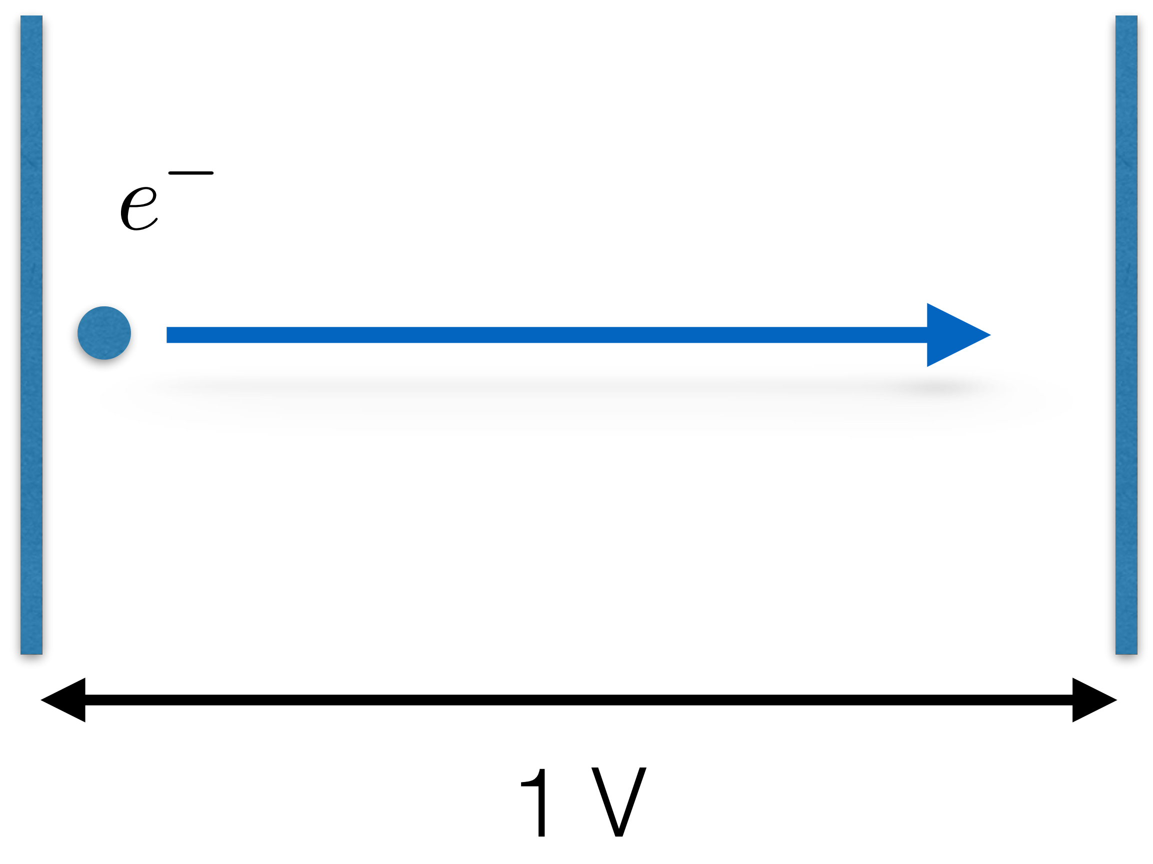
Bradley J Kavanagh
Instituto de Fisica de Cantabria (CSIC-UC)

CERN Summer School - Monday 12th July 2021

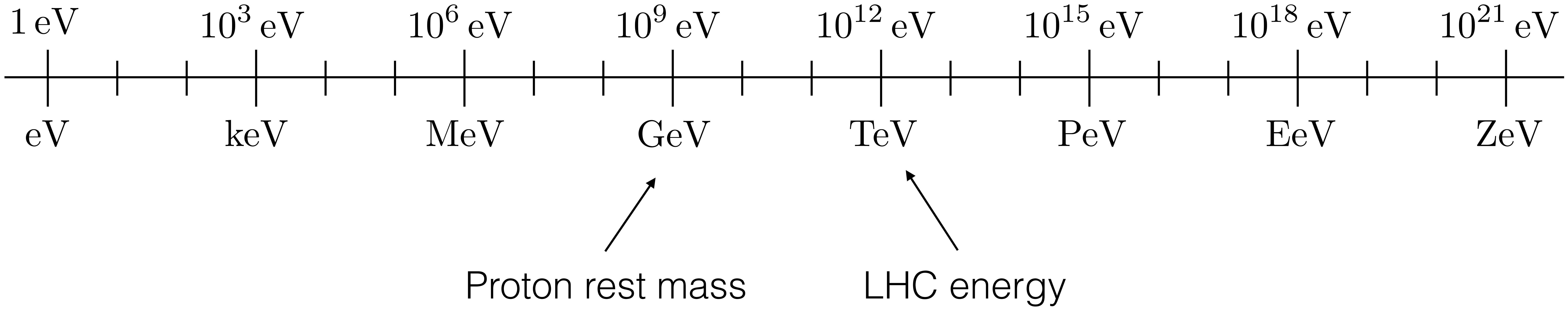


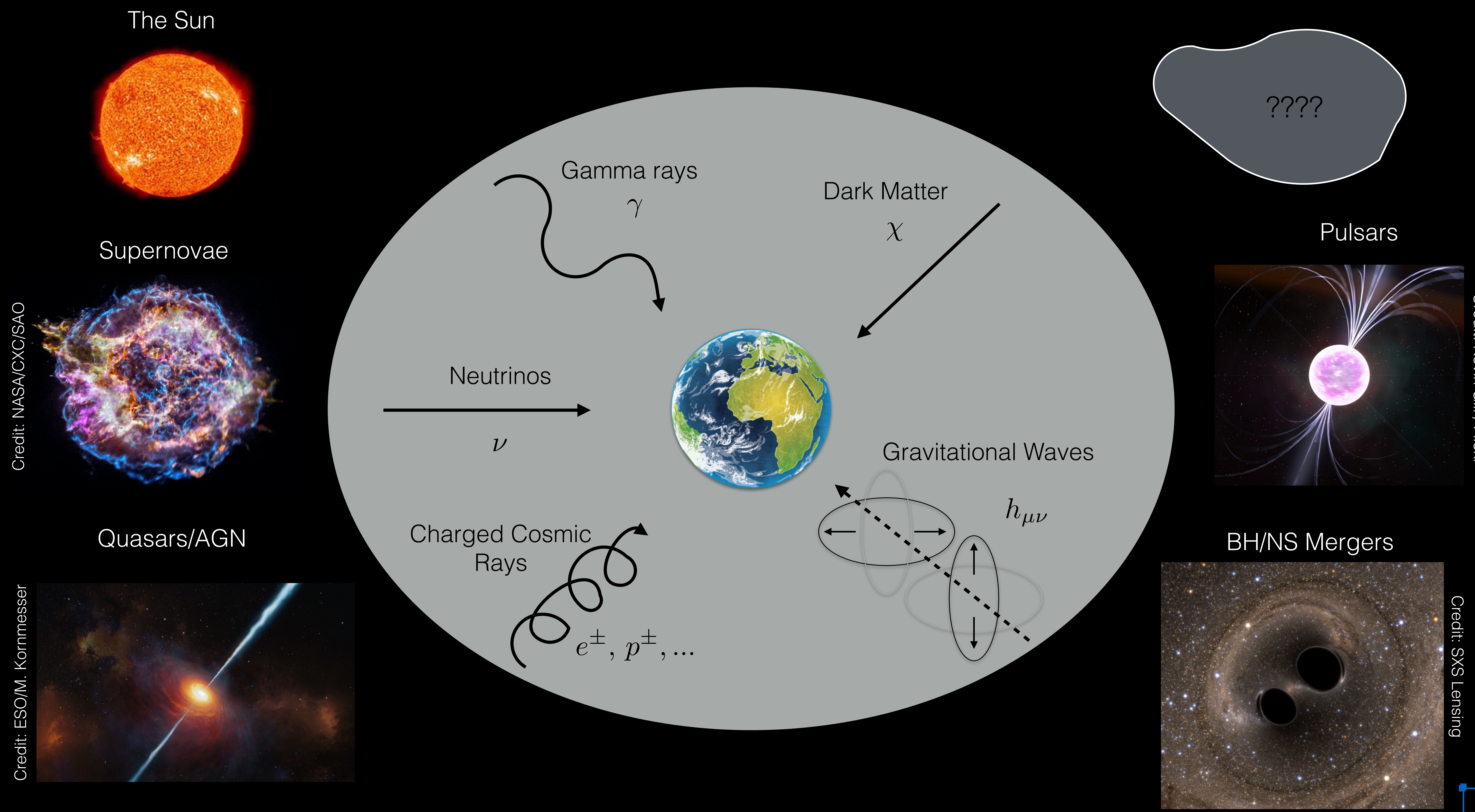
A huge range of energy scales…

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



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




The Sun
Supernovae
Credit: NASA/CXC/SAO
Quasars/AGN
Credit: ESO/M. Kornmesser
Gamma rays
γ
Dark Matter
χ
Neutrinos
ν
Charged Cosmic Rays
$e^{\pm}, p^{\pm}, \ldots$
Gravitational Waves
$h_{\mu\nu}$
????
Pulsars
Credit: Kevin Gill / Flickr
BH/NS Mergers
Credit: SXS Lensing


The Sun
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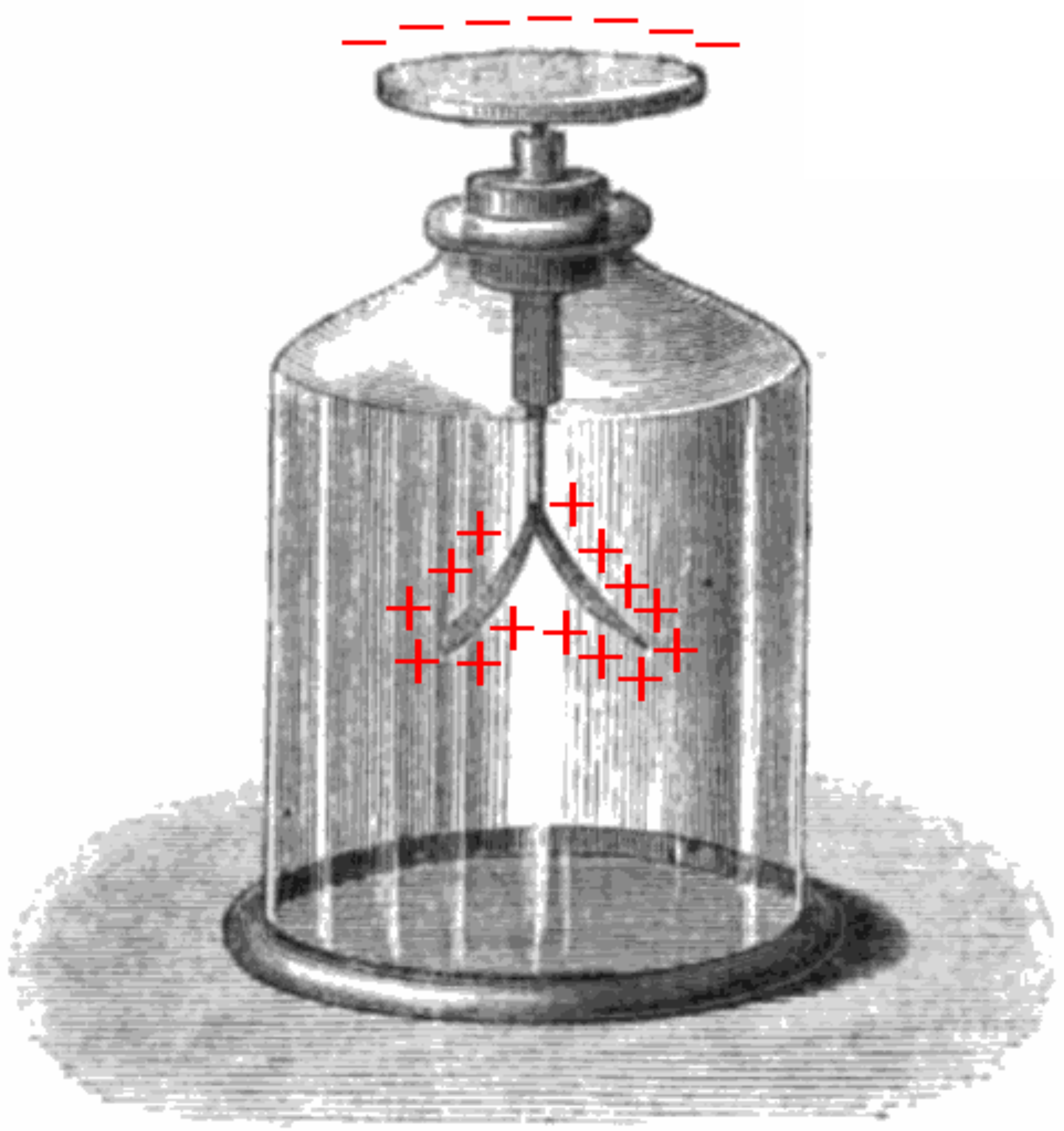
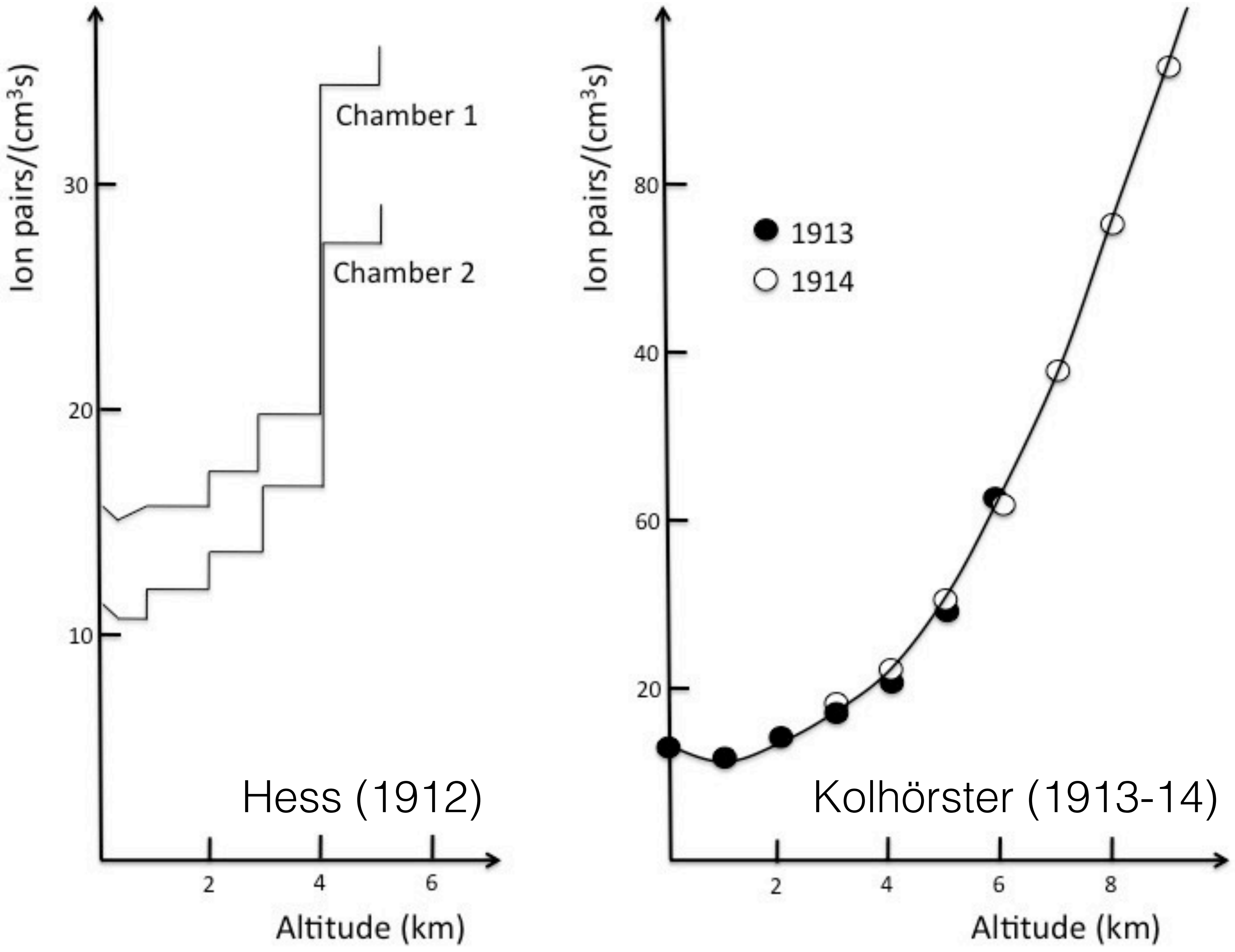
$h_{\mu\nu}$
Pulsars
Credit: Kevin Gill / Flickr
BH/NS Mergers
Credit: SXS Lensing

History of astroparticles

Victor Hess
(1883 - 1964)

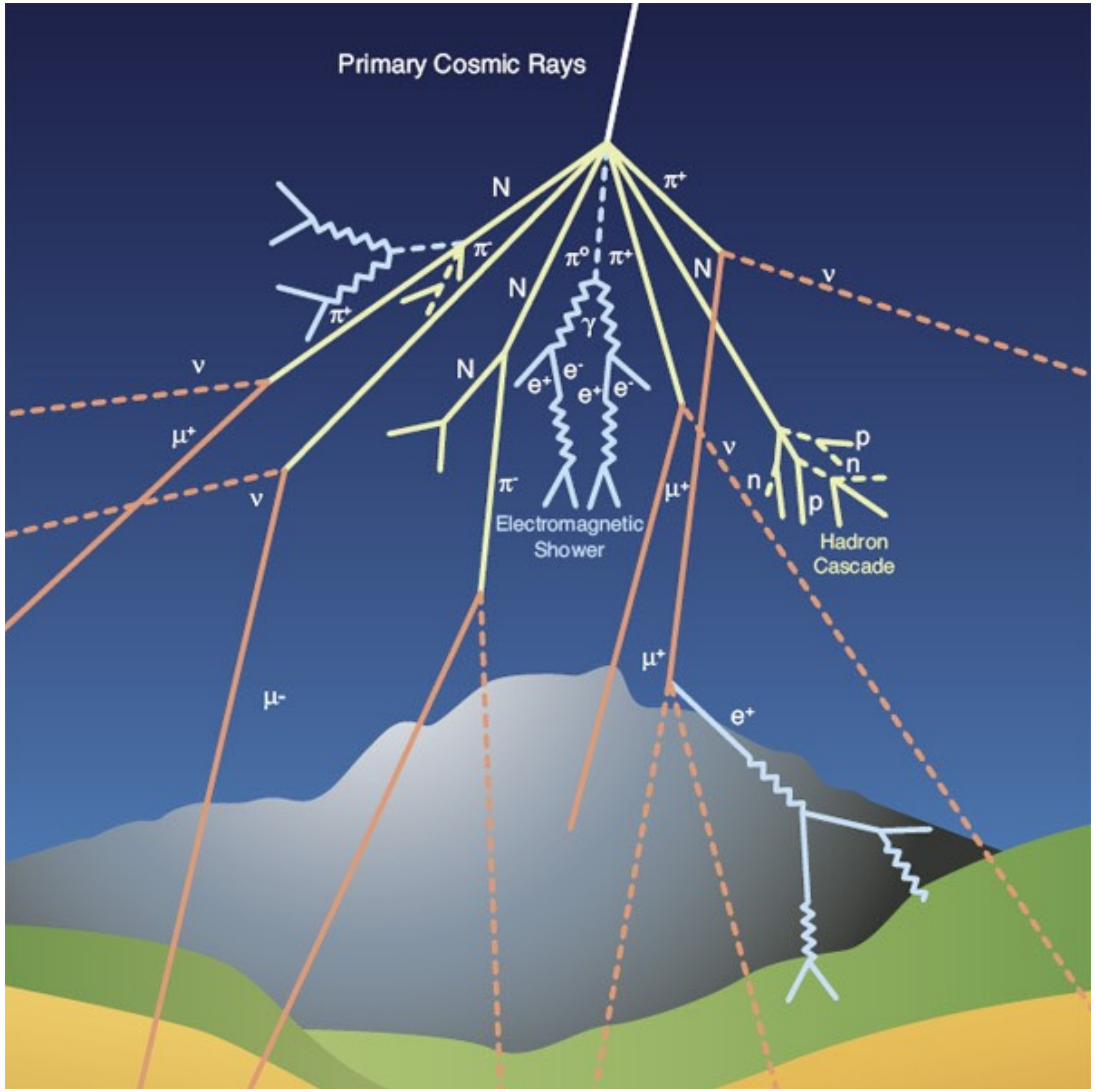


Credit: Sylvanus P. Thompson (1881), Chetvorno (2008)

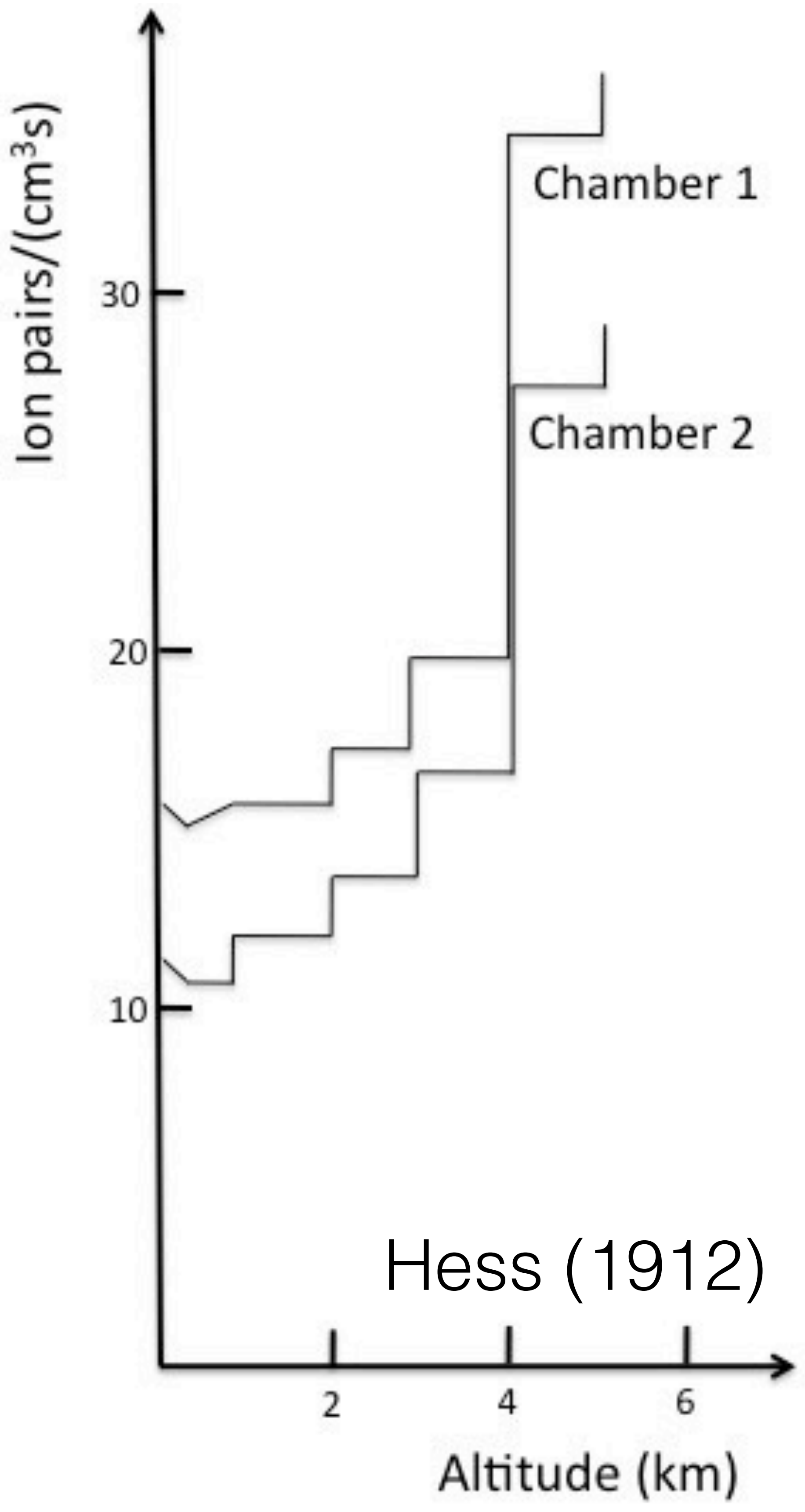


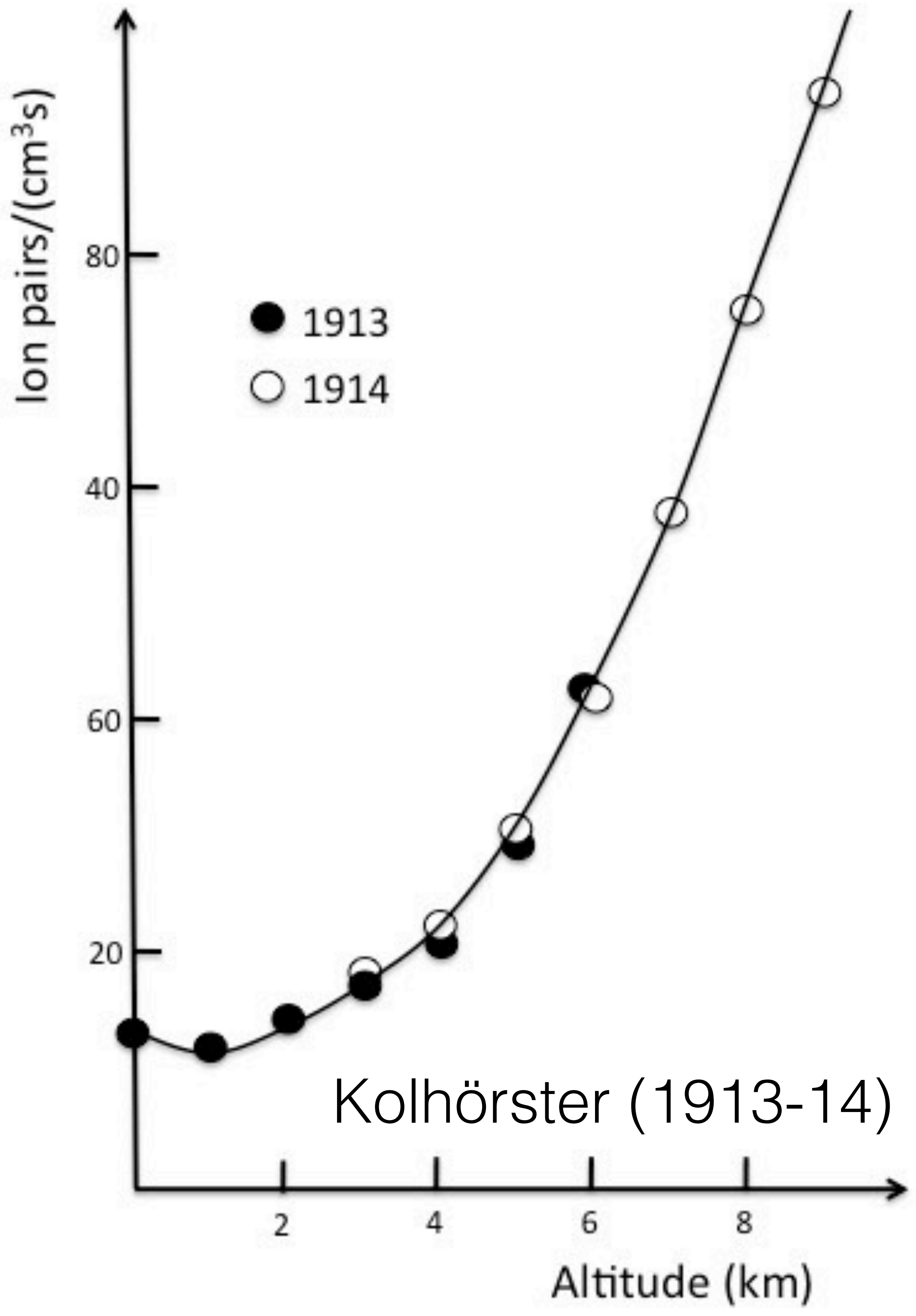
Credit: Alessandro De Angelis

History of astroparticles



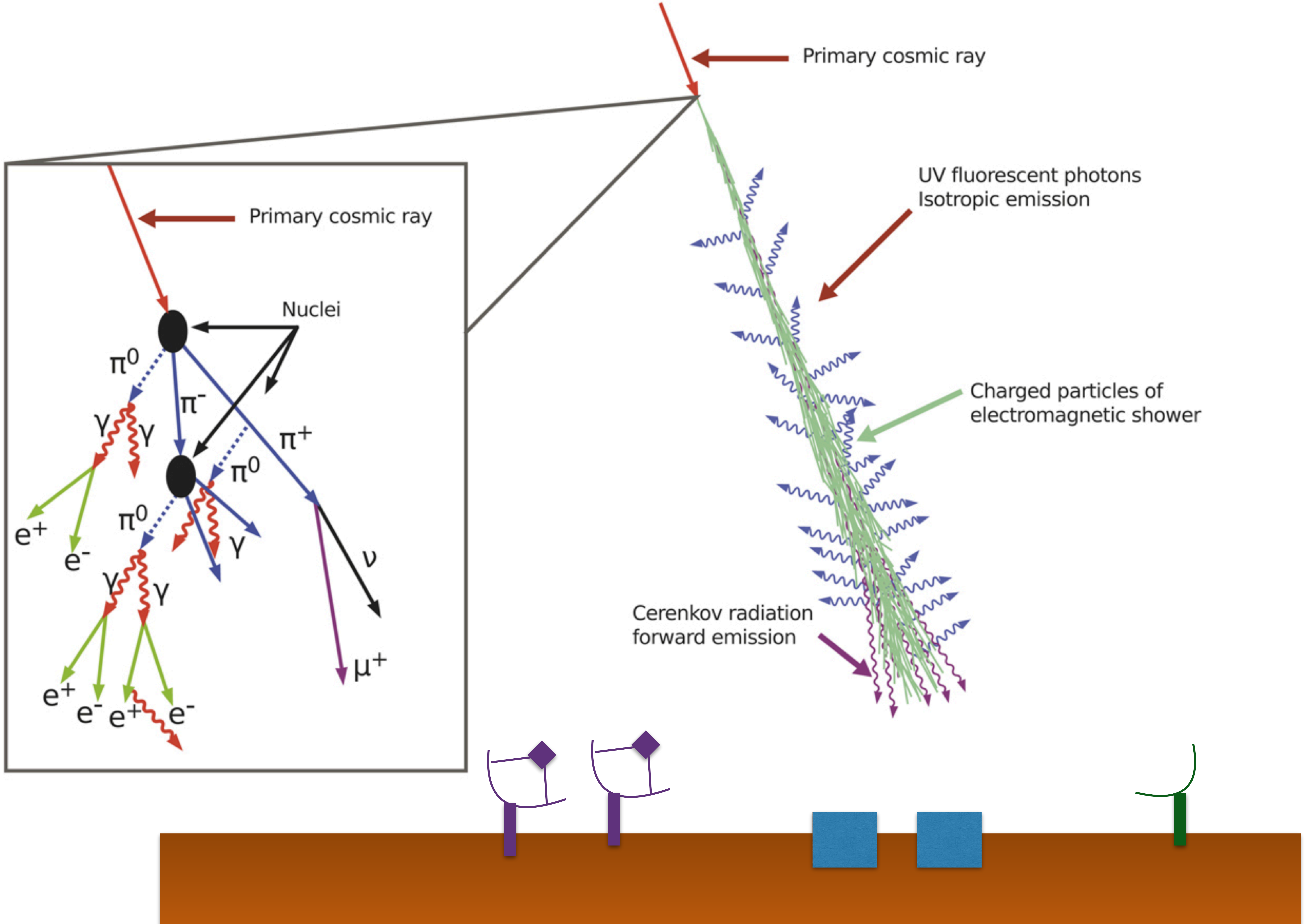
Credit: CERN





Credit: Alessandro De Angelis

Detection of cosmic rays (Earth)

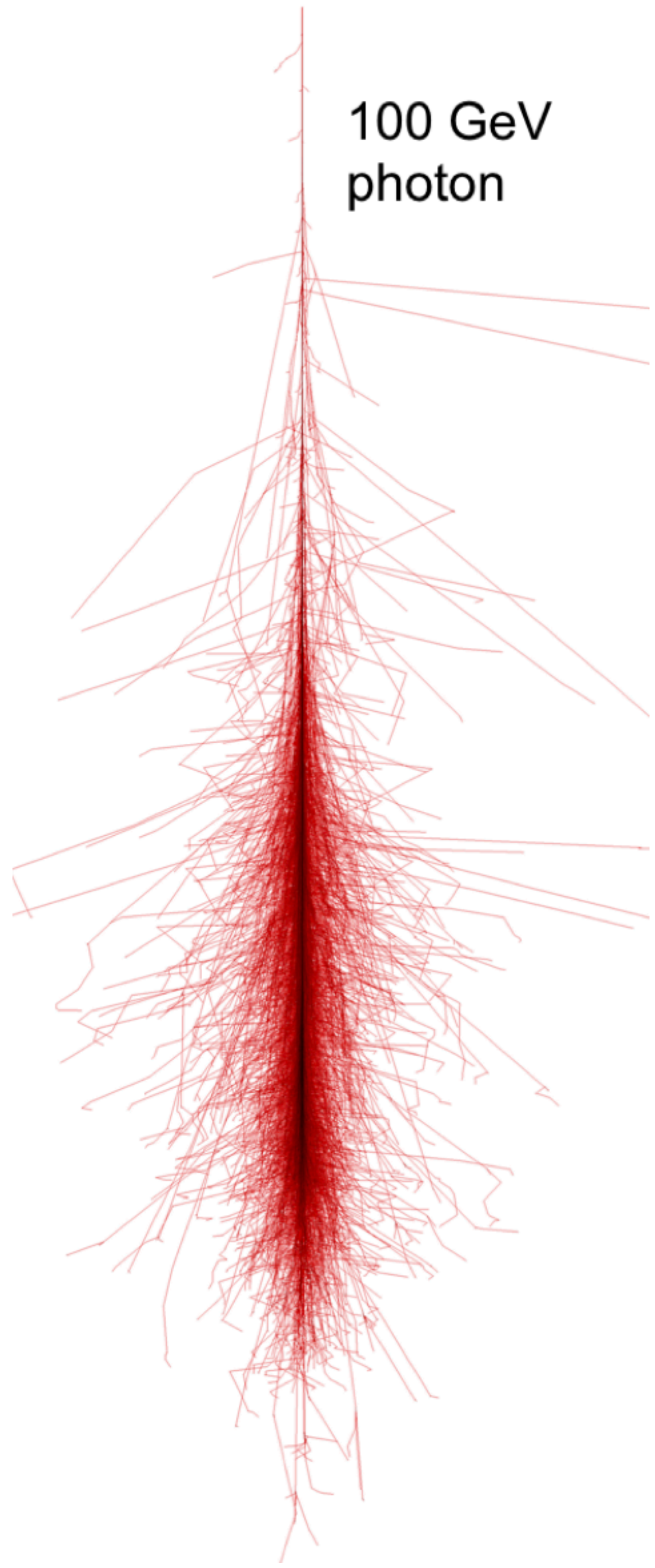


Fluorescence
(e.g. Fly's Eye, Auger observatory)

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



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

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

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

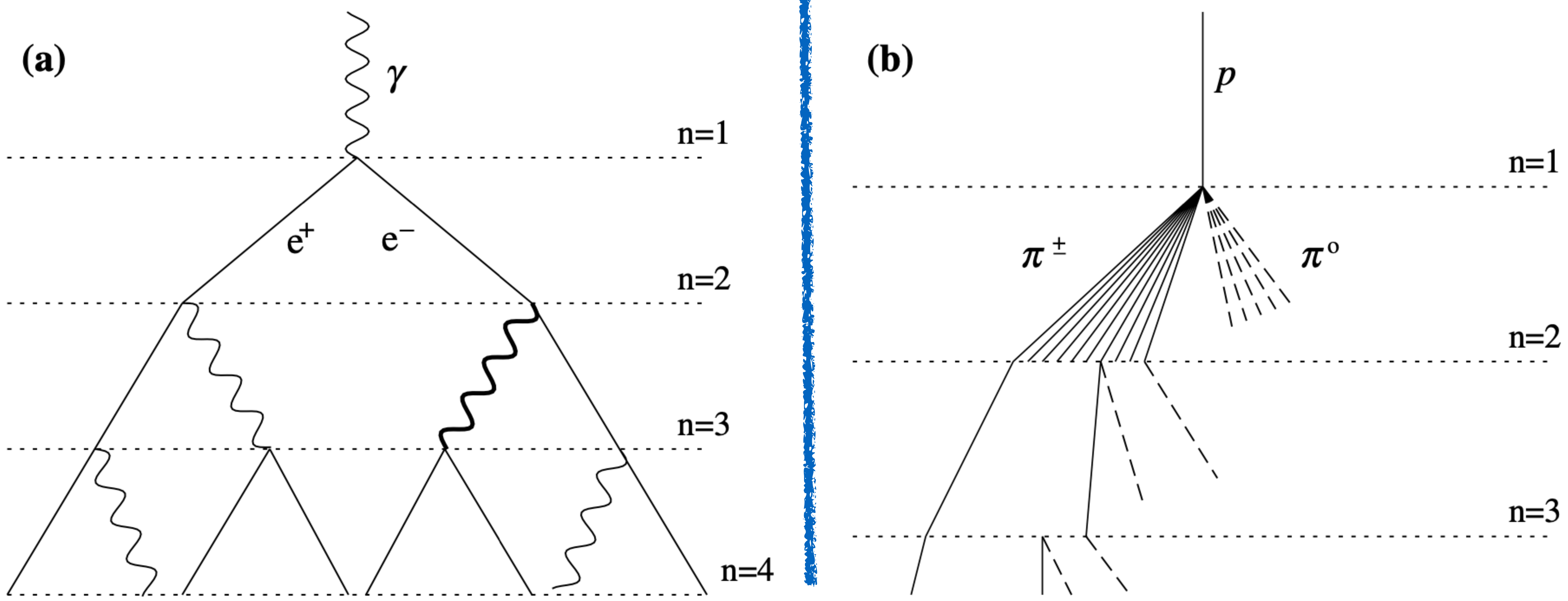
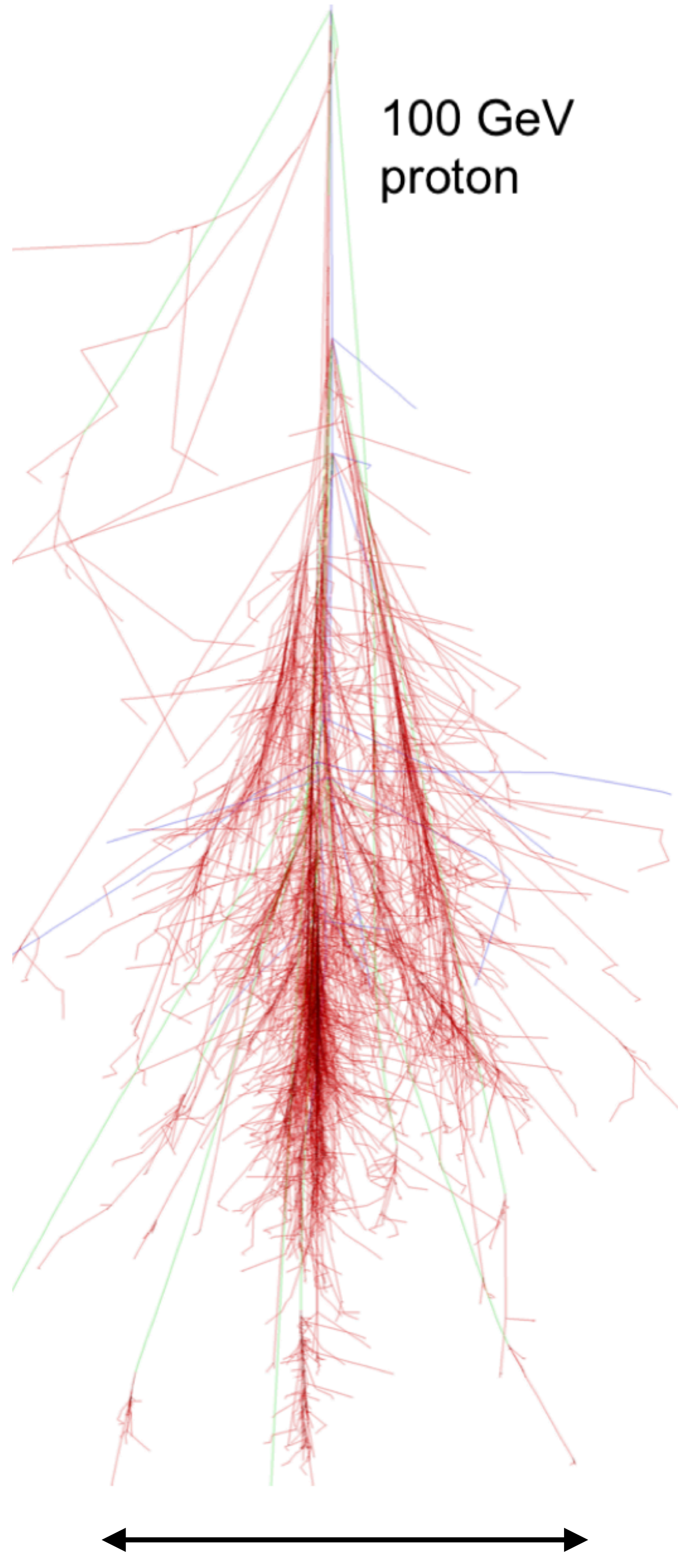


Fig. 1. Schematic views of (a) an electromagnetic cascade and (b) a hadronic shower. In the hadron shower, dashed lines indicate neutral pions which do not re-interact, but quickly decay, yielding electromagnetic subshowers (not shown). Not all pion lines are shown after the $n = 2$ level. Neither diagram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

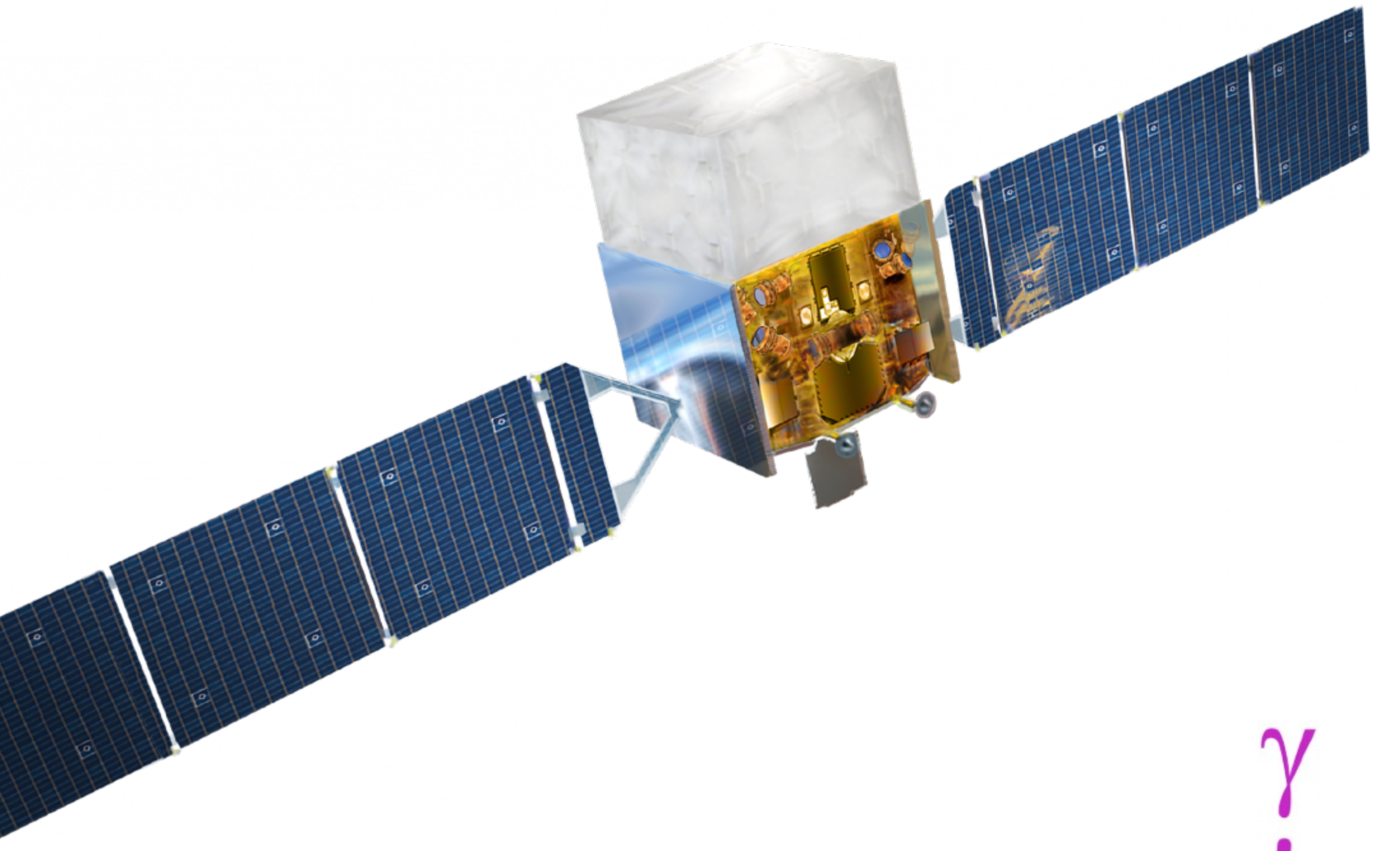


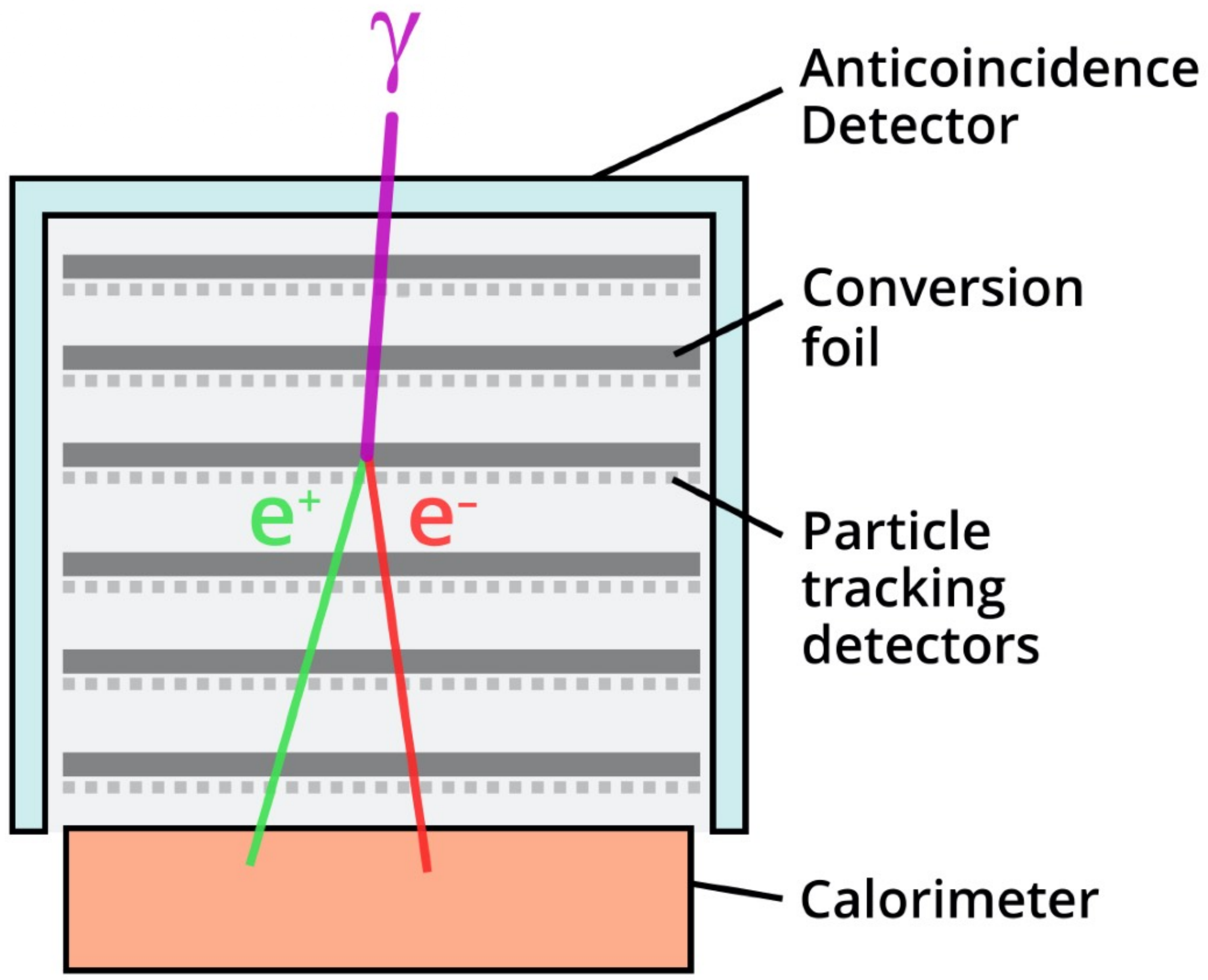
1510.05675

Credit: Matthews (2005)

Detection of cosmic rays (Space)

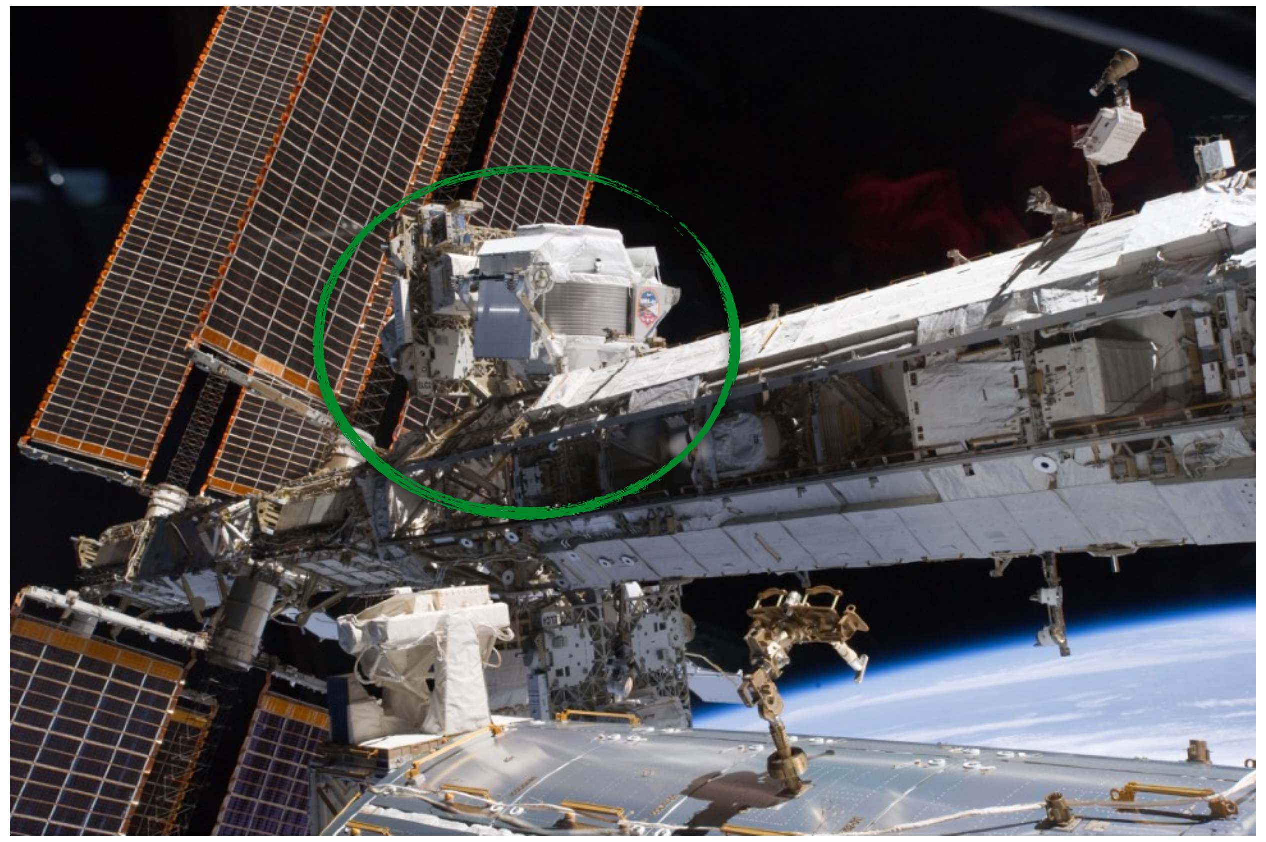
Fermi-LAT (2008-)



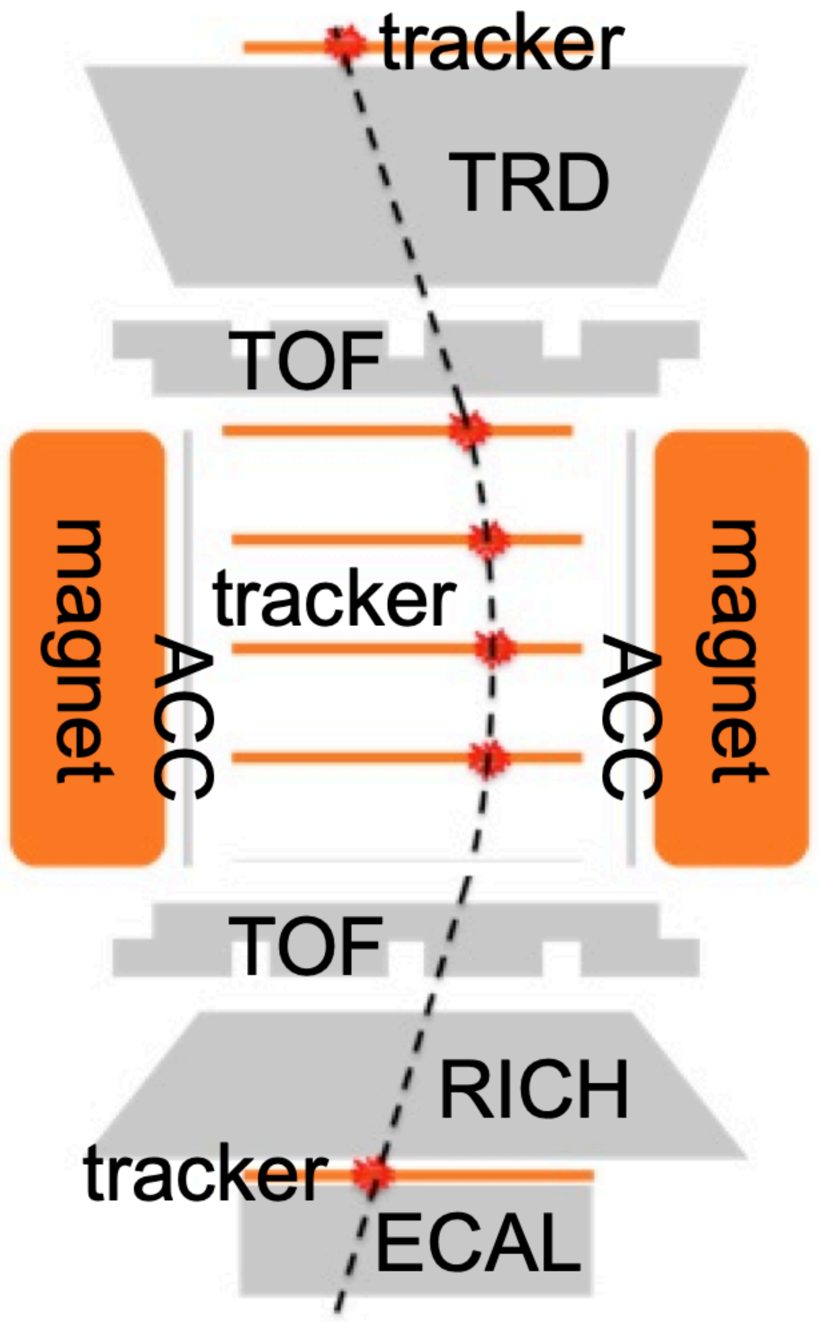


Credit: NASA's Goddard Space Flight Center

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



AMS (2011-)



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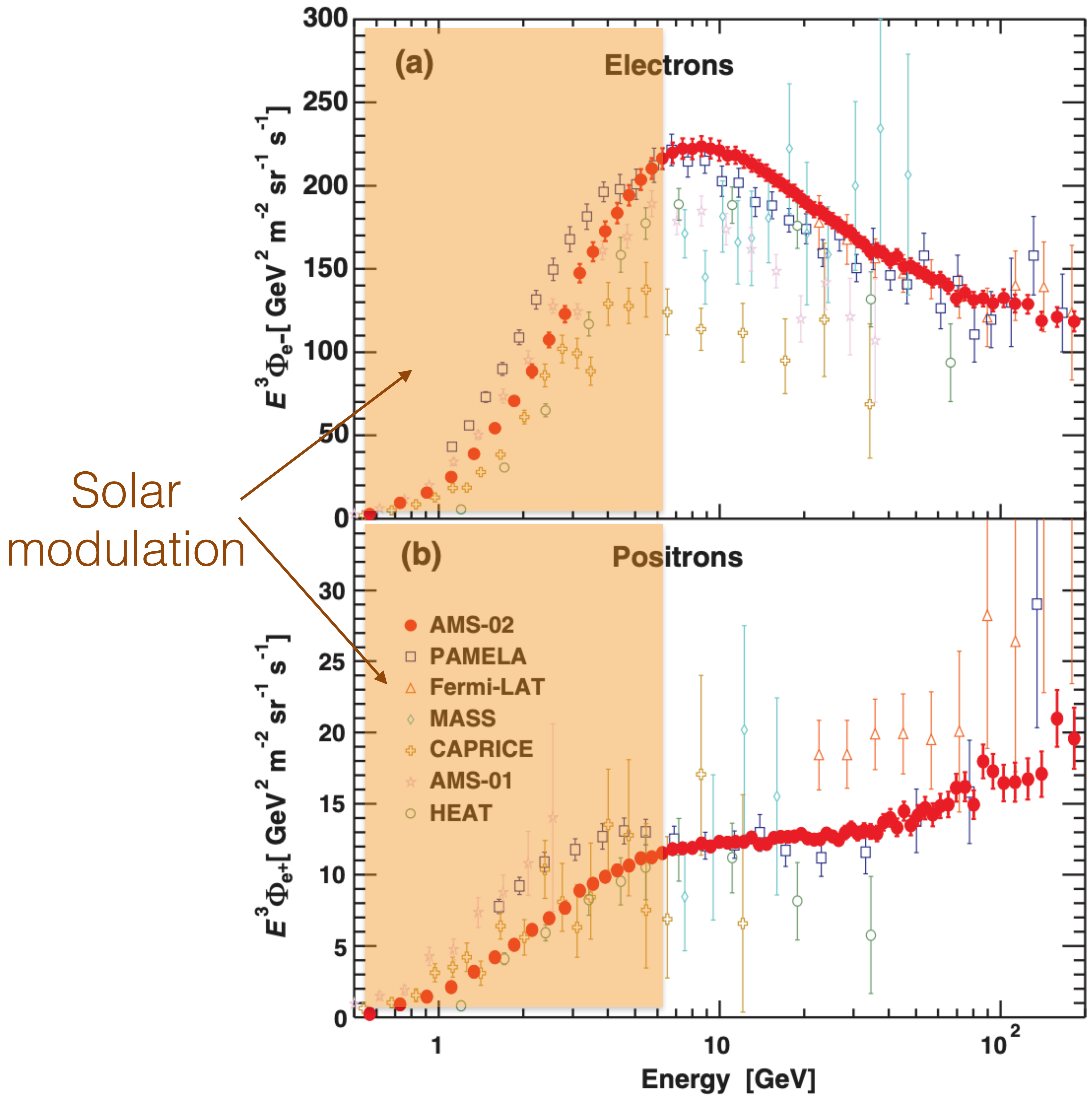
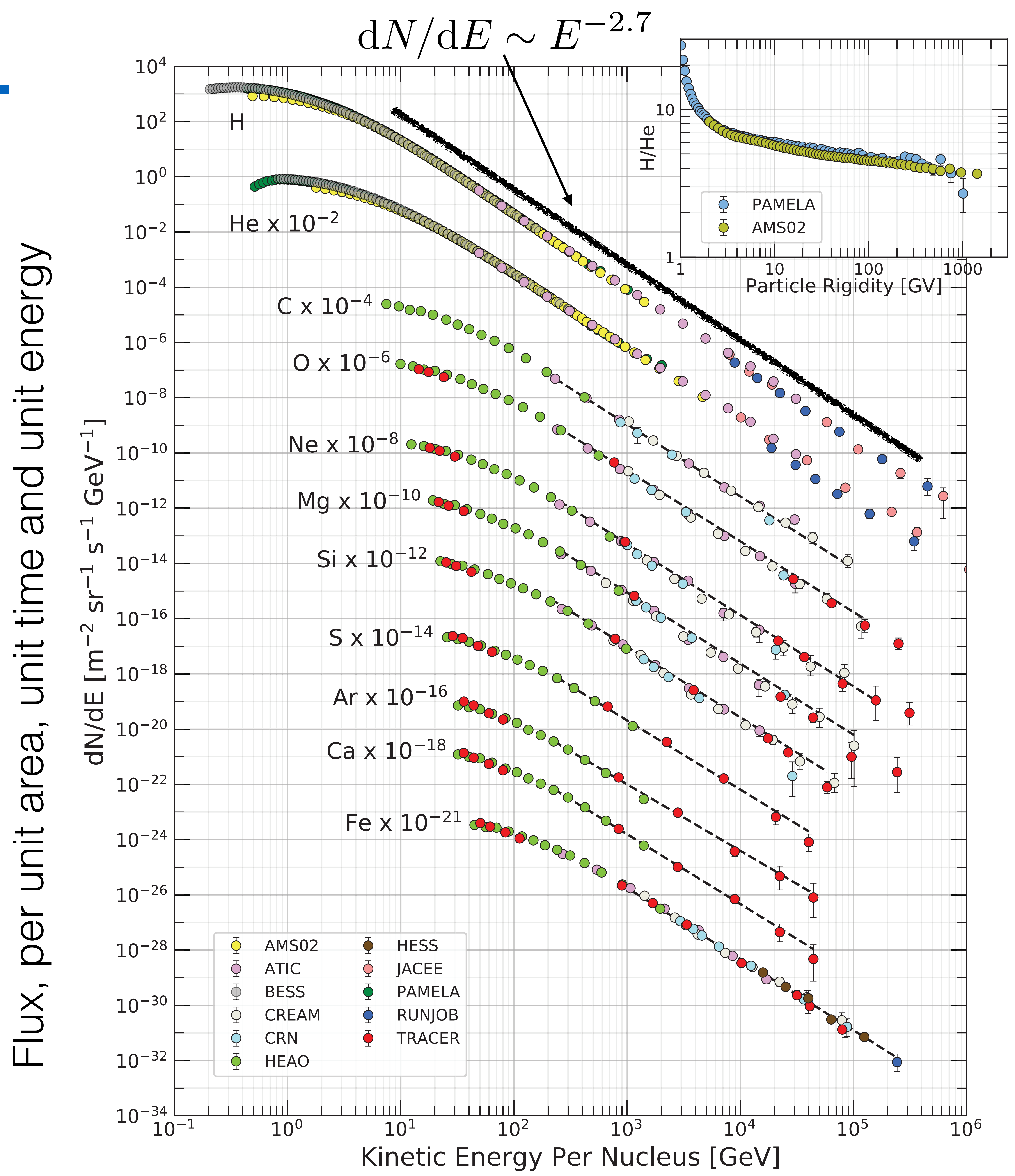
Detection of $e^{\pm}$, $p^{\pm}$ and heavier nuclei
in the range 1 GeV - 2 TeV

Cosmic ray composition



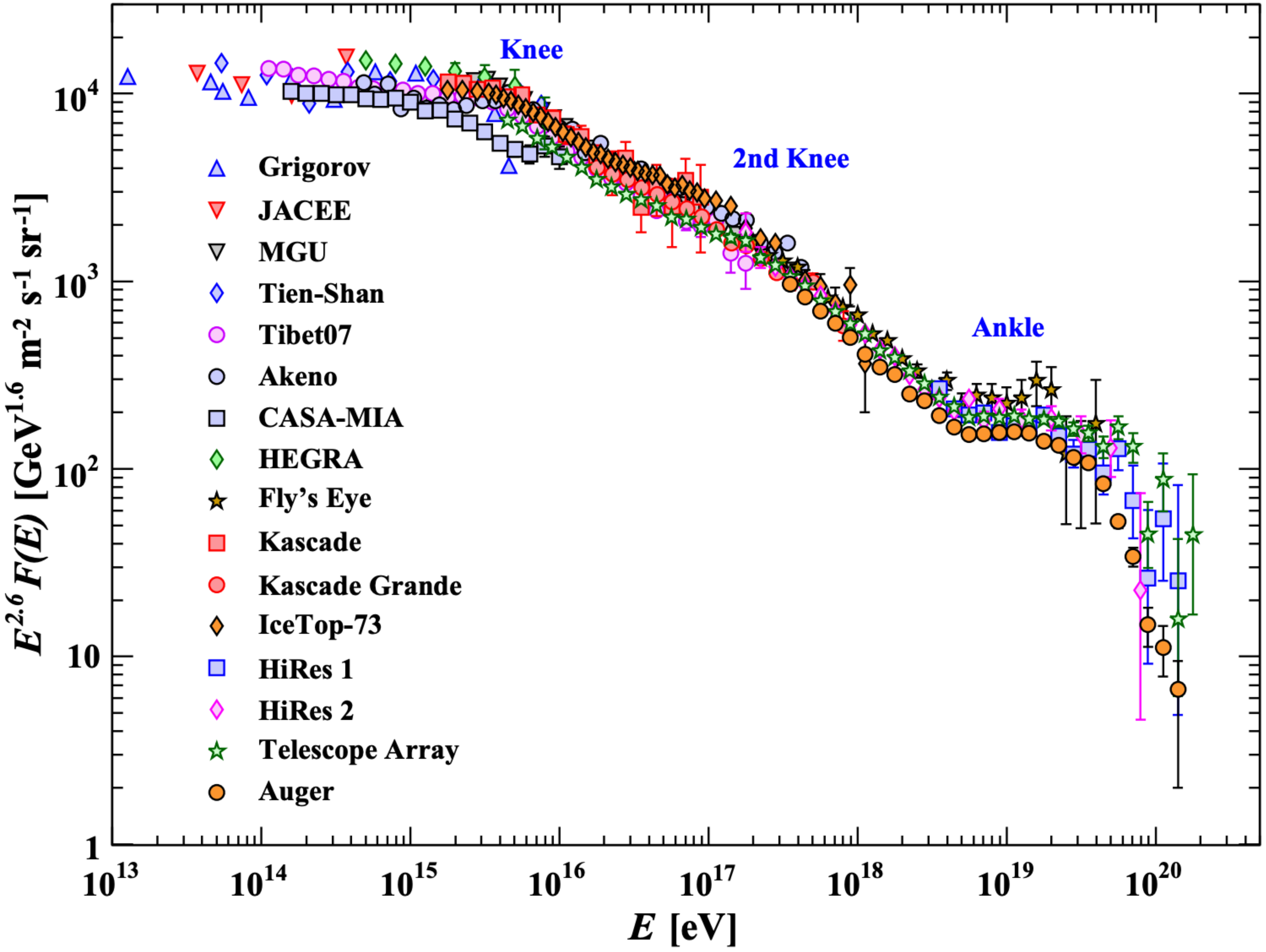
Credit: M. Aguilar et al. (AMS Collaboration), 2014



Credit: Particle Data Group (2020)

Ultra high-energy cosmic rays

All particle cosmic ray spectrum

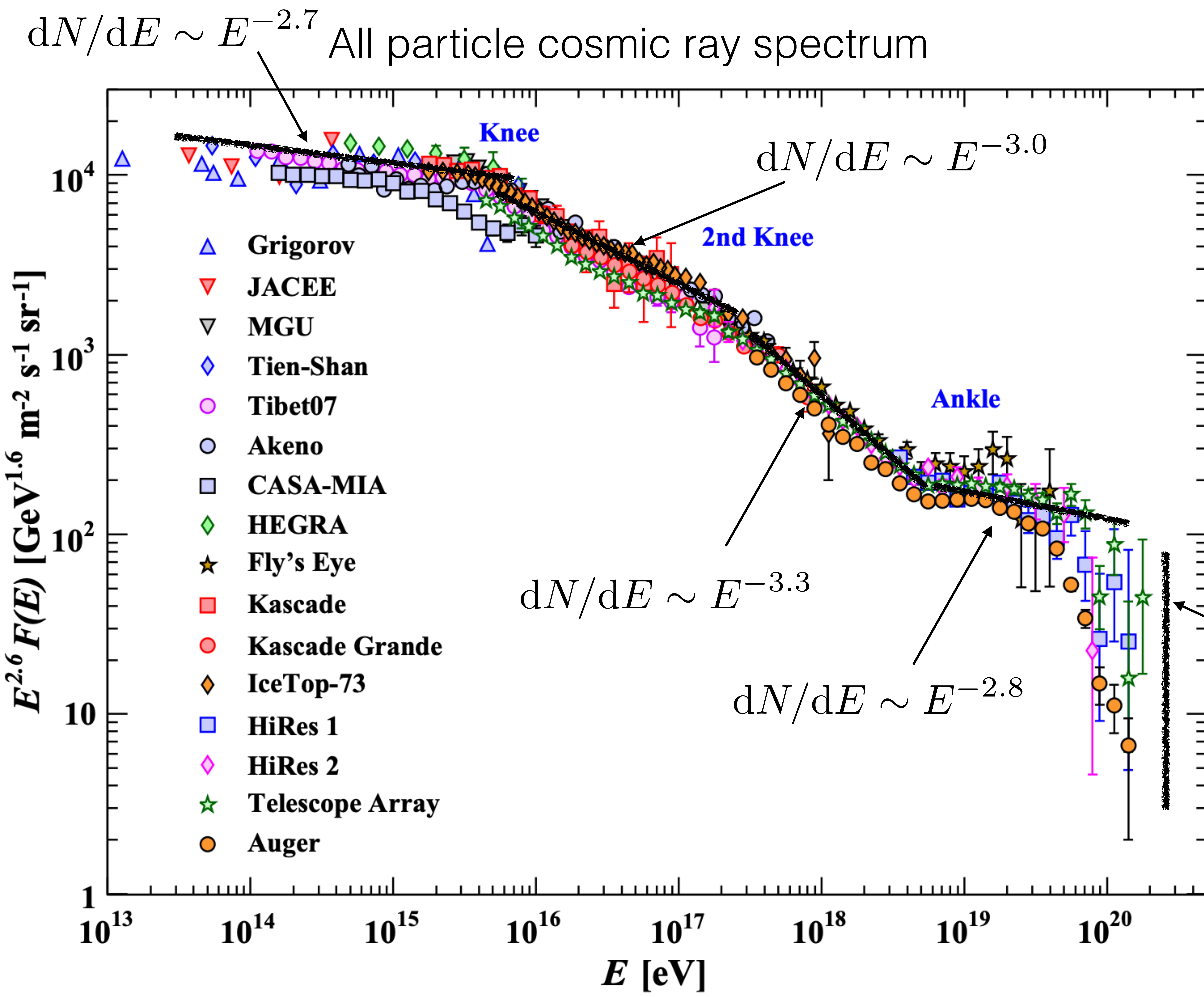


Credit: Particle Data Group (2020)

Ultra high-energy cosmic rays

Extragalactic CRs begin to dominate above the ankle.

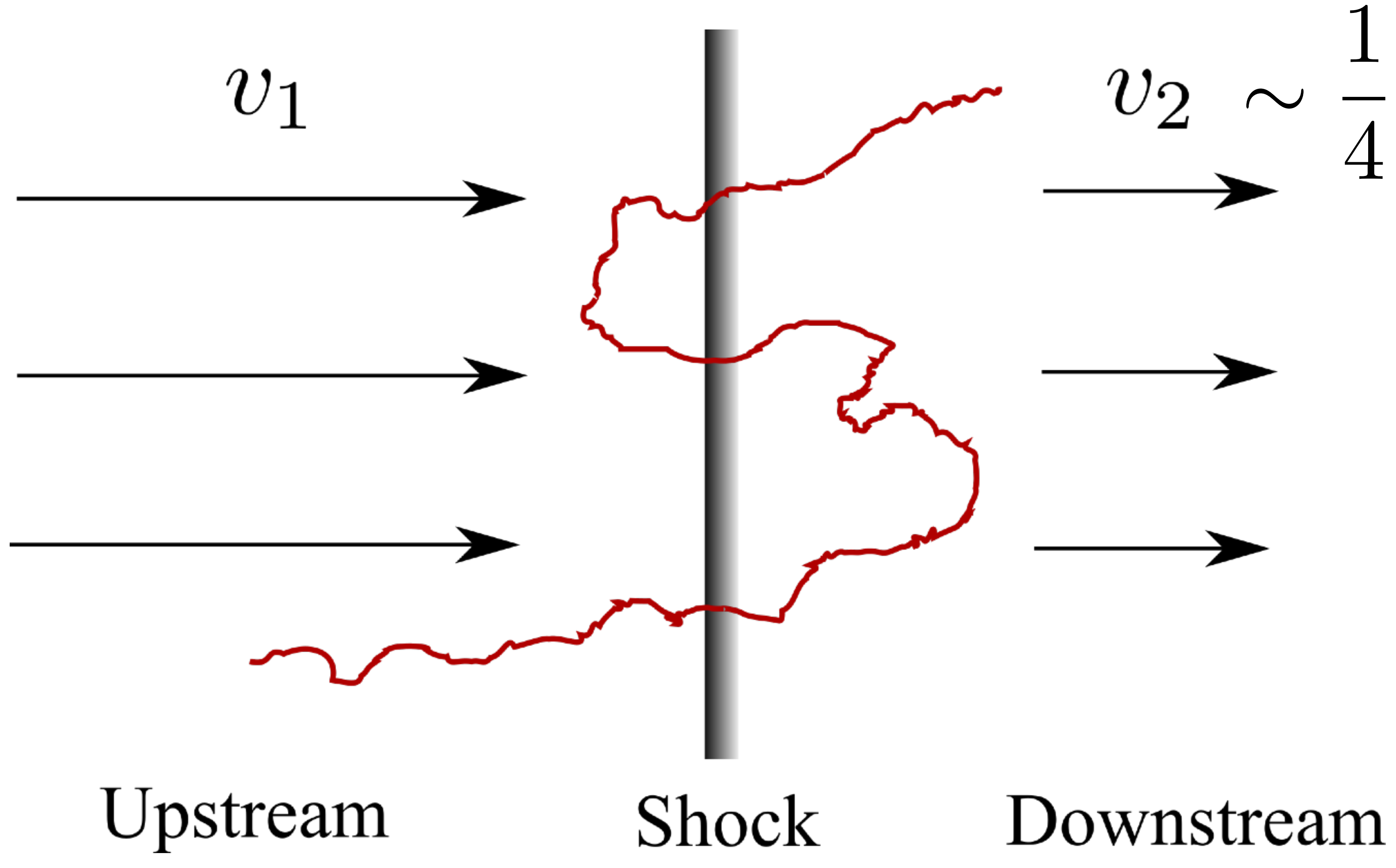
Heavier nuclei begin to dominate above the 2nd knee.



Credit: Particle Data Group (2020)

Production of cosmic rays

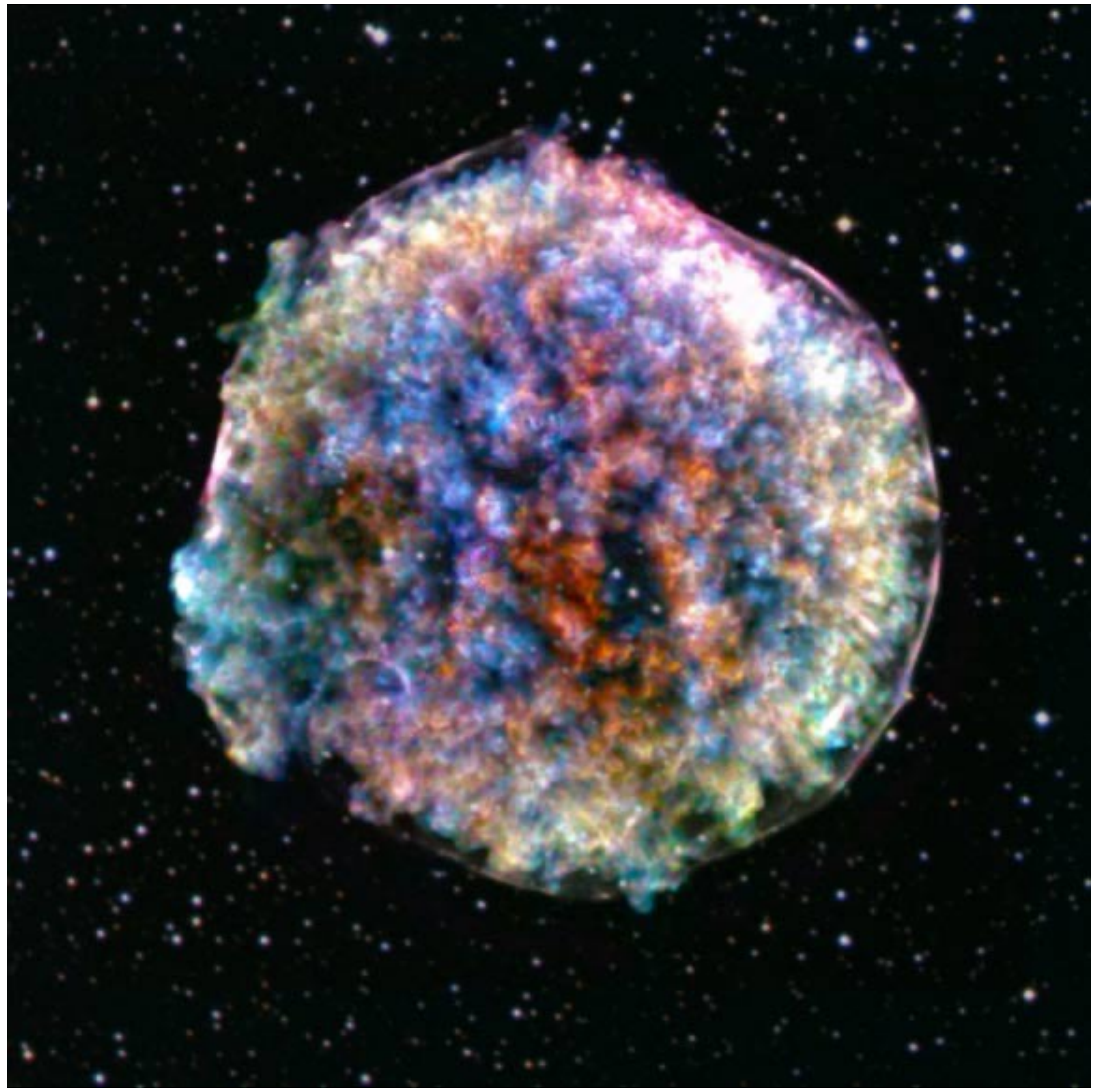
Diffusive shock acceleration (or **Fermi Acceleration**)



$$v_2 \sim \frac{1}{4} v_1 \sim \frac{1}{4} v_s$$

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

Tycho Supernova remnant



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

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: $f(E > E_n) = \sum_{m=n}^{\infty} (1 - P_{\rm esc})^m = \left(\frac{E_n}{E_0} \right)^{P_{\rm esc}/\xi}$

→ Injected flux of particles: $\frac{{\rm d}N_{\rm inj}}{{\rm d}E} \propto \frac{{\rm d}f}{{\rm d}E} = \left(\frac{E}{E_0} \right)^{-2}$

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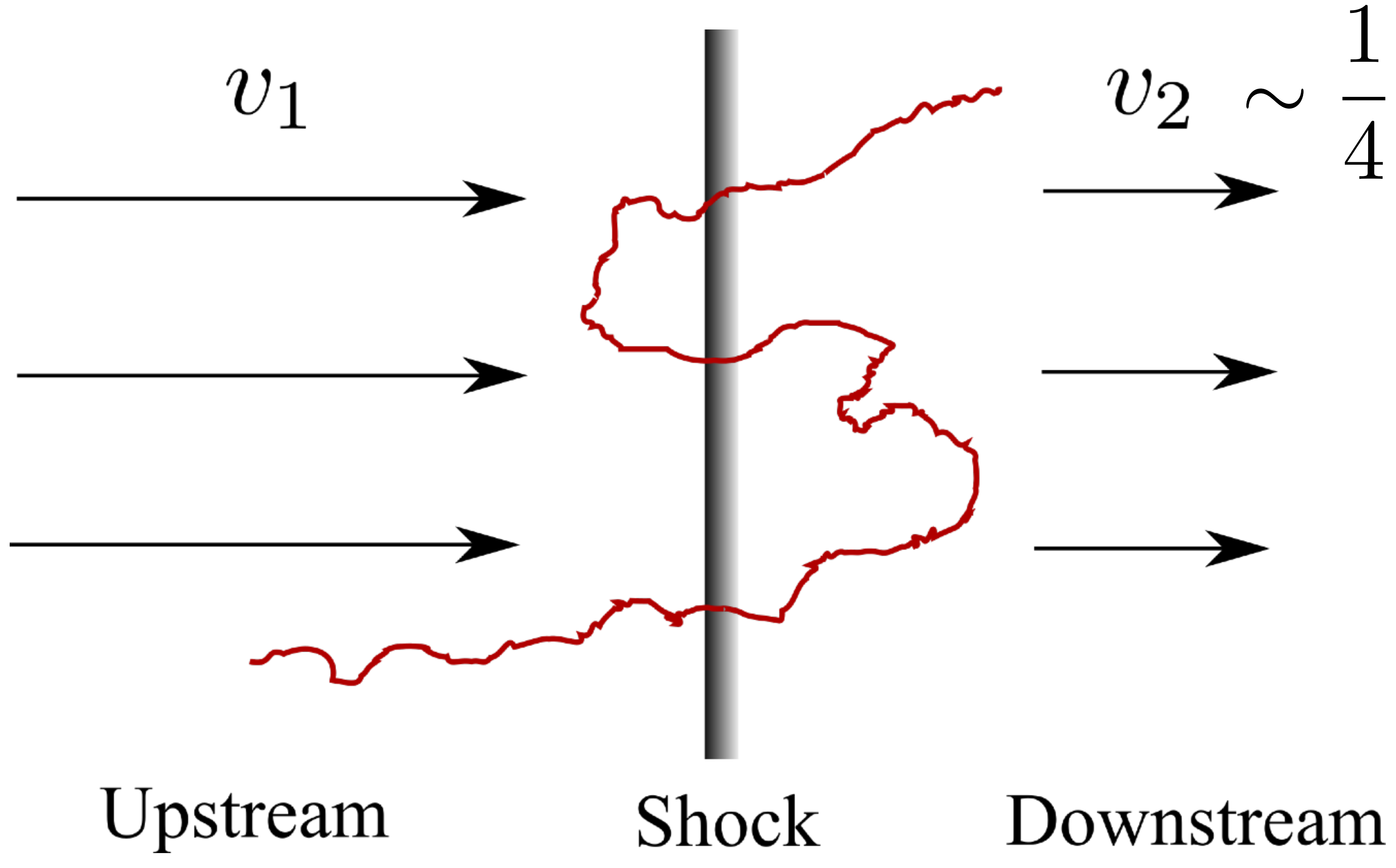

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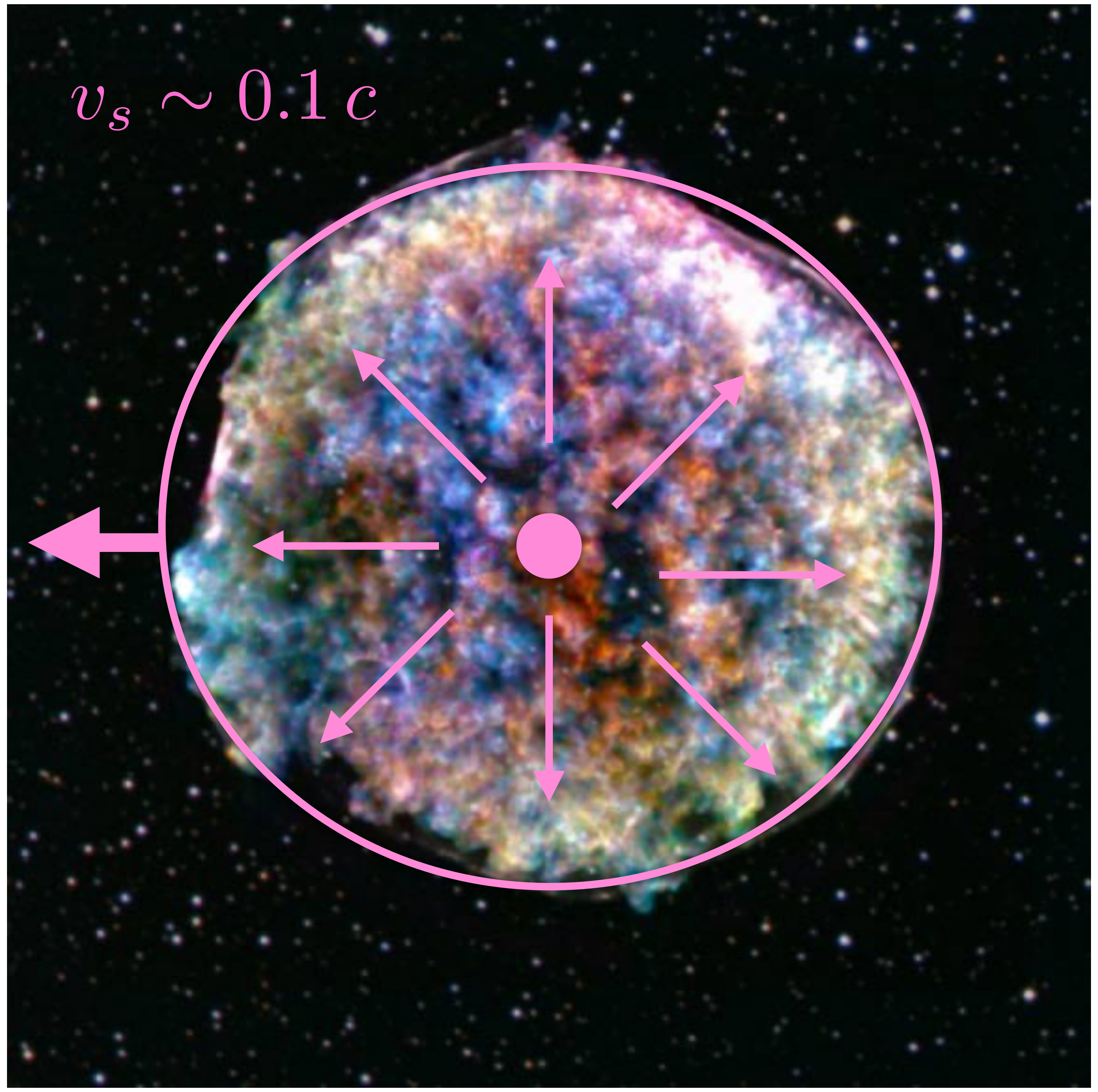

Credit: NASA / CXC / RIKEN / NASA's Goddard Space Flight Center / T. Sato et al / DSS

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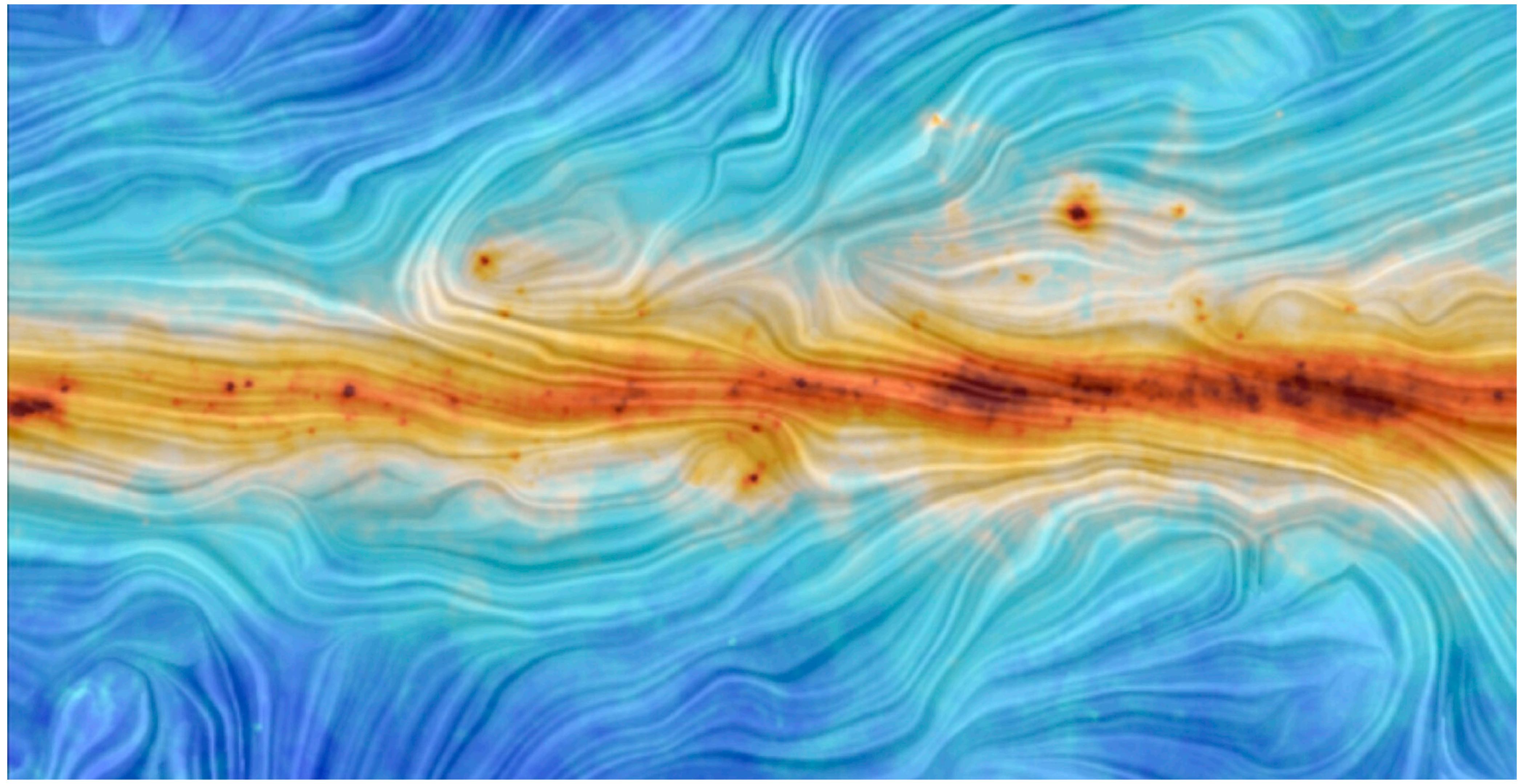
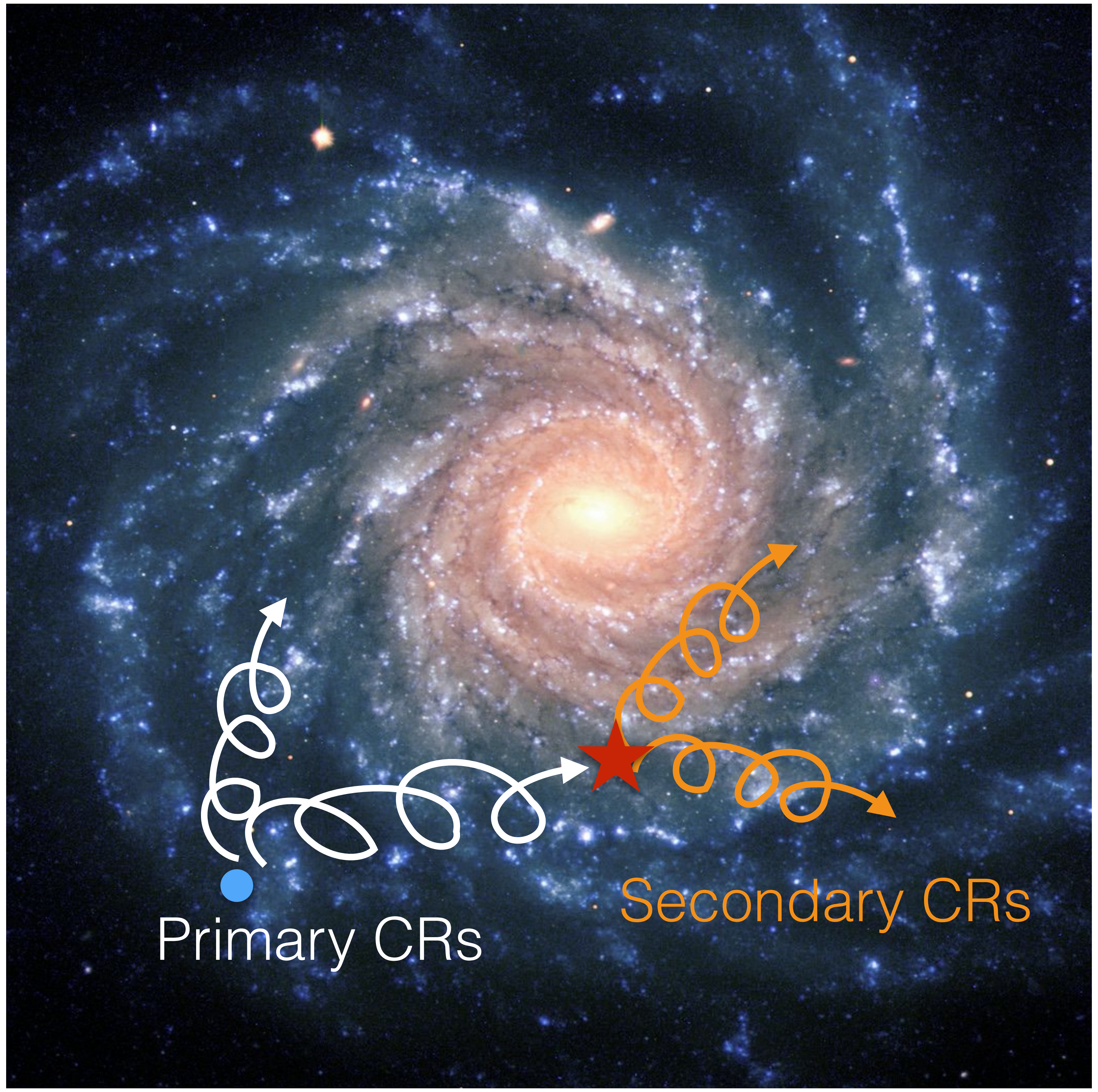
Propagation of CCRs

Credit: ESA/Planck Collaboration



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



Diffusion

Escape and attenuation

Sources

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

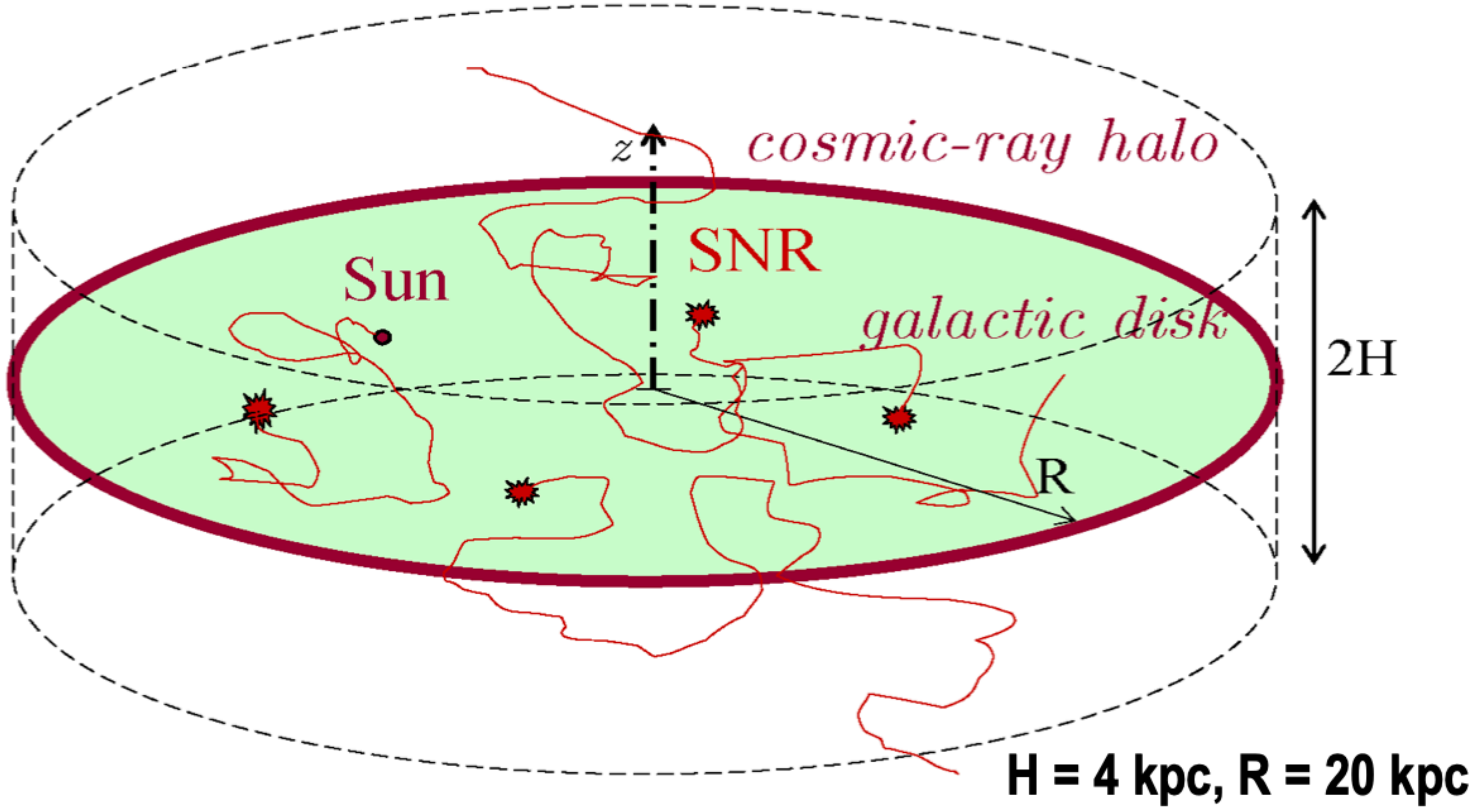
Energy losses

Production (by spallation)

Modelling CR propagation

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

Credit: Vladimir Ptuskin



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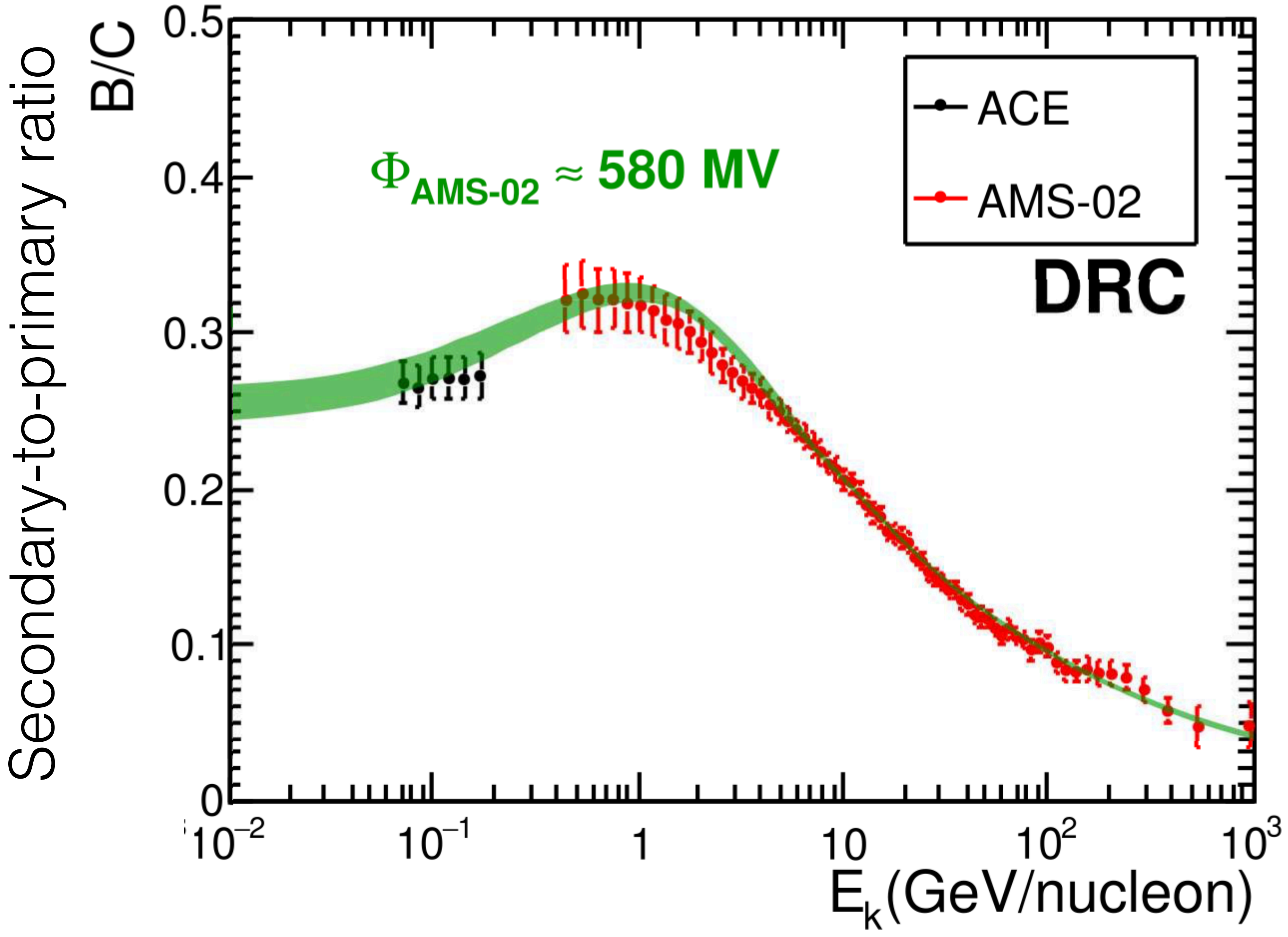
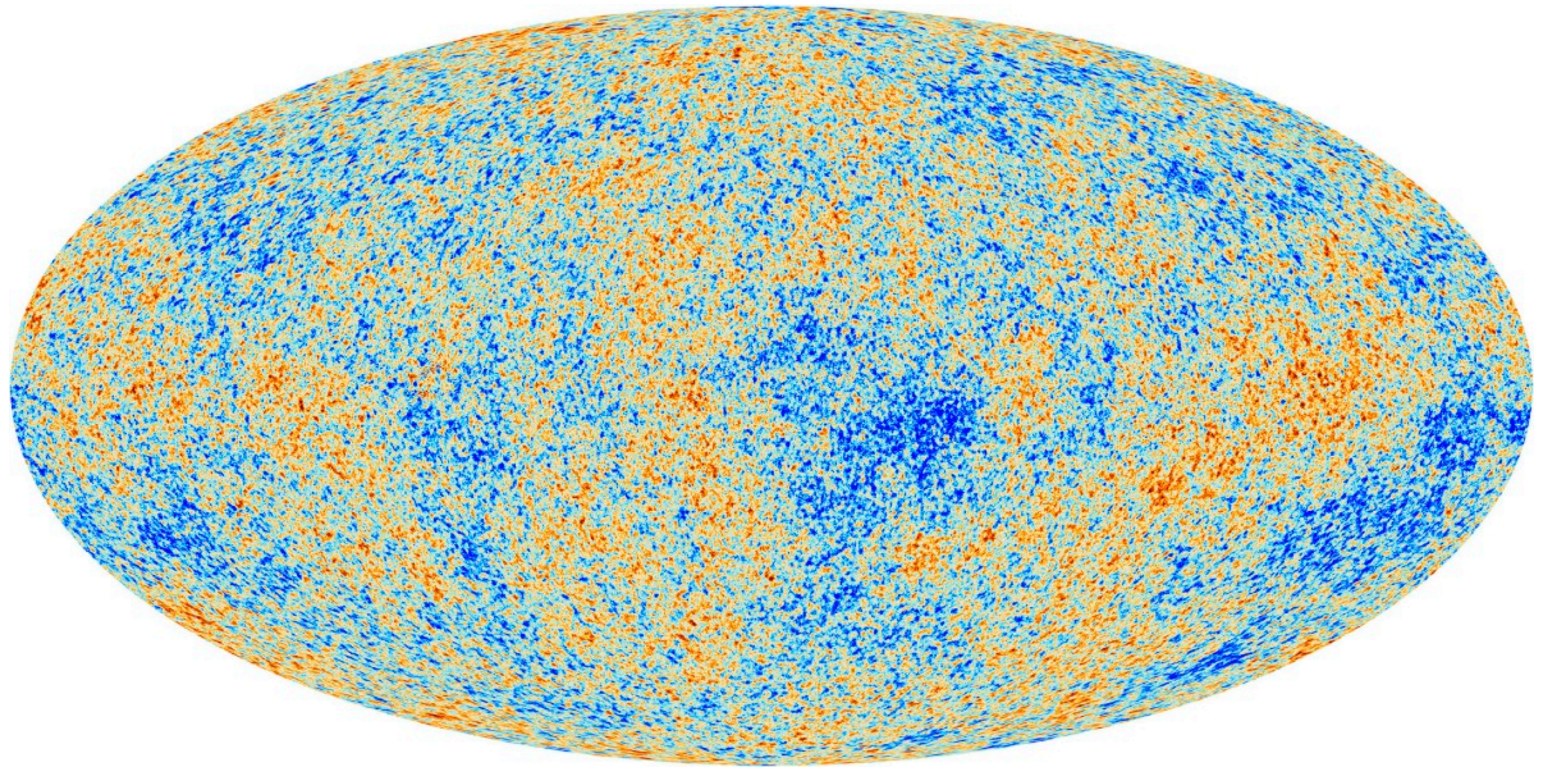


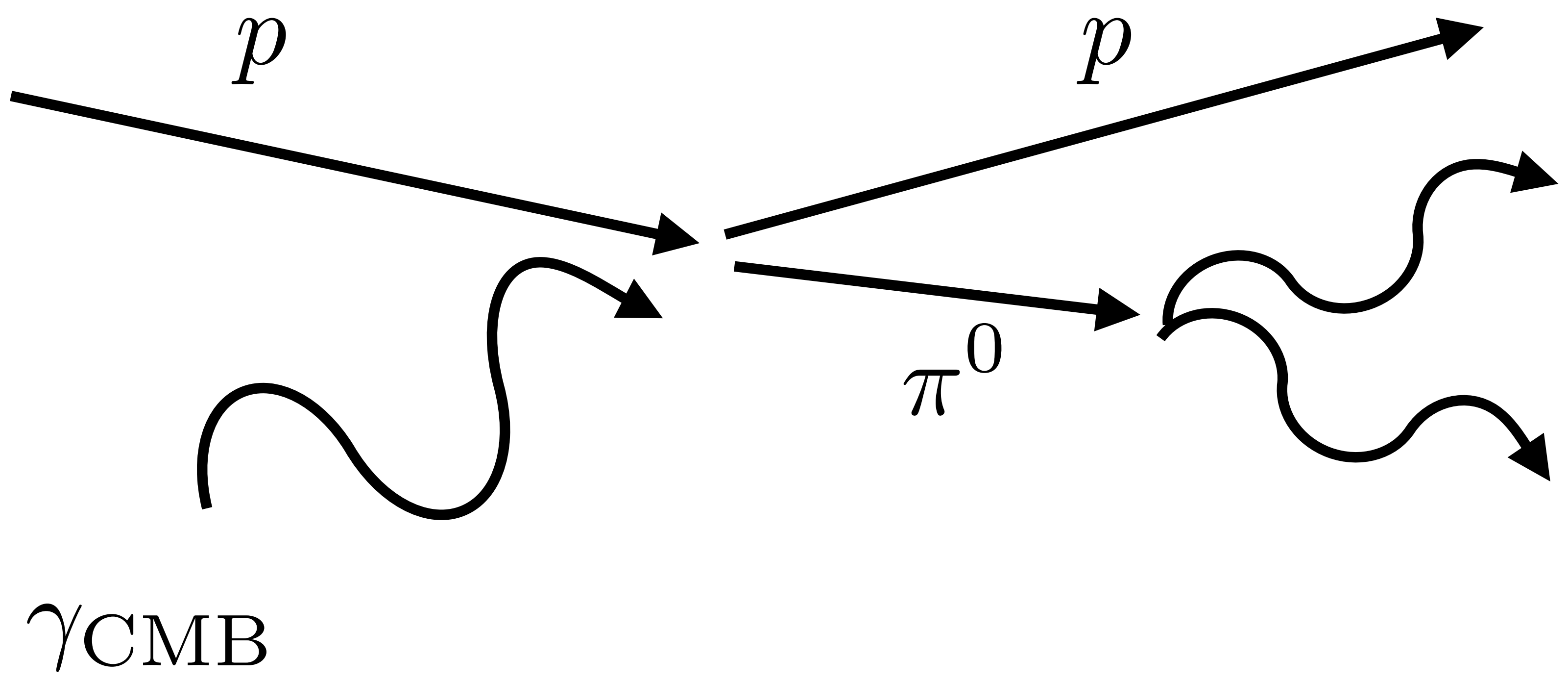
Typical diffusion distance $\langle R^2 \rangle \sim D(E)t$. Coefficient $D(E)$ grows with E,
steepening the observed CR spectrum…

GZK cut-off

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

Credit: ESA/Planck





$$\mathrm{p} + \gamma_{\mathrm{CMB}} \to \mathrm{p} + \pi_0$$

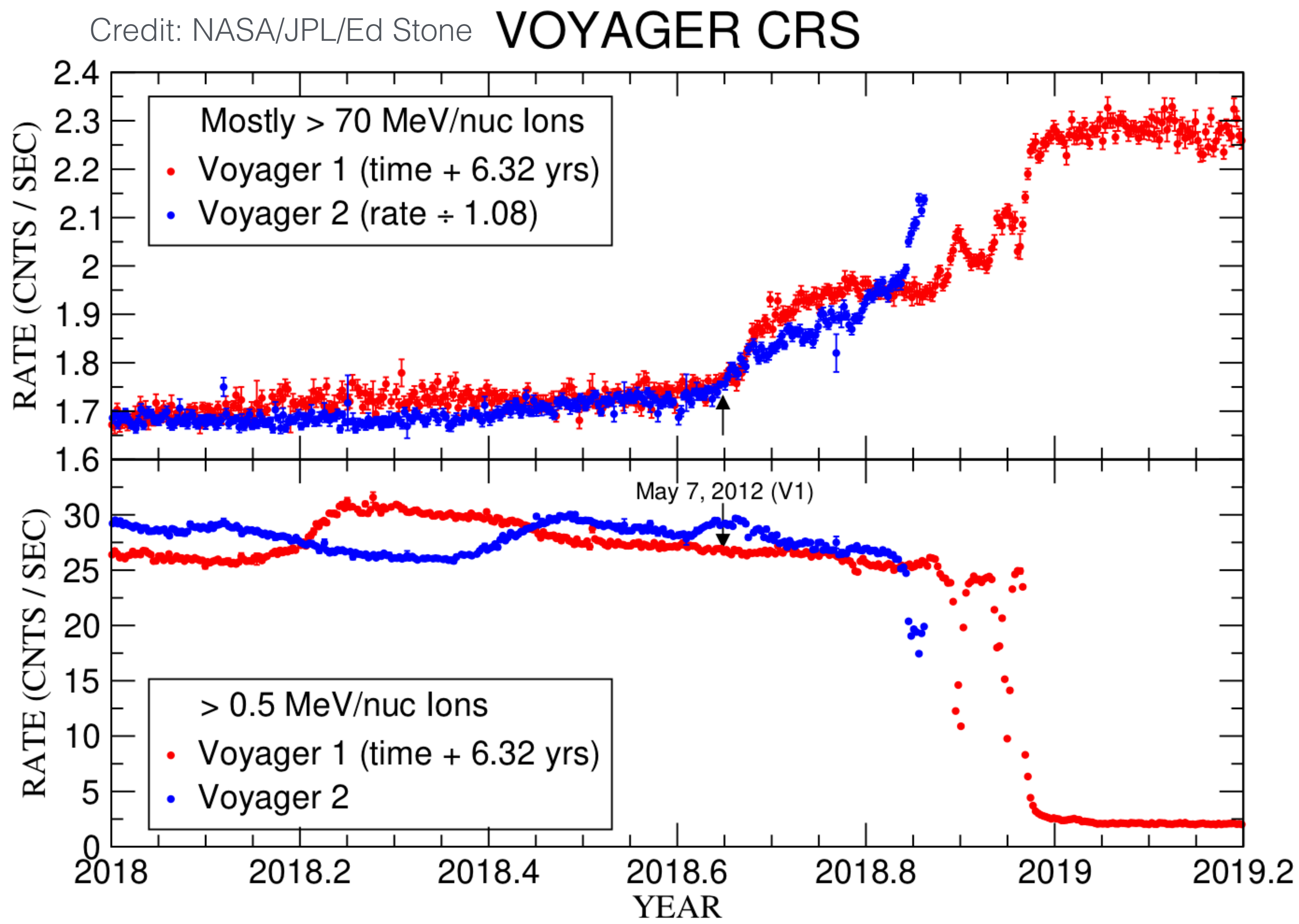
Threshold energy for this process gives rise to the Greisen–Zatsepin–Kuzmin (GZK) cut-off:

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

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

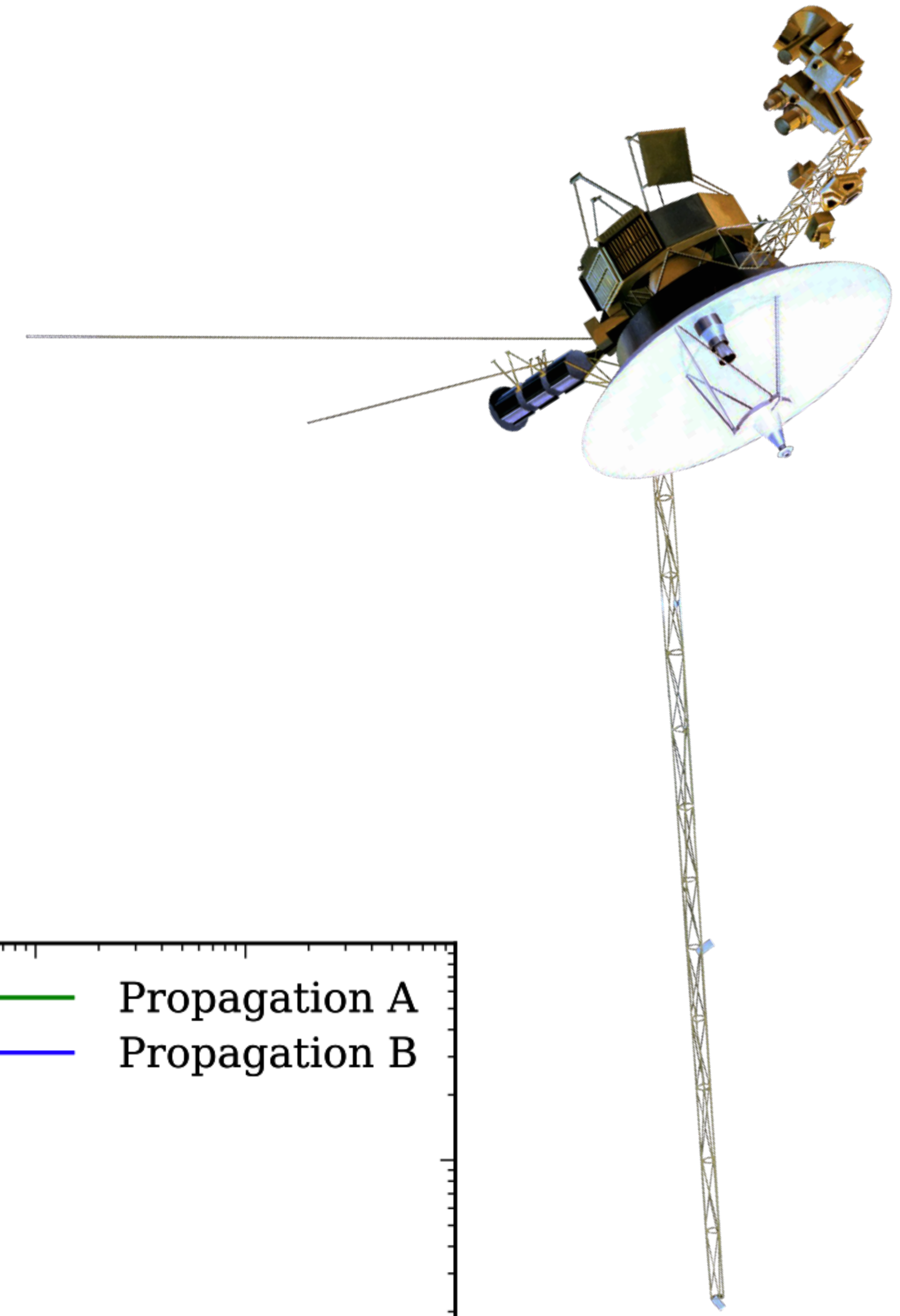
Voyager (and solar modulation)

Credit: NASA/JPL/Ed Stone

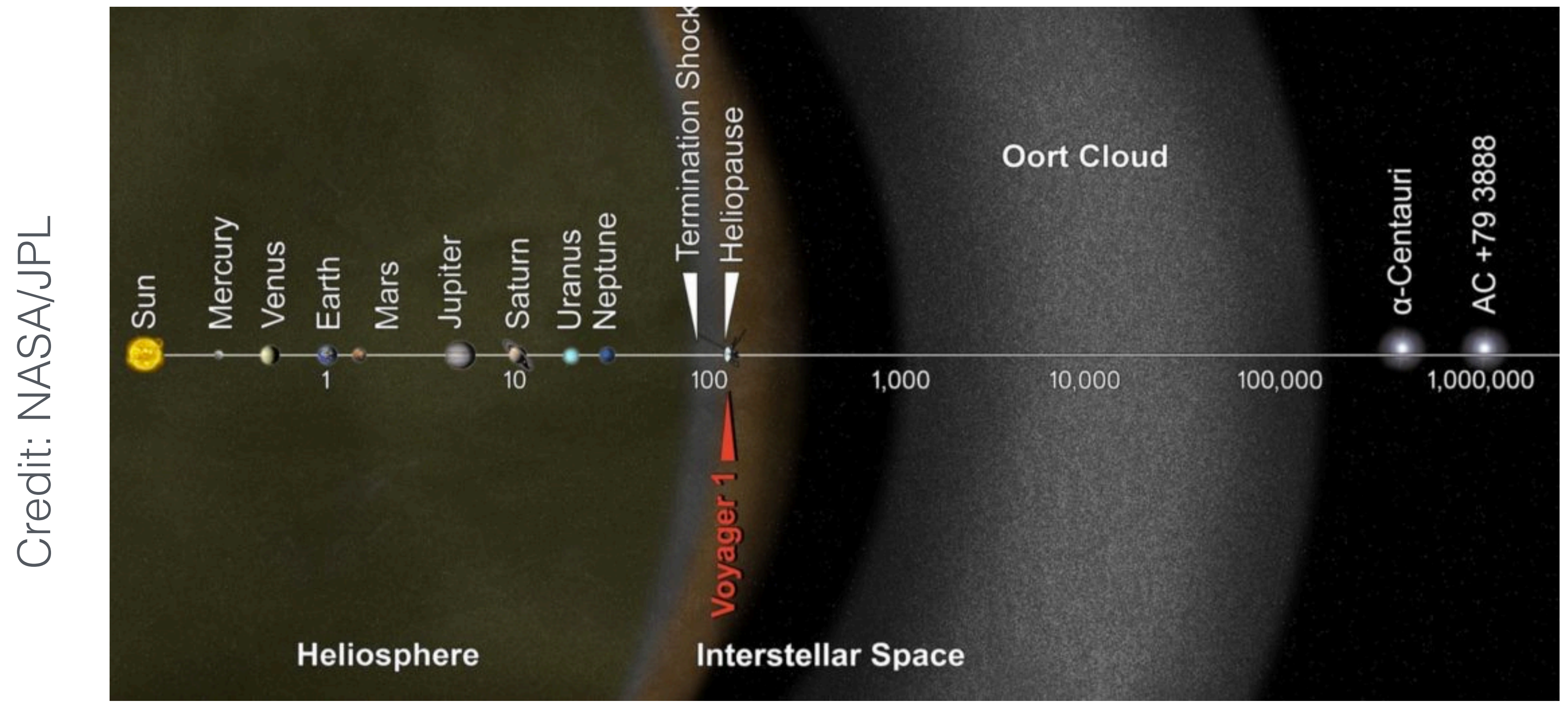


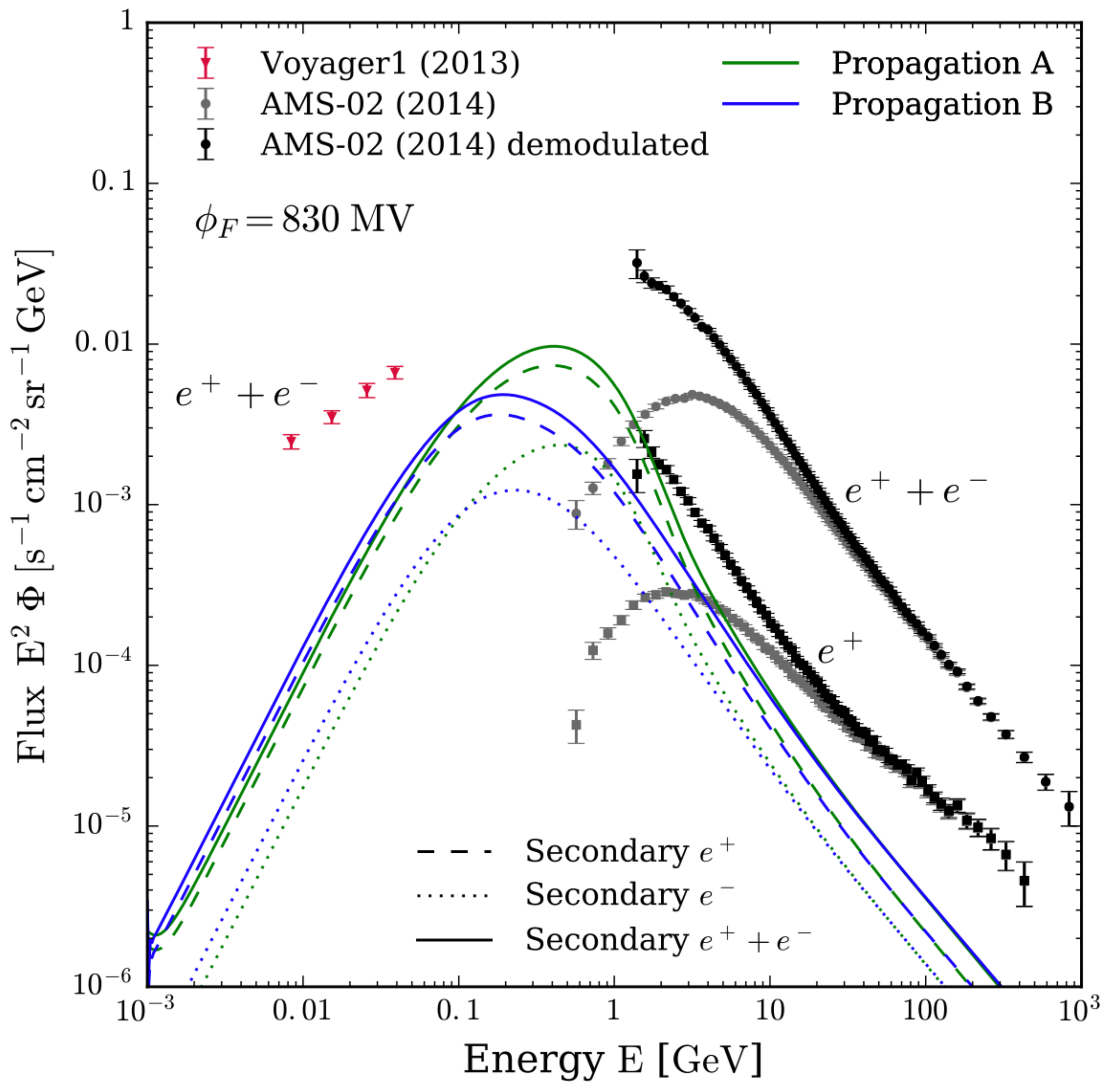
Voyager 1 - launched 1977, crossed heliopause 2012

Voyager 2 - launched 1977, crossed heliopause 2018



Credit: NASA/JPL

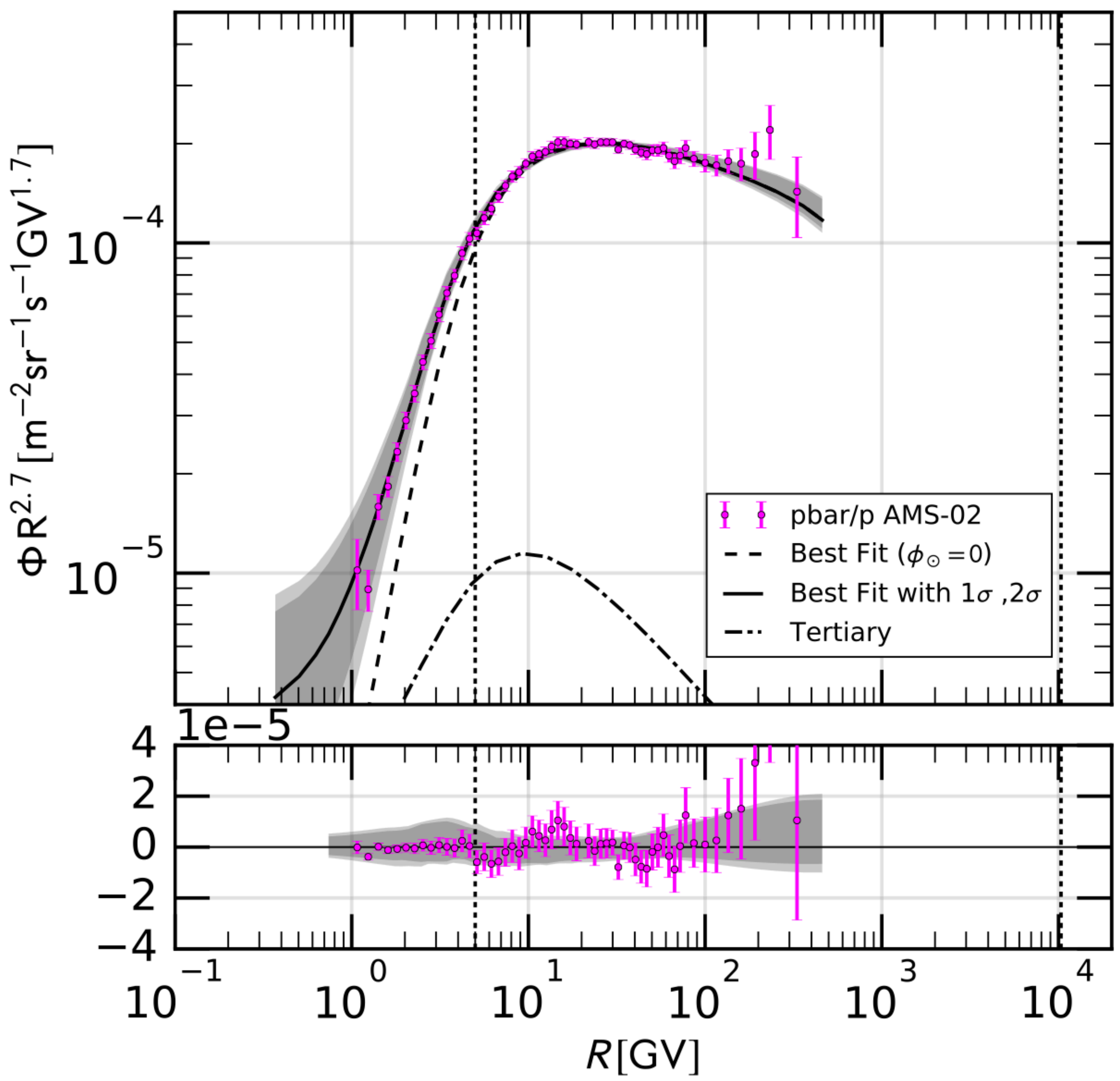




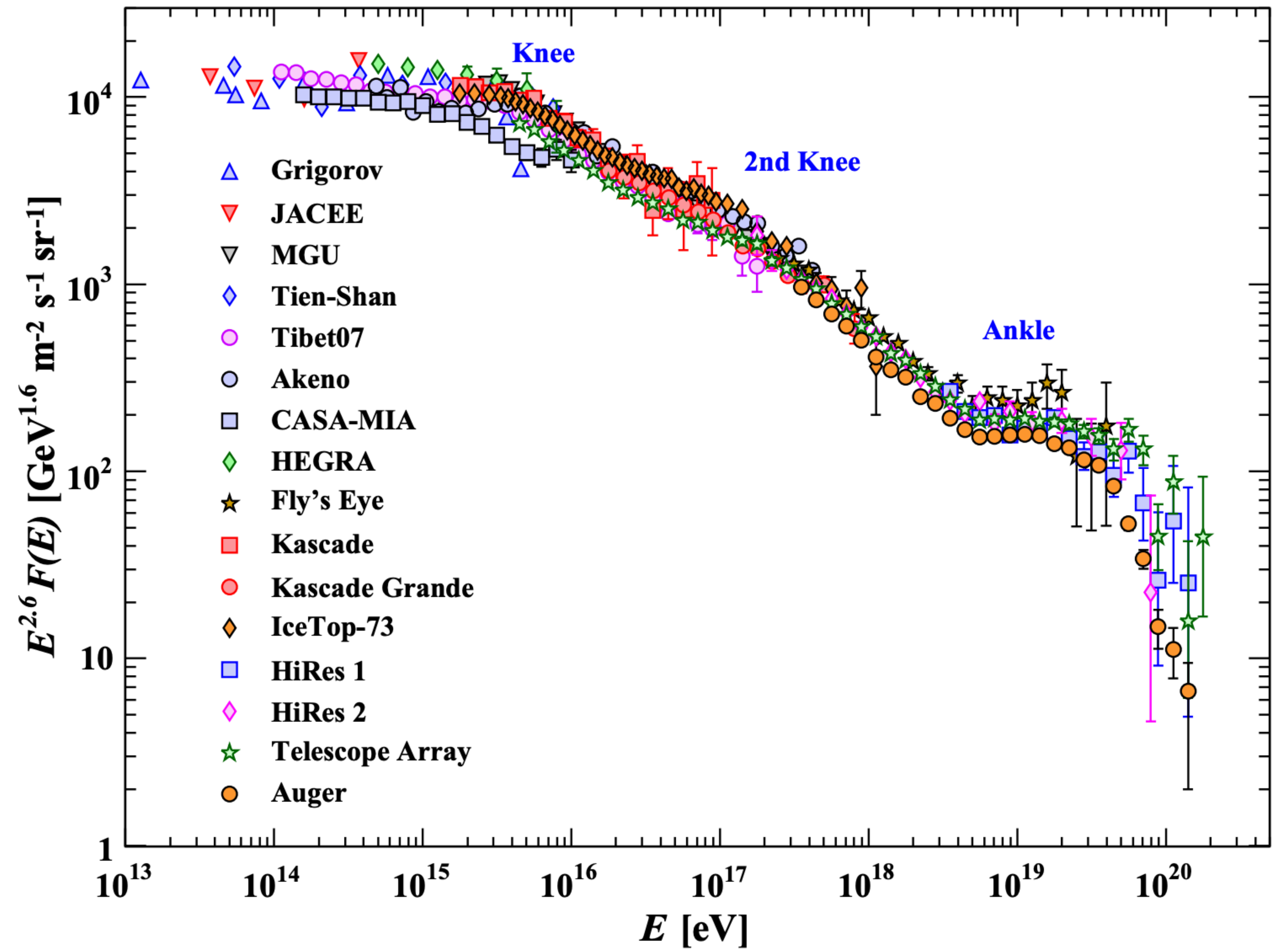
arXiv:1612.07698

CCR anomalies and questions

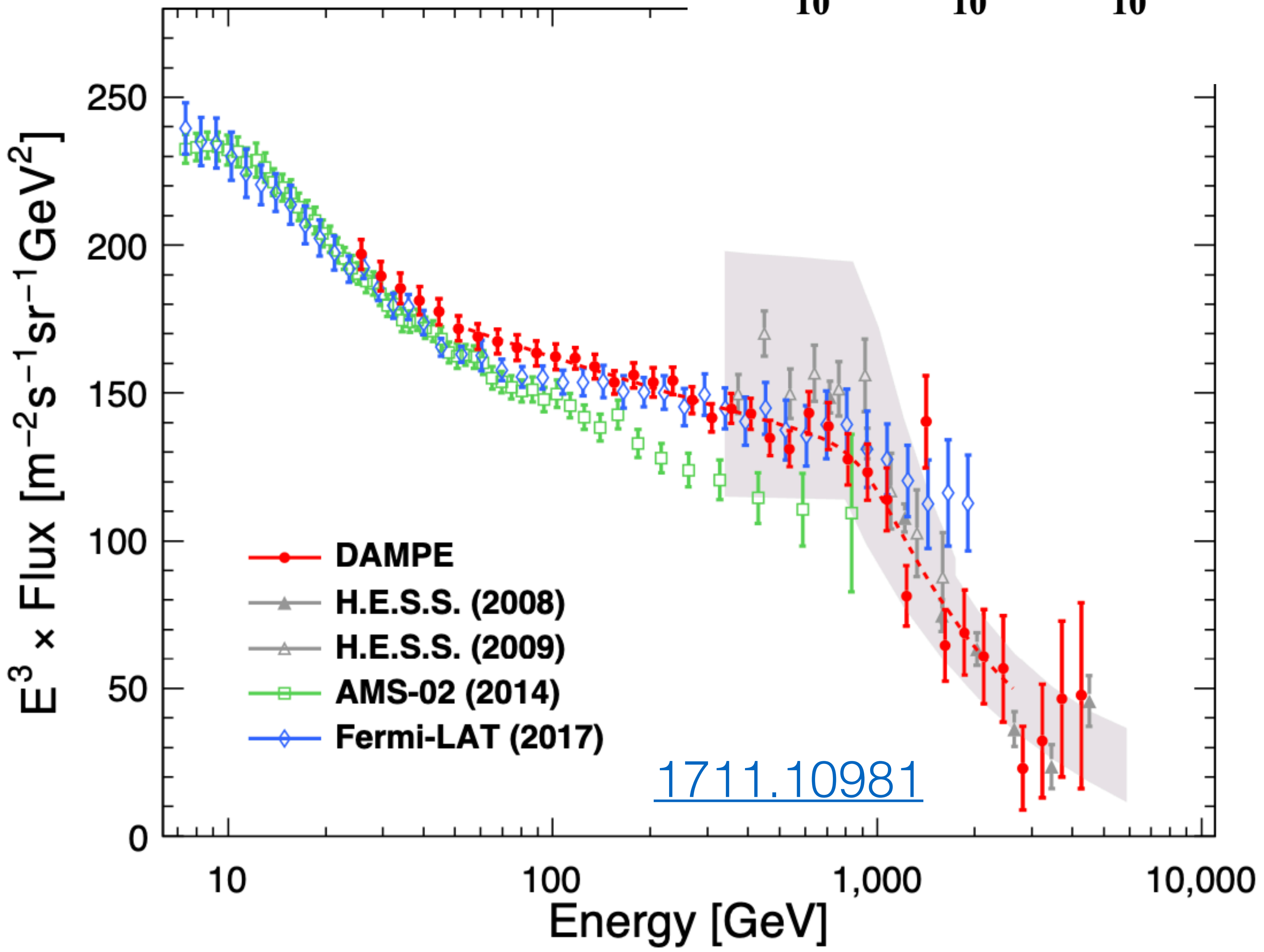
Excess in anti-protons?



1610.03071



Excess in electrons?

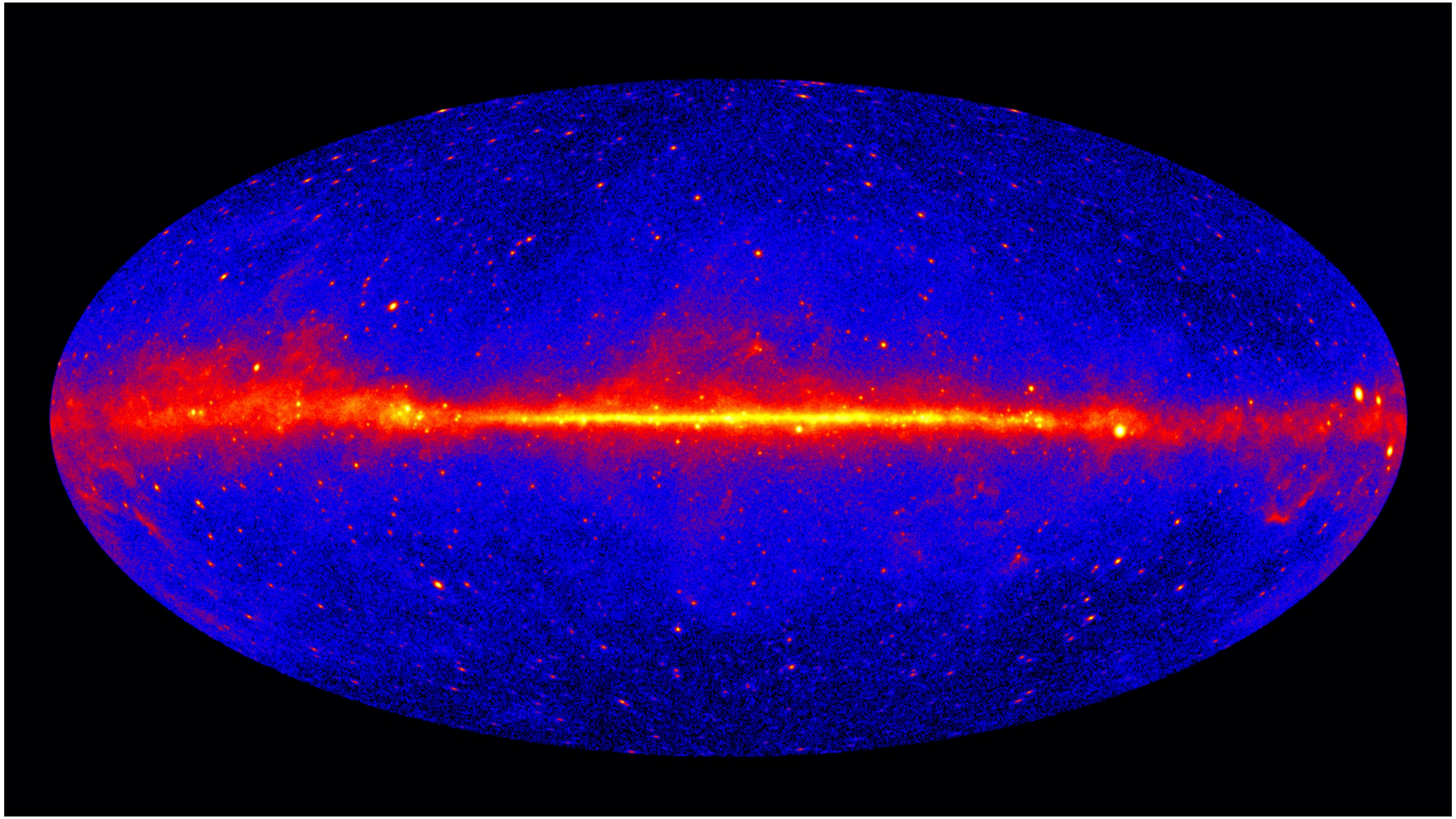


1711.10981

and others…

The Gamma-ray Sky

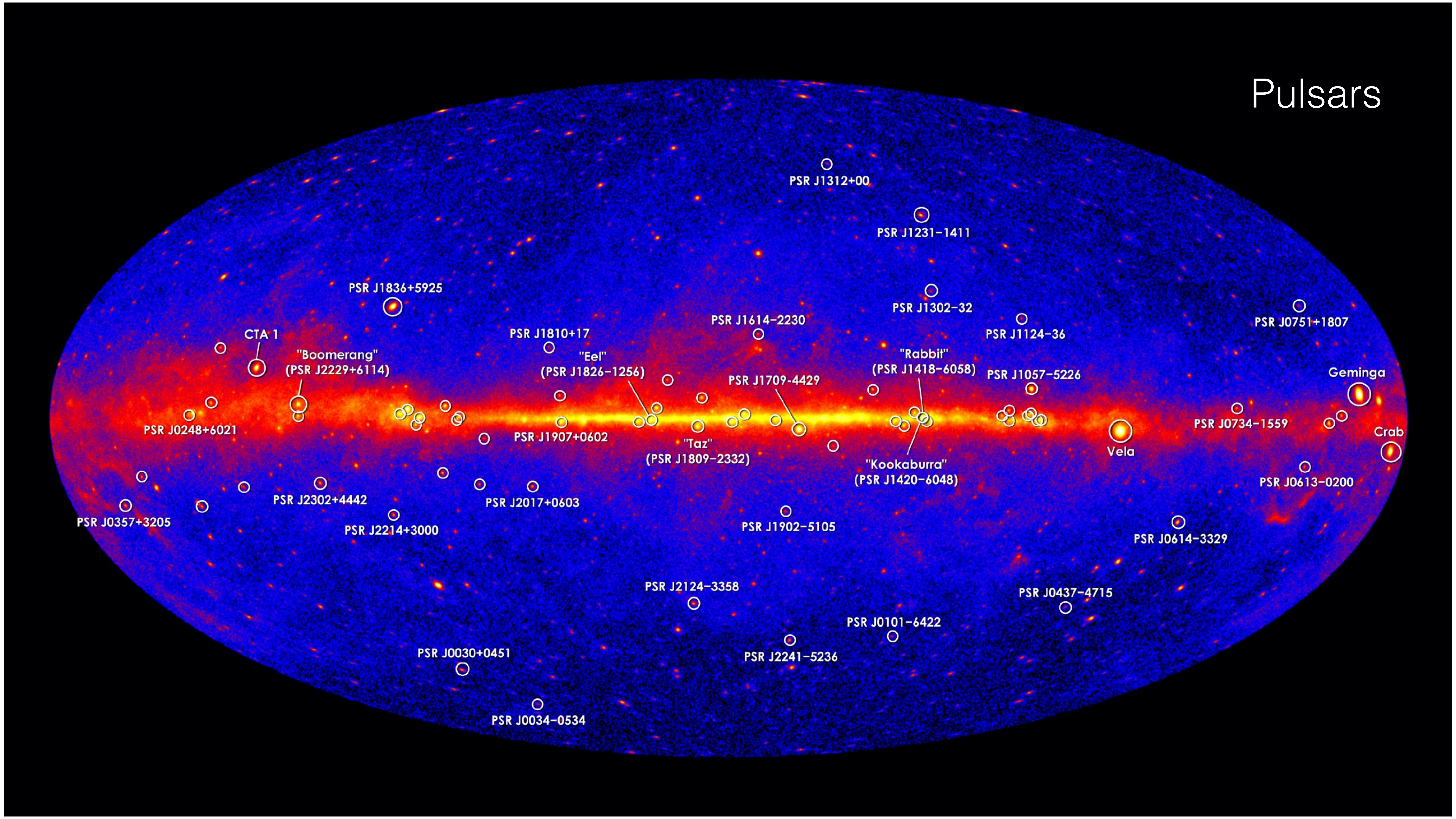
Gamma-ray Sky above 1 GeV, according to Fermi:

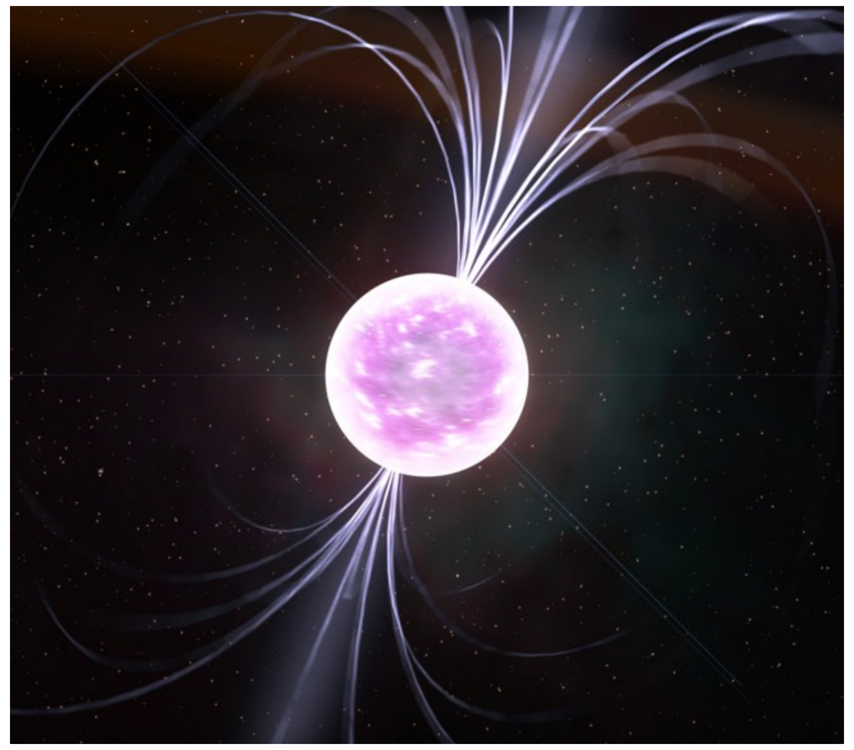


Credit: [NASA/DOE/Fermi LAT Collaboration]

The Gamma-ray Sky

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





Credit: Kevin Gill / Flickr

Credit: [NASA/DOE/Fermi LAT Collaboration]

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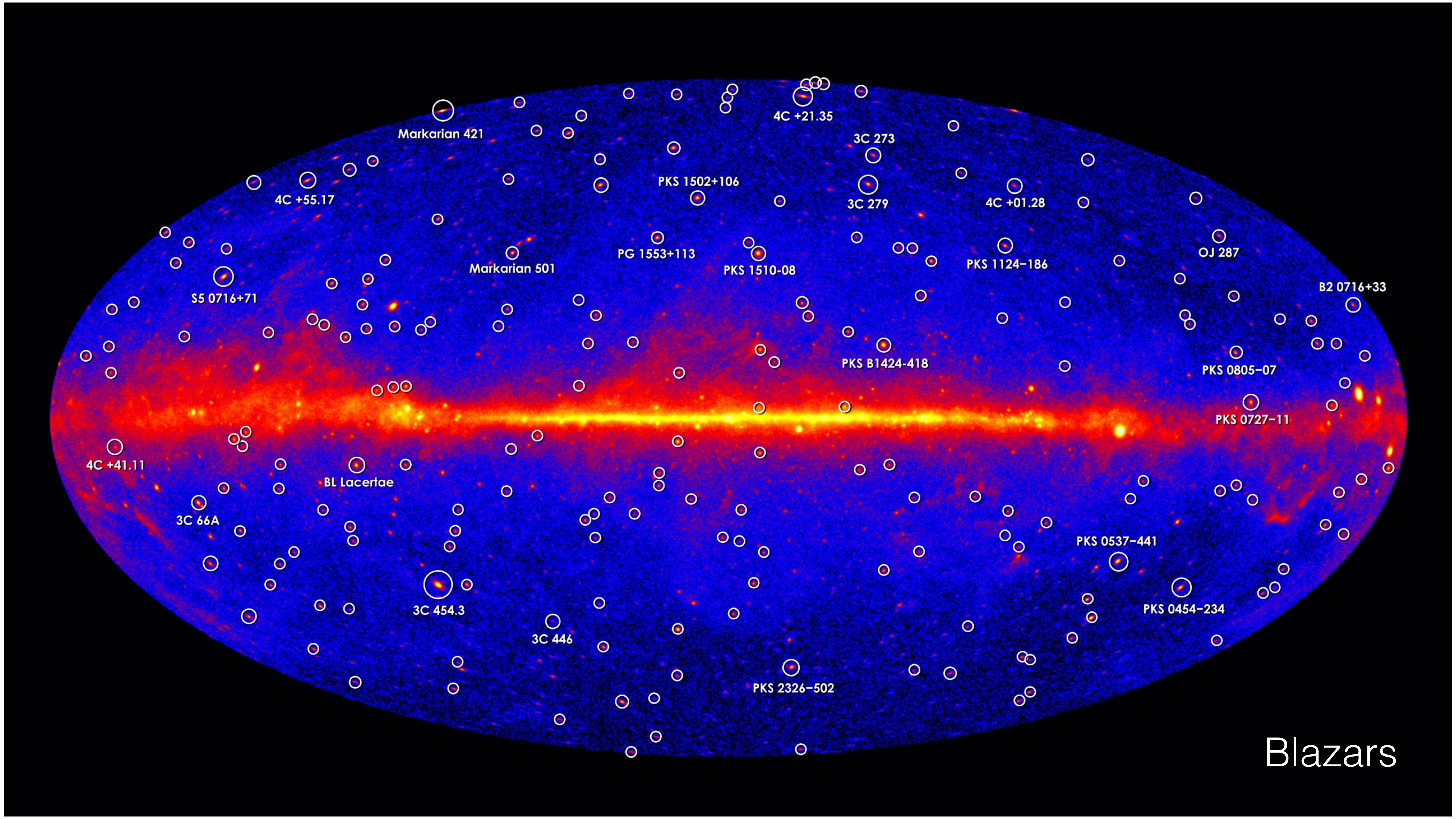
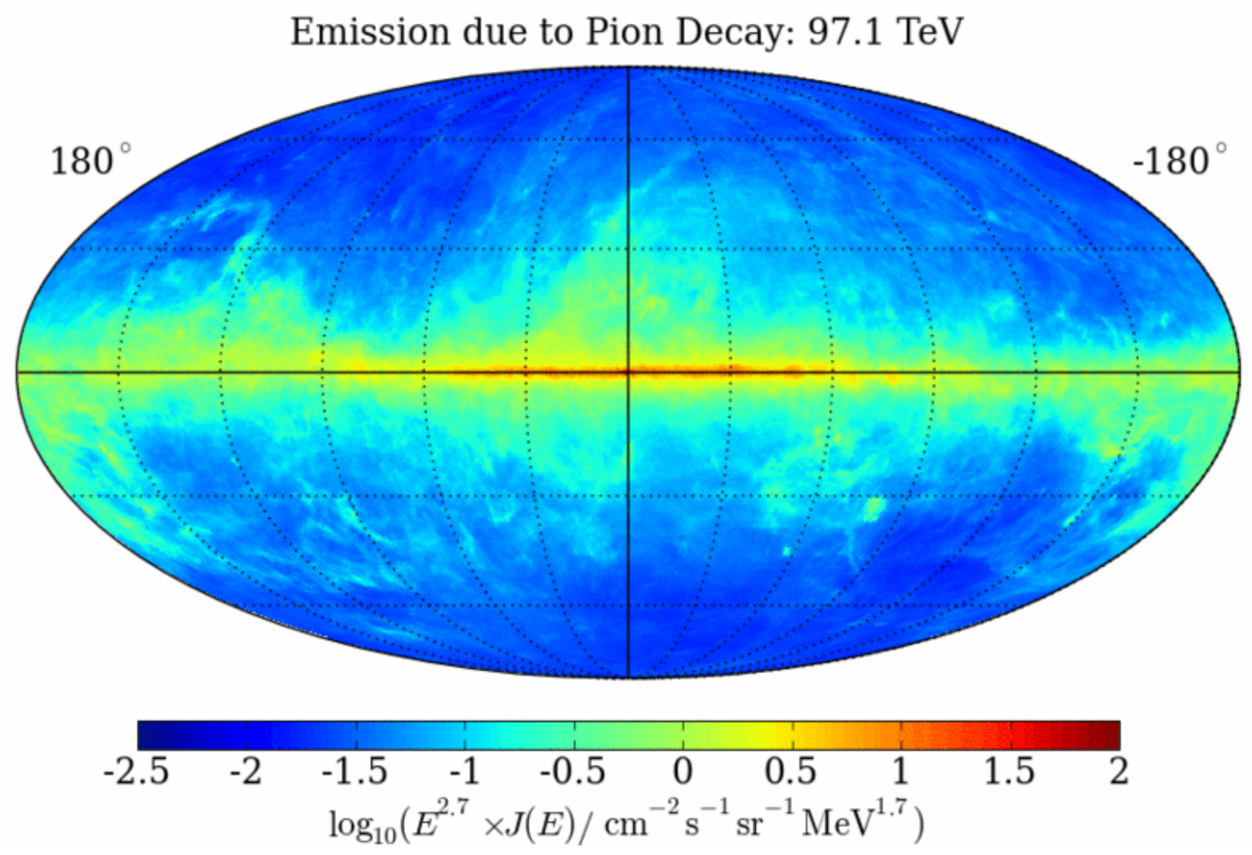


Credit: NASA/DOE/Fermi LAT Collaboration

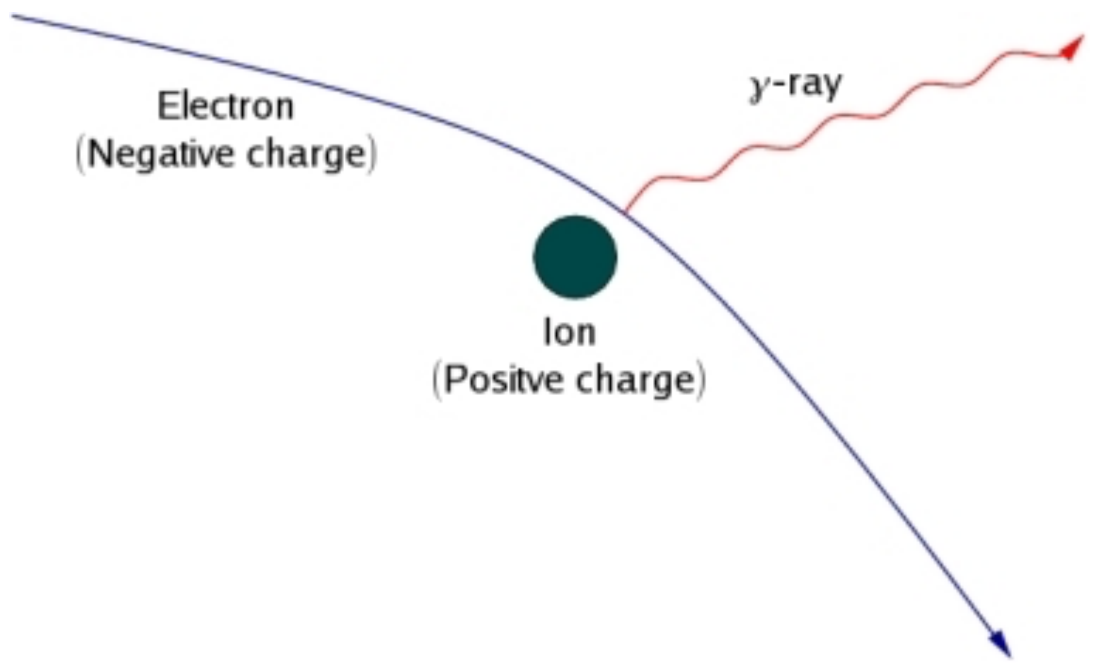
Credit: ESO/M. Kornmesser

Cosmic Ray Connection

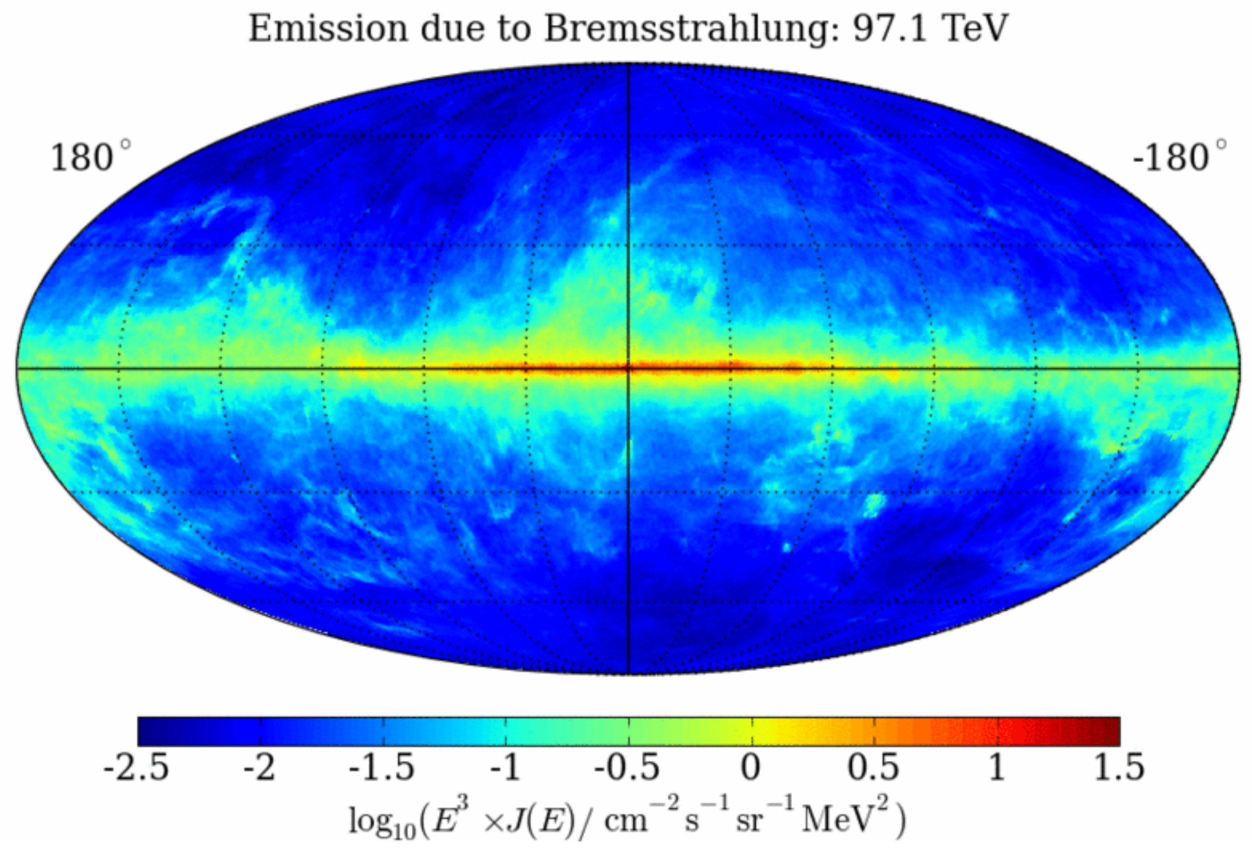
Pion Decay $p_{\rm CR} \longrightarrow p_{\rm ISM} \rightarrow \pi^0 \rightarrow \gamma\gamma$, $\; p_{\rm ISM} \rightarrow \ldots$ *CR protons + gas*



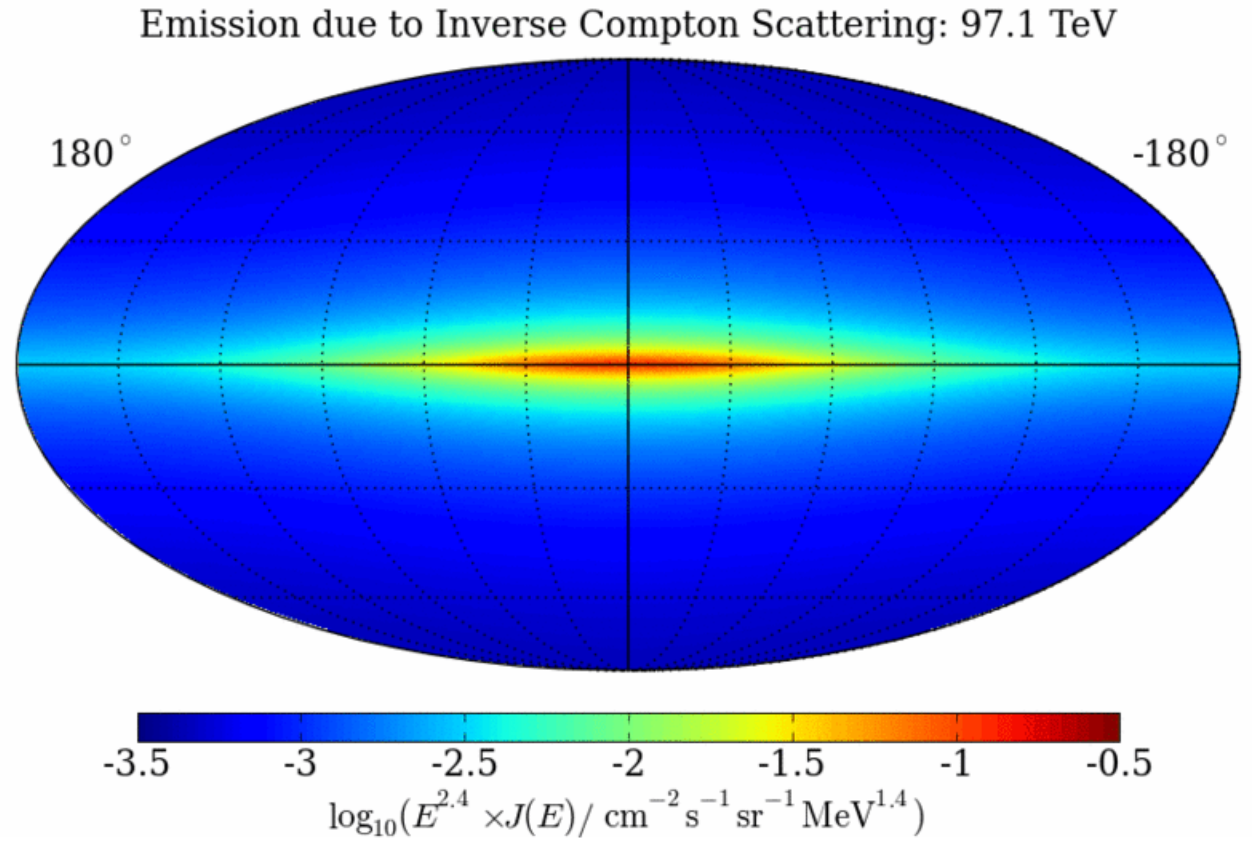
Brehmsstrahlung



CR electrons + gas



Inverse Compton $e^{\pm}_{\rm CR} \longrightarrow \gamma_{\rm ISRF} \rightarrow \gamma$, $\; \gamma_{\rm ISRF} \rightarrow e^{\pm}_{\rm CR}$ *CR electrons + light*



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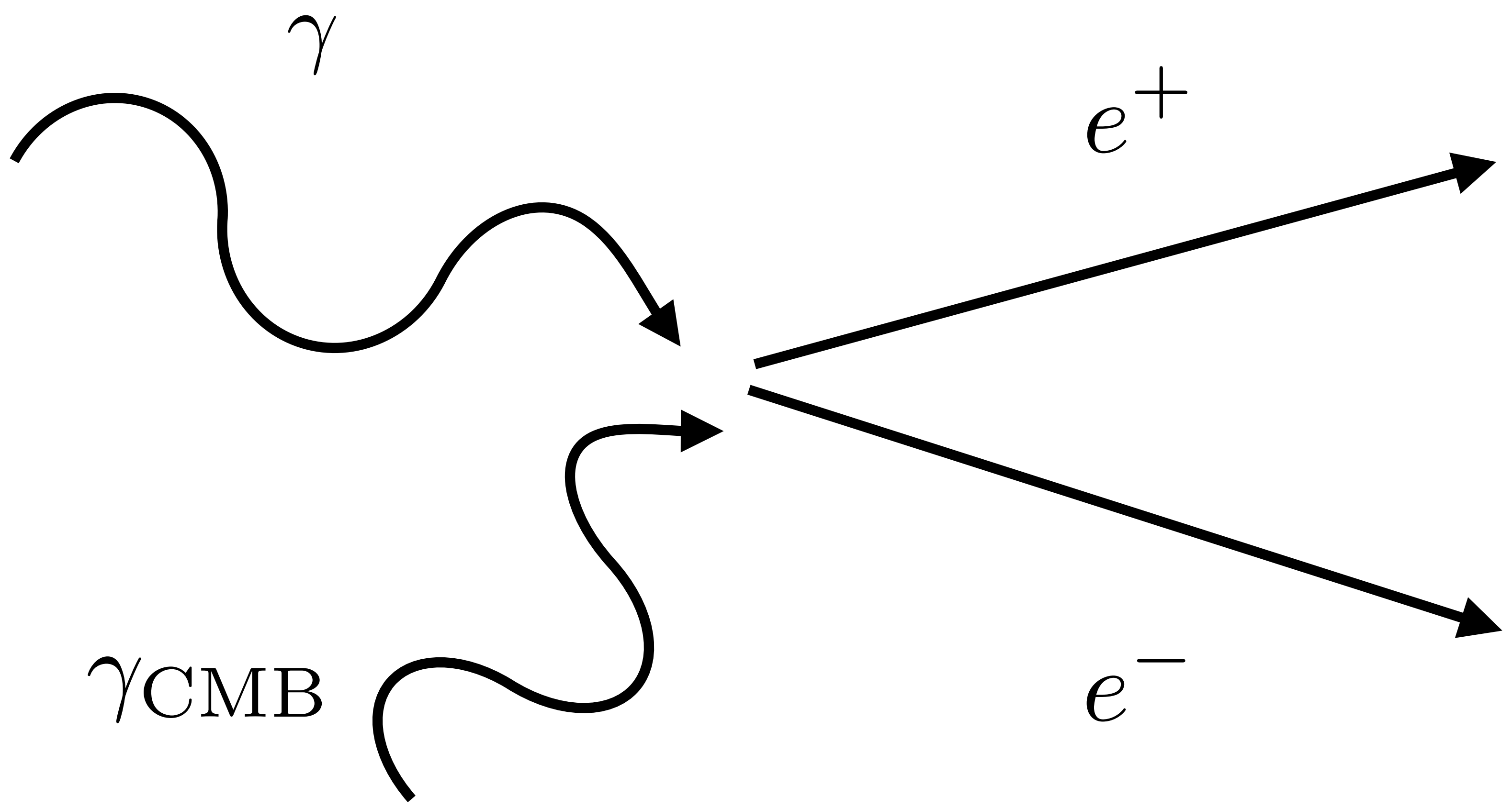
Gamma-ray horizon

Similar to the GZK cut-off…

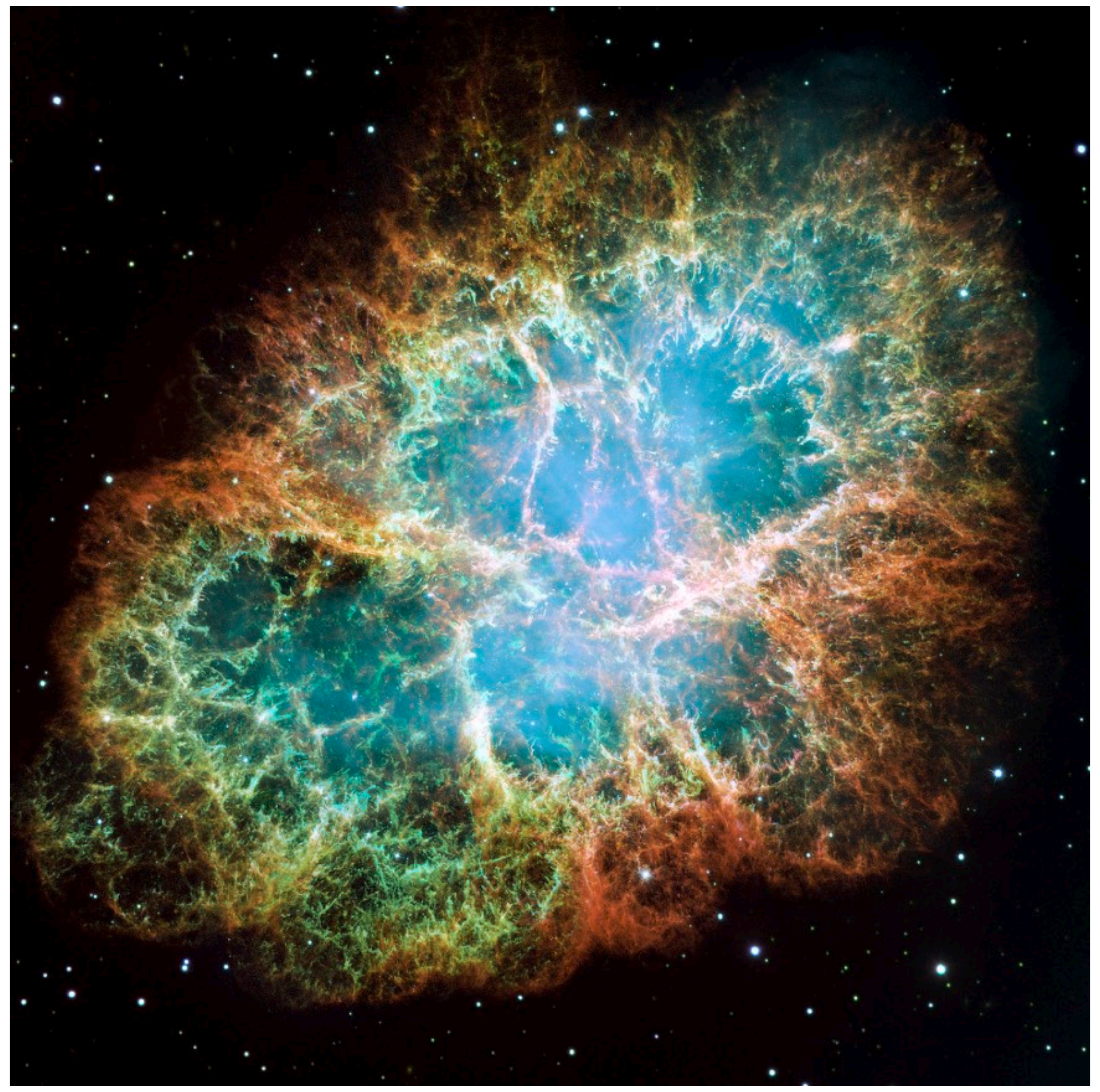


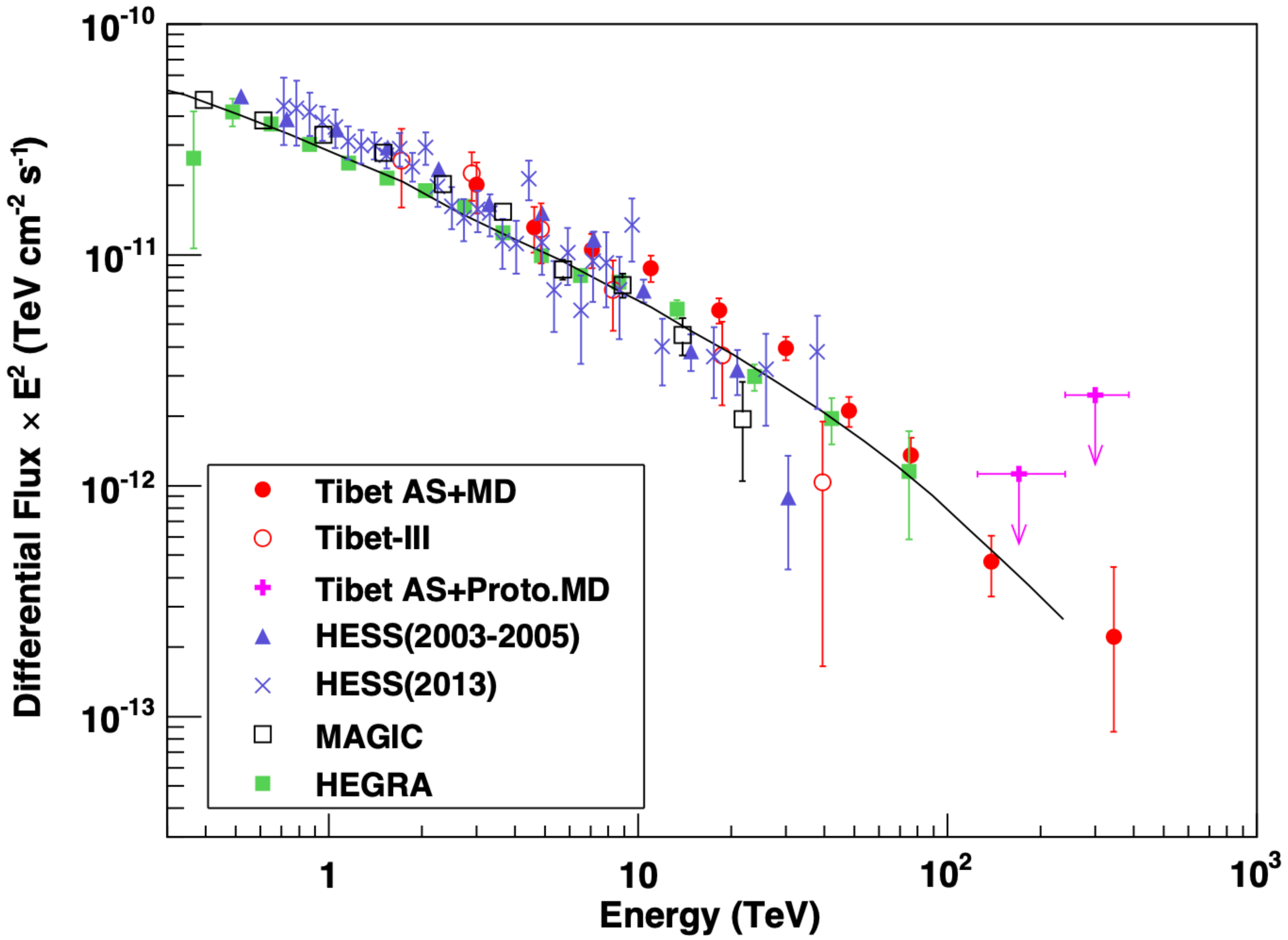
To produce an electron-positron pair, need a gamma-ray with energy greater than:

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

Credit: NASA/STScI

Crab Nebula





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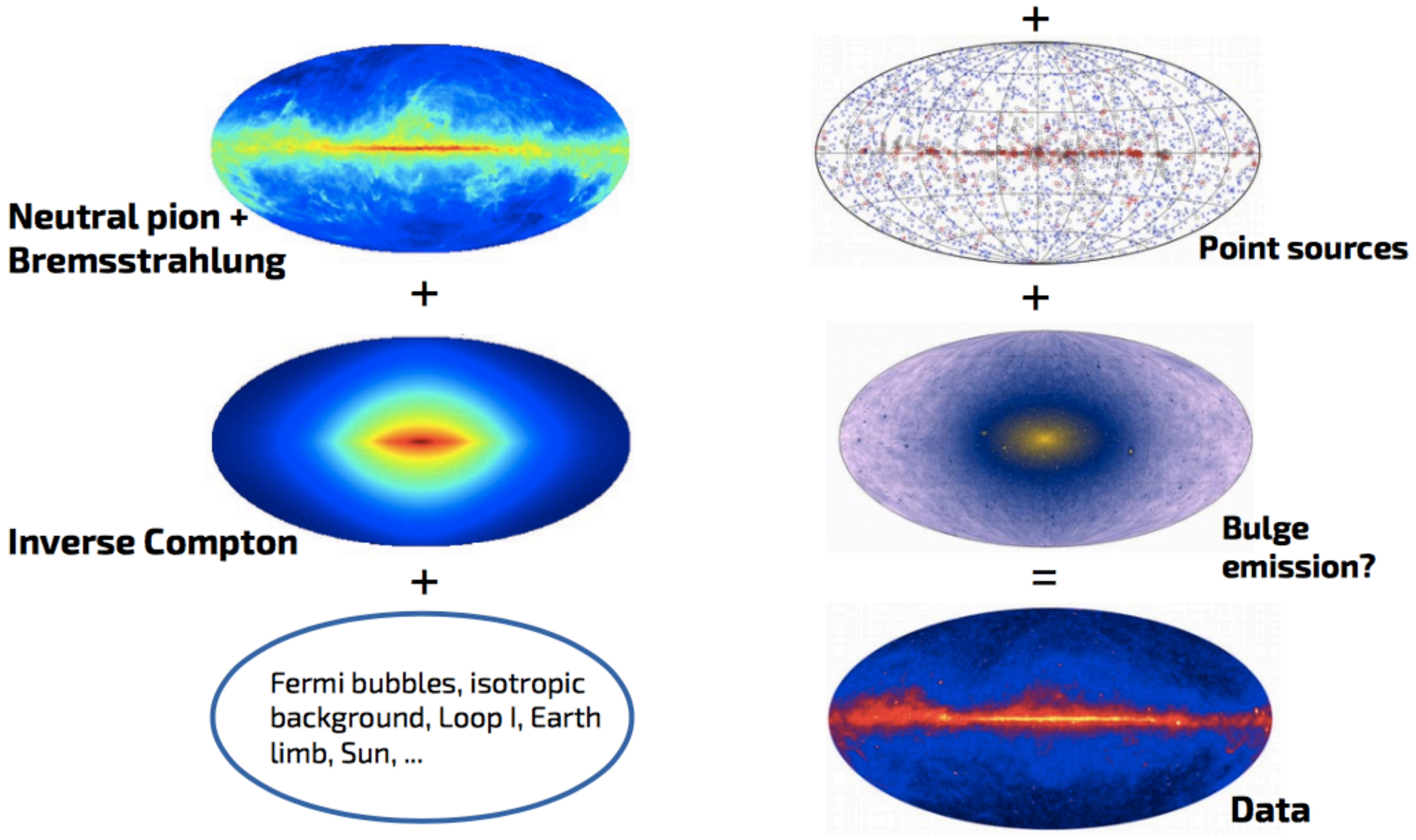
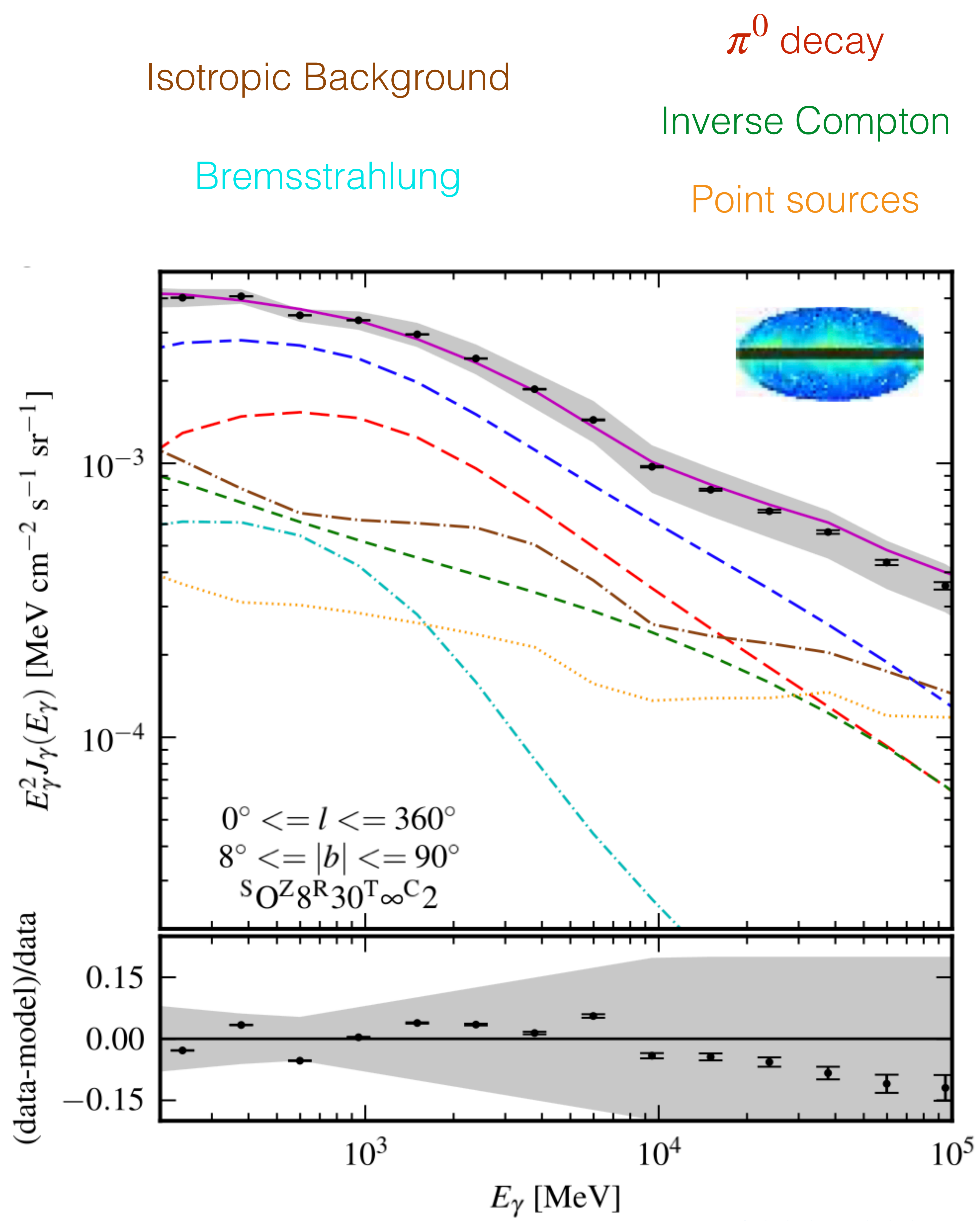
Modelling Gamma-ray emission



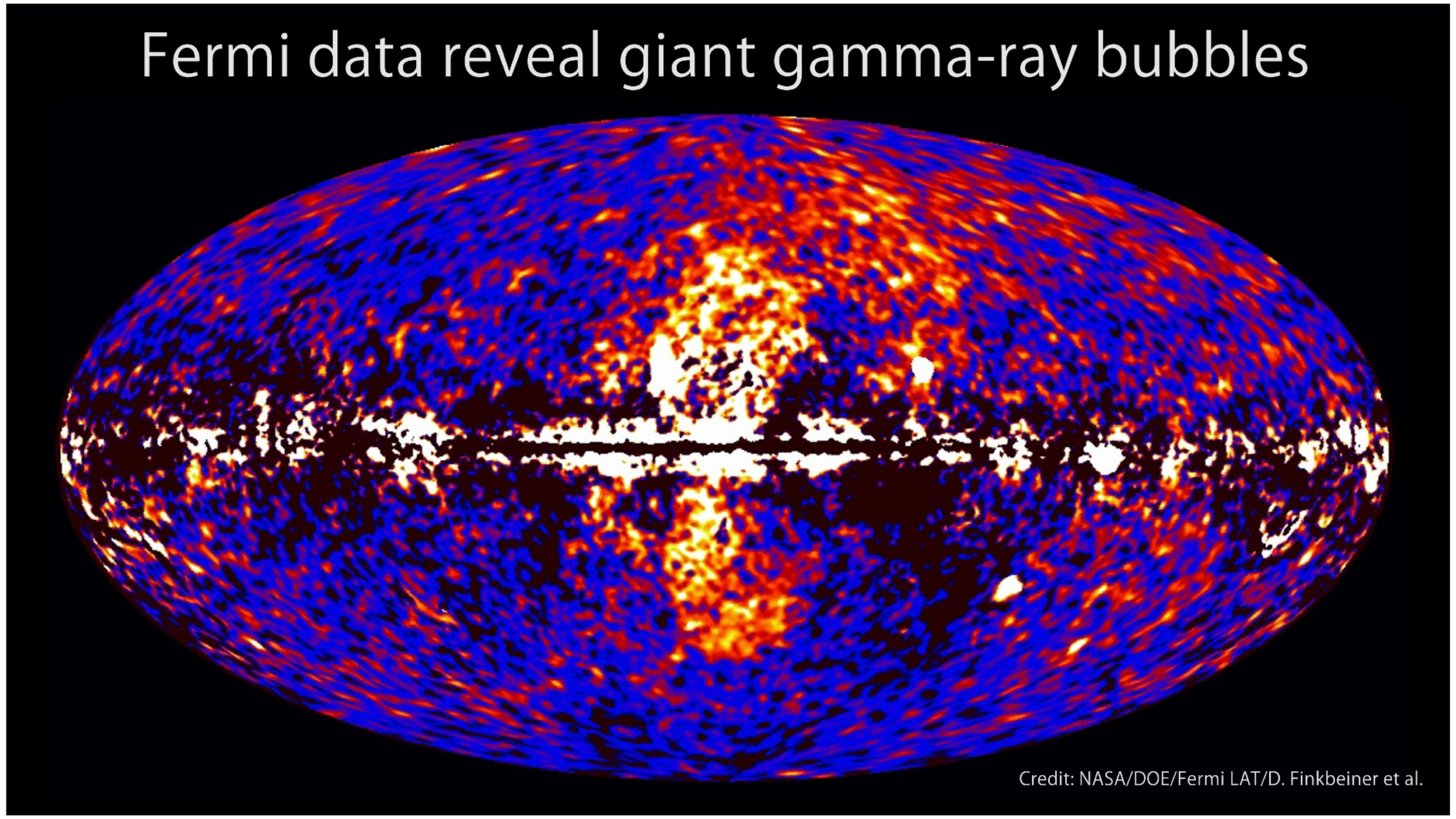


1202.4039

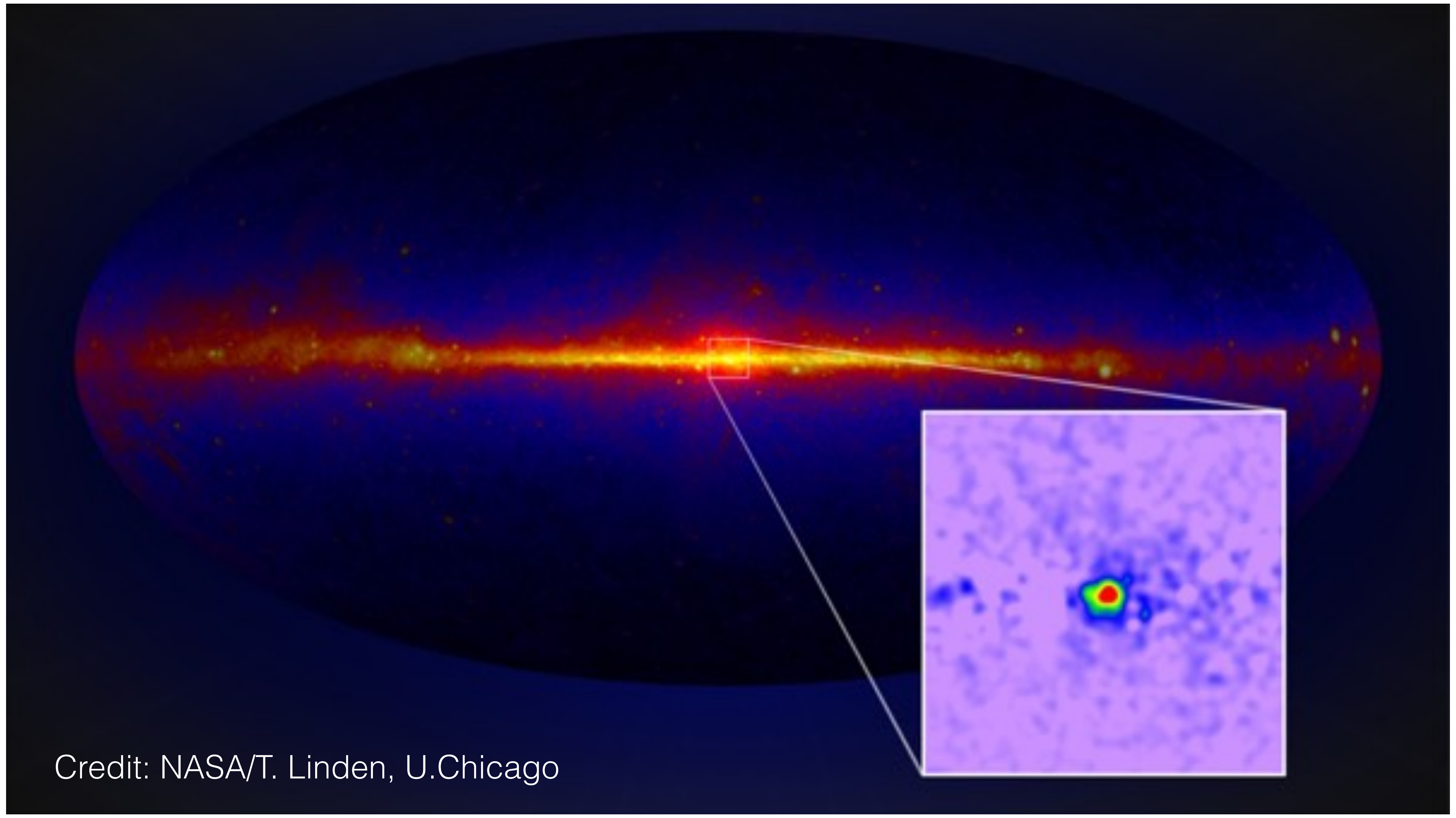
Credit: Christoph Weniger

Gamma-ray anomalies

Fermi Bubbles



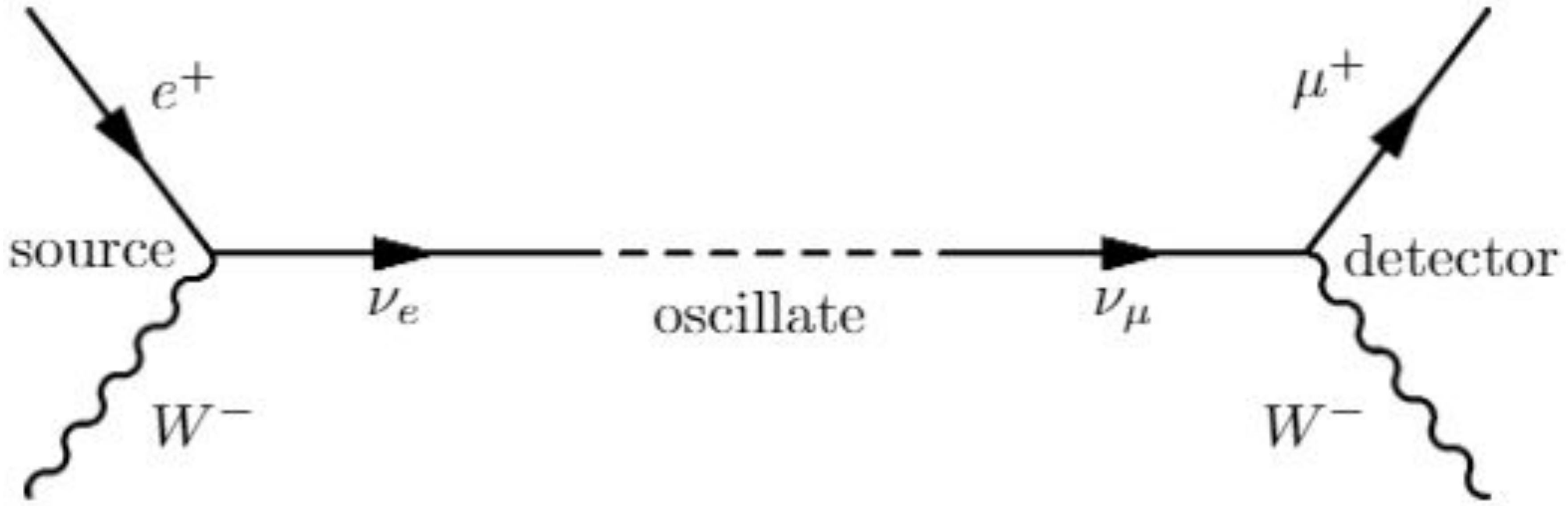
Galactic Centre Excess



and others…

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

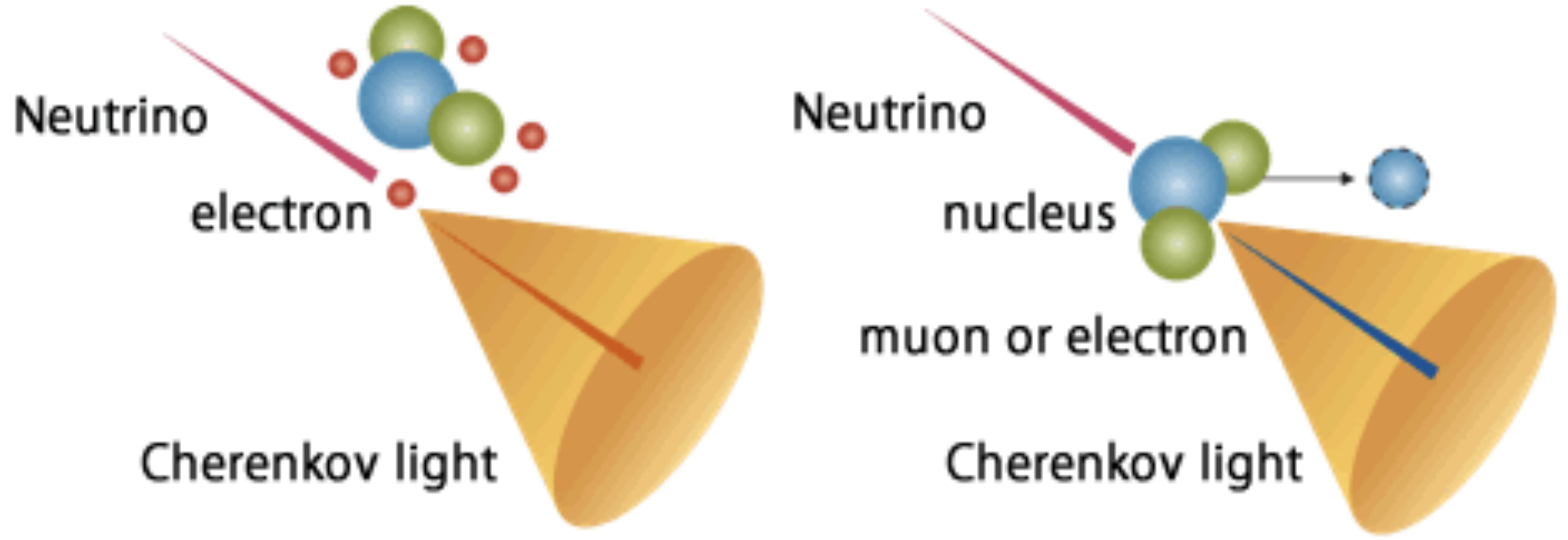
Neutrinos are produced with a definite flavor (e, μ, τ)
but they **oscillate** between the different flavors as they propagate.

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

IceCube

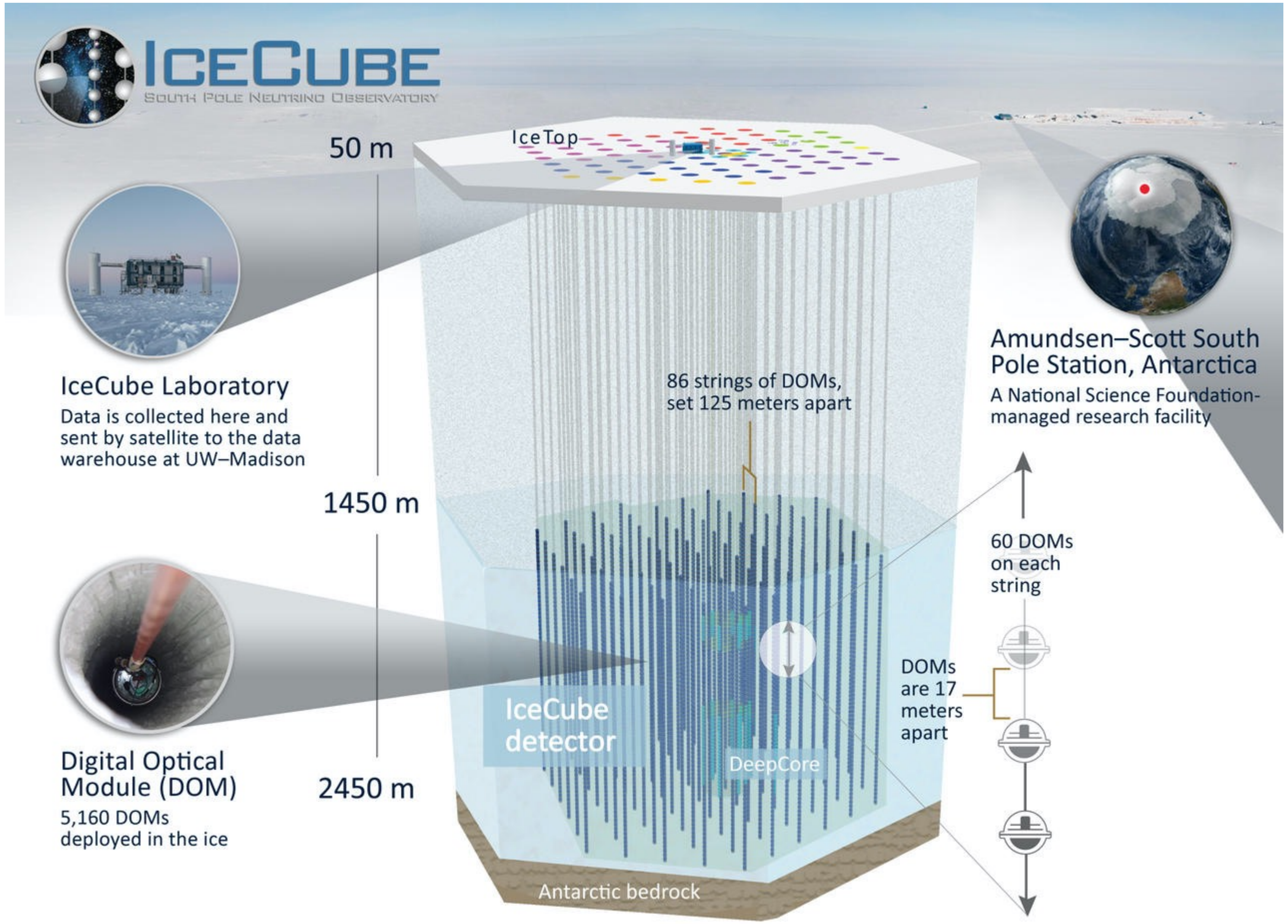
1701.03731

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



Credit: Hyper-Kamiokande

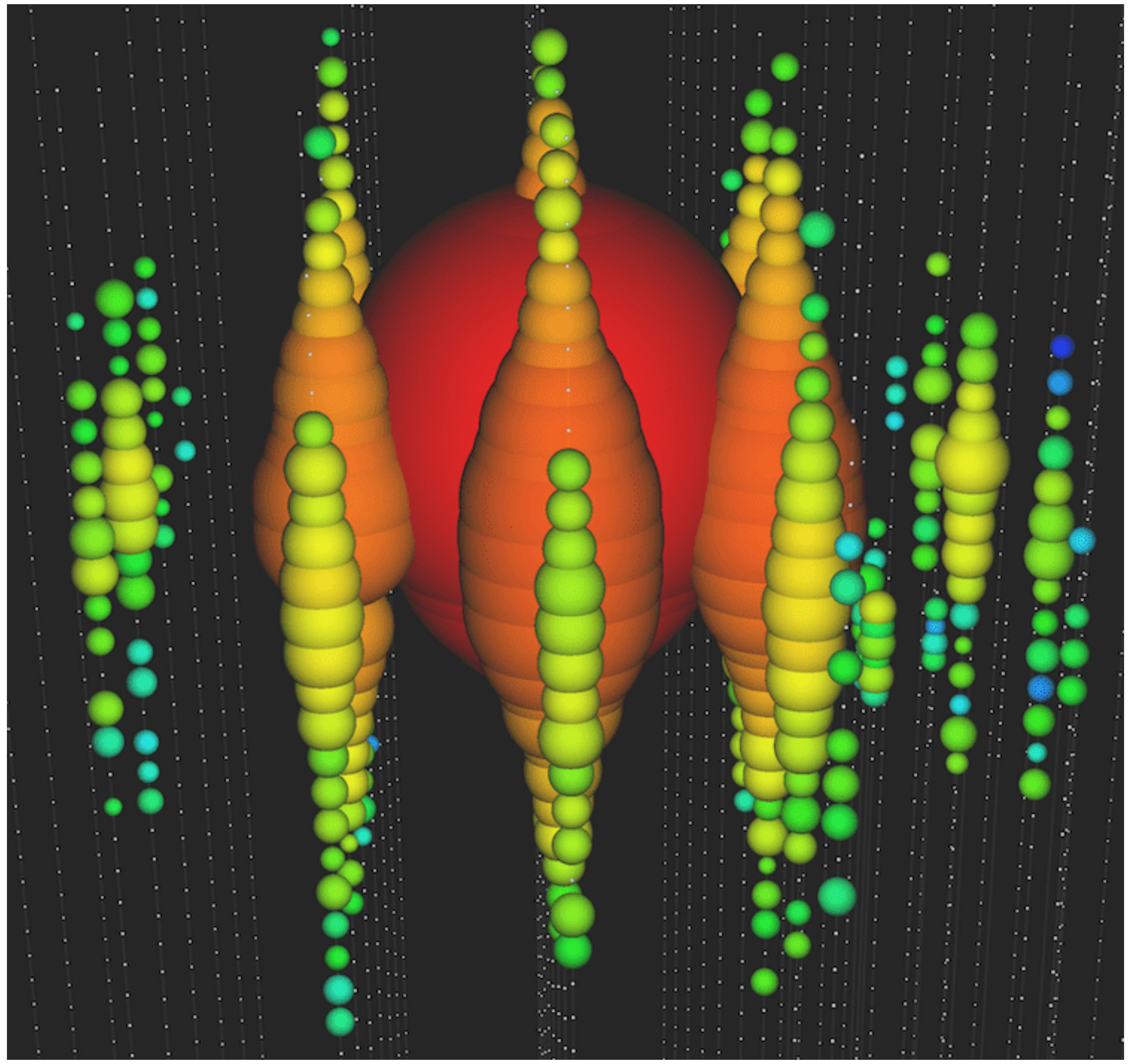
IceCube: a giant ice detector!
~1 km^3 of instrumented volume



See also SuperKamiokande, ANTARES, planned KM3NET

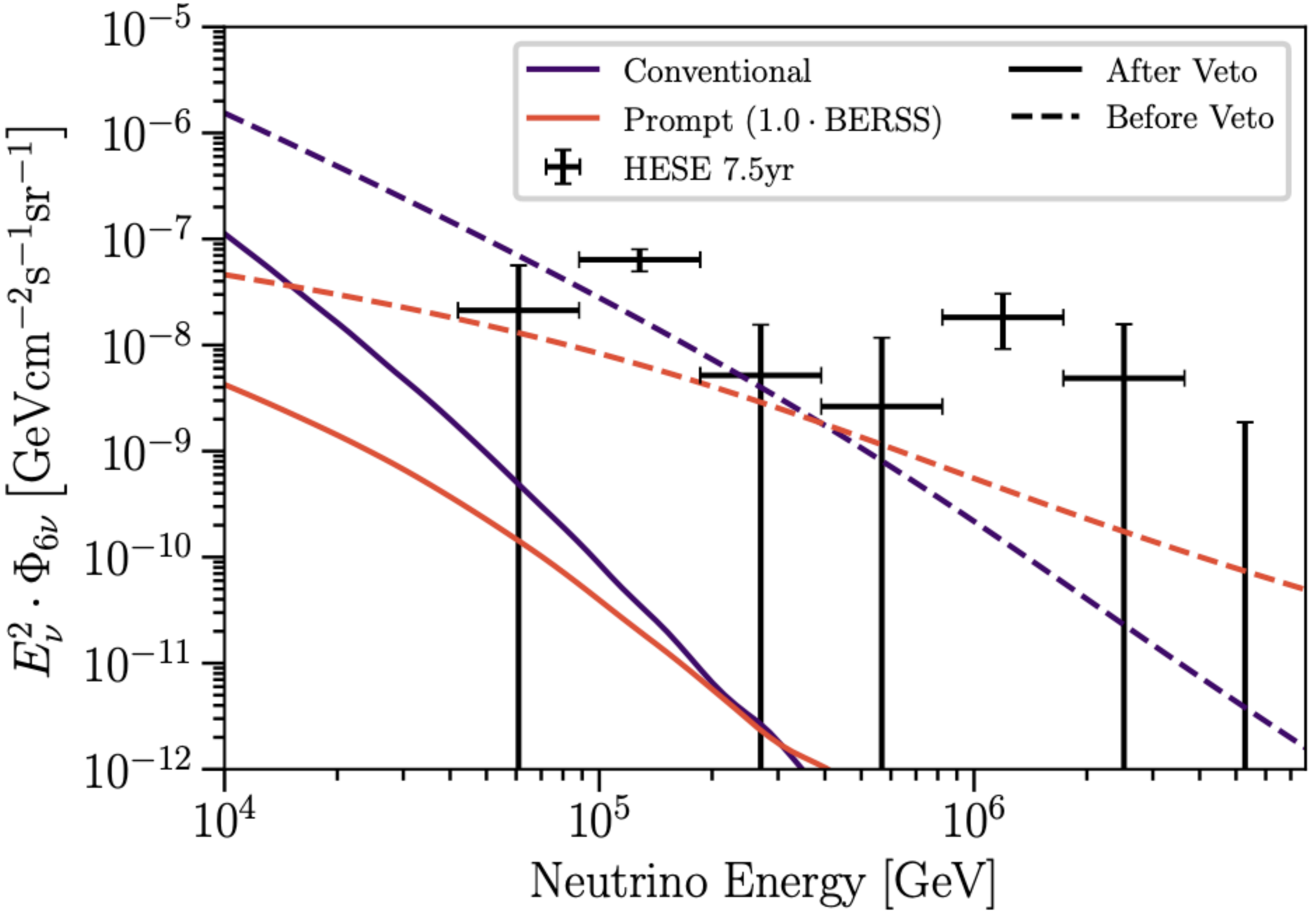
Ultra-high energy neutrinos

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



Credit: IceCube Collaboration

IceCube ‘high energy starting events’ (HESE)

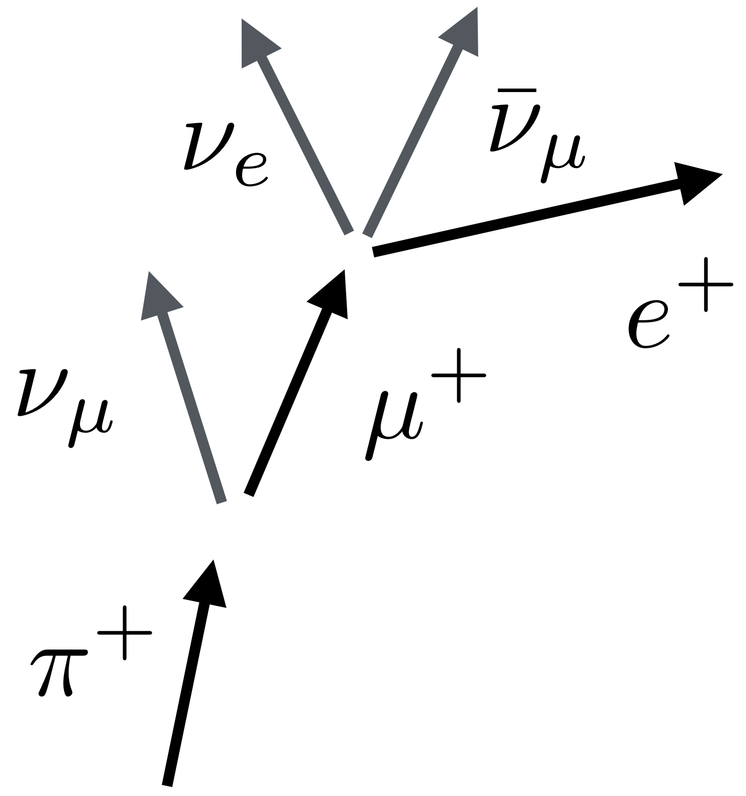


2011.03545

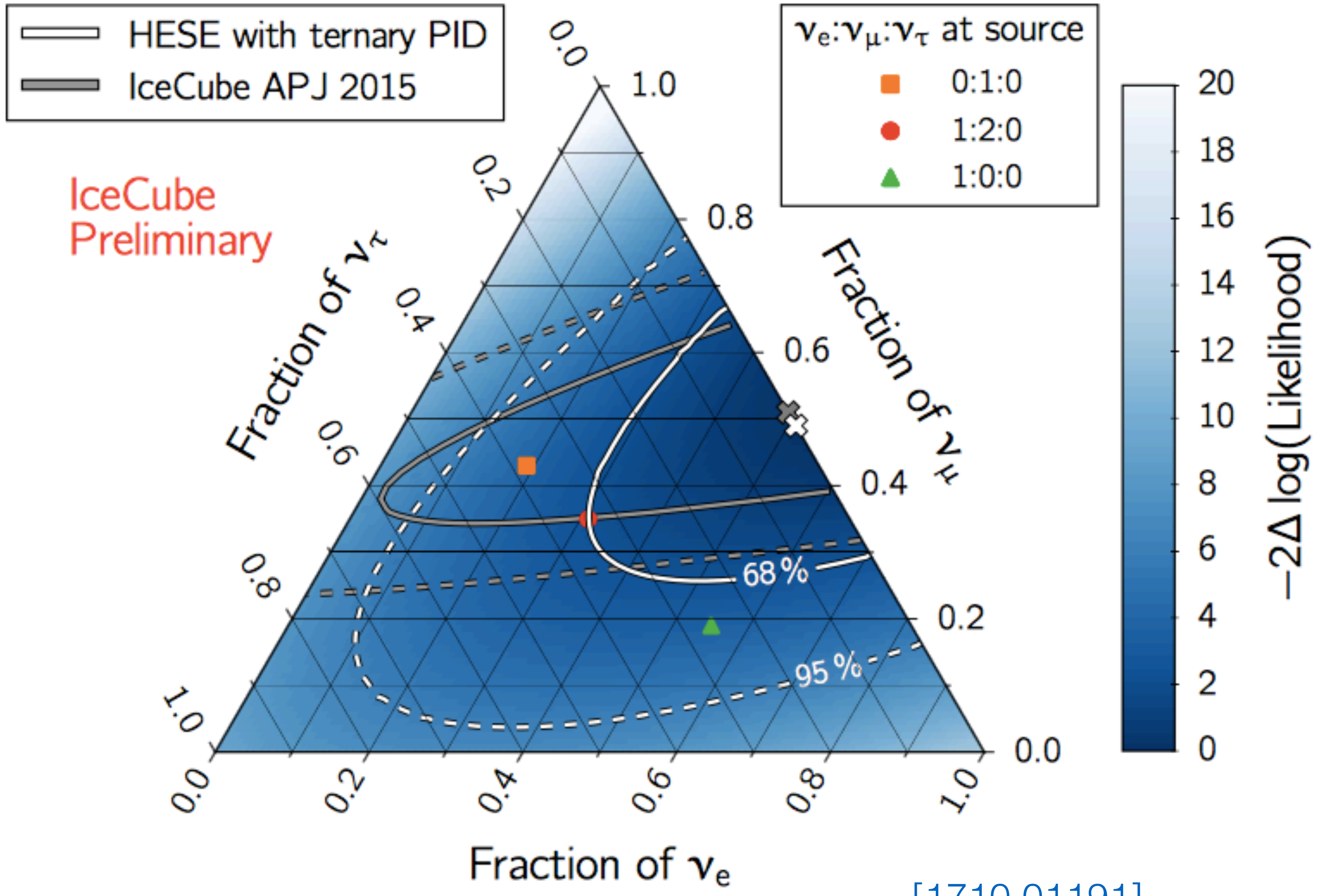
Origin of ultra high energy neutrinos?

Flavour composition can hint at how astrophysical neutrinos are produced:

E.g. decay of energetic pions:



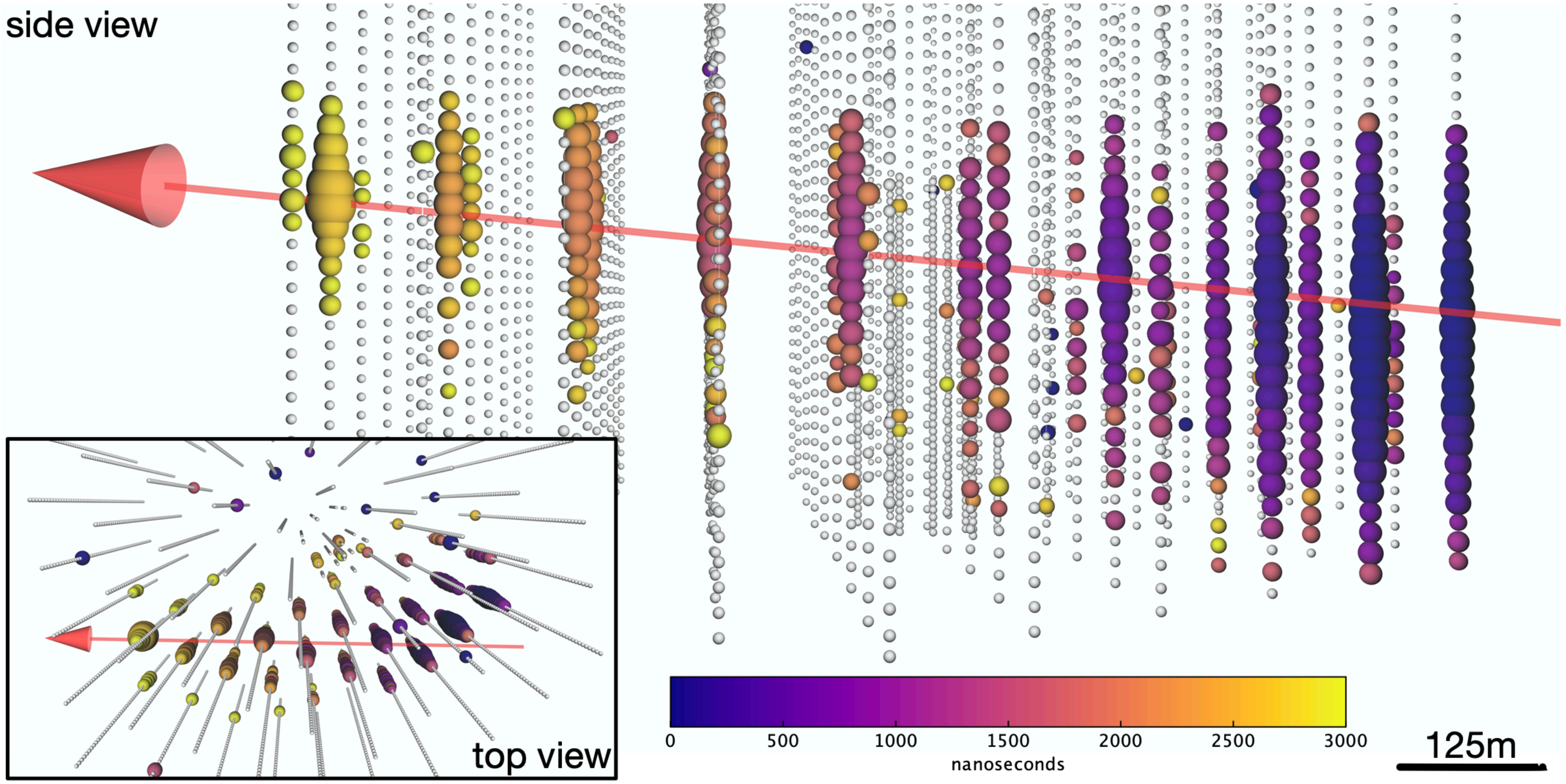
$$\Phi_e^0 : \Phi_\mu^0 : \Phi_\tau^0 = 1 : 2 : 0$$



[1710.01191]

IceCube-170922A

22 September 2017

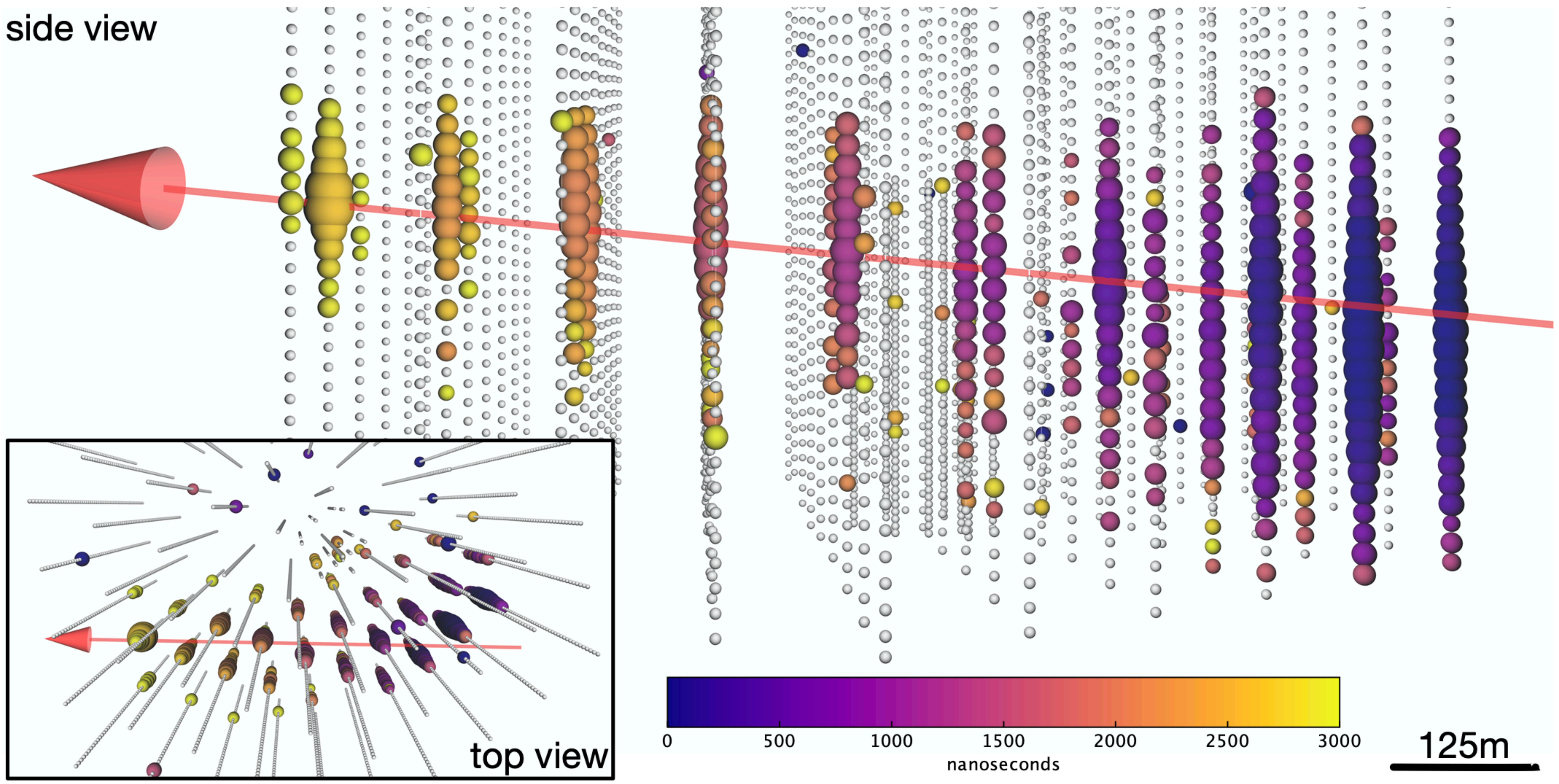


290 TeV

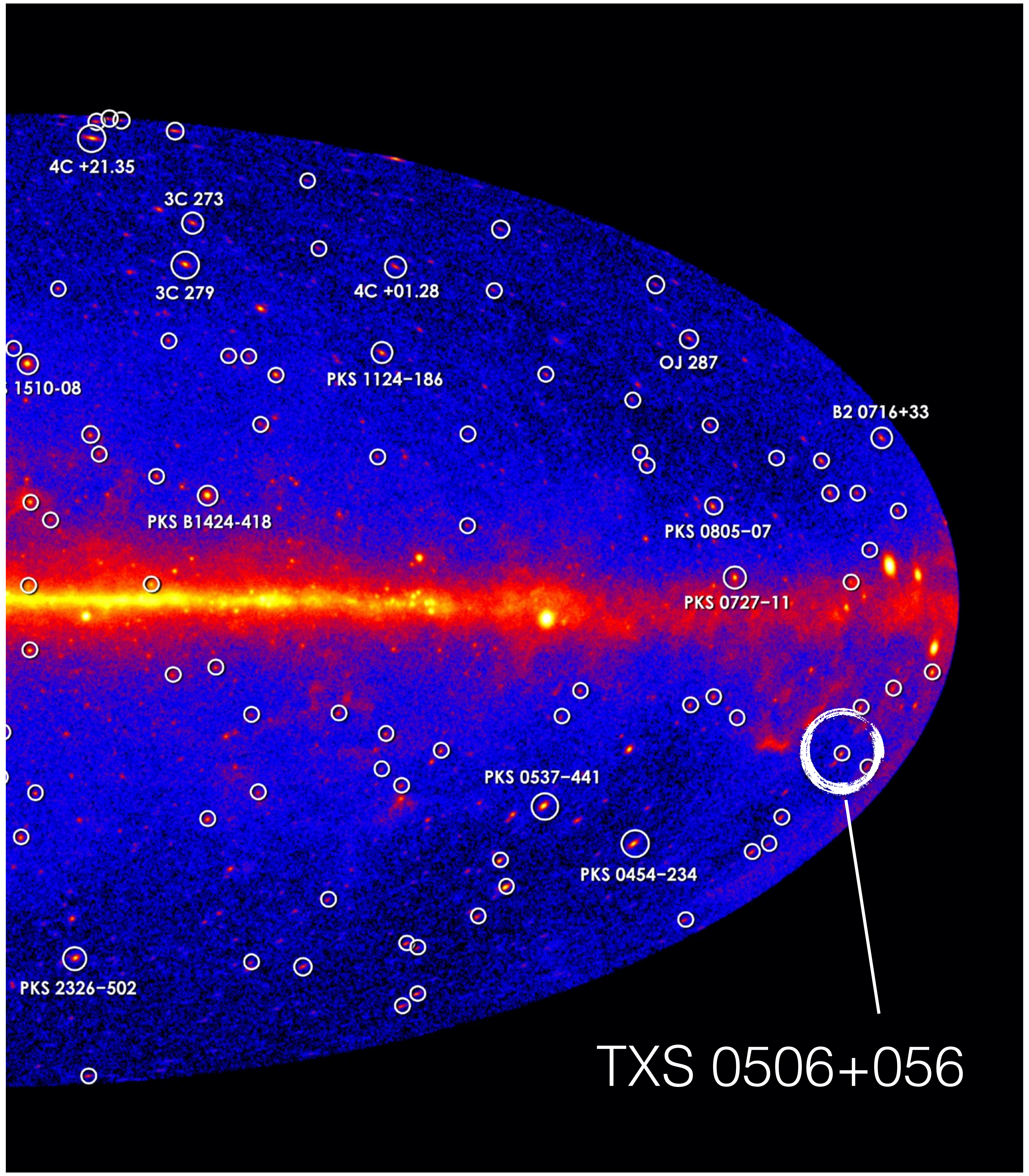
1807.08816

IceCube-170922A

22 September 2017

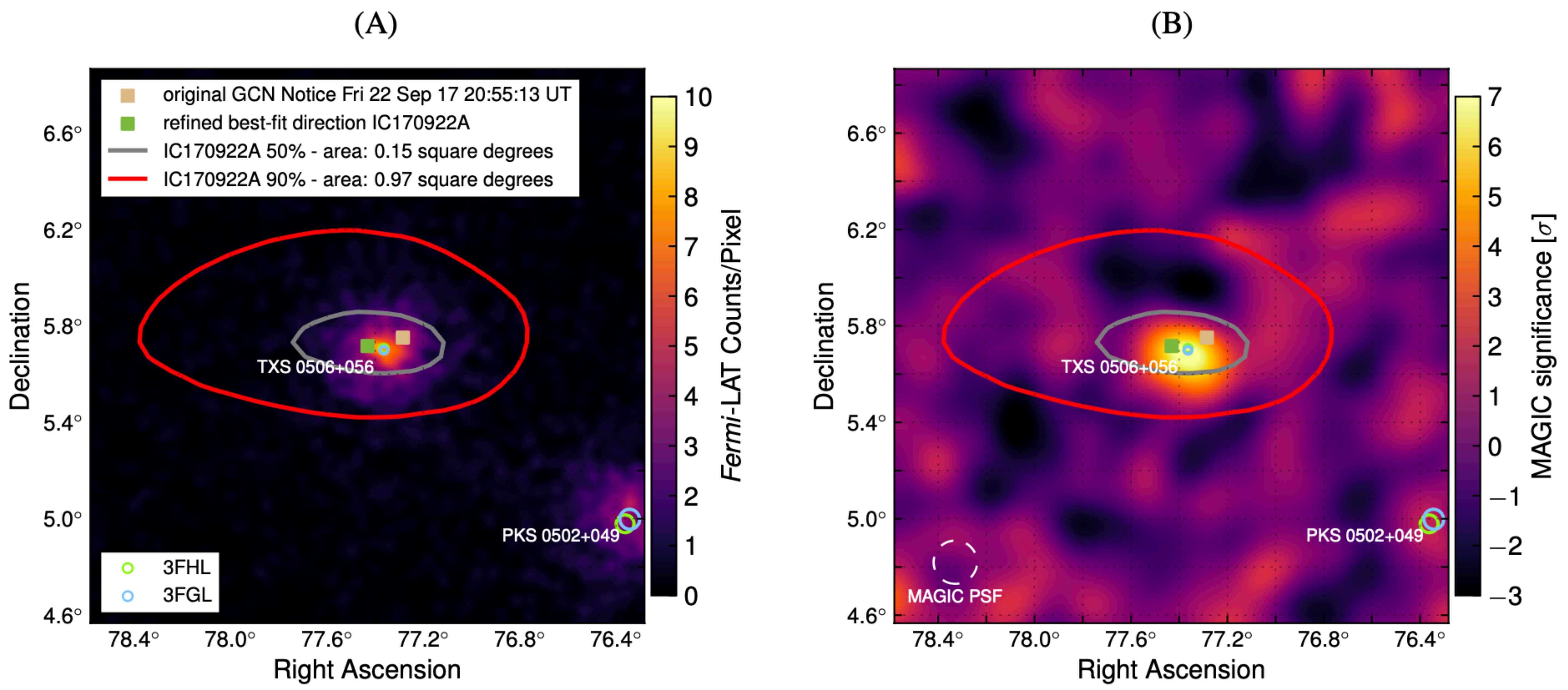


290 TeV



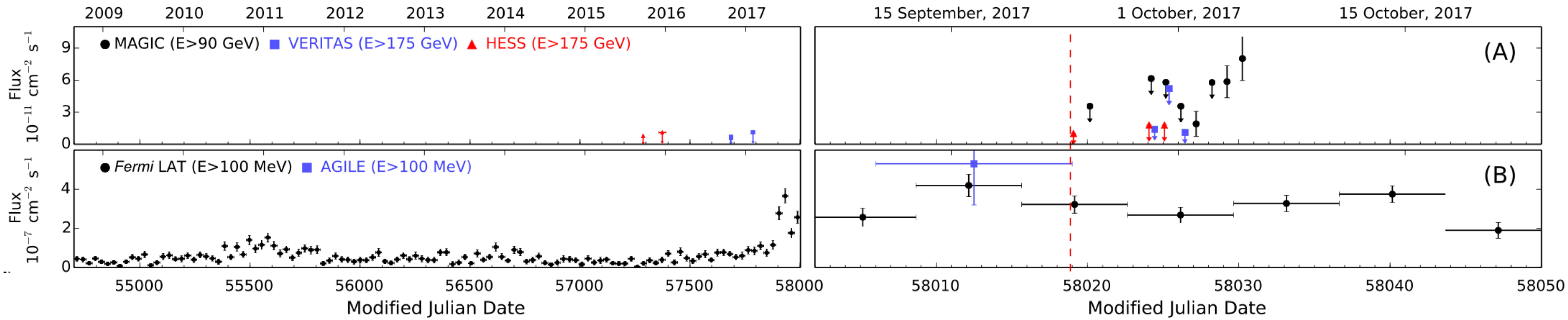
[1807.08816](https://arxiv.org/abs/1807.08816)

TXS 0506+056 in gamma-rays



TXS 0506+056 is a known blazar!

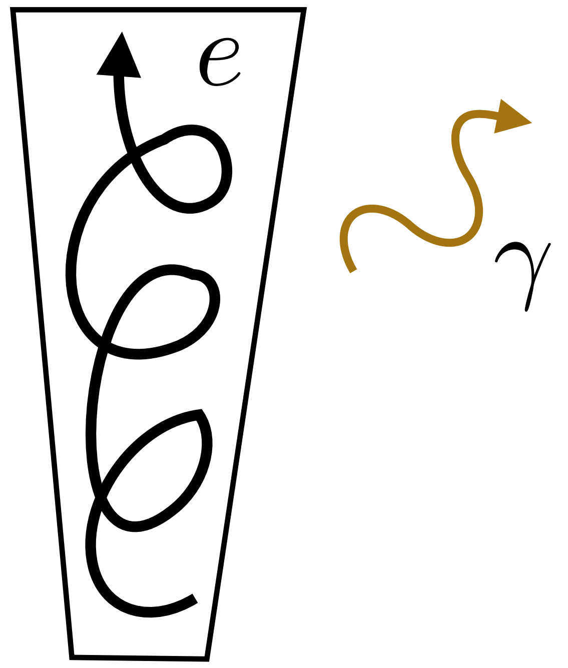
It was flaring at the time of IceCube-170922A!



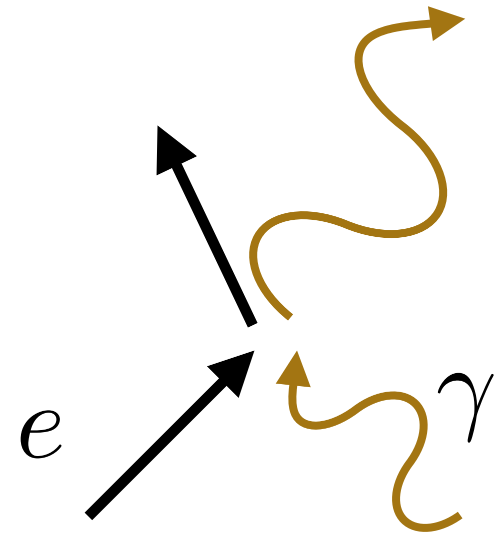
1807.08816

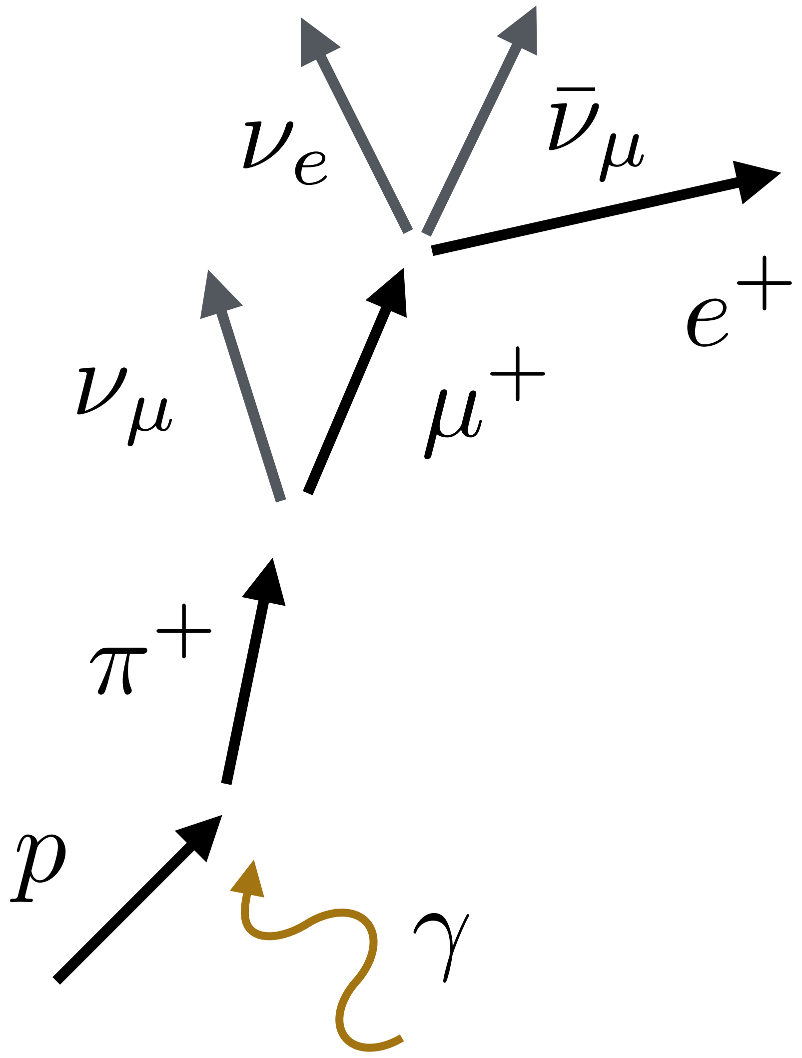
Blazar emission

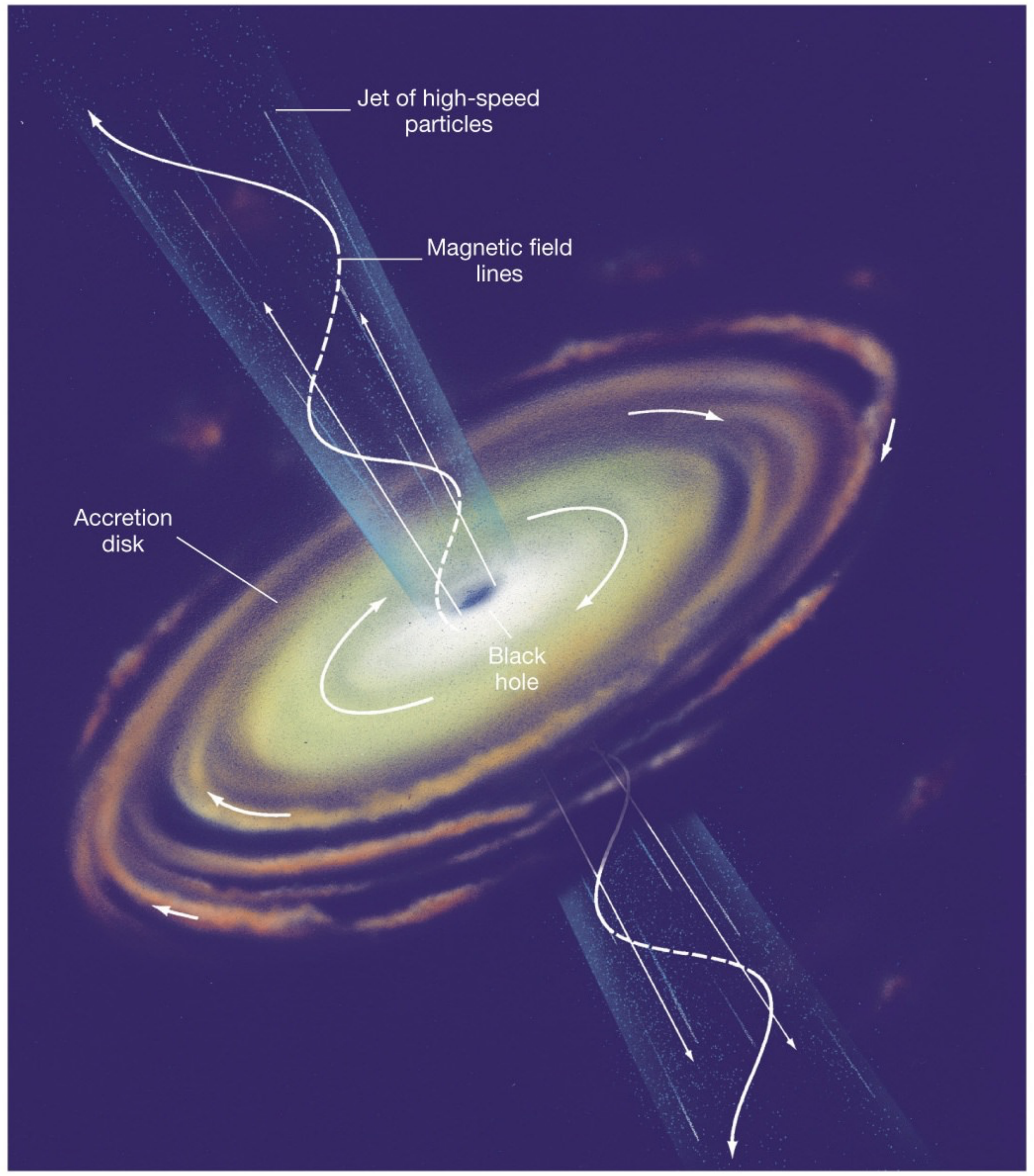
Electron synchrotron



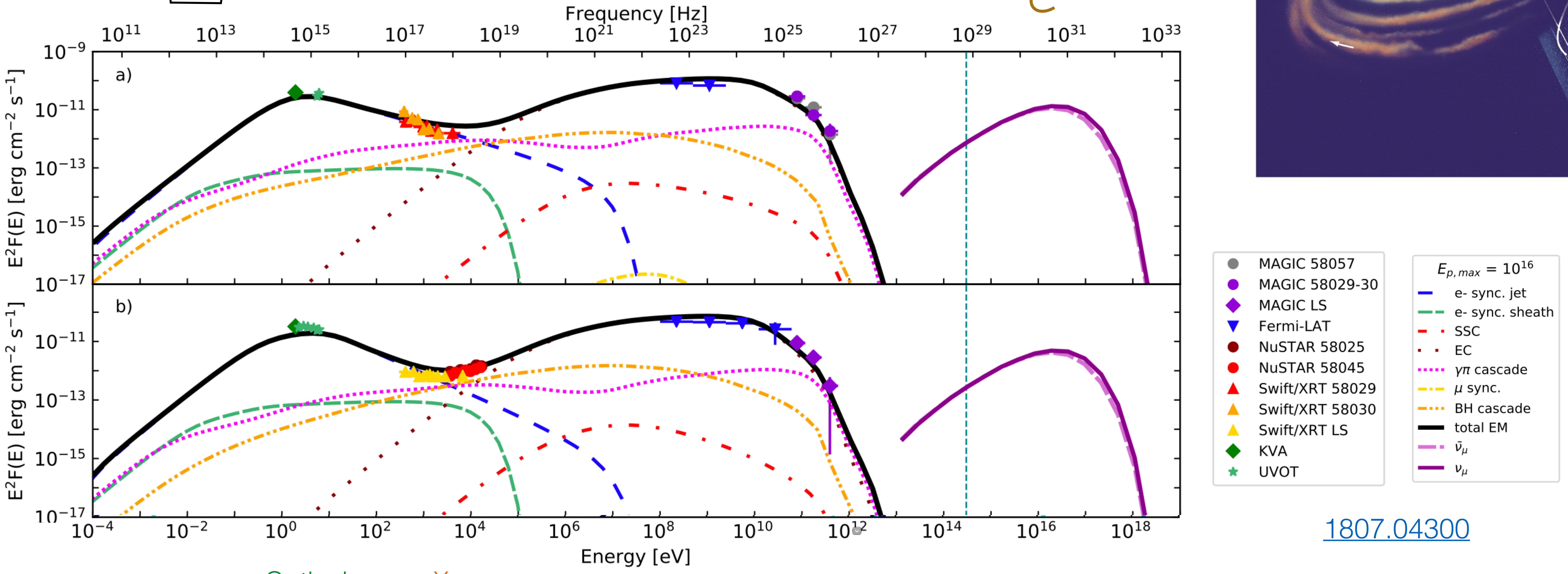
Inverse Compton







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



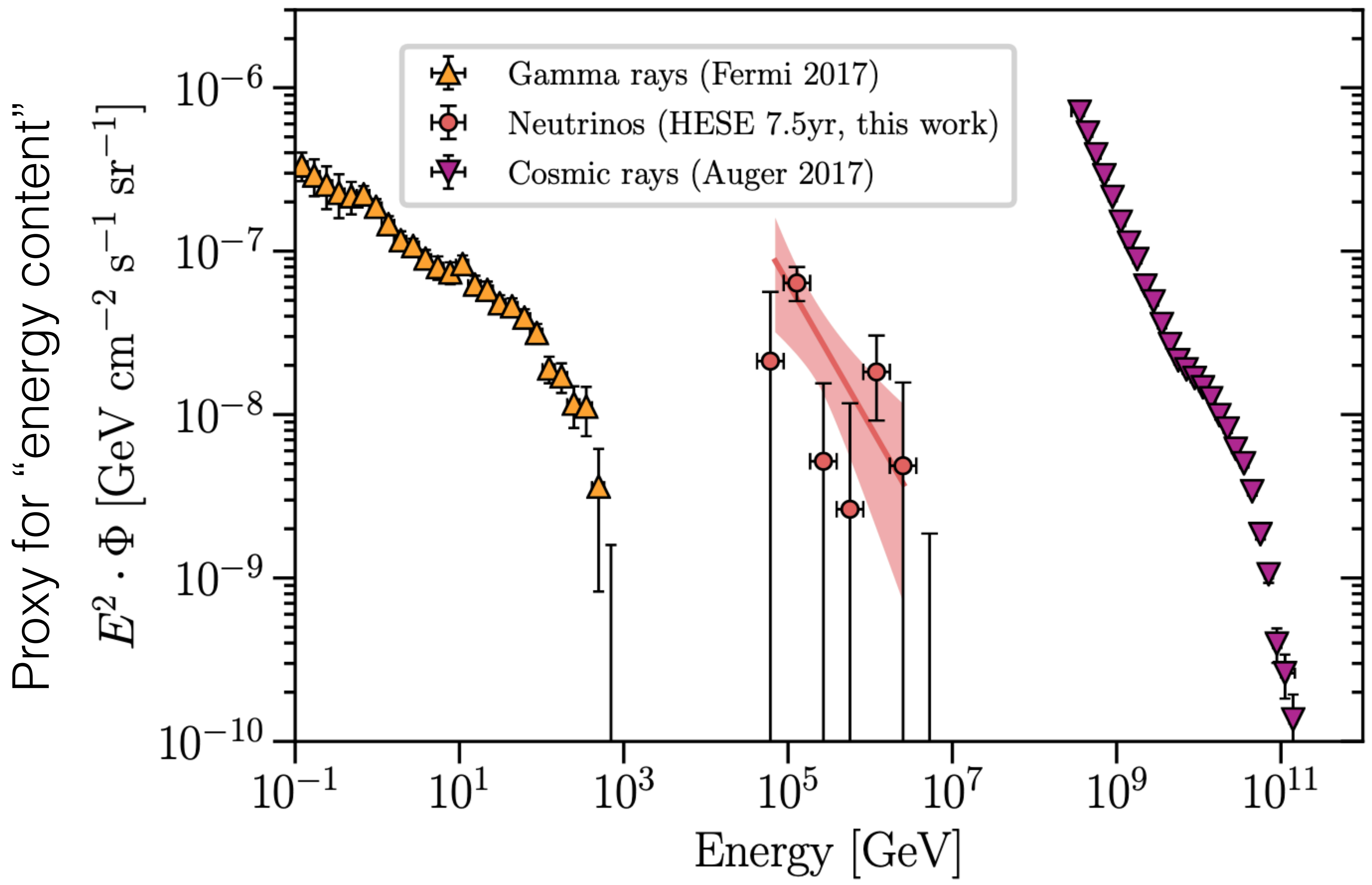
Optical X-ray Gamma-ray Neutrinos!

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

Violent and Energetic Universe

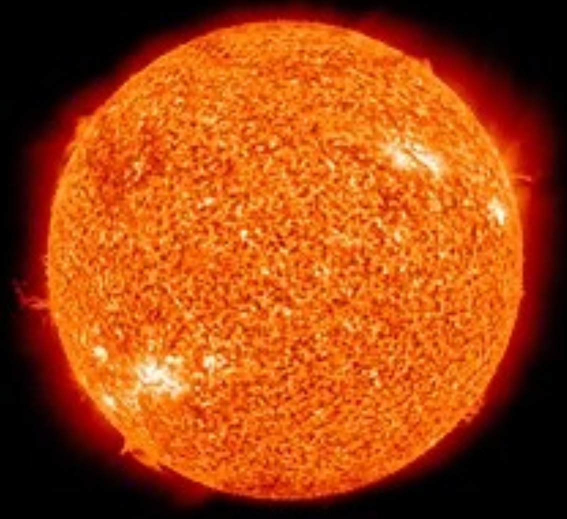
A complex and interconnected ecosystem:

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

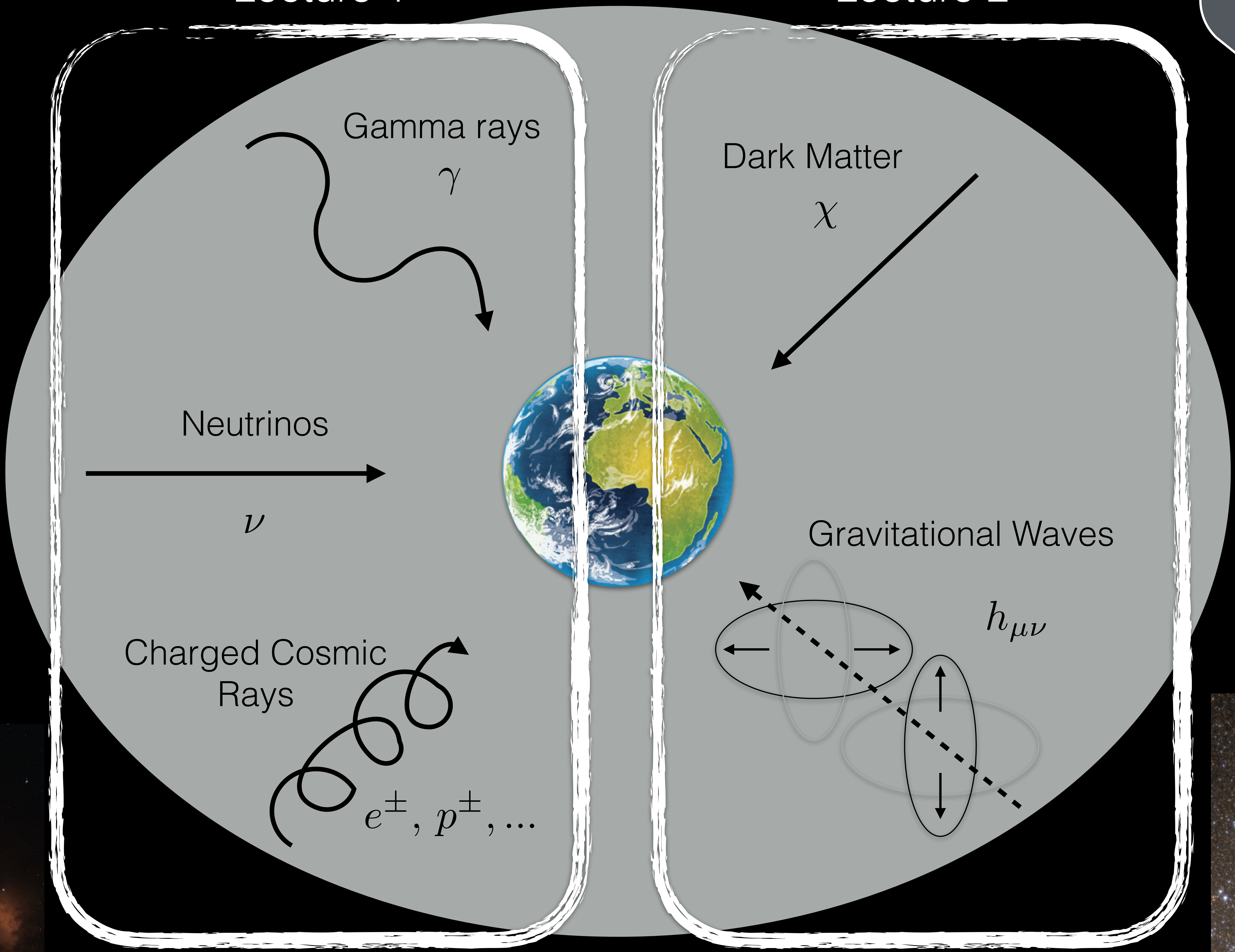
Credit: NASA/CXC/SAO

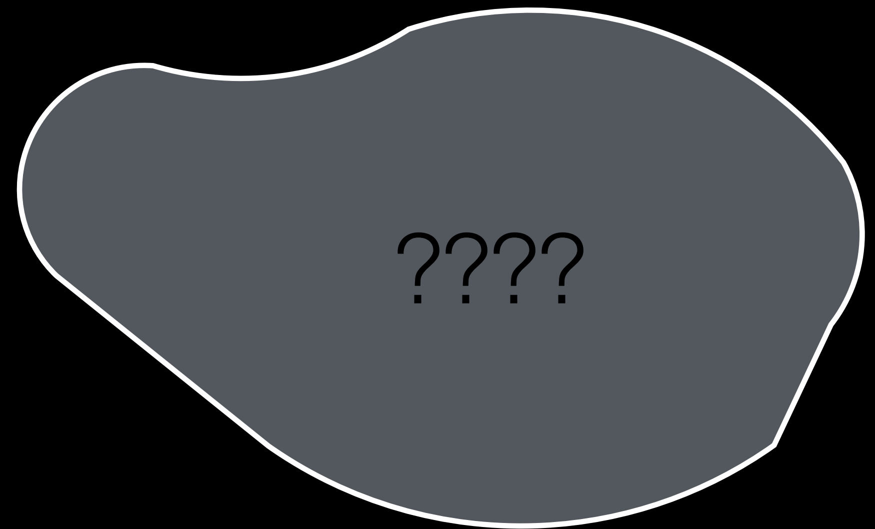
Quasars/AGN

Credit: ESO/M. Kornmesser

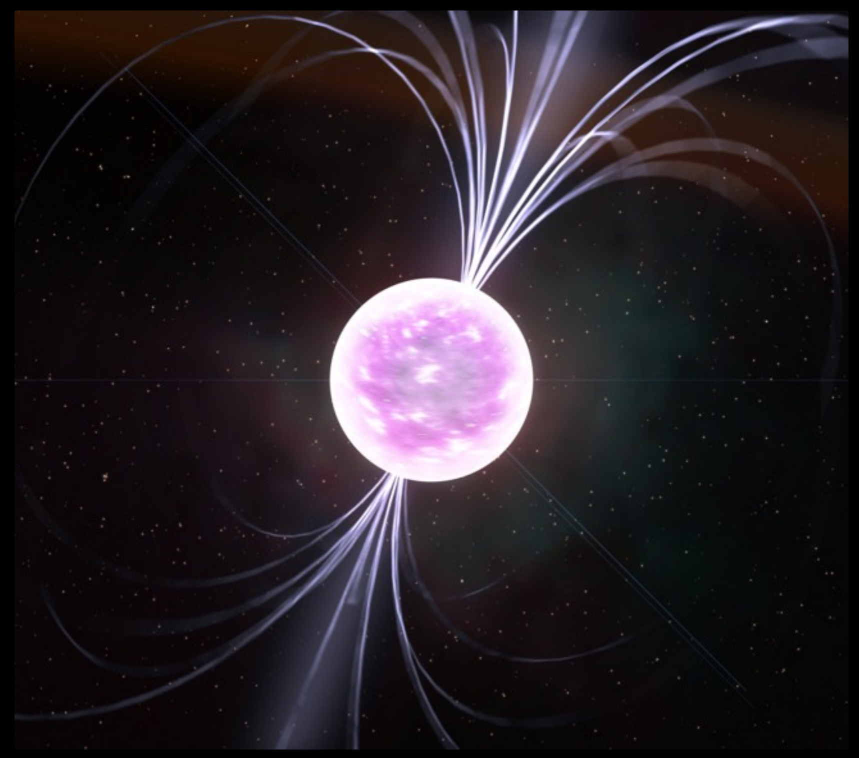
Lecture 1

Lecture 2





Pulsars



Credit: Kevin Gill / Flickr

BH/NS Mergers

Credit: SXS Lensing