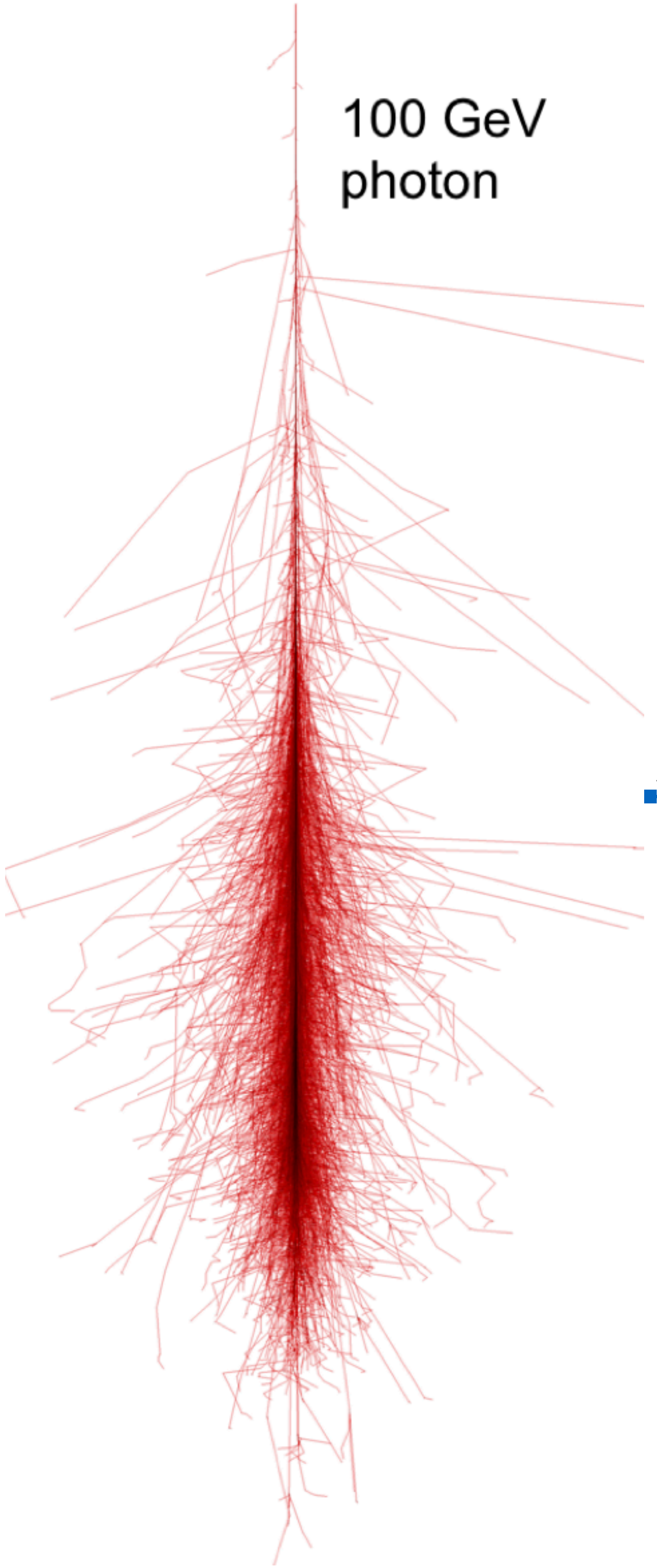


(An introduction to)

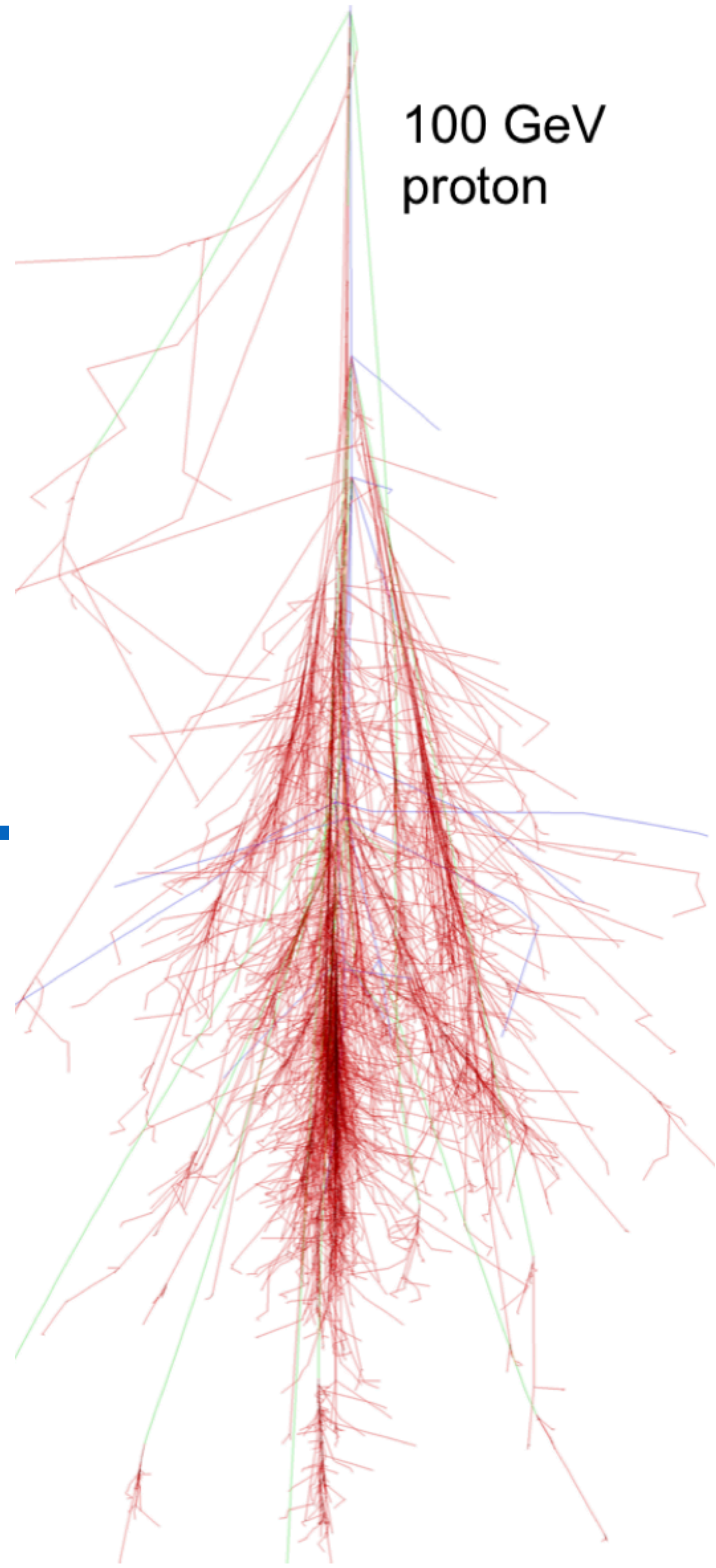
Astroparticle Physics

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 17th July 2024

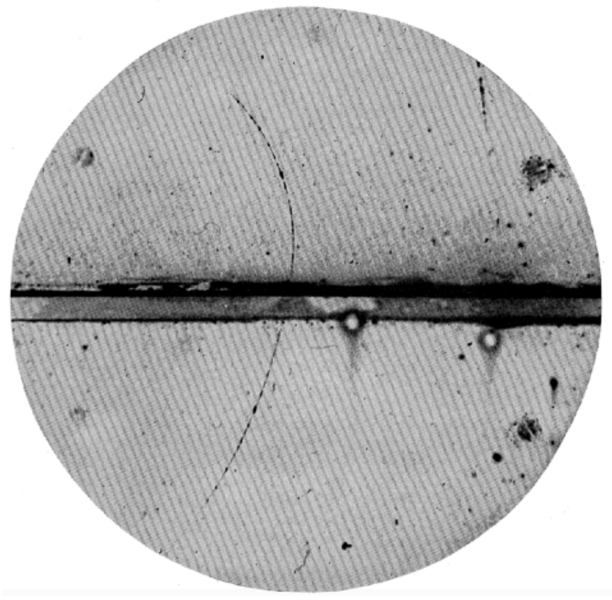
Slides here: bradkav.net/talks

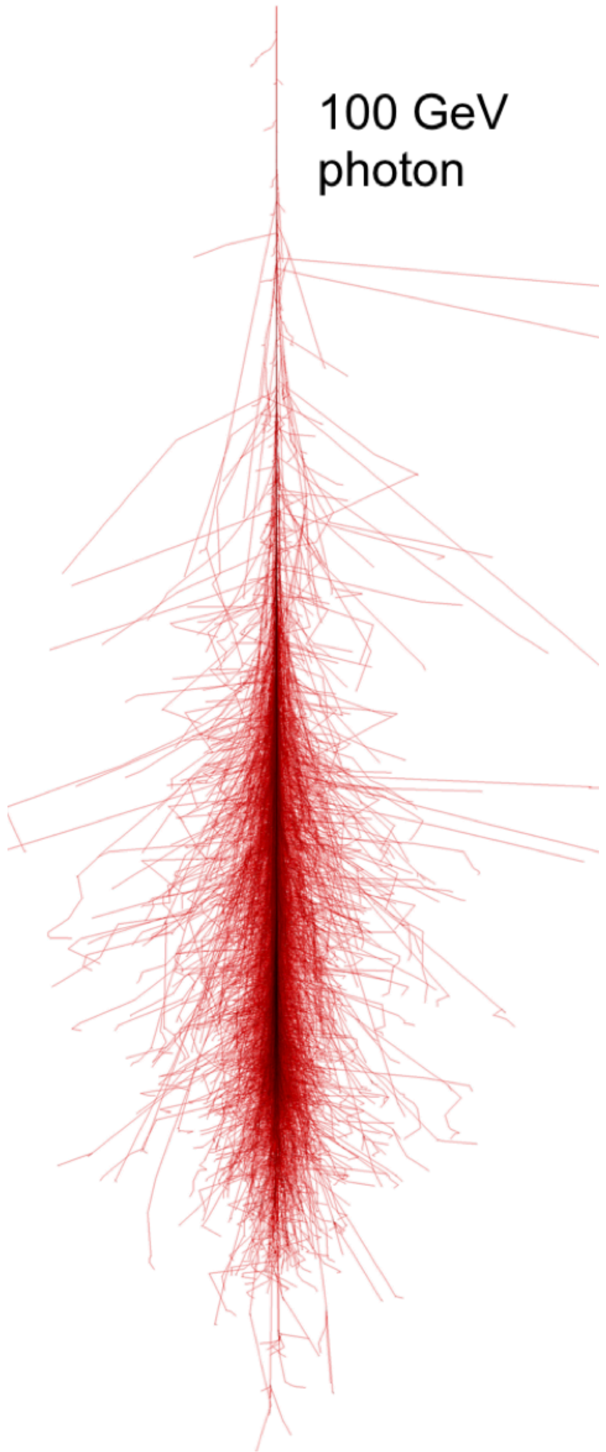


Timeline

1912: Hess discovers cosmic rays

1933: Anderson discovers the positron in Cosmic Ray tracks





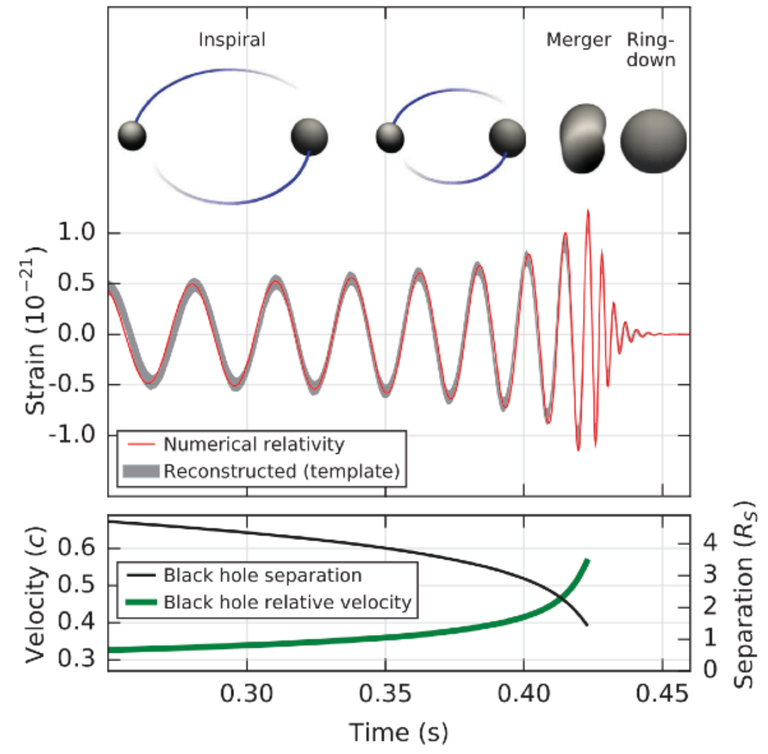
1939: Auger and collaborators demonstrate the existence of Cosmic Ray *air showers*

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

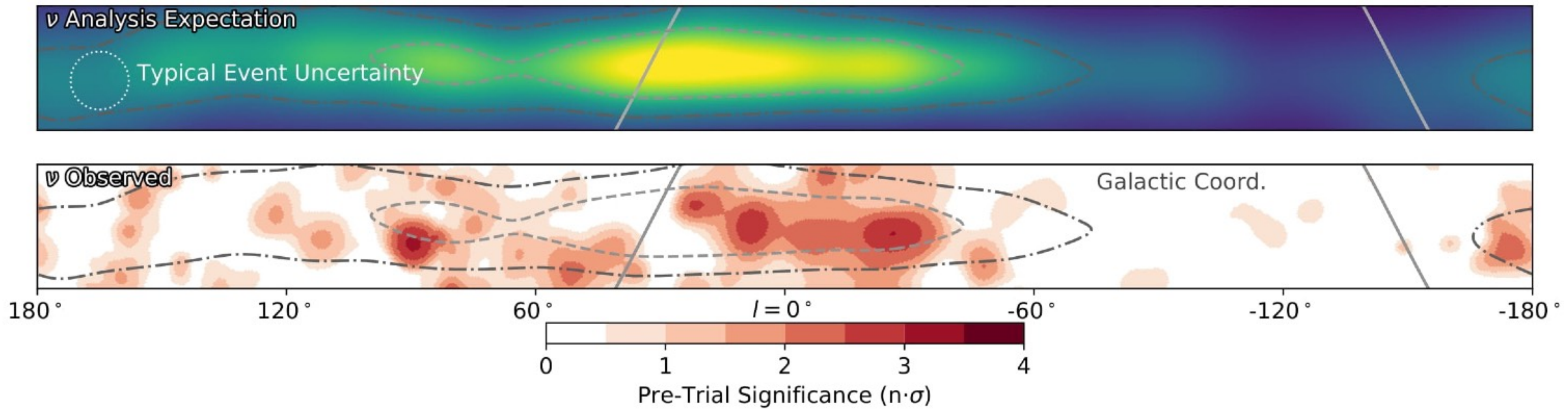
2015: GW150914 - First direct observation of GWs from Black Hole Binary Mergers



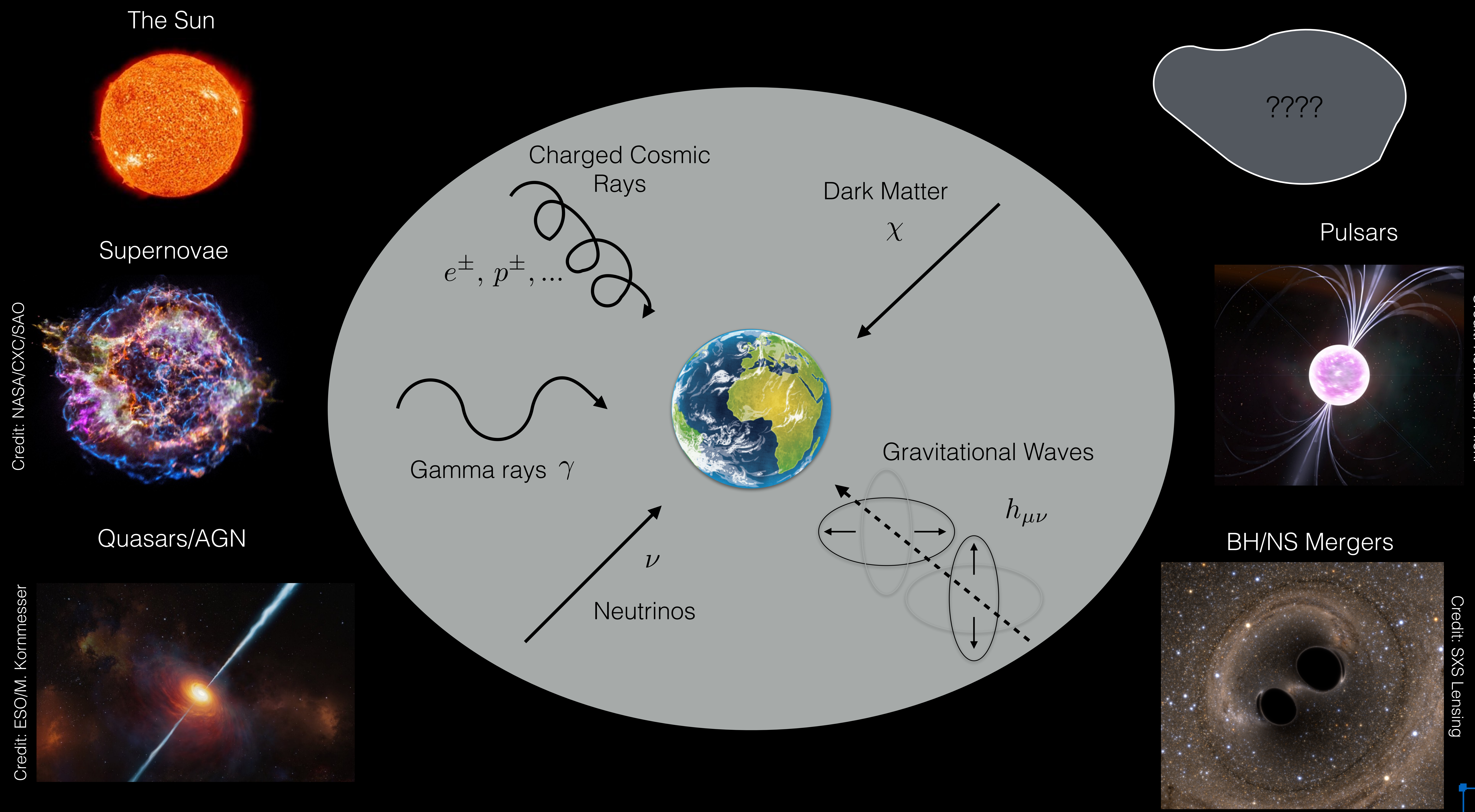
2017: TXS 0506+056 - First multimessenger detection of a blazar (neutrinos + gamma rays)

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

The Sun
Supernovae
Credit: NASA/CXC/SAO
Quasars/AGN
Credit: ESO/M. Kornmesser
Lecture 1
Lecture 2
Charged Cosmic Rays
$e^{\pm}, p^{\pm}, ...$
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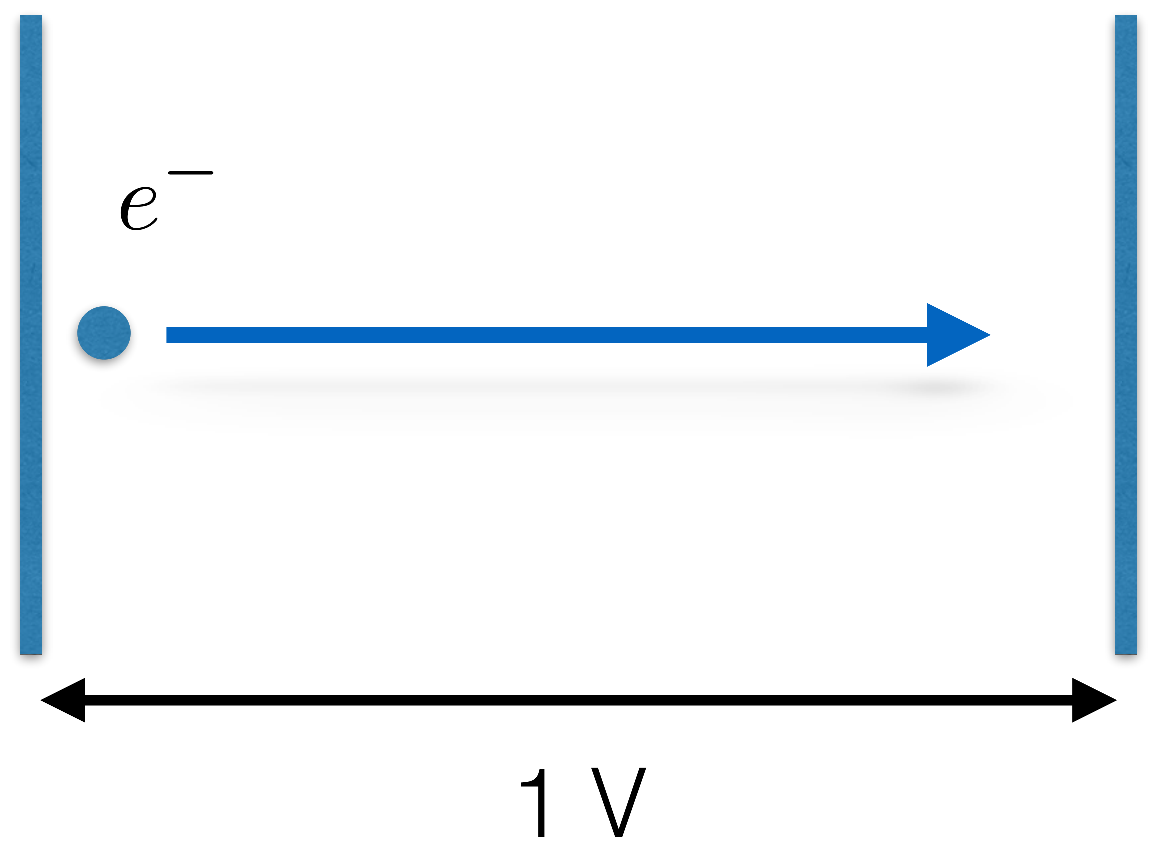
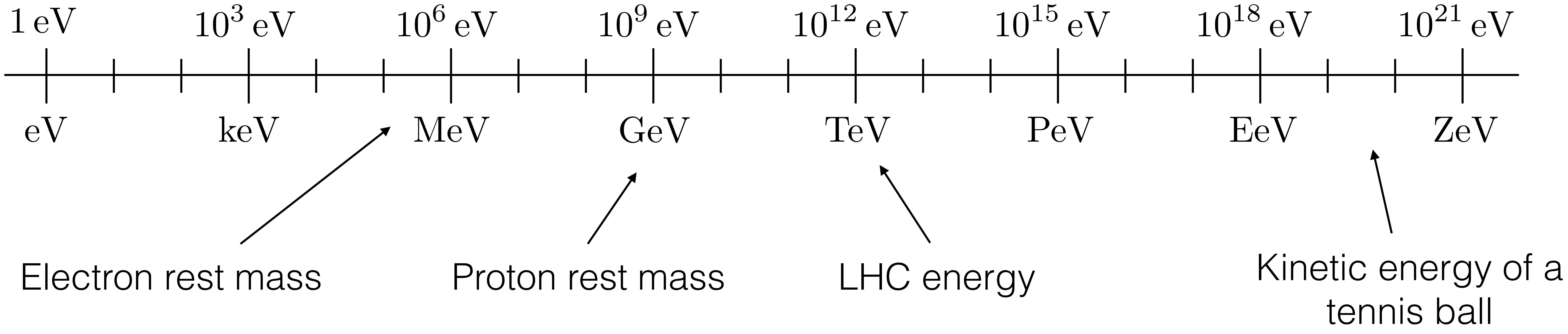
Neutrinos
Dark Matter
χ
Gravitational Waves
$h_{\mu\nu}$
????
Pulsars
Credit: Kevin Gill / Flickr
BH/NS Mergers
Credit: SXS Lensing

A huge range of energy scales…

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

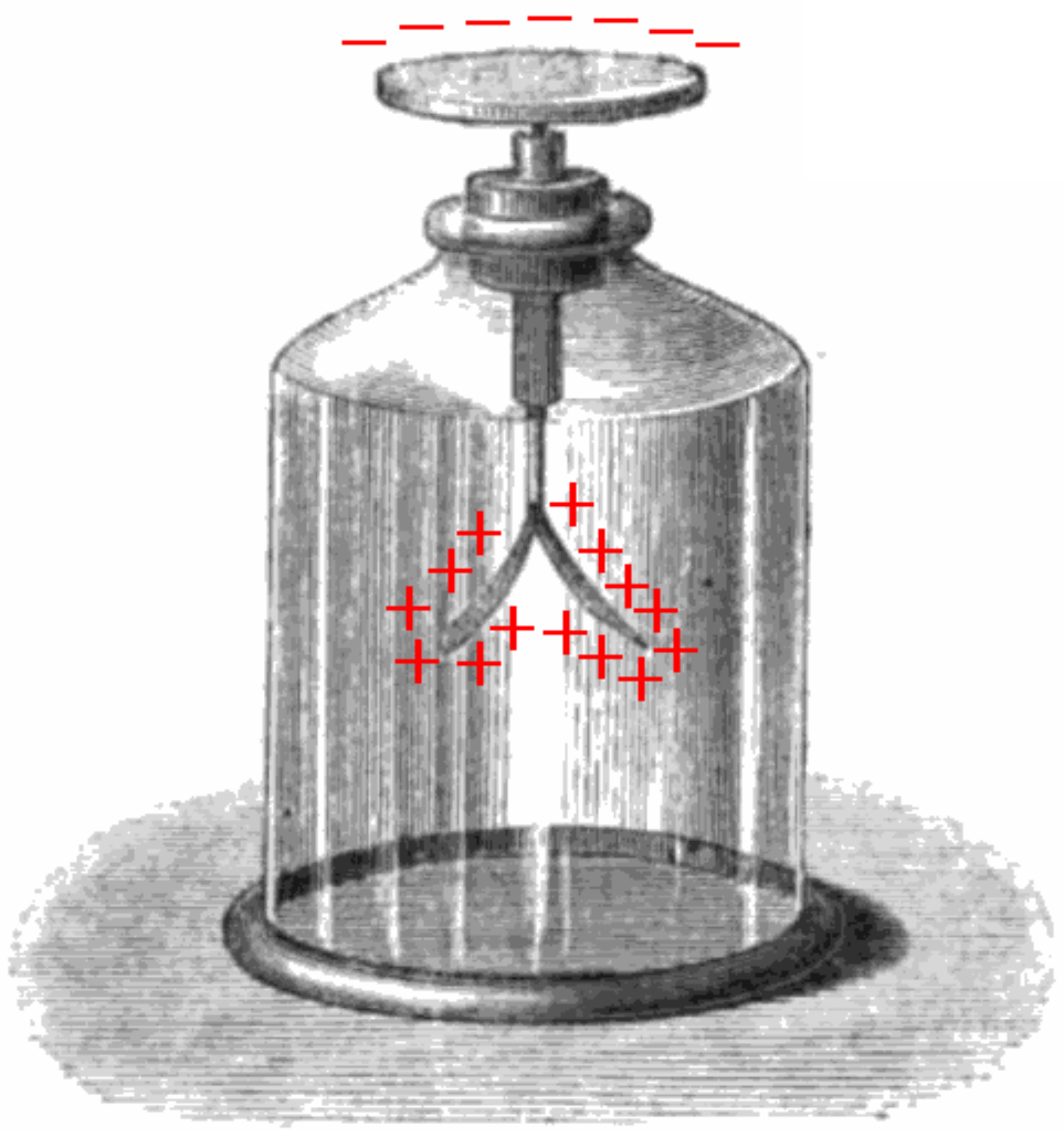


$$
\begin{aligned}
1\,\mathrm{eV} &\approx 1.6 \times 10^{-19}\,\mathrm{J} \\
&\approx 1.8 \times 10^{-36}\,\mathrm{kg} \\
&\approx 1.2 \times 10^{4}\,\mathrm{K}
\end{aligned}
$$

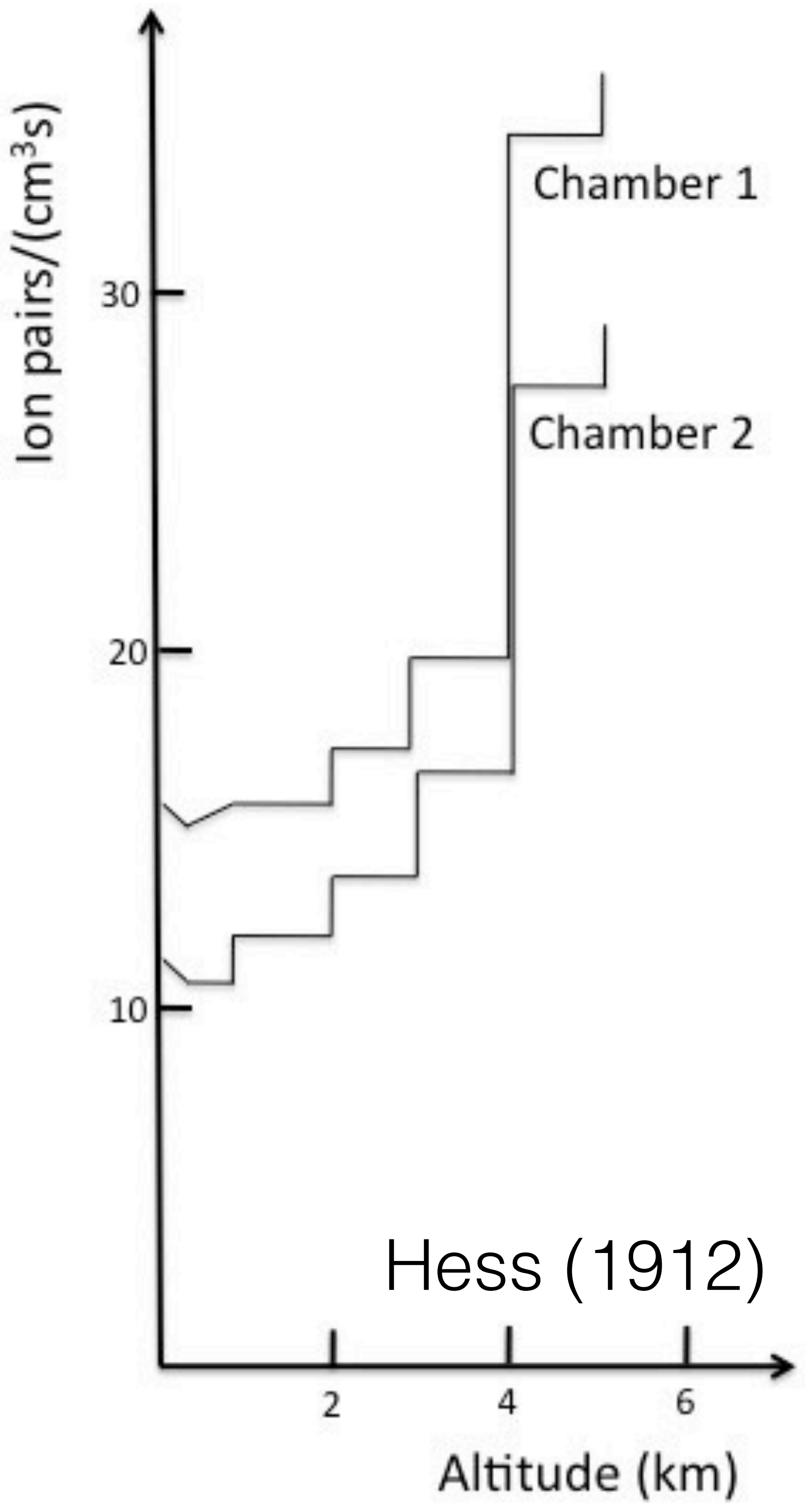


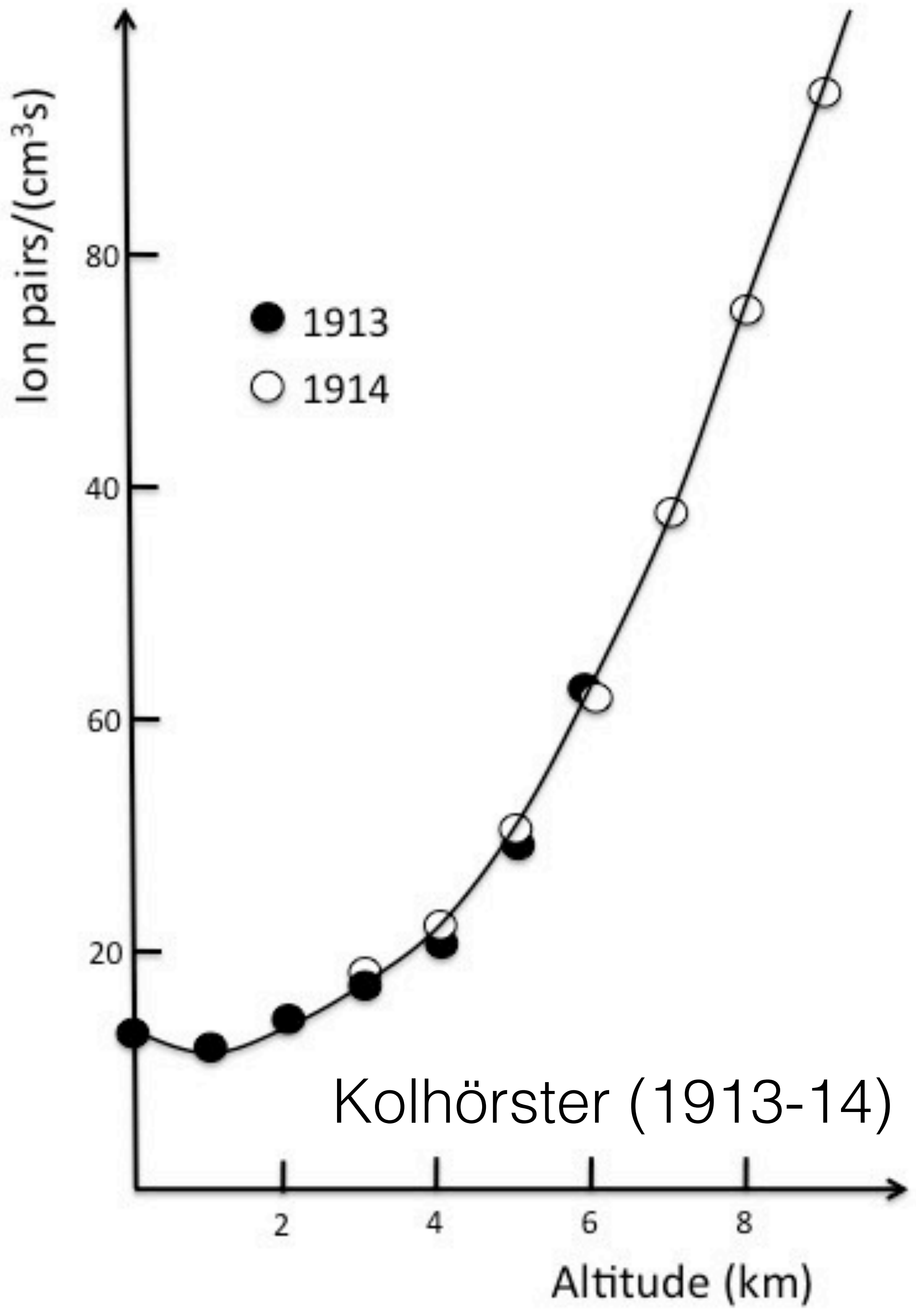
History of astroparticles

Victor Hess
(1883 - 1964)



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

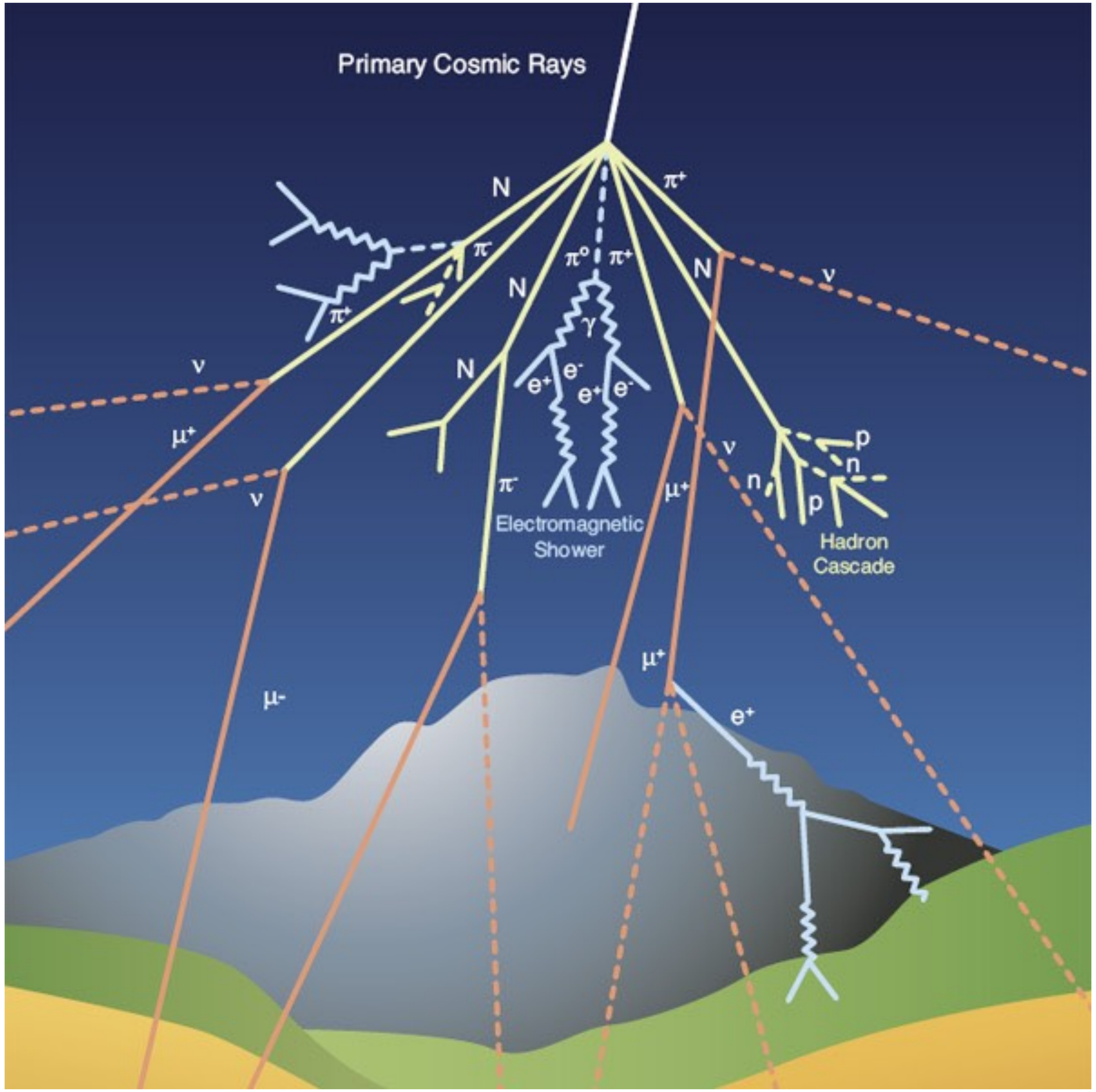




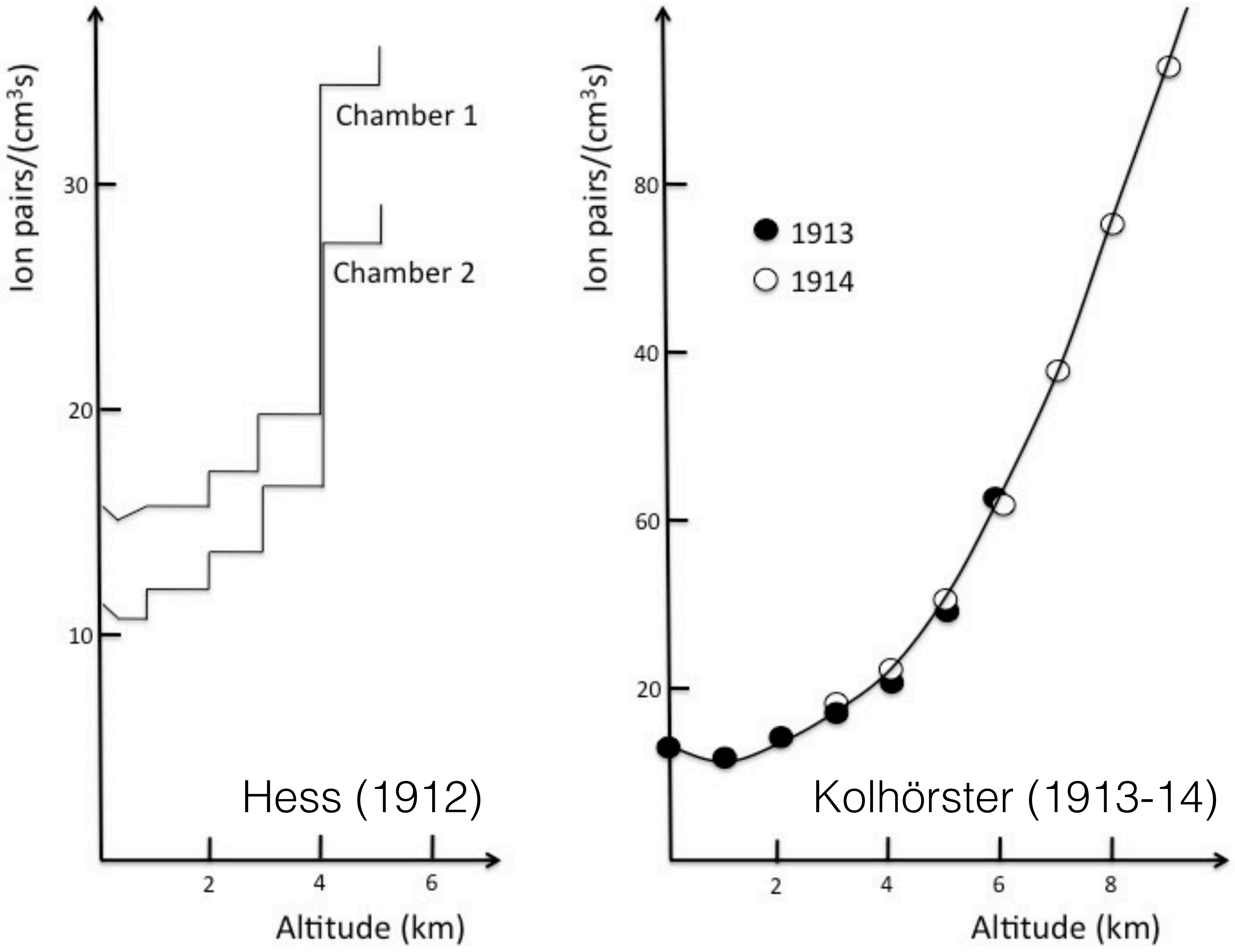
Credit: Alessandro De Angelis

History of astroparticles

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



Credit: CERN

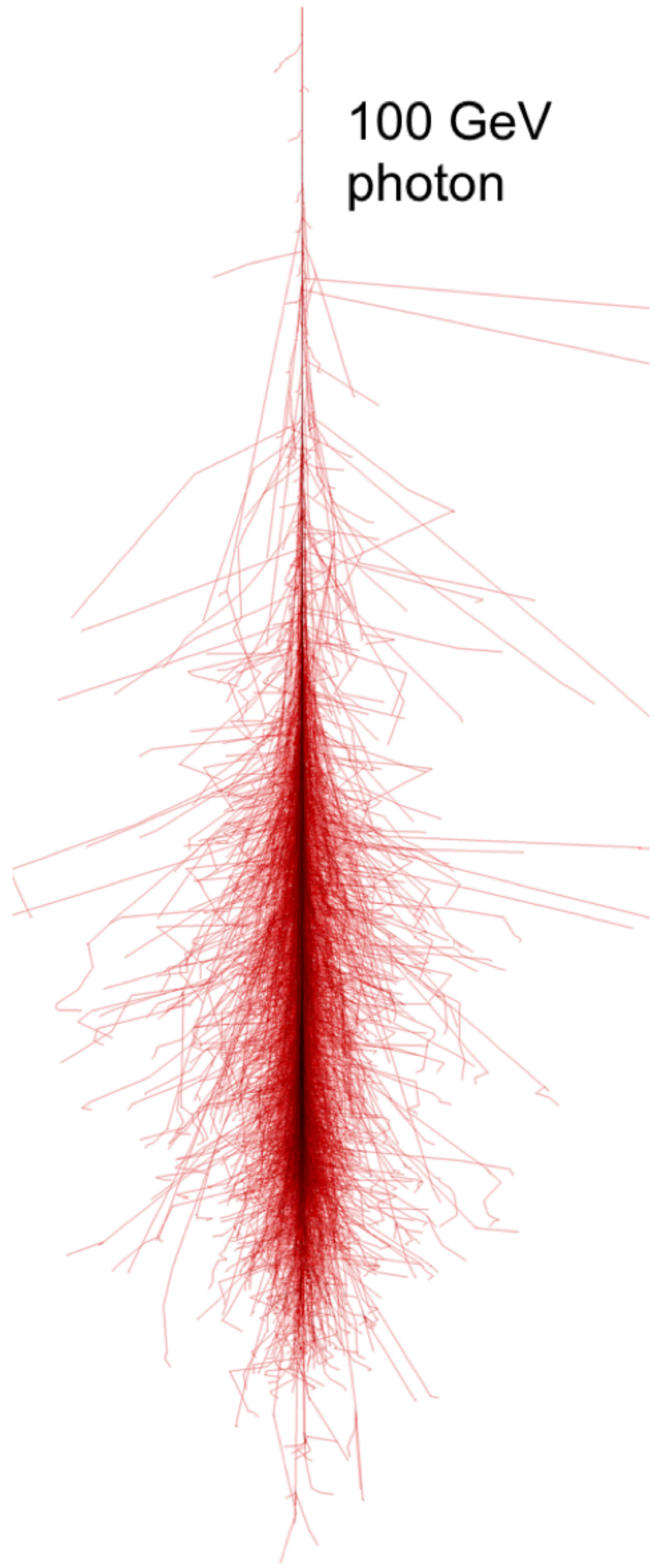


Credit: Alessandro De Angelis

Gamma rays vs Charged Cosmic rays

Gamma Rays

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



[1510.05675](1510.05675)

Protons/nuclei

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

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

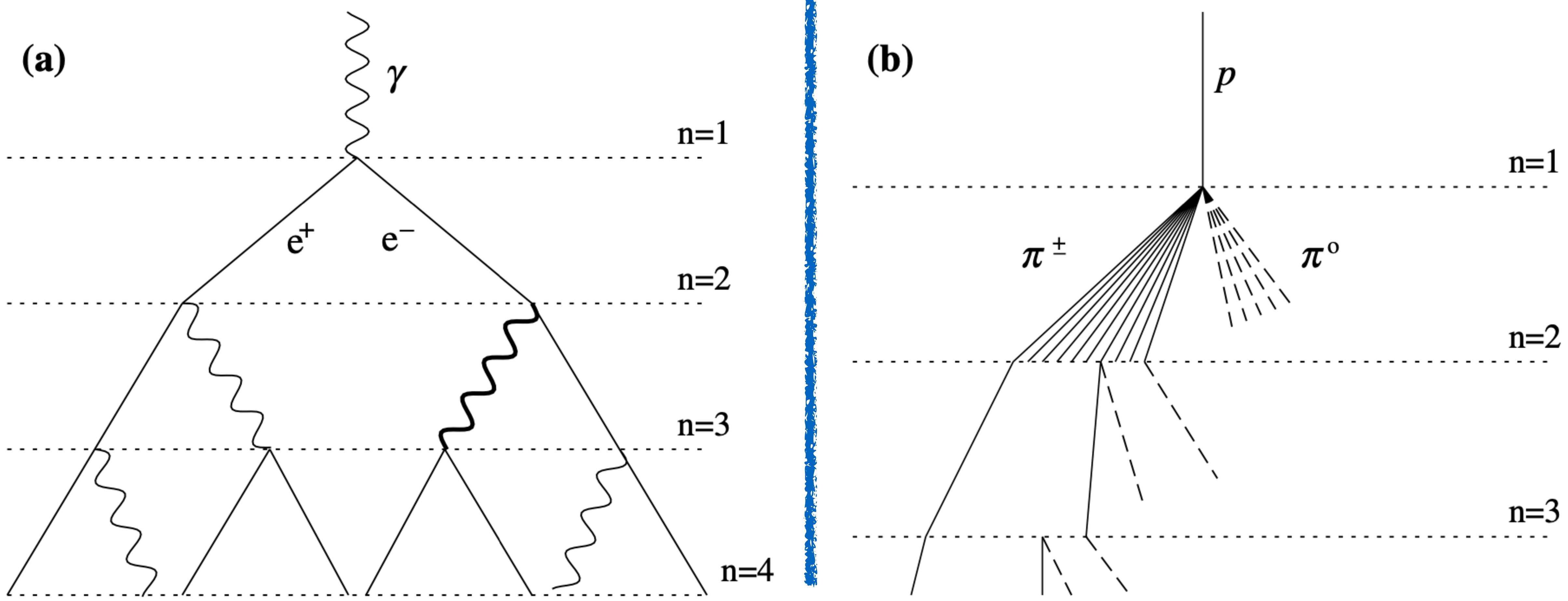
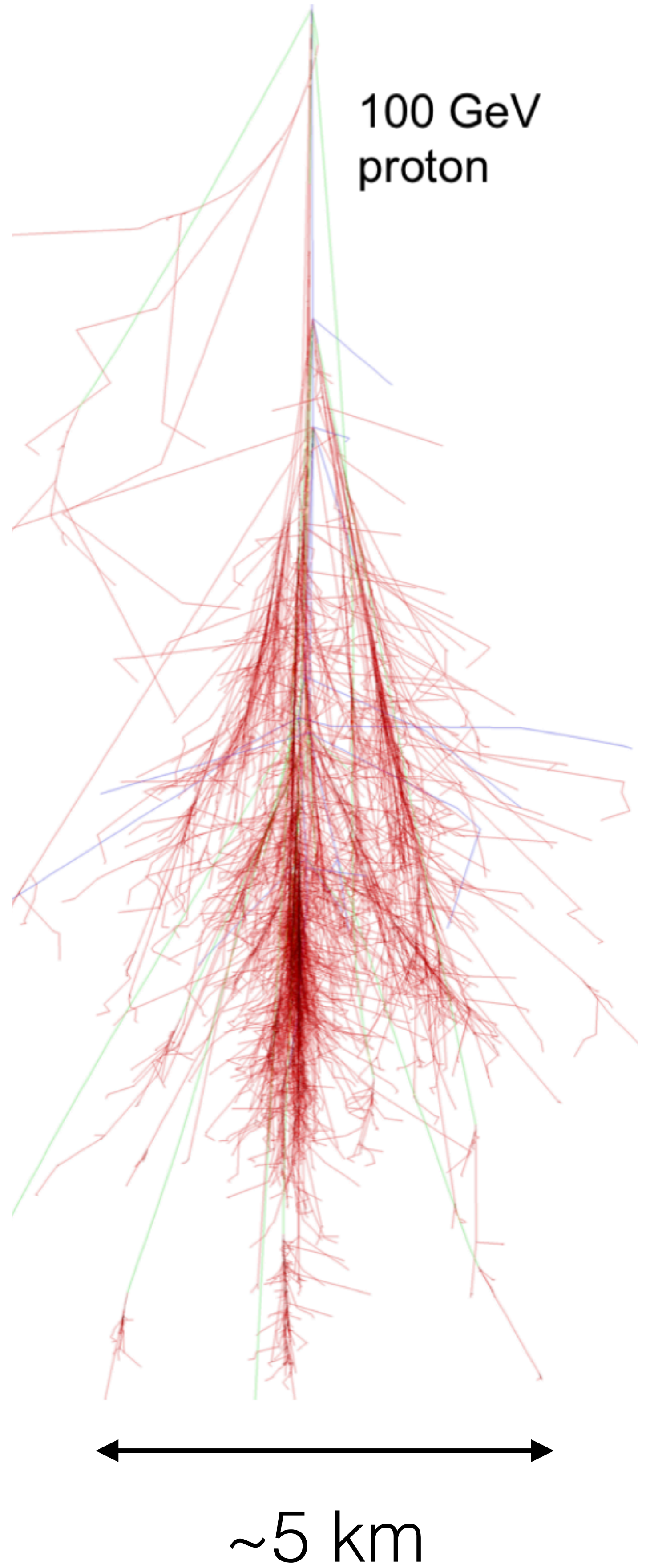
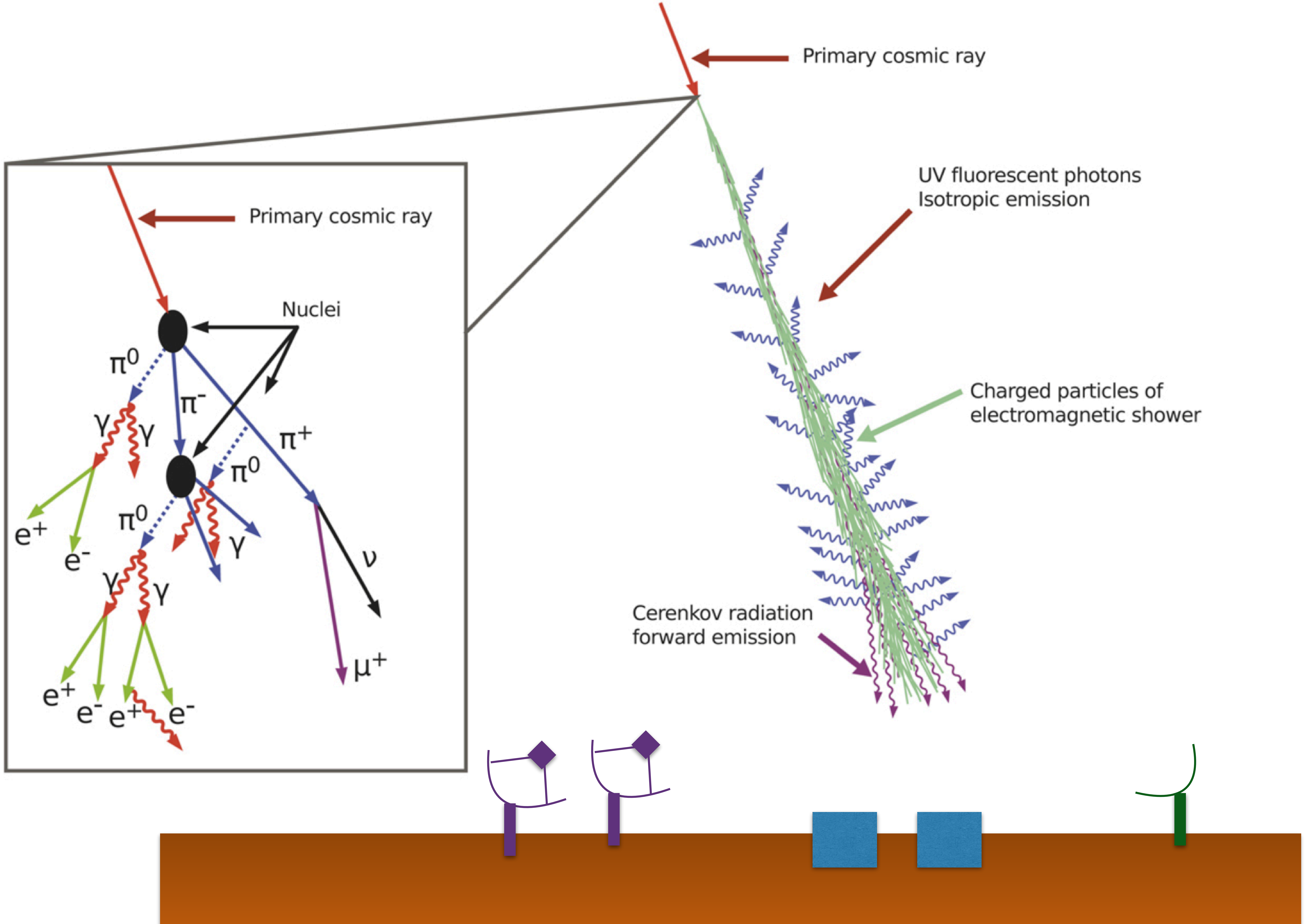


Fig. 1. Schematic views of (a) an electromagnetic cascade and (b) a hadronic shower. In the hadron shower, dashed lines indicate neutral pions which do not re-interact, but quickly decay, yielding electromagnetic subshowers (not shown). Not all pion lines are shown after the $n = 2$ level. Neither diagram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

Credit: Matthews (2005)



Detection of cosmic rays (Earth)



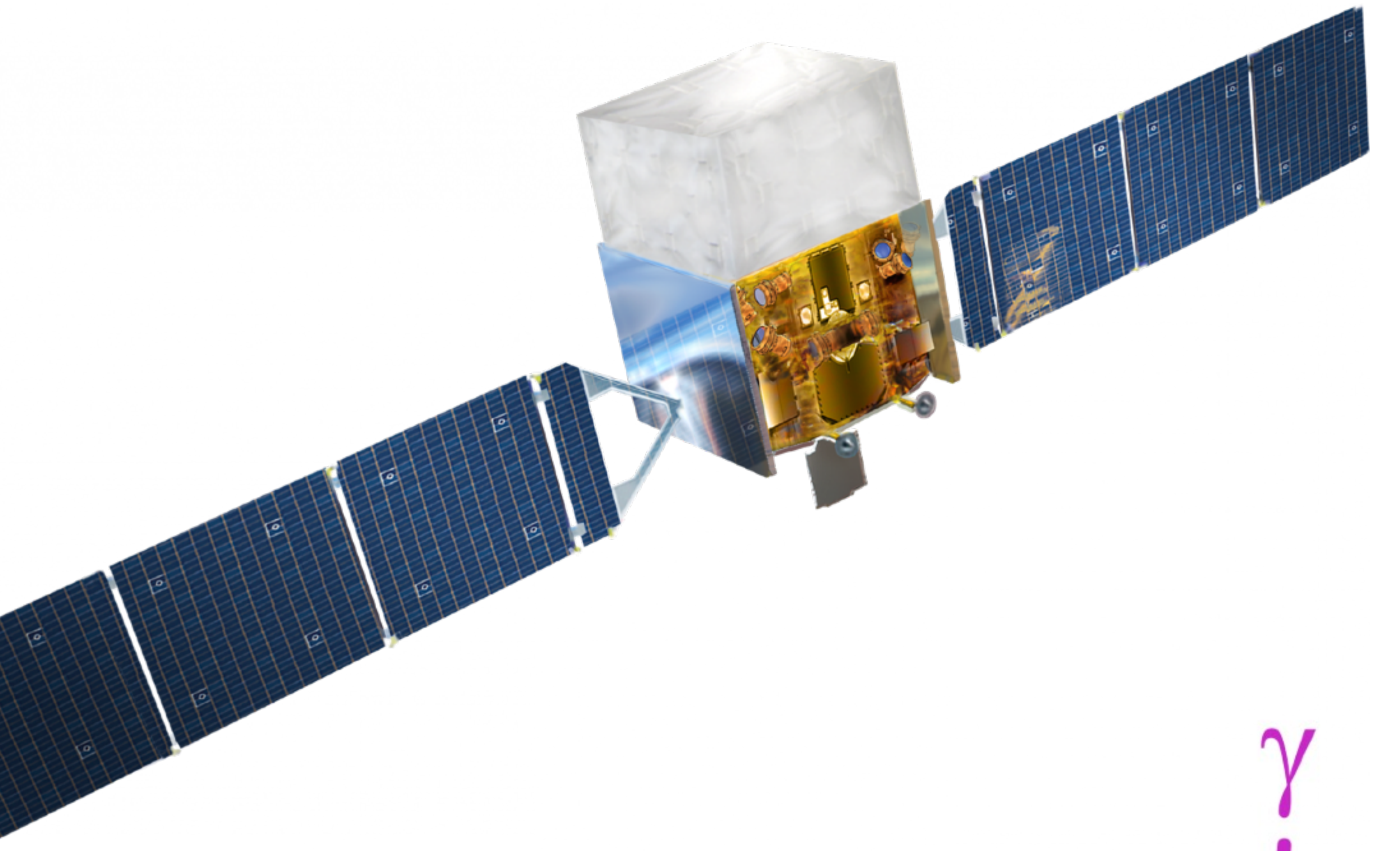
Fluorescence
(e.g. Fly's Eye, Auger observatory)

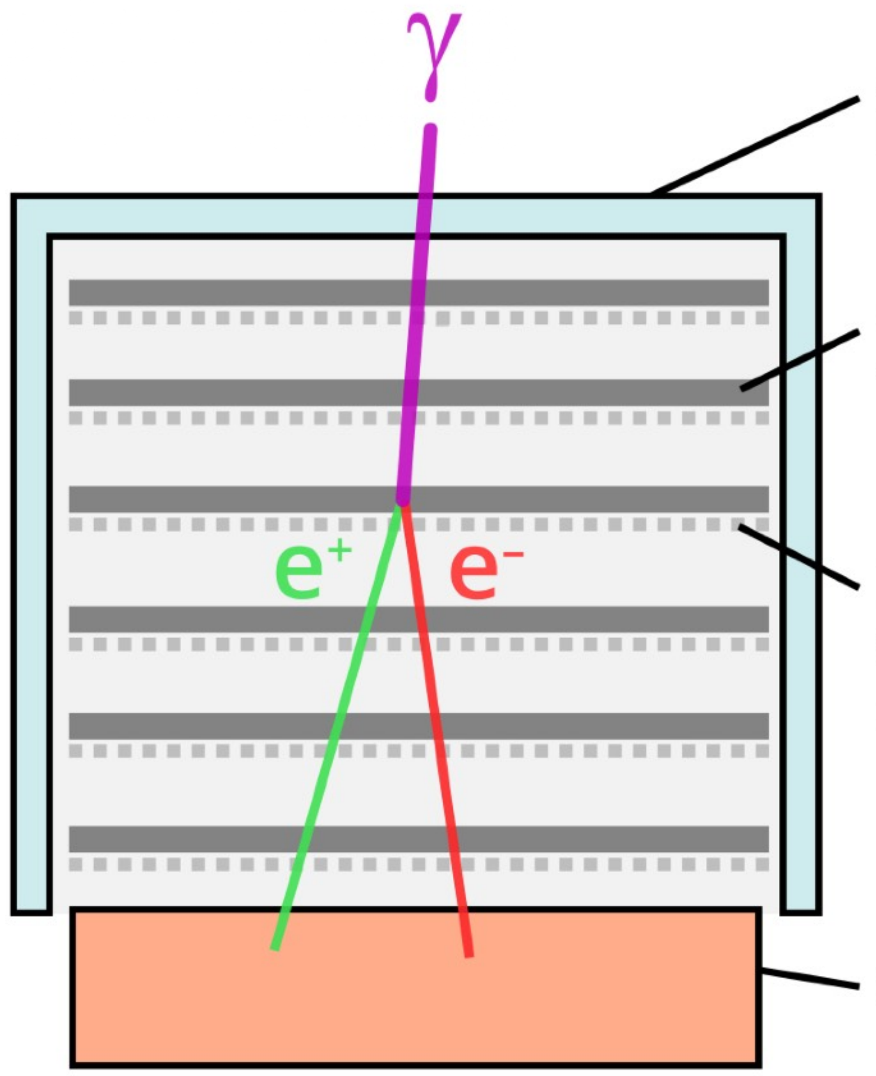
Imaging Air Cherenkov Telescope (IACT)
(e.g. MAGIC, VERITAS, HESS, planned CTA)

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

Detection of cosmic rays (Space)

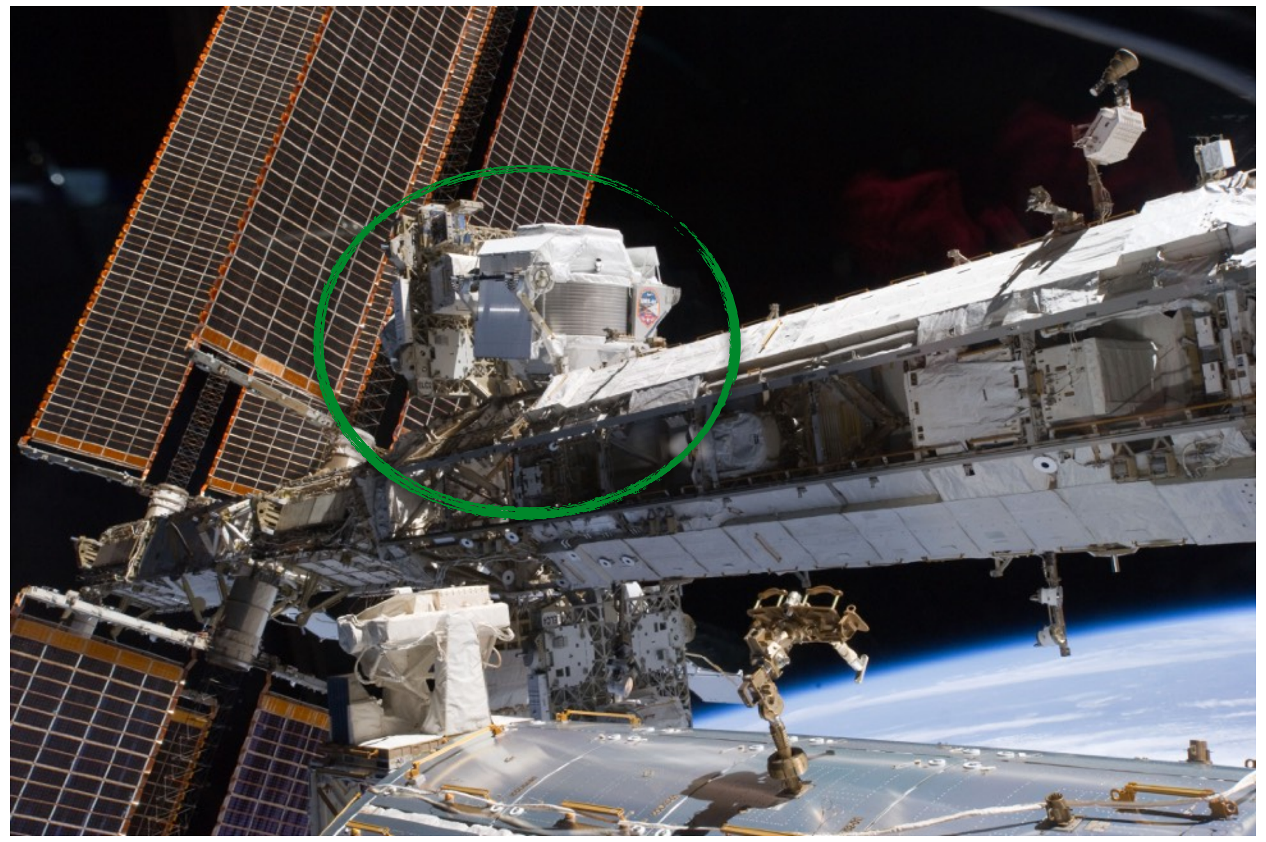
Fermi-LAT (2008-)



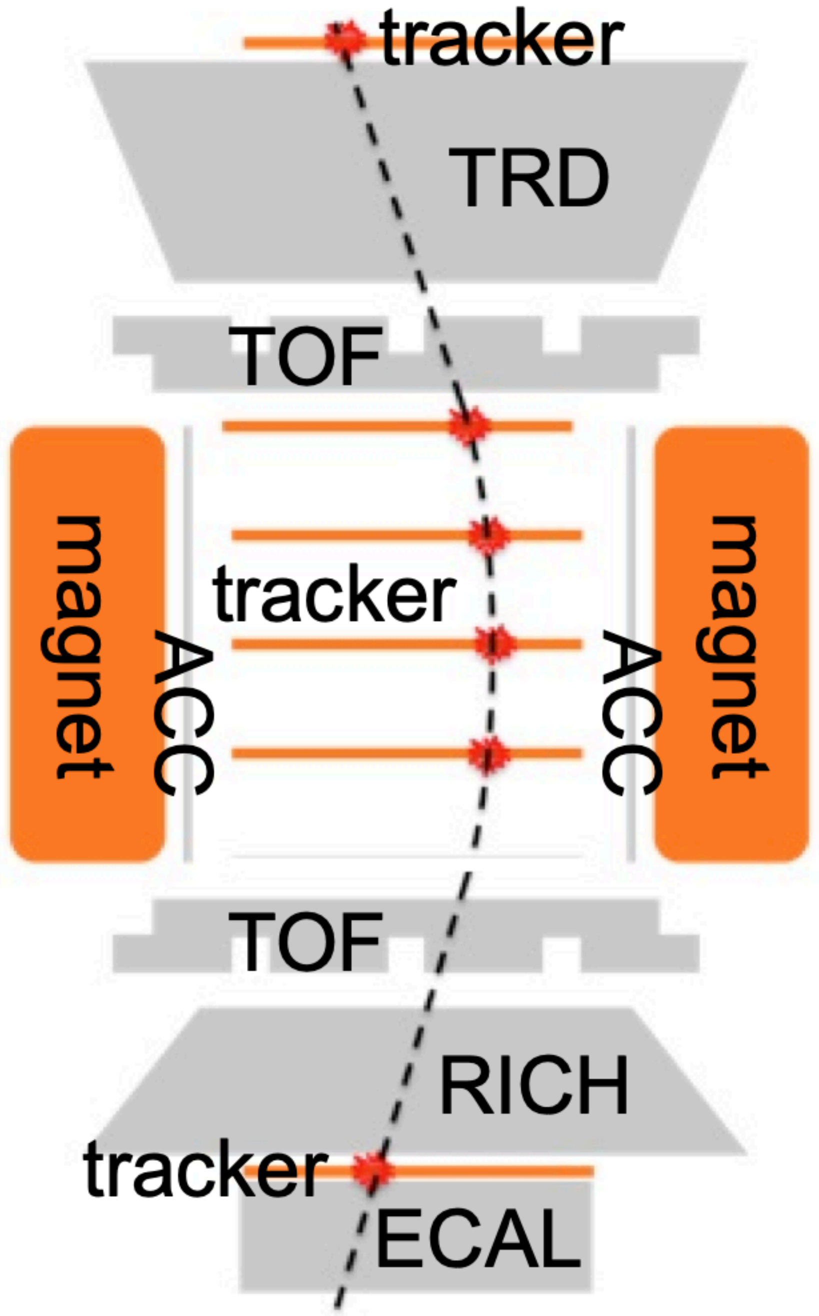


Credit: NASA's Goddard Space Flight Center

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



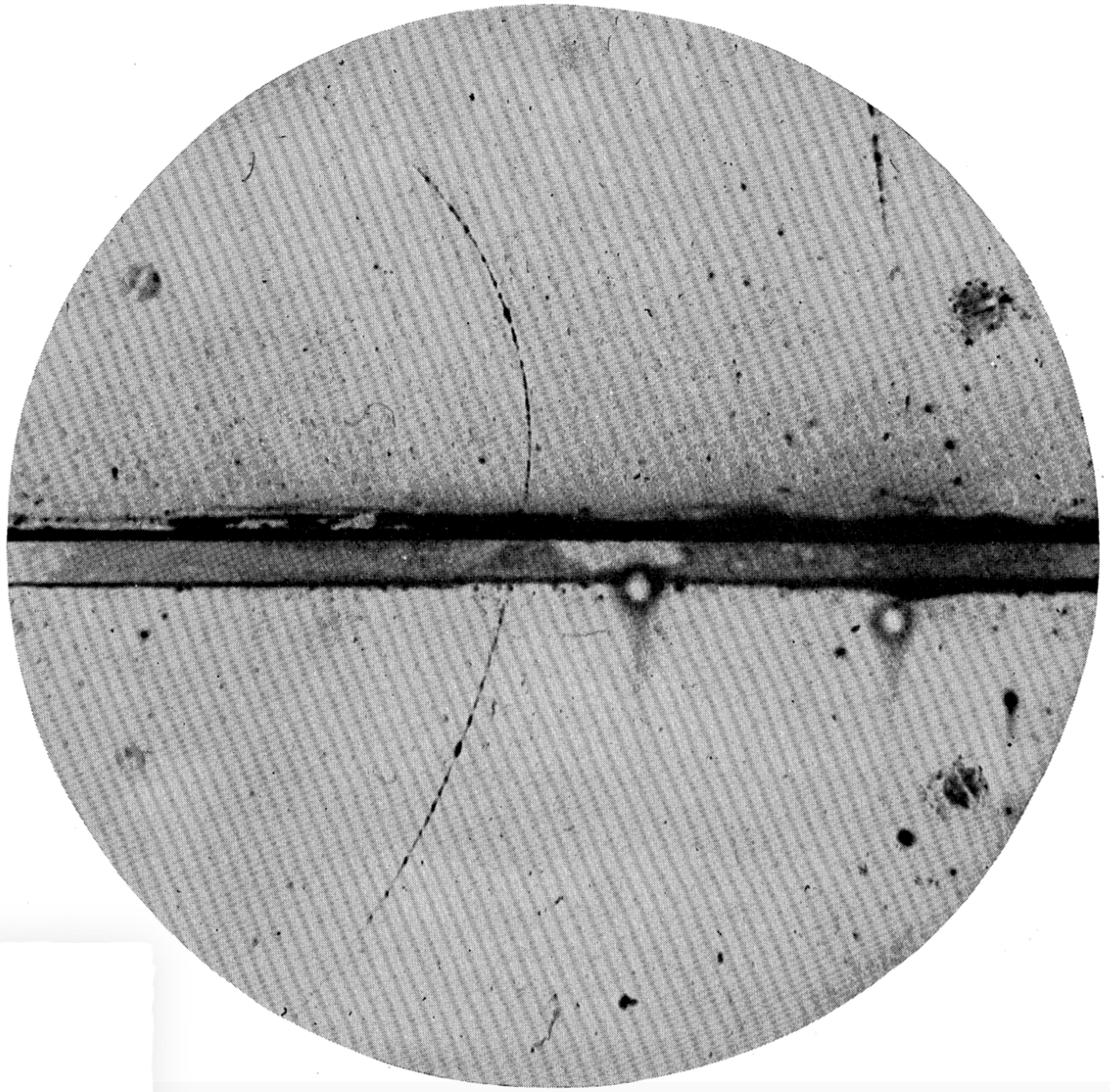
AMS (2011-)



1507.02712

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

The Positive Electron



The Positive Electron

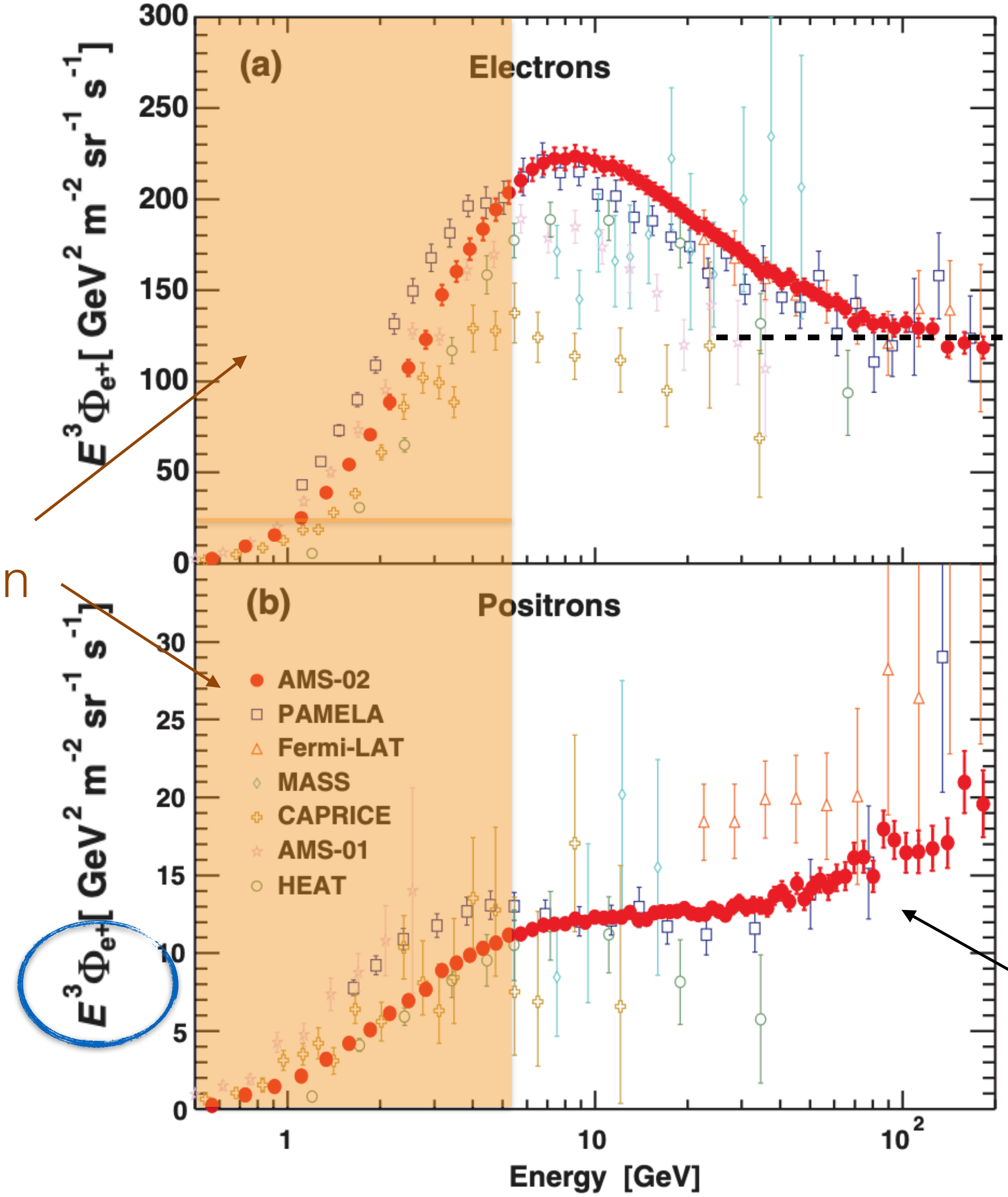
CARL D. ANDERSON, *California Institute of Technology, Pasadena, California*
(Received February 28, 1933)

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



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

$$\Phi \propto E^{-3}$$

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**)

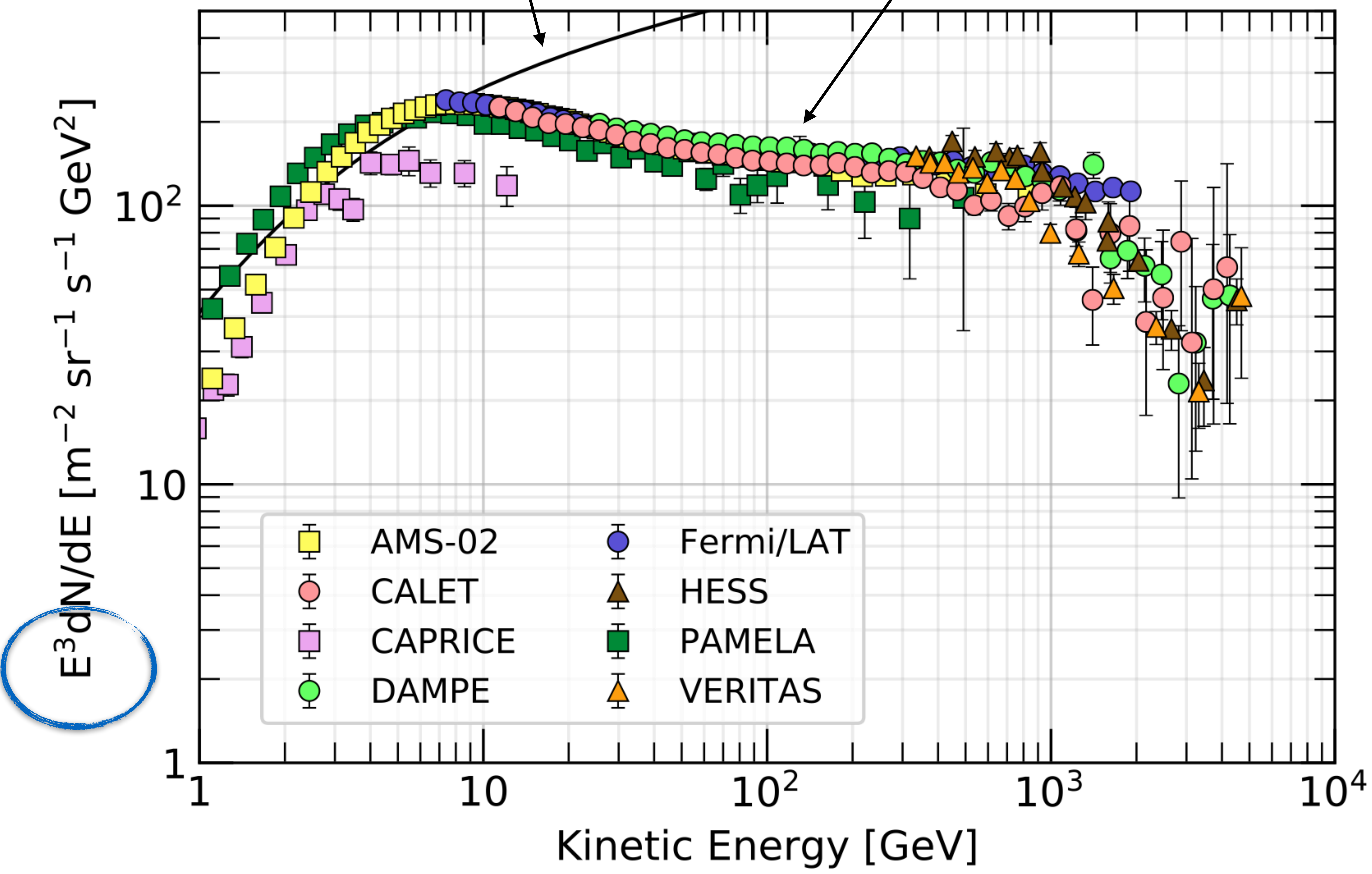
Expect different spectra. But, rise in positron flux at high energy is still not yet understood ("positron excess")!

E.g. 1303.0530

Electrons vs Protons

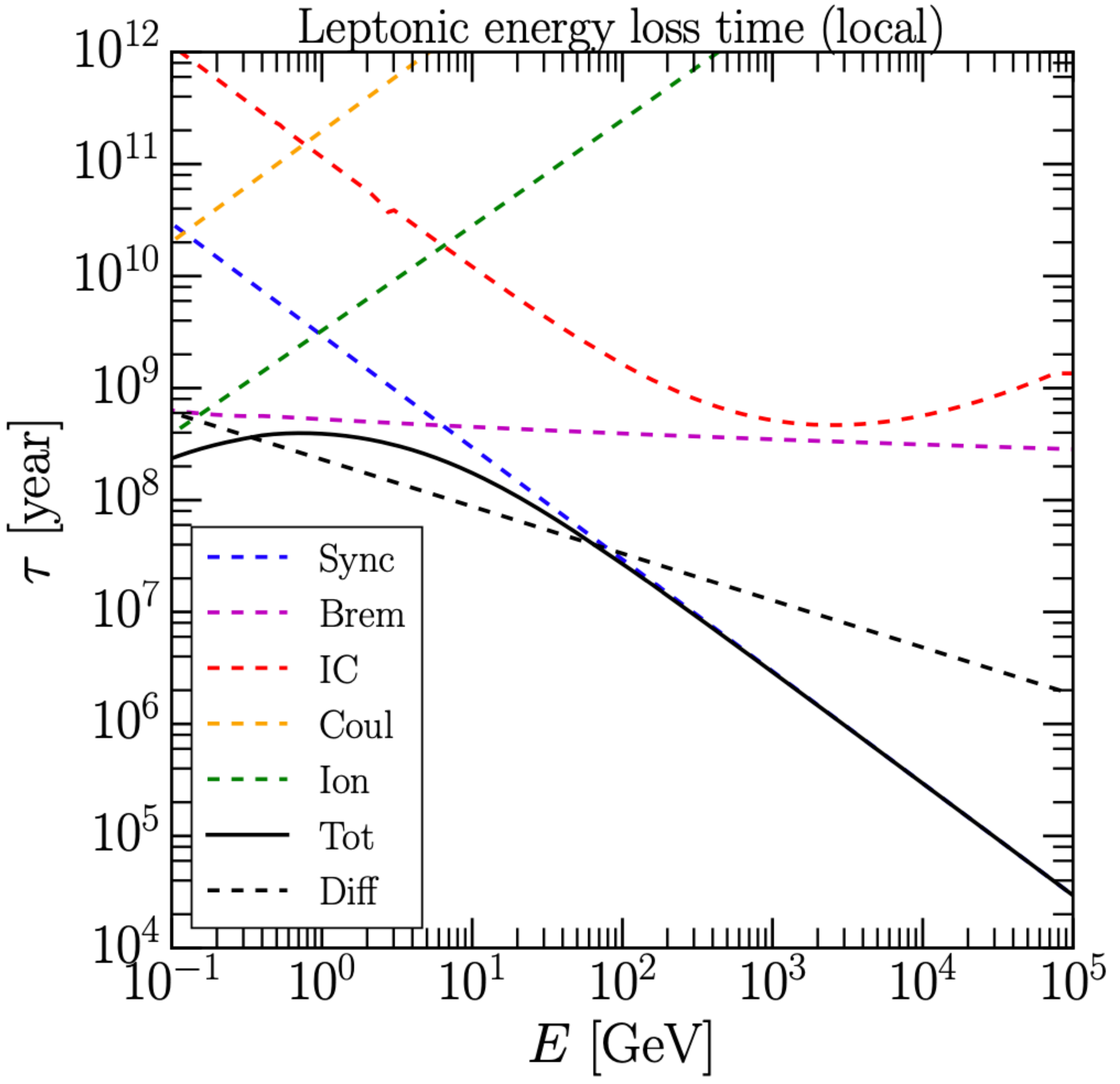
Proton Spectrum (x0.01)

Electron + Positron Spectrum



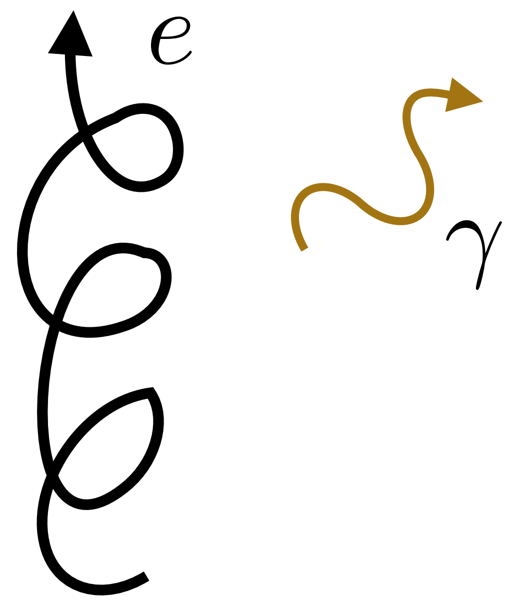
Credit: [Particle Data Group (2020)]

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



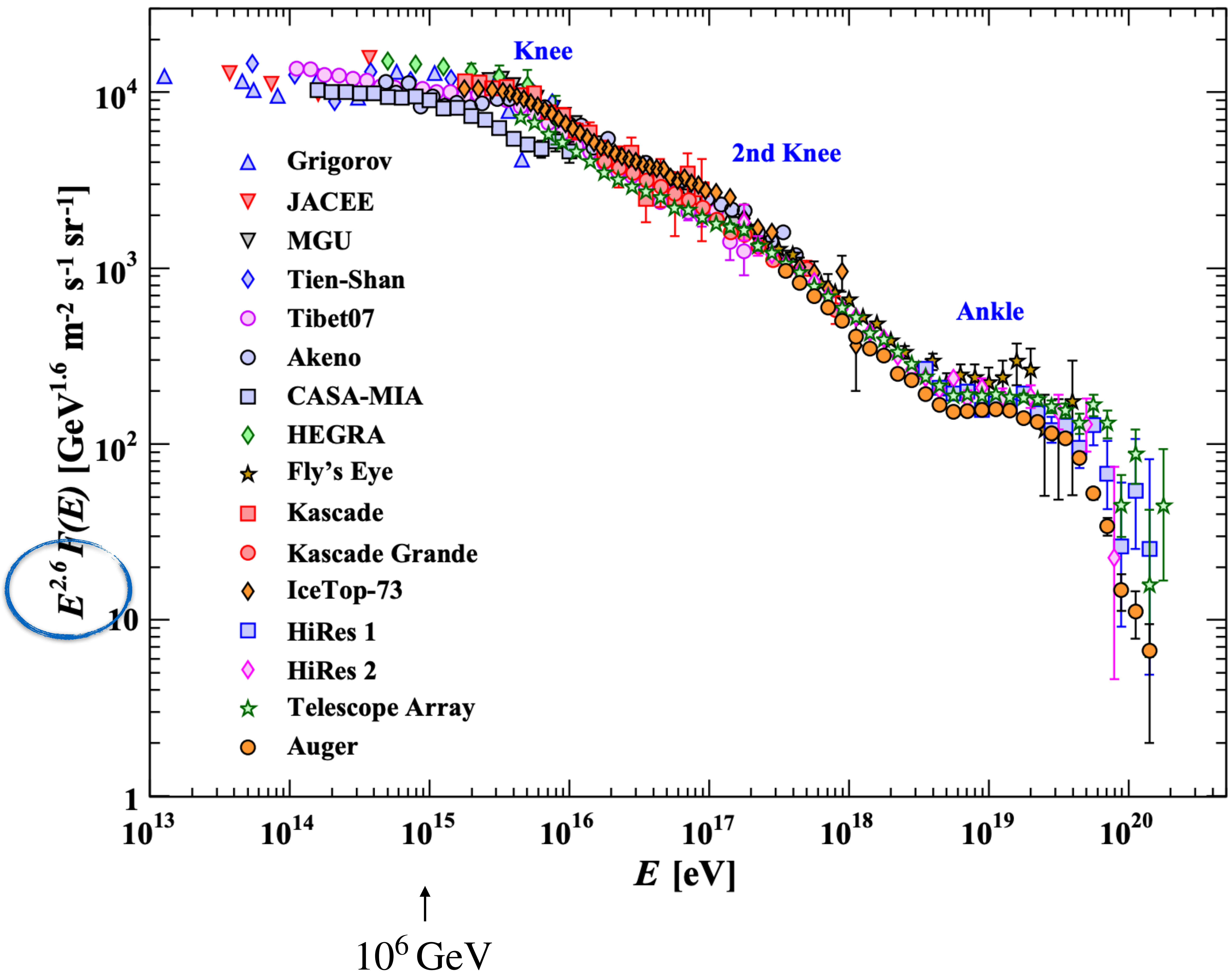
See e.g. Appendix C of [1607.07886]

Synchrotron



Ultra high-energy cosmic rays

All particle cosmic ray spectrum

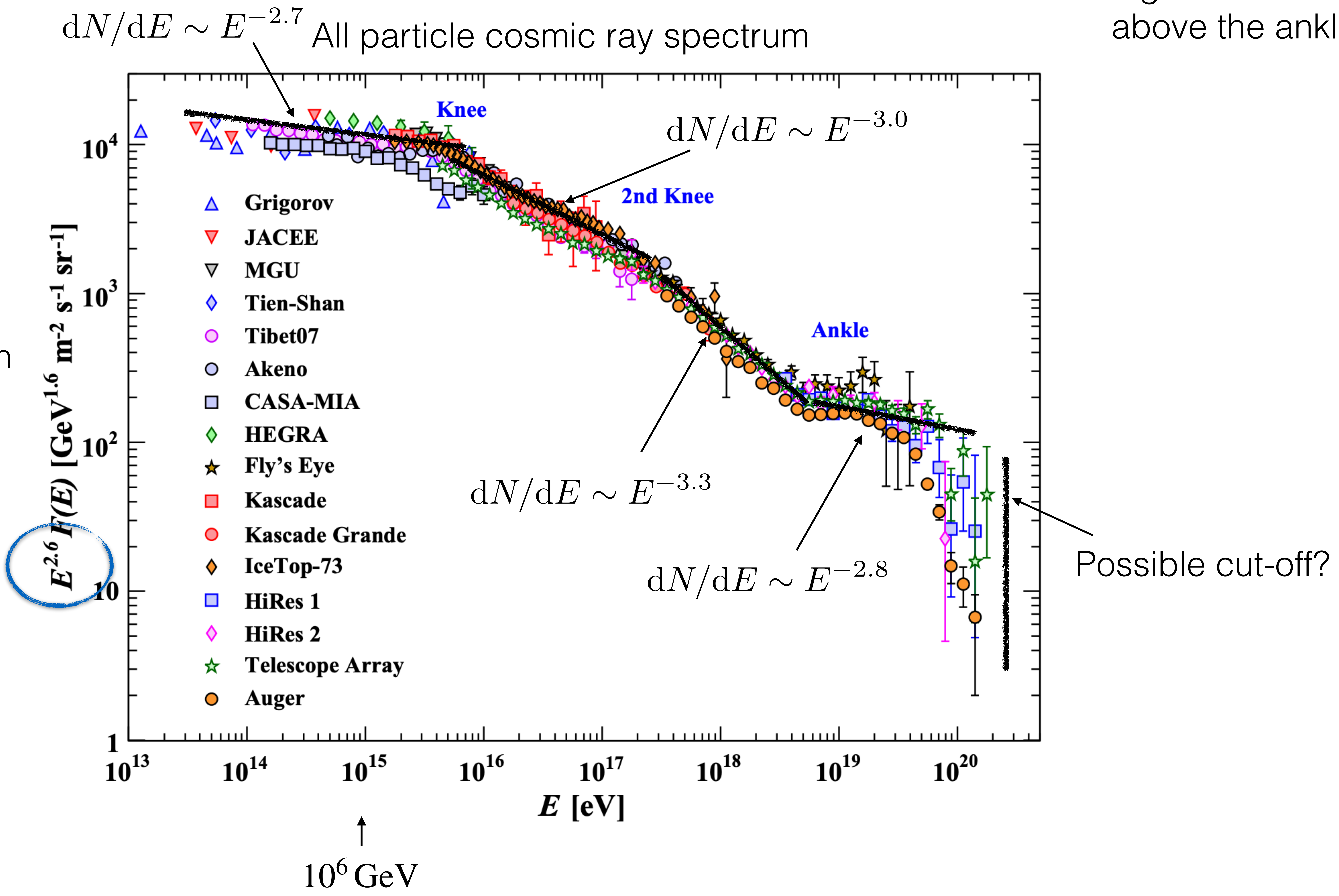


Credit: Particle Data Group (2020)

Ultra high-energy cosmic rays

Extragalactic CRs begin to dominate above the ankle.

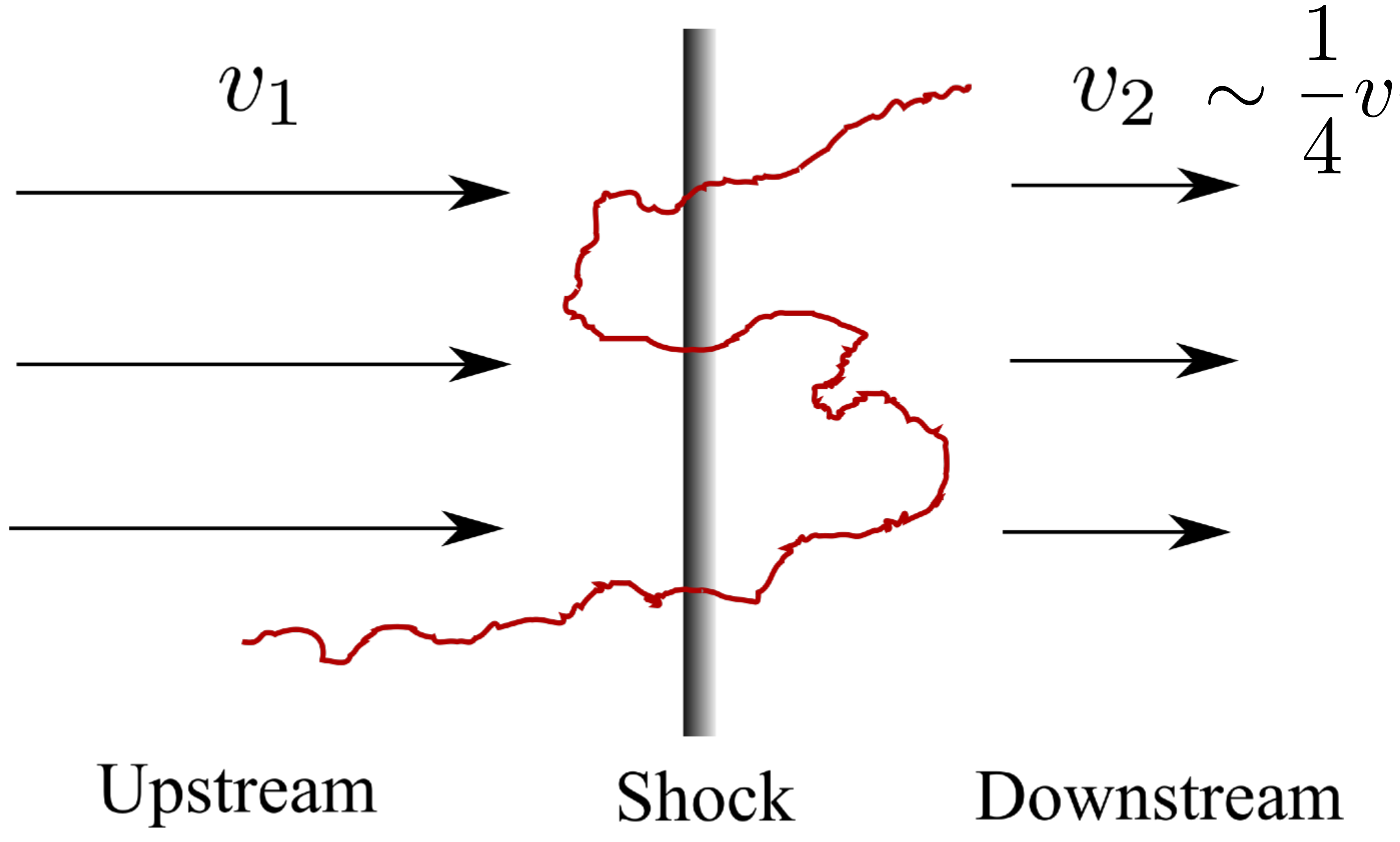
Heavier nuclei begin to dominate above the 2nd knee.



Credit: Particle Data Group (2020)

Production of cosmic rays

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



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

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

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

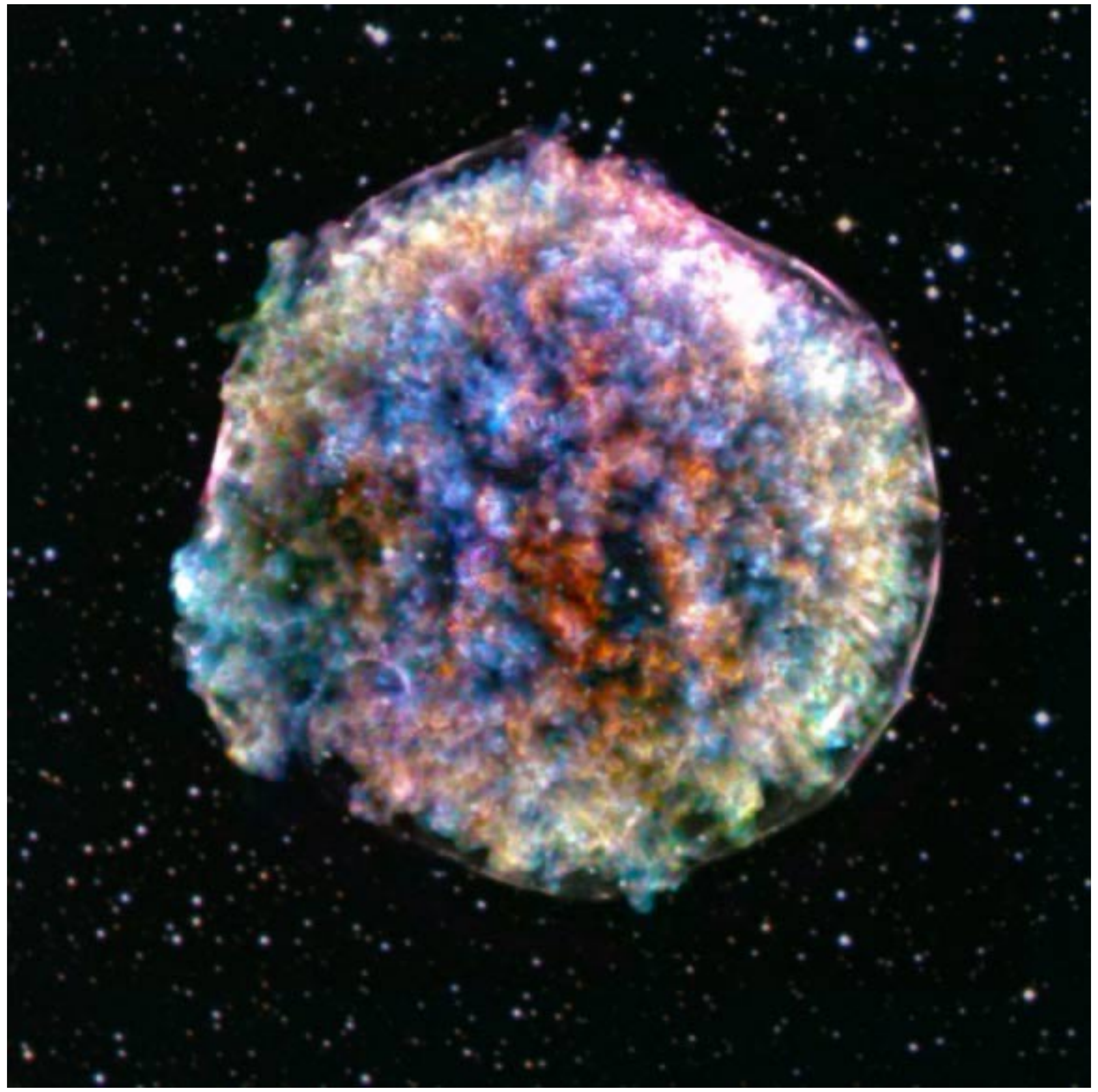
After *n* crossings: $E_n = (1+\xi)^n E_0$

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

E.g. [1910.06006](1910.06006)

Tycho Supernova remnant



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

Production of cosmic rays

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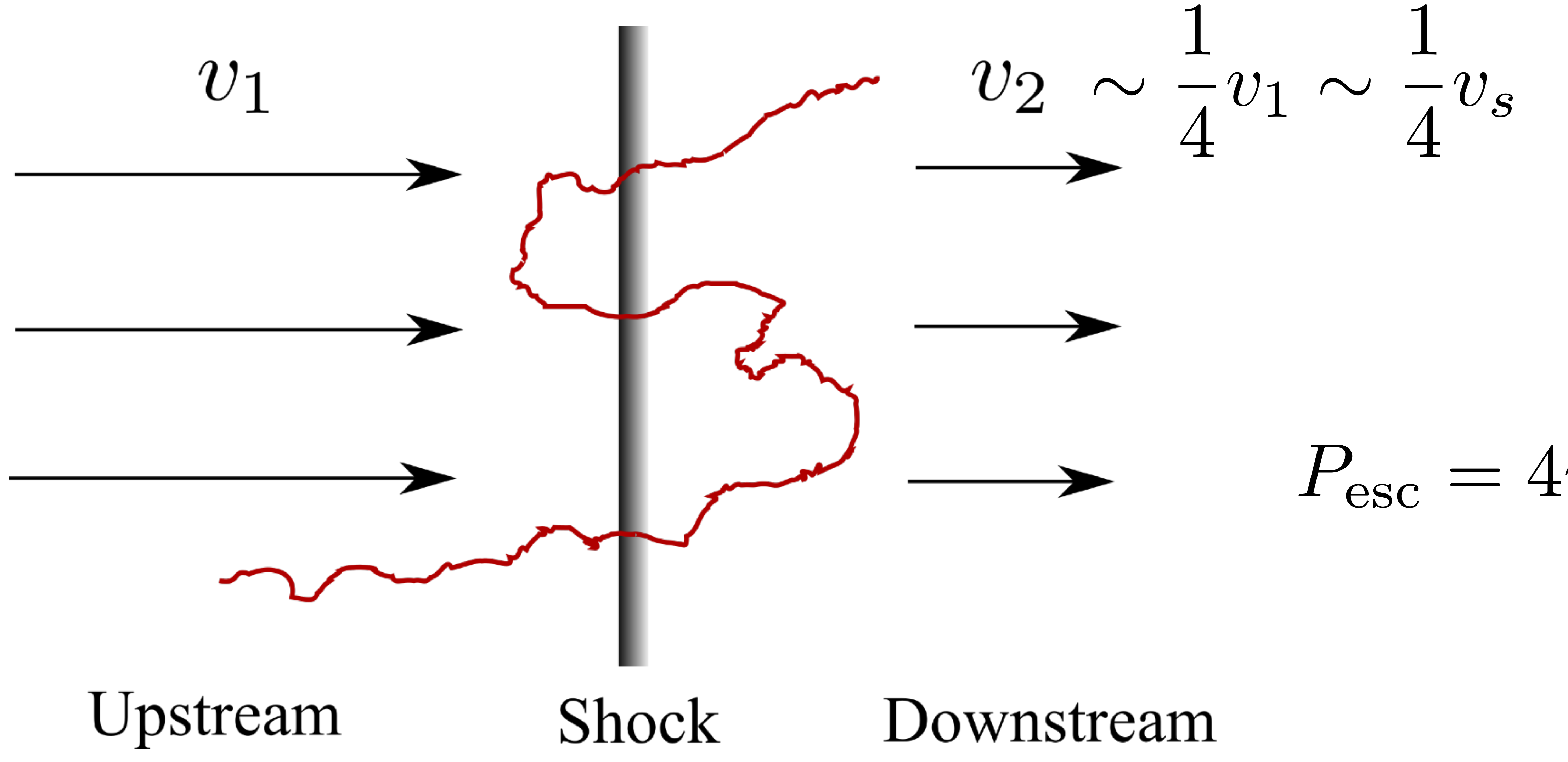

$$P_{\rm esc} = 4 v_2 / c$$

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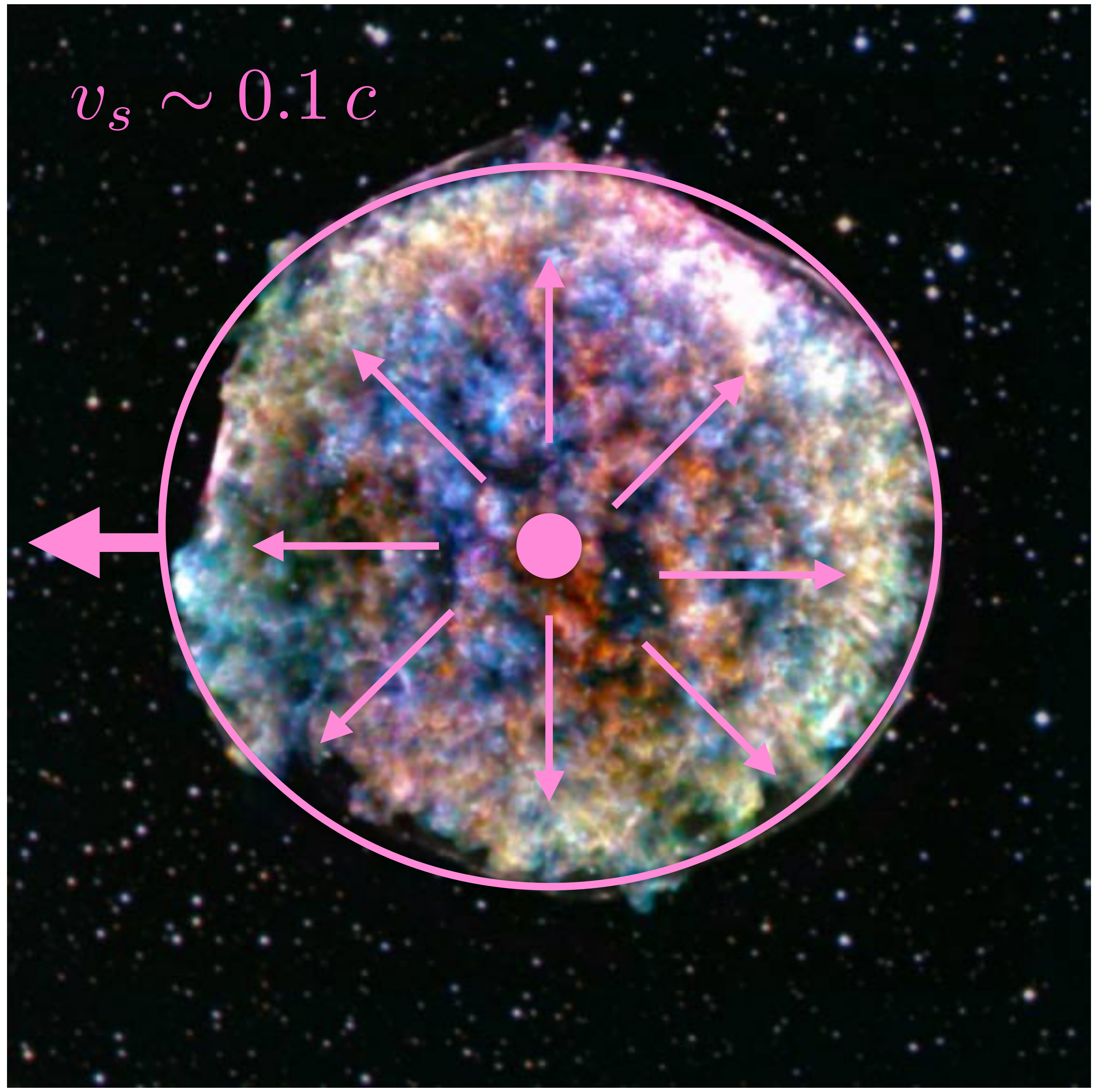

Credit: NASA / CXC / RIKEN / NASA's Goddard Space Flight Center / T. Sato et al / DSS

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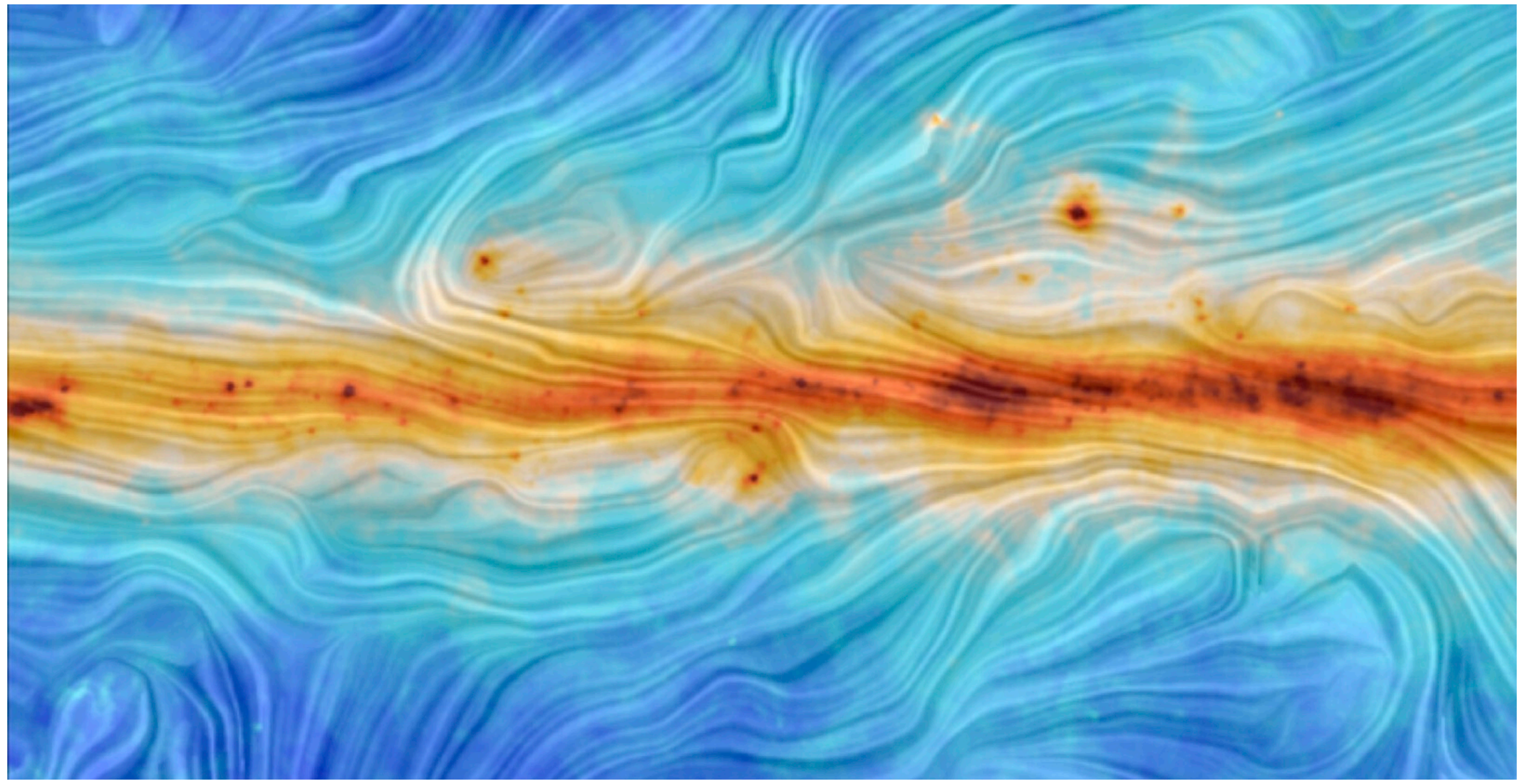
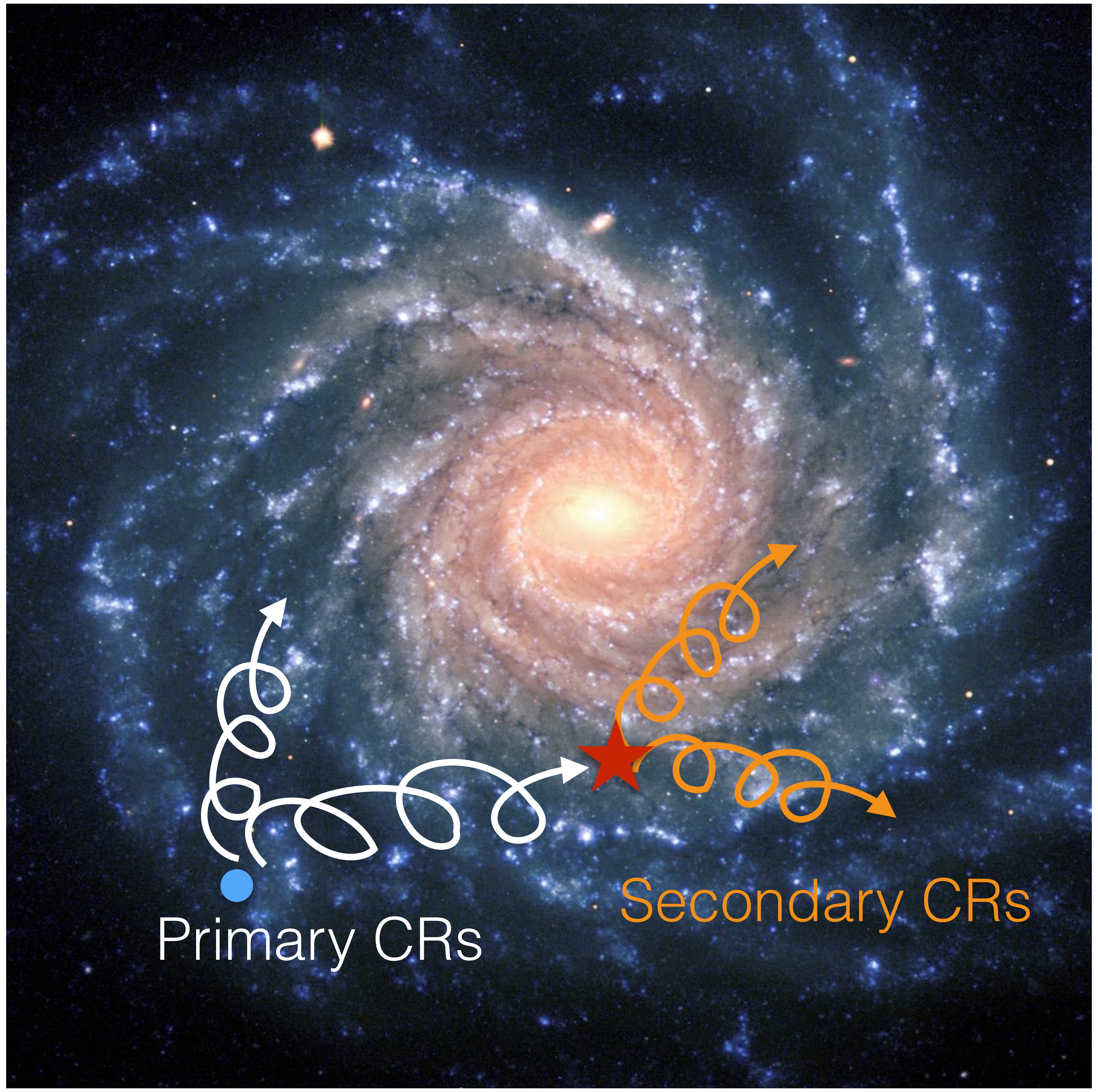
E.g. [1910.06006]

Propagation of CCRs

Credit: ESA/Planck Collaboration



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



Diffusion

Escape and attenuation

Sources

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

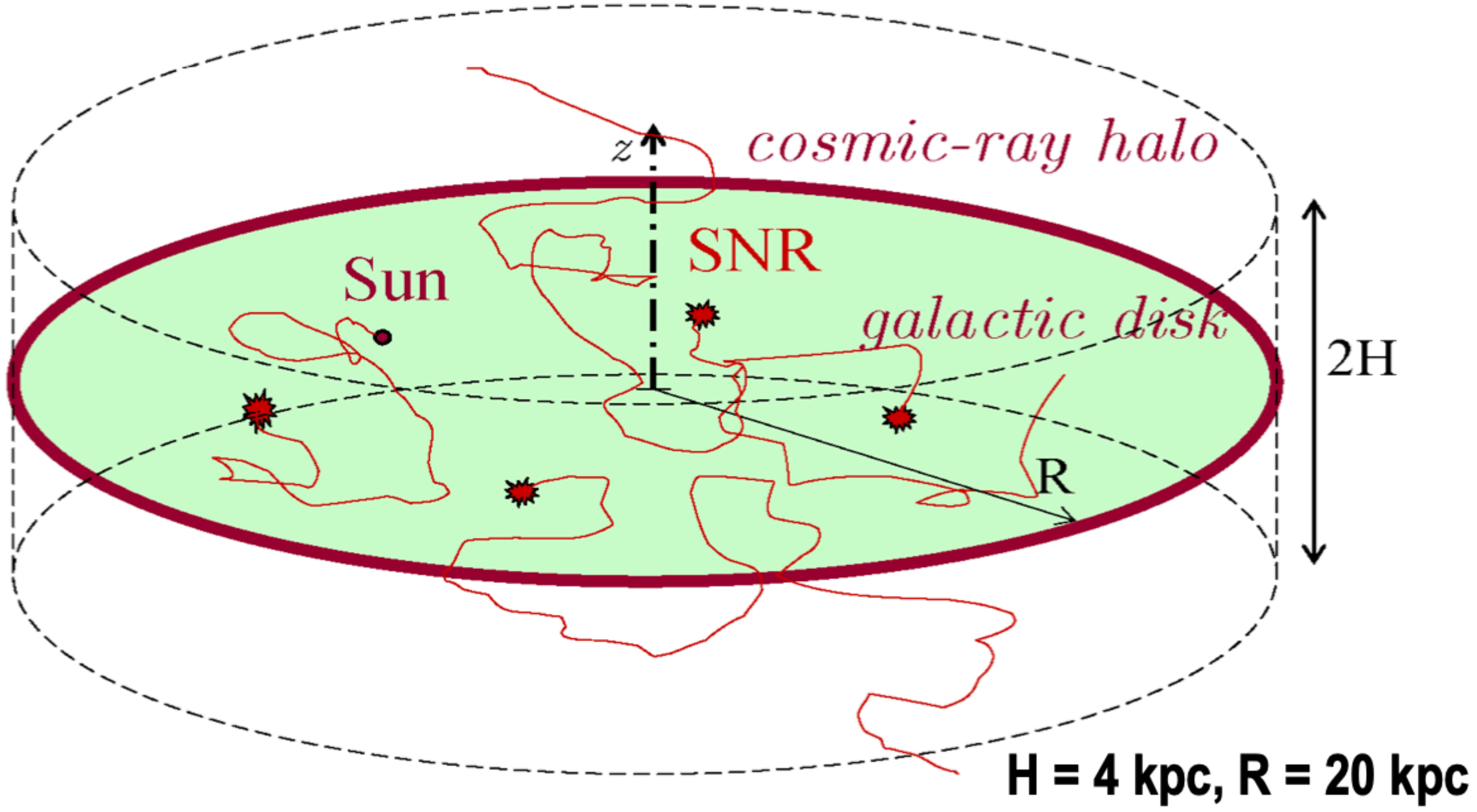
Energy losses

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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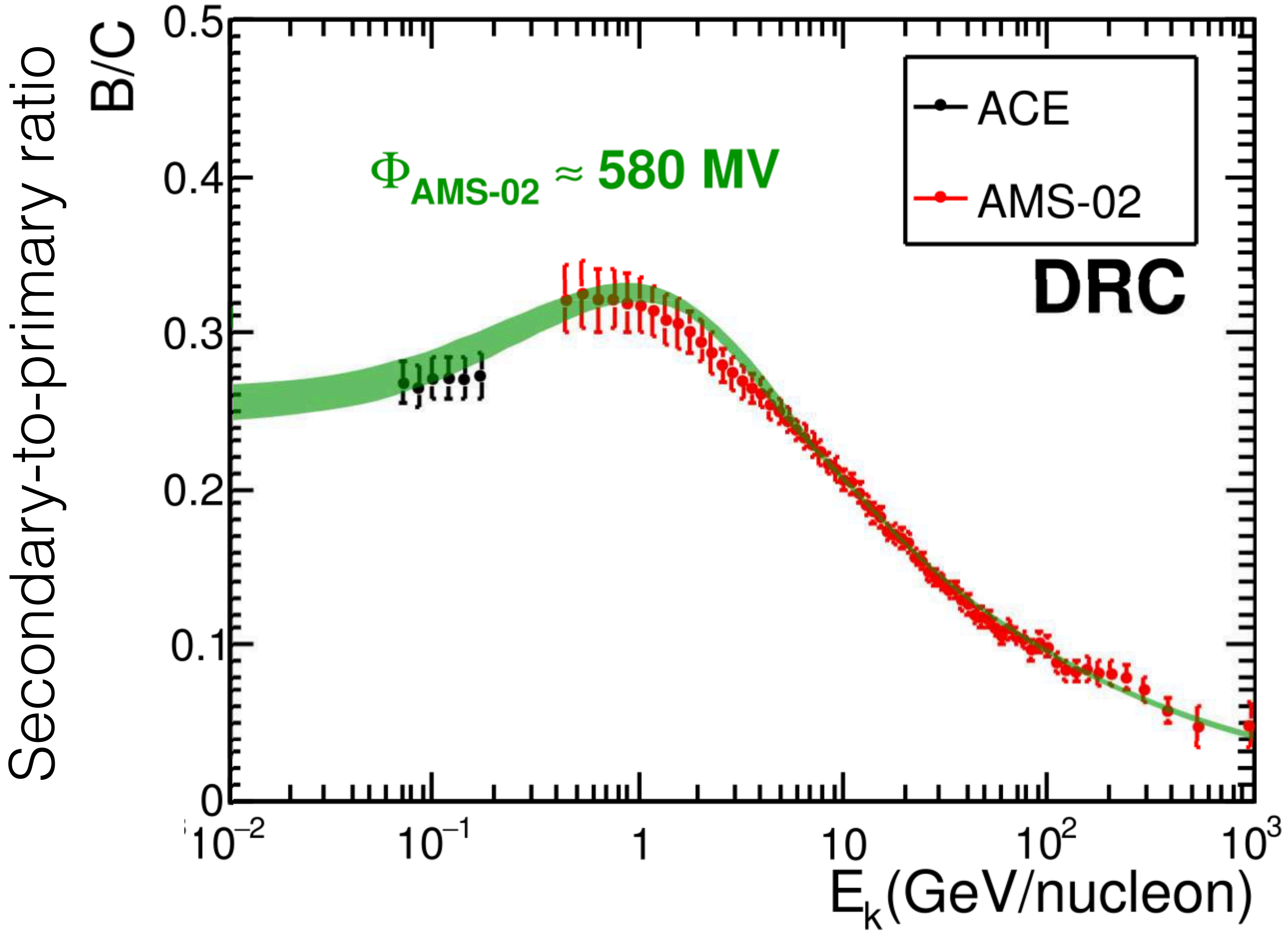
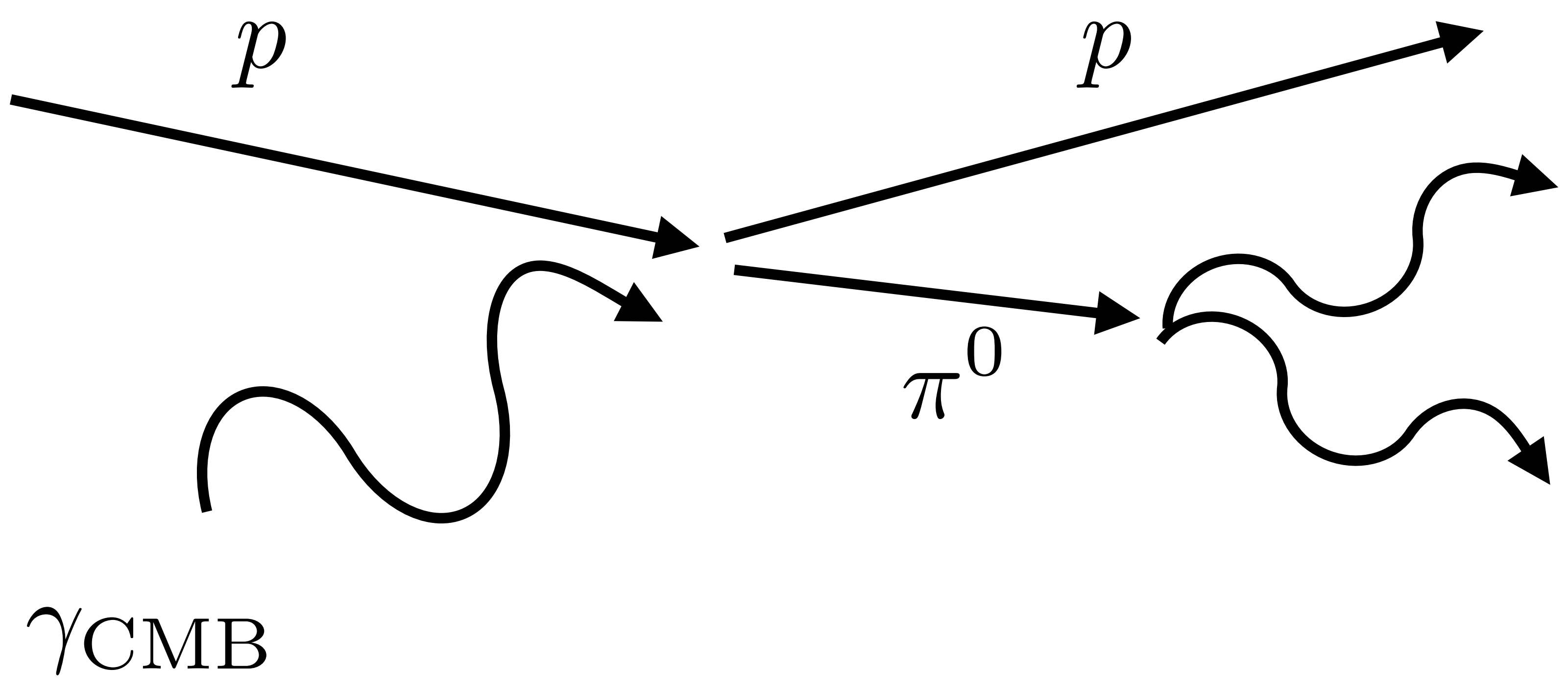
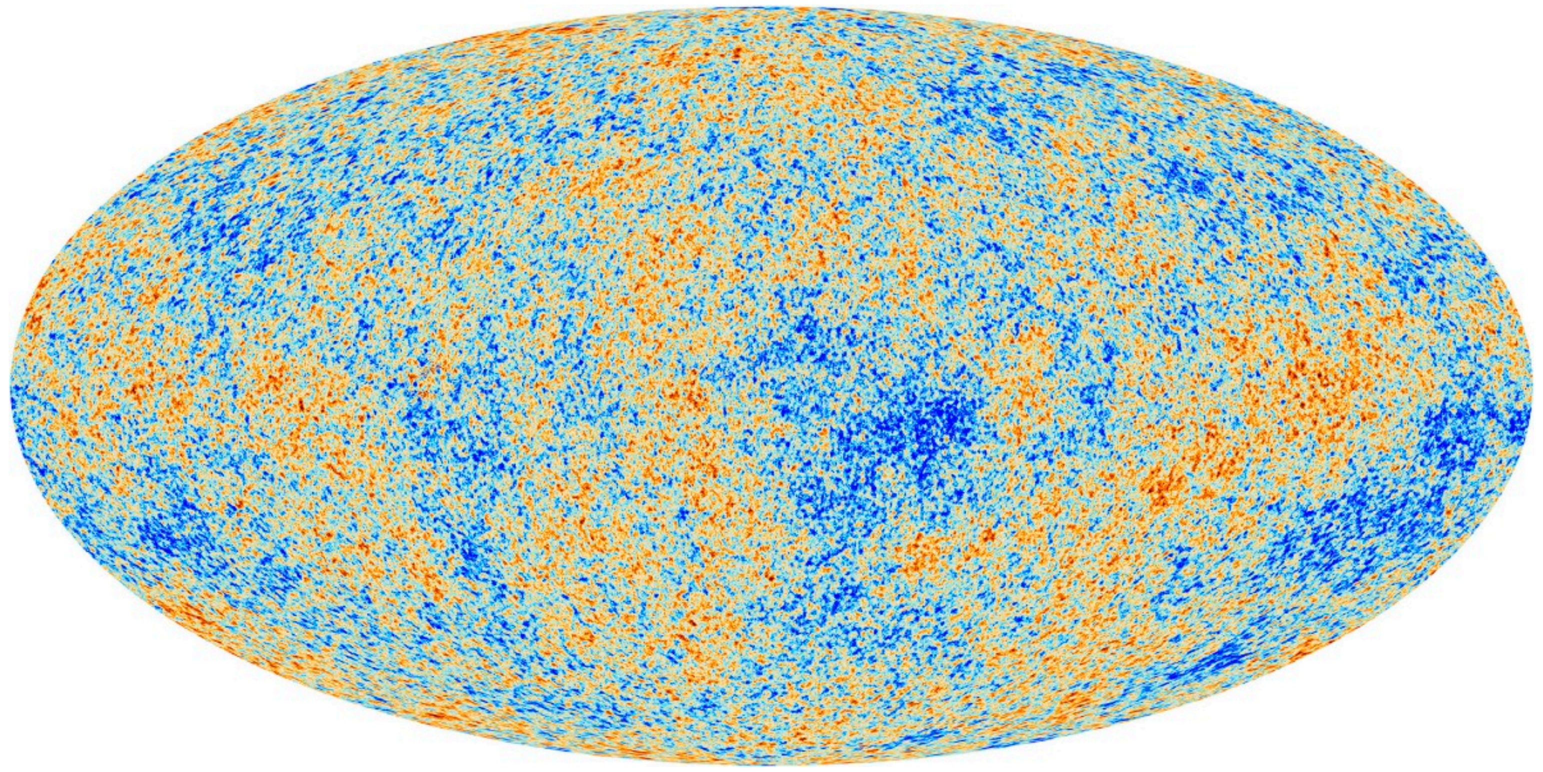


Typical diffusion distance $\langle R^2 \rangle \sim D(E)t$. Coefficient $D(E)$ grows with E,
steepening the observed CR spectrum…

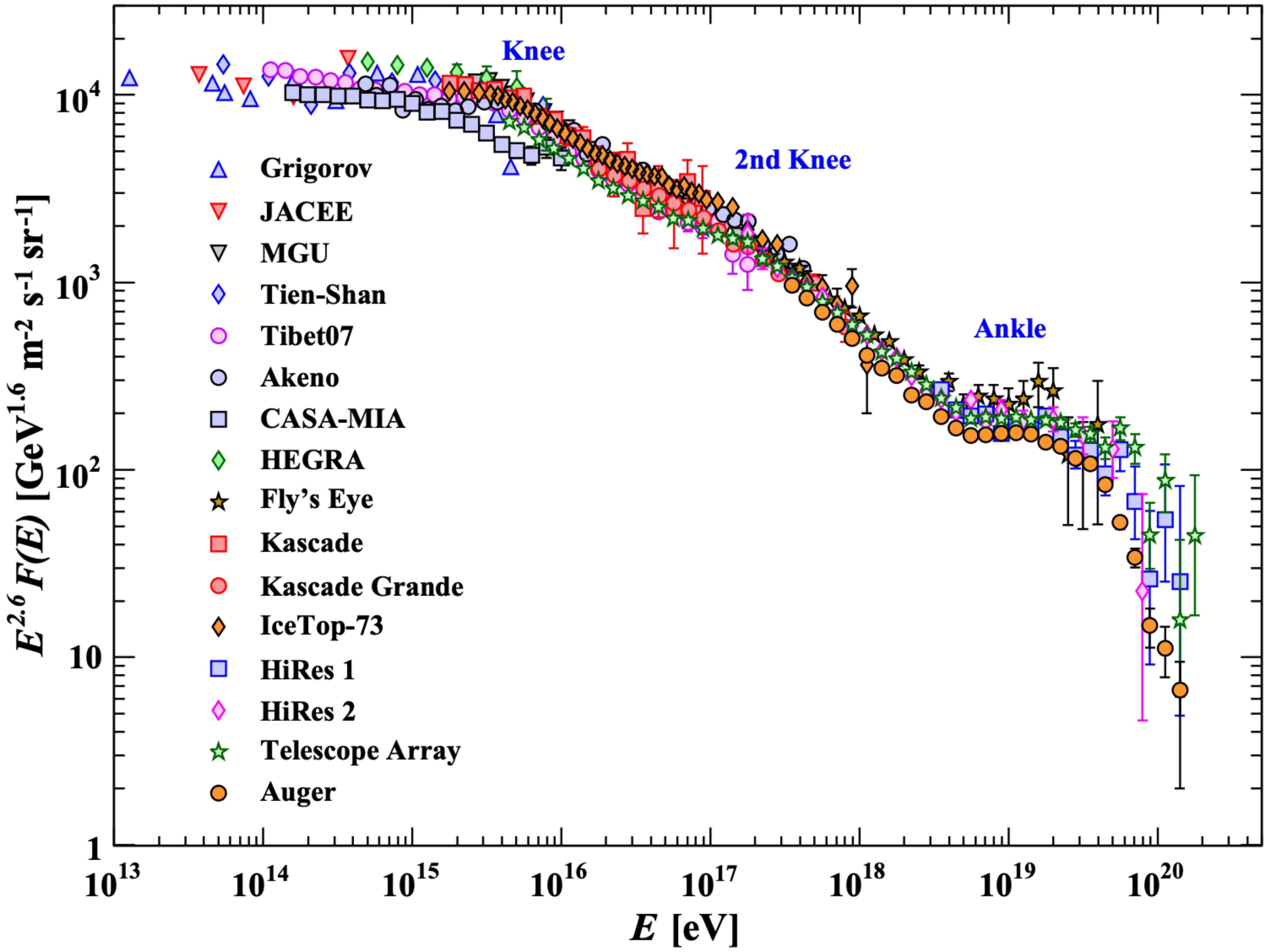
GZK cut-off

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





Credit: ESA/Planck



$$\mathrm{p} + \gamma_{\rm CMB} \rightarrow \mathrm{p} + \pi_0$$

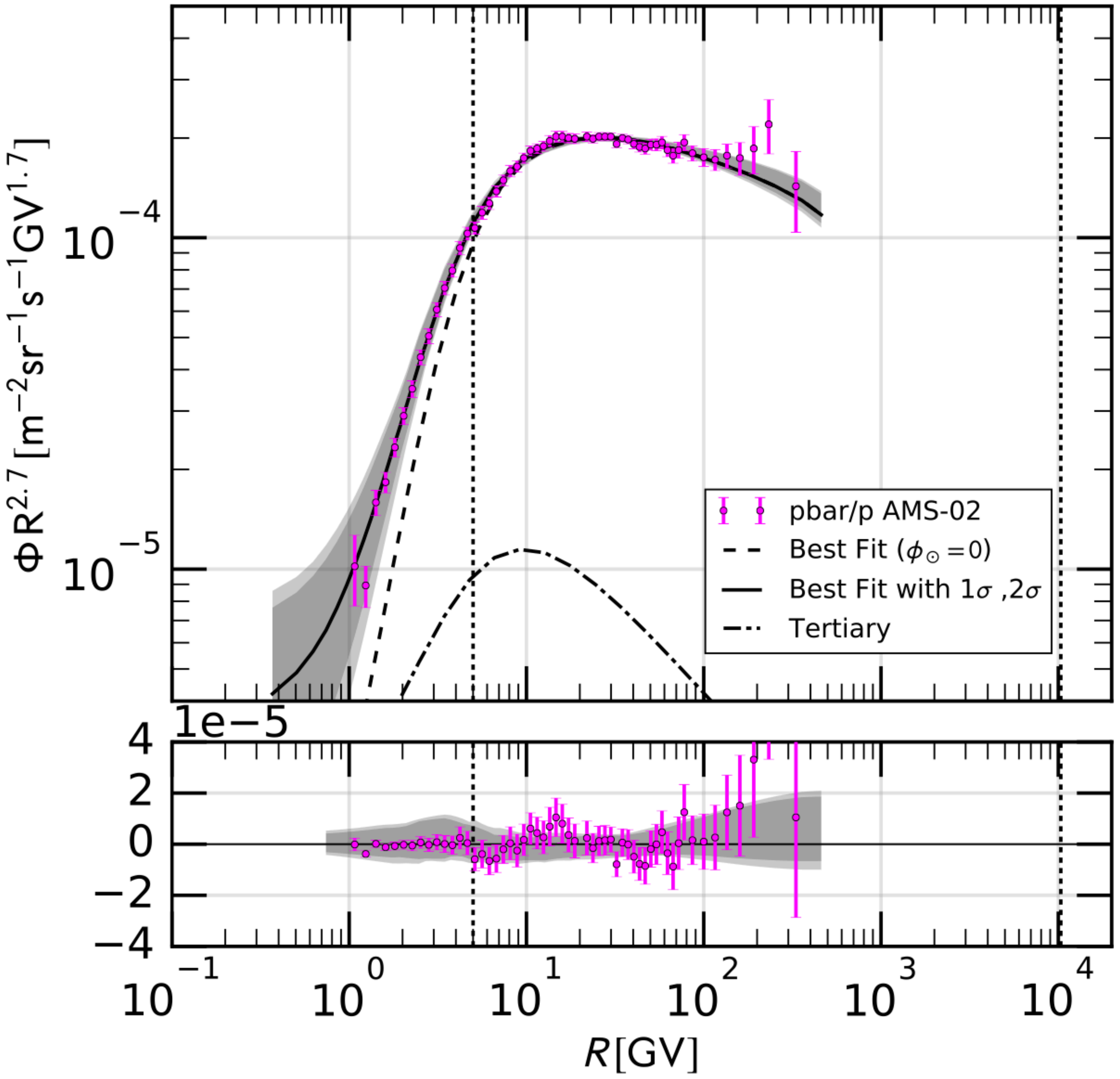
Threshold energy for this process gives rise to the Greisen–Zatsepin–Kuzmin (GZK) cut-off:

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

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

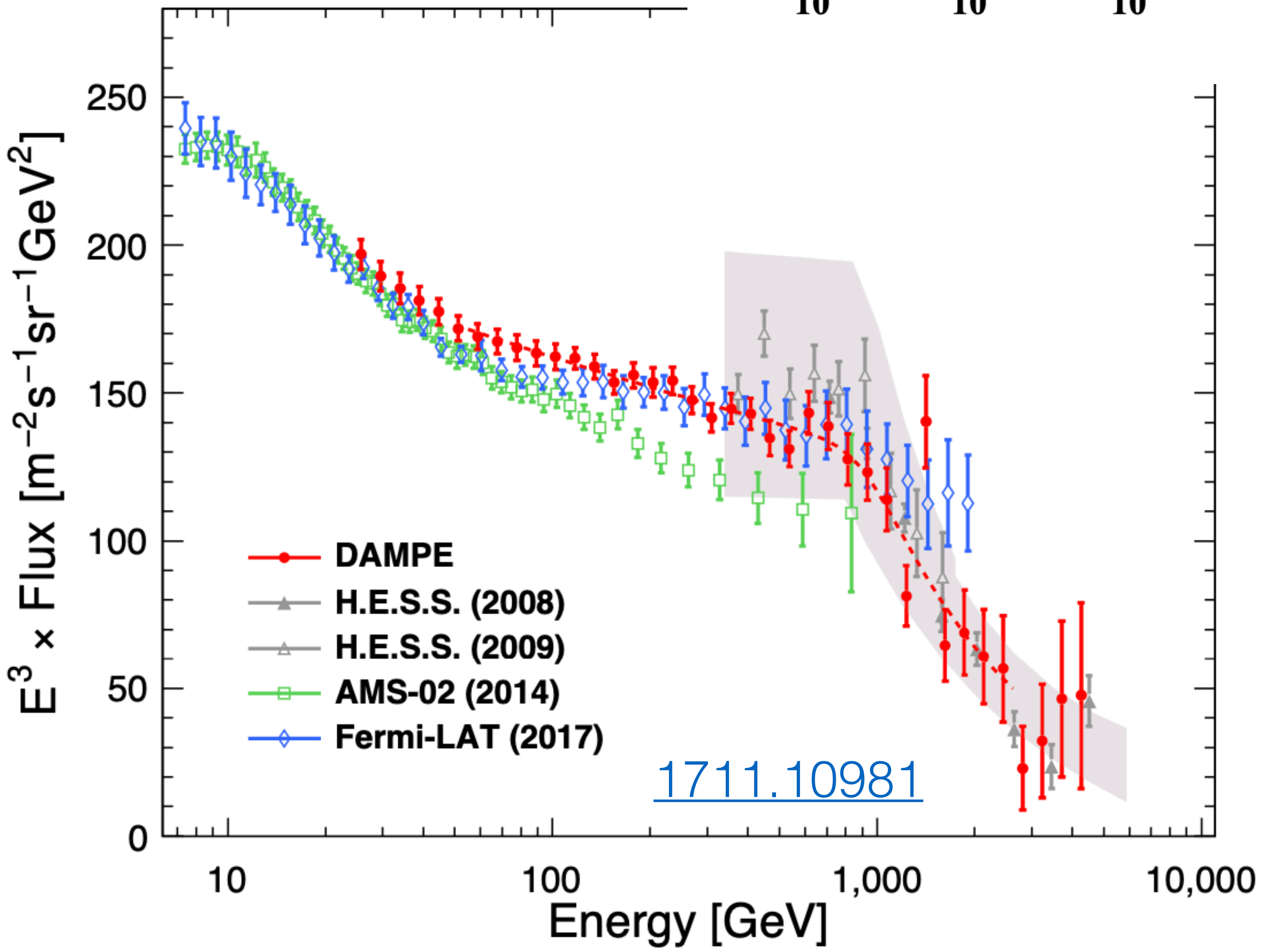
CCR anomalies and questions

Excess in anti-protons?

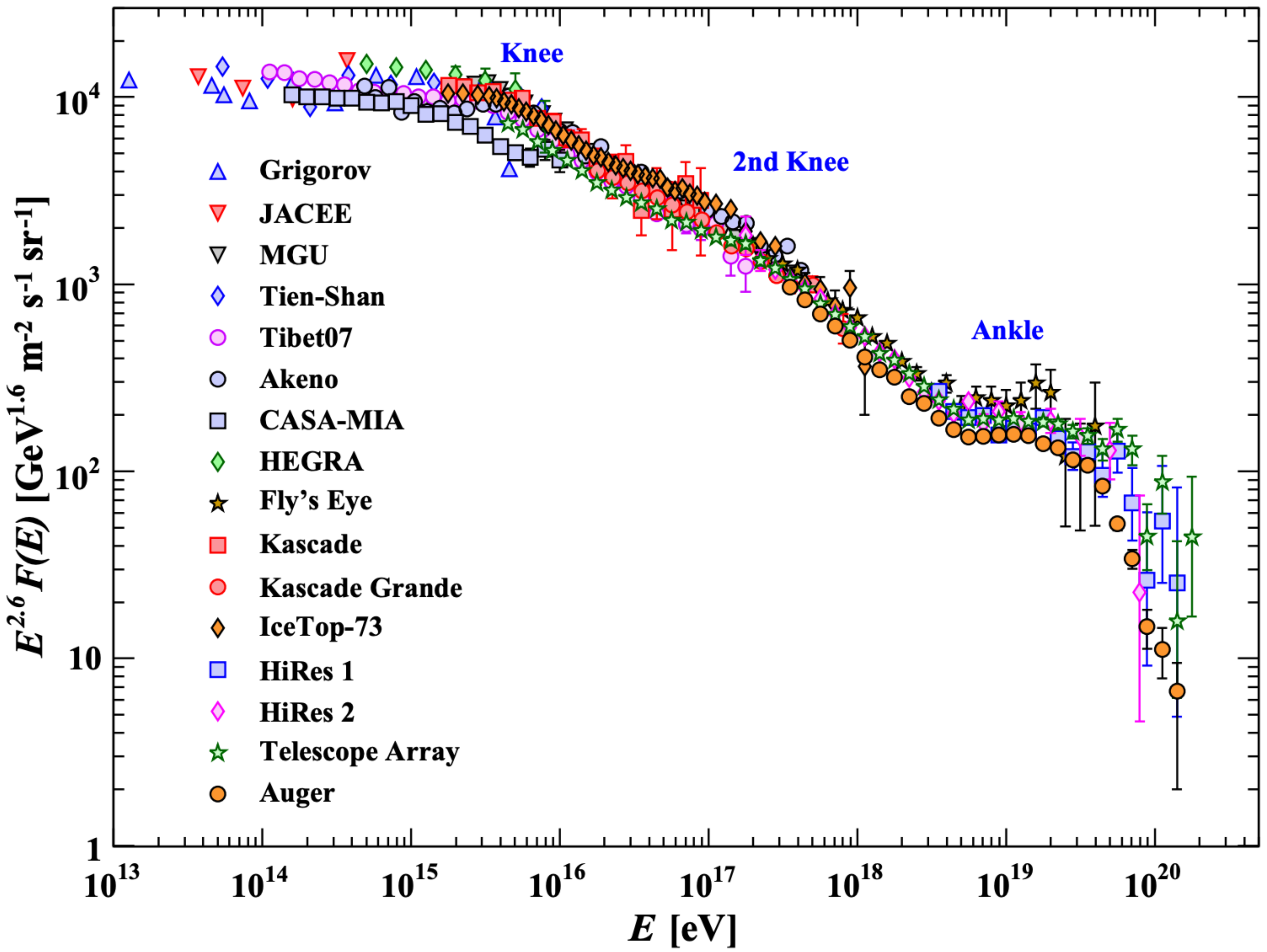


1610.03071

Excess in electrons?

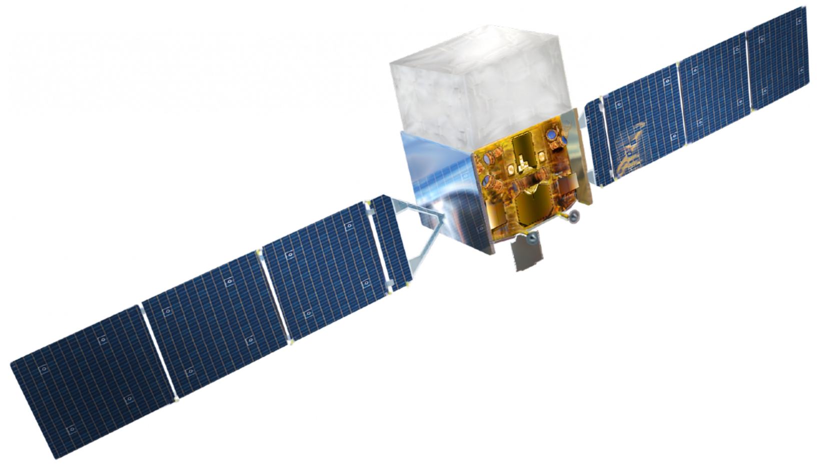


1711.10981

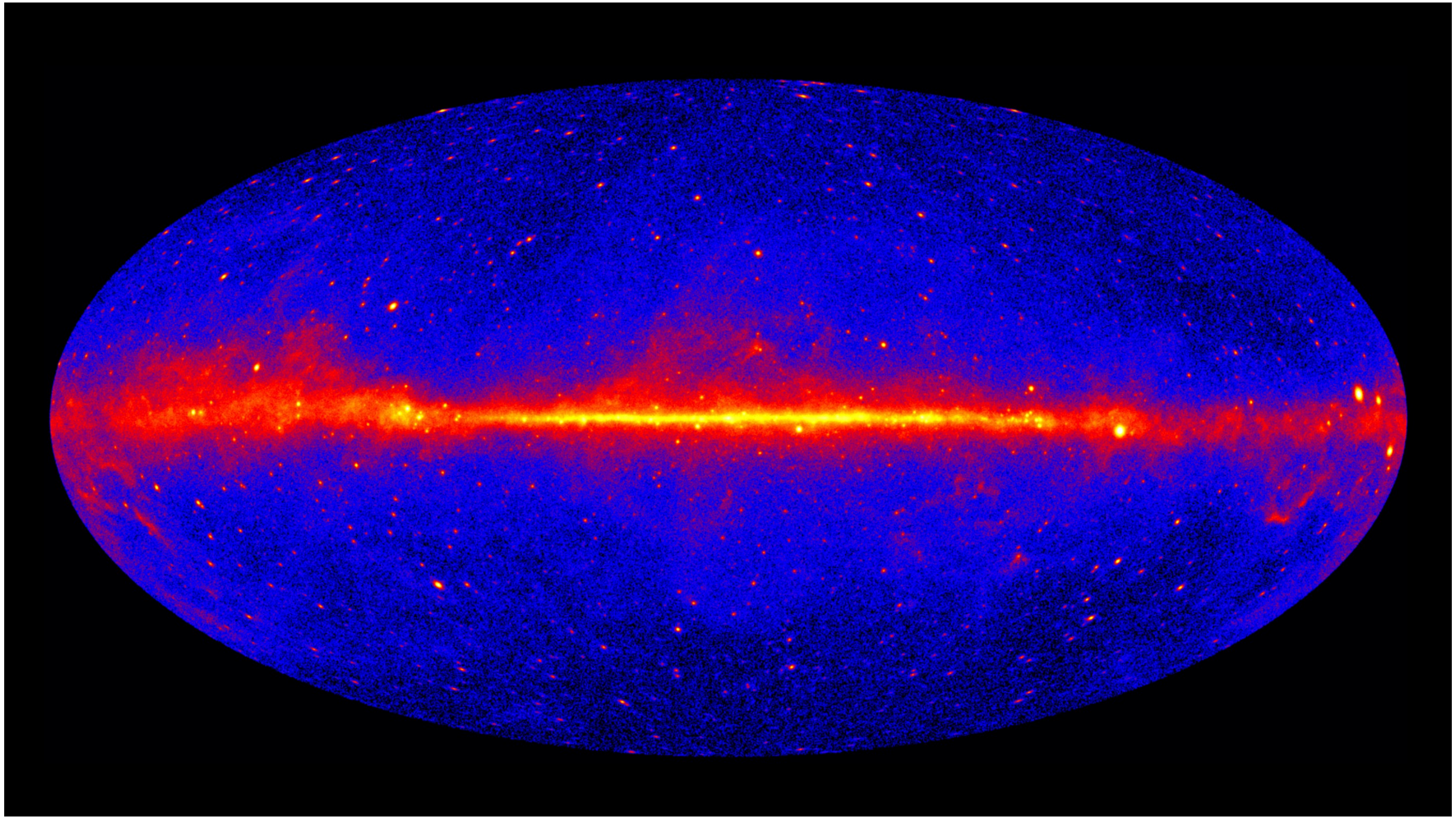


and others…

The Gamma-ray Sky



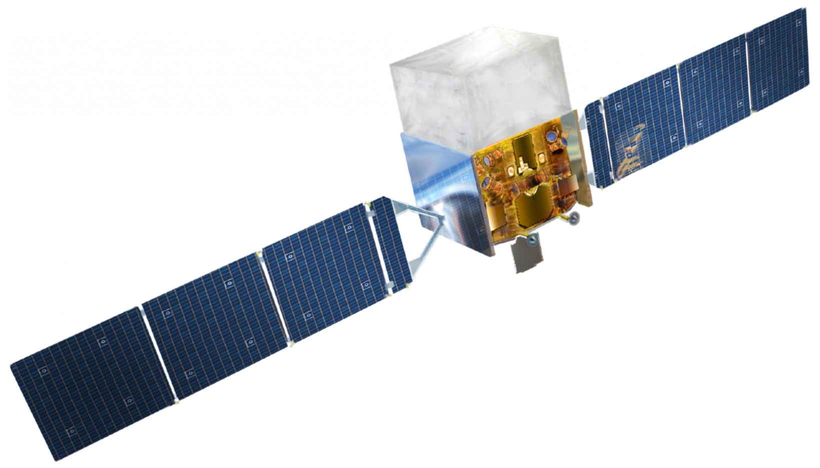
Gamma-ray Sky above 1 GeV, according to Fermi:

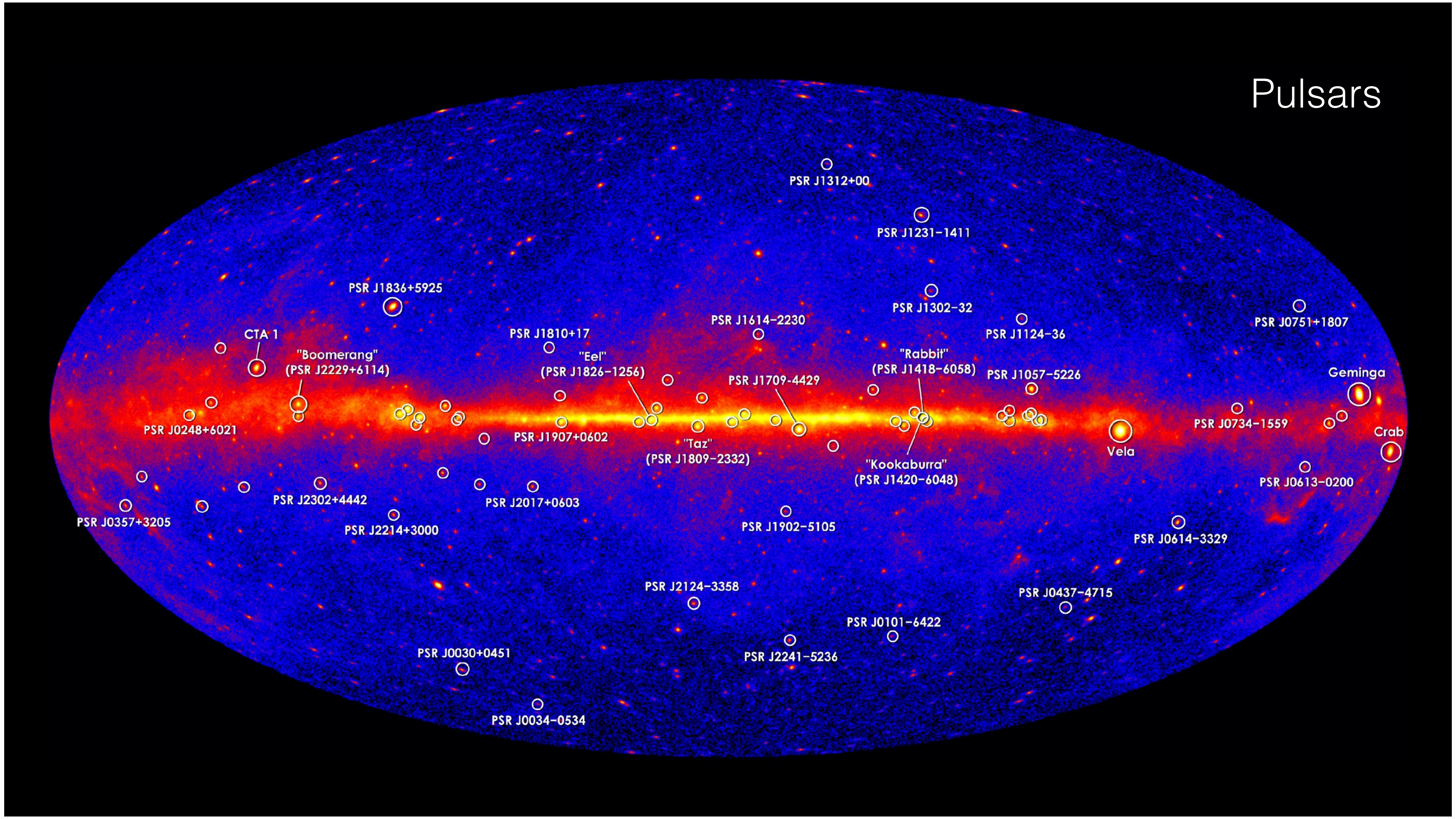


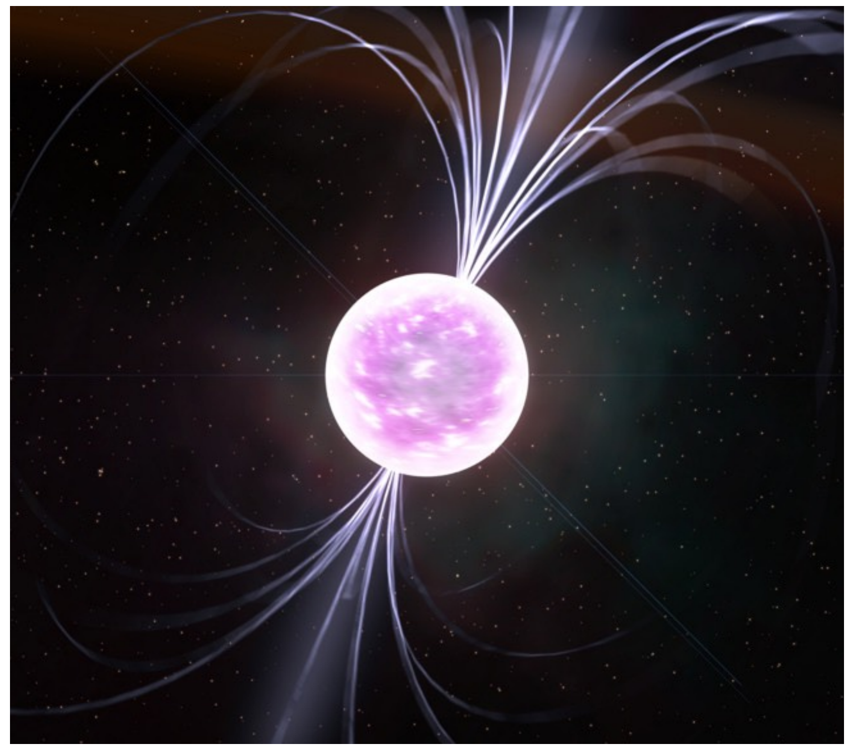
Credit: NASA/DOE/Fermi LAT Collaboration

The Gamma-ray Sky

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



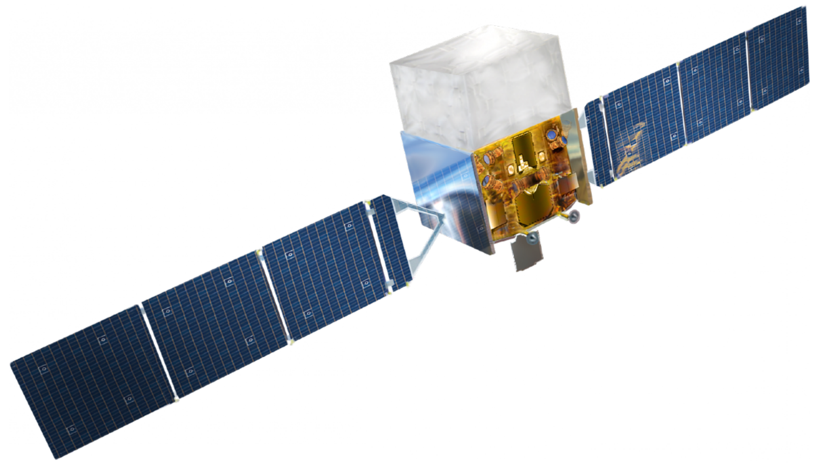




Credit: Kevin Gill / Flickr

Credit: NASA/DOE/Fermi LAT Collaboration

The Gamma-ray Sky



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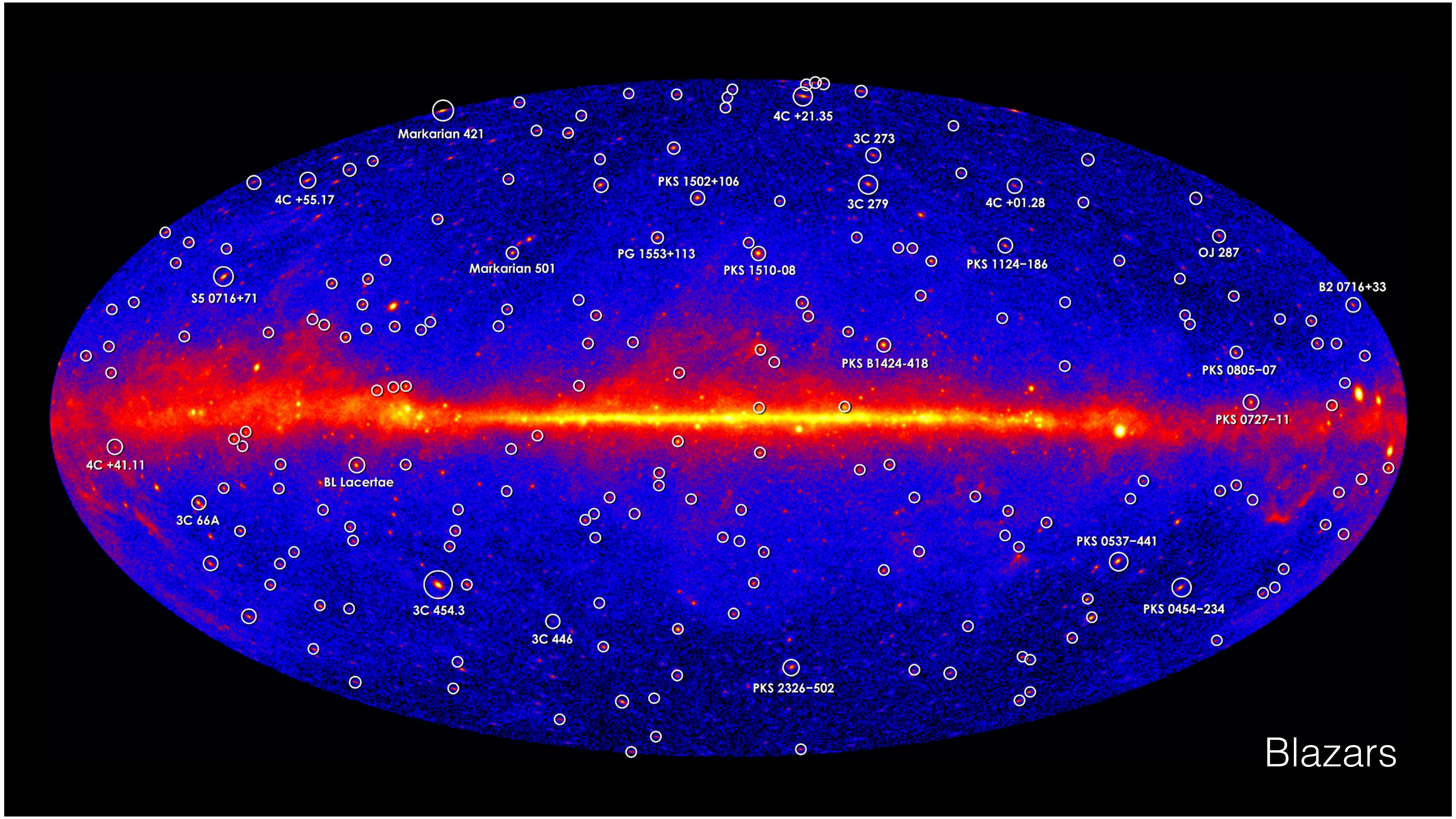


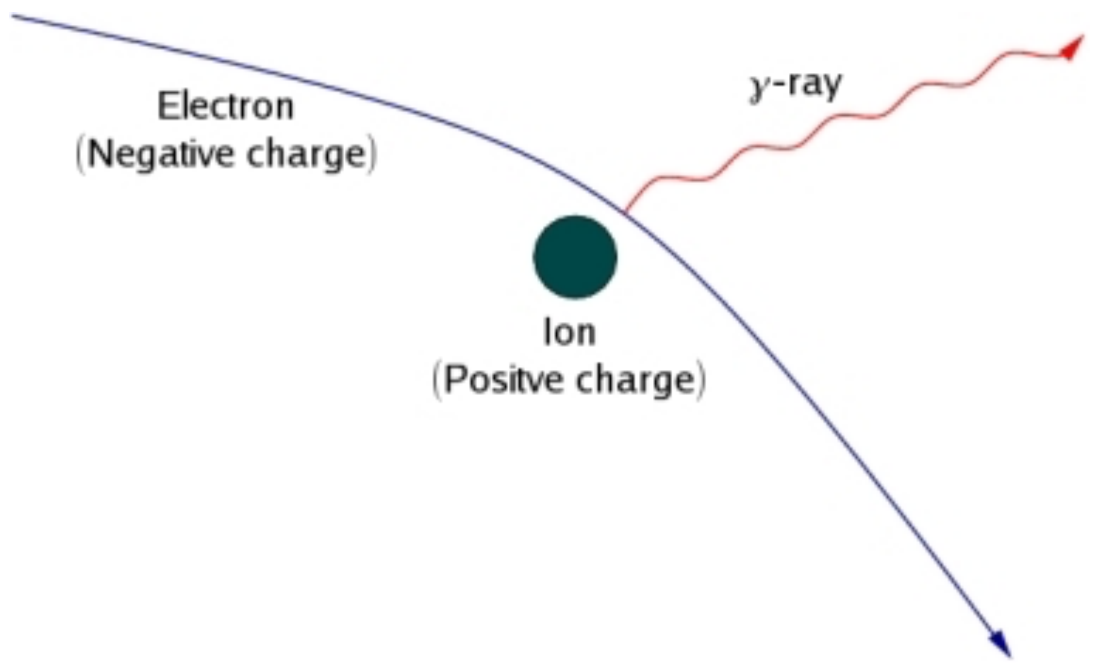
Credit: [NASA/DOE/Fermi LAT Collaboration]

Credit: ESO/M. Kornmesser

Cosmic Ray Connection

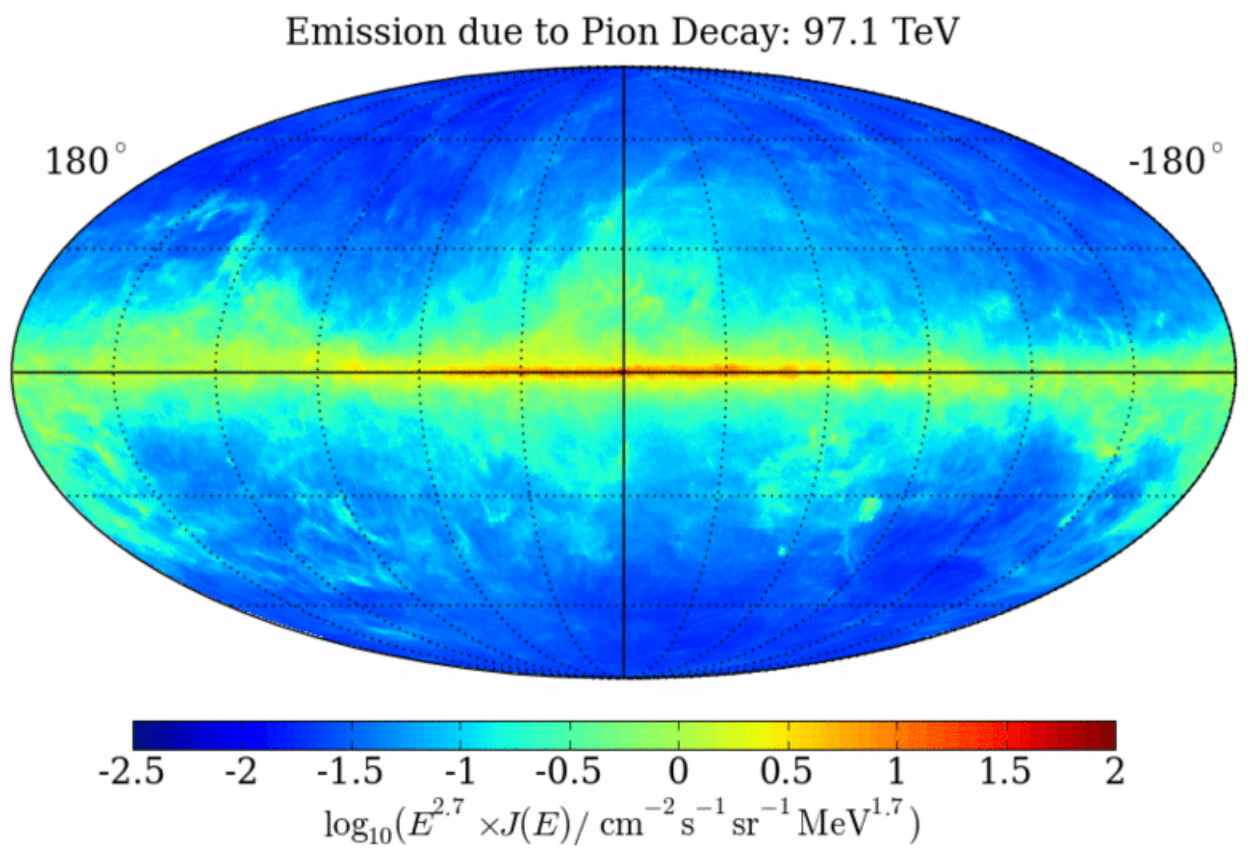
Pion Decay $p_{\rm CR} \longrightarrow p_{\rm ISM} \to \pi^0 \to \gamma\,\gamma$, $\ldots$ *CR protons + gas*

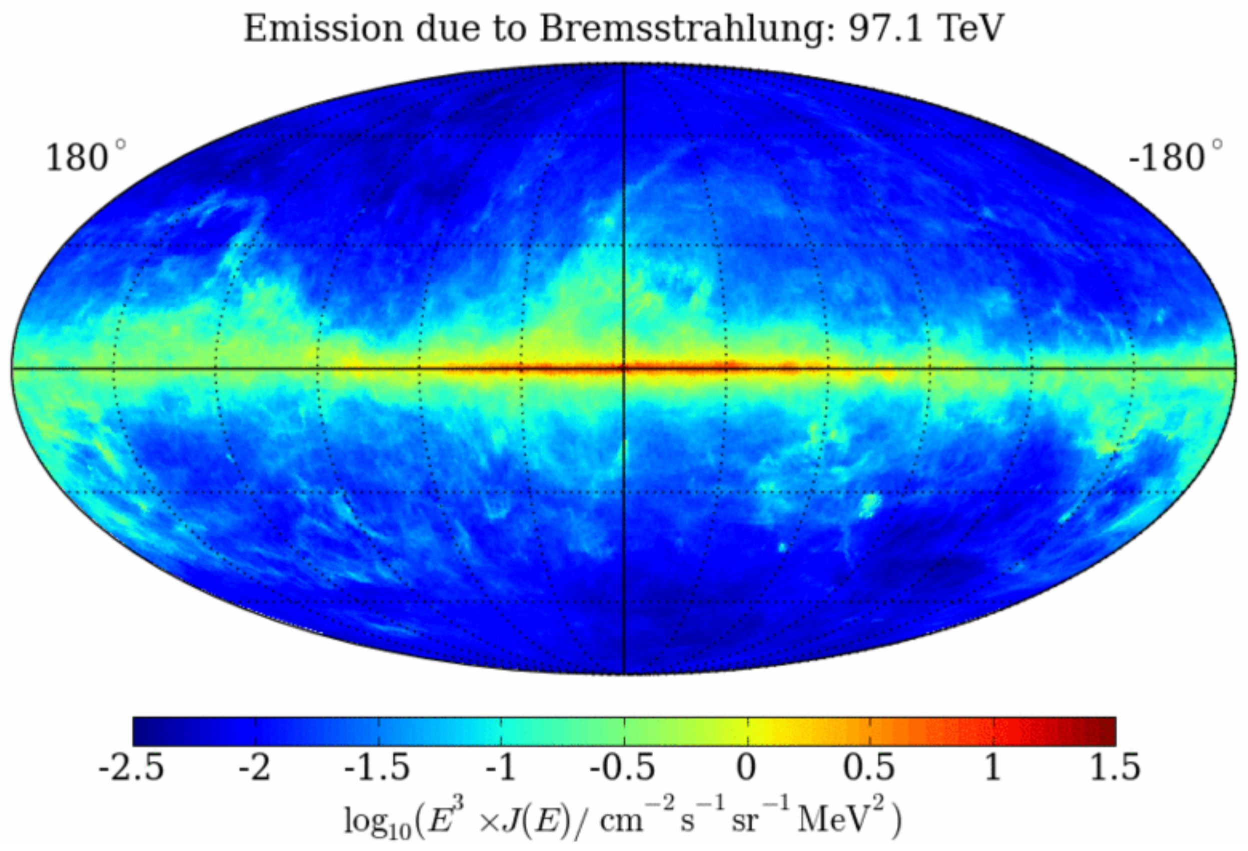
Brehmsstrahlung

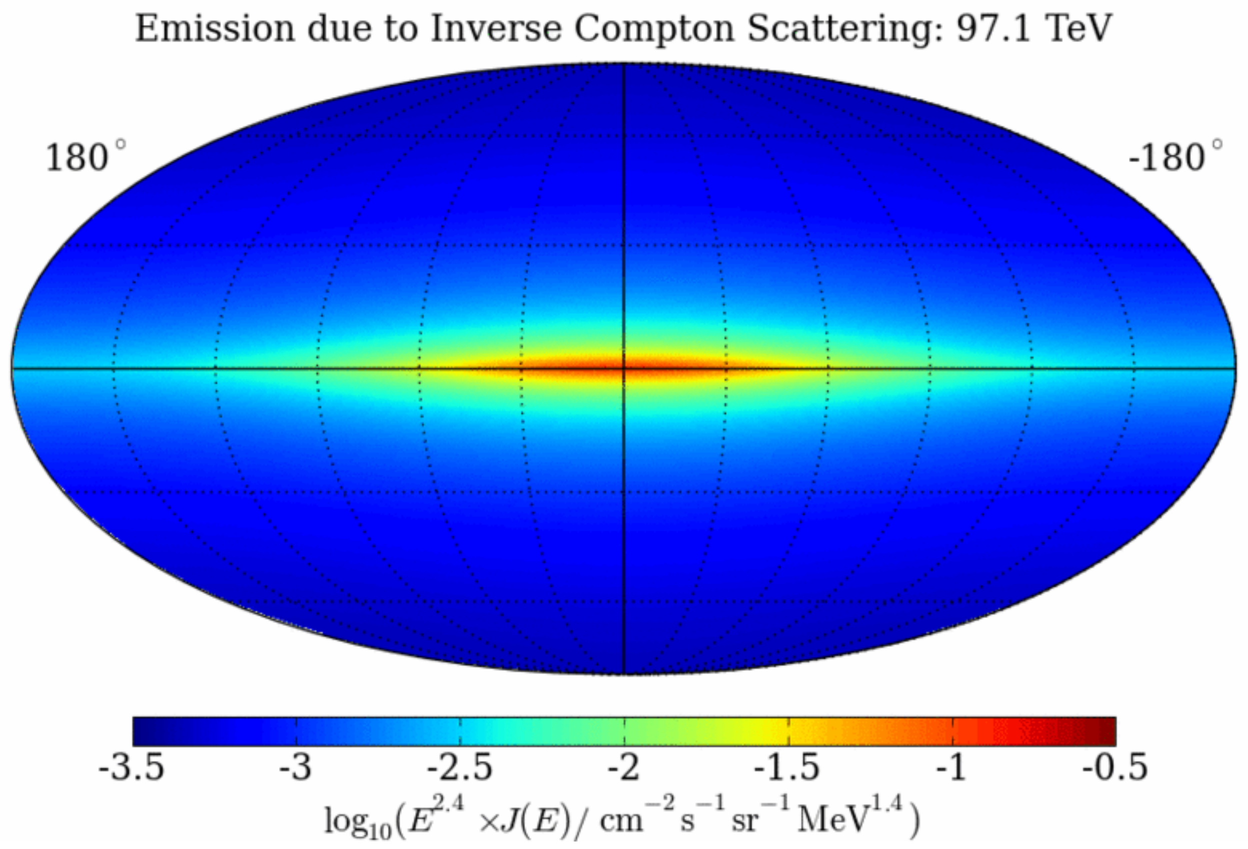


CR electrons + gas

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

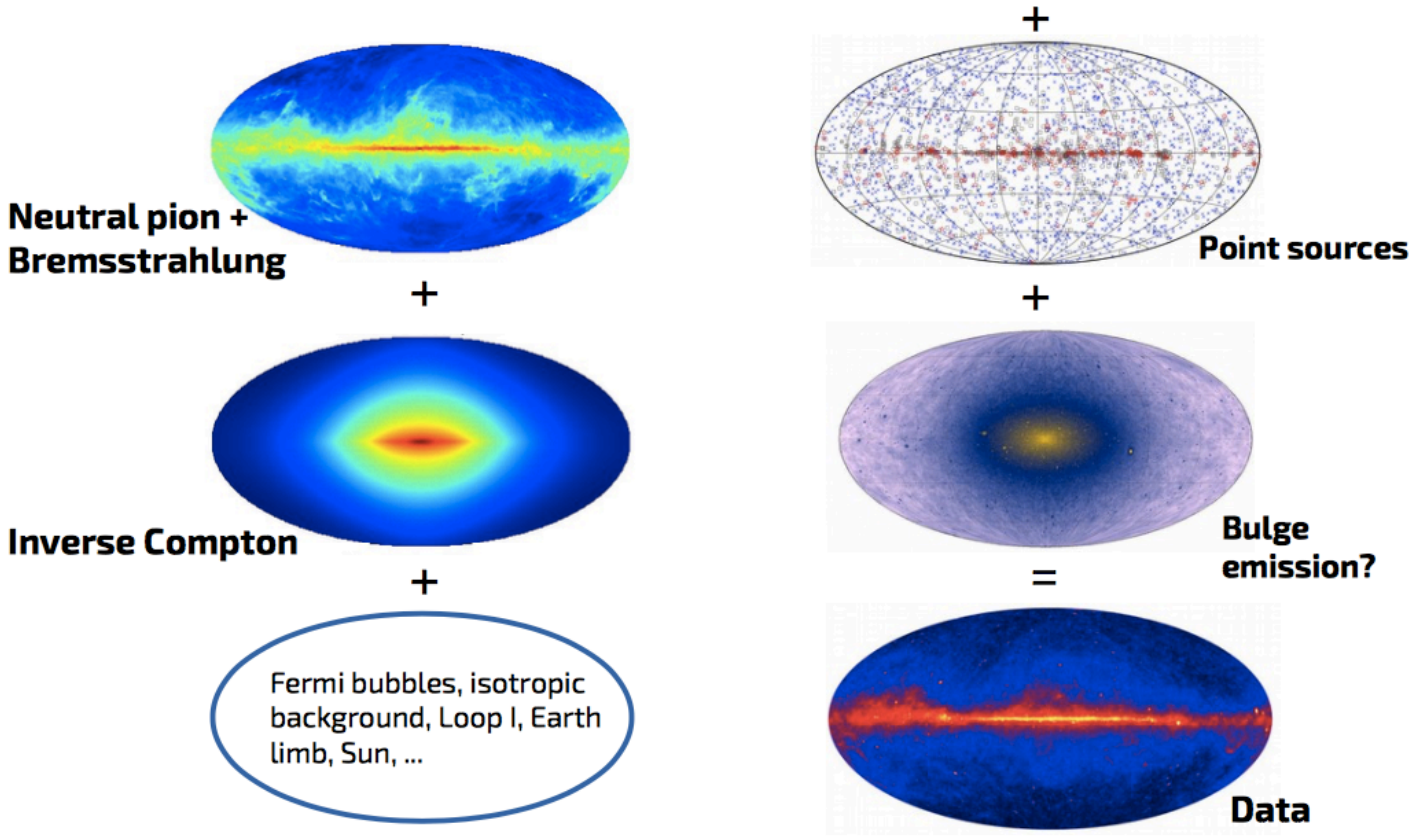




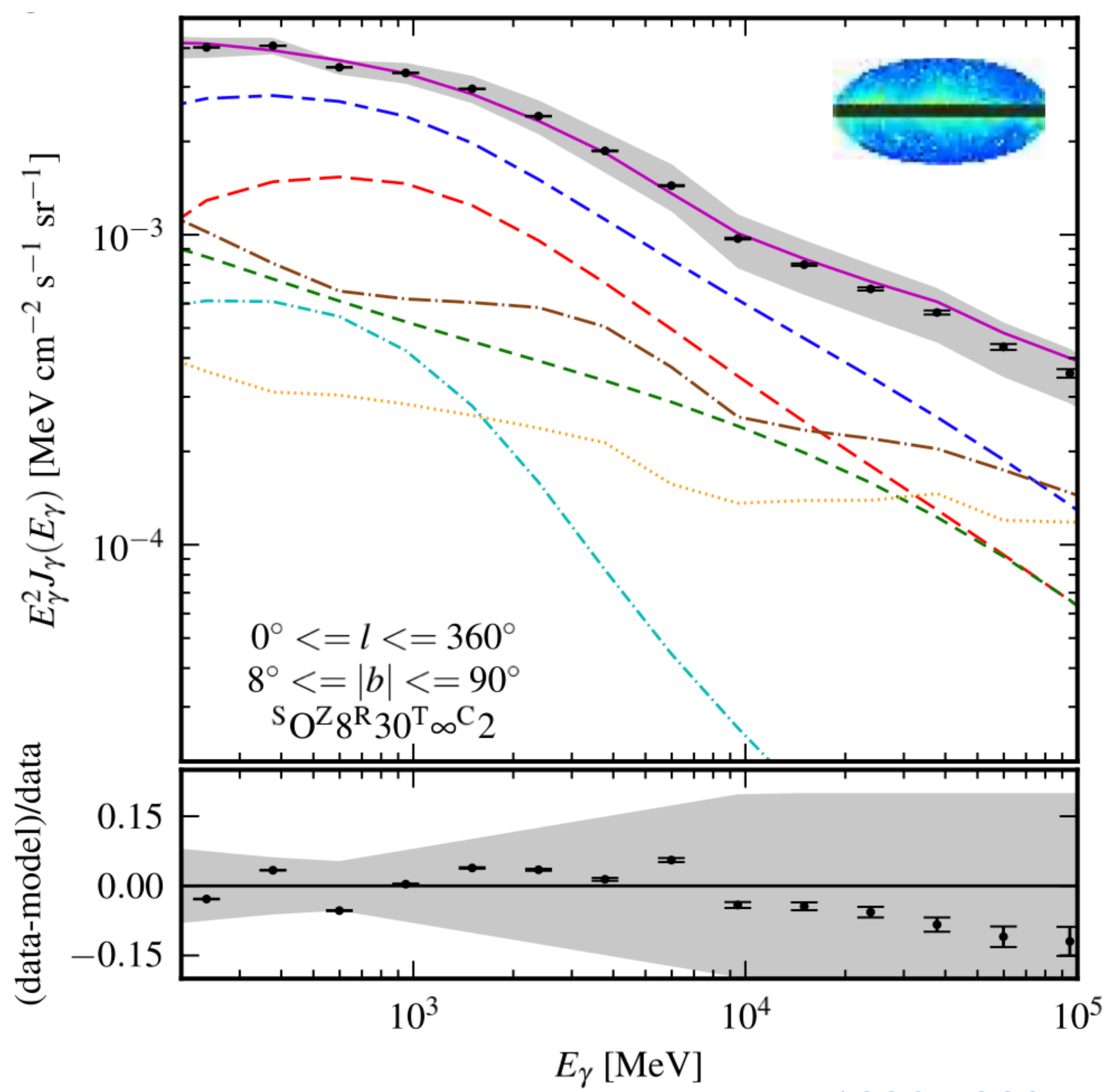


1708.07273

Modelling Gamma-ray emission



Isotropic Background
π^0 decay
Bremsstrahlung
Inverse Compton
Total Galactic
Point sources

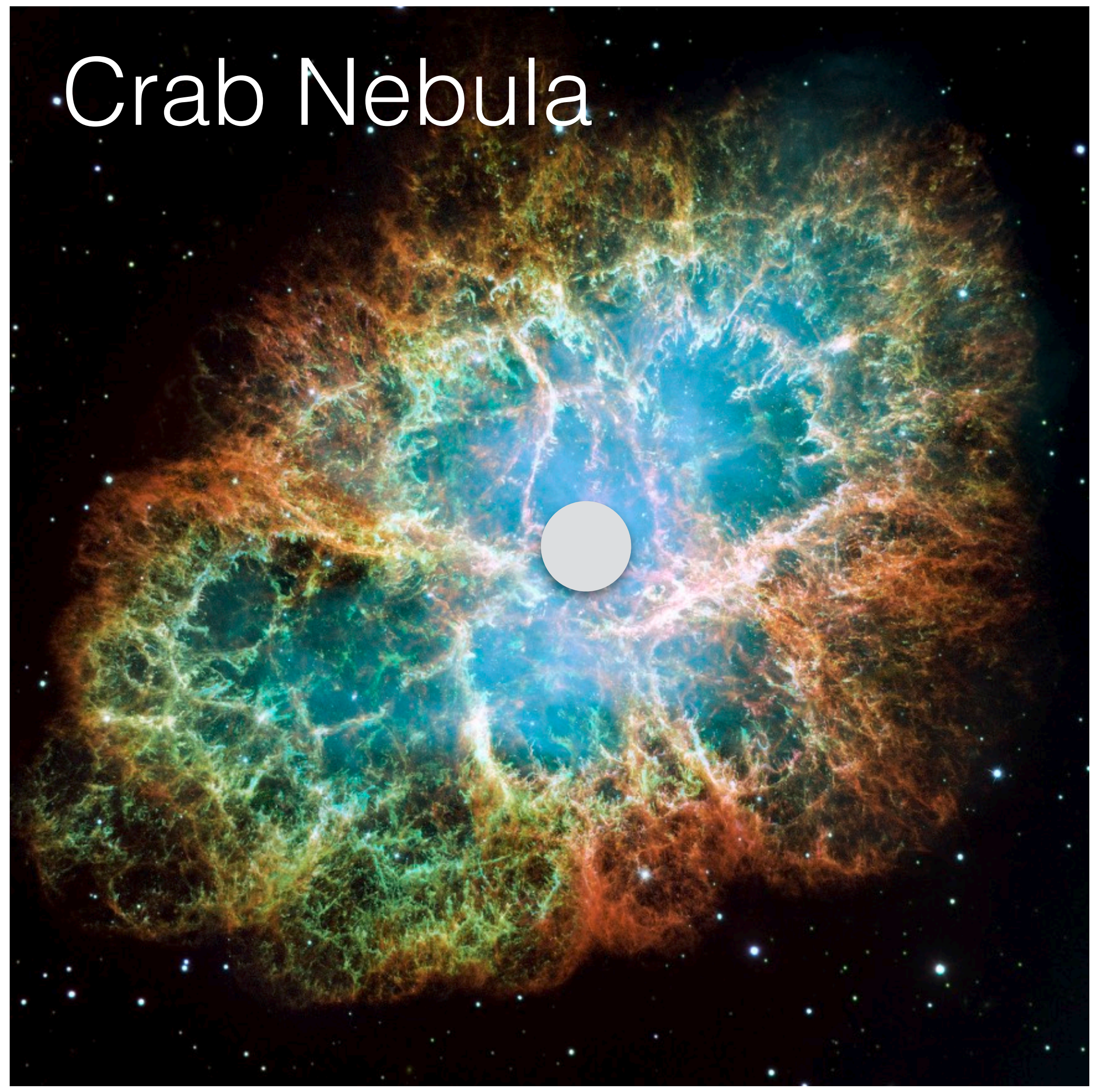


1202.4039

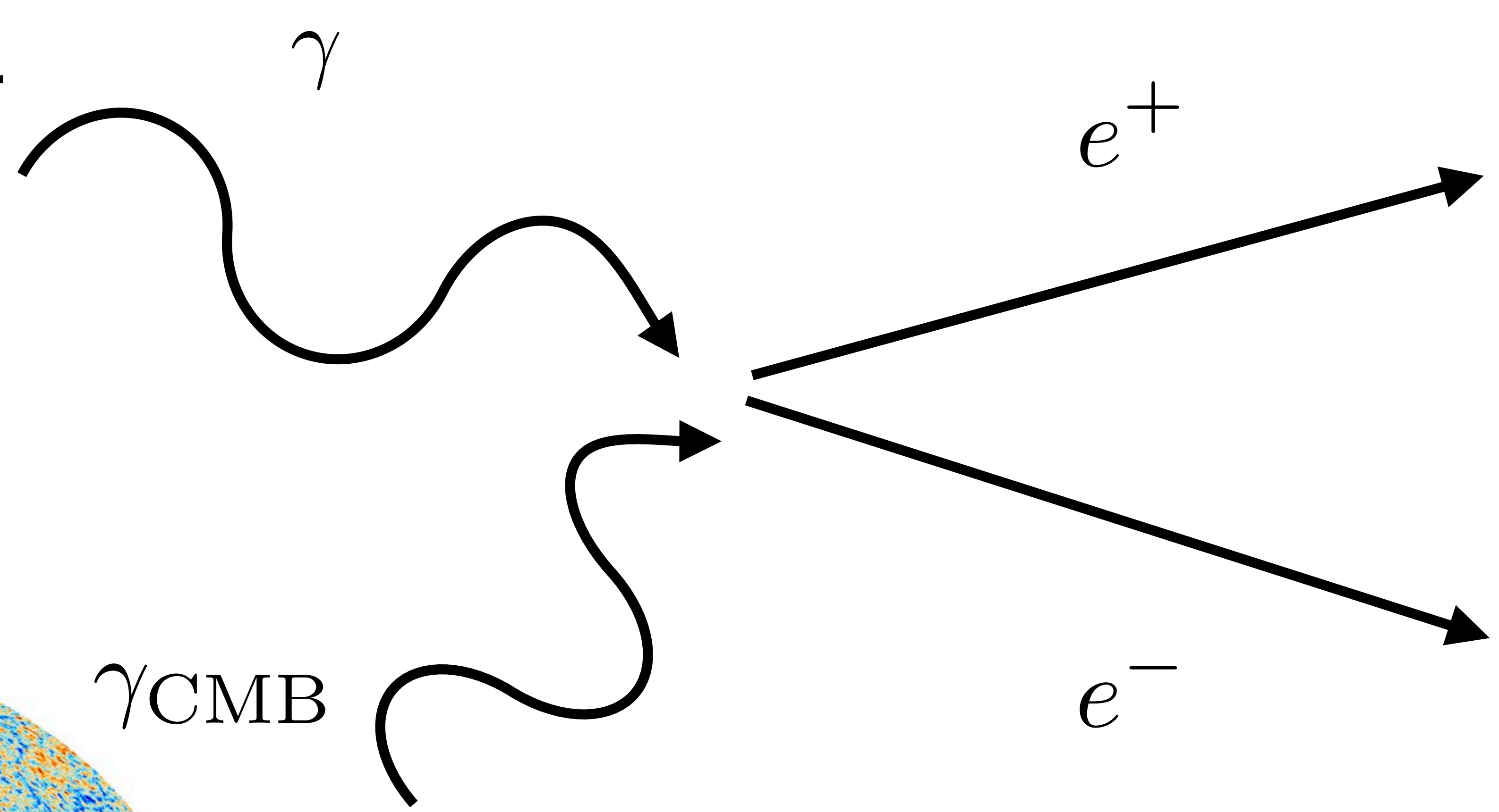
Credit: Christoph Weniger

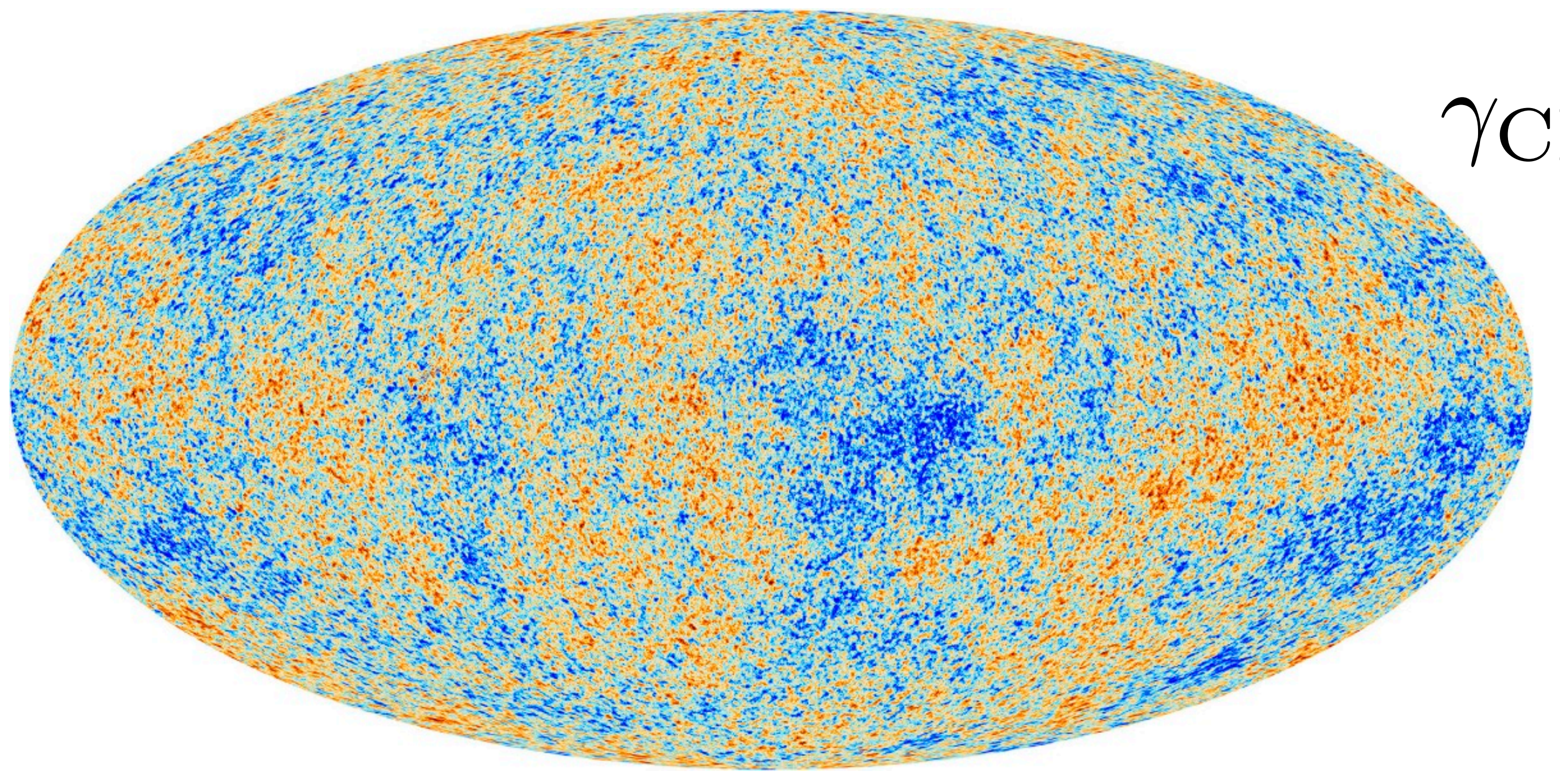
Gamma-ray horizon

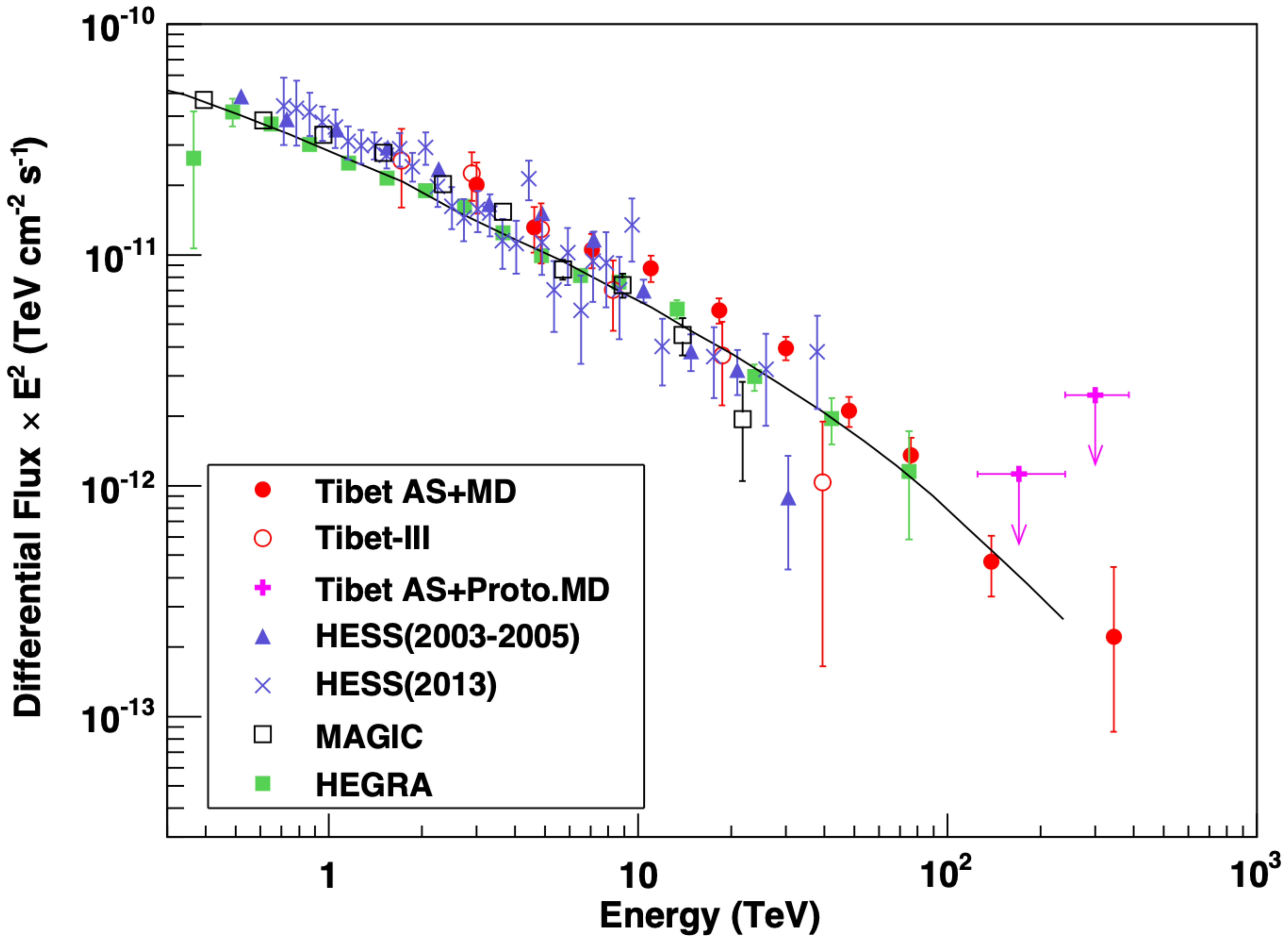
Credit: NASA/STScI



Similar to the GZK cut-off…







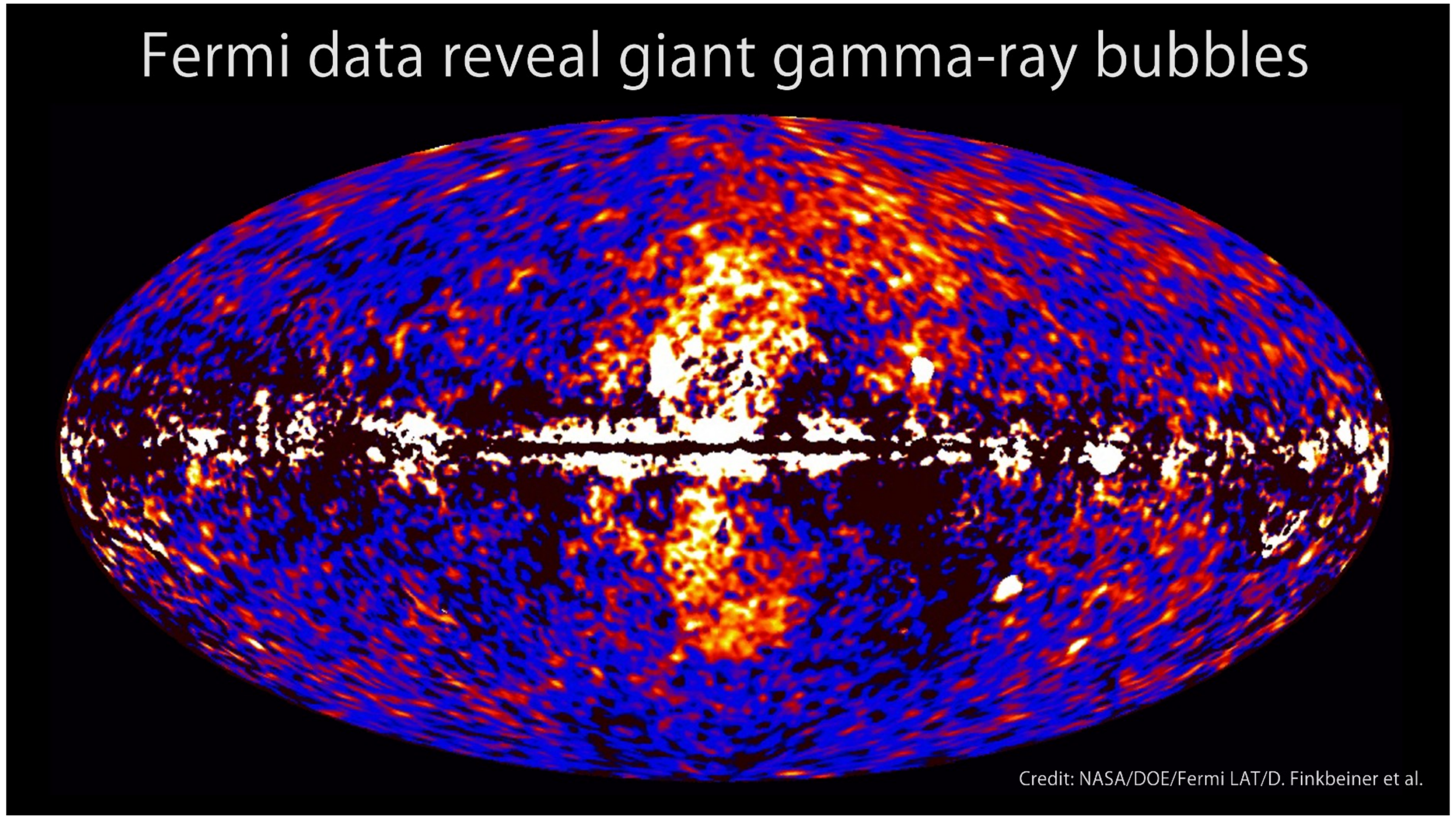
1906.05521

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

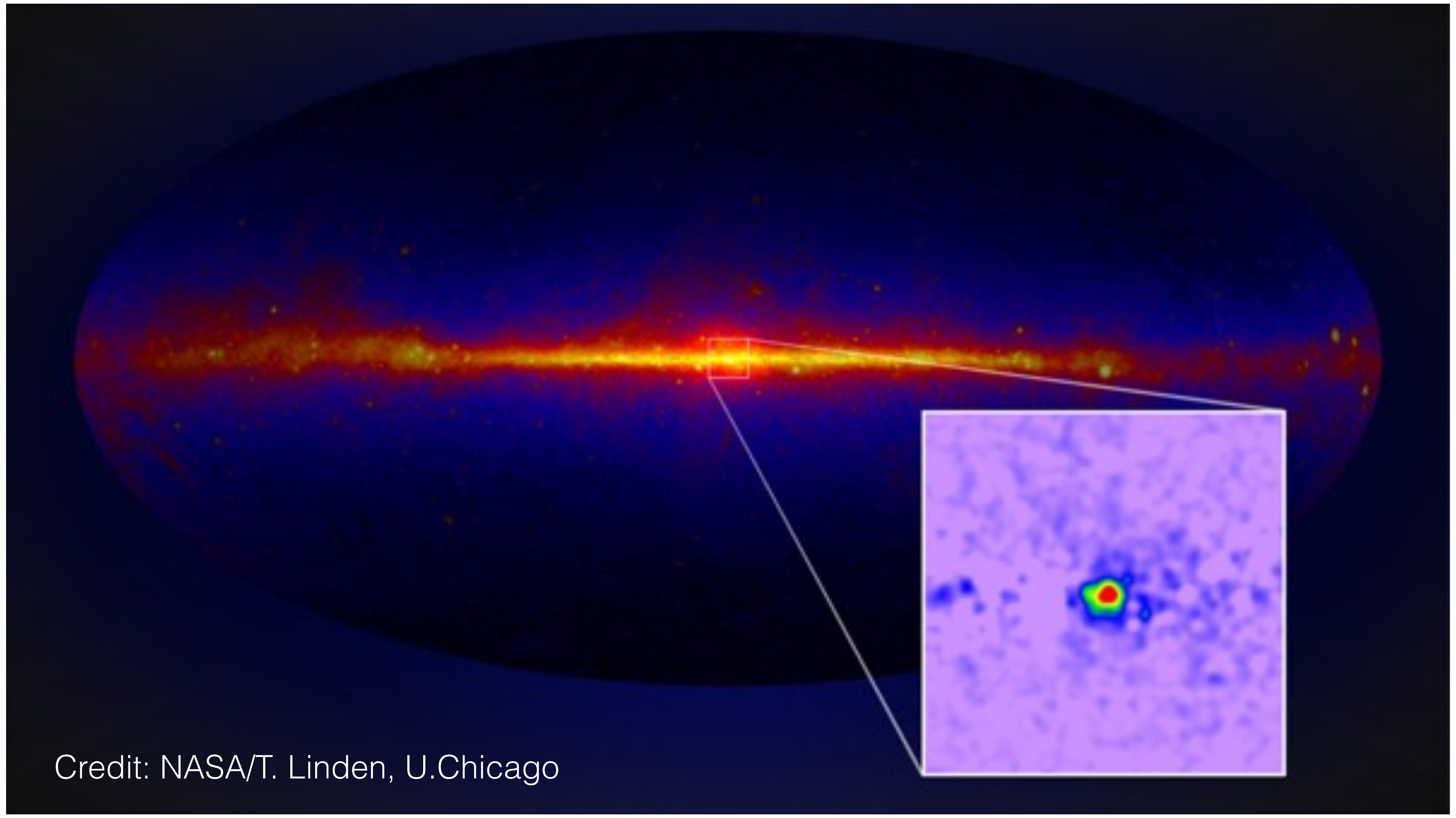
$$E_\gamma > \frac{2m_e^2}{E_{\rm bg}} \sim \begin{cases} 1\,\text{TeV} & \text{for scattering of IR background} \\ 800\,\text{TeV} & \text{for scattering of CMB} \end{cases}$$

Gamma-ray anomalies

Fermi Bubbles



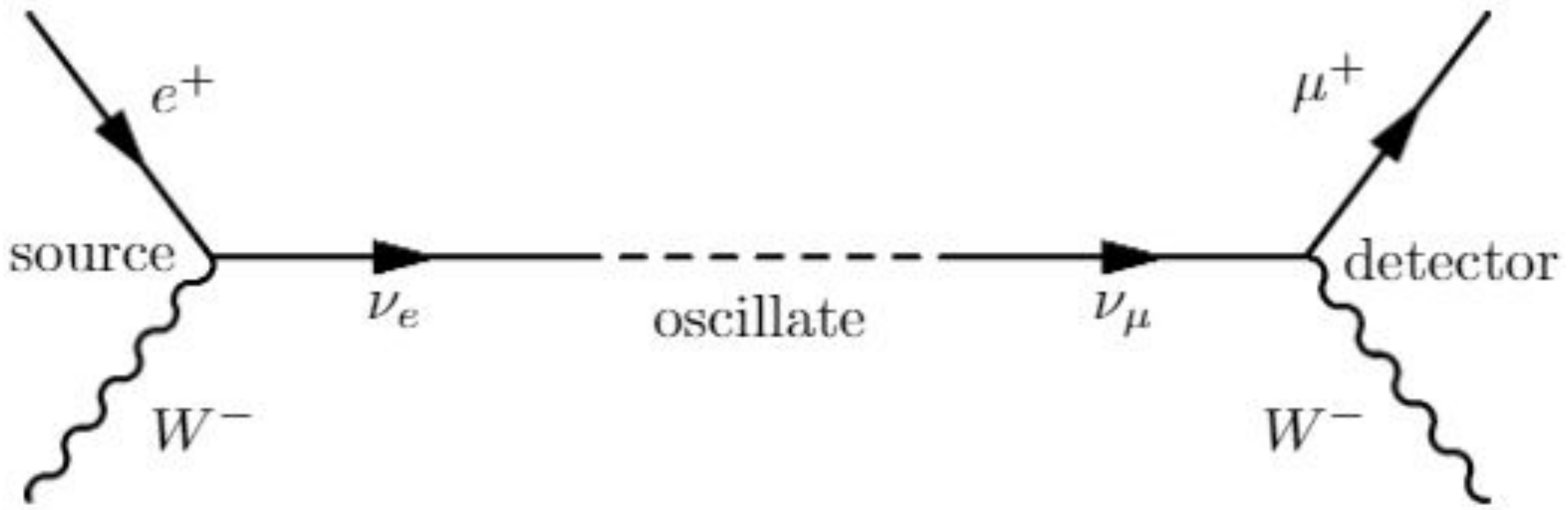
Galactic Centre Excess



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

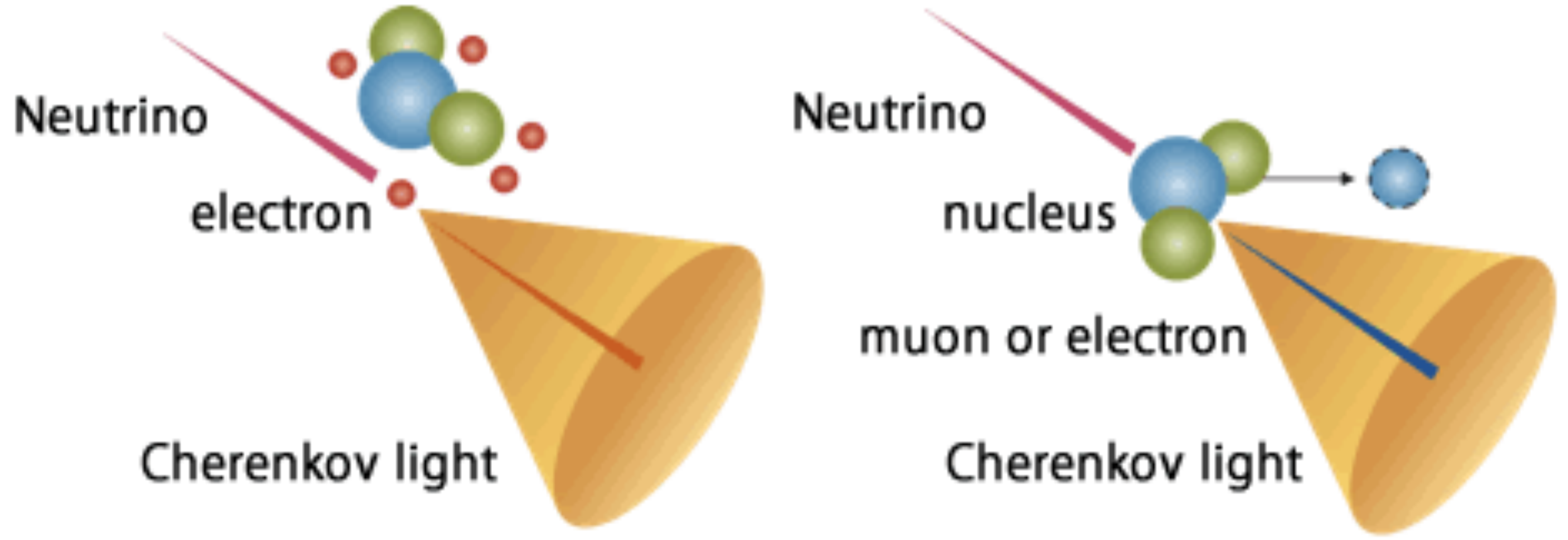
Neutrinos are produced with a definite flavor (e, μ, τ)
but they **oscillate** between the different flavors as they propagate.

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

IceCube

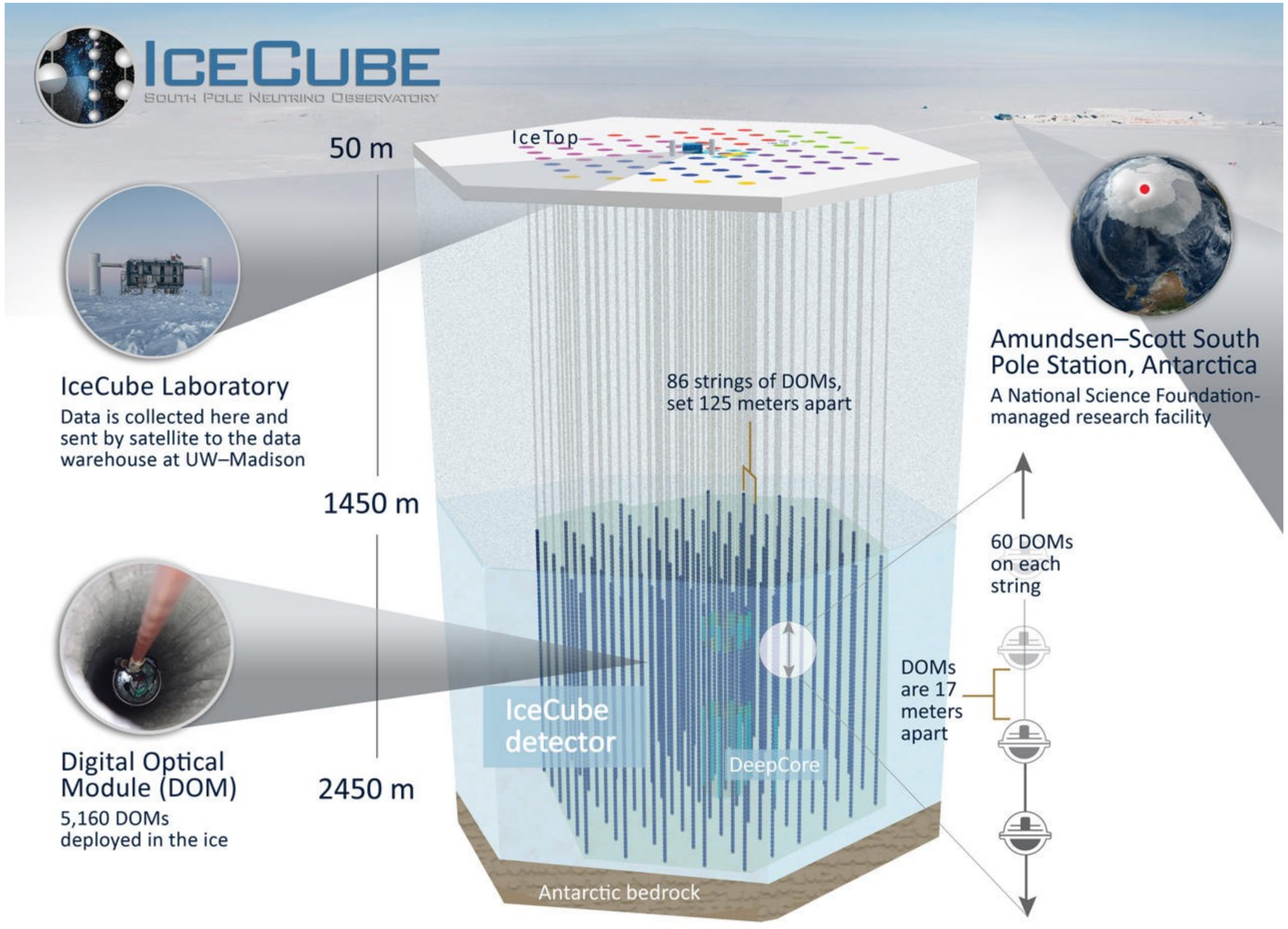
1701.03731

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



Credit: Hyper-Kamiokande

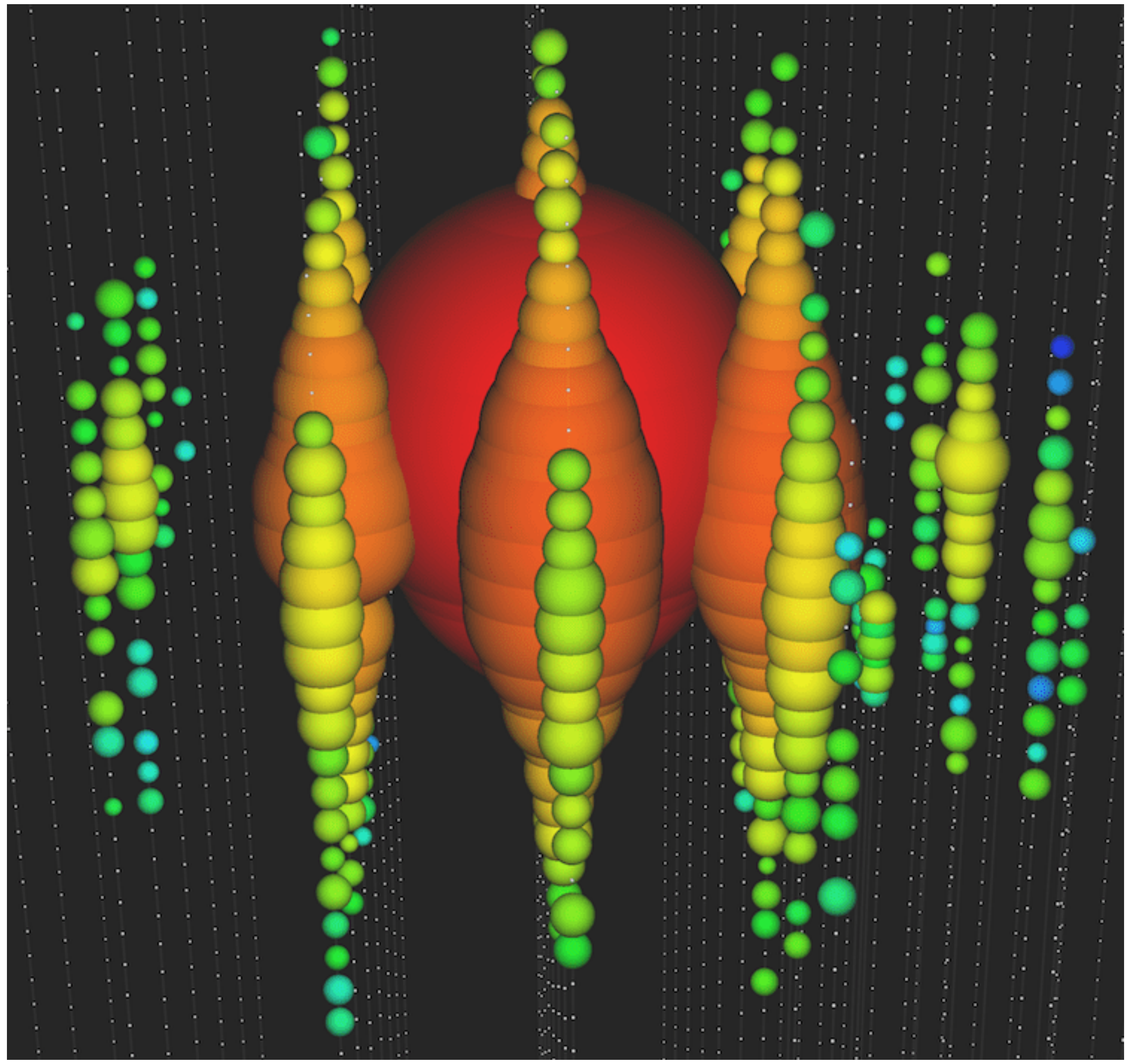
<u>IceCube</u>: a giant ice detector!
~1 km^3 of instrumented volume



See also SuperKamiokande, ANTARES, planned KM3NET

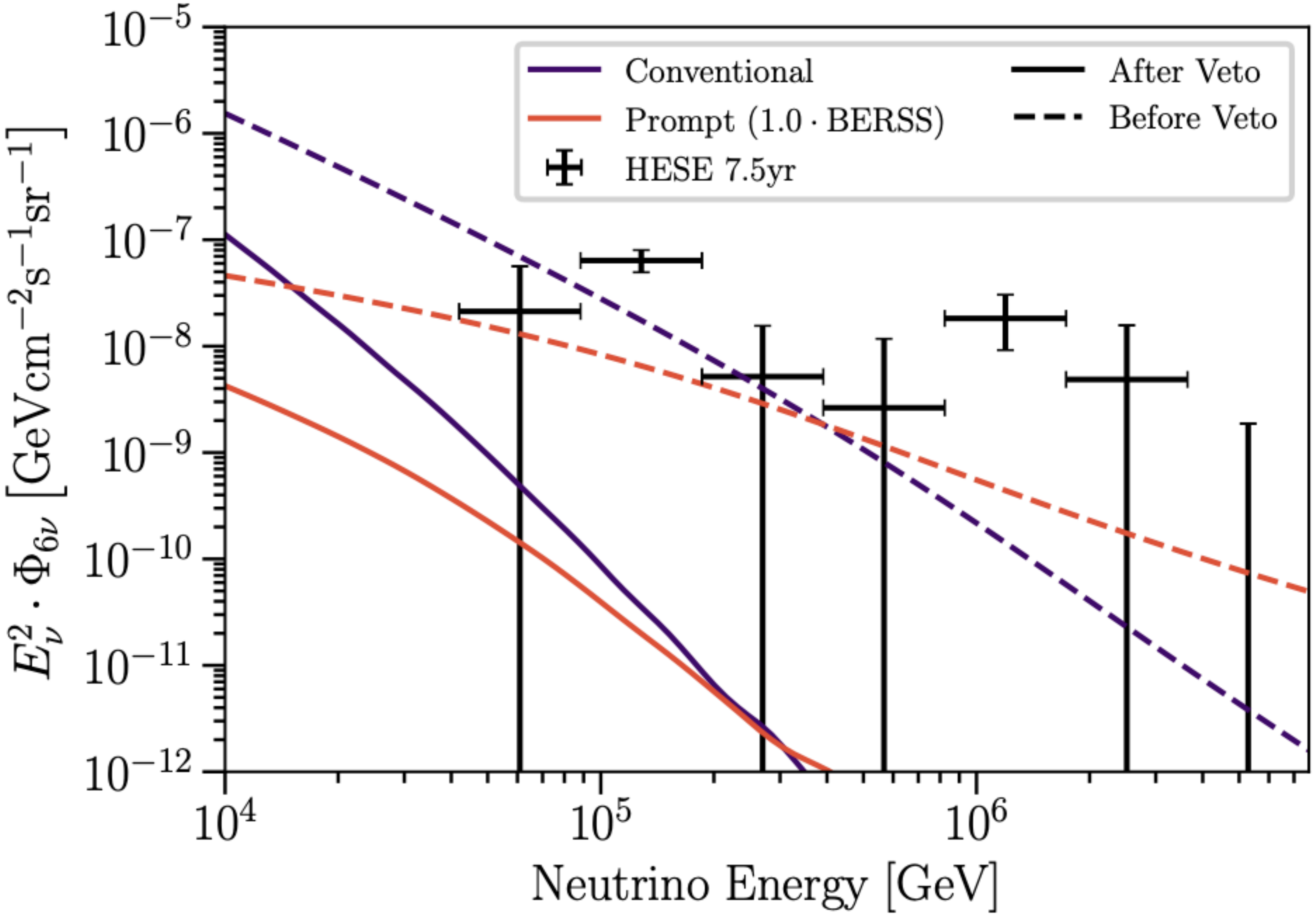
Ultra-high energy neutrinos

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



Credit: IceCube Collaboration

IceCube 'high energy starting events' (HESE)

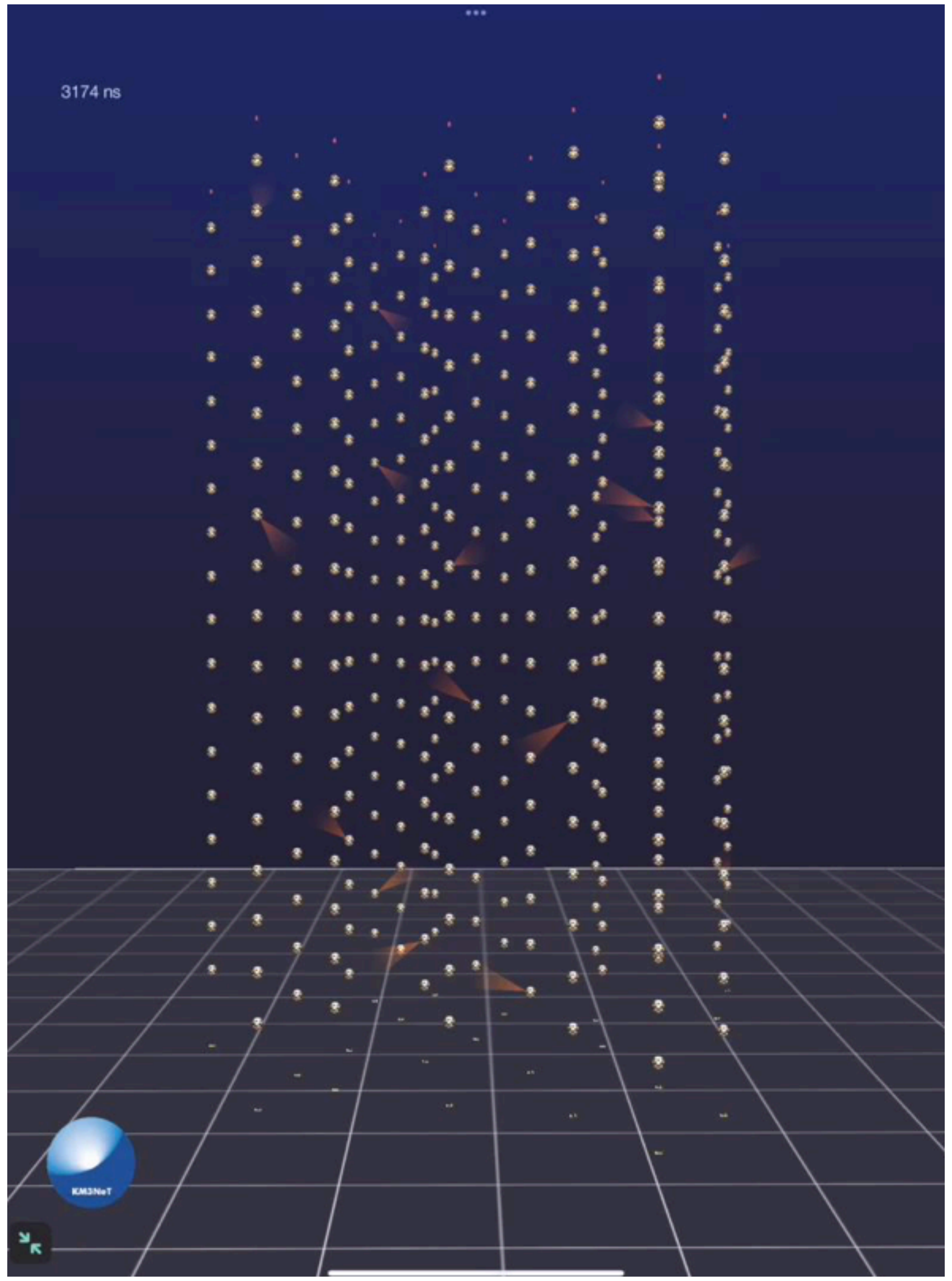


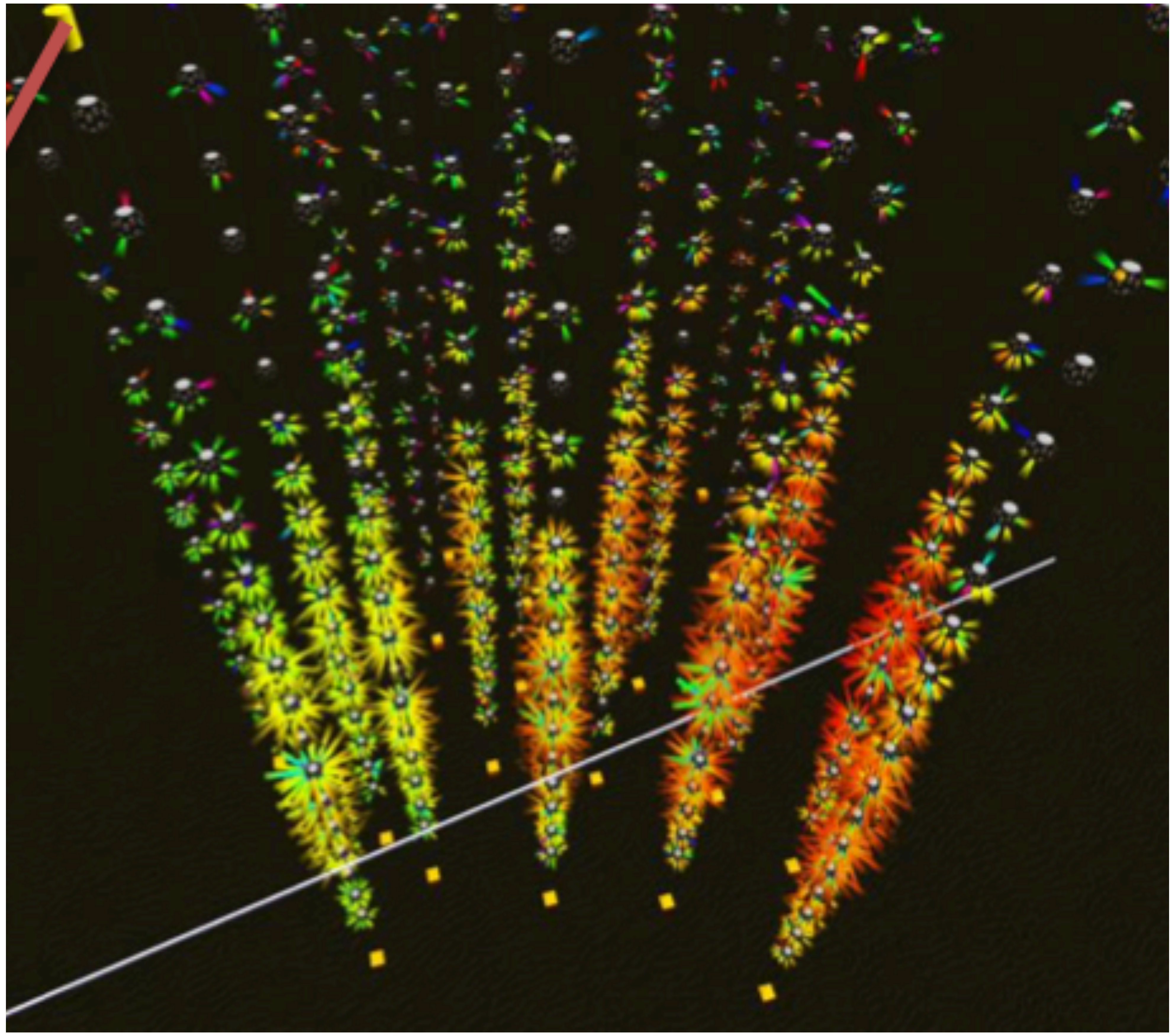
2011.03545

Unknown Territory

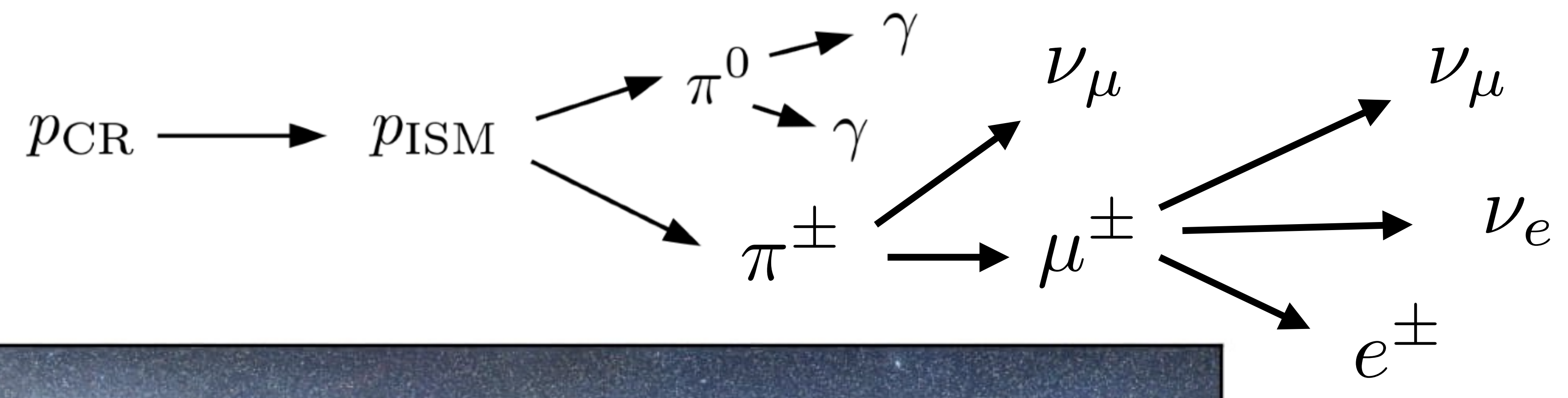
KM3NeT - A neutrino detector under development in the Mediterranean Sea

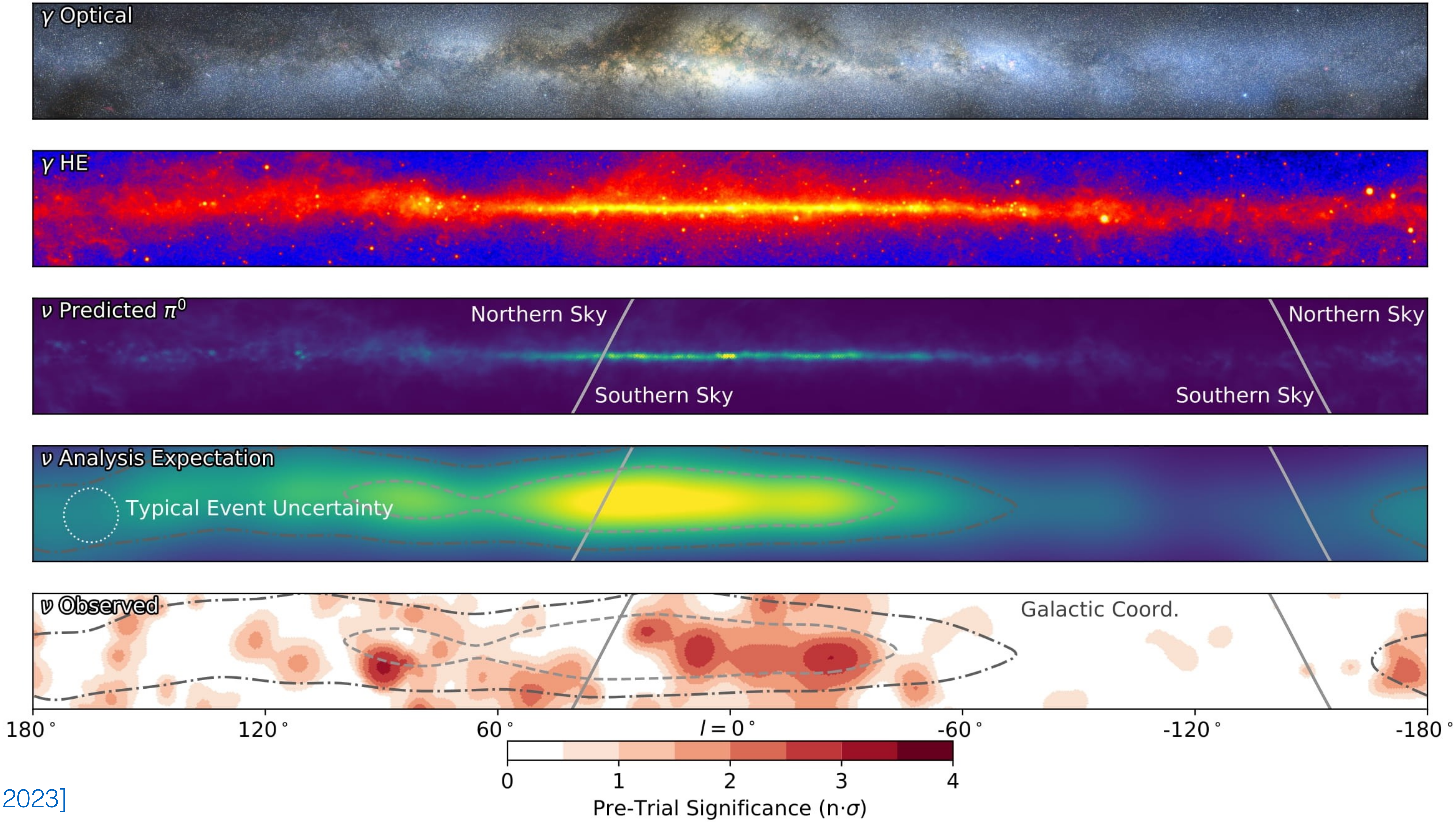
Recently reported a neutrino event with energy much much larger than $E \gg 10\,\mathrm{PeV} \sim 10^{16}\,\mathrm{eV}$





Milky Way shines bright in Neutrinos!



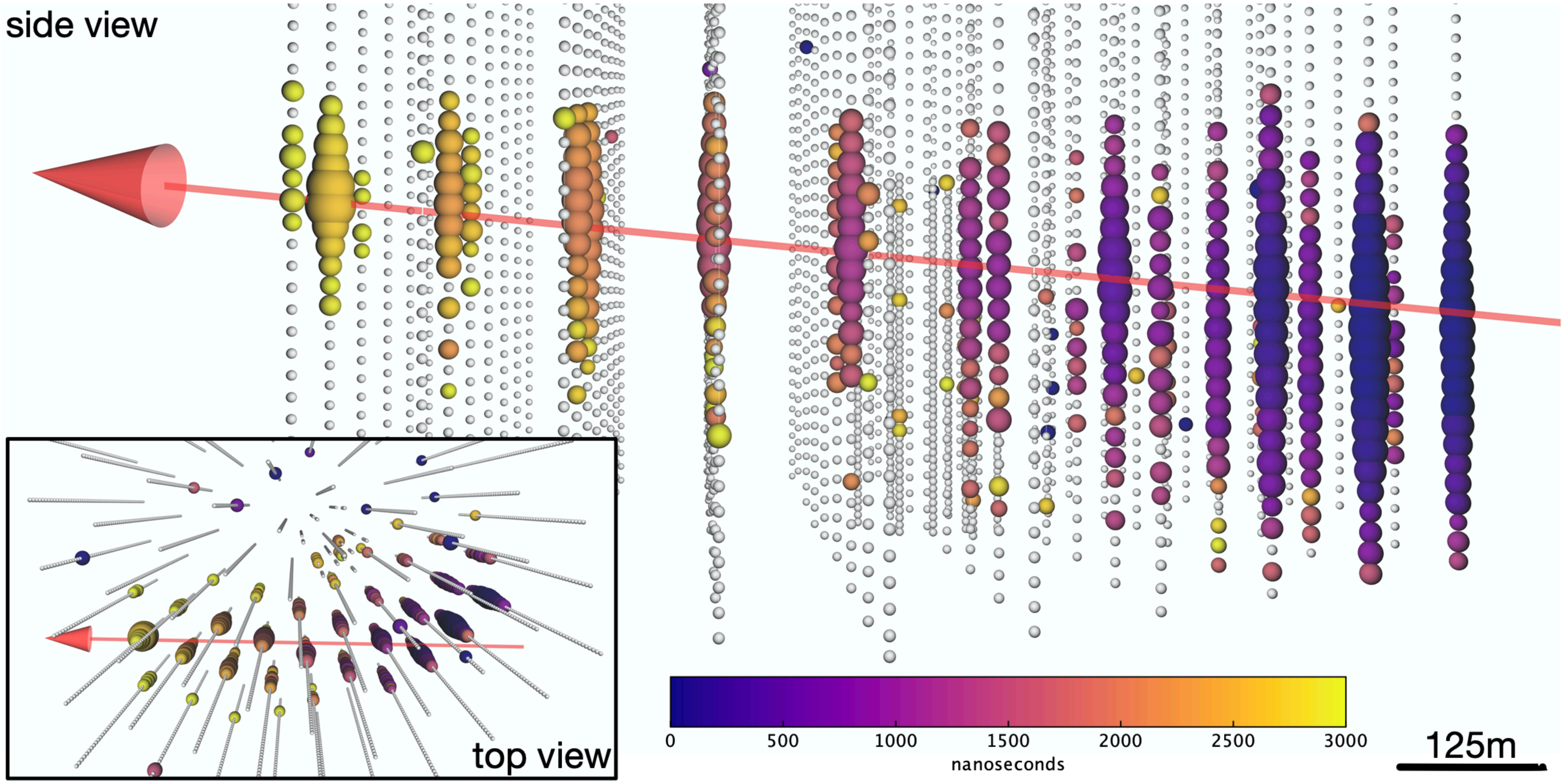


[IceCube, 2023]

IceCube-170922A

[1807.08816]

22 September 2017

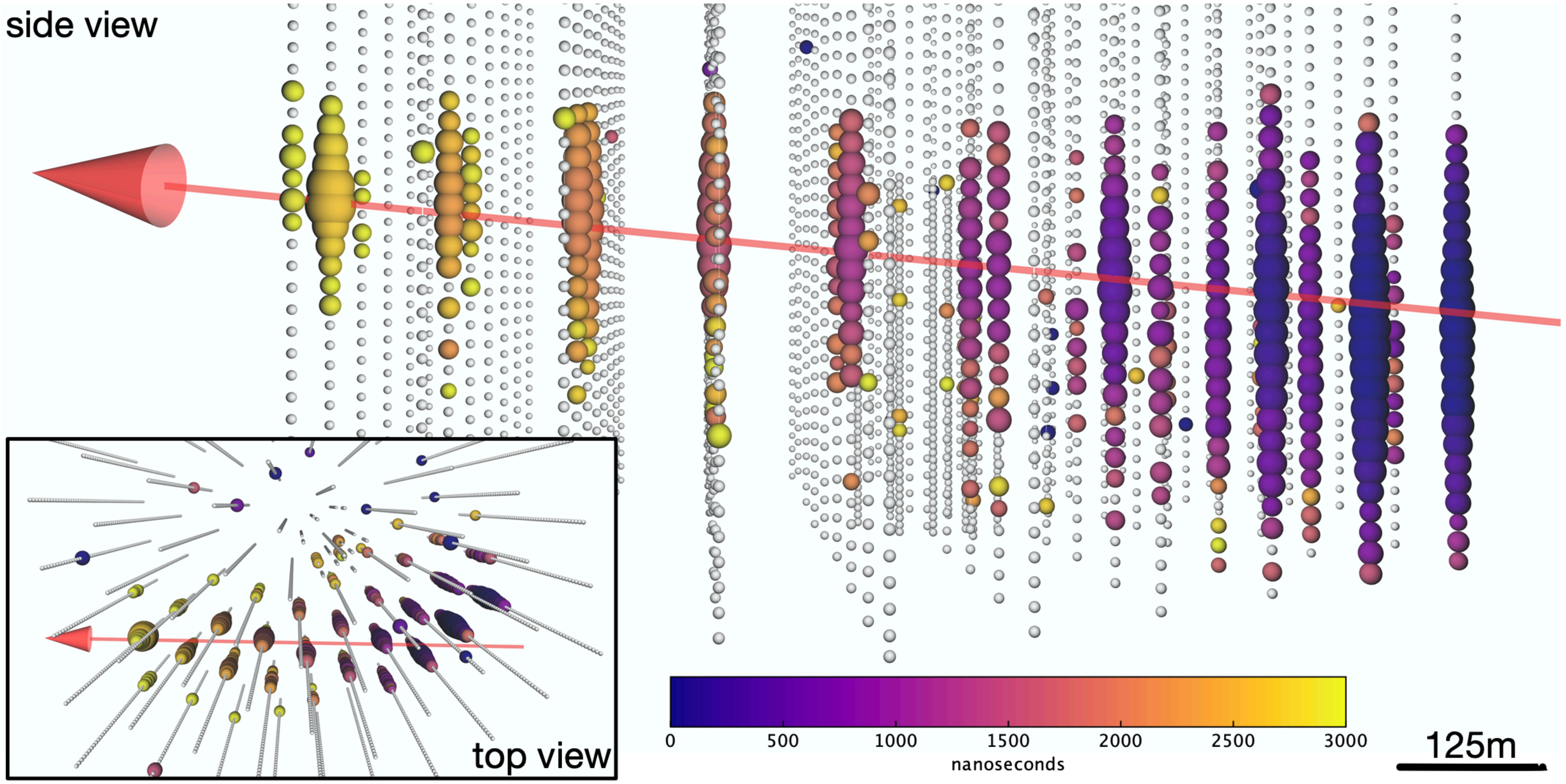


$$E_\nu \sim 290\,\mathrm{TeV}$$

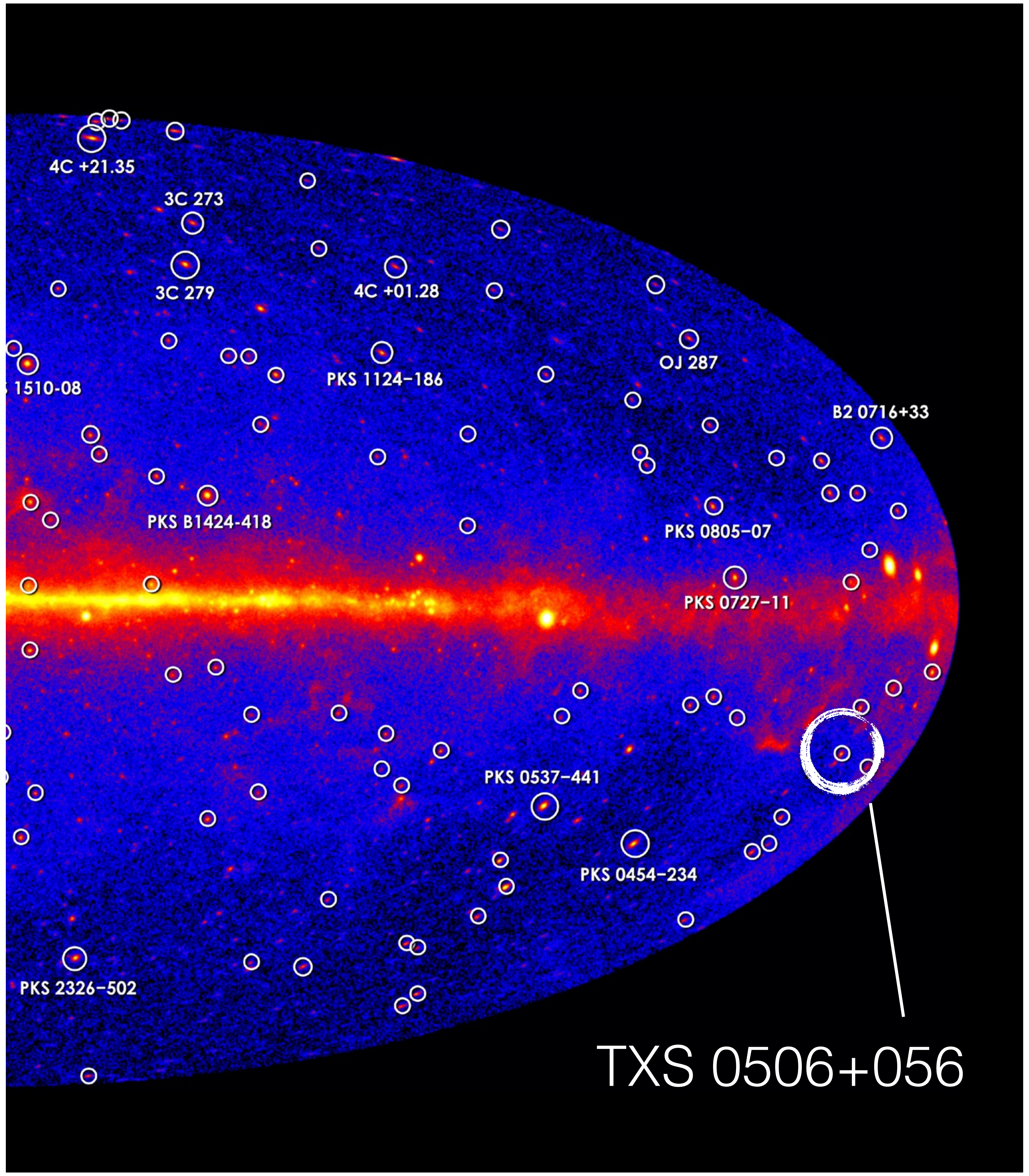
IceCube-170922A

[1807.08816]

22 September 2017



$E_\nu \sim 290\,\mathrm{TeV}$

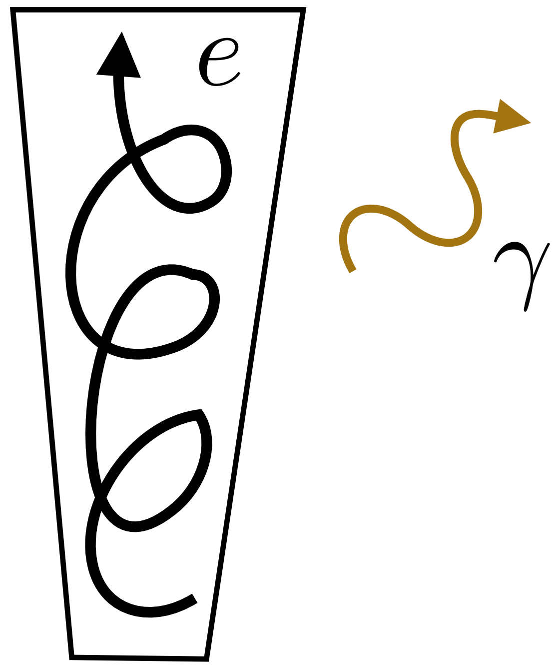


TXS 0506+056 is a known blazar!

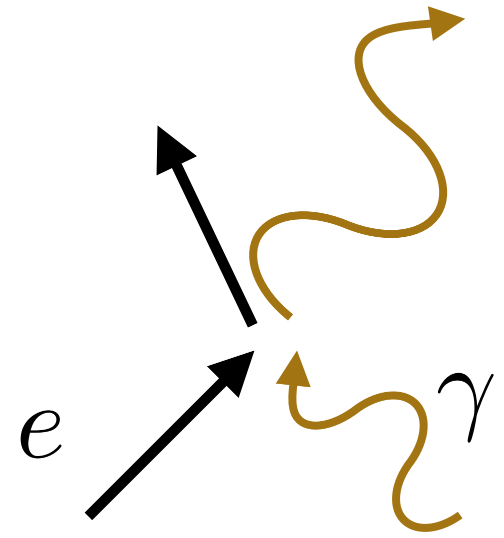
It was flaring at the time of IceCube-170922A!

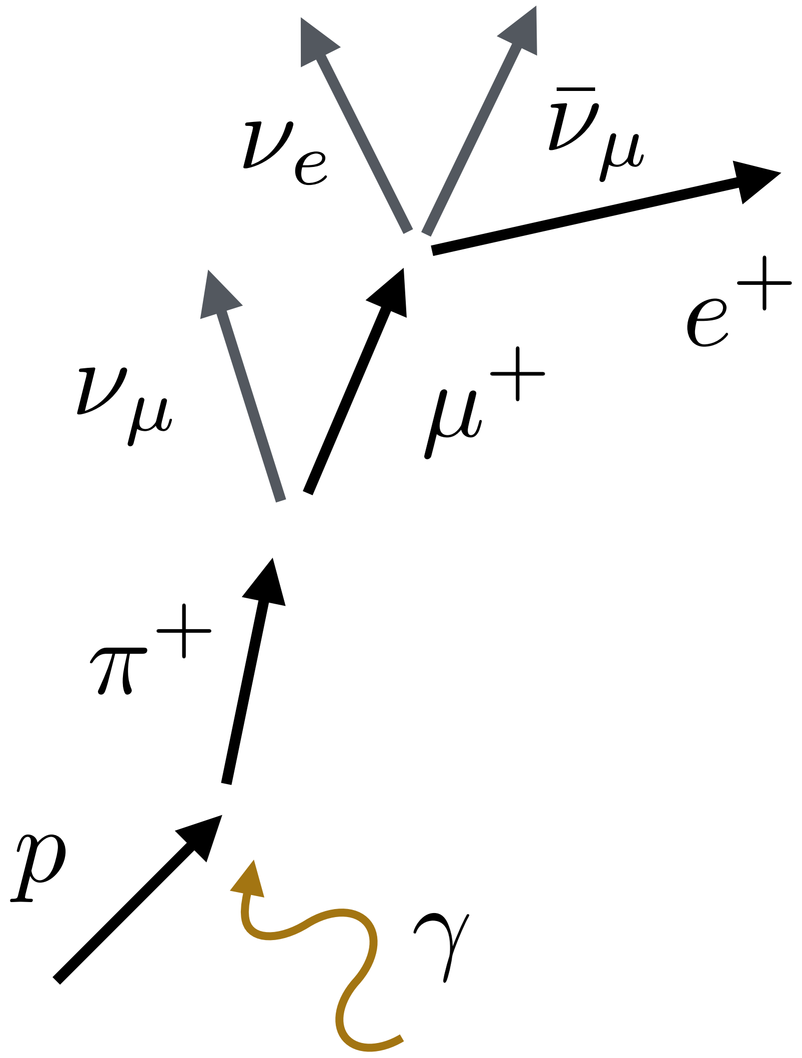
Blazar emission

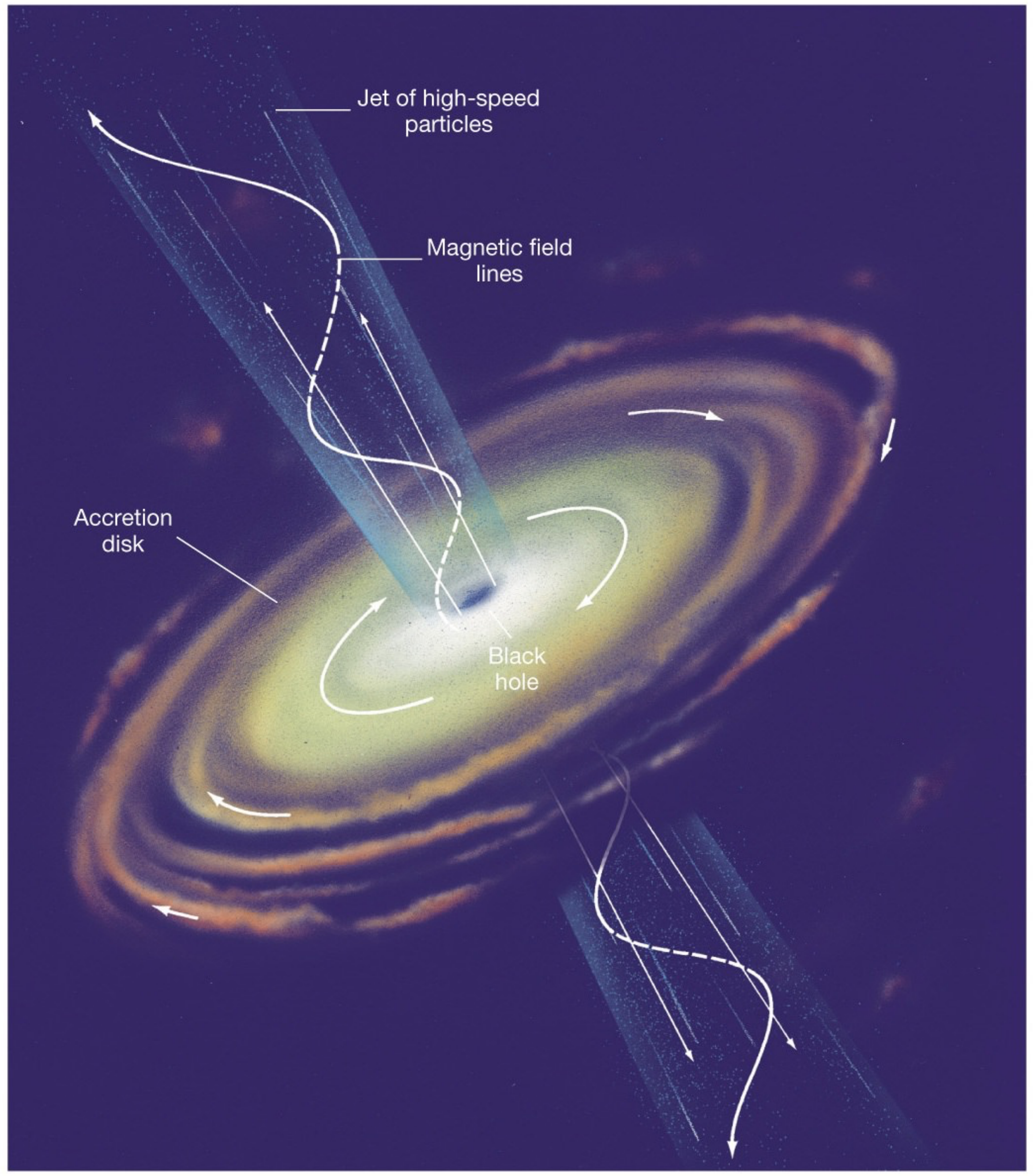
Electron synchrotron



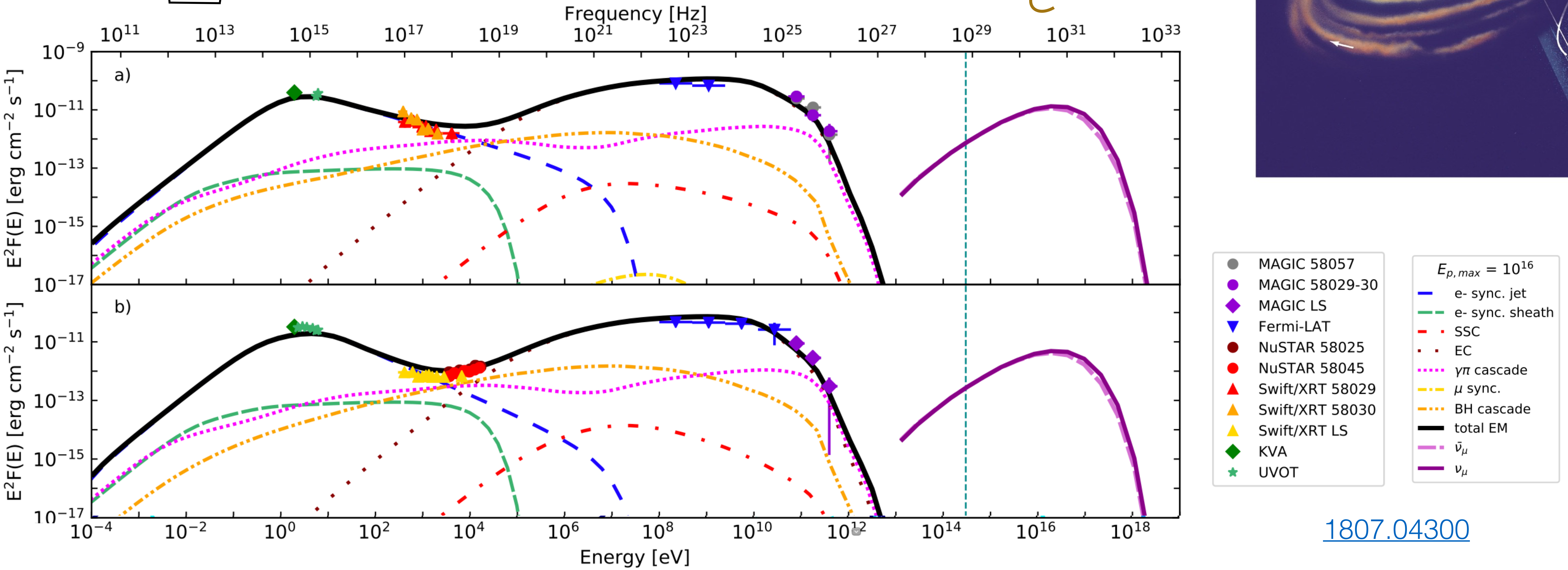
Inverse Compton







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



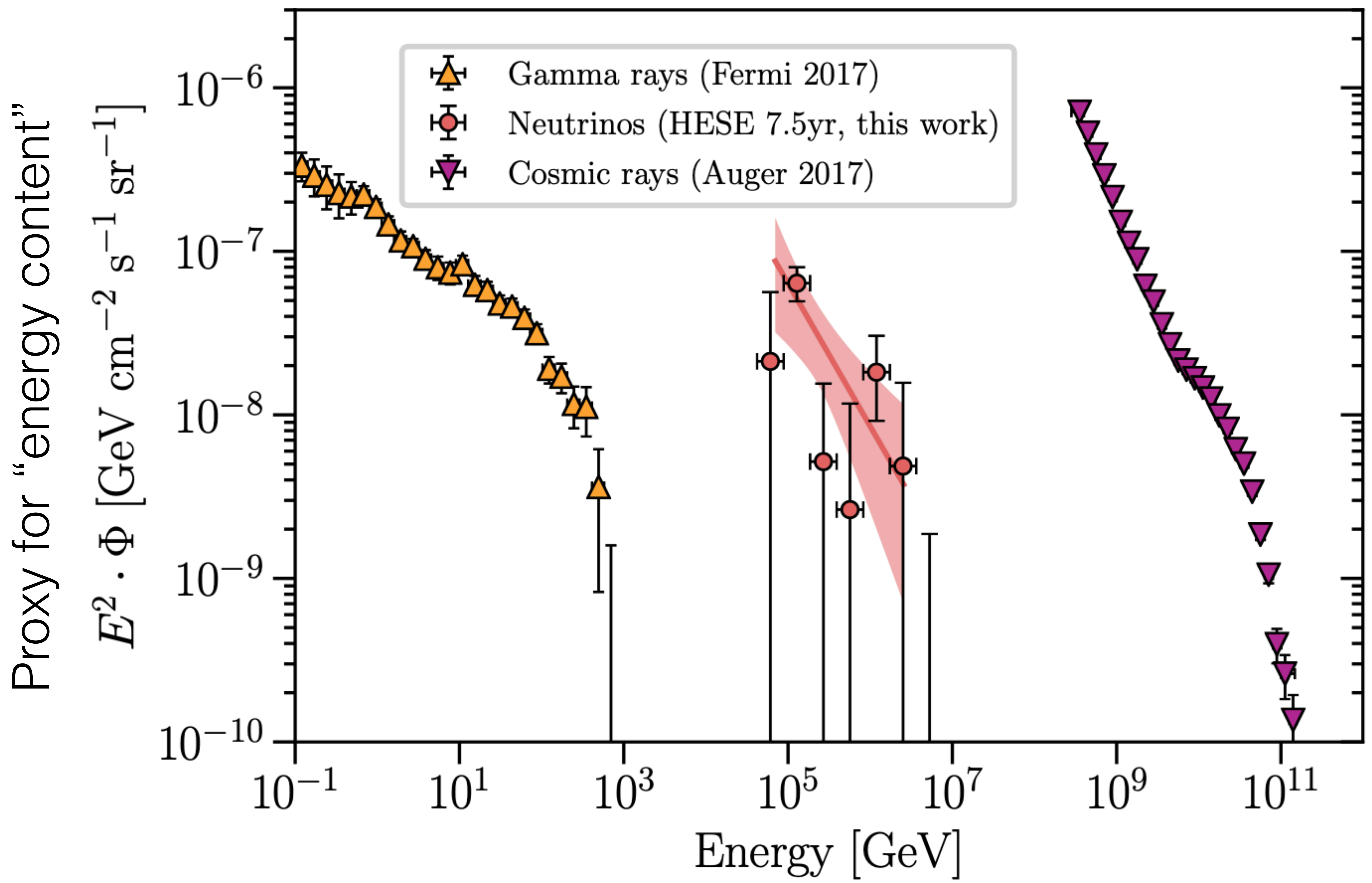
1807.04300

Optical X-ray Gamma-ray Neutrinos!

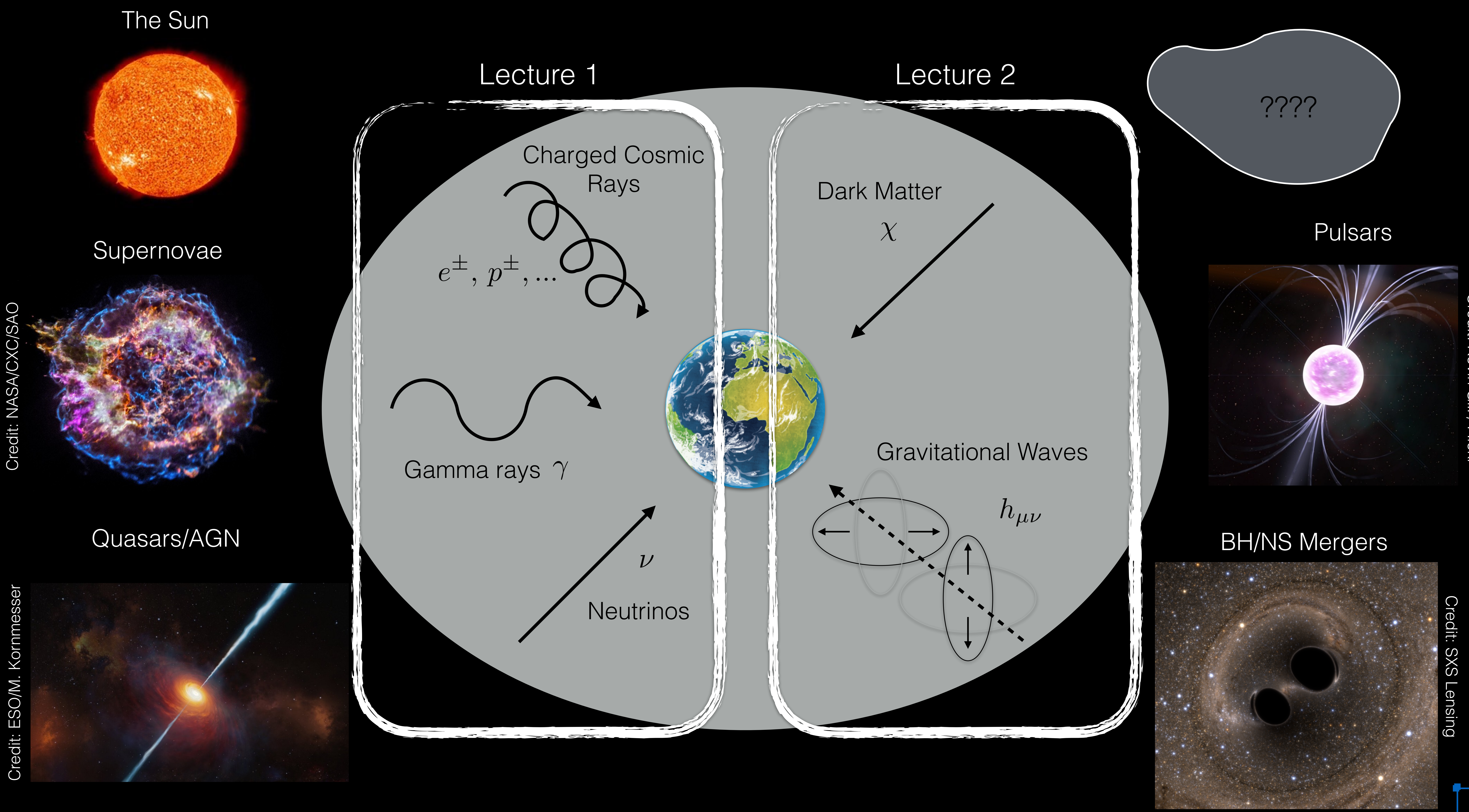
Violent and Energetic Universe

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
Charged Cosmic Rays
$e^{\pm}, p^{\pm}, \ldots$
Gamma rays γ
ν
Neutrinos
Lecture 2
Dark Matter
χ
Gravitational Waves
$h_{\mu\nu}$
????
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. Piattella, arXiv:1910.05610 (2019)

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

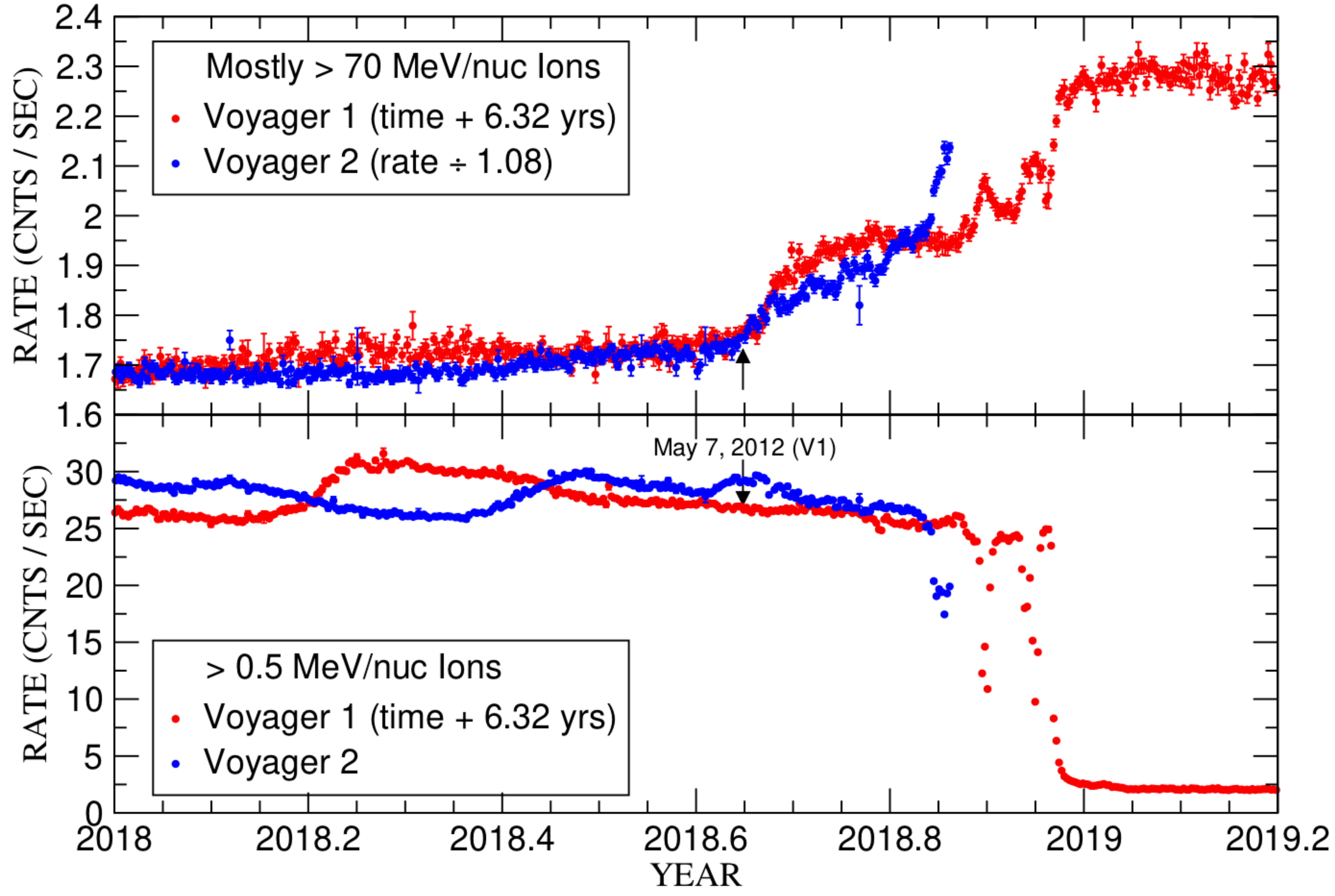
Check arXiv, and summaries on popular blogs like Sunny Vagnozzi's HisDarkCMB or Mauricio Bustamante's Daily arXiv Picks!

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

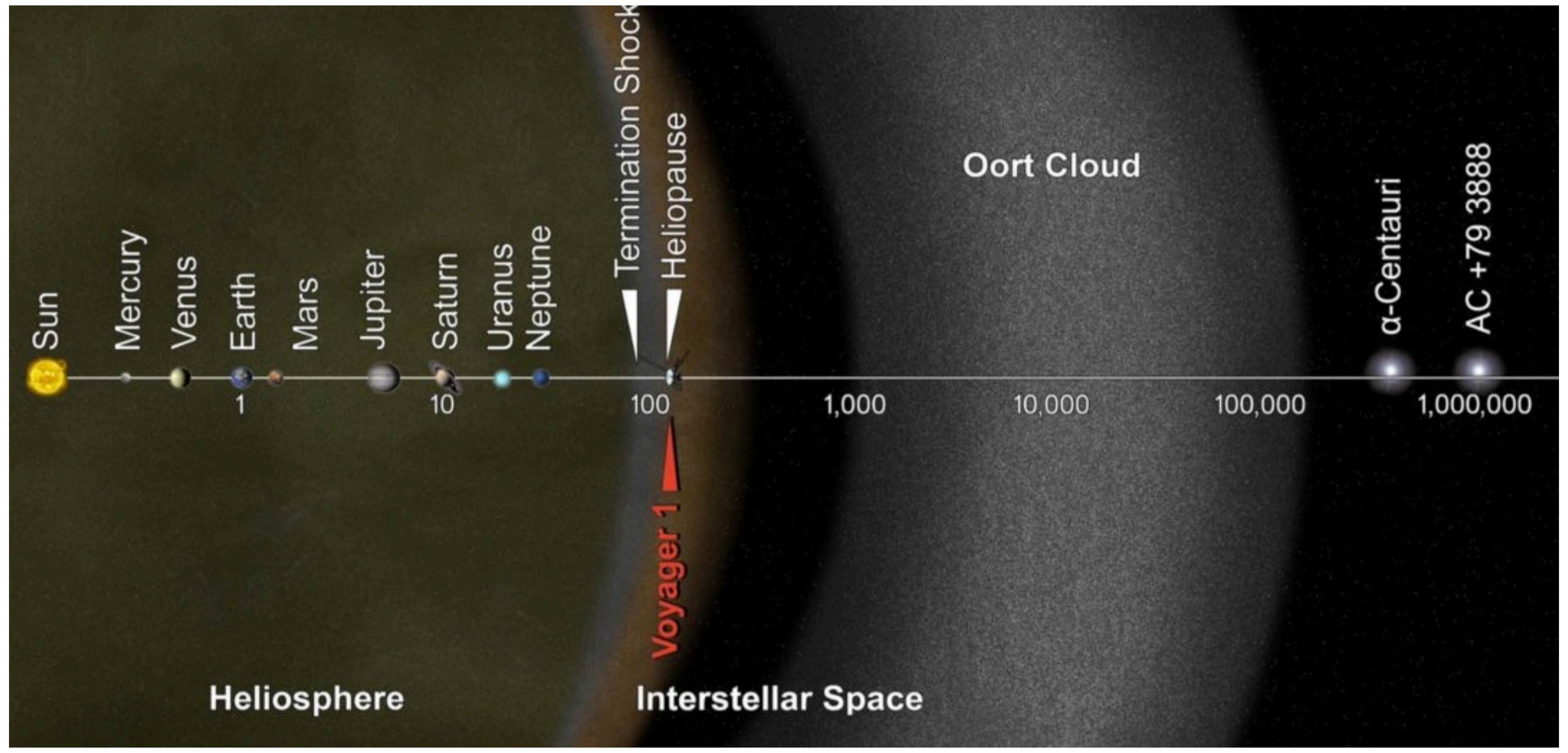
Additional Slides

Voyager (and solar modulation)

Credit: NASA/JPL/Ed Stone

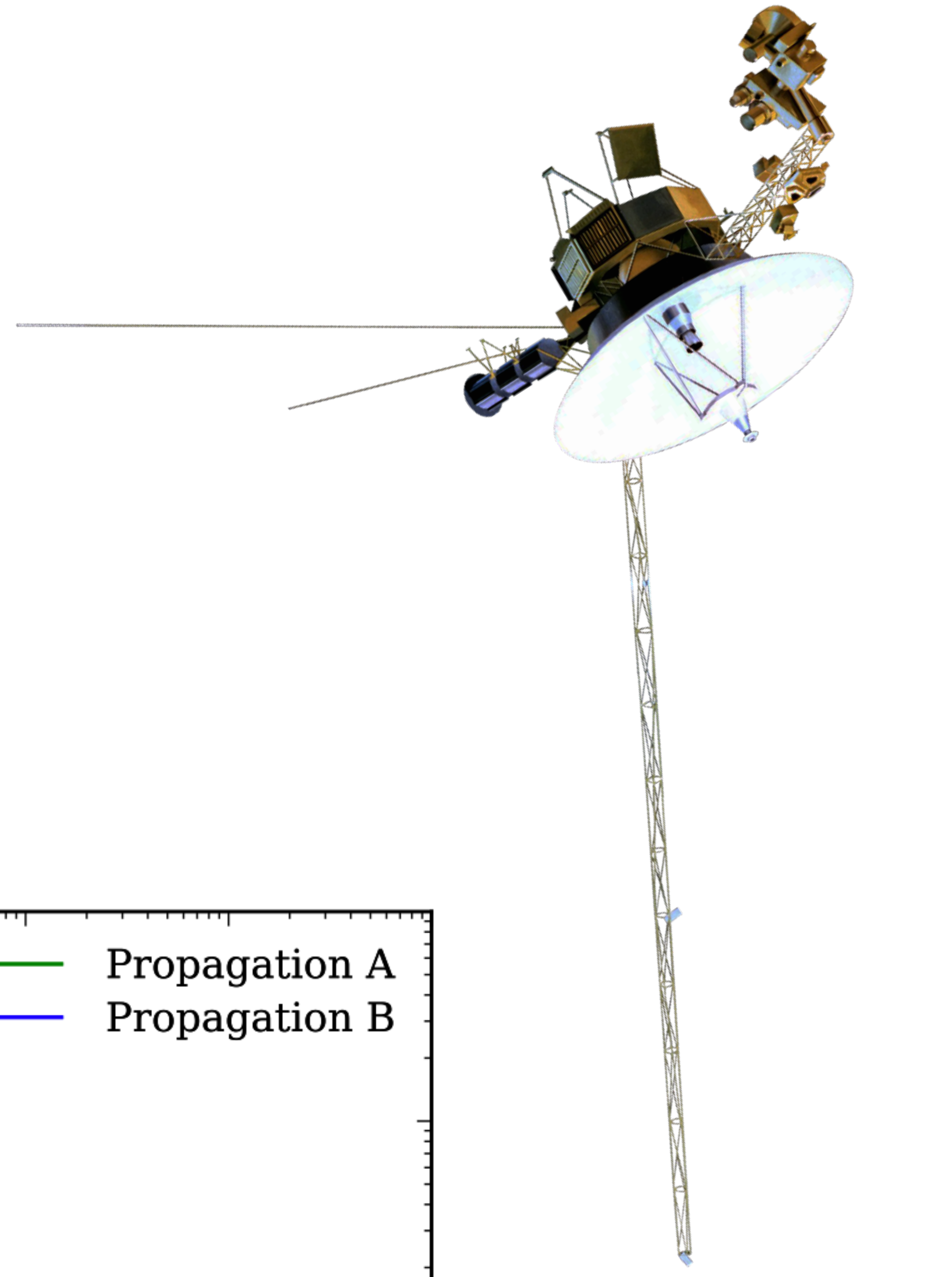


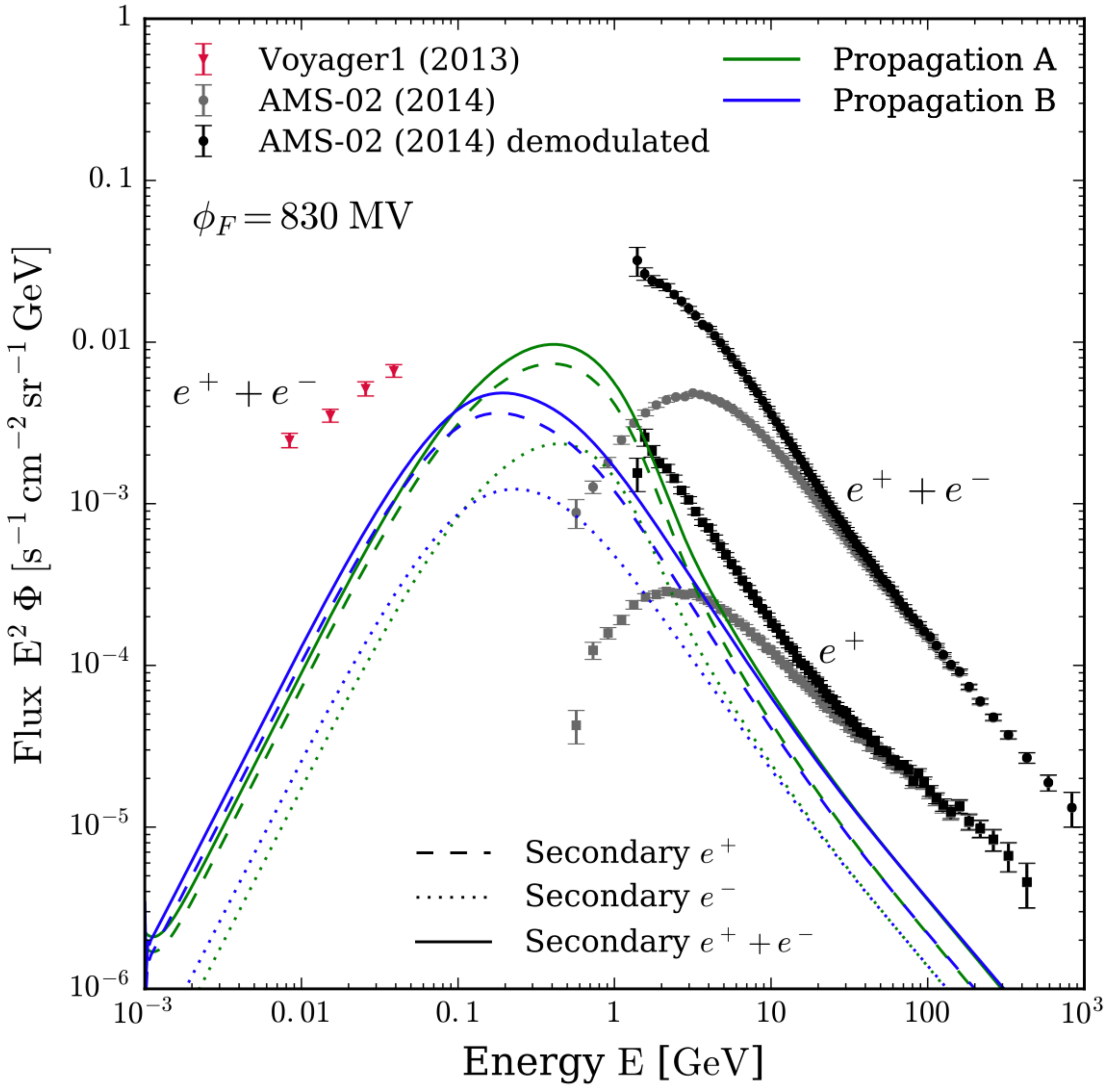
Credit: NASA/JPL



Voyager 1 - launched 1977, crossed heliopause 2012

Voyager 2 - launched 1977, crossed heliopause 2018



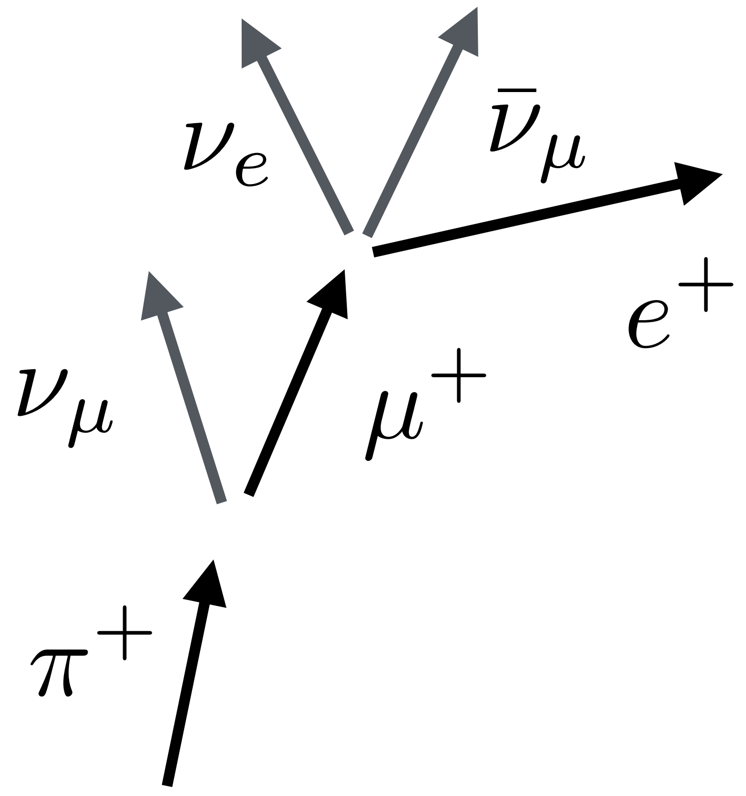


arXiv:1612.07698

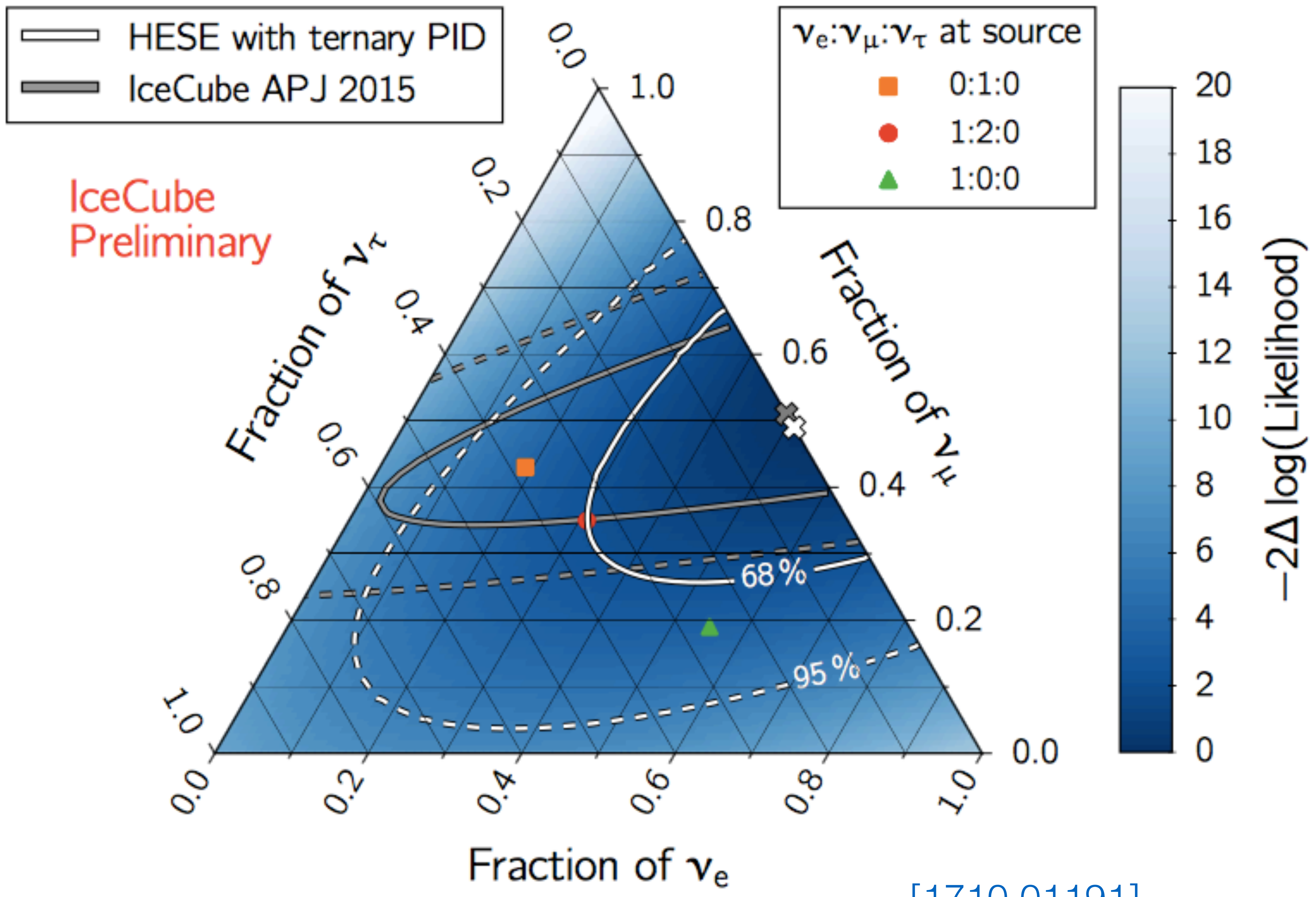
Origin of ultra high energy neutrinos?

Flavour composition can hint at how astrophysical neutrinos are produced:

E.g. decay of energetic pions:



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



[1710.01191]