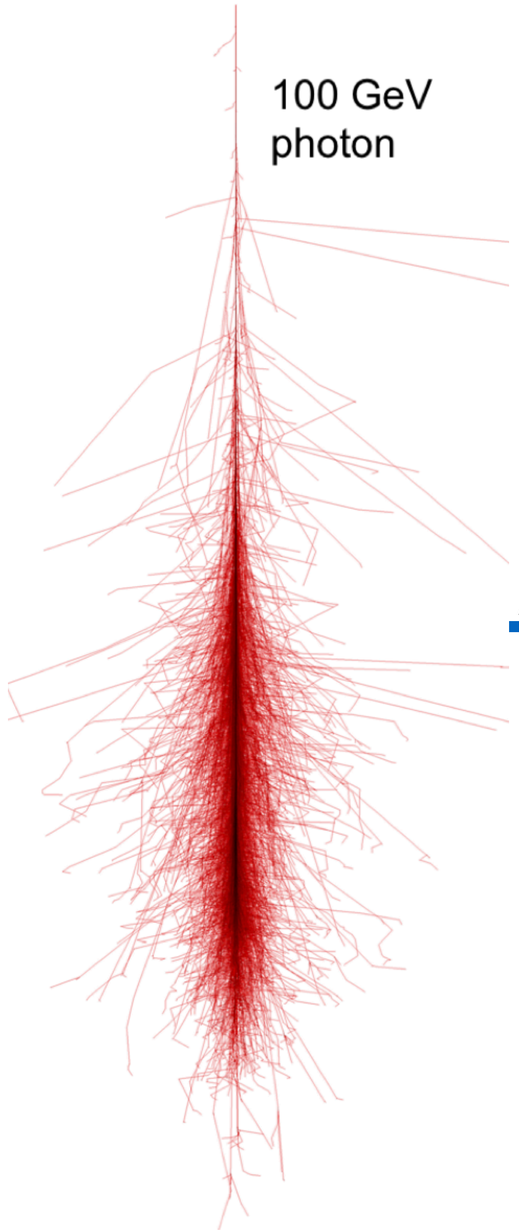
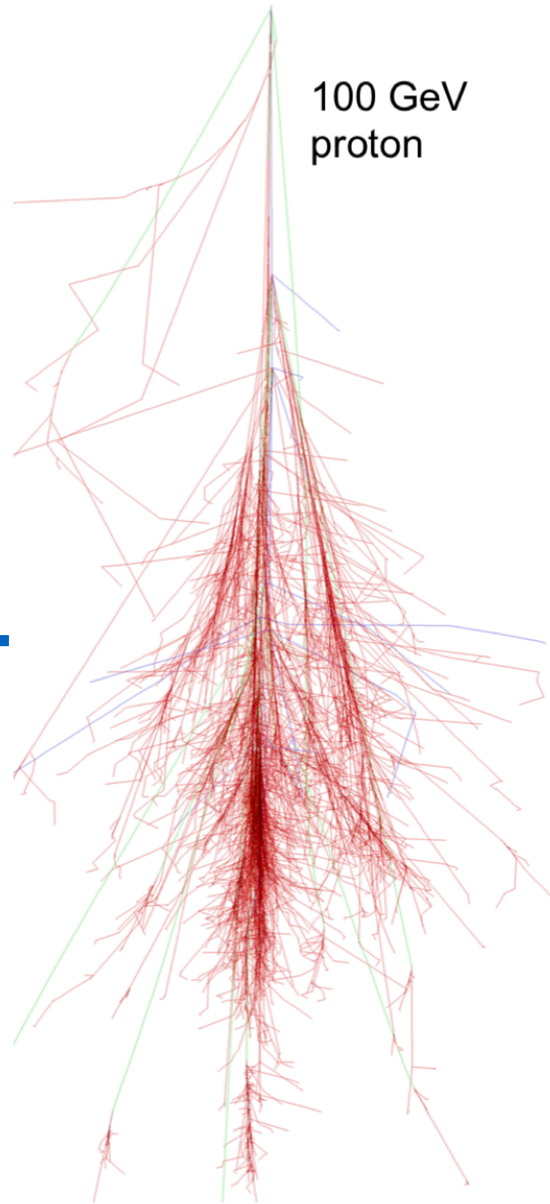




(An introduction to)

Astroparticle Physics

Lecture 1/2

Bradley J Kavanagh
Instituto de Fisica de Cantabria (CSIC-UC)
kavanagh@ifca.unican.es

Summer Student Lecture Programme - Thursday 14th July 2022

Slides here: bradkav.net/talks

Reading Suggestions

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)

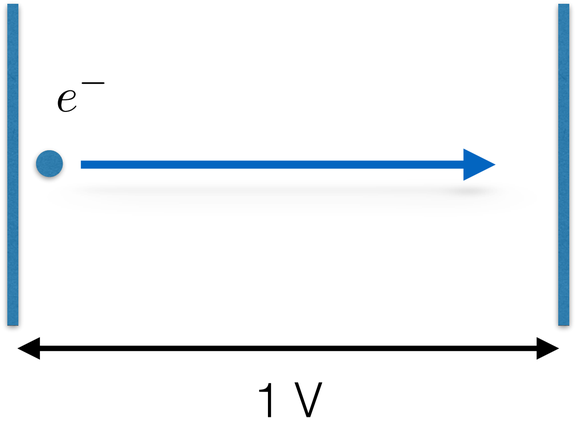
The basic physics of the binary black hole merger GW150914, LIGO & Virgo Collaborations, arXiv:1608.01940 (2016)

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

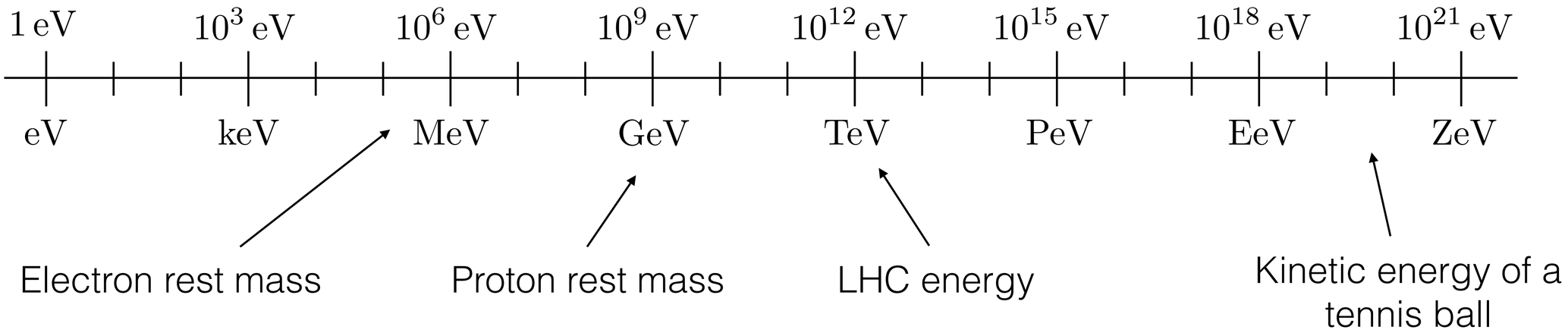
Feel free to email me at kavanagh@ifca.unican.es!

A huge range of energy scales…

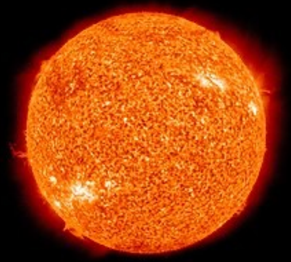
1 eV is the kinetic energy an electron gains from being accelerated across a potential of 1 V



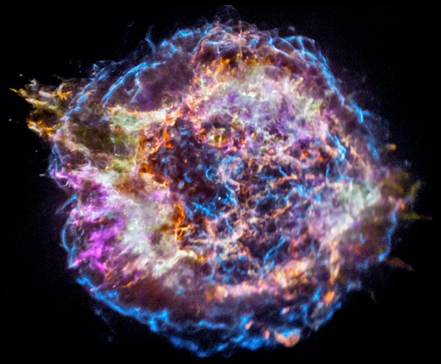
$$1\,\mathrm{eV} \approx 1.6 \times 10^{-19}\,\mathrm{J}$$
$$\approx 1.8 \times 10^{-36}\,\mathrm{kg}$$
$$\approx 1.2 \times 10^{4}\,\mathrm{K}$$



The Sun



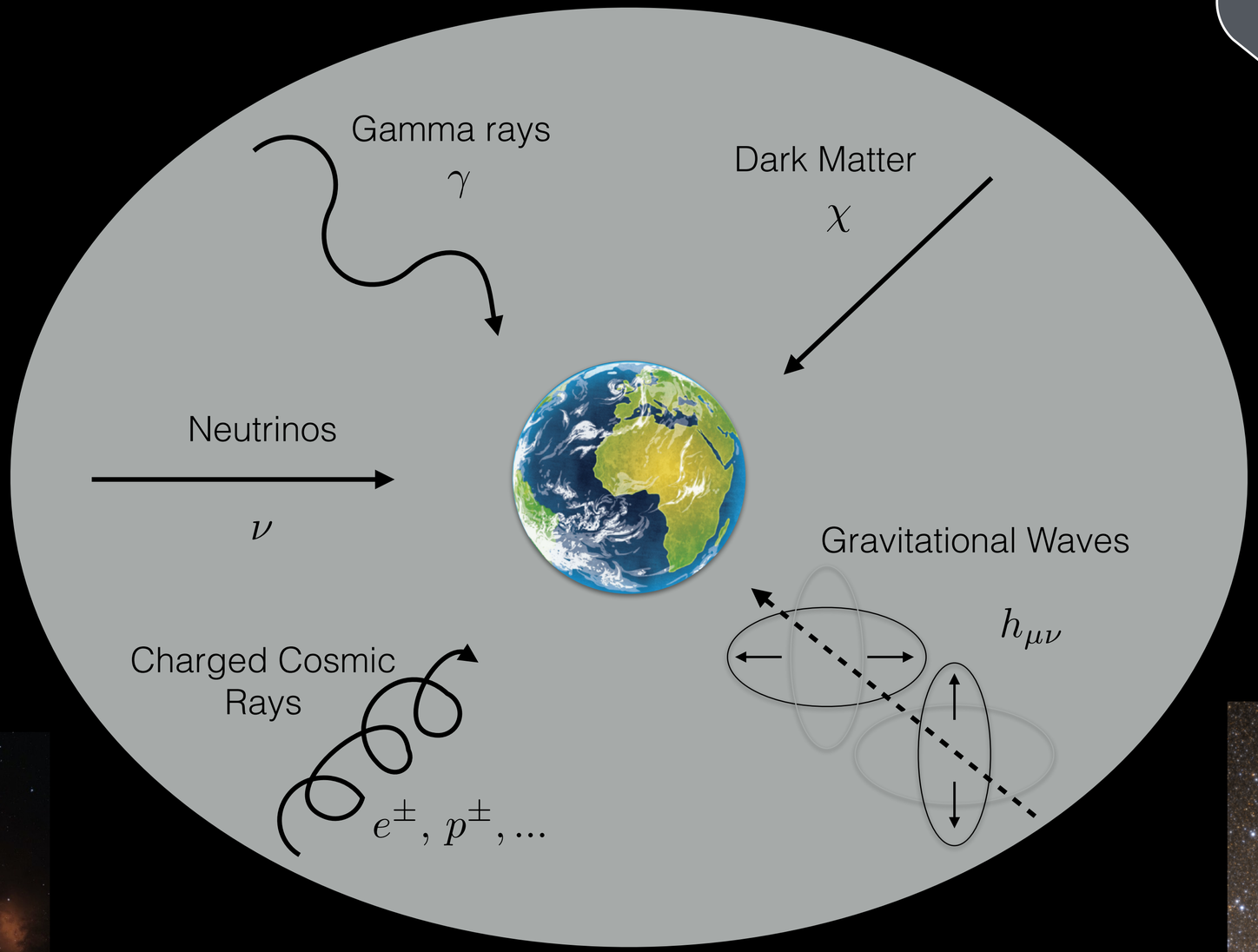
Supernovae



Credit: NASA/CXC/SAO

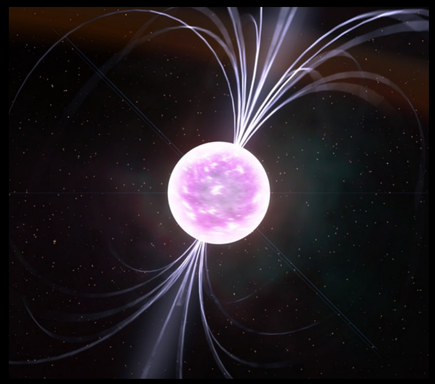
Quasars/AGN

Credit: ESO/M. Kornmesser



????

Pulsars

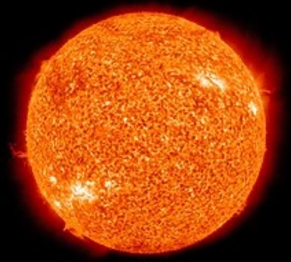


Credit: Kevin Gill / Flickr

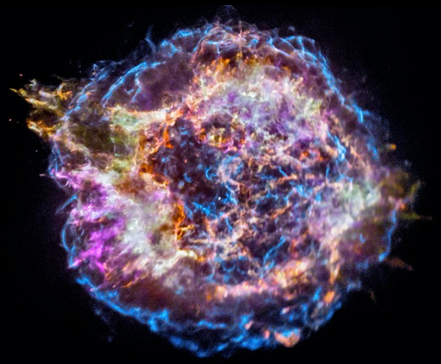
BH/NS Mergers

Credit: SXS Lensing

The Sun



Supernovae



Credit: NASA/CXC/SAO

Quasars/AGN

Credit: ESO/M. Kornmesser

Lecture 1

Gamma rays

γ

Neutrinos

ν

Charged Cosmic Rays

$e^{\pm}, p^{\pm}, \ldots$

Dark Matter

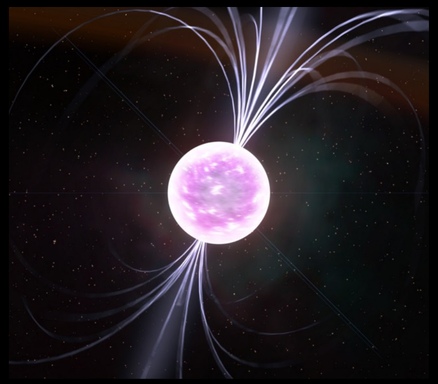
χ

Gravitational Waves

$h_{\mu\nu}$

????

Pulsars

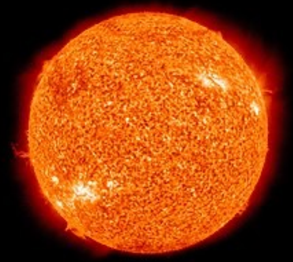


Credit: Kevin Gill / Flickr

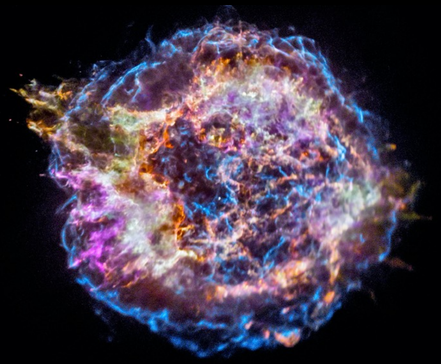
BH/NS Mergers

Credit: SXS Lensing

The Sun



Supernovae



Credit: NASA/CXC/SAO

Quasars/AGN

Credit: ESO/M. Kornmesser

Lecture 1

Lecture 2

Gamma rays

γ

Neutrinos

ν

Charged Cosmic Rays

$e^{\pm}, p^{\pm}, \ldots$

Dark Matter

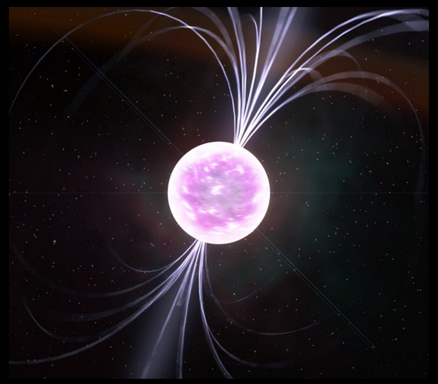
χ

Gravitational Waves

$h_{\mu\nu}$

????

Pulsars



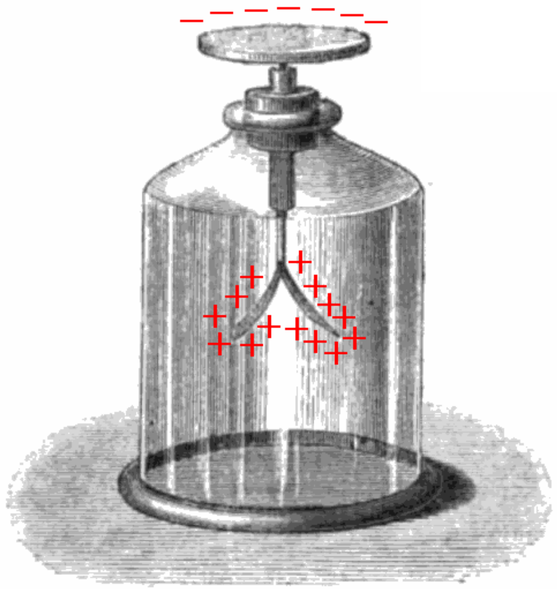
Credit: Kevin Gill / Flickr

BH/NS Mergers

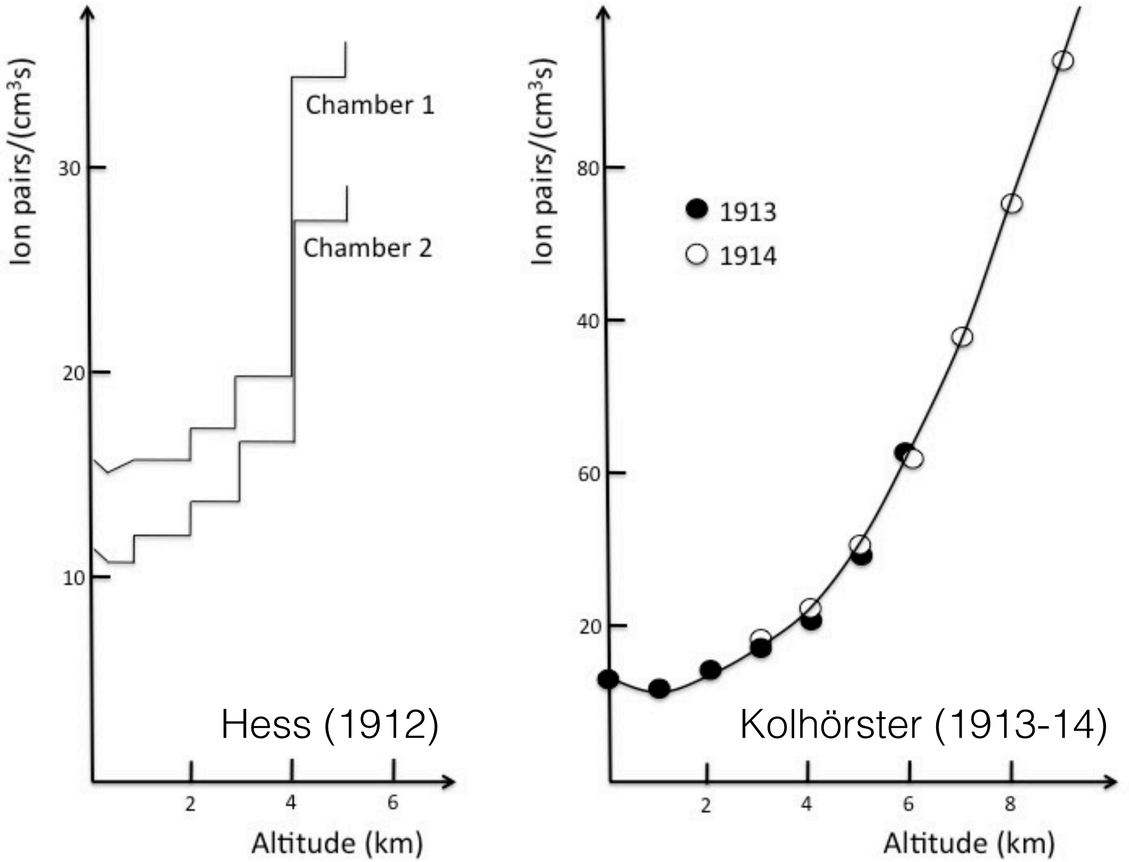
Credit: SXS Lensing

History of astroparticles

Victor Hess
(1883 - 1964)

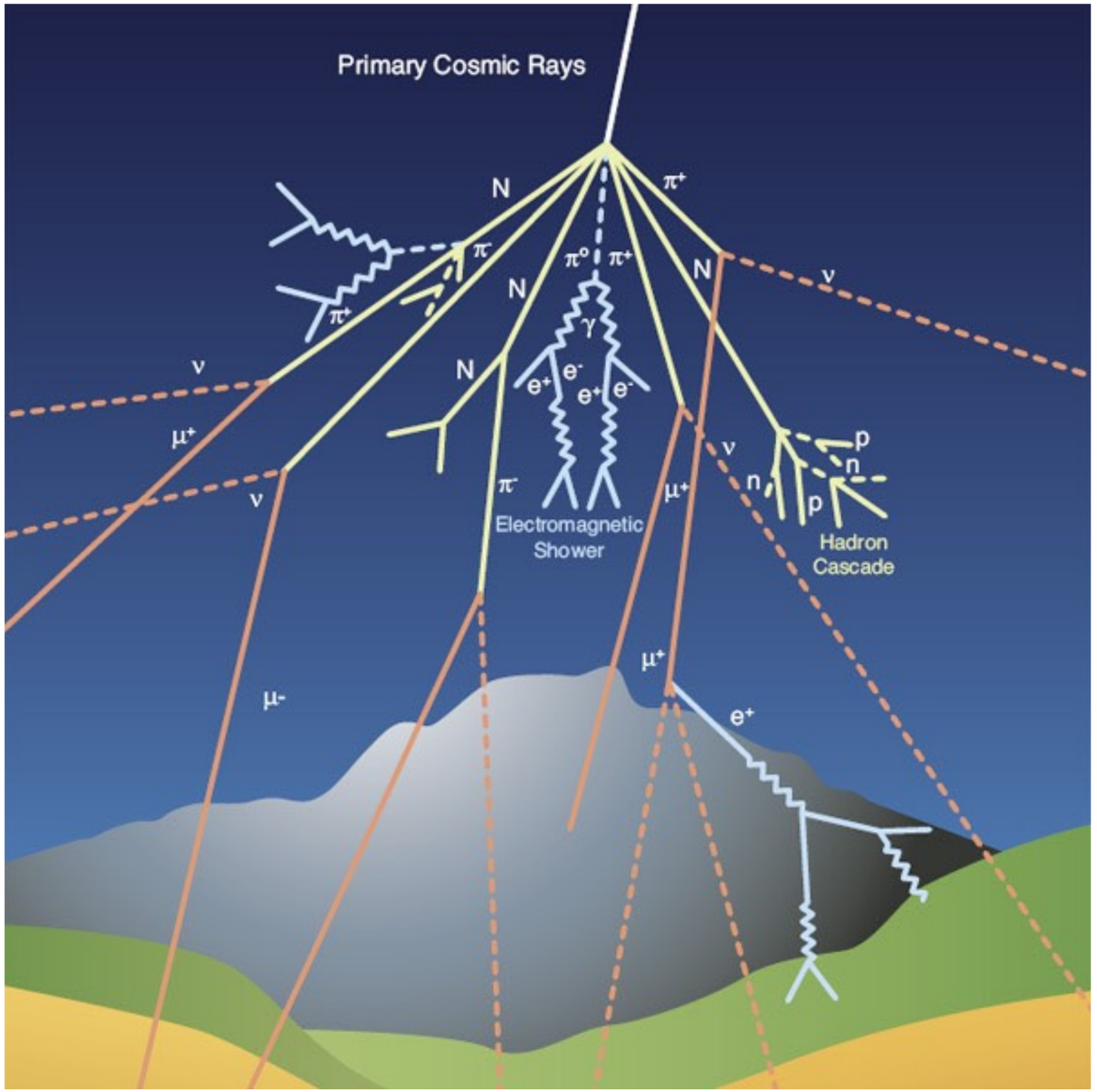


Credit: Sylvanus P. Thompson (1881), Chetvorno (2008)

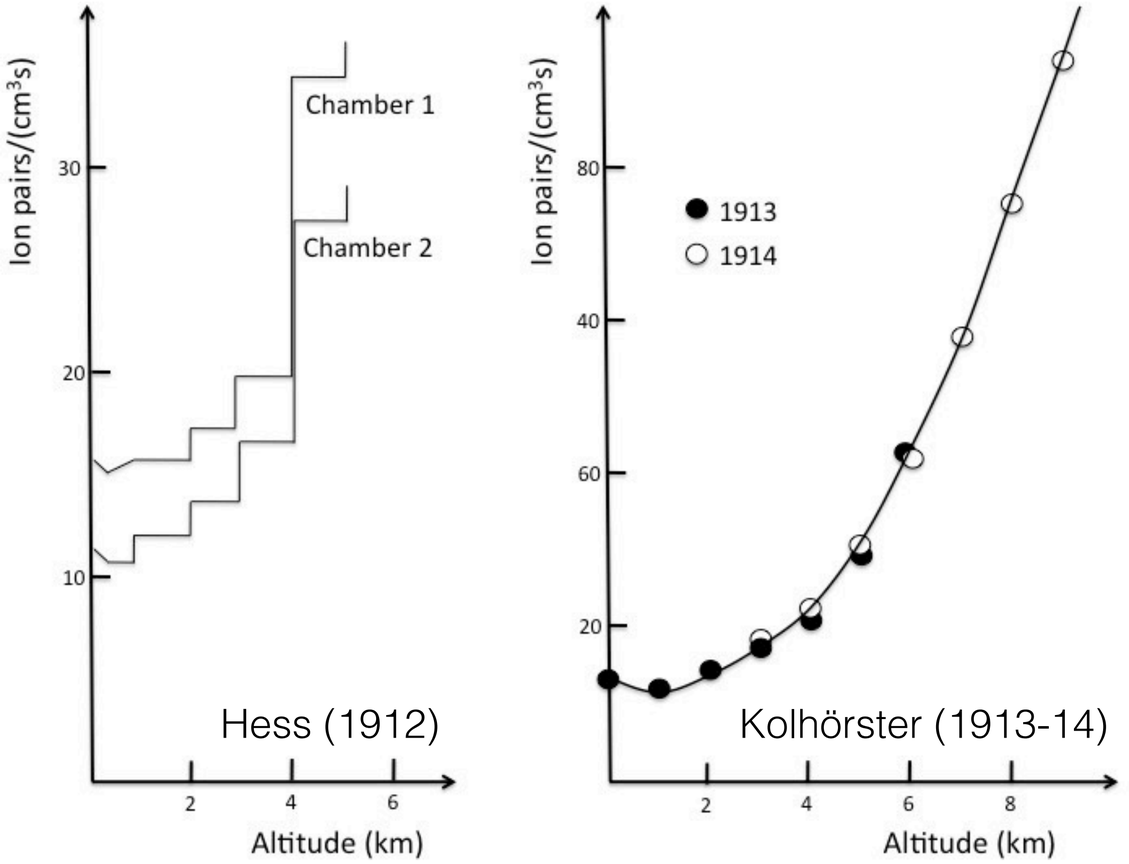


Credit: Alessandro De Angelis

History of astroparticles

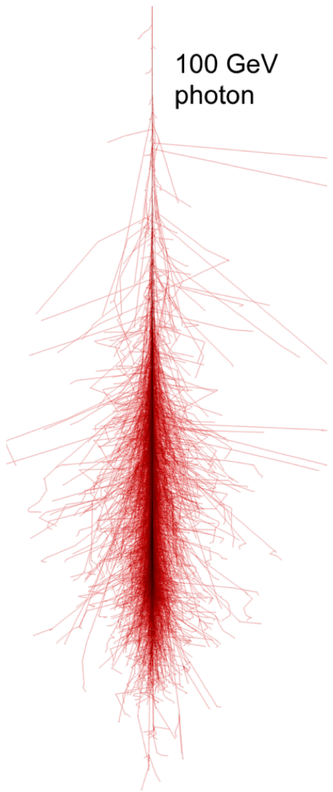


Credit: CERN



Credit: Alessandro De Angelis

Gamma rays vs Charged Cosmic rays



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

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

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

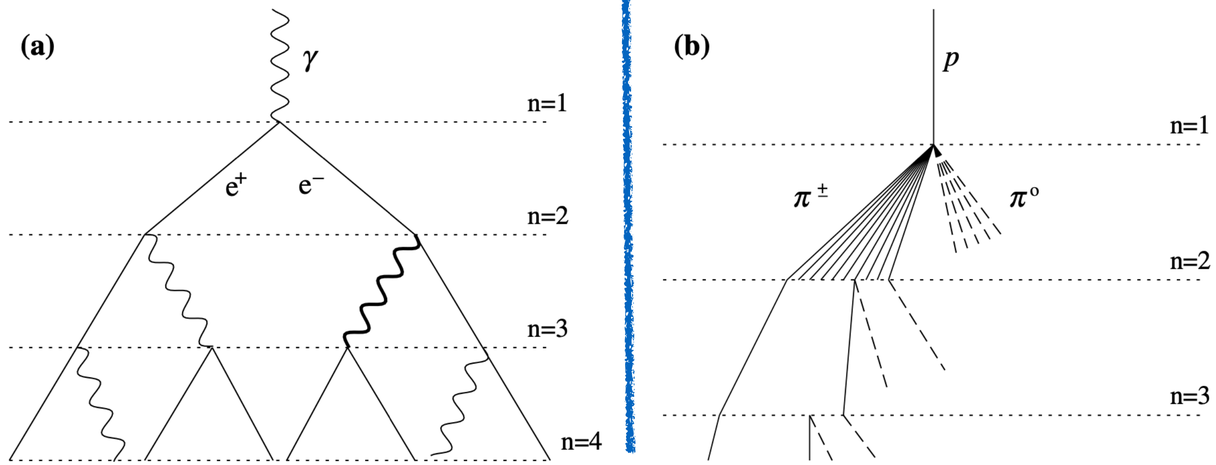
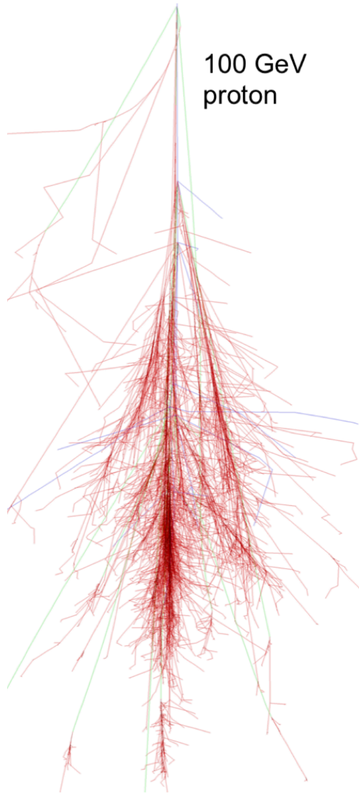


Fig. 1. Schematic views of (a) an electromagnetic cascade and (b) a hadronic shower. In the hadron shower, dashed lines indicate neutral pions which do not re-interact, but quickly decay, yielding electromagnetic subshowers (not shown). Not all pion lines are shown after the $n = 2$ level. Neither diagram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

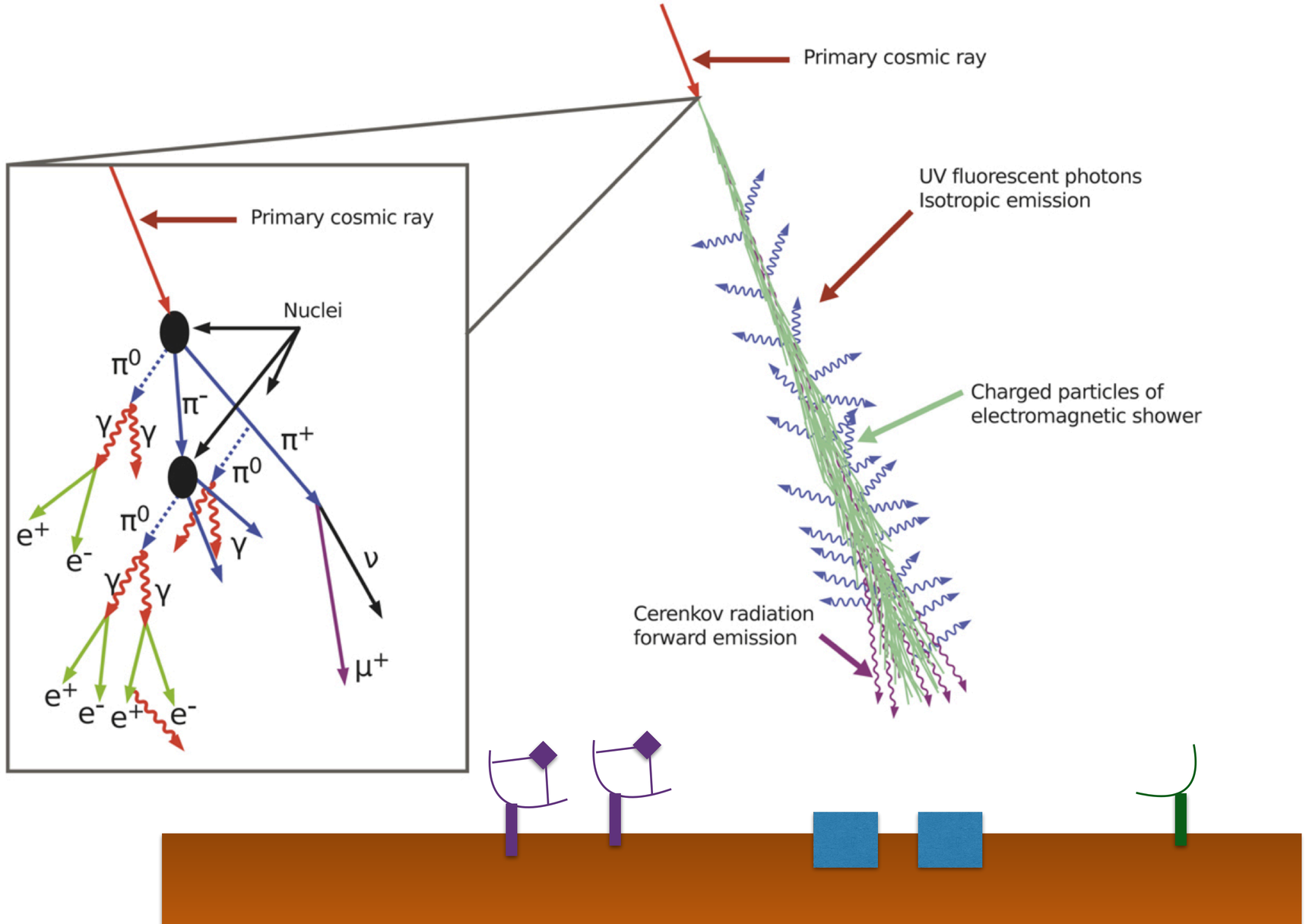


~5 km

1510.05675

Credit: Matthews (2005)

Detection of cosmic rays (Earth)



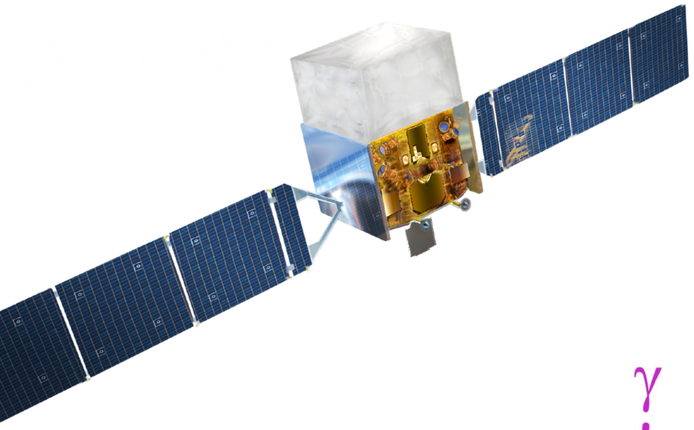
Fluorescence
(e.g. Fly's Eye, Auger observatory)

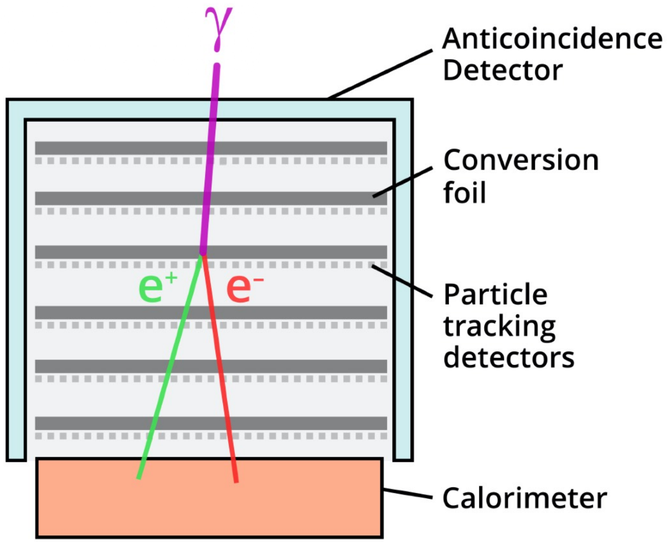
Imaging Air Cherenkov Telescope (IACT)
(e.g. MAGIC, VERITAS, HESS, planned CTA)

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

Detection of cosmic rays (Space)

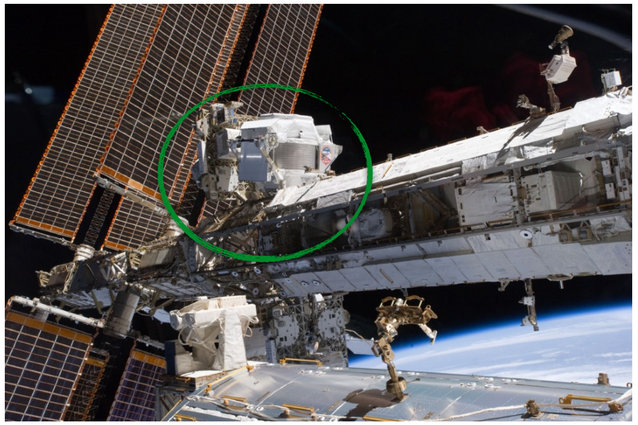
Fermi-LAT (2008-)



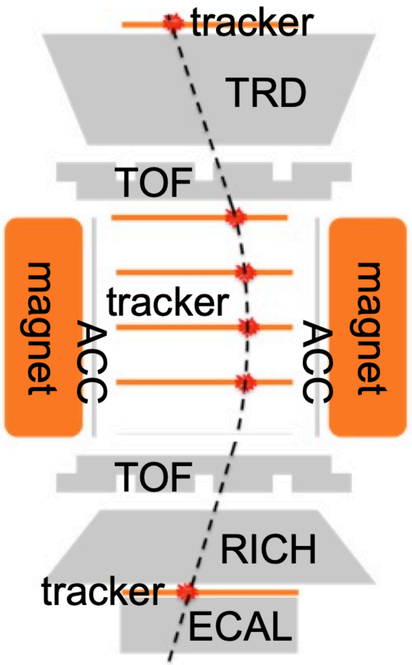


Credit: NASA's Goddard Space Flight Center

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



AMS (2011-)

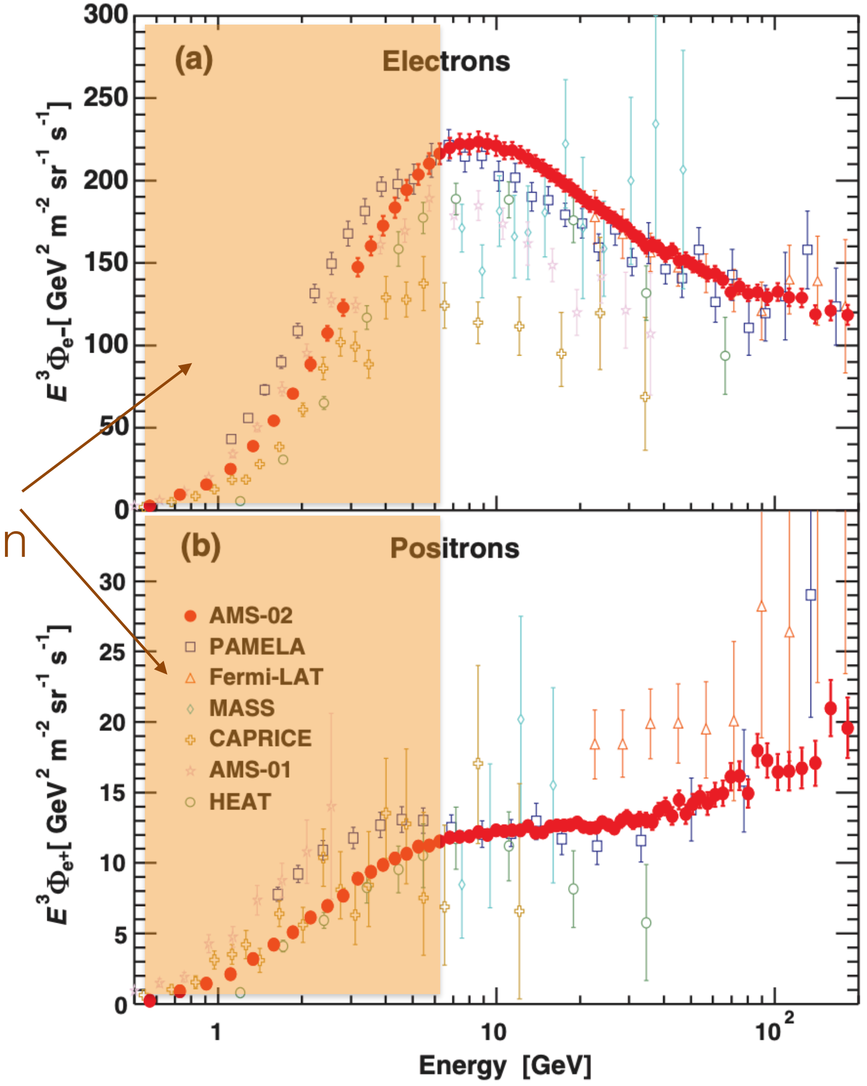


1507.02712

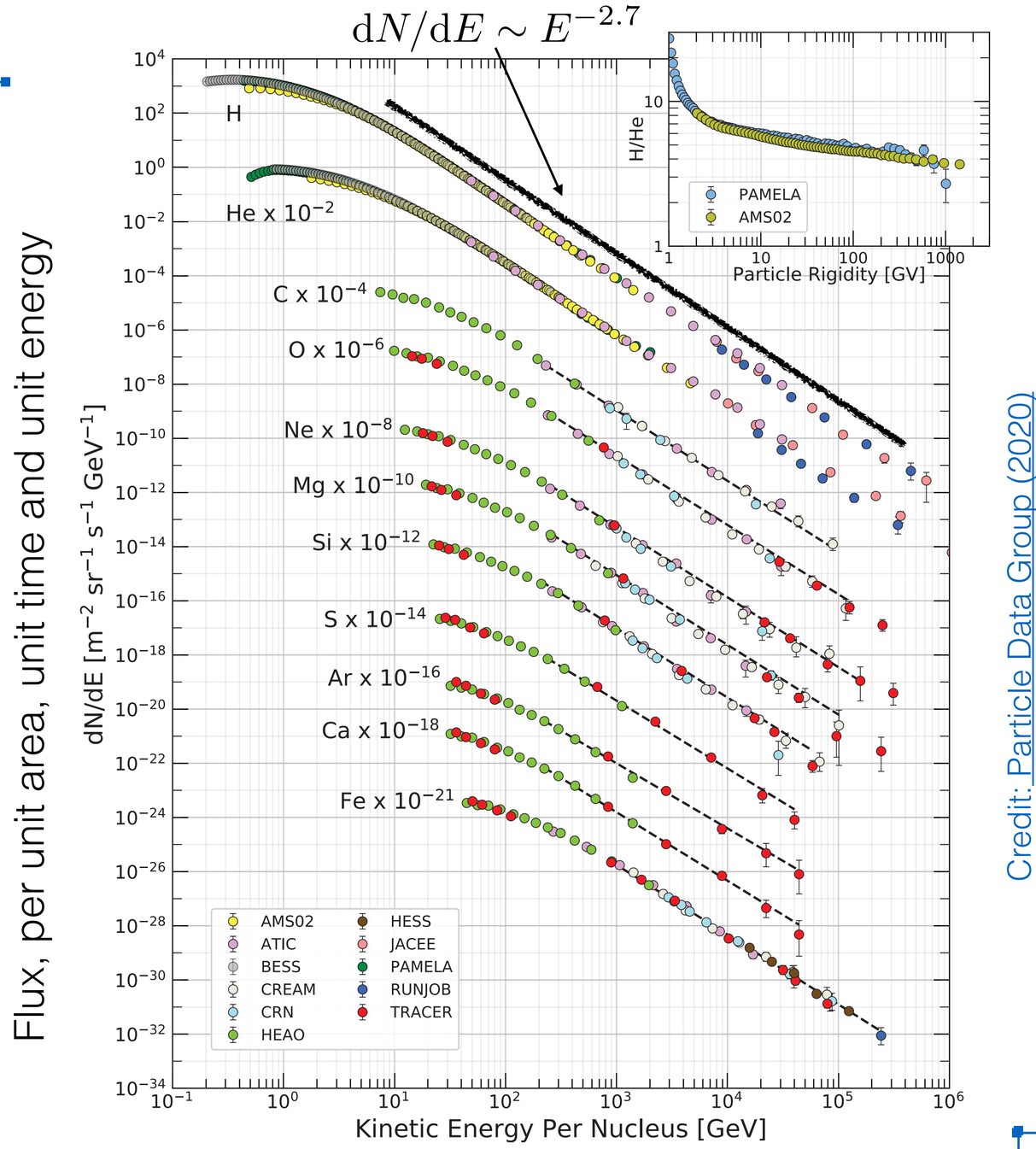
Detection of $e^{\pm}$, $p^{\pm}$ and heavier nuclei
in the range 1 GeV - 2 TeV

Cosmic ray composition

Solar modulation



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

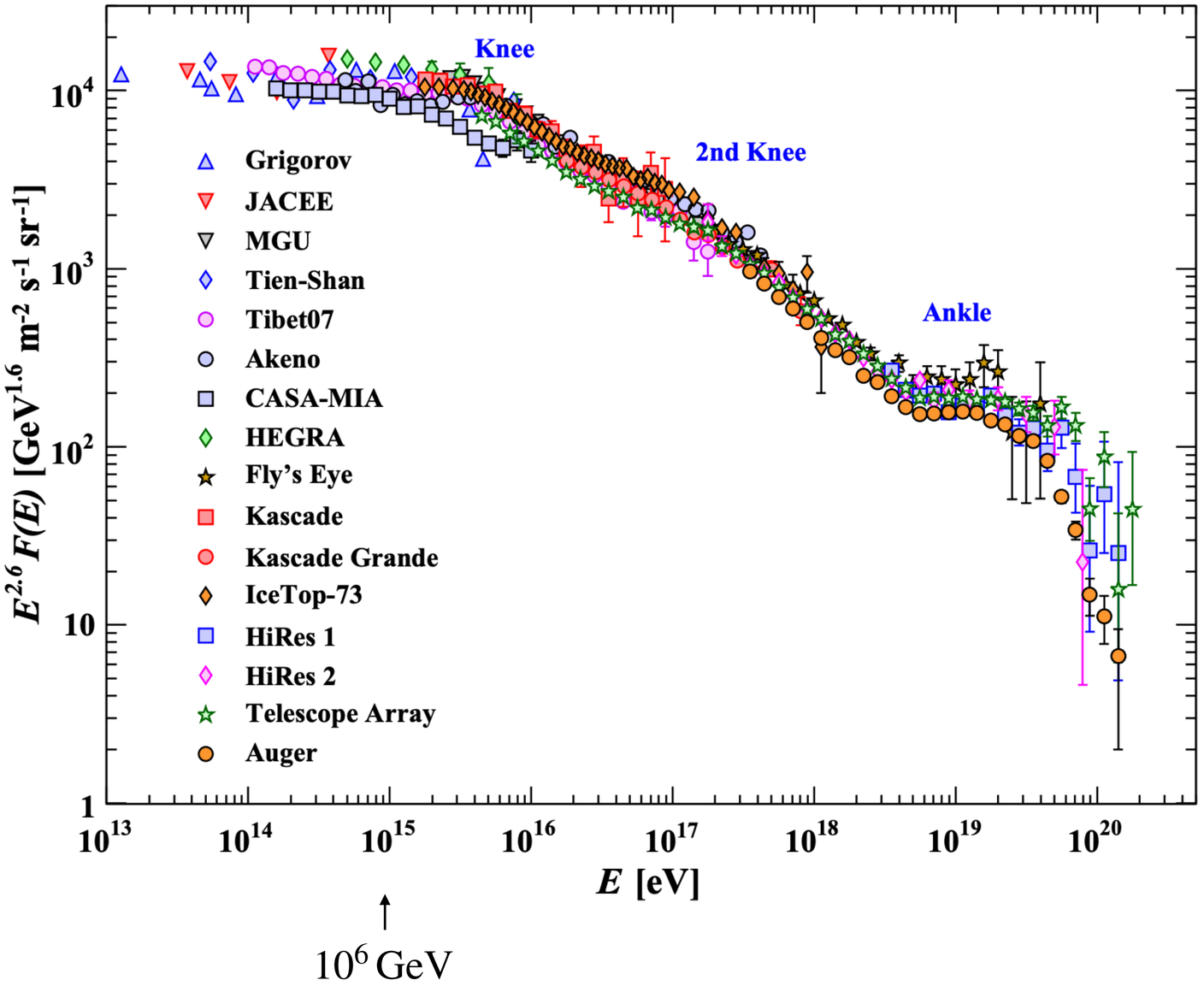


Flux, per unit area, unit time and unit energy

Credit: Particle Data Group (2020)

Ultra high-energy cosmic rays

All particle cosmic ray spectrum

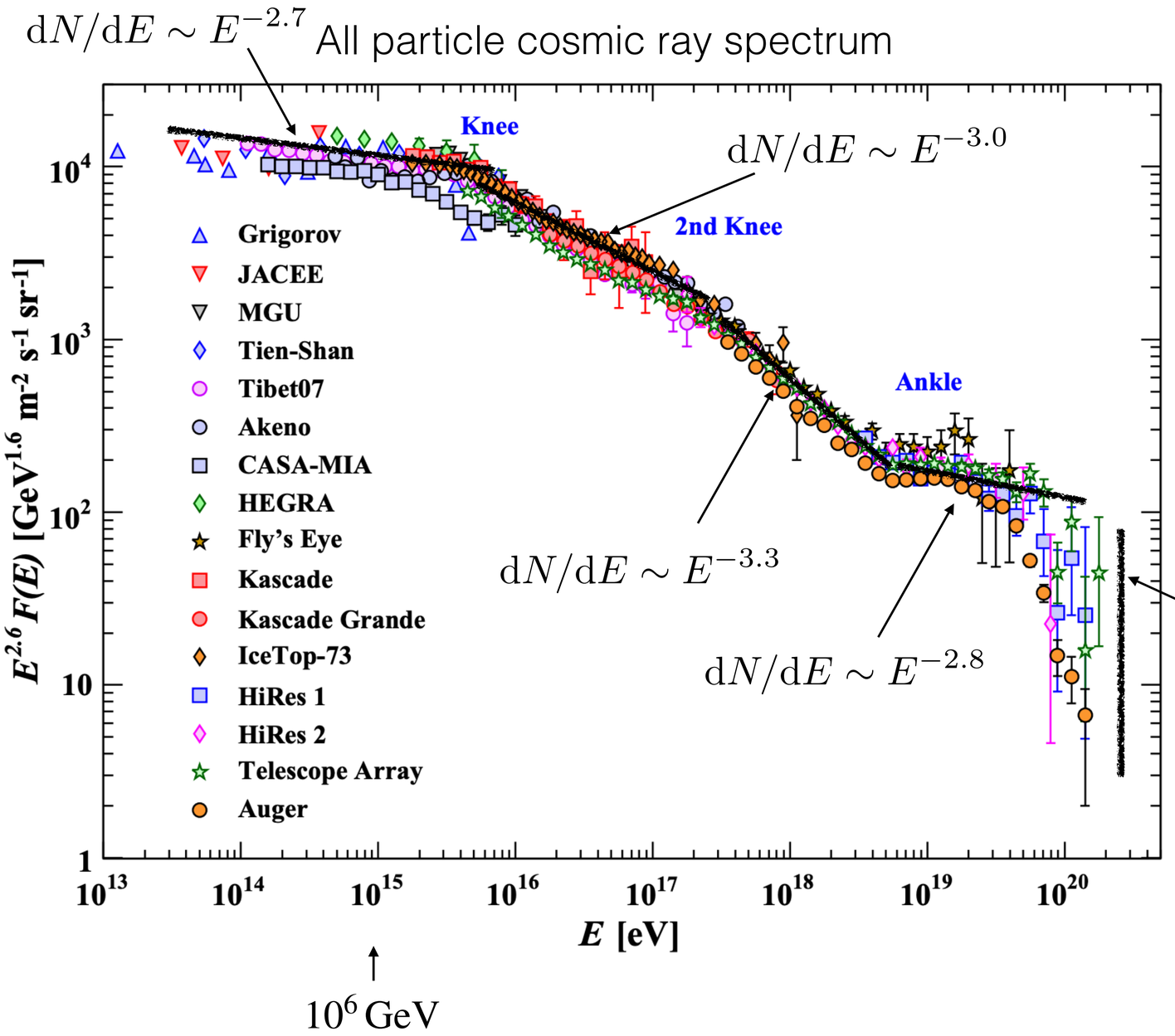


Credit: Particle Data Group (2020)

Ultra high-energy cosmic rays

Extragalactic CRs begin to dominate above the ankle.

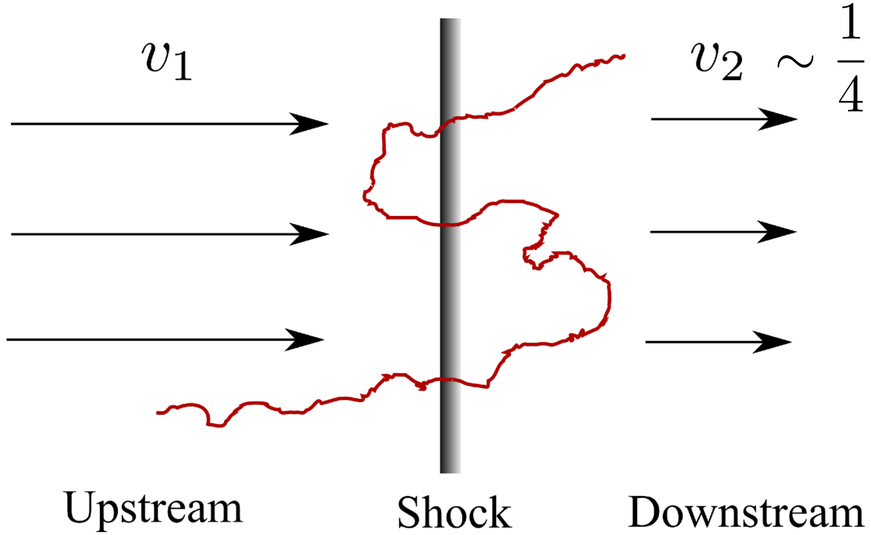
Heavier nuclei begin to dominate above the 2nd knee.



Credit: Particle Data Group (2020)

Production of cosmic rays

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



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

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

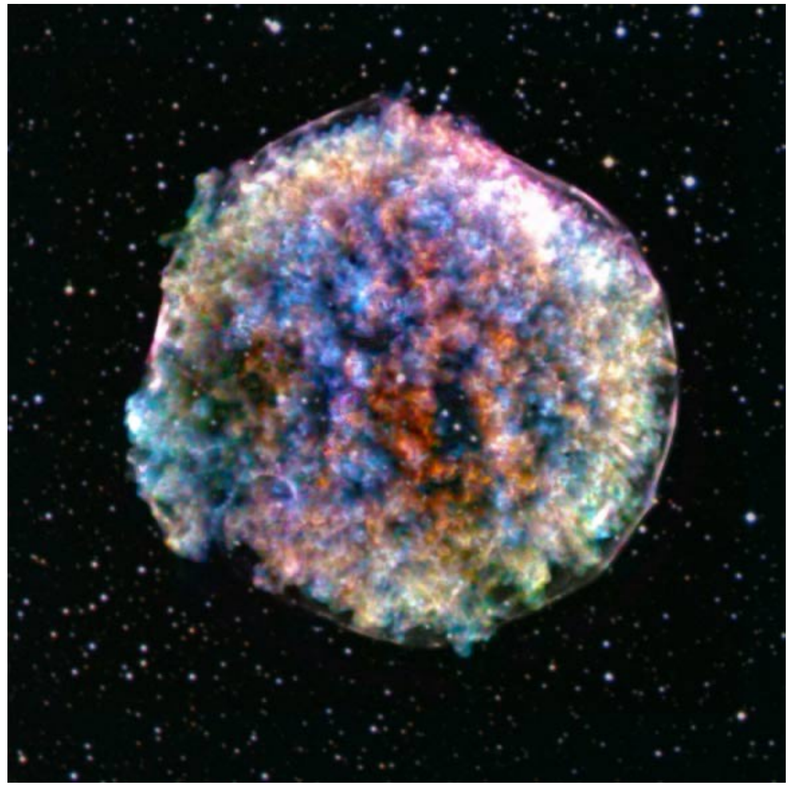
After *n* crossings: $$E_n = (1+\xi)^n E_0$$

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

→ 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

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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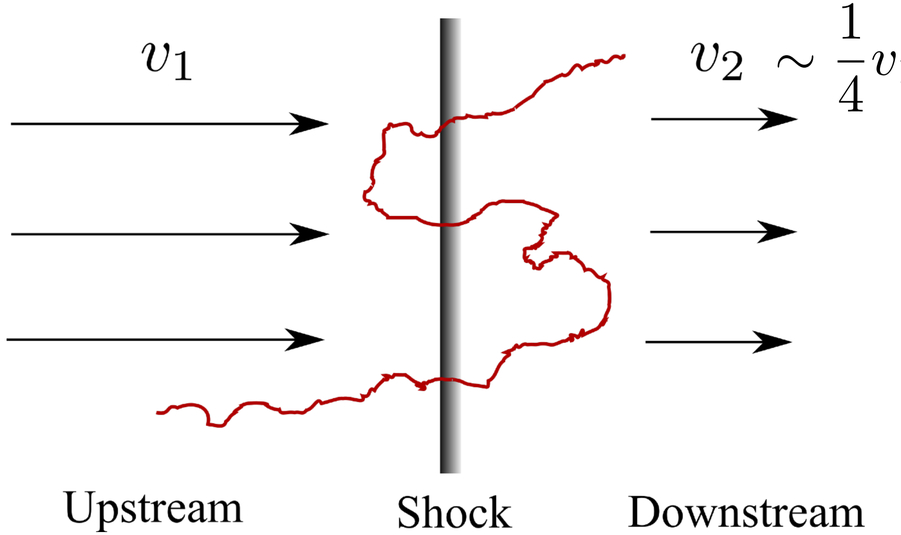

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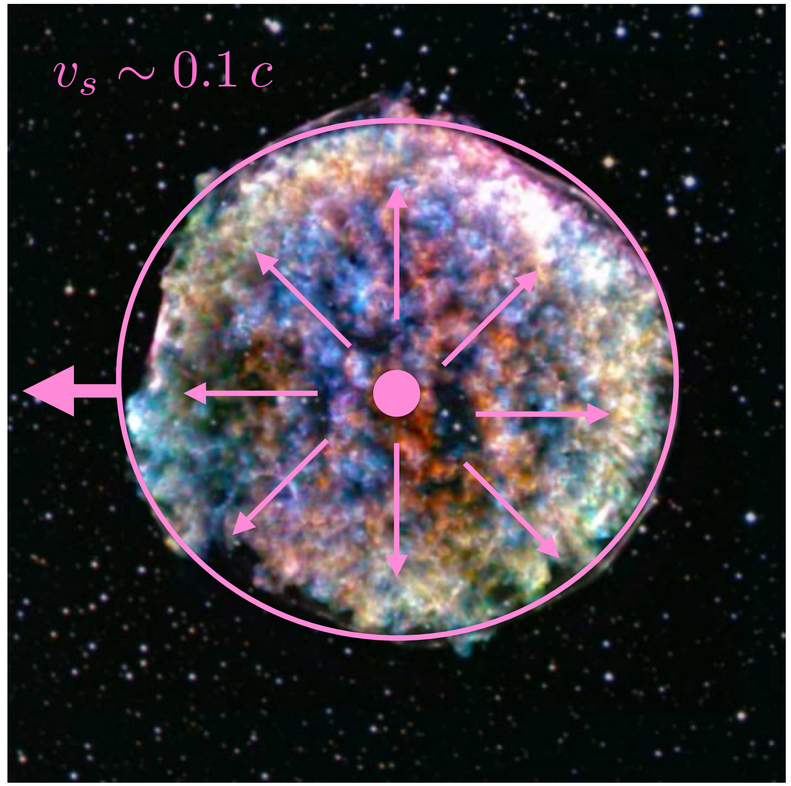
Tycho Supernova remnant



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

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

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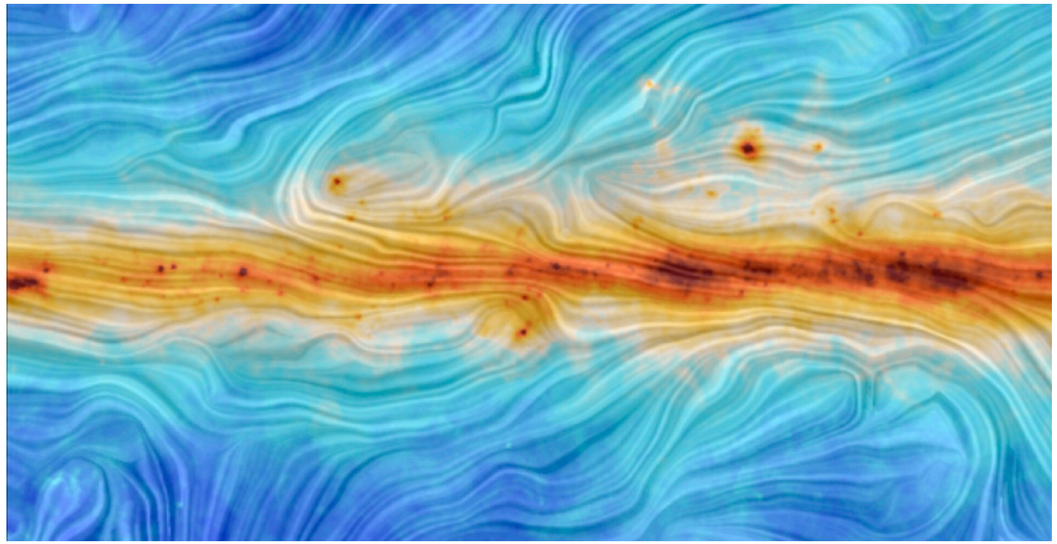
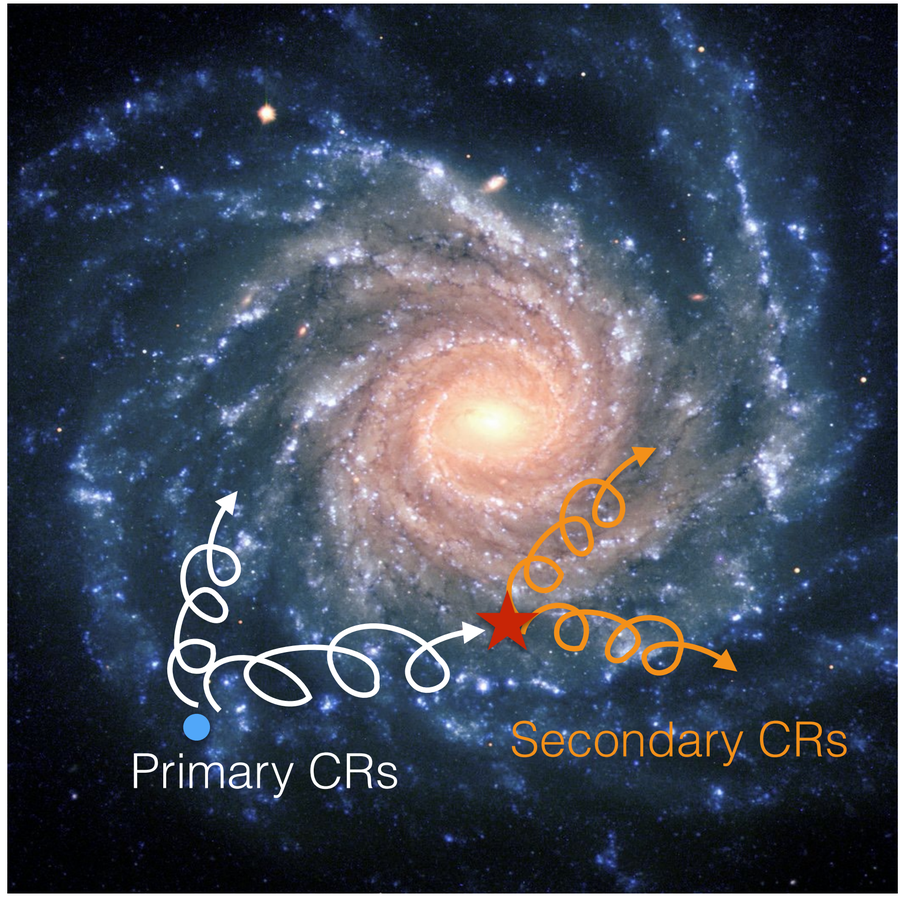
E.g. 1910.06006

Propagation of CCRs

Credit: ESA/Planck Collaboration



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



Diffusion — Escape and attenuation — Sources

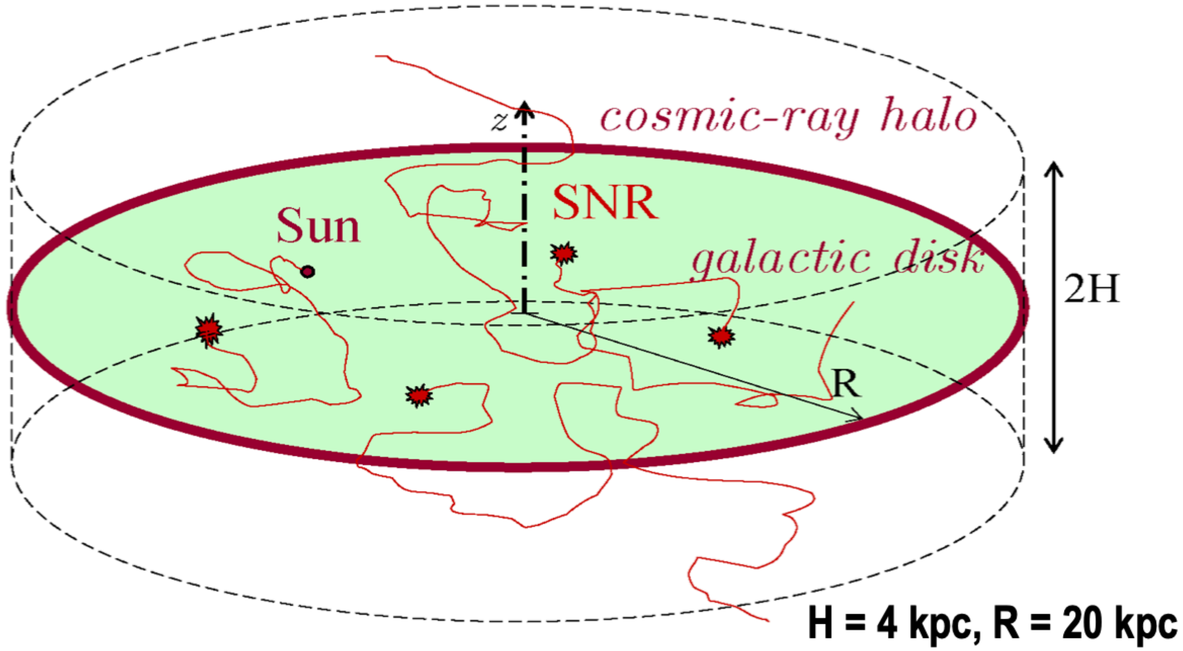
$$\frac{\partial N_i}{\partial t} = D(E)\nabla^2 N_i + \frac{\partial}{\partial E}\left[b(E)N_i\right] - \frac{N_i}{\tau_i} + \sum_{j>i}\frac{P_{ji}}{\tau_j}N_j + Q$$

Energy losses — Production (by spallation)

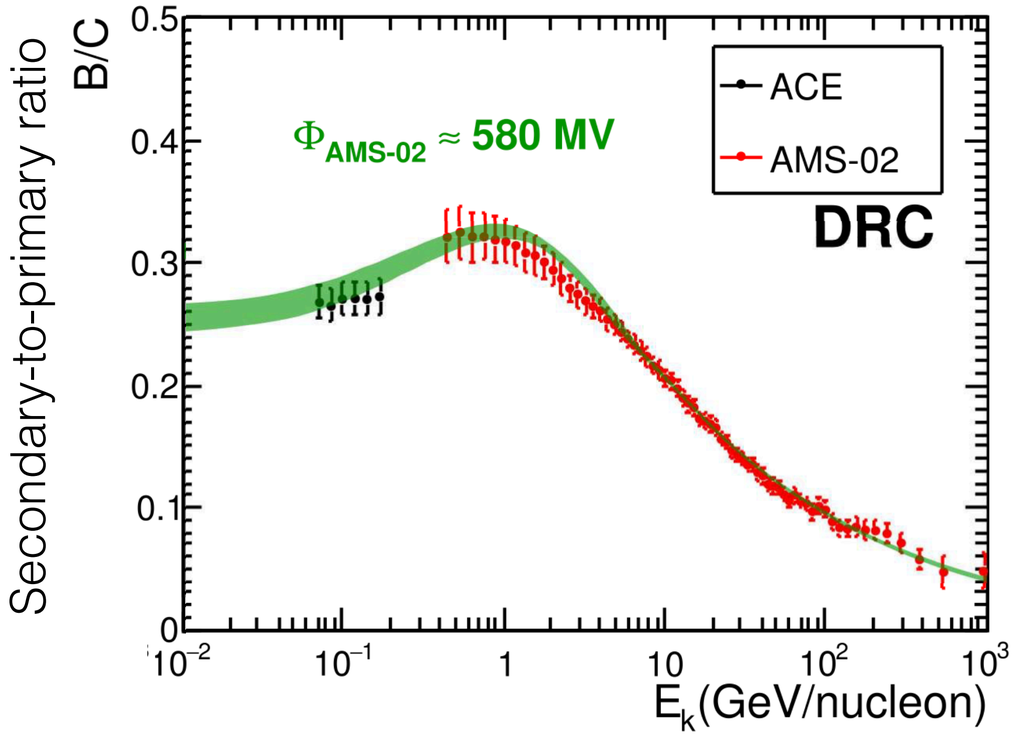
Modelling CR propagation

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

Credit: Vladimir Ptuskin



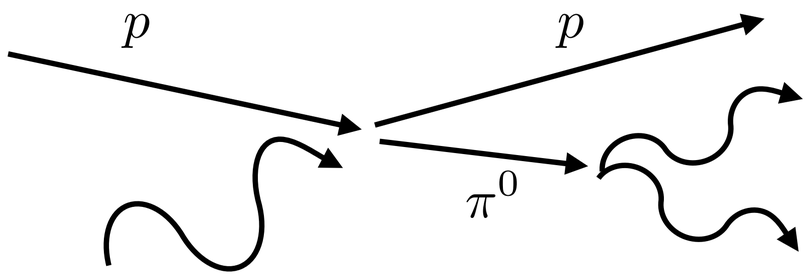
1701.06149

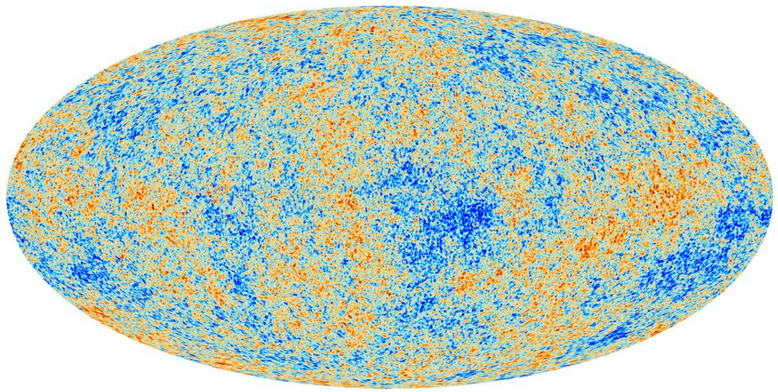


Typical diffusion distance $\langle R^2 \rangle \sim D(E)t$. Coefficient $D(E)$ grows with E,
steepening the observed CR spectrum…

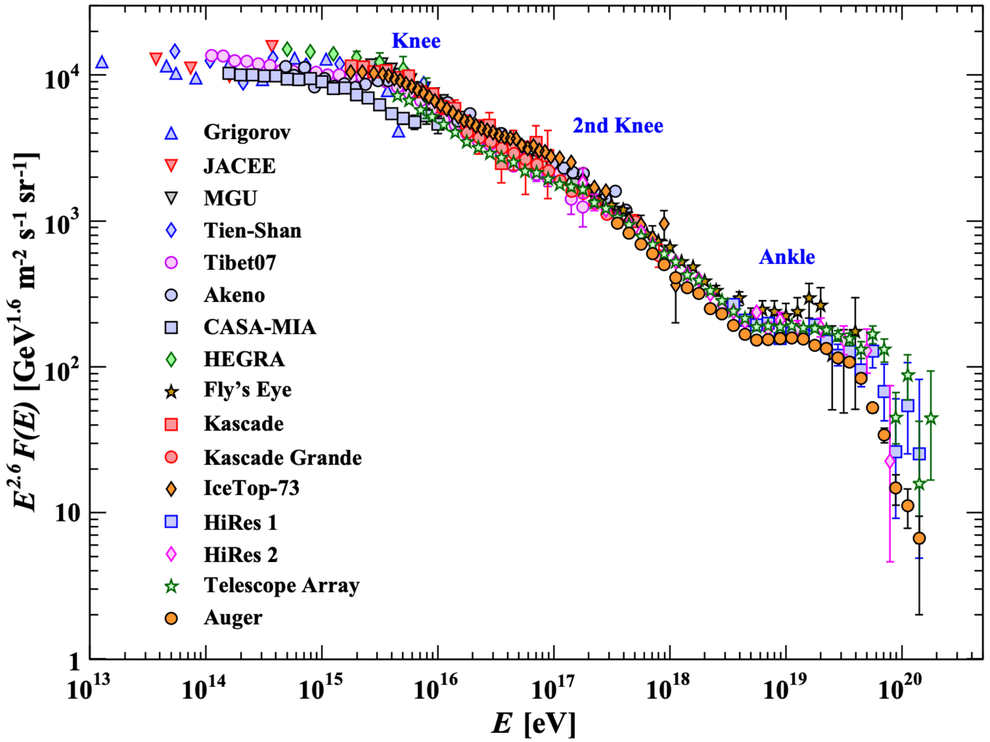
GZK cut-off

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





Credit: ESA/Planck



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

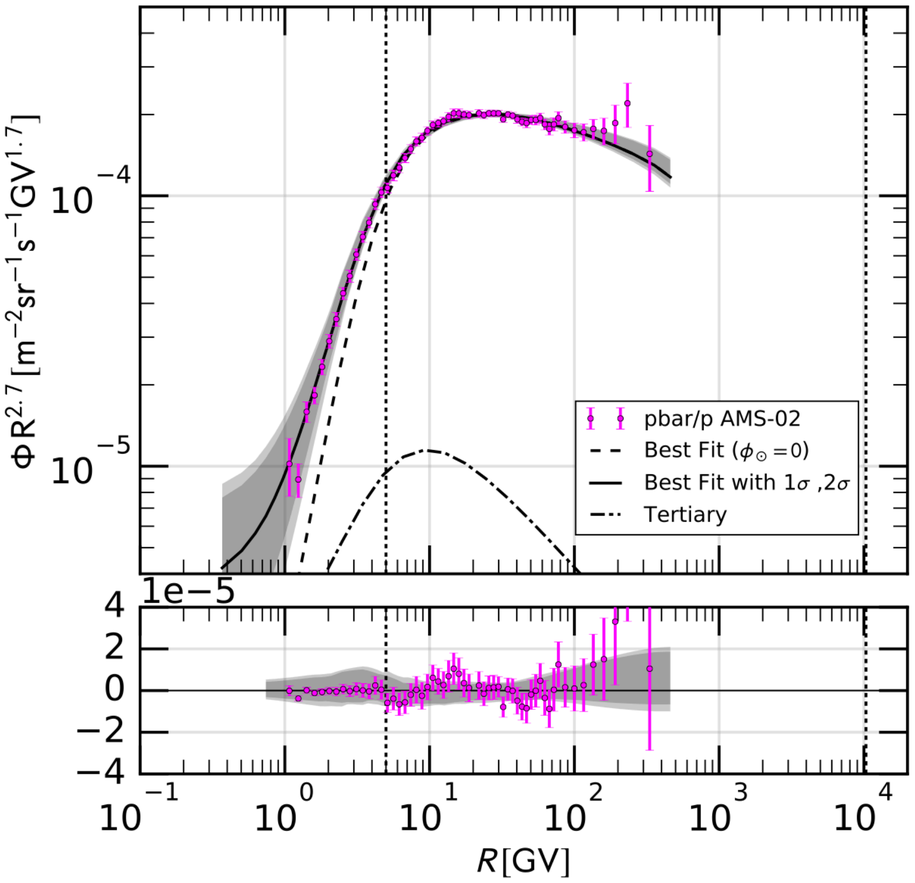
Threshold energy for this process gives rise to the Greisen–Zatsepin–Kuzmin (GZK) cut-off:

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

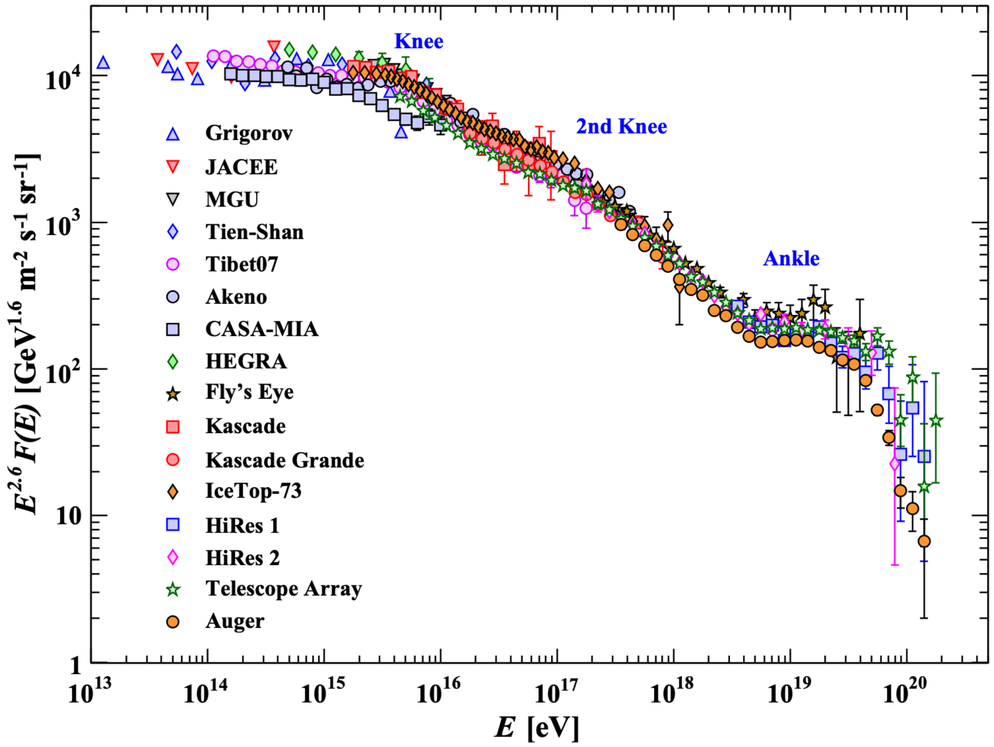
Ultra high energy CRs cannot propagate more than around $\ell_{\mathrm{GZK}} \sim 50\,\mathrm{Mpc}$ before being destroyed.

CCR anomalies and questions

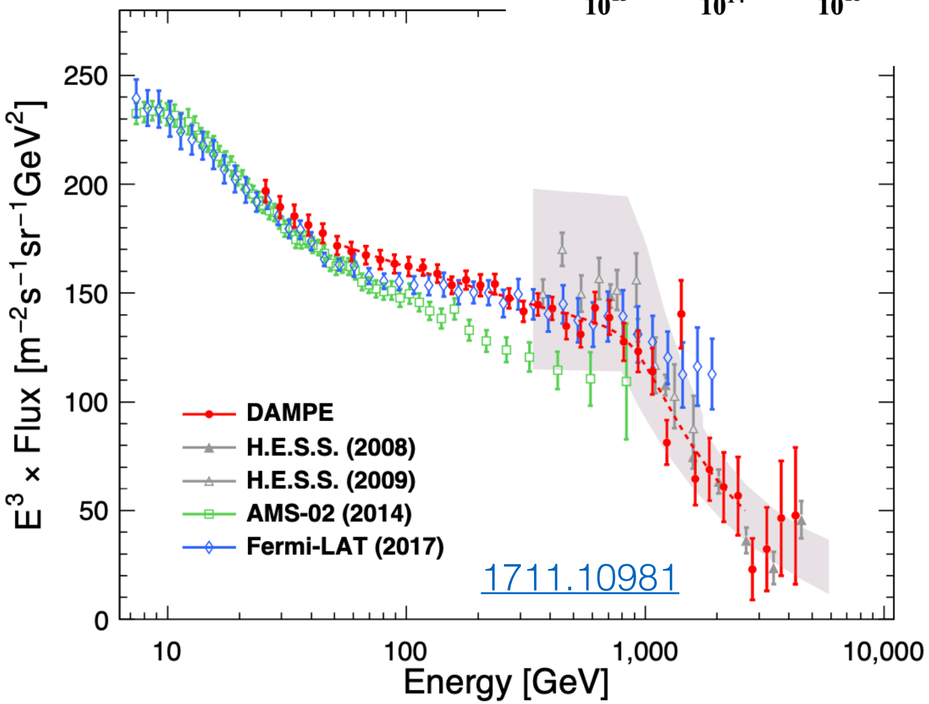
Excess in anti-protons?



1610.03071



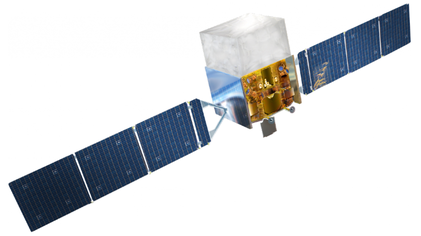
Excess in electrons?



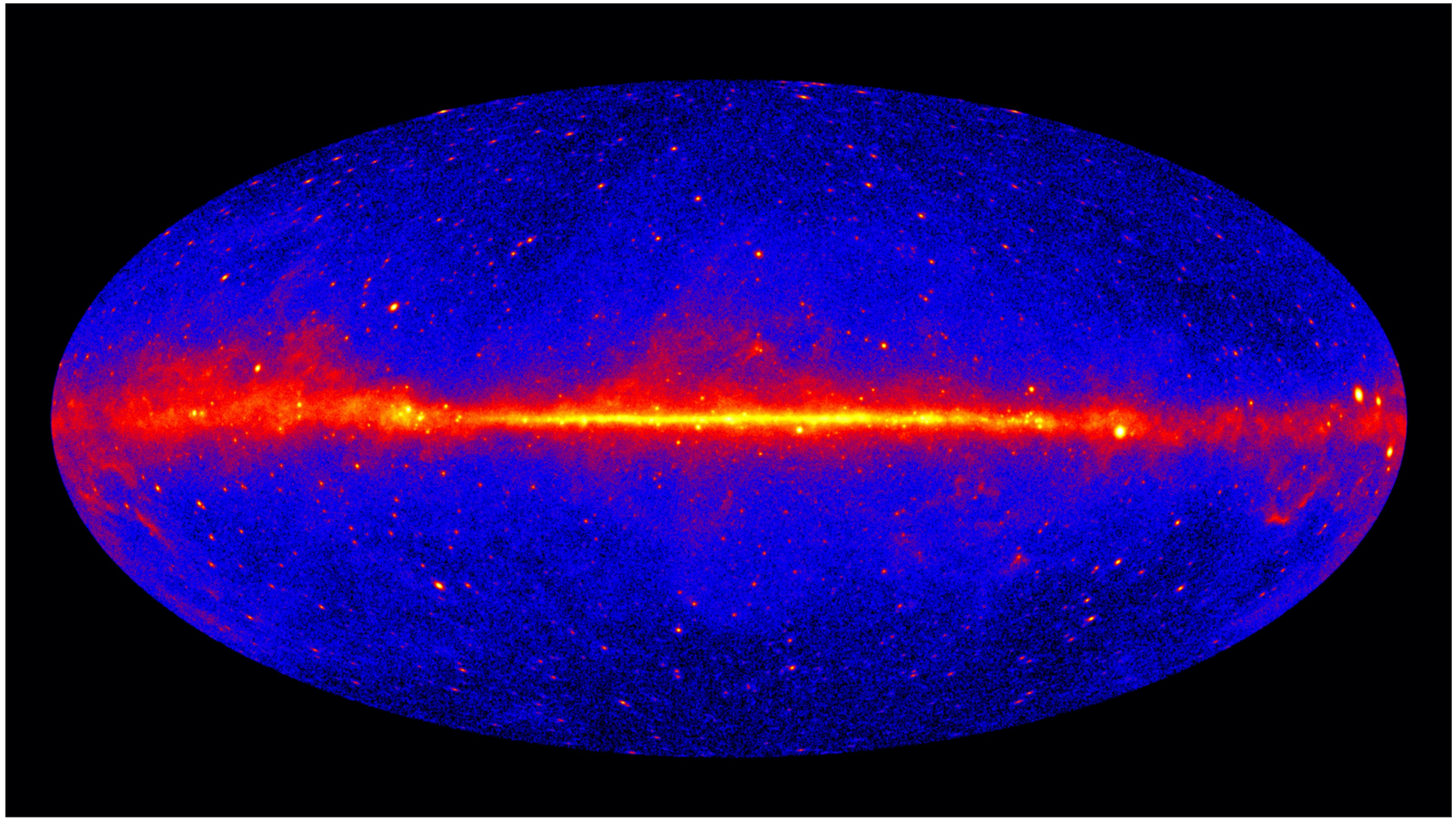
1711.10981

and others…

The Gamma-ray Sky

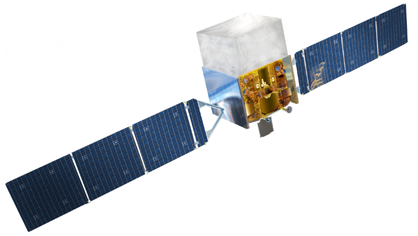


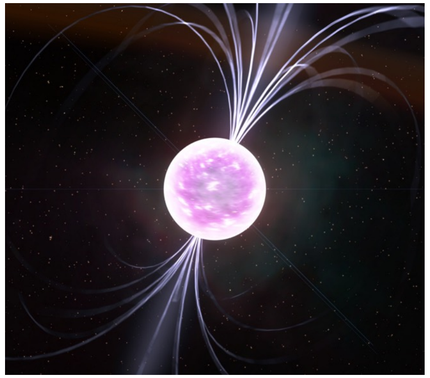
Gamma-ray Sky above 1 GeV, according to Fermi:



Credit: NASA/DOE/Fermi LAT Collaboration

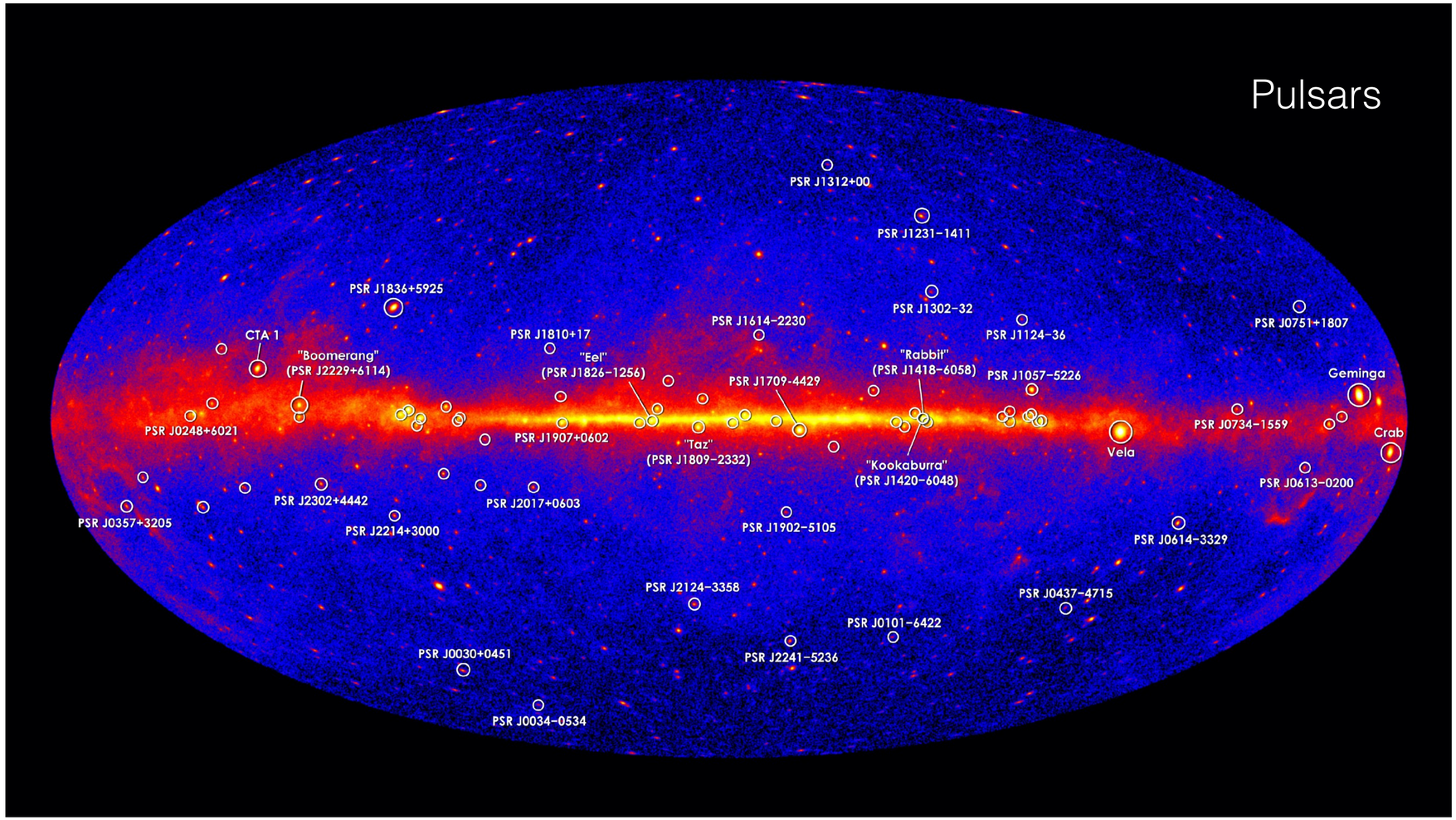
The Gamma-ray Sky





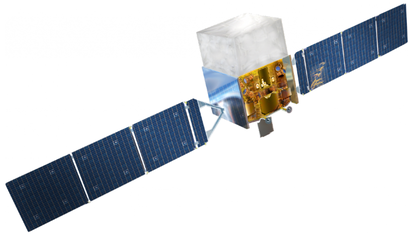
Credit: Kevin Gill / Flickr

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

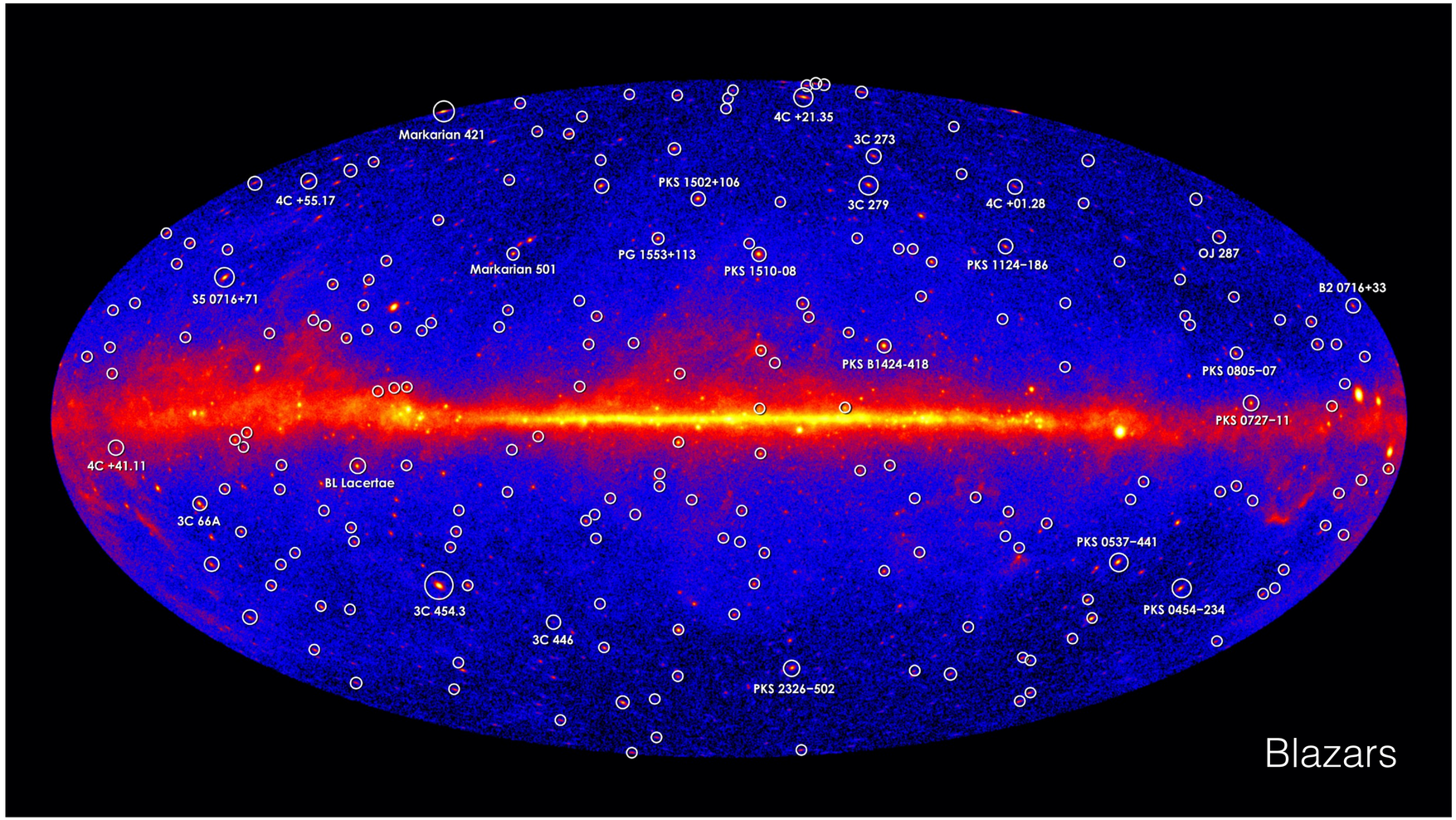


Credit: NASA/DOE/Fermi LAT Collaboration

The Gamma-ray Sky



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

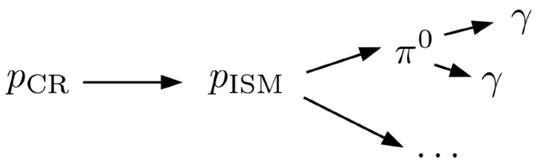


Credit: [NASA/DOE/Fermi LAT Collaboration]

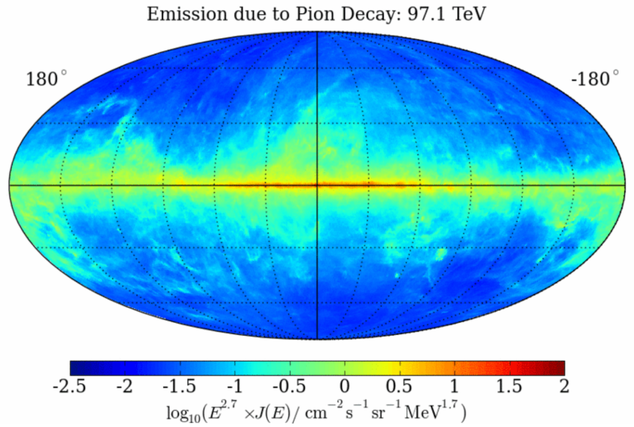
Credit: ESO/M. Kornmesser

Cosmic Ray Connection

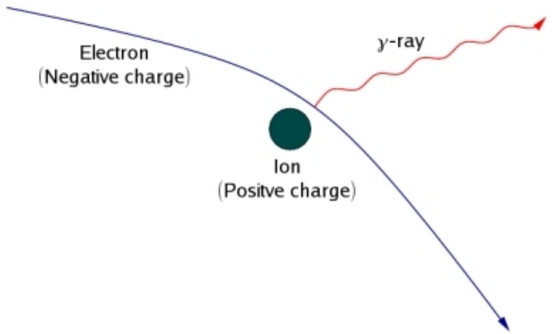
Pion Decay



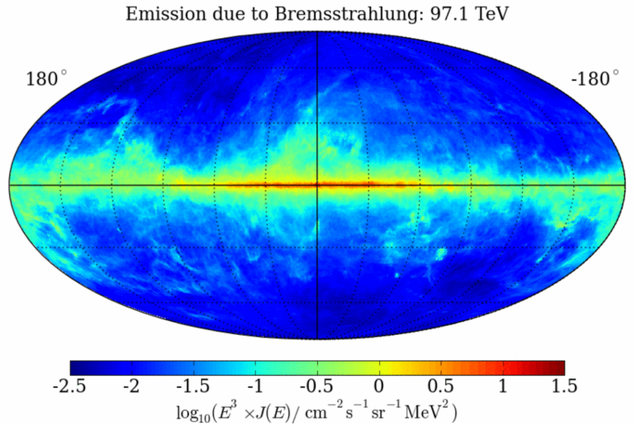
CR protons + gas



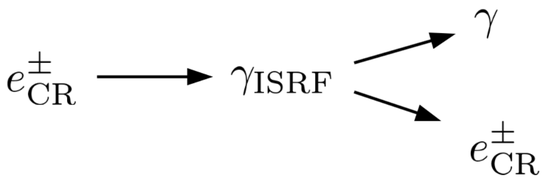
Brehmsstrahlung



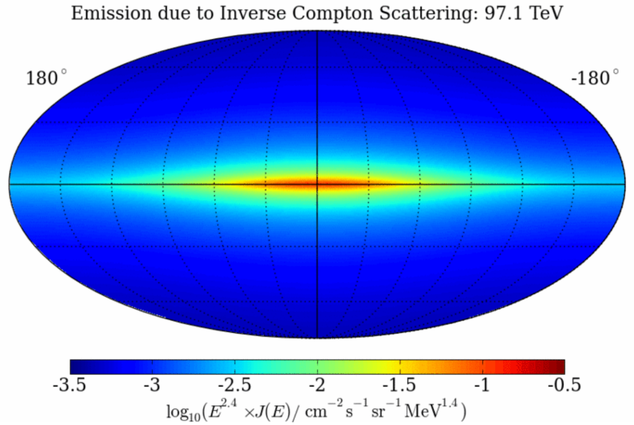
CR electrons + gas



Inverse Compton

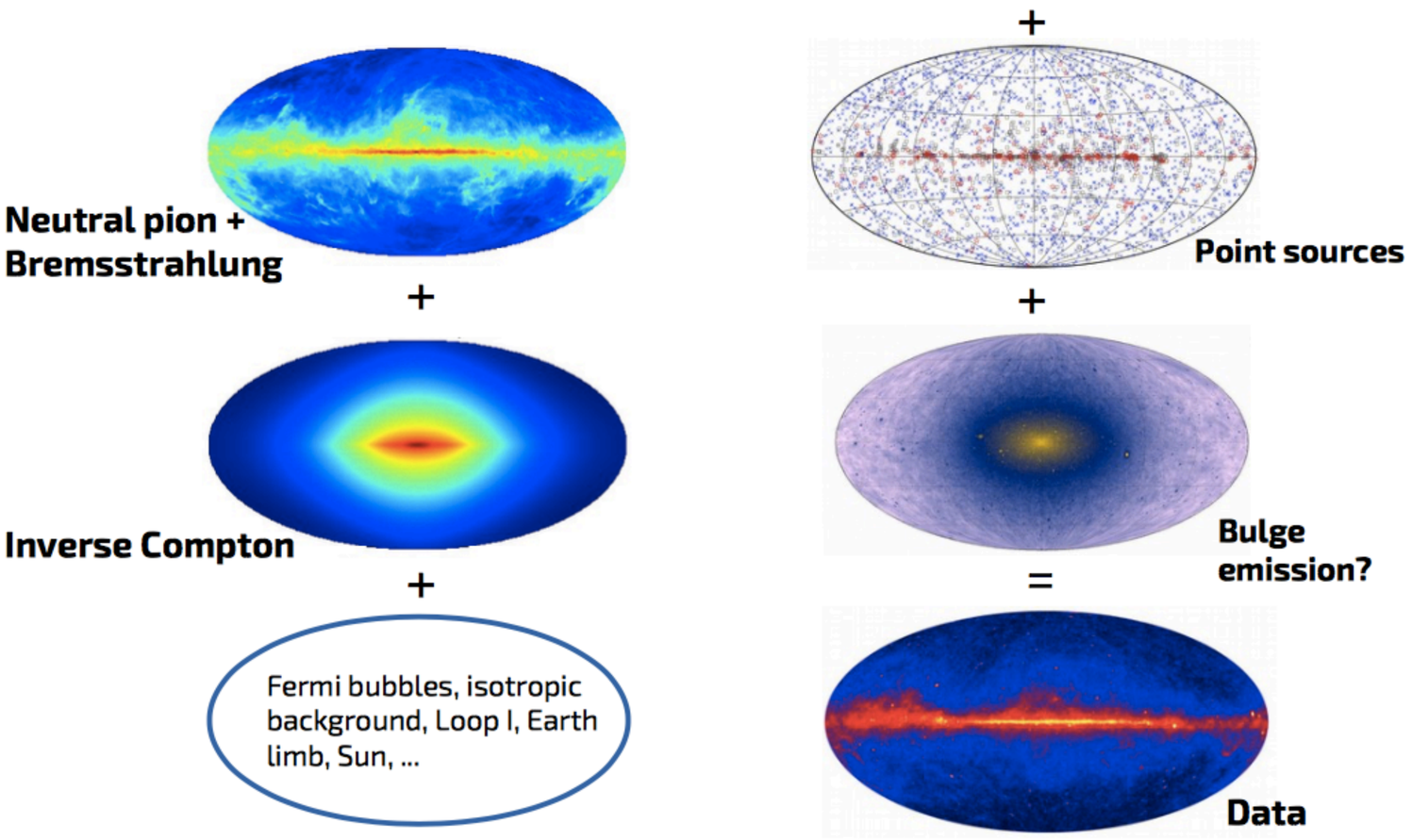


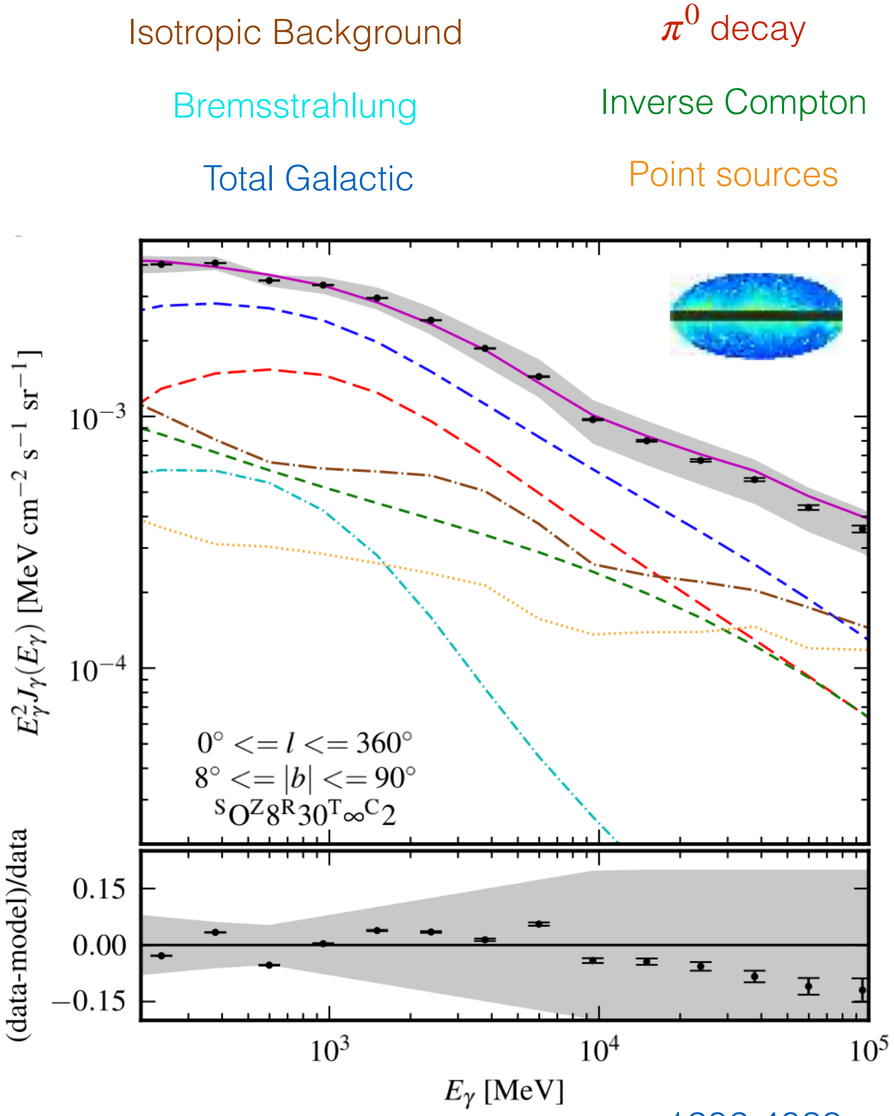
CR electrons + light



1708.07273

Modelling Gamma-ray emission



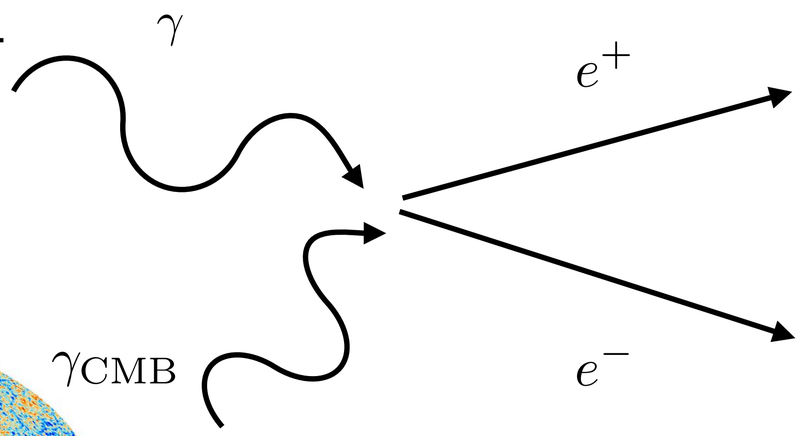


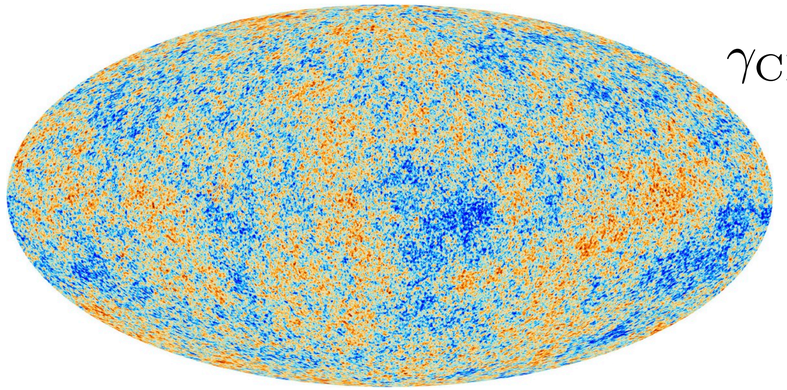
1202.4039

Credit: Christoph Weniger

Gamma-ray horizon

Similar to the GZK cut-off…

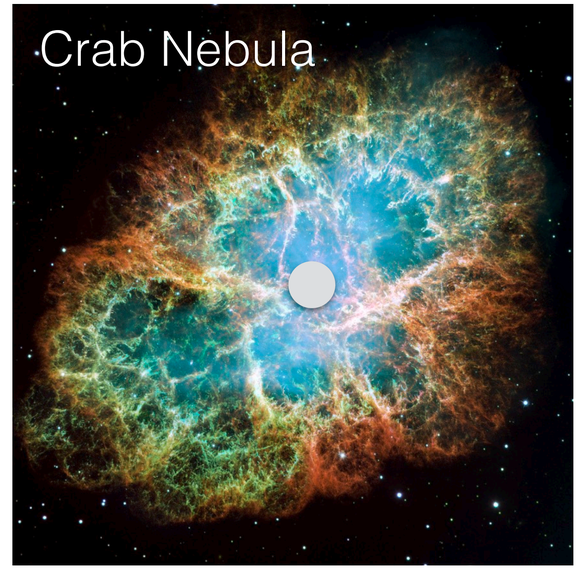


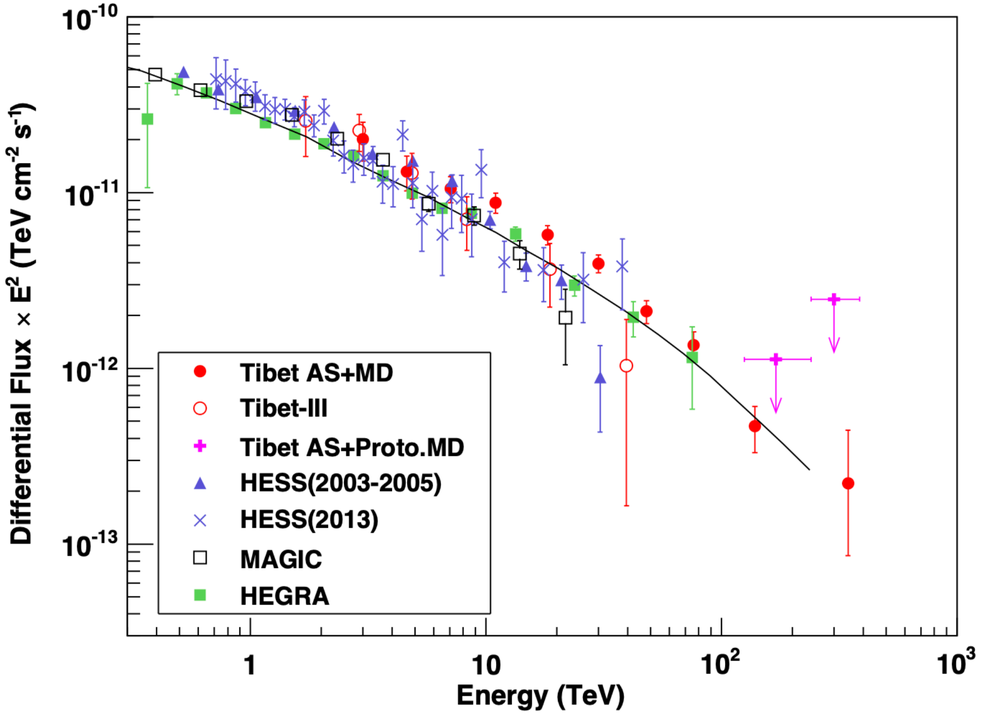


To produce an electron-positron pair, need a gamma-ray with energy greater than:

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

Credit: NASA/STScI

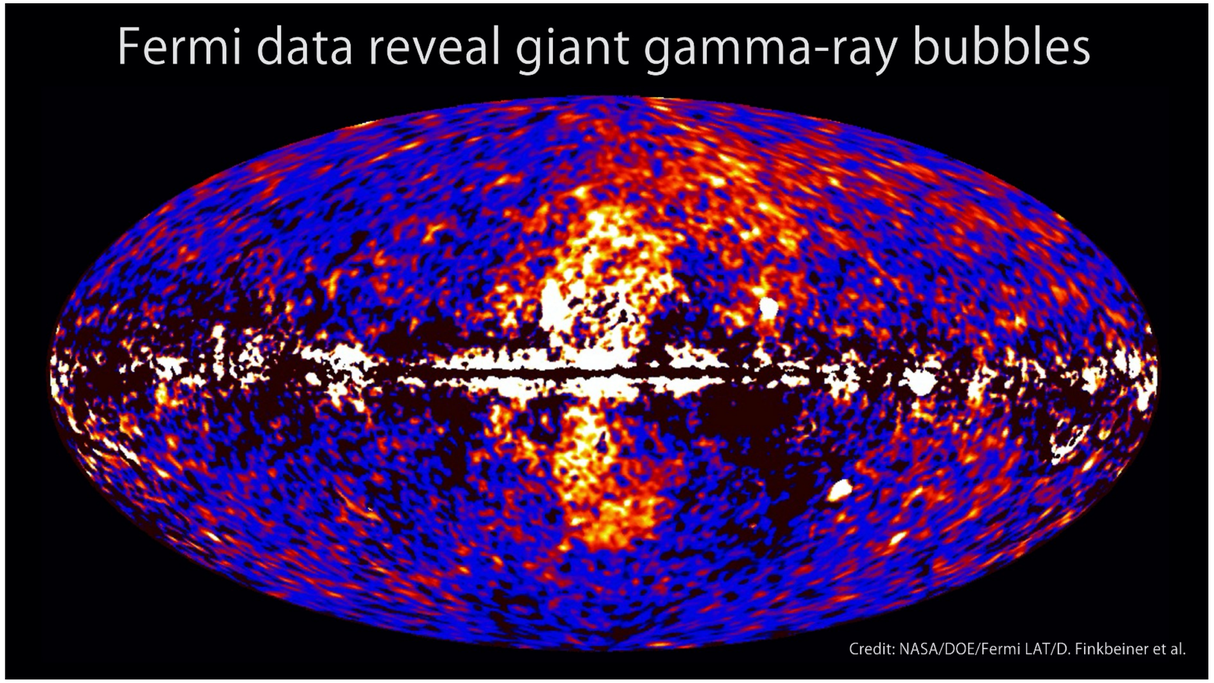




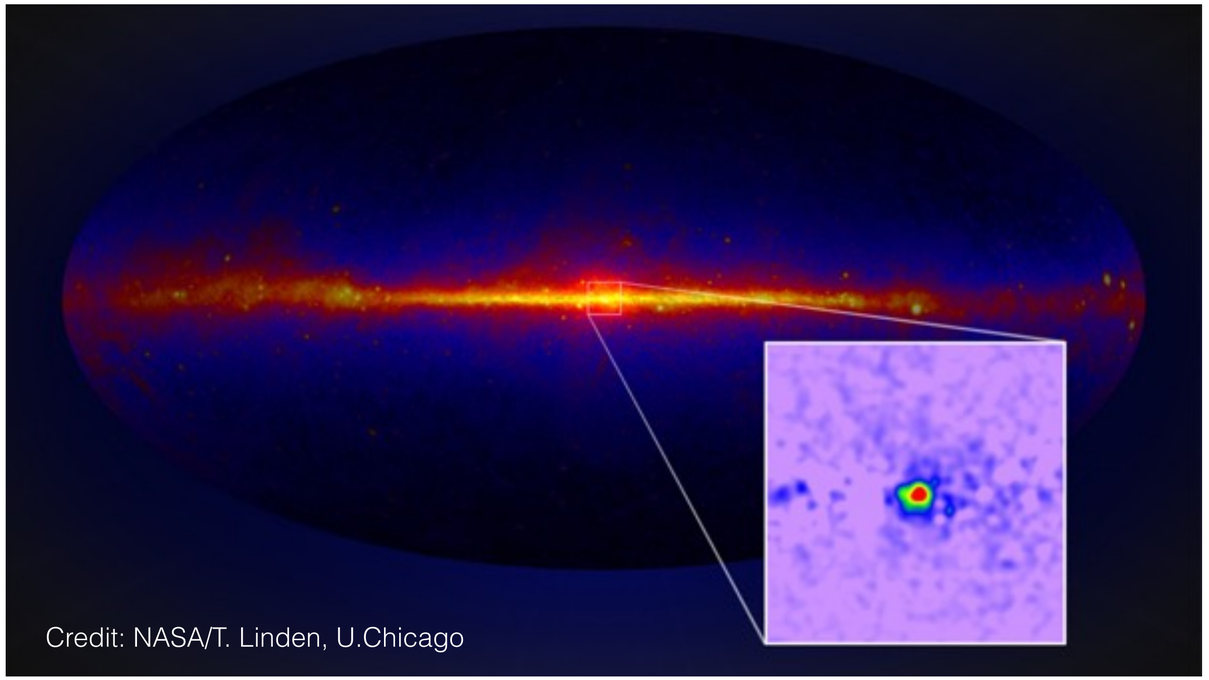
1906.05521

Gamma-ray anomalies

Fermi Bubbles

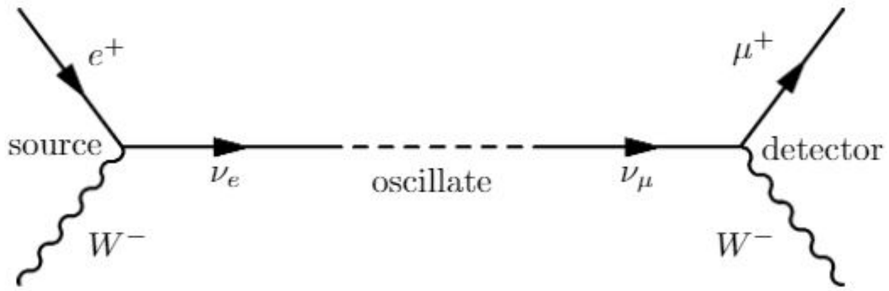


Galactic Centre Excess



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

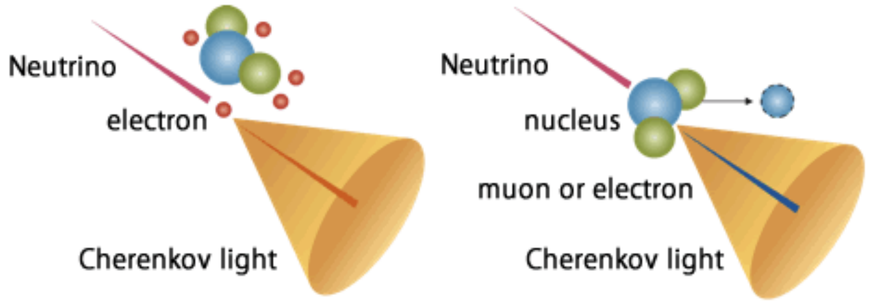
Neutrinos are produced with a definite flavor (e, μ, τ)
but they **oscillate** between the different flavors as they propagate.

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

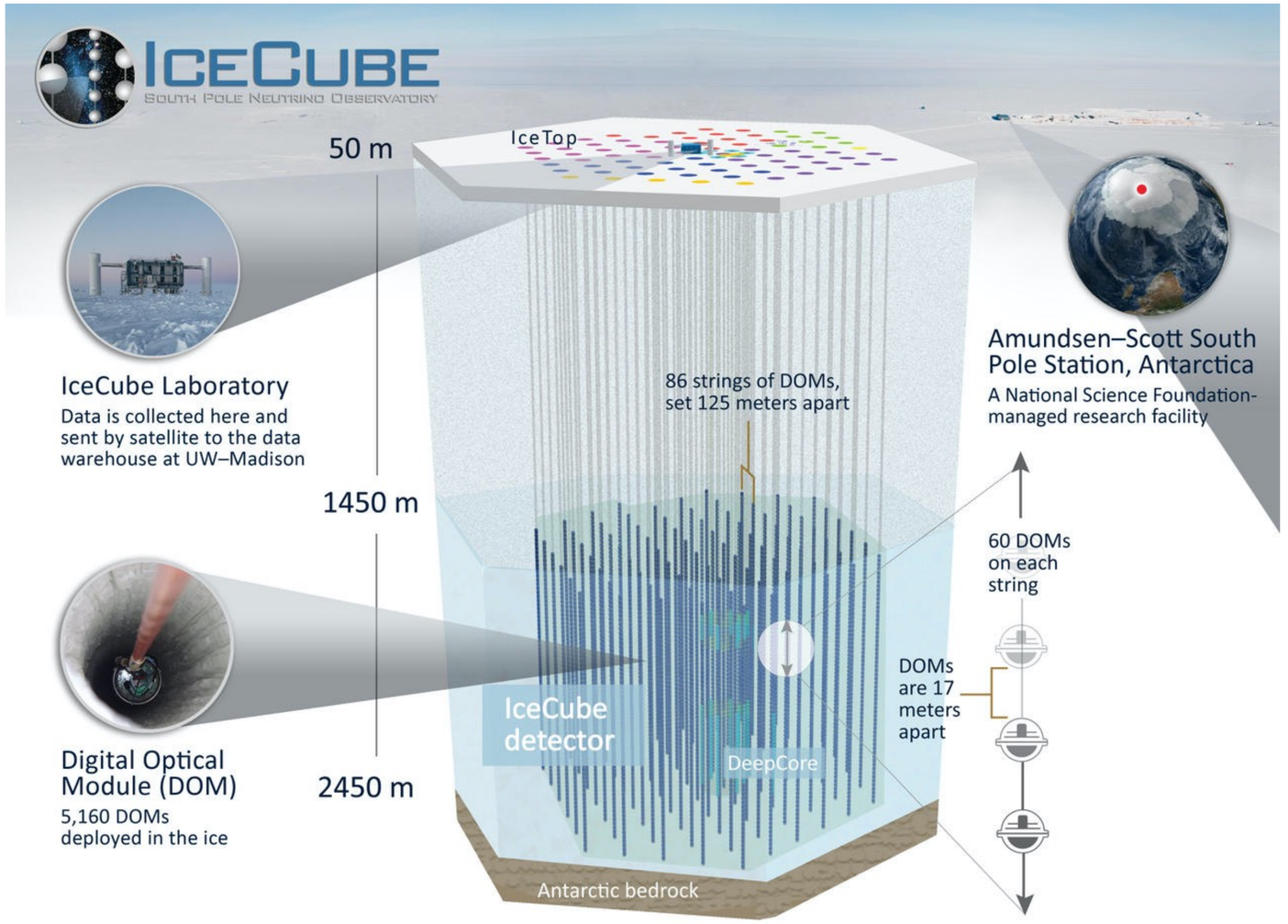
IceCube

1701.03731

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



Credit: Hyper-Kamiokande

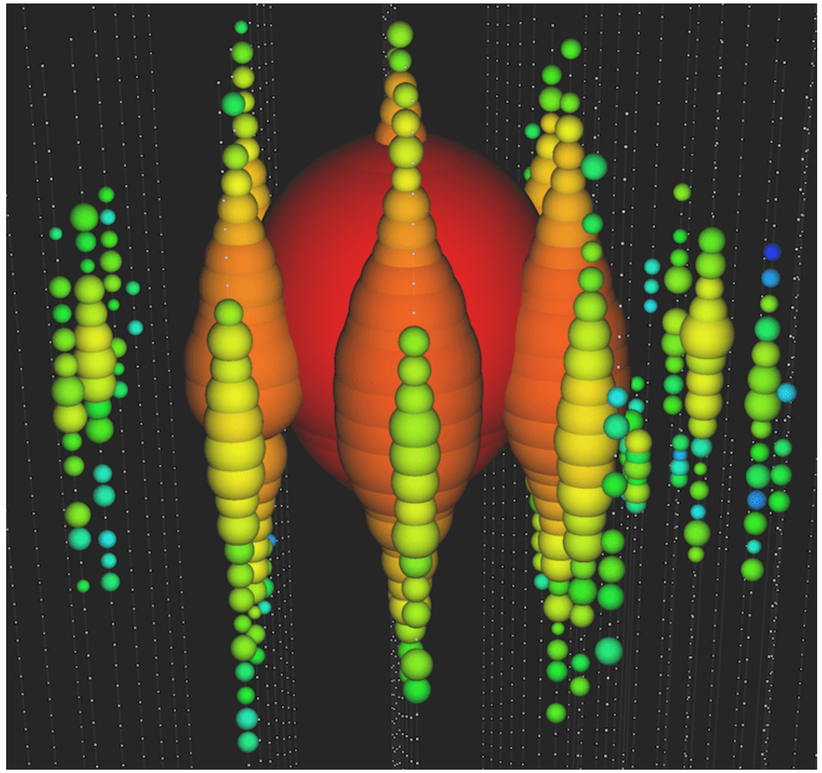


IceCube: a giant ice detector!
~1 km^3 of instrumented volume

See also SuperKamiokande, ANTARES, planned KM3NET

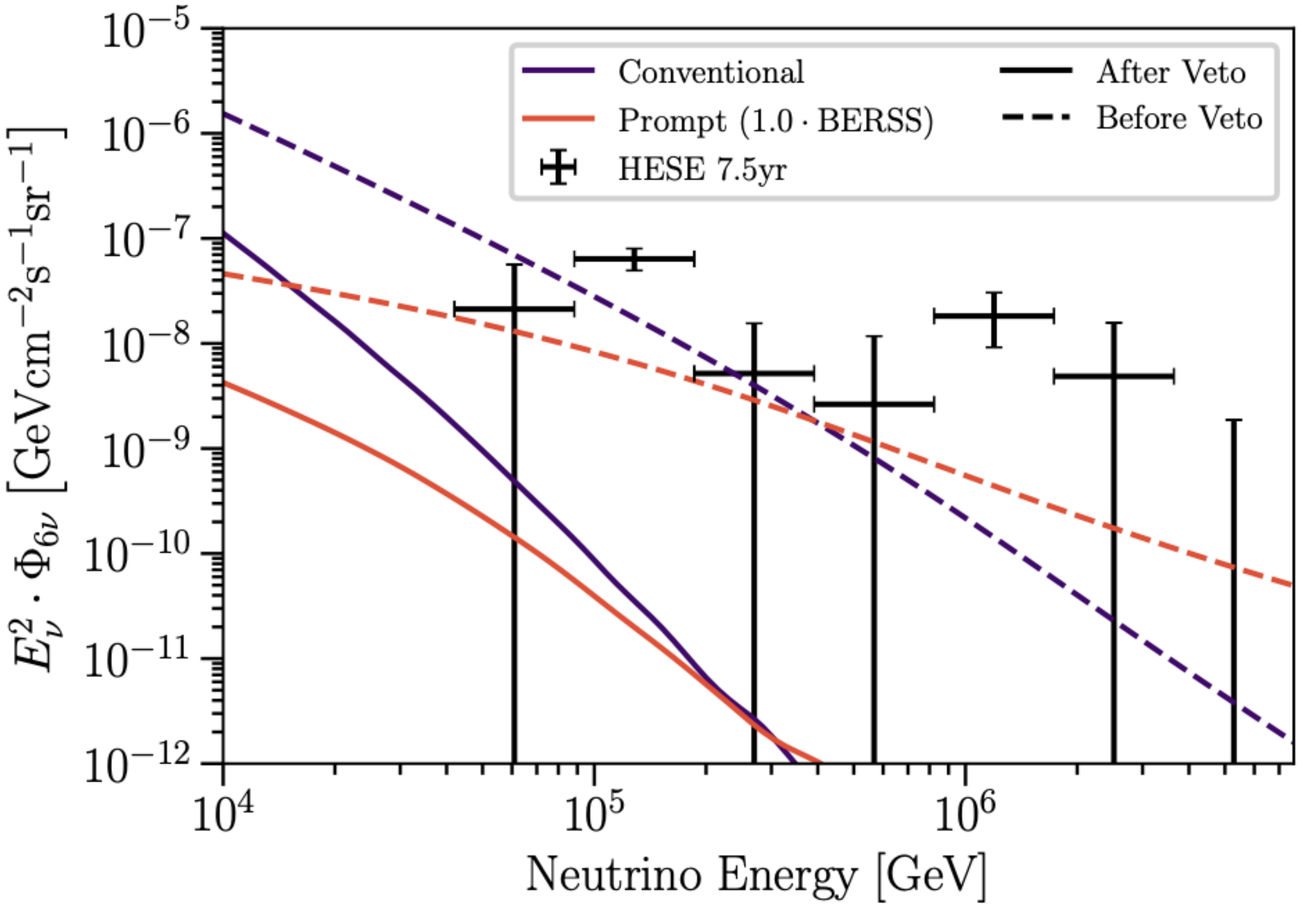
Ultra-high energy neutrinos

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



Credit: IceCube Collaboration

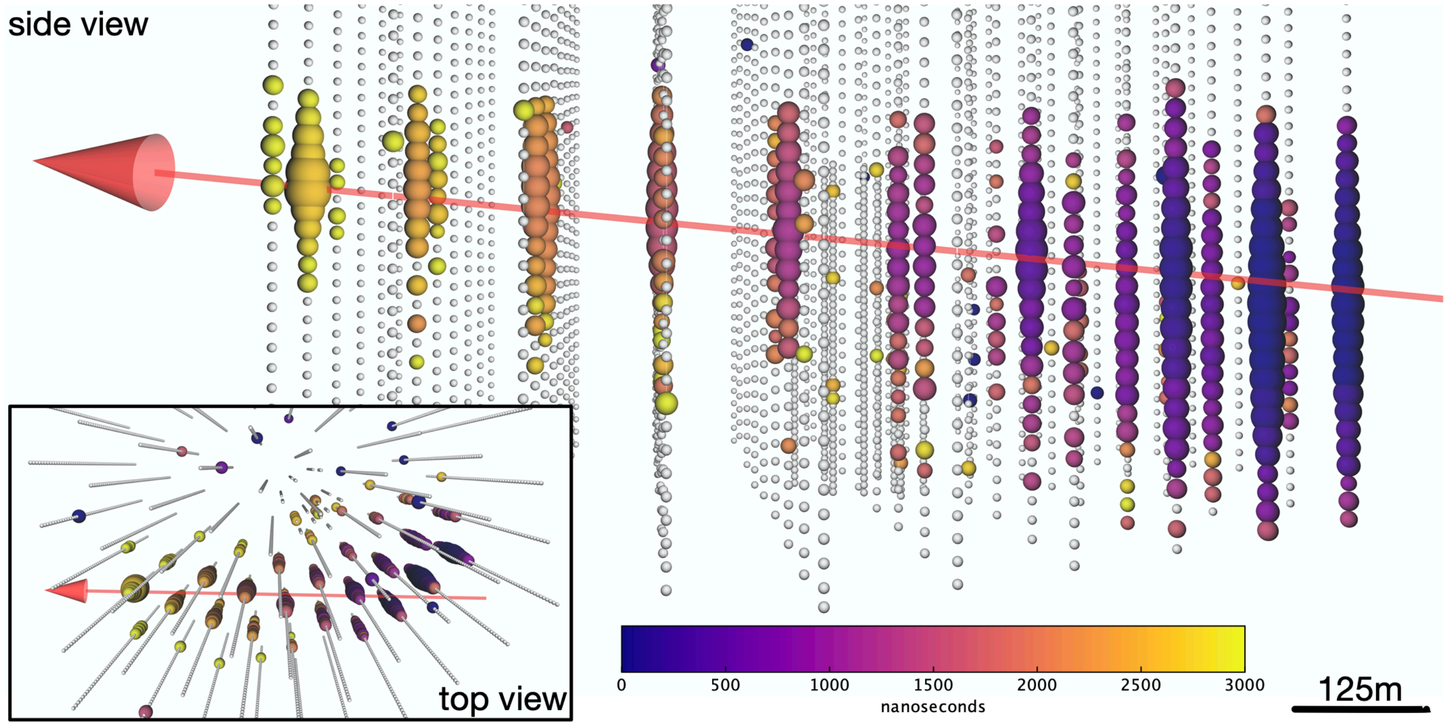
IceCube 'high energy starting events' (HESE)



2011.03545

IceCube-170922A

22 September 2017

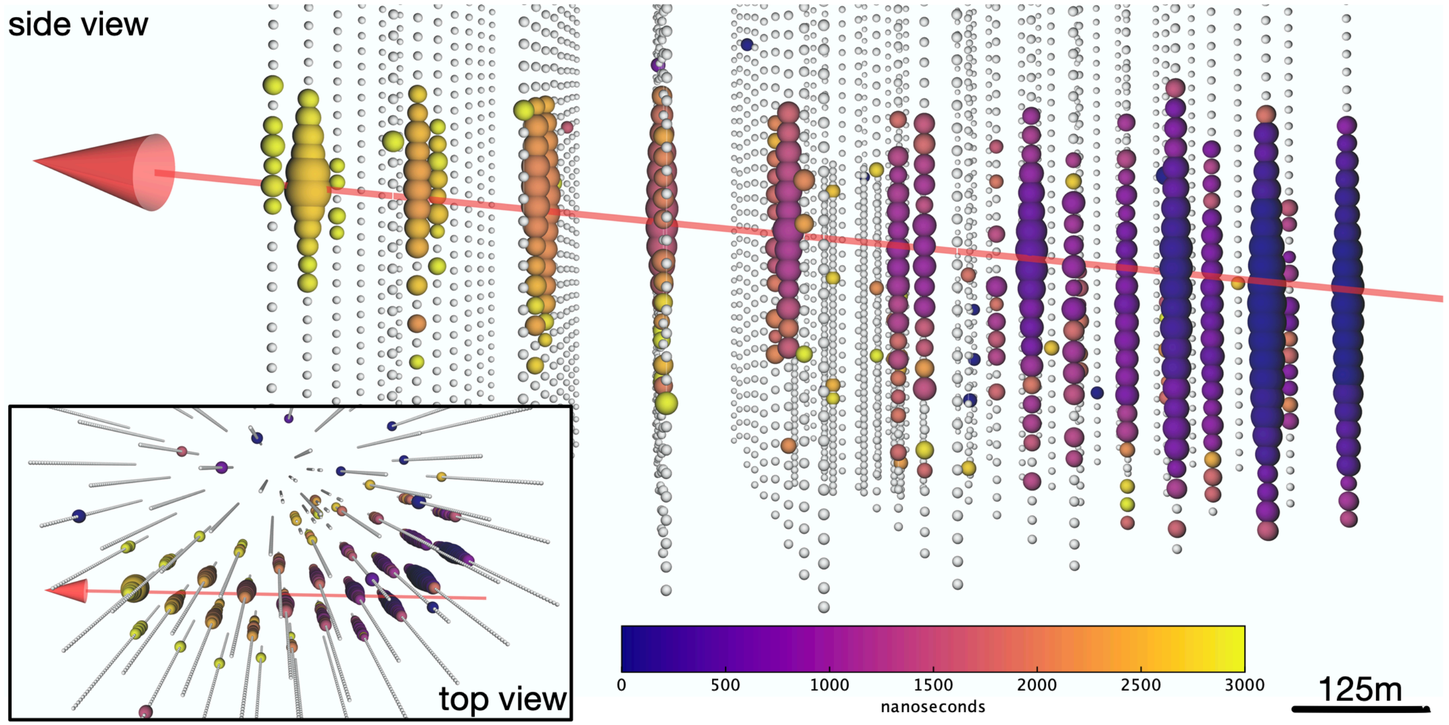


290 TeV

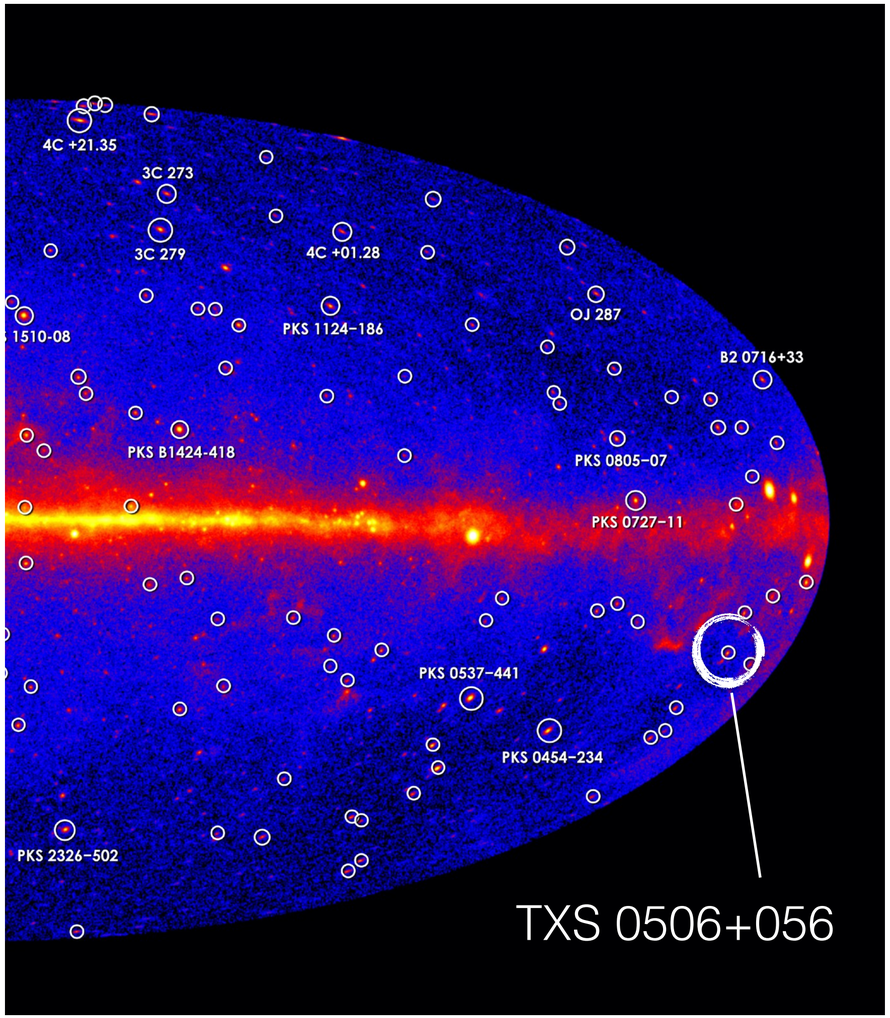
1807.08816

IceCube-170922A

22 September 2017

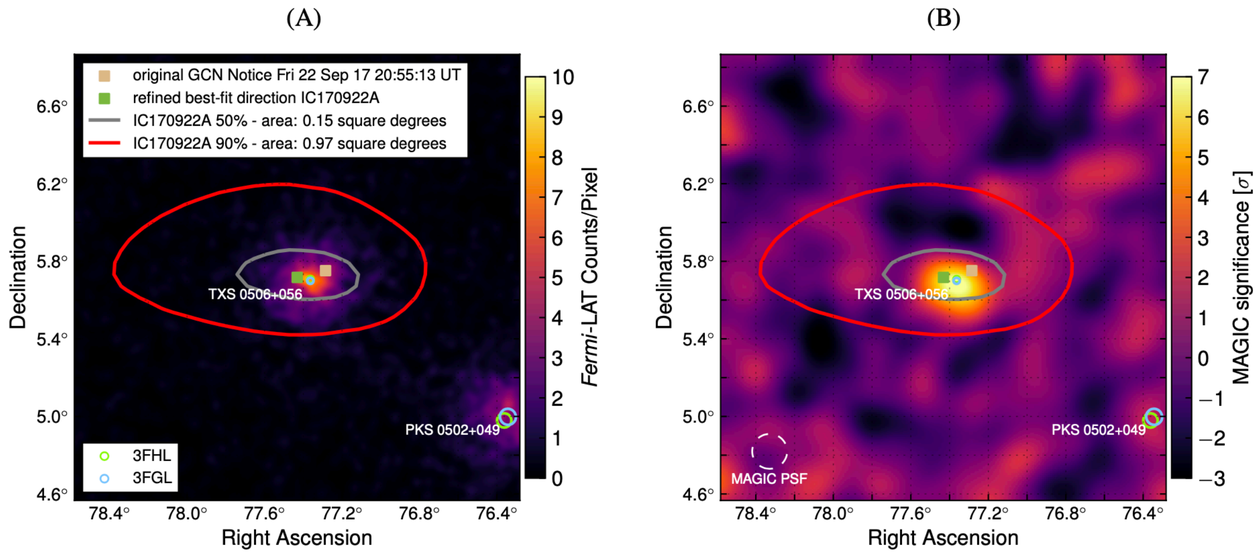


290 TeV



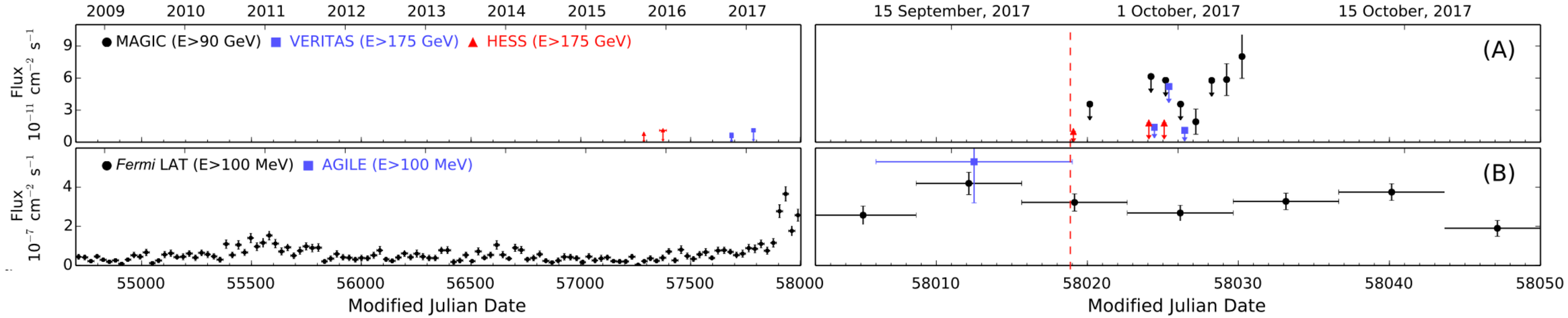
1807.08816

TXS 0506+056 in gamma-rays



TXS 0506+056 is a known blazar!

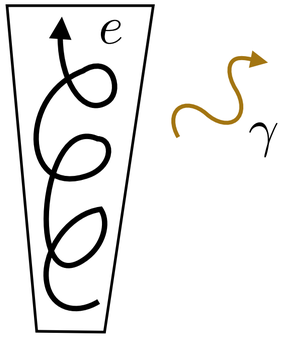
It was flaring at the time of IceCube-170922A!



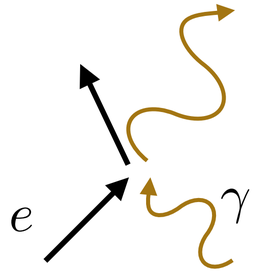
1807.08816

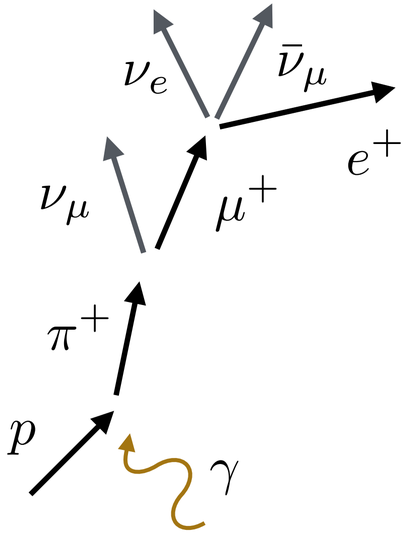
Blazar emission

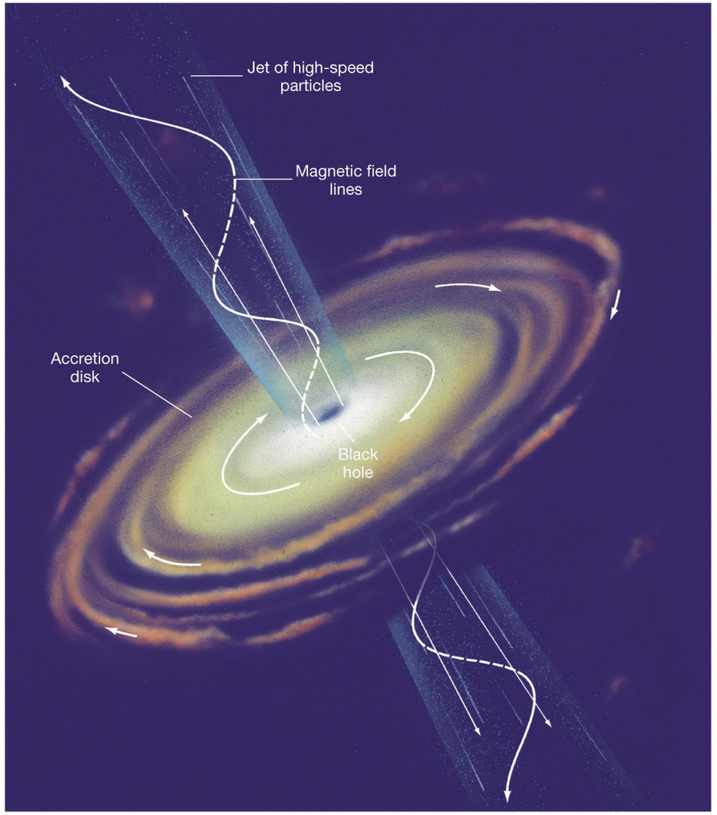
Electron synchrotron



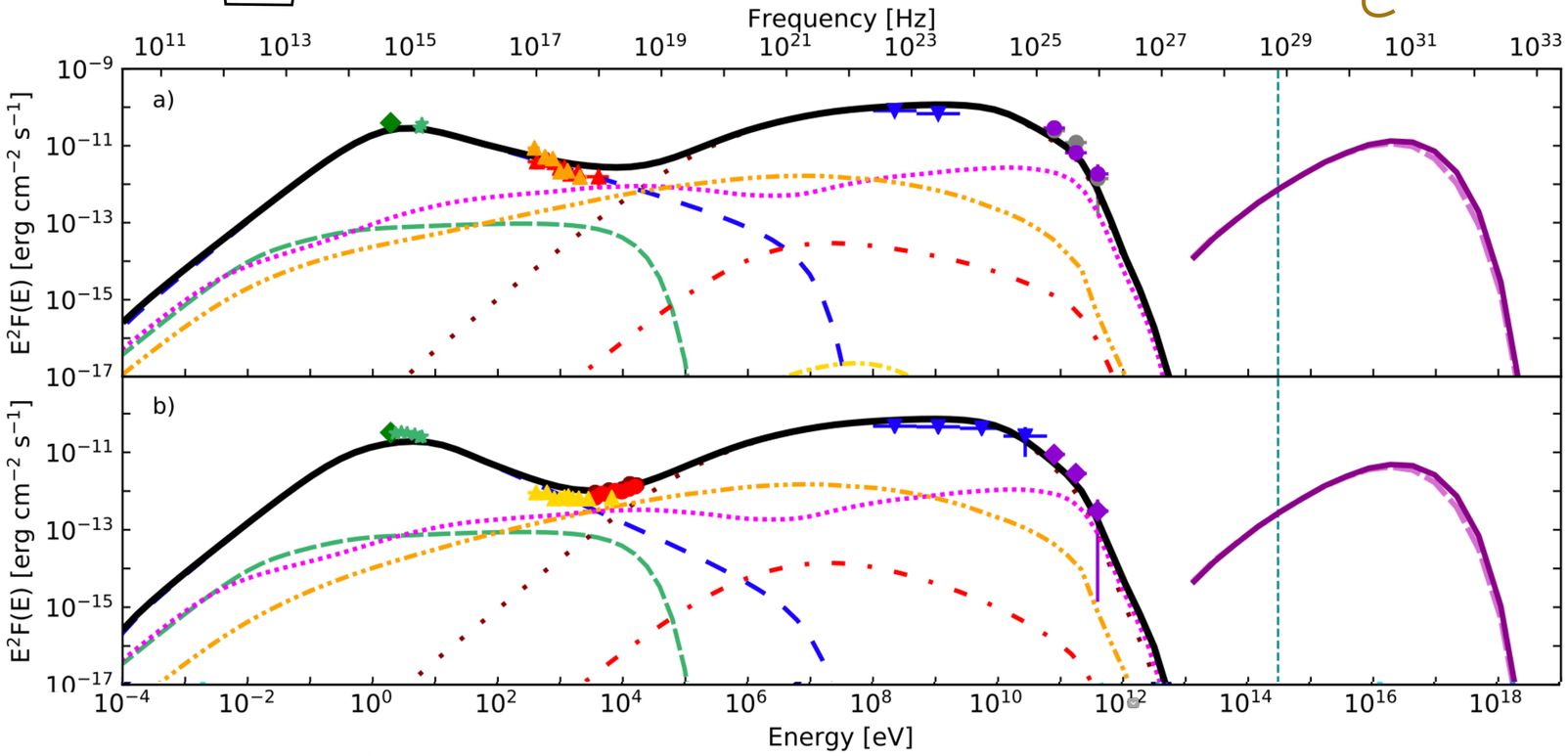
Inverse Compton

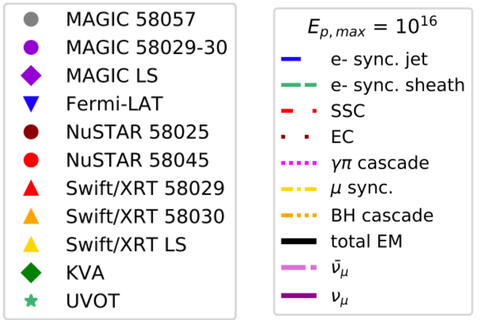






Credit: Pearson Education, Inc., Upper Saddle River, New Jersey





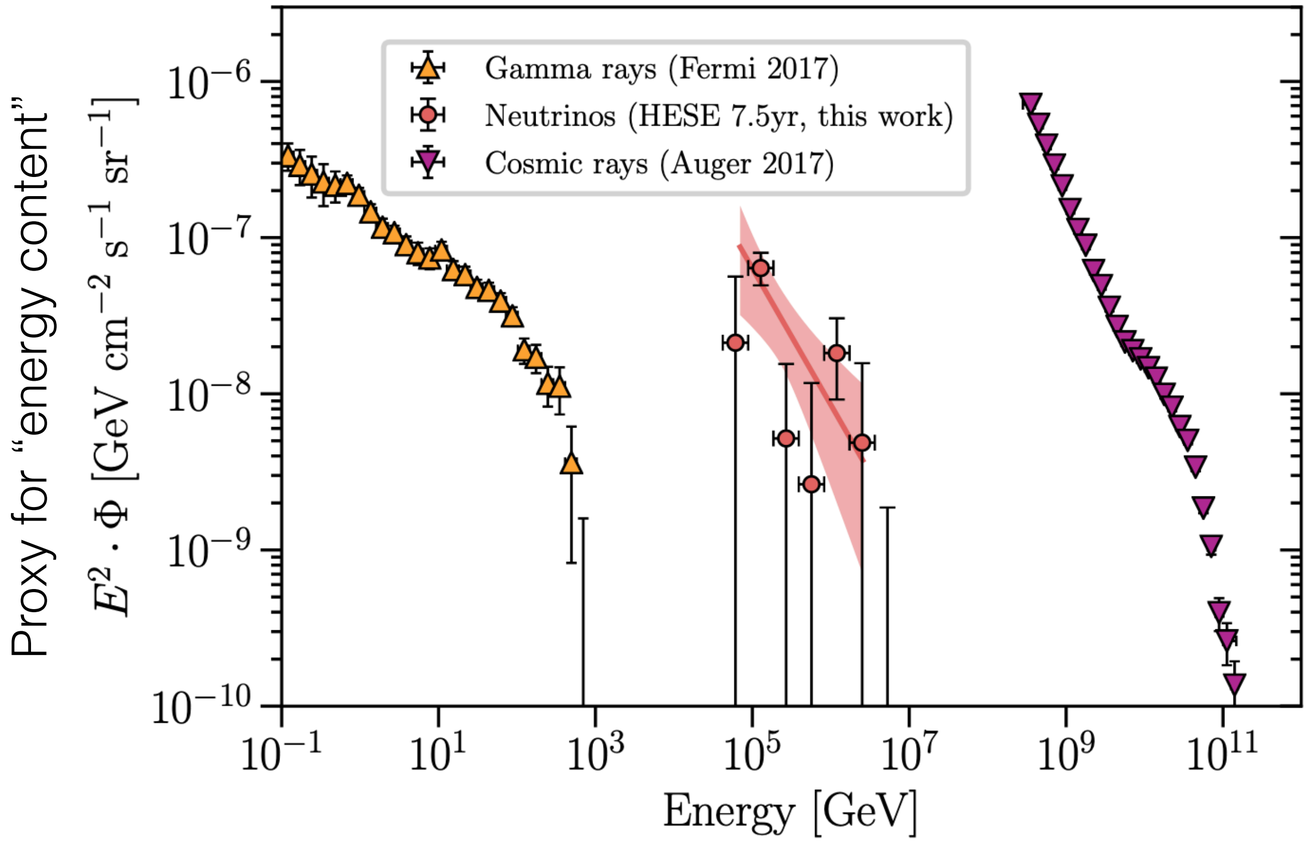
Optical X-ray Gamma-ray Neutrinos!

1807.04300

Violent and Energetic Universe

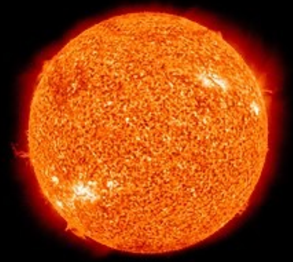
A complex and interconnected ecosystem:

2011.03545

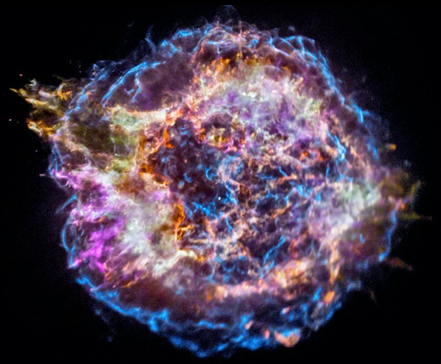


Understanding it could shed light on the most violent processes in the Universe,
and on New Physics yet to be discovered…

The Sun



Supernovae



Credit: NASA/CXC/SAO

Quasars/AGN

Credit: ESO/M. Kornmesser

Lecture 1

Lecture 2

Gamma rays

γ

Neutrinos

ν

Charged Cosmic Rays

$e^{\pm}, p^{\pm}, \ldots$

Dark Matter

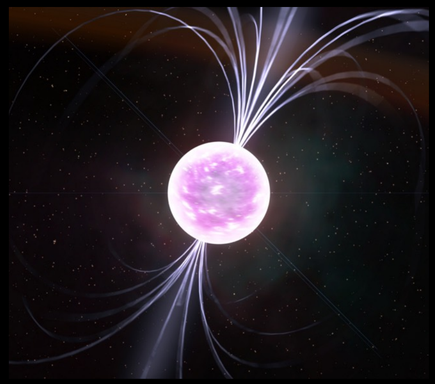
χ

Gravitational Waves

$h_{\mu\nu}$

????

Pulsars



Credit: Kevin Gill / Flickr

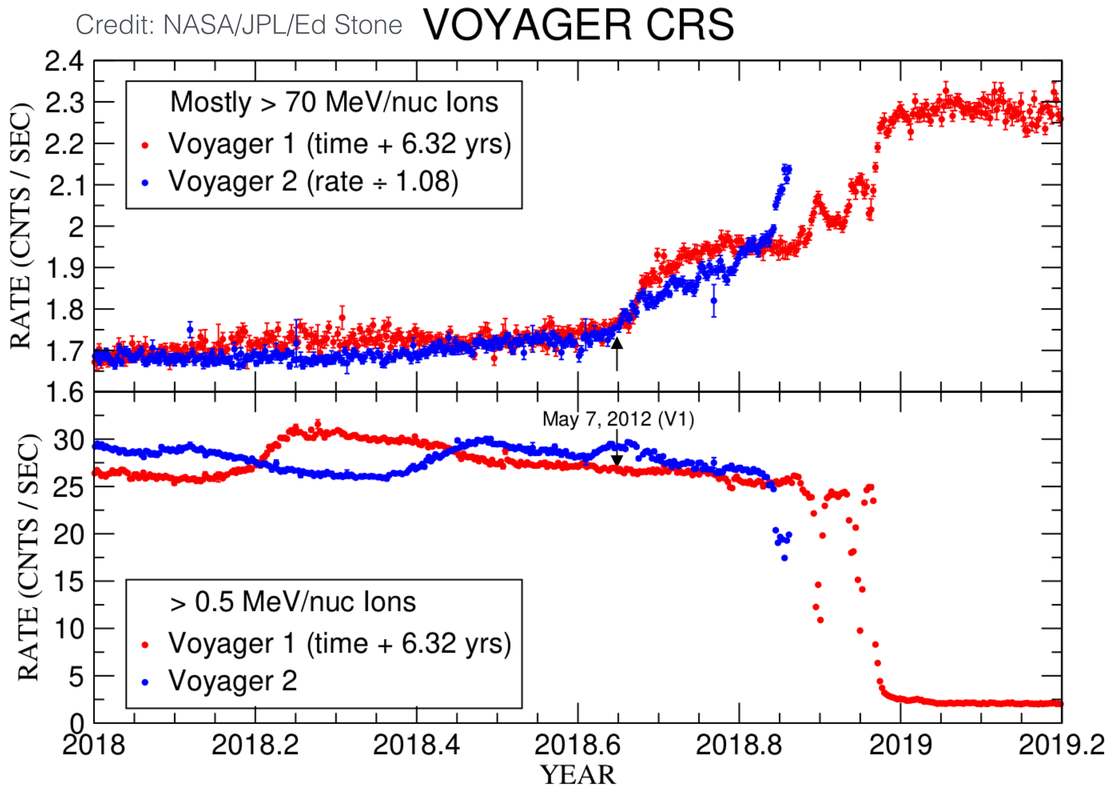
BH/NS Mergers

Credit: SXS Lensing

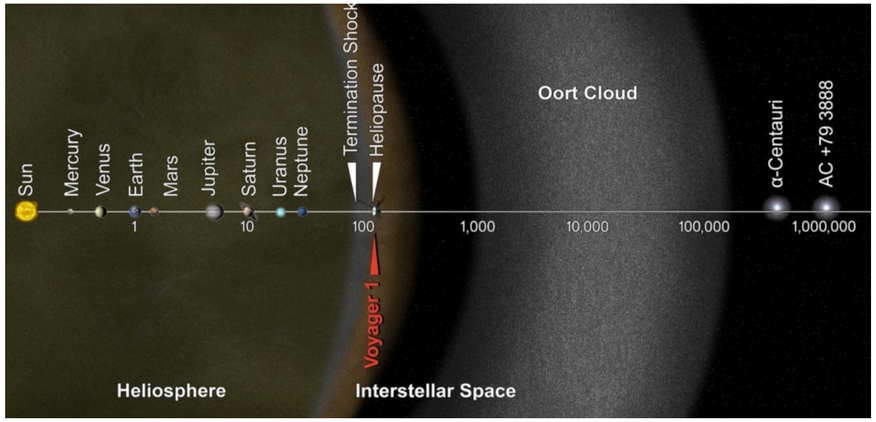
Additional Slides

Voyager (and solar modulation)

Credit: NASA/JPL/Ed Stone

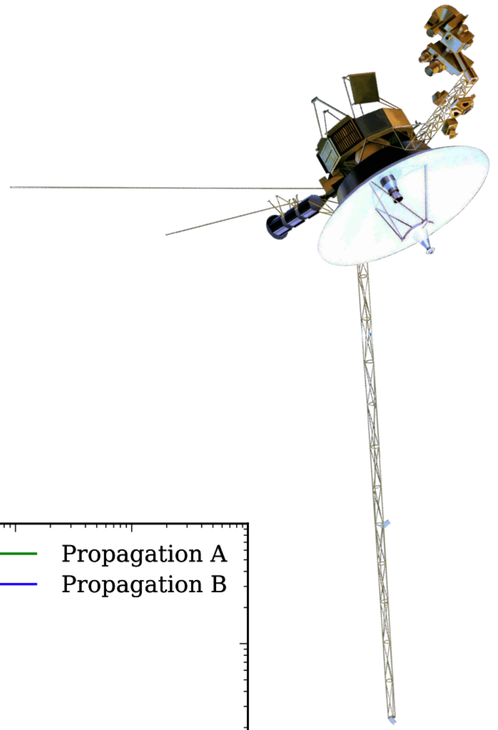


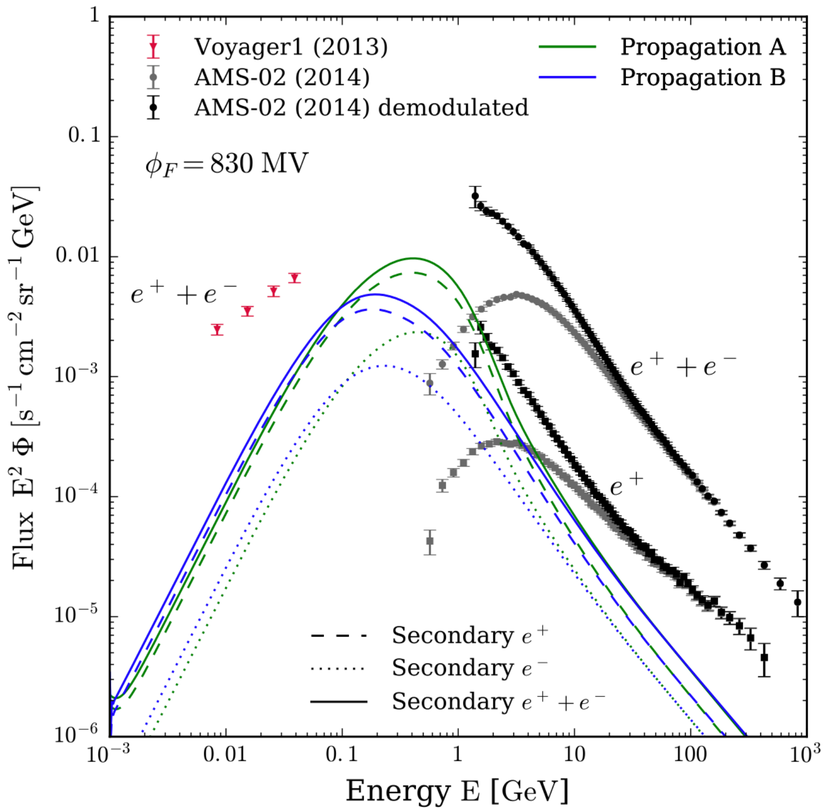
Credit: NASA/JPL



Voyager 1 - launched 1977, crossed heliopause 2012

Voyager 2 - launched 1977, crossed heliopause 2018



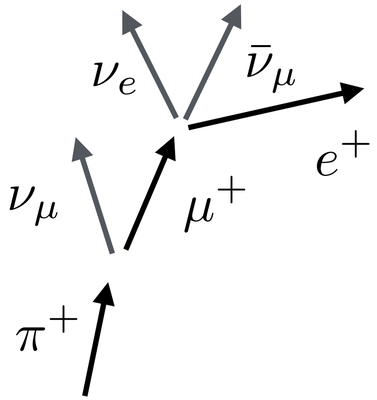


arXiv:1612.07698

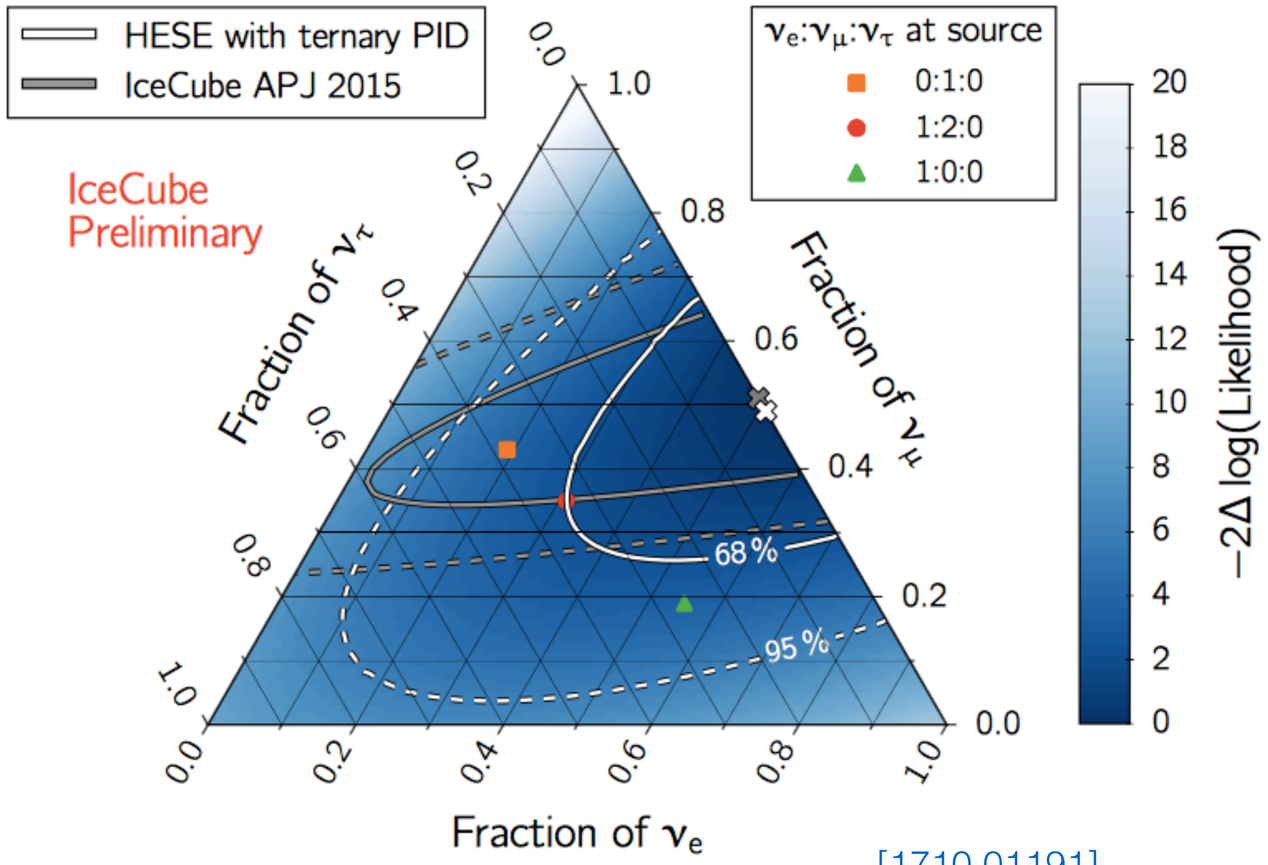
Origin of ultra high energy neutrinos?

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]