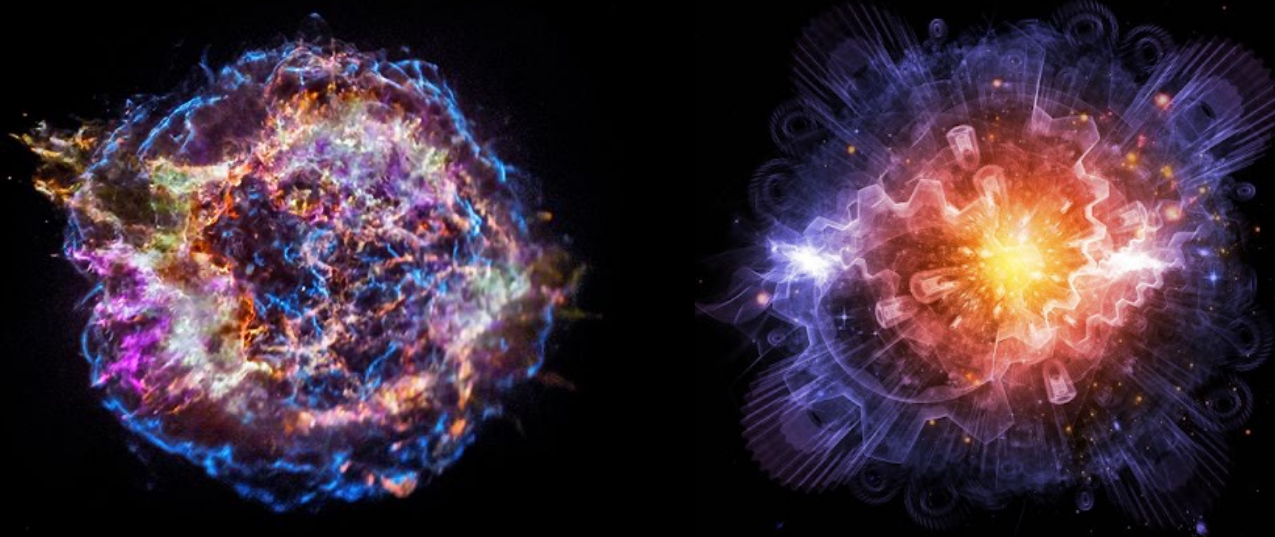


High-Energy Neutrino Astrophysics: Basics

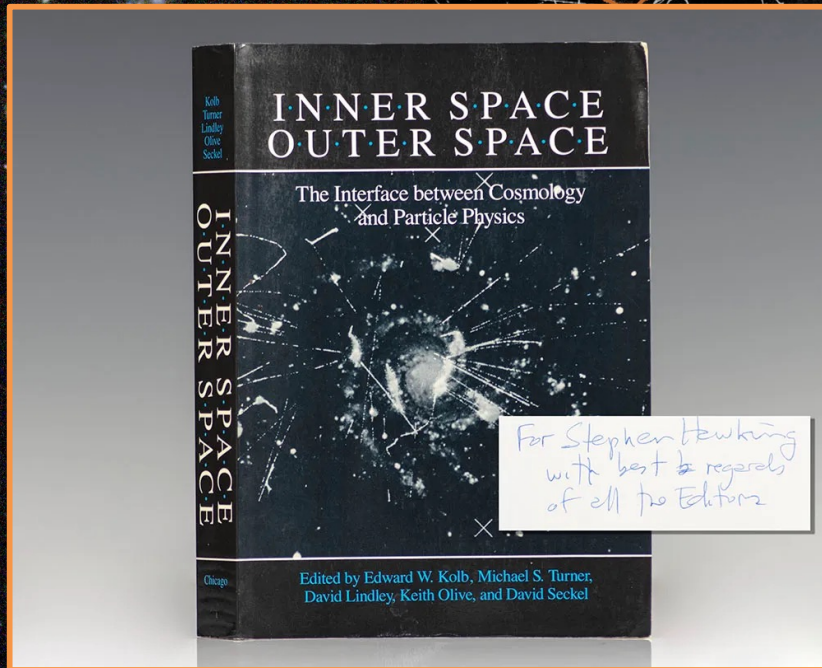
John Beacom, The Ohio State University



The Ohio State University's Center for Cosmology and AstroParticle Physics



Two Ways to Explore the Universe

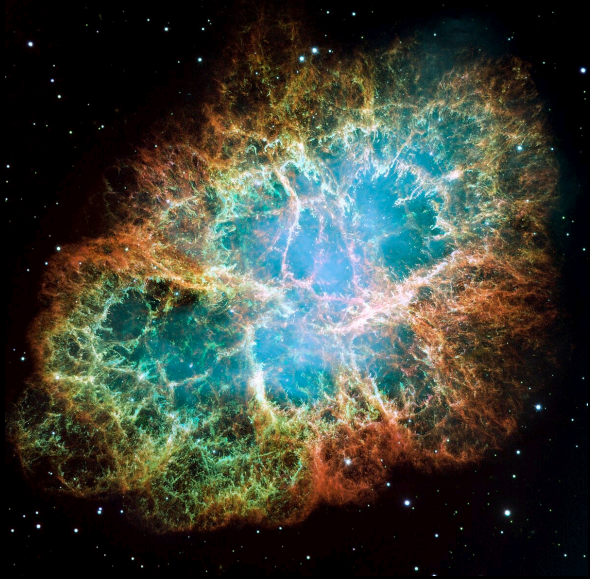


Groundbreaking conference
Fermilab, 1984

What Happens In the High-Energy Universe?

(c) The spectacular quasi-stellar radio sources, radio galaxies, and galactic optical synchrotron radiators such as the Crab nebula will be considered as possible candidates for detectable neutrino sources (as well as x ray, γ ray, etc.) as long as their origin remains uncertain. The observed synchrotron radiation suggests the

Malvin Ruderman (1965)



- 1. Where are cosmic rays accelerated?*
- 2. What are the high-energy sources?*

Loose Definitions of Energy Ranges

High energy (HE)	MeV (10^6 eV) – GeV (10^9 eV) range (inclusive)
Very-high energy (VHE)	TeV (10^{12} eV) – PeV (10^{15} eV) range (inclusive)
Ultra-high energy (UHE)	EeV (10^{18} eV) – ZeV (10^{21} eV) range (inclusive)

Outline

Opening

VHE astronomy

How it works

Neutrino production

Neutrino propagation

Neutrino detection

Key results

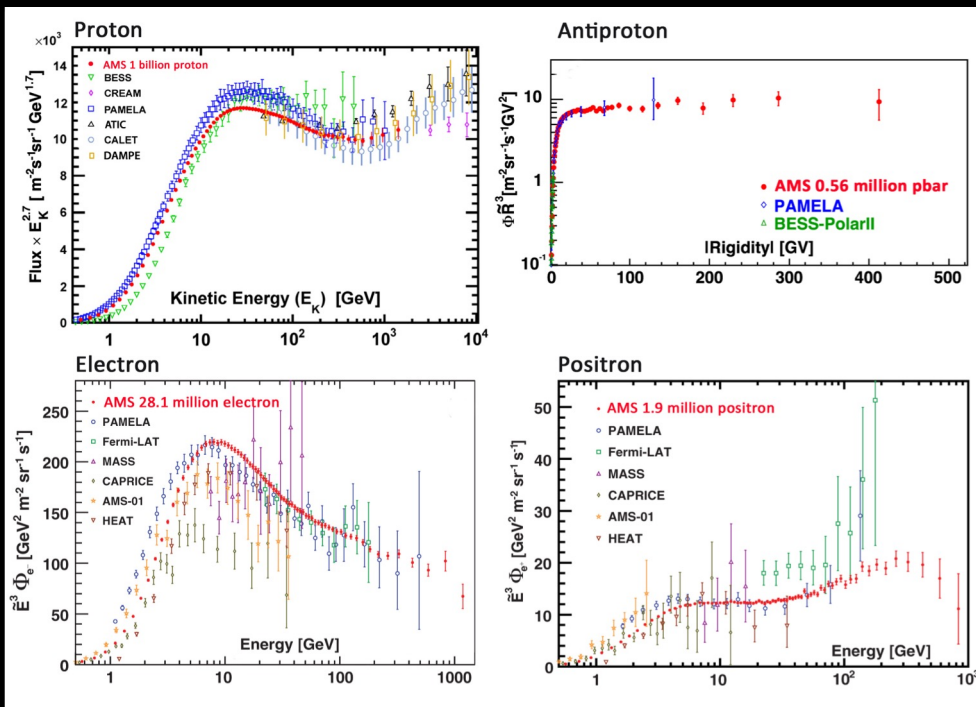
Discovery frontiers

Tomorrow's talk

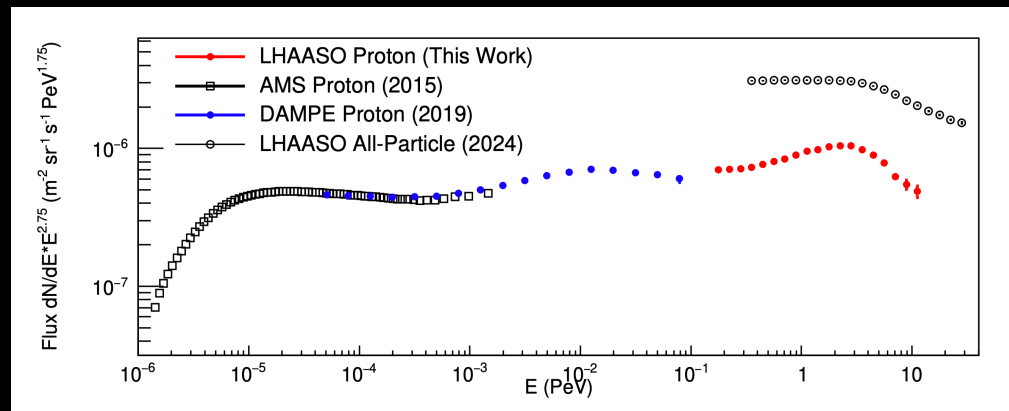
Neutrino Production

Do Astrophysical Accelerators Exist?

YES



AMS (2021)

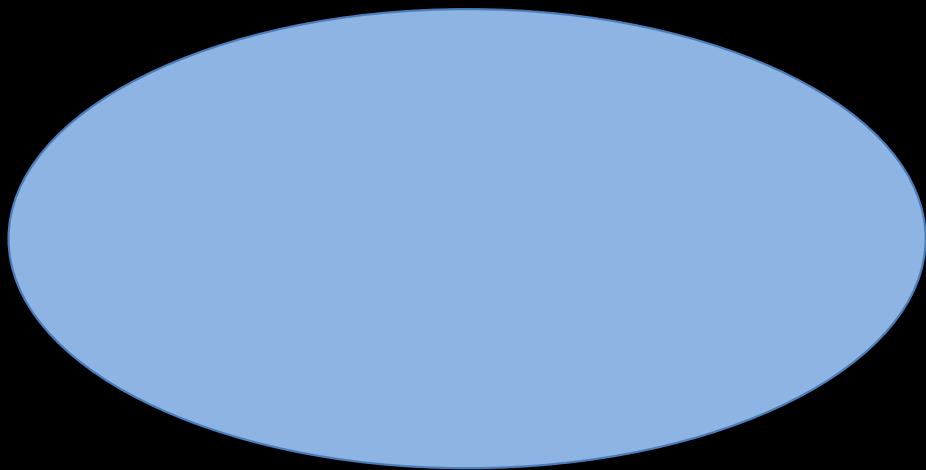


LHAASO (2025)

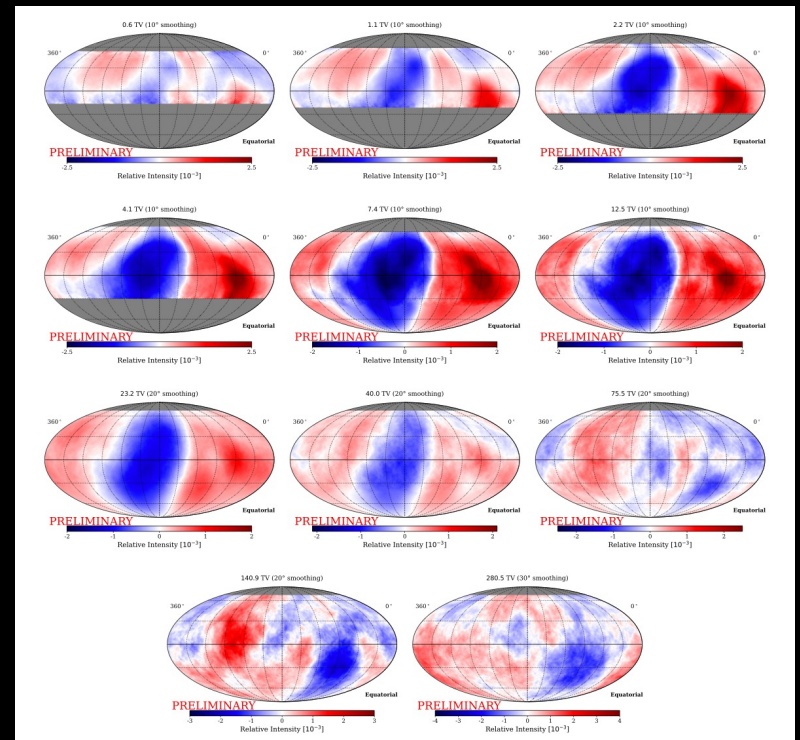
Mostly protons and alphas
 Some electrons, nuclei, and antiparticles

Do We Know Where the Accelerators Are?

NO

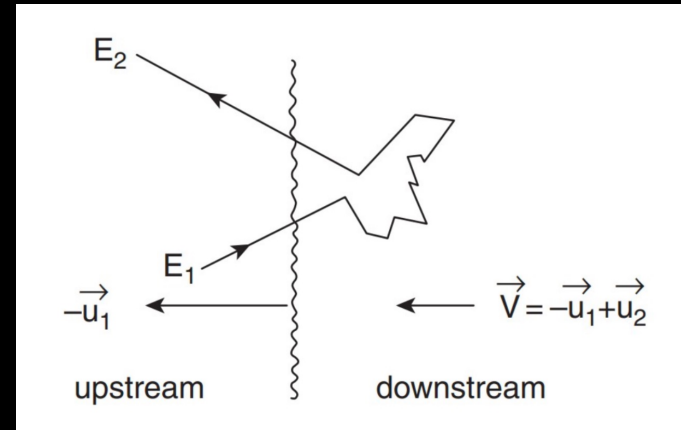


Cosmic ray skymaps seem uniform



Though have $\sim 10^{-3}$ anisotropies

How Could Cosmic Rays Be Accelerated?



Gaisser, Engel, Resconi (2016)

First-order Fermi acceleration

$$\Delta E \sim \beta_{\text{shock}} \text{ per trip}$$

Can show this leads to

$$dN/dE \sim E^{-(2+\epsilon)}$$

Where Could Acceleration Happen?

Luminosity requirement (1964)

Cosmic ray energy density in MW is constant
Loss rate due to escape can be estimated
Gain rate due to supernovae can be estimated

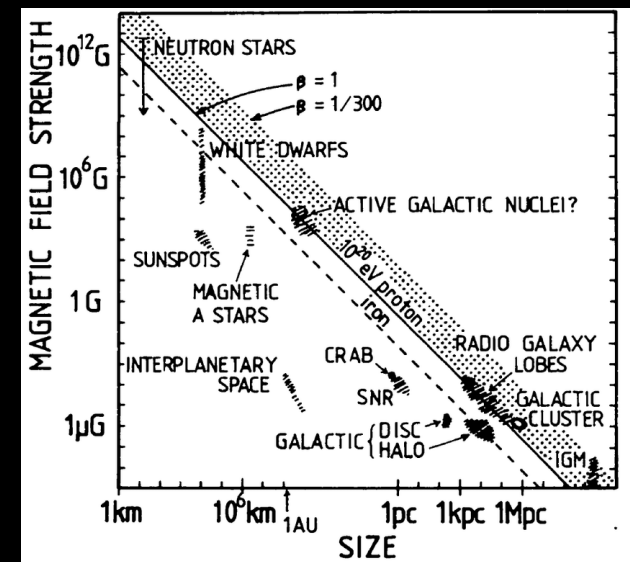
Offline homework:

Show that ~10% of the KE
of supernovae is enough to
power the MW cosmic rays

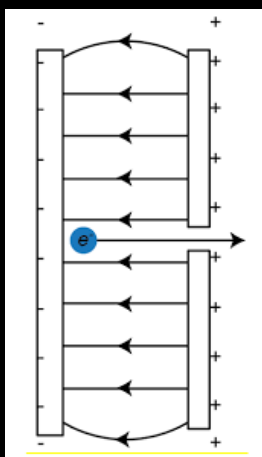
Ginzburg and Syrovatskii (1964)

Hillas Criterion (1984)

Larmor radius, $R_L = p / (Z e B)$
Must have $R_L < R_{\text{source}}$



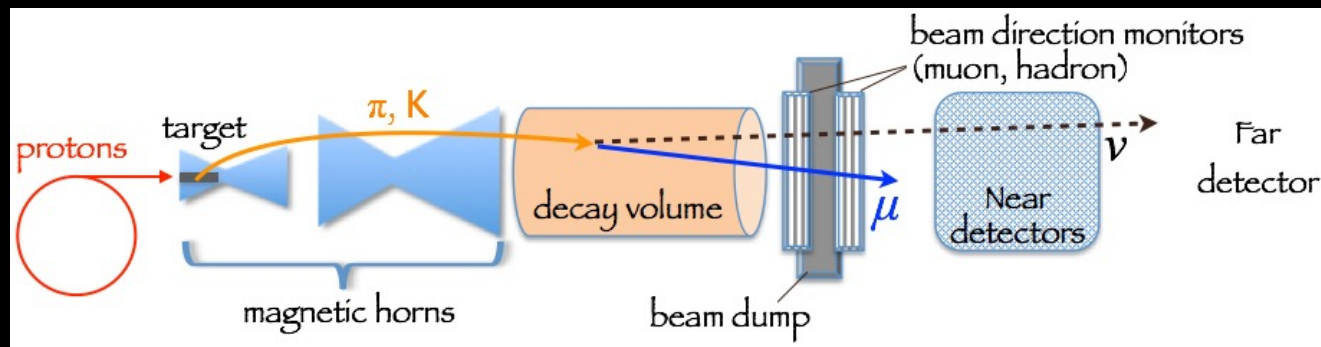
Acceleration Always Makes a Mess



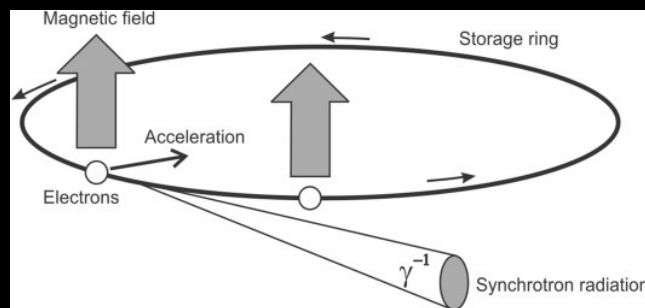
versus



Beams on targets



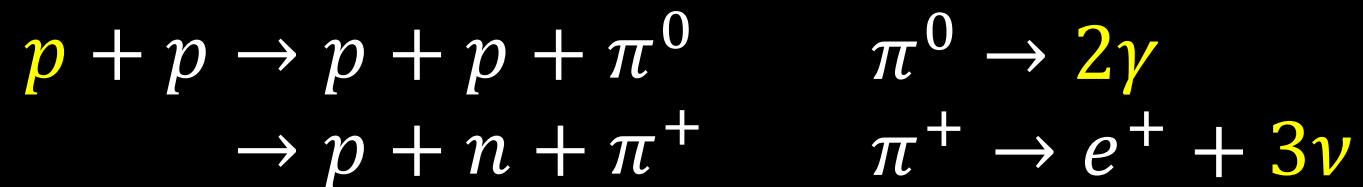
Beams in fields



Always have some production of secondary particles

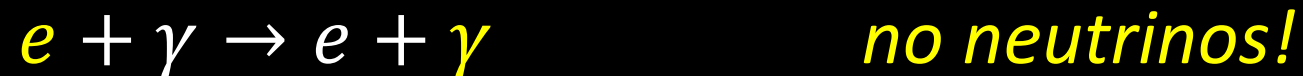
Key Production Processes

Hadronic mechanism:



Comparable fluxes and spectra of gamma rays and neutrinos

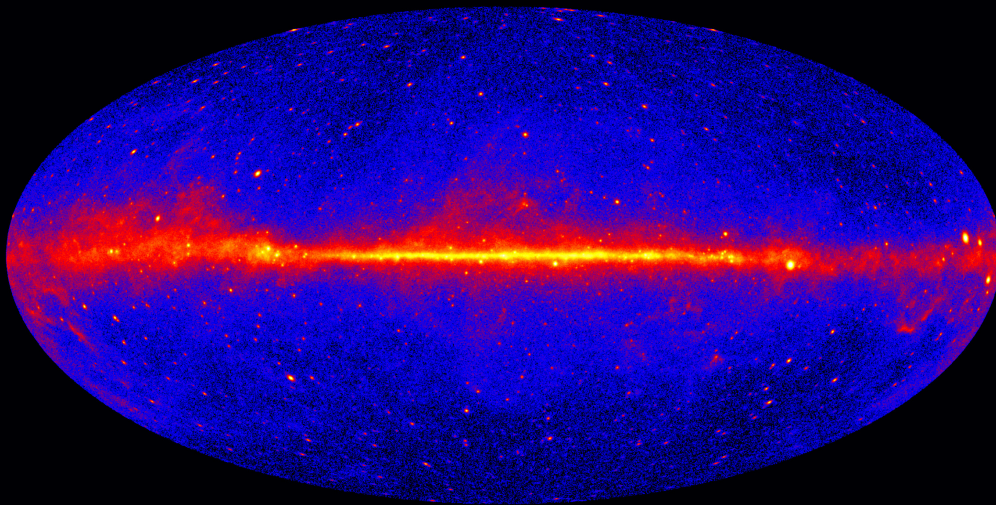
Leptonic mechanism:



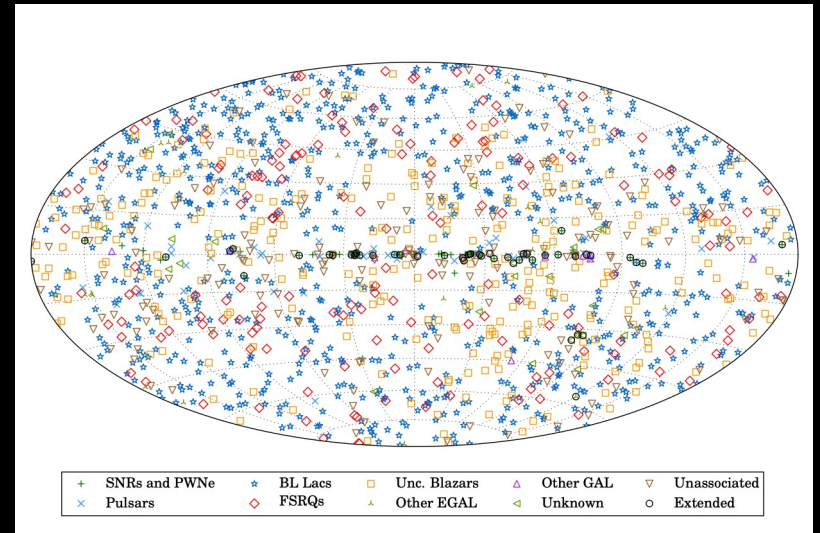
HE Gamma-Ray Observations

- ✓ Milky Way diffuse
- ✓ Milky Way sources

- ✓ Extragalactic diffuse
- ✓ Extragalactic sources



Fermi

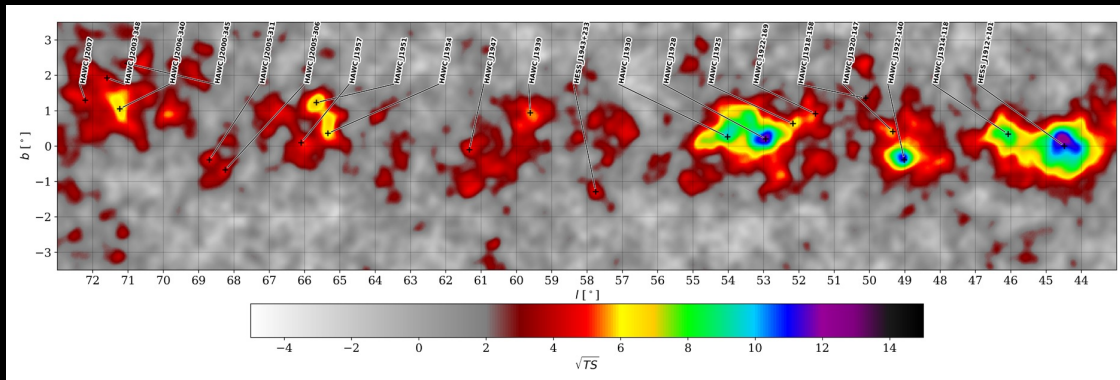


Fermi

VHE Gamma-Ray Observations

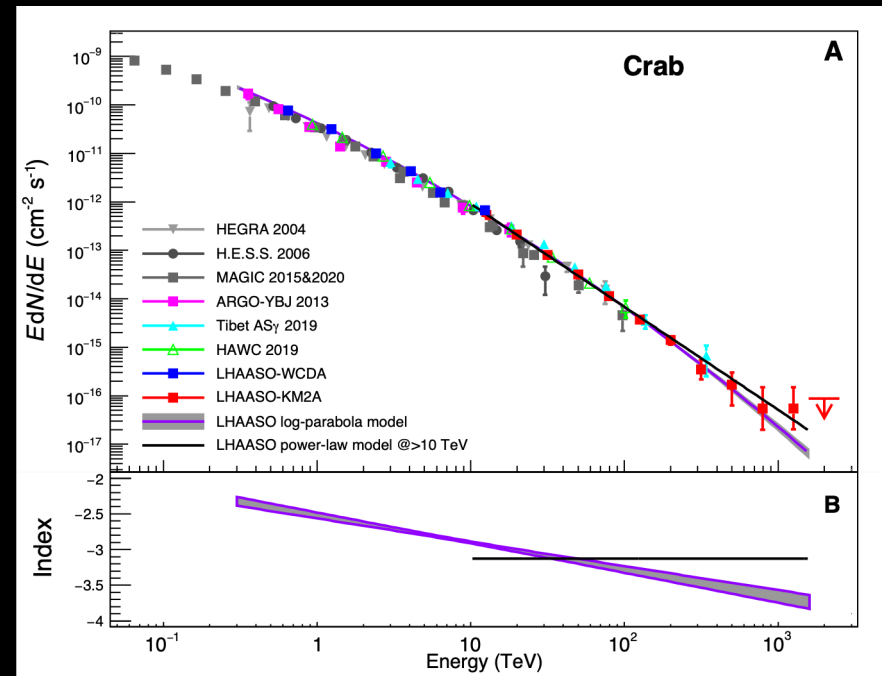
- ✓ Milky Way diffuse
- ✓ Milky Way sources

- ✗ Extragalactic diffuse
- ✓ Extragalactic sources



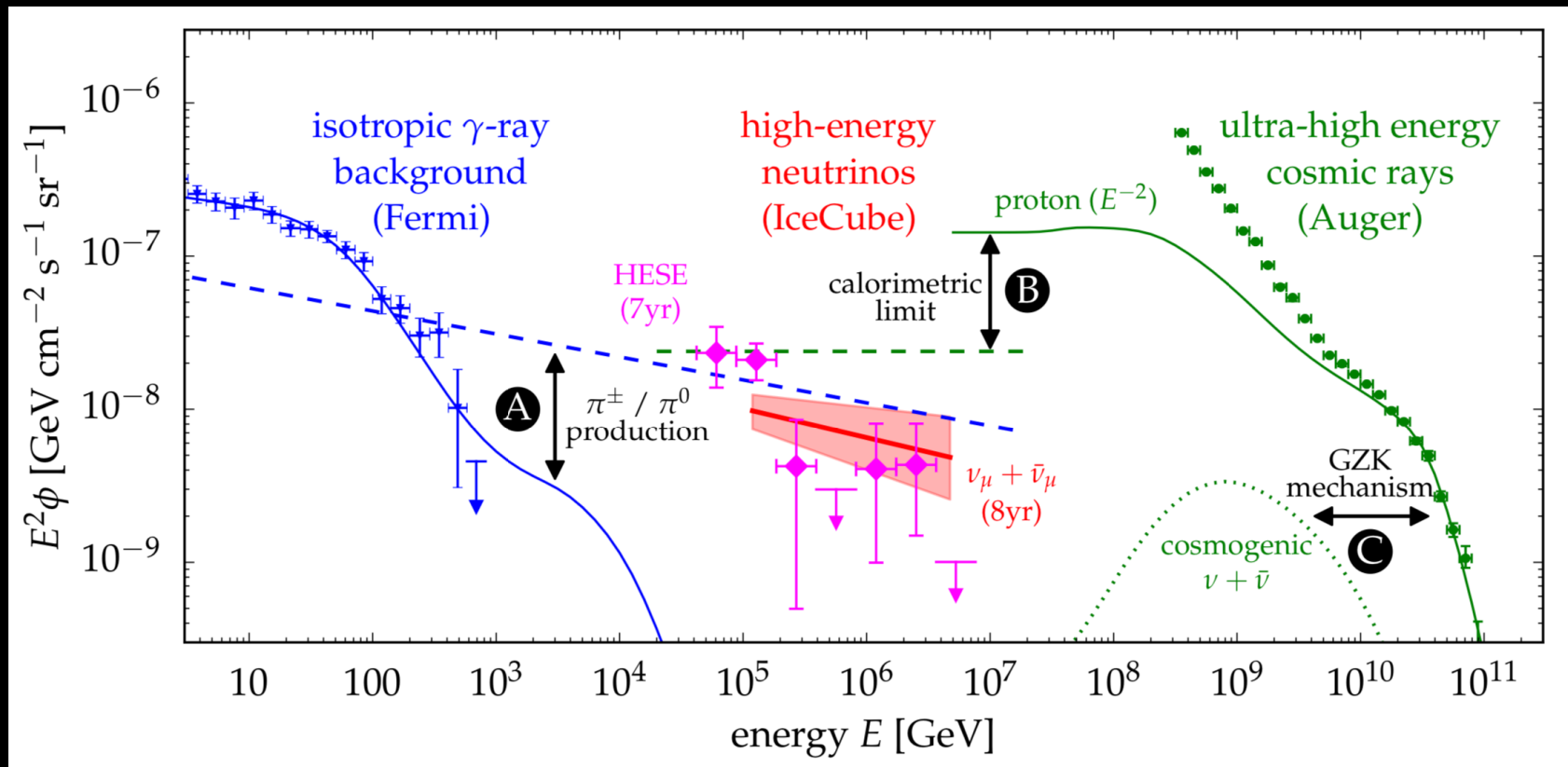
HAWC (2021)

Great, where are the neutrinos?



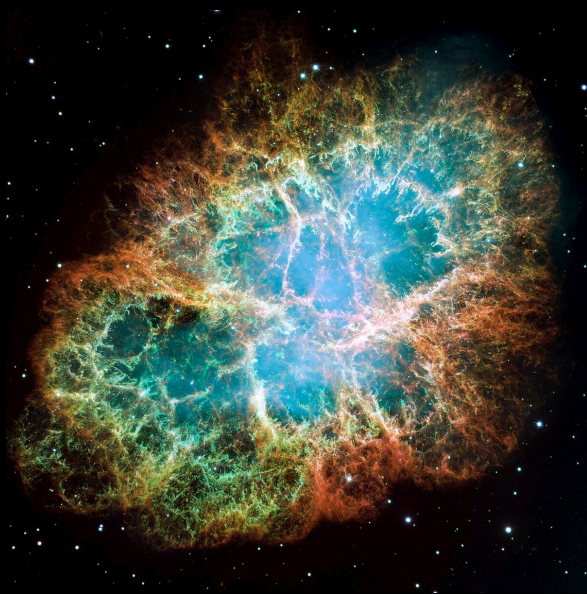
LHAASO (2021)

Hints From Multi-Messenger Data



Ahlers (2018)

Growing Questions



- 1. What are the high-energy sources?*
- 2. Where are cosmic rays accelerated?*

x 2 (Galactic and extragalactic)

- 3. What are the properties of neutrinos?*

Neutrino Propagation

Neutrino Propagation Through the Universe

Poisson expected number of scatterings, $\mu = L / \lambda = n L \sigma$

Offline homework:

What is the cosmic column density ($n L$) of baryons? Of electrons?

What is the cosmic column density ($n L$) of photons? Of neutrinos?

How big are neutrino cross sections?

Under ordinary circumstances, no interactions en route

Neutrino Mixing Hamiltonians

$$i\hbar \frac{\partial}{\partial t} \begin{bmatrix} \Psi_e(t) \\ \Psi_\mu(t) \end{bmatrix} = H_{\text{flavor}} \begin{bmatrix} \Psi_e(t) \\ \Psi_\mu(t) \end{bmatrix},$$

Time evolution operator

$$U \simeq \exp(-iHt/\hbar)$$

Vacuum mixing

$$H_{\text{flavor}} = \frac{\delta m^2}{4E} \begin{bmatrix} -\cos 2\theta_v & \sin 2\theta_v \\ \sin 2\theta_v & \cos 2\theta_v \end{bmatrix}.$$

Matter mixing

$$H_{\text{flavor}} = \frac{\delta m^2}{4E} \begin{bmatrix} \zeta(t) - \cos 2\theta_v & \sin 2\theta_v \\ \sin 2\theta_v & -\zeta(t) + \cos 2\theta_v \end{bmatrix},$$

$$\zeta(t) = \frac{2\sqrt{2}G_F N_e(t)}{\delta m^2/E},$$

Neutrino Mixing Length Scales

Vacuum Mixing

Appreciable when

$$(\delta m^2 / E) \times ct / (\hbar c) \sim 1$$

Offline homework:

Show this is < 1 pc

Size of Milky Way ~ 10 kpc

Distance to M31 ~ 1 Mpc

Size of Universe ~ 1 Gpc

Vacuum mixing only near sources

Matter Mixing

Appreciable when

$$G_F N_e \times ct / (\hbar c) \sim 1$$

Offline homework:

Show this is $10^{-33} \text{ cm}^2 \times N_e \text{ ct} \sim 1$

What are possible column densities for hadronic production of neutrinos?

Matter mixing negligible

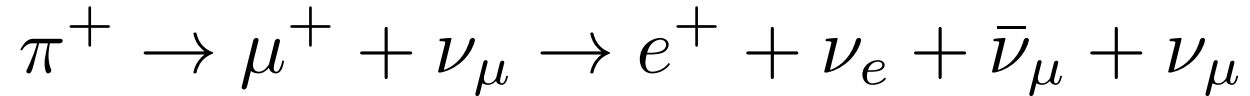
Initial and Final Flavor Ratios

Easiest case

Hadronic interactions produce equal numbers of all types of pions

Assume we cannot separate neutrinos and antineutrinos

Assume final-state particles equally share the energy



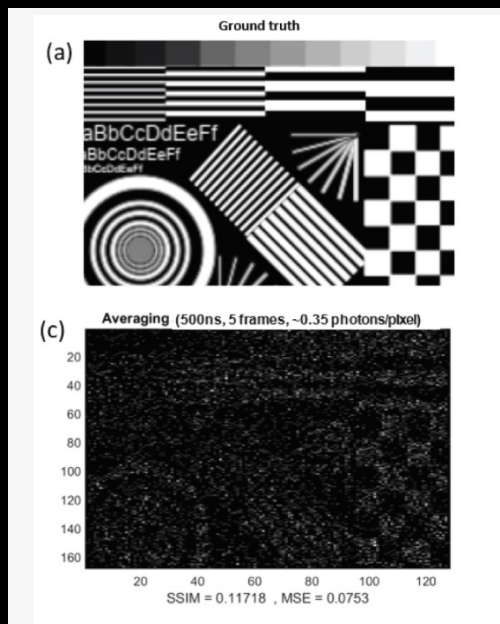
$$\text{initial ratios} \quad \Phi_e : \Phi_\mu : \Phi_\tau \simeq 1 : 2 : 0$$

$$\text{final ratios} \quad \Phi_e : \Phi_\mu : \Phi_\tau \simeq 1 : 1 : 1$$

Group discussion:
Why?

What Makes Neutrino Astronomy Hard?

Low Detected Counts



Poor Angular Resolution

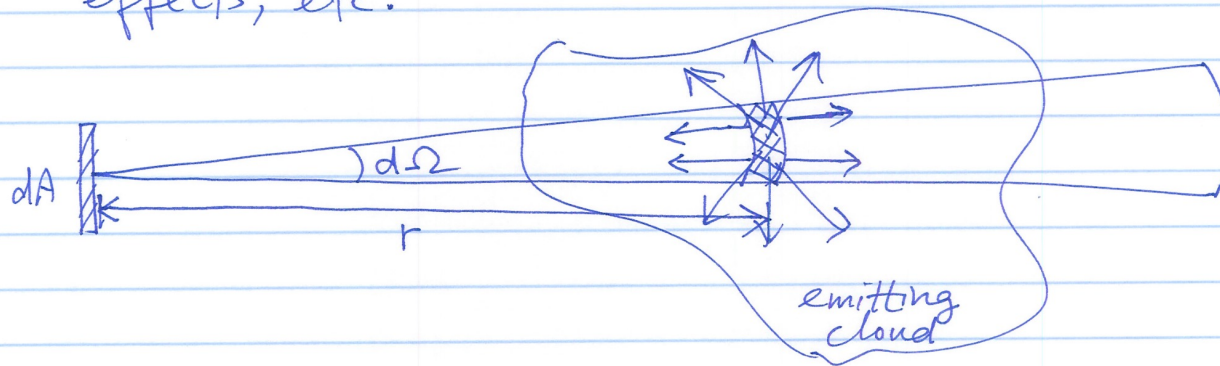


No Distance Information



Line of Sight Integral, Part 1/3

This is the simplest derivation, ignoring angular variations within the beam size $d\Omega$, attenuation of the flux, redshift effects, etc.



The idea is that every differential volume element of the cloud is emitting radiation isotropically. This is characterized by the emissivity $q = q(\vec{r})$, which varies throughout the cloud, and has units $[\text{volume}^{-1} \text{time}^{-1}]$.

Line of Sight Integral, Part 2/3

$$dF(\vec{r}) = \frac{1}{4\pi r^2} q(\vec{r}) dV \quad \text{flux from volume element}$$

$$= \frac{1}{4\pi r^2} q(\vec{r}) \cdot d\Omega r^2 dr \quad \begin{array}{l} \text{volume element} \\ \text{grows like } r^2; \\ \text{flux falls like } r^{-2} \end{array}$$

$$dI(\vec{r}) = \frac{dF(\vec{r})}{d\Omega} = \frac{q(\vec{r})}{4\pi} dr$$

flux has units $[\text{cm}^{-2} \text{s}^{-1}]$; intensity has
units $[\text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}]$.

Line of Sight Integral, Part 3/3

$$I = \frac{1}{4\pi} \int_{\text{LOS}} dr q(\vec{r})$$

[cm]

[cm⁻² s⁻¹ sr⁻¹]

hidden [sr⁻¹]

[cm⁻³ s⁻¹]

A hand-drawn diagram on lined paper showing the equation $I = \frac{1}{4\pi} \int_{\text{LOS}} dr q(\vec{r})$. The integral is enclosed in a rectangular box. Above the box, a vertical arrow points down to the dr term, labeled "[cm]". To the right of the box, a vertical arrow points up to the $q(\vec{r})$ term, labeled "[cm⁻³ s⁻¹]". Below the box, a vertical arrow points up to the 4π term, labeled "hidden [sr⁻¹]". To the right of the box, the units "[cm⁻² s⁻¹ sr⁻¹]" are written.

Some examples of emissivity functions:

- Cosmic ray collisions with gas, producing pions and subsequent γ, ν

$$q_\gamma(\vec{r}) \approx C n_{\text{CR}}(\vec{r}) \cdot n_{\text{gas}}(\vec{r}) \cdot \sigma_{pp}$$

Neutrino Detection

Cross Section Basics Near Threshold

Neutrino scattering on electrons

Total cross section $\sigma \sim G_F^2 E_\nu m_e$

Neutrino scattering on nucleons

Total cross section $\sigma \sim G_F^2 E_\nu m_N$

Offline homework:

Estimate those cross sections

Only certain reactions are allowed, with different energy thresholds:

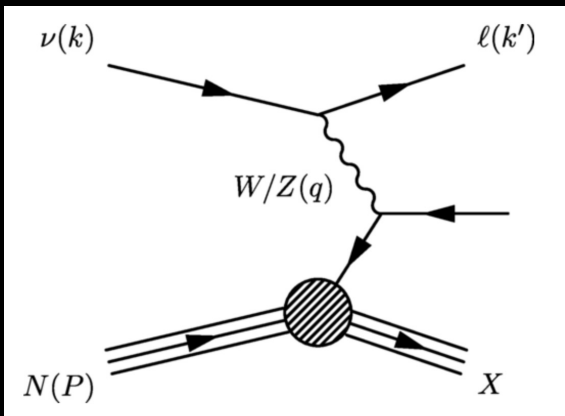
Charged current (W exchange)

$\nu_e + n \rightarrow e^- + p$
 $\nu_\mu + n \rightarrow \mu^- + p$
 $\nu_\tau + n \rightarrow \tau^- + p$
plus crossings

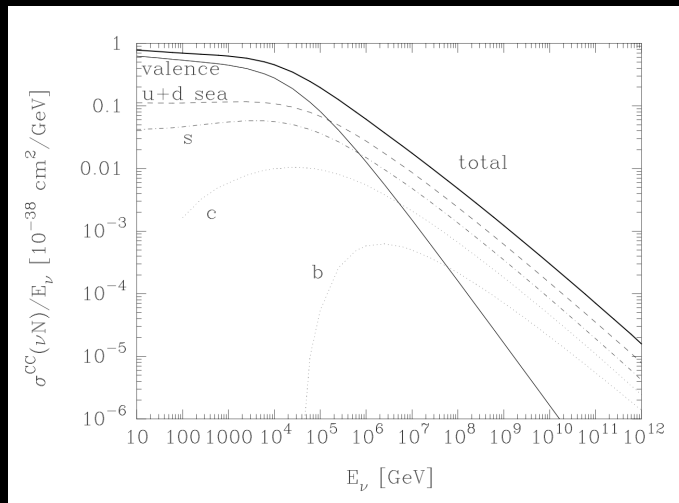
Neutral current (Z exchange)

$\nu_e + n \rightarrow \nu_e + n$
 $\nu_\mu + n \rightarrow \nu_\mu + n$
 $\nu_\tau + n \rightarrow \nu_\tau + n$
plus proton targets
plus antineutrinos

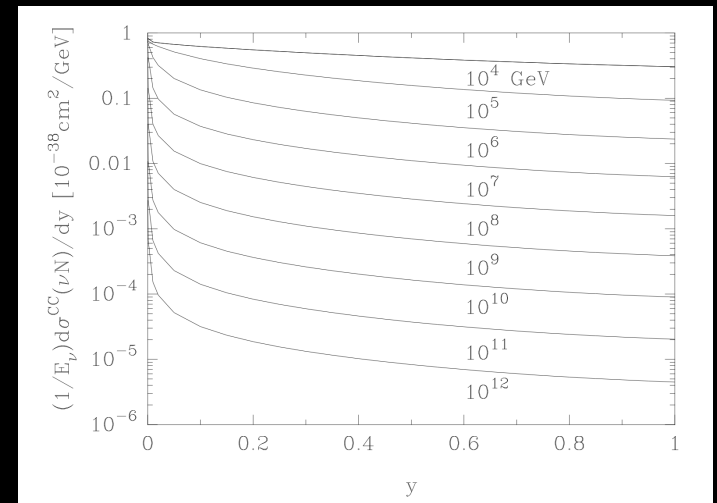
Cross Section Details at Higher Energies



Xie et al. (2024)



Gandhi, Quigg, Reno, Sarcevic (1995)

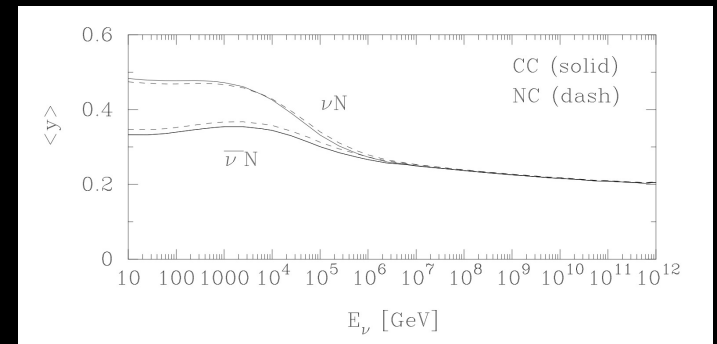


In the deep inelastic scattering regime

Many new channels

Cross section energy variation

Final lepton takes $(1 - y)E_\nu$ and hadrons take yE_ν



Long-Ranged Particles in a Medium

Lepton energy loss rate

$$-\frac{dE}{dX} = \alpha + \beta E$$

Mass column density, $X = \rho L$

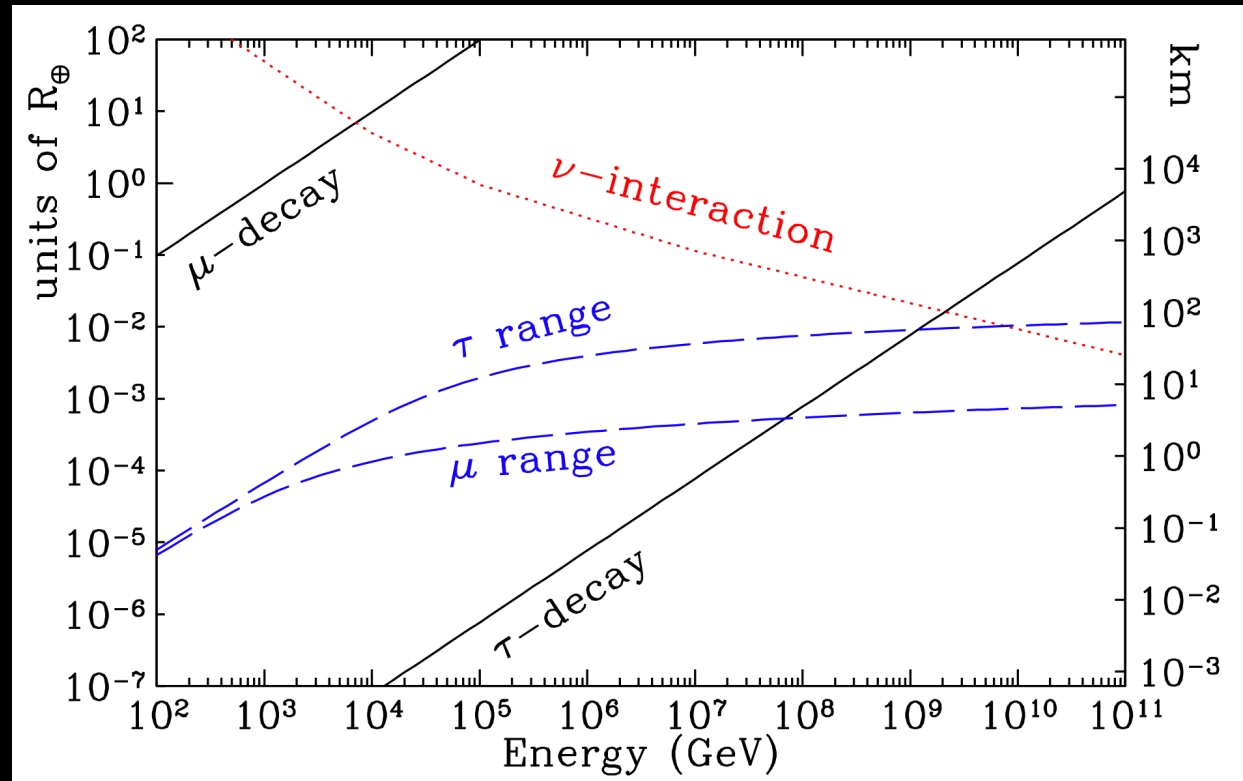
$\alpha \sim 2 \text{ MeV} / (\text{g}/\text{cm}^2)$

Ionization term

$\beta \sim 3 \times 10^{-6} / (\text{g}/\text{cm}^2)$

Radiation term

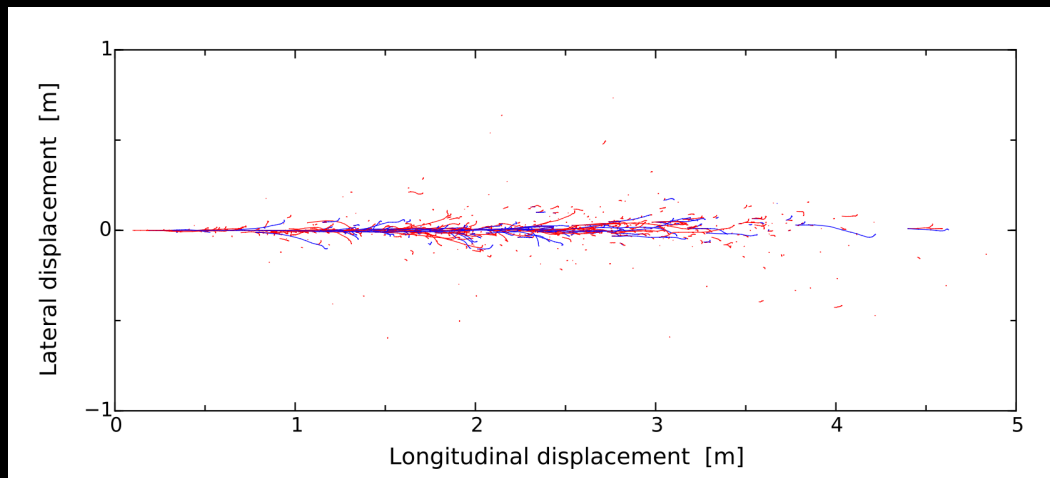
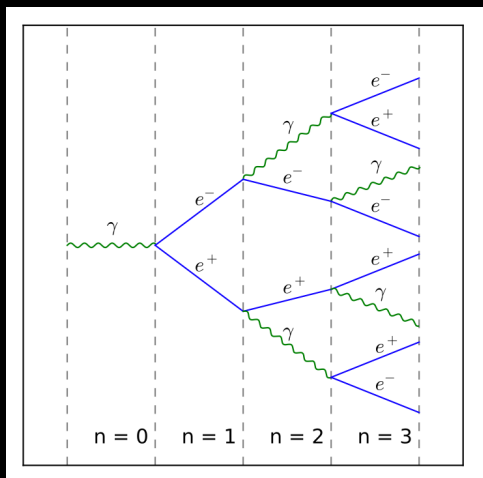
Dutta et al. (2001)



Beacom, Crotty, and Kolb (2001)

Short-Ranged Particles in a Medium

Electromagnetic
showers



Li and Beacom (2015)

Hadronic
showers

Similar idea, but with pions (imagine making π^+ , π^- , π^0 in each generation)
At each generation, 1/3 of the energy goes into an electromagnetic shower
Hadronic showers are more stochastic and wider than EM showers

IceCube: Location



John Beacom, The Ohio State University

PPPW16, Taiwan, June 2026

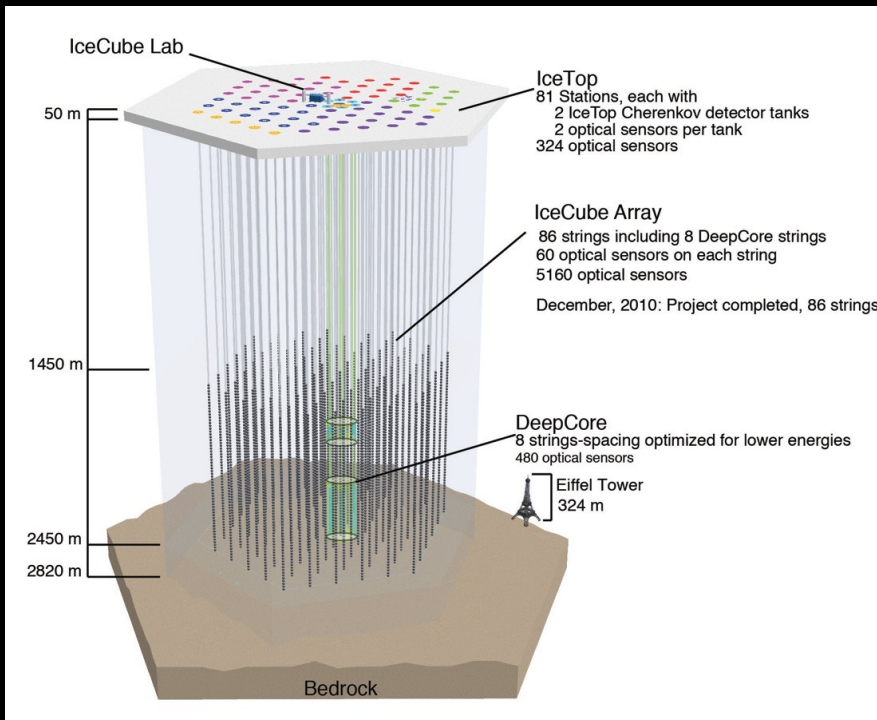
IceCube: Construction



John Beacom, The Ohio State University

PPPW16, Taiwan, June 2026

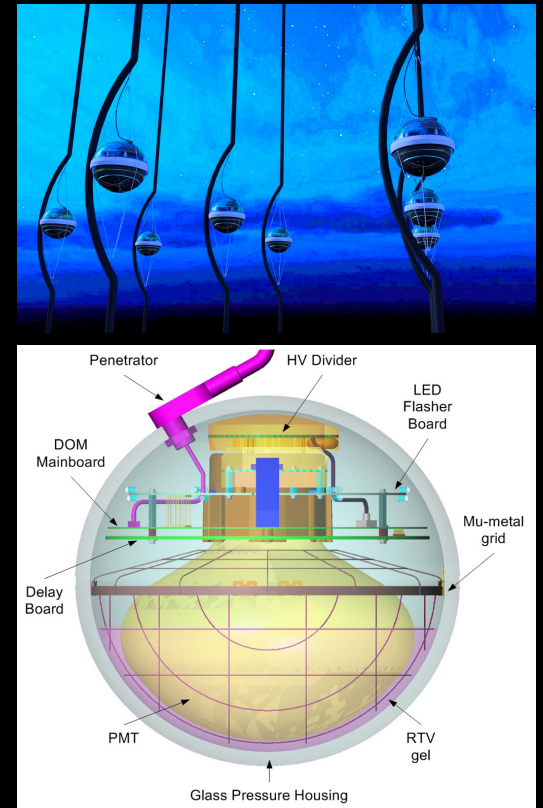
IceCube: Design



86 strings of PMTs
5160 total PMTs
1 km³ of deep ice

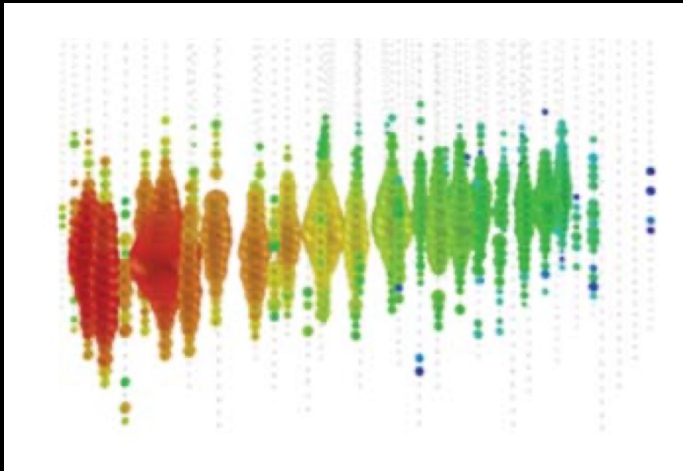
Detect Cherenkov
light from relativistic
charged particles

Event classes from
PMT hit patterns



Event Classes in IceCube

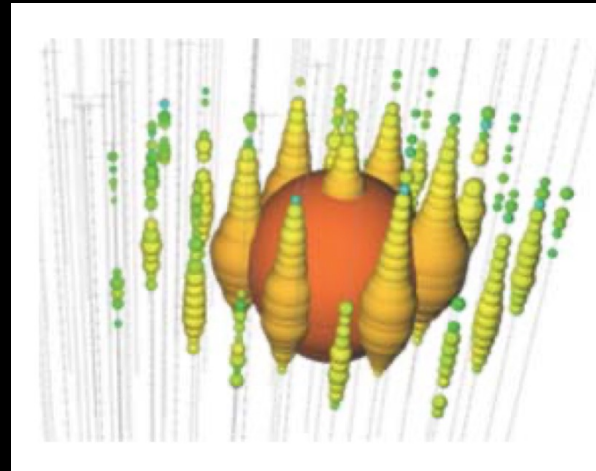
Tracks



ν_{μ} CC events

Inside or outside the detector

Showers



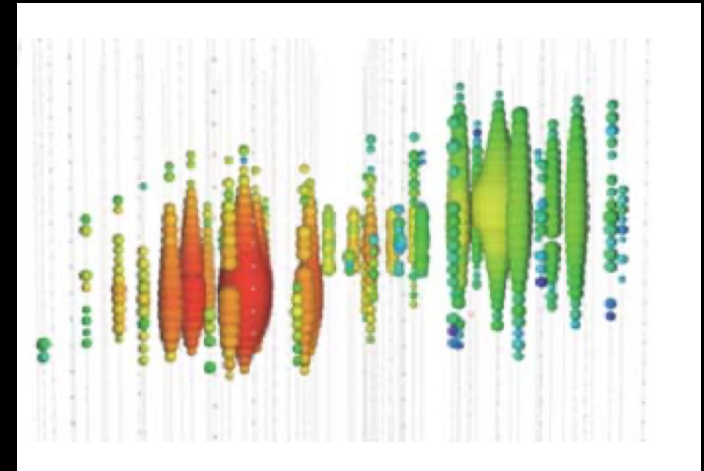
ν_e CC events

ν_{τ} CC events at low E

ν NC events

Inside the detector

Double Bangs



ν_{τ} CC events at high E

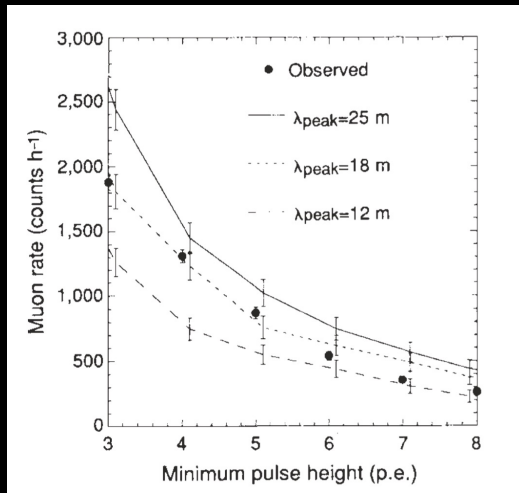
Inside the detector

Rare

See Beacom and Candia (2004)

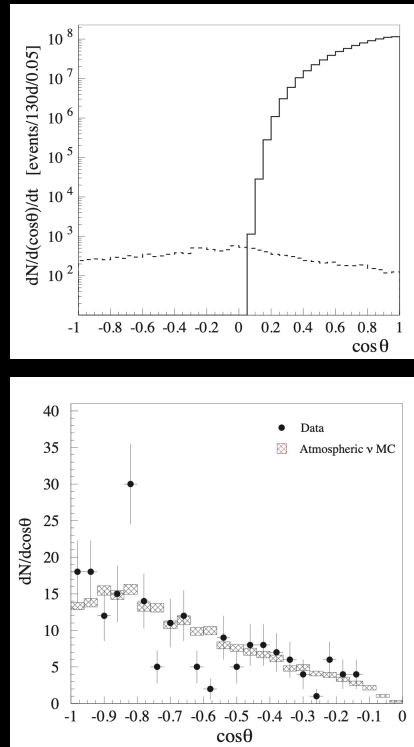
Slow Path of Progress

Avoid detector failure
Detect atmospheric muons



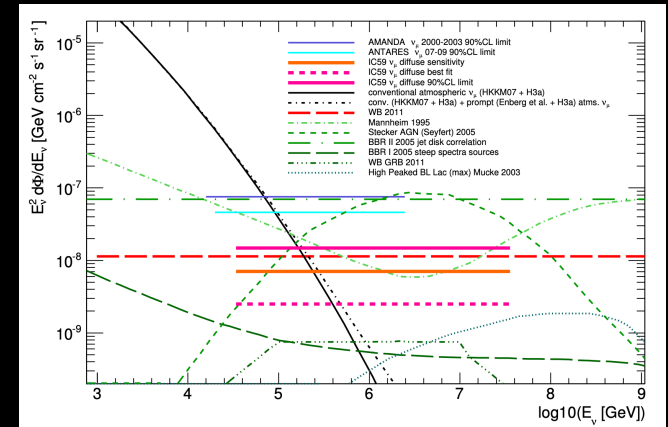
Lowder et al. (1991)

Avoid atm. muons
Detect atm. neutrinos



Amanda (2002)

Avoid atm. neutrinos
Probe astro. neutrinos

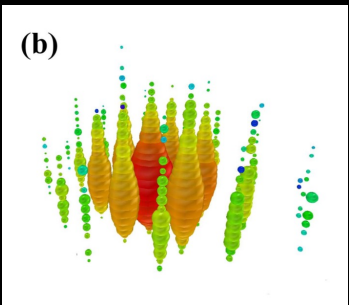
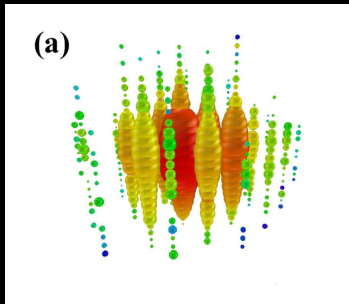


IceCube (2013)

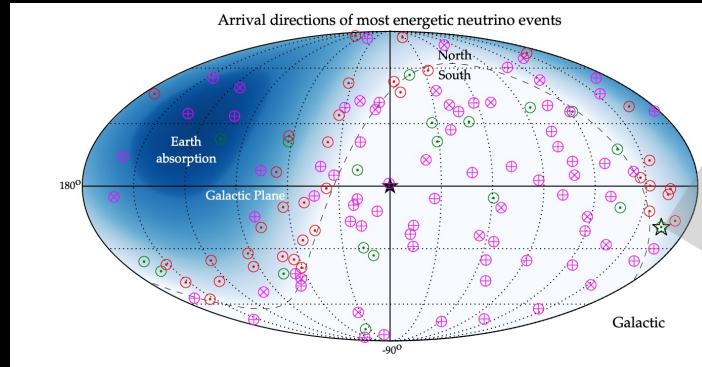
Key Results and Their Impact

Solid: Extragalactic Diffuse Flux

IceCube (2013)
Two cascades,
each ~ 1 PeV

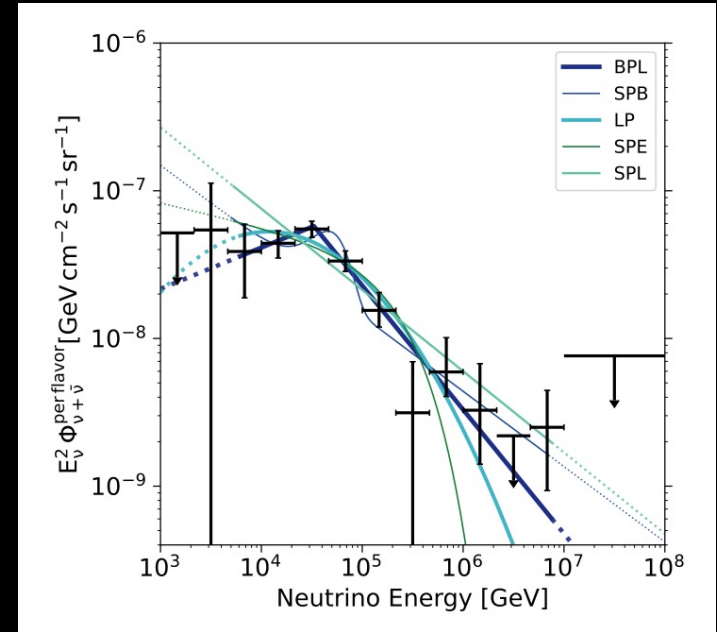


First high-energy astrophysical neutrinos!



IceCube (2019)

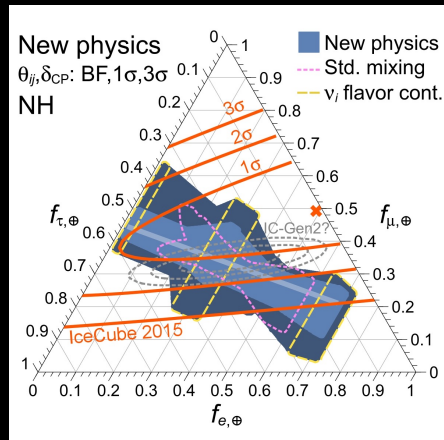
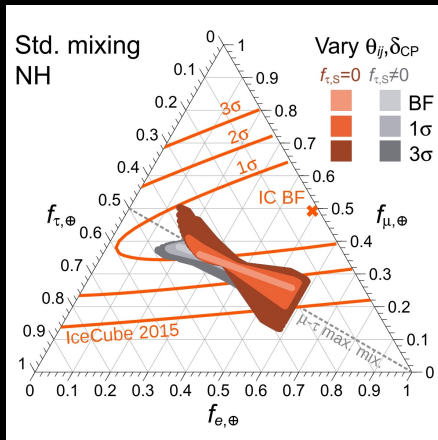
IceCube (2025)



Key points:

Clear detection of diffuse, steady, extragalactic flux
Sources unknown

Emerging: Flavor Triangle



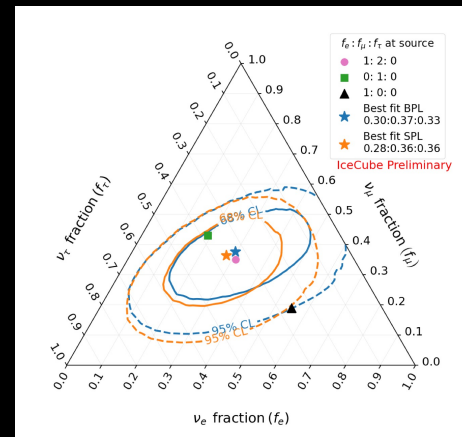
Bustamante, Beacom, Winter (2015)

Building on early work in, e.g.,
 Learned and Pakvasa (1994)
 Yasuda (2000)
 Gounaris and Moutaka (2003)
 Quigg and Barenboim (2003)

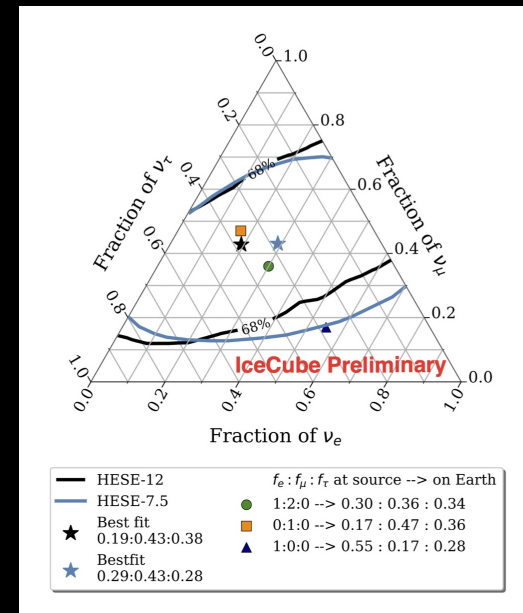
John Beacom, The Ohio State University

IceCube (2025)

MESE events



HESE events

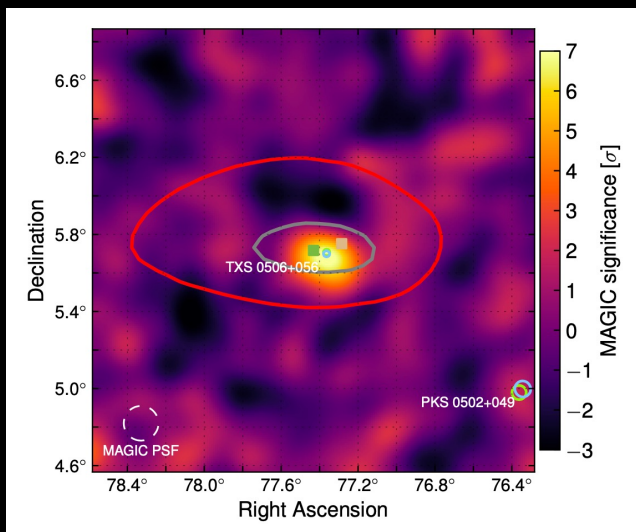


PPPW16, Taiwan, June 2026

Hints: Extragalactic Point Sources

Distant blazar TXS 0506+056

One neutrino at 290 TeV
Points to a known blazar
Found later as EM flare

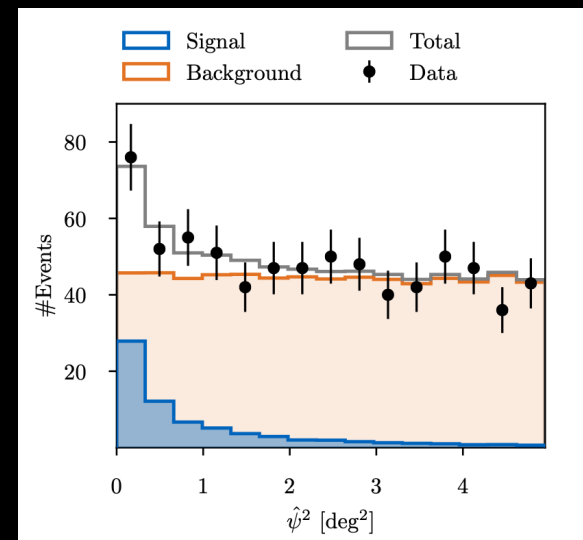


IceCube + Everyone (2017)

John Beacom, The Ohio State University

Nearby AGN NGC 1068

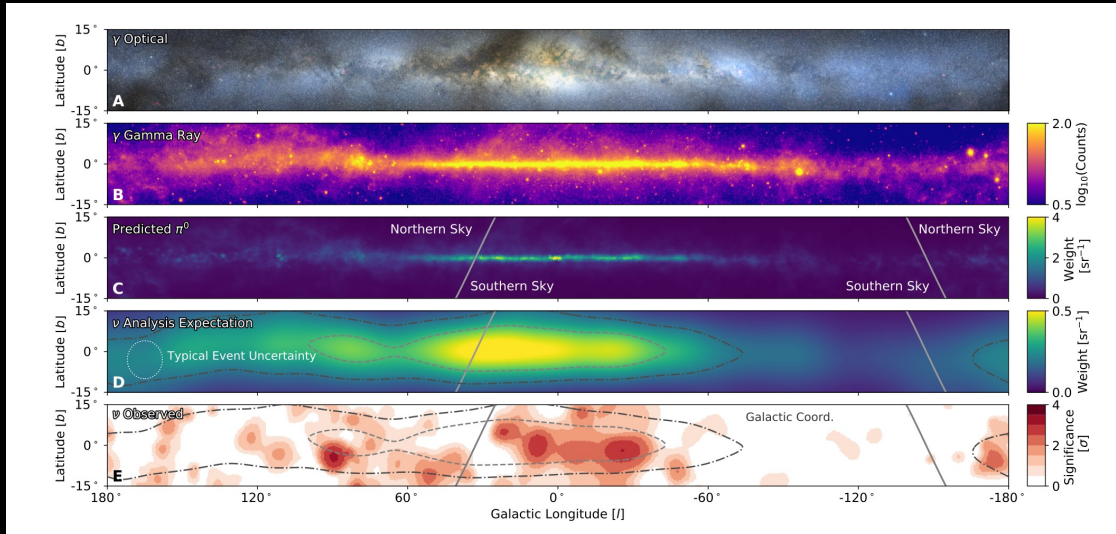
Excess of 80 +/- 20 events
Points to a known AGN
Must be gamma-dim



IceCube (2024)

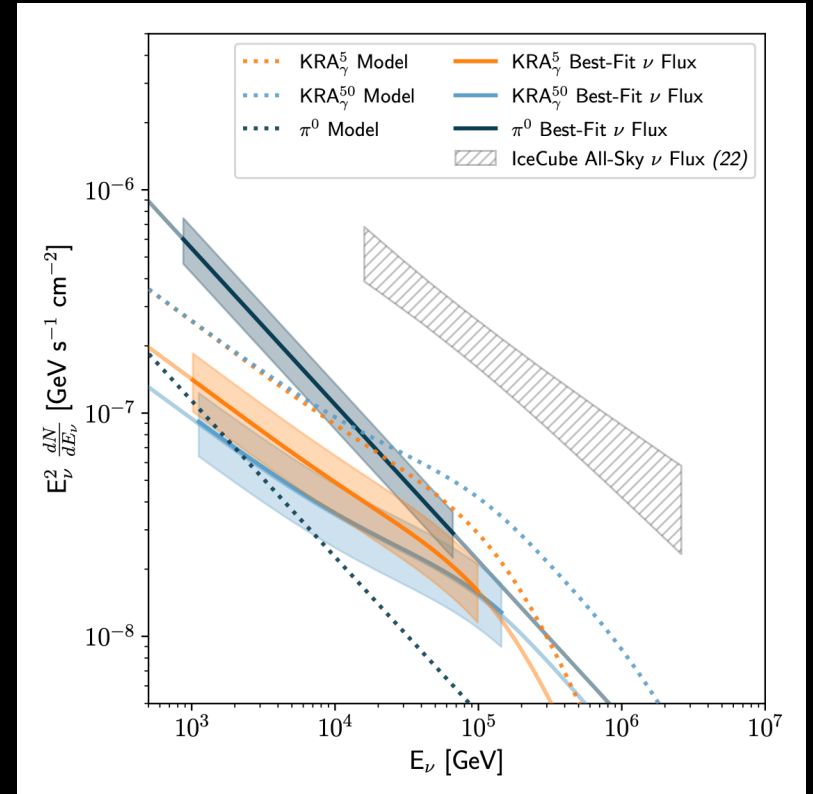
PPPW16, Taiwan, June 2026

Hints: Milky Way Plane



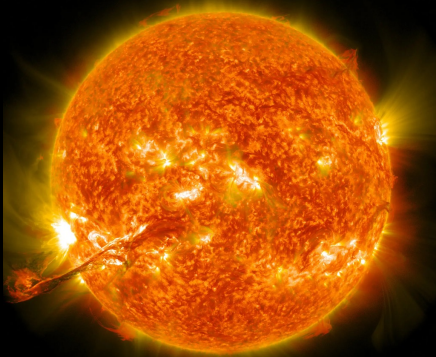
IceCube (2023)

Expected due to:
Cosmic-ray collisions with gas
Milky Way sources



Is Neutrino Astronomy Real?

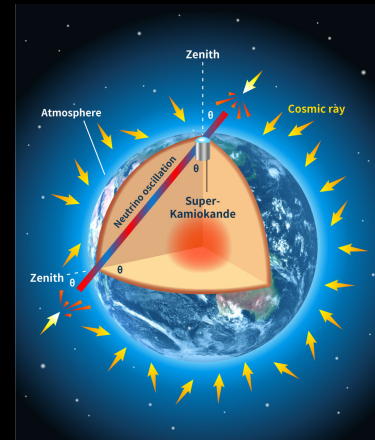
Sun



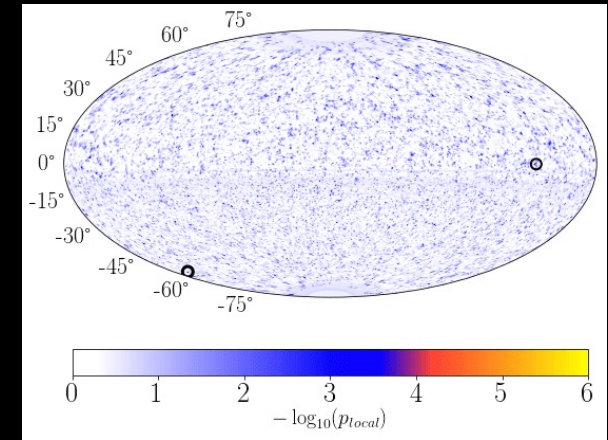
SN 1987A



Atmosphere



Extragalactic Sources



Closing Message

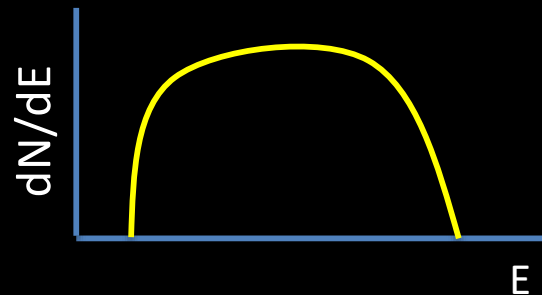
Neutrinos take patience, but they reward it richly

Bonus Material

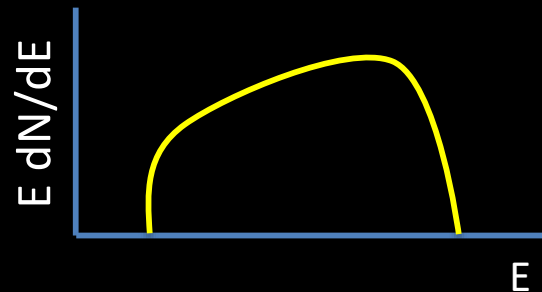
Log Integration, Part 1/5

Consider a spectrum, dN/dE , plotted on linear-linear axes

$$N_{\text{tot}} = \int dE \frac{dN}{dE}$$



$$E_{\text{tot}} = \int dE E \frac{dN}{dE}$$



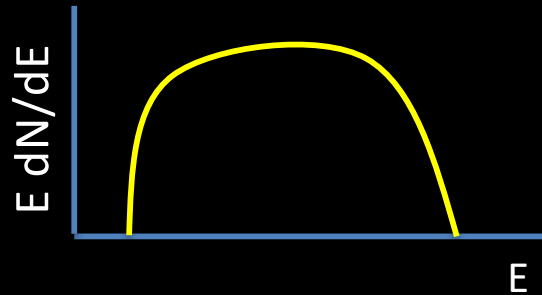
Offline homework:

Units of each?
Estimations?
Invariances?

Log Integration, Part 2/5

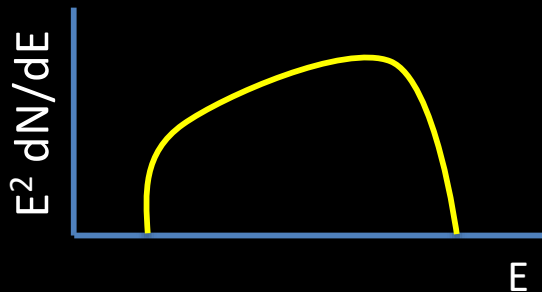
Consider a **new** spectrum, dN/dE , plotted on log-log axes

$$N_{\text{tot}} = \int \frac{dE}{E} E \frac{dN}{dE}$$



$$\frac{dE}{E} = d \ln E = 2.3 d \log E$$

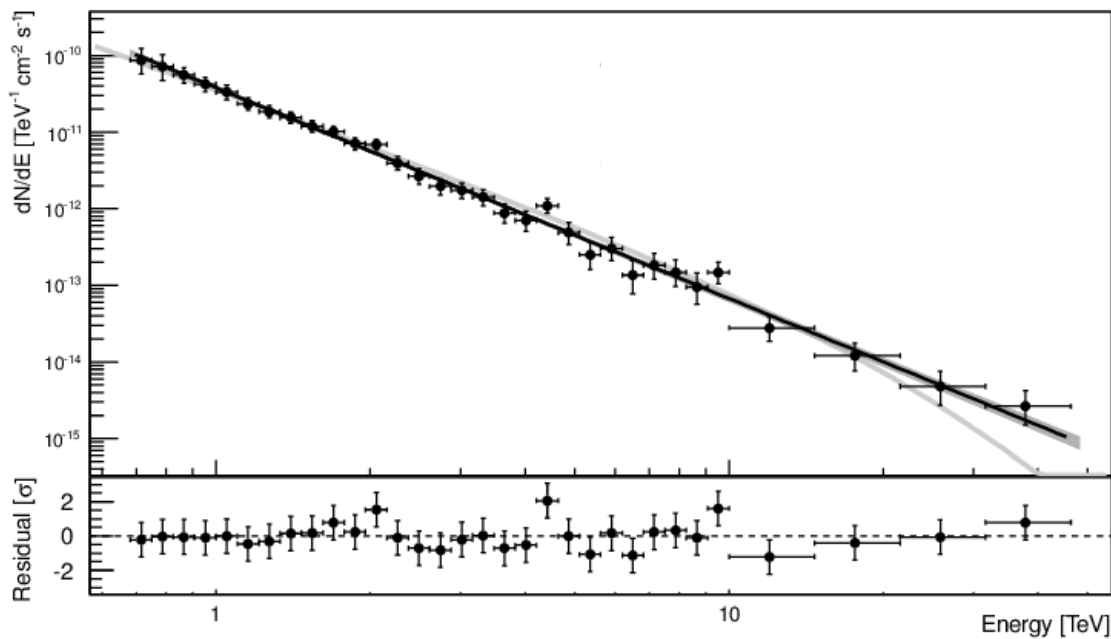
$$E_{\text{tot}} = \int \frac{dE}{E} E^2 \frac{dN}{dE}$$



Offline homework:

Units of each?
Estimations?
Invariances?

Log Integration, Part 3/5



Unnamed (2005)

NEVER make a plot like this

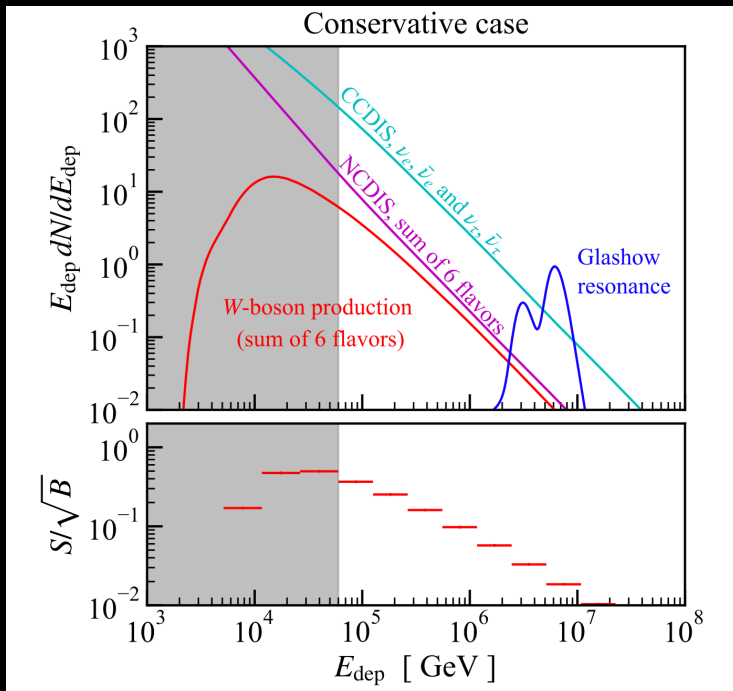
Relative heights are misleading

Integral cannot be estimated

Makes no sense to plot dN/dE versus $\log E$

Especially when using $\log E$ bins!

Log Integration, Part 4/5



Zhou and Beacom (2020)

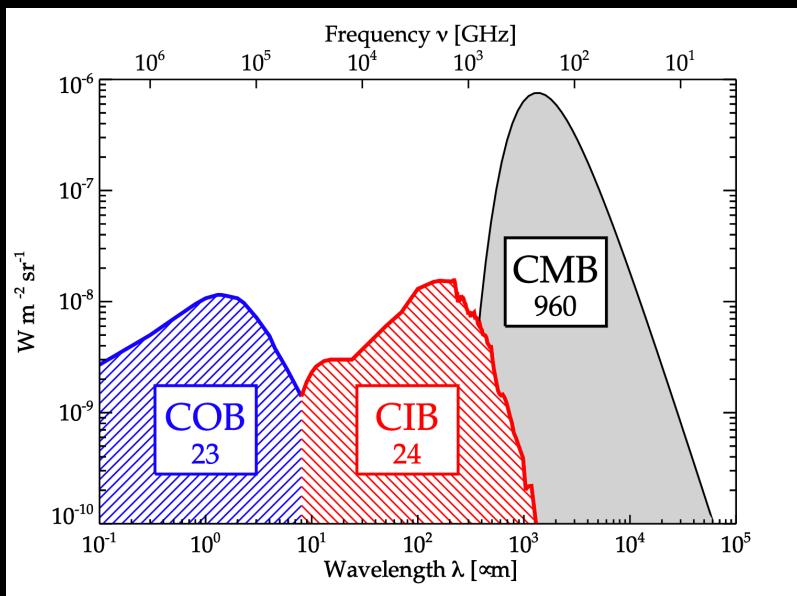
A plot like this makes it easy to estimate N_{tot}

For the complete red curve on the top:
 Height ~ 10 (dimensionless)
 Width $\sim \Delta(\ln E) \sim 2$ (dimensionless)
 Area ~ 20 counts

Don't let the log range on the y-axis fool you about the width of the peak; you want the main part of the curve, not the small tails

Log Integration, Part 5/5

A plot like this makes it easy to estimate E_{tot}
How do we recognize this plot of intensity as
constant $\times E^2 dN/dE$ versus $\log E$?



Dole et al. (2006)

For the blue COB curve:

Height $\sim 10^{-8}$ W/m²/sr

Width $\sim \Delta(\ln E) \sim 2$ (dimensionless)

Area ~ 20 nW/m²/sr

Offline homework:

Intensity = c (energy density) / 4π
Estimate energy density of CMB