The Niels Bohr International Academy

DARK

High-Energy Neutrino Astronomy and Astrophysics

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Advancing Theoretical Astrophysics
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Intended Learning Objectives

- Particle production and acceleration
- Multi-messenger connections
- Observations and experimental facilities

Neutrinos

ν_e

Ghostly

Abundant

ν_τ

Elusive

ν_μ

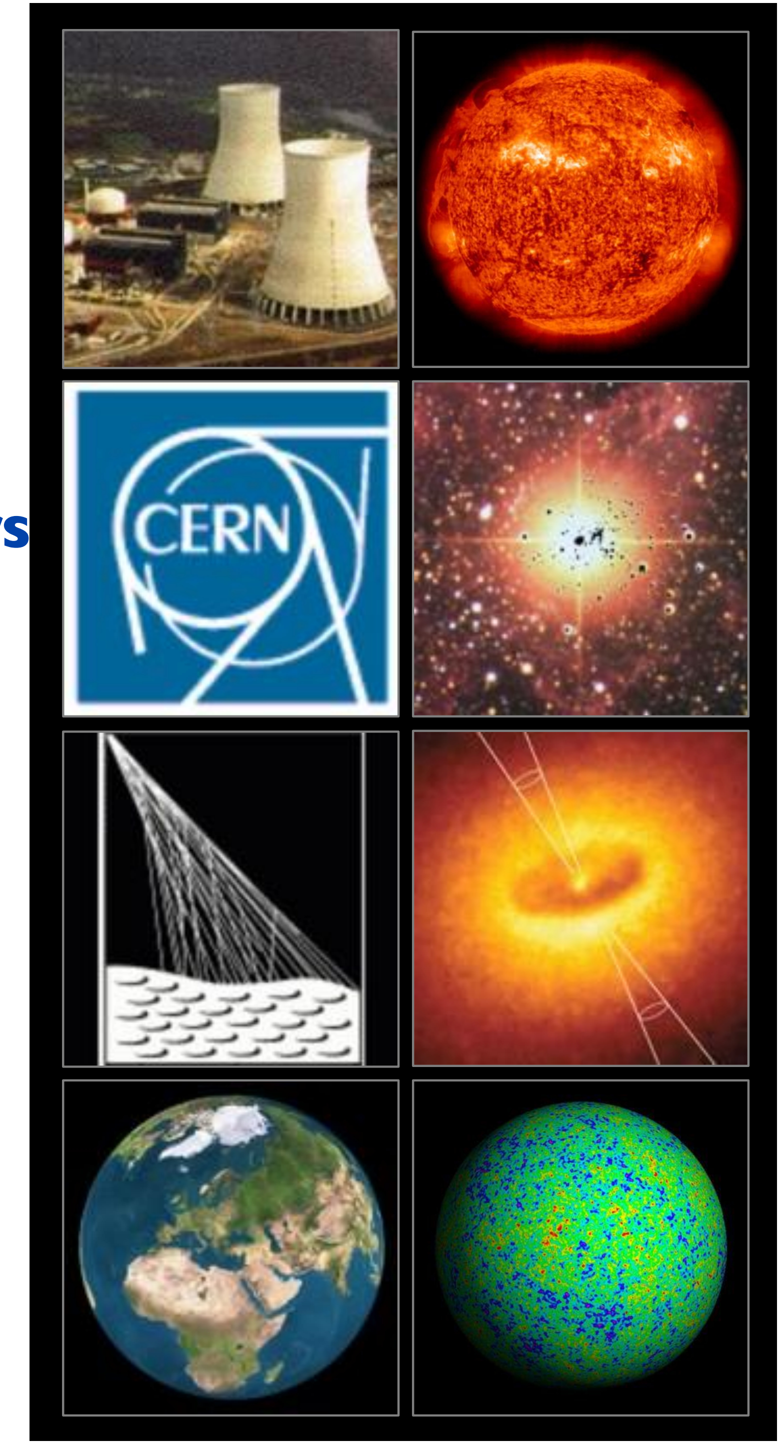
Where Are Neutrinos Produced?

Nuclear reactors

Particle accelerators

Atmosphere

Earth



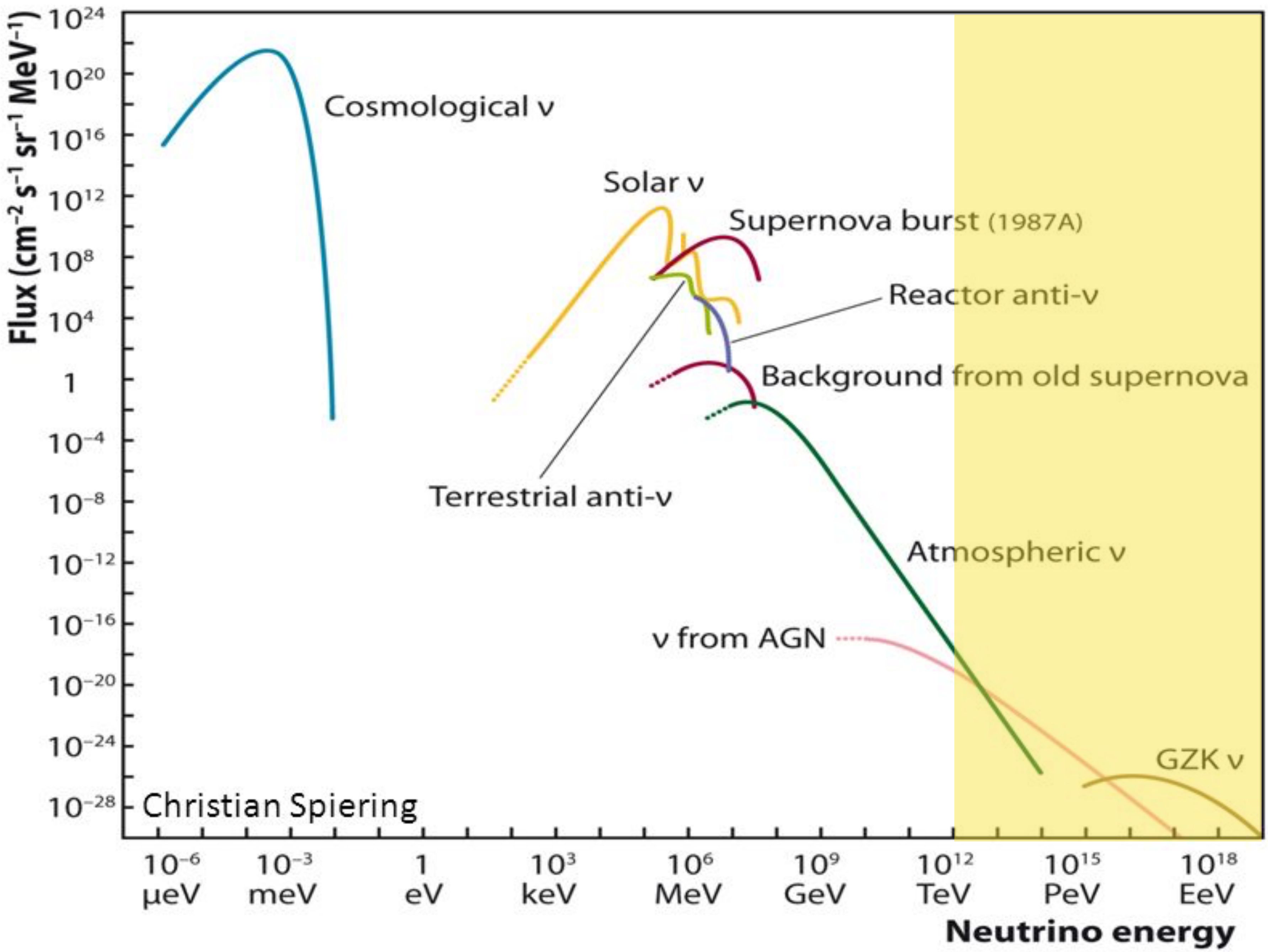
Sun

Supernovae

Gamma-ray bursts and other cosmic accelerators

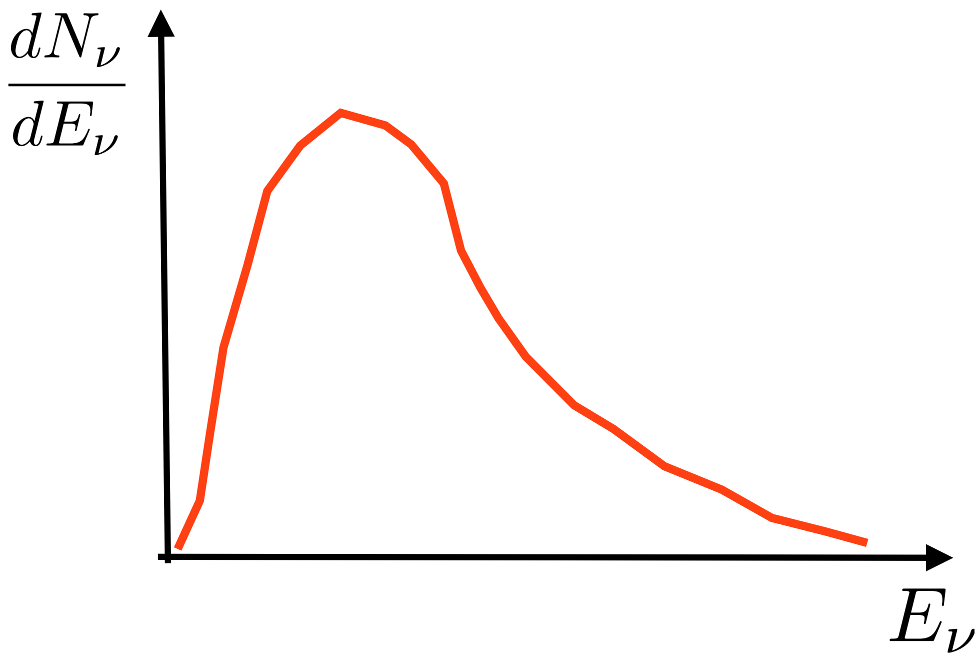
Big Bang

Neutrino Energy Spectrum



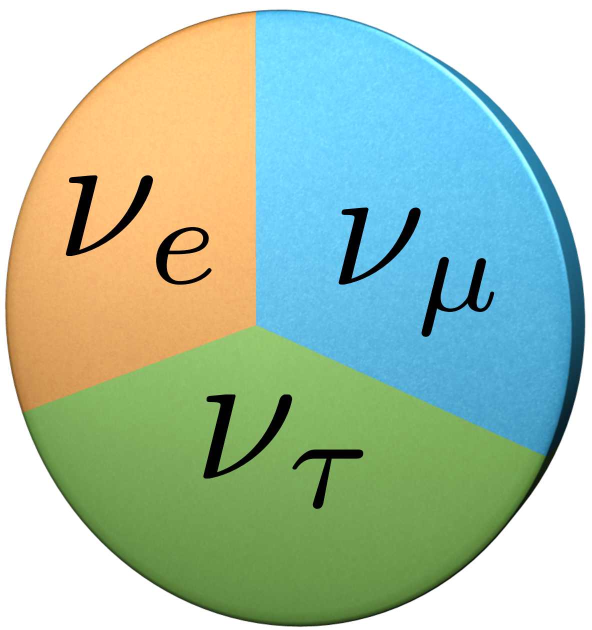
Powerful Probes in Astrophysics

Energy distribution



Similar to photons

Flavor ratio

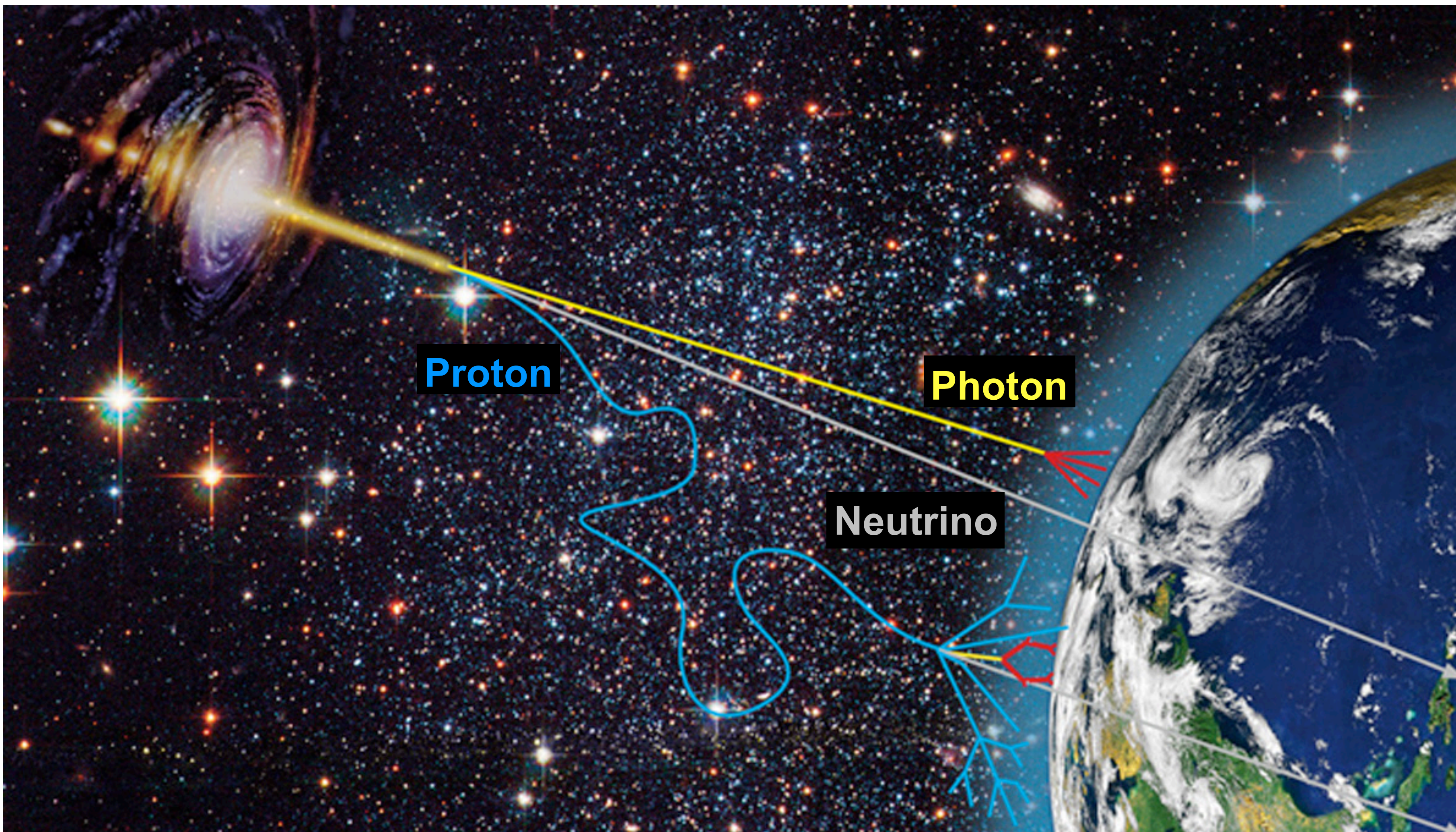


Neutrinos only!

Why neutrinos can be good astrophysical probes?

Ideal Messengers

Escaping unimpeded, neutrinos carry information about sources not accessible otherwise.



Multi-Messenger Astrophysics

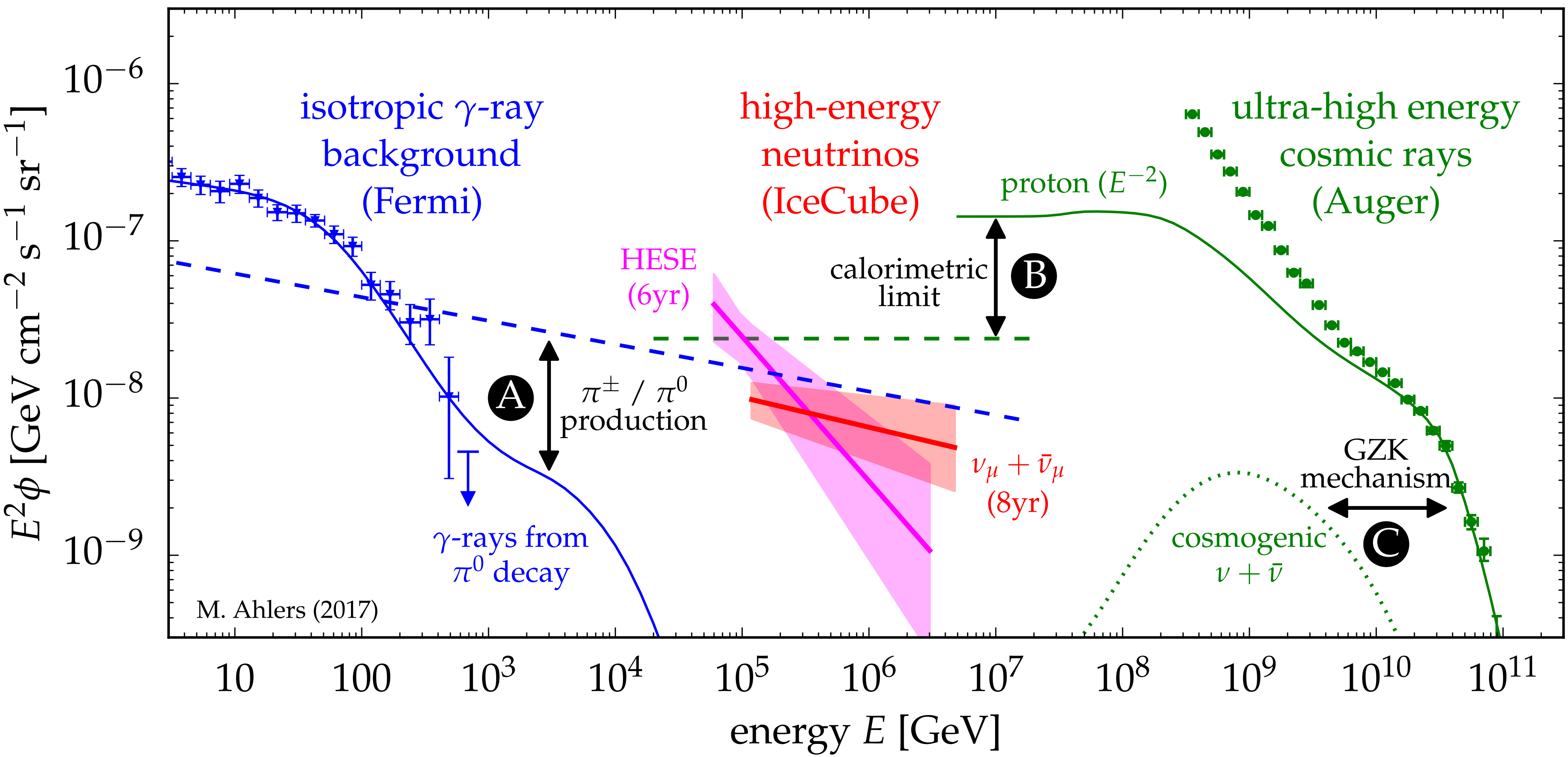
Neutrinos
IceCube, KM3NeT, Super-K, etc.

Gamma Rays
Fermi, HAWC, HESS,
MAGIC, etc.

Gravitational Waves
LIGO, Virgo, KAGRA, etc.

Cosmic Rays
PAMELA, AMS-02,
Auger, TA, etc.

Messengers of the High Energy Sky

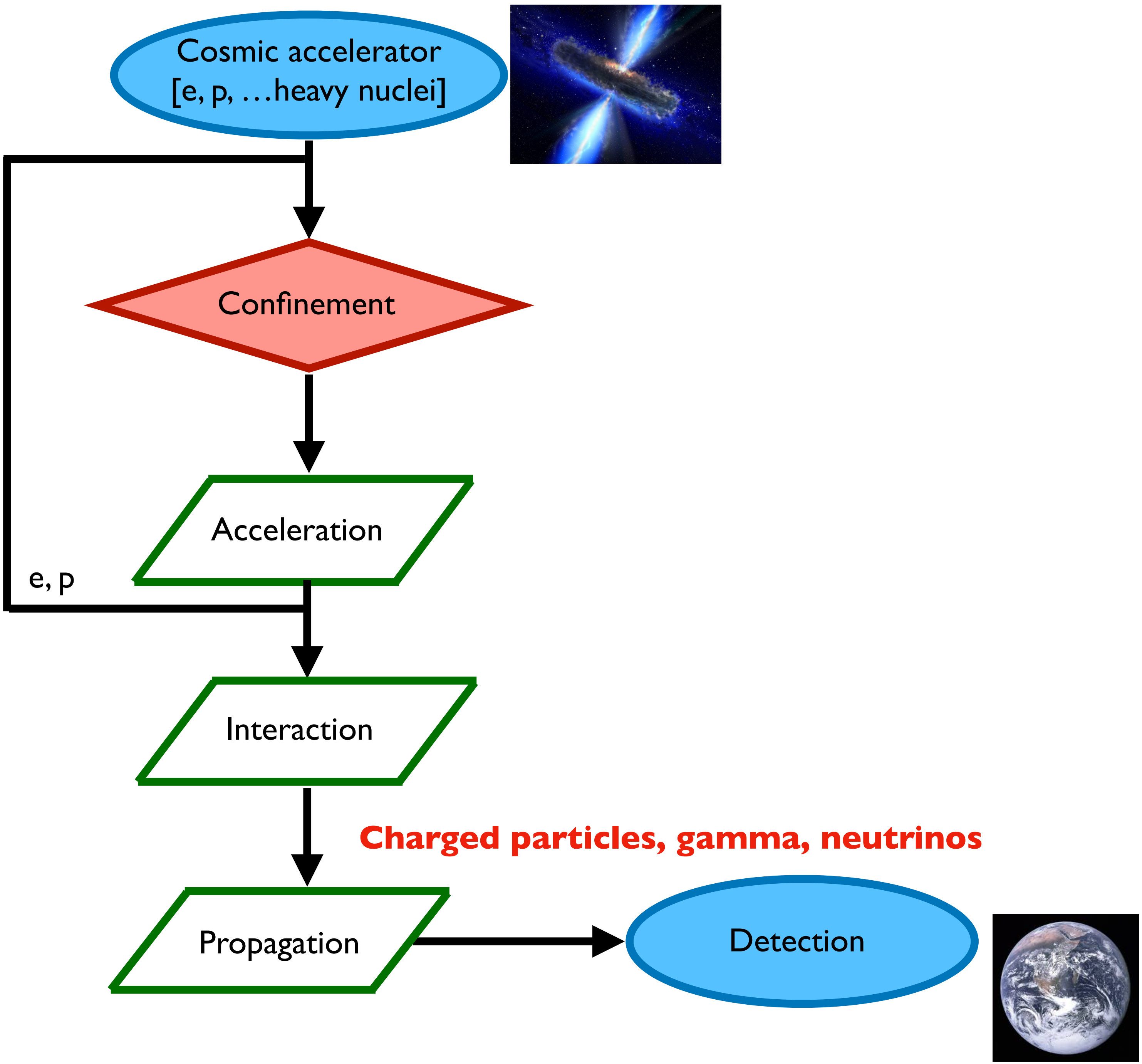


Neutrinos, gamma rays and cosmic rays have similar energies.

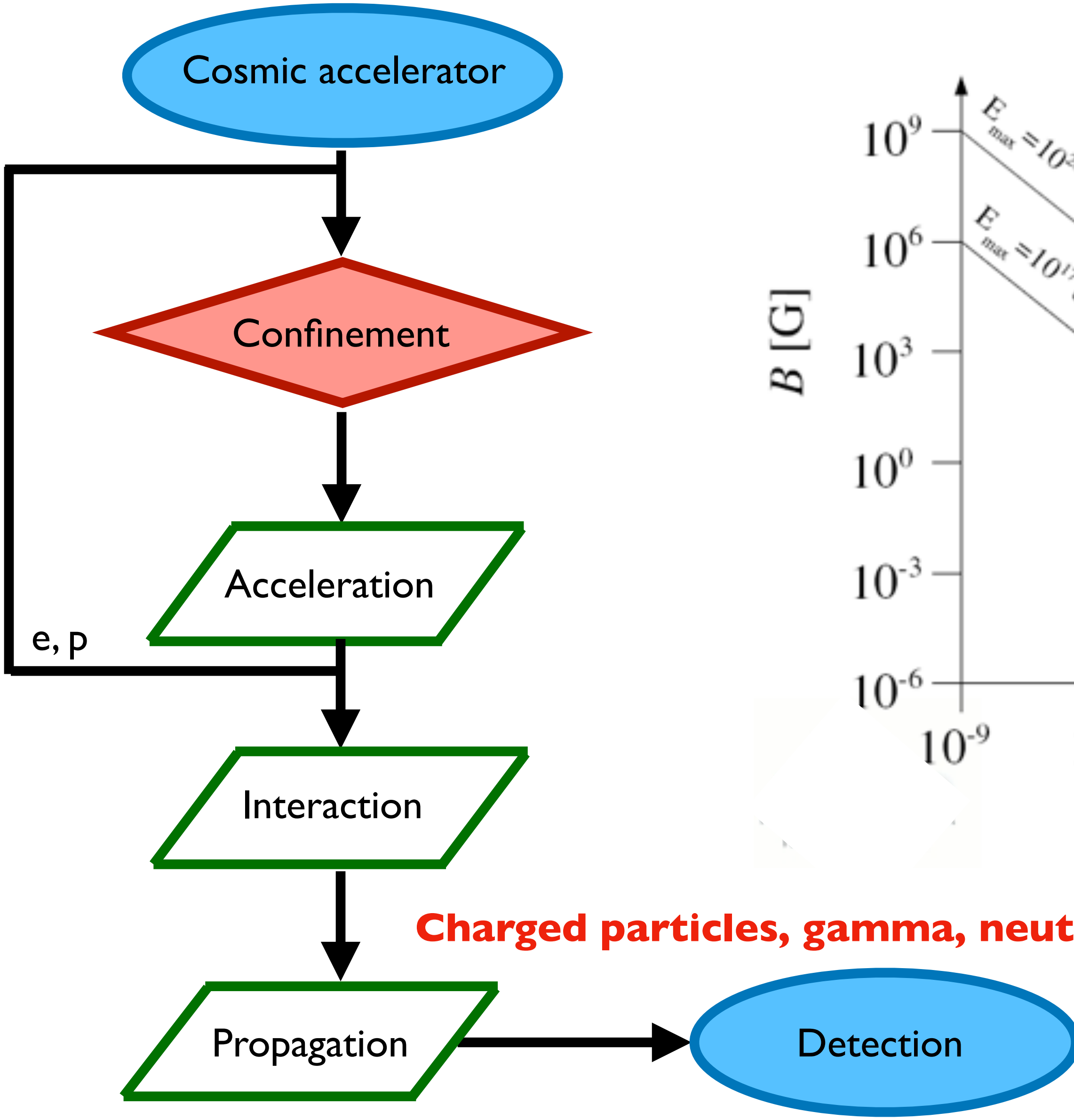
Figure taken from Ahlers & Halzen, Prog. Part. Phys. (2018).

How are particles produced in cosmic accelerators?

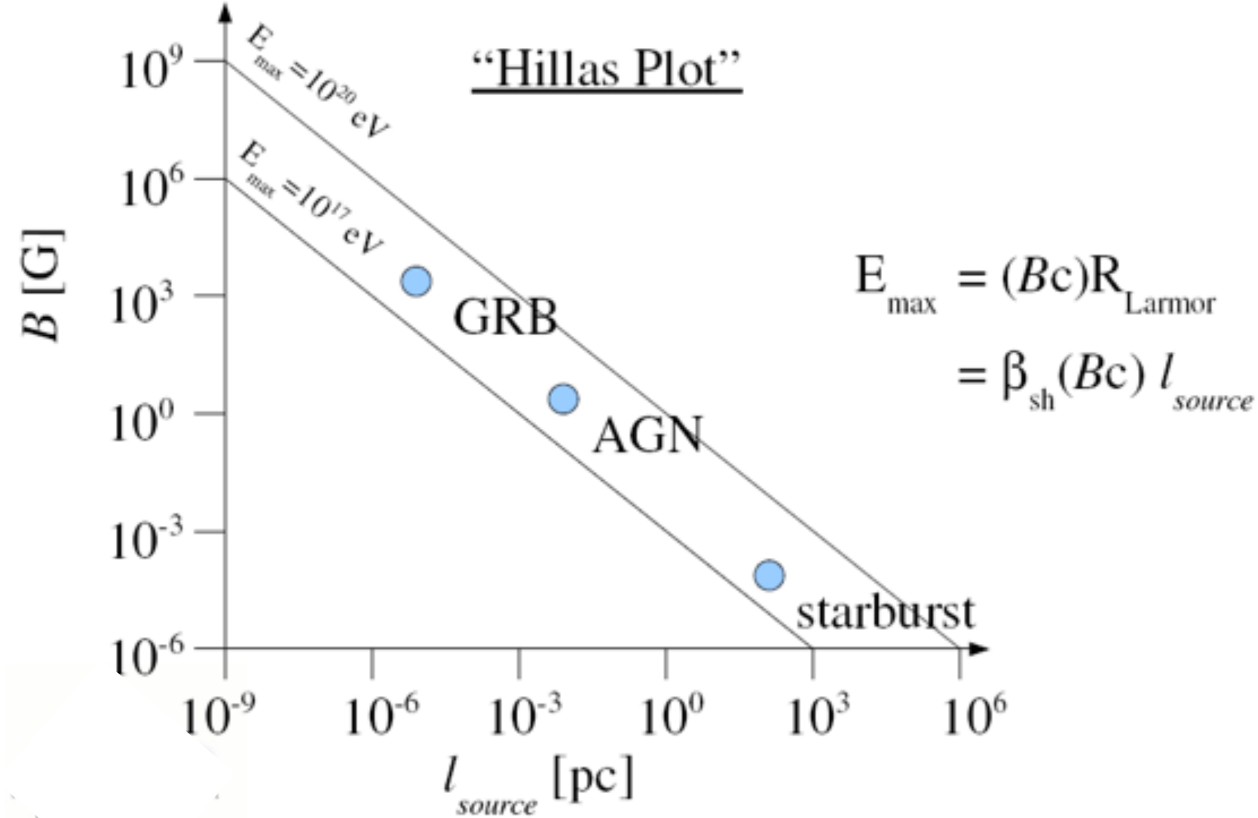
Particle Production and Acceleration



Confinement

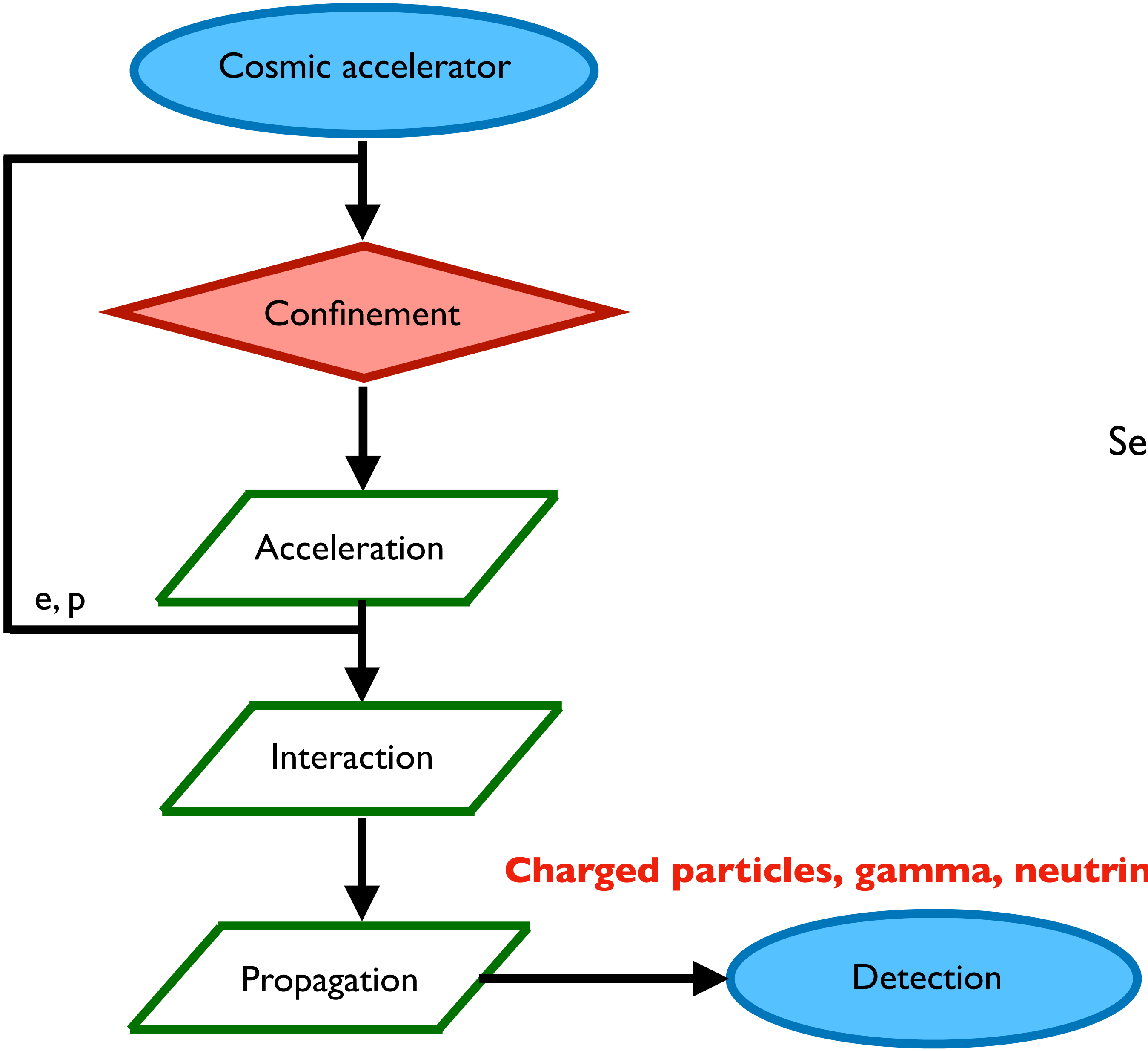


Magnetic field vs. accelerator size



Hillas, Ann. Rev. Astron. Astrophys. 22 (1984) 425. Image credit: A. Taylor.

Acceleration

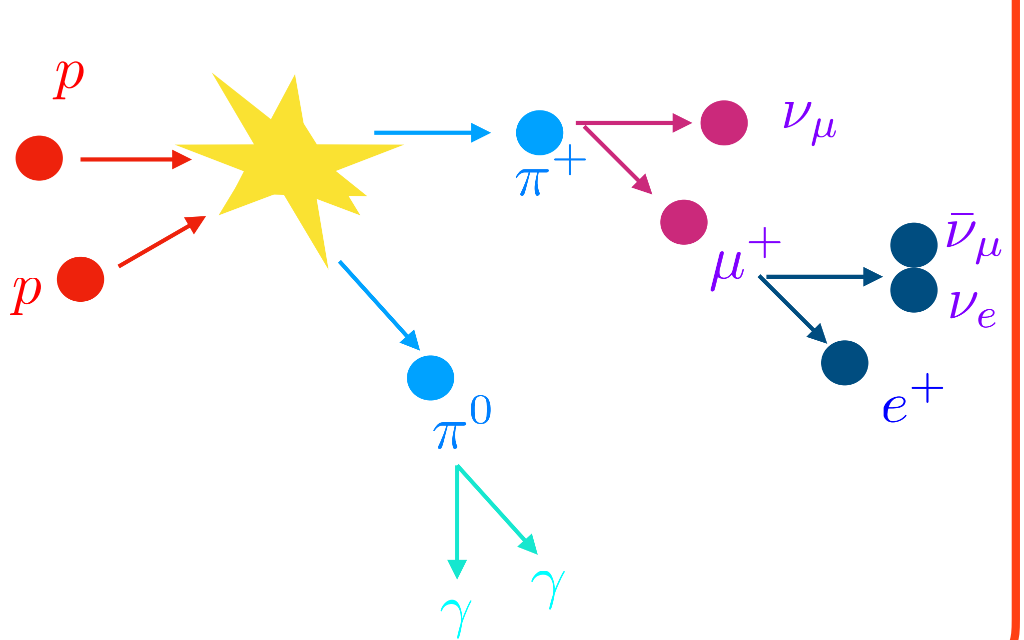


See previous lecture!

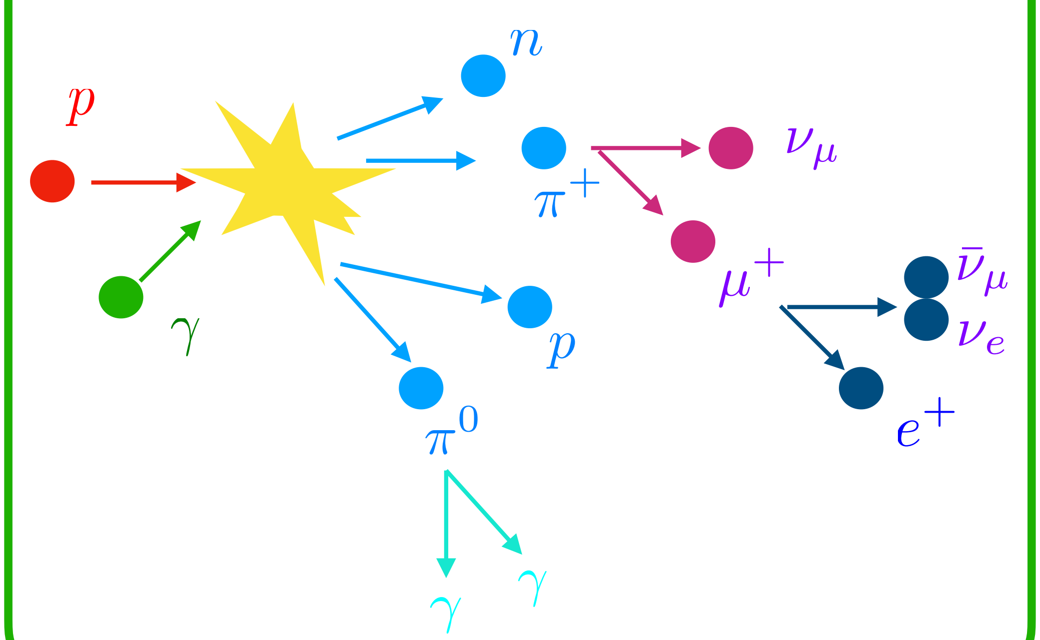
Charged particles, gamma, neutrinos

Interaction

Proton-proton interactions



Proton-photon interactions



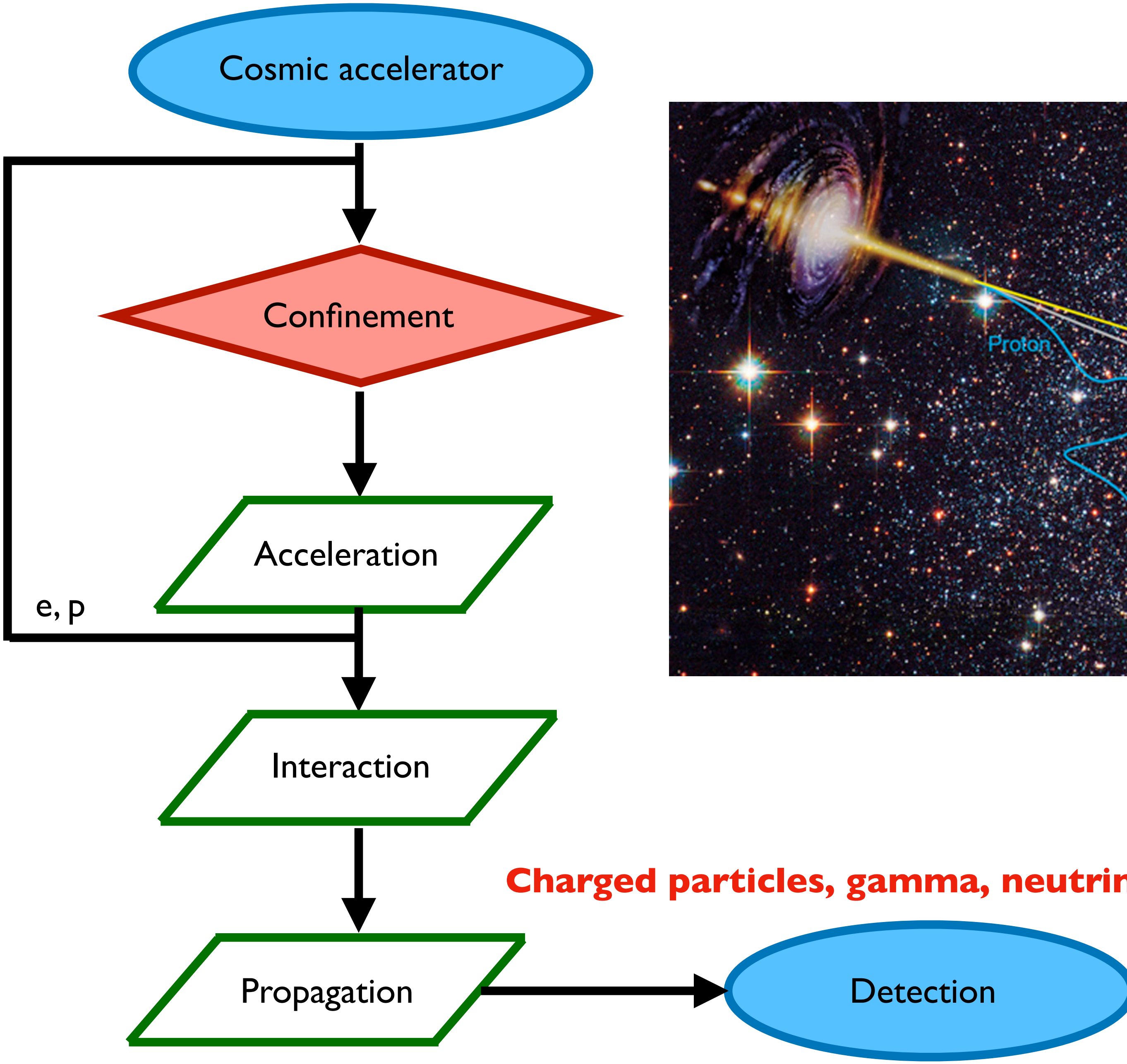
Electron and muon neutrinos are produced by charged pion decay.

Gamma-ray photons are produced by neutral pion decay.

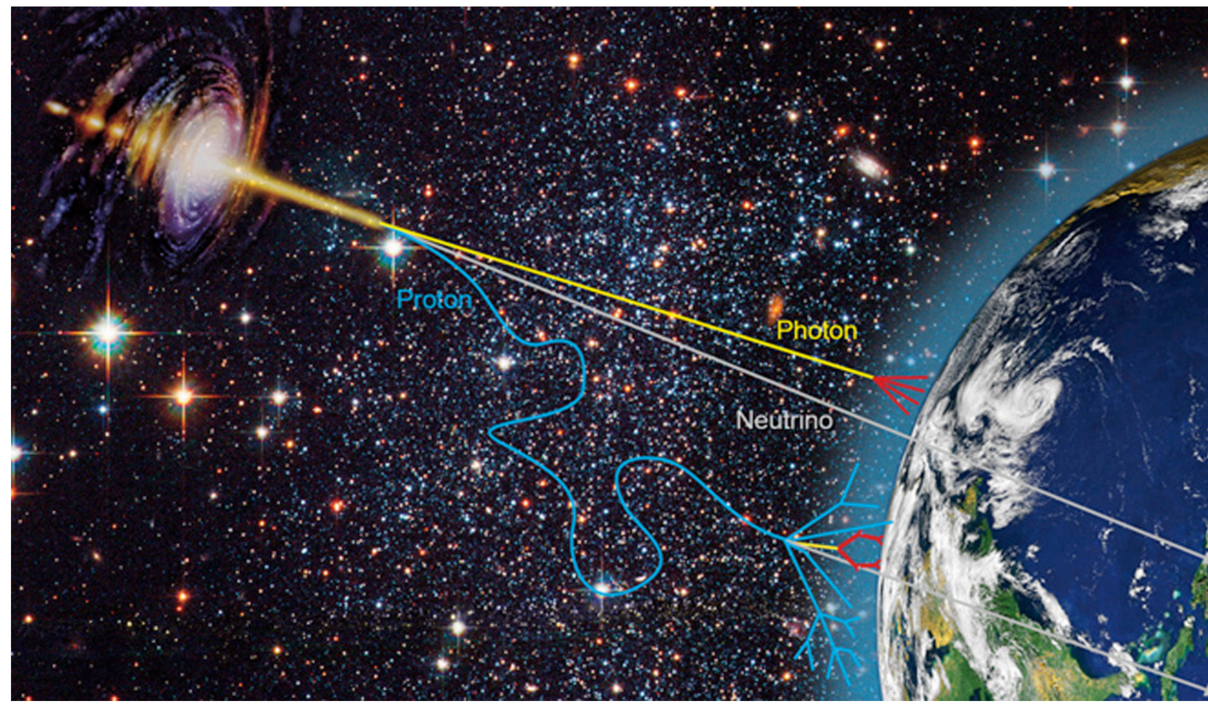
Charged particles, gamma-rays, and neutrinos carry information about the source.

Anchordoqui et al., PLB (2004). Kelner, Aharonian, Bugayov, PRD (2006). Kelner, Aharonian, PRD (2008).

Propagation and Interaction



Charged particles, gamma, neutrinos



Cosmic Rays and Gamma-Rays

Cosmic rays

- Charged nuclei are deflected by magnetic fields.
- The directional information carried by cosmic rays is lost at low-medium energies.
- Cosmic rays preserve the directional information at the highest energies; bending radius is large against propagation distance ($R = \frac{pc}{Ze} = B \times r_L$).

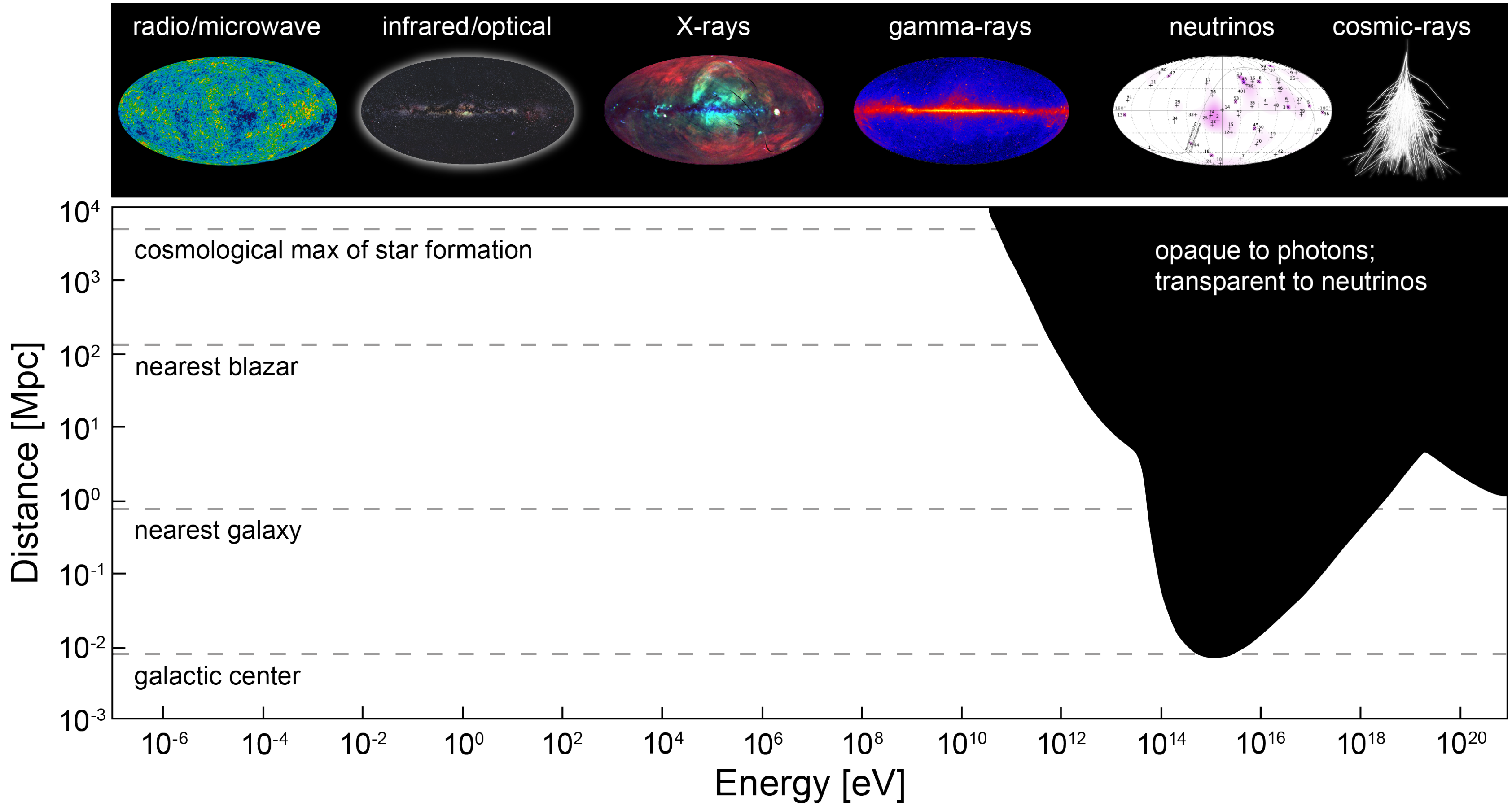
Anchordoqui, Phys. Rep. 801 (2019) 1-93, arXiv: 1807.09645.

Photons

- Photons are neutral, point back to the source.
- Interact with charged particles via inverse Compton, annihilation to electron positron pairs.
- The observable distance in photons is limited.

Hinton and Hofmann, Ann. Rev. Astron. Astrophys. 47 (2009) 523-565, arXiv: 1006.5210.

Neutrinos



Neutrinos

- Neutrinos are neutral, point back to the source, come in three flavors.
- Neutrinos do not interact with medium particles; ideal messengers.
- Sensitive to distant (far away) sources.
- Cross sections are very small. Neutrinos are hard to detect.
- Neutrinos cover blind spots of astronomy.

Image credits: https://icecube.wisc.edu/science/highlights/neutrino_astronomy

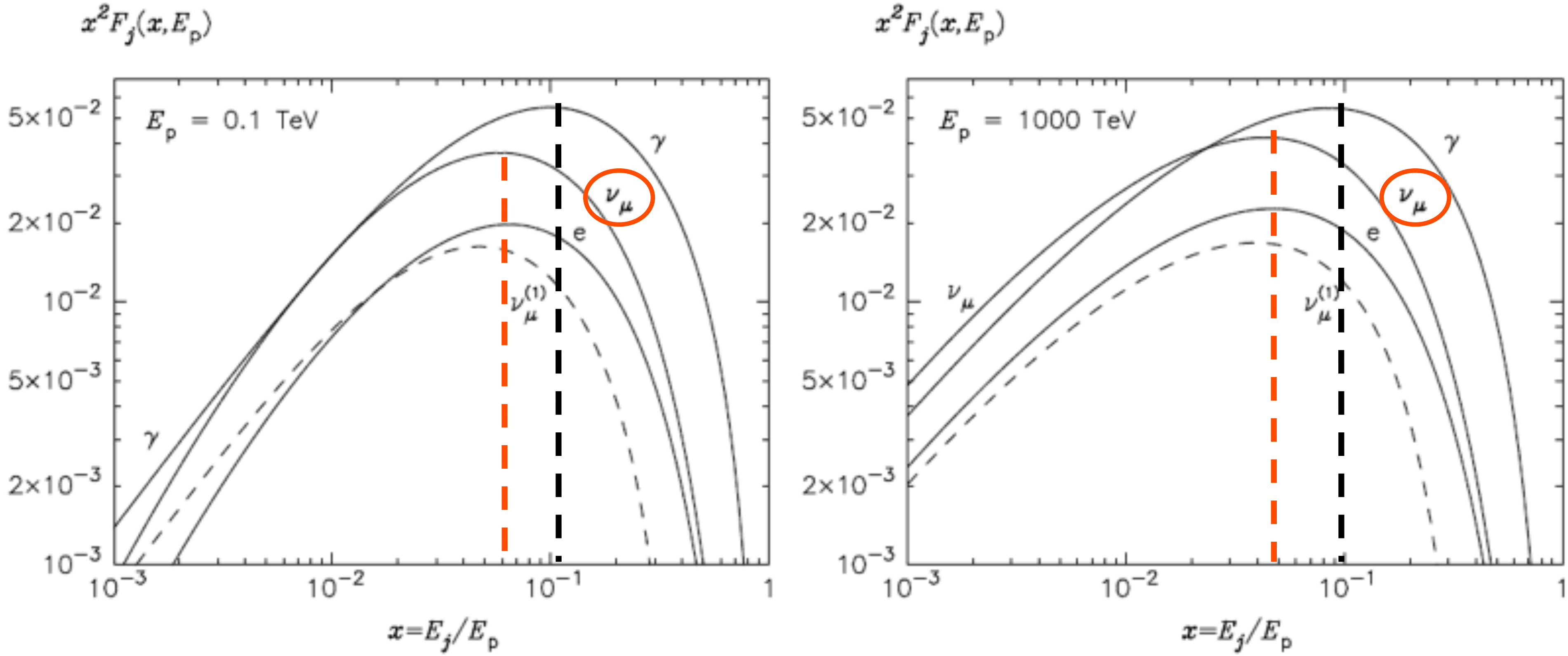
Which features does an astrophysical object need to accelerate particles?

General Features of Acceleration Sites

- **Geometry**: The accelerated particle should stay within the astrophysical object during acceleration.
- **Power**: The source needs to have enough energy to accelerate particles.
- **Radiative losses**: The energy gained by the particle should not be less than its energy loss.
- **Interaction losses**: The energy lost by a particle in interactions with other particles should not be greater than its energy gain.
- **Population**: The density and power of sources must be high enough to account for the observed CR, nu and gamma fluxes.

Connections Among Messengers

Average Energy Fractions of Messengers



The typical energies of protons, photons and neutrinos are connected

$$\boxed{E_p : E_\gamma : E_\nu = 1 : 0.1 : 0.05}$$

Kelner, Aharonian, Bugayov, PRD 74 (2006) 034018. Kelner, Aharonian, PRD 78 (2008) 034013. Reimer et al., SOPHIA Monte Carlo, http://ebl.stanford.edu/

Proton-Photon Interactions

On average 1/3 of the proton energy goes into pions

$$p + \gamma \to \Delta^+ \to \Delta^+ \to p + \pi^0 \qquad 2/3$$

$$p + \gamma \to \Delta^+ \to \Delta^+ \to n + \pi^+ \qquad 1/3$$

On average 1/2 of the pion energy goes into each photon and1/4 goes into each neutrino

$$\pi^0 \to \gamma + \gamma$$

$$\pi^+ \to \mu^+ + \nu_\mu \to (e^+ \nu_e \bar{\nu}_\mu) + \nu_\mu$$

Assuming $\dfrac{dN_p}{dE_p} \propto E_p^{-2} \to \dfrac{dN_p}{dE_p} \propto E_p^{-2} = E_\nu^{-2} x_\nu^2$

Since $\dfrac{E_\nu}{E_p} = x_\nu \sim \dfrac{1}{20} \to dE_p = x_\nu^{-1} dE_\nu$

$$\frac{dN_\gamma}{dE_\gamma} \propto 2 \times \frac{2}{3} E_\gamma^{-2} x_\gamma^{-1} \frac{dN_p}{dE_p} = 2 \times \frac{2}{3} E_\gamma^{-2} x_\gamma = 2 \times \frac{2}{3} \times \frac{1}{10} E_\gamma^{-2}$$

$$\frac{dN_\nu}{dE_\nu} \propto 2 \times \frac{1}{3} E_\nu^{-2} x_\nu^{-1} \frac{dN_p}{dE_p} = 2 \times \frac{1}{3} E_\nu^{-2} x_\nu = 2 \times \frac{1}{3} \times \frac{1}{20} E_\nu^{-2}$$

$$\boxed{\frac{dN_\nu}{dE} \simeq \frac{1}{4} \frac{dN_\gamma}{dE}}$$

Proton-Proton Interactions

$$p + p \to \pi^+ : \pi^- : \pi^0$$

If all muons decay and for a proton spectrum going like E_p^{-2}

Remembering that $x_\gamma = \frac{E_\gamma}{E_p} = \frac{1}{10}$ and $x_\nu = \frac{E_\nu}{E_p} = \frac{1}{20}$

$$\frac{dN_\nu}{dE} \propto 2 \times \frac{2}{3} \times \frac{1}{20}$$

(2 pions x 1/3 of energy of each pion)

$$\frac{dN_\gamma}{dE} \propto 2 \times \frac{1}{3} \times \frac{1}{10}$$

There is a factor of 1 between the gamma and the neutrino flux

$$\boxed{\frac{dN_\nu}{dE} \sim \frac{dN_\gamma}{dE}}$$

Messenger Connection at Source

$$\frac{dN_\nu}{dE} \sim \frac{1}{4}\frac{dN_\gamma}{dE}$$

For proton-photon interactions

$$\frac{dN_\nu}{dE} \sim \frac{dN_\gamma}{dE}$$

For proton-proton interactions

What happens during propagation of messengers to us?

Propagation at Earth

The ratio of flavors at the source is expected to be $\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$

Neutrinos **convert** into each other by flavor mixing, because of their tiny non-vanishing mass.

Flavor eigenstates **Mass eigenstates**

ν_e ν_1

ν_μ **= Linear combination** ν_2

ν_τ ν_3

The distance to the source is much larger than the oscillation length. When arriving at Earth, the original flavor admixture mixes up to $\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$

For more details see Anchordoqui et al., JHEAp 1-2 (2014) 1-30, arXiv: 1312.6587

Messenger Connection at Earth

$$\frac{dN_\nu}{dE} \sim \frac{1}{8}\frac{dN_\gamma}{dE}$$

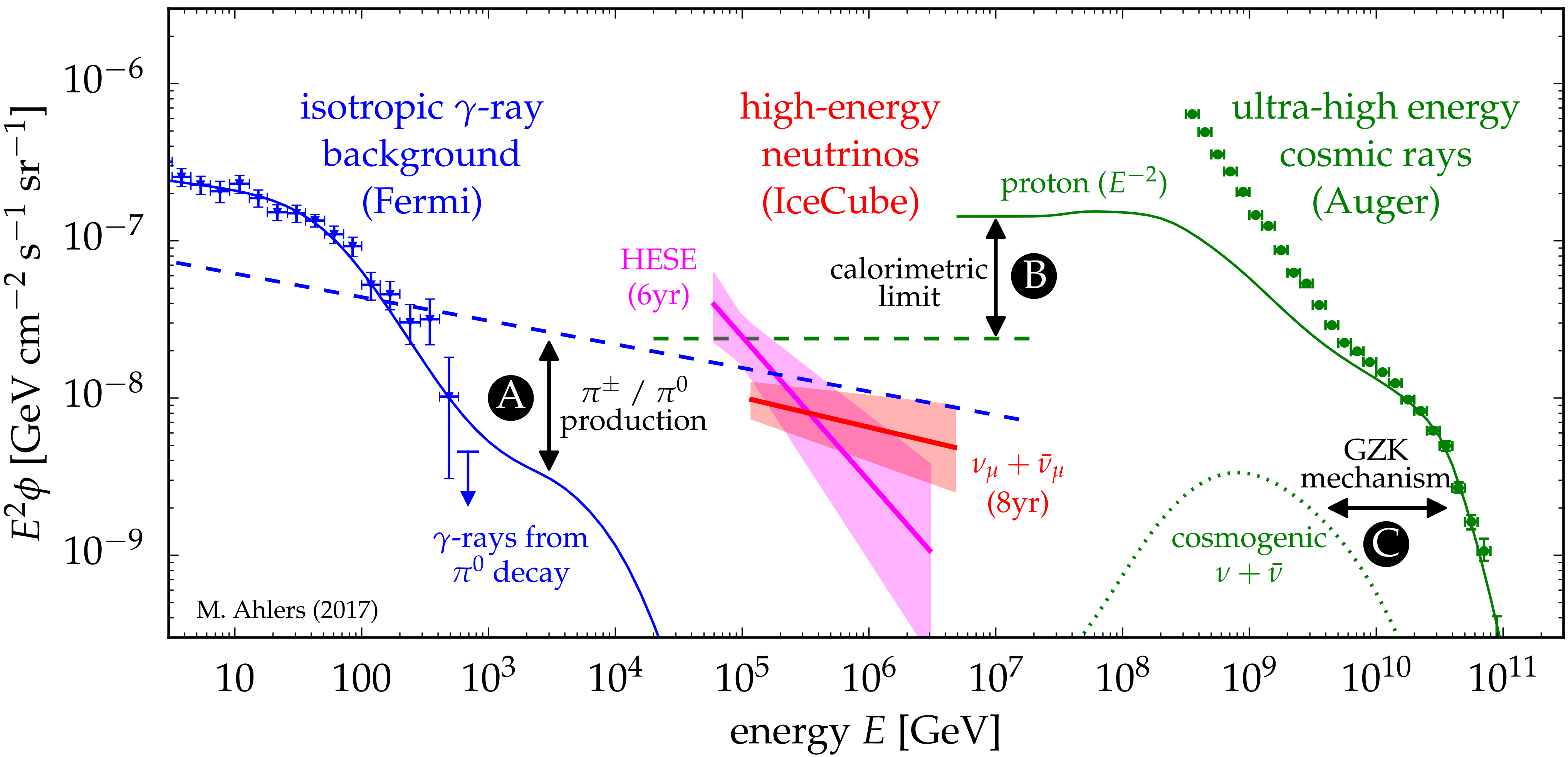
For proton-photon interactions

$$\frac{dN_\nu}{dE} \sim \frac{1}{2}\frac{dN_\gamma}{dE}$$

For proton-proton interactions

Warning: We neglected absorption of photons.

Messengers of the High Energy Sky



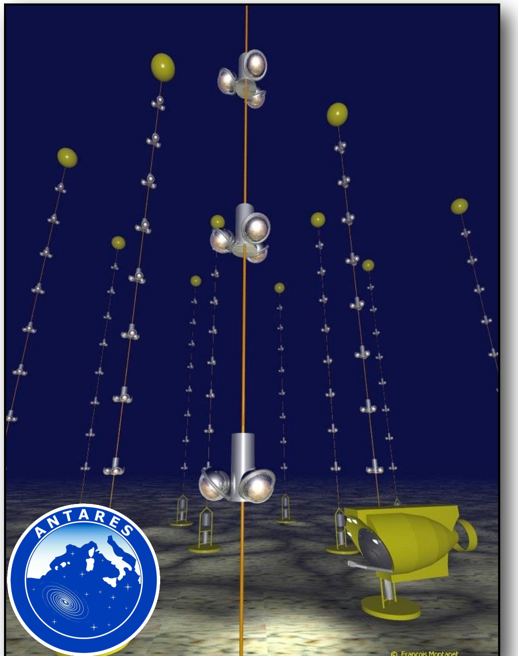
Neutrinos, gamma rays and cosmic rays have similar energies.

Figure taken from Ahlers & Halzen, Prog. Part. Phys. (2018).

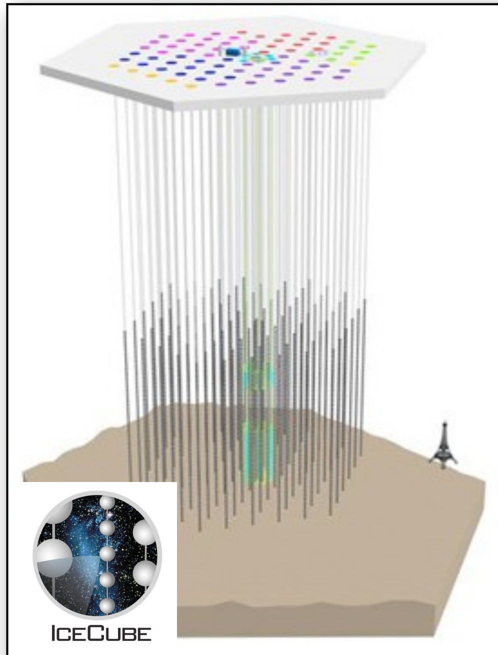
Observations

Cherenkov Neutrino Observatories

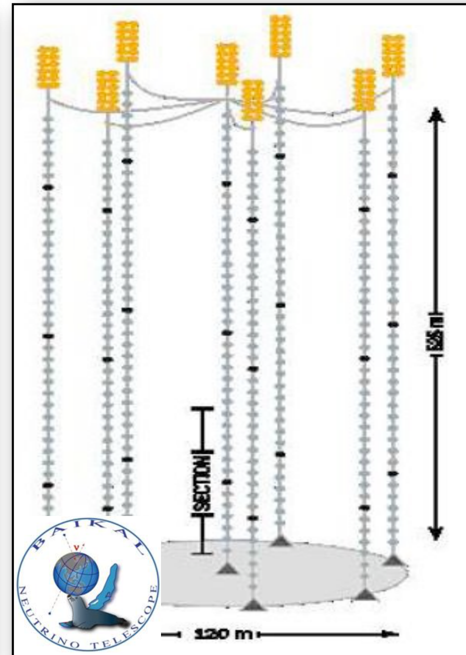
Antares



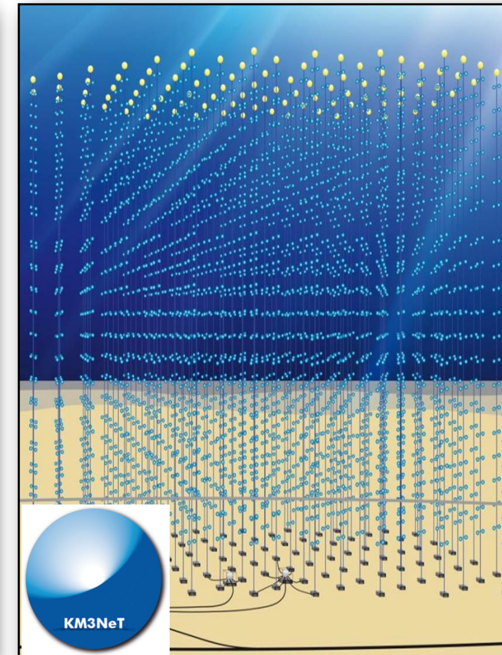
IceCube



Baikal-GVD



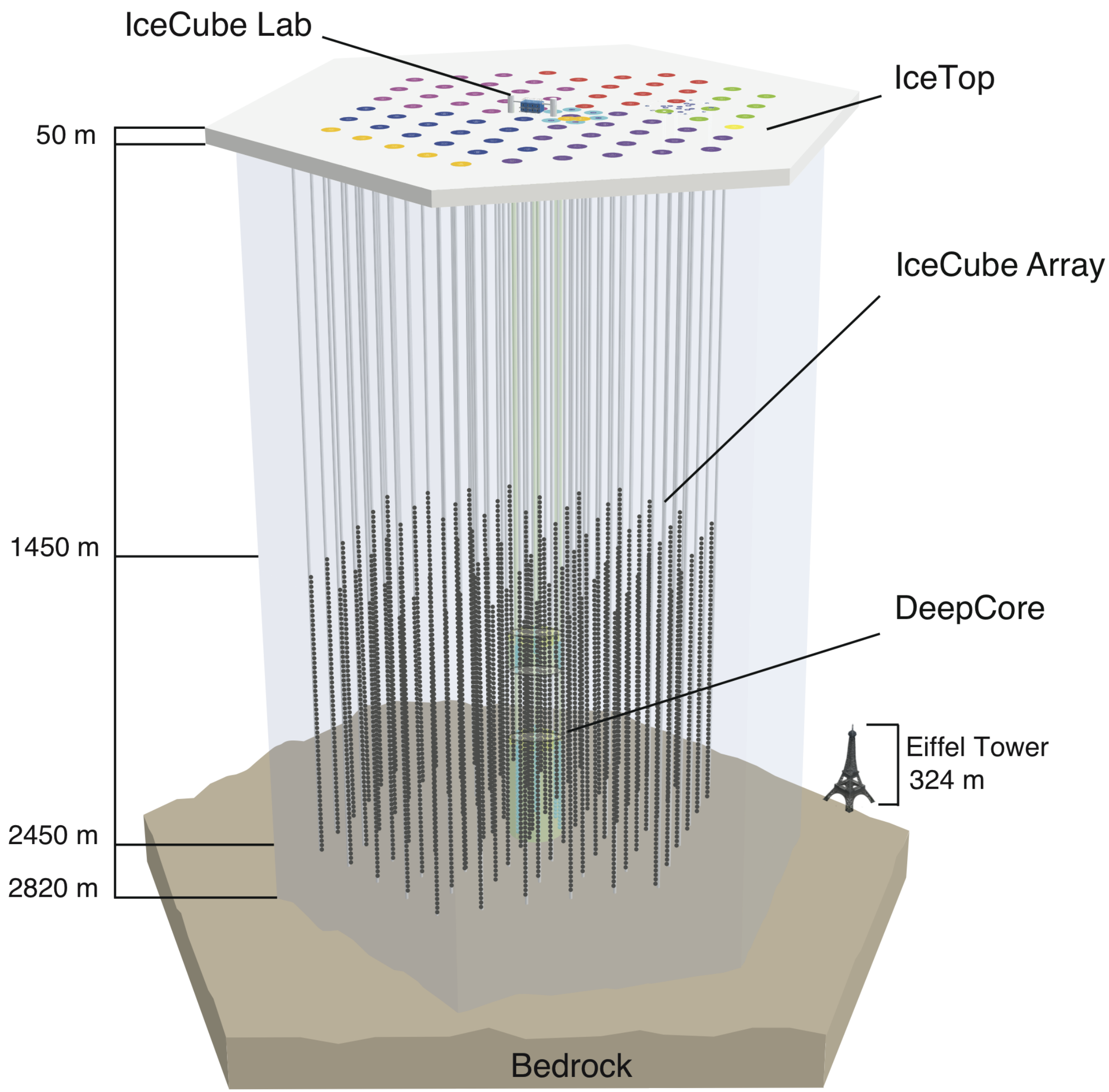
KM3NeT / ARCA



Mediterranean	South Pole	Lake Baikal	Mediterranean
2008–2019	fully instrumented since 2011	under construction (3 out of 8 clusters)	under construction (3 out of 230 DUs)
~0.01 km^3	~1 km^3	~0.4 km^3 (Phase 1) ~1km^3	~0.1 km^3 (Phase 1) ~1 km^3
885 OMs (10″)	5160 OMs (10″)	2304 OMs (10″)	4140 OMs (31x3″)

Figure adapted from M. Ahlers.

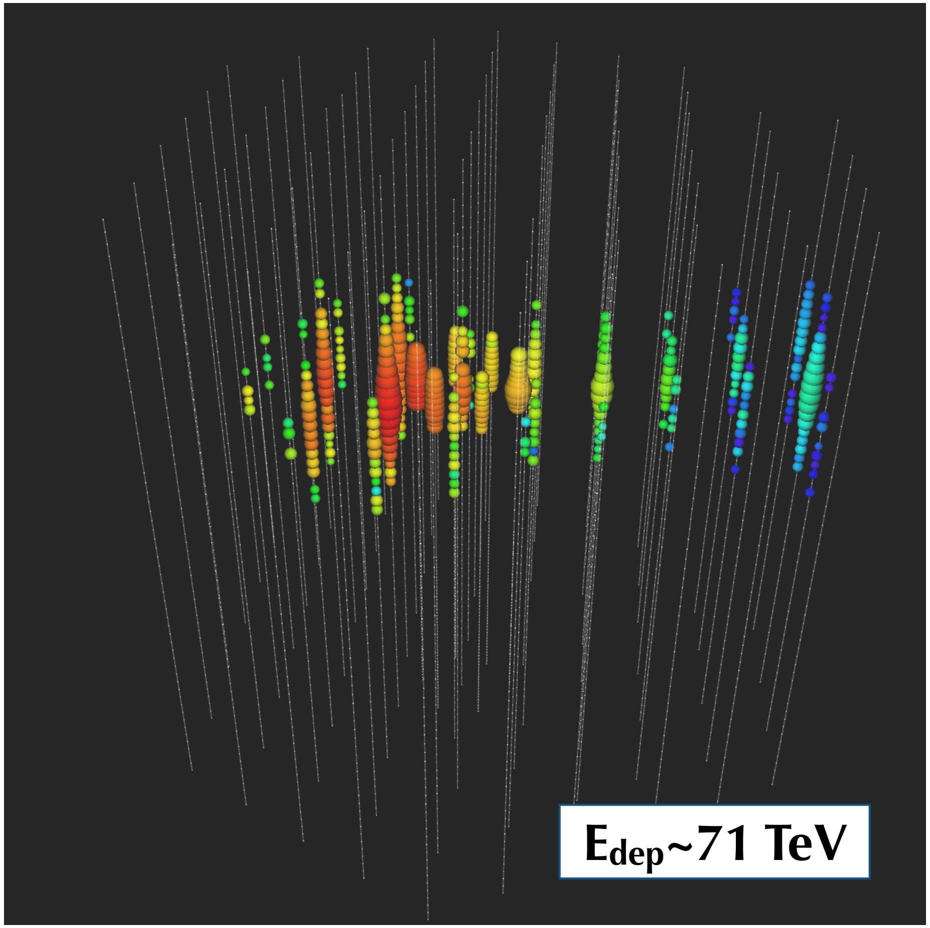
IceCube Neutrino Observatory



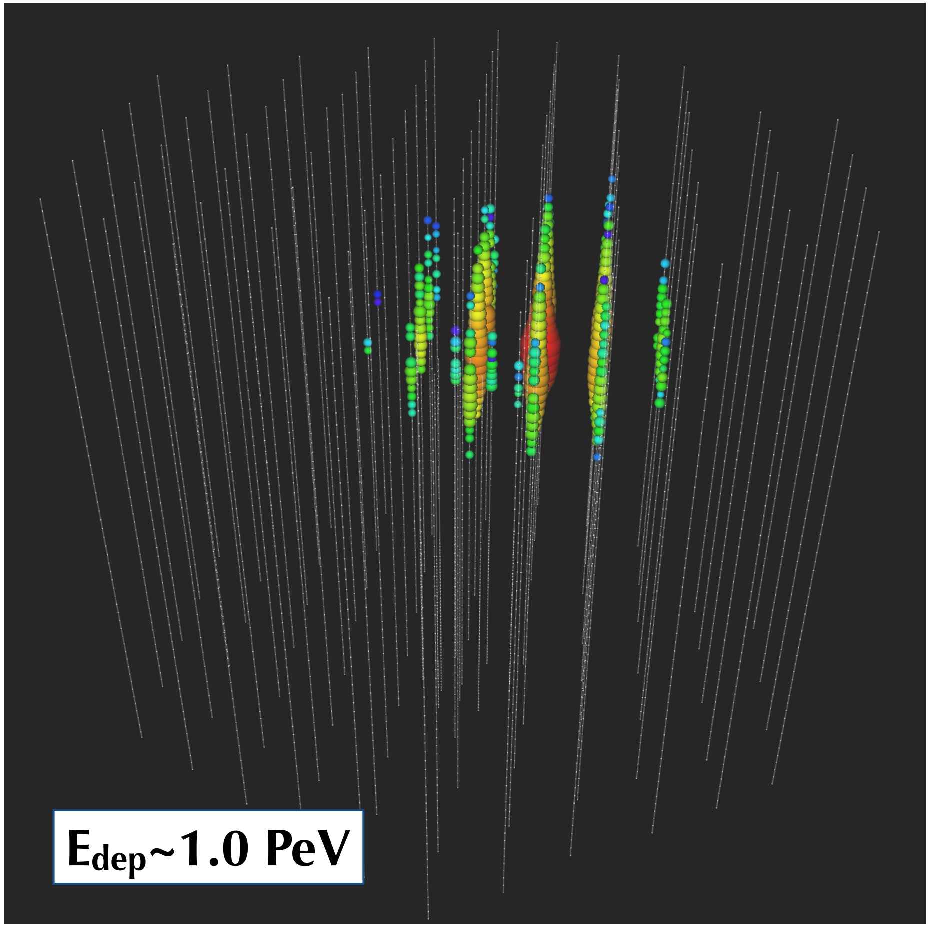
- Giga-ton Cherenkov telescope at the South Pole
- 60 digital optical modules (DOMs)/string
- 78 IceCube strings
- 8 DeepCore strings
  (DOMs in particularly clear ice)

Observation of High-Energy Neutrinos

“Track event”
(muon neutrino scattering)



“Cascade event”
(all flavors)



(neutrino event signature: early to late light detection)

IceCube Coll., Science 342 (2013); IceCube Coll., Astrophys. J. 833 (2016).

Diffuse TeV-PeV Neutrinos

High-Energy Starting Events (HESE, 7 yrs)
Bright events above 30 TeV starting inside IceCube
Efficient removal of atmospheric backgrounds by veto layer

Up-going muon-neutrino tracks (8 yrs)
Large effective volume
Efficient removal of atmospheric muon backgrounds by Earth-absorption

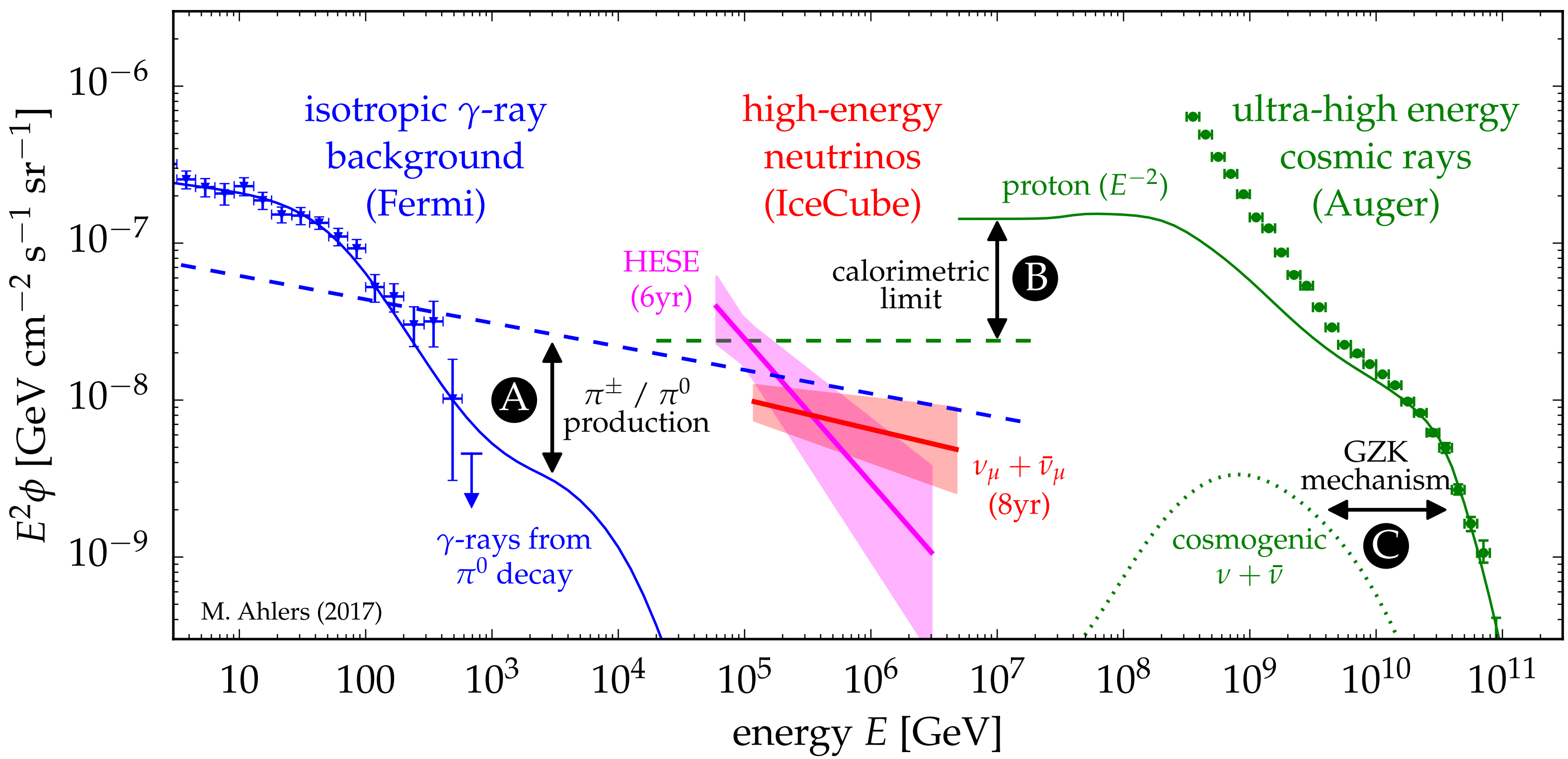
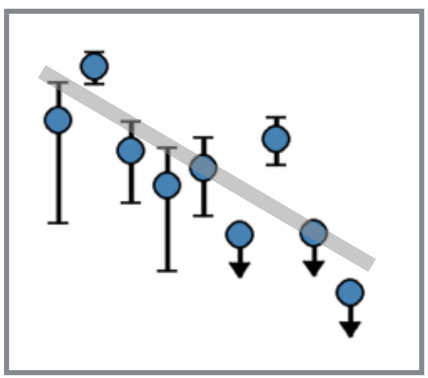
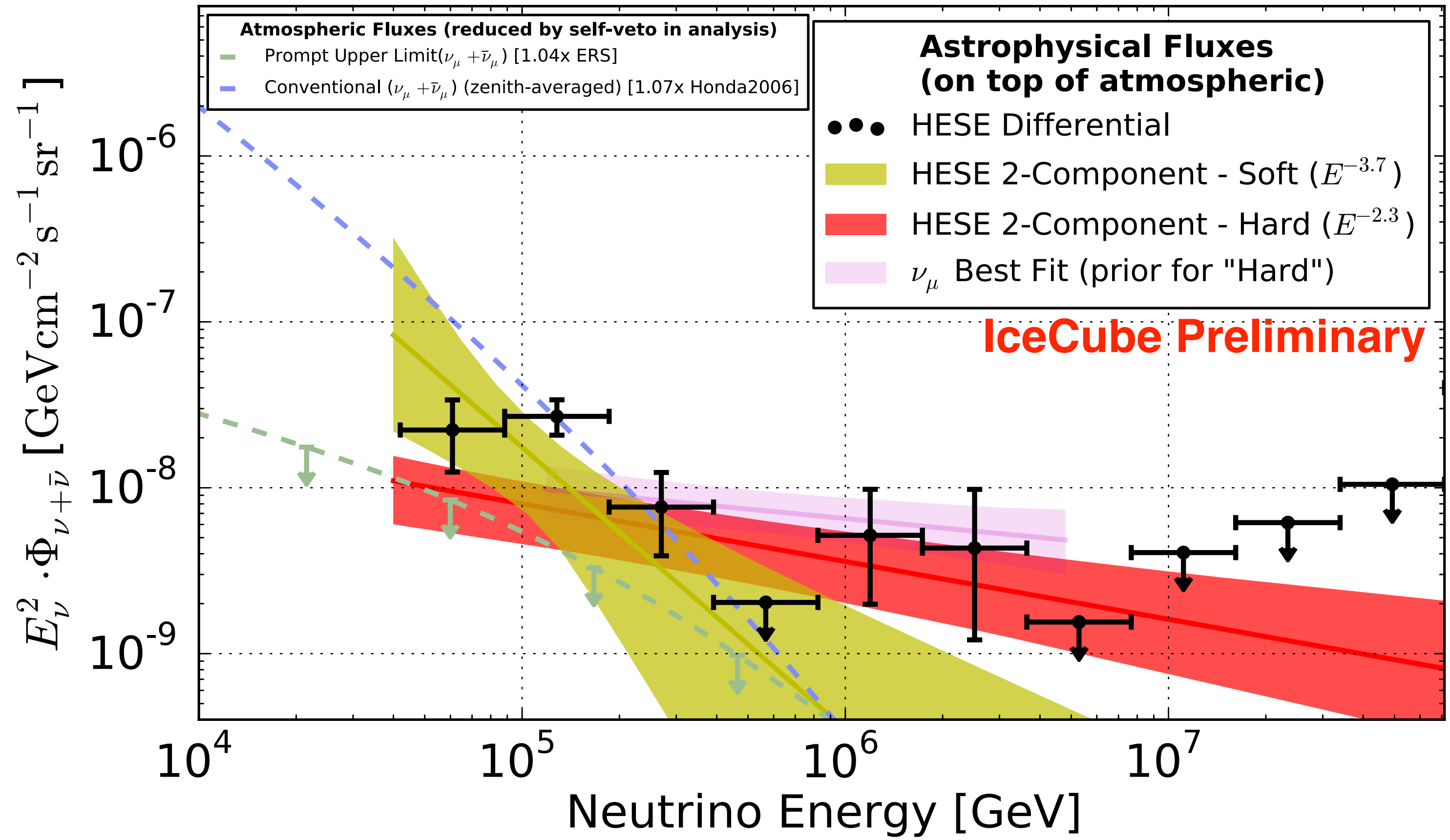
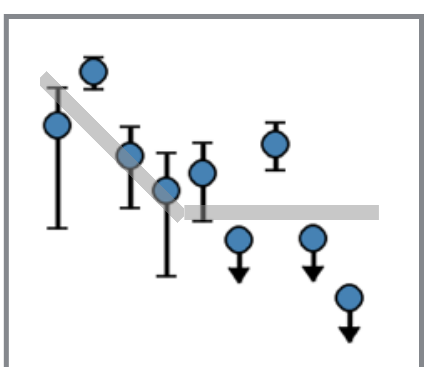


Figure taken from Ahlers & Halzen, Prog. Part. Phys. (2018).
IceCube Coll., Science 342 (2013); IceCube Coll., Astrophys. J. 833 (2016).

Measured Astrophysical Neutrino Flux



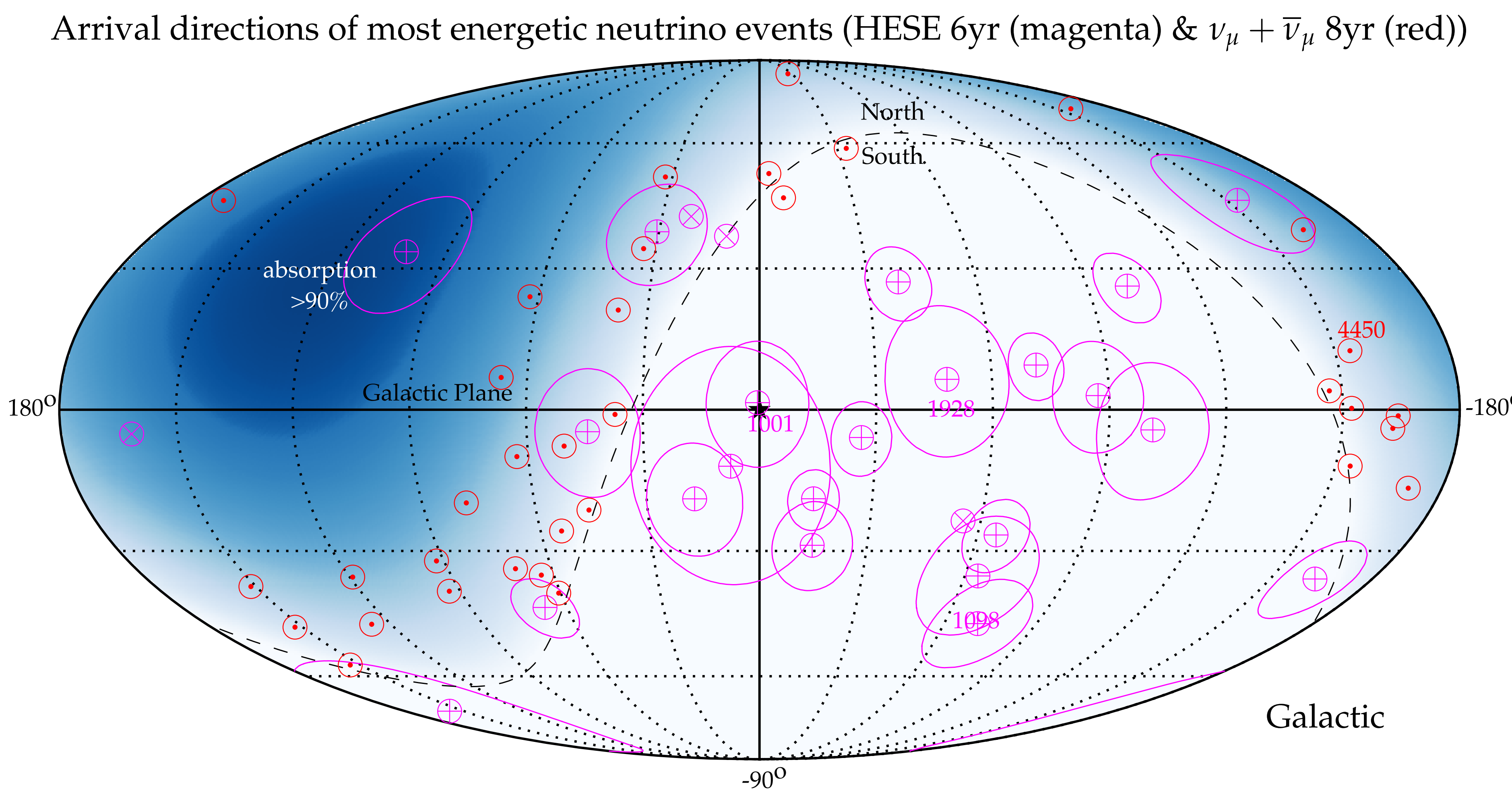




Are we seeing a spectral flattening of energy spectrum?

Figure taken from Ahlers & Halzen, Prog. Part. Phys. (2018).

Arrival Directions of IceCube Neutrinos

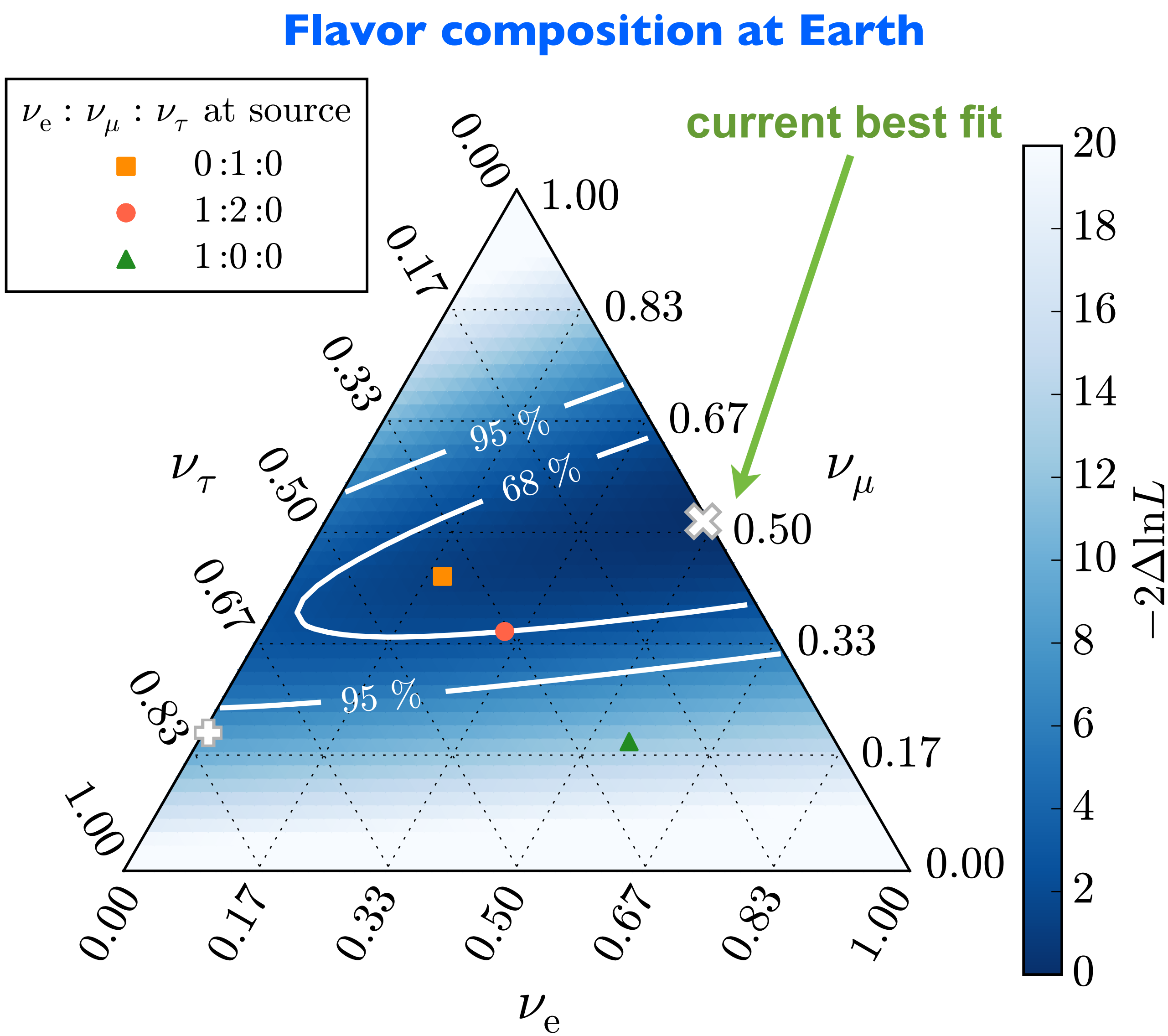


No evidence of clustering in arrival directions of HE neutrinos → Isotropic distribution

→ **Neutrinos of extragalactic origin**.

Figure taken from Ahlers & Halzen, Prog. Part. Phys. (2018).

Measured Neutrino Flavor Ratio



Not yet possible to pinpoint the production mechanism.

IceCube Collaboration, ApJ 809 (2015) 1, 98.

Emerging Tasks

- Find the sources of IceCube's high energy neutrinos.
- Identify any connection with UHECR, electromagnetic emission, and gravitational waves.
- Understand production mechanisms of high energy cosmic particles.
- Use multi-messenger data to obtain a unique view on sources.


Source Identification

Neutrino Sources

What are the sources detectable in neutrinos?

Let us suppose that there is a class of sources with typical luminosity in neutrinos L_ν and density ρ in space. The total rate of neutrinos per unit area will be

$$F_\nu = \int L_\nu \rho \frac{d^3 r}{4\pi r^2} = \frac{1}{4\pi} \int L_\nu \rho d\Omega dr$$

The flux per unit of solid angle is

$$\frac{dF_\nu}{d\Omega} = \xi \frac{L_\nu \rho R_H}{4\pi}$$

where the Hubble radius is $R_H = c/H_0 \simeq 4000 \text{ Mpc}$

The factor $\xi \sim 2-3$ accounts for the cosmological evolution of the sources.

Neutrino Sources

If we equate this to the flux observed by IceCube, we have

$$\xi \frac{L_\nu \rho R_H}{4\pi} = \frac{E_\nu dN_\nu}{d\Omega d\ln(E_\nu)} = 2.8 \times 10^{-8} \; \frac{\mathrm{GeV}}{\mathrm{cm}^2 \; \mathrm{s} \; \mathrm{sr}} = 1.3 \times 10^{46} \; \frac{\mathrm{erg}}{\mathrm{Mpc}^2 \; \mathrm{yr} \; \mathrm{sr}}$$

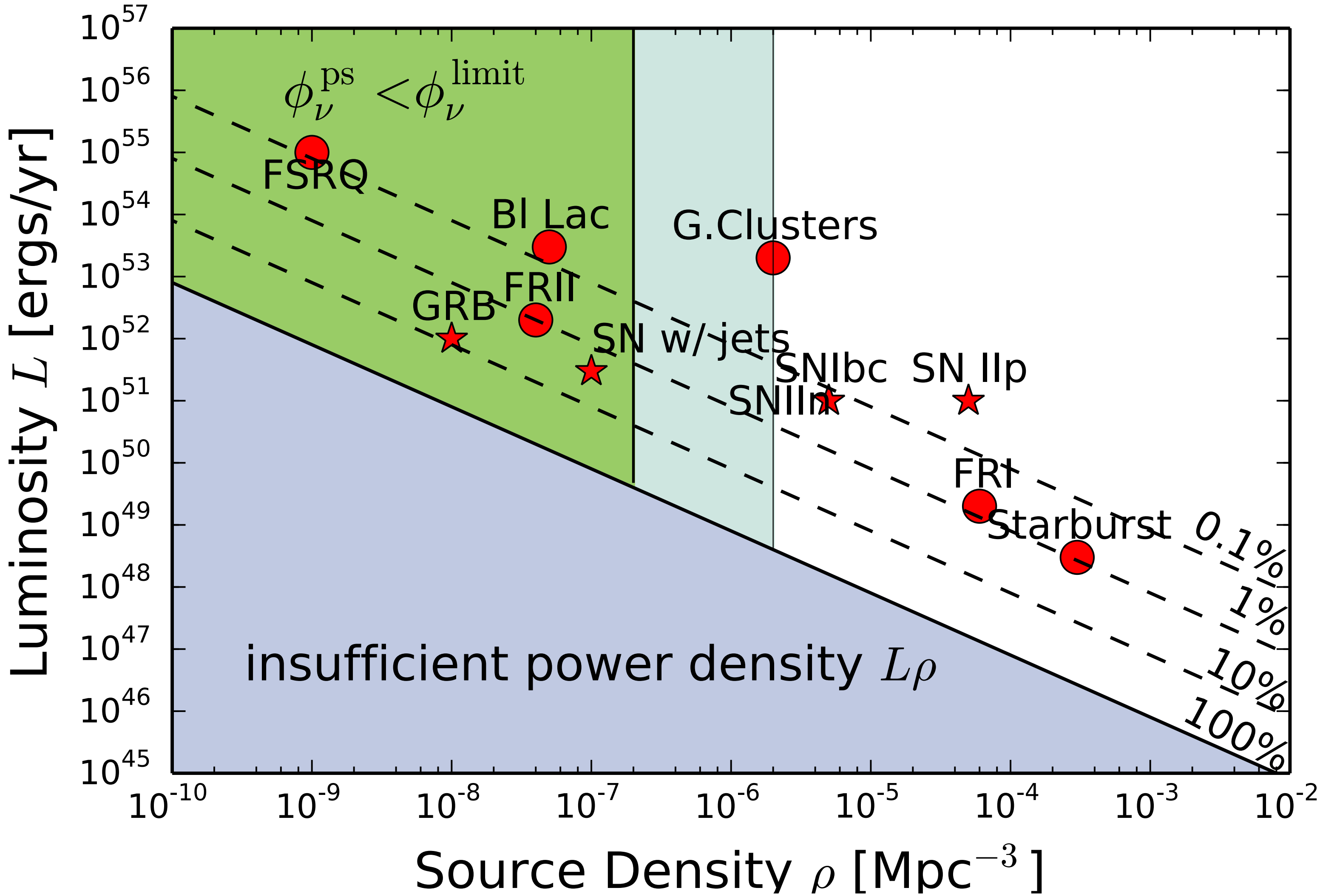
where the flux is normalized to the IceCube measurement for the sum of all three neutrino flavors and E^{-2} spectrum.

Inverting the equation above, one obtains the minimum power-density needed to produce the observed neutrino flux as

$$\boxed{\rho L_\nu = \frac{4 \times 10^{43}}{\xi} \; \frac{\mathrm{erg}}{\mathrm{Mpc}^3 \; \mathrm{yr}} \sim 10^{43} \; \frac{\mathrm{erg}}{\mathrm{Mpc}^3 \; \mathrm{yr}}}$$

Viable sources must be above the line given from the equation above in luminosity-density space, otherwise they are not sufficiently luminous to produce the observed flux.

Neutrino Sources

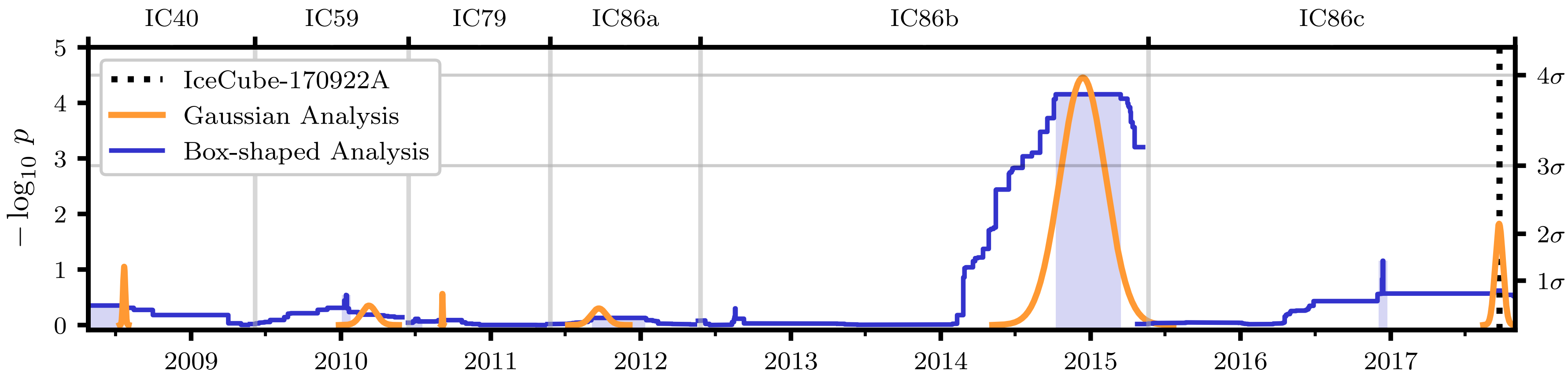


The solid line shows the minimum total neutrino luminosity needed to provide the observed flux per flavor. The broken lines show the minimum luminosity if the efficiency for neutrino production is 0.1-10% of the total.

Kowalski, arXiv: 1411.4385

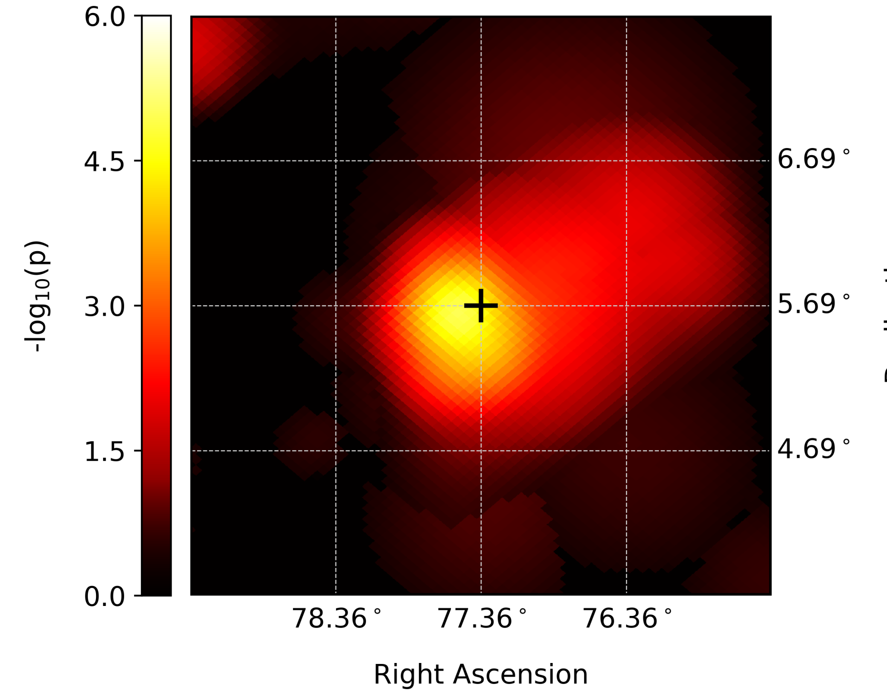
Neutrino Point Sources

TXS 0506+056 & IC 170922A



First high-energy neutrino traced back to its birthplace?

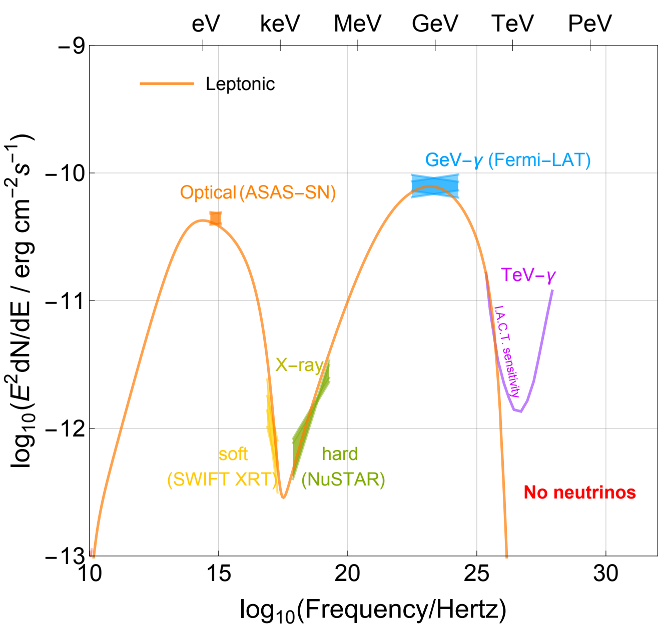
Among 50 brightest blazars in 3LAC.



IceCube Coll., Science 2018. Blaufuss (IceCube), GCN Circular 21916, Tanaka et al. (Fermi-LAT), AT 10791, Fox et al. (Swift and NuSTAR), AT 10845, Mirzoyan et al. (MAGIC), AT 10817, de Naurois et al. (HESS), AT 10787, Mukherjee et al. (VERITAS), AT 10833.

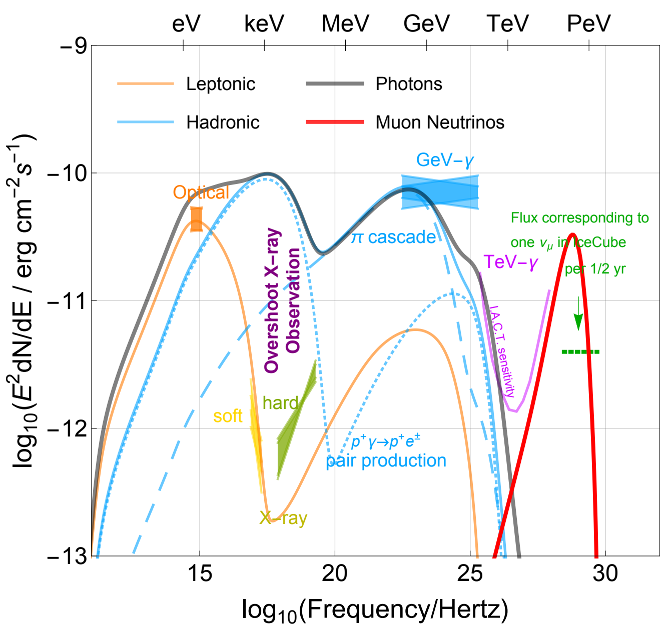
TXS 0506+056 & IC 170922A

Leptonic Model



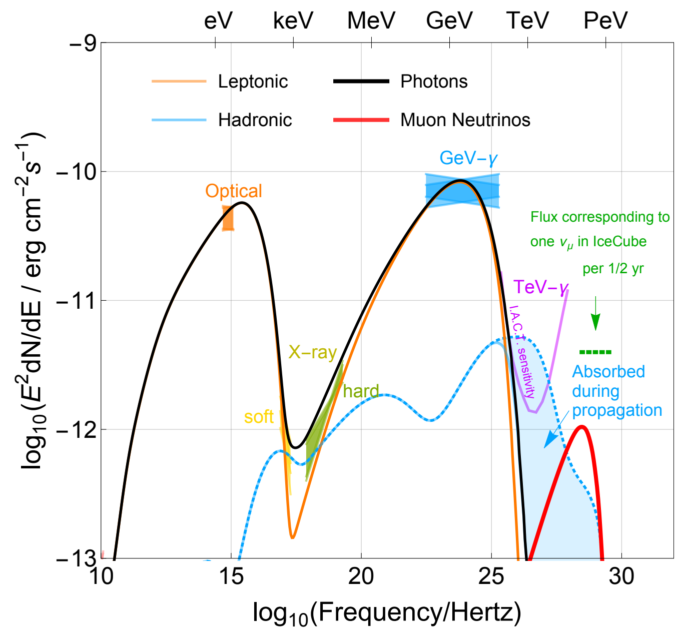
No neutrino production

Hadronic Model



Observed x-ray flux overshot

Hybrid Model

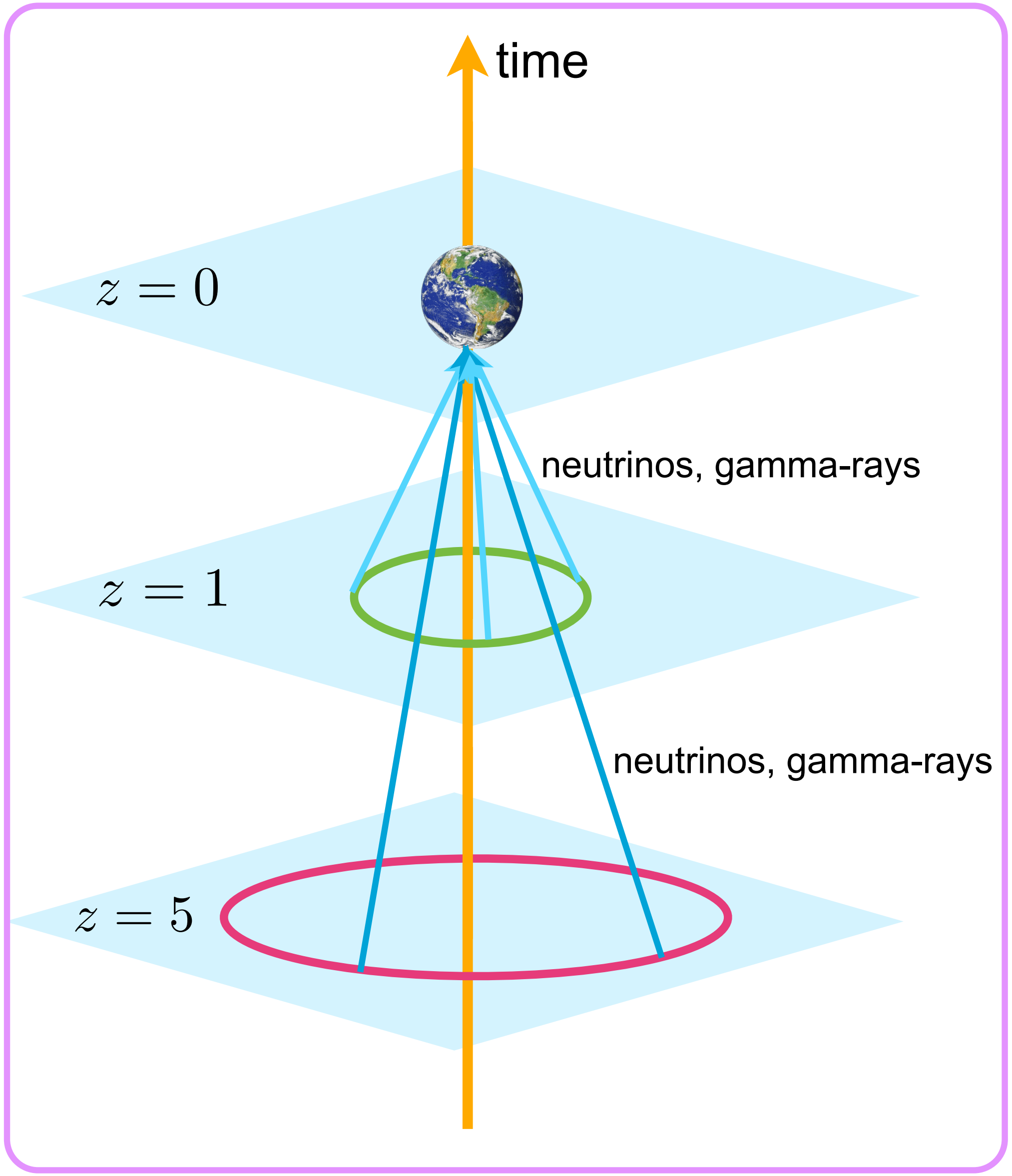


All spectra well reproduced

TXS 0506+056 is likely a "masquerading BL-Lac" (i.e., flat-spectrum radio quasar with hidden broad lines and a standard accretion disk).

Gao et al., Nat. Astron. (2019). Padovani et al., MNRAS (2019).

Diffuse Neutrino Backgrounds



- Spectral energy distribution
- Distribution of sources with redshift
- Distribution of sources with luminosity
- Comoving volume (cosmology)

Waxman-Bahcall Limit

- High-energy tail of UHECR spectrum has extra-galactic origin. Further interactions of cosmic rays should lead to neutrino production.

- The energy production rate in cosmic rays is

$$(E_p^2 Q_p(E_p))_{10^{19.5}\ \mathrm{eV}} \simeq 8 \times 10^{43}\ \mathrm{erg\ Mpc^{-3} yr^{-1}}$$

- We can connect the total neutrino emission rate density to the one of cosmic rays ($K_\pi = 1 - 2$).

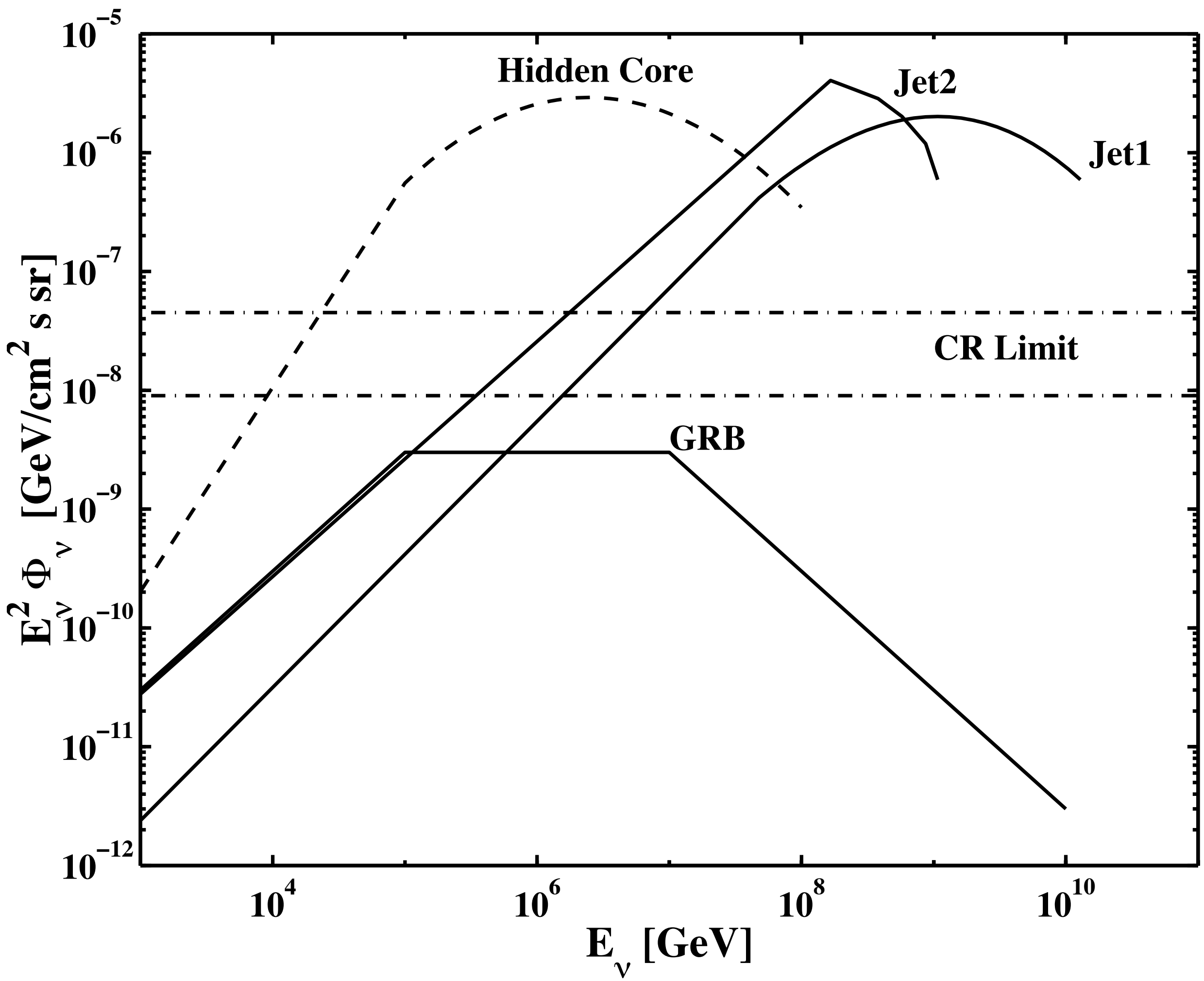
$$\frac{1}{3}\sum_{\nu_\alpha} E_\nu^2 Q_{\nu_\alpha}(E_\nu) \simeq \frac{f_\pi}{4}\frac{K_\pi}{1+K_\pi}(E_N^2 Q_N(E_N))_{E_N=4E_\nu/k_\pi}$$

- Neutrino flux estimated (ξ_z accounts for redshift evolution)

$$\underbrace{E_\nu^2 \phi_\nu(E_\nu)}_{\text{Detected neutrino flux}} \simeq f_\pi \underbrace{\frac{\xi_z K_\pi}{1+K_\pi}}_{\text{Factor of O(1)}} 1.5 \times 10^{-8}\ \mathrm{GeV\ cm^{-2}\ s^{-1}\ sr}$$

Waxman & Bahcall, PRD (1999), arXiv: hep-ph/9807282.

Waxman-Bahcall Limit



This is an upper bound to the intensity of high-energy neutrinos produced by photo-meson interactions in sources of size not much larger than the proton photo-meson mean-free-path. The Waxman-Bahcall bound can be evaded if neutrinos are produced in sources where the proton photo-meson"optical depth" is much higher than unity, in which case only the neutrinos escape the source ("hidden core" models).

Take Home Messages

- Multi-messenger observations help to understand the physics of sources.
- High energy neutrinos of astrophysical origin are now observed but origin still unknown.
- Observable distributions of neutrinos, gamma-rays, and cosmic rays are connected.

Exercise

- Pick up one of the TeV point-like sources in http://tevcat.uchicago.edu/ that you think could be a good neutrino emitter.
- Describe the source and its main features.
- Describe the most relevant electromagnetic observations; characterize the energy distribution and the relevant energy range.
- Explain why the source can be a good candidate neutrino emitter and why you chose it.
- Select the neutrino production mechanism that can produce the majority of neutrinos in the source (proton-proton interaction or proton- gamma interactions).
- Estimate the neutrino spectral distribution from the measured gamma-ray one. Do so by using average numbers as during the lecture and assuming that gamma absorption is negligible.

References

- Gaisser, Engel, Resconi, Cosmic Rays and Particle Physics, 2nd edition, Cambridge University Press.
- Ahlers & Halzen, Rept. Prog. Phys. 78 (2015) no. 12, 126901.
- Anchordoqui et al., JHEAp (2014).