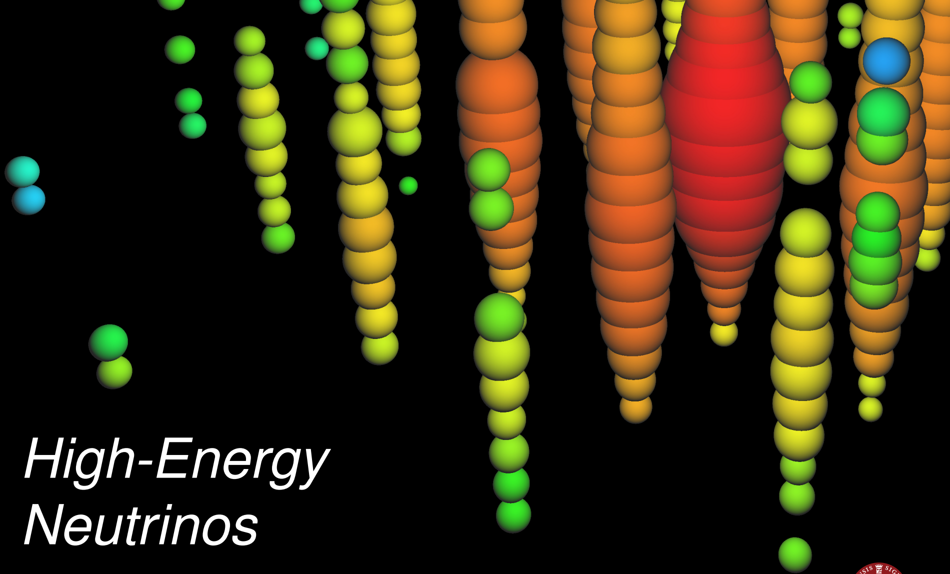


High-Energy Neutrinos

Markus Ahlers, Niels Bohr Institute

ISAPP, Texel, June 29, 2017

UNIVERSITY OF COPENHAGEN

High-Energy Cosmic Neutrinos

- produced in **collisions of cosmic rays with gas and radiation**, *e.g.*

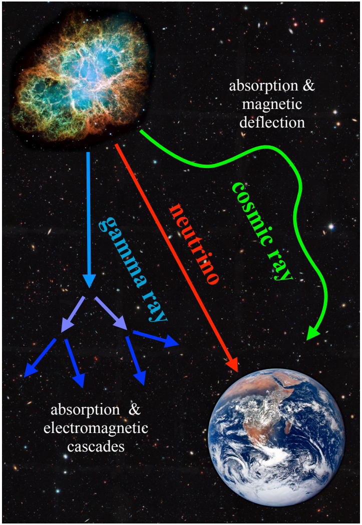
$$p + p\,\text{(gas)} \rightarrow X\,\text{(rest)} + \pi^-\,\text{(pion)}$$

$$p + \gamma\,\text{(radiation)} \rightarrow X\,\text{(rest)} + \pi^-\,\text{(pion)}$$

$$\pi^-\,\text{(pion)} \rightarrow \mu^-\,\text{(muon)} + \bar{\nu}_\mu$$

$$\mu^-\,\text{(muon)} \rightarrow e^-\,\text{(electron)} + \nu_\mu + \bar{\nu}_e$$

- **“smoking-gun”** of cosmic ray sources
- **no deflection** in magnetic fields (➜ point source detection)
- (practically) **no absorption** (➜ distant sources)
- . . . anyway, what is a neutrino?



Brief History

- β-decay (as understood at the beginning of the 20th century), *e.g.* “radium E”

$$^{210}\mathrm{Bi} \underbrace{\rightarrow}_{\simeq 5d} {}^{210}\mathrm{Po} + e^-$$

✘ two-body decay at rest:

$$E_e = \frac{m_{Bi}^2 - m_{Po}^2 + m_e^2}{2m_{Bi}}$$

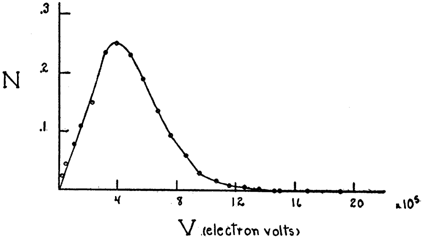


FIG. 5. Energy distribution curve of the beta-rays.

[Scott’35]

- 1915: **Chadwick** showed that “β-ray” spectrum is continuous
- 1930: **Pauli** introduced the “neutrons” to remedy this issue

1930: Pauli's Famous Letter

Dear Radioactive Ladies and Gentlemen,

As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, how because of the "wrong" statistics of the N and Li6 nuclei and the continuous beta spectrum, I have hit upon a **desperate remedy to save the "exchange theorem" of statistics and the law of conservation of energy**. Namely, the possibility that **there could exist in the nuclei electrically neutral particles, that I wish to call neutrons, which have spin 1/2 and obey the exclusion principle** and which further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses.

(. . .)

Unfortunately, I cannot appear in Tübingen personally since I am indispensable here in Zurich because of a ball on the night of 6/7 December. With my best regards to you, and also to Mr Back.

Your humble servant,

Wolfgang Pauli

Brief History

- 1932: **Chadwick** discovers the neutron (the “actual” neutron)
- 1933: **Fermi** establishes his theory of β-decay
- 1956: **Cowan & Reines** detect **electron neutrinos** from a nuclear reactor (Los Alamos) by inverse β-decay

$$\bar{\nu}_e + p \rightarrow n + e^+$$

- 1957: **Goldhaber, Grodzins & Sunyar** show that neutrinos are left-handed
- 1962: **Lederman, Schwartz & Steinberger** detect the **muon neutrino**

➜ neutrinos come in flavours

- 1968: **Davis** (Homestake) detects electron neutrinos from the Sun
  - measured flux is lower than expected

➜ solar neutrino problem

$$\nu_e + {}^{37}\mathrm{Cl} \rightarrow {}^{37}\mathrm{Ar} + e^-$$

Brief History

- 1976: **Perl** et al. discovery the **tau lepton**
  - eventually leads to the discovery of the tau neutrino
- 1980s: **IMB & KamiokaNDE** (nucleon decay experiments) start observing atmospheric neutrinos

$$\nu_e + N \to e^- + X \qquad \nu_\mu + N \to \mu^- + X$$

- 1985: **IMB & Kamiokande** observe atmospheric neutrino anomaly
- 1986: **Kamiokande** confirms solar neutrino deficit

$$\nu_e + e^- \to \nu_e + e^-$$

- 1987: **IMB & Kamiokande** observe Supernova 1987A
  - our only extra-terrestrial neutrino source, so far!
- 1988: Noble Prize to Lederman, Schwartz and Steinberger (muon neutrino)

Brief History

- 1989: **LEP (CERN) & SLC (SLAC)** show that there are only **three light active neutrinos**
- 1995: Nobel Prize to Reines and Perl (electron and tau neutrino)
- 1998/2000: **Super-Kamiokande** reports atmospheric muon neutrino oscillations mostly to tau neutrino
- 2001/2: **SNO** shows that solar deficit is caused by oscillations

$$\nu_e + d \to e^- + p + p \qquad \nu_x + d \to \nu_x + p + n$$

- 2002: Noble Prize to Koshiba and Davis (solar/supernova neutrinos)
- 2012: **Daya Bay** and **RENO** measure non-zero θ_{13}
  - important for CP violating phases
- 2013: **IceCube** observes PeV neutrinos
- 2015: Noble Prize to Kajita and McDonald (neutrino oscillation and mass)

Neutrino Mixing

- neutrinos have three active flavours that are superpositions of mass eigenstates

$$|\nu_\alpha\rangle = \sum_j U^*_{\alpha j}|\nu_j\rangle$$

- Pontecorvo-Maki-Nakagawa-Sakata (PMNS) mixing matrix:

$$U = R_{23}(\theta_{23}) \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} R_{12}(\theta_{12}) \begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- Dirac phase δ, two Majorana phase $\alpha_{1/2}$, and three rotations θ_{ij}
- evolution of states governed by Liouville equation:

$$\dot{\rho} = -\mathrm{i}[H,\rho] \qquad H = \underbrace{\sum_i \frac{m_i^2}{2E_\nu}|\nu_i\rangle\langle\nu_i|}_{\text{free Hamiltonian}} + V_{\text{matter}}$$

Vacuum Oscillations

- vacuum case ($V_{\rm matter} \to 0$):

$$\dot\rho_{ij} = \frac{{\rm i}\Delta m^2_{ij}}{2E_\nu}\rho_{ij} \qquad \text{with mass splitting} \qquad \Delta m^2_{ij} \equiv m_i^2 - m_j^2$$

- neutrinos originate via weak interactions as flavour eigenstates $|\nu_\alpha\rangle$:

$$\rho(L) = \sum_{i,j} U^*_{\alpha i} U_{\alpha j} \exp\left(\frac{{\rm i}\Delta m^2_{ij} L}{2E_\nu}\right)|\nu_i\rangle\langle\nu_j|$$

- survival probability $P_{\nu_\alpha\to\nu_\beta} = {\rm Tr}[\rho_\alpha(L)\Pi_\beta]$:

$$P_{\nu_\alpha\to\nu_\beta} = \delta_{\alpha\beta} - 4\sum_{i>j}\Re\left(U^*_{\alpha i}\,U_{\beta i}\,U_{\alpha j}\,U^*_{\beta j}\right)\,\sin^2\Delta_{ij} + 2\sum_{i>j}\underbrace{\Im\left(U^*_{\alpha i}\,U_{\beta i}\,U_{\alpha j}\,U^*_{\beta j}\right)}_{\text{possible CP violation}}\,\sin 2\Delta_{ij}$$

- oscillation phase:

$$\Delta_{ij} \equiv \frac{\Delta m^2_{ij} L}{4E_\nu} \simeq 1.27\left(\frac{\Delta m^2_{ij}}{\rm eV^2}\right)\left(\frac{L}{\rm km}\right)\left(\frac{E_\nu}{\rm GeV}\right)^{-1}$$

Vacuum Oscillations

- Most neutrino flavour oscillation phenomena can be understood as a **two-level system**:

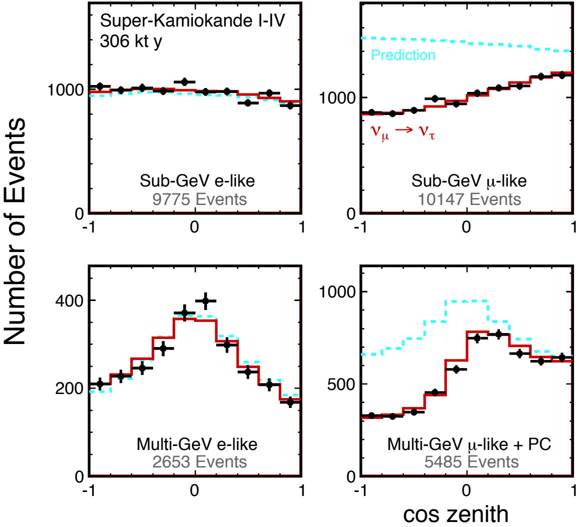
$$\begin{pmatrix} |\nu_\alpha\rangle \\ |\nu_x\rangle \end{pmatrix} \simeq \begin{pmatrix} \cos\theta_{\rm eff} & \sin\theta_{\rm eff} \\ -\sin\theta_{\rm eff} & \cos\theta_{\rm eff} \end{pmatrix} \begin{pmatrix} |\nu'_1\rangle \\ |\nu'_2\rangle \end{pmatrix}$$

- survival probablity:

$$P_{\nu_\alpha\to\nu_\alpha} \simeq 1 - \sin^2(2\theta_{\rm eff})\sin^2\frac{\Delta m^2_{\rm eff}L}{4\bar{E}}$$

Source	Type of ν	$\overline{E}$[MeV]	L[km]	$\min(\Delta m^2)$[eV^2]
Reactor	$\overline{\nu}_e$	~ 1	1	$\sim 10^{-3}$
Reactor	$\overline{\nu}_e$	~ 1	100	$\sim 10^{-5}$
Accelerator	$\nu_\mu,\overline{\nu}_\mu$	$\sim 10^3$	1	~ 1
Accelerator	$\nu_\mu,\overline{\nu}_\mu$	$\sim 10^3$	1000	$\sim 10^{-3}$
Atmospheric ν's	$\nu_{\mu,e},\overline{\nu}_{\mu,e}$	$\sim 10^3$	10^4	$\sim 10^{-4}$
Sun	ν_e	~ 1	1.5×10^8	$\sim 10^{-11}$

Atmospheric Neutrino Problem



[Super-Kamiokande'98; **>5000 citations!**]

Matter Effects

- non-universal matter effects for electron neutrinos:

$$V_{\rm matter} = \sqrt{2} G_F N_e |\nu_e\rangle\langle\nu_e|$$

- full Hamiltonian (in mass eigenstates of the free Hamiltonian)

$$H = \frac{1}{4E}\begin{pmatrix} \Delta m_0^2 & 0 \\ 0 & -\Delta m_0^2 \end{pmatrix} + \frac{G_F N_e}{\sqrt{2}}\begin{pmatrix} \cos 2\theta_0 & \sin 2\theta_0 \\ \sin 2\theta_0 & -\cos 2\theta_0 \end{pmatrix} + \text{phases}$$

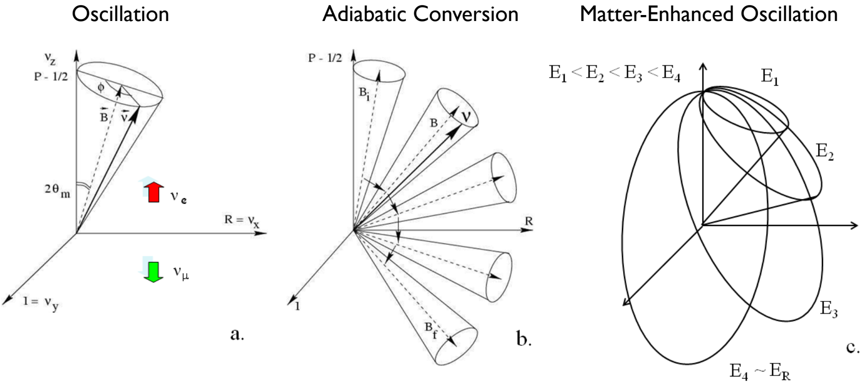
- *effective* mass difference and mixing in matter:

$$\Delta m^2_{\rm matter} = \Delta m_0^2 \left[\left(1 - \frac{N_e}{N_{\rm res}}\right)^2 \cos^2 2\theta_0 + \sin^2 2\theta_0\right]^{\frac{1}{2}} \qquad N_{\rm res} = \frac{\Delta m_0^2 \cos 2\theta_0}{\sqrt{2} 2 E G_F}$$

$$\tan 2\theta_{\rm matter} = \left(1 - \frac{N_e}{N_{\rm res}}\right)^{-1} \tan 2\theta_0$$

➜ **Mikheyev-Smirnov-Wolfenstein (MSW) effect**

Matter Effects



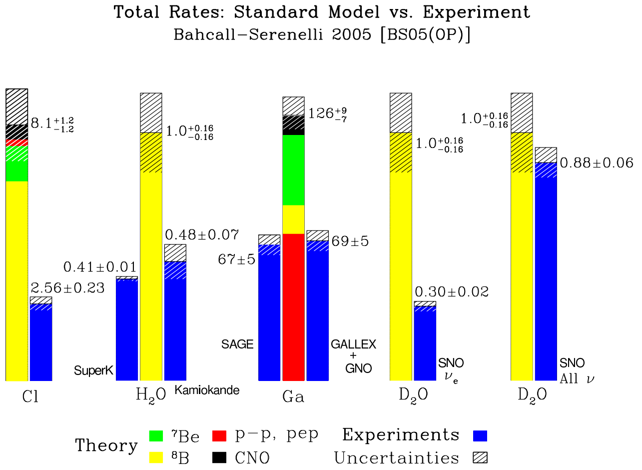
Oscillation

Adiabatic Conversion

Matter-Enhanced Oscillation

[Smirnov'16]

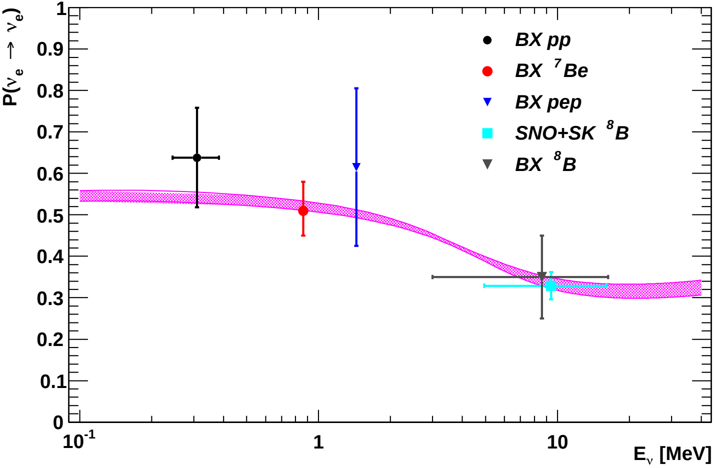
Solar Neutrino Problem



[Bahcall'04]

solution: low energy (pp) oscillation average / high energy adiabatic conversion of ν_e (MSW)

Solar Neutrino Problem



[PDG'17]

solution: low energy (pp) oscillation average / high energy adiabatic conversion of ν_e (MSW)

Present Status

- solar neutrino oscillations with **small mass splitting**: [www.nu-fit.org]

$$\Delta m^2_\odot \simeq \Delta m^2_{21} = 7.50^{+0.19}_{-0.17} \times 10^{-5}\mathrm{eV}^2$$

- **unknown mass ordering:** normal $m_1 < m_2 < m_3$ (inverted $m_3 < m_1 < m_2$)
- atmospheric oscillations with **large mass splitting**:

$$\Delta m^2_{\rm atm} \simeq |\Delta m^2_{3\ell}| = 2.524^{+0.039}_{-0.040} \times 10^{-3}\mathrm{eV}^2 \left(2.514^{+0.038}_{-0.041} \times 10^{-3}\mathrm{eV}^2\right)$$

- best-fit **mixing** parameters:

$$\theta_{12}/^\circ \simeq 33.56^{+0.77}_{-0.75} \qquad \theta_{23}/^\circ \simeq 41.6^{+1.5}_{-1.2} \left(50.0^{+1.1}_{-1.4}\right) \qquad \theta_{13}/^\circ \simeq 8.46^{+0.15}_{-0.15} \left(8.49^{+0.15}_{-0.15}\right)$$

- CP violating **Dirac phase**: $\delta_{\rm CP}/^\circ \simeq 261^{+51}_{-59} \left(277^{+40}_{-46}\right)$
- limit on the **sum of neutrino masses** from cosmology: $\sum_i m_i < 0.23\mathrm{eV}$ [Planck'15]

? Dirac or Majorana, absolute mass scale, sterile neutrinos, origin of mass,. . .

Non-Anthropogenic Neutrino Fluxes

1. cosmic neutrino background

$$\langle E_\nu \rangle \simeq 1.95K \simeq 168\mu\mathrm{eV}$$

2. solar neutrinos

$$0.1\mathrm{MeV}(\text{pp}) \lesssim \langle E_\nu \rangle \lesssim 10\mathrm{MeV}(^8\text{Be})$$

3. supernova neutrinos

$$\langle E_\nu \rangle \simeq \mathcal{O}(10)\mathrm{MeV}$$

4. atmospheric neutrinos

$$\langle E_\nu \rangle \simeq 100\ \mathrm{MeV}\text{, with power-law tail: } E^{-3.7}$$

5. (diffuse) Galactic neutrinos

$$\langle E_\nu \rangle \simeq 100\ \mathrm{MeV}\text{, with power-law tail: } E^{-2.7}$$

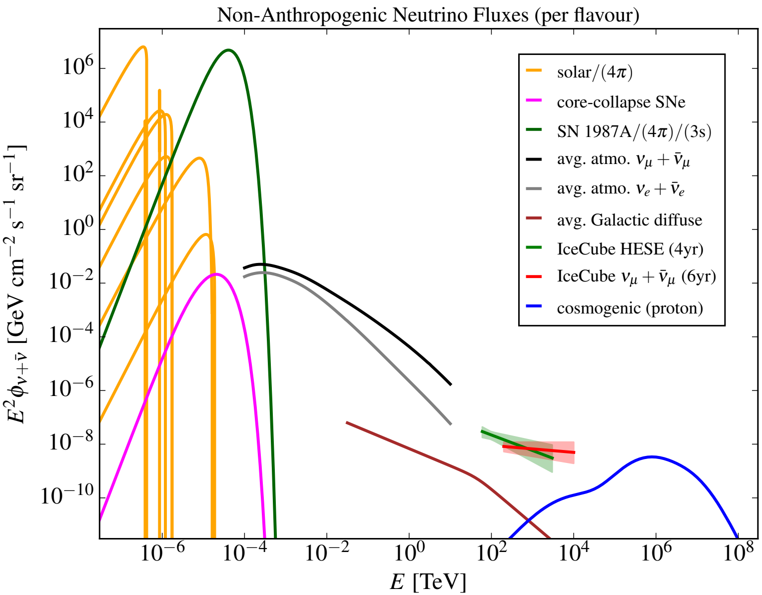
6. extragalactic neutrinos

$$\text{observed range: } 10\mathrm{TeV} \lesssim E_\nu \lesssim 10\mathrm{PeV}$$

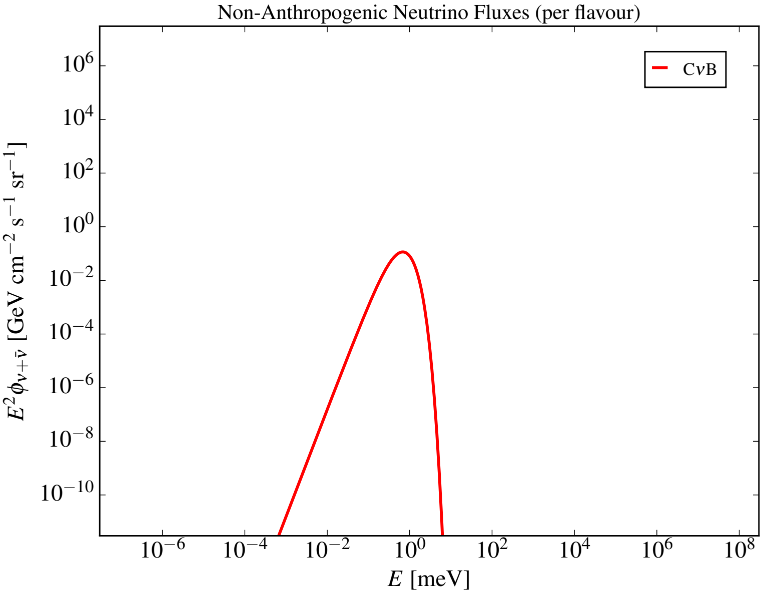
7. cosmogenic neutrinos

$$\langle E_\nu \rangle \simeq 1\mathrm{EeV}$$

Non-Anthropogenic Neutrino Fluxes



Non-Anthropogenic Neutrino Fluxes



Cosmic Neutrino Background

- Fermions in the early Universe follow a Fermi-Dirac distribution:

$$f(E,T) = (1 + \exp[(E-\mu)/k_B T])^{-1}$$

- number density in the early Universe (neglecting chemical potentials / g : degrees of freedom)

$$n = \frac{g}{(2\pi)^3}\int \mathrm{d}^3 p f(E,T) = g\frac{3\zeta(3)}{4\pi}(k_B T)^3$$

- neutrinos are in thermal equilibrium in the early Universe:

$$\nu_e + \bar{\nu}_e \leftrightarrow e^+ + e^- \qquad e^\pm + \nu_e \leftrightarrow e^\pm + \nu_e \qquad e^\pm + \bar{\nu}_e \leftrightarrow e^\pm + \bar{\nu}_e$$

- weak interaction cross sections

$$\sigma_{e\nu} \simeq \mathcal{O}(1)\frac{G_F^2}{\pi}s$$

- collision time

$$t \simeq (n_e \sigma_{e\nu})^{-1} \simeq \mathcal{O}(1)\frac{G_F^2}{\pi}T^{-5}$$

➜ **freeze-out** temperature determined by $t_{\rm Hubble} \simeq t_c$ ➜ $k_B T_{\nu_e} \simeq 1.5$ MeV

Cosmic Neutrino Background

- temperature-dependence of entropy density is:

$$s_f = \frac{7\pi^2}{180} g_f T^3 \quad s_b = \frac{2\pi^2}{45} g_b T^3 \qquad \frac{s_f}{s_b} = \frac{7}{8}\frac{g_f}{g_b}$$

- degrees of freedom for bosons (b) and fermions (f)

$$g_\gamma = 2 \qquad g_{e^\pm} = 2 \times 2 = 4 \qquad g_\nu = 2 \times (1+1+1) = 6$$

- after neutrino freeze-out at $k_B T_{\nu_e} \simeq 1.5$ MeV, still $T_\gamma = T_\nu$
- shortly afterwards, at $k_B T_{\nu_e} \simeq m_e$: e^+e^- pairs annihilate and **heat up** the photons
- **entropy-ratio remains constant**:

$$\frac{s_\gamma}{s_\gamma + s_{e^\pm}} = 1 = \left(\frac{T_\gamma^{\rm after}}{T_\gamma^{\rm before}}\right)^3 \frac{g_\gamma}{g_\gamma + \frac{7}{8} g_{e^\pm}} = \left(\frac{T_\gamma^{\rm after}}{T_\gamma^{\rm before}}\right)^3 \frac{4}{11}$$

- fixed temperature ratio remains until today:

$$T_{\rm C\nu B} = \left(\frac{4}{11}\right)^{\frac{1}{3}} T_{\rm CMB} \simeq 1.95{\rm K} \qquad (168\mu{\rm eV})$$

Cosmic Neutrino Background

- neutrino energy density is **large** in early Universe

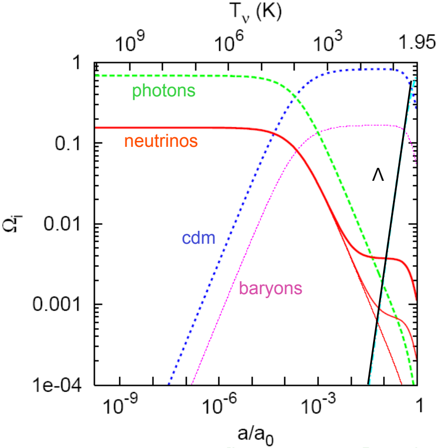
➜ allows to constrain the number of active light neutrino species

- massive neutrino change the expansion history near the epoch of matter-radiation equality

➜ alters temperature anisotropies of the CMB

- "free-streaming" of neutrinos influences the growth of large-scale structure

➜ reduces matter power spectrum at low wavelength



[Lesgourgues & Pastor'12]

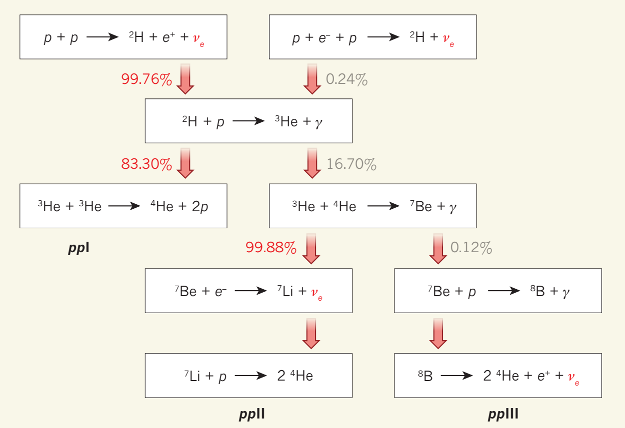
$m_2 = 0.01\text{eV}$ & $m_3 = 0.05\text{eV}$

Solar Neutrinos

- The Sun's luminosity is sustained by **thermo-nuclear fusion**:

$$4p + 2e^- \rightarrow {}^4\mathrm{He} + 2\nu_e + 26.73\mathrm{MeV} - E_\nu$$

- average neutrino energy is $\langle E_\nu \rangle \simeq 0.6$ MeV



$p + p \longrightarrow {}^2\mathrm{H} + e^+ + \nu_e$

$p + e^- + p \longrightarrow {}^2\mathrm{H} + \nu_e$

99.76%

0.24%

${}^2\mathrm{H} + p \longrightarrow {}^3\mathrm{He} + \gamma$

83.30%

16.70%

${}^3\mathrm{He} + {}^3\mathrm{He} \longrightarrow {}^4\mathrm{He} + 2p$

${}^3\mathrm{He} + {}^4\mathrm{He} \longrightarrow {}^7\mathrm{Be} + \gamma$

***pp*I**

99.88%

0.12%

${}^7\mathrm{Be} + e^- \longrightarrow {}^7\mathrm{Li} + \nu_e$

${}^7\mathrm{Be} + p \longrightarrow {}^8\mathrm{B} + \gamma$

${}^7\mathrm{Li} + p \longrightarrow 2\,{}^4\mathrm{He}$

${}^8\mathrm{B} \longrightarrow 2\,{}^4\mathrm{He} + e^+ + \nu_e$

***pp*II**

***pp*III**

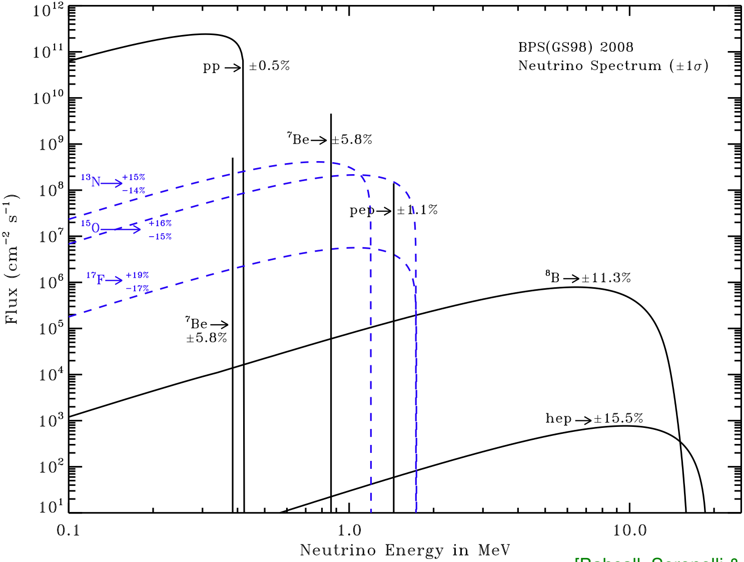
[Haxton'14]

Solar Neutrinos

Reaction	Abbr.	Flux ($\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$)
$pp \to d\, e^+\, \nu$	pp	$5.97(1 \pm 0.006) \times 10^{10}$
$pe^- p \to d\, \nu$	pep	$1.41(1 \pm 0.011) \times 10^{8}$
$^3\mathrm{He}\, p \to {}^4\mathrm{He}\, e^+ \nu$	hep	$7.90(1 \pm 0.15) \times 10^{3}$
$^7\mathrm{Be}\, e^- \to {}^7\mathrm{Li}\, \nu + (\gamma)$	$^7\mathrm{Be}$	$5.07(1 \pm 0.06) \times 10^{9}$
$^8\mathrm{B} \to {}^8\mathrm{Be}^*\ e^+ \nu$	$^8\mathrm{B}$	$5.94(1 \pm 0.11) \times 10^{6}$
$^{13}\mathrm{N} \to {}^{13}\mathrm{C}\ e^+ \nu$	$^{13}\mathrm{N}$	$2.88(1 \pm 0.15) \times 10^{8}$
$^{15}\mathrm{O} \to {}^{15}\mathrm{N}\ e^+ \nu$	$^{15}\mathrm{O}$	$2.15(1^{+0.17}_{-0.16}) \times 10^{8}$
$^{17}\mathrm{F} \to {}^{17}\mathrm{O}\ e^+ \nu$	$^{17}\mathrm{F}$	$5.82(1^{+0.19}_{-0.17}) \times 10^{6}$

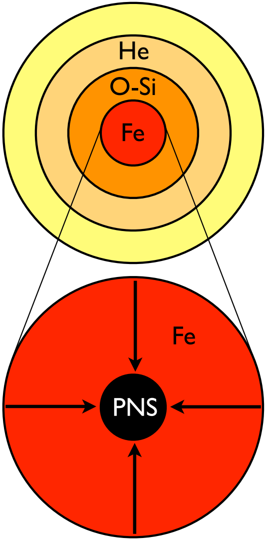
[Particle Data Group'17]

Solar Neutrinos



[Bahcall, Serenelli & Basu'08]

Core-Collapse Supernovae



- massive star ($\gtrsim 8M_\odot$) at the end of its lifetime
- hydrostatic equilibrium:
  shells of nuclear burning material
- Fe core grows until **electron degeneracy pressure** can not balance **gravitational force**.

➜ **Chandrasekhar limit**: ($M \simeq 1.5M_\odot$)

- collapse to a proto-neutron star (PNS) with matter density $\rho_{\rm PNS} \simeq 3 \times 10^{14}{\rm g/cm}^3$
- Infalling matter bounces off PNS and drives a shock wave.

➜ **About 99% of gravitational binding energy of iron core released in neutrinos**!

Core-Collapse Supernovae

- hydrostatic equilibrium (virialised system):

$$-\frac{1}{2}\langle\Phi_{\rm gravity}\rangle = \langle E_{\rm kin}\rangle = \frac{3}{2}k_BT$$

- size of the proto-neutron star:

$$M \simeq 1.5M_\odot \quad \& \quad \rho \simeq 3\times10^{14}{\rm g/cm}^3 \quad \to \quad R_{\rm PNS} \simeq 13{\rm km}$$

- gravitational binding energy (homogenous sphere):

$$\Phi_{\rm tot} = -\frac{3}{5}G_N\frac{M^2}{R} \qquad \to \qquad \langle\Phi_{\rm gravity}\rangle = -\frac{3}{5}G_N\frac{Mm_p}{R}$$

- virial temperature:

$$k_BT \simeq 30{\rm MeV}$$

Core-Collapse Supernovae

- time scale of emission determined by neutrino diffusion in dense nuclear $(N = n, p)$ medium

$$\nu_e + n \leftrightarrow p + e^-$$

$$\bar{\nu}_e + p \leftrightarrow n + e^+$$

$$\nu_x + N \to \nu_x + N$$

$$\bar{\nu}_x + N \to \bar{\nu}_x + N$$

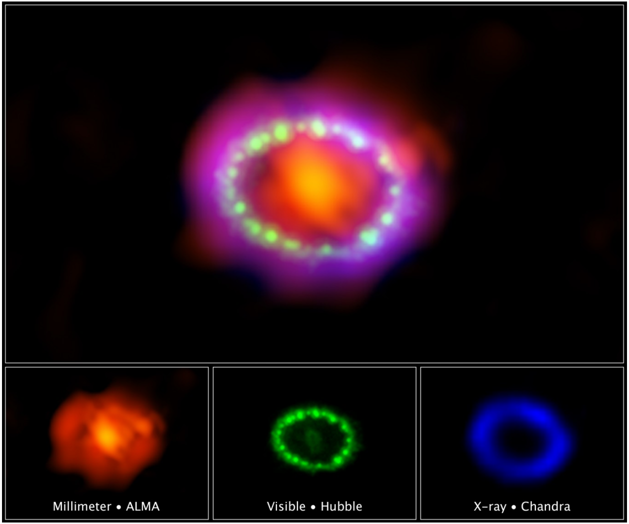
- scattering length in PNS with $\sigma_{\nu N} \simeq (G_F^2/\pi)(k_b T)^2$:

$$\lambda_{\rm int} = \frac{m_p}{\rho\sigma_{\nu N}} \simeq 3.3{\rm cm}\left(\frac{k_B T}{30{\rm MeV}}\right)^{-2}$$

- diffusion time-scale out of PNS:

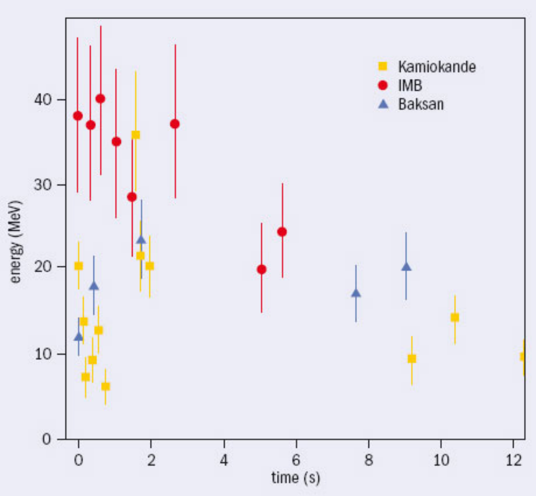
$$t_{\rm diff} \simeq \frac{R_{\rm PNS}^2}{c\lambda_{\rm int}} \simeq 17{\rm s}\left(\frac{k_B T}{30{\rm MeV}}\right)^{2}$$

Supernova 1987A



core-collapse SN observed in the Large Magellanic Cloud ($\simeq 50$kpc)

Supernova 1987A



neutrino burst ($\simeq 10$s) observed with Kamiokande, Baksan, and Irvine-Michigan-Brookhaven experiment

Neutrino Flux Calculation

- After emission, neutrinos only undergo adiabatic (redshift) losses.

$$\frac{\mathrm{d}E}{\mathrm{d}t} = -H(z)E \quad \rightarrow \quad \frac{\mathrm{d}E}{\mathrm{d}z} = \frac{E}{1+z} \quad \rightarrow \quad E(z) = (1+z)E_0$$

- By definition, the observed neutrino (energy) flux relates to the luminosity $\mathcal{L}$ as

$$\int \mathrm{d}E_\nu E_\nu F_\nu(E_\nu) = \frac{\mathcal{L}}{4\pi d_L^2(z)}$$

- luminosity distance $d_L(z)$ can be calculated in a given cosmology:

$$d_L = (1+z)\int_0^z \frac{\mathrm{d}z'}{H(z')}$$

- "ΛCDM" cosmology : $\Omega_m \simeq 0.3$, $\Omega_\Lambda \simeq 0.7$ & $H_0 \simeq 70\mathrm{km/s/Mpc}$:

$$H(z) = H_0\sqrt{\Omega_\Lambda + (1+z)^3\Omega_\mathrm{m}}$$

Neutrino Flux Calculation

- For a source at redshift z with neutrino emission spectrum Q_ν we have:

$$F_\nu(z,E) = \frac{(1+z)^2}{4\pi d_L^2(z)} Q_\nu((1+z)E)$$

- diffuse flux from a population of sources

$$\phi_\nu(E) = \frac{c}{4\pi}\int\limits_0^\infty \mathrm{d}z \frac{\mathrm{d}\mathcal{V}_c}{\mathrm{d}z}\rho(z)F_\nu(z,E)$$

- co-moving number density $\rho(z)$ encodes the source number evolution
- co-moving volume:

$$\mathcal{V}_c(z) = \frac{4\pi}{3}d_c^3(z) = \frac{4\pi}{3}\left(\frac{d_L(z)}{1+z}\right)^3 \quad \rightarrow \quad \frac{\mathrm{d}\mathcal{V}_c}{\mathrm{d}z} = 4\pi\left(\frac{d_L(z)}{1+z}\right)^2\frac{1}{H(z)}$$

- together:

$$\phi_\nu(E) = \frac{c}{4\pi}\int\limits_0^\infty \mathrm{d}z \frac{\rho(z)}{H(z)} Q_\nu((1+z)E)$$

Example: Diffuse Supernova Neutrino Flux

- time-integrated neutrino spectrum (all flavours): [Horiuchi, Beacom & Dwek'09]

$$Q_\nu(E) \simeq E_{\rm tot}\frac{120}{7\pi^4}\frac{E_\nu^2}{(k_BT)^4}\frac{1}{1+\exp\left(\frac{E_\nu}{k_BT}\right)}$$

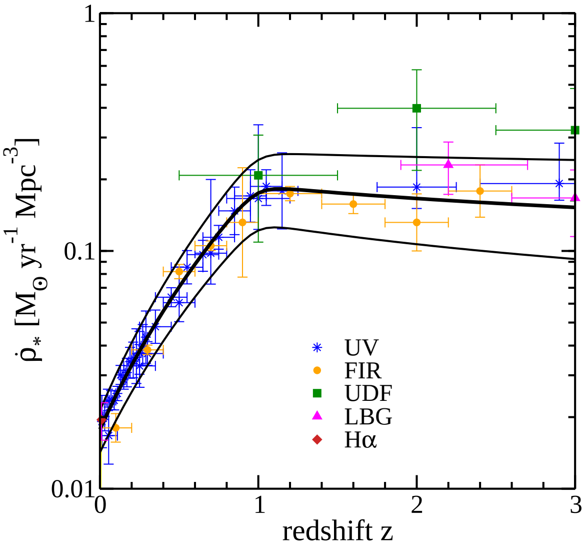
- from earlier discussion we take $k_BT \simeq 10$ MeV for $M \simeq 1.5M_\odot$ (Chandrasekhar mass limit)
- almost all of the gravitational binding energy goes into neutrinos ($R_{\rm PNS} \simeq 13$ km)

$$E_{\rm tot} \simeq -\Phi_{\rm tot} \simeq \frac{3}{5}G_N\frac{M^2}{R_{\rm PNS}} \simeq 3\times 10^{53}\ {\rm erg} \simeq 2\times 10^{53}\ {\rm TeV}$$

- core-collapse supernova rate proportional to star-formation rate $\dot\rho_*$ and initial mass function $\psi(M)$

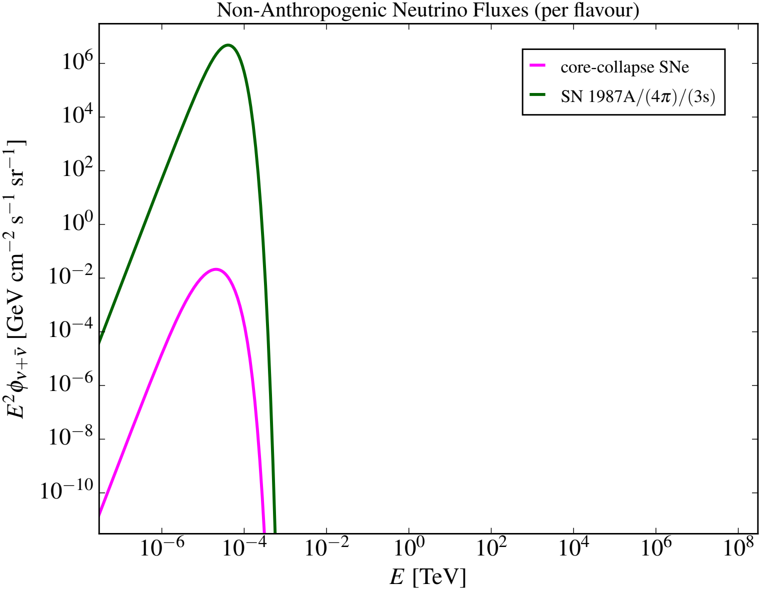
$$\dot\rho(z)/\dot\rho_*(z) \simeq \left(\int\limits_8^{50}{\rm d}M\psi(M)\right)\Bigg/\left(\int\limits_{0.1}^{100}{\rm d}MM\psi(M)\right) \simeq \frac{0.01}{M_\odot}$$

Example: Diffuse Supernova Neutrino Flux

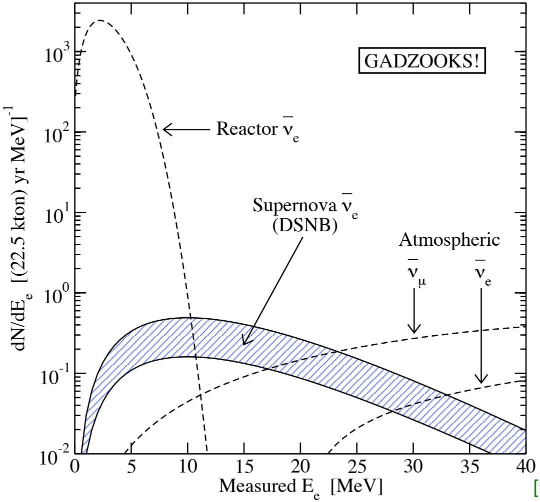


[Horiuchi, Beacom & Dwek'09]

Example: Diffuse Supernova Neutrino Flux



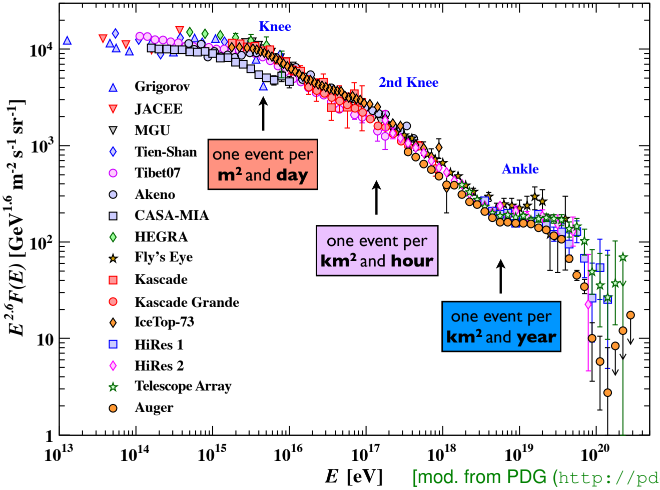
Example: Diffuse Supernova Neutrino Flux



[Beacom & Vagins'04]

Gadolinium **A**ntineutrino **D**etector **Z**ealously **O**utperforming **O**ld **K**amiokande, **S**uper!

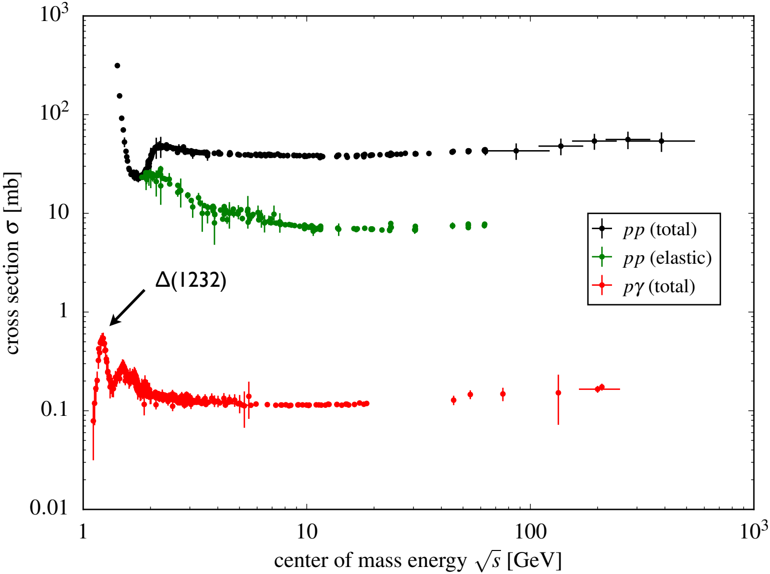
Cosmic Ray Spectrum



[mod. from PDG (`http://pdg.lbl.gov`)]

- Cosmic ray observations either **direct** (satellite/balloon) or **indirect** (atmospheric showers)
- steeply falling broken power-law spectra: $\mathrm{d}N/\mathrm{d}E \propto E^{-\Gamma}$ with $\Gamma \simeq 2.7 - 3.0$

Cosmic Ray Interactions



[data from PDG (`http://pdg.lbl.gov`)]

Pion Production Efficiency

- pion production depend on target opacity $\tau = \ell\sigma n$
- "bolometric" pion production efficiency (inelasticity κ):

$$f_\pi = 1 - \exp(-\kappa\tau)$$

- inelasticity per pion : $\kappa_\pi = \kappa/\langle N_{\text{all }\pi}\rangle \simeq 0.17 - 0.2$
- "bolometric" relation of the production rates Q:

$$\frac{E_\pi^2 Q_{\pi^\pm}(E_\pi)}{\langle N_{\pi^+}\rangle + \langle N_{\pi^-}\rangle} \simeq \left[\frac{f_\pi E_N^2 Q_N(E_N)}{\langle N_{\pi^0}\rangle + \langle N_{\pi^+}\rangle + \langle N_{\pi^-}\rangle}\right]_{E_N = E_\pi/\kappa_\pi}$$

- charged-to-neutral pion ratio:

$$K_\pi \equiv \frac{\langle N_{\pi^+}\rangle + \langle N_{\pi^-}\rangle}{\langle N_{\pi^0}\rangle} \simeq \begin{cases} 2 & pp \\ 1 & p\gamma \end{cases}$$

- or in more compact form with K_π:

$$E_\pi^2 Q_{\pi^\pm}(E_\pi) \simeq f_\pi \frac{K_\pi}{1+K_\pi} \left[E_N^2 Q_N(E_N)\right]_{E_N = E_\pi/\kappa_\pi}$$

Neutrinos from Pion Decay

- Cosmic rays interact with gas and radiation in sources or en-route to Earth.
- neutrinos from meson production

$$\pi^+ \to \mu^+ + \nu_\mu \quad \text{and} \quad \pi^- \to \mu^- + \bar{\nu}_\mu$$

- **energy fraction** x carried by secondary particles distributed as:

$$F_{\pi^+ \to \nu_\mu}(x_\nu) = F_{\pi^- \to \bar{\nu}_\mu}(x_\nu) = \frac{1}{1 - r_\pi}\Theta(1 - r_\pi - x_\nu)$$

$$F_{\pi^+ \to \mu^+}(x_\mu) = F_{\pi^- \to \mu^-}(x_\mu) = \frac{1}{1 - r_\pi}\Theta(x_\mu - r_\pi)$$

- muon-to-pion mass ratio: $r_\pi \equiv m_\mu^2 / m_\pi^2 \simeq 0.57$
- average energy fraction of ν_μ ($\bar{\nu}_\mu$):

$$\langle x \rangle_{\pi^+ \to \nu_\mu} = \langle x \rangle_{\pi^- \to \bar{\nu}_\mu} = \frac{1 - r_\pi}{2} \simeq 21\%$$

Neutrinos from Muon Decay

- pion rest-frame: right-handed μ^- ($h = 1$) & left-handed μ^+ ($h = -1$)
- in ultra-relativistic frame:

$$\langle h_{\pi^+\to\mu^+}\rangle(x_\mu) = \frac{2r_\pi}{(1-r_\pi)x_\mu} - \frac{1+r_\pi}{1-r_\pi}$$

$$\langle h_{\pi^-\to\mu^-}\rangle(x_\mu) = -\langle h_{\pi^+\to\mu^+}\rangle(x_\mu)$$

- neutrino spectrum from muon decay depend on helicity:

$$F_{\mu^+\to\bar\nu_\mu}(x_\nu,h) = \left(\frac{5}{3} - 3x_\nu^2 + \frac{4}{3}x_\nu^3\right) + h\left(-\frac{1}{3} + 3x_\nu^2 - \frac{8}{3}x_\nu^3\right)$$

$$F_{\mu^+\to\nu_e}(x_\nu,h) = \left(2 - 6x_\nu^2 + 4x_\nu^3\right) + h\left(2 - 12x_\nu + 18x_\nu^2 - 8x_\nu^3\right)$$

$$F_{\mu^-\to\nu_\mu}(x_\nu,h) = F_{\mu^+\to\bar\nu_\mu}(x_\nu,-h)$$

$$F_{\mu^-\to\bar\nu_e}(x_\nu,h) = F_{\mu^+\to\nu_e}(x_\nu,-h)$$

Summary: Average Neutrino Energy

- neutrino spectra of second of $\bar{\nu}_\mu$ (ν_μ) and ν_e ($\bar{\nu}_e$)

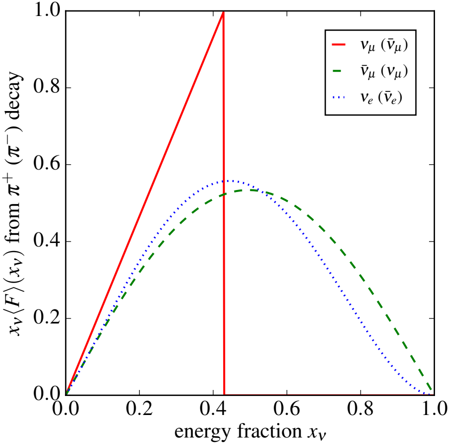
$$F(x_\nu) = \int \mathrm{d}x_\mu F(x_\nu, x_\mu)$$

$$F_{\pi^+\to\mu^+\to\bar{\nu}_\mu}(x_\mu, x_\nu) = F_{\pi^+\to\mu^+}(x_\mu) \times F_{\mu^+\to\bar{\nu}_\mu}(x_\nu, \langle h_{\pi^+\to\mu^+}\rangle(x_\mu))$$

$$F_{\pi^+\to\mu^+\to\nu_e}(x_\mu, x_\nu) = F_{\pi^+\to\mu^+}(x_\mu) \times F_{\mu^+\to\nu_e}(x_\nu, \langle h_{\pi^+\to\mu^+}\rangle(x_\mu))$$

$$F_{\pi^-\to\mu^-\to\nu_\mu}(x_\mu, x_\nu) = F_{\pi^+\to\mu^+\to\bar{\nu}_\mu}(x_\mu, x_\nu)$$

$$F_{\pi^-\to\mu^-\to\bar{\nu}_e}(x_\mu, x_\nu) = F_{\pi^+\to\mu^+\to\nu_e}(x_\mu, x_\nu)$$



Summary: Average Neutrino Energy

- average neutrino energy fraction

$$\langle x\rangle = \int \mathrm{d}x_\mu \mathrm{d}x_\nu x_\mu x_\nu F(x_\mu, x_\nu)$$

- in summary:

$$\langle x\rangle_{\pi^+\to\nu_\mu} = \langle x\rangle_{\pi^-\to\bar\nu_\mu} = \frac{1-r_\pi}{2} \simeq 21\%$$

$$\langle x\rangle_{\pi^+\to\nu_\mu} = \langle x\rangle_{\pi^-\to\bar\nu_\mu} = \frac{3+4r_\pi}{20} \simeq 26\%$$

$$\langle x\rangle_{\pi^+\to\nu_e} = \langle x\rangle_{\pi^-\to\bar\nu_e} = \frac{2+r_\pi}{10} \simeq 26\%$$

- *to cut a long story short*:

$$\langle x\rangle_{\nu_x} \simeq \langle x\rangle_{\bar\nu_x} \simeq \frac{1}{4} \quad \& \quad \kappa_\pi \simeq \frac{1}{5} \quad \to \quad \frac{\langle E_\nu\rangle}{E_N} \simeq \frac{1}{20}$$

➜ We will use this approximation from now on!

Atmospheric Neutrinos

- Atomsphere is constantly bombarded with an isotropic flux of cosmic rays (CRs)

$$\phi_N \simeq 1.8 \times 10^4 \left(\frac{E_N}{\text{GeV}}\right)^{-2.7} \frac{1}{\text{m}^2\,\text{s}\,\text{sr}\,\text{GeV}}$$

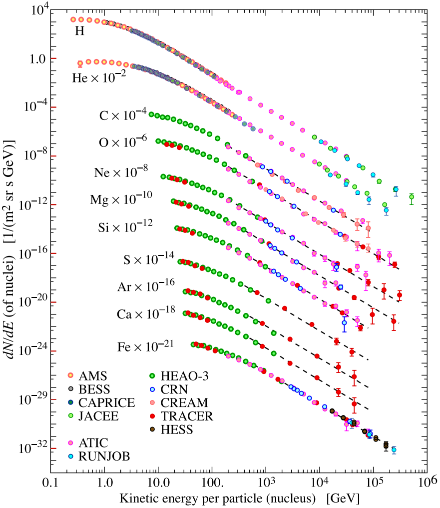
$$(10\text{GeV} \lesssim E_N \lesssim 100\text{ TeV})$$

- CR interactions in the atmosphere produce extended air showers
- neutrinos from meson production, *e.g.*:

$$\pi^+ \to \mu^+ + \nu_\mu$$

- high-energy muons can be considered stable over atmospheric length scales:

$$\lambda_\mu \simeq 15\text{km}\frac{E_\mu}{2.4\text{GeV}}$$



[PDG'17]

Atmospheric Neutrinos

- Nucleons attenuated in the atmosphere $x \equiv ct\rho$:

$$\partial_x \phi_N = -\frac{\phi_N}{\lambda_N} \quad \rightarrow \quad \phi_N = e^{-x/\lambda_N} \phi_N^{(0)}$$

- Meson decay ($\tau_M \propto E_M$) competes with meson interactions (λ_M).

$$\partial_x \phi_M = -\frac{\phi_M}{\lambda_M} - \frac{\phi_M}{c\rho\tau_M} + Z_{NM}(E)\frac{\phi_N}{\lambda_N}$$

- **low energy** ($\tau_M \ll \lambda_M$) :

$$\phi_M(x) \rightarrow Z_{NM}\frac{c\tau_M\rho}{\lambda_N} e^{-x/\lambda_N} \phi_N^{(0)} \propto E_N^{-1.7}$$

- **high energy** ($\tau_M \gg \lambda_M$) :

$$\phi_M(x) \rightarrow Z_{NM}\frac{e^{-x/\lambda_M} - e^{-x/\lambda_N}}{1 - \lambda_N/\lambda_M} \phi_N^{(0)} \propto E_N^{-2.7}$$

Atmospheric Neutrinos

- neutrino spectrum determined by:

$$\phi_\nu \simeq \int\limits_0^{x_{\max}} \mathrm{d}x \int\limits_{E_\nu}^{\infty} \mathrm{d}E' \, \frac{1}{c\tau'\rho} F(E',E_\nu)\phi_M(E',x)$$

- pion decay in the ultra-relativistic limit:

$$F(E',E_\nu) = \frac{\Theta((1-r)E' - E_\nu)}{(1-r)E'} \qquad r \equiv \frac{m_\mu^2}{m_\pi^2}$$

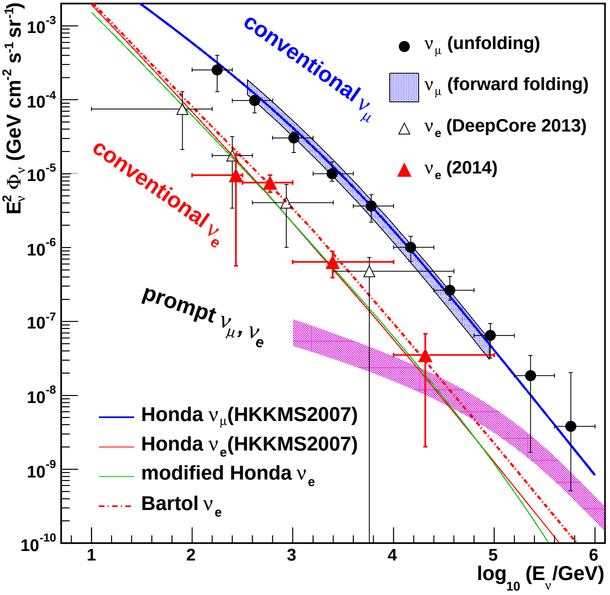
- energy scaling of the atmospheric neutrino spectrum:

$$\phi_\nu \propto \int\limits_{E_\nu}^{\infty} \mathrm{d}E' \, \underbrace{\frac{1}{E'}}_{\tau'} \times \underbrace{\frac{1}{E'}}_{F} \times \underbrace{\begin{cases} E'^{-1.7} & \tau'_M \ll \lambda_M \\ E'^{-2.7} & \tau'_M \gg \lambda_M \end{cases}}_{\phi_M} \propto \begin{cases} E_\nu^{-2.7} & \tau_M \ll \lambda_M \\ E_\nu^{-3.7} & \tau_M \gg \lambda_M \end{cases}$$

- typical analytic approximation: [Lipari'93]

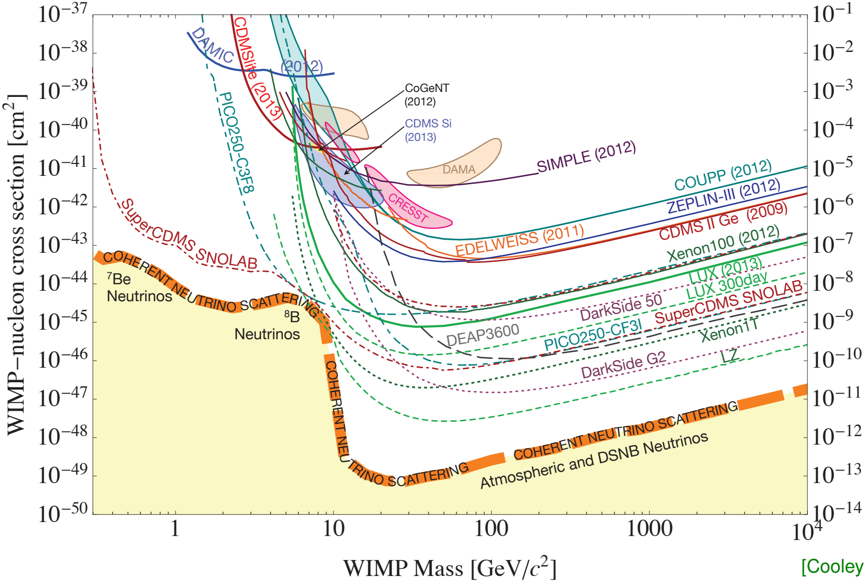
$$\phi_\nu \simeq \sum_M \frac{\phi^{\rm low}_{M\to\nu}\phi^{\rm high}_{M\to\nu}}{\phi^{\rm low}_{M\to\nu} + \phi^{\rm high}_{M\to\nu}}$$

Atmospheric Neutrinos



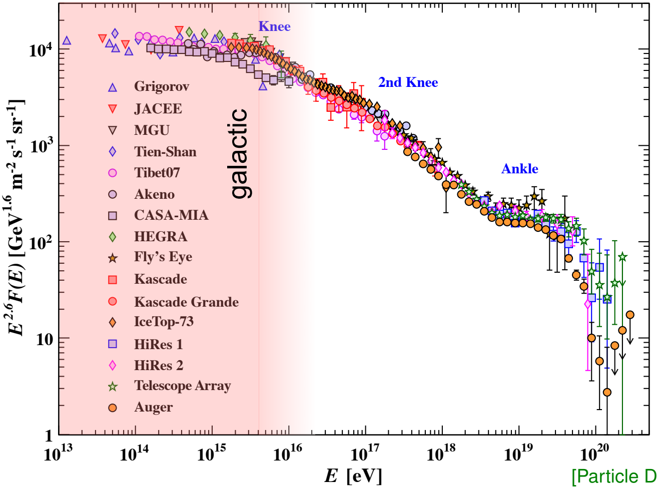
[IceCube'15]

Neutrino Floor for DM searches



[Cooley'14]

Cosmic Ray Spectrum



[Particle Data Group'13]

- Cosmic ray observations either **direct** (satellite/balloon) or **indirect** (atmospheric showers)
- steeply falling broken power-law spectra: $\mathrm{d}N/\mathrm{d}E \propto E^{-\Gamma}$ with $\Gamma \simeq 2.7 - 3.0$

Galactic Cosmic Rays

- *Standard paradigm:* Galactic CRs accelerated in **supernova remnants**

✔ sufficient power: $\sim 10^{-3} \times \mathrm{M}_\odot$ with a rate of ~ 3 SNe per century

[Baade & Zwicky'34]

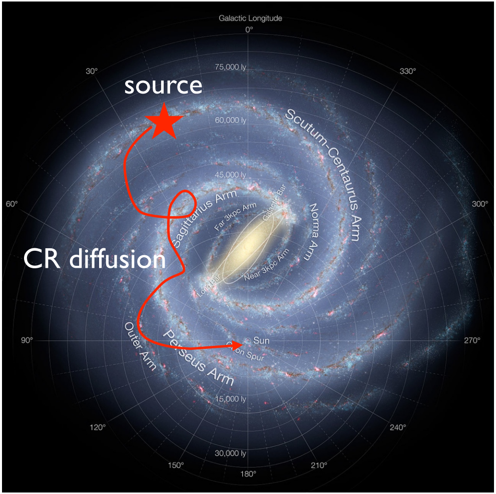
- galactic CRs via diffusive shock acceleration?

$$n_{\mathrm{CR}} \propto E^{-\gamma} \qquad \text{(at source)}$$

- energy-dependent **diffusion** through Galaxy

$$n_{\mathrm{CR}} \propto E^{-\gamma-\delta} \qquad \text{(observed)}$$

- arrival direction **mostly isotropic**

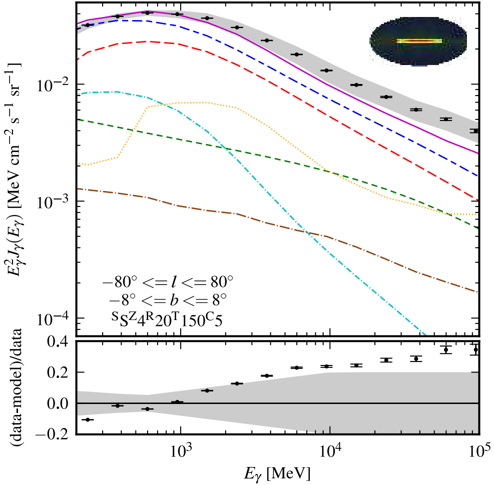


Diffuse Galactic Neutrinos

- Interactions of cosmic rays with gas in the Milky Way creates a flux of γ**-rays and neutrinos**.

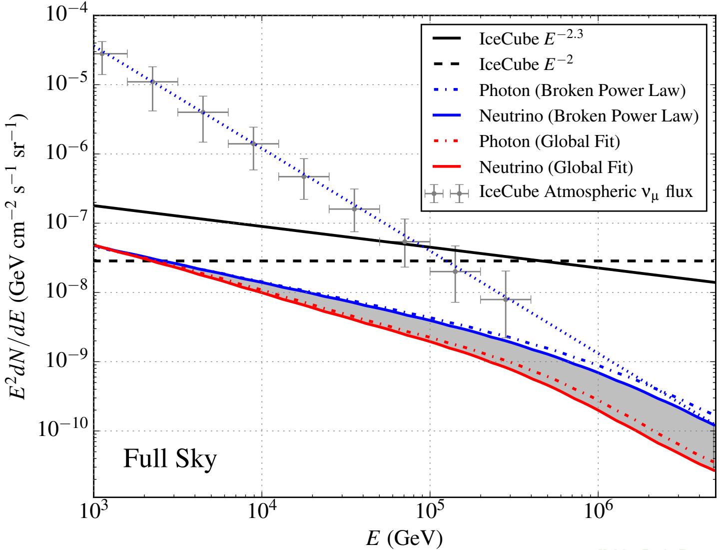
→ This has been be observed and inferred by **Fermi-LAT**.

- **0th order approximation:**
  - use locally observed CR density as a proxy for the average Galactic distribution
  - approximate gas target density
- **1st order approximation:**
  - solve the 3D steady state solution (e.g. GALPROP)
  - “realistic” gas target density
- . . . results very similar.



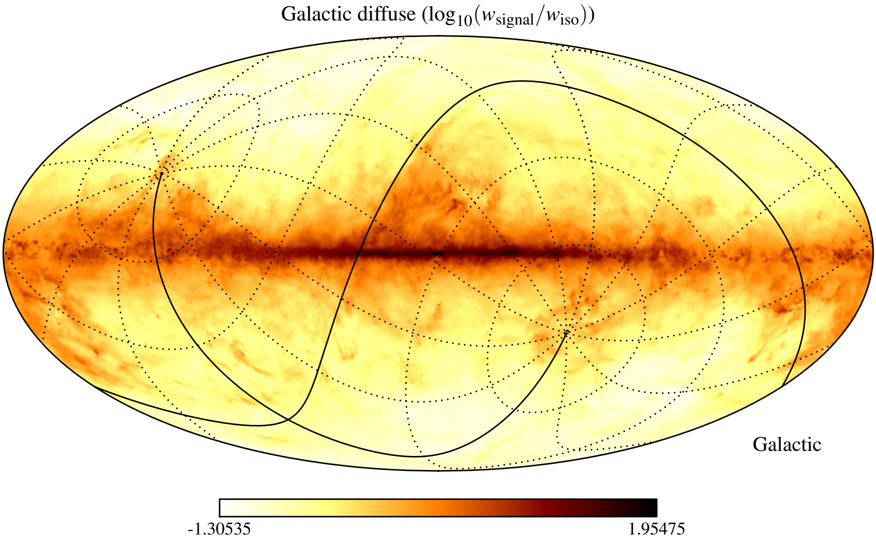
[Fermi’12]

Diffuse Galactic Neutrinos



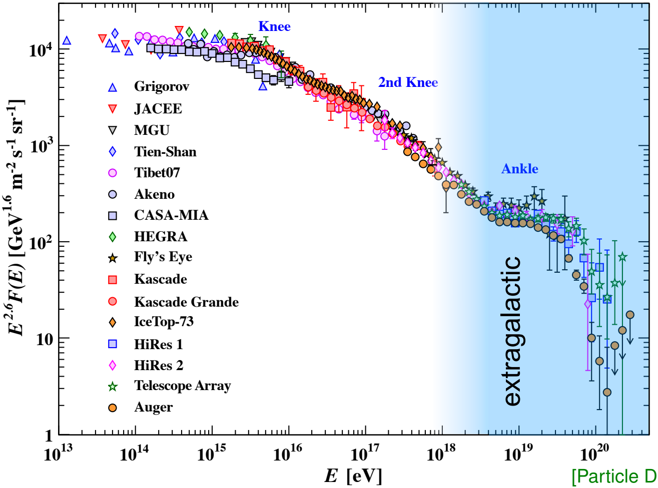
[MA, Bai, Barger & Lu'16]

Diffuse Galactic Neutrinos



[MA, Bai, Barger & Lu'16]

Cosmic Ray Spectrum



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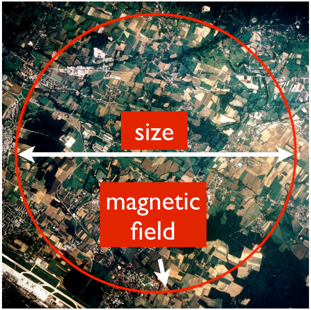
Cosmic Ray Accelerators?

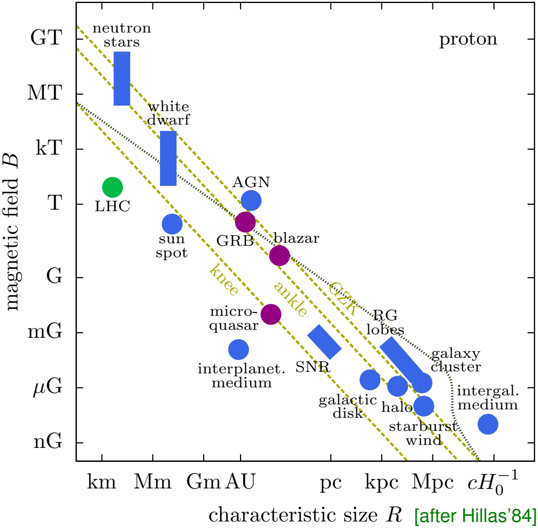
- *Hillas:* fundamental energy bound on cosmic accelerators

➜ accelerators with size **R** and magnetic field strength **B**:

$$E_{\max} \simeq 0.9\beta Z\left(\frac{B}{\mu\mathrm{G}}\right)\left(\frac{R}{\mathrm{kpc}}\right)\mathrm{EeV}$$



"Hillas plot"



[after Hillas'84]

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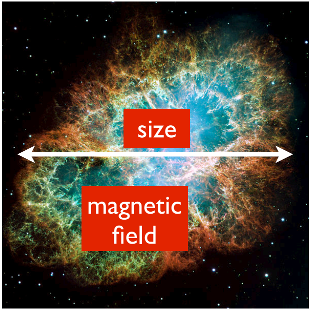

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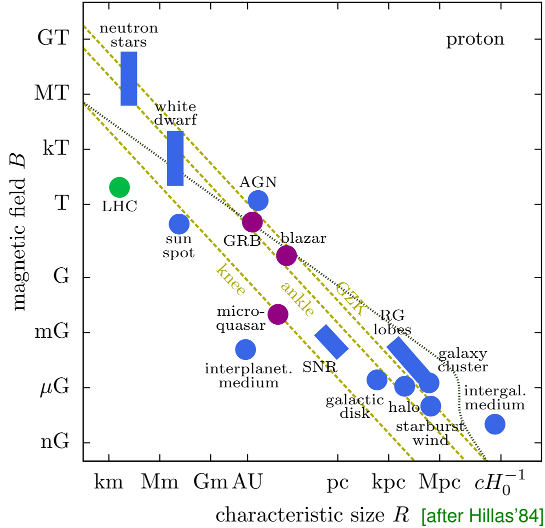
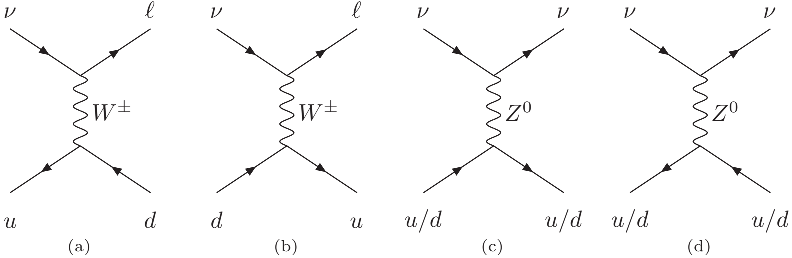


[after Hillas'84]

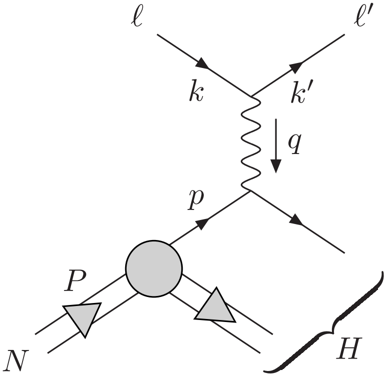
High-energy Neutrino Interactions

- **Low-energy** ($E_\nu \lesssim 10$ GeV) neutrino interaction with matter in quasi-elastic or resonant interactions.
- **High-energy** neutrinos interact with nuclei in deep inelastic scattering processes.
- “Charged” (a/b) and “neutral” (c/d) current interactions with partons:



- Process is “deep inelastic”: **hadronization** of struck nucleus.

Deep Inelastic Scattering



$$s \equiv (P+k)^2 \quad t \equiv q^2 \equiv -Q^2$$

$$M^2 \equiv P^2 \quad W^2 \equiv (P+q)^2$$

$$x \equiv \frac{Q^2}{2\,q\cdot P} \quad y \equiv \frac{q\cdot P}{k\cdot P}$$

(Bjorken − x) (inelasticity)

$$Q \gg M \quad W \gg M$$

(deep) (inelastic)

Deep Inelastic Scattering

- **charged current**: [*e.g.* Gandhi, Quigg, Reno & Sarcevic'98]

$$\frac{\mathrm{d}^2\sigma_{\mathrm{CC}}}{\mathrm{d}Q^2\mathrm{d}x} = \frac{G_F^2}{\pi}\left(\frac{m_W^2}{Q^2+m_W^2}\right)^2\left(q(x,Q^2)+\bar{q}(x,Q^2)(1-y^2)\right)$$

- structure functions $q(x,Q^2) = f_d + f_s$ and $\bar{q}(x,Q^2) = f_{\bar{u}} + f_{\bar{c}}$
- **neutral current**:

$$\frac{\mathrm{d}^2\sigma_{\mathrm{NC}}}{\mathrm{d}Q^2\mathrm{d}x} = \frac{G_F^2}{4\pi}\left(\frac{m_Z^2}{Q^2+m_Z^2}\right)^2\left(q^0(x,Q^2)+\bar{q}^0(x,Q^2)(1-y^2)\right)$$

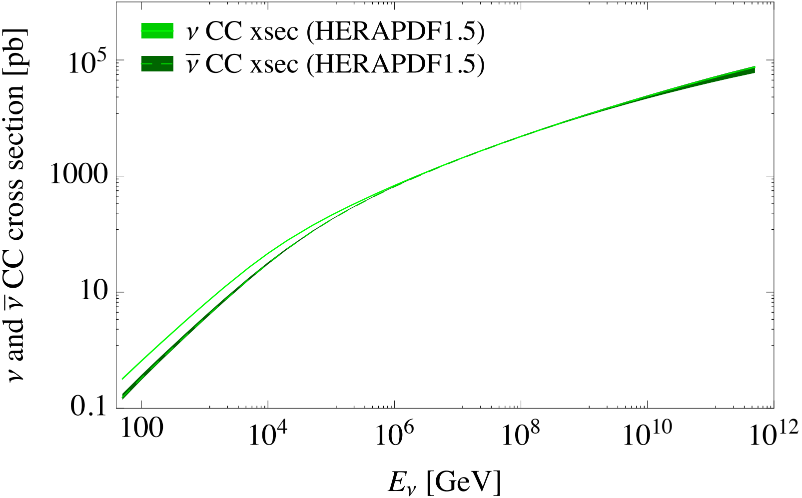
- structure functions:

$$q^0 = (f_u+f_c+f_t)L_u^2 + (f_{\bar{u}}+f_{\bar{c}}+f_{\bar{t}})R_u^2 + (f_d+f_s+f_b)L_d^2 + (f_{\bar{d}}+f_{\bar{s}}+f_{\bar{b}})R_d^2$$
$$\bar{q}^0 = (f_u+f_c+f_t)R_u^2 + (f_{\bar{u}}+f_{\bar{c}}+f_{\bar{t}})L_u^2 + (f_d+f_s+f_b)R_d^2 + (f_{\bar{d}}+f_{\bar{s}}+f_{\bar{b}})L_d^2$$

- chiral couplings (θ_W : Weinberg angle):

$$L_u = 1 - \frac{4}{3}\sin^2\theta_W \quad L_d = -1 + \frac{2}{3}\sin^2\theta_W \quad R_u = -\frac{4}{3}\sin^2\theta_W \quad R_d = \frac{2}{3}\sin^2\theta_W$$

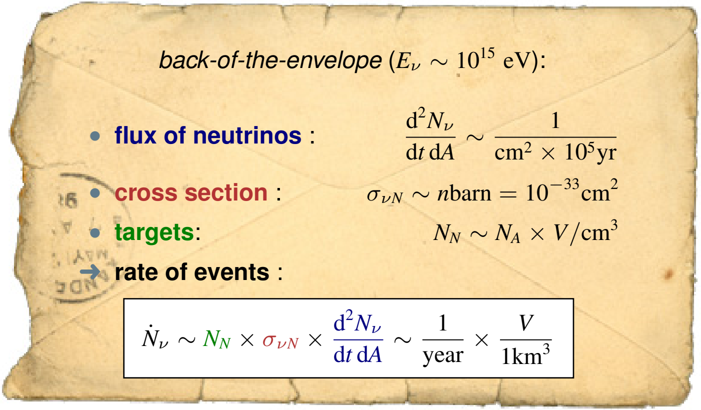
Deep Inelastic Scattering



[Mertsch, Cooper-Sarkar & Sarkar'11]

High-energy Neutrino Detection

- ✘ High energy neutrino collisions with nuclei are **rare**.
- ✘ Backgrounds are huge and partially irreducible!



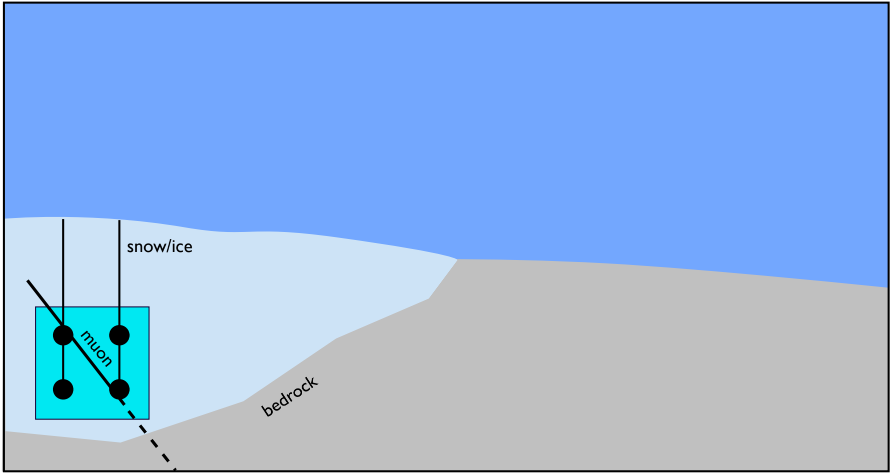
back-of-the-envelope ($E_\nu \sim 10^{15}$ eV):

- **flux of neutrinos** : $\frac{\mathrm{d}^2 N_\nu}{\mathrm{d}t\,\mathrm{d}A} \sim \frac{1}{\mathrm{cm}^2 \times 10^5\mathrm{yr}}$
- **cross section** : $\sigma_{\nu N} \sim n\mathrm{barn} = 10^{-33}\mathrm{cm}^2$
- **targets**: $N_N \sim N_A \times V/\mathrm{cm}^3$

→ **rate of events** :

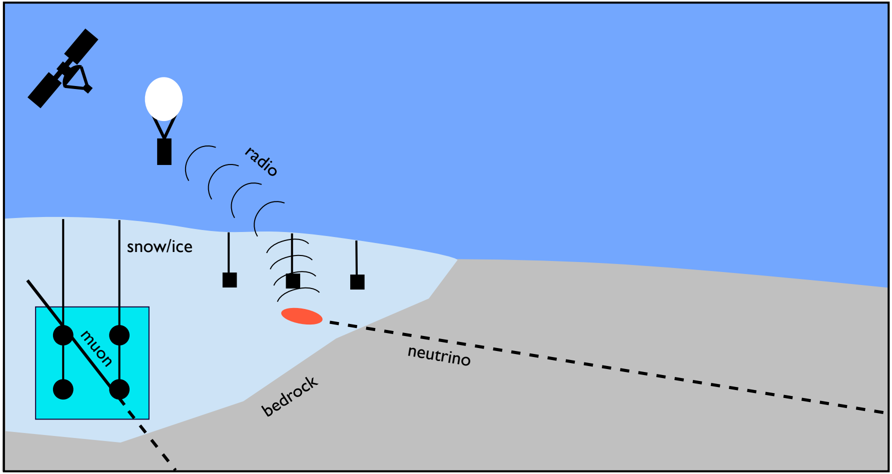
$$\boxed{\dot{N}_\nu \sim N_N \times \sigma_{\nu N} \times \frac{\mathrm{d}^2 N_\nu}{\mathrm{d}t\,\mathrm{d}A} \sim \frac{1}{\mathrm{year}} \times \frac{V}{1\mathrm{km}^3}}$$

Neutrino observation at very high energies



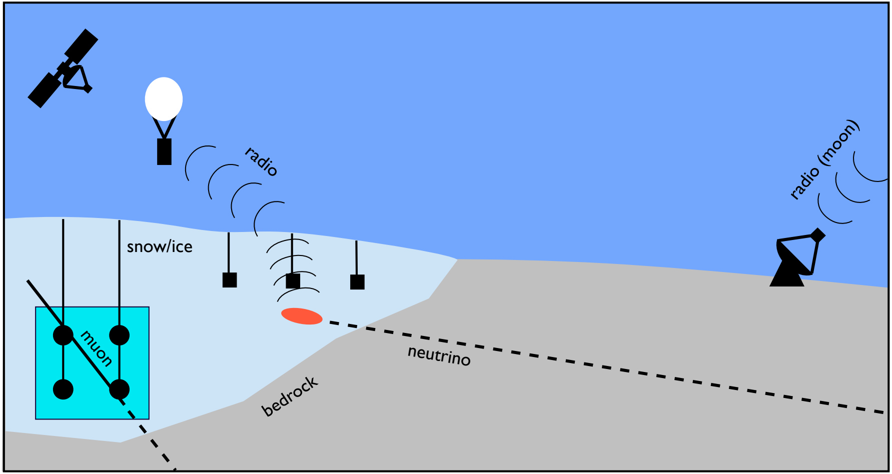
Cherenkov radiation in transparent media (glaciers, lakes, oceans,. . .).

Neutrino observation at very high energies



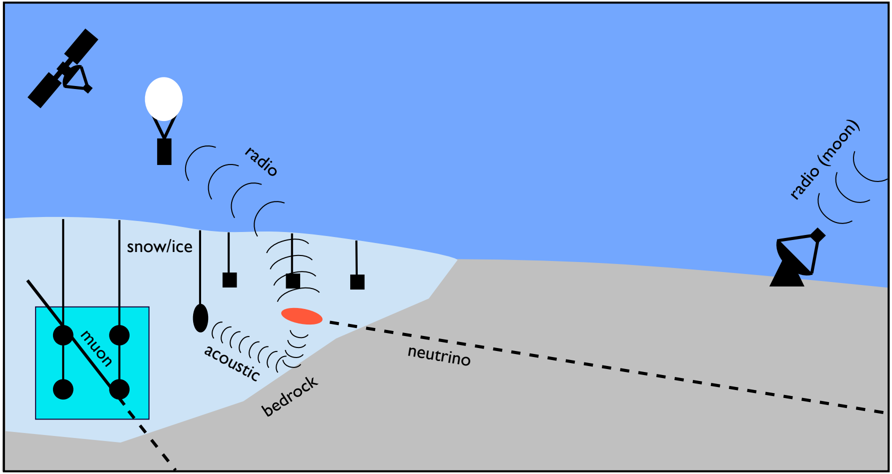
Coherent radio Cherenkov emission (Askaryan effect).
Observation in-situ, balloons or satellites.

Neutrino observation at very high energies



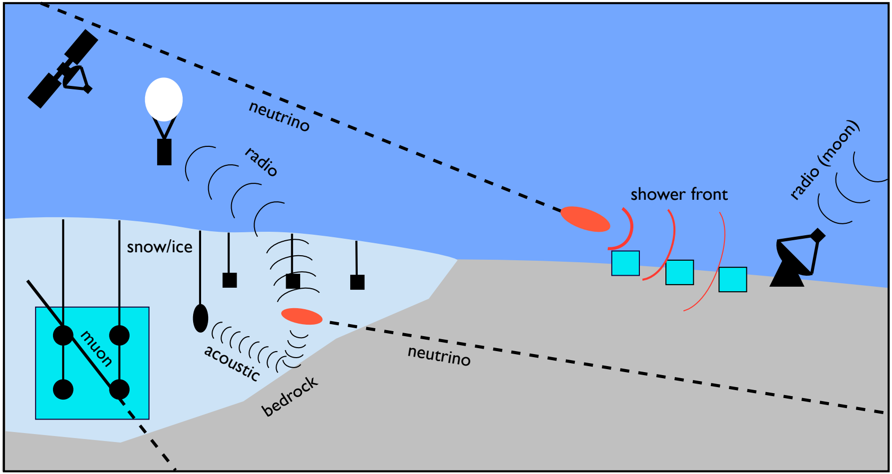
Coherent radio Cherenkov emission (Askaryan effect).
Observation from lunar regolith.

Neutrino observation at very high energies



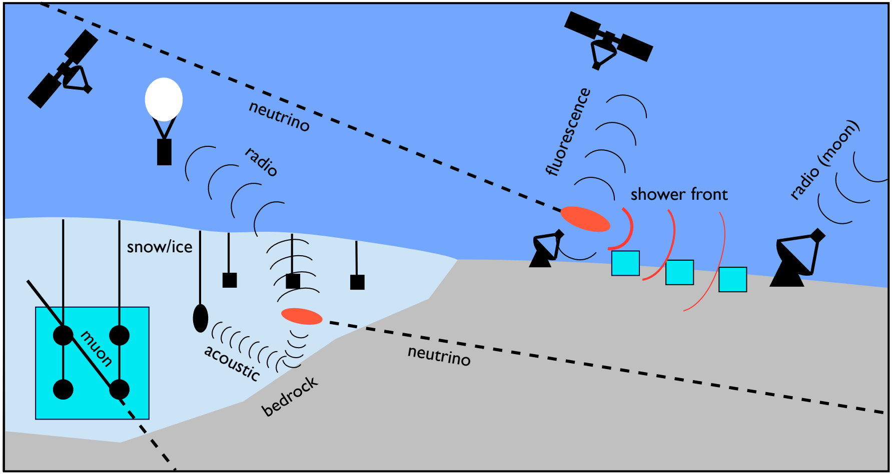
Acoustic detection?

Neutrino observation at very high energies



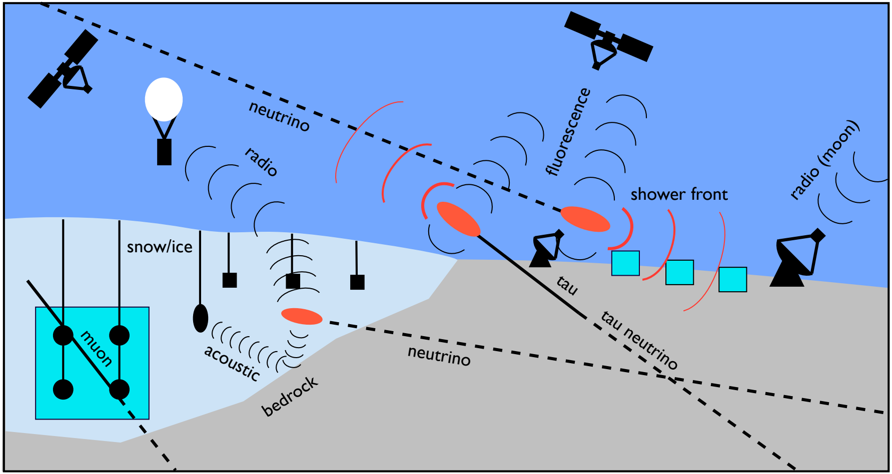
Deeply penetrating quasi-horizontal showers.
Observation by CR surface arrays.

Neutrino observation at very high energies



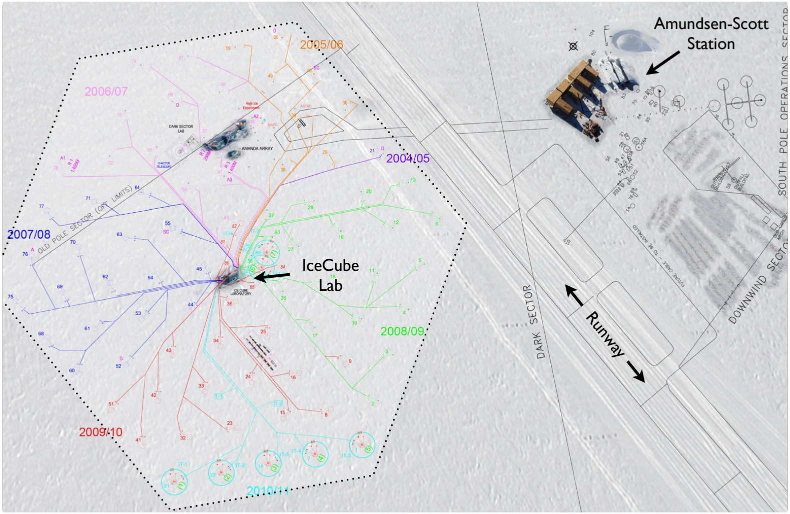
Observation by CR surface arrays and/or fluorescence detectors/satellites.

Neutrino observation at very high energies



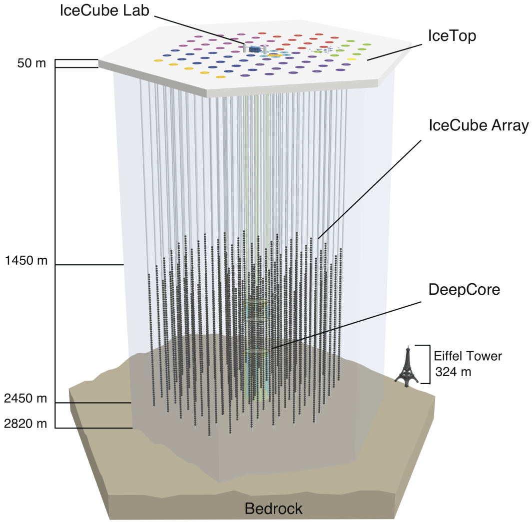
Earth-skimming tau neutrinos.

The IceCube Observatory



South Pole area overview

The IceCube Observatory



- Giga-ton **Cherenkov telescope** at the South Pole
- 60 digital **optical modules** (DOMs) per string
- **78 IceCube strings**
  125 m apart on triangular grid
- **8 DeepCore strings**
  DOMs in particularly clear ice
- **81 IceTop stations**
  two tanks per station, two DOMs per tank
- 7 year construction phase (2004-2011)
- price tag: **30 cents per ton**

The IceCube Observatory

THE ICECUBE COLLABORATION

AUSTRALIA
University of Adelaide

BELGIUM
Université libre de Bruxelles
Universiteit Gent
Vrije Universiteit Brussel

CANADA
SNOLAB
University of Alberta–Edmonton

DENMARK
University of Copenhagen

GERMANY
Deutsches Elektronen-Synchrotron
ECAP, Universität Erlangen-Nürnberg
Humboldt–Universität zu Berlin
Ruhr-Universität Bochum
RWTH Aachen University
Technische Universität Dortmund
Technische Universität München
Universität Mainz
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Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)
Federal Ministry of Education and Research (BMBF)
German Research Foundation (DFG)
Deutsches Elektronen-Synchrotron (DESY)
Japan Society for the Promotion of Science (JSPS)
Knut and Alice Wallenberg Foundation
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The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
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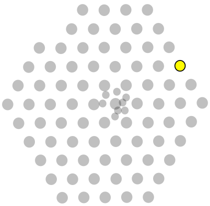
ICECUBE South Pole Neutrino Observatory
icecube.wisc.edu

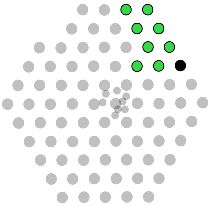
The IceCube Observatory

04-05 Season



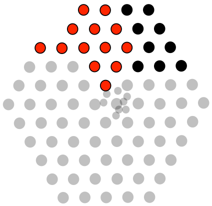
IC-1(IT-4)

05-06 Season



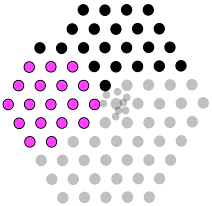
IC-9 (IT-16)

06-07 Season



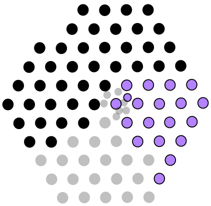
IC-22 (IT-26)

07-08 Season



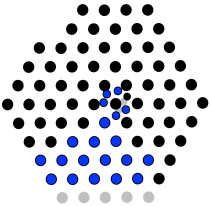
IC-40 (IT-40)

08-09 Season



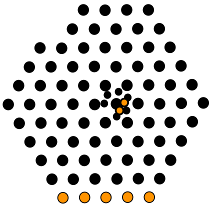
IC-59 (IT-59)

09-10 Season



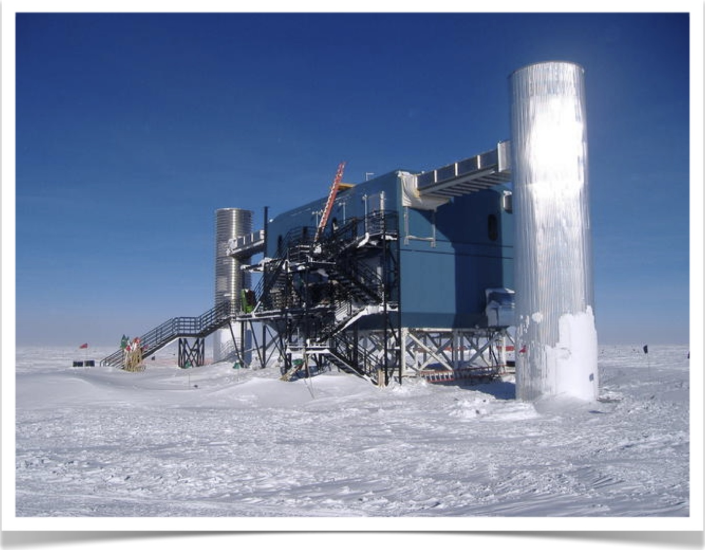
IC-79 (IT-73)

10-11 Season



IC-86 (IT-81)

The IceCube Observatory



IceCube Lab

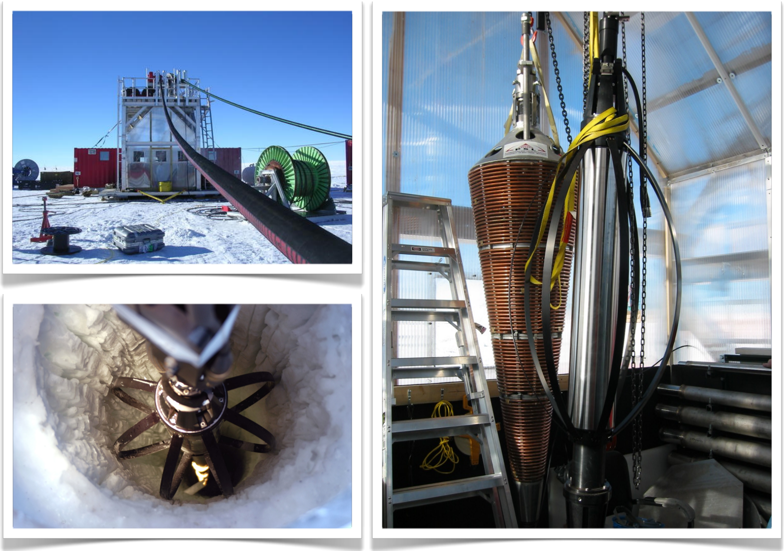
The IceCube Observatory

Drilling with new IceTop tanks

The IceCube Observatory

Inside an IceTop Tank

The IceCube Observatory



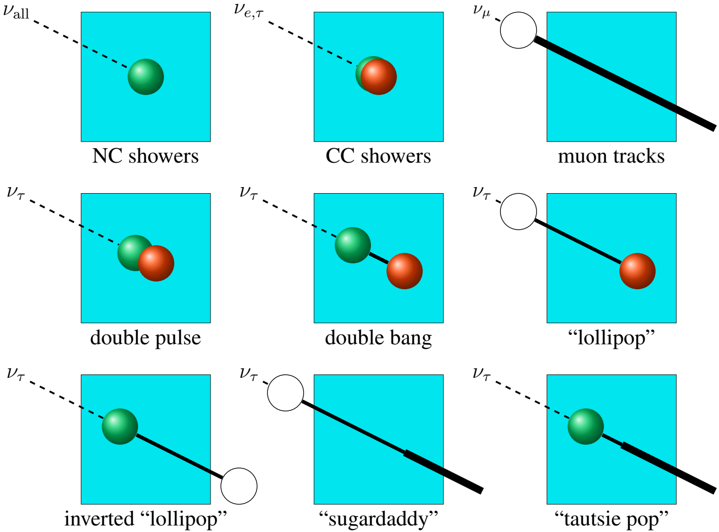
Firn & Ice Drilling

The IceCube Observatory

String & Optical Module

Neutrino Event Signatures

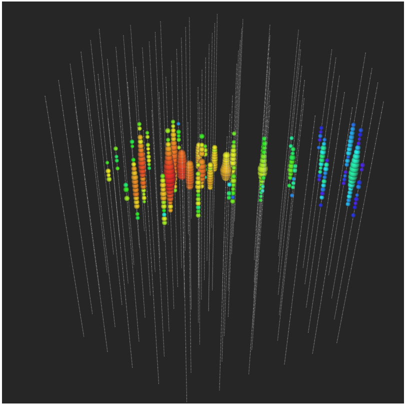
inelastic scattering of neutrinos via charged and neutral current (CC/NC) interactions



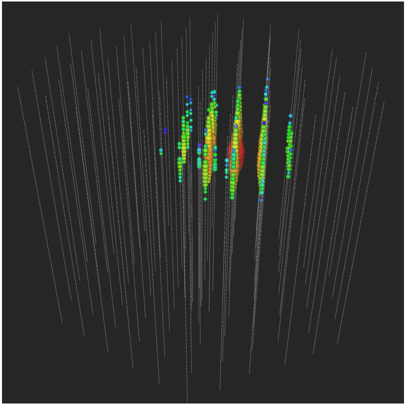
Tracks and Cascades

- “cascades”: **good** energy, but **poor** angular resolution ($\Delta\theta > 10^\circ$)
- “muon tracks”: **poor** energy, but **good** angular resolution ($\Delta\theta \lesssim 0.5^\circ$)
- **time-dependent** signal: early to late light detection

track event (IC-79)



cascade event (IC-86)

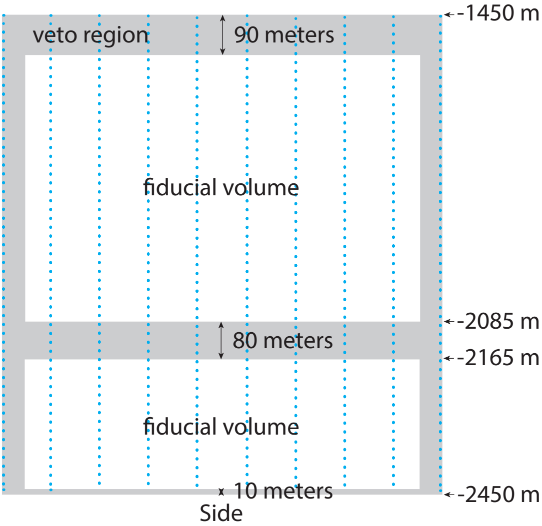


[two examples from the high-energy starting event (HESE) analysis; IceCube Science 342 (2013)]

High-energy starting event (HESE) analysis

- **veto region** marked as gray area (incl. dust layer)
- event passes if less than 3 of 250 first photo electrons (PE) are in veto region
- require high charge (> 6000 PE) to ensure high statistics
- background of atmospheric muons can be estimated from data
- high efficiency above 50-100 TeV

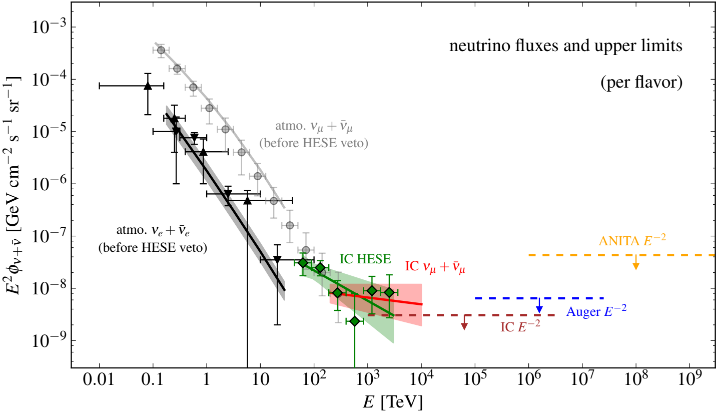
➜ **excess** beyond ~ 60 TeV



[IceCube Collaboration'15]

First (and Second) Light!

- **High-Energy Starting Events (HESE) (6.5σ in 4yrs):** [Science 342 (2013)]
  - bright events ($E_{\rm th} \gtrsim 30$TeV) starting inside IceCube
  - efficient removal of atmospheric backgrounds by veto layer
- **Up-going muon-neutrino tracks (5.6σ in 6yrs):** [Astrophys.J. 833 (2016)]
  - large effective volume due to ranging in tracks
  - efficient removal of atmospheric muon backgrounds by Earth-absorption



Neutrino Flavors

- initial composition: $\nu_e : \nu_\mu : \nu_\tau$

  pion & muon decay: $1 : 2 : 0$

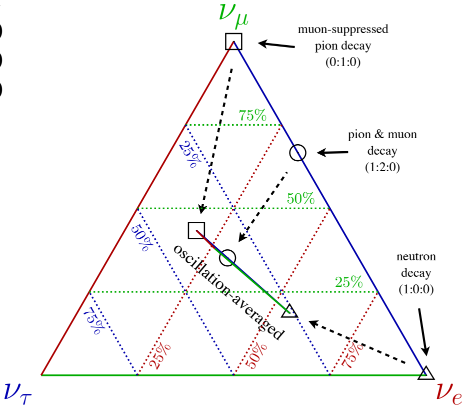
  neutron decay: $1 : 0 : 0$

  muon-damped pion decay: $0 : 1 : 0$

$$p + p \to \pi^+ + X$$
$$\hookrightarrow \mu^+ + \nu_\mu$$
$$\hookrightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

- oscillation-averaged probability:

$$P_{\nu_\alpha \to \nu_\beta} \simeq \sum_i |U_{\alpha i}|^2 |U_{\beta i}|^2$$



- "NuFit 1.3": $\sin^2\theta_{12} = 0.304$ / $\sin^2\theta_{23} = 0.577$ / $\sin^2\theta_{13} = 0.0219$ / $\delta = 251^\circ$

✔ observed events **consistent with equal contributions of all neutrino flavors**

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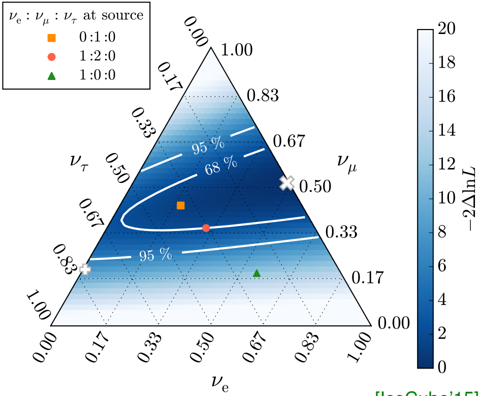

[IceCube'15]

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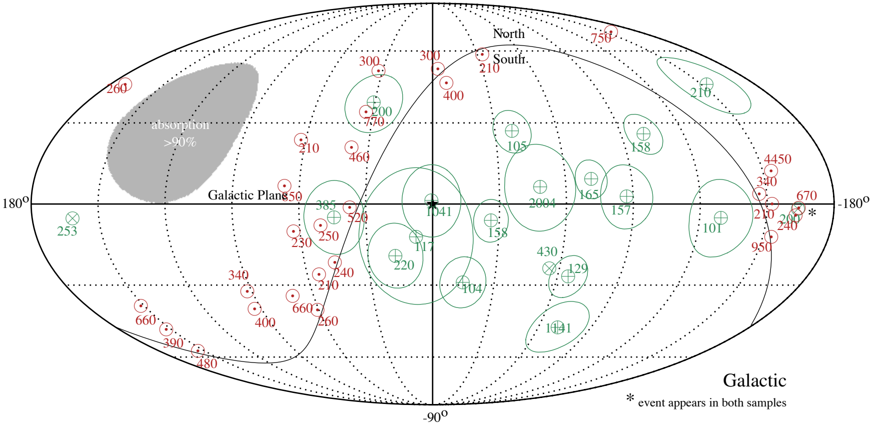
Neutrino Arrival Directions

HESE 4yr with $E_{\mathrm{dep}} > 100$ TeV (green) / Classical $\nu_\mu + \bar{\nu}_\mu$ 6yr with $E_\mu > 200$ TeV (red)



- **16 “cascade events” (circles) and 3 “tracks events” (diamonds)** with $E_{\mathrm{dep}} \gtrsim 100$ TeV
- **28(+1) up-going muon neutrino** events with $E_\mu \gtrsim 200$ TeV [IceCube’15]

✘ **no significant spatial or temporal correlation of events**

Multi-messenger Paradigm

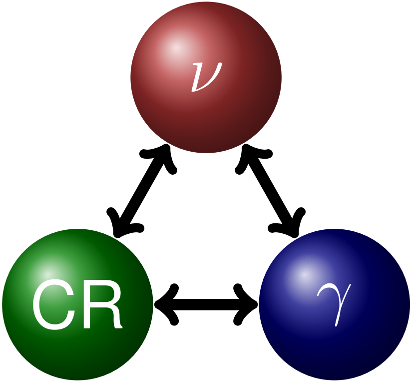
- Neutrino production is closely related to the production of cosmic rays (CRs) and γ-rays.

➜ pion production in CR interactions with gas (“pp”) or radiation (“$p\gamma$”); neutrinos with about 5% of CR nucleon energy

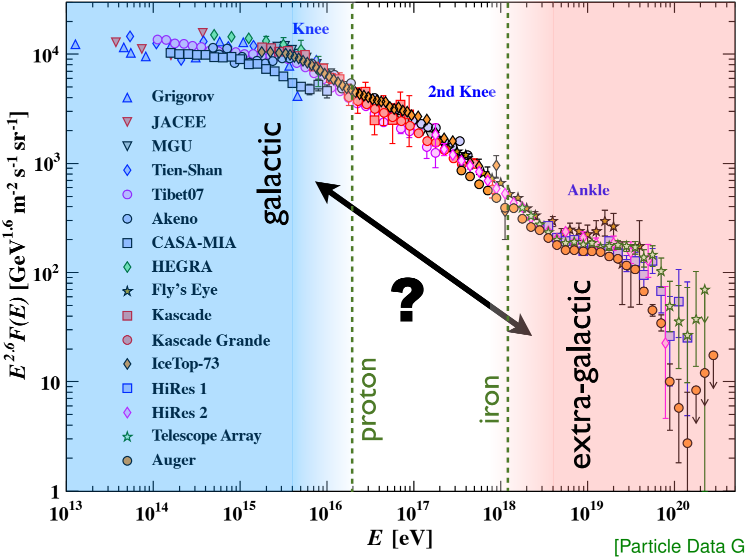
- 1 PeV neutrinos correspond to 20 PeV CR nucleons and 2 PeV γ-rays

➜ **very interesting** energy range:

  - Glashow resonance?
  - galactic or extragalactic?
  - isotropic or point-sources?



The Cosmic "Beam"



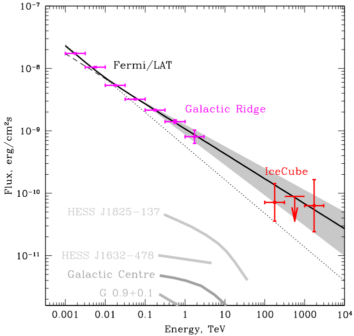
[Particle Data Group'13]

Proposed Source Candidates I

- **Galactic:** (full or partial contribution)
  - diffuse Galactic γ-ray emission [MA & Murase'13; Joshi J C, Winter W and Gupta'13] [Kachelriess and Ostapchenko'14; Neronov, Semikoz & Tchernin'13] [Neronov & Semikoz'14,'16; Guo, Hu & Tian'14; Gaggero, Grasso, Marinelli, Urbano & Valli'15]
  - unidentified Galactic γ-ray emission [Fox, Kashiyama & Meszaros'13] [Gonzalez-Garcia, Halzen & Niro'14]
  - *Fermi Bubbles* [MA & Murase'13; Razzaque'13] [Lunardini, Razzaque, Theodoseau & Yang'13; Lunardini, Razzaque & Yang'15]
  - supernova remnants [Mandelartz & Tjus'14]
  - pulsars [Padovani & Resconi'14]
  - microquasars [Anchordoqui, Goldberg, Paul, da Silva & Vlcek'14]
  - Sagitarius A* [Bai, Barger, Barger, Lu, Peterson & Salvado'14; Fujita, Kimura & Murase'15,'16]
  - Galactic Halo [Taylor, Gabici & Aharonian'14]
  - heavy dark matter decay [Feldstein, Kusenko, Matsumoto & Yanagida'13] [Esmaili & Serpico '13; Bai, Lu & Salvado'13; Cherry, Friedland & Shoemaker'14] [Murase, Laha, Ando, MA'15; Boucenna *et al.*'15 ; Chianese, Miele, Morisi & Vitagliano'16]

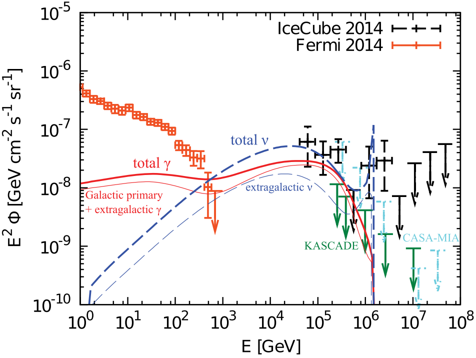
Galactic Emission Models: Two Examples

Hard Galactic Diffuse Emission



[Neronov, Semikoz & Tchernin'14]

PeV Dark Matter Decay (*e.g.* DM$\to \nu\bar{\nu}/q\bar{q}$)

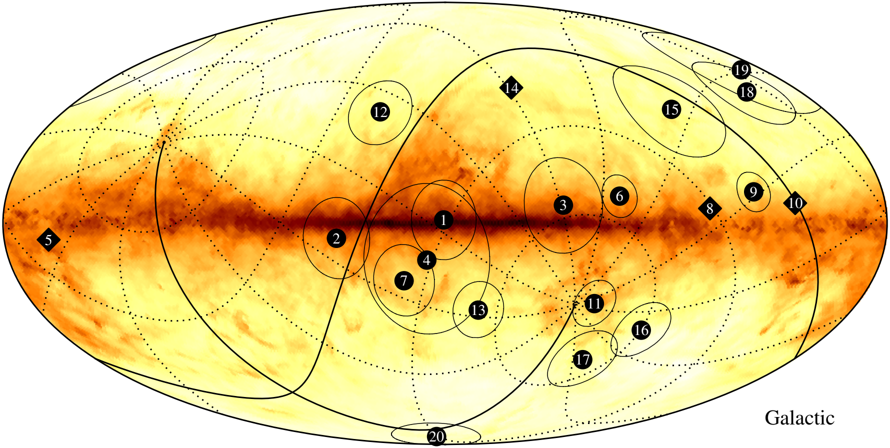


[*e.g.* Murase, Laha, Ando & MA'15]

- anisotropy limits on Galactic emission [MA & Bai, Barger & Yang'15]
- limits on Galactic contribution from PeV γ-ray observation [Gupta'14; MA & Murase'14]

Example: Galactic Diffuse Emission

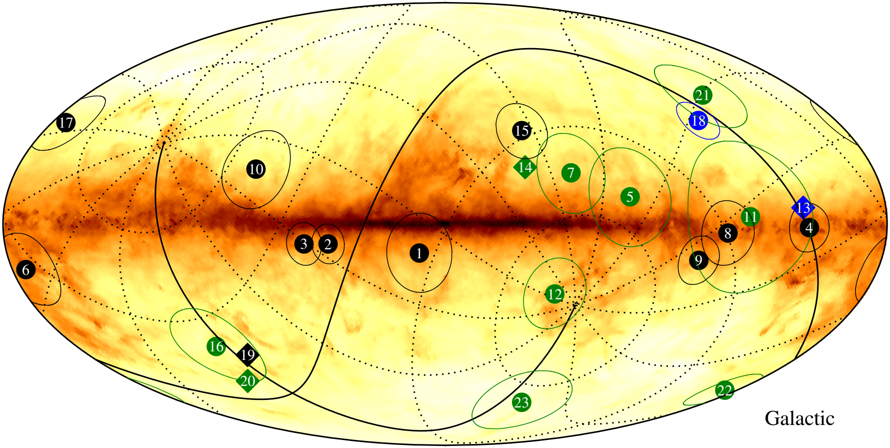
HESE 3yr with $E_{\mathrm{dep}} > 60$ TeV, $n_{\mathrm{tot}} = 20$, $f_{\mathrm{iso}} = 0.81$, $\lambda = 0.74$



- Strong Galactic diffuse emission up to PeV? [Neronov, Semikoz & Tchernin'13'14]
- tracks (◇) and cascades (○) from HESE 3yr with $E_{\mathrm{dep}} > 60$ TeV; circles indicate angular uncertainty

Example: Galactic Diffuse Emission

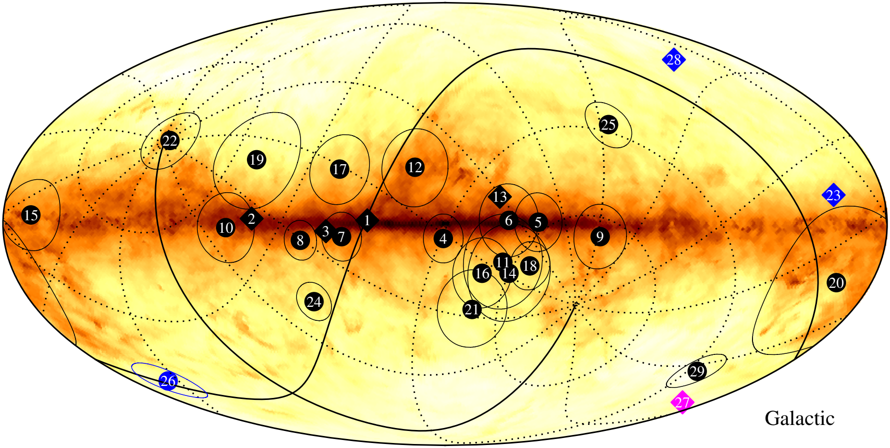
sample with $f_{\rm iso} = 0.50$, $n_{\rm tot} = 23$, $f_{\rm iso} = 0.76$, $\lambda = 0.86$



- Galactic diffuse emission template derived with GALPROP [Strong & Moskalenko'98]
- **simulated** map: ◇/○ : Galactic ν | ◇/○ : isotropic ν | ◇/○ : atmospheric ν | ◇/○ : atmospheric μ

Example: Galactic Diffuse Emission

sample with $f_{\rm iso} = 0.00$, $n_{\rm tot} = 29$, $f_{\rm iso} = 0.09$, $\lambda = 26.03$



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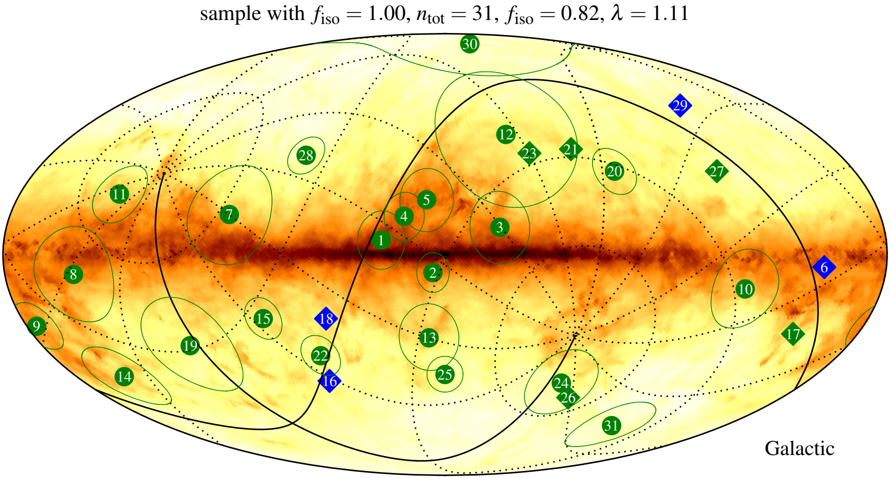
Example: Galactic Diffuse Emission



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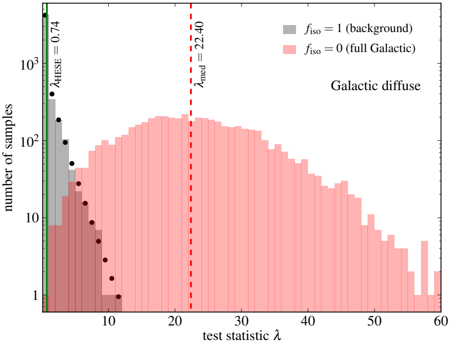
Anisotropy Test

- unbinned maximum LH test statistic:

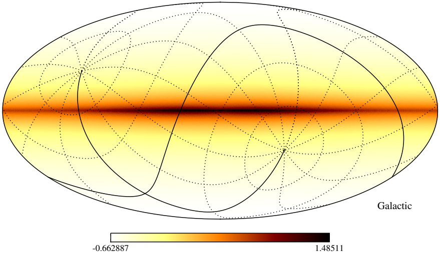
$$\lambda = 2\ln \prod_{\text{event } j}\left[\frac{\mu_j^{\rm sig}(\widehat{f}_{\rm iso}) + \mu_j^{\rm bgr}(\widehat{f}_{\rm iso})}{\mu_j^{\rm bgr}(1)}\right]$$

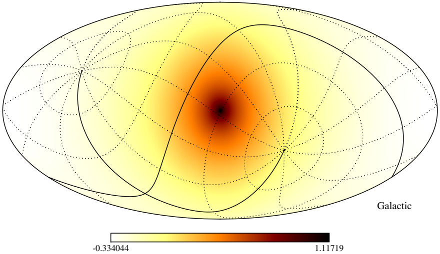
- $\widehat{f}_{\rm iso}$: fraction of isotropic events at maximum LH
- 90% C.L. **sensitivity** :
  $f_{\rm iso}$ with 90% of samples $\lambda_{\rm MC} > \lambda^{\rm bgr}_{\rm med}$
- 5σ C.L. **discovery potential** :
  $f_{\rm iso}$ with 50% of samples $\lambda_{\rm MC} > \lambda^{\rm bgr}_{5\sigma}$
- 90% C.L. **upper limit** :
  $f_{\rm iso}$ with 90% of samples $\lambda_{\rm MC} > \lambda_{\rm HESE}$

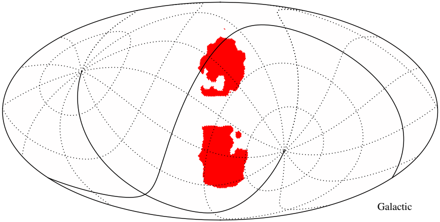


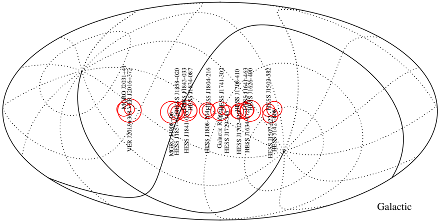
grey: background distribution ($f_{\rm iso} = 1$)
red: maximal signal distribution ($f_{\rm iso} = 0$)

Other Extended Galactic Emission


SNR ($\log_{10}(w_{\rm signal}/w_{\rm iso})$)


DM decay ($\log_{10}(w_{\rm signal}/w_{\rm iso})$)


Fermi Bubbles


Unidentified & Dark Sources

Sensitivity & Upper Limits

	HESE 3yr observation				sensitivity for $f_{\mathrm{Gal}}{}^{\star}$		
template	λ	p-value*	$\widehat{f}_{\mathrm{Gal}}{}^{\star}$	$f_{\mathrm{Gal}}^{90\%\star}$	HESE 3 yr	HESE 10 yr	Northern ν_μ 3 yr
Galactic diffuse ν #	0.74	0.19	0.19	0.50	0.30	0.15	0.25
SNR [65]	1.68	0.10	0.34	0.65	0.35	0.20	0.30
PWN [66]	1.77	0.09	0.30	0.60	0.30	0.15	0.25
DM decay [81]	1.48	0.11	0.46	–	0.60	0.30	0.85
Fermi Bubbles [74]	0.36	0.27	0.07	0.25	0.20	0.10	–
UnID TeV [7]	0.43	0.25	0.07	0.25	0.20	0.10	–

The emission template is using `GALPROP`. We estimate the systematic uncertainty of f_{Gal} from the diffusion model to be at the level of ±10%.

* The p-value is calculated from λ assuming a background distribution $[\delta(\lambda)+\chi^2_1(\lambda)]/2$.

⋆ The Galactic fraction is defined as $f_{\mathrm{Gal}} = 1 - f_{\mathrm{iso}}$.

[MA, Bai, Barger & Lu'15]

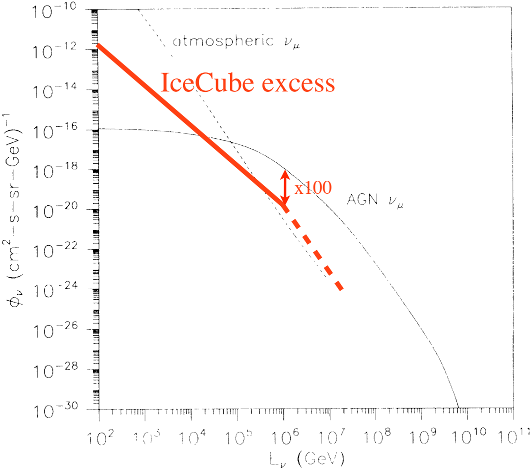
- **stronger** sensitivity in combination with spectral and flavor analysis ➜ ongoing IceCube analysis
- classical $\nu_\mu + \bar{\nu}_\mu$ search with good angular resolution (but limited FoV)

Proposed Source Candidates II

- **Extragalactic:**
  - association with sources of UHE CRs [Kistler, Stanev & Yuksel'13]
    [Katz, Waxman, Thompson & Loeb'13; Fang, Fujii, Linden & Olinto'14;Moharana & Razzaque'15]
  - association with diffuse γ-ray background [Murase, MA & Lacki'13]
    [Chang & Wang'14; Ando, Tamborra & Zandanel'15]
  - active galactic nuclei (AGN) [Stecker'13;Kalashev, Kusenko & Essey'13]
    [Murase, Inoue & Dermer'14; Kimura, Murase & Toma'14; Kalashev, Semikoz & Tkachev'14]
    [Padovani & Resconi'14; Petropoulou *et al.*'15; Padovani *et al.*'16; Kadler *et al.*'16; Wang & Loeb'16]
  - gamma-ray bursts (GRB) [Murase & Ioka'13; Dado & Dar'14; Tamborra & Ando'15]
    [Senno, Murase & Meszaros'16]
  - galaxies with intense star-formation
    [He, Wang, Fan, Liu & Wei'13; Yoast-Hull, Gallagher, Zweibel & Everett'13; Murase, MA & Lacki'13]
    [Anchordoqui, Paul, da Silva, Torres& Vlcek'14; Tamborra, Ando & Murase'14; Chang & Wang'14]
    [Liu, Wang, Inoue, Crocker & Aharonian'14; Senno, Meszaros, Murase, Baerwald & Rees'15]
    [Chakraborty & Izaguirre'15; Emig, Lunardini & Windhorst'15; Bechtol *et al.*'15]
  - galaxy clusters/groups [Murase, MA & Lacki'13; Zandanel, Tamborra, Gabici & Ando'14]
  - . . .

Active Galactic Nuclei

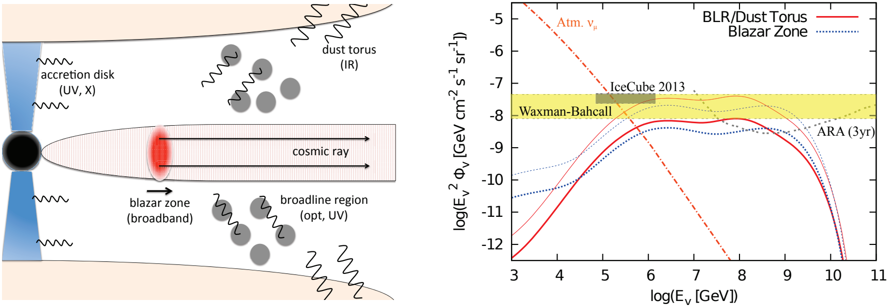
- neutrino interactions from $p\gamma$ interactions in AGN cores [Stecker*et al.*'91]
- AGN diffuse emission normalized to X-ray background
- revised model predicts 5% of original estimate [Stecker'05;'13]



[Stecker *et al.*'91]

Active Galactic Nuclei

- neutrino from $p\gamma$ interactions in AGN jets [Mannheim'96; Halzen & Zas'97]
- complex spectra due to various photon backgrounds
- typically, deficit of sub-PeV and excess of EeV neutrinos



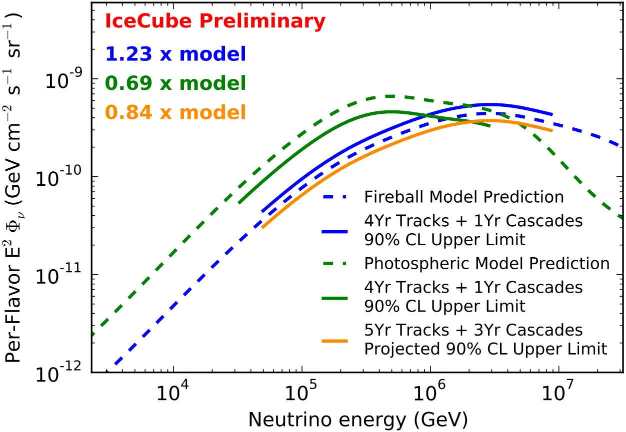
[Murase, Inoue & Dermer 1403.4089]

Gamma-ray Bursts

- strong limits on neutrino emission associated with the fireball model [Abbasi *et al.*'12]

➜ IceCube excess exceeds IC40+59 limit by factor ~ 5

- **loophole:** undetected low-power γ-ray bursts (GRB) [Murase & Ioka 1306.2274]



[IceCube'16]

Neutrino Features from Photon Backgrounds

- Breit-Wigner approximation (width $\Gamma_\Delta \simeq 0.11$ GeV and $\sigma_0 \simeq 34\ \mu$b)

$$\sigma_{p\gamma}(\epsilon') \simeq \underbrace{\frac{s}{\epsilon'^2}\frac{\sigma_0\Gamma_\Delta^2 s}{(s-m_\Delta^2)^2+\Gamma_\Delta^2 s}}_{\text{Breit-Wigner}} \simeq \underbrace{\frac{s}{\epsilon'^2}\Gamma_\Delta\sqrt{s}\sigma_0\pi\delta(s-m_\Delta^2)}_{\text{narrow-width approximation}}$$

- interaction rate averaged over isotropic spectrum ($\epsilon' = \gamma\epsilon(1-\cos\theta)$)

$$\Gamma_{p\gamma}(E) \equiv \frac{1}{2}\int\limits_{-1}^{1}\mathrm{d}\cos\theta\int\mathrm{d}\epsilon\,(1-\cos\theta)n_\gamma(\epsilon)\sigma_{p\gamma}(\epsilon')$$
$$= \frac{1}{2\gamma^2}\int\mathrm{d}\epsilon'\epsilon'\sigma_{p\gamma}(\epsilon')\int\limits_{\epsilon'/2\gamma}\frac{\mathrm{d}x}{x^2}n_\gamma(x)$$

- for power-law spectra $n_\gamma \propto \epsilon^{-\alpha}$ and narrow-width approximation:

$$\Gamma_{p\gamma}(E) \propto E^{\alpha-1}$$

Example: Gamma-Ray Burst Spectra

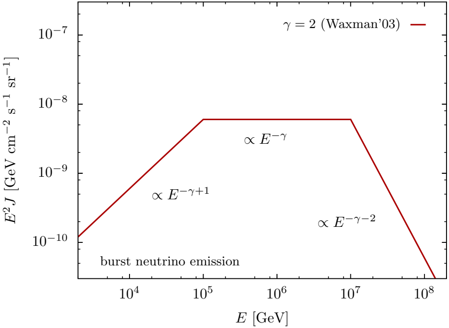
- γ-ray emission of GRBs follow a "Band" spectrum: [Band *et al.*'93]

$$n_\gamma \propto \begin{cases} (\epsilon/\epsilon_0)^{-1} & \epsilon \ll \epsilon_0 \\ (\epsilon/\epsilon_0)^{-2} & \epsilon \gg \epsilon_0 \end{cases}$$

- resulting neutrino spectrum: [Waxman & Bahcall'97]

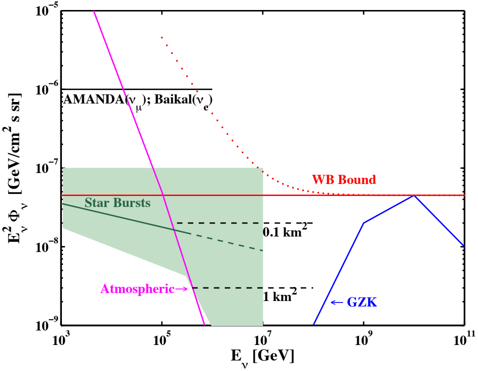
$$\phi_\nu \propto \Gamma_{p\gamma}\phi_p \propto \begin{cases} E_\nu^{-\Gamma+2-1} \sim E_\nu^{-1} \\ E_\nu^{-\Gamma+1-1} \sim E_\nu^{-2} \end{cases}$$

- Actual ν spectrum becomes softer at high energies due to **synchrotron loss** of muons an pion before decay.



Starburst galaxies

- intense CR interactions (and acceleration) in dense starburst galaxies
- cutoff/break feature $(0.1 - 1)$ PeV at the CR knee (of these galaxies), but very uncertain
- plot shows muon neutrinos on production ($3/2$ of total)



Messier 82 (M82)

[Loeb & Waxman’06]

Extragalactic: Diffuse vs. Point-Source

- diffuse flux $\phi_{\rm diff}$ is superposition of individual point sources with flux $\phi_{\rm PS}$:

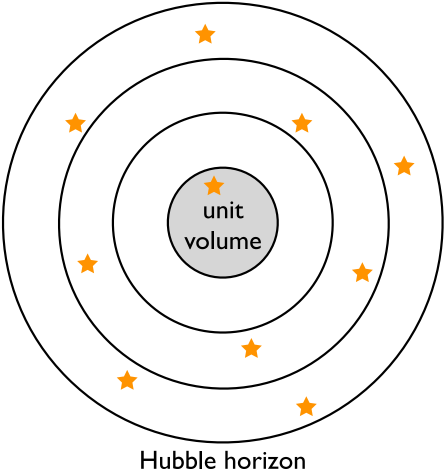
$$\phi_{\rm diff} = \frac{1}{4\pi}\int {\rm d}z\,\frac{{\rm d}\mathcal{V}_C}{{\rm d}z}\,\rho(z)\,\underbrace{\frac{L}{4\pi d_L^2(z)}}_{\phi_{\rm PS}} \simeq \mathcal{O}(1)\,\frac{1}{4\pi}\,\frac{\rho(0)}{H_0}L$$

- *effective* local density $\rho(0)$ of extra-galactic sources is:
  - $\sim 10^{-3}\,{\rm Mpc}^{-3}$ for **low-luminosity AGN**
  - $\sim 10^{-5}\,{\rm Mpc}^{-3}$ for **starburst galaxies**
  - $\sim 10^{-5}\,{\rm Mpc}^{-3}$ for **galaxy clusters**
  - $\gtrsim 10^{-5}\,{\rm Mpc}^{-3}$ for **UHE CR sources**
  - $\sim 10^{-8} - 10^{-7}\,{\rm Mpc}^{-3}$ for **radio galaxies**
  - $\sim 10^{-8}\,{\rm Mpc}^{-3}$ for **BL Lacs**
  - $\sim 10^{-11} - 10^{-10}\,{\rm Mpc}^{-3}$ for **flat-spectrum radio quasars**

[Ahlers & Halzen'14; Murase & Waxman'16; Mertsch, Rameez & Tamborra'16]

➜ *How does this relate to the non-observation of individual sources?*

Back-of-the-Envelope Estimate



- expect one source per **unit volume**:

$$V_1\rho(0) = 1$$

A total number of **unit shells** contributing as much as the closest source

$$n_{\rm shell} \simeq (n_{\rm source})^{\frac{1}{3}}$$

➜ e.g., required number of events to see a **doublet** from radio galaxies

$$\bar{N} = 2 \times (n_{\rm source})^{\frac{1}{3}} \simeq 100 - 300$$

B brightest source at distance

$$d_1 \simeq \left(\frac{3}{4\pi\rho(0)}\right)^{\frac{1}{3}}$$

➜ compare to **point-source sensitivity**

Flux Distribution of a Standard Candle

- flux F ($[F] = \mathrm{erg/s/cm^2}$) and luminosity L ($[L] = \mathrm{erg/s}$)

$$F = \frac{L}{4\pi r^2} \qquad \to \qquad |\mathrm{d}F| = 2\frac{L}{4\pi r^3}\mathrm{d}r$$

- point-source number N

$$N(<r) = (4\pi/3)r^3\rho \qquad \to \qquad \mathrm{d}N = 4\pi r^2\rho\mathrm{d}r$$

- flux distribution

$$\frac{\mathrm{d}N}{\mathrm{d}F} \propto r^5 \propto F^{-5/2}$$

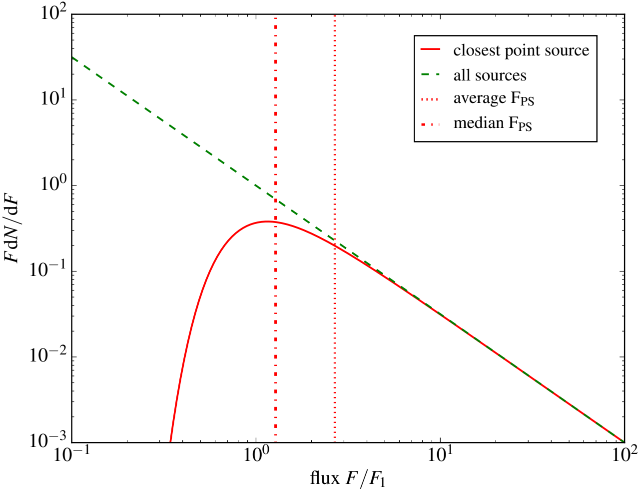
- distribution of the closest source ($F_1 \equiv L/(4\pi d_1^2)$)

$$F\frac{\mathrm{d}p}{\mathrm{d}F} = \frac{3}{2}\left(\frac{F_1}{F}\right)^{\frac{3}{2}} e^{-\left(\frac{F_1}{F}\right)^{\frac{3}{2}}}$$

- expected flux contribution

$$\langle F\rangle = 3\Gamma(4/3)F_1 \simeq 2.7F_1$$

Flux Distribution of a Standard Candle



Neutrino Point-Source Limits

- Diffuse neutrino flux **normalizes** the contribution of individual sources

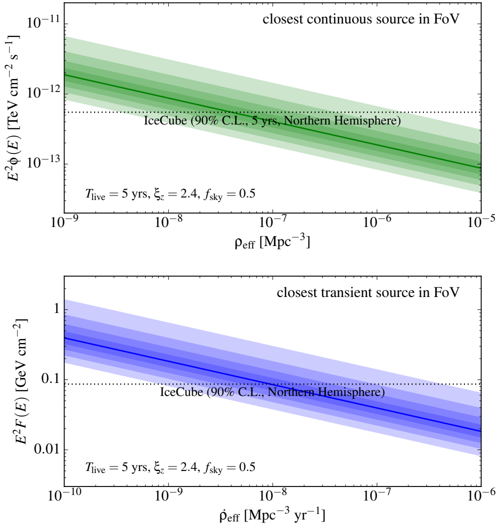
→ **non-observation** of individual neutrino sources exclude source classes, *e.g.*

✘ blazars
$(\rho_{\rm eff} \lesssim 10^{-8}{\rm Mpc}^{-3})$

✘ gamma-ray bursts
$(\dot\rho_{\rm eff} \simeq 10^{-9}{\rm Mpc}^{-3}{\rm yr}^{-1})$

→ **stronger limits** possible via source "stacking"

[MA & Halzen'14; Murase & Waxman'16]
[Mertsch, Rameez & Tamborra'16]



[MA & Halzen'14]

Hadronic Gamma-Ray Emission

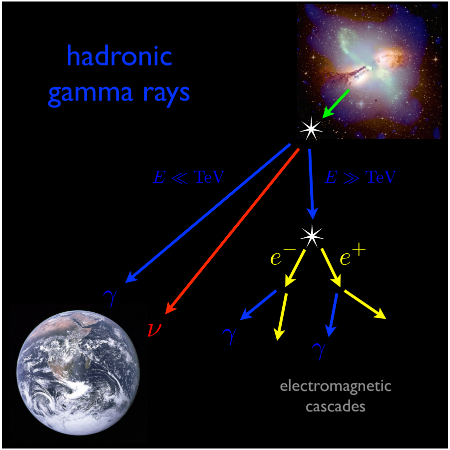
- **hadronic** γ-rays from neutral pion production in CR interactions:

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

➜ cross-correlation of γ-ray and neutrino sources

✗ electromagnetic cascades of super-TeV γ-rays in CMB

✔ Isotropic Diffuse Gamma-Ray Background (IGRB) constraints the energy density of hadronic γ-rays & neutrinos



Neutrino and Gamma-Ray Emission

- neutrino emission from pion decay

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

- neutrino and γ-ray emission are related as

$$\frac{1}{3}\sum_\alpha \frac{E_\nu Q_{\nu_\alpha}(E_\nu)}{\langle N_{\pi^+}\rangle + \langle N_{\pi^-}\rangle} \simeq \frac{1}{2}\left[\frac{E_\gamma Q_\gamma(E_\gamma)}{\langle N_{\pi^0}\rangle}\right]_{E_\gamma = 2E_\nu}$$

- again, a more compact form with K_π:

$$\frac{1}{3}\sum_\alpha E_\nu^2 Q_{\nu_\alpha}(E_\nu) \simeq \frac{K_\pi}{4}\left[E_\gamma^2 Q_\gamma(E_\gamma)\right]_{E_\gamma = 2E_\nu}$$

- γ-ray emission is attenuated in sources and, in particular, in the extragalactic radiation background

Gamma-Ray Opacity

- production and decay of neutral pions into gamma rays

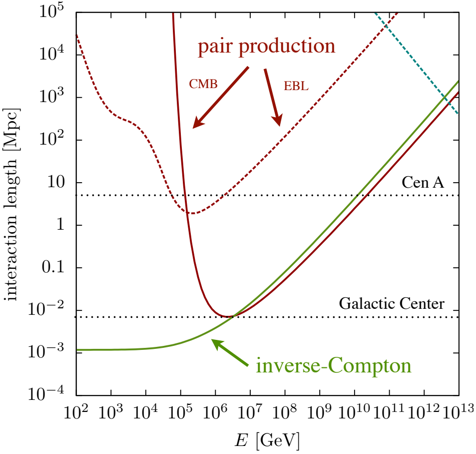
✘ strong pair production (PP) in CMB: $\gamma + \gamma_{\rm CMB} \to e^+ + e^-$

➜ PeV gamma-ray only observable locally ($\lesssim 10$kpc)

✔ recyling of gamma-rays via inverse Compton scattering (ICS): $e^\pm + \gamma_{\rm CMB} \to e^\pm + \gamma$

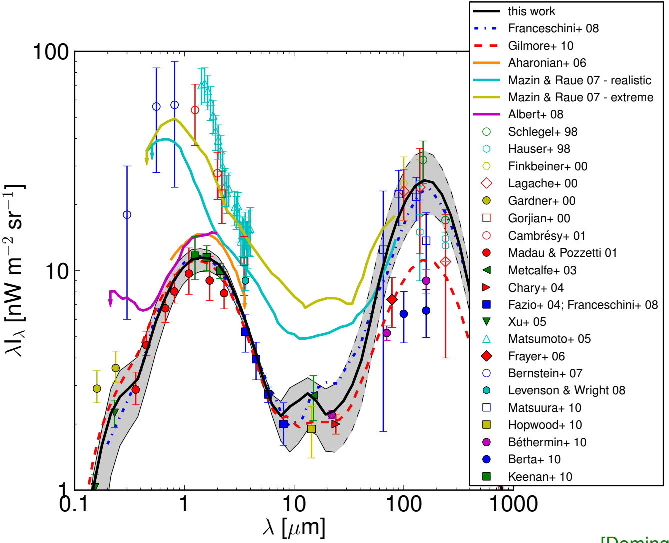
- rapid cascade interactions produce universal GeV-TeV emission

[Berezinsky&Smirnov'75]



[MA'11]

Extra-galactic background light (EBL)



[Dominguez *et al.* '10]

Tension with Gamma-Ray Background

- neutrino and γ-ray fluxes from CR collisions with gas (pp scenario) follow initial CR spectrum $\propto E^{-\Gamma}$

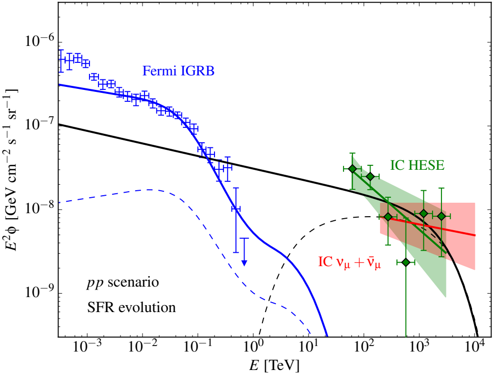
➜ constrained by *Fermi* IGRB:
[Murase, MA & Lacki'13; Chang & Wang'14]

$$\Gamma \lesssim 2.15 - 2.2$$

✘ combined IceCube analysis:

$$\Gamma \simeq 2.4 - 2.6$$

- *Are the sources responsible for 1-10 TeV neutrinos hidden?*
[Murase, Guetta & MA'15]



[Murase, MA & Lacki'14; Tamborra, Ando & Murase'14]
[Ando, Tamborra & Zandanel'15]
[Bechtol, MA, Ajello, Di Mauro & Vandenbroucke'15]

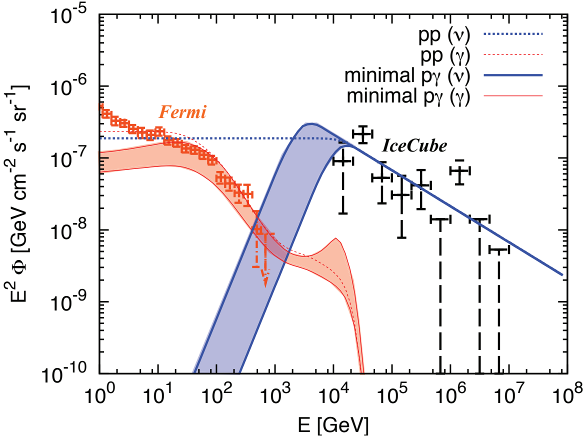
Fermi IGRB and $p\gamma$ Scenarios?

- also strong constraints from cascade emission of $p\gamma$ scenarios

- **high pion production efficiency** implies strong $\gamma\gamma$ absorption in sources

➜ Are strong neutrino sources **hidden** in γ-rays?

[Murase, Guetta & MA'15]



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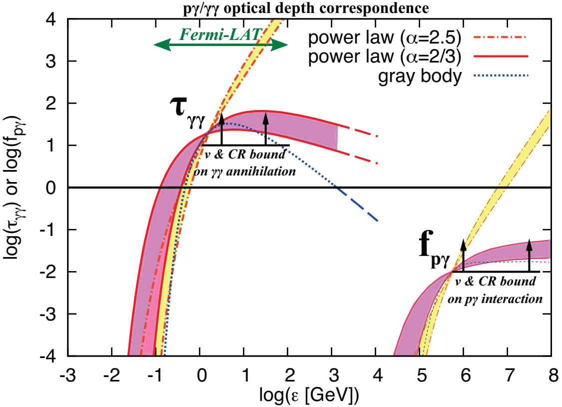


Ultra-High Energy Cosmic Rays

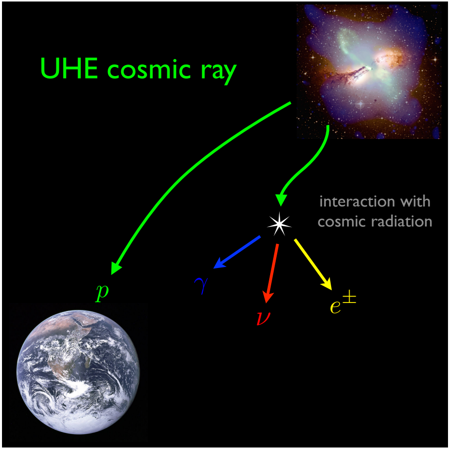
- particle confinement during acceleration requires: [Hillas'84]

$$E \lesssim 10^{18}\,\mathrm{EeV}\,(B/1\mu\mathrm{G})\,(R/1\mathrm{kpc})$$

✘ *low statistics:*
large uncertainties in chemical composition and spectrum!

✘ *"GZK" horizon* ($\lesssim 200$ Mpc):
resonant interactions of CR nuclei with CMB photons
[Greisen'66;Zatsepin & Kuzmin'66]

✔ "guaranteed flux" of **secondary γ-ray and neutrino emission**
[Berezinsky&Zatsepin'70;Berezinsky&Smirnov'75]



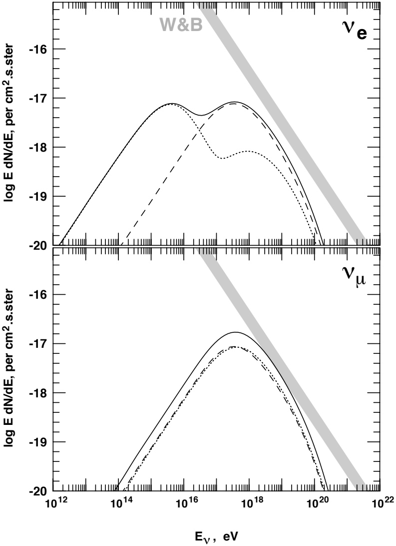
Cosmogenic ("GZK") Neutrinos

- Greisen-Zatsepin-Kuzmin (GZK) interactions of ultra-high energy CRs with cosmic microwave background (CMB) [Greisen'66;Zatsepin/Kuzmin'66]
- "GZK"-neutrinos at EeV energies from pion decay [Berezinsky/Zatsepin'69]
- three neutrinos ($\nu_\mu/\bar{\nu}_\mu/\nu_e$) from π^+:

$$E_{\nu_\pi} \simeq \frac{1}{4}\langle x\rangle E_p \simeq \frac{1}{20}E_p$$

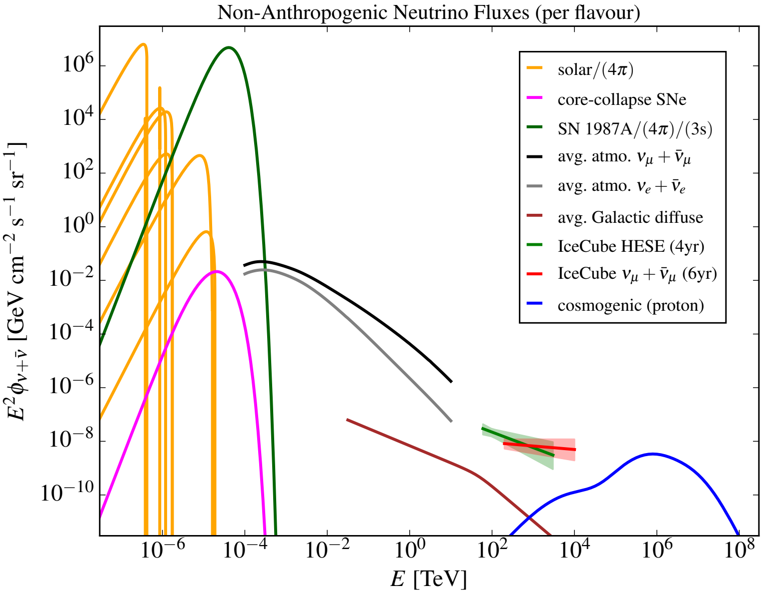
- one neutrino from neutron decay:

$$E_{\bar{\nu}_e} \simeq \frac{m_n - m_p}{m_n}E_p \simeq 10^{-3}E_p$$



[Engel, Stanev & Seckel'01]

Non-Anthropogenic Neutrino Fluxes



Cosmogenic (“GZK”) Neutrinos

- Observation of UHE CRs and extragalactic radiation backgrounds “guarantee” a flux of high-energy neutrinos, in particular via resonant production in CMB.

  [Berezinsky & Zatsepin’69]

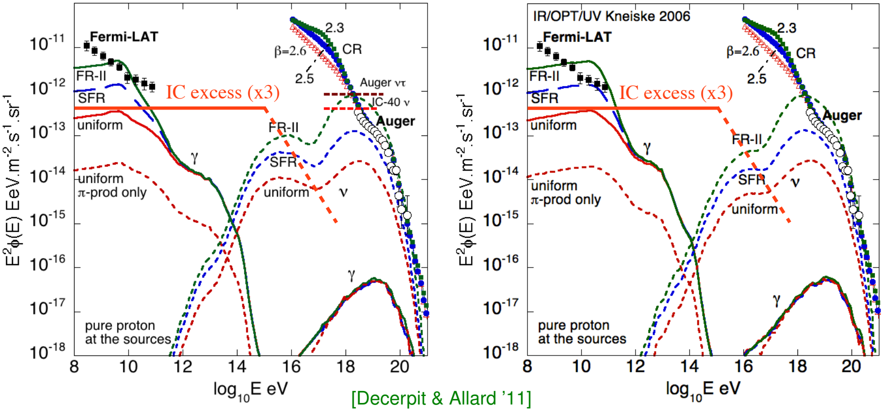
- “Guaranteed”, but with many model uncertainties and constraints:
  - **(low cross-over) proton models + CMB (+ EBL)**

    [Berezinsky & Zatsepin’69; Yoshida & Teshima’93; Protheroe & Johnson’96; Engel, Seckel & Stanev’01; Fodor, Katz, Ringwald &Tu’03; Barger, Huber & Marfatia’06; Yuksel & Kistler’07; Takami, Murase, Nagataki & Sato’09, MA, Anchordoqui & Sarkar’09, Heinz, Boncioli, Bustamante & Winter’15]
  - **+ mixed compositions**

    [Hooper, Taylor & Sarkar’05; Ave, Busca, Olinto, Watson & Yamamoto’05; Allard, Ave, Busca, Malkan, Olinto, Parizot, Stecker & Yamamoto’06; Anchordoqui, Goldberg, Hooper, Sarkar & Taylor’07; Kotera, Allard & Olinto’10; Decerprit & Allard’11; MA & Halzen’12]
  - **+ extragalactic γ-ray background limits**

    [Berezinsky & Smirnov’75; Mannheim, Protheroe & Rachen’01; Keshet, Waxman, & Loeb’03; Berezinsky, Gazizov, Kachelriess & Ostapchenko’10; MA, Anchordoqui, Gonzalez–Garcia, Halzen & Sarkar’10; MA & Salvado’11; Gelmini, Kalashev & Semikoz’12]

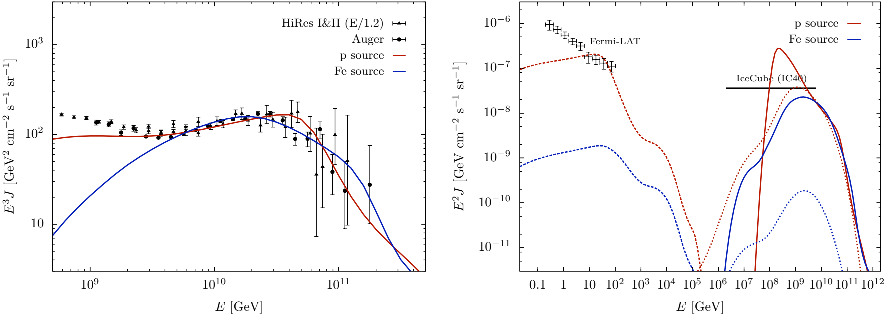
Cosmogenic (“GZK”) Neutrinos



[Decerpit & Allard ’11]

- ➜ neutrino flux depend on source **evolution model** (strongest for “FR-II”) and **EBL model** (highest for “Stecker” model)
- ✘ “Stecker” model disfavored by Fermi observations of GRBs
- ✘ strong evolution disfavored by Fermi diffuse background

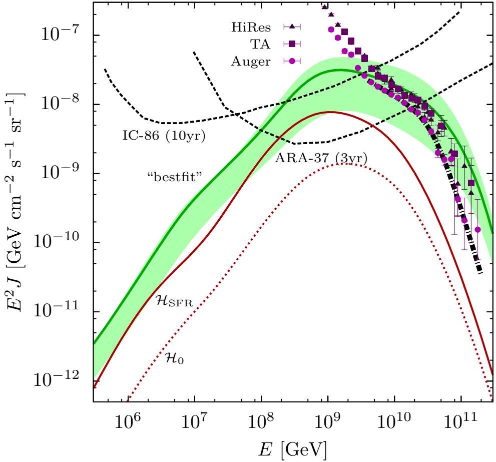
GZK Neutrinos from Heavy Nuclei



- UHE CR emission toy-model:
  - 100% proton: $n = 5$ & $z_{\rm max} = 2$ & $\gamma = 2.3$ & $E_{\rm max} = 10^{20.5}$ eV
  - 100% iron: $n = 0$ & $z_{\rm max} = 2$ & $\gamma = 2.3$ & $E_{\rm max} = 26 \times 10^{20.5}$ eV
- Diffuse spectra of cosmogenic γ-rays (dashed lines) and neutrinos (dotted lines) **vastly different**. [MA&Salvado'11]

Guaranteed Cosmogenic Neutrinos

- ➜ **minimal** GZK flux from proton dominated models can be estimated from observed spectrum
- dependence on cosmic evolution of sources:
  - no evolution (dotted)
  - star-formation rate (solid)
- ➜ **ultimate test** of UHE CR proton models feasible with future observatories like ARA.



[MA & Halzen'12]

Neutrinos from the Sources of UHE CRs

- UHE CR proton emission rate density:

$$E_p^2 Q_p(E_p) \simeq (1-2)\times 10^{44}\,\mathrm{erg\,Mpc^{-3}\,yr^{-1}}$$

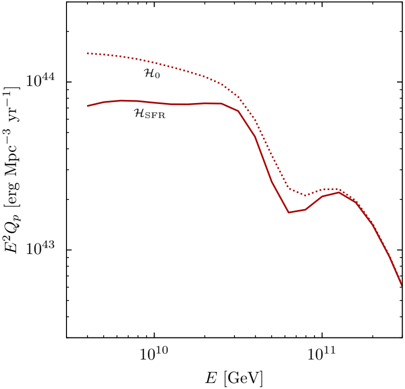
- two models for cosmic evolution
  - no evolution:

$$\rho_0(z) = \rho(0)\Theta(2-z)$$

  - evolution following the star-formation rate (SFR):

$$\rho_{\rm SFR}(z) = \begin{cases} (1+z)^{3.4} & z<1\,, \\ N_1\,(1+z)^{-0.3} & 1<z<4\,, \\ N_1\,N_4\,(1+z)^{-3.5} & z>4 \end{cases}$$

[Hopkins&Beacom'98]



[MA&Halzen'12]

Calorimetric Limit

- corresponding per flavour neutrino flux ($\xi_z \simeq 0.5 - 2.4$ and $K_\pi \simeq 1 - 2$):

$$E_\nu^2 \phi_\nu(E_\nu) \simeq f_\pi \frac{\xi_z K_\pi}{1 + K_\pi} (2 - 4) \times 10^{-8}\,\mathrm{GeV\,cm^{-2}\,s^{-1}\,sr}$$

- **Waxman-Bahcall bound:** $f_\pi \leq 1$ [Waxman & Bahcall'98]

- $f_\pi \simeq 1$ requires efficient pion production

✘ how to reach $E_{\max} \simeq 10^{20}$ eV in environments of high energy loss?

➜ two-zone models: **accelerator + calorimeter**?

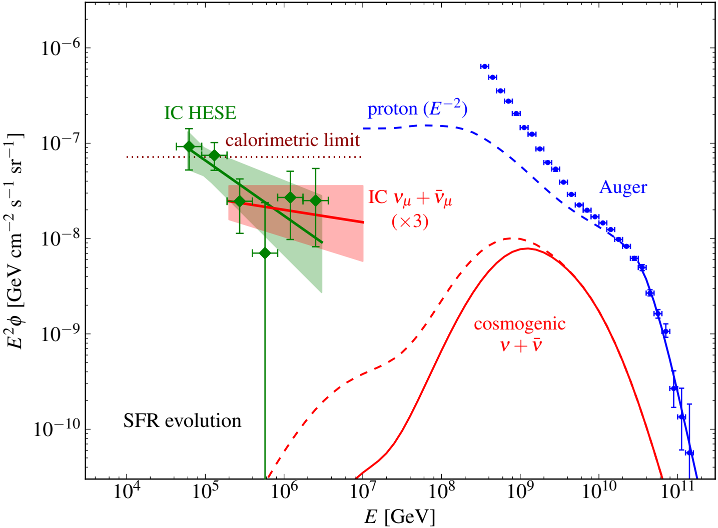
  - starburst galaxies [Loeb & Waxman'06]
  - galaxy clusters

[Berezinsky, Blasi & Ptuskin'96]

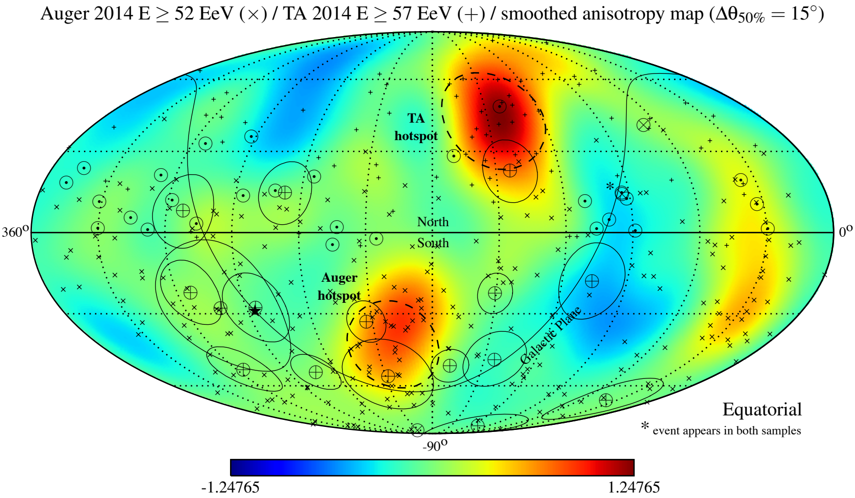
[Beacom & Murase'13]

Messier 82 (M82)

Calorimetric Limit

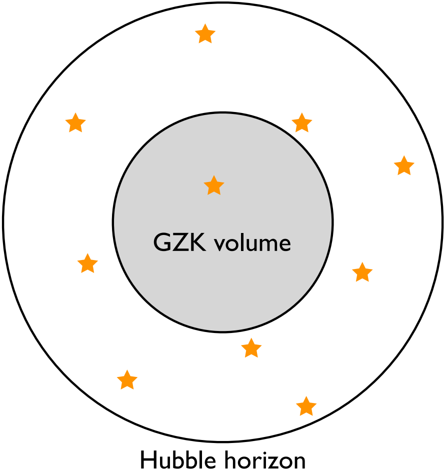


Probe: Cross-Correlation with UHE CRs



- $\theta_{\rm rms} \simeq 1^\circ \; (D/\lambda_{\rm coh})^{1/2}(E/55{\rm EeV})^{-1}(\lambda_{\rm coh}/1{\rm Mpc})\;(B/1{\rm nG})$ [Waxman & Miralda-Escude'96]
- "hot spots" (dashed), but no significant auto-correlation in Auger and Telescope Array data

Identification of Extragalactic Point-Sources?



- Do astrophysical neutrinos correlate with sources of UHE CRs?
- UHE CRs trace sources within

$$\lambda_{\rm GZK} \simeq 200\ \text{Mpc}$$

- neutrinos visible up to Hubble horizon

$$\lambda_{\rm Hubble} \simeq 4.4\ \text{Gpc}$$

➜ maximal overlap:

$$\lambda_{\rm GZK}/\lambda_{\rm Hubble} \sim 5\%$$

- HESE 4yr : ca. 30 signal events

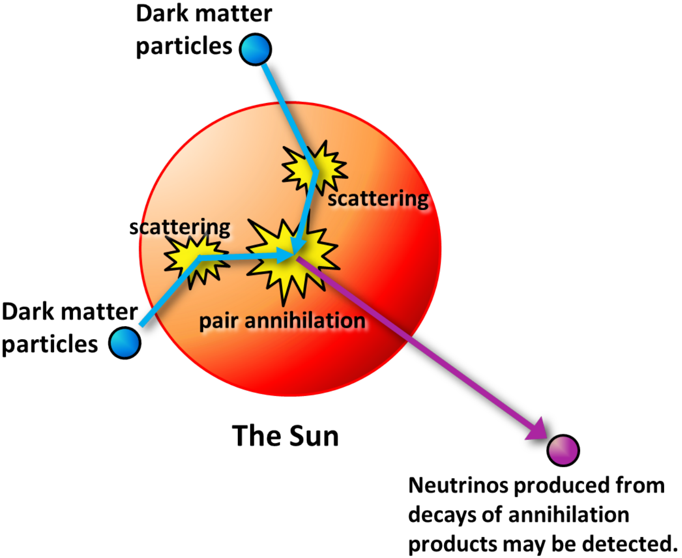
✘ only $1-2$ neutrinos expected to correlate

✘ magnetic deflections, angular resolution, incompleteness,. . .

Exotics at Neutrino Telescopes

- Exotic Cherenkov signals:
  - Monopoles (+ Q-Balls & Nuclearities)
  - long-lived CHAMPs, *e.g.* NLSPs, NLKPs
- Exotic flavor compositions:
  - quantum decoherence, violation of Lorentz invariance,. . .
- Exotic neutrino interactions:
  - cross section, inelasticities, multiplicities, neutrino decay. . .
- Exotic neutrino sources:
  ➜ WIMP annihilation and decay
  - alternative DM candidates
  - non-standard DM messengers
- Exotic “noise” ?:
  - supernova detetection, photon oscillations,. . .
- . . .

Dark Matter and the Sun



[Super-Kamiokande]

Dark Matter and the Sun

- Number of dark matter particles N in Sun determined by annihilation (A) and capture (C):

$$\dot{N} = C^{\odot} - A^{\odot} N^2$$

- spin-dependent interactions:

$$C^{\odot}_{\rm SD} \simeq 3.35 \times 10^{20} \frac{\rho_{0.3}}{\bar{v}^3_{270}} \left(\frac{\sigma_{\rm H,SD}}{10^{-6}\,{\rm pb}}\right) \left(\frac{100\,{\rm GeV}}{m_{\rm DM}}\right)^2 {\rm s}^{-1}$$

- spin-independent interactions:

$$C^{\odot}_{\rm SI} \simeq 3.35 \times 10^{20} \frac{\rho_{0.3}}{\bar{v}^3_{270}} \left(\frac{\sigma_{\rm H,SI} + 0.07\,\sigma_{\rm He,SI}}{10^{-6}\,{\rm pb}}\right) \left(\frac{100\,{\rm GeV}}{m_{\rm DM}}\right)^2 {\rm s}^{-1}$$

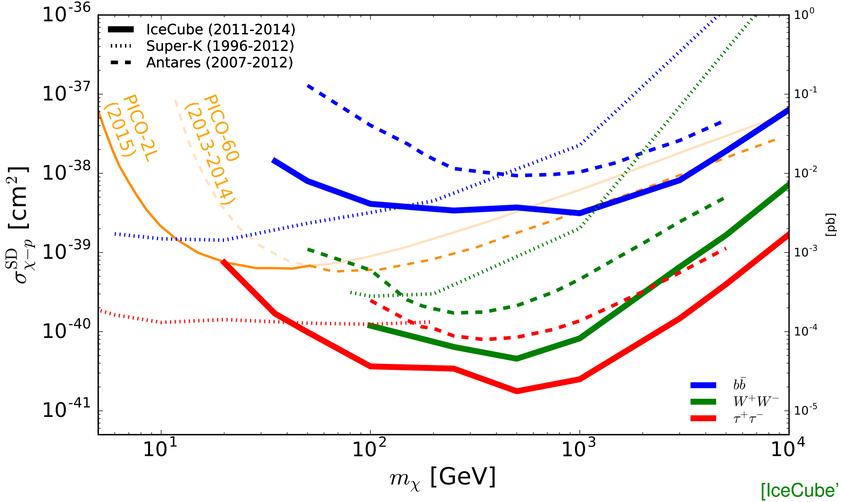
- annihilation:

$$A^{\odot} = \frac{\langle \sigma v \rangle}{V_{\rm eff}}$$

- equilibrium ($\dot{N} = 0$) decay rate:

$$\Gamma = \frac{1}{2} A^{\odot} N^2 = \frac{1}{2} C^{\odot}$$

Solar Limits

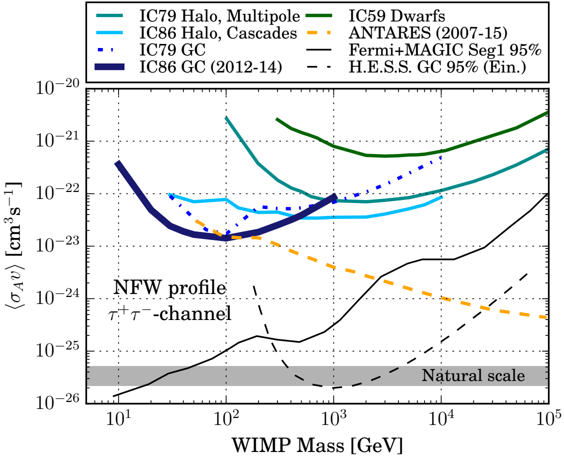


[IceCube'16]

90% CL **upper limit on the spin-dependent WIMP-nucleon cross section**

for hard to soft ($\tau^+\tau^-$, W^+W^-, $b\bar{b}$) annihilation channels

Comparison of DM Annihilation Limits



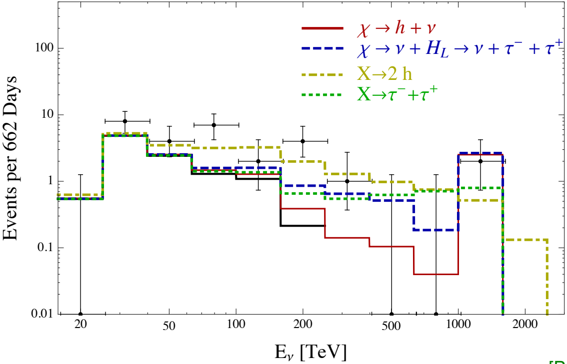
[IceCube'16]

90% CL **upper limit on the DM annihilation cross section** for $\tau^+\tau^-$ emission

PeV Dark Matter Decay???

- Is heavy (>PeV) DM decay responsible for IceCube's observation? [Feldstein *et al.*'13]
- **Initially** motivated by PeV "line-feature", but continuum spectrum with/without line spectrum also possible.

➜ Could be probed by **PeV γ-rays** from the Milky Way halo=. [MA & Murase'13]



[Bai, Lu & Salvado'13]

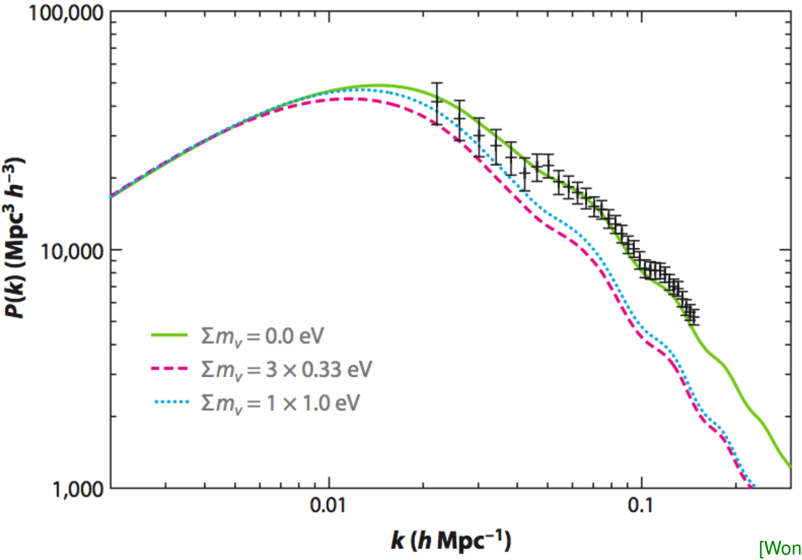
Summary

- Neutrinos are ideal cosmic messengers. . .
  - ✔ no deflection in magnetic fields
  - ✔ negligible absorption during propagation
  - ✔ “cleaner” astrophysical backgrounds
- . . . but hard to catch.
  - ✘ small neutrino cross section requires large detector
  - ✘ sophisticated background shielding/rejection
- Predicted astrophysical neutrino background range from **meV** (CνB) to **EeV** (cosmogenic neutrinos).
- Some neutrino fluxes have **well-known origin** (solar neutrinos, atmospheric neutrino, core-collapse supernovae) and can be used as **probes of fundamental neutrino properties**.
- Very-high energy neutrino emission is presently **poorly understood** and needs to be identified.

➜ Multi-messenger astronomy can provide guidance.

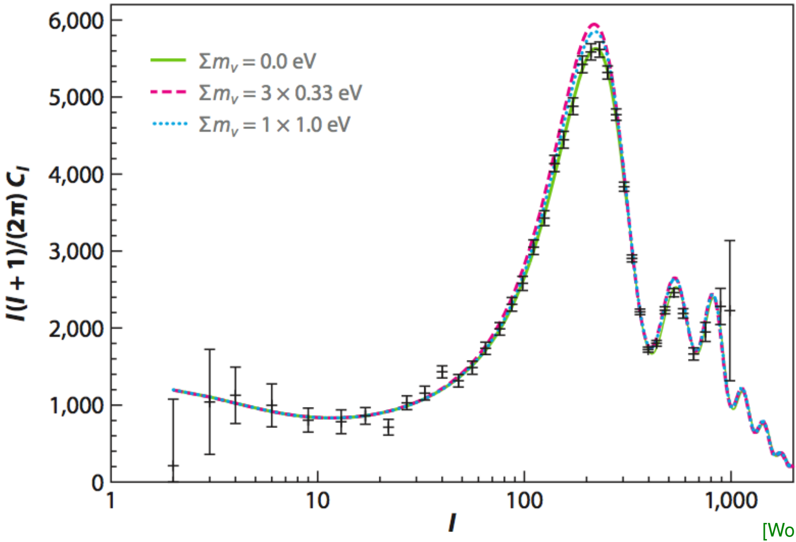
Appendix

Cosmic Neutrino Mass Bounds



[Wong'11]

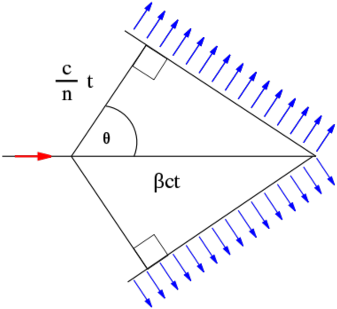
Cosmic Neutrino Mass Bounds

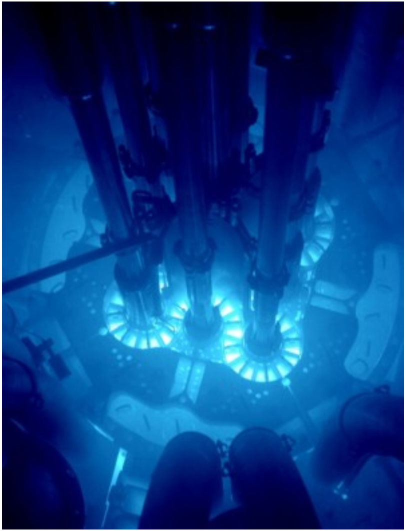


[Wong'11]

Cherenkov Radiation

- neutrino interaction creates high-energetic charged particle
- charged particles have velocity faster than the speed of light (in water or ice)
- Cherenkov light is emitted along the particle tracks





[Advanced Test Reactor (Idaho)]

“Nu-Fit” results

NuFIT 3.0 (2016)

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 0.83$)		Any Ordering
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range	3σ range
$\sin^2\theta_{12}$	$0.306^{+0.012}_{-0.012}$	$0.271 \to 0.345$	$0.306^{+0.012}_{-0.012}$	$0.271 \to 0.345$	$0.271 \to 0.345$
$\theta_{12}/^\circ$	$33.56^{+0.77}_{-0.75}$	$31.38 \to 35.99$	$33.56^{+0.77}_{-0.75}$	$31.38 \to 35.99$	$31.38 \to 35.99$
$\sin^2\theta_{23}$	$0.441^{+0.027}_{-0.021}$	$0.385 \to 0.635$	$0.587^{+0.020}_{-0.024}$	$0.393 \to 0.640$	$0.385 \to 0.638$
$\theta_{23}/^\circ$	$41.6^{+1.5}_{-1.2}$	$38.4 \to 52.8$	$50.0^{+1.1}_{-1.4}$	$38.8 \to 53.1$	$38.4 \to 53.0$
$\sin^2\theta_{13}$	$0.02166^{+0.00075}_{-0.00075}$	$0.01934 \to 0.02392$	$0.02179^{+0.00076}_{-0.00076}$	$0.01953 \to 0.02408$	$0.01934 \to 0.02397$
$\theta_{13}/^\circ$	$8.46^{+0.15}_{-0.15}$	$7.99 \to 8.90$	$8.49^{+0.15}_{-0.15}$	$8.03 \to 8.93$	$7.99 \to 8.91$
$\delta_{\rm CP}/^\circ$	261^{+51}_{-59}	$0 \to 360$	277^{+40}_{-46}	$145 \to 391$	$0 \to 360$
$\dfrac{\Delta m^2_{21}}{10^{-5}\ {\rm eV}^2}$	$7.50^{+0.19}_{-0.17}$	$7.03 \to 8.09$	$7.50^{+0.19}_{-0.17}$	$7.03 \to 8.09$	$7.03 \to 8.09$
$\dfrac{\Delta m^2_{3\ell}}{10^{-3}\ {\rm eV}^2}$	$+2.524^{+0.039}_{-0.040}$	$+2.407 \to +2.643$	$-2.514^{+0.038}_{-0.041}$	$-2.635 \to -2.399$	$\begin{bmatrix} +2.407 \to +2.643 \\ -2.629 \to -2.405 \end{bmatrix}$

[Esteban, Gonzalez-Garcia, Maltoni, Martinez-Soler & Schwetz’16; `www.nu-fit.org`]