Cosmic Ray Anisotropy Workshop

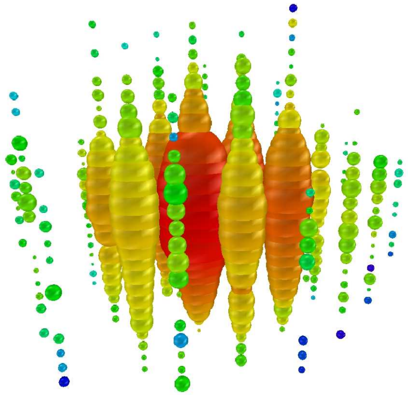
Sept 2013

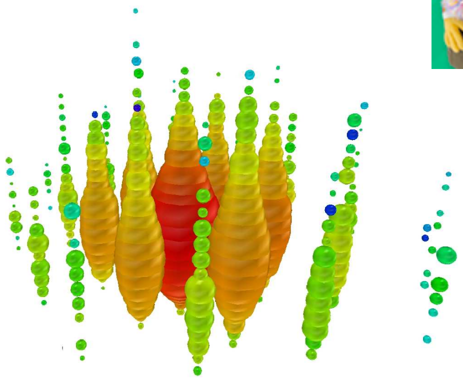
Large scale anisotropy of cosmic rays and directional neutrino signals from Galactic sources

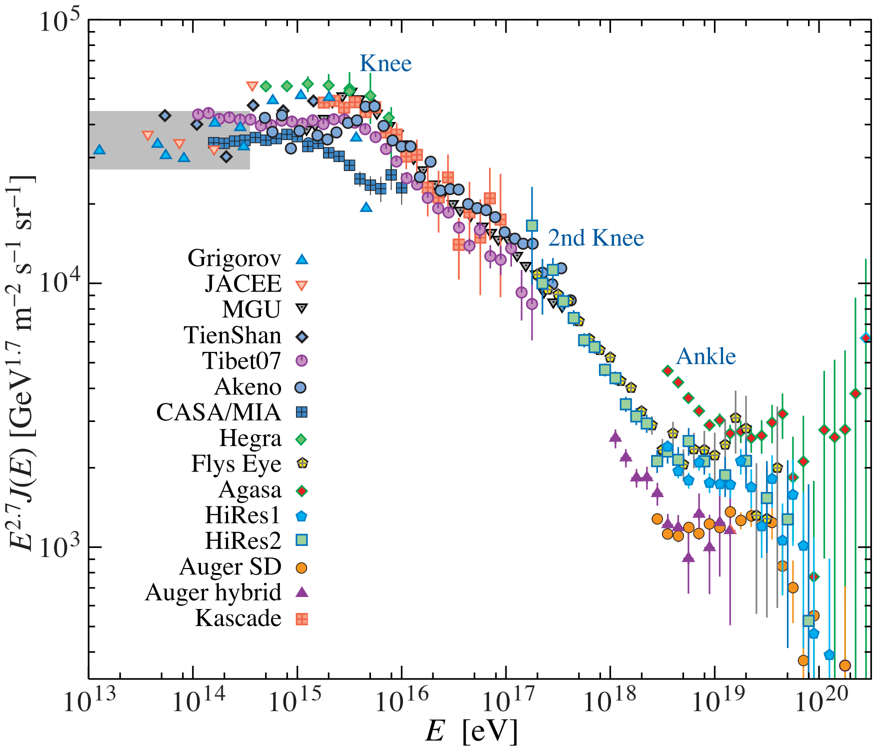
Luis A. Anchordoqui

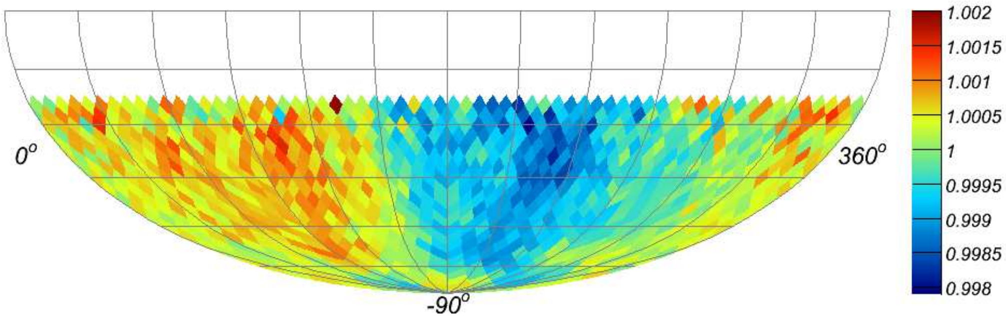
Outline

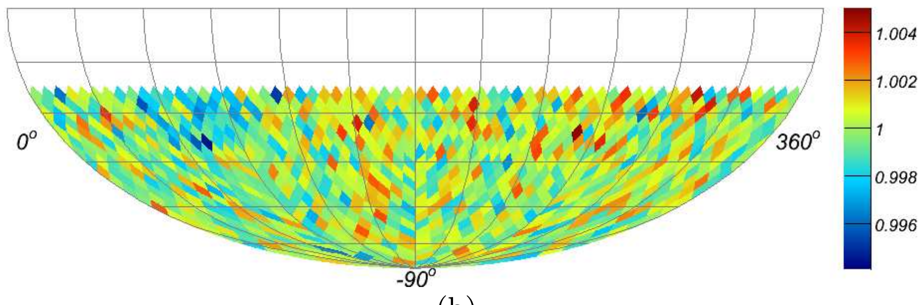
➢ Shape of the source spectrum











Outline

- **Shape of the source spectrum**
- **Waxman-Bahcall energetics**
- **Consistency with upper limits on the diffuse gamma-ray flux**
- **Conclusions**

Based on:

1- LAA, Goldberg, Lynch, Olinto, Paul, Weiler, arXiv:1306.5021

2- LAA, Goldberg, Olinto, Paul, Vlcek, Weiler, to appear

Hypothesis: cosmic neutrino flux per flavor follows unbroken power law

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- ➢ 26 events $E_\nu/\text{PeV} \in (0.05, 1)$ ☛ 10 atmospheric background
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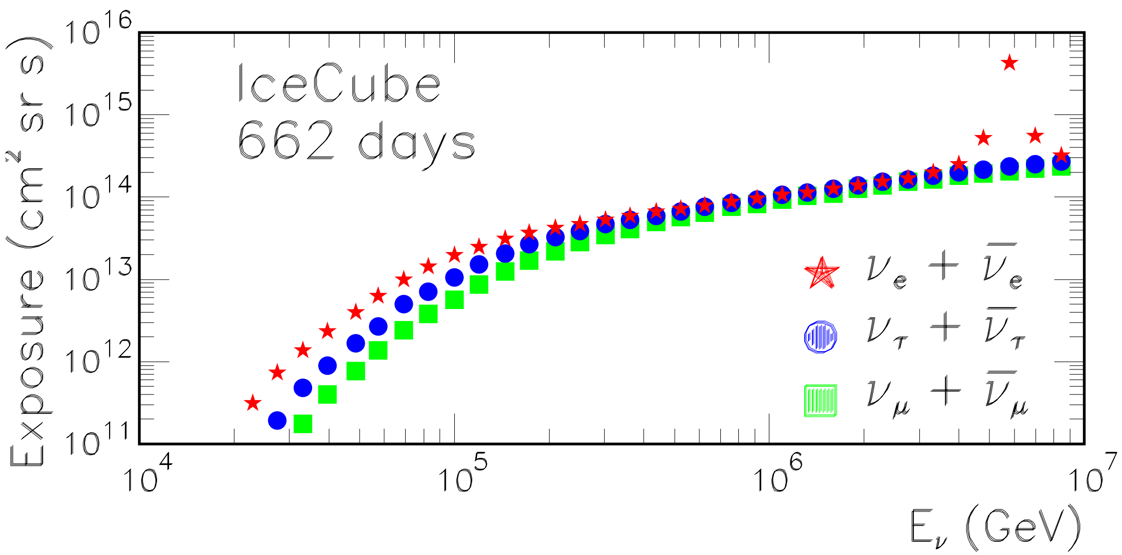
Fit neutrino flux using IceCube's energy-dependent flavor-dependent exposure



Flavor-averaged normalization Φ_0 in units of $(\mathrm{GeV} \cdot \mathrm{cm}^2 \cdot \mathrm{s} \cdot \mathrm{sr})^{-1}$

Γ	$\Phi_0^{E<1\mathrm{PeV}}$	$\Phi_0^{1\mathrm{PeV}<E<2\mathrm{PeV}}$	$\Phi_{68}^{\max}$	$\Phi_{90}^{\max}$
2.0	1.66×10^{-8}	9.50×10^{-9}	3.94×10^{-9}	7.44×10^{-9}
2.1	5.70×10^{-8}	3.91×10^{-8}	1.84×10^{-8}	3.49×10^{-8}
2.2	1.95×10^{-7}	1.61×10^{-7}	0.862×10^{-7}	1.63×10^{-7}
2.3	6.63×10^{-7}	6.62×10^{-7}	4.02×10^{-7}	7.61×10^{-7}
2.4	2.24×10^{-6}	2.72×10^{-6}	1.88×10^{-6}	3.55×10^{-6}
2.5	7.54×10^{-6}	11.2×10^{-6}	8.73×10^{-6}	16.5×10^{-6}

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-and hence with hypothesis of unbroken power law-

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- Overall consistency of $\Gamma = 2.3$ across all 3 energy bins is at $\approx 1.5\sigma$ level

Comparing $E_{\pi^\pm}$ at source to E_ν detected at Earth one gets energy conservation relation

$$\epsilon_\nu \, \epsilon_{\pi^\pm} \int_{E_1}^{E_2} \frac{dF^p_{\rm CR}}{dE\, dA\, dt} \, E dE = \int_{E_{\nu 1}}^{E_{\nu 2}} \frac{dF_\nu}{dE_\nu \, dA\, dt} \, E_\nu dE_\nu$$

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Assumption of flavor equilibration ☛ $\Phi_0^{\rm total} = 3\Phi_0$

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$$= A\, C^p_{\rm CR} \frac{\left({E_1}^{(2-\Gamma)} - {E_2}^{(2-\Gamma)}\right)}{\Gamma - 2}$$

Inverting this result and using the fact that ${E_2}^{(2-\Gamma)} \ll {E_1}^{(2-\Gamma)}$

☛ $$C^p_{\rm CR} = \frac{(\Gamma - 2)\, E_1^{(\Gamma-2)} \frac{d\epsilon^p_{\rm CR}}{dt}[E_1, E_2]}{A}$$

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Leaky Box Model ☛ cosmic rays propagate freely in Galaxy contained by $\vec{B}$-field but with some probability to escape which is constant in time

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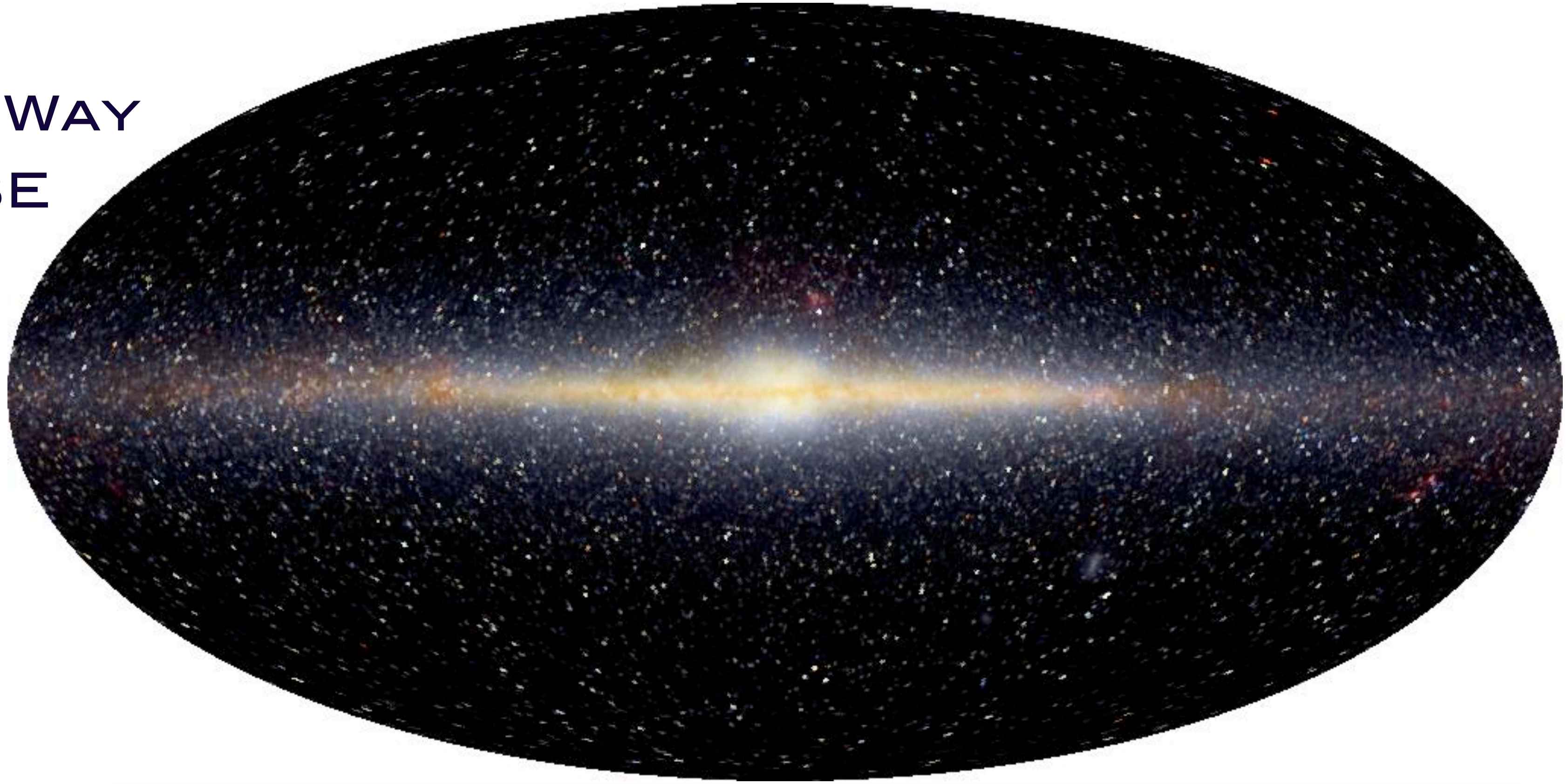
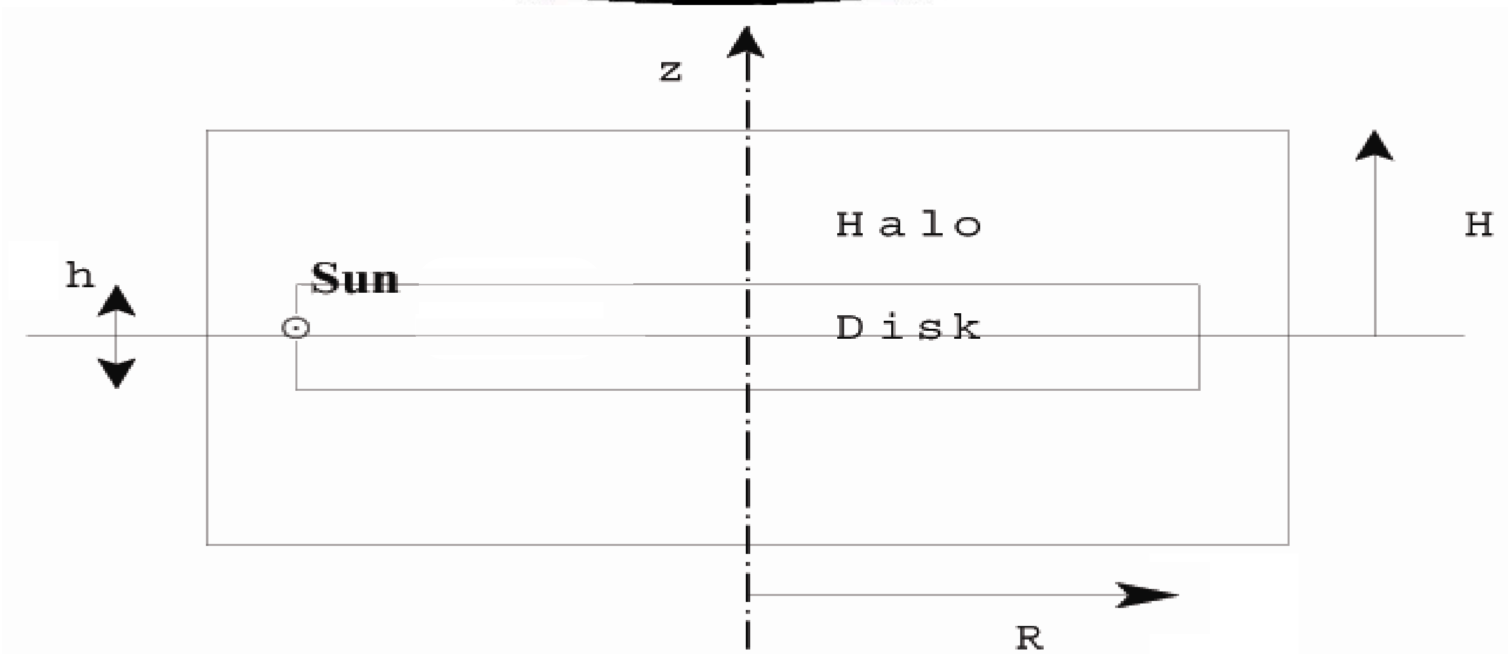
- This implies steeper cosmic ray injection spectrum ☛ $\alpha \simeq 2.4$

First Order Approximation

Milky Way
COBE





First Order Approximation (cont'd)

Steady-state diffusion equation

$$\nabla_i D_{ij}(\vec{r},E)\nabla_j n_{\rm CR}(\vec{r},E) + Q(\vec{r},E) = 0$$

$$D_{ij} = (D_\parallel - D_\perp)b_i b_j + D_\perp \delta_{ij} + D_A \epsilon_{ijk} b_k$$ diffusion tensor

$$b_i = B_{{\rm reg},i}/B_{\rm reg}$$ ☛ unit vector along regular galactic magnetic field

➢Symmetric terms of D_{ij} contain diffusion coefficients parallel (field-aligned $D_\parallel$) and perpendicular (transverse $D_\perp$) which describe diffusion due to small-scale turbulent fluctuations

➢Antisymmetric (Hall) diffusion coefficient D_A responsible for macroscopic drift currents

cosmic ray current ☛ $J_i = -D_{ij}\nabla_j n_{\rm CR}$

➢Anisotropy vector $\delta_i = \dfrac{3\ J_i(\vec{r},E)}{n_{\rm CR}(\vec{r},E)\,c}$

➢Under assumption of azimuthal symmetry of system

$$J_r = -D_\perp \frac{\partial n_{\rm CR}}{\partial r} + D_A \frac{\partial n_{\rm CR}}{\partial z} \qquad J_\phi = 0 \qquad J_z = -D_A \frac{\partial n_{\rm CR}}{\partial r} - D_\perp \frac{\partial n_{\rm CR}}{\partial z}$$

Observatories which experience stable operation over a period of a year or more attain uniform exposure in right ascension ☛ α

Right ascension distribution of flux arriving at detector can be characterized by amplitudes and phases of its Fourier expansion

For n measurements α_i ☛

$$y = \frac{2}{N} \sum_{i=1}^{n} \frac{1}{\omega(\delta_i)} \sin \alpha_i$$

$$A = \sqrt{x^2 + y^2} \qquad \phi = \arctan \frac{y}{x}$$

$$x = \frac{2}{N} \sum_{i=1}^{n} \frac{1}{\omega(\delta_i)} \cos \alpha_i$$

$$N = \sum_{i=1}^{n} \frac{1}{\omega(\delta_i)}$$

relative exposure for declination δ_i

latitude of direction where flux is maximum

Component of anisotropy along Earth rotation axis ☛ $\delta_{\|} = \vec{\delta} \sin \lambda$

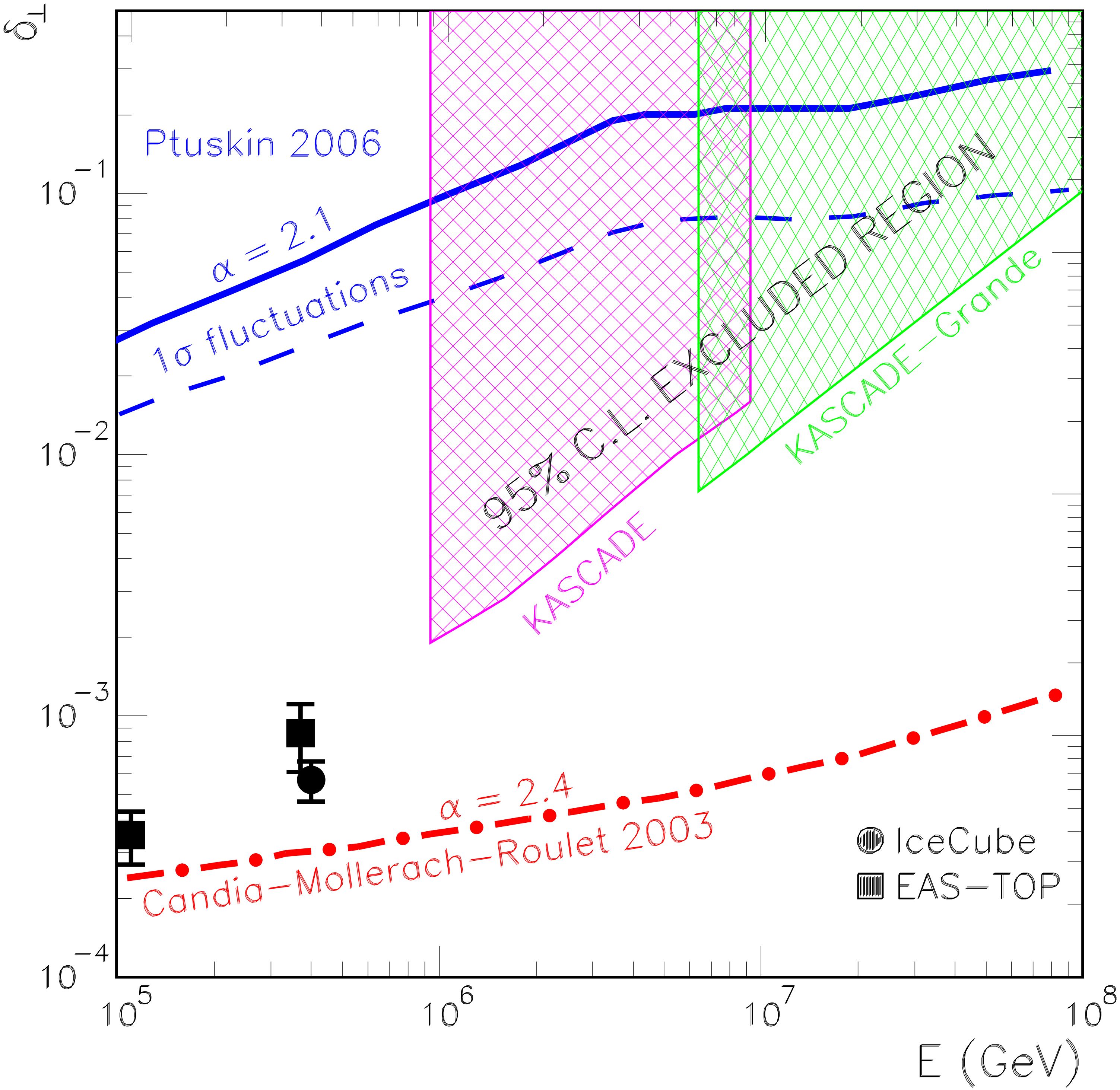
cannot be recovered from right ascension harmonic analysis

Component of anisotropy in equatorial plane $\delta_{\perp} = \vec{\delta} \cos \lambda = A/\overline{c_\delta}$

mean value of cosine of event declinations

[Aublin and Parizot, A.&A. **441** (2005) 407]

Theory and Observations



Profesionally done

$\alpha = 2.1$ excluded

$\alpha = 2.4$hhhmmm may be

[Amato and Blasi, JCAP **1201** (2012) 011]

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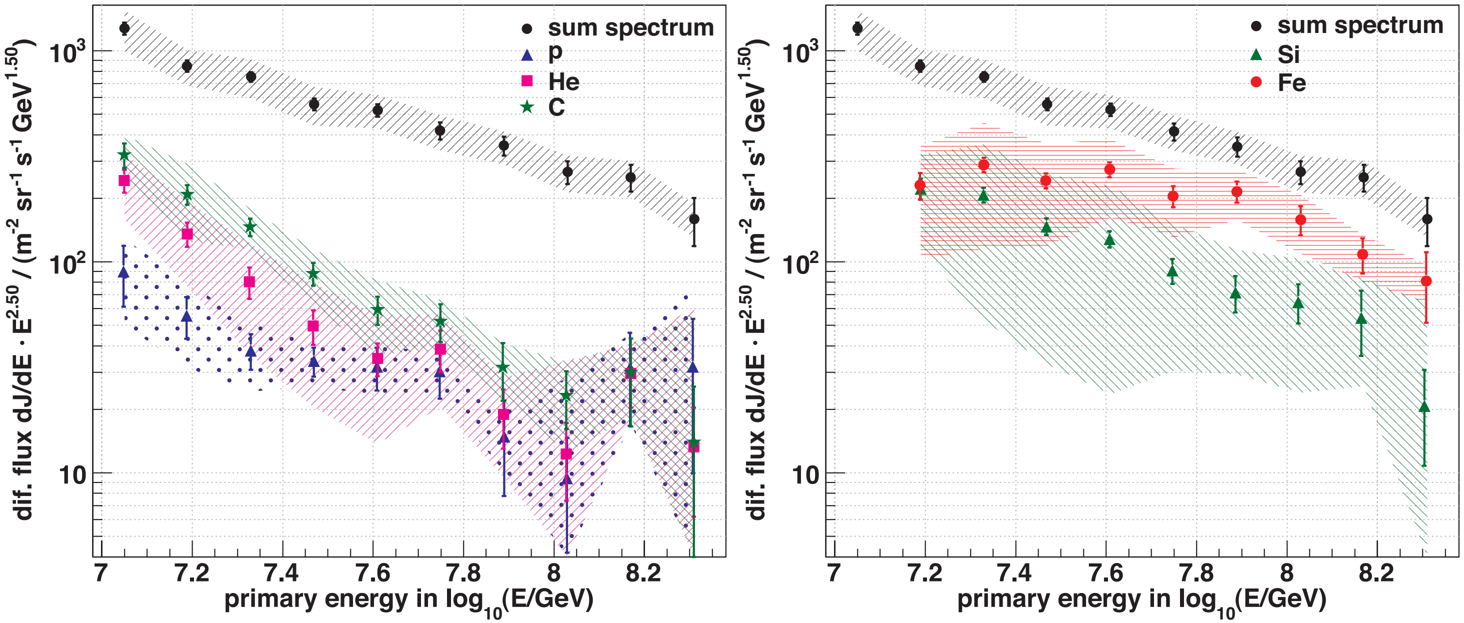
- Data from KASCADE-Grande indicate that at ~ 30 PeV

  flux of protons is about an order of magnitude smaller than all-species CR flux



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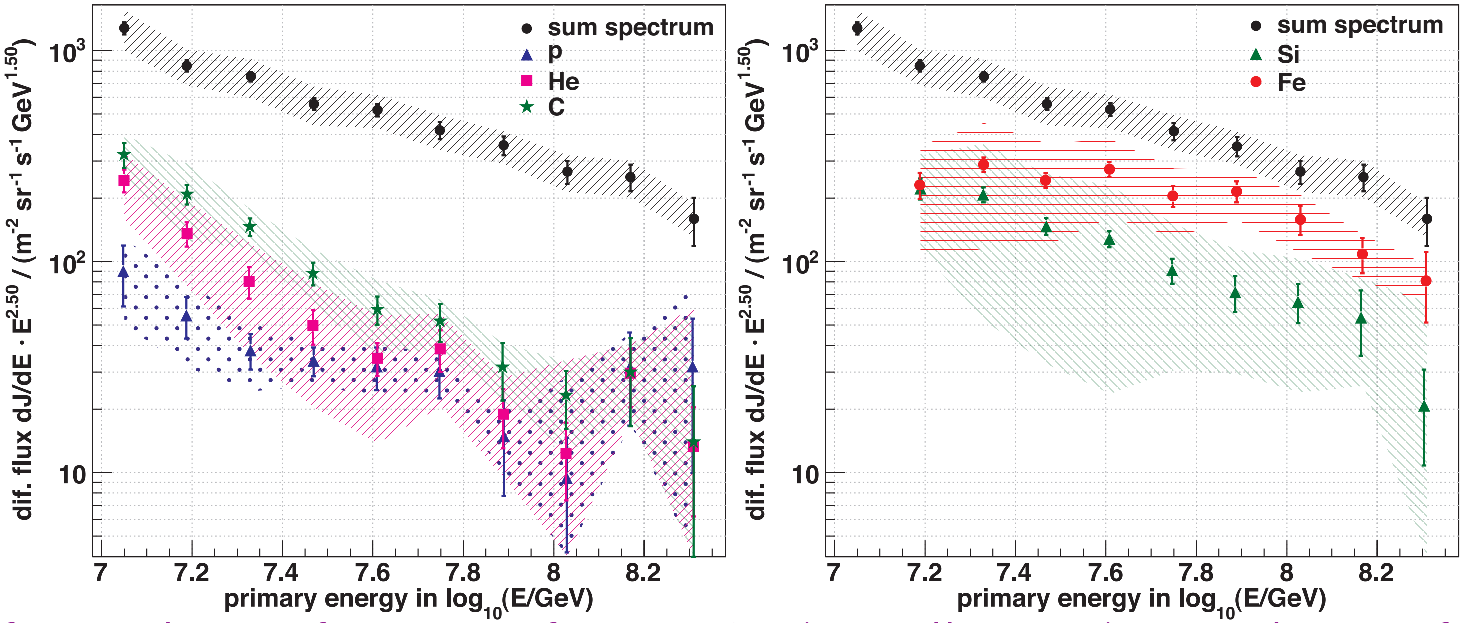

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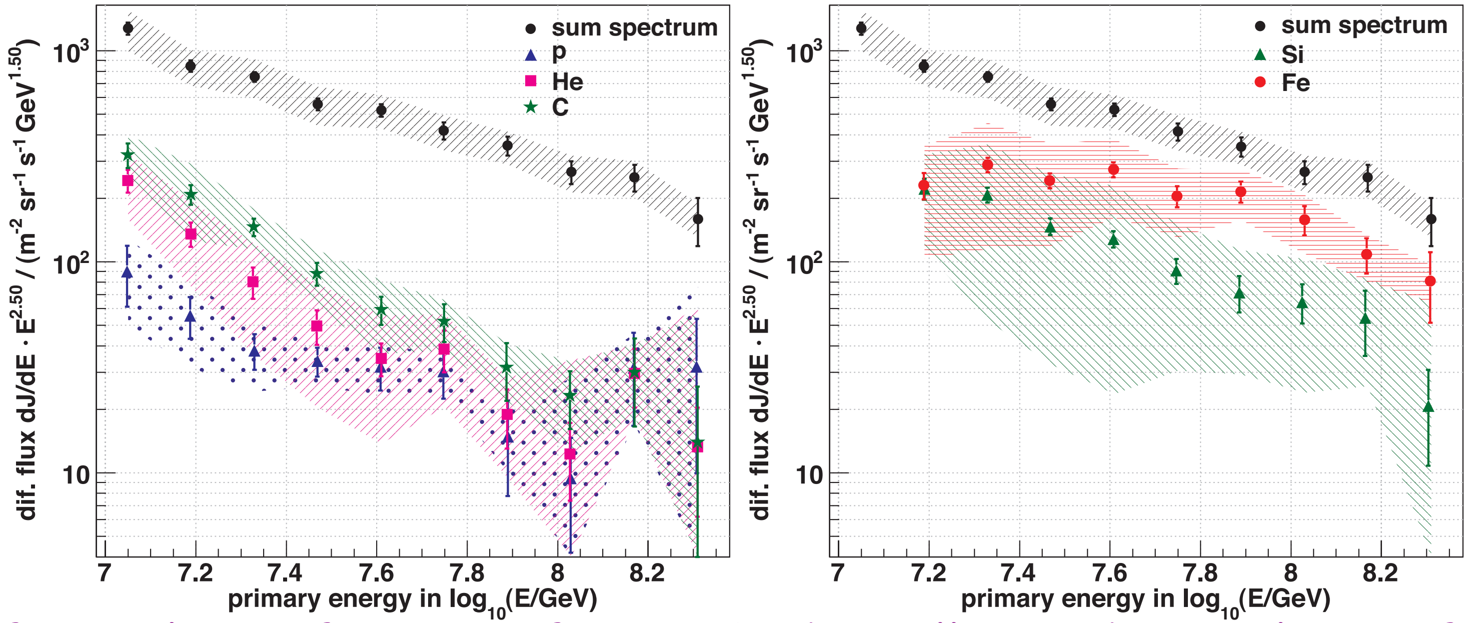

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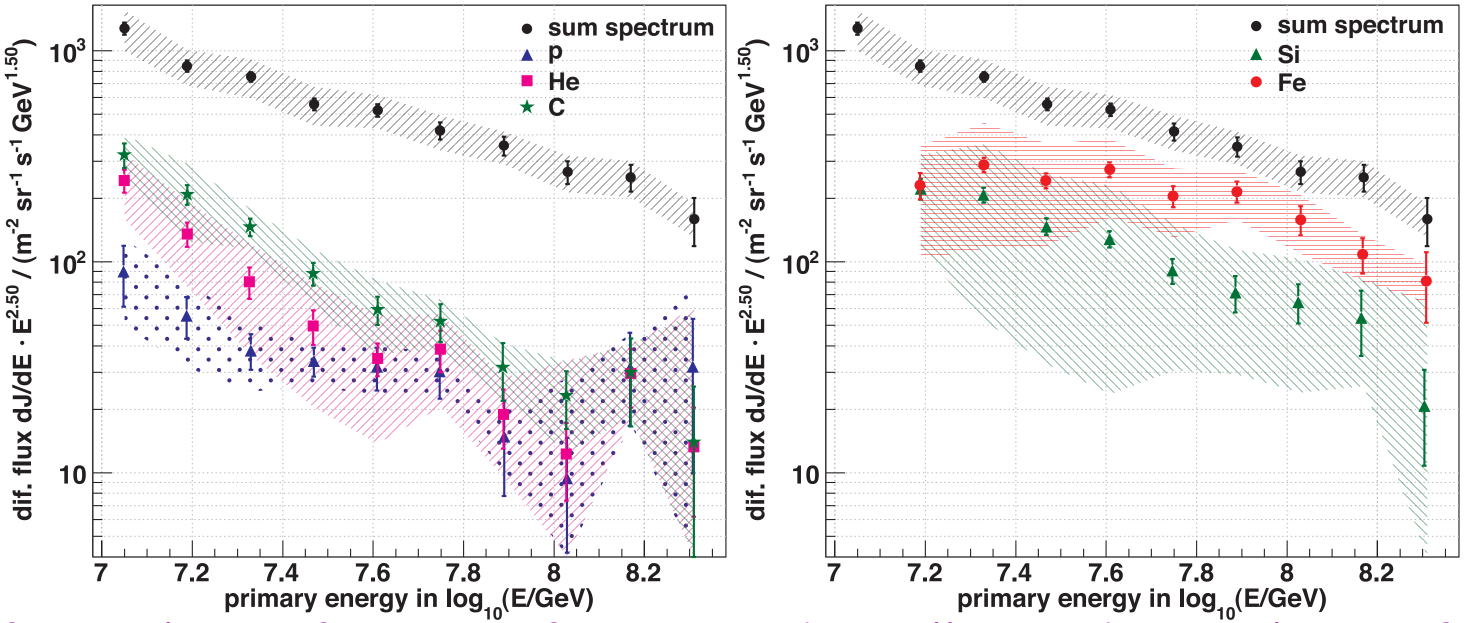

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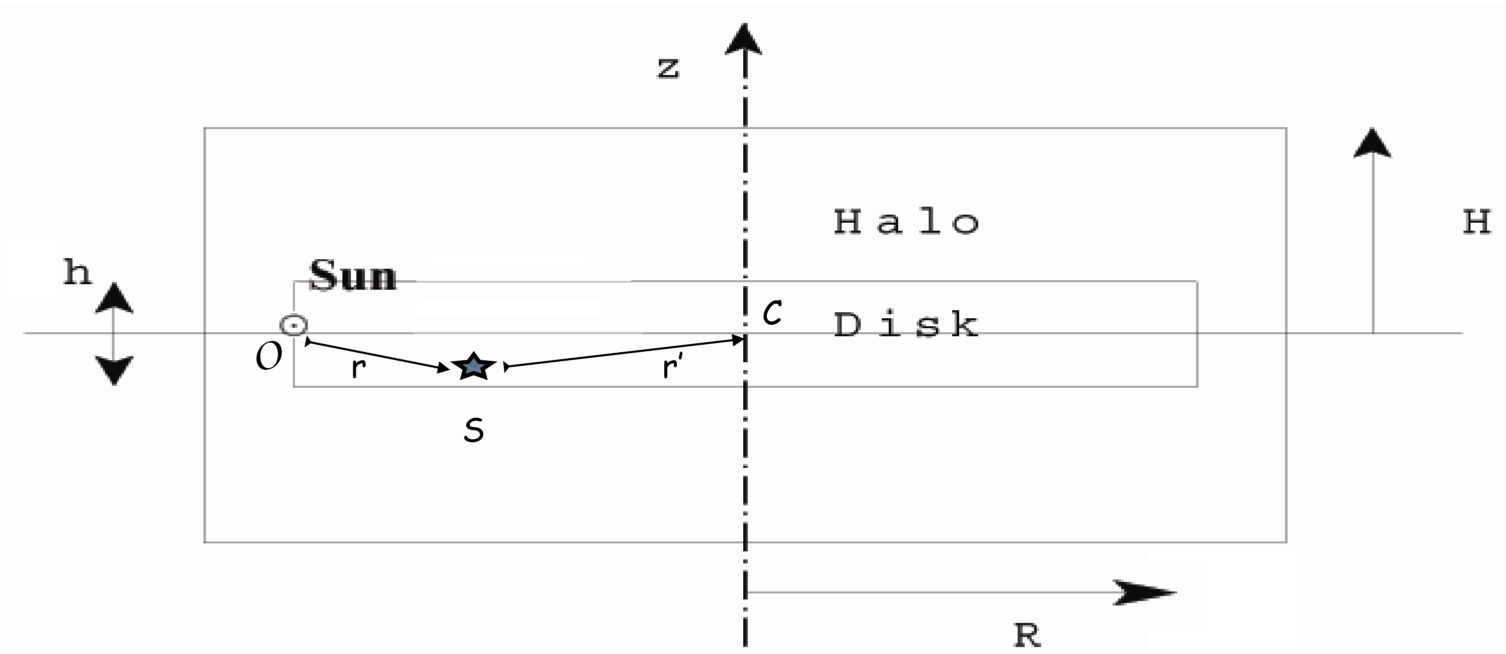
➢ From functional form of $\tau(E/Z)$

estimate survival probability for protons at 30 PeV to be 46% of that at $E_{\rm knee}$

proton fraction of total flux at injection ☛ $\zeta = 0.1/0.46 = 0.22$

Appropriately Weighted Surface Area for Arriving Flux



Energy-weighted neutrino flux from Galactic source distribution

(with normal incidence at O)

$$E_\nu \frac{dF_{\nu_\alpha}}{dAdtdE_\nu} = \frac{1}{4\pi} \sum_i \frac{P_i}{{r_i}^2}$$

$$= \frac{1}{4\pi} \sum_i \frac{P_i}{R^2 + 2R\, r_i' \cos\theta_i' + r_i'^2}$$

P_i is power output of source i and θ_i' is angle subtended by $\vec{r}_i{}'$ and $\vec{R}$

Assuming equal power for all sources (and thus equal power density per unit area of disk)

$$
\begin{aligned}
E_\nu \frac{dF_{\nu_\alpha}}{dA dt dE_\nu} &= \frac{1}{4\pi} \frac{P}{\pi R^2} \int_0^{r'_{\max}} r' dr' \int_0^{2\pi} d\theta' \frac{1}{R^2 + 2r' R \cos\theta' + r'^2} \\
&= \frac{1}{4\pi} \frac{P}{\pi R^2} \frac{1}{2} \int_0^{{r'_{\max}}^2} dr'^2 \frac{2\pi}{R^2 - r'^2} \\
&= \frac{P}{4\pi R^2} \ln\left[\frac{1}{1 - (r'_{\max}/R)^2}\right]
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Divergence is avoided by cutting off integral for sources within ring of radius h

at position of observer ☛ $r'_{\max} = R - h$

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$$= \frac{1}{4\pi}\frac{P}{\pi R^2}\frac{1}{2}\int_0^{{r'_{\rm max}}^2} dr'^2 \frac{2\pi}{R^2 - r'^2}$$

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After this regularization ☛ energy-weighted neutrino flux at Earth becomes

$$E_\nu \frac{dF_{\nu_\alpha}}{dA dt dE_\nu} = \frac{P}{4\pi R^2} \ln\left[\frac{1}{\tau(2-\tau)}\right]$$

↓ $\tau \equiv h/R$

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$$E_\nu \frac{dF_{\nu_\alpha}}{dAdtdE_\nu} = \frac{1}{4\pi}\frac{P}{\pi R^2}\int_0^{r'_{\rm max}} r'dr' \int_0^{2\pi} d\theta' \frac{1}{R^2 + 2r'R\cos\theta' + r'^2}$$

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For $h/R = 0.1$ ➡ $E_\nu \frac{dF_{\nu_\alpha}}{dAdtdE_\nu} = 1.66 \frac{P}{4\pi R^2}$

$$C^{p}_{\rm CR}(2.3) = \frac{0.3 \times (0.1\,{\rm PeV})^{0.3} \times 2\bar{\zeta} \times 10^{39}{\rm erg/s}}{4\pi(10\,{\rm kpc})^2}$$

$$\epsilon_{\pi^\pm}(2.3) = \left(\frac{1}{16}\right)^{-0.3} \frac{C_\nu(2.3)}{\epsilon_\nu\, C^{p}_{\rm CR}(2.3)} = \frac{0.08}{\bar{\zeta}\,\epsilon_\nu}$$

for pp collisions ☛ $\epsilon_\pi = \frac{3}{2}\,\epsilon_{\pi^\pm}$

for $p\gamma$ collisions ☛ $\epsilon_\pi = 2\,\epsilon_{\pi^\pm}$

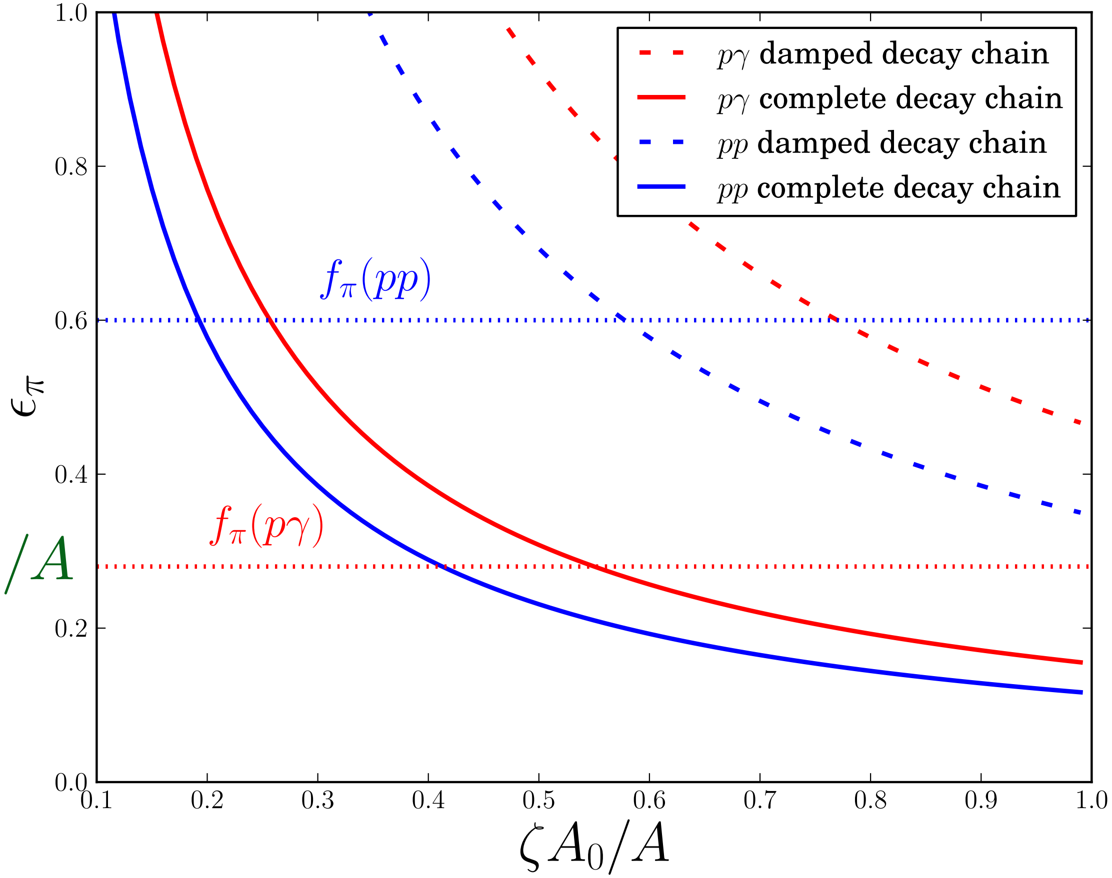
complete pion decay chain ☛ $\epsilon_\nu = \frac{3}{4}$

damped pion decay chain ☛ $\epsilon_\nu = \frac{1}{4}$

➢ We consider wide range for $\bar{\zeta} \equiv \zeta A_0/A$

with $0.22 \lesssim \bar{\zeta} \lesssim 0.44$

seemingly most realistic range



Consider uniform distribution of sources

$$\int_{E_\gamma^{\rm min}} \frac{dF_\gamma}{d\Omega dA dt dE_\gamma} dE_\gamma = \frac{1}{2} \int_{E_\gamma^{\rm min}/2} \sum_i e^{-\frac{r_i}{\lambda_{\gamma\gamma}}} \frac{dF_{\nu_\alpha}}{d\Omega dA dt dE_\nu} dE_\nu$$

[LAA, Goldberg, Halzen, and Weiler, PLB **600** (2004) 202]

For $\frac{E_\gamma^{\rm min}}{\rm GeV} = 3.30 \times 10^5,\ 7.75 \times 10^5,\ 2.450 \times 10^6$

CASA-MIA $90\%{\rm CL}$ upper limits on integral γ-ray flux are

$$\frac{I_\gamma}{\rm cm^{-2}\ s^{-1}\ sr^{-1}} < 1.0 \times 10^{-13},\ 2.6 \times 10^{-14},\ 2.1 \times 10^{-15}$$

Neglecting photon absorption on CMB

$$\frac{1}{\rm cm^{-2}\ s^{-1}\ sr^{-1}} \int_{E_\gamma^{\rm min}} \frac{dF_\gamma}{d\Omega dA dt dE_\gamma} dE_\gamma = 4.2 \times 10^{-14},\ 1.4 \times 10^{-14},\ 3.1 \times 10^{-15}$$

At 1 PeV absorption on CMB leads to 12% reduction in photon flux

Setting upper limit of integration to

$$\frac{E_\gamma^{\max}}{\mathrm{PeV}} = 6,\ 7,\ 8$$

we obtain

$$\int_{E_\gamma^{\min}}^{E_\gamma^{\max}} \frac{dF_\gamma}{d\Omega dA dt dE_\gamma} dE_\gamma = 2.1 \times 10^{-15},\ 2.3 \times 10^{-15},\ 2.4 \times 10^{-15}$$

Existing data still allow sufficient plausible wiggle room

for consistency with Galactic origin of IceCube flux

even if sources are optically thin

Moreover ☛ sources which are optically thin up to $E_\gamma \sim 100\ \mathrm{TeV}$

may not be optically thin at $E_\gamma > 100\ \mathrm{TeV}$

suggesting ☛ importance of photon bounds in establishing origin of IceCube events

should be considered with some caution

Take Home Message

- ➢ Explored level at which IceCube excess
  is consistent with unbroken power law spectrum
- ➢ Value of spectral index of 2.3 is in reasonable agreement with data
- ➢ pp collisions appear to be favored mechanism for ν production
- ➢ More data is needed...

MORE DATA IS COMING!!!