What cosmic-ray anisotropy tells us

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Topics

1. Introduction
2. Measurements
3. Modeling
4. Intermittency
5. Outlook

Introduction

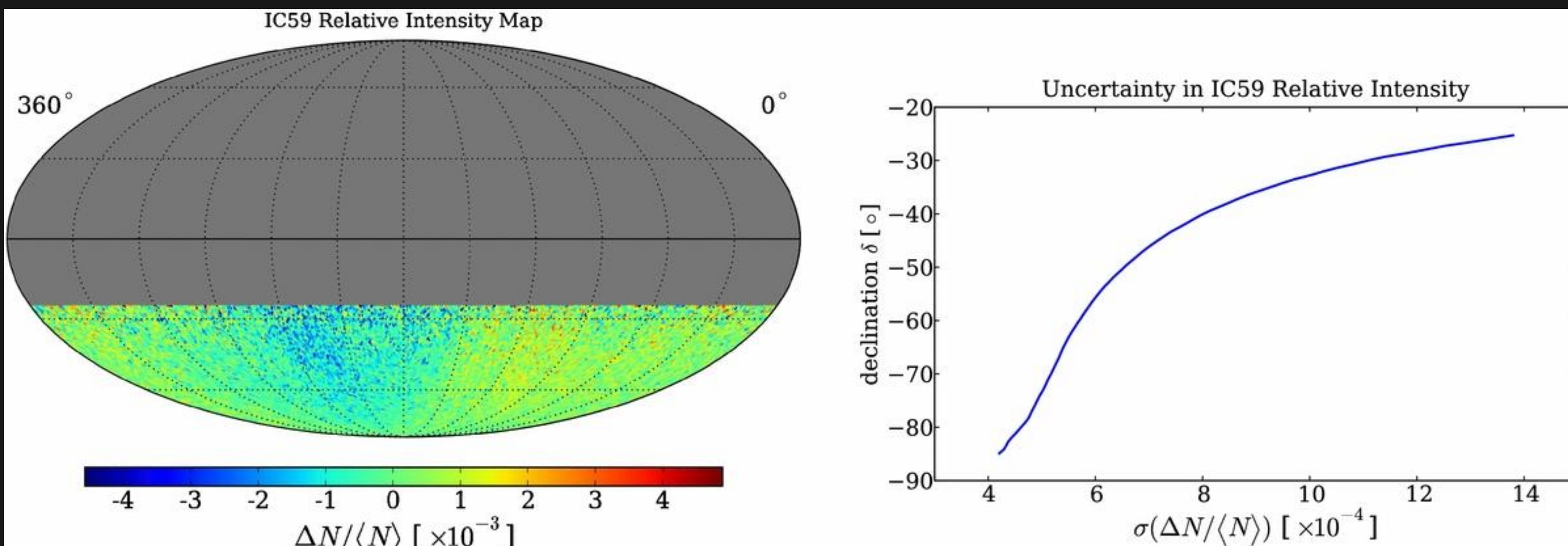
Observables in cosmic-ray research

1. Spectrum
2. Composition
3. Survival fraction of unstable nuclei
4. Secondary-to-primary ratios
5. Anisotropy

Conventionally used in, e.g., Galprop, Usine, Dragon

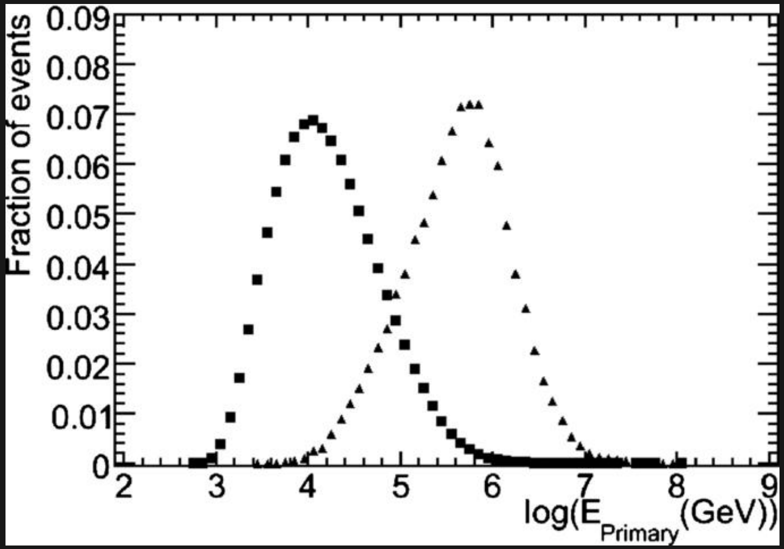
Measurements

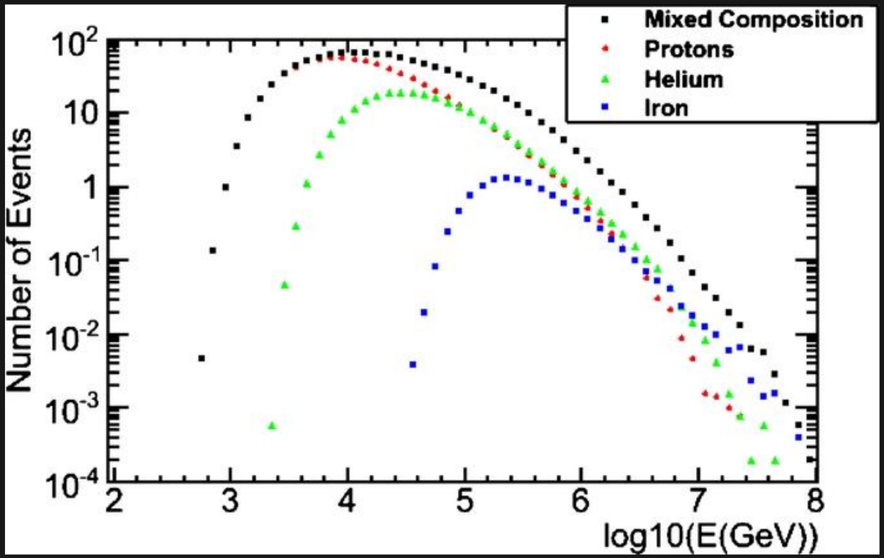
TeV-band measurements with IceCube



Measurements

2 energy bands, median 20 TeV and 400 TeV





Measurements

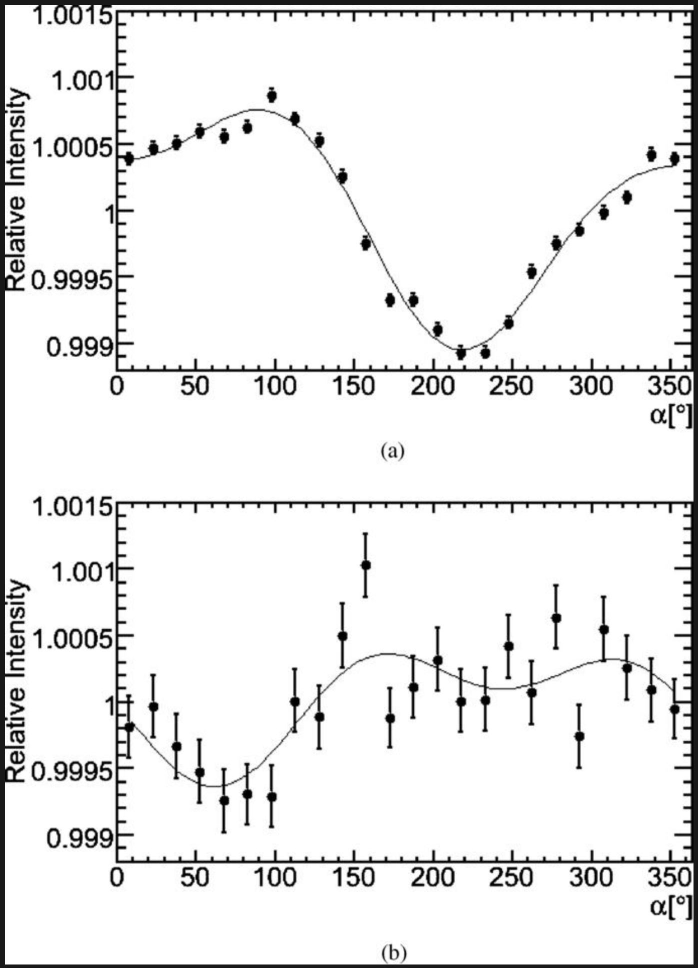
Anisotropy

along RA

Real anisotropy

is a bit larger

~ 0.1 %



20 TeV

400 TeV

Modeling

Cosmic rays undergo diffusion

not necessarily isotropic w.r.t. large-scale magnetic field

Small-scale anisotropy reflects residual MF structure
and individual elements of diffusion tensor.

Write continuity equation for isotropic part of distribution function

→ dipole anisotropy related to diffusive flux

Modeling

For one source

$$\frac{\partial N}{\partial t} - \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 D \frac{\partial N}{\partial r} \right) = Q(E)\delta(t)\frac{\delta(r)}{4\pi r^2}$$

$$N(r,t,E) = \frac{\Theta(t)Q(E)}{(4\pi Dt)^{1.5}} \exp\left(-\frac{r^2}{4Dt} \right)$$

Easy to add contributions from many sources

Escape and boundary condition by mirror method

Modeling

Beware of singularities!

Make sources active for finite time and represent a thin shell of radius R

➔

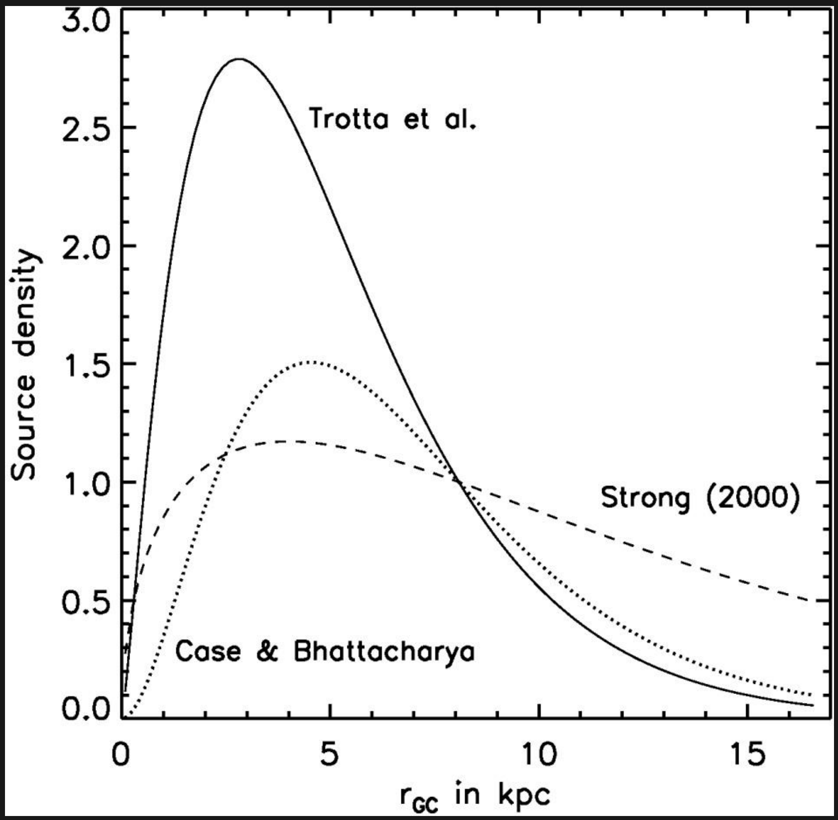
$$N(r,t,E) = \frac{\Theta(t)Q(E)}{(4\pi Dt)^{1.5}} \exp\left(-\frac{r^2+R^2}{4Dt}\right)\frac{2Dt}{rR}\sinh\left(\frac{rR}{2Dt}\right)$$

Modeling

Now fix
propagation parameters

Most important :

source distribution



Modeling

Use results of Trotta et al. (Large-scale fit @ GeV with Galprop)

$$D = D_0 \left(\frac{E}{4\,\mathrm{GeV}} \right)^{\delta}$$

$$D_0 = (1.2 + 1.3H) \cdot 10^{28}\ \mathrm{cm^2 s^{-1}}$$

Parameters	Symbol	Value
Injection index	s	2.4
Energy dependence of diffusion	δ	0.3
Source distribution	a	1.25
Source distribution	b	3.56
Source rate	P_Q	10^{-2} yr^{-1}
Source lifetime		$2 \cdot 10^3$ yr
Source radius	R	10 pc

Modeling

Randomly place
cosmic ray sources

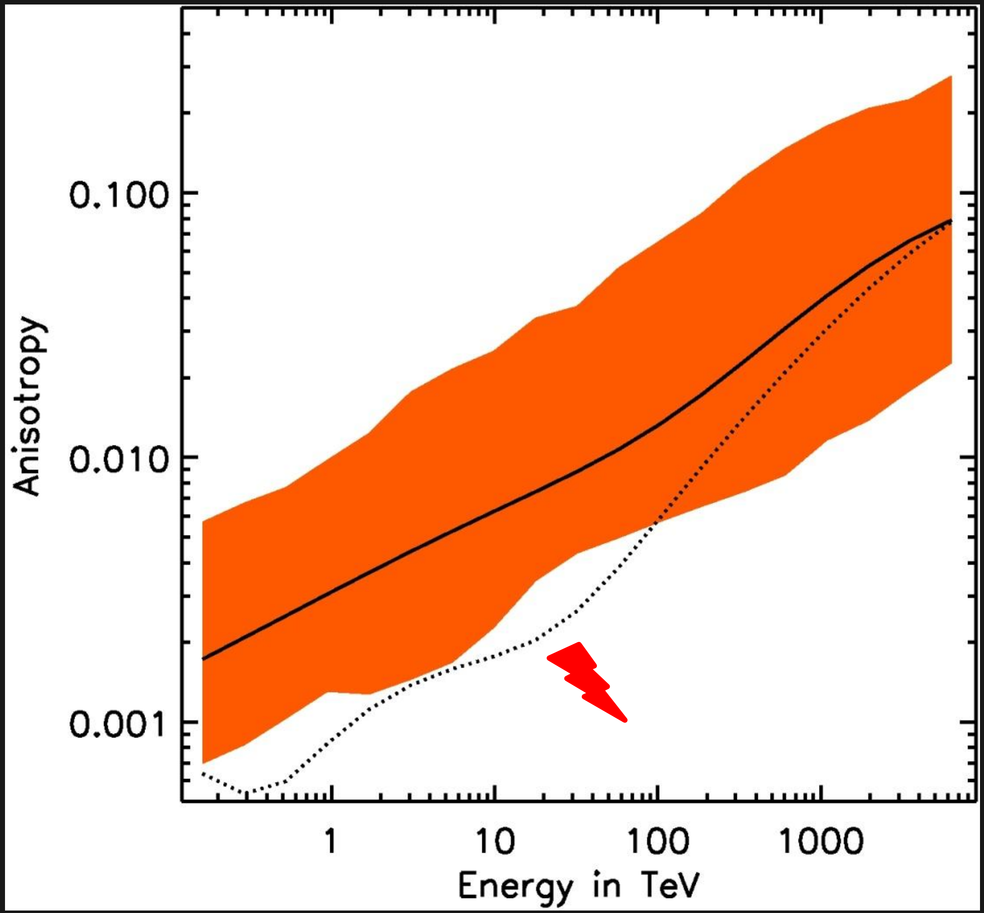
Simulate many times

→ The actual source
distribution matters

Central 90% band of
expected anisotropy

with median

and one real example



Modeling

Anisotropy is

$$\delta = \lambda_{mfp} \frac{1}{N} \frac{\partial N}{\partial r} = \frac{D}{3cN} \frac{\partial N}{\partial r}$$

For continuous and steady sources
related to source distribution.

Gradient scale is a few kpc for Trotta et al.
MFP at 20 TeV is about 25 pc → 0.1%-1% anisotropy

May need flat source distribution
Gradient scale of Strong et al is 8 kpc!

Modeling

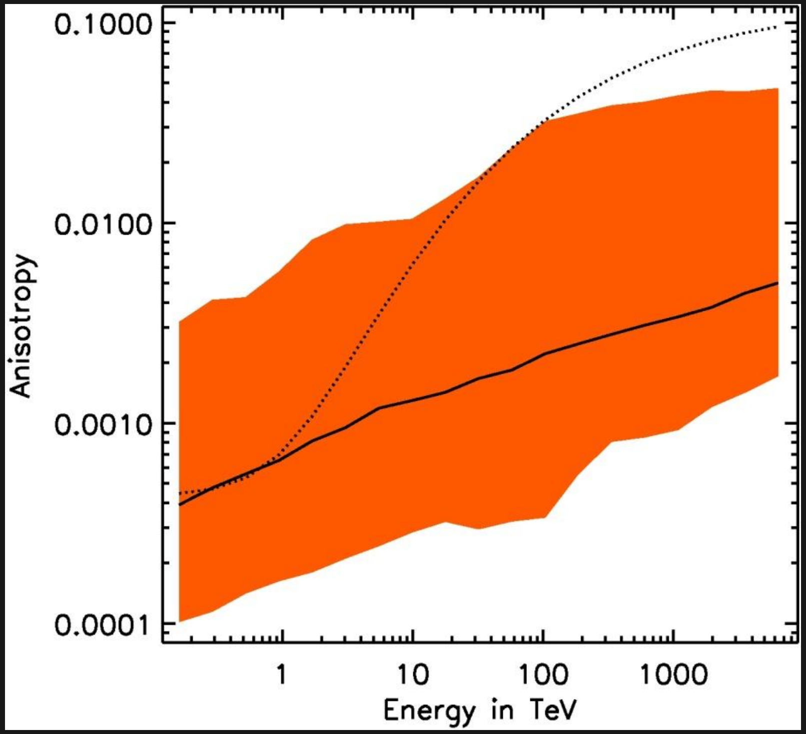
Try flat source distribution a la Strong et al.

and propagation parameters by Putze et al.

$$D_0 \cong H \cdot 10^{28} \ \mathrm{cm^2 s^{-1}}$$

Seems to work marginally

Check out further!

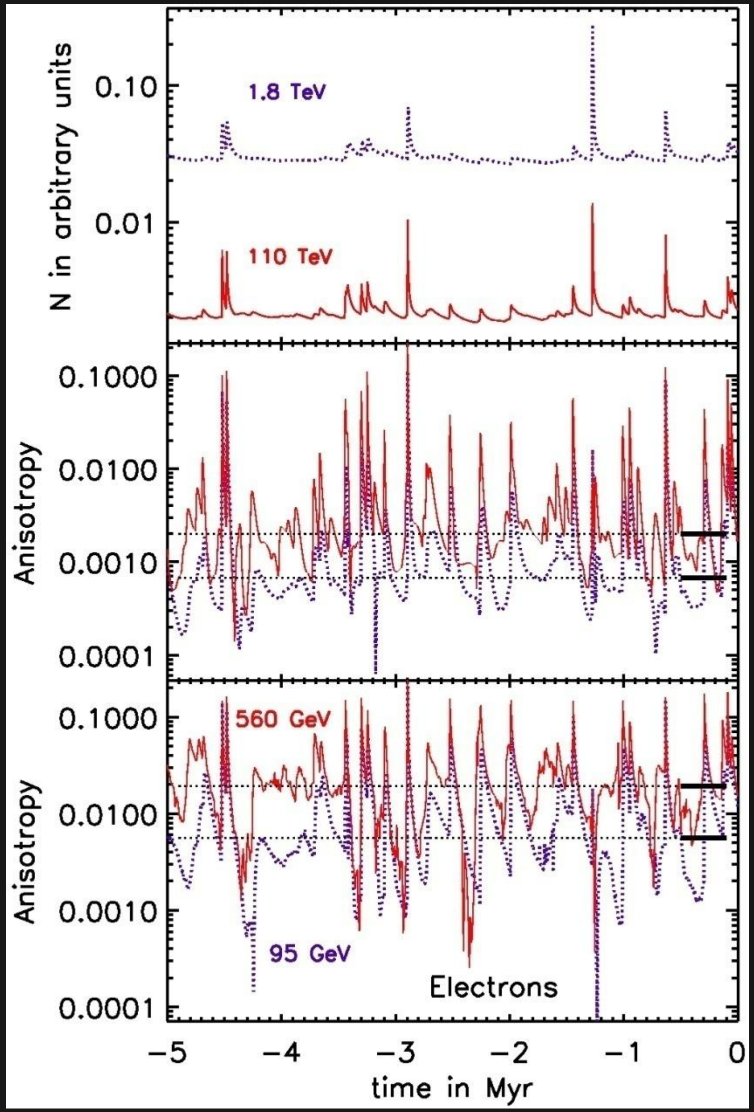


IceCube comparison

Rare spikes in flux from nearby SNe

Wild fluctuations in anisotropy

Do we live in am anisotropy lull?



IceCube comparison

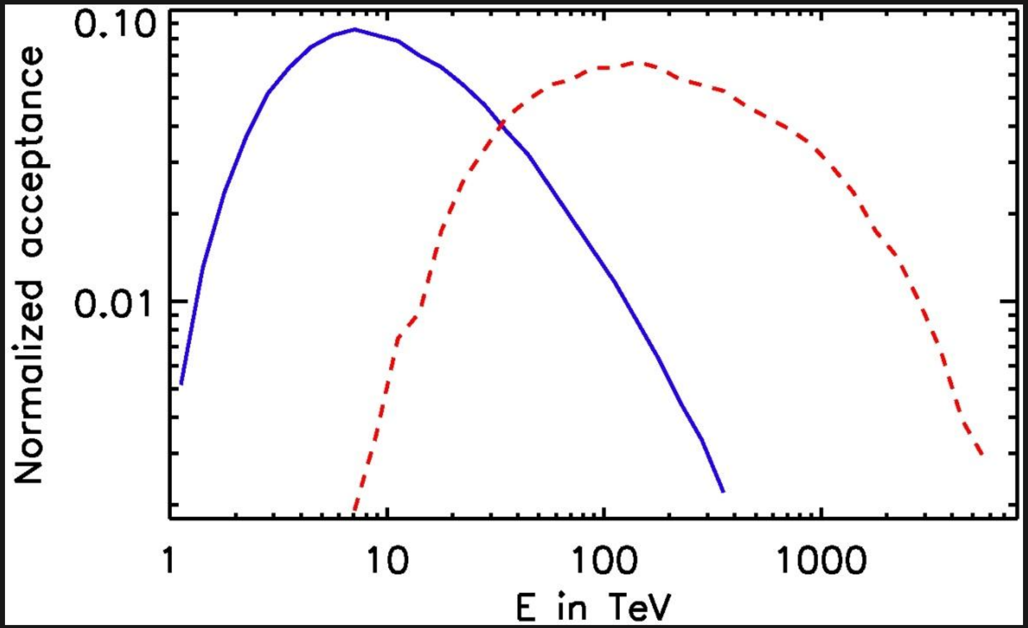
Adapt to IceCube data selection, scale to protons

Important:

Asymmetry of fluctuations

Correlations across spectrum

Account for direction

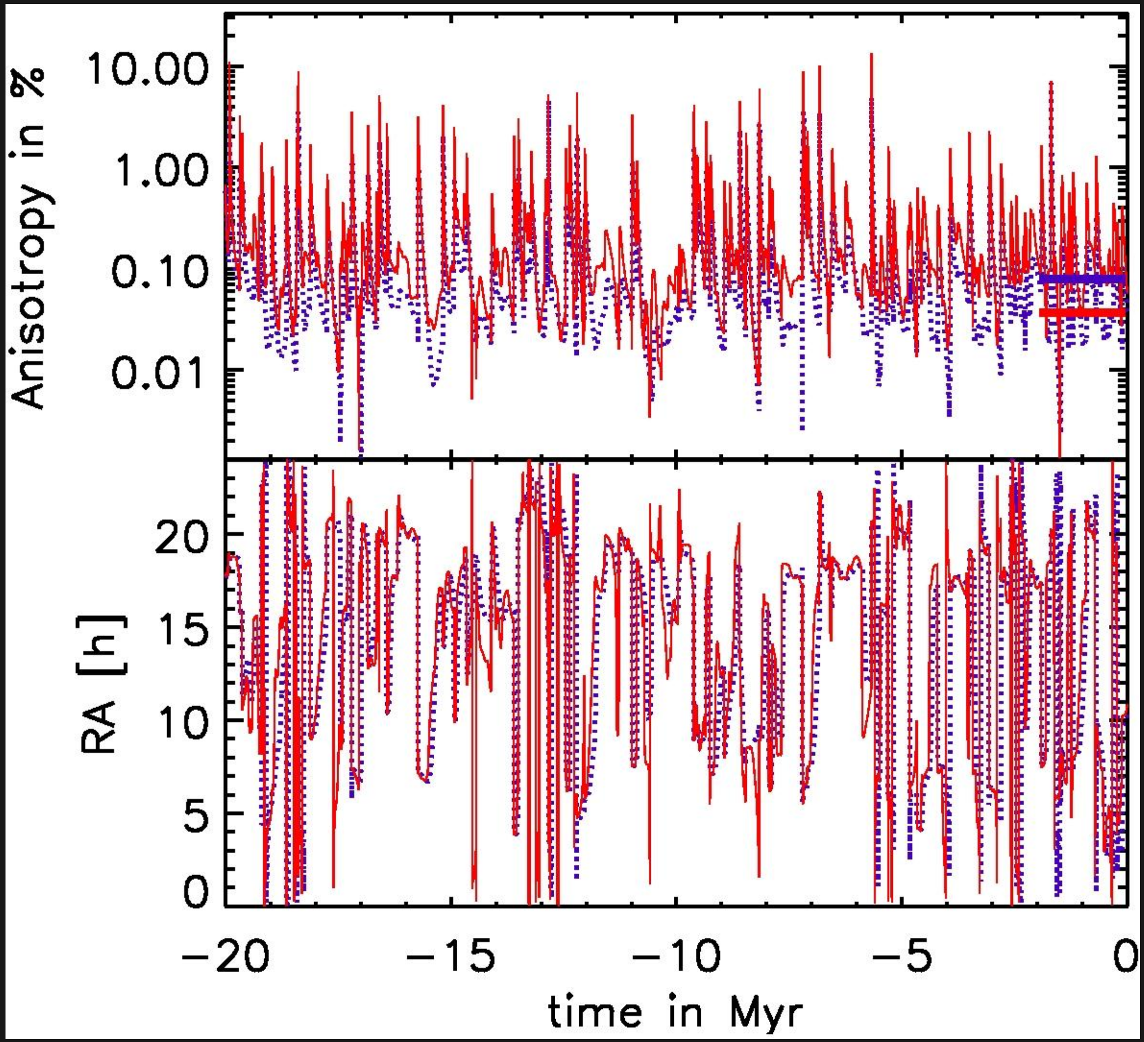


IceCube Comparison

Project on IceCube declination band

~10% probability to meet data

Anisotropy direction varies strongly



IceCube comparison

Vary source rate and increase halo size (dotted curves)

→ Doesn't help

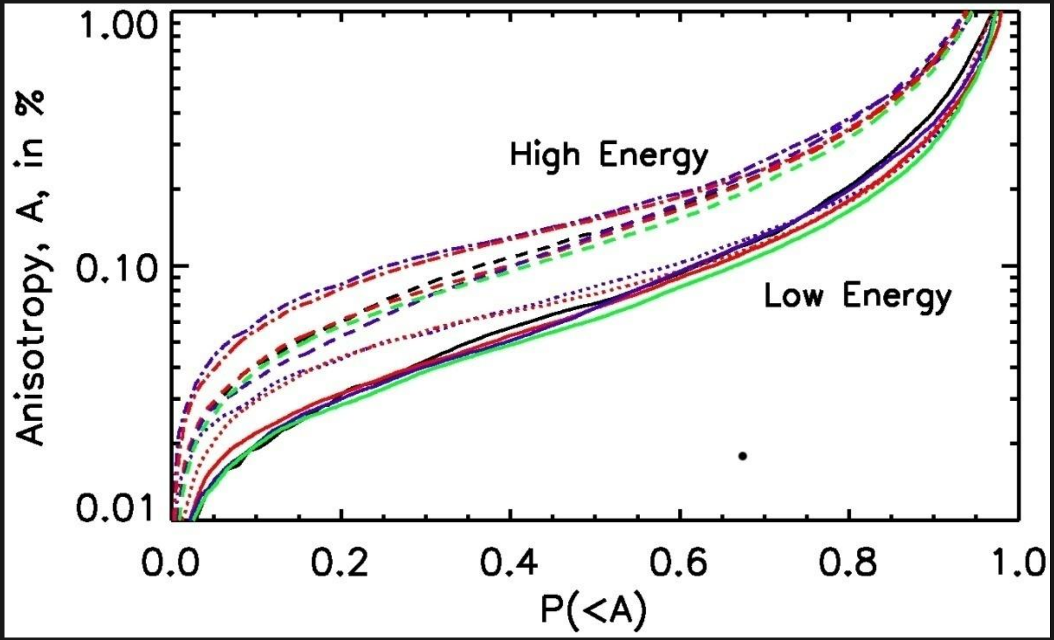
Measured

LE

$$(7.9 \pm 0.1_{st} \pm 0.3_{sy}) \cdot 10^{-2}\ \%$$

HE

$$(3.7 \pm 0.7_{st} \pm 0.7_{sy}) \cdot 10^{-2}\ \%$$



Only 11% probability for absolutely flat source distribution

Discussion

Calculation of cosmic-ray dipole anisotropy

Specifically accounts for intermittency and 3-D structure

Intermittency effects are large

Difficult to reproduce 0.1-% level over wide energy bands

Need flat source distribution

Also need small diffusion coefficient beyong 10 TeV

What are the sources of cosmic rays?