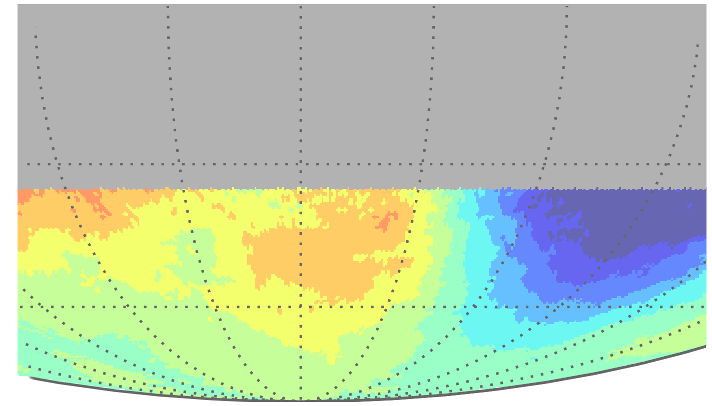
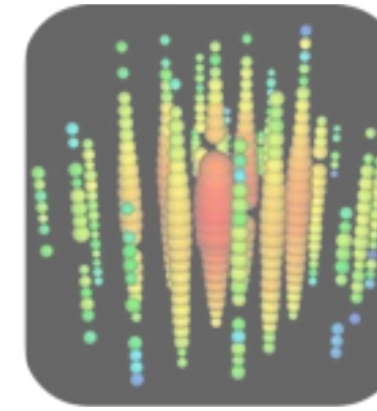
WISCONSIN ICECUBE
PARTICLE ASTROPHYSICS CENTER





Cosmic Ray (and Neutrino) Astrophysics with the IceCube Observatory

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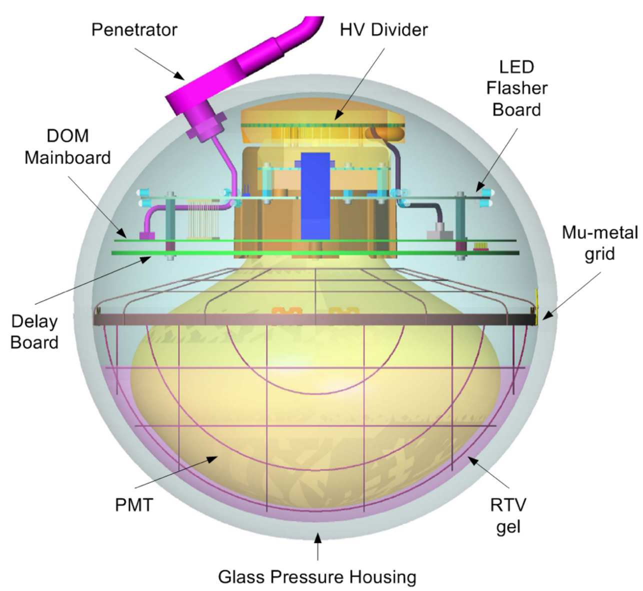
February 26, 2016

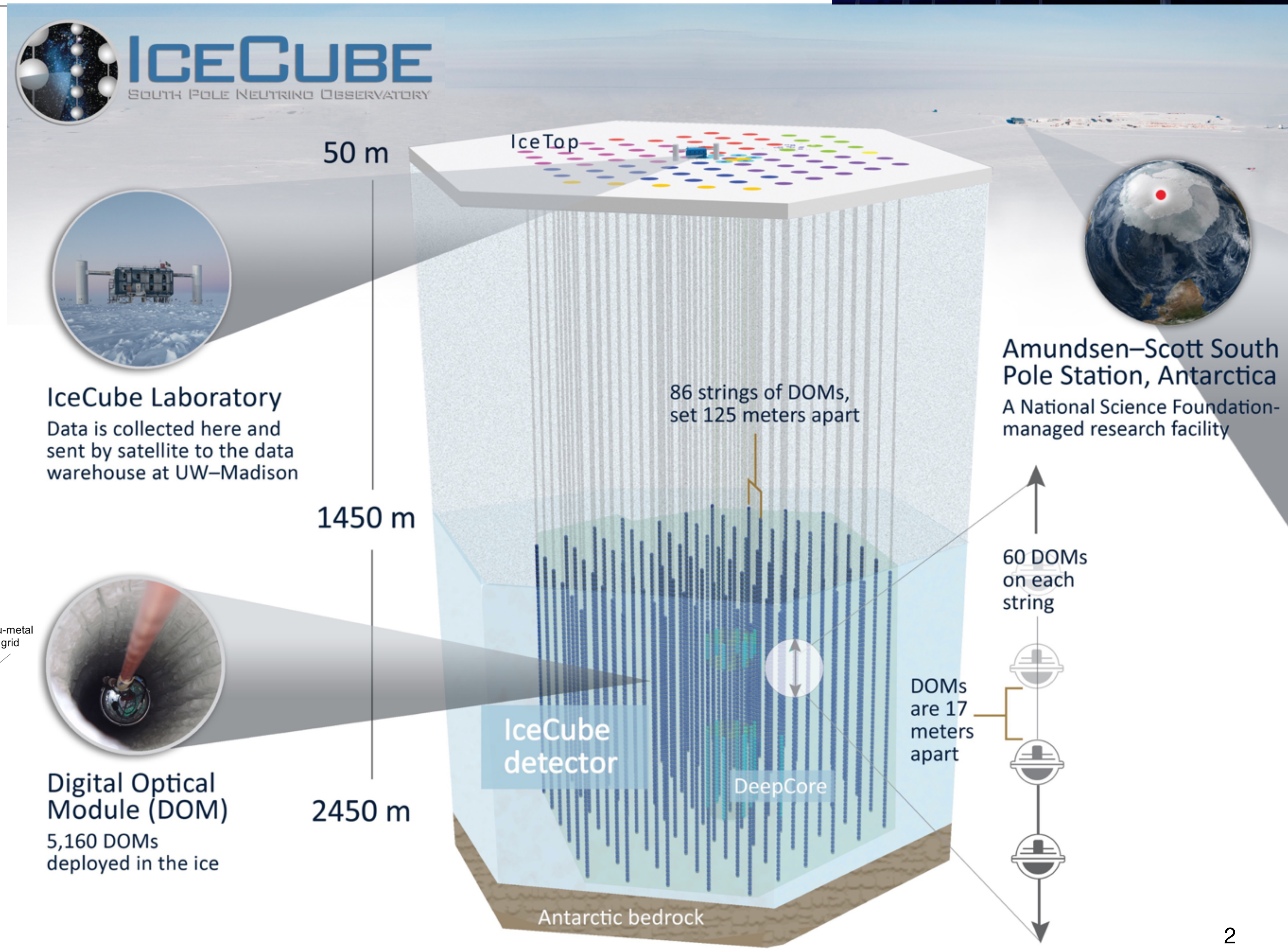
Vrije Universiteit Brussel

IceCube Observatory
the instrumentation

Digital Optical Module (DOM)

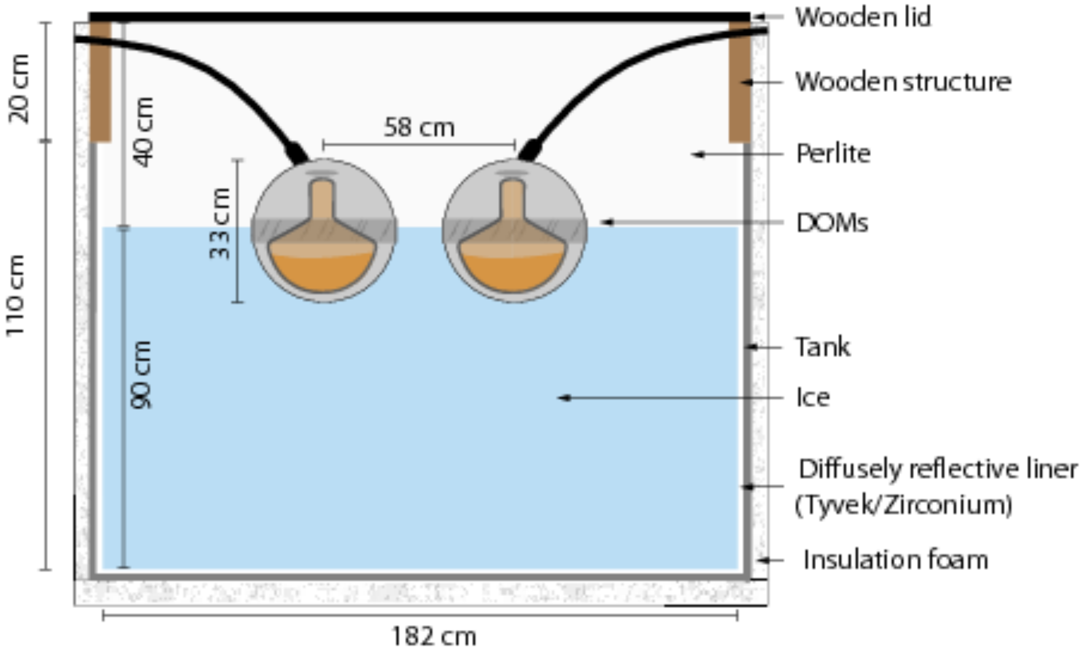
with 10” PMT
&
local DAQ electronics



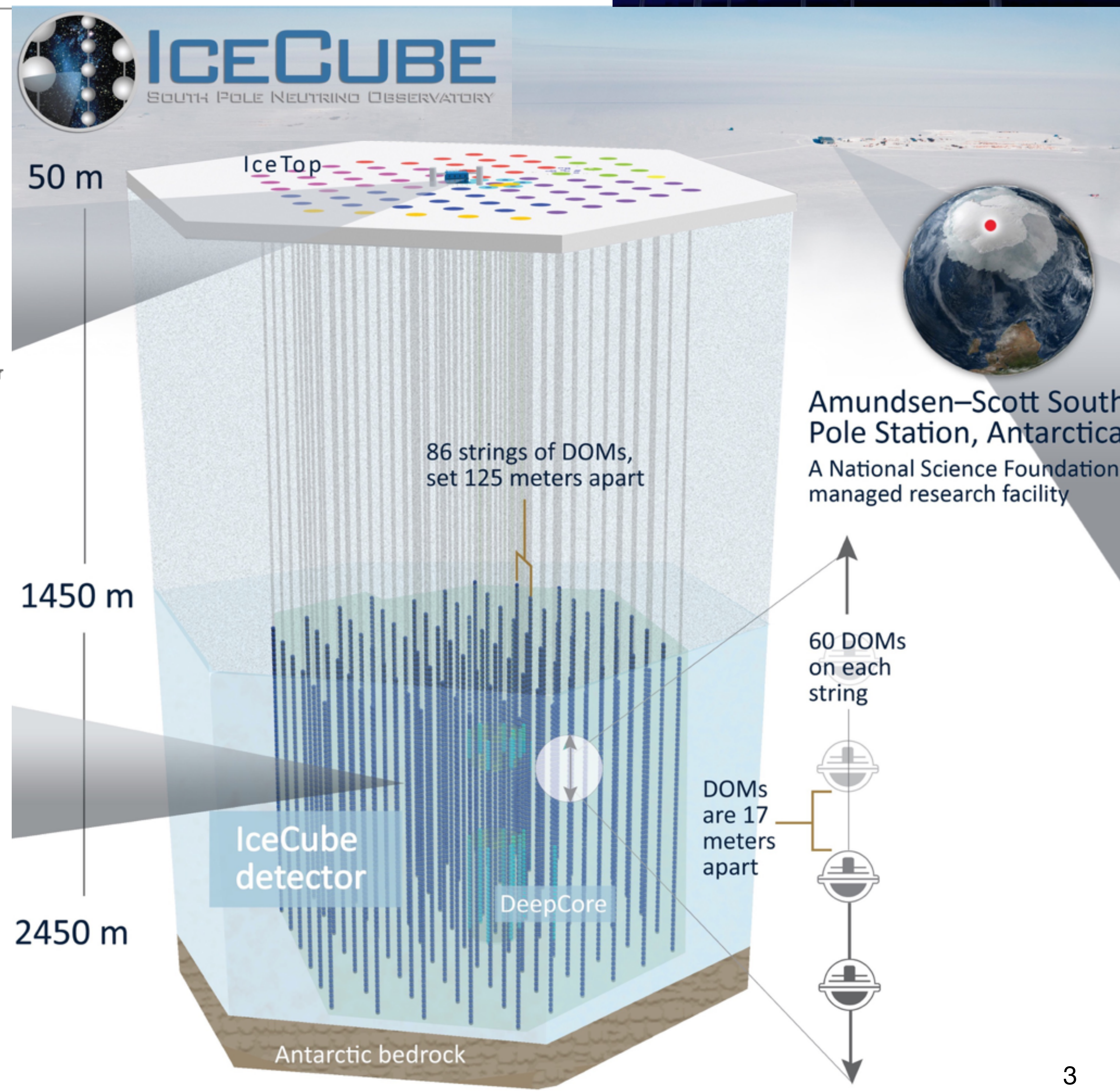


IceCube Observatory
the instrumentation

KM^3 OBSERVATORY



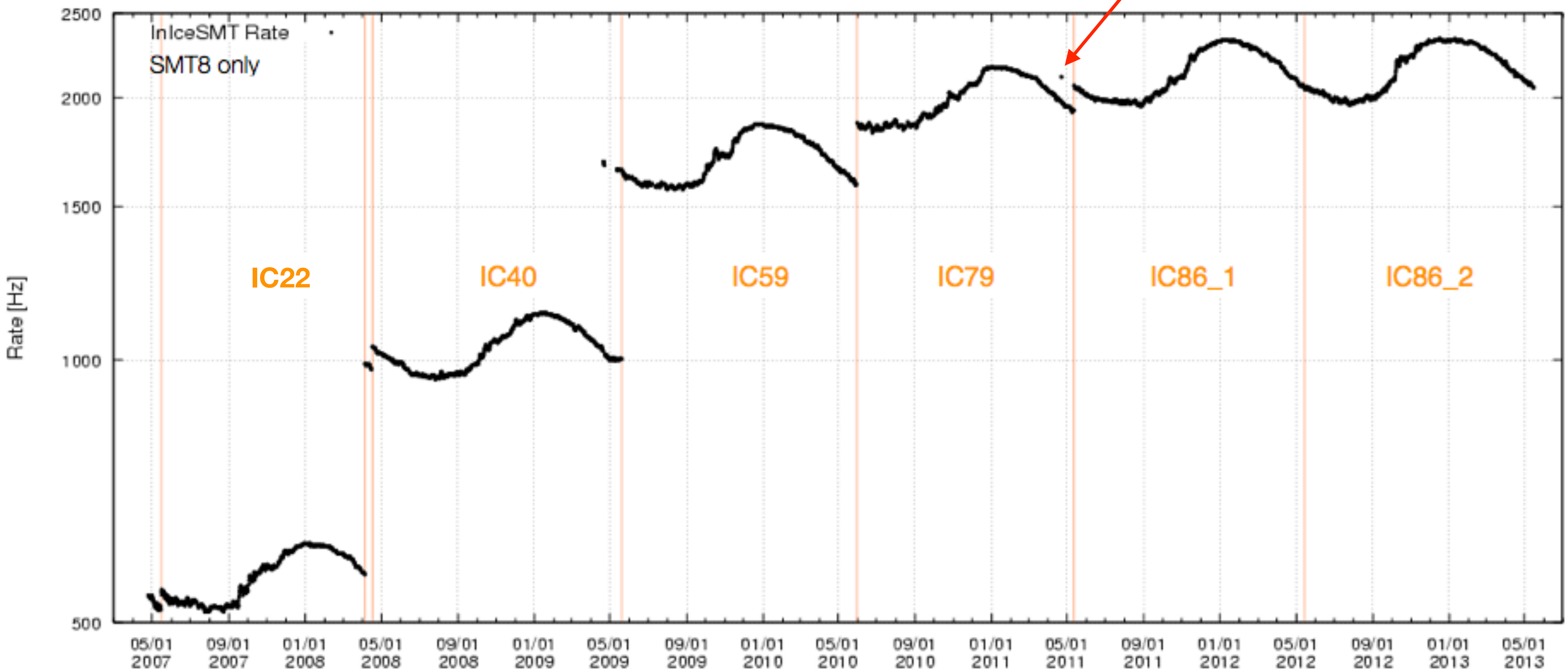
two tanks of one IceTop station



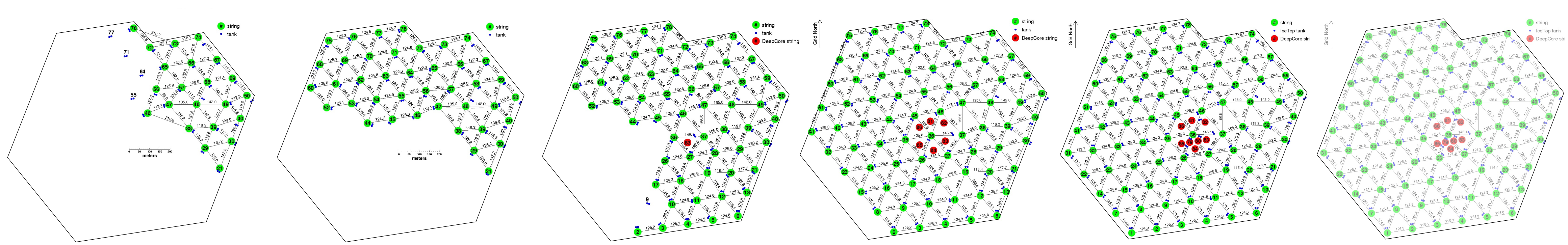
event rate in IceCube

growing experiment

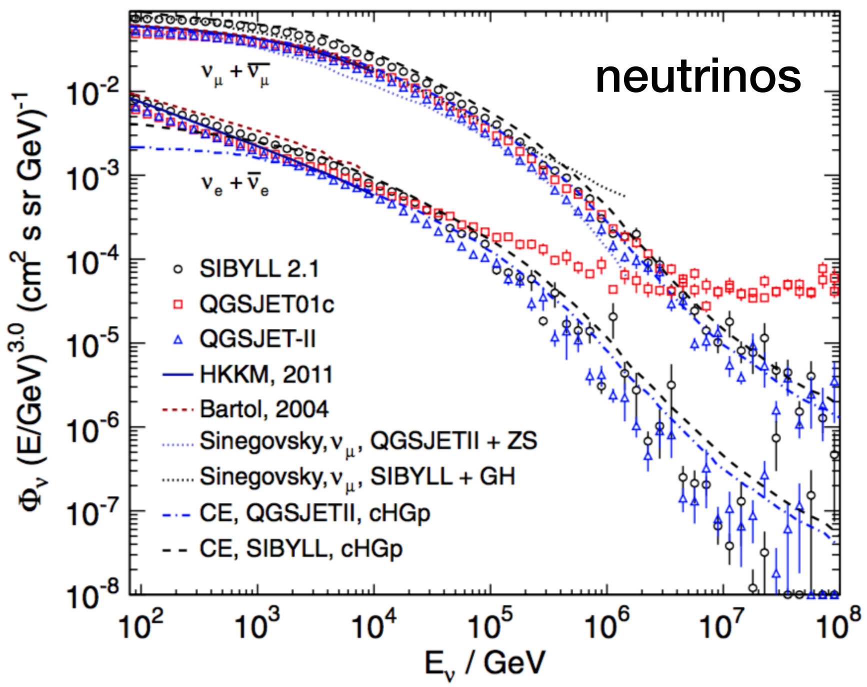
IceCube completed
December 18, 2010

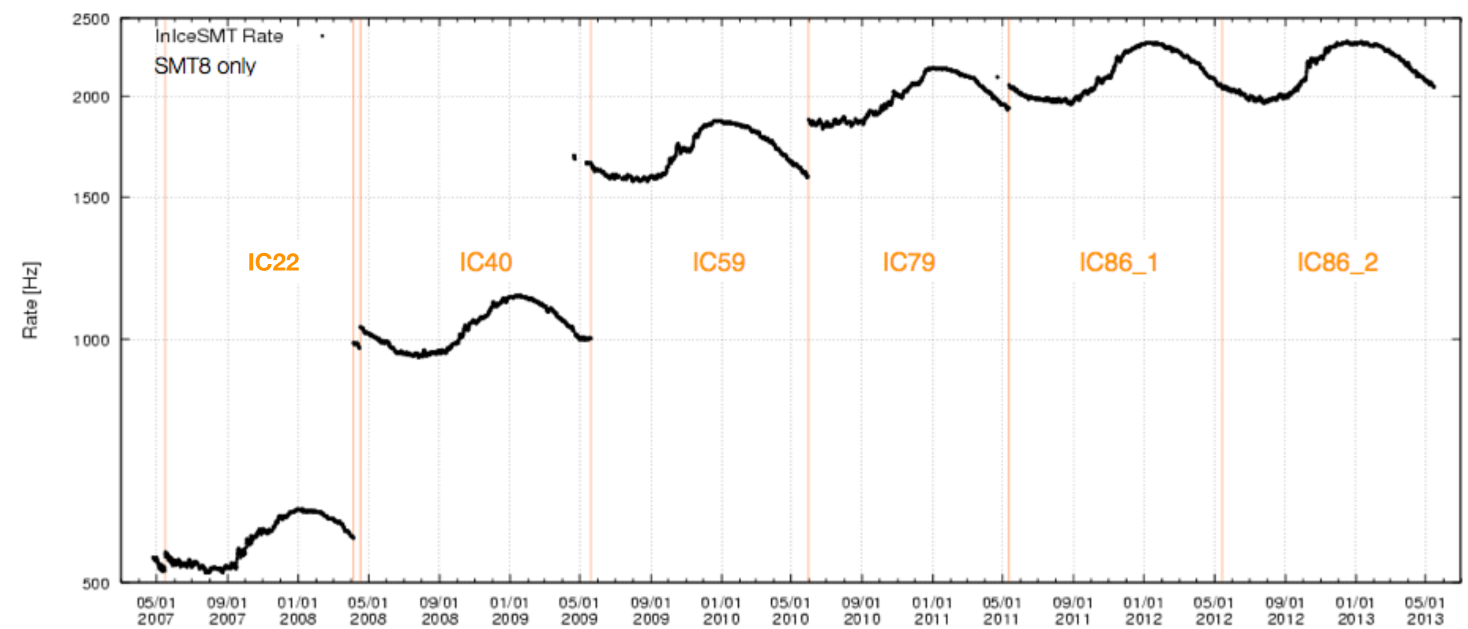


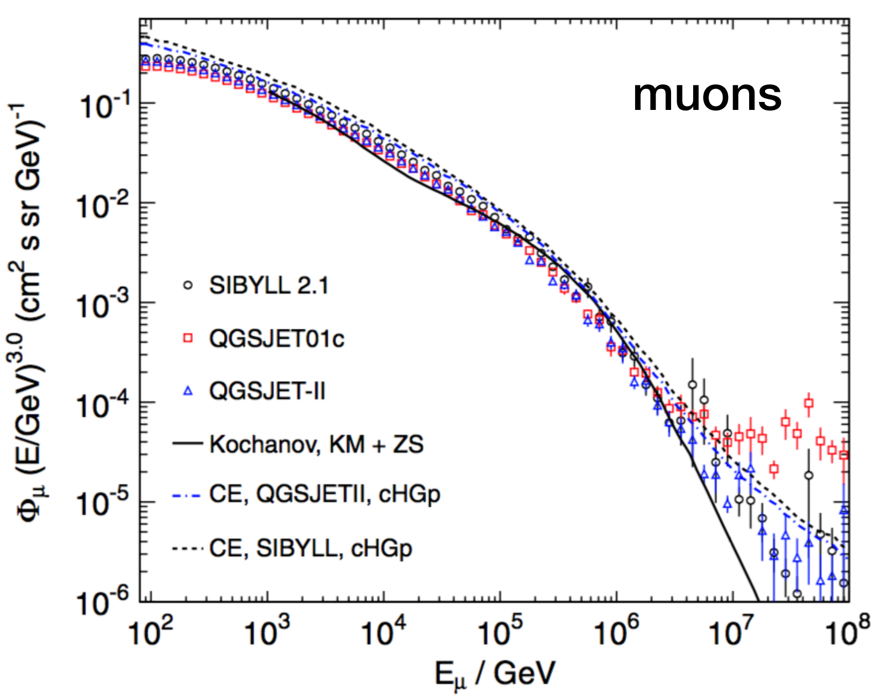
2007-08 2008-09 2009-10 2010-11 2011-12 2012-13 >>

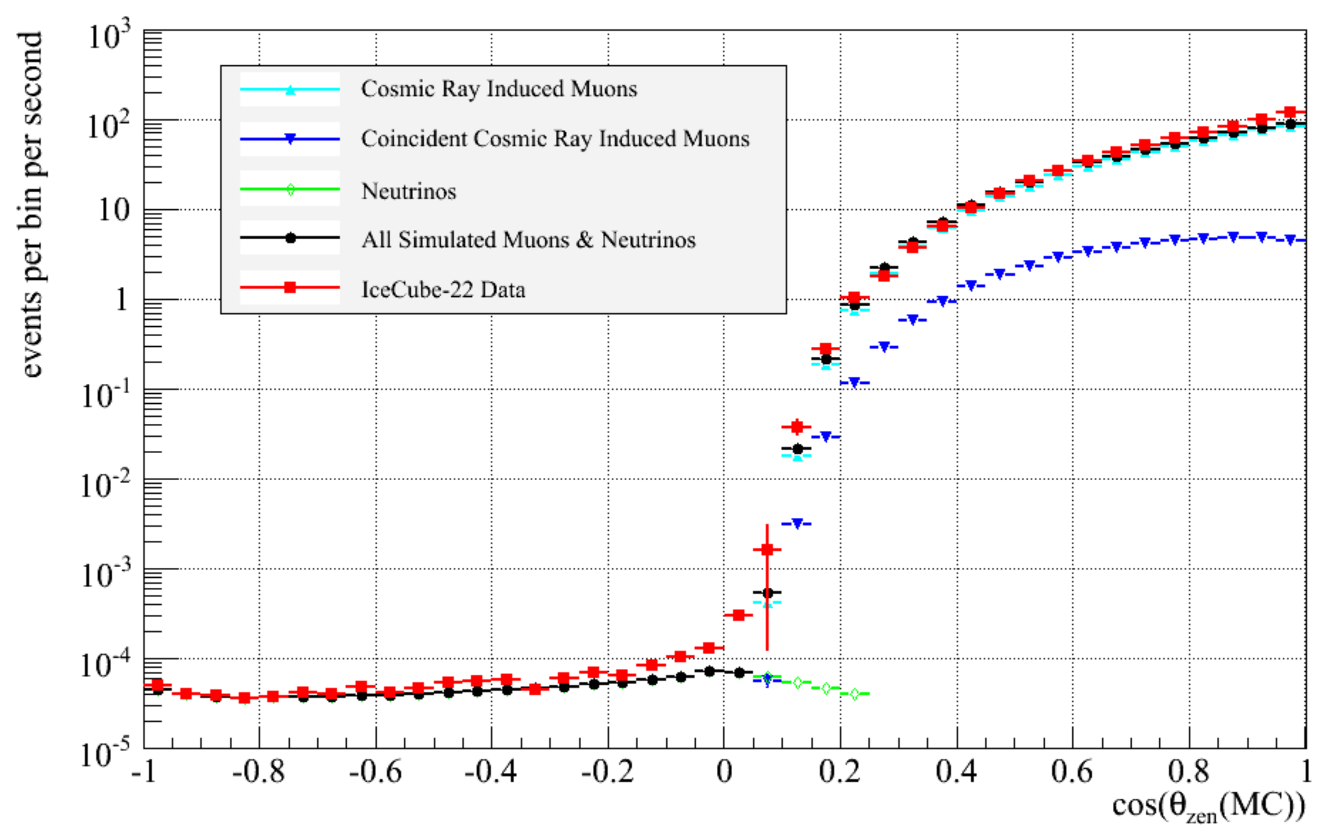


cosmic ray muons and neutrinos









Fedynitch, Becker Tjus, PD, PRD 86, 114024

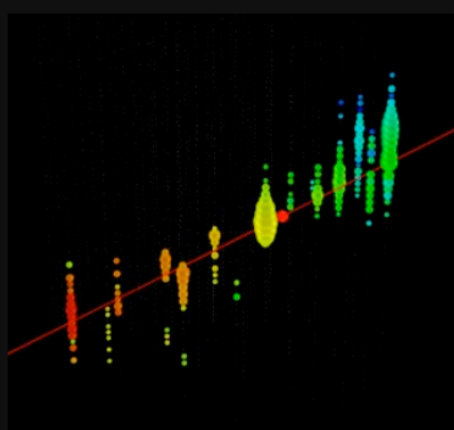
neutrino detection

event topologies

time

track

CC Muon Neutrino



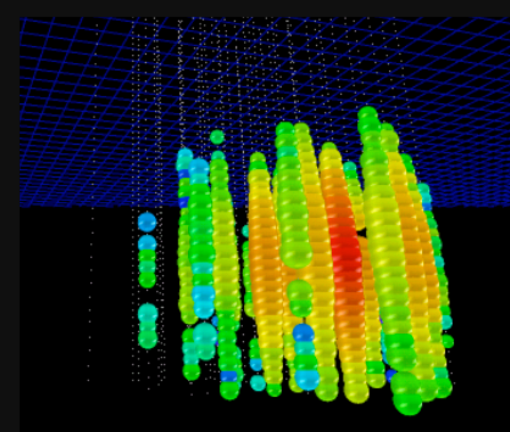
$$\nu_\mu + N \rightarrow \mu + X$$

track (data)

factor of ≈ 2 energy resolution
< 1° angular resolution

cascade

Neutral Current /Electron Neutrino



$$\nu_e + N \rightarrow e + X$$

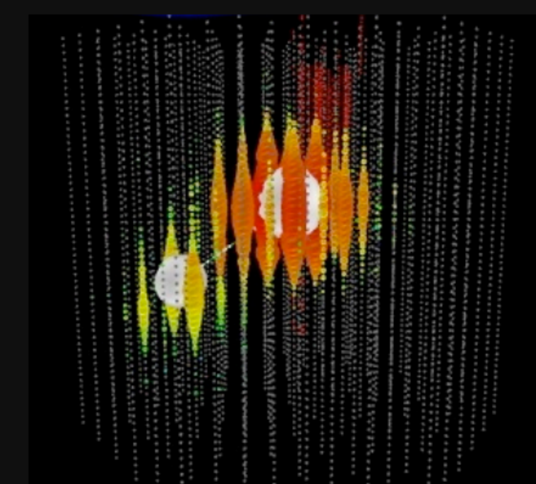
$$\nu_x + N \rightarrow \nu_x + X$$

cascade (data)

≈ ±15% deposited energy resolution
≈ 10° angular resolution
(at energies ≳ 100 TeV)

hybrid

CC Tau Neutrino



$$\nu_\tau + N \rightarrow \tau + X$$

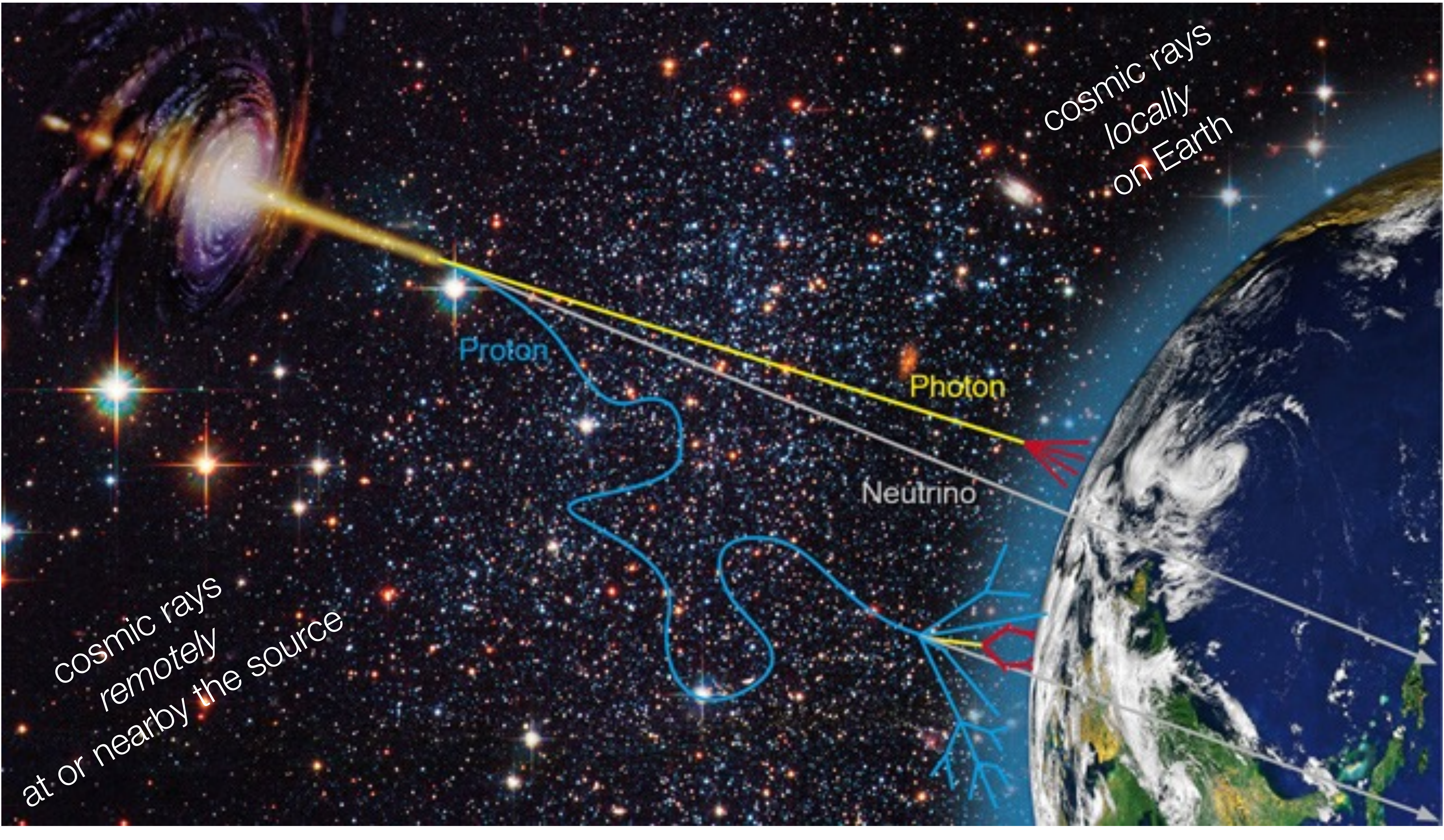
"double-bang" and other signatures
(simulation)

(not observed yet)

C. Kopper

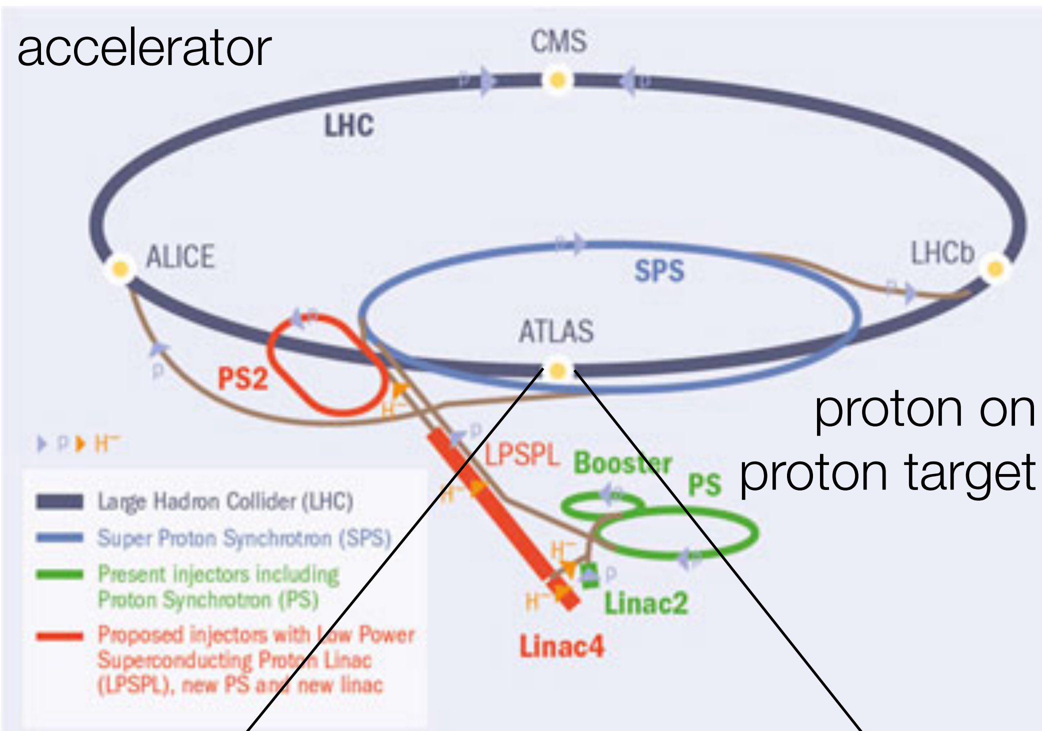
cosmic rays

a long journey



cosmic rays

a natural laboratory

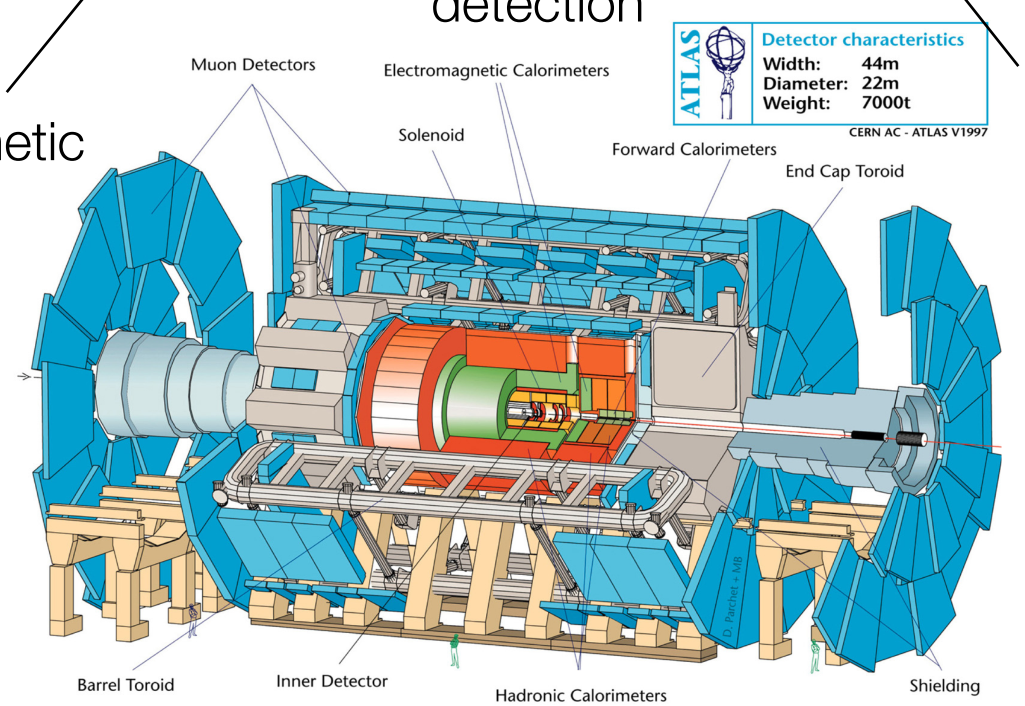


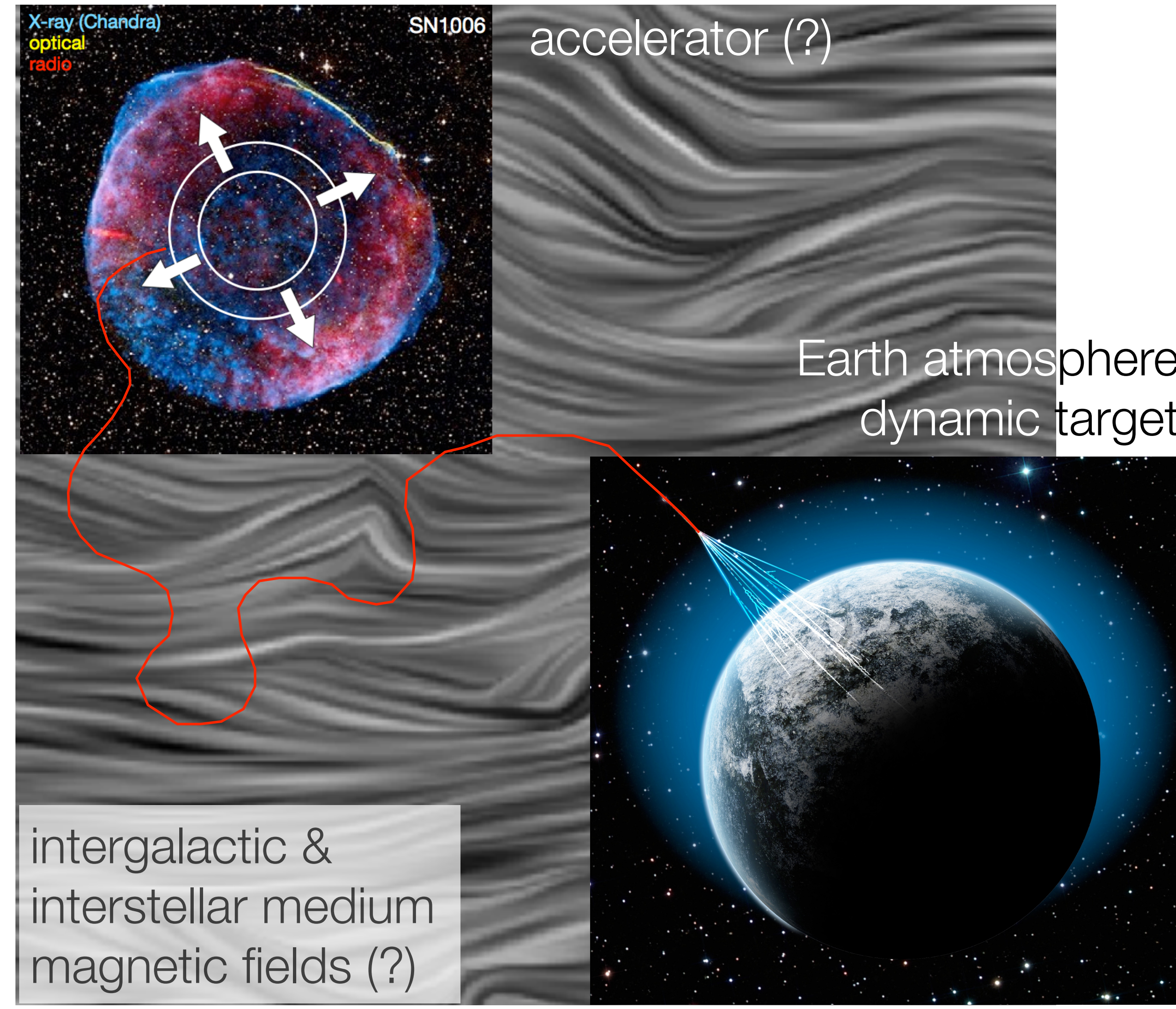
proton on
proton target

propagation

detection

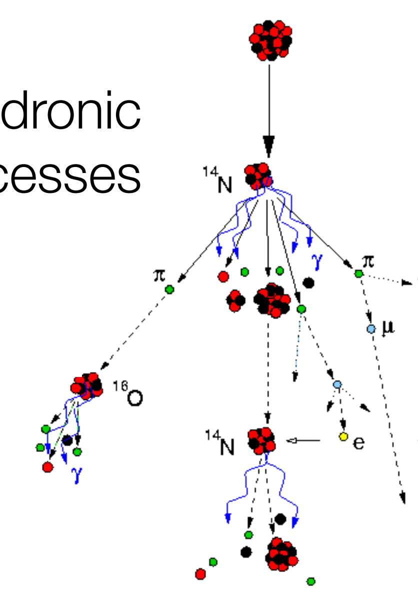
magnetic
fields

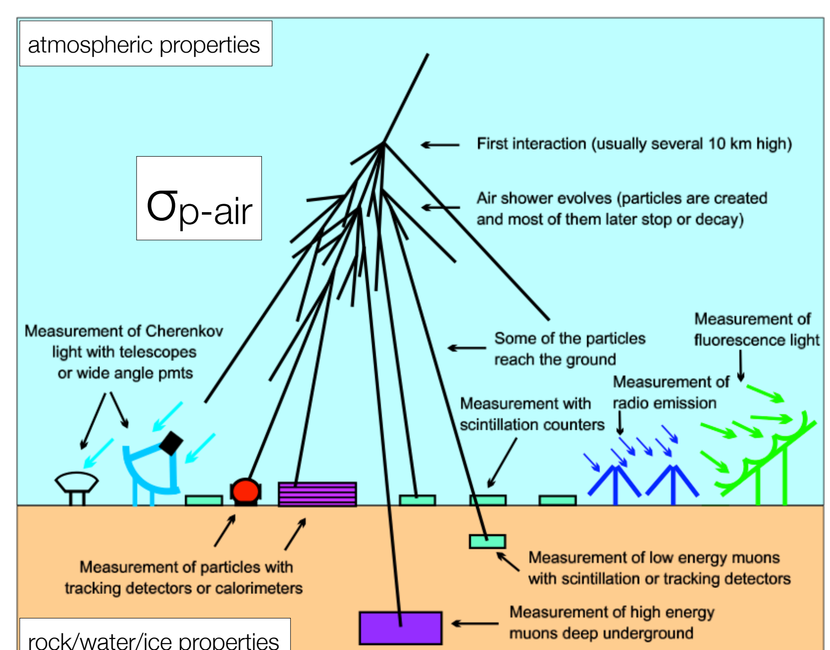




propagation

nuclear & hadronic
processes





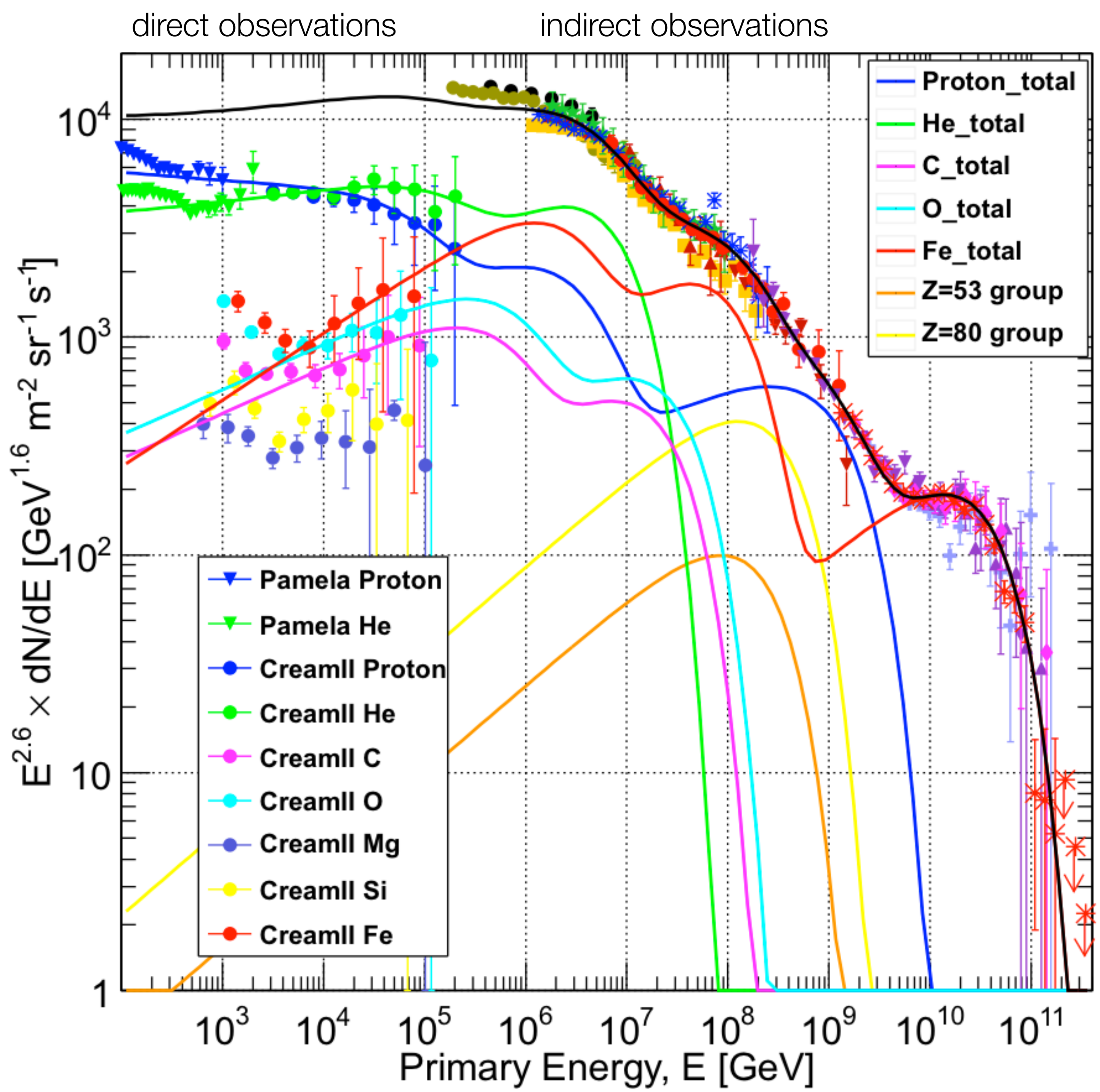
cosmic ray detection

primary cosmic rays

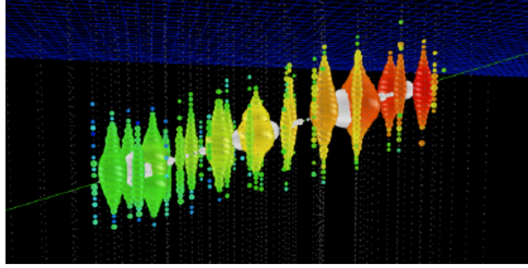
spectrum

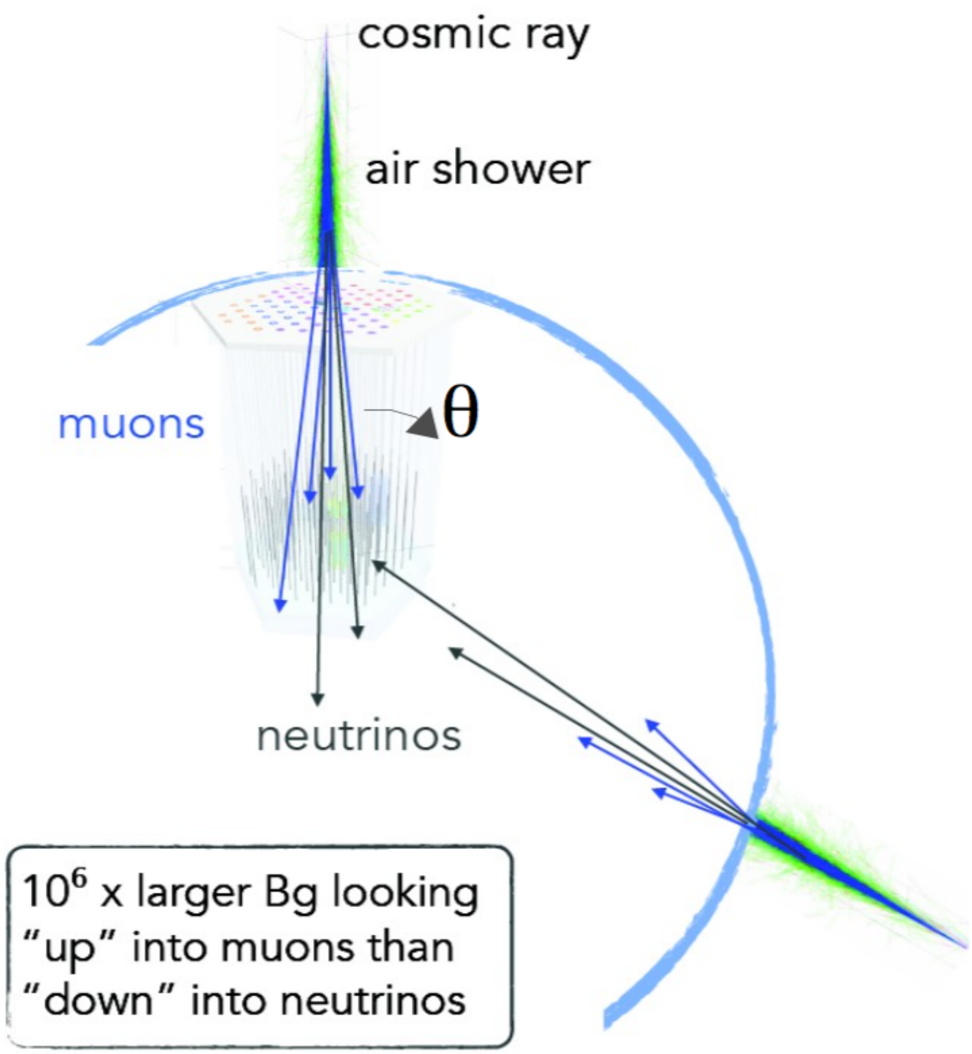
- **~E^{-2}** (+cutoff) cosmic ray spectrum the sources
- cosmic ray spectrum at Earth **steeper**
- **knee** traces the end of galactic contribution ?
- **ankle** traces cross-over with extra-galactic contribution ?

Gaisser, Stanev, Tilav, 2013 - arXiv:1303.3565



searching for neutrinos
background rejection

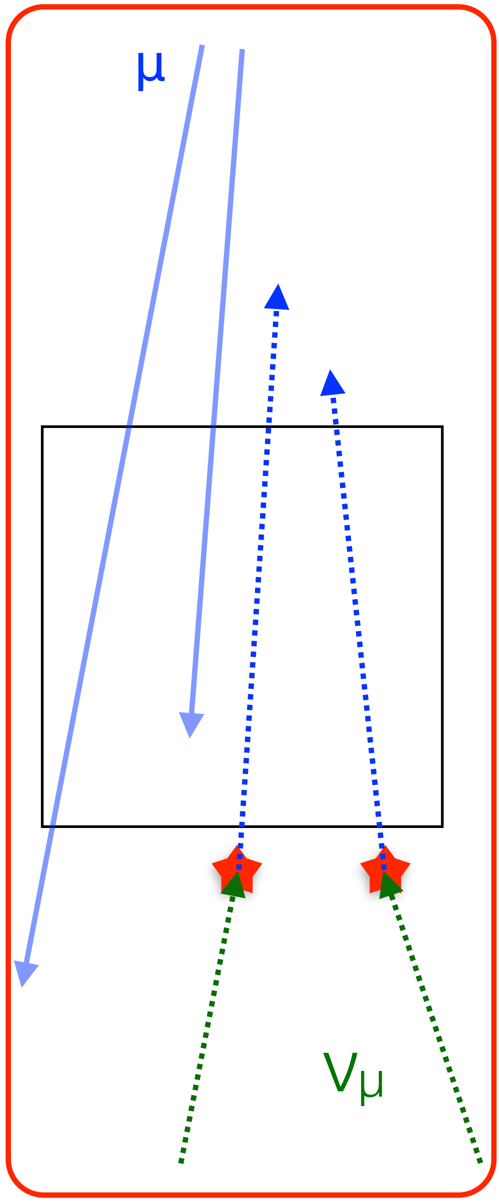




- use Earth as natural background absorber
- search for up-going trajectories
- wrongly reconstructed trajectories

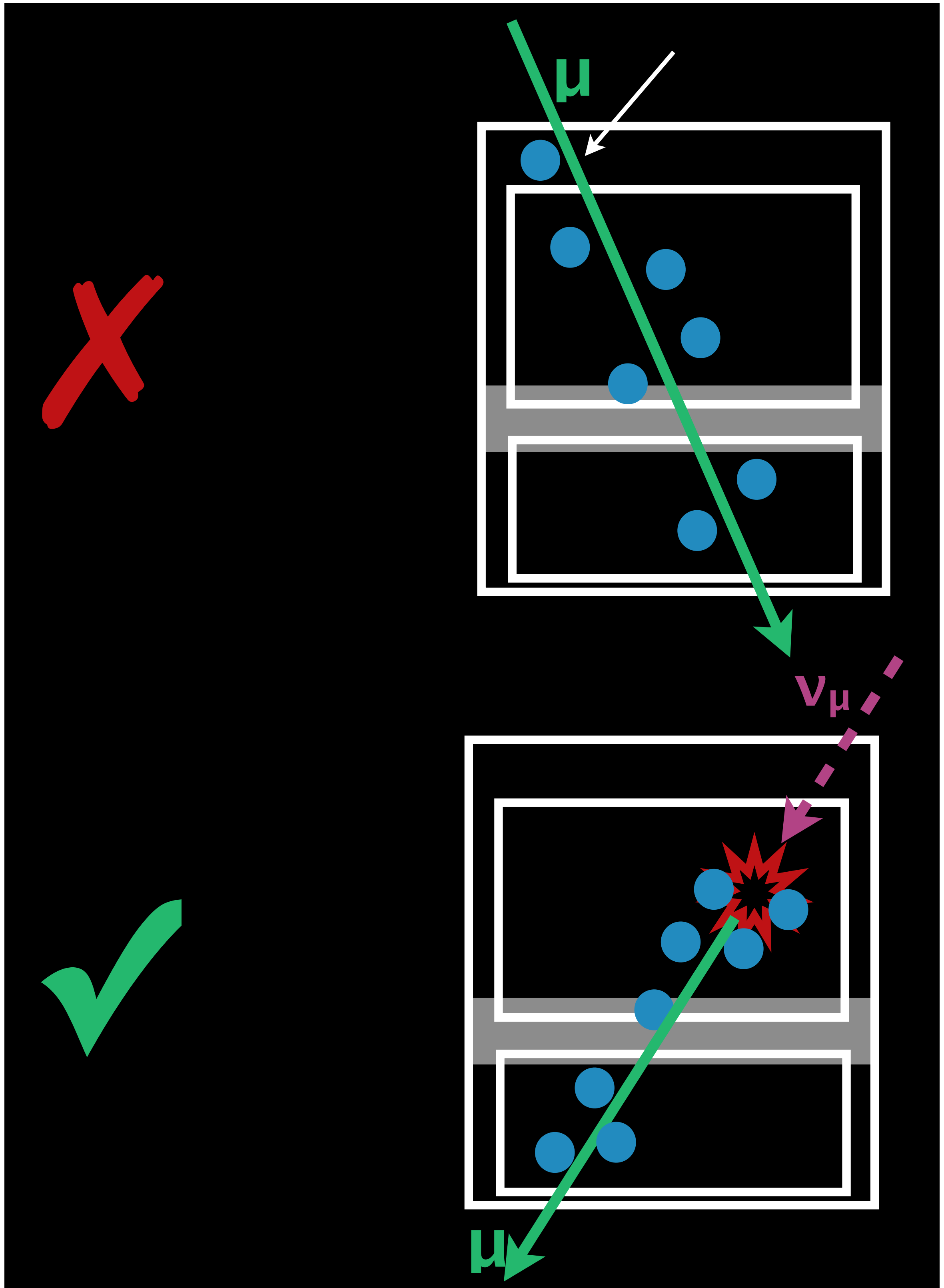
- sensitive to ν_μ
- sensitive to **northern sky**

up-going through-going (tracks)

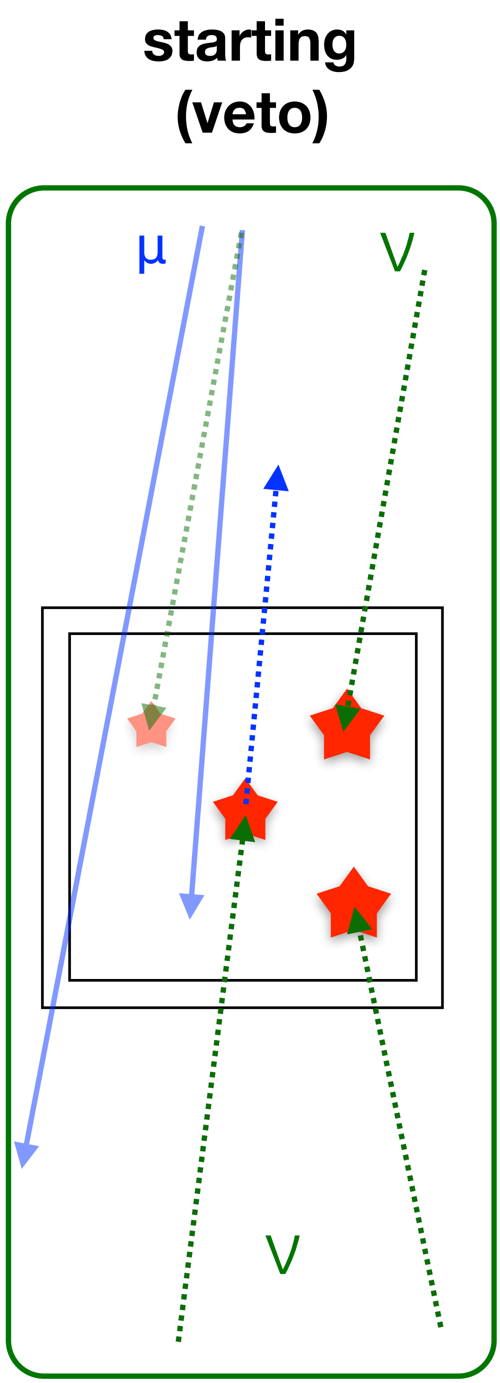


neutrino identification

active veto

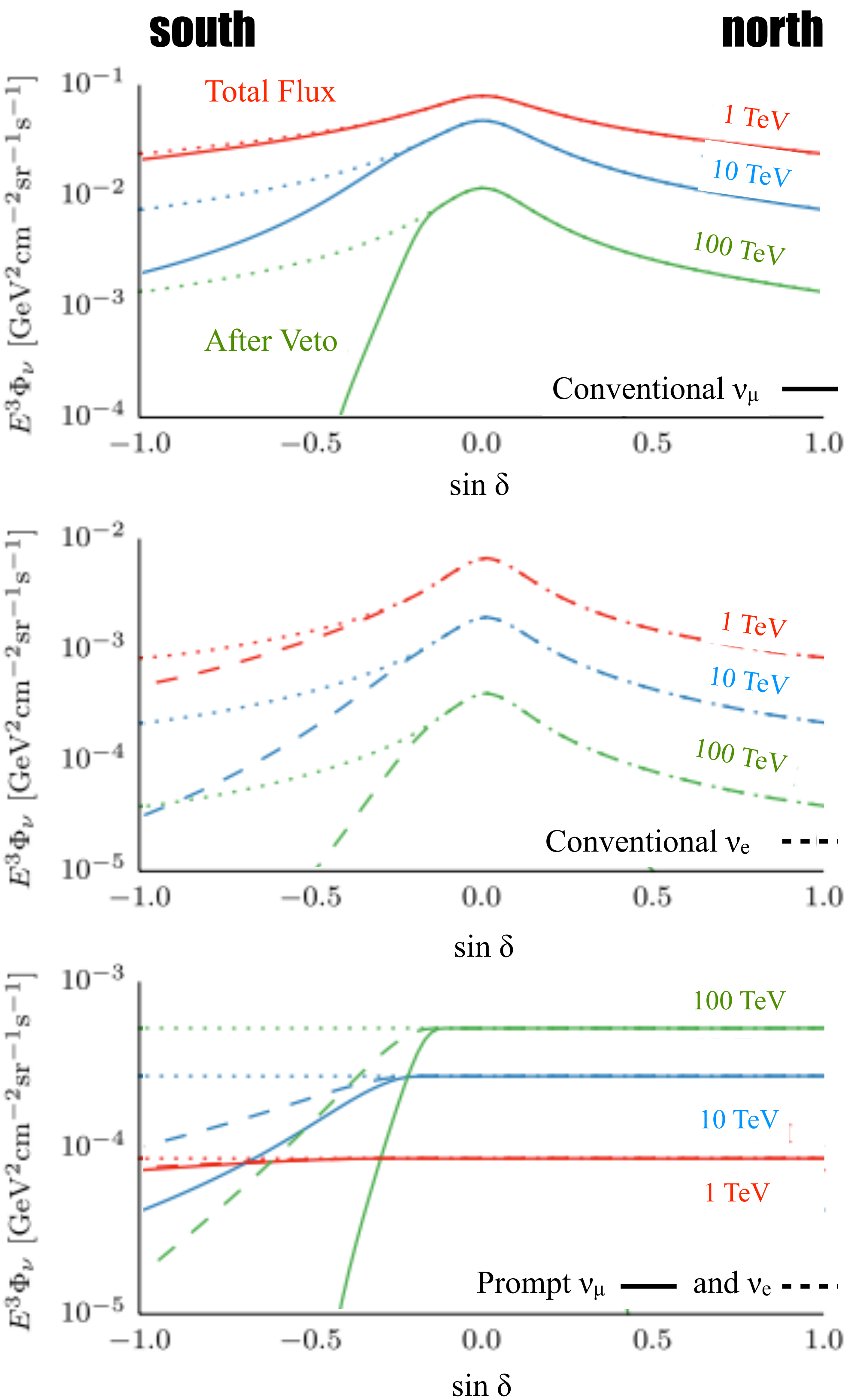


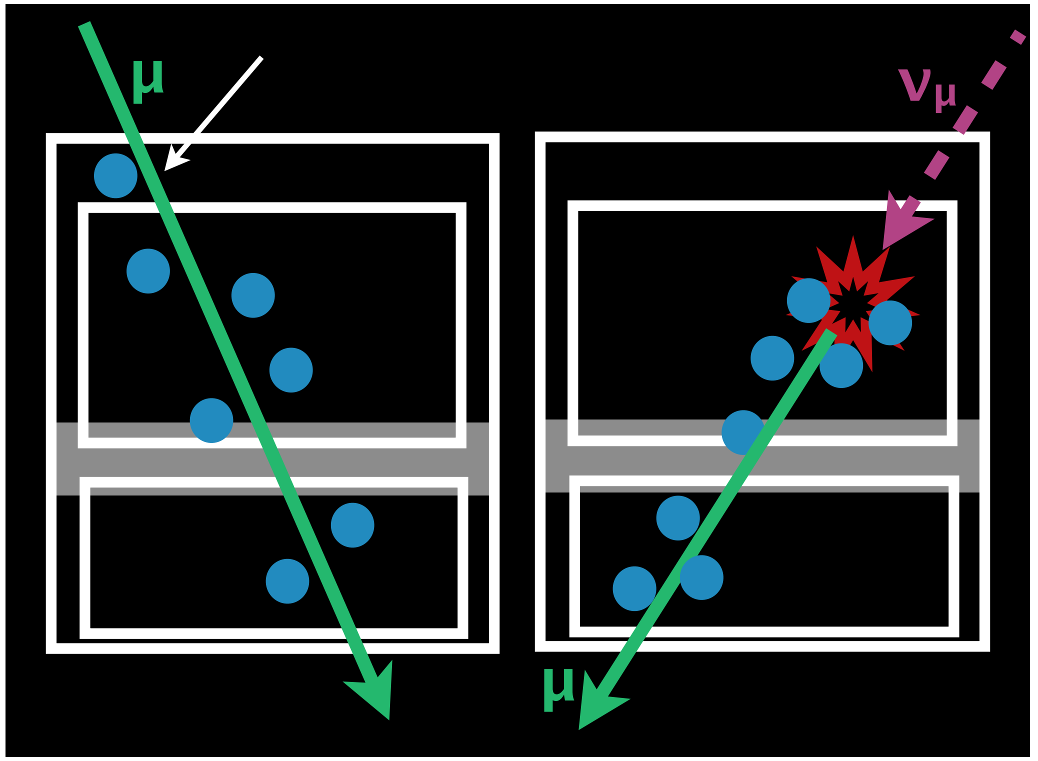
- outer detector veto to **reject muon tracks** passing the experiment boundary
- collect **bright events** with total charge > 6000 p.e.
- identify only events **starting inside** the instrumented volume
- active volume **420 Mton**!
- sensitive to **all flavors**
- sensitive to **whole sky**

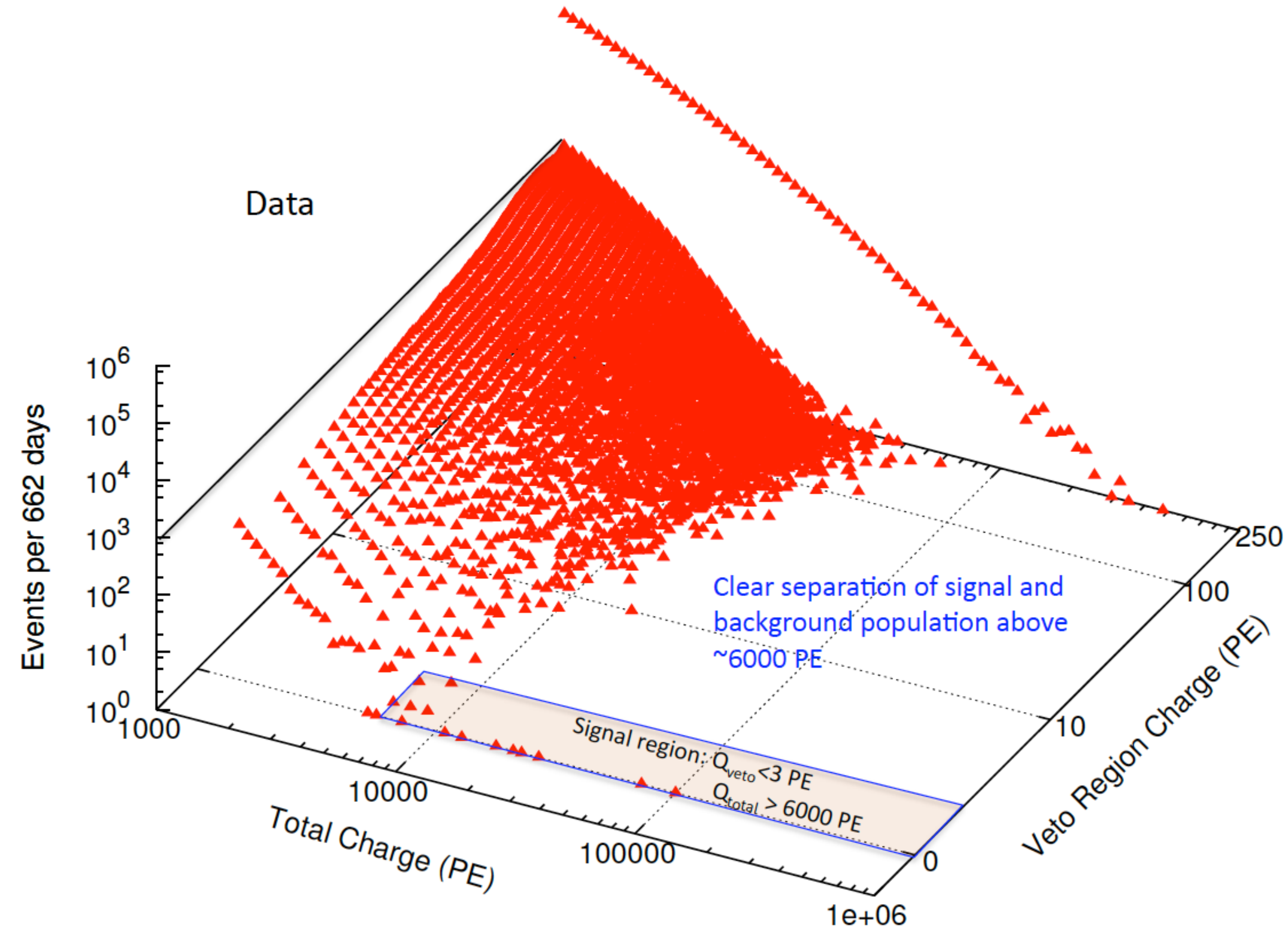


neutrino identification

southern self veto







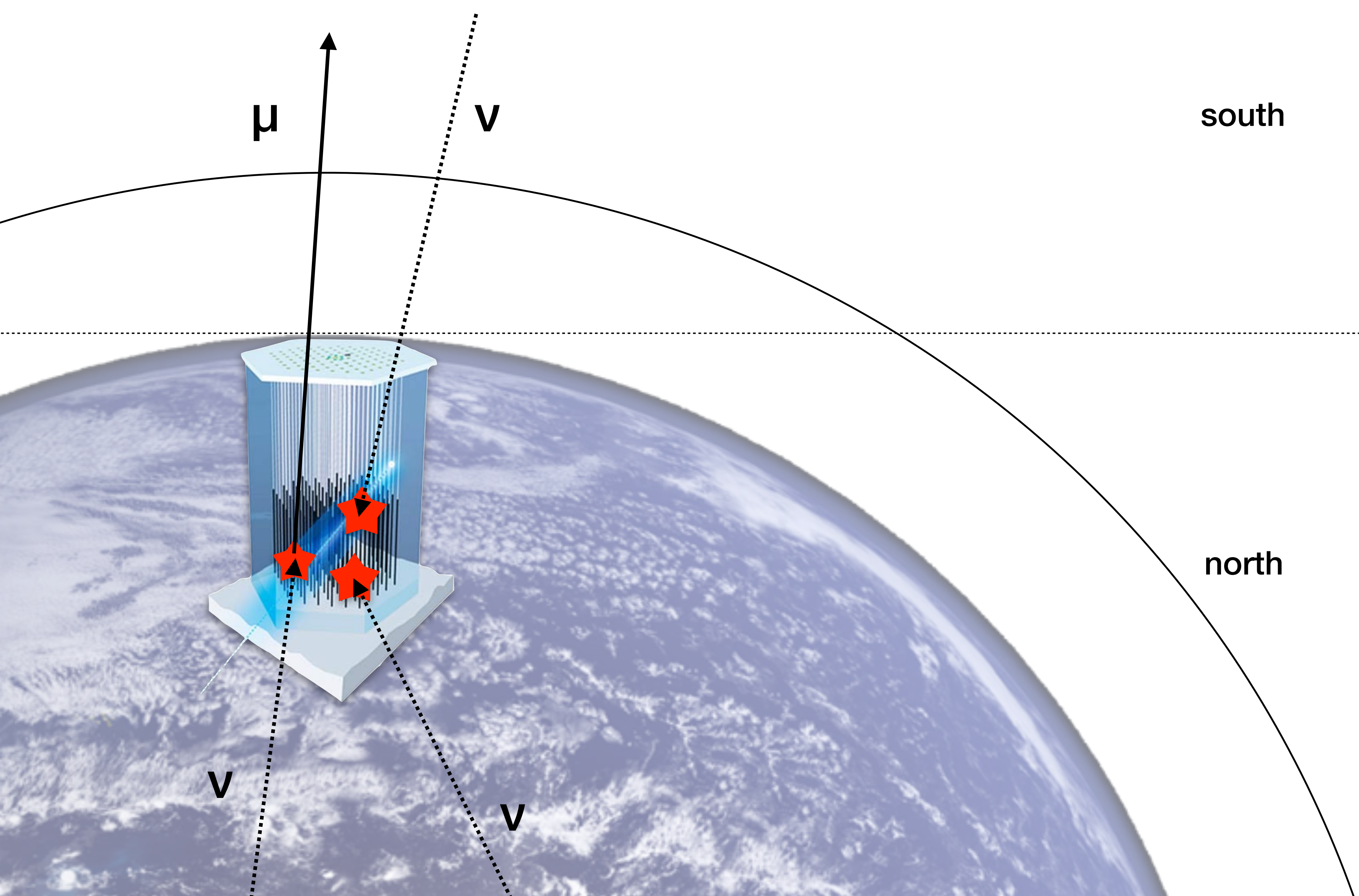
Schönert et al. Phys.Rev.D 79 (2009) 043009
Gaisser et al. Phys.Rev.D 90 (2014) 023009

neutrino identification

diffuse flux

veto efficiency increases with energy

a window to **high energy astrophysical neutrino discovery**



rejection of
HE atmospheric μ and ν
conventional & prompt

retention of
HE astrophysical ν

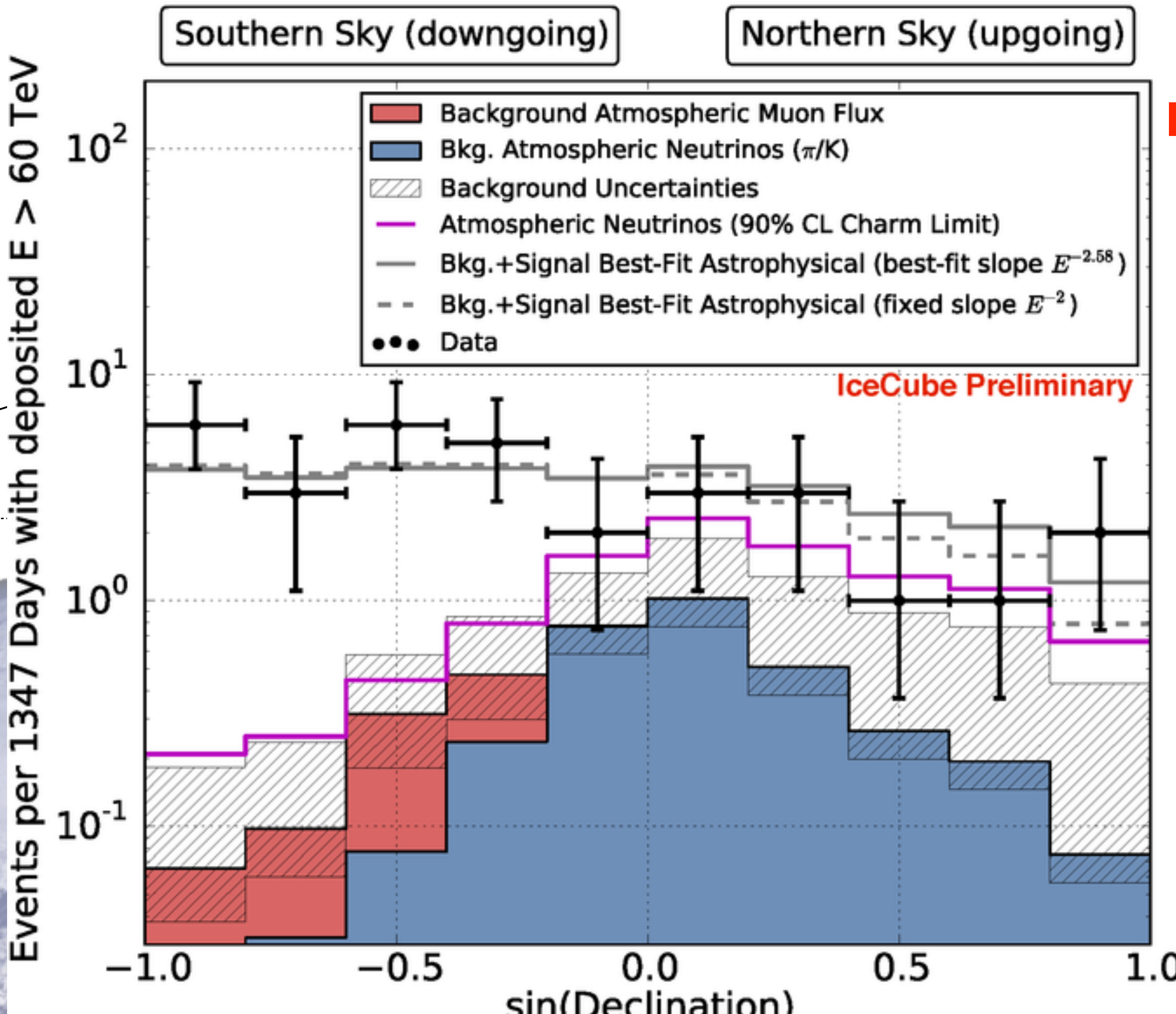
rejection of
HE atmospheric μ

retention of
HE atmospheric ν
HE astrophysical ν

neutrino identification

astrophysical neutrinos

4 years of HE starting events
E_ν > 60 TeV



ICRC 2015

south

rejection of
HE atmospheric μ and ν
conventional & prompt

retention of
HE astrophysical ν

north

rejection of
HE atmospheric μ

retention of
HE atmospheric ν
HE astrophysical ν

neutrino identification

astrophysical neutrinos

- 53(+1) events found
- estimated background

$9.0^{+8.0}_{-2.2}$ atm. neutrinos

12.6±5.1 atm. muons

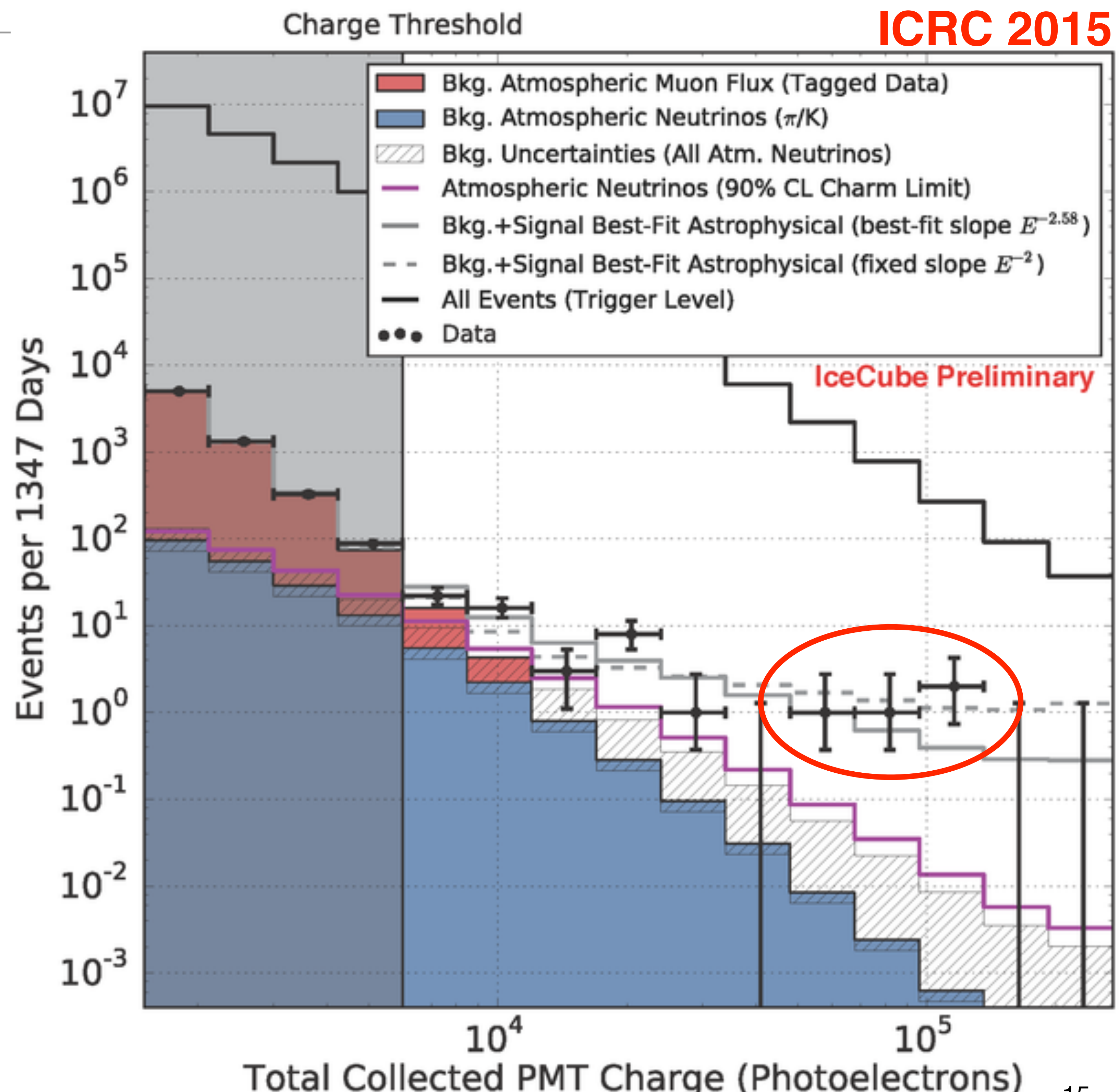
1 atm. muon passing veto

coincident CR showers

6.5 σ significance

4 years of HE starting events

ICRC 2015

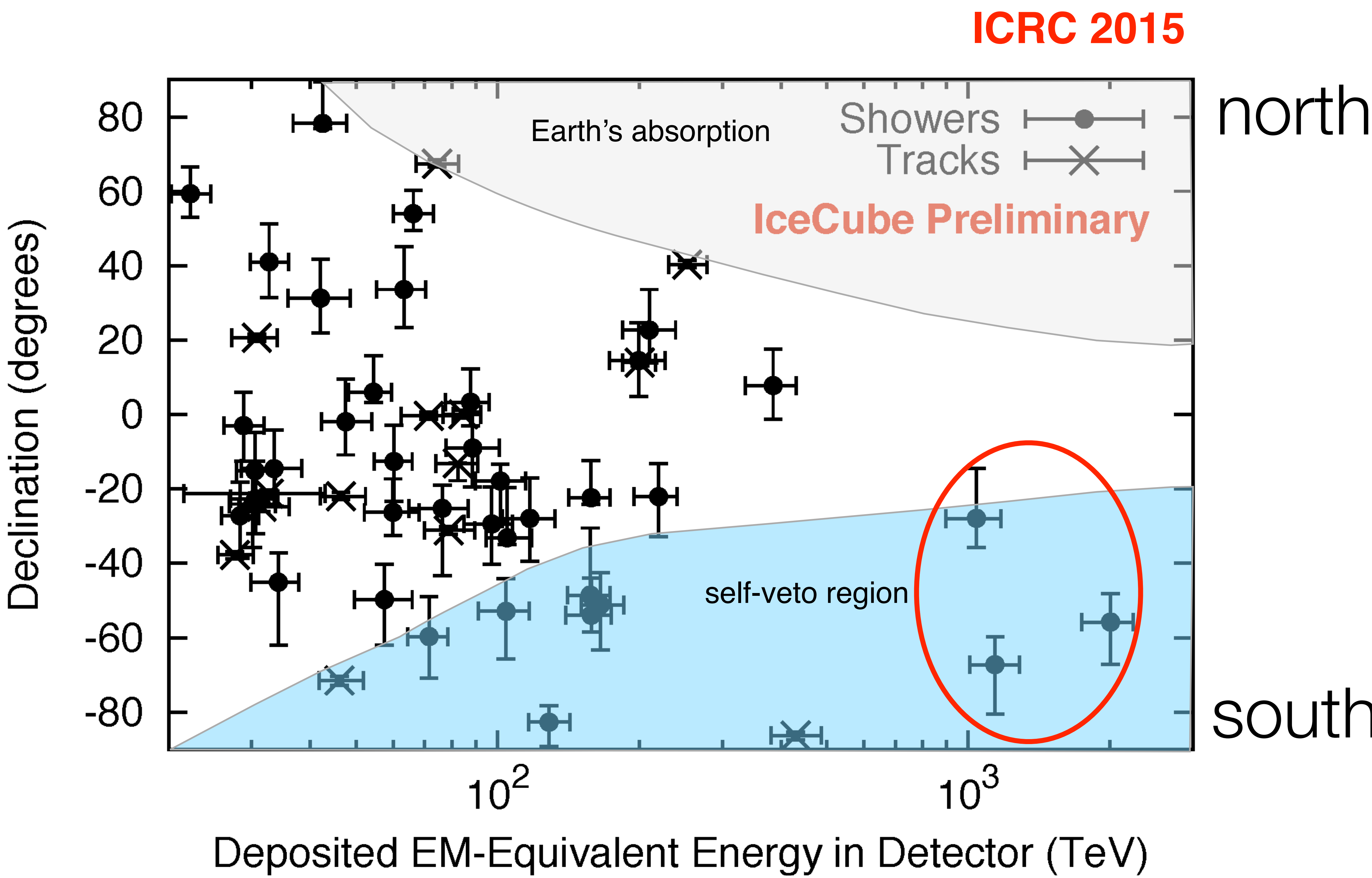


Aartsen et al. PRD 88 (2013) 112008
Aartsen et al. Science 342 (2013) 1242856
Aartsen et al. PRL 113 (2014) 101101

neutrino identification

astrophysical neutrinos

4 years of HE starting events
E_ν > 10 TeV

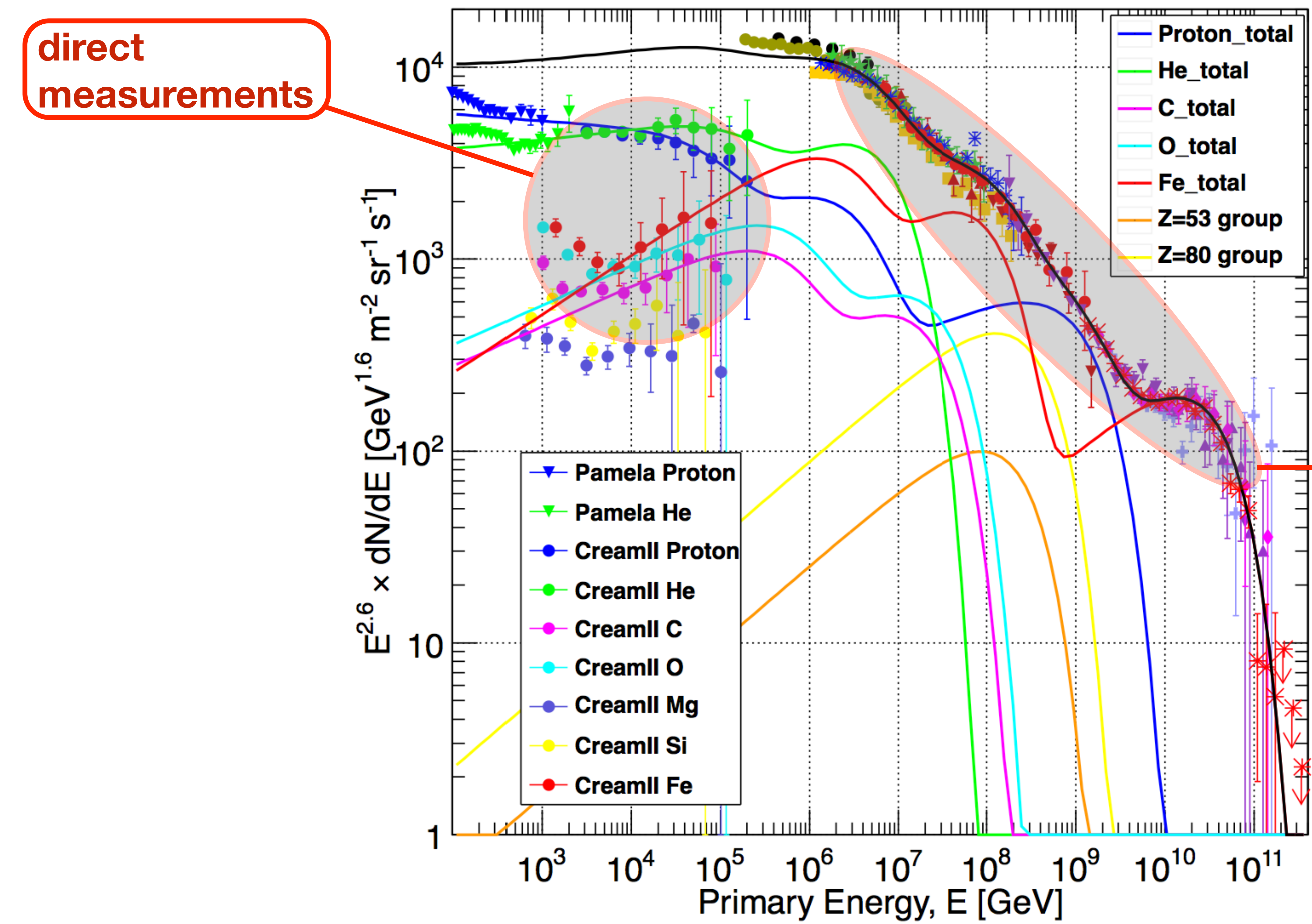


14 tracks
40 cascades

primary cosmic rays

spectrum and composition

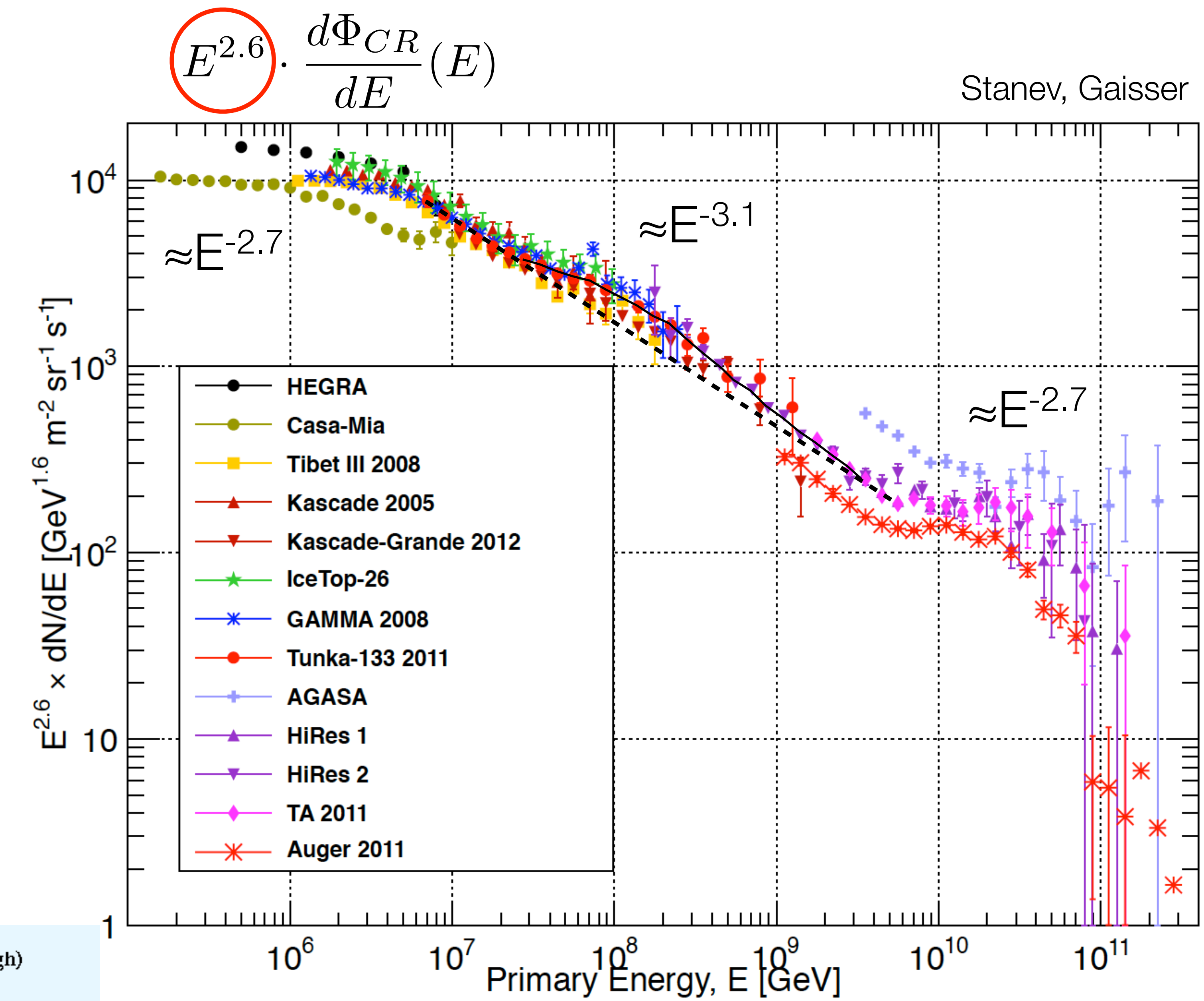
disentangle astrophysics and particle physics

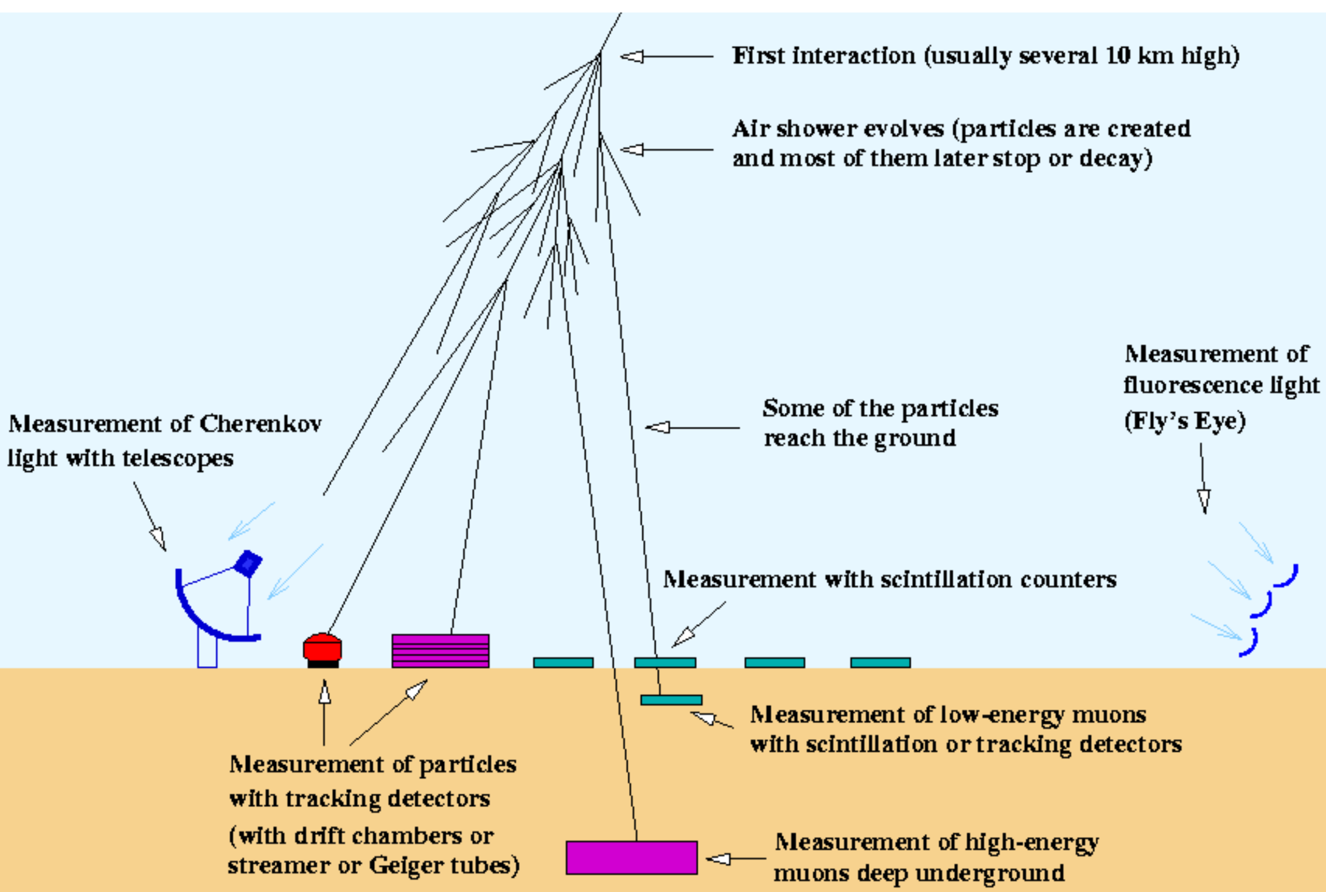


Gaisser, Stanev, Tilav
arXiv:1303.3565

cosmic rays spectrum
indirect observations

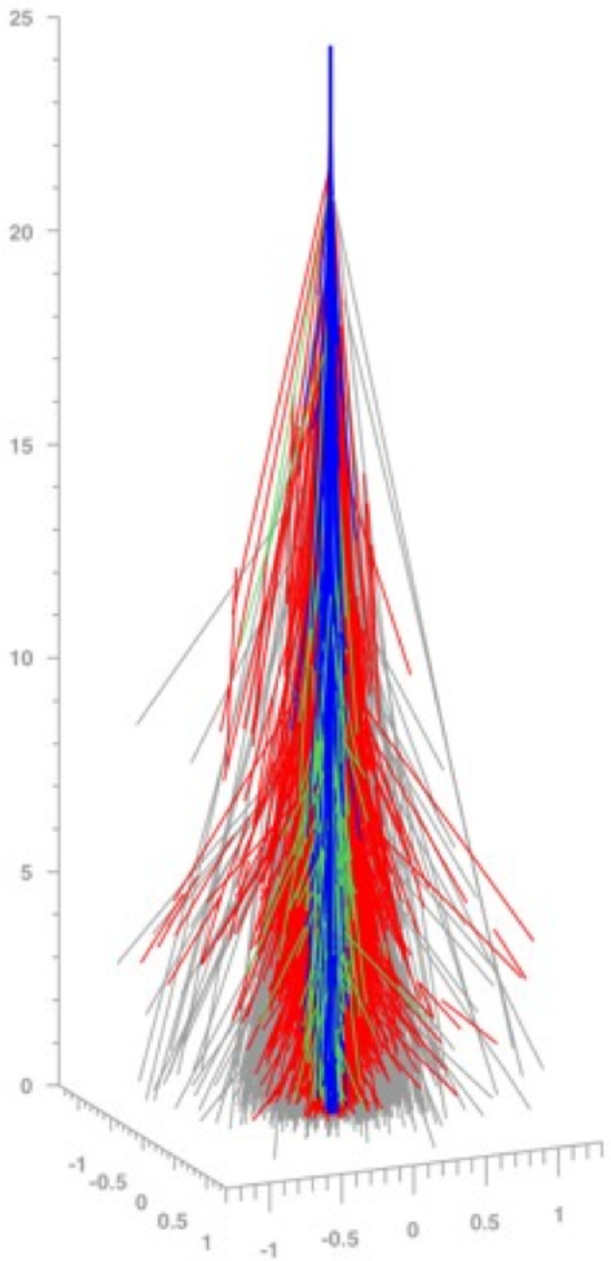
- at **high energy** flux too small for direct observations
- ground-based, under-ground / water / ice detection





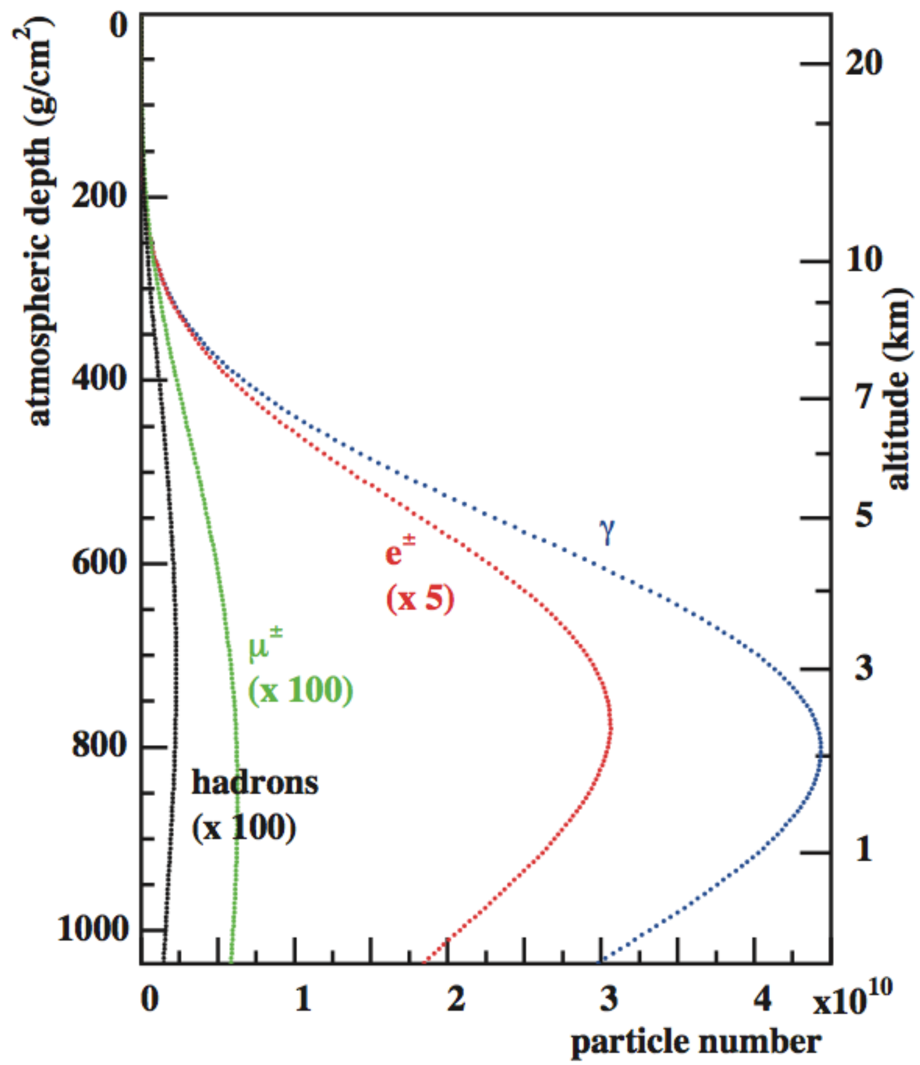
- **atmosphere** & **interaction** properties
- energy & mass observations **tangled**
- lower energy & mass **resolution**

extensive air showers



proton @ 10^{19} eV

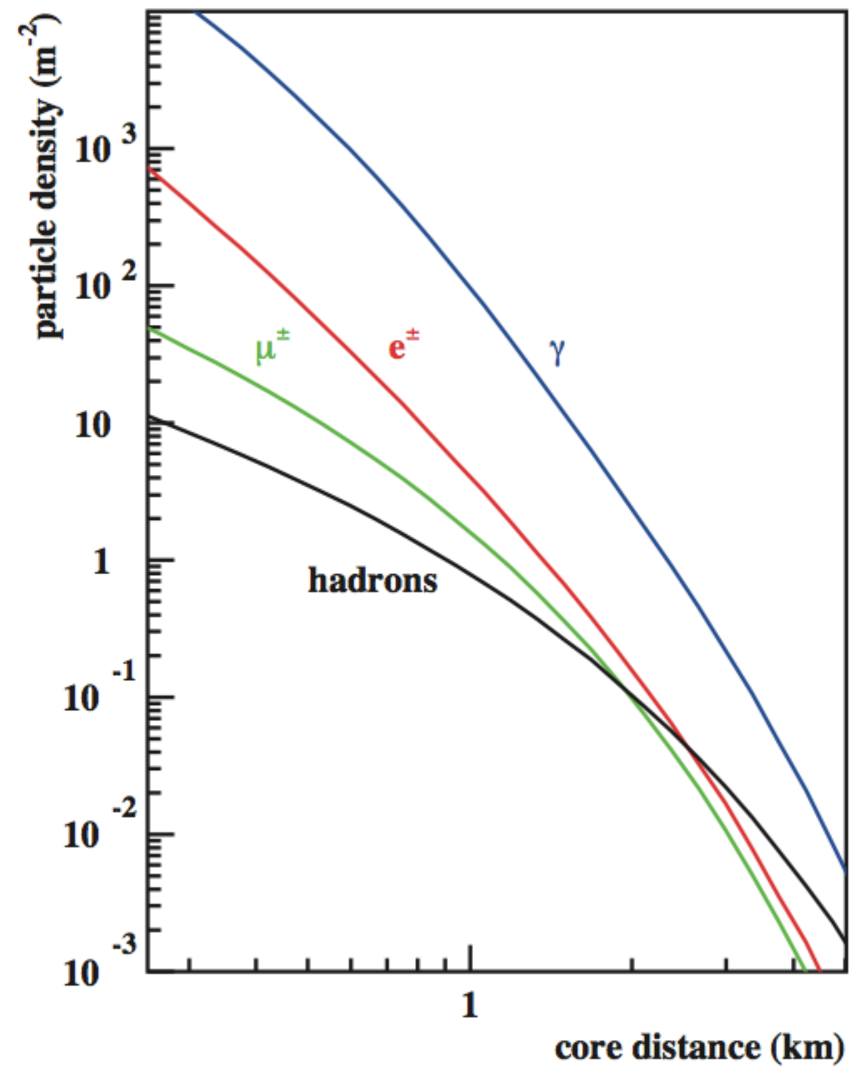
longitudinal profile



detected via:
Cherenkov light
fluorescence light of N_2

lateral profile

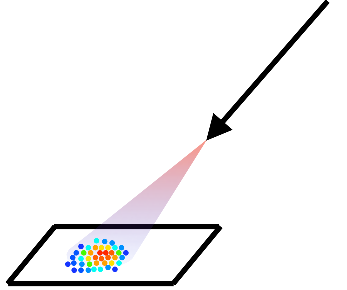
Engel, Pierog, Heck, ARNPS 2011

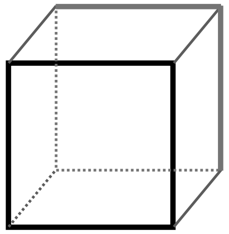


detected via:
particle detector array on the ground

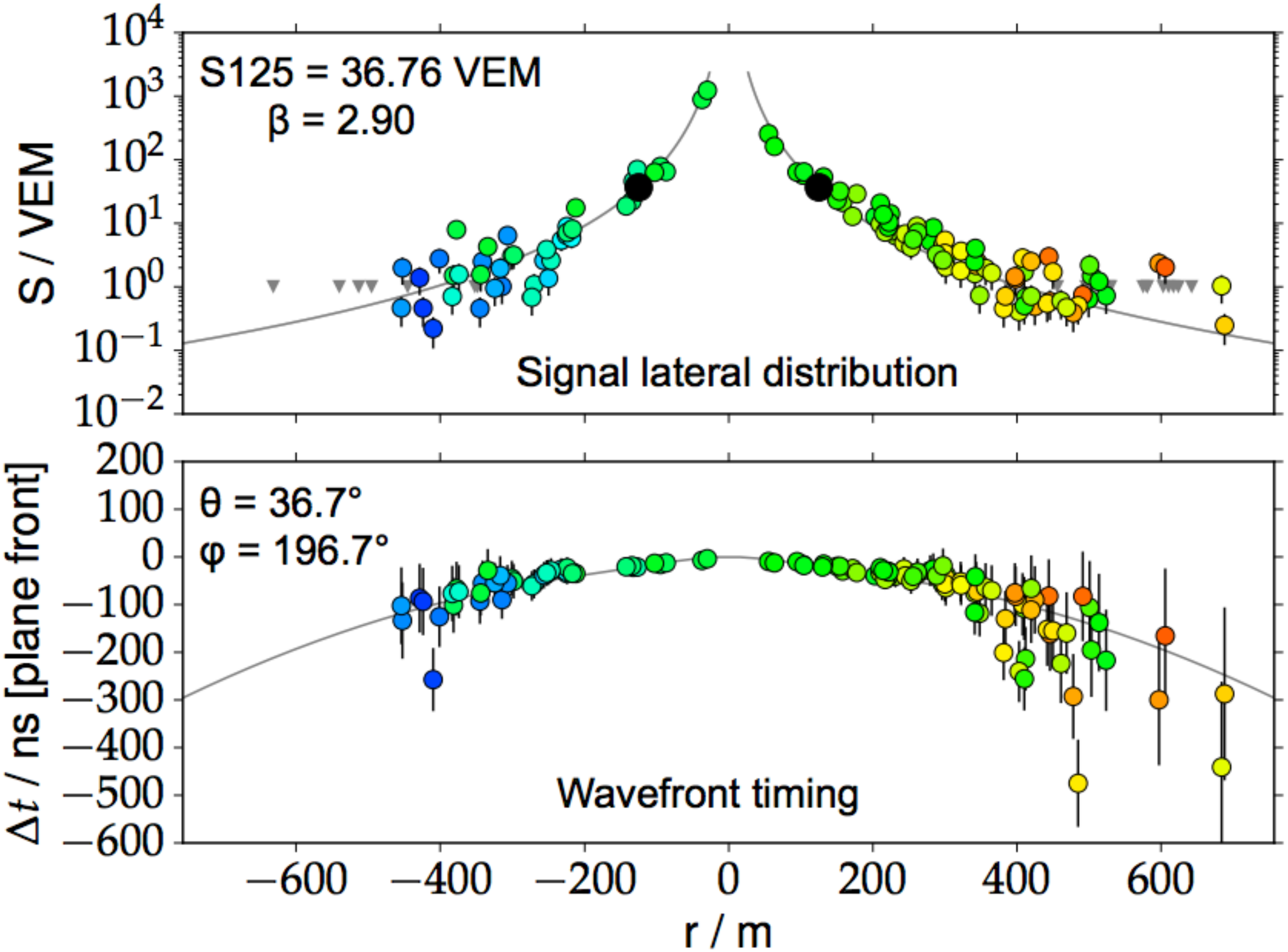
cosmic rays spectrum

all-particle energy spectrum





IceTop



Signal lateral distribution:

$$S(r) = S_{125} e^{-\frac{d \sec\theta}{\lambda}} \left(\frac{r}{125\,\mathrm{m}}\right)^{-\beta-\kappa \log\left(\frac{r}{125\,\mathrm{m}}\right)}$$

Correction for attenuation in snow

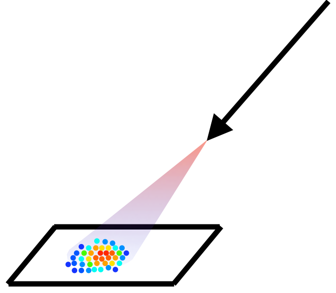
Wavefront timing:

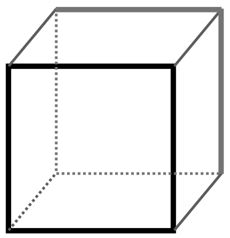
$$t(\vec{x}) = t_0 + \frac{1}{c}(\vec{x} - \vec{x}_c) \cdot \vec{n} + \Delta t(r)$$

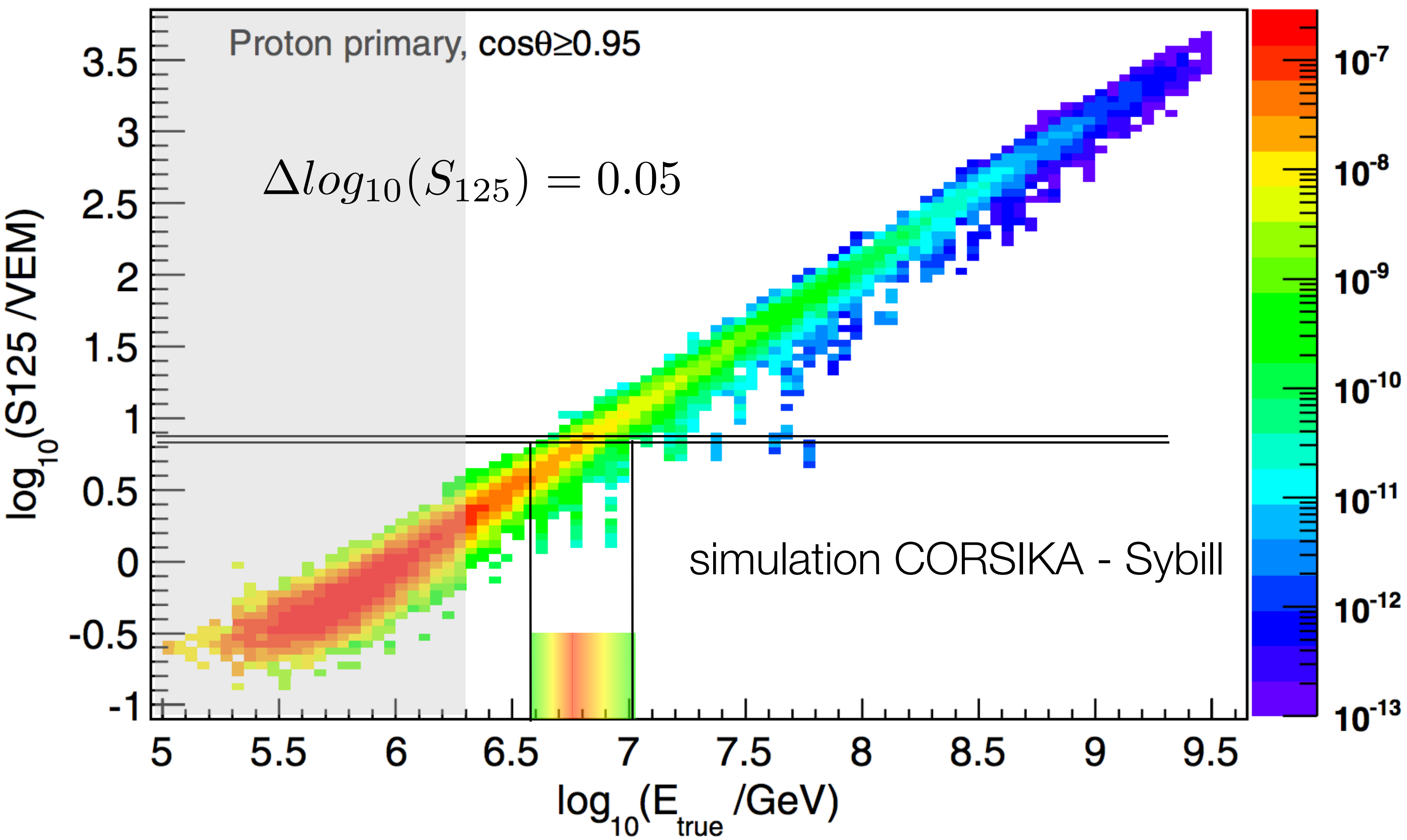
$$\Delta t(r) = ar^2 + b\left(1 - \exp\left(-\frac{r^2}{2\sigma^2}\right)\right)$$

cosmic rays spectrum

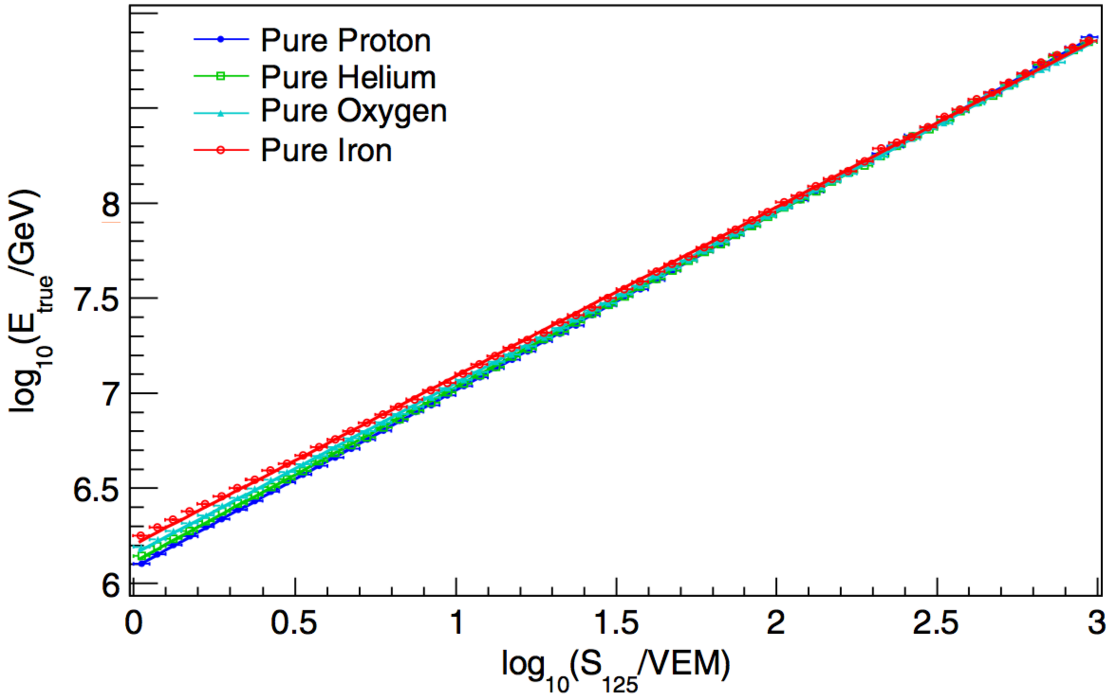
all-particle energy spectrum







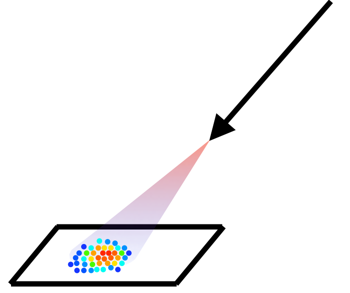
Aartsen et al. PRD 88 (2013) 042004

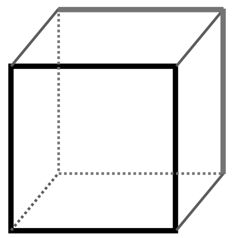


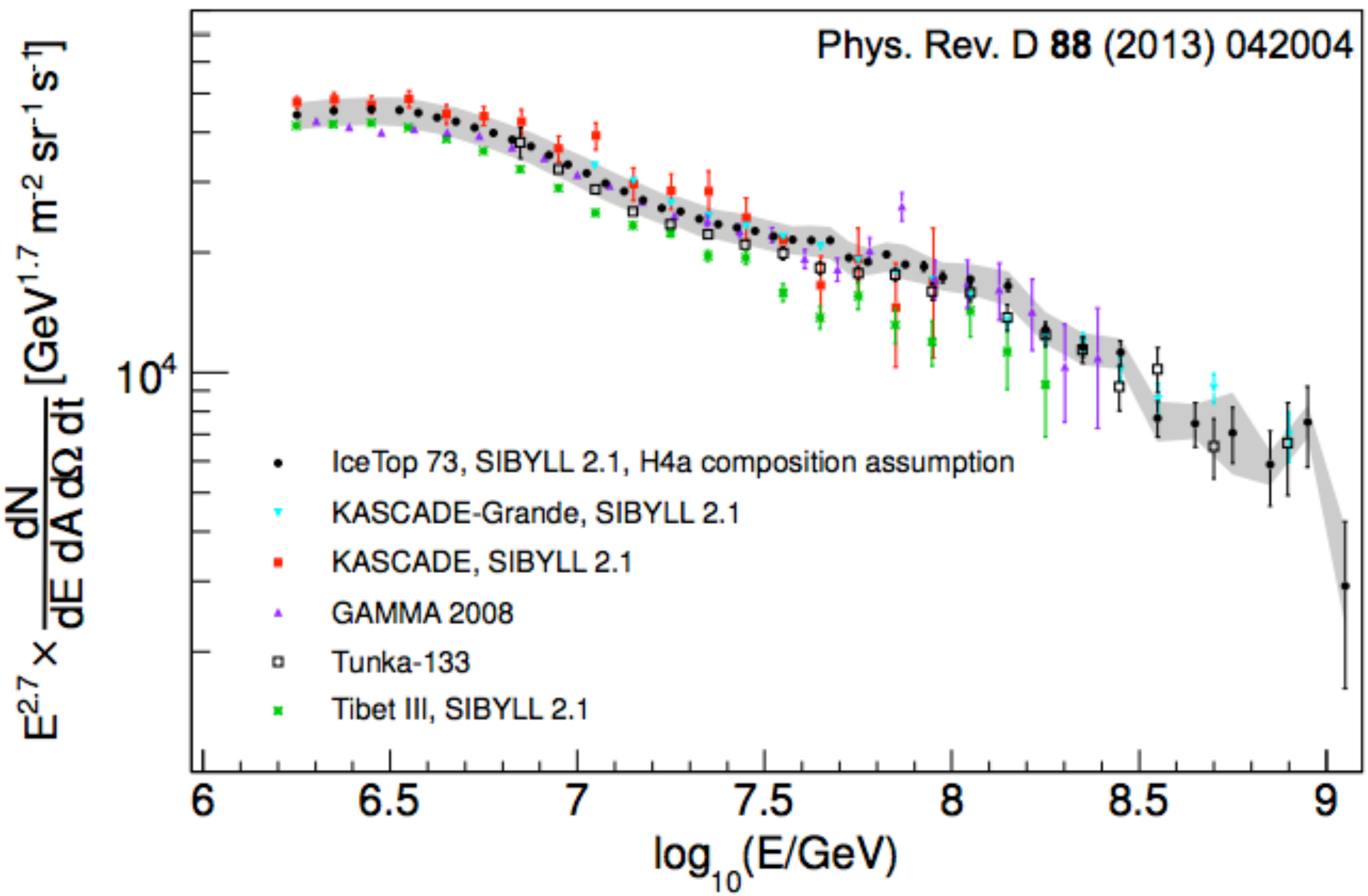
the relationship between S_{125} and primary energy depends on **mass** and **zenith angle**

cosmic rays spectrum

all-particle energy spectrum



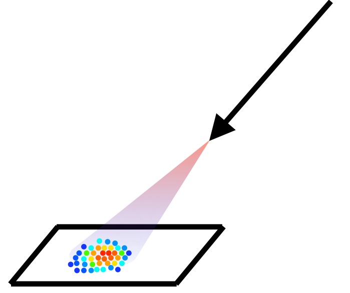


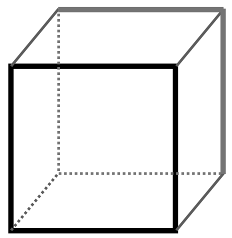


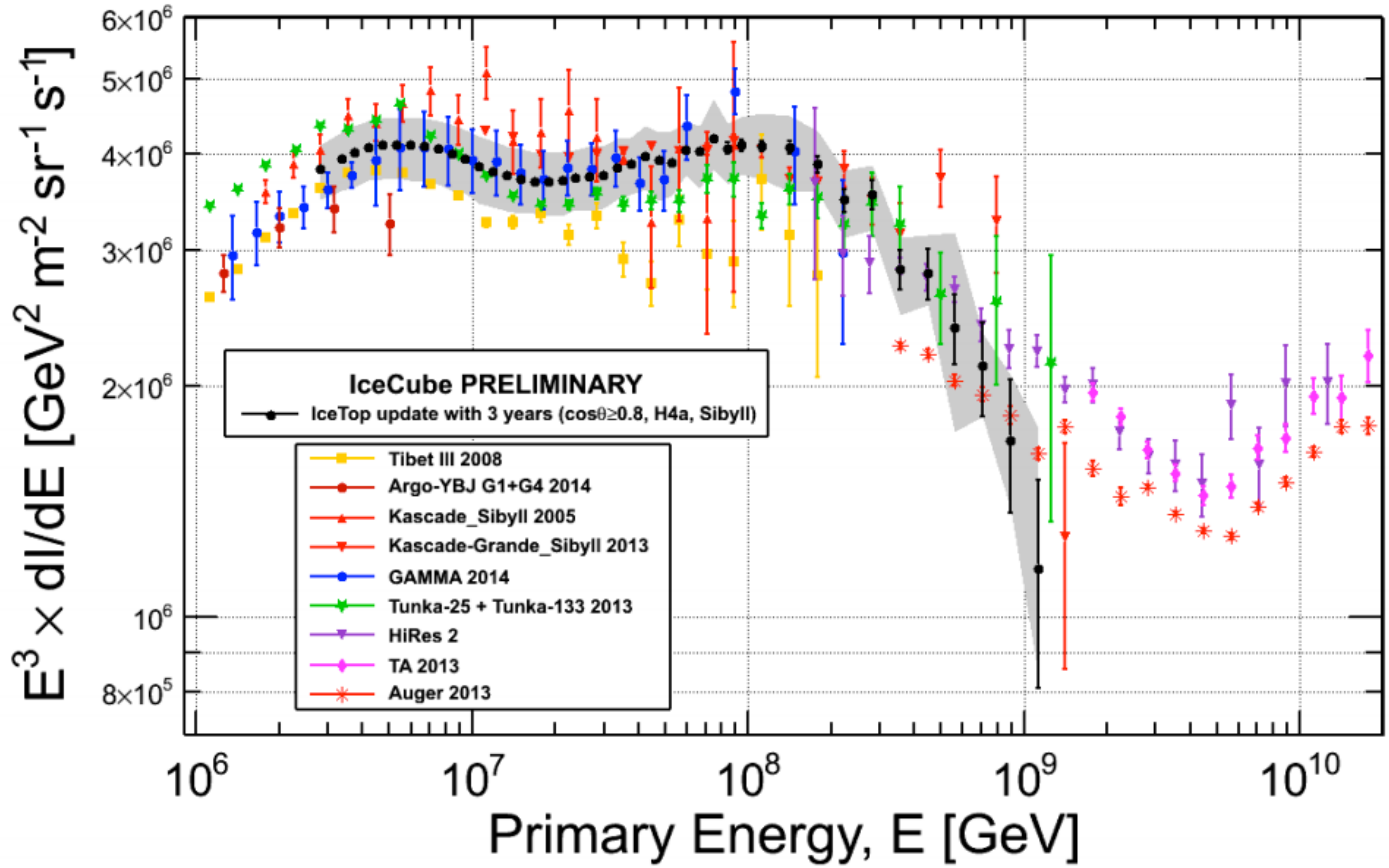
all-particle spectrum depends on the ***assumed*** mass composition of primary particles

cosmic rays spectrum

all-particle energy spectrum



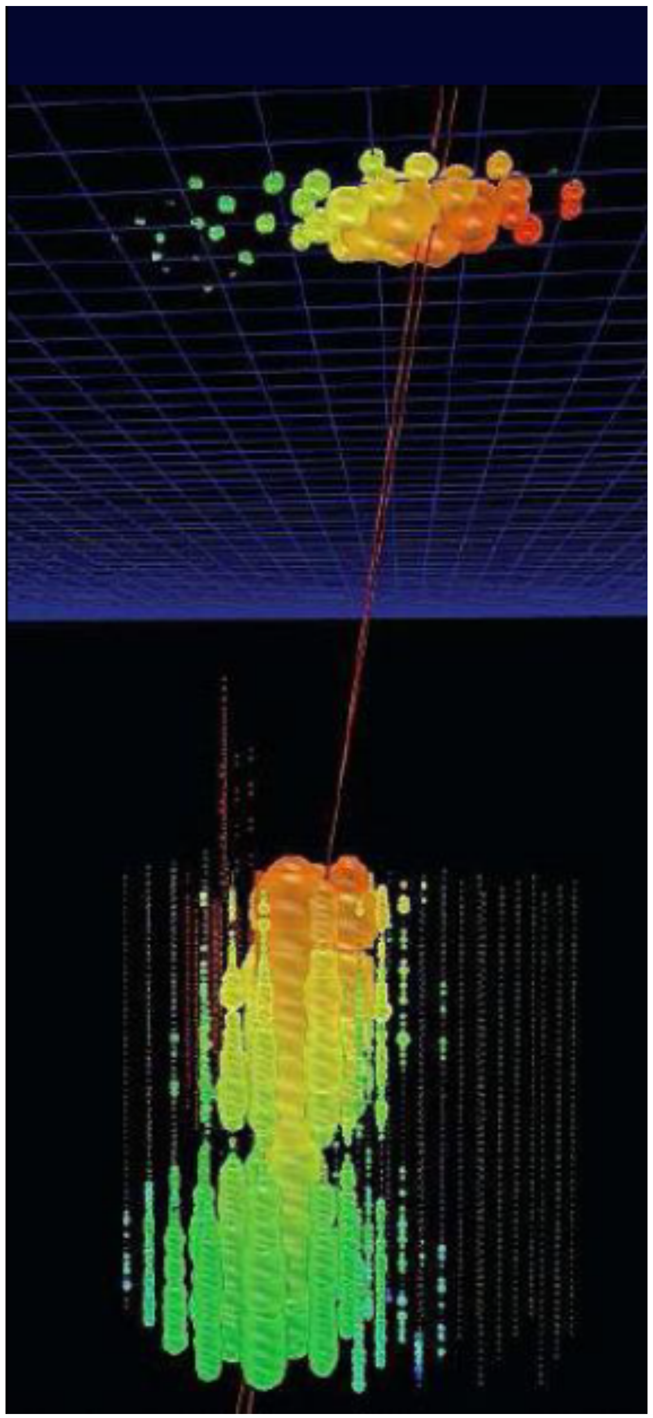


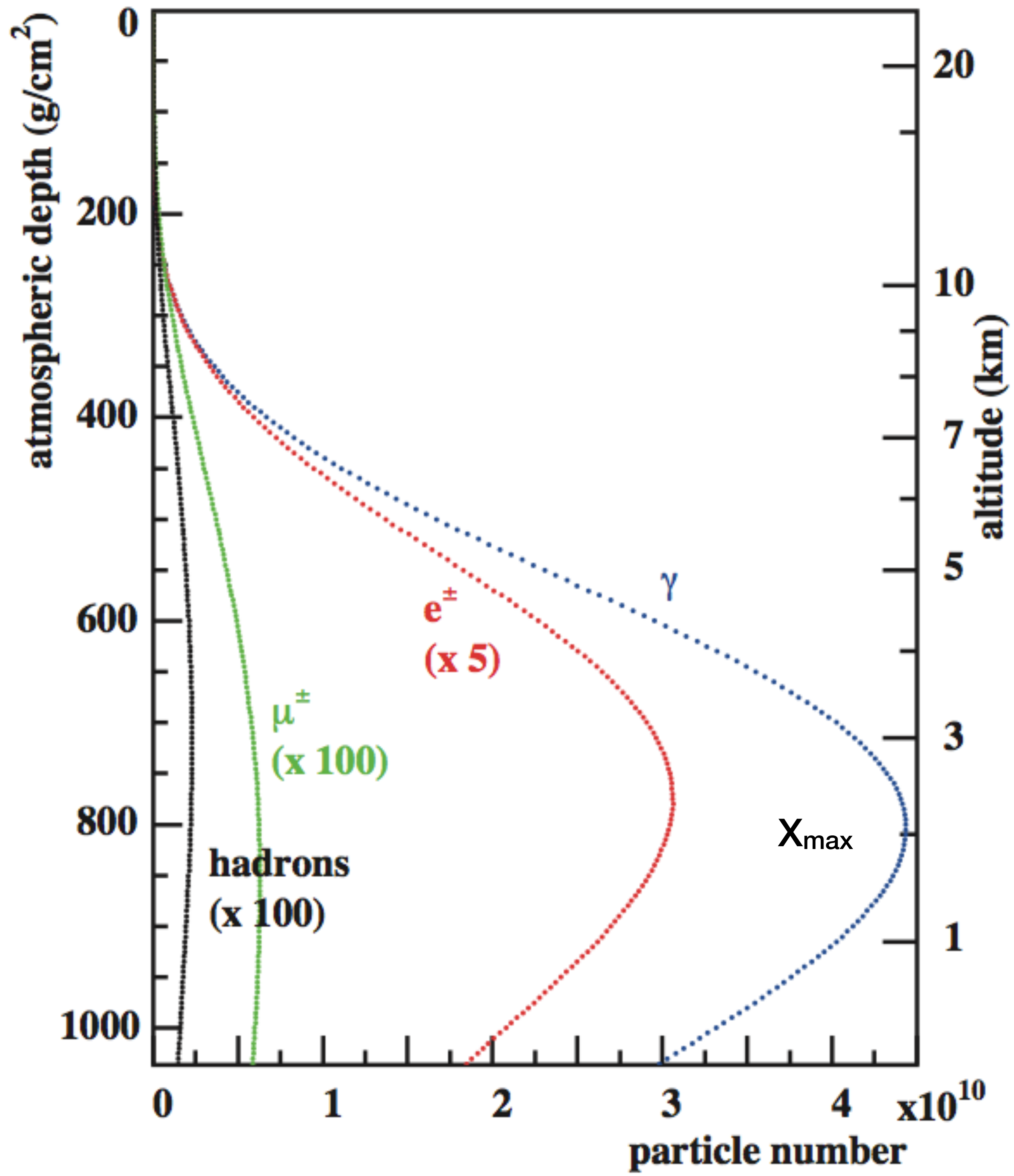


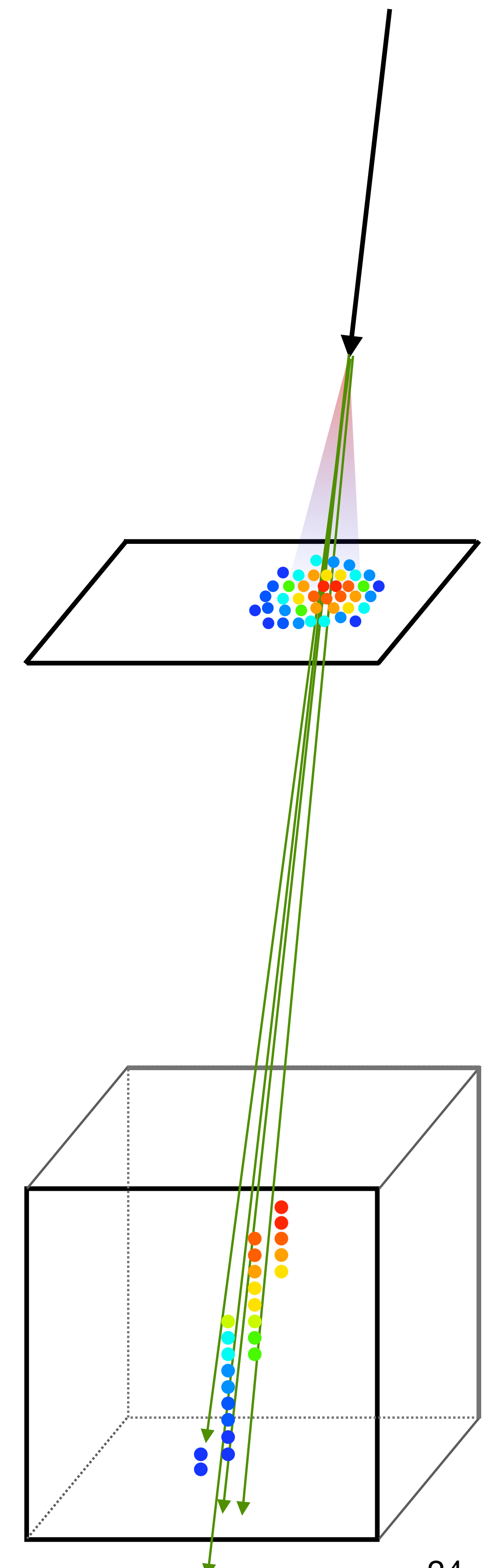
all-particle spectrum depends on the ***assumed*** mass composition of primary particles

cosmic rays composition

coincident events



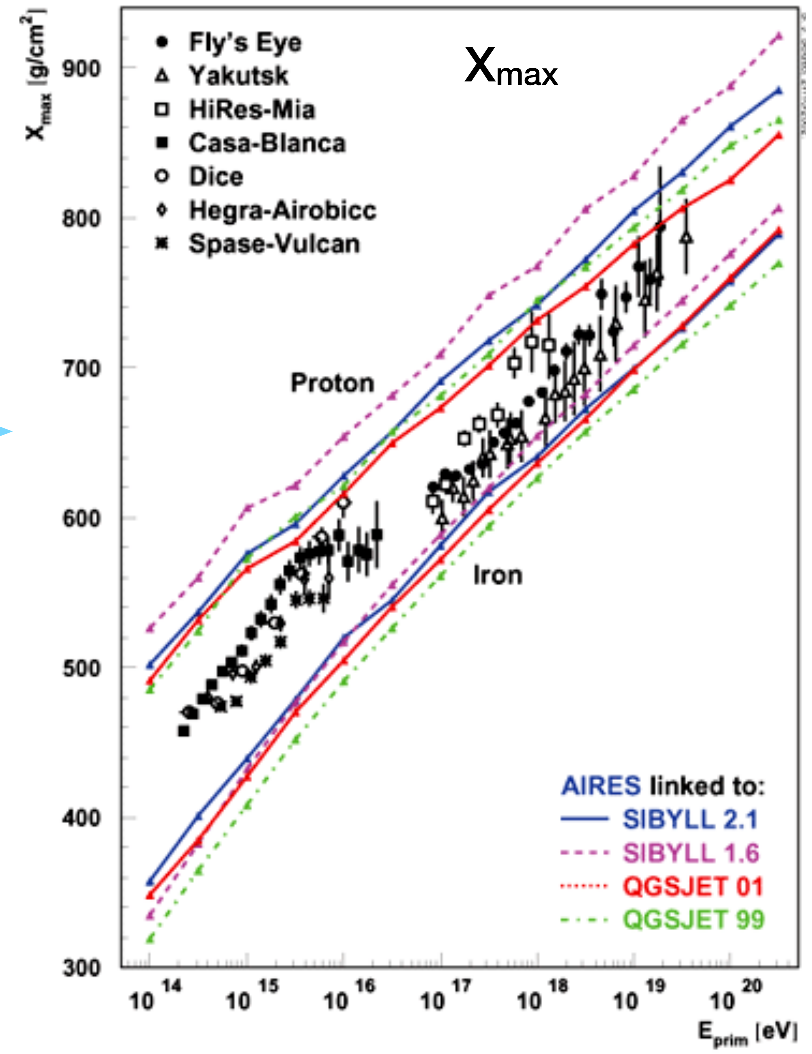


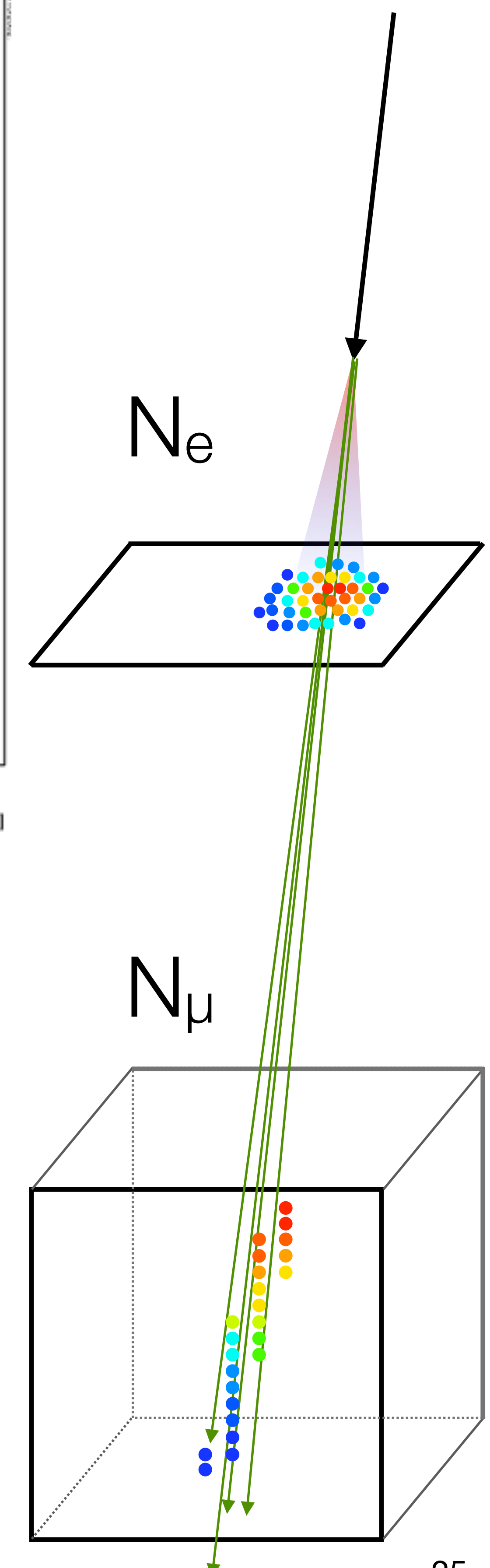


cosmic rays composition
coincident events

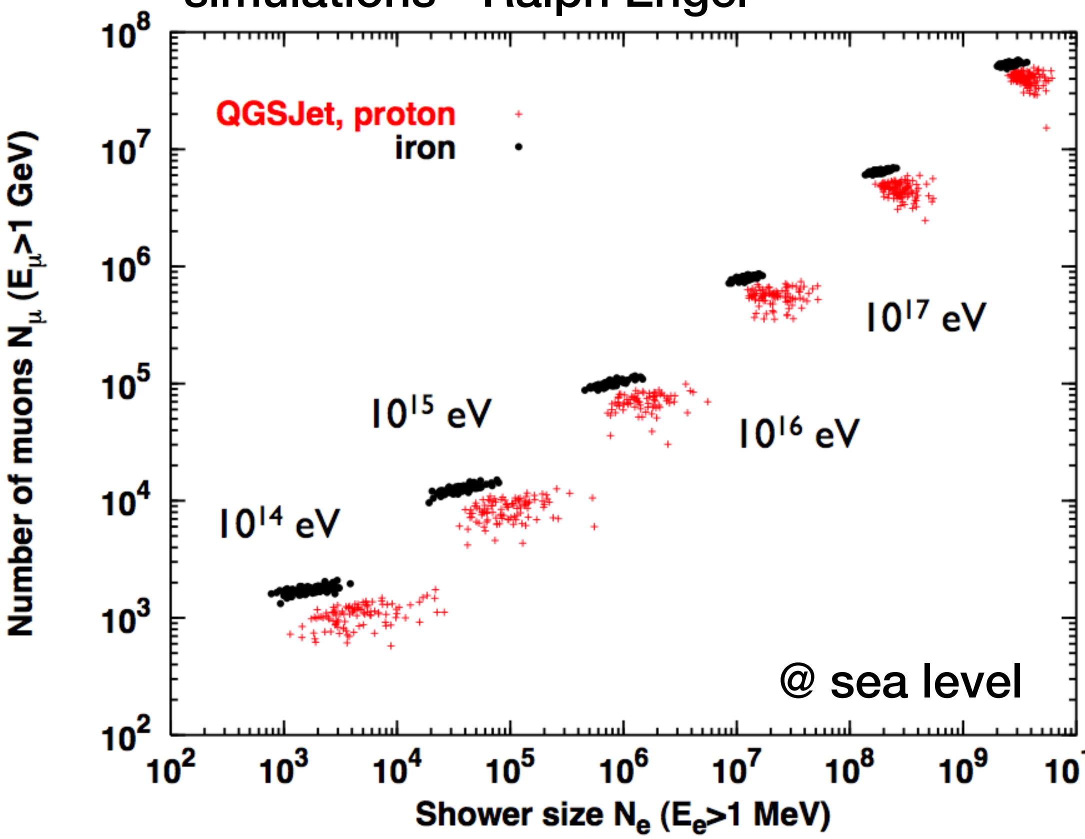
@Antarctica

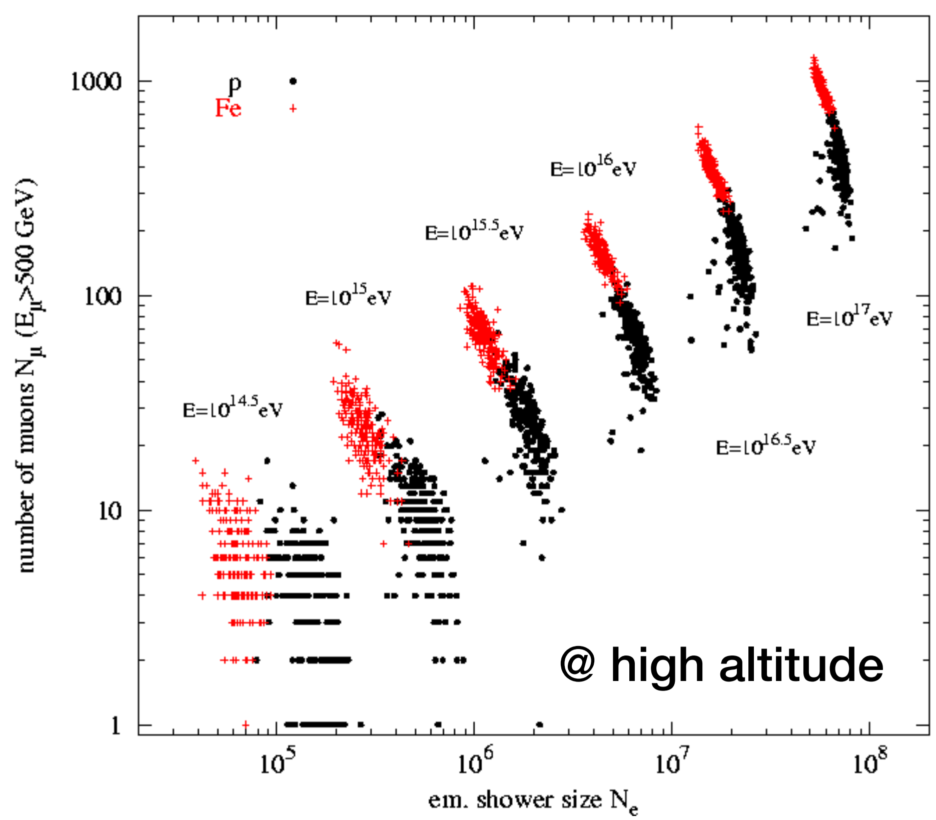
@sea level





simulations - Ralph Engel



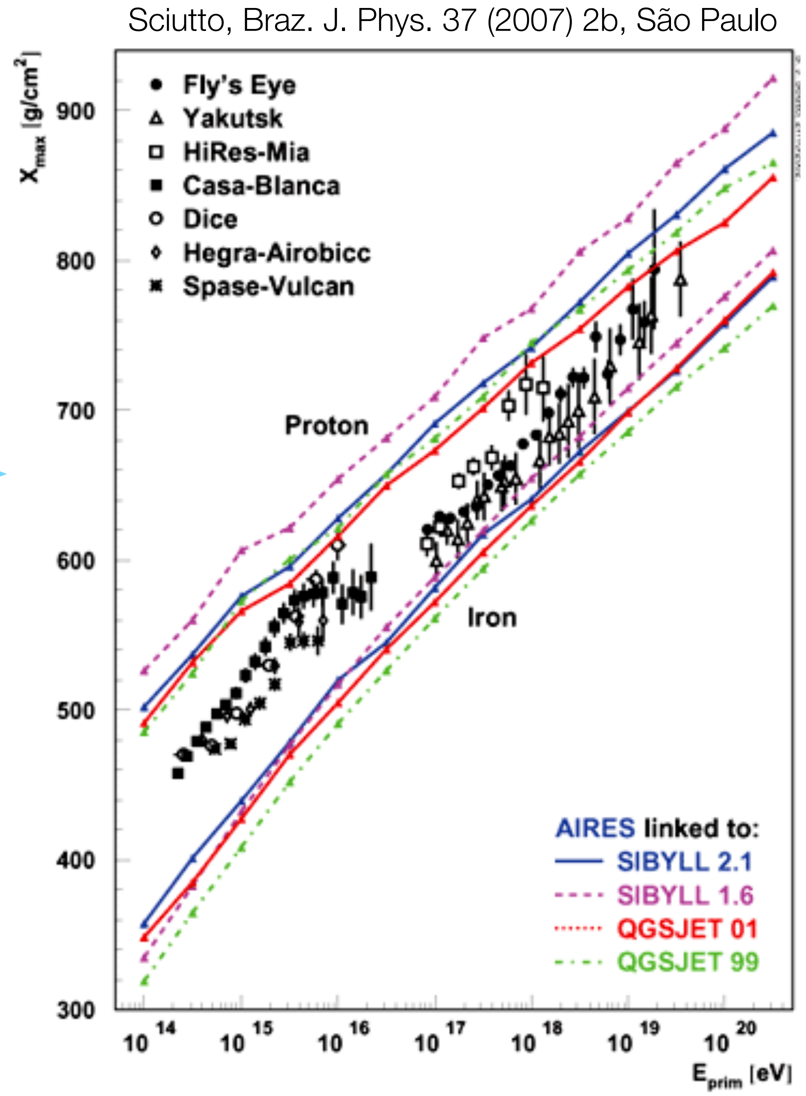


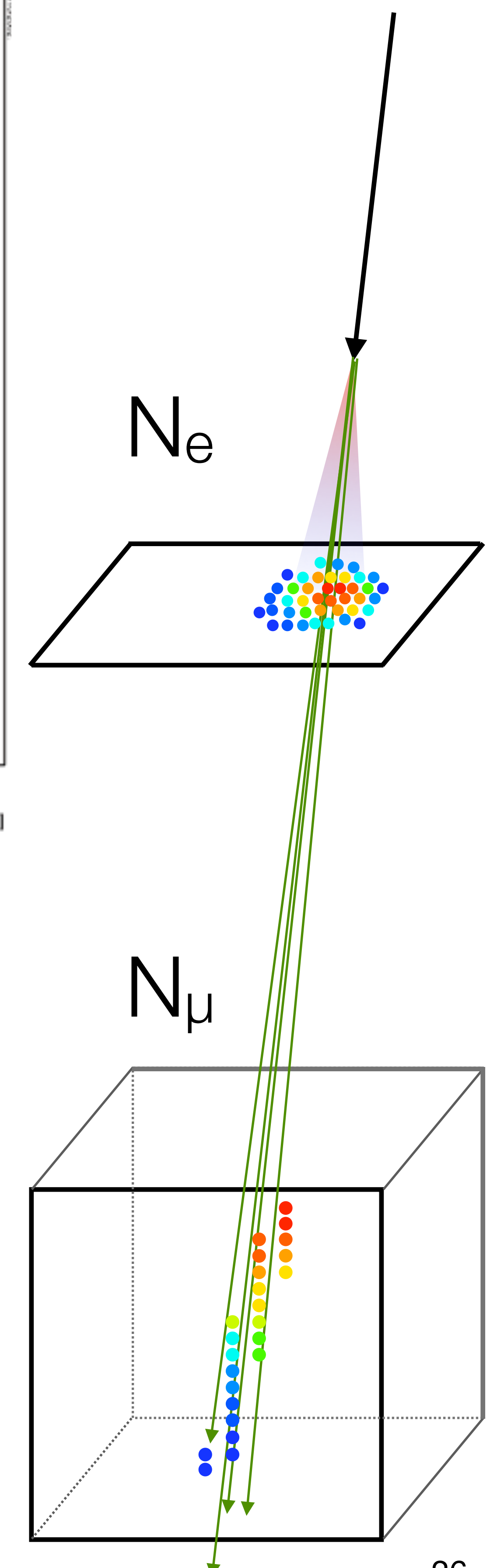
cosmic rays composition

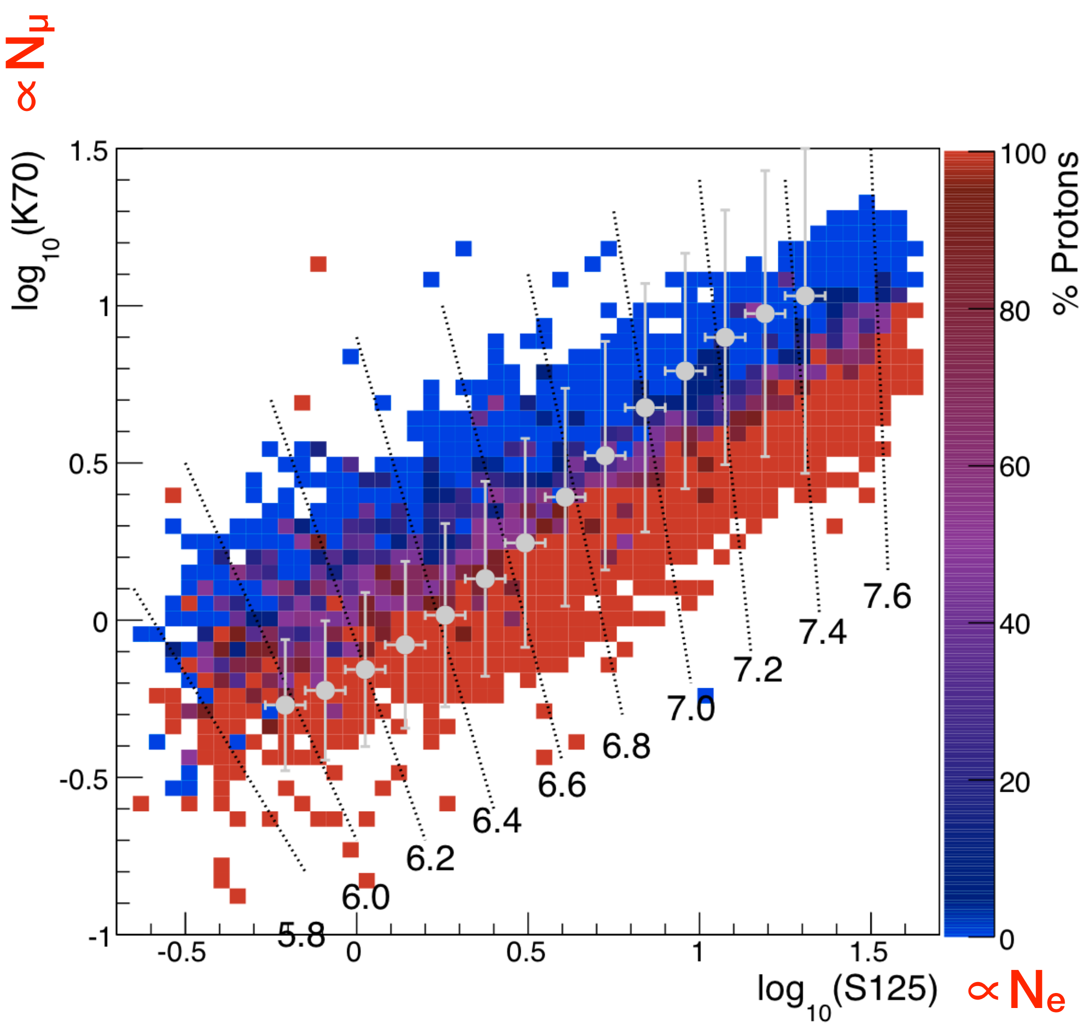
coincident events

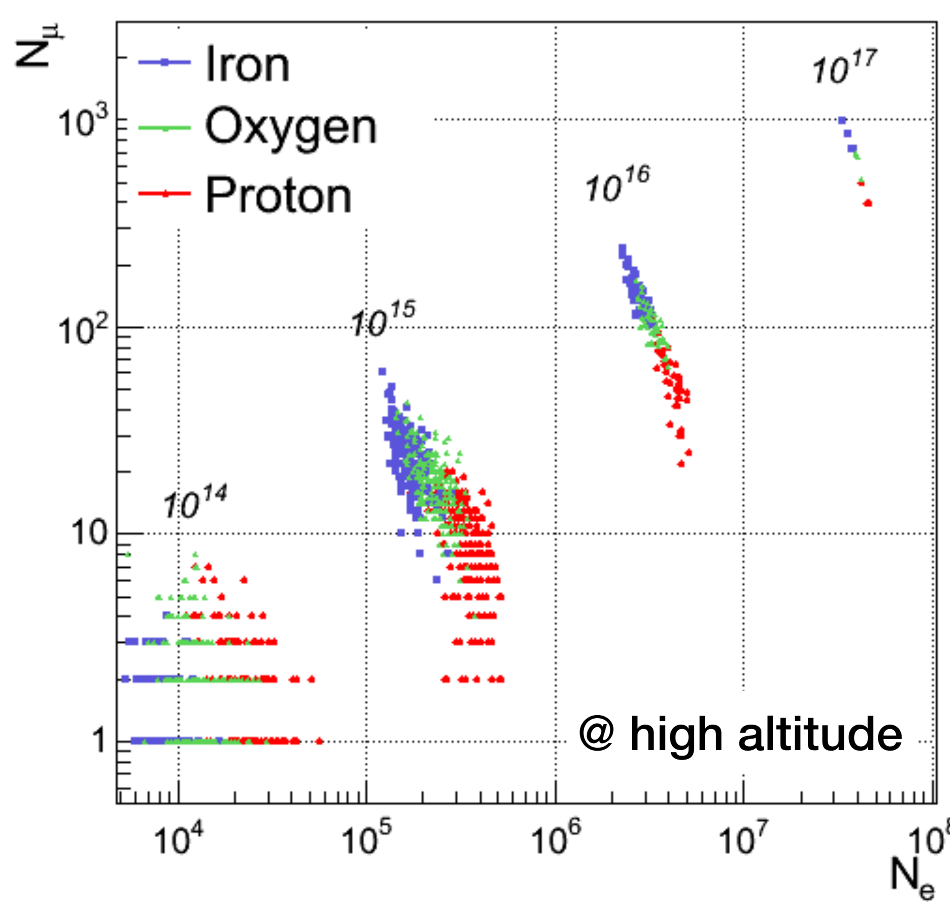
@Antarctica

@sea level







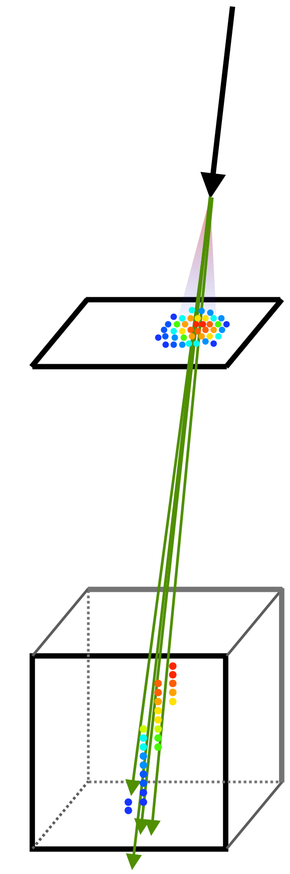


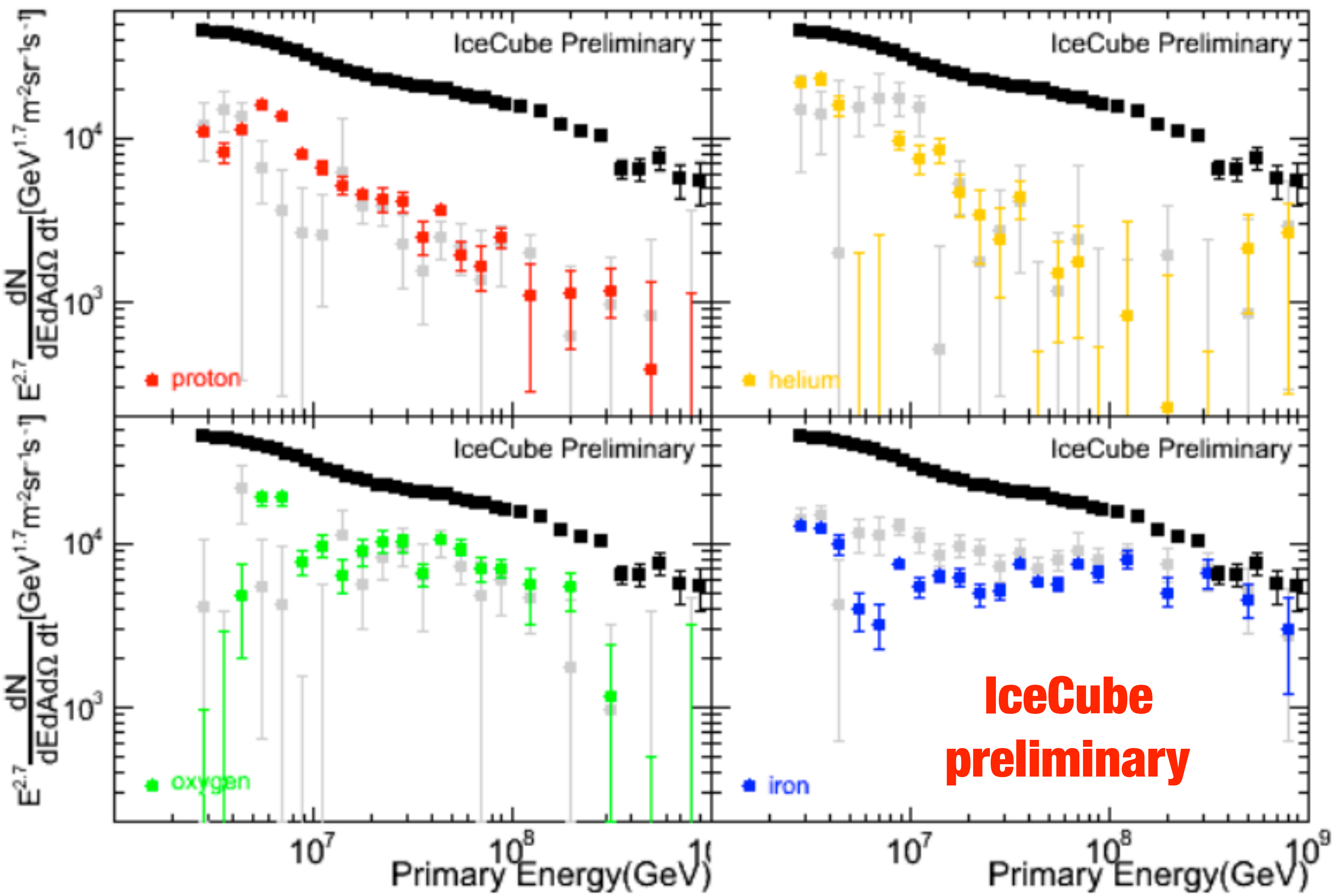
cosmic rays composition

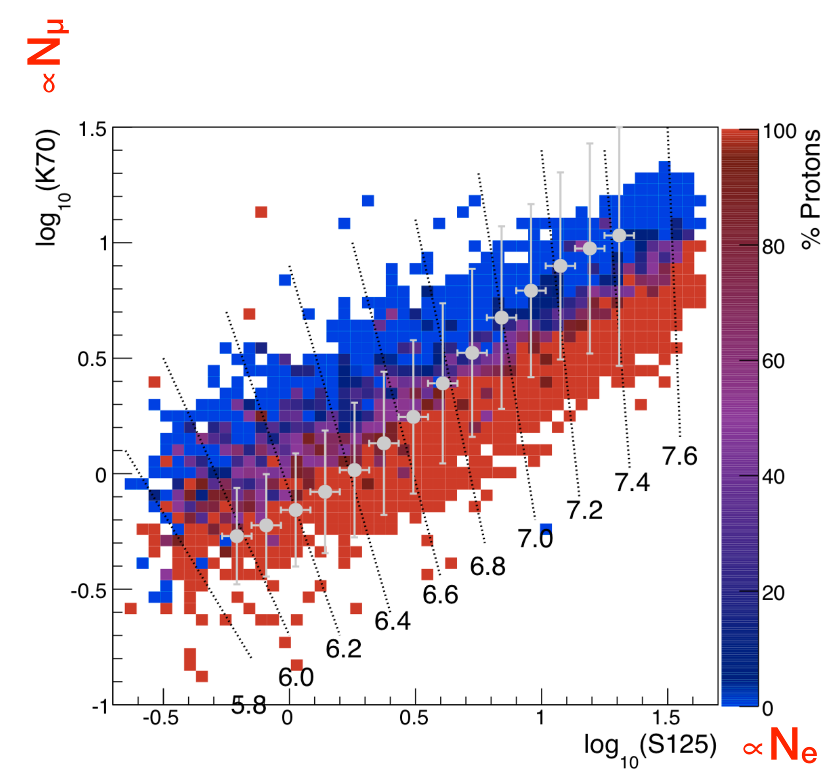
coincident events

Colors = SIBYLL 2.1
Grey = QGSJET-II-03

effect of hadronic interaction models

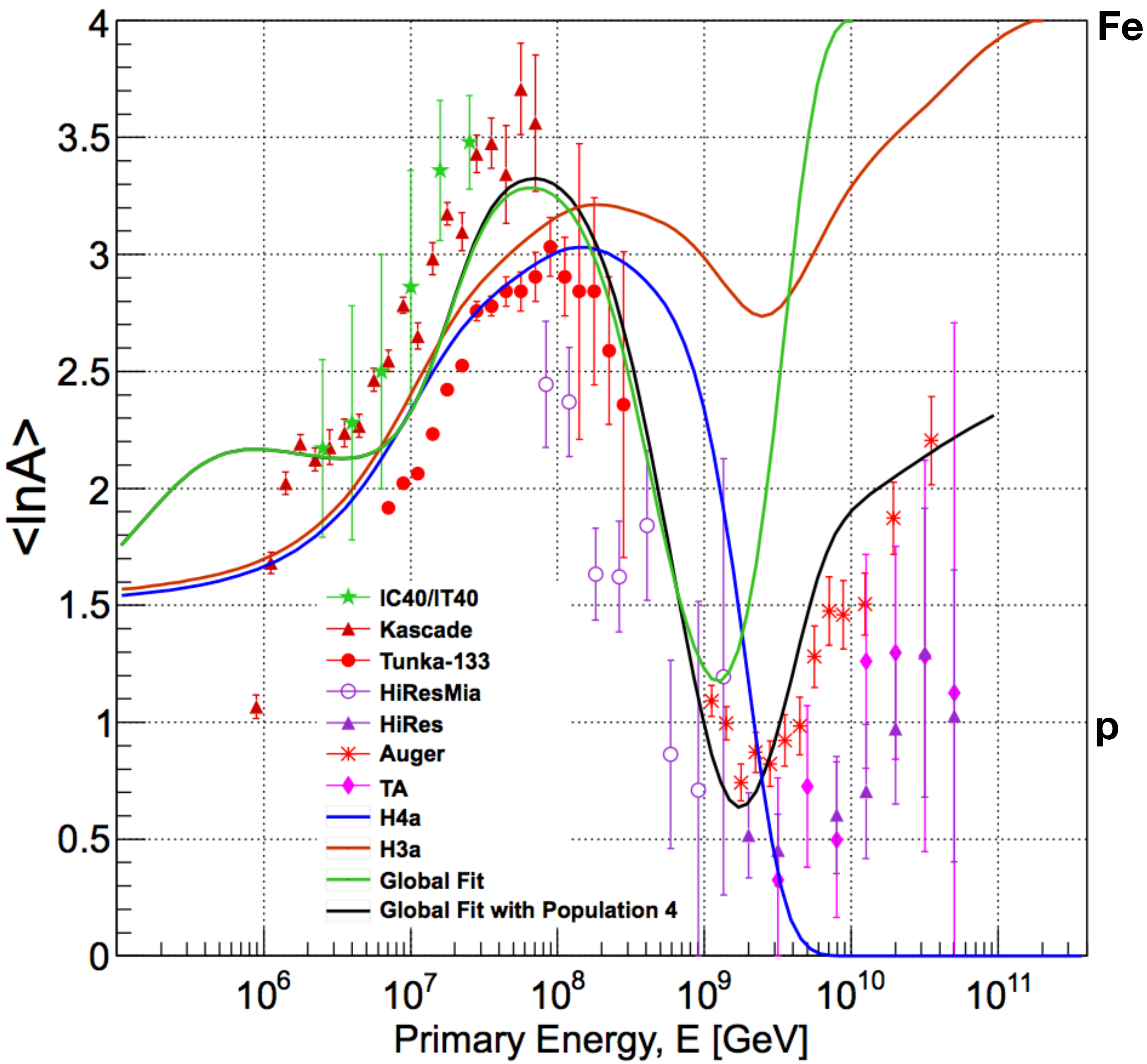






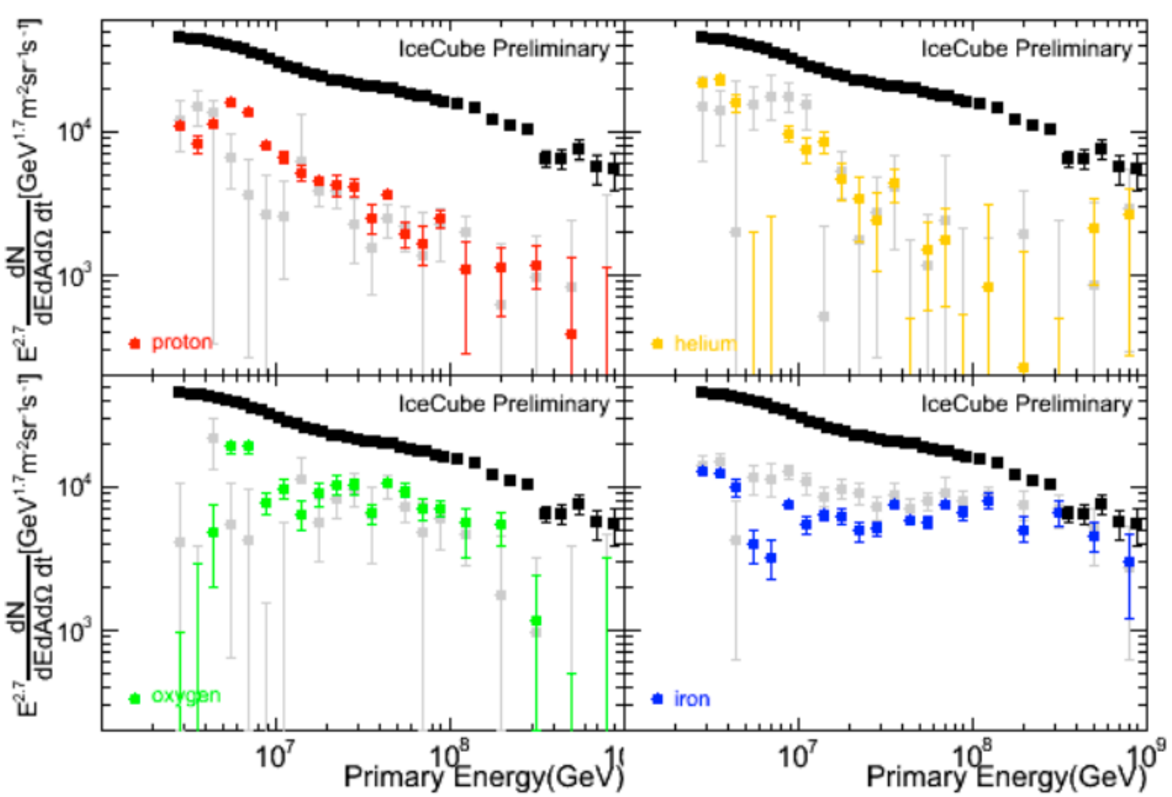
cosmic rays composition

other experiments



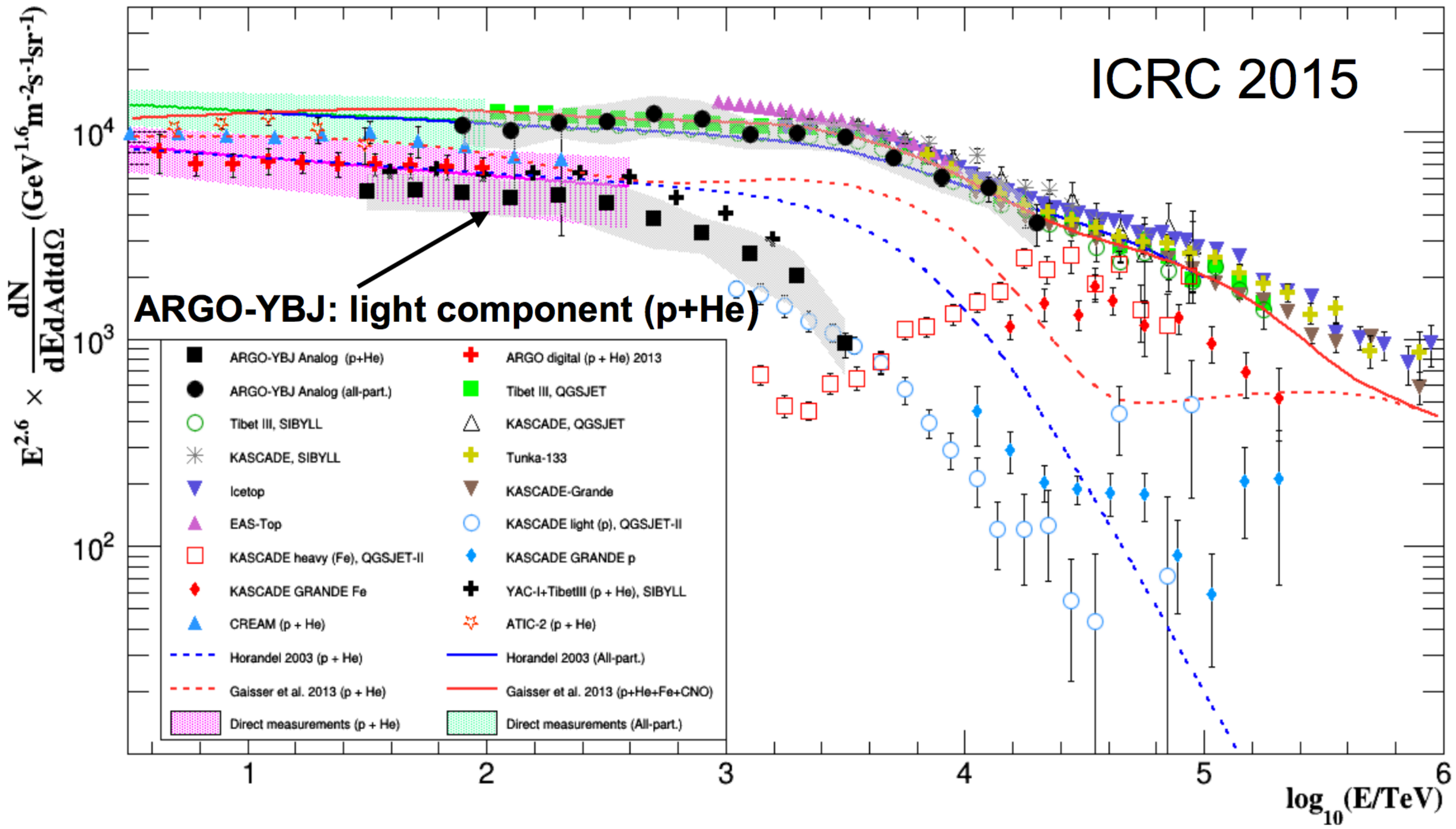
cosmic ray composition in **indirect** measurements is **DIFFICULT**

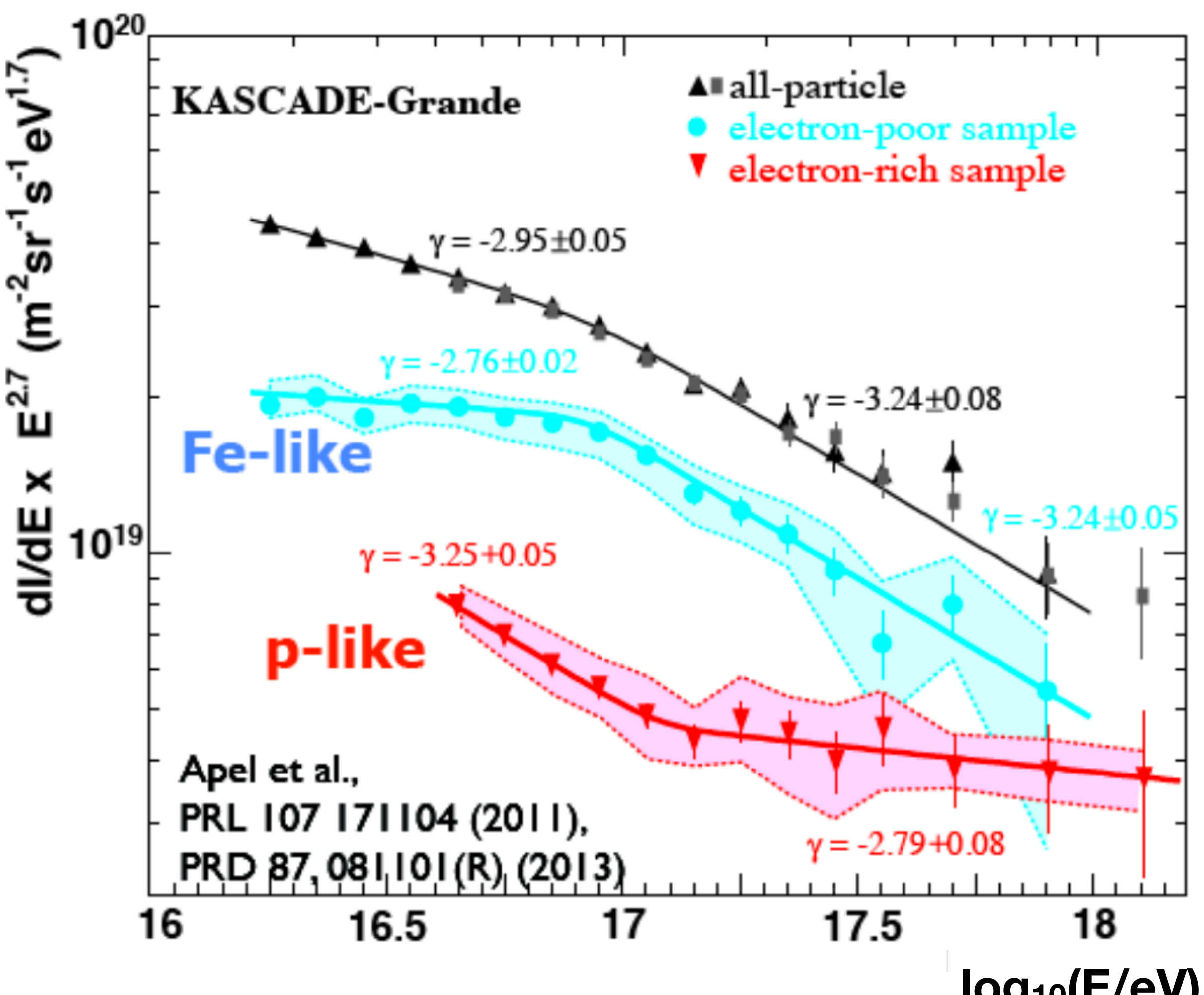
understanding **hadronic** interaction models at high energy is **NOT EASY**



cosmic rays composition

other experiments



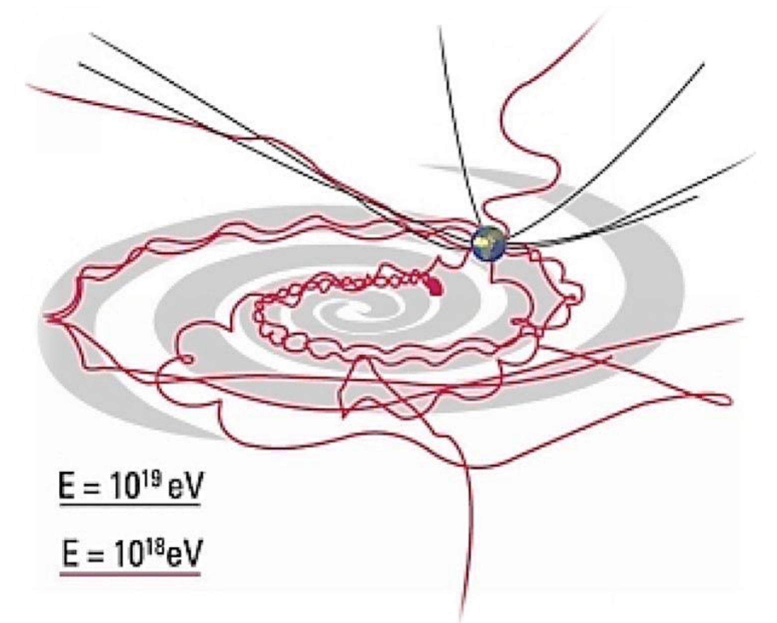


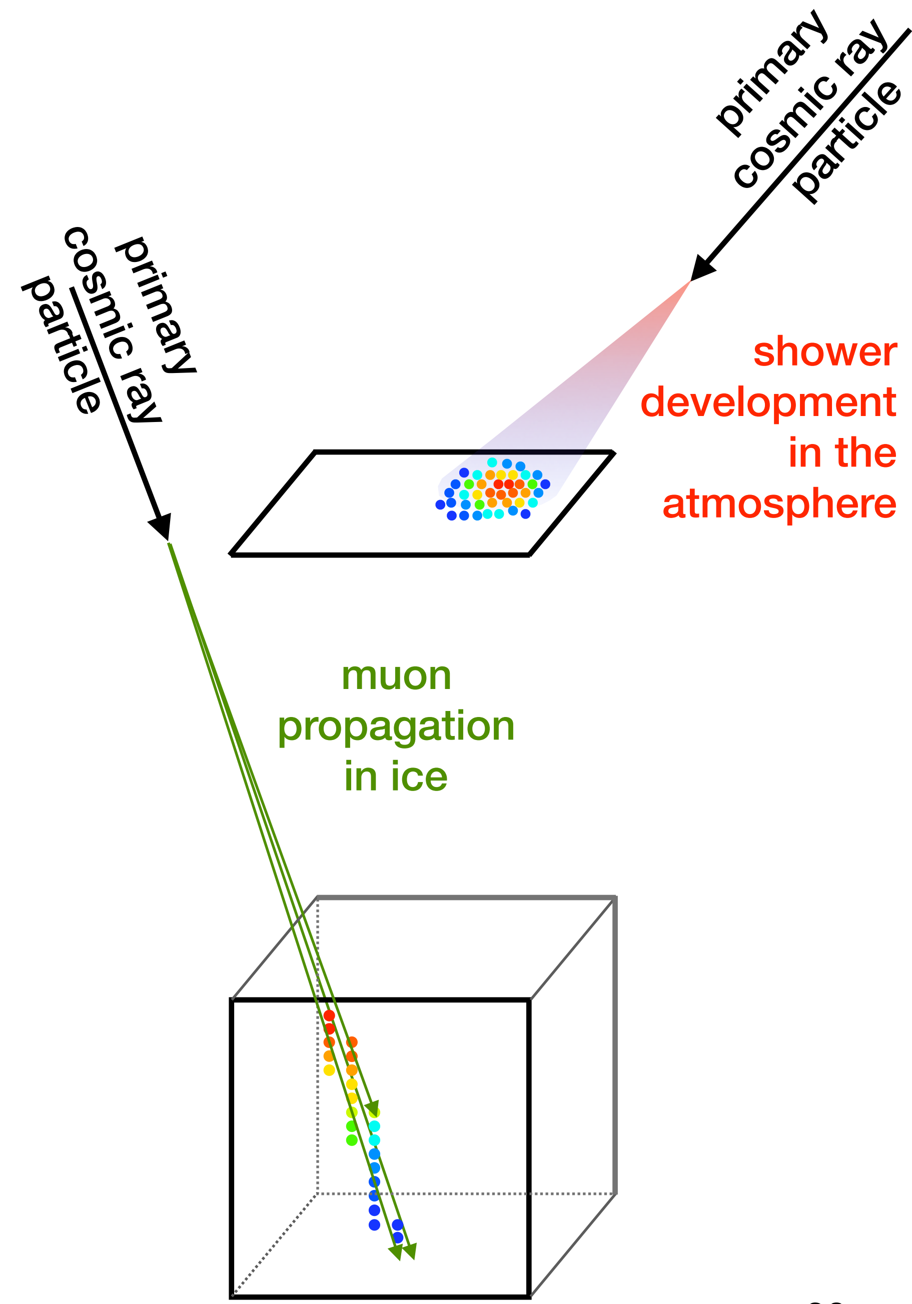
cosmic ray composition in **indirect** measurements is **DIFFICULT**

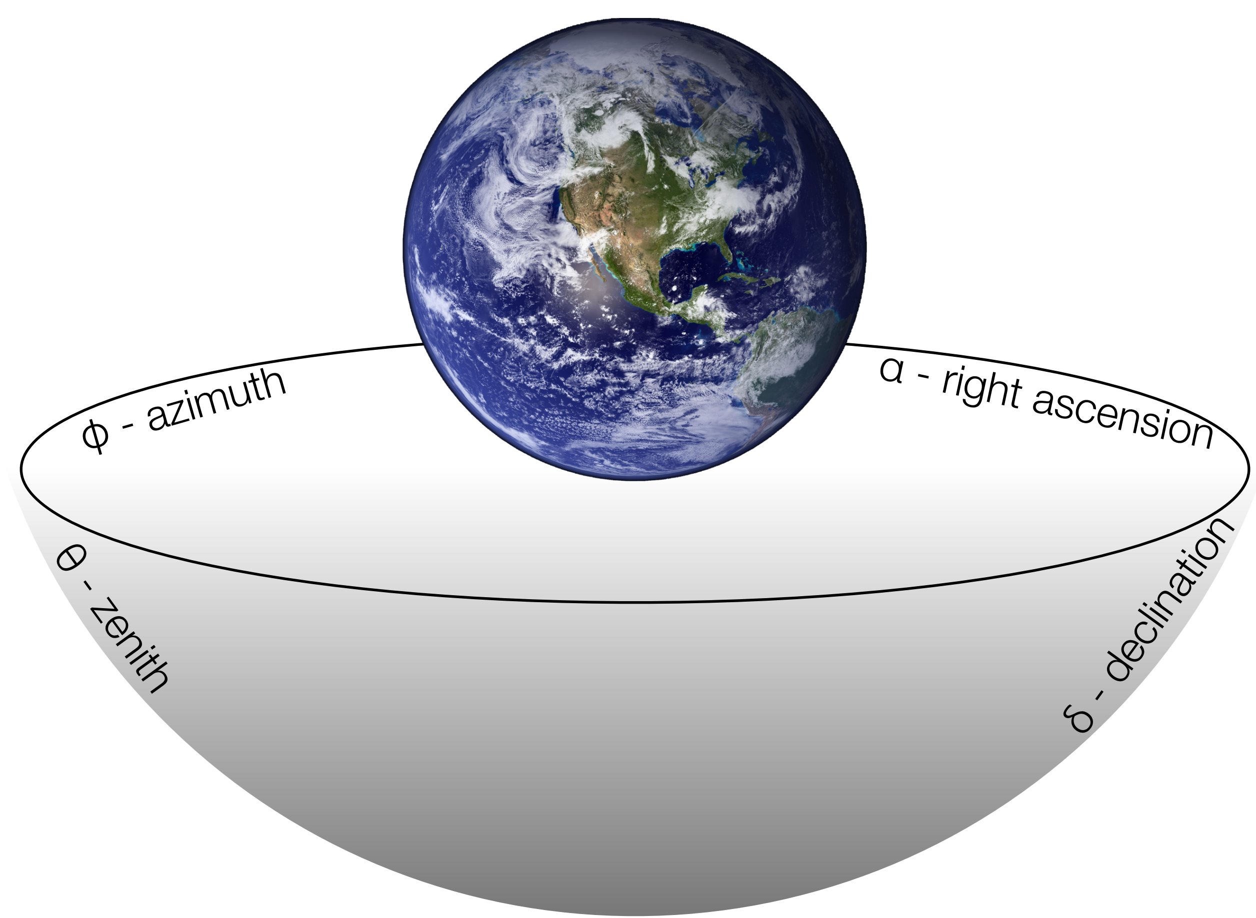
understanding **hadronic** interaction models at high energy is **NOT EASY**

cosmic rays anisotropy
arrival direction distribution

- cosmic rays expected to be ***almost*** isotropic
- ***scrambled*** by galactic magnetic field
- what does ***isotropy*** look like in IceCube ?

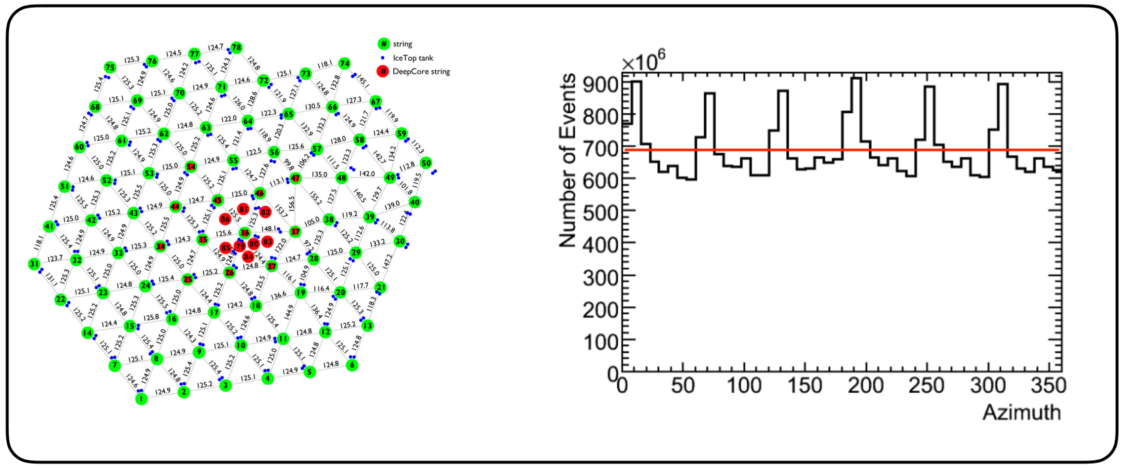






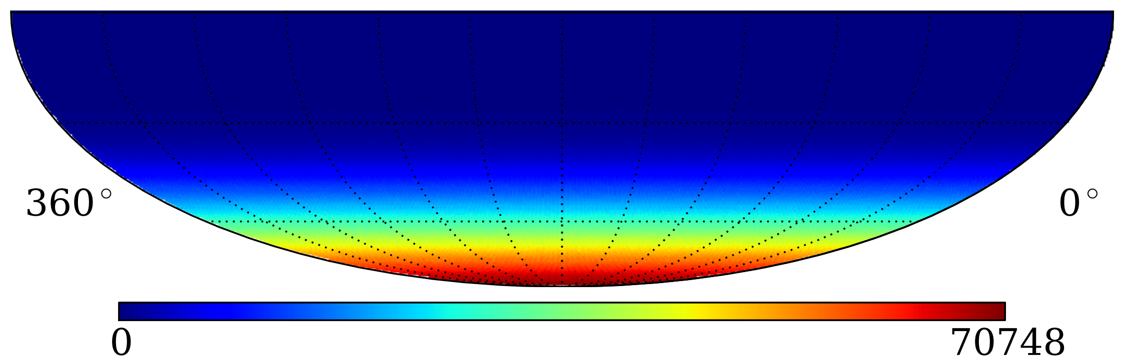
cosmic rays anisotropy

arrival direction distribution



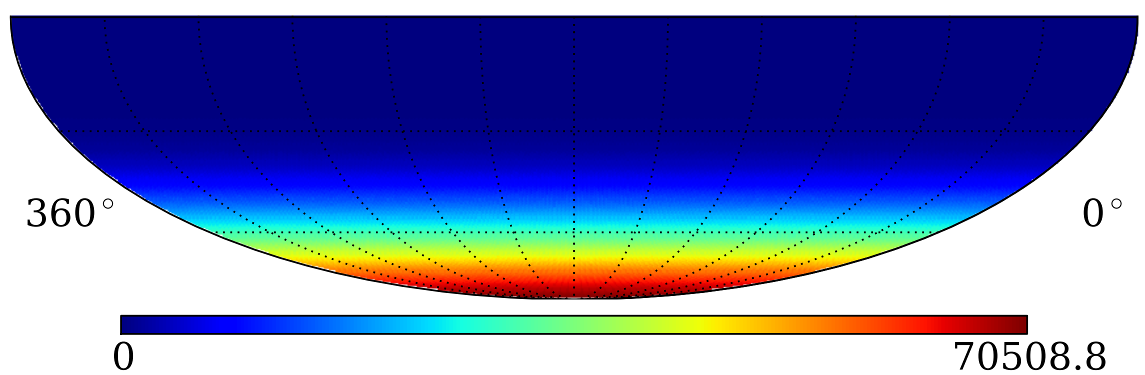
raw map of events in equatorial coordinates $(\alpha,\delta)_i$

1 month of data



reference map from events scrambled over 24hr in α (or time)

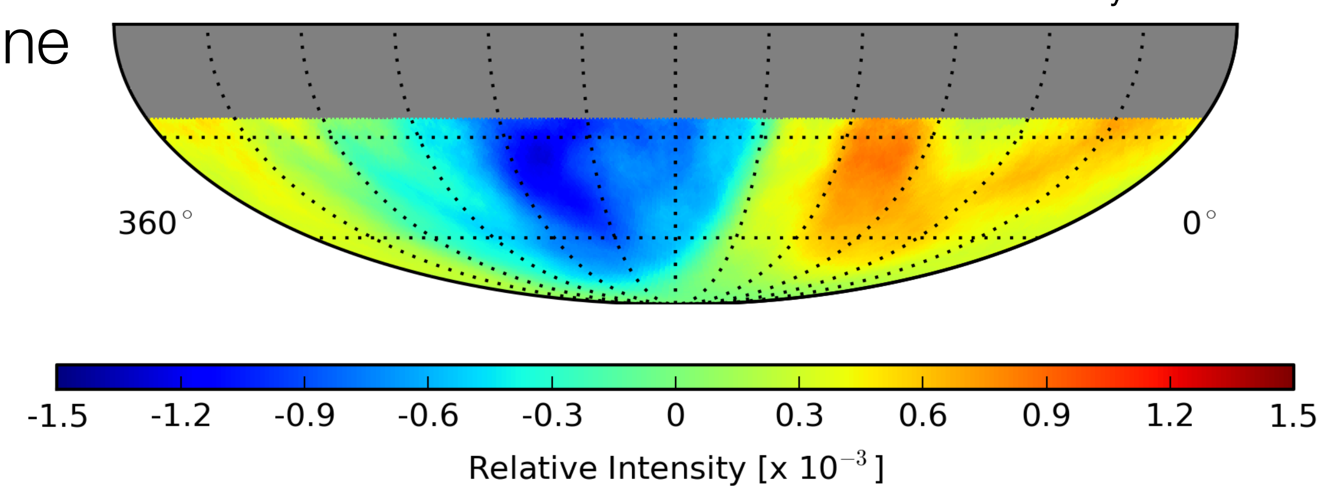
1 month of data



subtract reference map from raw map to determine the residual *relative intensity* map

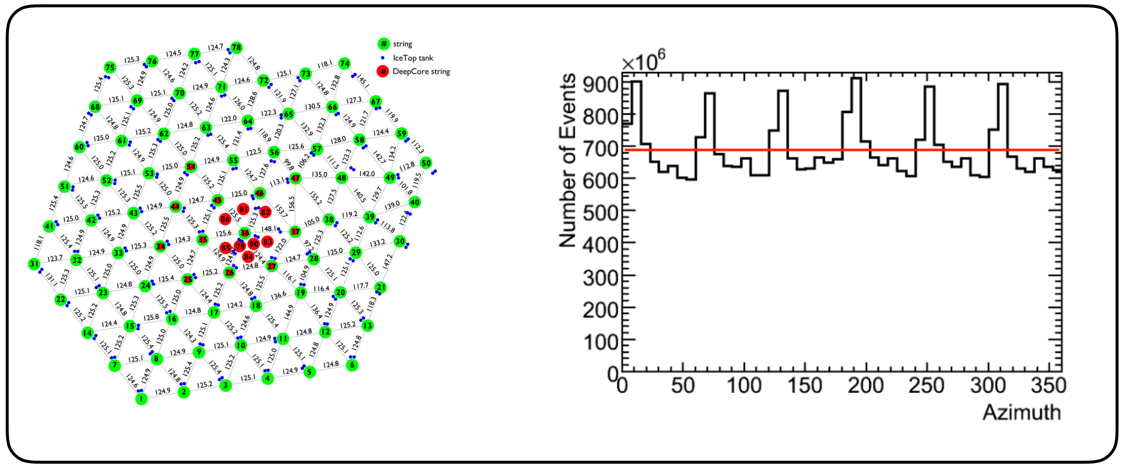
$$\boxed{\frac{\Delta I}{\langle I\rangle} \equiv \frac{N_i - \langle N\rangle}{\langle N\rangle}}$$

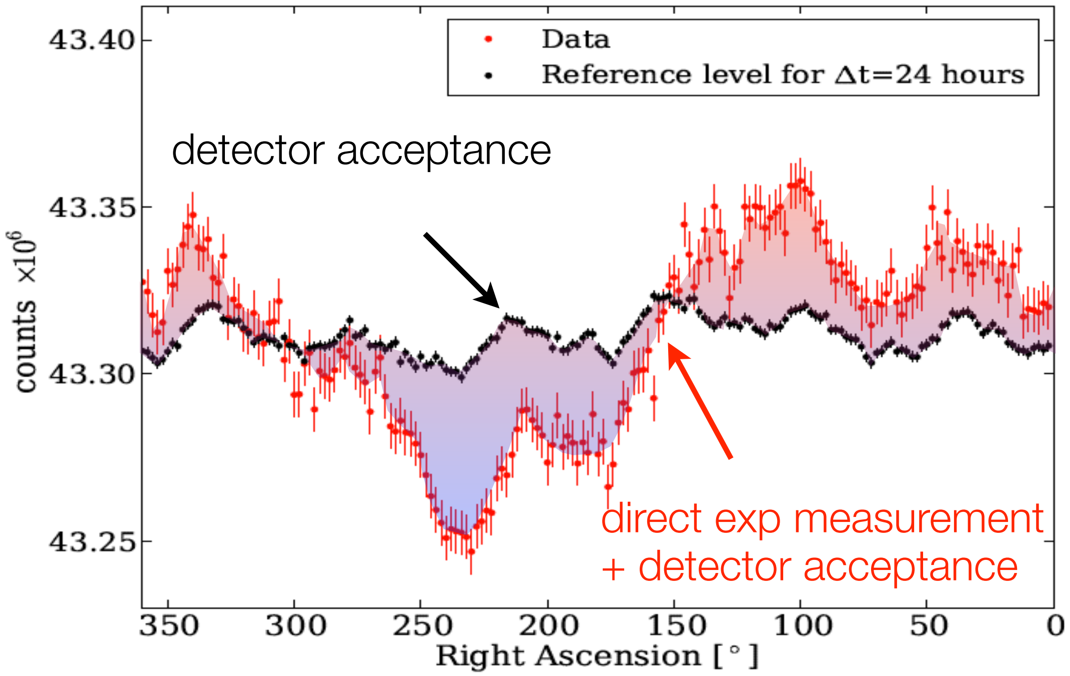
6 years of data

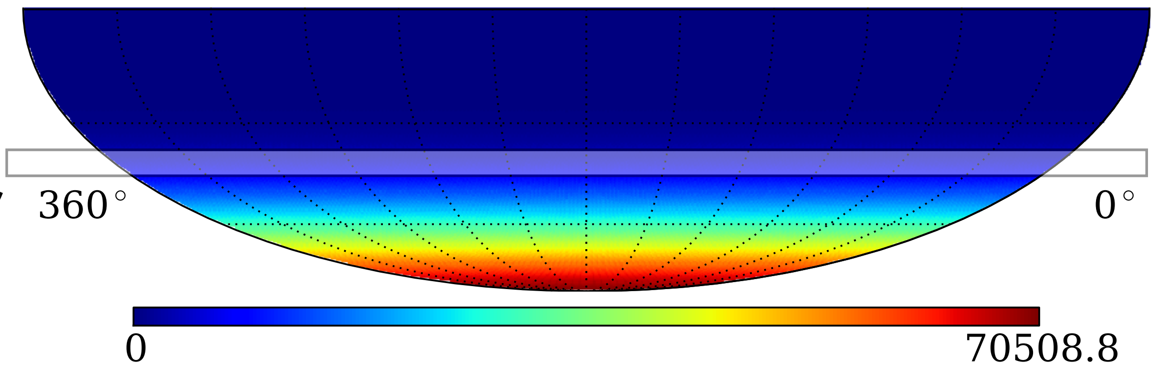


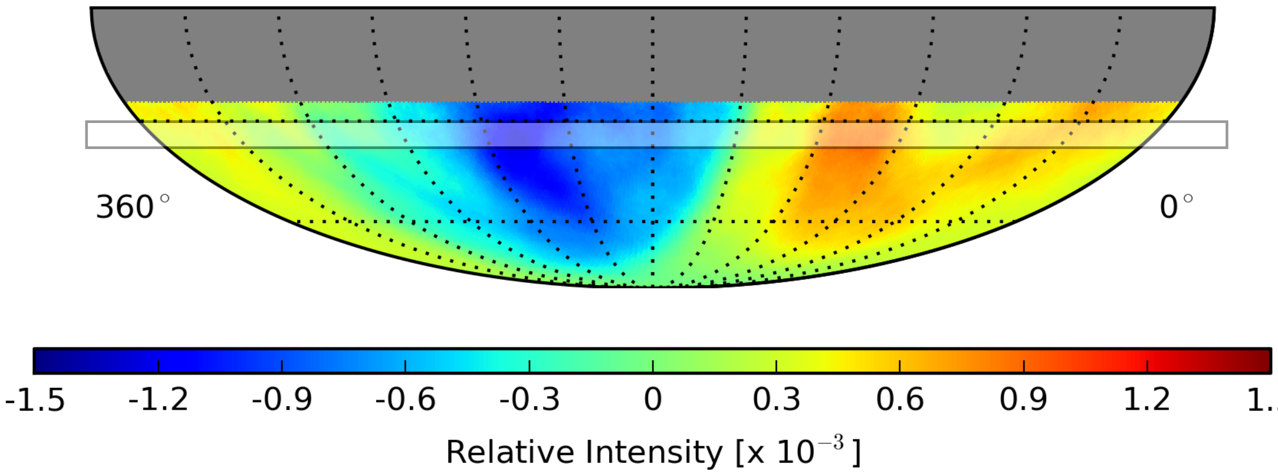
cosmic rays anisotropy

arrival direction distribution







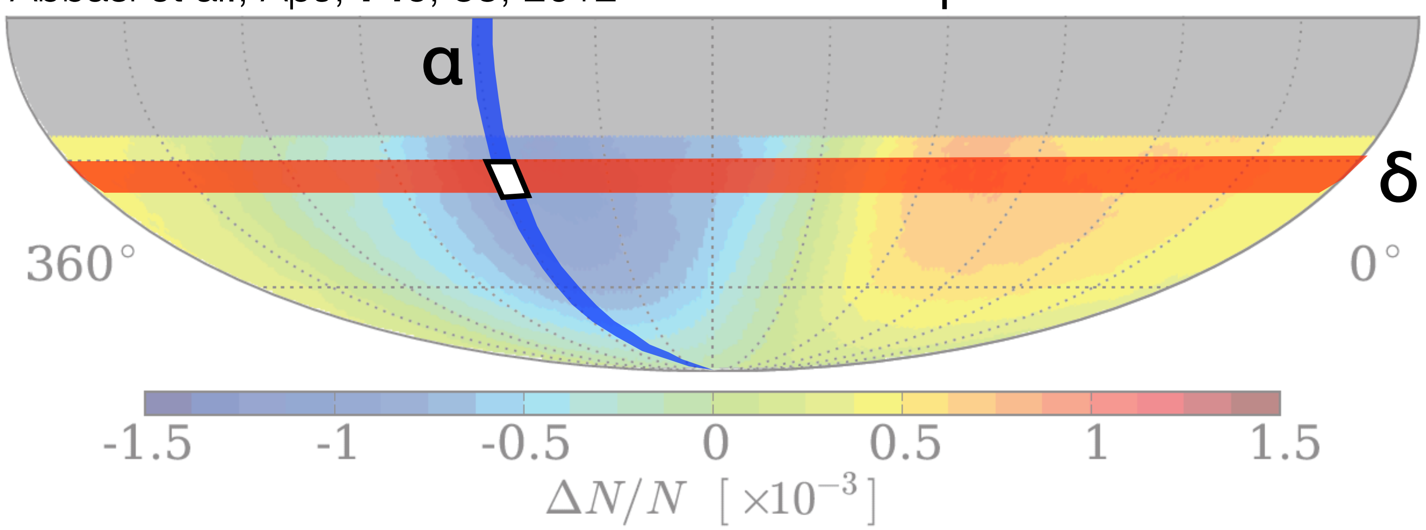


$$\frac{\Delta I}{\langle I \rangle} \equiv \frac{N_i - \langle N \rangle}{\langle N \rangle}$$

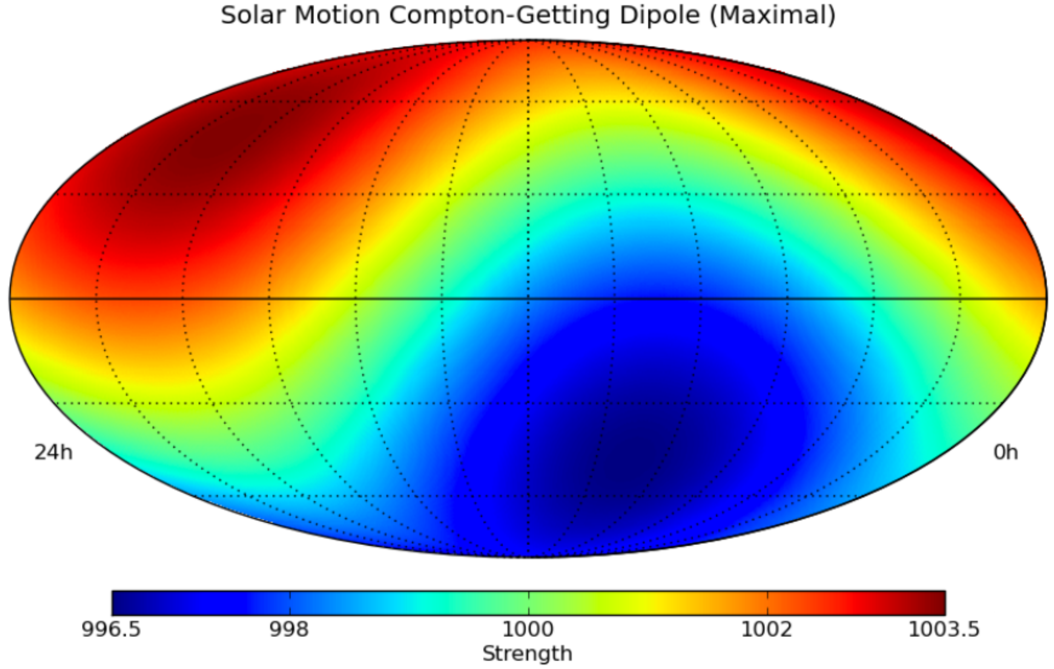
measuring cosmic ray anisotropy
relative intensity

DISCLAIMER

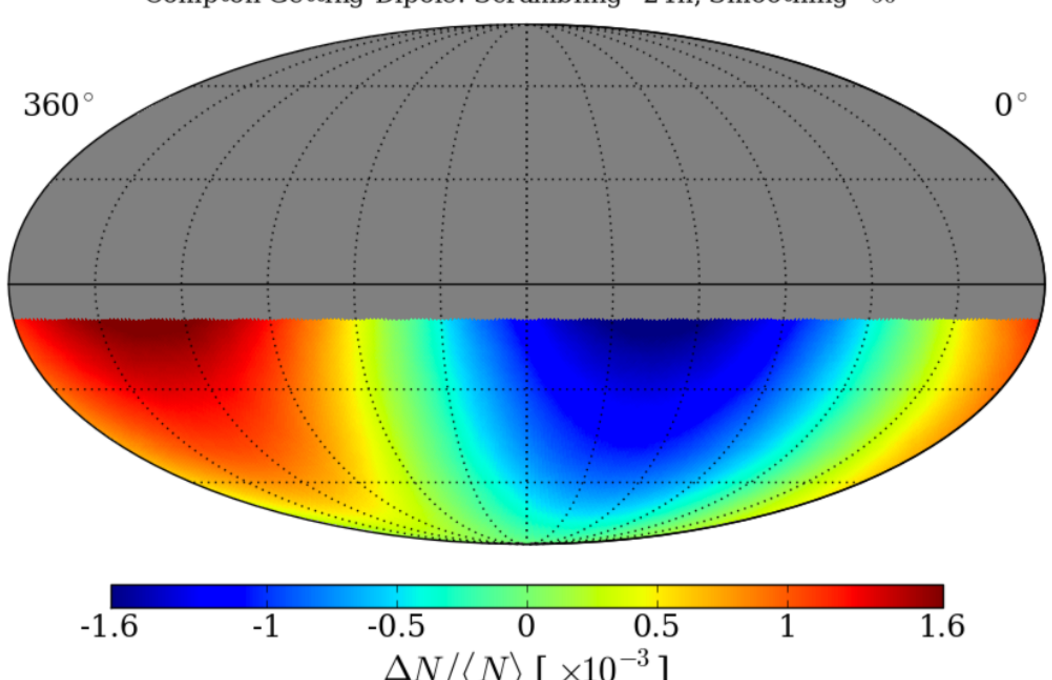
Abbasi et al., ApJ, **746**, 33, 2012



$$\frac{\Delta N_i}{\langle N \rangle_i} = \frac{N_i(\alpha,\delta) - \langle N_i(\alpha,\delta)\rangle}{\langle N_i(\alpha,\delta)\rangle}$$



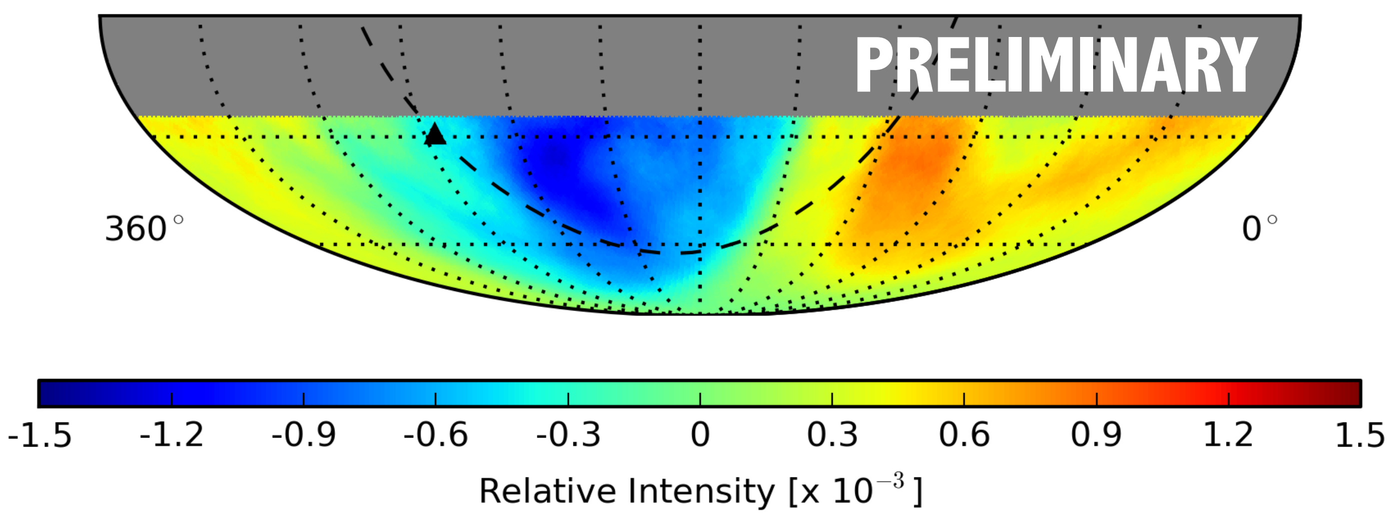
$\Delta N/\langle N \rangle = 7\times10^{-3}$

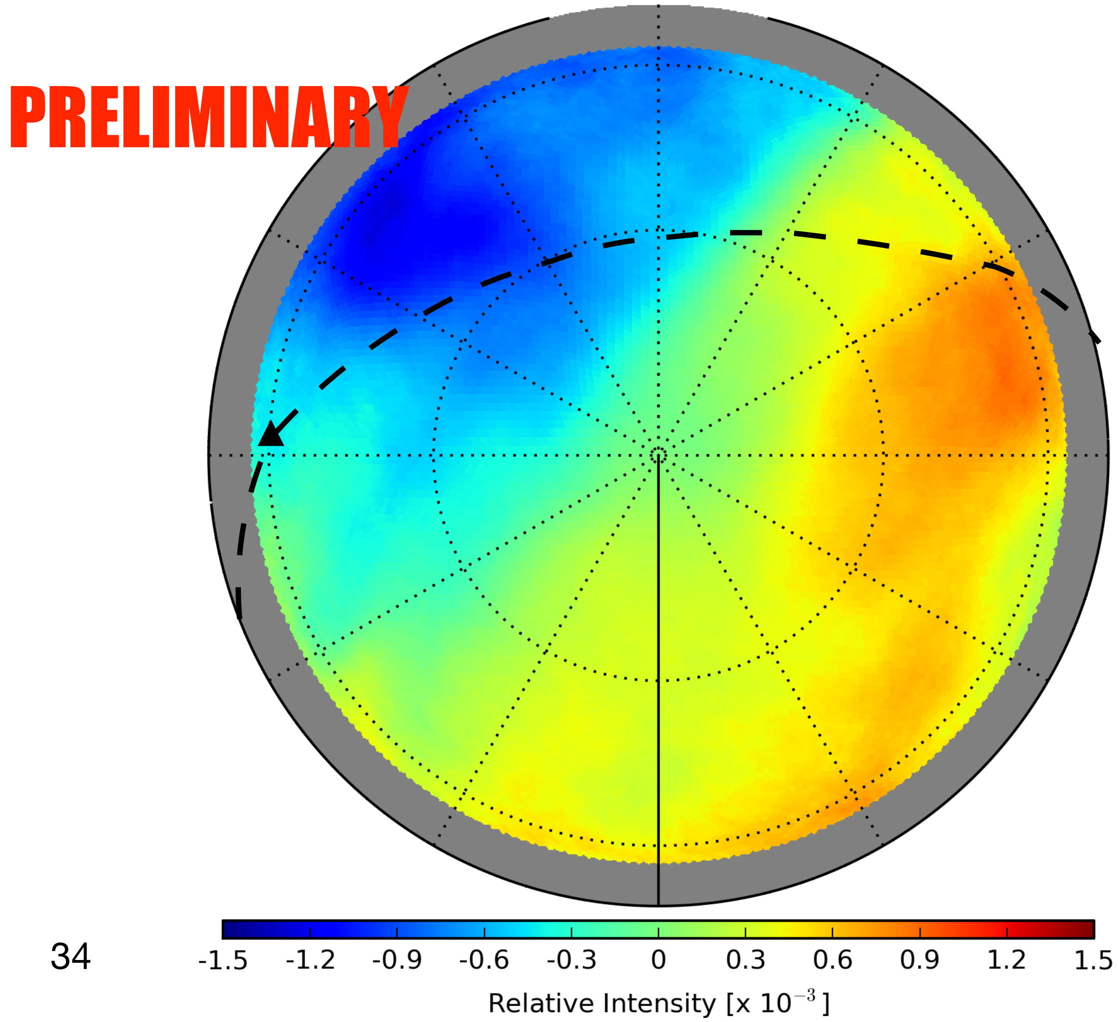


- sky maps show **ONLY** modulations across right ascension and **NOT** declination

cosmic rays anisotropy
arrival direction distribution

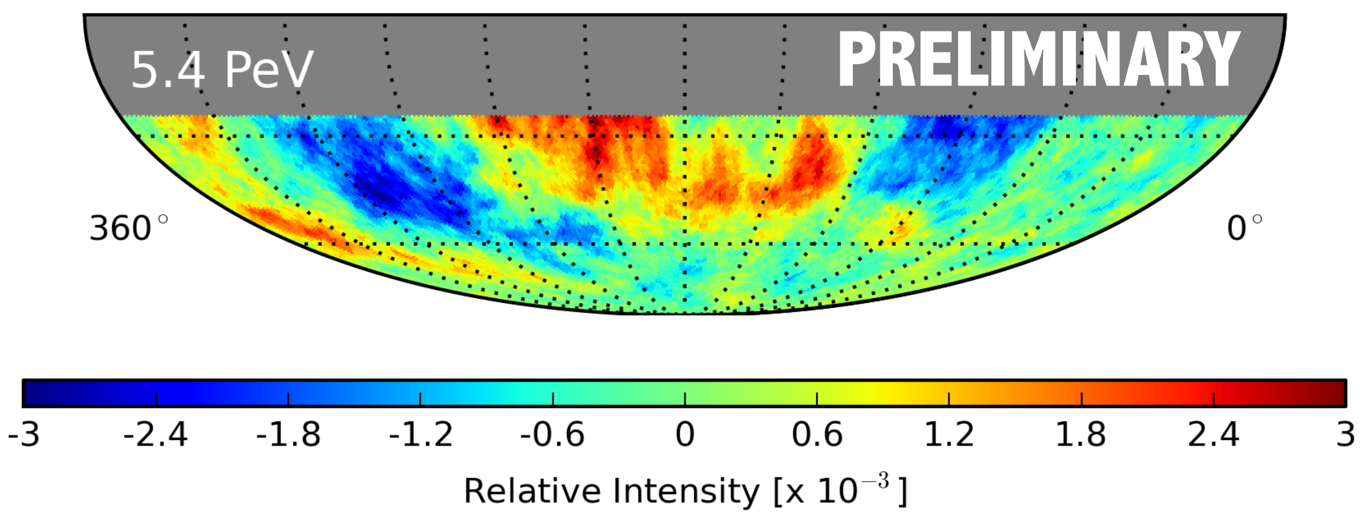
to be submitted to ApJ

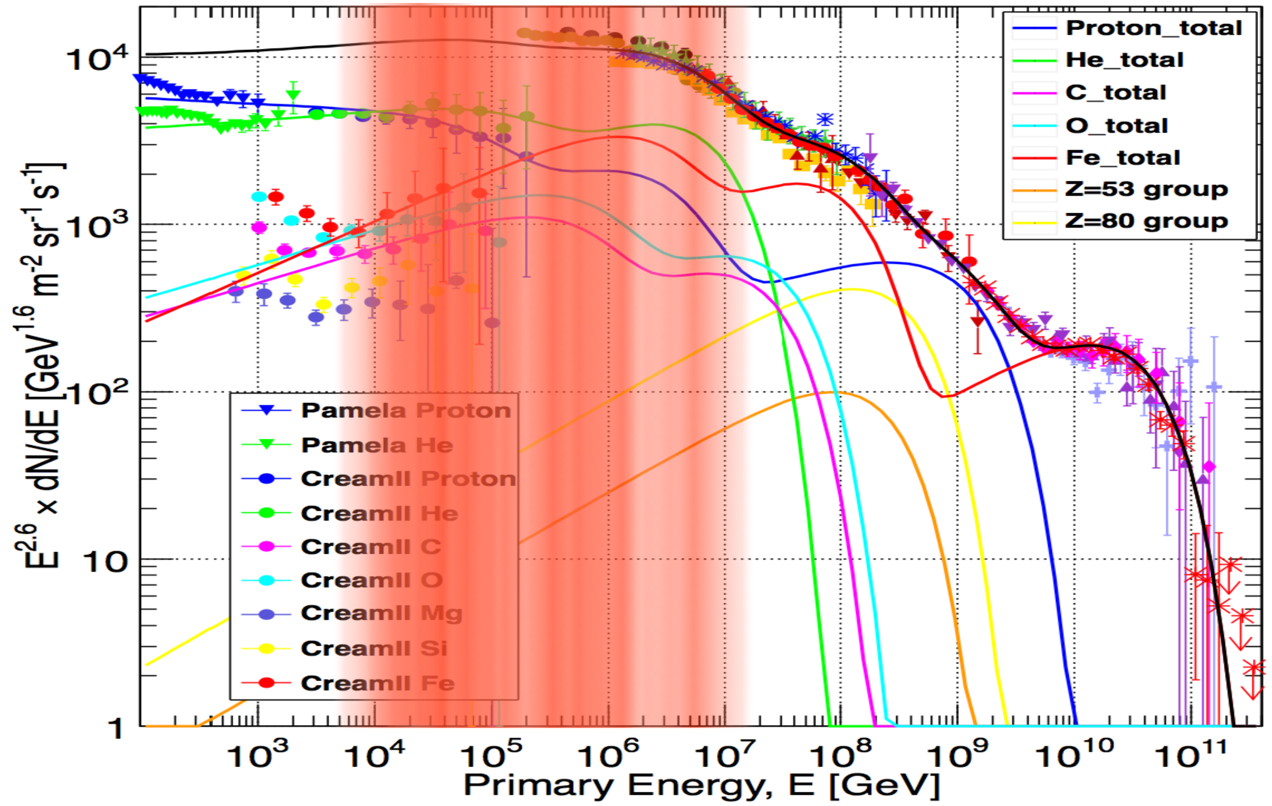


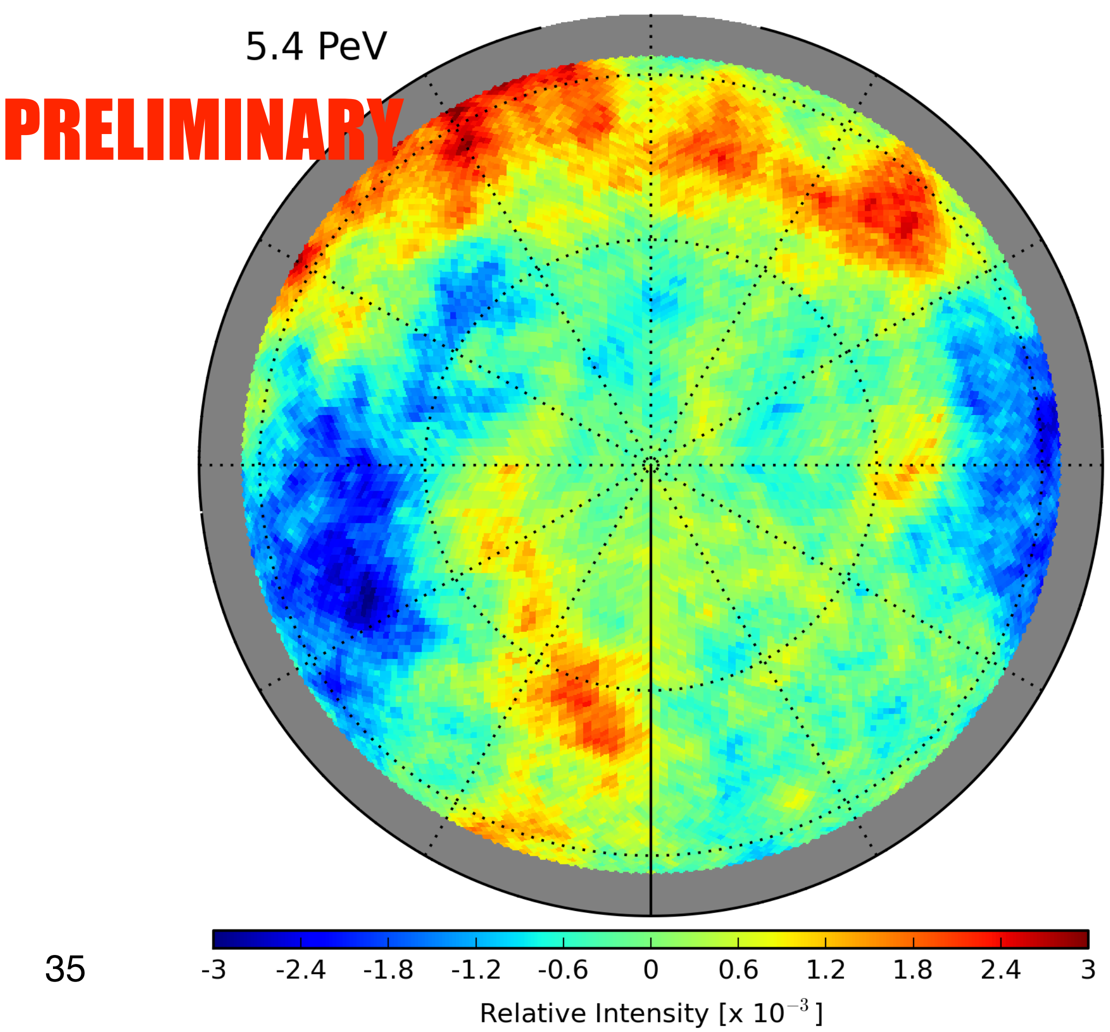


- 6 years of IceCube
- 300 billion events
- anisotropy on the level of 10^{-3}
- median cosmic ray energy **20 TeV**
- trace sources ? Magnetic fields ?

cosmic rays anisotropy
arrival direction distribution







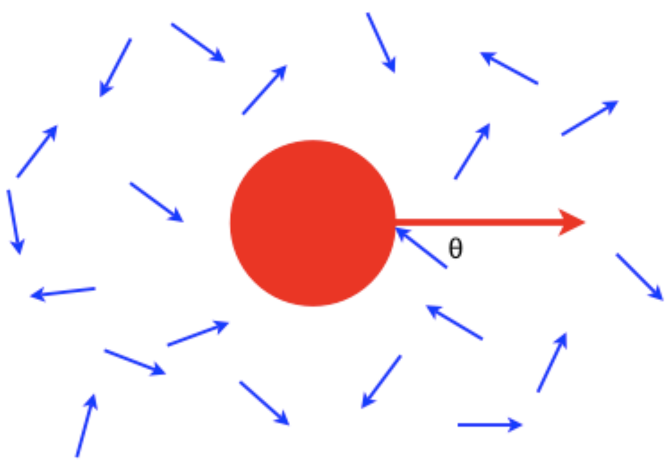
5.4 PeV **IceTop**

- high energy observations **MISSING** in the northern hemisphere
- **overlapping observations** extending across the equator will help
- capable of energy/mass measurement

a known anisotropy

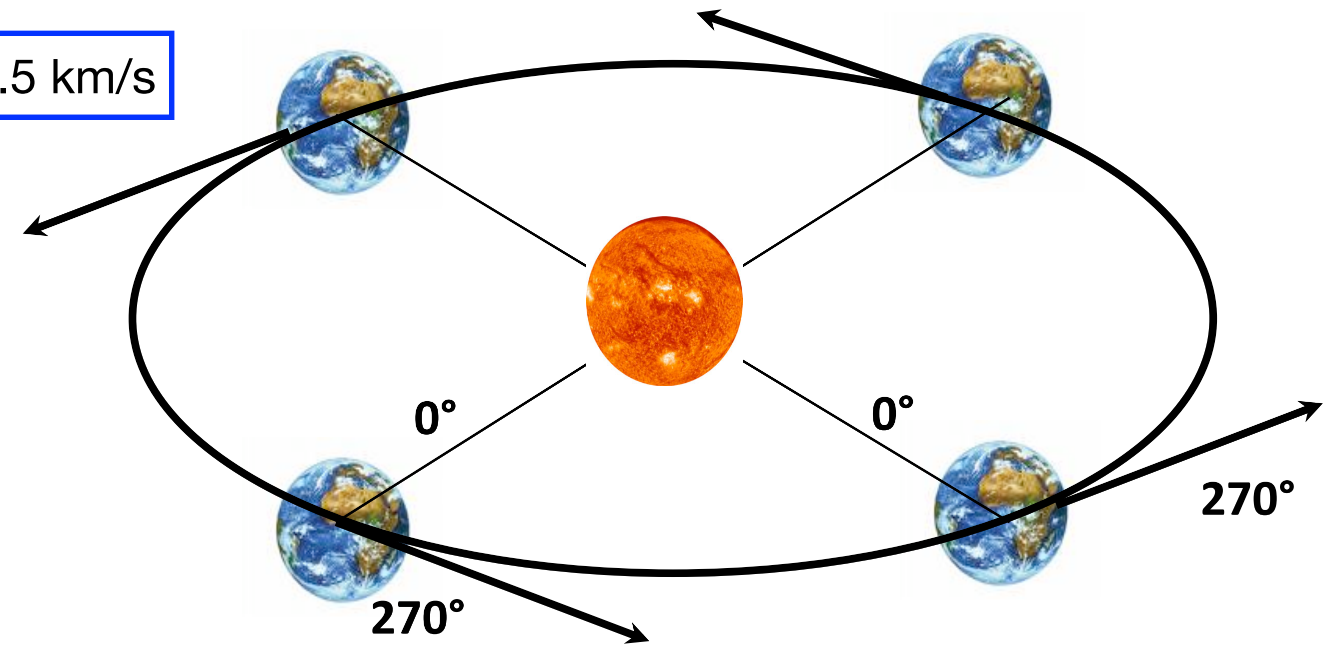
Earth's motion around the Sun

Compton & Getting, Phys. Rev. 47, 817 (1935)
Gleeson, & Axford, Ap&SS, 2, 43 (1968)

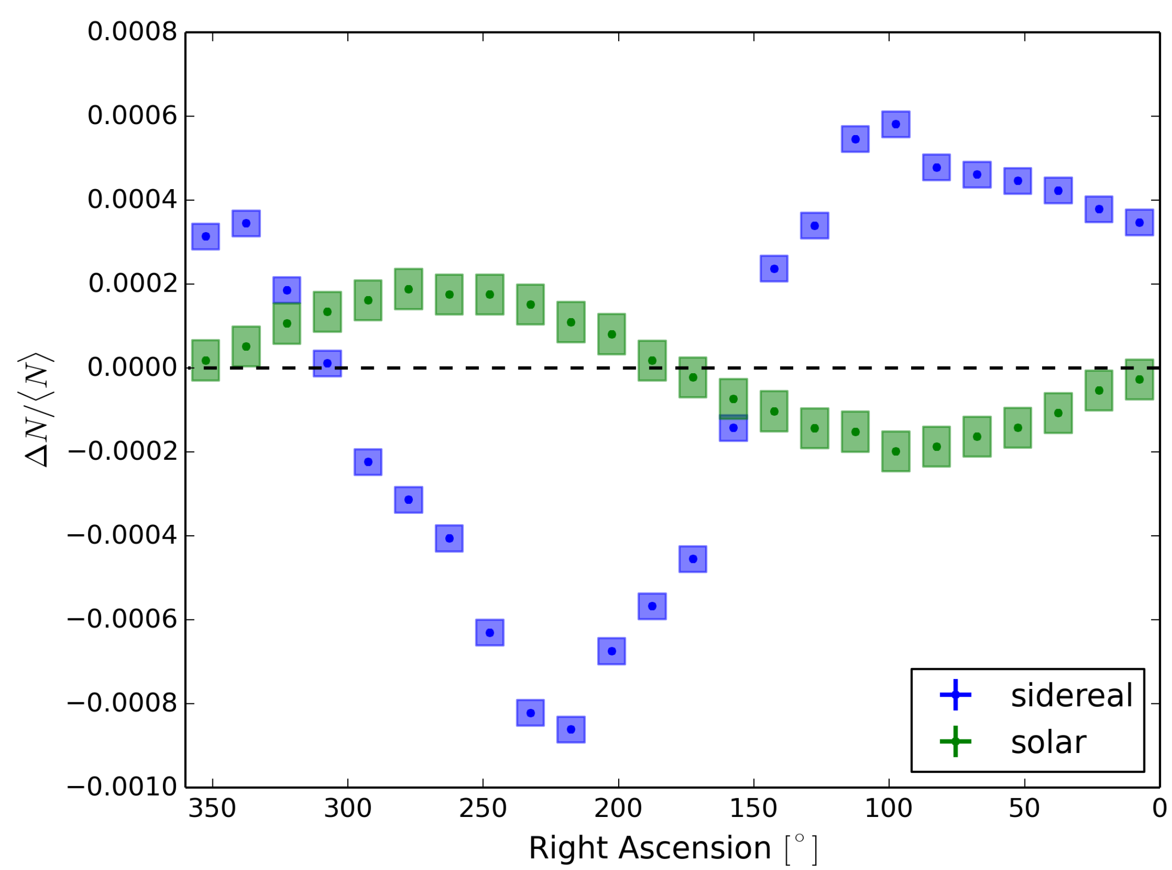


v = 29.8 ± 0.5 km/s

$$\frac{\Delta I}{I} = (\gamma + 2)\frac{v}{c}\cos\theta$$



- produced by Earth's revolution around the Sun
- visible as **solar diurnal modulation**
- **predictable** and used as **benchmark**

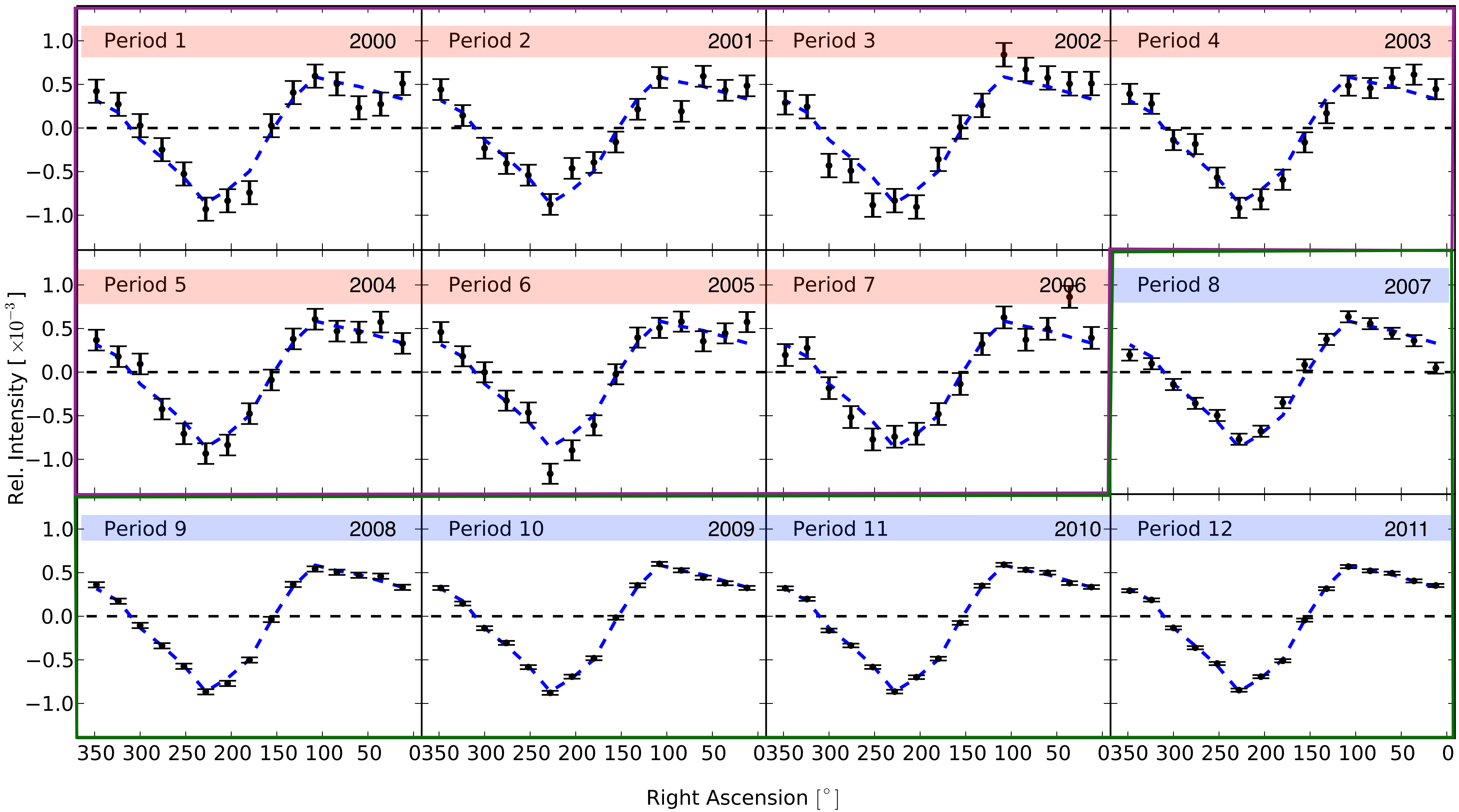


cosmic ray anisotropy

AMANDA-IceCube 2000-2011

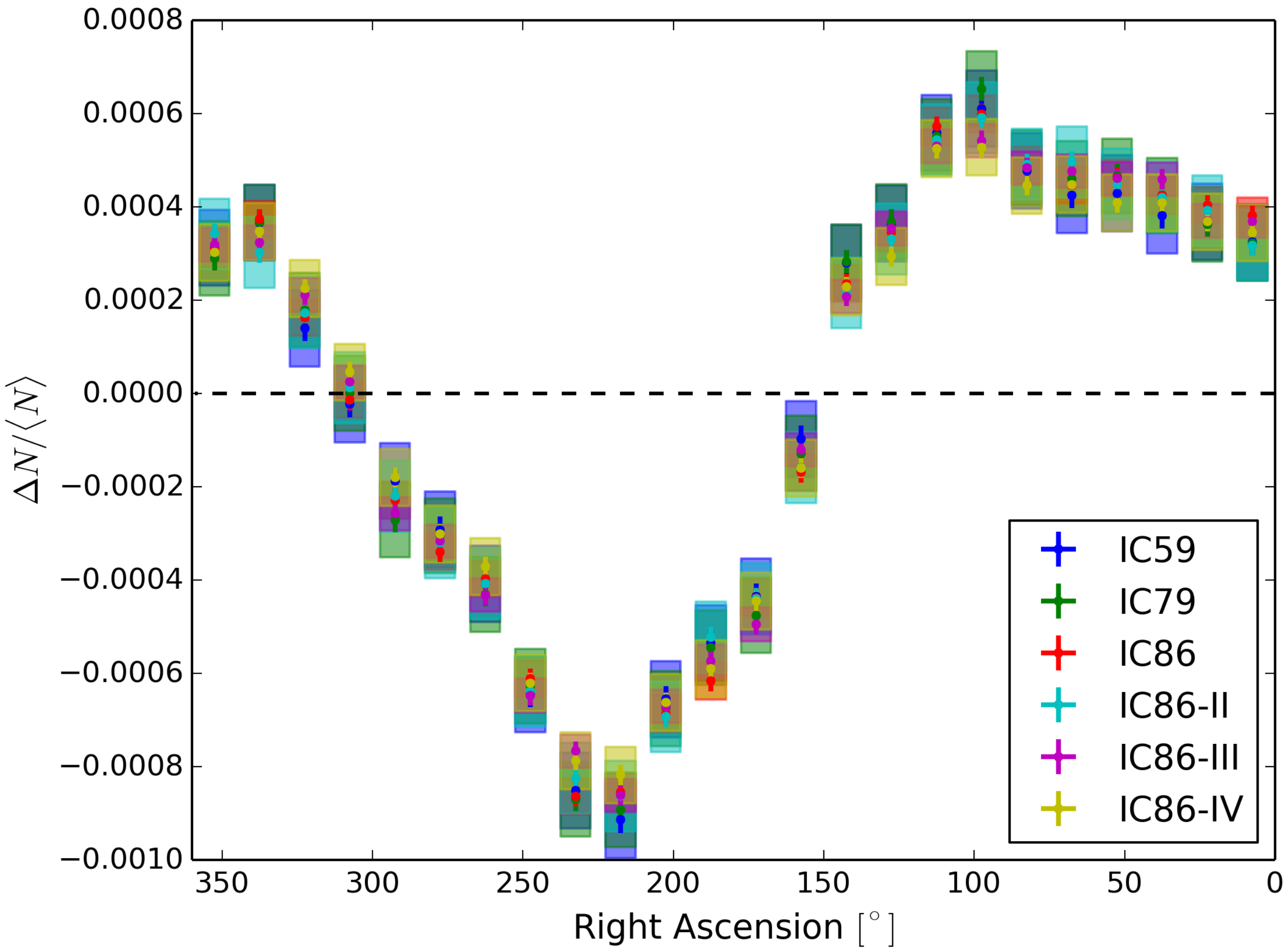
ICRC 2013

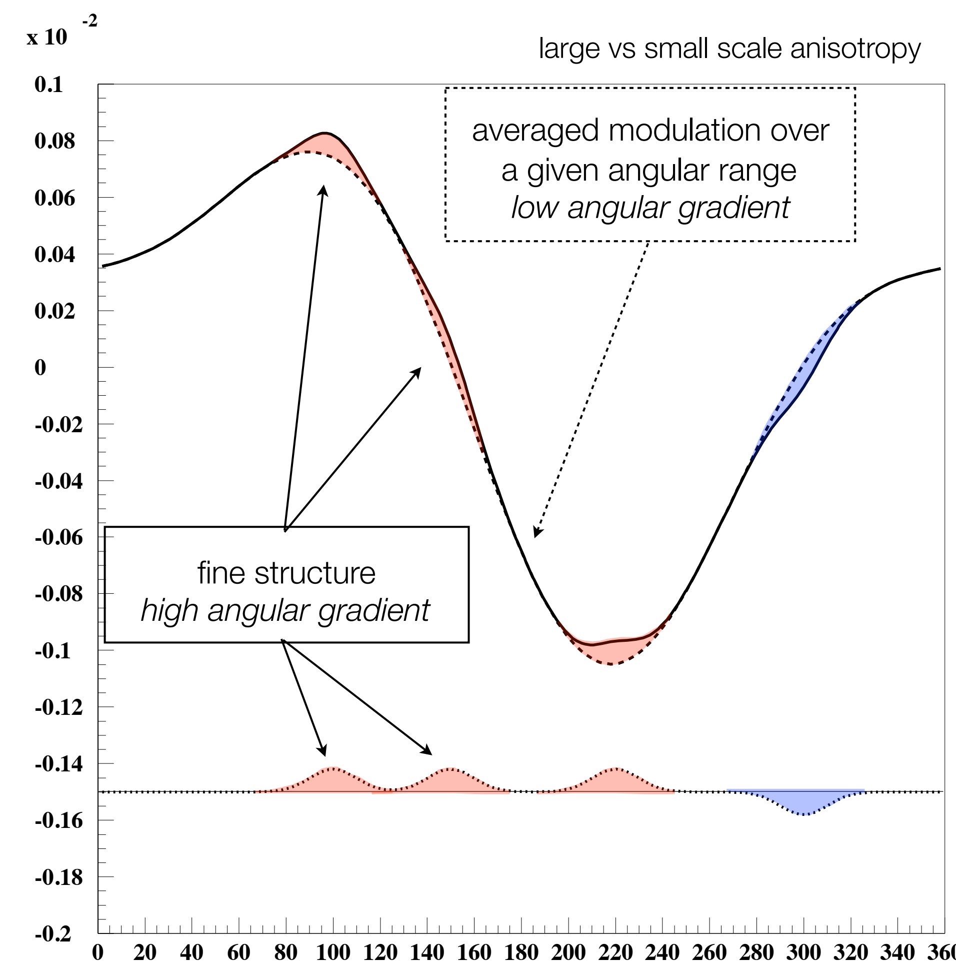
20 TeV

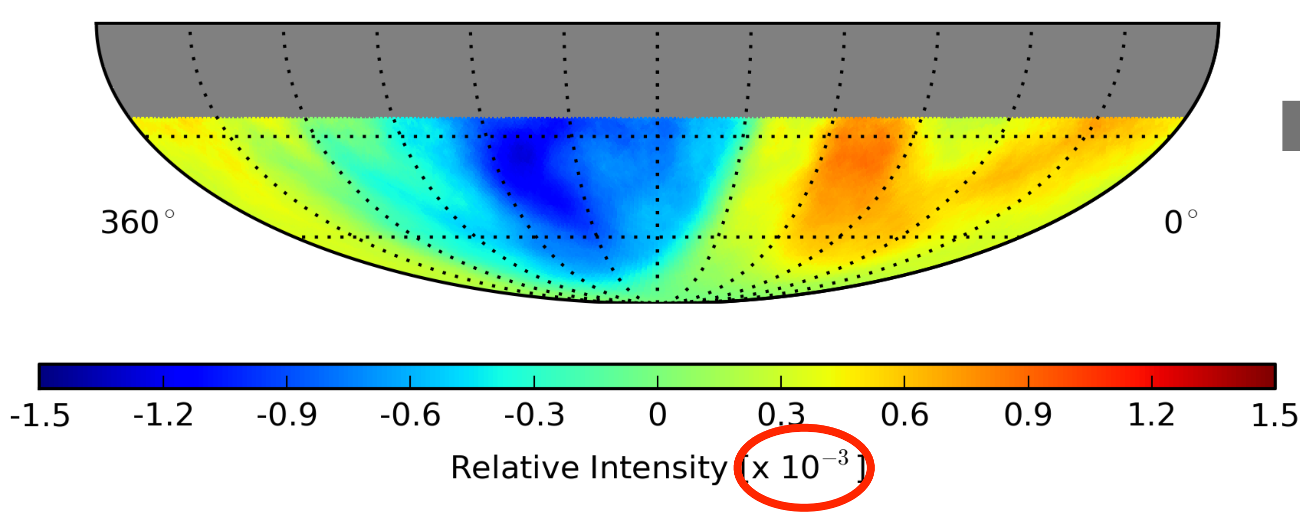


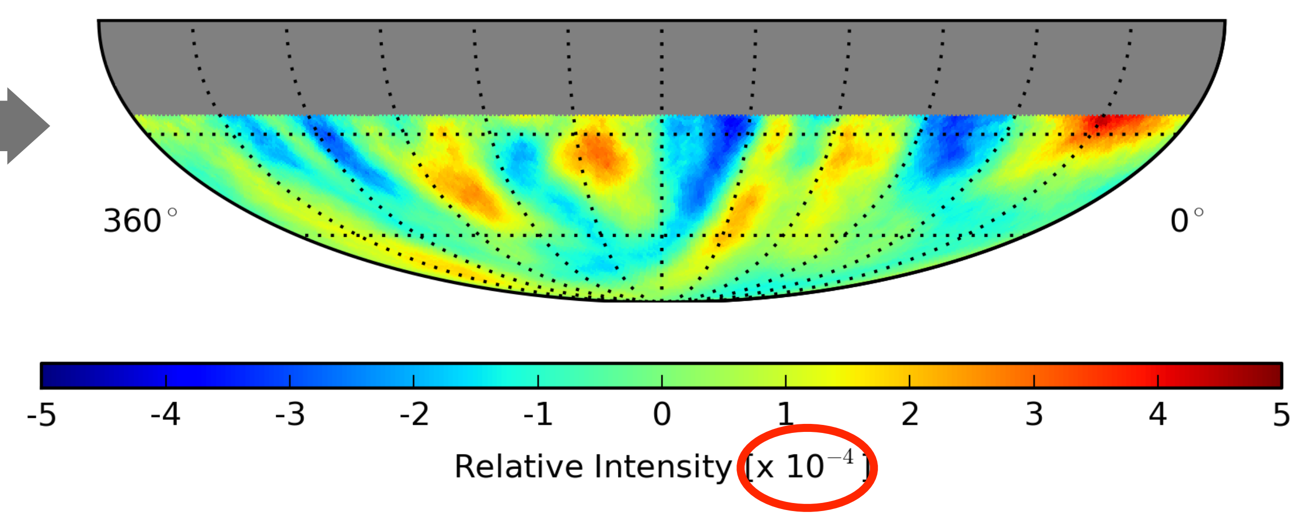
cosmic rays anisotropy

large and small angular scale



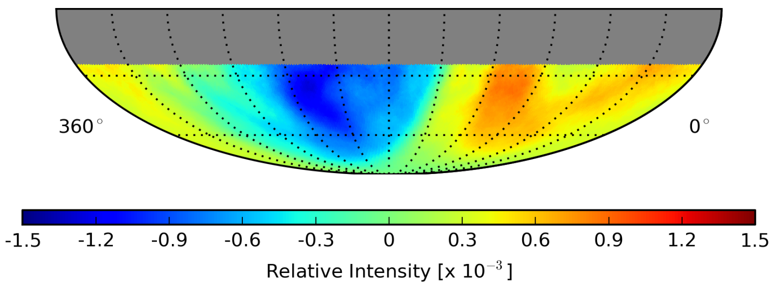


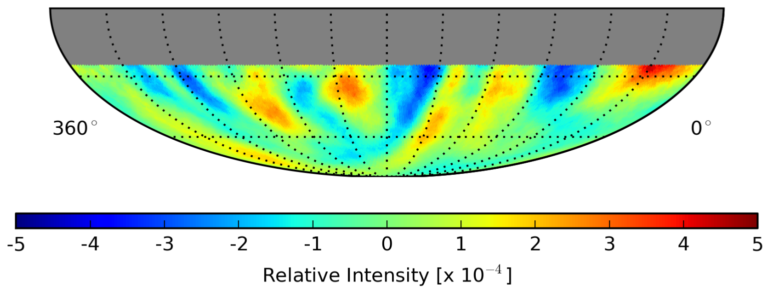


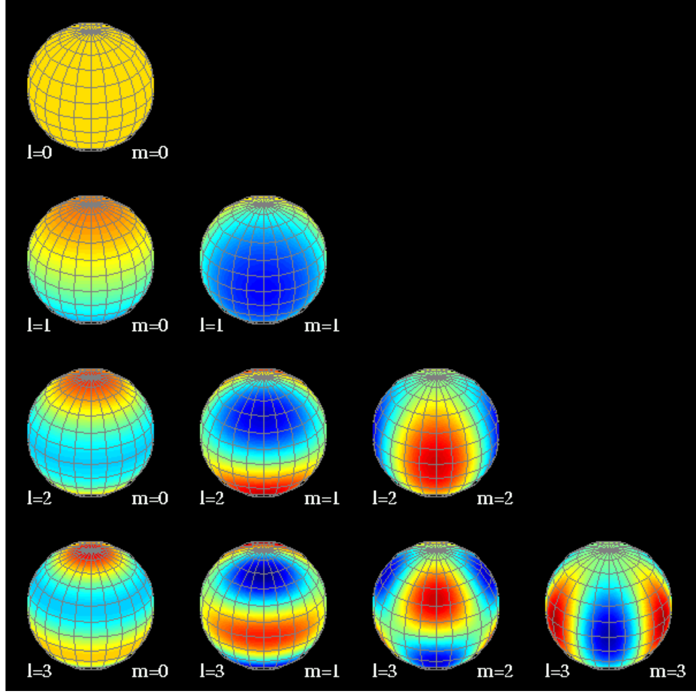


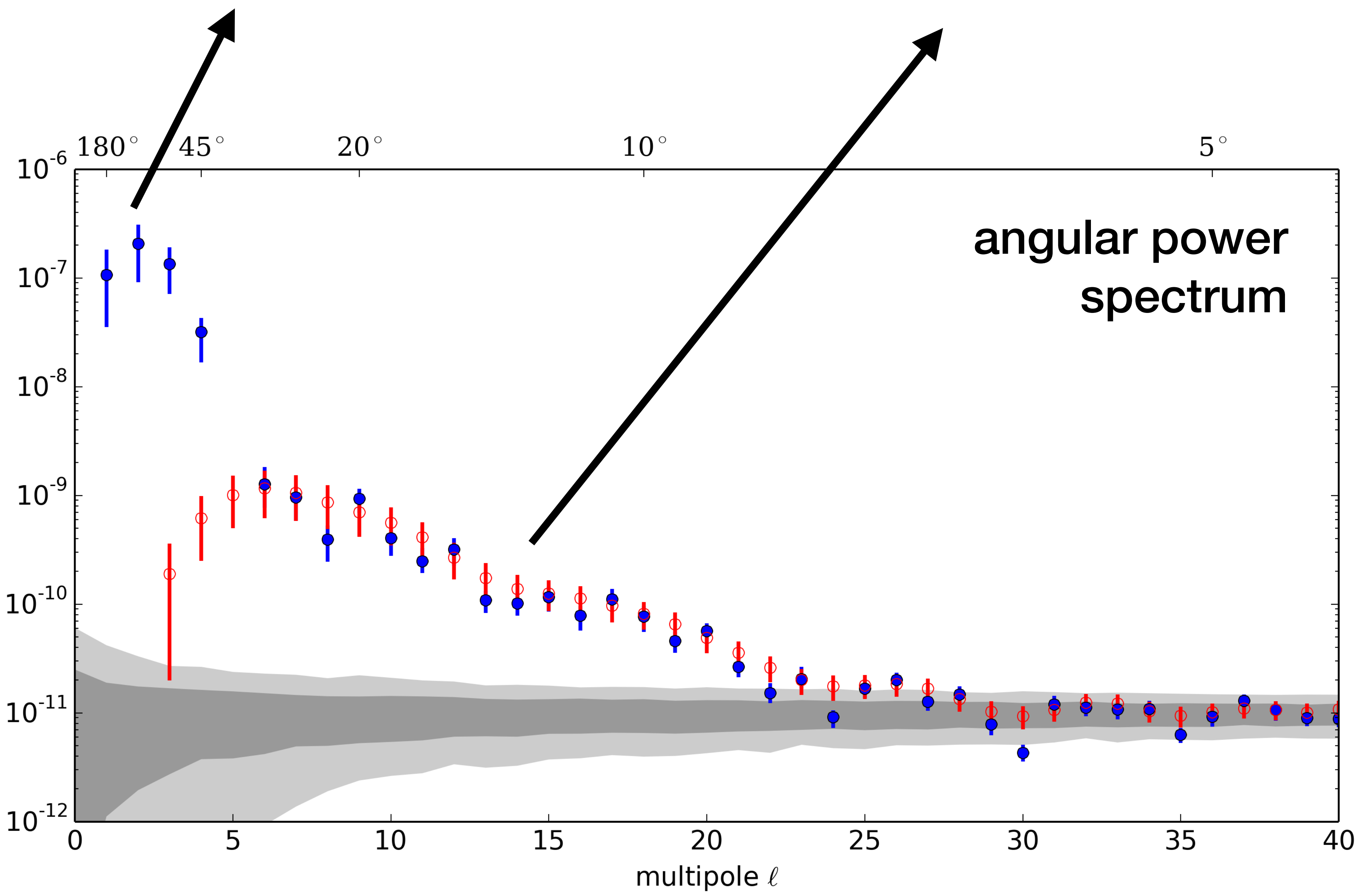
cosmic rays anisotropy

large and small angular scale









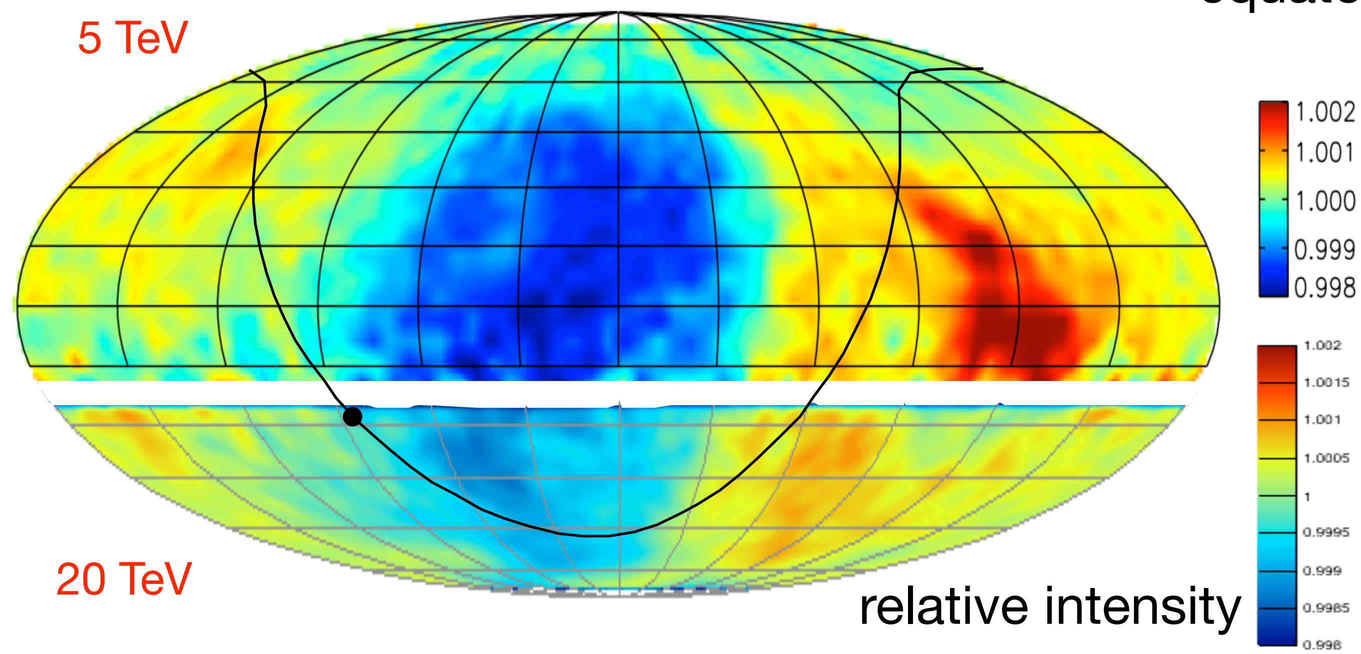
TeV sidereal anisotropy

equatorial coordinates

Tibet-III

Amenomori et al., ICRC 2011

5 TeV



IceCube-59

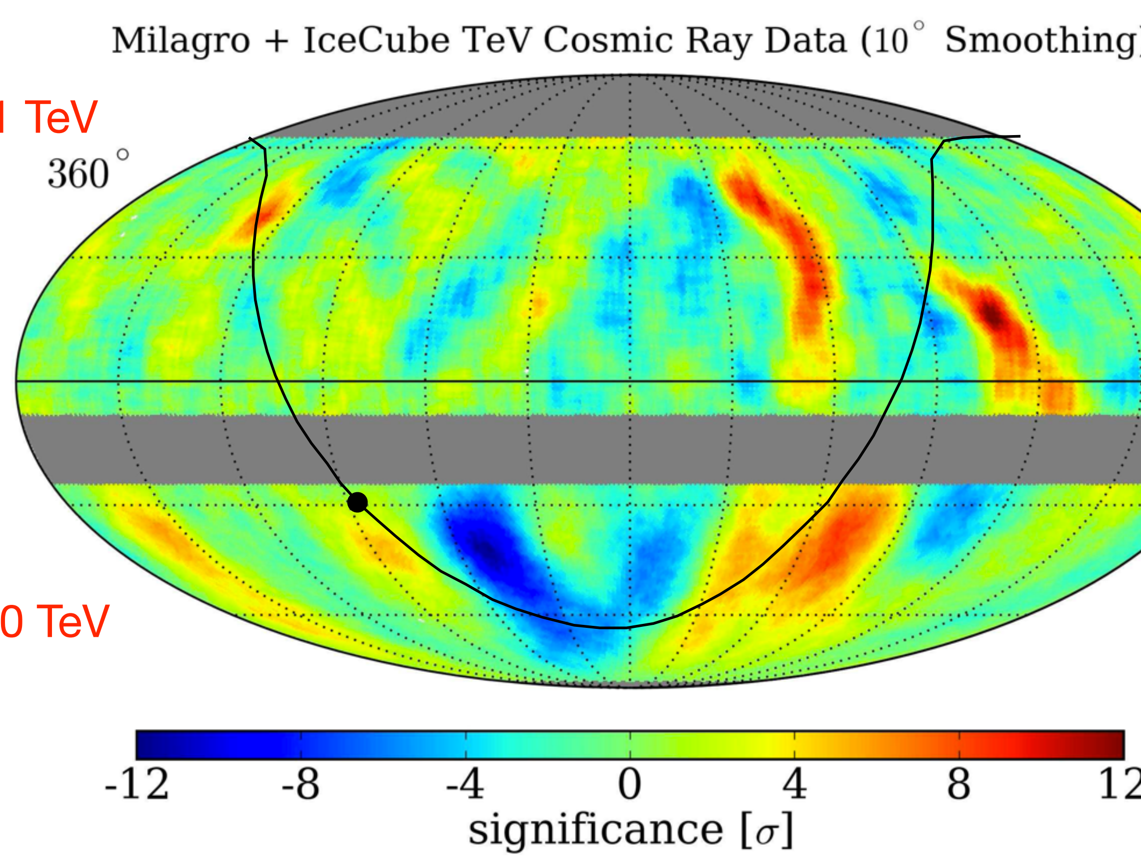
Abbasi et al., ApJ, **746**, 33, 2012

20 TeV

Milagro

Abdo et al., PRL, **101**, 221101, 2008

1 TeV



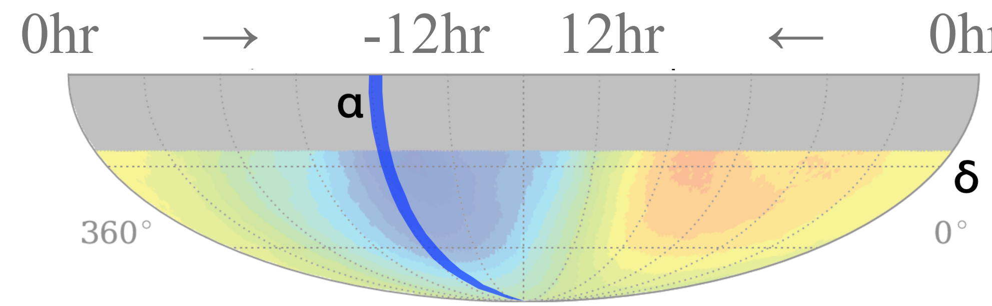
IceCube-59

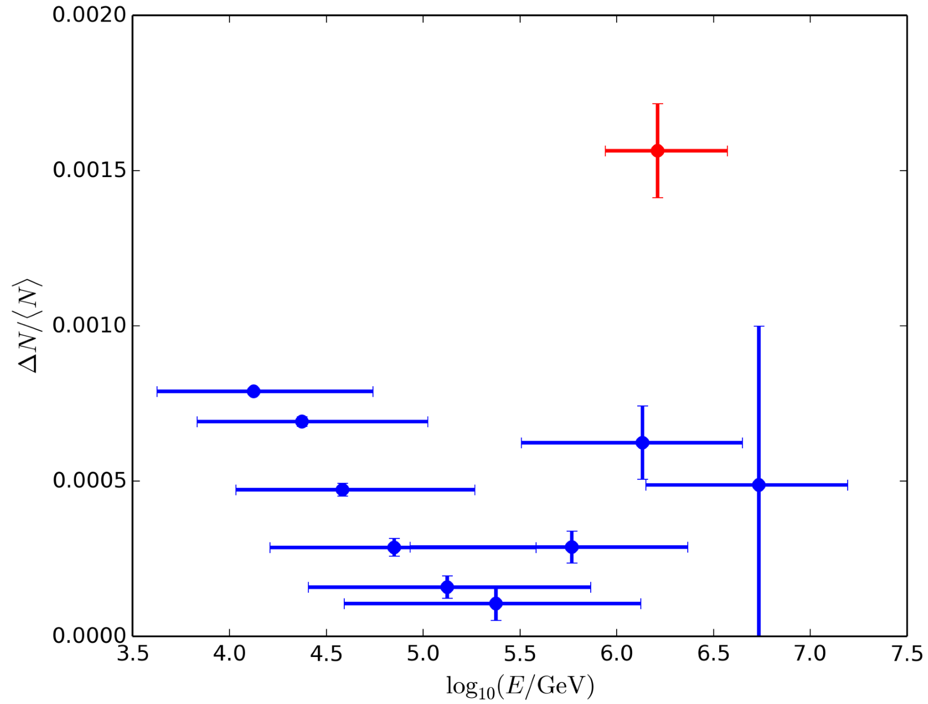
Abbasi et al., ApJ, **740**, 16, 2011

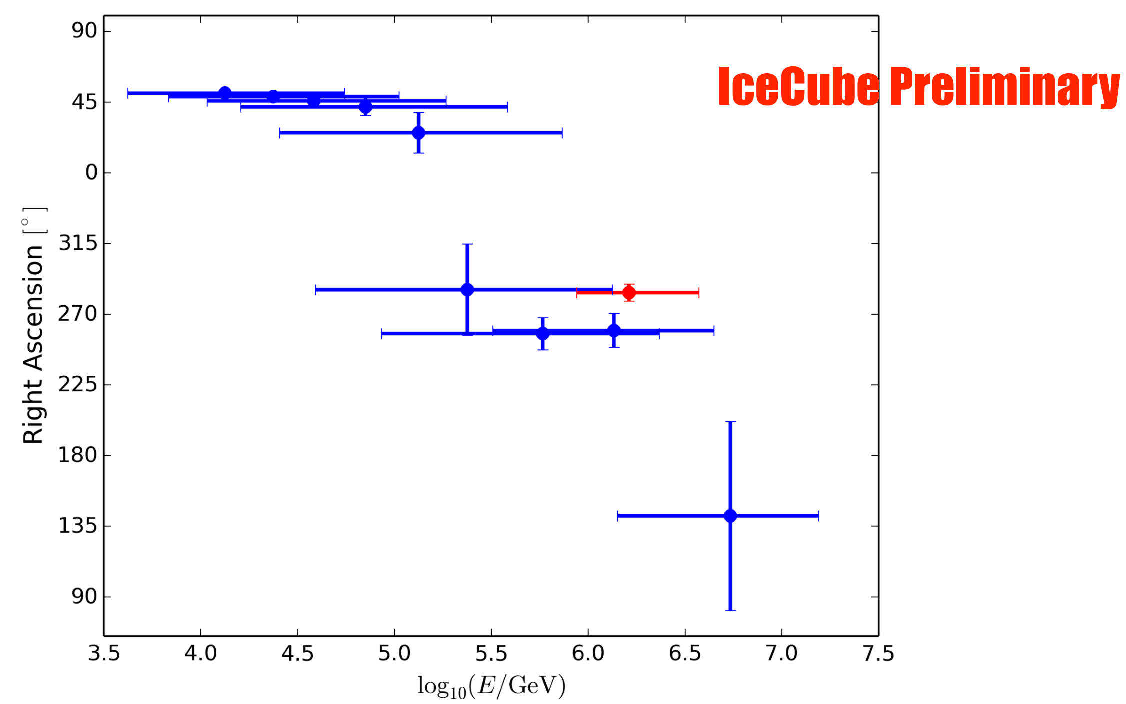
20 TeV

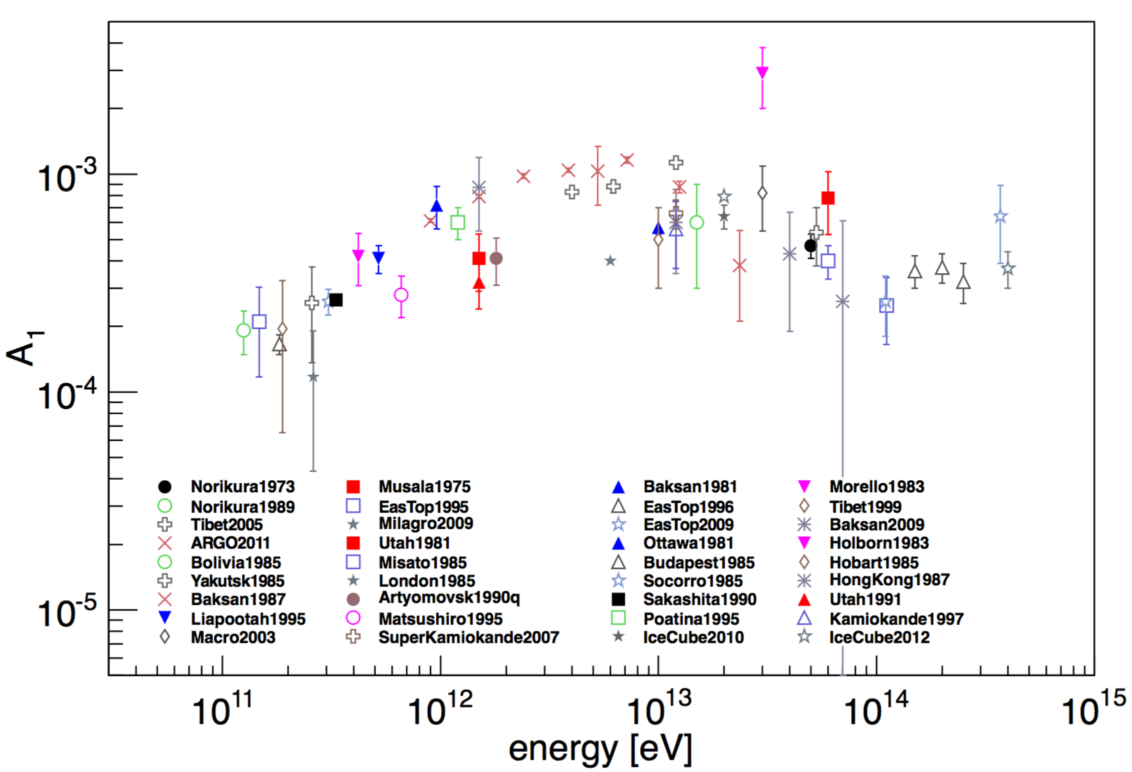
large scale anisotropy

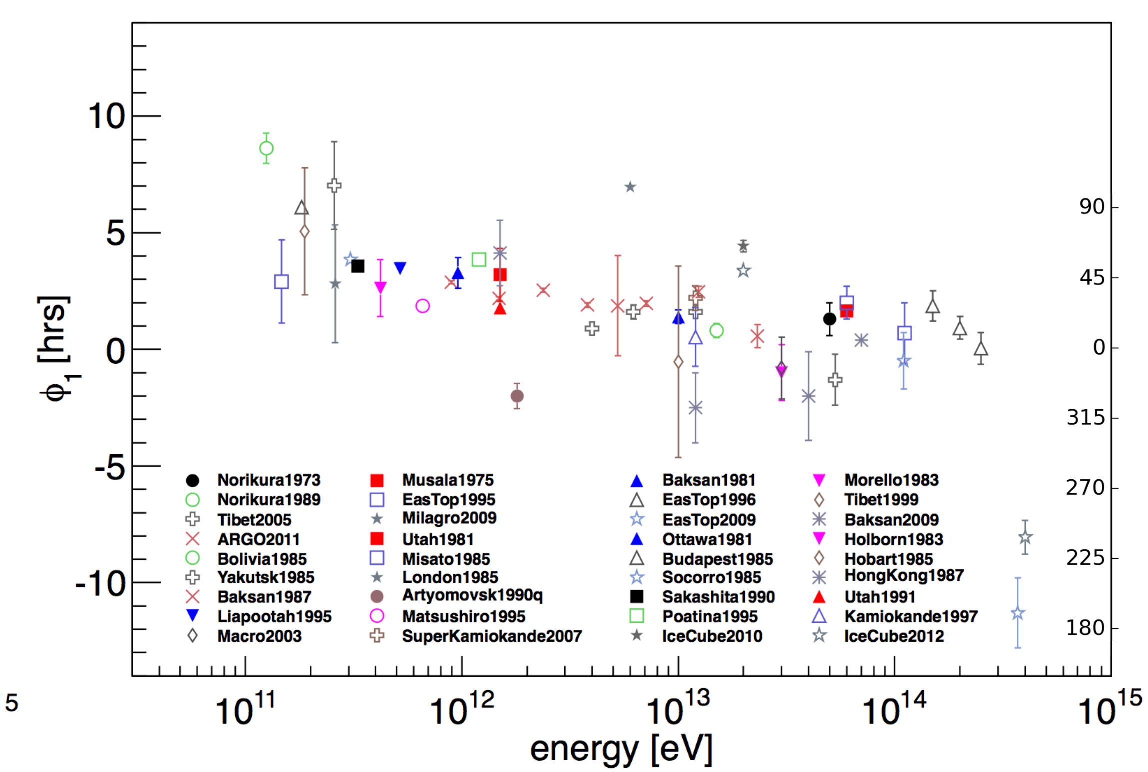
dipole energy dependence









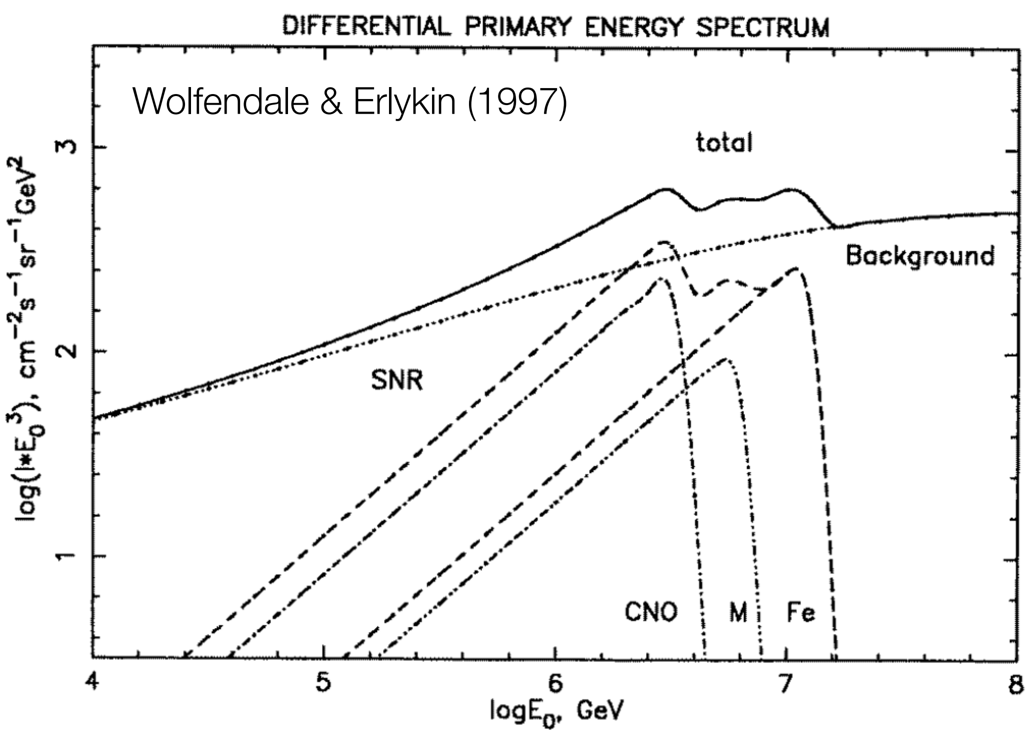


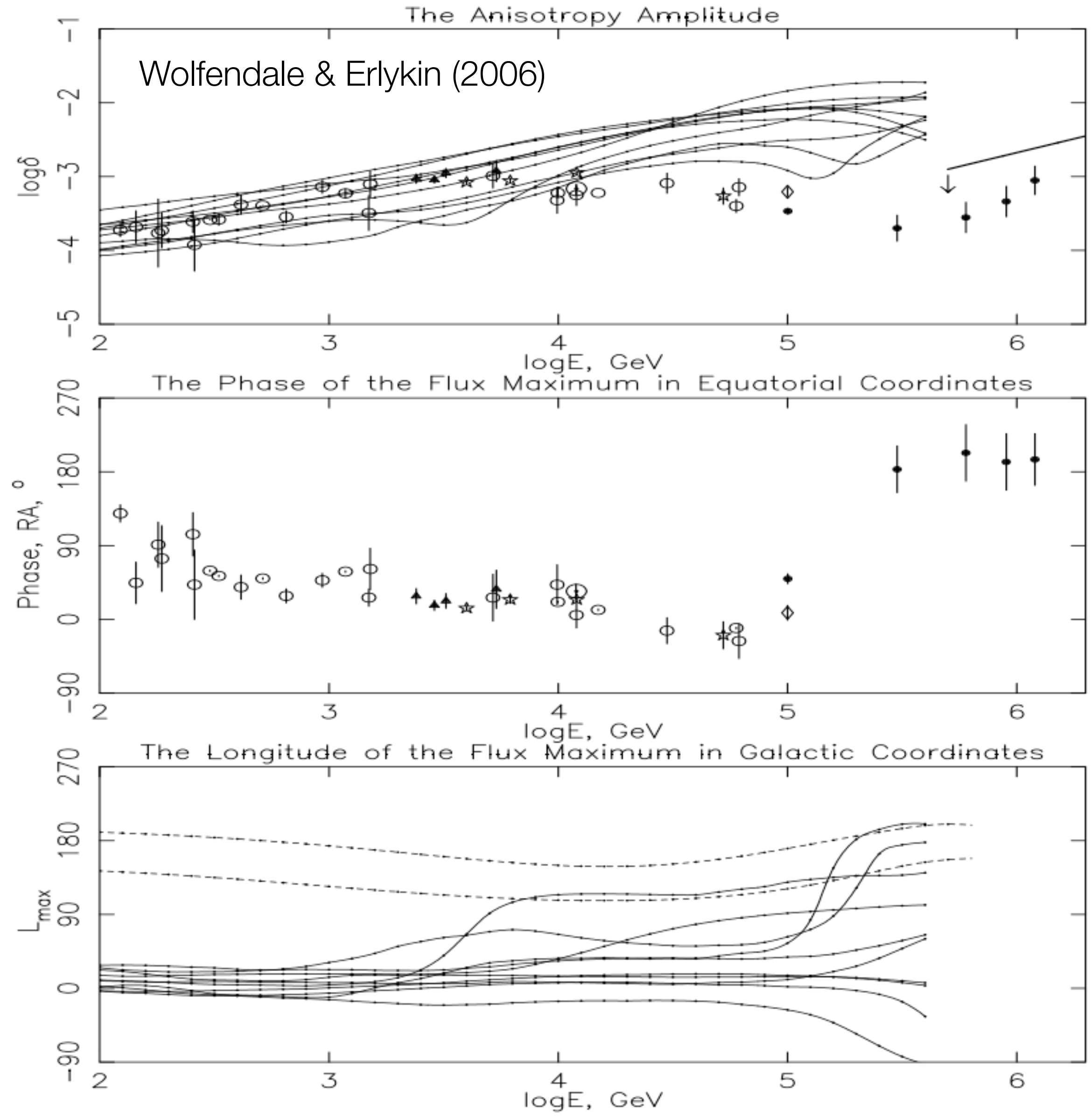
astrophysics of cosmic ray anisotropy

probing sources & propagation of cosmic rays ?

- stochastic effect of **nearby & recent sources** & temporal correlations

Erlykin & Wolfendale, Astropart. 2006
Blasi & Amato, 2011
Ptuskin+, 2012
Pohl & Eichler, 2012
Sveshnikova+, 2013
Kumar & Eichler, 2014
Mertsch & Funk, 2014





single source hypothesis ***explaining*** **spectral structure & anisotropy connections ?**

astrophysics of cosmic ray anisotropy
probing sources & propagation of cosmic rays ?

- stochastic effect of **nearby & recent sources** & temporal correlations

Erlykin & Wolfendale, Astropart. 2006
Blasi & Amato, 2011
Ptuskin+, 2012
Pohl & Eichler, 2012
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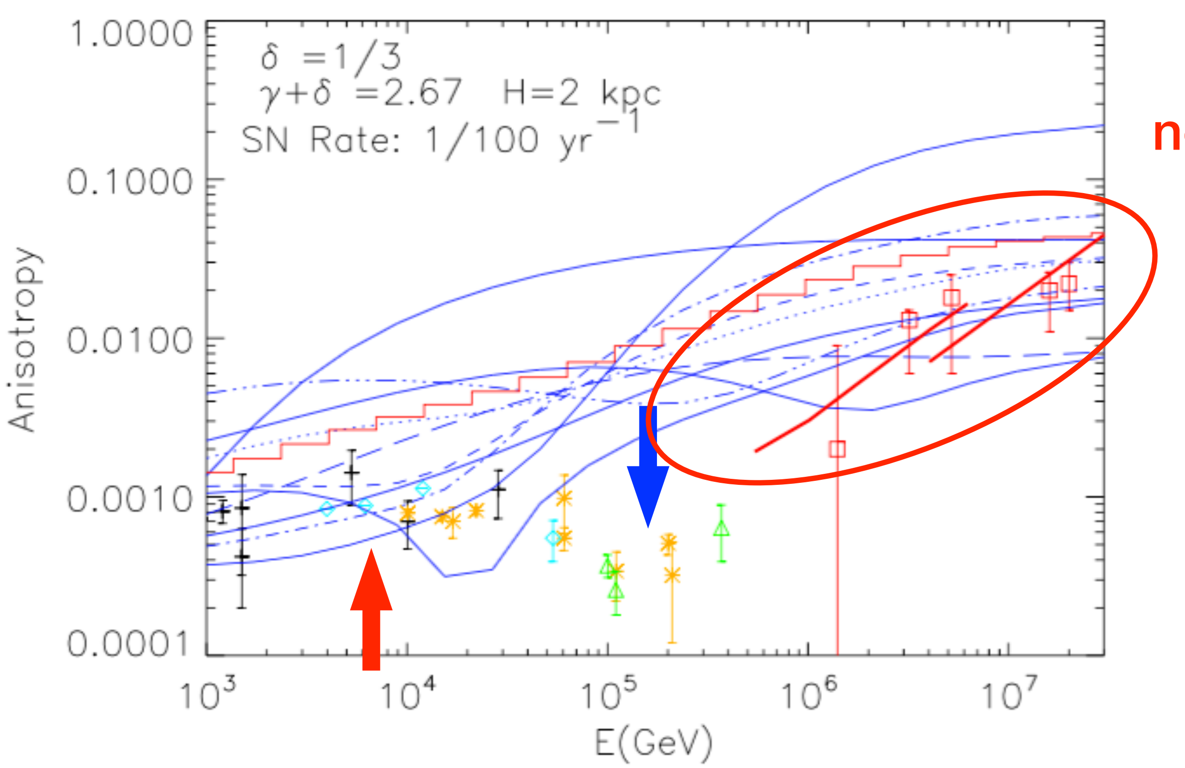
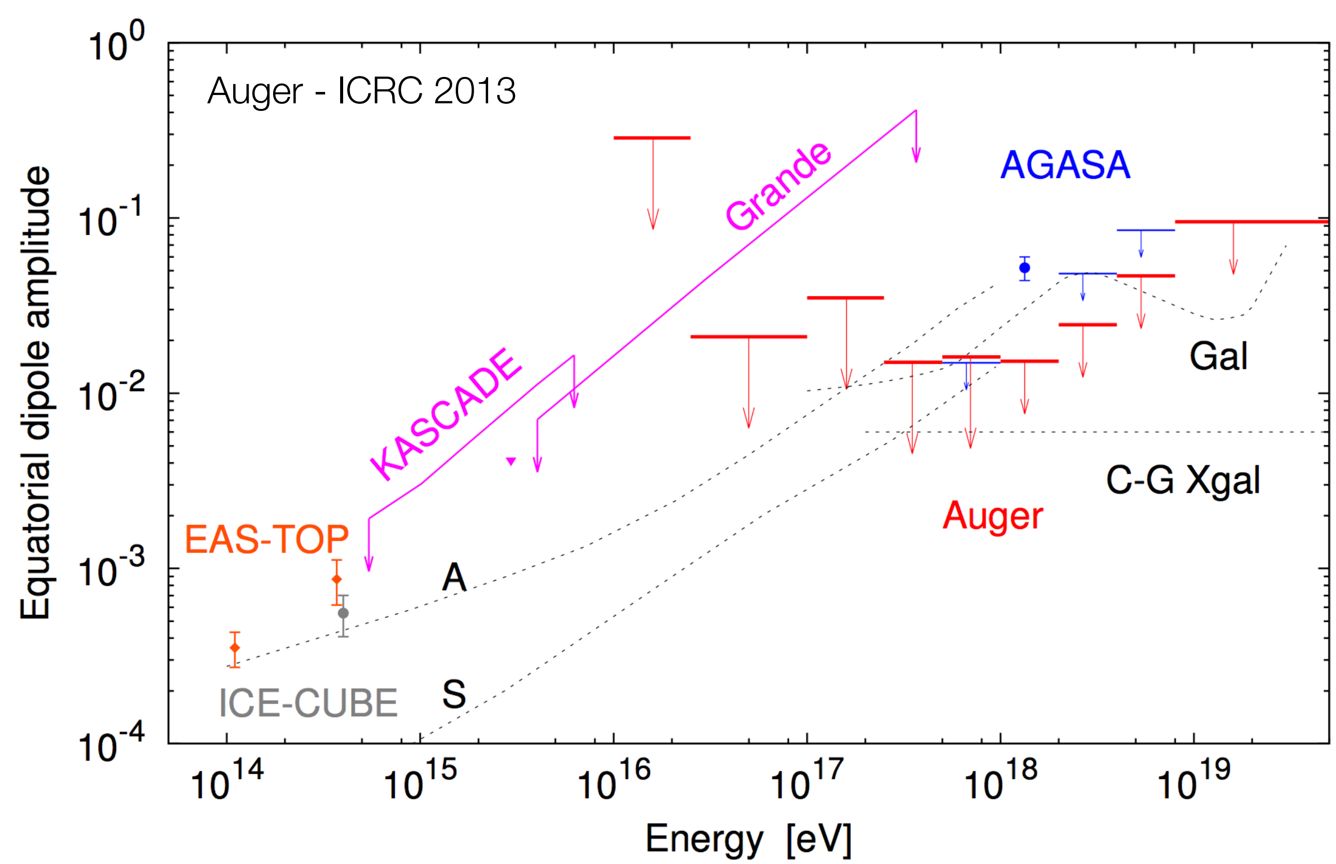
Kumar & Eichler, 2014
Mertsch & Funk, 2014

dipole amplitude **Blasi & Amato, 2011**



not dipole observations

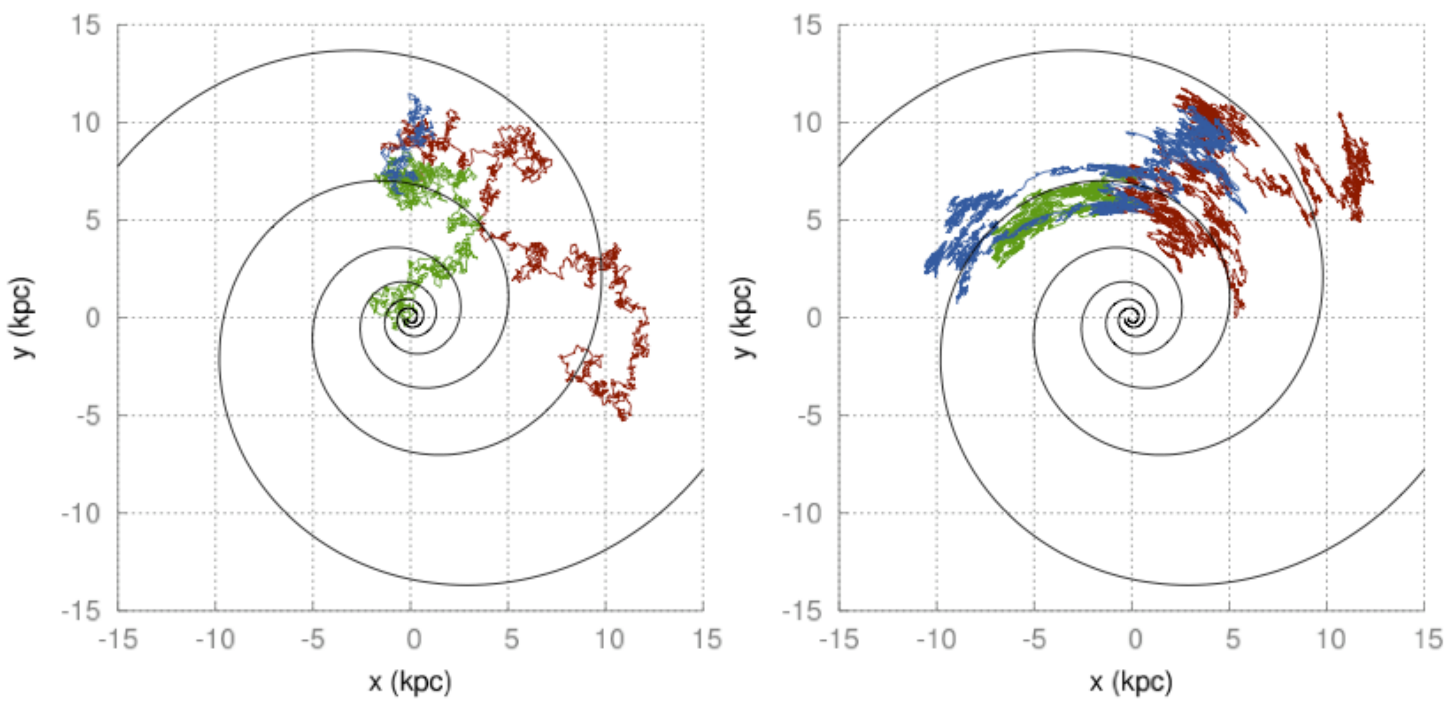


dipole components of the anisotropy typically **overestimated** by models

cosmic ray anisotropy
probing diffusion properties

anisotropic diffusion

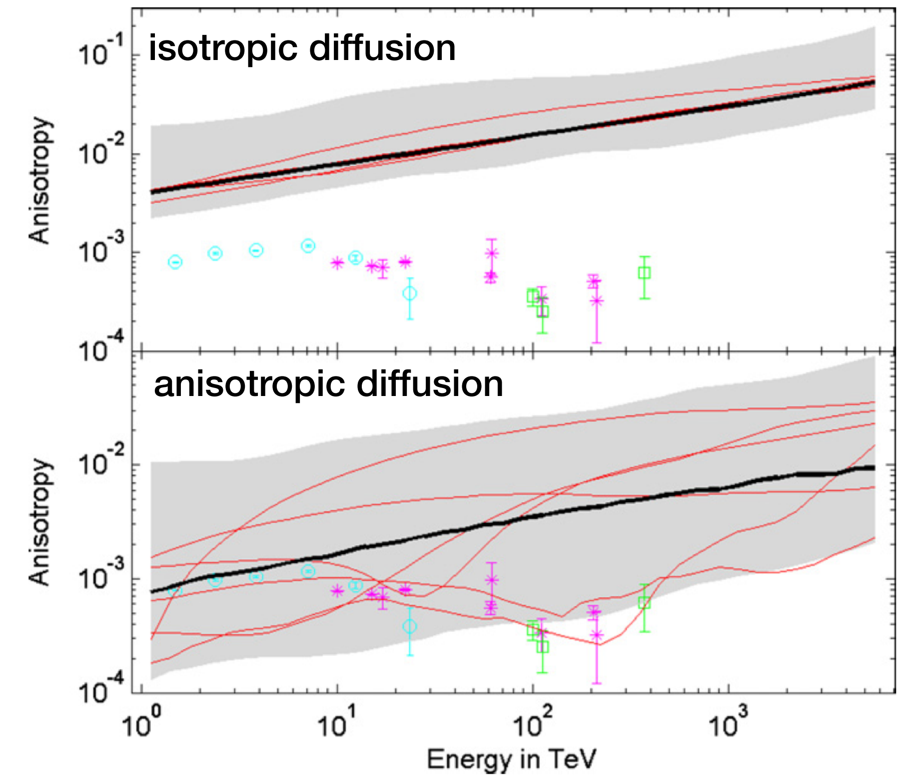
Effenberger+, 2012



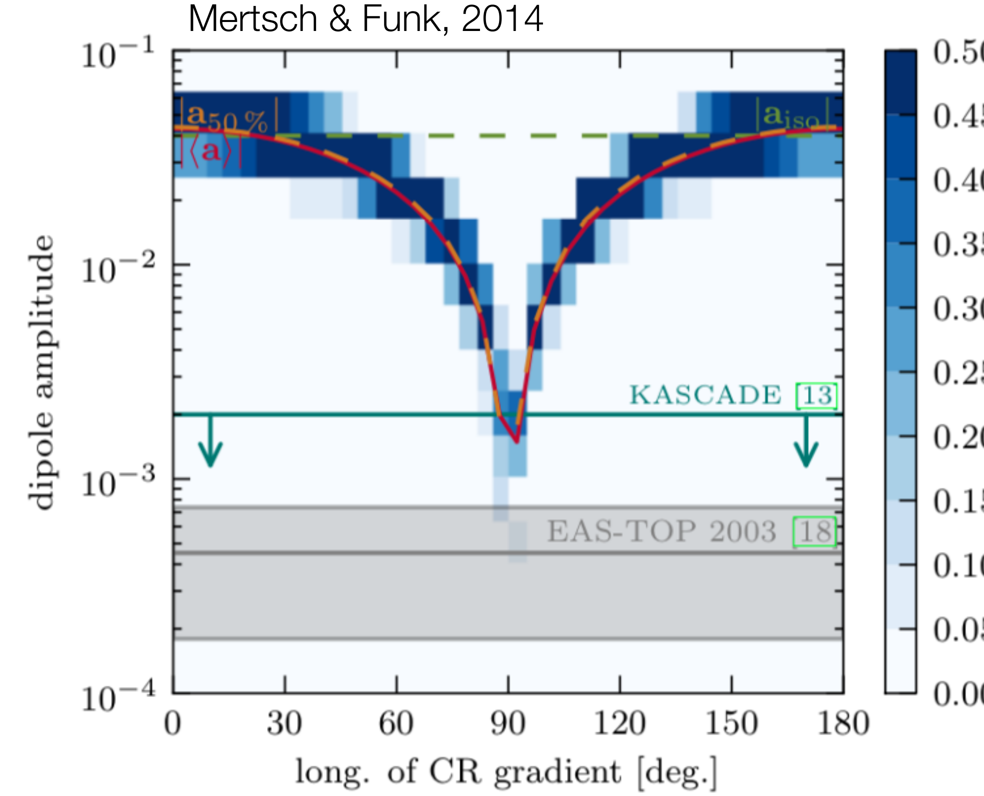
- **$D_{\perp}/D_{\parallel}$ << 1** - parallel projection of anisotropy
- cosmic ray **sources concealed** by propagation effects

diffusion coefficient hardly a single power law, homogeneous and isotropic

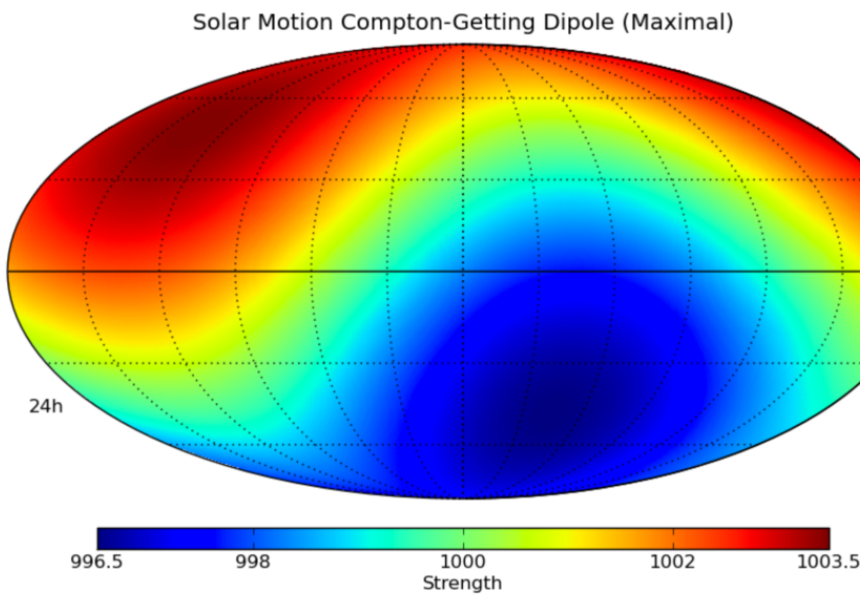
Kumar & Eichler, 2014



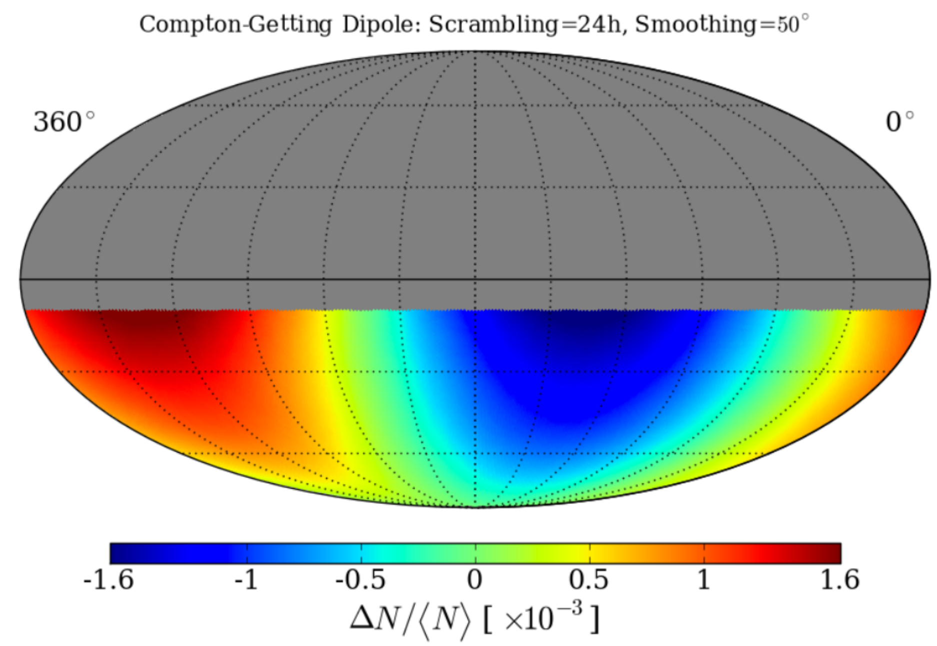
Mertsch & Funk, 2014



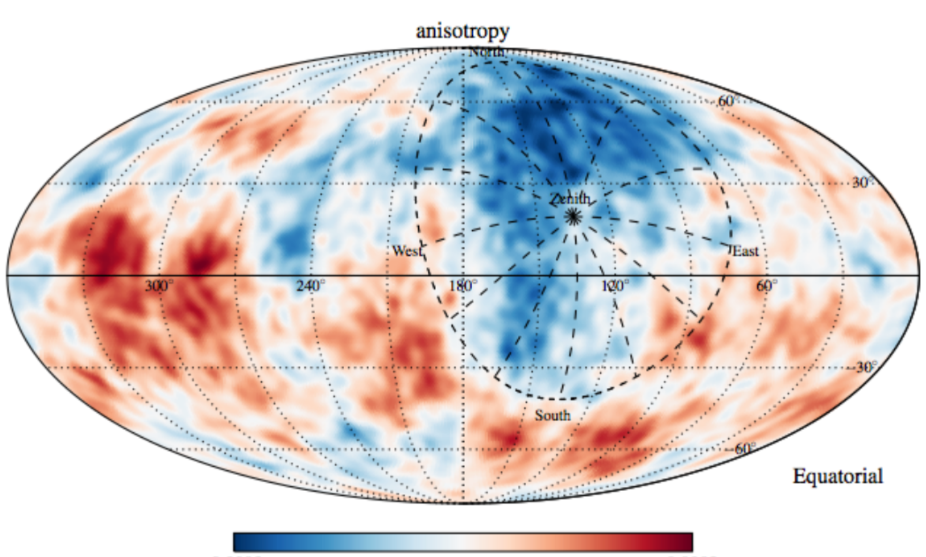
cosmic ray anisotropy
experimental biases

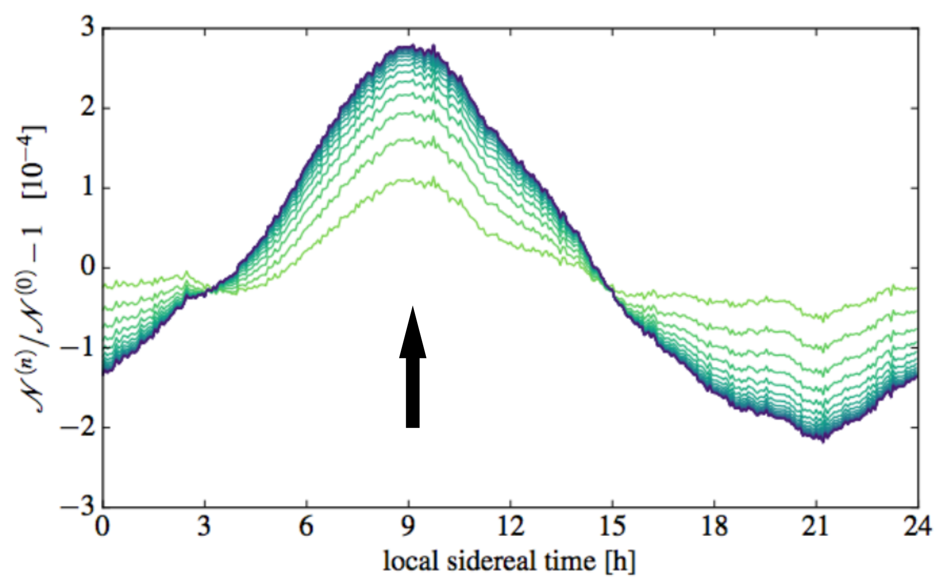


$\Delta N/\langle N \rangle = 7\times10^{-3}$



sky maps show **ONLY** modulations across right ascension and **NOT** declination





wrong background estimation to be recovered with **iterative methods**

Ahlers, BenZvi, PD, Díaz Vélez, Fiorino, Westerhoff
arXiv:1601.07877

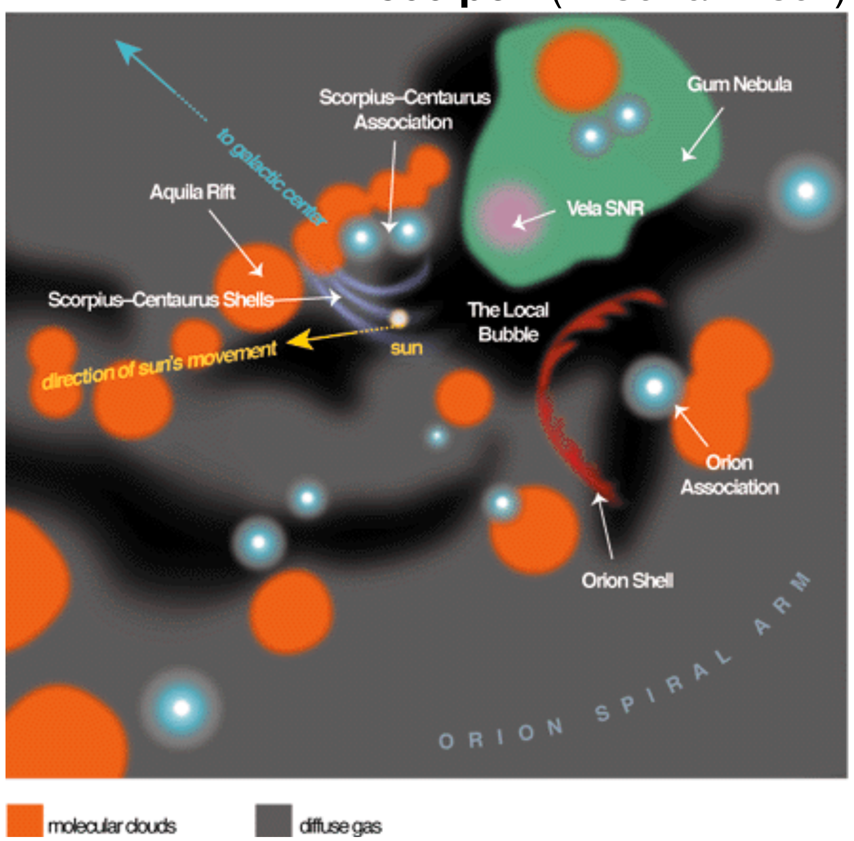
cosmic ray anisotropy

local interstellar medium

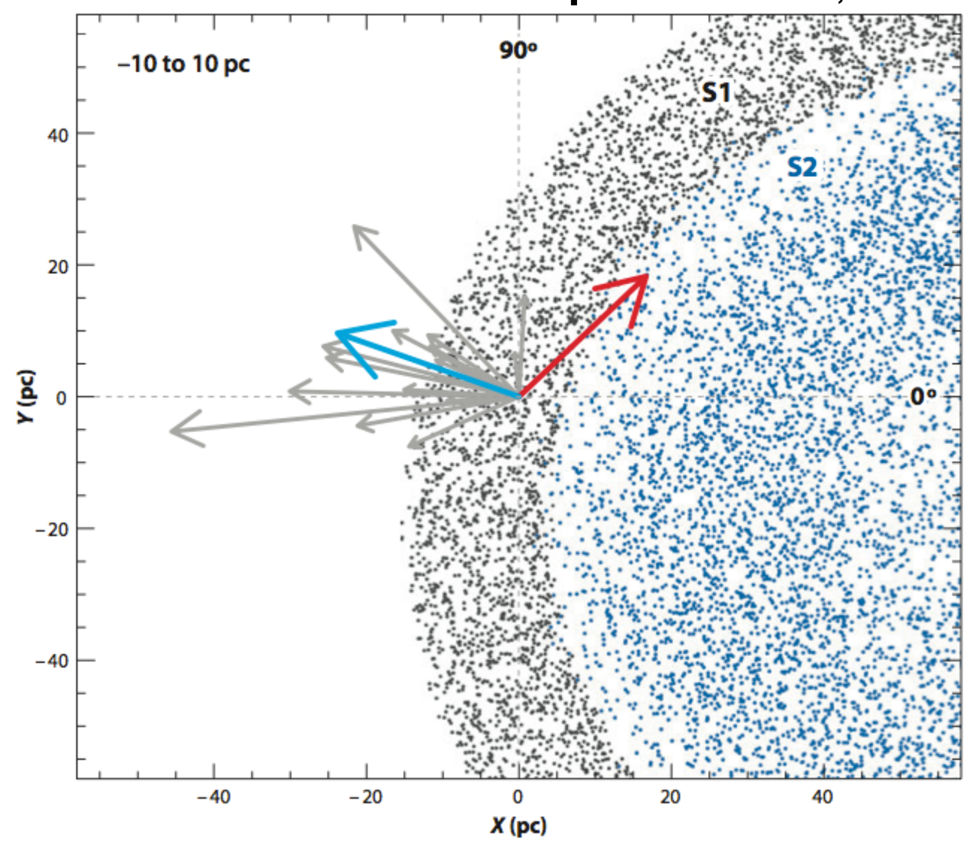
local ISMF shaped by LOOP I expansion sub-shell (with center ~60 pc away in Scorpius-Centaurus OB Association)

local cloudlets fragments of the shell moving at similar velocities

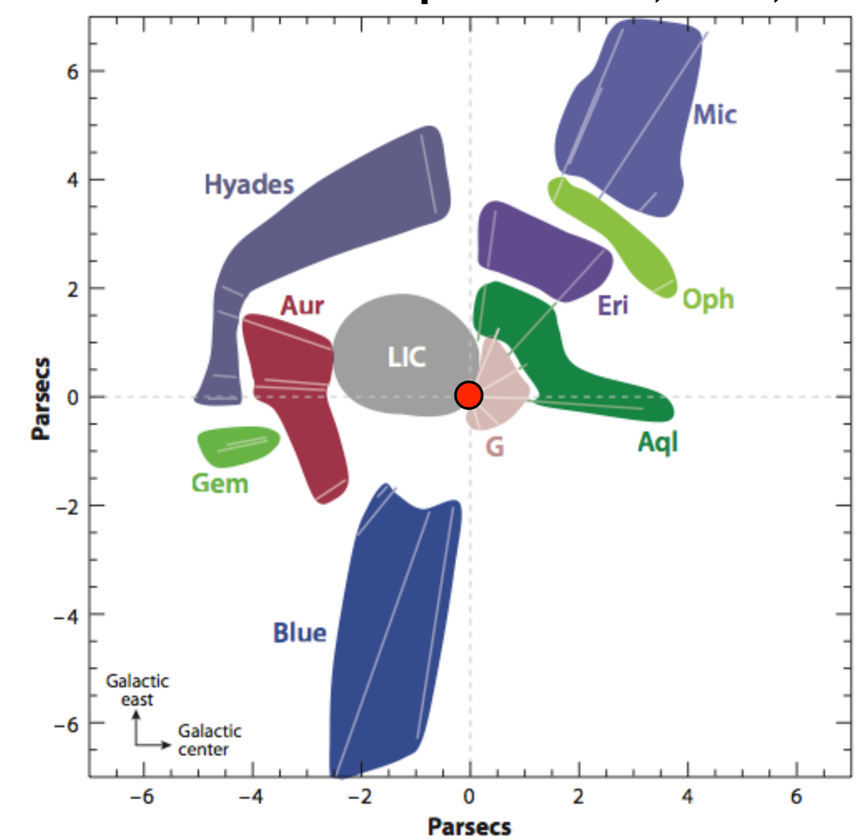
500 pc - (Priscilla Frisch)



100 pc - Wolleben, 2007



14 pc - Frisch+, 2011, 14



- interstellar magnetic field affected by inhomogeneities

Redfield & Linsky, 2008

Frisch+, 2011

- local ISMF relatively uniform over spacial scales of order 60-100 pc (**inter-arm**)

Frisch+, 2012, 14

- magnetic turbulence affects propagation and diffusion properties

Giacalone & Jokipii, 1994, 99
Yan, Lazarian, 2002,04,08

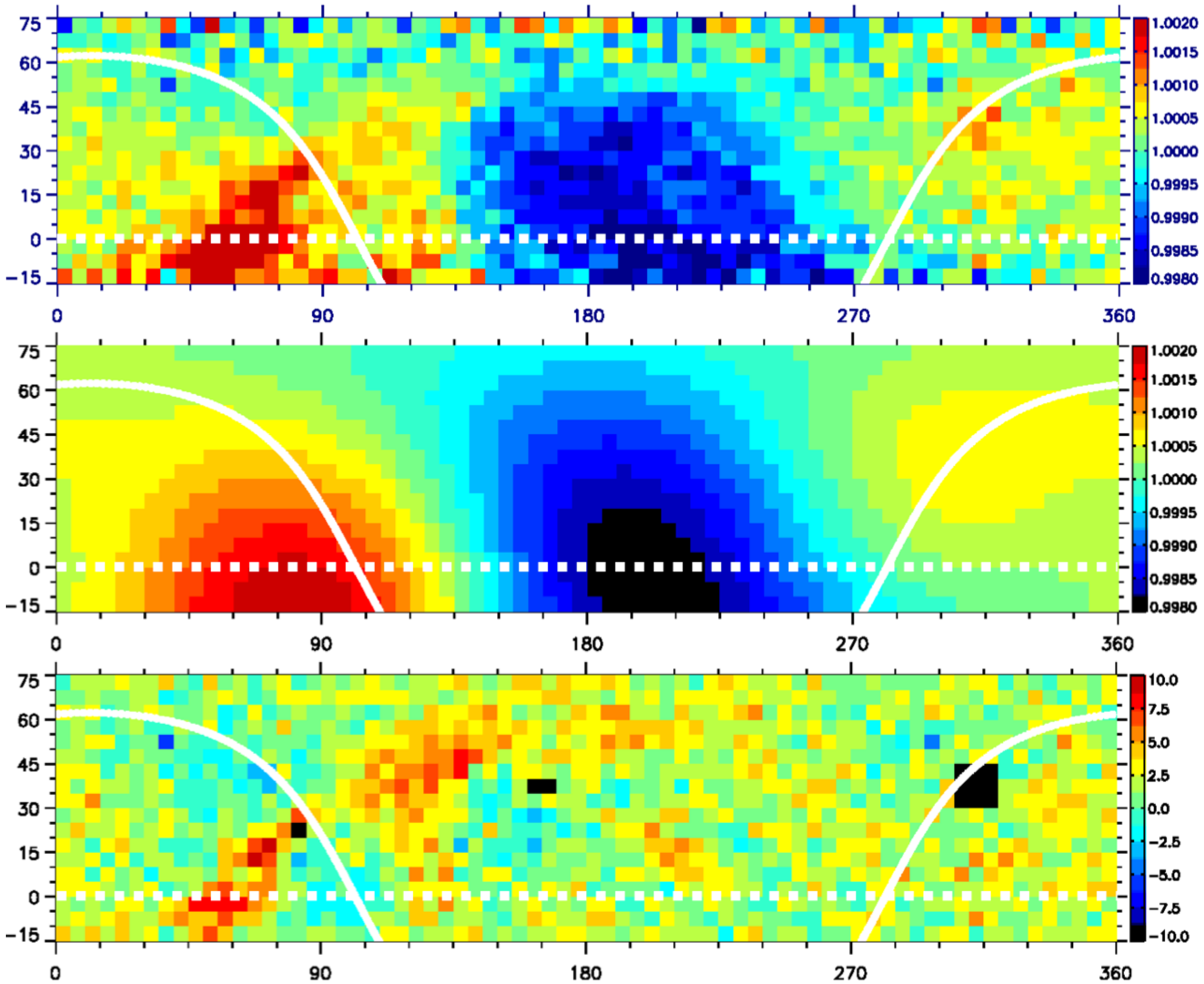
large scale anisotropy

topology

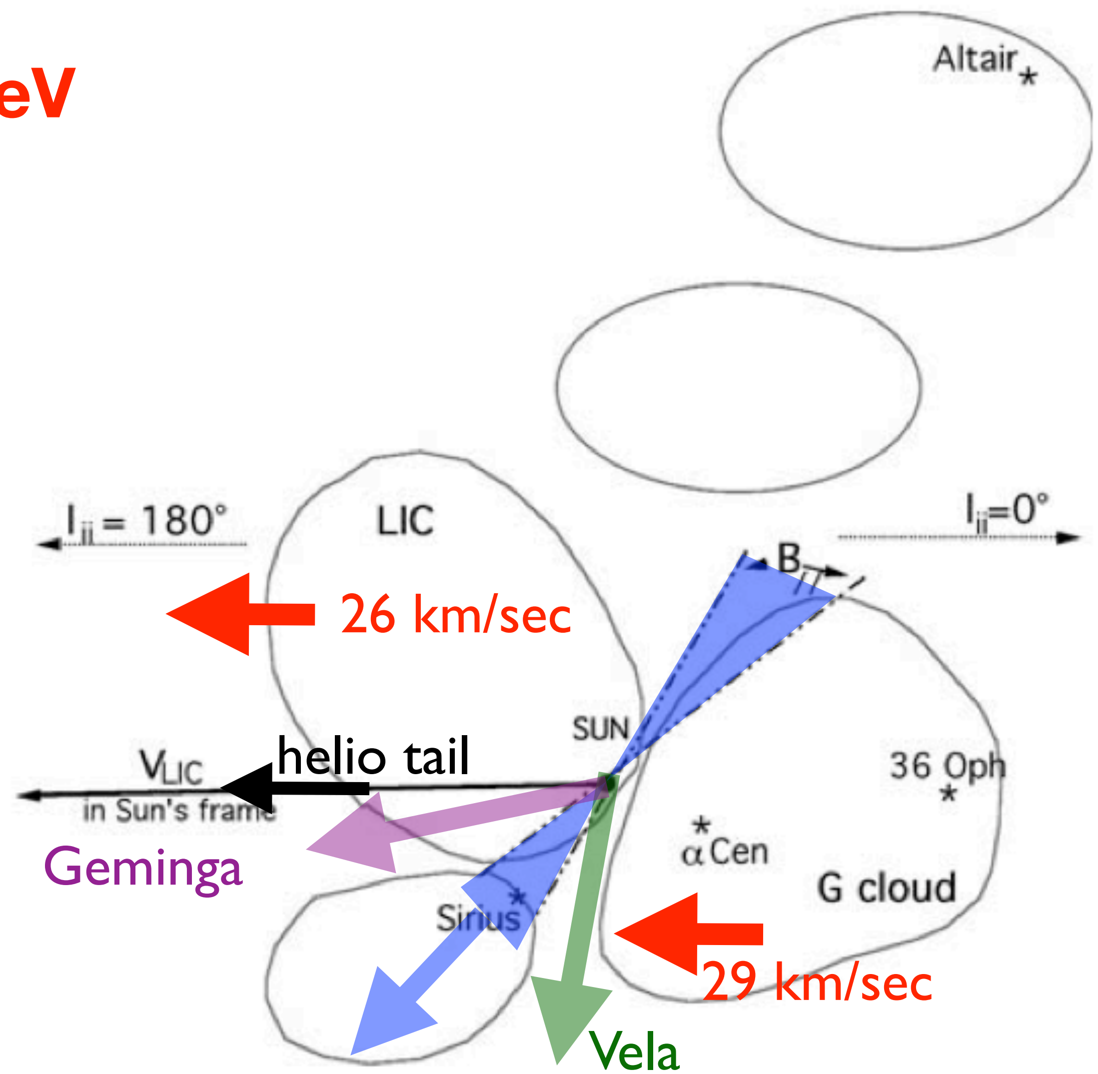
ANISOTROPY IS COMPLEX

Local Interstellar Medium

Tibet ASγ Amenomori et al., ICRC 2007



4 TeV



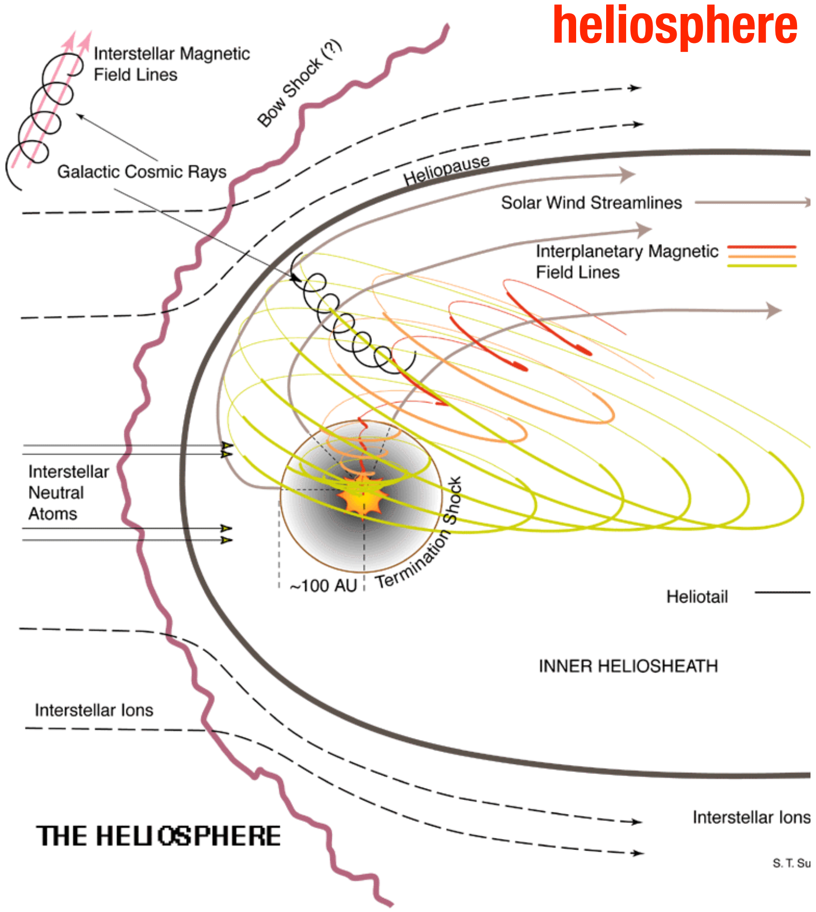
uni-directional (**dipole**) & bi-directional (**quadrupole**) anisotropy from CR density and Local Magnetic Field **gradients**

cosmic ray anisotropy

heliosphere

$$r_L \approx \frac{200}{Z}\frac{E(TeV)}{B(\mu G)}AU$$

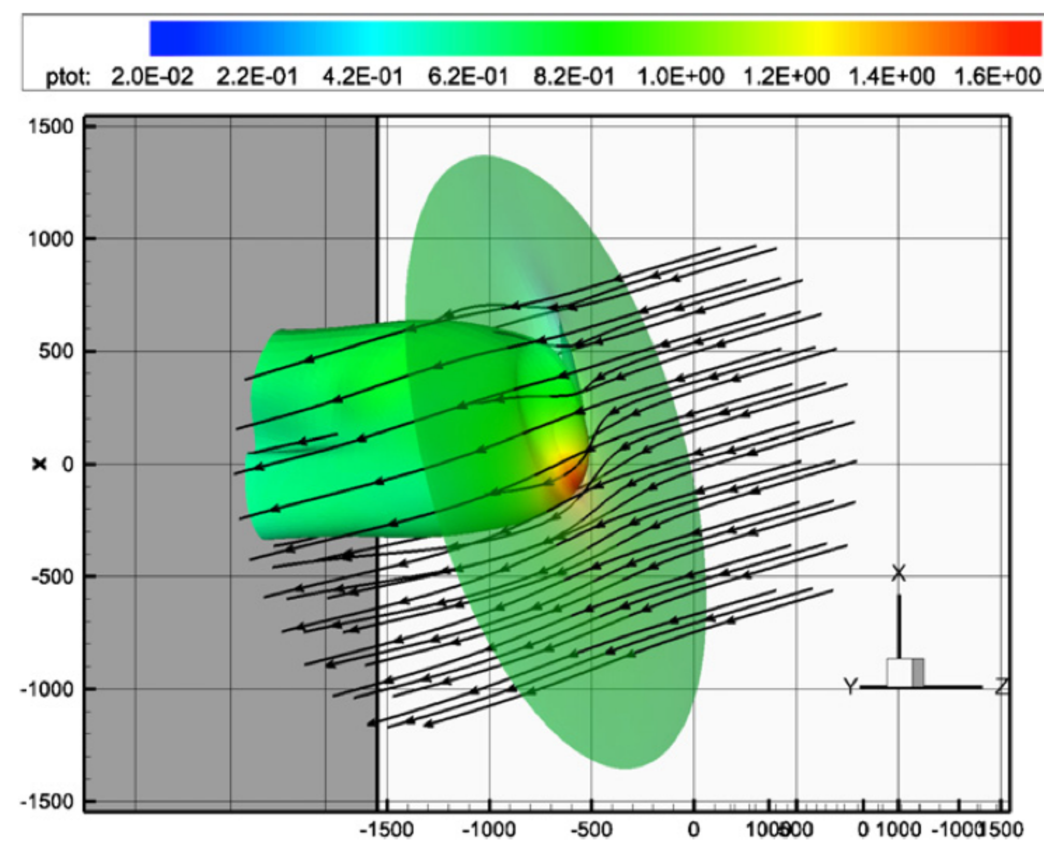
heliosphere



heliotail

local ISMF draping around heliosphere

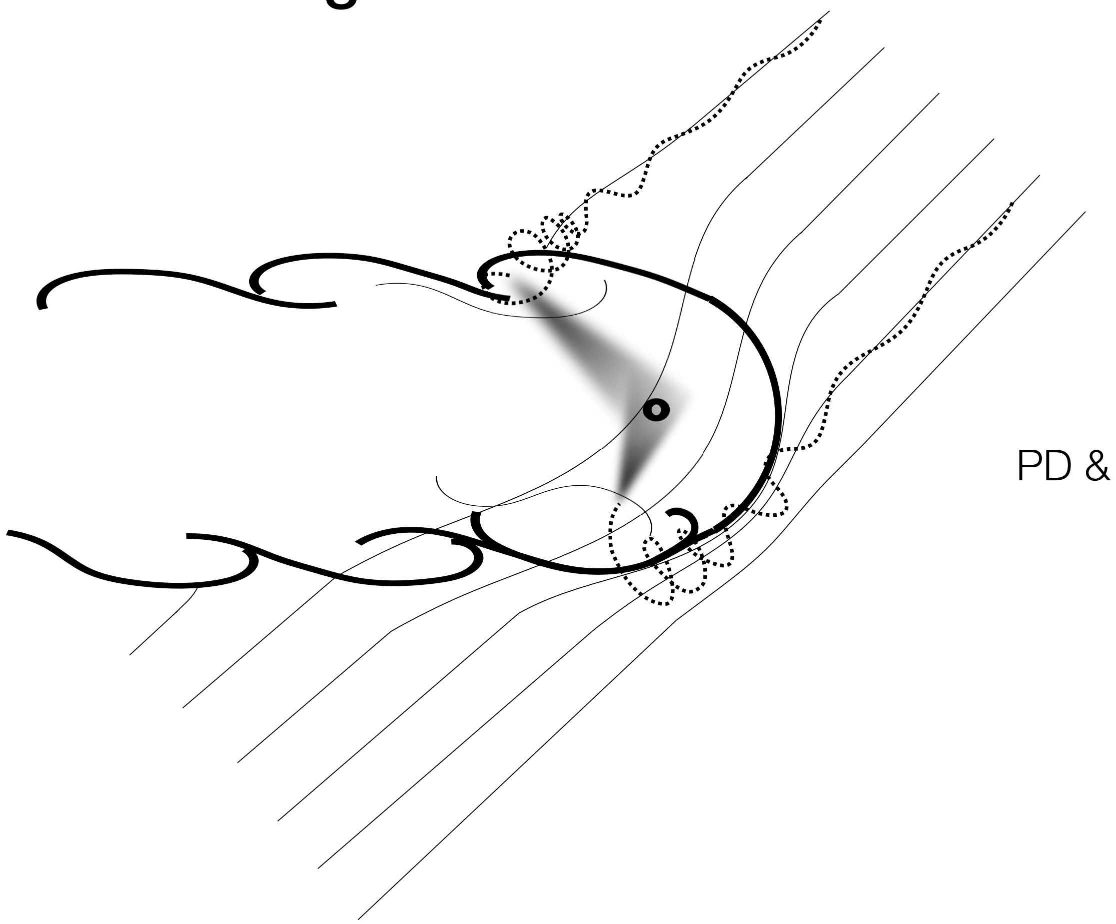
Pogorelov+ 2011



- heliosphere as O(100-1000) AU **magnetic perturbation of local ISMF** PD & Lazarian, 2013
- influence on ≲ 10 TeV protons (R_L ≲ 600 AU)
- cosmic rays >100's TeV influenced by interstellar magnetic field (**change of anisotropy**)

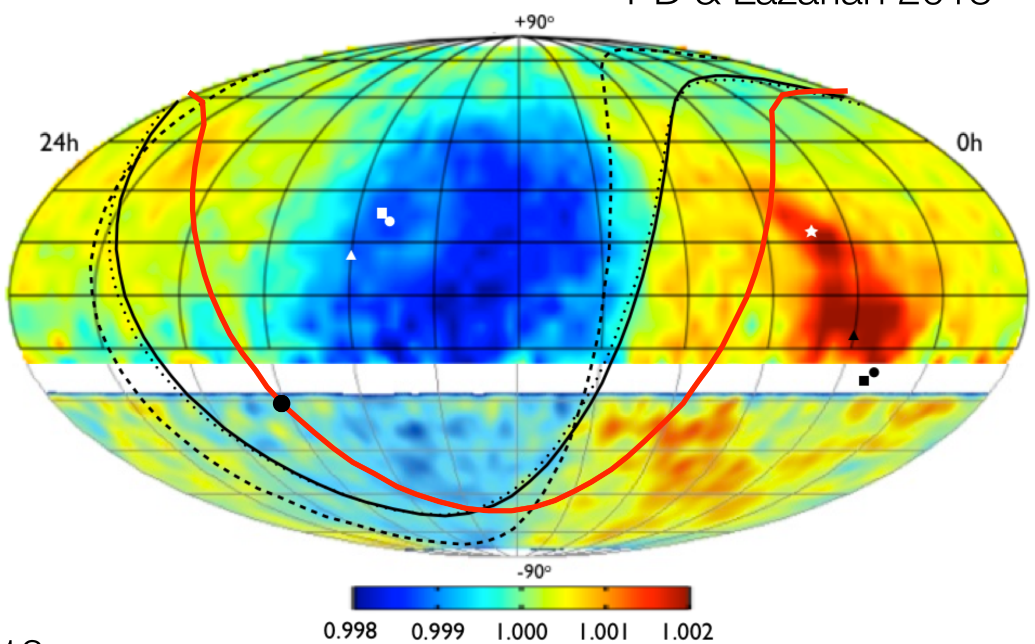
scattering at heliospheric boundary
heuristic model

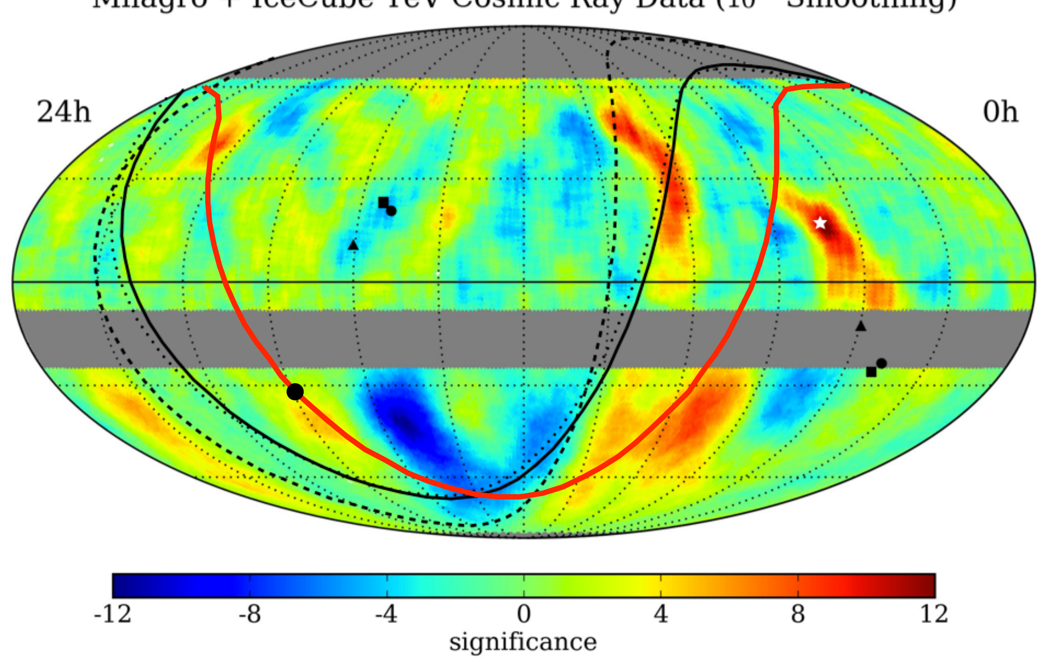
- resonant scattering to **re-direct** CR distribution
- **back-scattering** @ flanks back from downstream



PD & Lazarian 2013

PD & Lazarian 2013



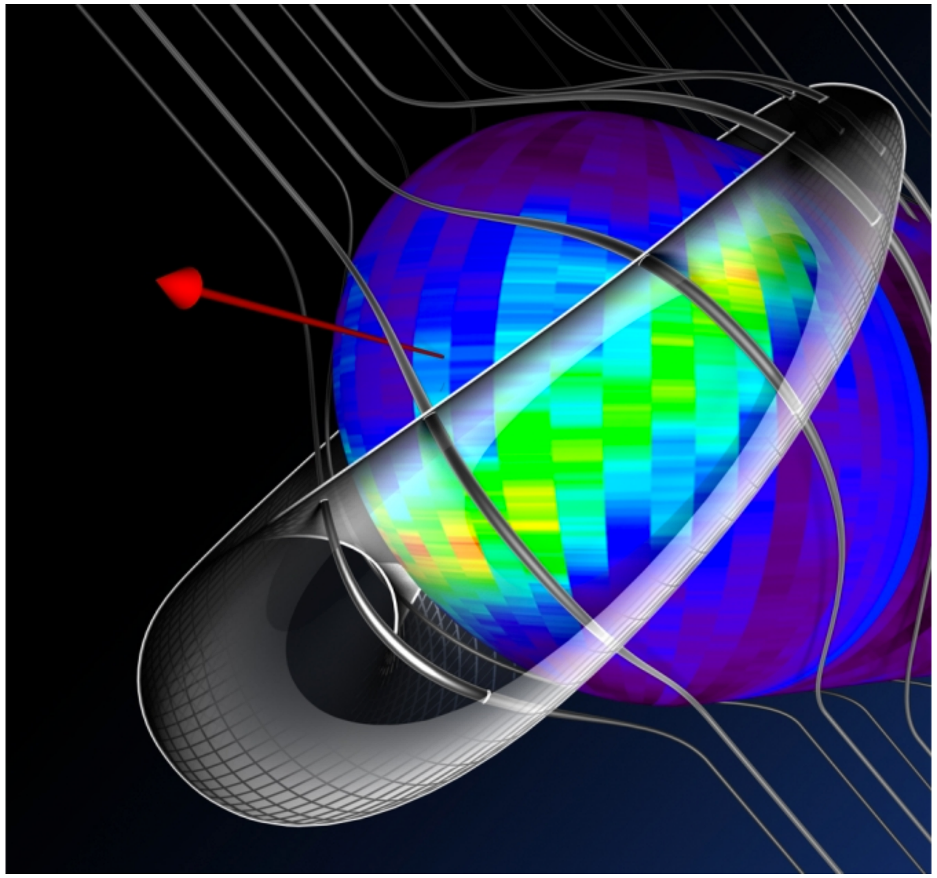


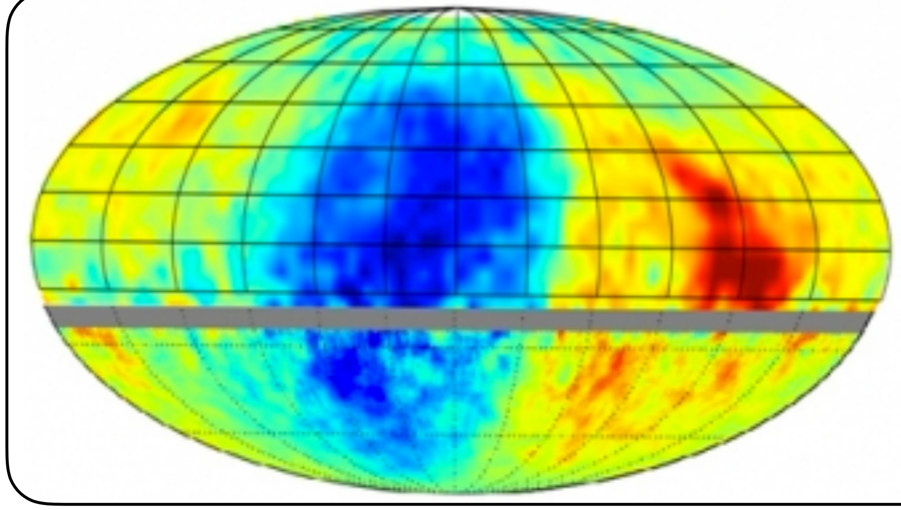
- global anisotropy with **large edge gradients**
- **magnetic reconnection**

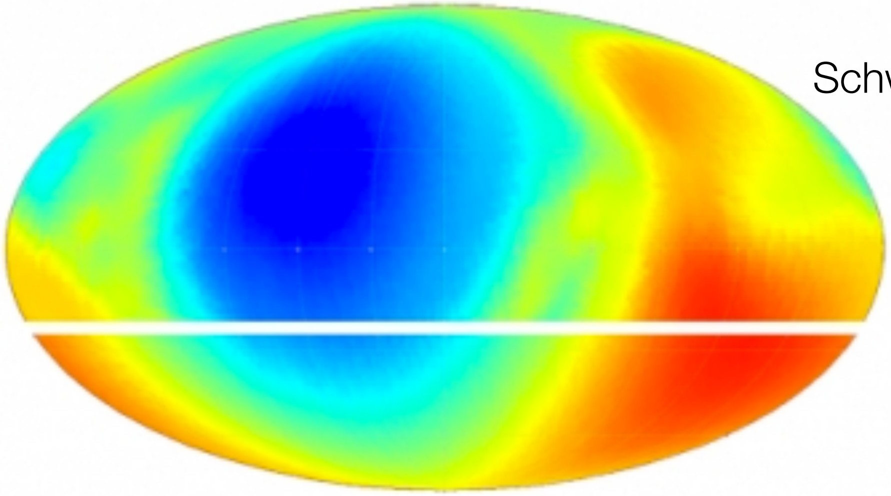
Lazarian & PD 2010
PD & Lazarian 2012

anisotropy and local galactic environment
low to high energy connection

- IBEX observations of keV Energetic Neutral Atoms
- determination of interstellar flow direction
- determination of interstellar magnetic field direction
- investigating the role of heliospheric turbulence







Schwadron, Adams, Christian, PD, Frisch, Funsten, Jokipii, McComas, Möbius, Zank
Science, 1245026 (2014)

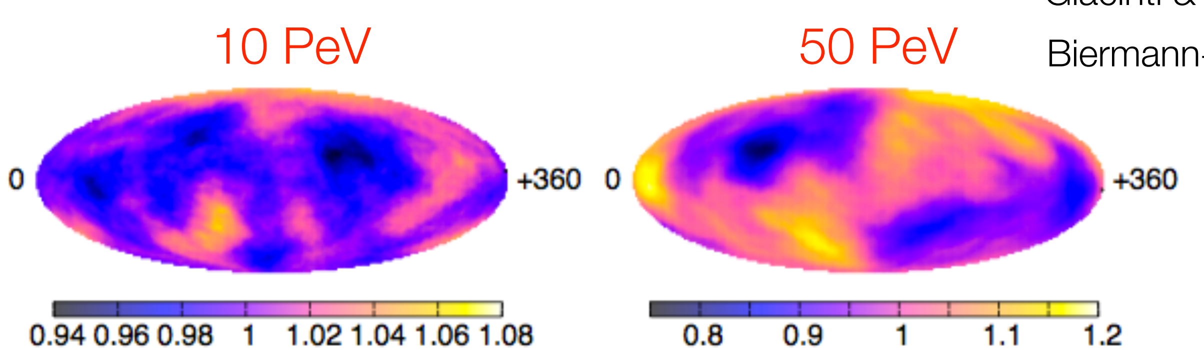
perturbation from heliospheric magnetic field

other study - Zhang, Zuo & Pogorelov ApJ 790, 5 (2014)

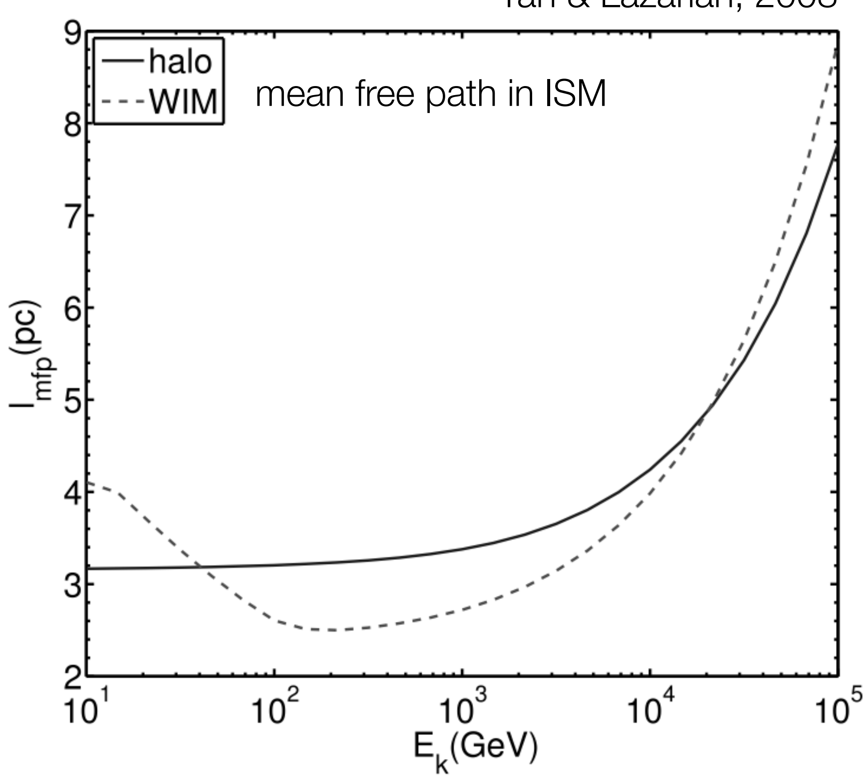
cosmic ray anisotropy
probing magnetic field turbulence ?

- propagation effect from turbulent realization of interstellar magnetic field within scattering mean free path

Giacinti & Sigl, 2012
Biermann+, 2012

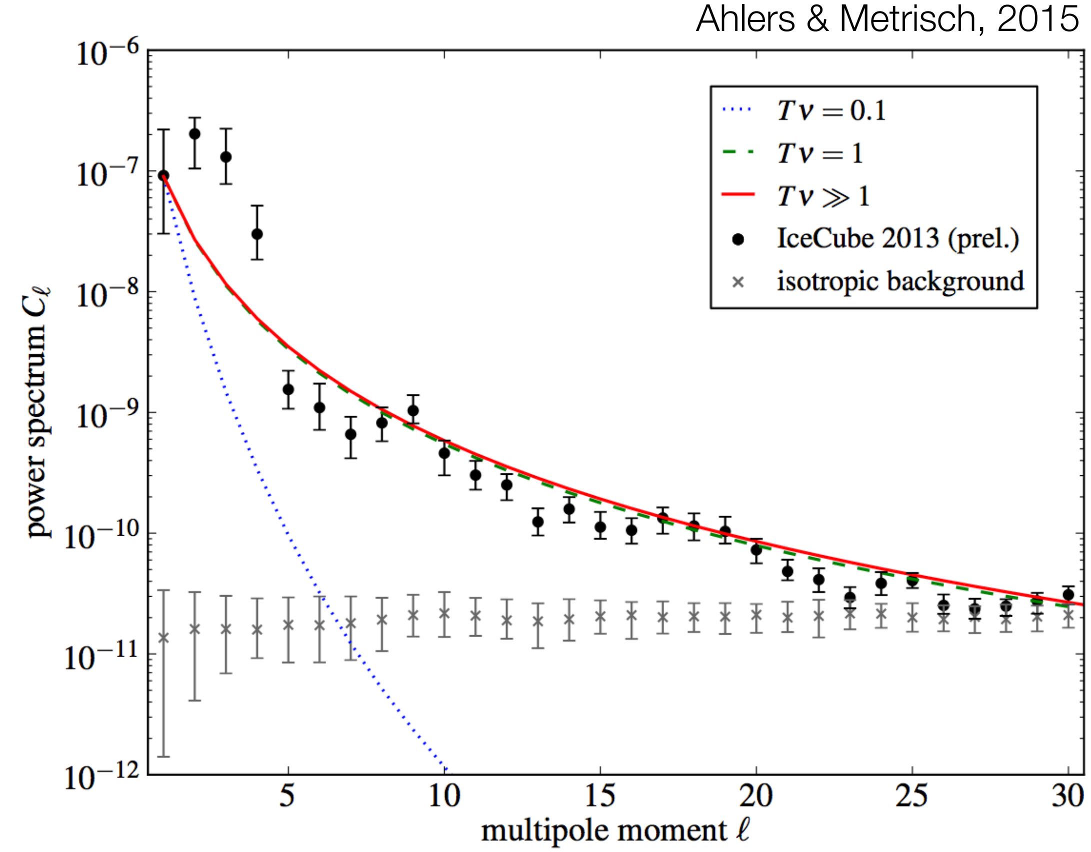


Yan & Lazarian, 2008



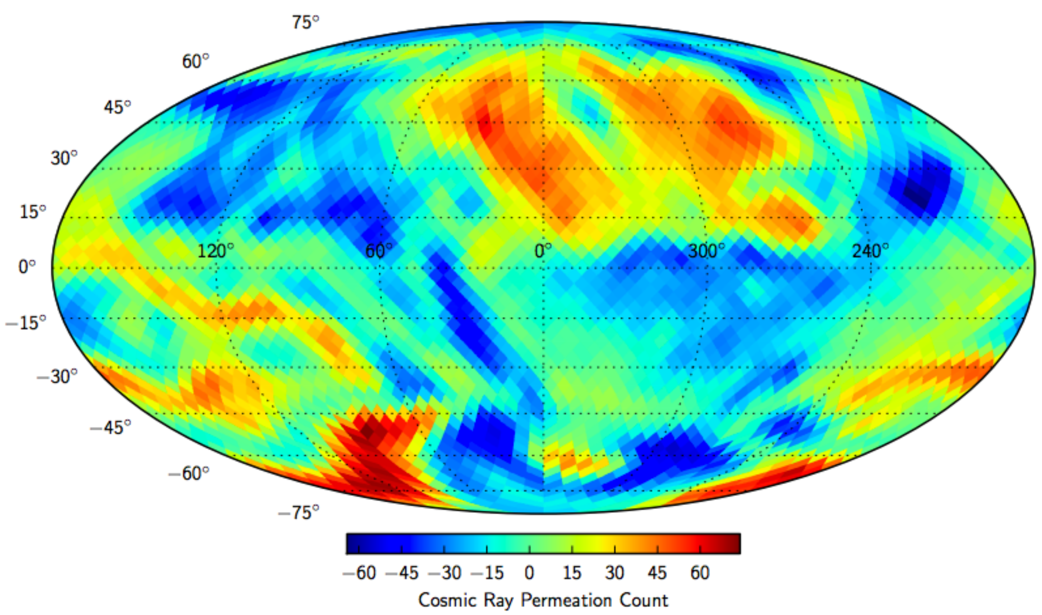
- angular structure of anisotropy spontaneously generated from a global dipole anisotropy as a consequence of Liouville Theorem in the presence of a local turbulent magnetic field (sum of multipoles is conserved)

Ahlers, 2014
Ahlers & Metrisch, 2015

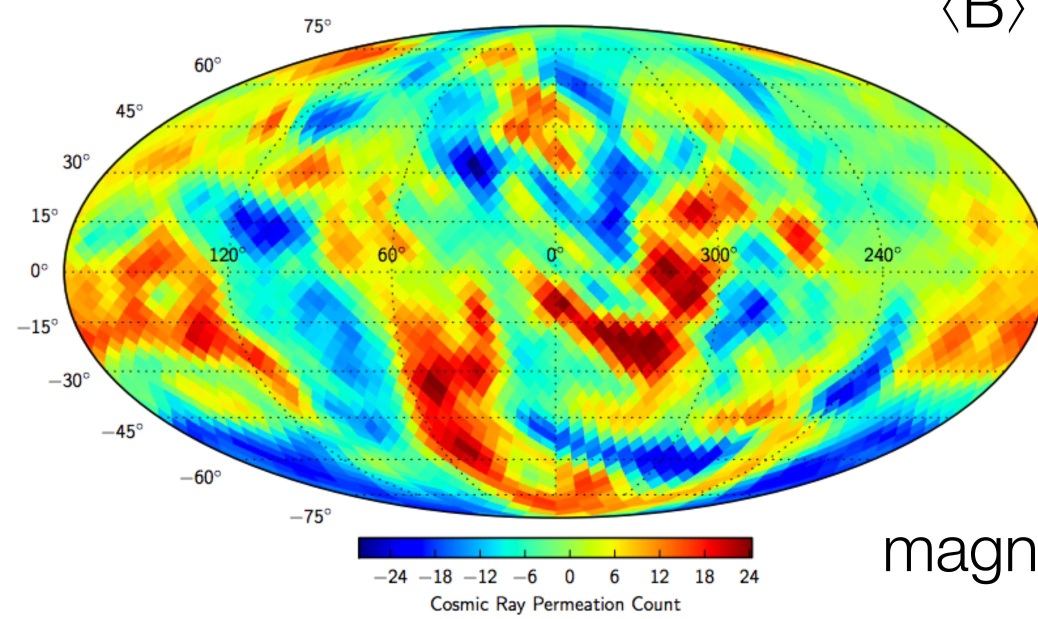


cosmic ray anisotropy
probing magnetic field turbulence ?

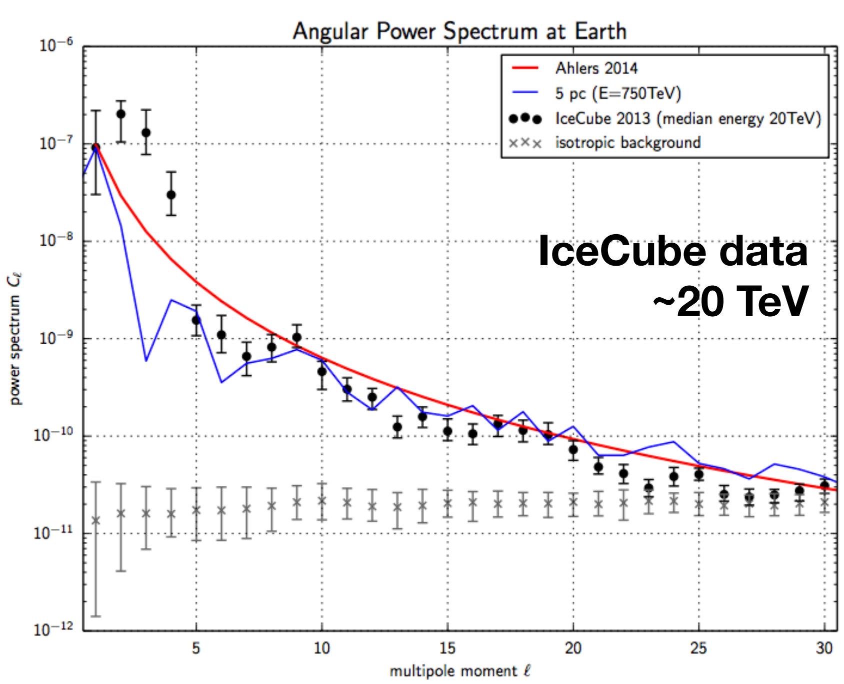
MHD turbulence with
⟨B⟩ = 3 μG and M_A ~ 0.7

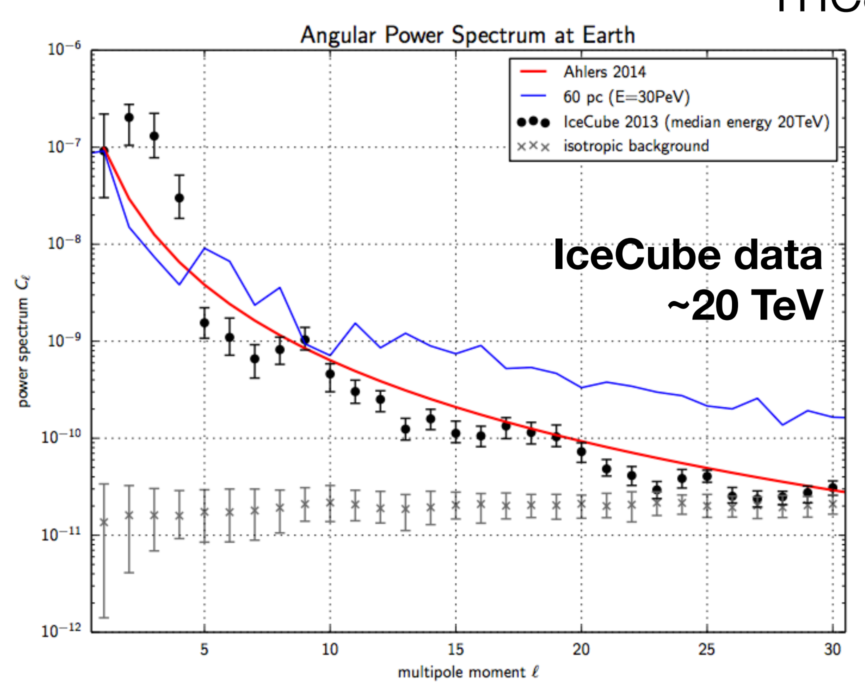


750 TeV



30 PeV



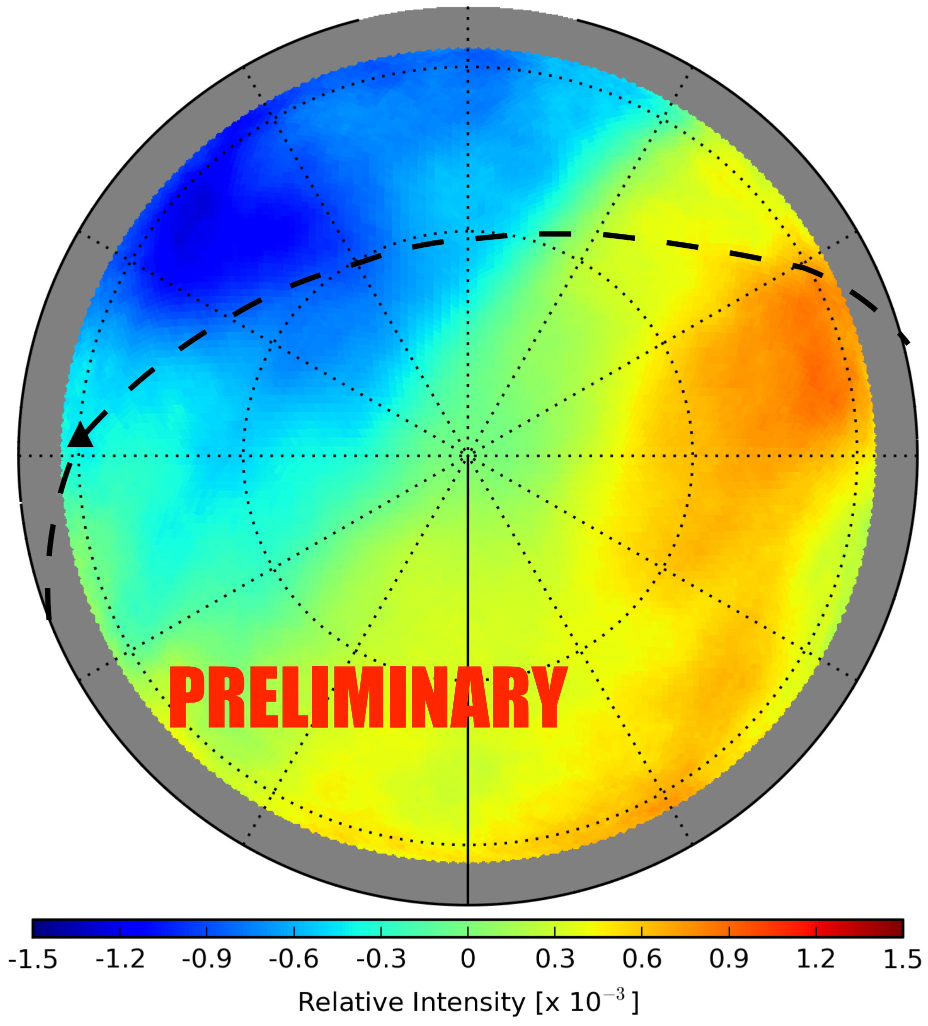


effect of **scattering** in magnetic turbulence modes

mean free path as evolution *horizon*

López-Barquero, Xu, Farber, PD, Lazarian
arXiv:1509.00892

THANK YOU


PRELIMINARY
-1.5
-1.2
-0.9
-0.6
-0.3
0
0.3
0.6
0.9
1.2
1.5
Relative Intensity [x 10^{-3}]

possible origin of cosmic ray particles

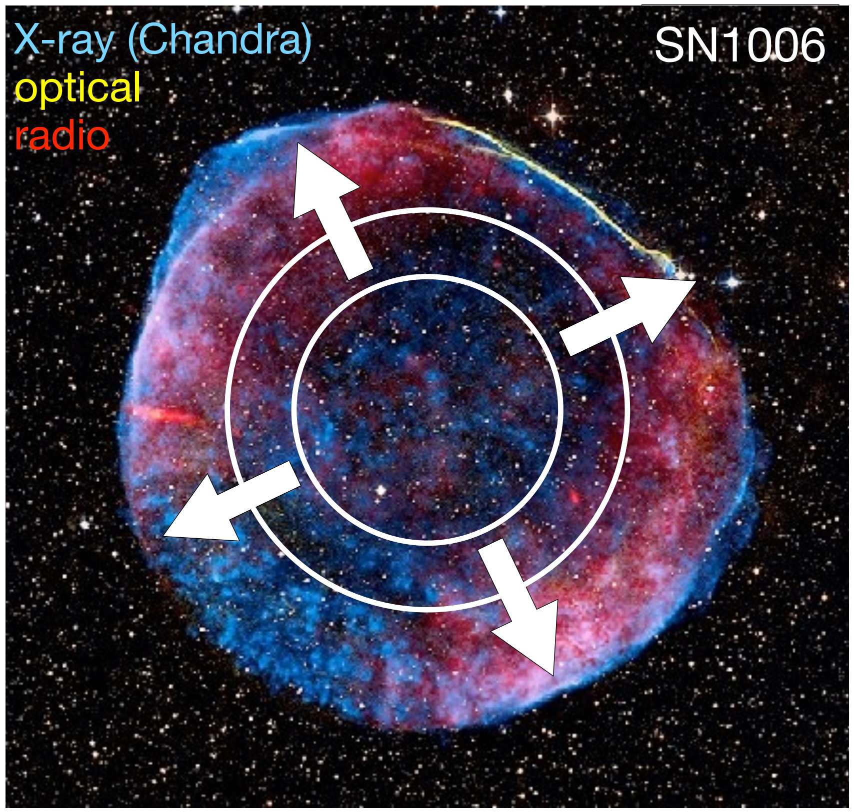
- bulk of cosmic rays of **similar** composition of local interstellar medium - OB associations within superbubbles

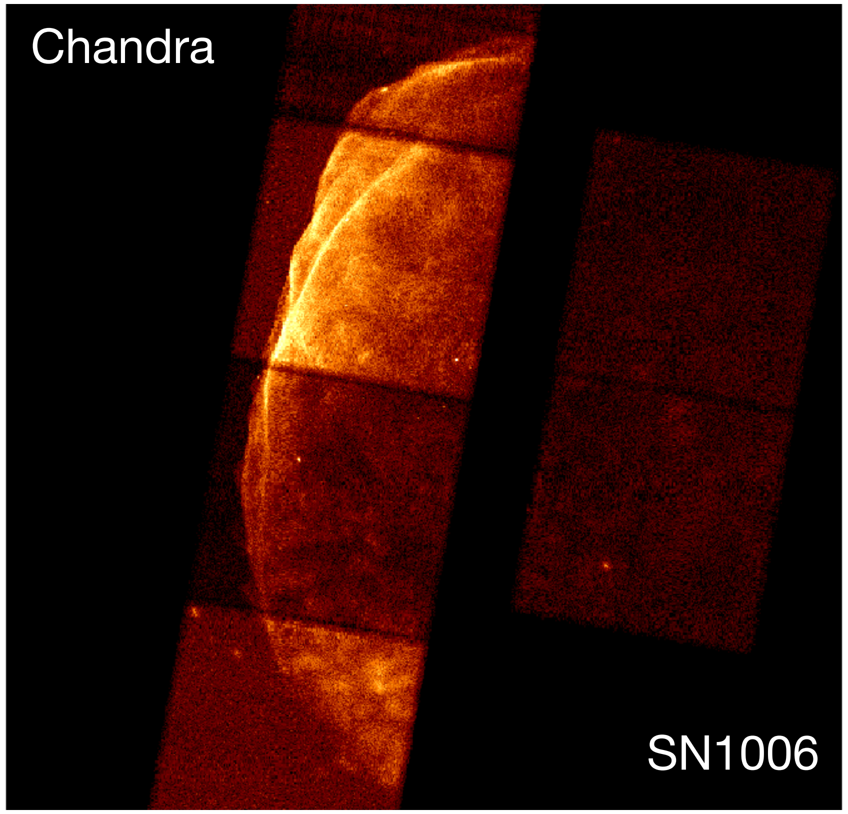
- **energy** needed to maintain galactic cosmic ray population - diffusive shock acceleration in SNR

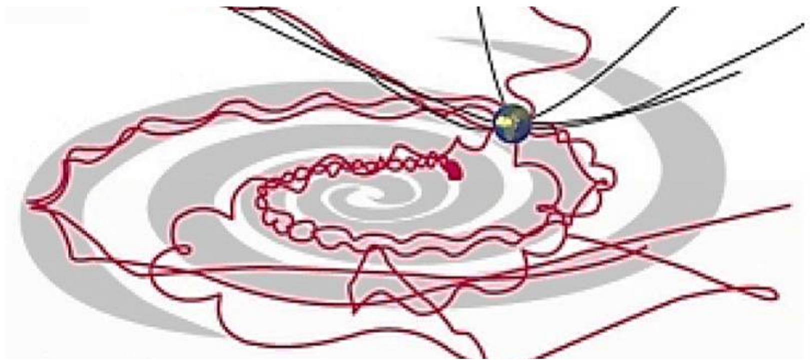
- back reaction of accelerated particles lead to non-linear magnetic field amplification & **efficient acceleration**

- **spectral concavity** @ acceleration sites

- **propagation** in interstellar medium & **escape**

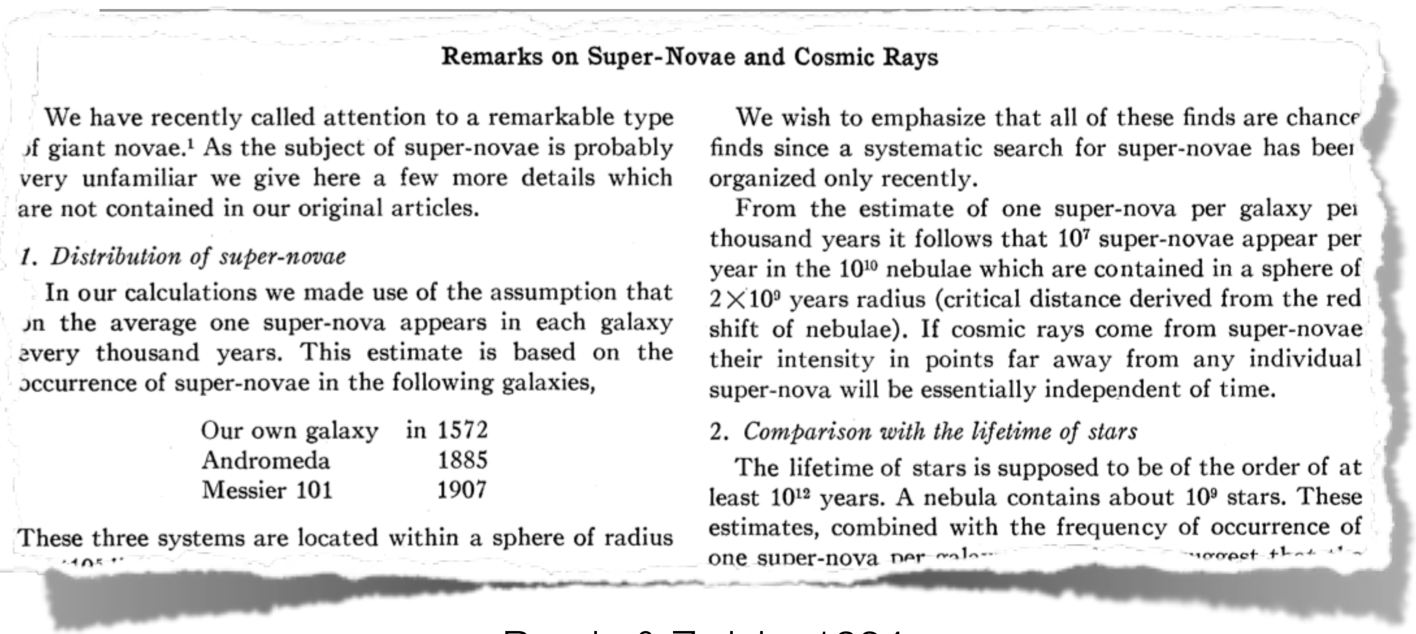






cosmic ray acceleration

in supernova remnants



Remarks on Super-Novae and Cosmic Rays

We have recently called attention to a remarkable type of giant novae.[1] As the subject of super-novae is probably very unfamiliar we give here a few more details which are not contained in our original articles.

1. Distribution of super-novae

In our calculations we made use of the assumption that on the average one super-nova appears in each galaxy every thousand years. This estimate is based on the occurrence of super-novae in the following galaxies,

Our own galaxy	in 1572
Andromeda	1885
Messier 101	1907

These three systems are located within a sphere of radius

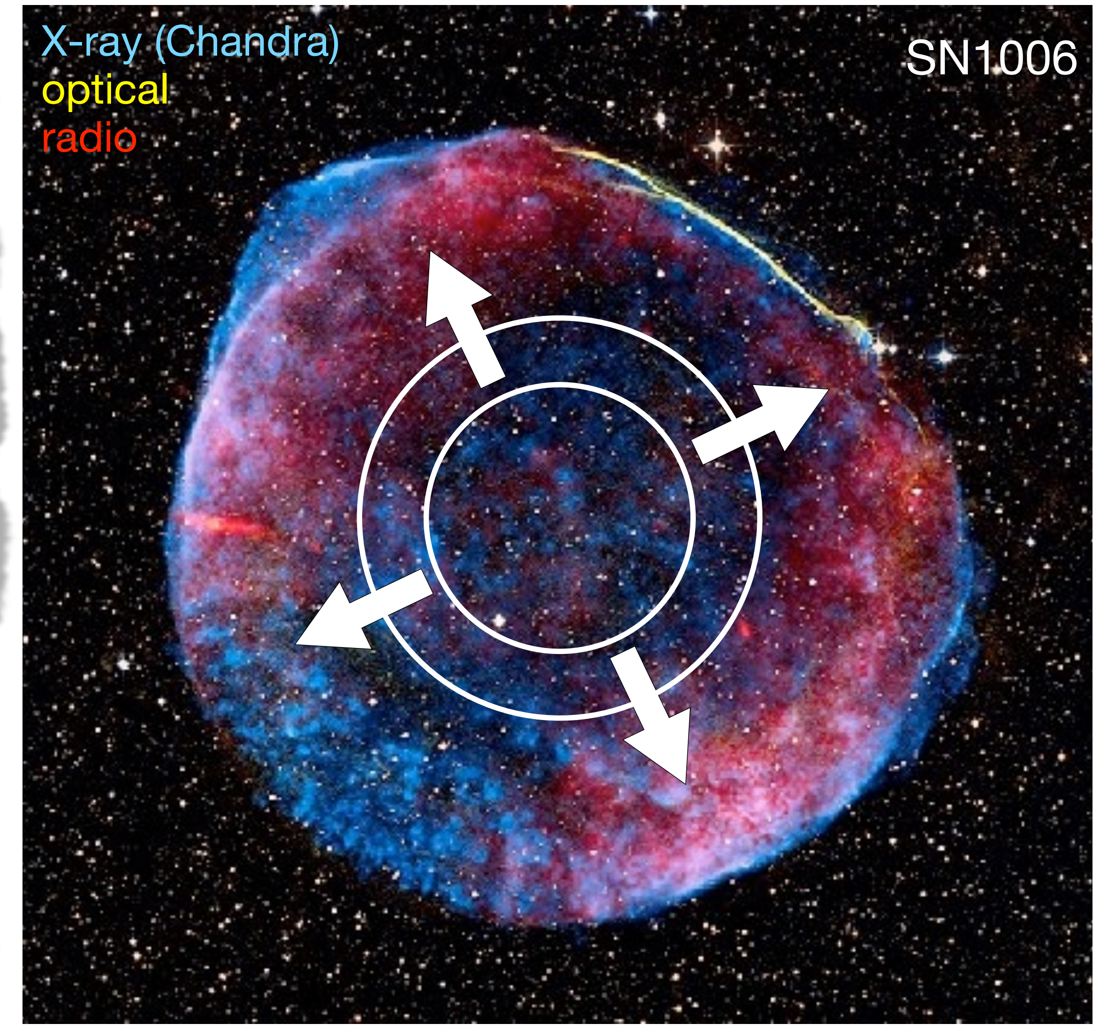
We wish to emphasize that all of these finds are chance finds since a systematic search for super-novae has been organized only recently.

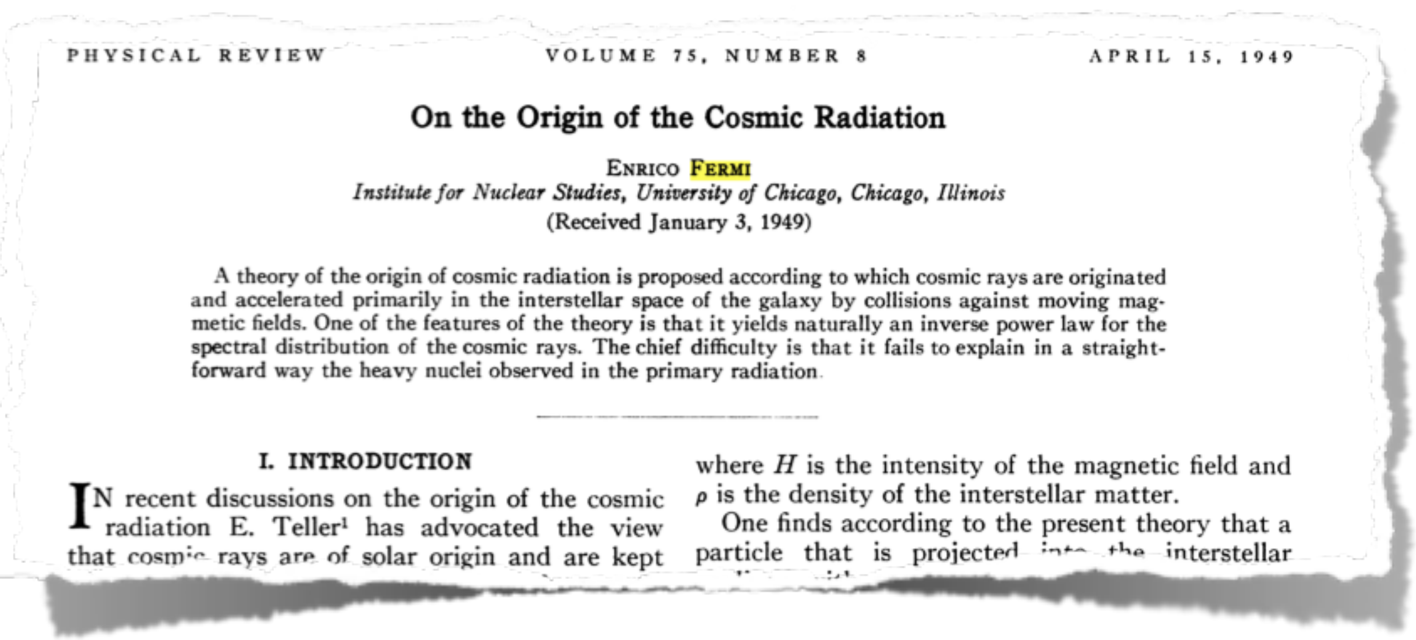
From the estimate of one super-nova per galaxy per thousand years it follows that 10^7 super-novae appear per year in the 10^{10} nebulae which are contained in a sphere of 2×10^9 years radius (critical distance derived from the red shift of nebulae). If cosmic rays come from super-novae their intensity in points far away from any individual super-nova will be essentially independent of time.

2. Comparison with the lifetime of stars

The lifetime of stars is supposed to be of the order of at least 10^{12} years. A nebula contains about 10^9 stars. These estimates, combined with the frequency of occurrence of one super-nova per galaxy

Baade & Zwicky 1934





PHYSICAL REVIEW VOLUME 75, NUMBER 8 APRIL 15, 1949

On the Origin of the Cosmic Radiation

ENRICO FERMI
Institute for Nuclear Studies, University of Chicago, Chicago, Illinois

(Received January 3, 1949)

A theory of the origin of cosmic radiation is proposed according to which cosmic rays are originated and accelerated primarily in the interstellar space of the galaxy by collisions against moving magnetic fields. One of the features of the theory is that it yields naturally an inverse power law for the spectral distribution of the cosmic rays. The chief difficulty is that it fails to explain in a straightforward way the heavy nuclei observed in the primary radiation.

I. INTRODUCTION

IN recent discussions on the origin of the cosmic radiation E. Teller[1] has advocated the view that cosmic rays are of solar origin and are kept

where H is the intensity of the magnetic field and ρ is the density of the interstellar matter.

One finds according to the present theory that a particle that is projected into the interstellar

Fermi 1949

- diffusive shock acceleration in galactic **supernova remnants**

possible origin of
cosmic ray energy

- **energy** needed to maintain galactic cosmic ray population

$$E_{GCR} \approx 10^{41}\, erg\, s^{-1} = 10^{34}\, W$$

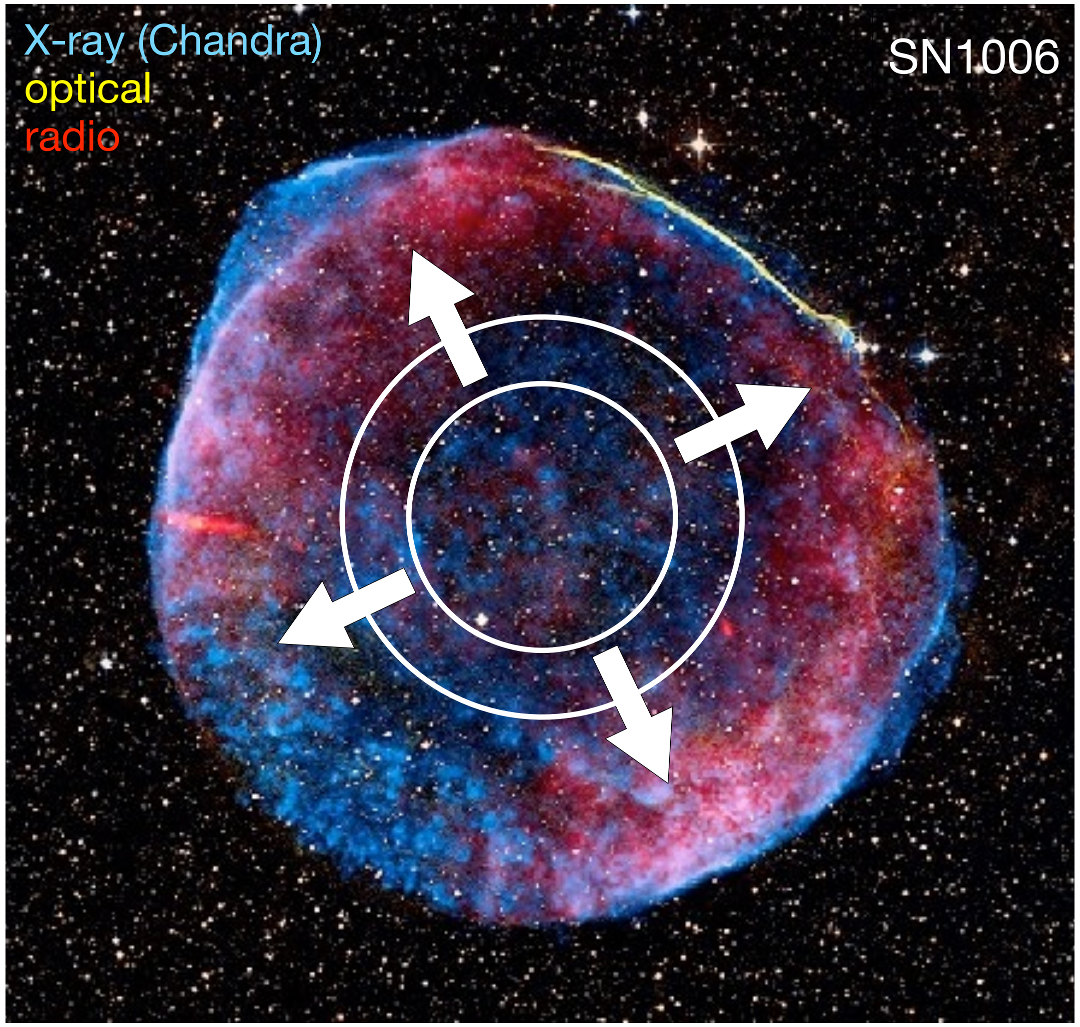
- energy released by **supernovae** that goes into particle acceleration

$$E_{SN} \approx \frac{10^{44}\, J}{30\, yr} \times 10\% \approx 10^{34}\, W$$

released mechanical energy

galactic supernova rate

energy into acceleration



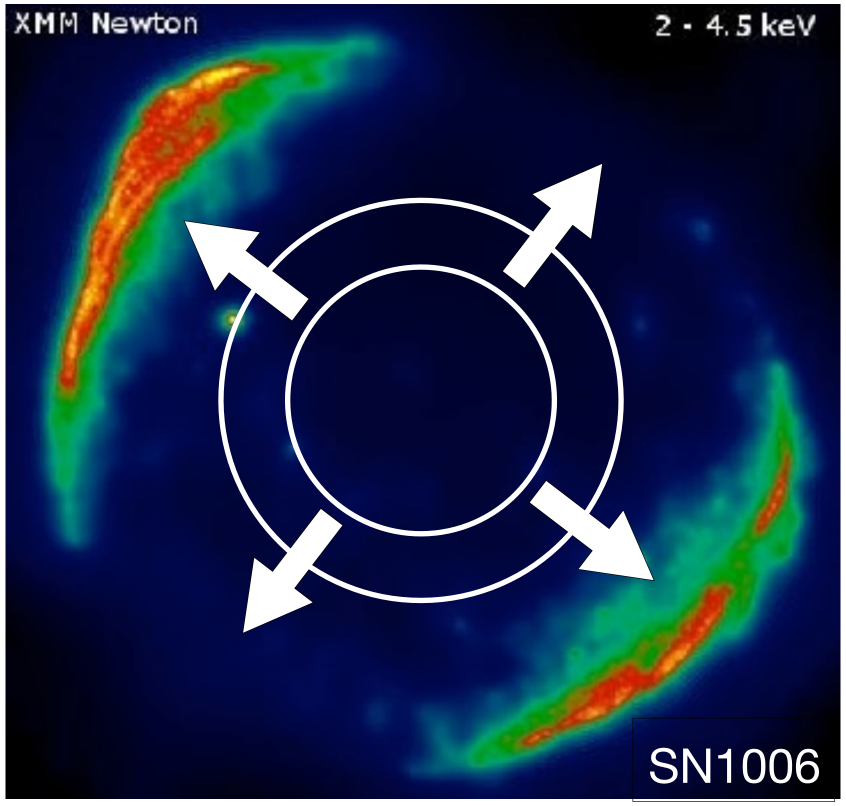
- E_{max} associated to the knee of cosmic rays at ~ 3 PeV

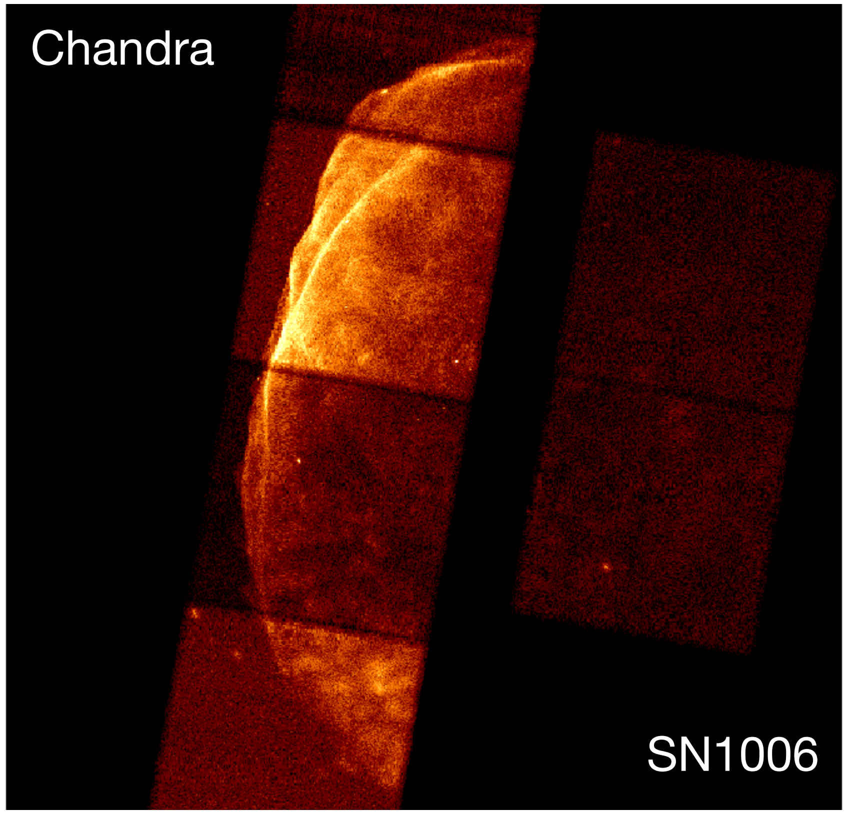
cosmic ray acceleration
in supernova remnants

- **efficient acceleration:** dynamical reaction of CR particle on SNR magnetic field
    - streaming instability induced by accelerated particles leads to **magnetic field amplification upstream**
    - in addition to magnetic field amplification by compression downstream

➡ non-linear diffusive shock acceleration

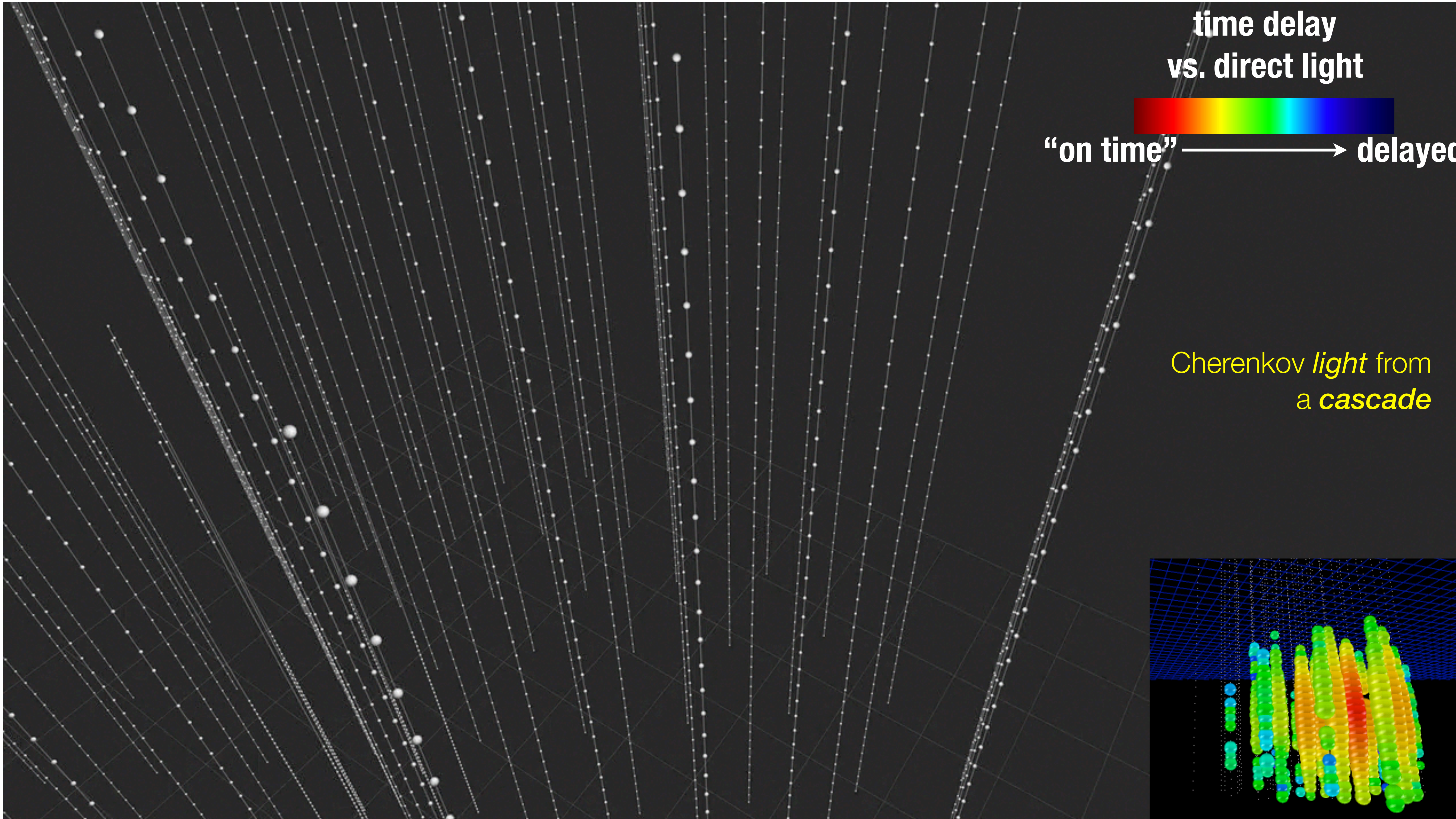
➡ predicts ∝ $\mathbf{E^{-2}}$ (or **concave spectra**)





detection principle - *cascade*

ν_e ν_τ CC-int & ν_i NC-int

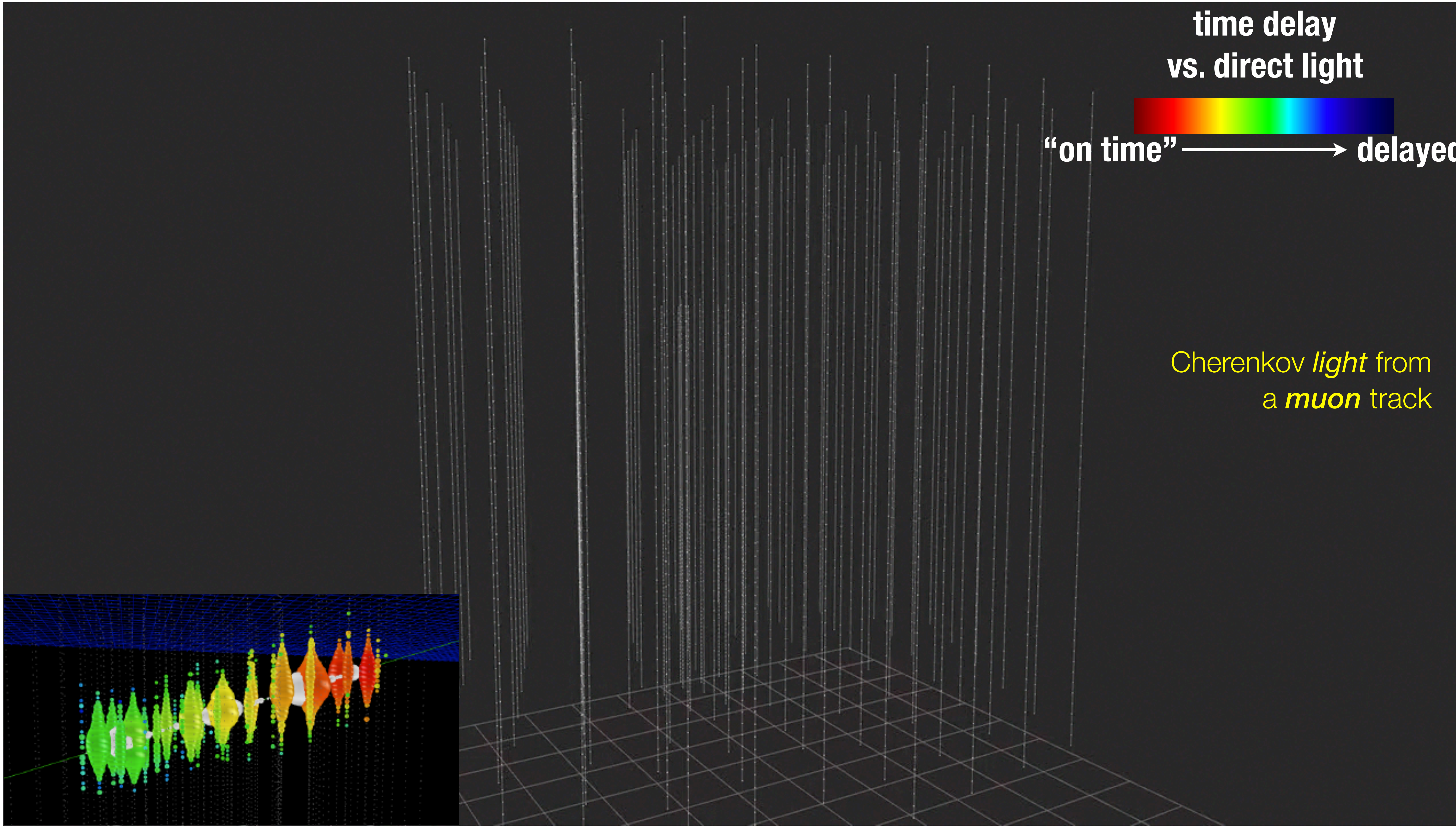


Claudio Kopper - WIPAC

≈ ±15% deposited energy resolution
≈ 10° angular resolution
(at energies ≳ 100TeV)

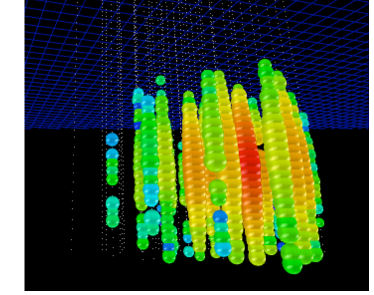
detection principle - *track*

ν_μ CC-int



Claudio Kopper - WIPAC

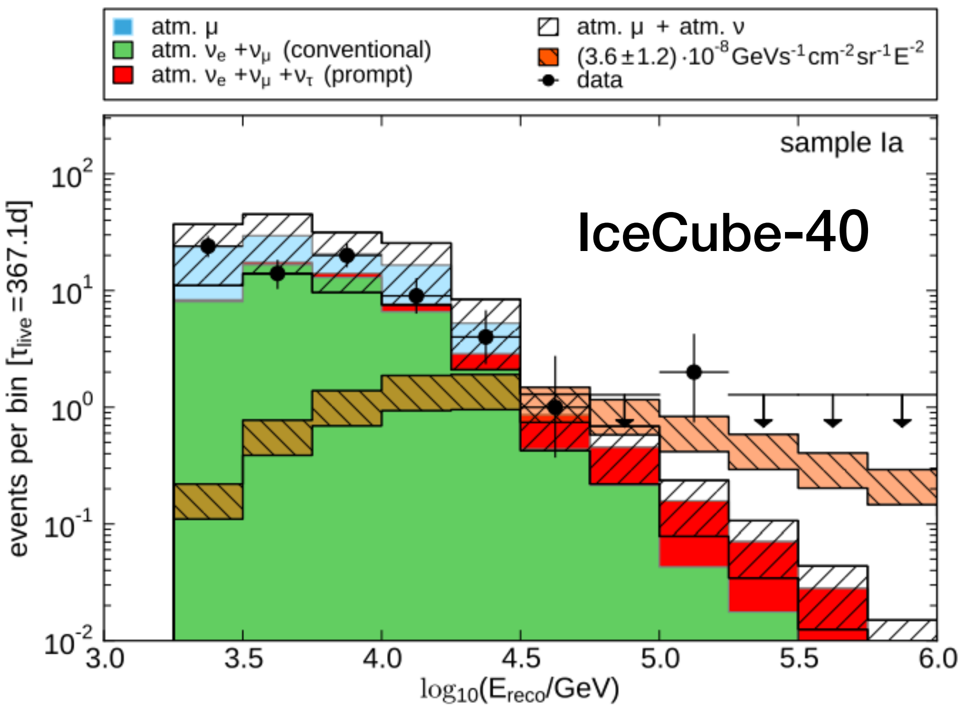
factor of ≈ 2 energy resolution
< 1° angular resolution



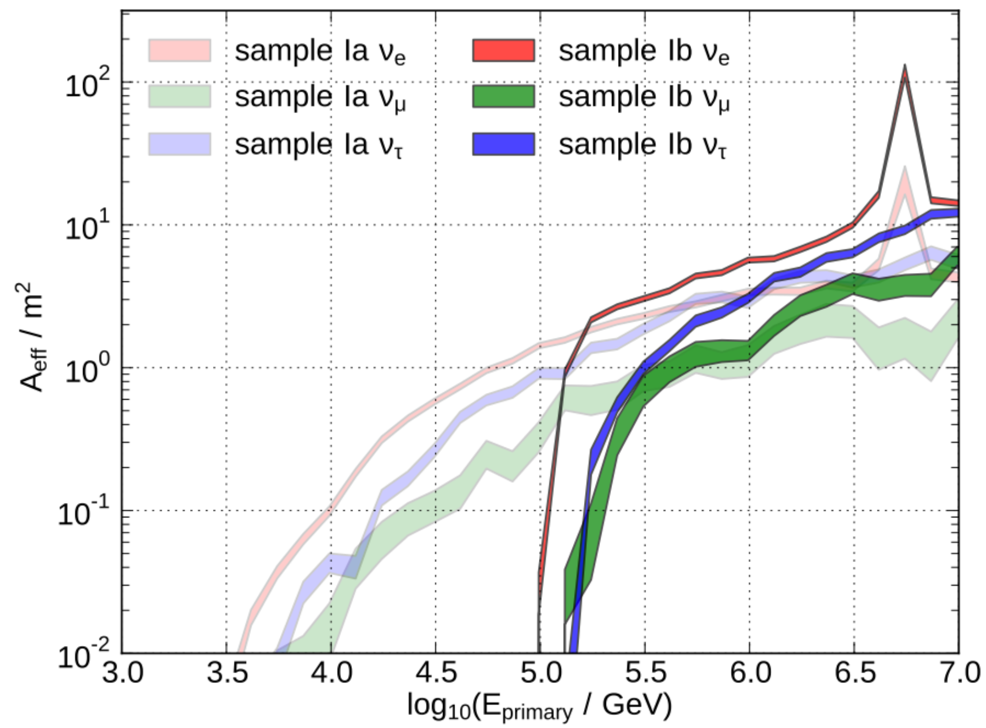
neutrino identification

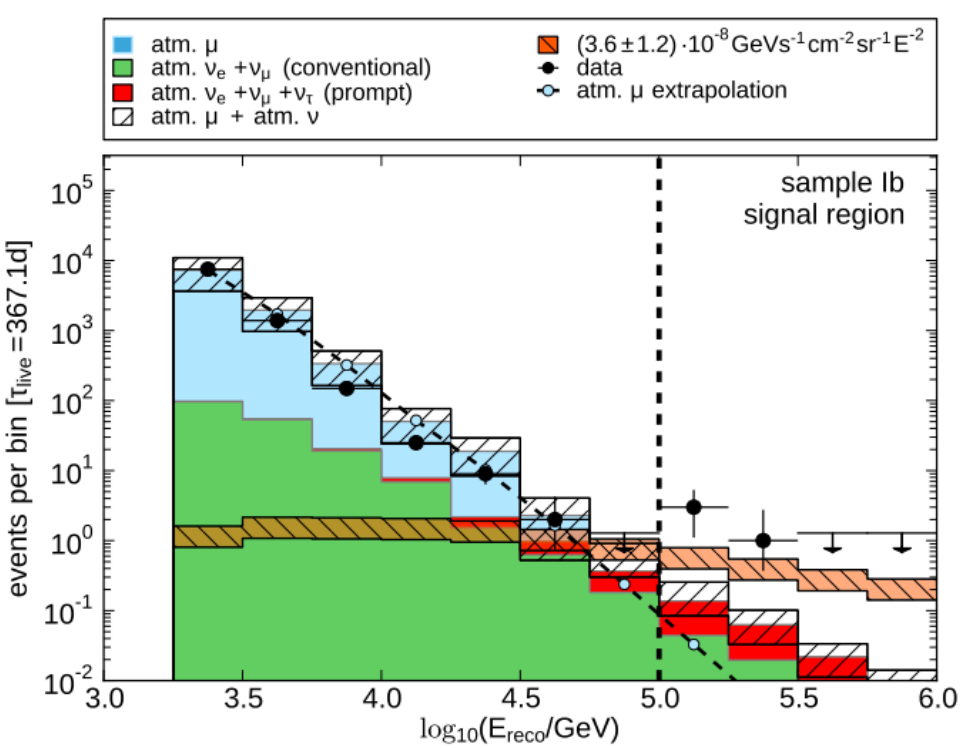
diffuse flux

Aartsen et al. Phys.Rev. D89 (2014) 10, 102001



(a) Deposited Energy in sample Ia



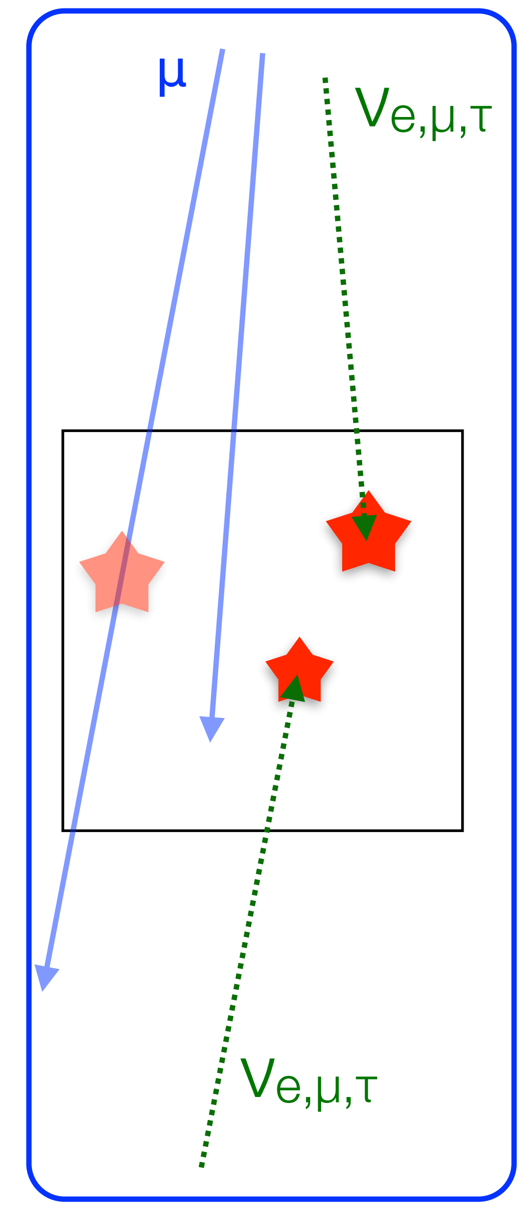


2.4 σ excess over atmospheric expectation

$$\Phi^{astro}_{90\%CL}(E) = 7.46 \times 10^{-8} \times E^{-2}\ GeV^{-1}cm^{-2}s^{-1}sr^{-1}$$

all-flavor

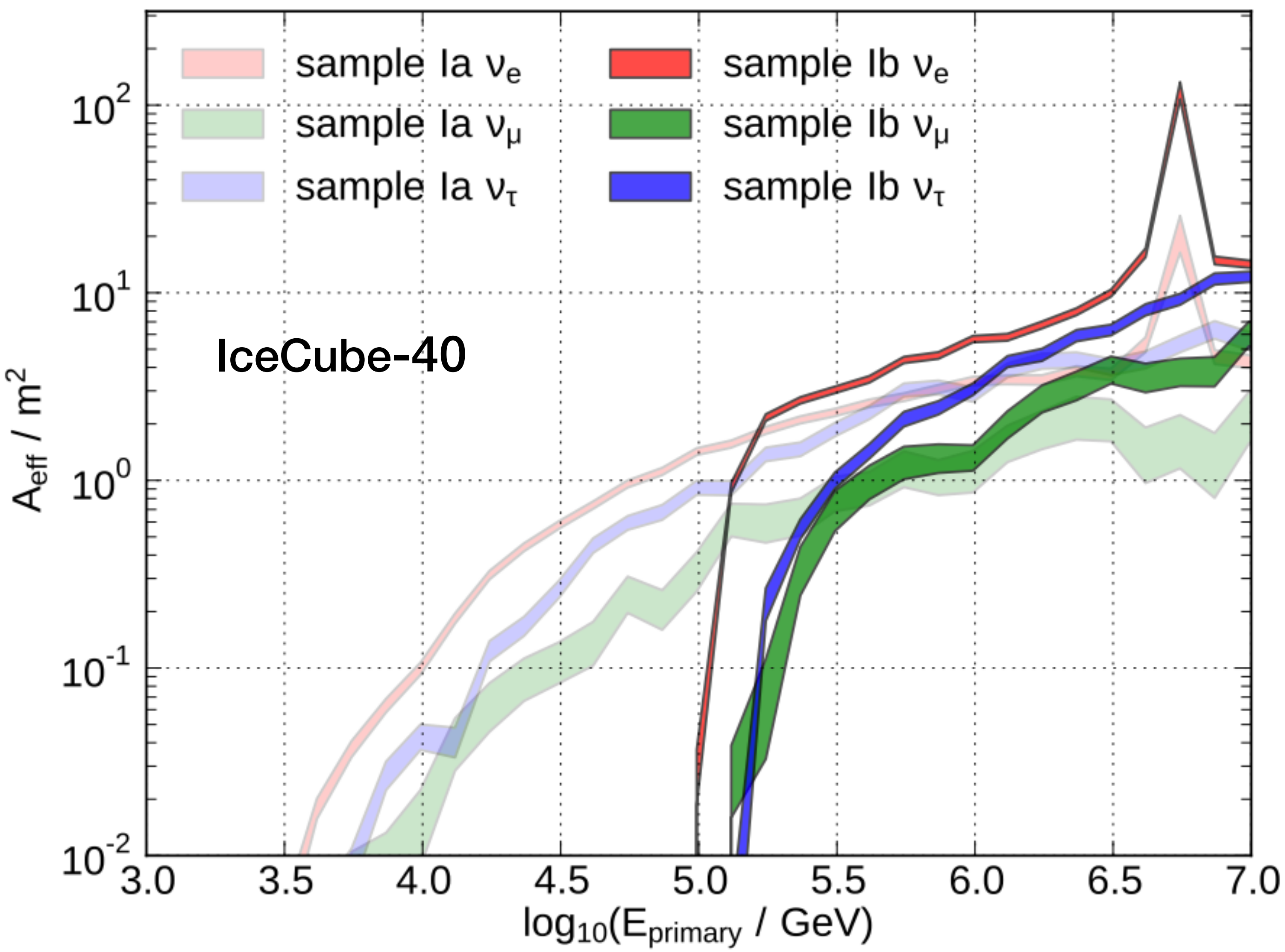
contained (cascades)



neutrino identification
diffuse flux

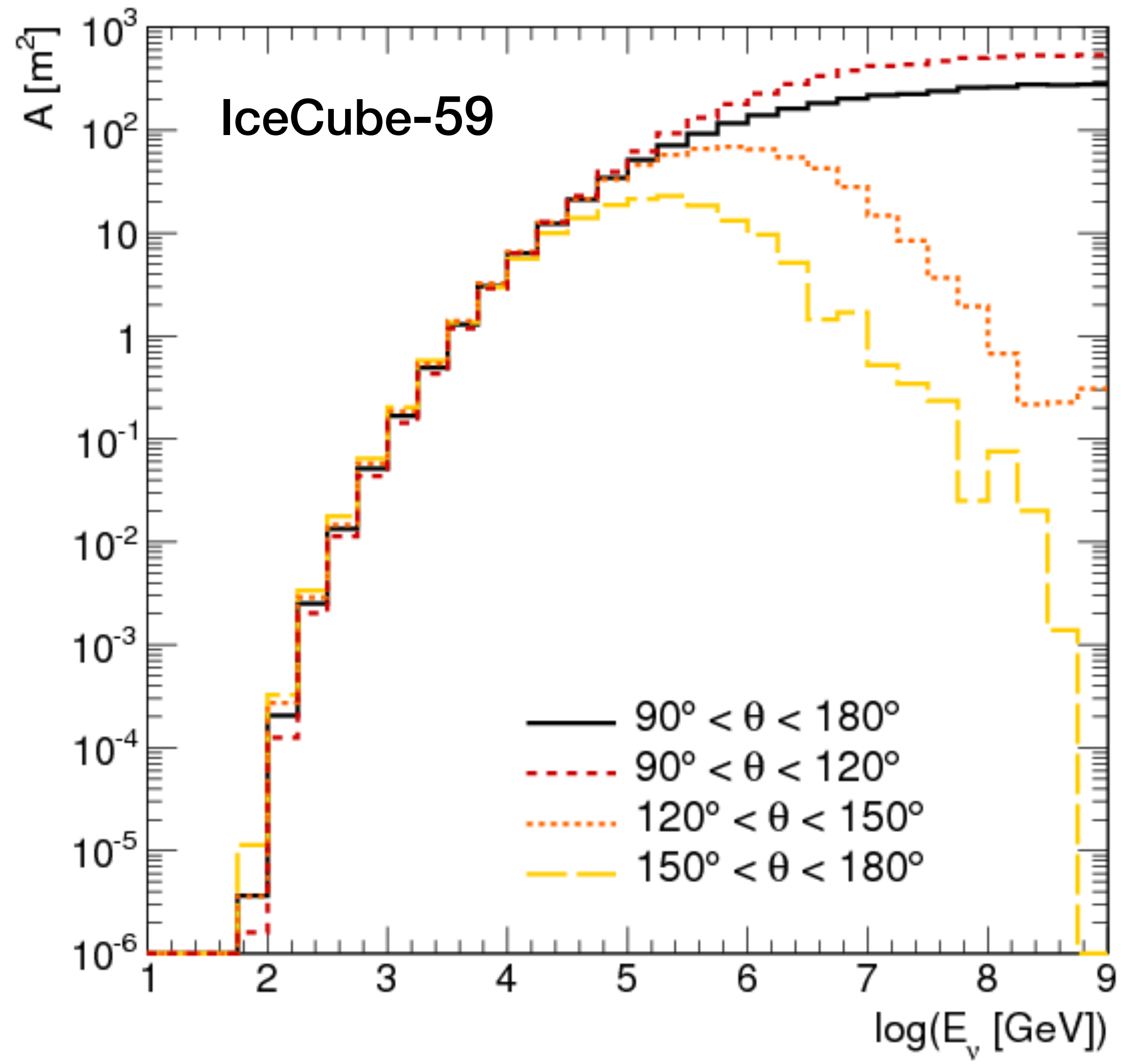
neutrino effective area

Aartsen et al. Phys.Rev. D89 (2014) 10, 102001



cascade-like events
all neutrinos NC interactions &
electron/tau neutrinos CC interactions

Aartsen et al. Phys. Rev. D 89 (2014), 062007



track-like events
muon neutrinos CC interactions

neutrino identification

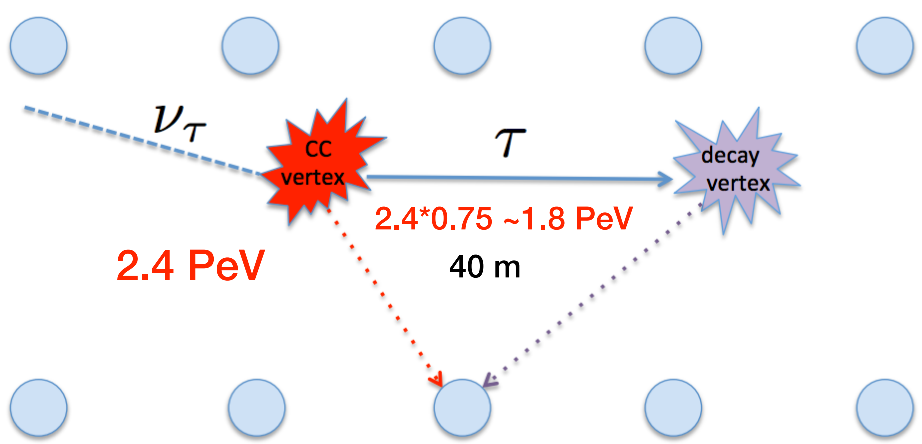
diffuse flux

tau neutrino searches

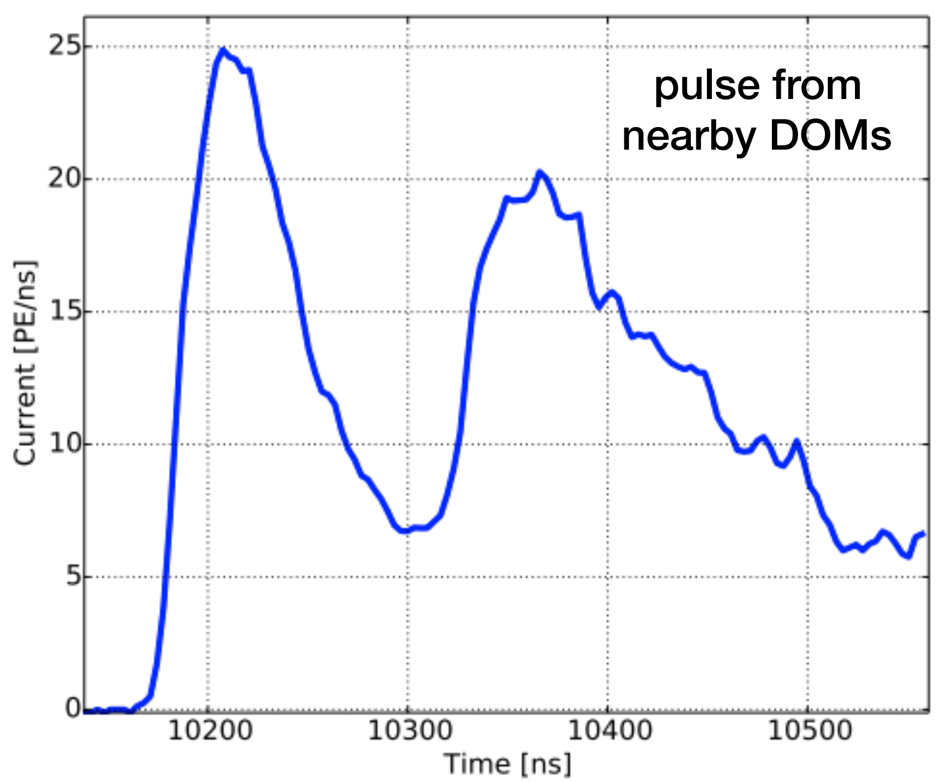
IceCube-86 × 3

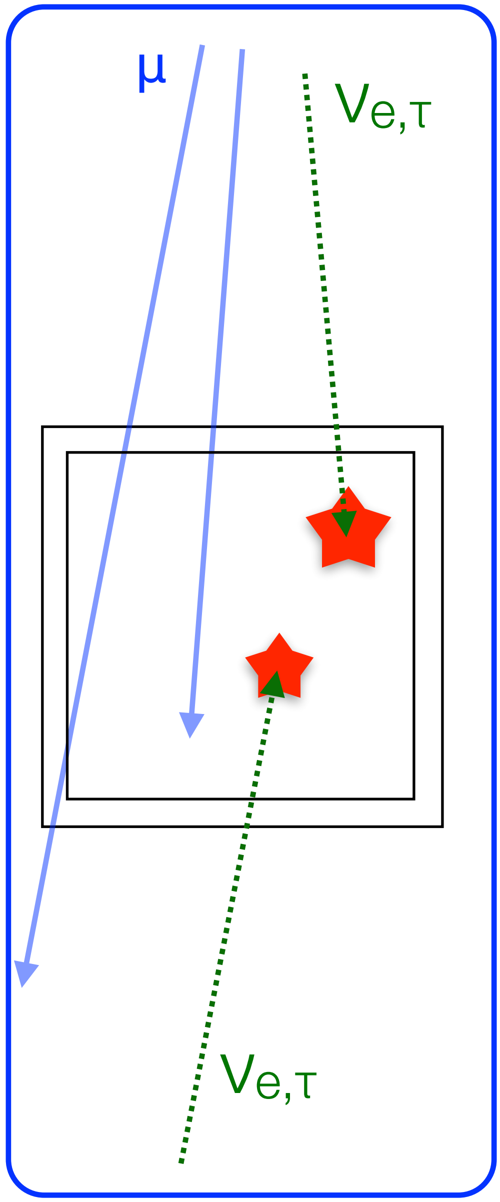
contained (cascades)

Aartsen et al. arXiv:1509.06212



close double bang events





no contained events with double pulses found in 3 years of IceCube-86 data

$$\Phi^{\nu_\tau}_{90\%CL}(E) = 5.1 \times 10^{-8} \times E^{-2}\ GeV^{-1} cm^{-2} s^{-1} sr^{-1}$$

214 TeV - 72 PeV

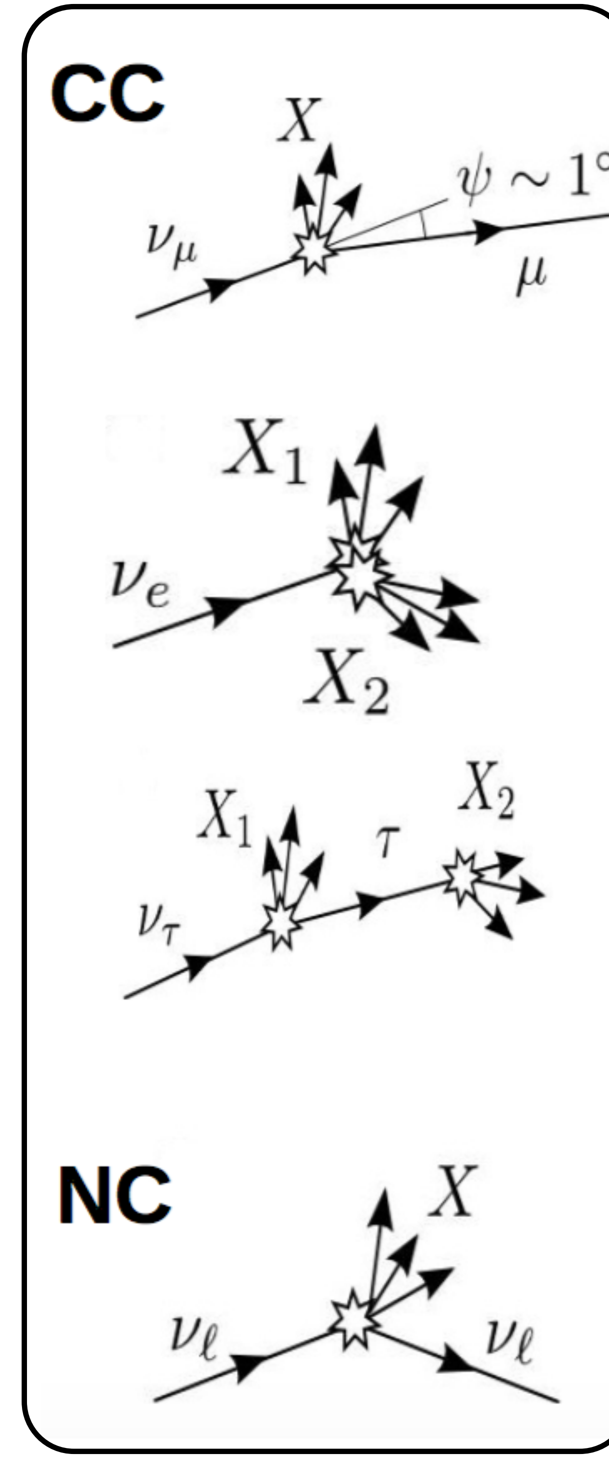
neutrino identification

flavor sensitivity

TOO FEW TRACK-LIKE EVENTS ?

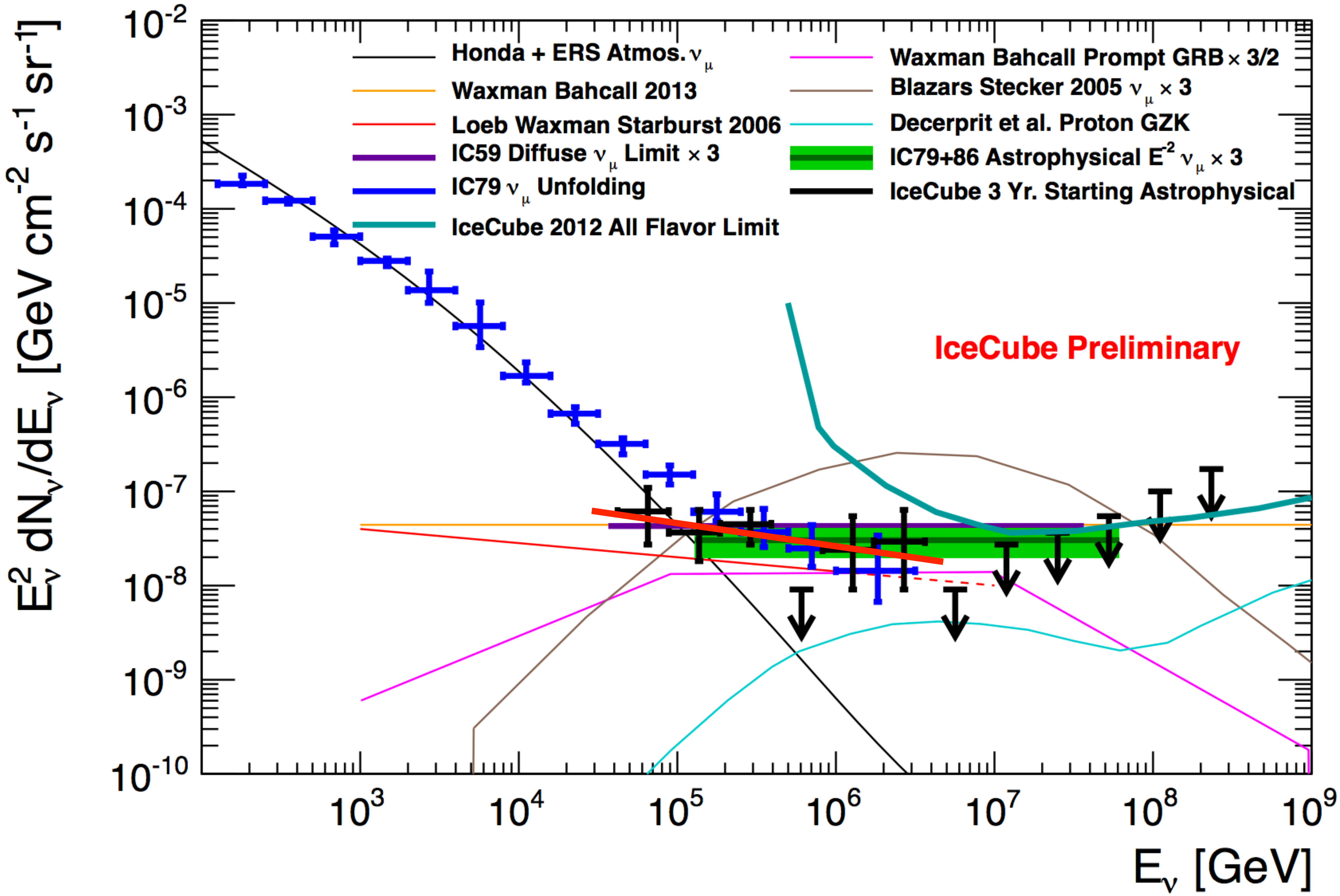
- track-like & cascade-like is an **experimental** definition
- in all-flavor searches track-like events are not common
- all flavors look alike in NC interactions
- μ in CC interactions may be concealed in showers
- τ have short tracks except above PeV energies

- flavor identification requires simulation data



high energy neutrinos

transition from atmospheric to astrophysical

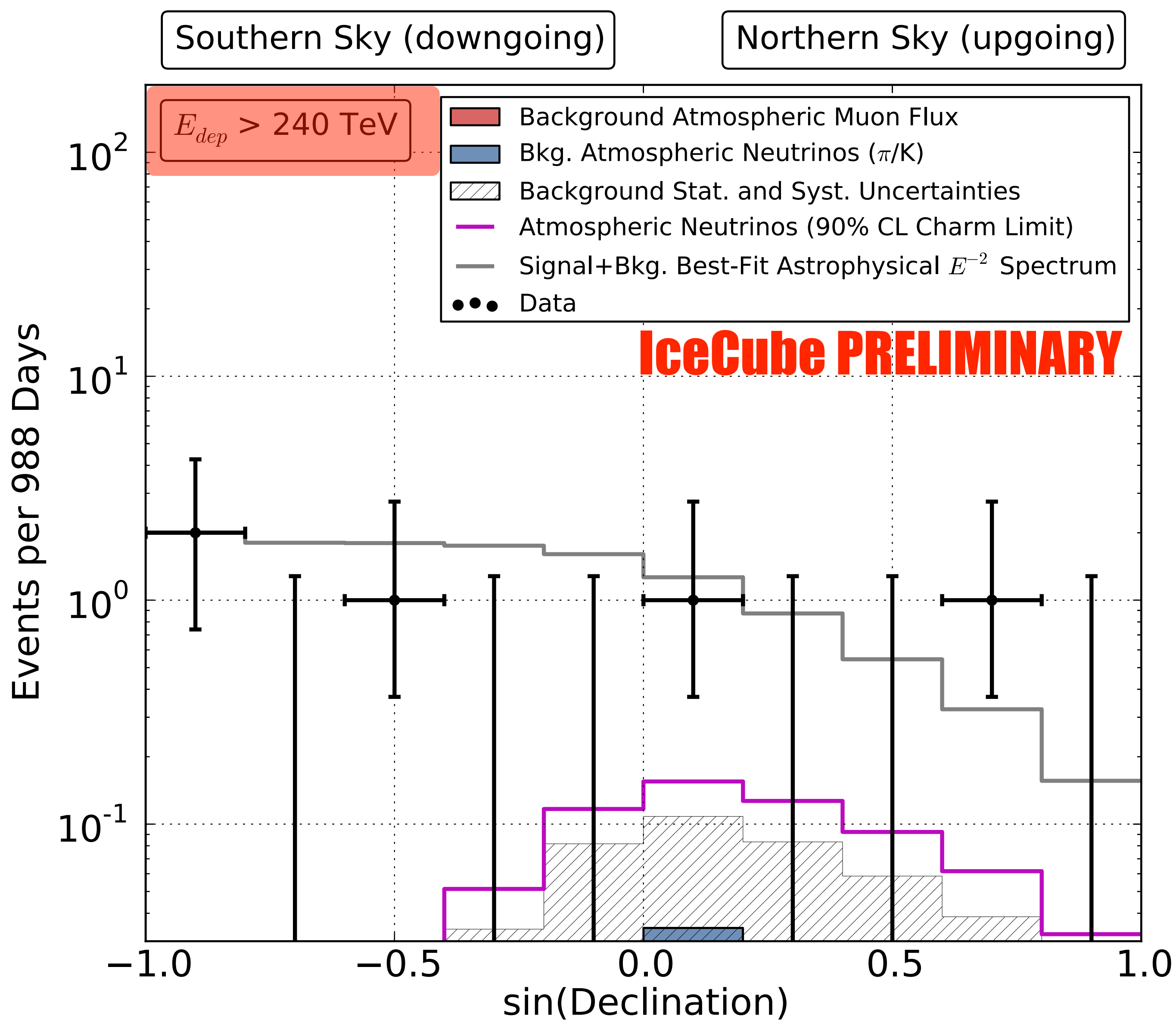


Paolo Desiati

high energy "*starting*" events
angular distribution

Aartsen et al. Science 342 (2013) 1242856

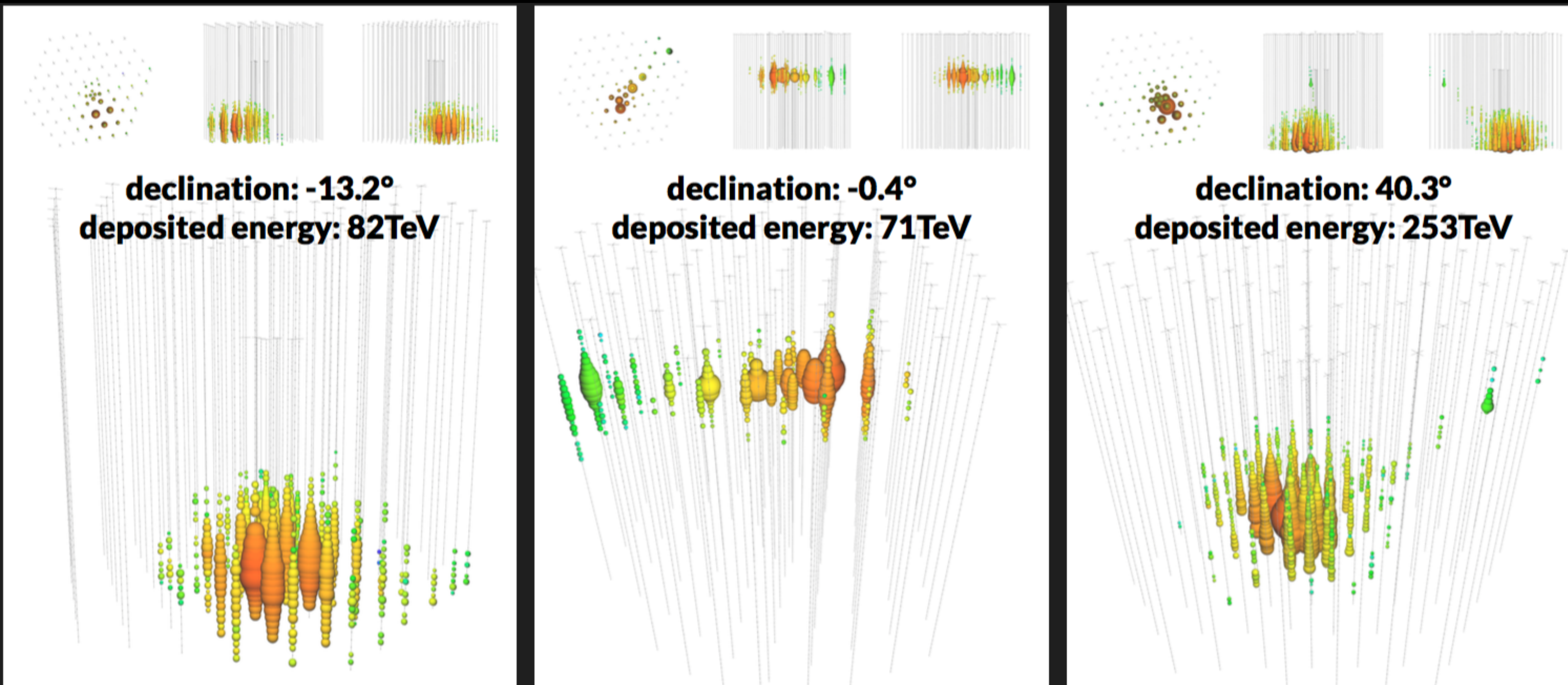
- compatible with isotropic flux
- Earth absorption from Northern Hemisphere
- excess from south (self-veto)
- **charm production @north**
  - forward physics with IceCube



south north

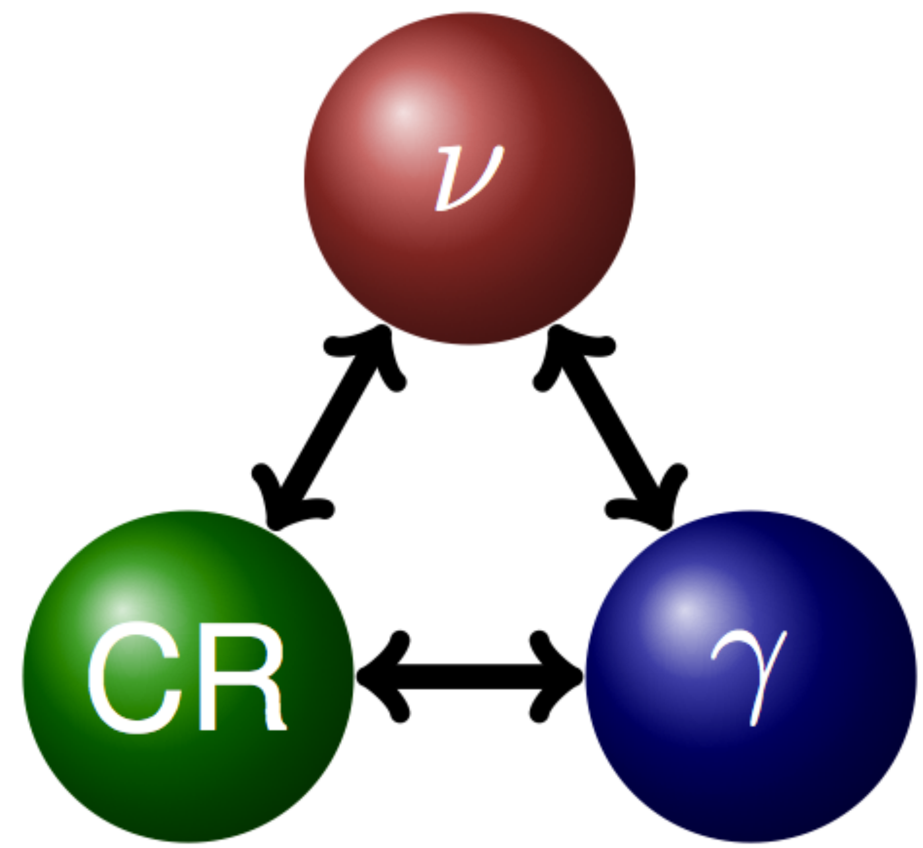
neutrino identification

astrophysical neutrinos

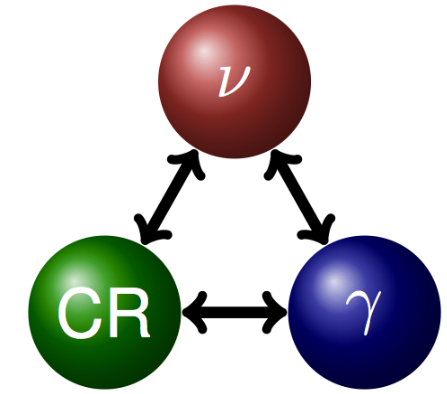


origin of high energy neutrinos ?

- Glashow resonance ?
- galactic or extragalactic ?
- isotropic or point sources ?
- cosmic ray composition ?
- pp or pγ origin ?
- **1 PeV neutrinos** ~ **20 TeV CR nucleon** ~ **2 PeV γ-rays**



origin of high energy neutrinos ?



1 PeV neutrinos ~ **20 TeV CR nucleon** ~ **2 PeV γ-rays**

- **extragalactic sources:**
  - relation to the sources of UHE CRs [Kistler, Stanev & Yuksel 1301.1703]
  - GZK from low $E_{\max}$ blazars [Kalashev, Kusenko & Essey 1303.0300]
  - cores of active galactic nuclei (AGN) [Stecker *et al.*'91;Stecker 1305.7404]
  - low-power γ-ray bursts (GRB) [Murase & Ioka 1306.2274]
  - starburst galaxies [Loeb&Waxman'06; He *et al.* 1303.1253; Murase, MA & Lacki 1306.3417]
  - hypernova in star-forming galaxies [Liu *et al.* 1310.1263]
  - galaxy clusters/groups [Berezinksy, Blasi & Ptuskin'97; Murase, MA & Lacki 1306.3417]
- **Galactic sources:**
  - heavy dark matter decay [Feldstein *et al.* 1303.7320; Esmaili & Serpico 1308.1105]
  - peculiar hypernovae [Fox, Kashiyama & Meszaros 1305.6606; MA & Murase 1309.4077]
  - diffuse Galactic γ-ray emission [*e.g.* Ingelman & Thunman'96; MA & Murase 1309.4077]
- **γ-ray association:**
  - unidentified Galactic TeV γ-ray sources [Fox, Kashiyama & Meszaros 1306.6606]
  - sub-TeV diffuse Galactic γ-ray emission [Neronov, Semikoz & Tchernin 1307.2158]

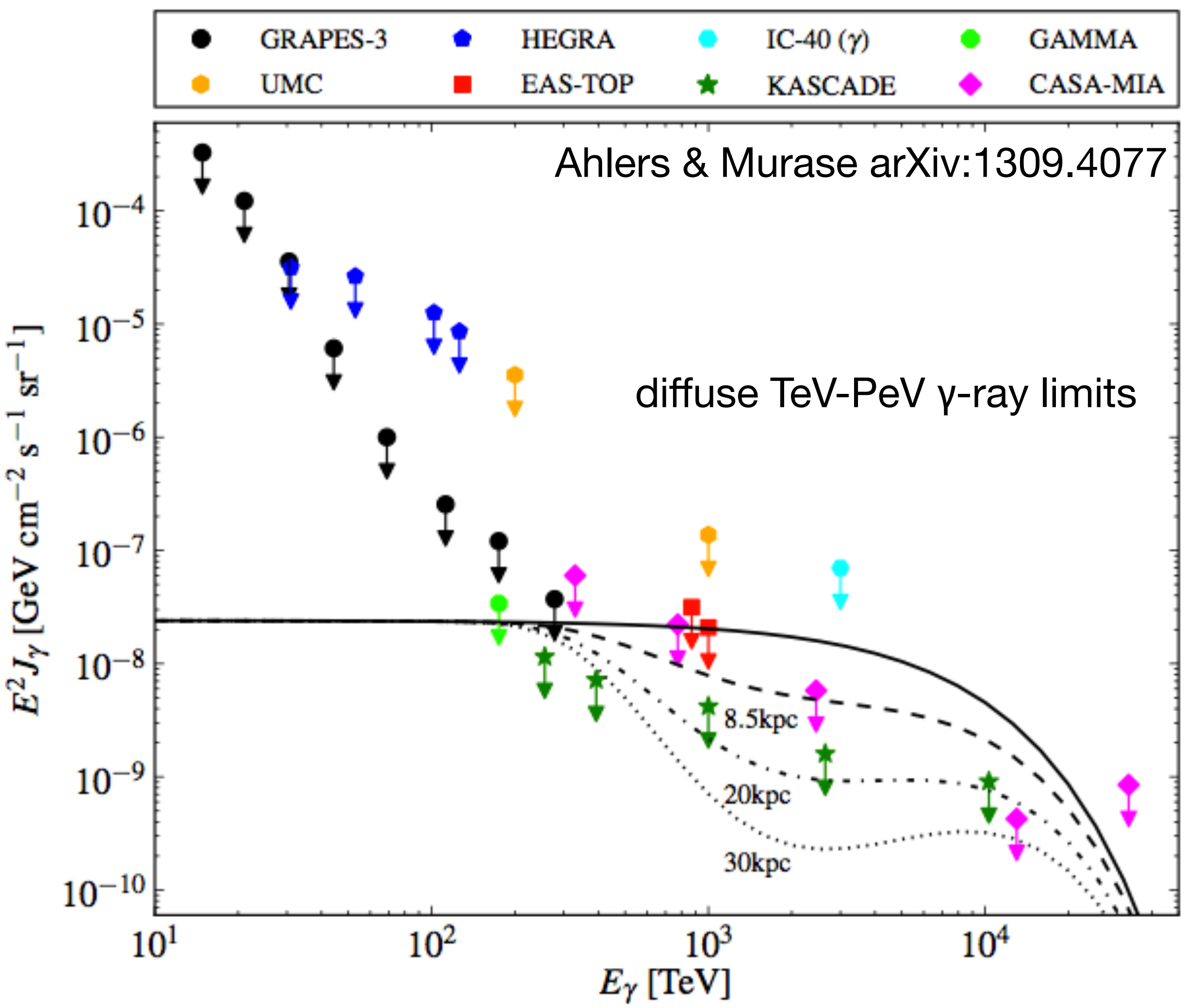
M Ahlers

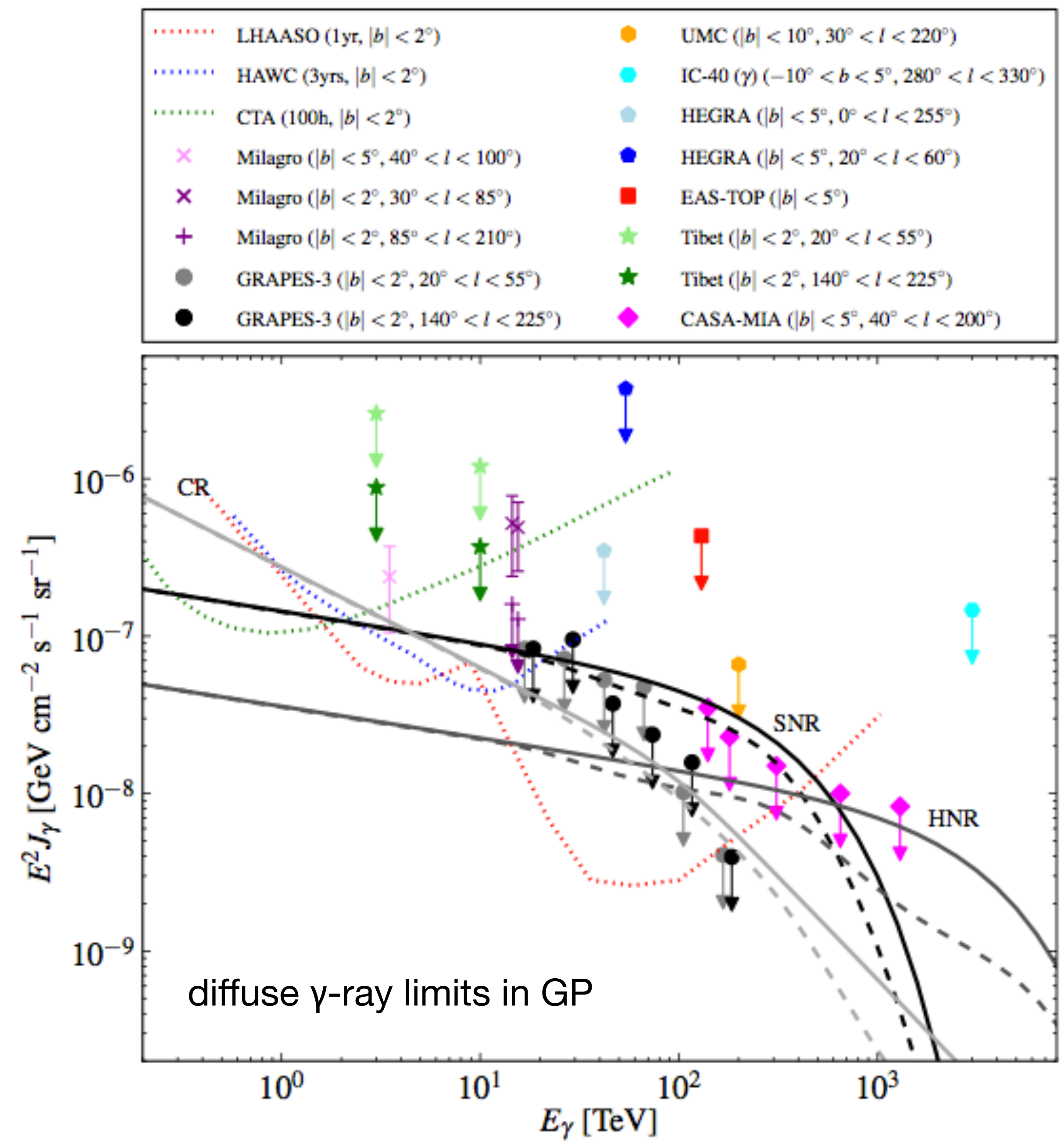
origin of high energy neutrinos ?

IceCube Coll. PRD 87, 062002, 2013

- strong **constraints** of galactic isotropic emission of γ-rays

- **disfavor** contribution from SNR & HyperNovae





cosmic rays
propagation effects

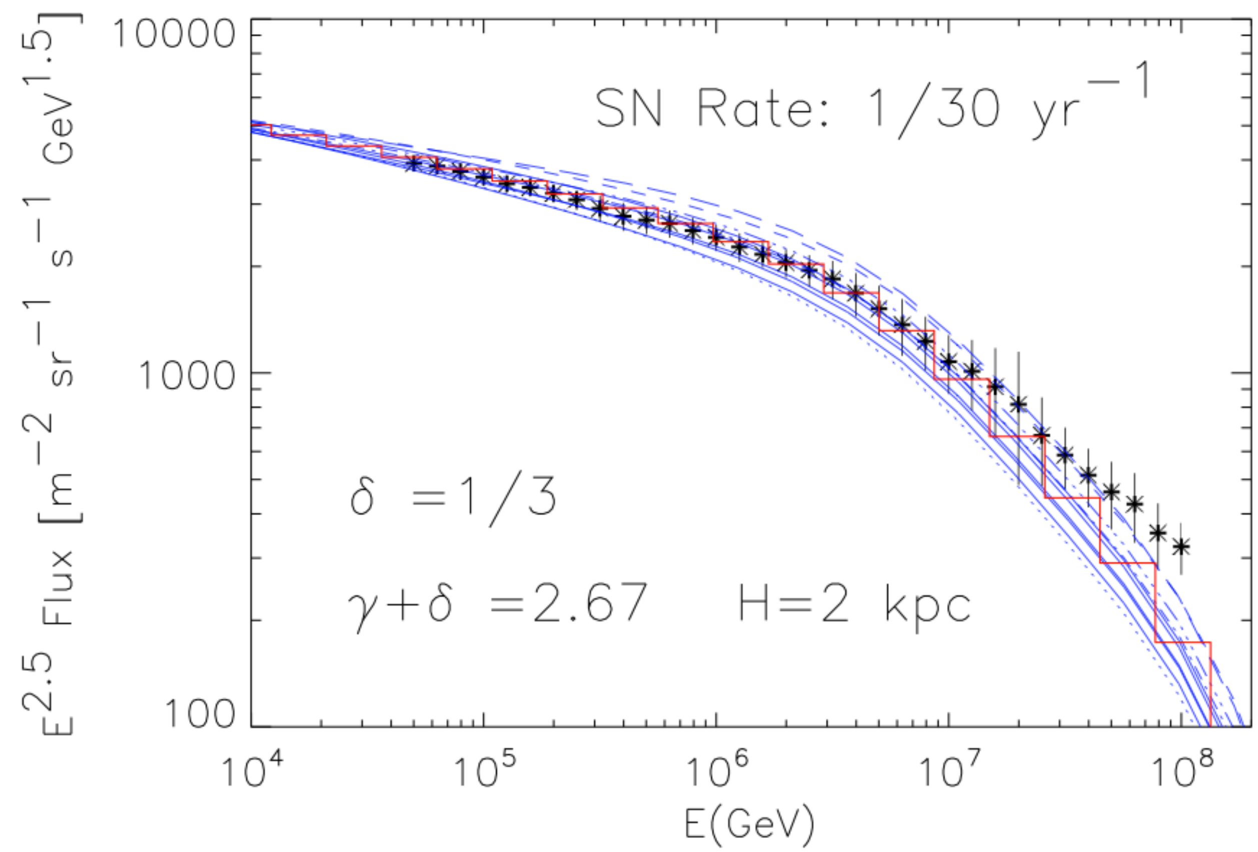
- cosmic ray spectrum affected by **propagation**
- escape faster with energy: **diffusion** coefficient

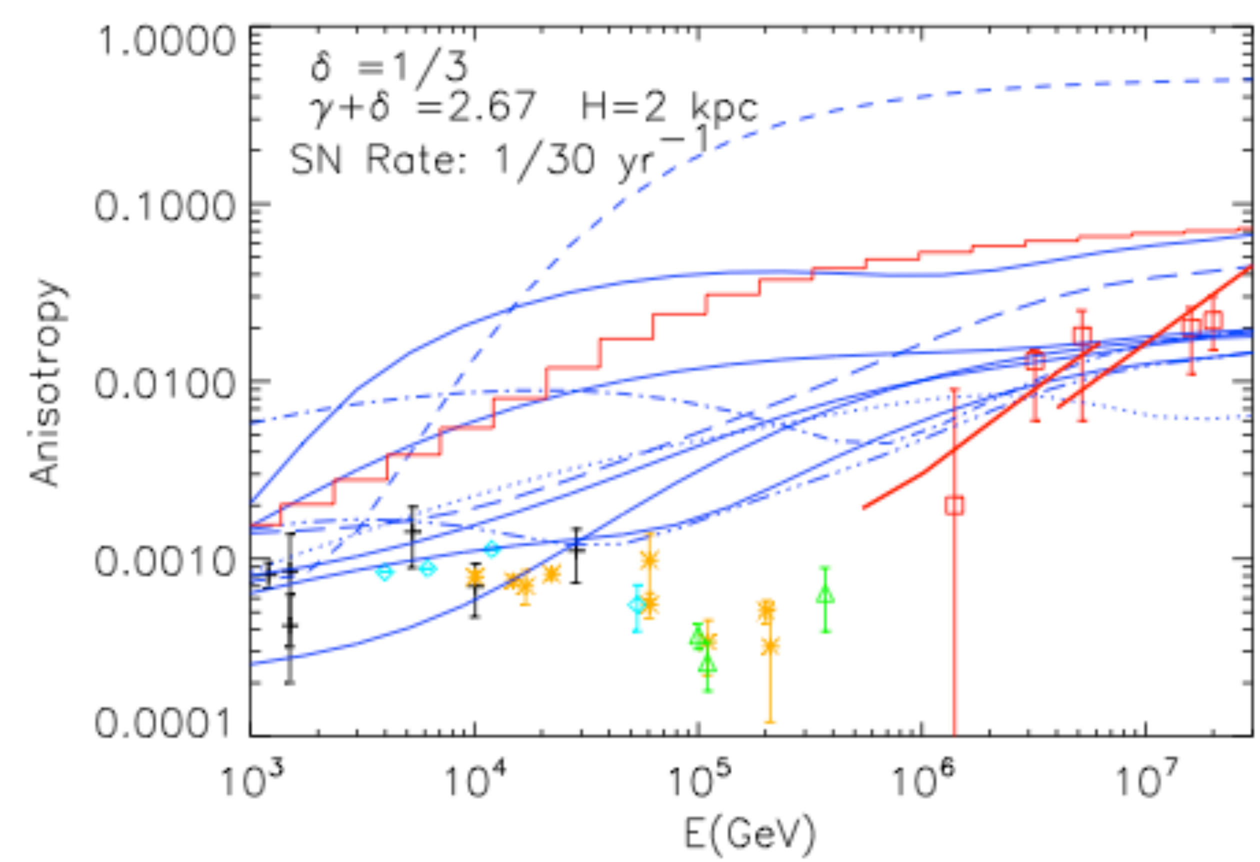
$$\frac{dN_{CR}}{dE} \approx E^{-\gamma_{inj}-\delta} \qquad D(E) \propto E^{\delta} \qquad \delta \sim 0.3 - 0.6$$

- stochastic effects from individual sources
- spectral features & anisotropy

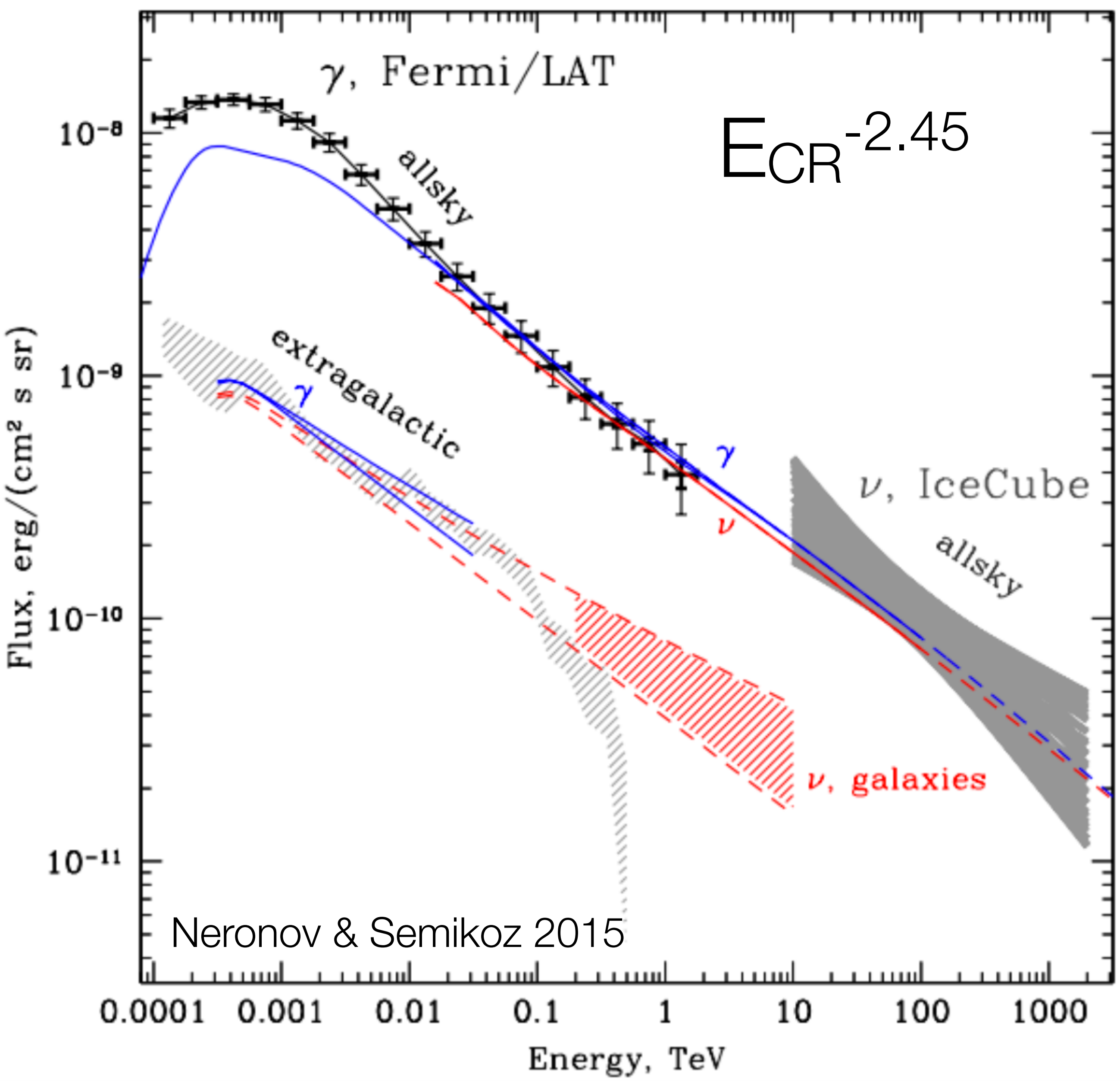
➡ simple diffusion model not sufficient

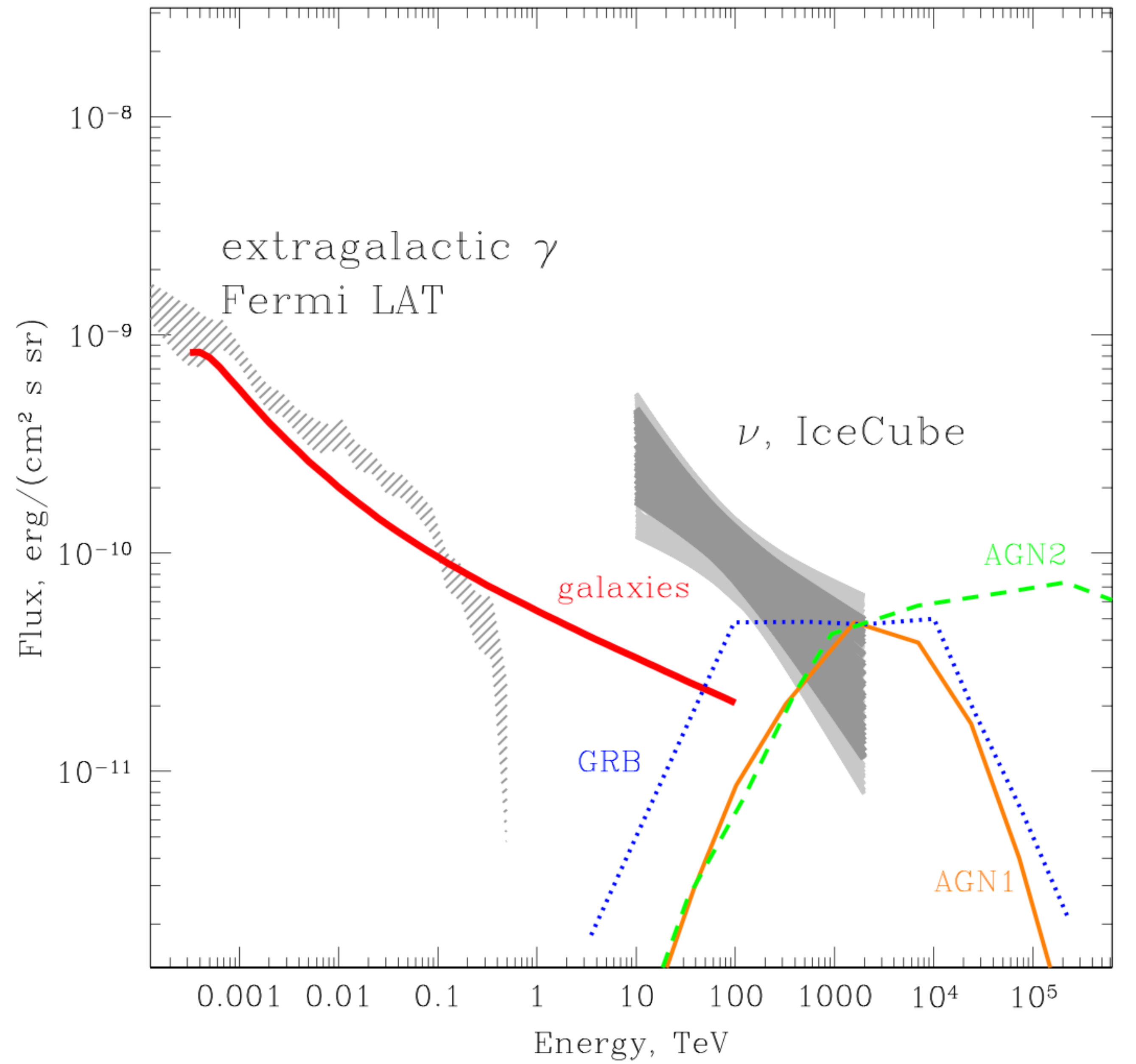
➡ non-diffusive processes within mean free path





astrophysical neutrinos
galactic origin

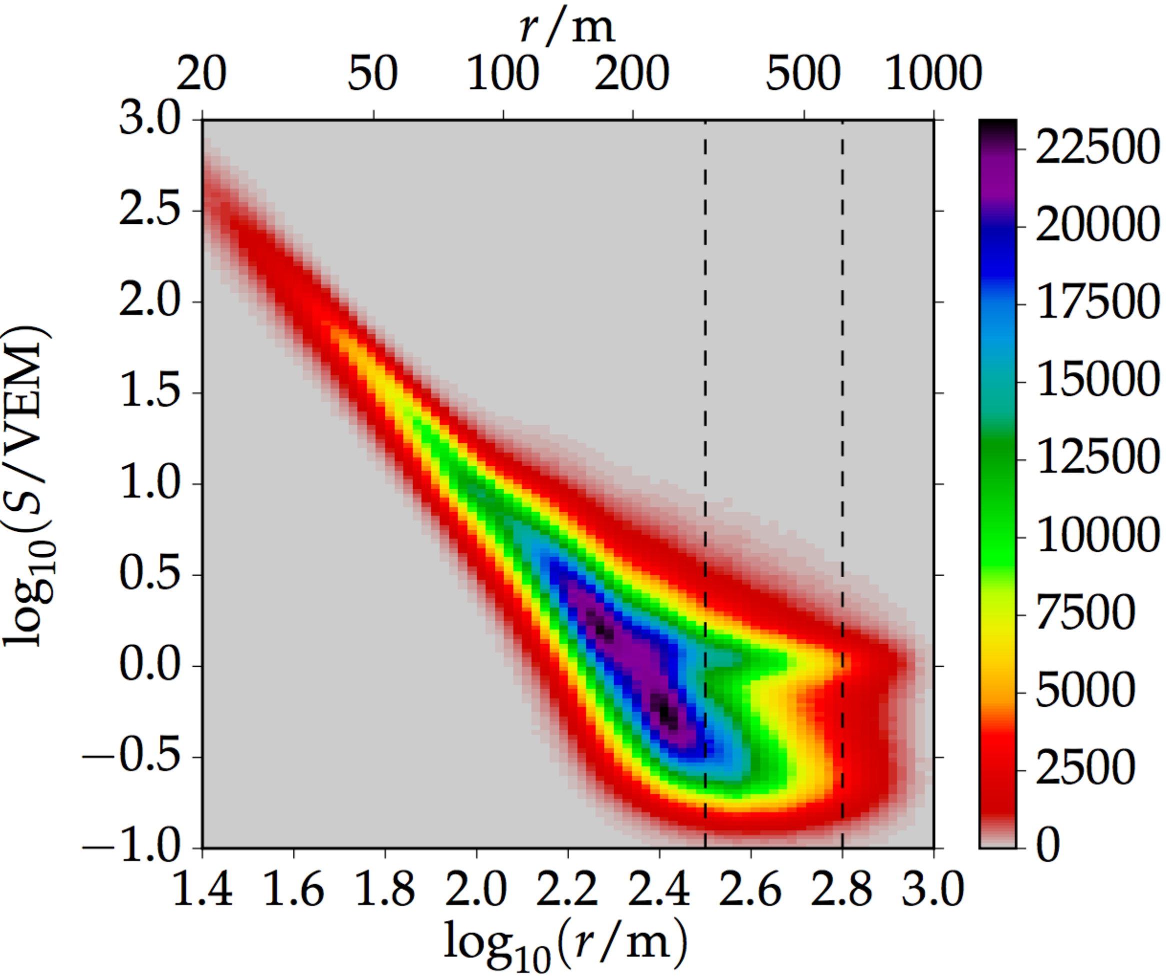




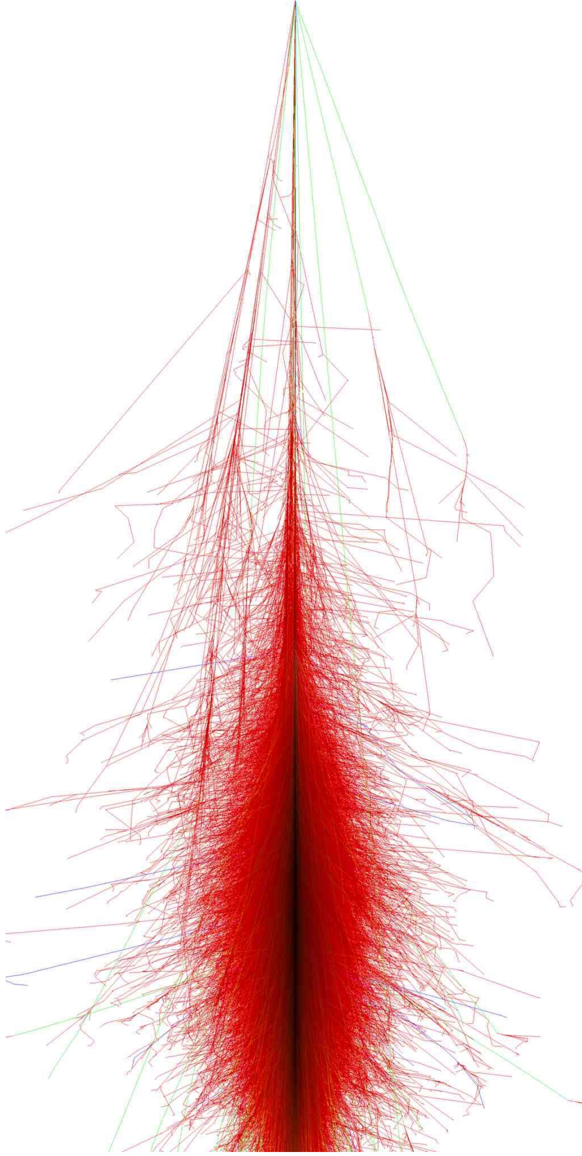
galactic cosmic rays with cut-off of 10 PeV ?

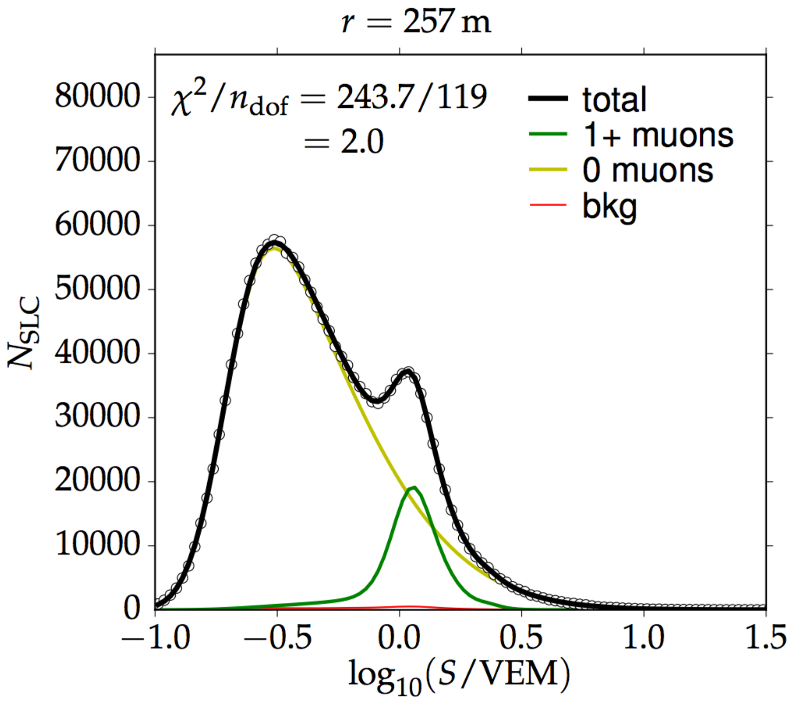
cosmic ray muons

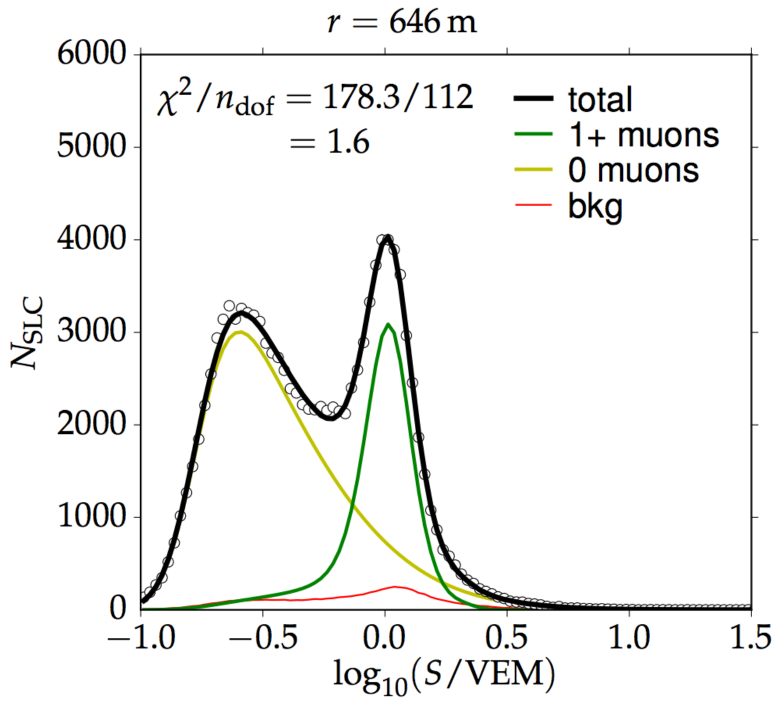
low energy muons in CR showers



muons at the **edge** of atmospheric showers



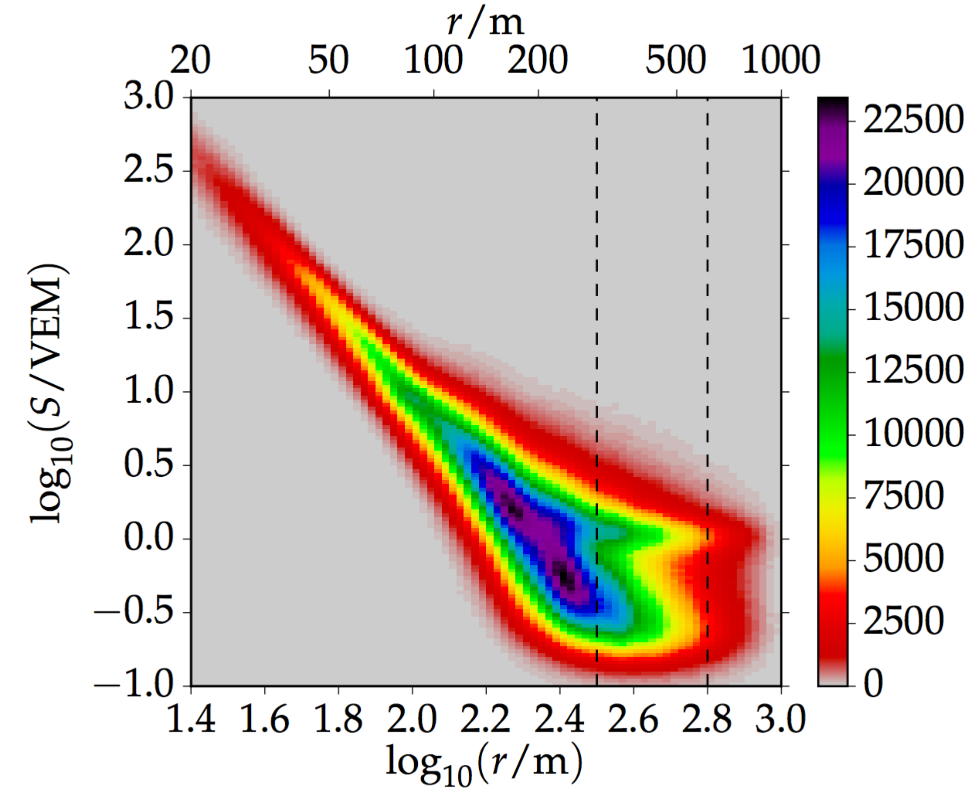


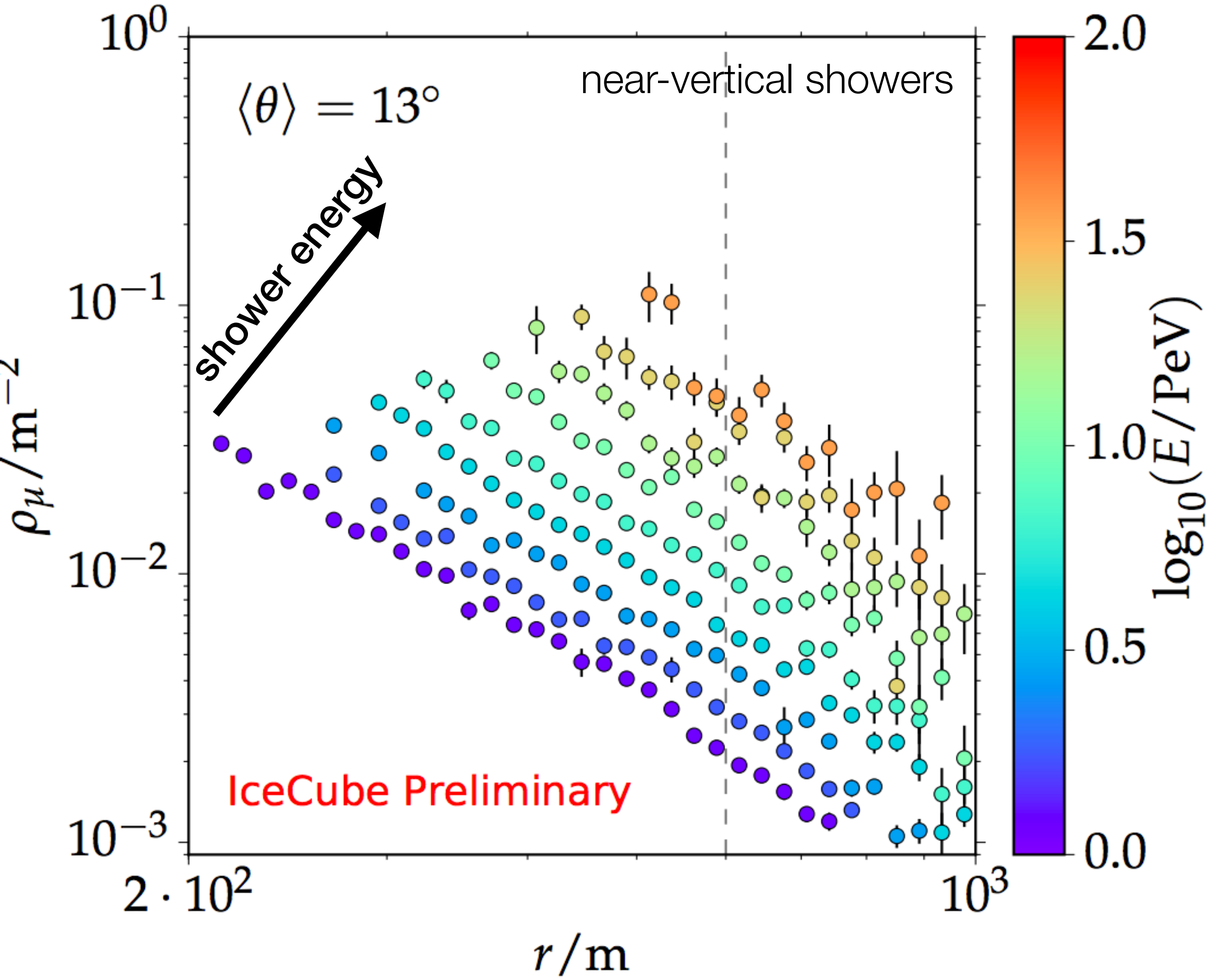


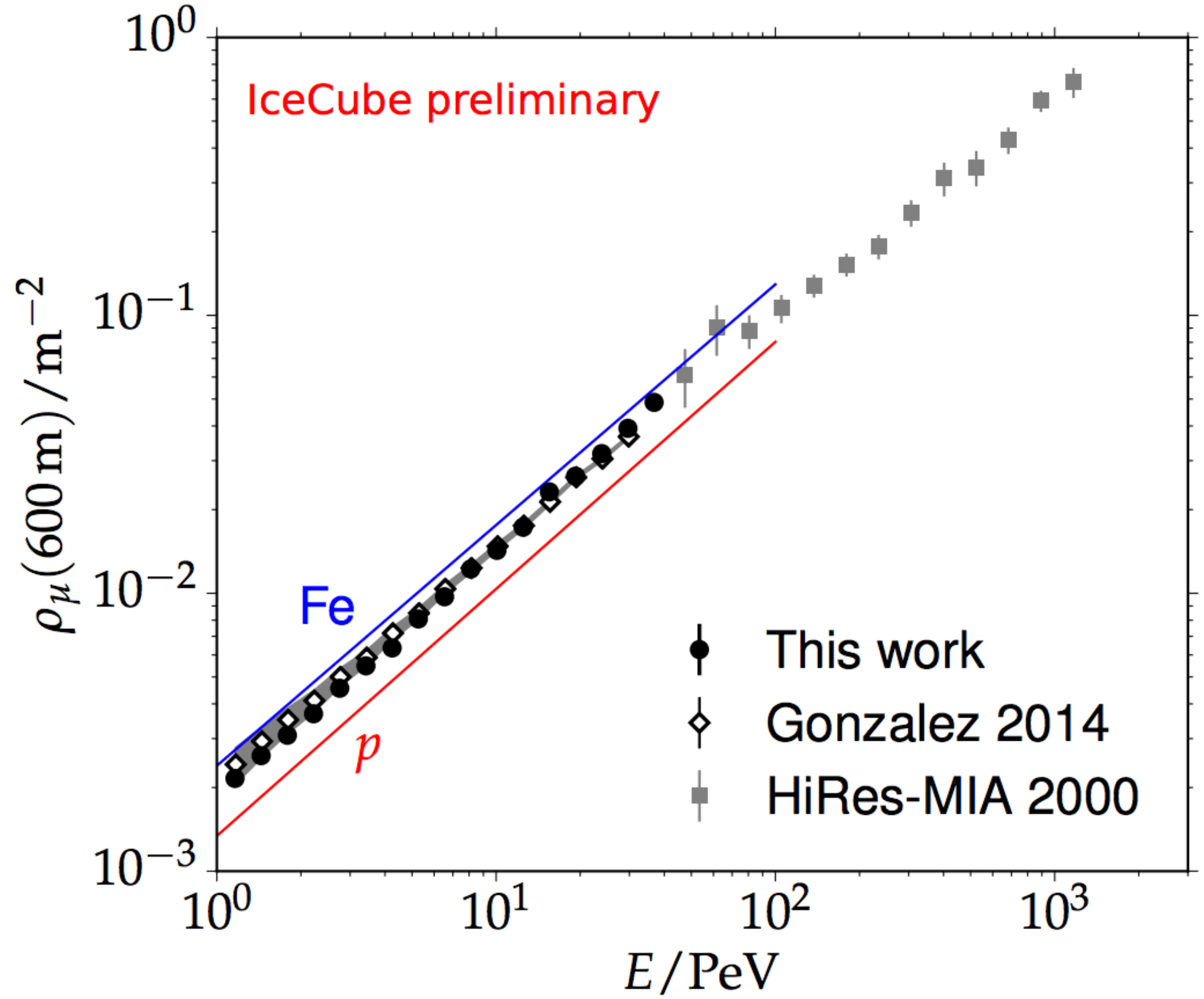
cosmic ray muons

low energy muons in CR showers

muons **lateral** distribution function
at 1-30 PeV CR energy





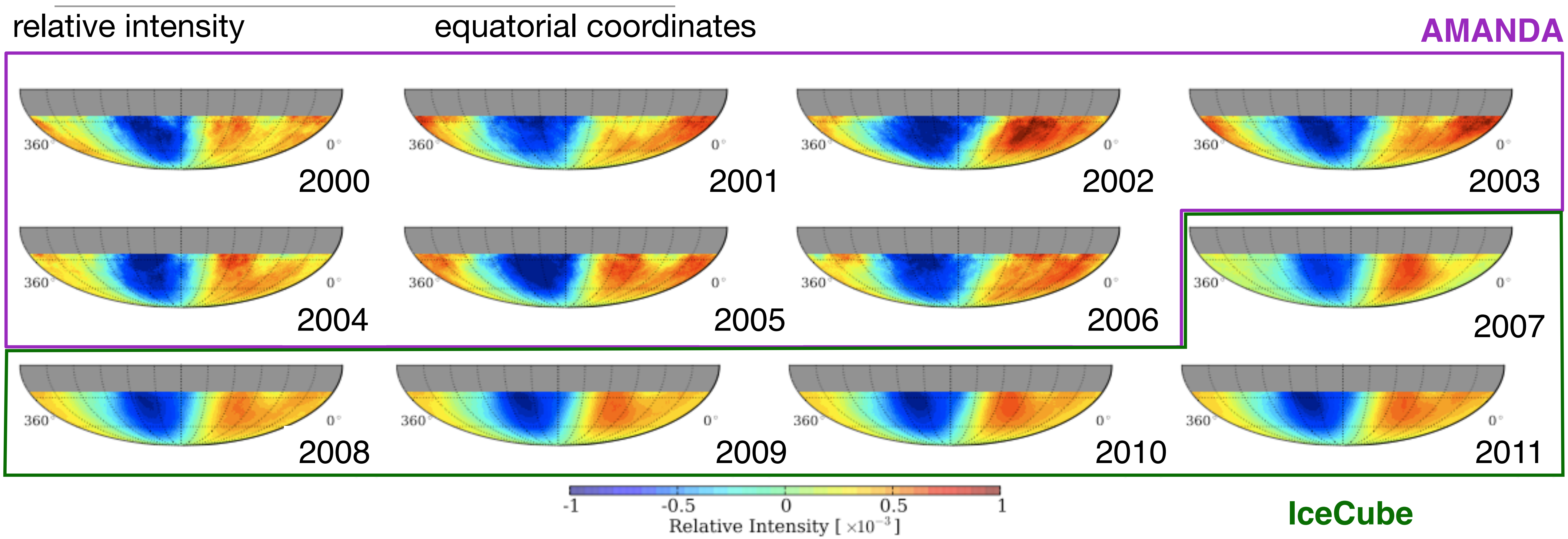


cosmic ray anisotropy

AMANDA-IceCube 2000-2011

ICRC 2013

20 TeV

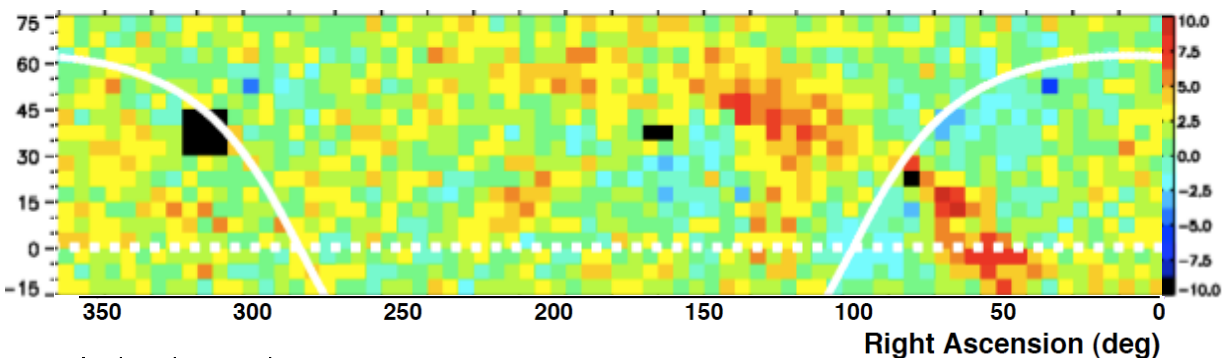


- AMANDA and IceCube yearly data show long **time-scale stability** of global anisotropy within statistical uncertainties
    - no apparent effect correlated to solar cycles

high energy cosmic rays
small scale anisotropy

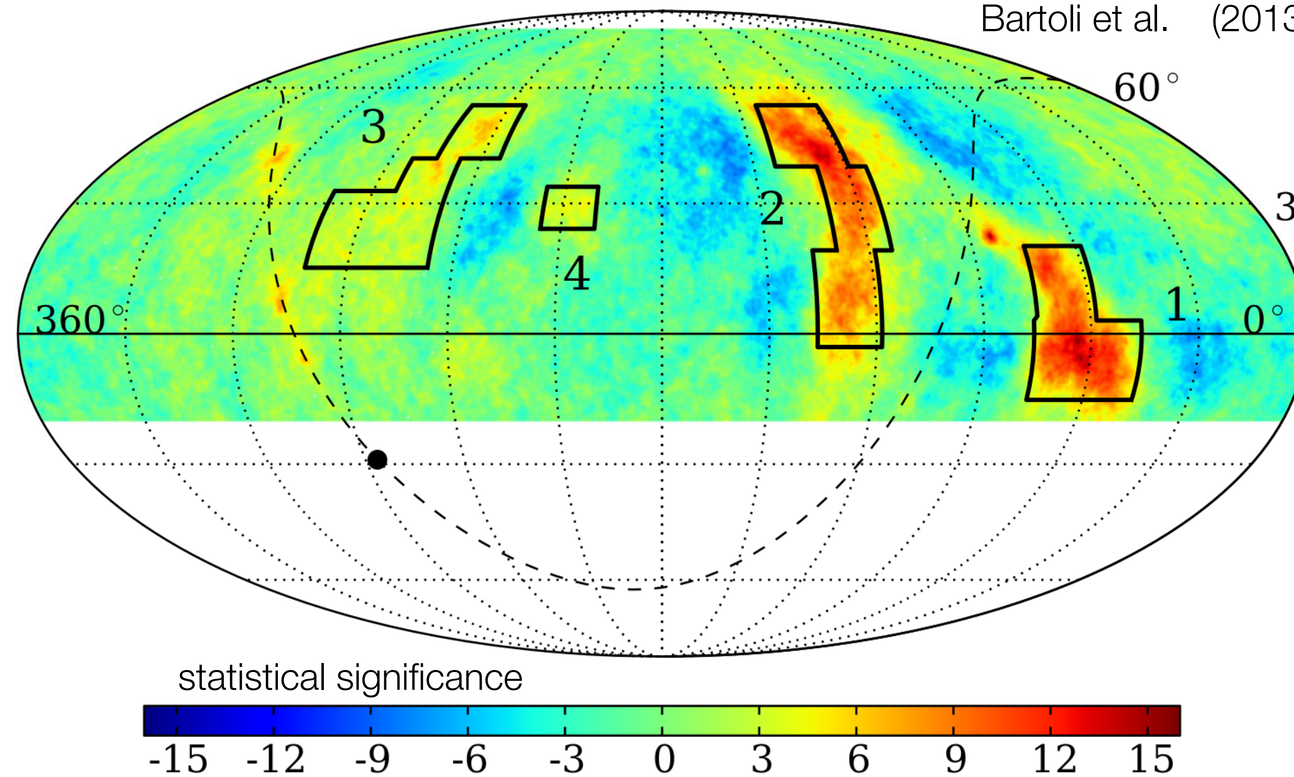
1-5 TeV $\sim 10^{-4}$

Tibet-III
Amenomori et al. ICRC (2007)

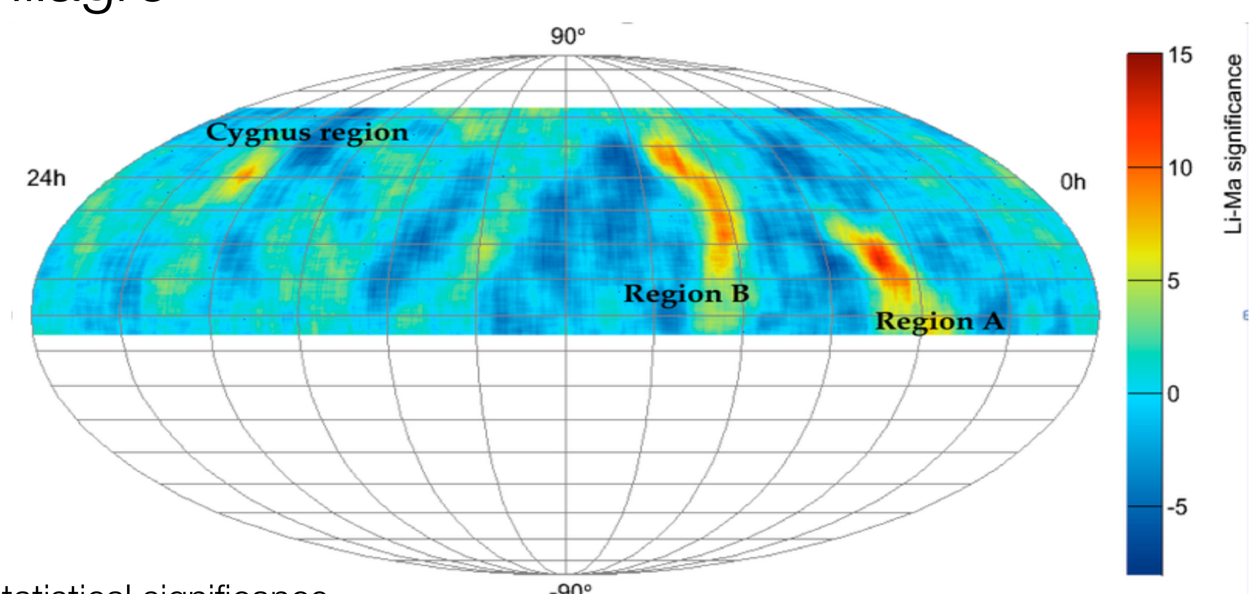


relative intensity

ARGO-YBJ
Vernetto et al. (2009)
Iuppa et al. (2011)
Bartoli et al. (2013)

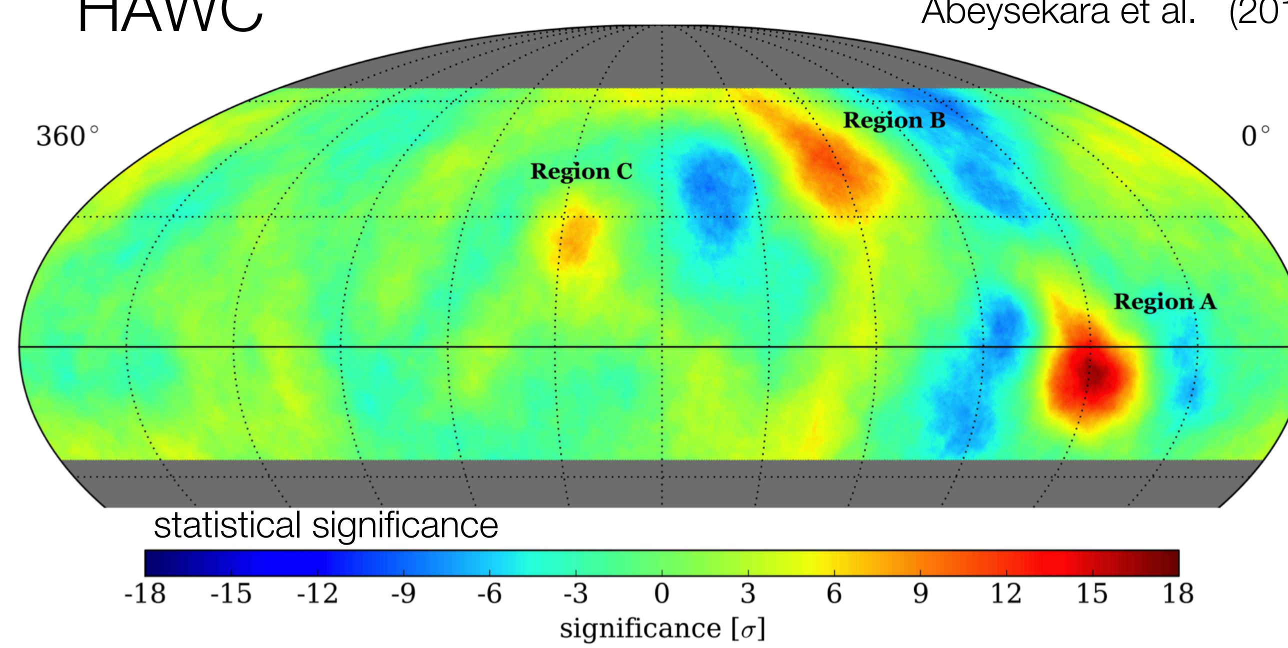


Milagro
Abdo et al. (2008)



statistical significance

HAWC
BenZvi et al. ICRC (2013)
Abeysekara et al. (2014)

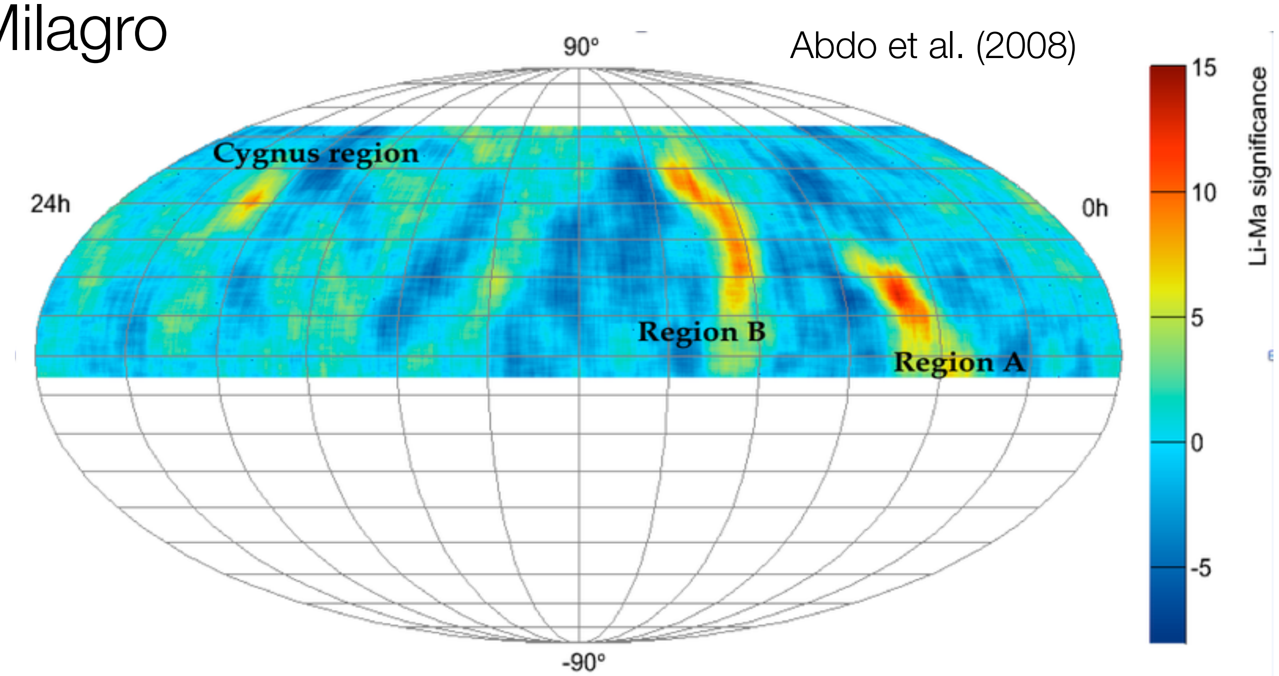


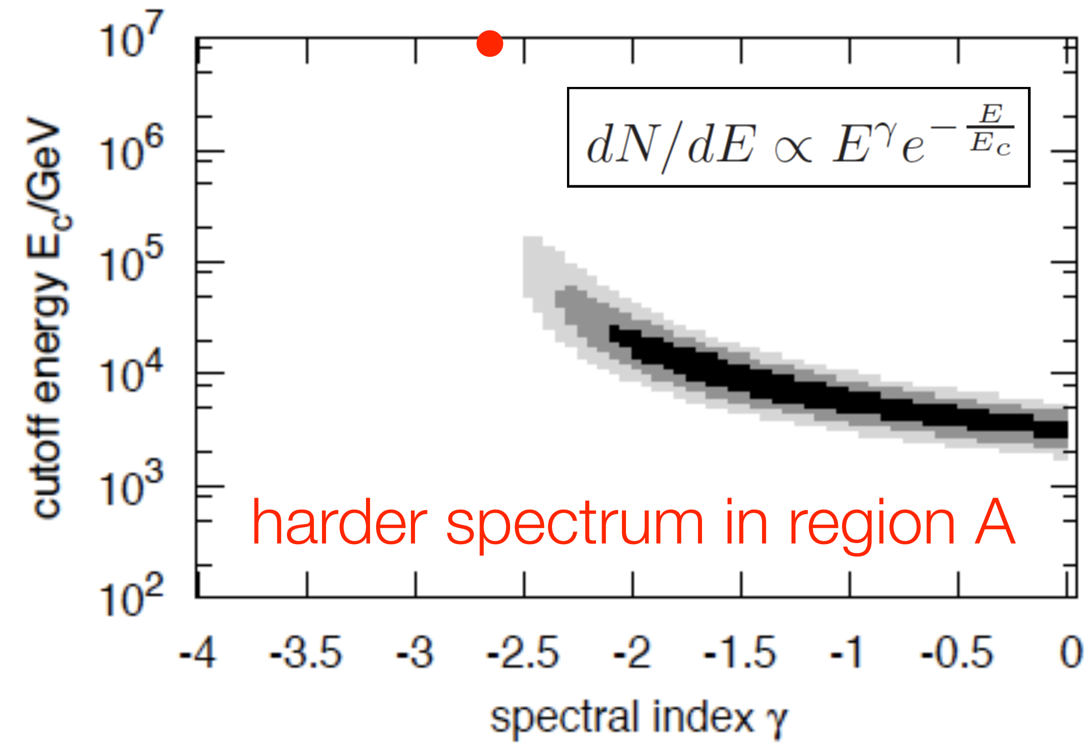
high energy cosmic rays
anisotropy & energy spectrum

HAWC results by S. BenZvi

Milagro

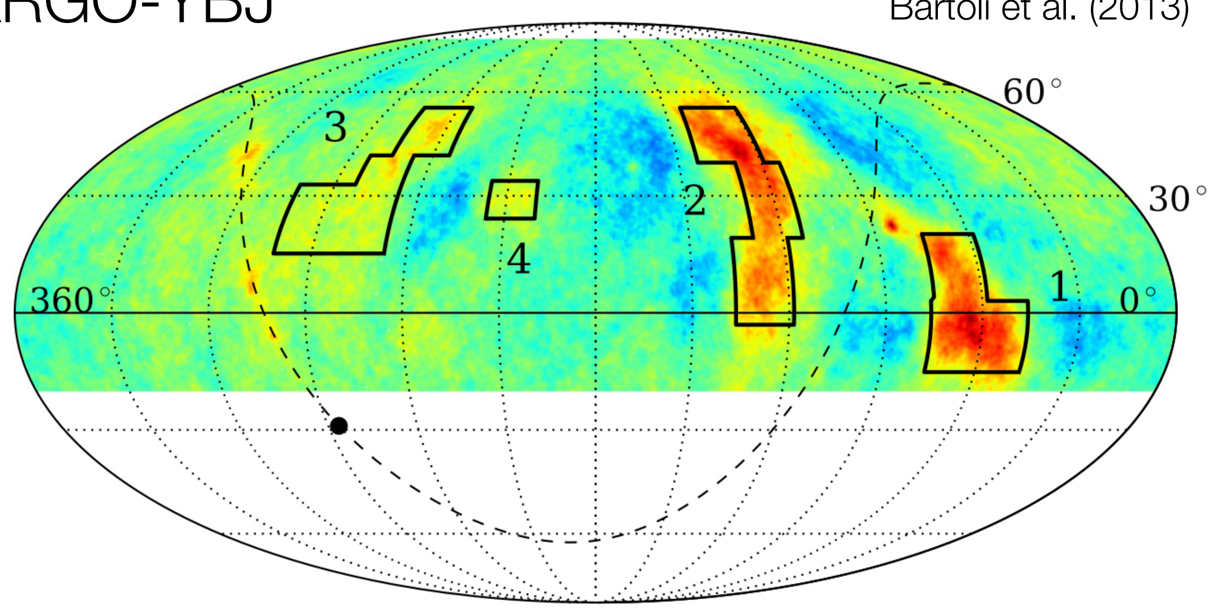
Abdo et al. (2008)

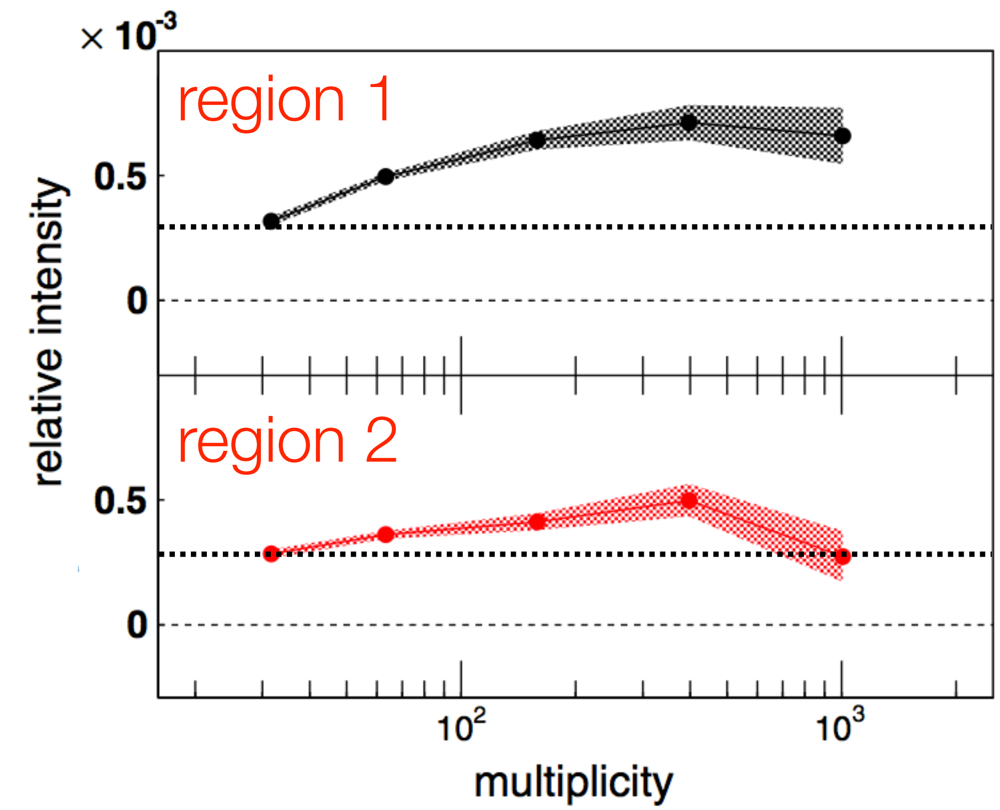




ARGO-YBJ

Bartoli et al. (2013)



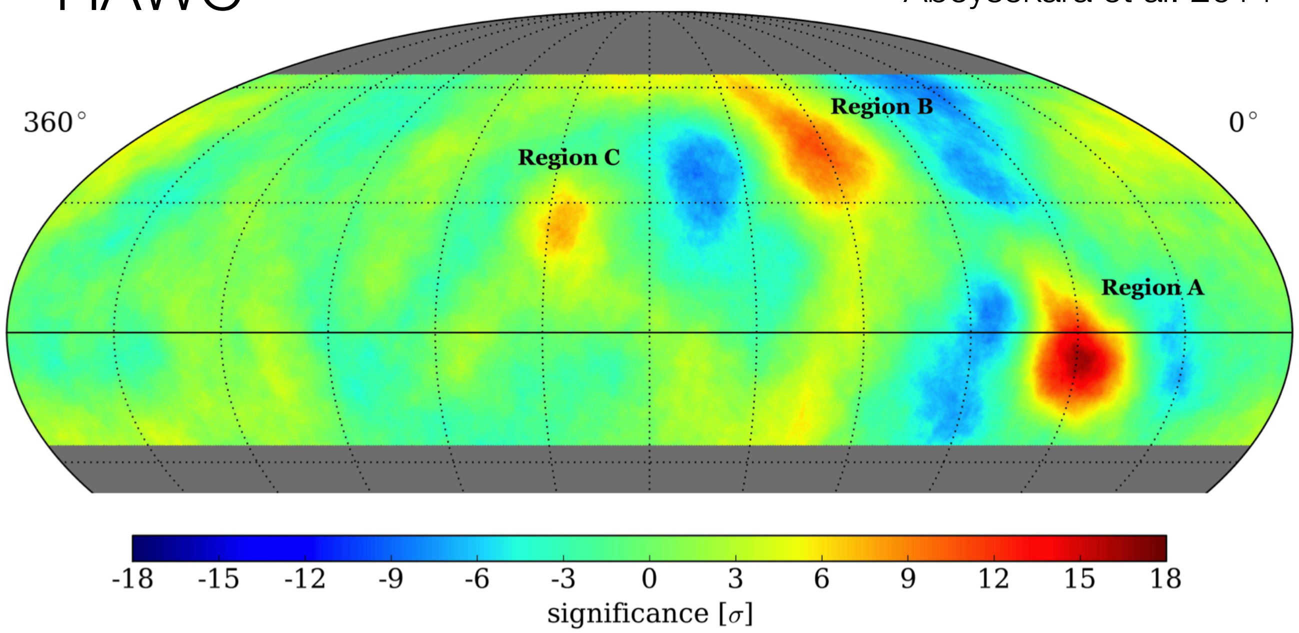


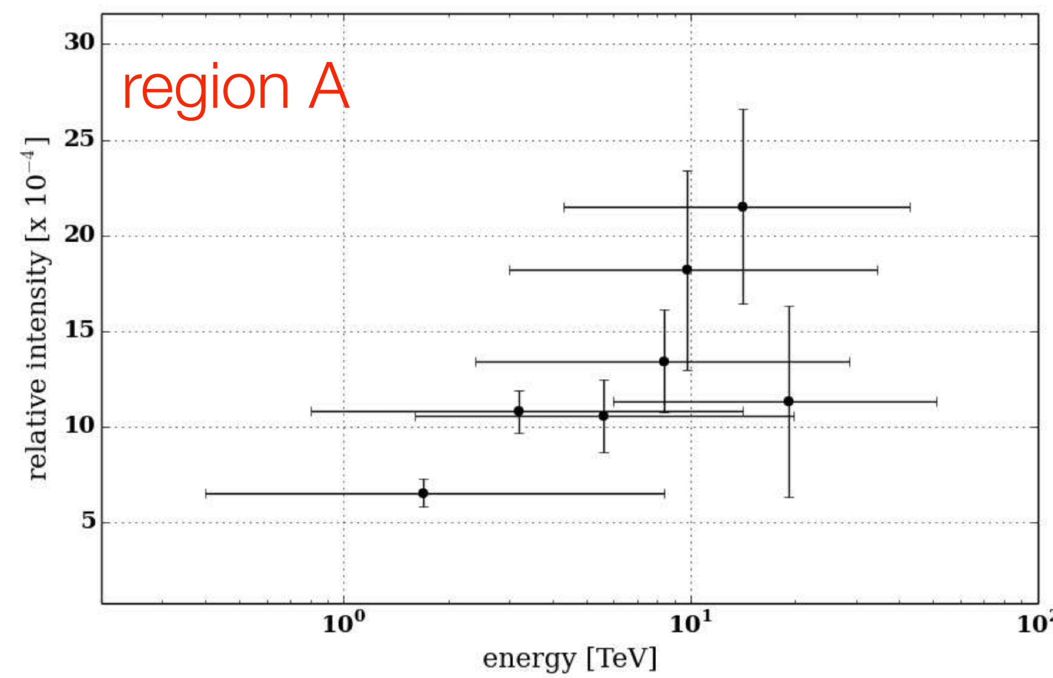
Paolo Desiati

high energy cosmic rays
anisotropy & energy spectrum

HAWC

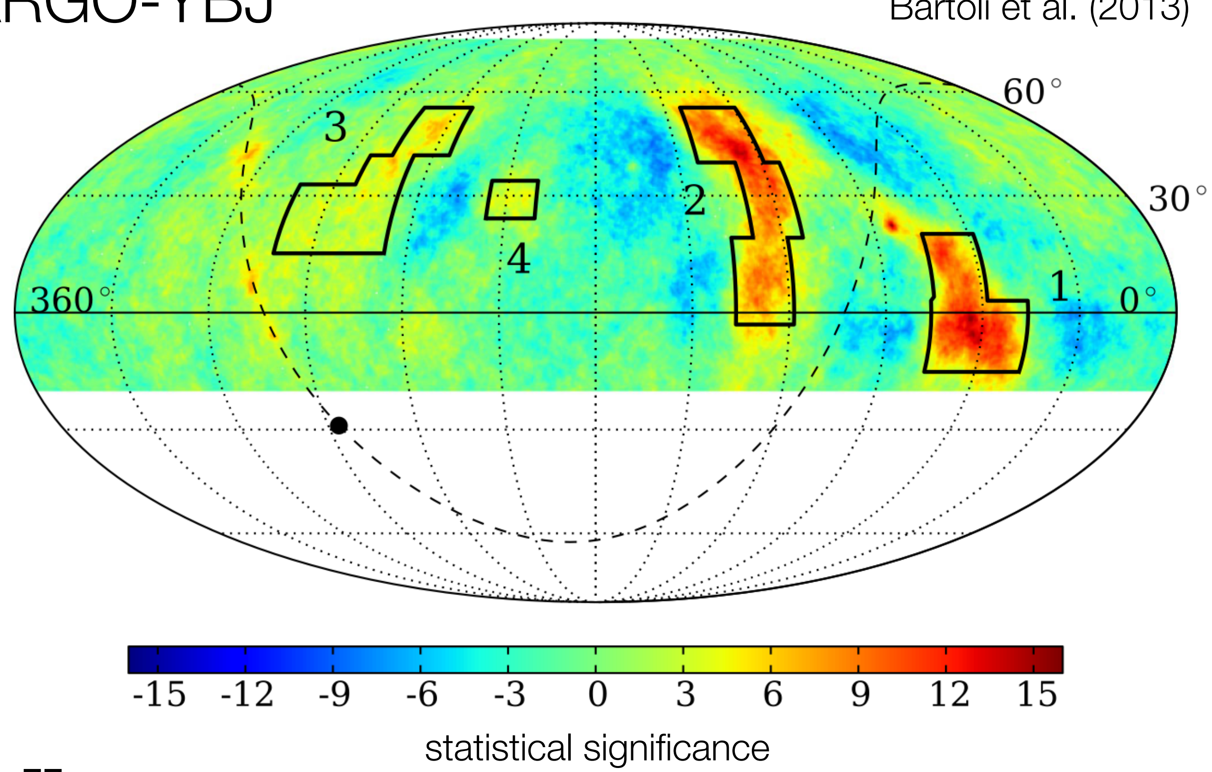
Abeysekara et al. 2014

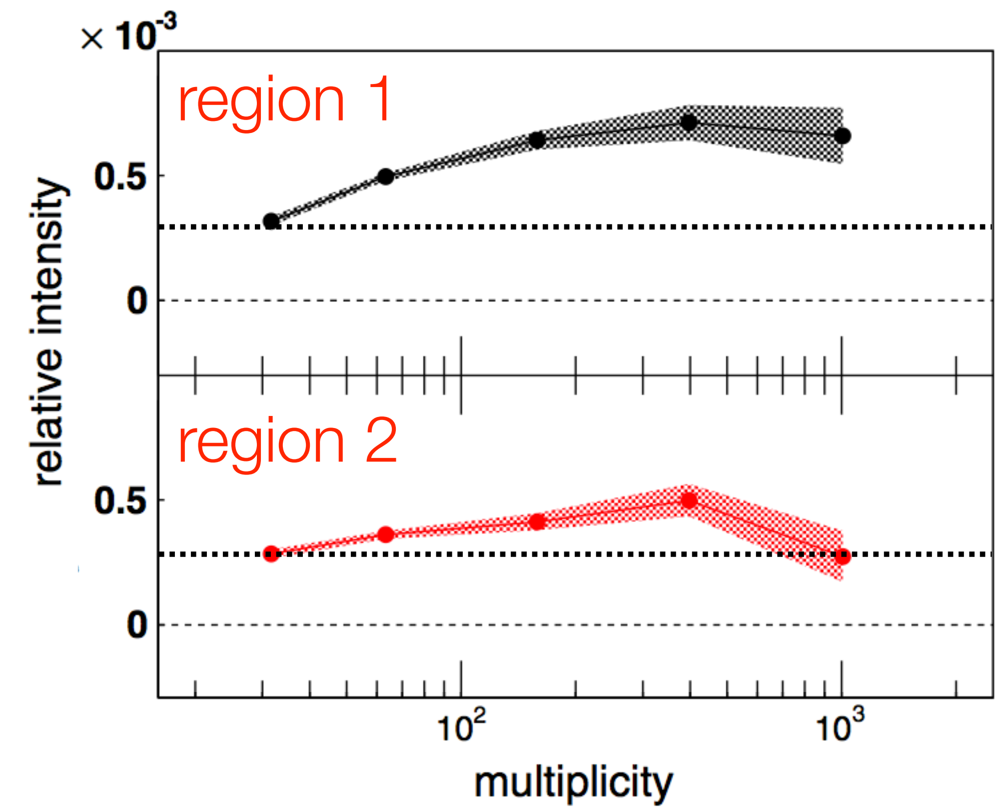




ARGO-YBJ

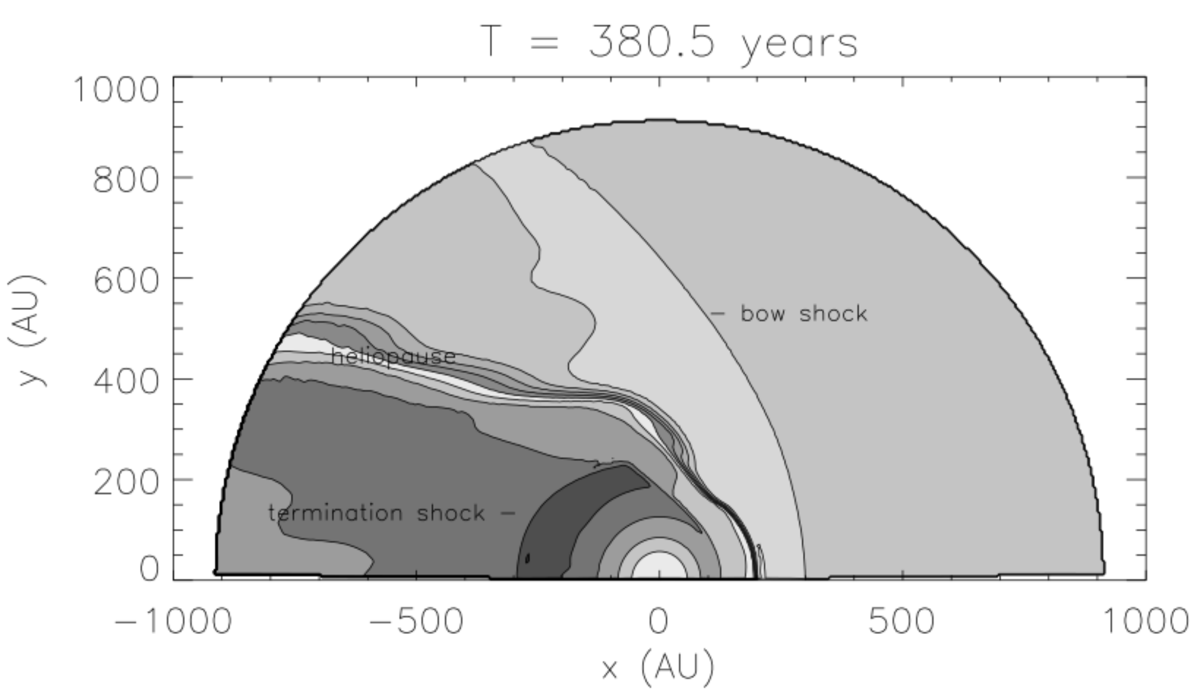
Bartoli et al. (2013)



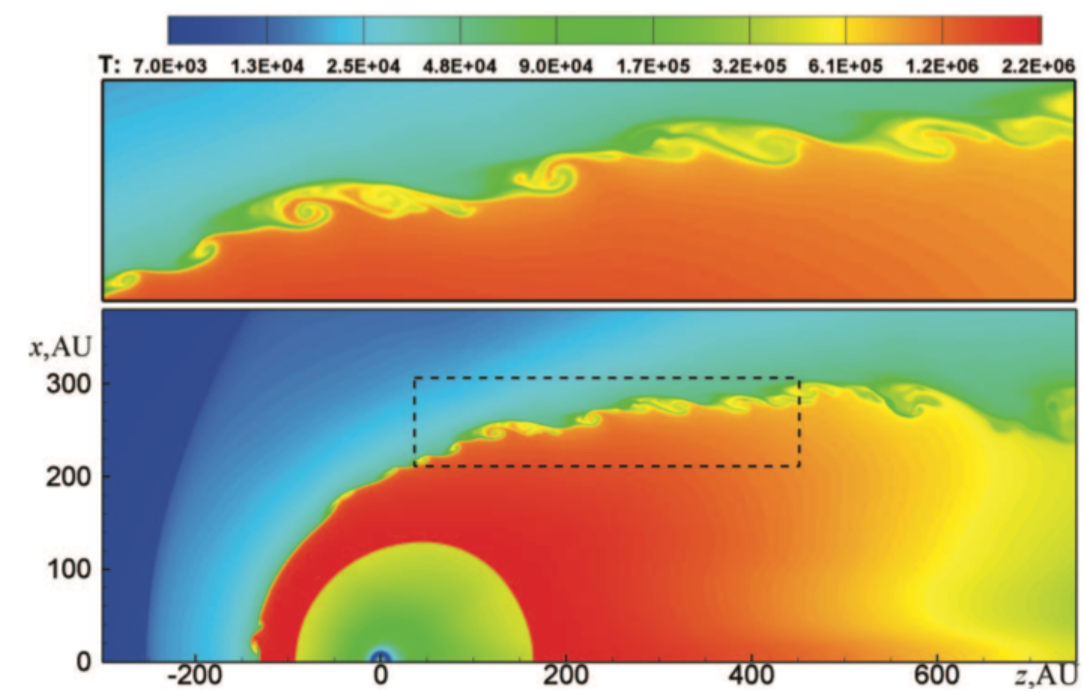


heliospheric perturbations
heliopause instabilities

- Rayleigh-Taylor instabilities driven and mediated by interstellar neutral atoms
- plasma-fluid instabilities at the flank of HP by charge exchange processes



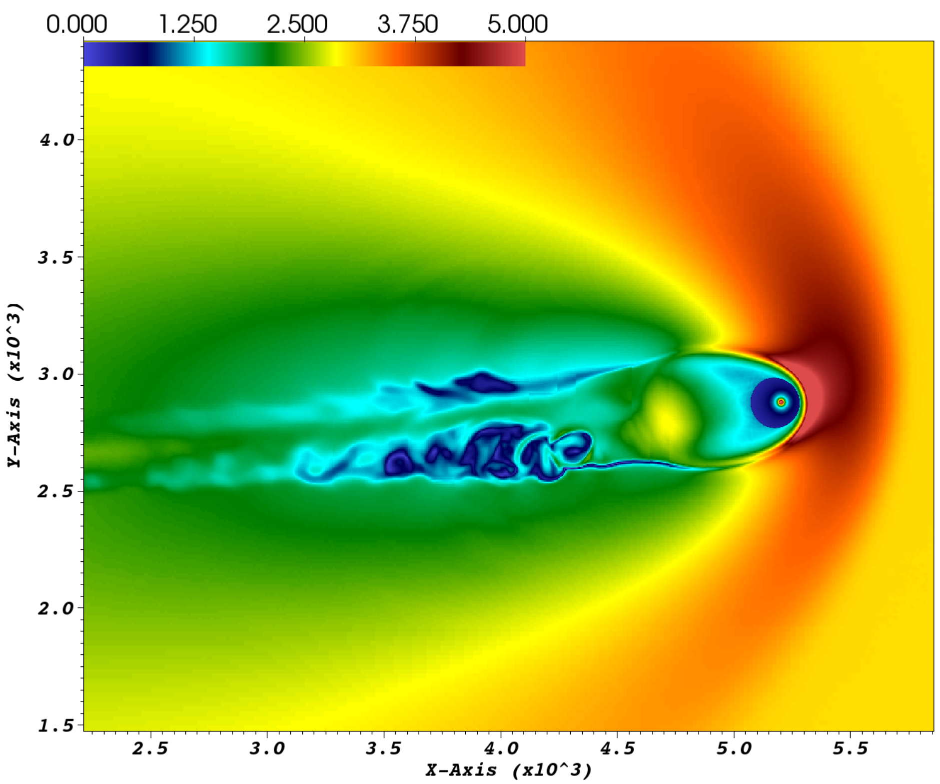
Liewer+ 1996
Zank+ 1996



Zank 1999
Florinski++ 2005
Borovikov+ 2008
Zank 2009
Shaikh & Zank 2010

cosmic ray anisotropy

probing heliospheric magnetic structure

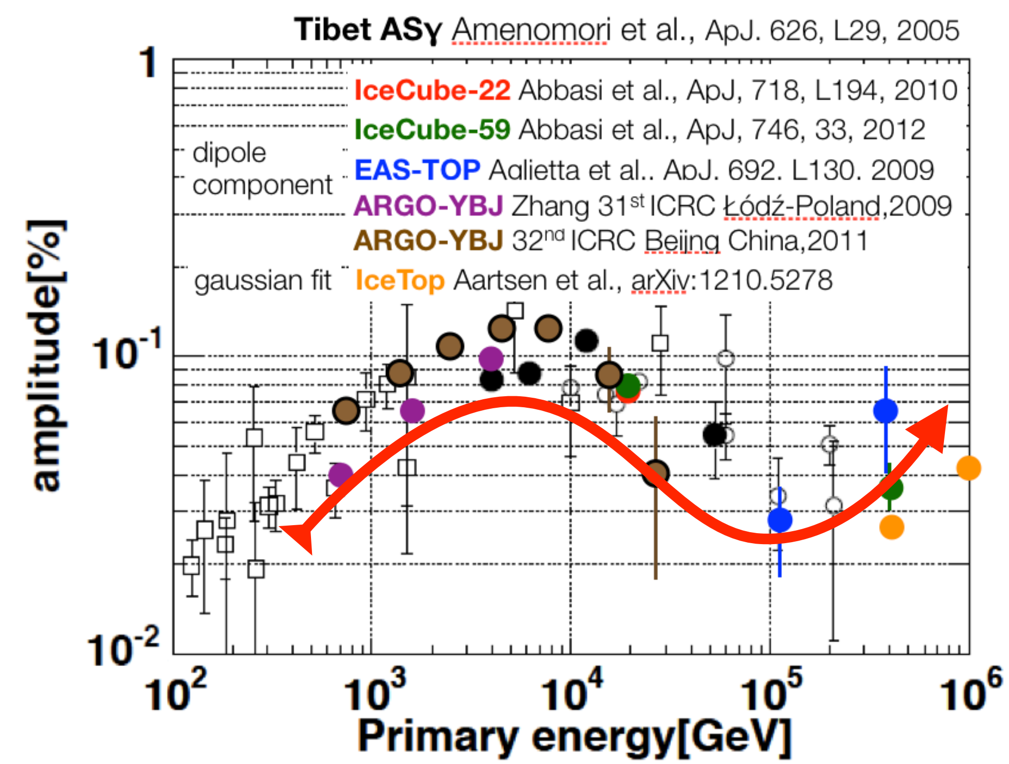


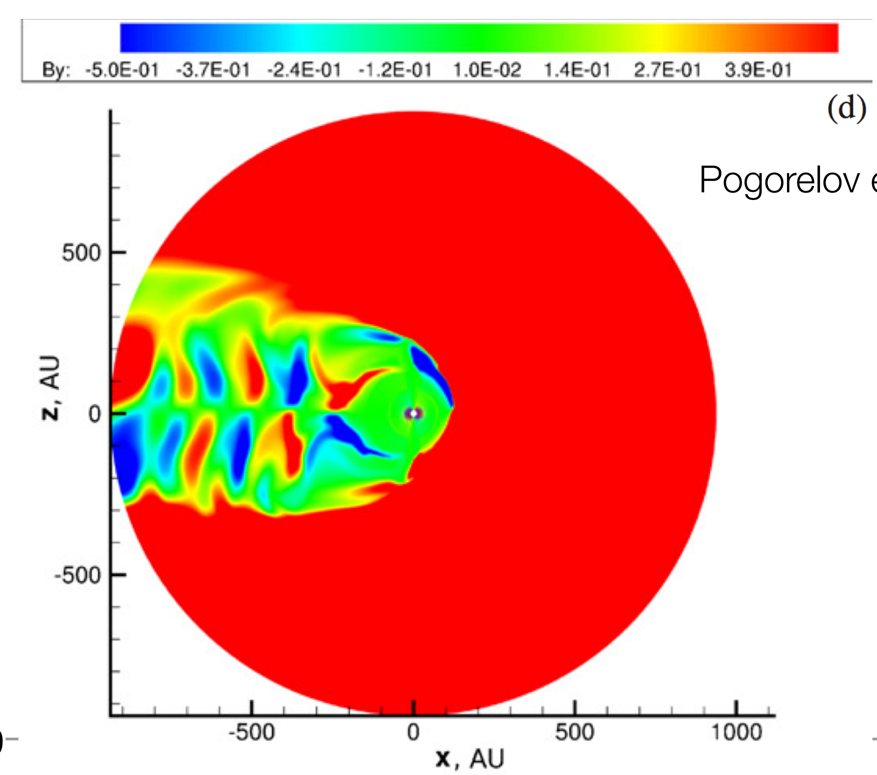
Borovikov, Heerikhuisen, Pogorelov

downstream instabilities on the flanks of heliotail

PD & Lazarian 2013

López-Barquero, Xu, PD, Lazarian





Pogorelov et al., 2009

effects of magnetic polarity reversals from solar cycles

magnetic reconnection

Lazarian & PD 2010
PD & Lazarian 2012