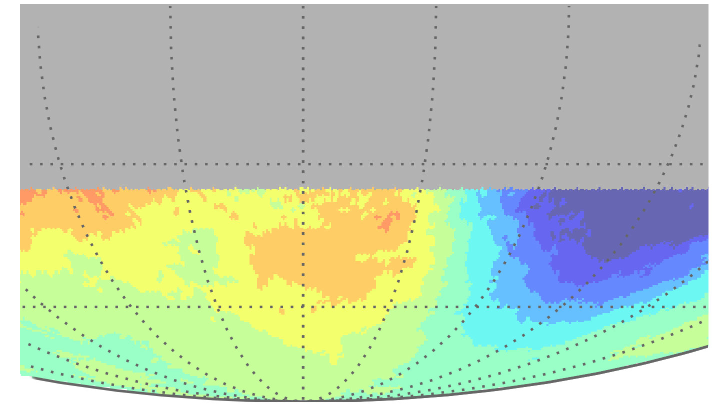
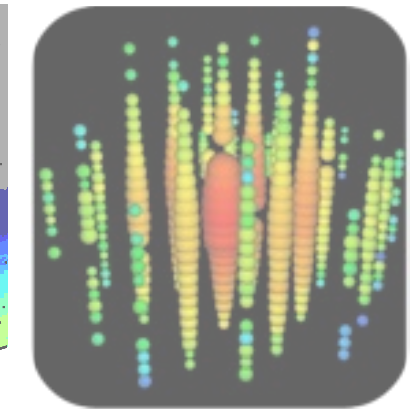




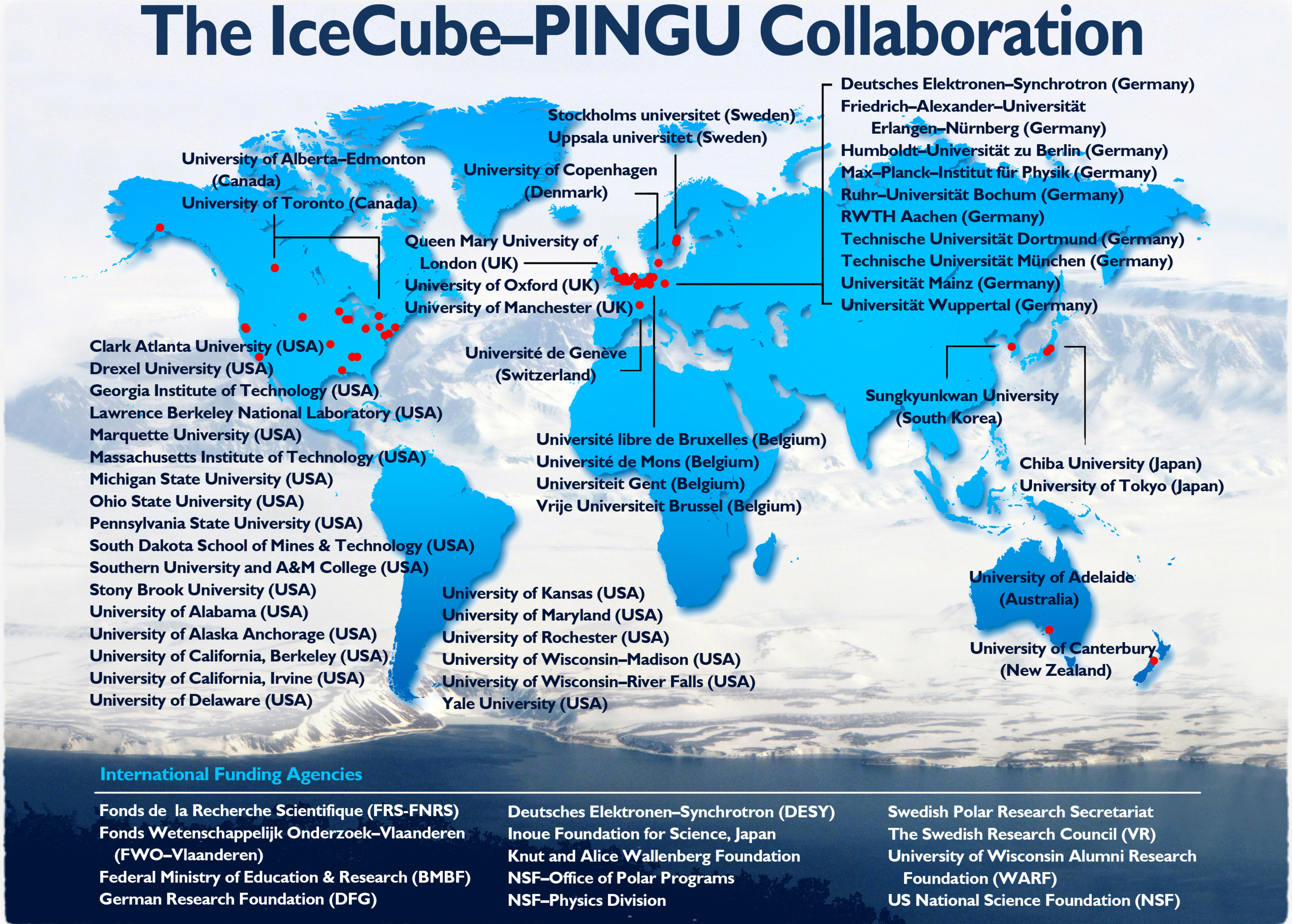
Neutrino and Cosmic Ray Astrophysics with the IceCube Observatory

Paolo Desiati

WIPAC & Department of Astronomy
University of Wisconsin - Madison

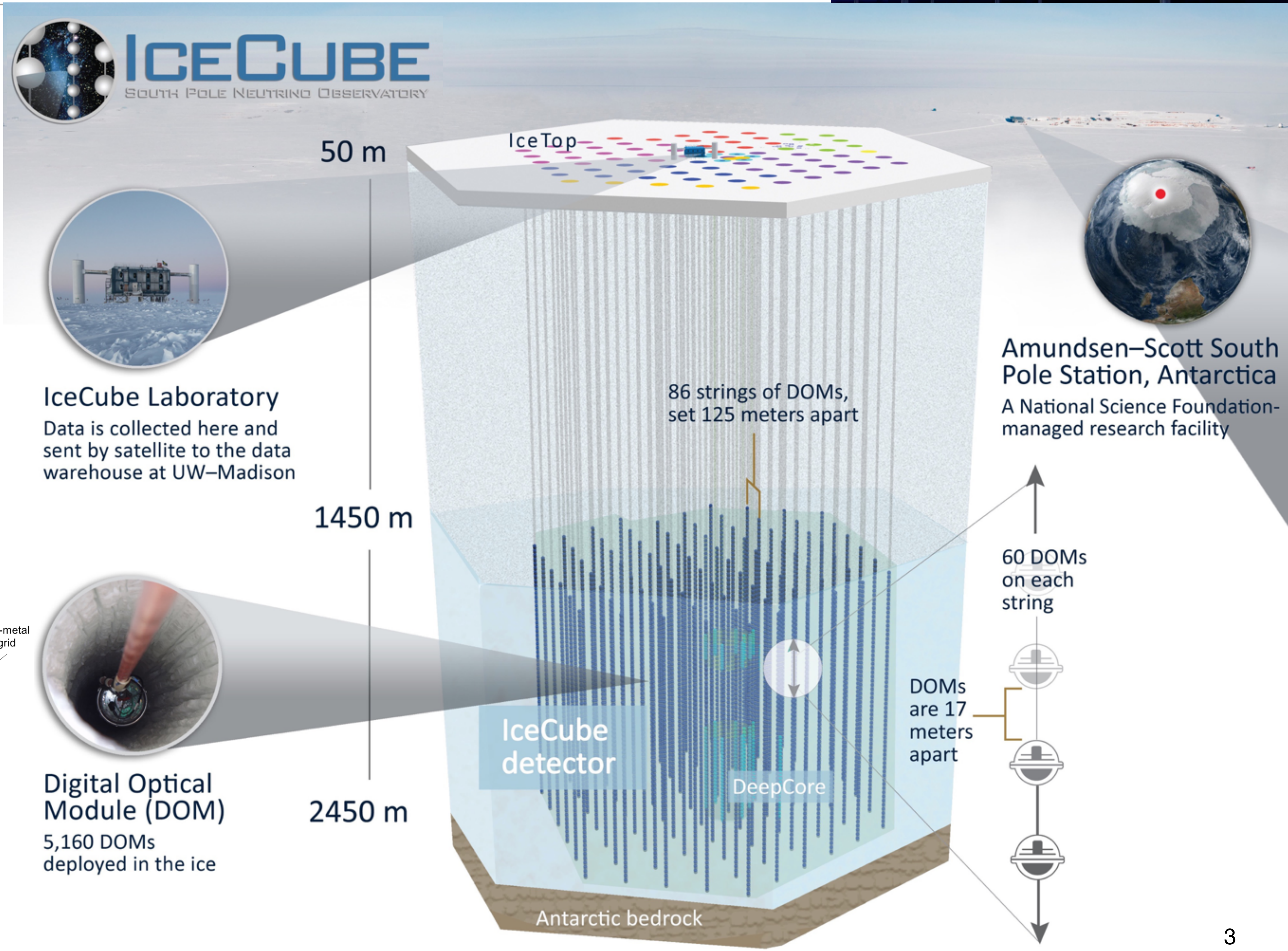
<desiati@wipac.wisc.edu>

La Sapienza - Università di Roma
12 Gennaio 2016



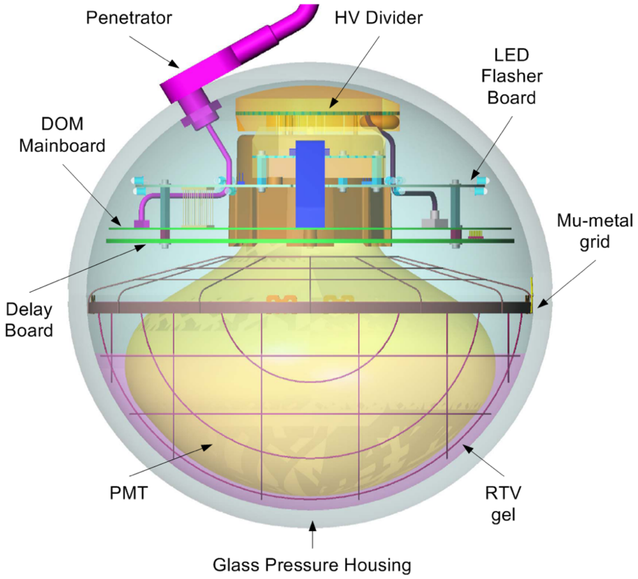
The international IceCube collaboration includes over 300 members from 48 institutions in 12 countries

IceCube Observatory
the instrumentation

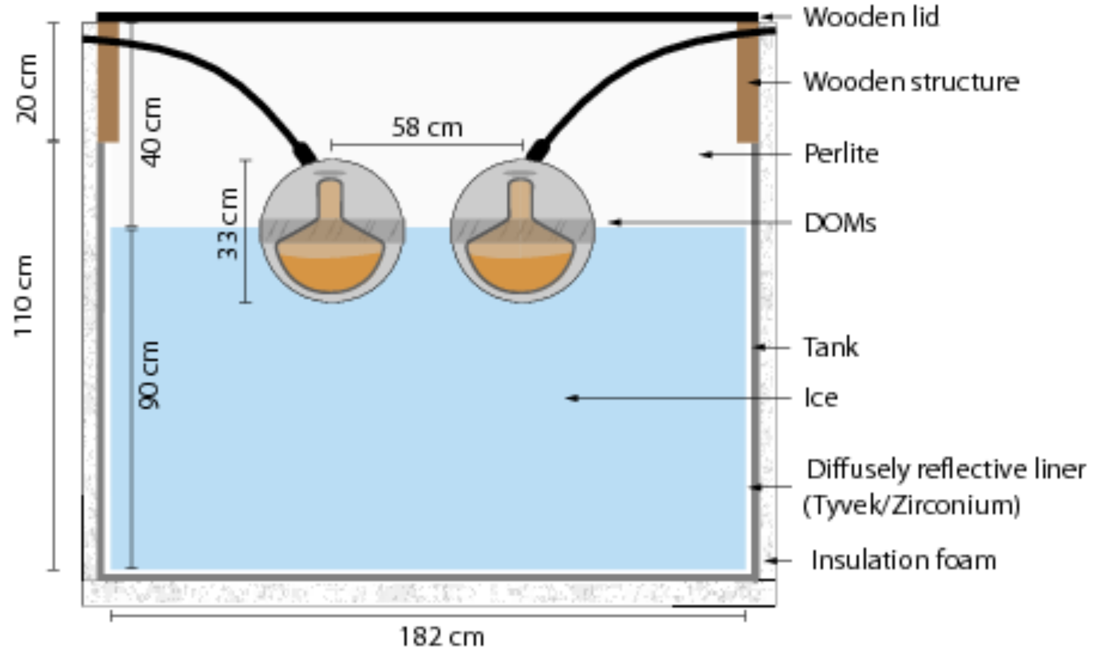


Digital Optical Module (DOM)

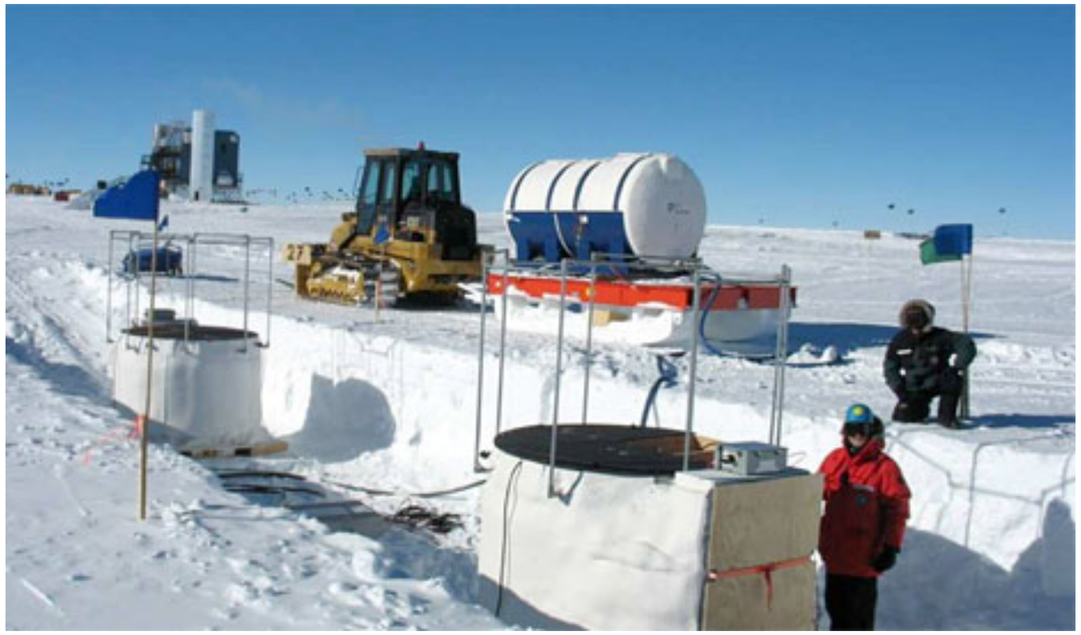
with 10” PMT
&
local DAQ electronics

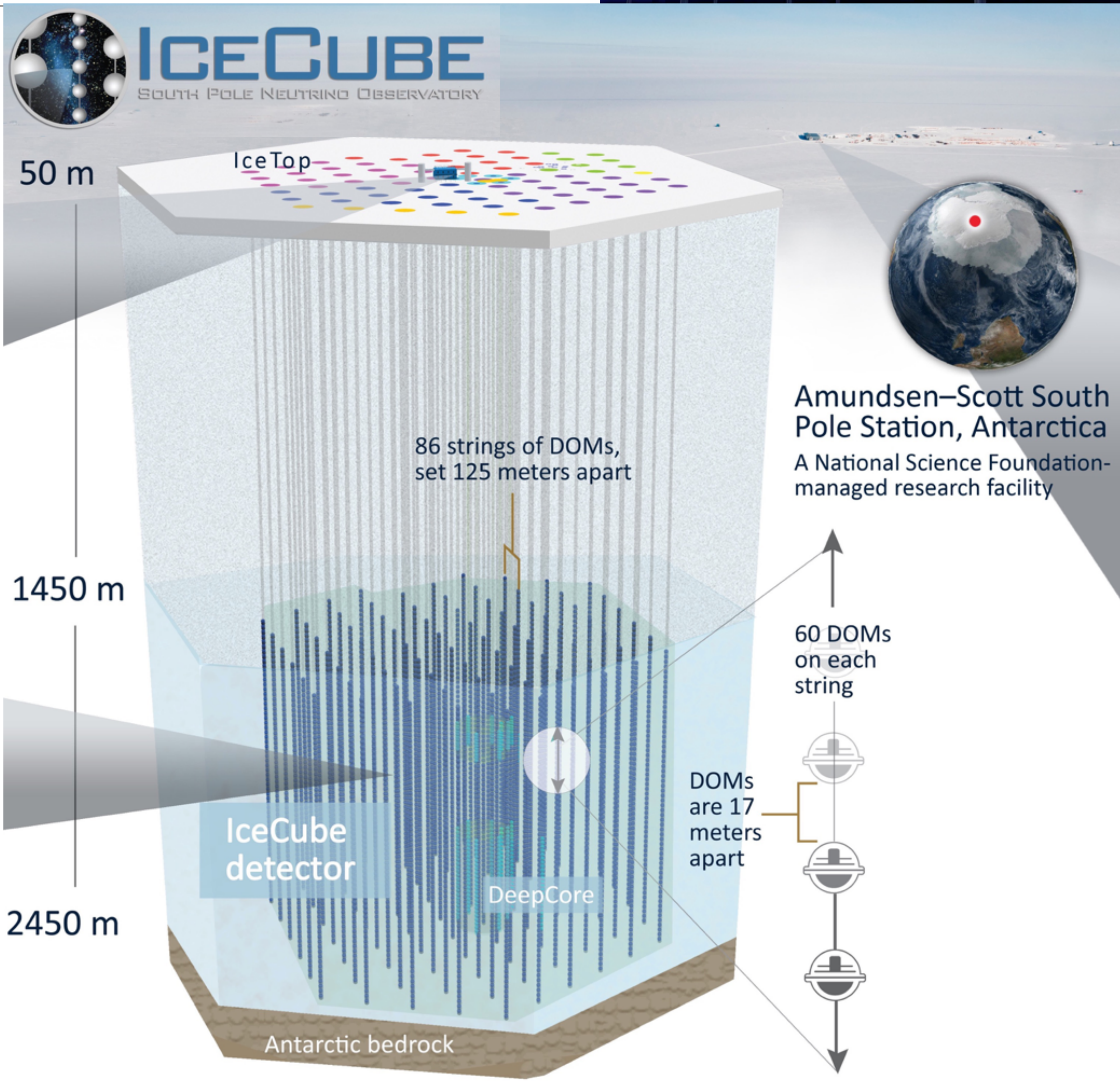


IceCube Observatory
the instrumentation



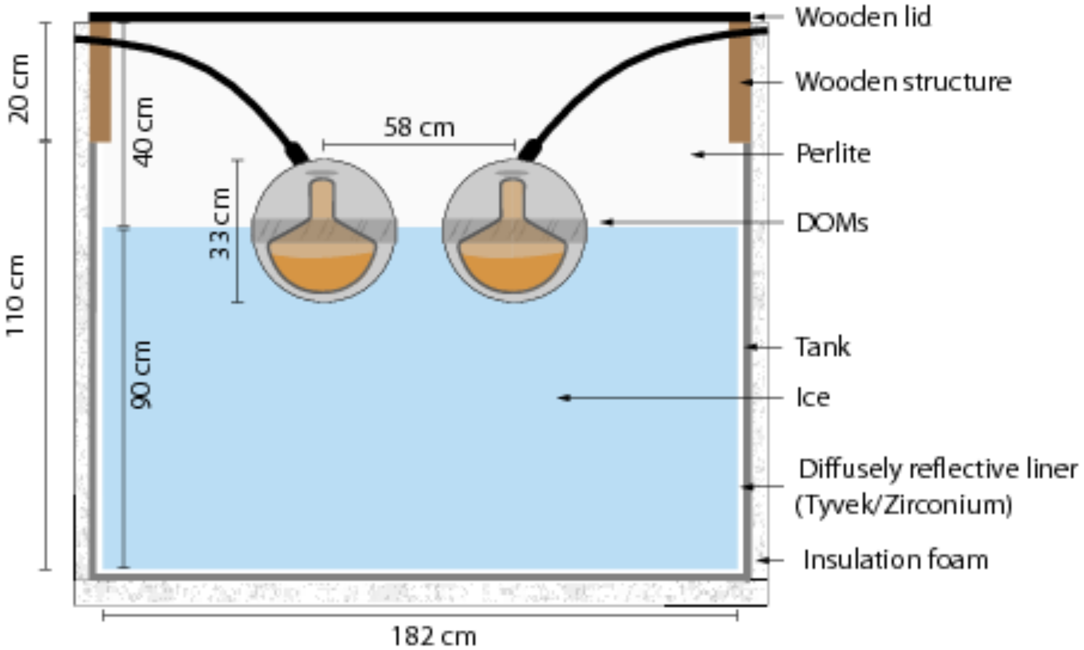
two tanks of one IceTop station



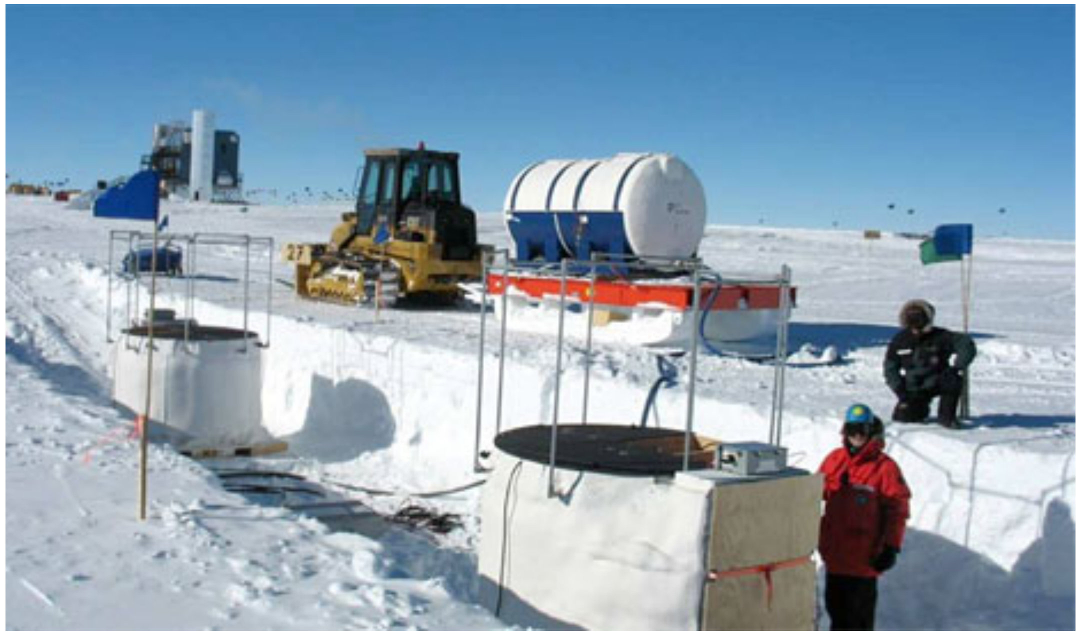


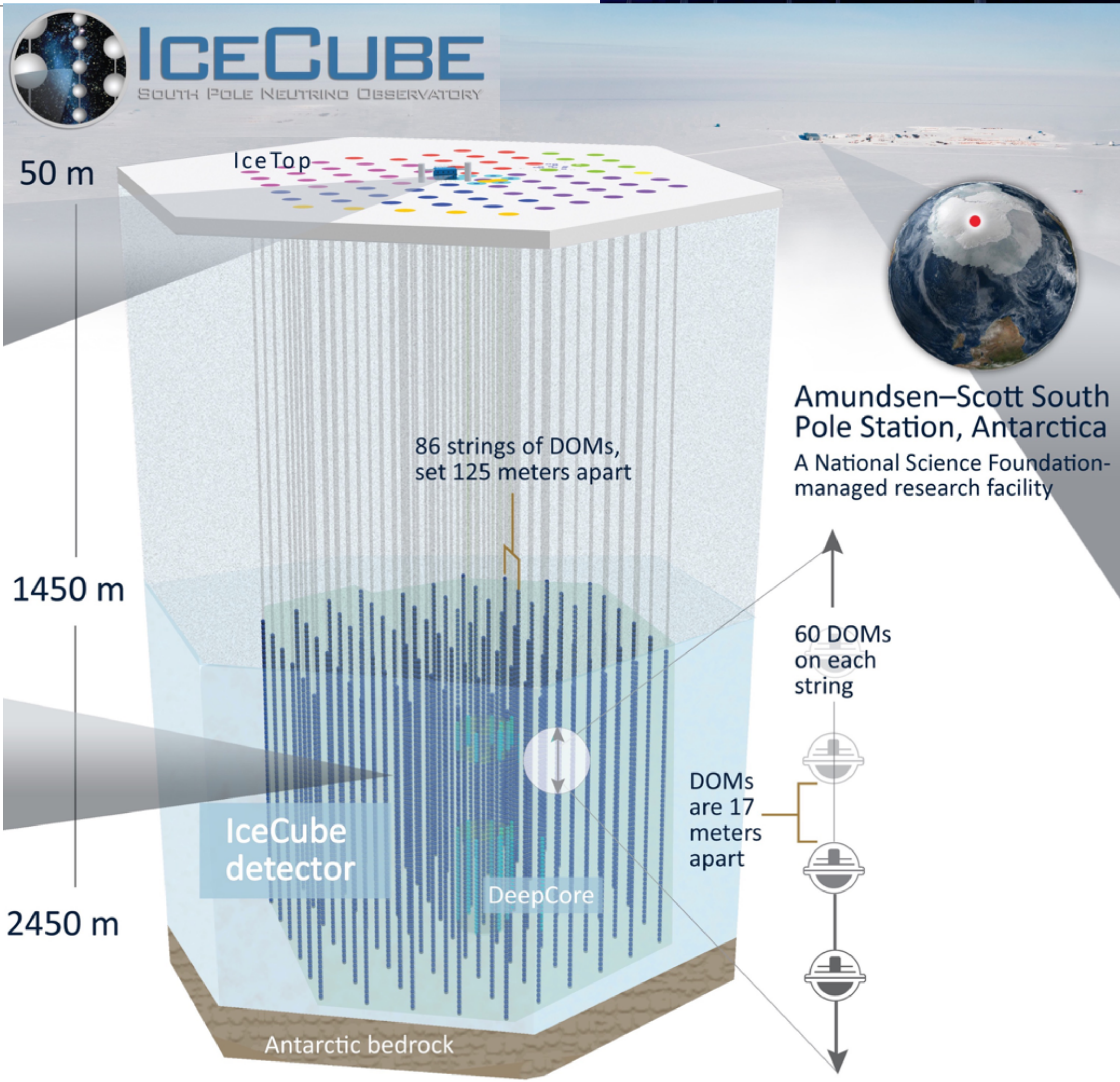
IceCube Observatory
the instrumentation

KM^3 OBSERVATORY



two tanks of one IceTop station

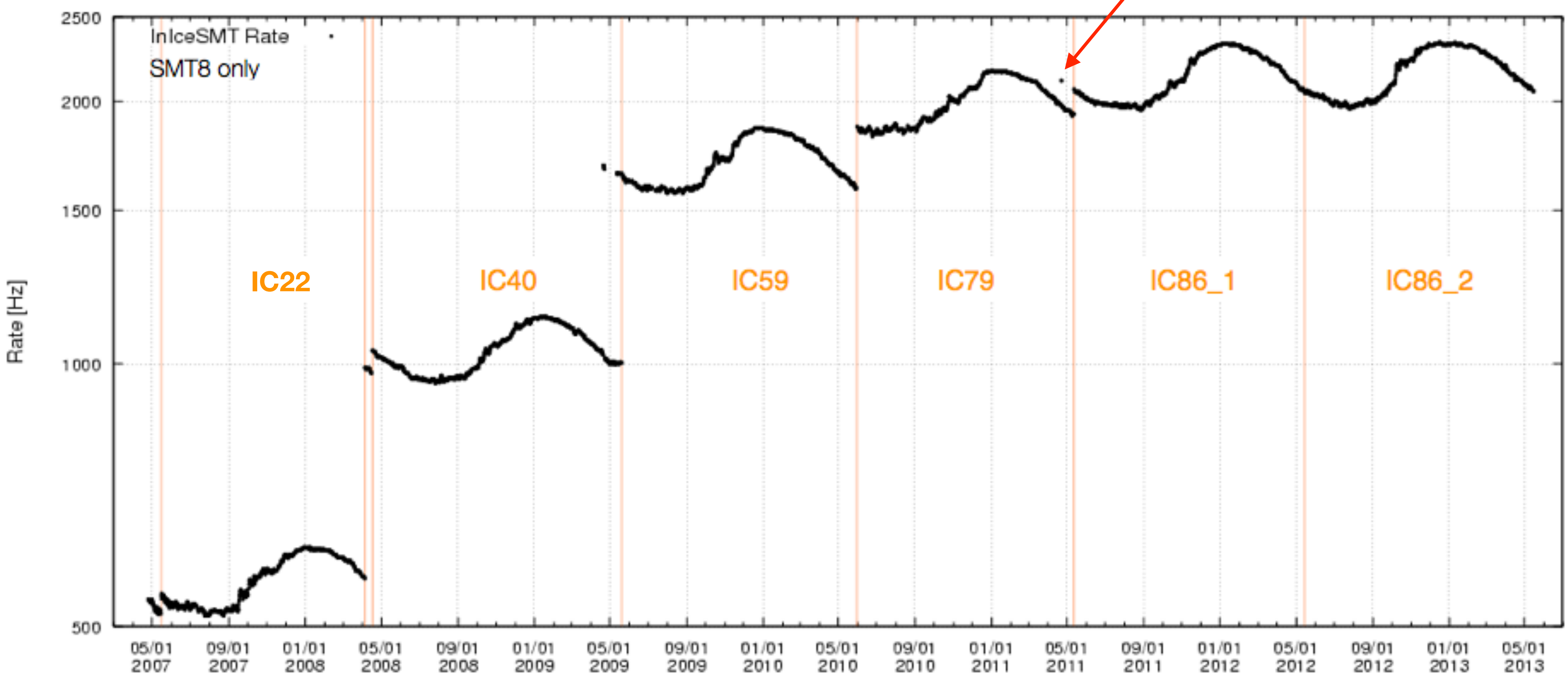




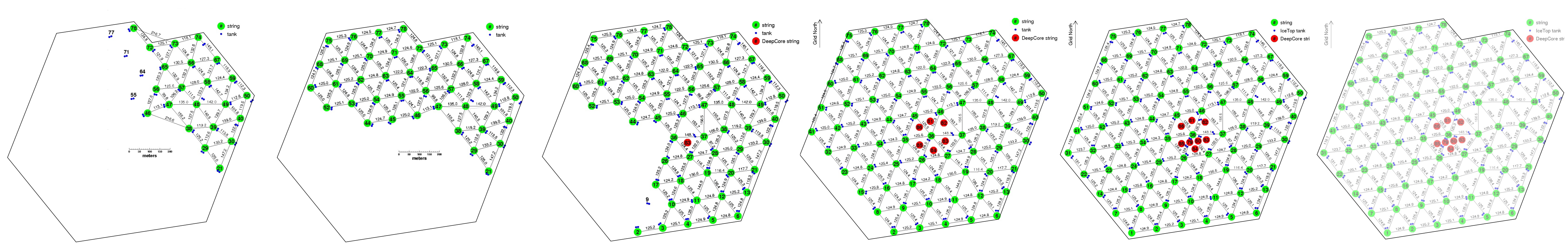
event rate in IceCube

growing experiment

IceCube completed
December 18, 2010

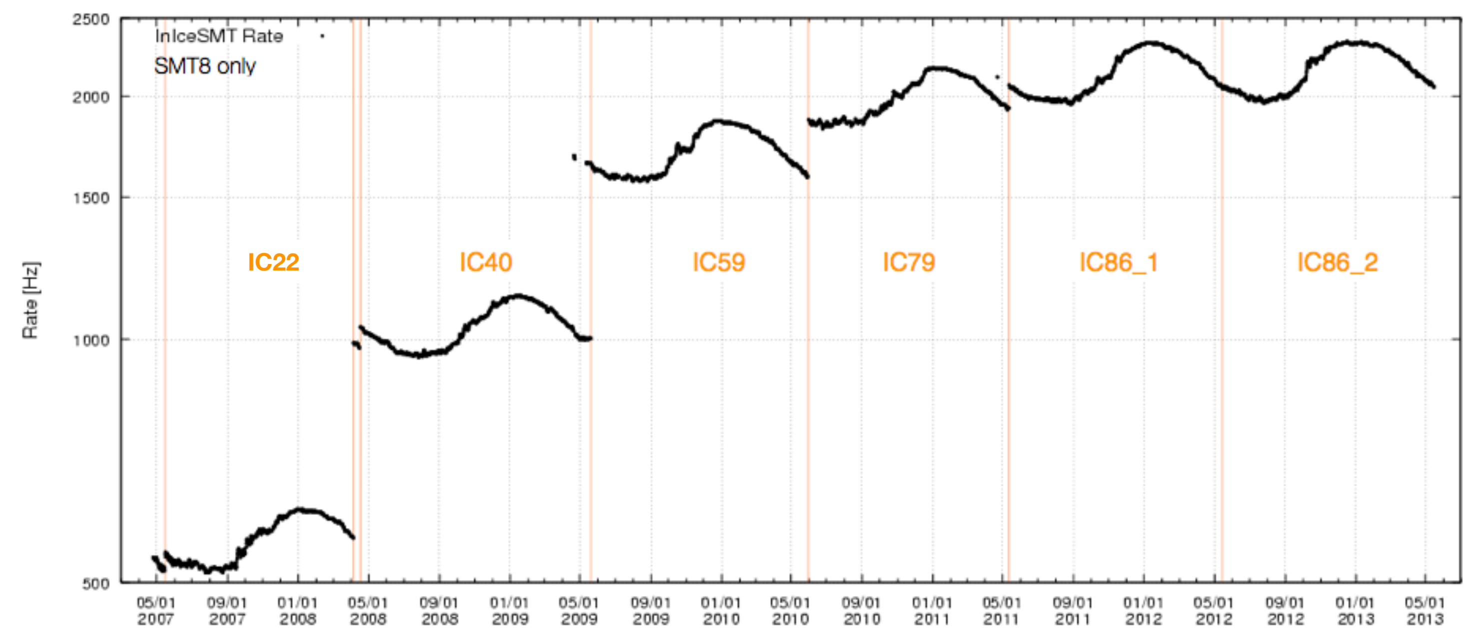


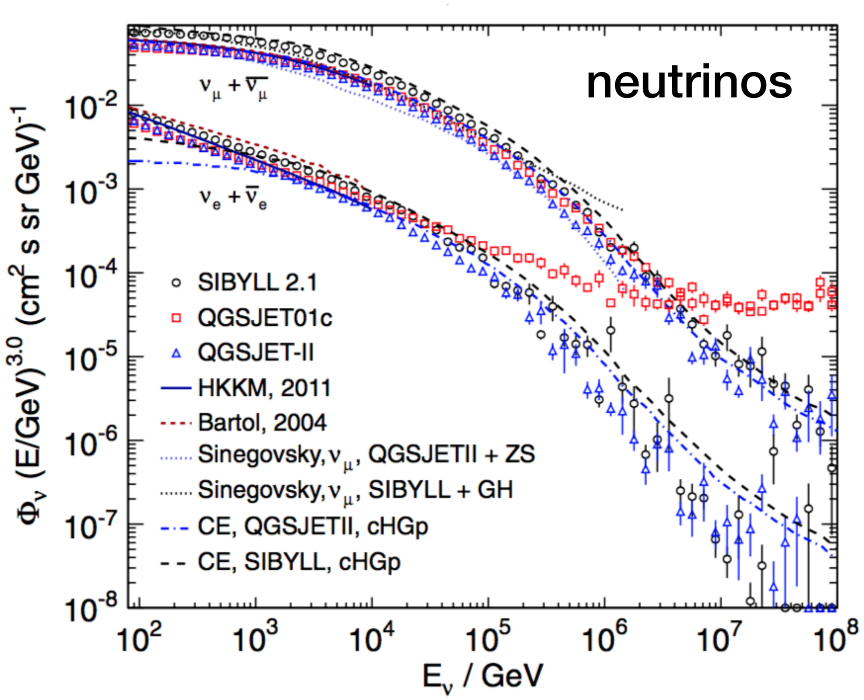
2007-08 2008-09 2009-10 2010-11 2011-12 2012-13 >>



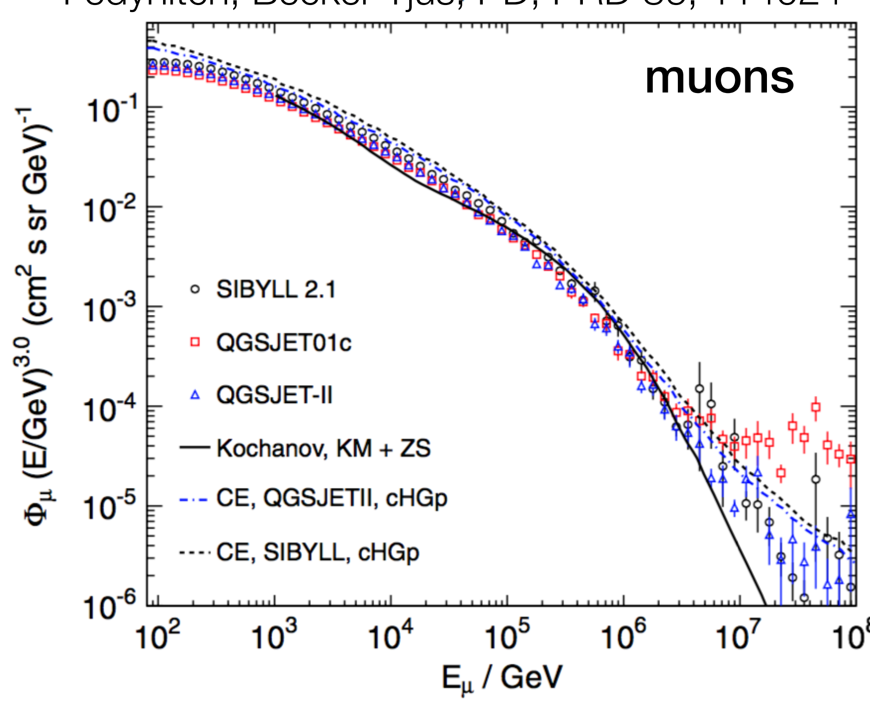
cosmic ray muons and neutrinos

- R_{event} ~ 2200 Hz
- μ and ν produced in the atmosphere by **cosmic rays**
- atmospheric temperature seasonal variations





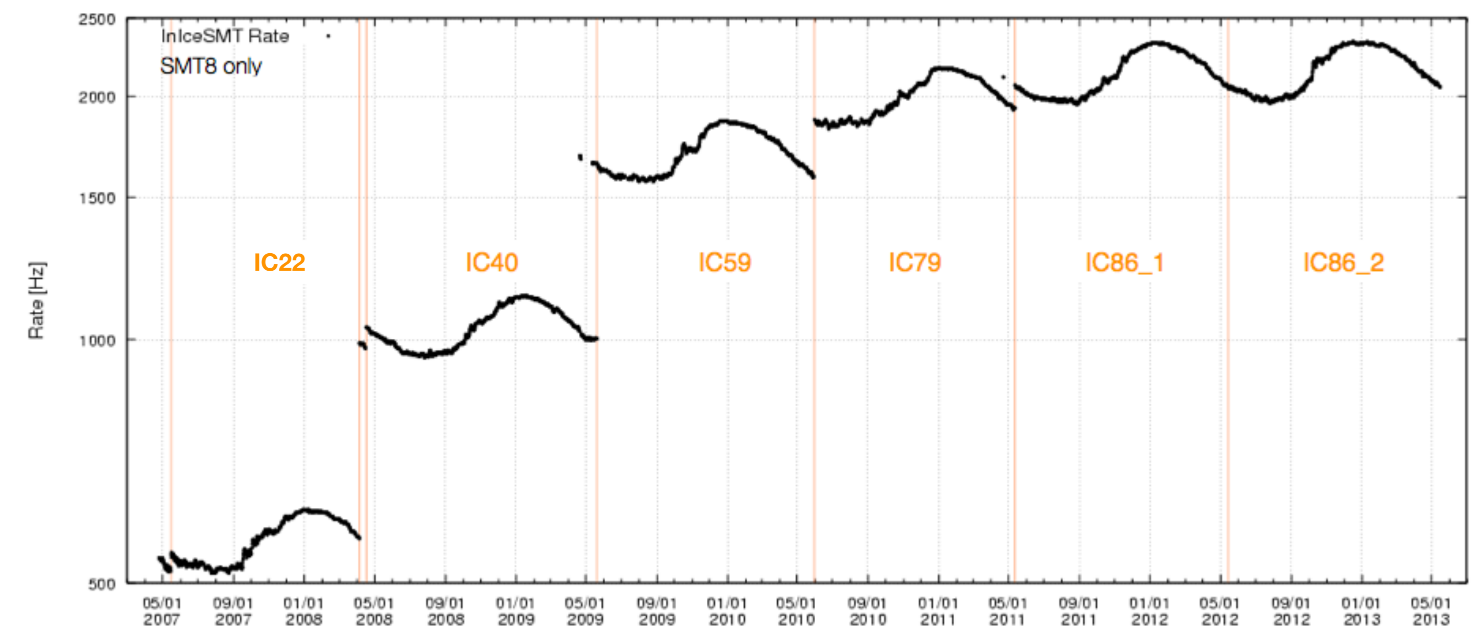
Fedynitch, Becker Tjus, PD, PRD 86, 114024



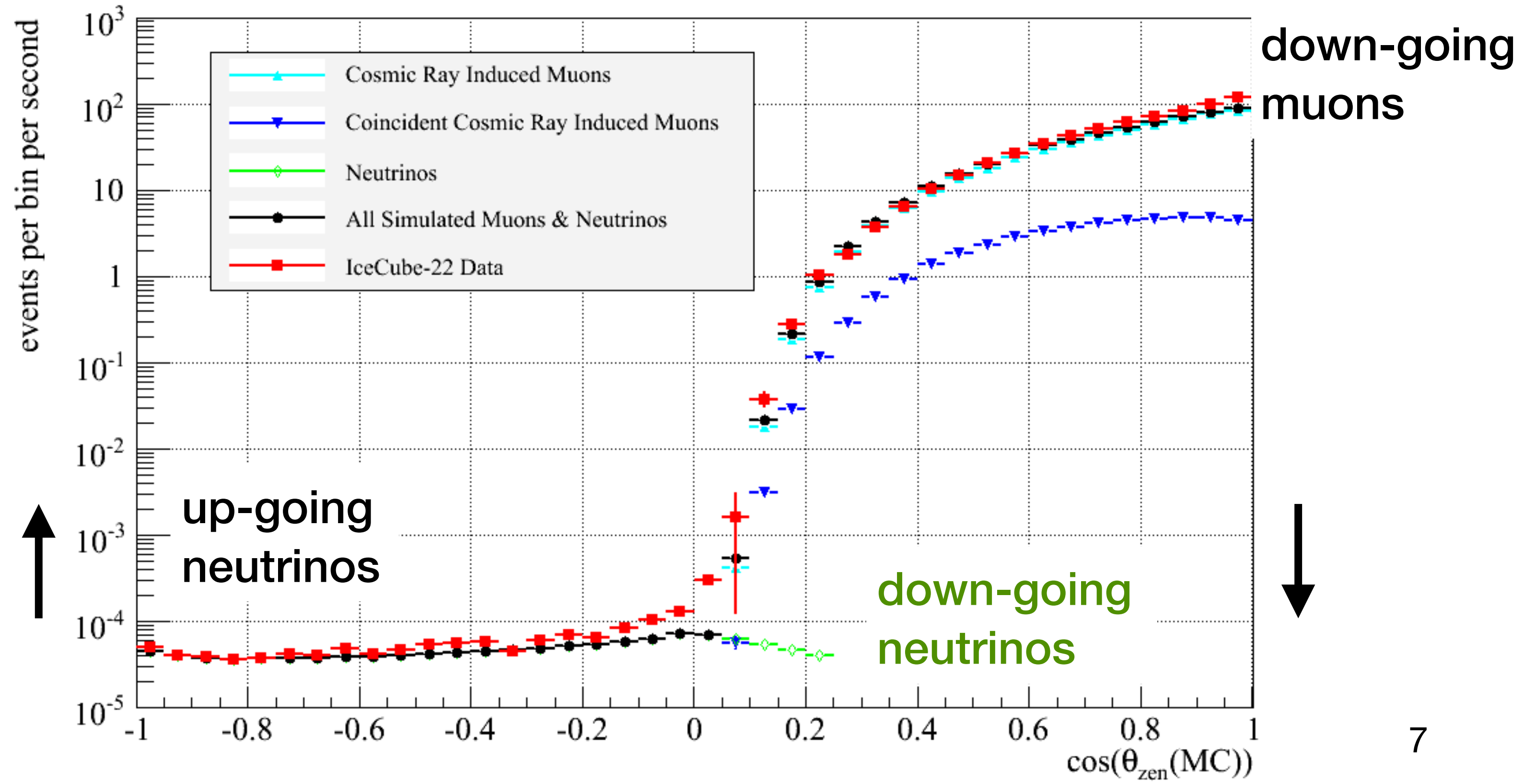
- ~ equal amount of μ and ν

cosmic ray muons and neutrinos

- R_{event} ~ 2200 Hz
- μ and ν produced in the atmosphere by **cosmic rays**
- atmospheric temperature seasonal variations

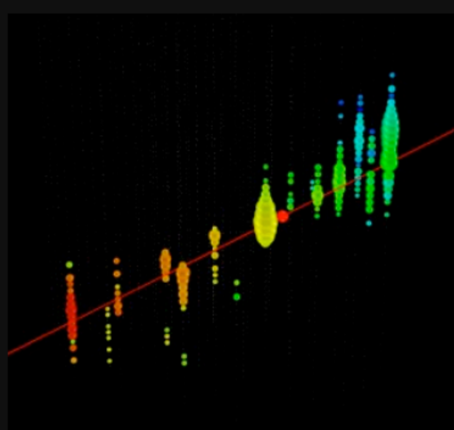
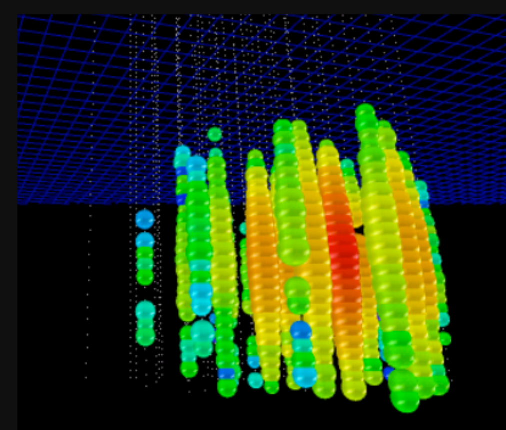
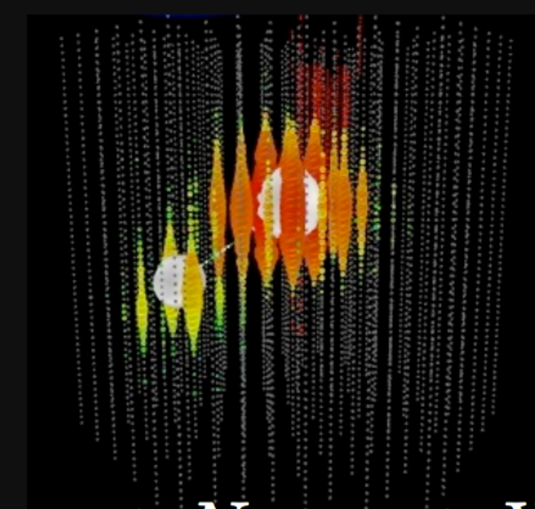


- ~1/10^6 TeV neutrinos interact in the ice and is detected and reconstructed in IceCube



neutrino detection

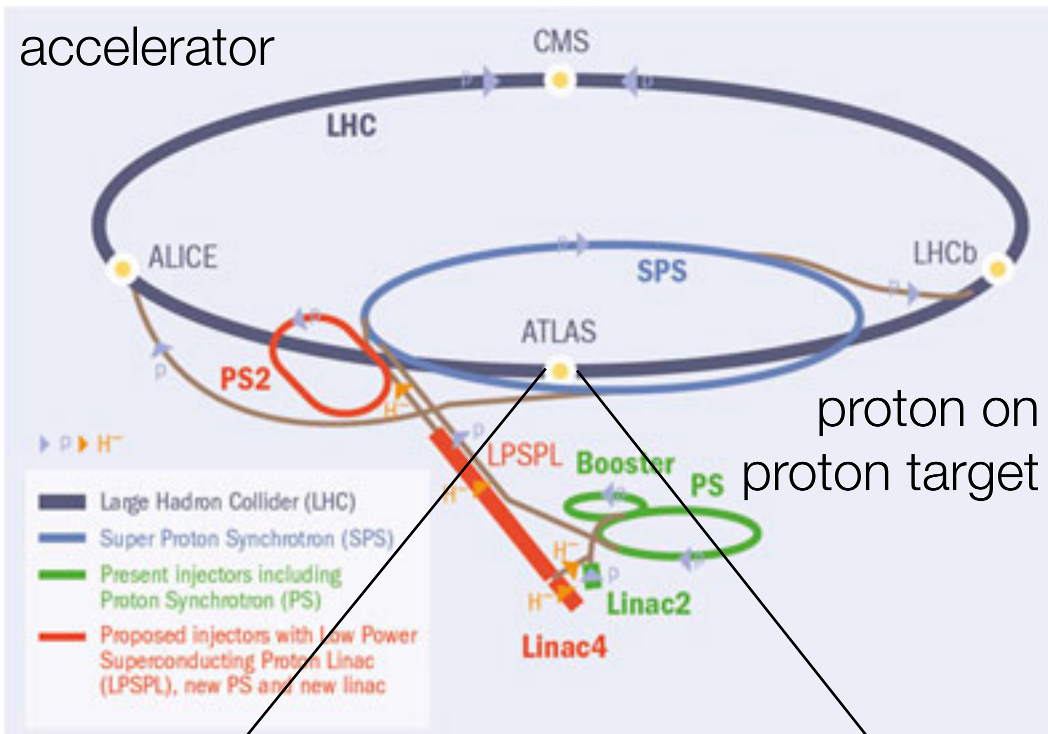
event topologies

track	**cascade**	**hybrid**
CC Muon Neutrino	**Neutral Current /Electron Neutrino**	**CC Tau Neutrino**
		
$\nu_\mu + N \rightarrow \mu + X$	$\nu_e + N \rightarrow e + X$ $\nu_x + N \rightarrow \nu_x + X$	$\nu_\tau + N \rightarrow \tau + X$
track (data)	cascade (data)	"double-bang" and other signatures (simulation)
factor of ≈ 2 energy resolution $< 1°$ angular resolution	$\approx \pm 15\%$ deposited energy resolution $\approx 10°$ angular resolution (at energies $\gtrsim 100$ TeV)	(not observed yet)

C. Kopper

cosmic rays
a natural laboratory

accelerator

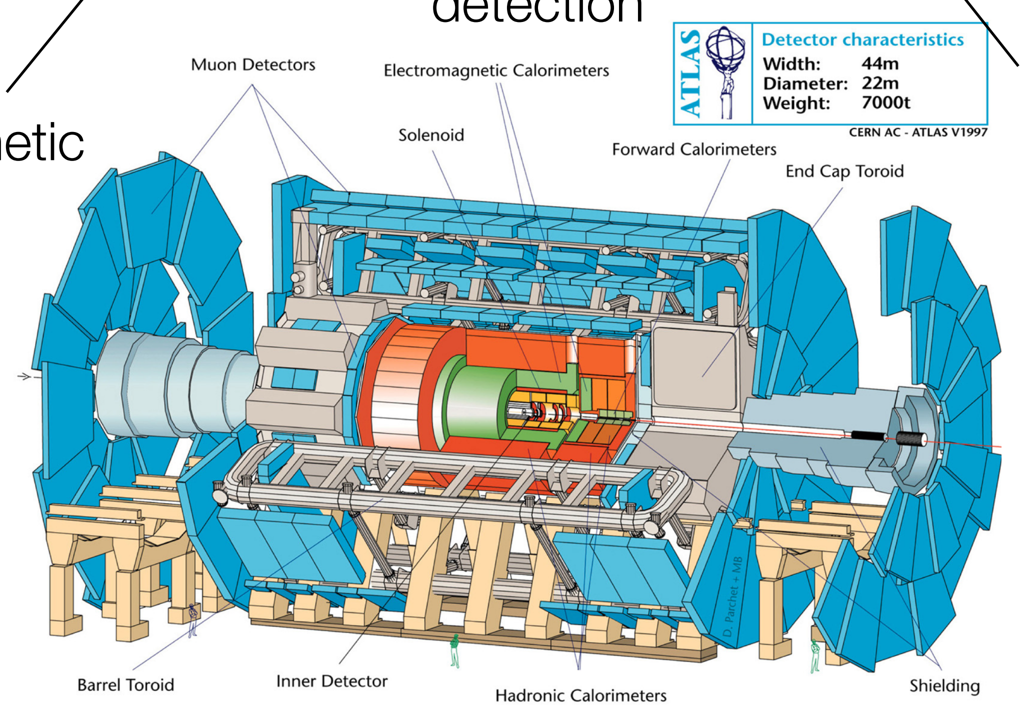


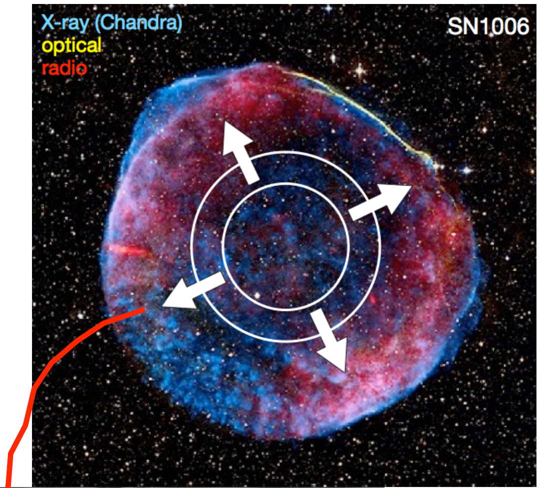
proton on proton target

propagation

detection

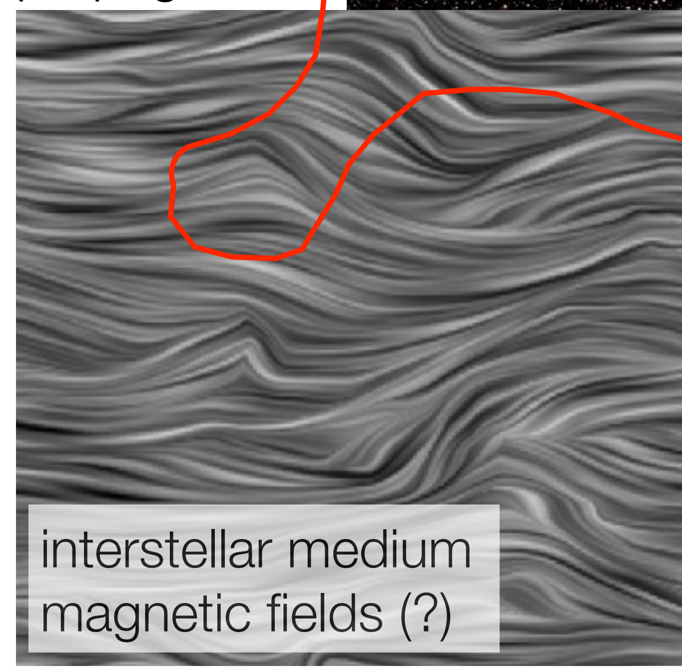
magnetic fields



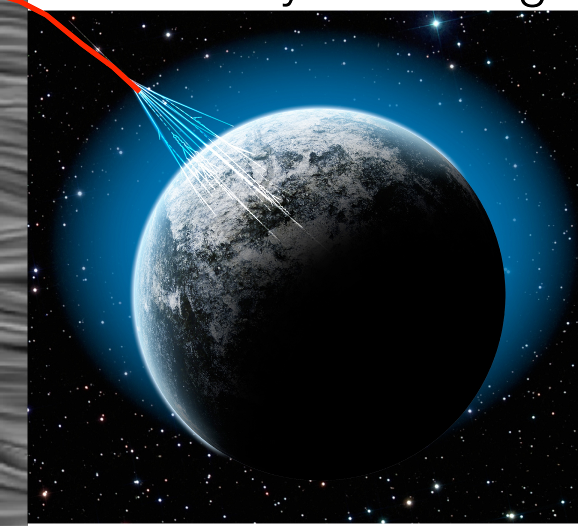


accelerator (?)

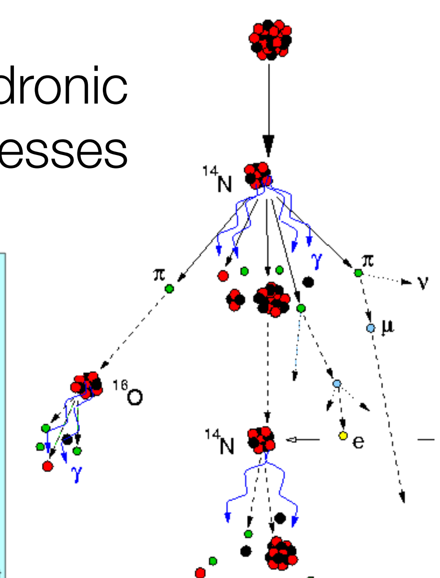
propagation

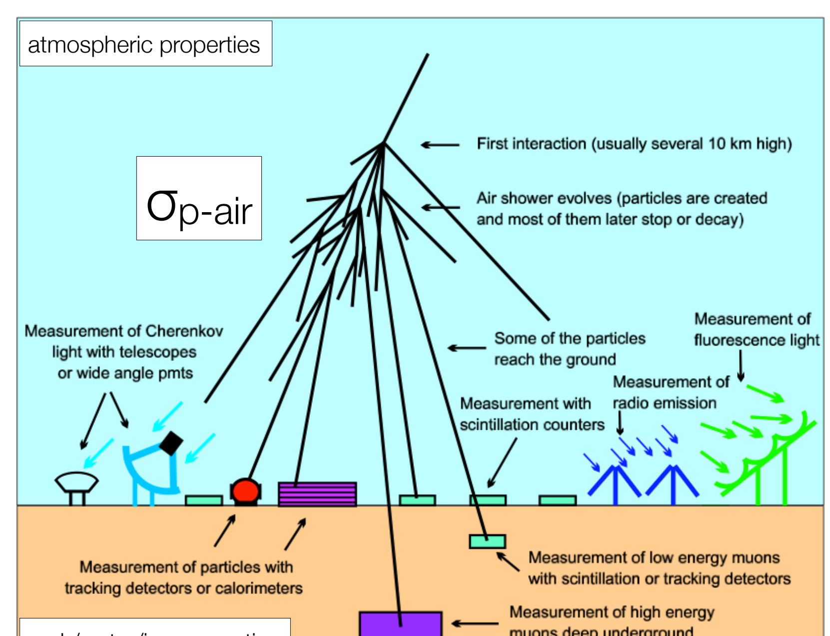


Earth atmosphere
dynamic target



nuclear & hadronic
processes





detection

cosmic ray acceleration mechanisms

where do cosmic ray come from ?

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 12×10^5 light-years.

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 per 10^3 years suggest that the

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 magmetic 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

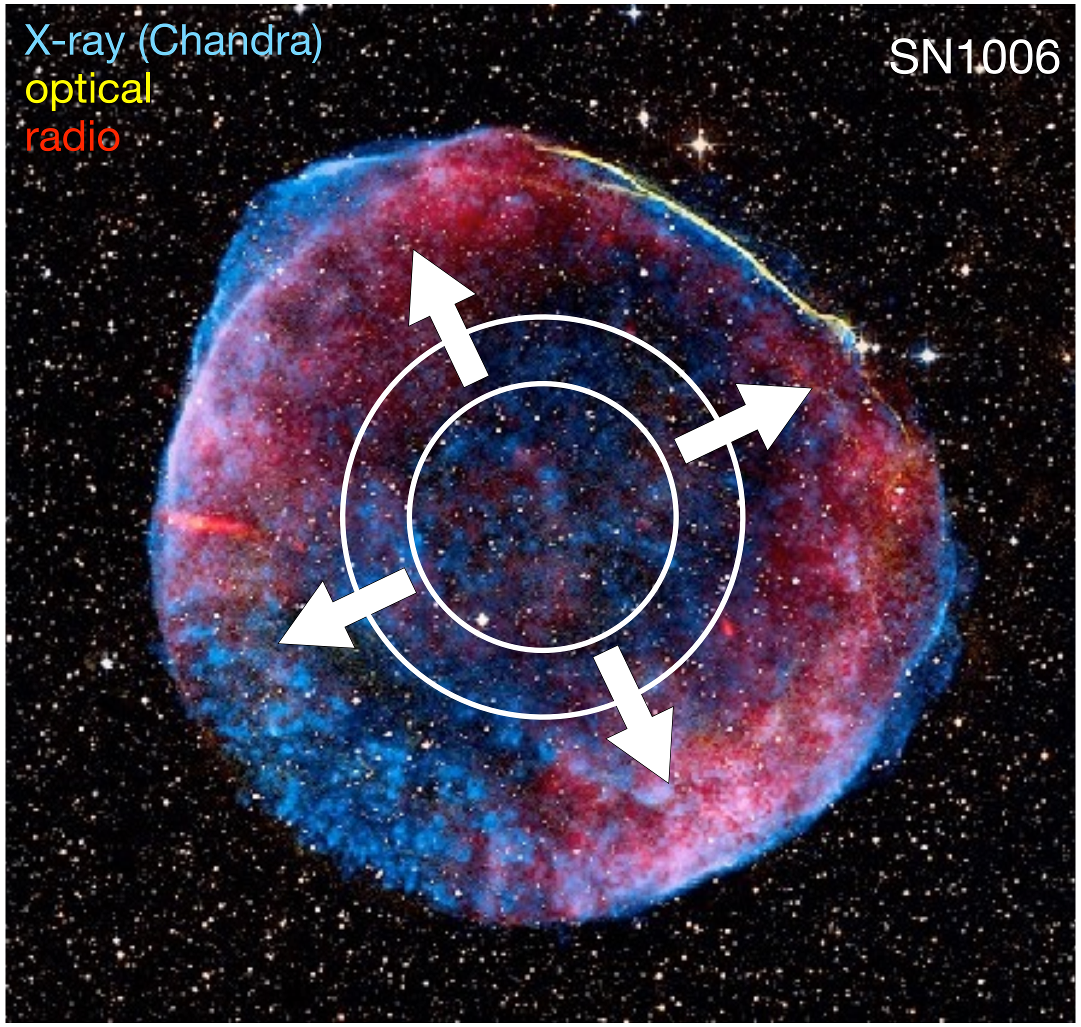
cosmic ray acceleration in supernova remnants

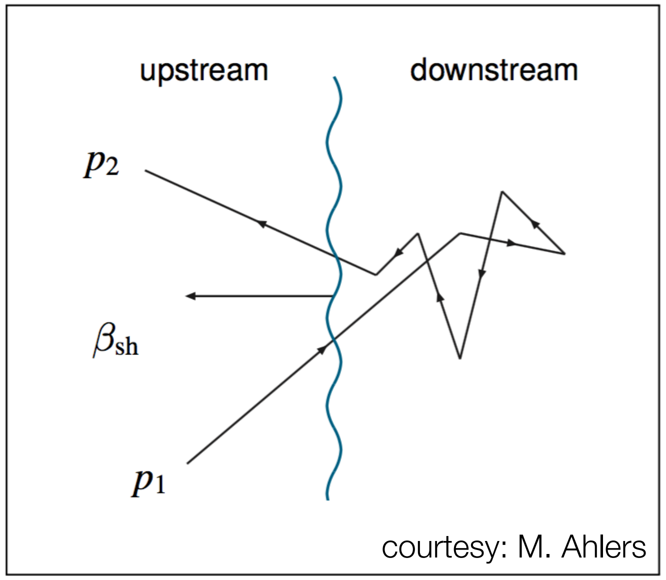
- energy density of cosmic rays **below the knee** consistent with **10%** of energy emitted by SNR every **30 years** in the Galaxy

- composition of **low energy** cosmic rays consistent with **OB Associations**

- diffusive shock acceleration and $\mathbf{E^{-2}}$

- some particles interacts and some escape and **propagate** across the interstellar medium





cosmic rays

reconstruct their history

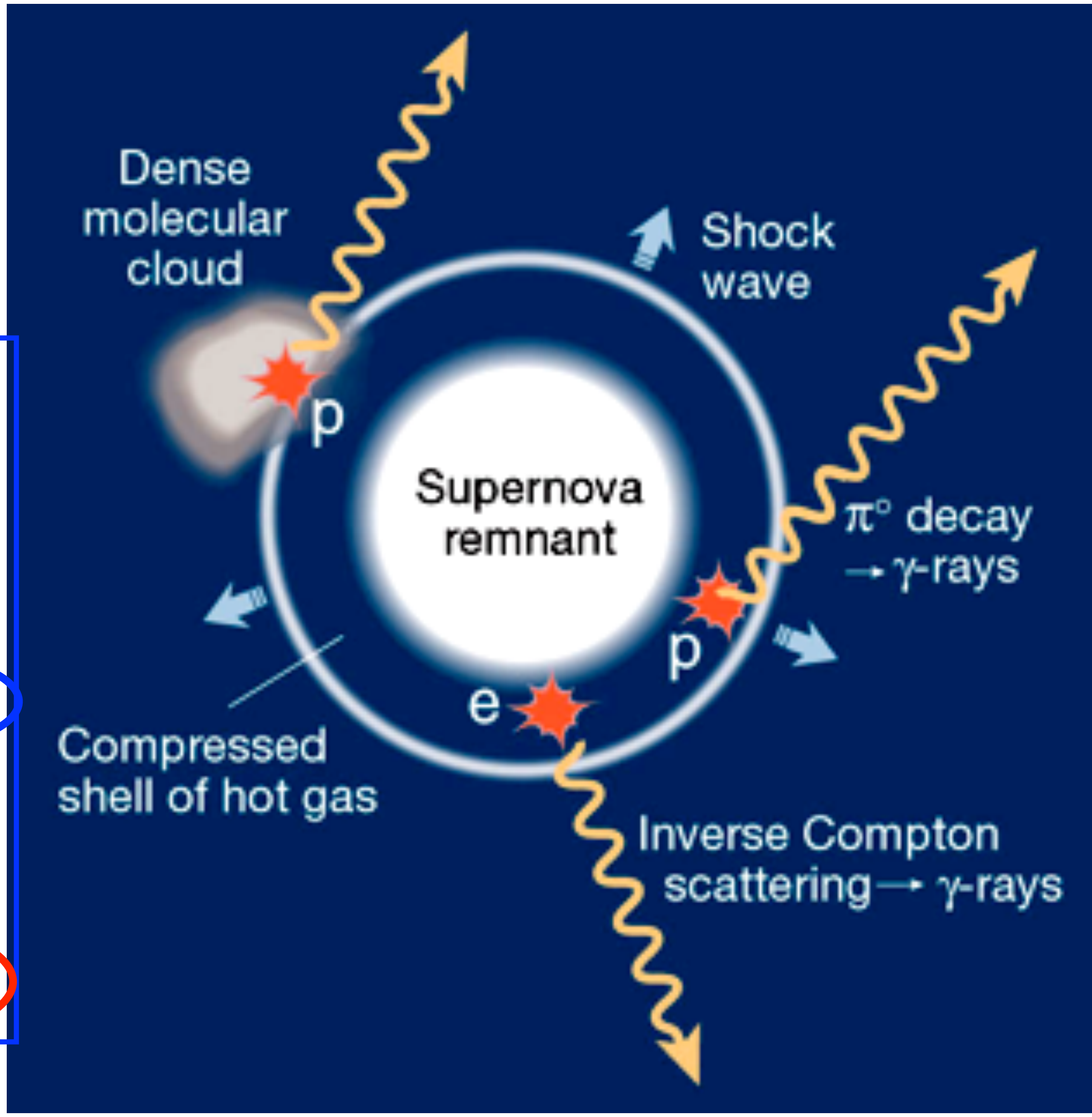
$$p + N \rightarrow p(n) + \pi^+ + \pi^- + \pi^0$$

$$\pi^0 \rightarrow \gamma + \gamma$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

hadronic emission



$$e^\pm + B \rightarrow e^\pm + \gamma_{synchrotron}$$

$$e^\pm + \gamma_{soft} \rightarrow e^\pm + \gamma_{Inverse\ Compton}$$

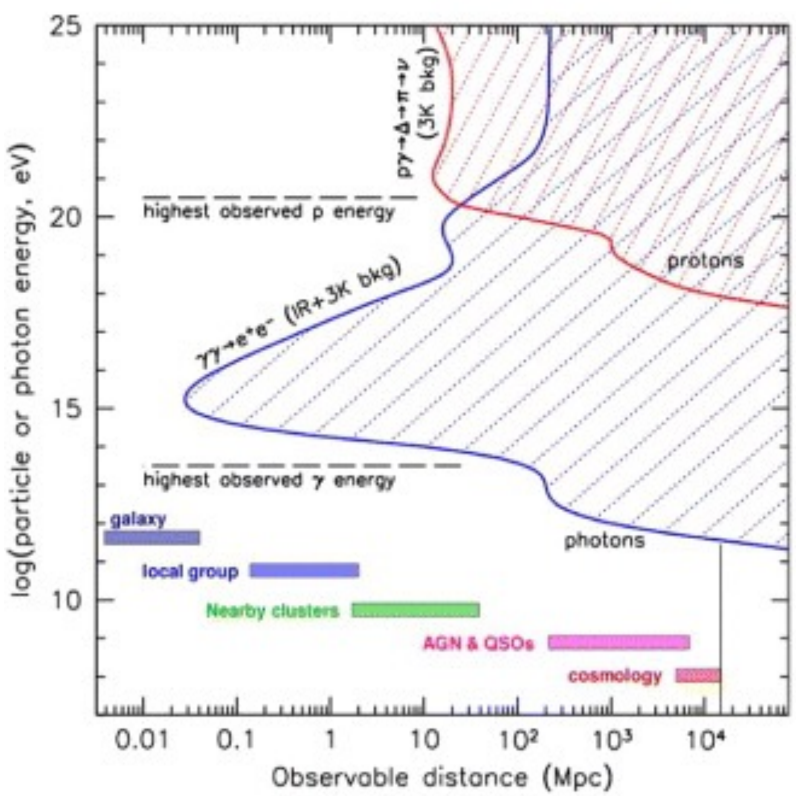
electromagnetic emission

leptonic & hadronic processes

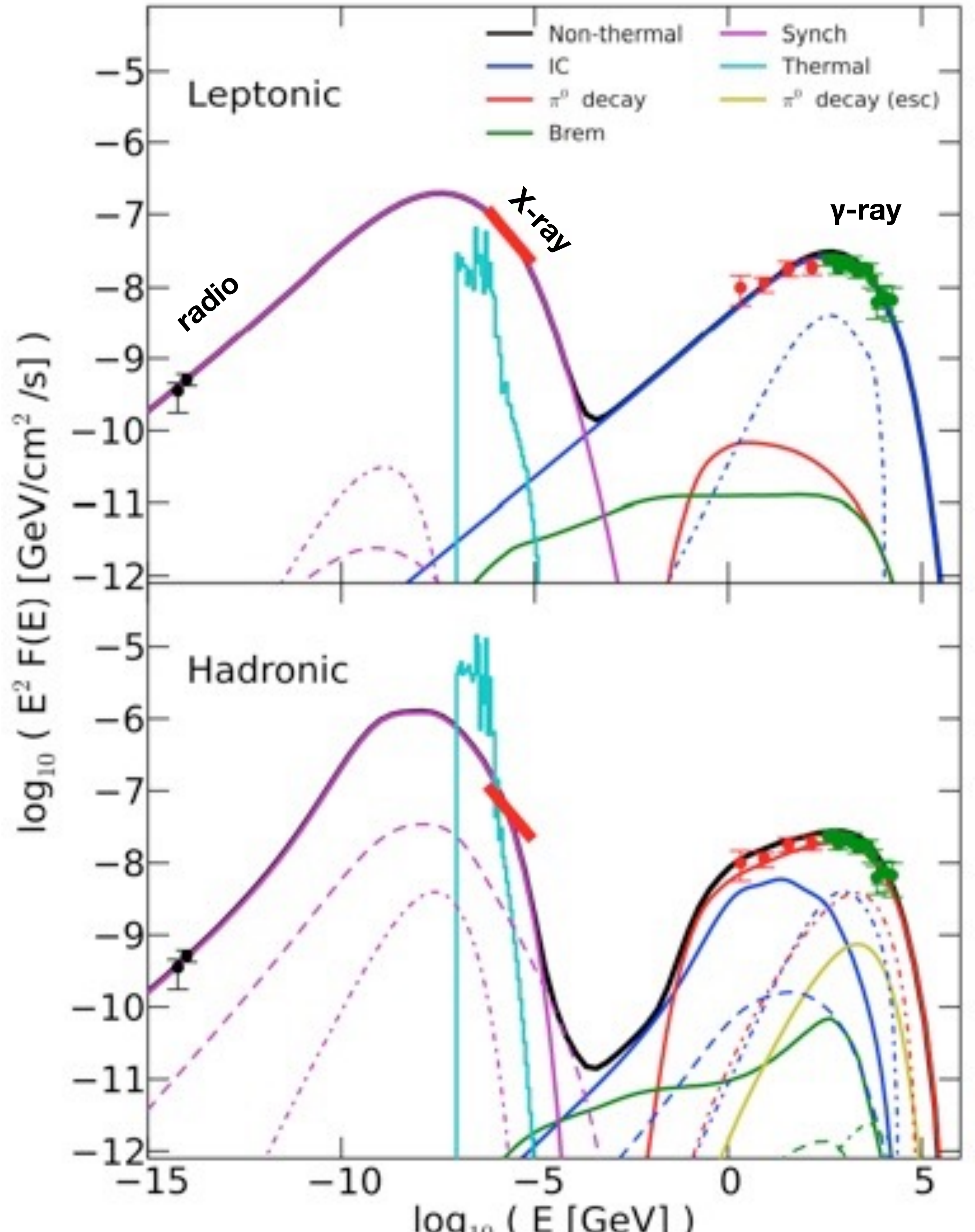
importance of neutrinos

multi-wavelength spectrum of young SNR Vela Jr.

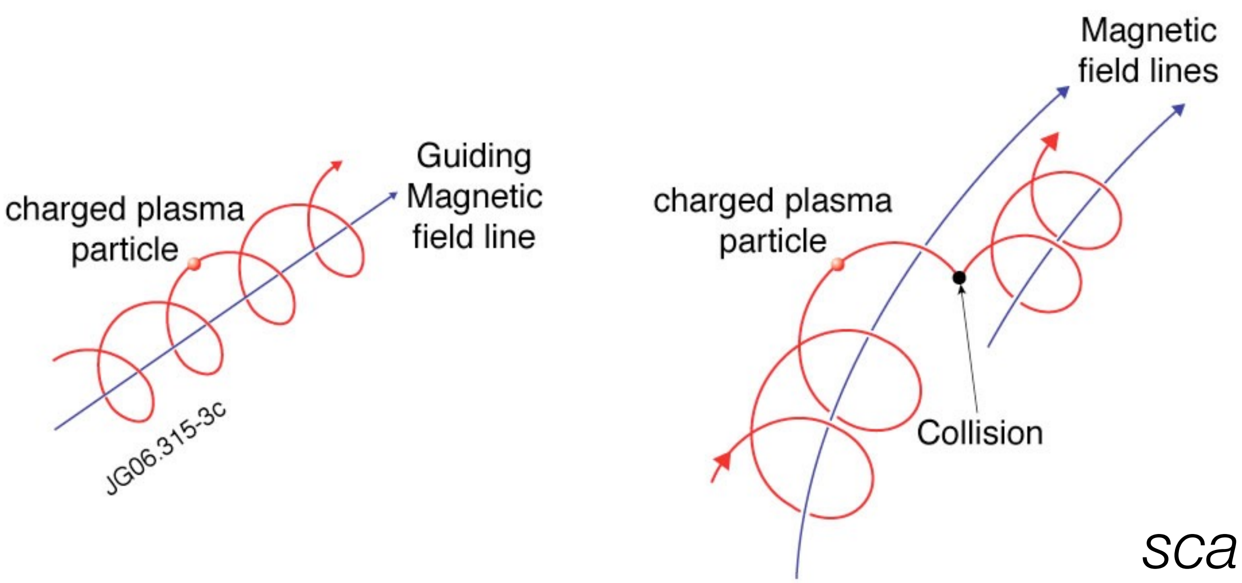
- neutral particles
- point back to sources
- limited observable distance
- HE gamma rays absorbed in space



P. Gorham

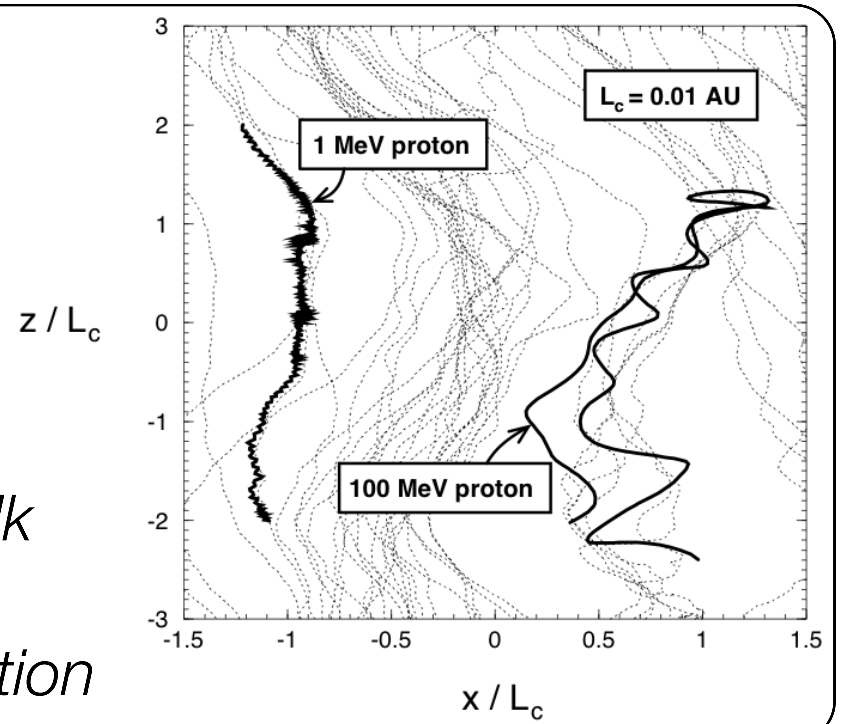


cosmic ray propagation in interstellar medium



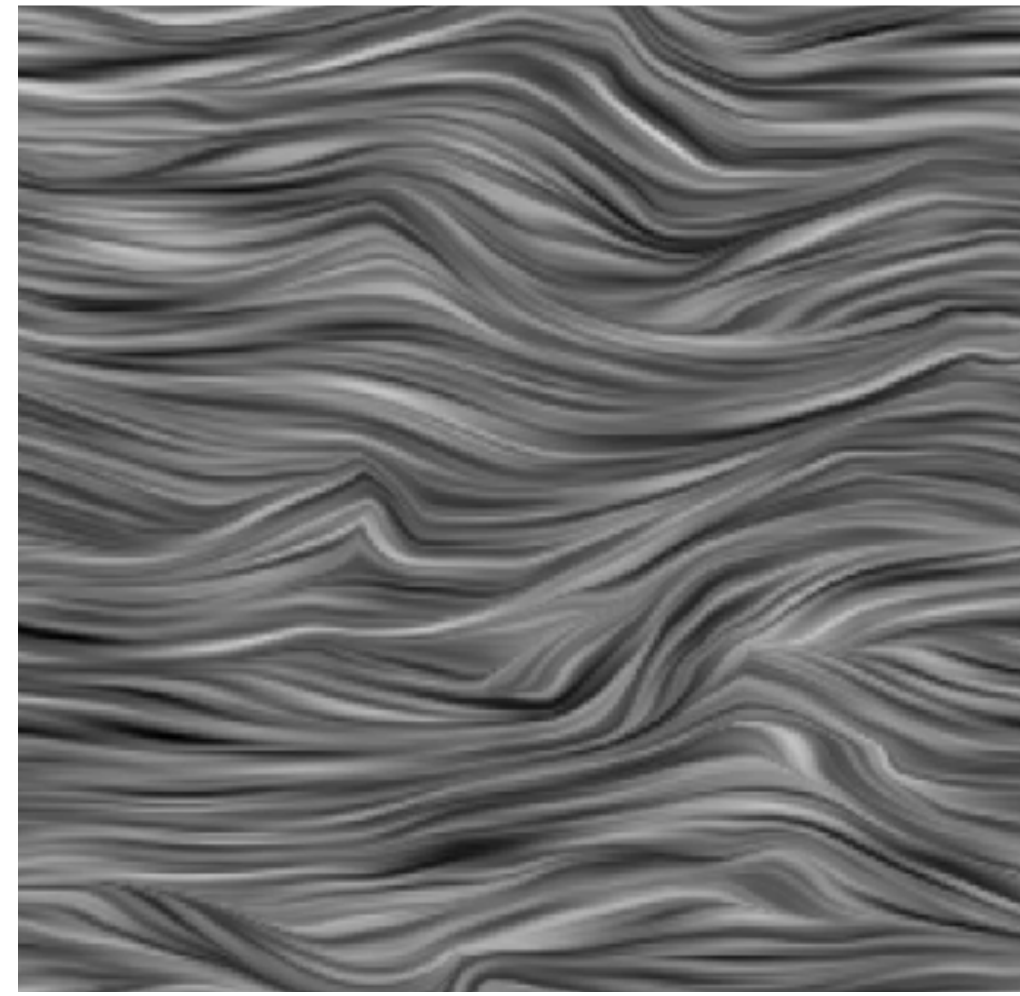
scattering

collisionless scattering



field line random walk
&
cross fieldline propagation

astrophysical turbulence properties



propagation leads to **diffusion**

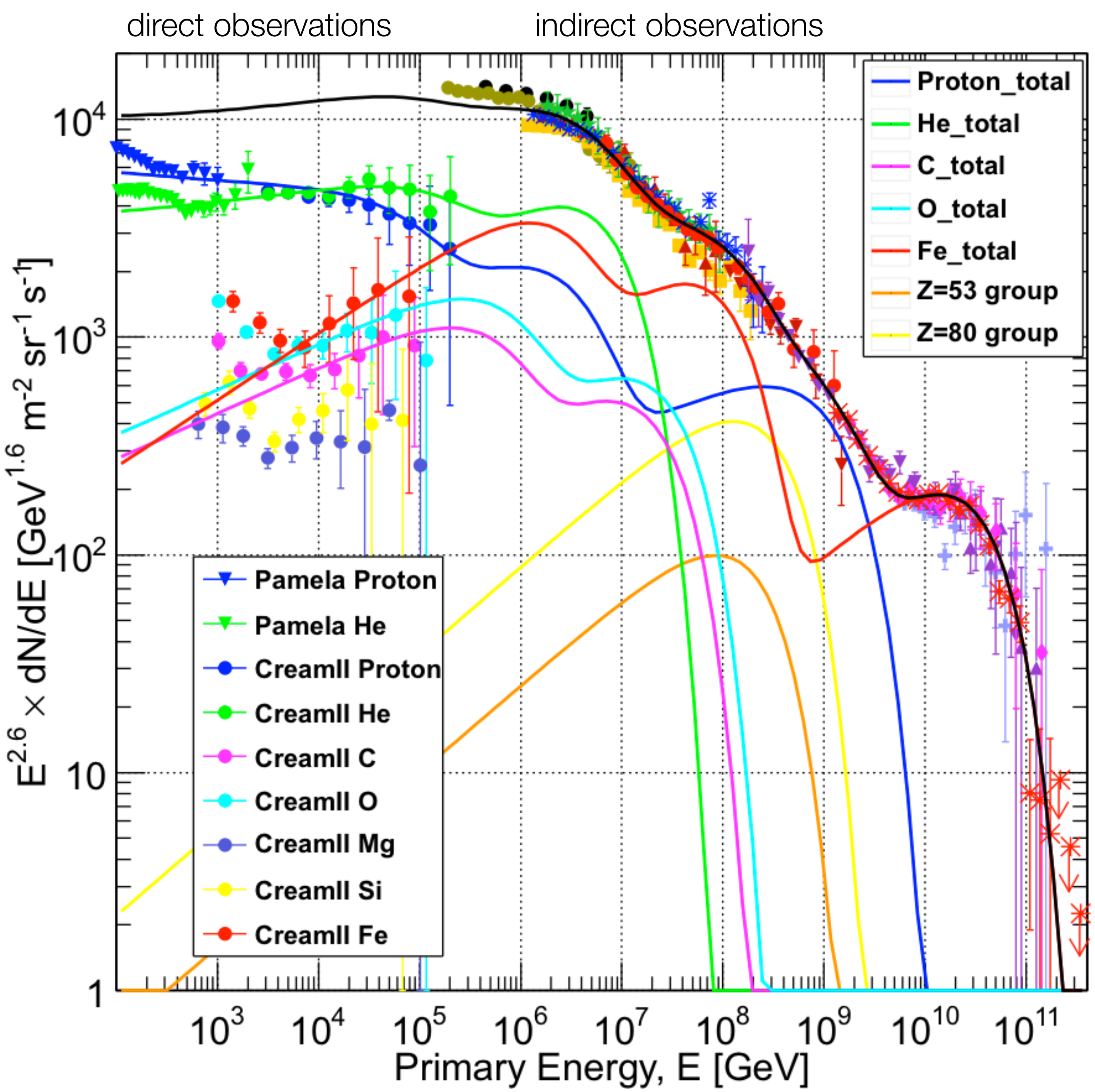
depends on interstellar **magnetic field properties**

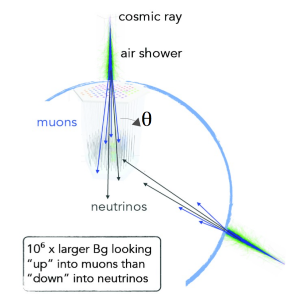
primary cosmic rays

spectrum

Gaisser, Stanev, Tilav, 2013 - arXiv:1303.3565

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

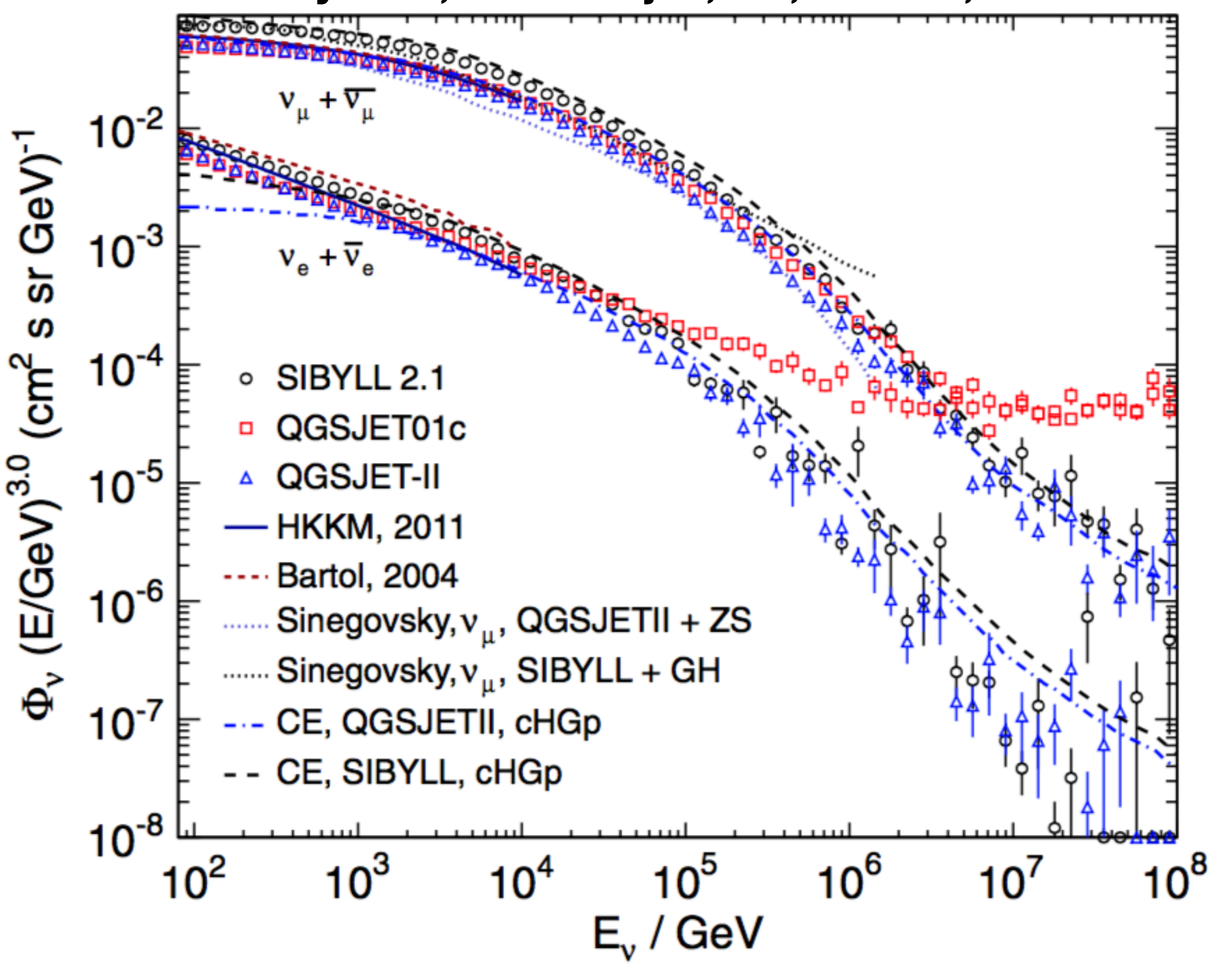


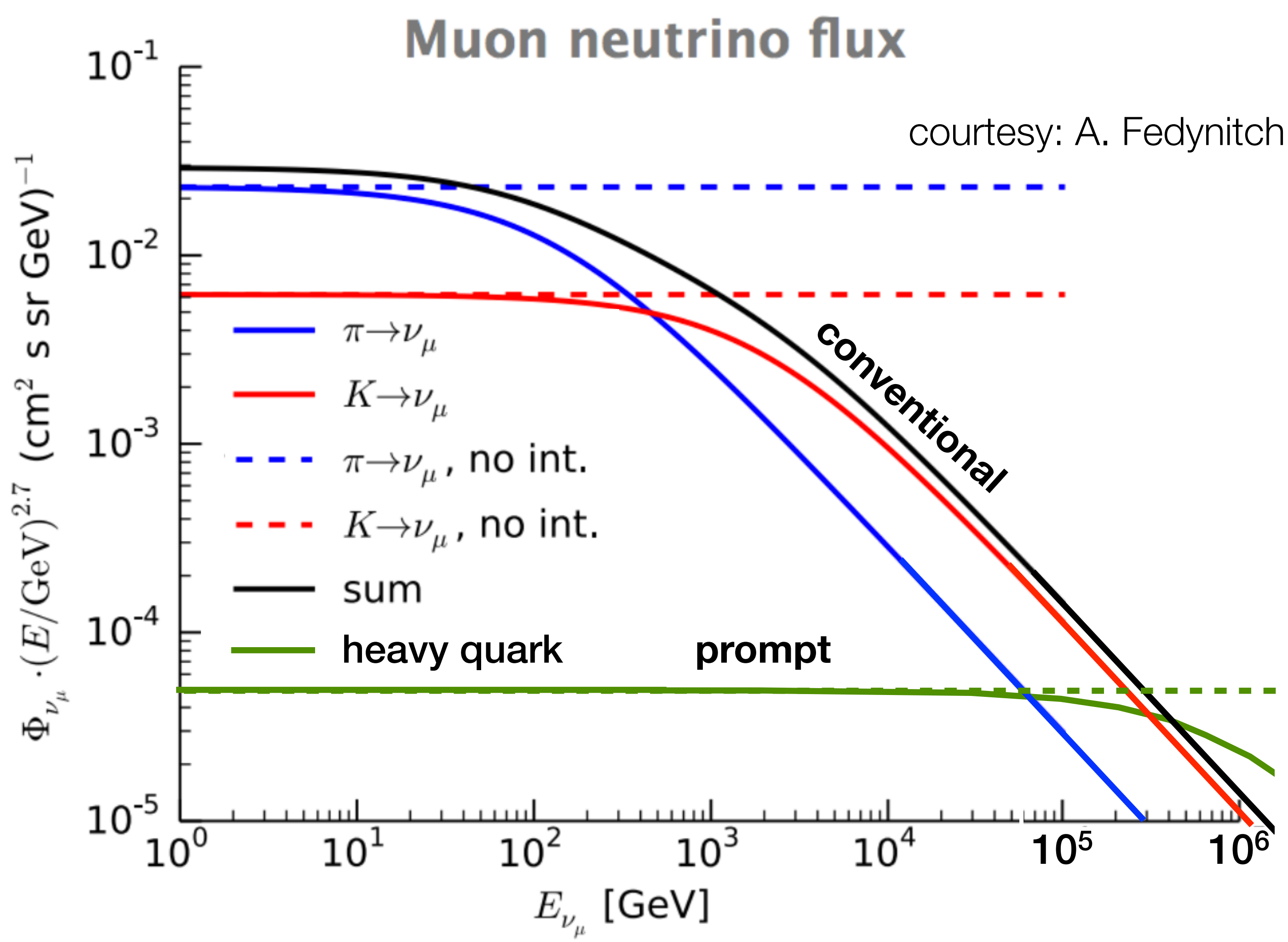


atmospheric neutrinos

energy spectrum

Fedynitch, Becker Tjus, PD, PRD 86, 114024

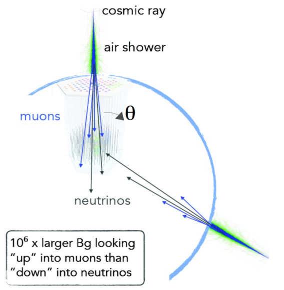




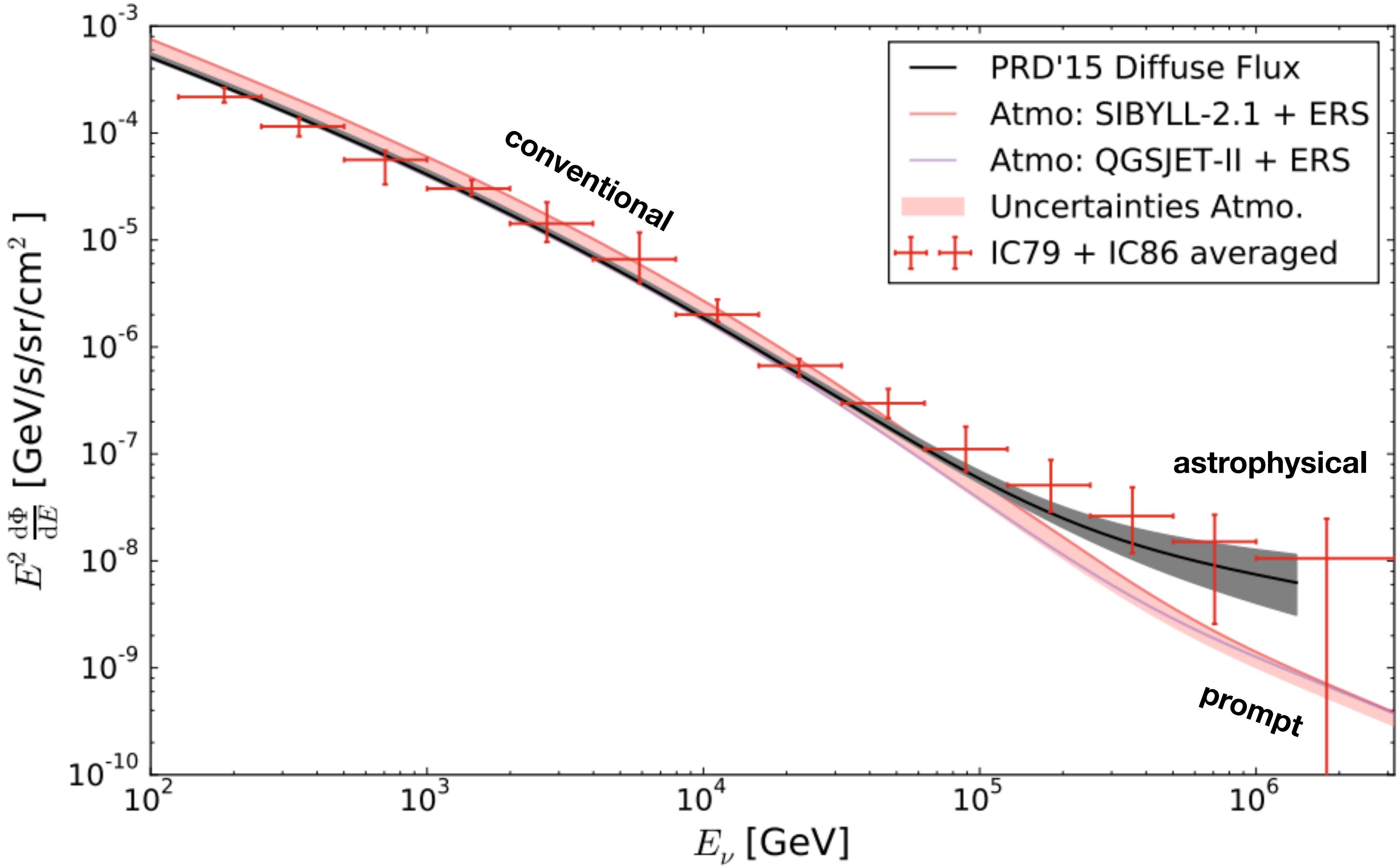
- neutrinos and muons produced by **cosmic rays** in the **atmosphere** from **meson decay**
- **large uncertainties** on high energy **hadronic interaction models** in **forward region**

atmospheric neutrinos

energy window to astrophysical neutrinos

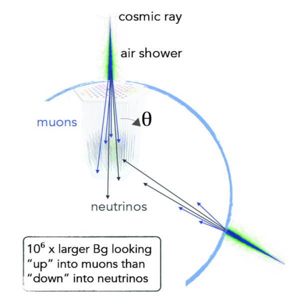


ICRC 2015 - Den Haag, NL



atmospheric neutrinos

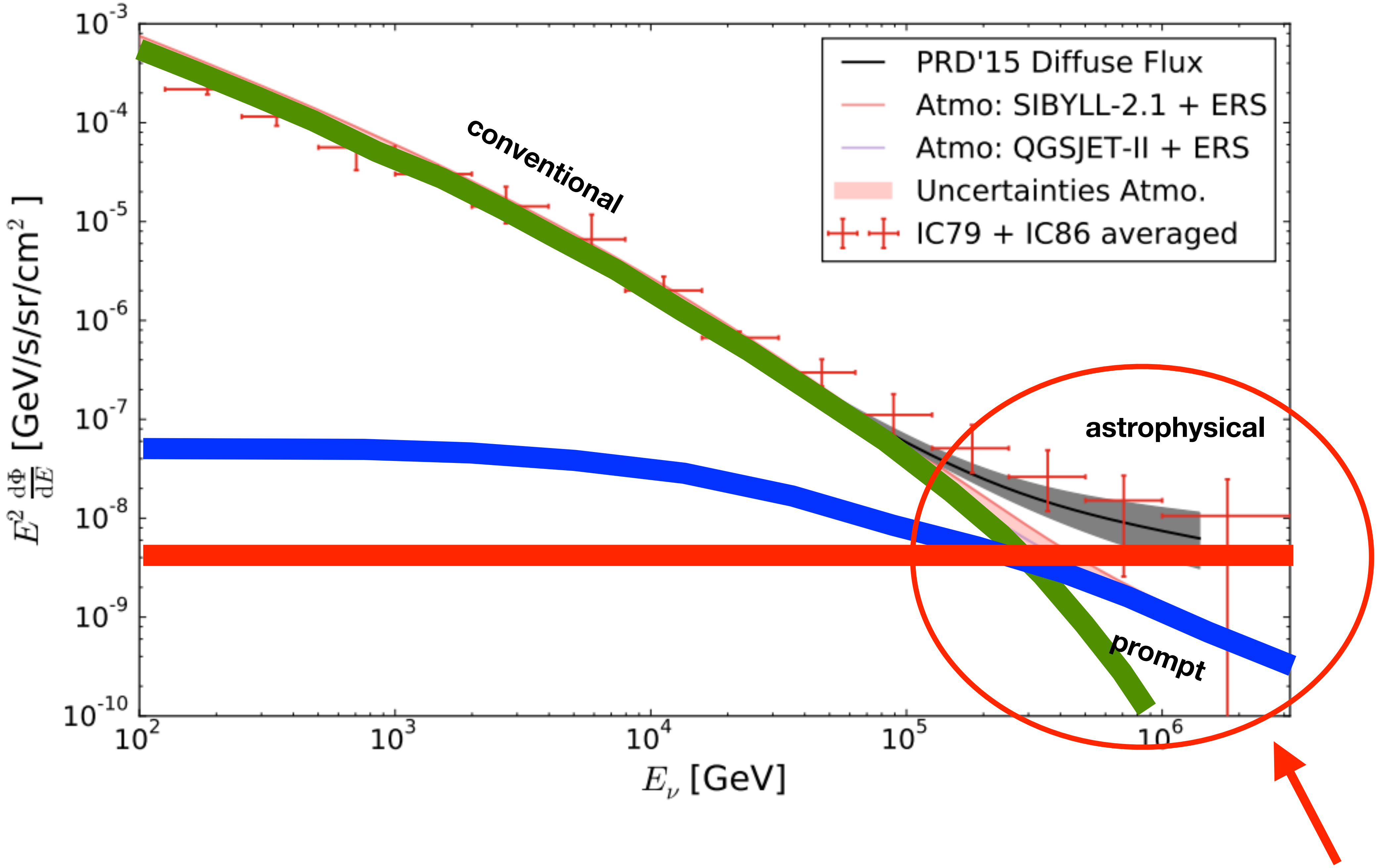
energy window to astrophysical neutrinos



ICRC 2015 - Den Haag, NL

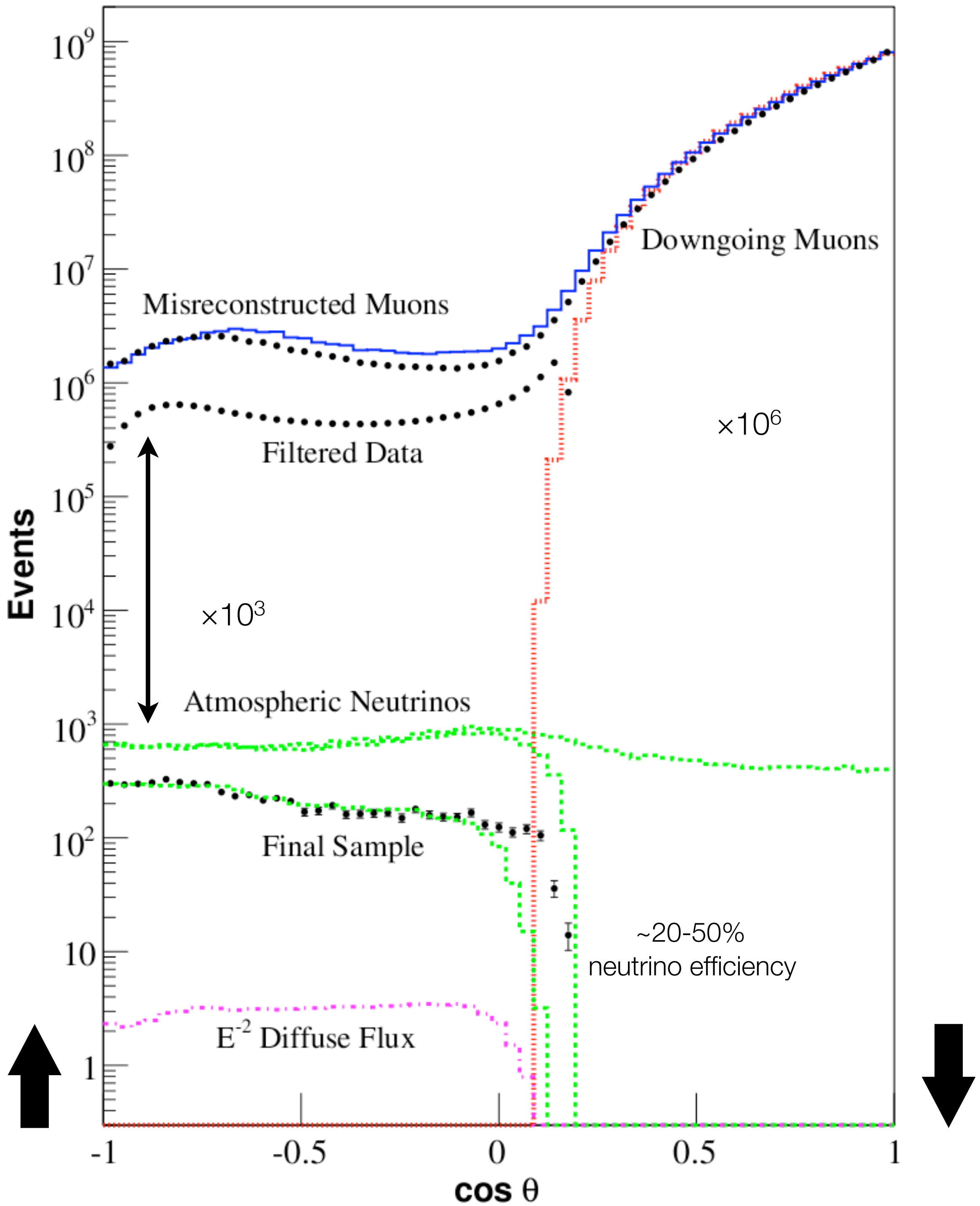
π, K

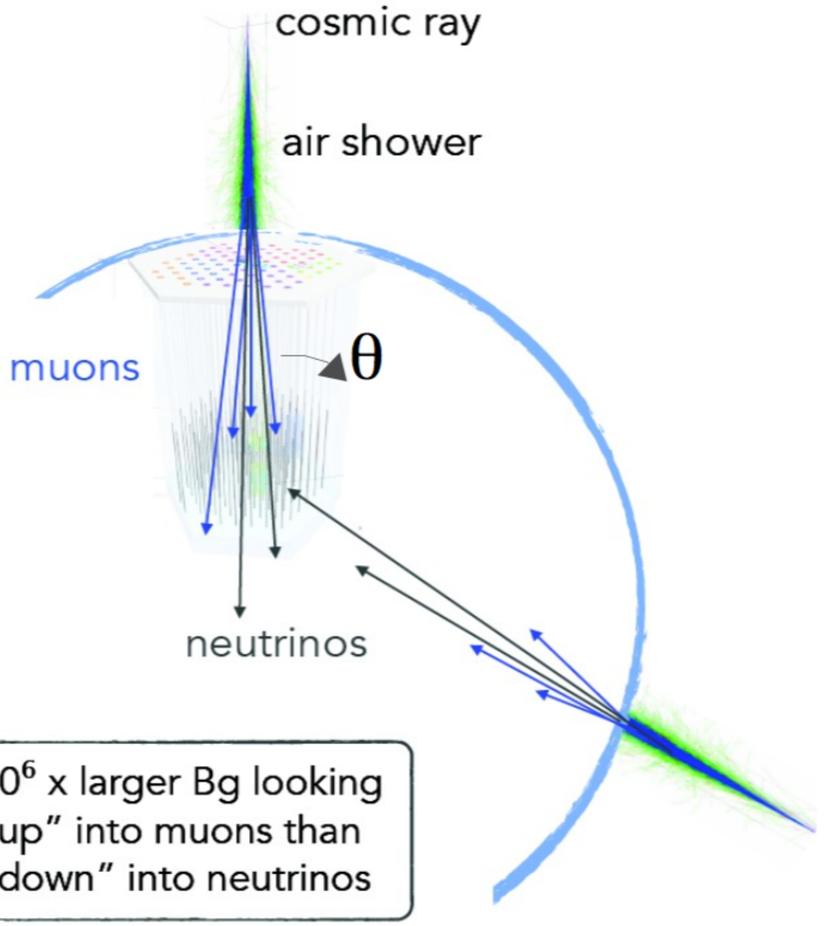
D, Λ with charm quark



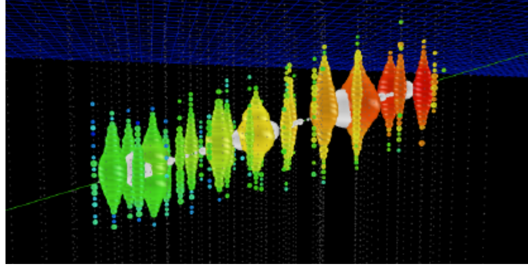
LET’S EXPLORE RIGHT AWAY THE ASTROPHYSICAL SEARCH WINDOW

searching for neutrinos
background rejection

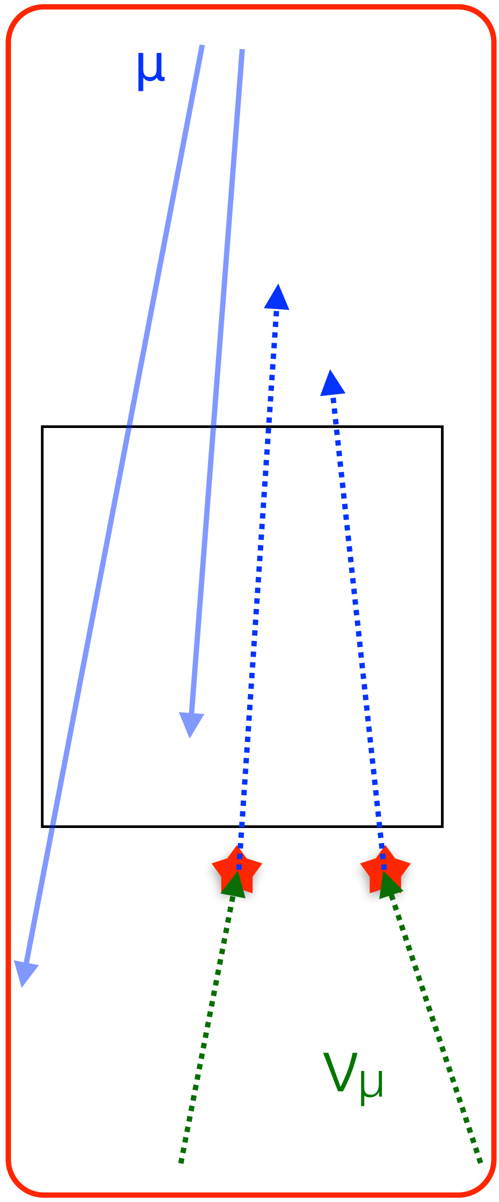




10^6 x larger Bg looking "up" into muons than "down" into neutrinos

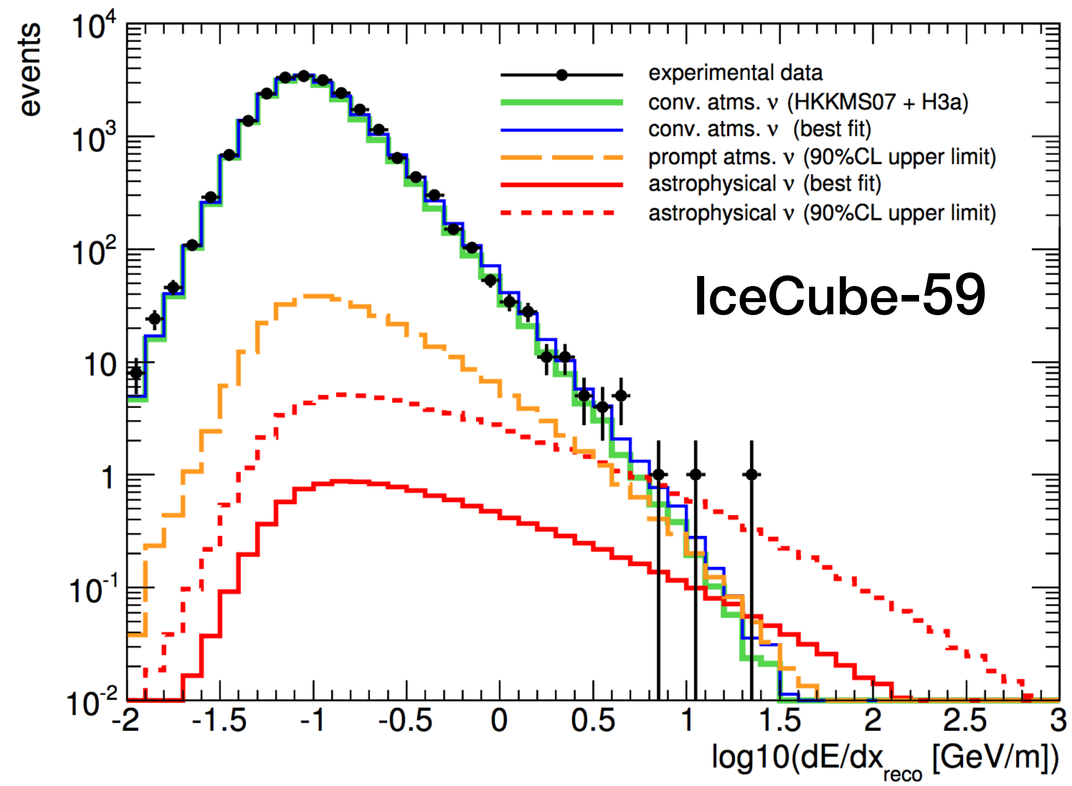


up-going through-going (tracks)

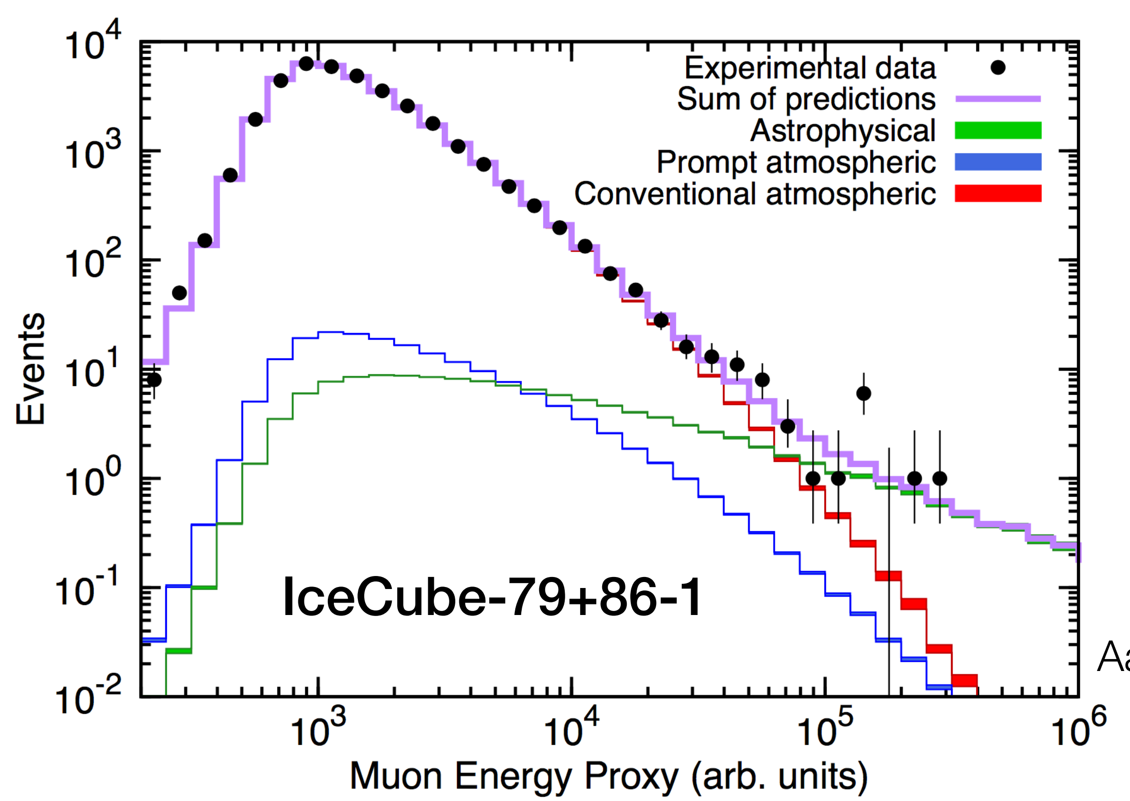


neutrino identification

diffuse flux

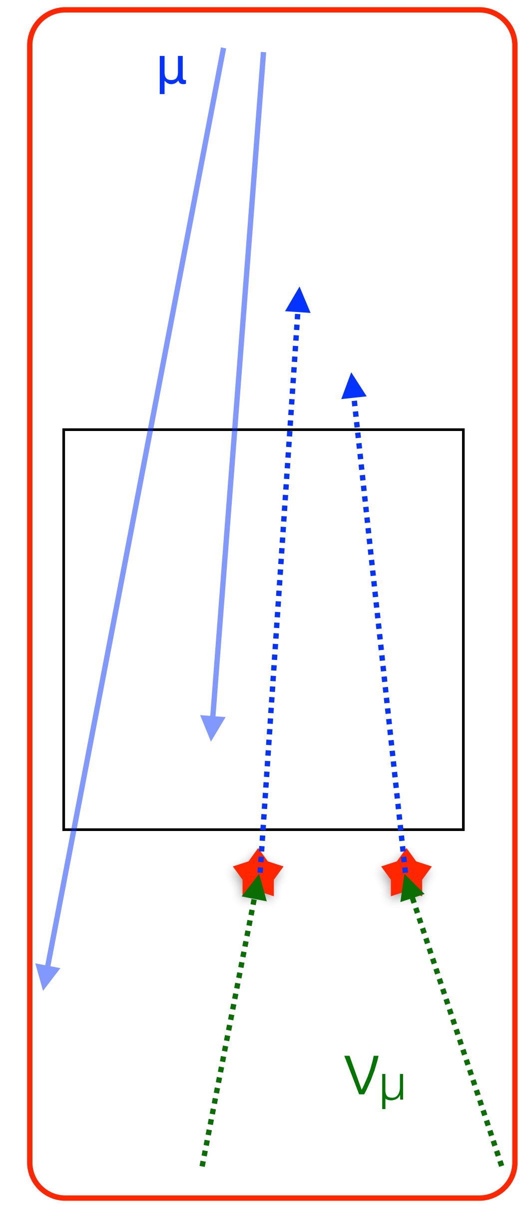


Aartsen et al. Phys. Rev. D 89 (2014), 062007



Aartsen et al. Phys.Rev.Lett. 115 (2015) 8, 081102

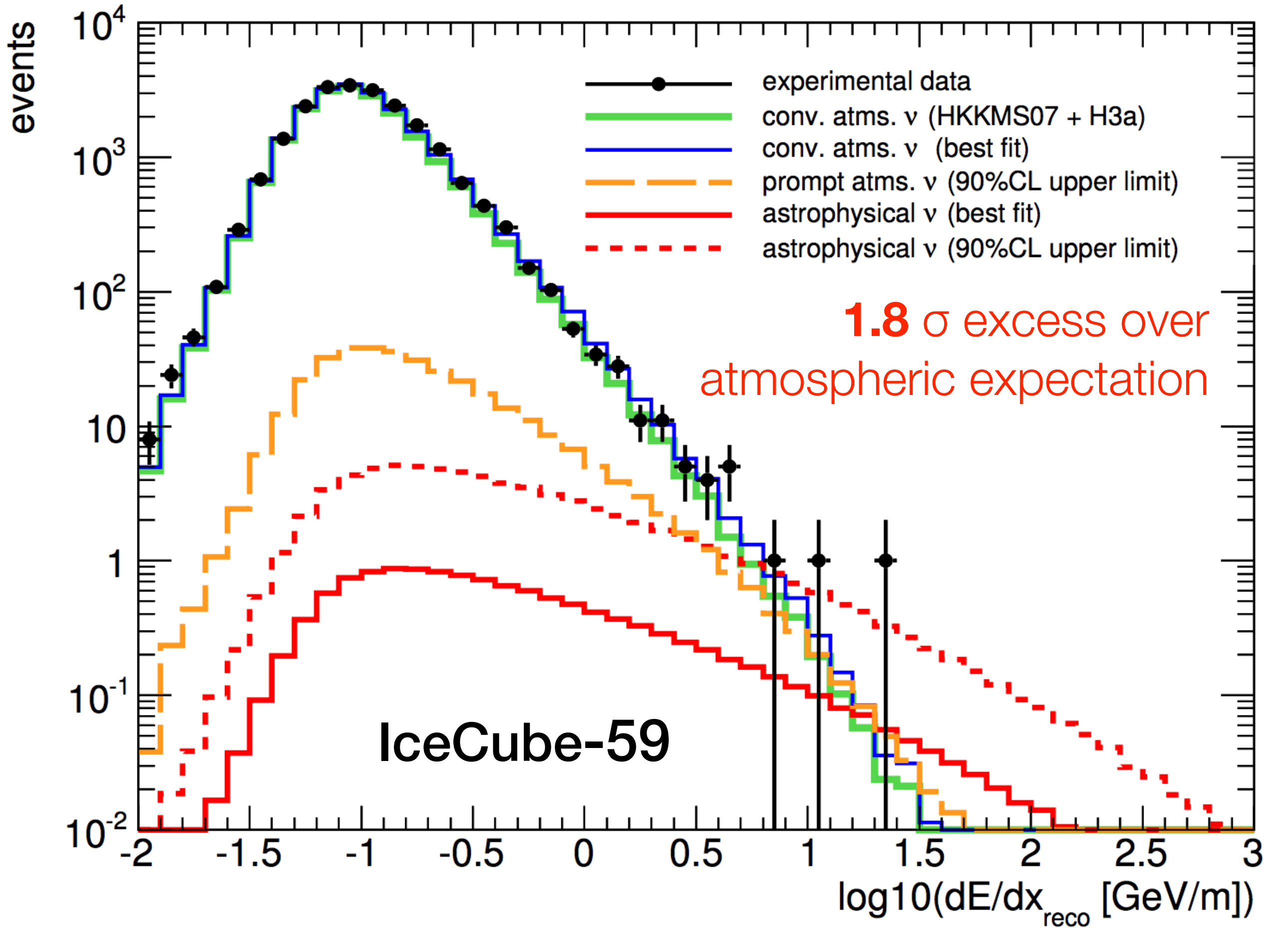
up-going through-going (tracks)



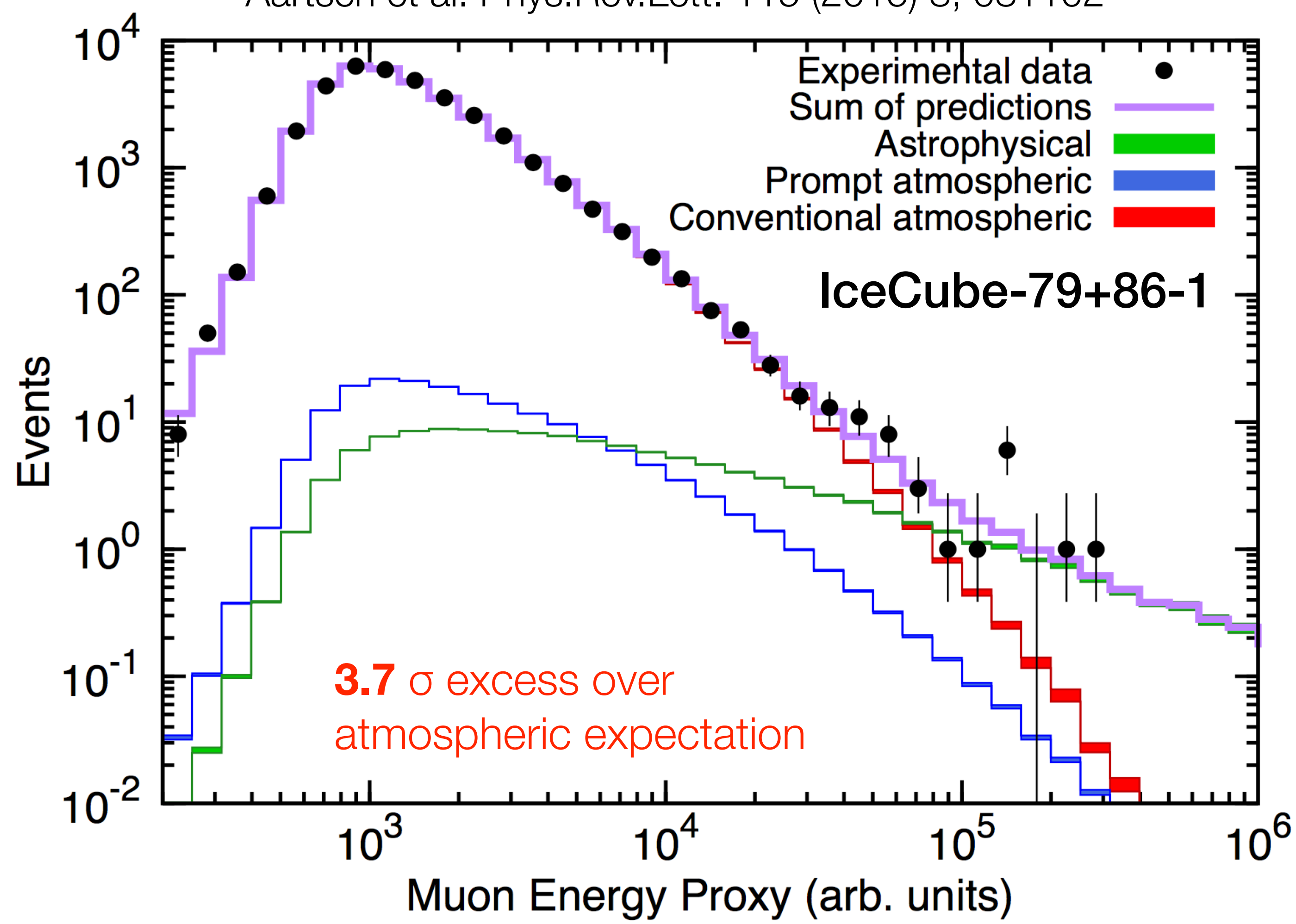
ERS: Enberg, Reno, Sarcevic 2008

neutrino identification
diffuse flux

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



Aartsen et al. Phys.Rev.Lett. 115 (2015) 8, 081102



$$\Phi^{astro}_{fit}(E) = 0.25 \times 10^{-8} \times E^{-2}\ GeV^{-1} cm^{-2} s^{-1} sr^{-1}$$
$$\Phi^{prompt}_{fit}(E) = 0$$

$$\Phi^{astro}_{90\%CL}(E) = 1.44 \times 10^{-8} \times E^{-2}\ GeV^{-1} cm^{-2} s^{-1} sr^{-1}$$
$$\Phi^{prompt}_{90\%CL}(E) = 3.8 \cdot \Phi_{ERS}(E)$$

$$\Phi^{astro}_{fit}(E) = 9.9 \times 10^{-19} \times \left(\frac{E}{100\,TeV}\right)^{-2}\ GeV^{-1} cm^{-2} s^{-1} sr^{-1}$$
$$\Phi^{prompt}_{fit}(E) = 0.94 \cdot \Phi_{ERS}(E)$$

$$\Phi^{astro}_{fit}(E) = 1.7 \times 10^{-18} \times \left(\frac{E}{100\,TeV}\right)^{-2.2}\ GeV^{-1} cm^{-2} s^{-1} sr^{-1}$$
$$\Phi^{prompt}_{fit}(E) = 0$$

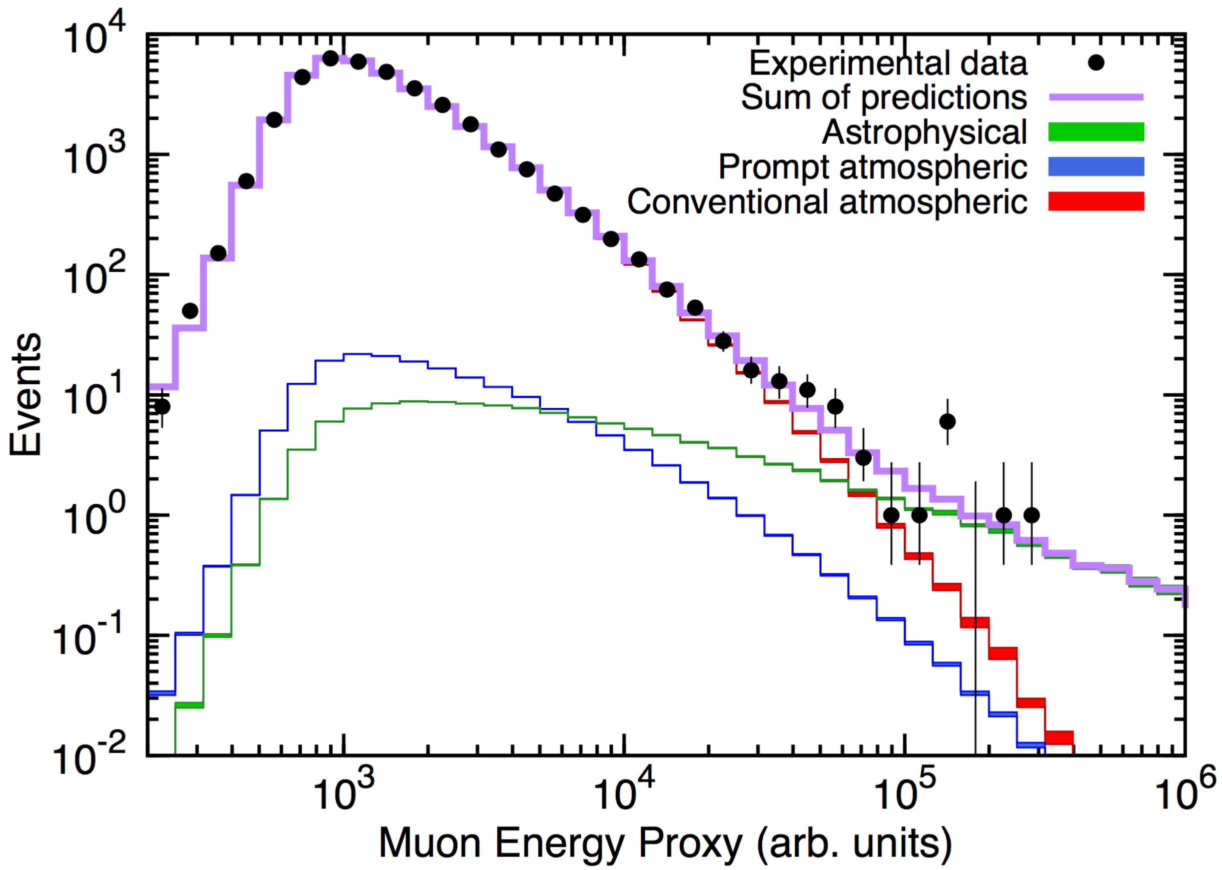
neutrino identification

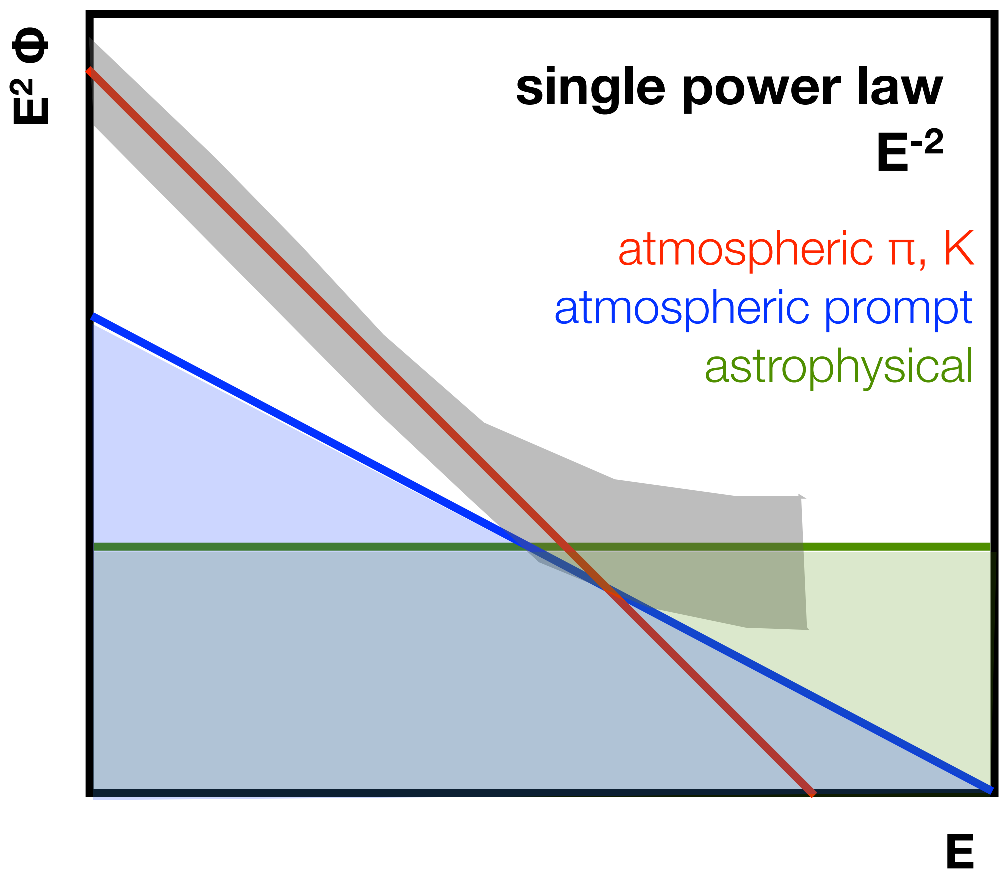
diffuse flux

- **conventional ν_μ**: Honda et al. 2004 - extended to high energy
- **prompt ν_μ**: Enberg et al. 2008
- **new** calculations available with updated cosmic ray spectrum & composition

- the **harder** astrophysical spectrum the **higher** prompt neutrino needed to fit data
- **low statistics**: results consistent

Aartsen et al. Phys.Rev.Lett. 115 (2015) 8, 081102

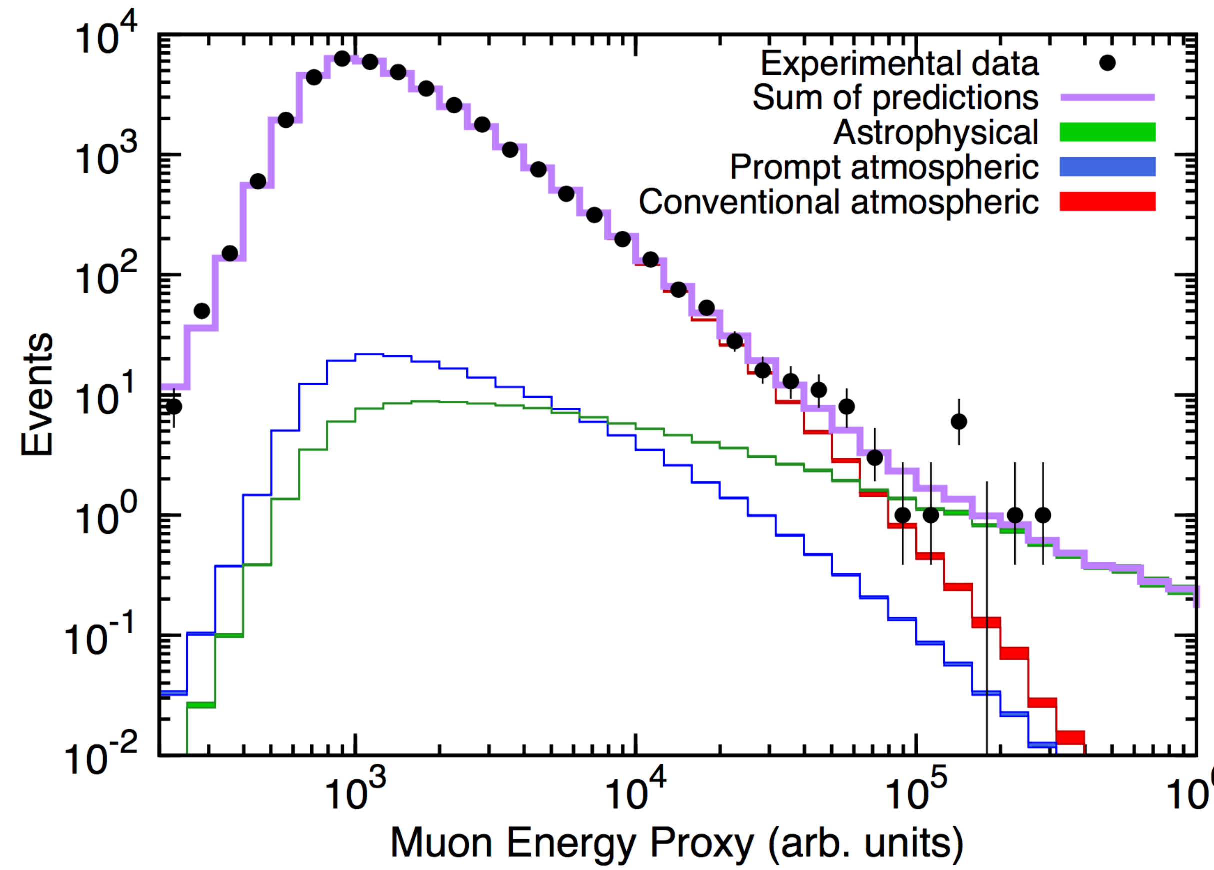


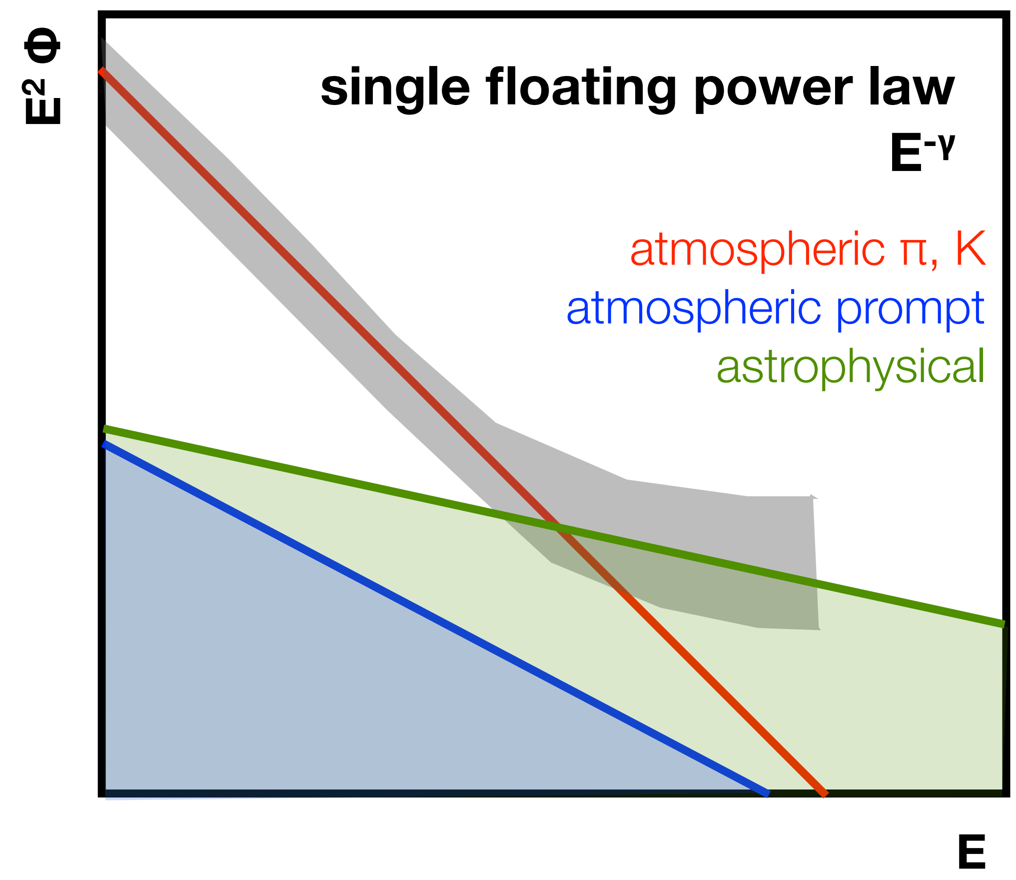


Aartsen et al. Phys.Rev.Lett. 115 (2015) 8, 081102

neutrino identification
diffuse flux

- **conventional ν_μ**: Honda et al. 2004 - extended to high energy
- **prompt ν_μ**: Enberg et al. 2008
- cosmic ray spectrum & composition with **knee** included after original calculations
- **new** calculations available with updated cosmic ray spectrum & composition
- the **harder** astrophysical spectrum the **higher** prompt neutrino needed to fit data
- **low statistics**: results consistent



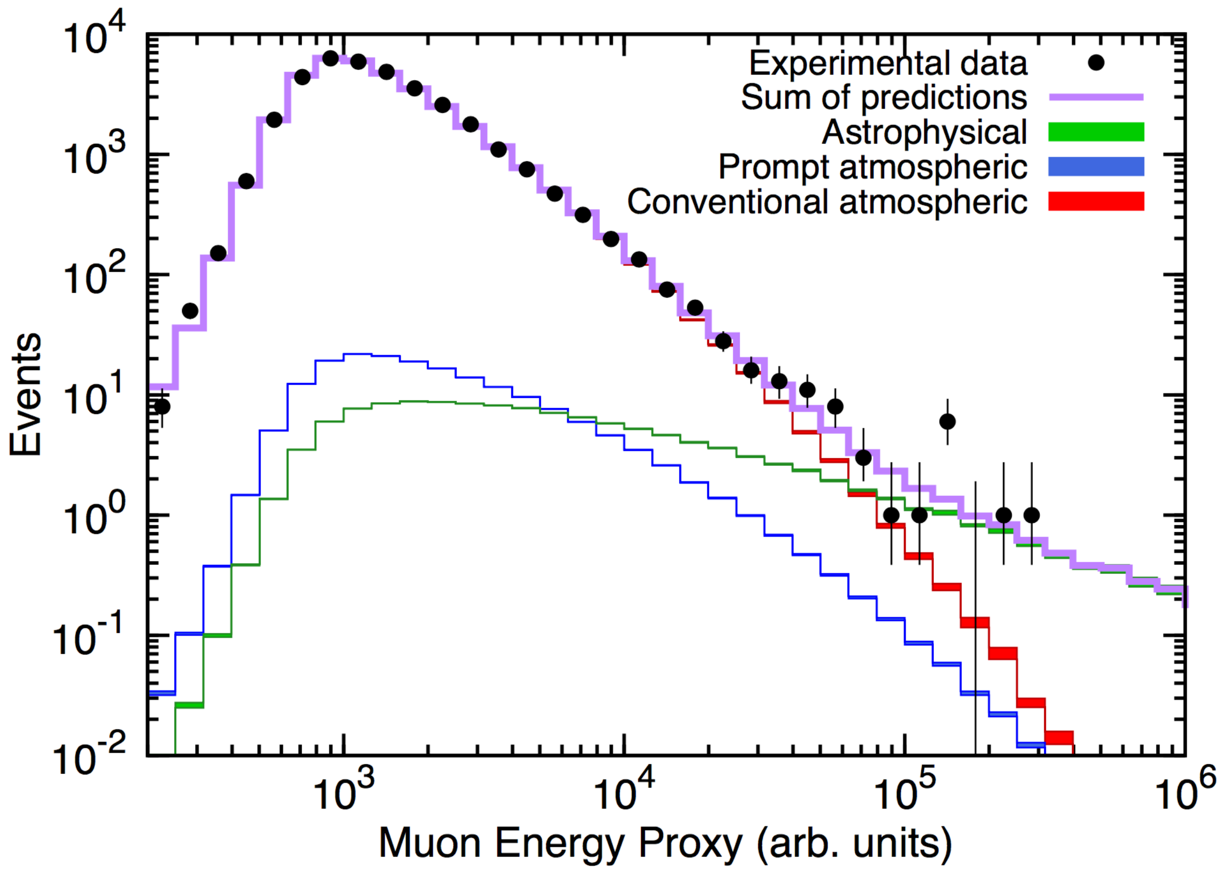


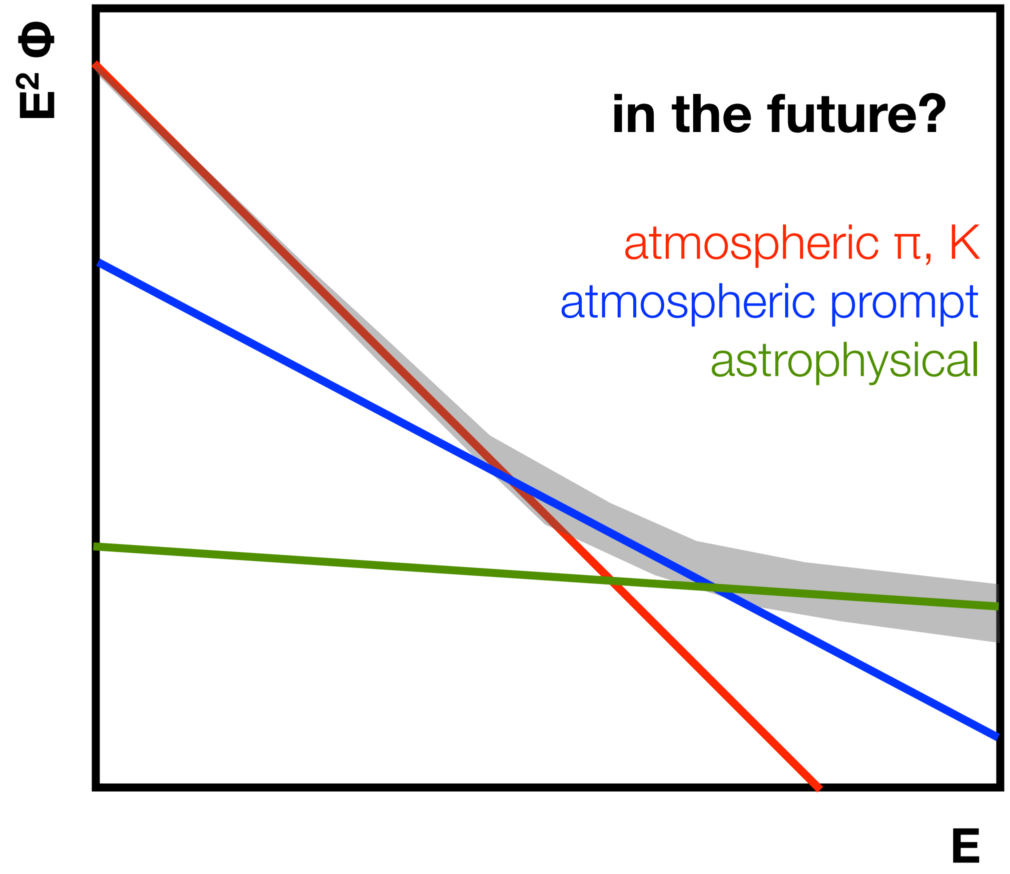
neutrino identification

diffuse flux

- **conventional ν_μ**: Honda et al. 2004 - extended to high energy
- **prompt ν_μ**: Enberg et al. 2008
- cosmic ray spectrum & composition with **knee** included after original calculations
- **new** calculations available with updated cosmic ray spectrum & composition
- the **harder** astrophysical spectrum the **higher** prompt neutrino needed to fit data
- **low statistics**: results consistent

Aartsen et al. Phys.Rev.Lett. 115 (2015) 8, 081102

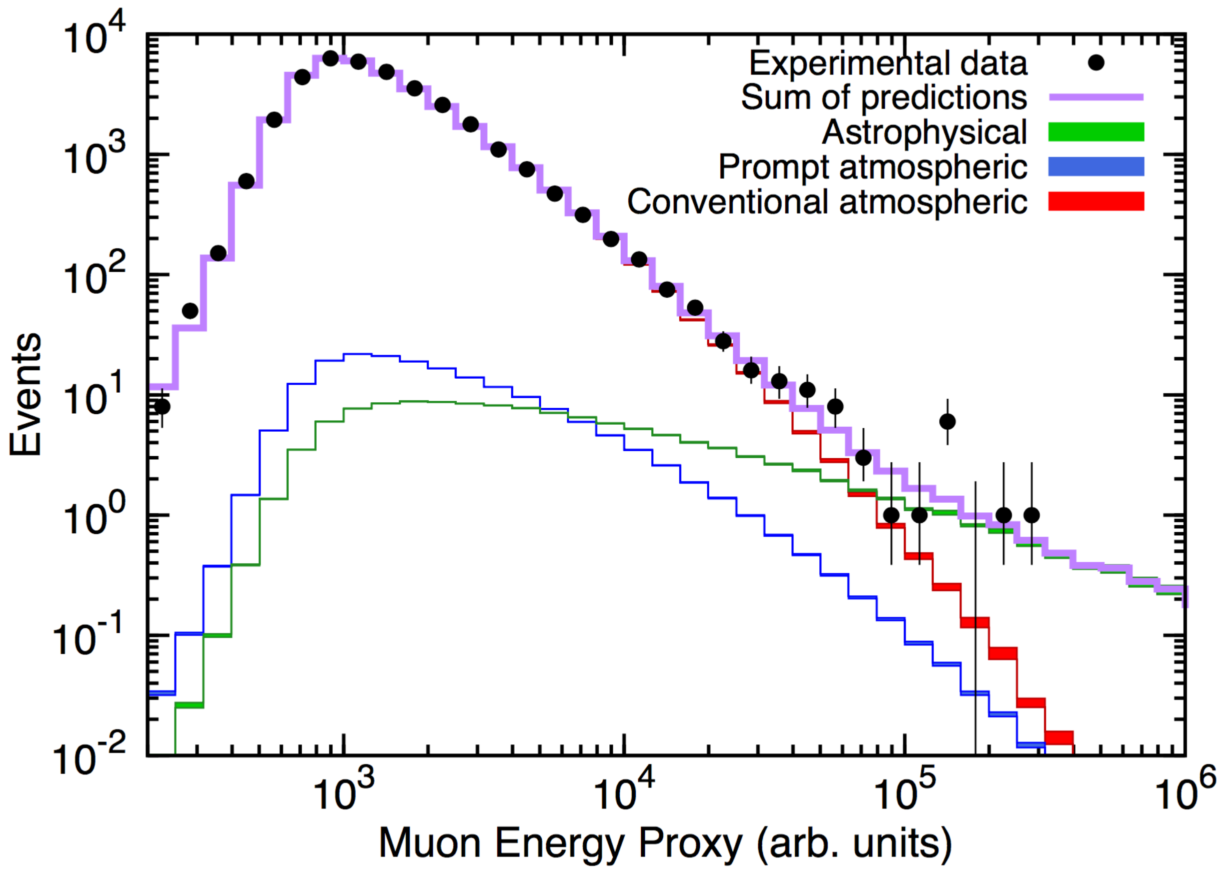


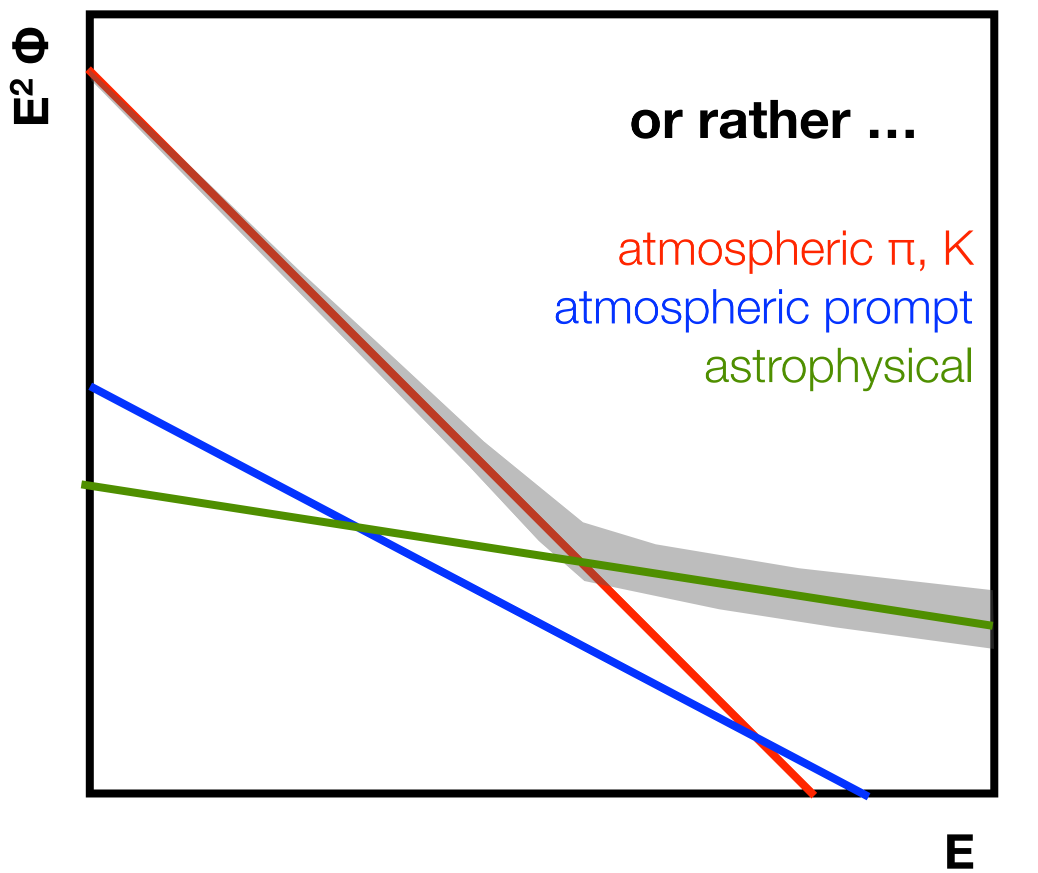


neutrino identification
diffuse flux

- **conventional ν_μ**: Honda et al. 2004 - extended to high energy
- **prompt ν_μ**: Enberg et al. 2008
- cosmic ray spectrum & composition with **knee** included after original calculations
- **new** calculations available with updated cosmic ray spectrum & composition
- the **harder** astrophysical spectrum the **higher** prompt neutrino needed to fit data
- **low statistics**: results consistent

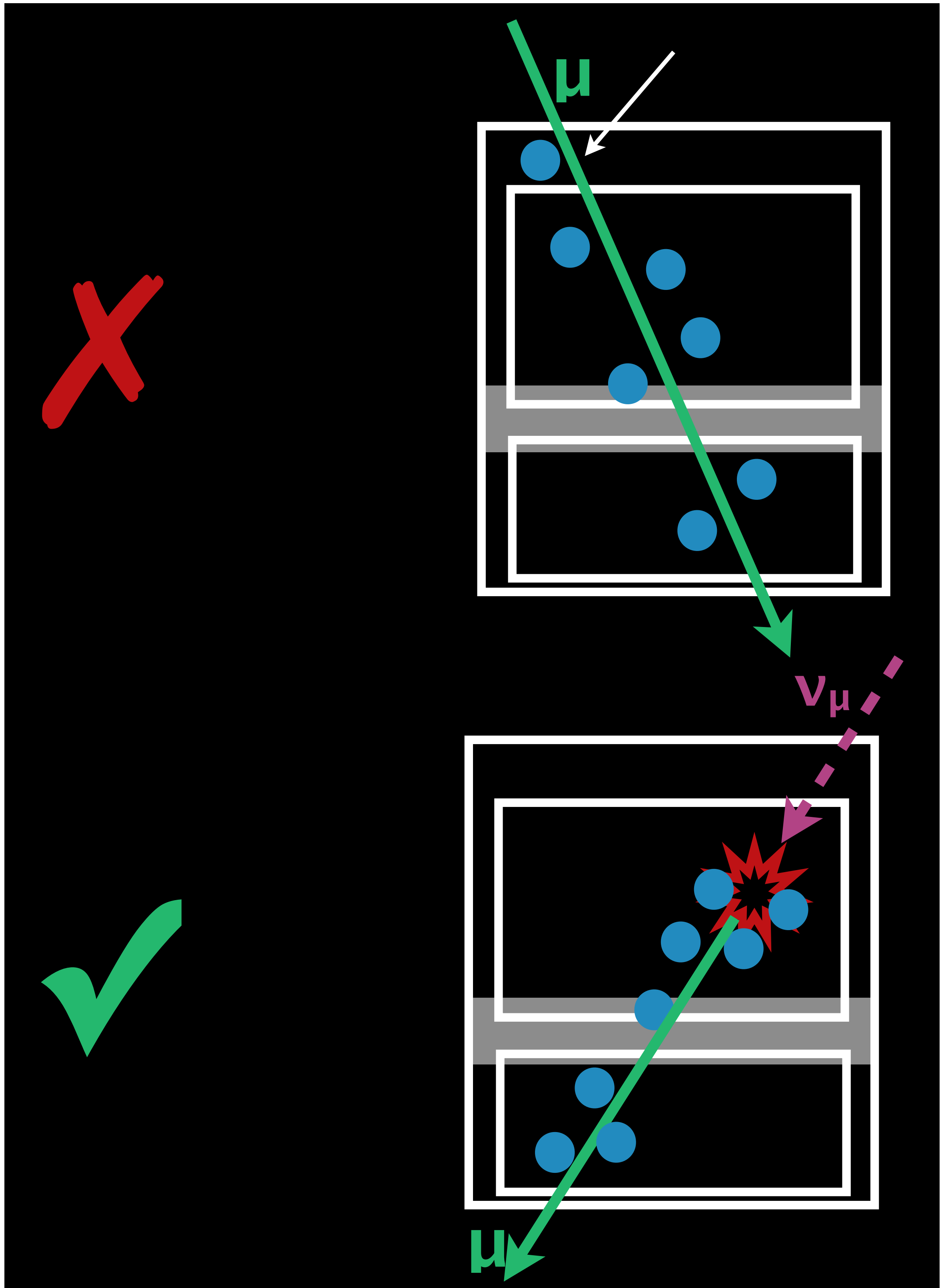
Aartsen et al. Phys.Rev.Lett. 115 (2015) 8, 081102





neutrino identification

active veto

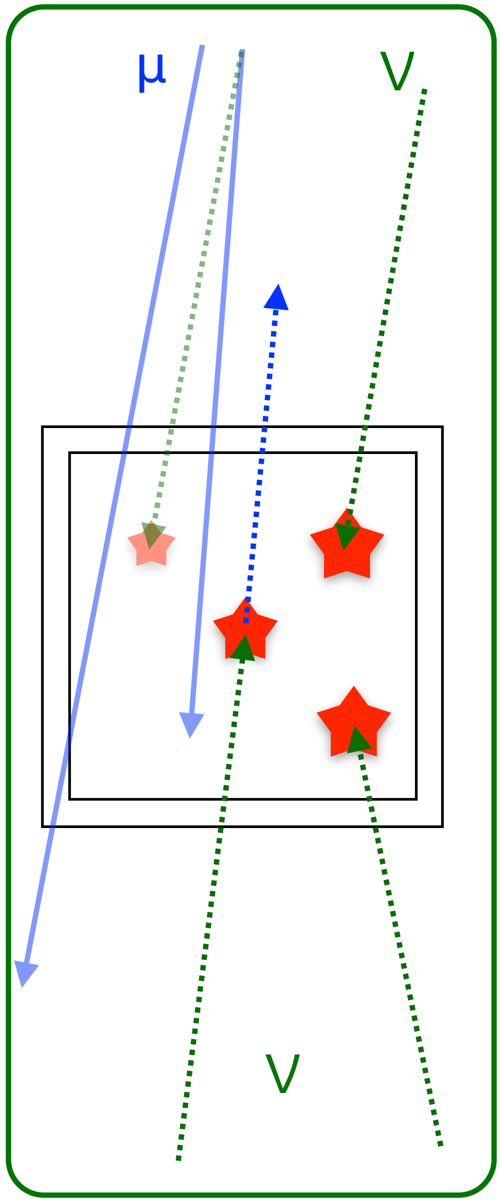


- outer detector veto to **reject muon tracks** passing the experiment boundary
- collect **bright events** with total charge > 6000 p.e.
- identify only events **starting inside** the instrumented volume
- active volume **420 Mton**!

▸ sensitive to **all flavors**

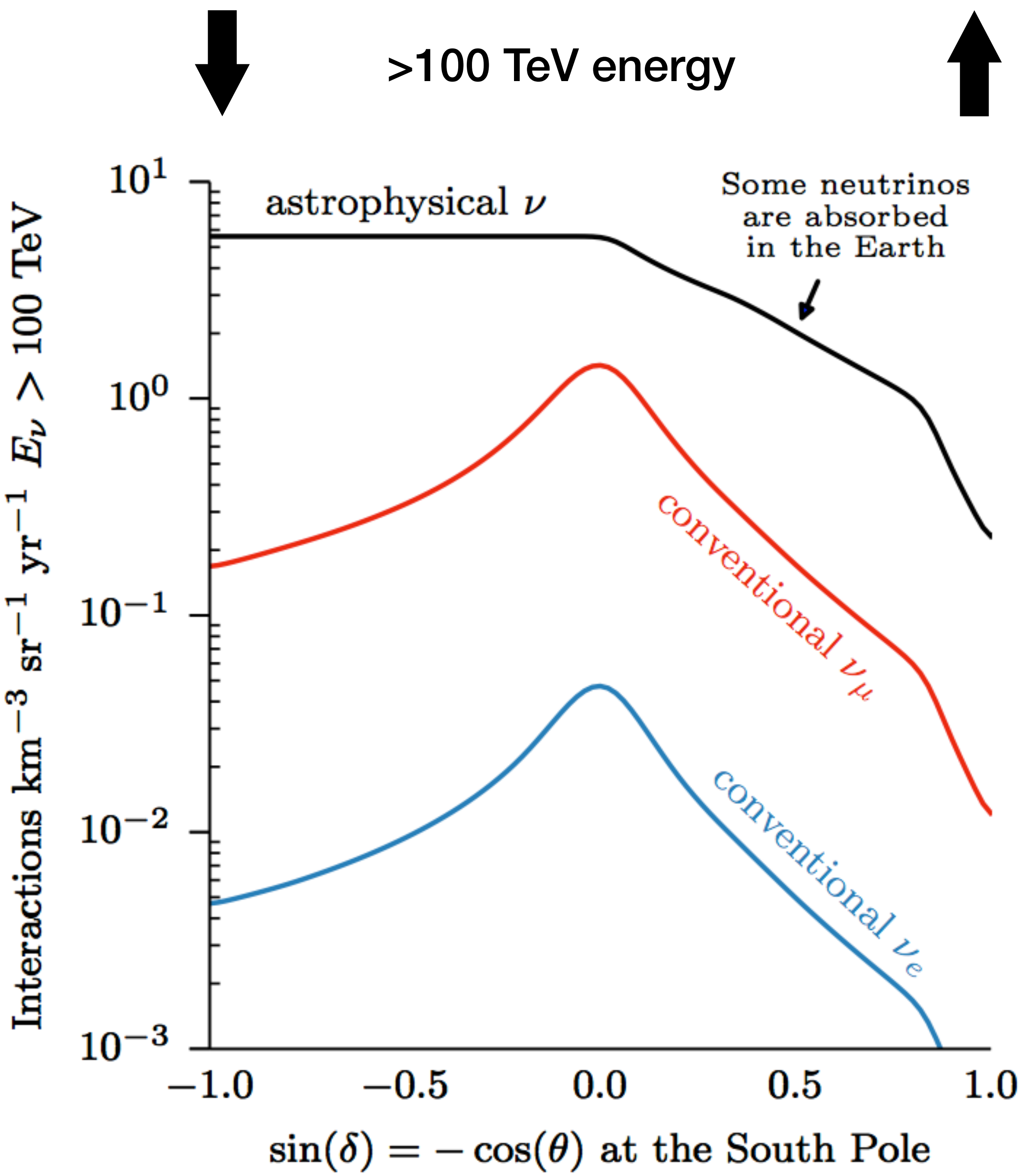
▸ sensitive to **whole sky**

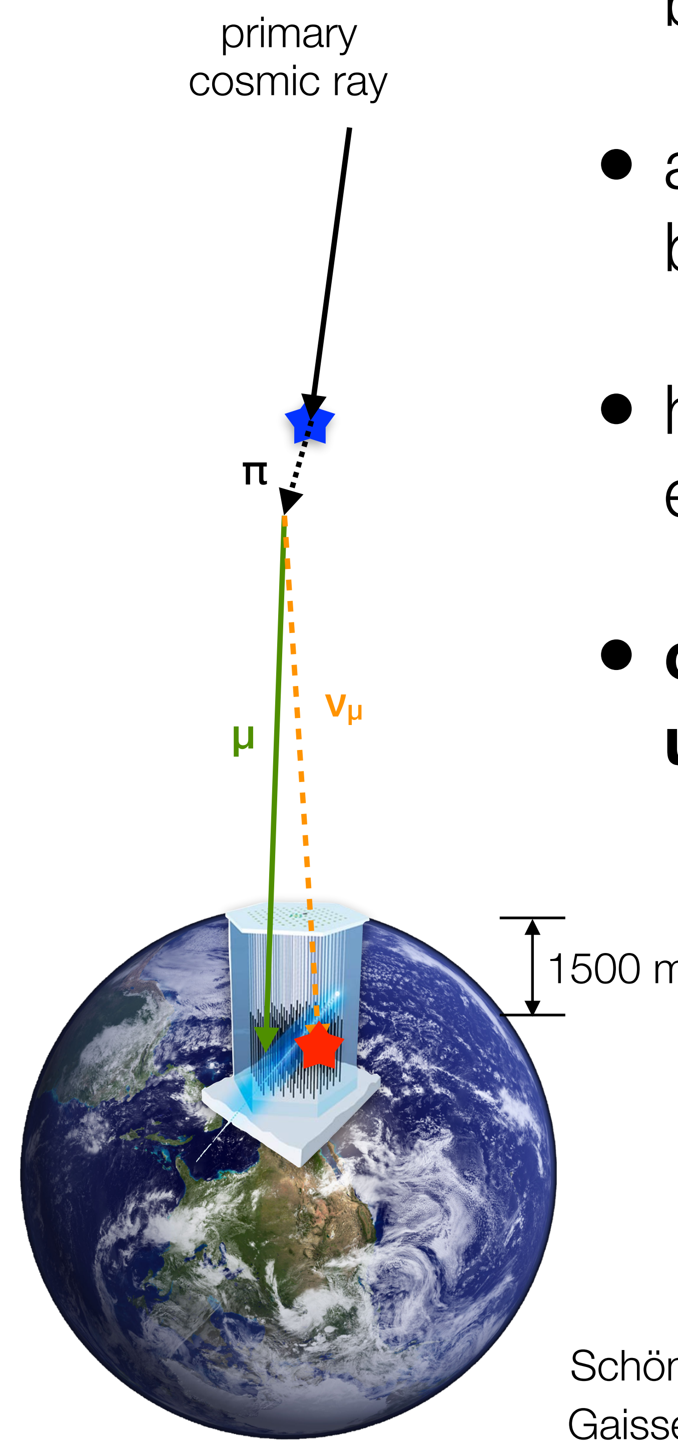
starting (veto)



neutrino identification

self veto





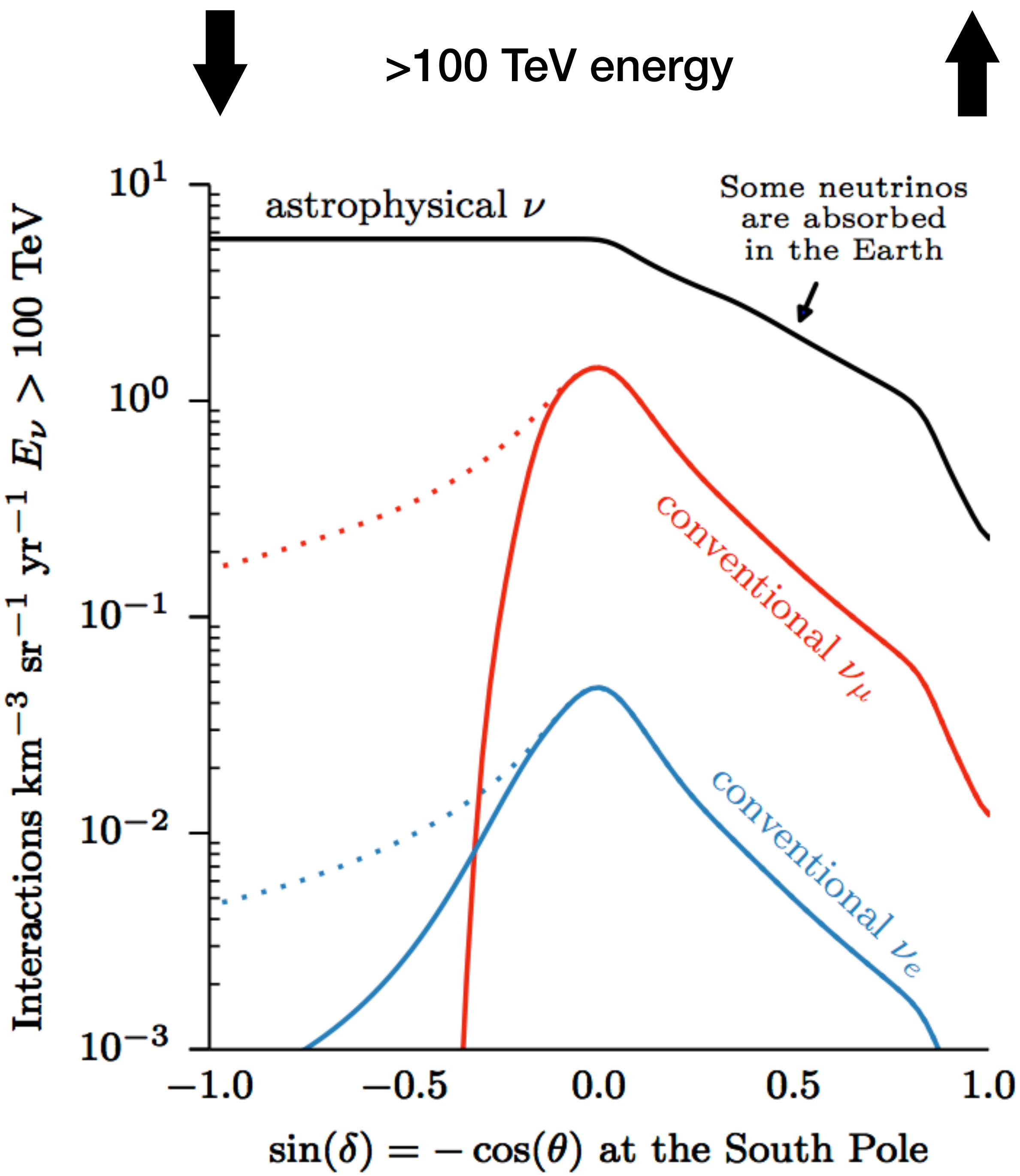
- vetoeing muons reject atmospheric neutrinos
- as long as muons can be detected in IceCube
- and are accompanied by neutrinos
- high energy vertical events best vetoed
- **correlated & uncorrelated** muons

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

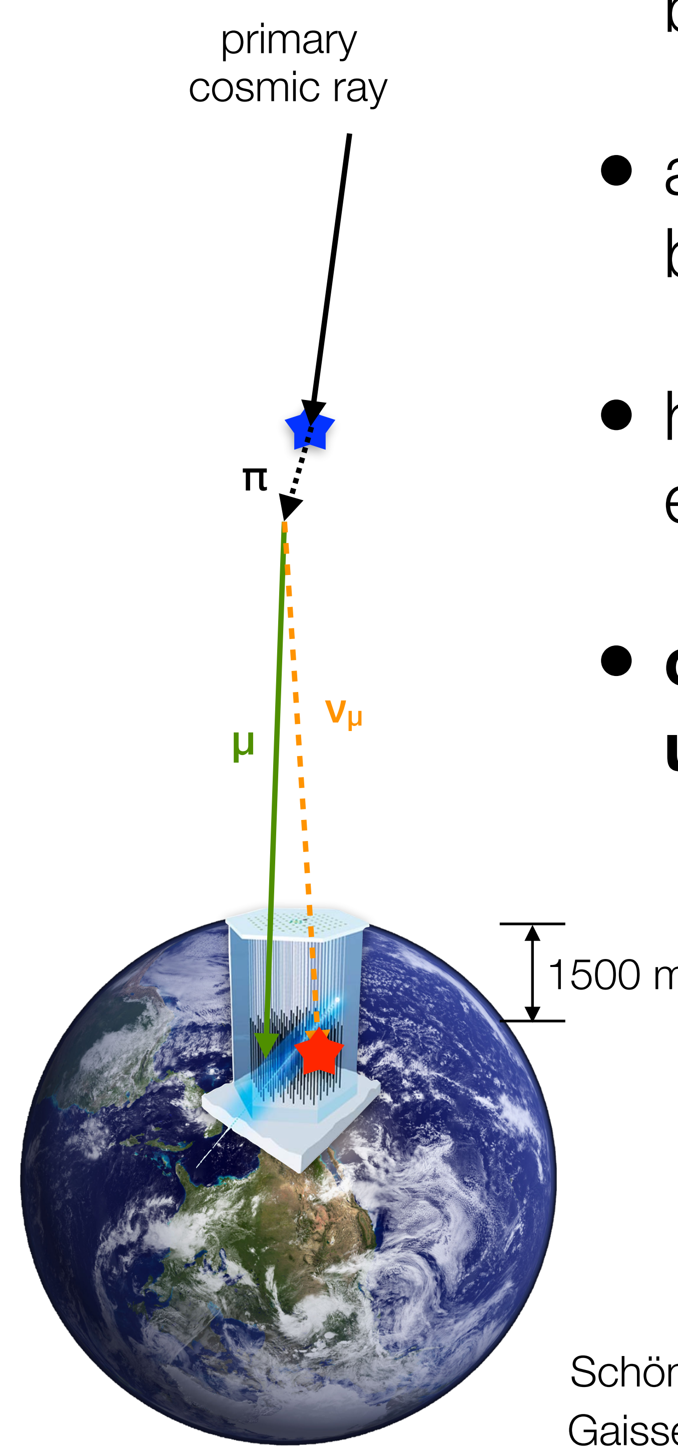
courtesy: J. van Santen

neutrino identification

self veto



courtesy: J. van Santen

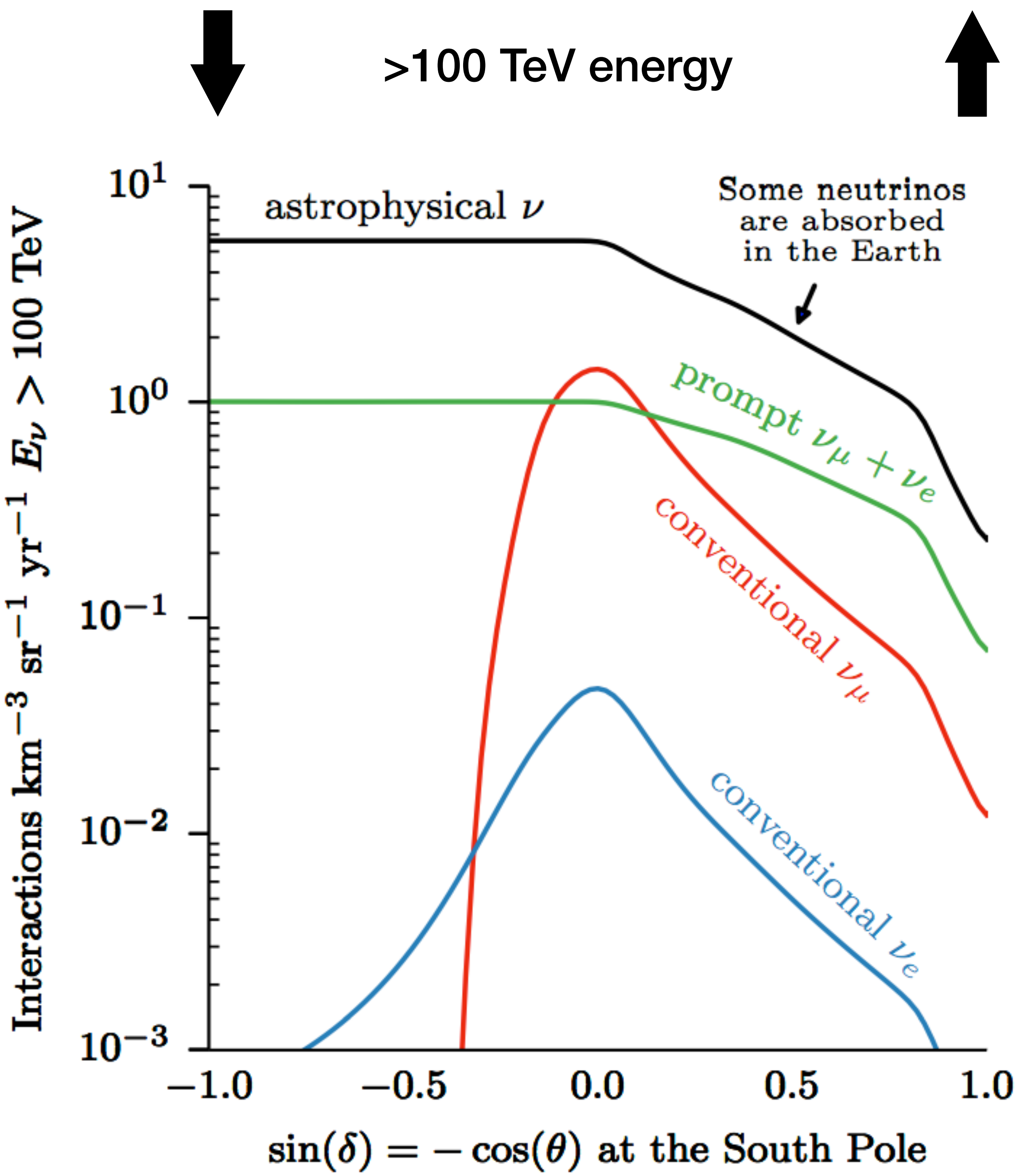


- vetoeing muons reject atmospheric neutrinos
- as long as muons can be detected in IceCube
- and are accompanied by neutrinos
- high energy vertical events best vetoed
- **correlated & uncorrelated** muons

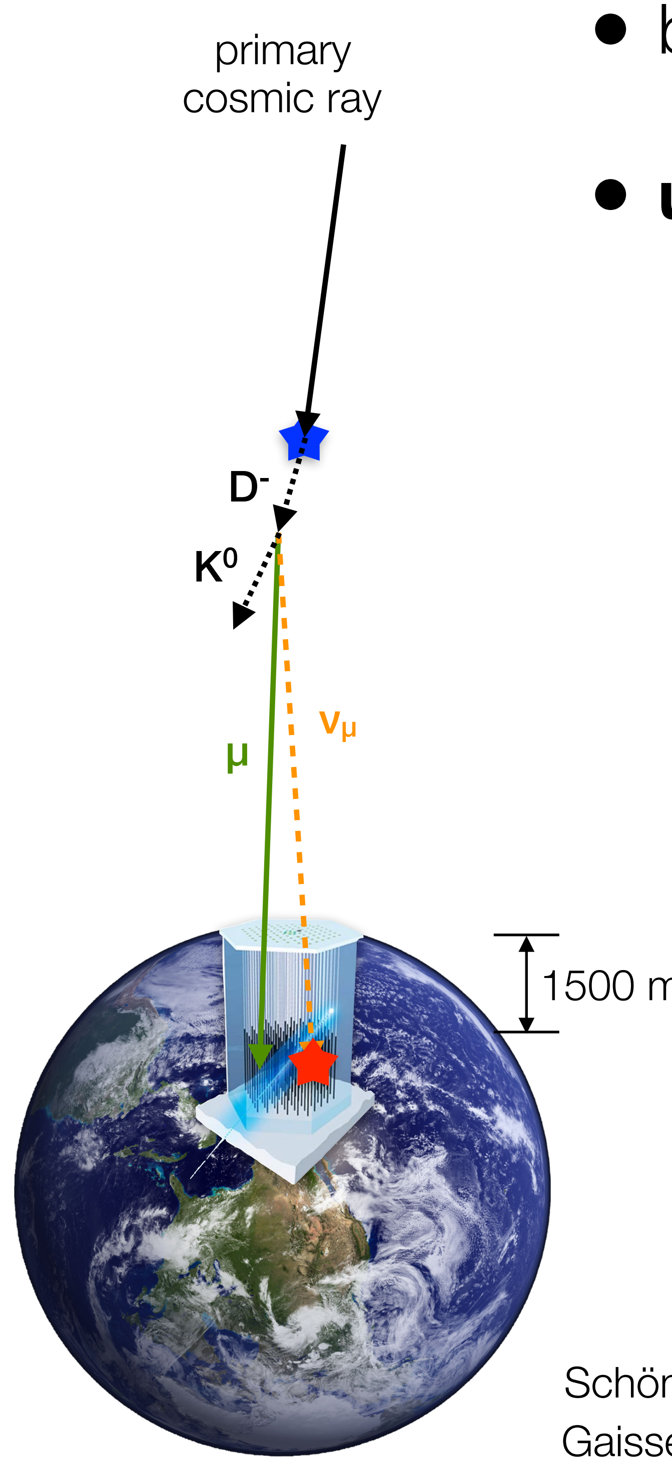
Schönert et al. Phys.Rev.D 79 (2009) 043009
Gaisser et al. Phys.Rev.D 90 (2014) 023009

neutrino identification

self veto



courtesy: J. van Santen



- prompt atmospheric neutrinos are rejected too
- but with lower efficiency
- **uncorrelated** muons

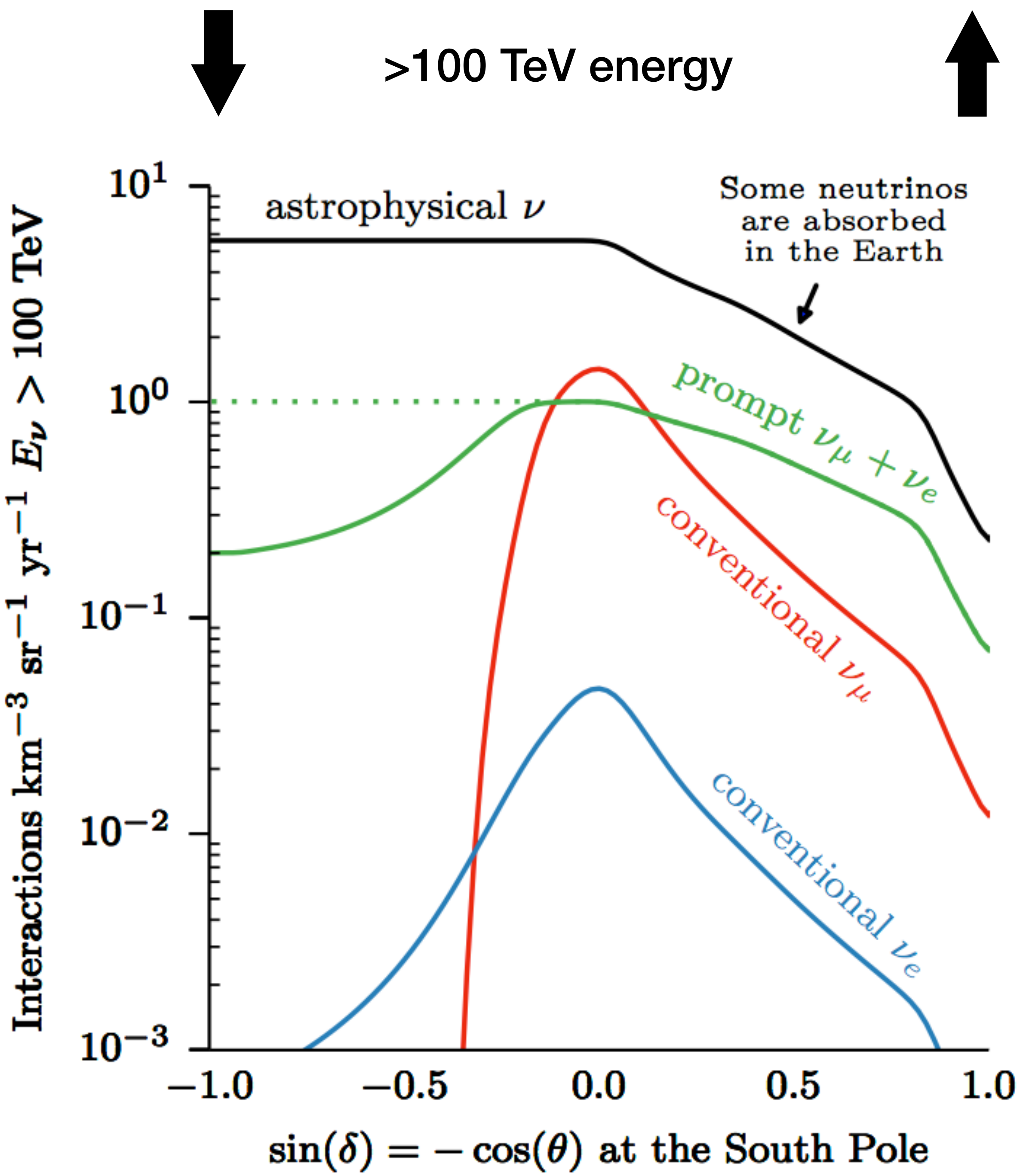
Schönert et al. Phys.Rev.D 79 (2009) 043009
Gaisser et al. Phys.Rev.D 90 (2014) 023009

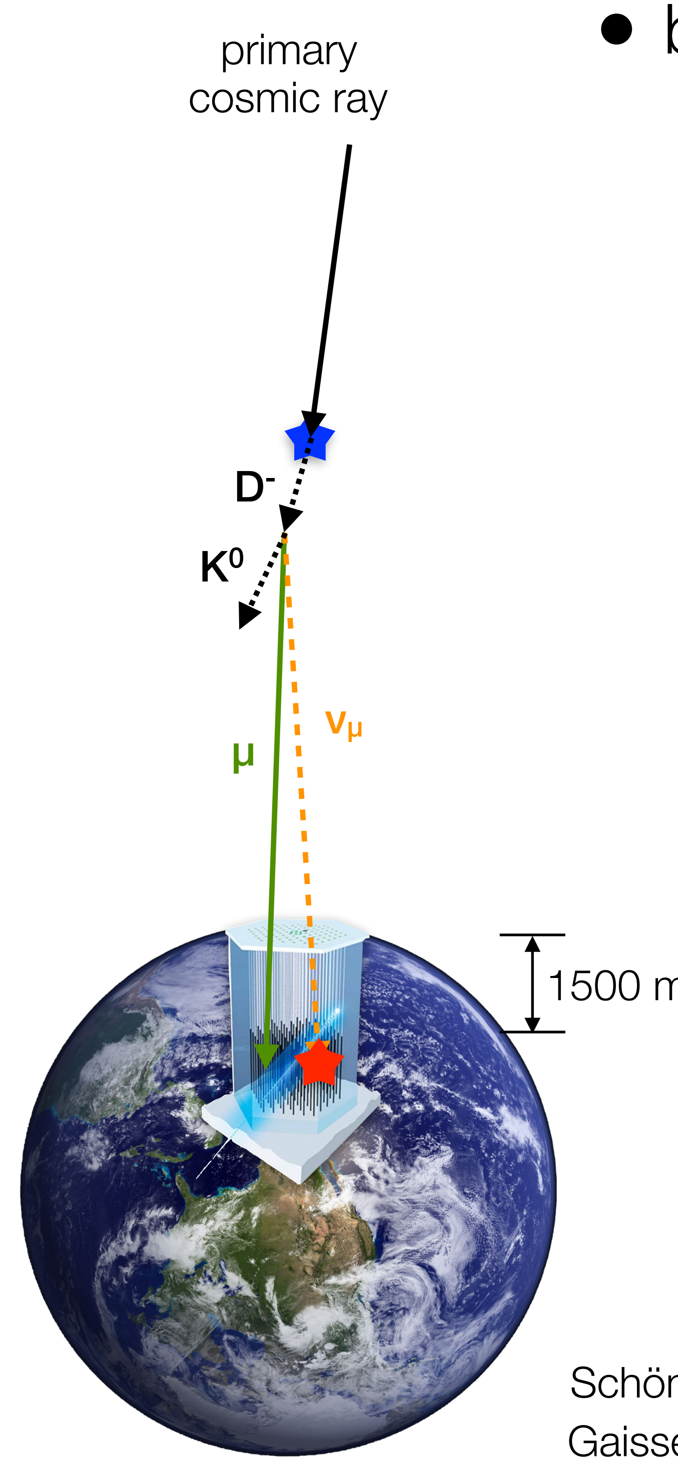
neutrino identification

self veto

- prompt atmospheric neutrinos are rejected too
- but with lower efficiency

>100 TeV energy



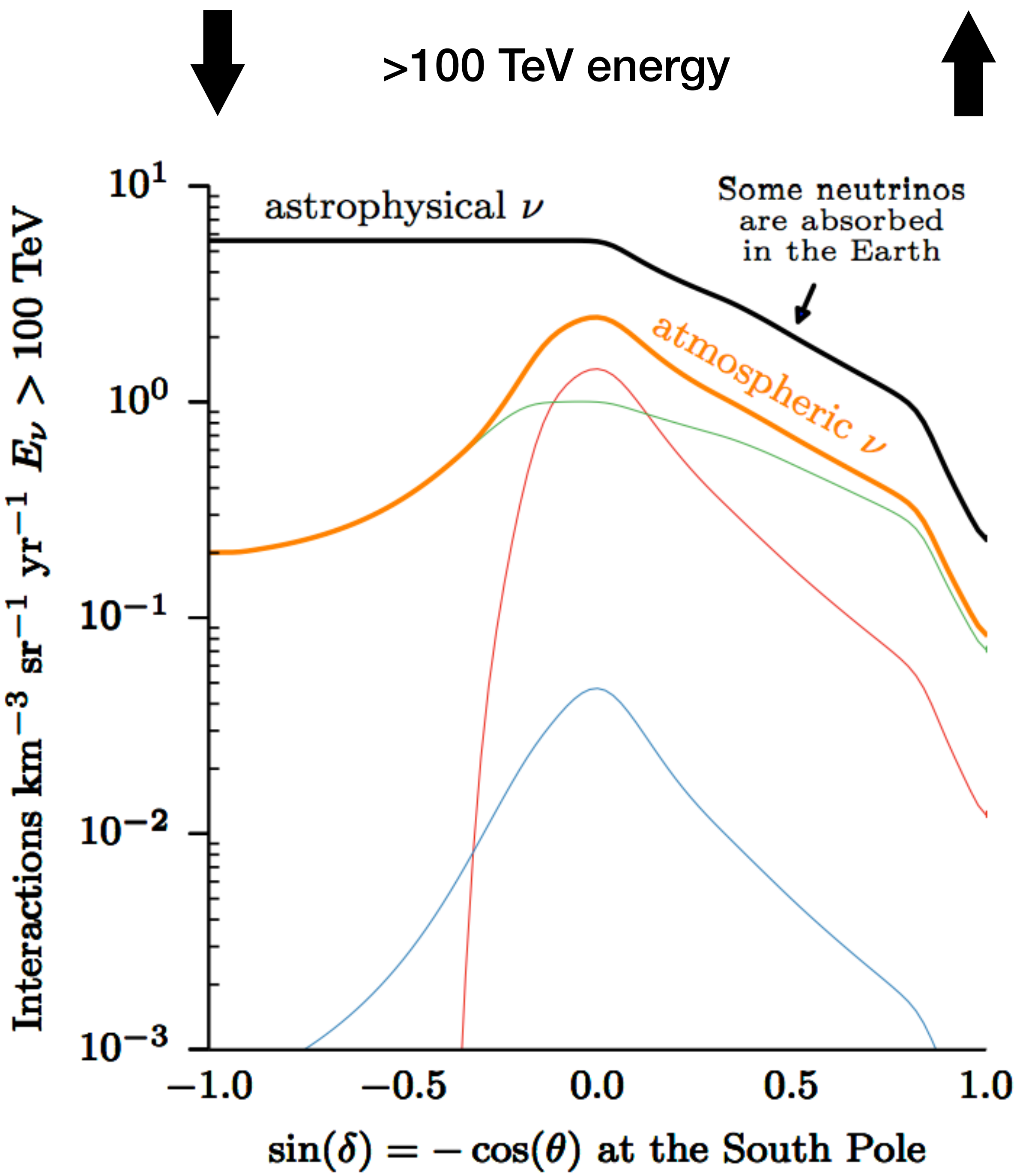


courtesy: J. van Santen

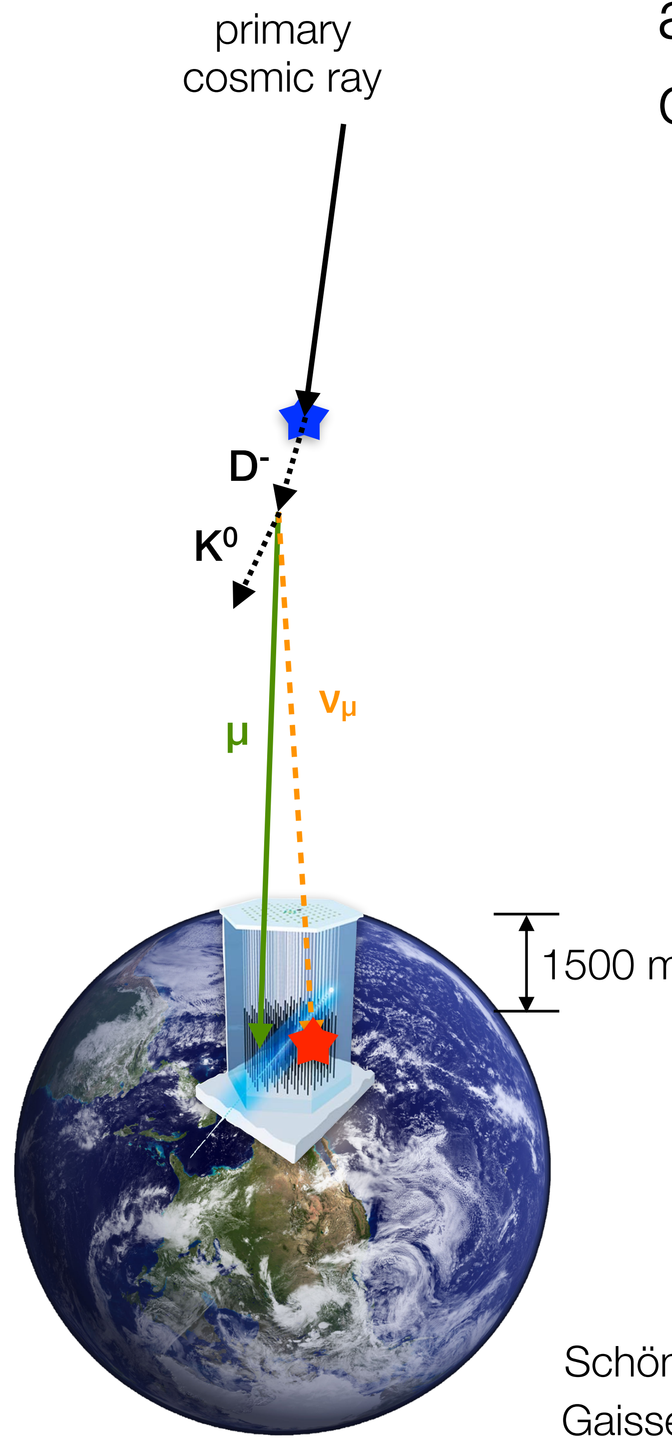
Schönert et al. Phys.Rev.D 79 (2009) 043009
Gaisser et al. Phys.Rev.D 90 (2014) 023009

neutrino identification

self veto



courtesy: J. van Santen



- The zenith distributions of high-energy astrophysical and atmospheric neutrinos are fundamentally different.

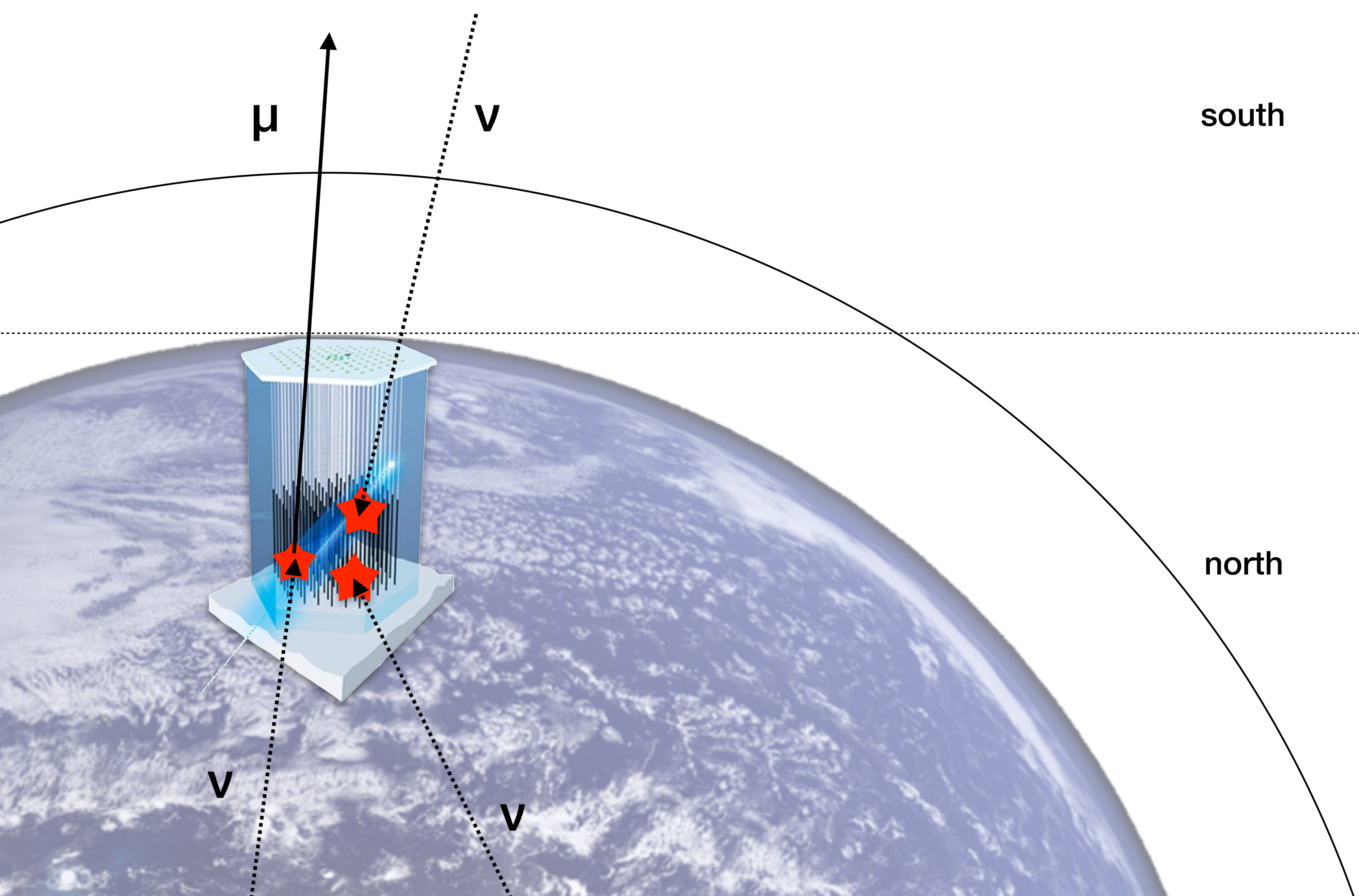
Schönert et al. Phys.Rev.D 79 (2009) 043009
Gaisser et al. Phys.Rev.D 90 (2014) 023009

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

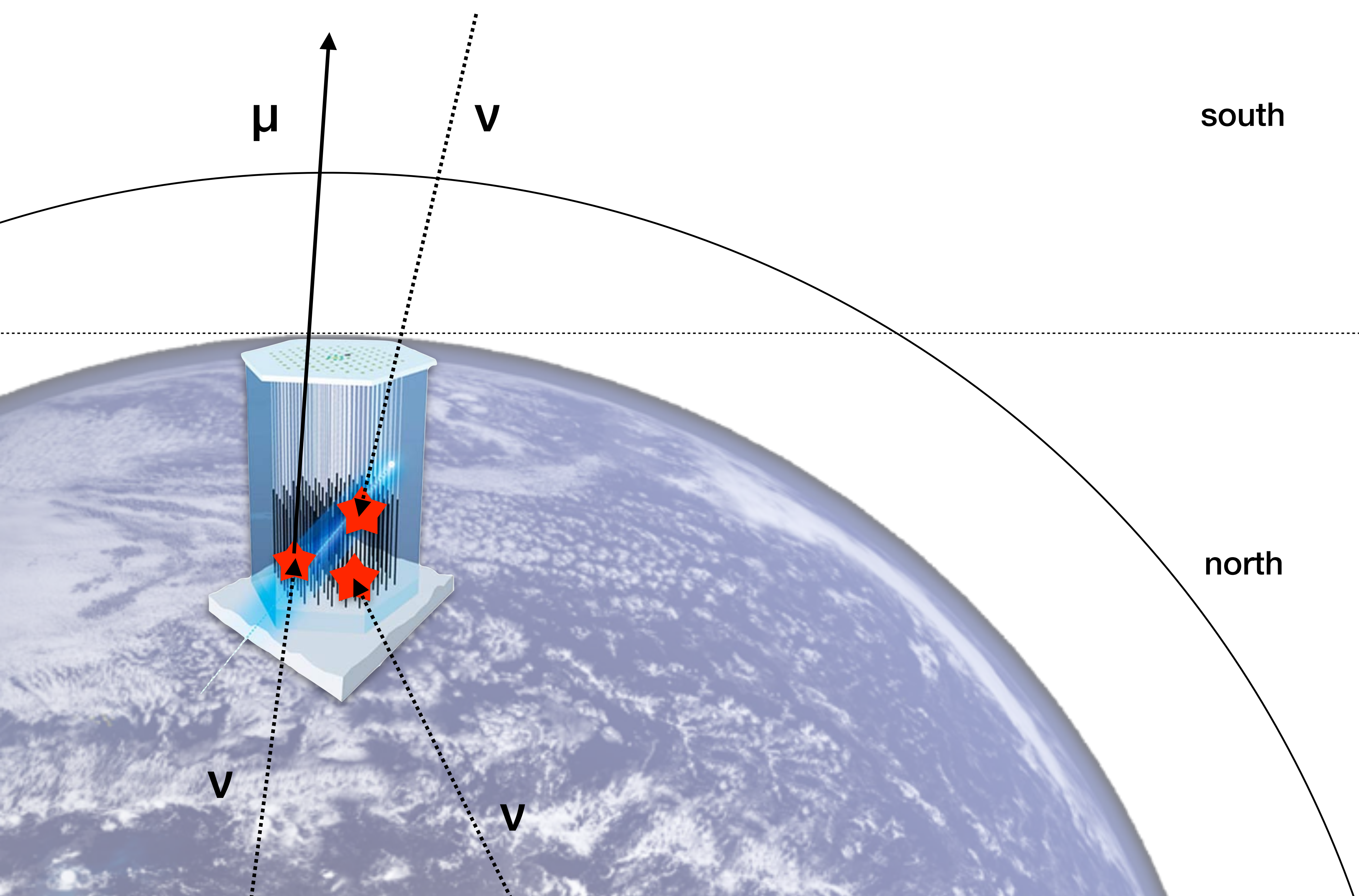
retention of
HE atmospheric ν
HE astrophysical ν

neutrino identification

astrophysical neutrinos

veto efficiency increases with energy

a window to **high energy astrophysical neutrino discovery** **ICRC 2015**



rejection of
HE atmospheric μ and ν
conventional & prompt

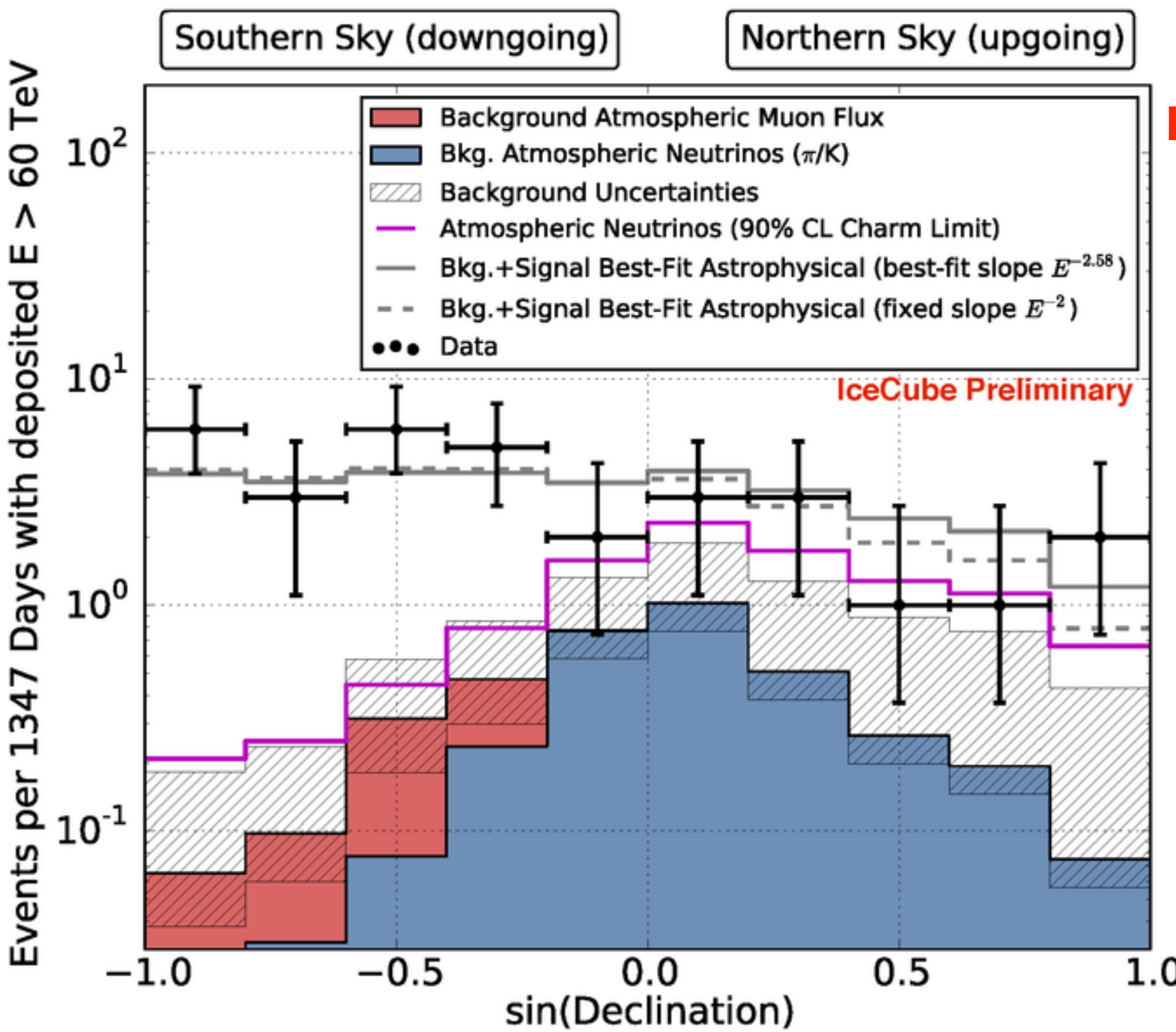
retention of
HE astrophysical ν

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

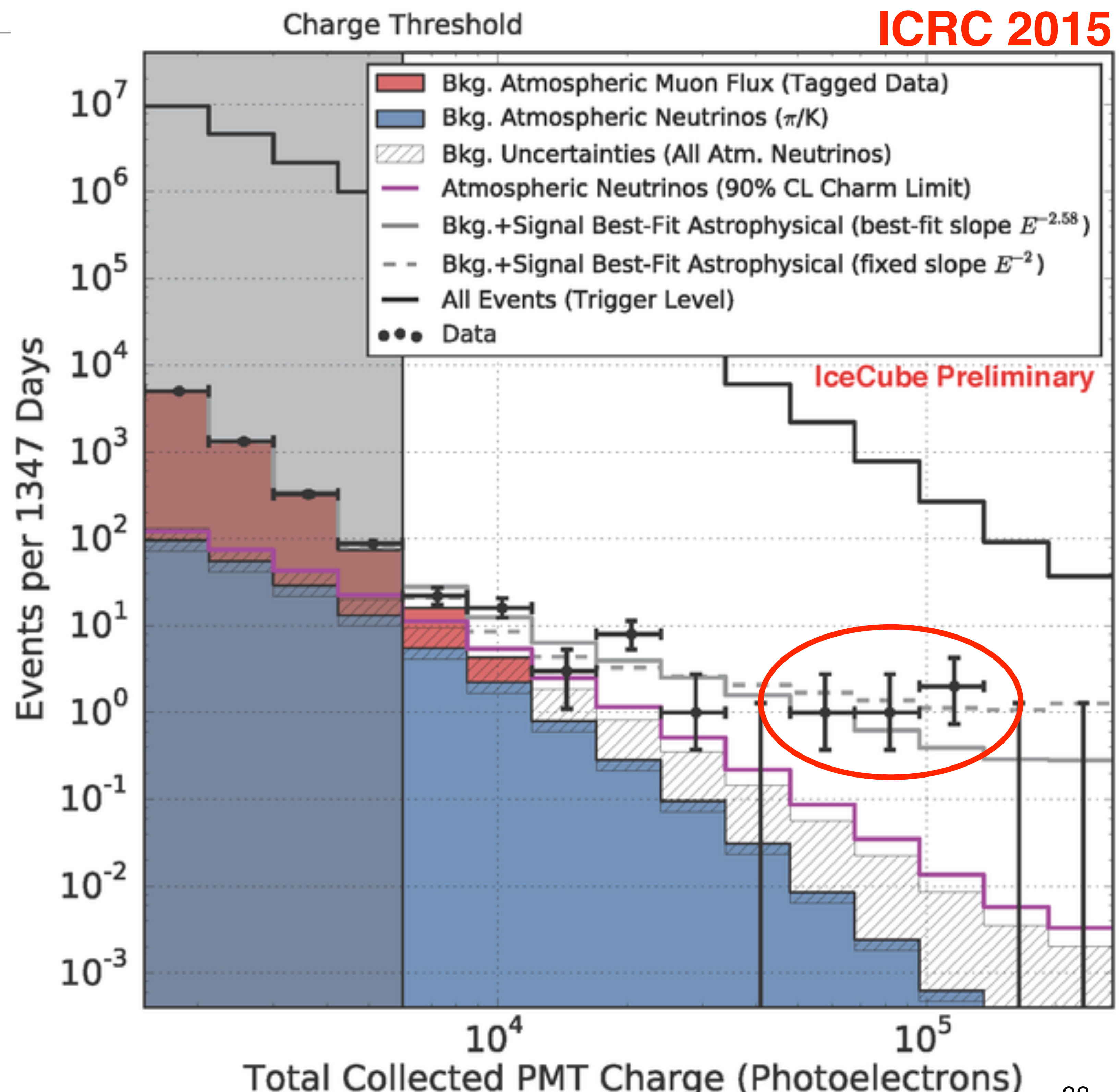
12.6±5.1 atm. muons

1 atm. muon passing veto

coincident CR showers

6.5 σ significance

4 years of HE starting events
E_ν > 60 TeV



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
$E_\nu > 60$ TeV

ICRC 2015

- 53(+1) events found
- estimated background

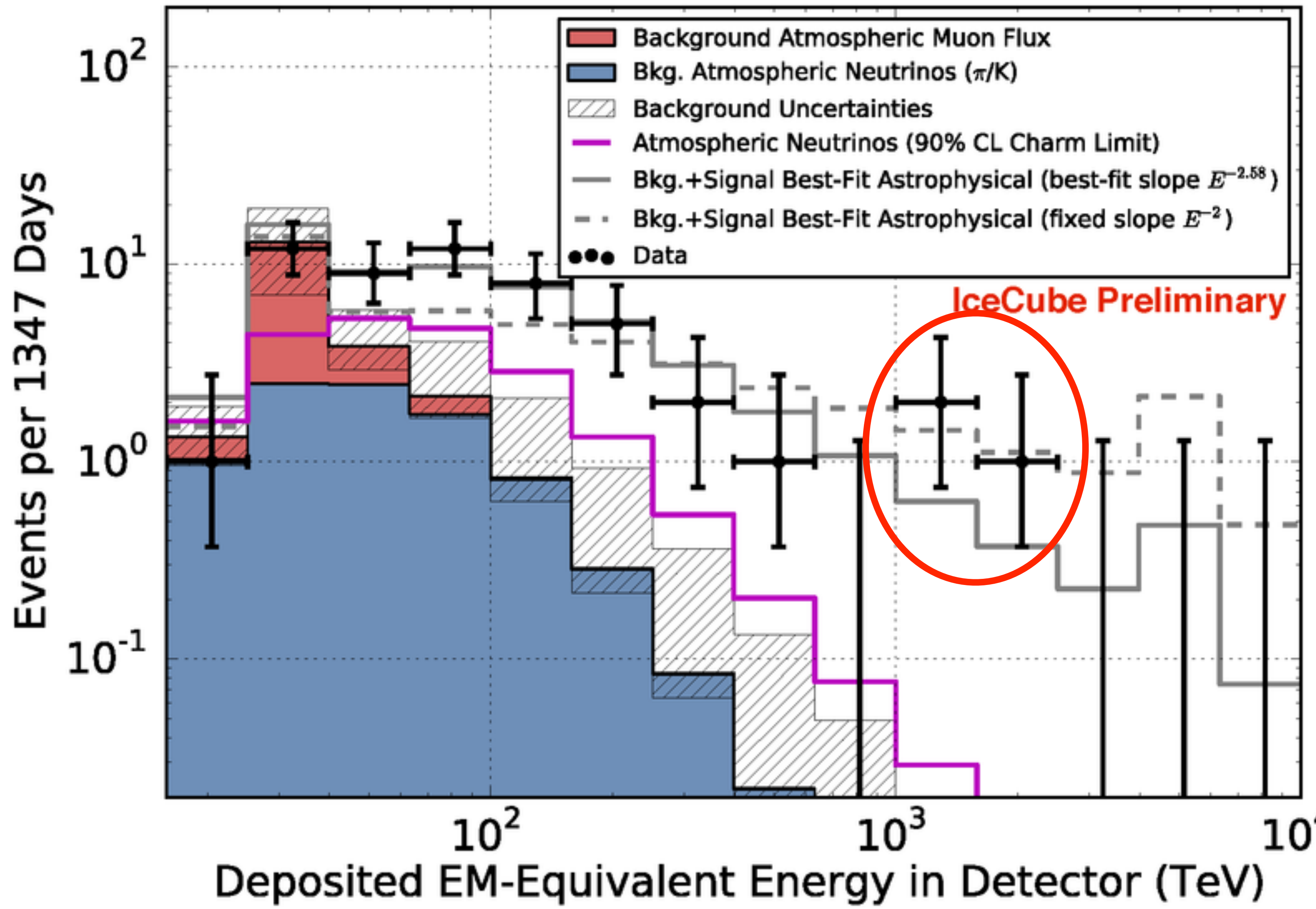
  $9.0^{+8.0}_{-2.2}$ atm. neutrinos

  12.6±5.1 atm. muons

  1 atm. muon passing veto

  coincident CR showers

  6.5 σ significance

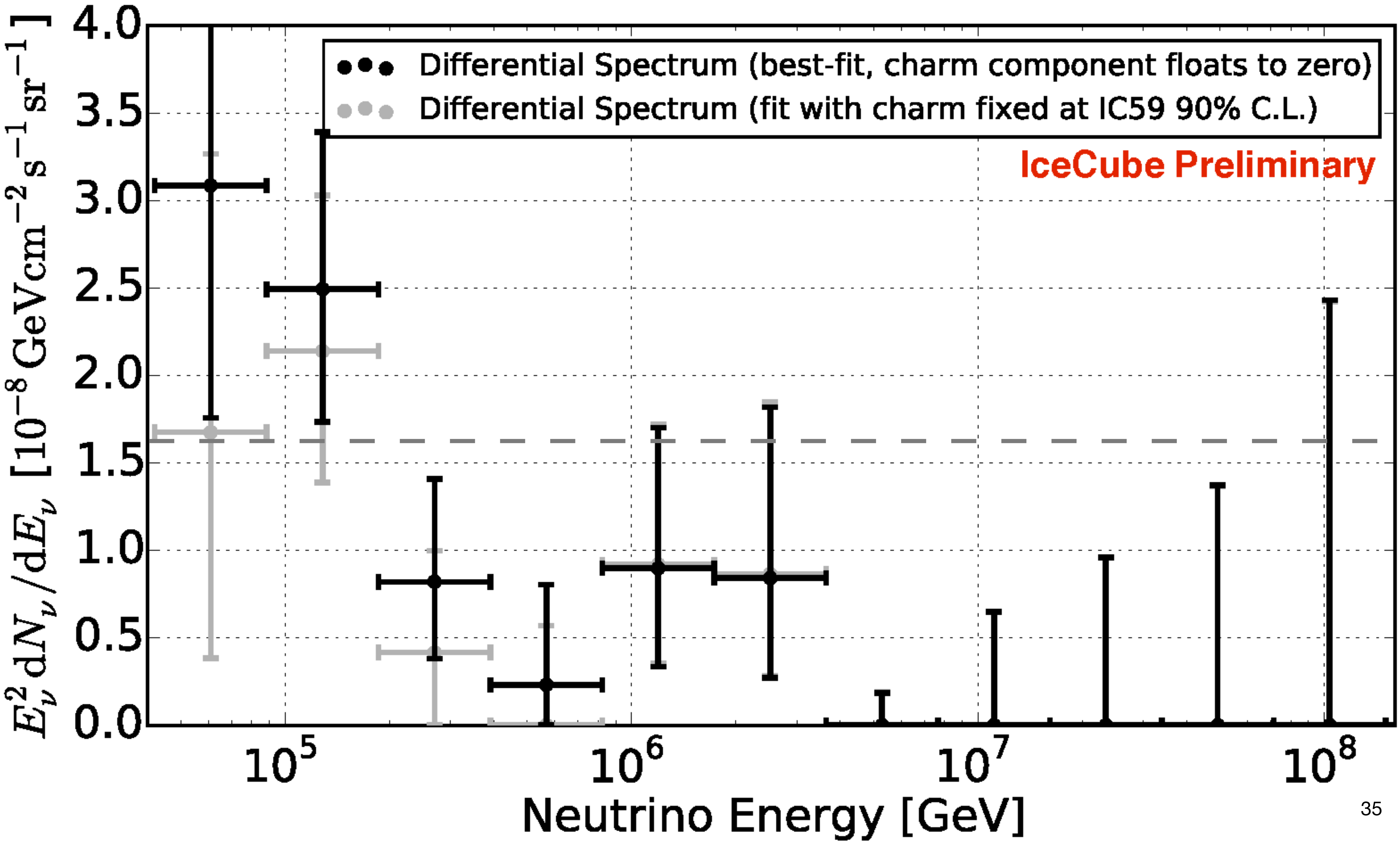


Aartsen et al. PRD 88 (2013) 112008
Aartsen et al. Science 342 (2013) 1242856
Aartsen et al. PRL 113 (2014) 101101

neutrino identification

astrophysical neutrinos

4 years of HE starting events
E_ν > 60 TeV

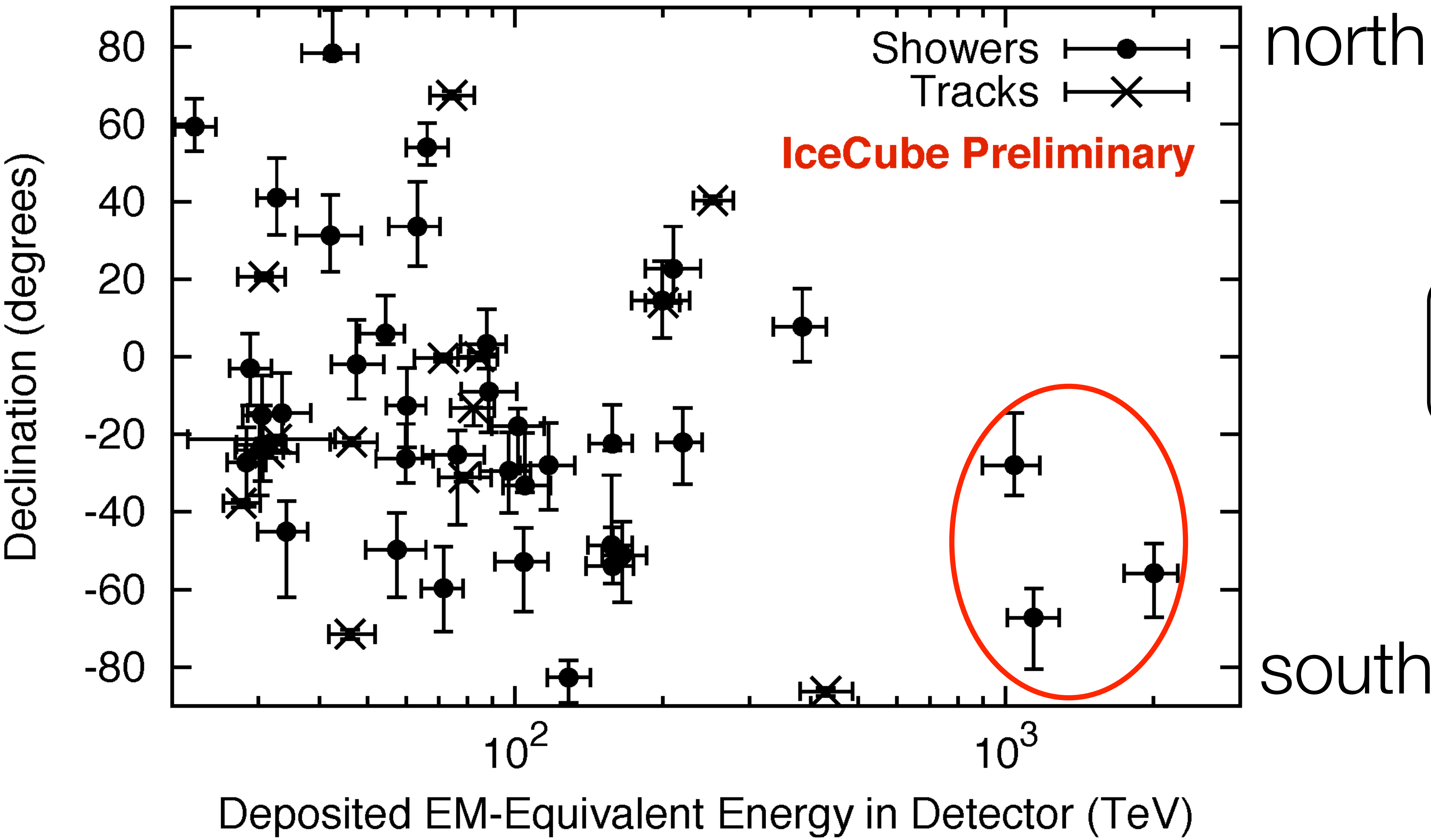


neutrino identification

astrophysical neutrinos

4 years of HE starting events
E_ν > 60 TeV

ICRC 2015



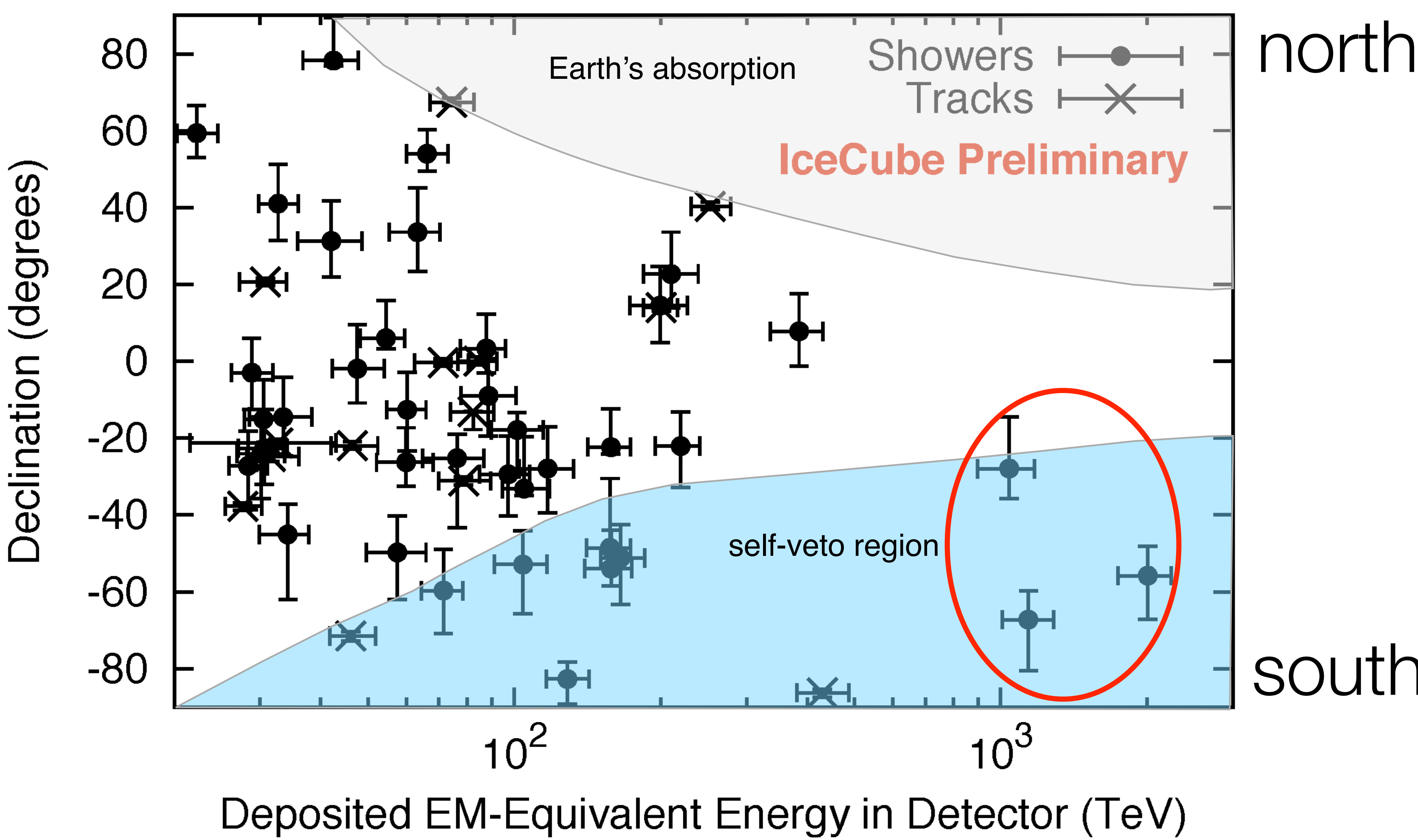
14 tracks
40 cascades

neutrino identification

astrophysical neutrinos

4 years of HE starting events
E_ν > 60 TeV

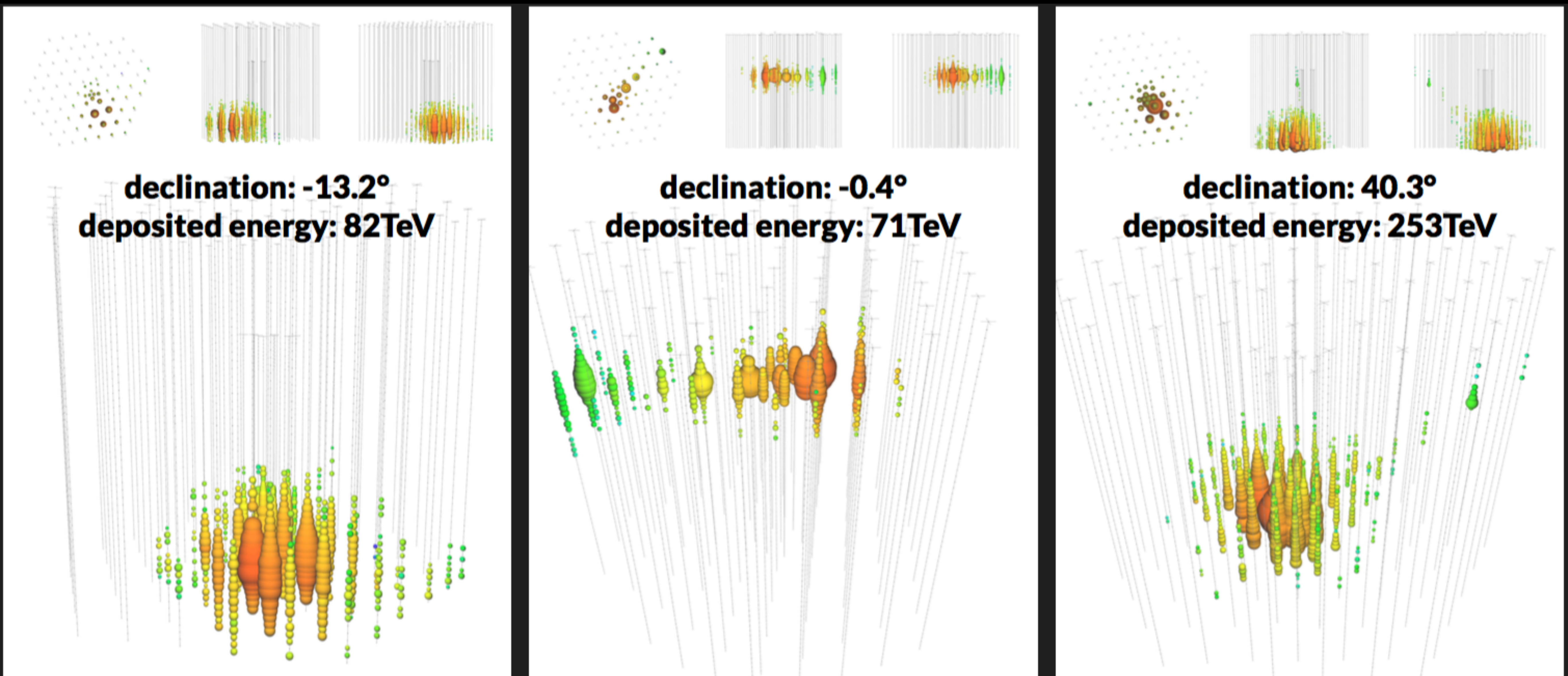
ICRC 2015



14 tracks
40 cascades

neutrino identification

astrophysical neutrinos



neutrino identification

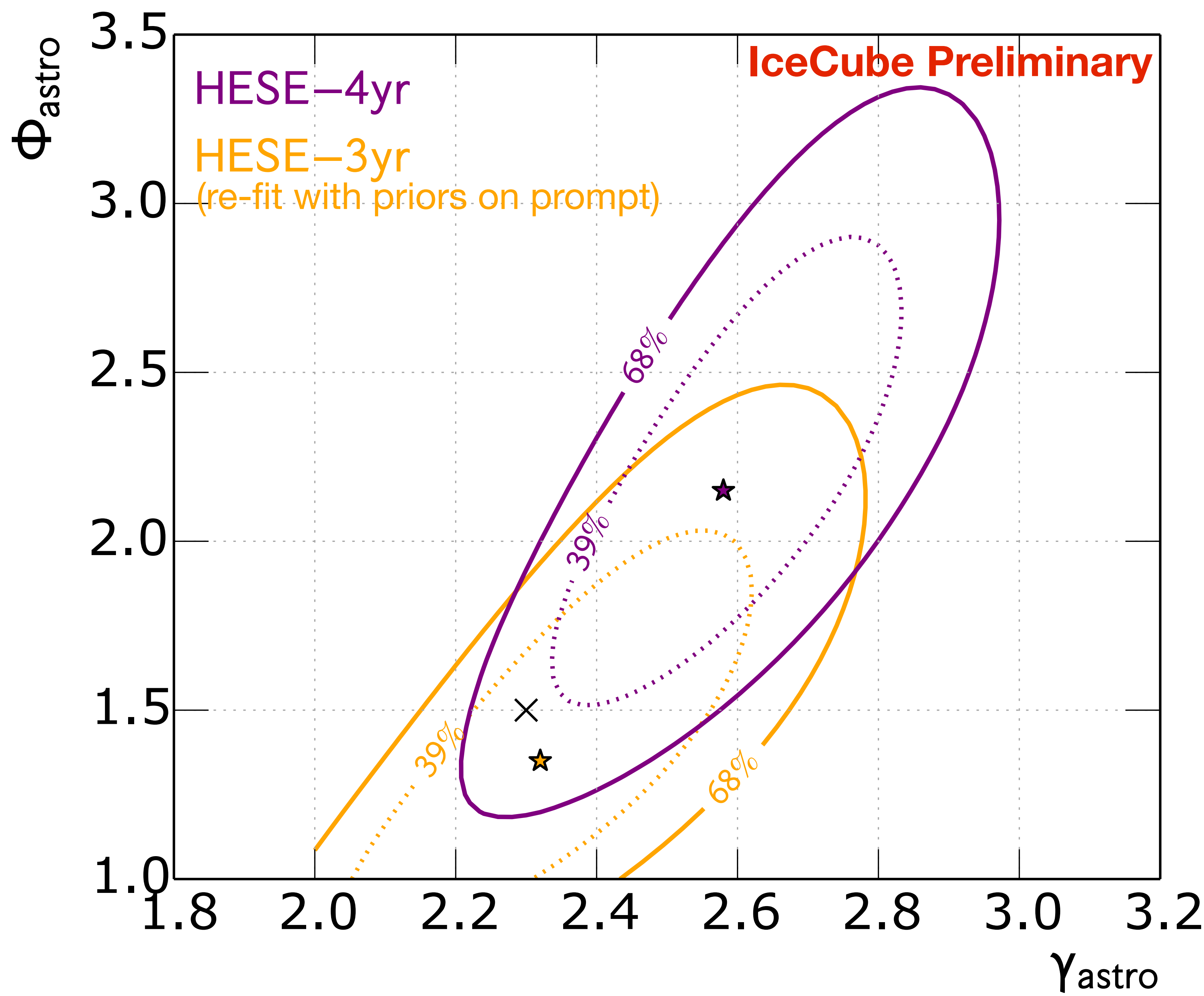
astrophysical neutrinos

4 years of HE starting events
E_ν > 60 TeV

- **likelihood fit** with priors for atmospheric conventional and prompt ν flux
- atmospheric flux assumed to be determined in **shape**
- best fit ***softer*** than **E^{-2}**

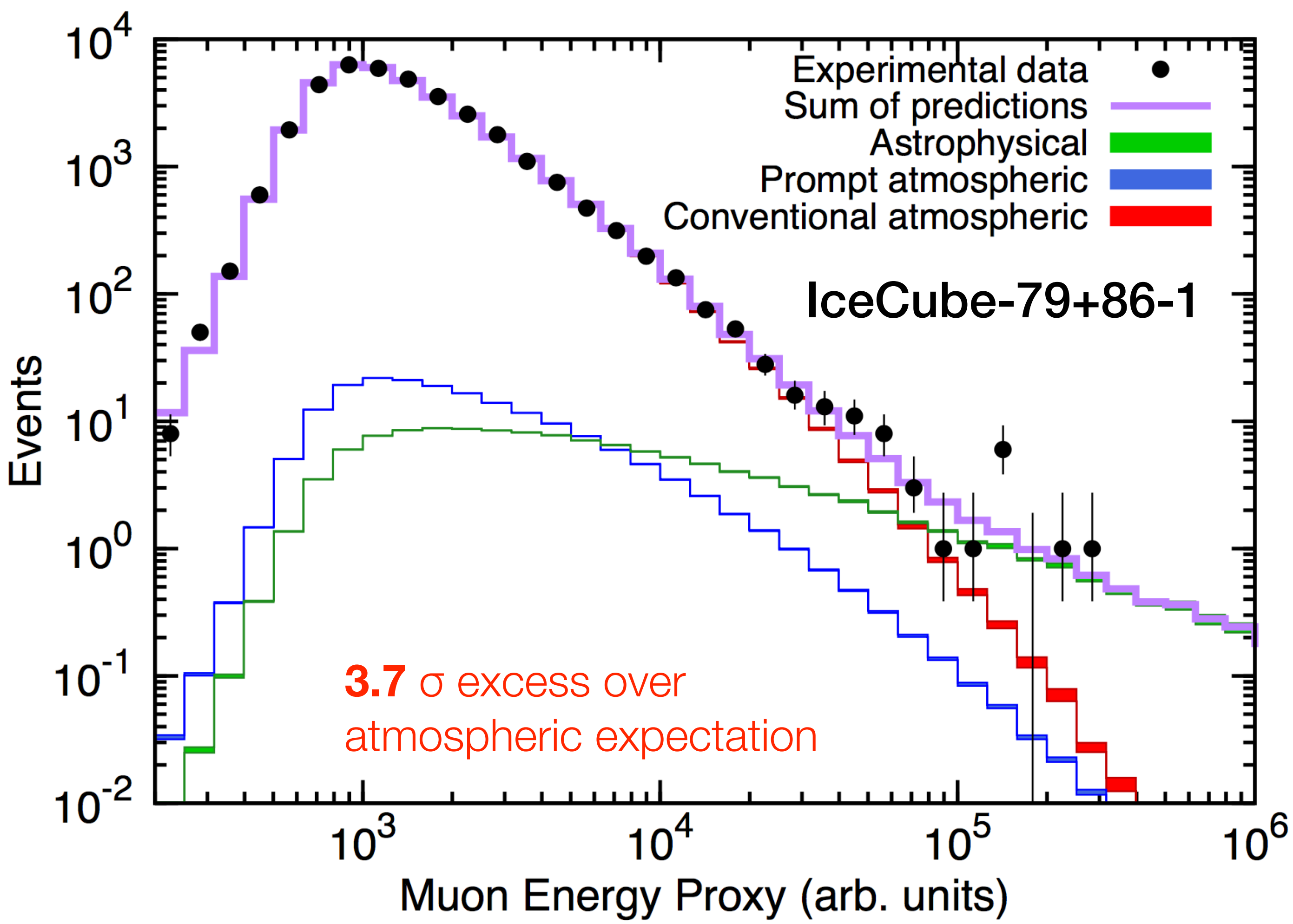
a problem ?

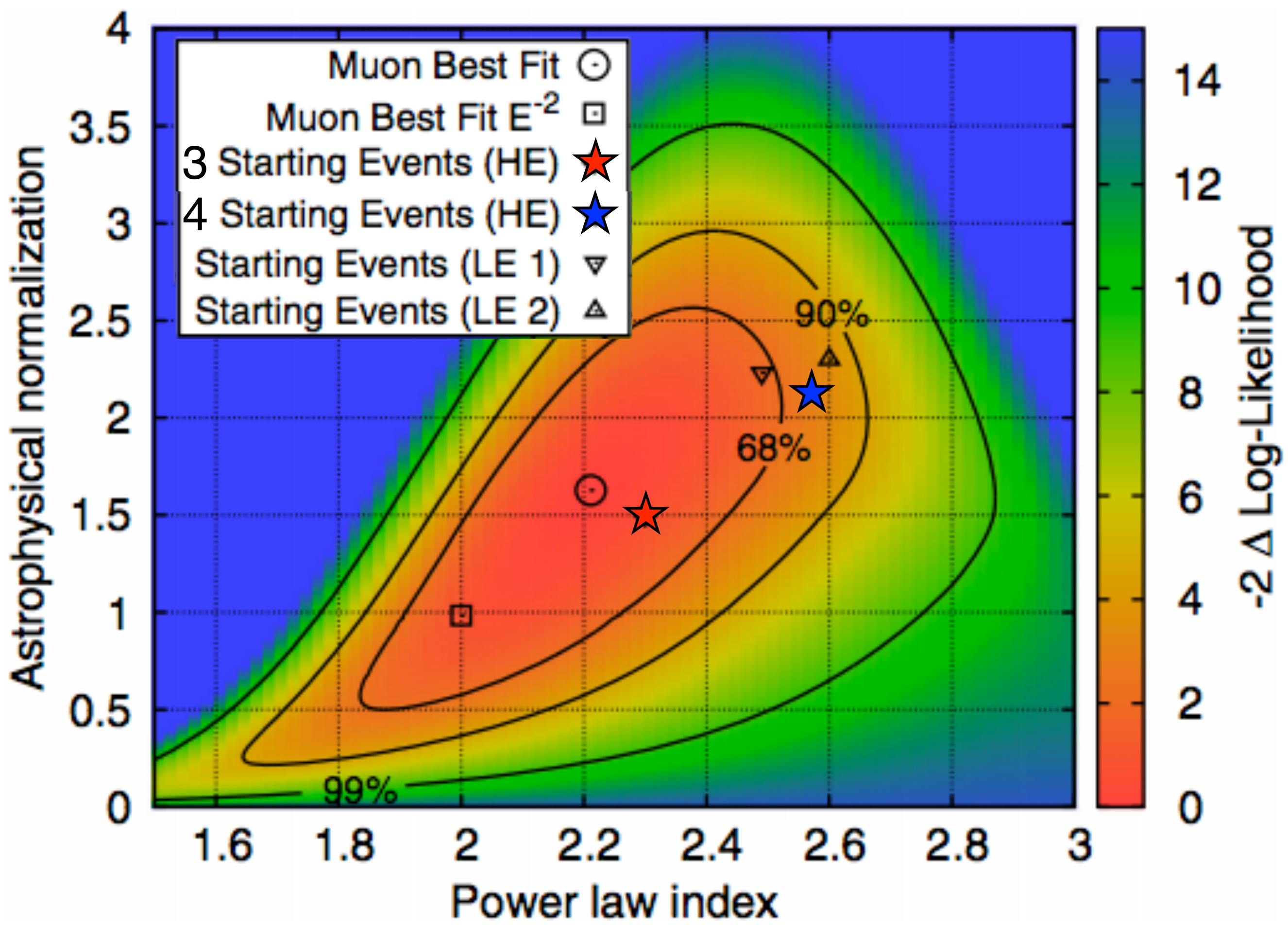
- prompt atmospheric component fit = 0



neutrino identification
astrophysical neutrinos

Aartsen et al. Phys.Rev.Lett. 115 (2015) 8, 081102





- up-going ν_μ events and HE starting events consistent within uncertainties
- **role of prompt neutrinos ? Need more events !**

neutrino identification

point sources ?

4 years of HE starting events
E_ν > 60 TeV

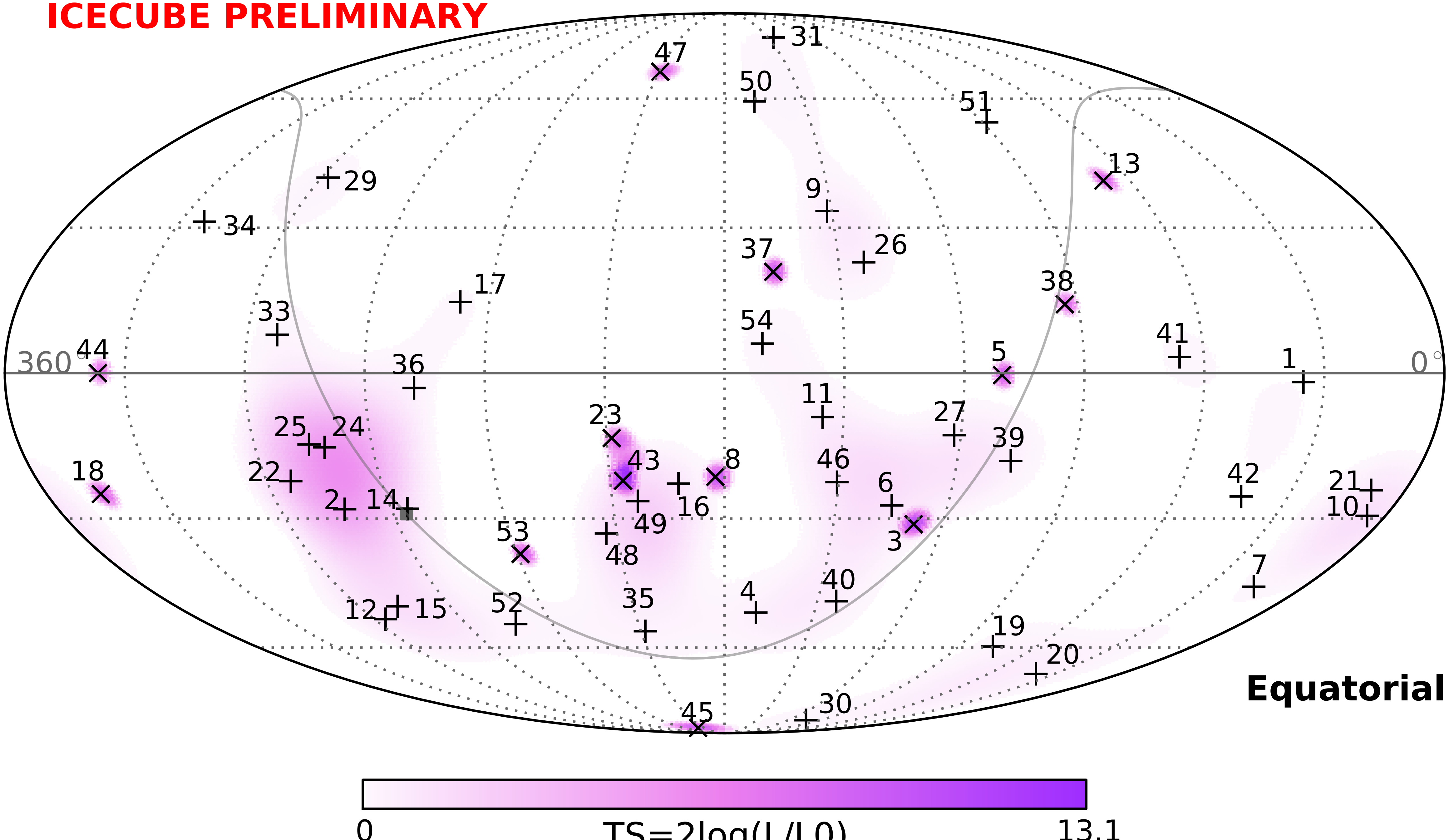
58% (post-trial) for all event clustering

44% (post-trial) for cascade-like event clustering

7% (post-trial) galactic plane with width 2.5°

2.5% (post-trial) galactic plane with **best** width 7.5°

ICECUBE PRELIMINARY

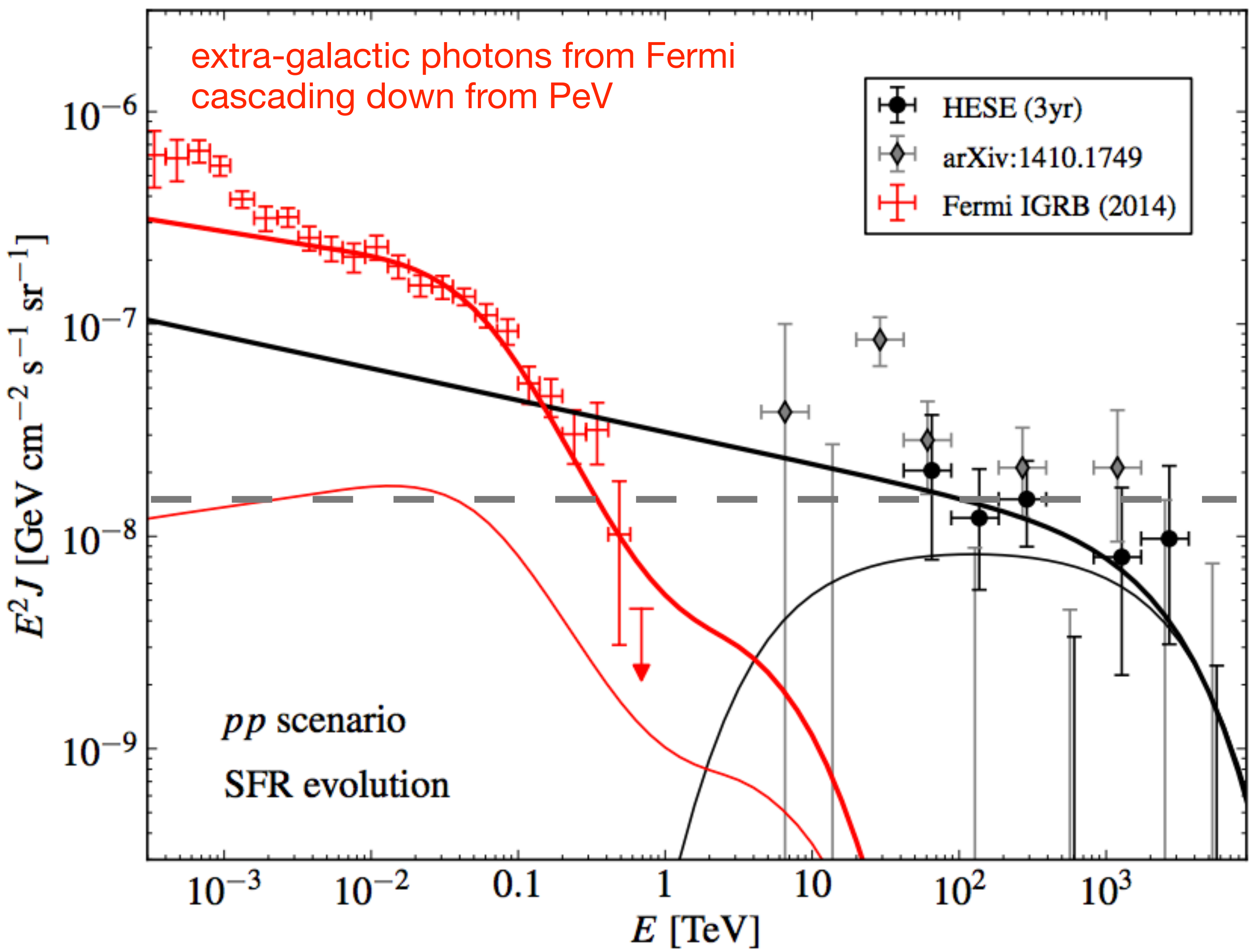


ICRC 2015

astrophysical neutrinos

extra-galactic origin

Aartsen et al. arXiv:1412.5106



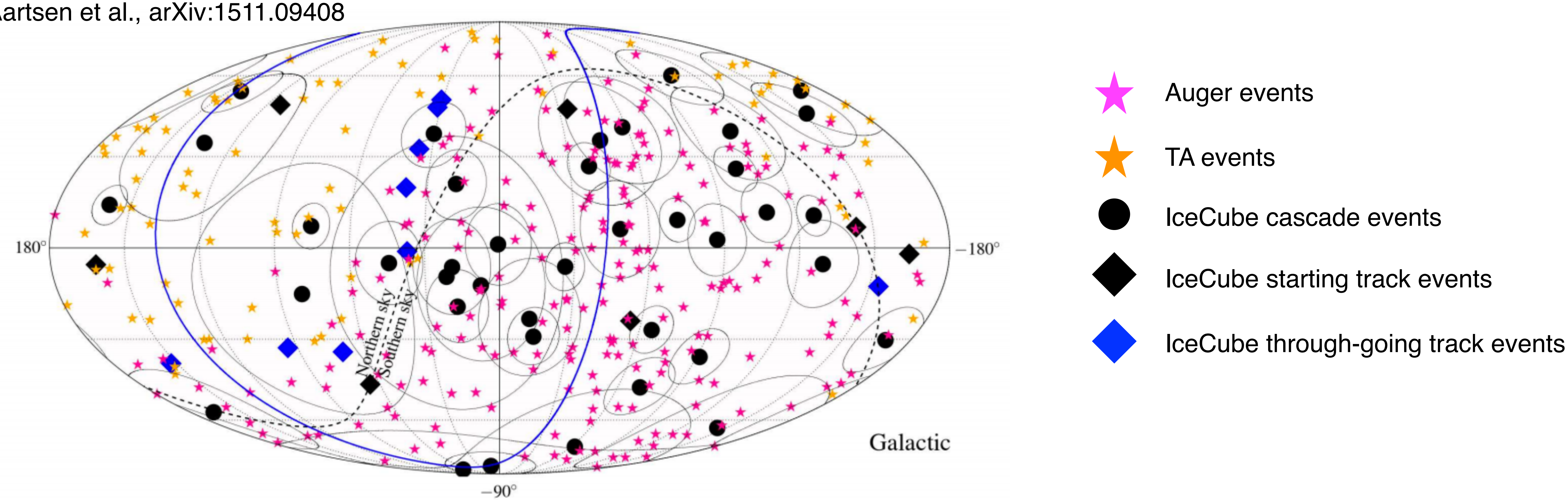
Murase, Ahlers & Lacki arXiv:1306.3417

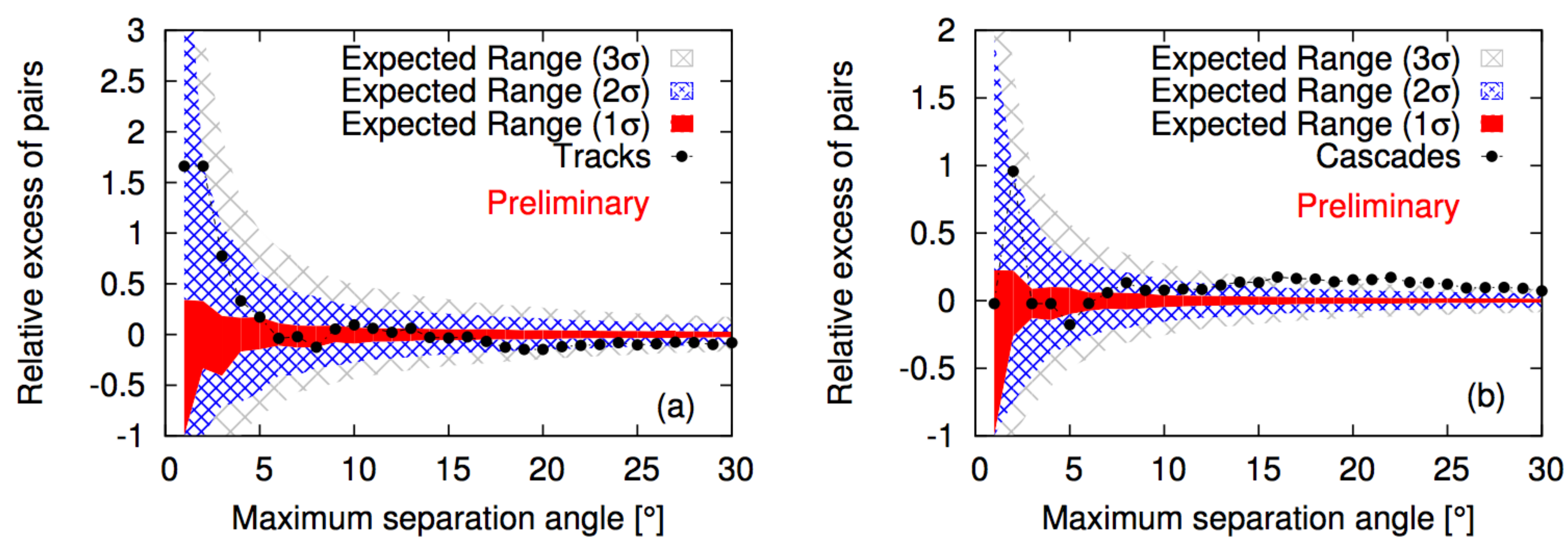
- γ-rays & ν's from pp interactions
- extra-galactic emission (cascaded in EBL): $E^{-2.1}$ - $E^{-2.2}$
- these cosmic ray sources contribute to 30%-40% of diffuse γ-ray background @100 GeV
- low energy tail of GeV-TeV neutrino/γ-ray spectra
- sources can be opaque in γ-ray
- ν to probe dense environments

astrophysical neutrinos
correlations with UHECR from Auger ?

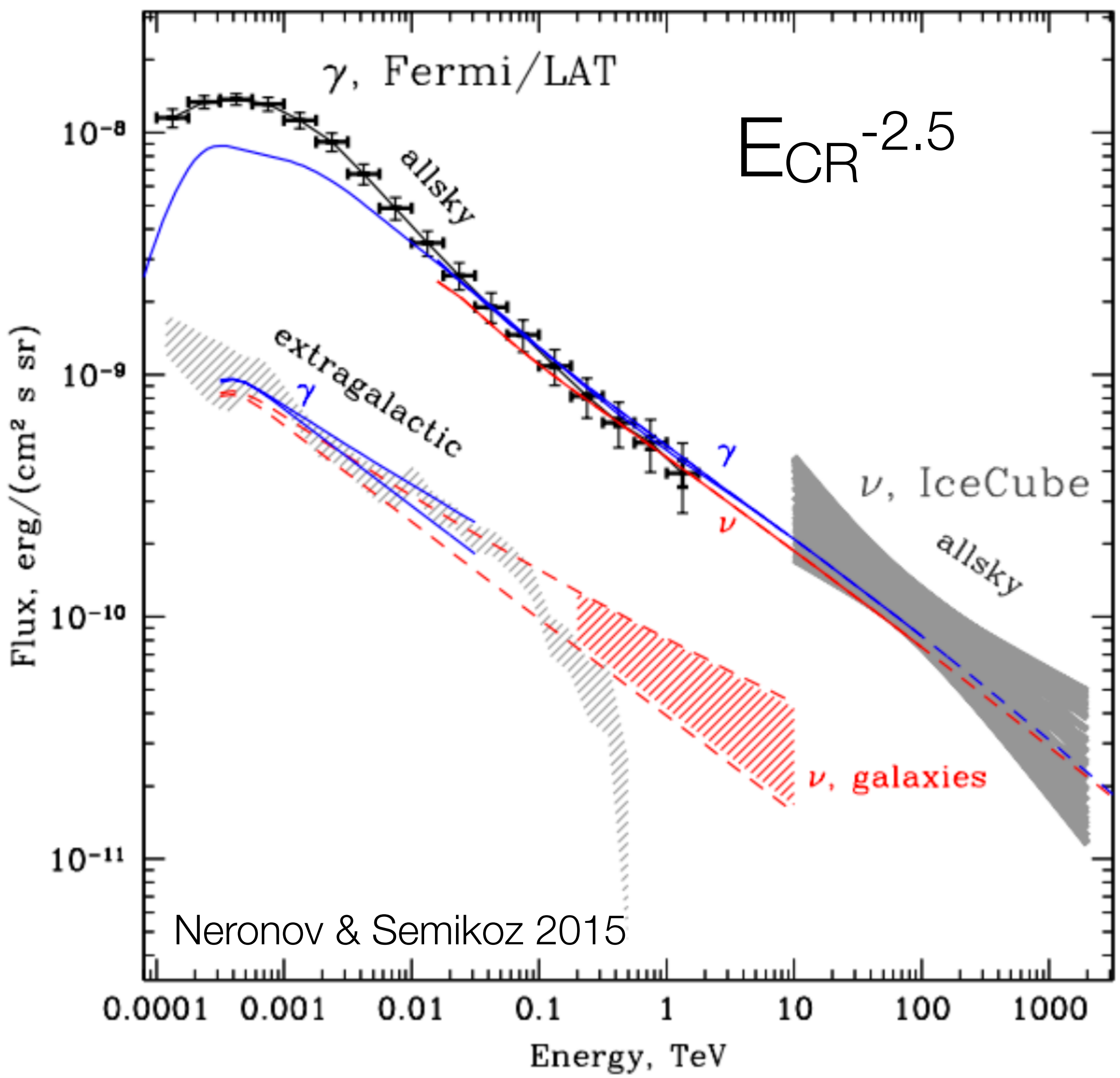
IceCube
Auger
TA

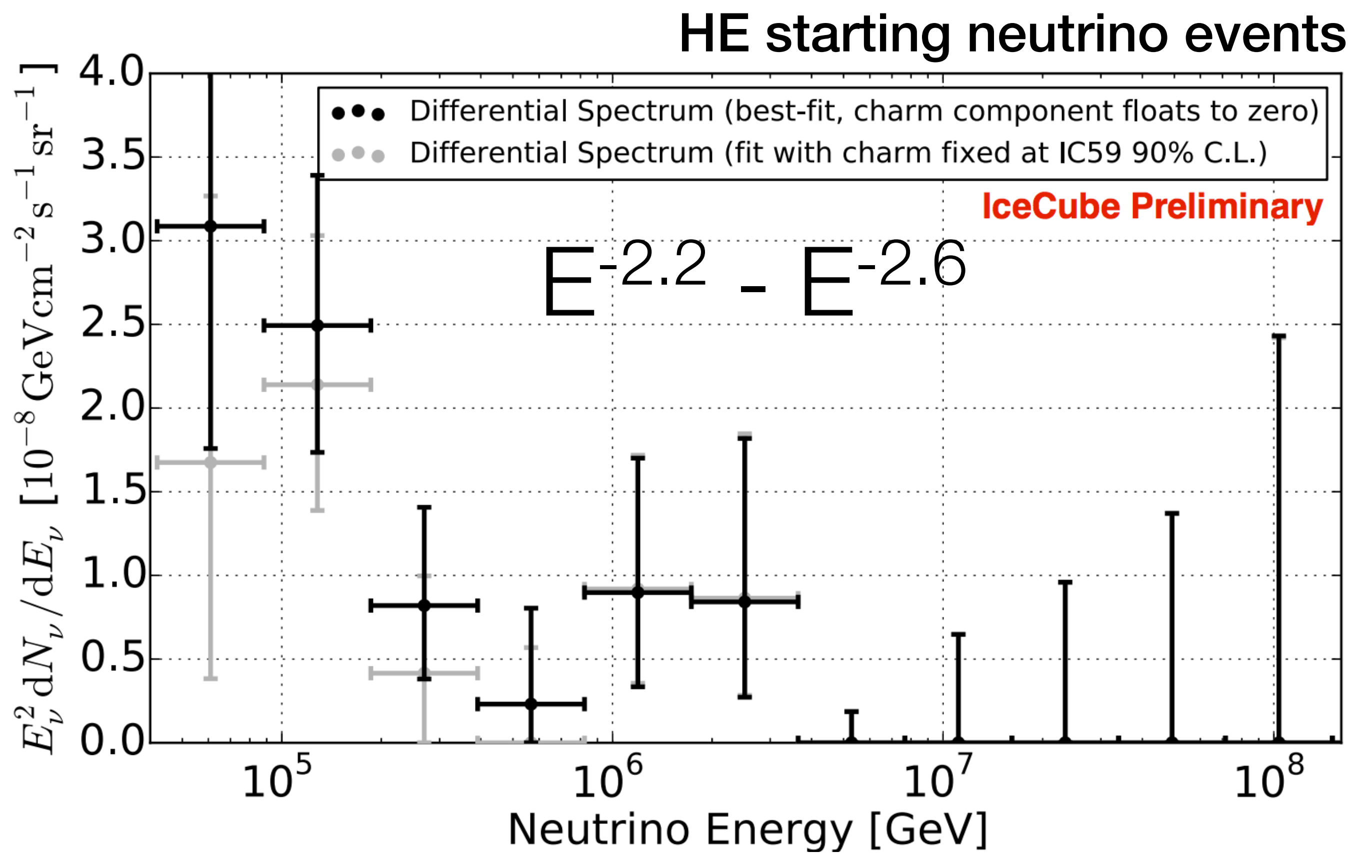
Aartsen et al., arXiv:1511.09408

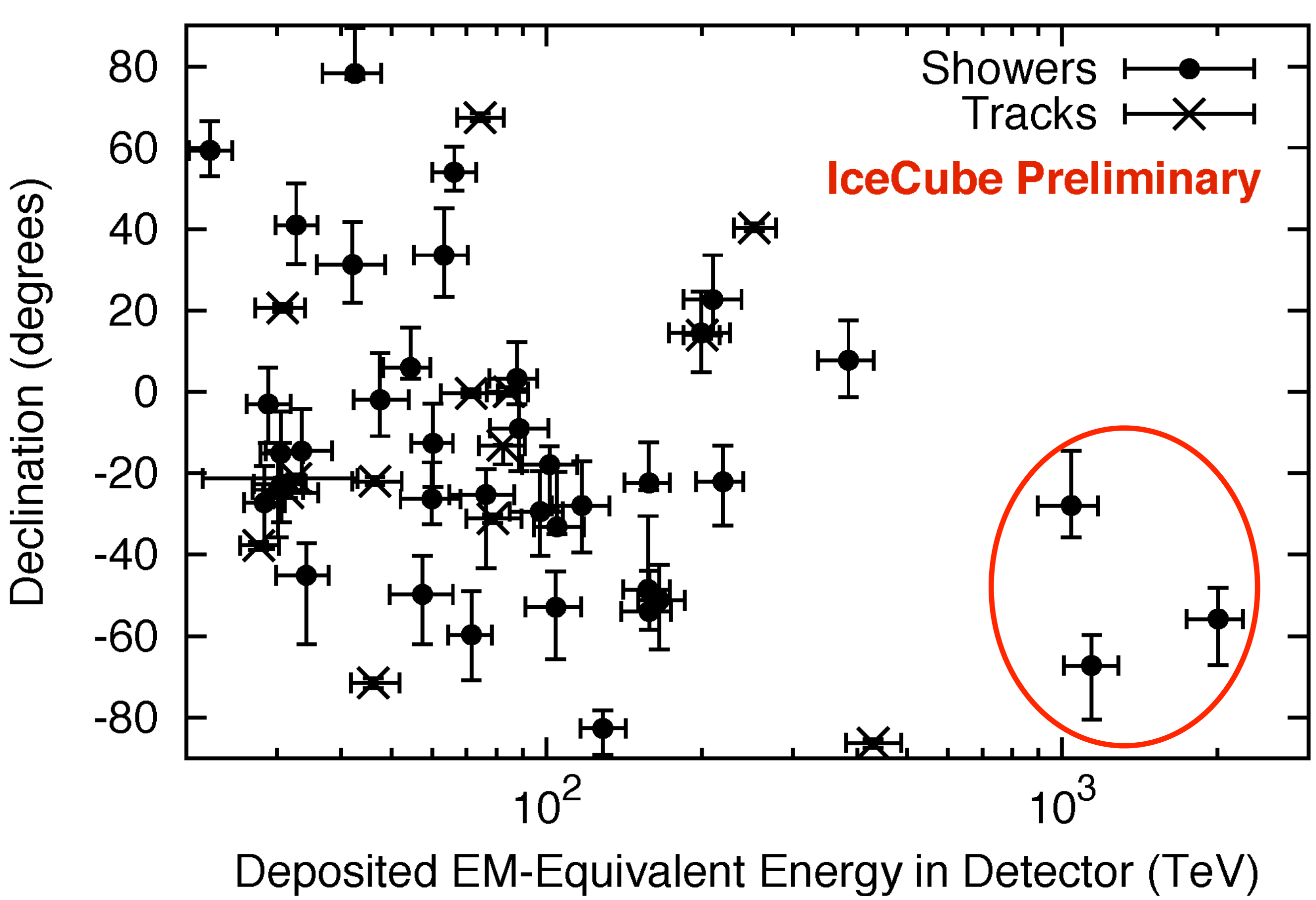




astrophysical neutrinos
galactic origin





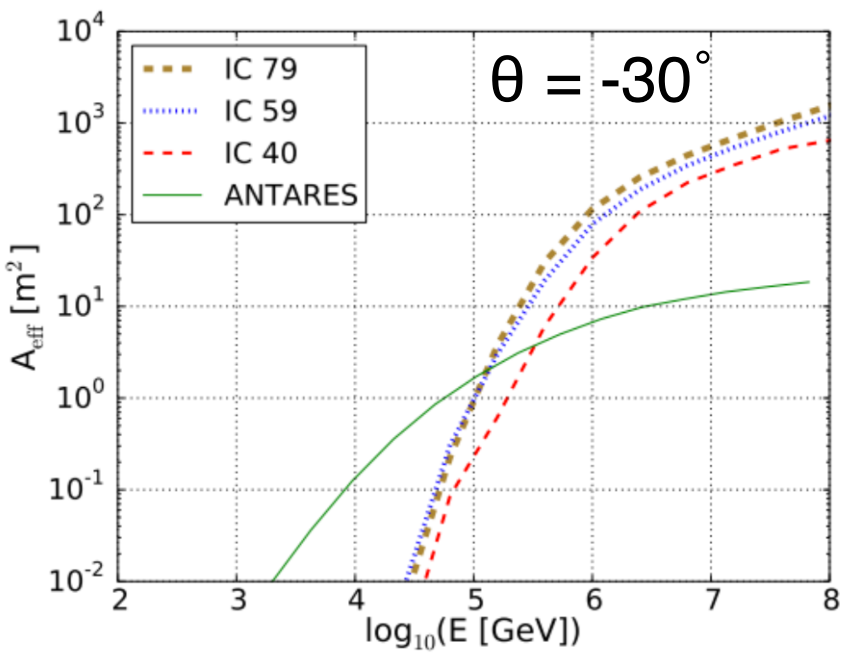


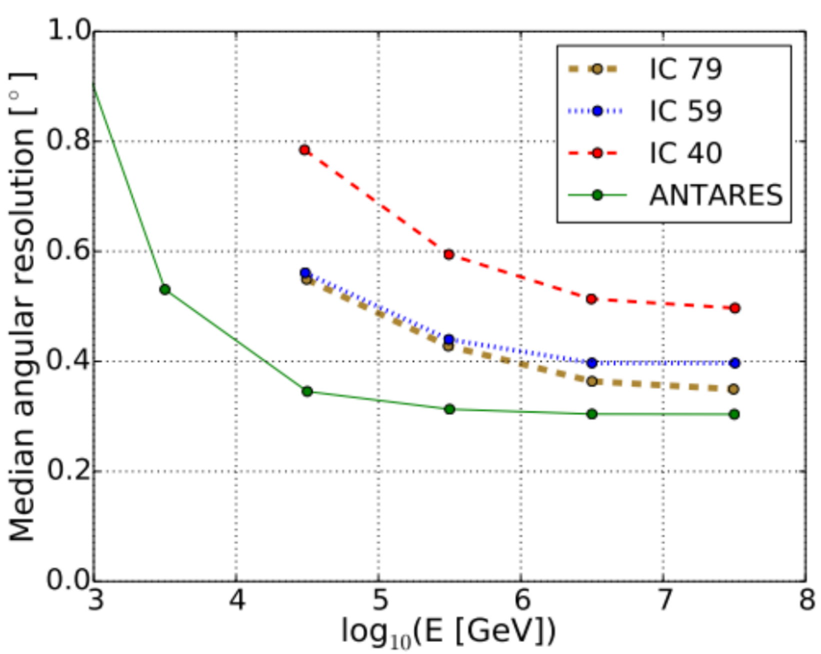
galactic cosmic rays with cut-off of 10 PeV ?

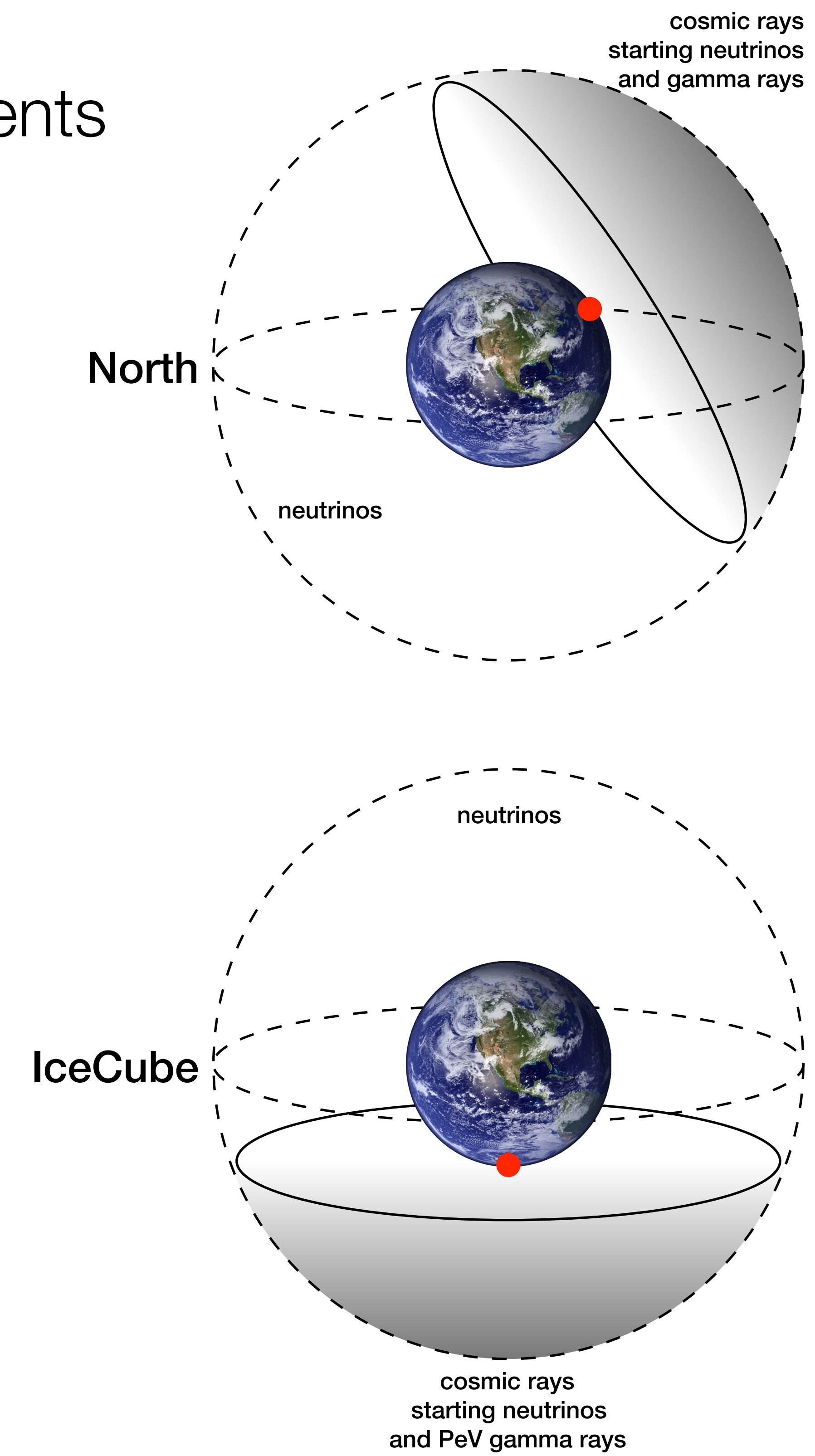
searching for point sources of neutrinos

full-sky

combine observations from *complementary* experiments





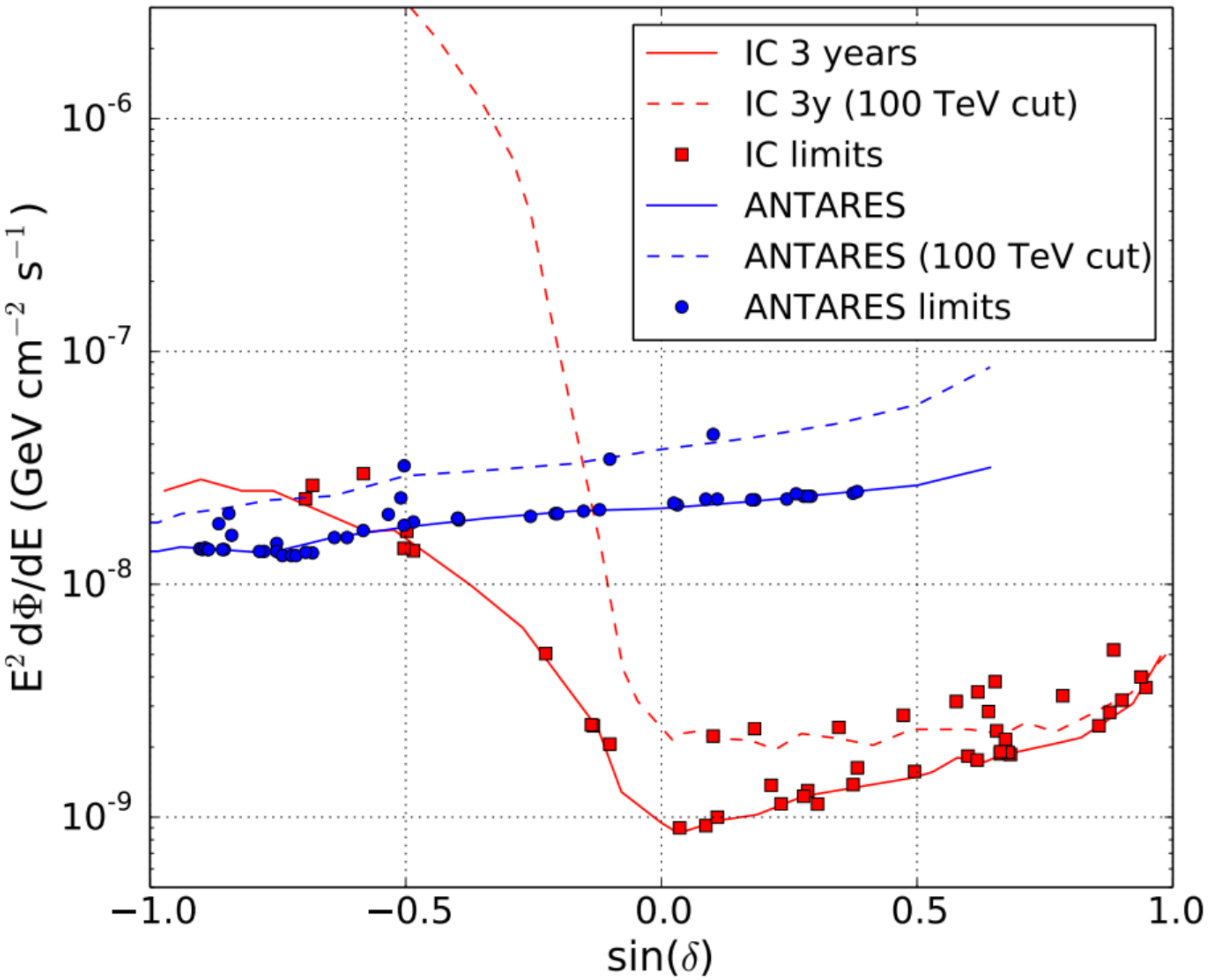


ANTARES & IceCube Collaborations, arXiv:1511.02149

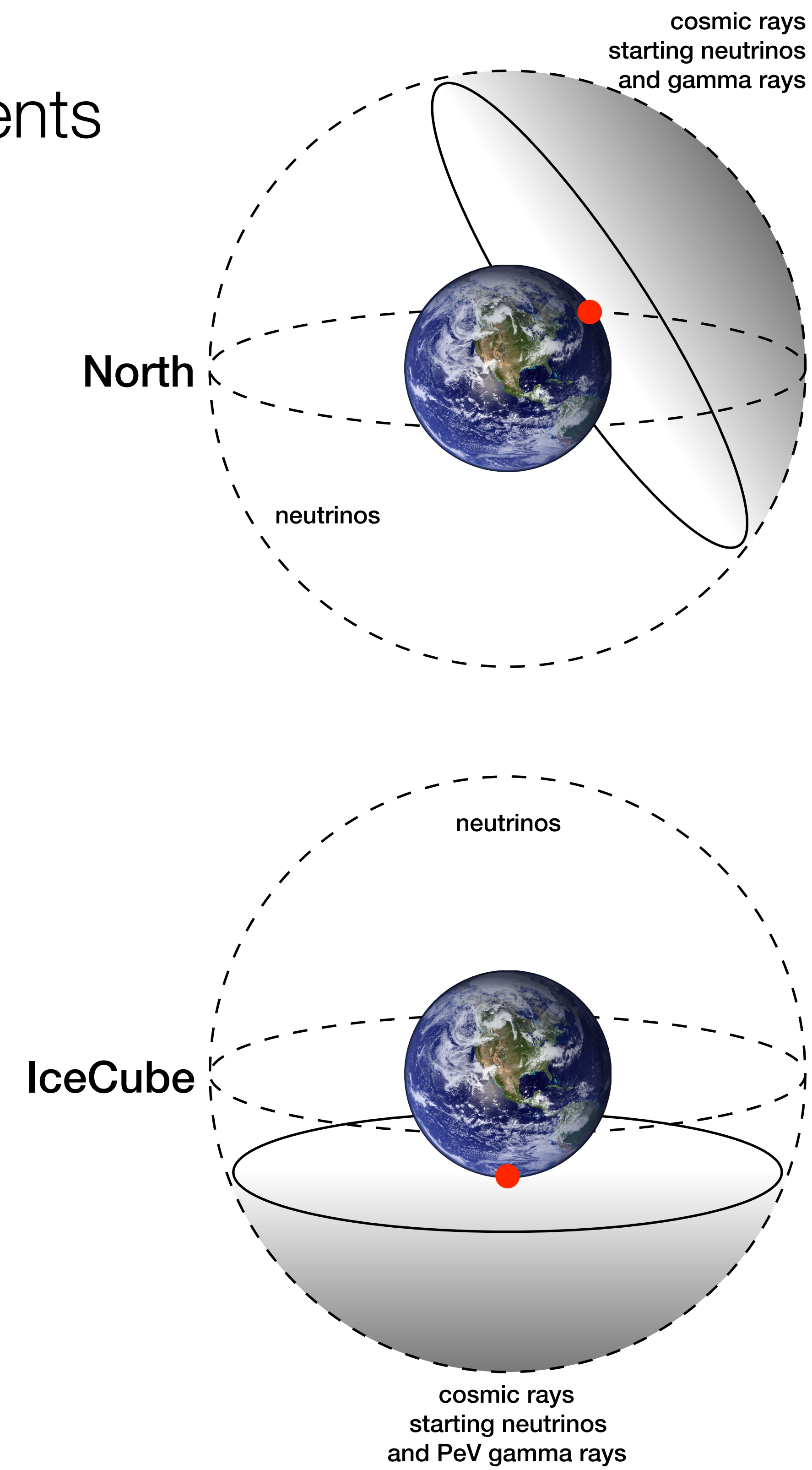
searching for point sources of neutrinos

full-sky

combine observations from *complementary* experiments



ANTARES & IceCube Collaborations, arXiv:1511.02149

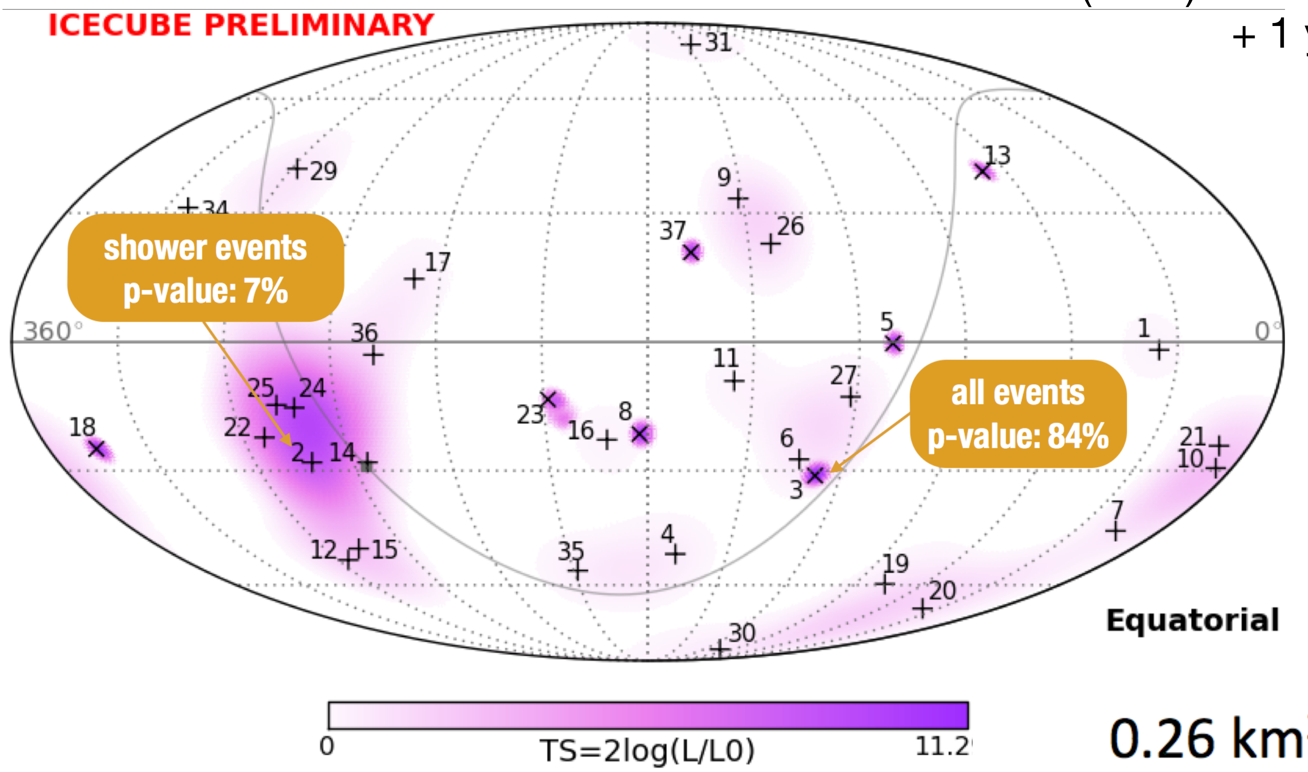


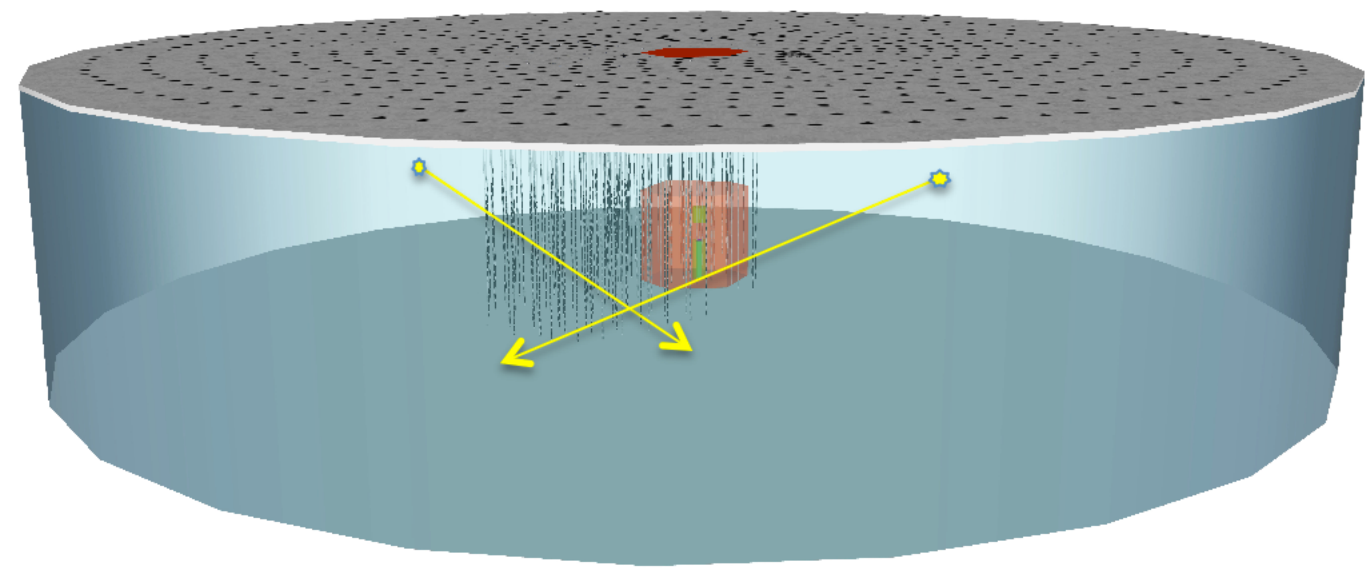
neutrino telescopes
large under-water/ice experiments

~ km³ … and more

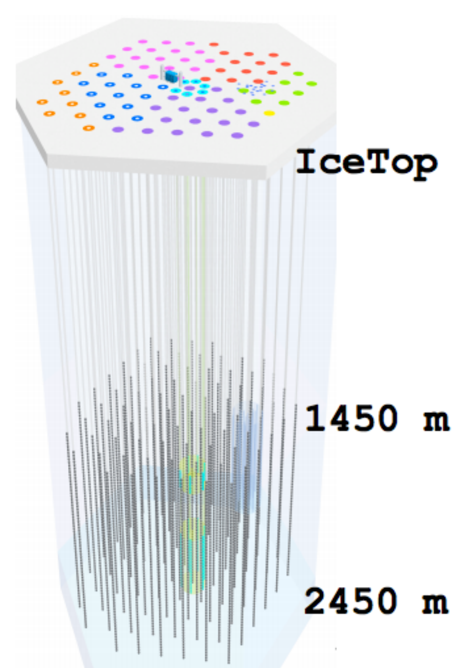
high energy extension Gen-2

Aartsen et al. Science 342 (2013) 1242856
+ 1 year

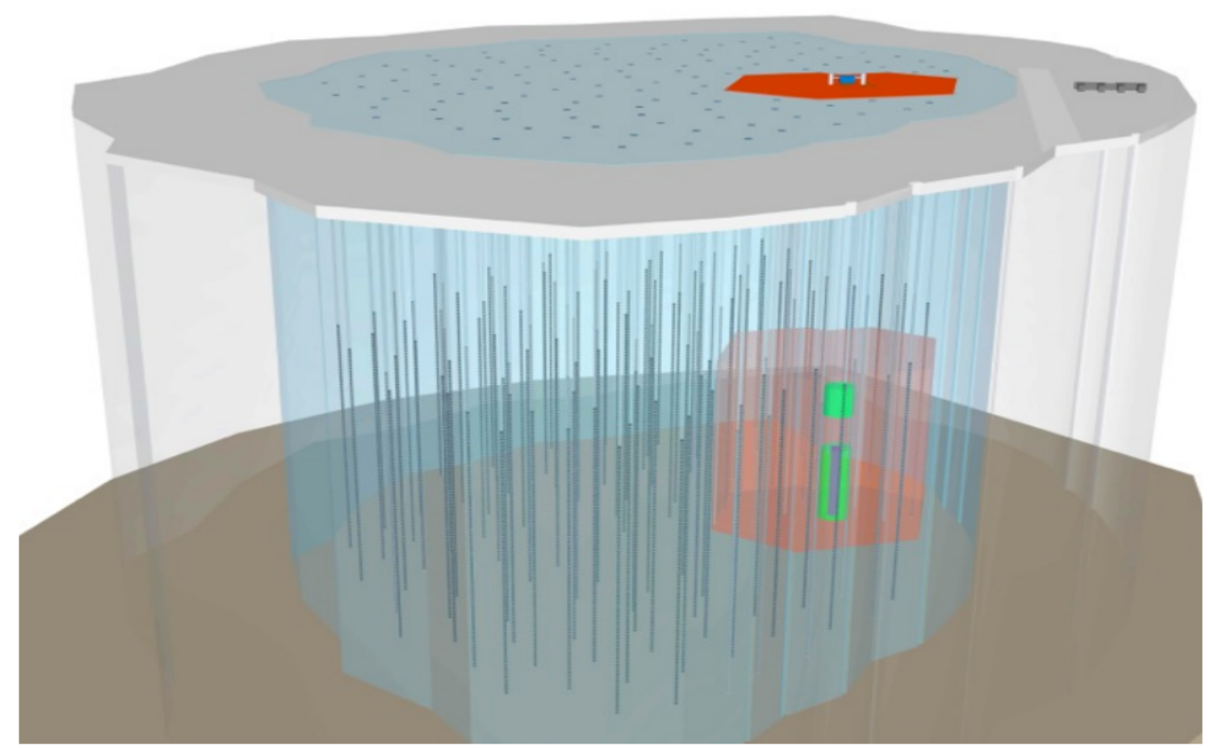




0.26 km² sr

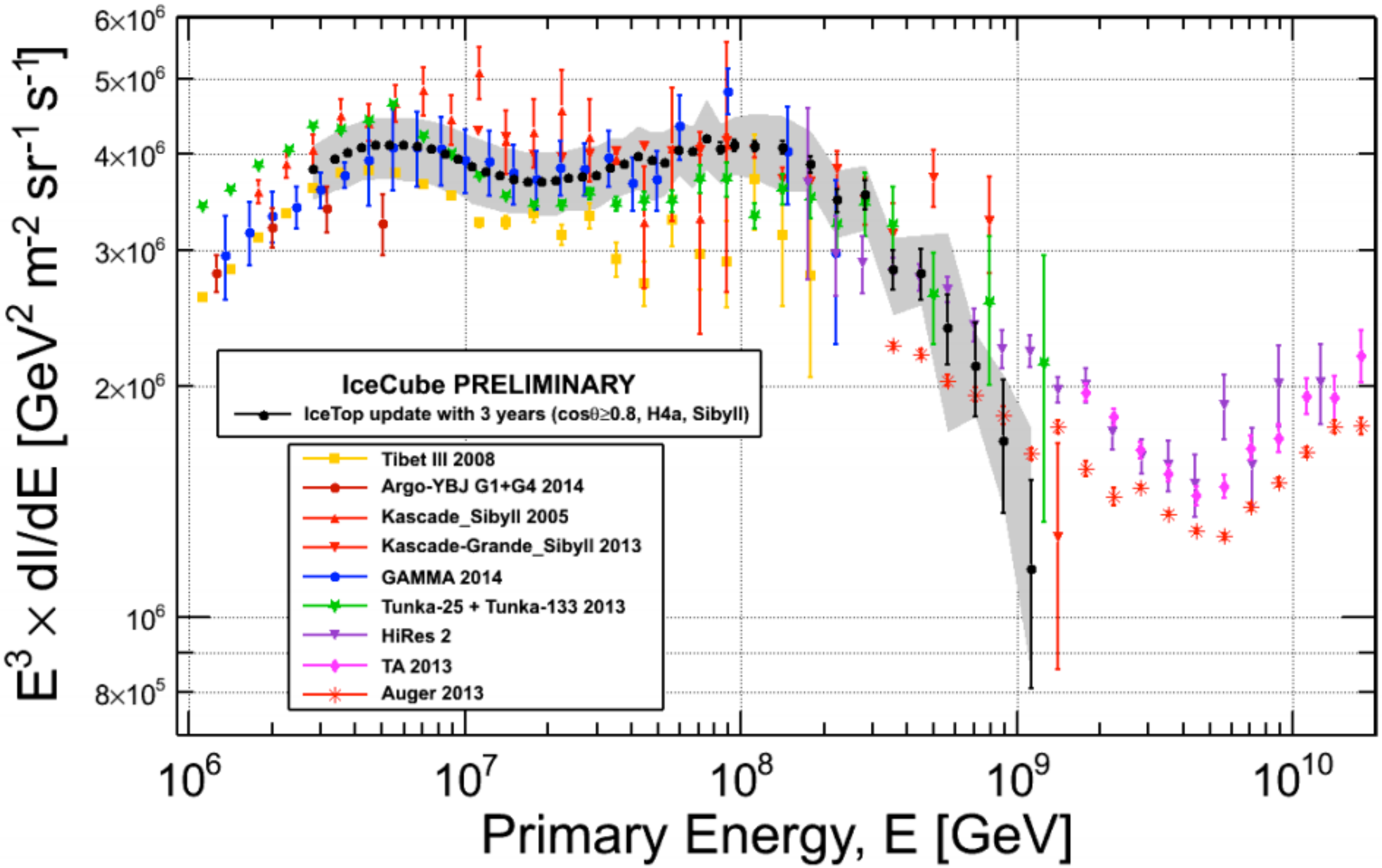


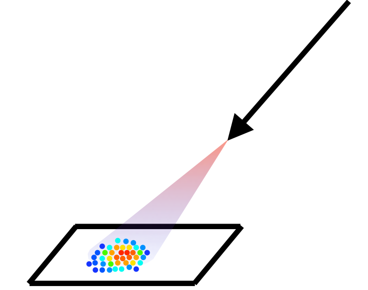
~ 10 km² sr

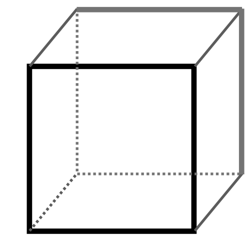


cosmic rays spectrum

all-particle energy spectrum

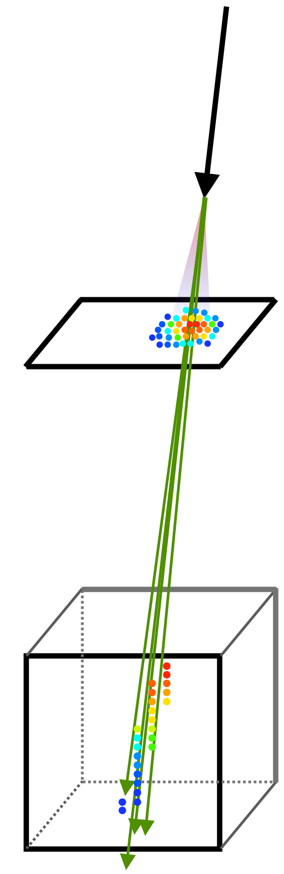






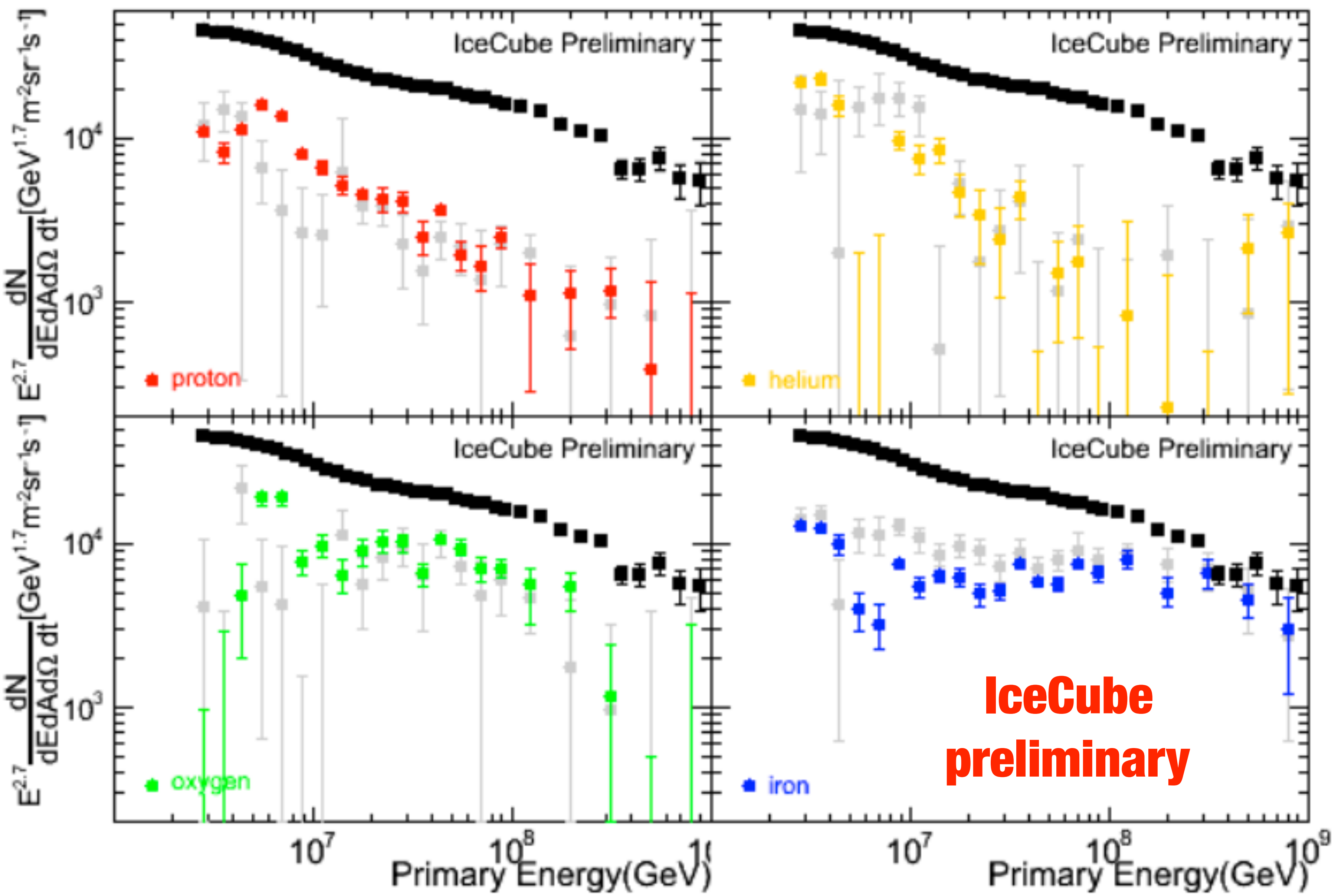
all-particle spectrum depends on the ***assumed*** mass composition of primary particles

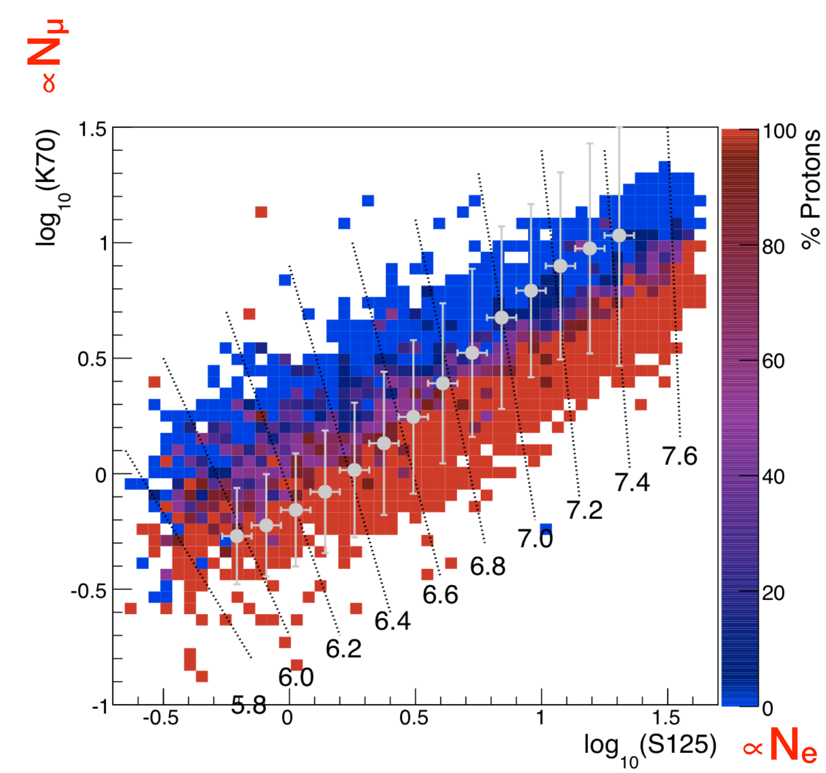
cosmic rays composition
coincident events



Colors = SIBYLL 2.1
Grey = QGSJET-II-03

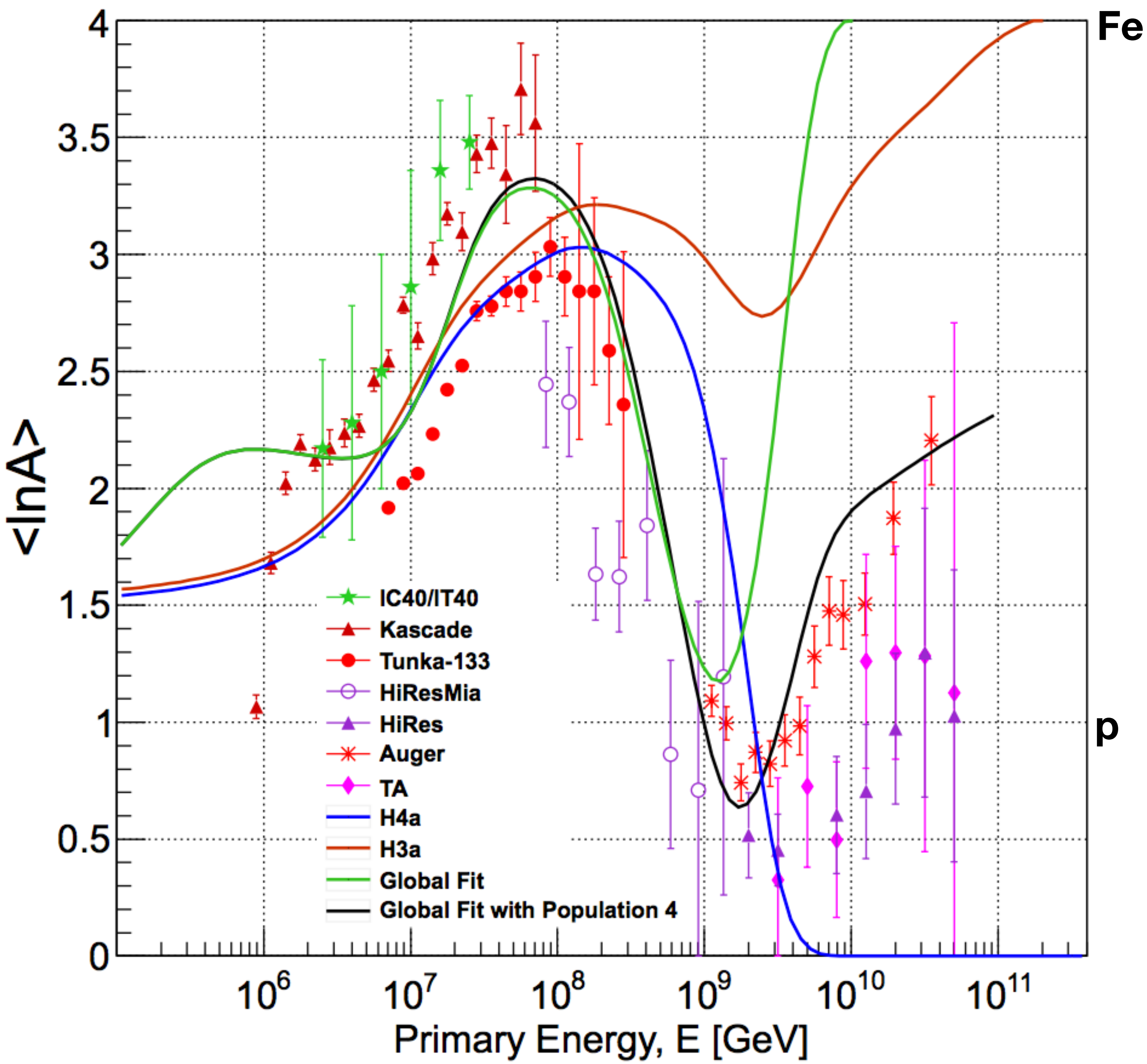
effect of hadronic interaction models





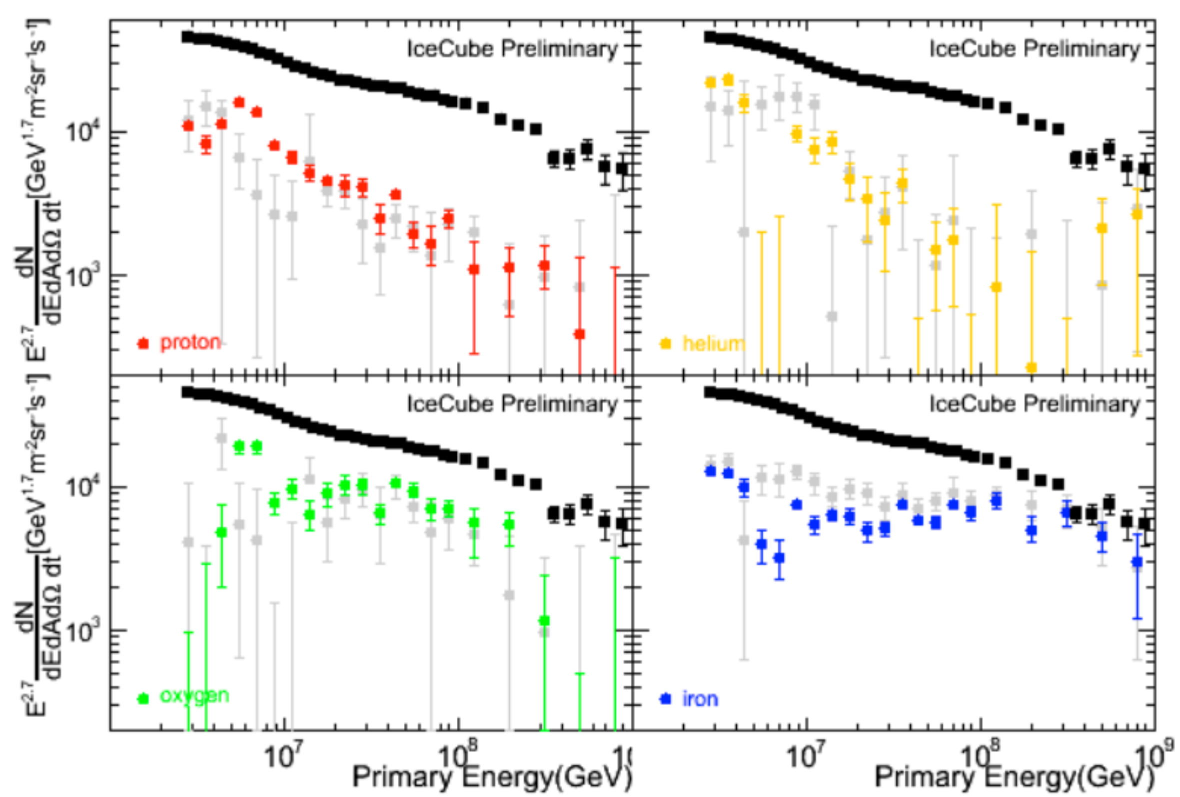
cosmic rays composition

other experiments



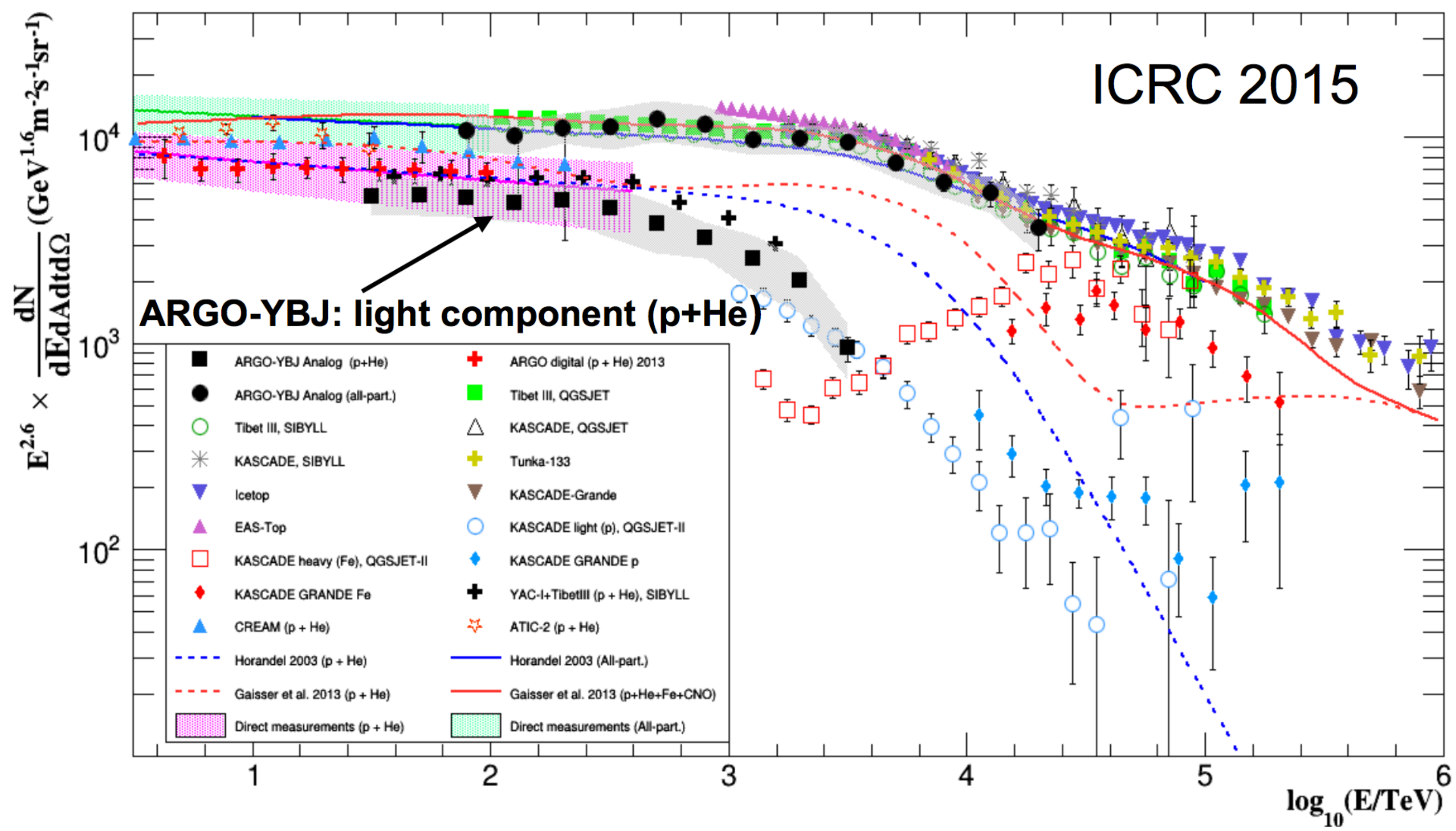
cosmic ray composition in **indirect** measurements is **DIFFICULT**

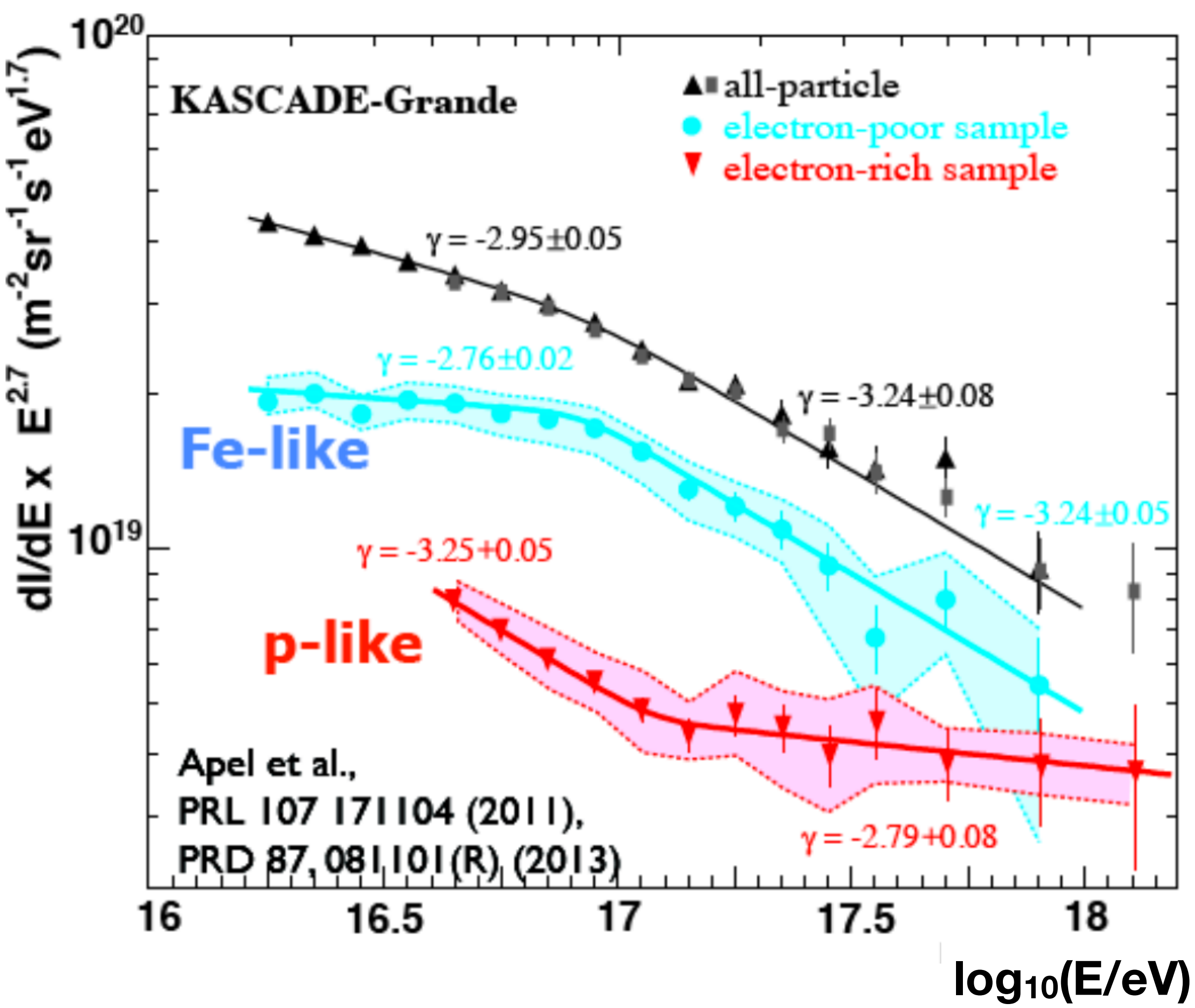
understanding **hadronic** interaction models at high energy is **NOT EASY**



cosmic rays composition

other experiments





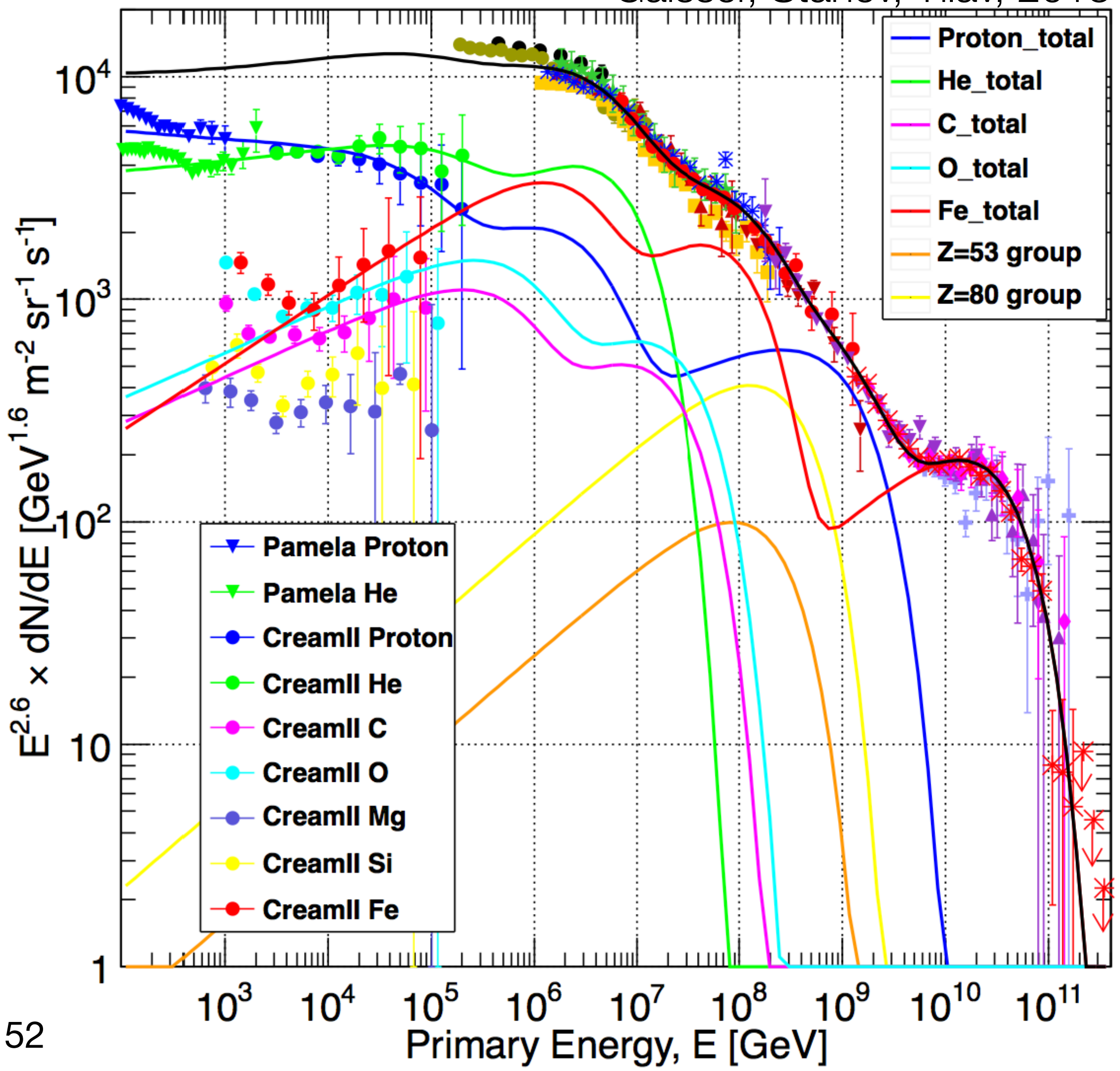
cosmic ray composition in **indirect** measurements is **DIFFICULT**

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

cosmic ray propagation in interstellar medium

- cosmic ray spectrum **shaped** by acceleration at the **source**

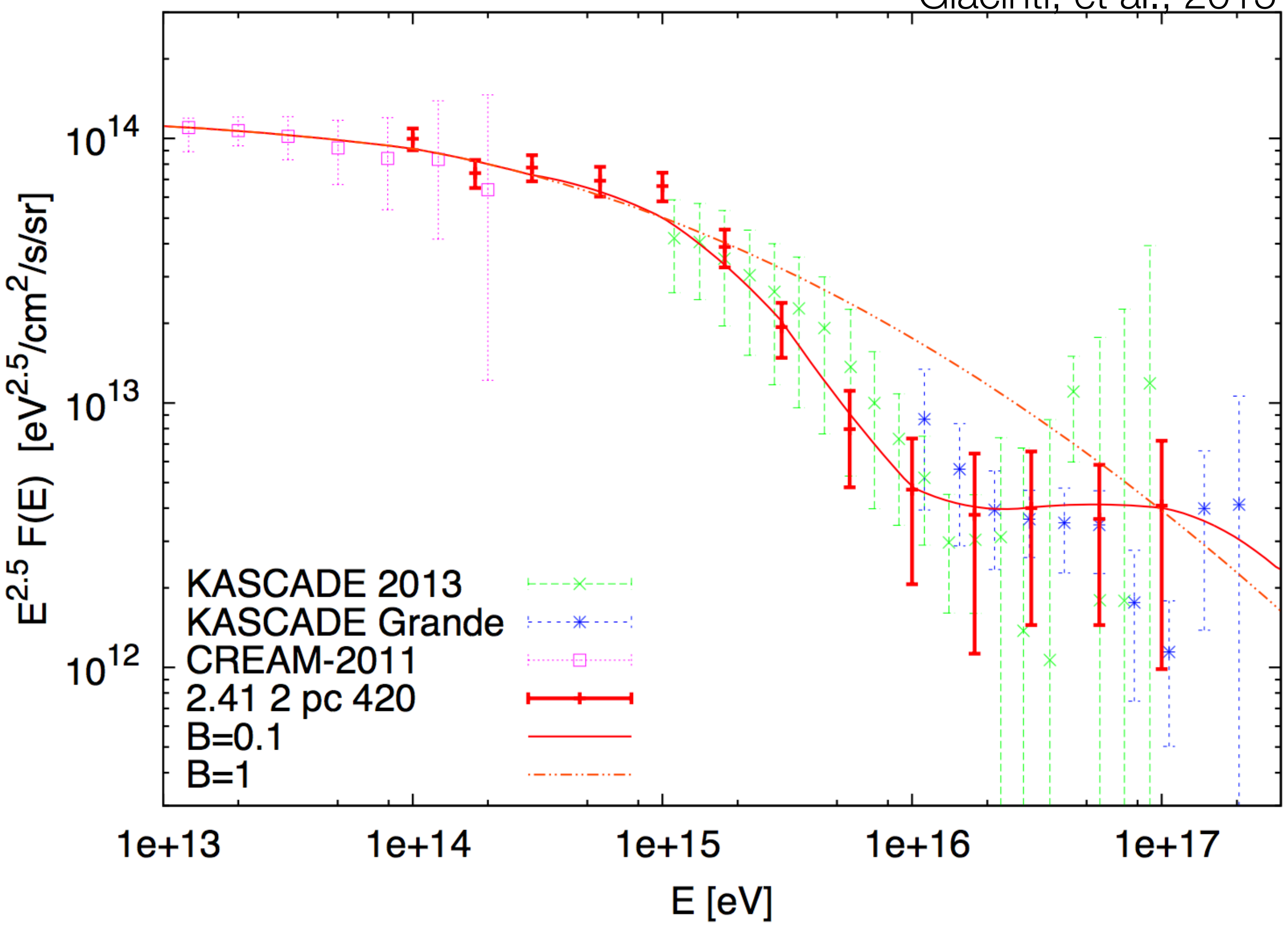
Gaisser, Stanev, Tilav, 2013



- the **knee** of cosmic rays and spectral **features** from **escape** from the Galaxy

- determines the level of **turbulence**

Giacinti, et al., 2015



TeV sidereal anisotropy

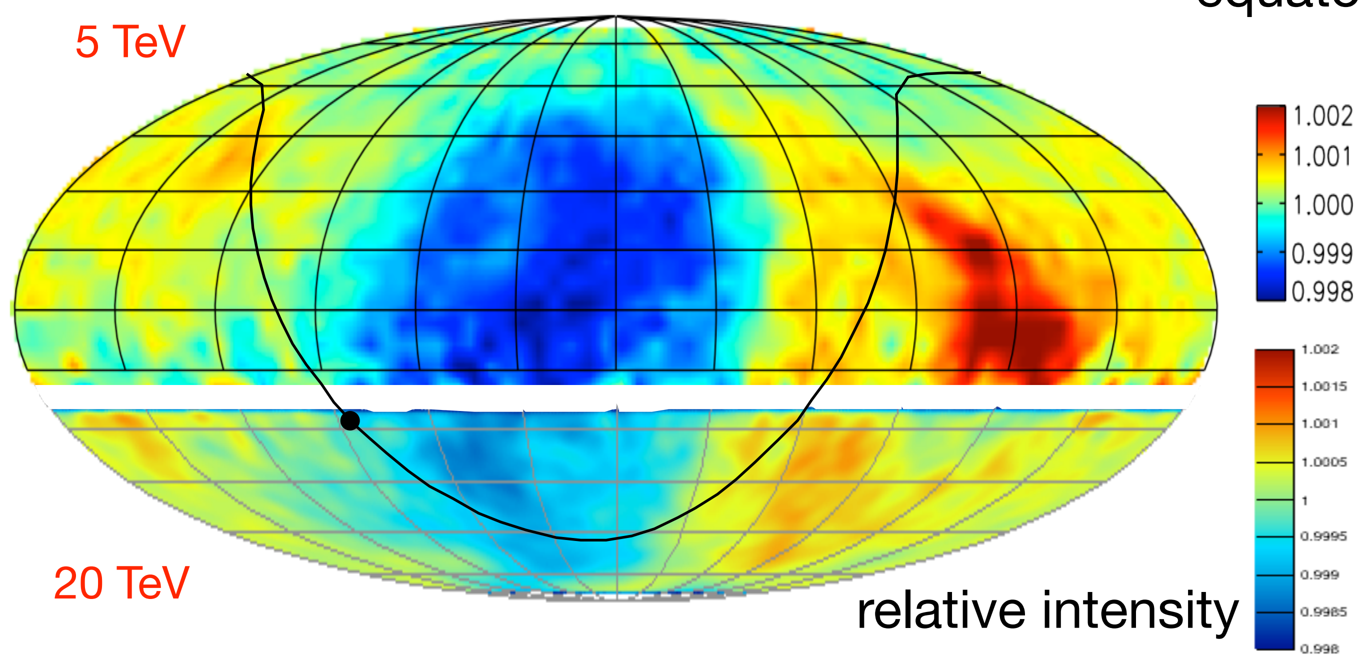
equatorial coordinates

Tibet-III

Amenomori et al., ICRC 2011

IceCube-59

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

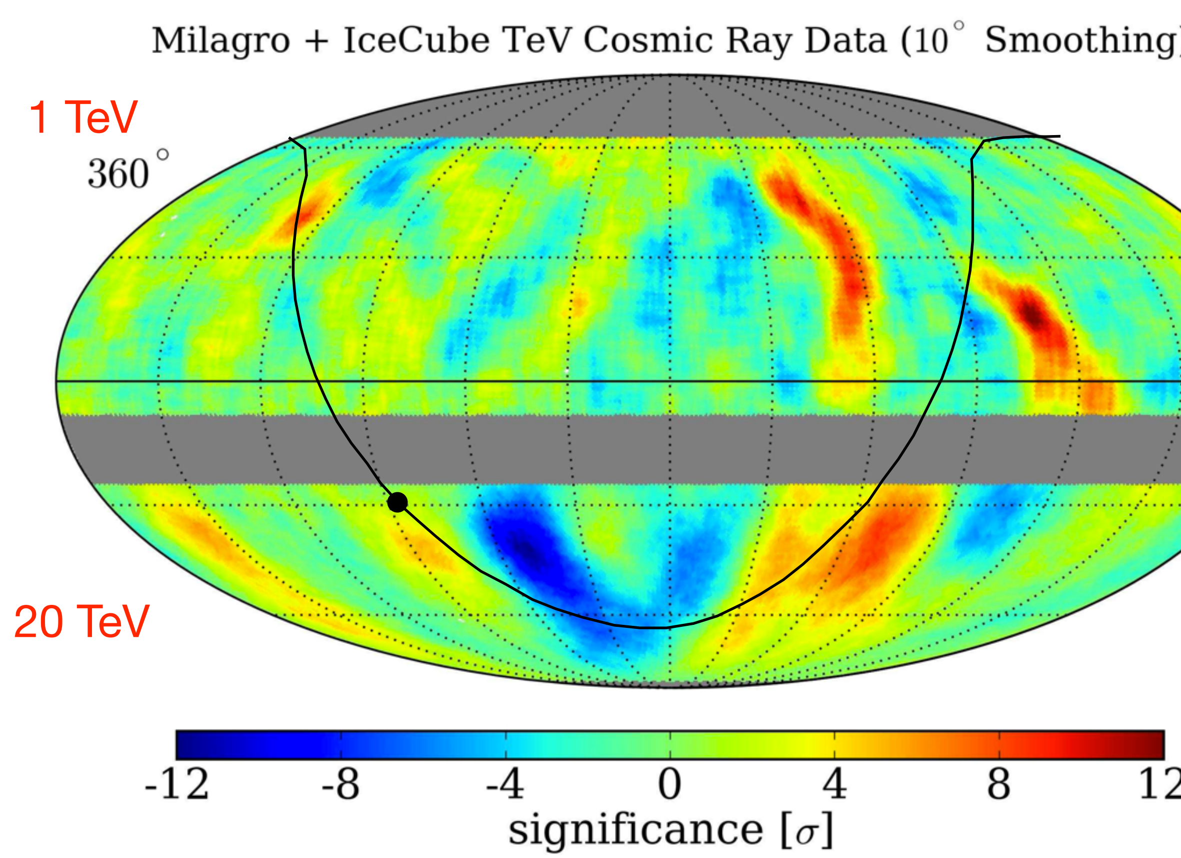


Milagro

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

IceCube-59

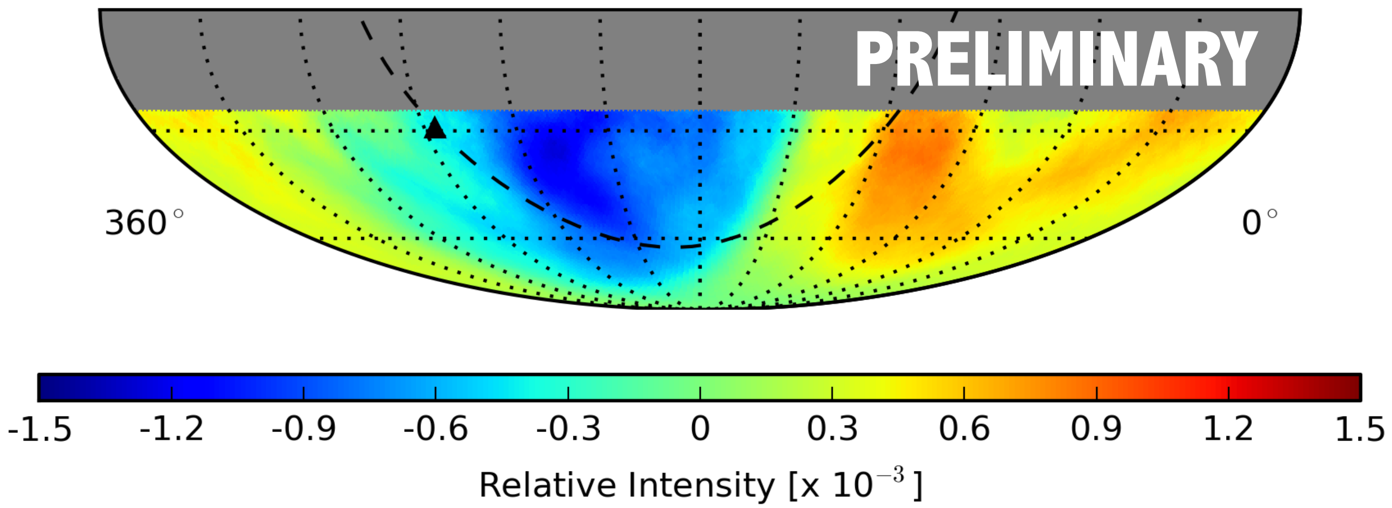
Abbasi et al., ApJ, **740**, 16, 2011



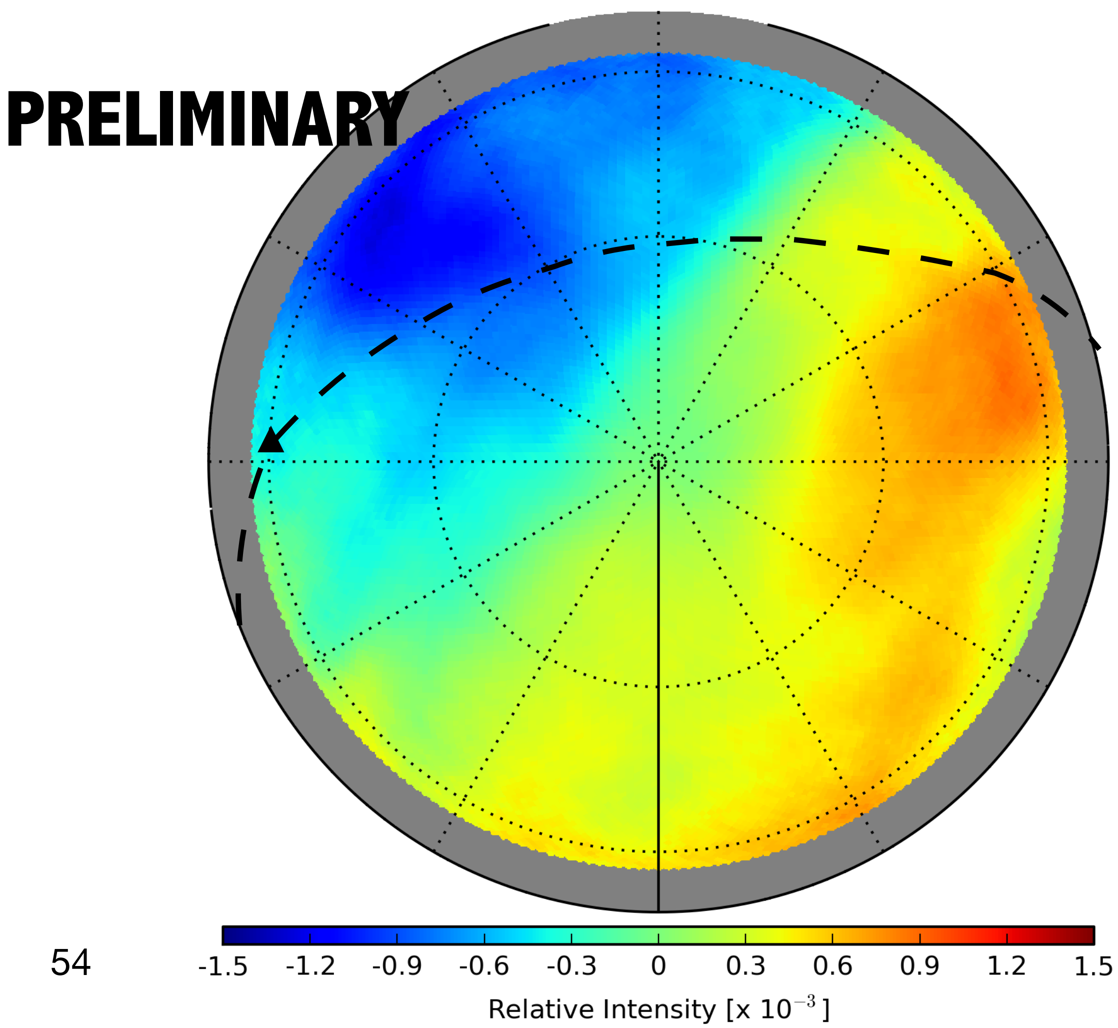
cosmic rays anisotropy

arrival direction distribution

to be submitted to ApJ



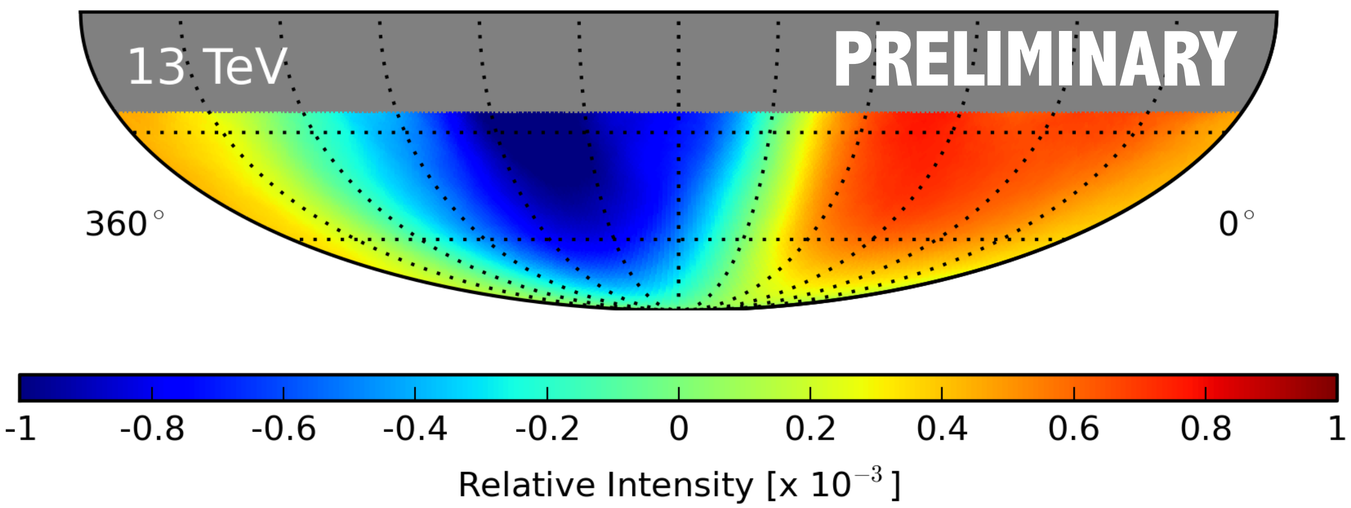
- 6 years of IceCube
- 300 billion events

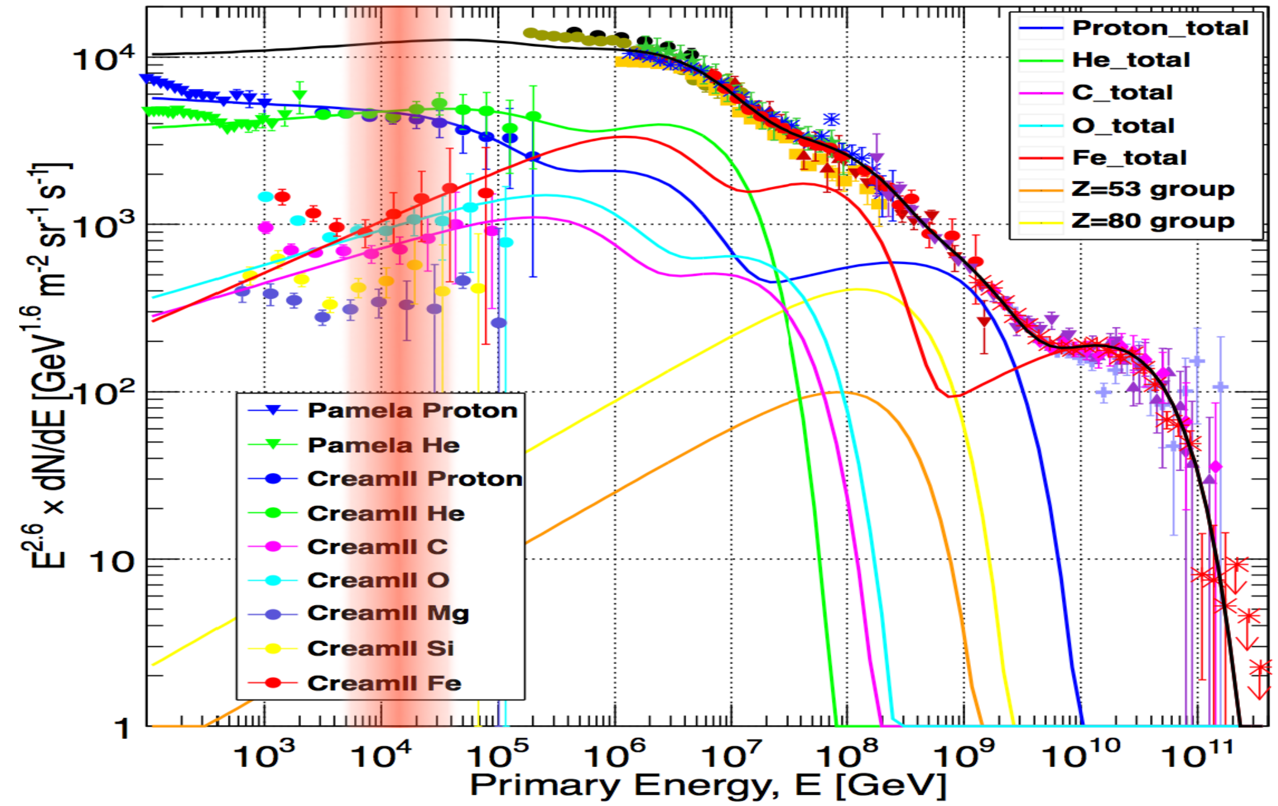


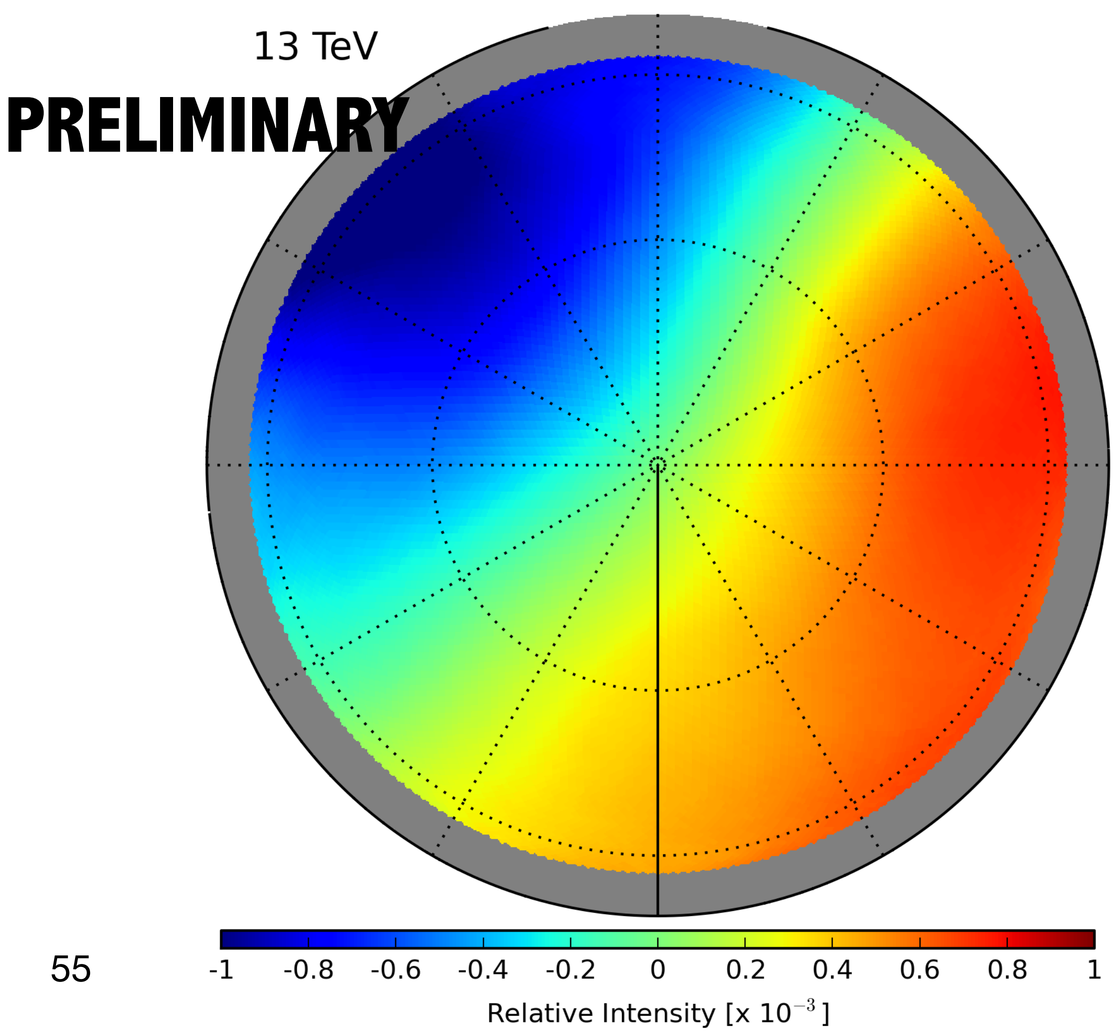
- anisotropy on the level of 10^{-3}
- median cosmic ray energy **20 TeV**
- trace sources ? Magnetic fields ?

cosmic rays anisotropy

arrival direction distribution





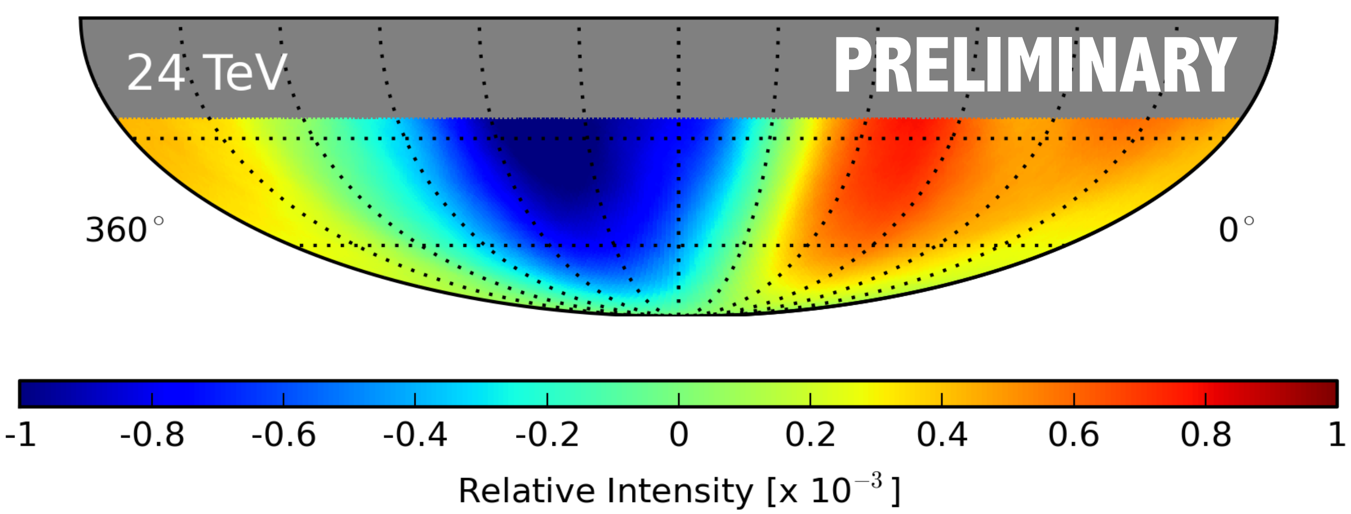


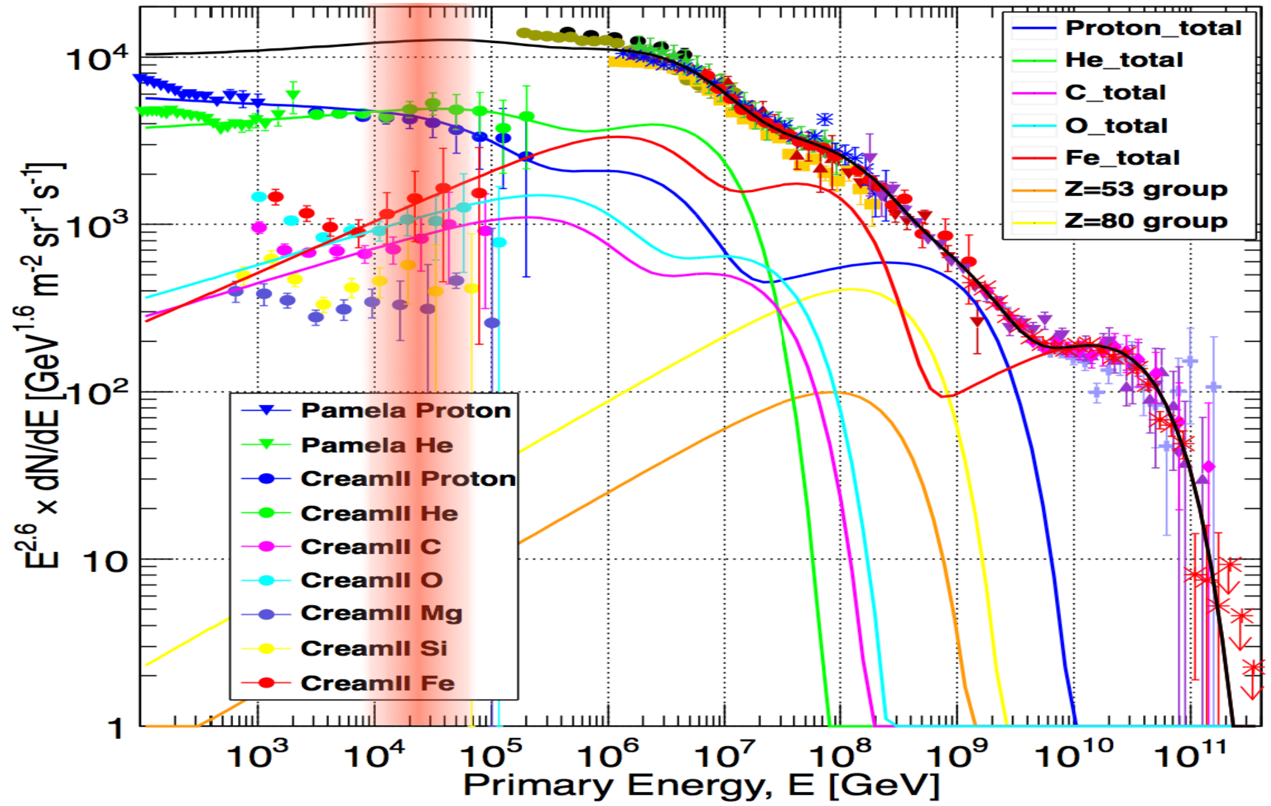
13 TeV **IceCube**

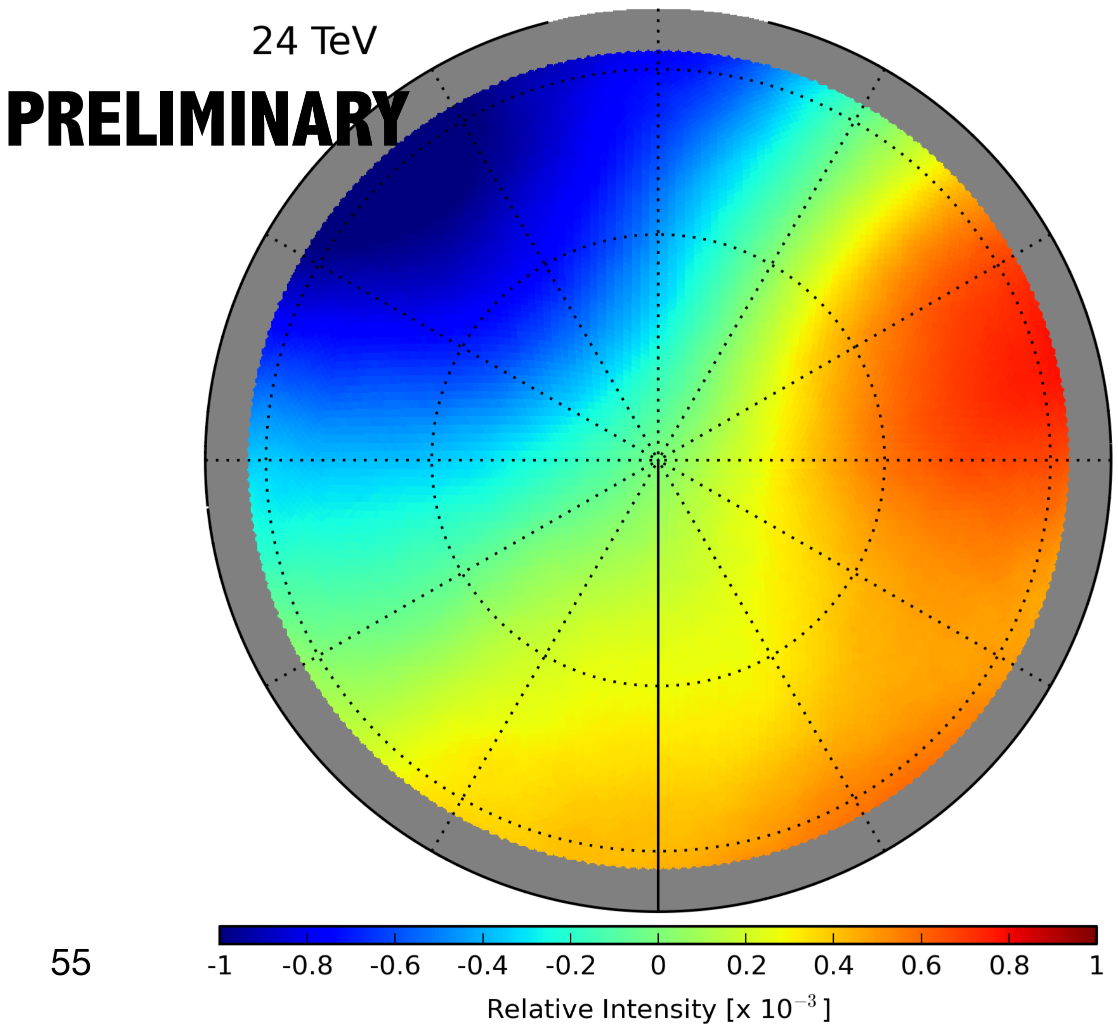
- high energy observations **MISSING** in the northern hemisphere
- **overlapping observations** extending across the equator will help
- capable of energy/mass measurement

cosmic rays anisotropy

arrival direction distribution





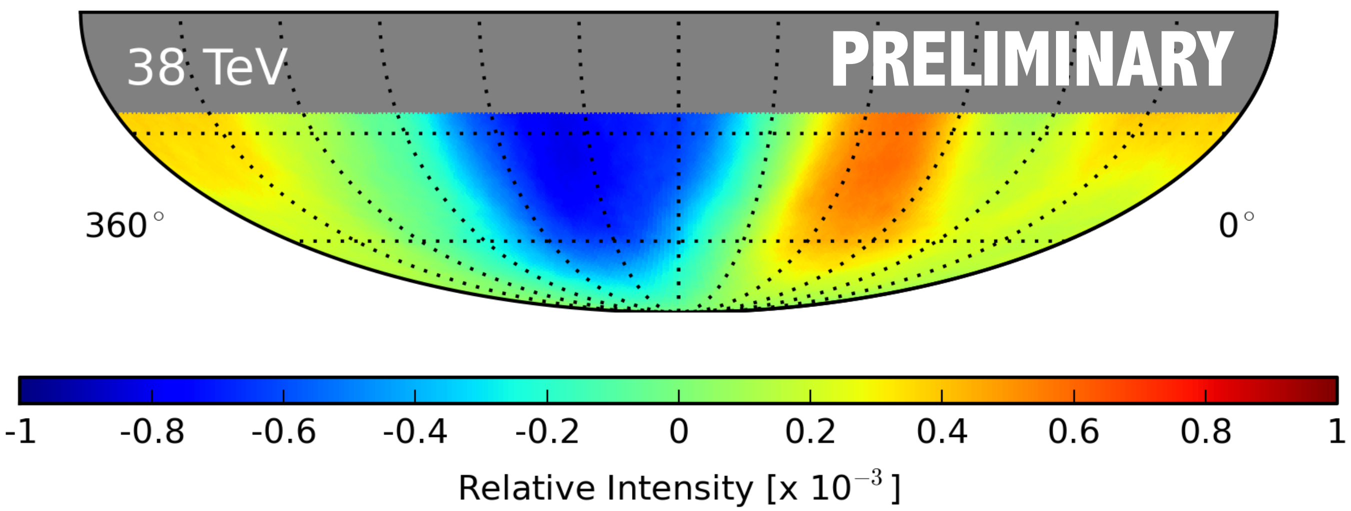


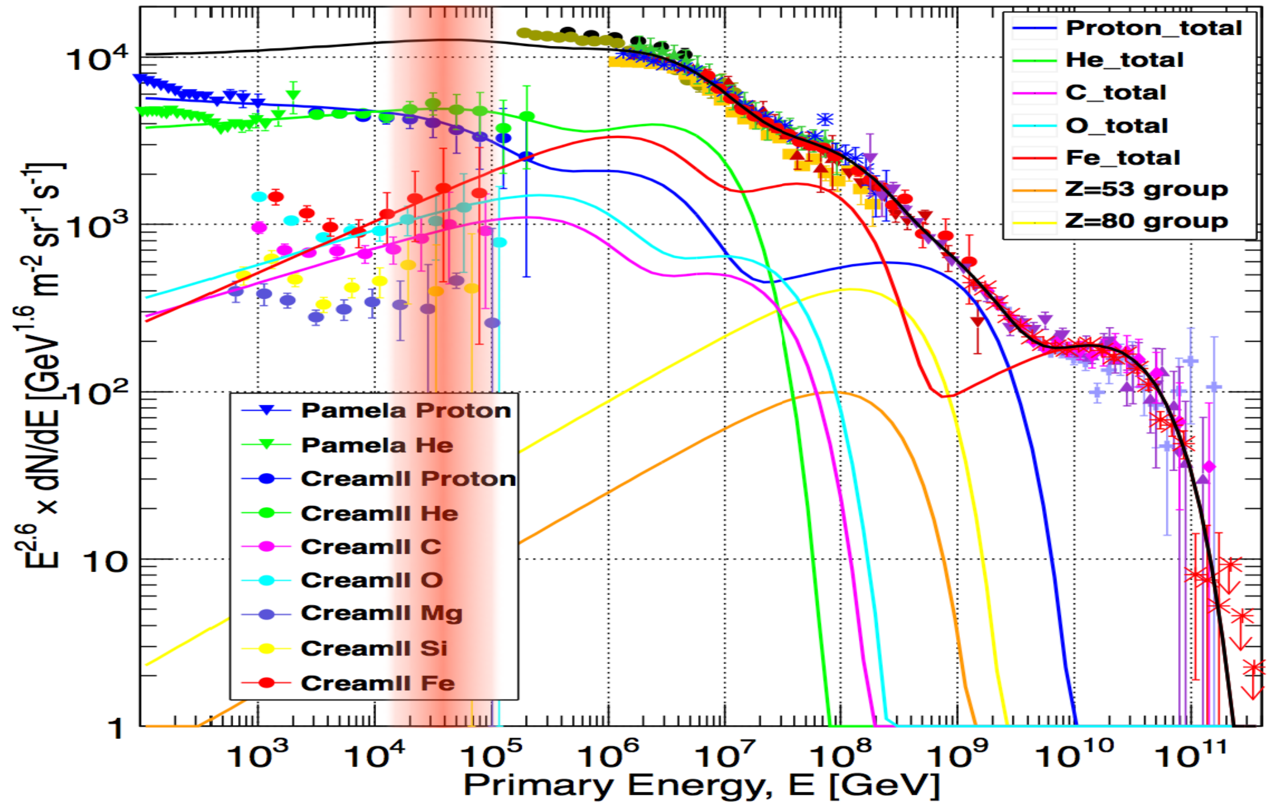
24 TeV **IceCube**

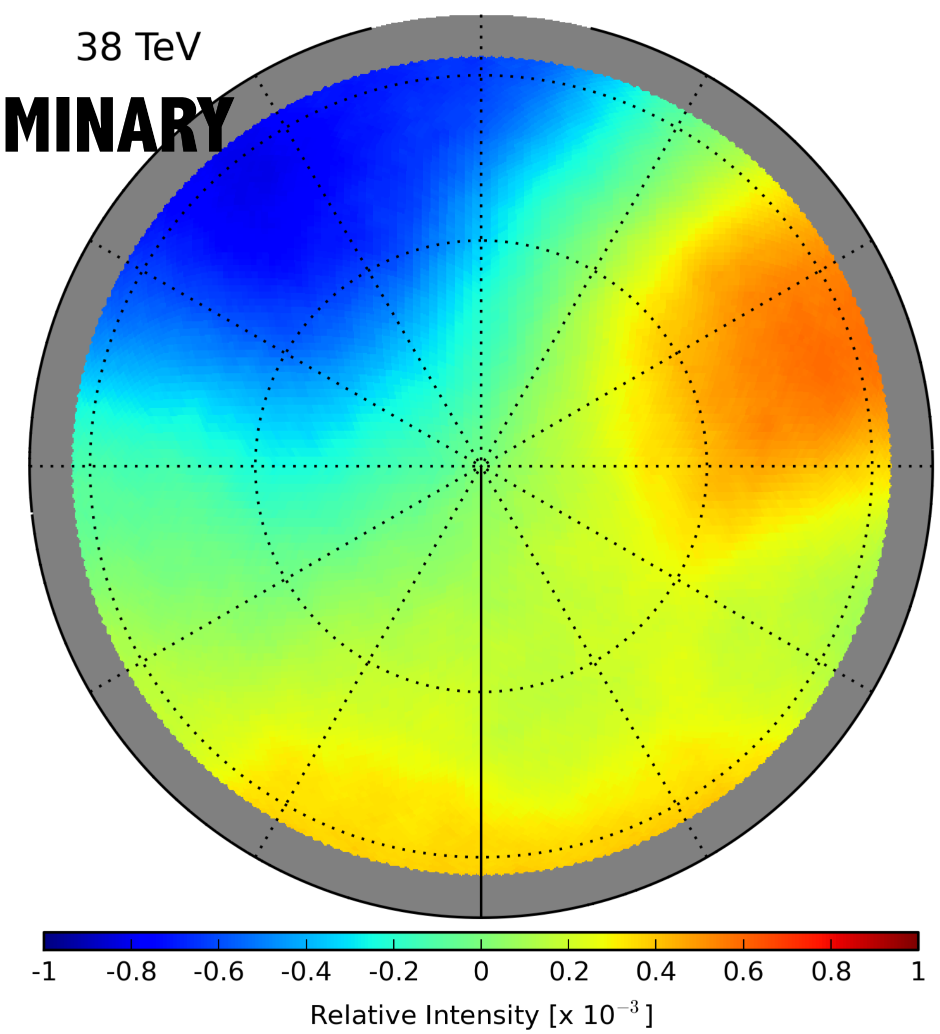
- high energy observations **MISSING** in the northern hemisphere
- **overlapping observations** extending across the equator will help
- capable of energy/mass measurement

cosmic rays anisotropy

arrival direction distribution





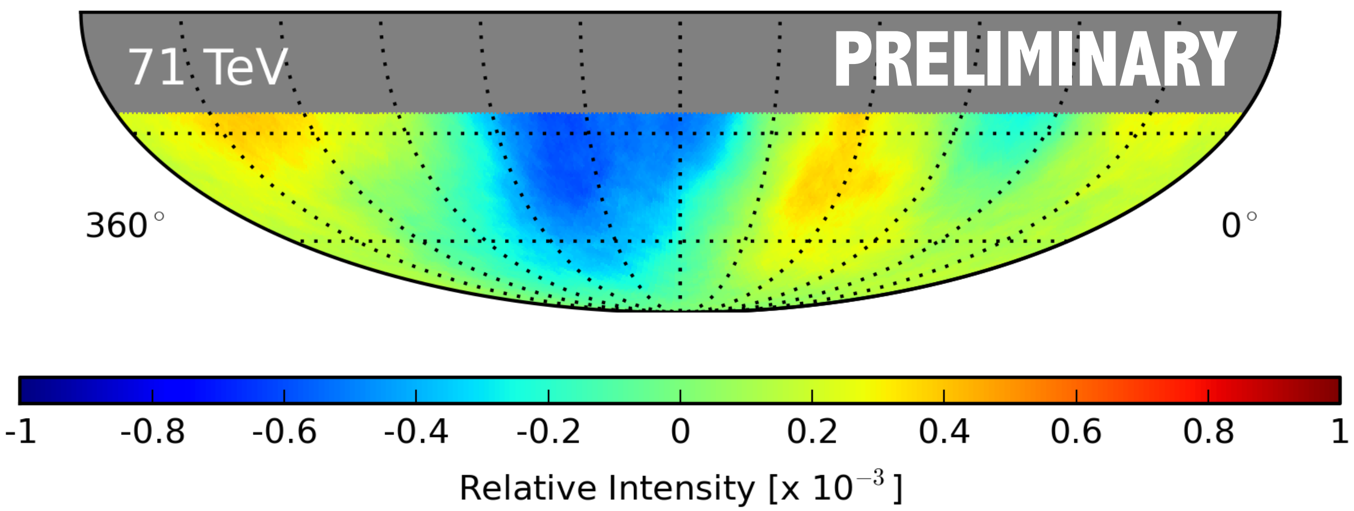


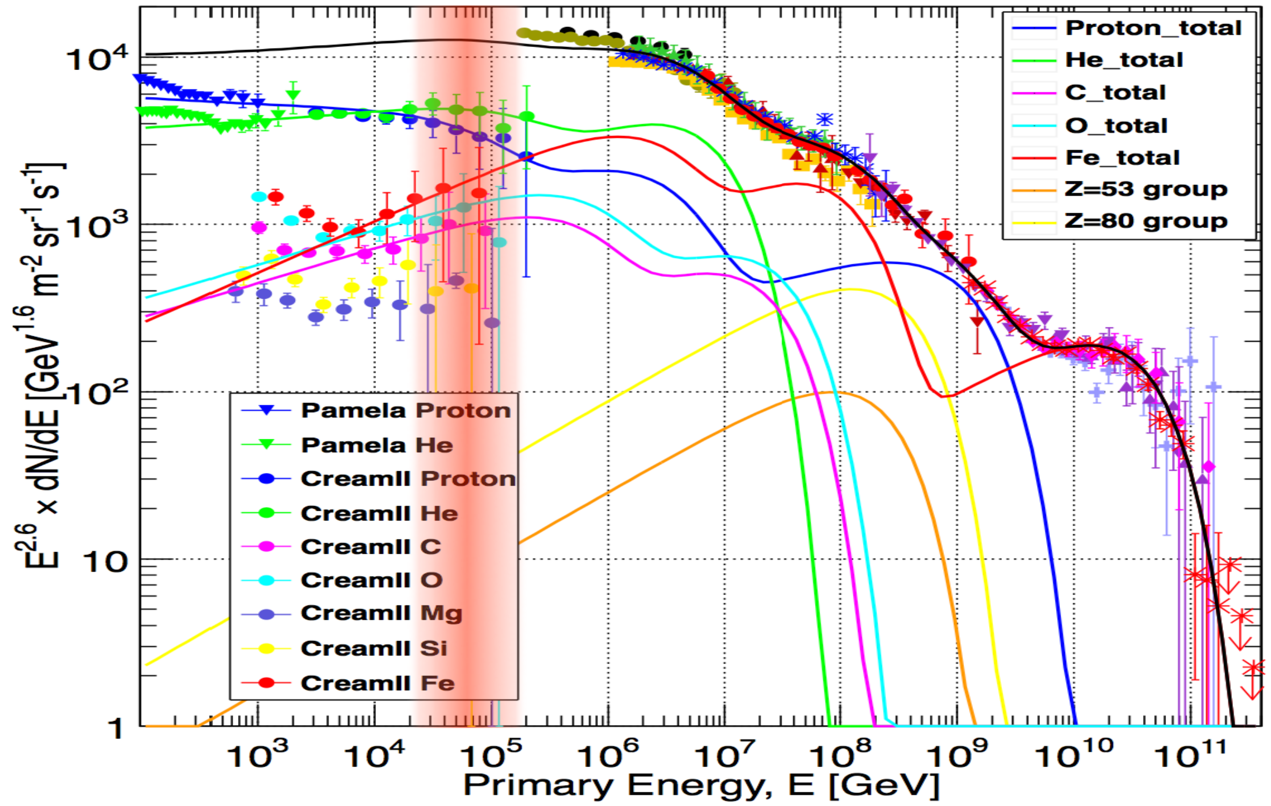
38 TeV **IceCube**

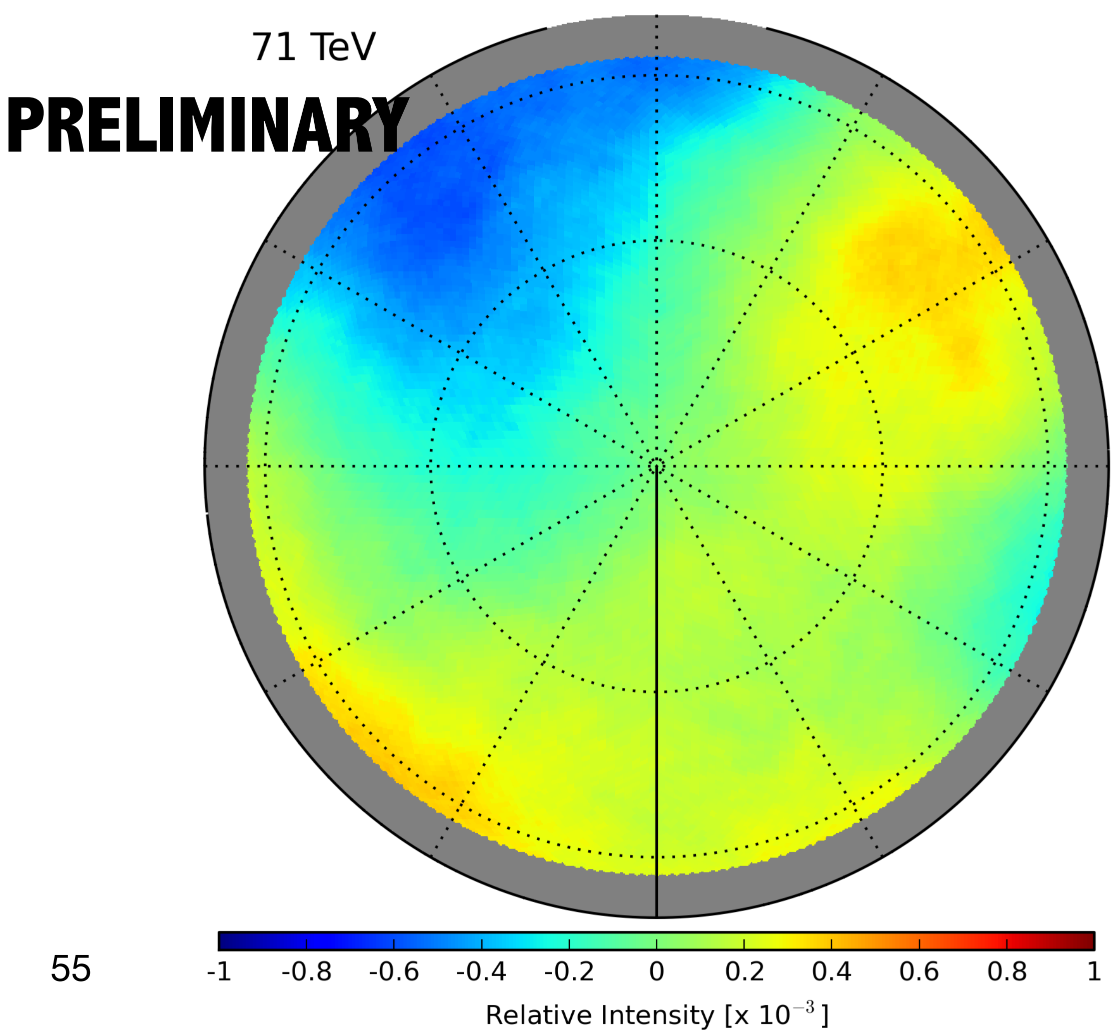
- high energy observations **MISSING** in the northern hemisphere
- **overlapping observations** extending across the equator will help
- capable of energy/mass measurement

cosmic rays anisotropy

arrival direction distribution





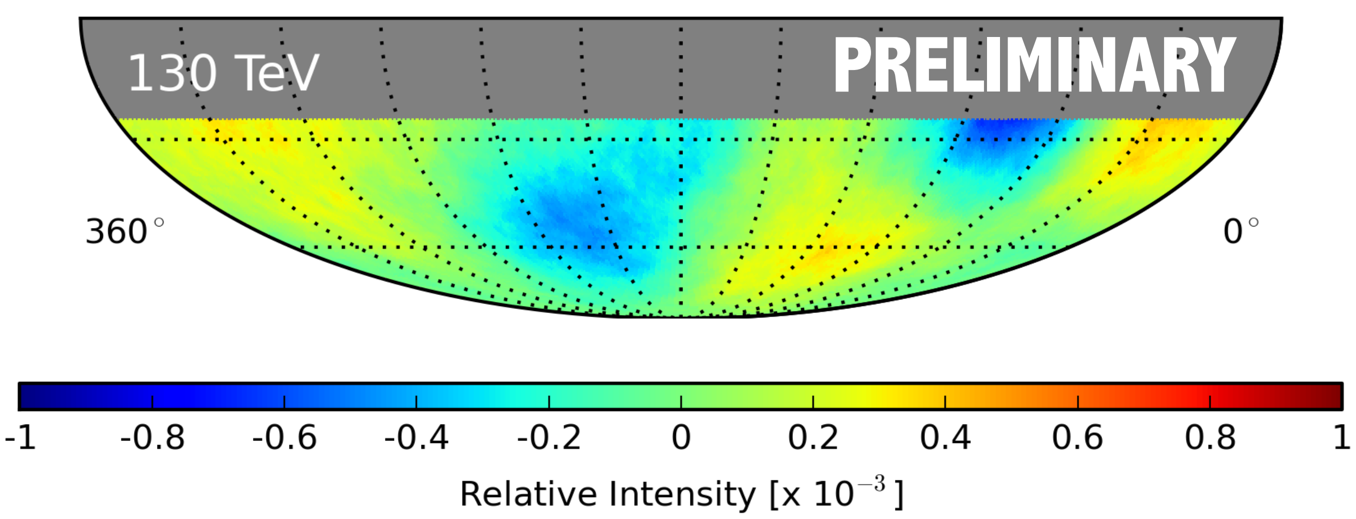


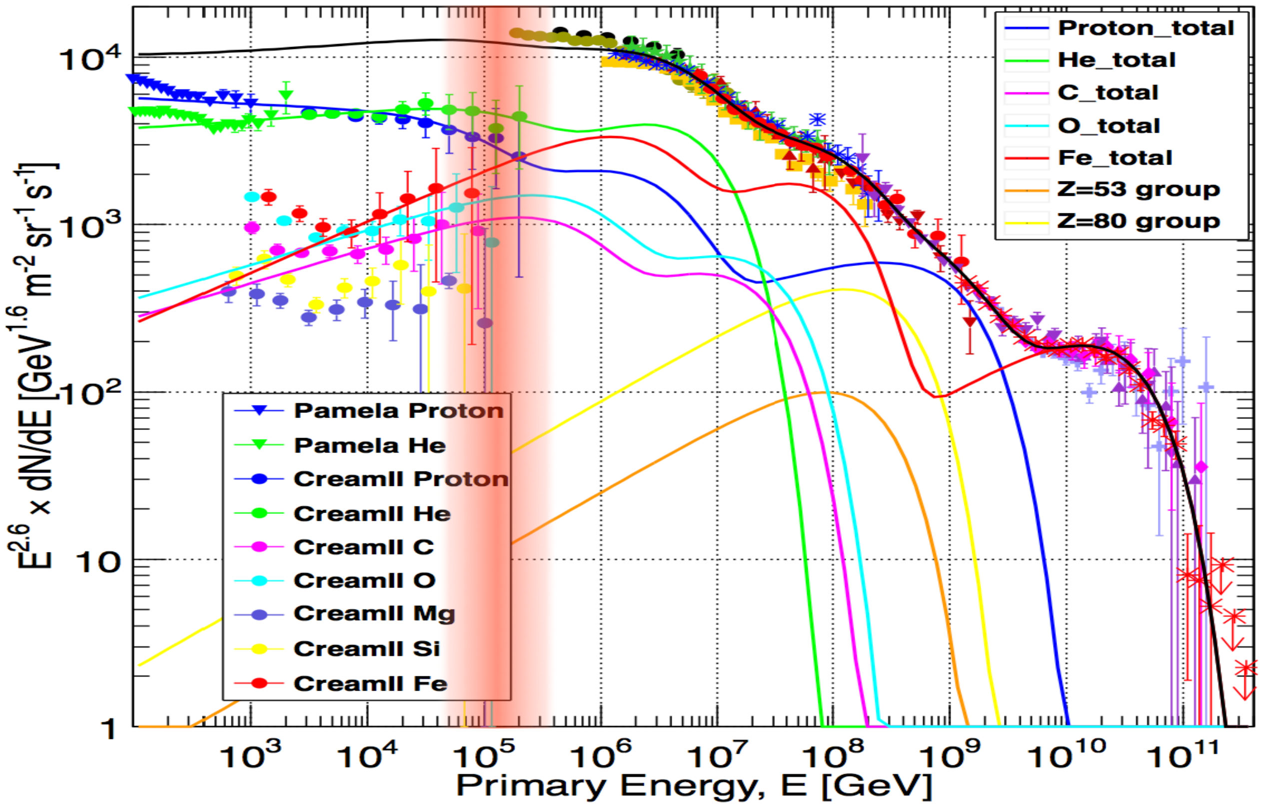
71 TeV **IceCube**

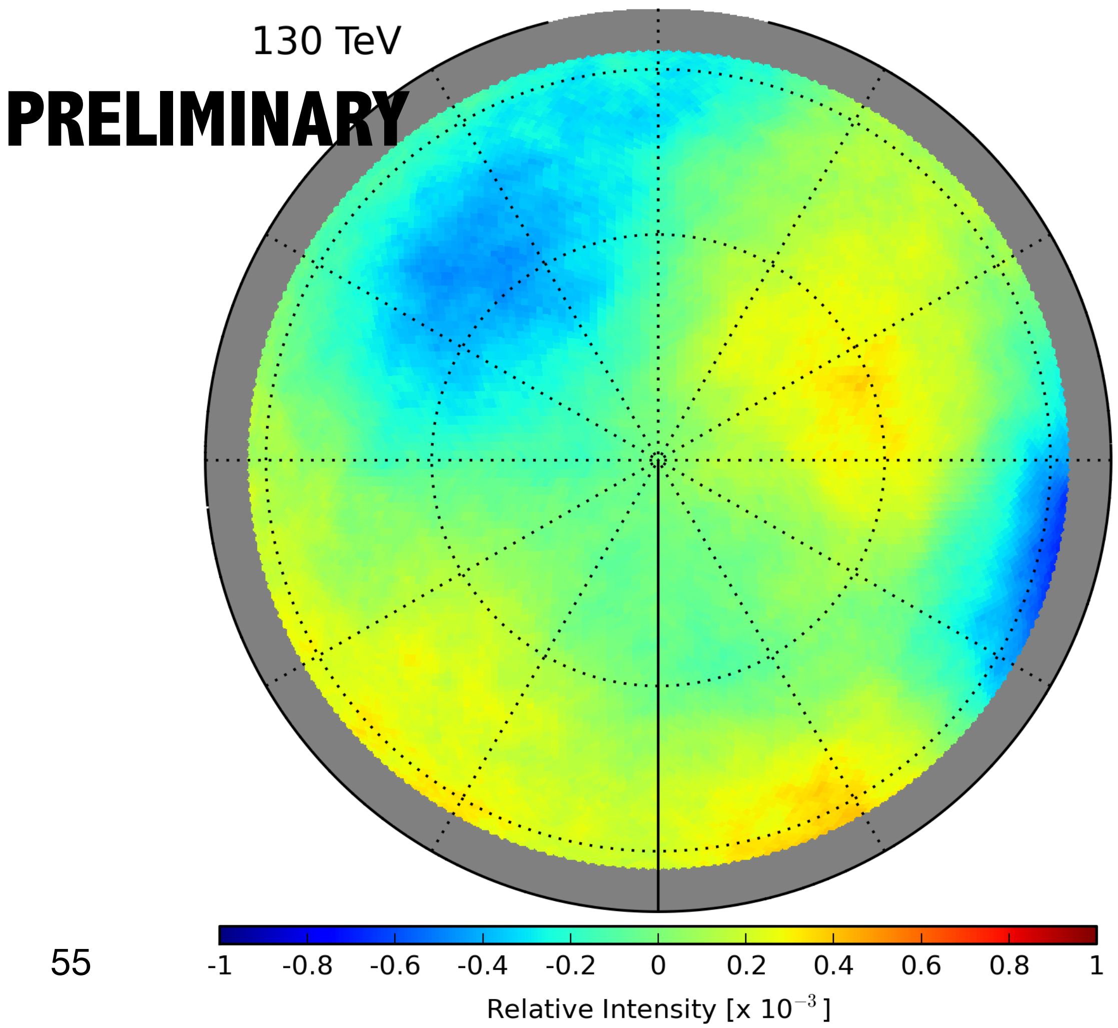
- high energy observations **MISSING** in the northern hemisphere
- **overlapping observations** extending across the equator will help
- capable of energy/mass measurement

cosmic rays anisotropy

arrival direction distribution



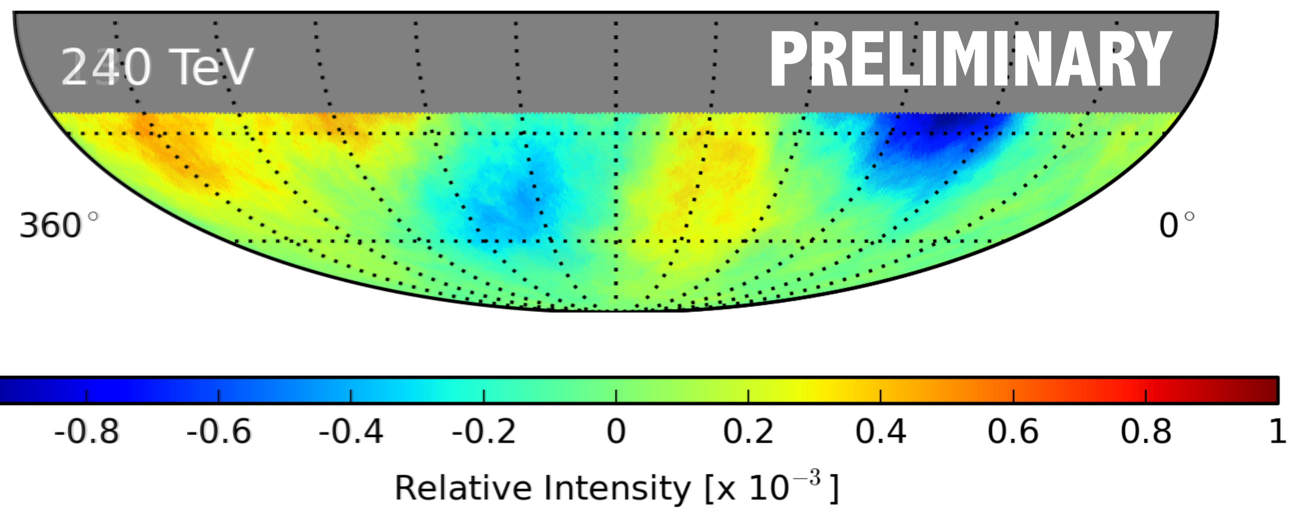


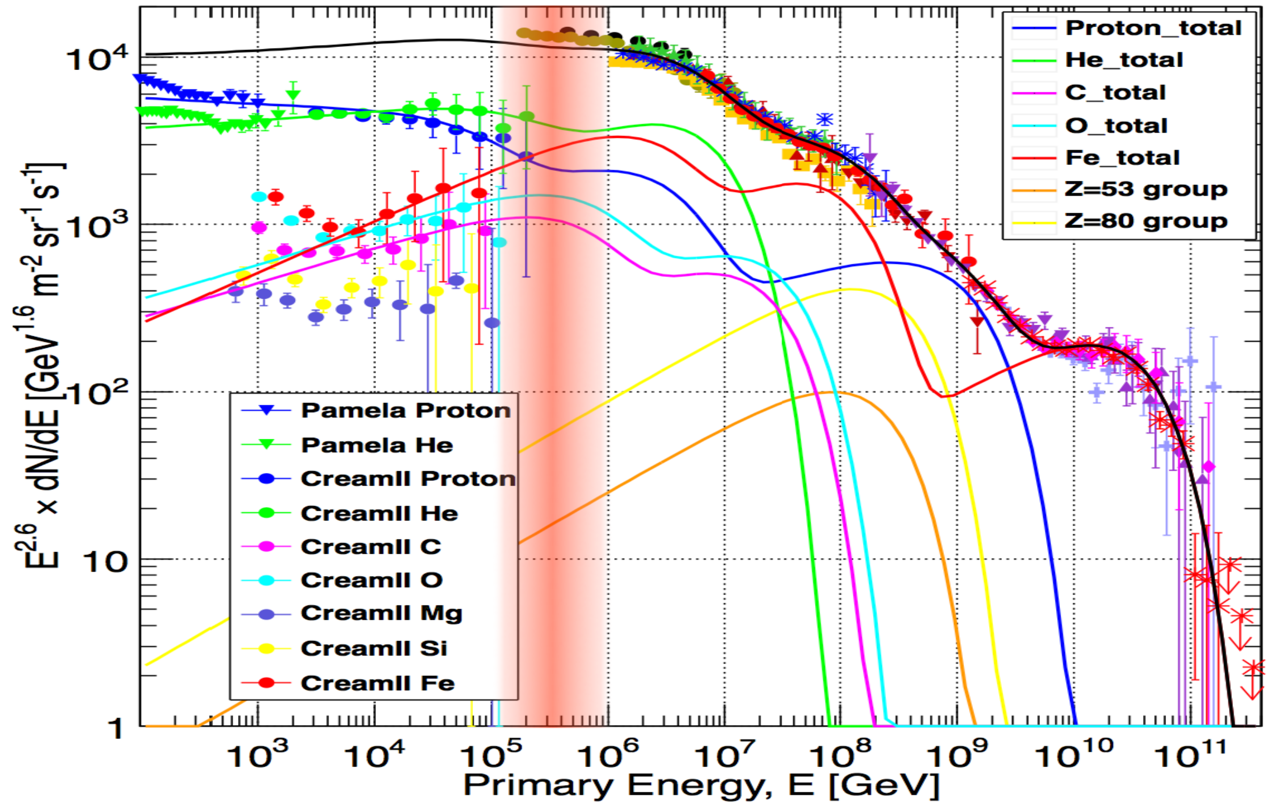


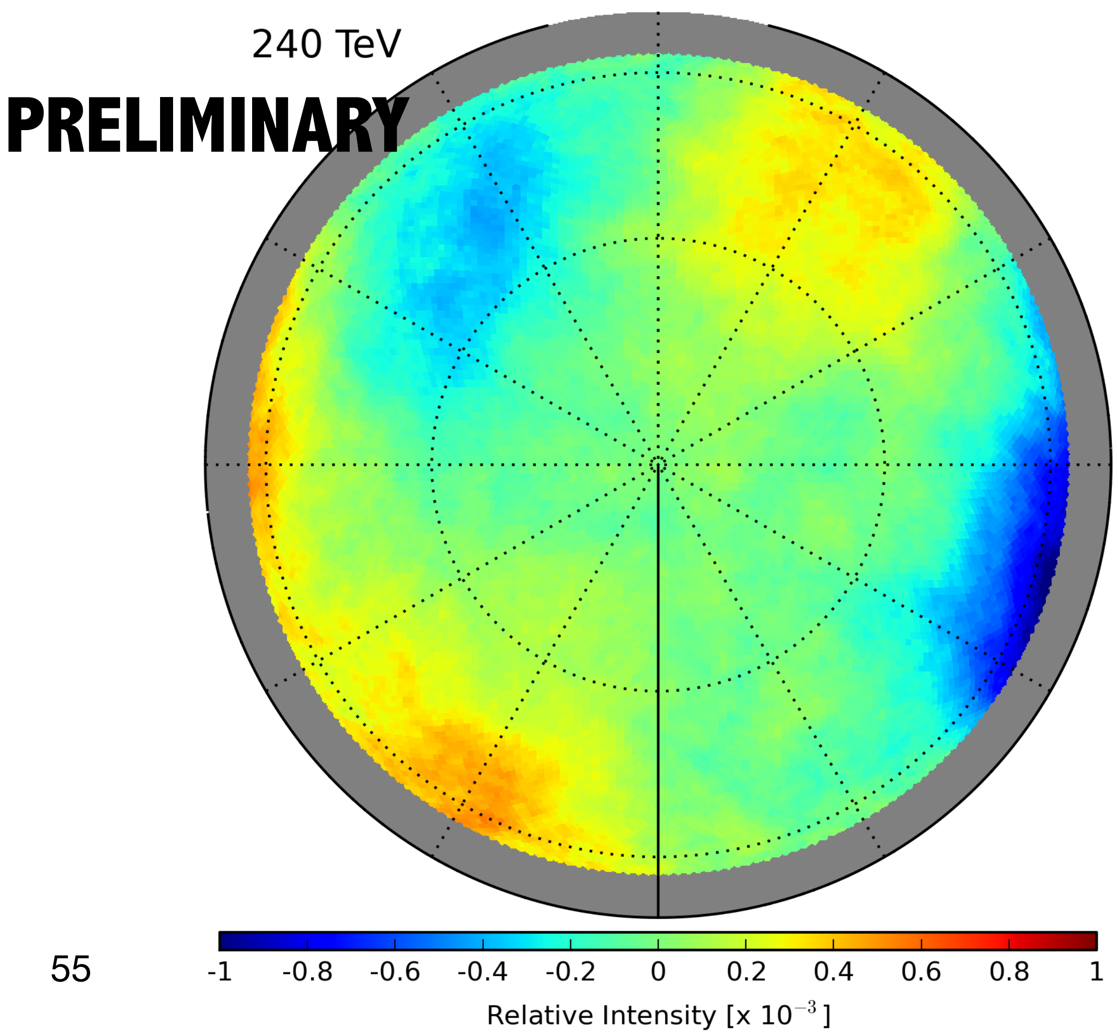
130 TeV **IceCube**

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

cosmic rays anisotropy
arrival direction distribution





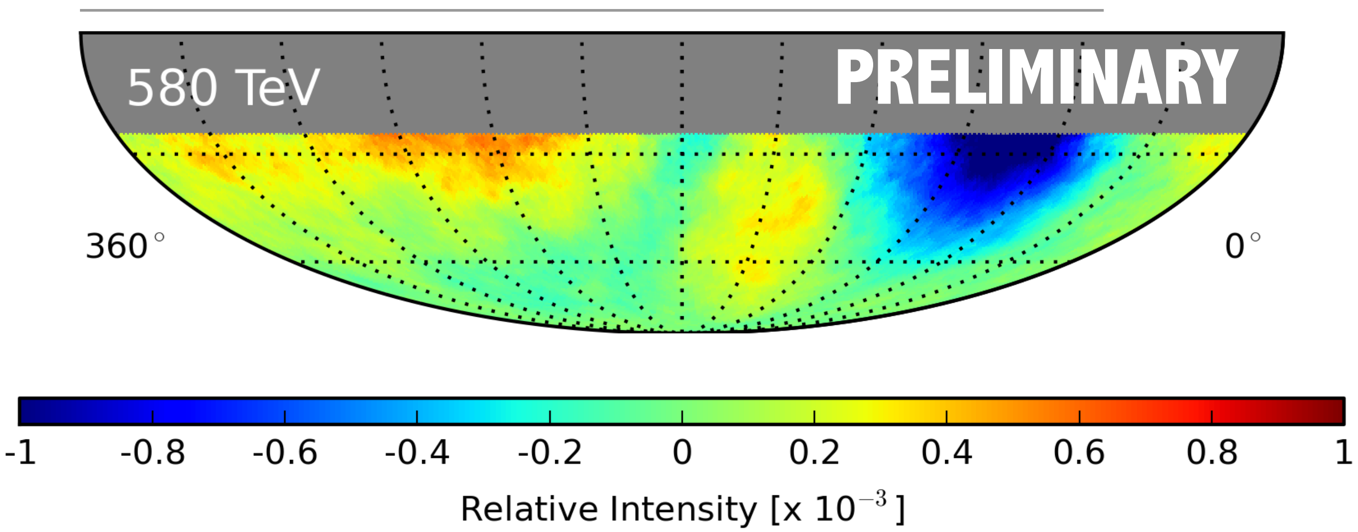


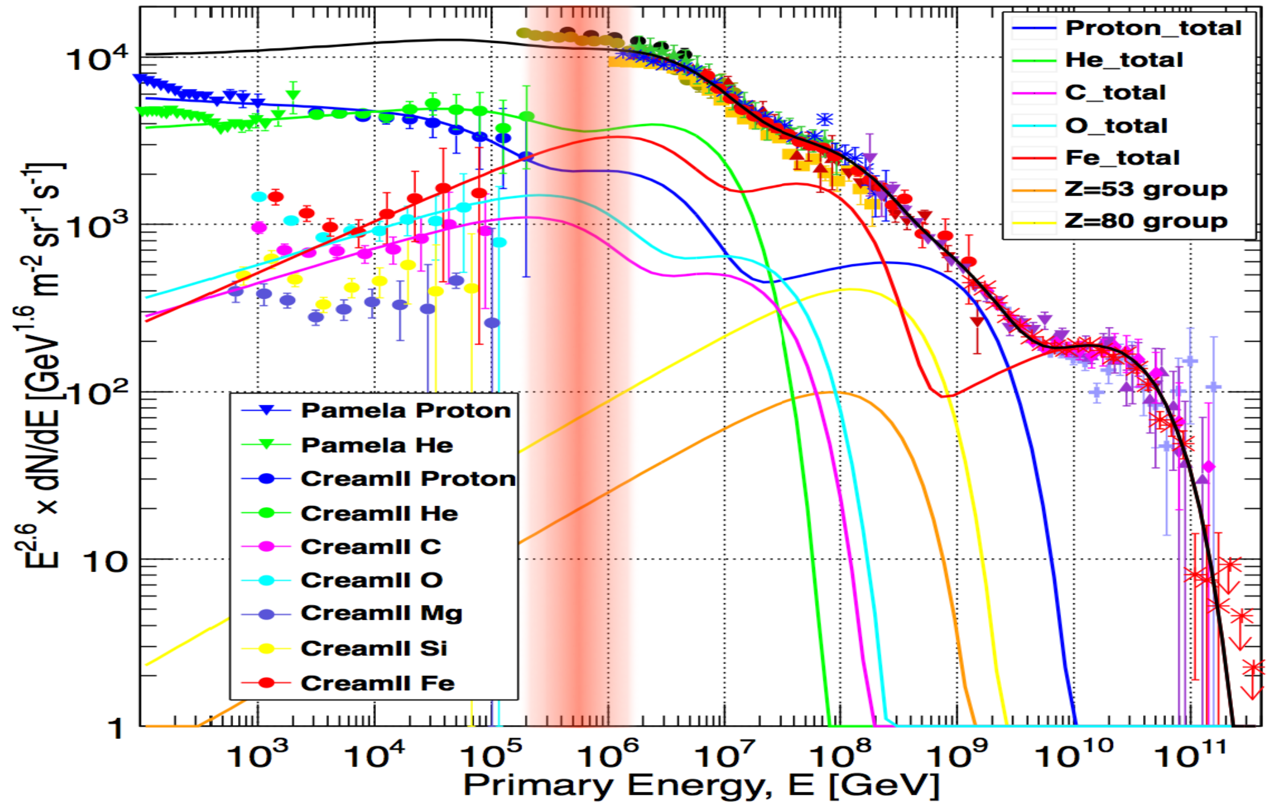
240 TeV **IceCube**

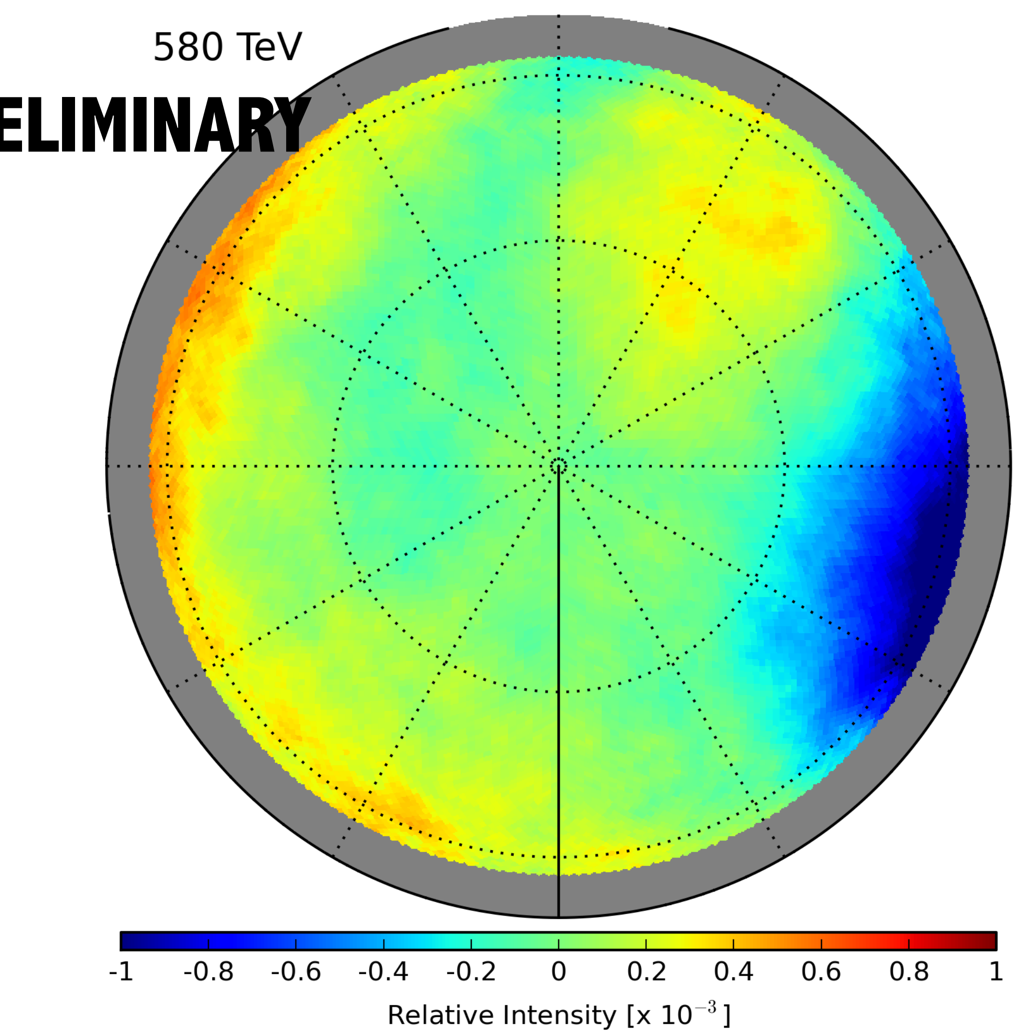
- high energy observations **MISSING** in the northern hemisphere
- **overlapping observations** extending across the equator will help
- capable of energy/mass measurement

cosmic rays anisotropy

arrival direction distribution





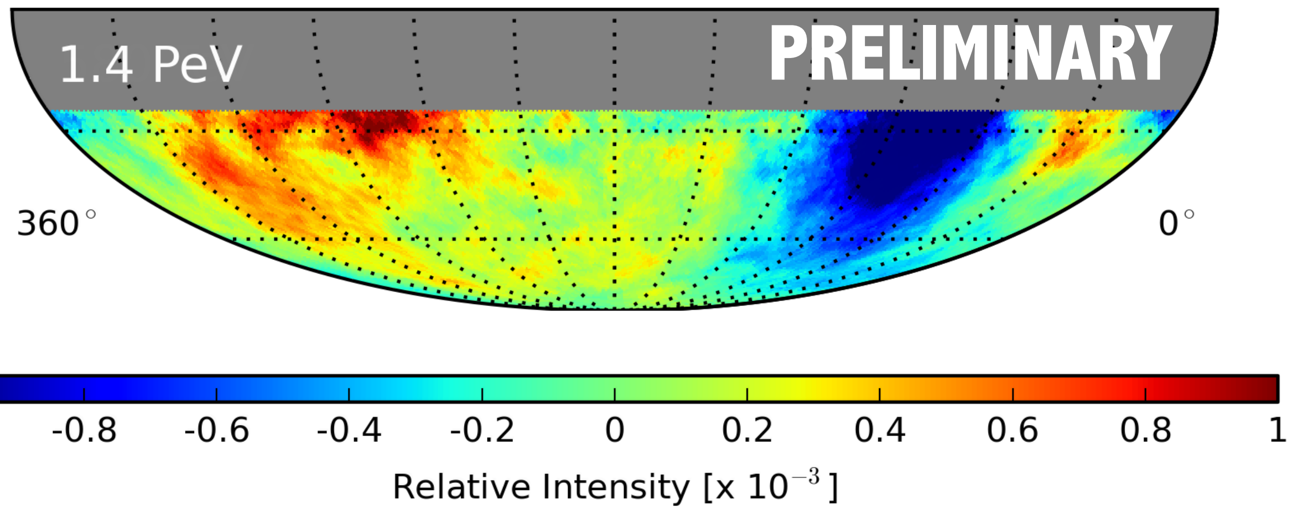


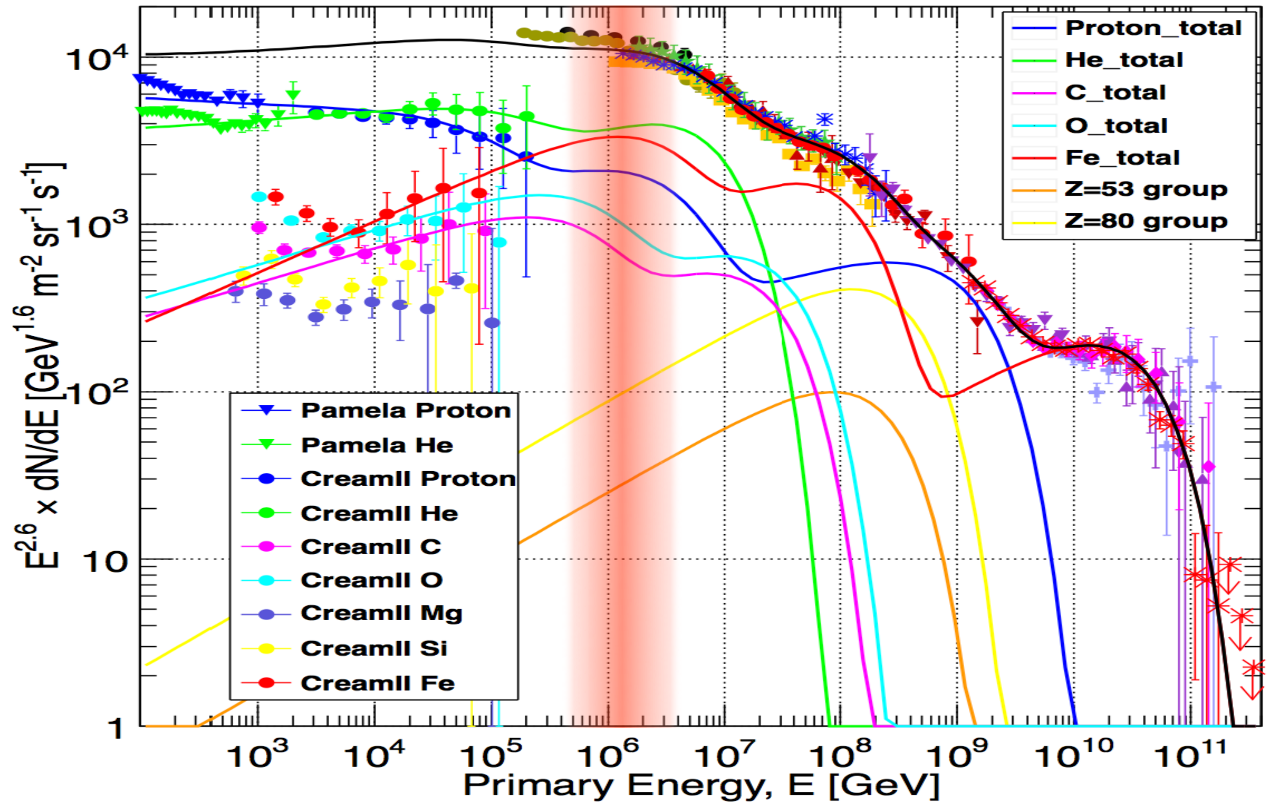
580 TeV **IceCube**

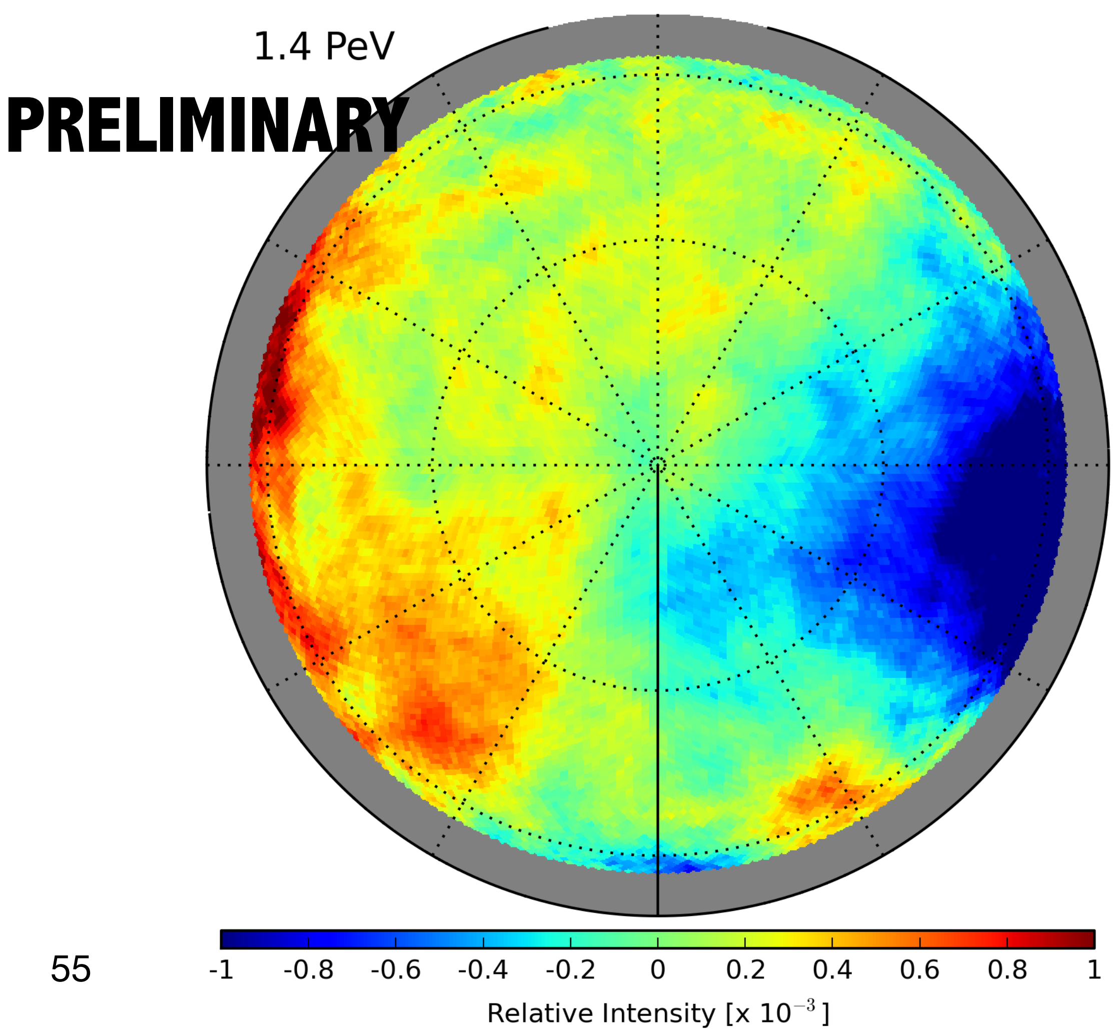
- high energy observations **MISSING** in the northern hemisphere
- **overlapping observations** extending across the equator will help
- capable of energy/mass measurement

cosmic rays anisotropy

arrival direction distribution





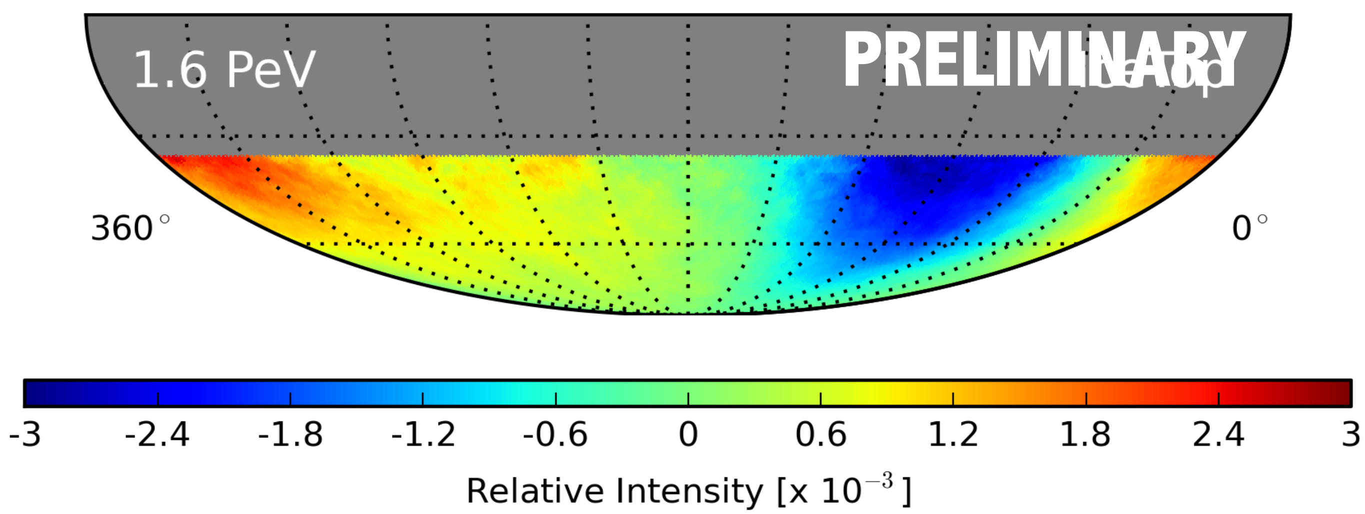


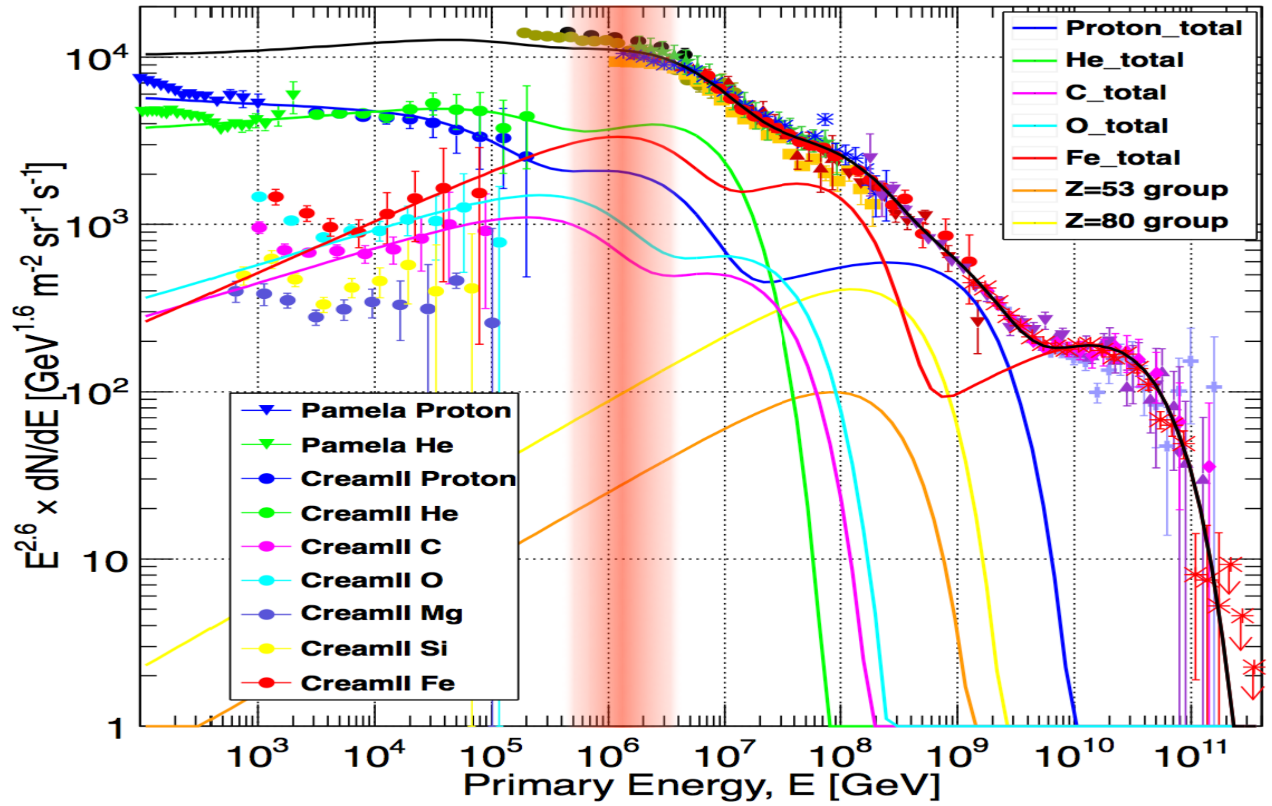
1.4 PeV **IceCube**

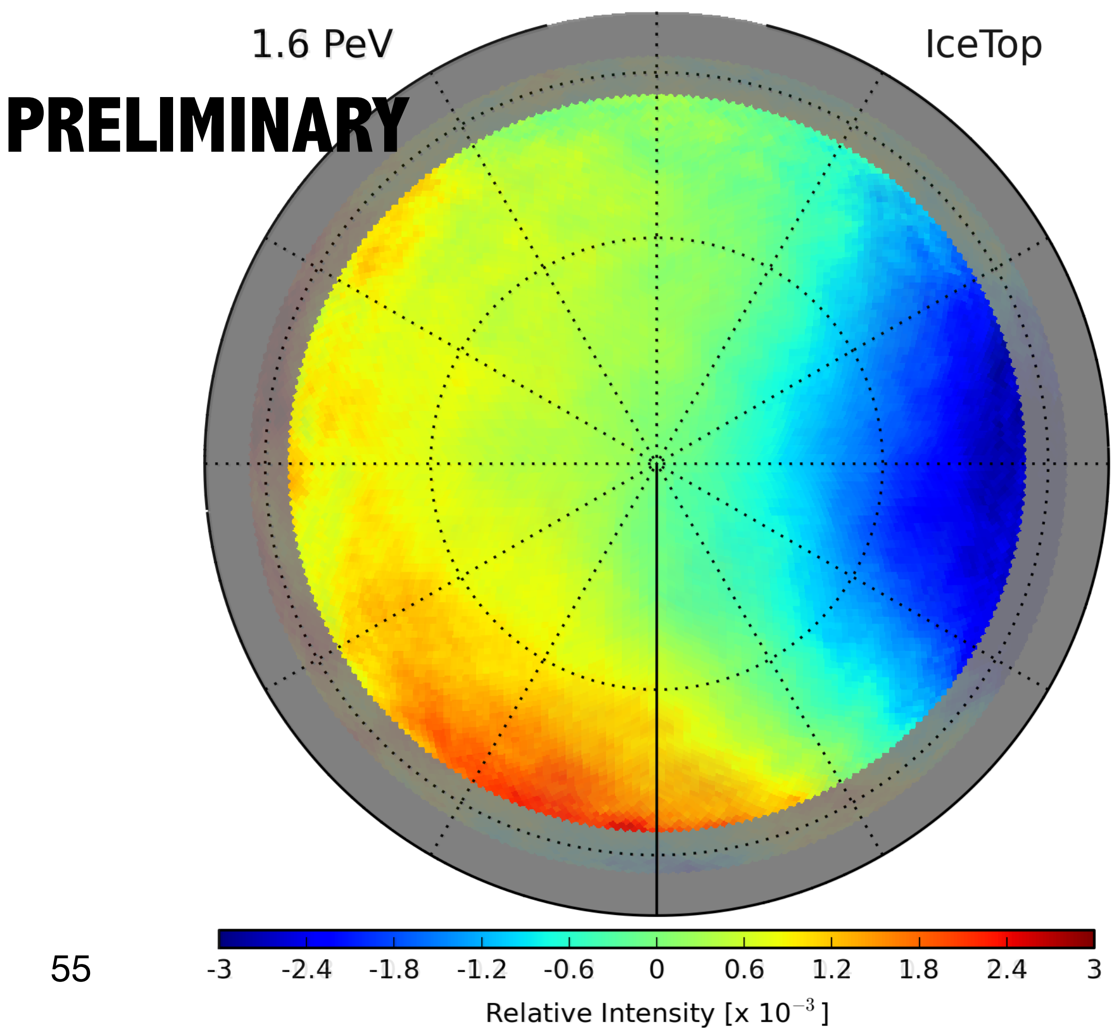
- high energy observations **MISSING** in the northern hemisphere
- **overlapping observations** extending across the equator will help
- capable of energy/mass measurement

cosmic rays anisotropy

arrival direction distribution





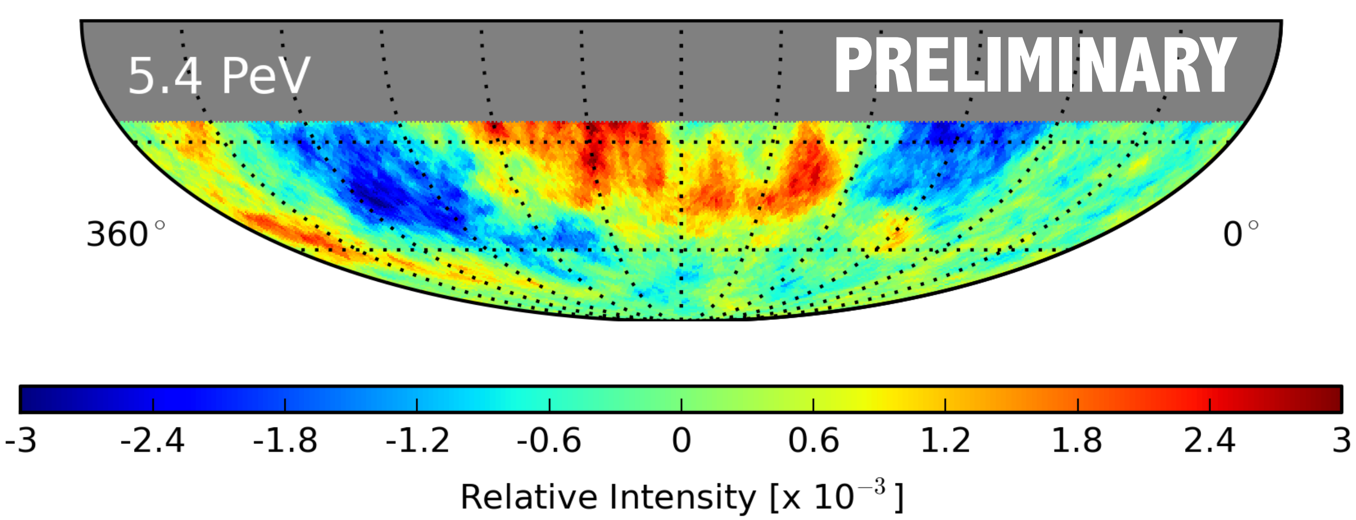


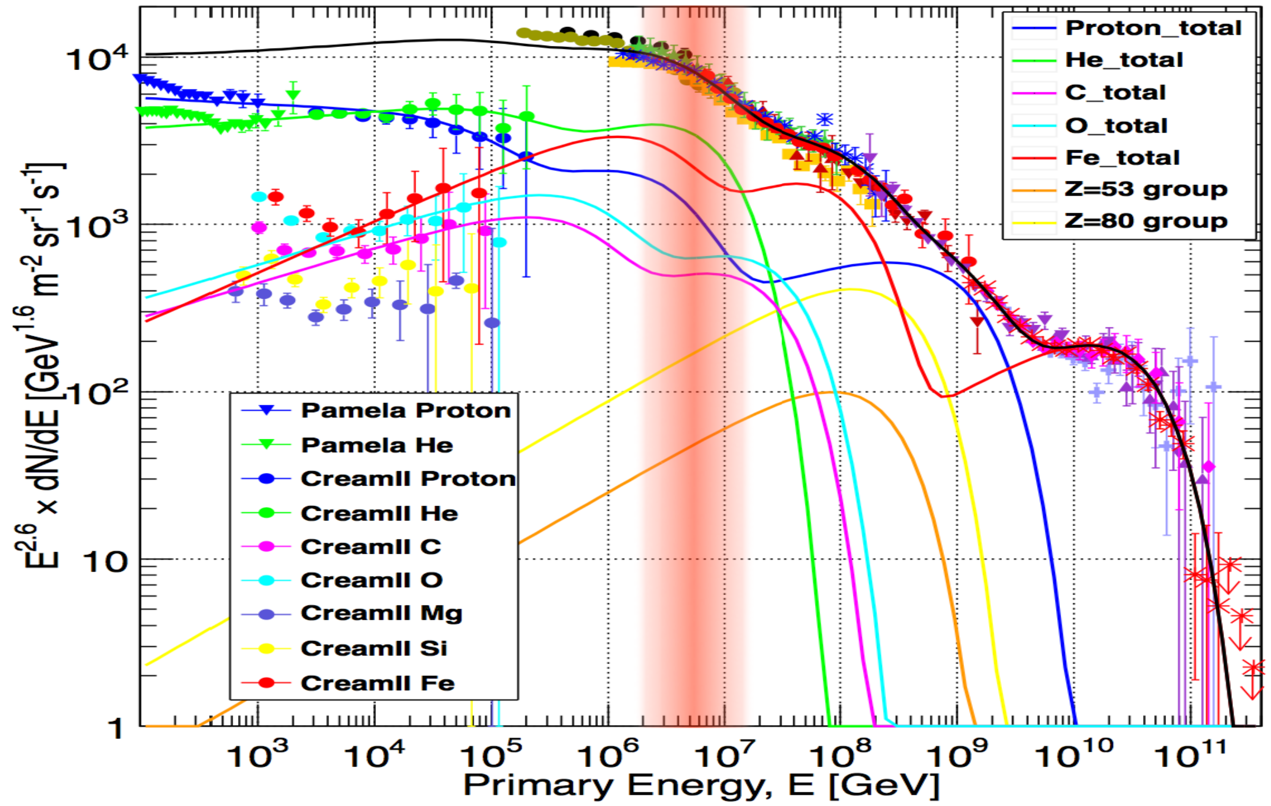
1.6 PeV **IceTop**

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

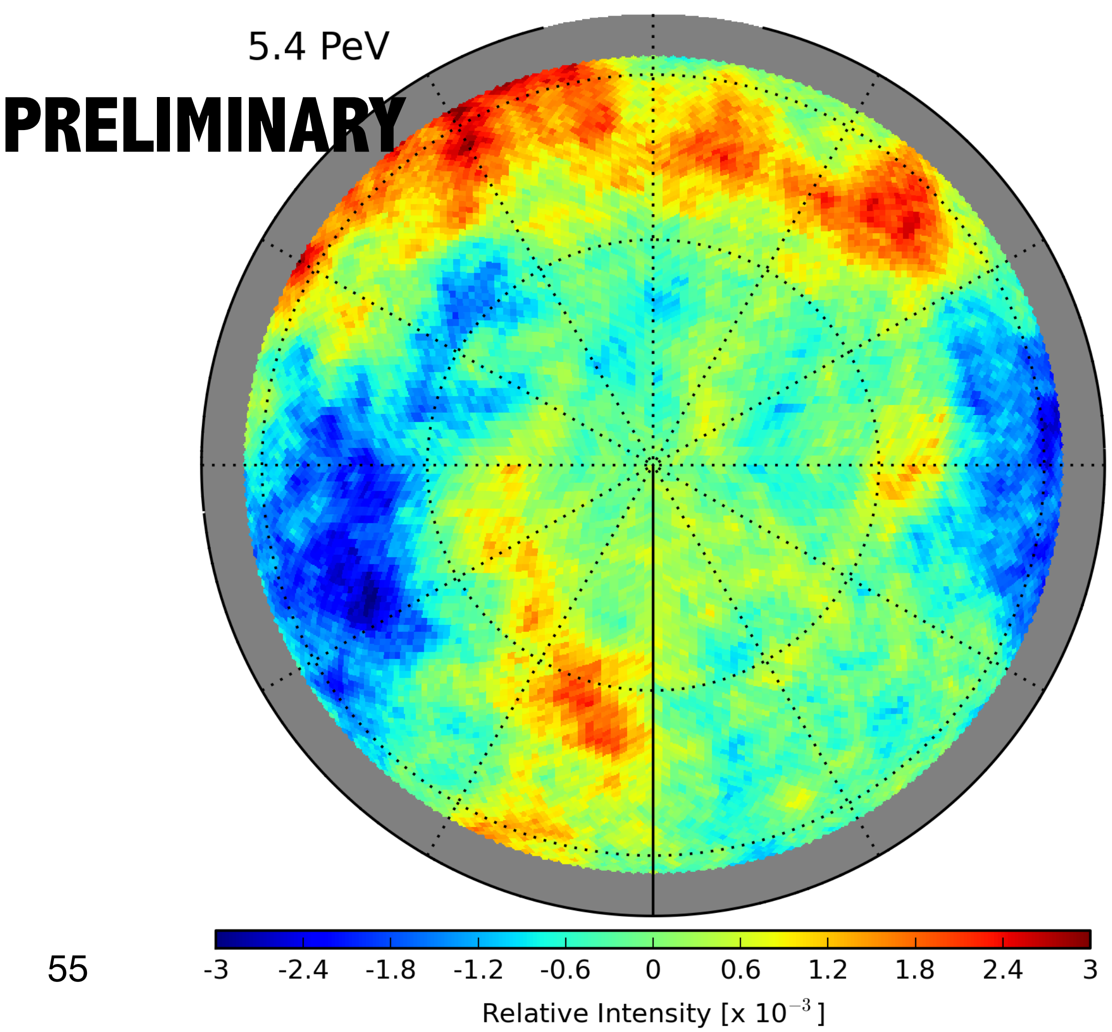
cosmic rays anisotropy

arrival direction distribution





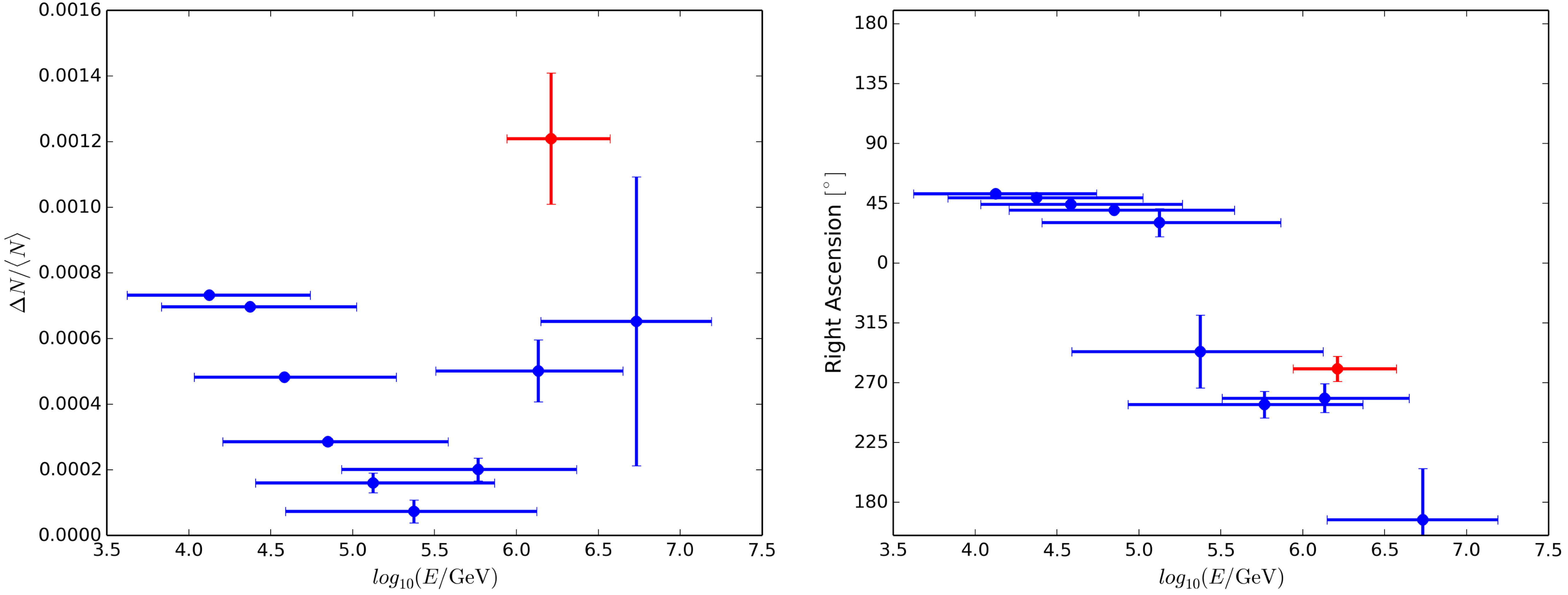
5.4 PeV **IceCube**



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

cosmic rays anisotropy

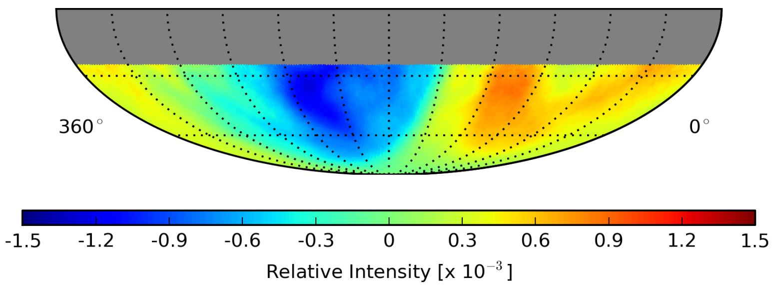
simple directional interpretation

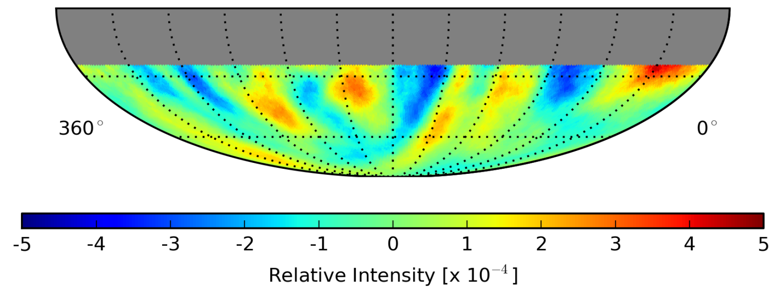


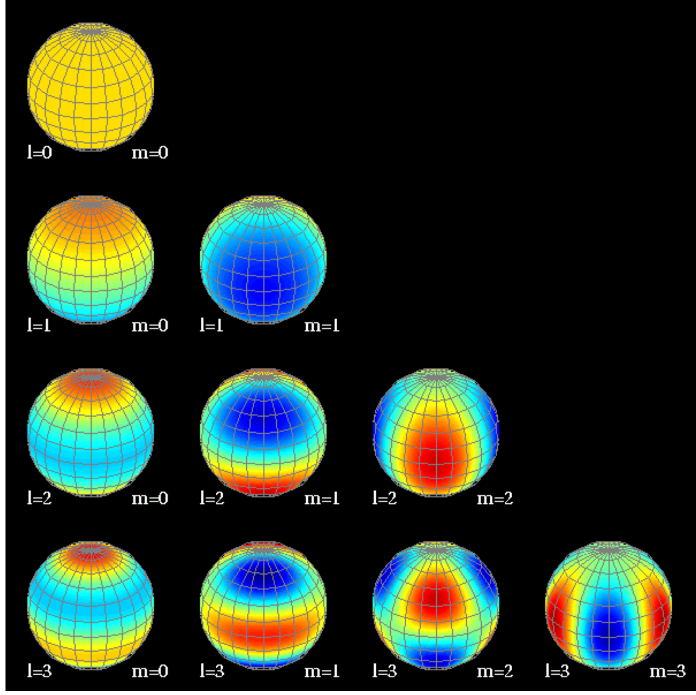
- **dipole component** of the anisotropy fit (in 1D) vs. cosmic ray particle energy

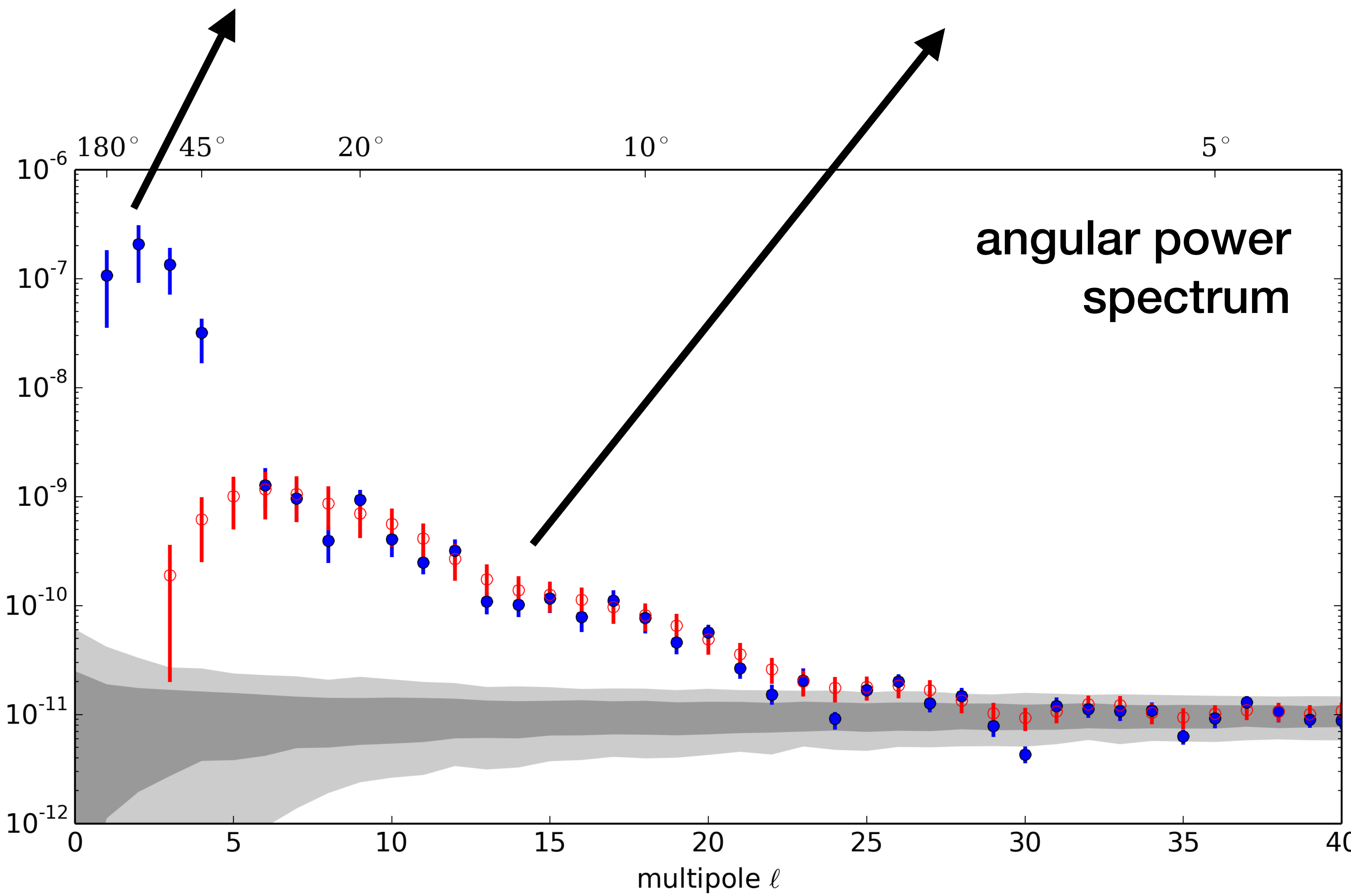
cosmic rays anisotropy

large and small angular scale









Giacinti & Sigl 2012

Ahlers 2014

Ahlers & Mertsch 2015

López-Barquero, Farber, Xu, PD, Lazarian 2015

cosmic rays anisotropy

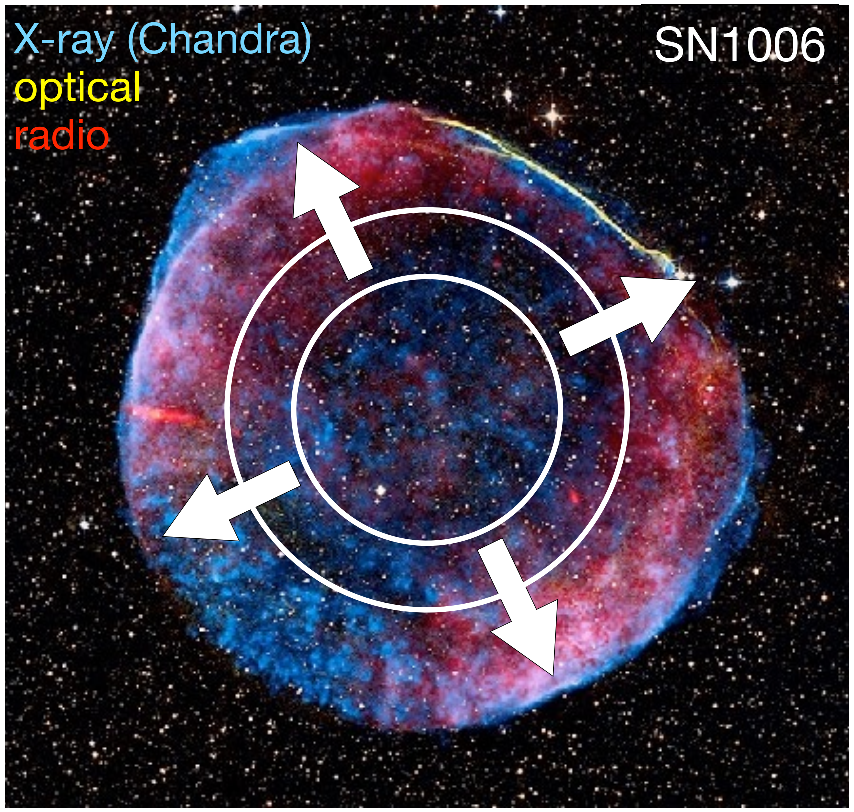
- anisotropy influenced by **source distribution** in the galaxy …
- … and **propagation properties** in the interstellar magnetic fields
- **anisotropy vs. energy** to probe larger portion of interstellar medium volume
- **anisotropy vs. mass** to probe rigidity dependent magnetic influences
- anisotropy as probe into interstellar magnetic field properties, in combination of other observations

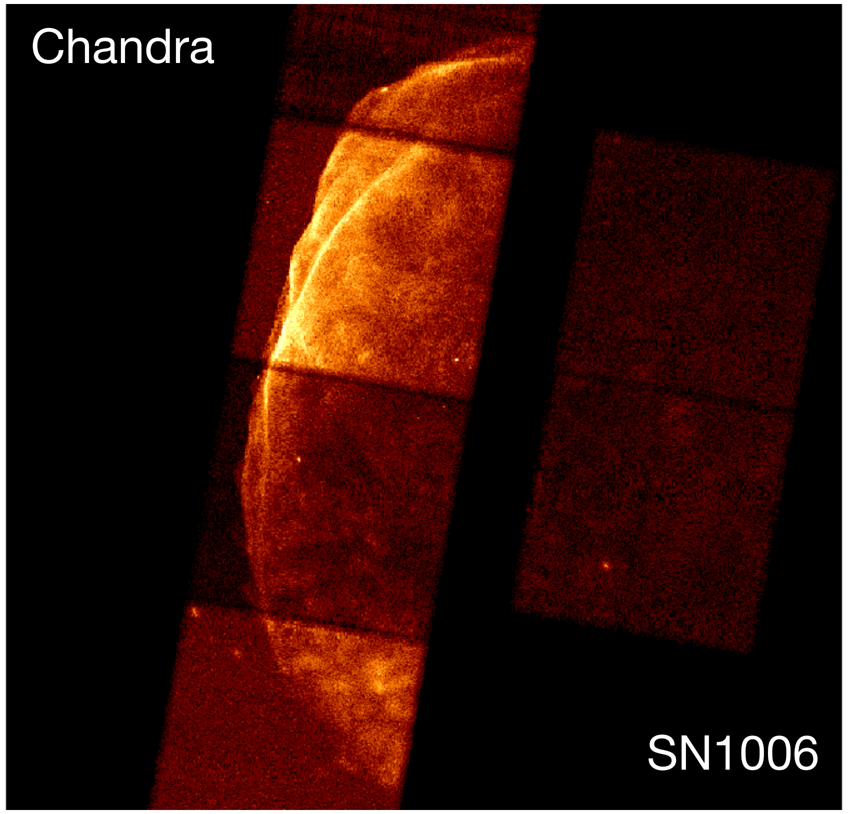
GRAZIE!

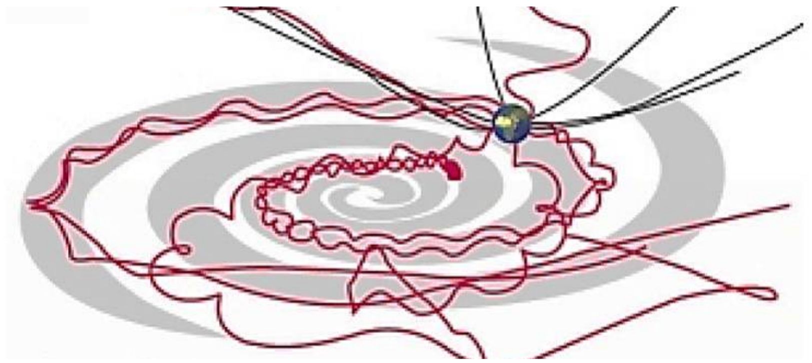
backup slides

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**

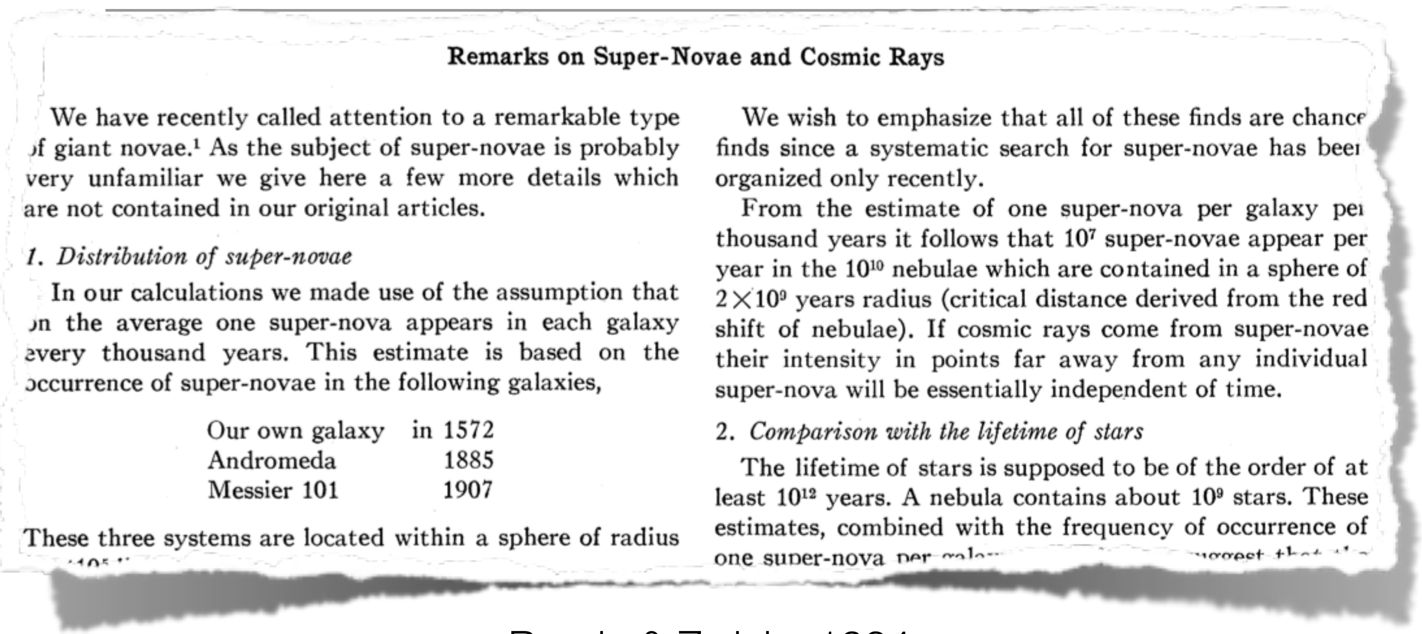






cosmic ray acceleration

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

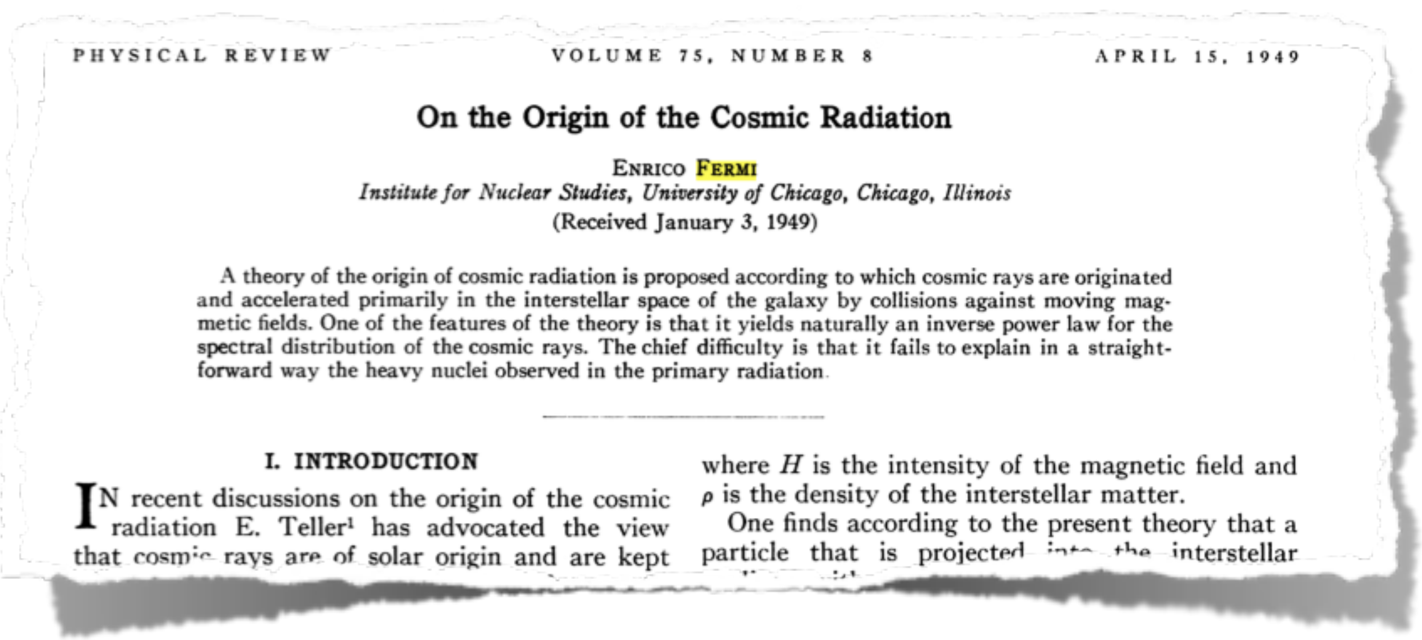
We wish to emphasize that all of these finds are chance finds since a systematic search for super-novae has been organized only recently.

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.

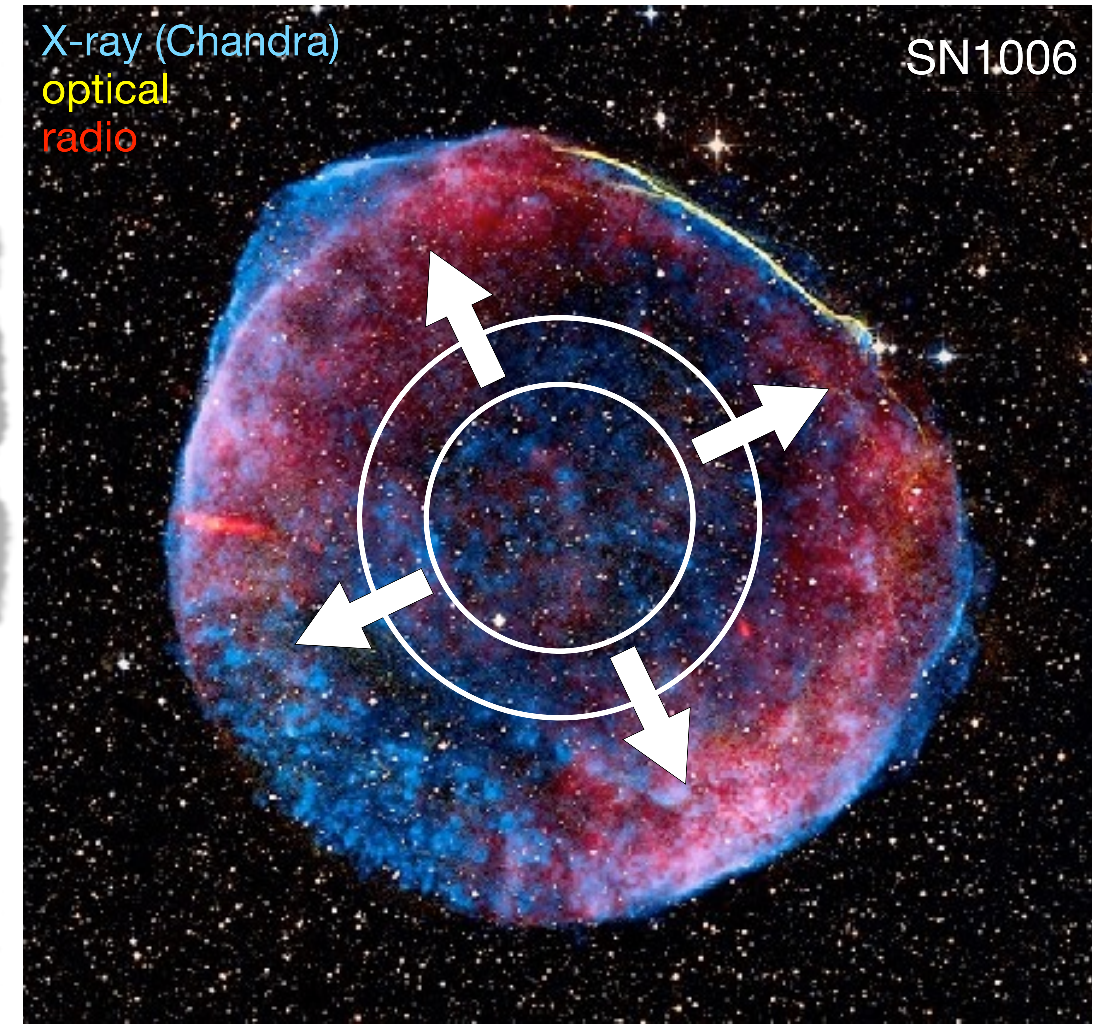
I. INTRODUCTION

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

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

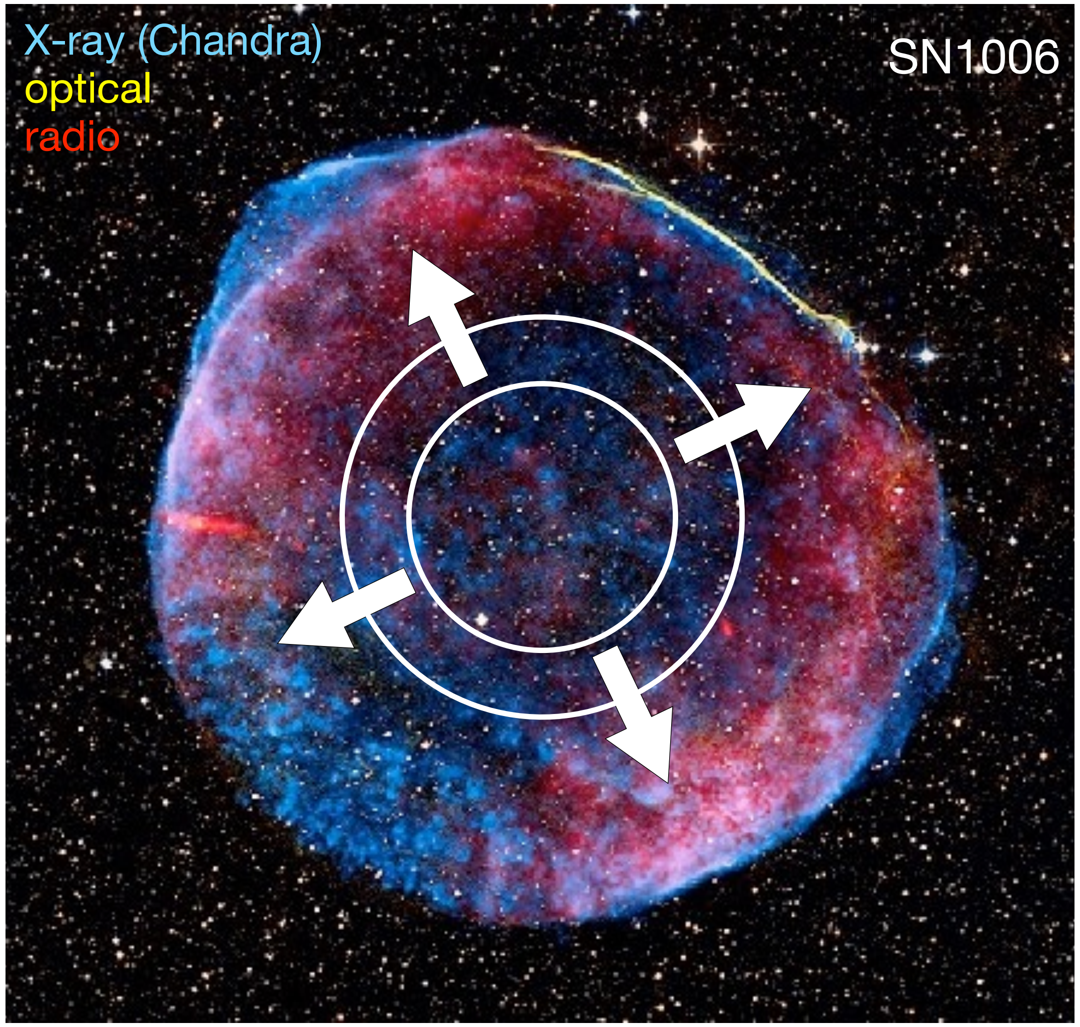
- energy released by **supernovae** that goes into particle acceleration

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

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

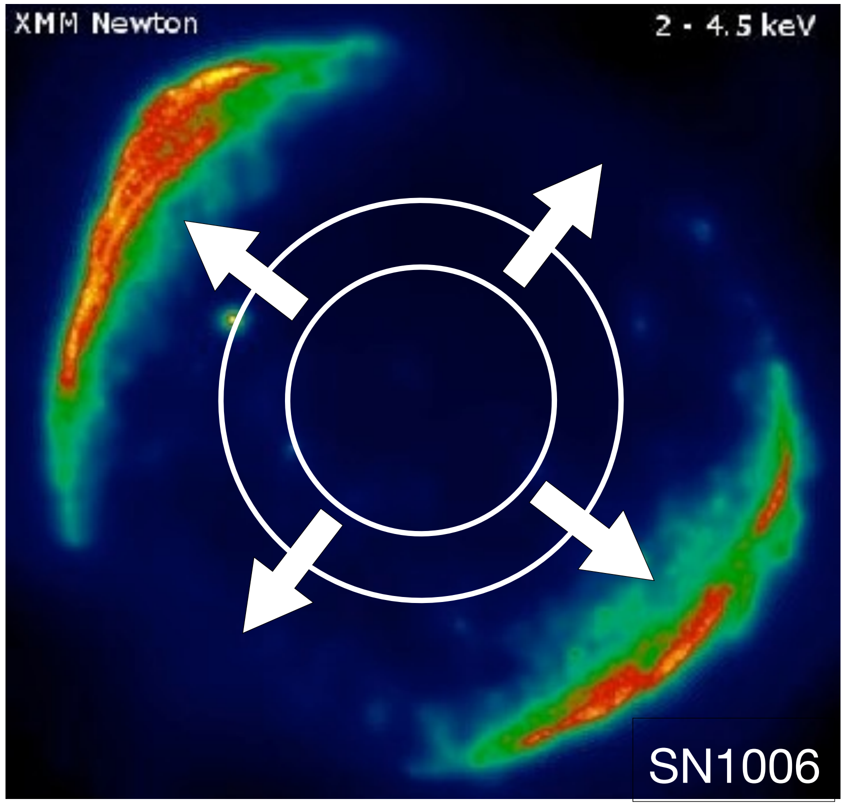
- **efficient acceleration:** dynamical reaction of CR particle on SNR magnetic field

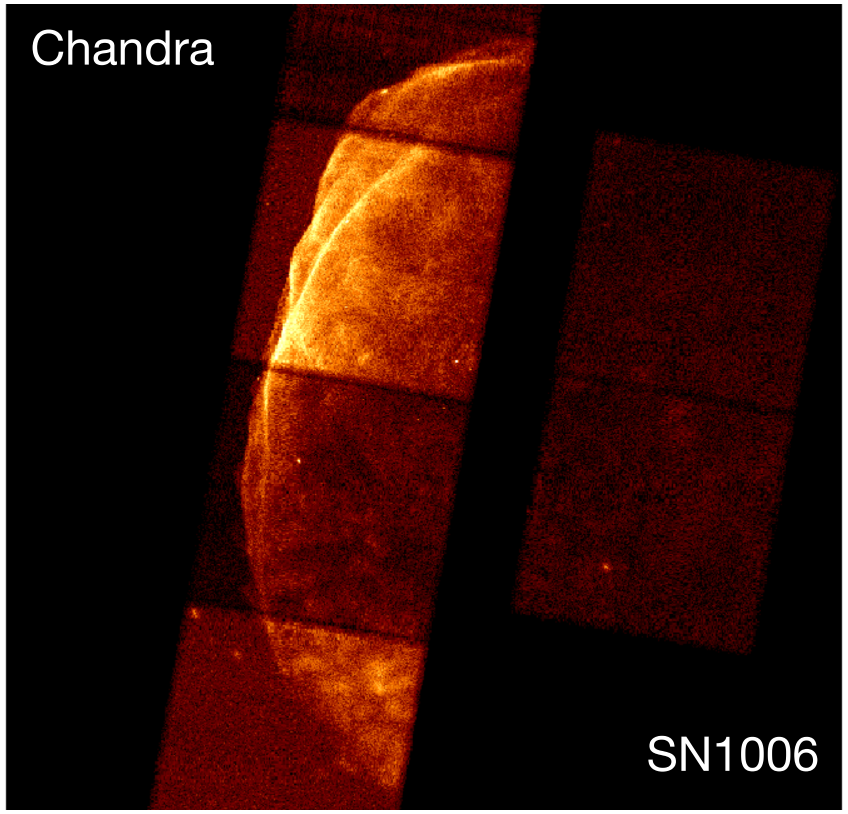
  - streaming instability induced by accelerated particles leads to **magnetic field amplification upstream**

  - in addition to magnetic field amplification by compression downstream

➡ non-linear diffusive shock acceleration

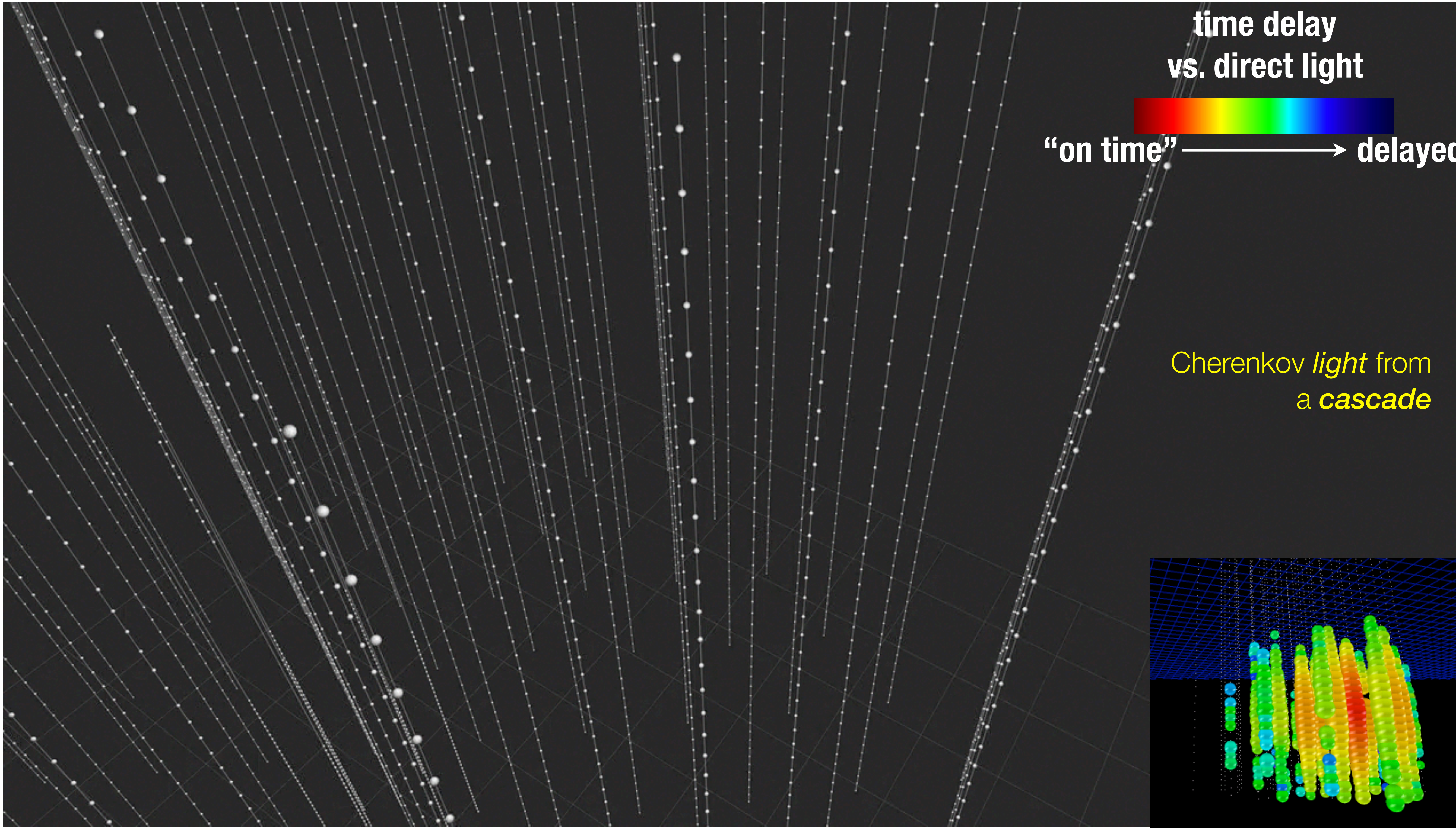
➡ predicts ∝ $\mathbf{E^{-2}}$ (or **concave spectra**)





detection principle - *cascade*

ν_e ν_τ CC-int & ν_i NC-int

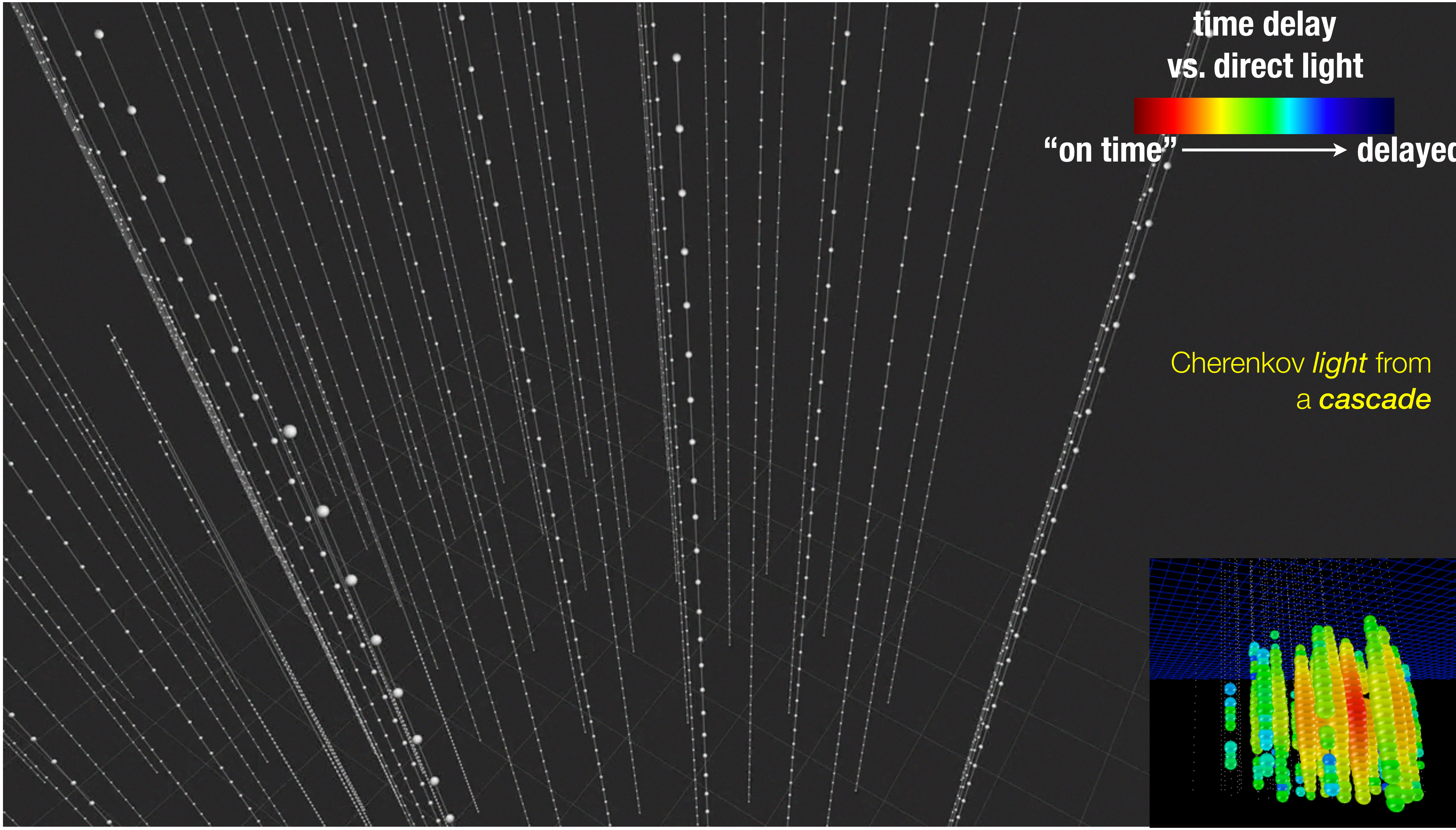


≈ ±15% deposited energy resolution
≈ 10° angular resolution
(at energies ≳ 100TeV)

Claudio Kopper - WIPAC

detection principle - *cascade*

ν_e ν_τ CC-int & ν_i NC-int

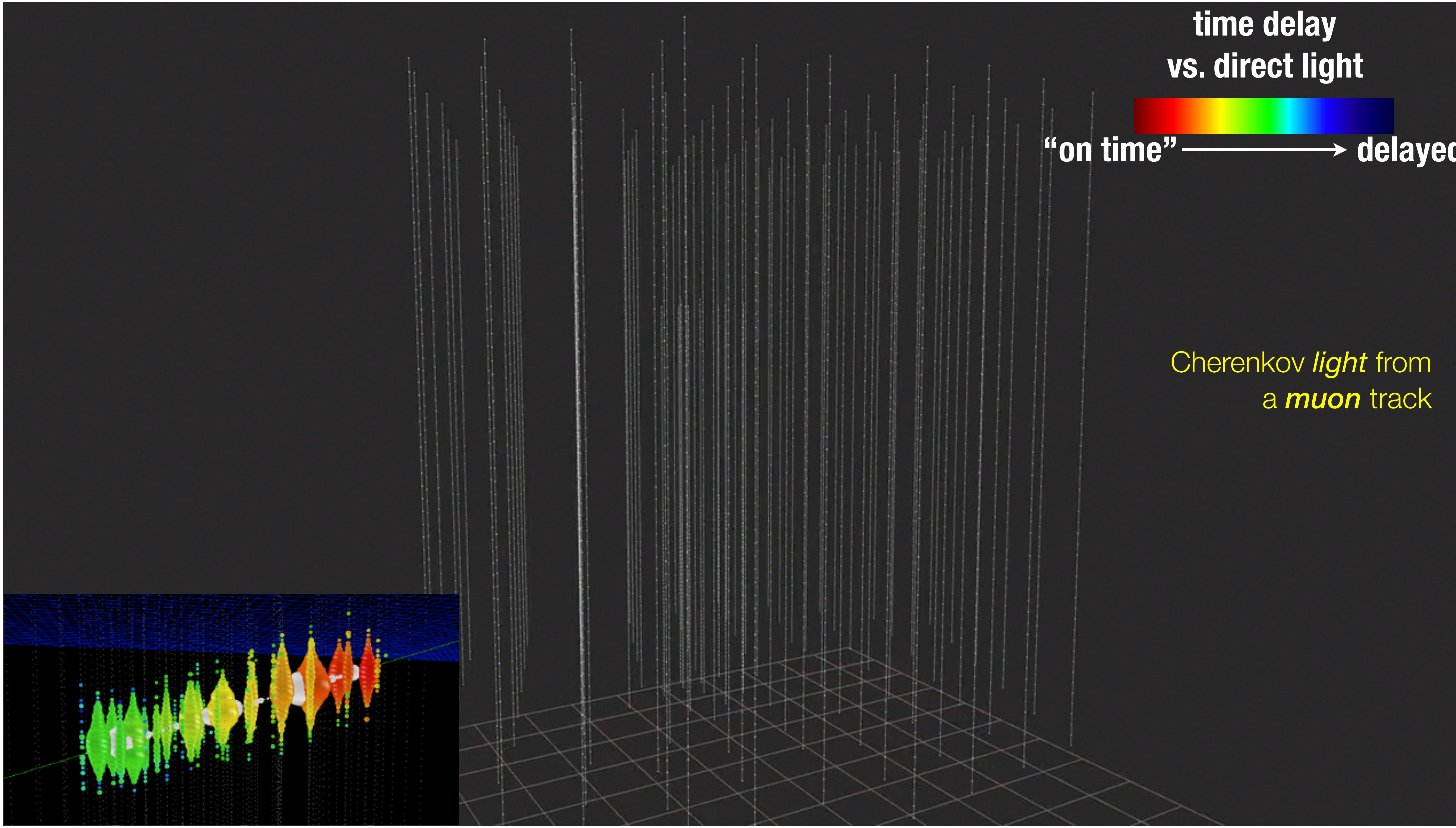


Claudio Kopper - WIPAC

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

detection principle - *track*

ν_μ CC-int

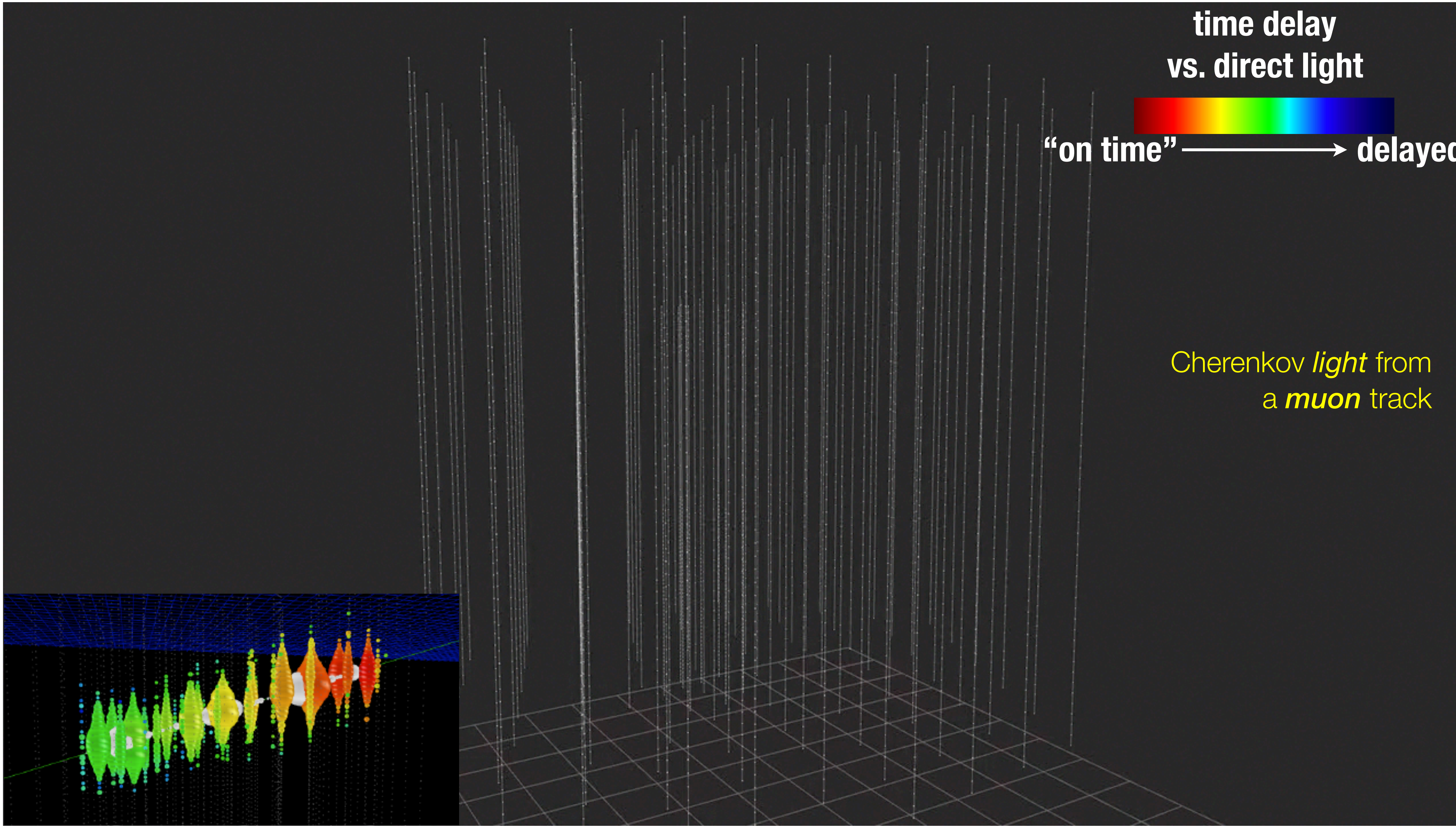


Claudio Kopper - WIPAC

factor of ≈ 2 energy resolution
< 1° angular resolution

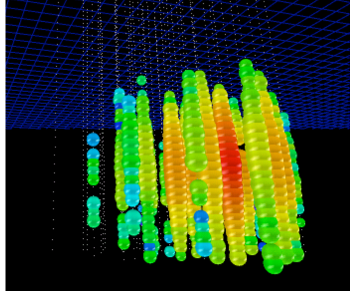
detection principle - *track*

ν_μ CC-int



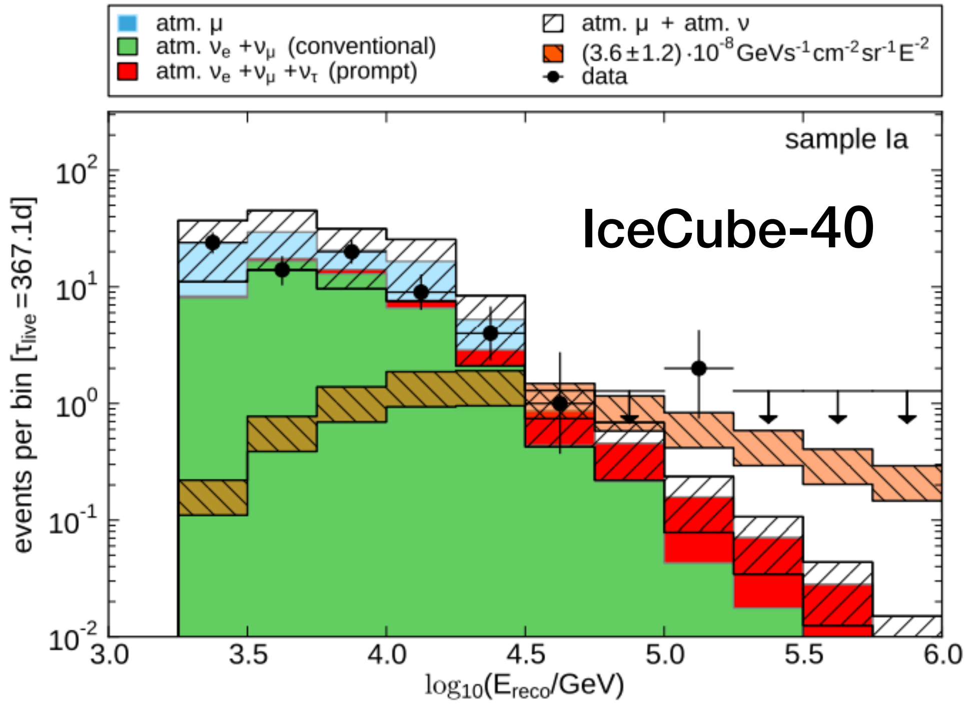
Claudio Kopper - WIPAC

factor of ≈ 2 energy resolution
< 1° angular resolution



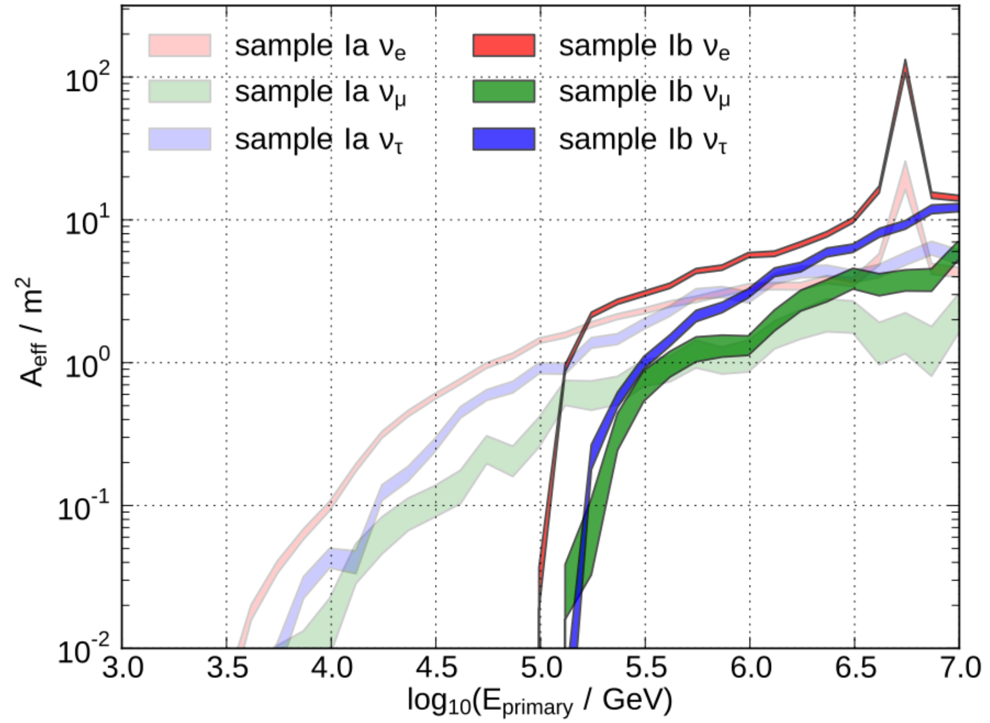
neutrino identification

diffuse flux

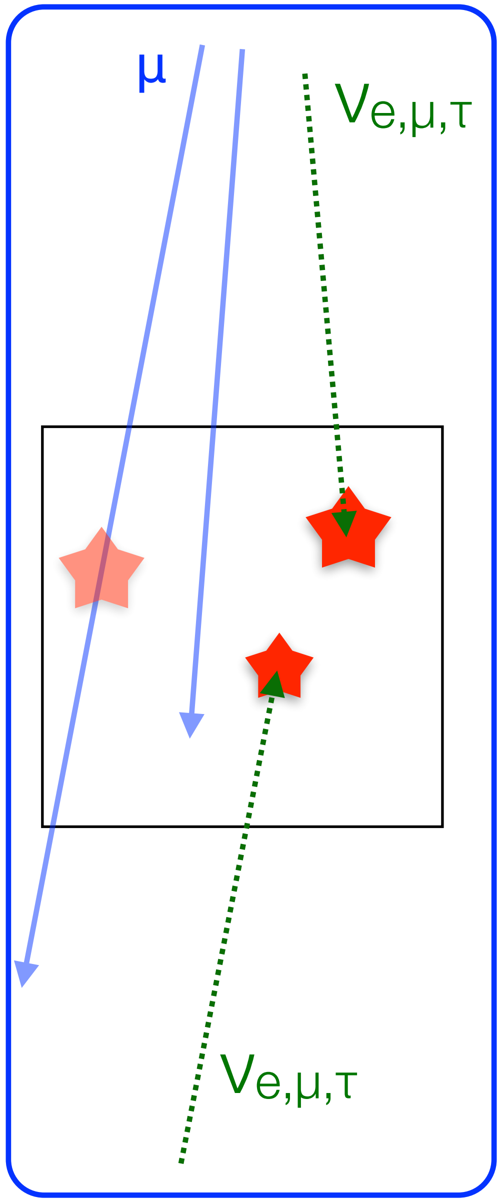


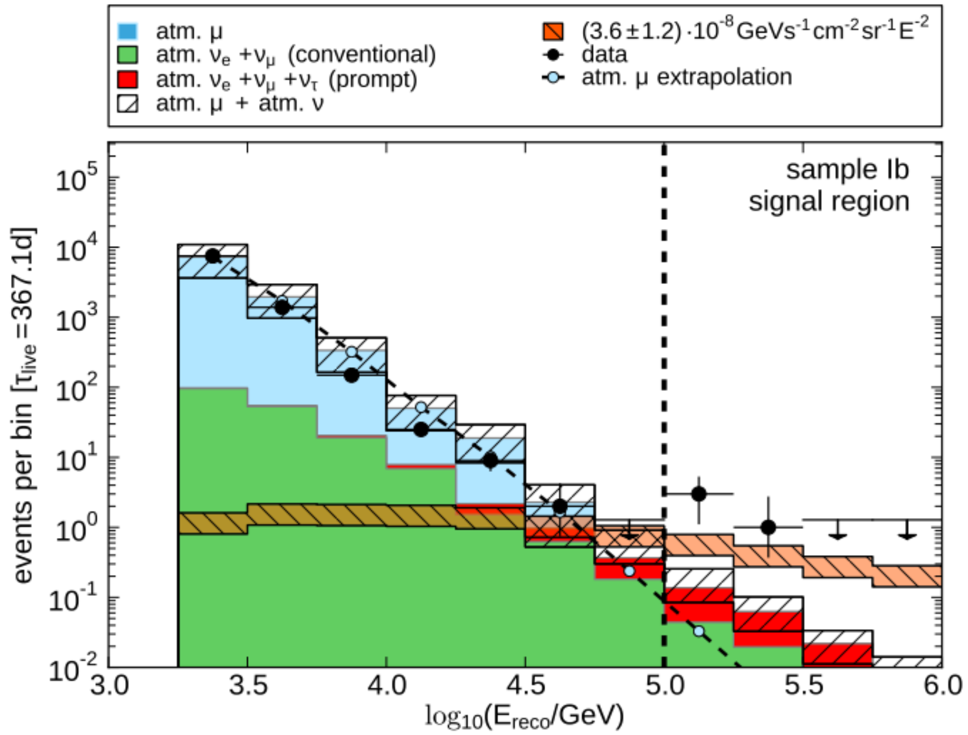
(a) Deposited Energy in sample Ia

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



contained (cascades)





2.4 σ excess over atmospheric expectation

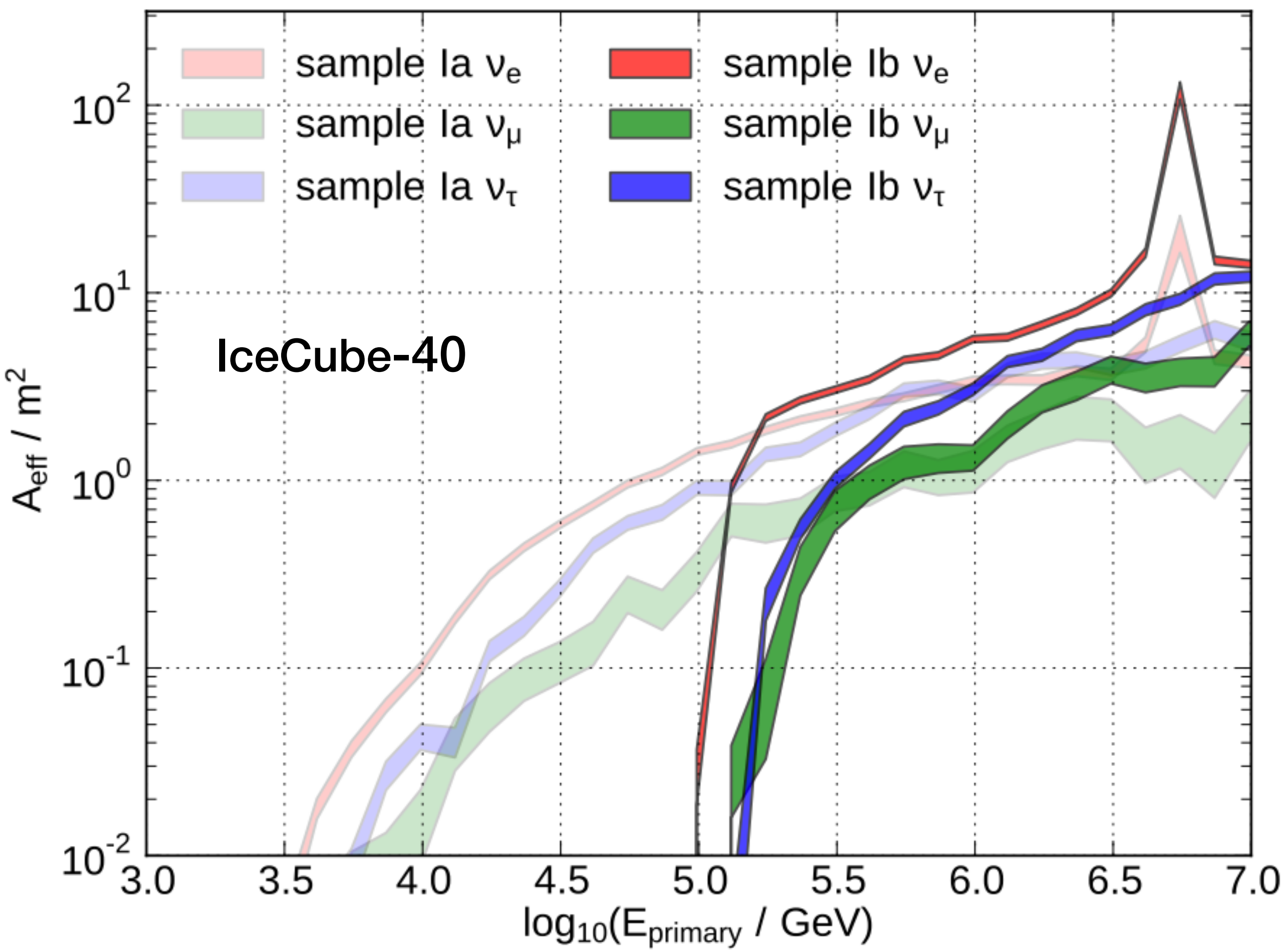
$$\Phi^{astro}_{90\%CL}(E) = 7.46 \times 10^{-8} \times E^{-2}\ GeV^{-1} cm^{-2} s^{-1} sr^{-1}$$

all-flavor

neutrino identification
diffuse flux

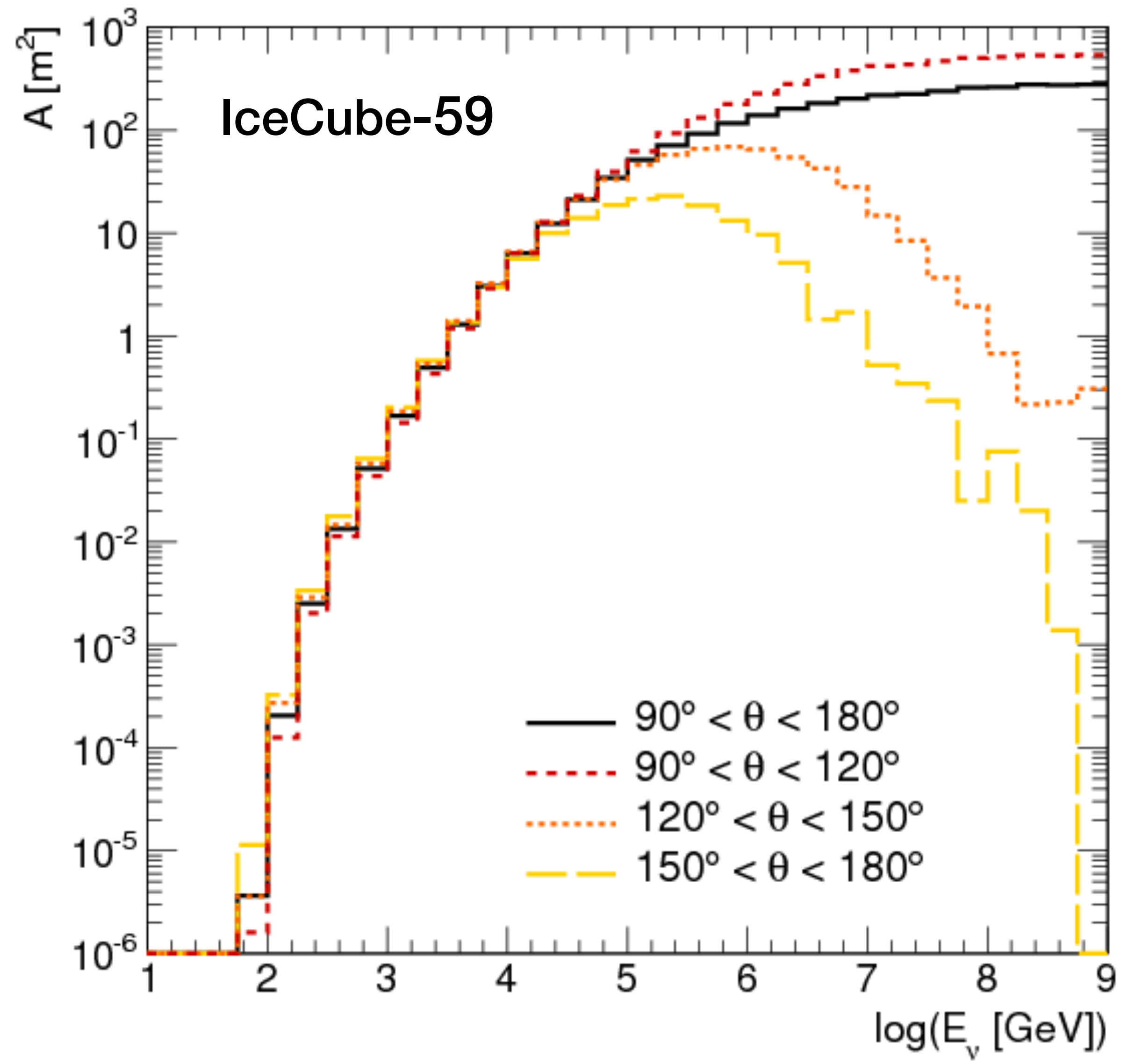
neutrino effective area

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

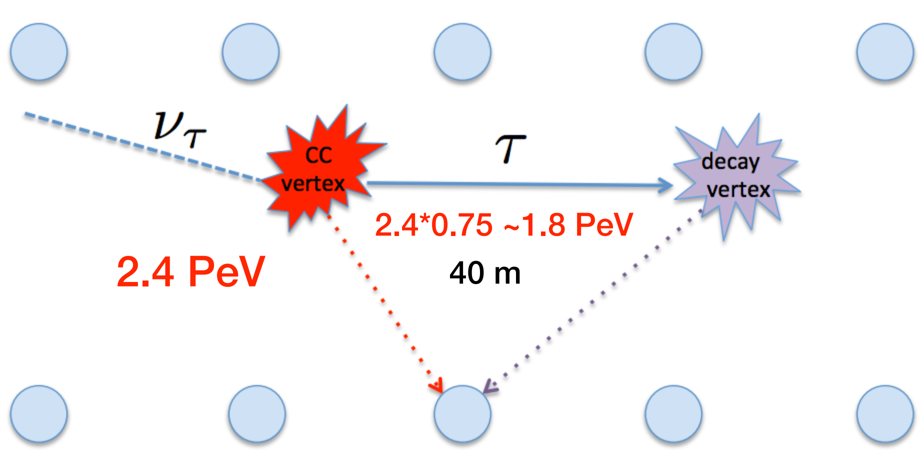
neutrino identification
diffuse flux

tau neutrino searches

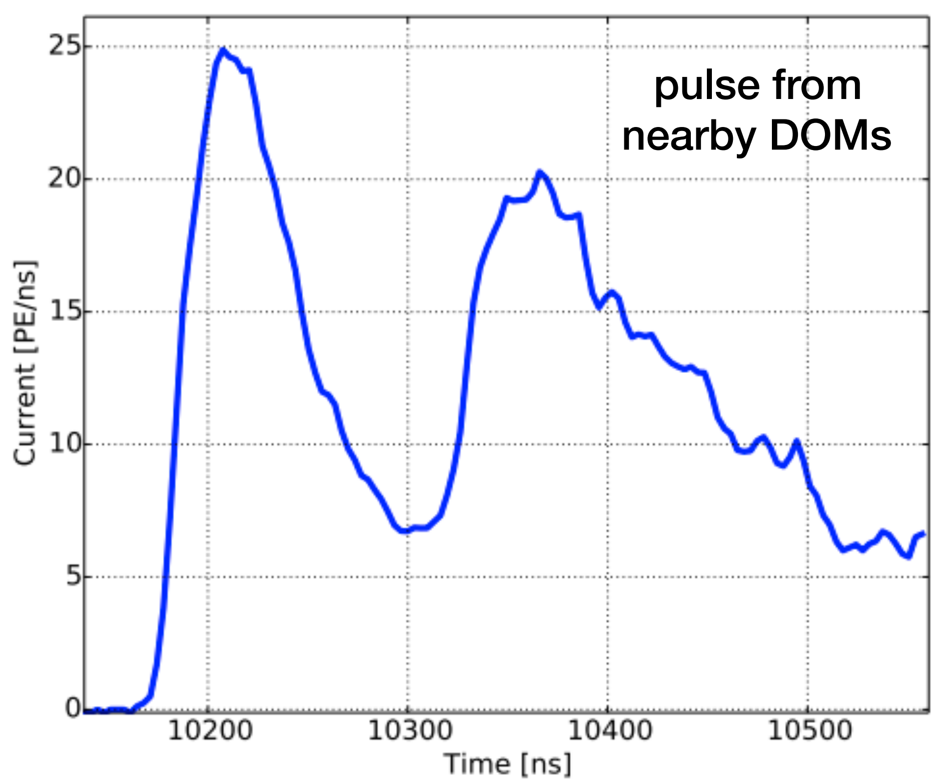
IceCube-86 × 3

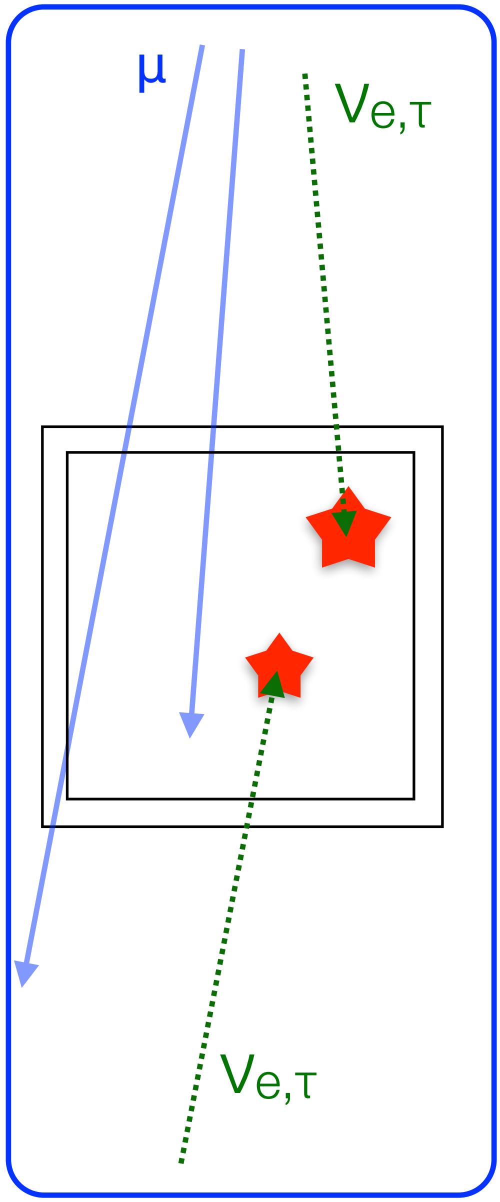
contained (cascades)

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

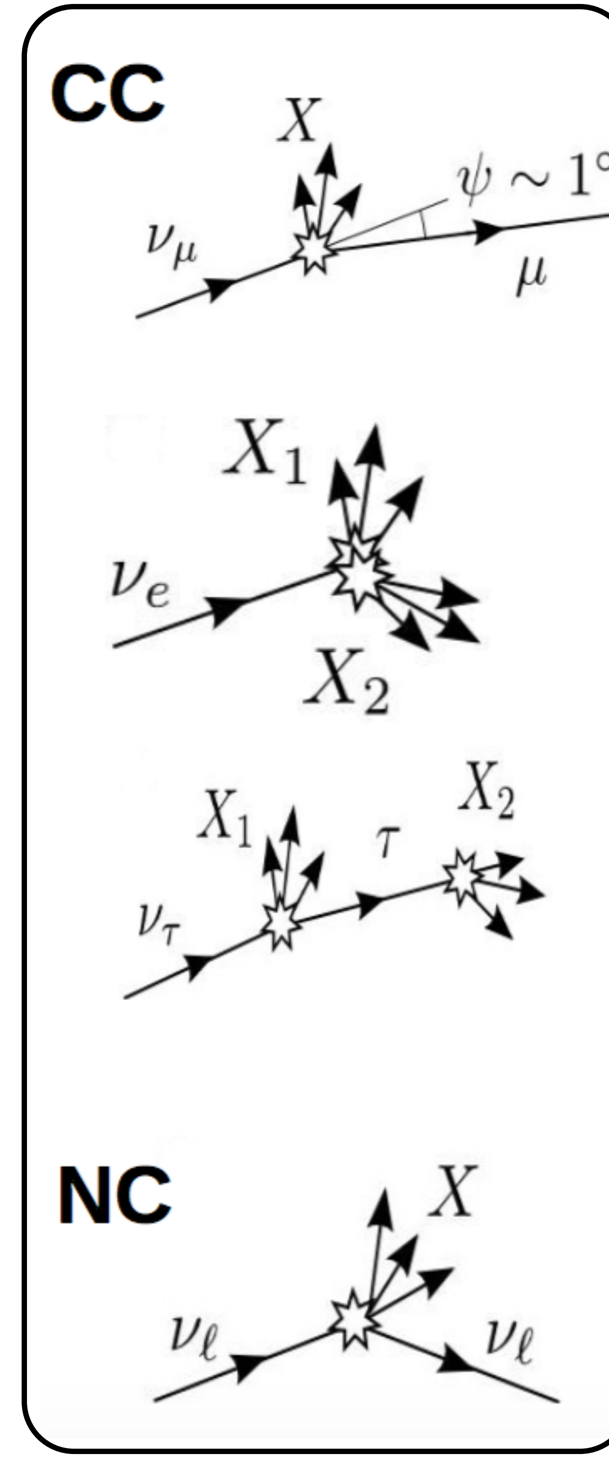
neutrino identification

flavor sensitivity

TOO FEW TRACK-LIKE EVENTS ?

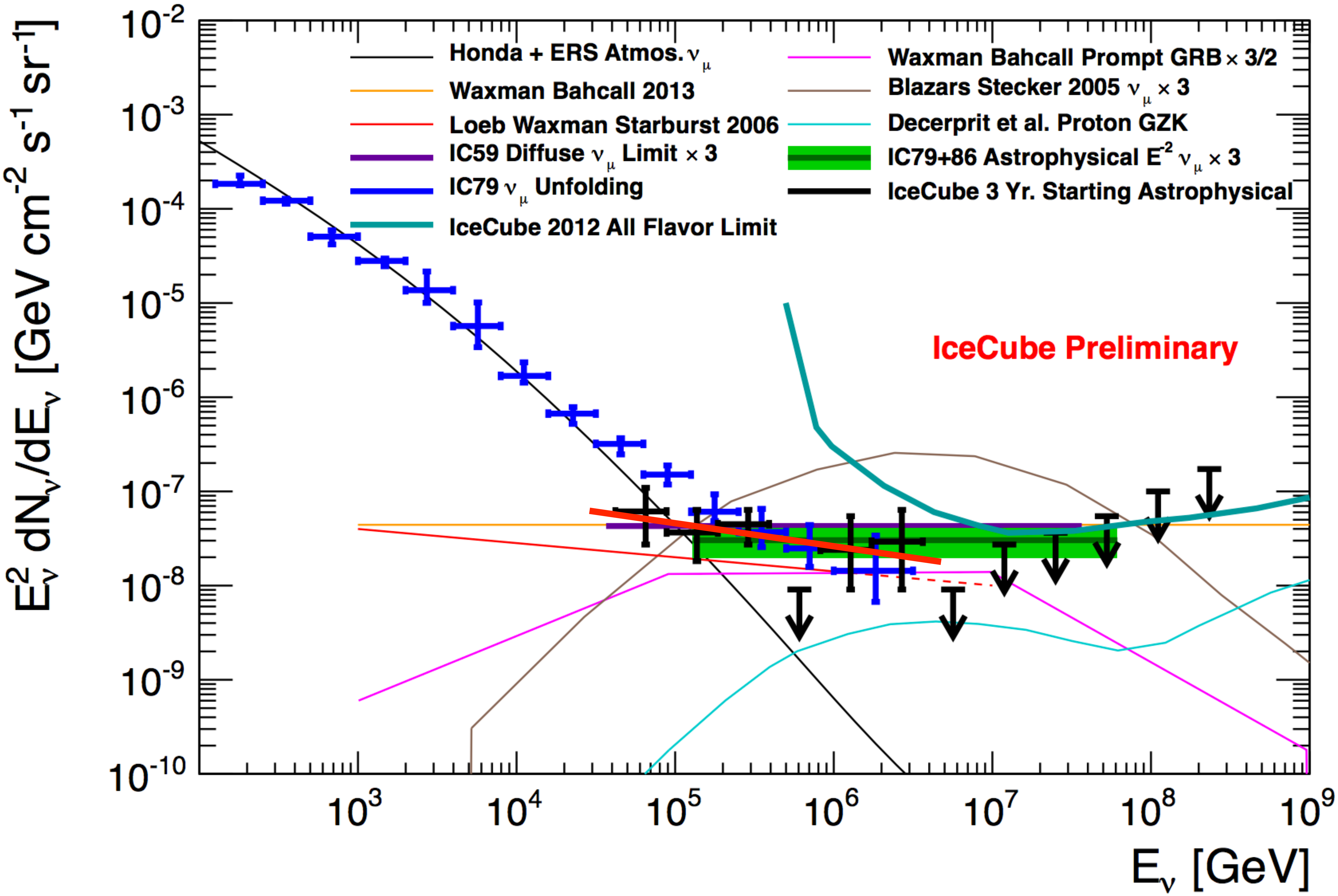
- track-like & cascade-like is an **experimental** definition
- in all-flavor searches track-like events are not common
- all flavors look alike in NC interactions
- μ in CC interactions may be concealed in showers
- τ have short tracks except above PeV energies

- flavor identification requires simulation data



high energy neutrinos

transition from atmospheric to astrophysical

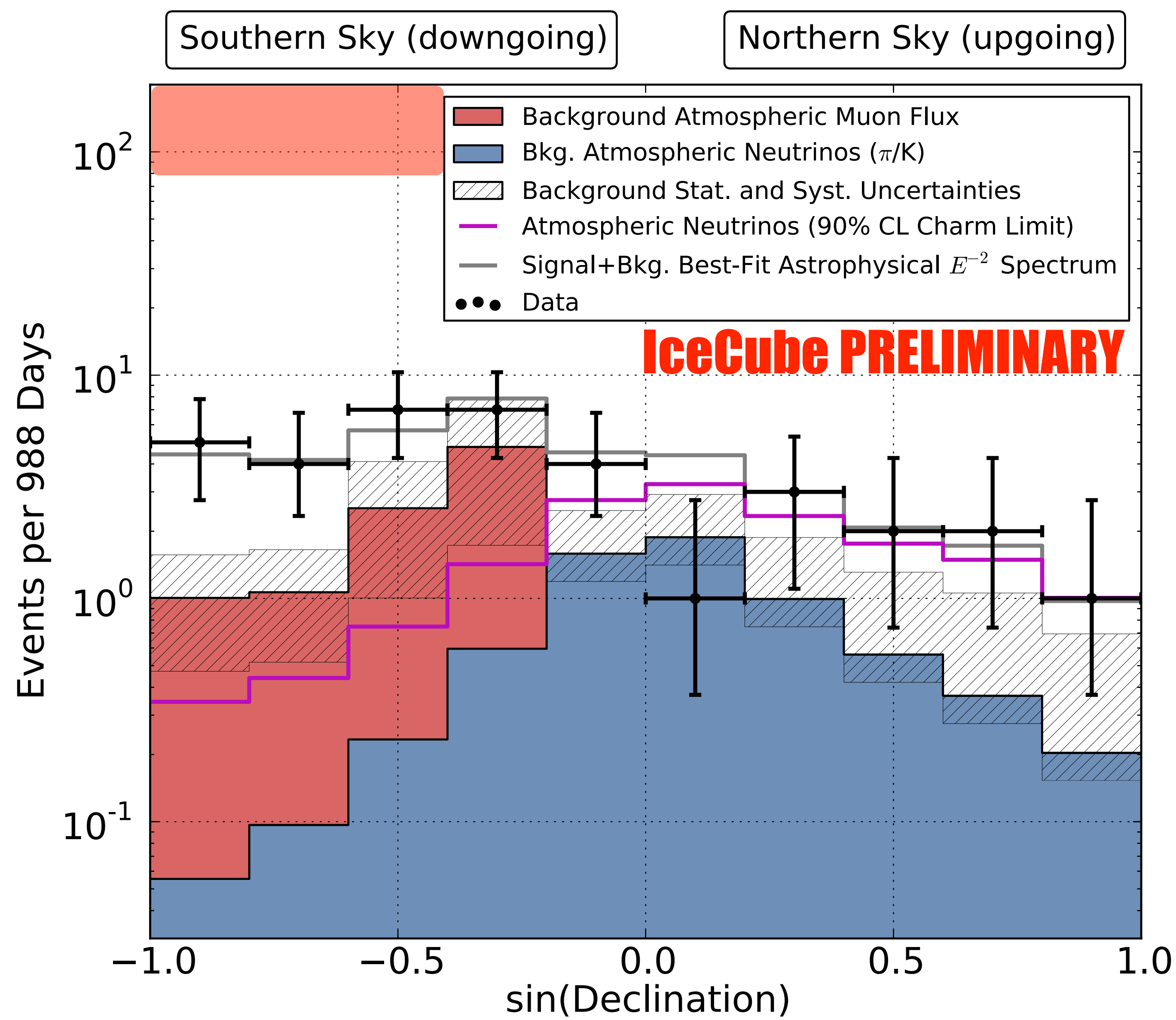


high energy "*starting*" events

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



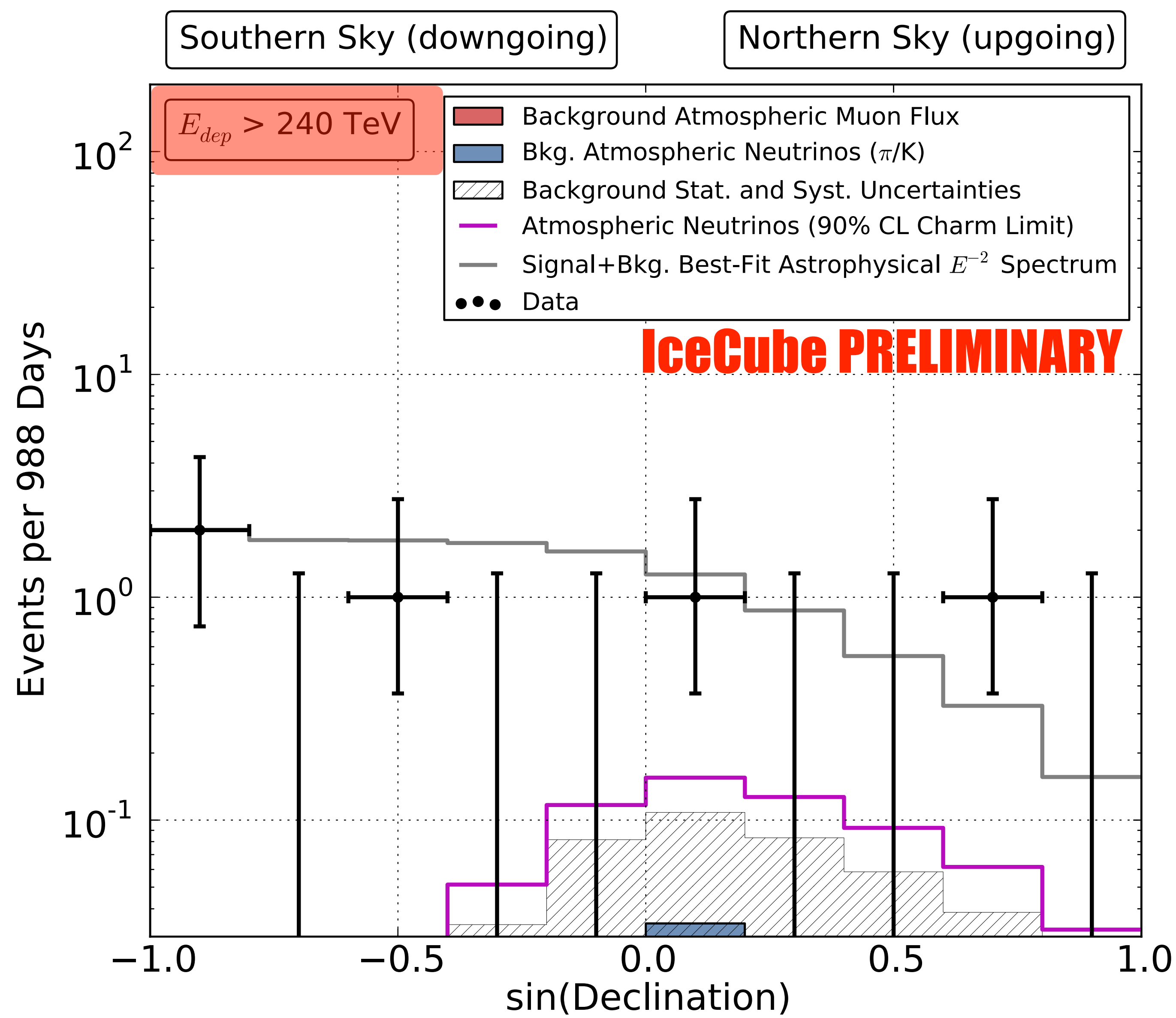
south north

high energy "*starting*" events

angular distribution

Aartsen et al. Science 342 (2013) 1242856

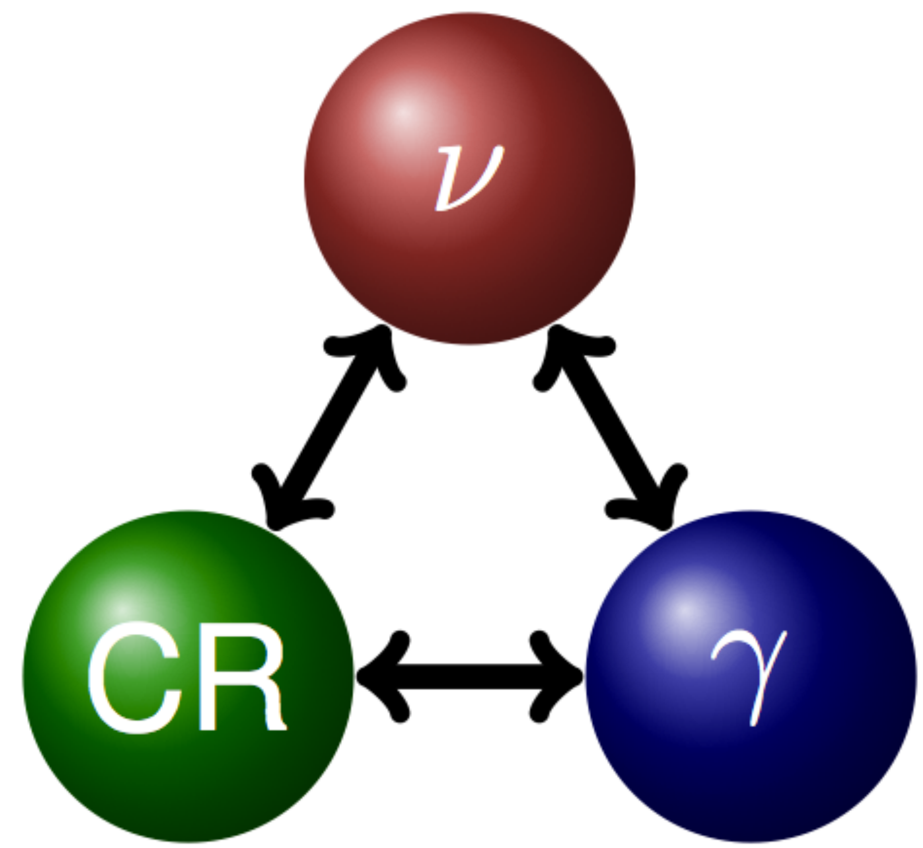
- compatible with isotropic flux
- Earth absorption from Northern Hemisphere
- excess from south (self-veto)
- **charm production @north**
  - forward physics with IceCube



south north

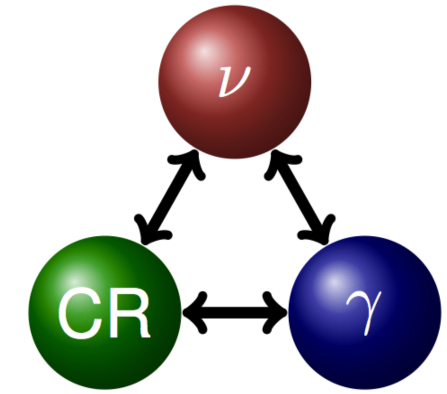
origin of high energy neutrinos ?

- 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**

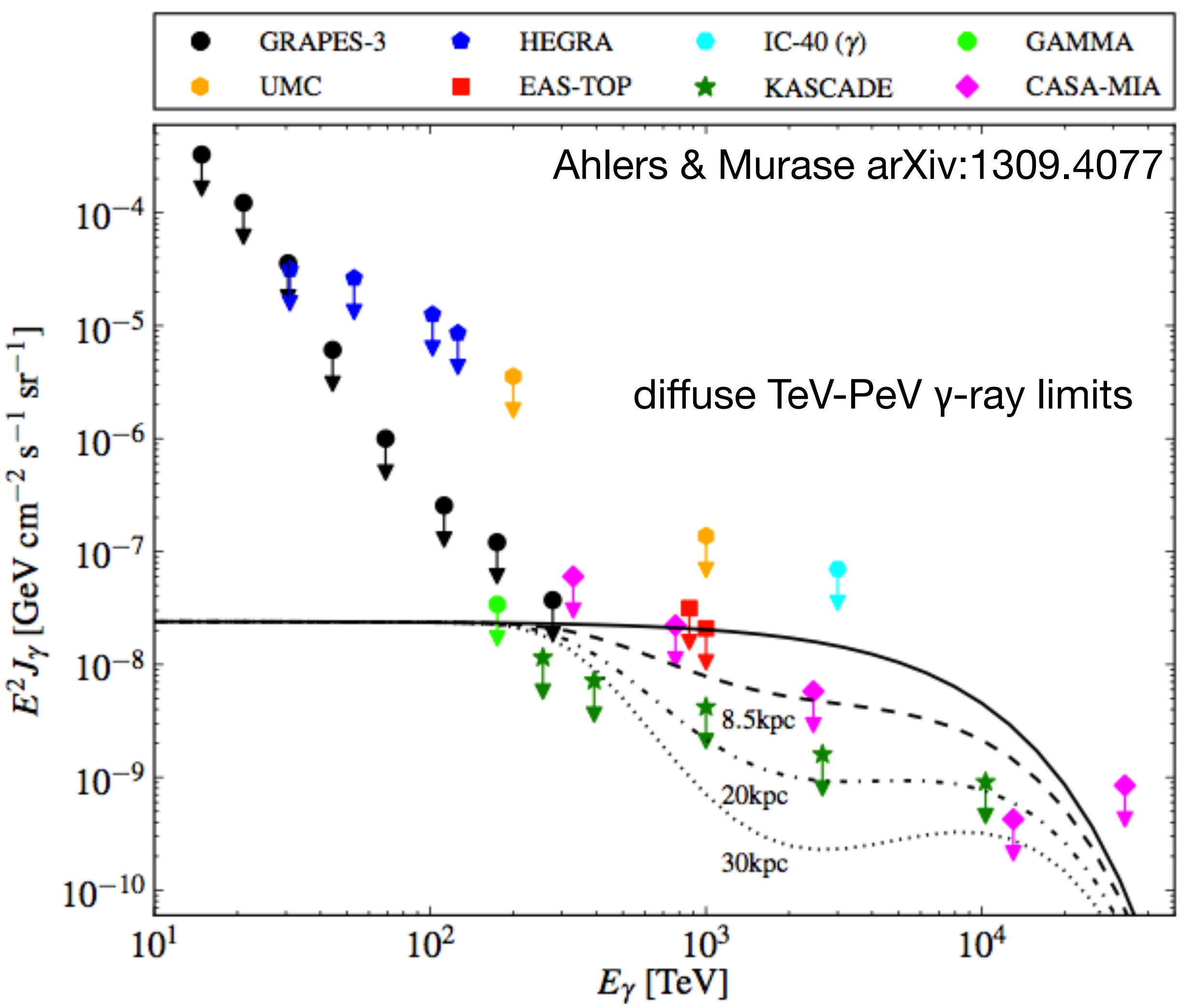
- **extragalactic sources:**
  - relation to the sources of UHE CRs [Kistler, Stanev & Yuksel 1301.1703]
  - GZK from low $E_{\max}$ blazars [Kalashev, Kusenko & Essey 1303.0300]
  - cores of active galactic nuclei (AGN) [Stecker *et al.*'91;Stecker 1305.7404]
  - low-power γ-ray bursts (GRB) [Murase & 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]

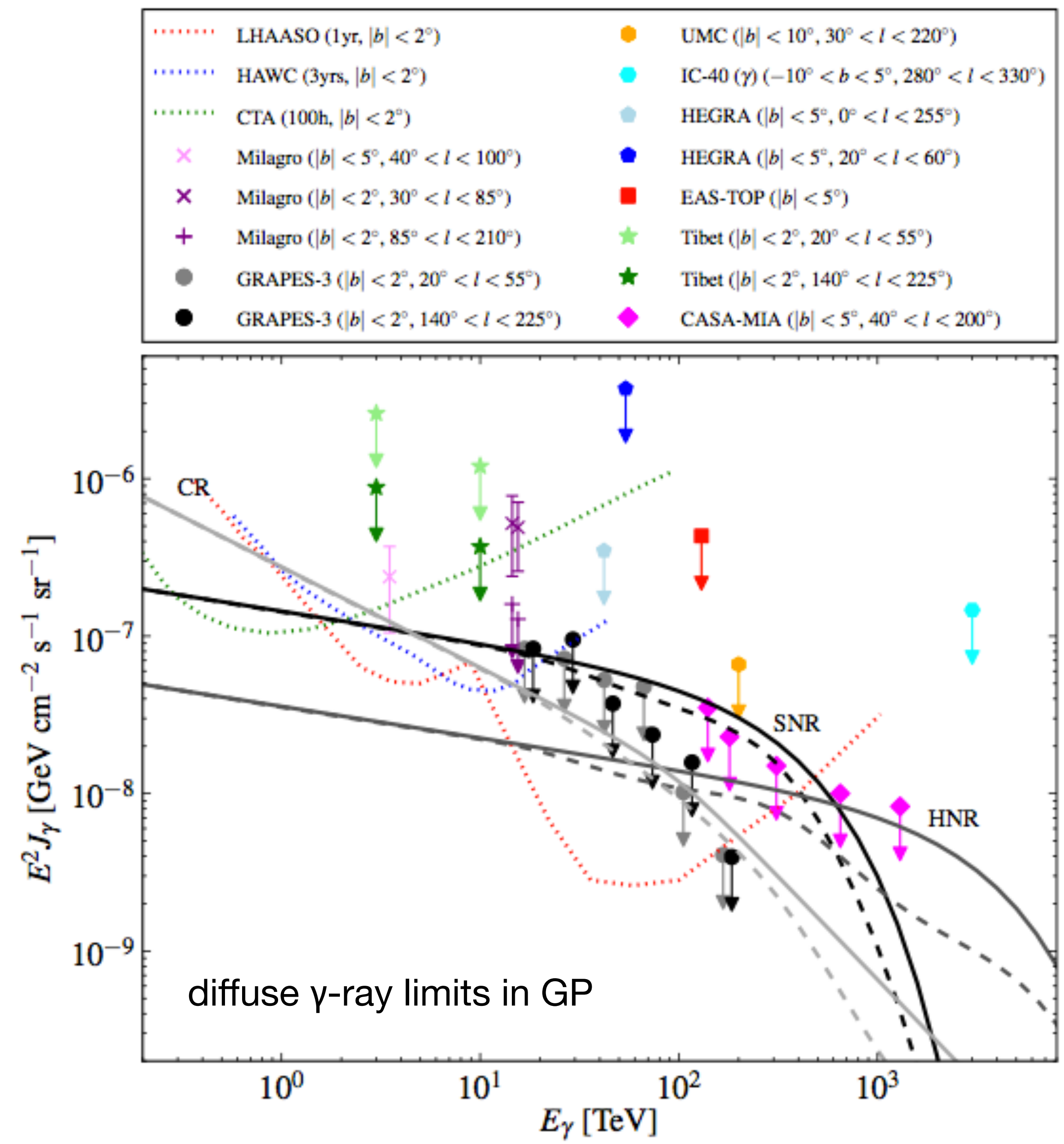
M Ahlers

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

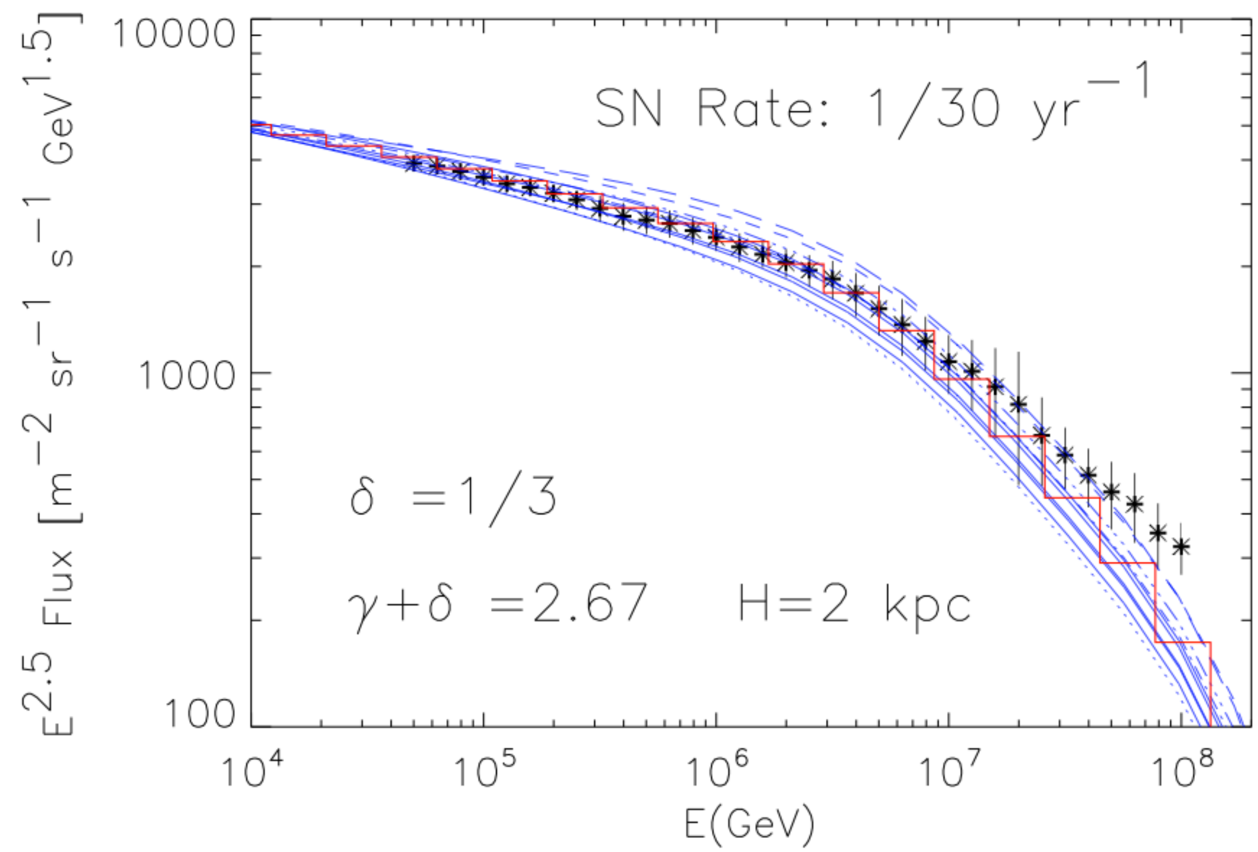
- cosmic ray spectrum affected by **propagation**
- escape faster with energy: **diffusion** coefficient

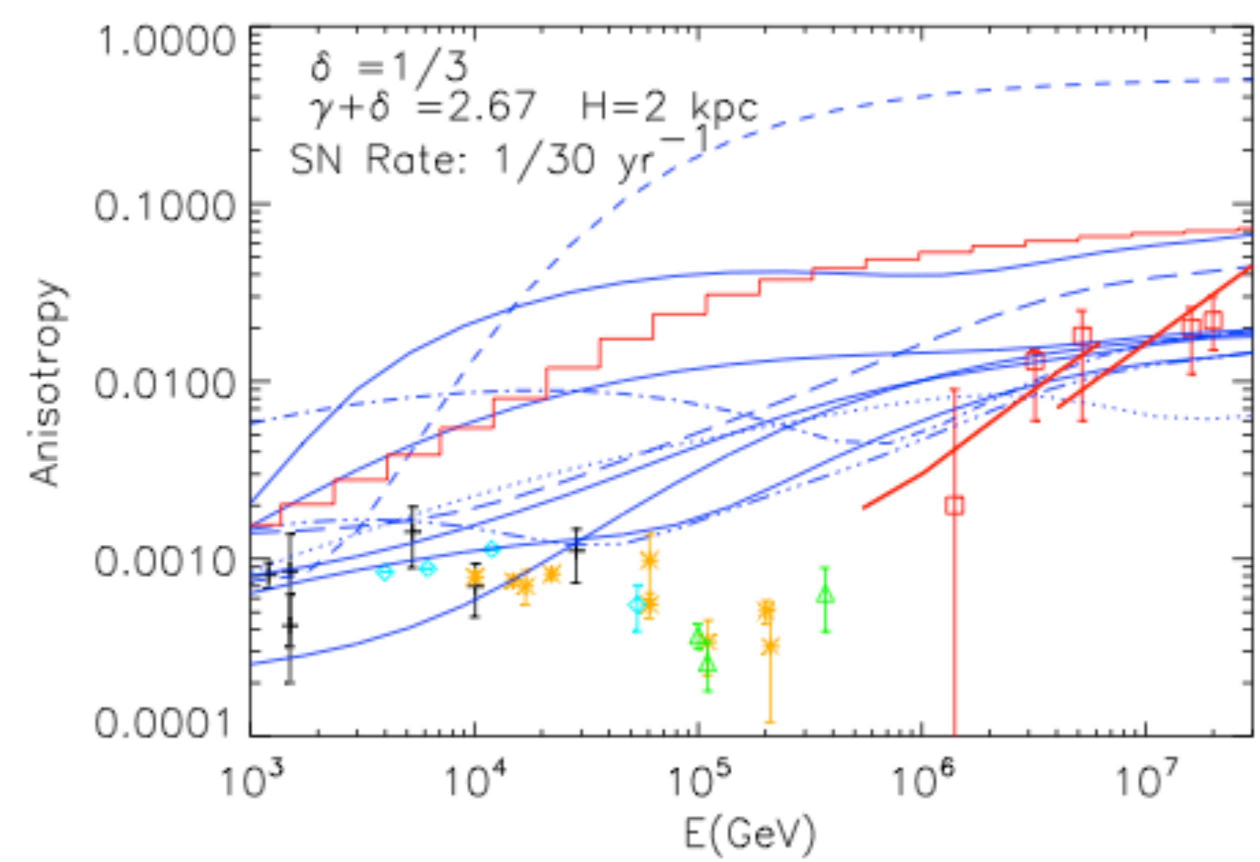
$$\frac{dN_{CR}}{dE} \approx E^{-\gamma_{inj}-\delta} \qquad D(E) \propto E^{\delta} \qquad \delta \sim 0.3 - 0.6$$

- stochastic effects from individual sources
- spectral features & anisotropy

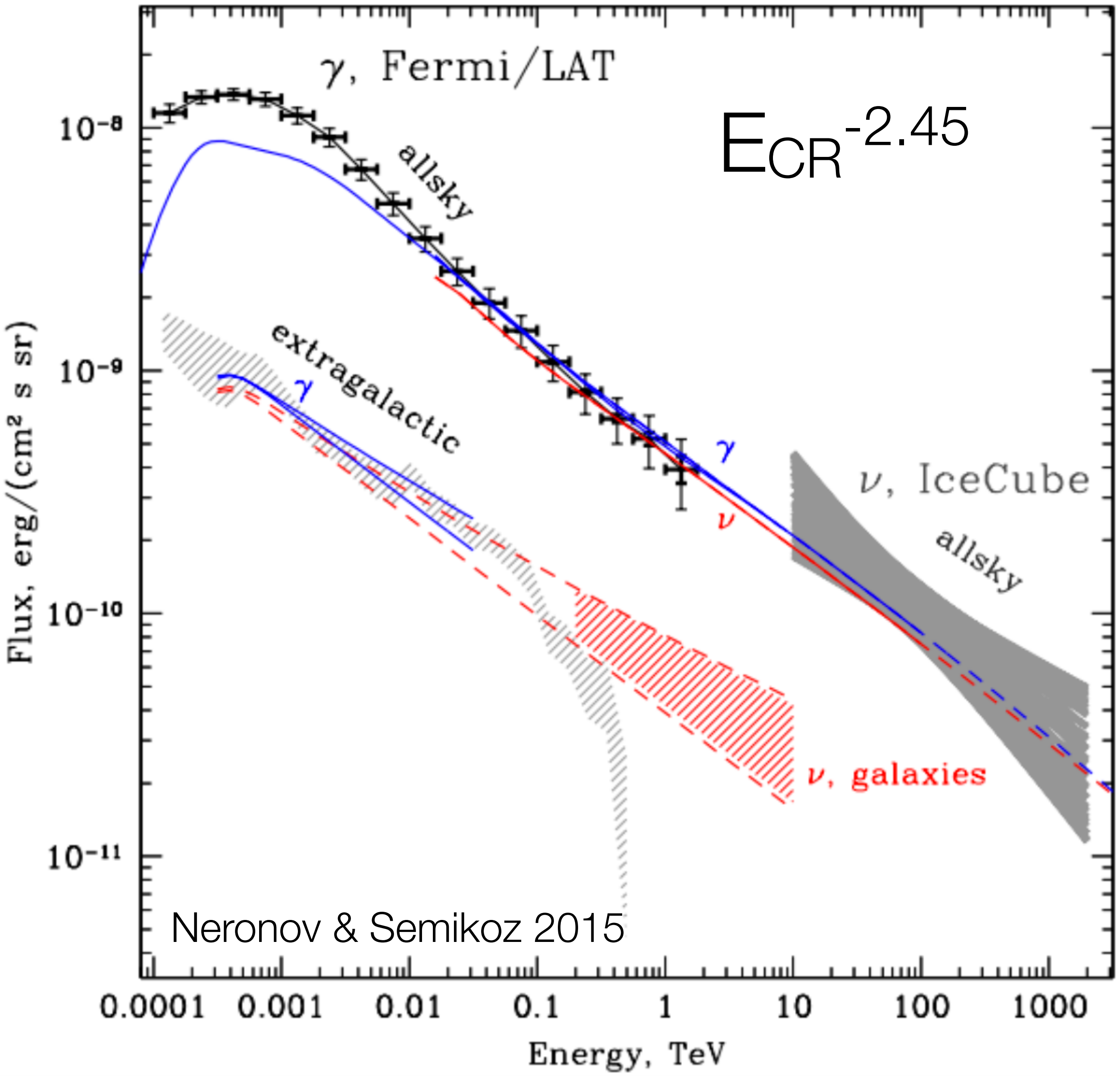
➡ simple diffusion model not sufficient

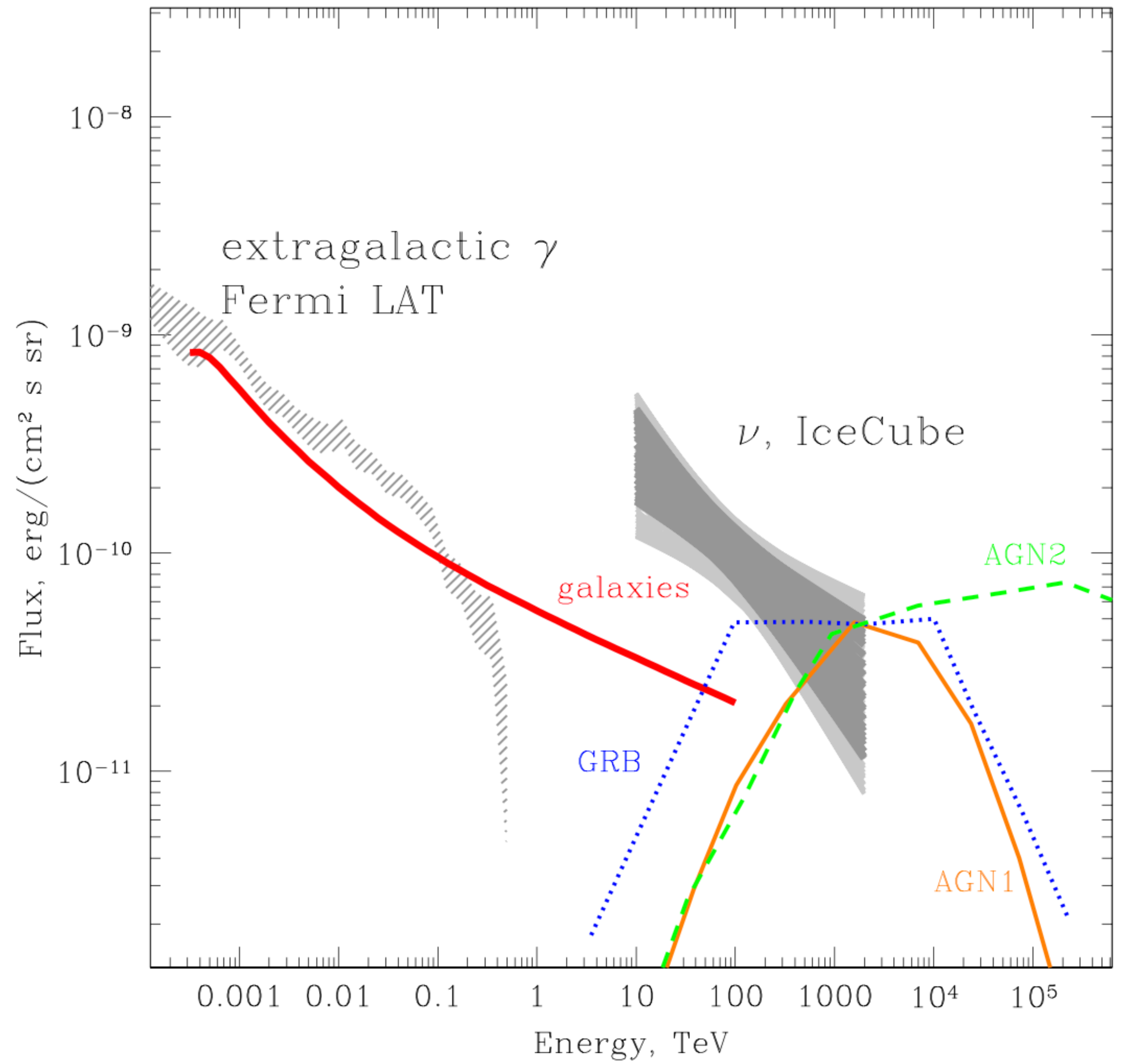
➡ non-diffusive processes within mean free path





astrophysical neutrinos
galactic origin

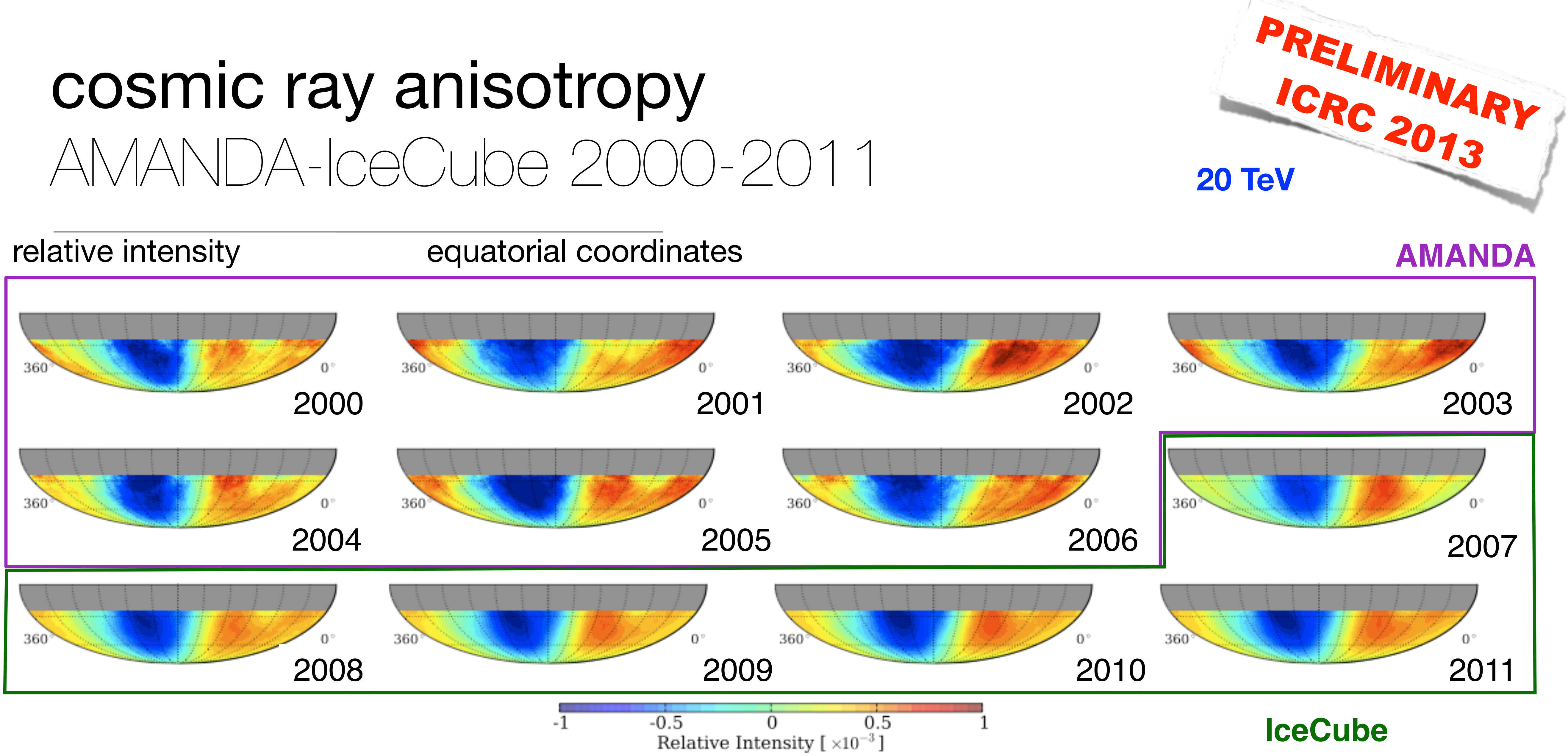




galactic cosmic rays with cut-off of 10 PeV ?

cosmic ray anisotropy

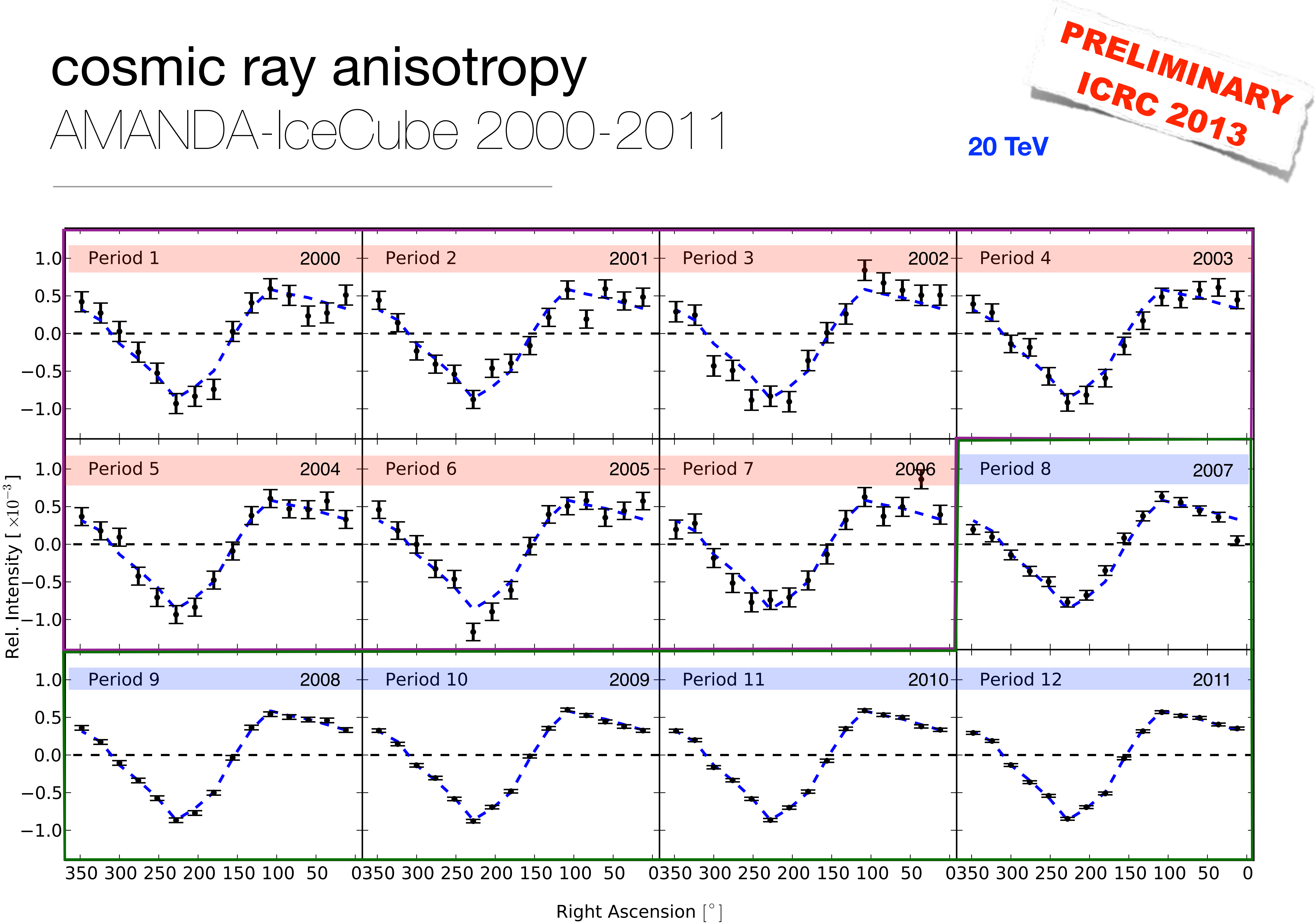
AMANDA-IceCube 2000-2011



- AMANDA and IceCube yearly data show long **time-scale stability** of global anisotropy within statistical uncertainties

  - no apparent effect correlated to solar cycles

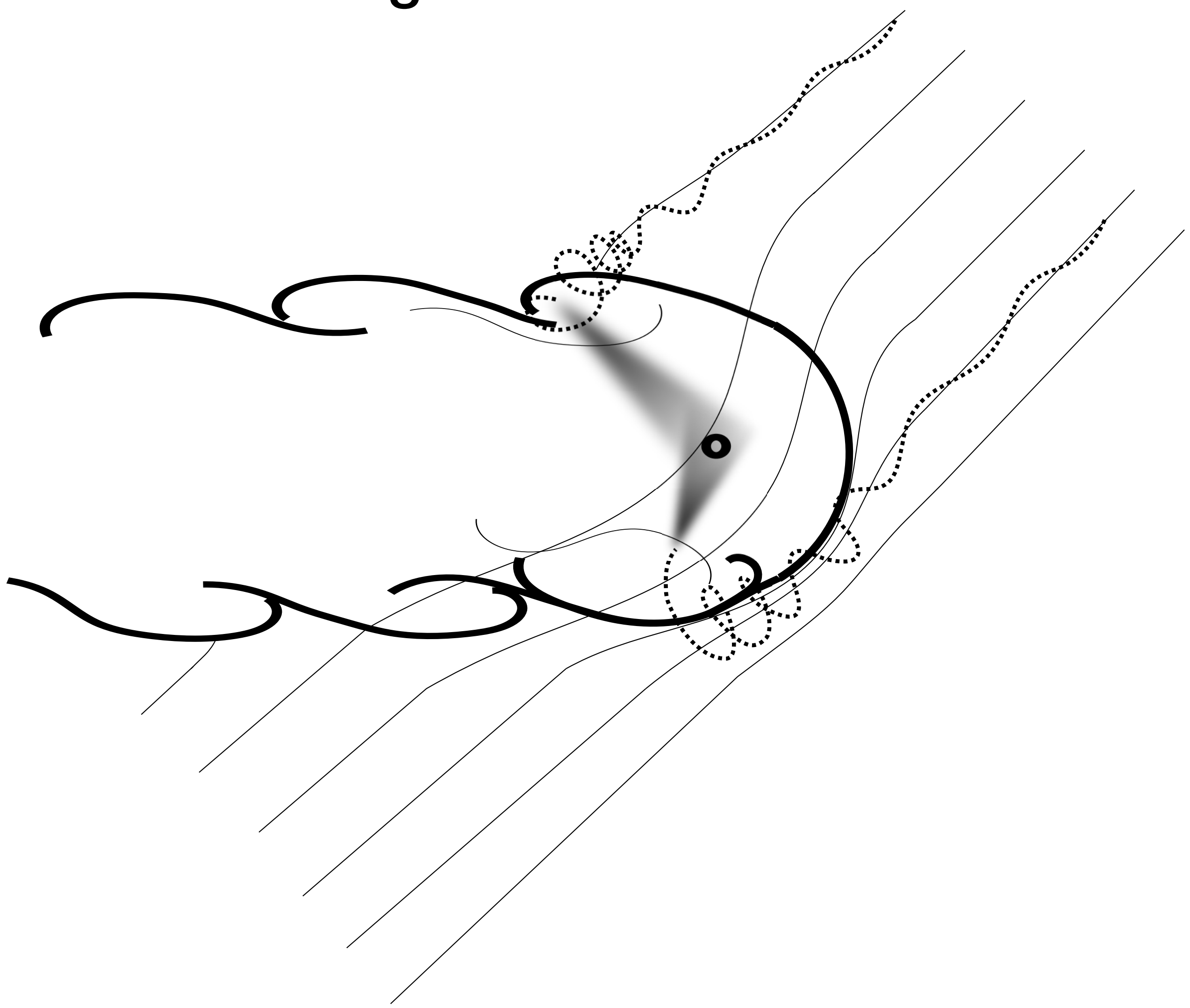
cosmic ray anisotropy
AMANDA-IceCube 2000-2011



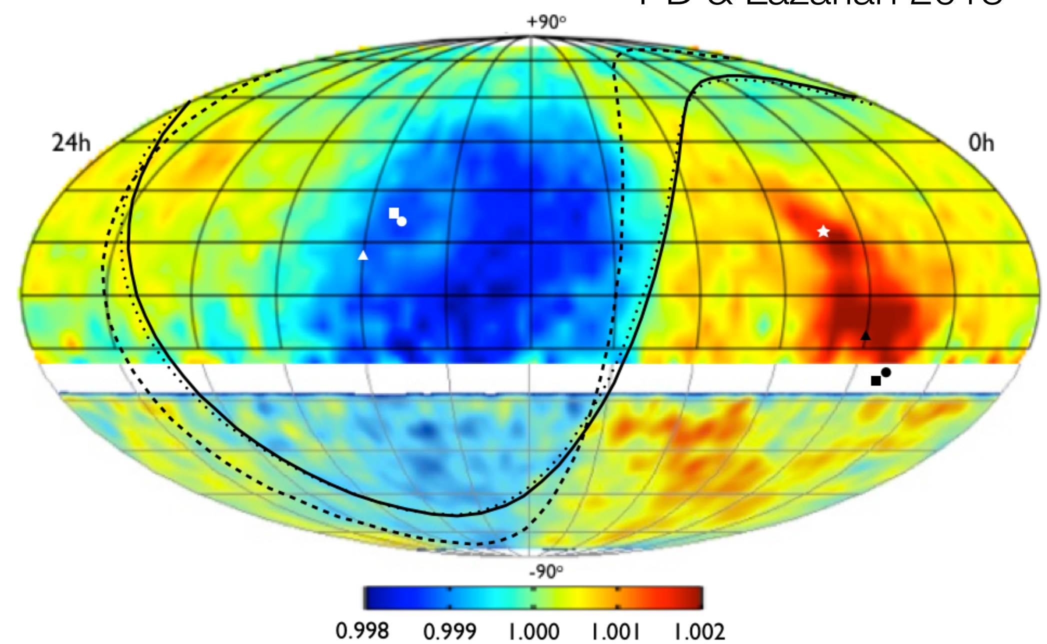
Paolo Desiati

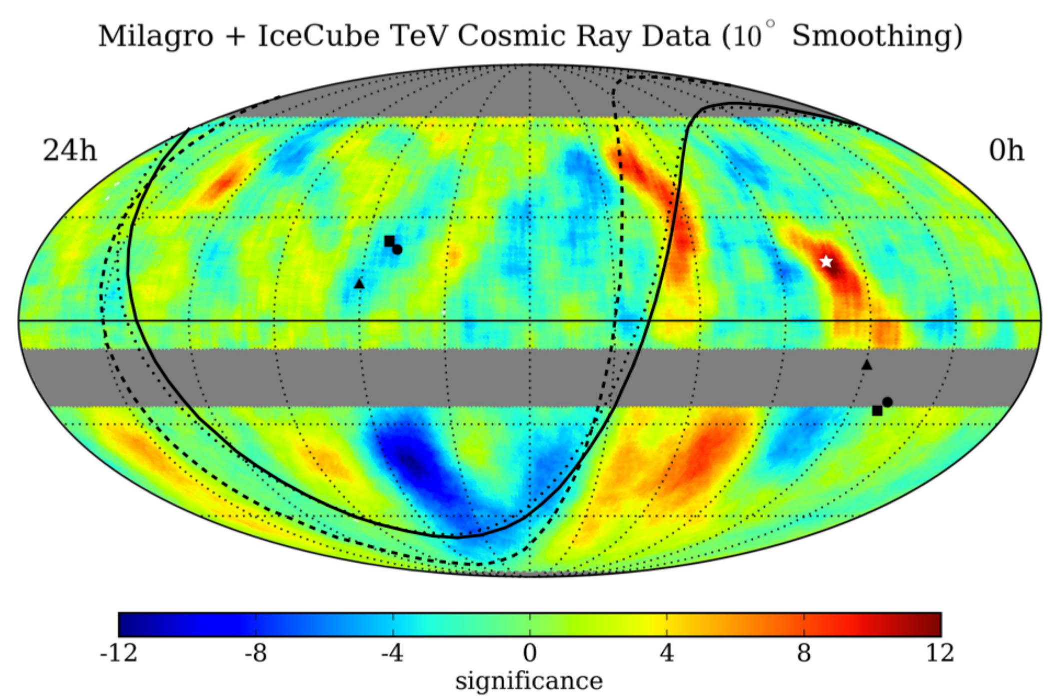
scattering at heliospheric boundary
heuristic model

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



PD & Lazarian 2013

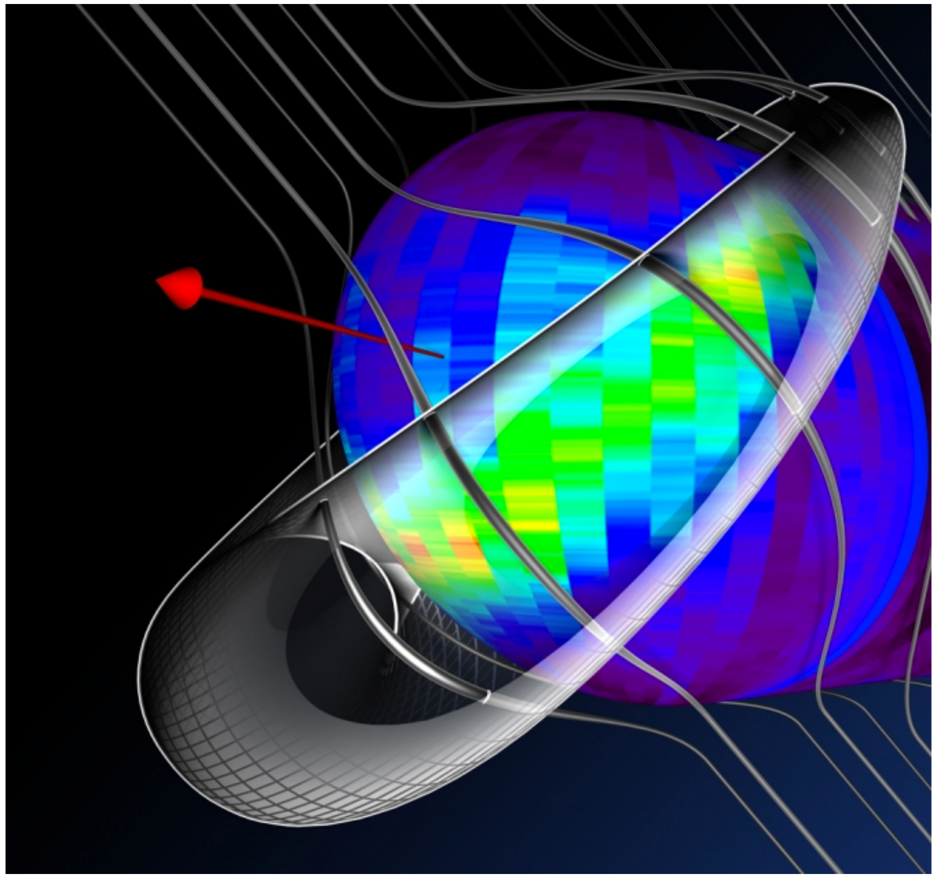


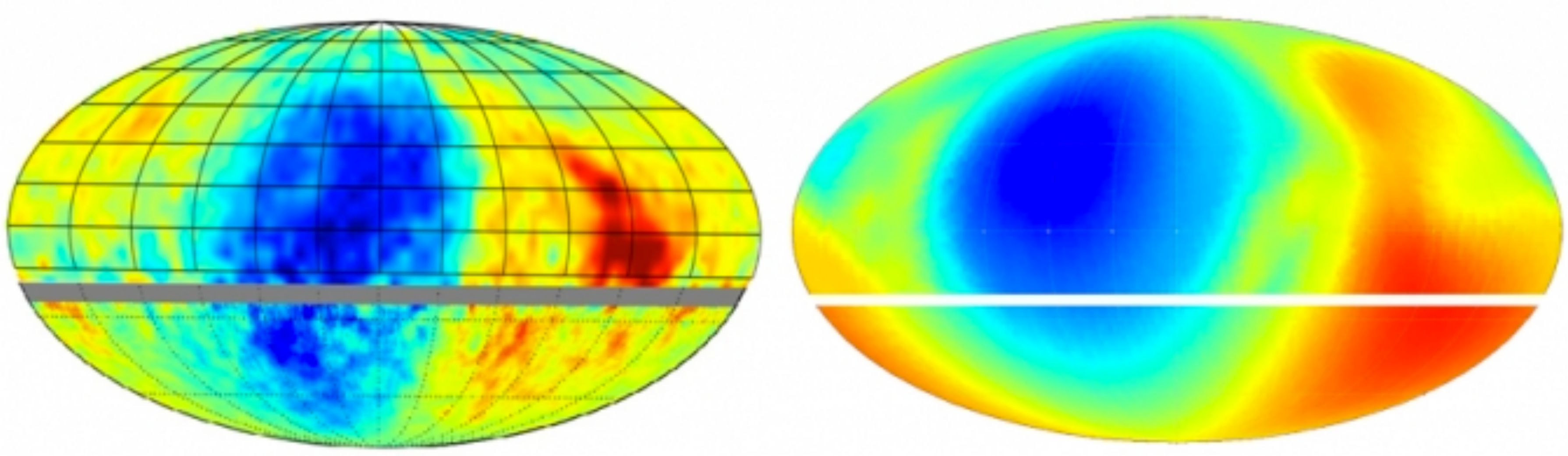


- global anisotropy with **large edge gradients**

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

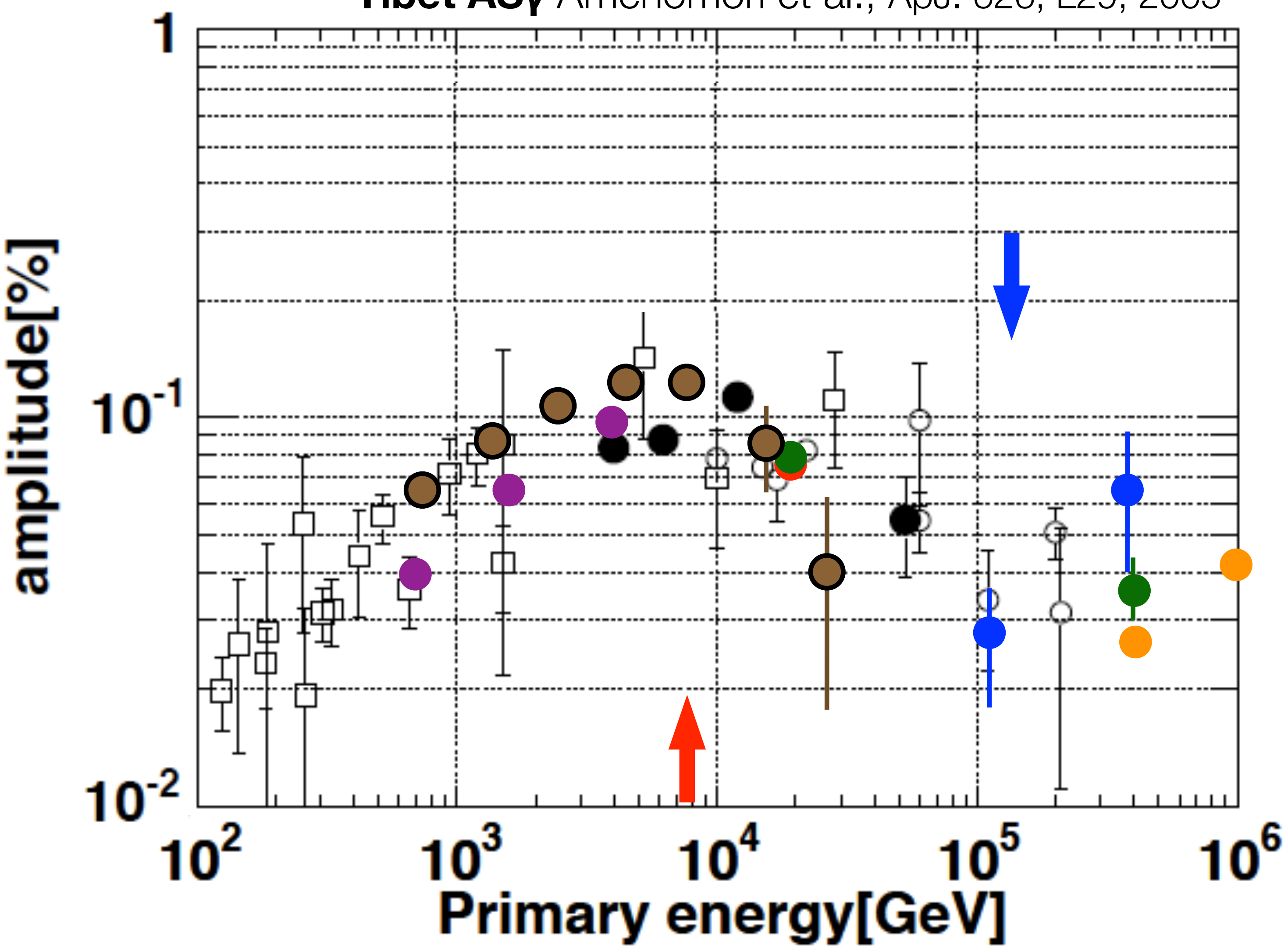




Schwadron, et al., Science, 1245026 (2014)

cosmic ray anisotropy
and energy

Tibet ASγ Amenomori et al., ApJ. 626, L29, 2005



dipole component
IceCube-22 Abbasi et al., ApJ, 718, L194, 2010
IceCube-59 Abbasi et al., ApJ, 746, 33, 2012
EAS-TOP Aglietta et al., ApJ, 692, L130, 2009
ARGO-YBJ Zhang 31st ICRC Łódź-Poland,2009
ARGO-YBJ 32nd ICRC Beijng China,2011

gaussian fit **IceTop** Aartsen et al., ApJ, 765, 55, 2013

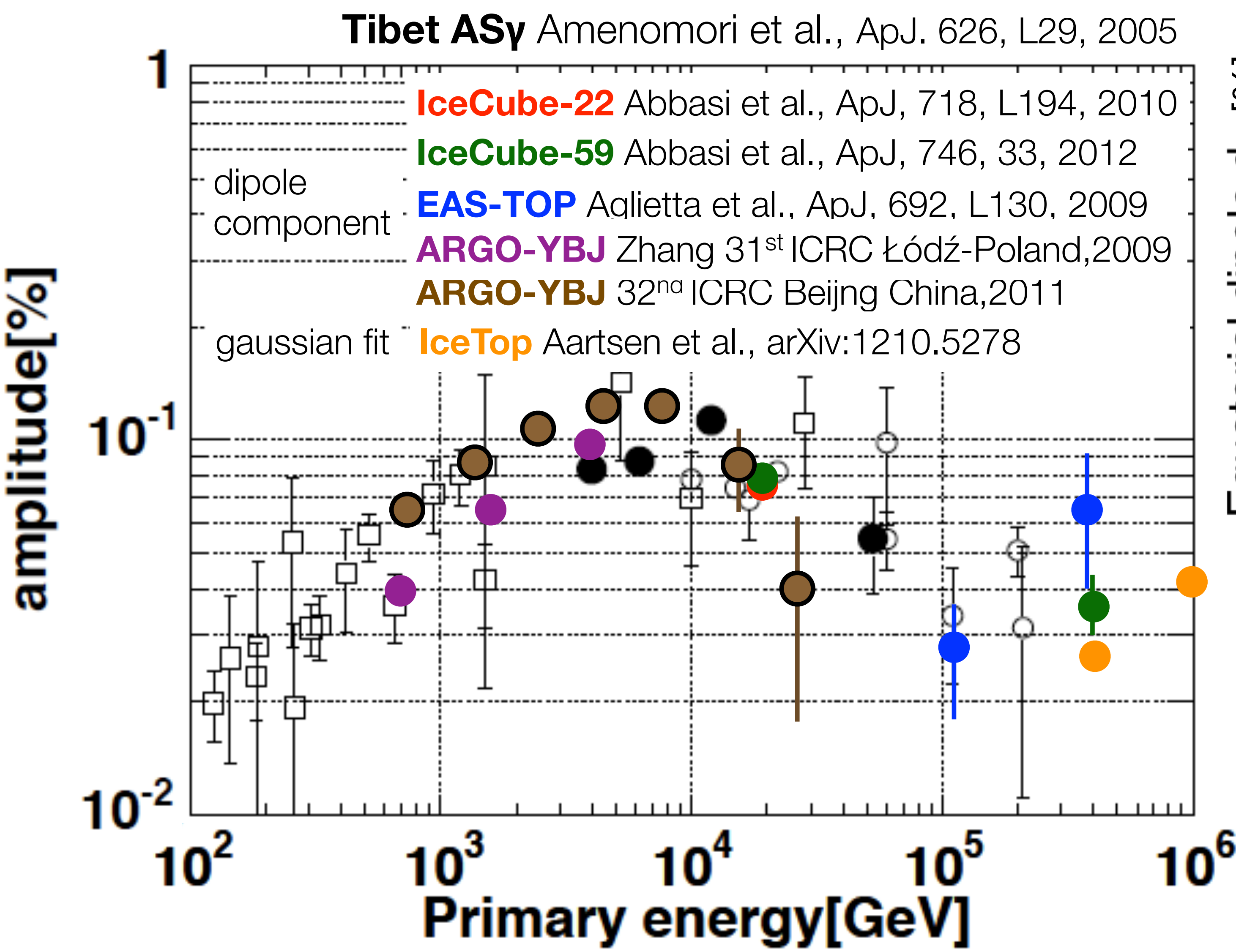
- modulation in amplitude of **dipole component**
- corresponds to **transition in anisotropy topology**

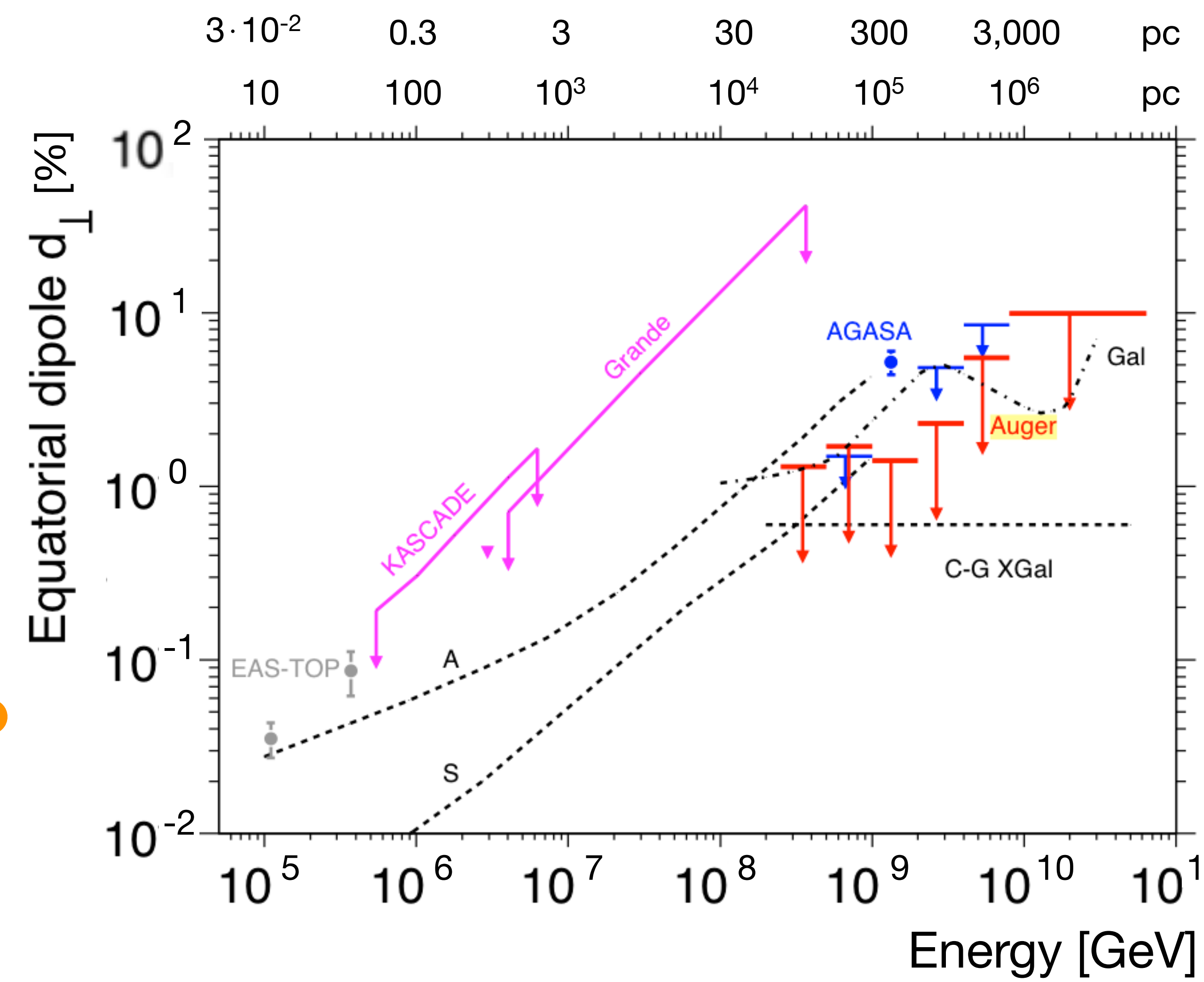
cosmic ray anisotropy large scale

energy dependency

(3 μG)

(~0.01 μG)





Abreu et al., Astrop. Phys., 34, 627, 2011

					(3 μG)
$3\cdot10^{-5}$	$3\cdot10^{-4}$	$3\cdot10^{-3}$	$3\cdot10^{-2}$	0.3	gyro-radius (pc)
7	70	700	7,000	70,000	gyro-radius (AU)

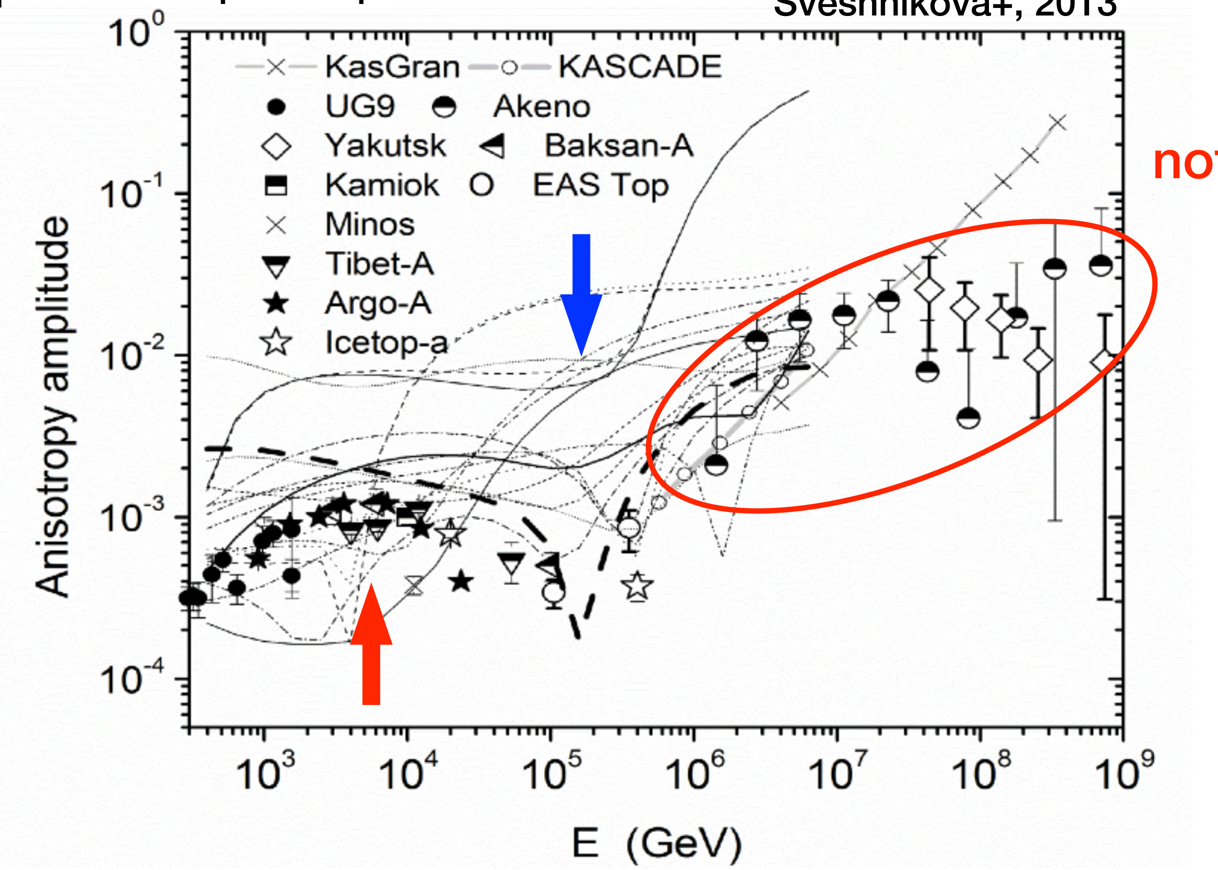
cosmic ray anisotropy

probing sources & propagation of cosmic rays ?

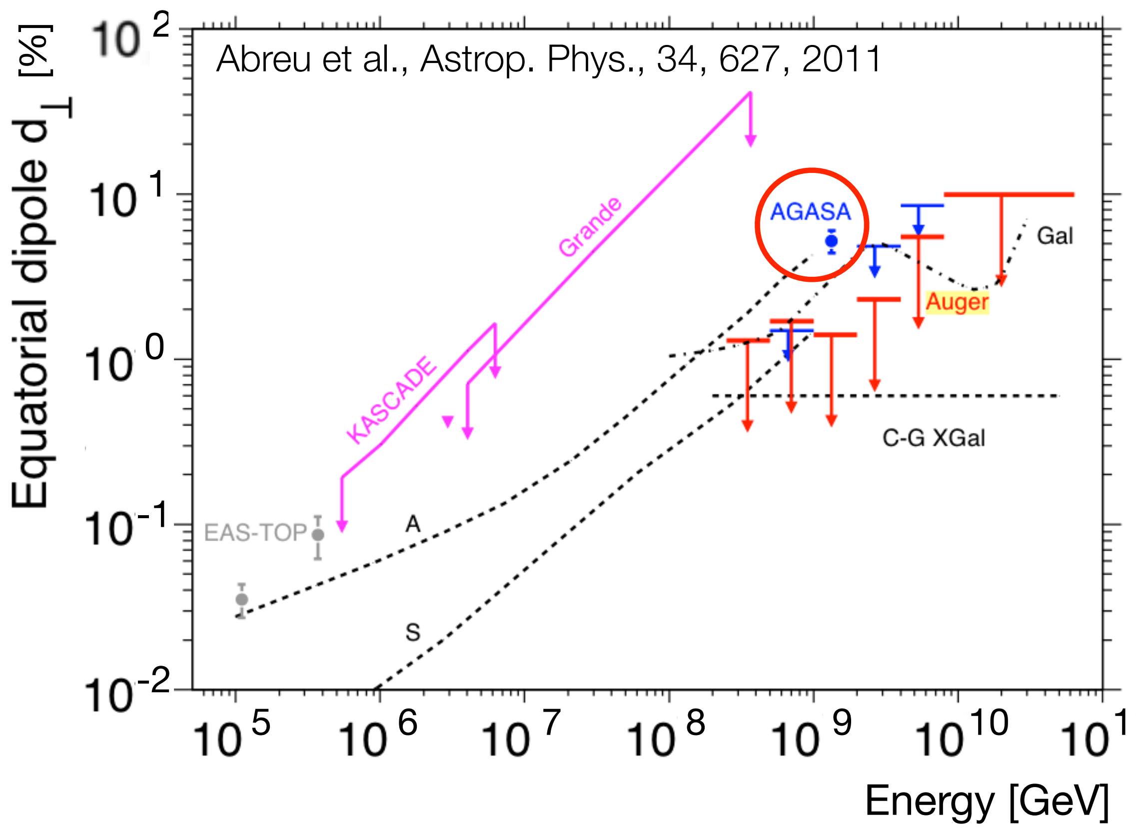
- stochastic effect of **nearby & recent sources** & temporal correlations

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

dipole amplitude **Sveshnikova+, 2013**



not dipole observations



dipole components of the anisotropy

cosmic ray anisotropy
probing sources & propagation of cosmic rays ?

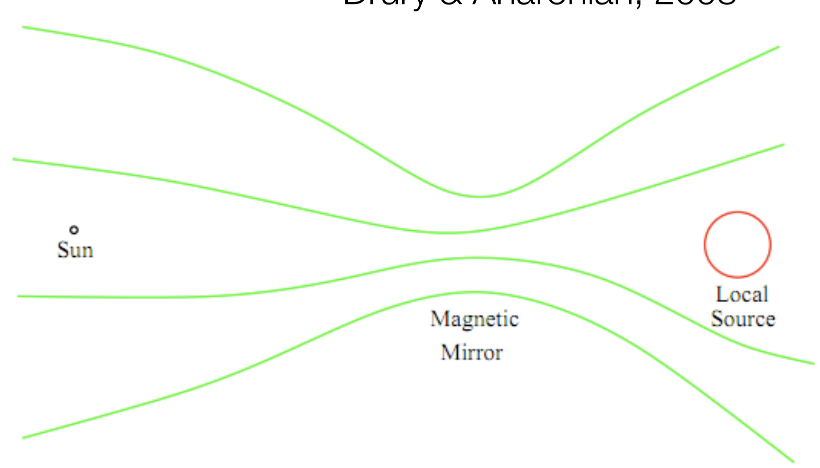
- stochastic effect of **nearby & recent sources** & temporal correlations

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

- propagation effect from a near by source to produce localized excess

Salvati & Sacco, 2008
Drury & Aharonian, 2008
Salvati, 2010
Malkov+, 2010

Drury & Aharonian, 2008



cosmic ray anisotropy
probing sources & propagation of cosmic rays ?

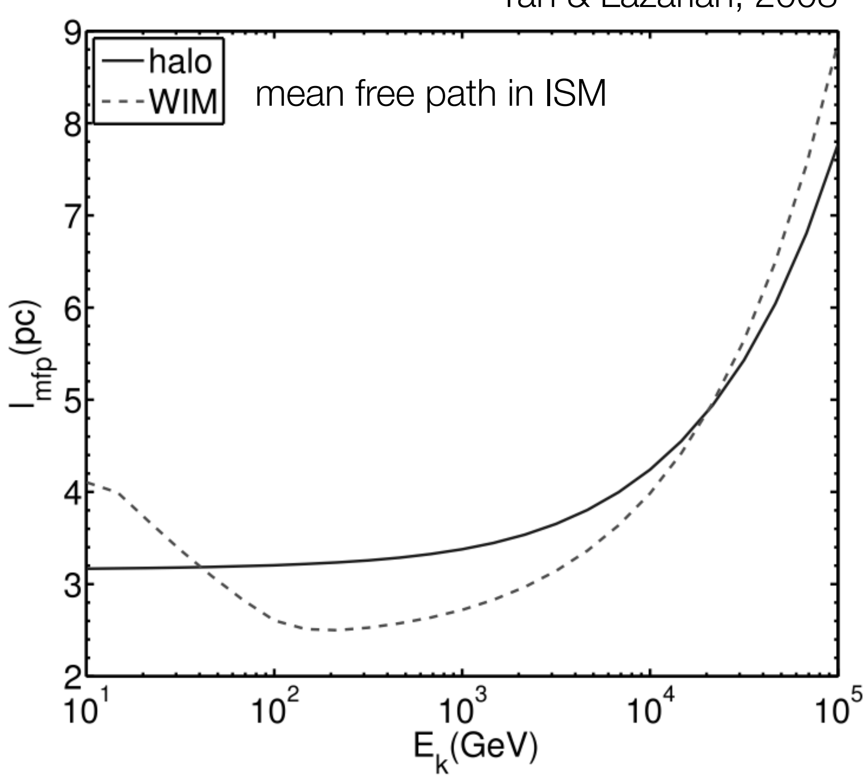
- stochastic effect of **nearby & recent sources** & temporal correlations

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

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

Giacinti & Sigl, 2012
Biermann+, 2012

Yan & Lazarian, 2008



Giacinti & Sigl, 2012

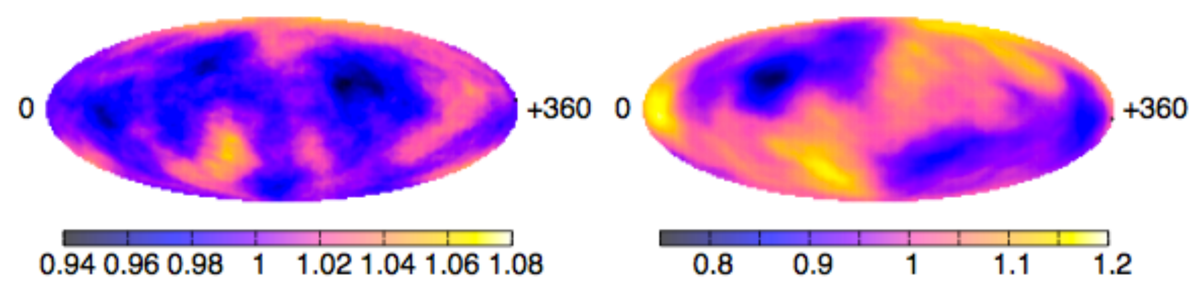
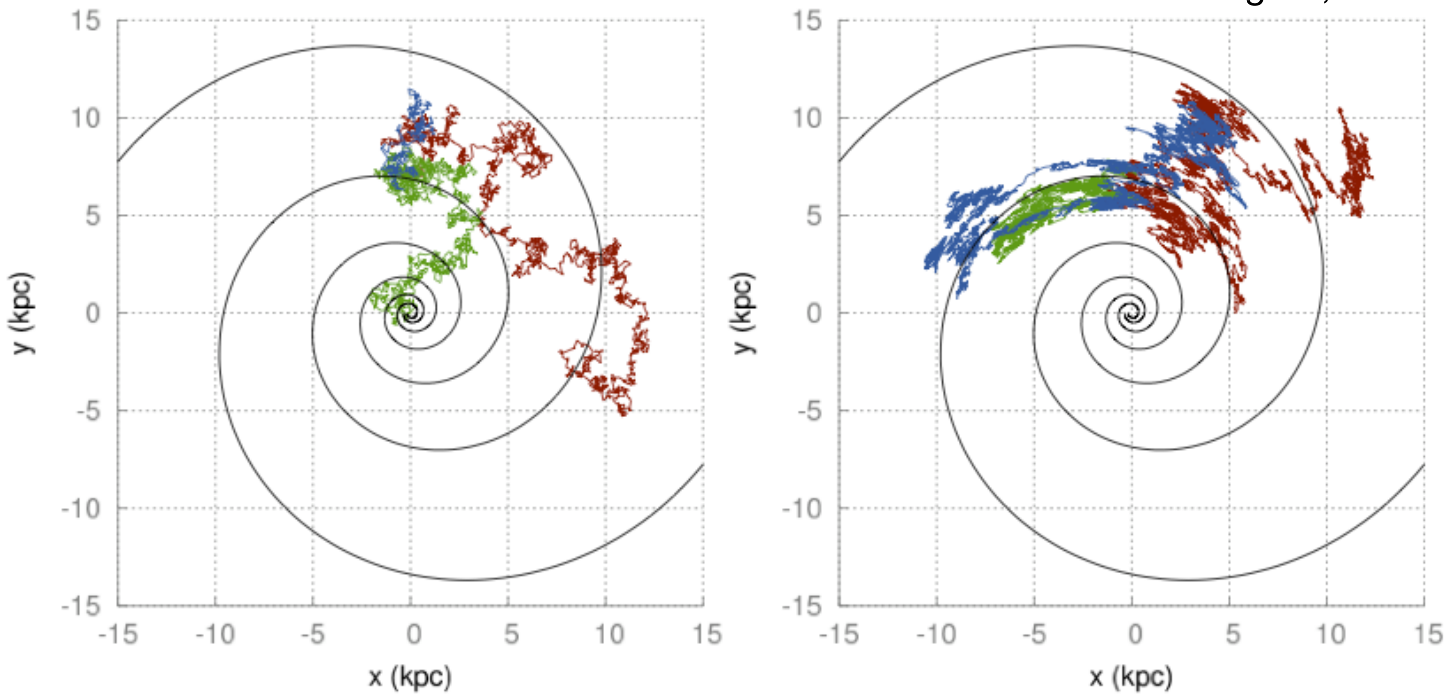


FIG. 1. Renormalized CR flux predicted at Earth for a concrete realization of the turbulent magnetic field, *after subtracting the dipole* and smoothing on 20° radius circles. Primaries with rigidities $p/Z = 10^{16}$ eV (*left panel*) and 5×10^{16} eV (*right panel*). See text for the field parameters and boundary conditions on the sphere of radius $R = 250$ pc.

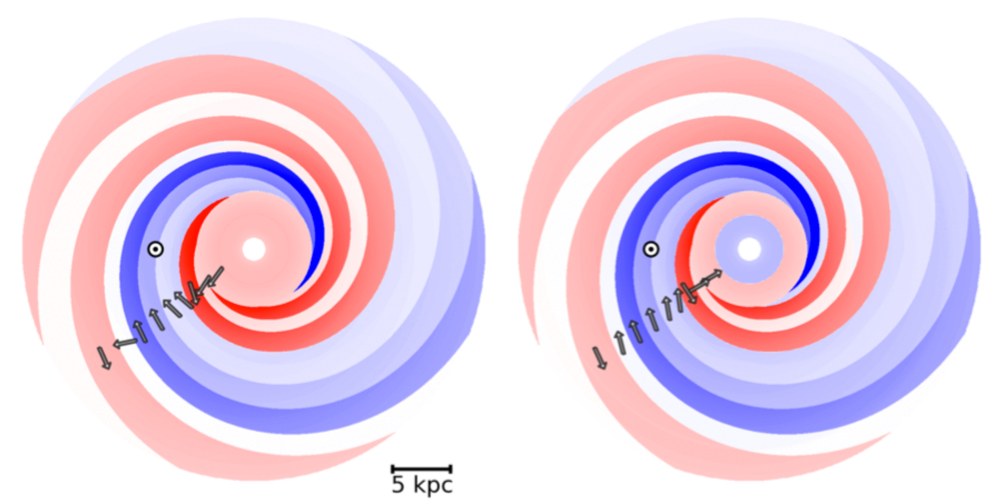
cosmic ray anisotropy
probing sources & propagation of cosmic rays ?

anisotropic diffusion

Effenberger+, 2012



Jansson & Farrar, 2012

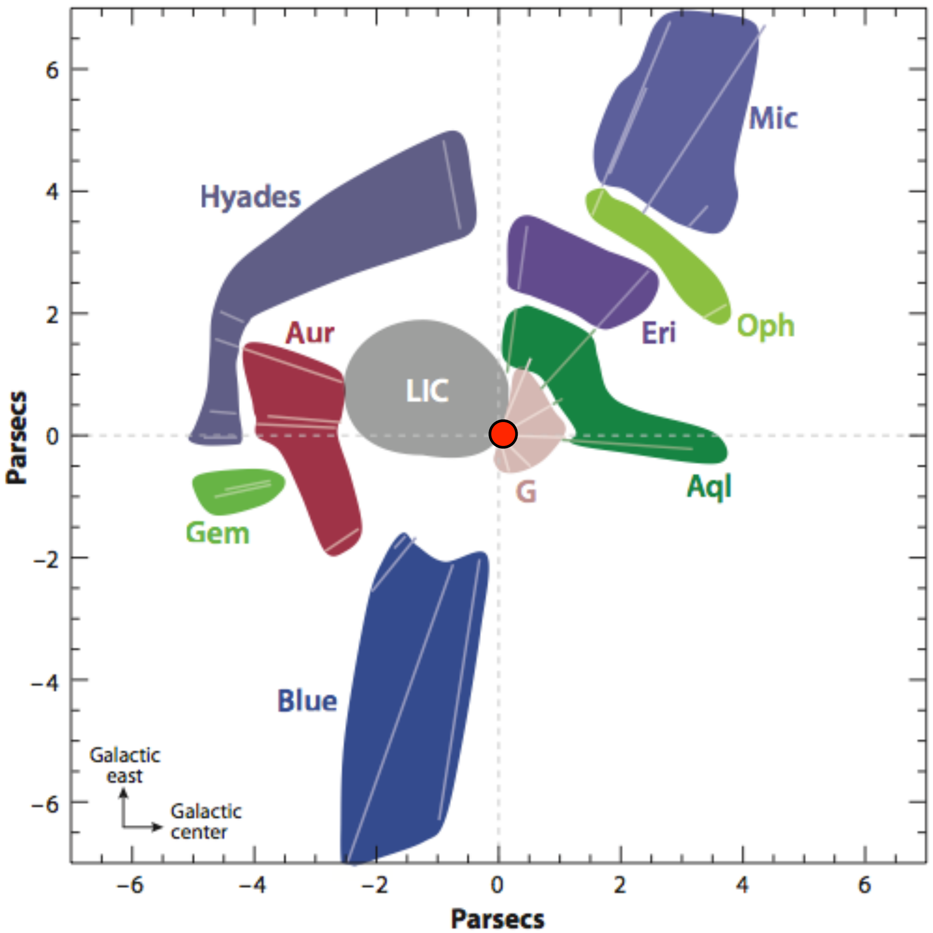


- diffusion coefficient hardly a single power law, homogeneous and isotropic

Effenberger+, 2012

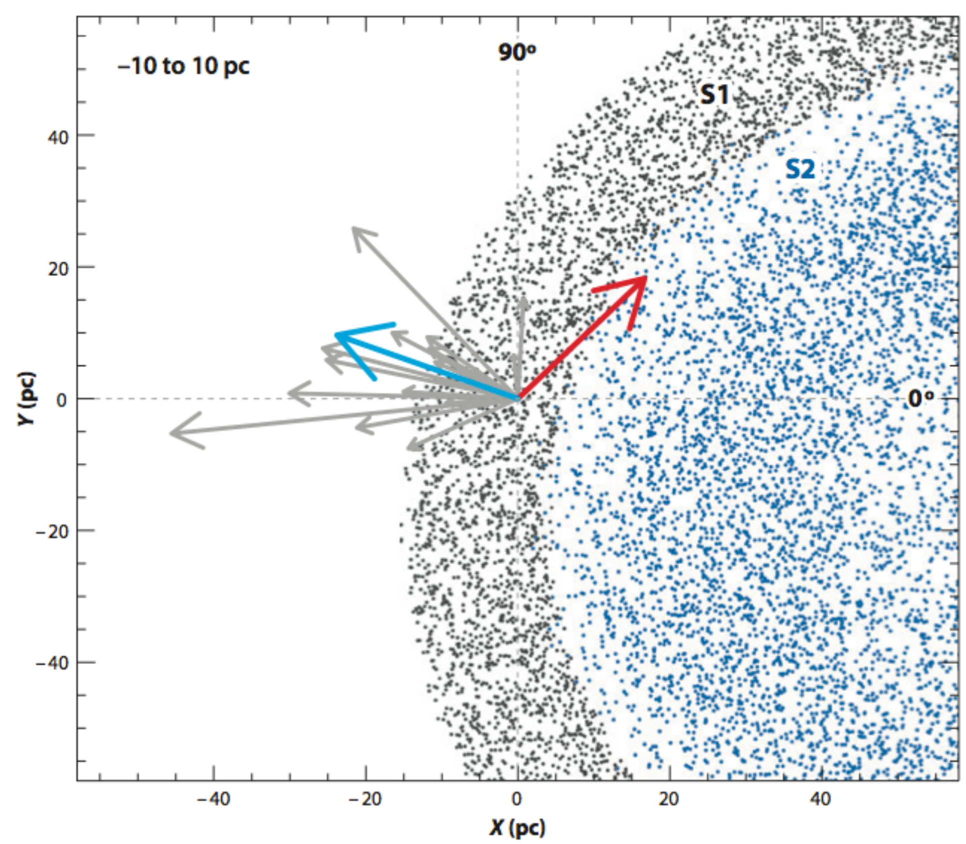
cosmic ray anisotropy

probing sources & propagation of cosmic rays ?



Frisch+, 2011

(Wolleben, 2007)



local ISMF shaped by LOOP I expansion sub-shell (with center ~90 pc away in Scorpius-Centaurus OB Association)

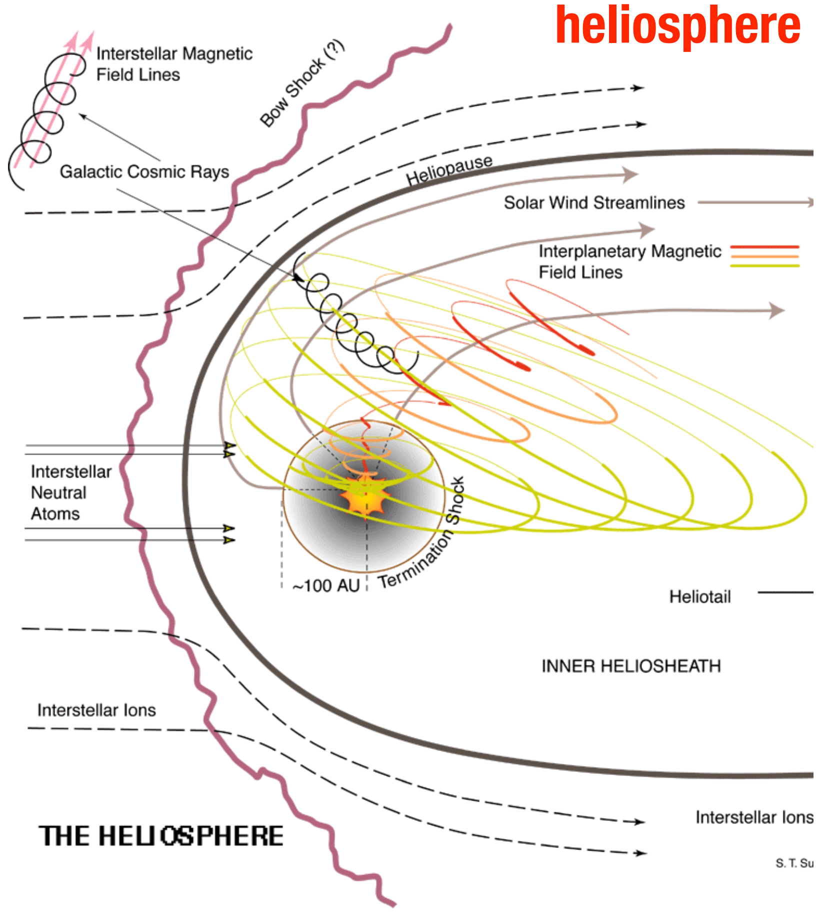
local cloudlets fragments of the shell moving at similar velocities

- interstellar magnetic field affected by inhomogeneities — Redfield & Linsky, 2008; Frisch+, 2011
- local ISMF relatively uniform over spacial scales of order 100-200 pc (**inter-arm**) — Frisch+, 2012

cosmic ray anisotropy

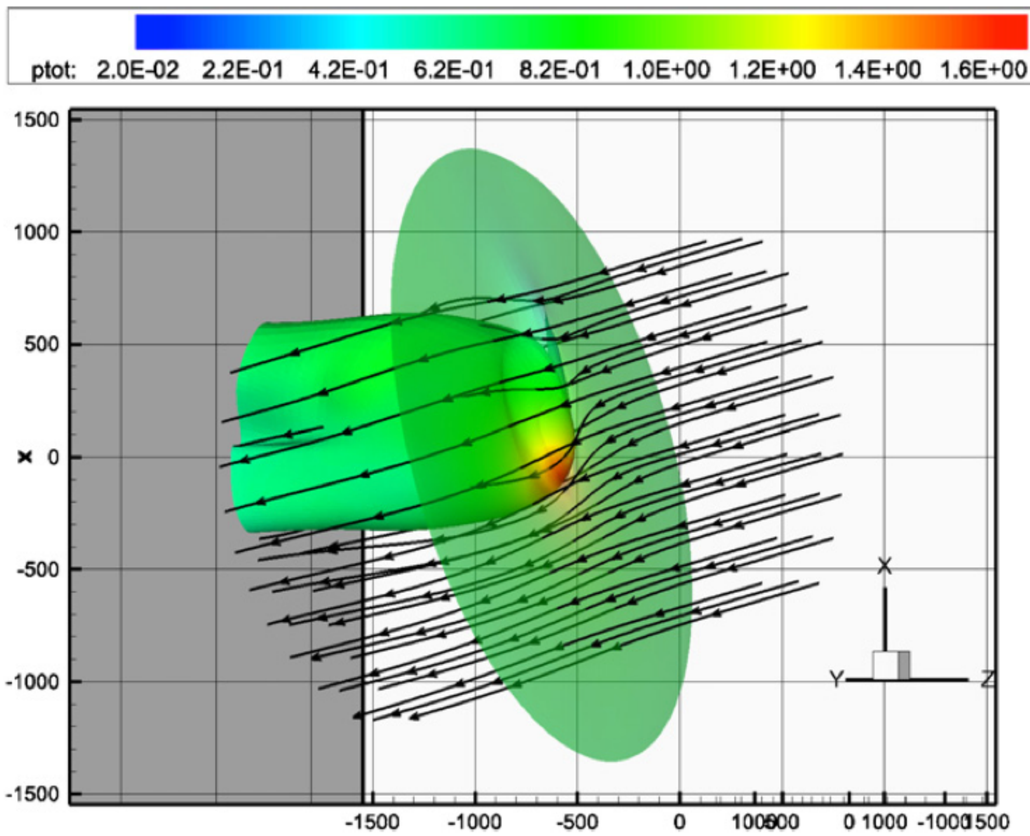
probing sources & propagation of cosmic rays ?

heliosphere



heliotail

Pogorelov+ 2011



local ISMF draping around heliosphere

- heliosphere as O(100-1000) AU **magnetic perturbation of local ISMF**

PD & Lazarian, 2013

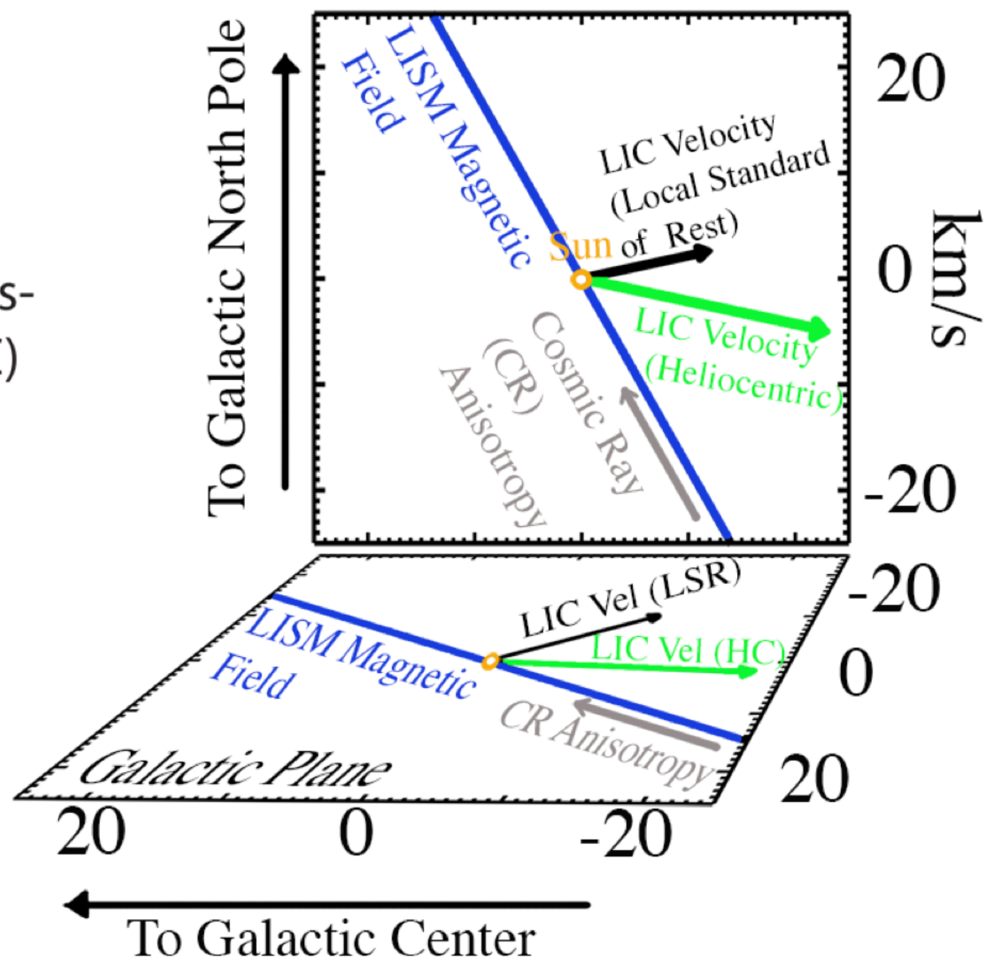
- influence on ≲10 TeV protons (R_L ≲ 600 AU)
- cosmic rays >100 TeV ifluenced by interstellar magnetic field

cosmic ray anisotropy

probing heliospheric magnetic structure

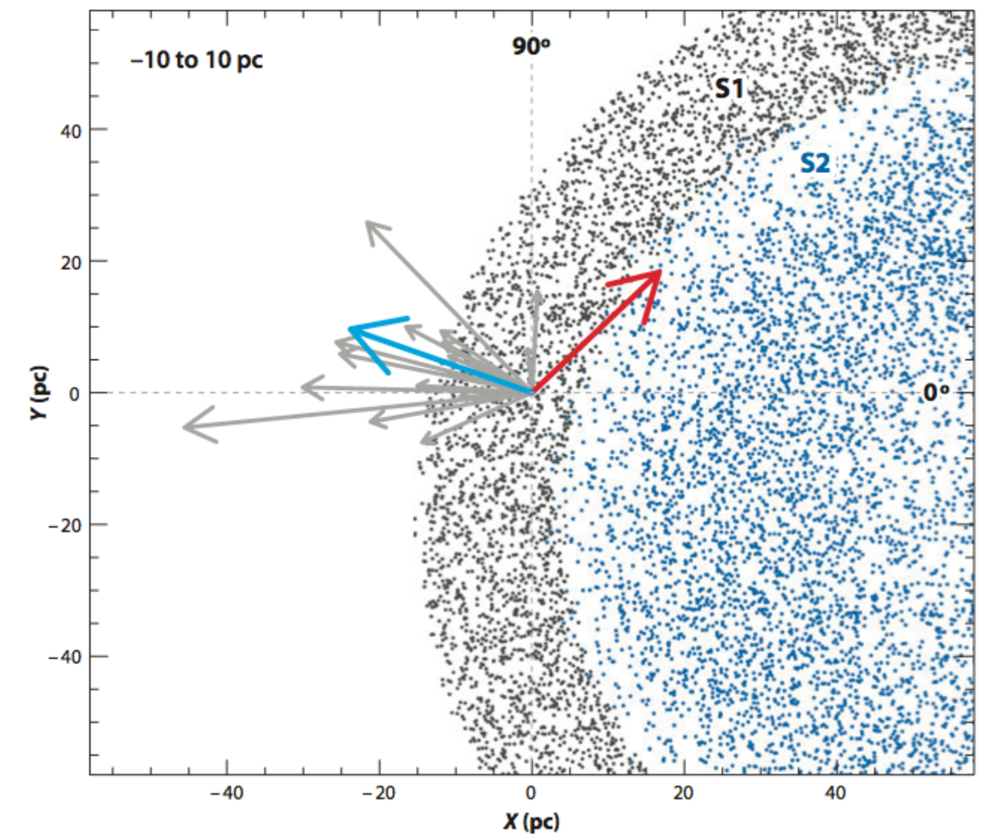
Schwadron et al., Science 2014

Lower Centaurus-Crux (LCC)



Frisch+, 2011

(Wolleben, 2007)

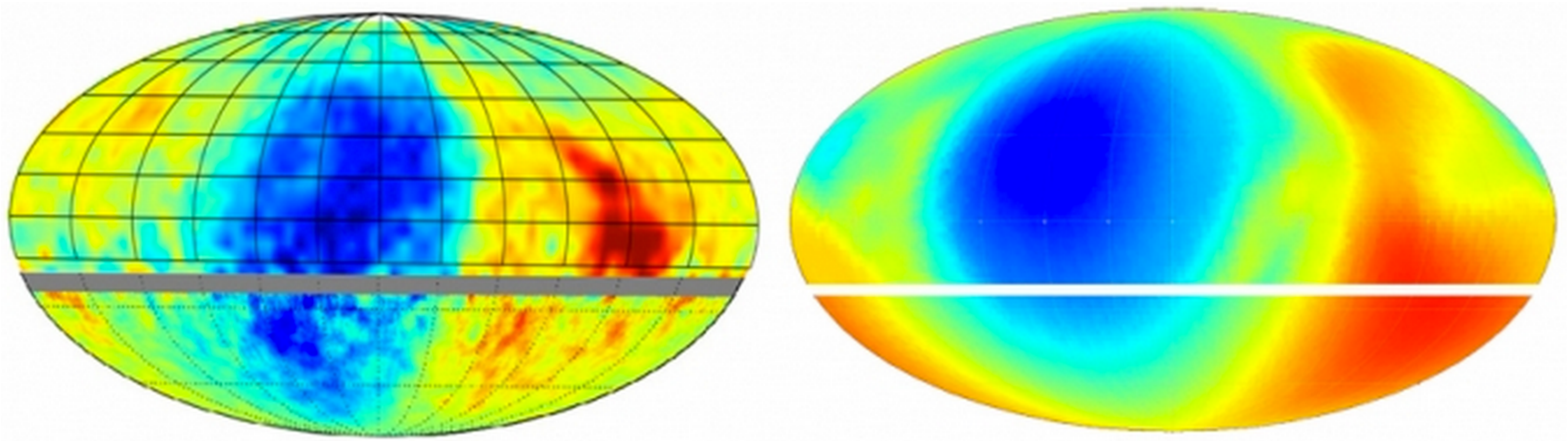


Local Interstellar Magnetic Field & Interstellar Flow Velocity

from IBEX observations

cosmic ray anisotropy
probing heliospheric magnetic structure

Schwadron et al., Science 2014



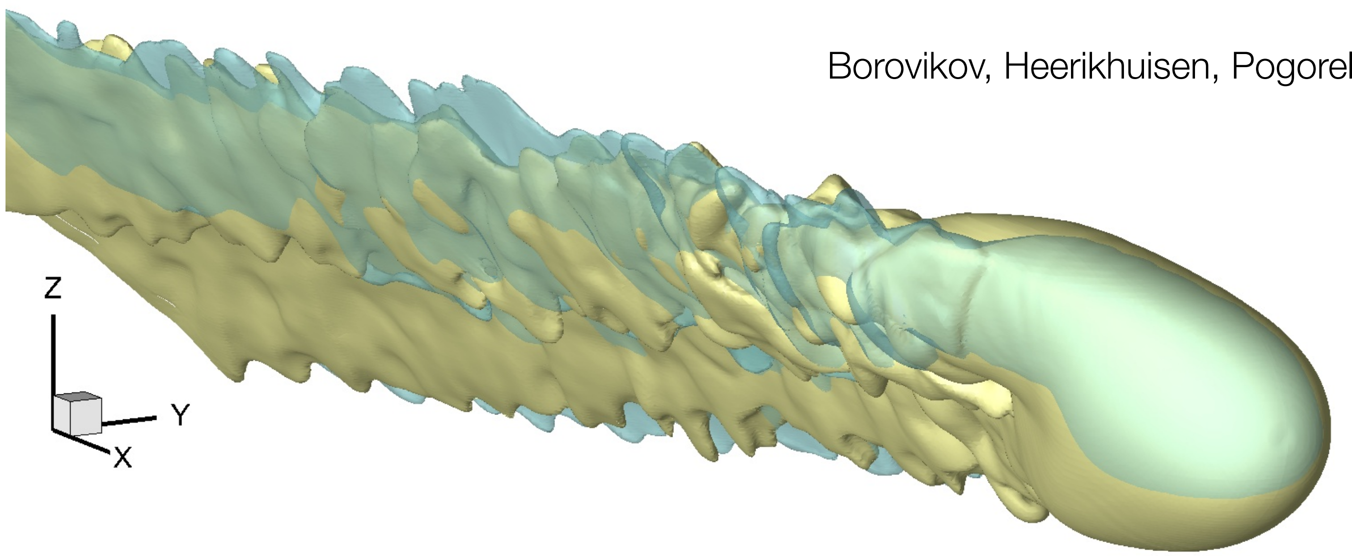
On the left, a map of cosmic ray arrival data gathered by IceCube and Tibet AS-gamma. On the right, an IBEX prediction of cosmic ray data. Red signifies a concentration of cosmic rays, and blue a deficit. Credit: NASA/IBEX/UNH

heliospheric magnetic field produces a perturbation

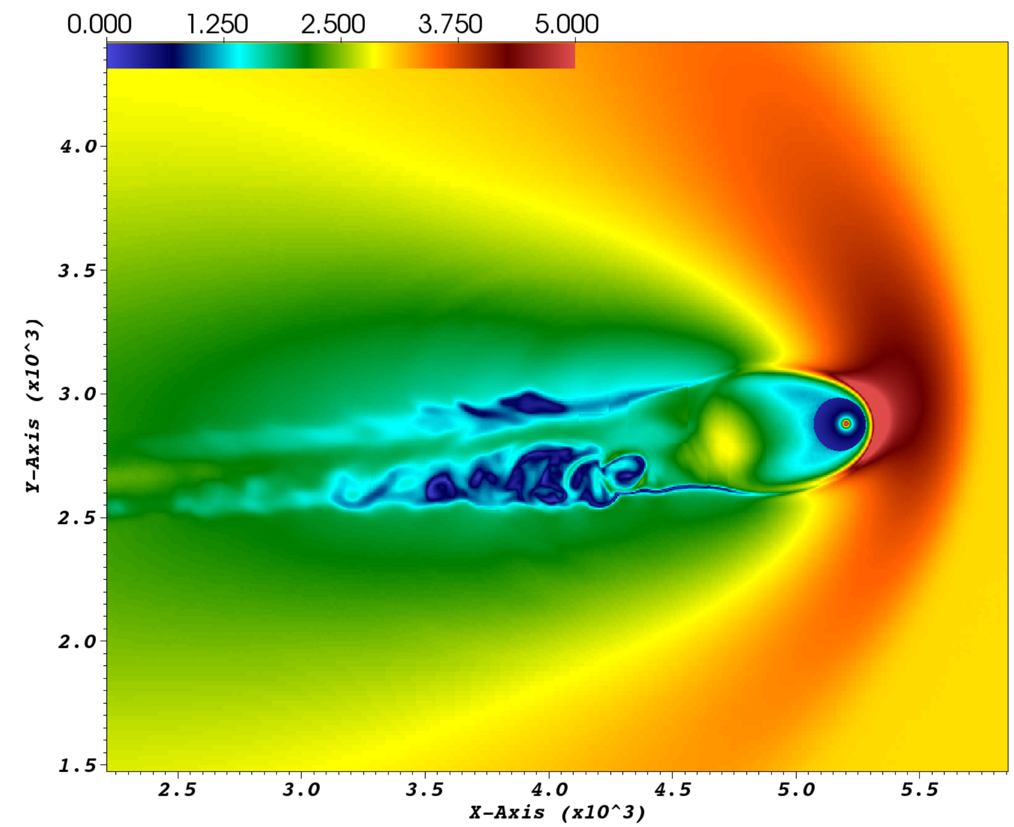
in the arrival direction of cosmic rays

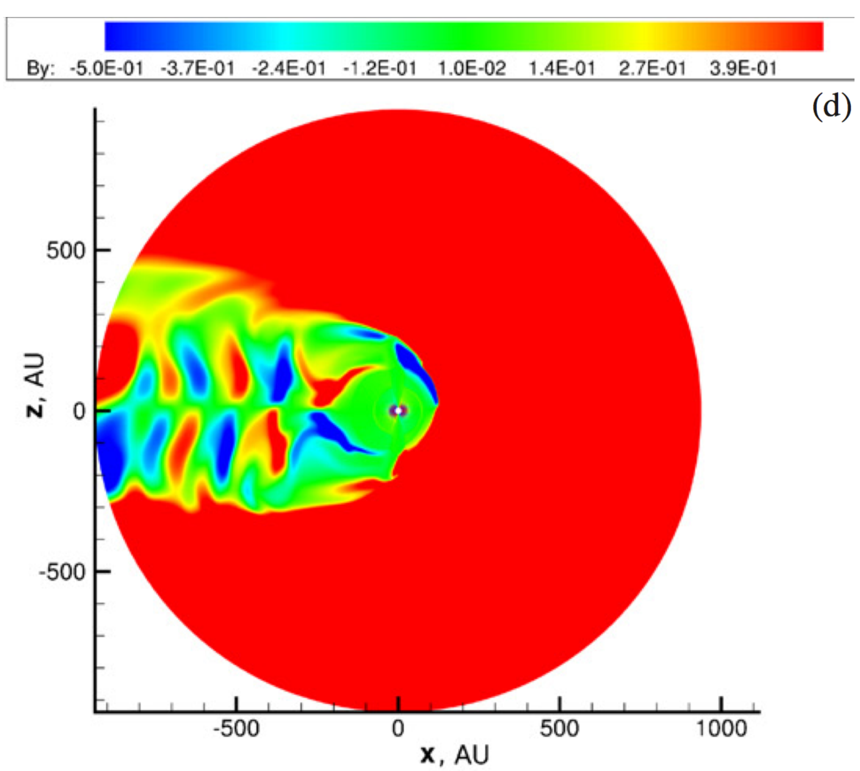
cosmic ray anisotropy
probing heliospheric magnetic structure

Borovikov, Heerikhuisen, Pogorelov



downstream instabilities on the flanks of heliotail





Pogorelov et al., 2009

effects of magnetic polarity reversals from solar cycles