Cosmic ray spectrum, composition and arrival direction distribution & PeV γ rays at the South Pole

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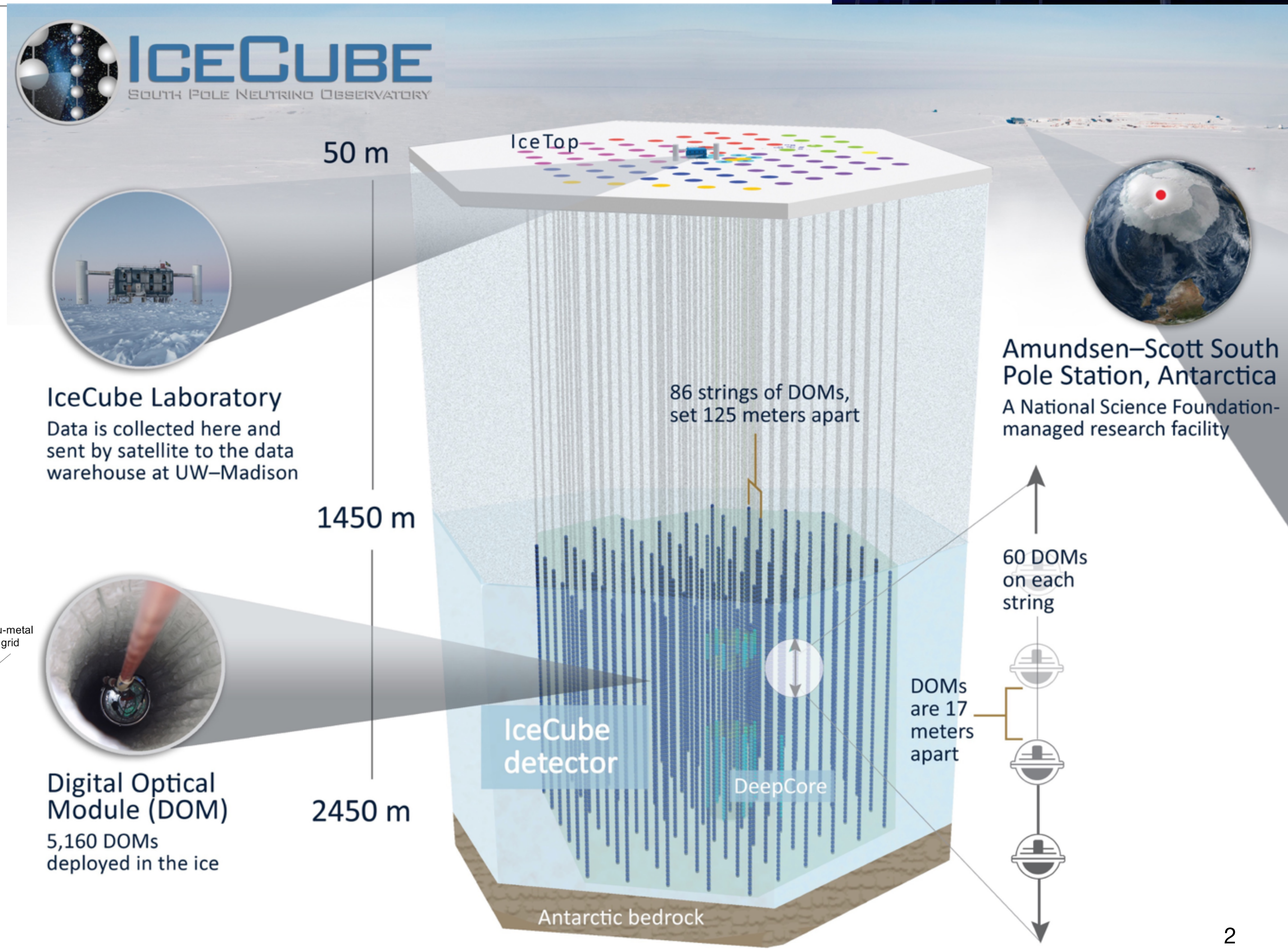
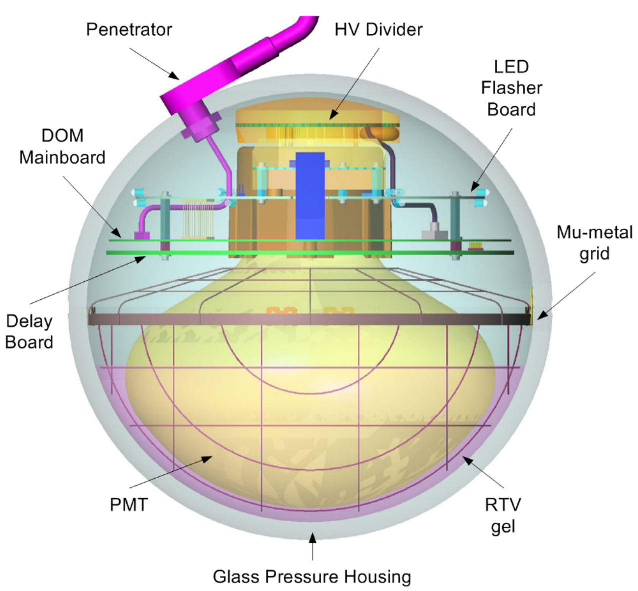
Towards a Large Field-of-View TeV Experiment in the South
Università di Roma Tor Vergata - January 14-15, 2016

IceCube Observatory
the instrumentation



Digital Optical Module (DOM)

with 10” PMT
&
local DAQ electronics



IceCube Observatory
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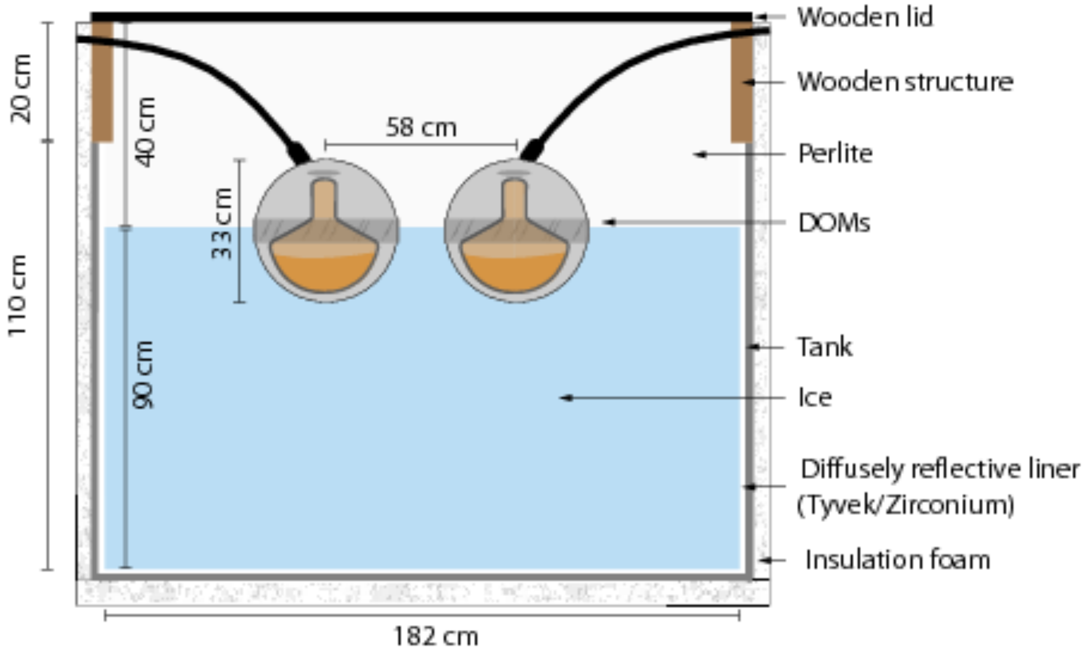
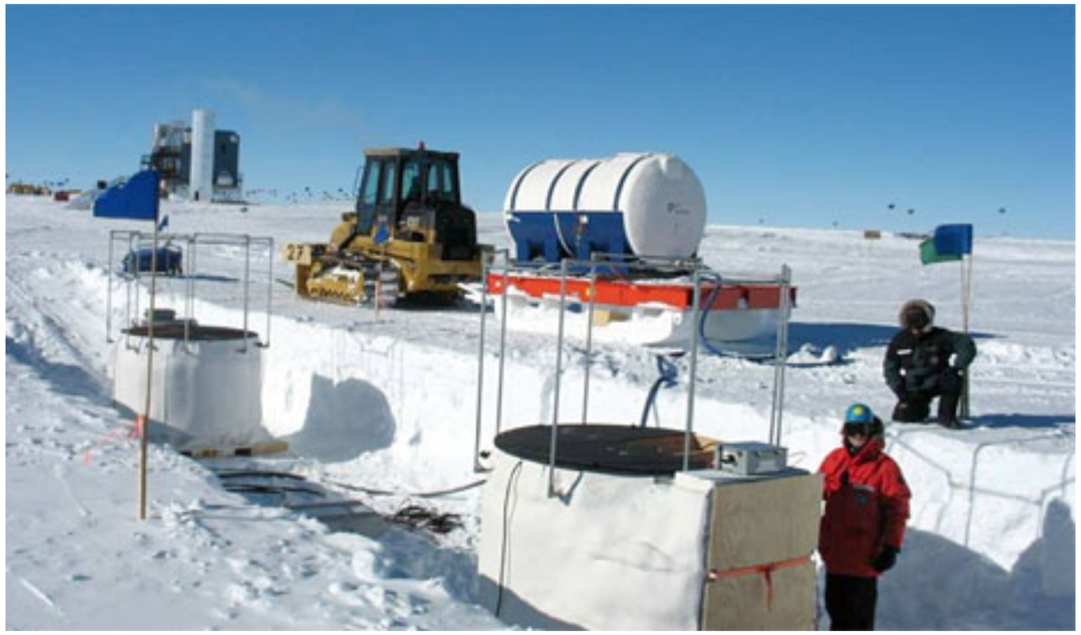
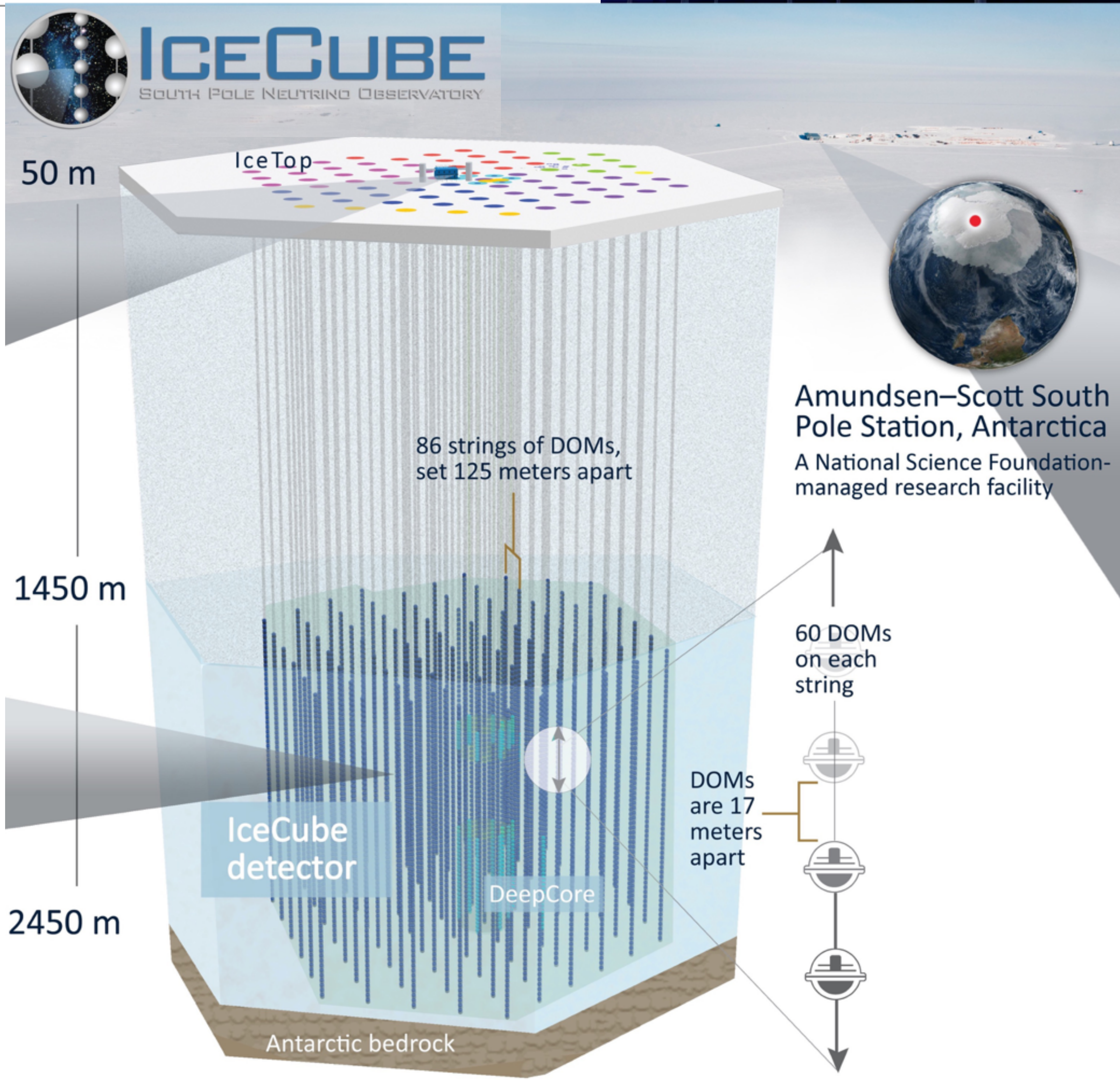


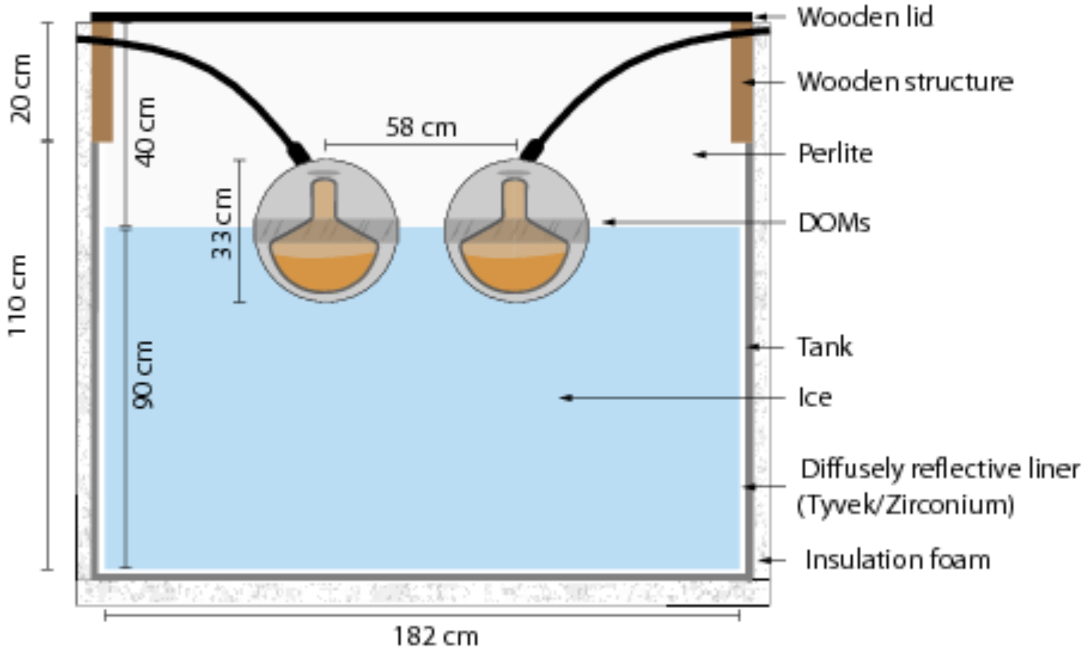
two tanks of one IceTop station





IceCube Observatory
the instrumentation

KM^3 OBSERVATORY



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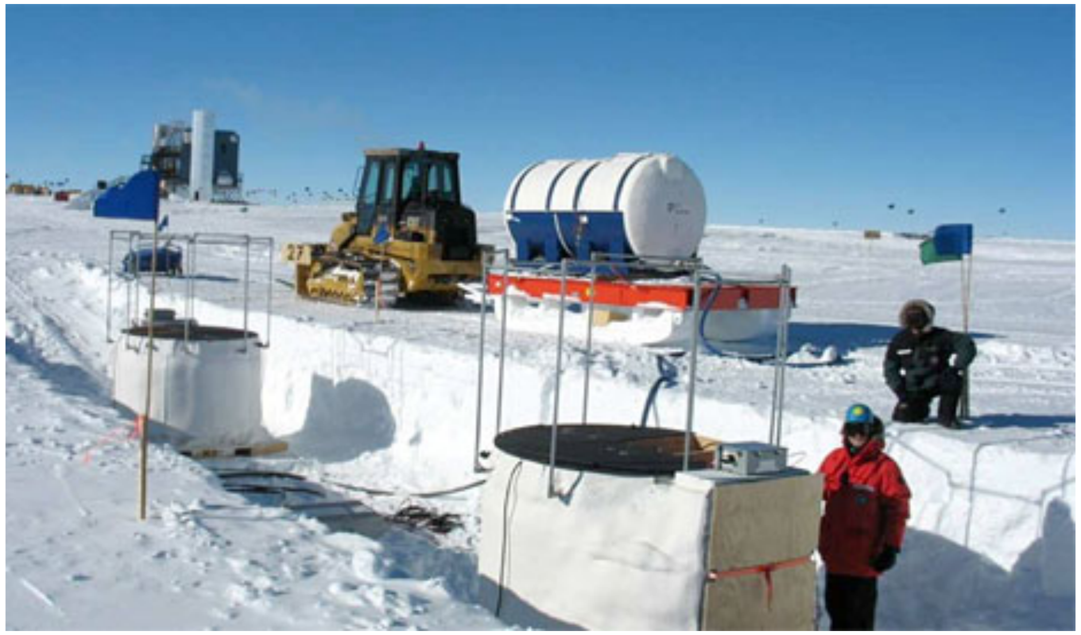
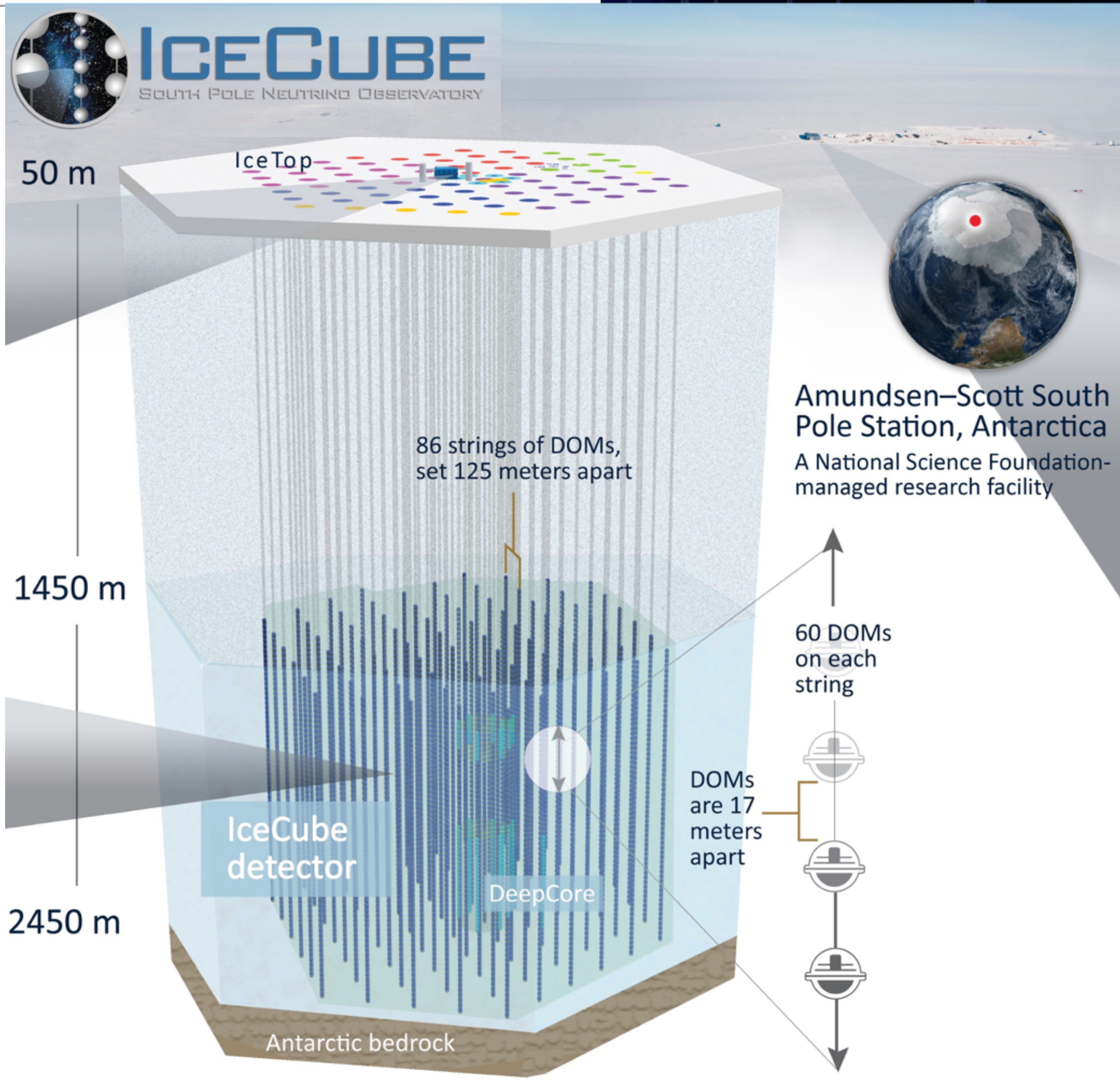
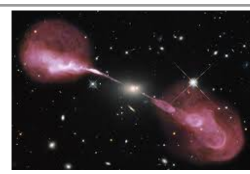




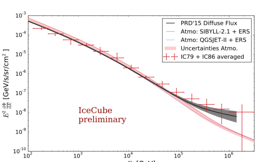
IceCube Observatory
main physics goals

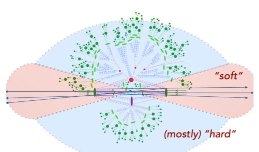

supernova remnants


gamma ray bursts

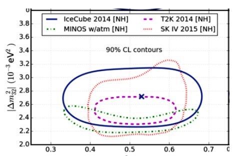

active galactic nuclei

- **astrophysical neutrinos** from the sources of cosmic rays

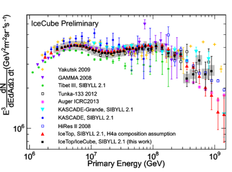

energy spectrum

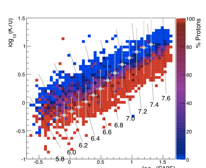


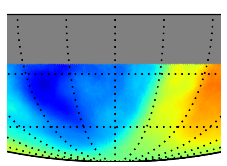
hadronic models


neutrino oscillations

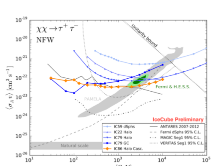
- **atmospheric neutrinos:** charm production, oscillations

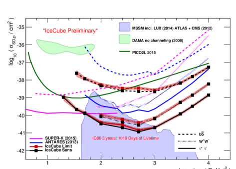

spectrum

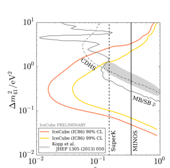

composition


anisotropy

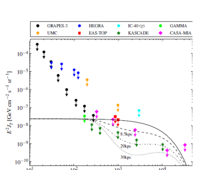
- **cosmic rays:** spectrum, composition & anisotropy

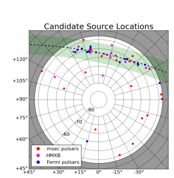

halo WIMPS


solar WIMPS spin dependent

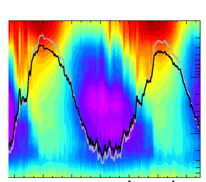

sterile neutrinos

- **beyond standard model & dark matter**


PeV gamma rays



neutron point sources


stratospheric temperature seasonal variations

- **PeV γ-rays, neutron point sources** *& Earth sciences*

IceCube Observatory

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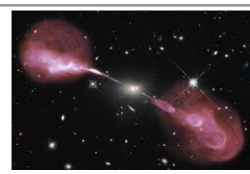
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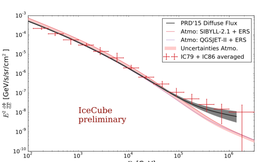
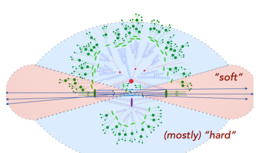

energy spectrum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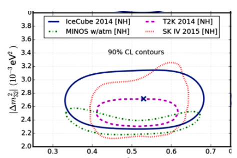
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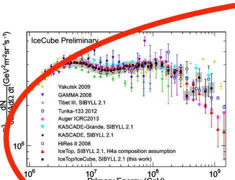
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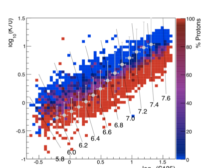
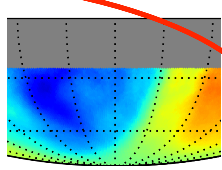

composition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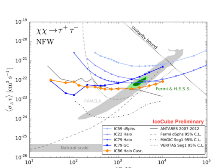
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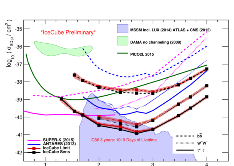
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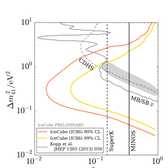
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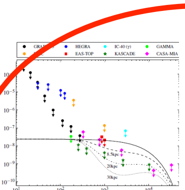
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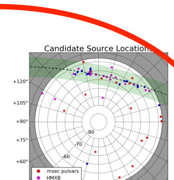
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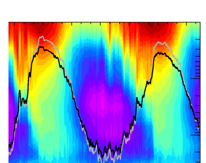

stratospheric temperature seasonal variations

- **PeV γ-rays, neutron point sources** *& Earth sciences*

neutrino identification

astrophysical neutrinos

- 53(+1) events found
- estimated background

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

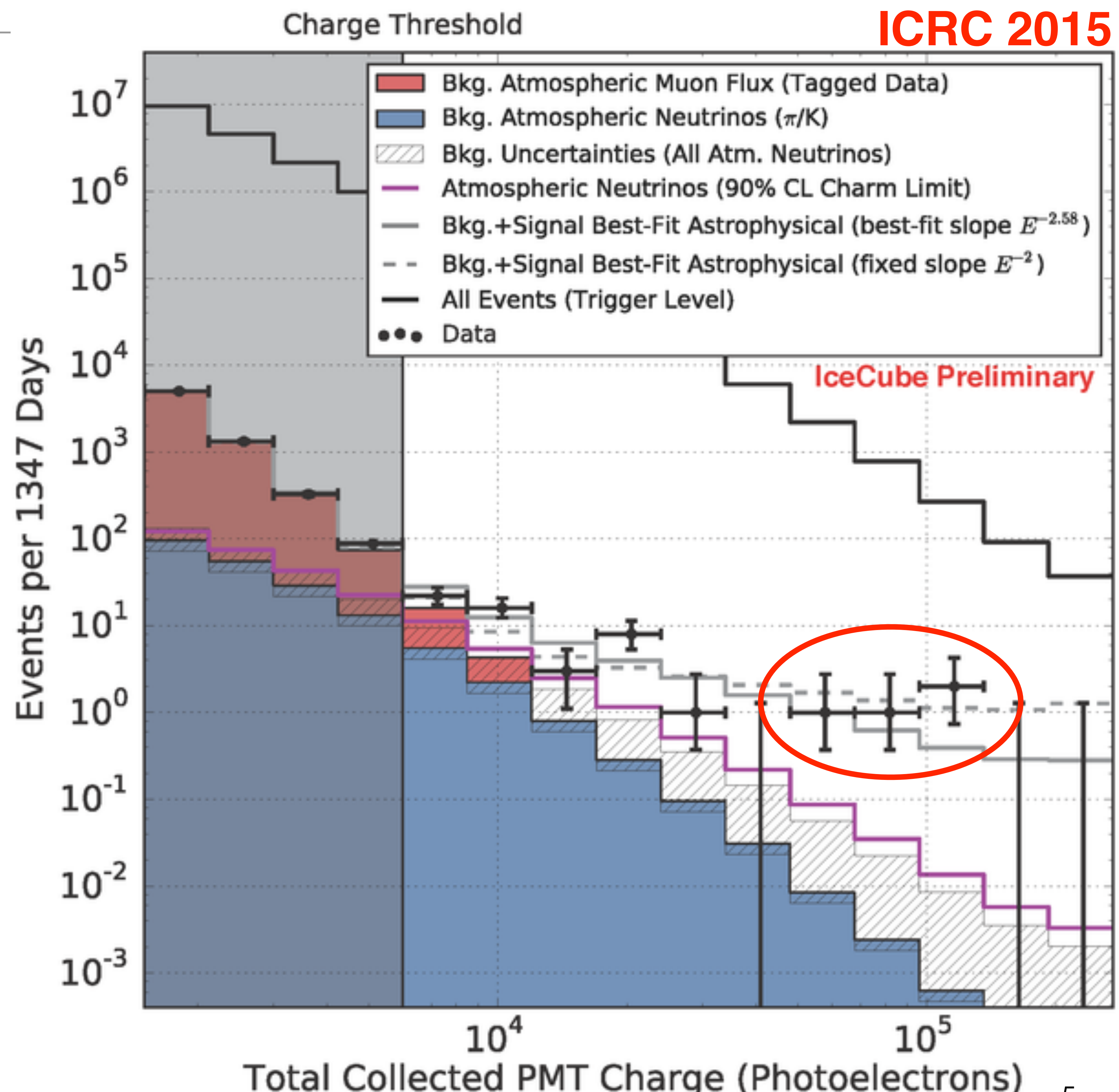
  12.6±5.1 atm. muons

  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

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ICRC 2015

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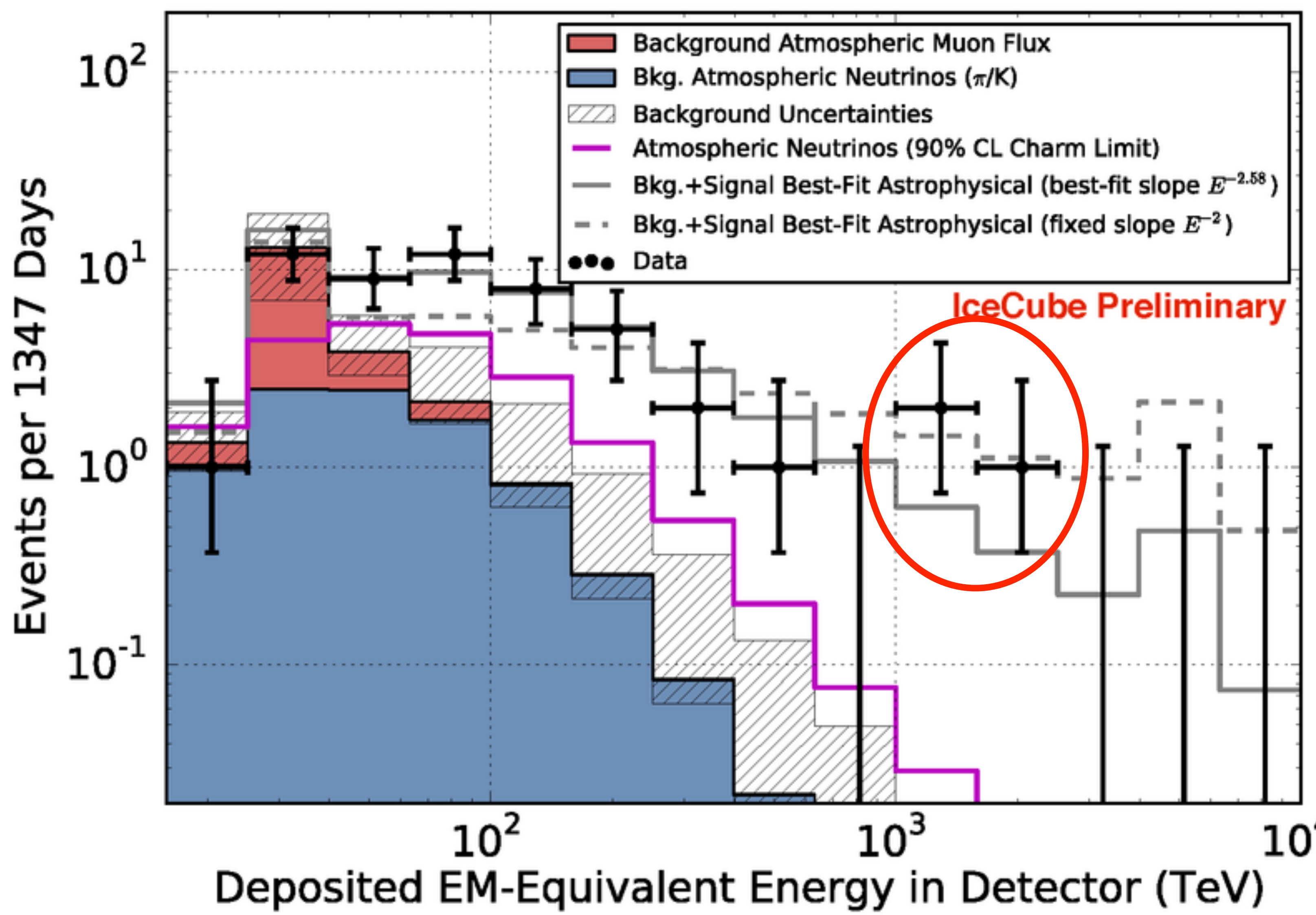

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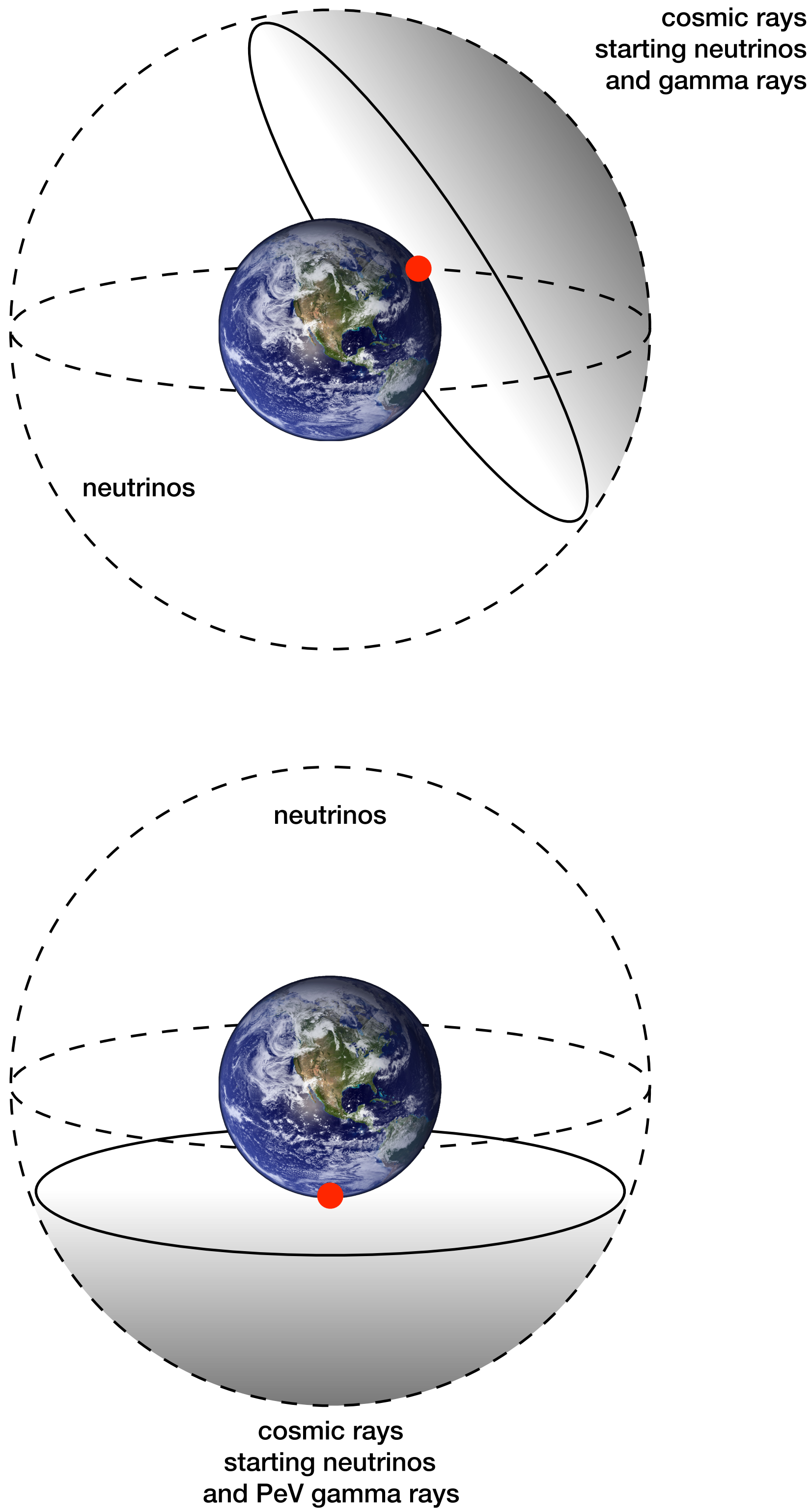
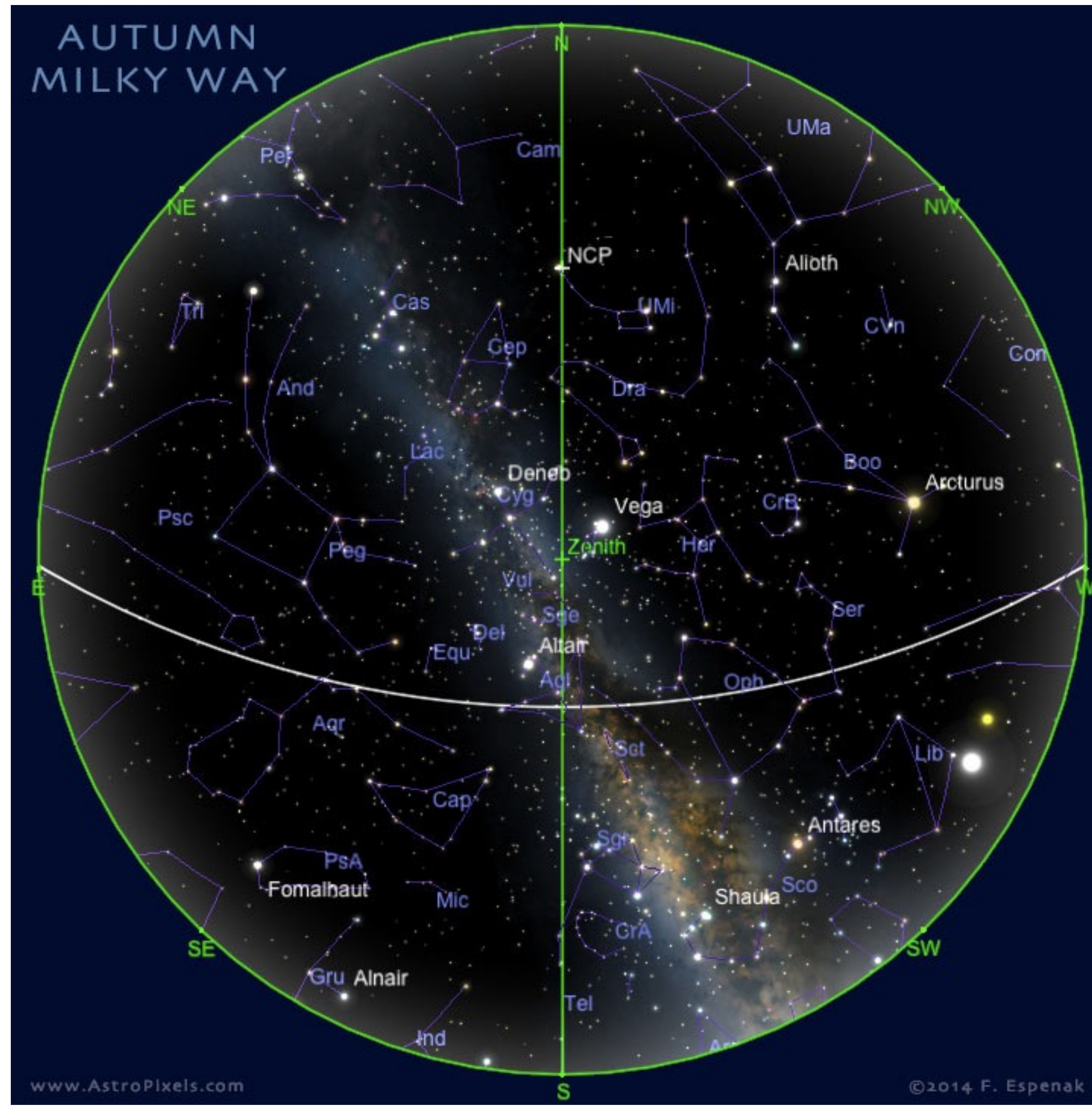
full sky observations
multi-experiment approach

North

IceCube





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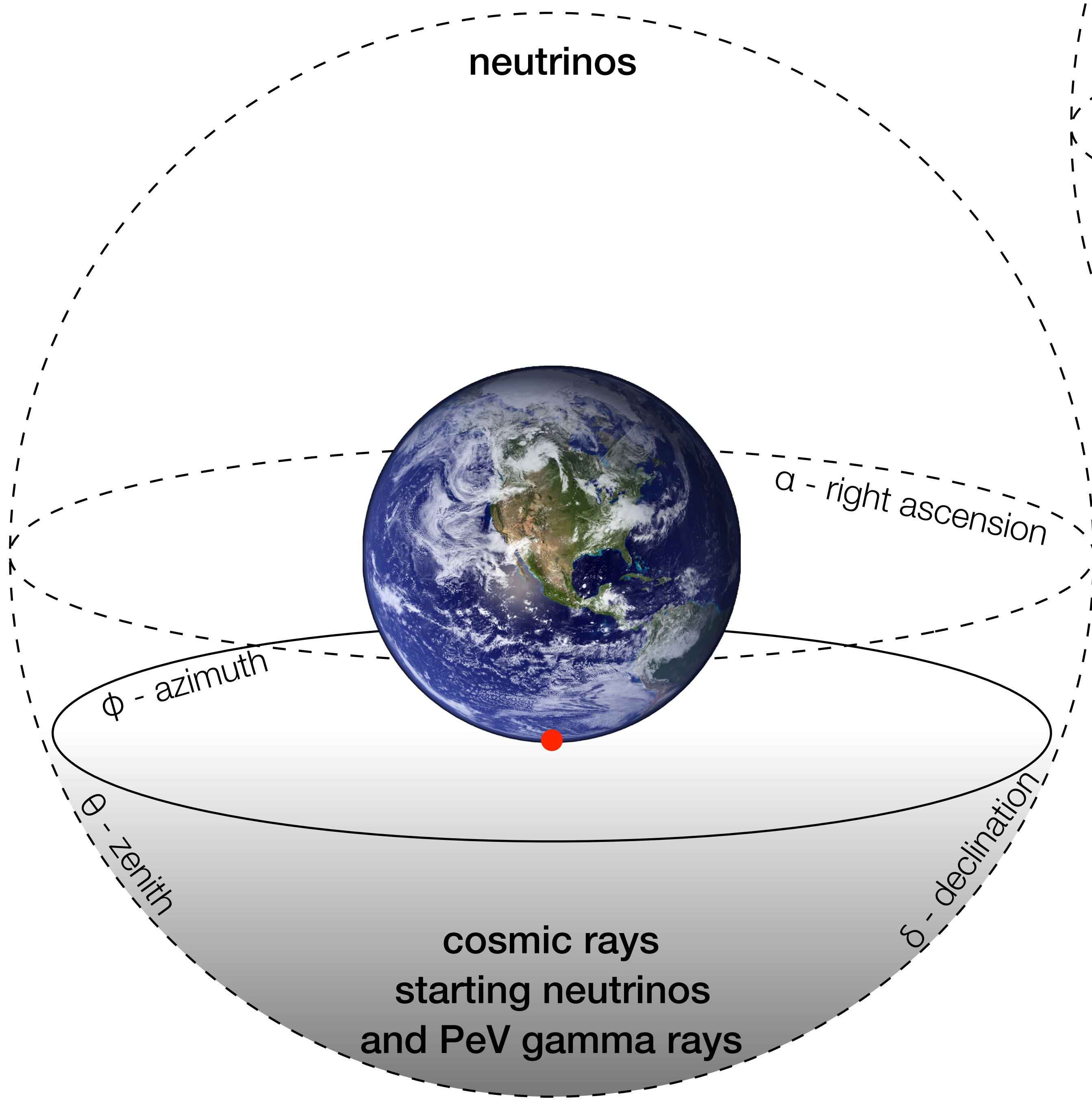
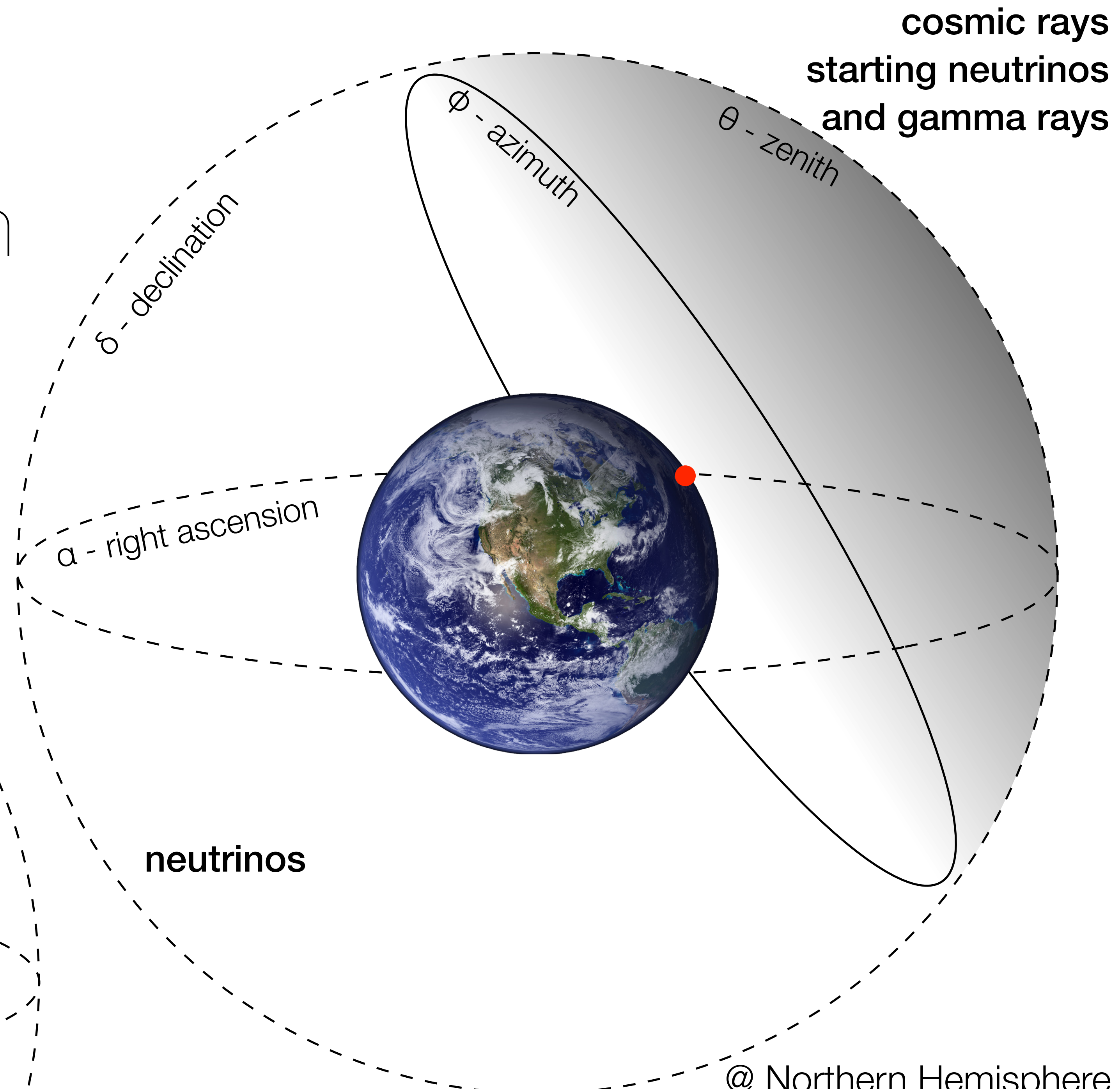


@ South Pole

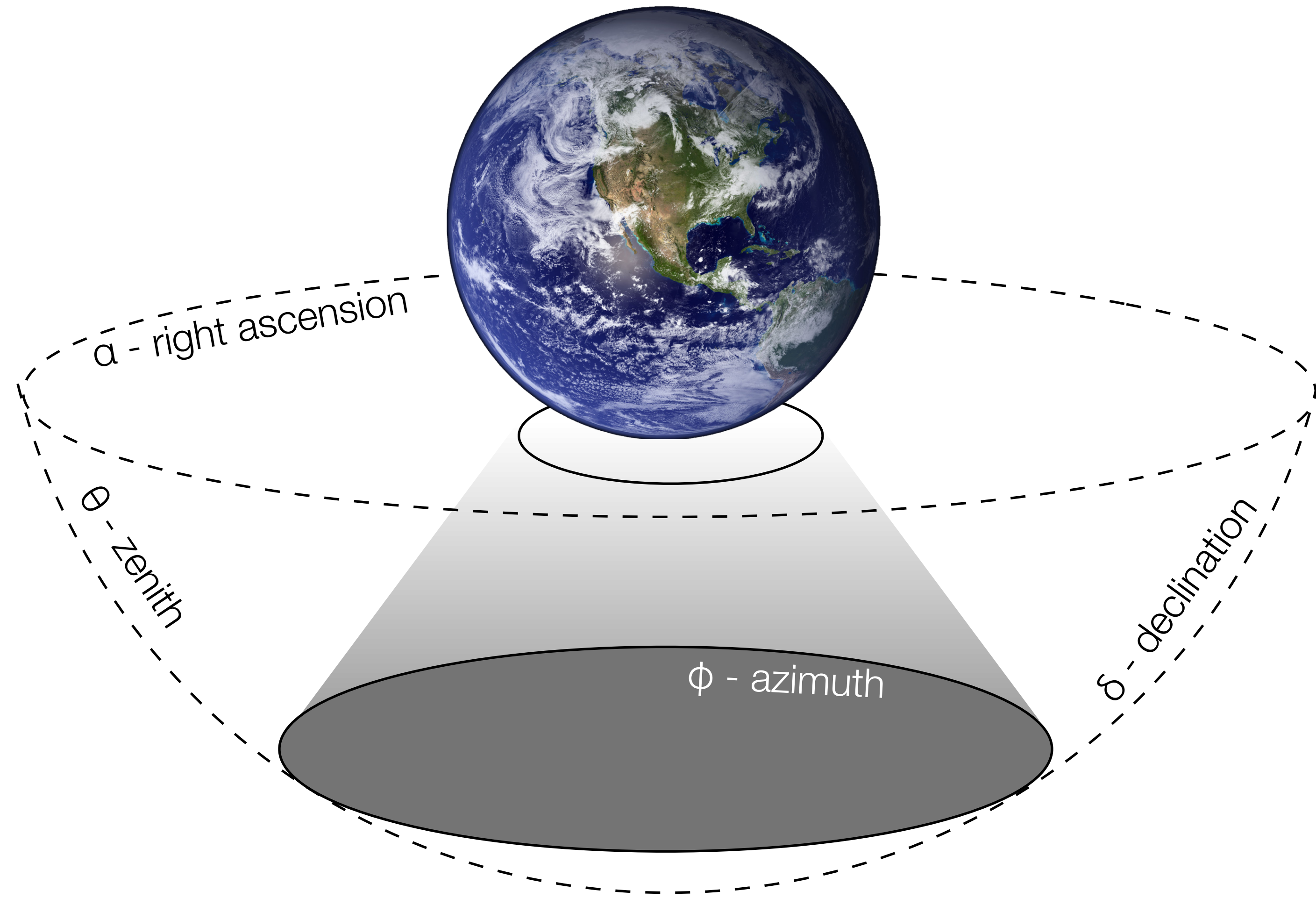


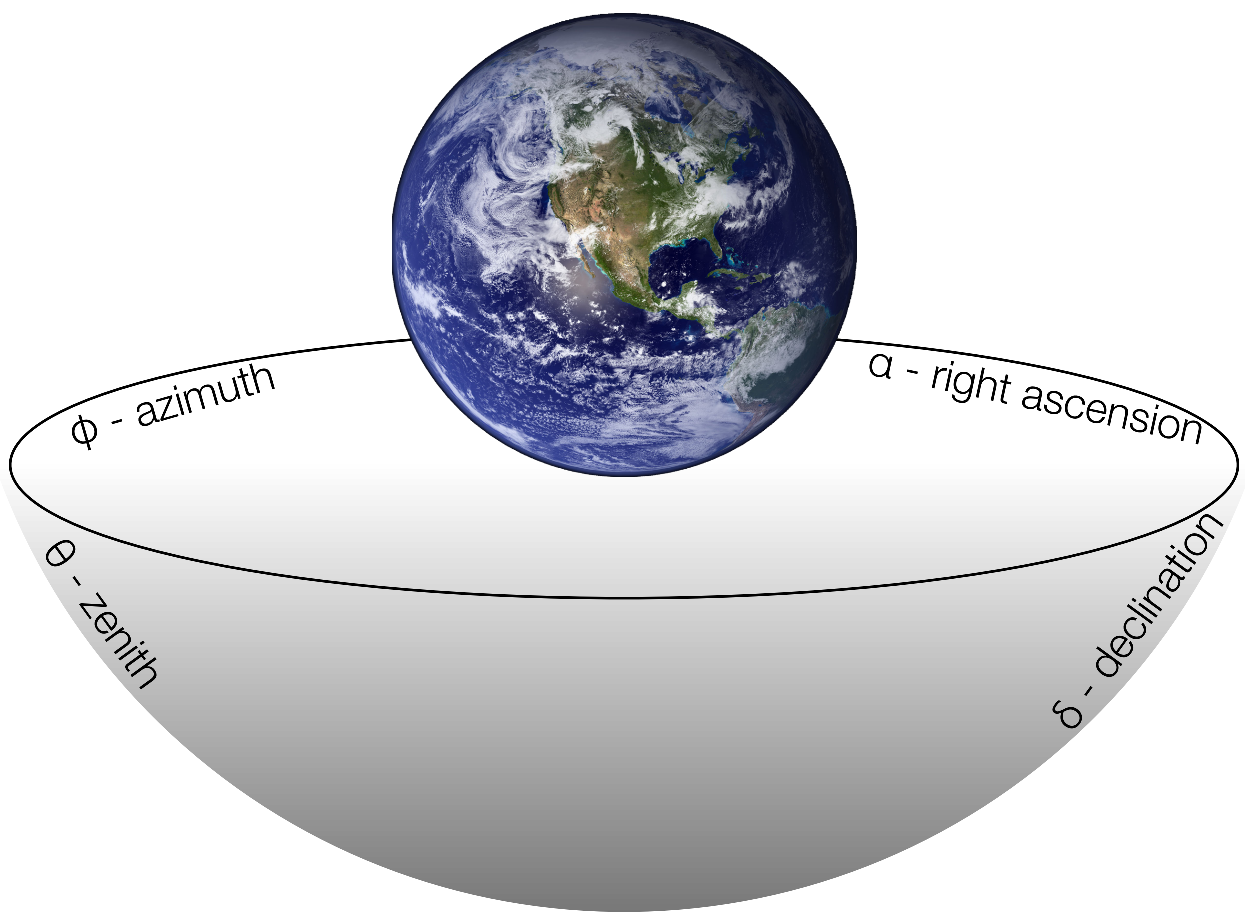
@ Northern Hemisphere

- complementary and overlapping regions of the sky
- IceCube/Antares (arXiv:1511.02149)
- Auger/TA (arXiv:1409.3128)

cosmic and γ rays observations

- @Pole same sky visible at all times
- effectively largest statistics < 60°-70°

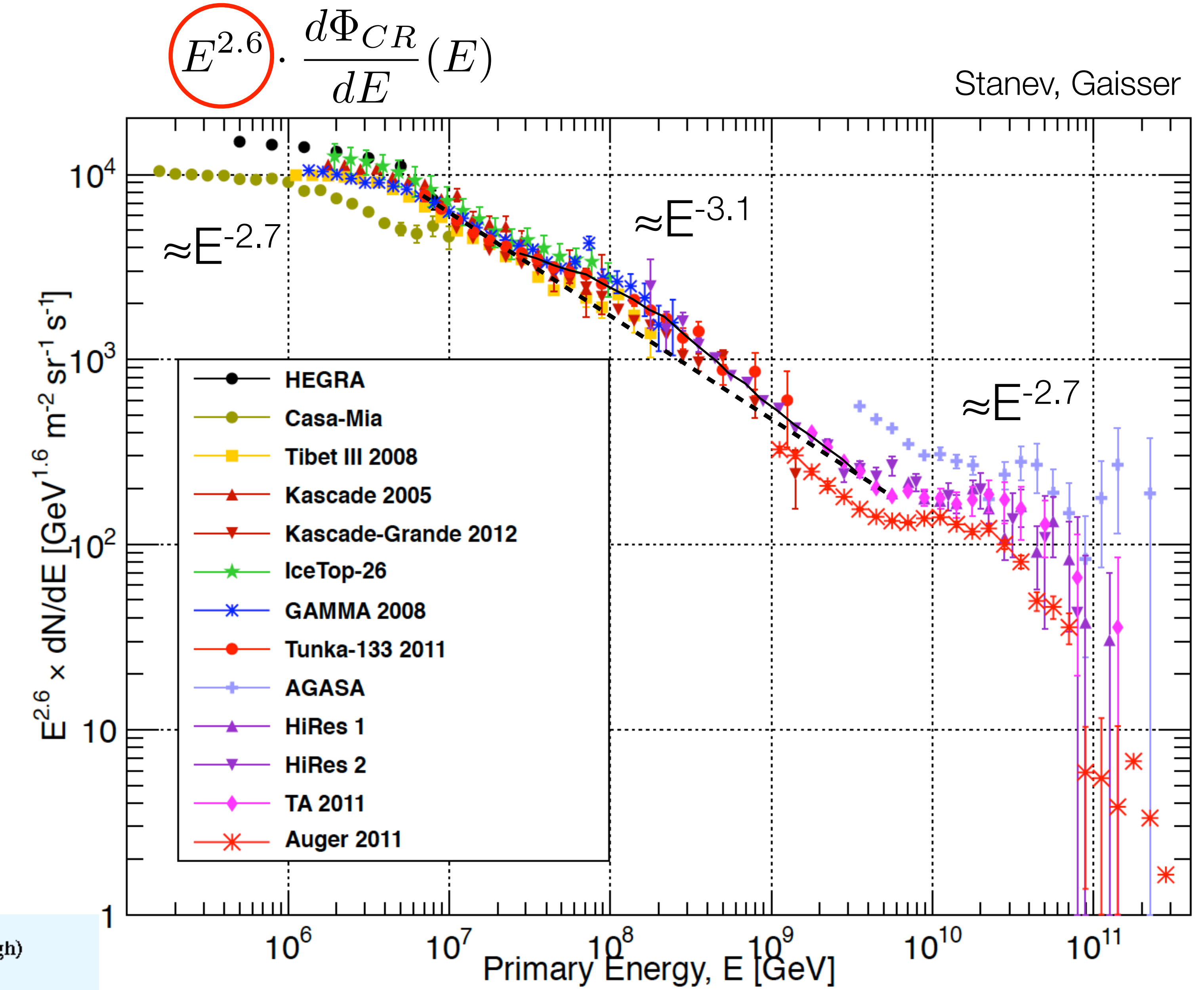


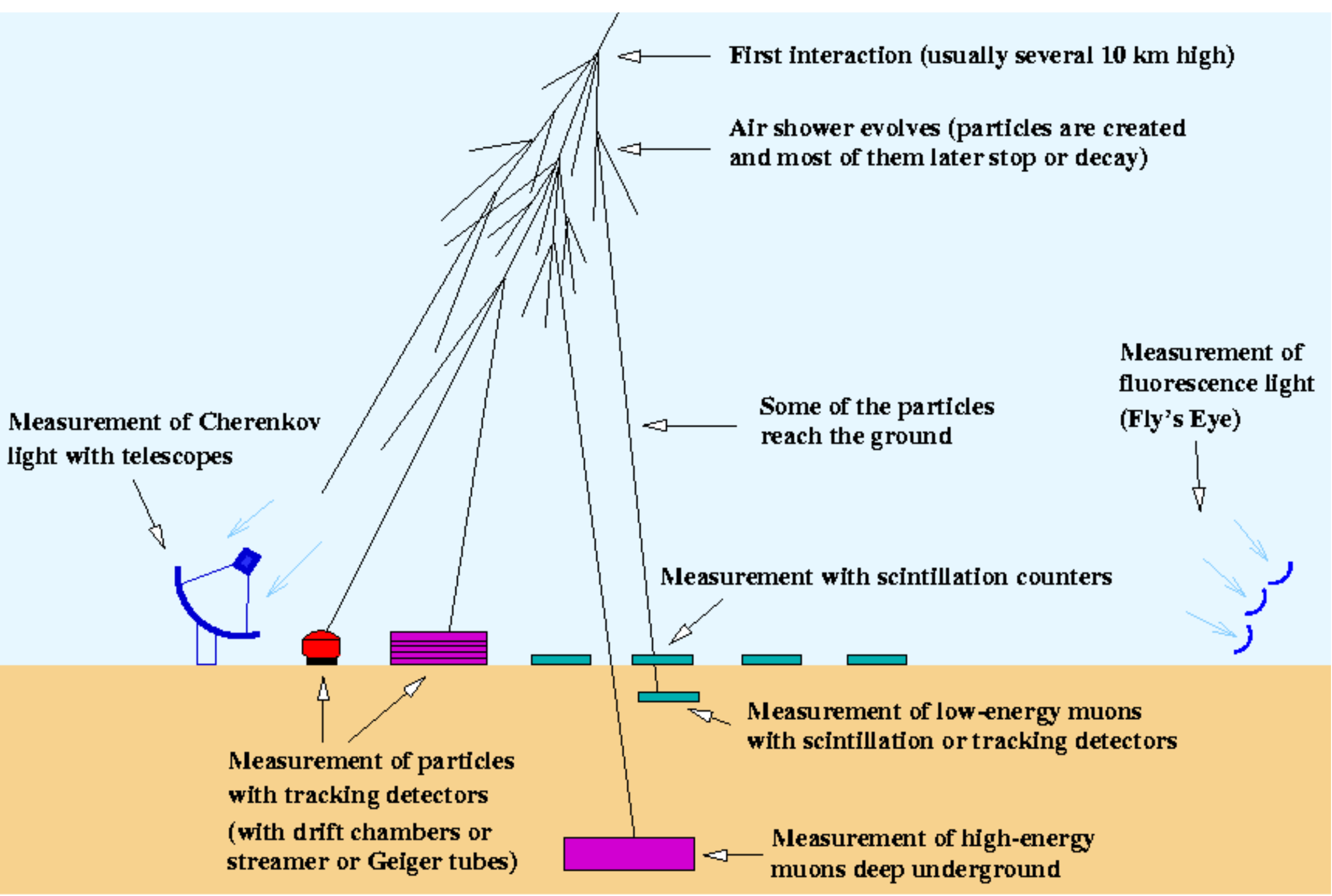


cosmic rays spectrum

indirect observations

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

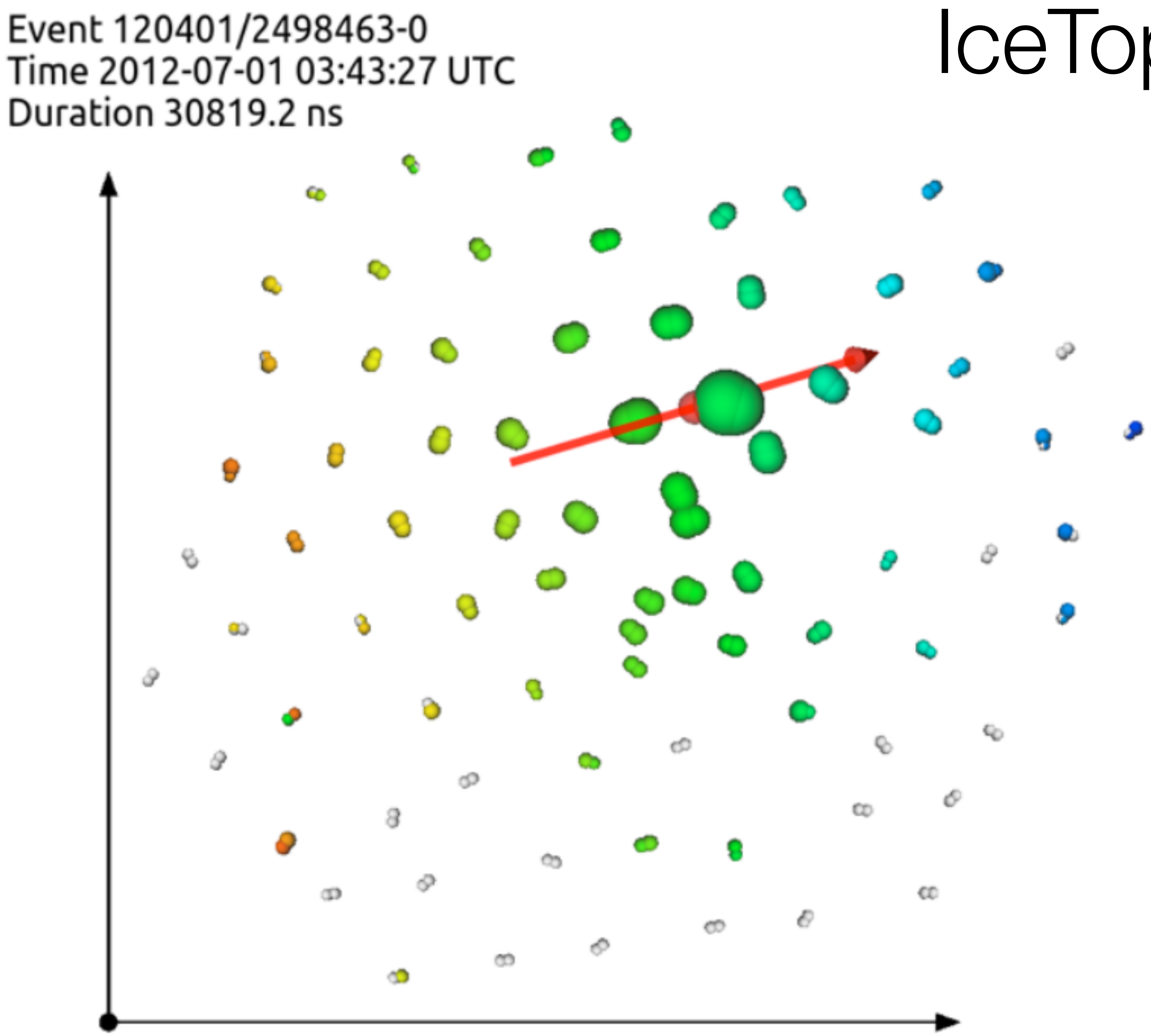




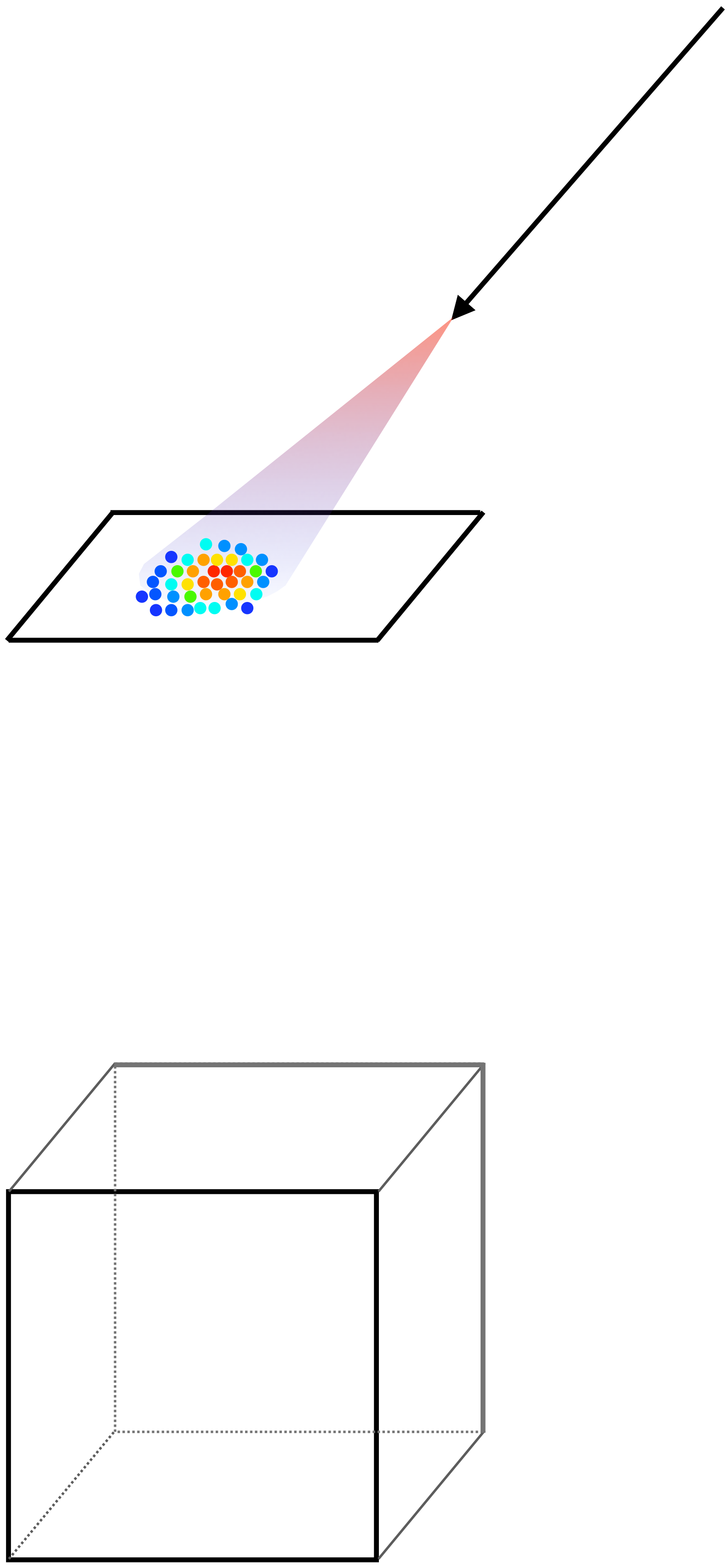
- **atmosphere** & **interaction** properties
- energy & mass observations **tangled**
- limited energy & mass **resolution**

cosmic rays spectrum

all-particle energy spectrum

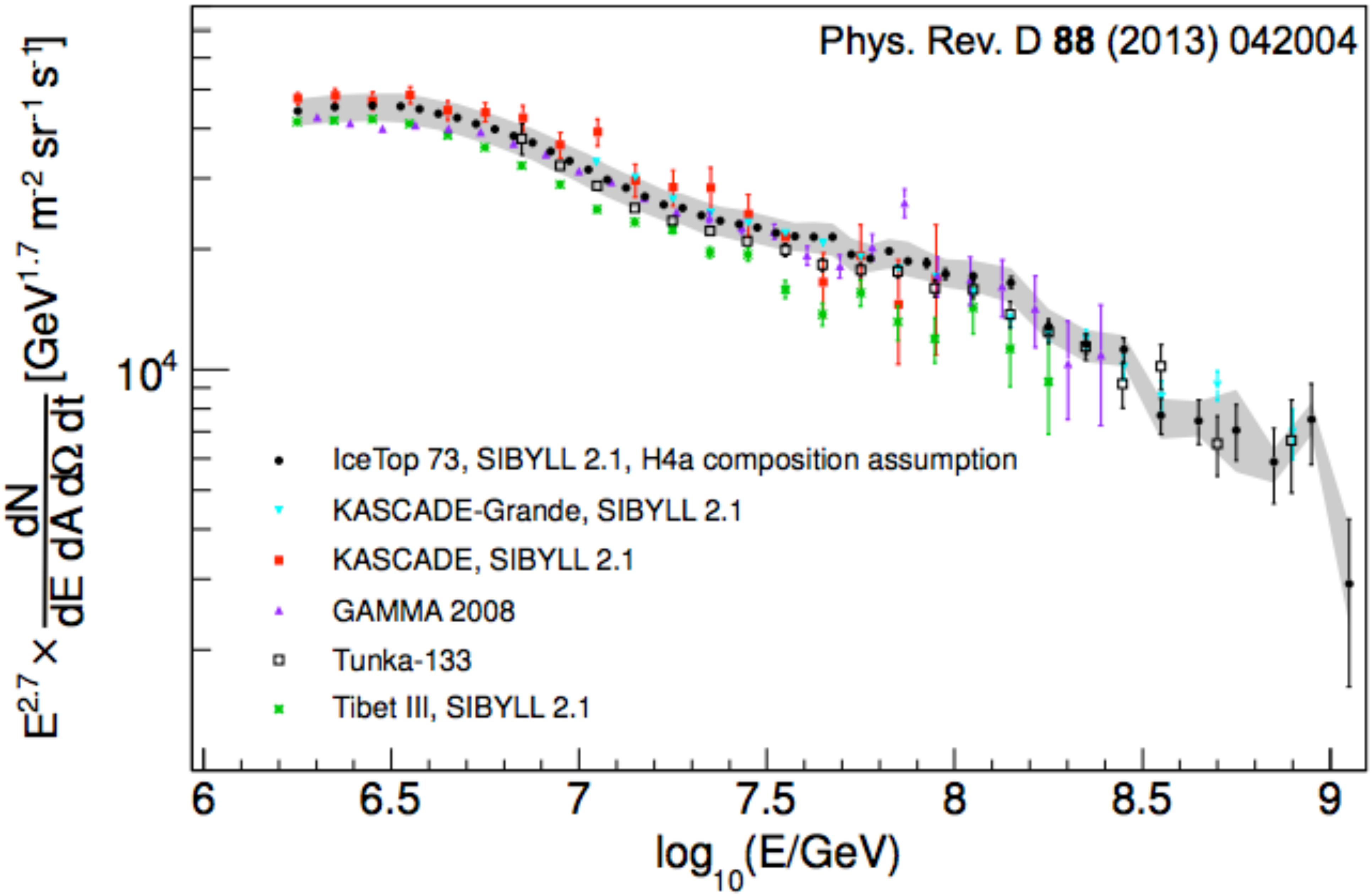


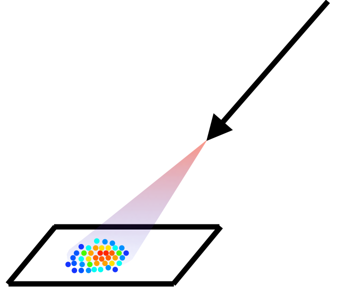
IceTop

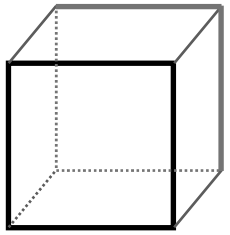


cosmic rays spectrum

all-particle energy spectrum



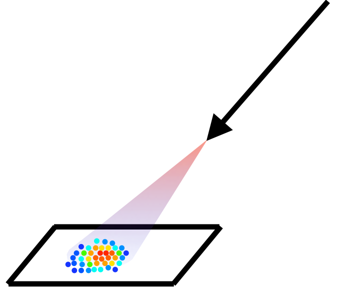


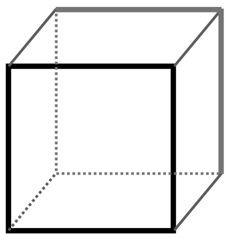


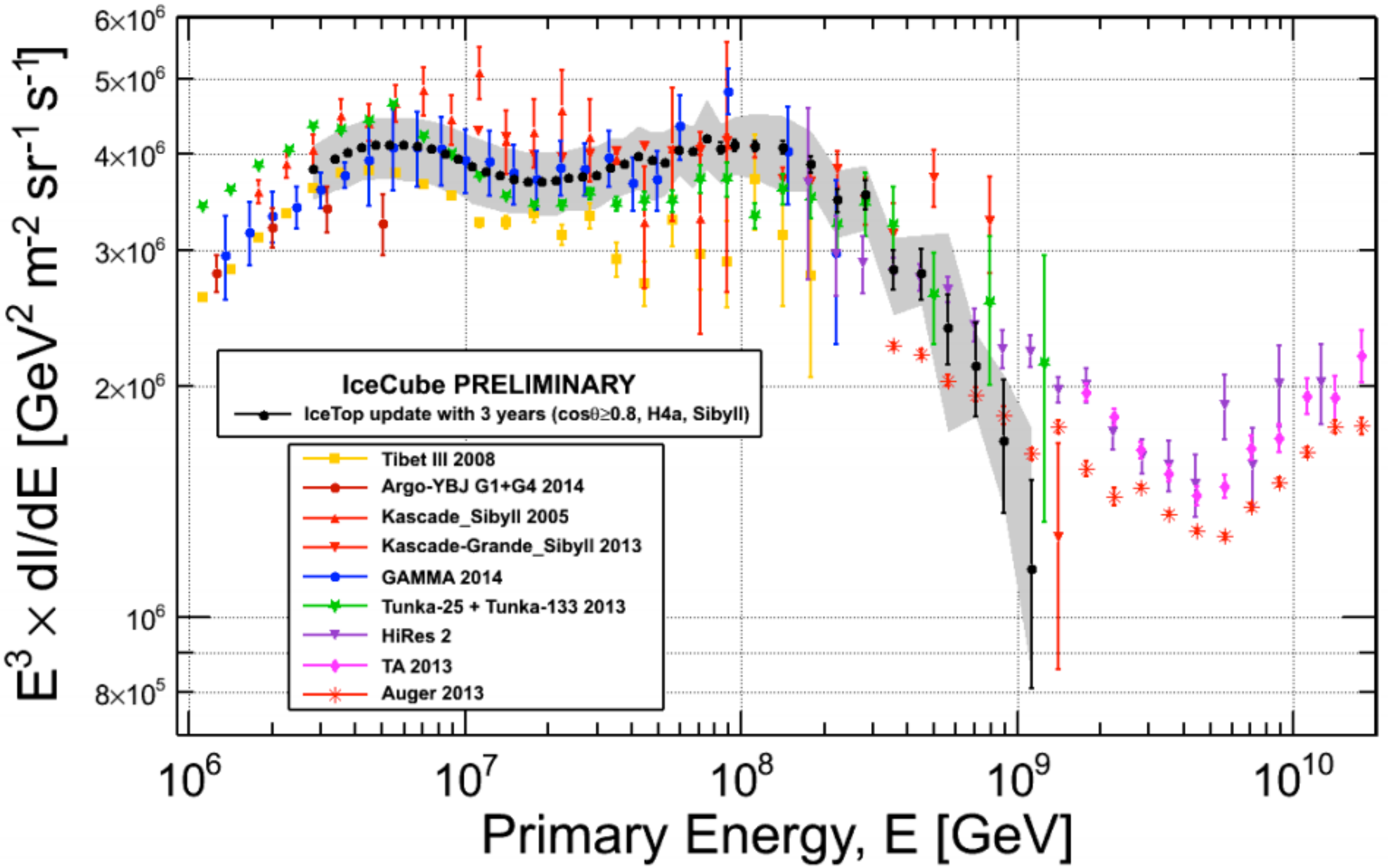
all-particle spectrum depends on the ***assumed*** mass composition of primary particles

cosmic rays spectrum

all-particle energy spectrum







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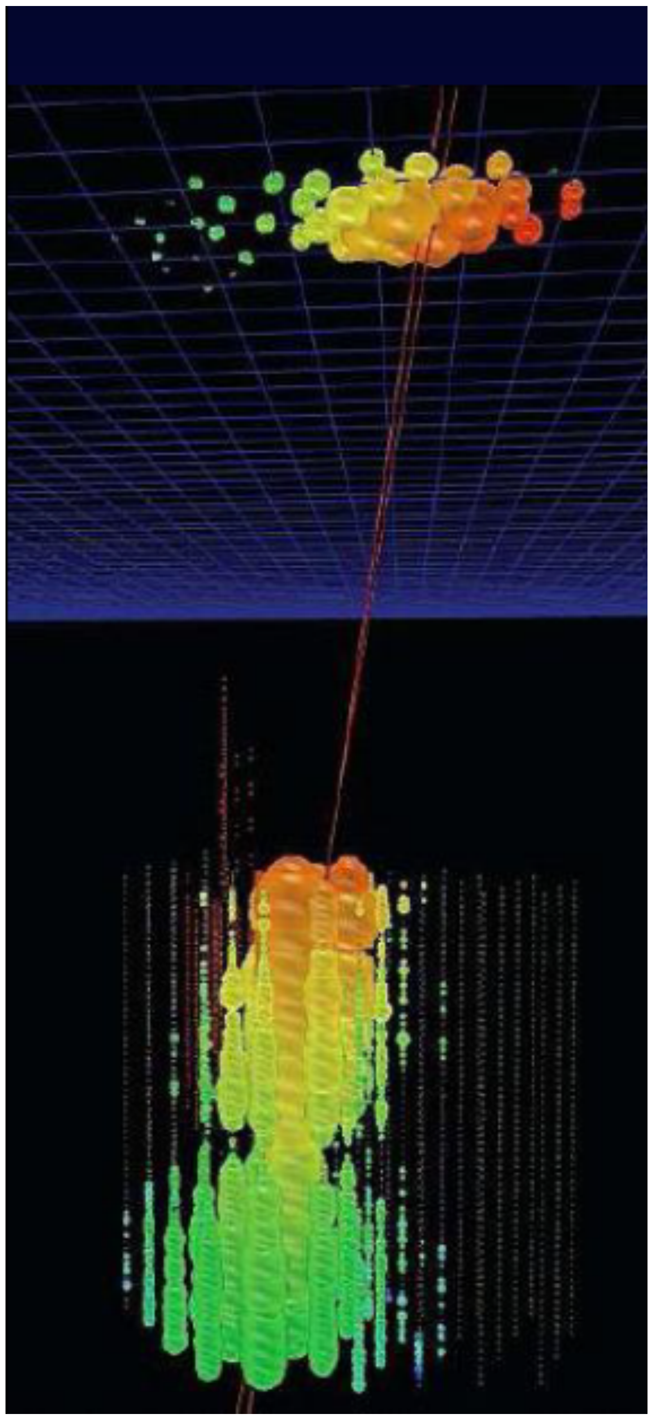
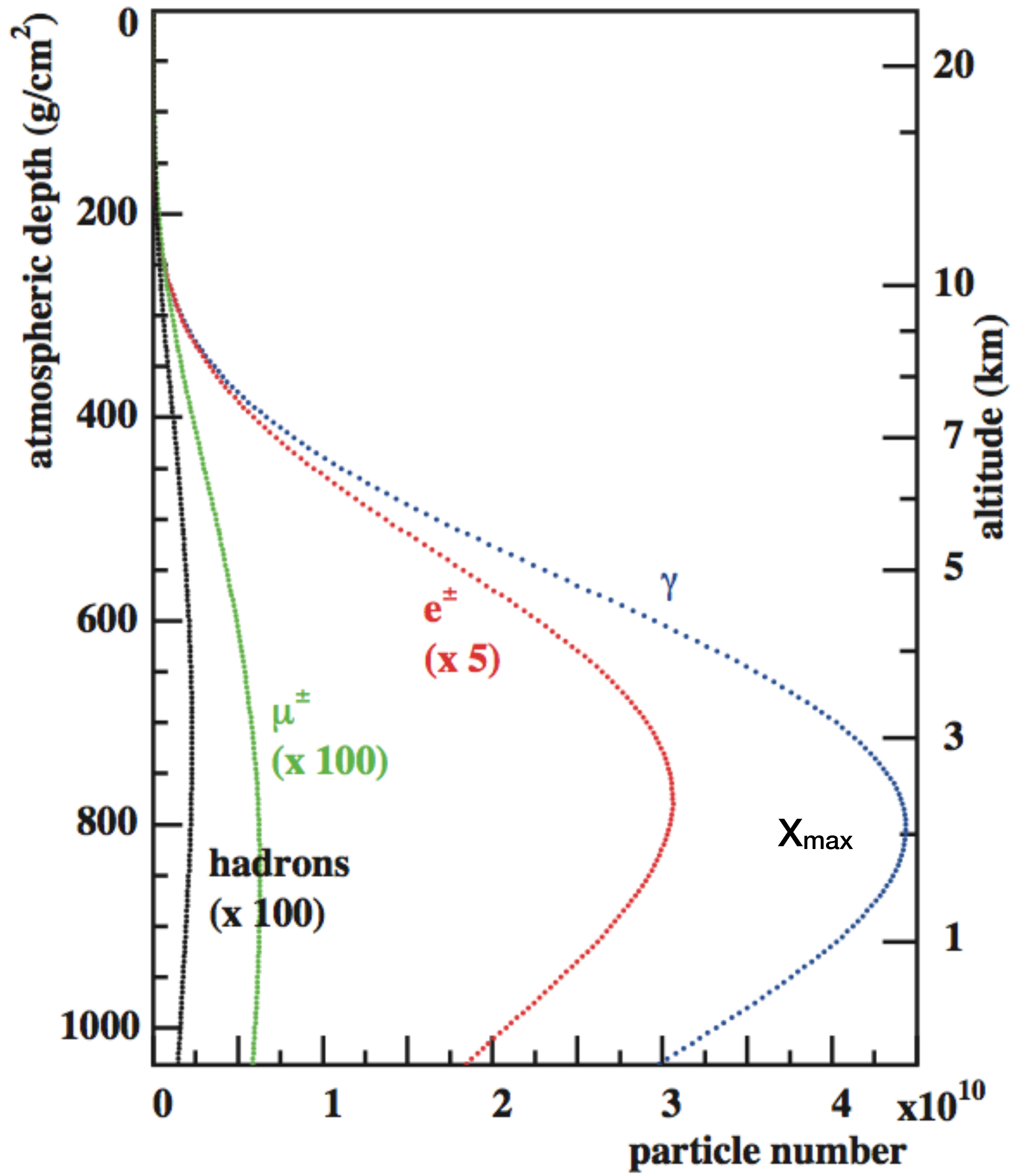
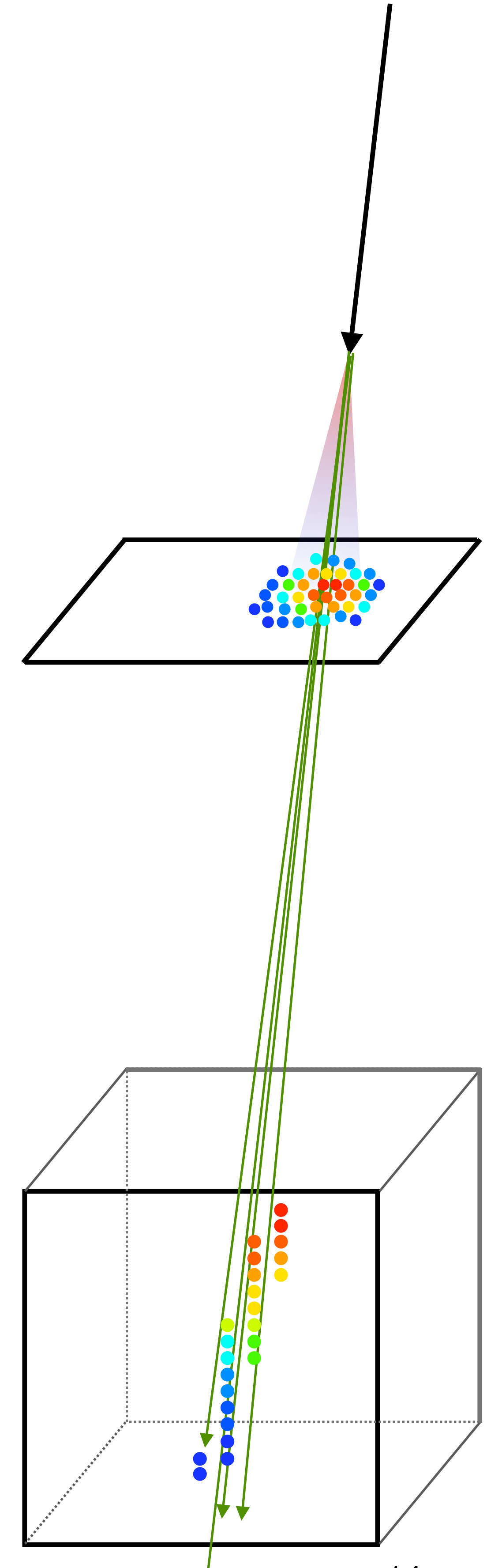
cosmic rays composition

coincident events







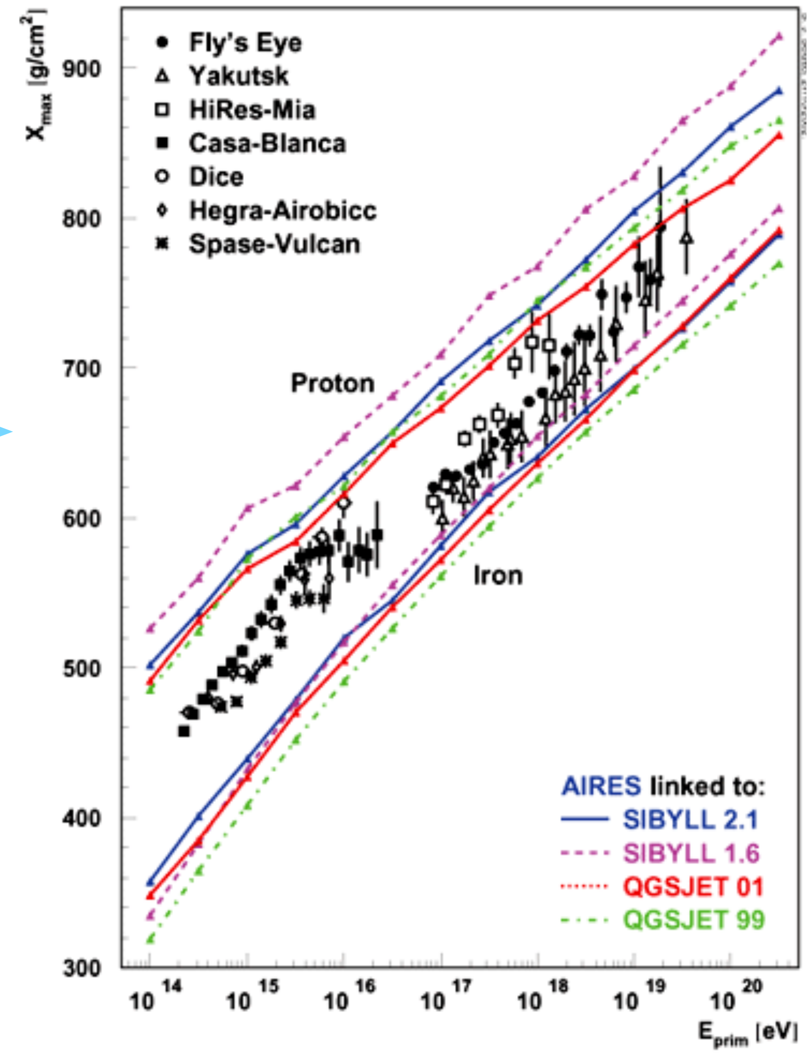
cosmic rays composition

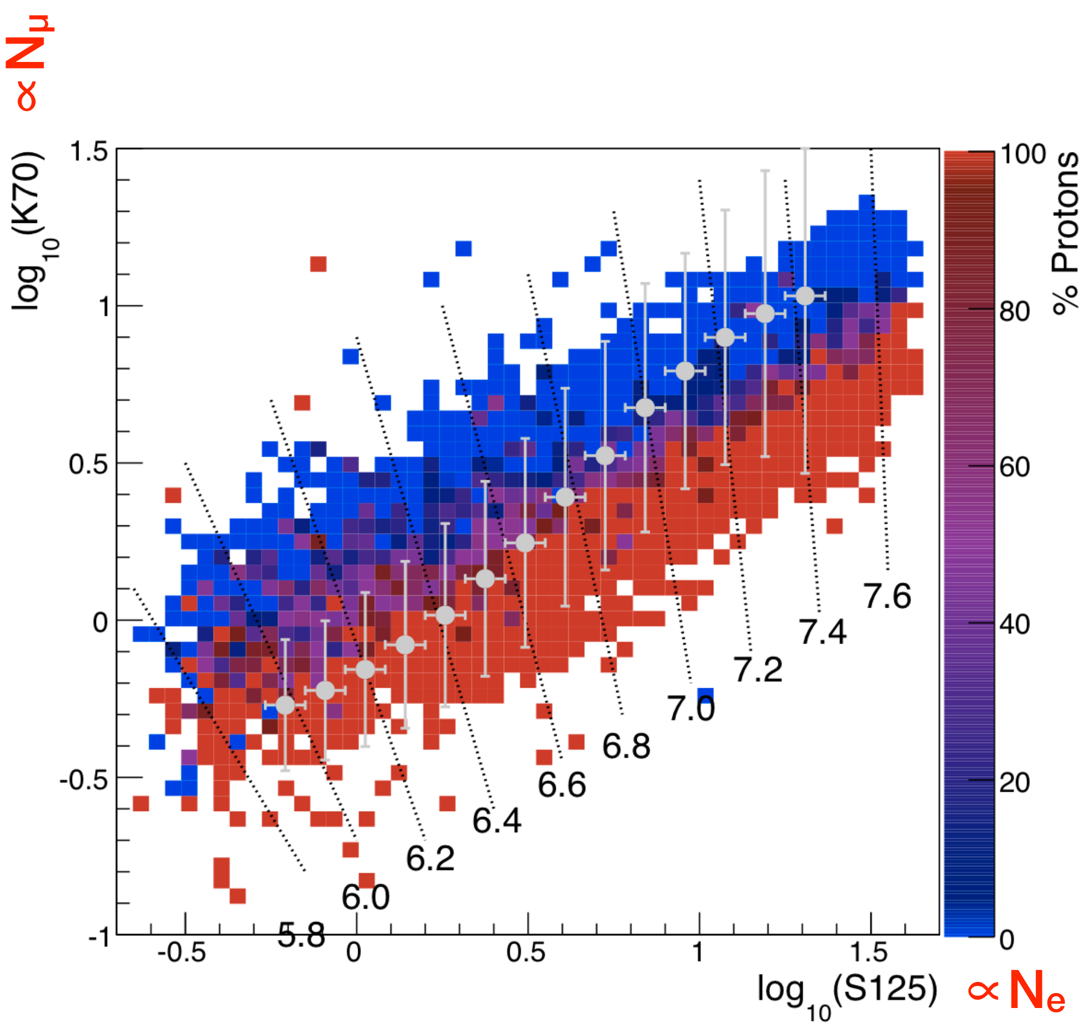
coincident events

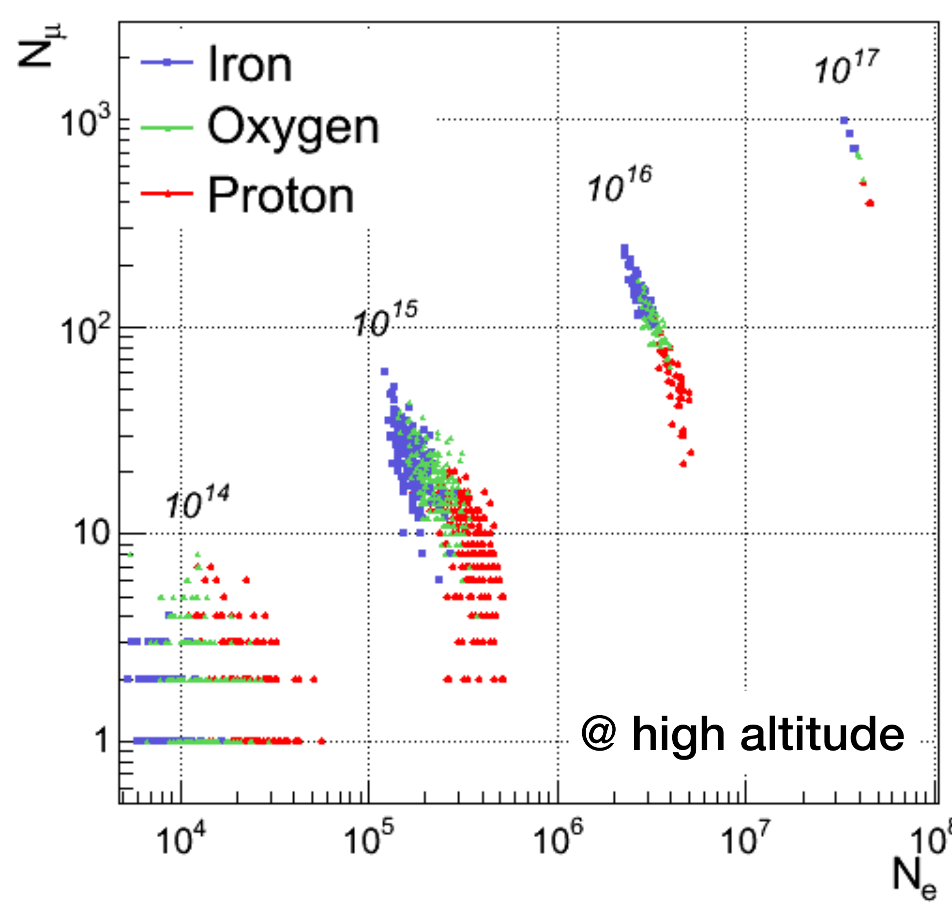
Sciutto, Braz. J. Phys. 37 (2007) 2b, São Paulo

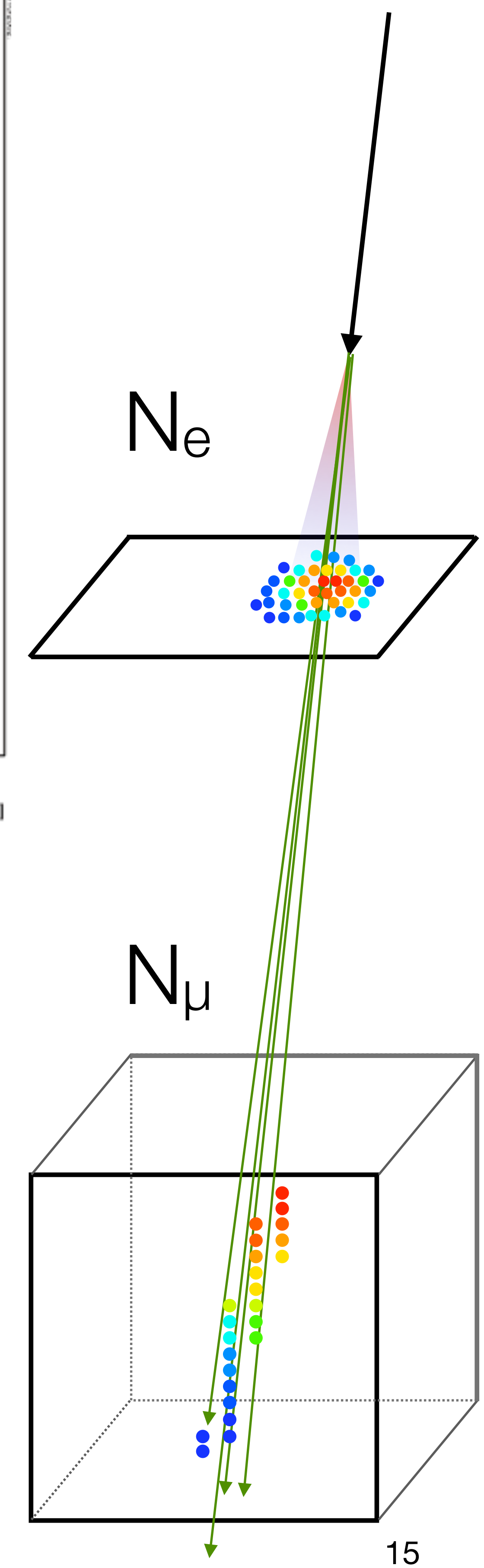
@sea level

@Antarctica







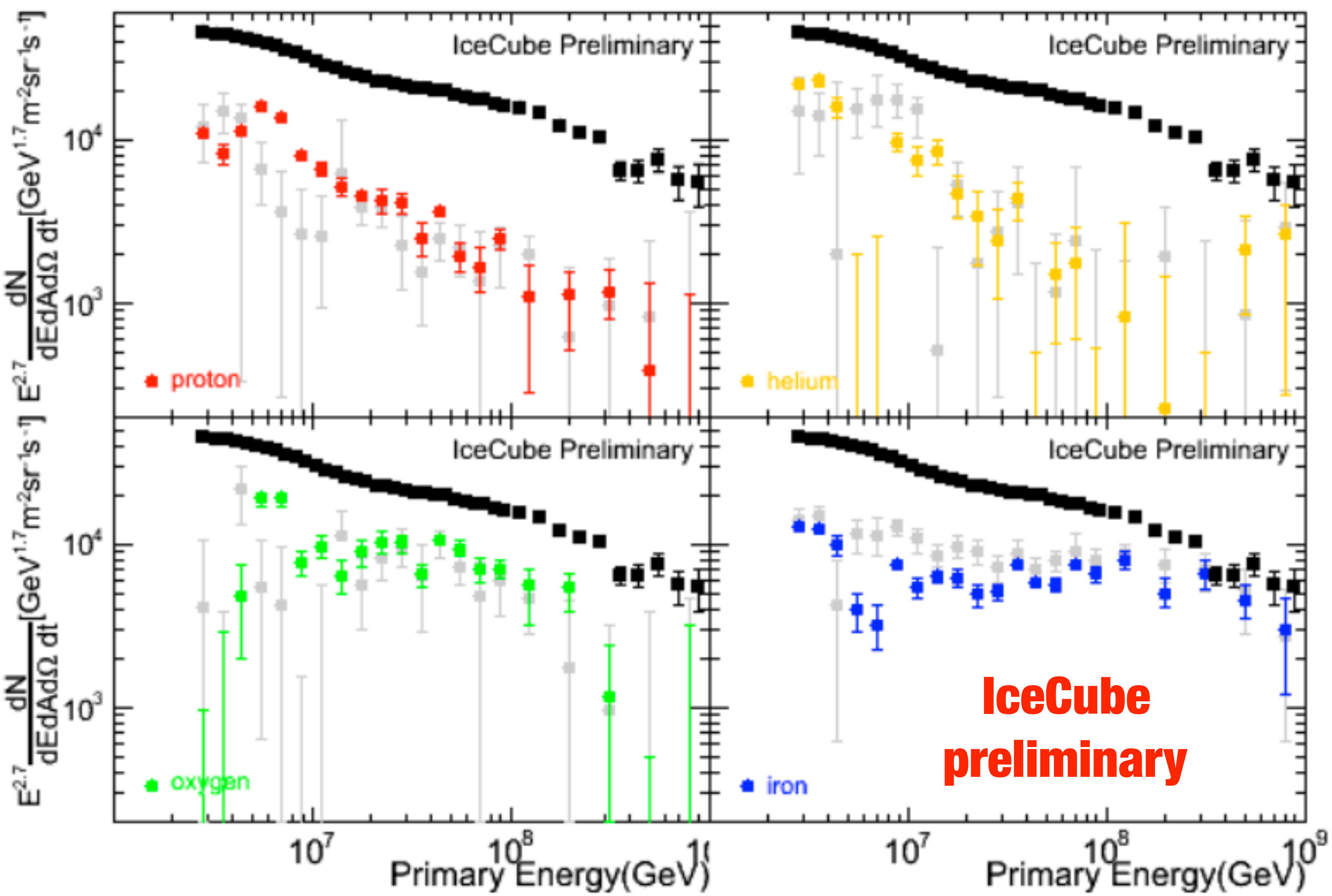


cosmic rays composition

coincident events

Colors = SIBYLL 2.1
Grey = QGSJET-II-03

effect of hadronic interaction models



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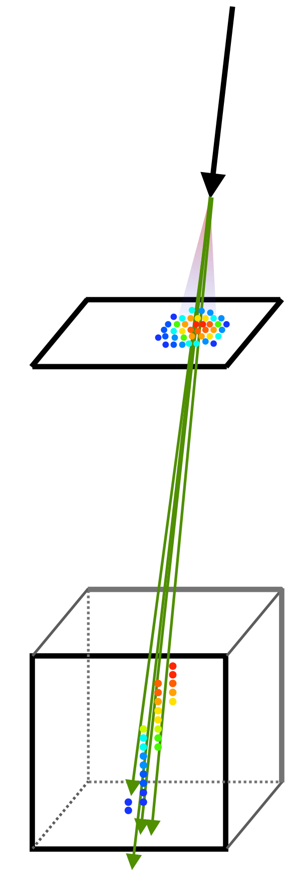
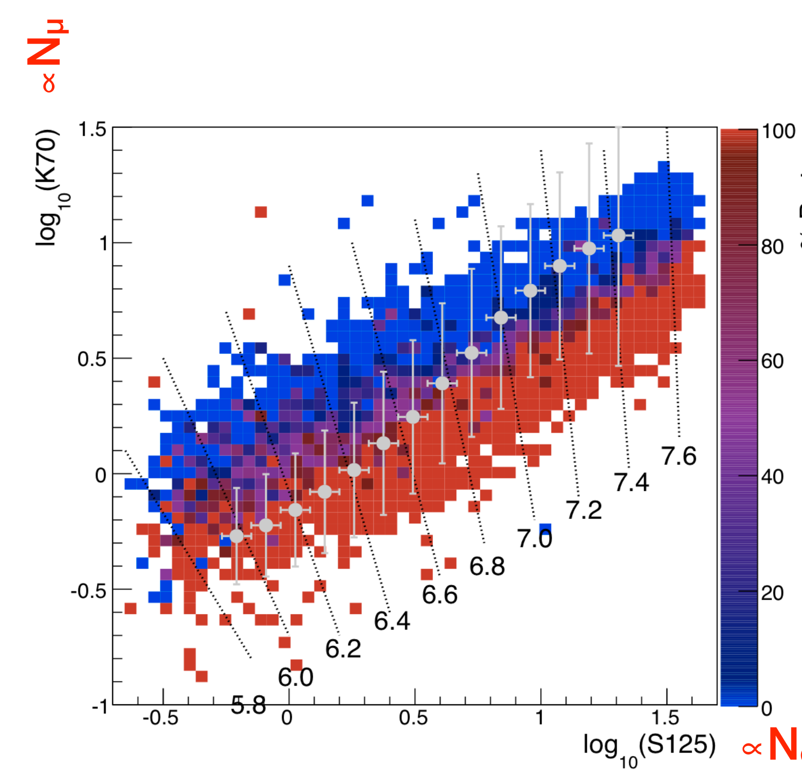
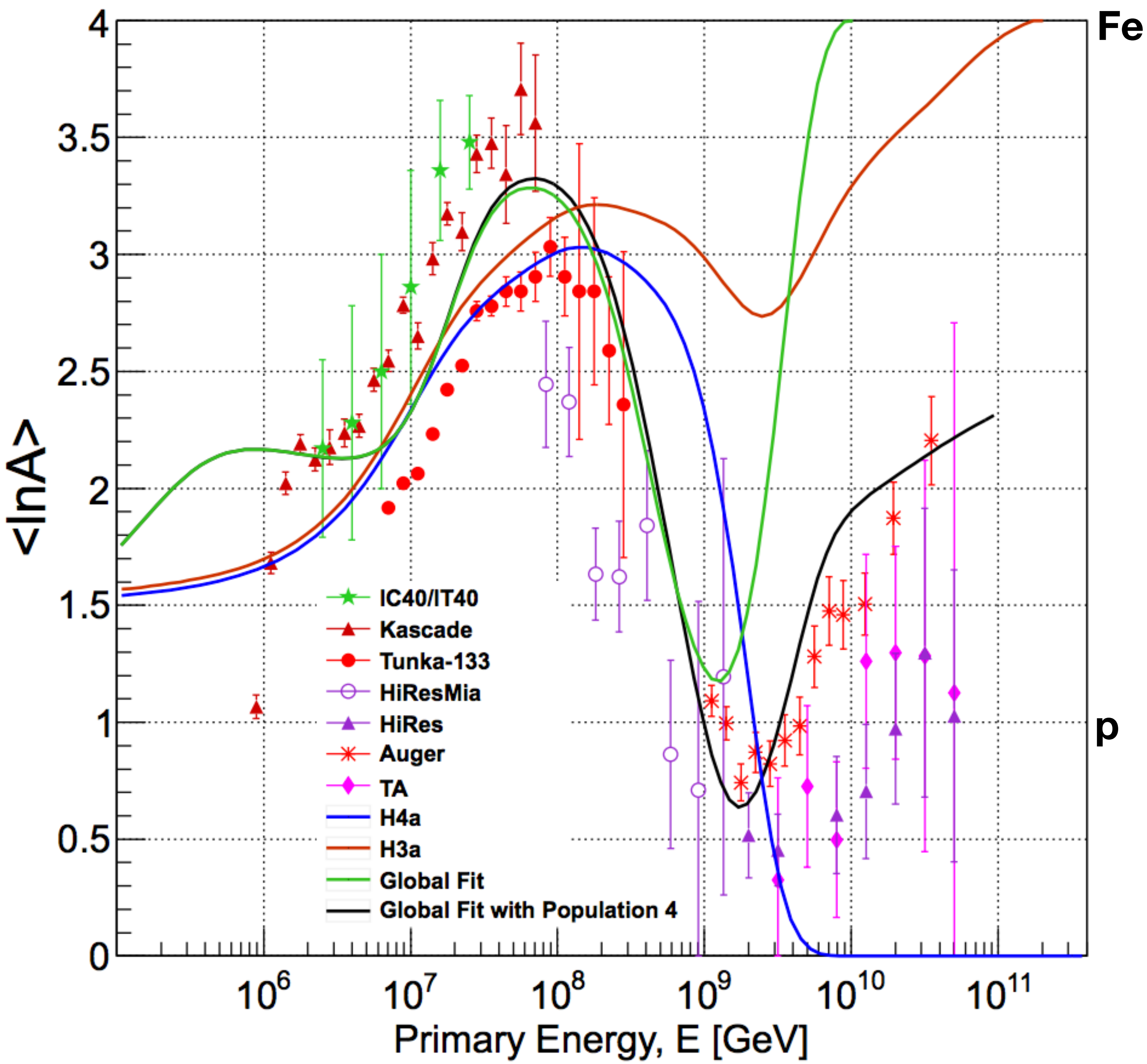




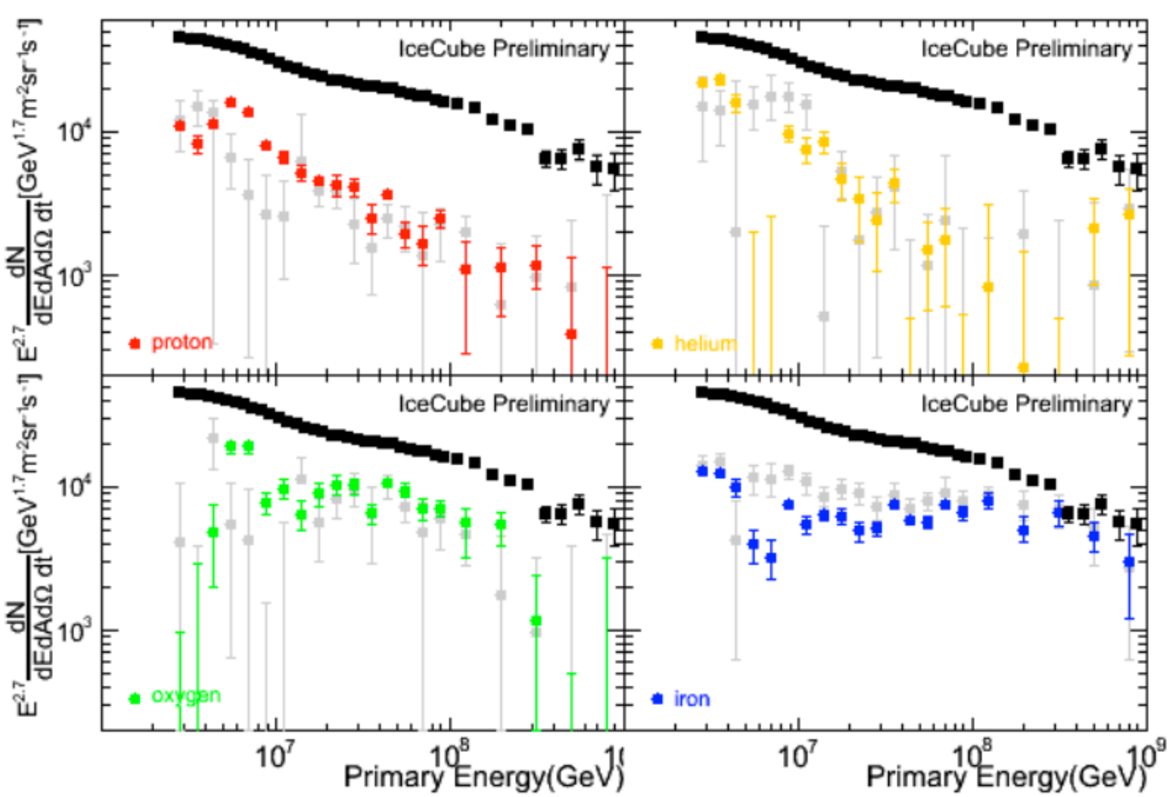
cosmic rays composition

other experiments



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

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



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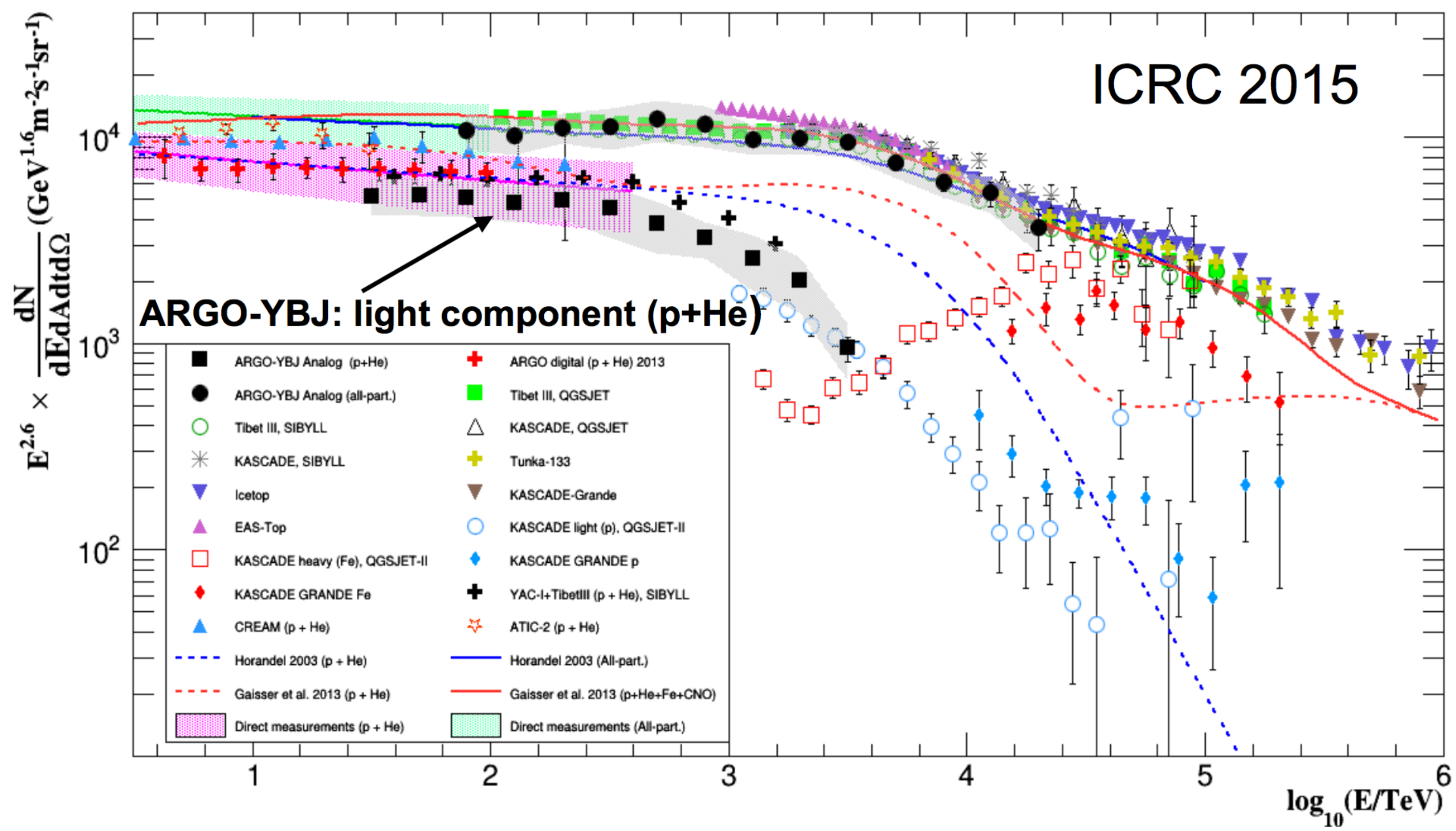

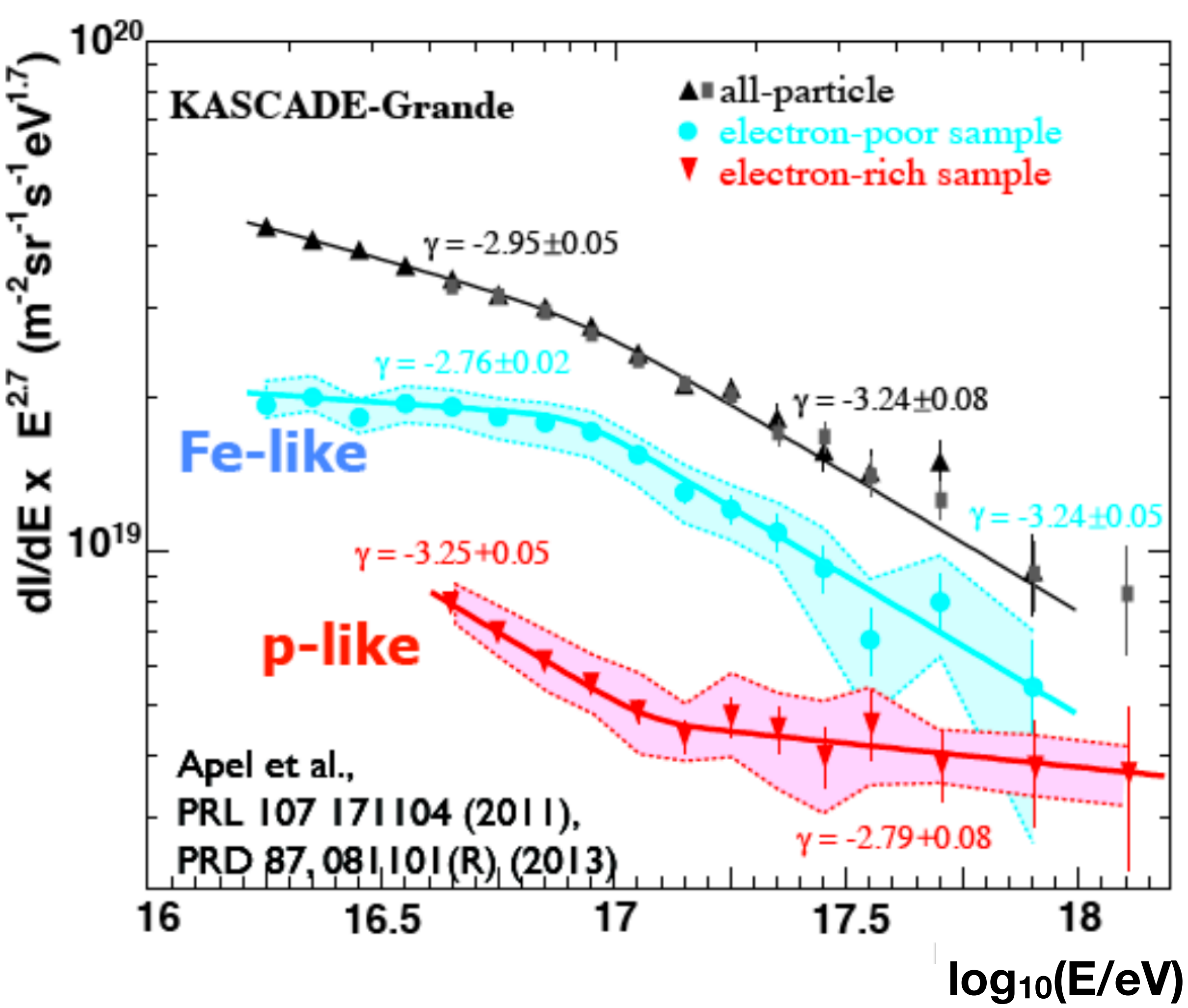

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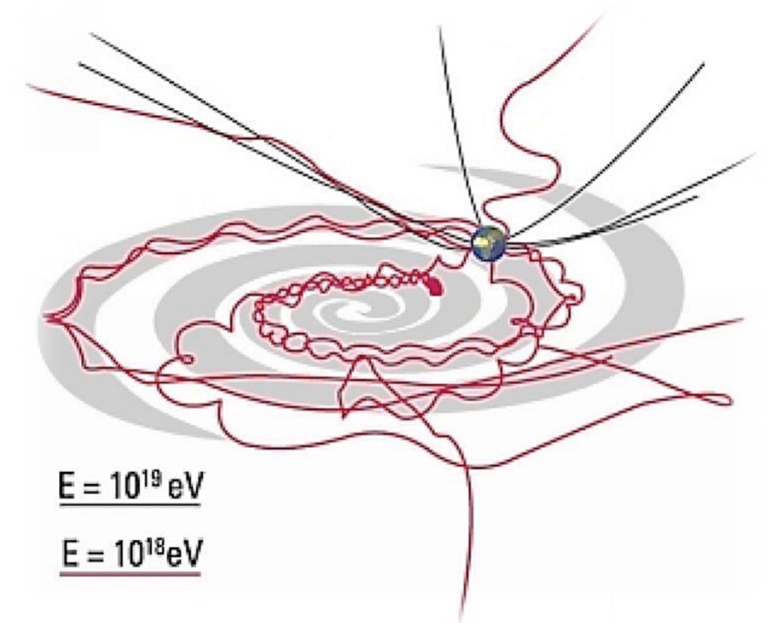
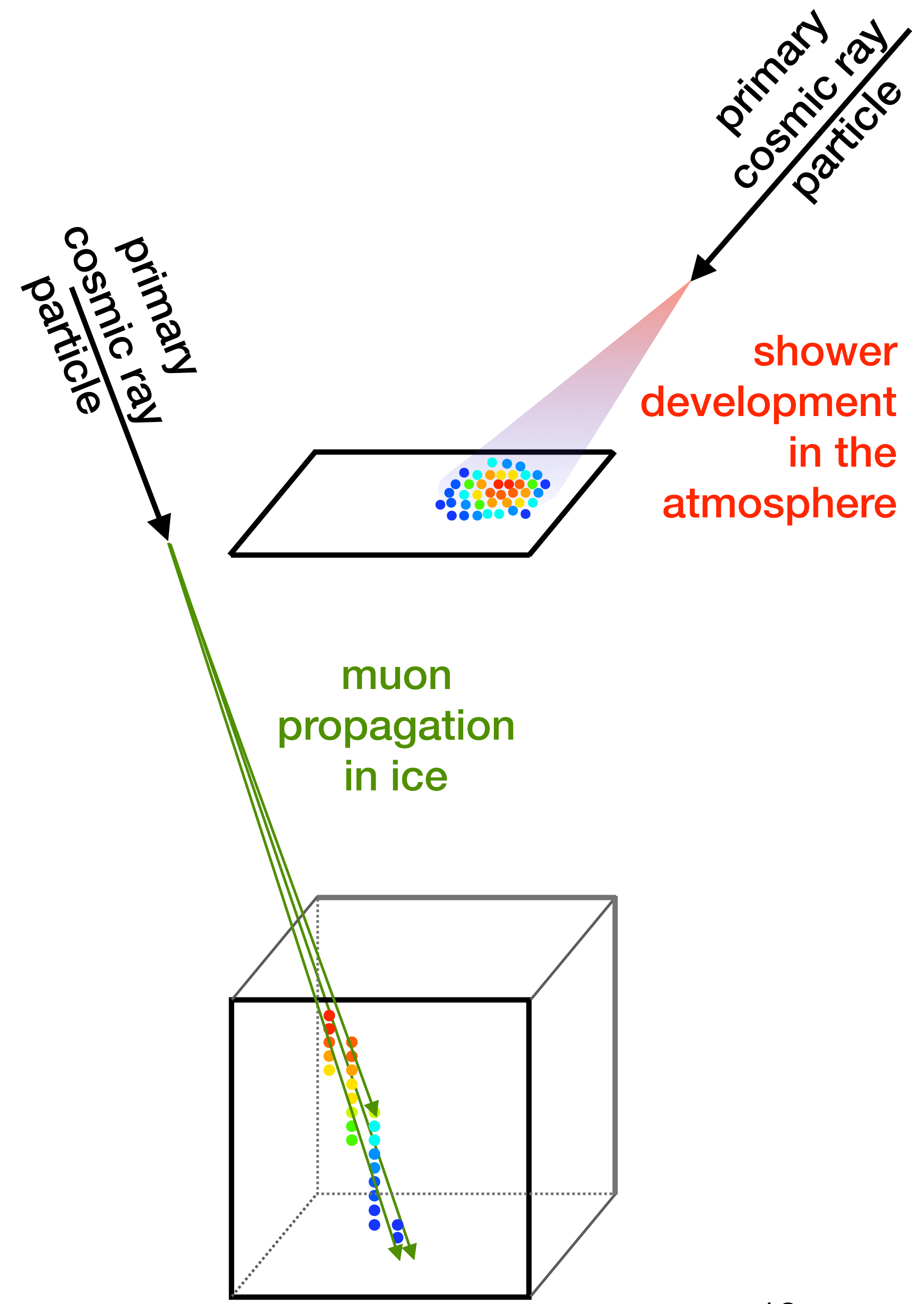
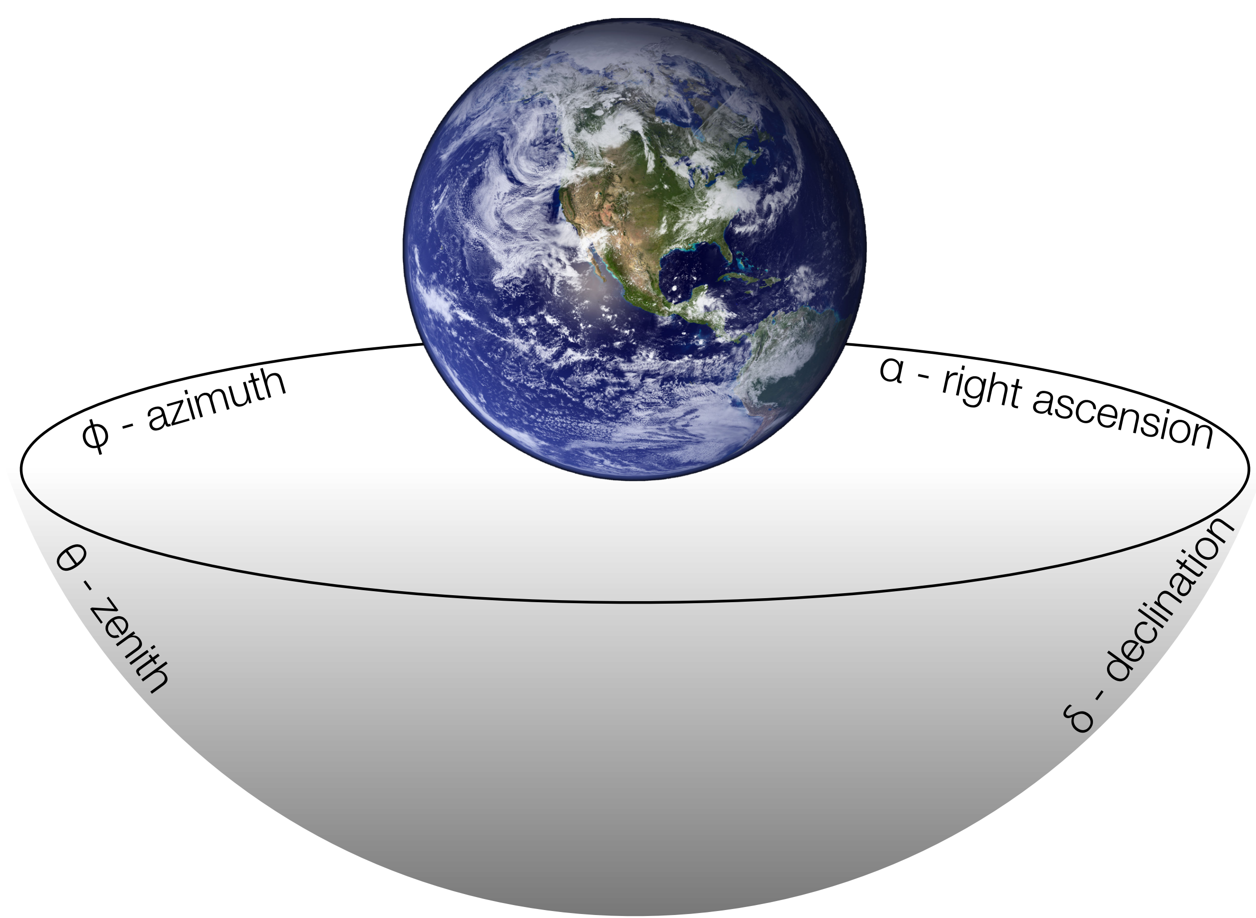
cosmic rays anisotropy

arrival direction distribution

- cosmic rays expected to be ***almost*** isotropic
- ***scrambled*** by galactic magnetic field
- ***anisotropy*** from source dist. & magnetic fields



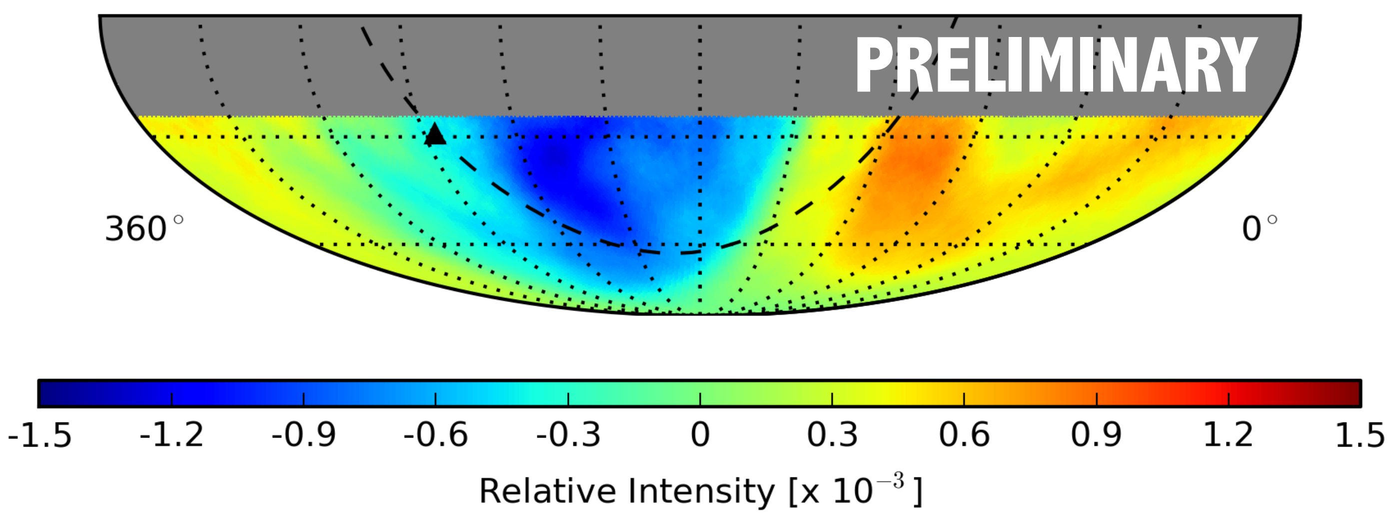




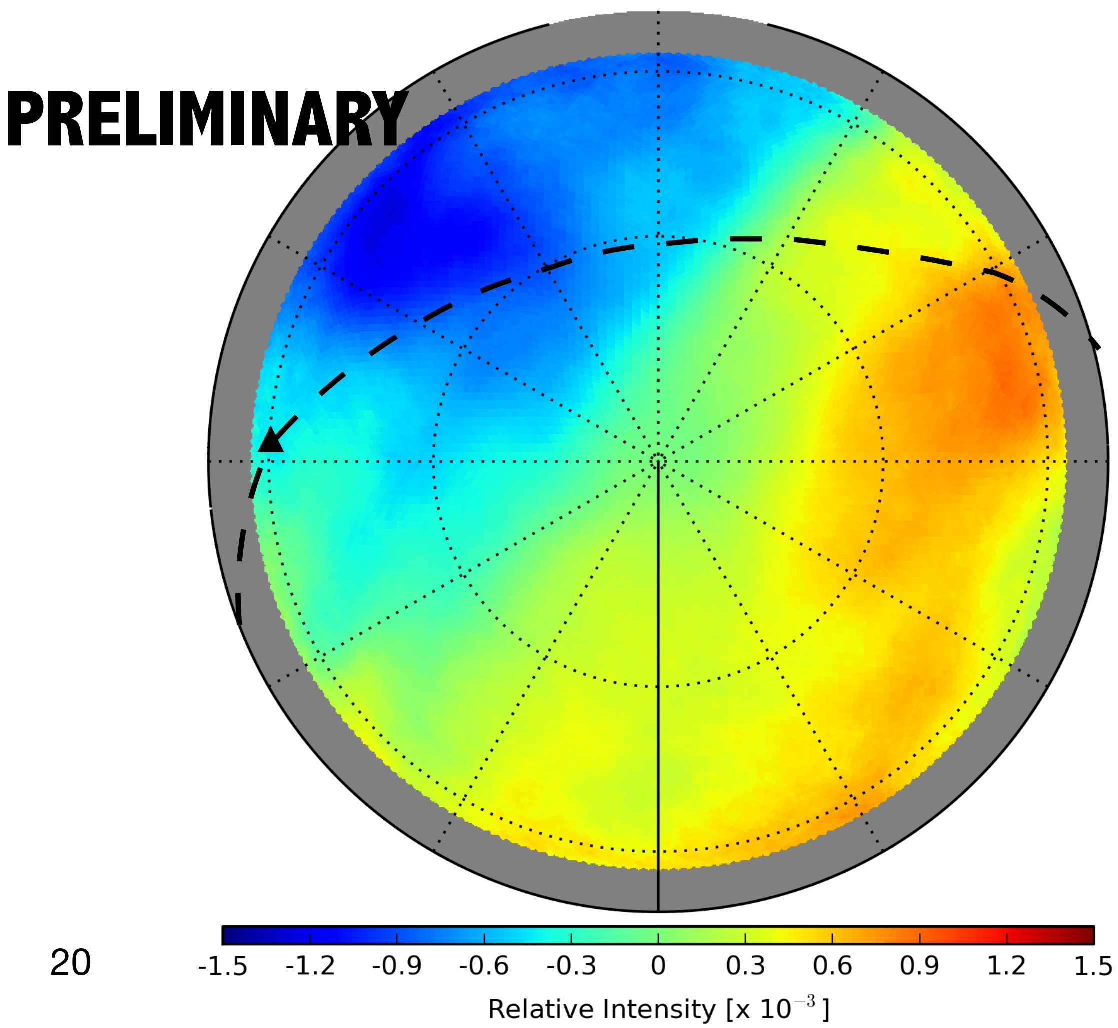
cosmic rays anisotropy

arrival direction distribution

to be submitted to ApJ



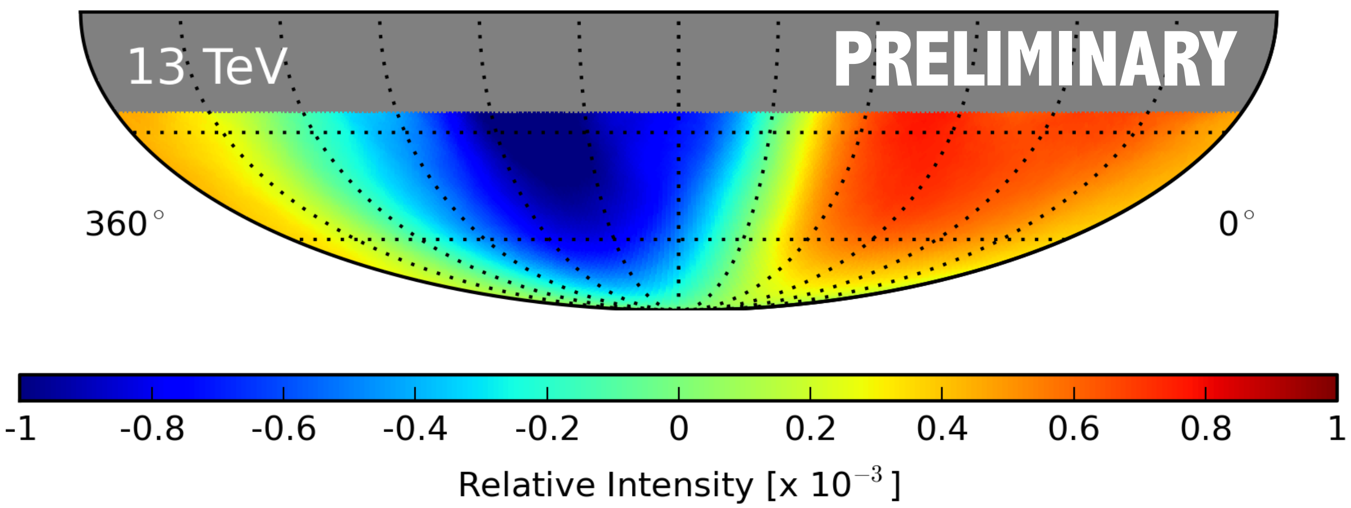
- 6 years of IceCube
- 300 billion events

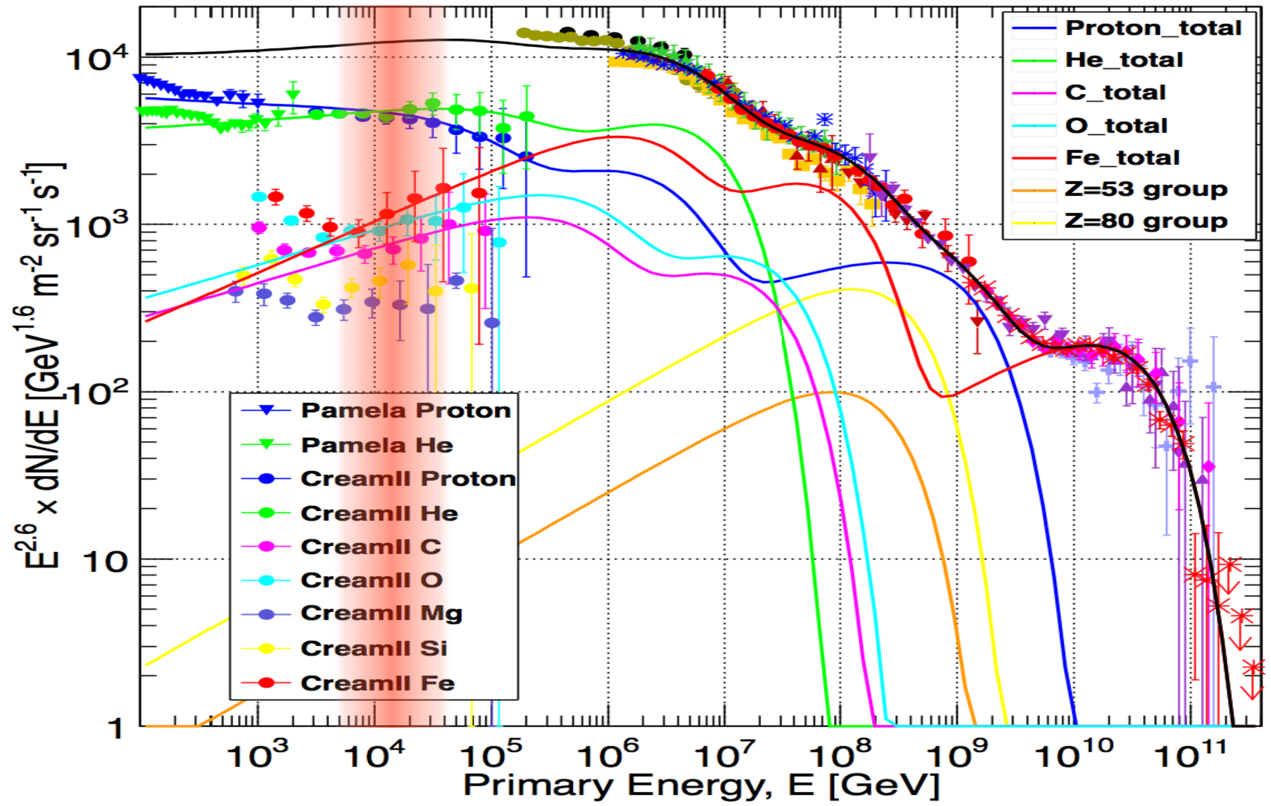


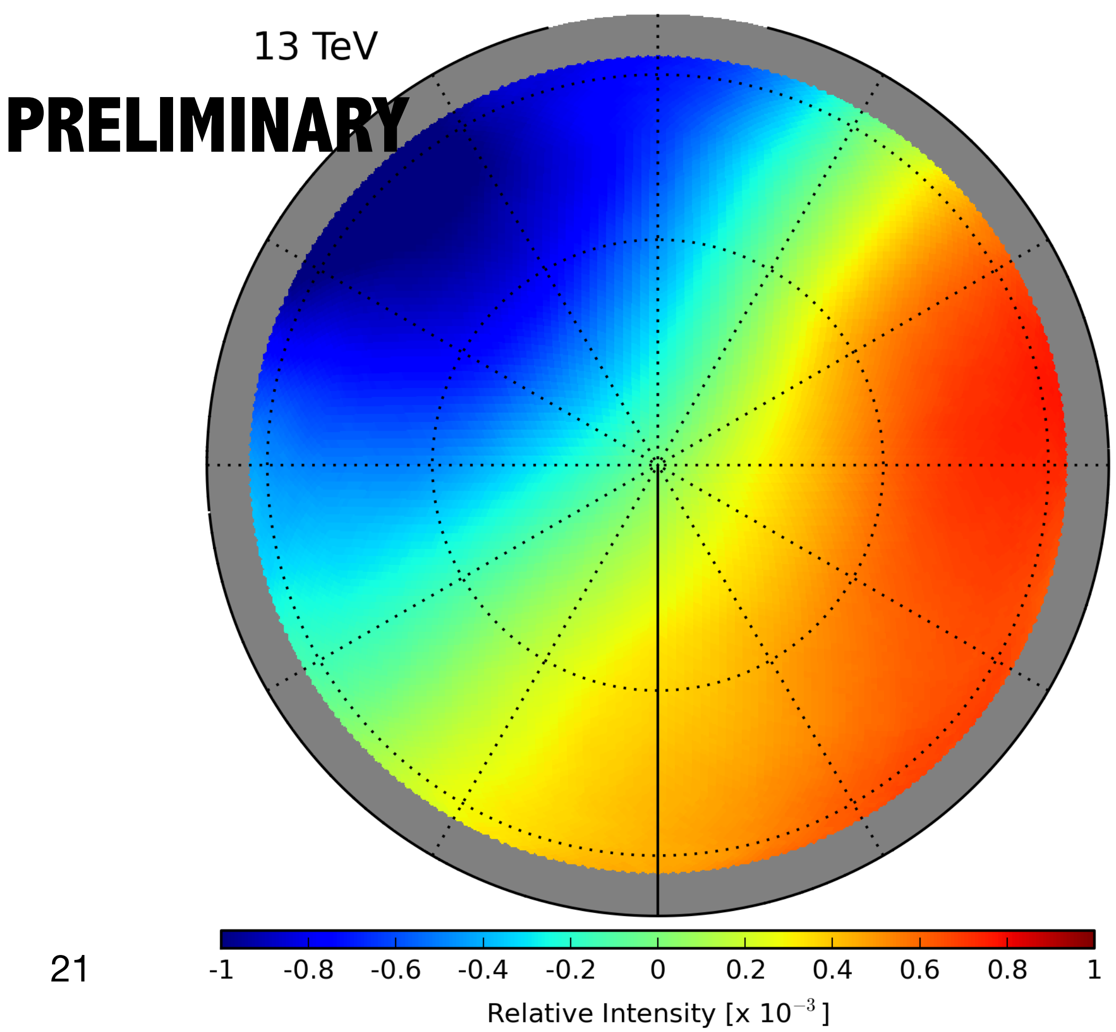
- anisotropy on the level of 10^{-3}
- median cosmic ray energy **20 TeV**
- trace sources ? Magnetic fields ?

cosmic rays anisotropy

arrival direction distribution



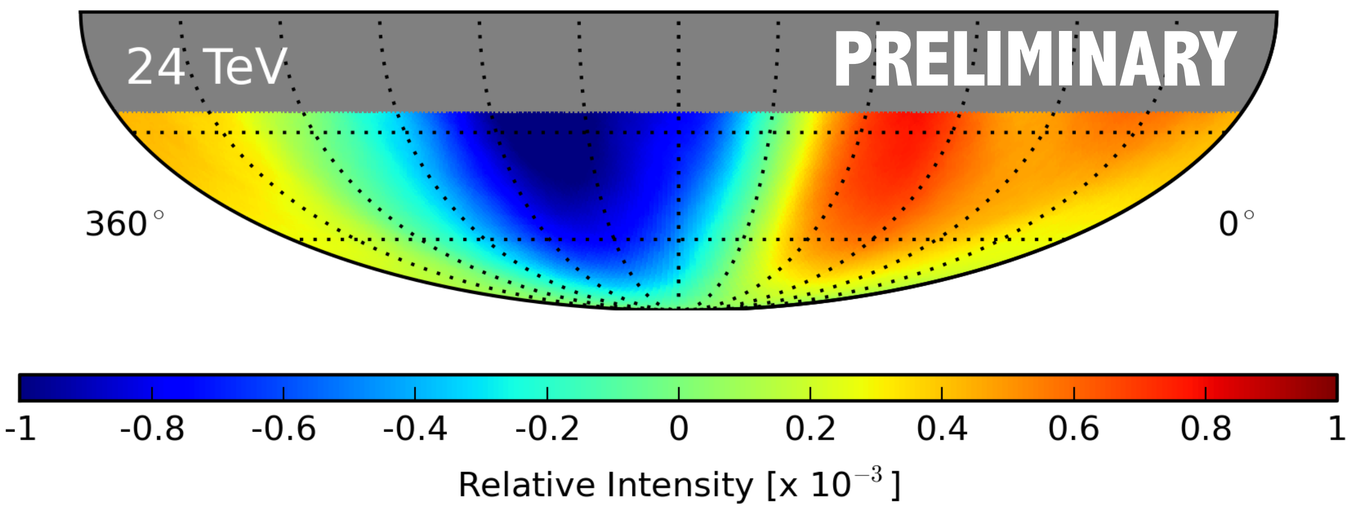


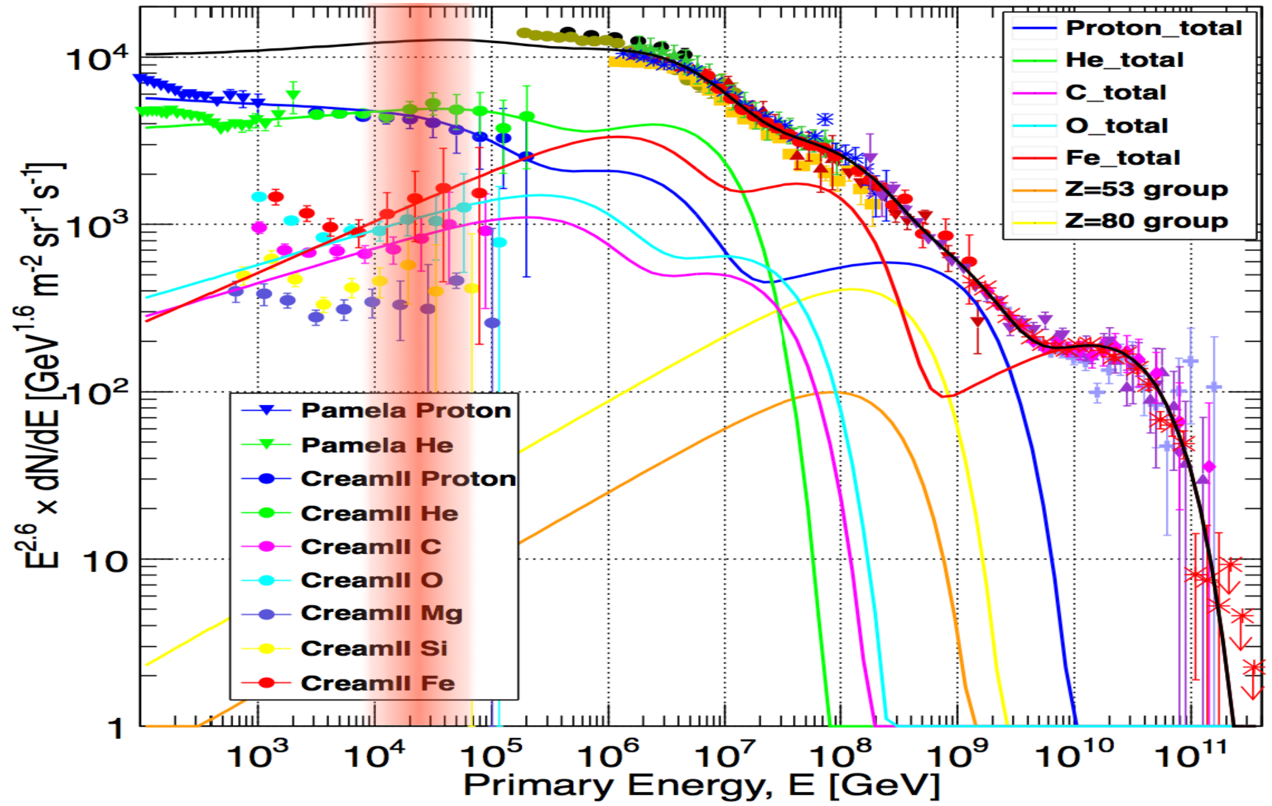


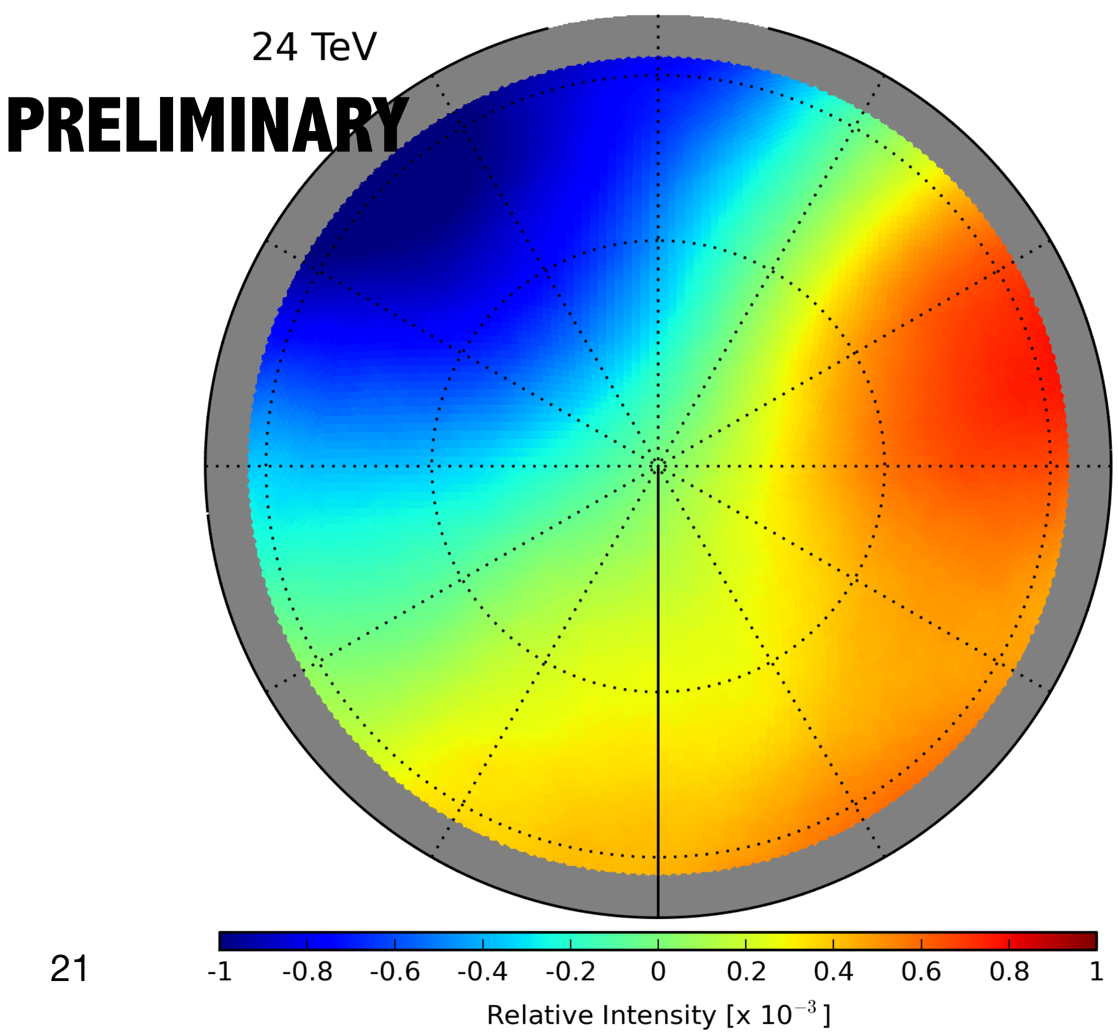
13 TeV **IceCube**

- 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





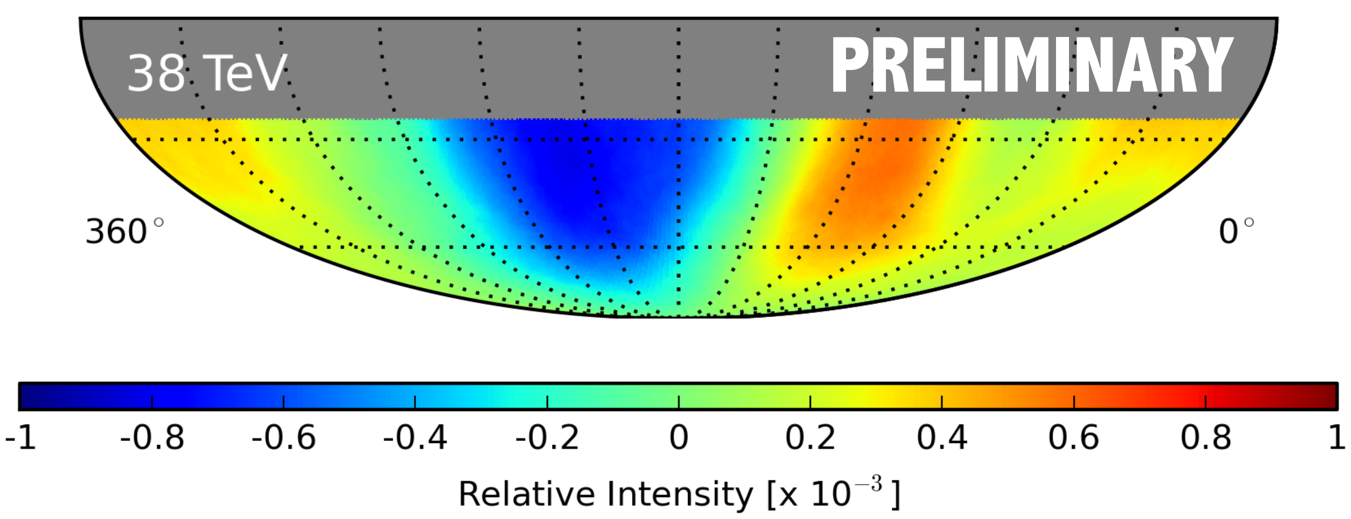


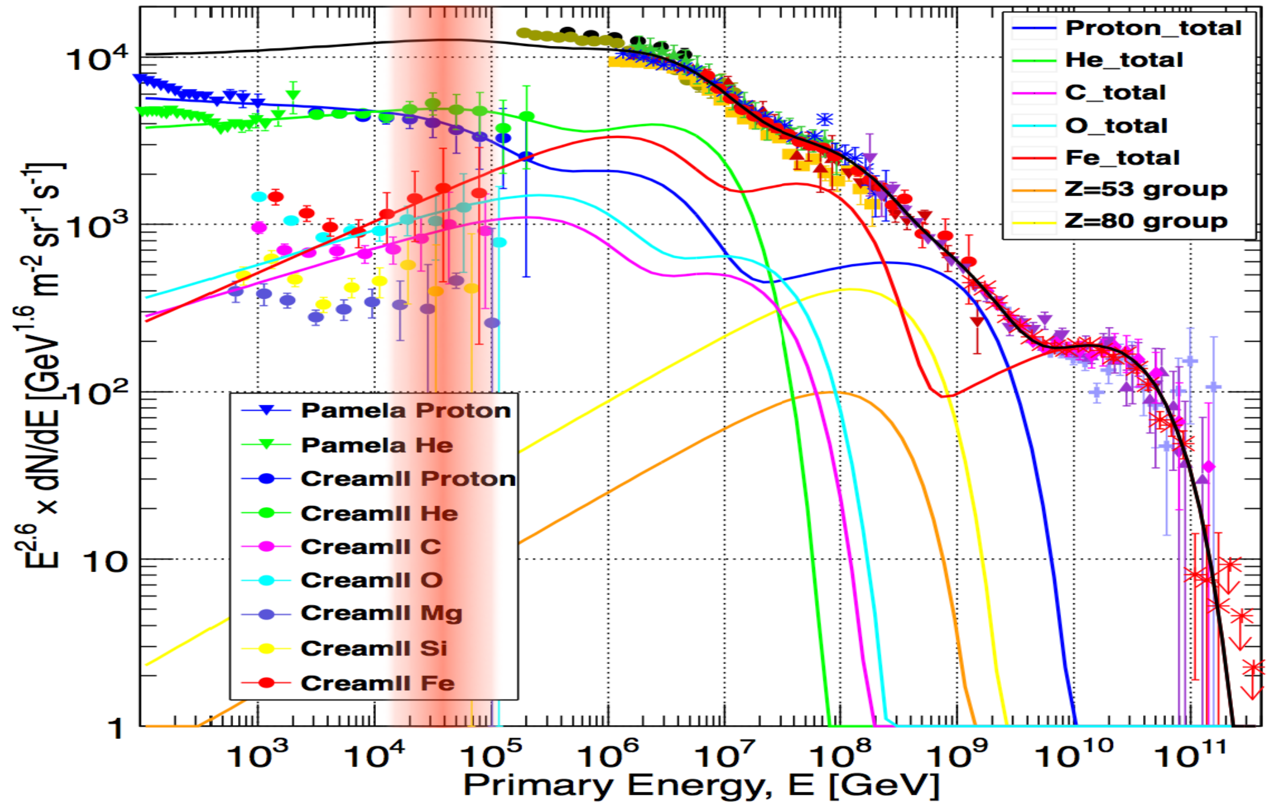
24 TeV **IceCube**

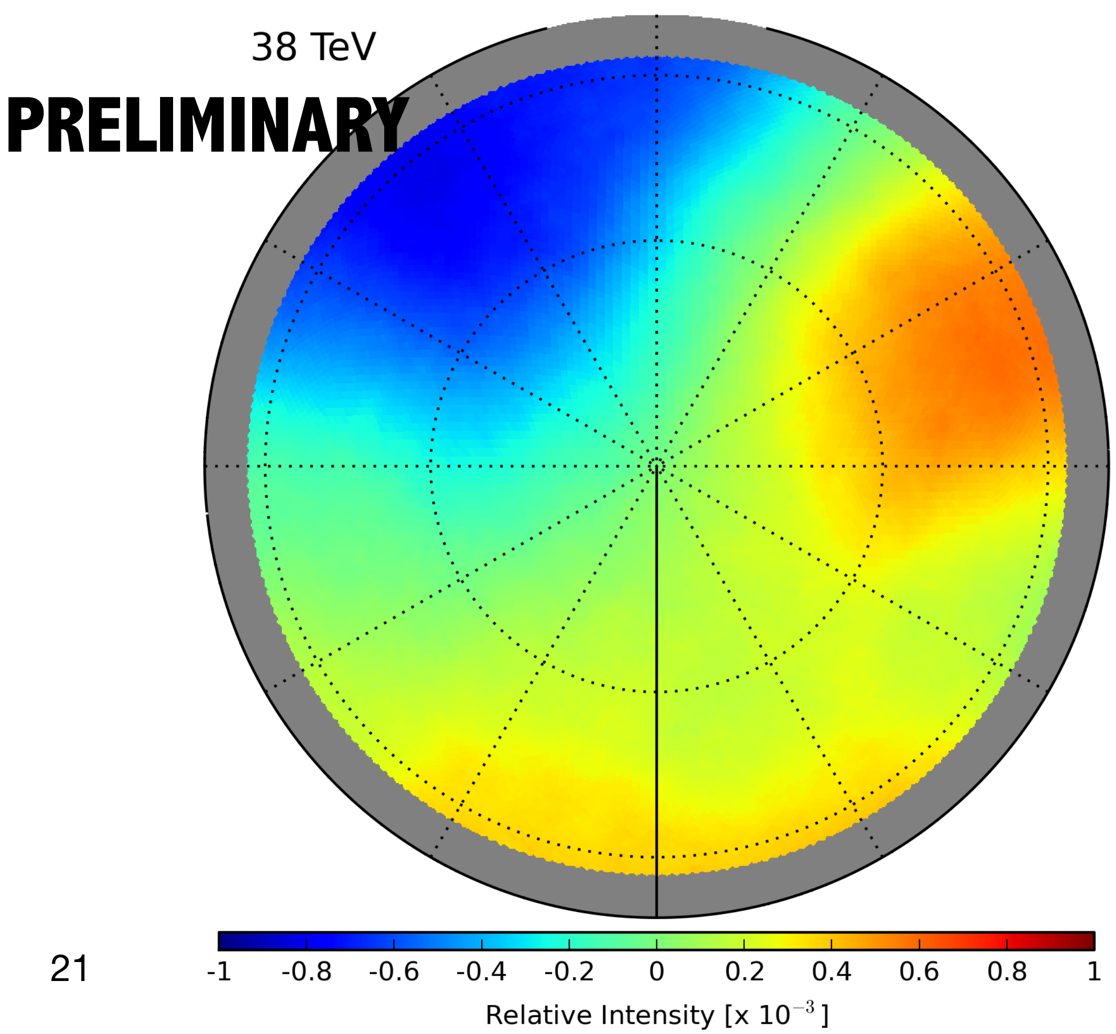
- high energy observations **MISSING** in the northern hemisphere
- **overlapping observations** extending across the equator will help
- capable of energy/mass measurement

cosmic rays anisotropy

arrival direction distribution





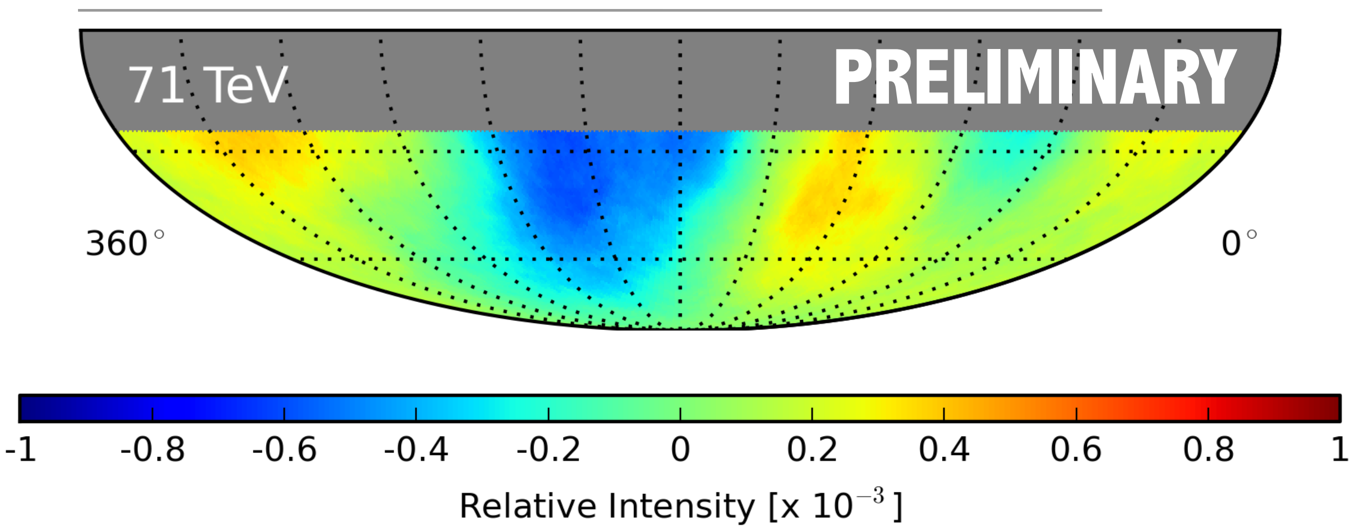


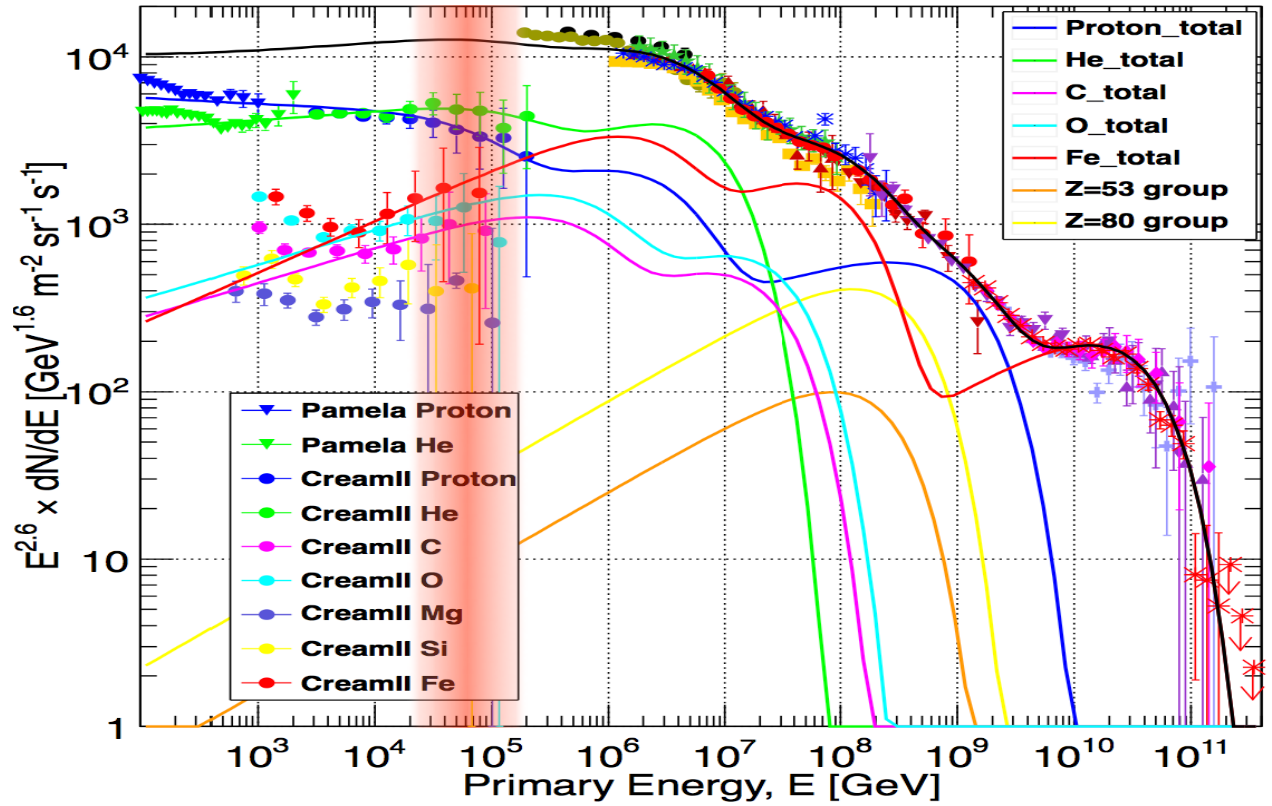
38 TeV **IceCube**

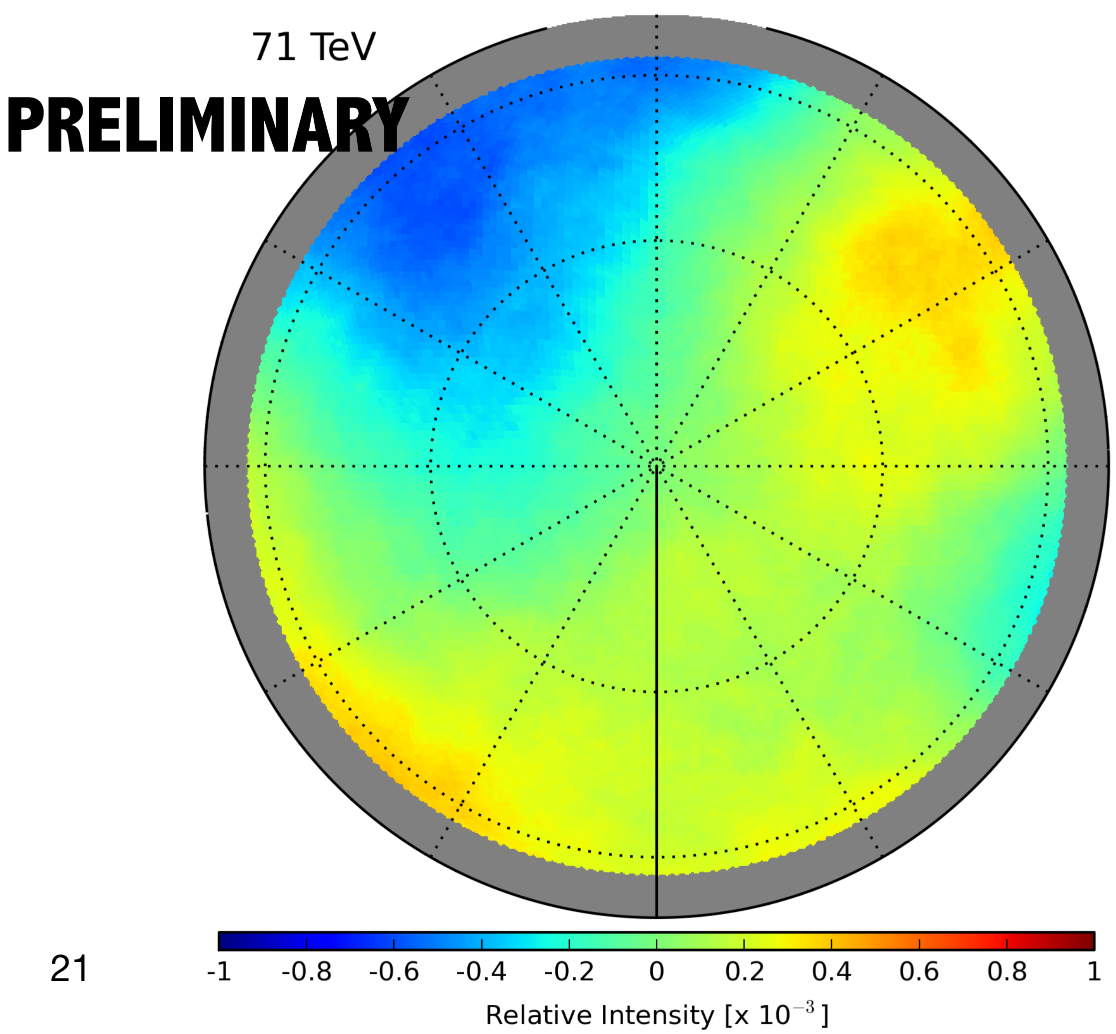
- high energy observations **MISSING** in the northern hemisphere
- **overlapping observations** extending across the equator will help
- capable of energy/mass measurement

cosmic rays anisotropy

arrival direction distribution





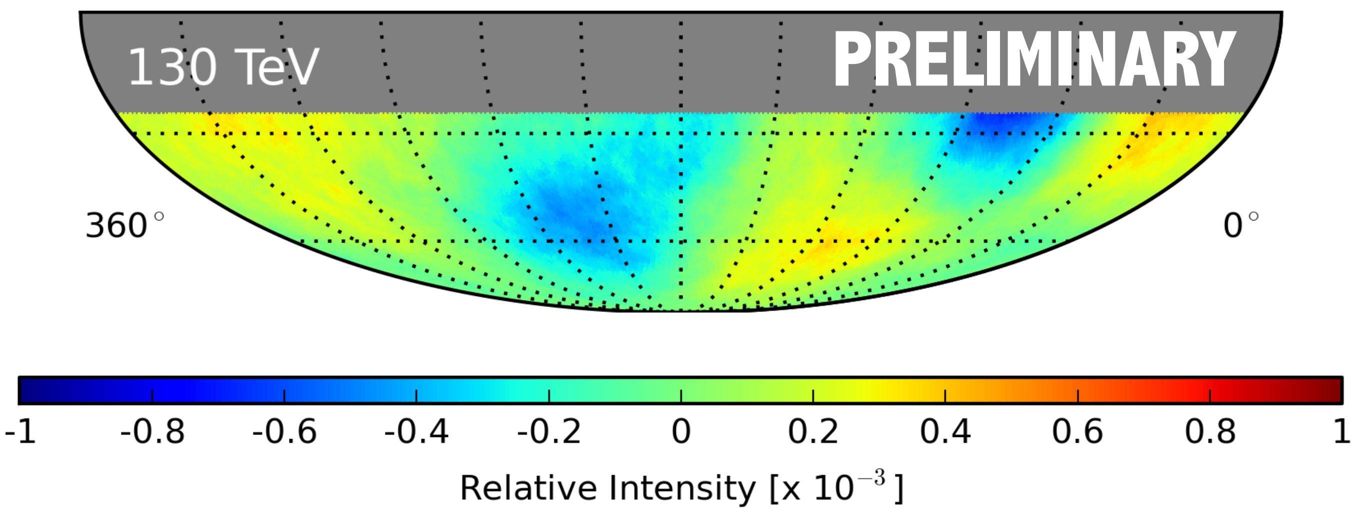


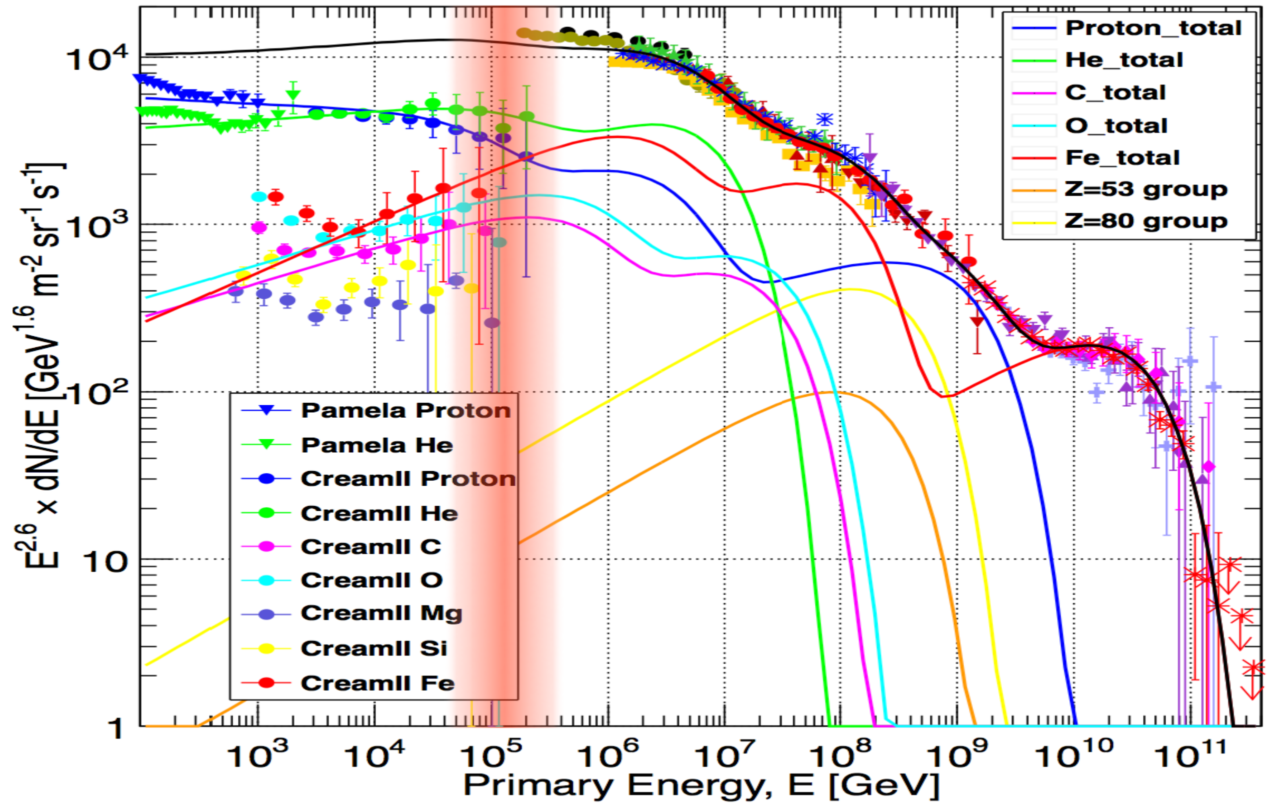
71 TeV **IceCube**

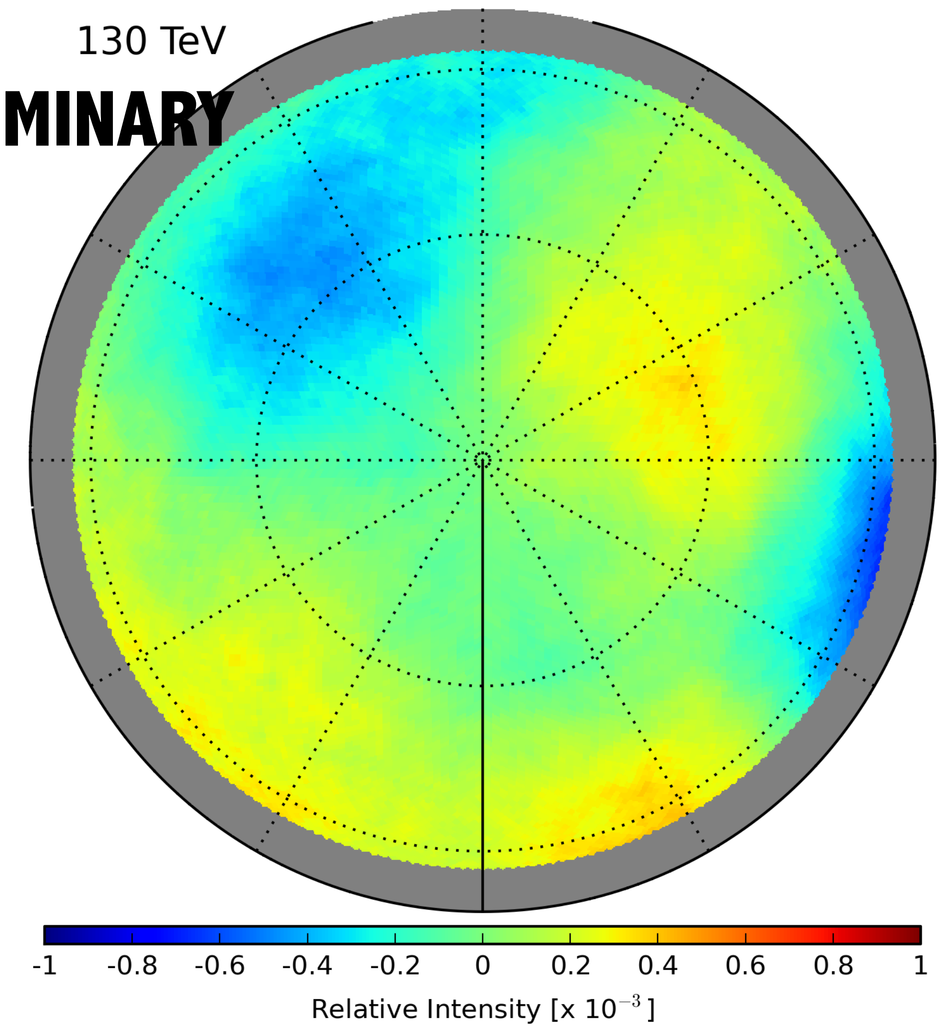
- high energy observations **MISSING** in the northern hemisphere
- **overlapping observations** extending across the equator will help
- capable of energy/mass measurement

cosmic rays anisotropy

arrival direction distribution





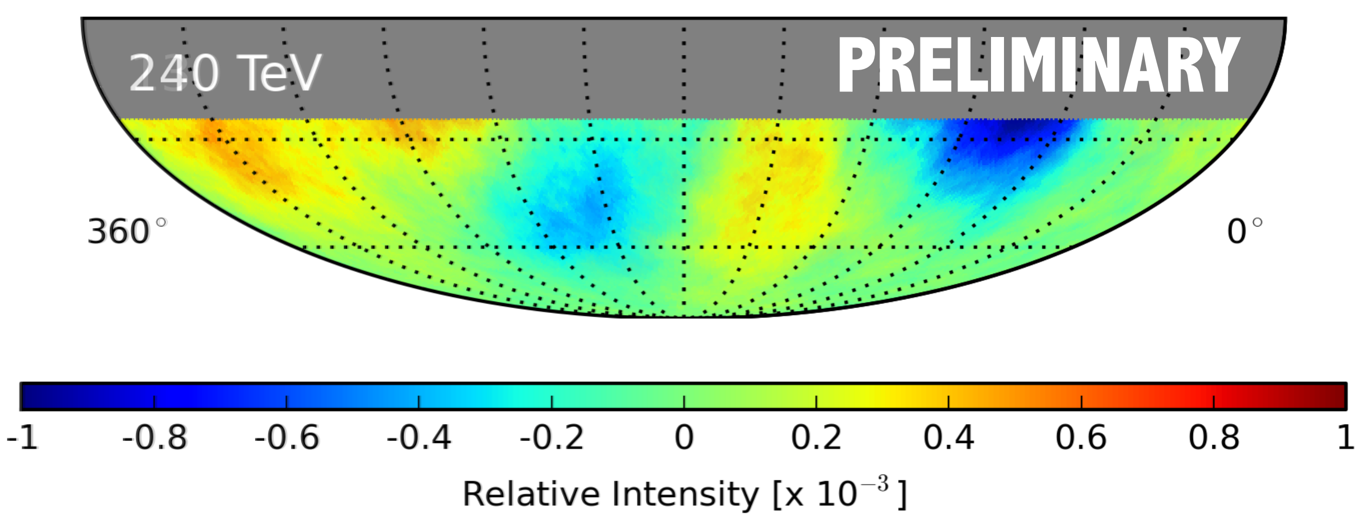


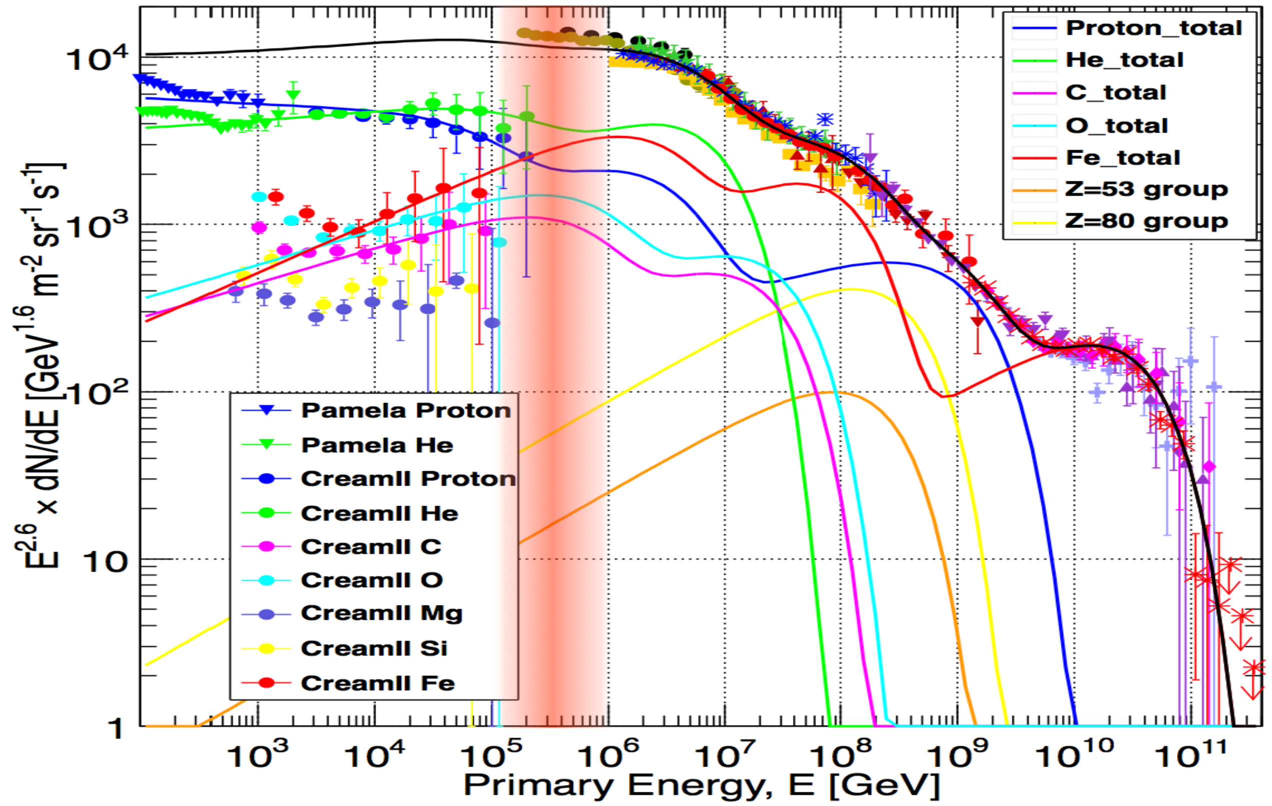
130 TeV **IceCube**

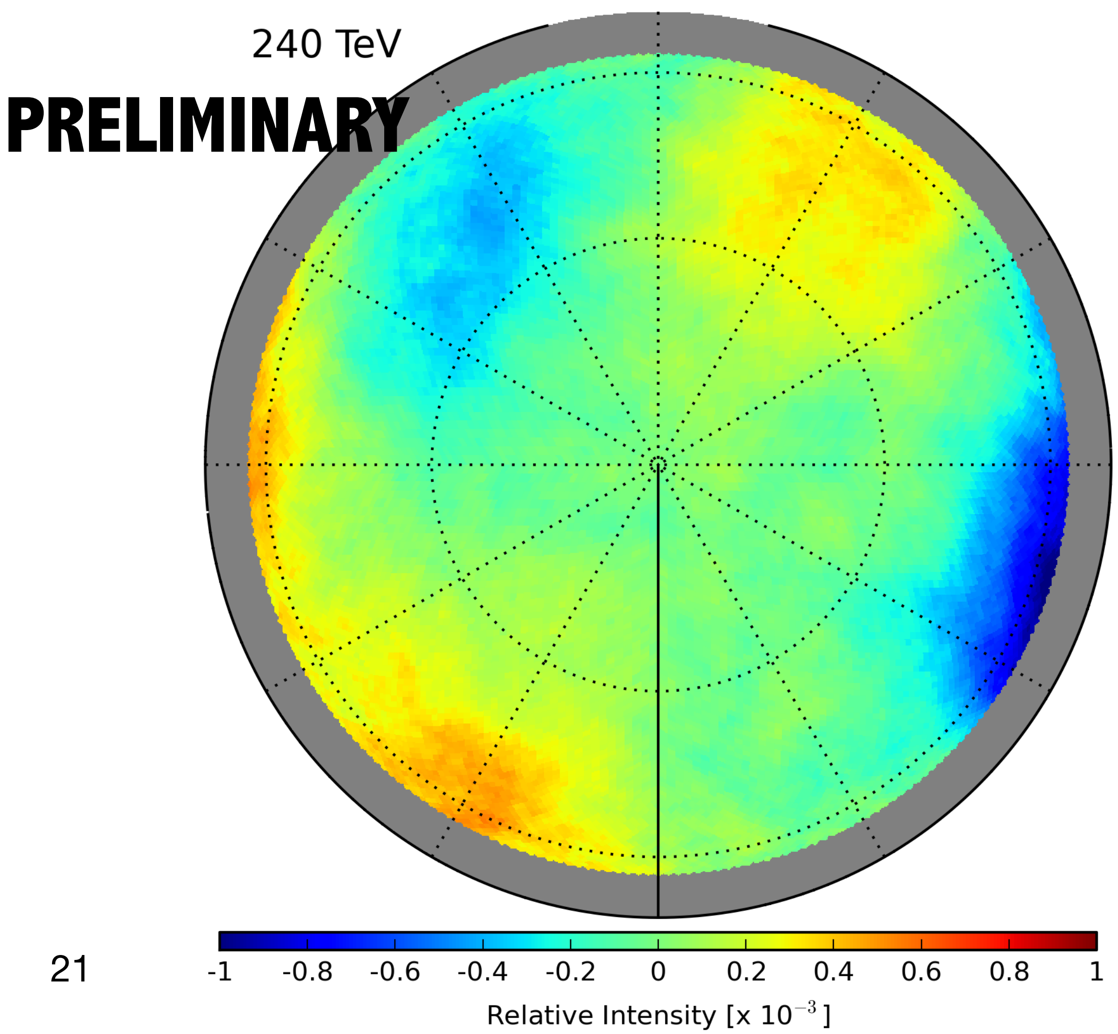
- high energy observations **MISSING** in the northern hemisphere
- **overlapping observations** extending across the equator will help
- capable of energy/mass measurement

cosmic rays anisotropy

arrival direction distribution





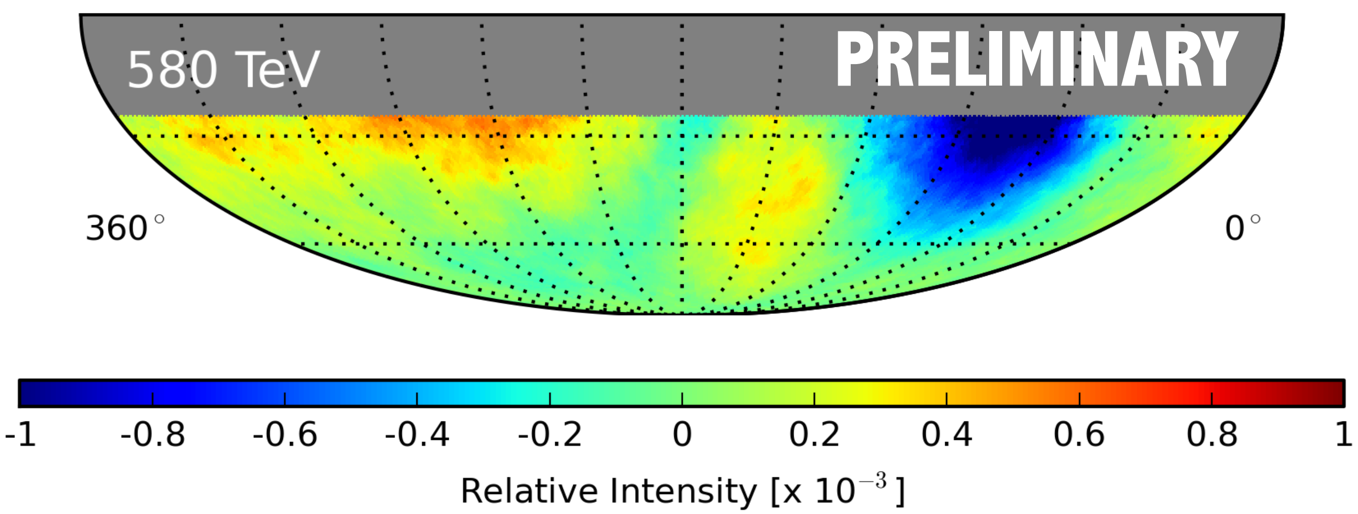


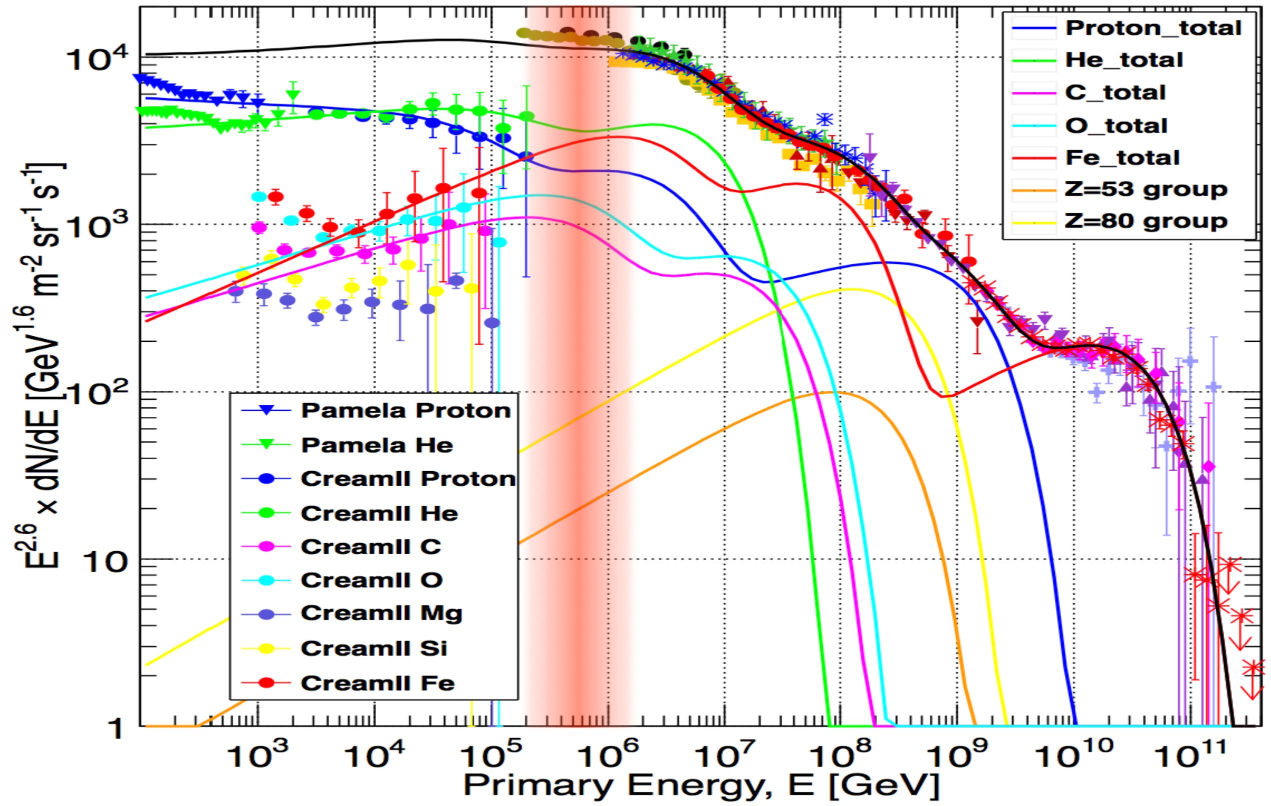
240 TeV **IceCube**

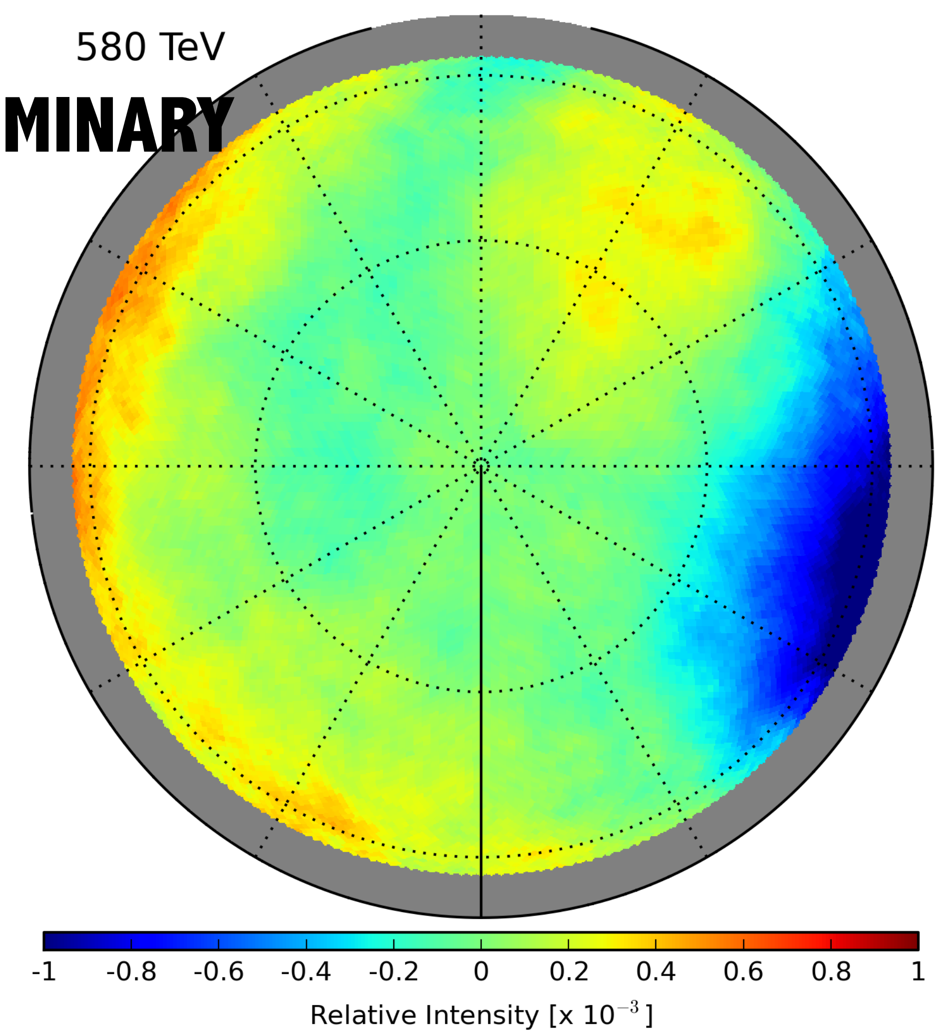
- high energy observations **MISSING** in the northern hemisphere
- **overlapping observations** extending across the equator will help
- capable of energy/mass measurement

cosmic rays anisotropy

arrival direction distribution





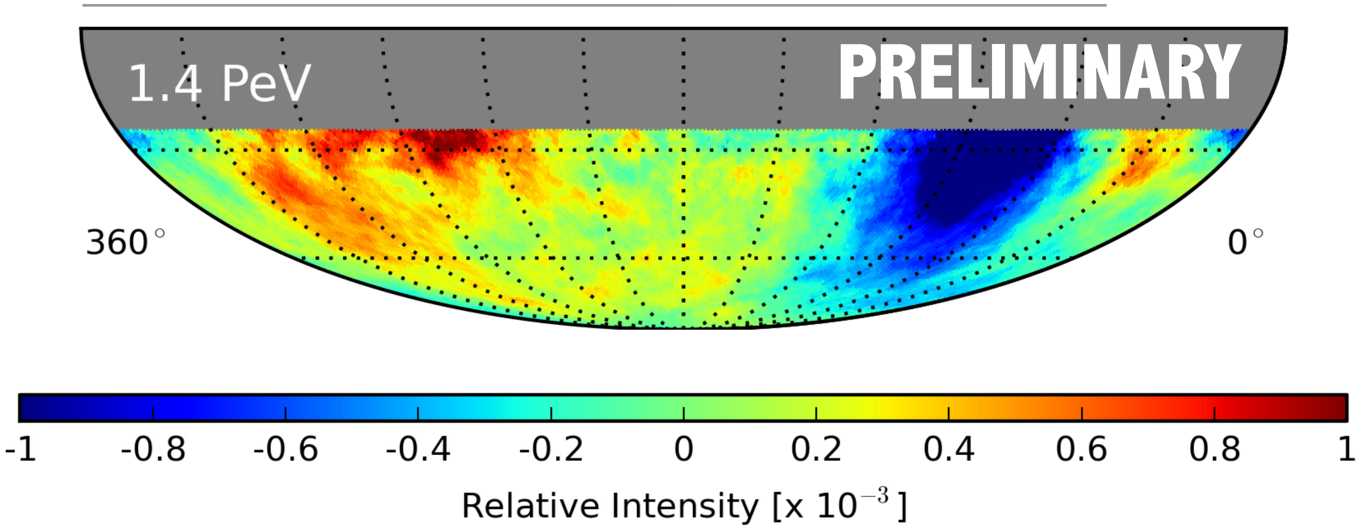


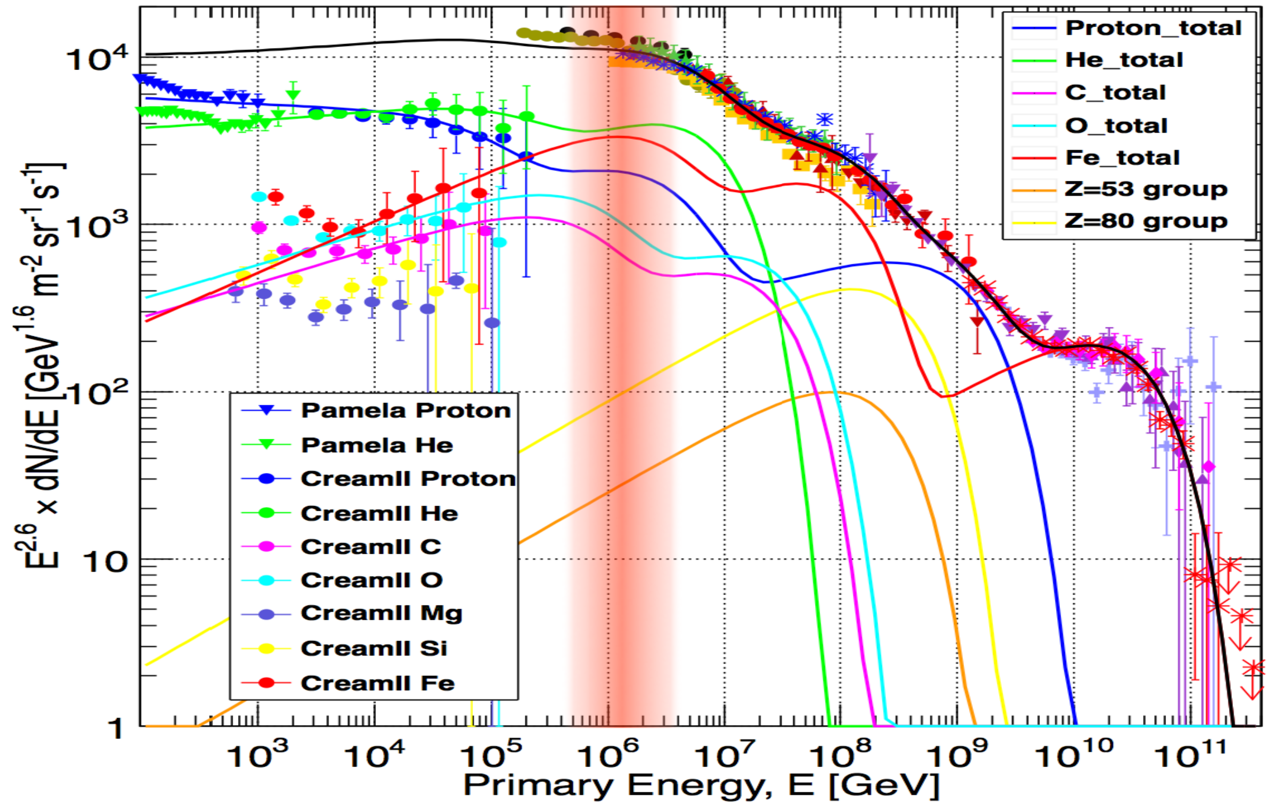
580 TeV **IceCube**

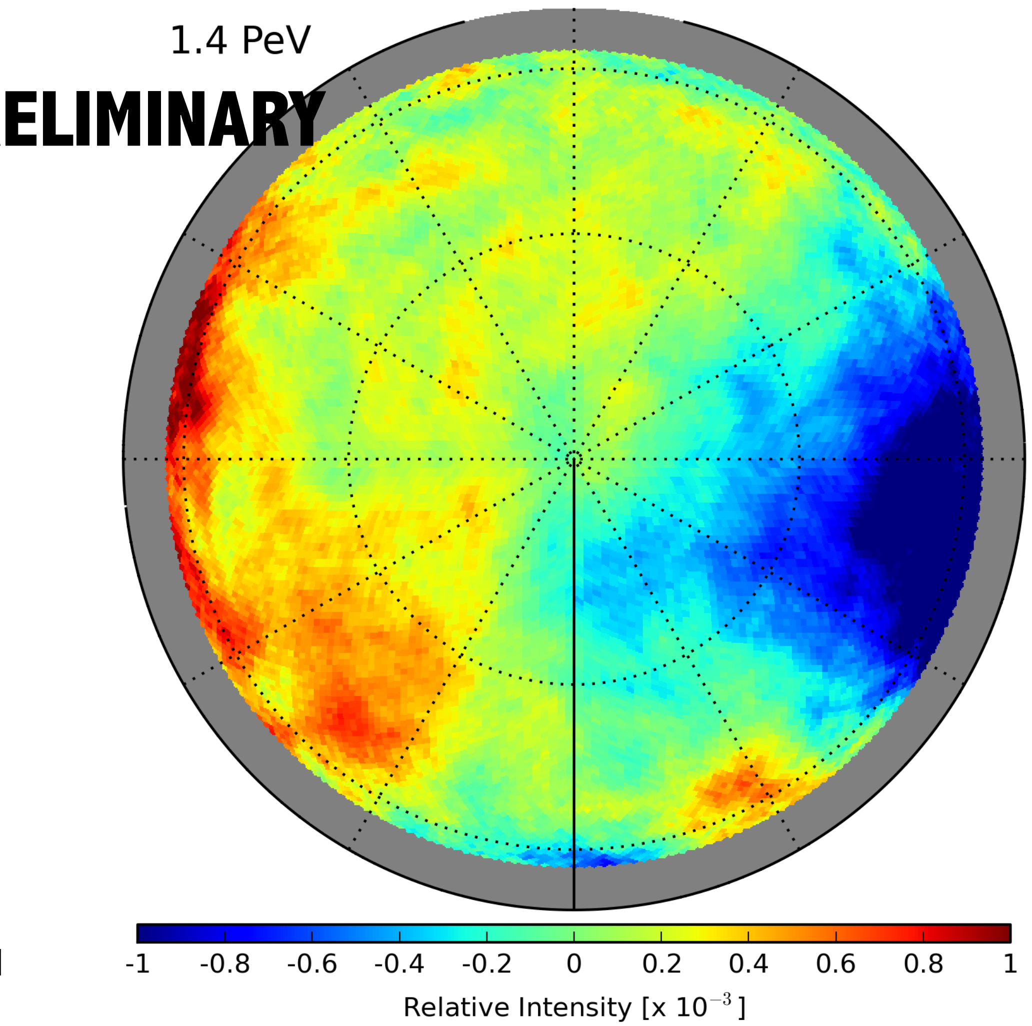
- high energy observations **MISSING** in the northern hemisphere
- **overlapping observations** extending across the equator will help
- capable of energy/mass measurement

cosmic rays anisotropy

arrival direction distribution



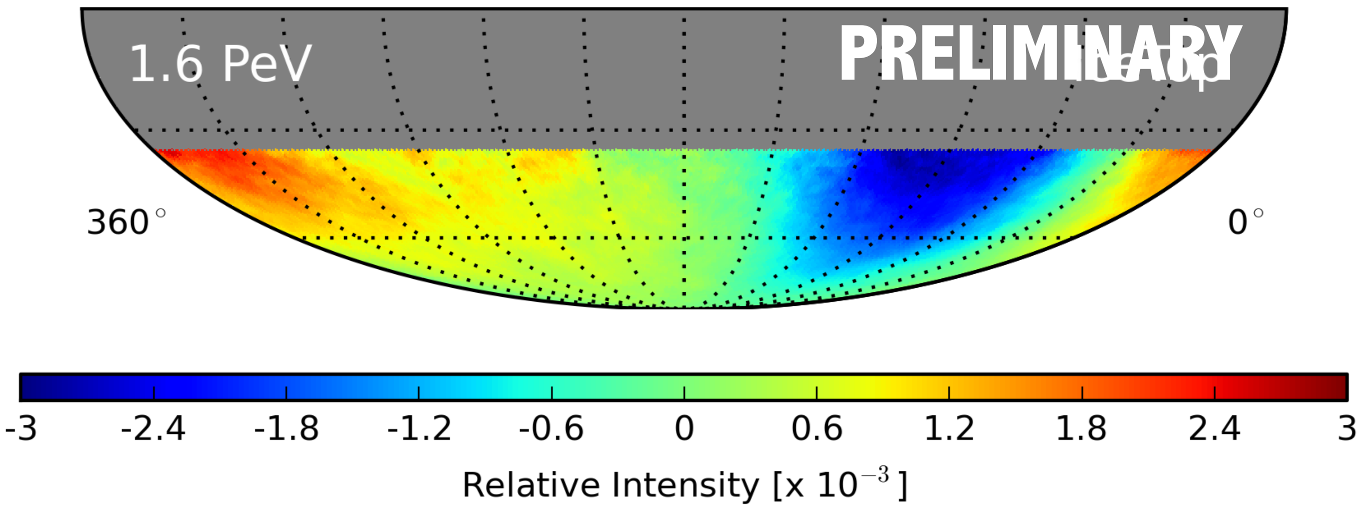


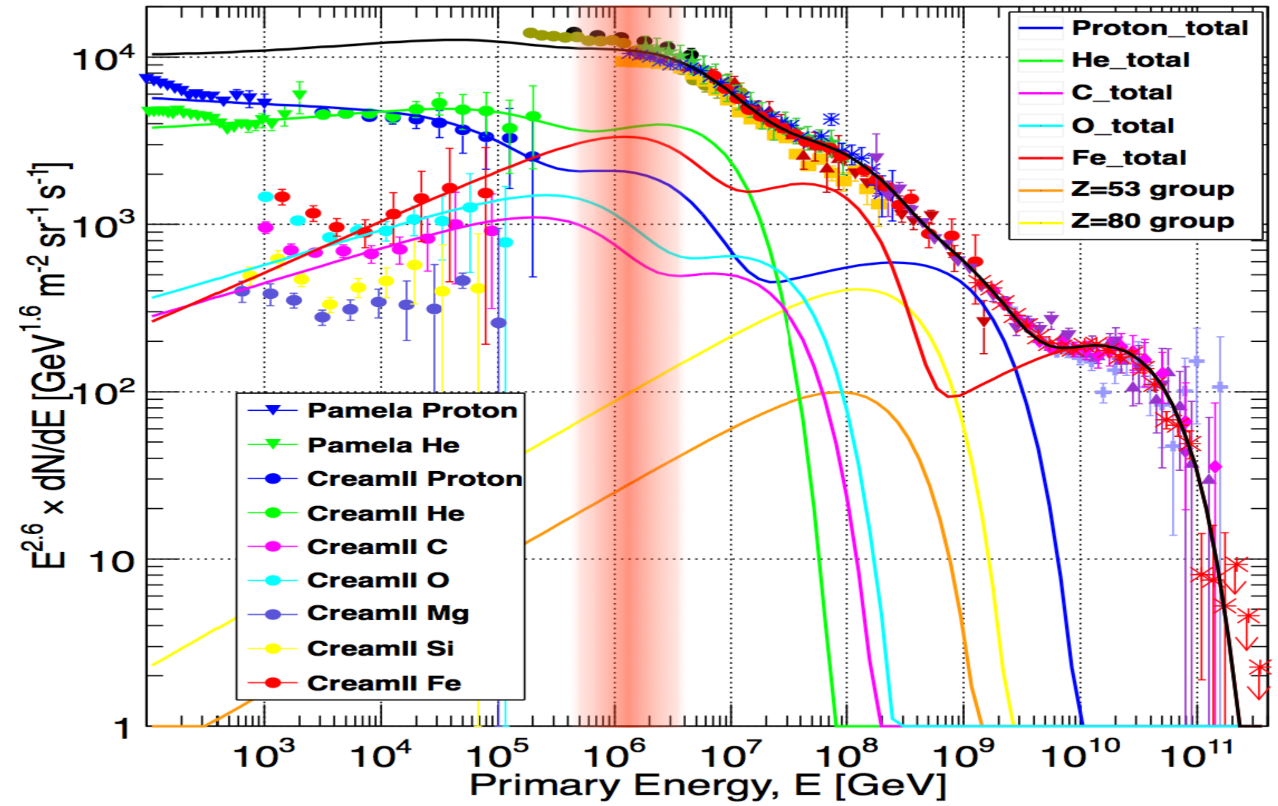


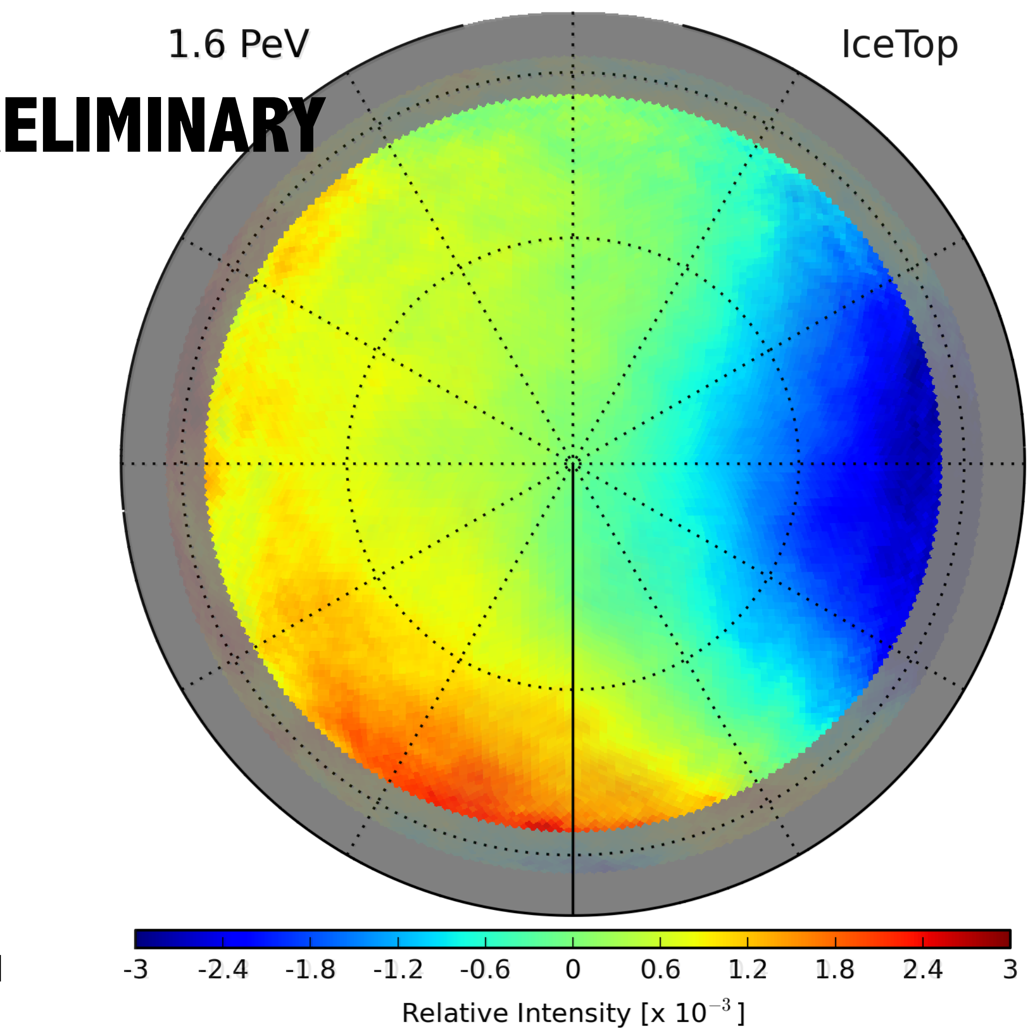
1.4 PeV **IceCube**

- 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





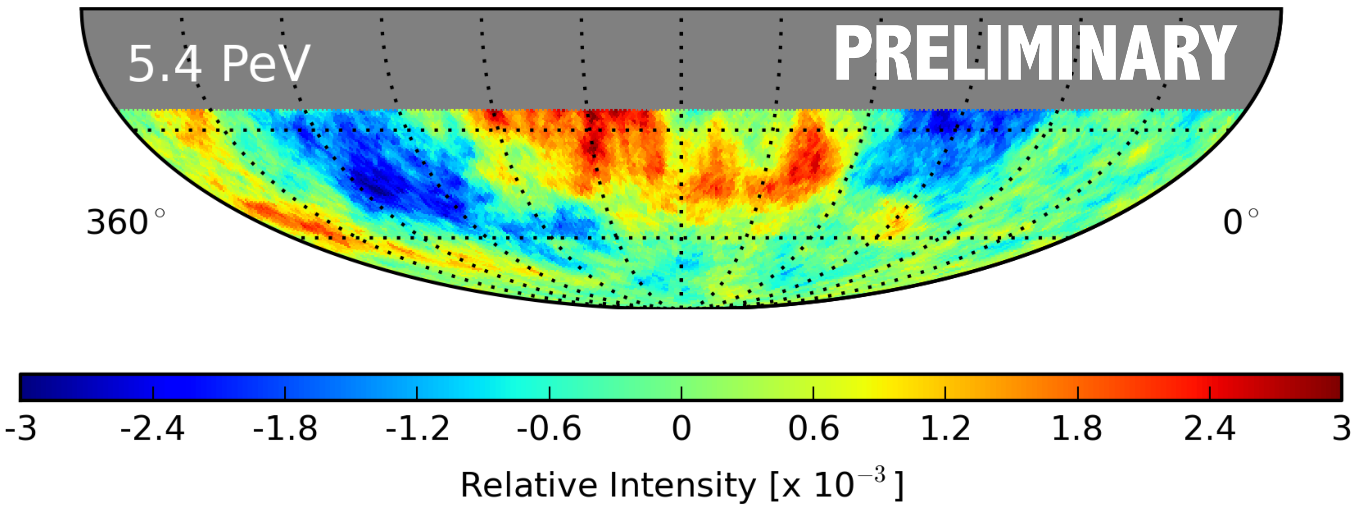


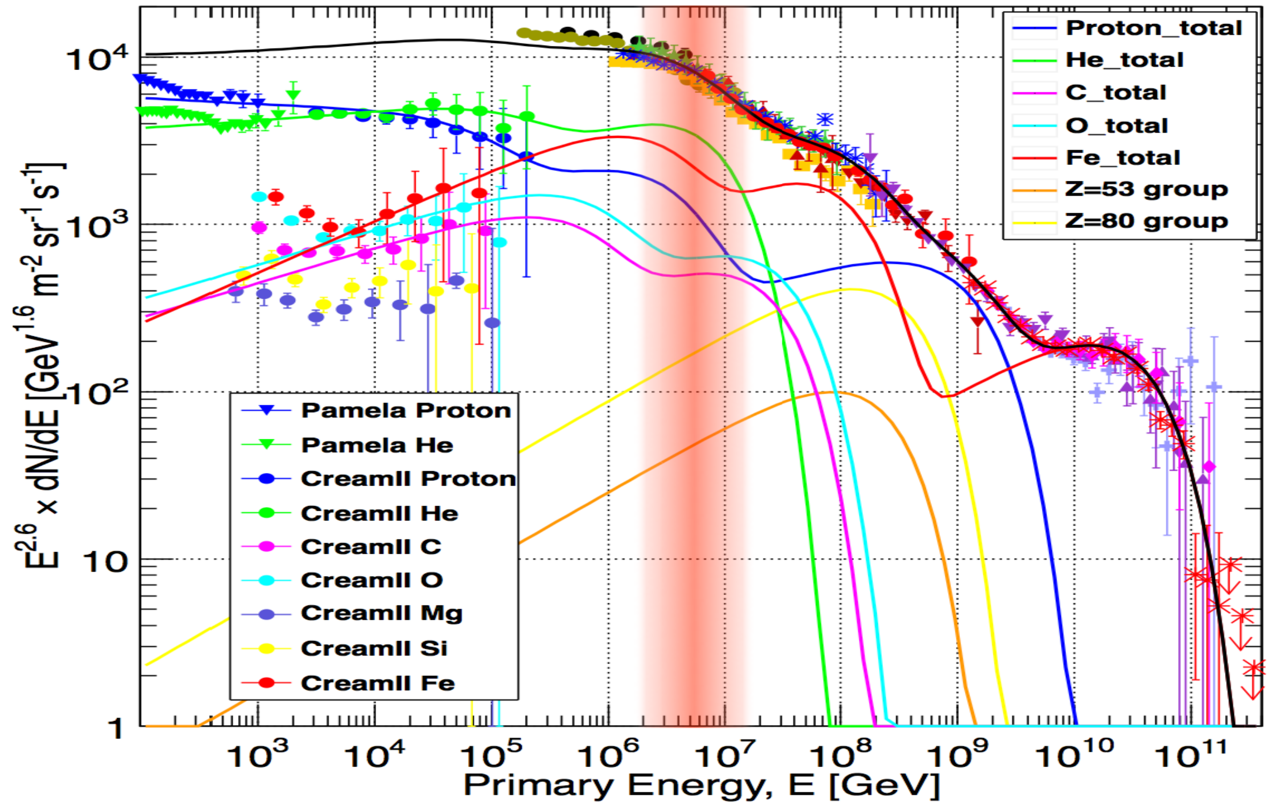
1.6 PeV **IceTop**

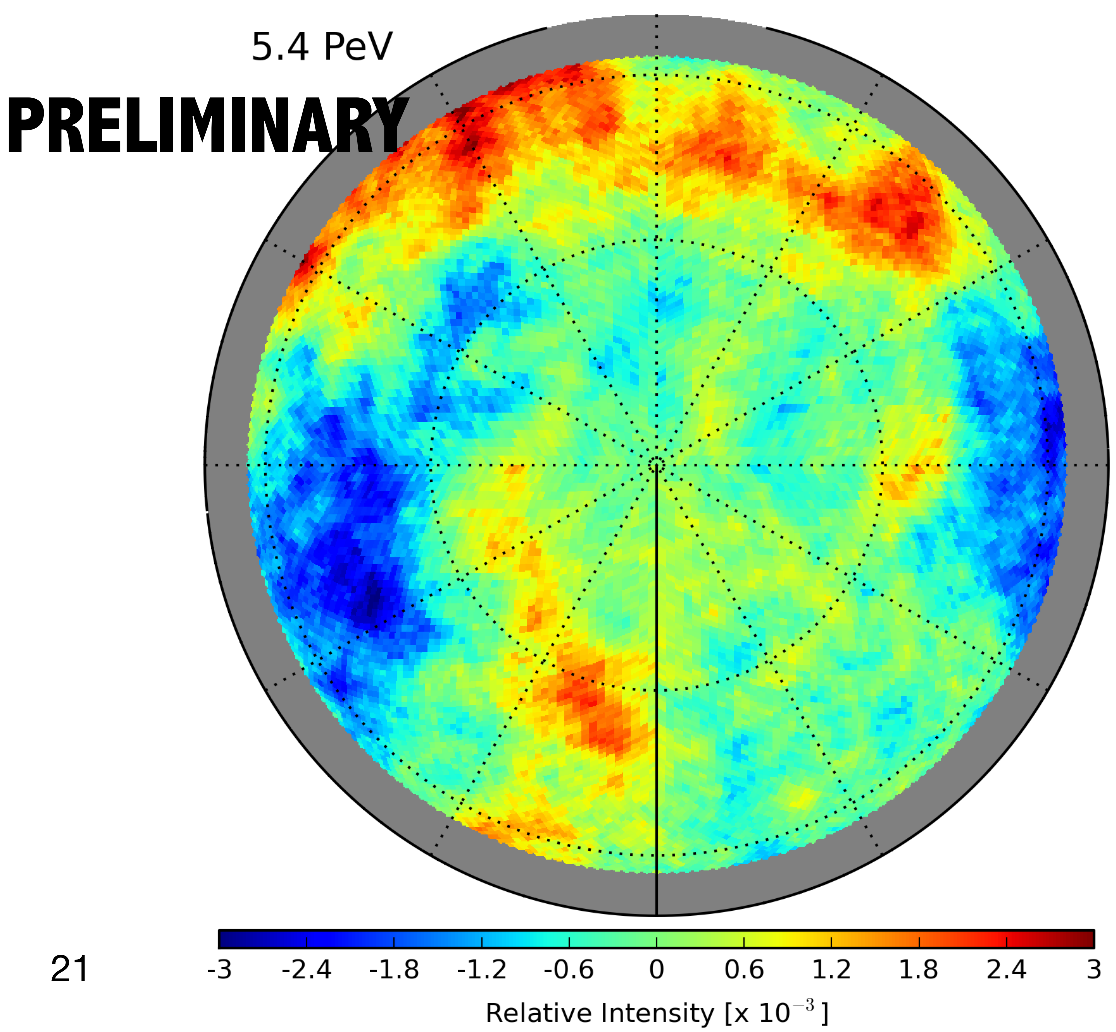
- high energy observations **MISSING** in the northern hemisphere
- **overlapping observations** extending across the equator will help
- capable of energy/mass measurement

cosmic rays anisotropy

arrival direction distribution







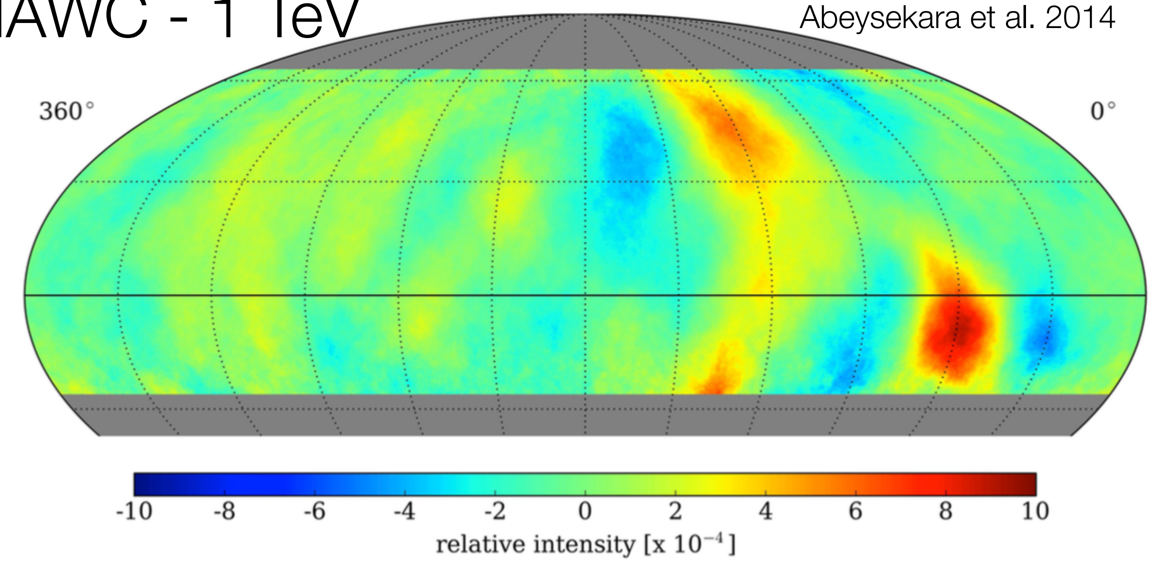
5.4 PeV **IceCube**

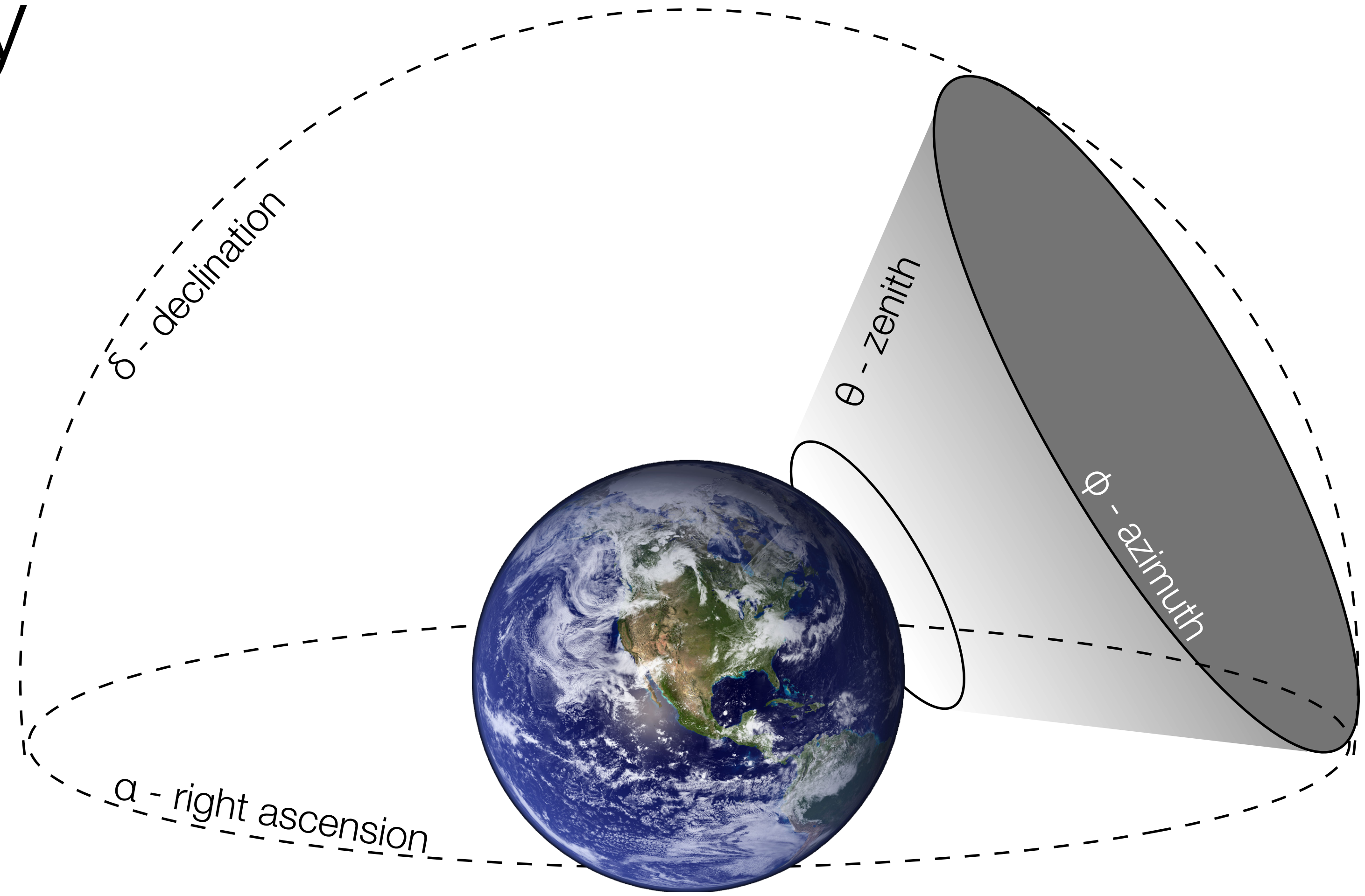
- high energy observations **MISSING** in the northern hemisphere
- **overlapping observations** extending across the equator will help
- capable of energy/mass measurement

cosmic rays anisotropy
full-sky coverage

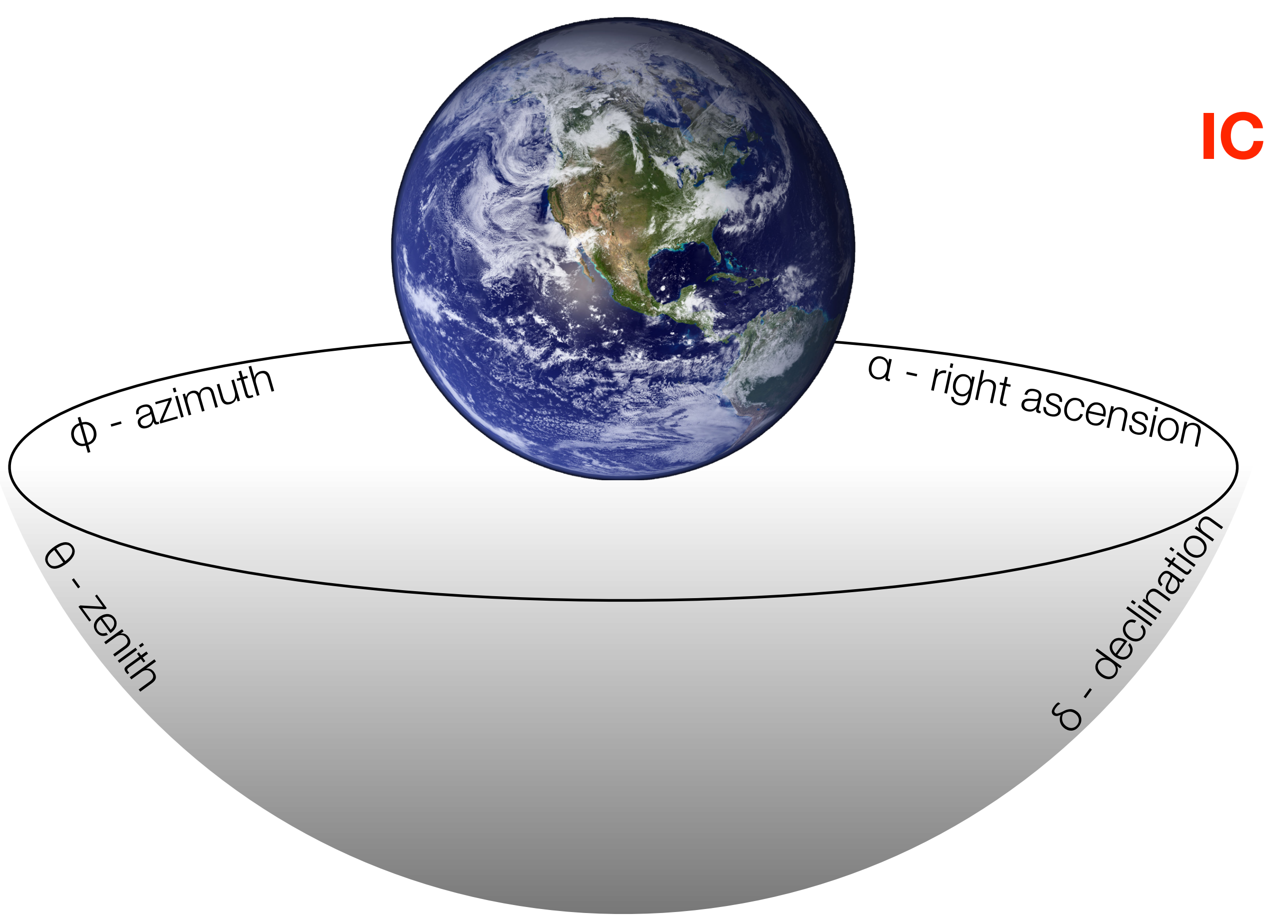
HAWC - 1 TeV

small scale anisotropy
Abeysekara et al. 2014



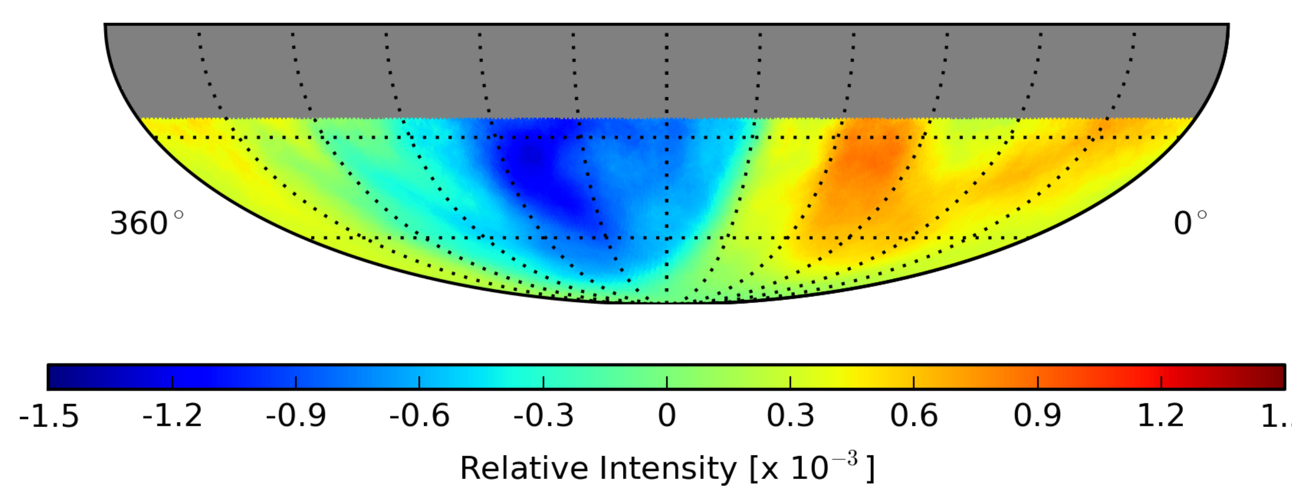


ICRC 2015

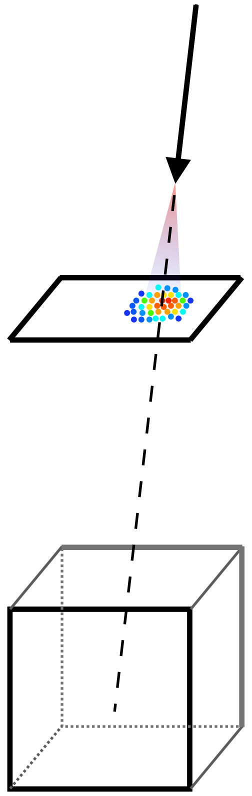


IceCube - 20 TeV

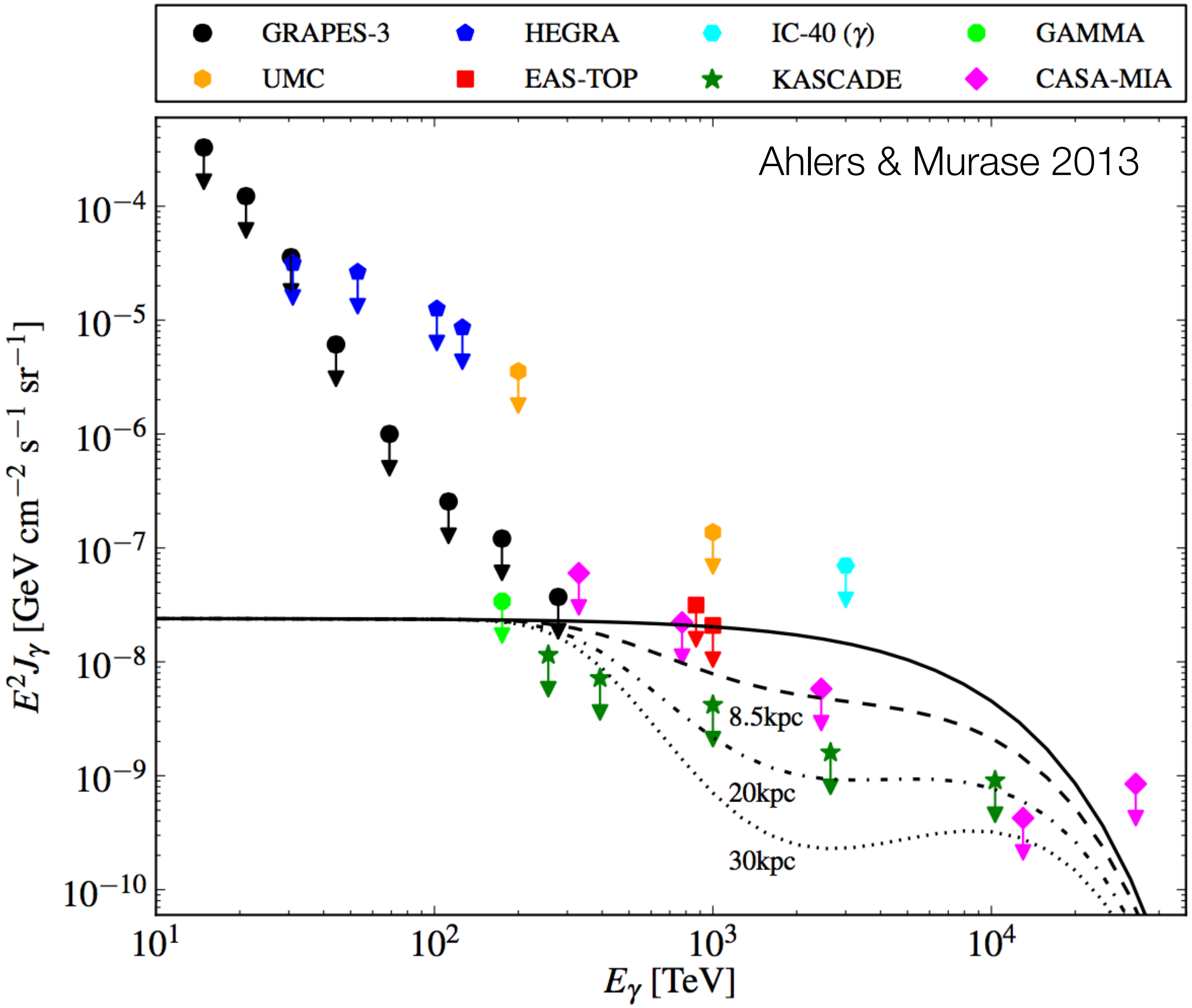
Abbasi et al. 2010, 11,12
Aartsen et al. 2013



PeV gamma rays
galactic origin



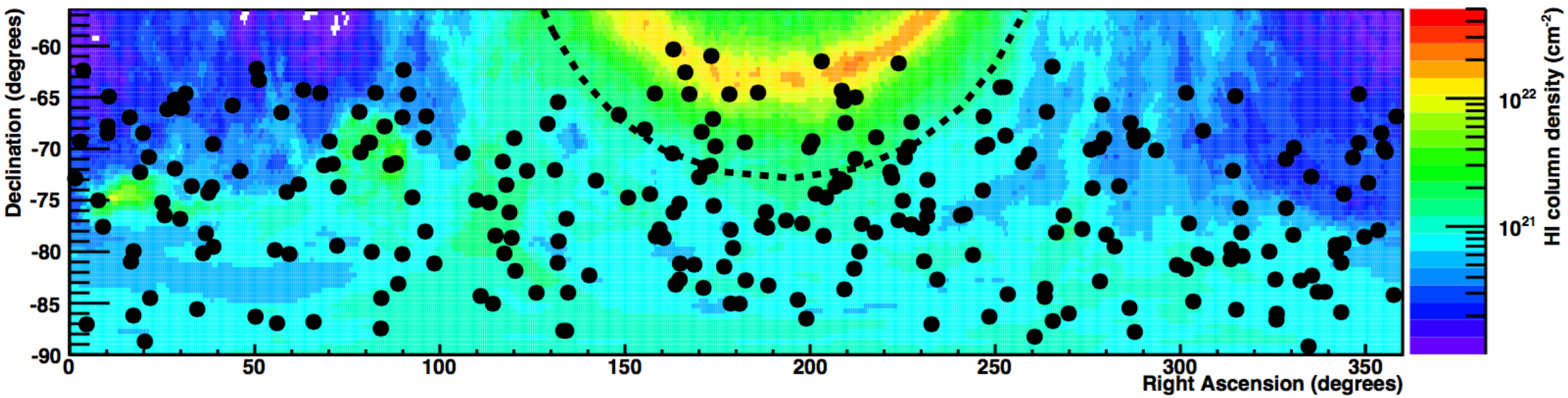
- galactic sources of PeV γ rays
- disfavored by CASA-MIA & KASCADE
- HAWC, LHAASO, HiSCORE ?
- IceCube the only experiment in **Southern Hemisphere**
- need to **reduce the blind region** in the southern hemisphere (where GC is located)

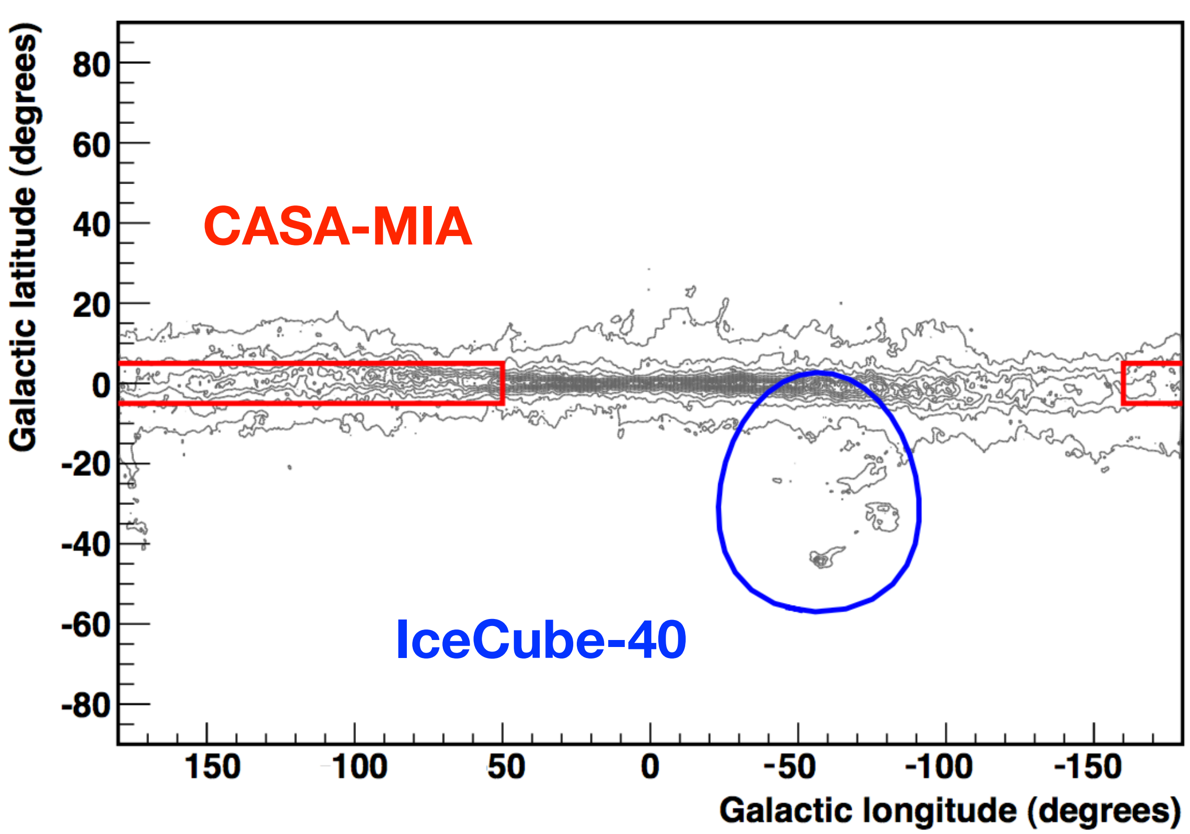


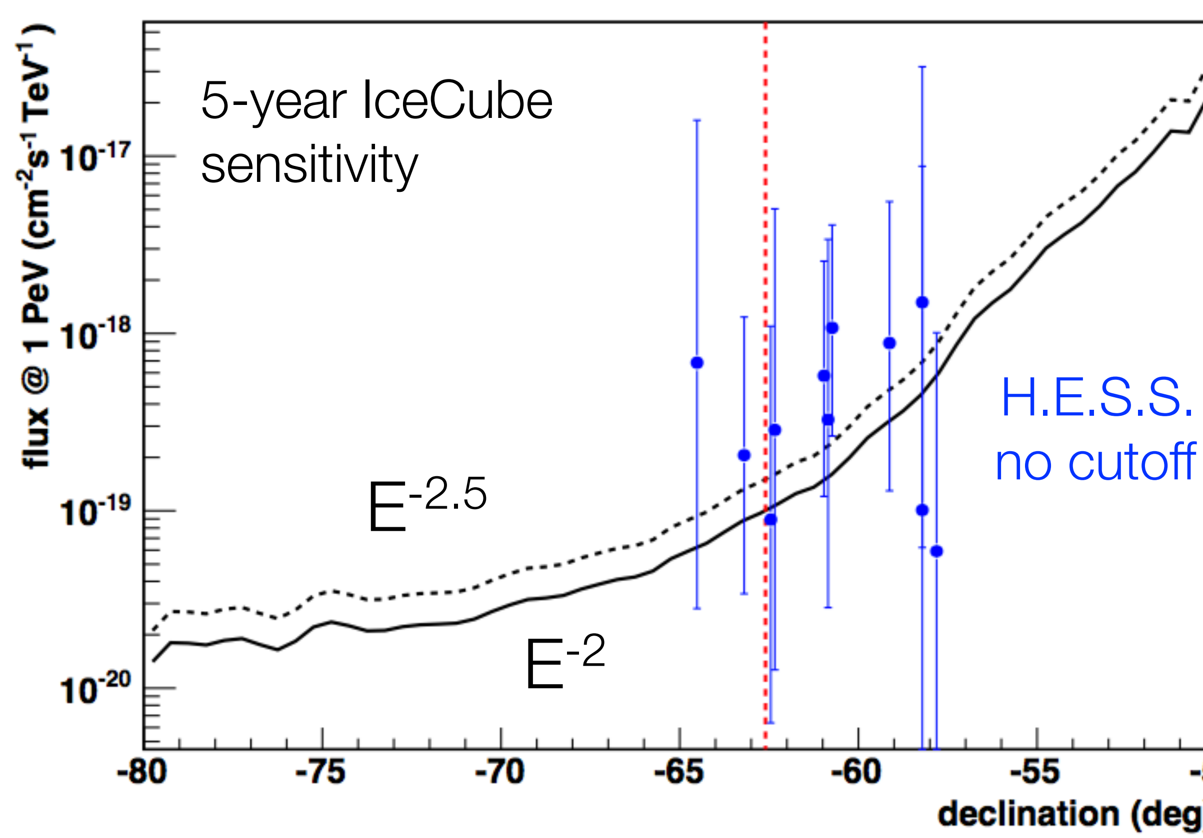
PeV gamma rays

galactic origin

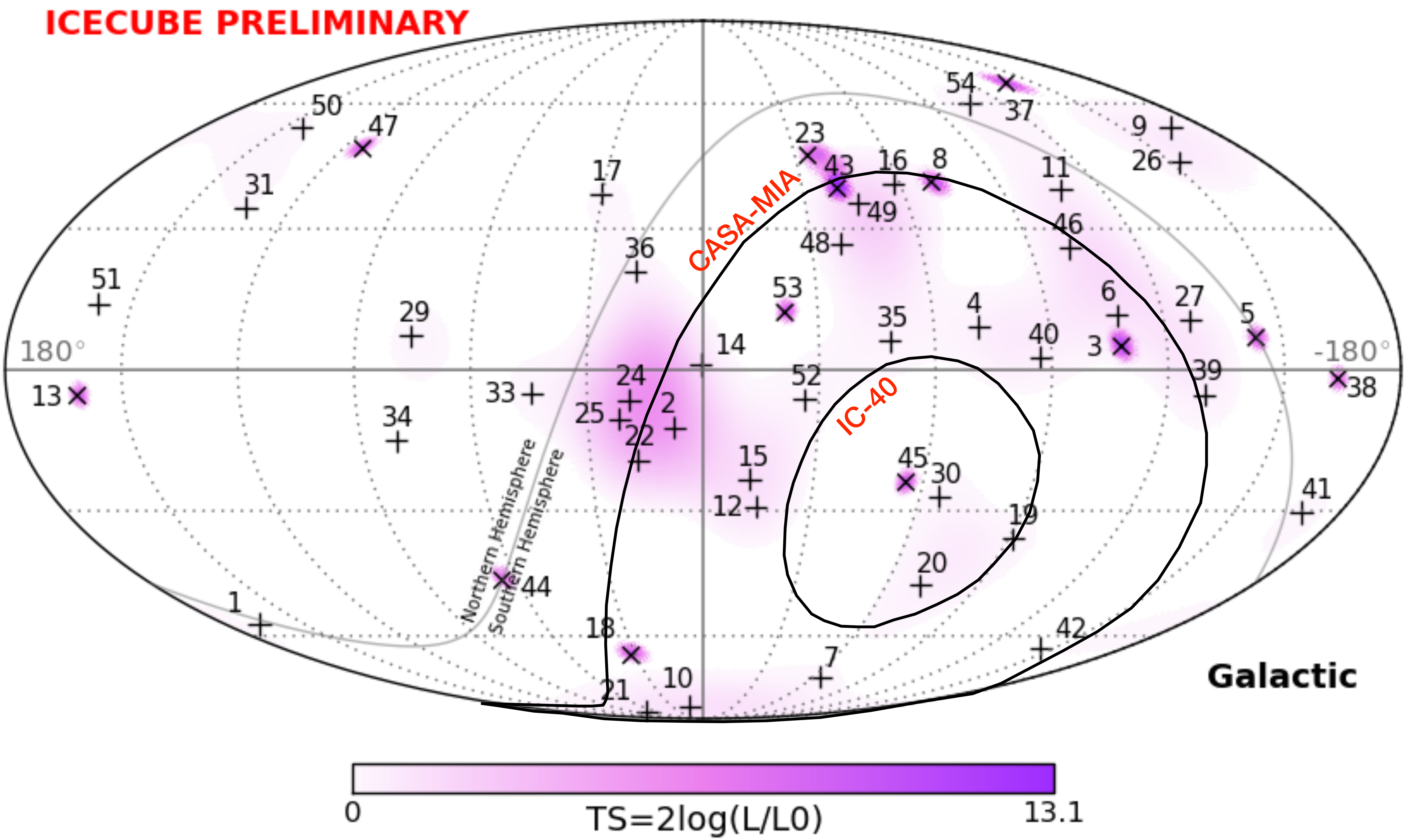
IC40 - Aartsen et al., 2012



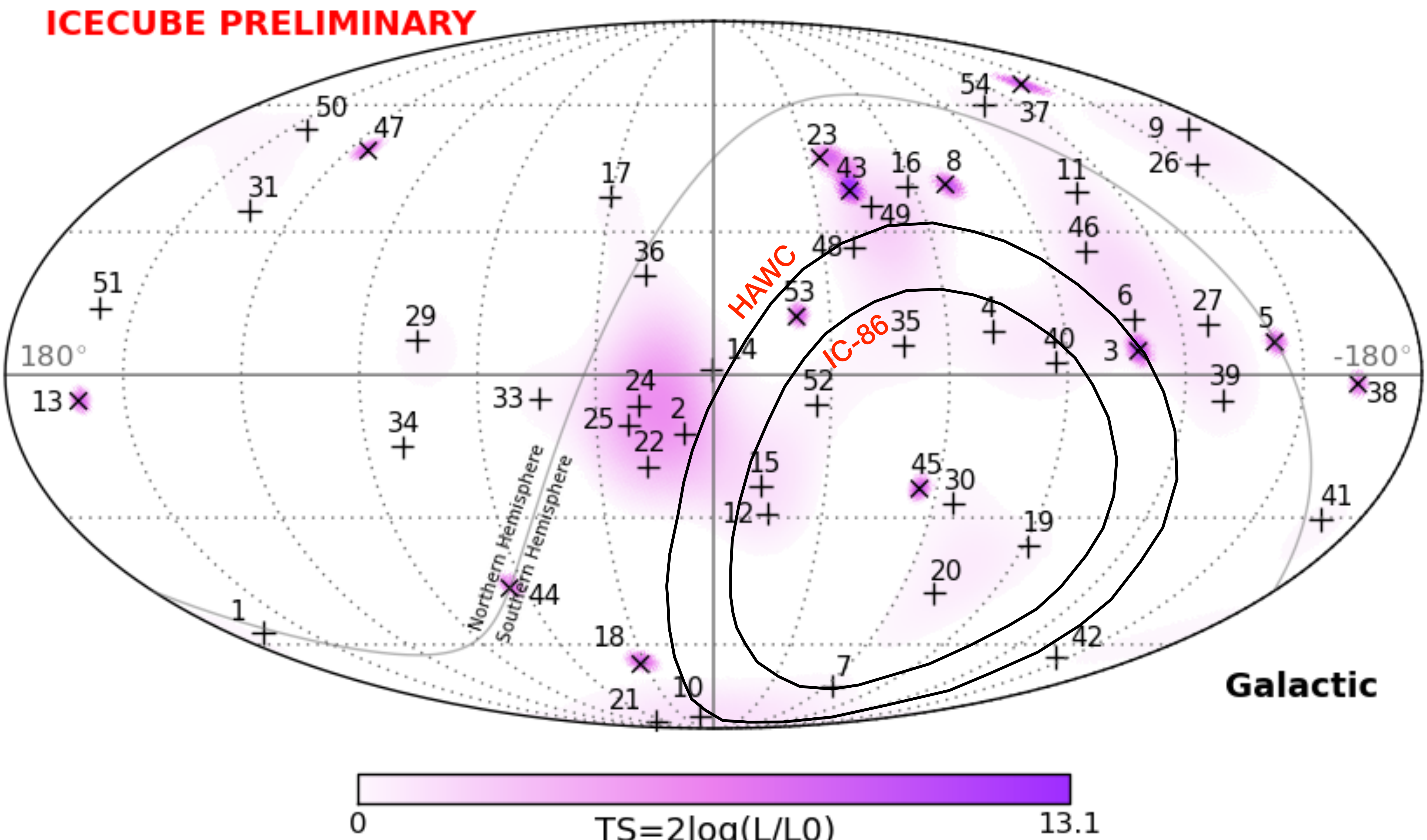




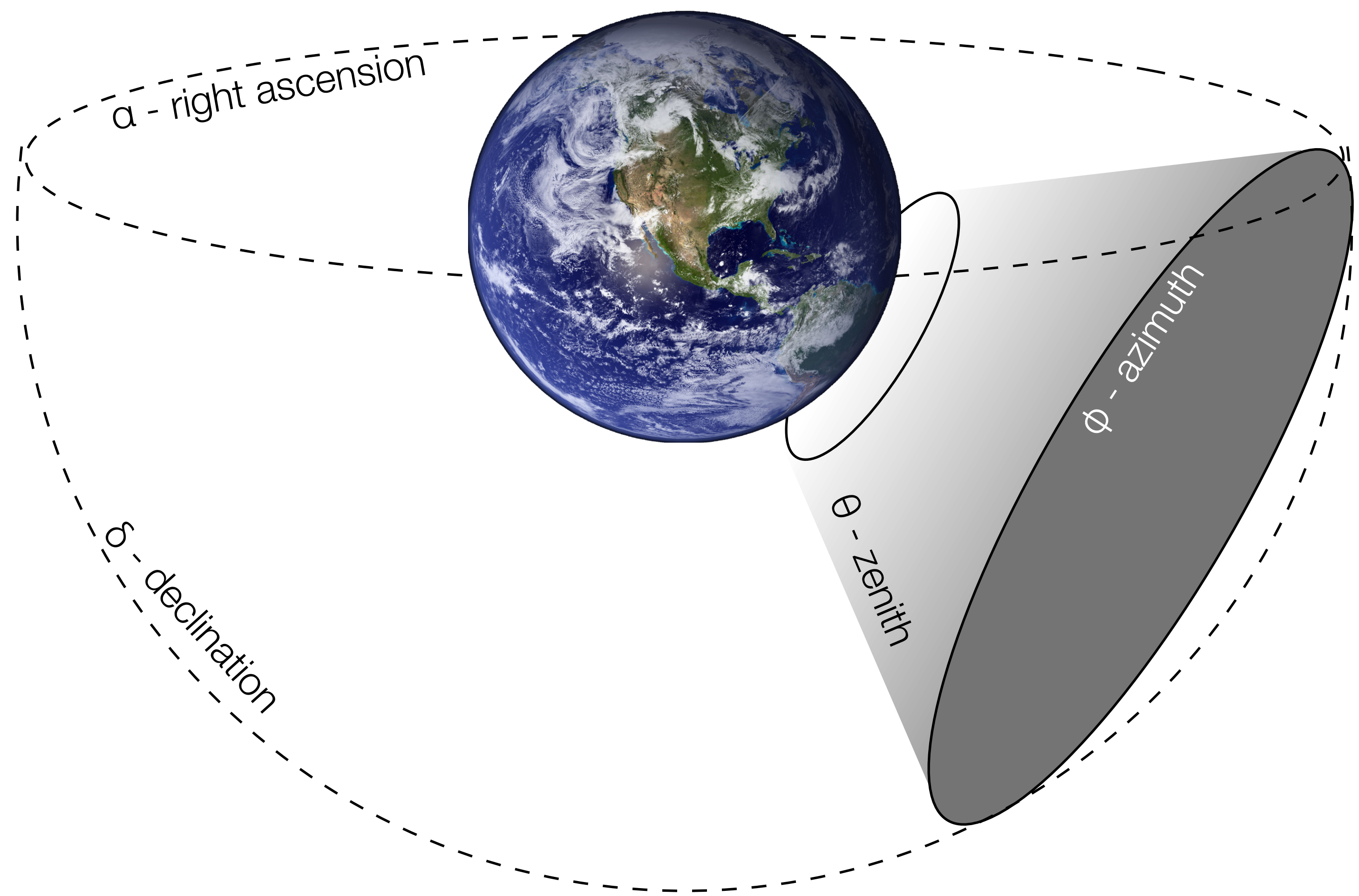
PeV gamma rays

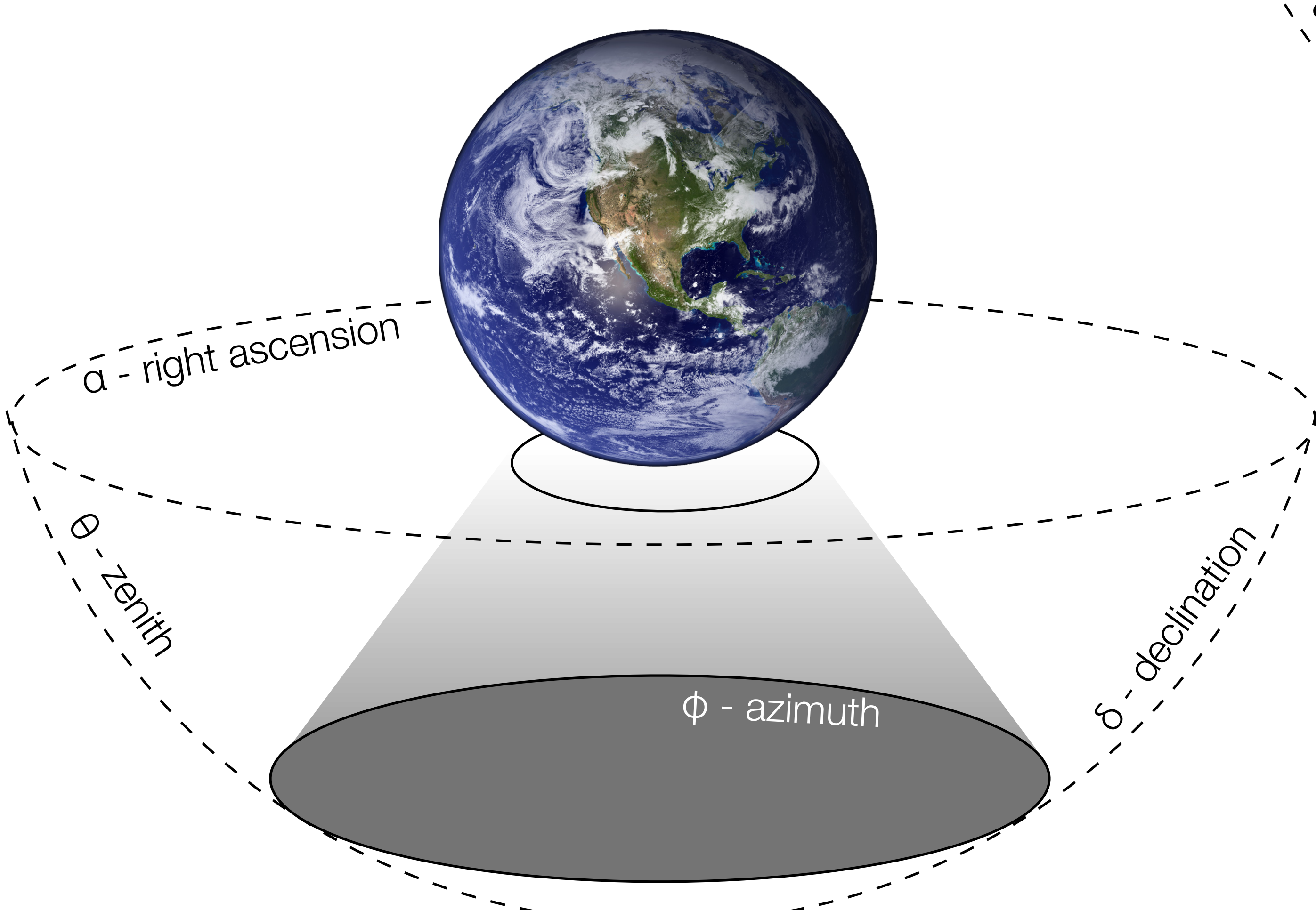


PeV gamma rays



cosmic and γ rays observations
extended sky coverage





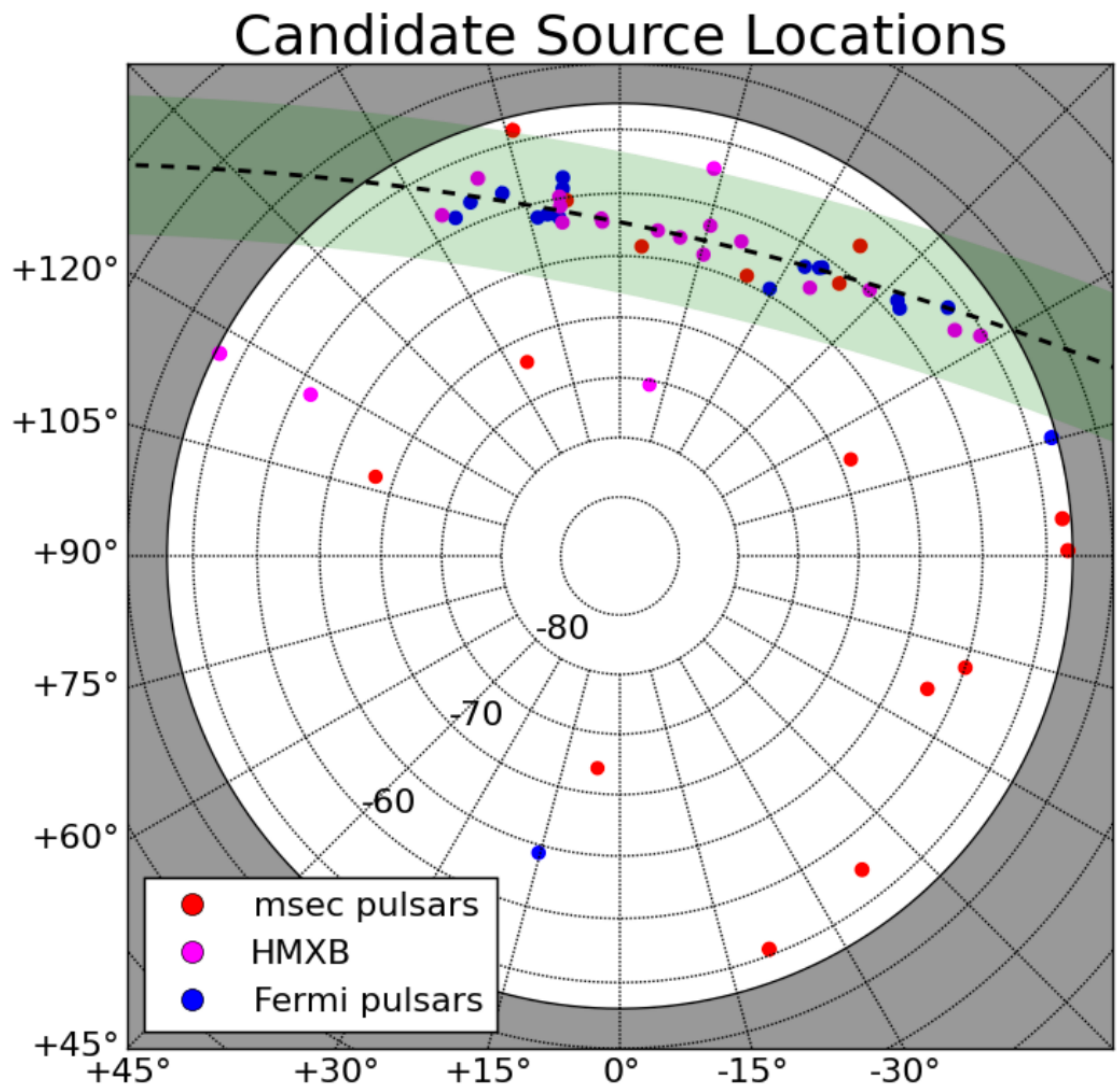
- sky **overlap** for cross-calibration and systematics
- **extension** of the observable sky

neutron point sources

nearby galactic sources with 4 years of IceTop

ICRC 2015

- cosmic ray neutron range **R ~ 10 pc × E_{PeV}**
- all-visible-sky search > 10 PeV
- targeted source search > 100 PeV

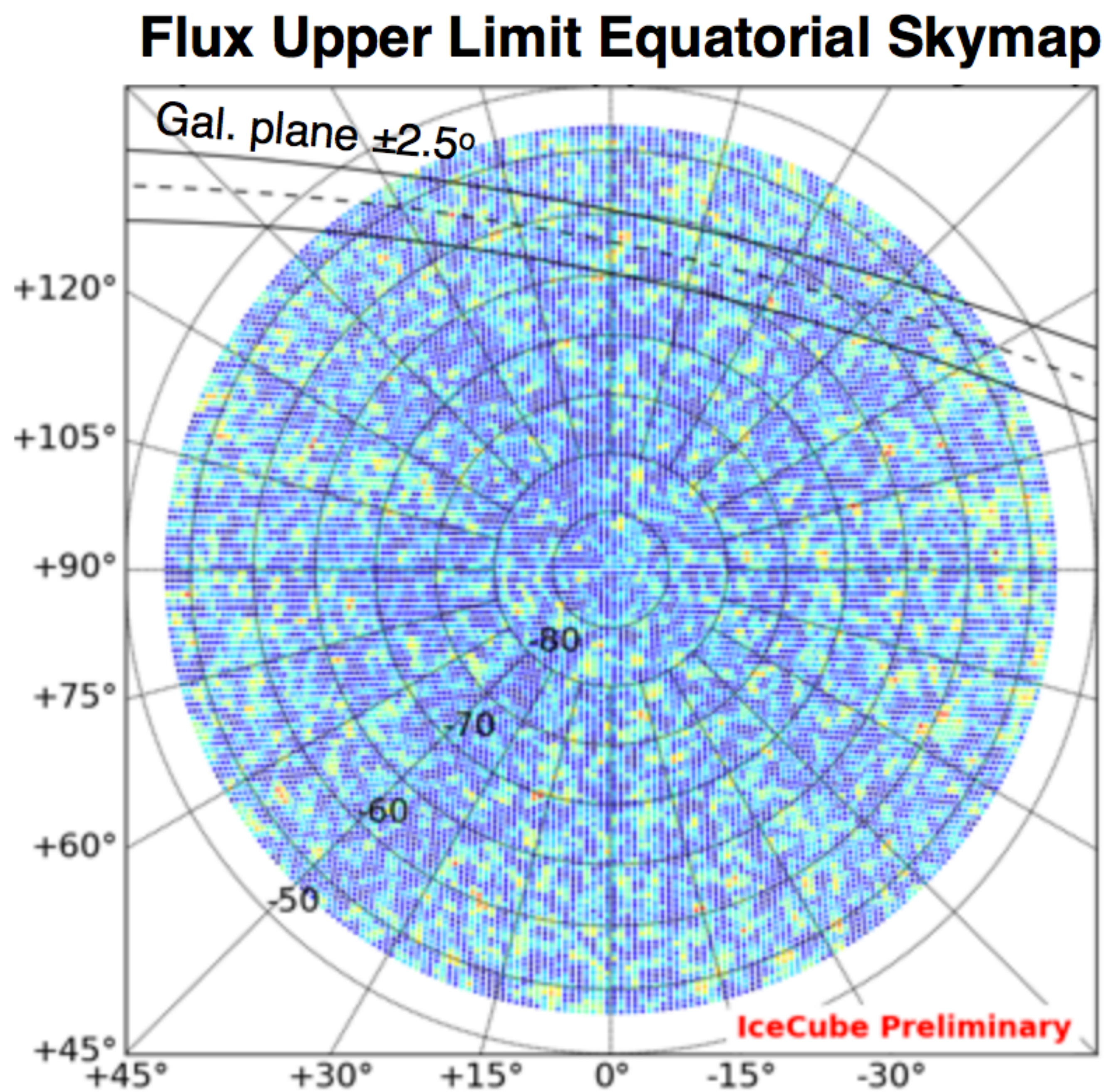


$\theta < 27^{\circ}$

neutron point sources
nearby galactic sources with 4 years of IceTop

- cosmic ray neutron range **R ~ 10 pc × E_{PeV}**
- all-visible-sky search > 10 PeV
- targeted source search > 100 PeV
- **no significant excess found in all-sky search**
- **no significant correlations found with candidate source catalogue**

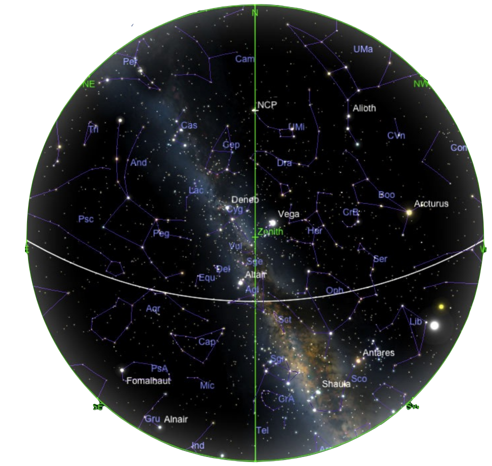
ICRC 2015



θ < 27°

conclusions

with extended or full sky coverage



<u>neutral messengers</u>

- important for astrophysics of cosmic ray origin
    - Earth $\boldsymbol{\nu}$ & $\boldsymbol{\gamma}$ observatories at comparable high energies (up to **PeV range**)
    - unveil **galactic** and/or **extra-galactic** sources of cosmic rays

<u>charged cosmic rays</u>

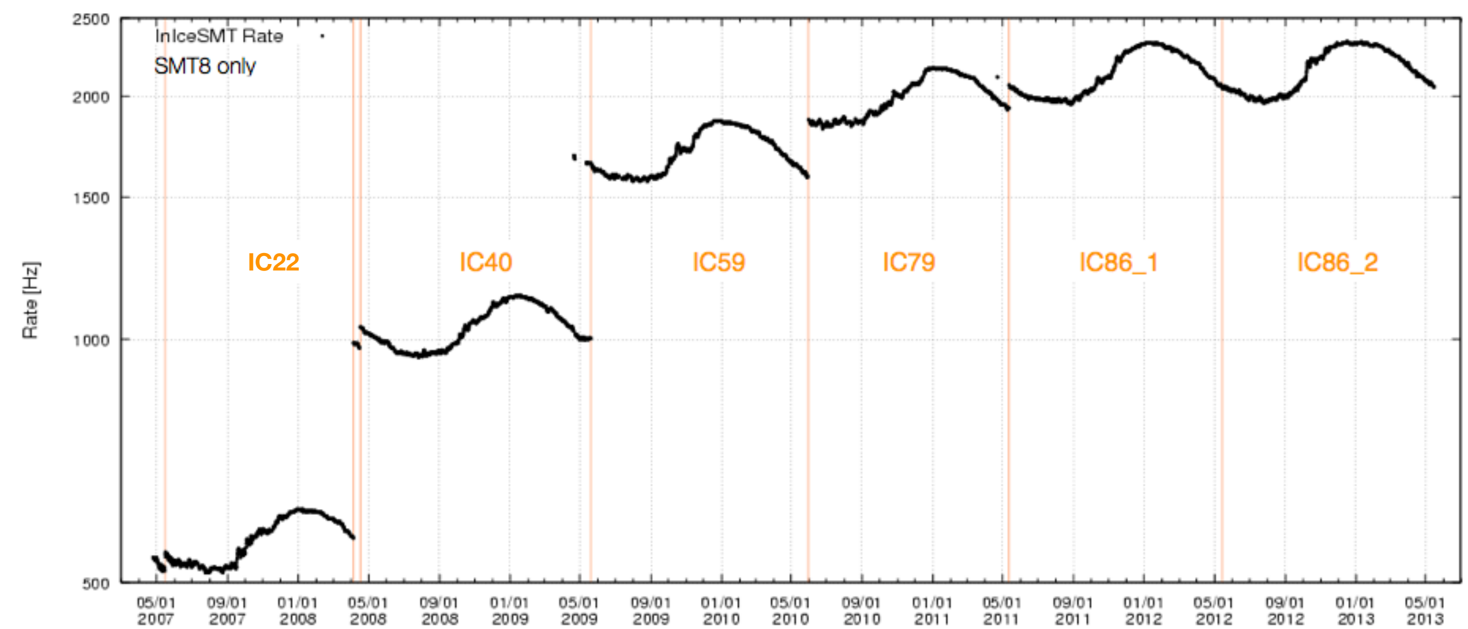
- important for **UHECR**: spectrum, composition & anisotropy (Auger & TA)
- bound to impact understanding of **TeV/PeV CR** anisotropy
    - probe into local interstellar medium: coherent and turbulent magnetic field
    - impact on e^-e^+ *anomalies* and disentanglement from astrophysical sources

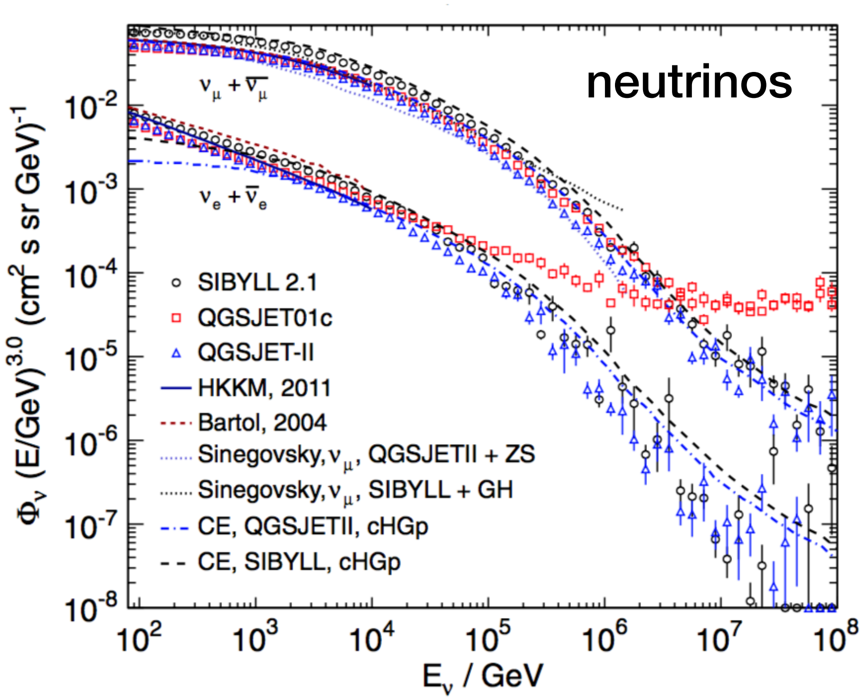
GRAZIE!

backup slides

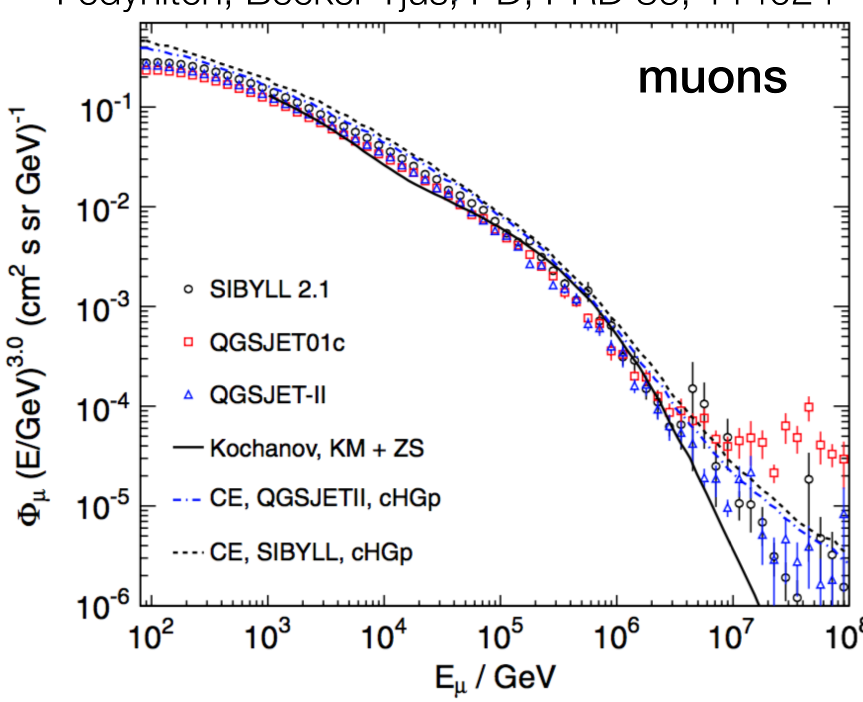
cosmic ray muons and neutrinos

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





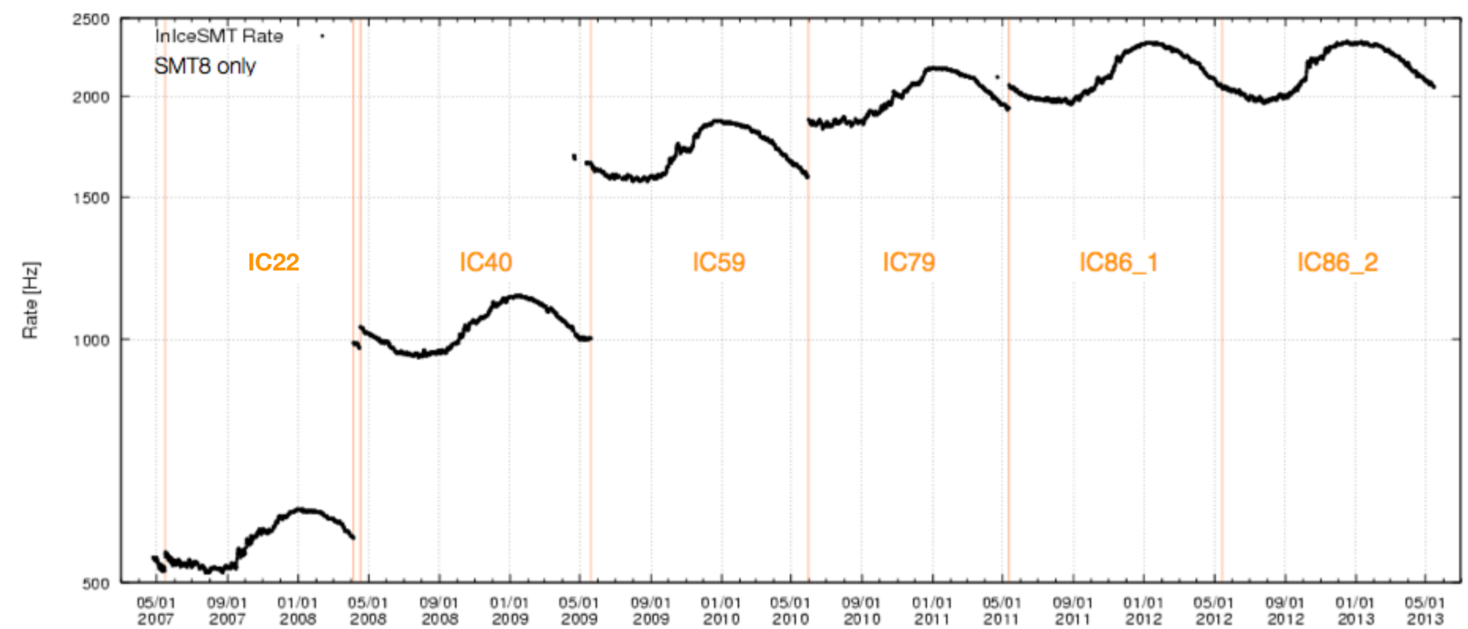
Fedynitch, Becker Tjus, PD, PRD 86, 114024

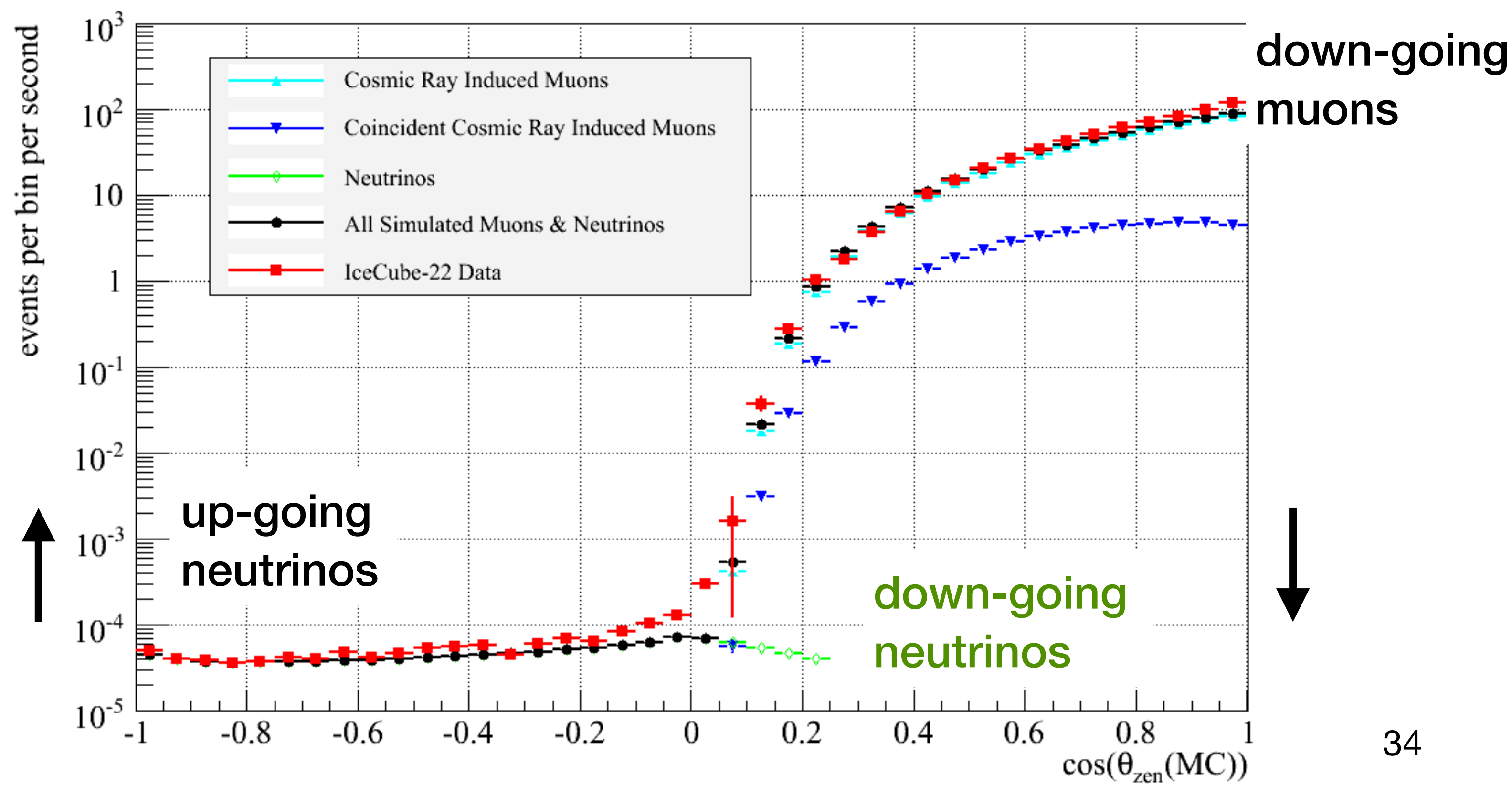


- ~ equal amount of μ and ν

cosmic ray muons and neutrinos

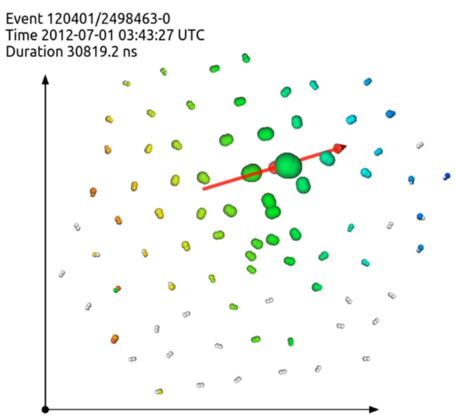
- R_{event} ~ 2200 Hz
- μ and ν produced in the atmosphere by **cosmic rays**
- atmospheric temperature seasonal variations
- ~1/10^6 TeV neutrinos interact in the ice and is detected and reconstructed in IceCube

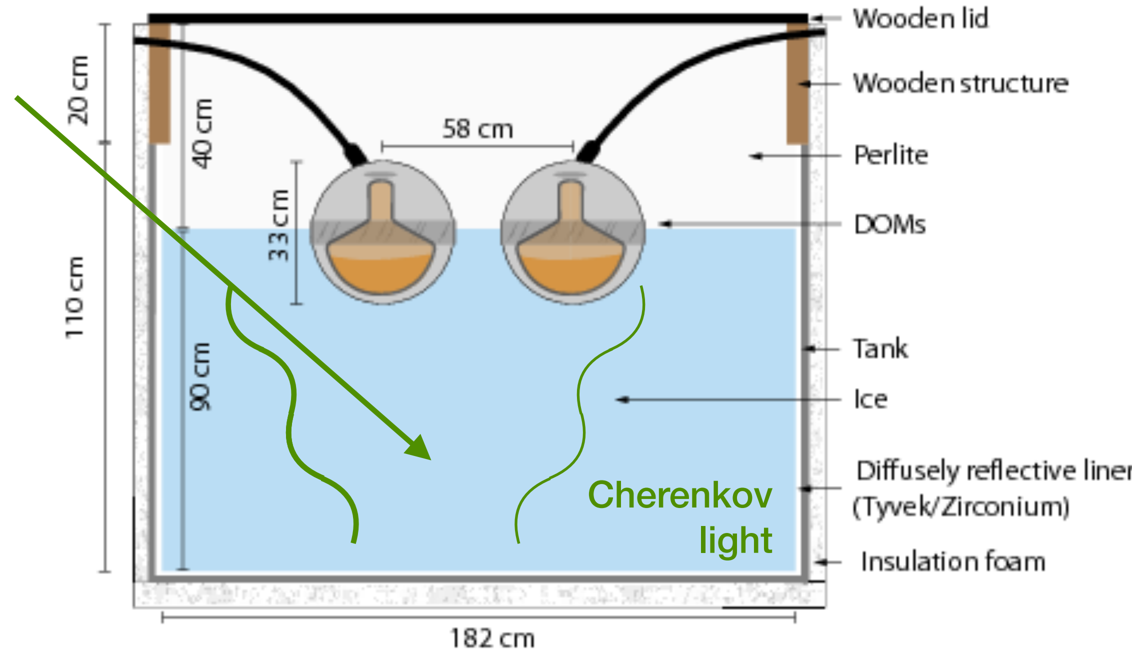


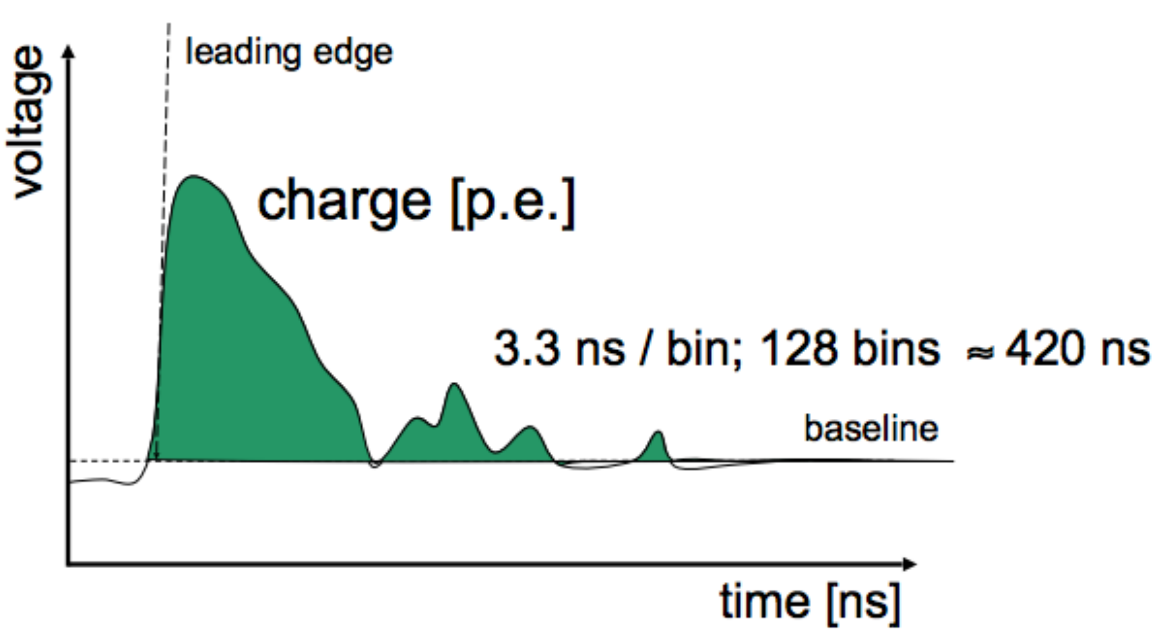


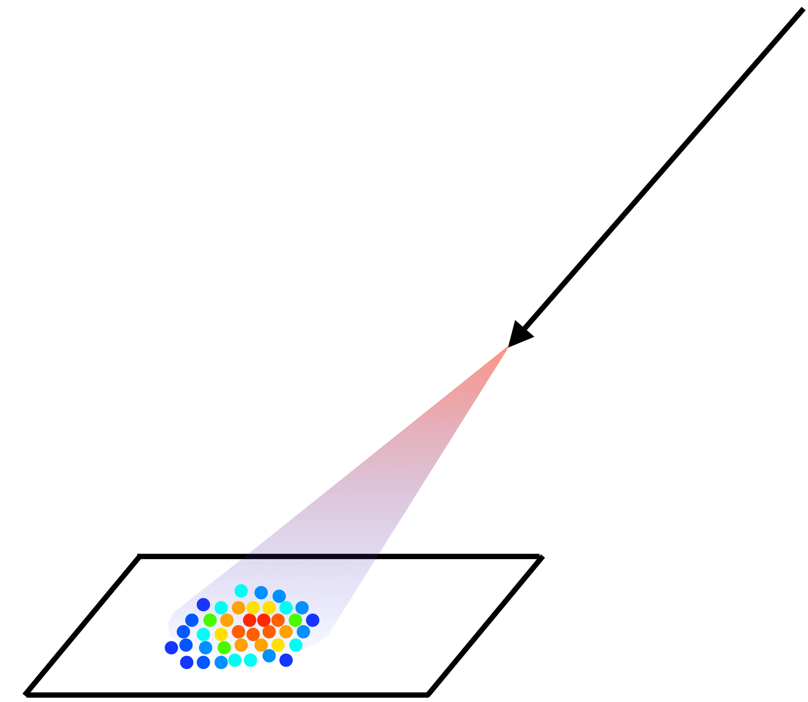
cosmic rays spectrum

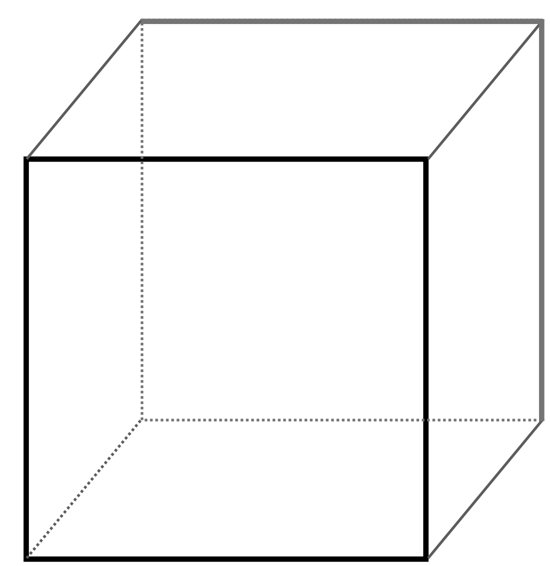
all-particle energy spectrum





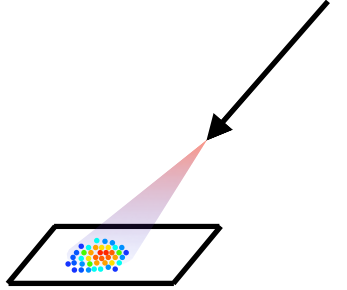


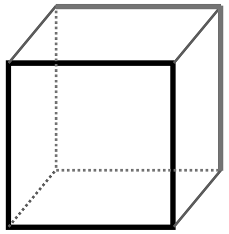


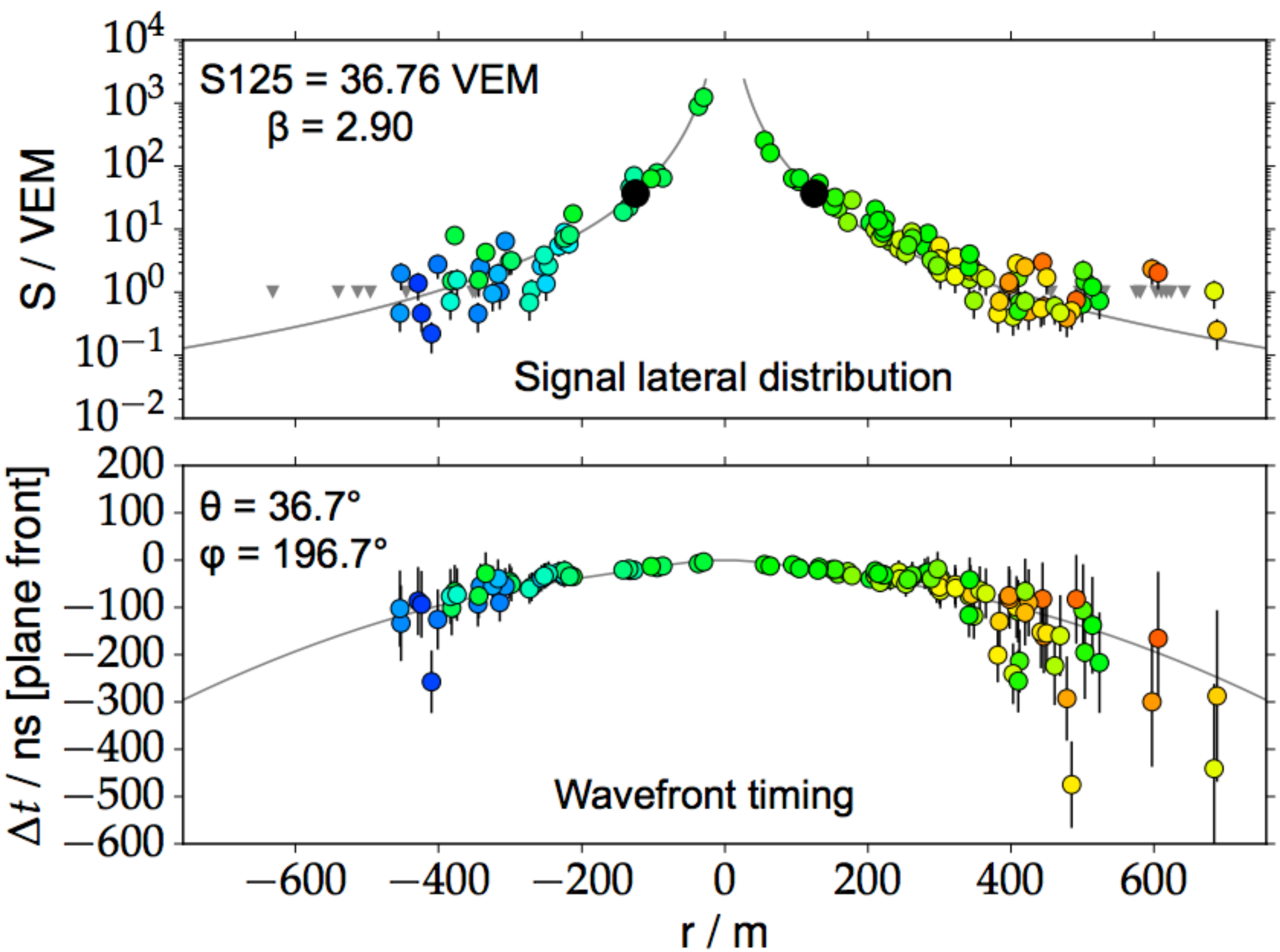


cosmic rays spectrum

all-particle energy spectrum







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

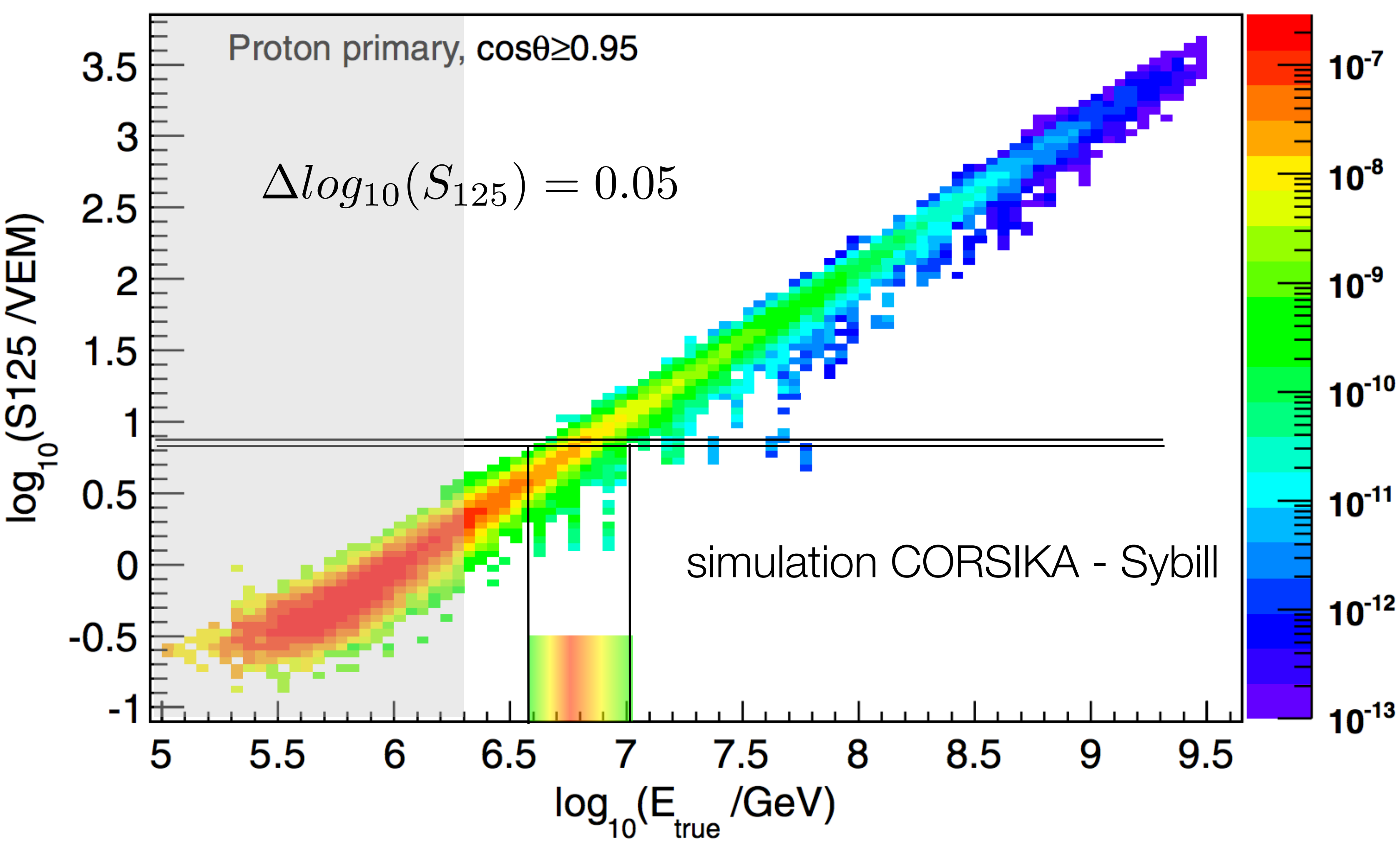
Wavefront timing:

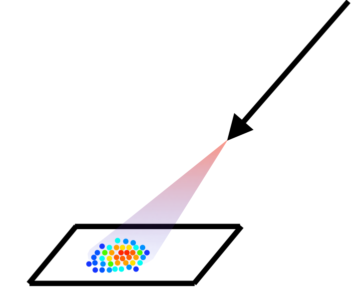
$$t(\vec{x}) = t_0 + \frac{1}{c}(\vec{x} - \vec{x}_c) \cdot \vec{n} + \Delta t(r)$$

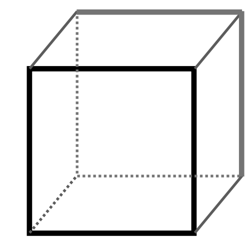
$$\Delta t(r) = a r^2 + b\left(1 - \exp\left(-\frac{r^2}{2\sigma^2}\right)\right)$$

cosmic rays spectrum

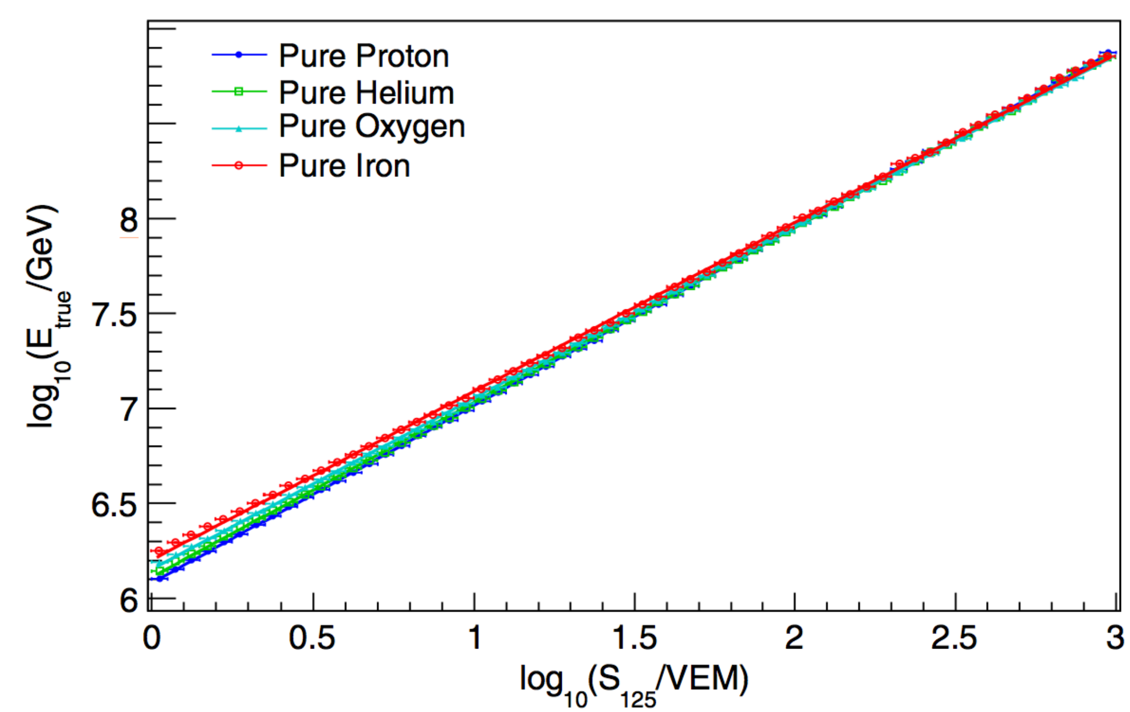
all-particle energy spectrum







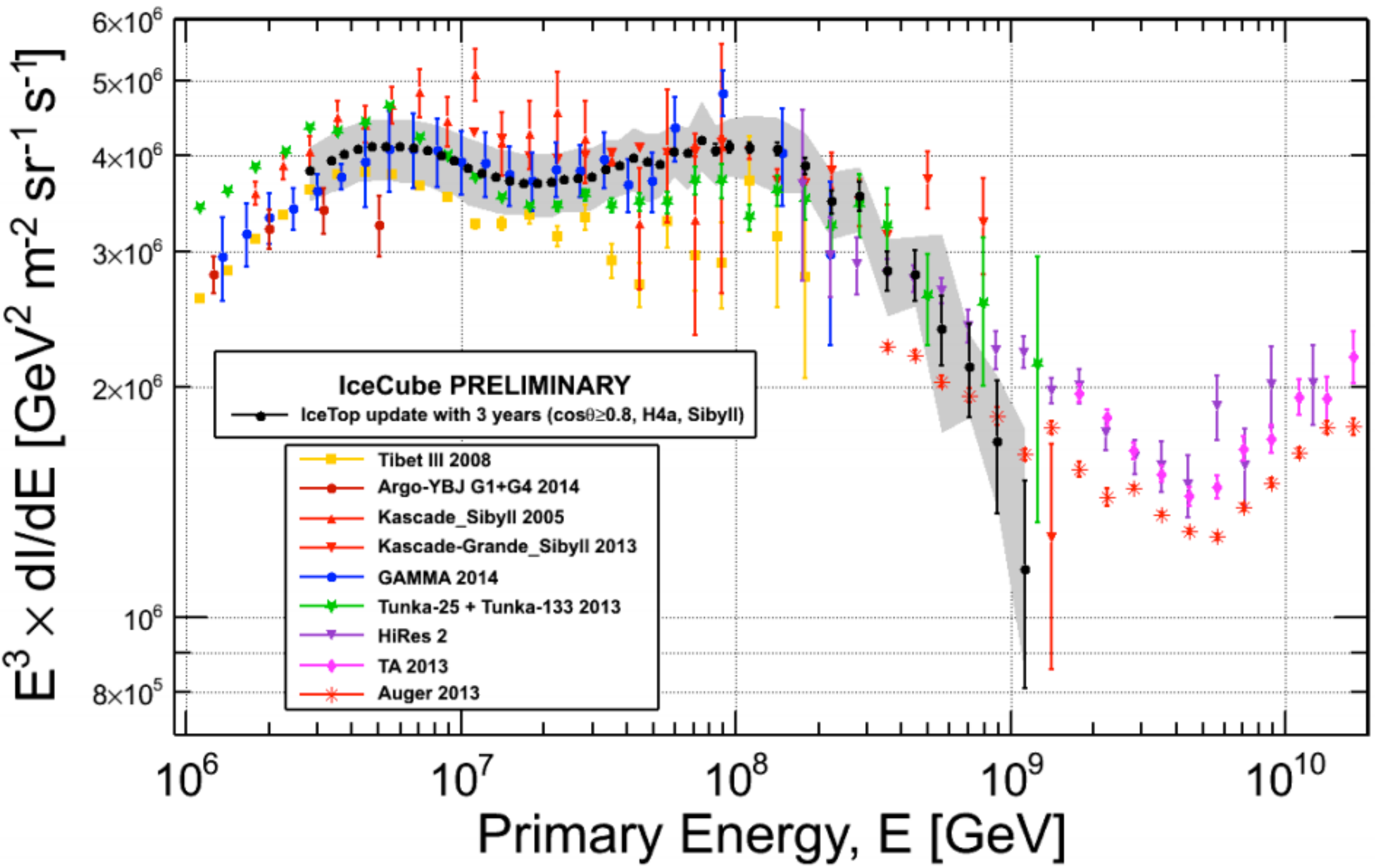
Aartsen et al. PRD 88 (2013) 042004

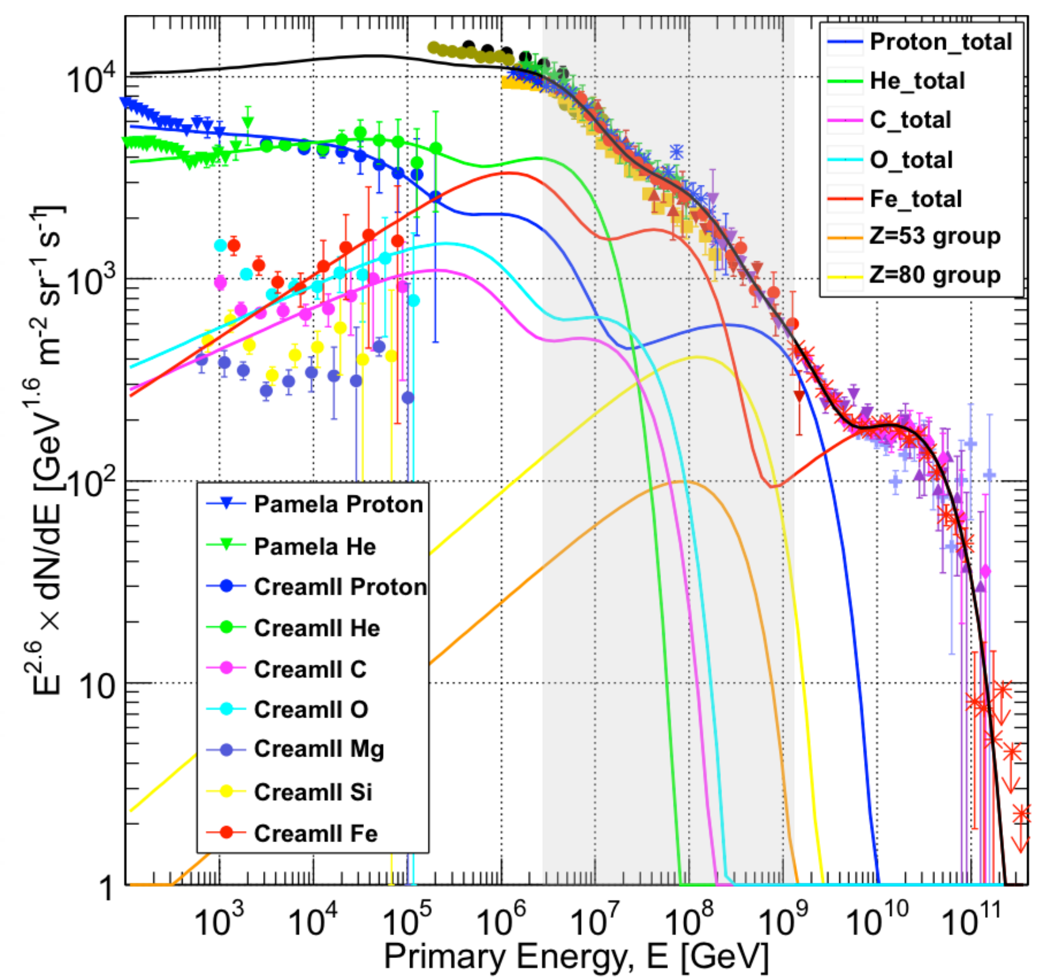


the relationship between S_{125} and primary energy depends on **mass** and **zenith angle**

cosmic rays spectrum

all-particle energy spectrum





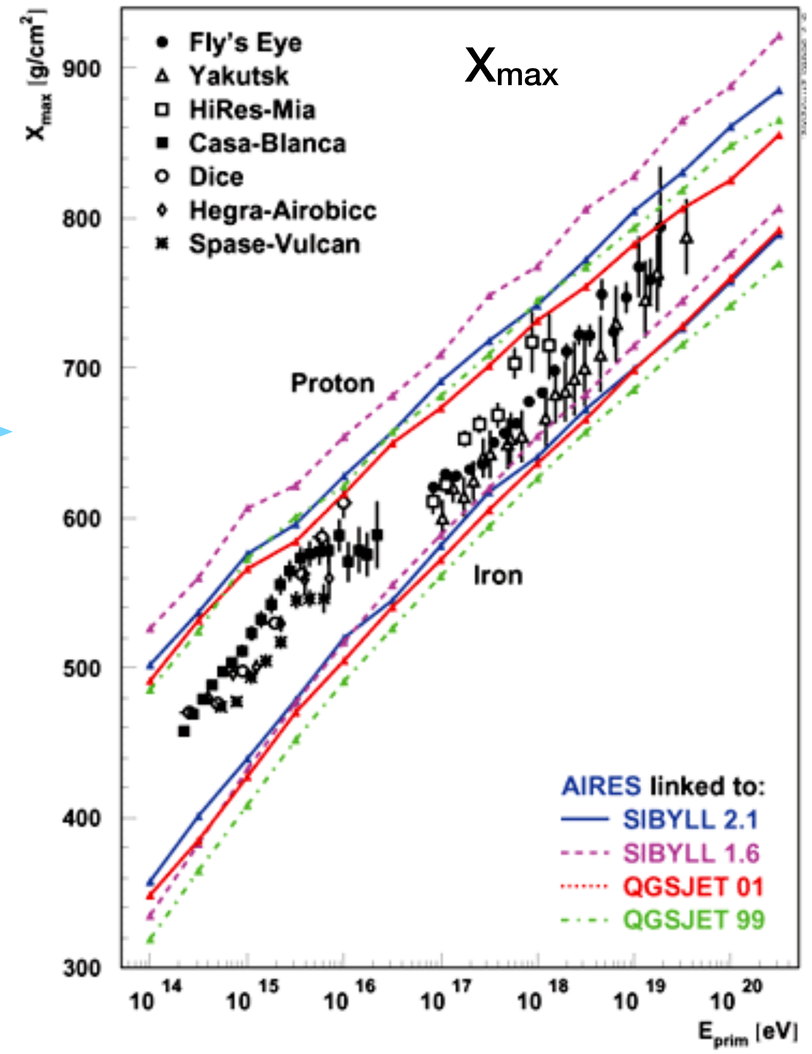
all-particle spectrum depends on the ***assumed*** mass composition of primary particles

cosmic rays composition

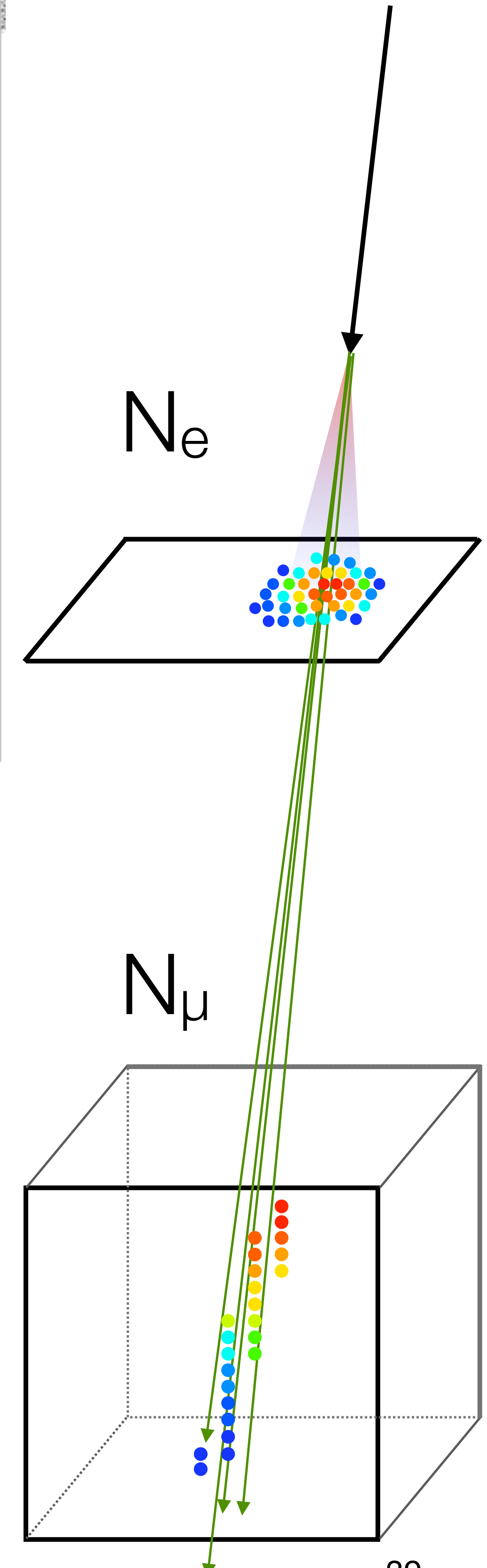
coincident events

@Antarctica

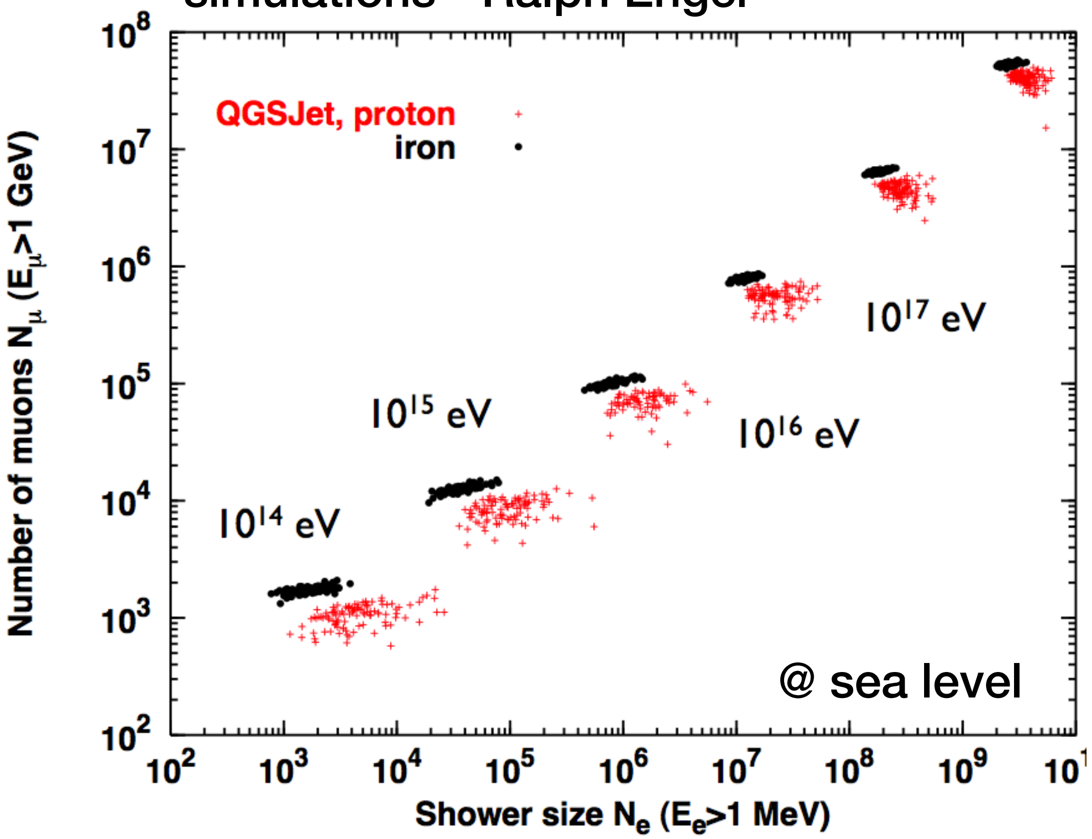
Sciutto, Braz. J. Phys. 37 (2007) 2b, São Paulo

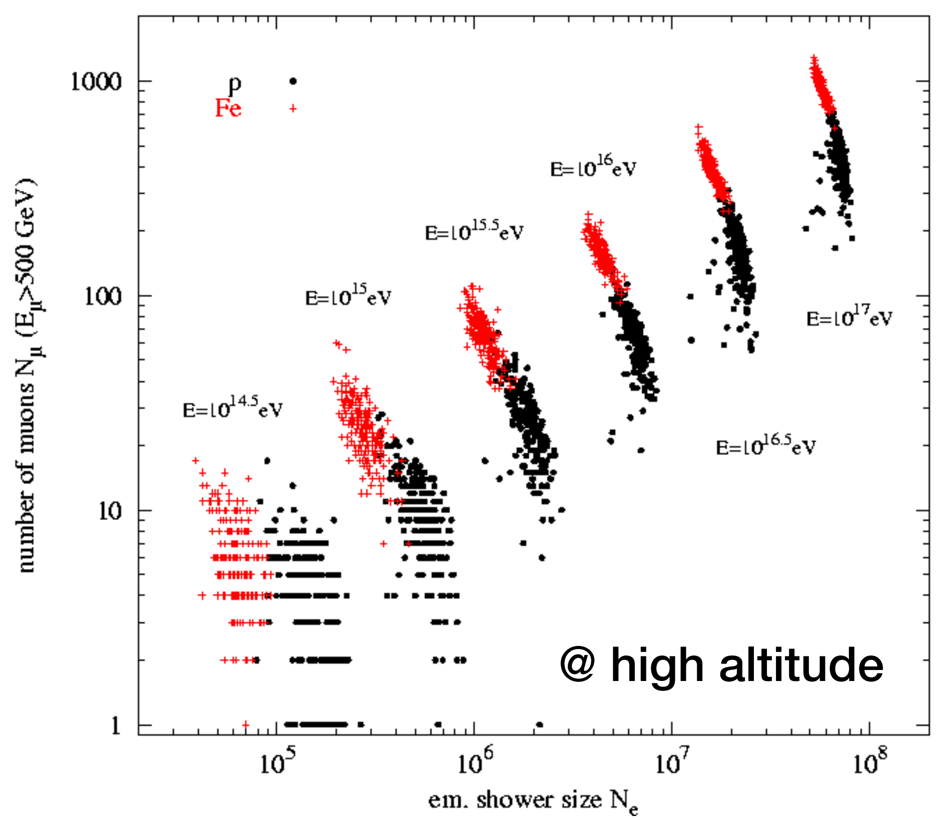


@sea level



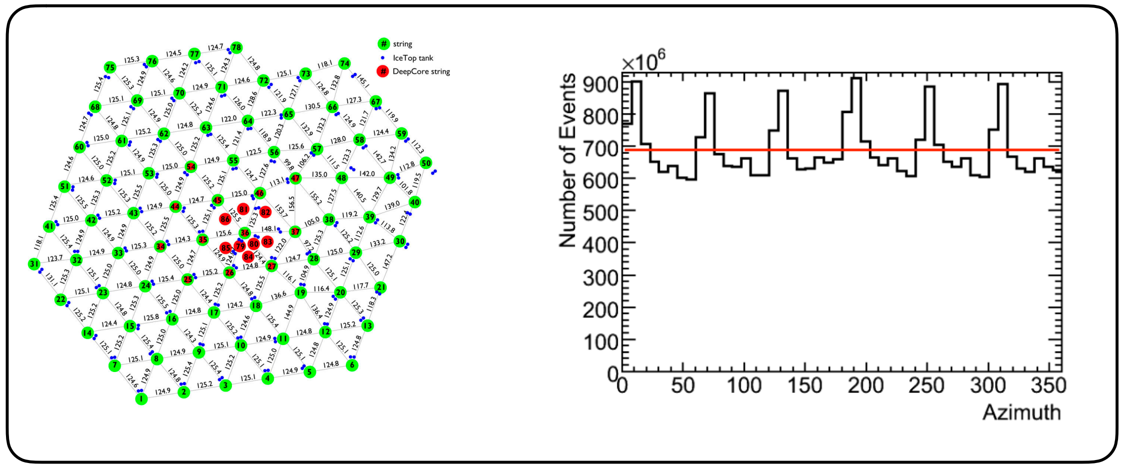
simulations - Ralph Engel



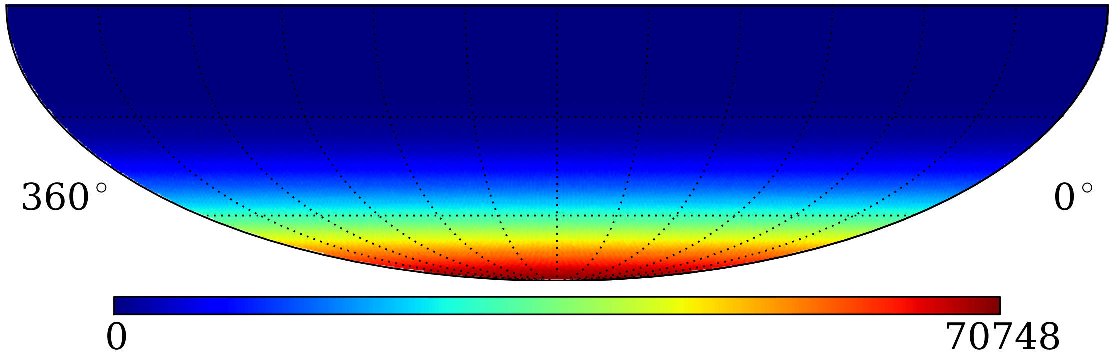


cosmic rays anisotropy

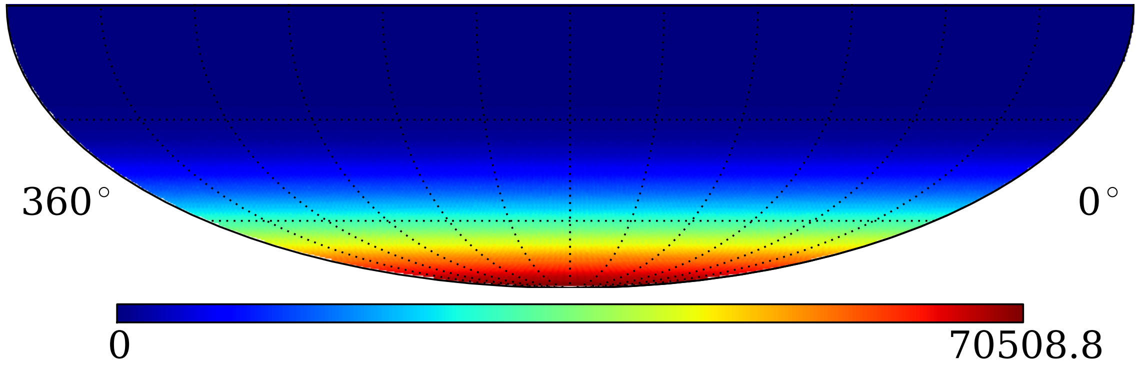
arrival direction distribution



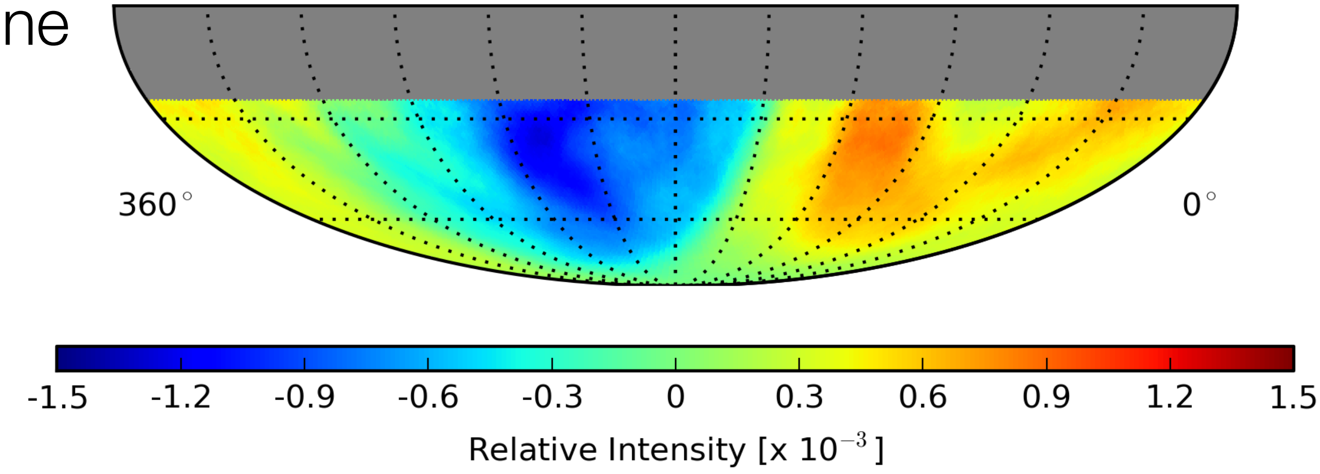
raw map of events in equatorial coordinates $(\alpha,\delta)_i$



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

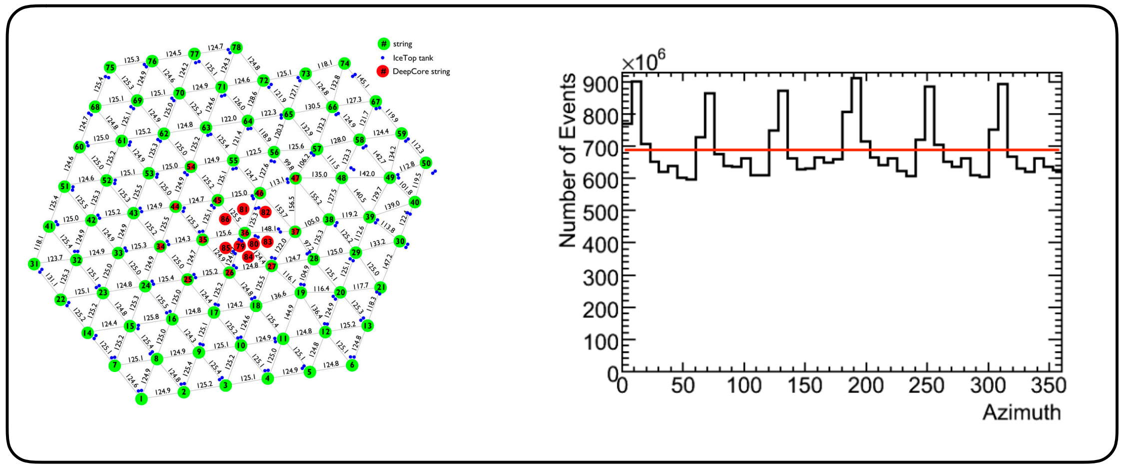


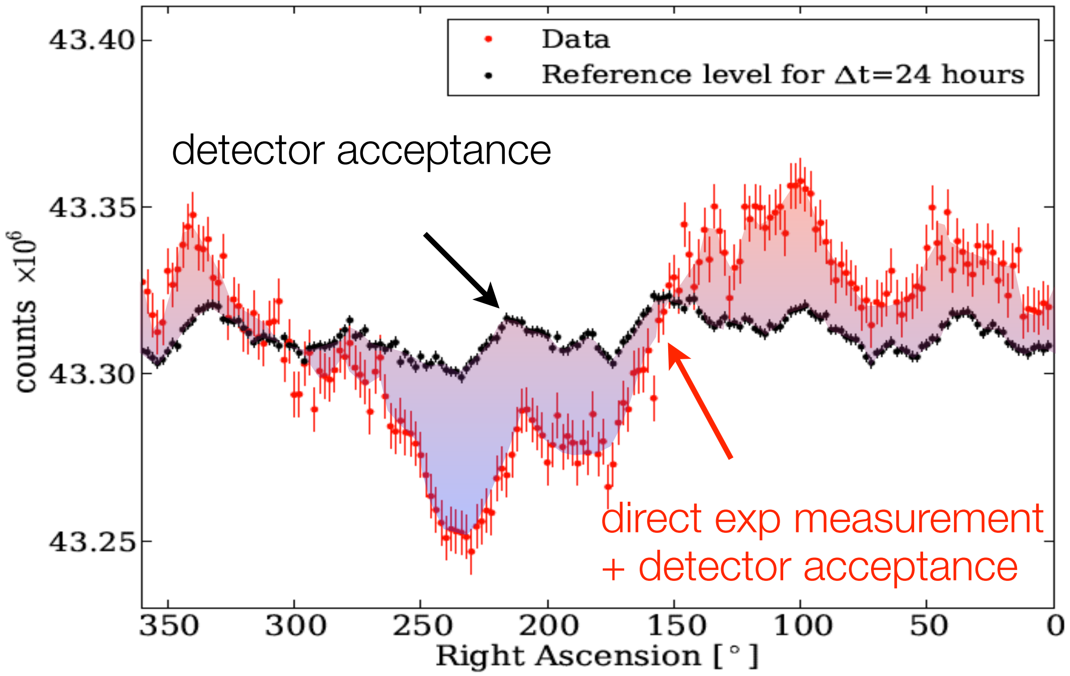
subtract reference map from raw map to determine the residual *relative intensity* map

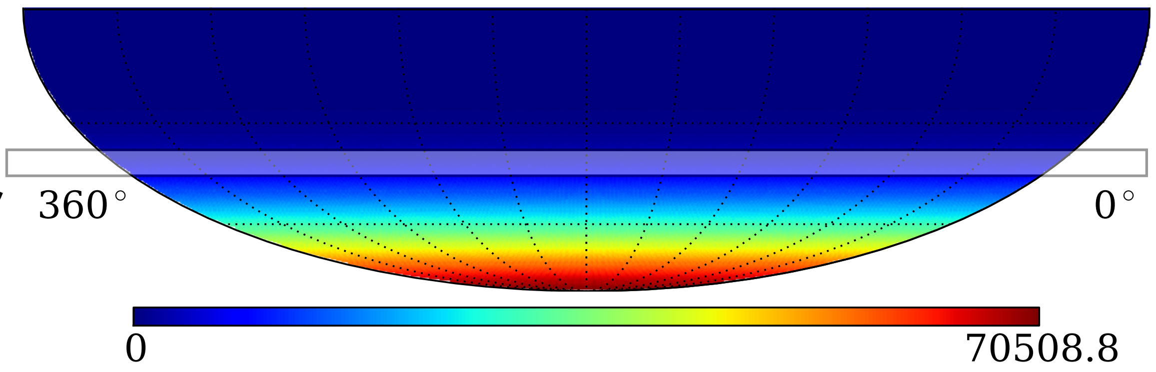


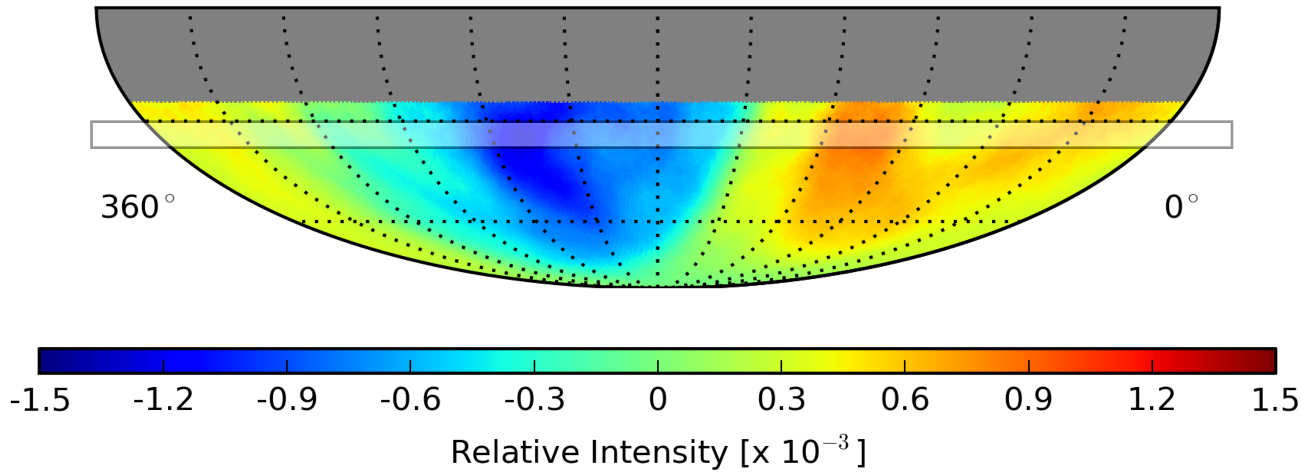
$$\frac{\Delta I}{\langle I \rangle} \equiv \frac{N_i - \langle N \rangle}{\langle N \rangle}$$

cosmic rays anisotropy
arrival direction distribution







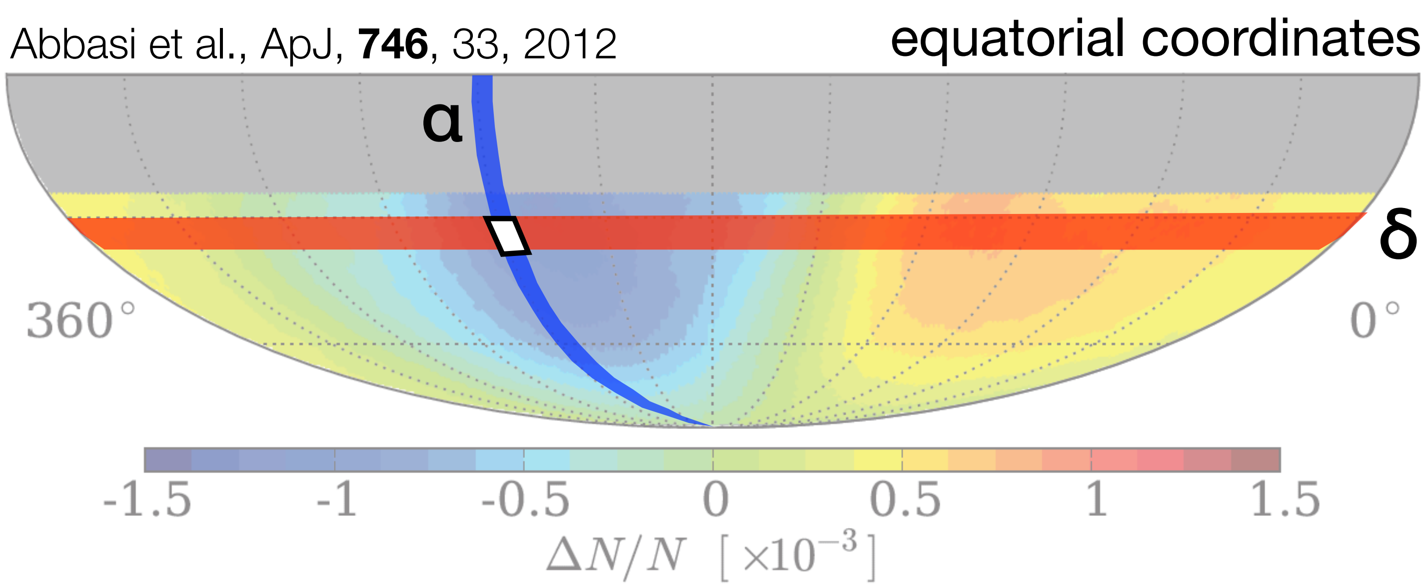


$$\frac{\Delta I}{\langle I \rangle} \equiv \frac{N_i - \langle N \rangle}{\langle N \rangle}$$

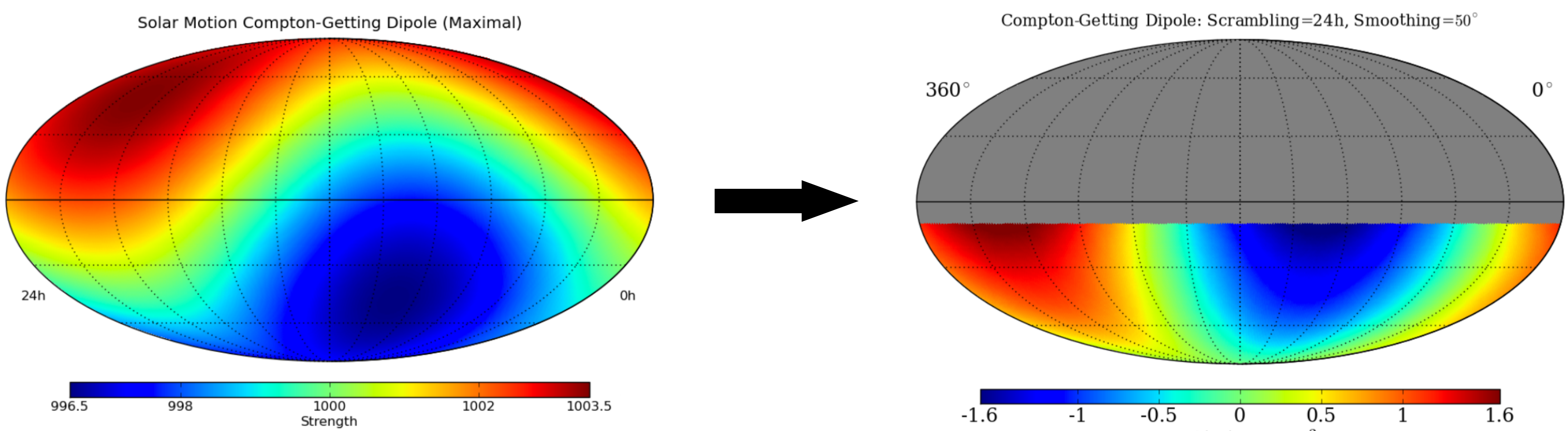
measuring cosmic ray anisotropy
relative intensity

DISCLAIMER

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



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



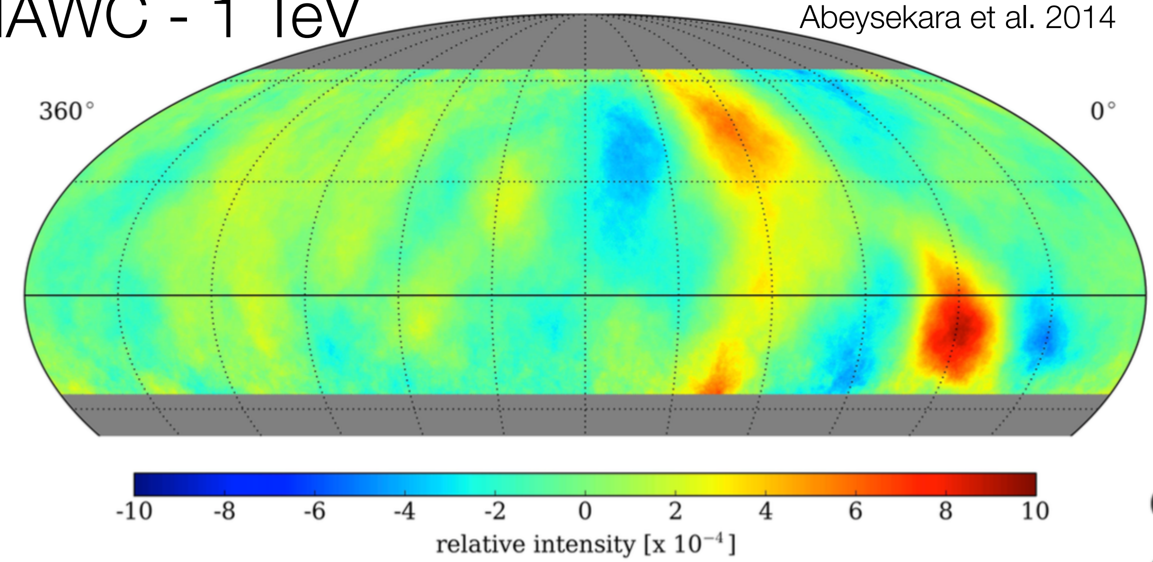
$\Delta N/\langle N\rangle = 7\times10^{-3}$

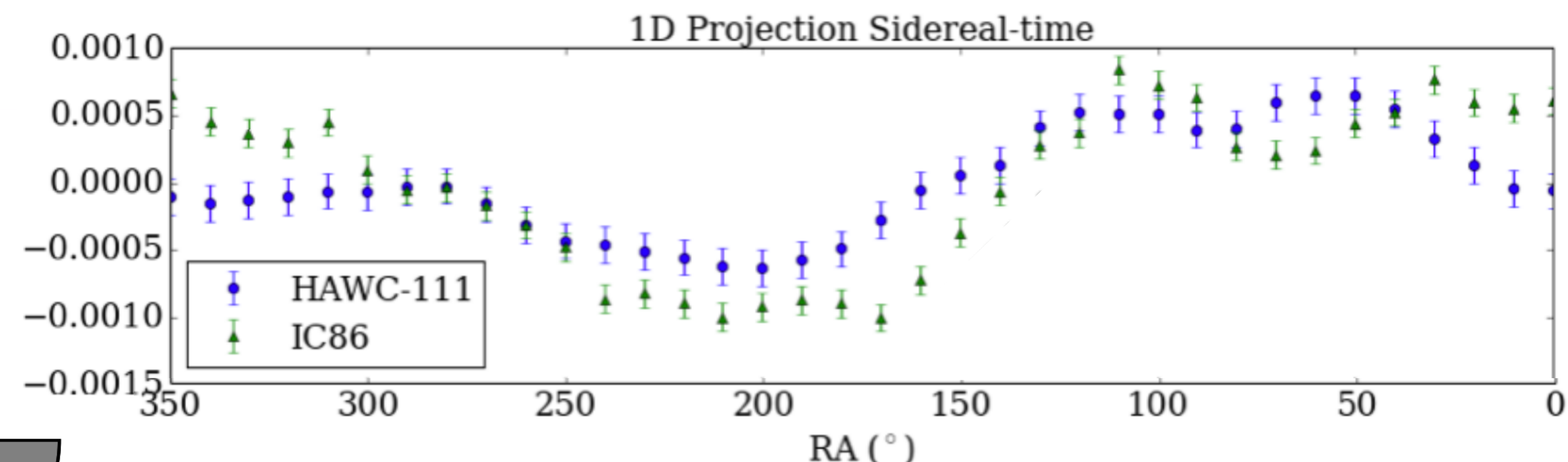
- sky maps show **ONLY** modulations across right ascension and **NOT** declination

cosmic rays anisotropy
arrival direction distribution

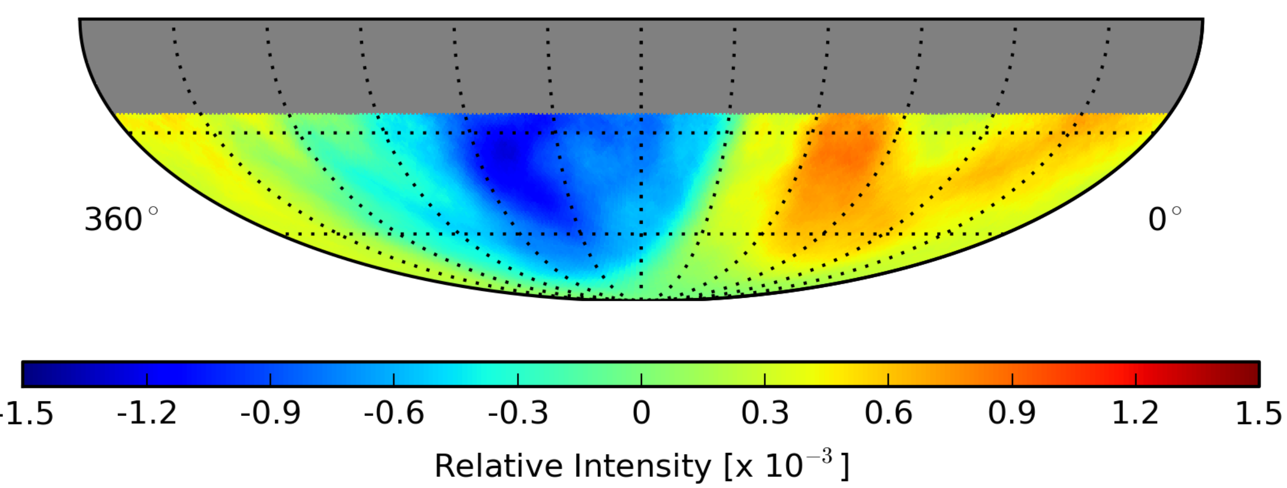
HAWC - 1 TeV

small scale anisotropy
Abeysekara et al. 2014





ICRC 2015



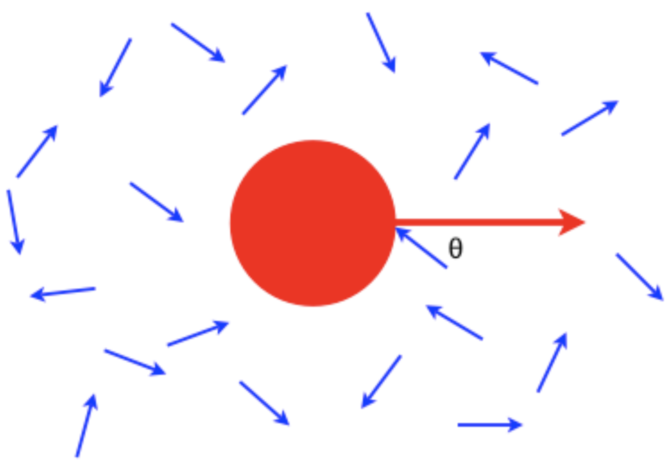
IceCube - 20 TeV

Abbasi et al. 2010, 11,12
Aartsen et al. 2013

a known anisotropy

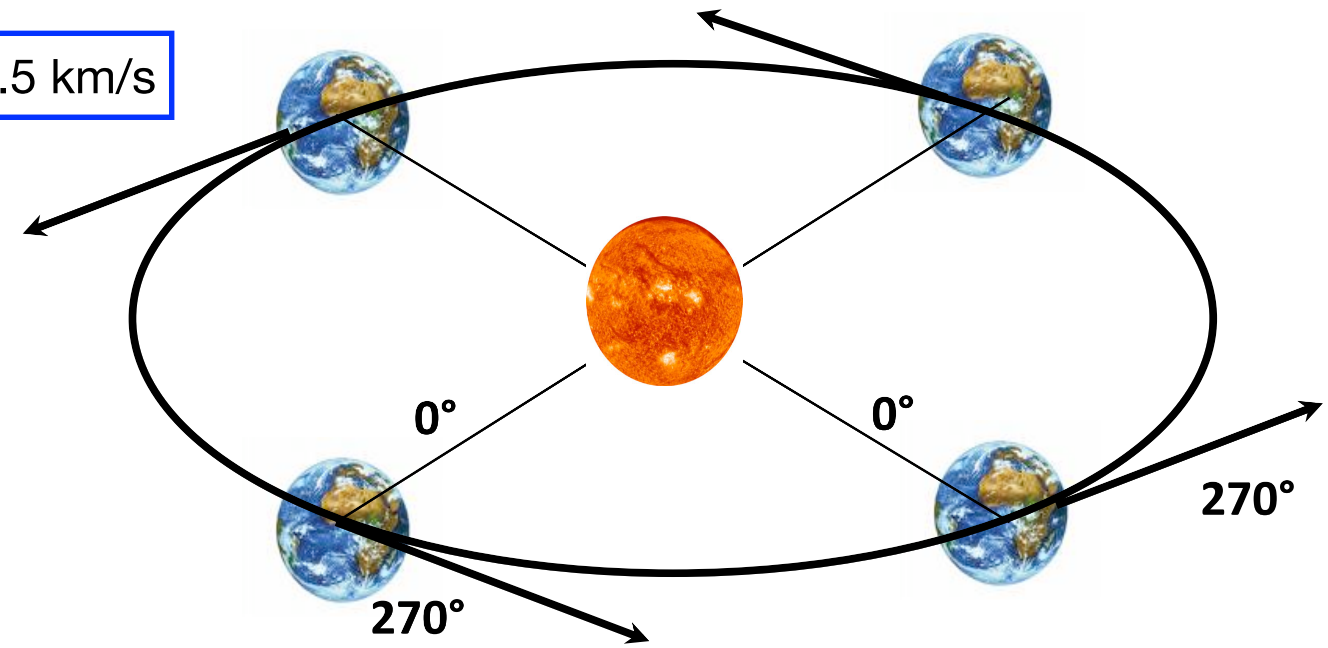
Earth's motion around the Sun

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

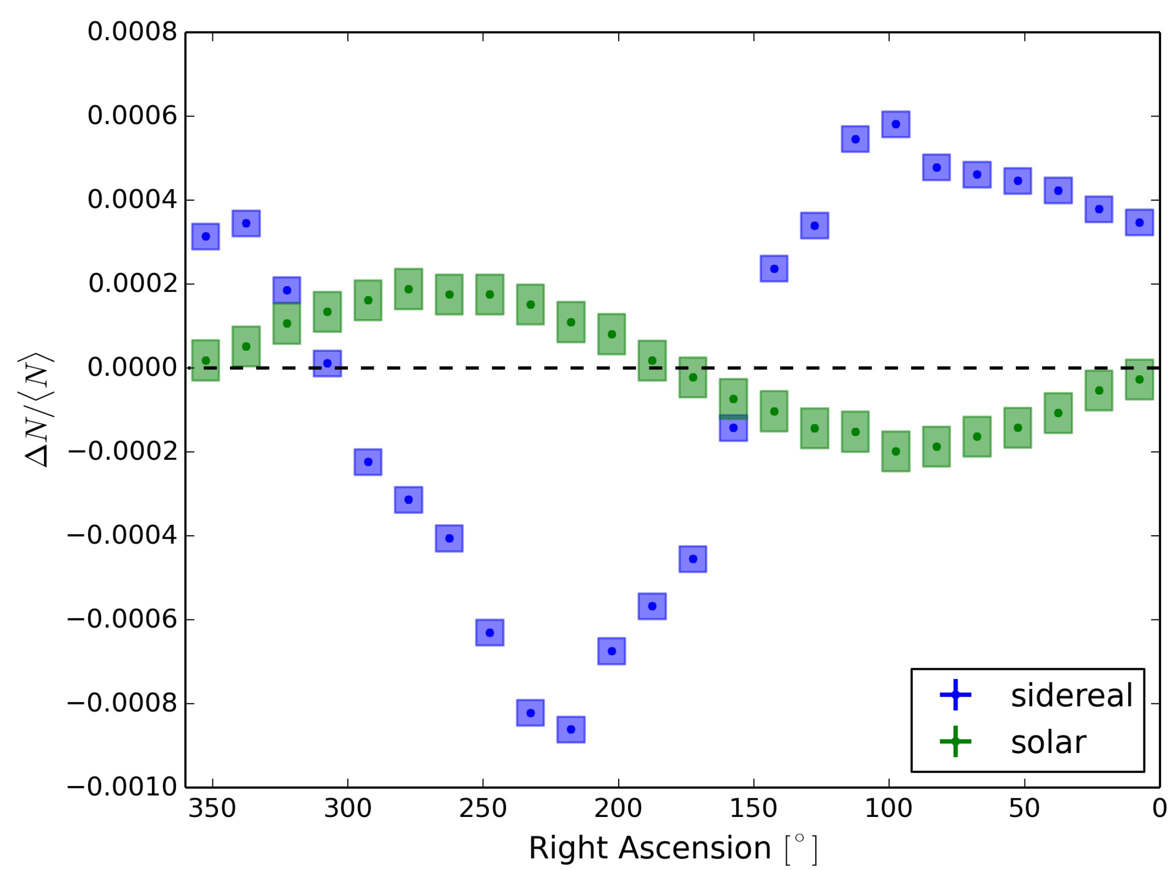


v = 29.8 ± 0.5 km/s

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

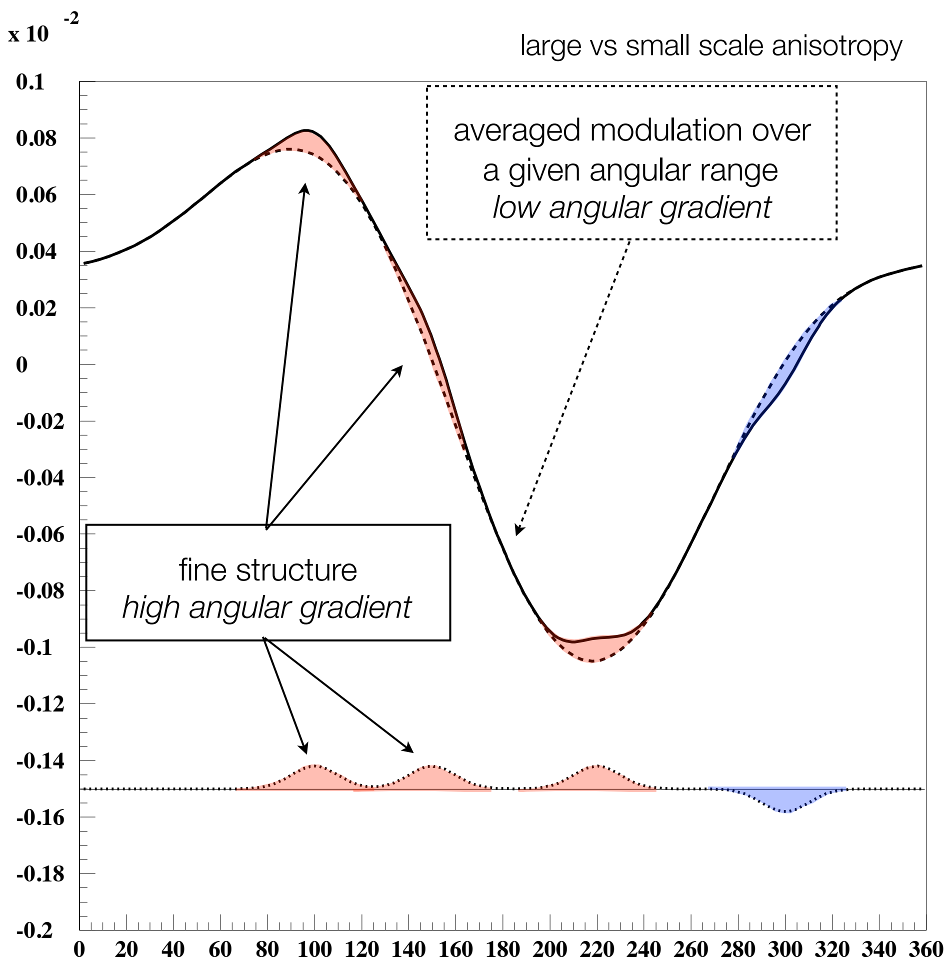


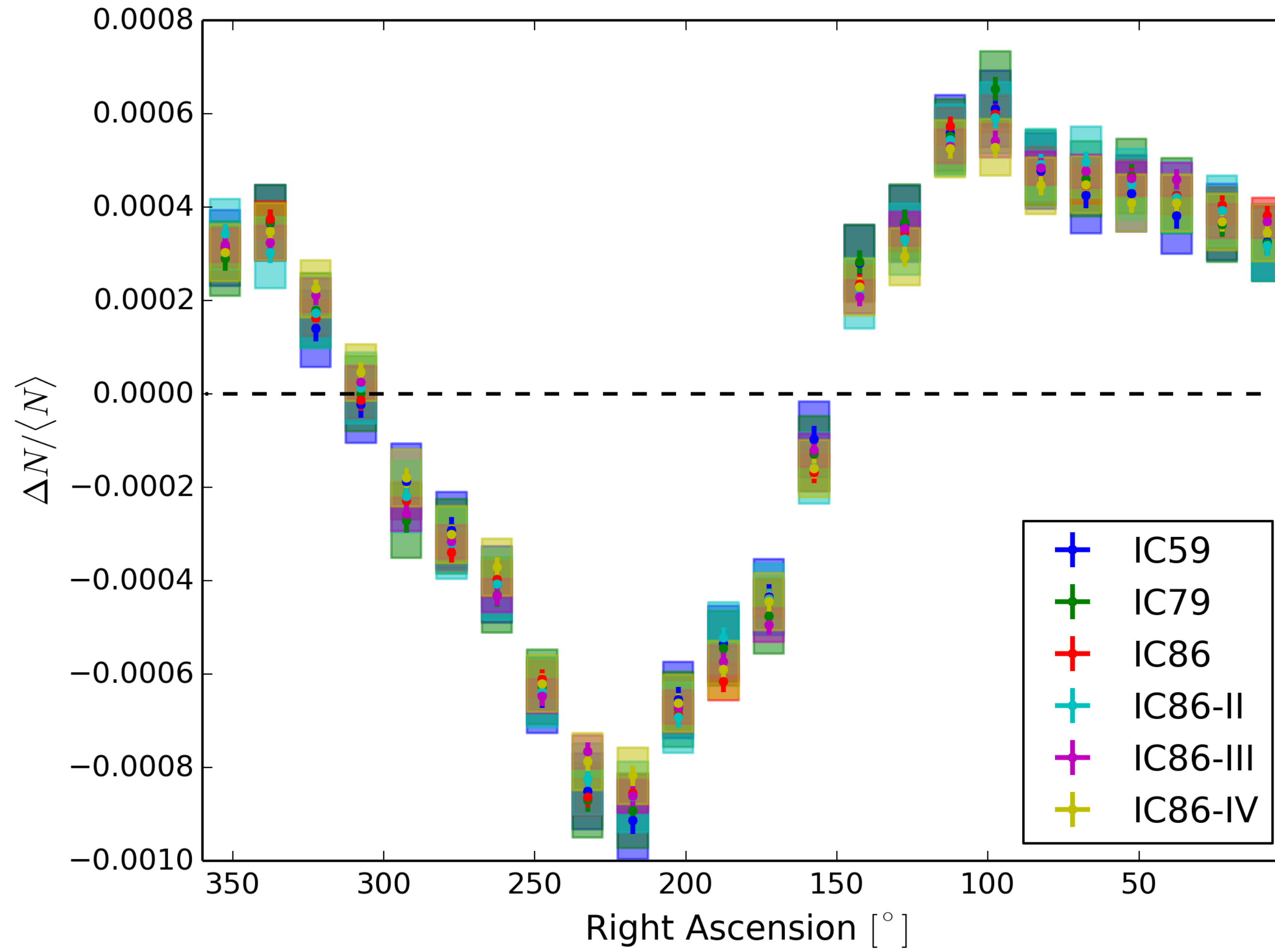
- produced by Earth's revolution around the Sun
- visible as **solar diurnal modulation**
- **predictable** and used as **benchmark**

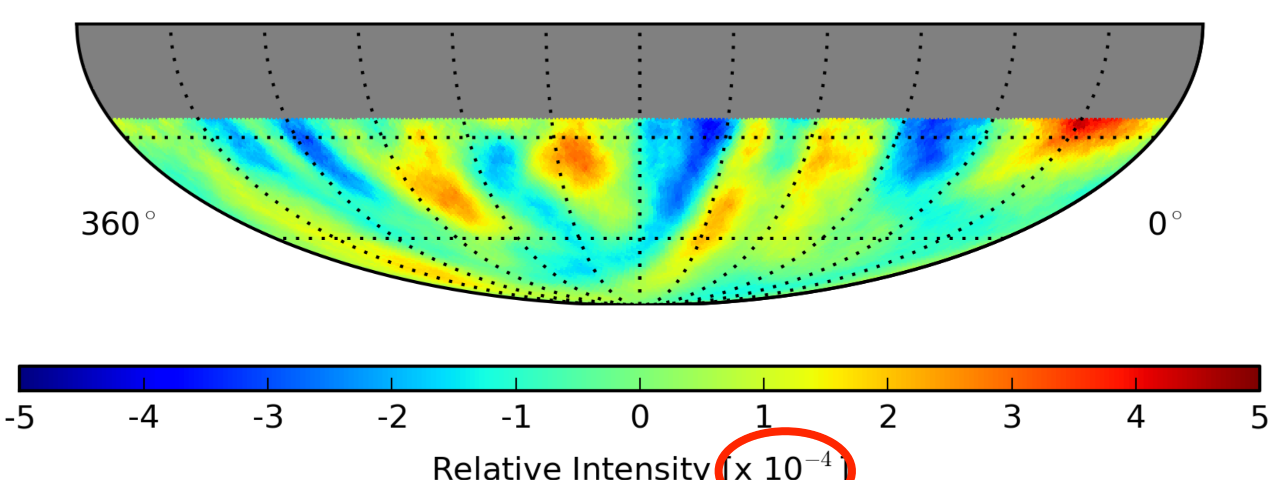


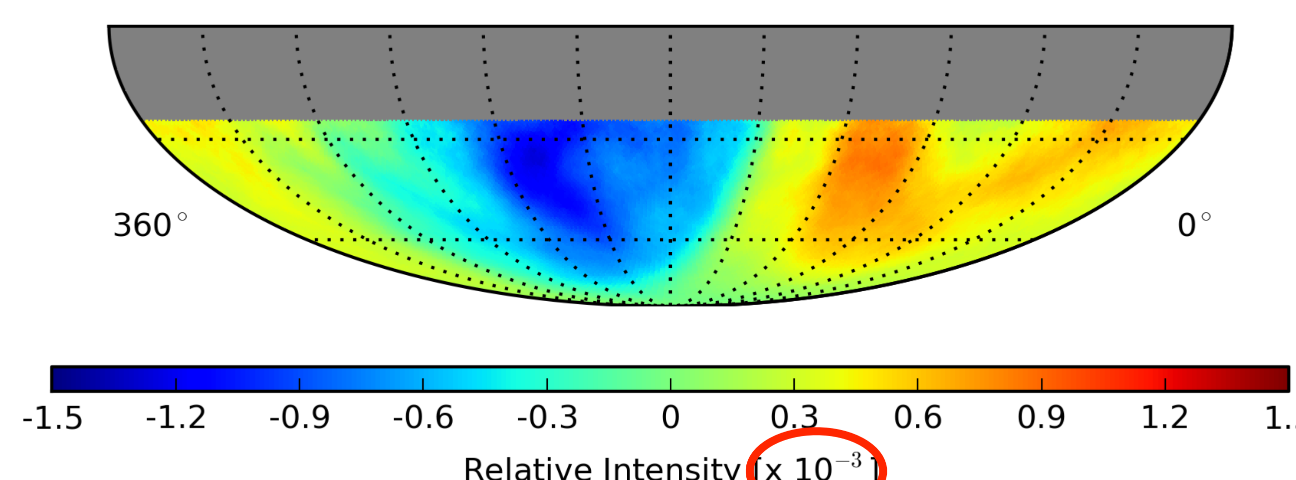
cosmic rays anisotropy

large and small angular scale



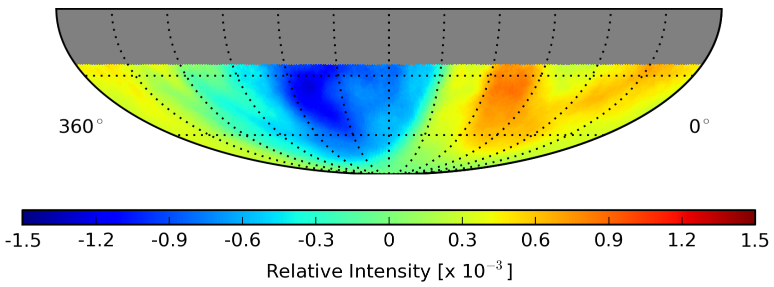


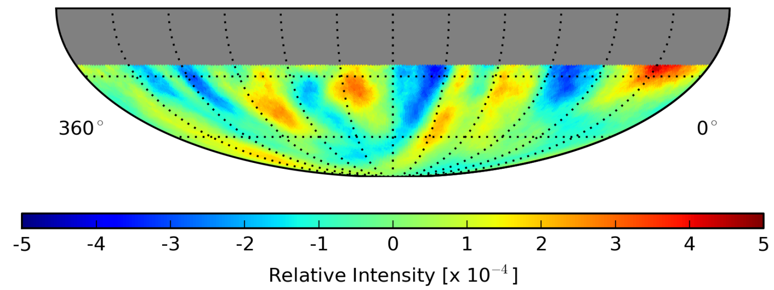


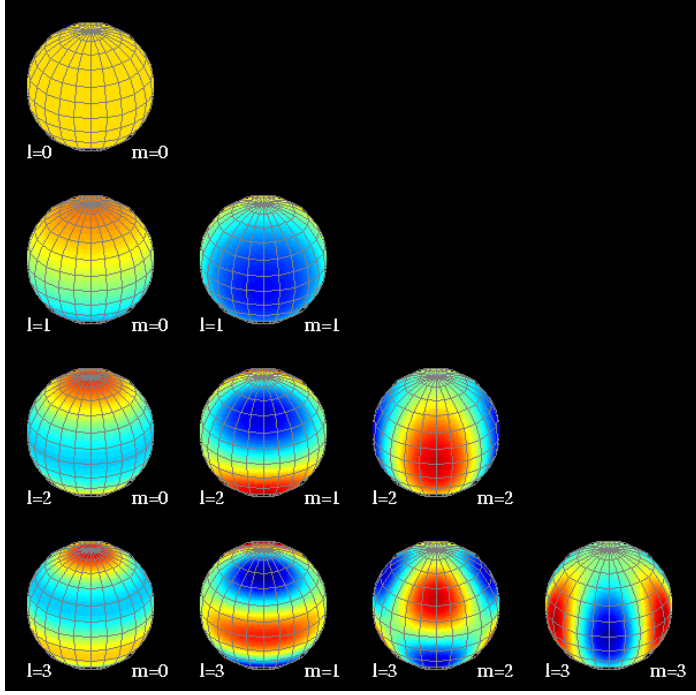


cosmic rays anisotropy

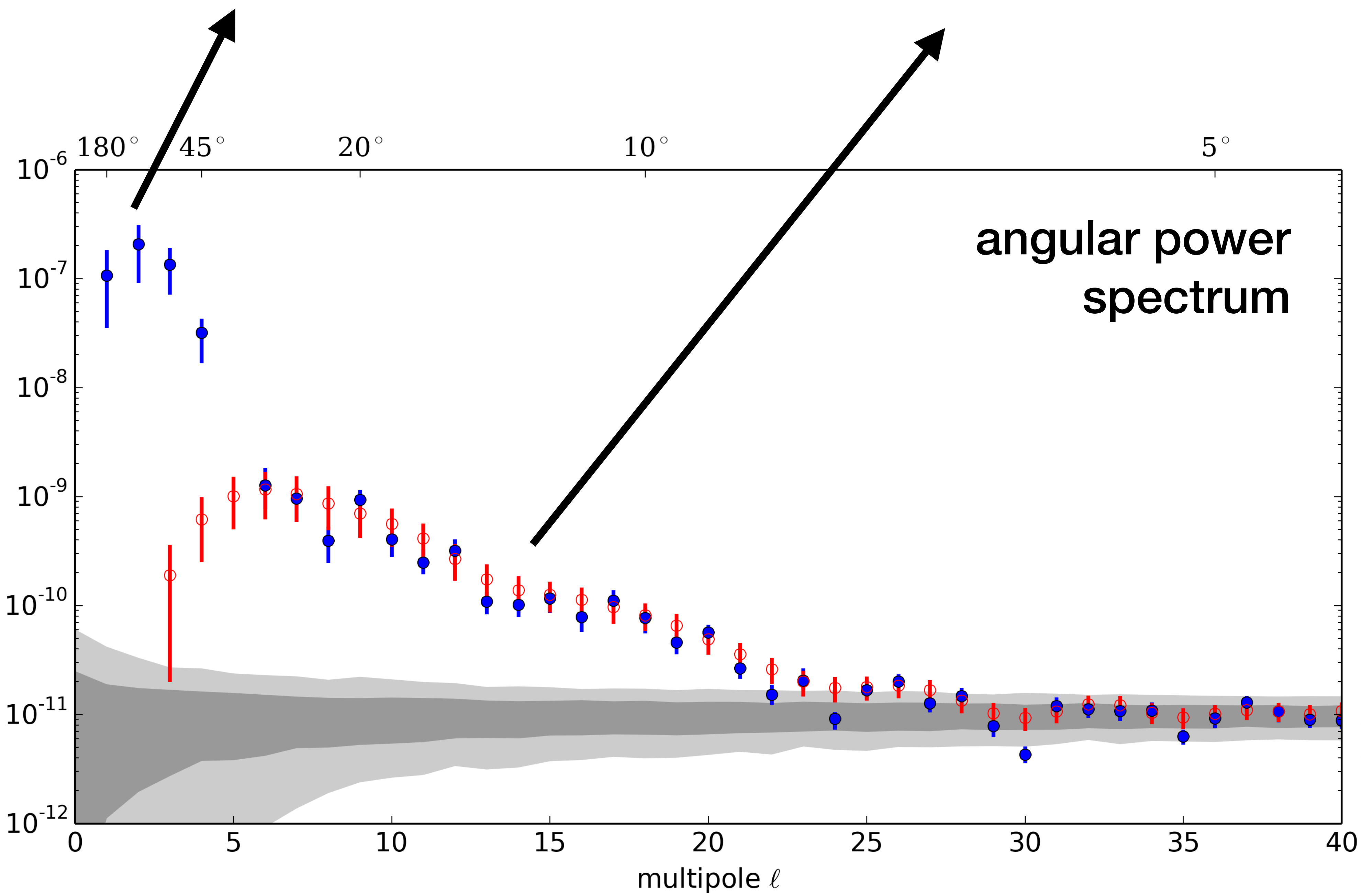
large and small angular scale







can angular power spectrum reveal fundamental physics properties ?

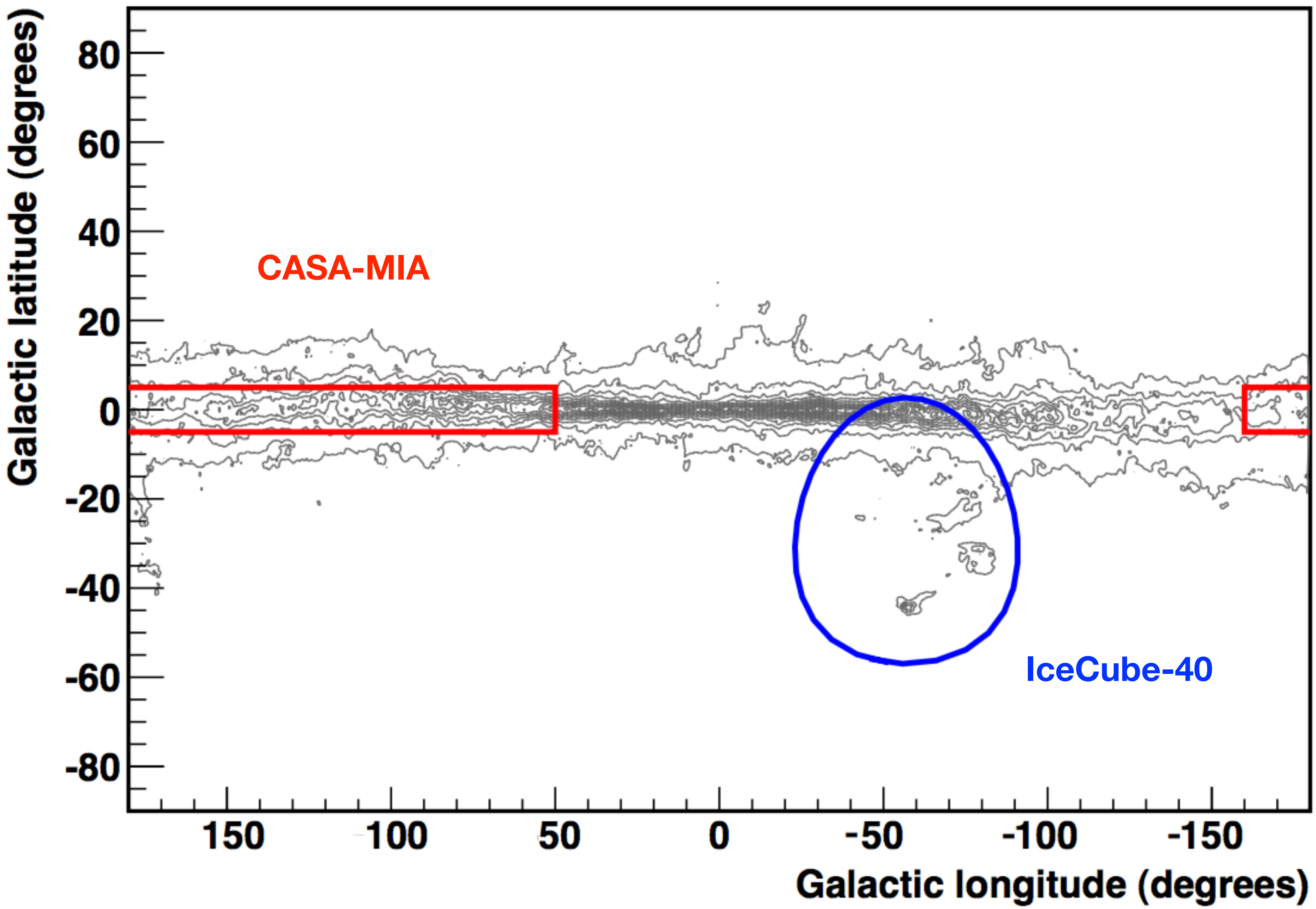


need extended/full sky coverage at equivalent rigidity

Giacinti & Sigl 2012
Ahlers 2014
Ahlers & Mertsch 2015
López-Barquero, Farber, Xu, PD, Lazarian 2015

PeV gamma rays
galactic origin

IC40 - Aartsen et al., 2012



neutron point sources

nearby galactic sources with 4 years of IceTop

ICRC 2015

Targeted search catalogs

M. Sutherland - OSU

What would comprise good Galactic source candidates?

- nearby, known distances, high energy γs with an adequate energy flux at Earth

msec pulsars [*Manchester et al. 2005*]:

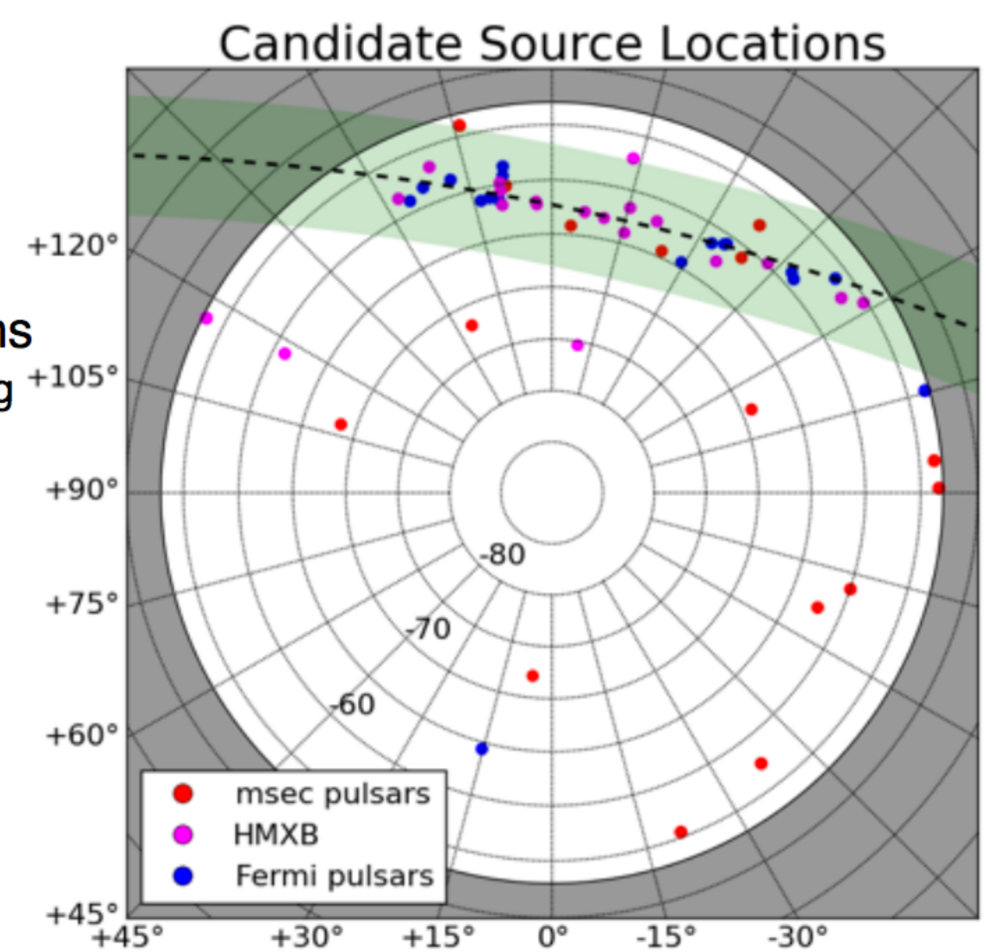
- http://www.atnf.csiro.au/research/pulsar/psrcat/
- 17 objects with $P < 10$ msec
- median distance ~ 1.9 kpc —> E_c ~ 220 PeV

γ pulsars [*Abdo et al. 2013*]: confirmed high energy photons

- http://fermi.gsfc.nasa.gov/ssc/data/access/lat/2nd_PSR_catalog
- 16 objects
- median distance ~ 2.7 kpc —> E_c ~ 320 PeV

HMXB [*Liu et al. 2007*]: compact object + massive star

- http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/442/1135
- 20 objects
- median distance ~ 4.2 kpc —> E_c ~ 480 PeV

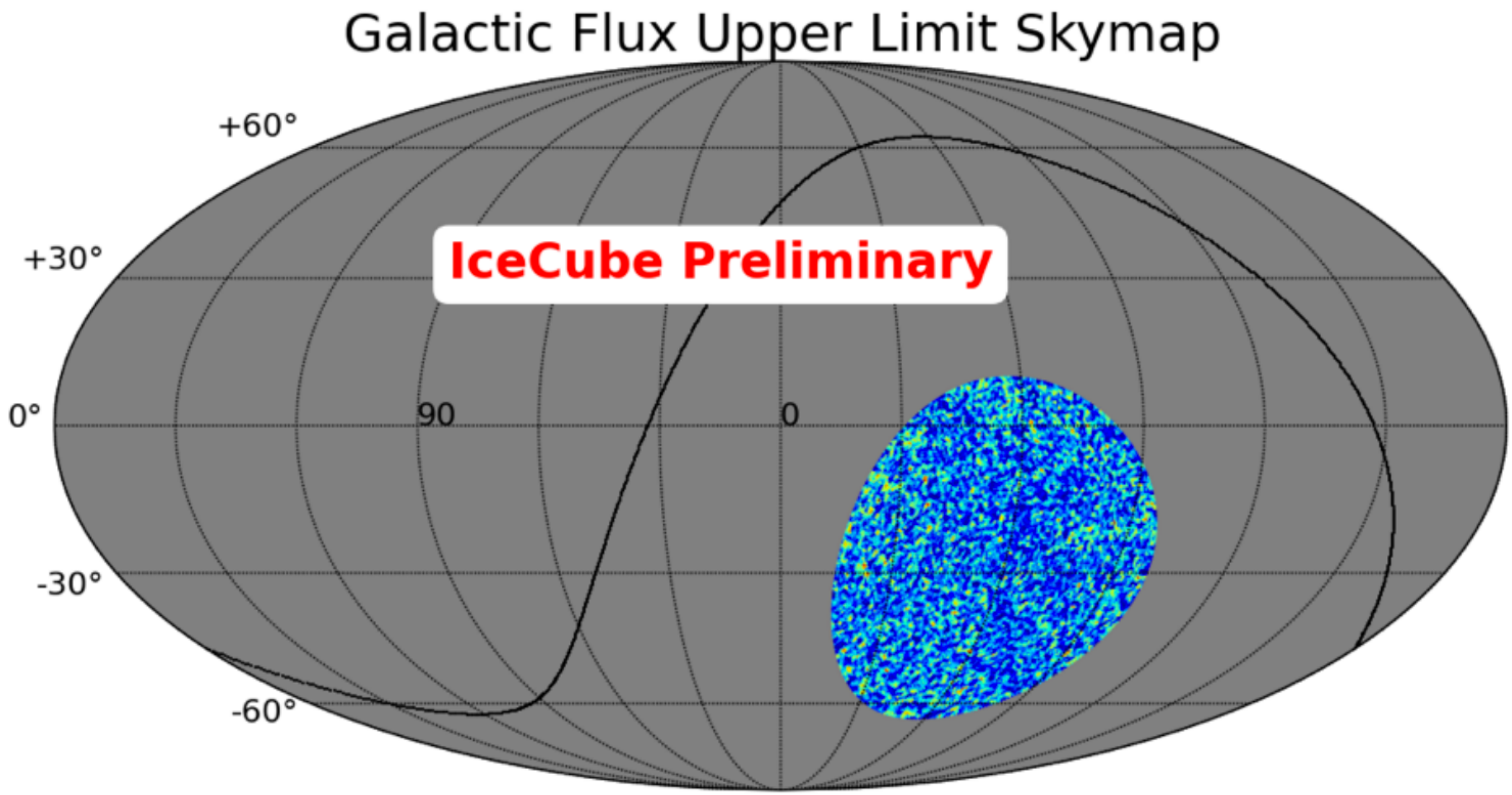


neutron point sources
nearby galactic sources with 4 years of IceTop

ICRC 2015

Results: all-sky search

M. Sutherland - OSU



neutron point sources

nearby galactic sources with 4 years of IceTop

ICRC 2015

Results: targeted search

M. Sutherland - OSU

Post-trials *p* = fraction of MC with corresponding value less than that in observed dataset

Underfluctuation near *b*=0º relative to background *plus* preferential catalog clustering produces artificially high *P*-values

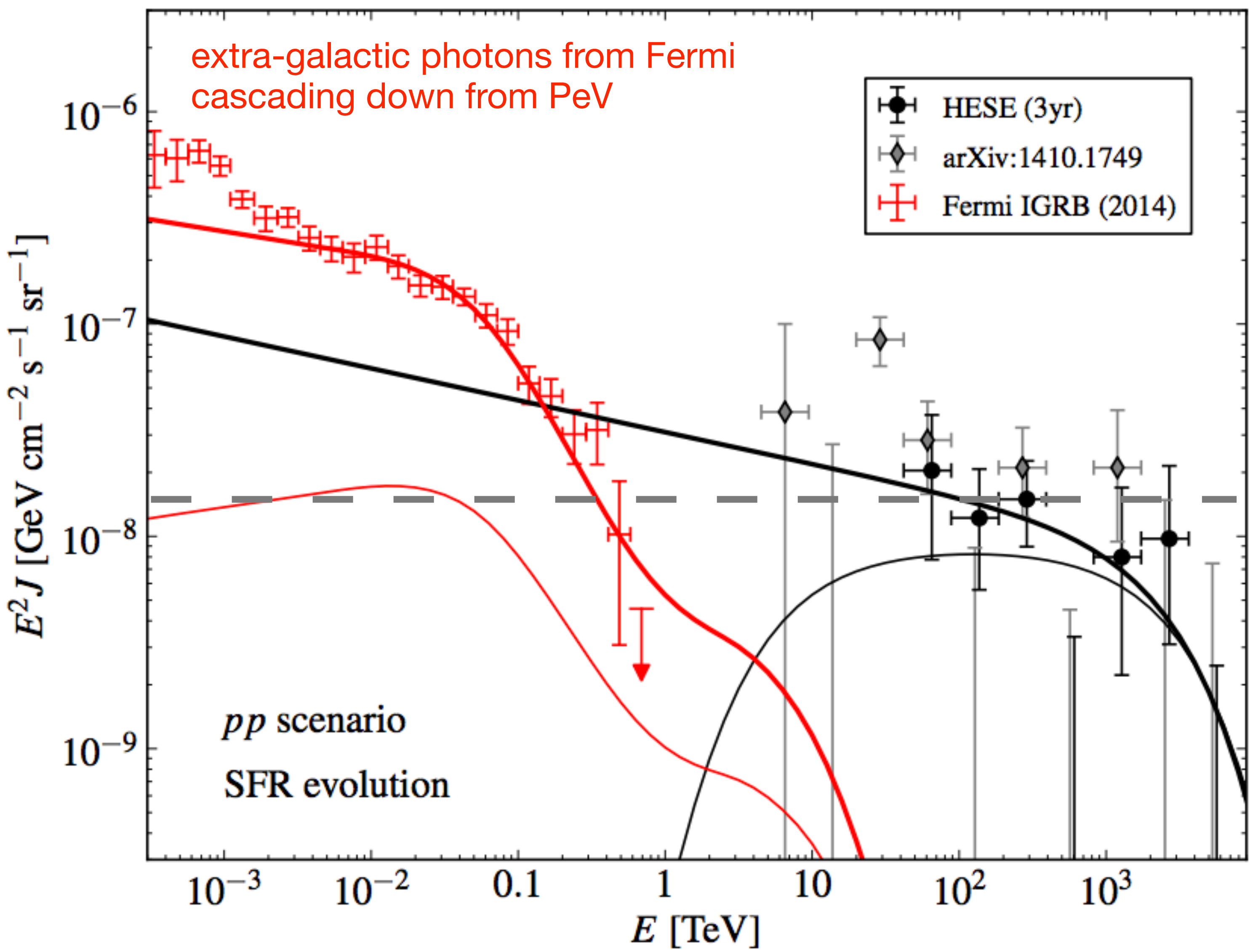
Catalog	Number of Objects	Fisher *P* (post-trials *p*)	Good *P* (post-trials *p*)
ɣ pulsars	17	0.998 (0.947)	0.887 (0.727)
msec pulsars	16	0.820 (0.457)	0.898 (0.791)
HMXB	20	0.999 (0.997)	0.945 (0.972)

No statistically significant correlations observed between candidate catalogs and (*E* > 100 PeV) cosmic rays

Catalog	Object Name	R.A. [deg]	Dec [deg]	Observed	Expected	N_{UL}	F_{UL} [km^{-2} yr^{-1}]	energy F_{UL} [eV cm^{-2} sec^{-1}]	Poisson *p* (post-trials *p*)
ɣ pulsars	J1048-5832	162.05	-58.53	5	2.40	7.60	11.35	0.65	0.095 (0.665)
msec pulsars	J1933-6211	293.39	-62.20	6	2.57	8.90	14.87	0.86	0.047 (0.419)
HMXB	2S1417-624	215.30	-62.70	4	2.65	5.95	10.11	0.58	0.274 (0.993)

astrophysical neutrinos
extra-galactic origin

Aartsen et al. arXiv:1412.5106



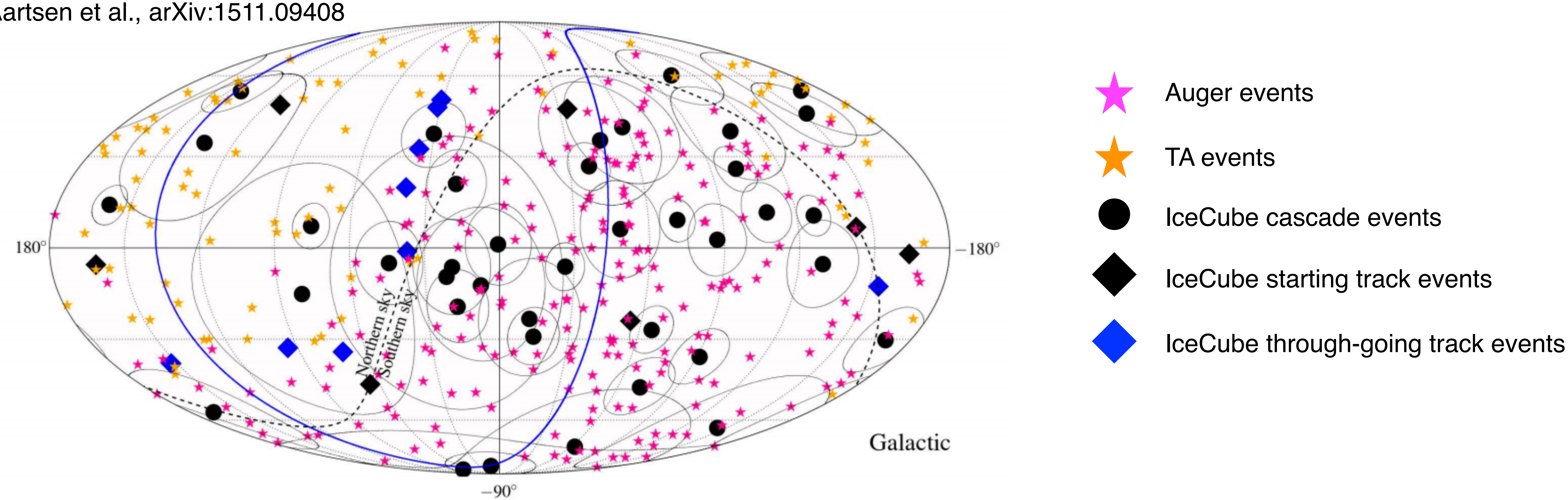
Murase, Ahlers & Lacki arXiv:1306.3417

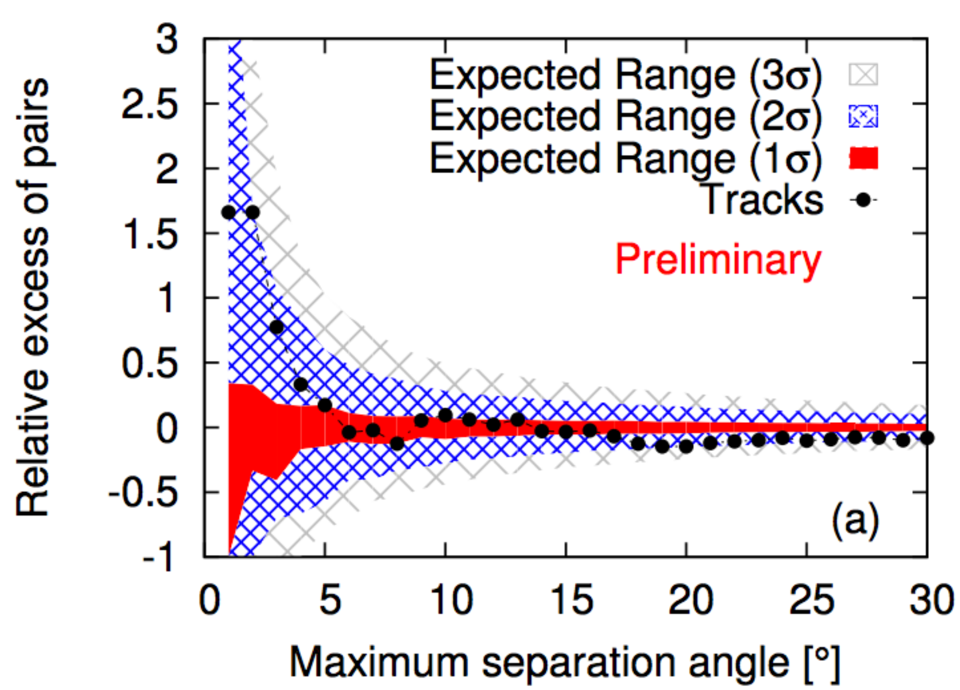
- γ-rays & ν's from pp interactions
- extra-galactic emission (cascaded in EBL): $E^{-2.1}$ - $E^{-2.2}$
- these cosmic ray sources contribute to 30%-40% of diffuse γ-ray background @100 GeV
- low energy tail of GeV-TeV neutrino/γ-ray spectra
- sources can be opaque in γ-ray
- ν to probe dense environments

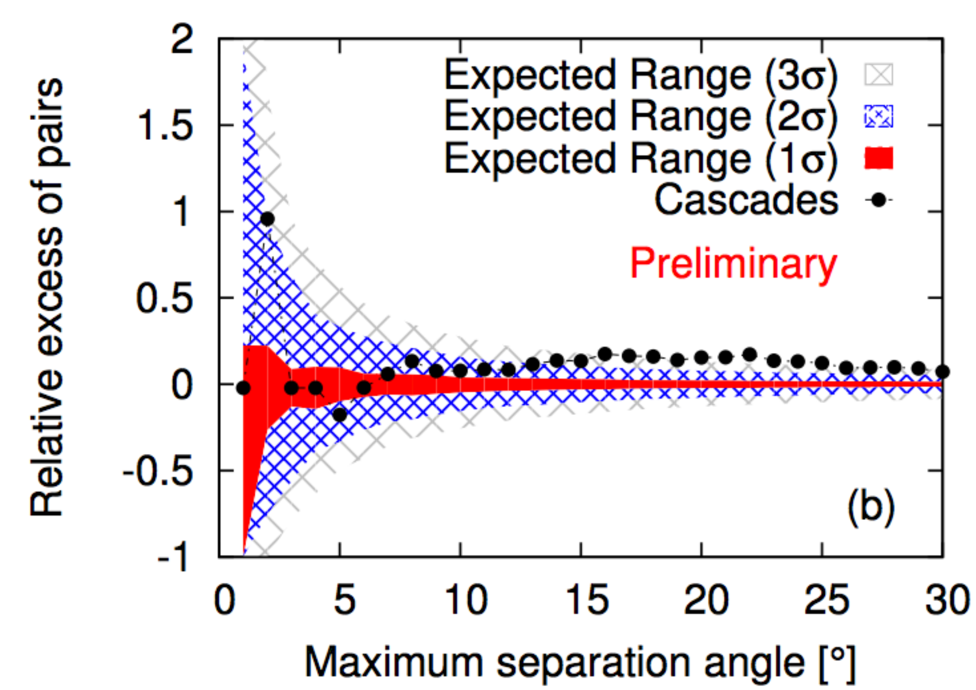
astrophysical neutrinos
correlations with UHECR from Auger ?

IceCube
Auger
TA

Aartsen et al., arXiv:1511.09408

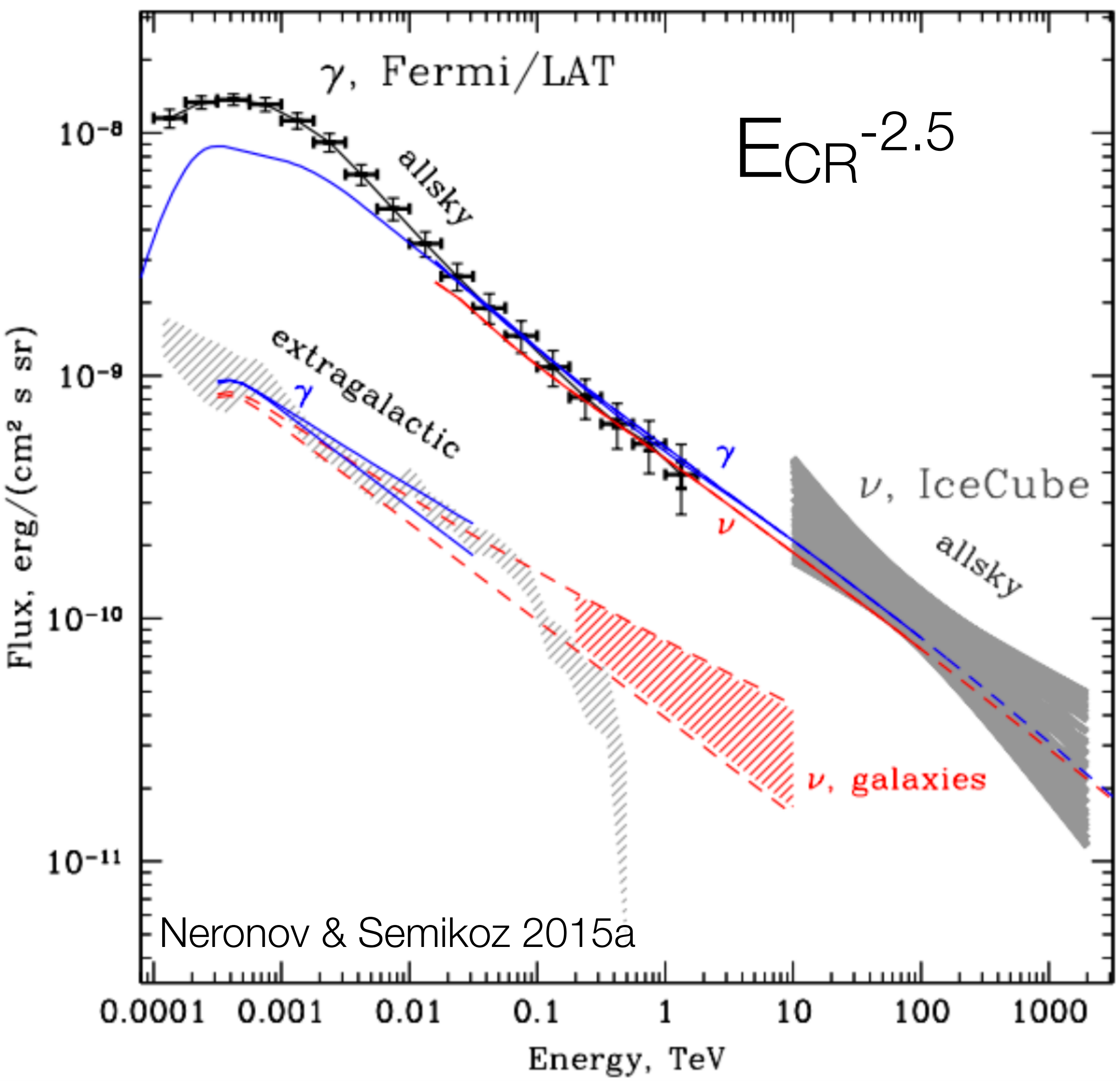


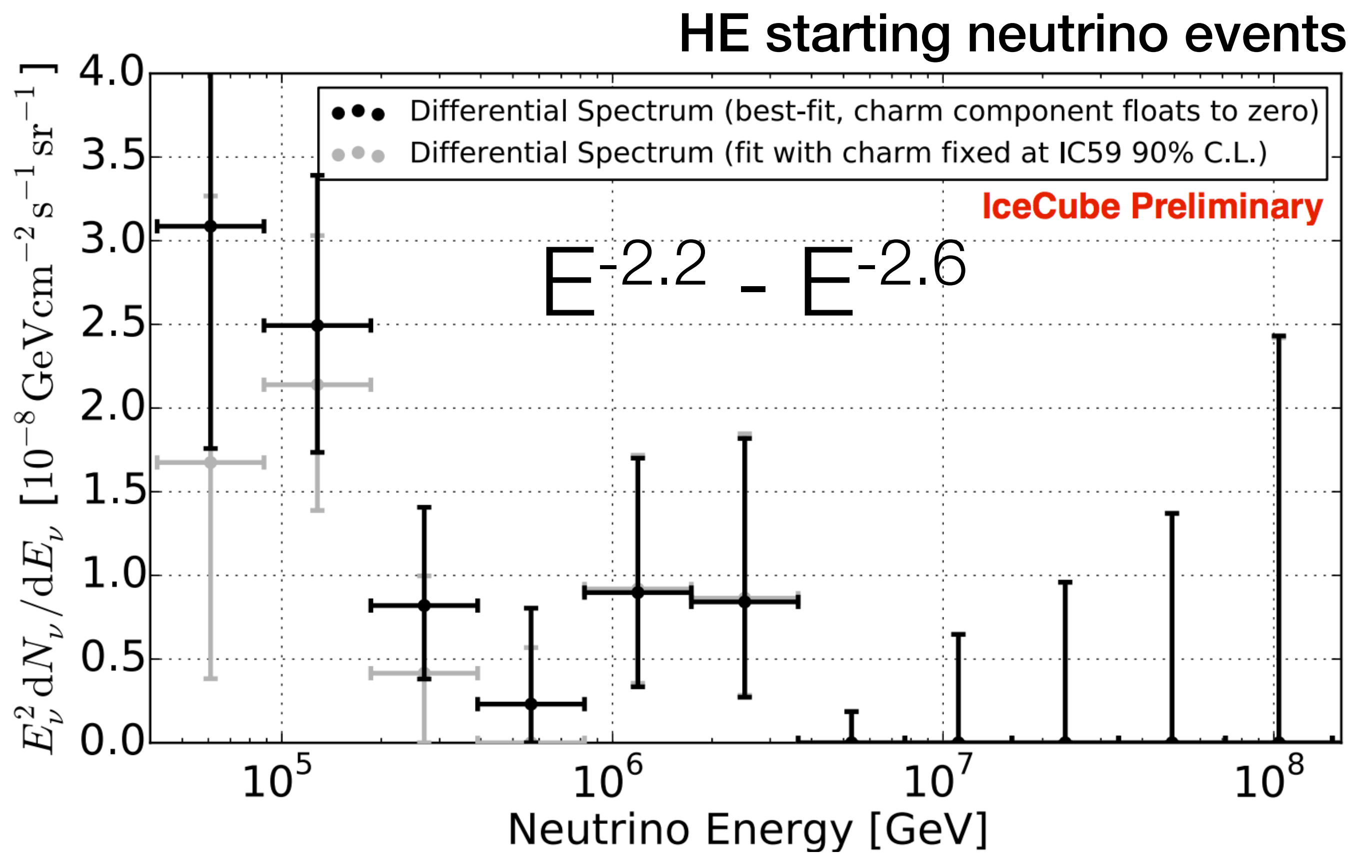


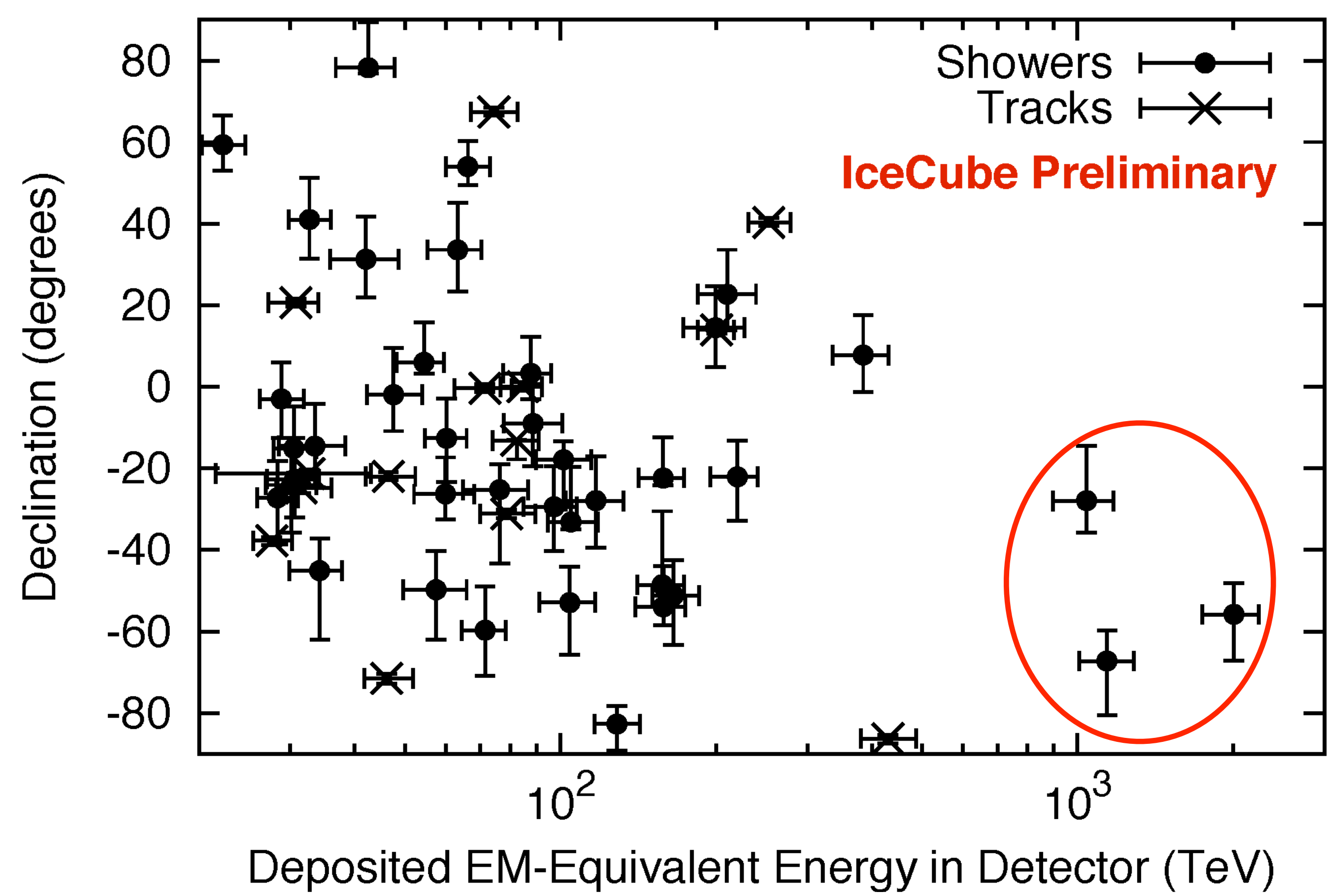


astrophysical neutrinos

galactic origin

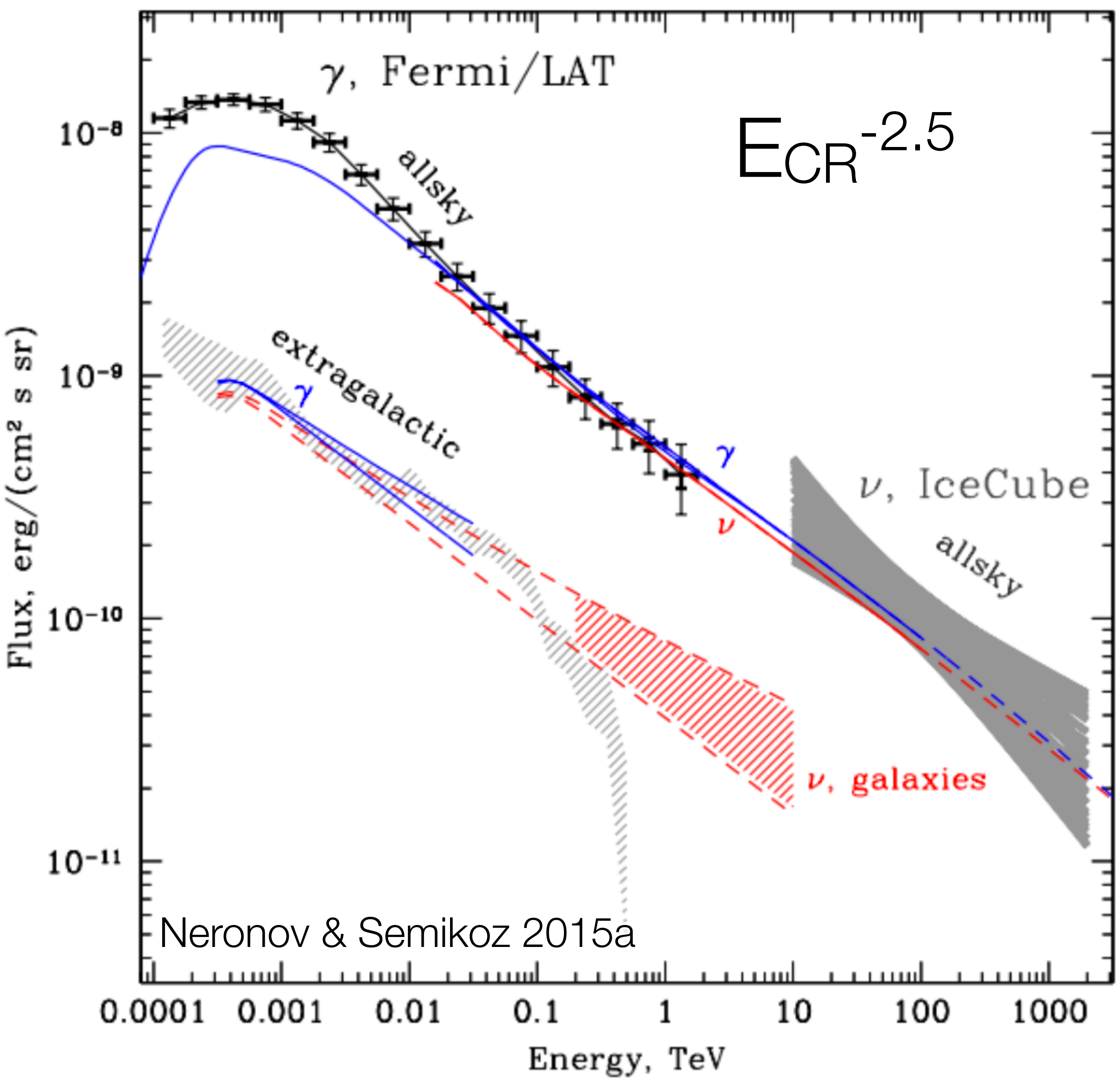




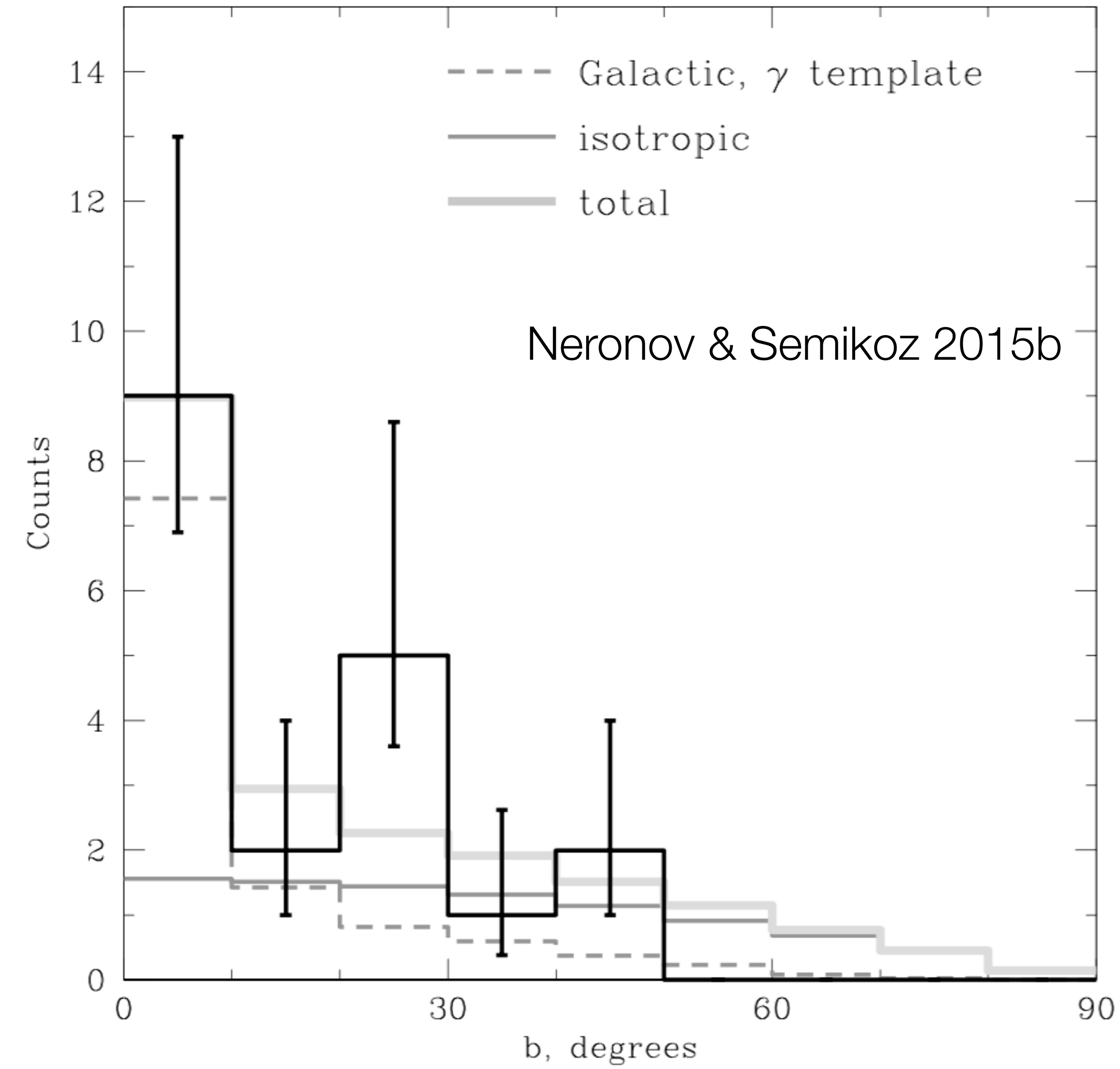


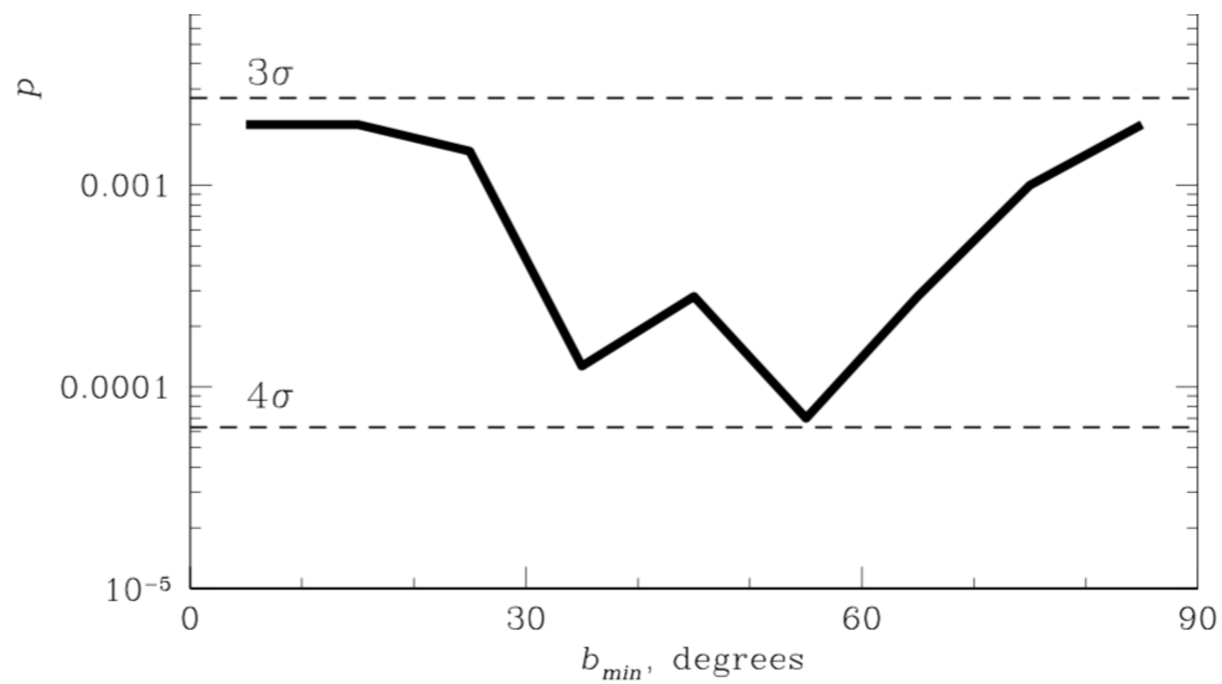
galactic cosmic rays with cut-off of 10 PeV ?

astrophysical neutrinos
galactic origin



galactic plane >100 TeV





galactic cosmic rays with cut-off of 10 PeV ?