Results from the IceCube Observatory

neutrinos and the origin of the cosmic rays

Paolo Desiati, for the IceCube Collaboration

Wisconsin IceCube Particle Astrophysics Center & Department of Astronomy
University of Wisconsin - Madison

<desiati@icecube.wisc.edu>

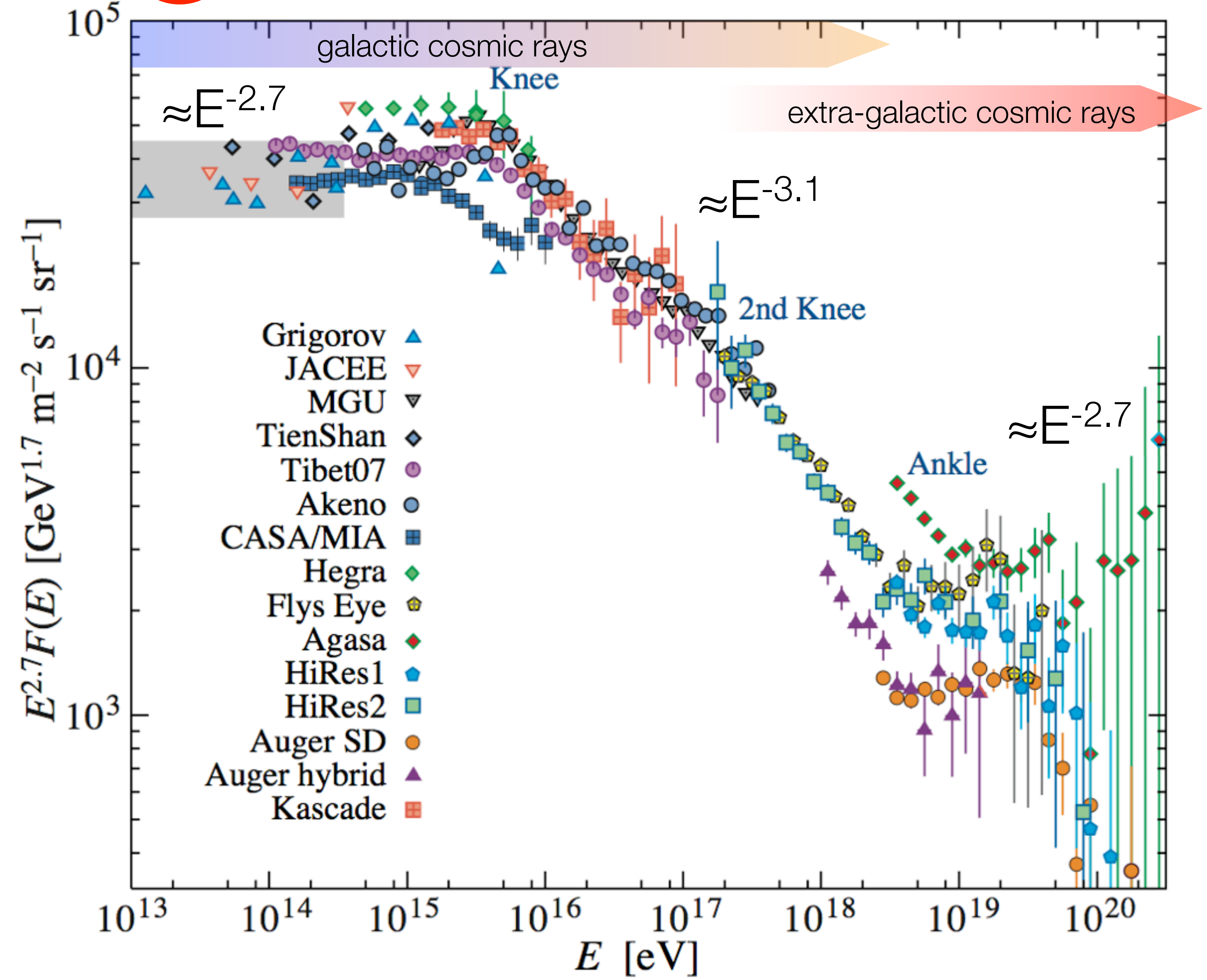
Vulcano Workshop 2012
May 28th - June 2nd, 2012

cosmic rays

- cosmic ray spectrum, composition and anisotropy, hold information on their **origin** and **propagation**
- transition between galactic and extra-galactic origin of cosmic rays is debated
- are the sources of cosmic rays also the site of their acceleration ?

$$E^{2.7} \cdot \frac{d\Phi_{CR}}{dE}(E)$$

Stanev, Gaisser, PDG



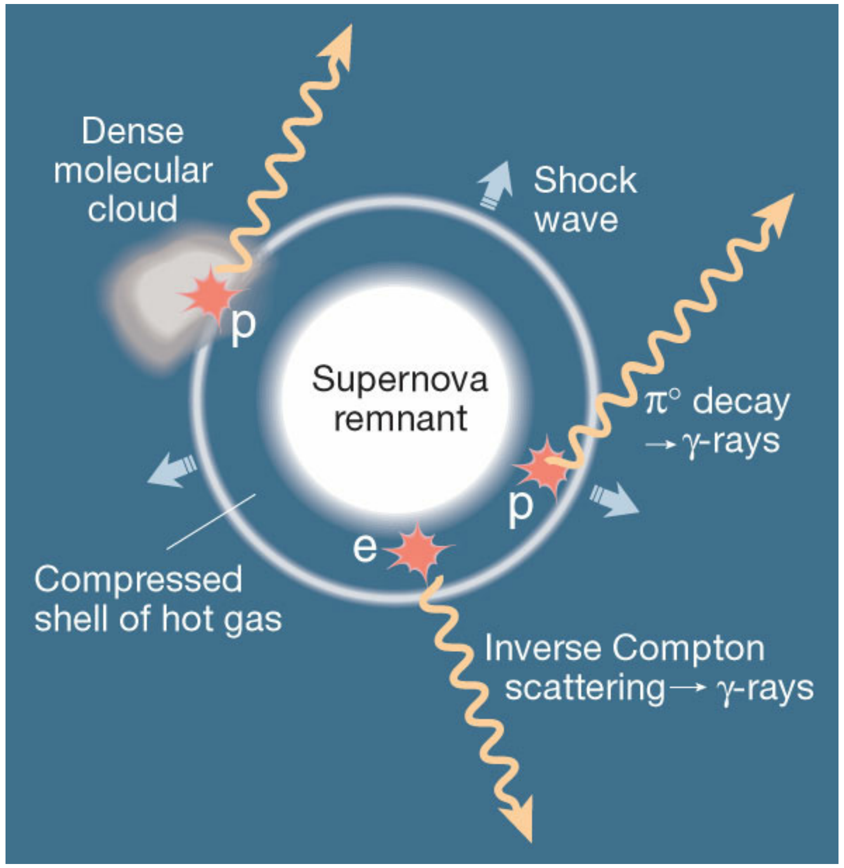
shock acceleration

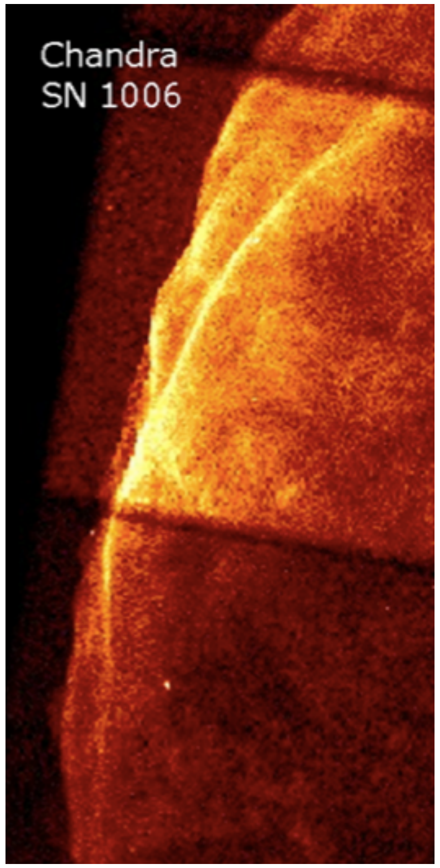
- acceleration processes may occur within their sources or on a larger scale

- properties of cosmic ray sources from high energy gamma rays and neutrinos generated at the source

- if hadronic acceleration occurs in galactic and extra-galactic shocks or jets, gamma rays and neutrinos are produced

Aharonian, 2002





$p + (p \text{ or } \gamma) \rightarrow \pi^{\pm} + X \rightarrow \nu_e, \nu_\mu + X$ **neutrinos ...**
$\rightarrow \pi^{o} + X \rightarrow \gamma, \gamma + X$ **gamma rays ...**

Flux $\sim E_p^{-2}$ **(Fermi acceleration)**

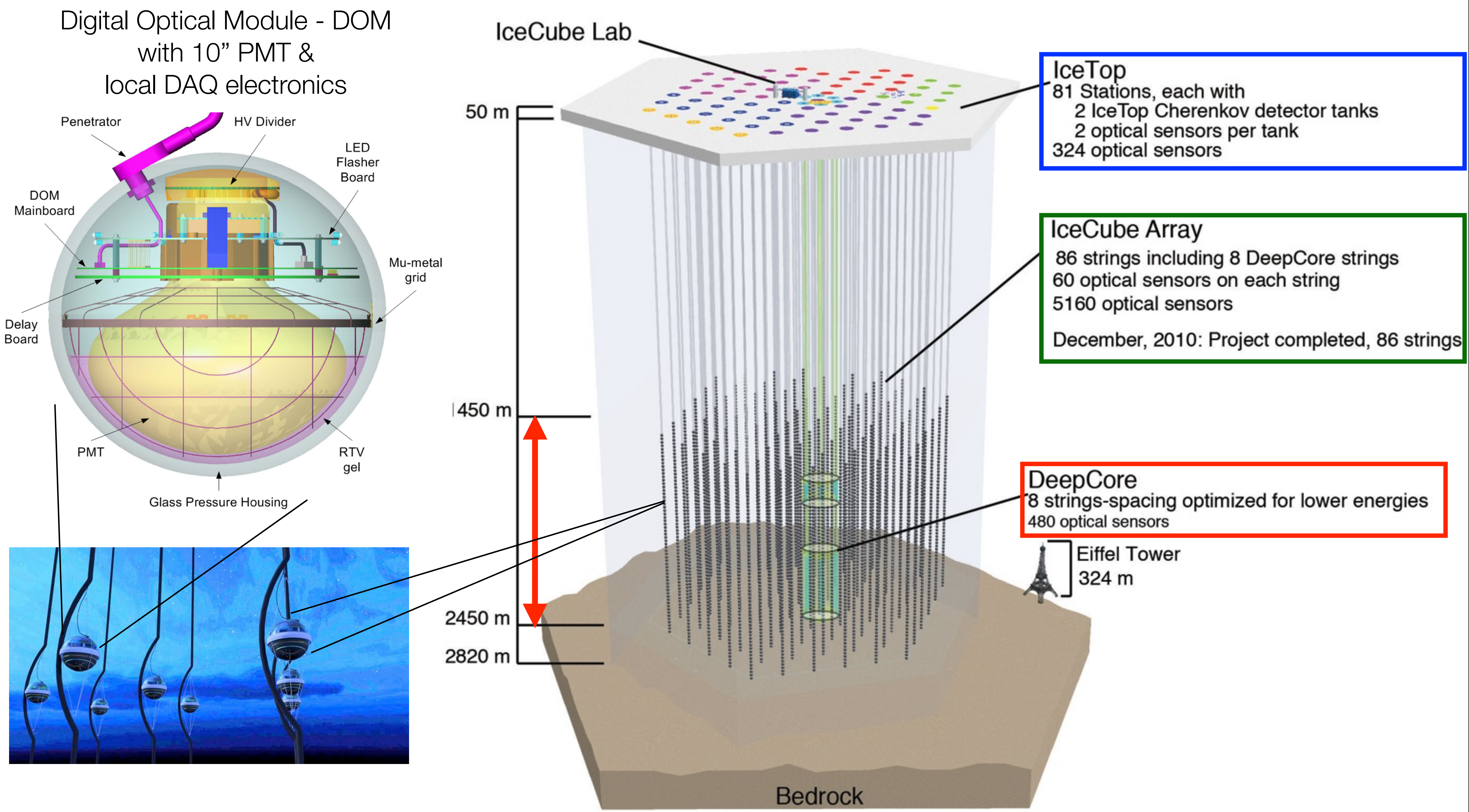
protons @ knee produce ~ 300 TeV γ rays

The IceCube Collaboration

International Funding Agencies

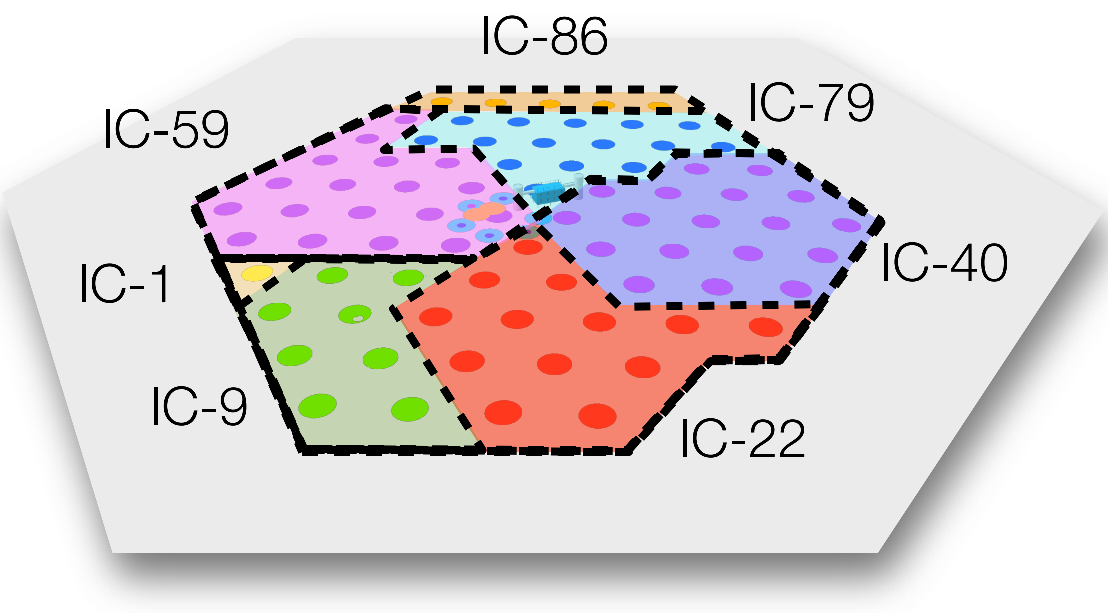
Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)
Federal Ministry of Education & Research (BMBF)
German Research Foundation (DFG)
Deutsches Elektronen-Synchrotron (DESY)
Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

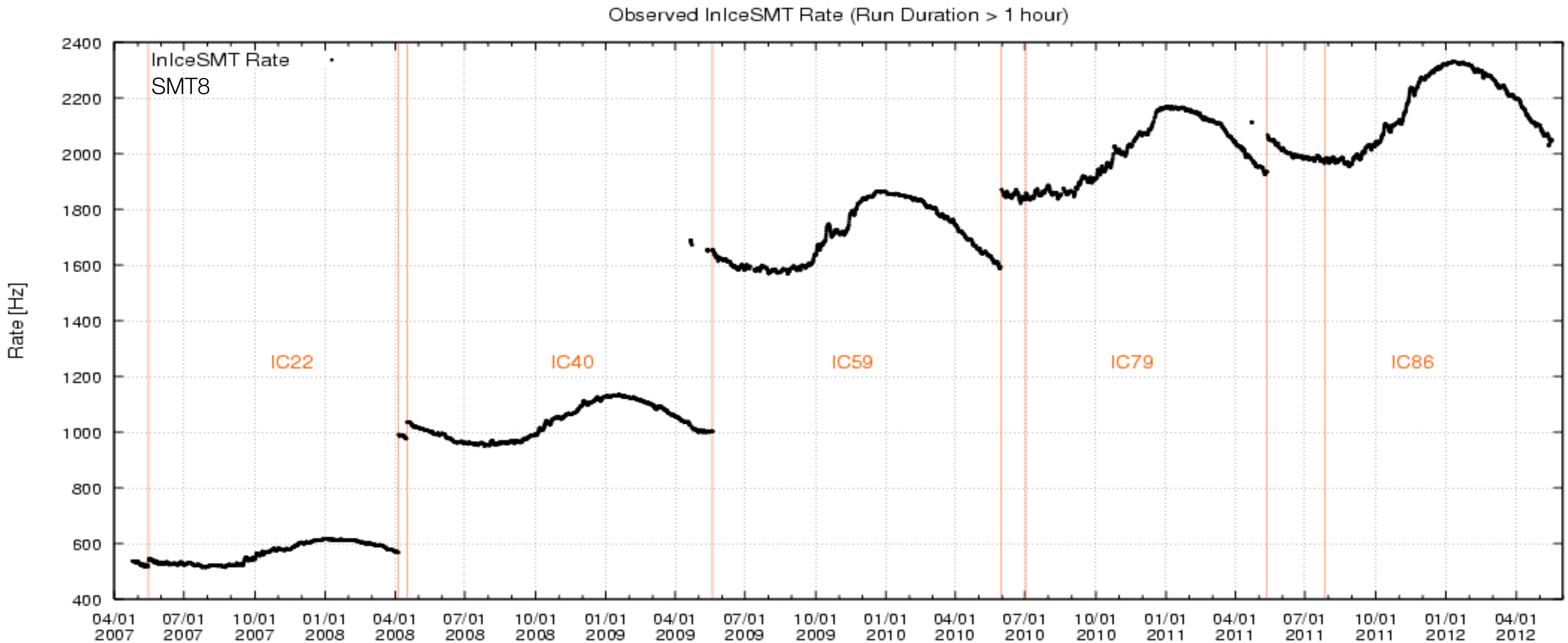
IceCube Observatory



growing IceCube
& event collection

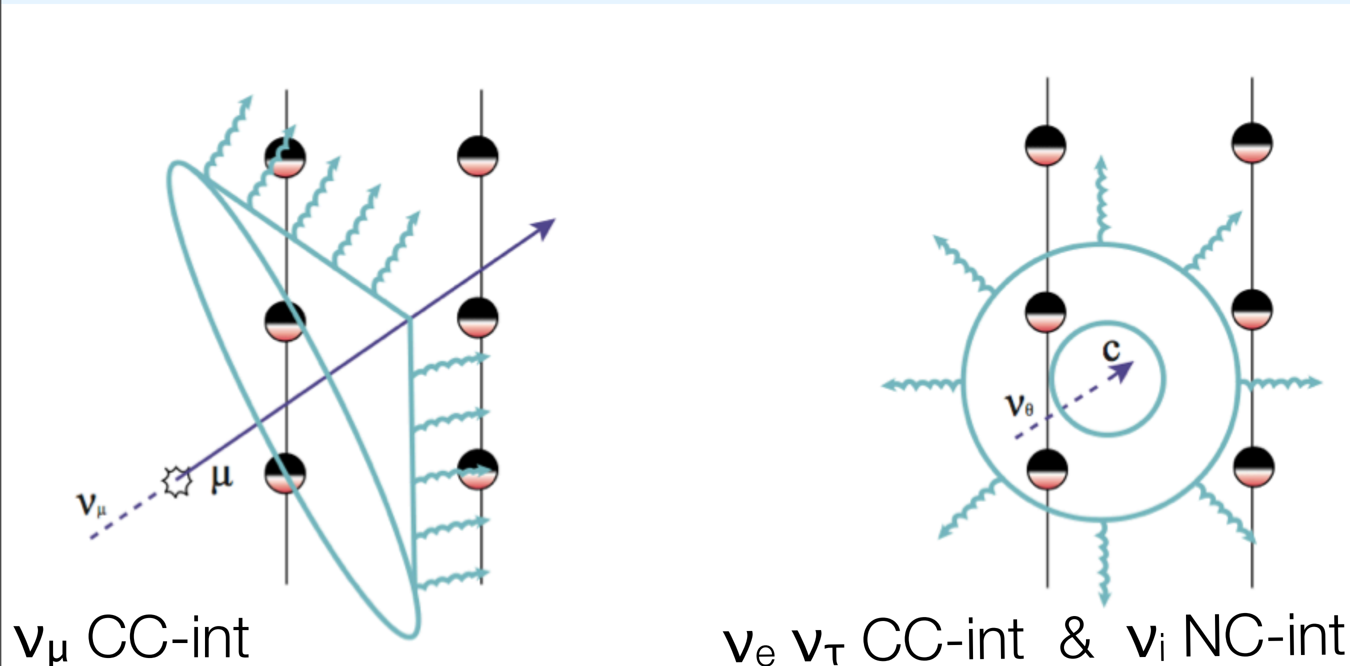
Strings	Year	μ rate
IC22	2007	500 Hz
IC40	2008	1100 Hz
IC59	2009	1700 Hz
IC79	2010	2000 Hz
IC86	2011	2100 Hz

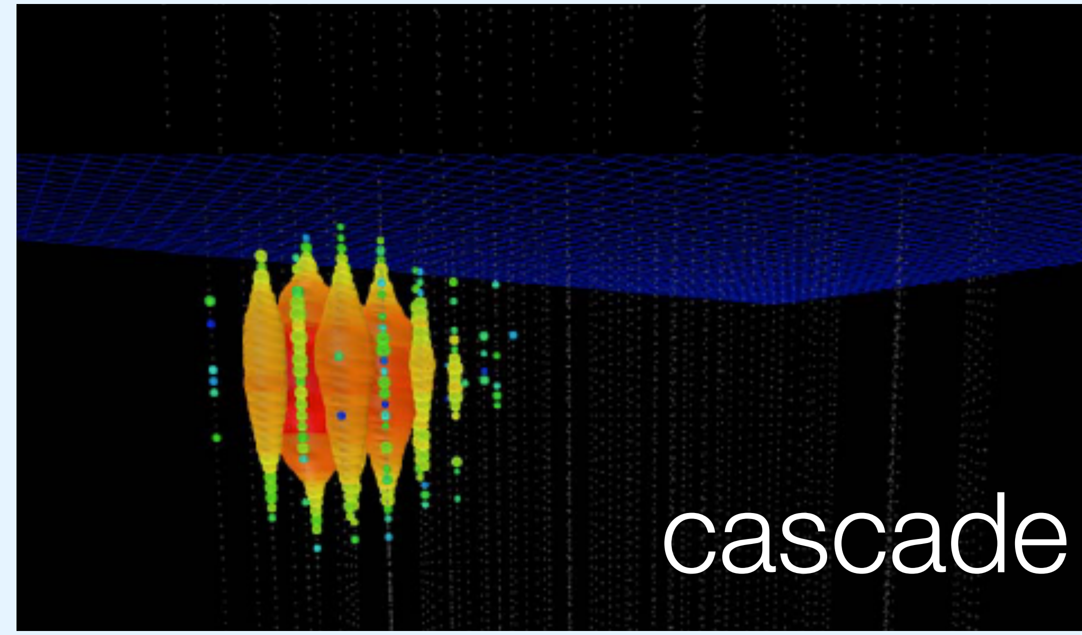


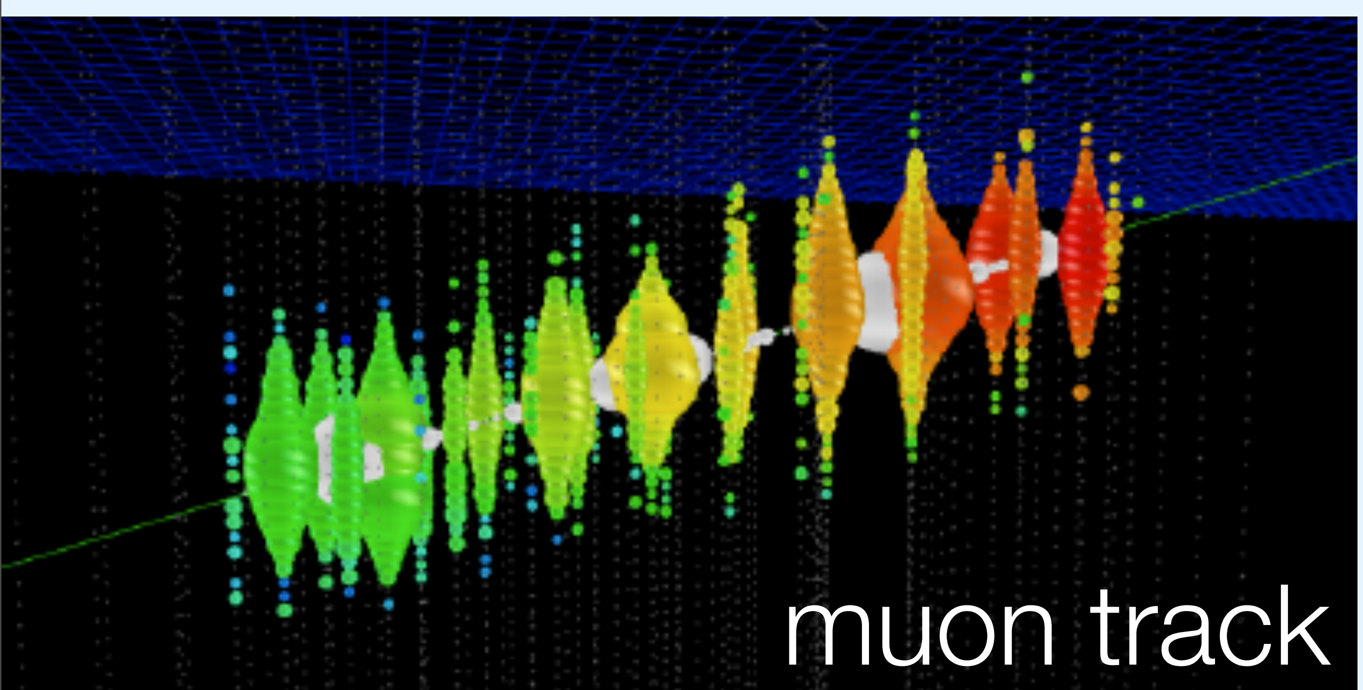


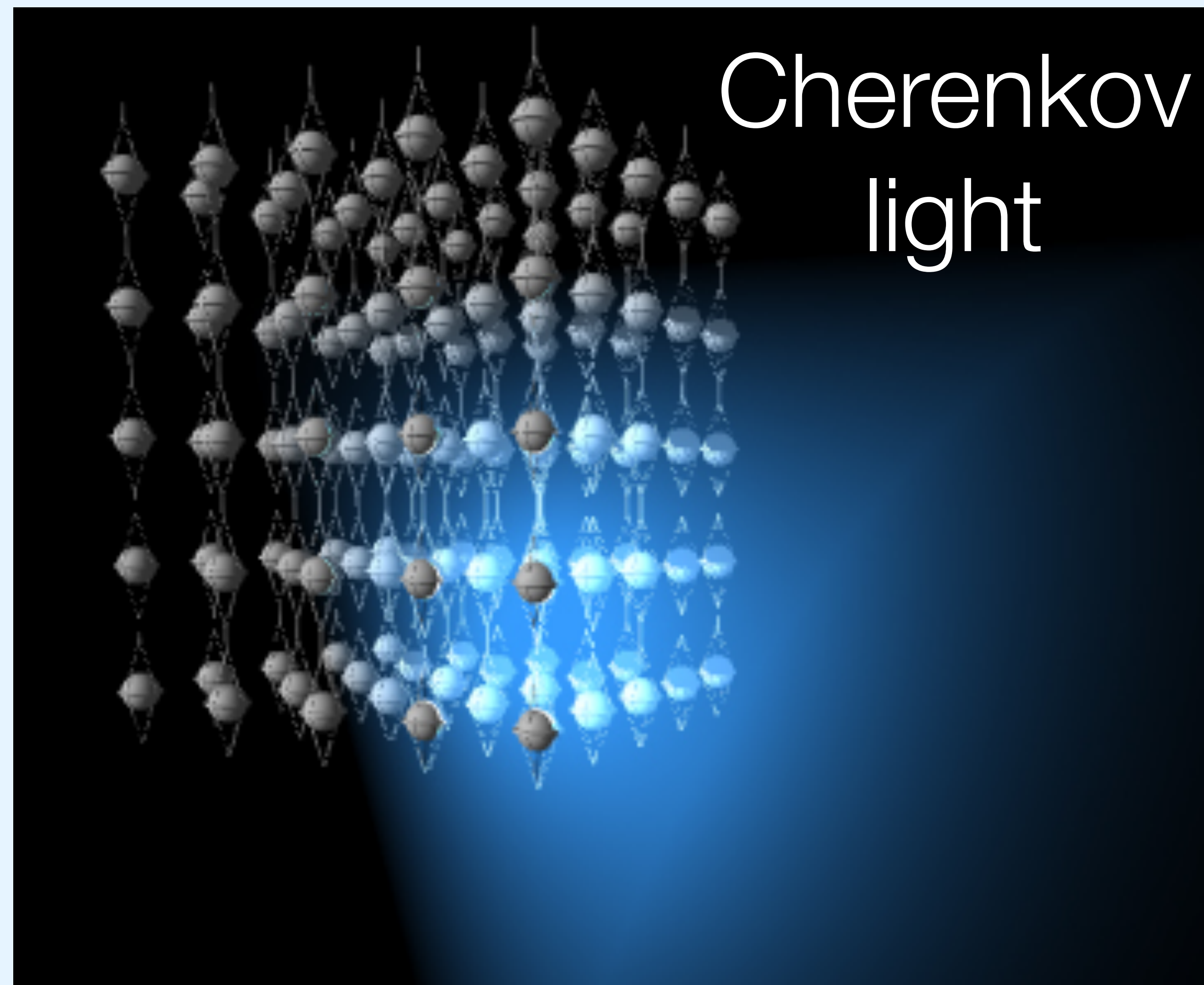
Paolo Desiati

detection principle

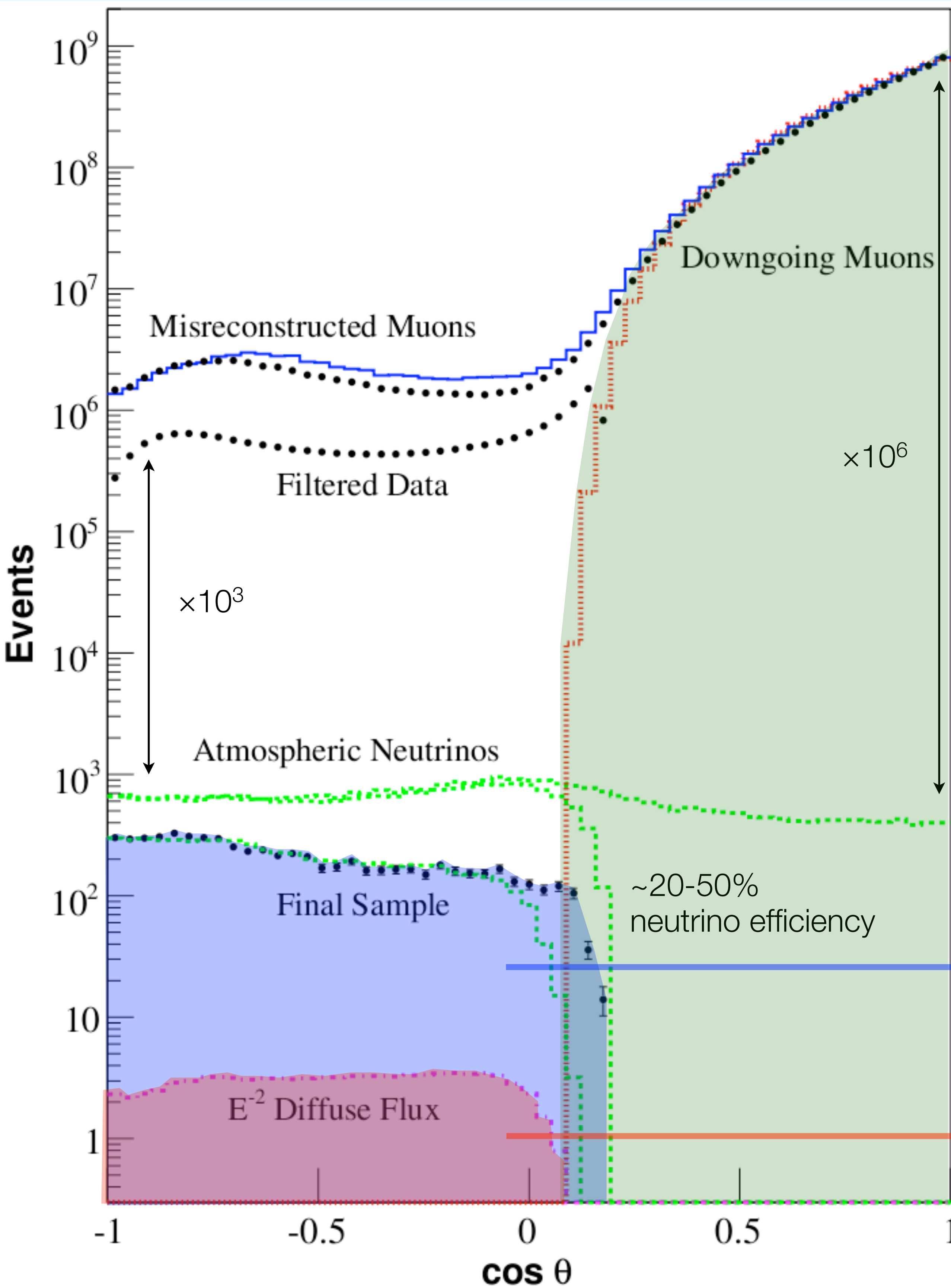


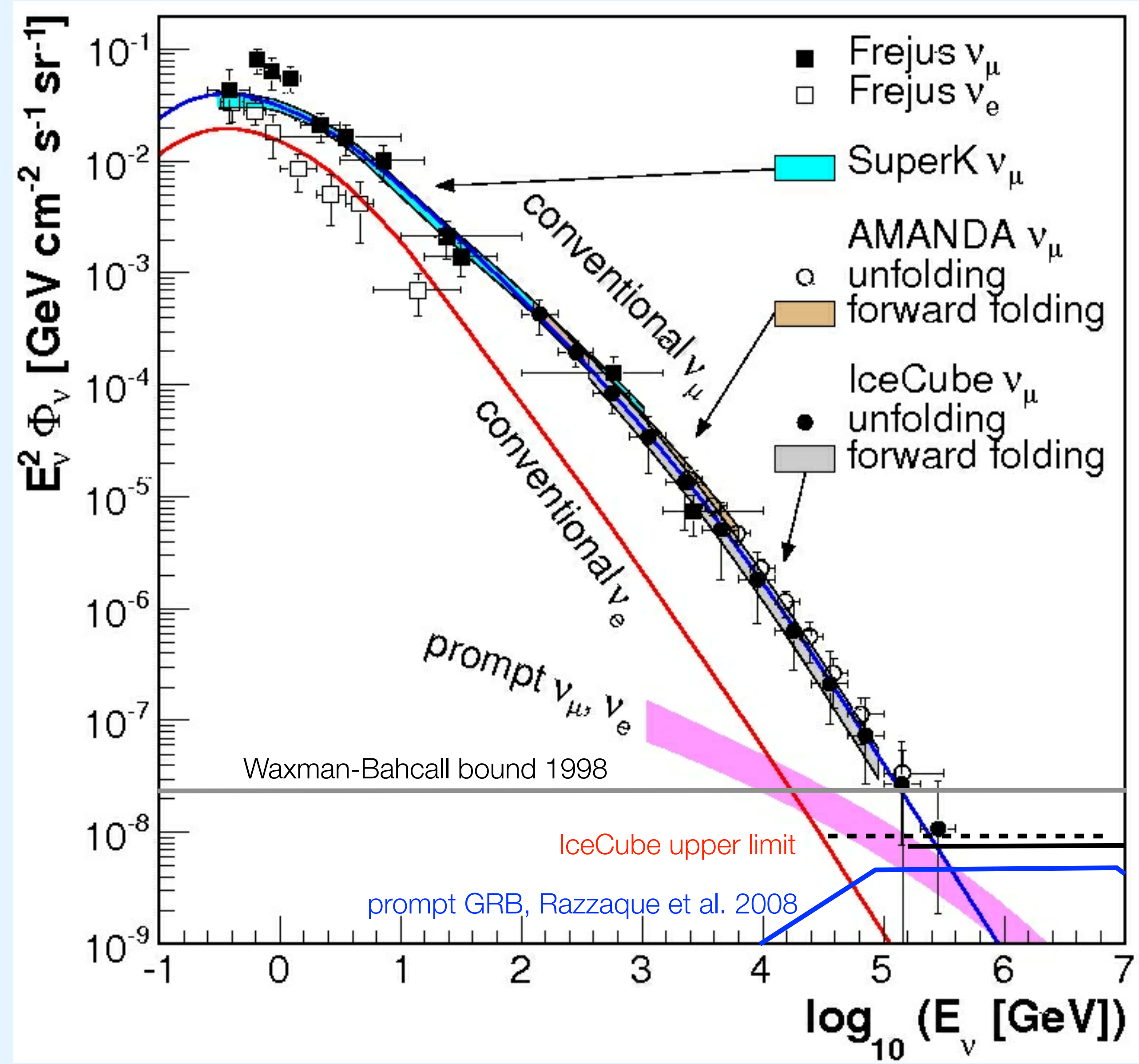






event identification

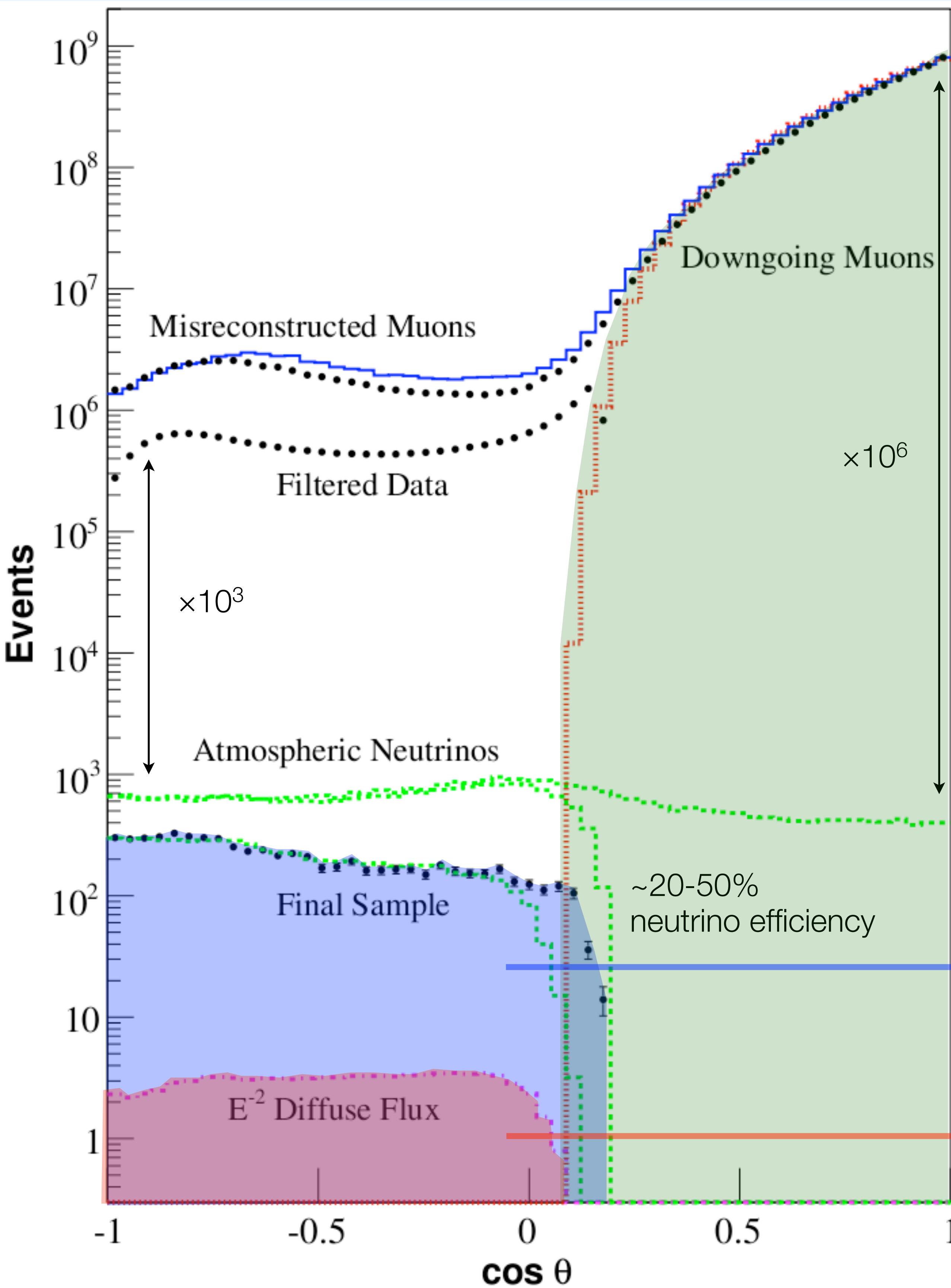




atmospheric neutrinos

extra-terrestrial neutrinos

event identification



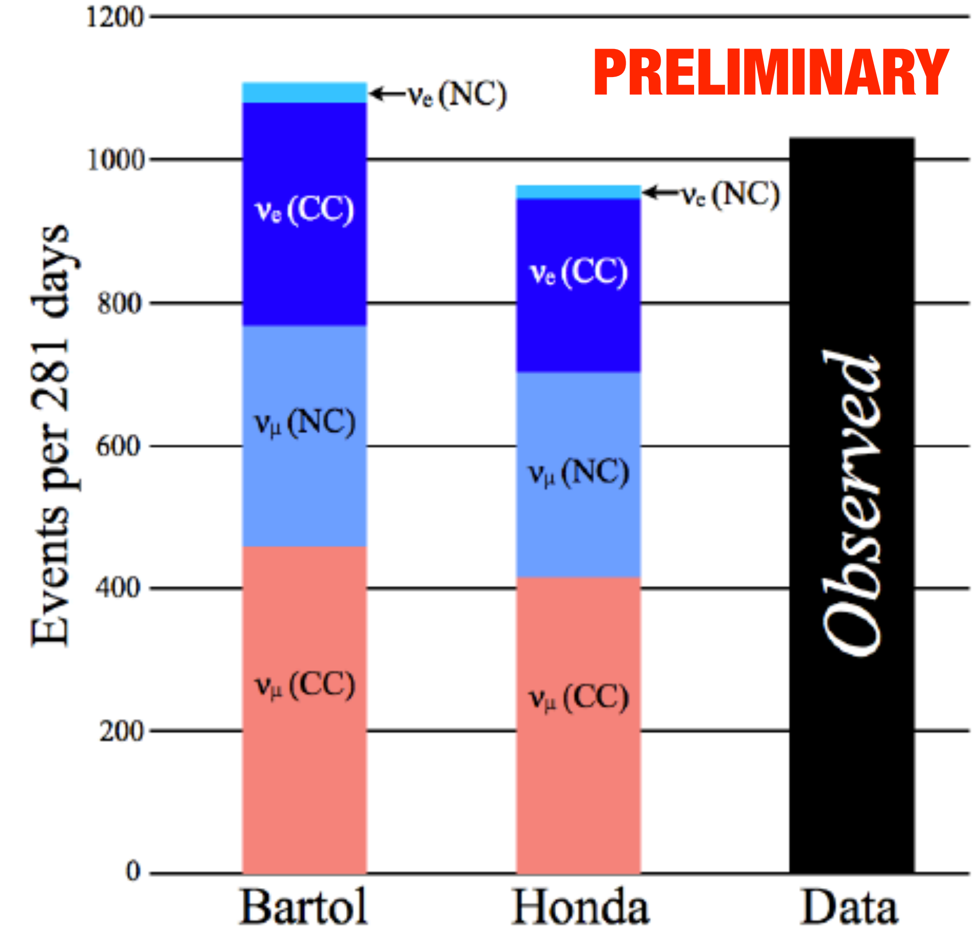
Strings	Year	μ rate	final ν_μ rate
IC22	2007	500 Hz	18 / day
IC40	2008	1100 Hz	40 / day
IC59	2009	1700 Hz	130 / day
IC79	2010	2000 Hz	~170 / day
IC86	2011	2100 Hz	~200 / day

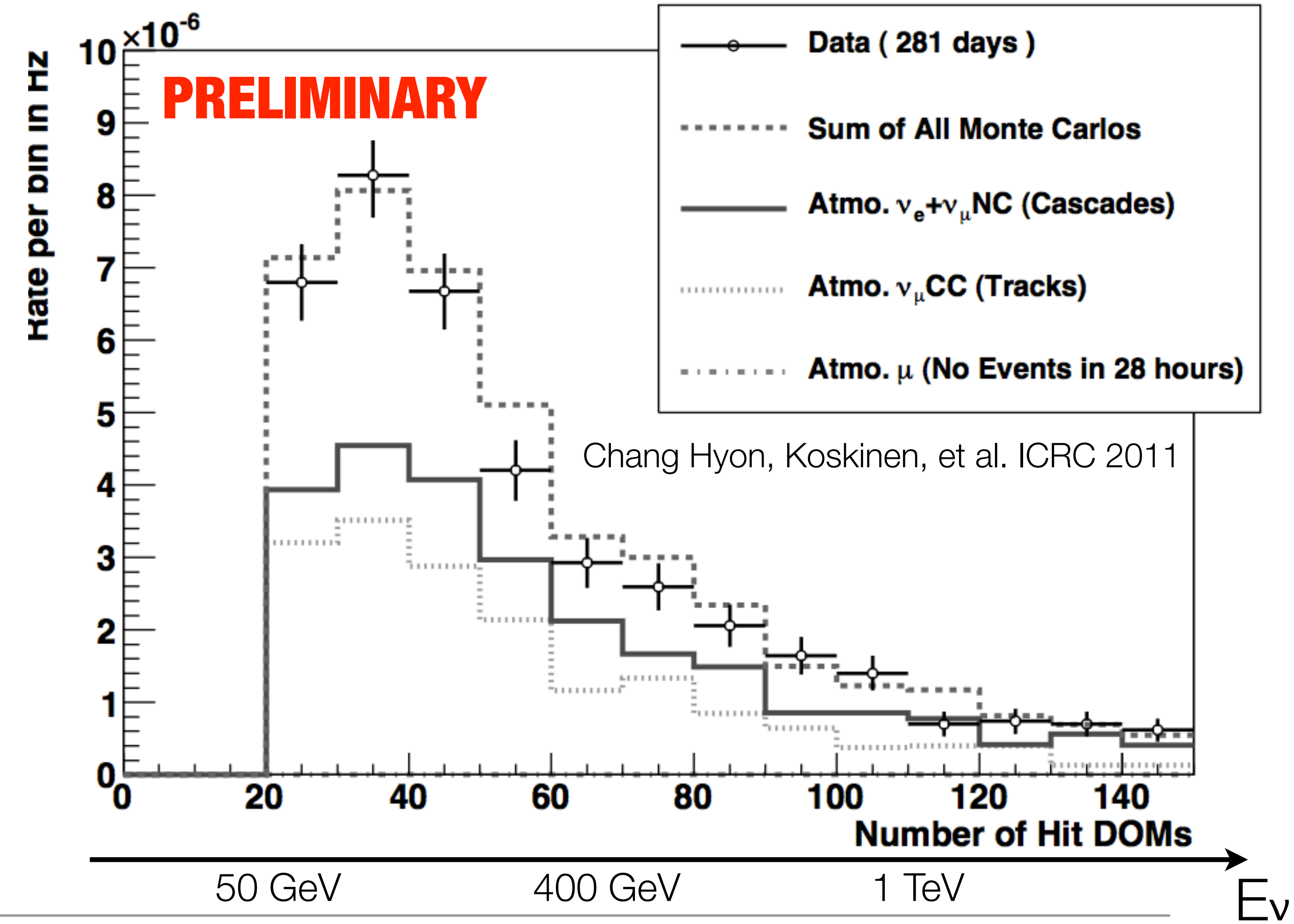
atmospheric neutrinos

extra-terrestrial neutrinos

identification of cascade atmospheric events

- IC79 experimental data with dense infill DeepCore
- CR- and ν_μ-induced muons rejected via veto with surrounding IceCube strings
- low energy events selection
- ~60% selected events from cascades

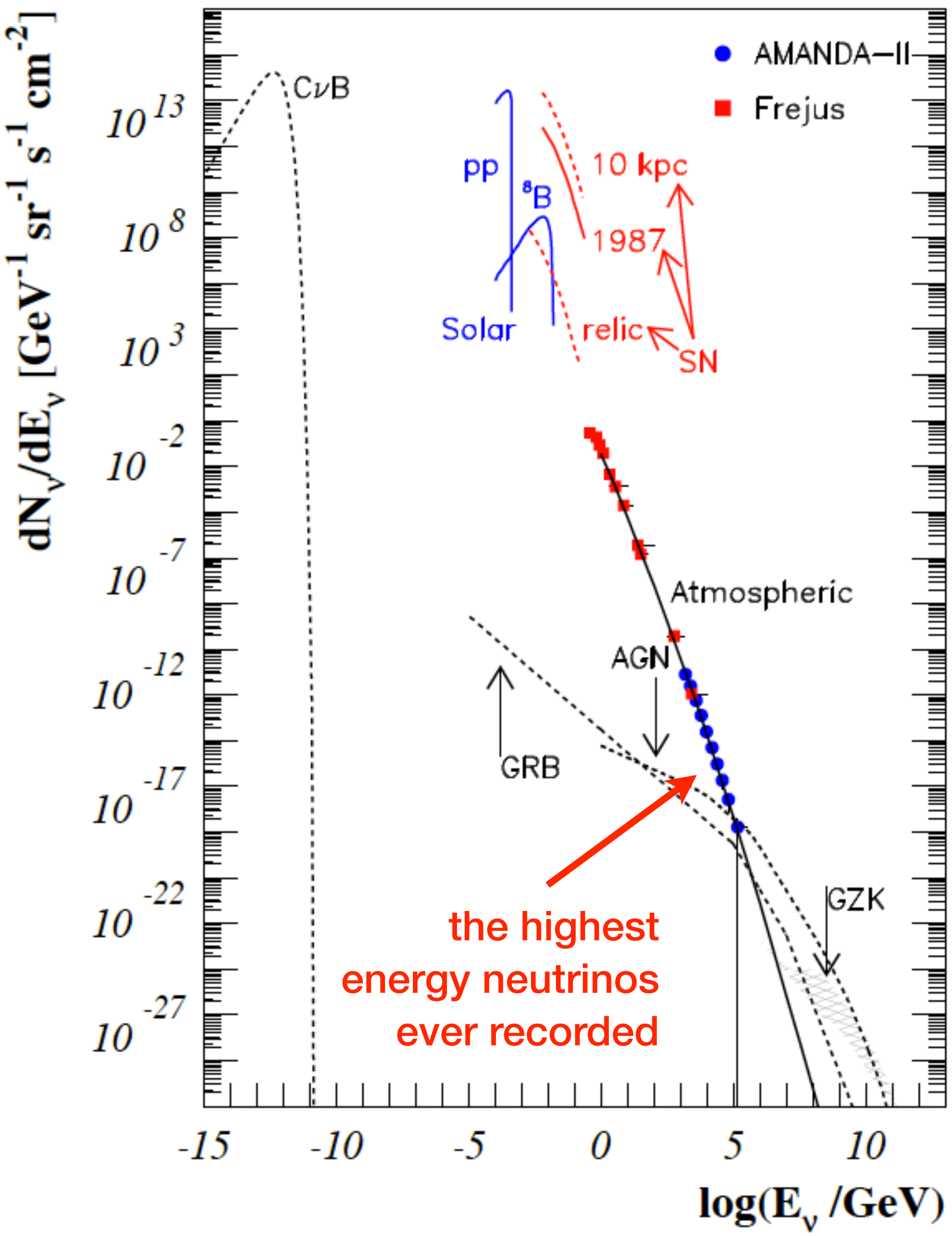


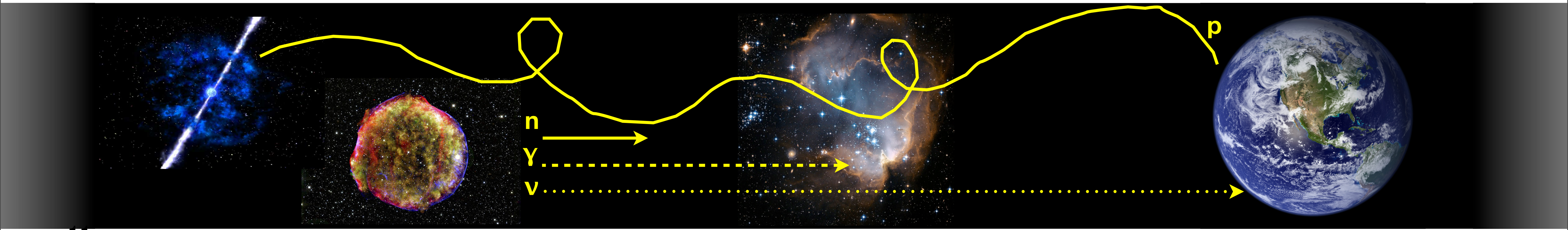


high energy neutrino astronomy

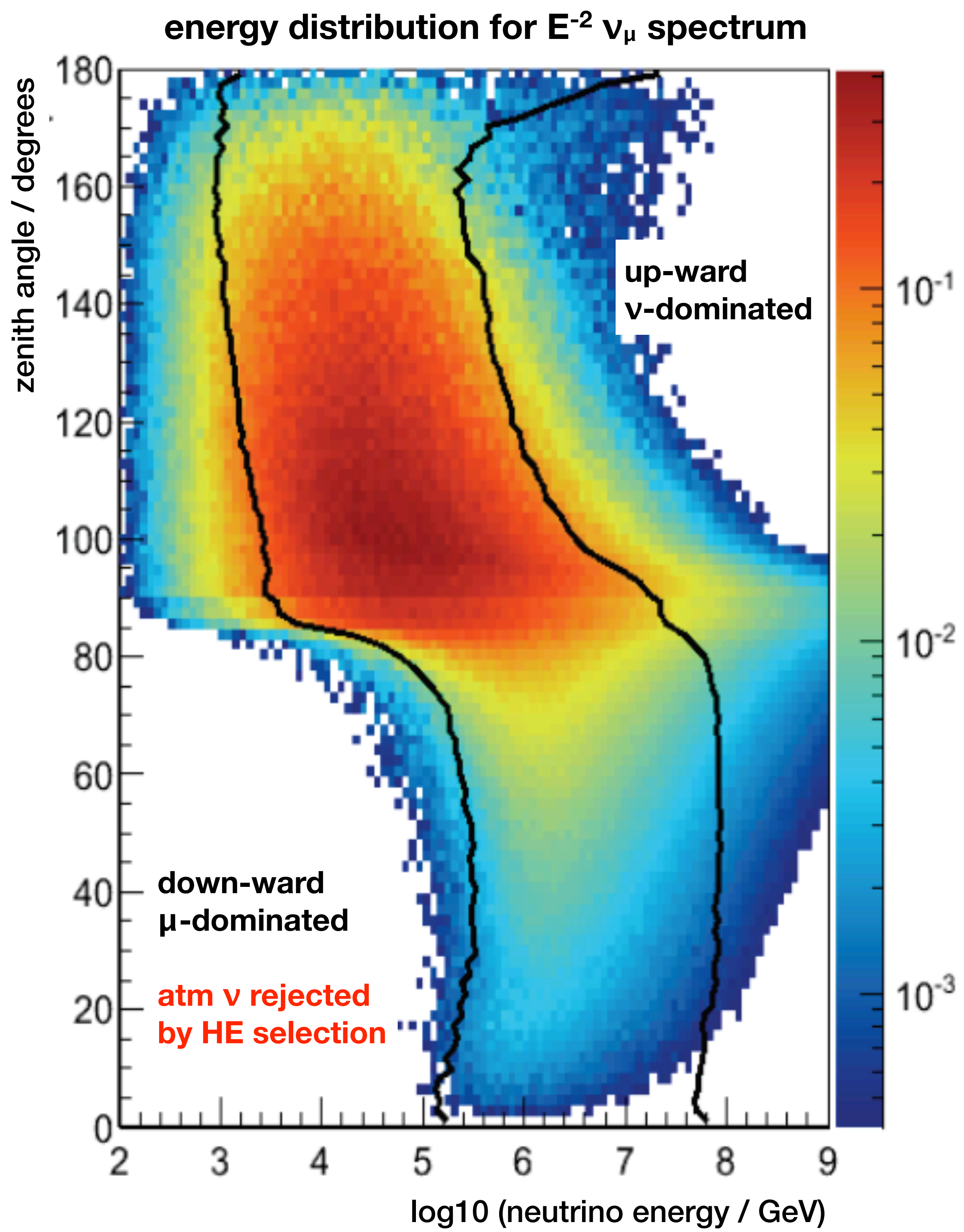
- galactic/extragalactic sources
- point (<1°) steady/transient/periodic sources
- extended (>1°) sources
- diffuse sources of HE/EHE neutrinos
  - origin of galactic and extra-galactic cosmic rays

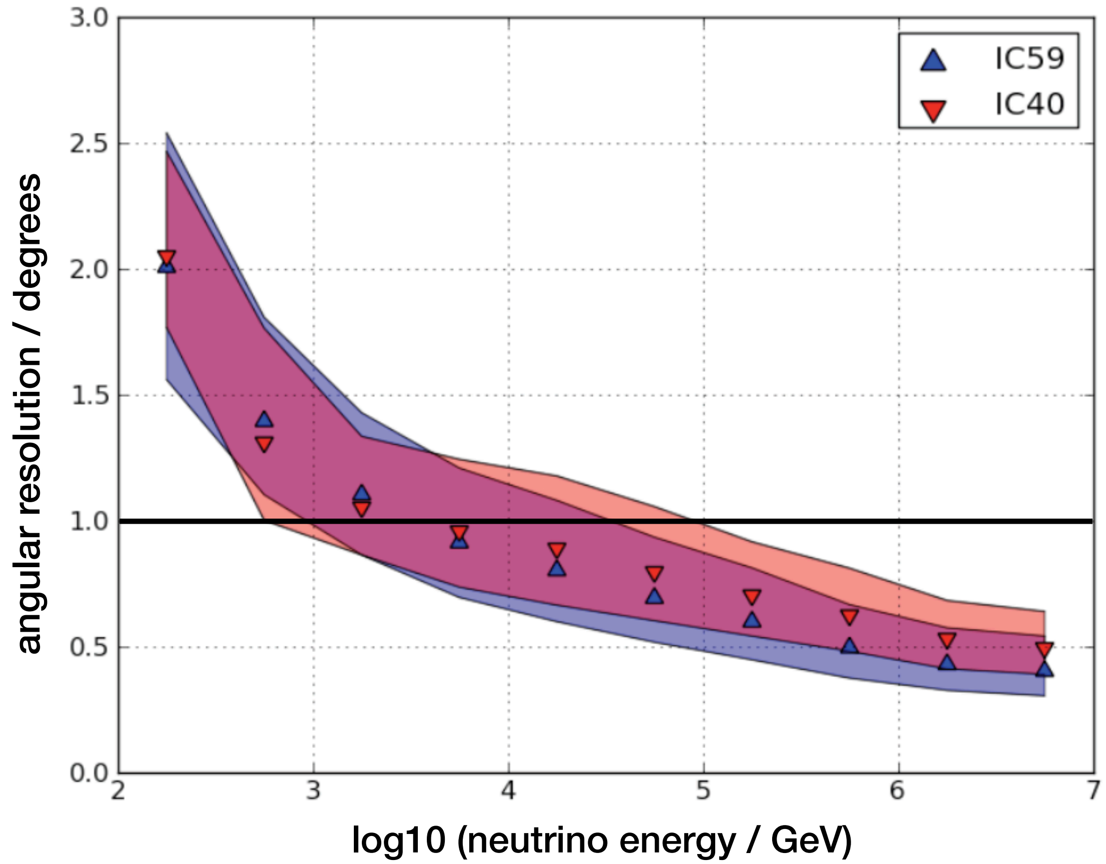
Becker J., Phys. Rept. **458**, 173 (2008)

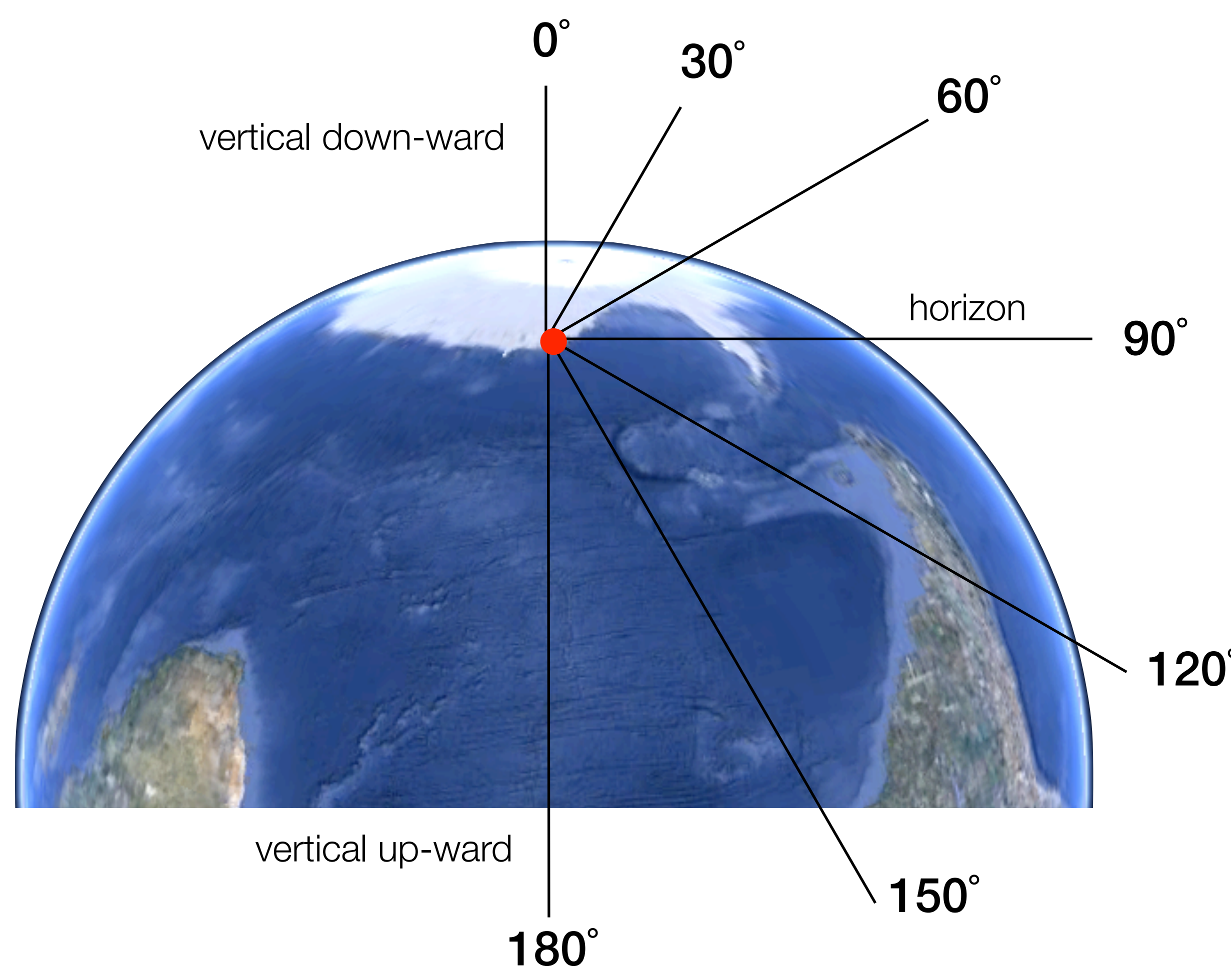




all-sky
steady point sources







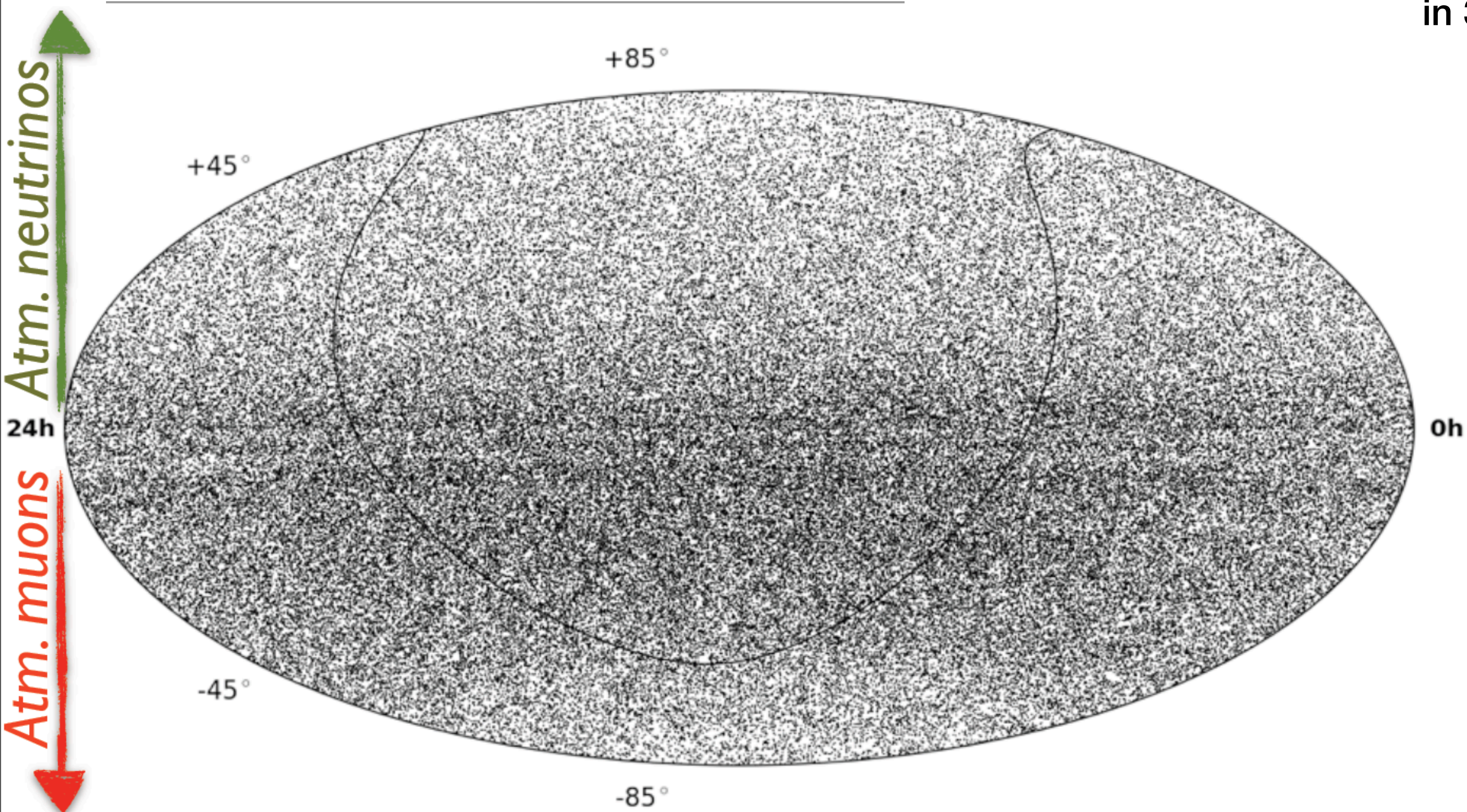
Paolo Desiati

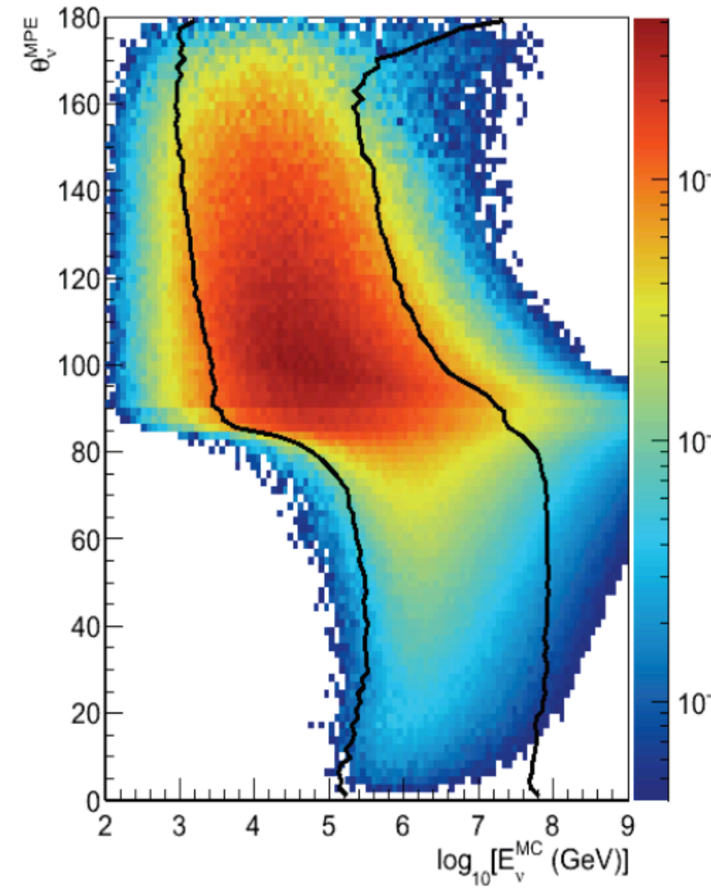
Friday, June 1, 2012

all-sky
steady point sources

43,339 up-ward + 64,230 downward

in 375 days (IC40) + 348 days (IC59)



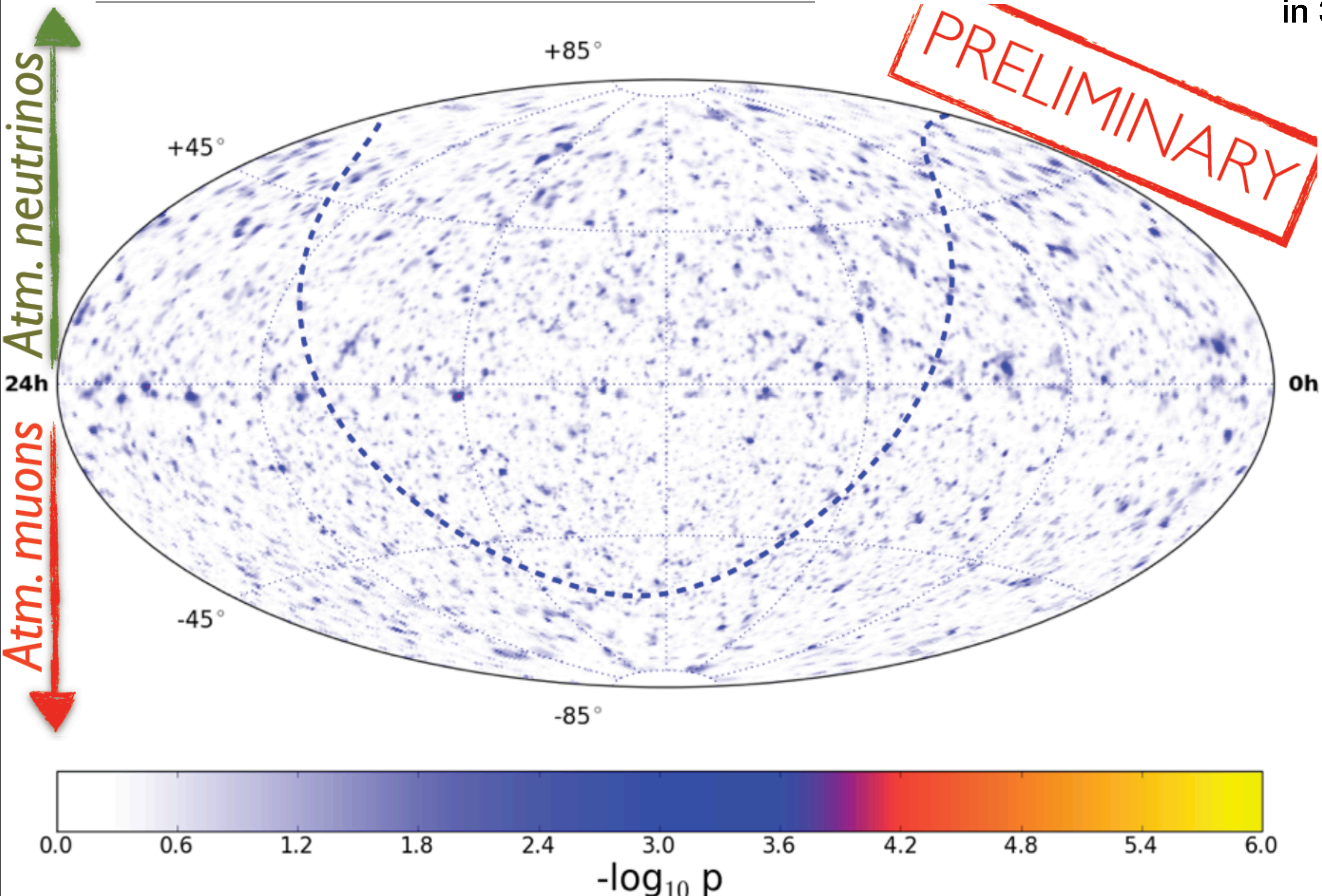


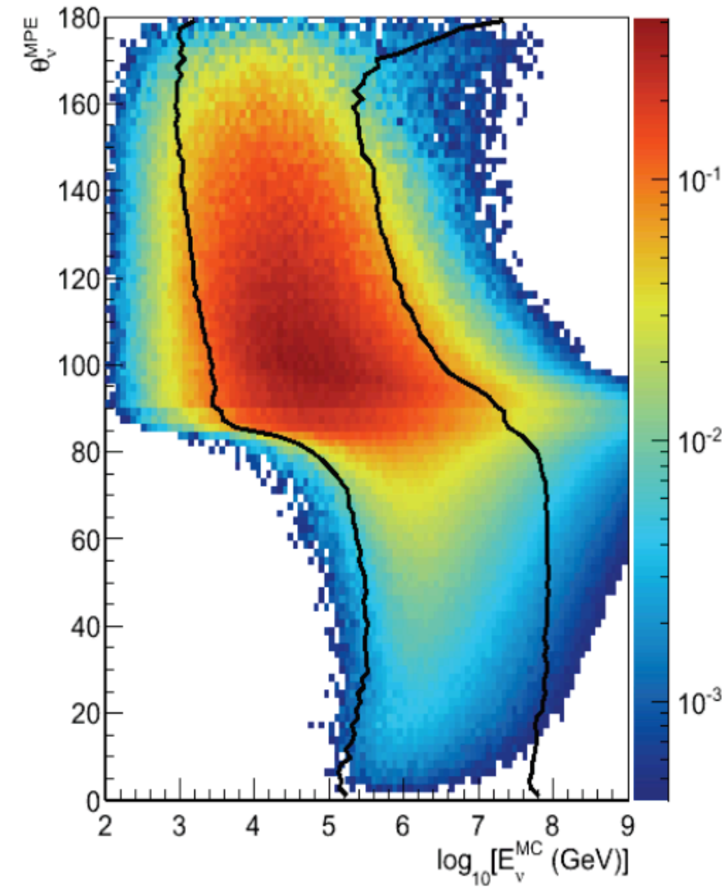
ApJ 732, 18 (2011) - arXiv:1012.2137

all-sky
steady point sources

43,339 up-ward + 64,230 downward

in 375 days (IC40) + 348 days (IC59)



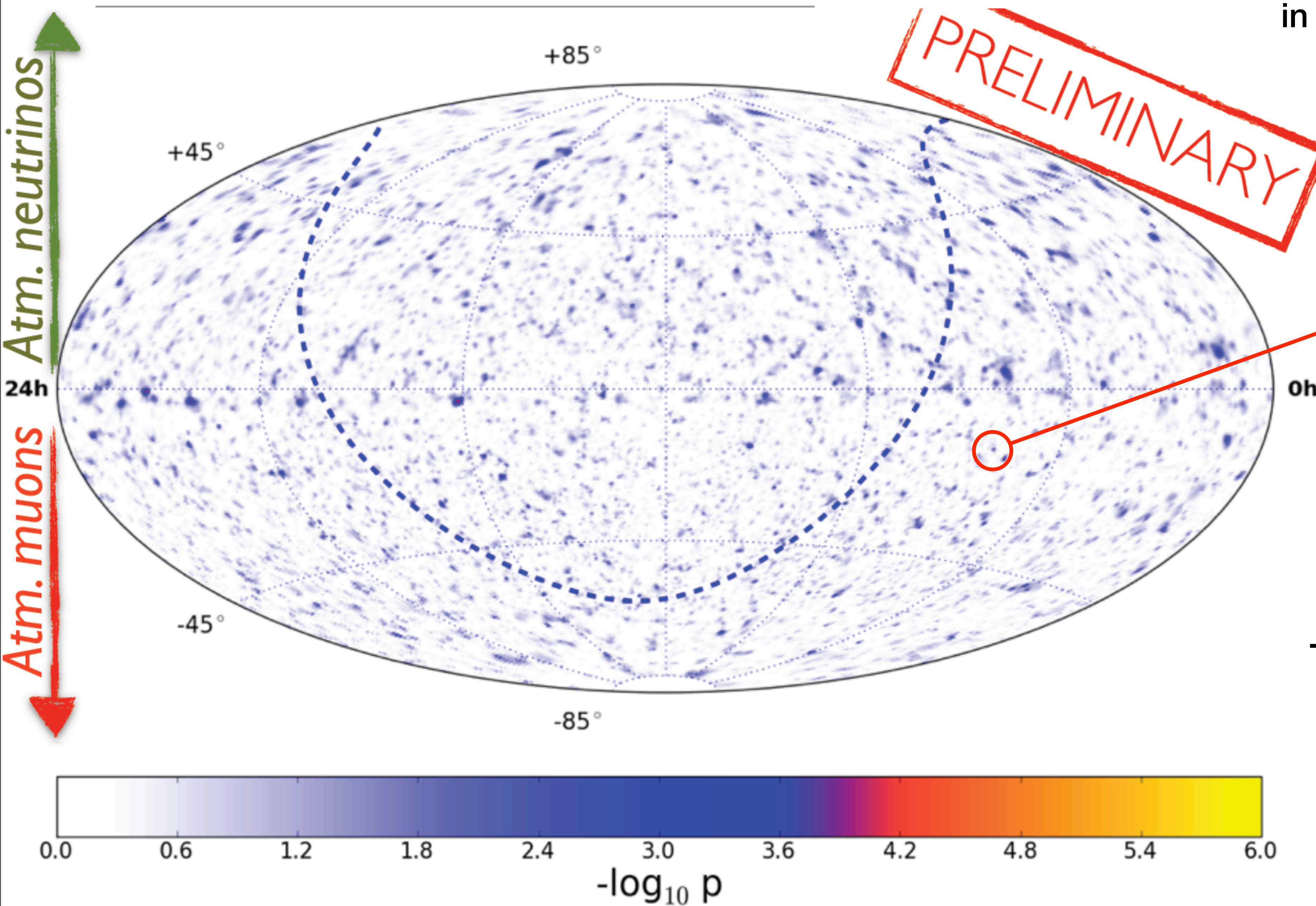


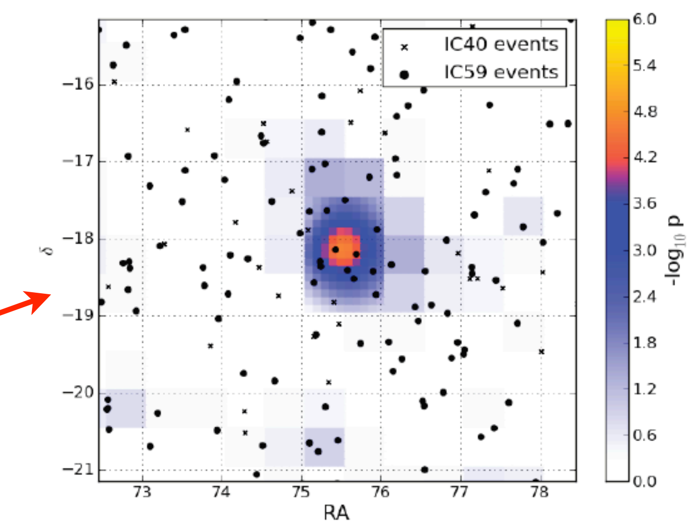
ApJ 732, 18 (2011) - arXiv:1012.2137

all-sky
steady point sources

43,339 up-ward + 64,230 downward

in 375 days (IC40) + 348 days (IC59)



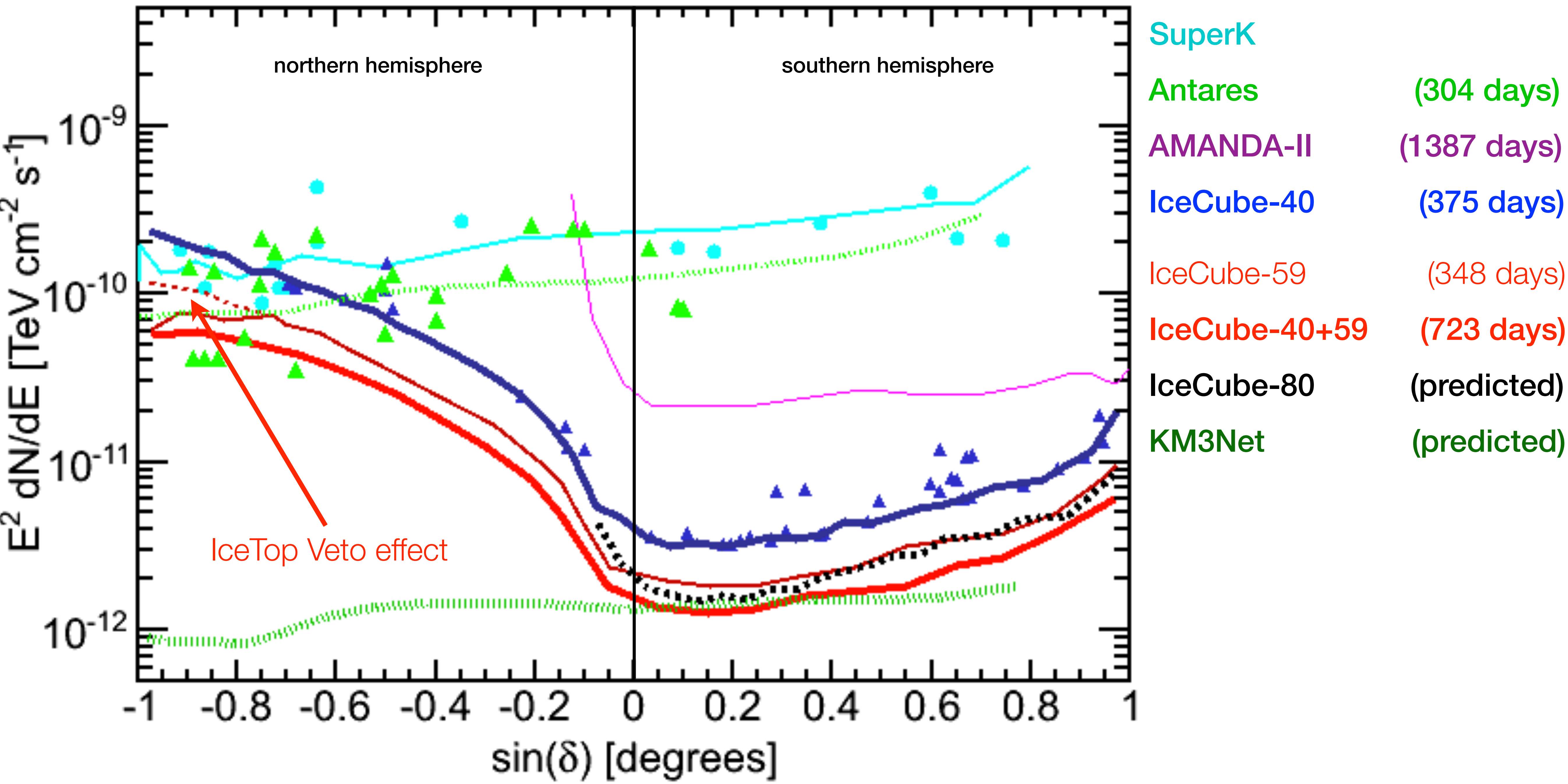


highest upper fluctuation

$-\log_{10}$(p-value) = 4.65
Ns = 18.3
γ = 3.9

post-trial chance probability ~ 67%

ApJ 732, 18 (2011) - arXiv:1012.2137



90% CL sensitivity for E^{-2} steady point sources

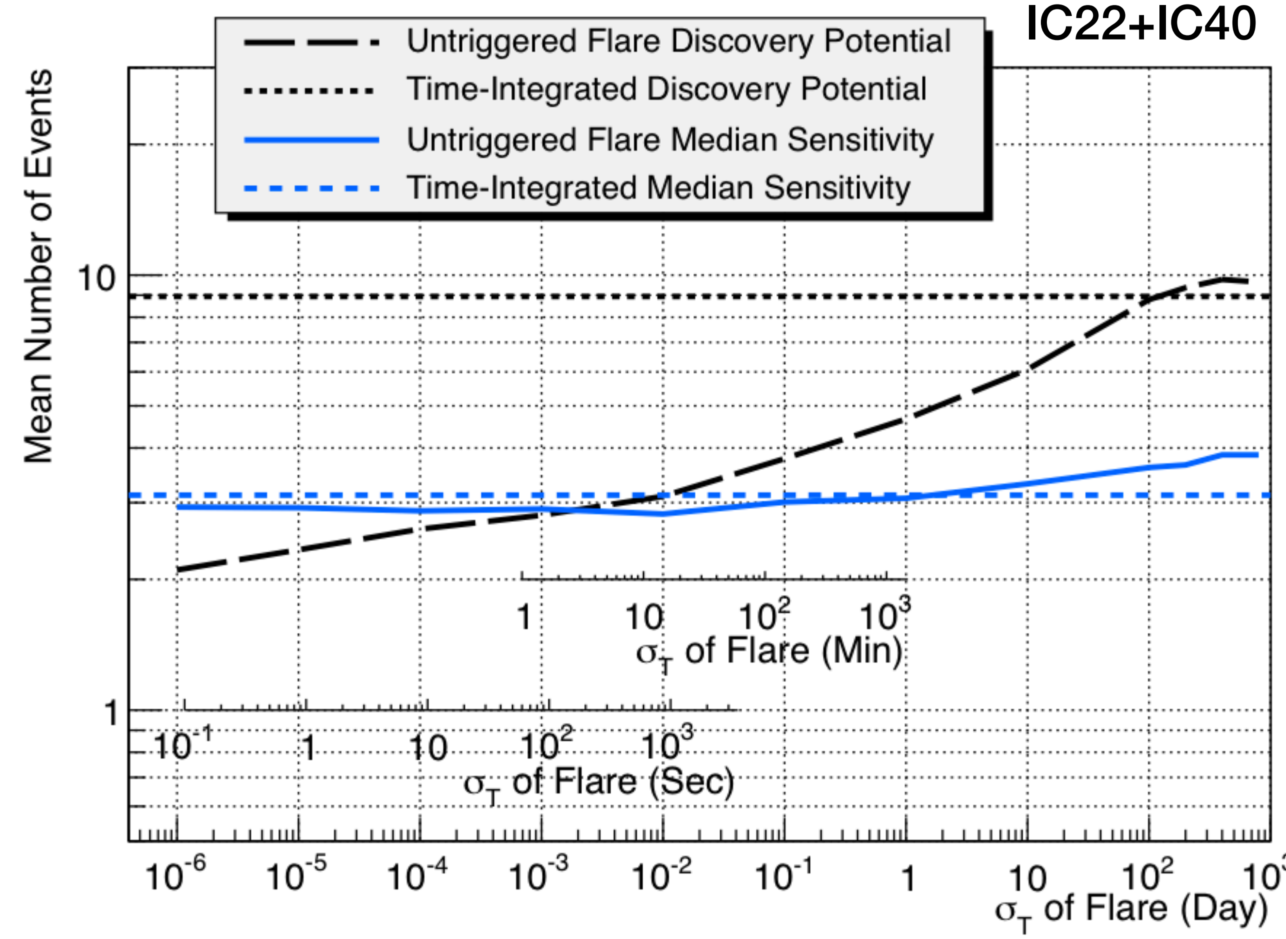
discovery potential (5σ, 50% of trials) is about ×3

Paolo Desiati

other point source searches

number of events needed for 5σ (50%) all-sky discovery potential at different flare scales

- time varying sources
  - untriggered all-sky time scan →
  - time scan for candidate variable sources from Fermi-LAT Bright Source List
  - triggered search based on flaring sources observed by Fermi (alerts from Public Release), H.E.S.S., MAGIC and VERITAS



ApJ 744, 1, 2012 - arXiv:1104.0075

  - periodic sources from catalogue of GeV-TeV binary systems

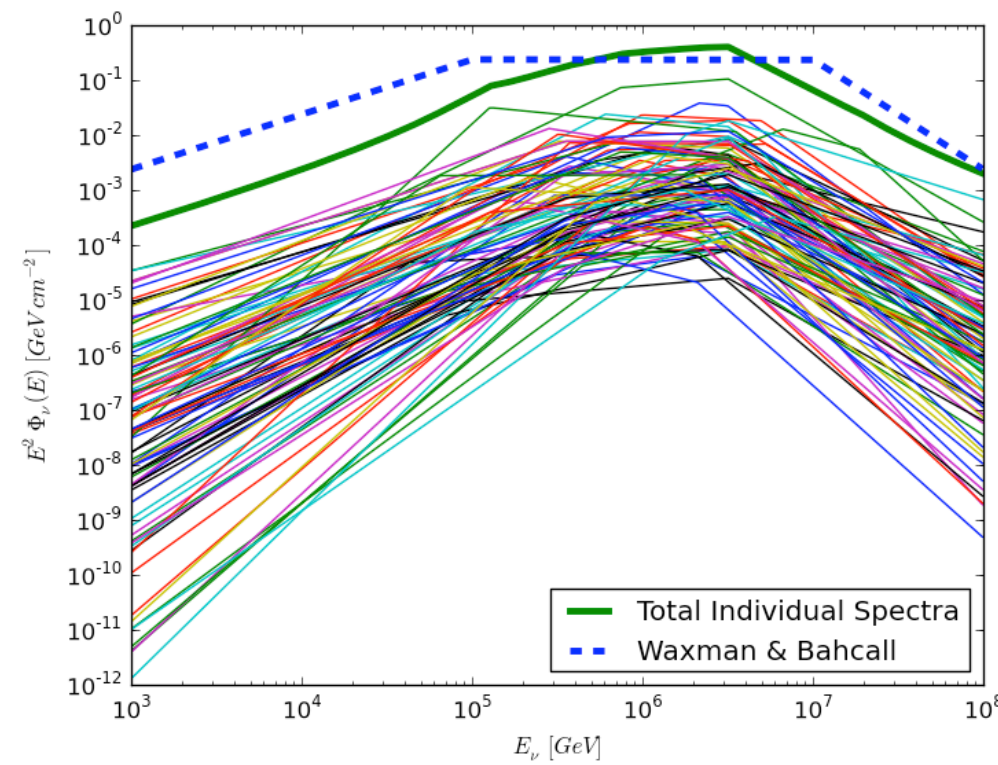
ApJ 748, 118, 2012 arXiv:1108.3023

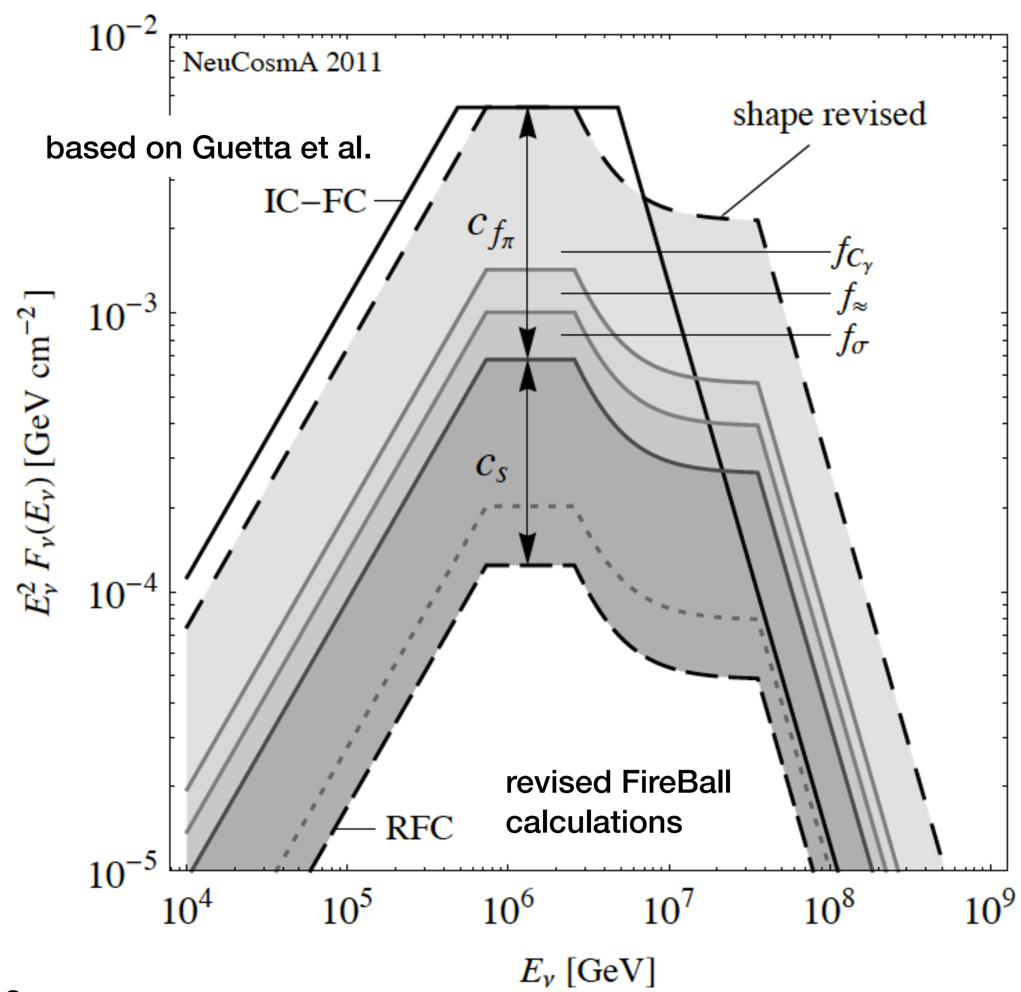
neutrinos from Gamma Ray Bursts

- search for stacked neutrinos in coincidence with observed γ ray from GRB in the northern hemisphere
- per-burst neutrino spectra calculated from γ ray spectra based on prescription by Guetta et al. Astrop. Phys. 20, 429 (2004)

assuming GRB as sources of UHE cosmic rays

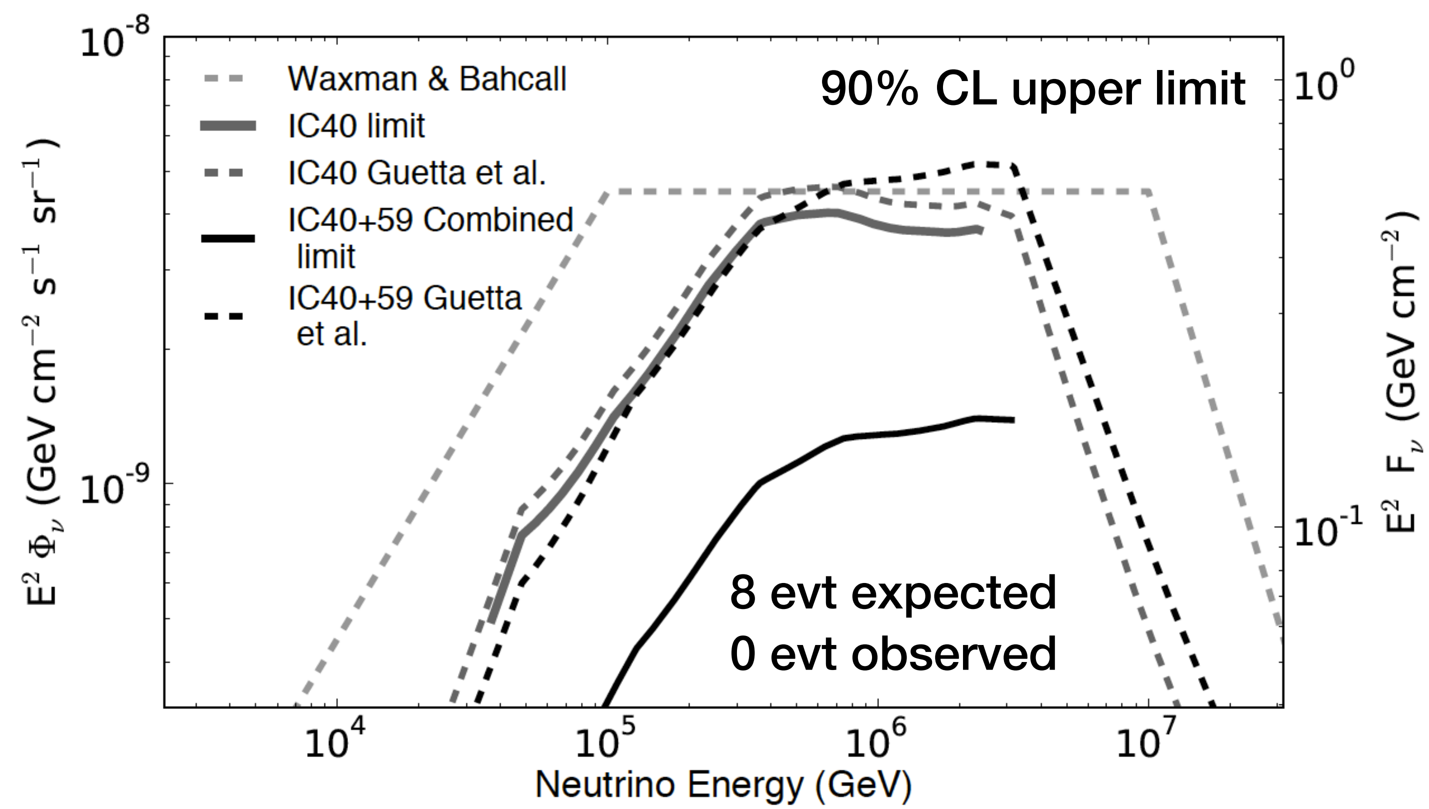
e.g. Ahlers et al., Astrop. Phys. 35-2, 87 (2011)





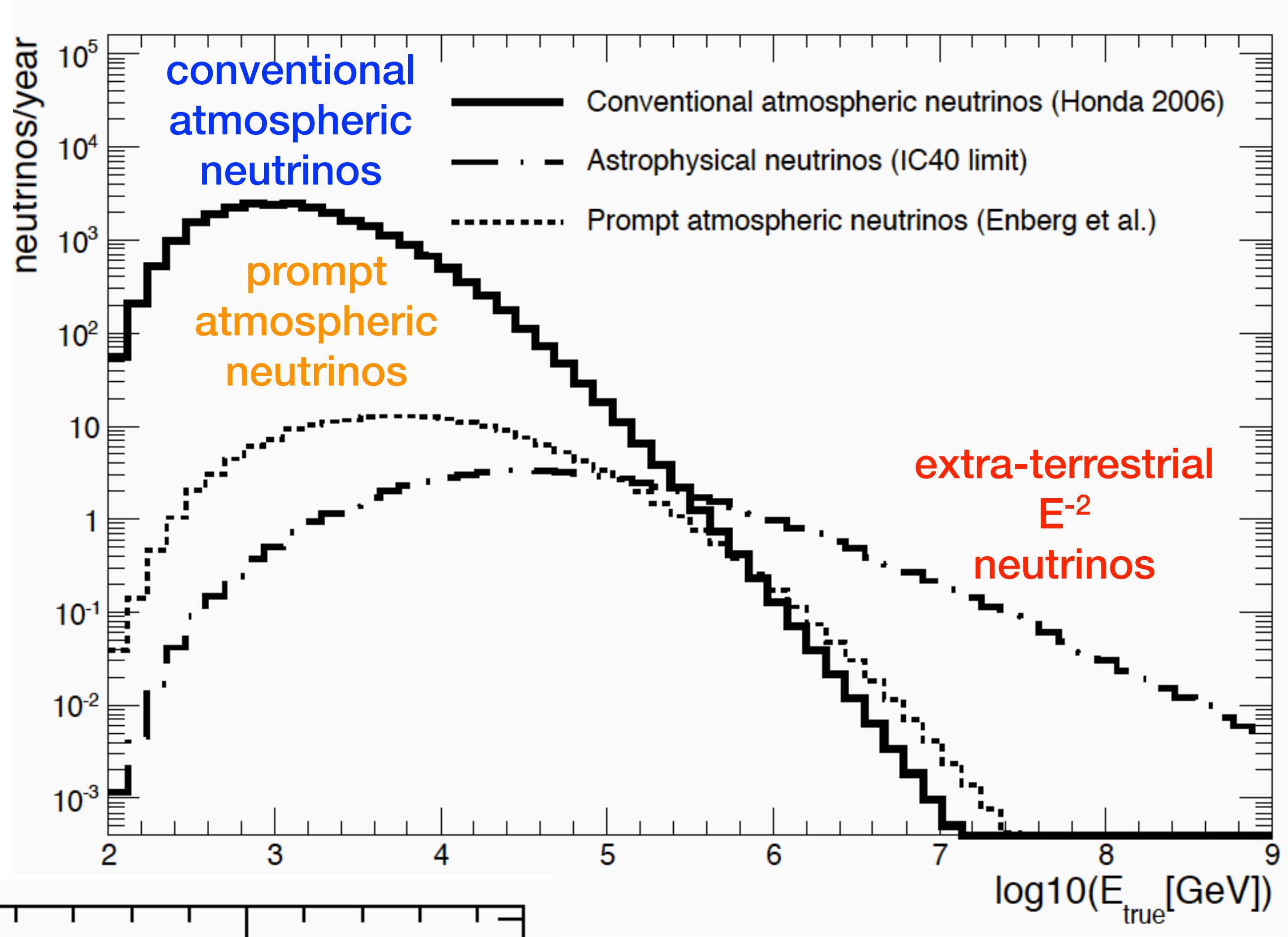
Hümmer et al. arXiv:1112.1076

Nature, 484, 351 (2012)

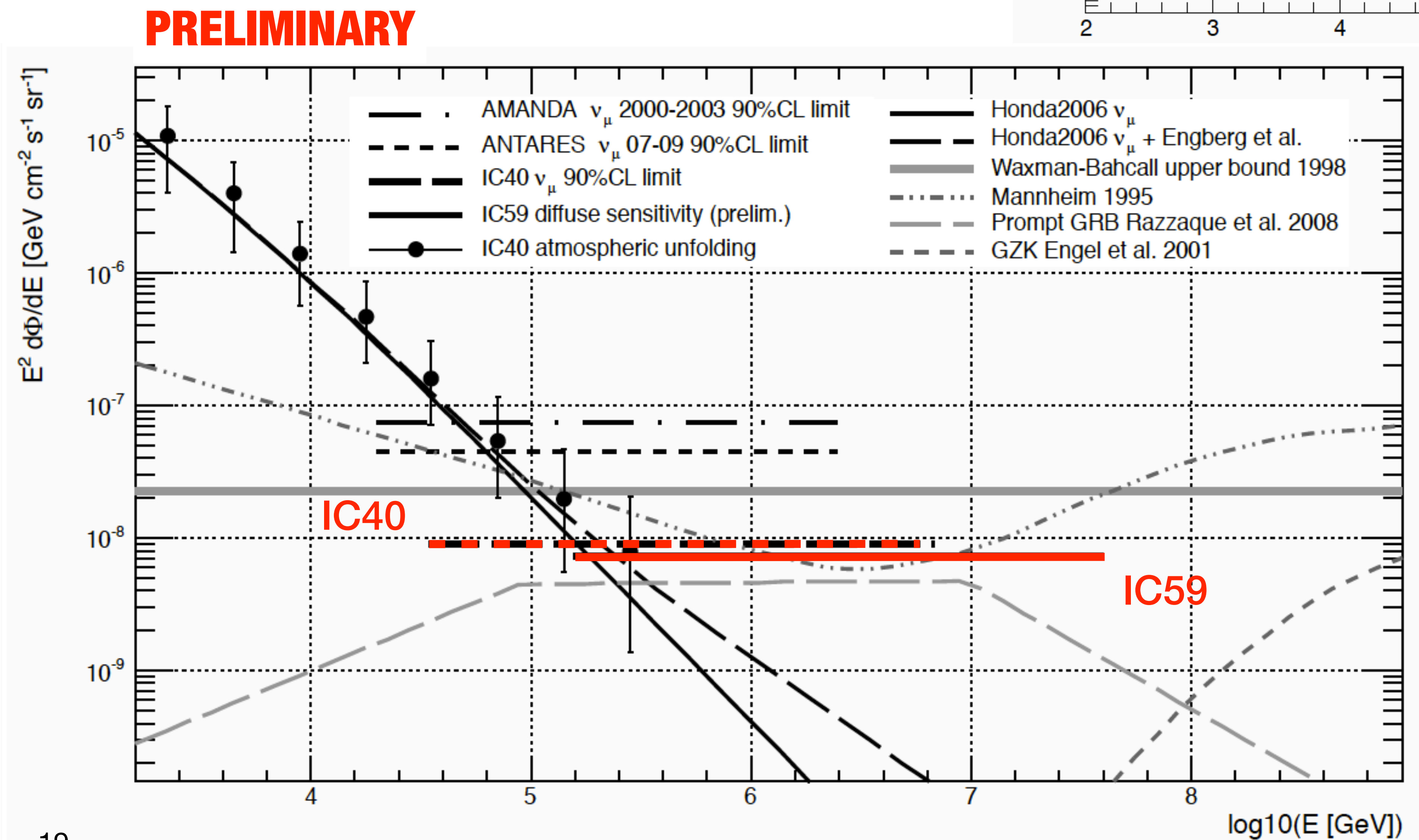


neutrinos from diffuse sources

- search for neutrinos from unresolved sources in the Universe (e.g. AGN)



Schukraft, Grullon, Wallraff, et al. ICRC 2011

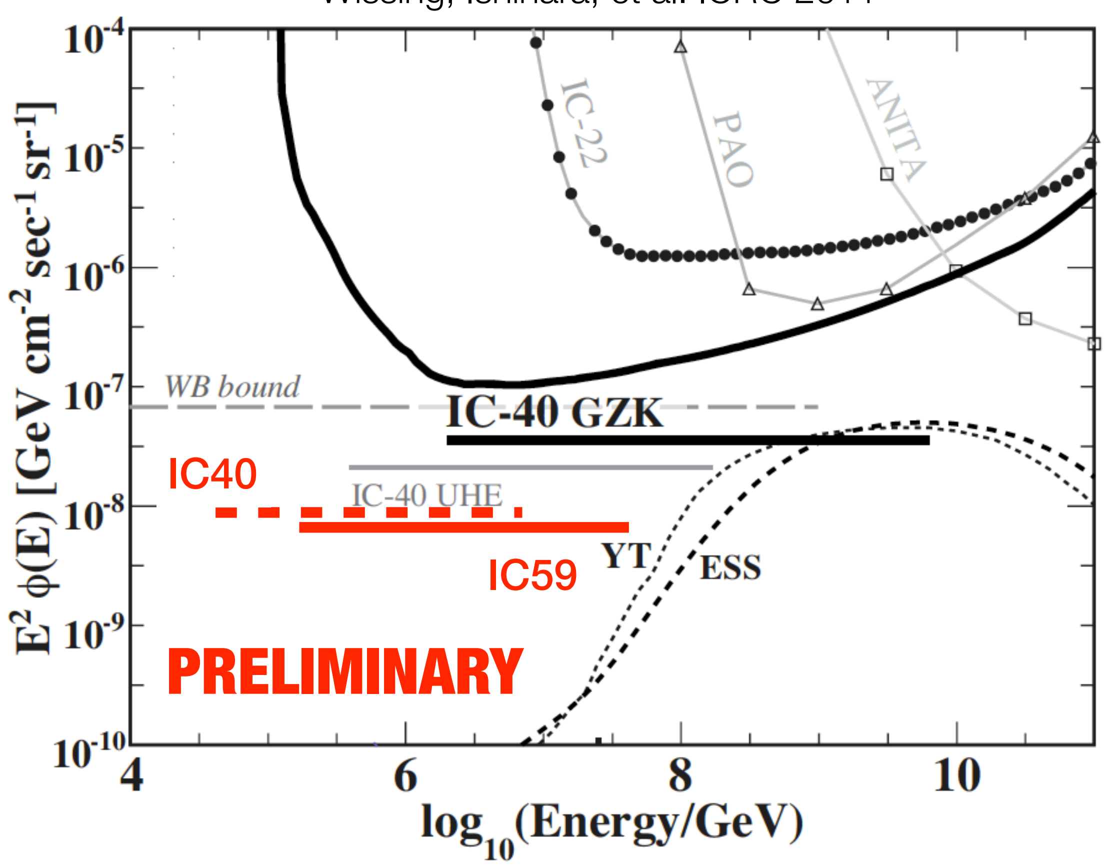


cosmogenic neutrinos

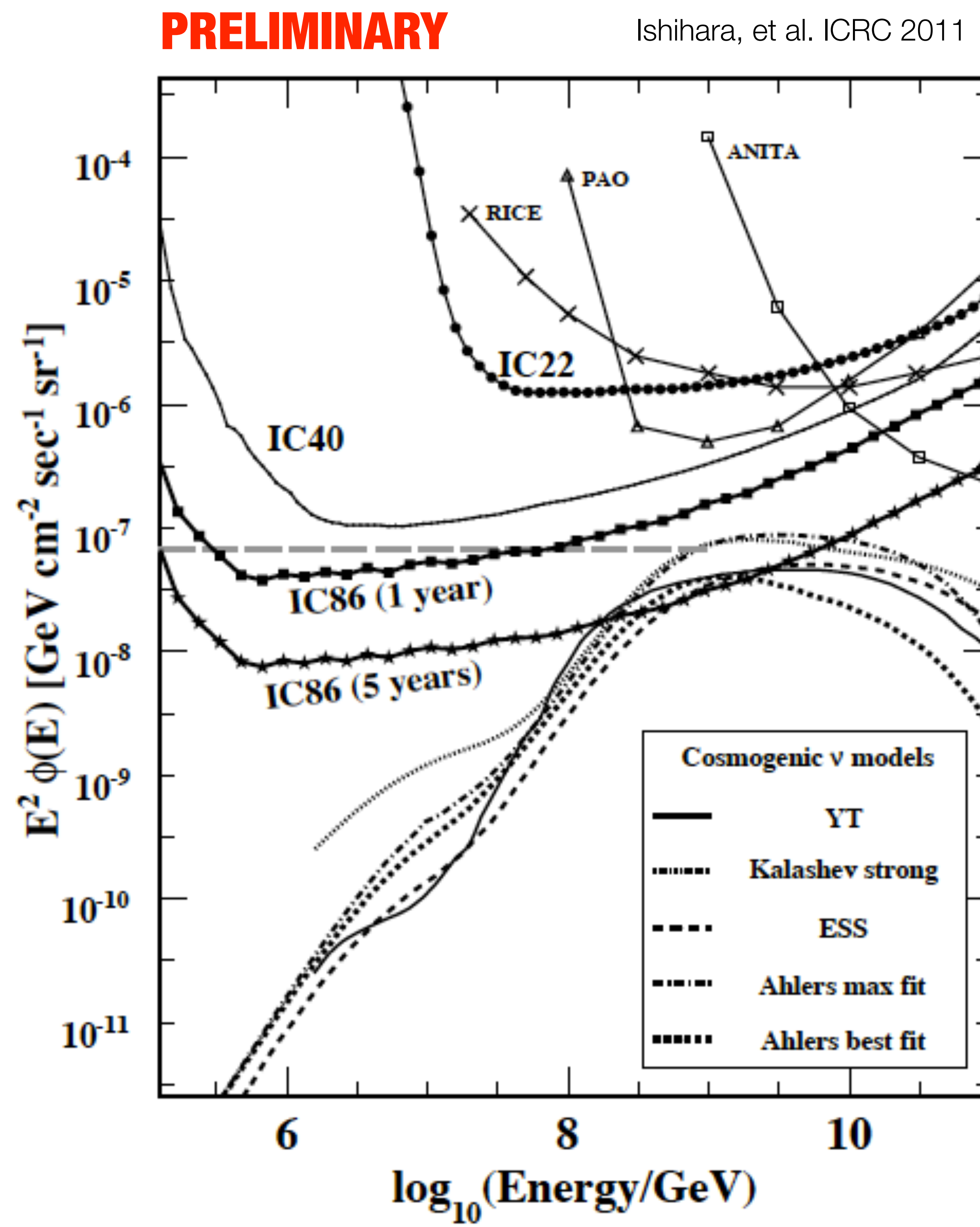
IC40
PRD 83, 092003 (2011)
PRD 84, 079902 (2011)

- cosmogenic neutrinos from photo-hadronic interactions of UHECR protons with the CMB
- constrain through the e^-, e^+ and γ-rays cascading on the CMB and intergalactic magnetic fields to lower energies and generating a γ-ray background in the GeV-TeV region

Wissing, Ishihara, et al. ICRC 2011

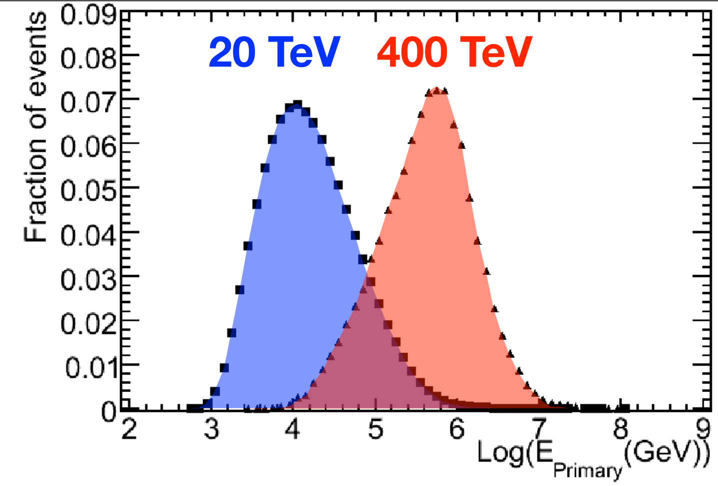


Ishihara, et al. ICRC 2011



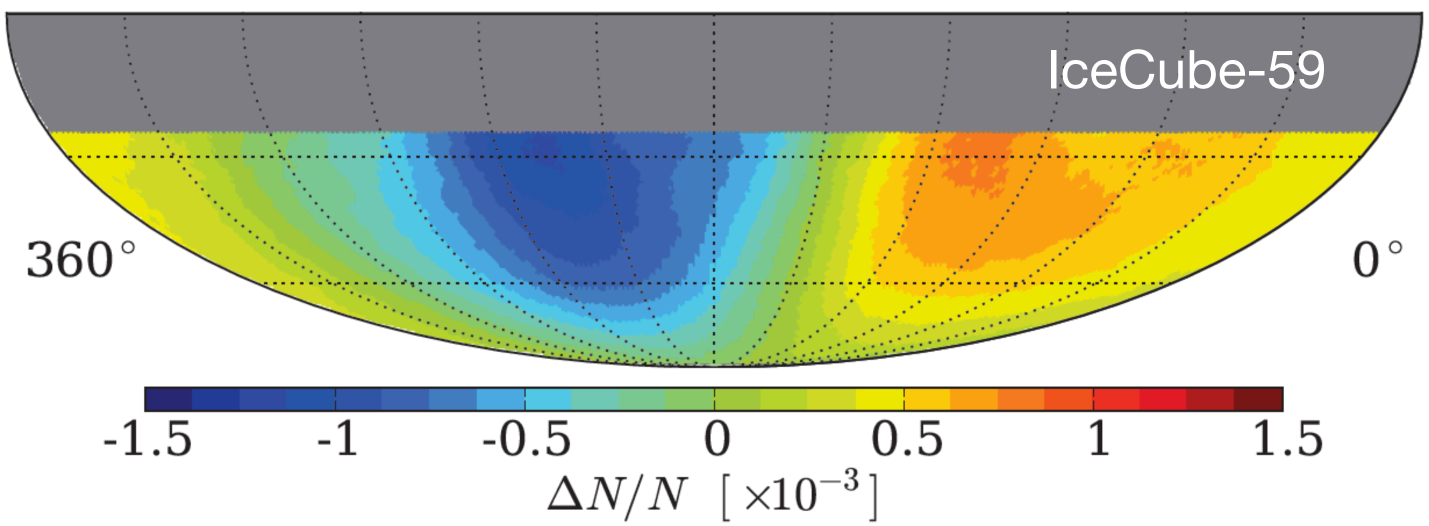
Ahlers et al., Astrop. Phys. 34, 106 (2010)
Ahlers et al., Astrop. Phys. 35-2, 87 (2011)

cosmic ray anisotropy

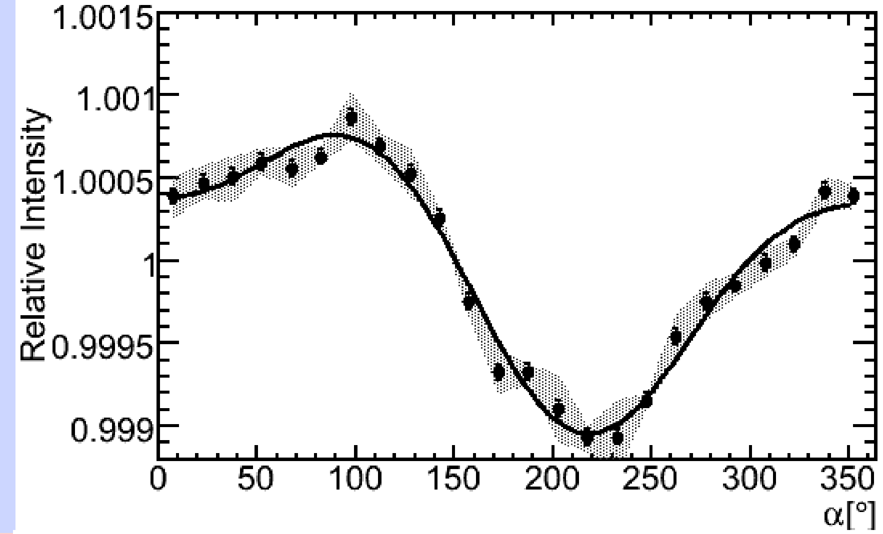


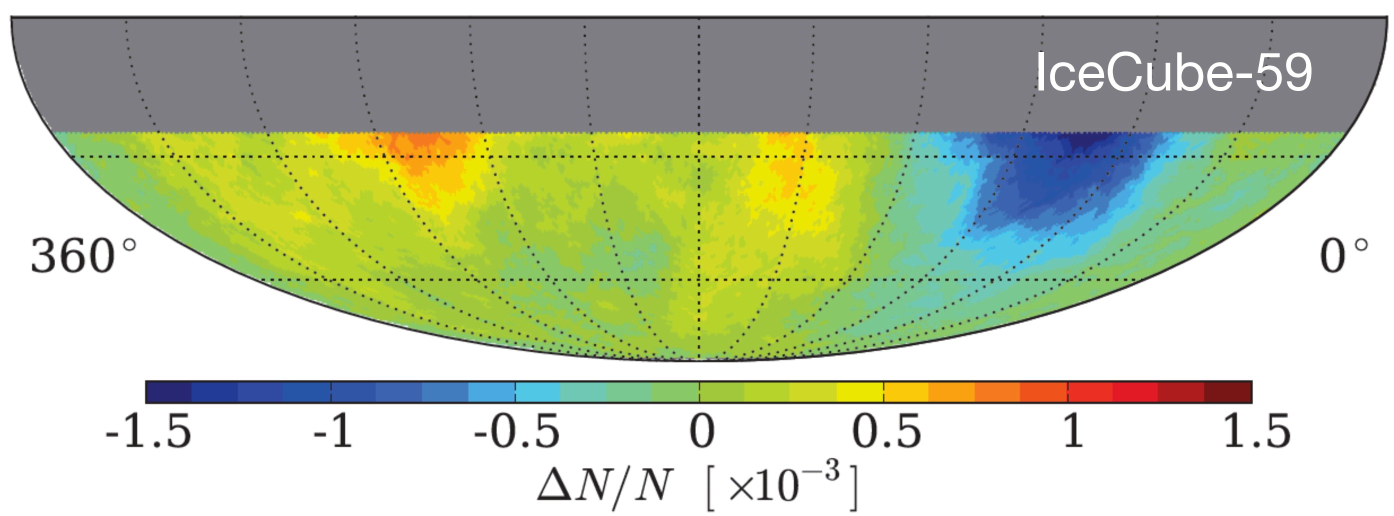
relative intensity

equatorial coordinates

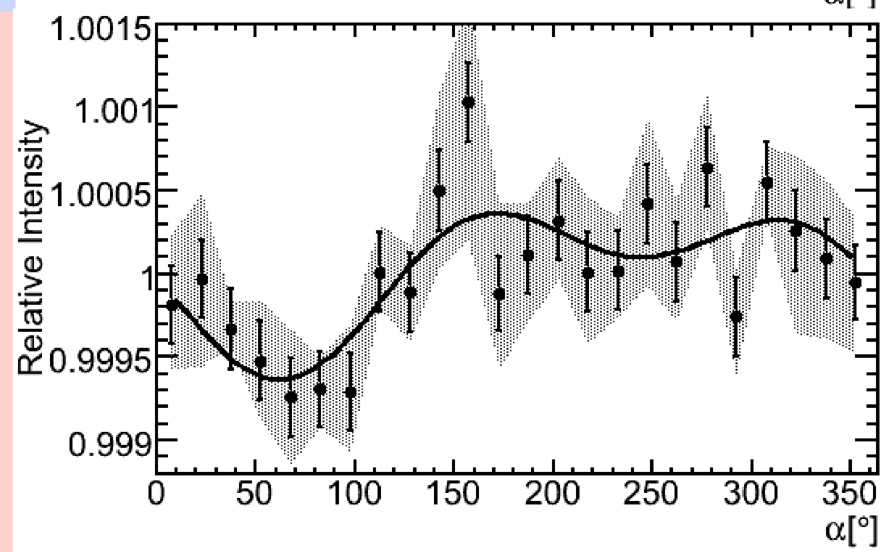


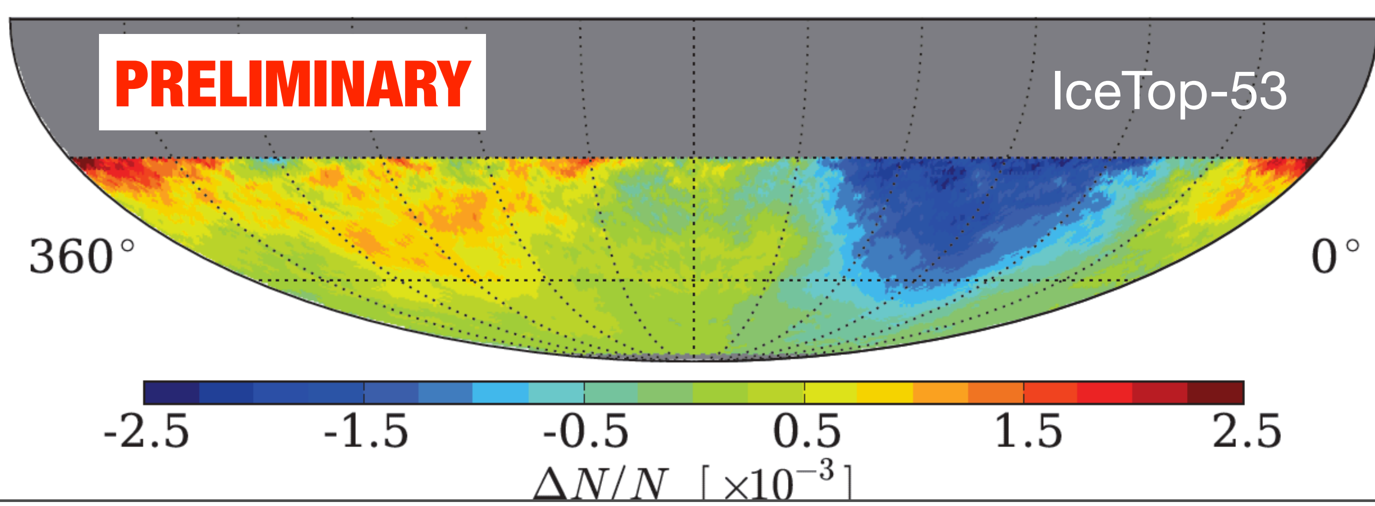
20 TeV





400 TeV





640 TeV

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

Santander et al., arXiv:1205.3969

equatorial coordinates

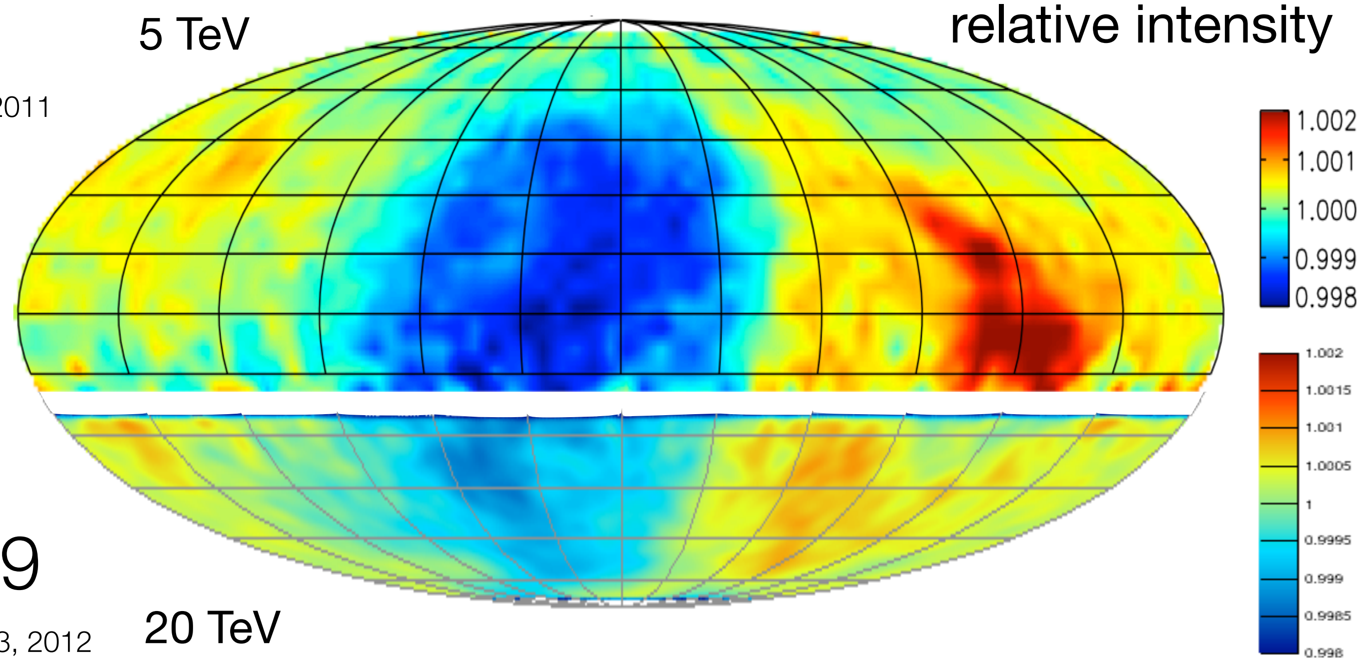
cosmic ray anisotropy

Tibet-III

Amenomori et al., ICRC 2011

IceCube-59

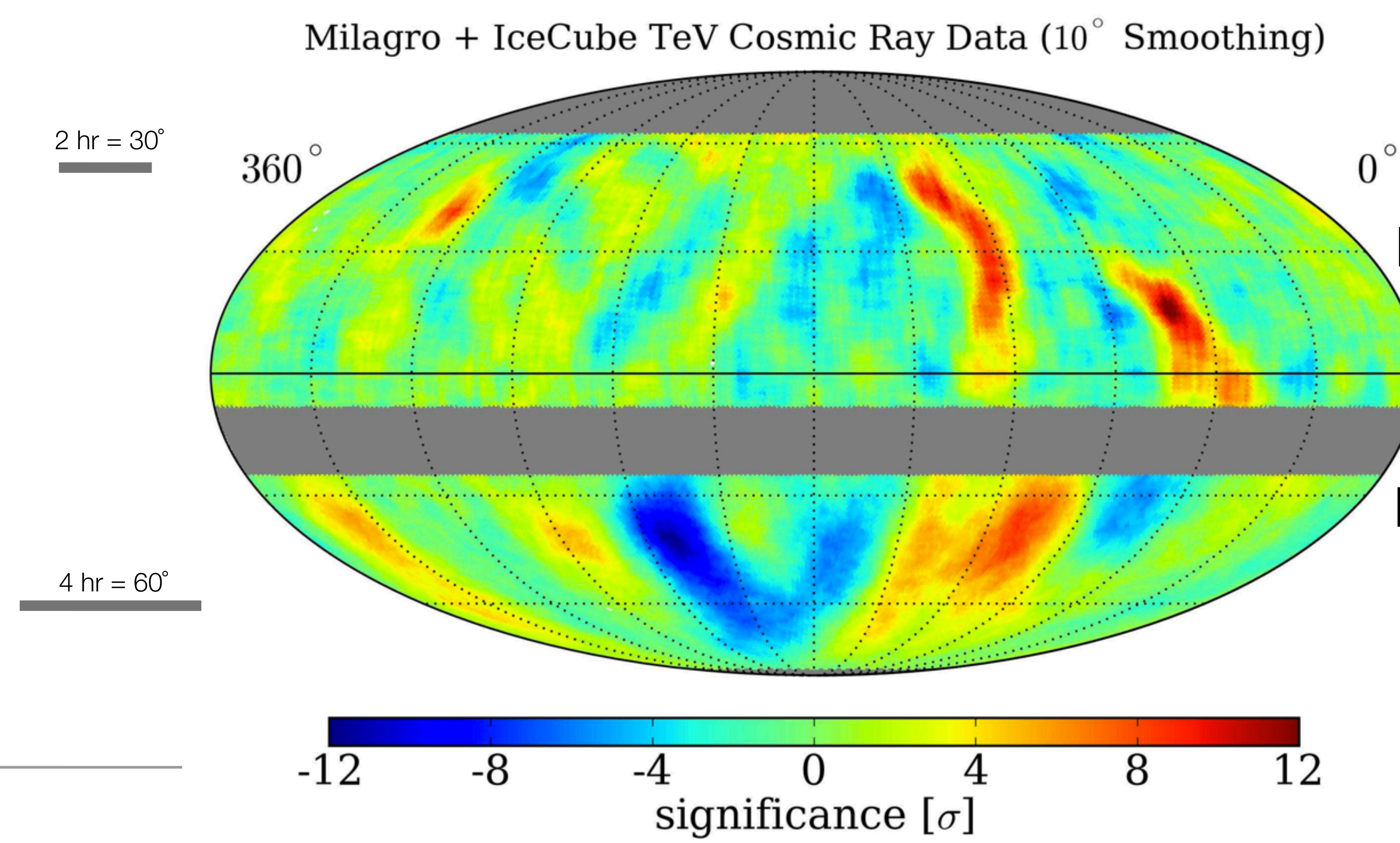
Abbasi et al., ApJ, **746**, 33, 2012



large scale anisotropy

statistical significance

small scale anisotropy



Milagro 1 TeV

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

IceCube 20 TeV

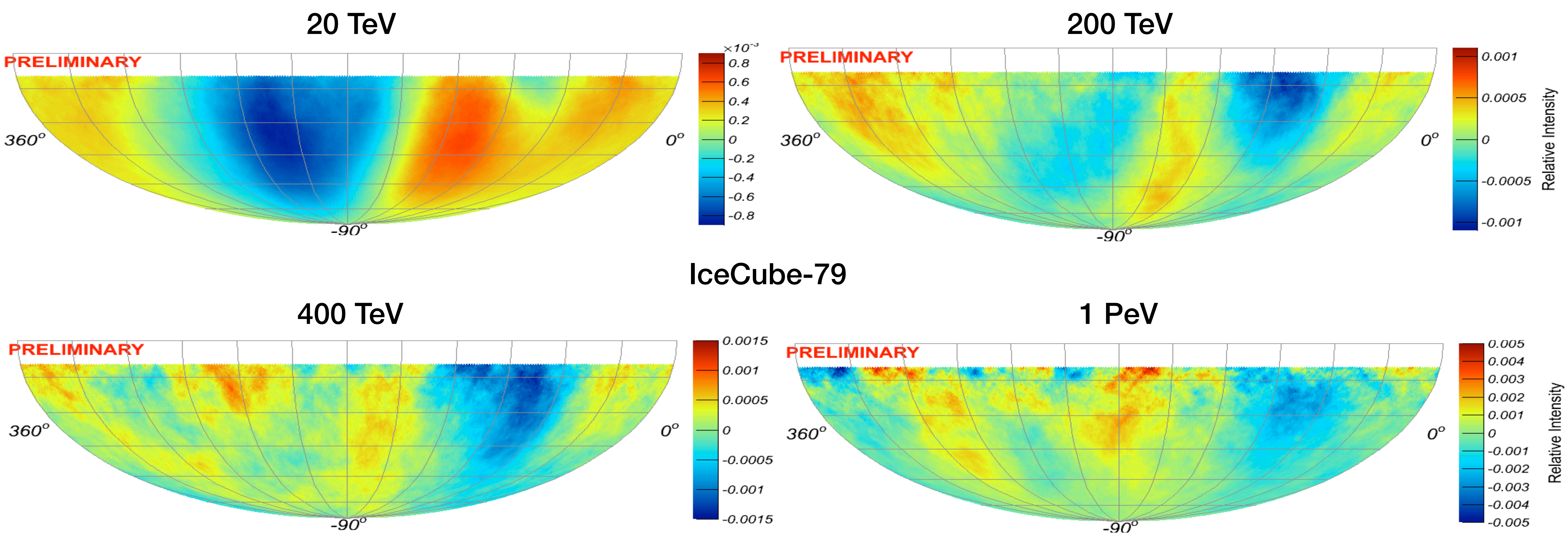
Abbasi et al., ApJ, **740**, 16, 2011

origin of *large scale* anisotropy ?

- stochastic effect from <0.1-1kpc young SNR & propagation

Erlykin & Wolfendale, Astropart. Phys., 25, 183 (2006)
Blasi & Amato, arXiv:1105.4529

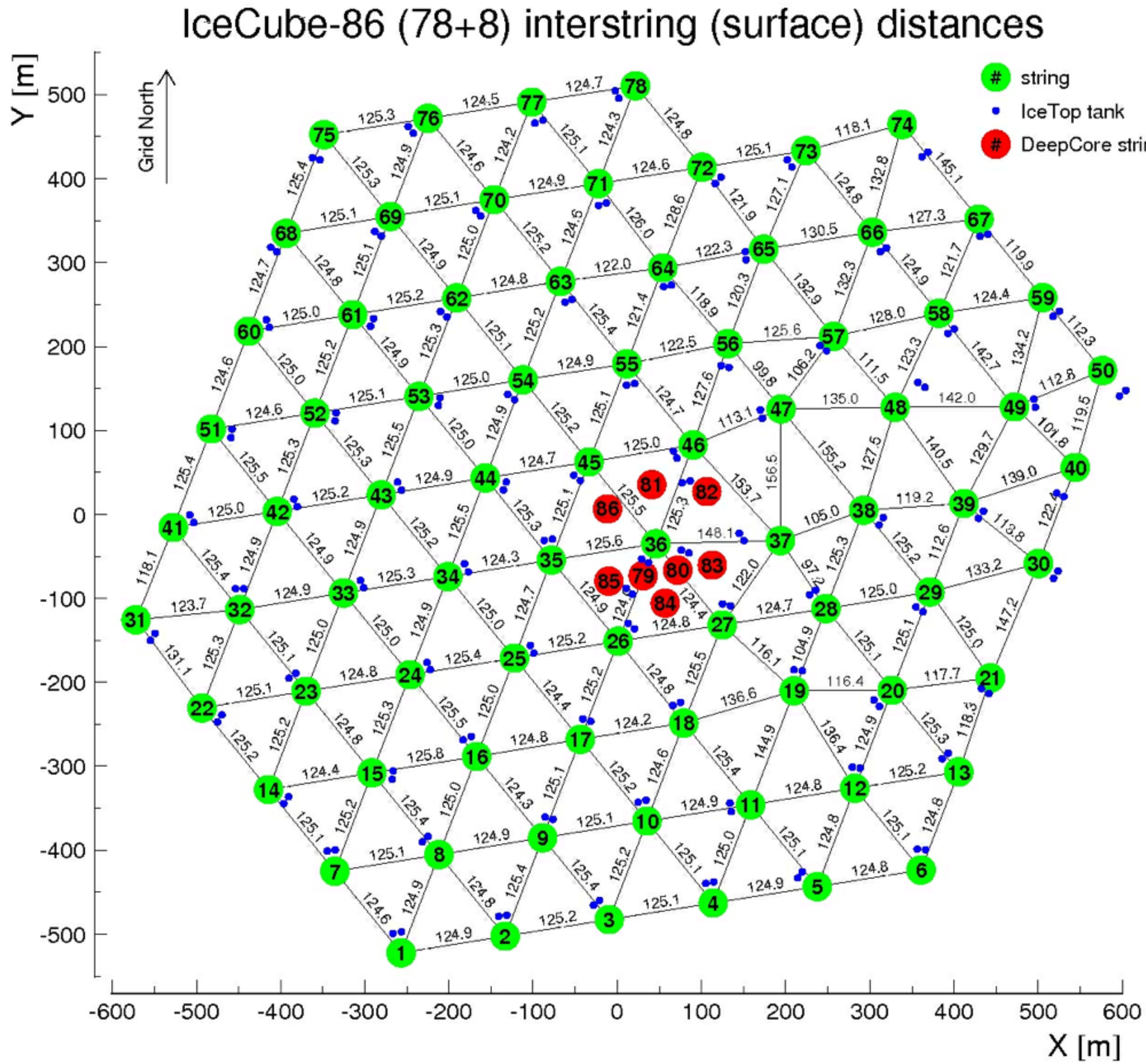
- TeV anisotropy as a possible probe into outer heliospheric properties
- >100 TeV anisotropy might uncover non-diffusive propagation effects or SNR connection



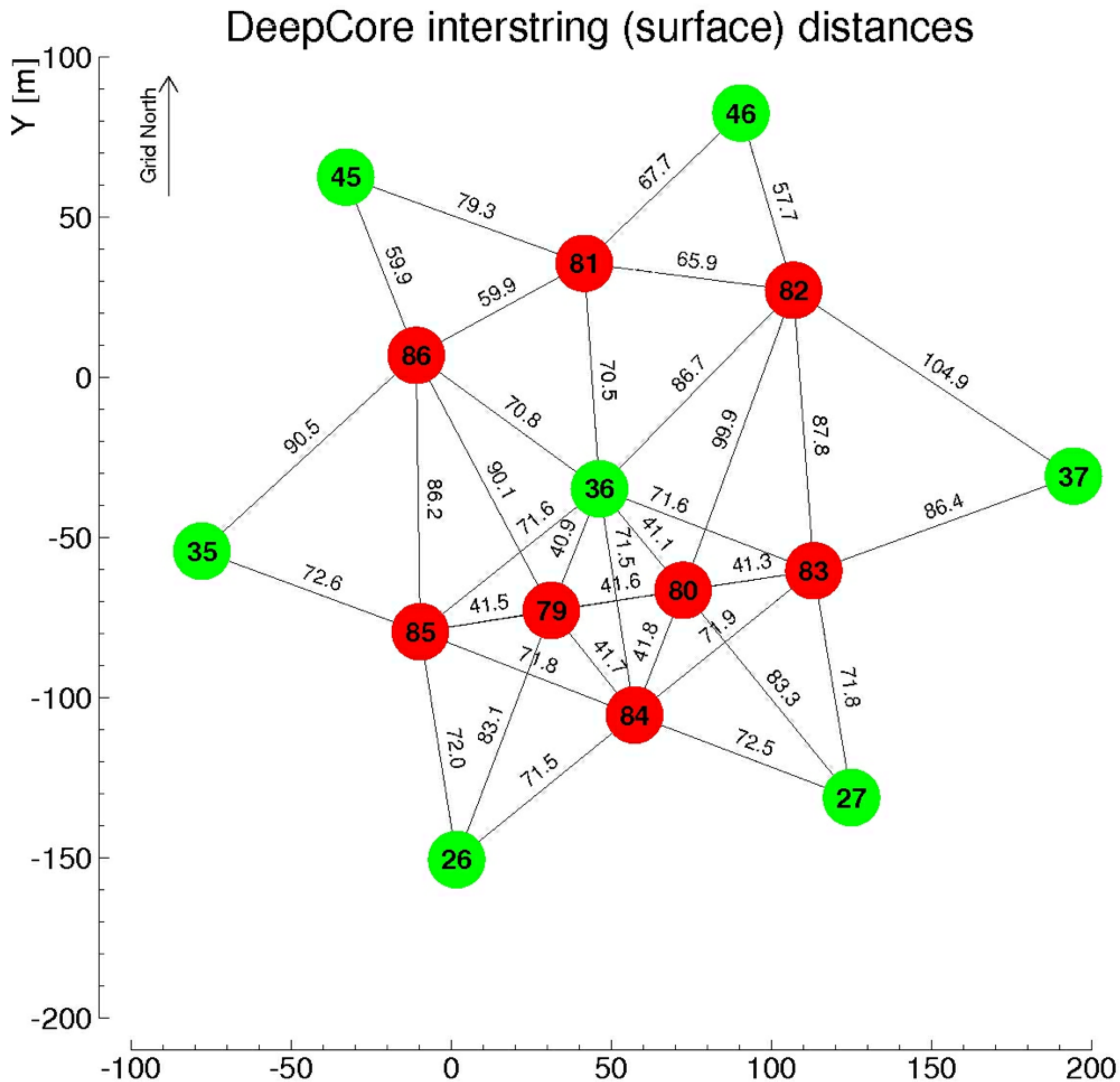
conclusions

- IceCube is a fully functional km^3 neutrino observatory: neutrino astronomy
- observed the highest energy (atmospheric) neutrinos
- providing very strong constrains related to the origin of cosmic rays
- low energy frontier (DeepCore, PINGU): particle physics, oscillations, mass hierarchy,…
- high energy frontier (ARA - Radio Detection): cosmogenic neutrinos
- multi-messenger campaigns undergoing
- cosmic ray anisotropy measured at 100’s TeV and 1’s PeV
- IceTop to measure cosmic ray spectrum & composition

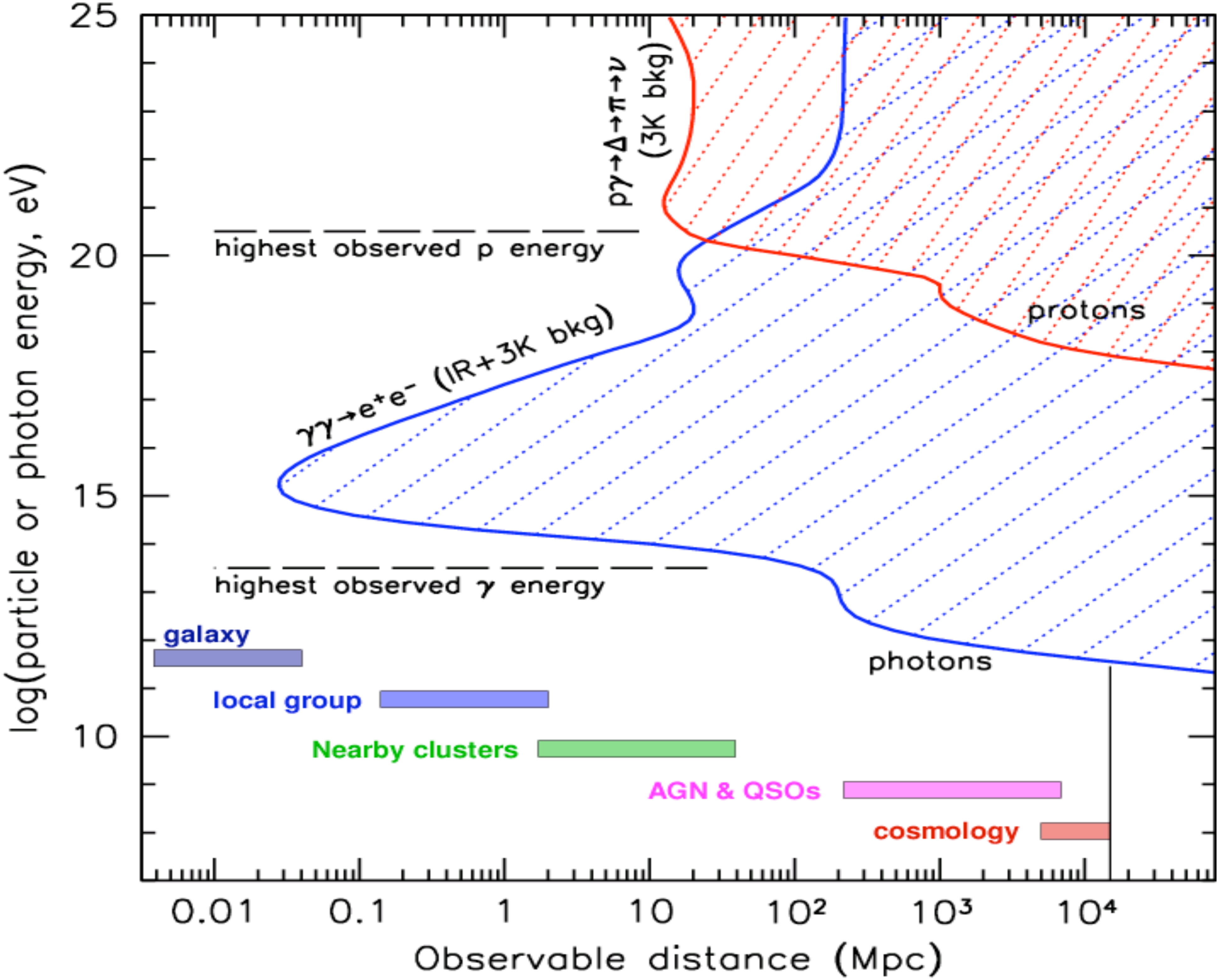
backup slides



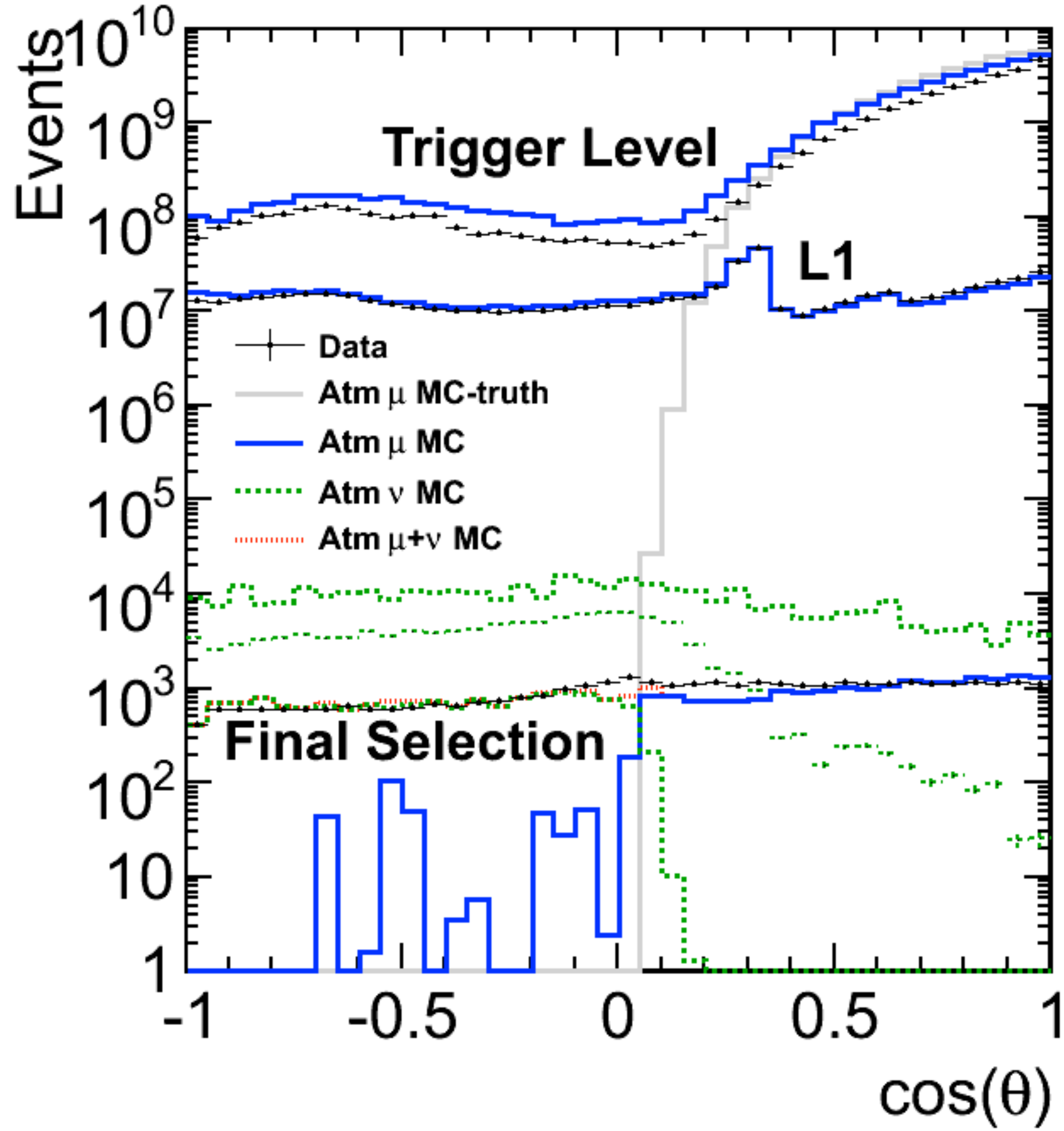
IceCube geometry



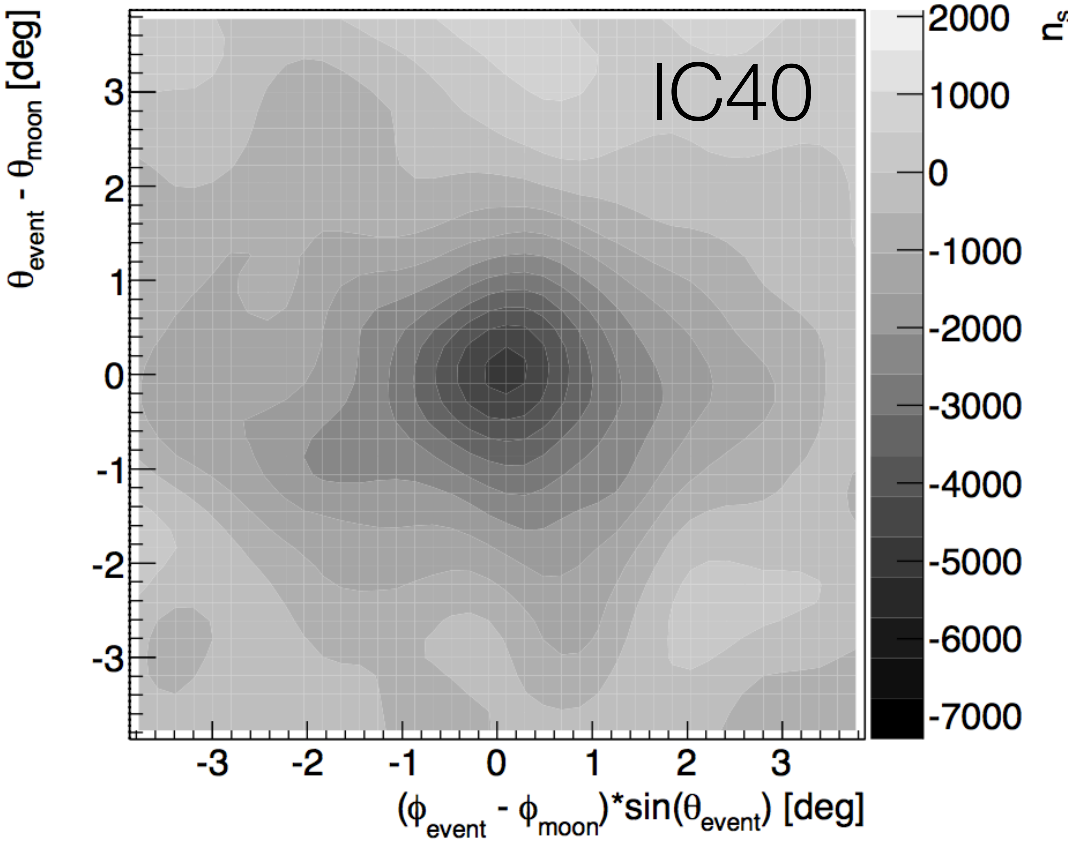
DeepCore geometry

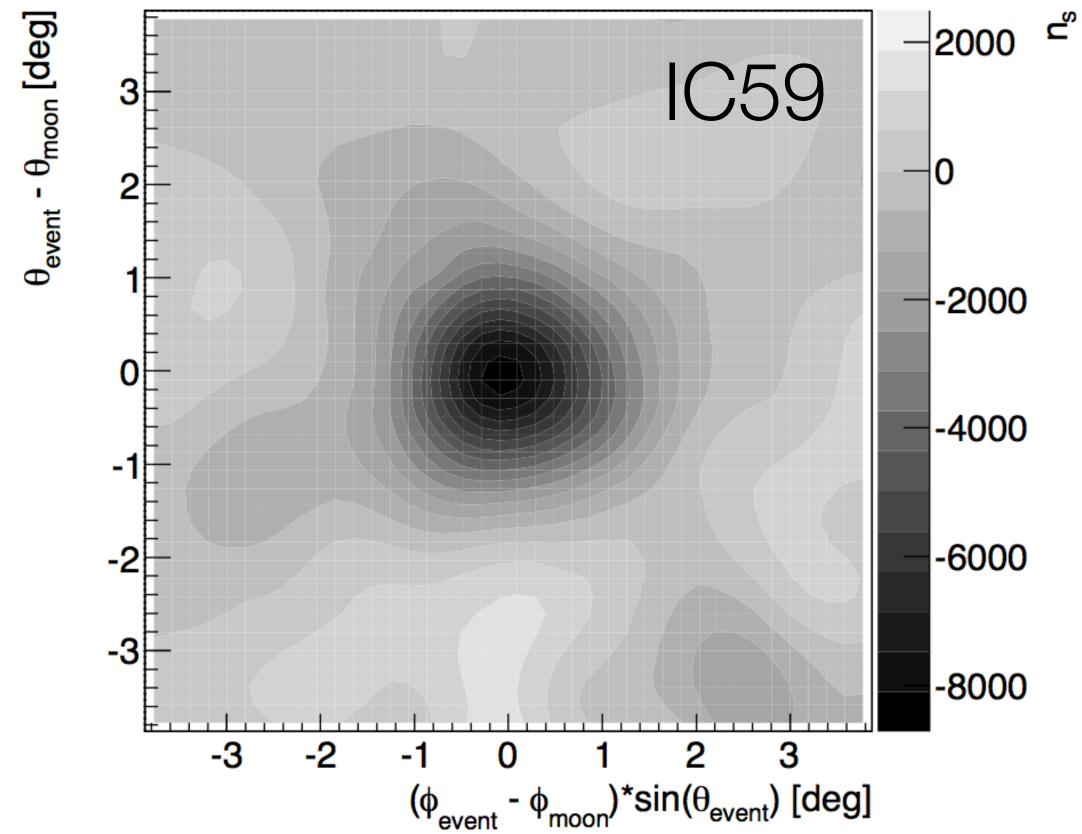


propagation depth of protons and gamma rays



all-sky neutrino search

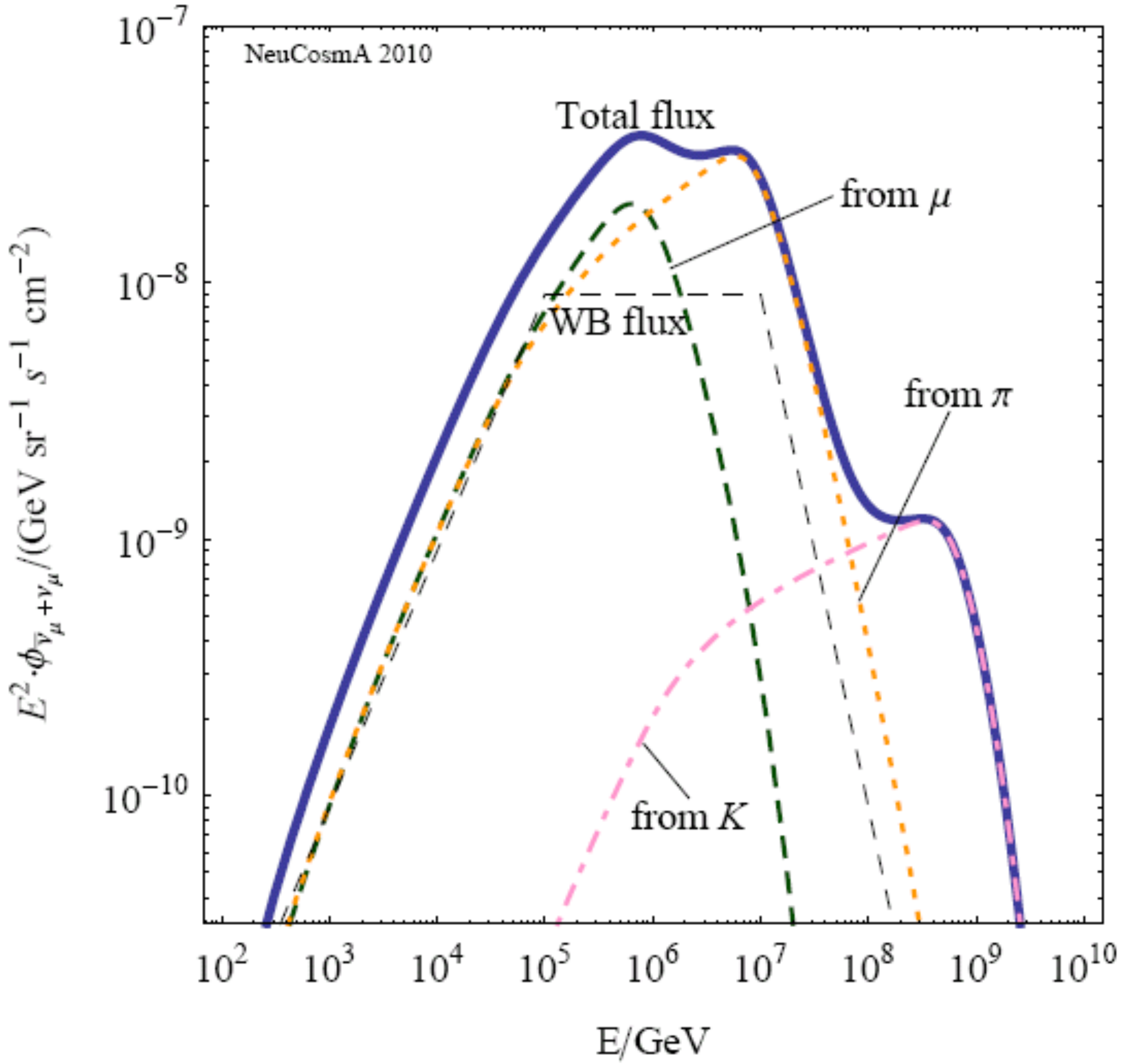




	40 strings	59 strings
orbital periods	15	14
expected deficit	5734 ± 76	8192 ± 91
observed deficit	$5326 \pm 544 \pm 498$	$8660 \pm 565 \pm 681$
significance	10-11σ	13-15σ
θ offset	0.0°	0.0°
ϕ offset	0.0°	0.0°

shadow of the moon

Boersma, Gladstone, Blumenthal, Stiebel, et al. ICRC 2011



Baerwald et al., Phys. Rev. D83 (2011) 067303

neutrinos from GRB

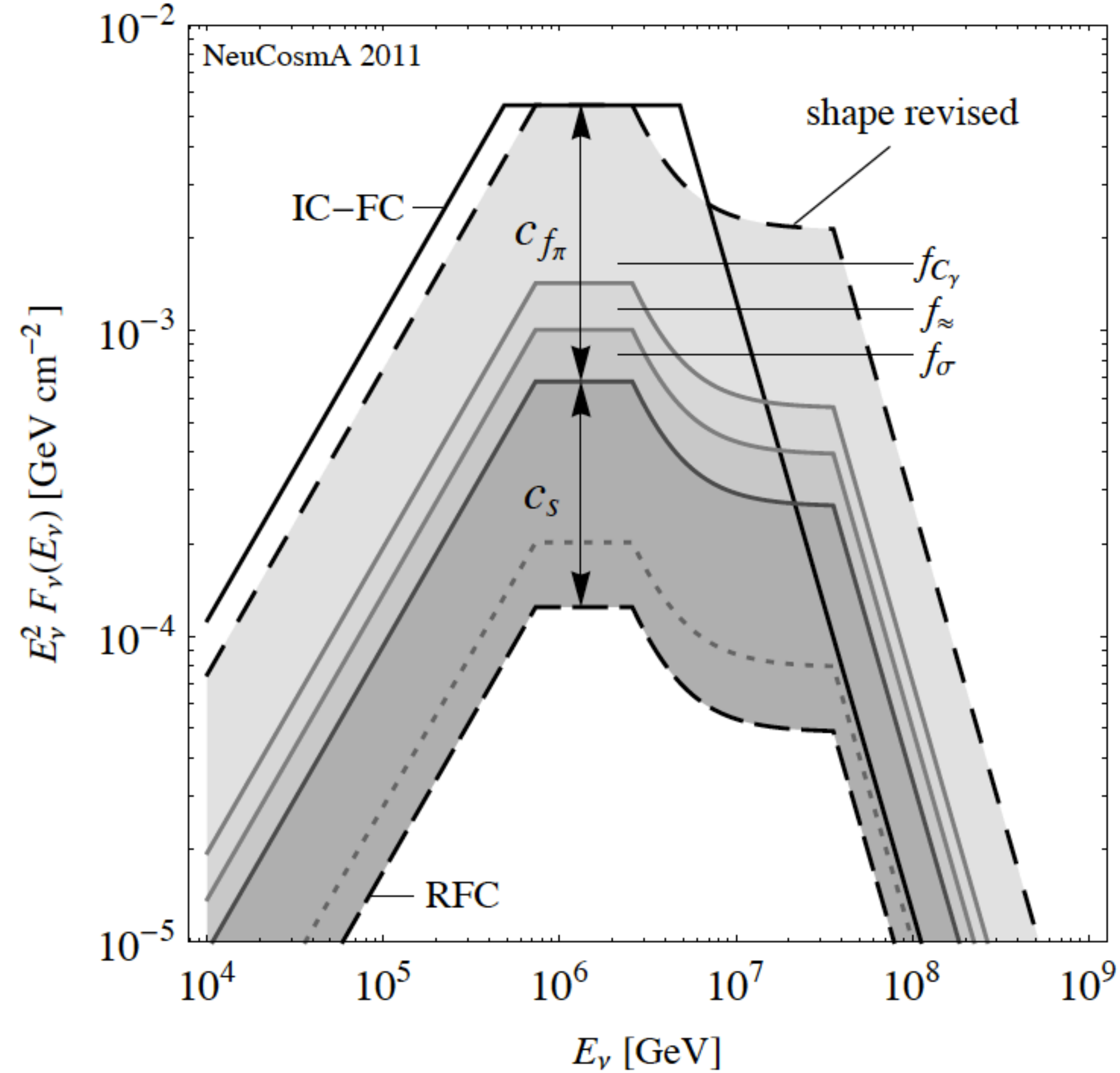
- different spectral shape

- normalization corrections

    - $f_{C\gamma}$ photon energy approximated by break energy

    - f_S spectral shape of neutrinos directly related to that of photons (not protons)

    - f_σ, $f_\approx$, f_{shift} corrections from approximation of mean free path of protons and some factors approximated in the original calculations



Hümmer et al. arXiv:1112.1076

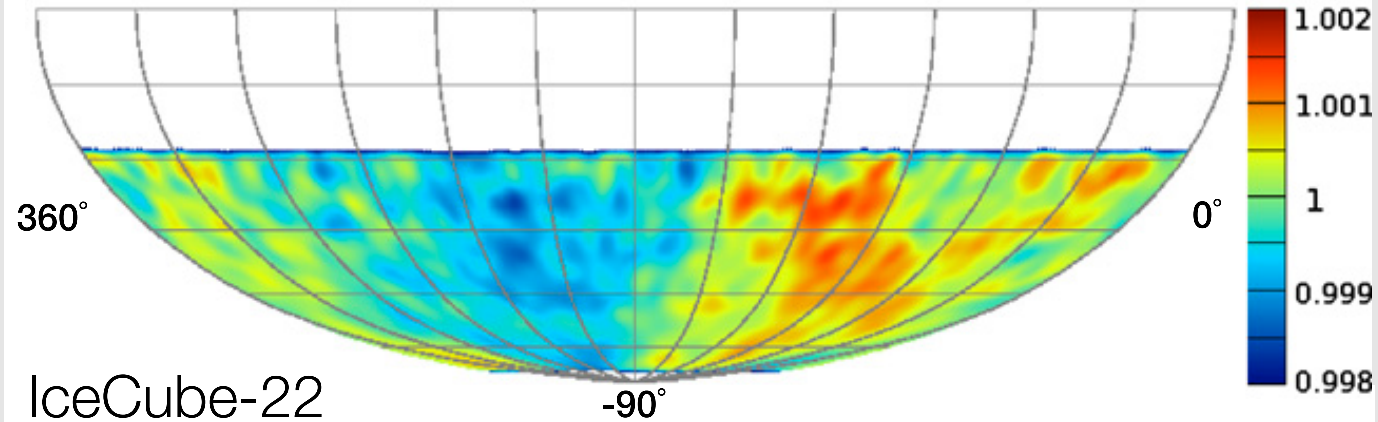
neutrinos from GRB

revised Fireball calculation

cosmic ray anisotropy in IceCube

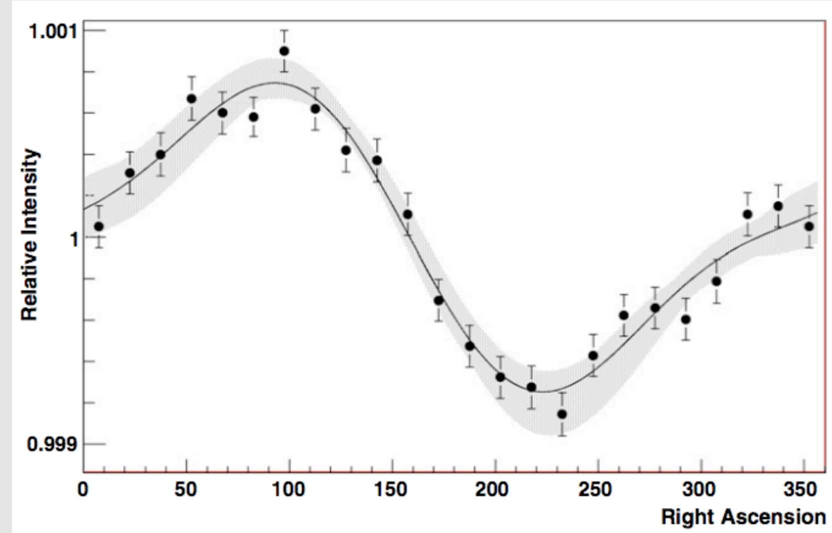
time

relative intensity equatorial coordinates

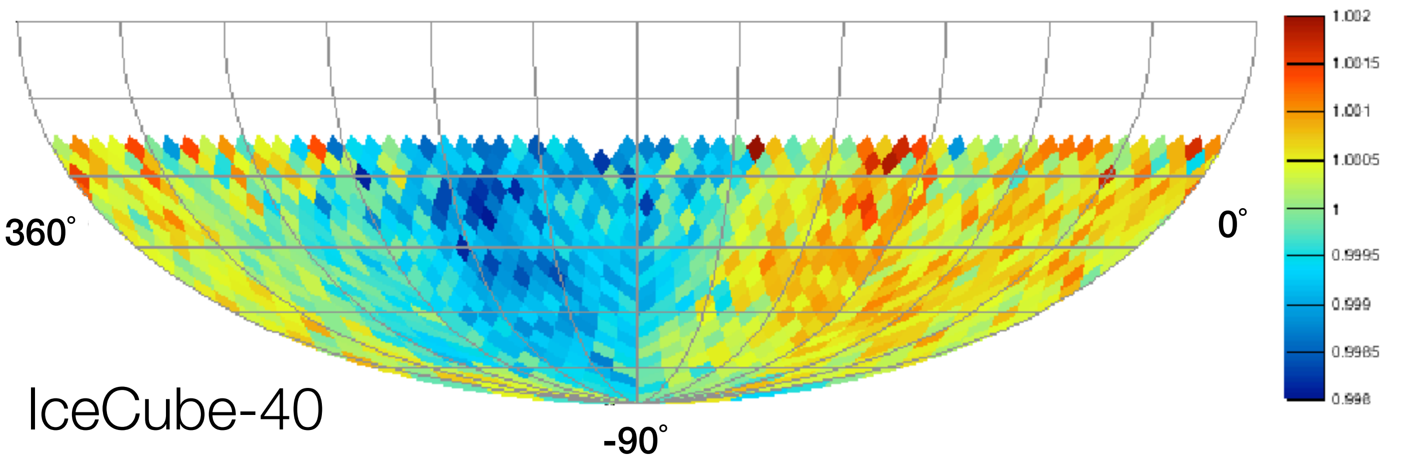


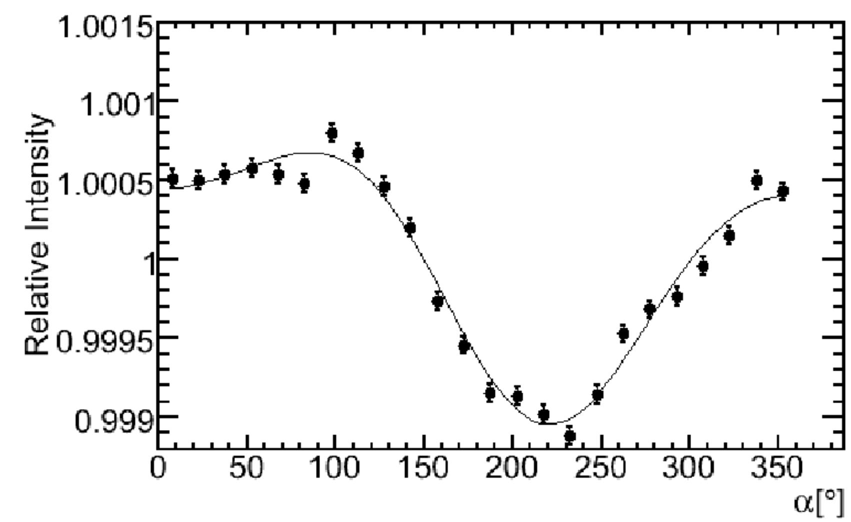
$$I_i = \frac{N_i(\alpha,\delta)}{\langle N_i(\delta)\rangle_\alpha}$$

20 TeV

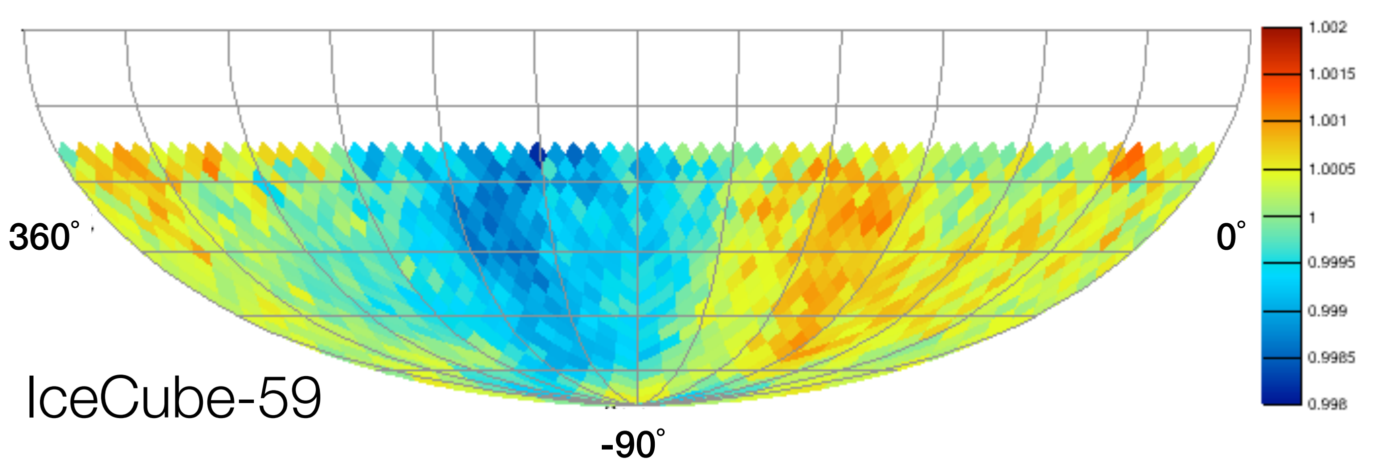


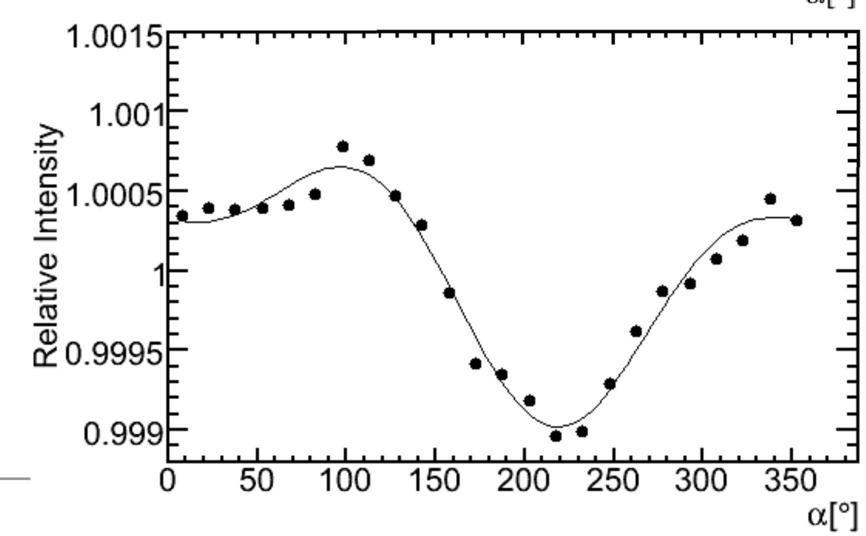
Abbasi et al., ApJ, **718**, L194, 2010



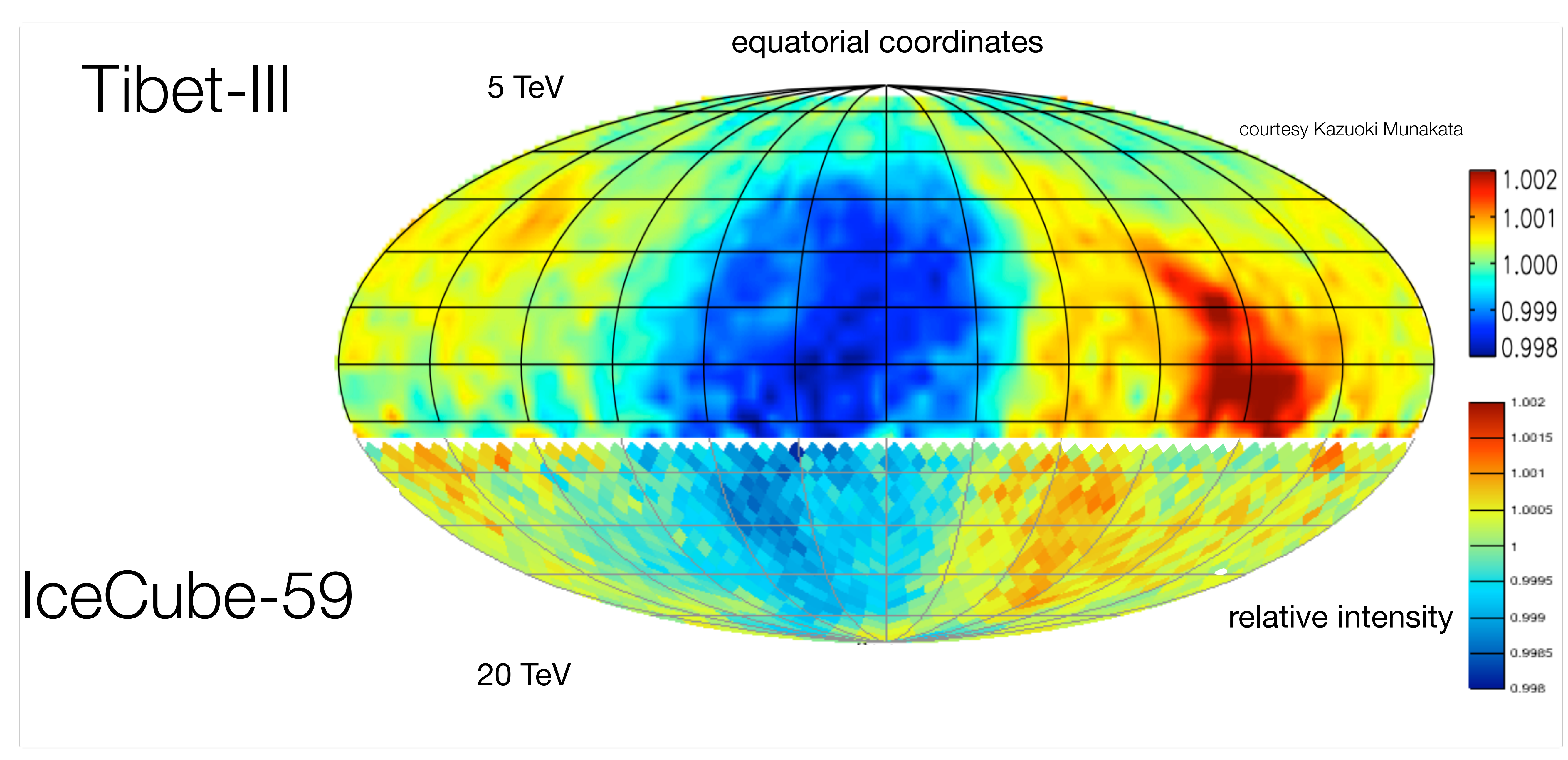


Abbasi et al., ApJ, **746**, 33, 2012

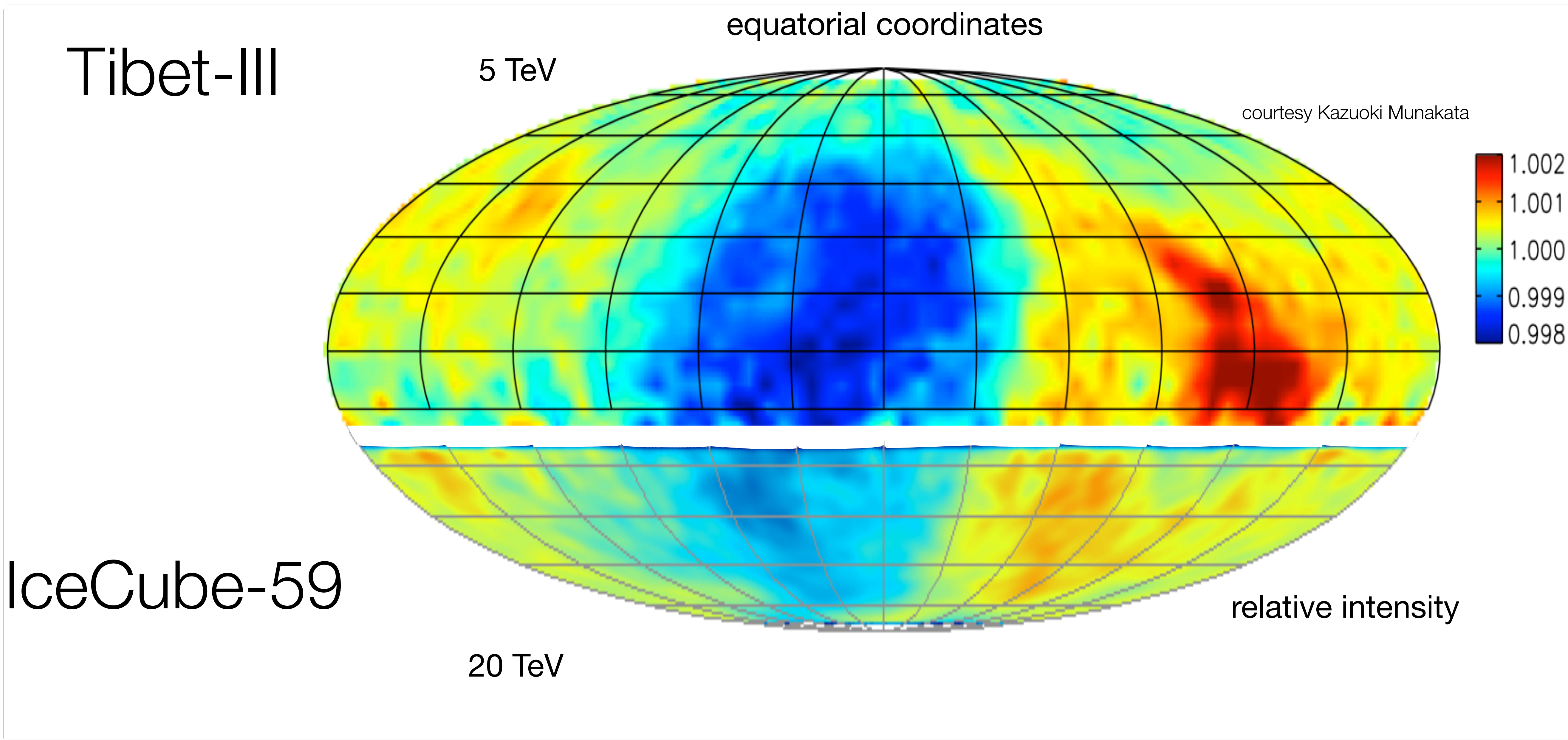




cosmic ray anisotropy in arrival direction

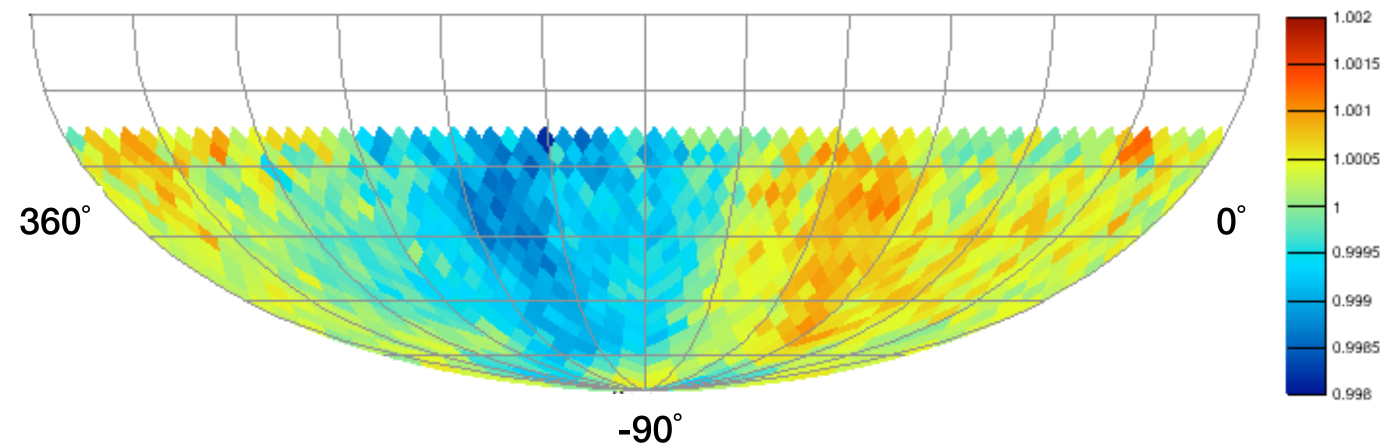


cosmic ray anisotropy in arrival direction

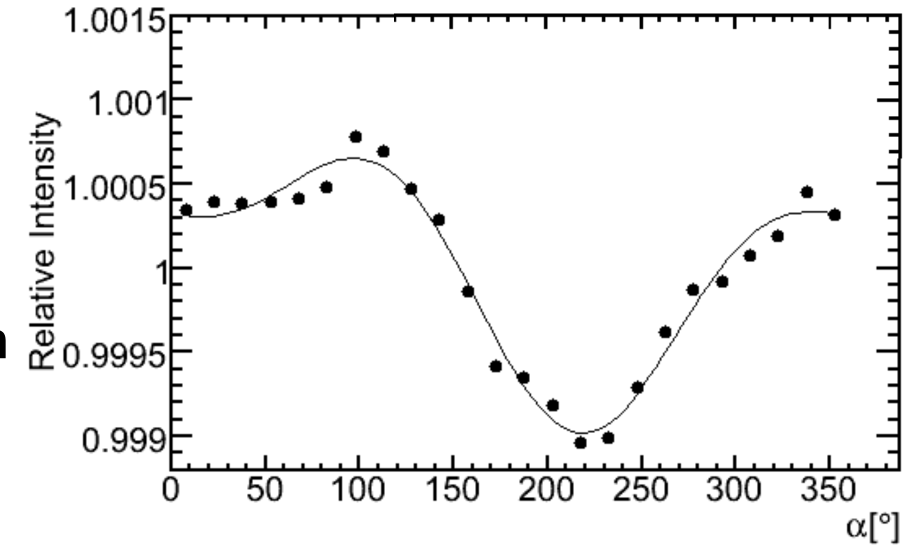


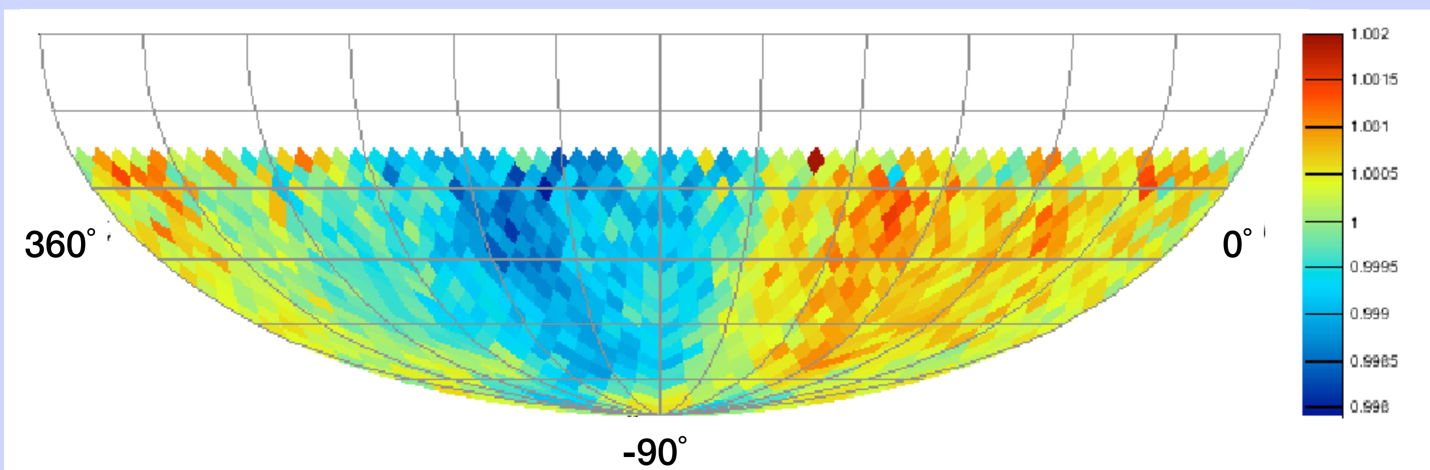
cosmic ray anisotropy vs energy in IceCube-59

relative intensity equatorial coordinates

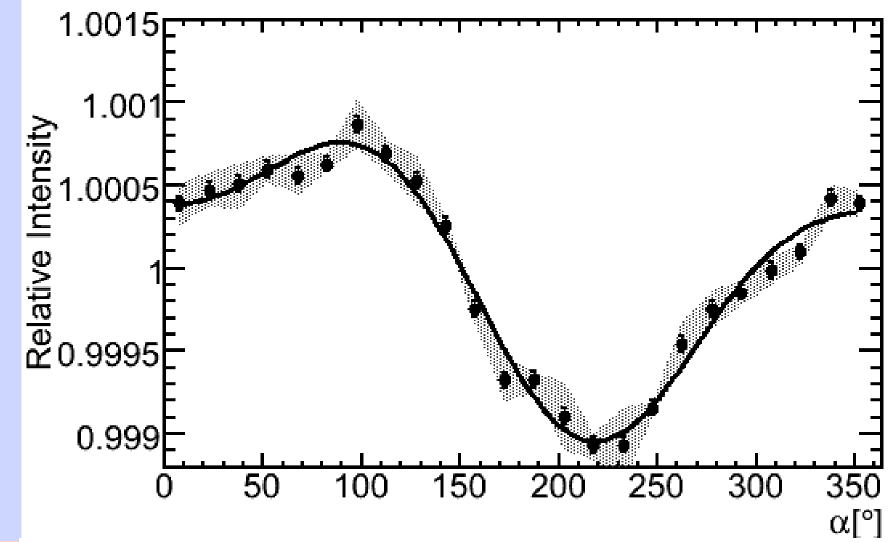


no energy selection

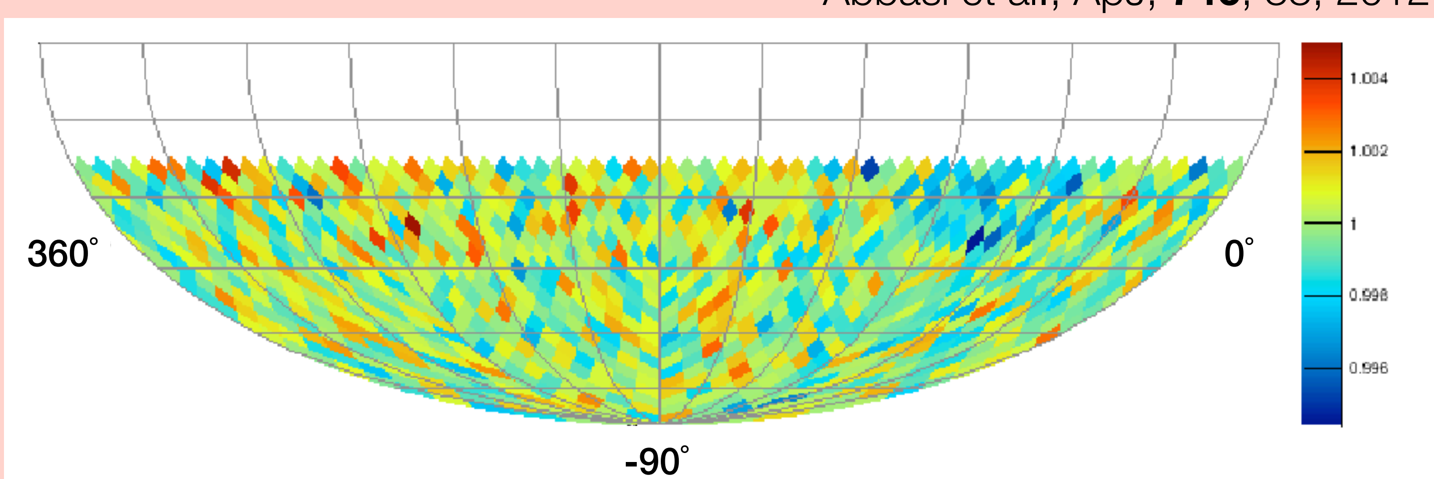




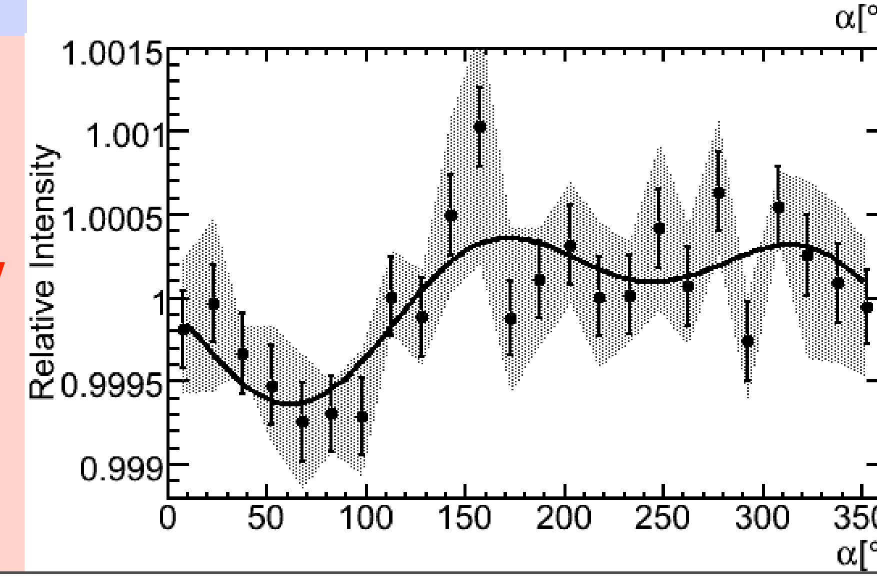
20 TeV

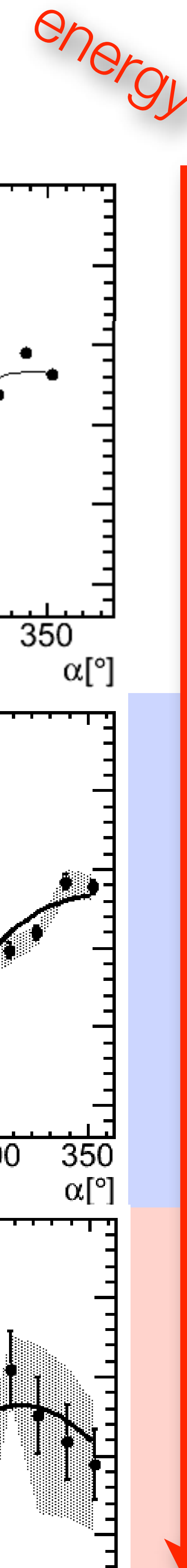


Abbasi et al., ApJ, **746**, 33, 2012



400 TeV





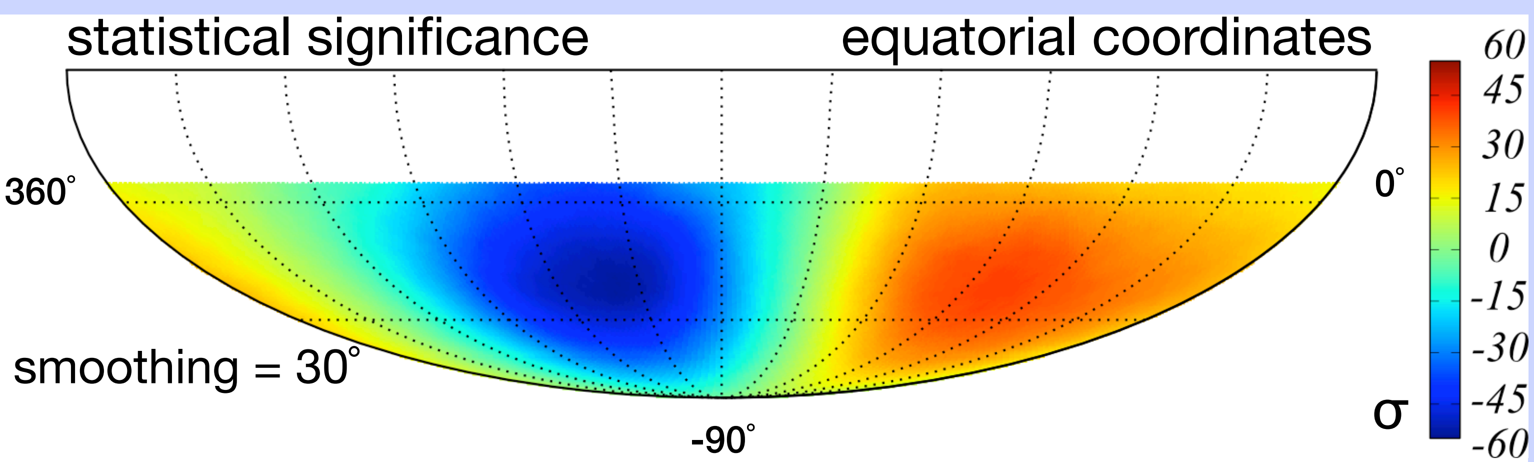
cosmic ray anisotropy vs energy in IceCube-59

energy

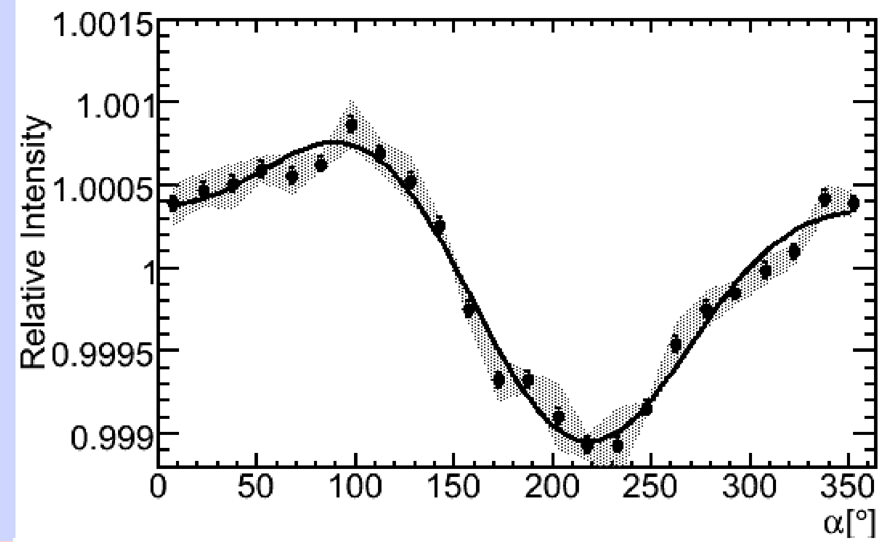
- reference map derived from data with time scrambling
- smoothing radius optimized on highest significance in excess/deficit region

$$s = \sqrt{2}\left\{ N_{\rm on} \ln\left[\frac{1+\alpha}{\alpha}\left(\frac{N_{\rm on}}{N_{\rm on}+N_{\rm off}}\right)\right] + N_{\rm off}\ln\left[(1+\alpha)\left(\frac{N_{\rm off}}{N_{\rm on}+N_{\rm off}}\right)\right]\right\}^{1/2} \qquad \alpha = 1/20$$

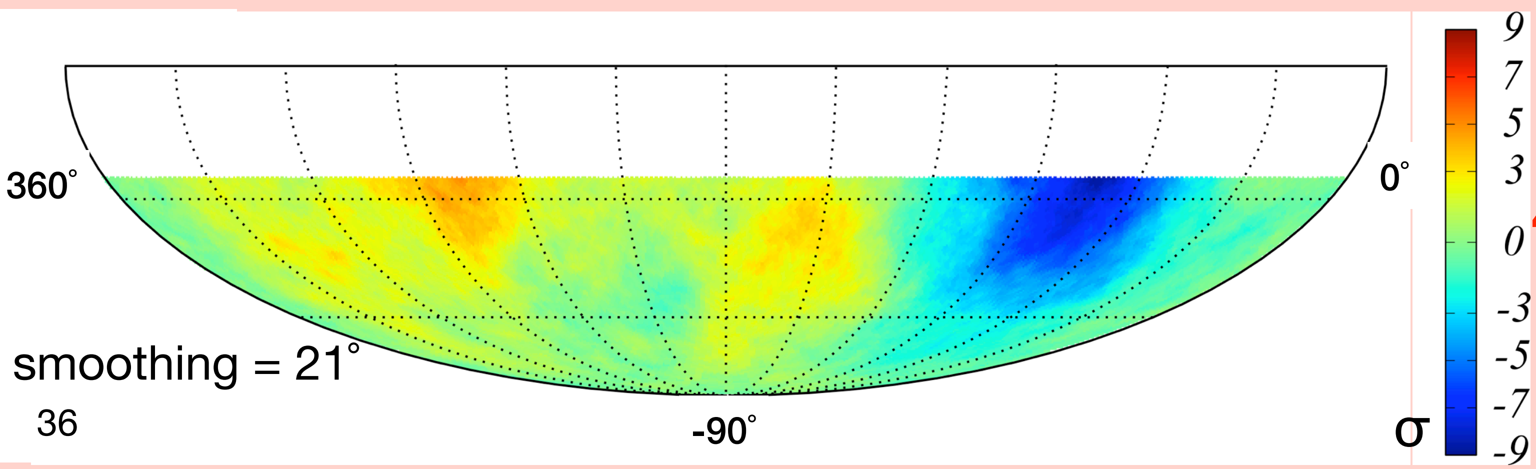
Li, T., & Ma, Y. 1983, ApJ, 272, 317



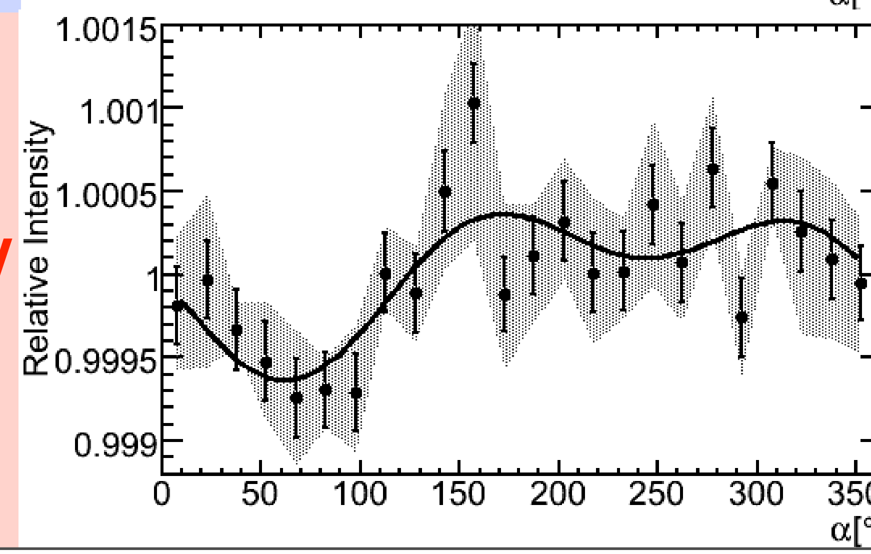
20 TeV



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



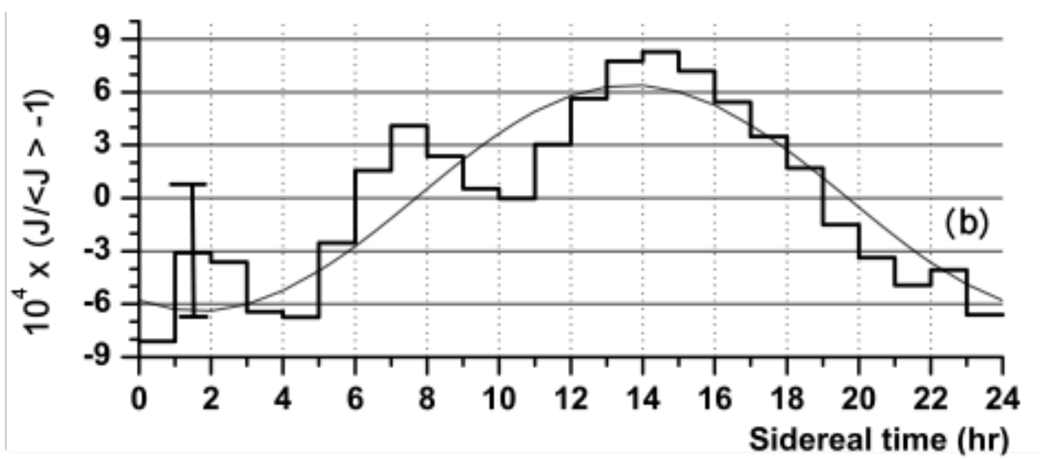
400 TeV



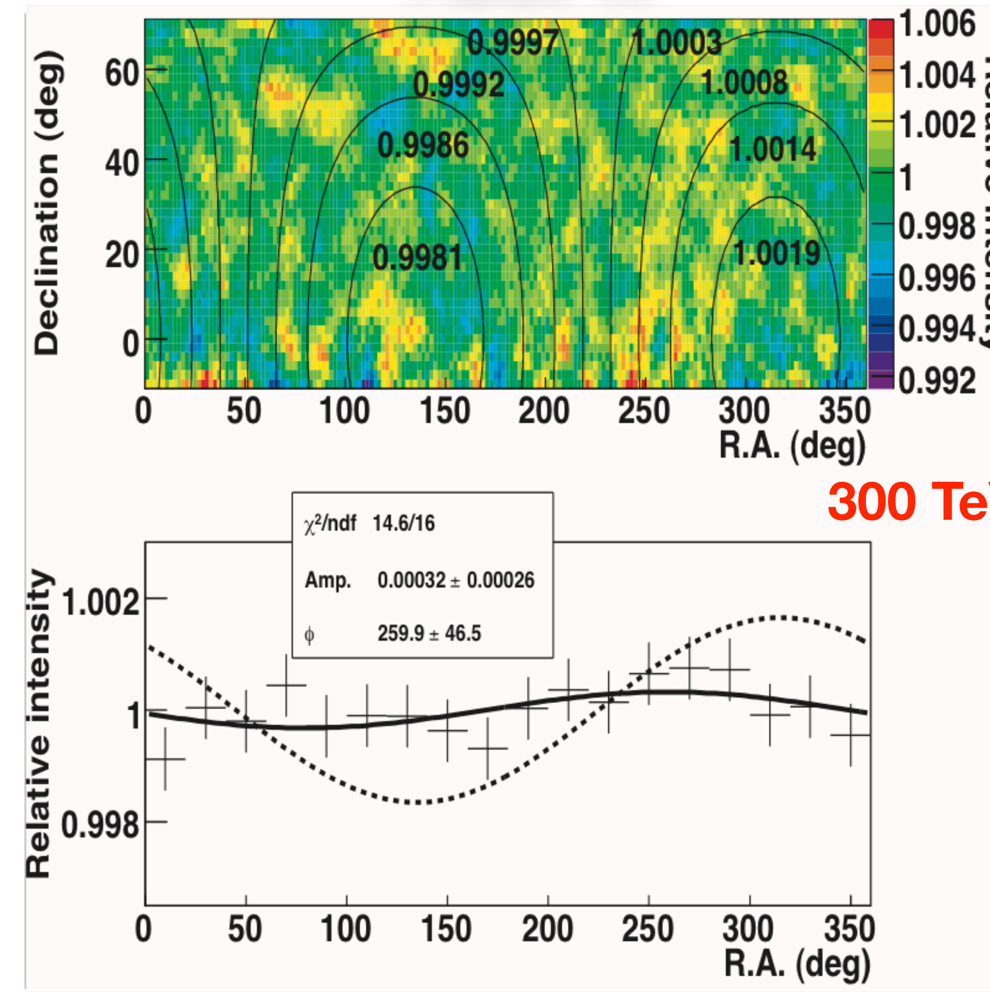
cosmic ray anisotropy vs energy in IceCube-59

EAS-TOP

370 TeV

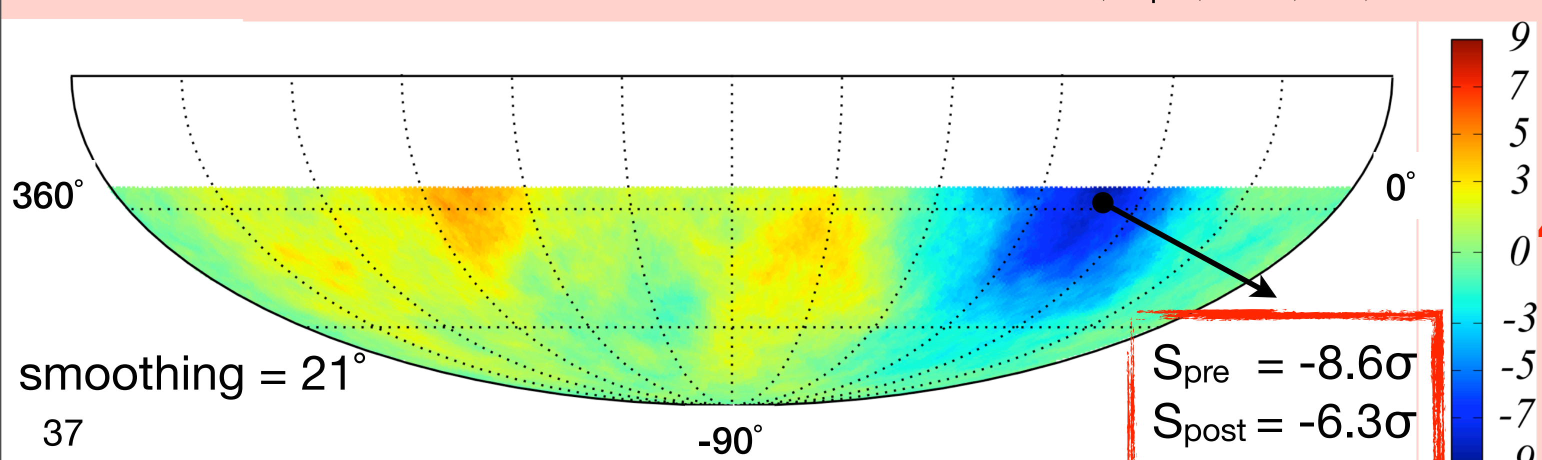


Tibet-III

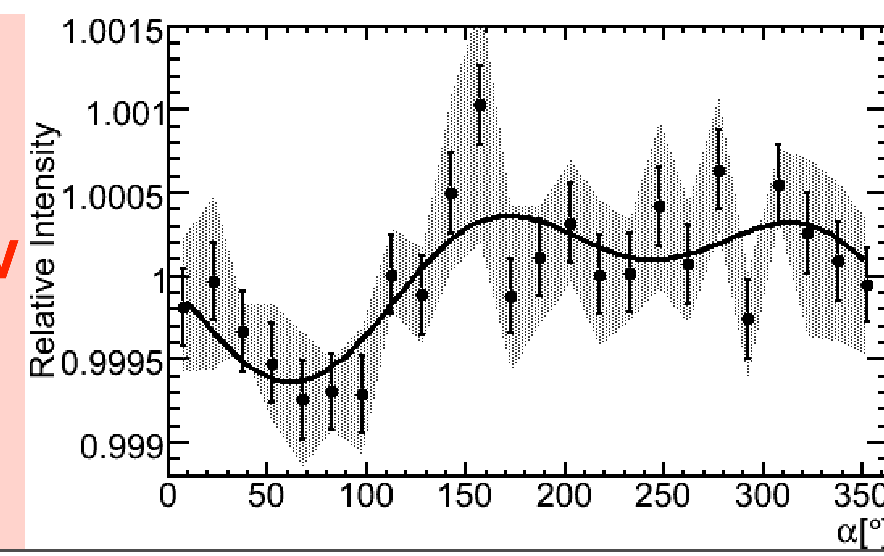


300 TeV

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

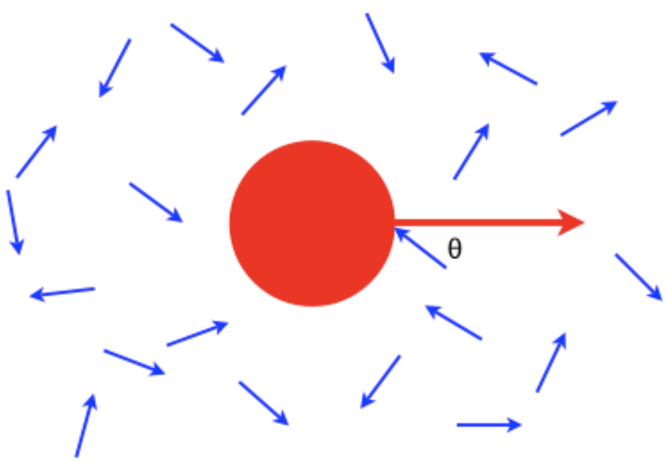


400 TeV



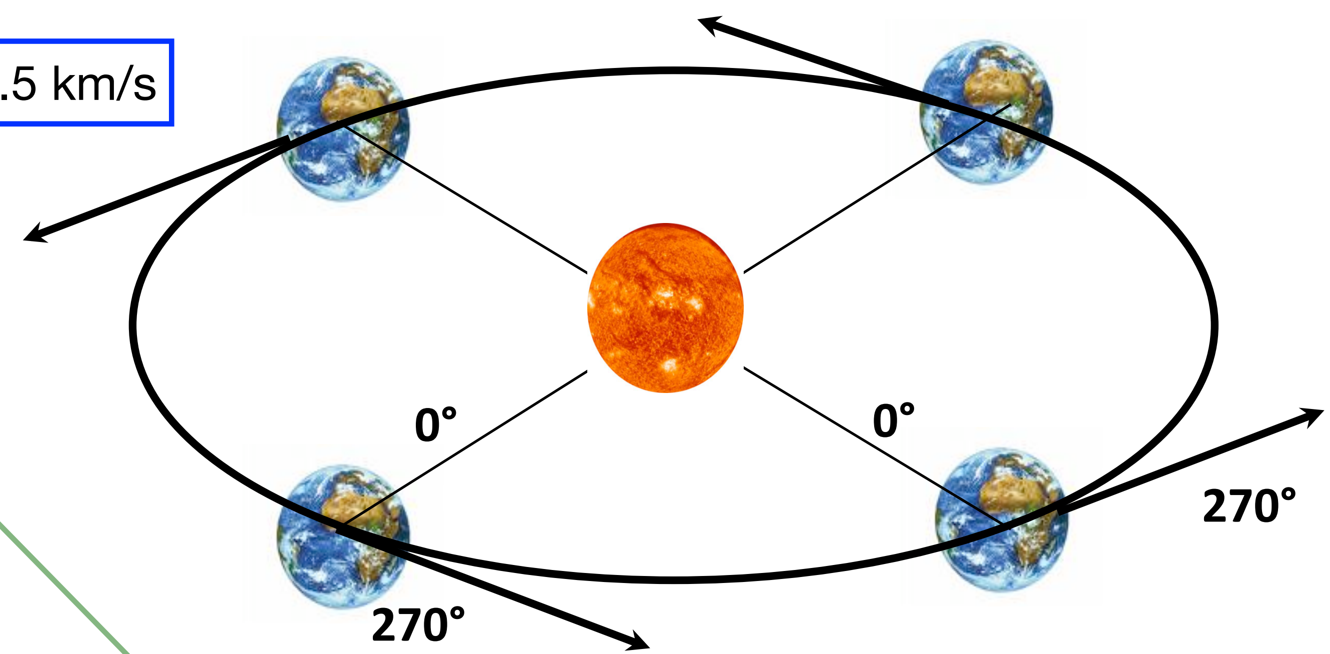
Compton & Getting, Phys. Rev. 47, 817 (1935)
Gleeson, & Axford, Ap&SS, 2, 43 (1968)

Earth's motion around the Sun

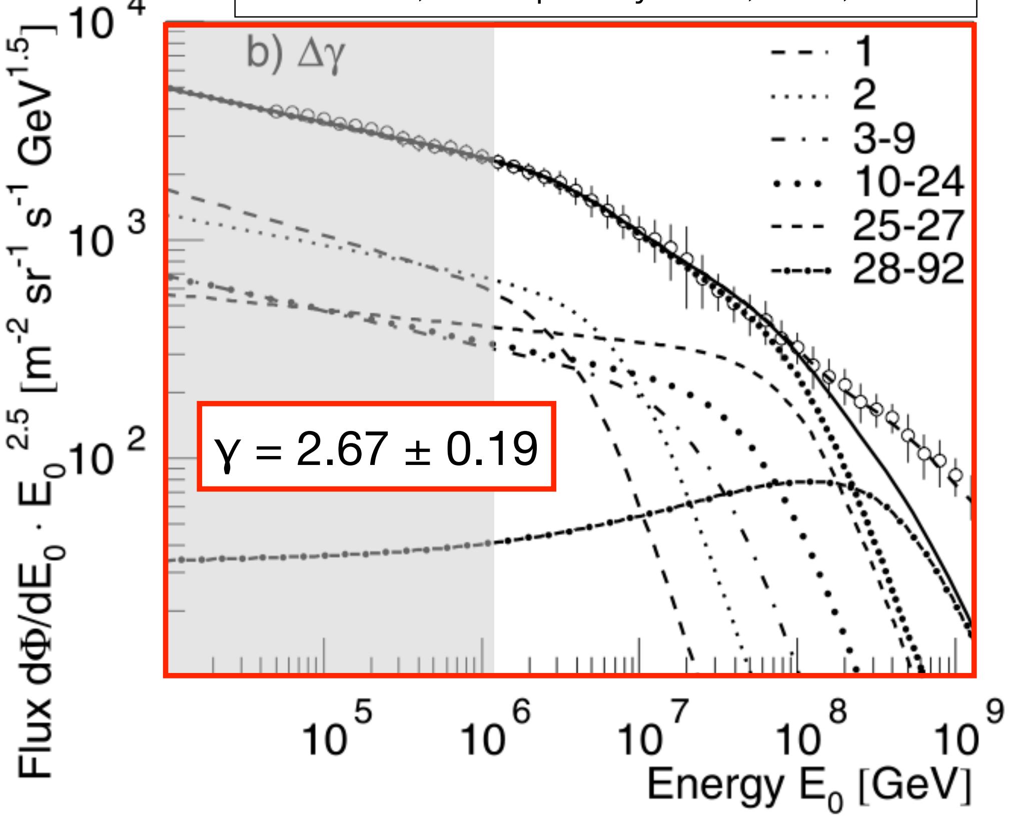


$$\frac{\Delta I}{I} = (\gamma + 2)\frac{v}{c}\cos\theta$$

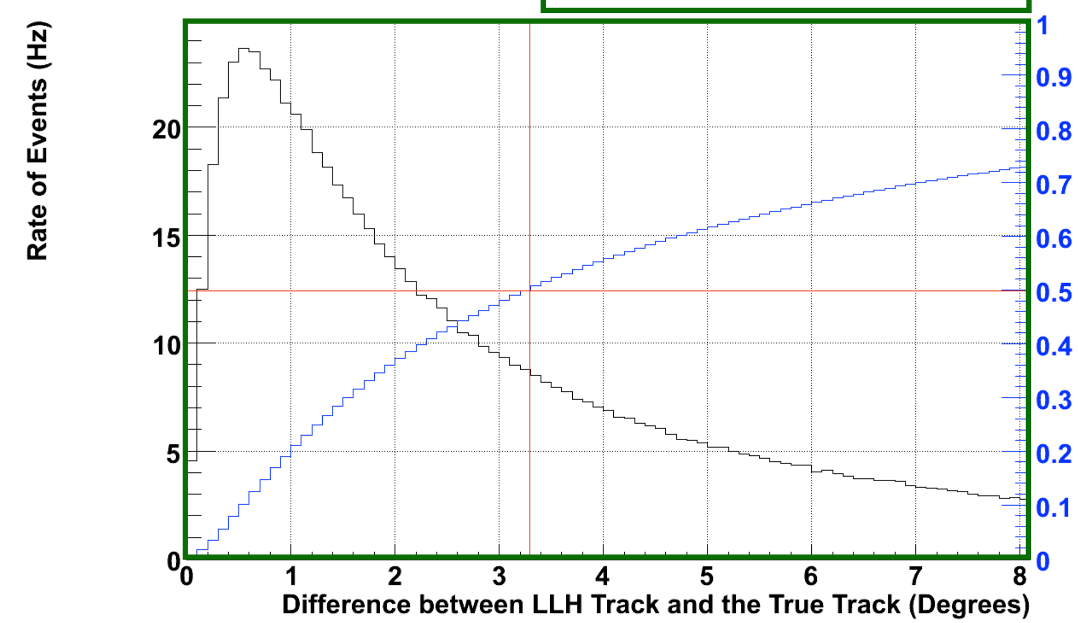
v = 29.8 ± 0.5 km/s



Hörandel, Astrop. Phys. 19, 193, 2003

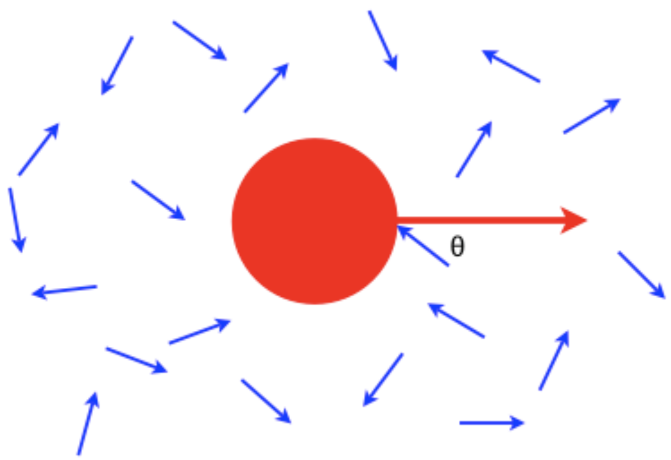


point spread function



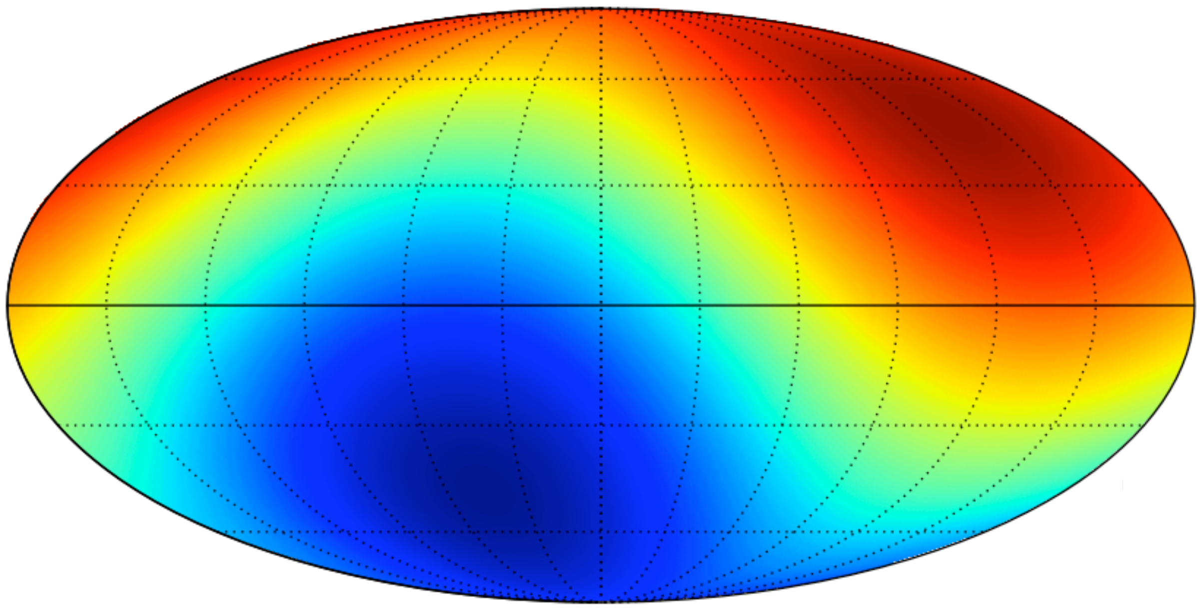
origin of large scale anisotropy : Compton-Getting Effect ?

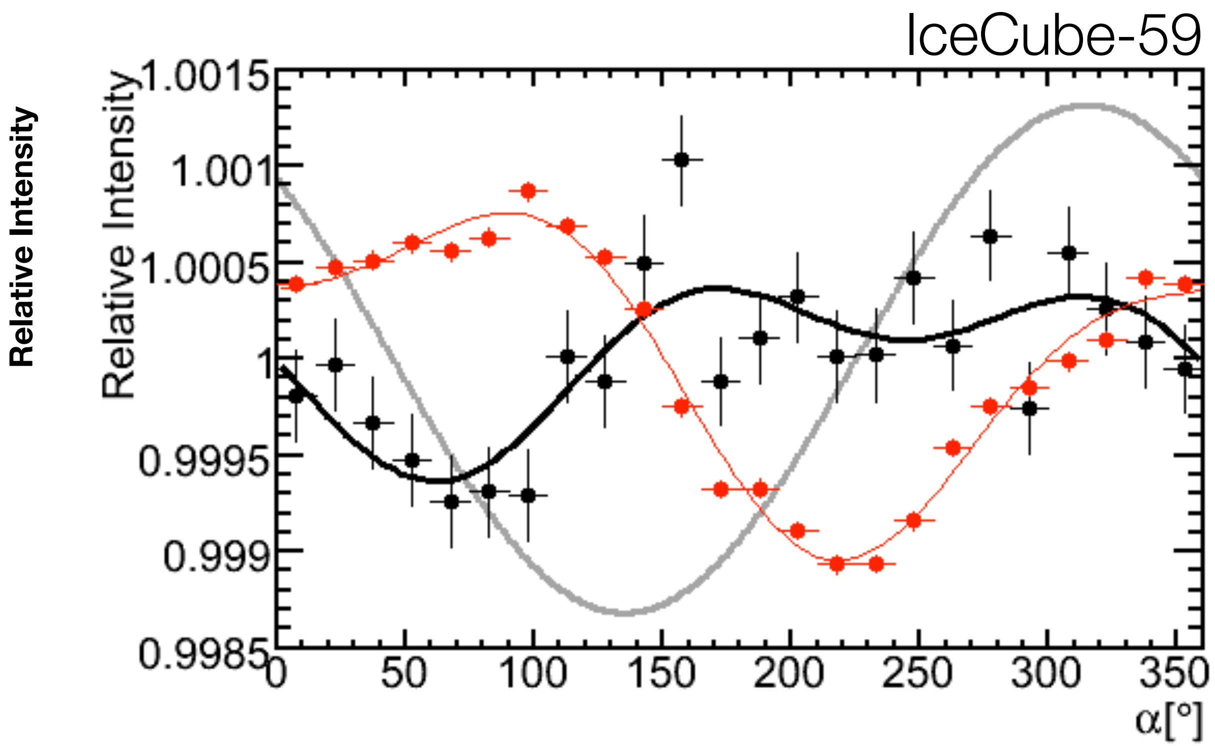
Compton & Getting, Phys. Rev. 47, 817 (1935)
Gleeson, & Axford, Ap&SS, 2, 43 (1968)



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

- apparent energy-independent ~10^{-3} dipole anisotropy due to relative motion of solar system through ISM
- motion of solar system around galactic center ~ 220 km/s
- reference system of cosmic rays is unknown

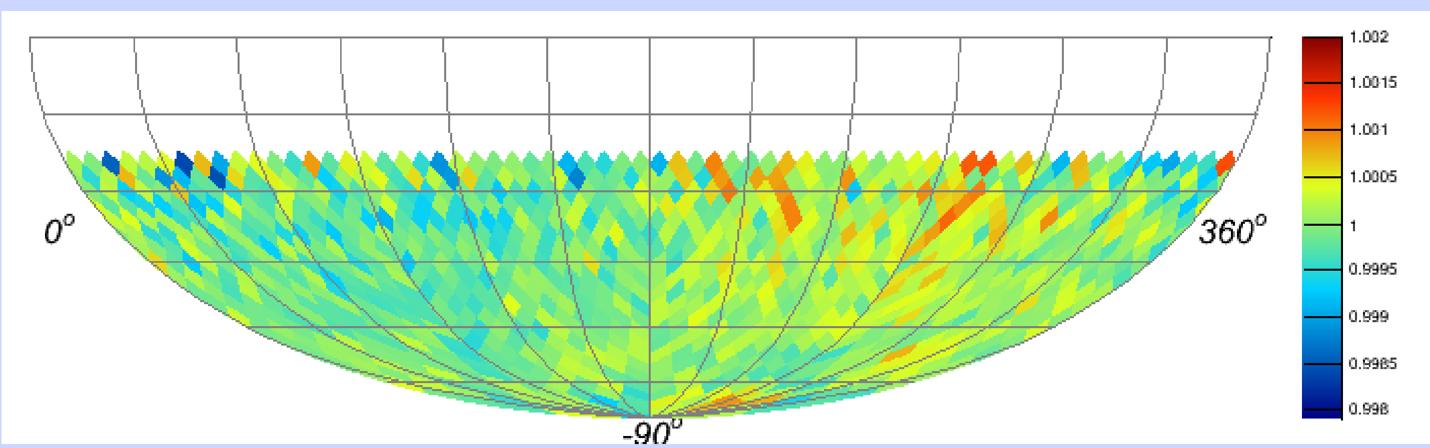




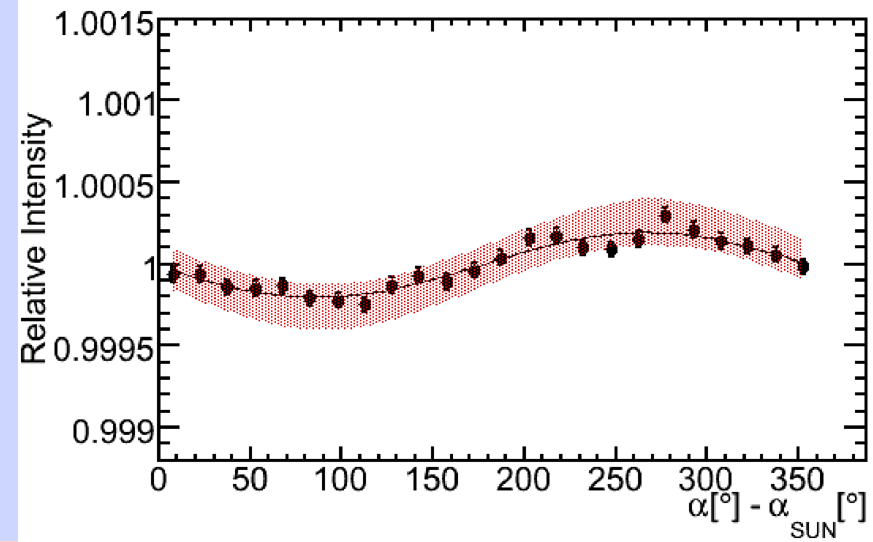
solar dipole anisotropy vs energy in IceCube-59

The observation of the solar dipole supports the observation of the sidereal anisotropy in cosmic ray arrival direction

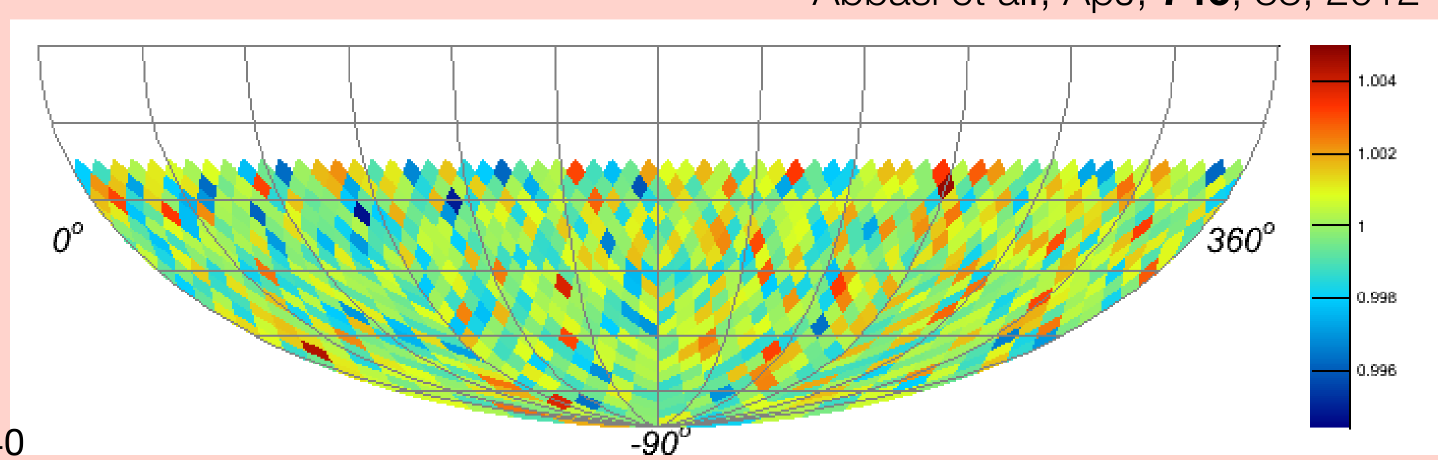
relative intensity $\alpha\,[^\circ] - \alpha_{SUN}\,[^\circ]$



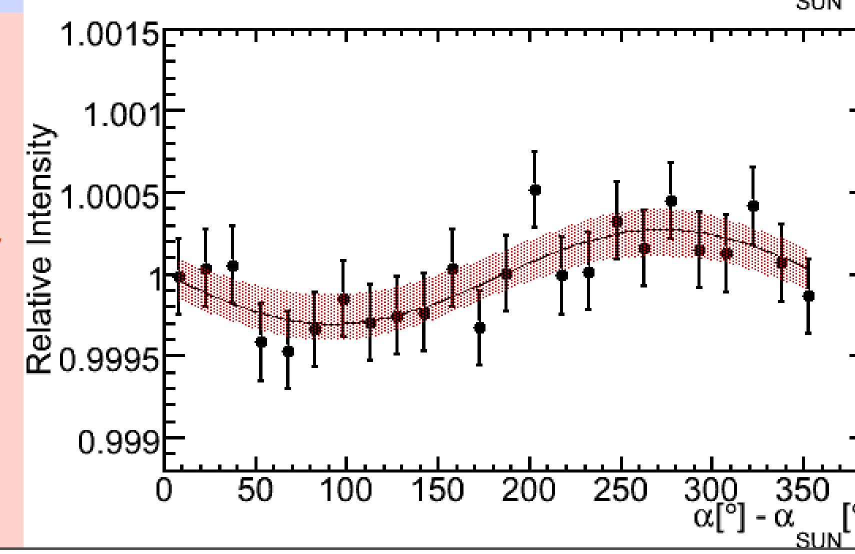
20 TeV



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



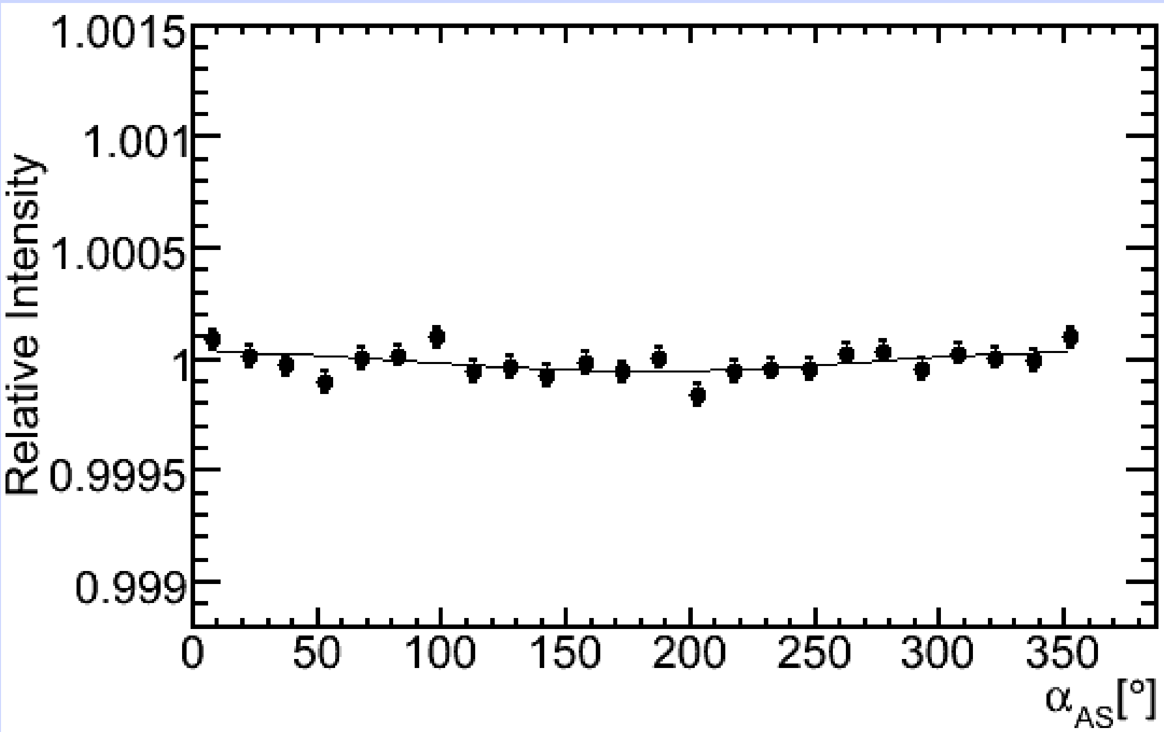
400 TeV

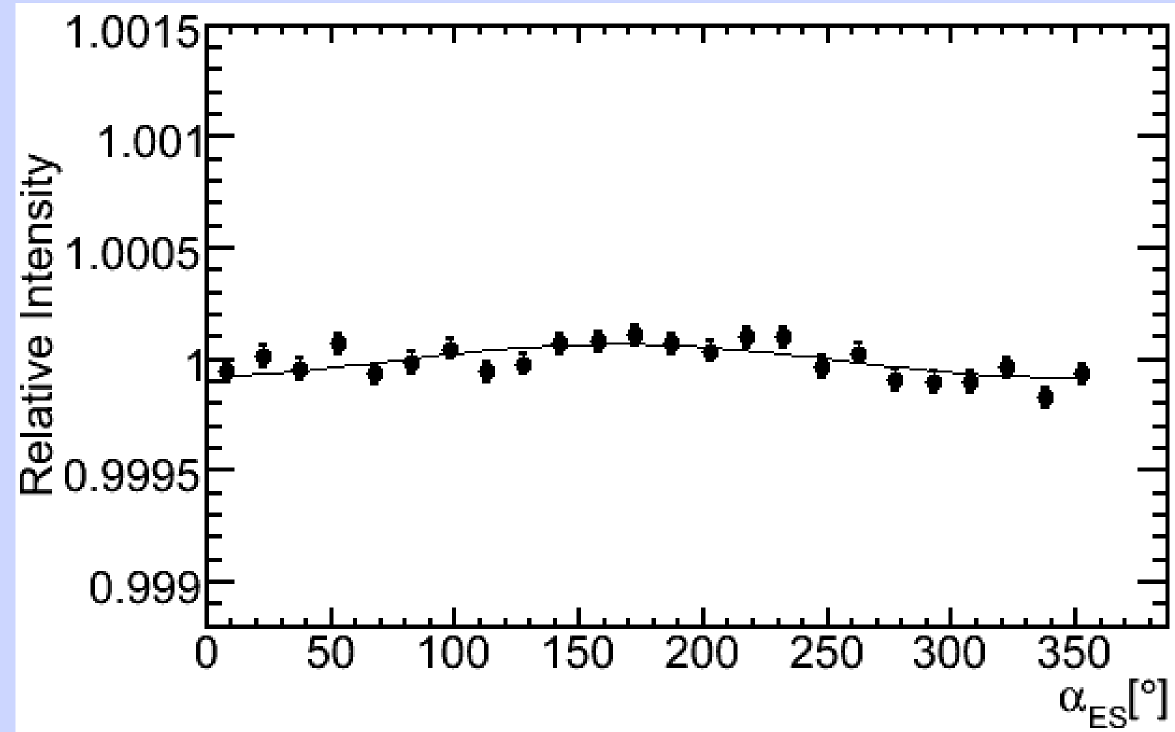


anti-/extended-sidereal distributions vs energy in IceCube-59

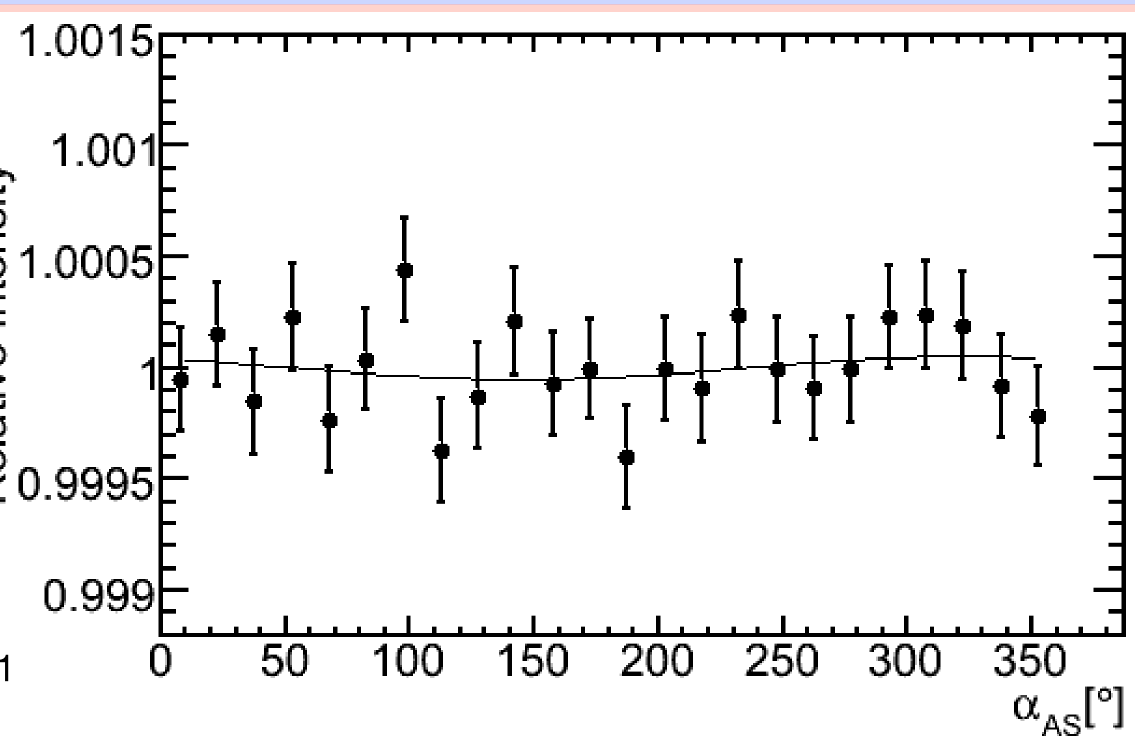
anti-sidereal distribution ~ solar dipole variability

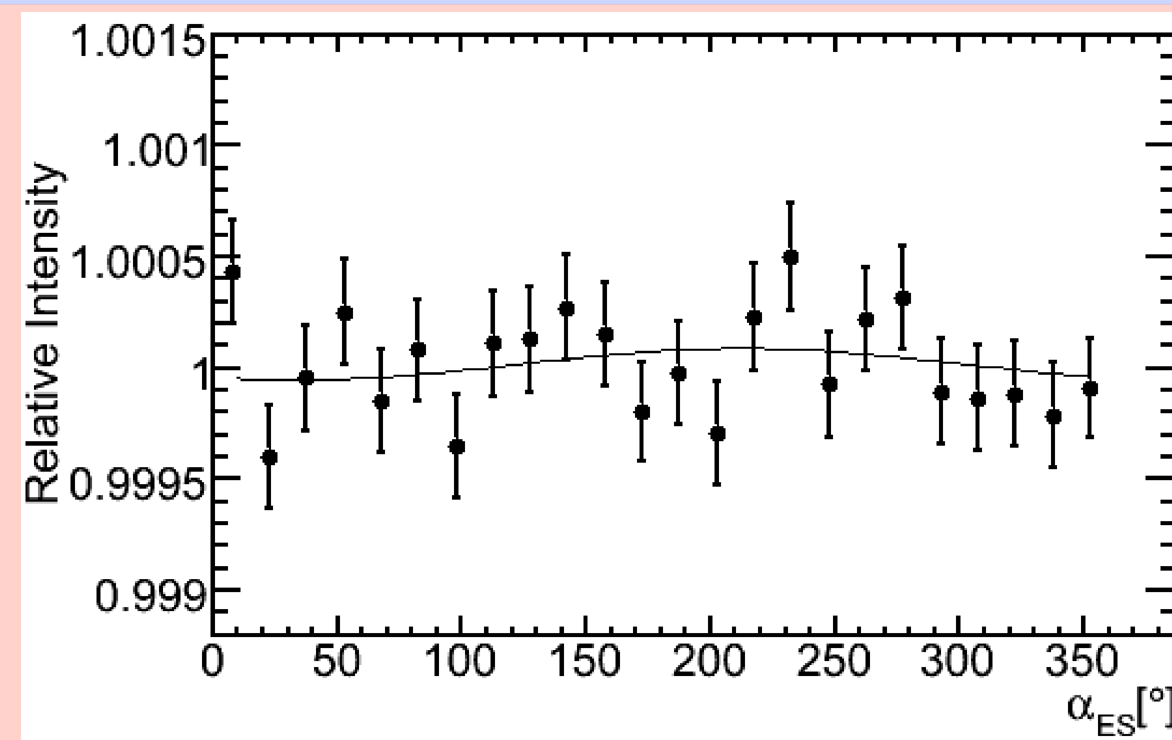
extended-sidereal distribution ~ sid. anis. variability





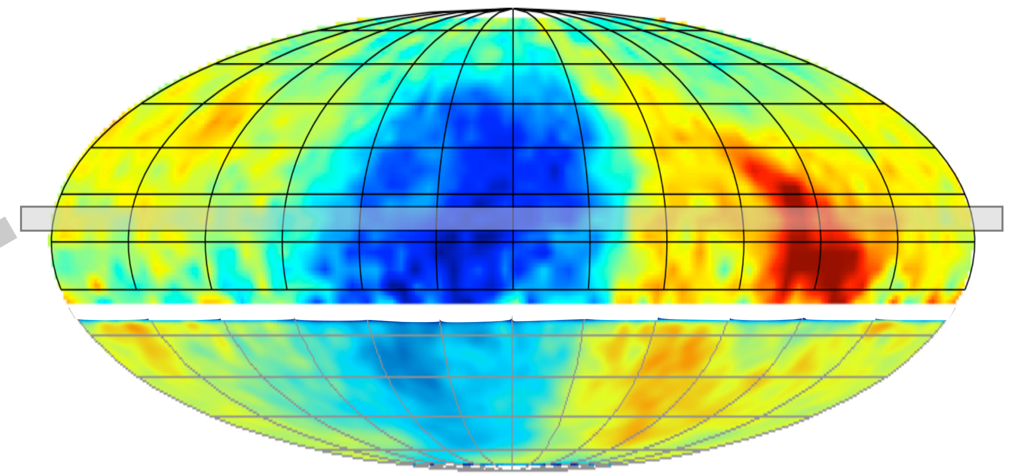
20 TeV

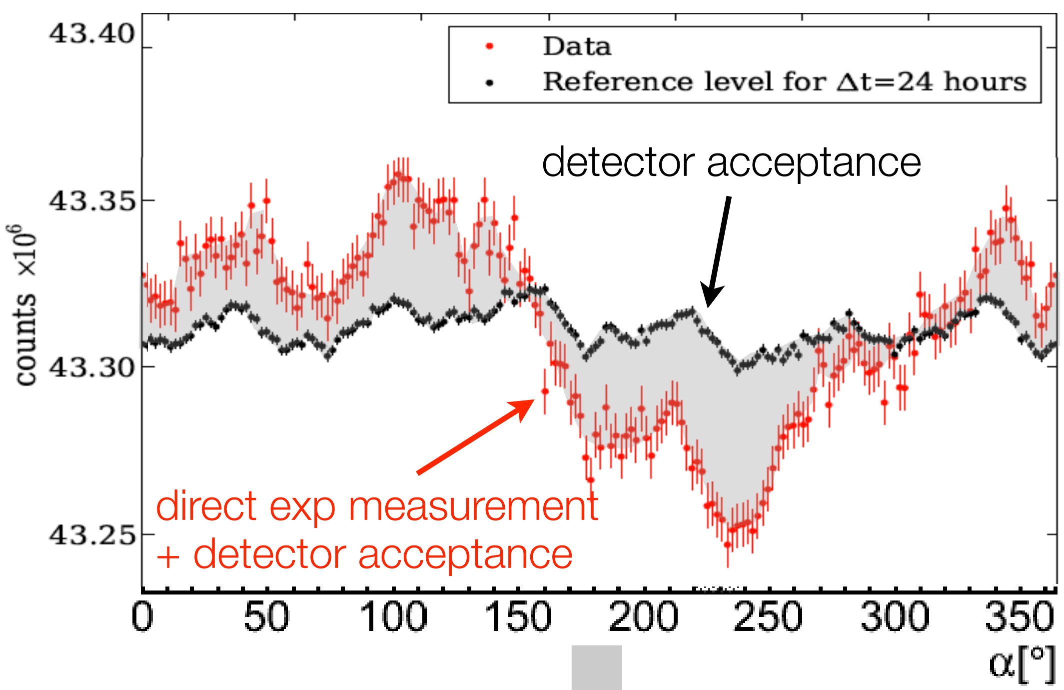


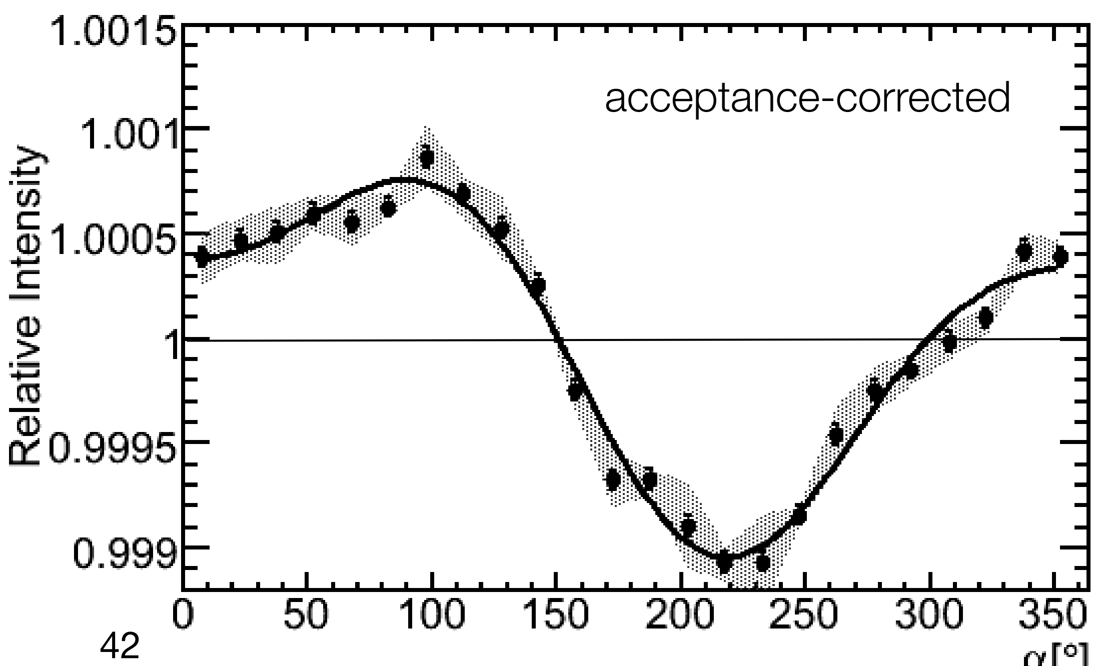


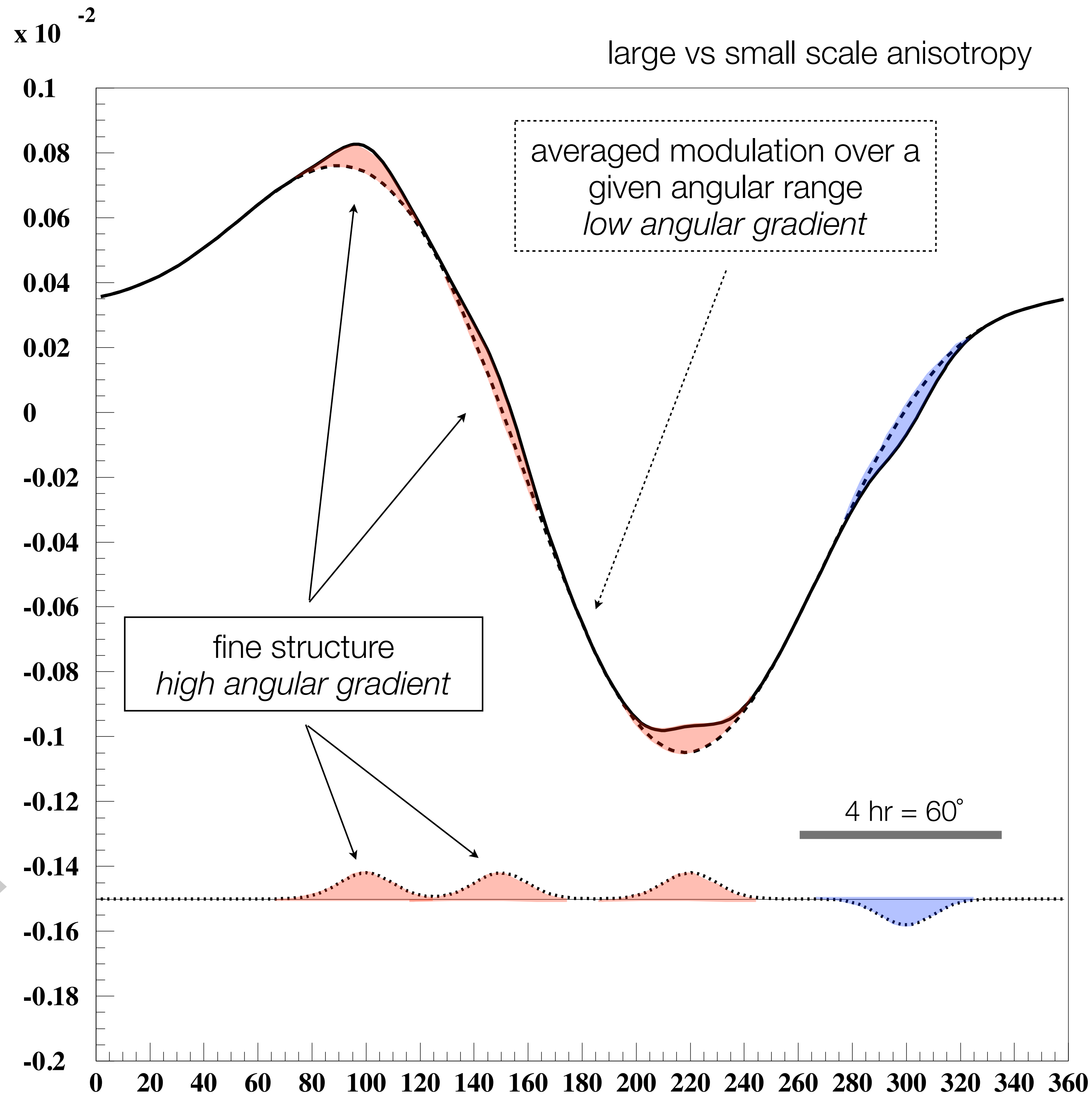
400 TeV

anisotropy vs. angular scale









Paolo Desiati