Beyond the standard models of particle physics, cosmology and astrophysics (beyond 2010)

Cape Town, South Africa

neutrino astrophysics & galactic cosmic ray anisotropy in IceCube

Paolo Desiati

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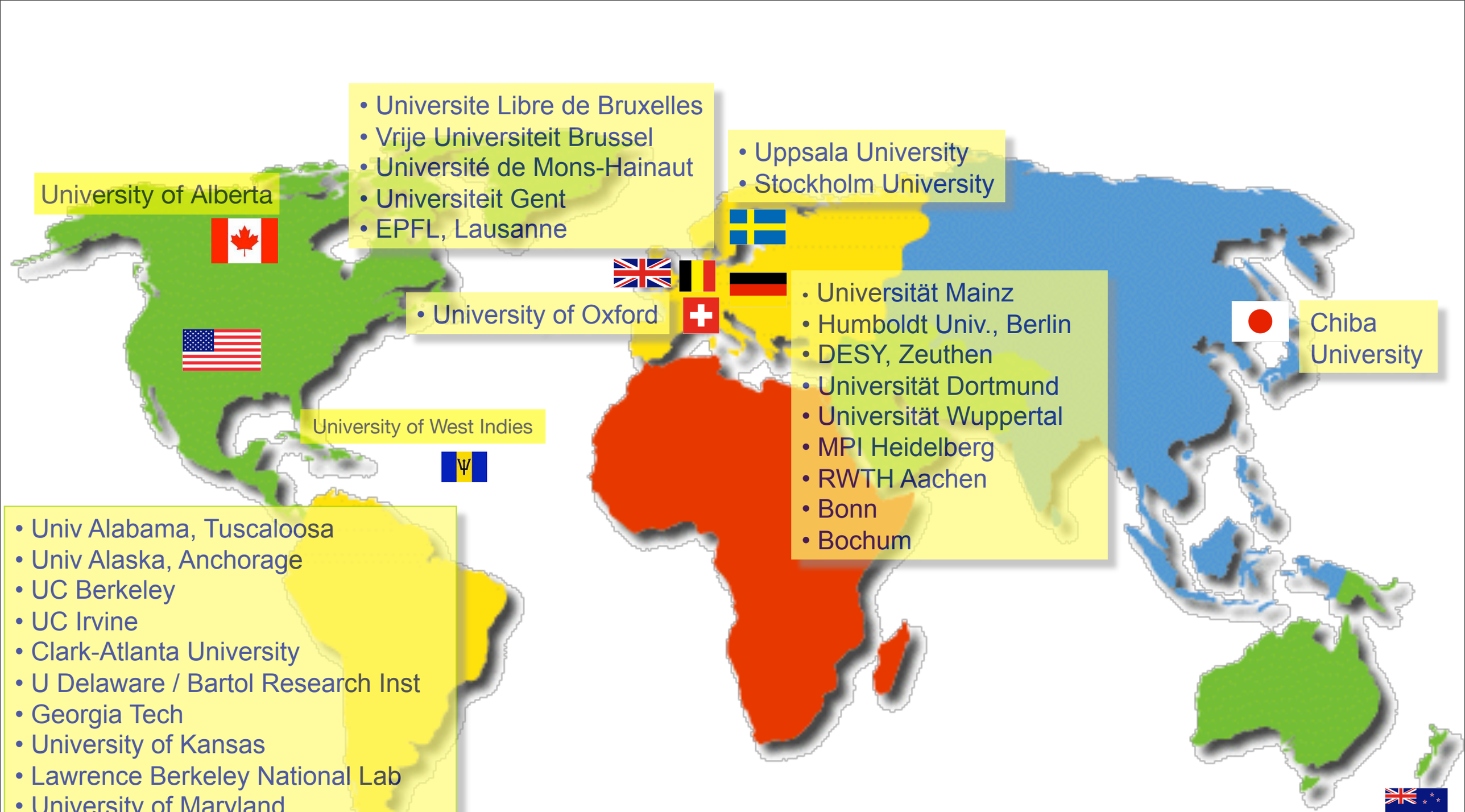
February 6, 2010

University of Wisconsin - Madison

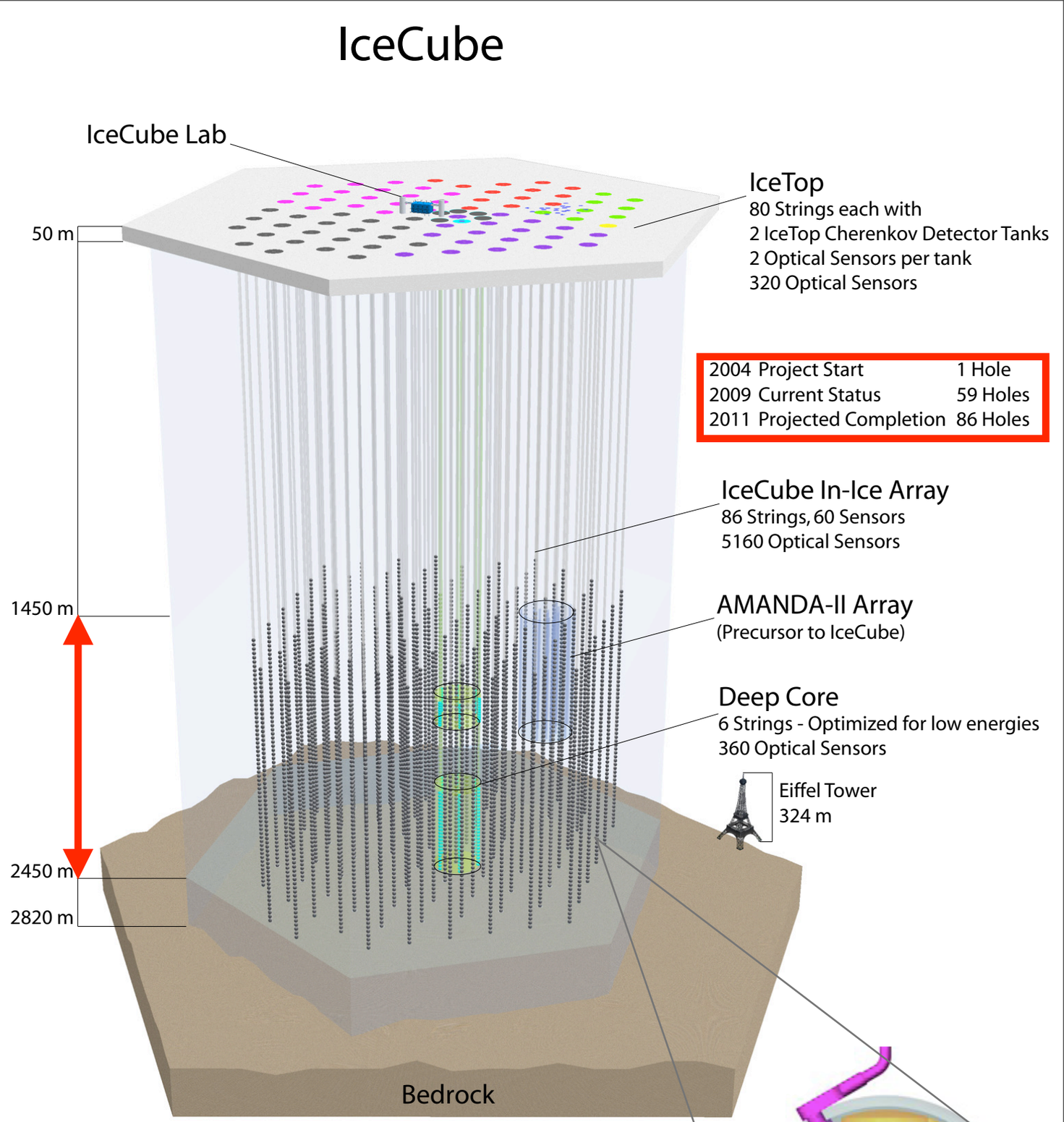


the IceCube Collaboration

36 institutions in 4 continents

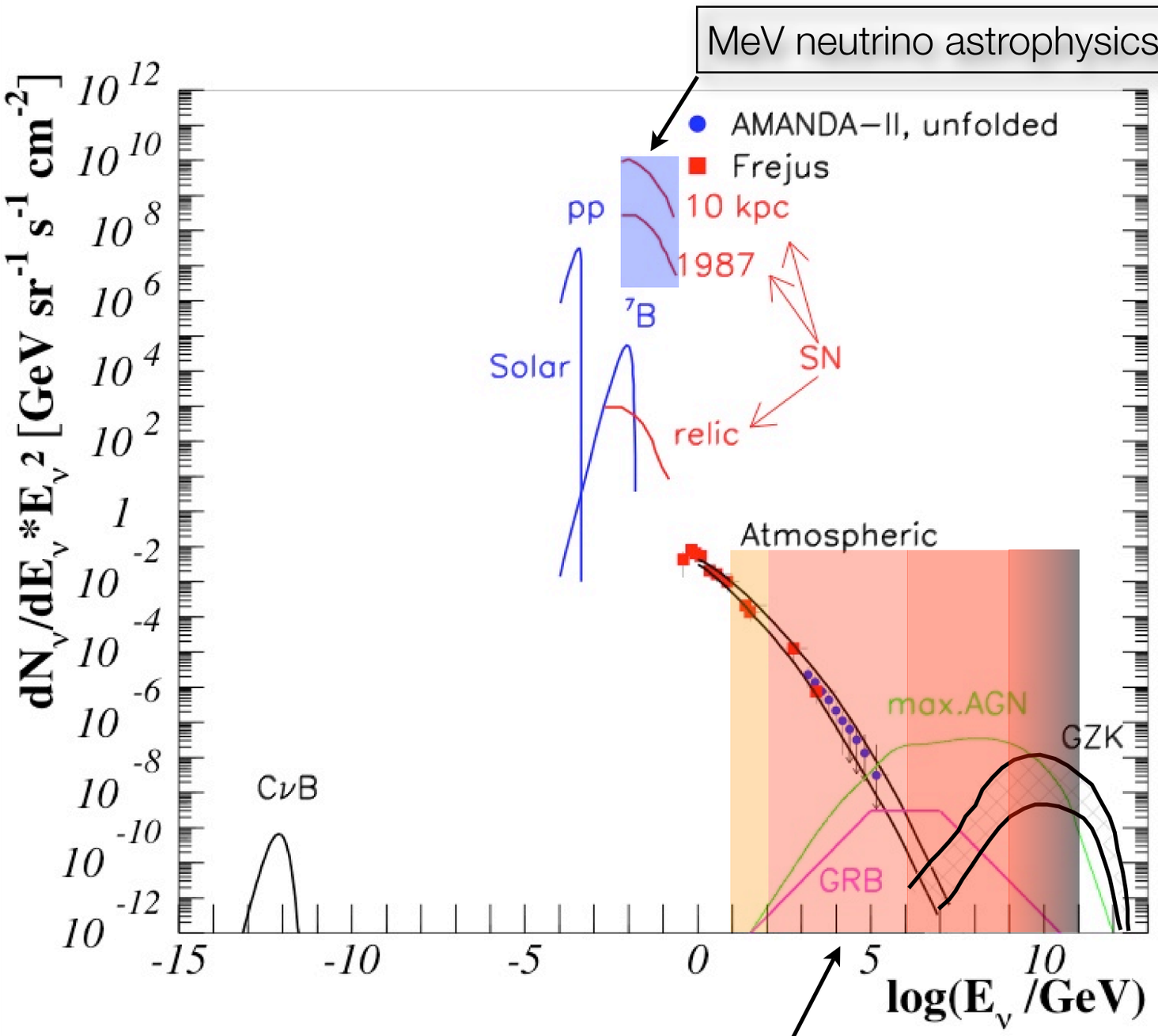
IceCube Observatory

- IceCube
  - physics run with 59 strings
  - currently 79 strings
  - 86 strings in 2011
  - 125 m inter-string spacing
  - 17 m DOM distance
- taking data during construction
- AMANDA decommissioned on May 11, 2009
- Deep Core completed with 6 strings

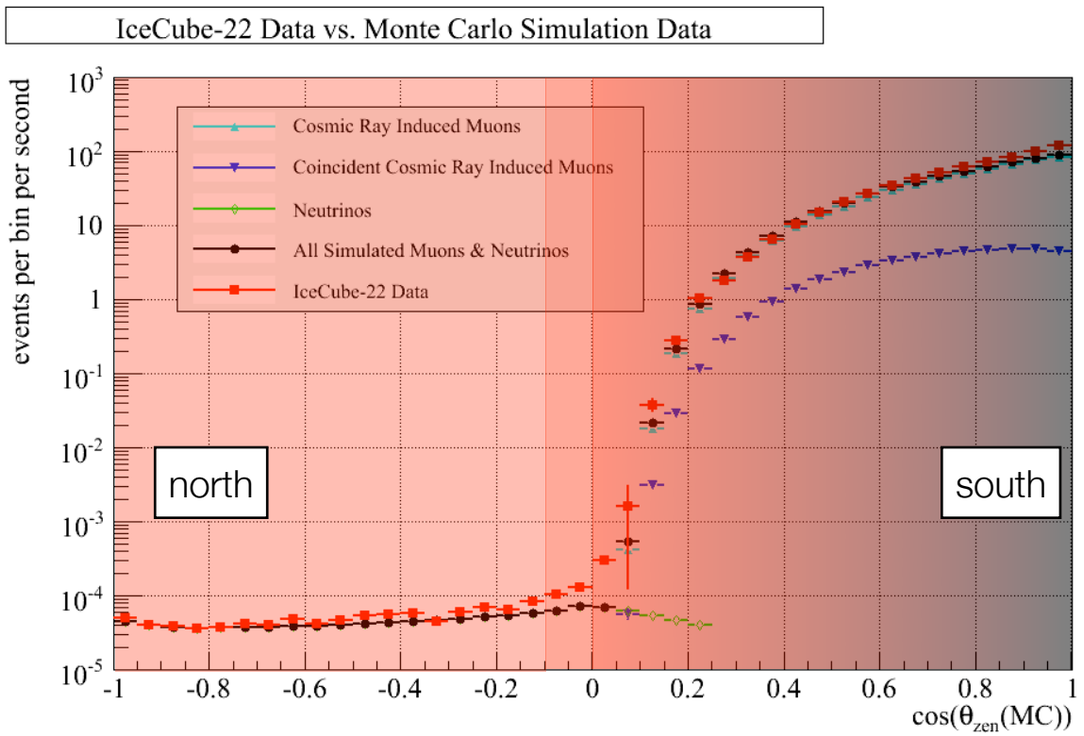


125 m

high energy neutrino astronomy



- search whole sky
- high background from south
  - high energy selection

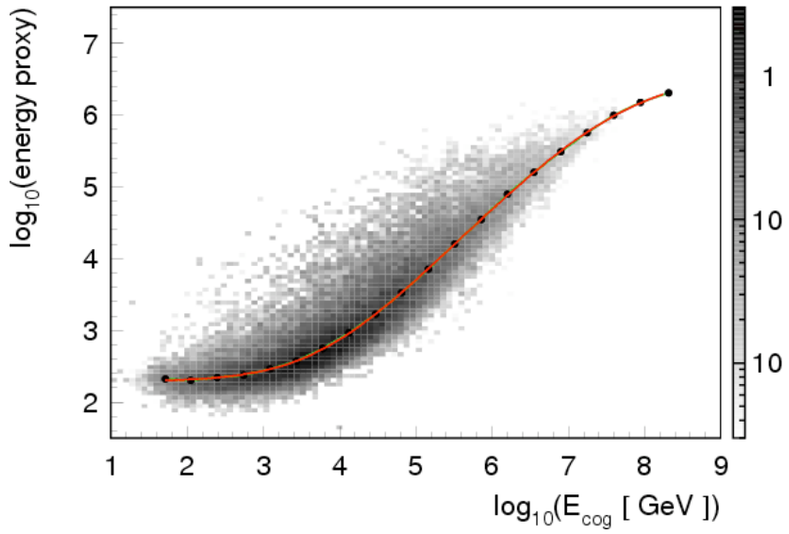


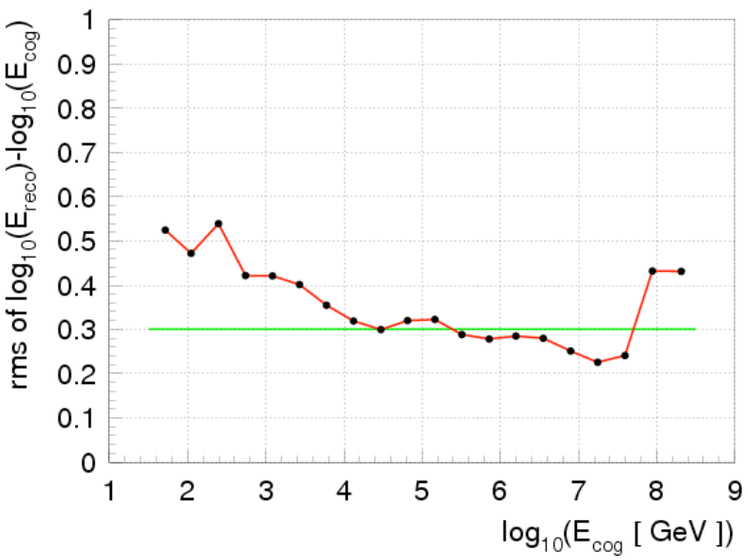
Patrick Berghaus, Kristin Rosenau

high energy neutrino astronomy

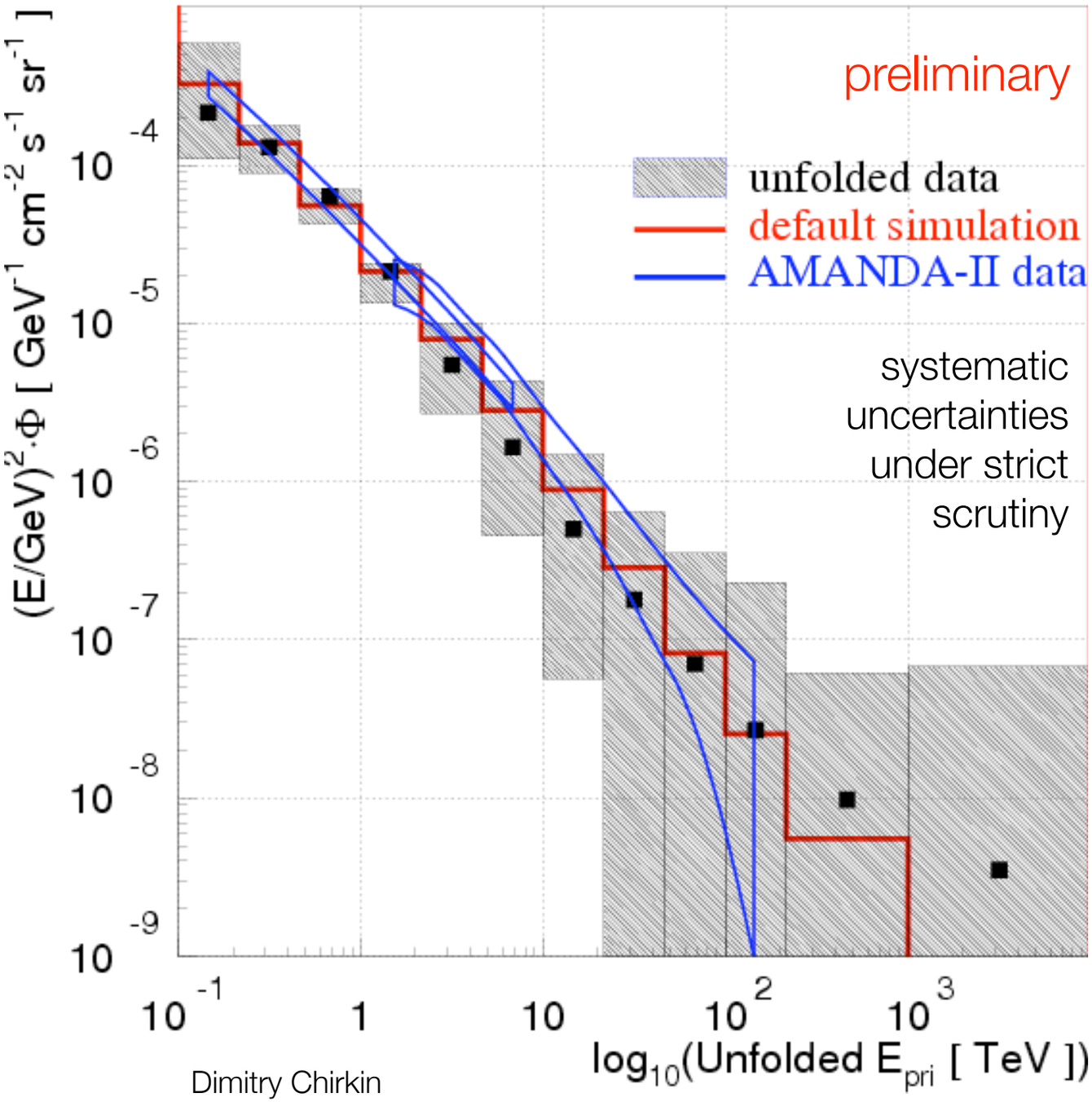
atmospheric neutrinos

IceCube 22 strings (2007)
unfolded atmospheric ν_μ spectrum



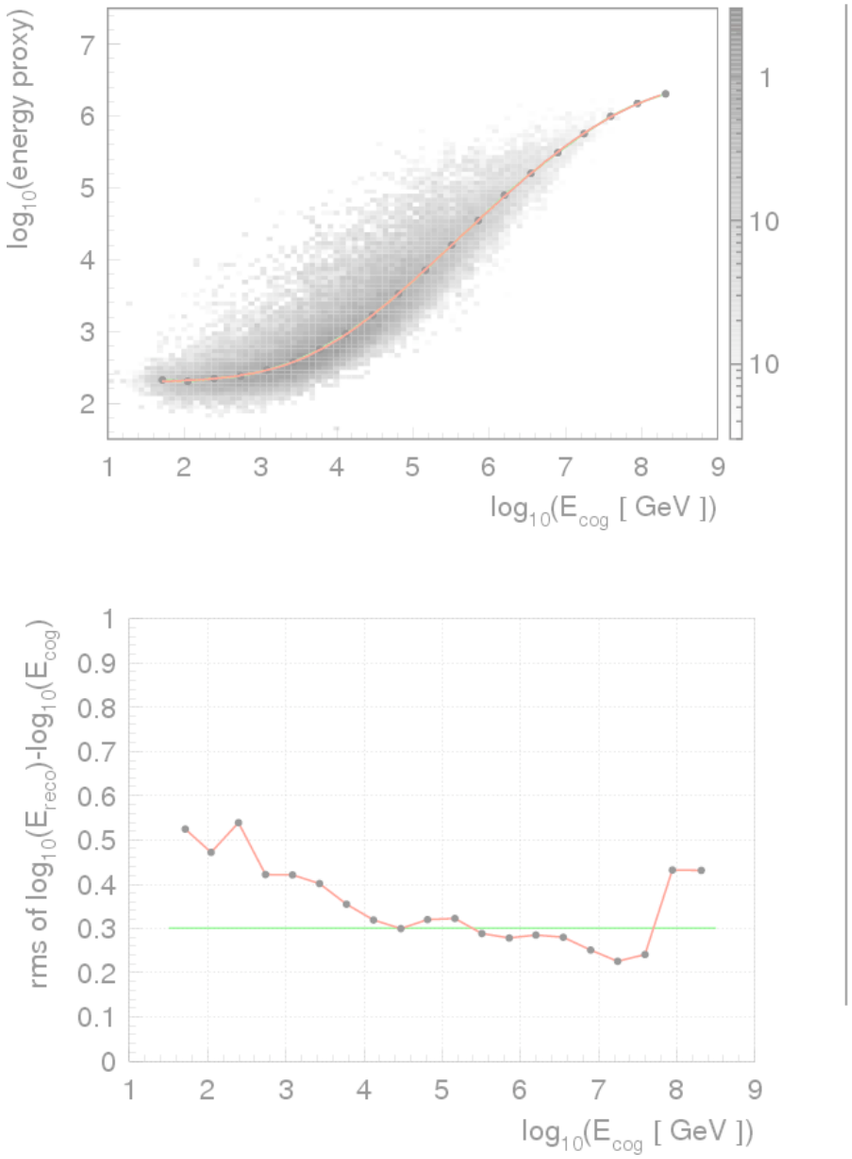


energy estimation resolution



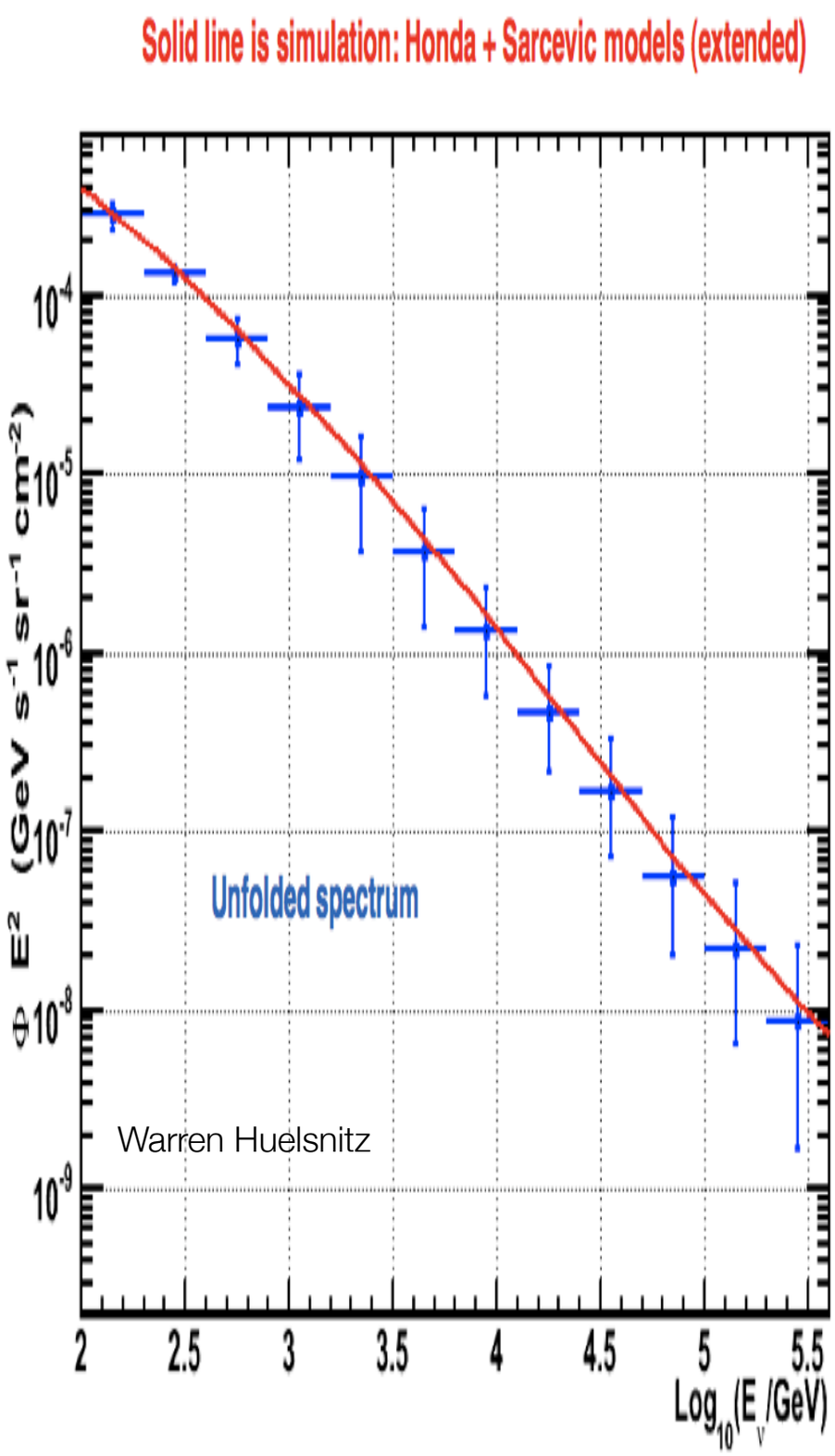
Dimitry Chirkin

atmospheric neutrinos



energy estimation resolution

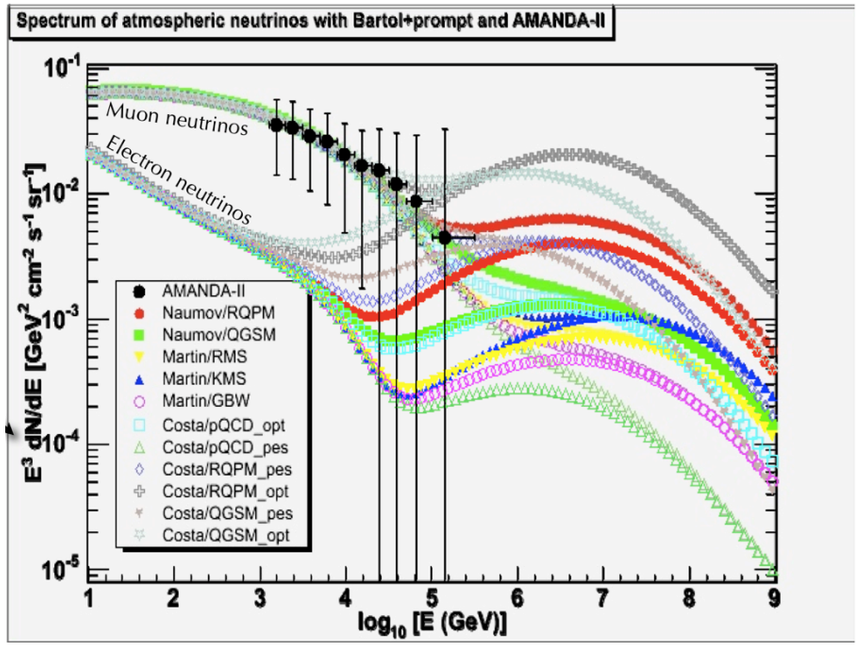
IceCube 40 strings (2008)
unfolded atmospheric ν_μ spectrum



preliminary

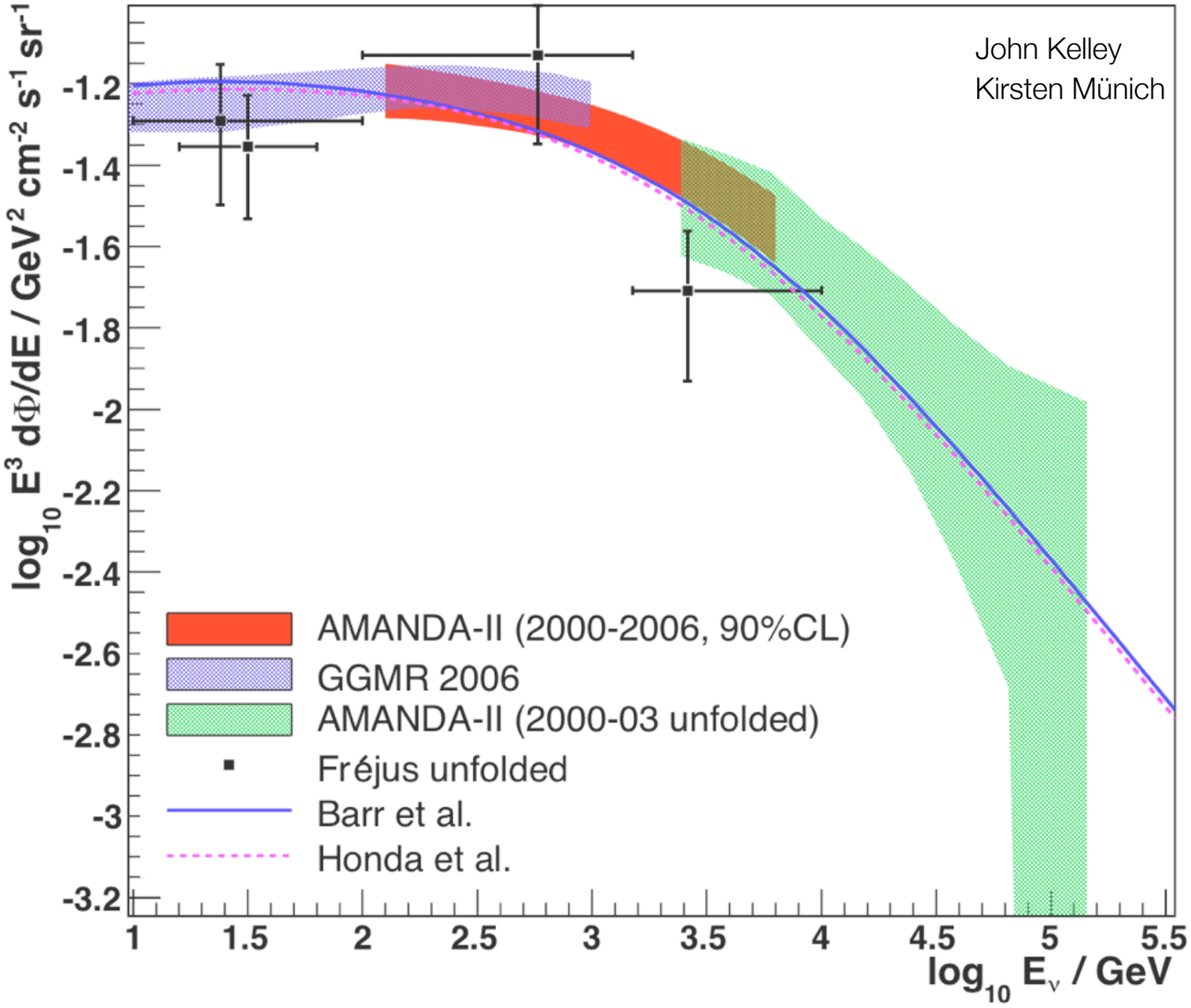
systematic uncertainties under strict scrutiny

atmospheric neutrinos



high energy neutrinos from charm

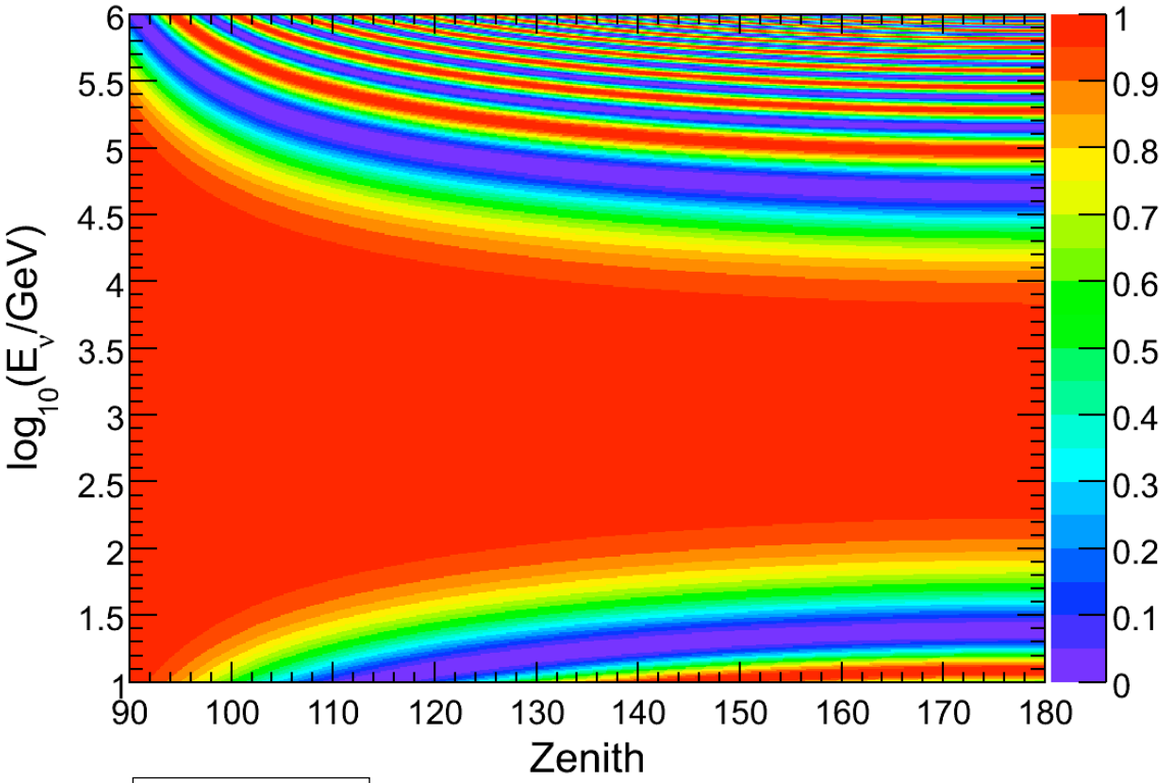
unfolded atmospheric ν_μ spectrum



Abbasi et al., Phys. Rev. D 79, 102005 (2009), arXiv:0902.0675

atmospheric neutrinos & non-standard oscillations

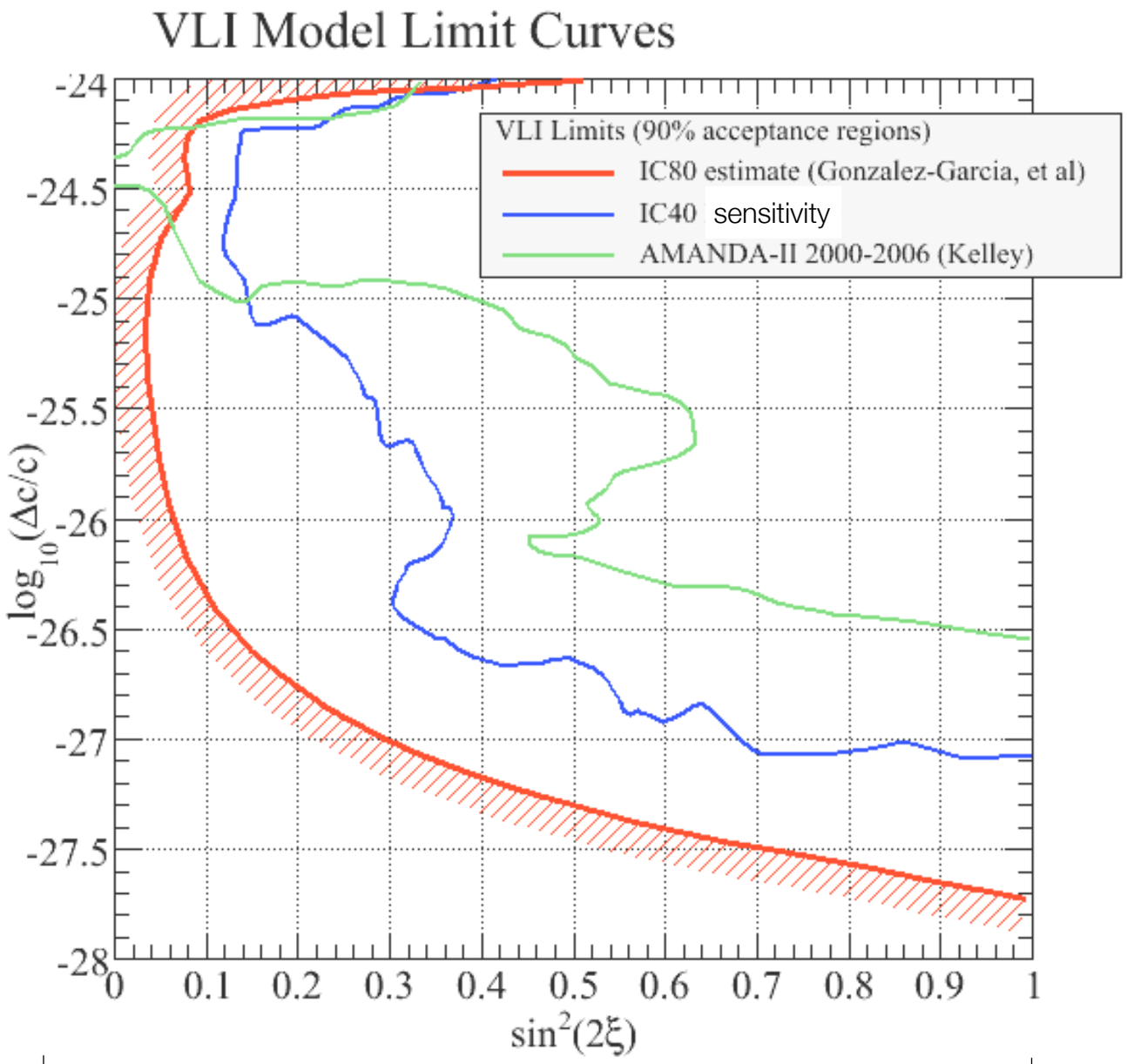
Violation of Lorentz Invariance



$$\frac{\delta c}{c} = 10^{-27}$$
$$\sin^2 2\theta_c = 1$$

González-García, Halzen, and Maltoni, PRD 71, 093010 (2005)

Abbasi et al., Phys. Rev. D 79, 102005 (2009), arXiv:0902.0675

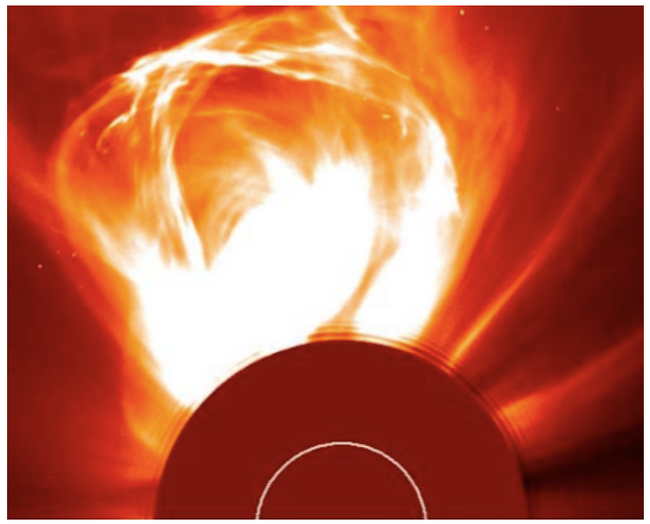


- IC40 preliminary : systematic uncertainties affecting energy/angular shape under scrutiny
- will constrain VLI, QD, and other models

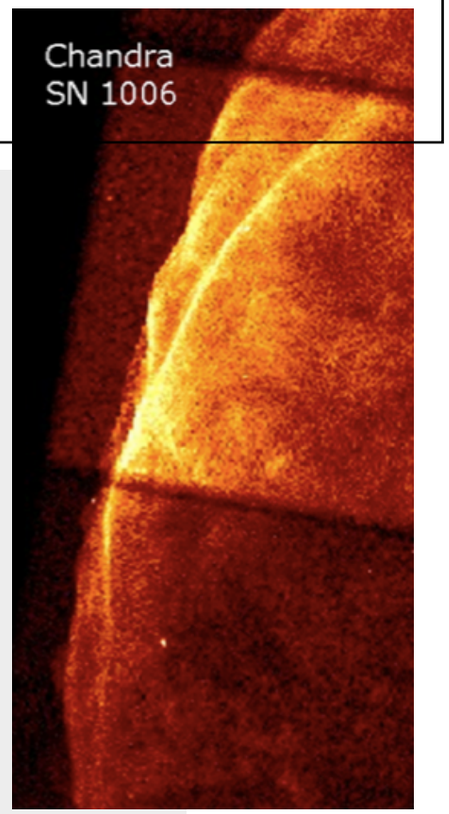
John Kelley (IC22) - Warren Huelsnitz (IC40)

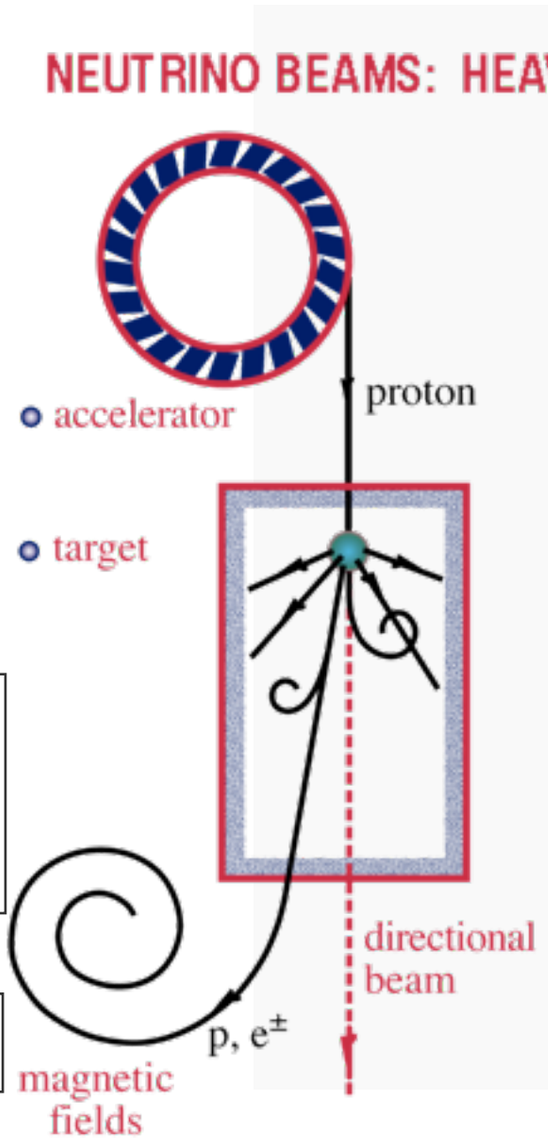
sources of astrophysical neutrinos

solar shock acceleration well known



observed shocks in SNR





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

$\rightarrow \pi^{o} + X \rightarrow \gamma\,\gamma + X$ **gamma rays ...**

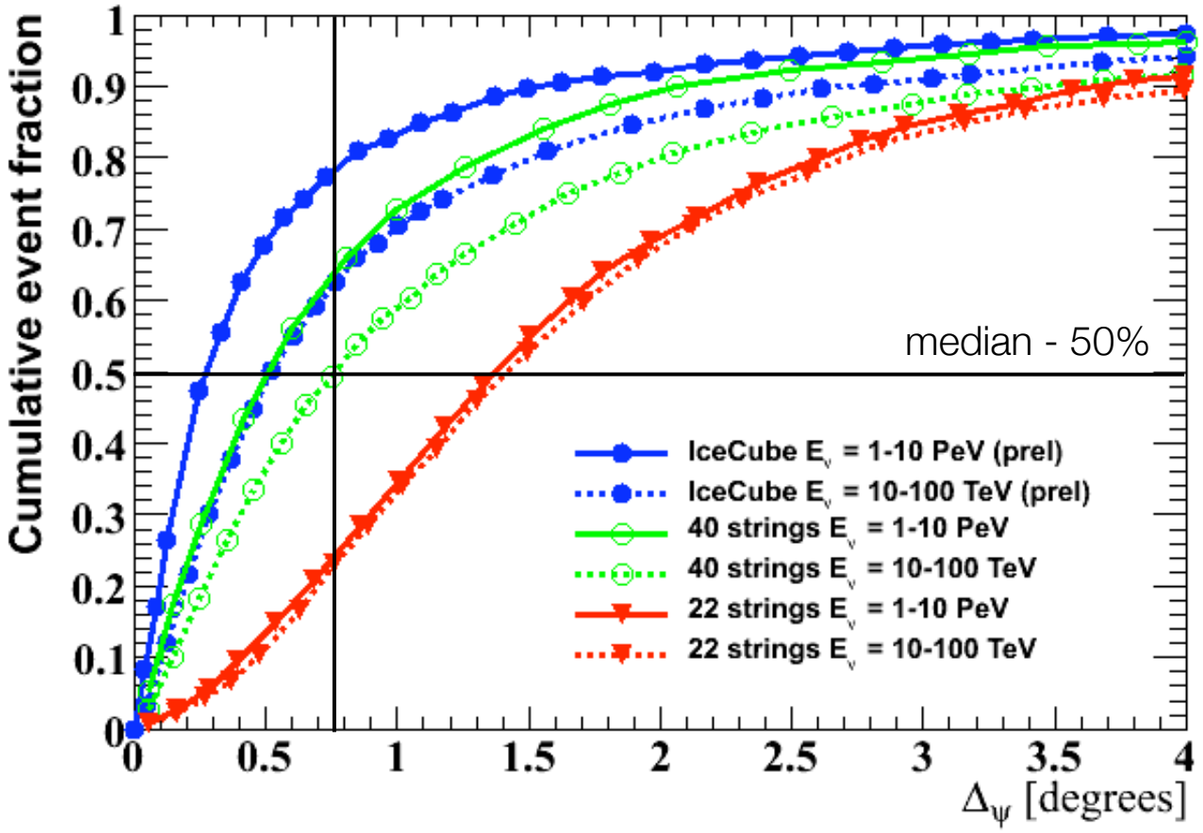
Flux $\sim E_p^{-2}$ **(Fermi acceleration)**

protons @ knee produce ~ 300 TeV γ rays

neutrino and gamma connection

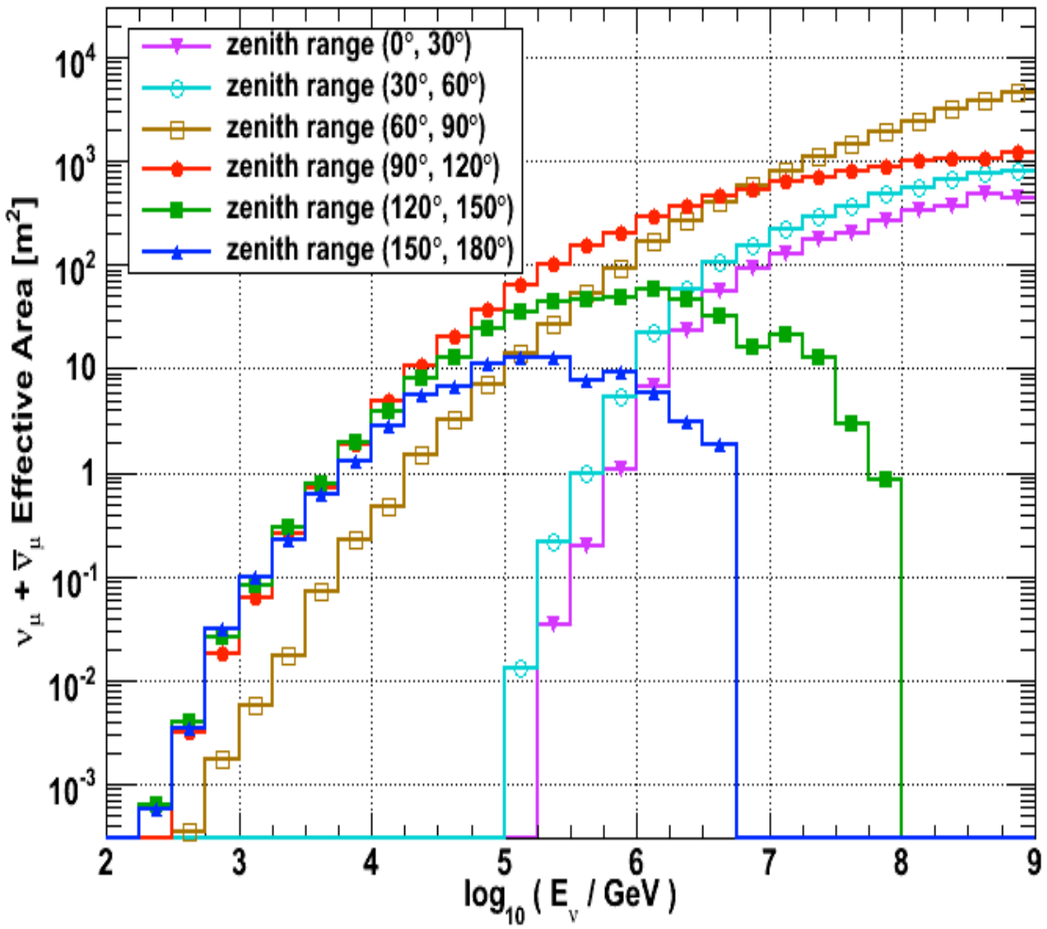
steady point sources

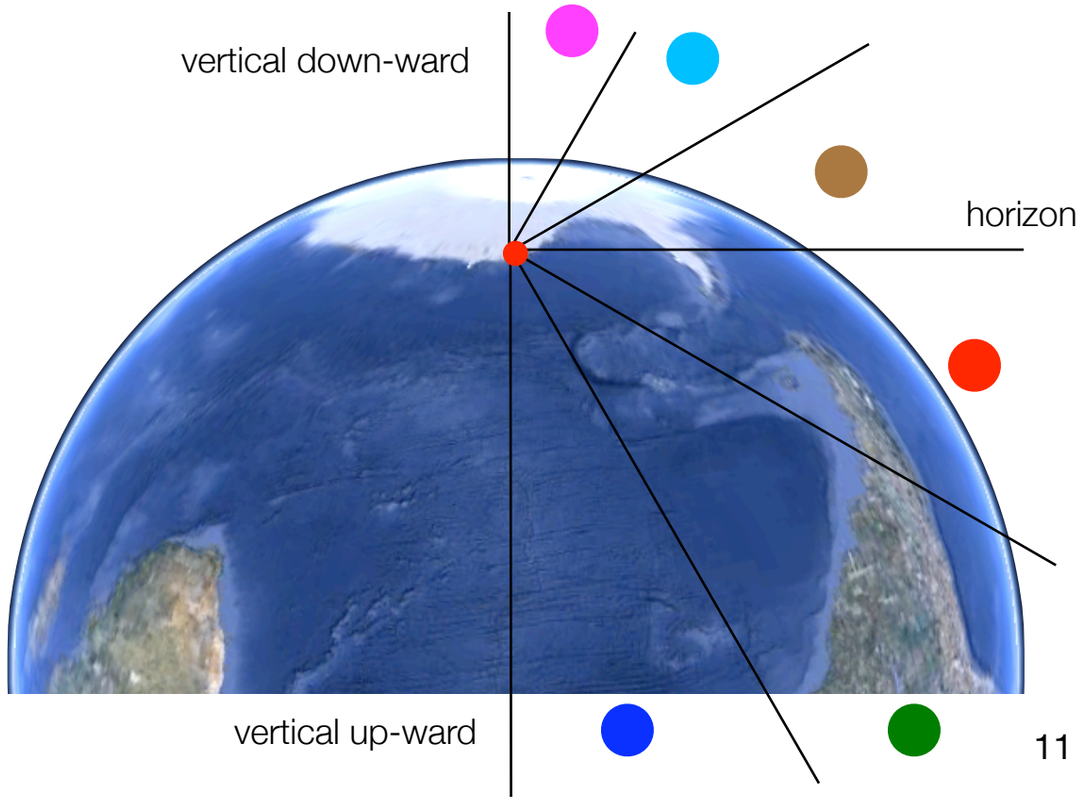
angular resolution



$$n_p(\nu) = T_{\text{live}} \cdot \int_{\Omega} \int_{E_\nu^{\min}}^{E_\nu^{\max}} A_{\text{eff}}^{\nu}(E_\nu, \delta) \frac{d\Phi_\nu}{d\Omega dE_\nu} d\Omega dE_\nu$$

neutrino effective area for IceCube 40





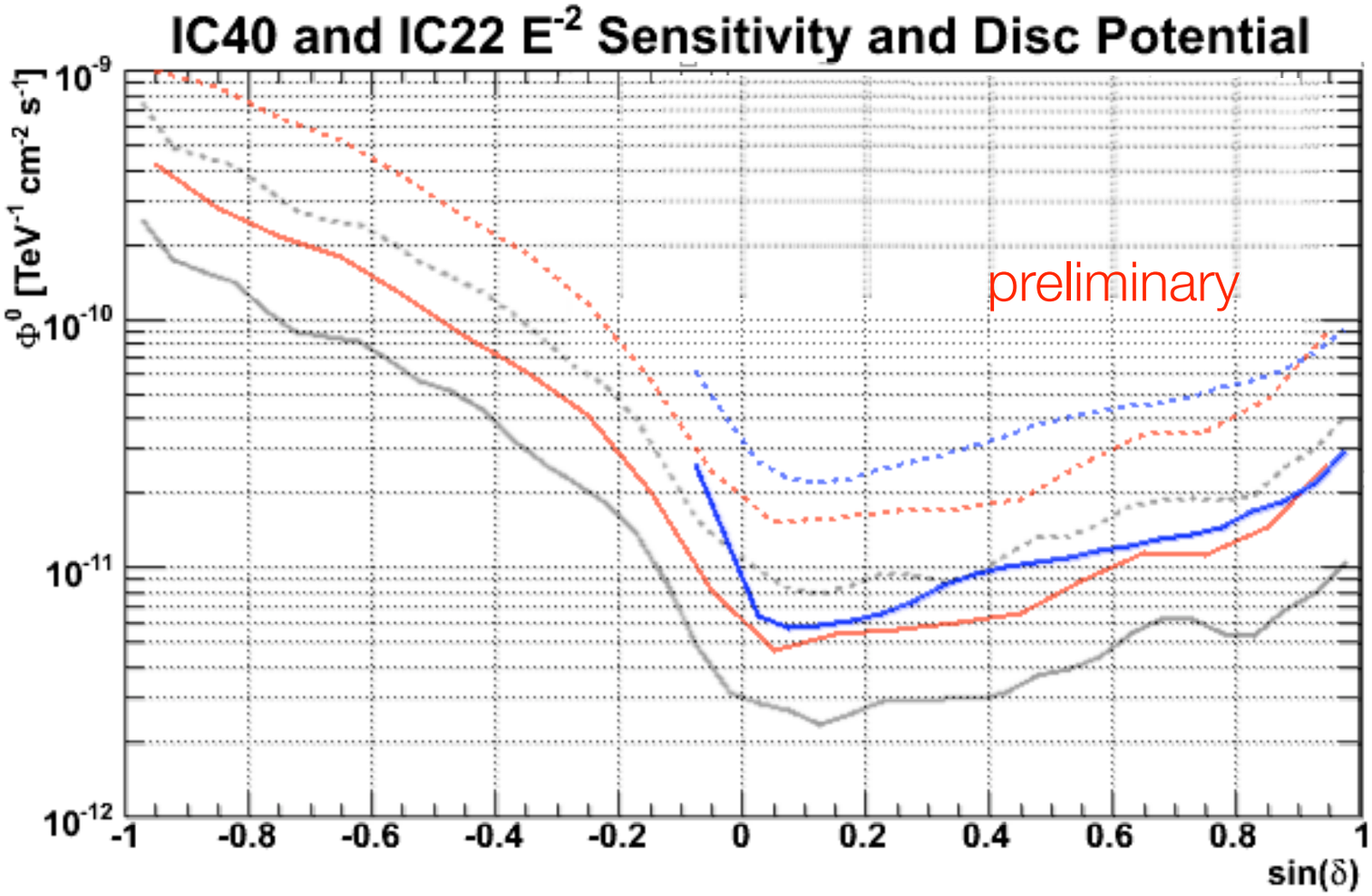
steady point sources

J Dumm, C Finley, T Montaruli

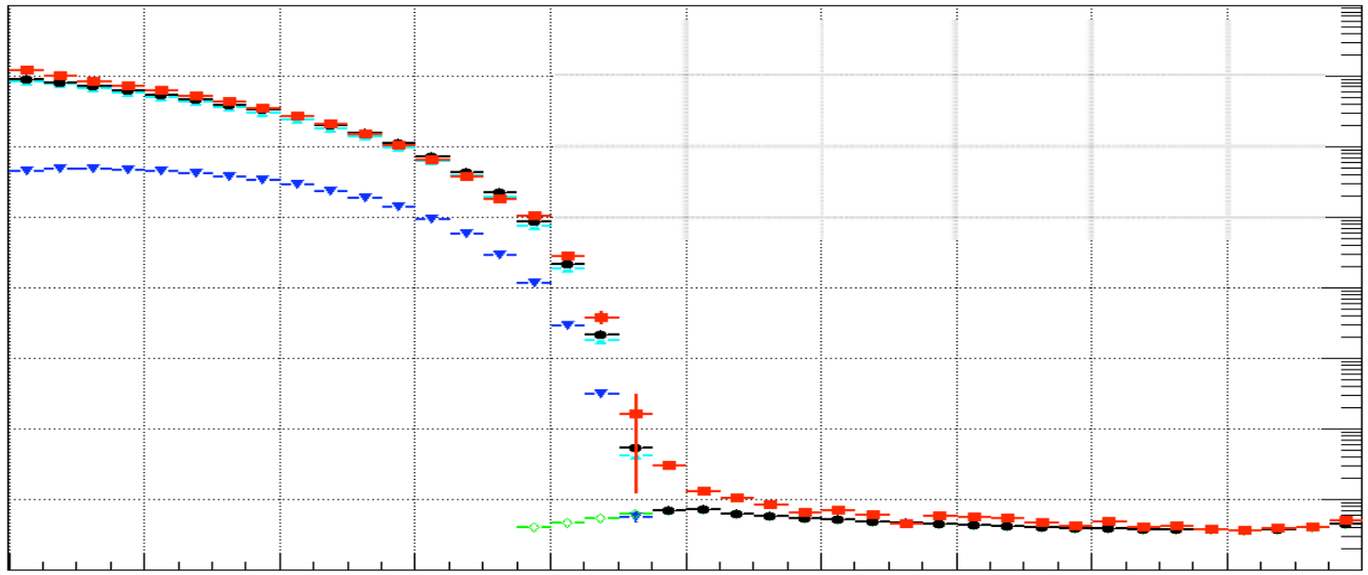
IC22 (275.7 d) : sensitivity
discovery potential

IC40 (175.5 d) : sensitivity
discovery potential

IC40 (275.6 d) : sensitivity
discovery potential



background



down-ward muons

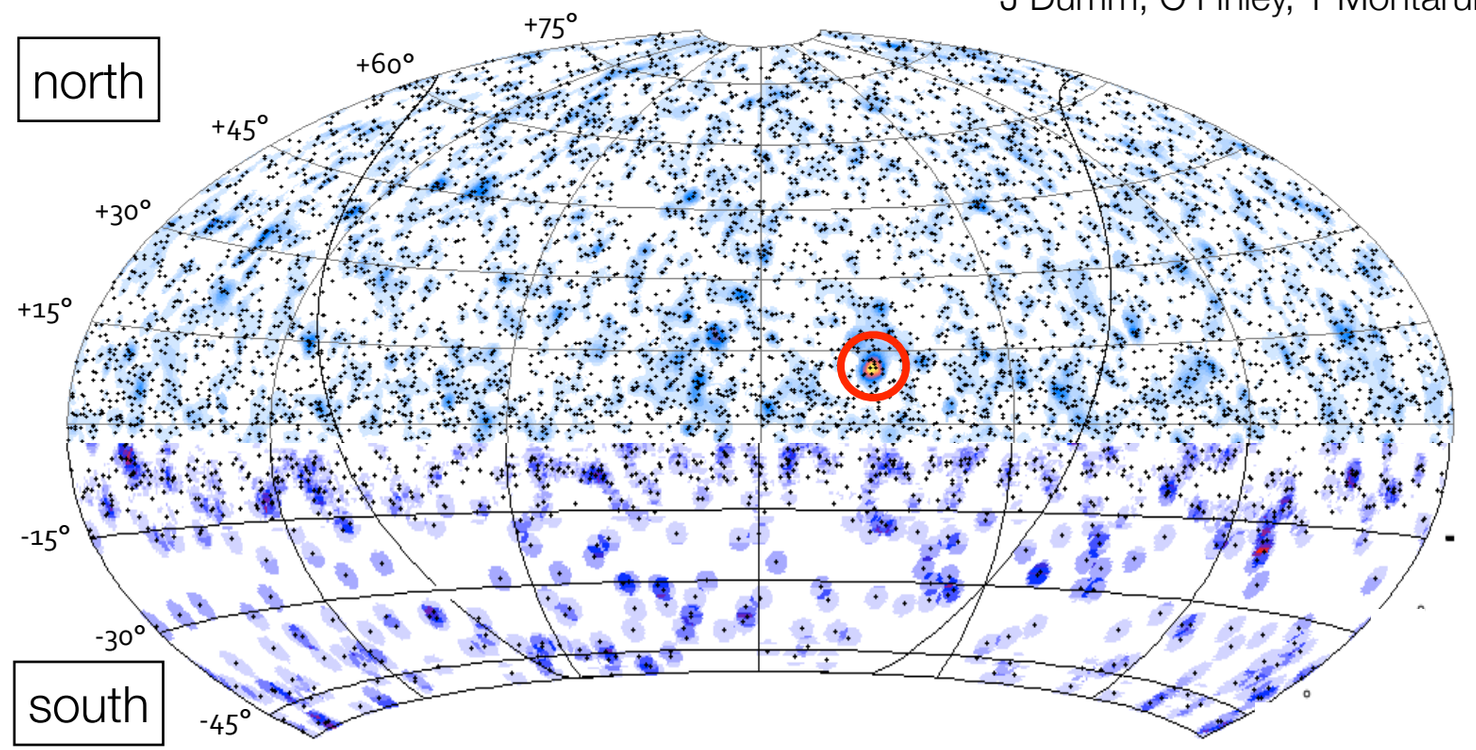
up-ward neutrinos

steady point sources

IceCube 22 strings (2007)

Abbasi et al., Astrophys.J.701:L47-L51 (2009), arXiv:0905.2253

J Dumm, C Finley, T Montaruli



R Lauer, E Bernardini

Abbasi et al., Phys.Rev.Lett.103:221102 (2009), arXiv:0911.2338

○ hottest spot @ α = 153.4°
δ = 11.04°

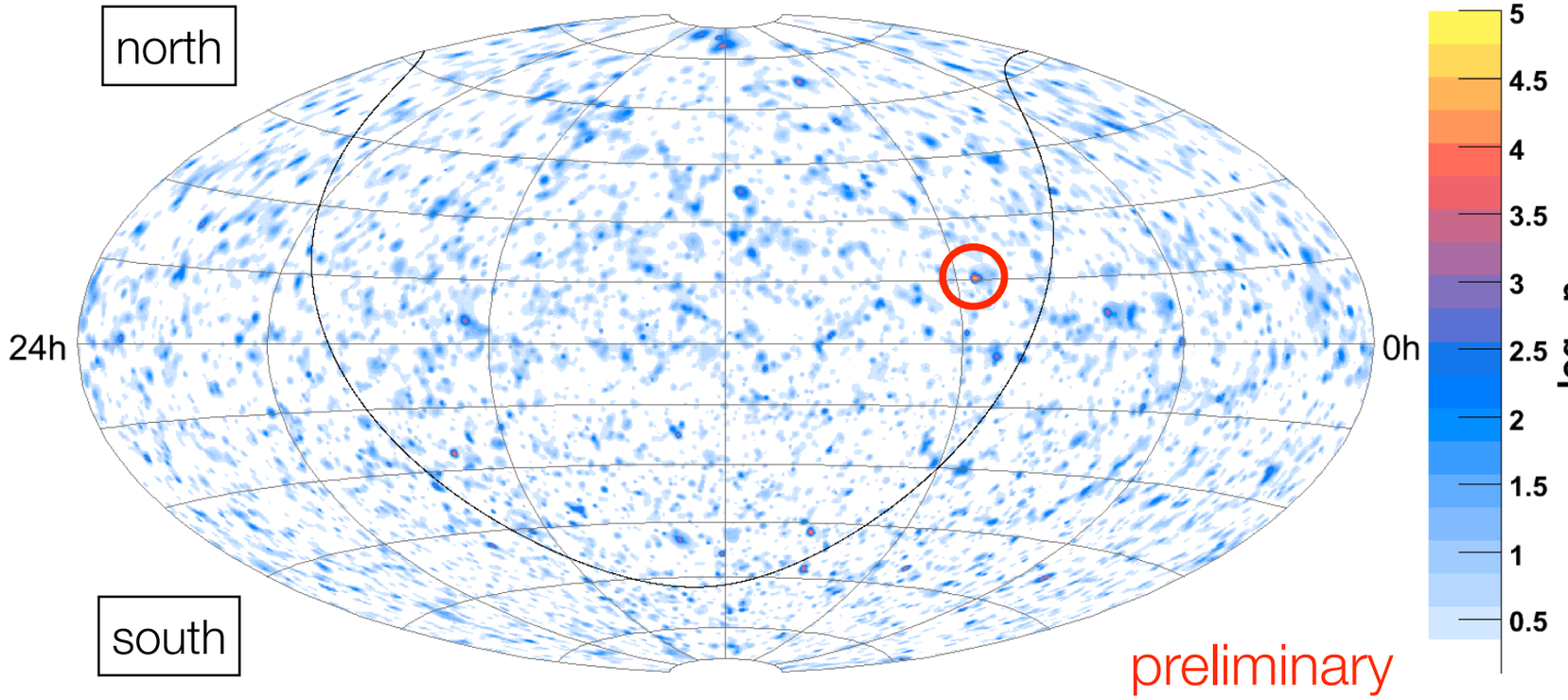
- post-trial -$\log_{10}$(p-value) = 1.34%
- = 2.2 σ

- 275.7 days livetime
- northern hemisphere
  - up-going atmospheric neutrino-induced muons
- southern hemisphere
  - down-going high energy muons up to -50°

steady point sources

IceCube 40 strings (6 months of 2008)

J Dumm, C Finley, T Montaruli



- hottest spot @ α = 114.95°
  δ = 15.35°
- pre-trial $-\log_{10}$(p-value) = 4.43
- best-fit # of source events = 7.1
- best-fit spectral index = 2.1
- all-sky p-value = 61%

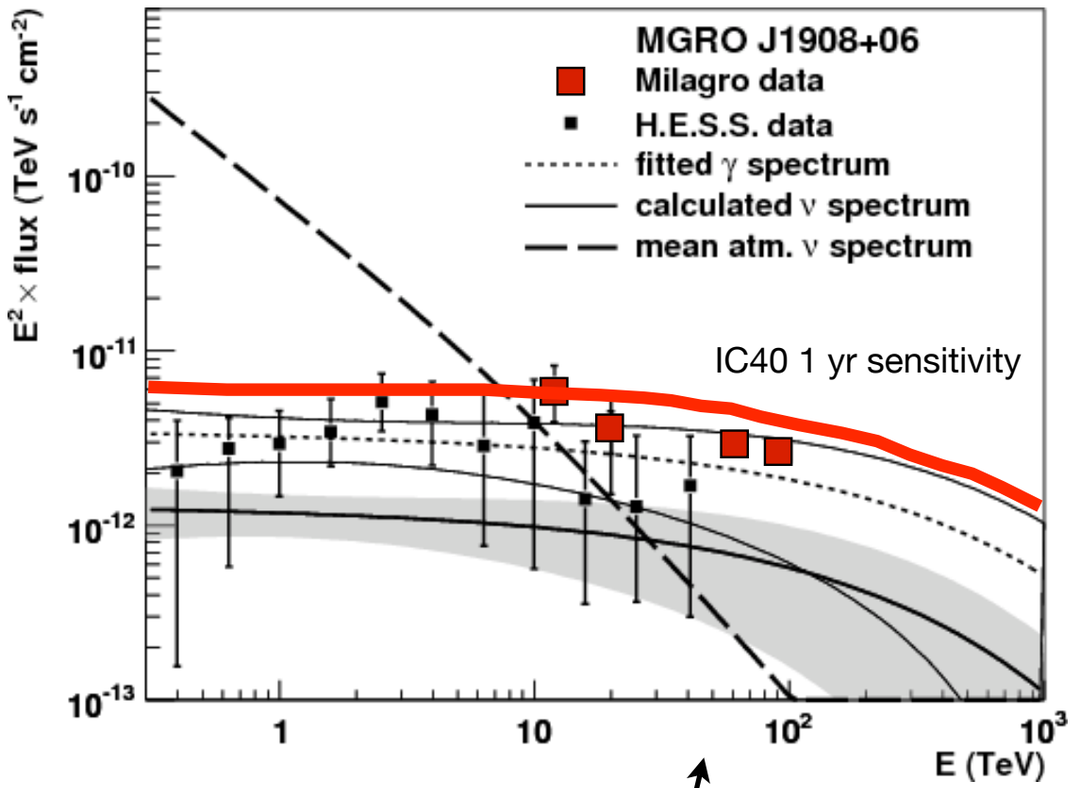
- 175.5 days livetime
- northern hemisphere
  - 6,796 up-going atmospheric neutrino-induced muons
- southern hemisphere
  - 10,981 down-going high energy muons
  - 10^{-5} background rejection through energy cut ($\gtrsim$ 100 TeV)
  - $\mu_\downarrow / \mu_\uparrow \sim 10^6$

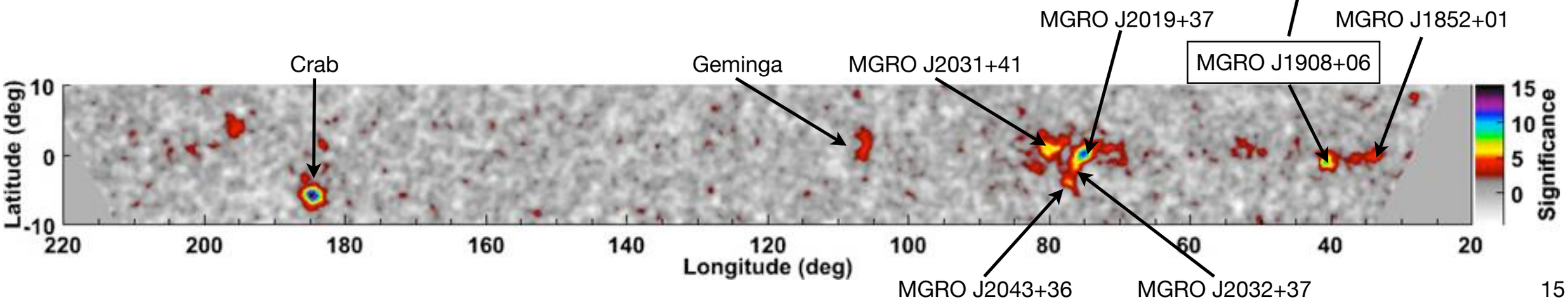
It is believed that Galactic accelerators are powered by the conversion of 10^{50} erg of energy into particle acceleration by diffusive shocks associated with young (1000–10,000 year old) supernova remnants expanding into the interstellar medium [1].

searching for point sources

- search for extended sources ?
  - CR interacting in molecular clouds
  - CR from galactic plane
- 1 yr of IC86 to improve > 2x
  - multi-wavelength
  - time variabilities

A. Kappes, F. Halzen, A.O'Murchadha, NIM A 602 (2009) 117

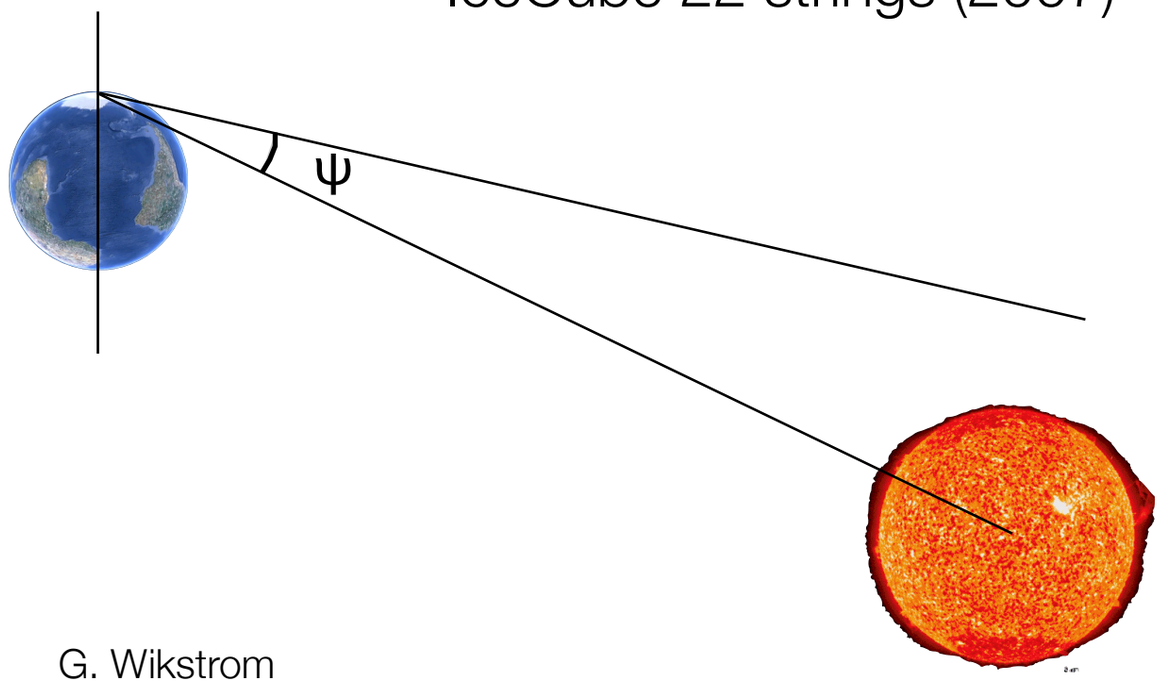




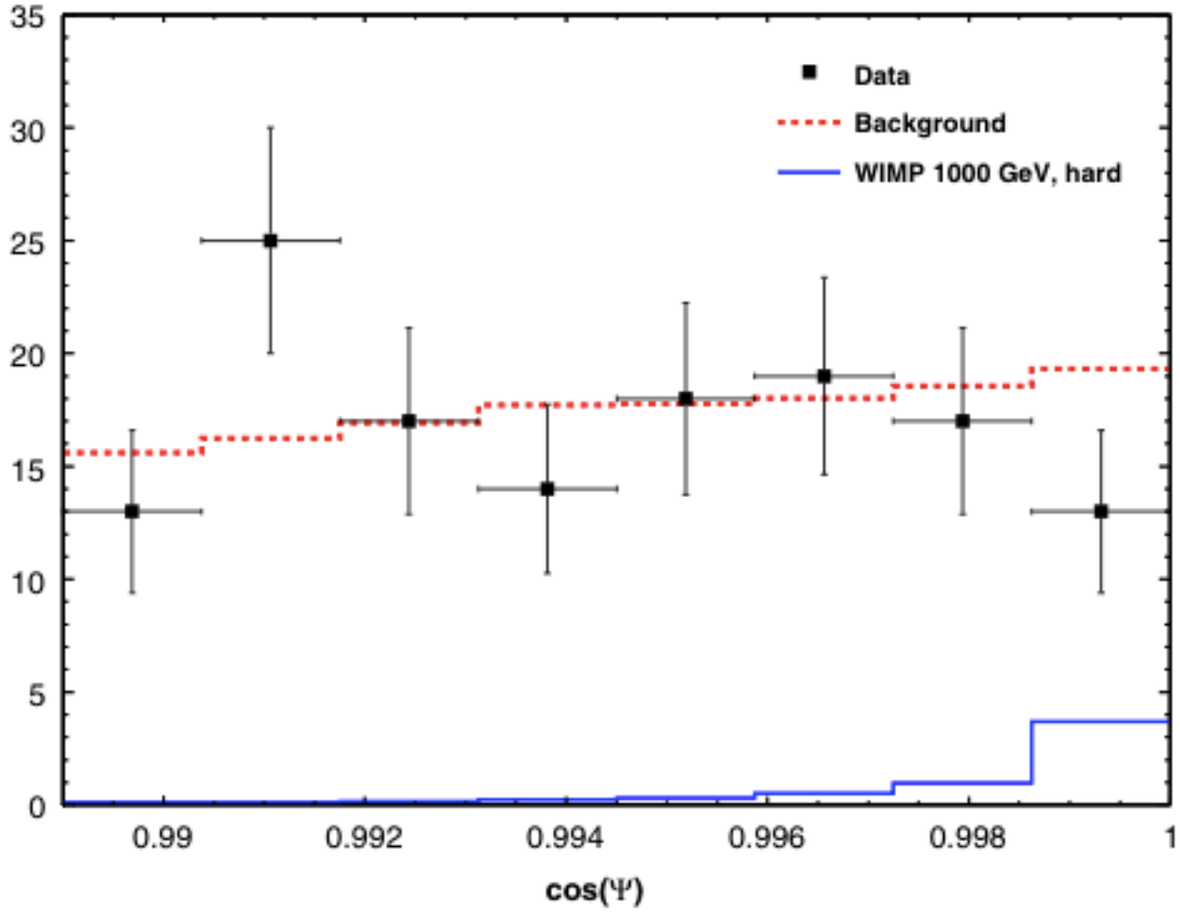
search for dark matter

- WIMP (χ) annihilation in the Sun

IceCube 22 strings (2007)



G. Wikstrom



search for dark matter

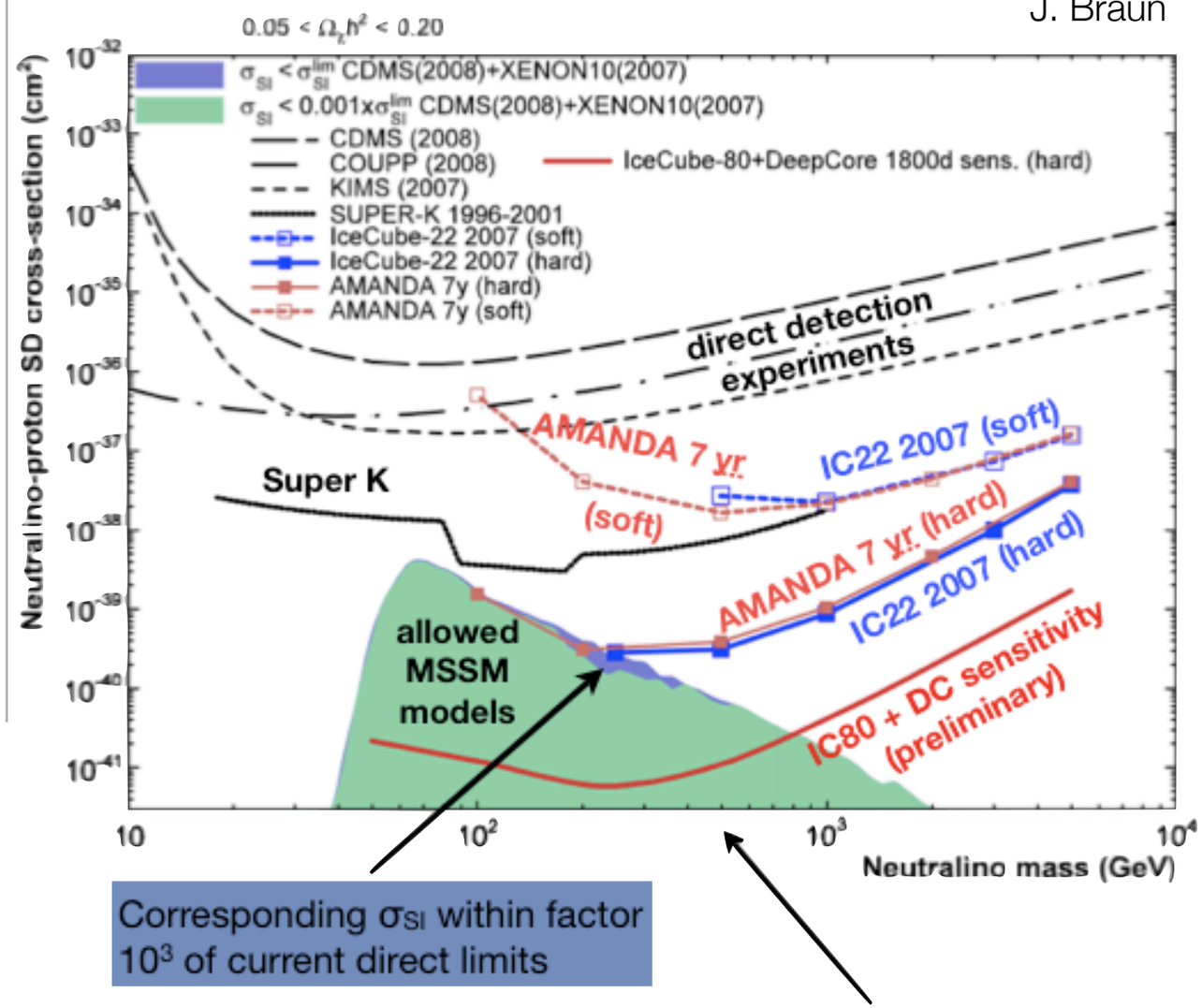
- WIMP (χ) annihilation in the Sun
  - muon flux
  - spin dependent cross section

- σ_{SI} well constraint by direct detection experiments
- require models of solar DM distribution & annihilation modes : W^+W^- (hard), $b\bar{b}$ (soft)

Abbasi et al., Phys.Rev.Lett.102:201302 (2009), arXiv:0902.2460

G. Wikstrom, M. Danninger, C. de los Heros

J. Braun



search for dark matter

- WIMP from galactic halo

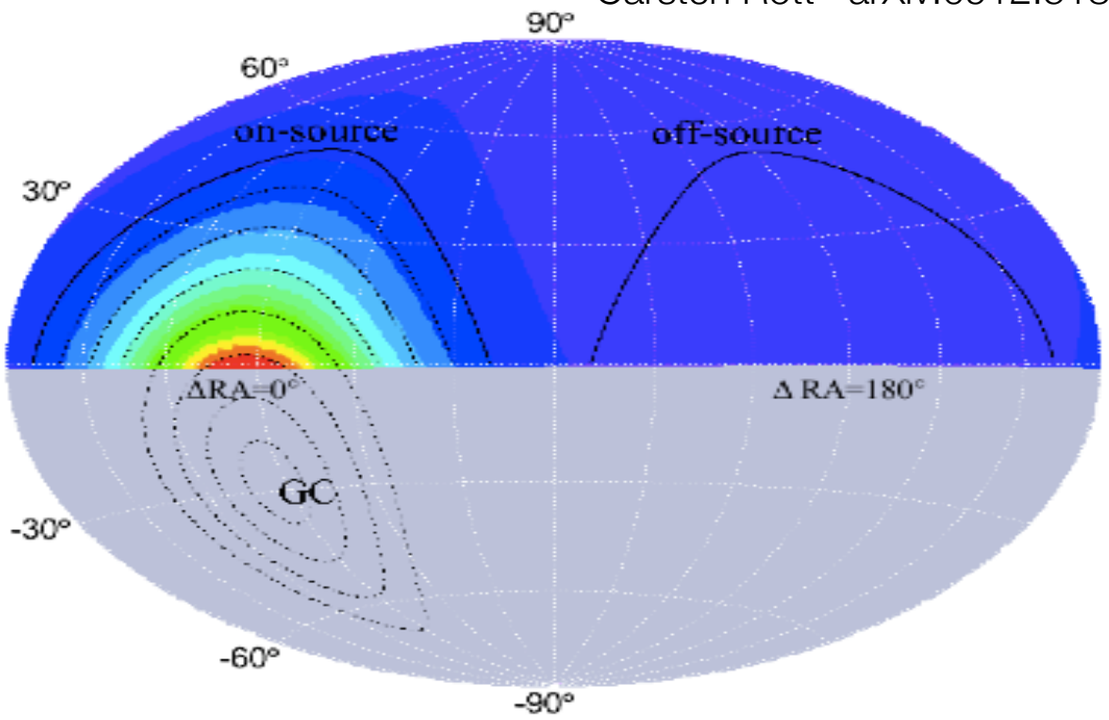
halo models

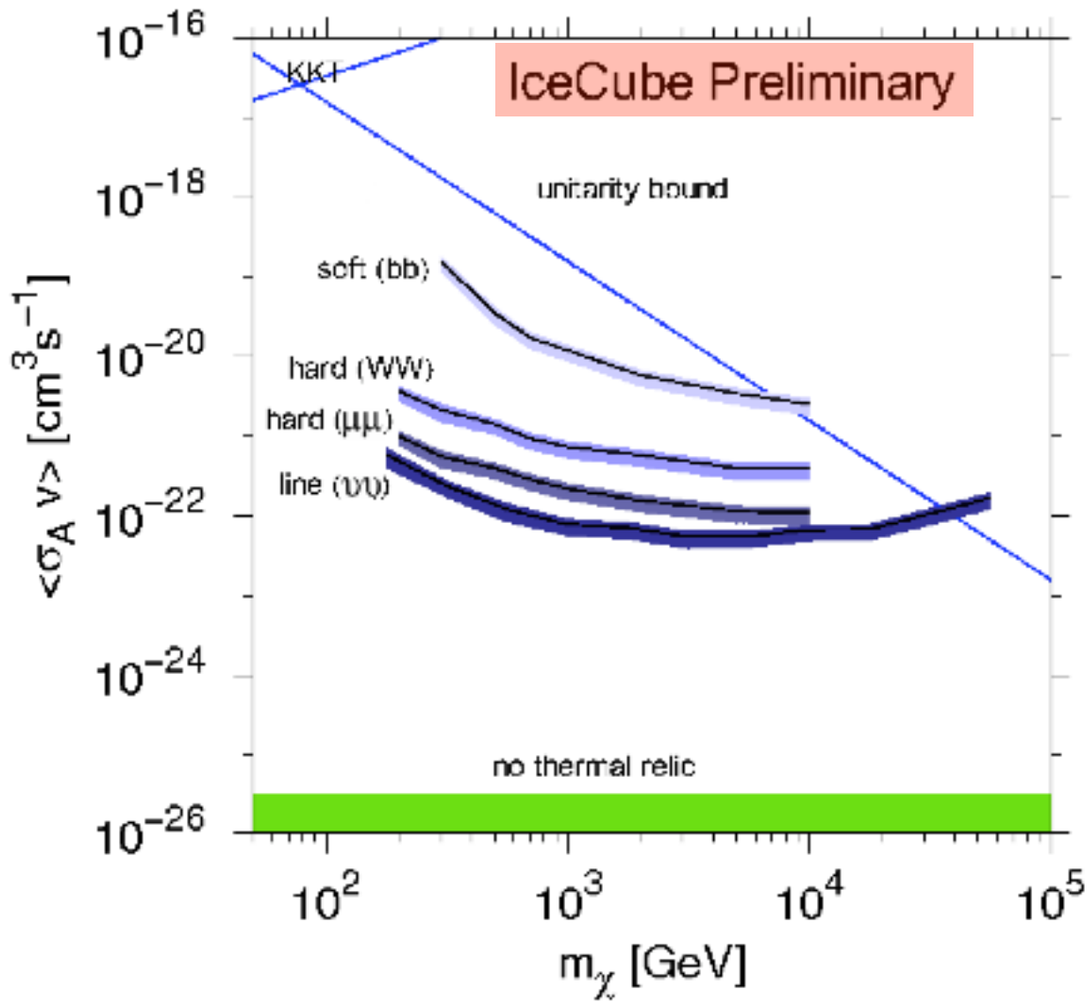
$$\frac{d\phi_\nu}{dE} = \frac{<\sigma_A v>}{2} J(\psi) \frac{R_{sc}\rho_{sc}^2}{4\pi m_\chi^2} \frac{dN_\nu}{dE}$$

measurement constrain SUSY models

improvement expected with Deep Core (low energy extension) & with further event selection optimization (@ lower energy)

Carsten Rott arXiv:0912.5183





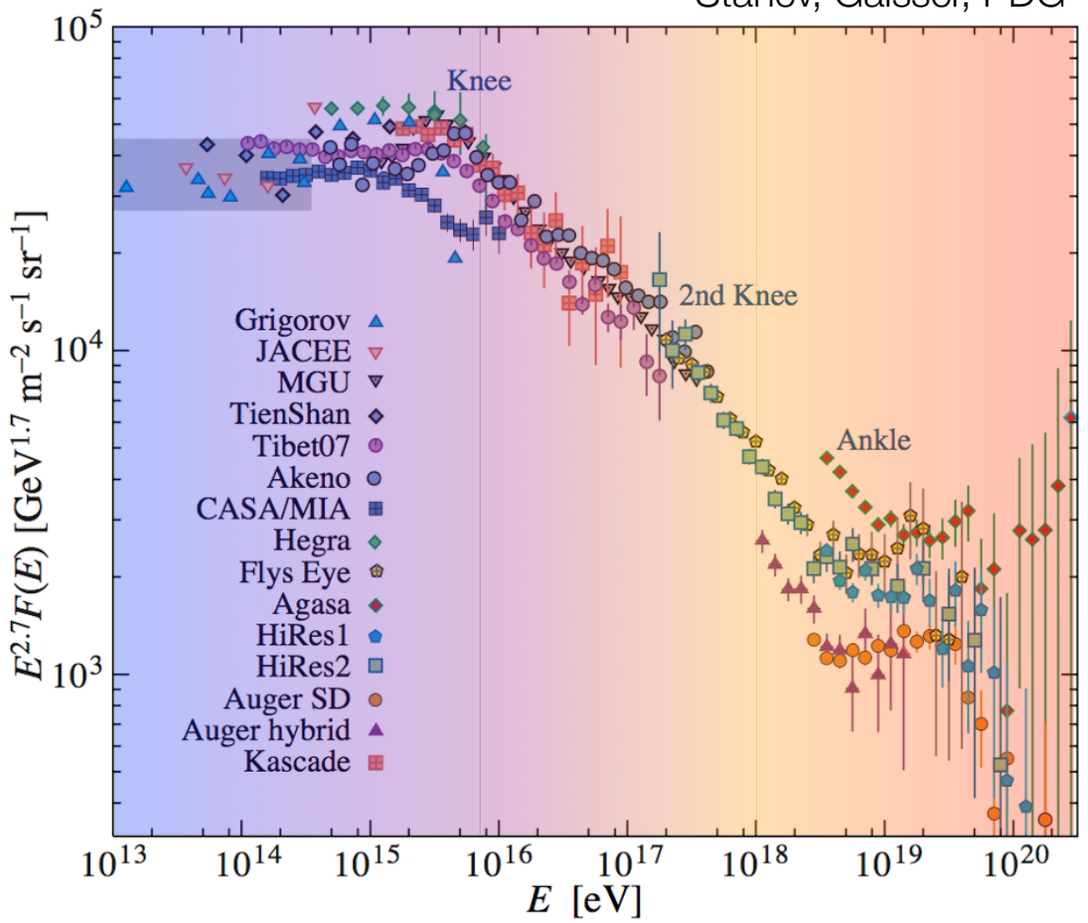
cosmic rays

- galactic CR believed to be accelerated in expanding shock waves initiated by supernova explosions

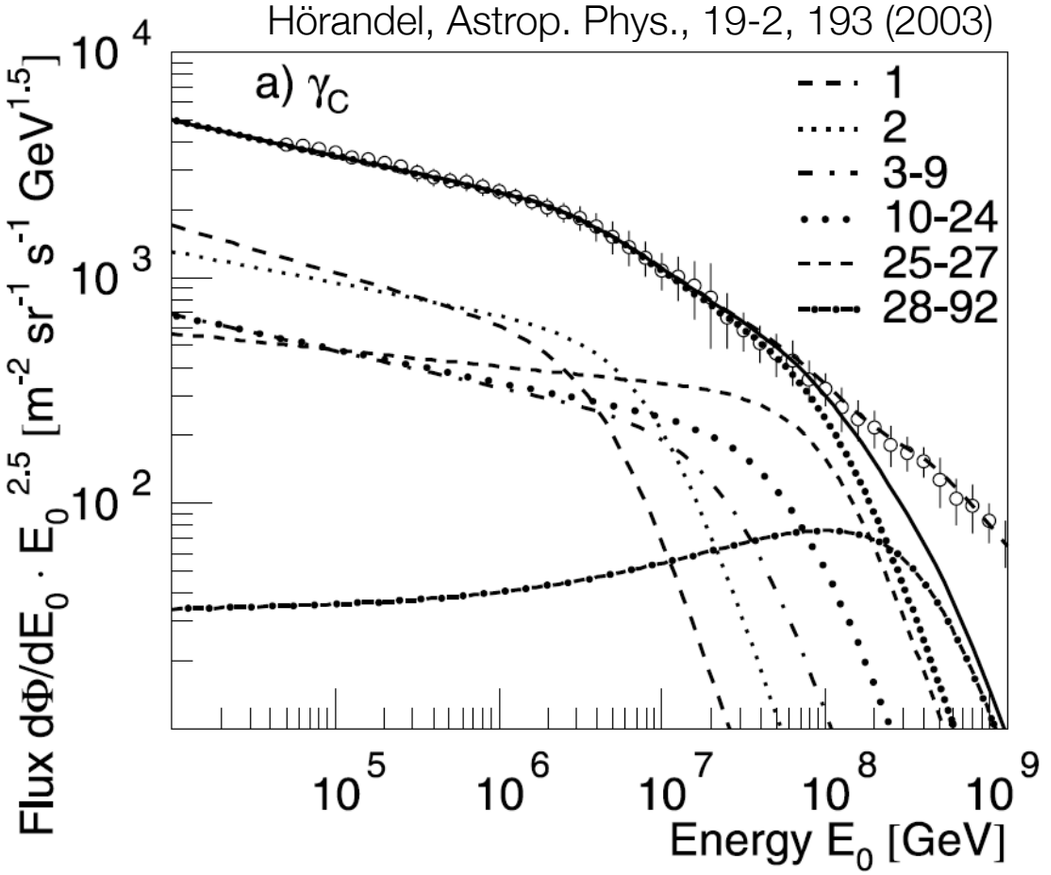
- SNe have enough power to sustain the CR population against escape from the Galaxy and energy losses, if there is a mechanism for channeling ~ O(1)% of the SN mechanical energy release into relativistic particles

- diffuse shock acceleration can accelerate CR up to $3 \cdot 10^{15} \cdot Z$ eV

Stanev, Gaisser, PDG



Hörandel, Astrop. Phys., 19-2, 193 (2003)



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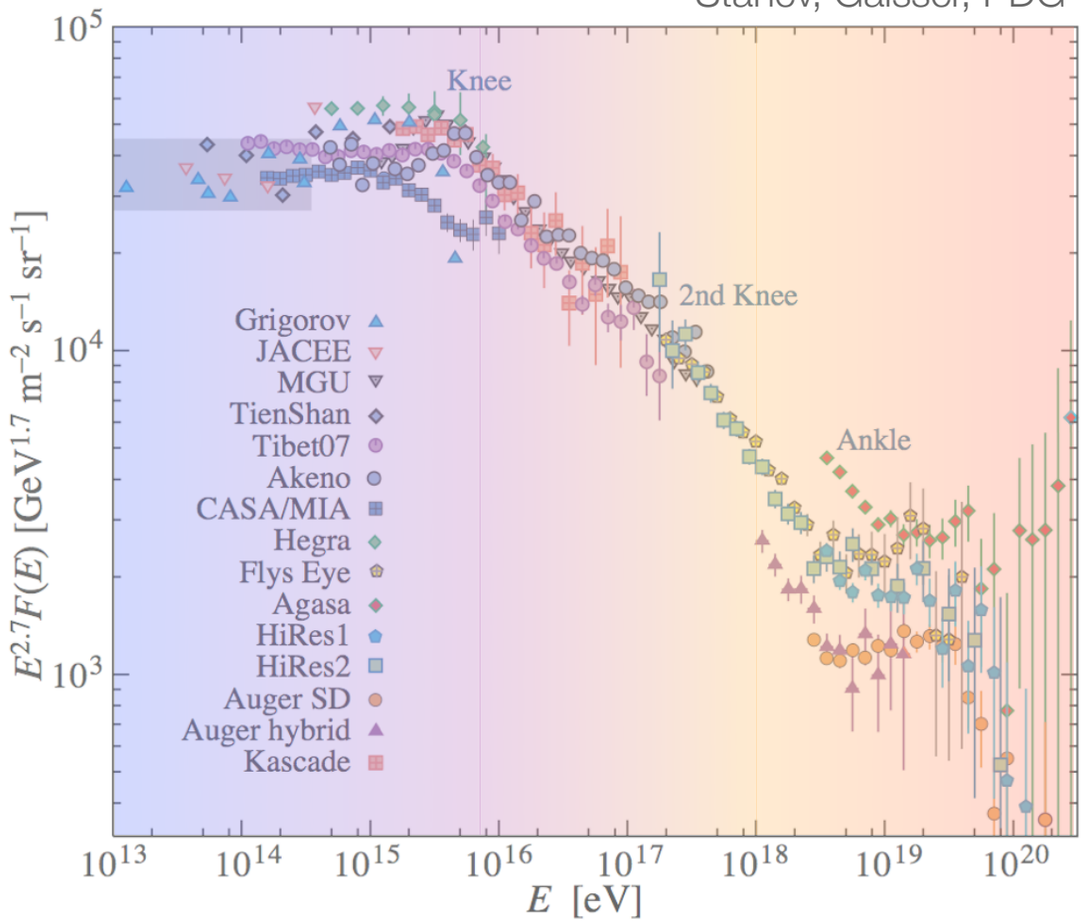
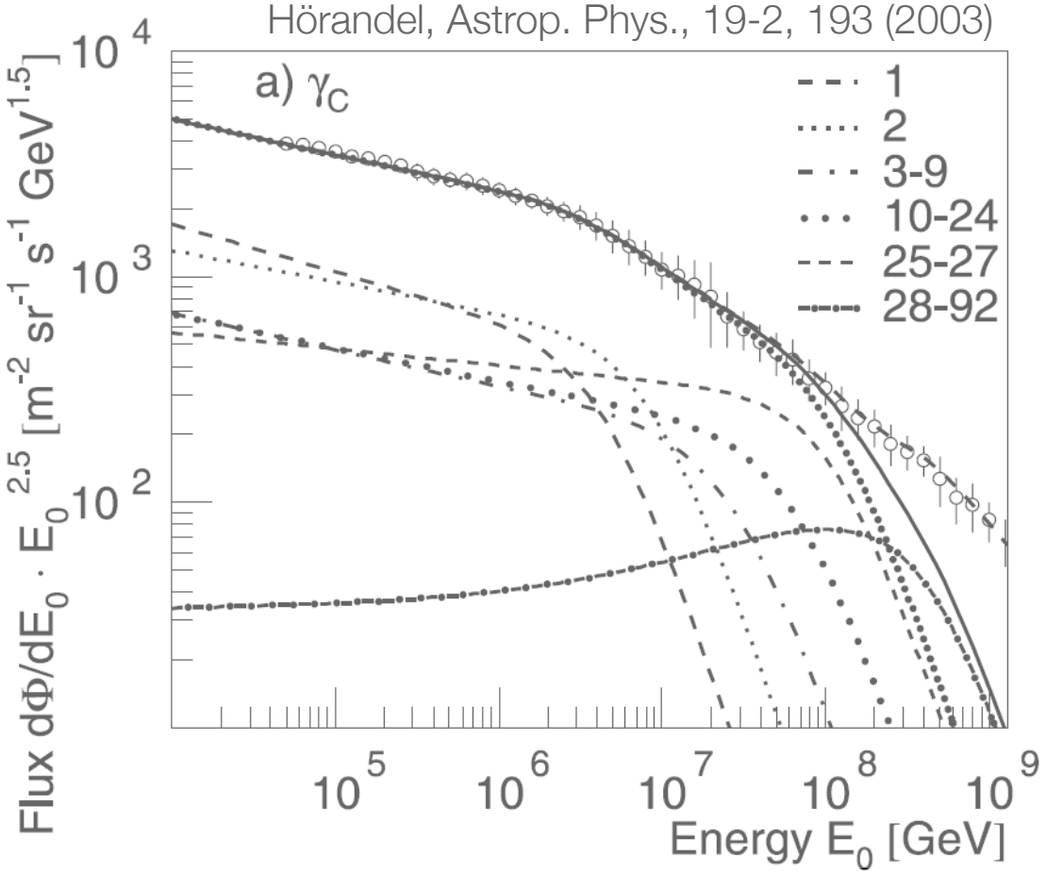
- diffuse shock acceleration can accelerate CR up to $3 \cdot 10^{15} \cdot Z$ eV

- galactic CR expected to be isotropic : scrambled by galactic magnetic field over very long time

Stanev, Gaisser, PDG

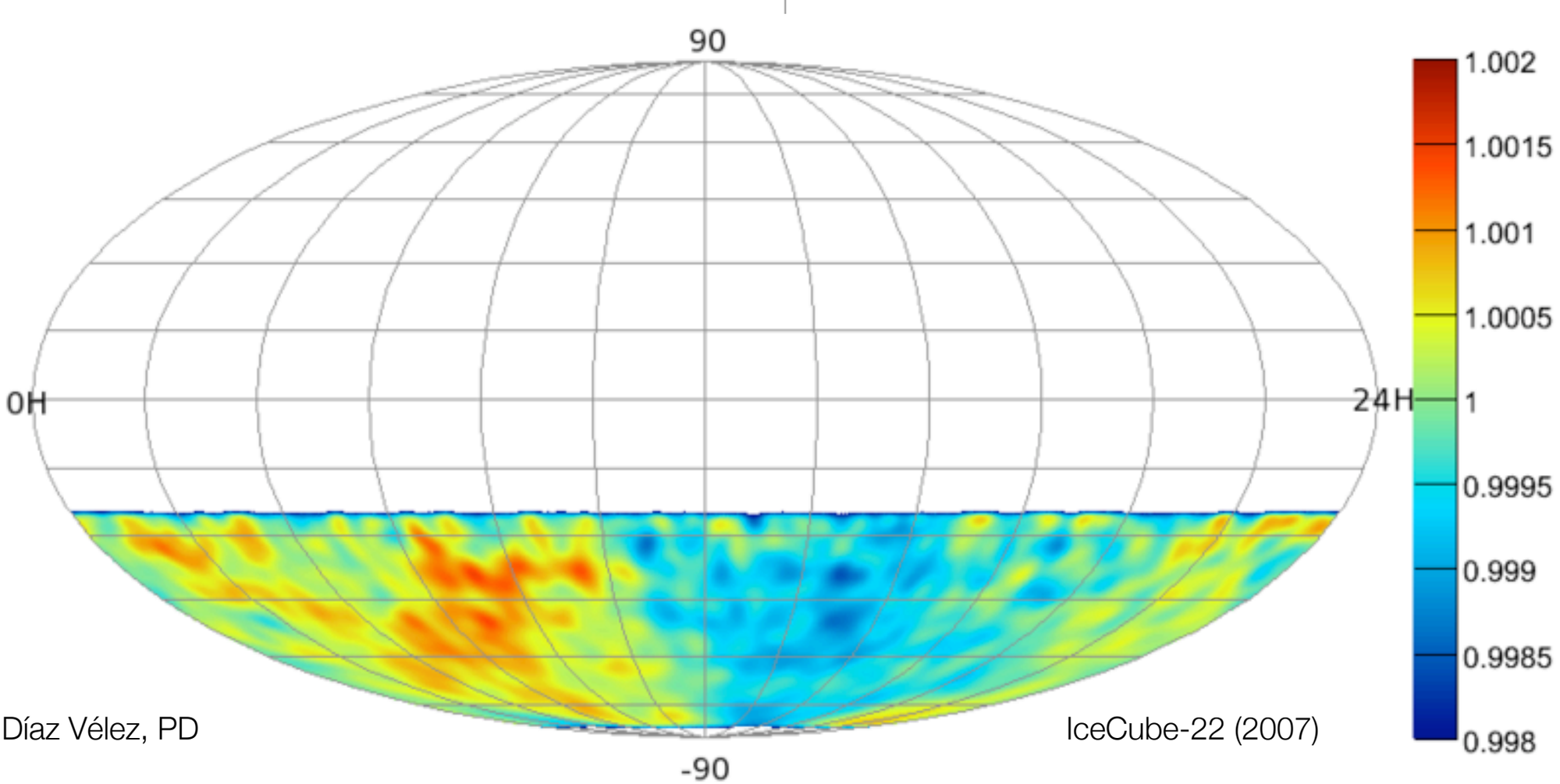


Hörandel, Astrop. Phys., 19-2, 193 (2003)



cosmic rays anisotropy

- measure relative CR variation in individual declination bands
- arrival direction anisotropy of O(10^{-4})



cosmic rays anisotropy

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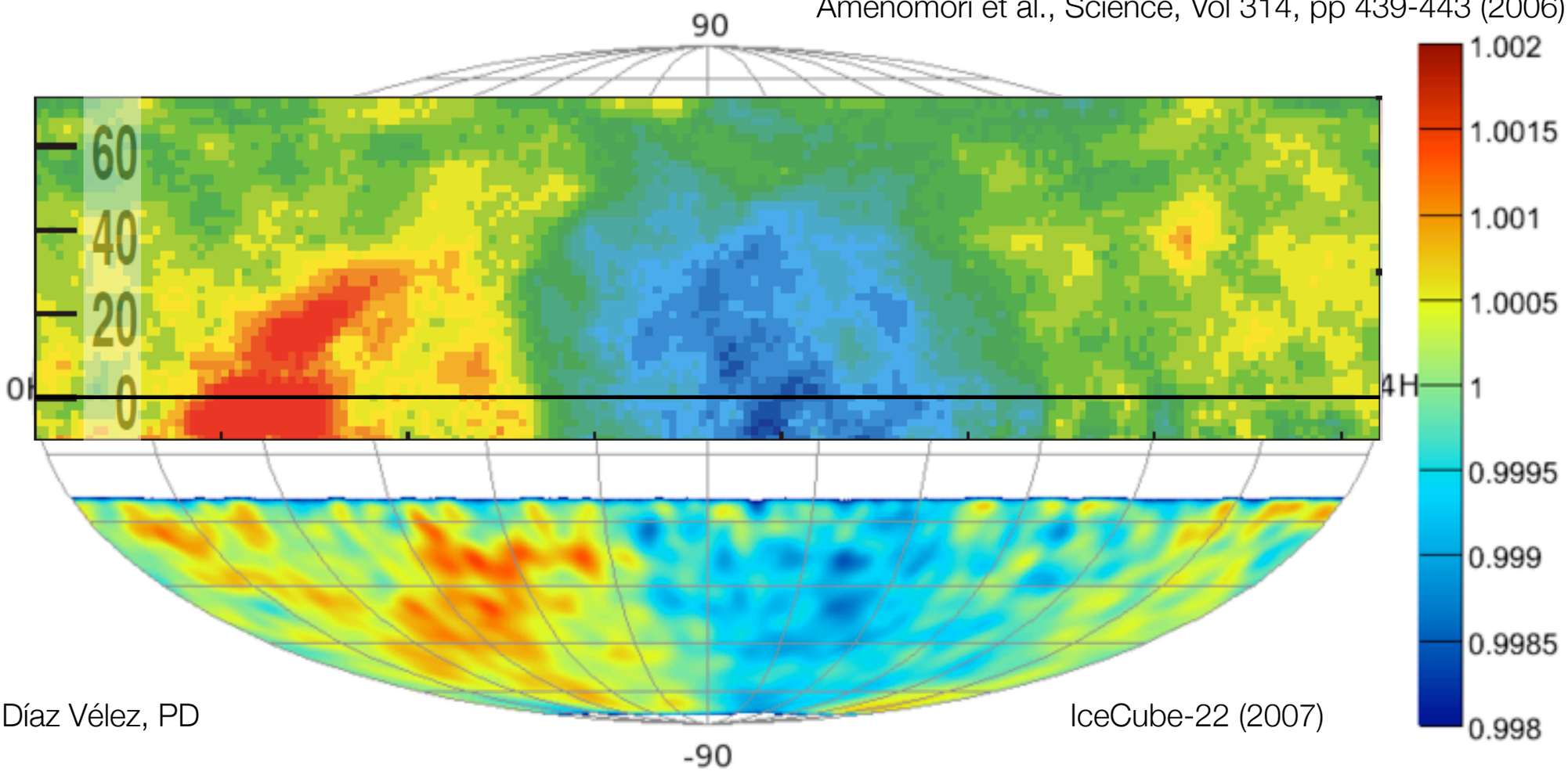
Amenomori et al., Science, Vol 314, pp 439-443 (2006)



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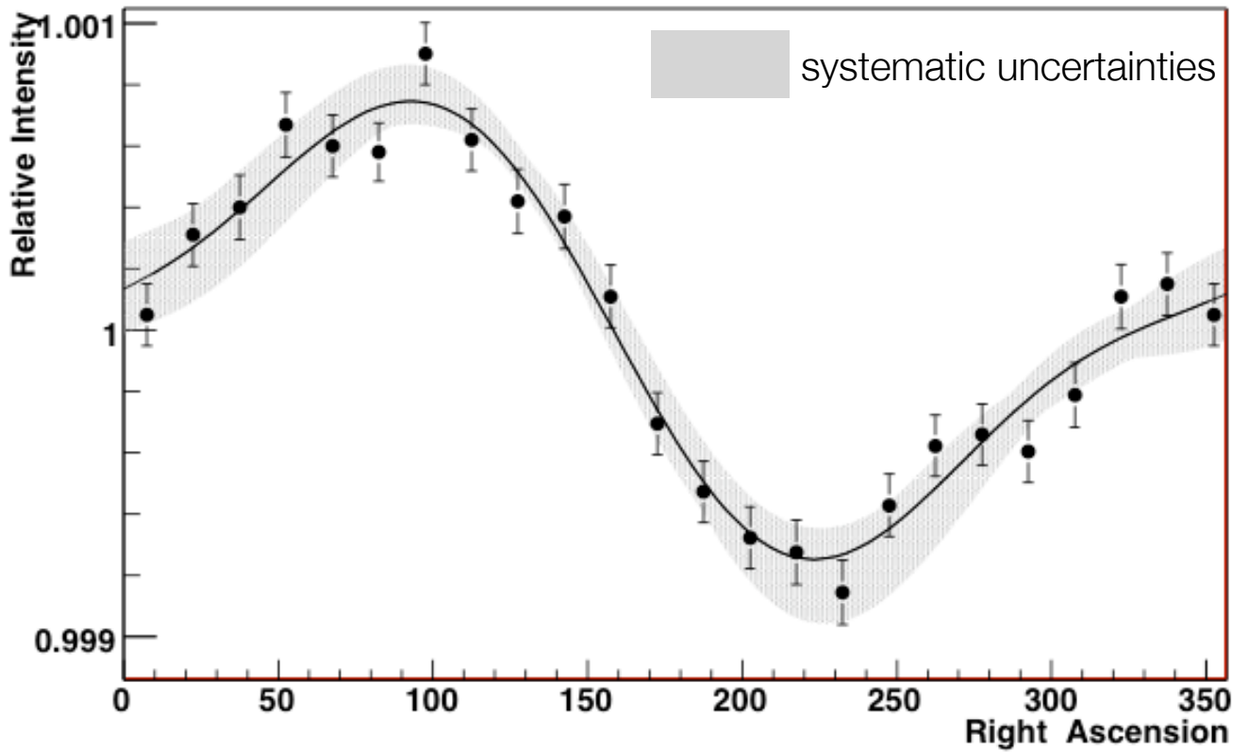
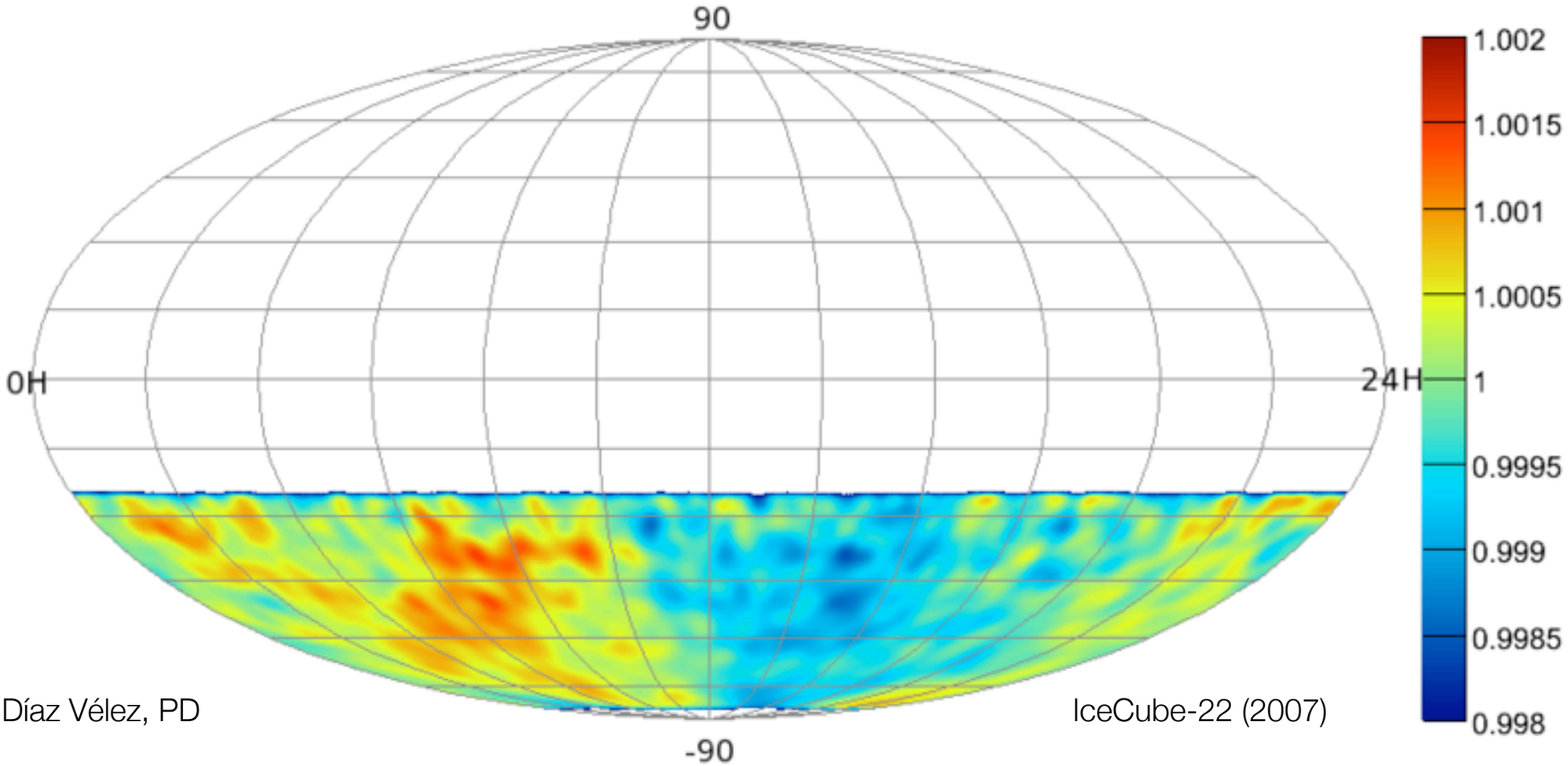
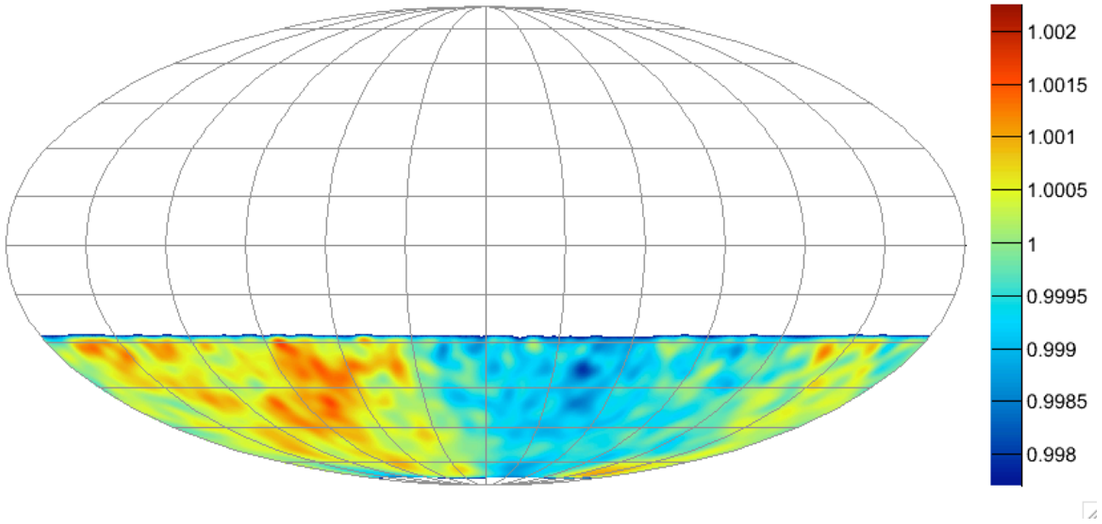
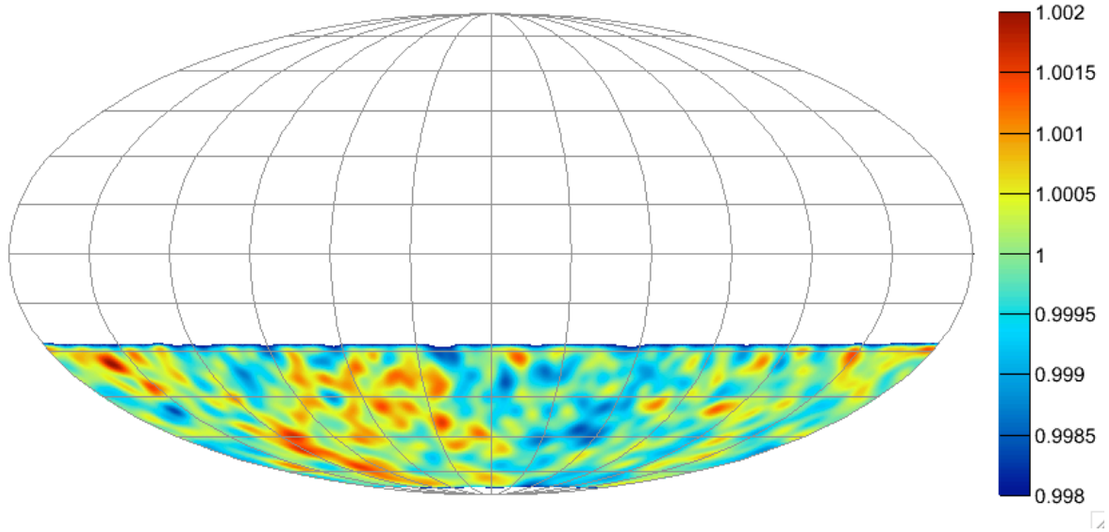
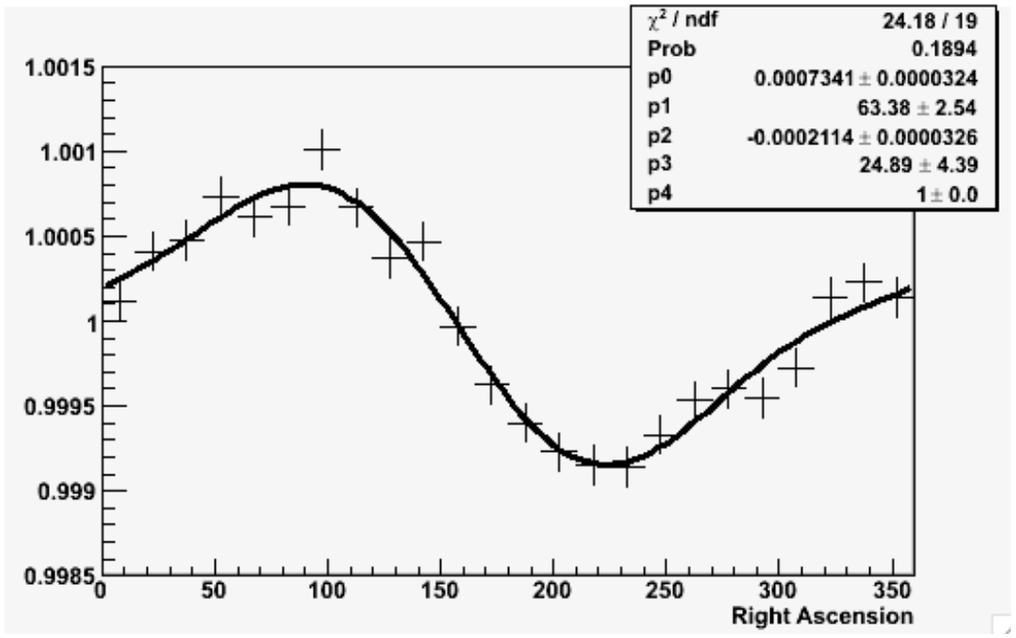


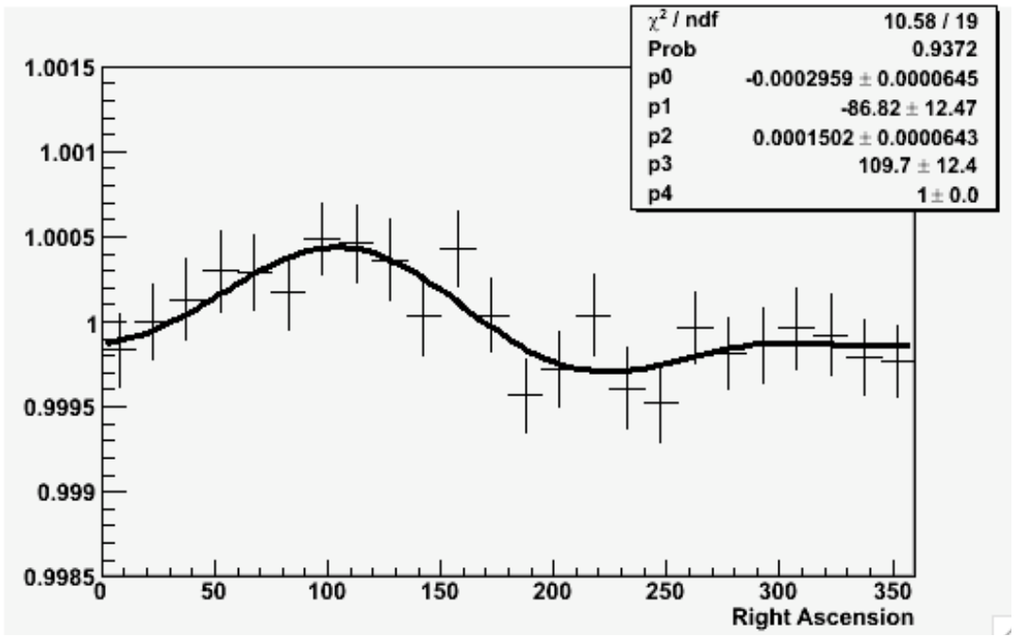


preliminary









E_{median} = 12 TeV

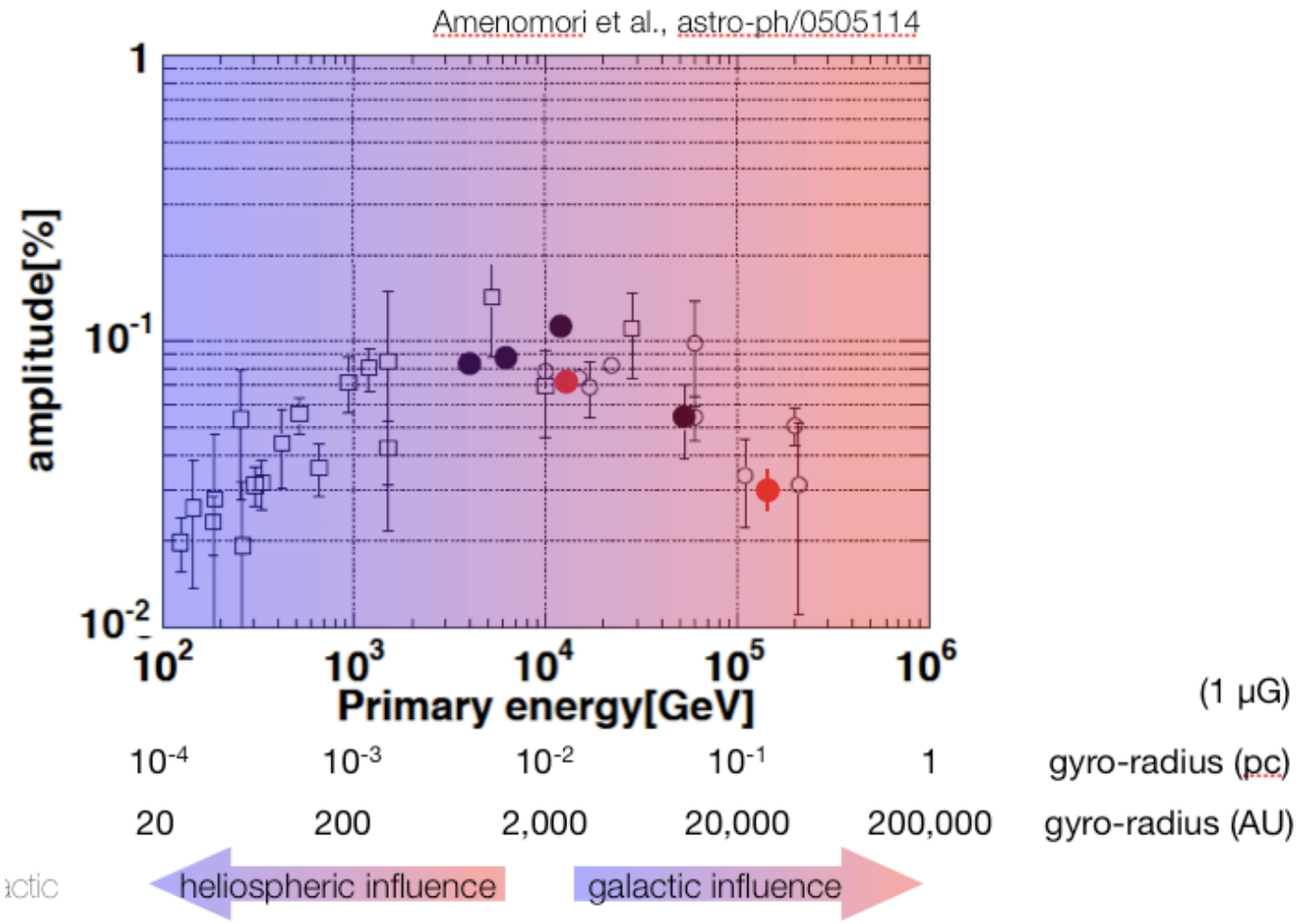
E_{median} = 126 TeV

IceCube-22 : anisotropy persists at high energy

R Abbasi, JC Díaz Vélez, PD

cosmic ray anisotropy

- probe for local environment
  - heliosphere ≲ TeV
  - interstellar matter ≳ TeV
- properties of interstellar magnetic field
  - galactic neighborhood (~ 1 pc)
  - diffusion of cosmic rays



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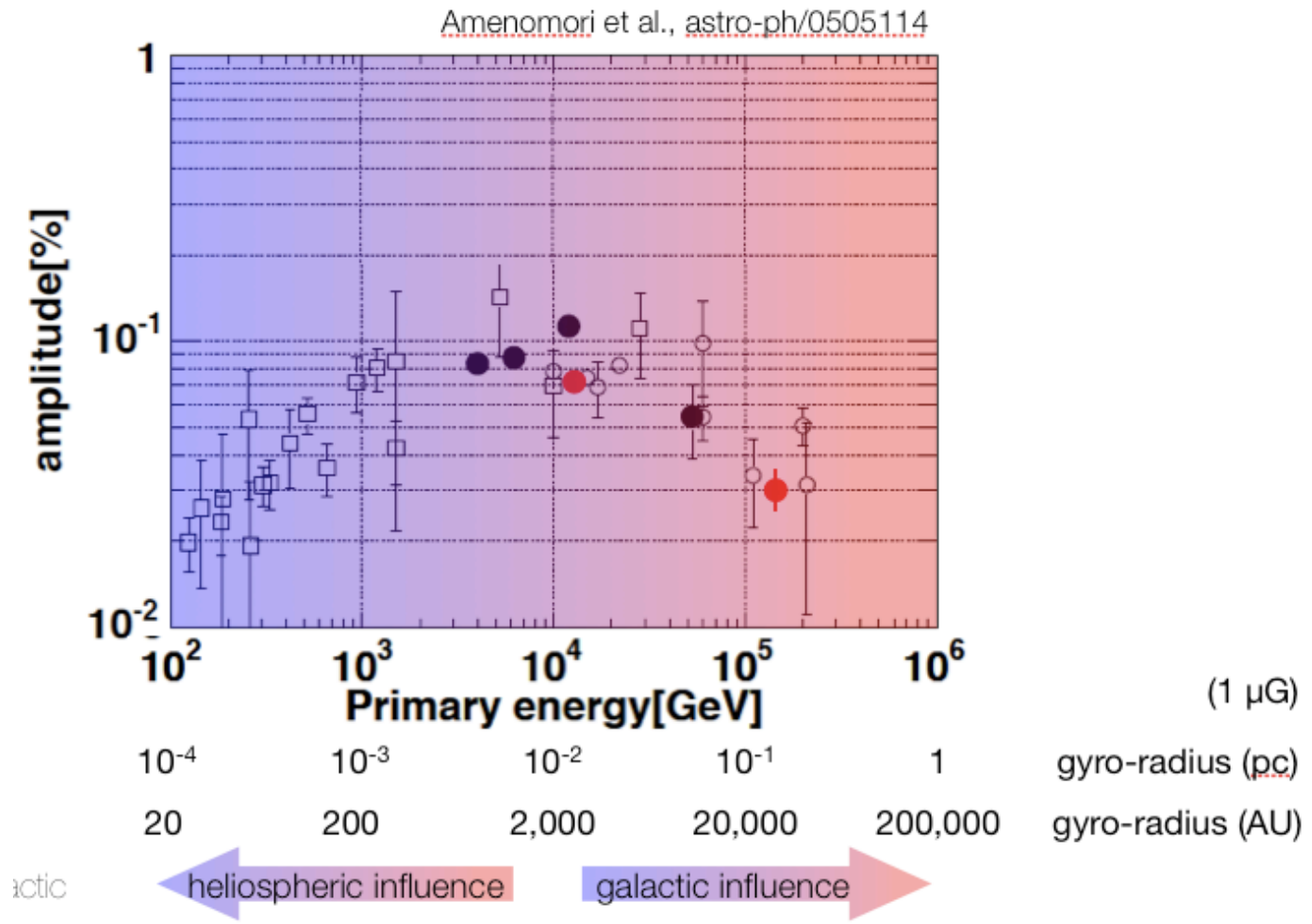
  - galactic neighborhood (~ 1 pc)
  - diffusion of cosmic rays



- connection to the origin of CR : contribution of nearby *recent* SN explosions
  - single source contribution to the knee of CR spectrum

arXiv:astro-ph/0601206, Erlykin & Wolfendale

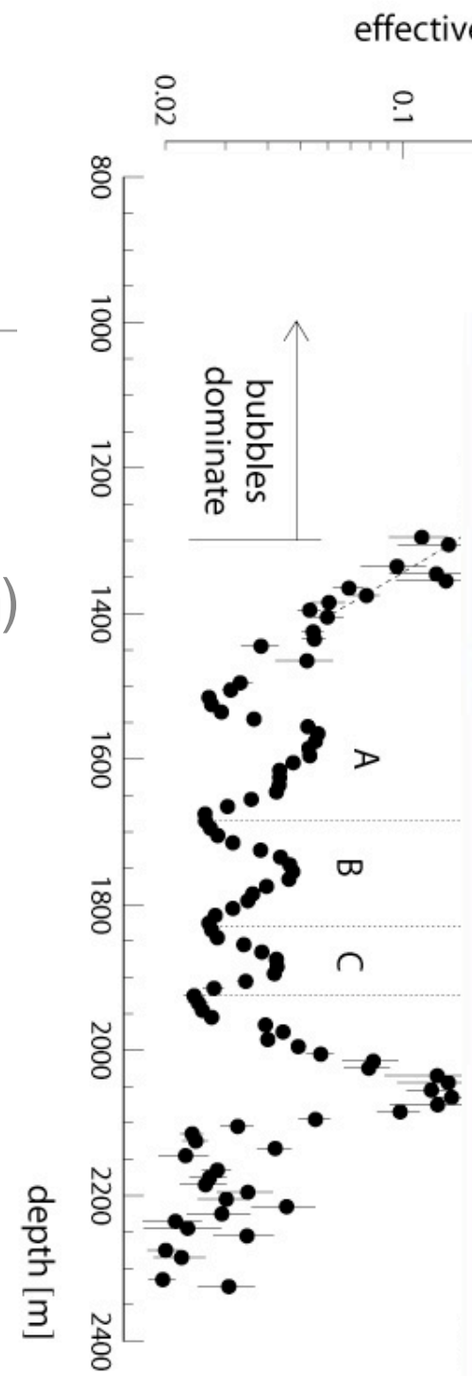
summary

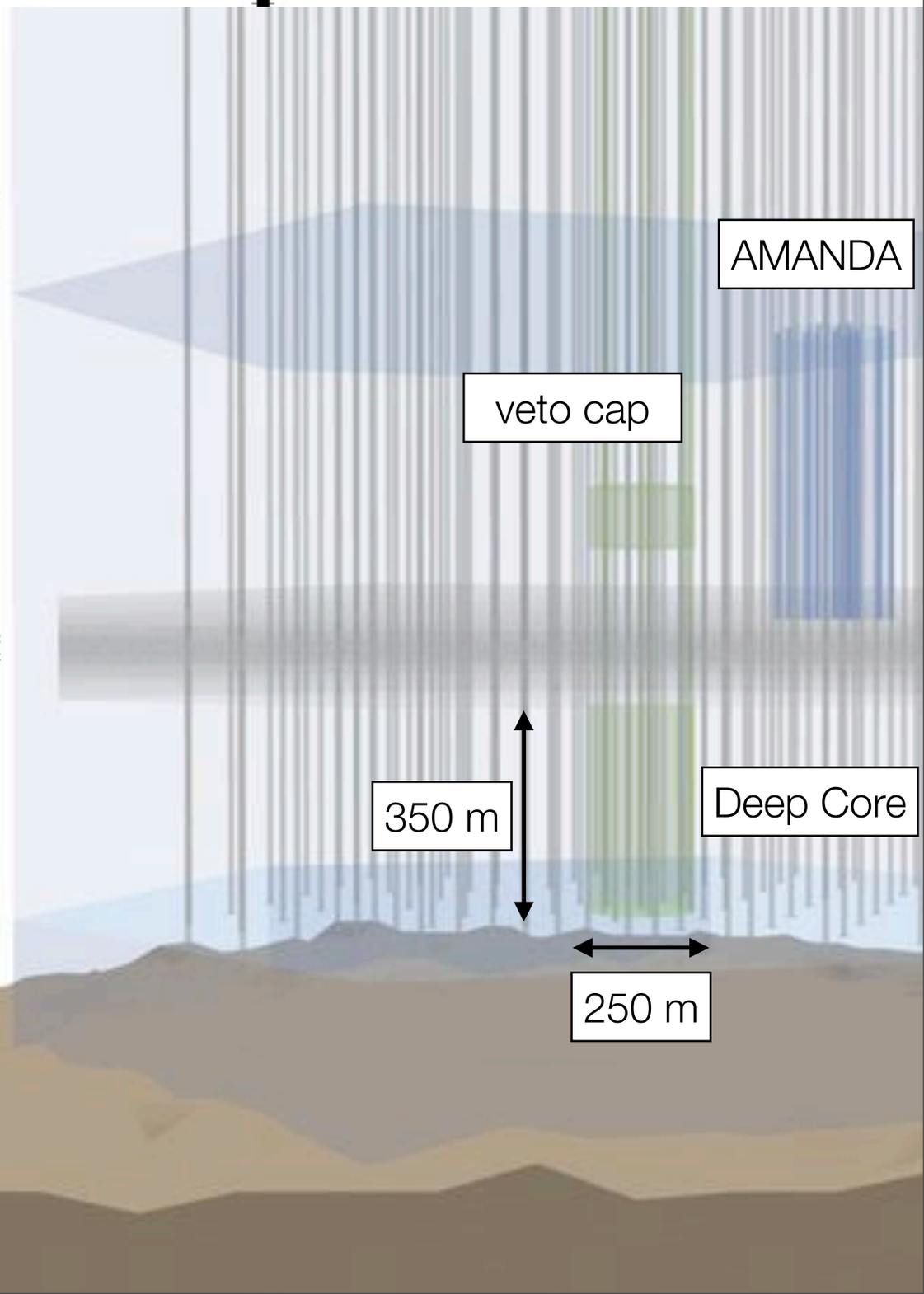
- IceCube will be completed at the beginning of 2011 : 86 strings
    - lower energy threshold with Deep Core : ~ 30 GeV
- sensitivity for neutrino searches will improve at least x 2 wrt IC-40
    - search of extended sources, UHE, EHE neutrinos
    - too soon to invoke *non standard* models
- search for non-std particle physics & indirect search for dark matter
- cosmic ray anisotropy as probe of local IS environment or of origin of CR's
    - energy dependence, small angular scale

backup slides

Deep Core

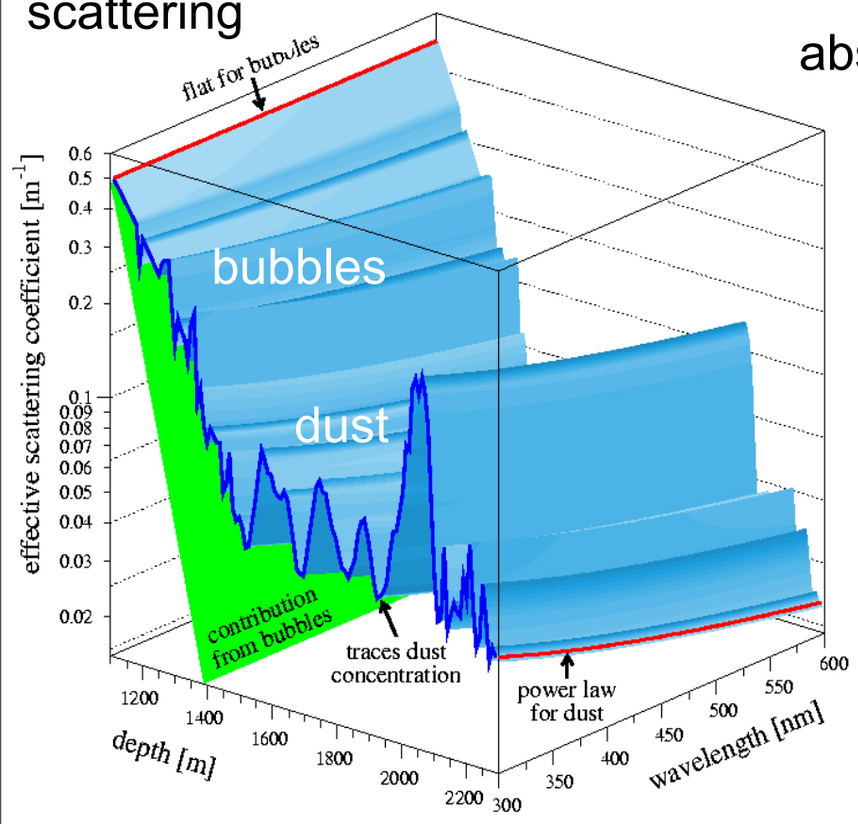
- 6 dedicated + 7 IceCube strings
  - 72m inter-string spacing (125m)
  - 7m DOM spacing (17m)
  - high QE PMT (38% higher)
    - ≳ 5x effective photocathode density
- IceCube as veto + veto cap
- in the clearest ice
  - λ_{atten} ~ 40-45m (cf. 20-25m in shallower ice)



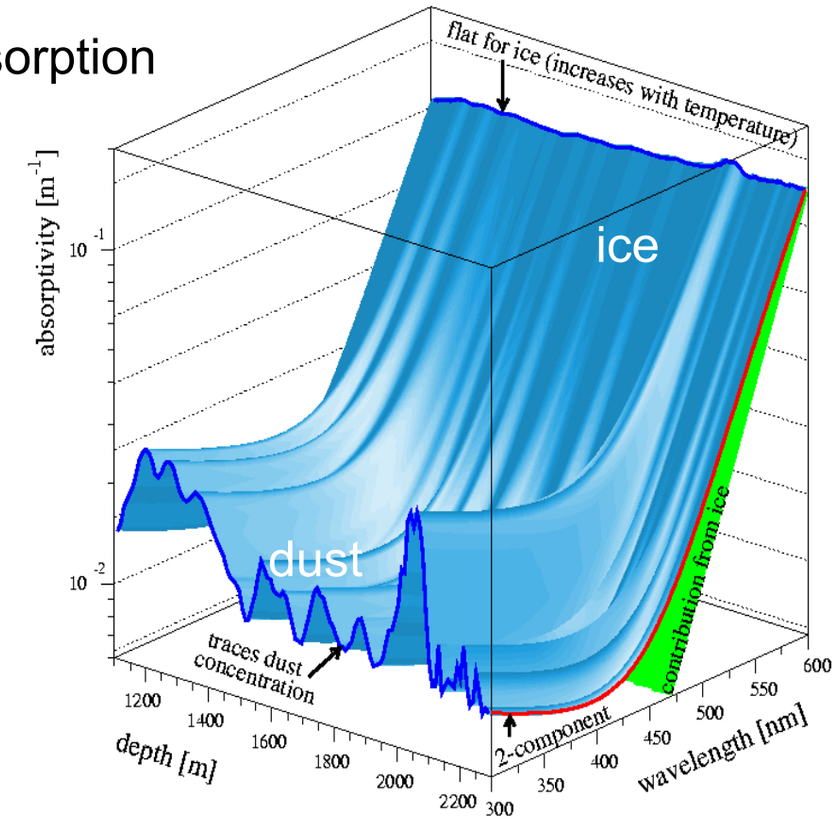


Polar ice optical properties

scattering

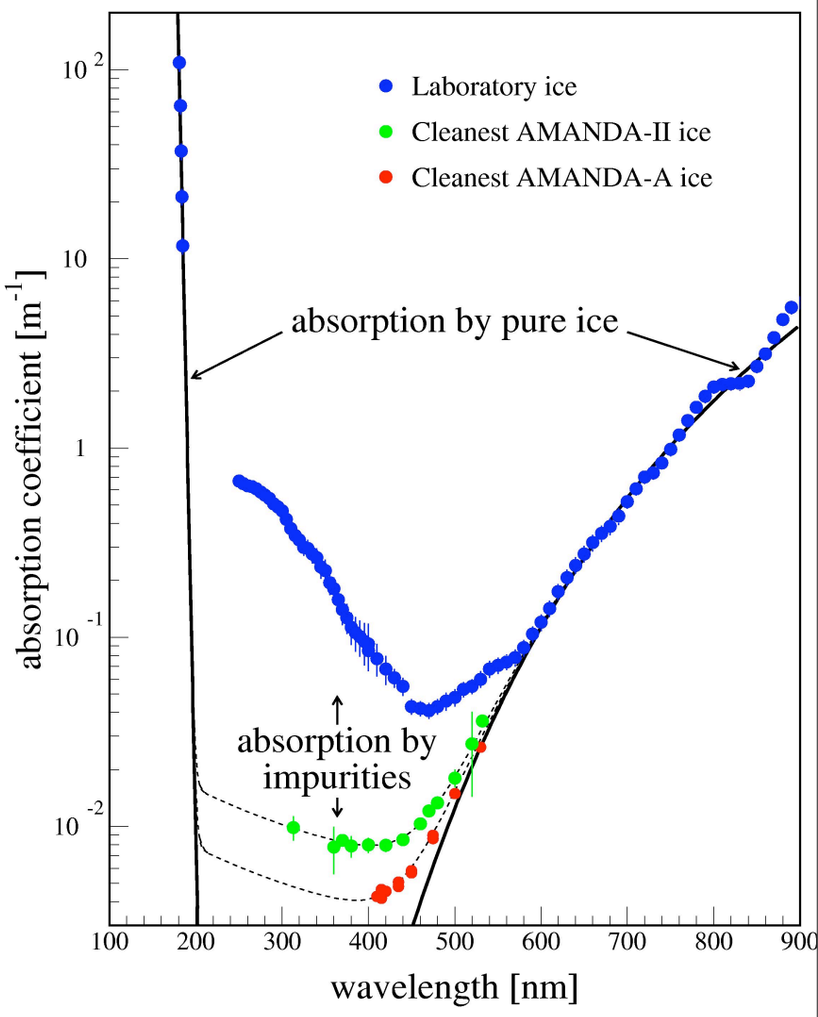


absorption

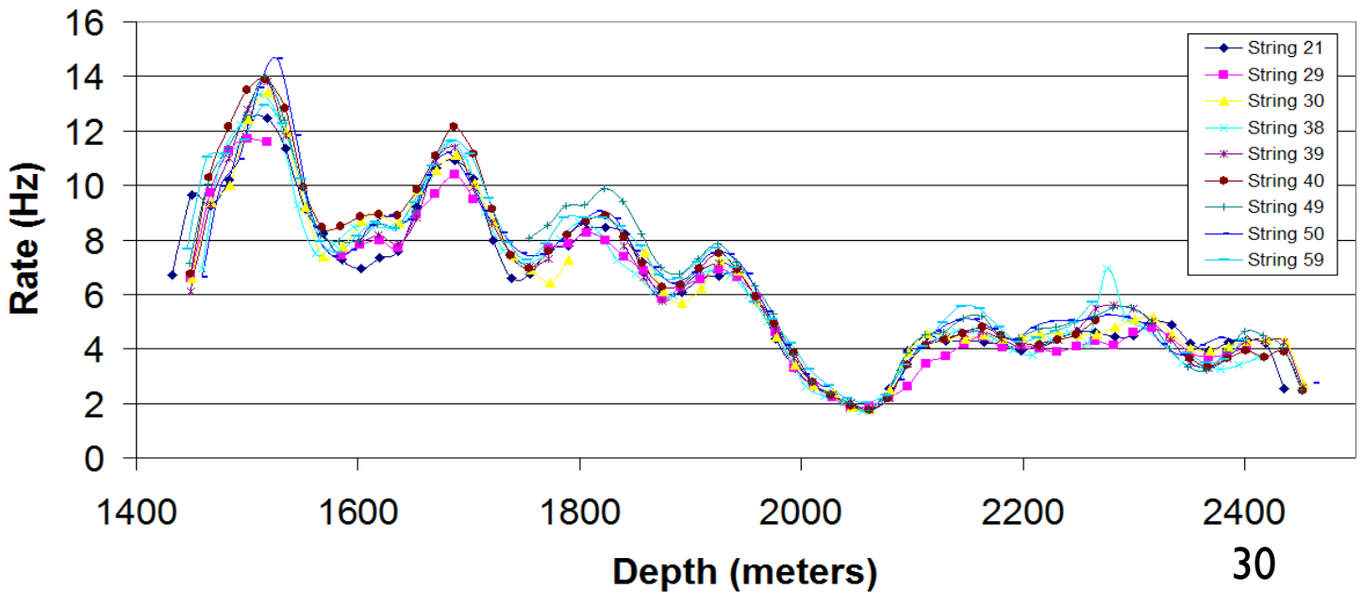


Measurements:

- in-situ light sources
- atmospheric muons



J. Geophys. Res. 111 (2006) D13203



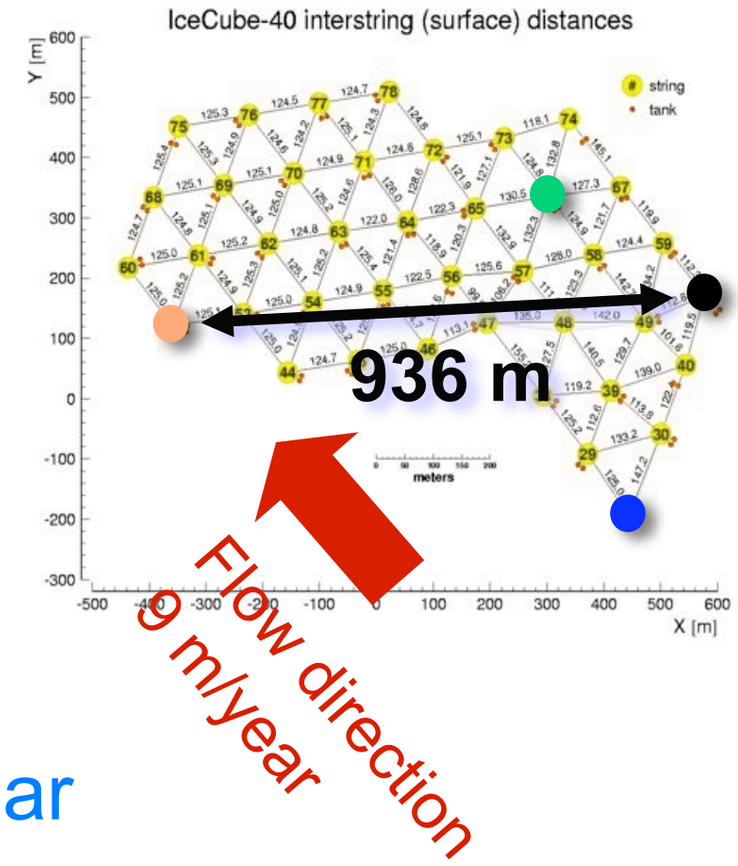
Average optical ice parameters:

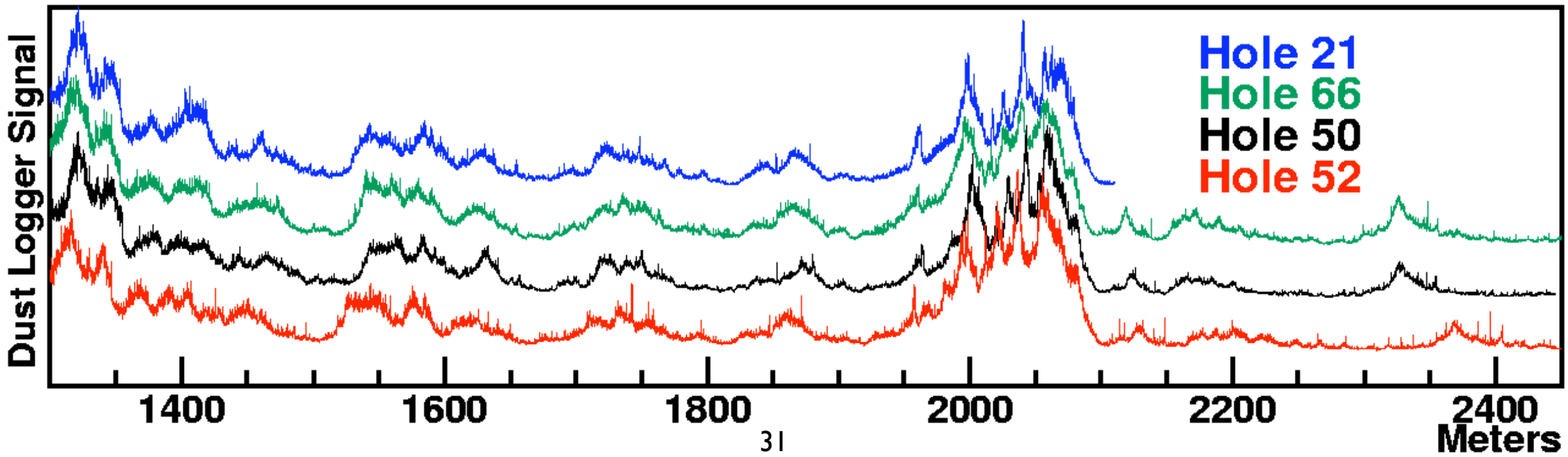
λ_{abs} ~ 110 m @ 400 nm

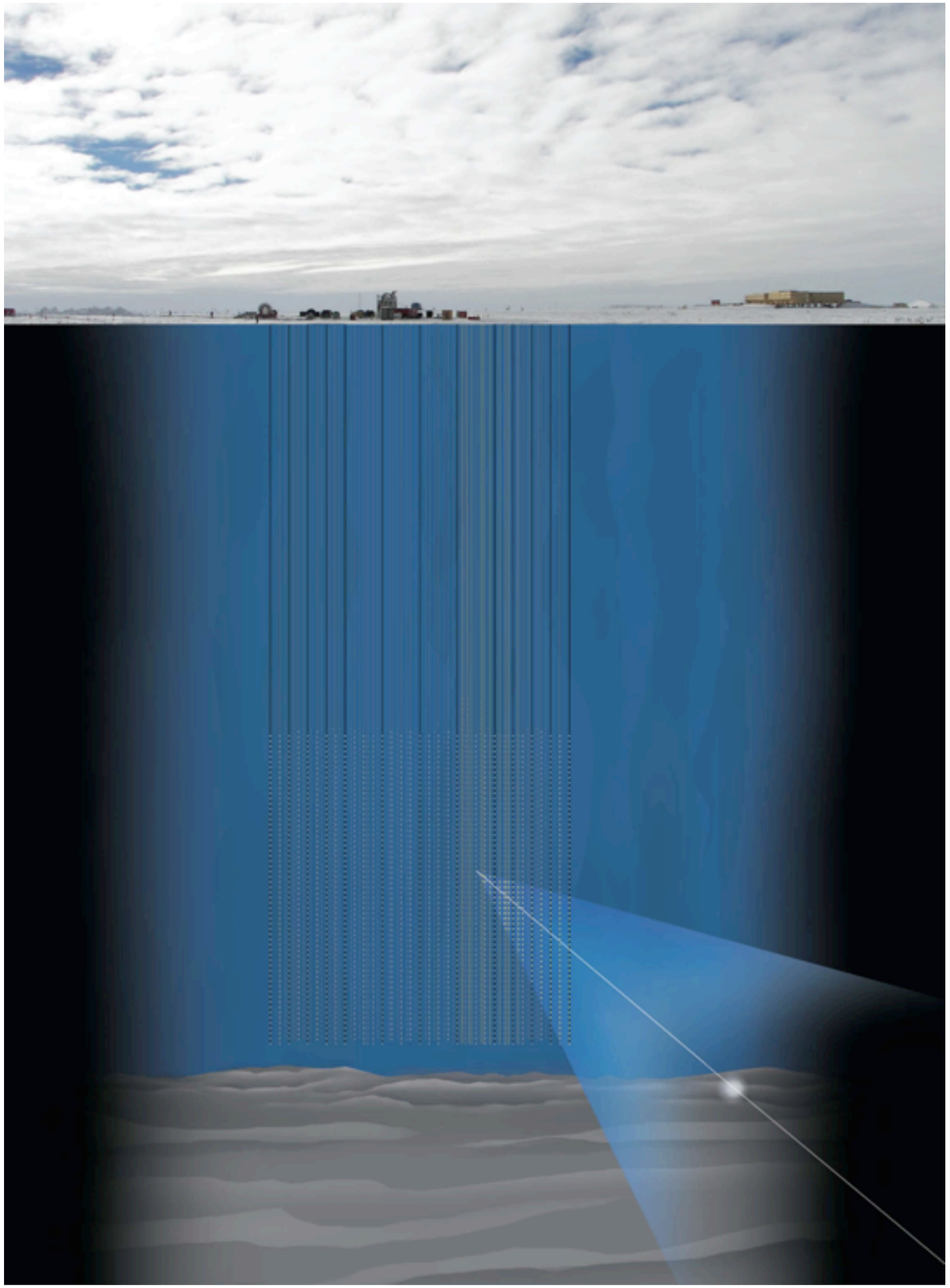
λ_{sca} ~ 20 m @ 400 nm

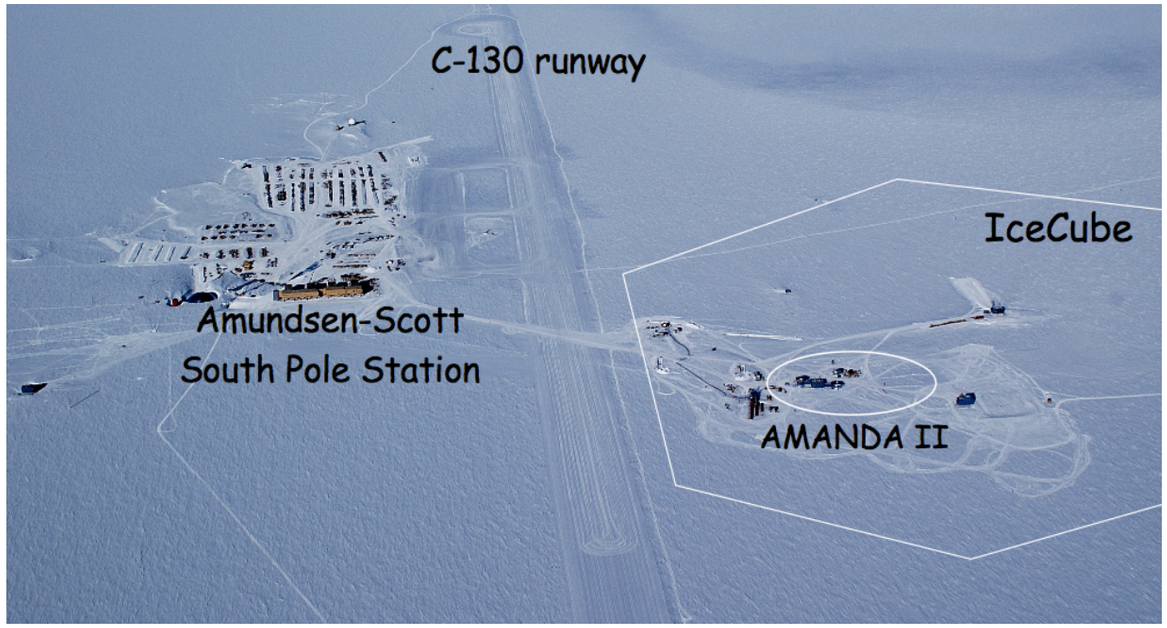
Ice Properties

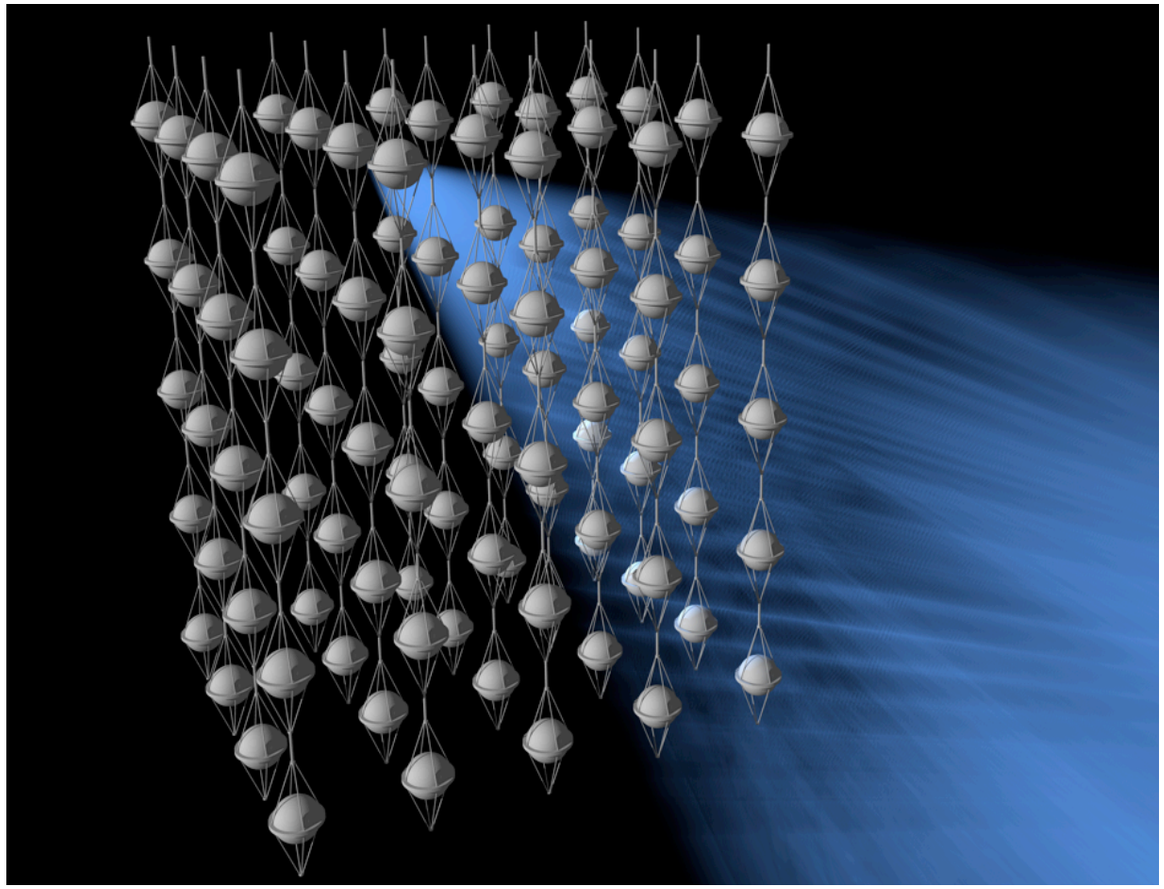
- Analyses are sensitive to the optical properties of the ice.
- Below 1400 m, dominated by impurities in the ice
- Measure with ‘dust logger’
  - Ice layers are not completely planar
    - Up to 70 m/km tilt









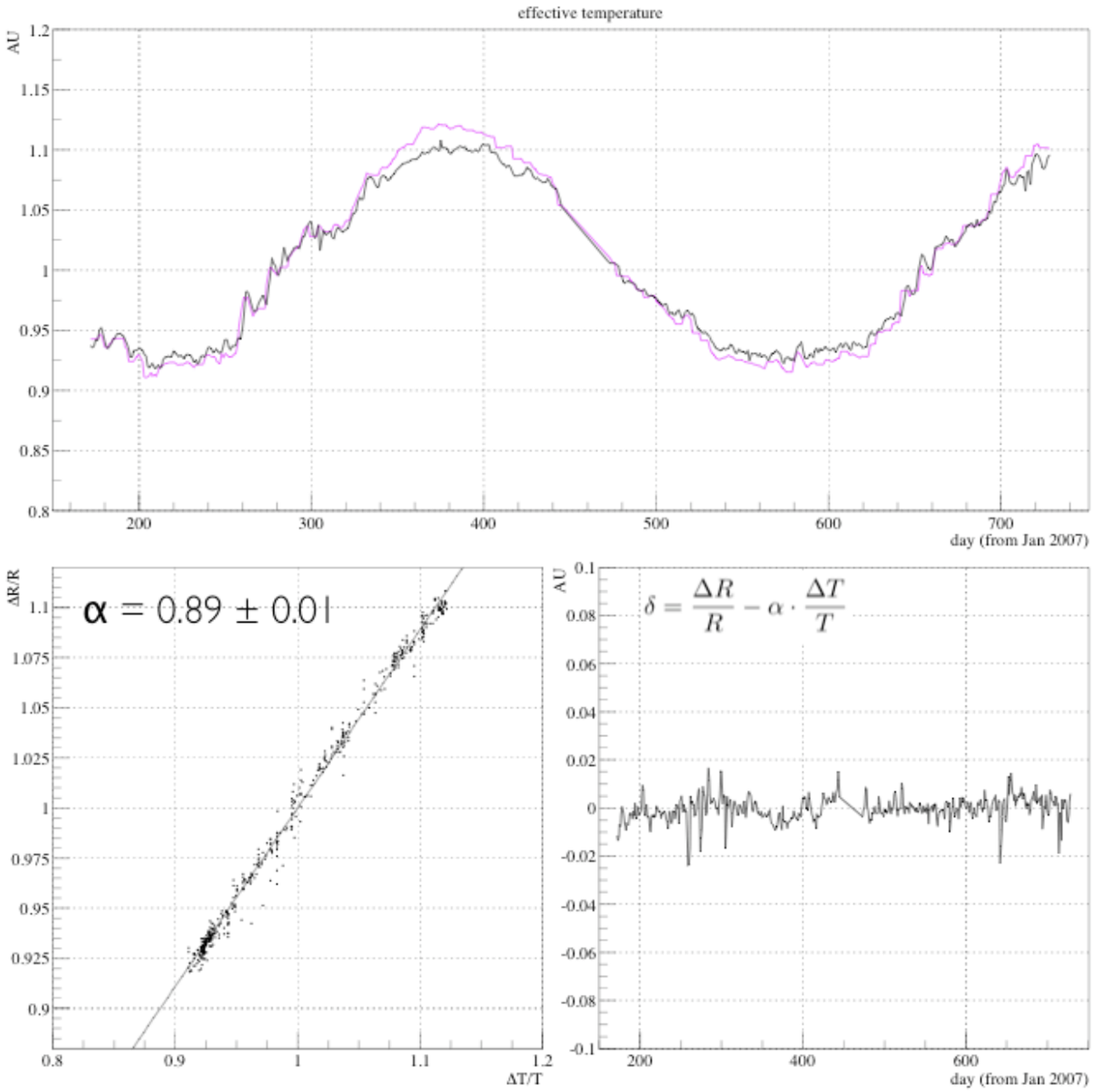


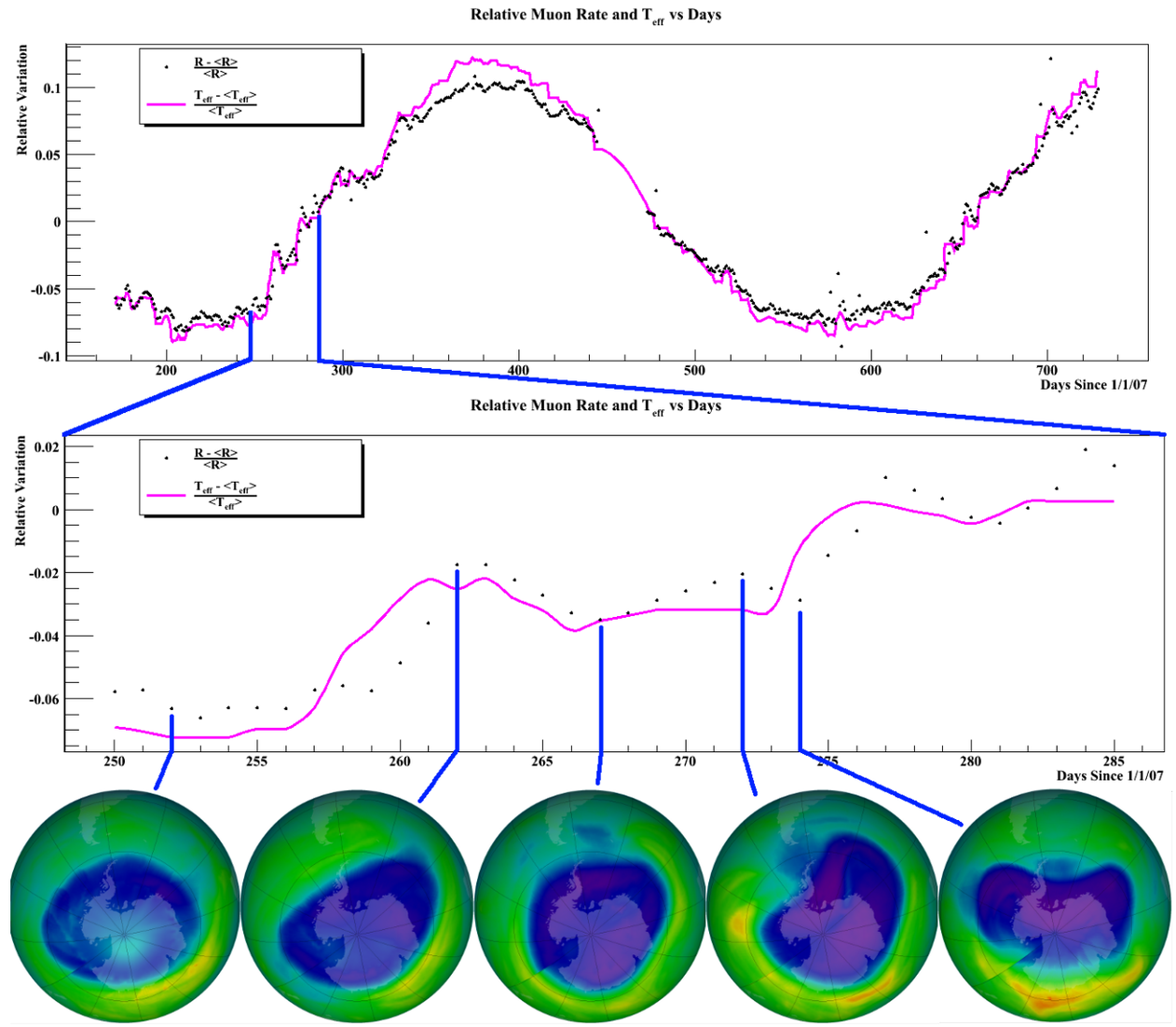
detection technique

growing IceCube

Strings	Year	Livetime	μ rate	ν rate
IC9	2006	137 days	80 Hz	1.7 / day
IC22	2007	275 days	550 Hz	28 / day
IC40	2008	~365 days	1000 Hz	110 / day
IC59	2009	~365 days	1500 Hz	160 / day
IC86*	2011	~365 days	1650 Hz	220 / day

seasonal variations in IceCube



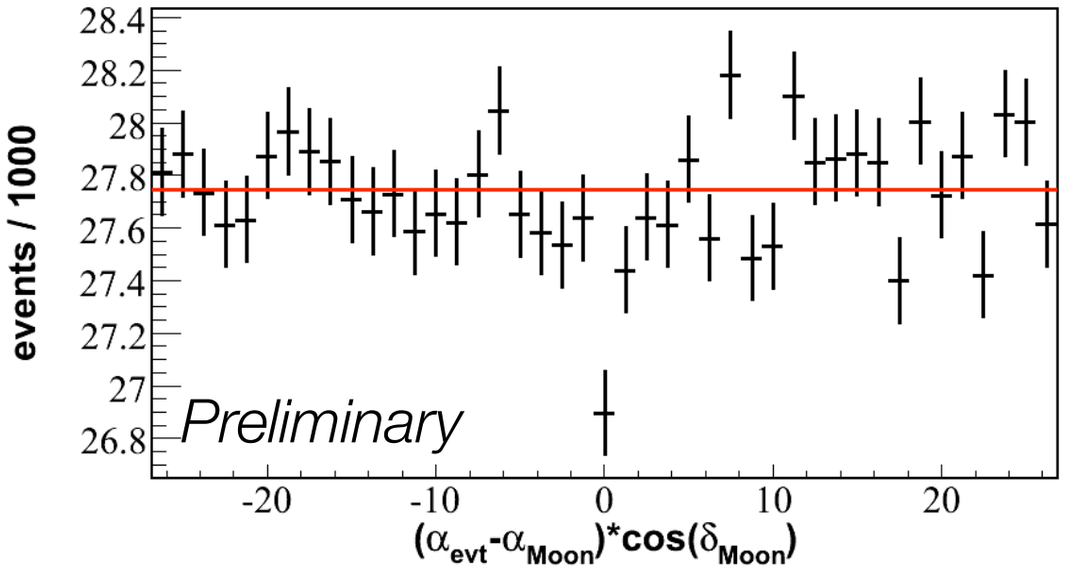


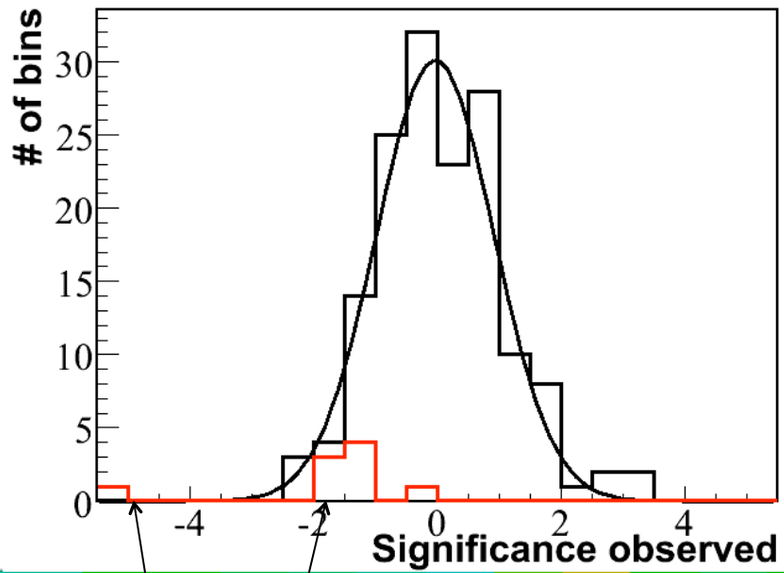
Dominick Rocco, PD

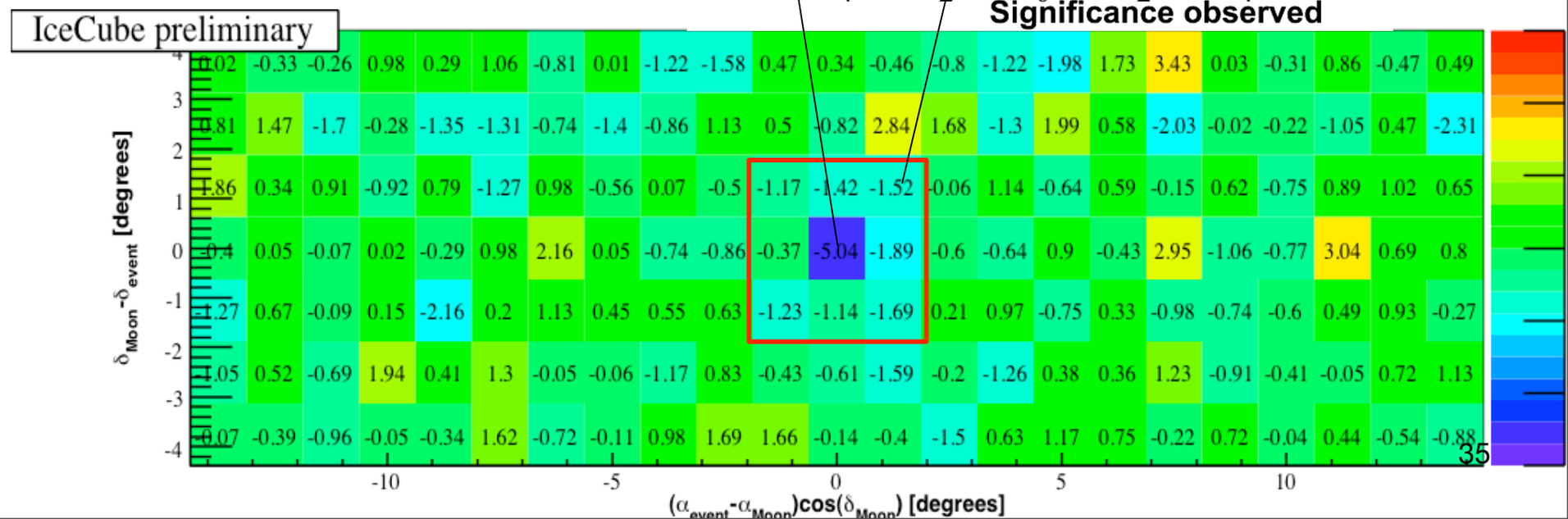
S. Tilav et al., arXiv:1001.xxxx

Moon shadow

- 5 months of IC40
- Moon max. altitude at the South Pole (2008): 28°
- Median primary cosmic ray energy: 30TeV
- Deficit: 5 σ (~900 events of ~28000) - consistent with expectation.
- Verification of angular resolution and absolute pointing.
- More statistics will allow study of angular response function

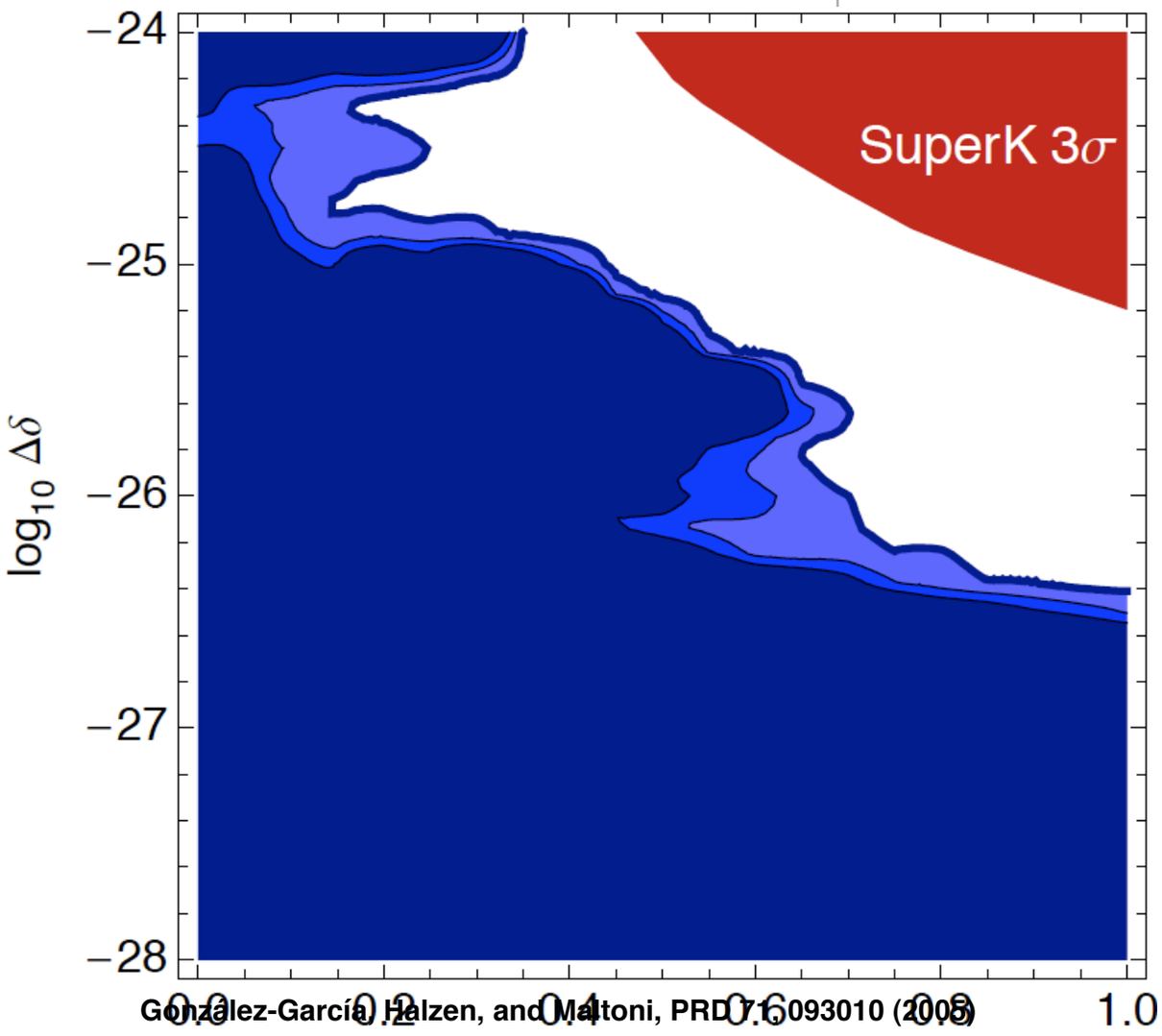






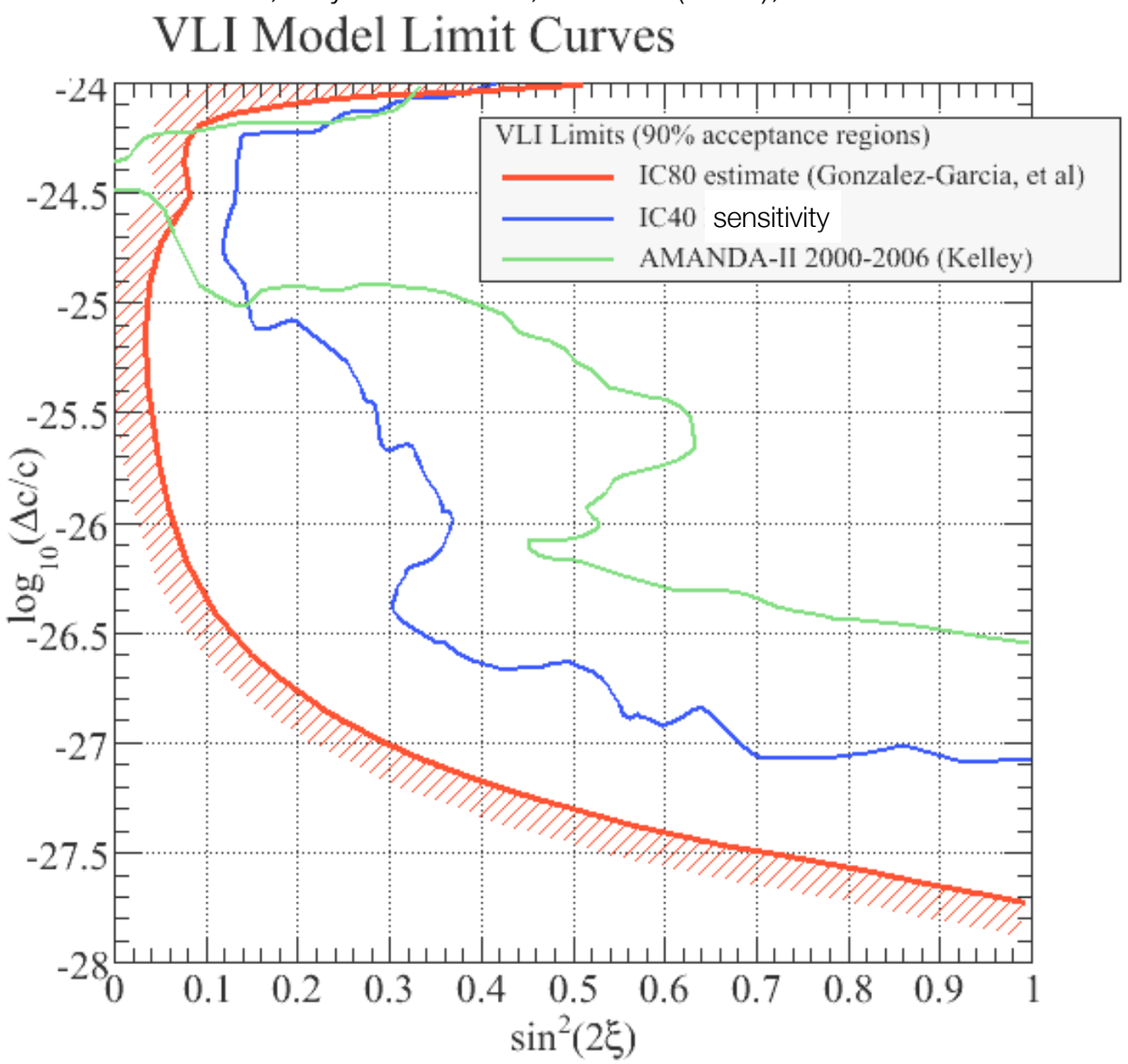
atmospheric neutrinos & non-standard oscillations

Violation of Lorentz Invariance



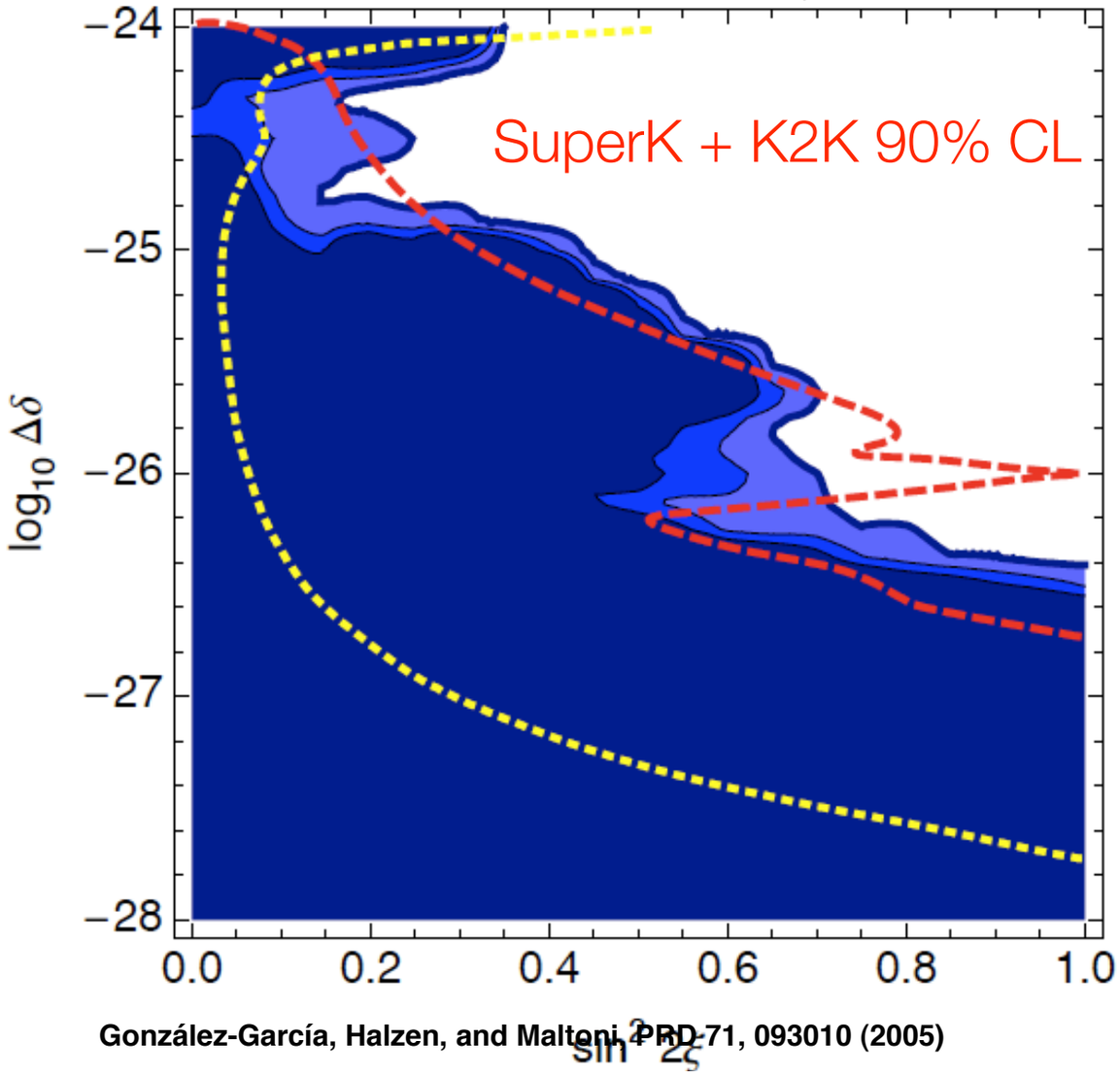
González-García, Halzen, and Maltoni, PRD 71, 093010 (2005)

Abbasi et al., Phys. Rev. D 79, 102005 (2009), arXiv:0902.0675



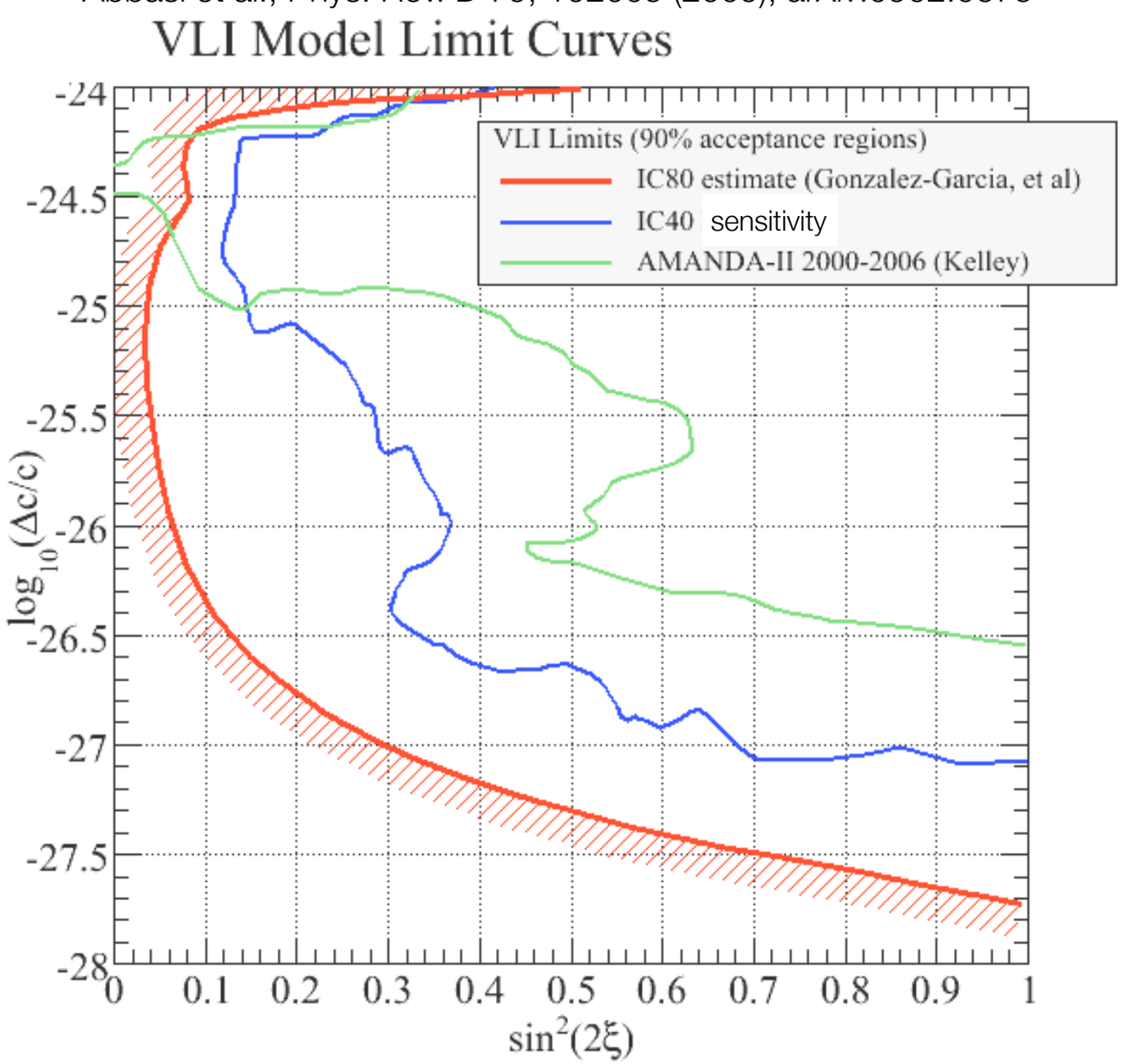
atmospheric neutrinos & non-standard oscillations

Violation of Lorentz Invariance



González-García, Halzen, and Maltoni, PRD-71, 093010 (2005)

Abbasi et al., Phys. Rev. D 79, 102005 (2009), arXiv:0902.0675



atmospheric neutrinos & non-standard oscillations

- *Vector Model*
- violation of rotational invariance of standard interaction coefficients
- oscillations as a function of E_ν, L and direction

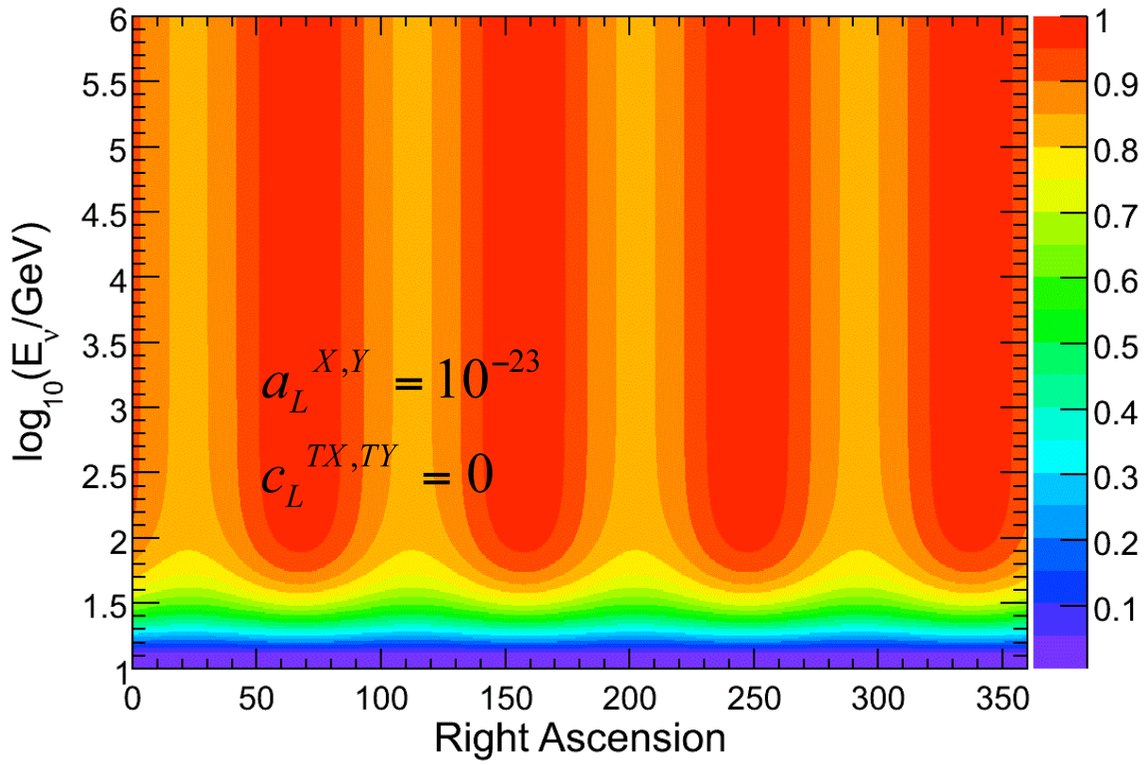
preliminary

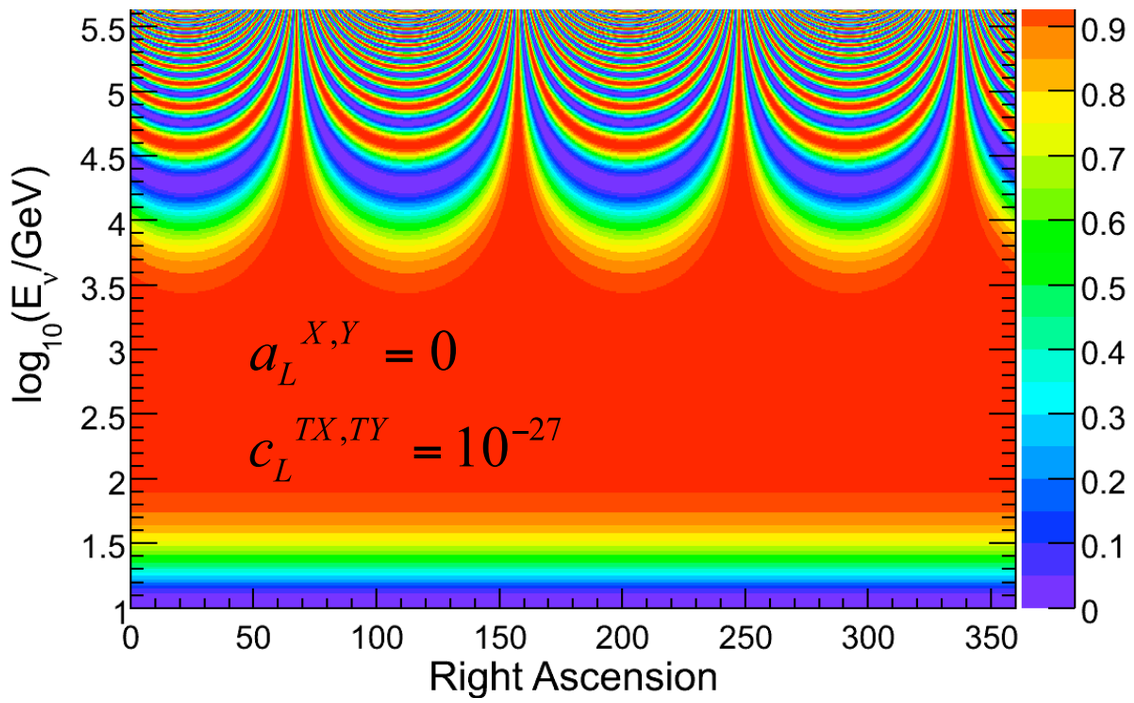
IC40:

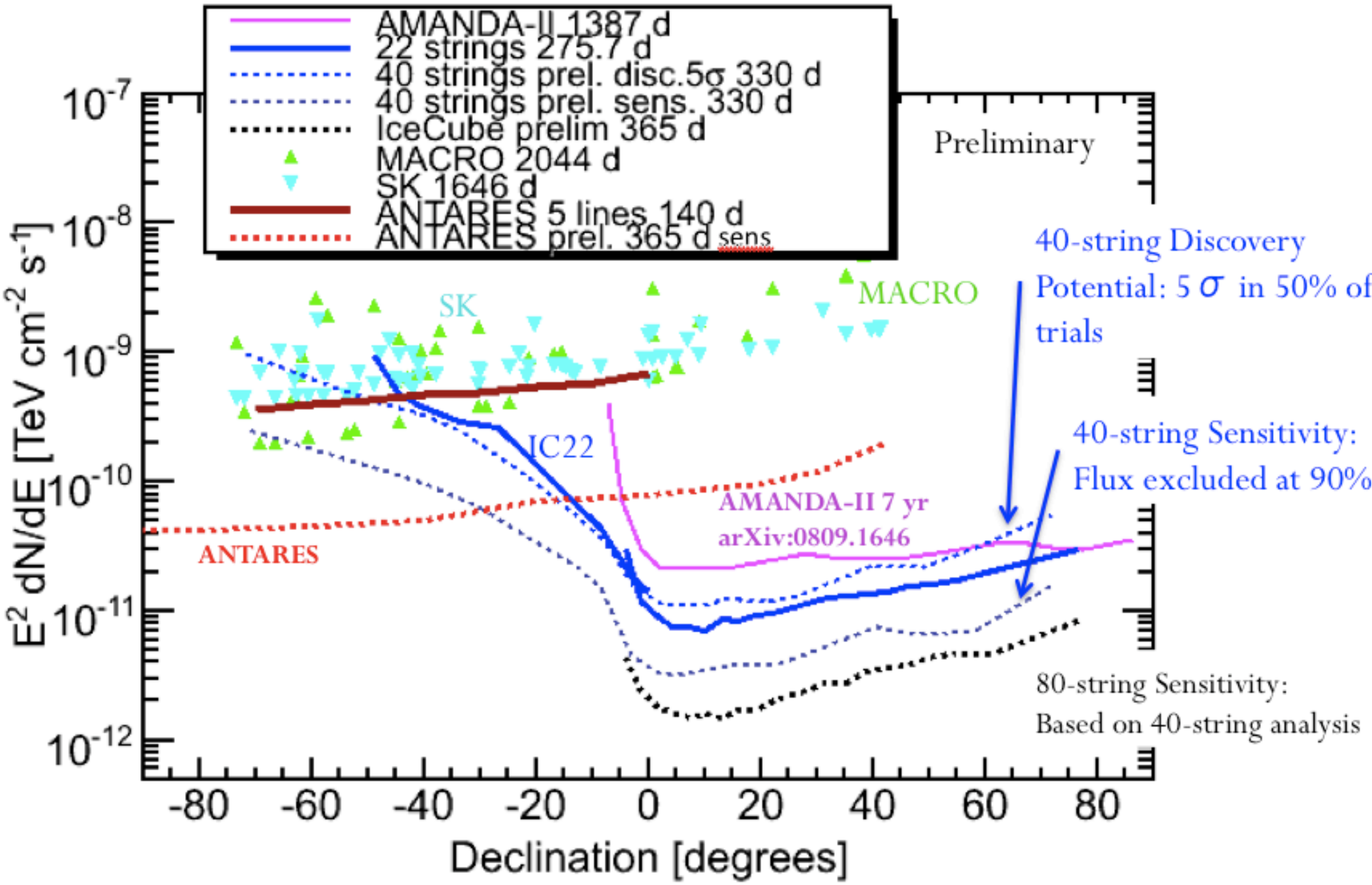
$$a_L^{X,Y} < 1.3 \times 10^{-23}$$

$$c_L^{TX,TY} < 2.5 \times 10^{-27}$$

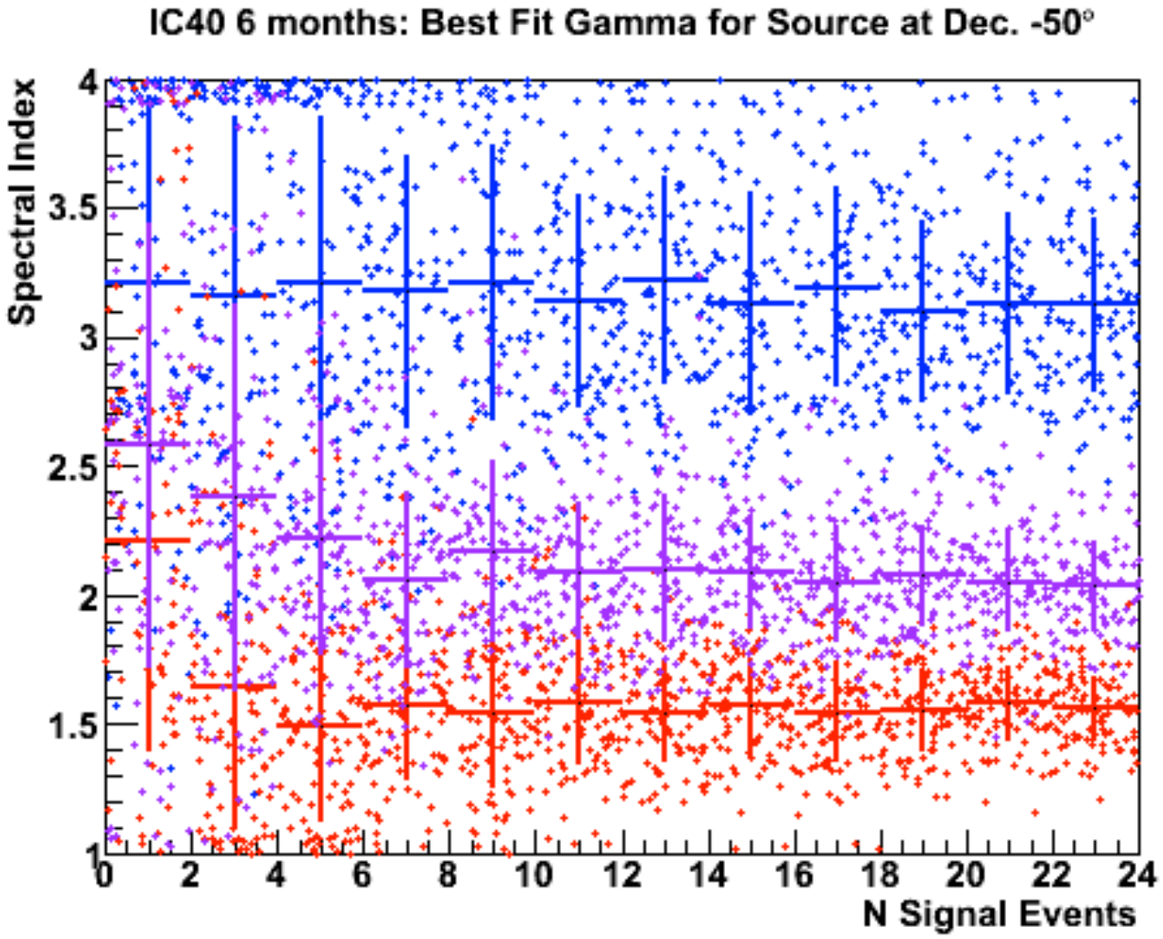
González-García, Halzen, and Maltoni, PRD 71, 093010 (2005)

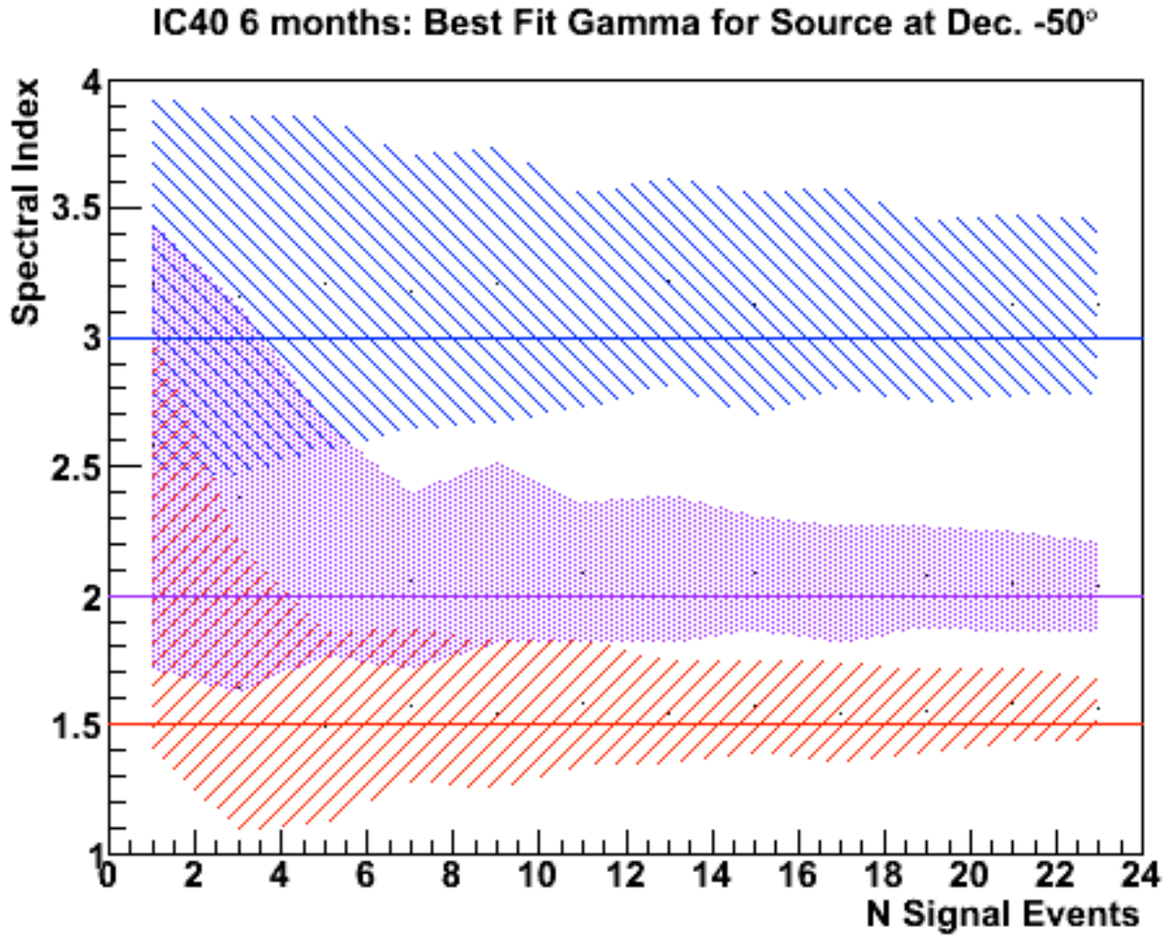




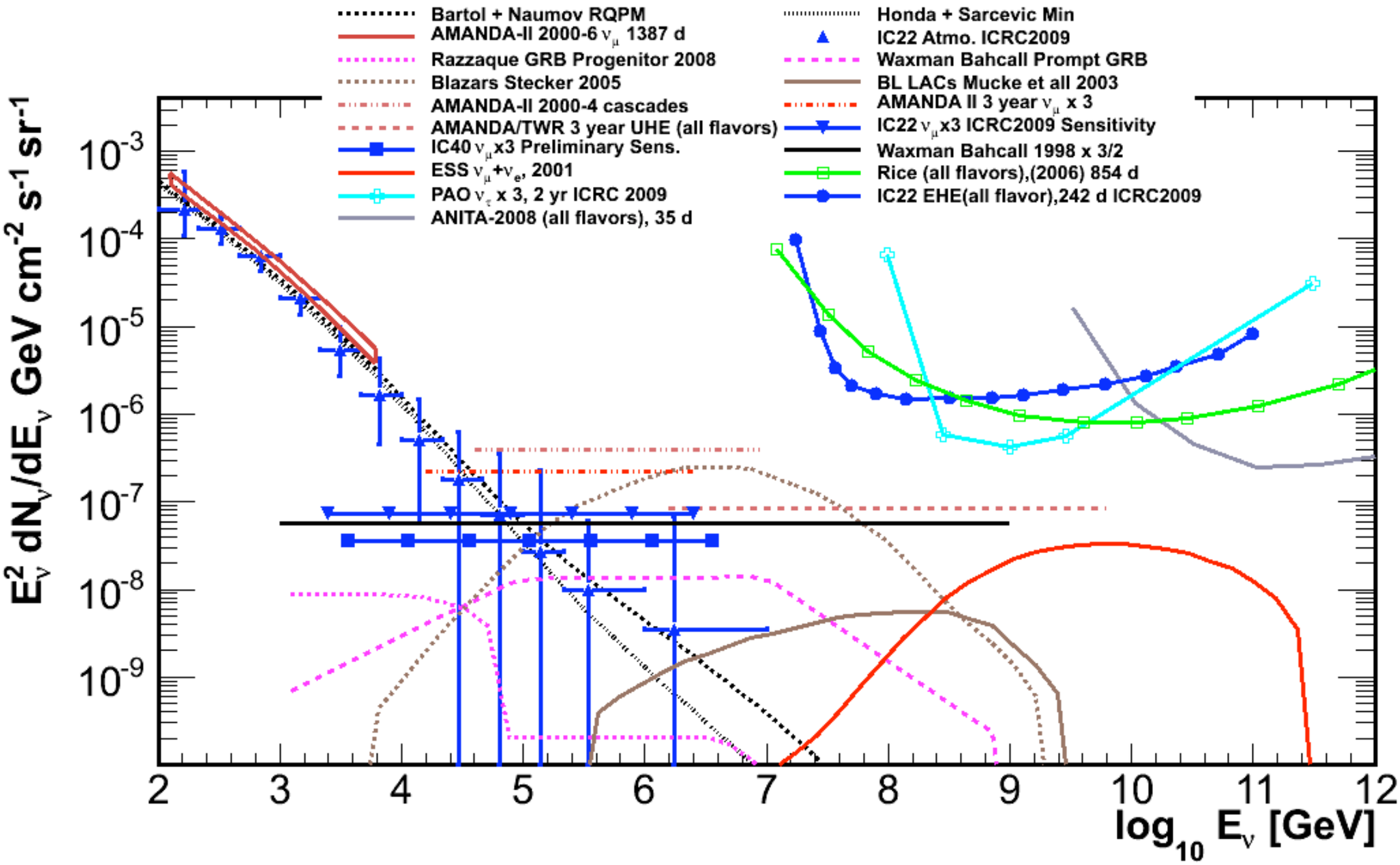


IceCube sensitivity for point source search





spectral index estimation

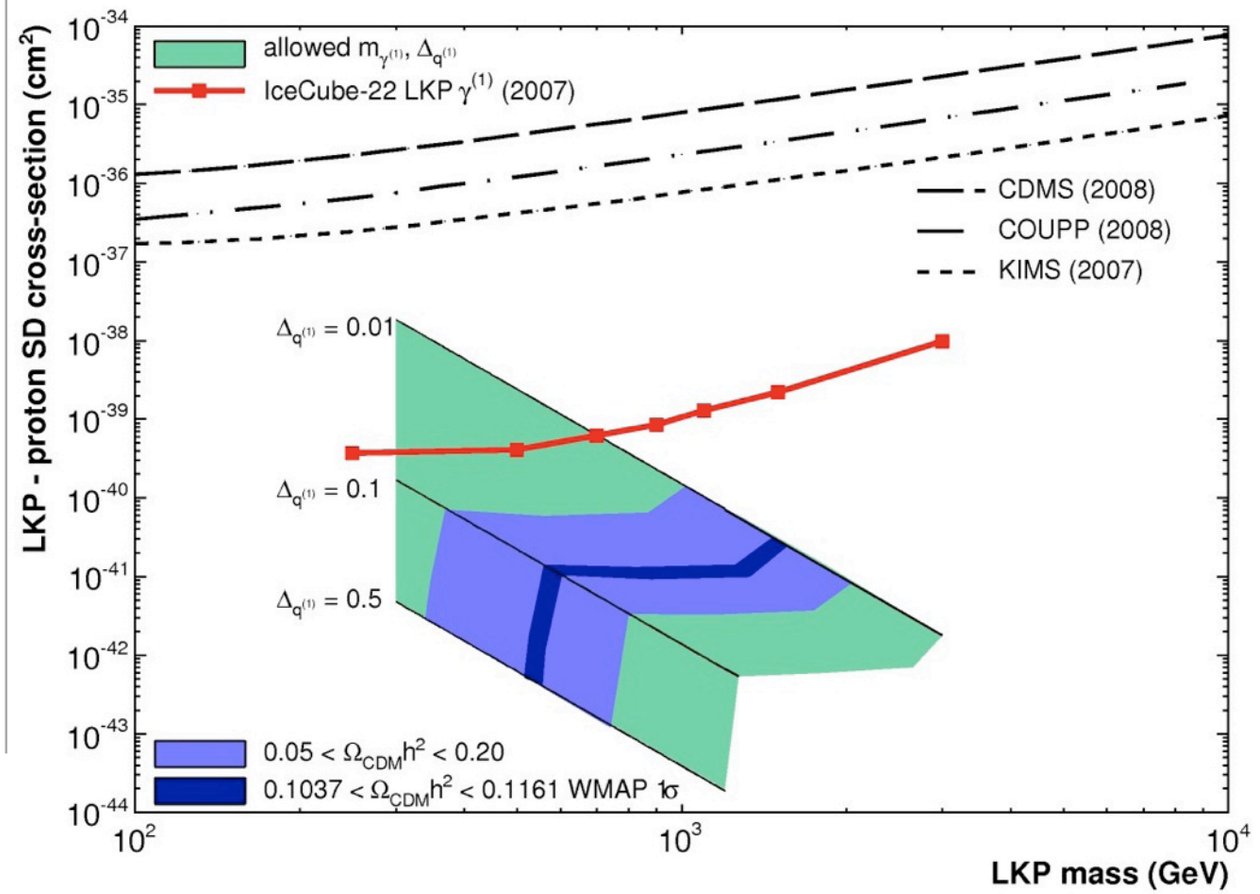


IceCube sensitivity for diffuse searches

search for dark matter

- Kaluza Klein Dark Matter
  - LKP is KK photons
  - model with 2 parameters : Δ_q, M_{LKP}
- in equilibrium in the Sun
- annihilate to SM particles
  - neutrinos

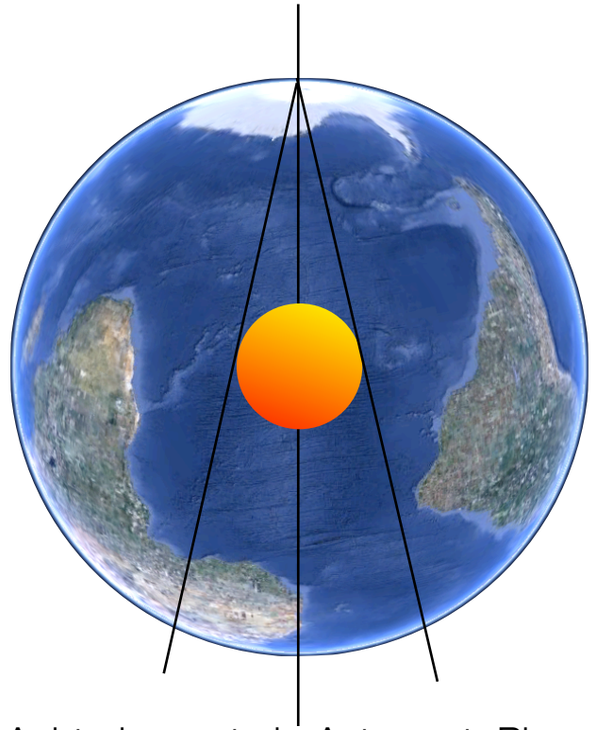
Abbasi et al., arXiv:0910.4480



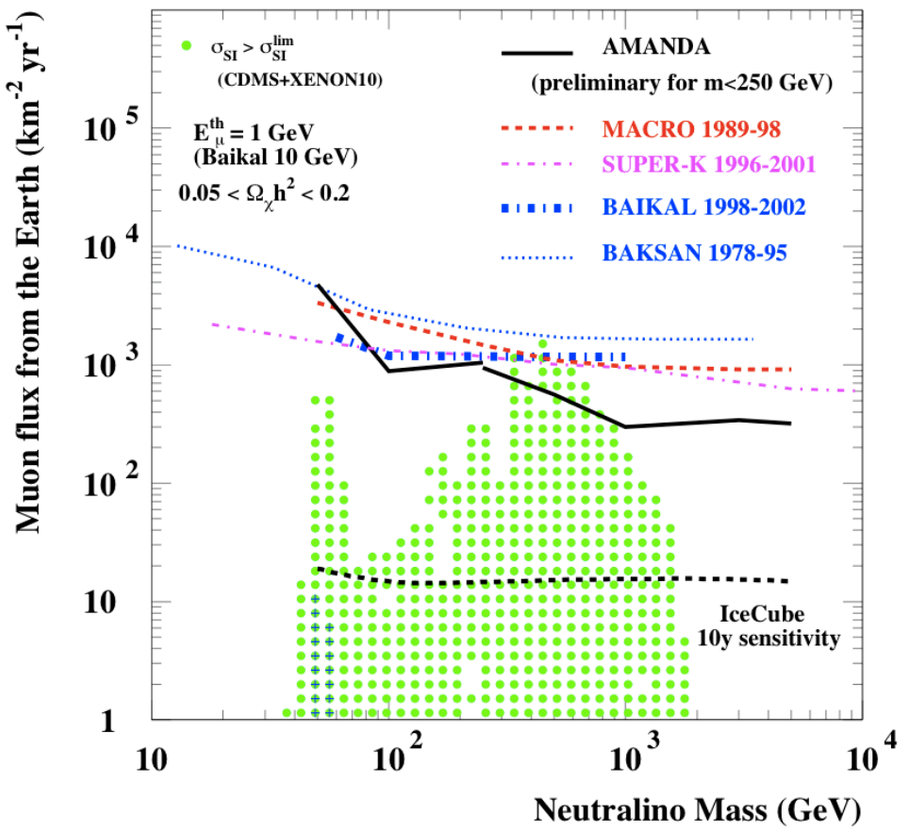
search for dark matter

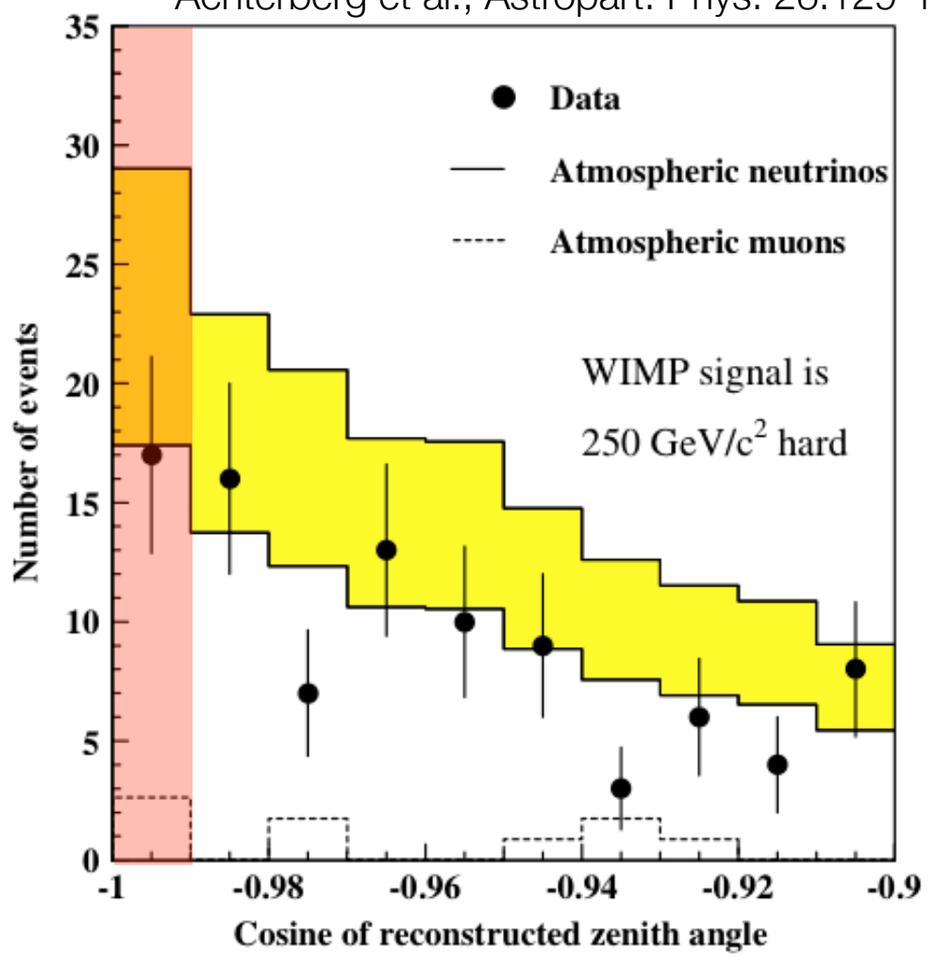
- WIMP (χ) annihilation in the Earth
  - muon flux

AMANDA (1997-99)



Achterberg et al., Astropart. Phys. 26:129-136 (2006)





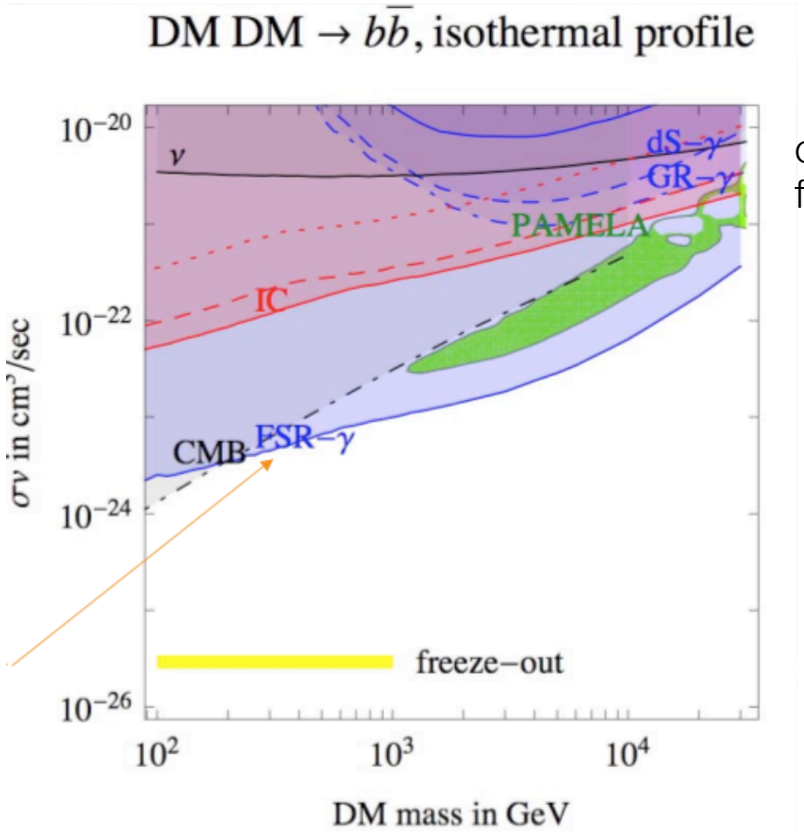
search for dark matter

- WIMP from galactic halo

halo models

$$\frac{d\phi_\nu}{dE} = \frac{<\sigma_A v>}{2} J(\psi) \frac{R_{sc}\rho_{sc}^2}{4\pi m_\chi^2} \frac{dN_\nu}{dE}$$

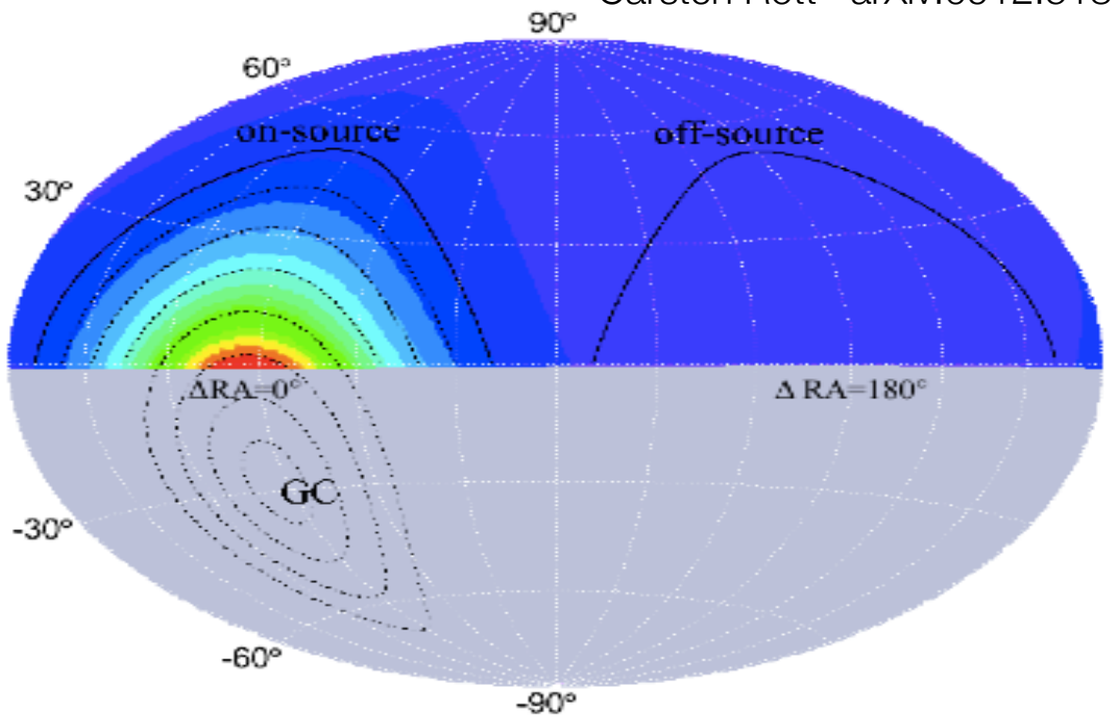
measurement constrain SUSY models

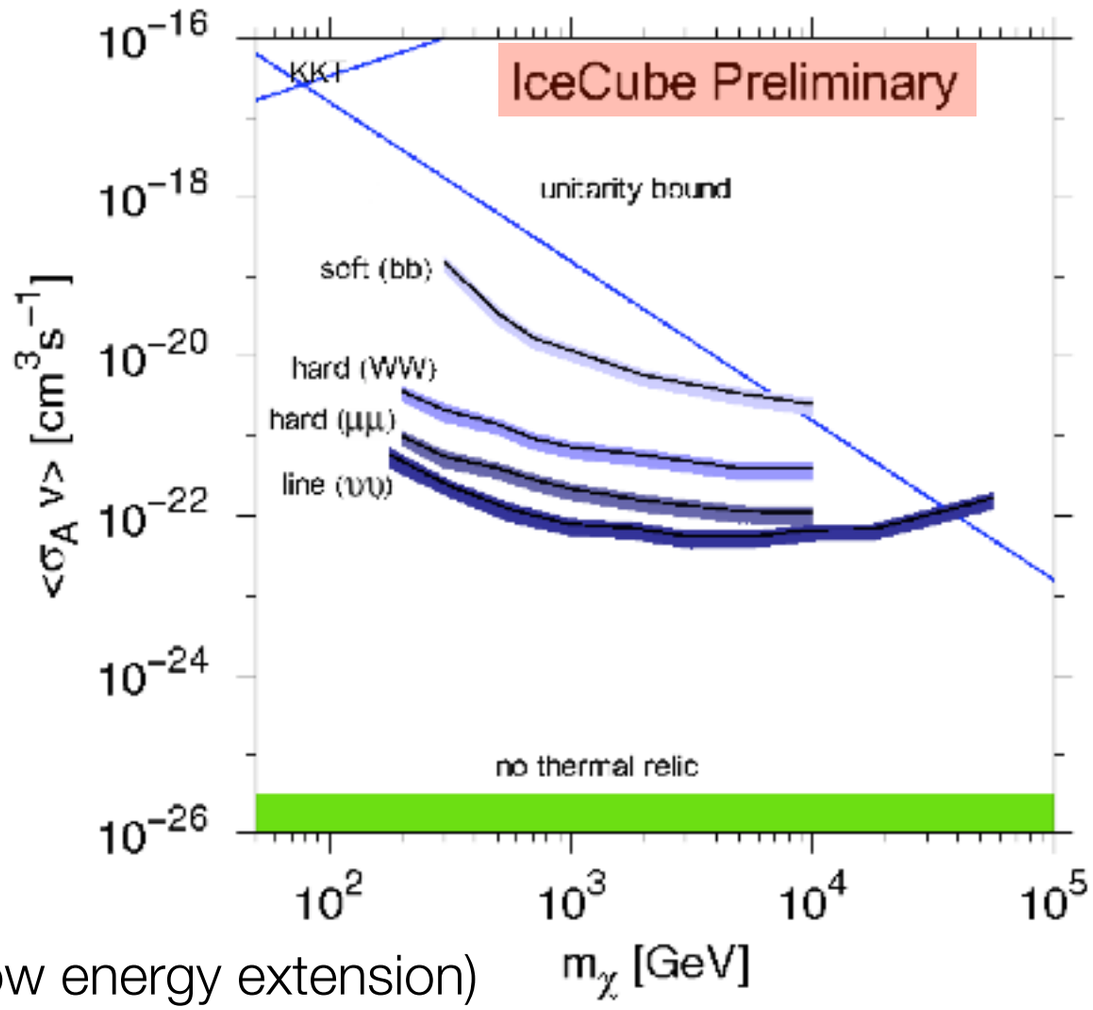


comparison with limits from γ ray detection

arXiv:0912.0742

Carsten Rott arXiv:0912.5183

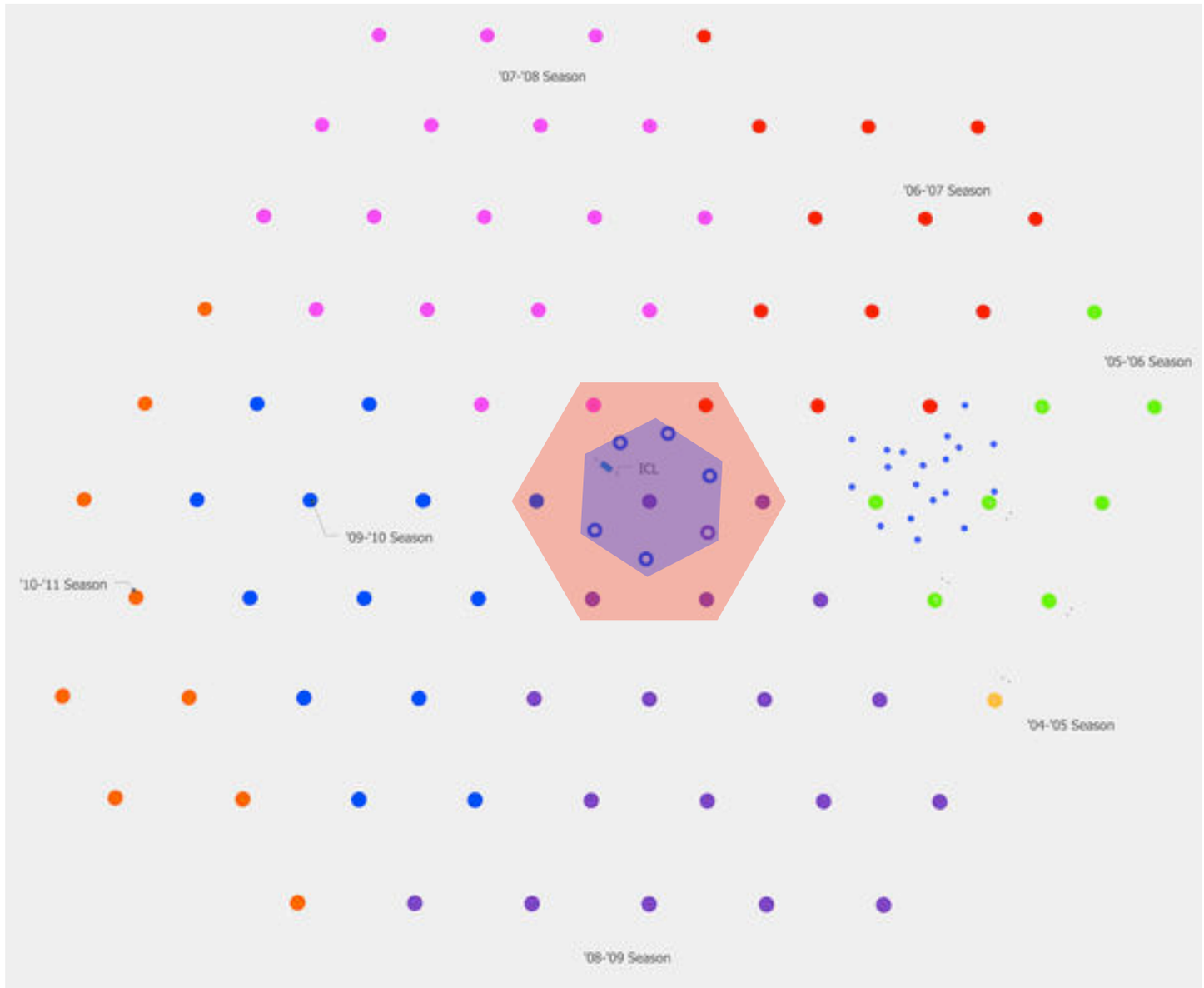




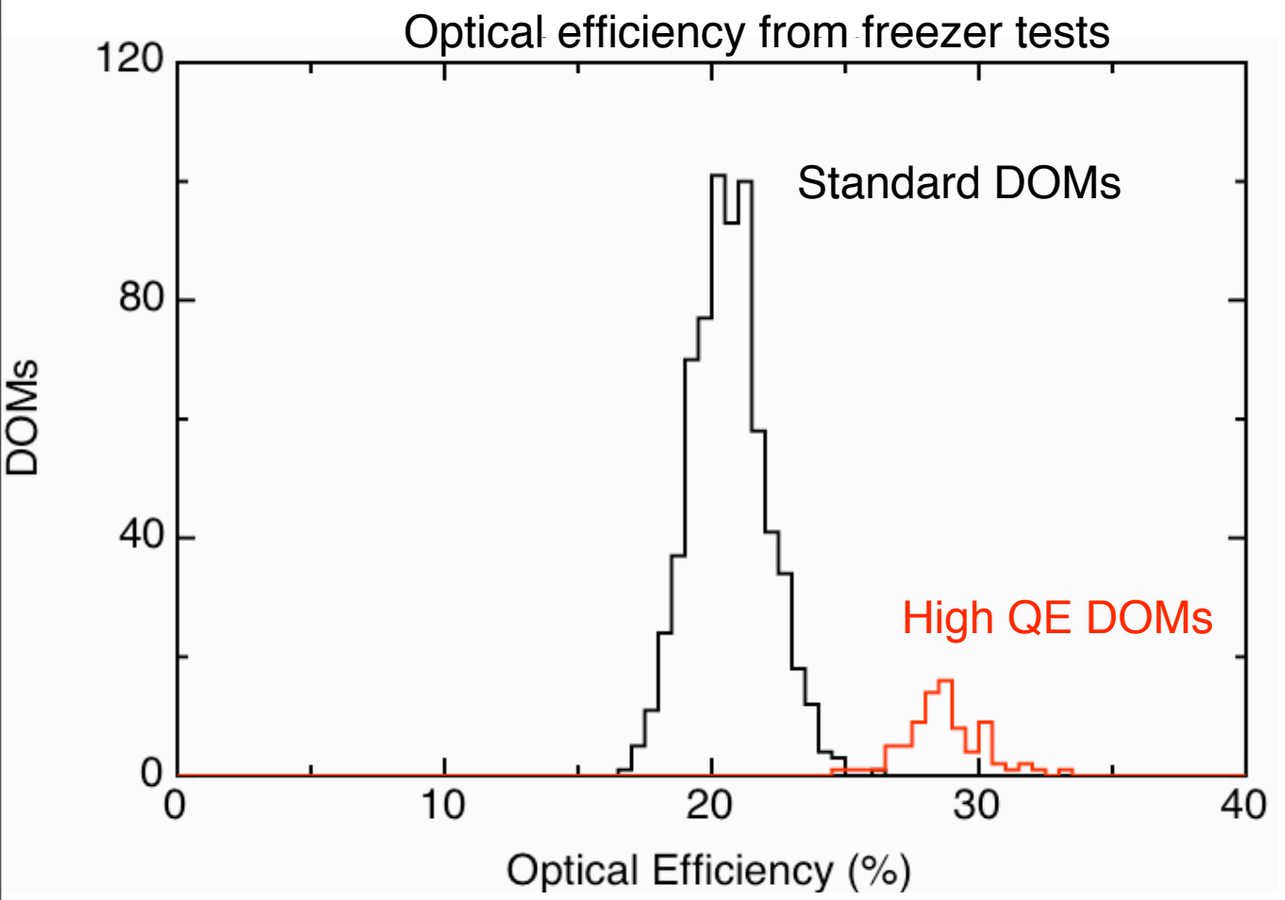
improvement expected with Deep Core (low energy extension)
& with further event selection optimization (@ lower energy)

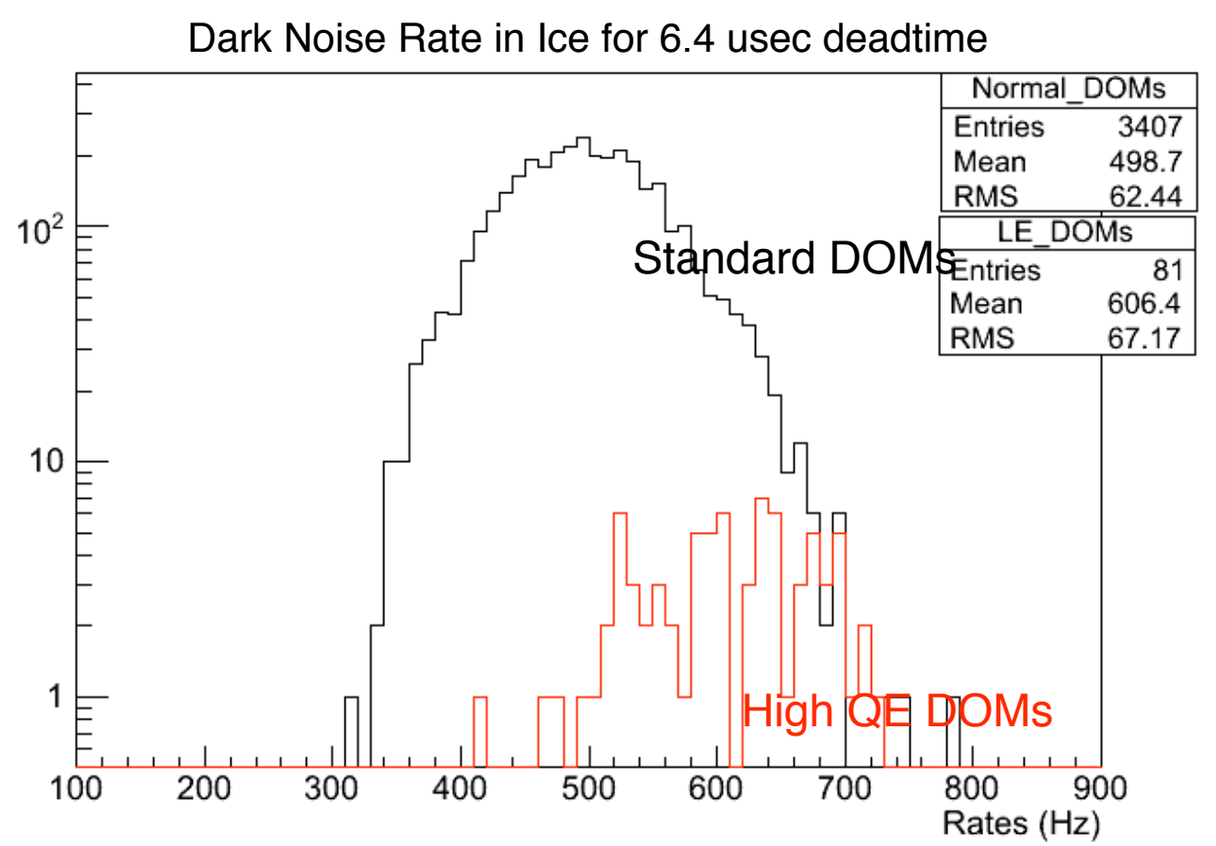
Deep Core from above

- 6 strings with hi QE PMT
  - 60 DOMs/string
- 7 surrounding IceCube strings
  - 22 DOMs in DC range



Deep Core PMT's



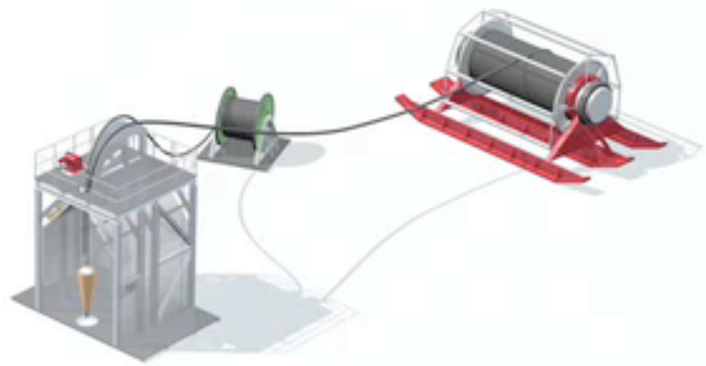


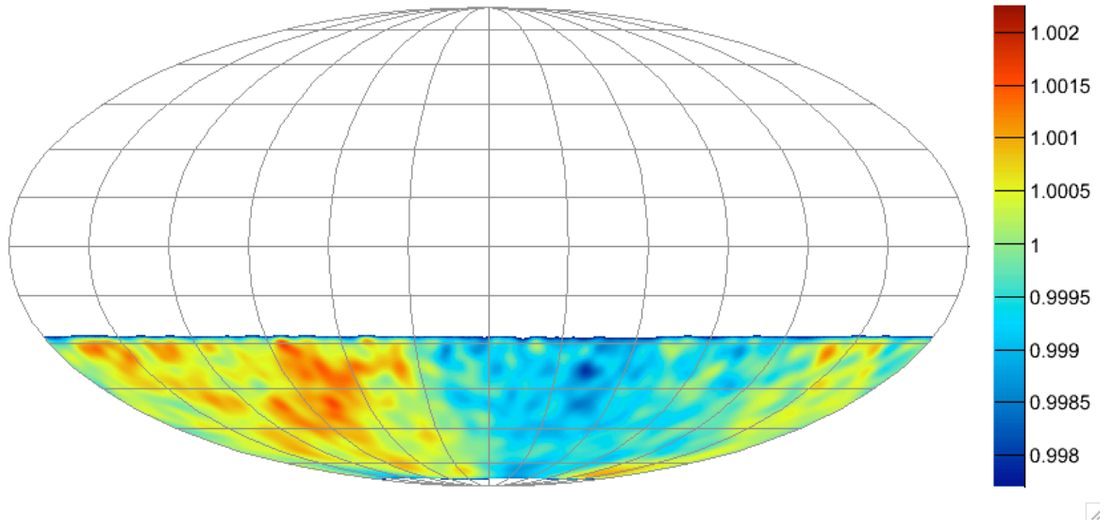
- quantum efficiency ~38% higher (405 nm, -40C), ~ 30% higher noise rate in ice.

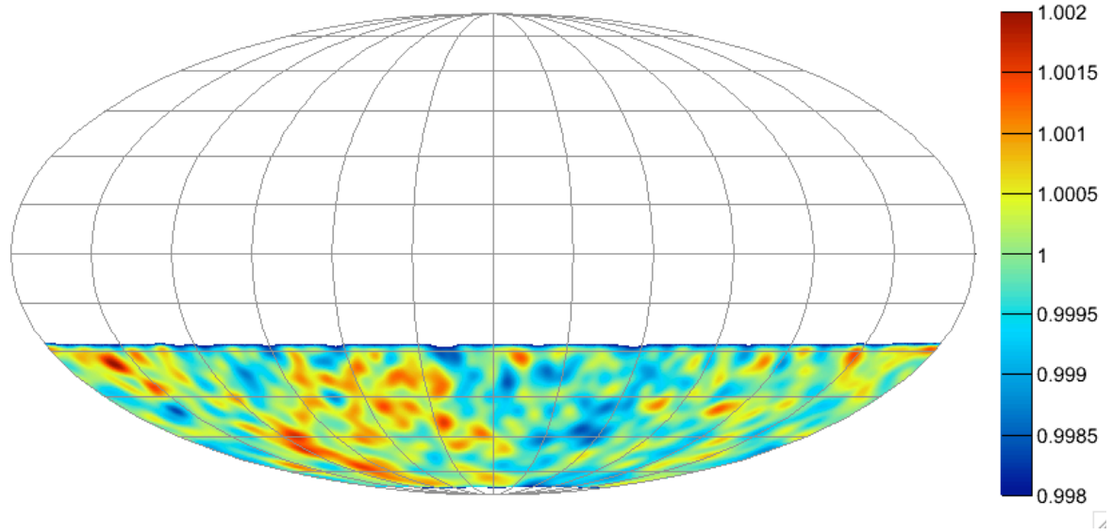
- low temperature (-40°C) noise behavior scales with quantum efficiency as expected.

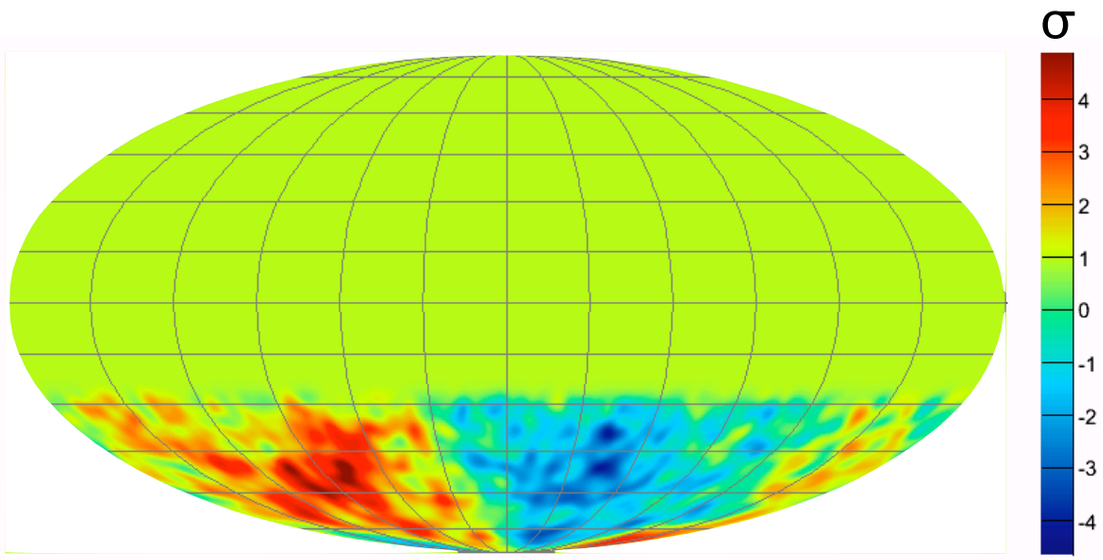
Deep Core (animation)

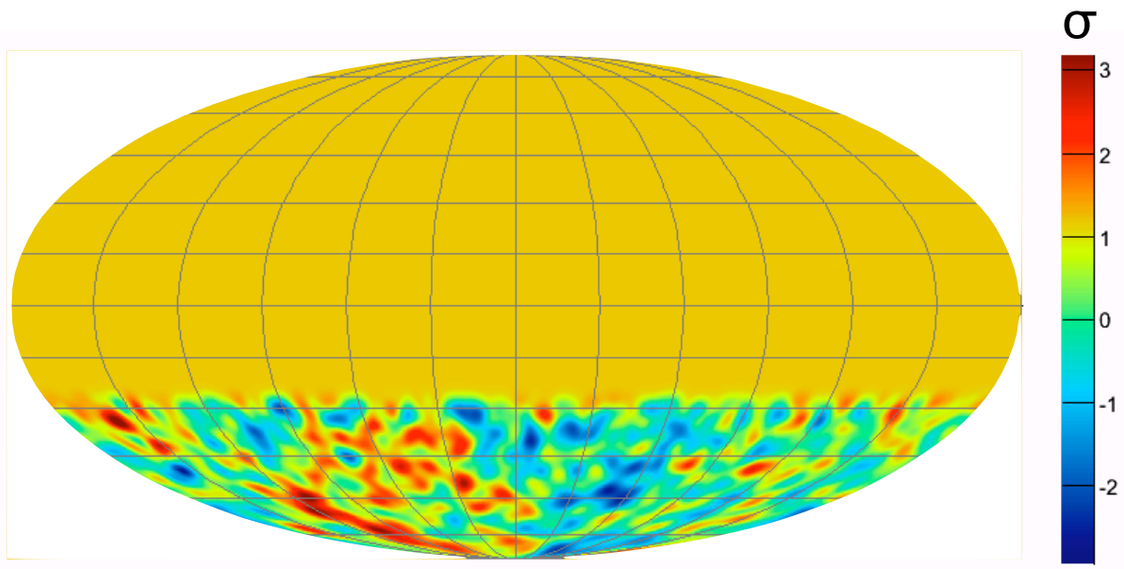
drill (animation)











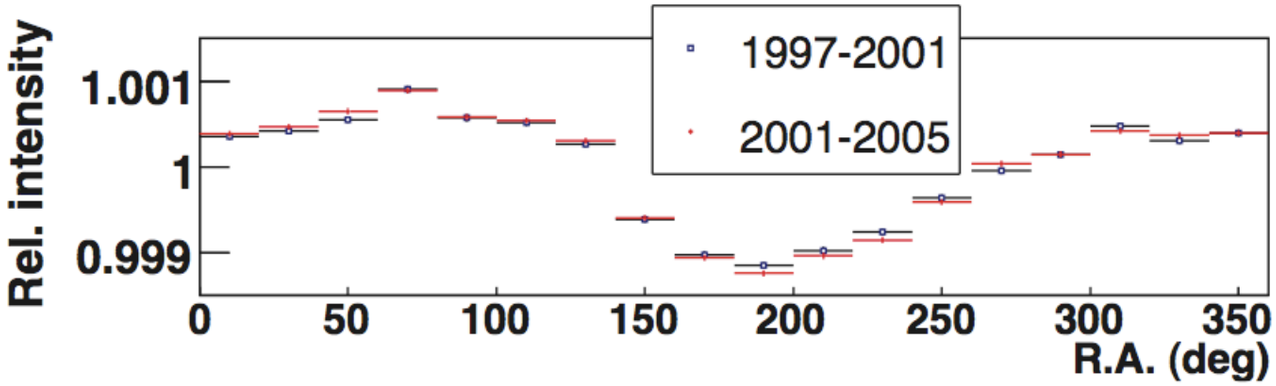
E_{median} = 12 TeV

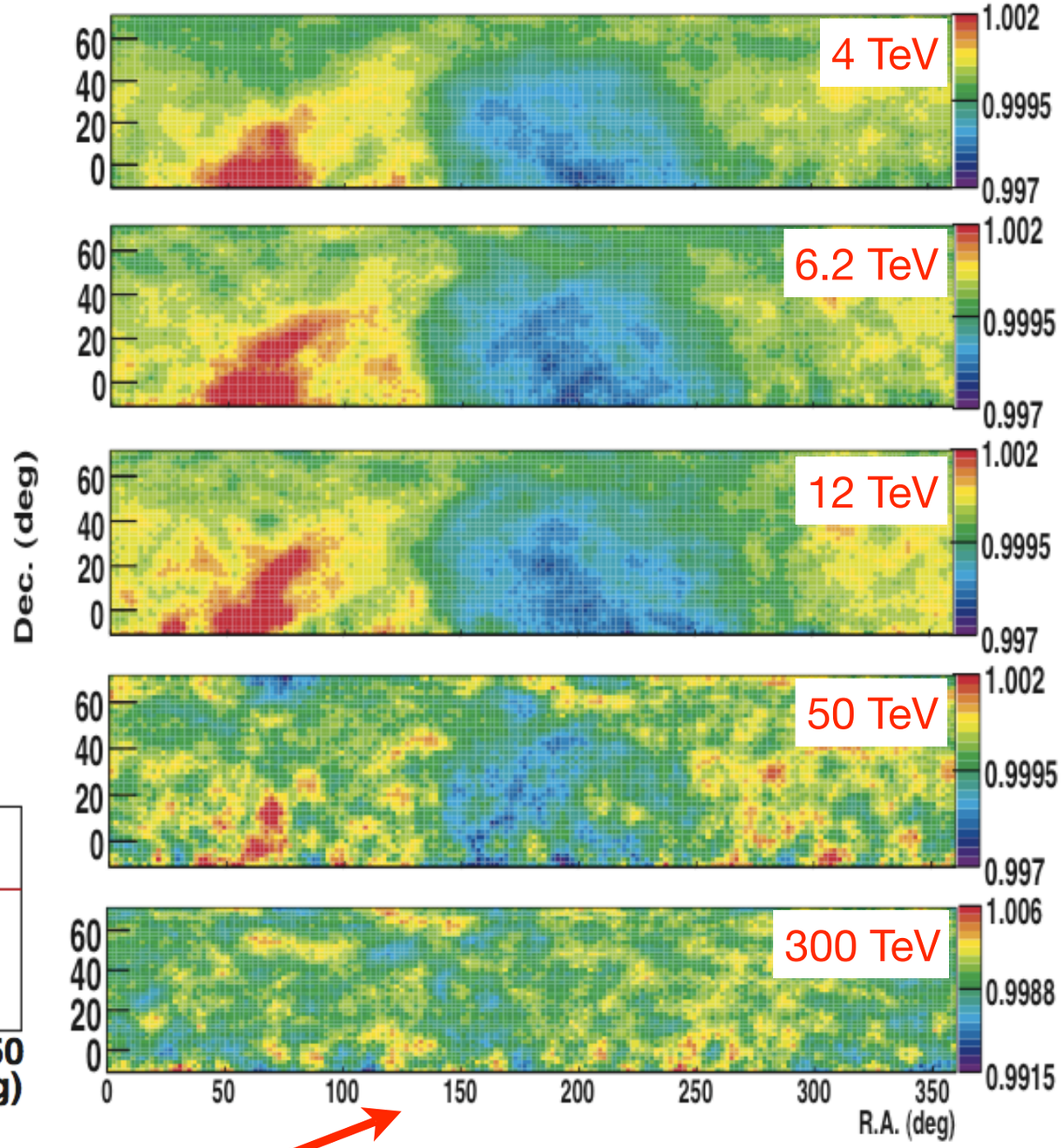
E_{median} = 126 TeV

IceCube-22 : significance

Rasha Abbasi

- data from 1997 to 2005
- 1874 days livetime
- $3.7 \cdot 10^{10}$ events
- angular resolution ~ 0.9°
- modal CR energy ~ 3 TeV



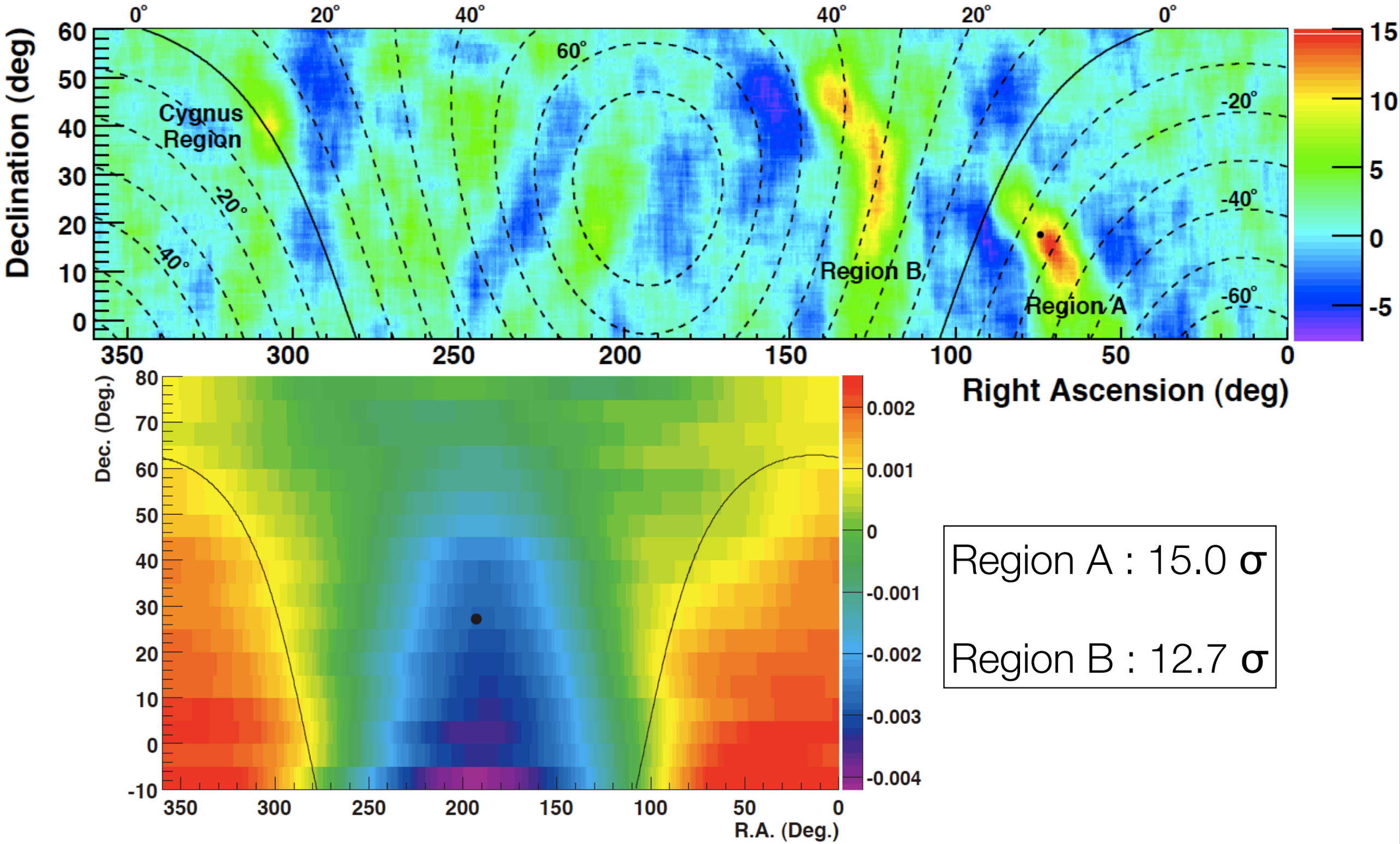


anisotropy seems to disappear :
co-rotation of cosmic rays ?

Tibet-III Array

2D skymap of relative intensity in arrival direction
(normalized in each declination band)

Amenomori et al., Science Vol. 314, pp. 439 (2006)

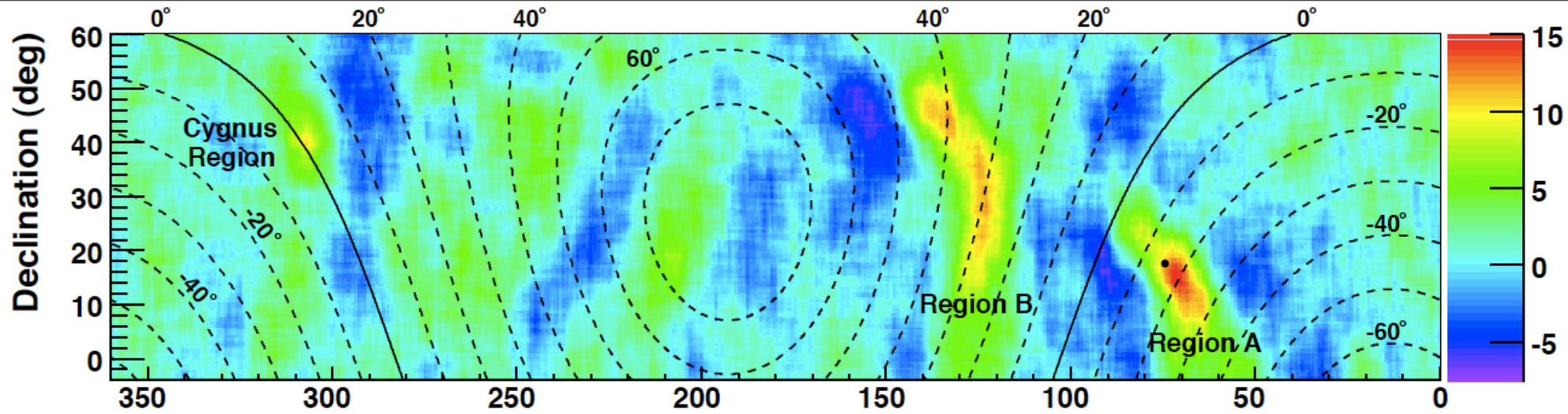


Region A : 15.0 σ

Region B : 12.7 σ

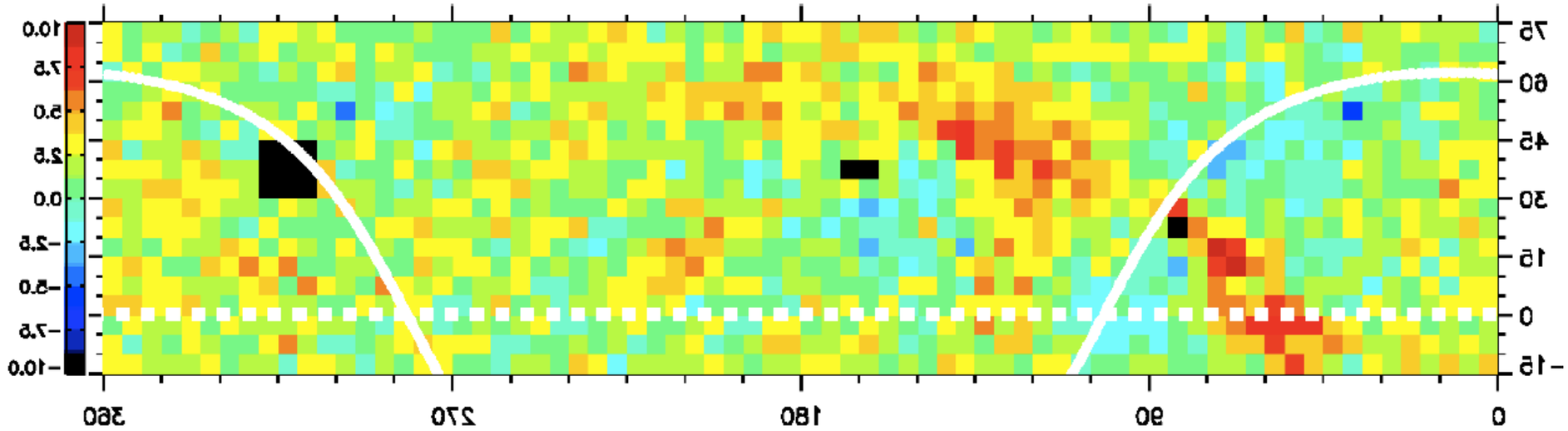
MILAGRO

arXiv:0801.3827



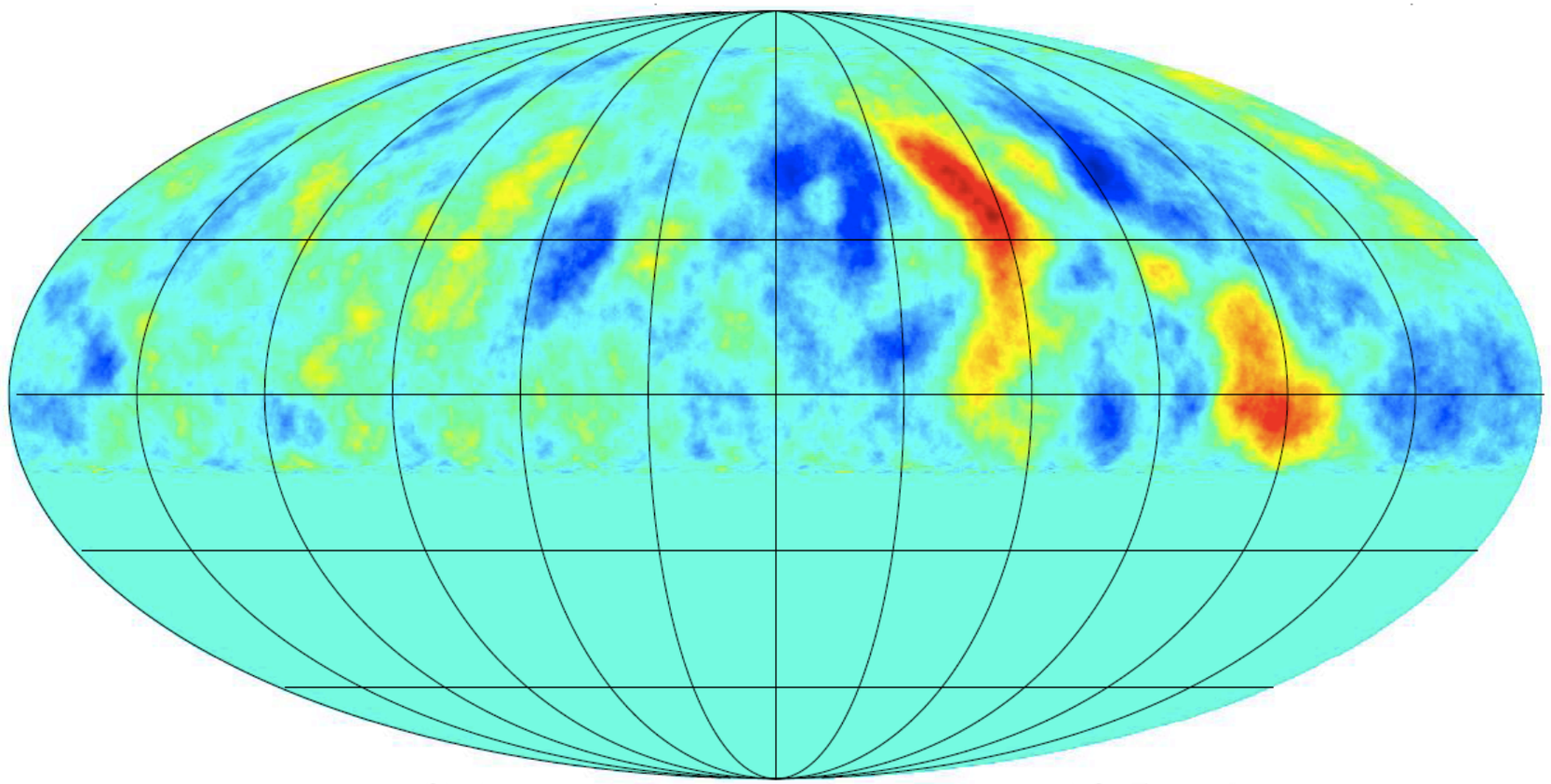
Milagro

direct integration



Tibet-III

global fit



ARGO-YBJ

time scrambling