IceCube - Astro- and Astroparticle Physics at the South Pole

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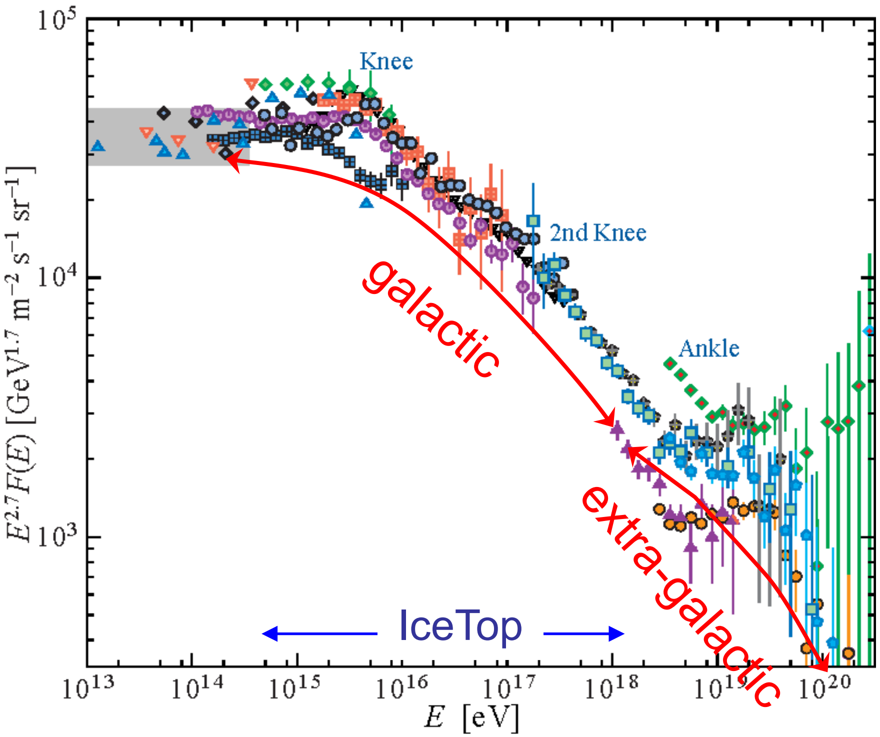
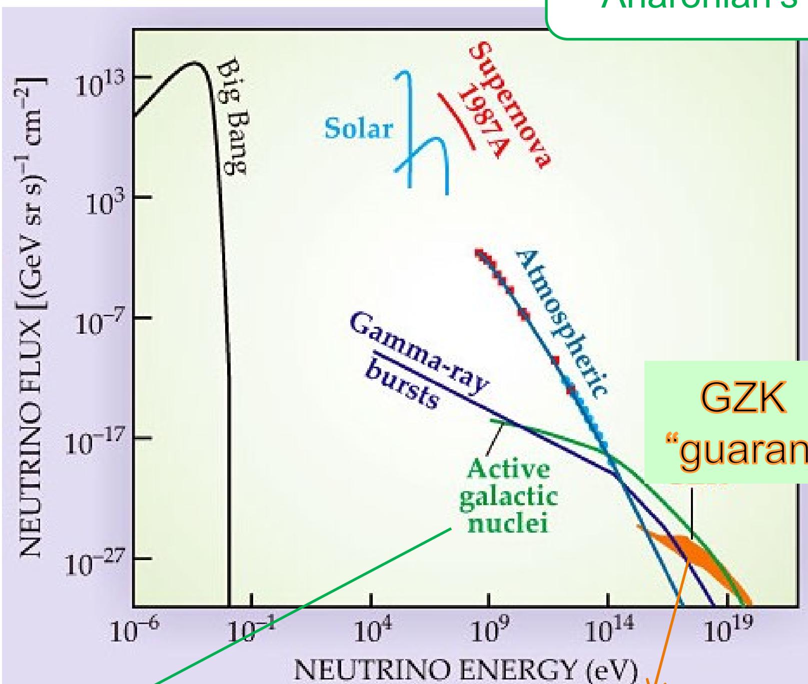
for the IceCube Collaboration

Cosmic Rays and Neutrinos

Driving theme: Origin of Cosmic Rays

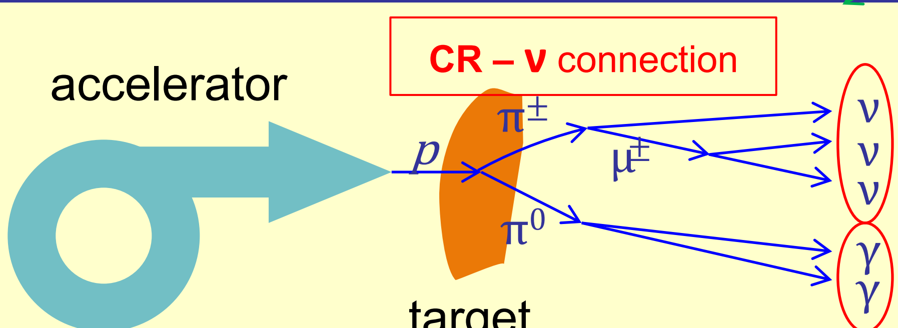
motivation given in Aharonian's talk





GZK ν's: "guaranteed"

$$\gamma_{cmb}\, p \to \Delta^+ \to \begin{matrix} n\,\pi^+ \to n\,\mu\nu \\ p\,\pi^0 \to p\,\gamma\gamma \end{matrix}$$



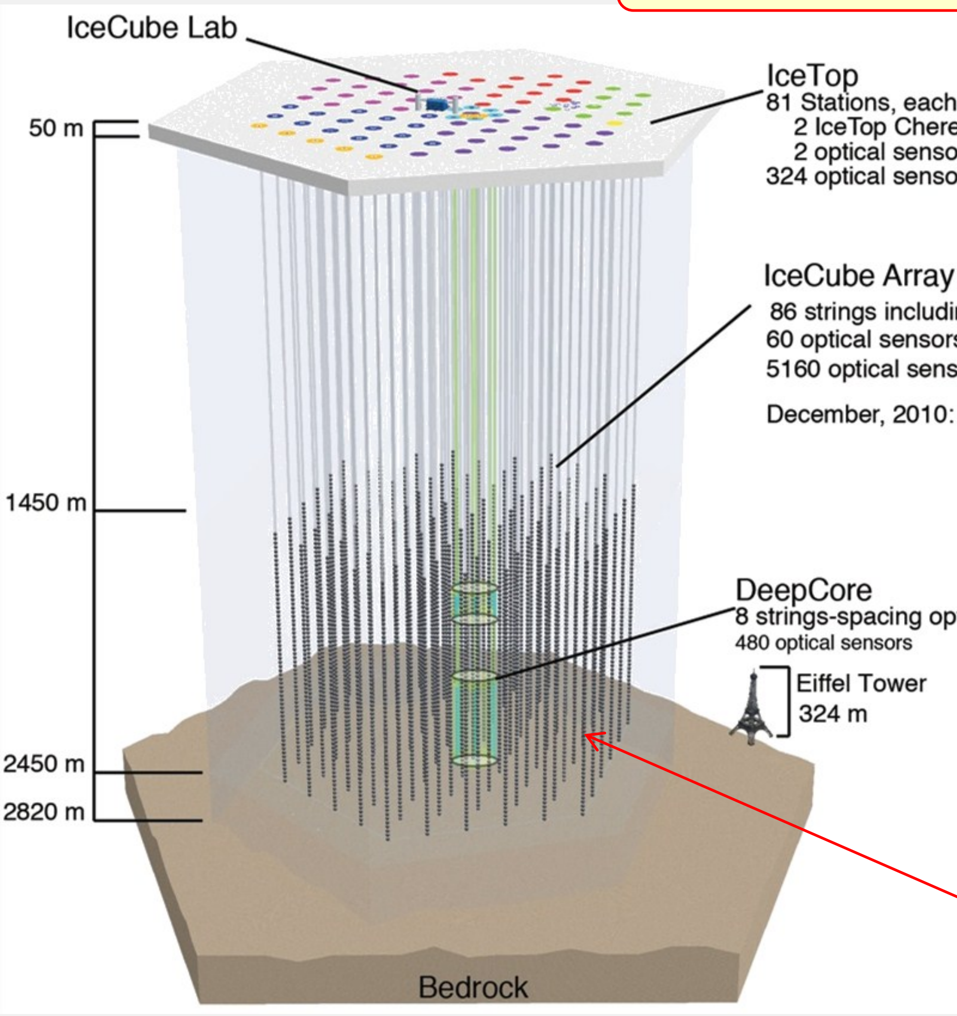
the γ – ν connection for hadronic accelerators

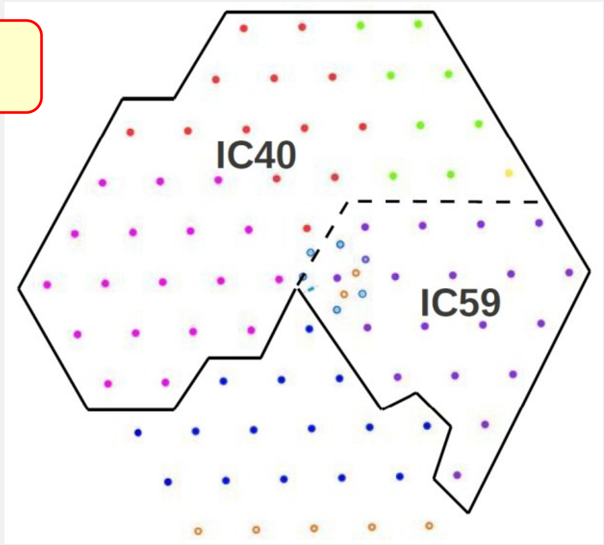
Outline

- Detector: IceCube, DeepCore, IceTop
- Neutrino Point Sources: integrated, time dependent, Multi-Messenger, GRB, Follow-Up
- Diffuse Flux of Neutrinos: Muon Neutrinos, Cascades and All-Flavour,
- Exotics: Dark Matter and Monopoles
- Cosmic Rays: Anisotropy, Composition, ..

IceCube Detector

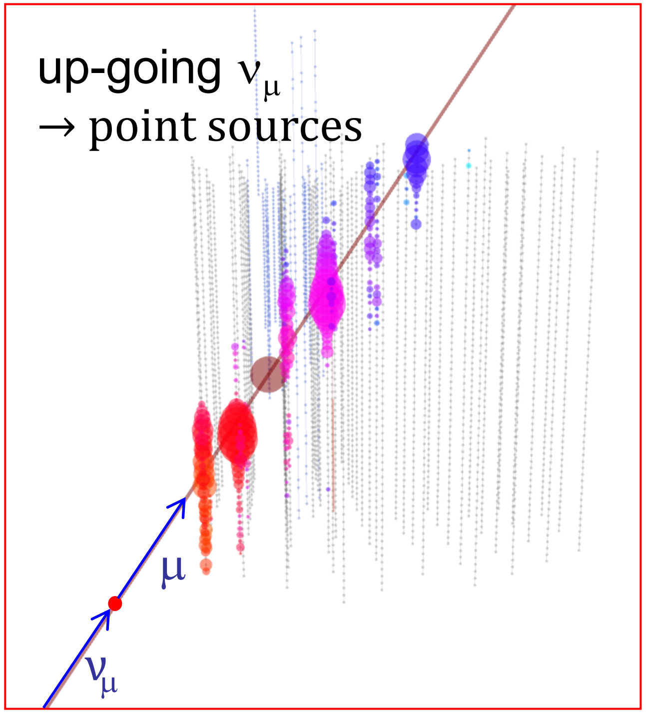
Detector Completion Dec 2010

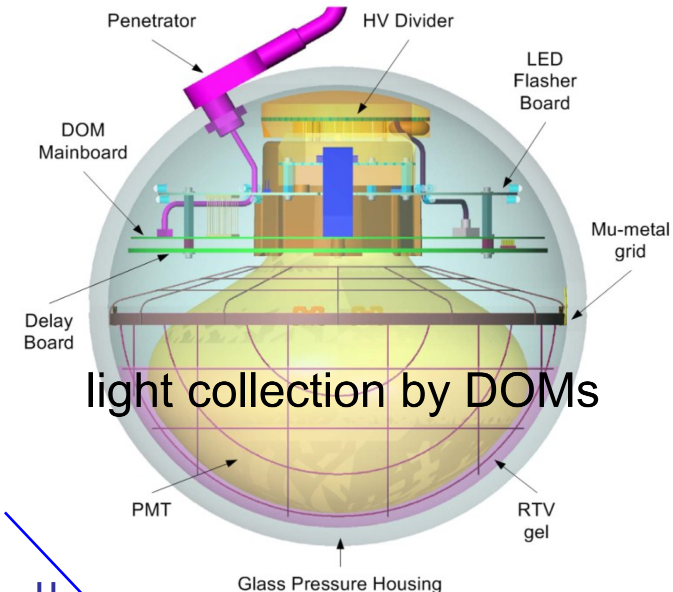


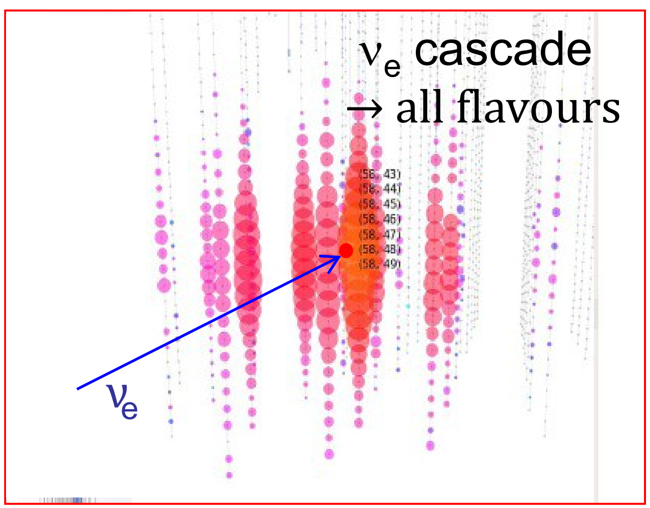


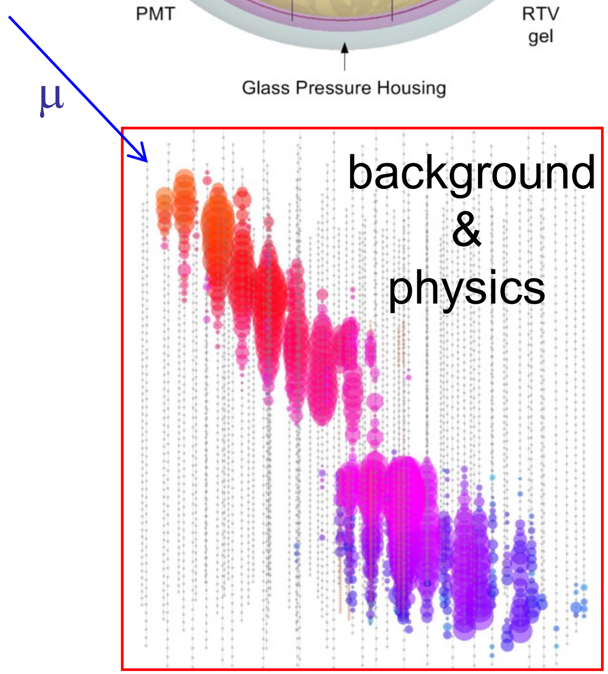
9 strings (2006)
22 strings (2007)
40 strings (2008)
59 strings (2009)
79 strings (2010)
86 strings (2011)

Detection Methods

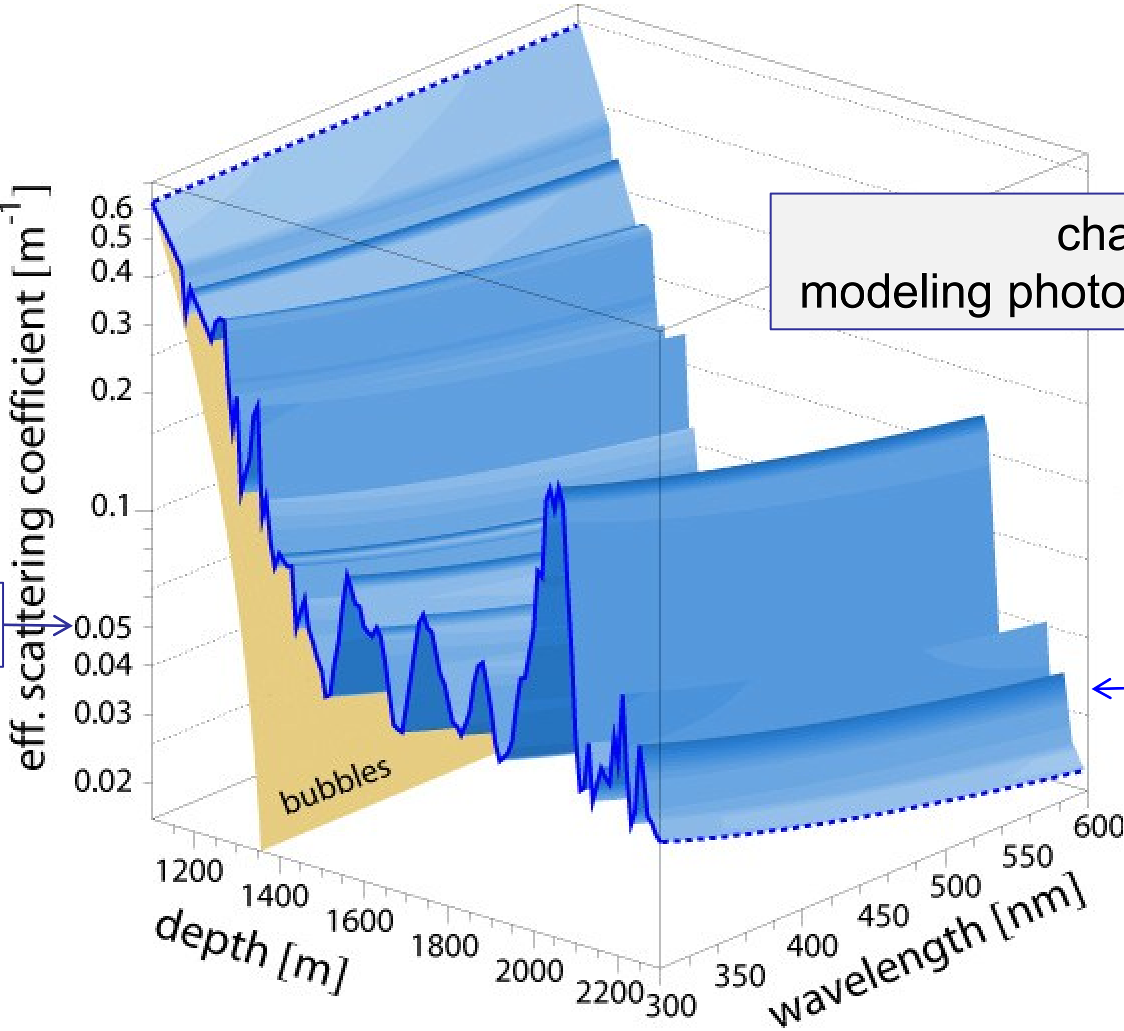








Ice Properties

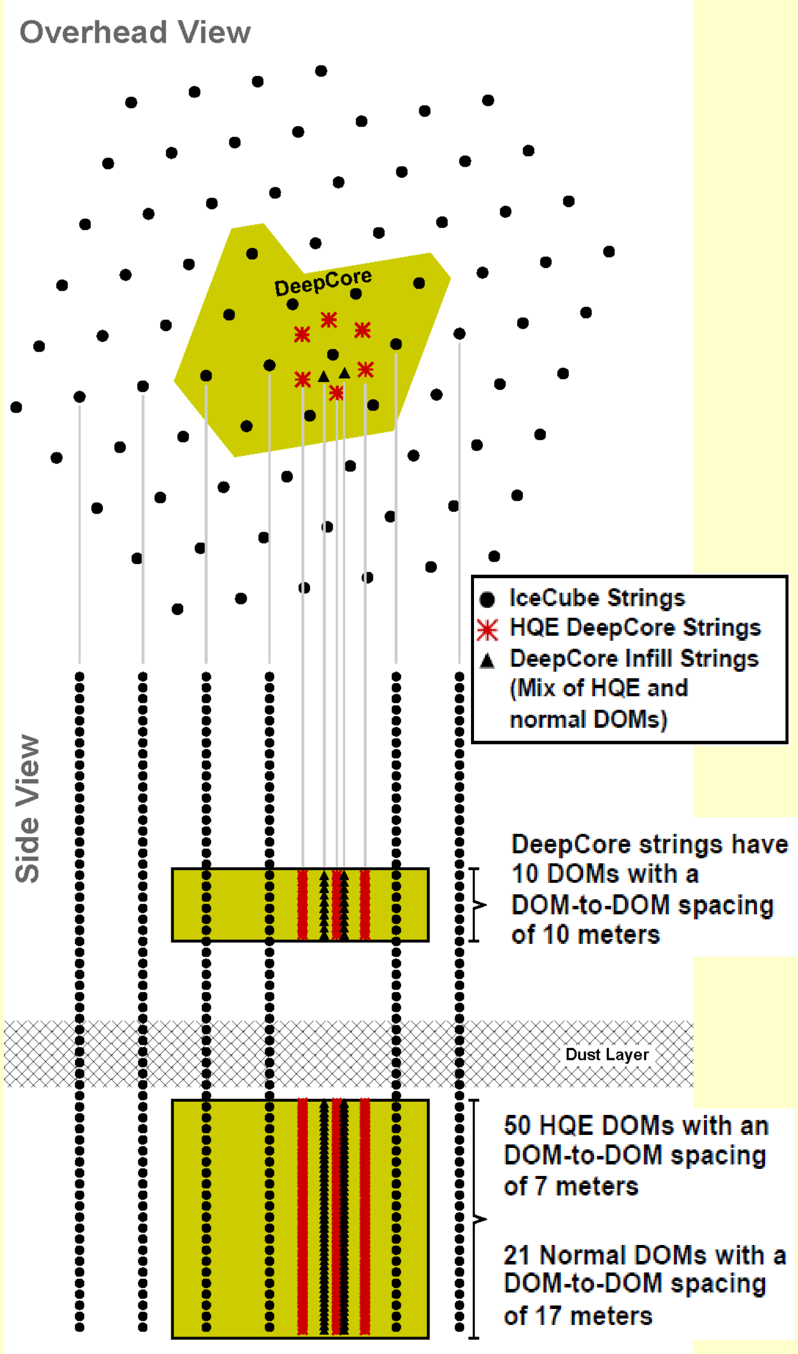


challenge:
modeling photon propagation in ice

λ_{eff} = 20 m

DeepCore

paper #333 Study of South Pole ice transparency with IceCube flashers



DeepCore

8 dense plus the 12 standard strings in clear ice

(in IC79 equivalently 6 + 7 strings)

Energy threshold:

- down to ~10 GeV (from ~ 1 TeV)

Extends physics:

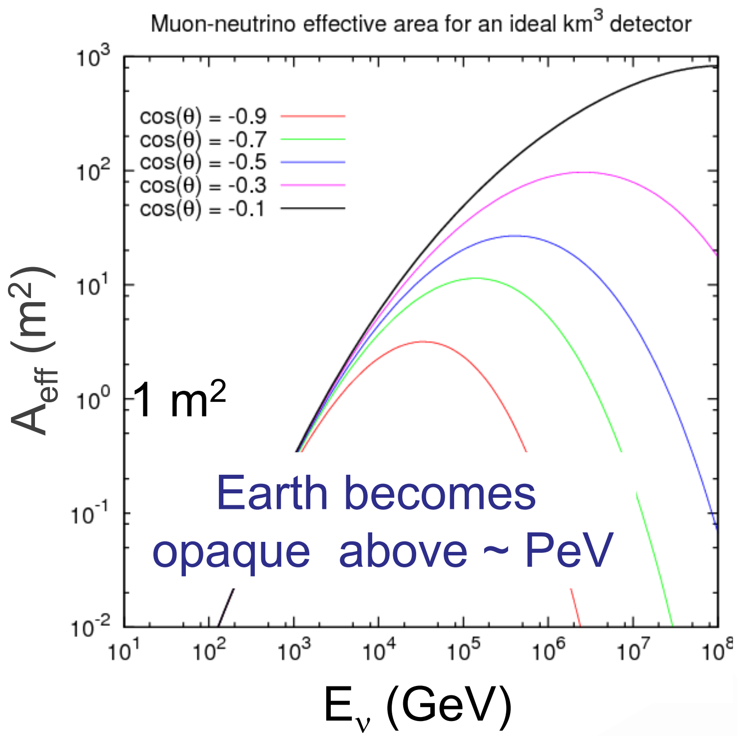
- atm ν oscillations,
- low mass WIMPS
- SN/GRB physics

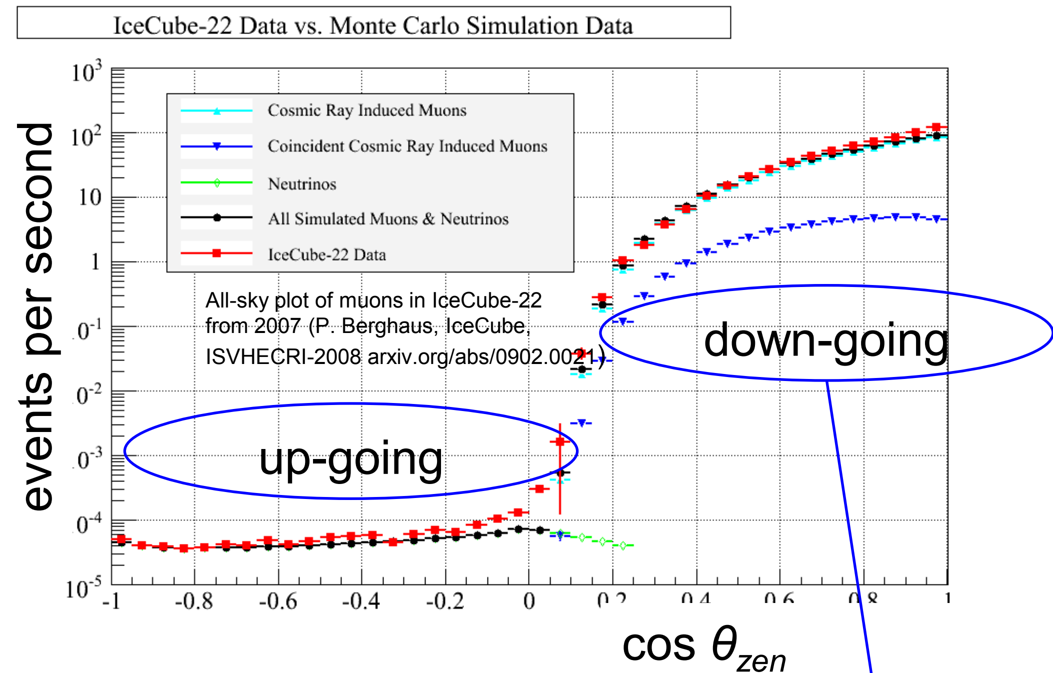
An early success:

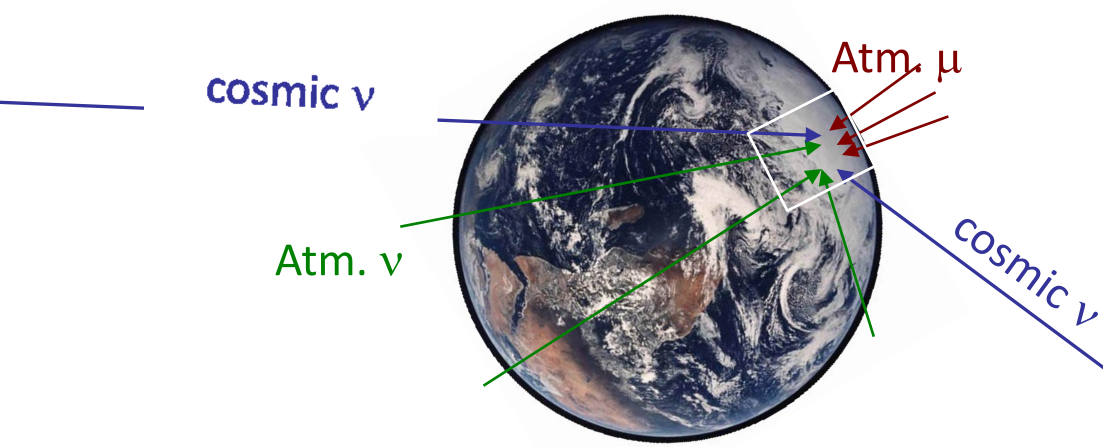
Observation of atmospheric neutrino-induced cascades in IceCube-DeepCore

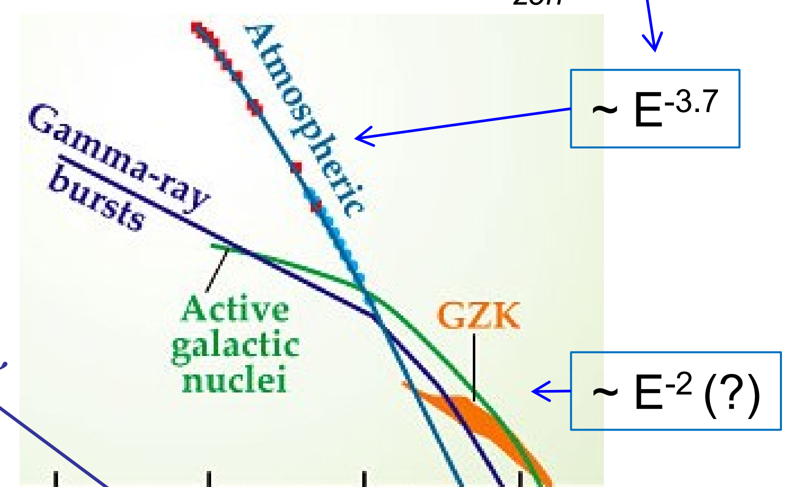
#324	Observation of Atmospheric Neutrino-induced Cascades in IceCube-DeepCore
#329	Atmospheric Neutrino Oscillations with DeepCore
#288	Search for choked GRBs using IceCube's DeepCore

Muon Neutrino Effective Area

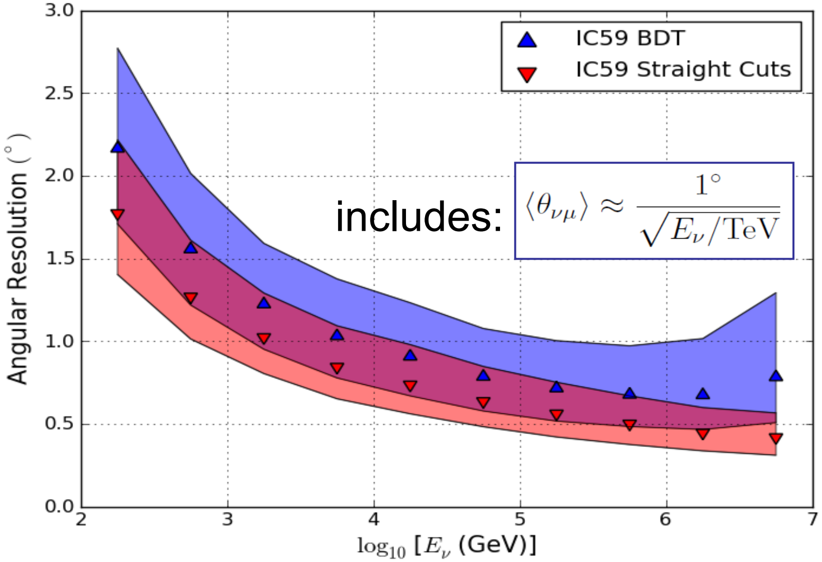






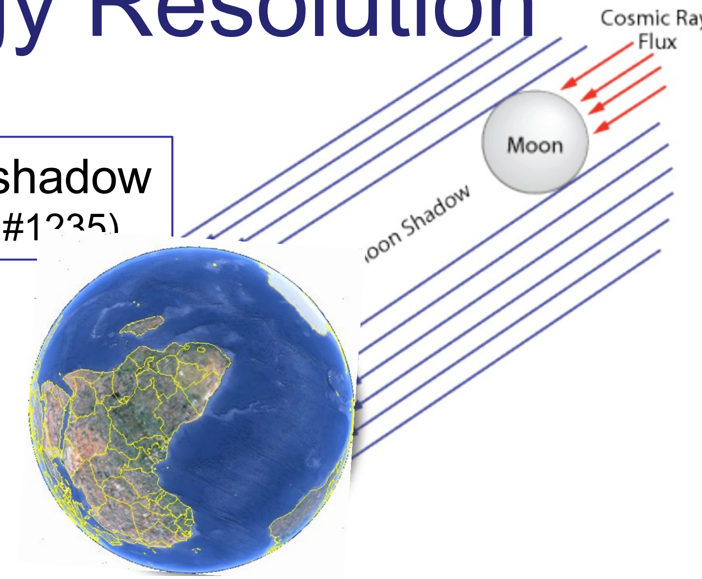


ν_μ Angular and Energy Resolution

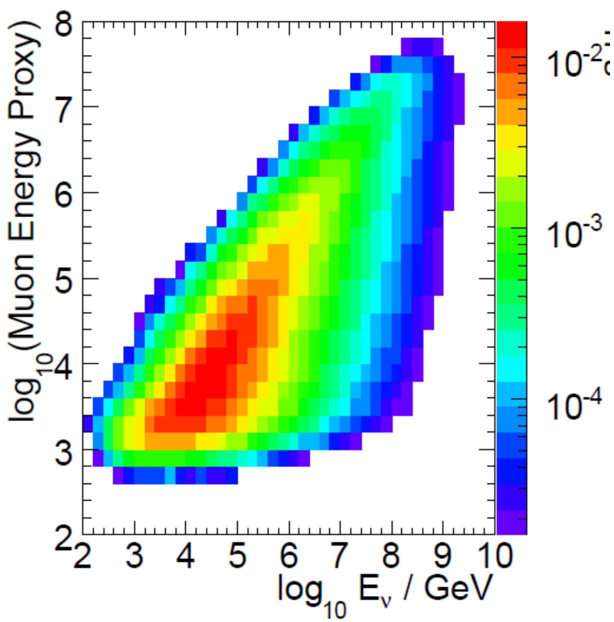


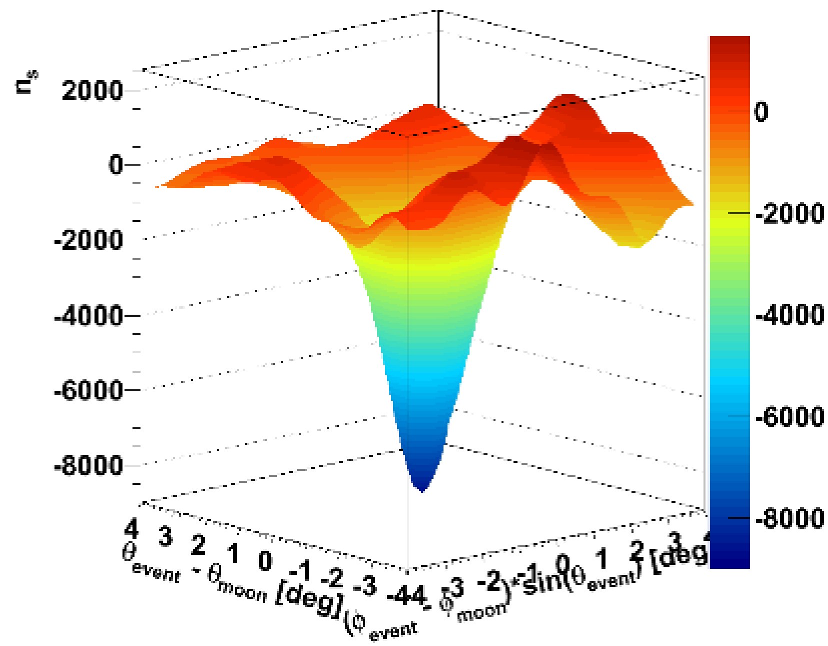
includes: $\langle\theta_{\nu\mu}\rangle \approx \frac{1^\circ}{\sqrt{E_\nu/\mathrm{TeV}}}$

Moon shadow
(paper #1235)

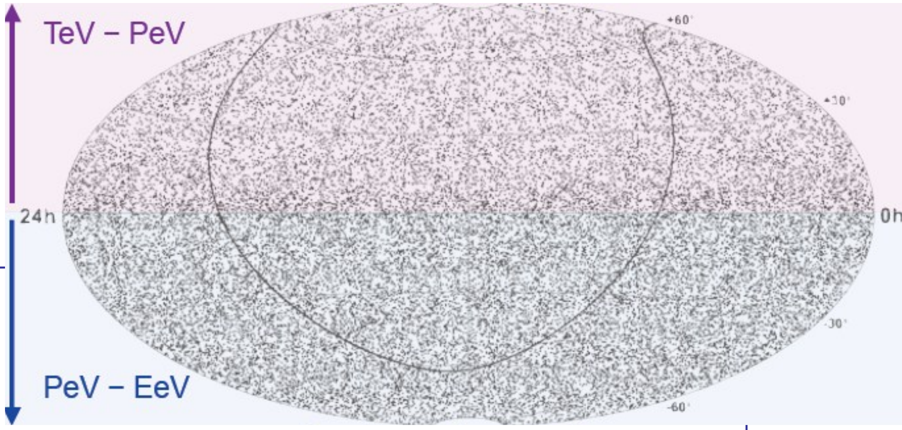


ν_μ energy estimated from dE/dx of muon (bremsstr.)





Point Source Search



- time integrated all sky scan

Trial factor, e.g. each point in sky checked, delutes significance

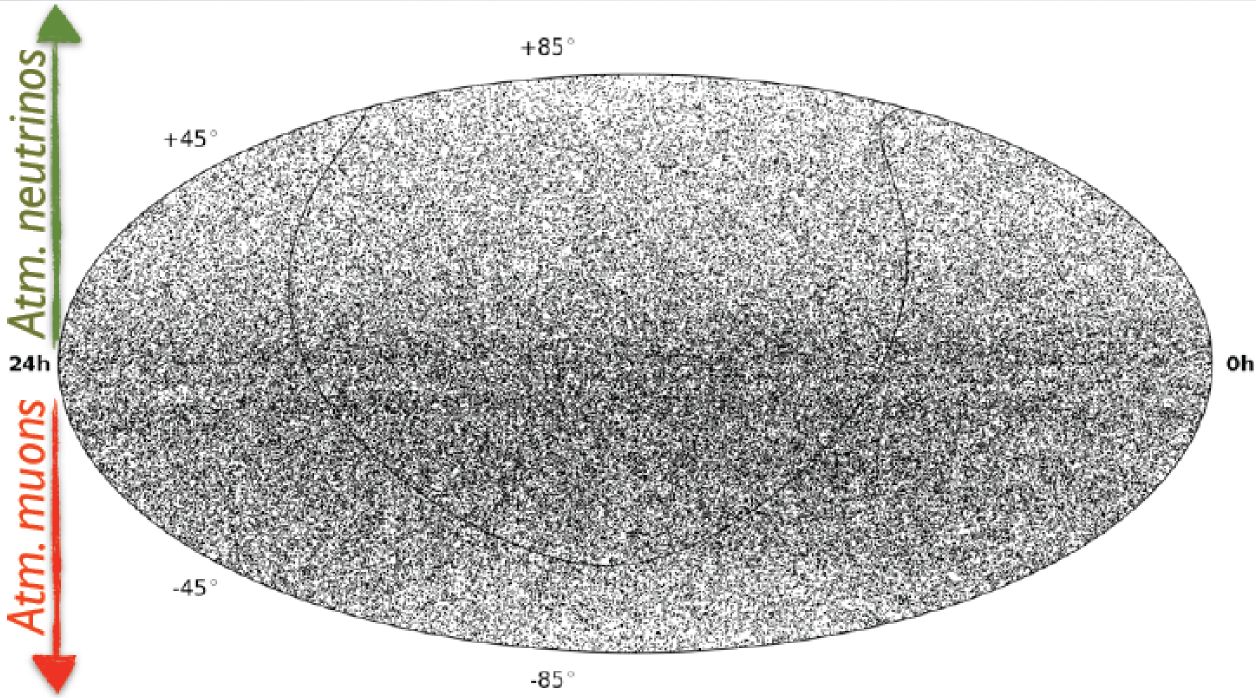
Measures to reduce trials and enhance significance by
correlation in space and time:

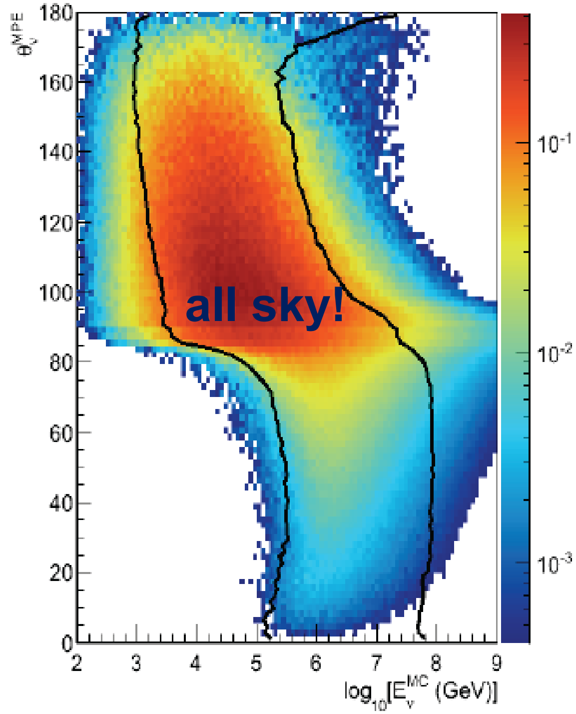
- list of candidate sources (single or stacking)
- transients + multi-messenger: flares, GRB, SN ...
- independent confirmation: follow-up program (optical, X-ray, γ-ray)

Beating Statistics:
Reduce Trials

Point Source Search in Skymap (IC40+59)

43339 up-going + 64230 down-going from 723 days





unbinned likelihood

$$L(n_s, \gamma) = \prod_{i=1}^{N} \left(\frac{n_s}{N} S_i + \left(1 - \frac{n_s}{N}\right) B_i \right)$$

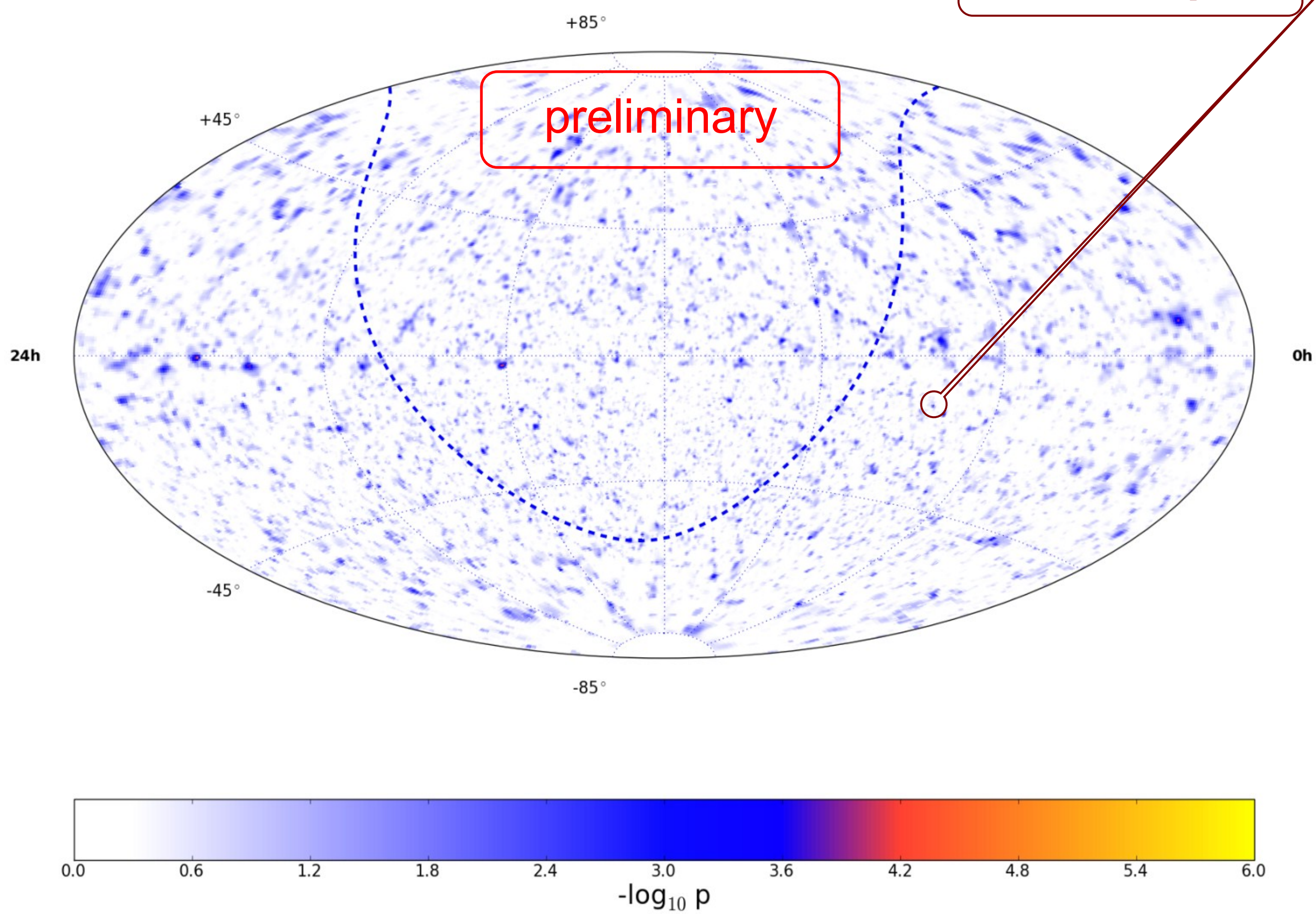
signal term contains angular and energy pdf

test statistics:

$$\lambda = \frac{L(\hat{n}_s, \hat{\gamma})}{L(n_s = 0)} \Rightarrow \mathrm{p-value}$$

Significance Skymap (IC40+59)

papers #909



Hottest spot:

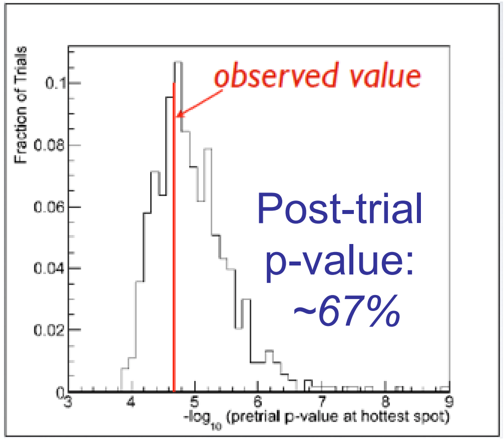
ra: 75.45 dec: - 18.15

$-\log_{10} p = 4.65$

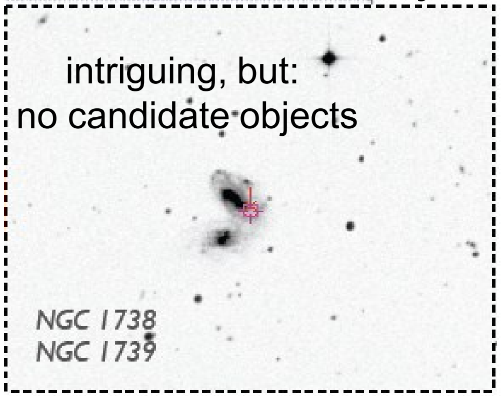
$\hat{n}_s = 18.3$

$\hat{\gamma} = 3.9$

but: $\mathcal{O}(100000)$ **trials**

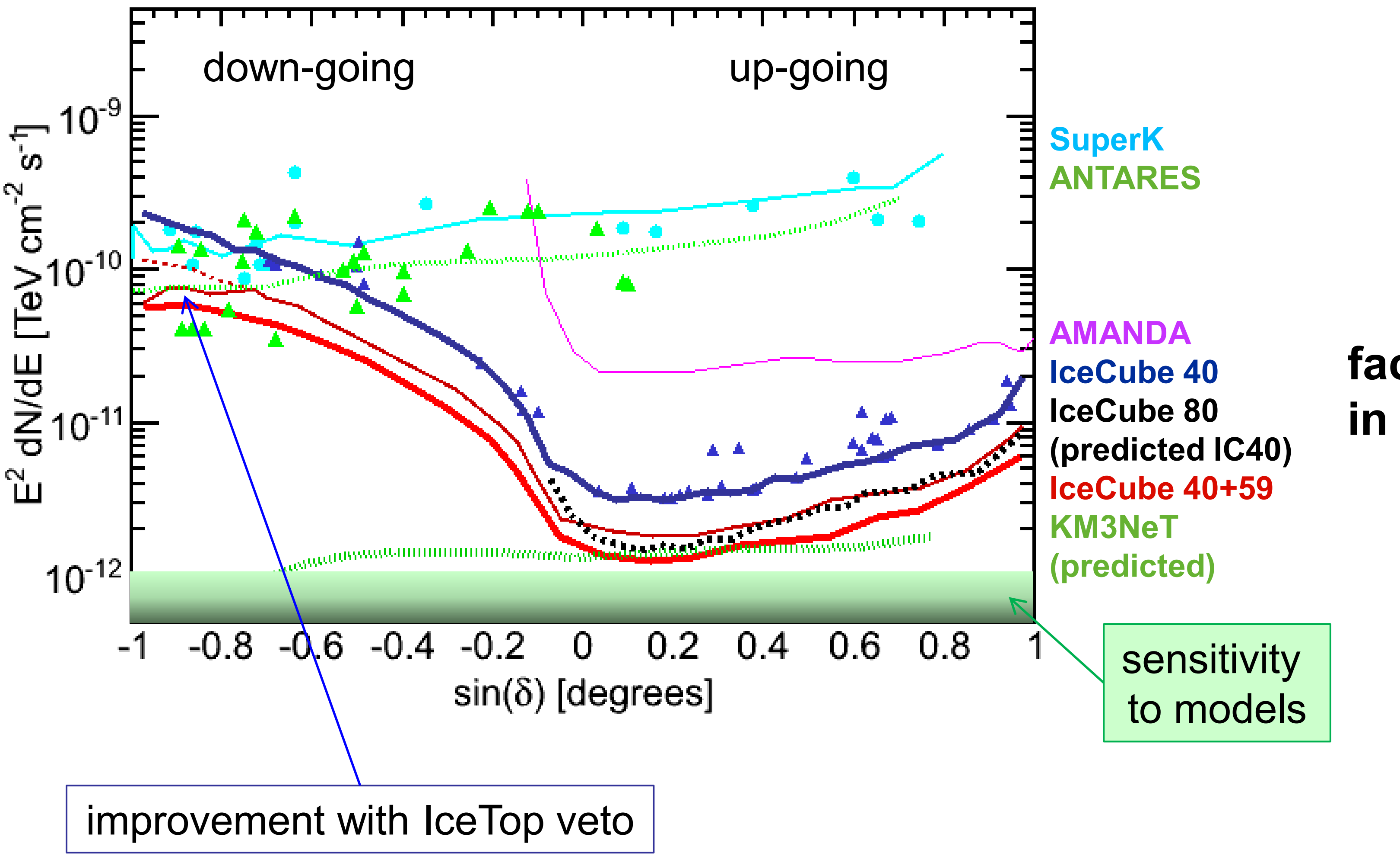


correlation with an object?



Neutrino Point Source Upper Limits

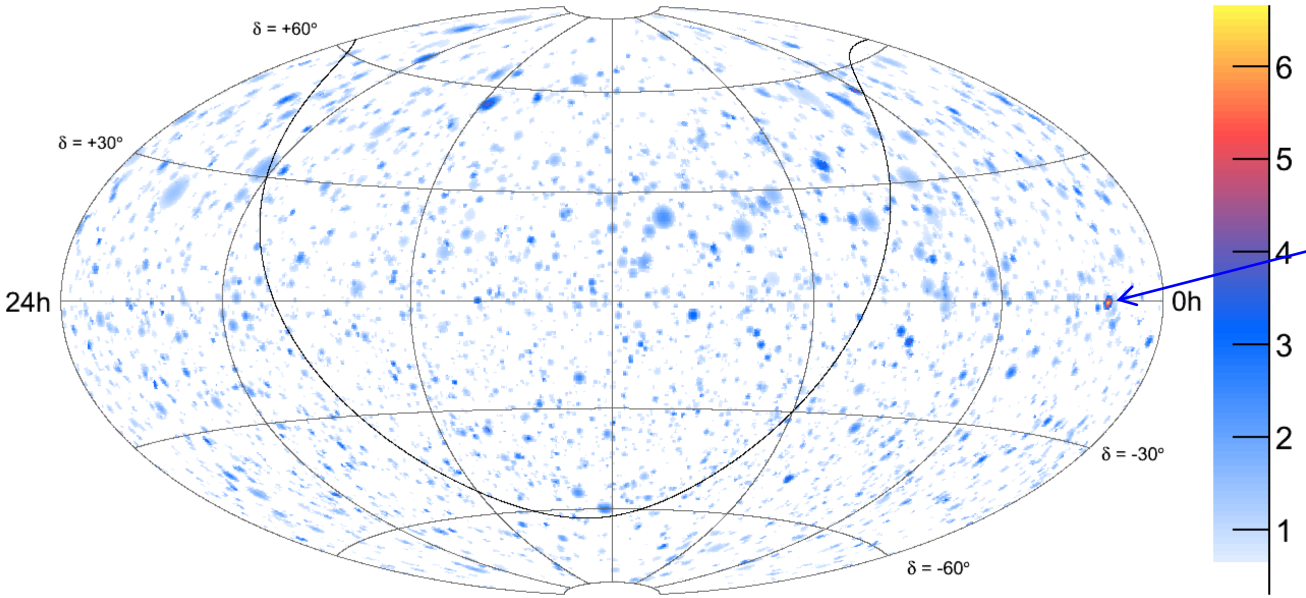
90% CL sensitivity for E-2 spectrum

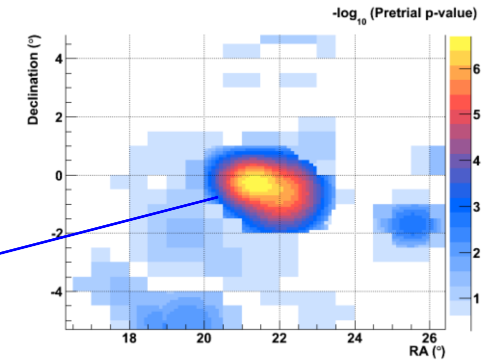


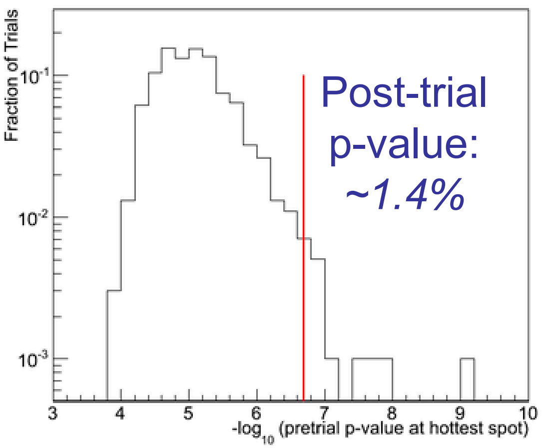
factor 1000 in 15 years

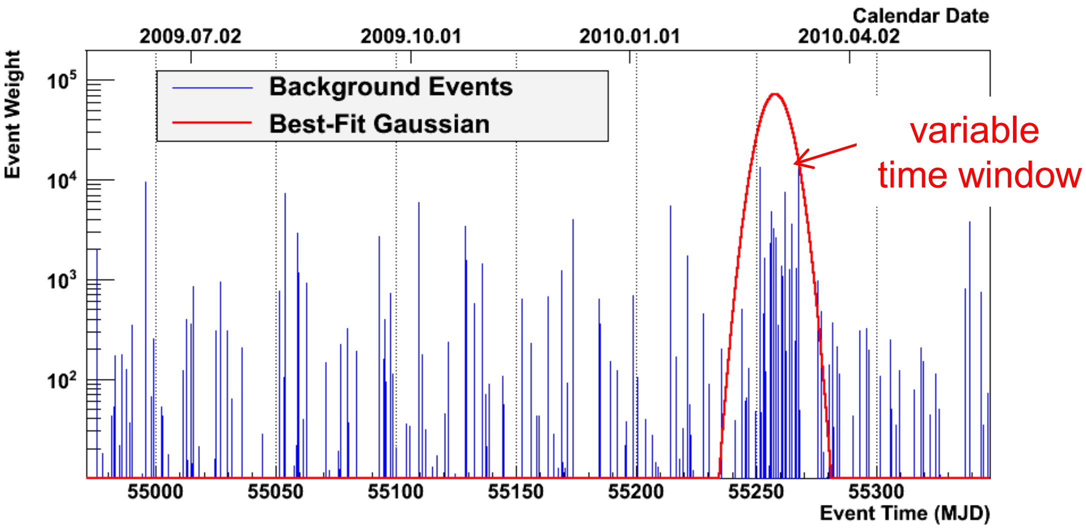
Time Dependent Point Source Searches

papers #784, #289









interesting fluctuation!
however, no known object
found in this region of sky

Follow-Up Programs

IceCube sees always the full sky!

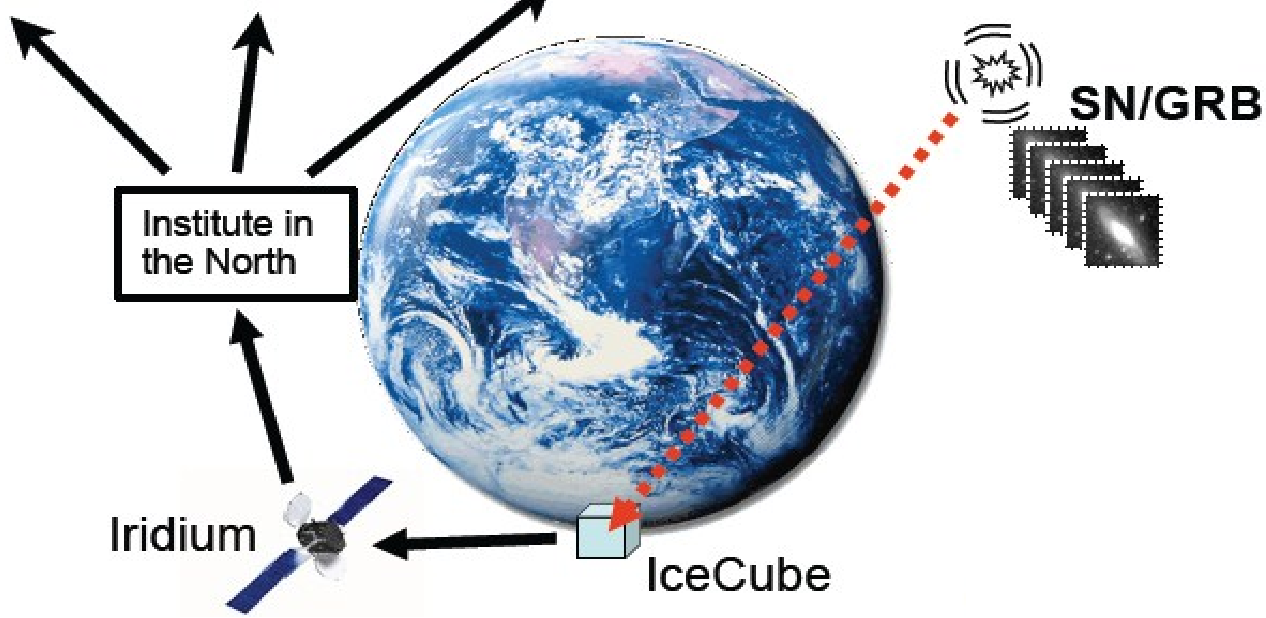
- **Trigger other instruments** (IACTs, X-ray satellites, optical telescopes . . .)

MAGIC

Swift

ROTSE, PTF

papers
#334
#535
#445

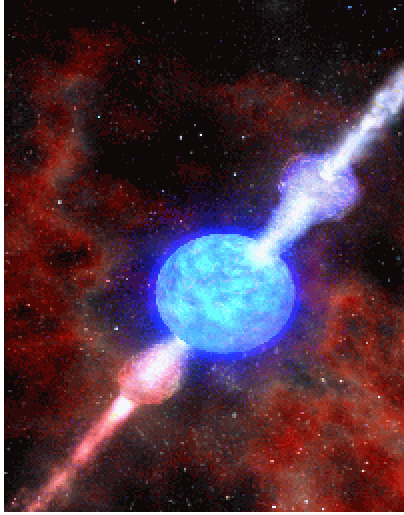


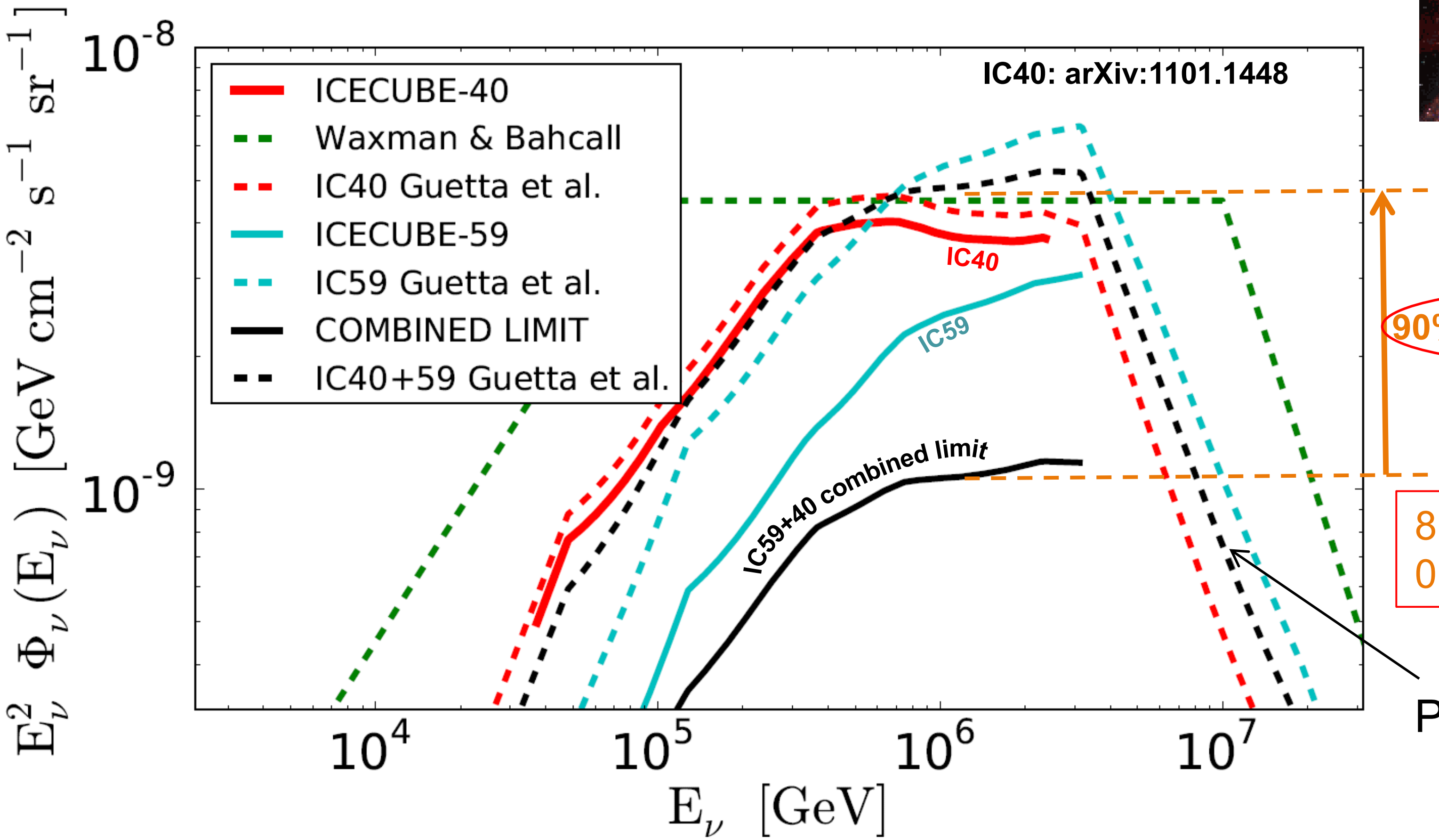
- **Multiplet trigger:** (example optical)
  - angular window 4°
  - time window 100 s
  - Delay < 5 min

Gamma Ray Bursts

papers #764

Searches for neutrinos produced
by p+γ interactions by internal jet





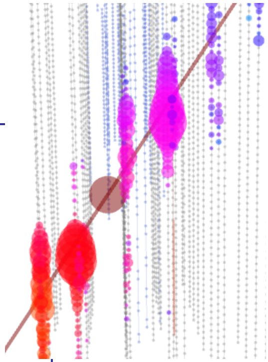
90% c.l. = 0.22 × model

8 events expected
0 events observed

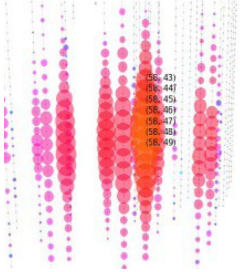
Parameters: boost and time scale

#288	Search for choked GRBs using IceCube's DeepCore

Search for a **Diffuse Flux** of Cosmic Neutrinos



- muon neutrino flux



- electron/tau neutrino flux (cascades)

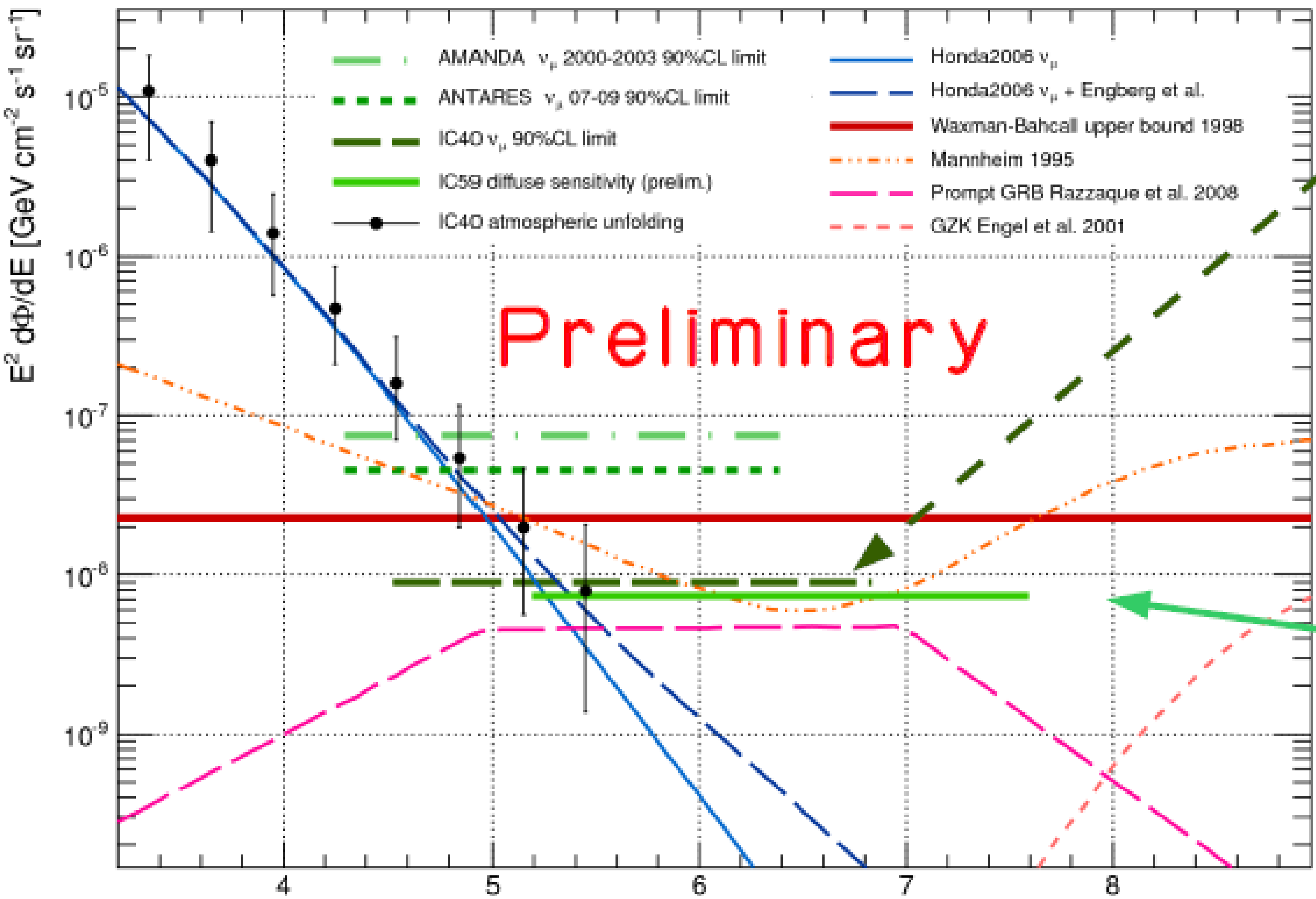
- Extremely-high Energy Cosmic Neutrino Flux

Background:

- atmospheric neutrinos at low energies
- cosmic ray muon bundles at high energy
- Rejection: mostly energy dependence, harder spectrum e.g. E^{-2}

Diffuse μ Neutrino Flux

papers #736
#833 (atm)



No systematics included in IC59 sensitivity, yet.

IC40 result

90%CL upper limit at

$8.9 * 10^{-9}$ GeV^{-1} cm^{-2} s^{-1} sr^{-1}

Factor 2.5 below the WB upper bound

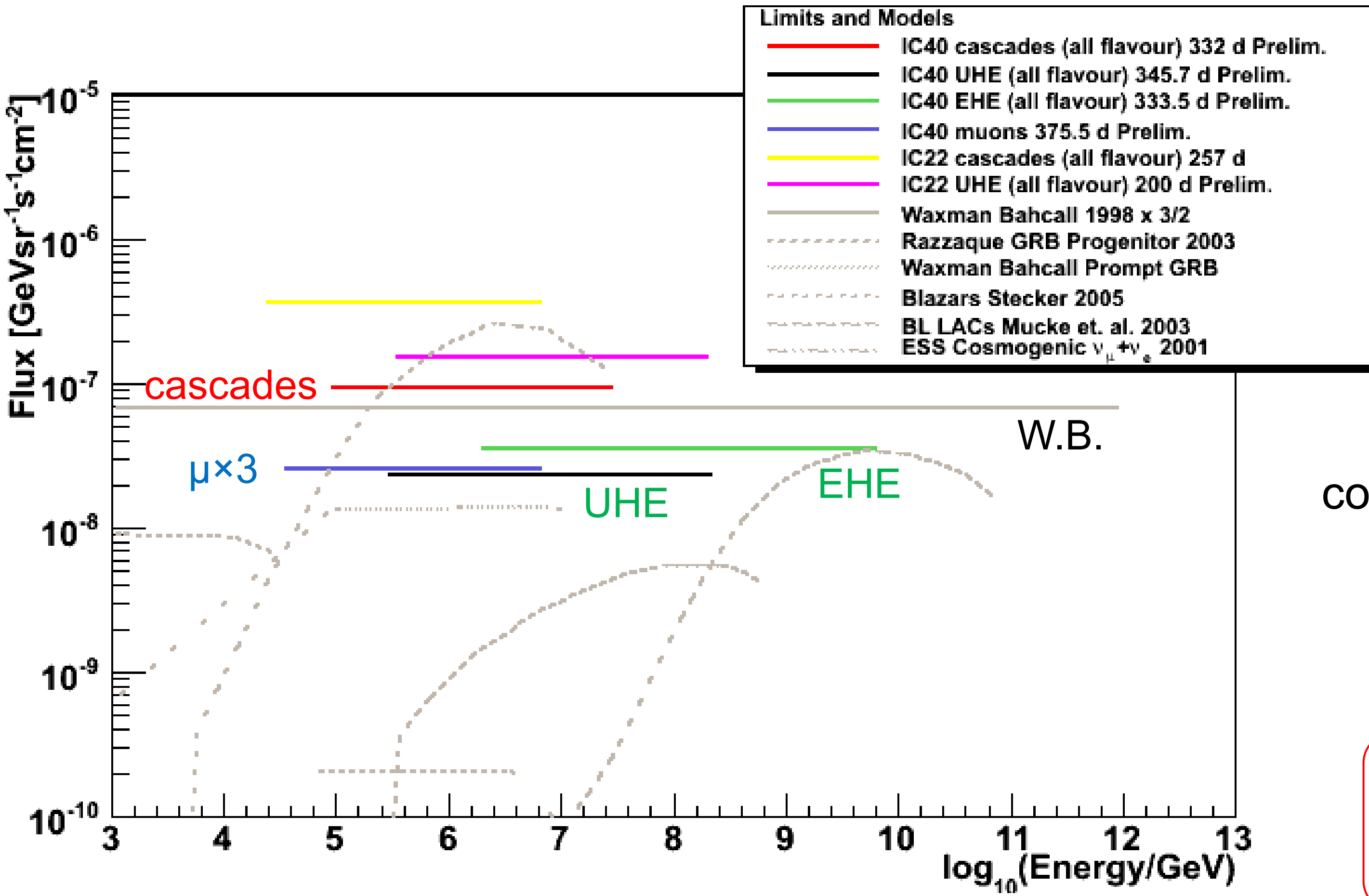
IC59 Prelim. sensitivity

$7.2 * 10^{-9}$ GeV^{-1} cm^{-2} s^{-1} sr^{-1} (without neutrino knee)

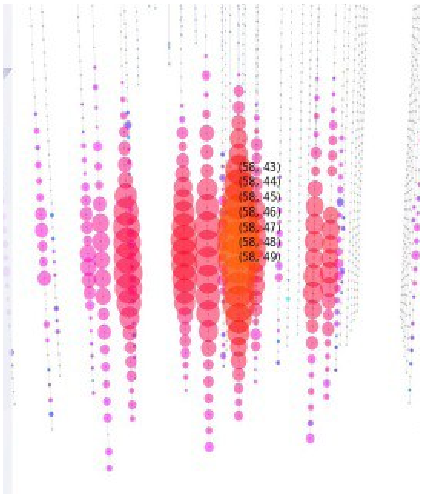
~ factor 3 below the WB upper bound

Diffuse All-Flavour Neutrino Flux

- Access to **all-flavour** fluxes,
- better **energy resolution** than for μ neutrinos
- IceCube starts seeing cascade candidates -- but understanding of background has to be worked on



Cascades

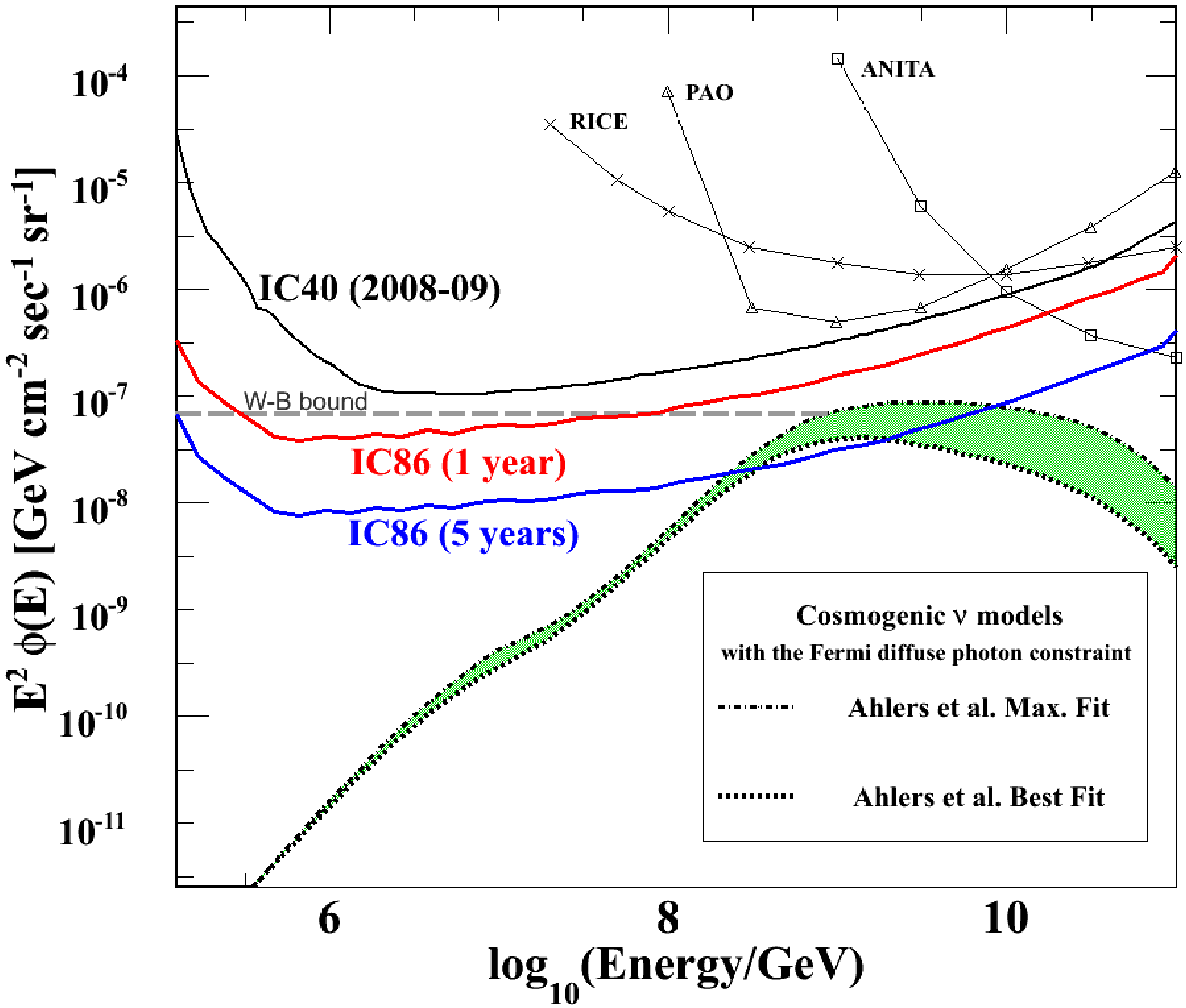


~10 candidates for cosmic ν's found in IC40

Background?
charm?

diffuse flux in cascades:
#0759 (IC40)
#1097 (atm)
#0324 (IC-DC IC79, atm)

Constraints on the EHE Neutrino Flux (IC40)



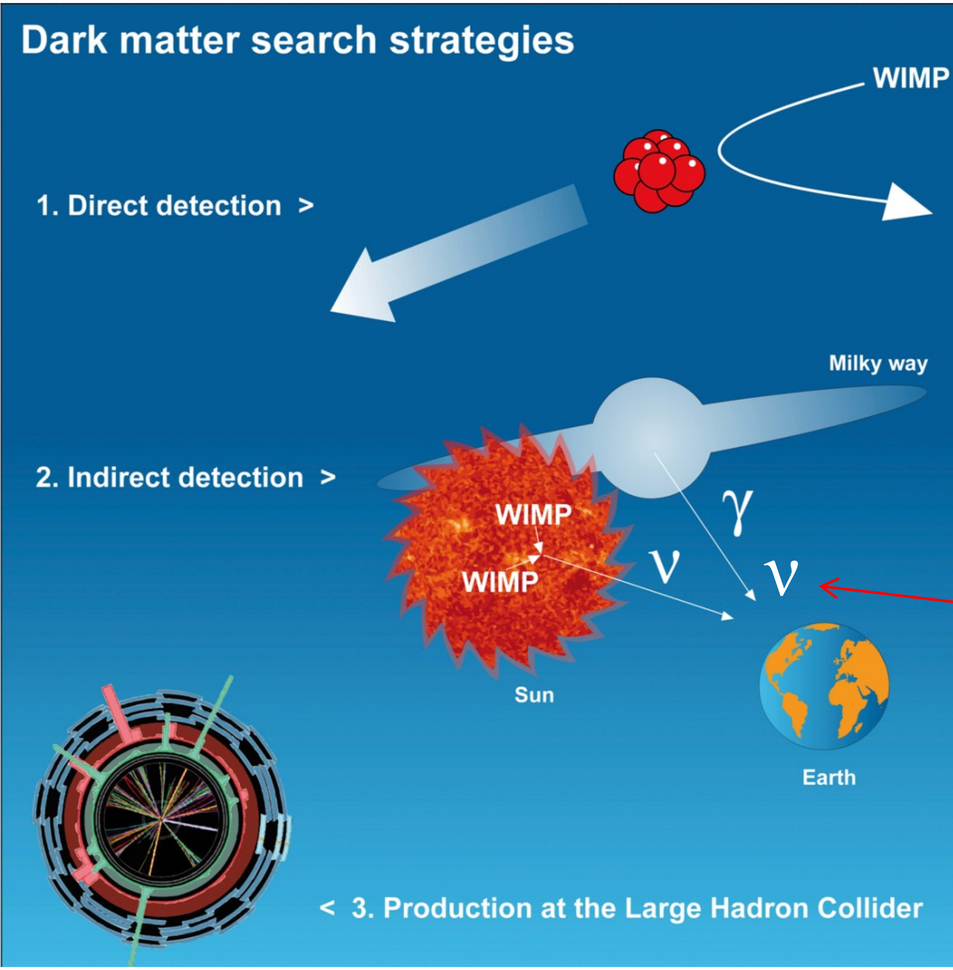
papers #949 #778 #773

possible improvements (e.g. IceTop veto)

limits are touching GZK predictions of “guaranteed” EHE neutrinos

Exotics: Dark Matter, Monopoles ....

Dark Matter Searches: SUSY, WIMPS, KK



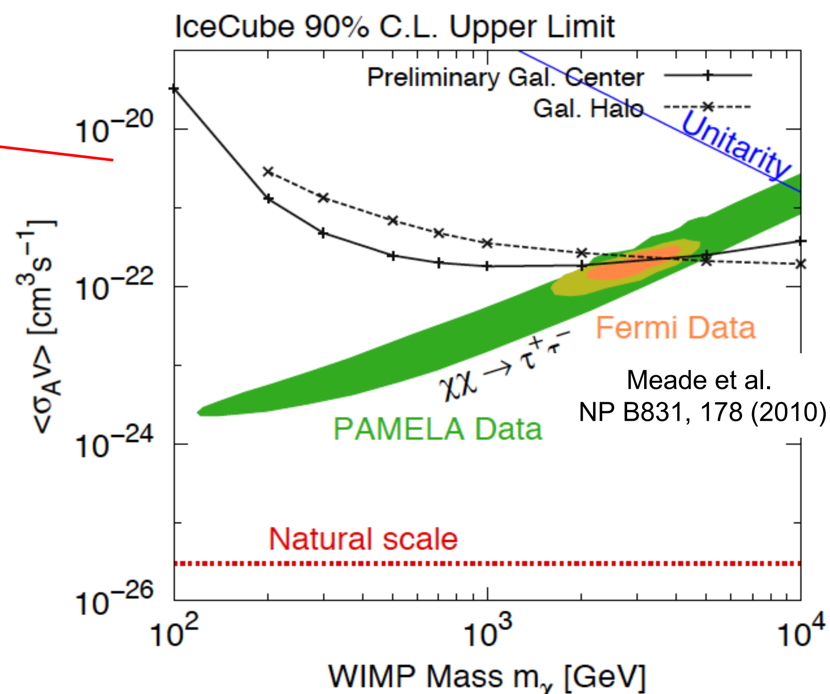
papers: Sun #327, #292 (IC+DC), Galaxy #1187, Dwarf Spheriodals #1024

cosmology constraint for DM:

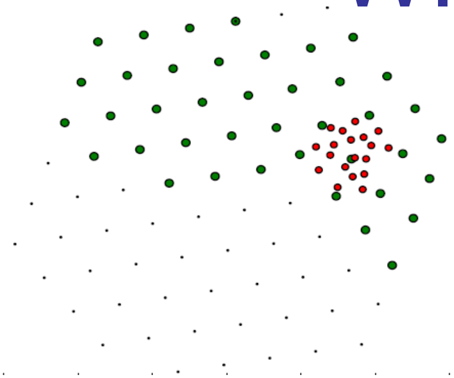
≈ 0.21 WMAP

$$\Omega_\chi = \frac{\rho_\chi}{\rho_{crit}} \approx \frac{10^{-25}}{\langle \sigma_{Ann} v \rangle} cm^3 s^{-1}$$

O(Weak interactions)



WIMP Annihilation in the Sun



Amanda+IC22+IC40 (2001-2008)
for Sun below horizon

paper #327

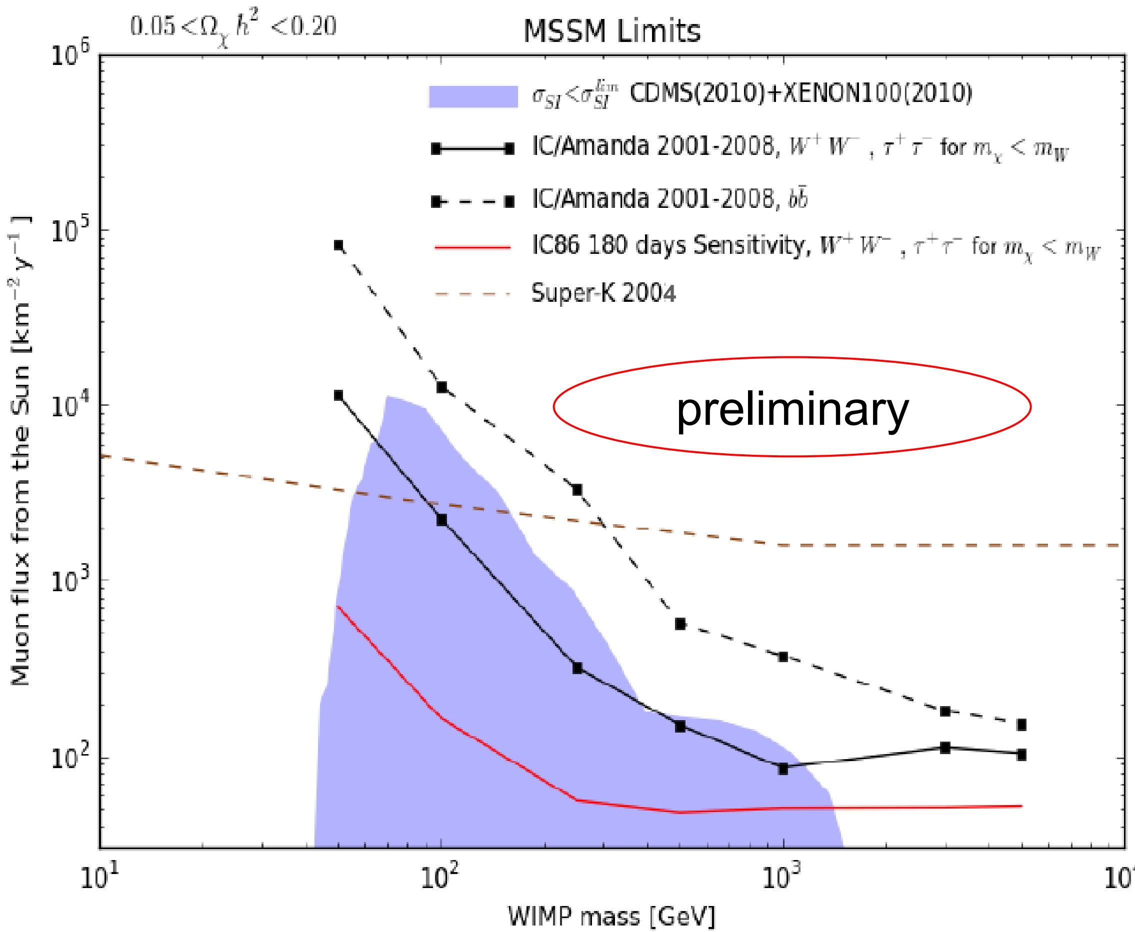
see also for IC22:
PRL 102 (2009) 201302

Model dependent conversion of μ flux to WIMP properties: χ-proton cross section:

- ρ_χ, $f(v)$
- σ_{ann} annihilation

} cosmo-logy

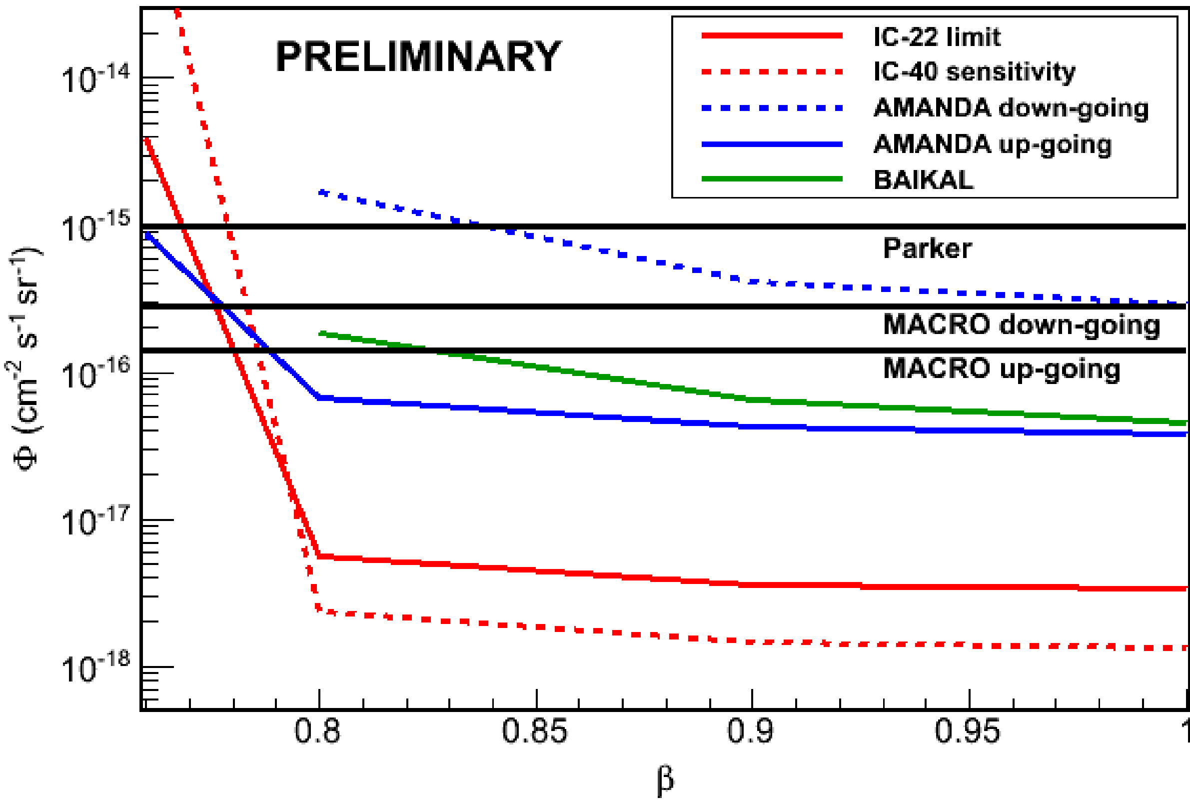
- $\sigma_{\chi p}$ → accumulation in Sun ← direct searches
- branching ratios ← theory (SUSY, ...)



Relativistic Monopole Search

paper #734

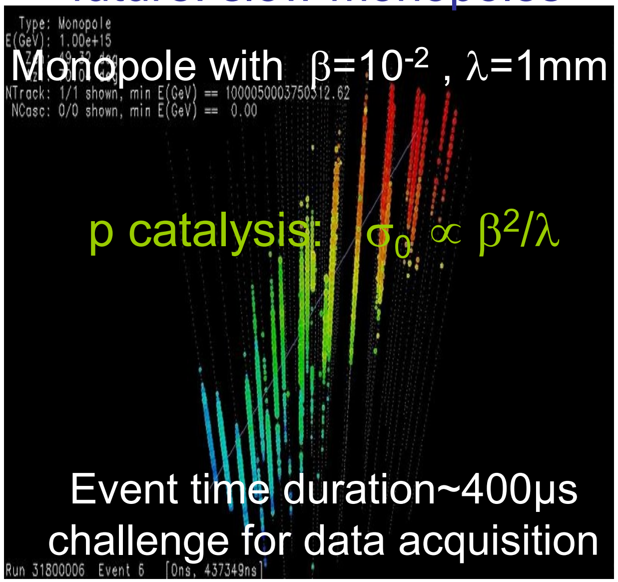
Monopole flux limits assuming an isotropic flux at the detector



GUT

existence of cosmic B-fields

future: slow monopoles



- O(1000) below bound from existence of galactic B-field (Parker)
- Limits seriously constraint GUT models

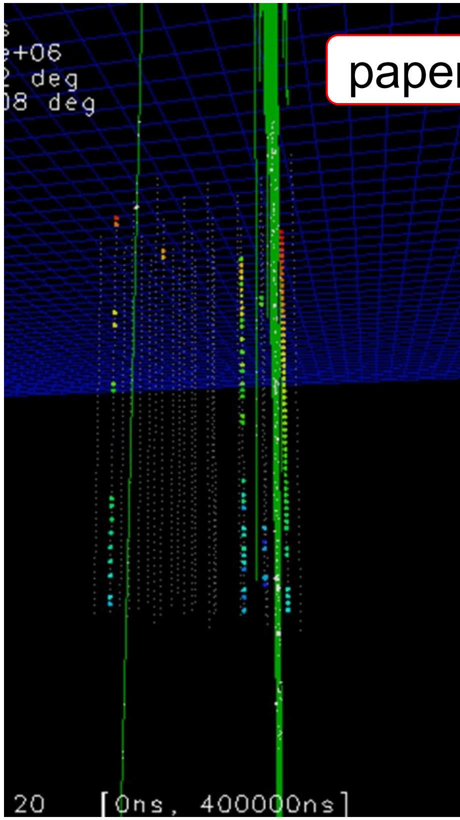
Cosmic Rays

IceCube with IceTop as a 3-dimensional cosmic ray detector

- atmospheric neutrino flux (all flavour)
- atmospheric muon flux
- Cosmic Ray anisotropy
- Cosmic Ray composition

Cosmic Rays: atmospheric muon flux

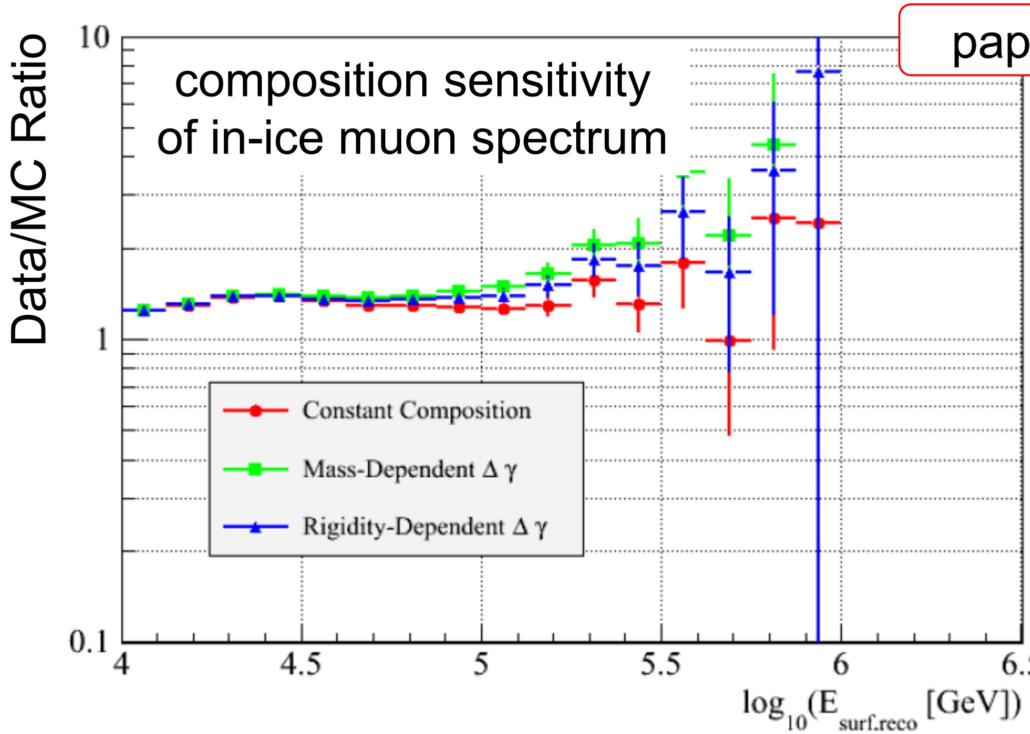
muon separation spectrum out to hundreds of meters



paper #323

The ice is an effective high-energy muon filter: unprecedented detector
→ Test of hadronic models and composition

paper #085



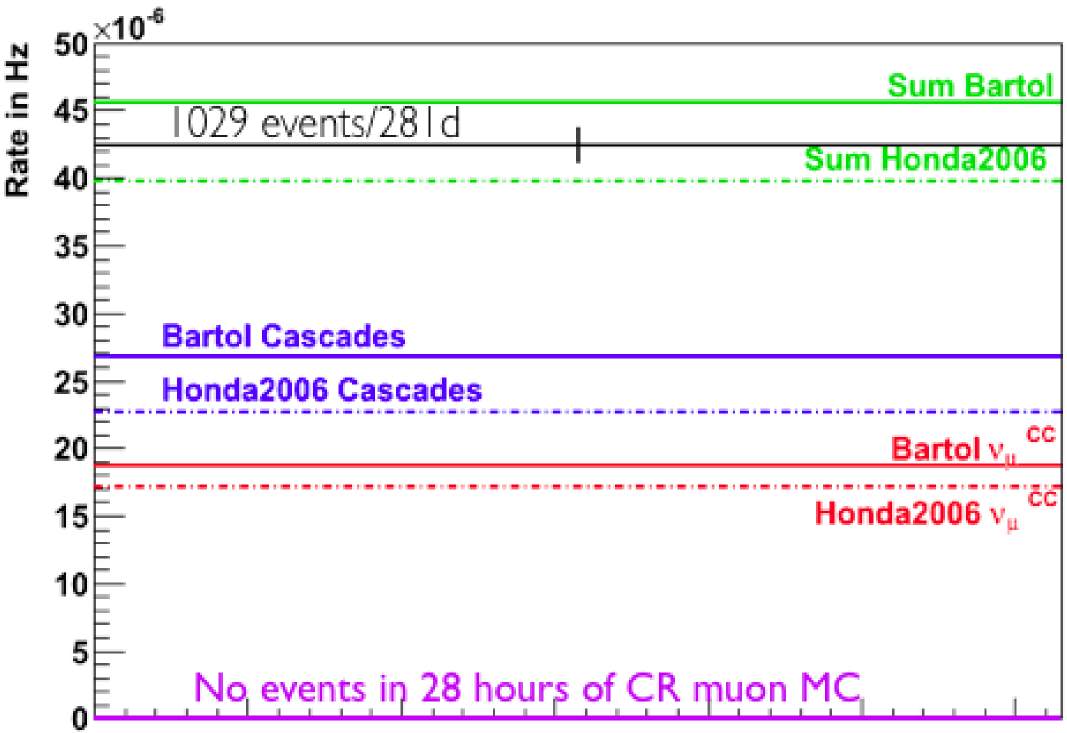
High-pT muons modeled by QCD simulation (π, K, c, b, ..)

#662 Seasonal variations of high energy cosmic ray muons observed by the IceCube Observatory as a probe of Kaon/pion ratio

Atmospheric Neutrinos in IC79-DeepCore

paper #324

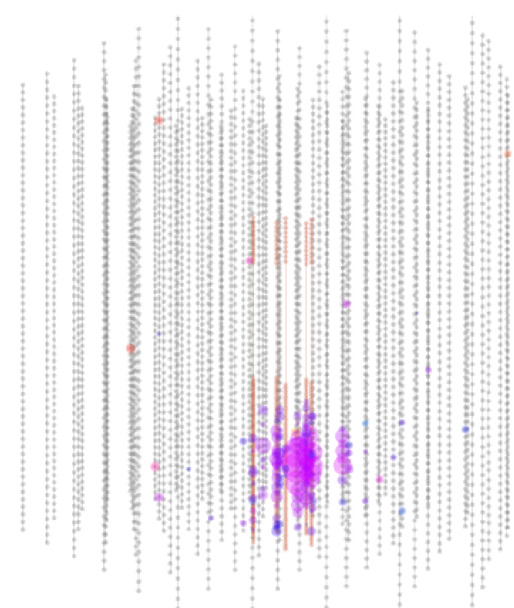
Results for 281 days (preliminary)
Systematic Uncertainties NOT included



$$C^{sig} = \nu_\mu^{NC} + \nu_e^{CC} + \nu_e^{NC}$$
$$C^{bg} = \nu_\mu^{CC}$$
$$N^{sig} = \nu_e^{CC} + \nu_e^{NC}$$
$$N^{bg} = \nu_\mu^{CC} + \nu_\mu^{NC}$$

← cascades

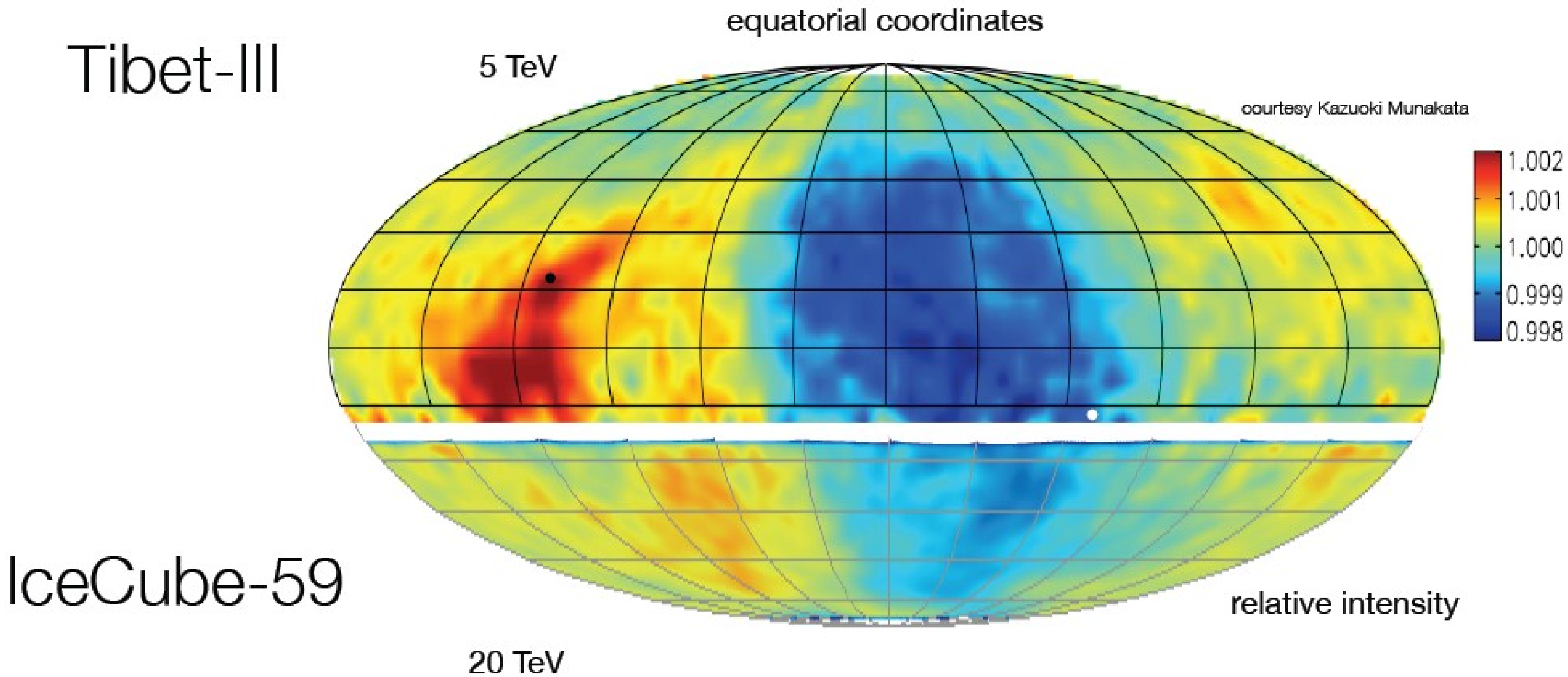
← ν_e



First clear observation of cascades in IceCube
at 10-300 GeV
➔ oscillation studies become possible (paper #329)

Cosmic Ray Anisotropy

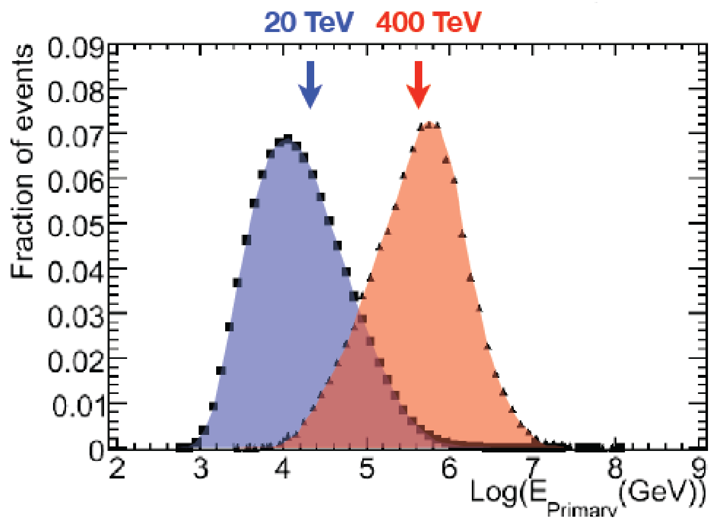
Compared to Northern Sky



the orientation of the dipole moment does **not** correspond to the relative motion in the Galaxy (Compton-Getting effect)

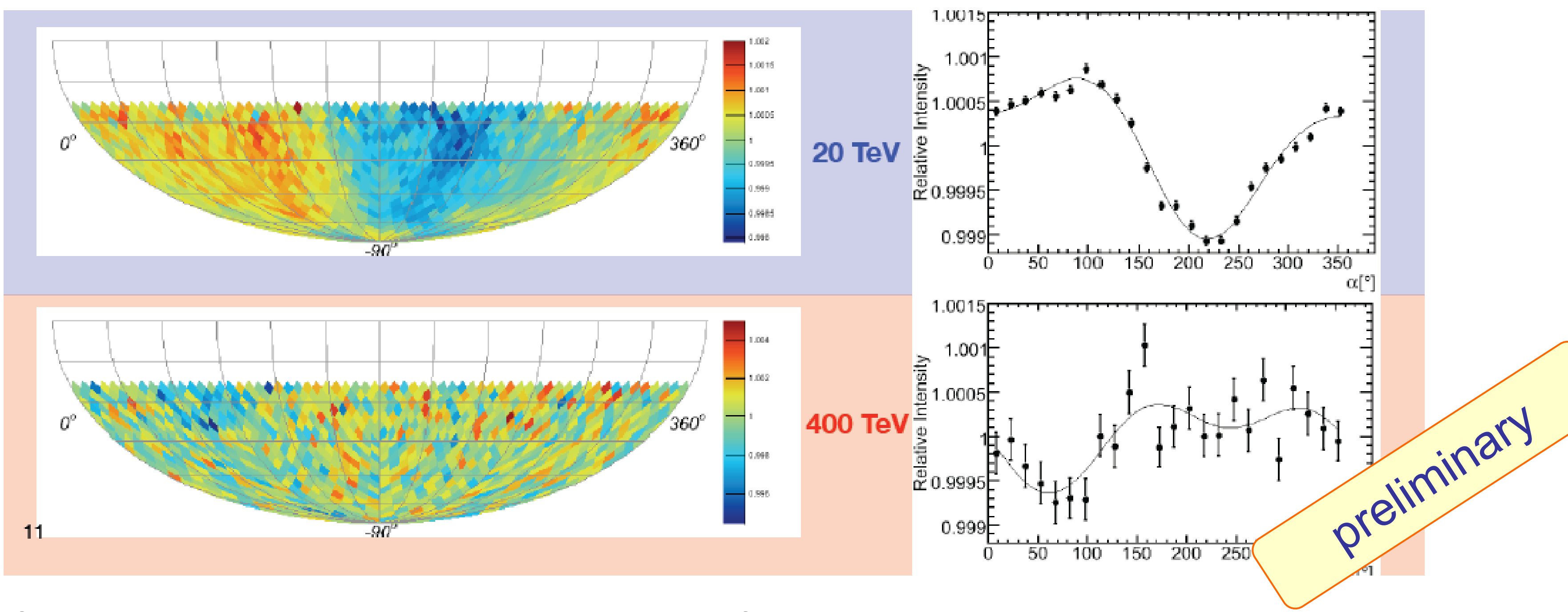
Cosmic Ray Anisotropy vs Energy in IceCube-59

papers #305, #308



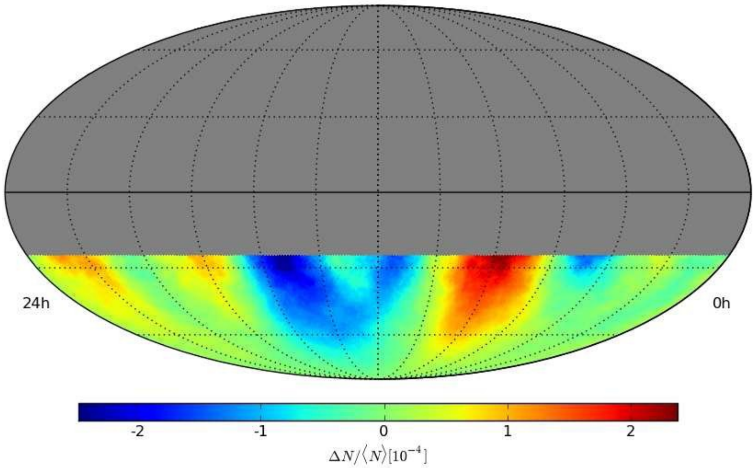
- first time structure at large energy observed
- structures at 20 TeV and 400 TeV differ

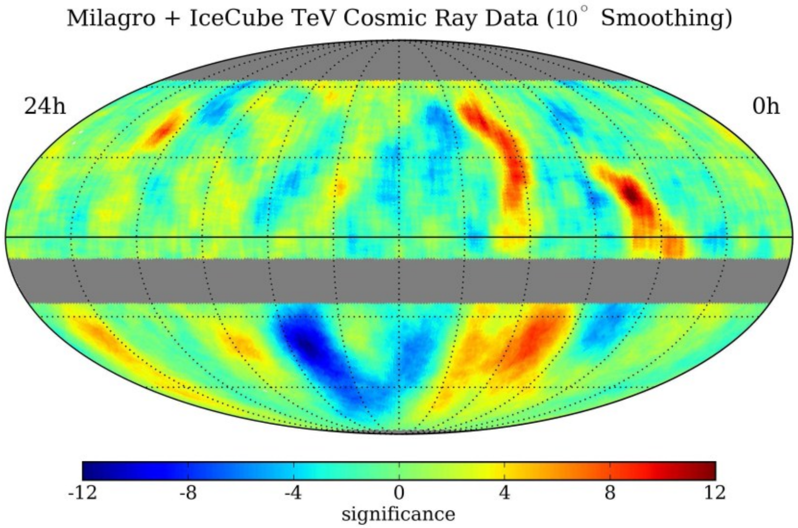
O(10^{10}) events

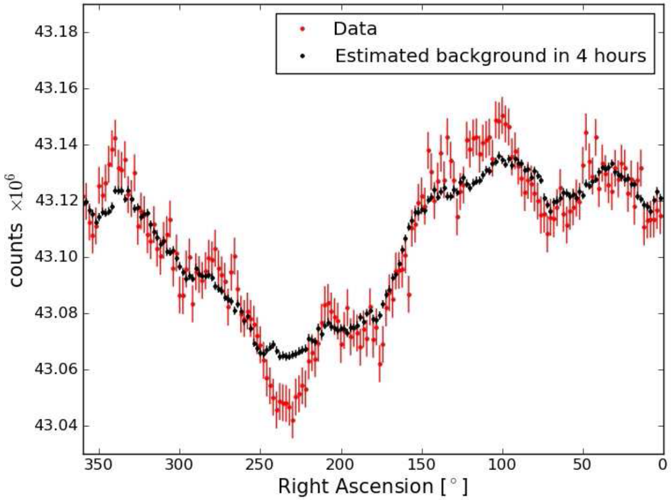


Multiple Scale CR Anisotropy

papers #306





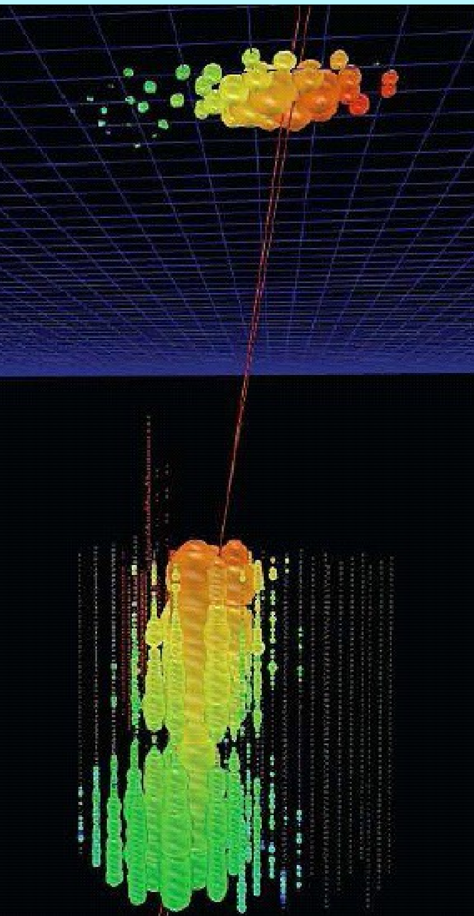


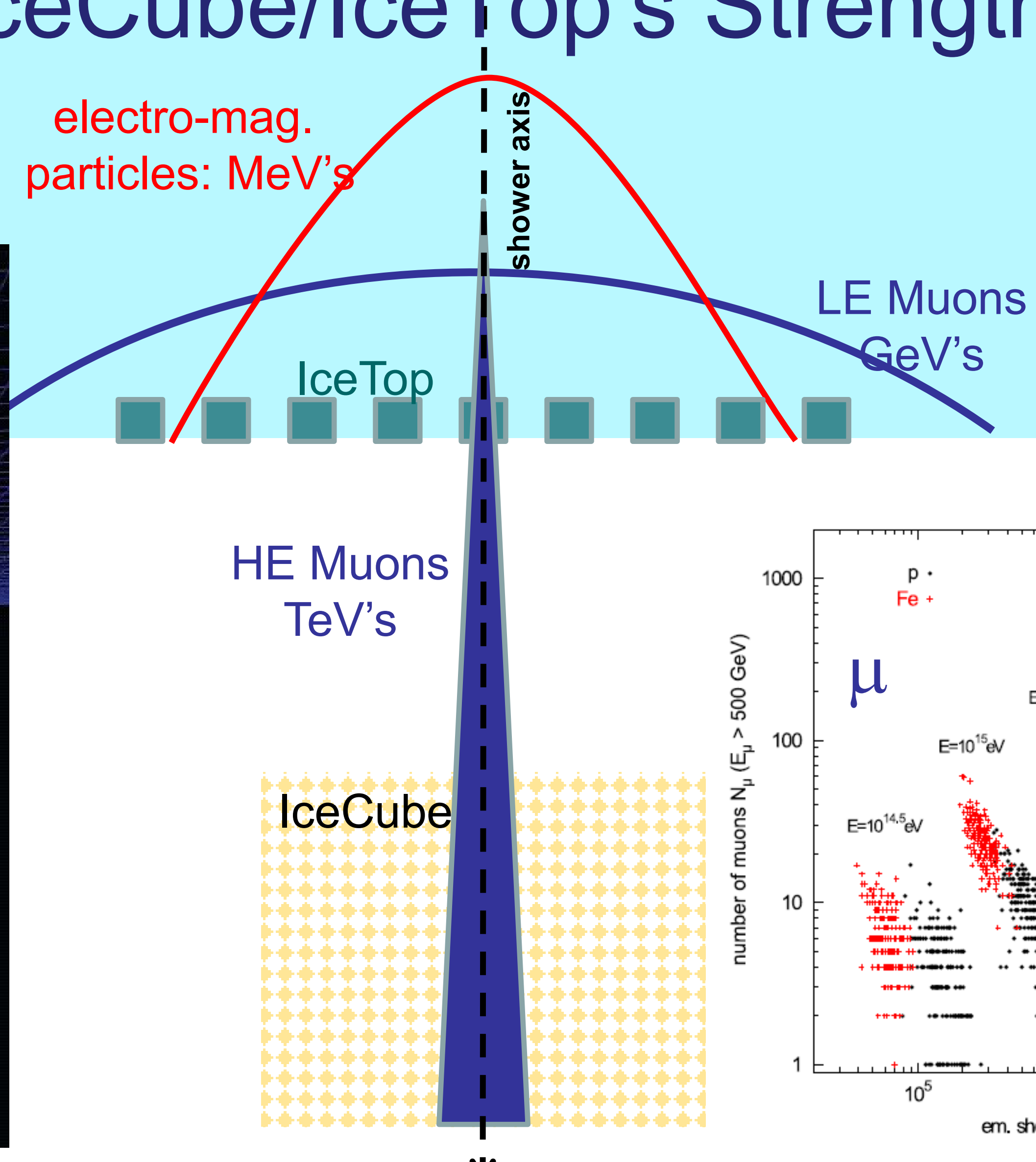
reference line from
time scrambling over 4 hours

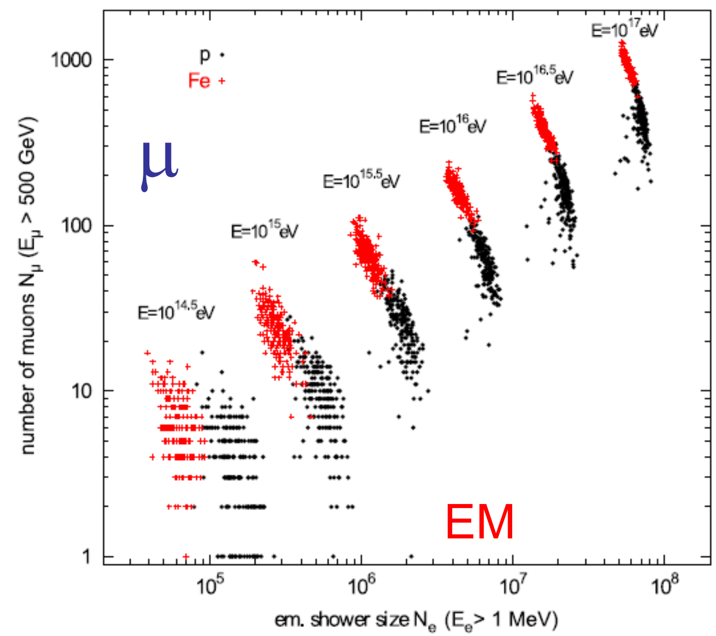
What makes the structures?
Does it tell us something
about our galactic neighbourhood?

Cosmic Rays: **spectrum and composition**

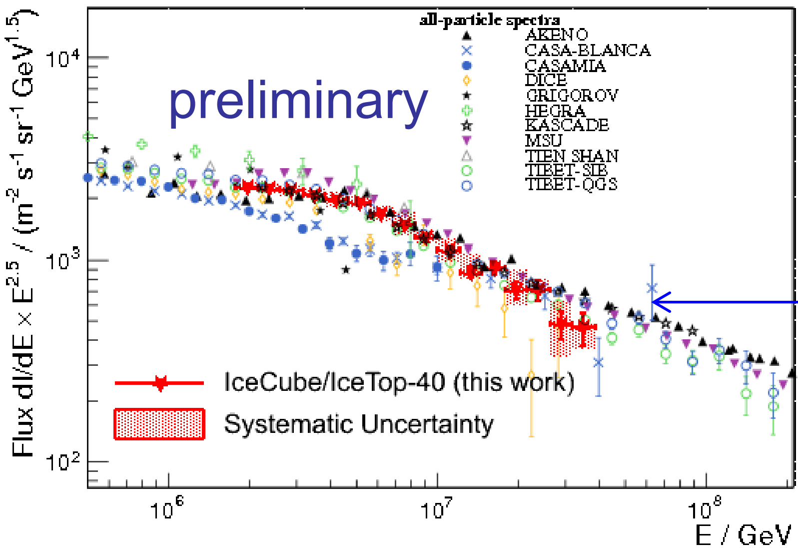
IceCube/IceTop's Strength







IceTop – InIce Coincidences

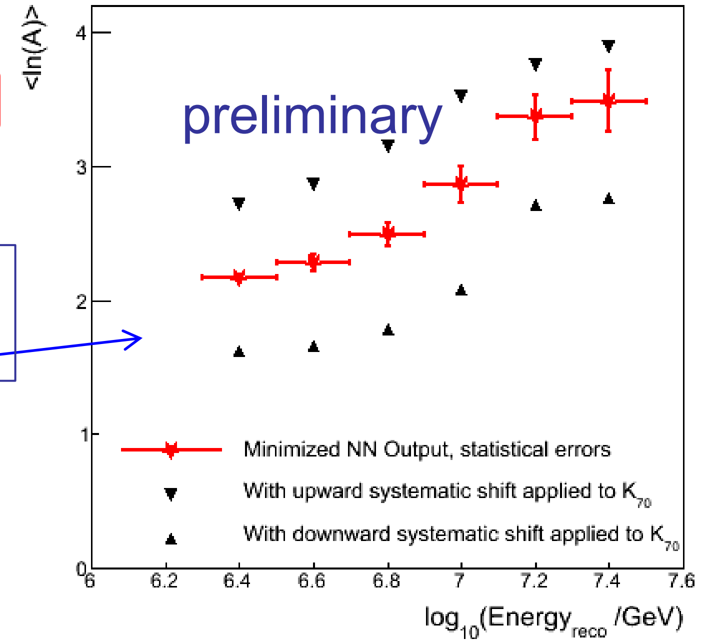


paper #923

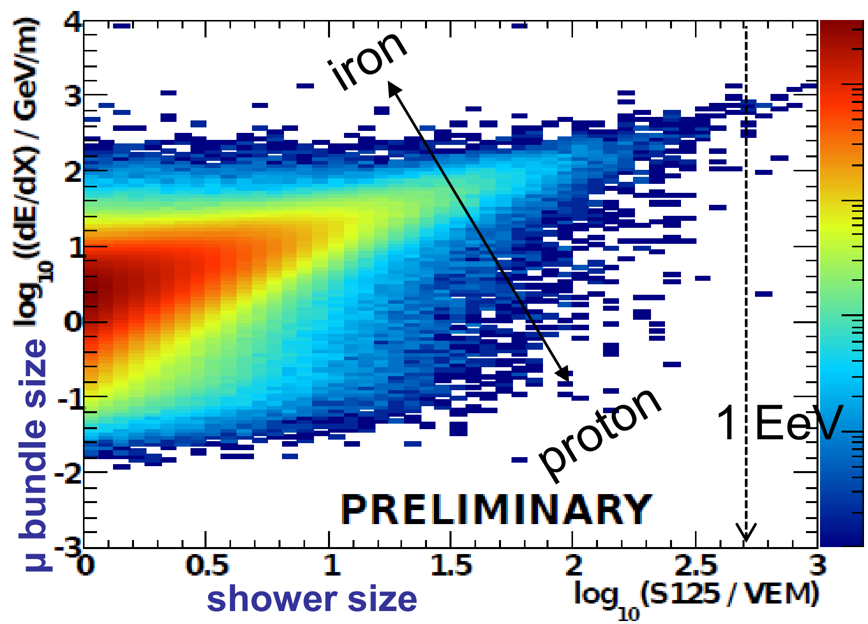
IC40:

unfolding:
energy & mass

still systematics dominated



Prospects IC79
(nearly complete detector):



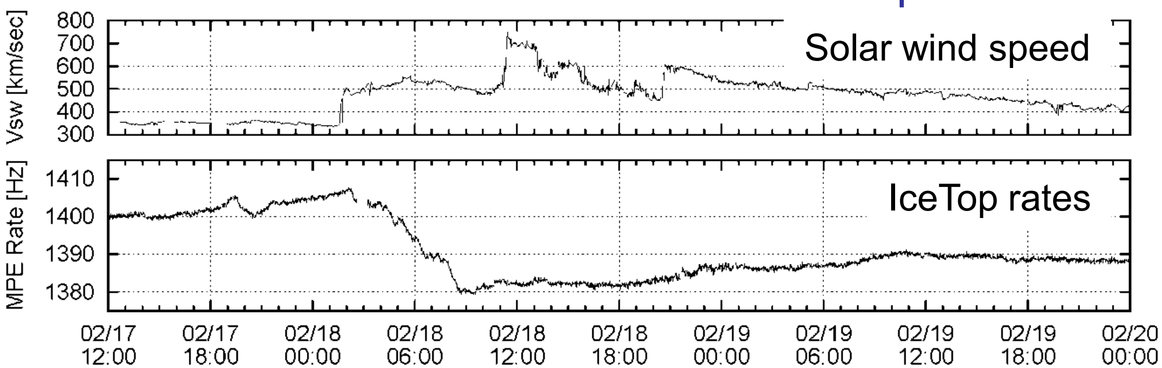
~ 15 ev./year
> 1 EeV

paper #838

related papers
#807, #379, #899, #939

Low energy transient rate variations from Sun, SN, GRB, ...

Forbush Decrease in IceTop #921

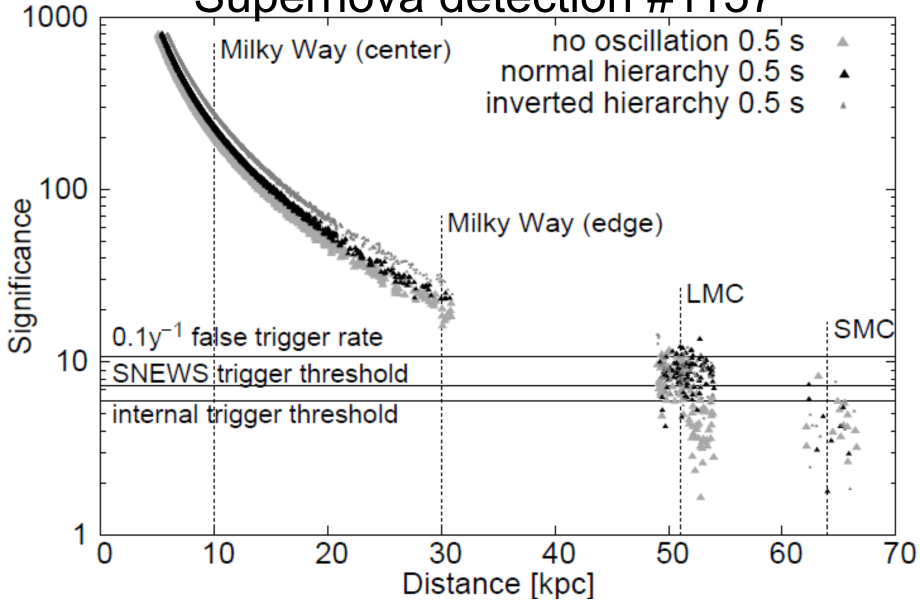


Since the first Sun flare observation Dec 13, 2006:

[ApJ Lett 689 (2008) L65]

IceTop increased spectral sensitivity taking differential rates at multiple thresholds

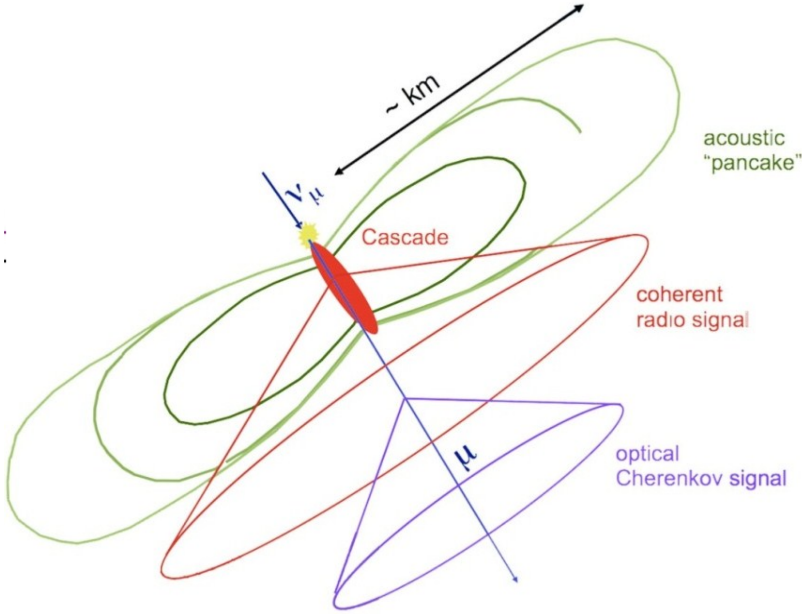
Supernova detection #1137



IceCube is the largest SN detector and part of SNEWS network

- detection by rate increase of 5160 DOM with $<noise>_{DOM}$ = 286 Hz; uptime $\approx 98\%$
- depending on distance sensitivity to details of SN development, star mass, ν-oscillation and hierarchy

Future



HE: radio, acoustics, ...
- cosmogenic neutrinos

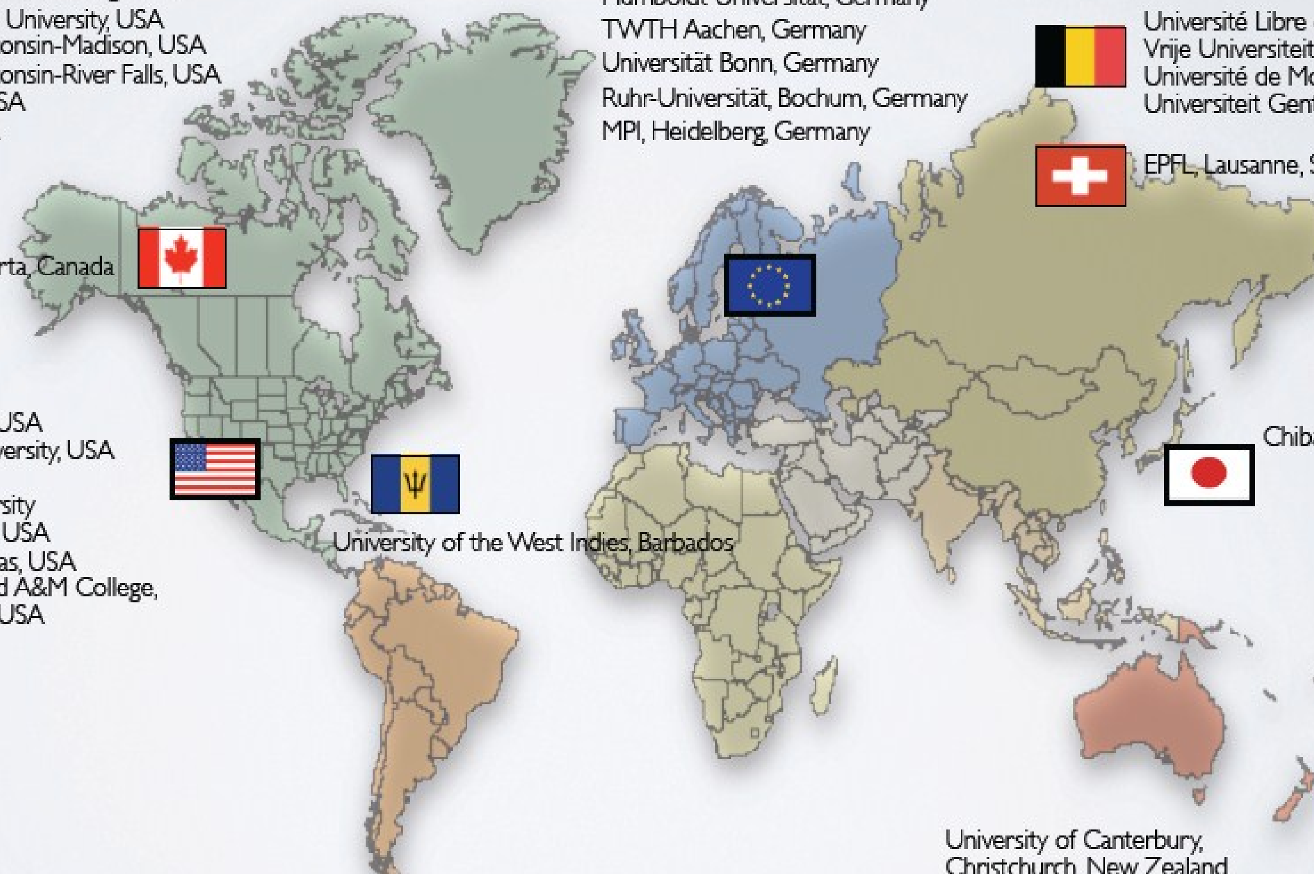
LE: DeepCore + extension (PINGU)
- oscillations
- galactic sources
- dark matter
- SN neutrinos
- proton decay

Pingu-I
18 additional strings with about 1000 DOMs in the 30 MT DeepCore ➔ Cherenkov imaging

#0325	First Step Towards A New Proton Decay Experiment In Ice
#1102	The Radio Air Shower Test Array (RASTA) – enhancing the IceCube observatory
#0316	Status and recent results of the South Pole Acoustic Test Setup
#1236	IceCube Radiofrequency extension

ICECUBE COLLABORATION

10 countries, 36 institutions, ~260 collaborators



Summary

- IceCube is complete and reached expected performance (or even better)
- Results from the partly completed detector (IC22,40,56,79) reached sensitivities which are becoming to seriously challenge models:
  - point source limits all sky, time (in)dependent, candidate list,
  - GRB limits exclude models (W&B model)
  - WIMP limits extend to not else excluded parameter space
  - Monopole limit well below “Parker Bound”
  - Diffuse: factor 4 below W&B bound; EHE: in the range of GZK predictions
- Improve sensitivity by multi-messenger methods
  - pre-selected candidate sources (single or stacking)
  - transients/time dep.: flares, GRB, SN ...
  - follow-up program (optical, X-ray, γ-ray)
- ... not only limits:
  - atmospheric neutrino and muon spectrum, large p_T muons
  - cosmic ray anisotropy on various angular scales
  - CR composition: IceCube/IceTop has unique capabilities
  - heliosperic physics
- Future: exploit existing, improve and extend:
  - DeepCore: low energy extension, atm. Oscillations, low mass WIMPS
  - high energy extensions: radio, acoustic, ..
  - Low energy: Cherenkov imaging, proton decay, ...