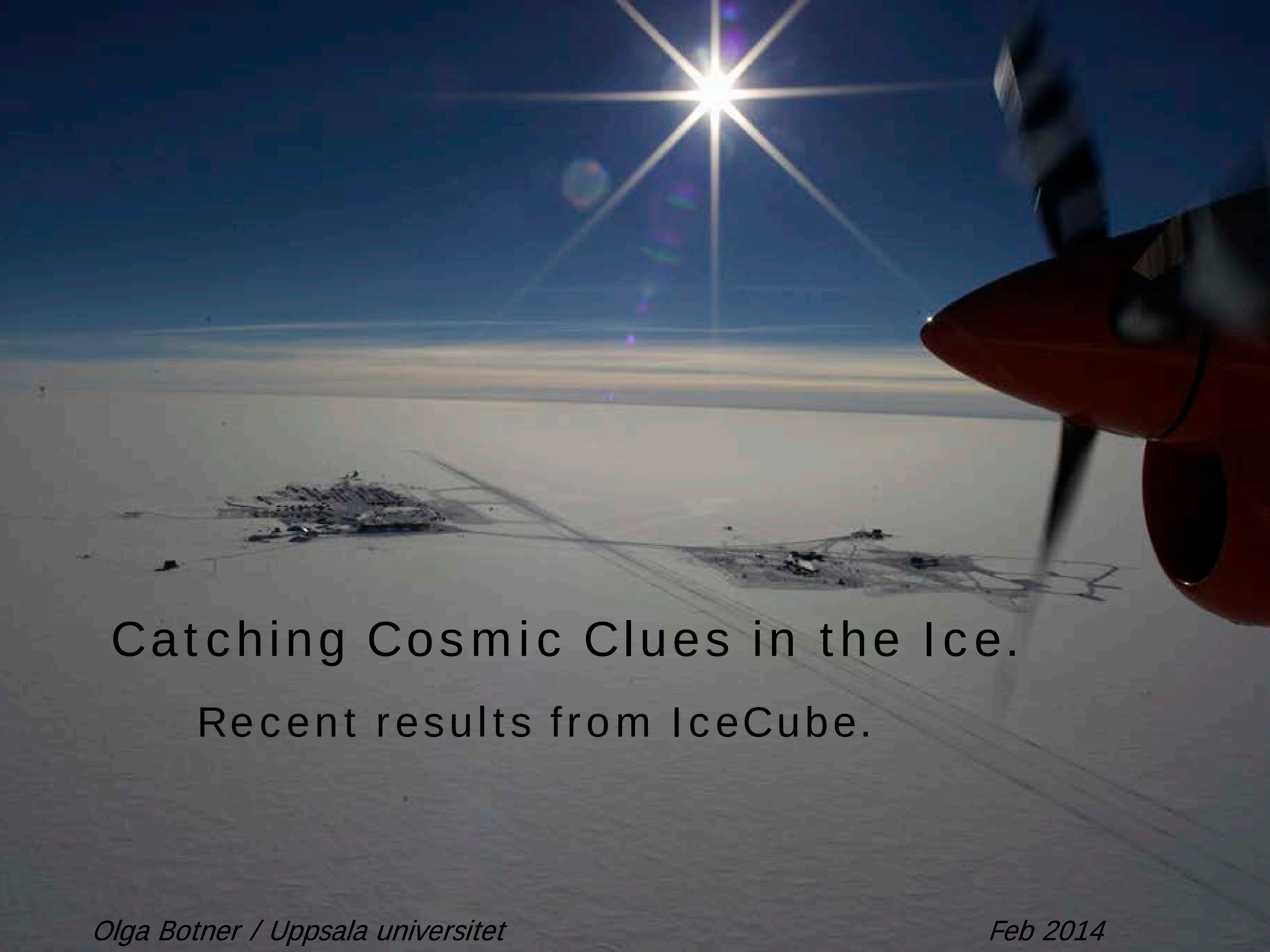


Catching Cosmic Clues in the Ice.

Recent results from IceCube.

Olga Botner / Uppsala universitet

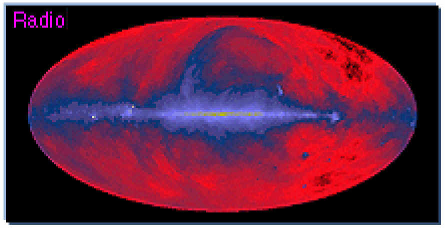
Feb 2014

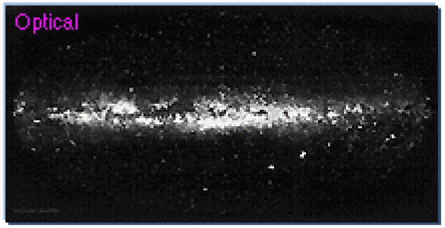
Outline

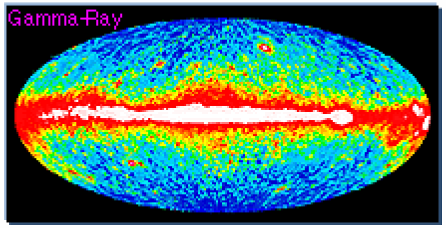
- Introduction to neutrino astronomy
- The IceCube detector; event signatures
- Science goals
- Data selection; neutrino identification
- Selected recent results
- Summary and outlook

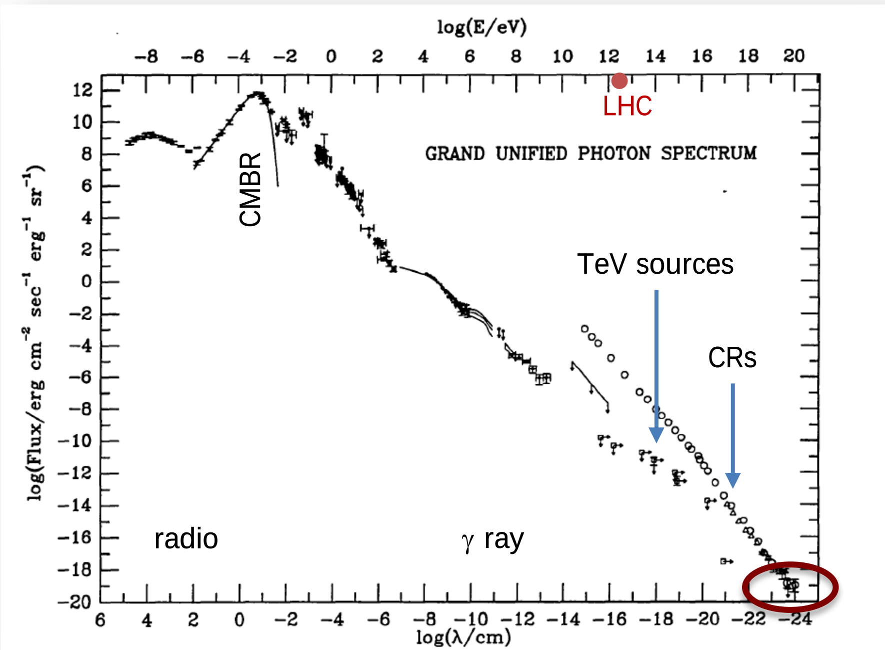
CR-ν connection: rationale for neutrino astronomy

- most of our knowledge of the universe comes from studying photons









M. Turner&T. Ressell, Comments in Astrophys. 14 (1990) 323

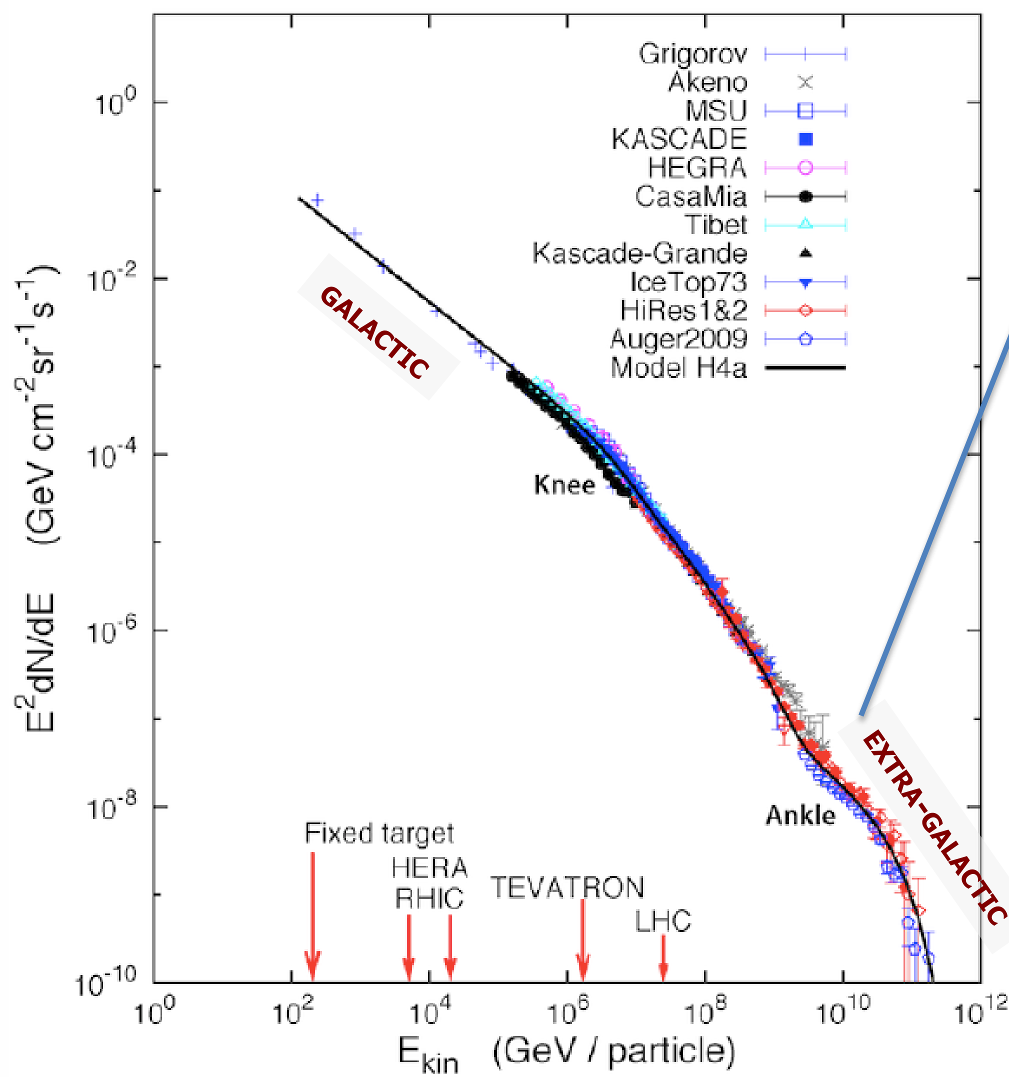
- ...and from studying cosmic rays

Cosmic rays hitting Earth. *Credit: NSF/J. Yang*

- What cosmic accelerators produce the observed spectrum of CRs ?

CR-ν connection: rationale for neutrino astronomy

Energies and rates of cosmic rays



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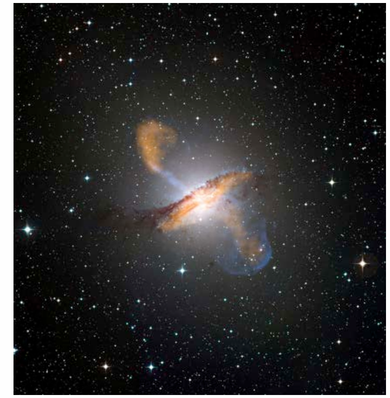
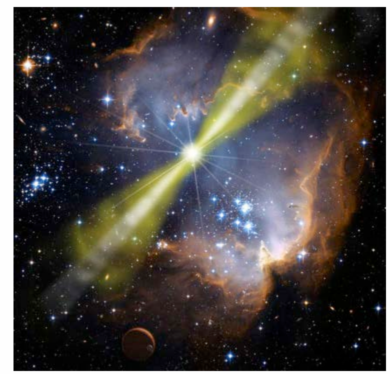


Active Galactic Nuclei



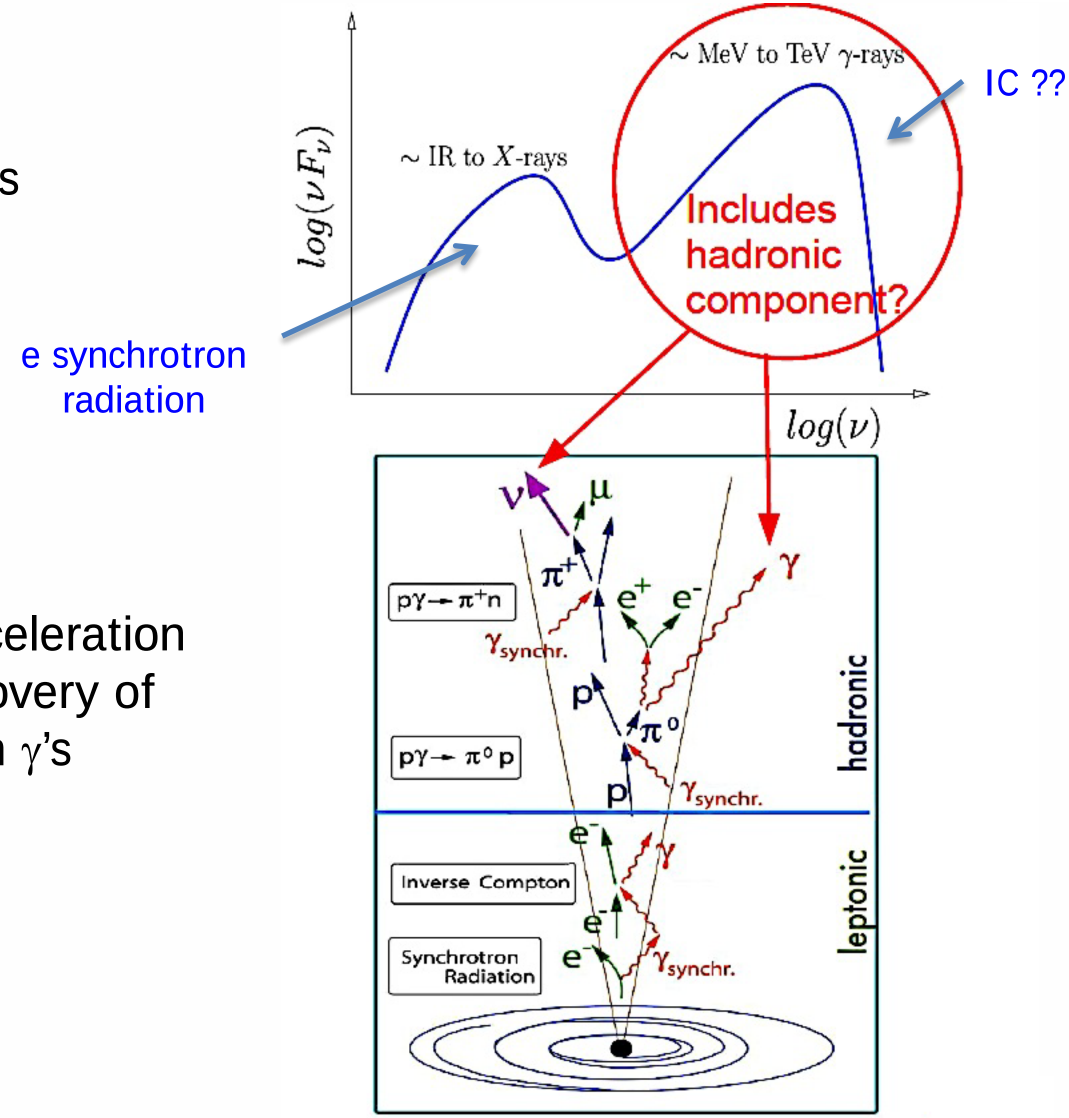
Gamma Ray Bursts

Do these objects really accelerate hadrons?

CR-ν connection: rationale for neutrino astronomy

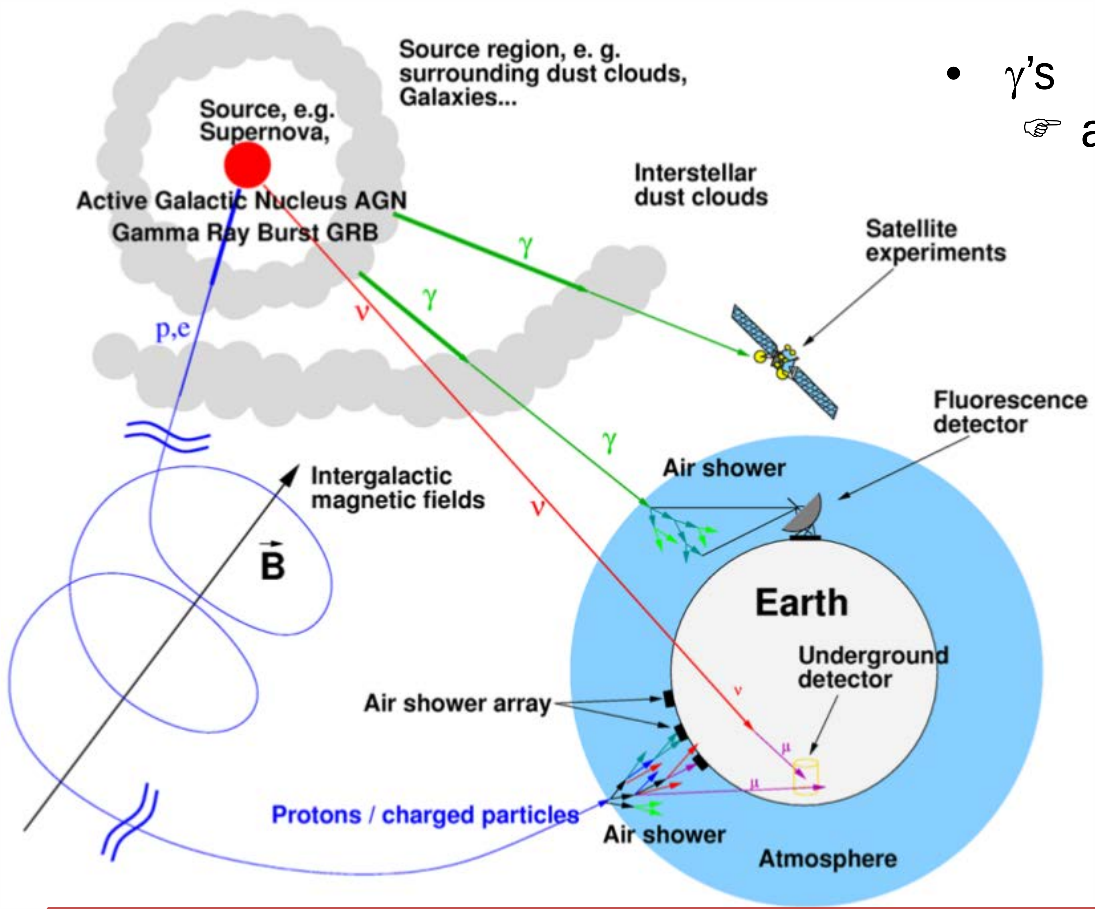
- AGN spectra of GeV – TeV γ's support the idea that these objects accelerate hadrons

- convincing evidence for acceleration of hadrons would be discovery of ν's in conjunction with γ's



CR-ν connection: rationale for neutrino astronomy

the sources of UHE CRs also produce neutrinos



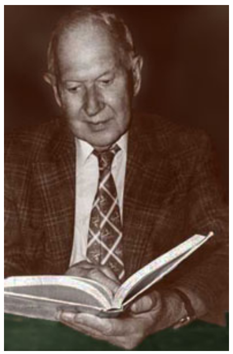
- γ's
  - ☞ absorbed on gas, dust, CMB
- CRs
  - ☞ deflected, lose pointing
- UHE CRs point
  - ☞ very rare
- UHE CRs interact with CMB
  - ☞ GZK mechanism

to observe the UHE universe – need a messenger unaffected by gas, dust or magnetic fields – the neutrino

Pioneers of neutrino astronomy

- the potential of the ν as a messenger from astrophysical sources was recognized soon after ν's were shown to exist (Reines & Cowan, 1956)

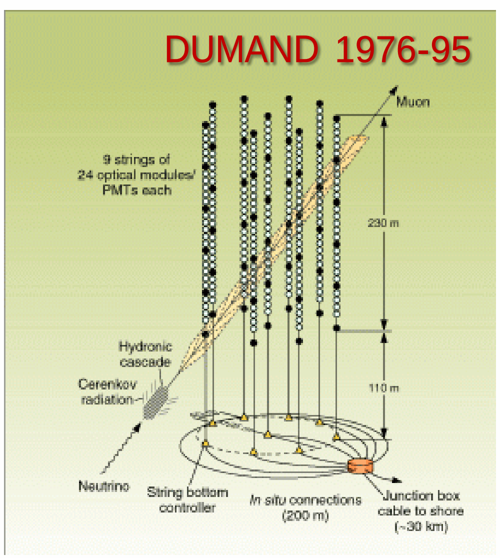
- ν's might allow us to see "hidden" sources

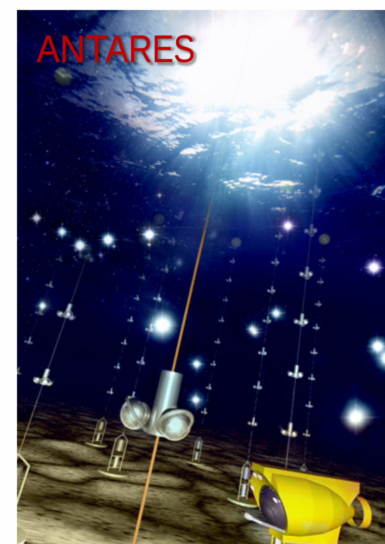


M. Markov, Proc. ICHEP 1960 (also K. Greisen, F. Reines, Ann. Rev. Nucl. Phys. 1960)

... proposes to install detectors deep in a lake or in the sea and to determine the direction of ν induced charged particles using Cherenkov radiation ...

- a kton or more required

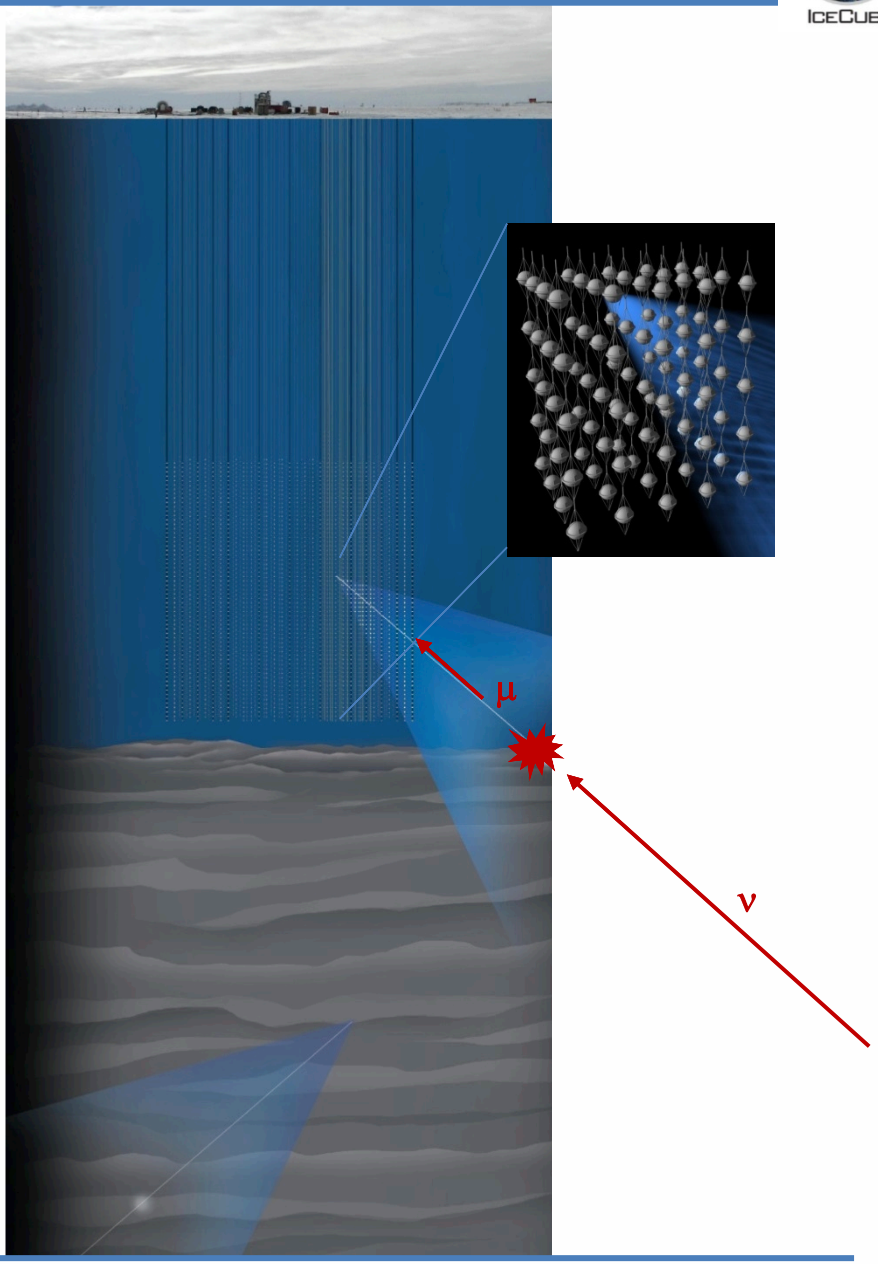




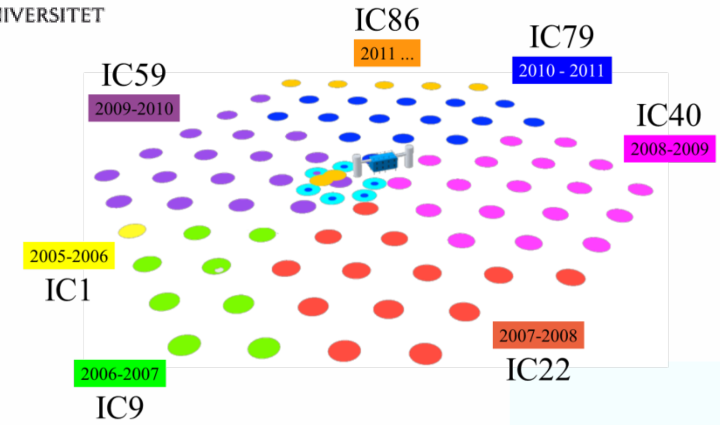
The next generation neutrino telescope

Detector principle

- ν interacts with a nucleus
  - produces a μ (e or τ)
  - and/or a cascade
- a charged particle moving at superluminal speed gives rise to Cherenkov rad. (cone ∠ 40°)
- radiation is detected by 3D array of optical sensors
- position, time and amplitude of hits allows reconstruction of tracks using likelihood optimization
- the lepton direction is aligned with the ν direction

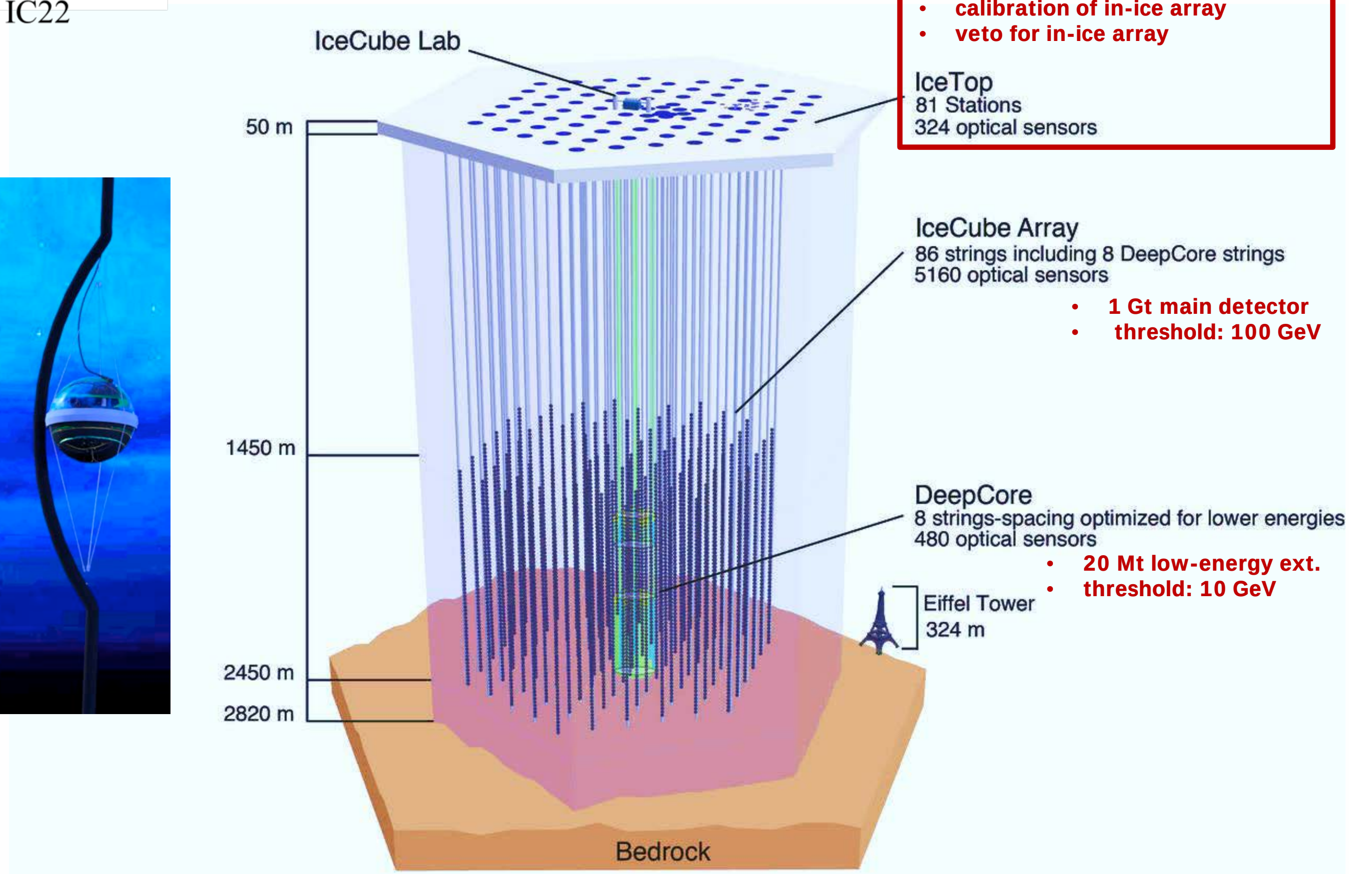


IceCube Neutrino Observatory



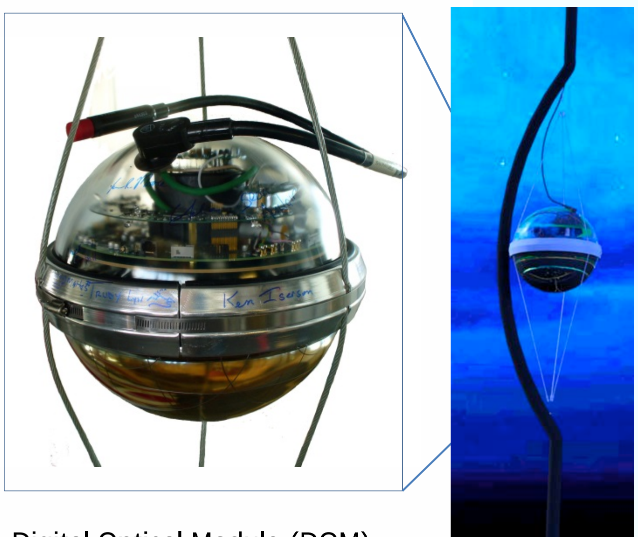
IceCube completed in Dec 2010
after 6 years construction.

- Extended Air Shower detector
- surface area 1 km^2
- cosmic ray physics $10^{14} - 10^{18}$ eV
- calibration of in-ice array
- veto for in-ice array



- 1 Gt main detector
- threshold: 100 GeV

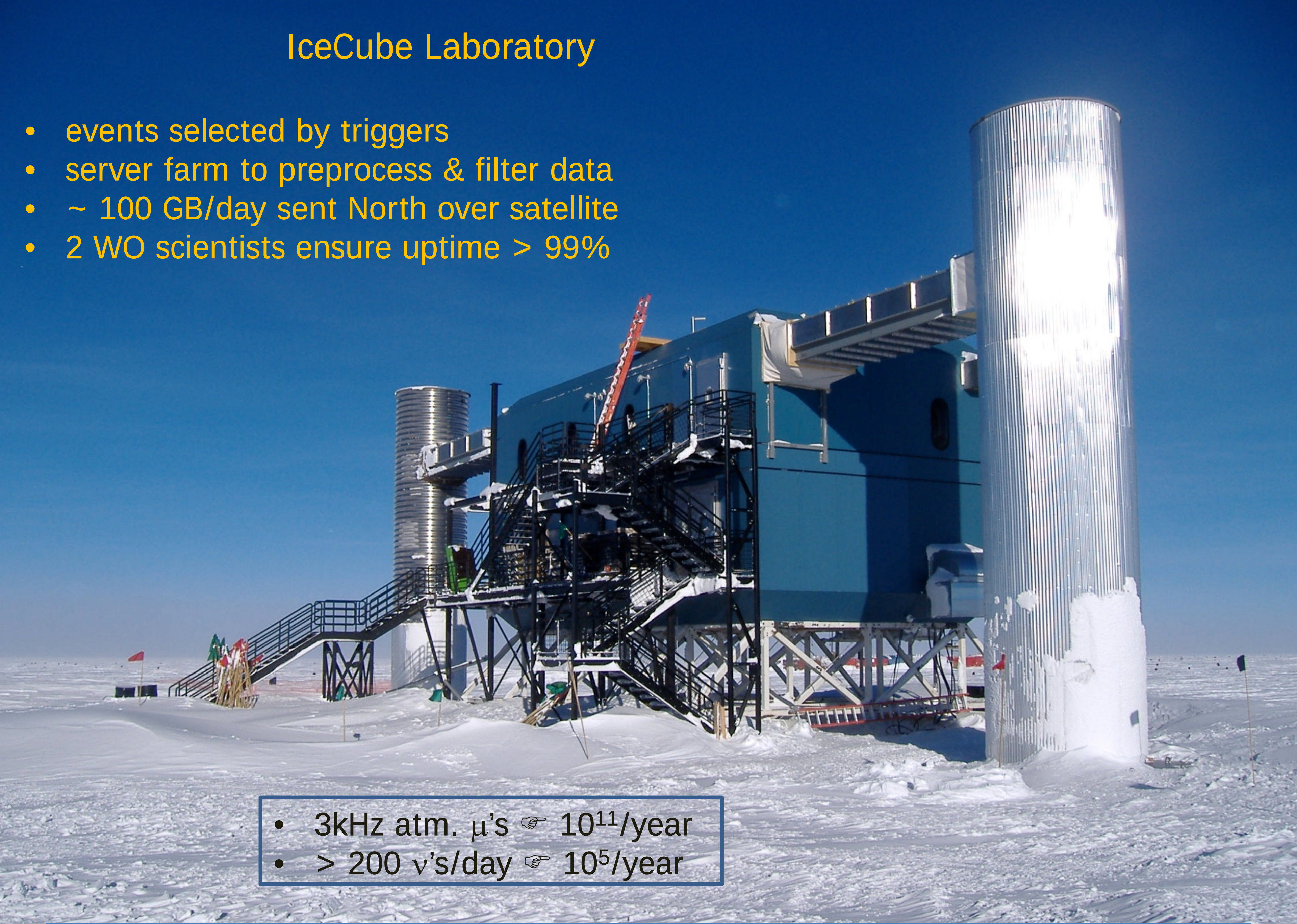
- 20 Mt low-energy ext.
- threshold: 10 GeV



Digital Optical Module (DOM)
- low noise rate < 500 Hz
- gains very stable < 0.3%
- high reliability, very few failures

IceCube Laboratory

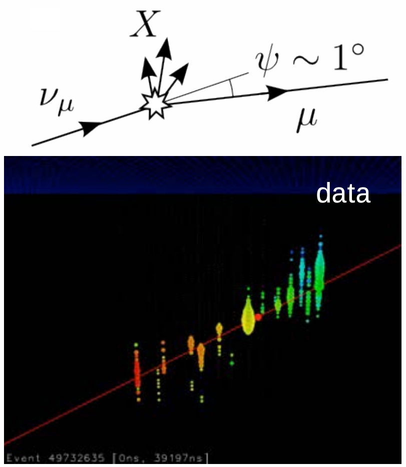
- events selected by triggers
- server farm to preprocess & filter data
- ~ 100 GB/day sent North over satellite
- 2 WO scientists ensure uptime > 99%

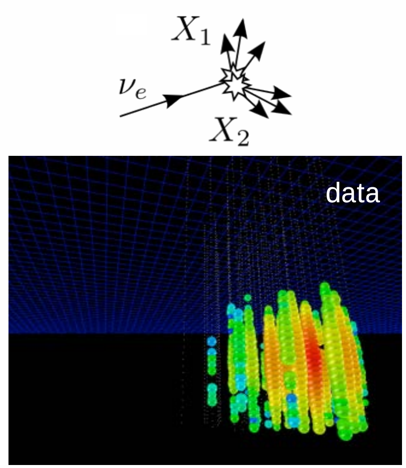


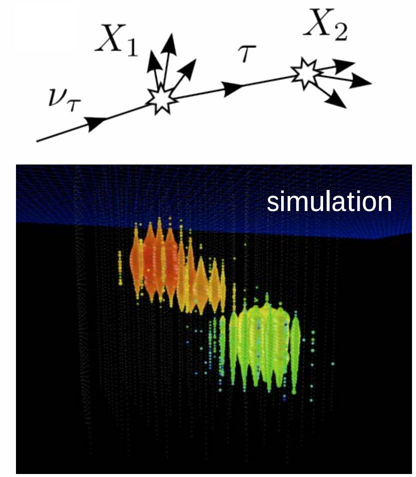
- 3kHz atm. μ's ☞ 10^{11}/year
- > 200 ν's/day ☞ 10^{5}/year

Event signatures in IceCube

- ν_l charged current interactions







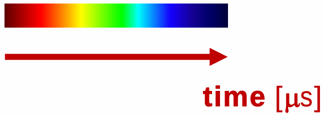
tracks

- ν_μ CC interaction
- ang. res. < 1°
- energy res. ~ x2
- V_{eff} >> IceCube vol.

cascades

- ν_e, ν_μ, ν_τ NC or ν_e CC
- ang. res. > 10°
- energy res. ~ 15%
- V_{eff} ~ IceCube vol.

- ν_τ CC interaction
- E_τ ~ 1 PeV



- ν_l neutral current interactions – only the hadronic cascade seen

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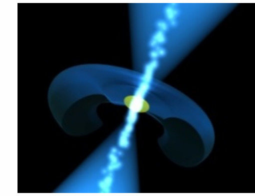
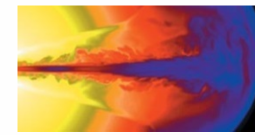
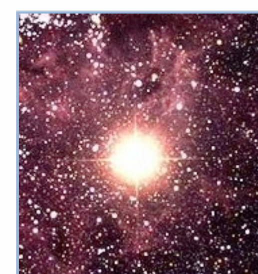
IceCube Science

ICECUBE

- Astrophysics
  - point sources of ν's (SNR, AGN ...)
  - extended sources
  - transients (GRB, AGN flares ...)
  - diffuse fluxes of ν's (all sky, cosmogenic, galactic plane ...)
- Cosmic ray physics
  - energy spectrum around ”knee”, composition, anisotropy
- Dark matter
  - indirect searches (Earth, Sun, galactic center/halo)
- Exotic sources of ν's
  - magnetic monopoles, Q balls ...
- Particle physics
  - ν oscillations
  - charm in CR interactions
  - violation of Lorentz invariance, quantum decoherence
- SNe (galactic/LMC)

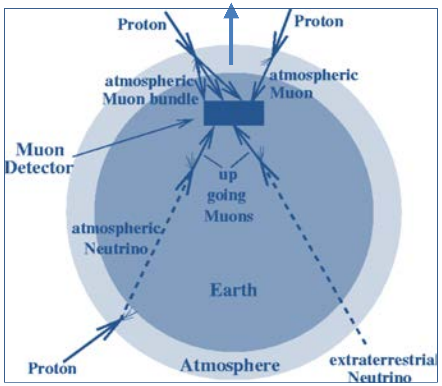




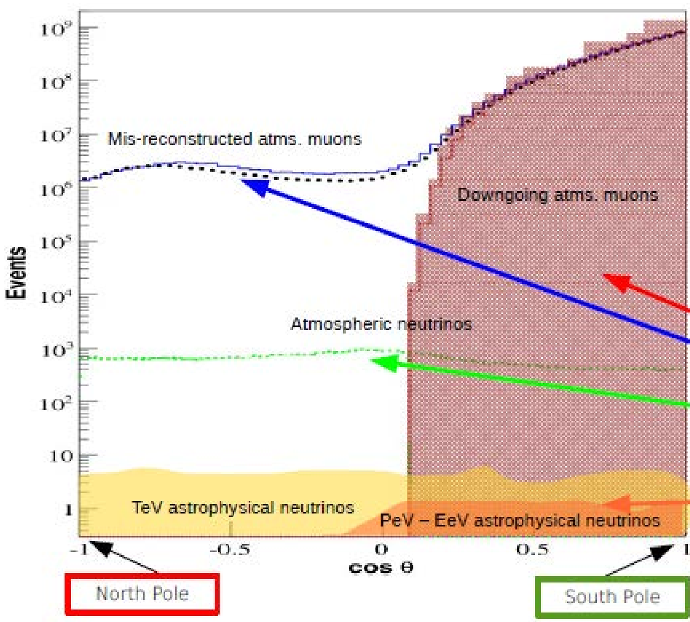


Data selection – ”looking for a needle in a haystack”

SP



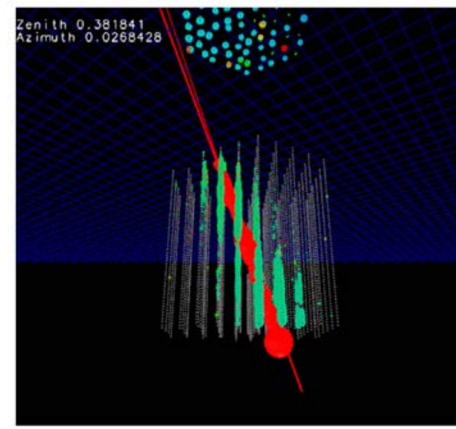
- ν rate ~2 mHz (200/day)
- atm. μ rate ~ 3 kHz



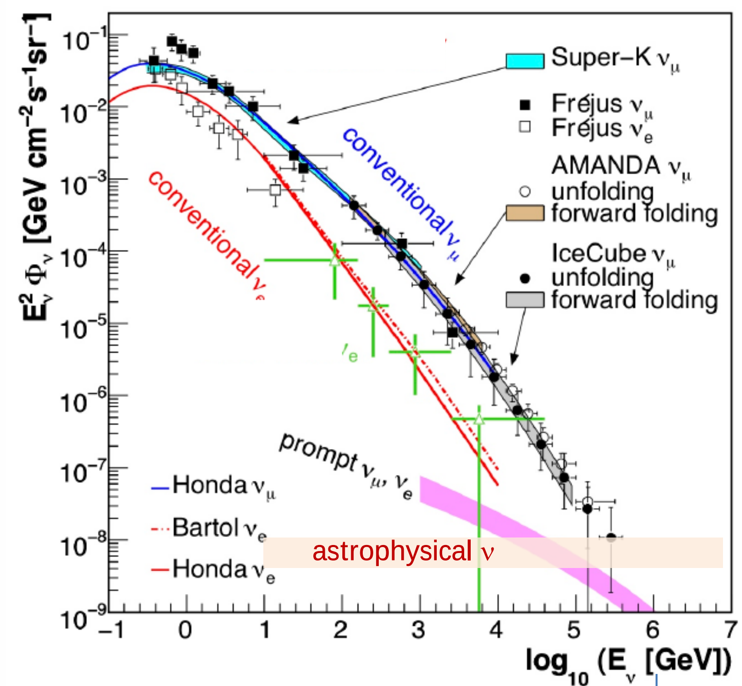
ATMOSPHERIC MUONS
- from ”above”
- ”filtered out” in the Earth

ATMOSPHERIC ν’s
- from all directions

EXTRATERRESTRIAL ν’s
- from all directions if energy < 1 PeV
- Earth becomes opaque to UHE ν’s



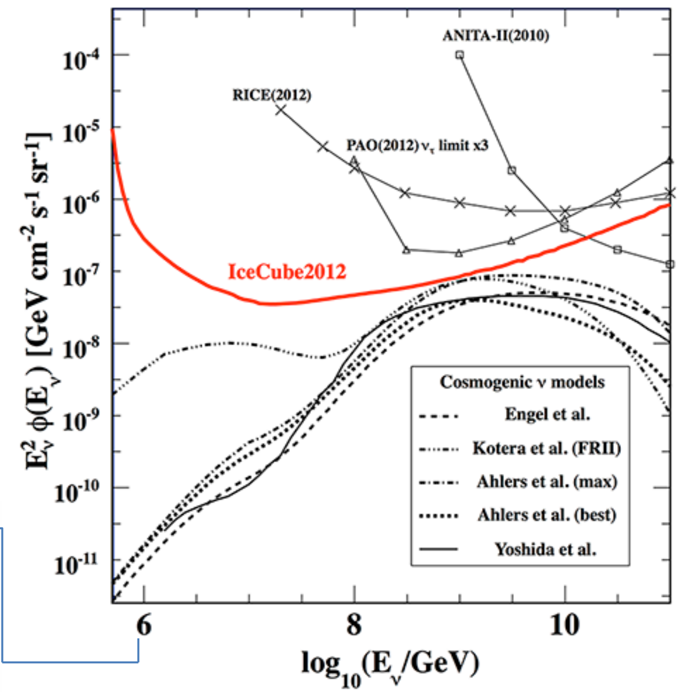
The ν spectrum



- ν_μ spectrum, IceCube PRD 83 (2011) 012001
- ν_e spectrum, IceCube PRL 110 (2013) 151105

cosmogenic Greisen-Zatsepin-Kuzmin ν's

$$p + \gamma_{CMB} \rightarrow n + \pi^+ \rightarrow n + \mu^+ + \nu_\mu$$
$$\hookrightarrow \bar{\nu}_\mu + e^+ + \nu_e$$



GZK models

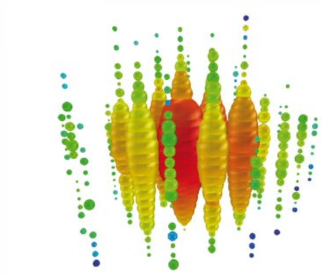
- conv. π/K ν's dominate < 100 TeV
- prompt ν's visible @ ~ 100 TeV
- astrophys. ν's (perhaps) > 100 TeV

- produced < 50 Mpc from source
- carry information on
  - location and cosmological evolution of the UHE CR sources

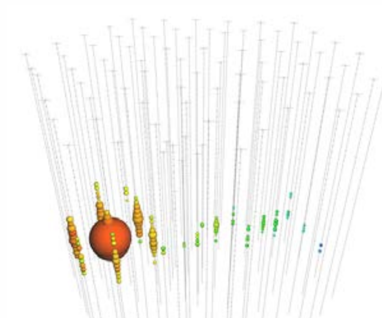
How to search for astrophysical ν's ?

imperative to remove the dominant CR muon bkg (3 kHz)

1. look for upgoing μ tracks
   advantage: Earth stops the CR μ background
   dis-advantage: hard to determine energy
   dis-advantage: Earth stops ν's > 1PeV



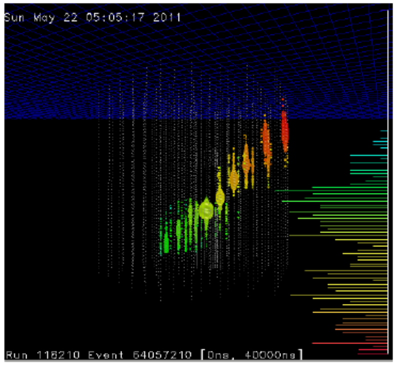
2. look at ultra-high energies
   advantage: bkg can be reduced to ~ zero
   dis-advantage: very low expected flux



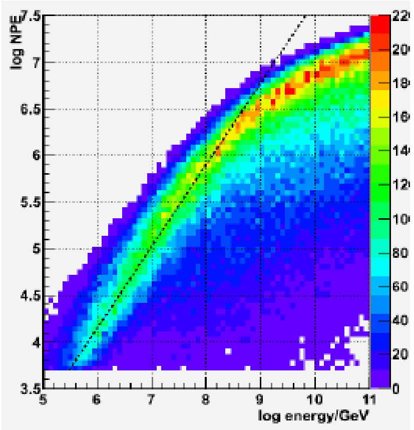
3. look for starting events (contained vertex)
   advantage: VETO region used to remove the CR μ's
   advantage: all charged tracks seen
   dis-advantage: limited effective volume

Search for cosmogenic ν's (May 2010 – May 2012 data)

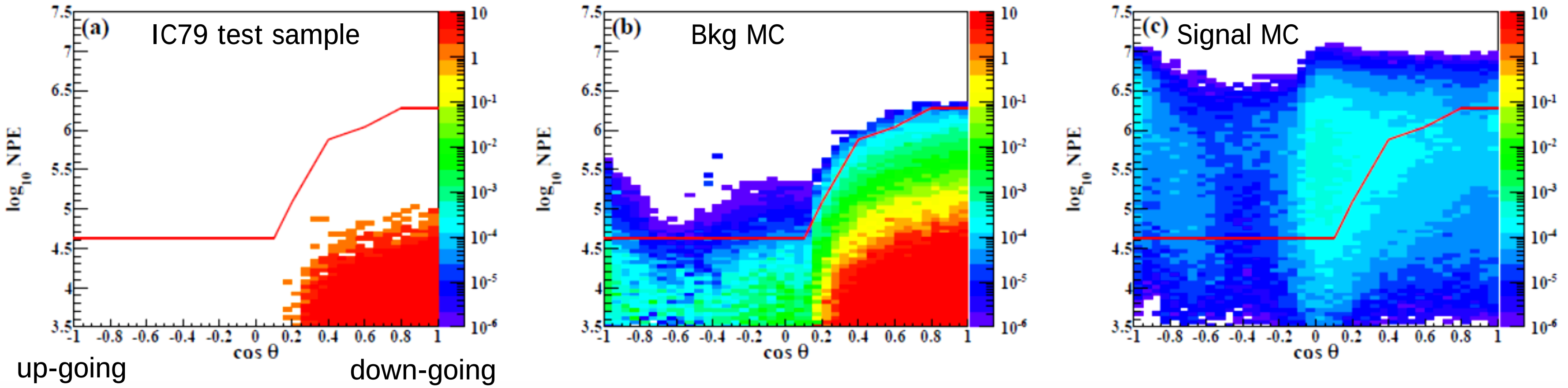
- target events with PeV – EeV energy
- look for lots of deposited energy (tracks/cascades)
- E ∝ # photo-electrons (NPE)



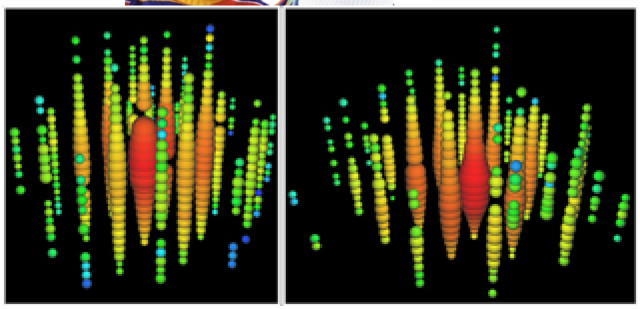
> 300 DOMs
> 41000 NPE



- cuts on direction and energy
- optimization fully based on MC
- verified on 10% data



Search for cosmogenic ν's

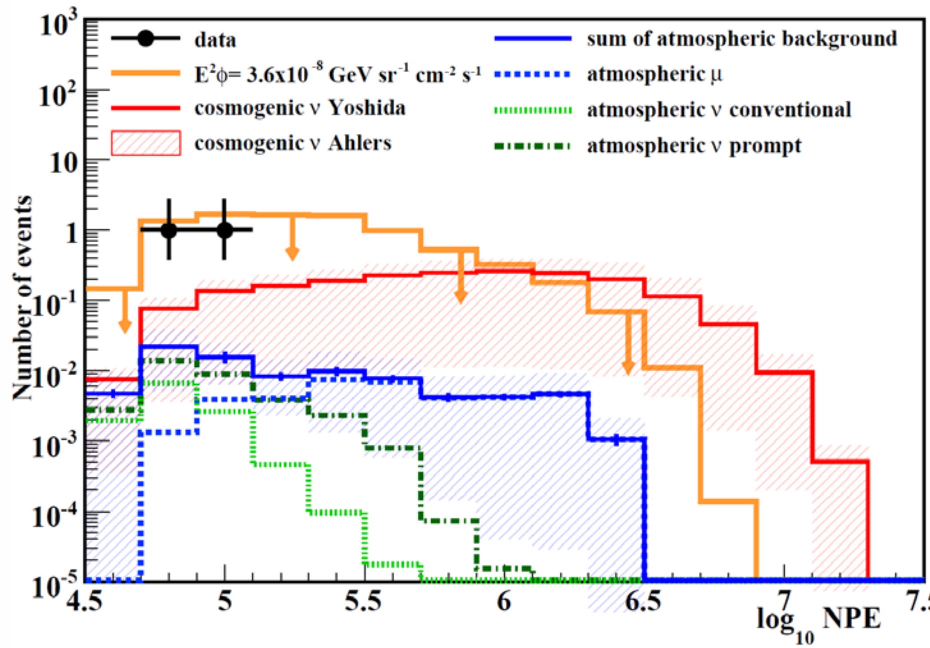


"Bert"	"Ernie"
1.04 PeV	1.14 PeV
Aug. 2011	Jan. 2012

- 2 events at threshold
- 2.8 σ excess over atm. bkg.
  (bkg. level 0.1 event)
  (incl. charm @ ERS baseline)

IceCube, PRL 111 (2013) 021103

Enberg, Reno, Sarcevic, PRD78:043005 (2008)

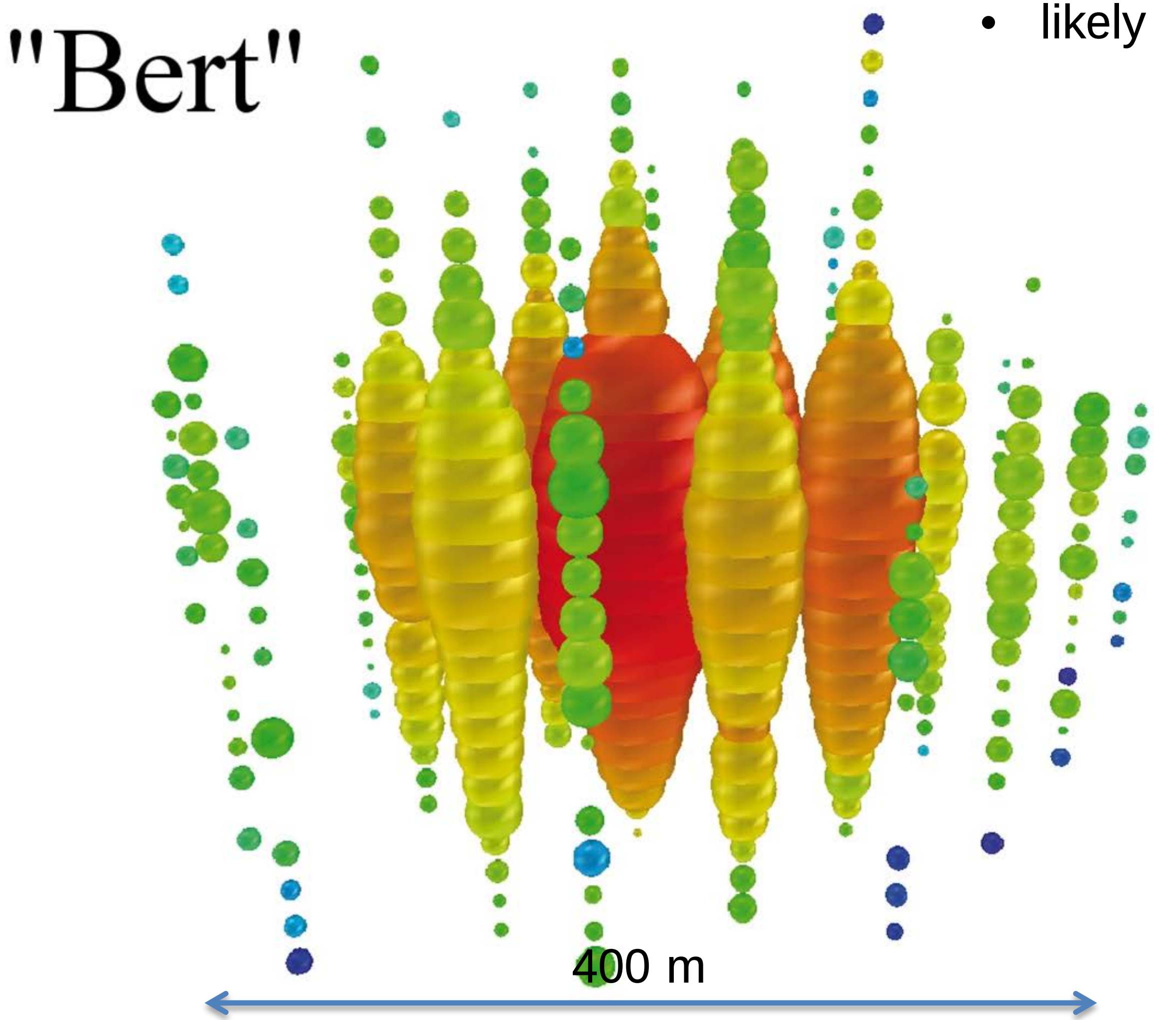


NPE distribution for 615.9 days live time

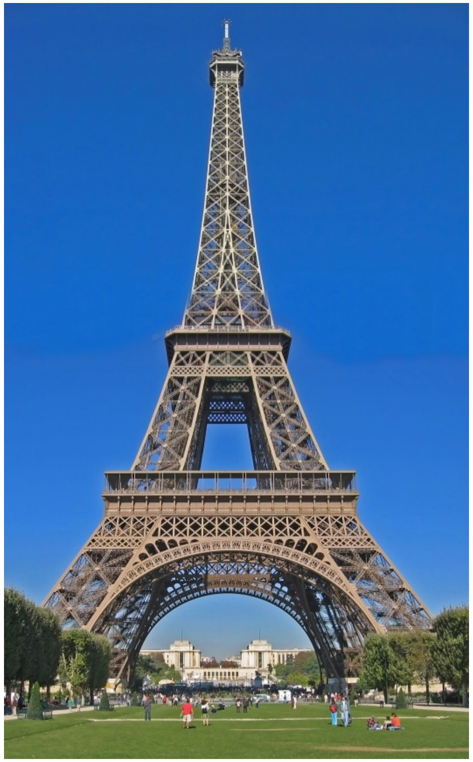
— E^{-2} power-law fit up to 10^9 GeV

- hint of possible astrophysical ν flux?

Search for cosmogenic ν's



- likely ν_e or ν_τ



Bert & Ernie ☞ MODIFIED SEARCH STRATEGY for astrophysical ν's

High energy starting events search - introduction

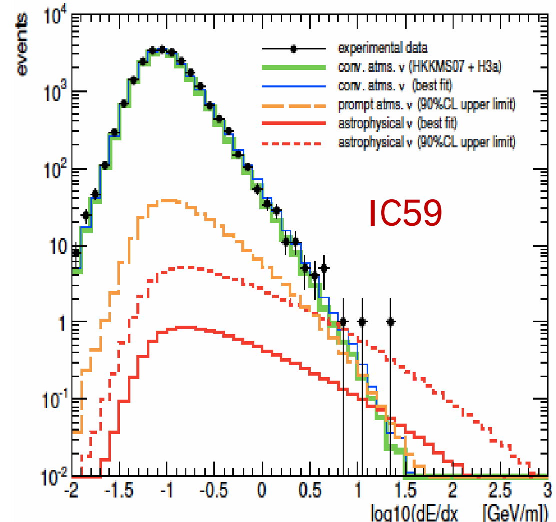
What we knew

- hints of deviation from bkg in upgoing muons (1.8σ)
- hints of dviations from bkg only in cascades (2.4σ)
- 2 PeV events in ~ 2 years data
  - downgoing
  - probably not cosmogenic
  - above expected bkg
- spectrum consistent with (broken) E^{-2}, seems not to extend much higher

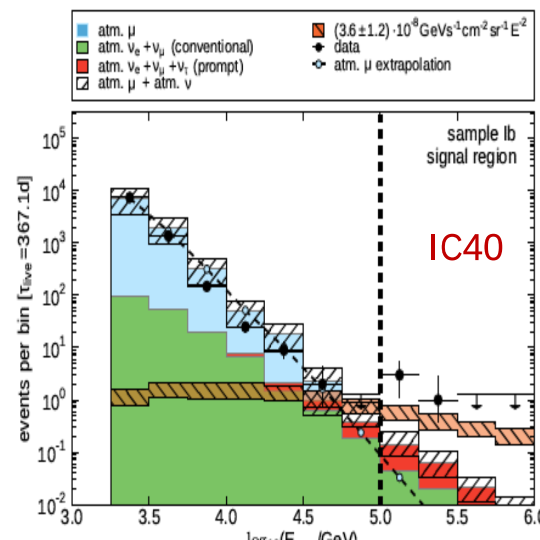
  would expect 8-9 events above 1 PeV from unbroken E^{-2}

What we wanted to know

- are the two PeV events tail of a distribution?



IceCube, arXiv:1311.7048



IceCube, arXiv:1312.0104

High energy starting events search – key points

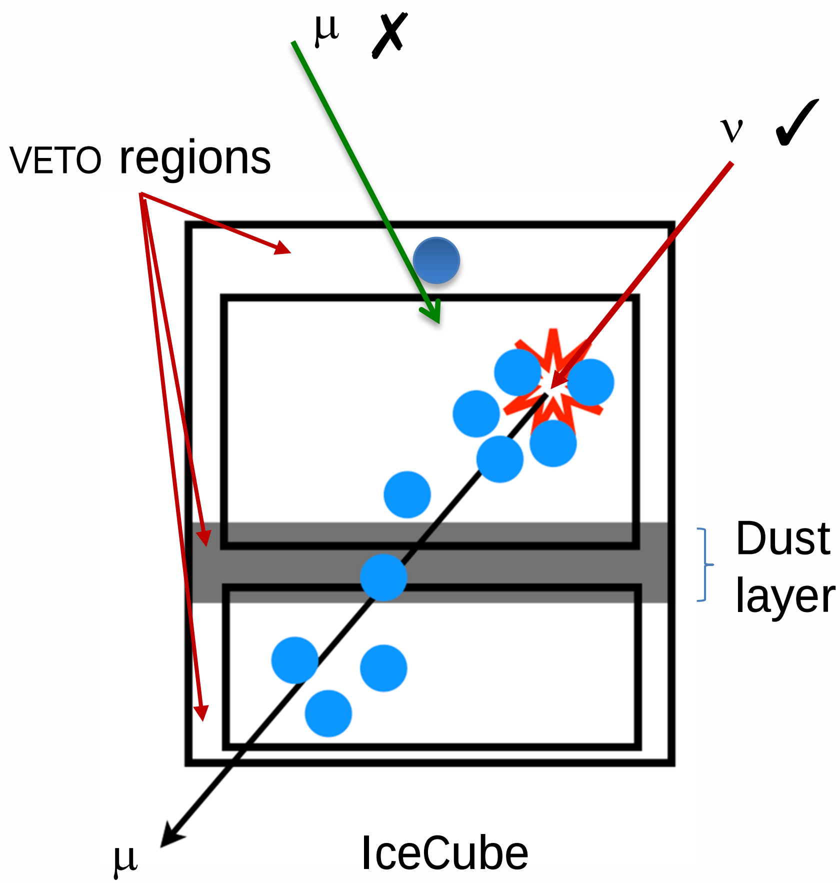
- events starting inside IceCube must be neutrinos!

define an outer VETO effective against

- atm. μ's
  - tracks from above
- atm. ν's
  - accompanied by atm. μ tracks if from above

look at event characteristics

- energy
  signal: high energies
- direction
  signal: horizontal and downgoing
- topology
  signal: mostly cascades



High energy starting events search

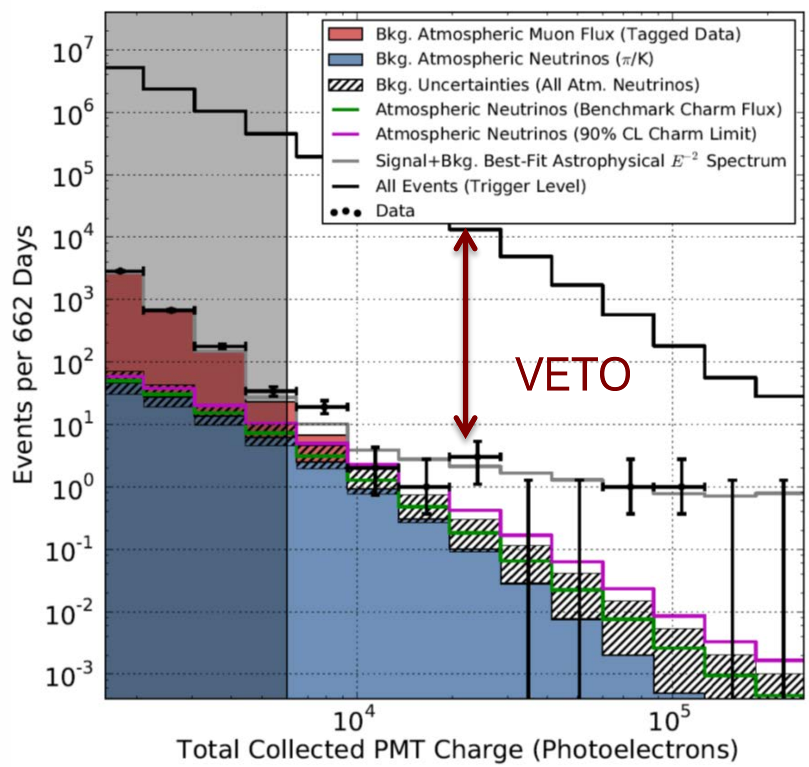
Total collected charge

Estimated

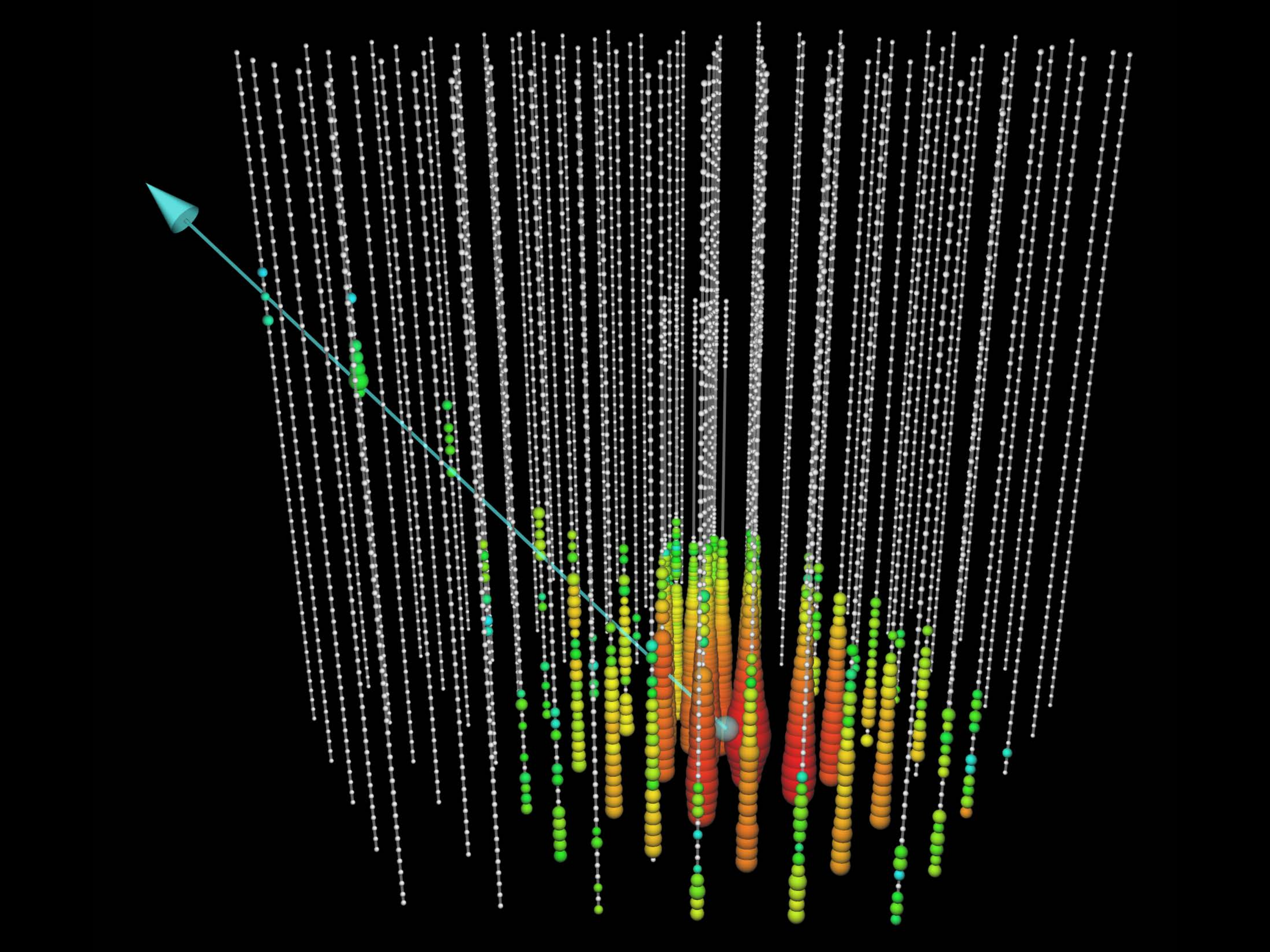
- bkg of atm. μ's – from data (red)
  double-layered veto
- bkg of atm. (π/K) ν's – extrapolated from IceCube measurement at lower energies (blue)
  scaled by prob. that the ν be un-accompanied by μ or bundle (MC)
- bkg from prompt ν's (charm) – from ERS
  90% C.L. upper limit from IceCube measurement at lower energies (= 0+σ)

Total background
☞ atm. μ 6 ± 3.4
☞ atm. ν $4.6^{+3.7}_{-1.2}$

NPE>6000



28 events observed
including Bert&Ernie



High energy starting events distribution inconsistent with bkg at 4.1 σ

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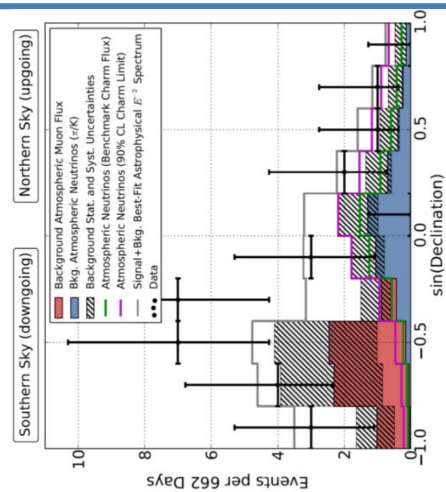
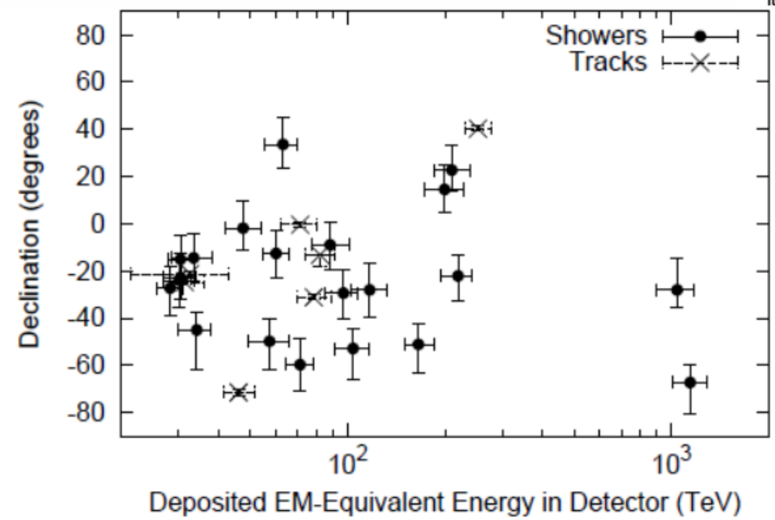


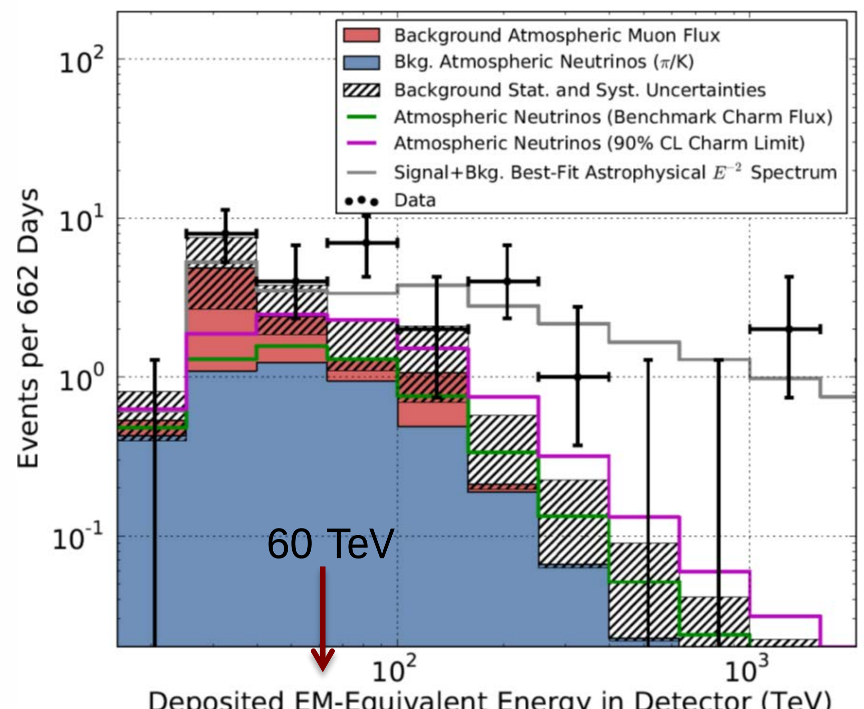


- mostly cascades (21/28)
- zenith distr. consistent with isotropic astrophysical flux
- energy spectrum > 60 TeV harder than that expected for atm. bkg
- consistent with bkg < 60 TeV

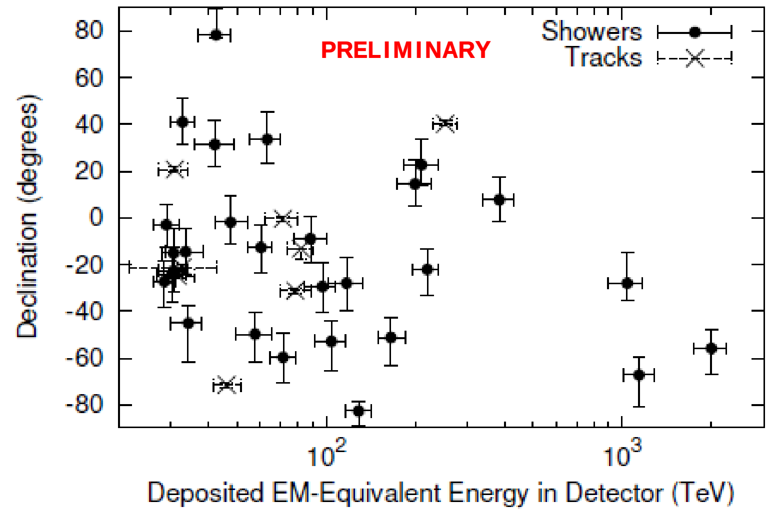
$$E^2\Phi = (3.6 \pm 1.2) \times 10^{-8}\,\mathrm{GeV cm^{-2} s^{-1} sr^{-1}}$$

60 TeV<E_{dep}<2 PeV

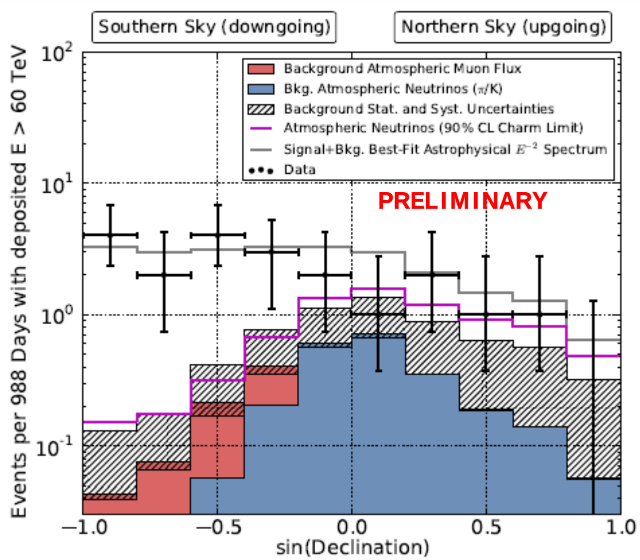
lack of events > 2 PeV implies break or cut-off

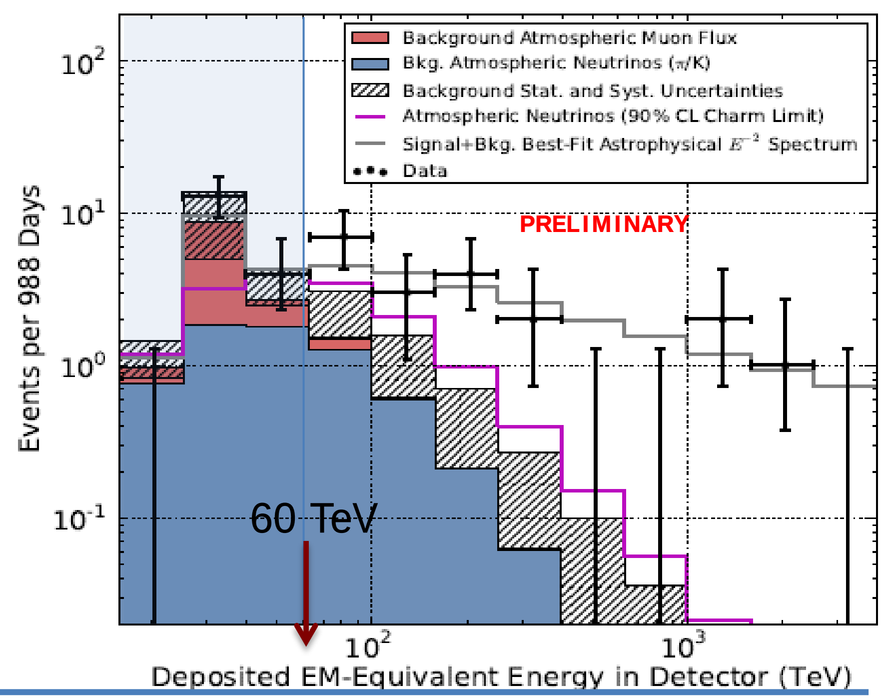


- 37 events in 988 days
- an event at 2 PeV
- spectrum and angular distribution consistent with published results



arrival angles of events with E_{dep} > 60 TeV



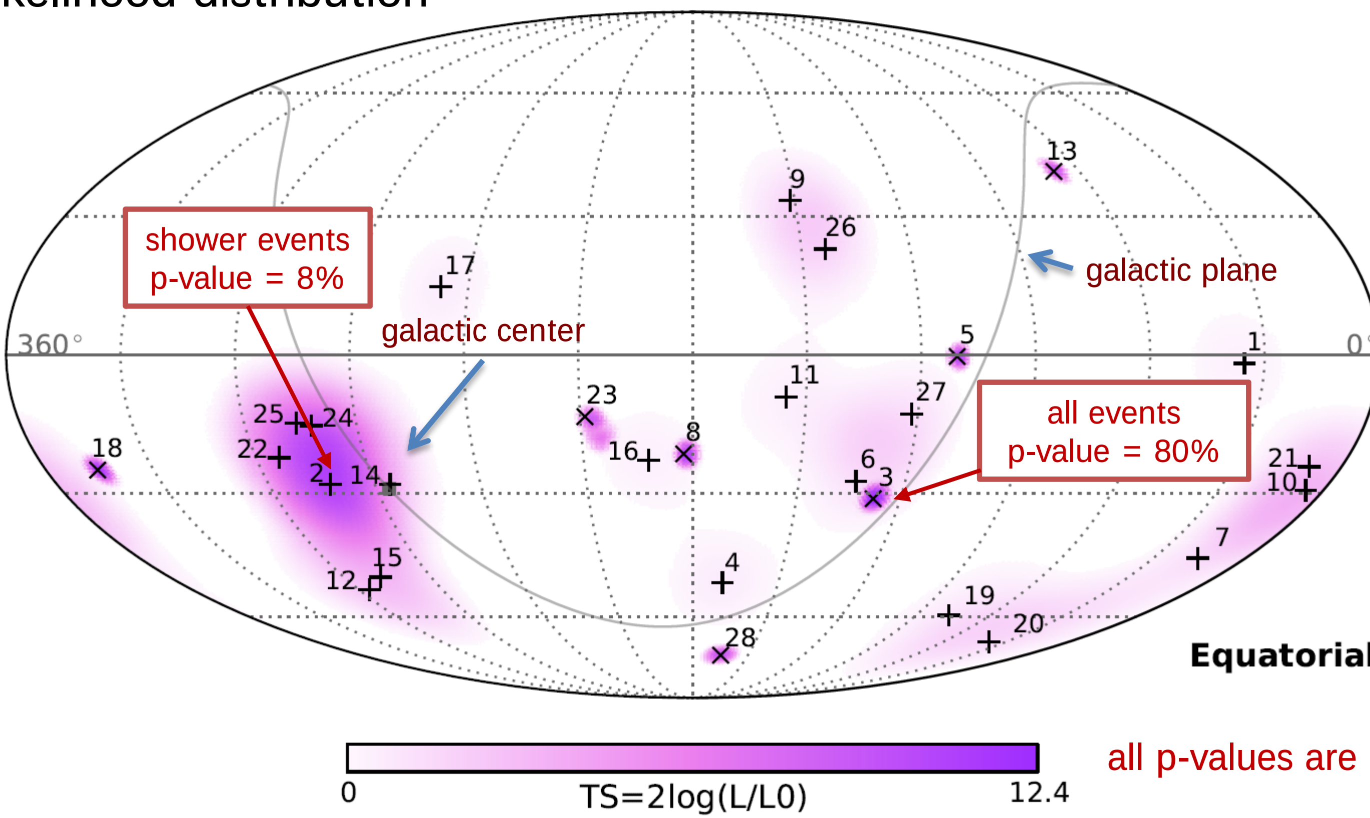


High energy starting events 2 yrs skymap compatible with isotropy

- too few events to identify sources

- every event has its own 2D directional likelihood distribution

IceCube, Science 342:1242856 (2013)



all p-values are post-trial

$$L(x)=\prod_{i}^{n_{tot}}\left\{\frac{n_s}{n_{tot}}S_i(x)+\left(1-\frac{n_s}{n_{tot}}\right)B_i(x)\right\}$$

signal plus bkg maximized likelihood

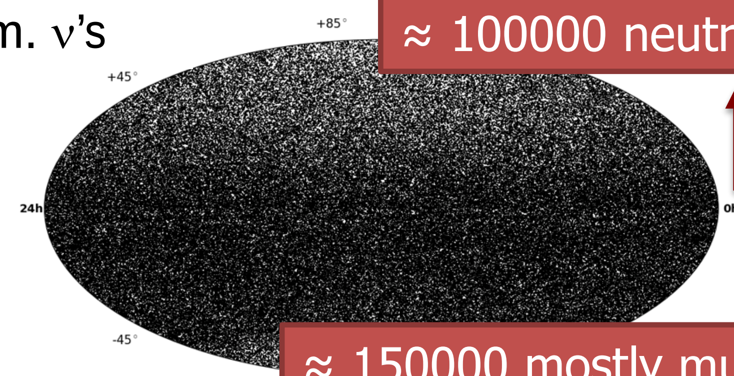
”Traditional” search for point sources of astrophysical neutrinos

- IceCube has collected data during construction
- allows search for clustering of neutrino arrival directions with a lower energy threshold
- present search with 3 years of data (April 2008 – May 2011)

IceCube, Astrophys. J 779:132 (2013)

- select well-reconstructed (ν_μ induced) μ tracks

Northern hemisphere dominated by atm. ν's



≈ 100000 neutrinos

≈ 150000 mostly muons

Southern hemisphere dominated by high energy atm. μ's

Point source searches – IC40+IC59+IC79 – 1040 live days

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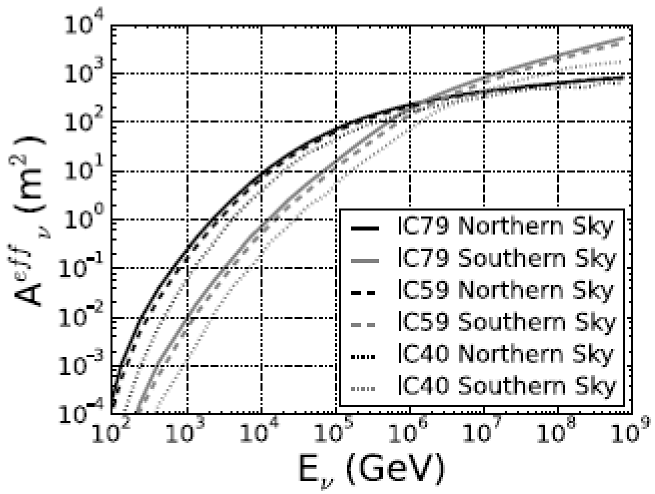
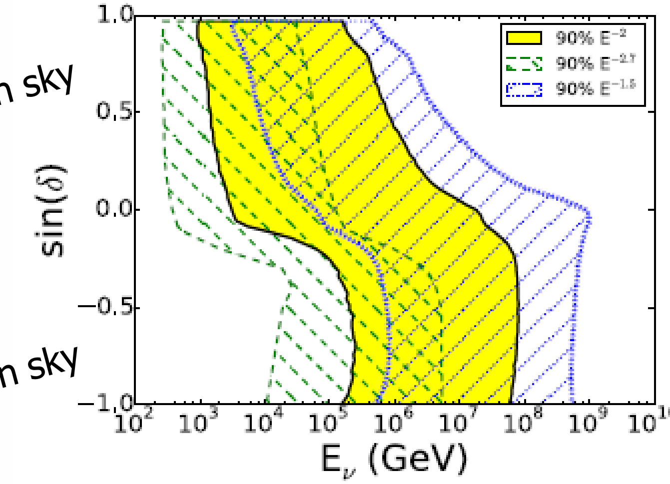


Effective areas

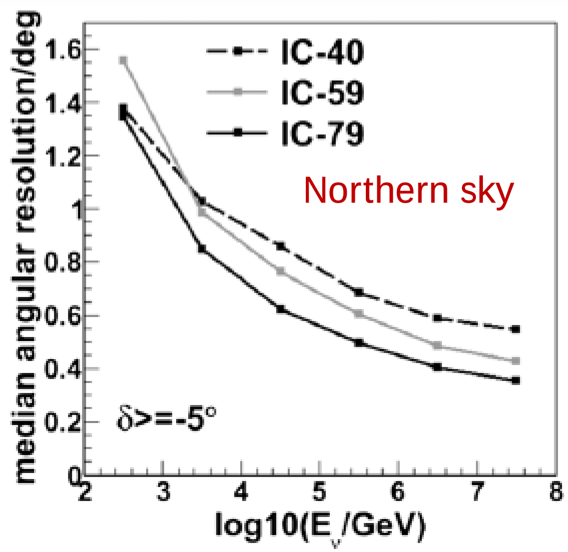
Northern sky

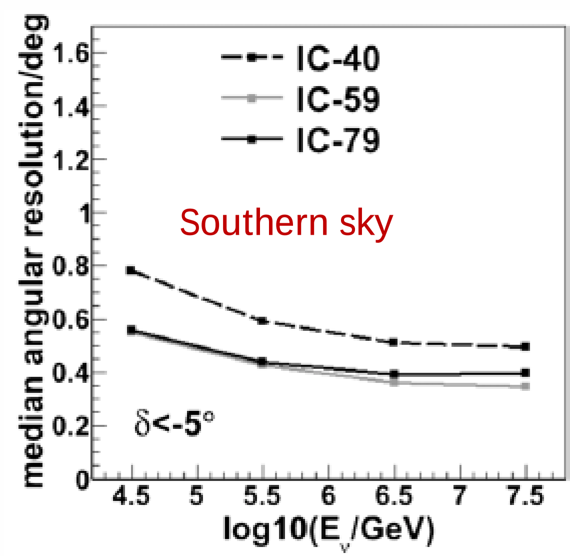
Southern sky



90% central signal containment region
3 different power law spectra

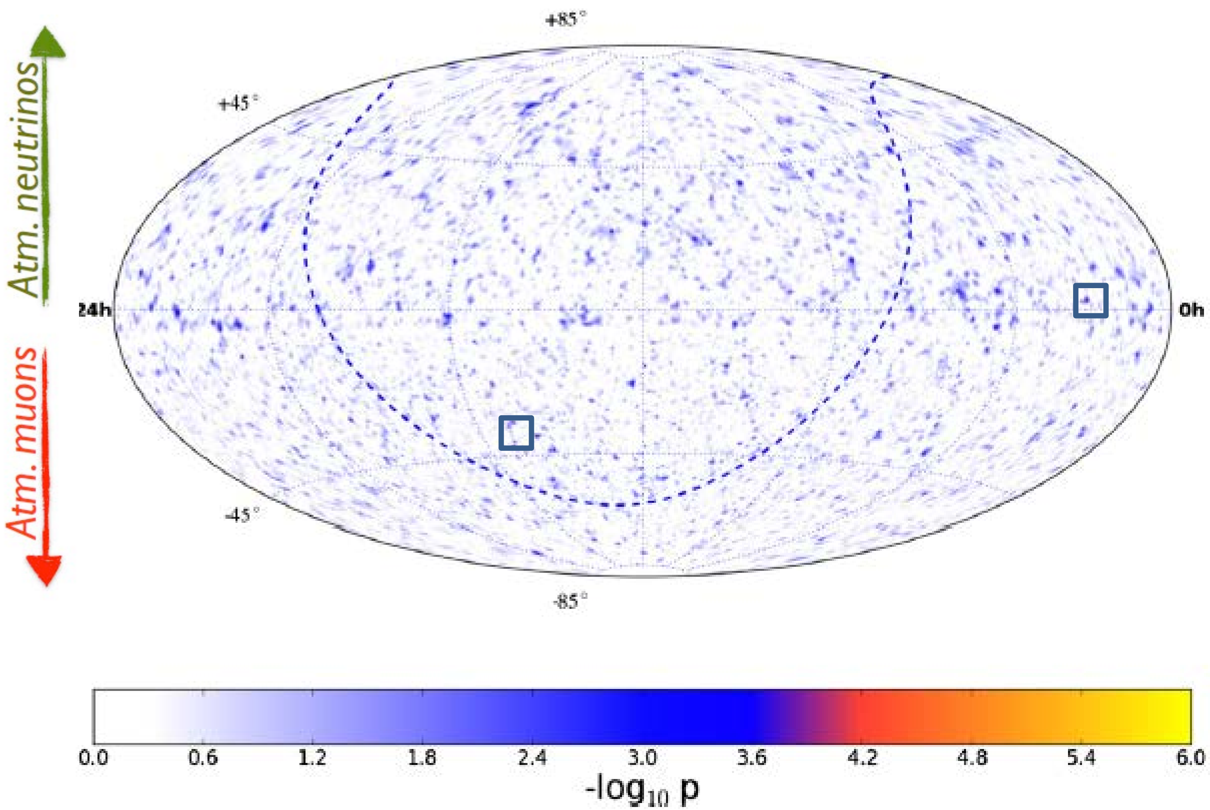
- Northern sky
  - remove mis-reconst.s
- Southern sky
  - stronger quality cuts
  - energy selection





Pre-trial significance map – equatorial coordinates

color indicates compatibility with background



most significant North

$-\log_{10}p=4.71$ (pre-trial)
r.a.: 34.25°
dec.: 2.75°
post-trial: 57%

most significant South

$-\log_{10}p=4.05$ pre-trial
r.a.: 219.25°
dec.: -38.75°
post-trial: 98%

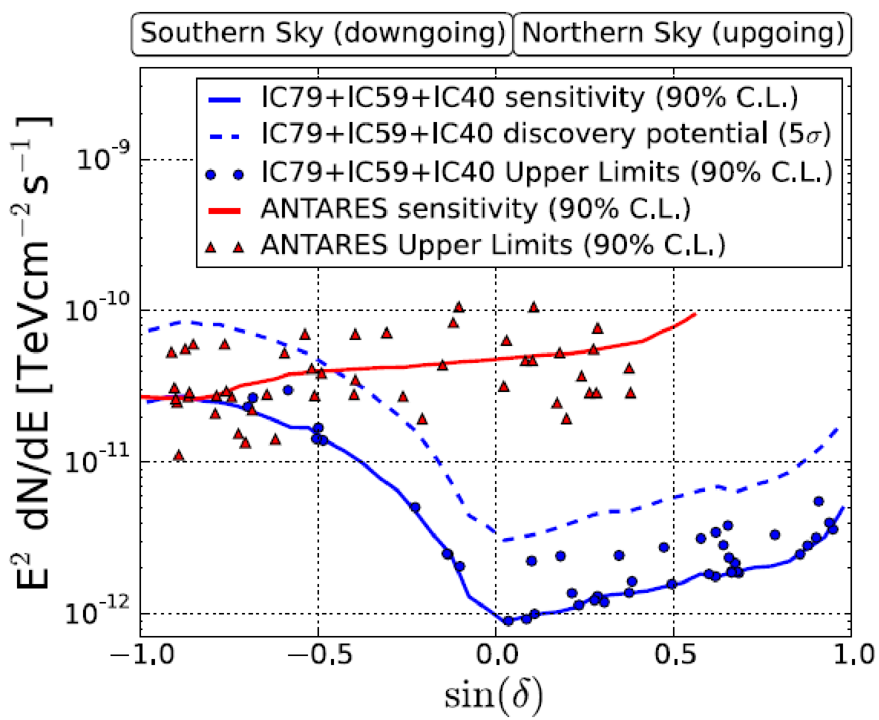
- no significant deviation from isotropy

IceCube, Astrophys. J 779:132 (2013)

Point source searches – IC40+IC59+IC79 – 1040 live days

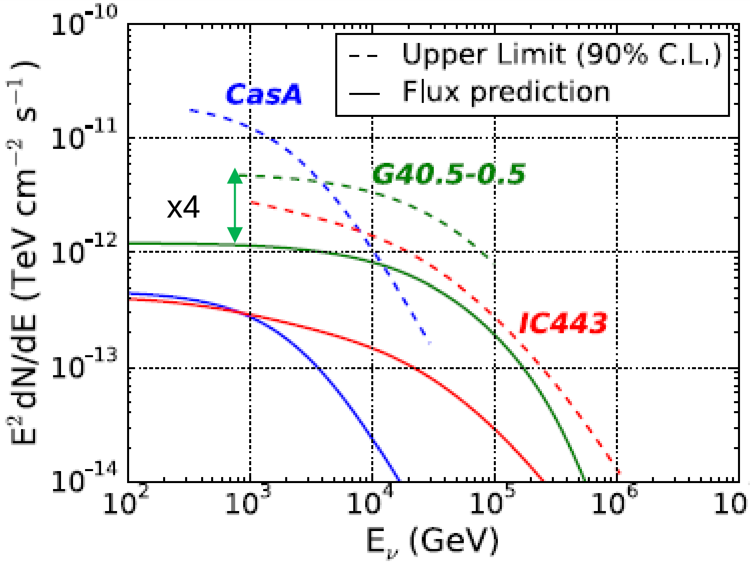
- selected sources (galactic/extra galactic)
- stacked sources
- extended sources

- time dependent flare searches



E^{-2} muon upper limits
1TeV-1 PeV North 100 TeV – 100 PeV South

Supernova remnants



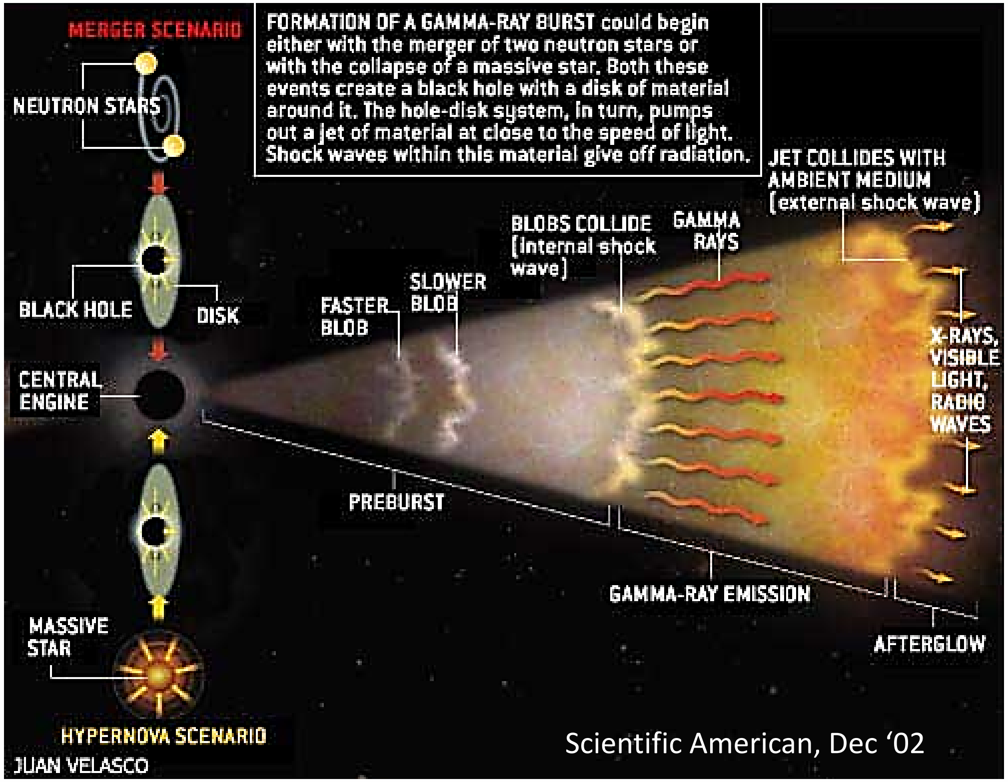
M. Mandelartz, J. Tjus, arXiv:1301.2437

ANTARES: S. Adriàn-Martinez et al. arXiv:1207.3105

Gamma Ray Bursts

- transient point sources
- localized in space and time
- data from incomplete IceCube (April 2008 – May 2010) ~ 300 GRBs constrained models
- upper limit ~ a factor 3 below predictions of the fireball model

IceCube, Nature 484 (2012) 351
IceCube, arXiv:1204.4219v2



CONCLUSION:

GRBs alone cannot account for the flux of very-high energy CRs

OR

the efficiency of neutrino production much lower than expected

- theoretical suggestions to reduce the GRB neutrino flux prediction are being tested with more data

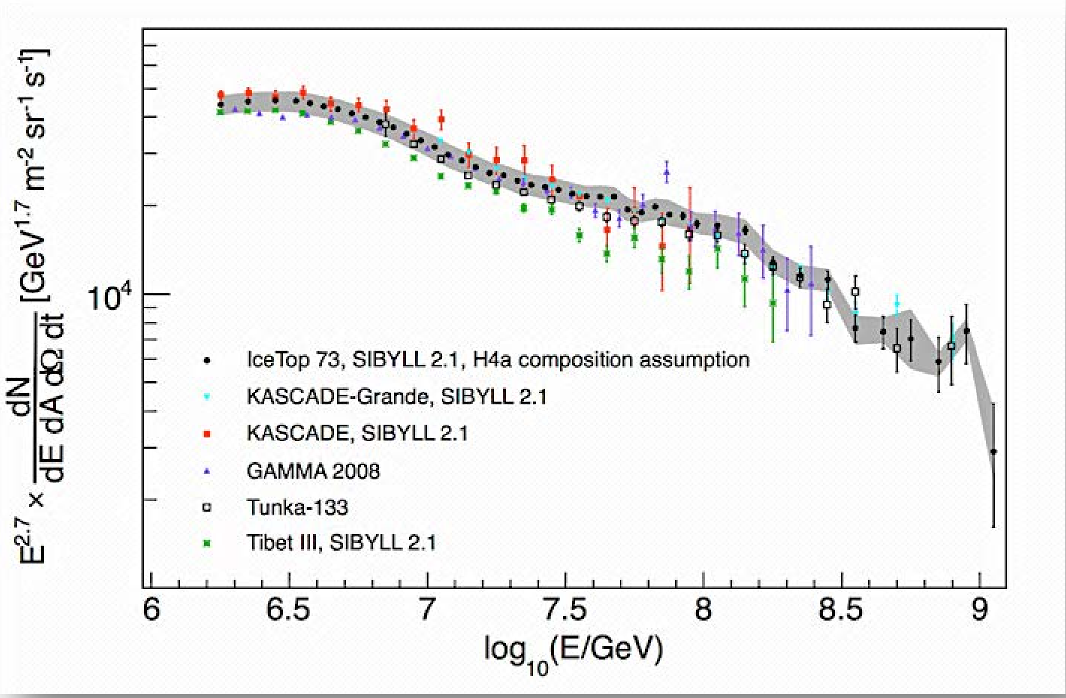
CR physics is related to neutrino astrophysics

- the cosmic settings which generate CRs also produce ν's
- CRs interacting in Earth's atmosphere produce the bkg for astrophysical ν's
  - atm. ν's and atm. μ's

Measure

- CR energy spectrum (IceTop)
- composition (IceTop + IceCube)
- anisotropy of the CR arrival directions

IceTop 73 energy spectrum
1.6 PeV to 1.3 EeV

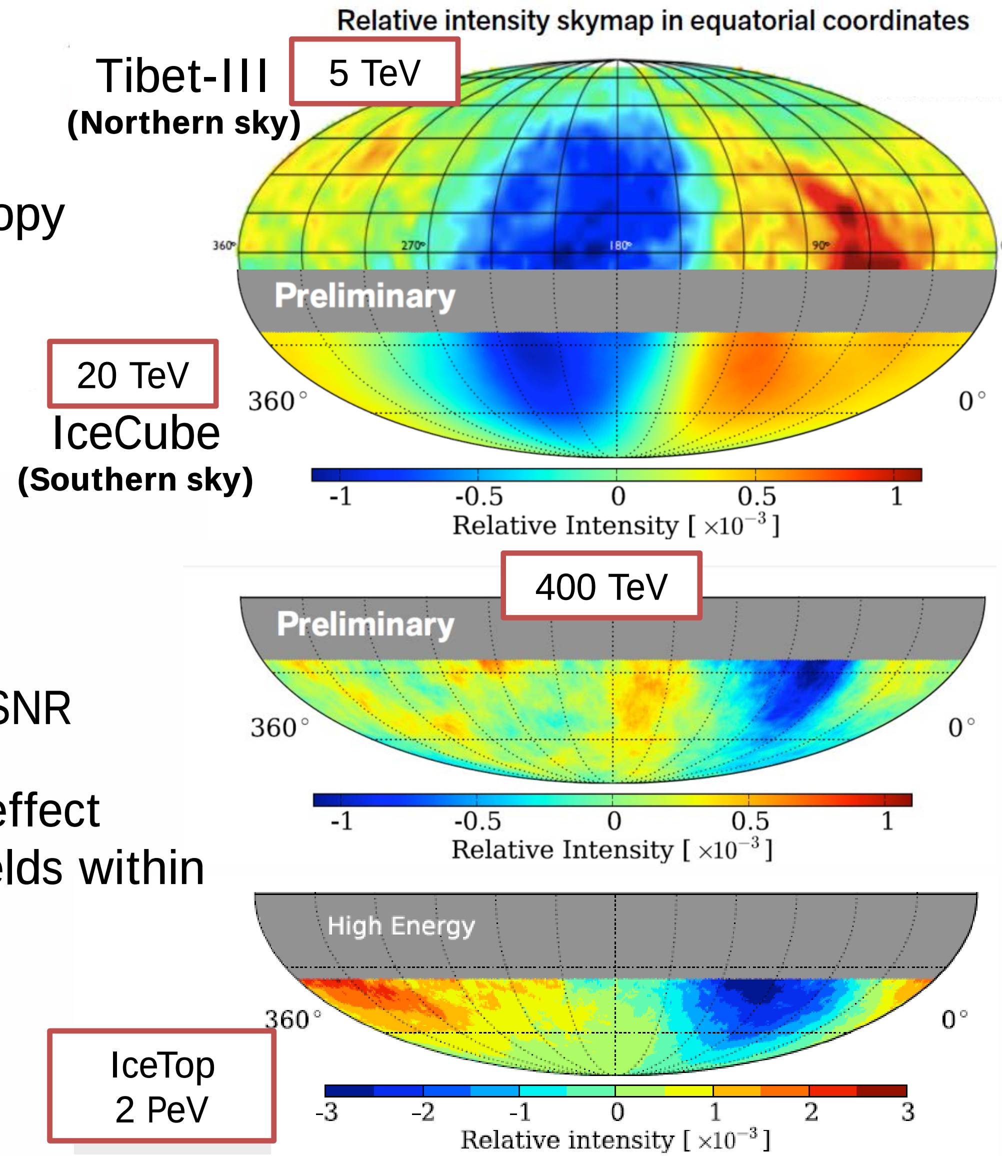


IceCube, PRD88:042004 (2013)

Cosmic ray anisotropy – understanding propagation in the galaxy

data smoothed on a 20° scale.

- a large angular scale structure – dipole, ampl. ~ 10^{-3}
- the phase of the large scale anisotropy changes between 20 and 400 TeV CR primary energy
- subtracting the dipole – structures observed at scales down to 5°, ampl. ~ 0.2×10^{-3}
- origin of the anisotropy unknown
- possibly signature of a few nearby SNR
- small scale anisotropy could be an effect of turbulent interstellar magnetic fields within few pc + interplay with heliosphere



IceCube searches for neutrinos from accumulations of WIMPs

Dwarf spheroidal Galaxies:

→ IceCube-59 limits

Clusters of Galaxies:

→ IceCube-59 limits

(arXiv:1210.3557 2012)

Galactic Halo:

→ IceCube-22 limits

(PRD 84 (2011) 022004)

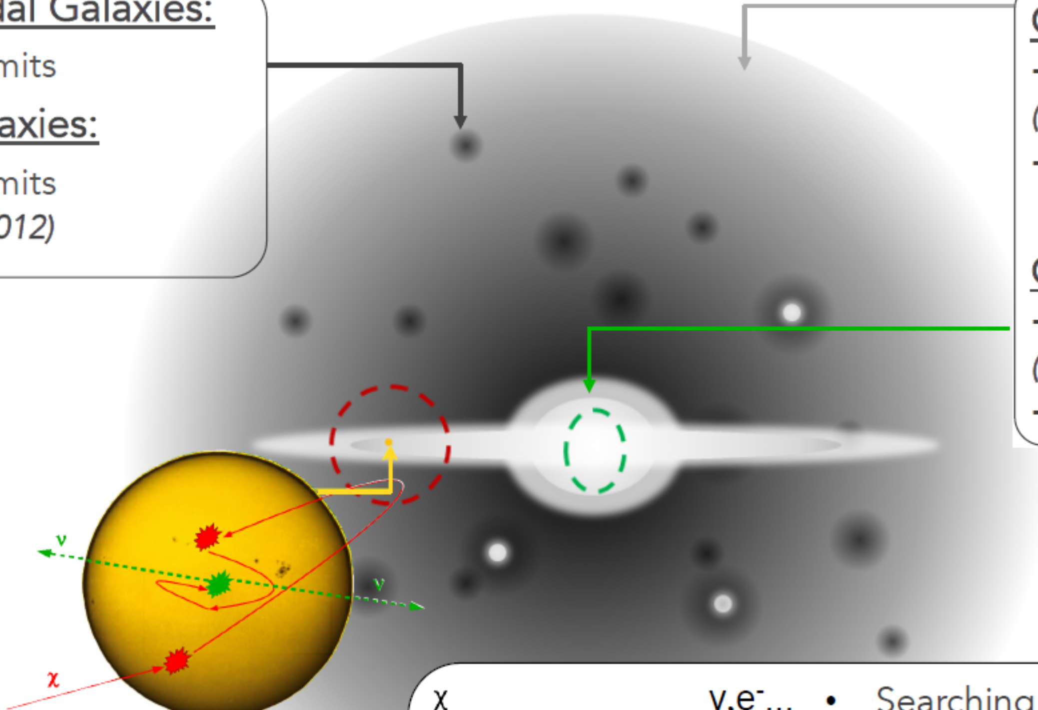
→ IceCube-79 limits

Galactic Center:

→ IceCube-40 limits

(arXiv:1210.3557 2012)

→ IceCube-79 sens



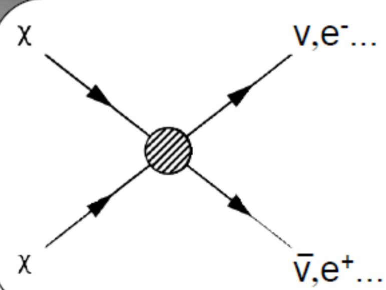
Local sources (Sun & Earth):

→ IceCube-79 limits

(PRL 110 (2013) 131302)

→ Specific models & Global fits

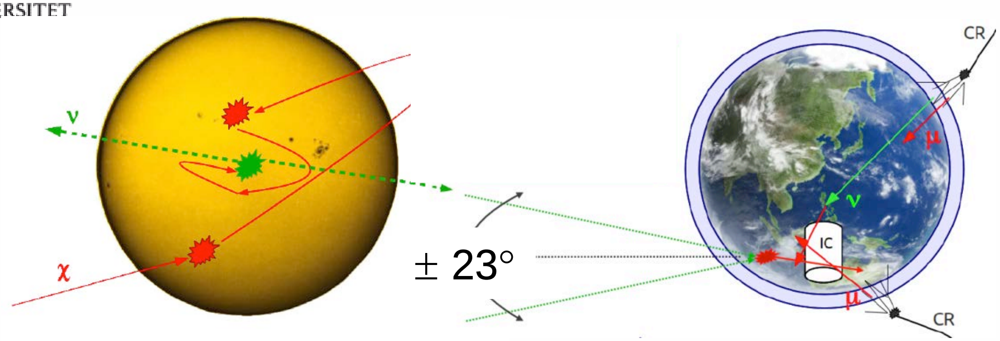
(JCAP 11 (2012) 057)



- Searching for DM-annihilations is in low energy regime for IceCube. (~10 GeV-TeV)
- Consider "extrema" to bracket possible neutrino spectrum. e.g. *hard* (W^+W^-) and *soft* ($b\bar{b}$)

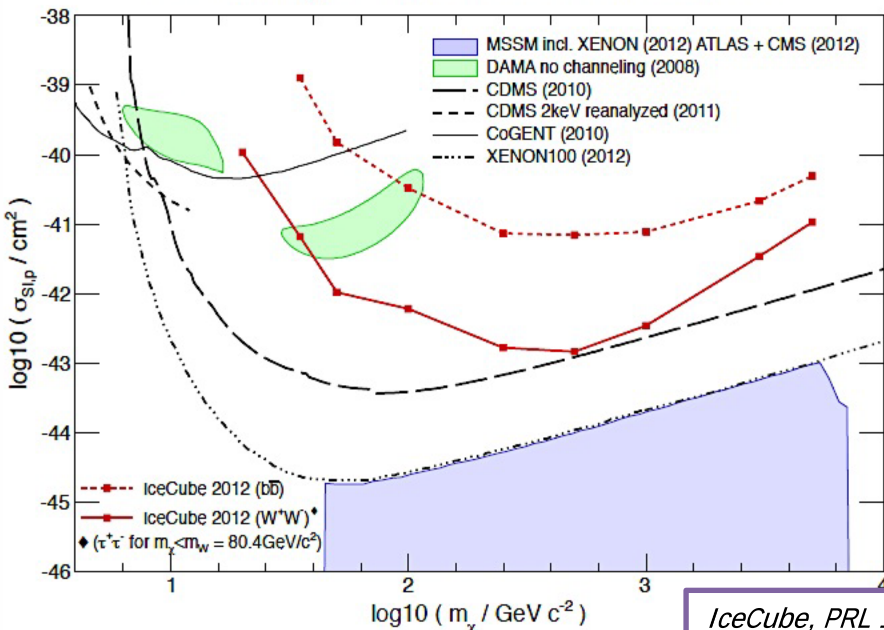
M. Danninger, TAUP 2013

Indirect dark matter searches – limits on DM annihilations in the Sun

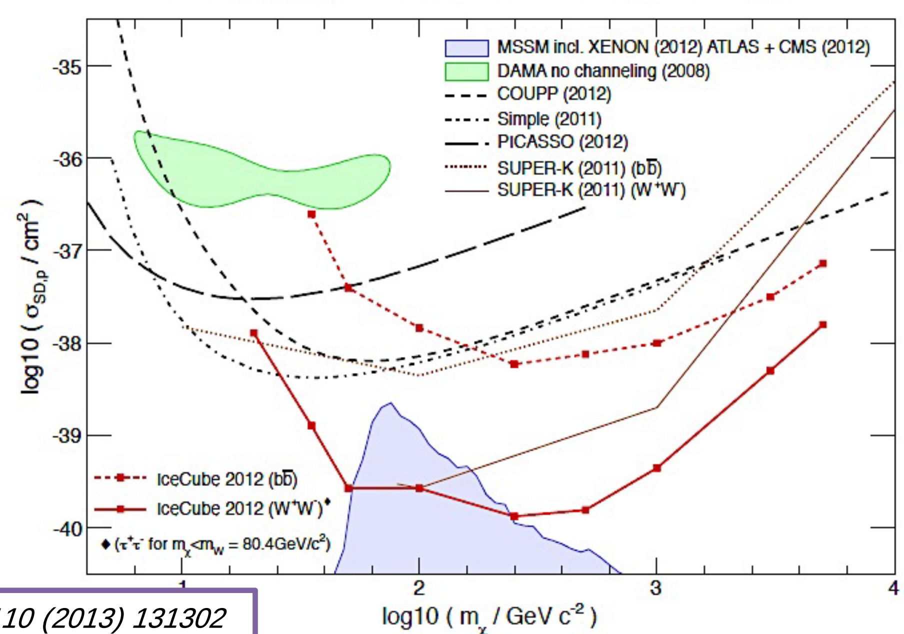


- signature: excess over bkg from the direction of the Sun
- observed angle to the Sun fit with signal and bkg pdf's
- Sun azimuth kept blind

SI WIMP-proton cross-section limit



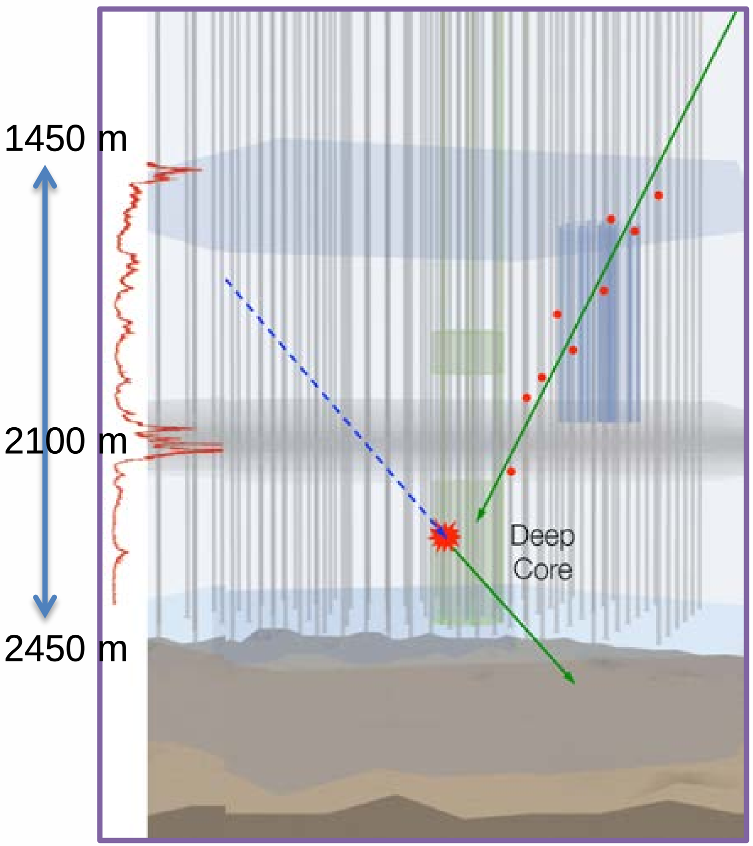
SD WIMP-proton cross-section limit



IceCube, PRL 110 (2013) 131302

- complementary to direct detection searches
- average over the DM structure of the halo on solar time scales

DeepCore



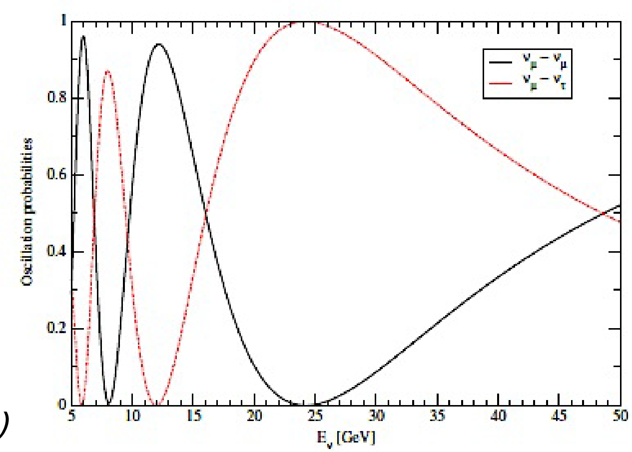
- improved sensitivity for low mass WIMPs
- sensitivity for Southern sky sources
- enhanced acceptance for low energy ν
  10 GeV – 200 GeV

- sensor density ~4×IceCube

~ 20 Mton detector (cf SK ~ 20 kt)
~ 10000 ν's/year

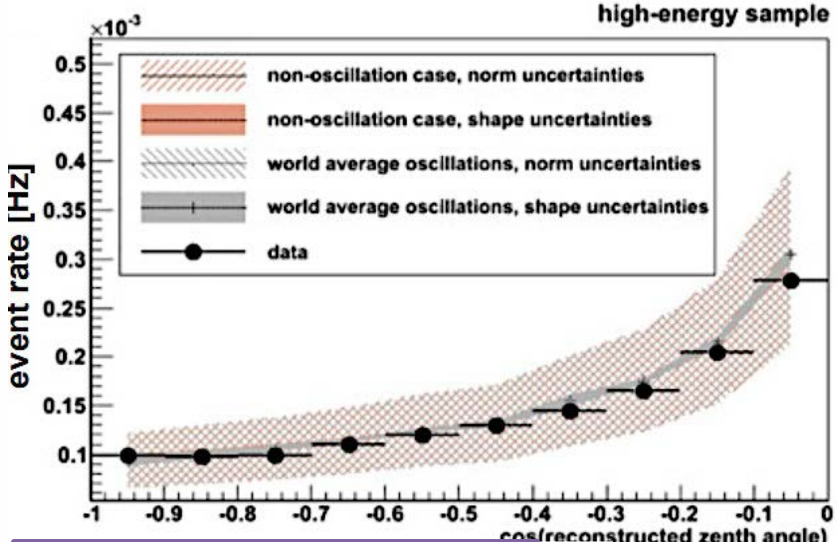
- allows observation of ν oscillations

all sky sensitivity
☞ use surrounding IceCube strings as veto

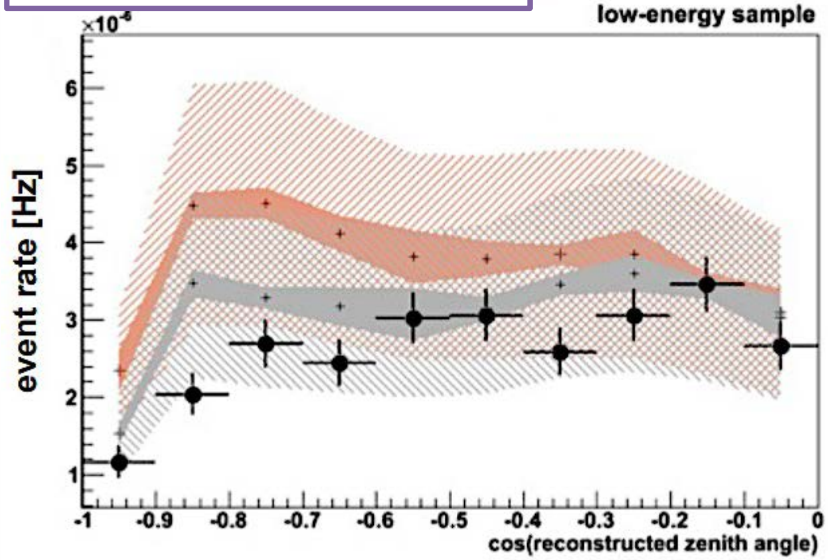


O. Mena et al., PRD 78:093003 (2008)

ν_μ oscillations with IC79

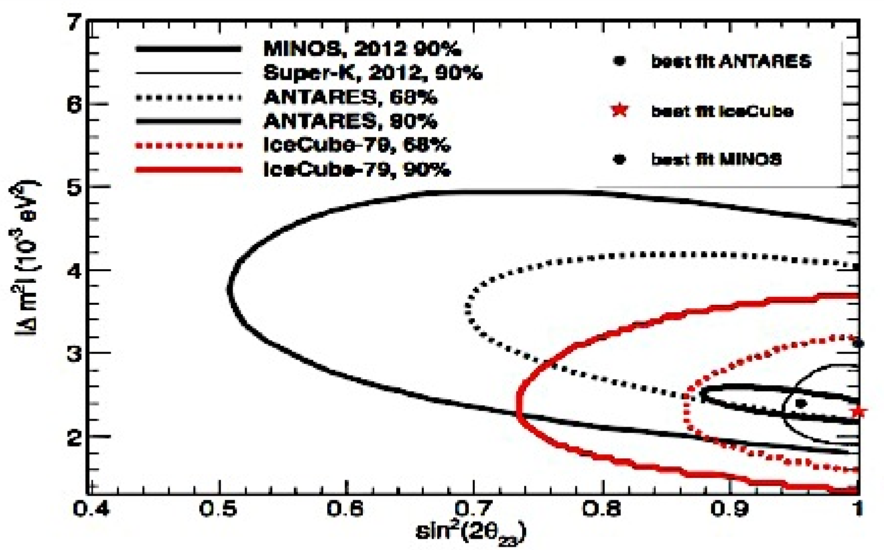


IceCube, PRL 111:081801 (2013)



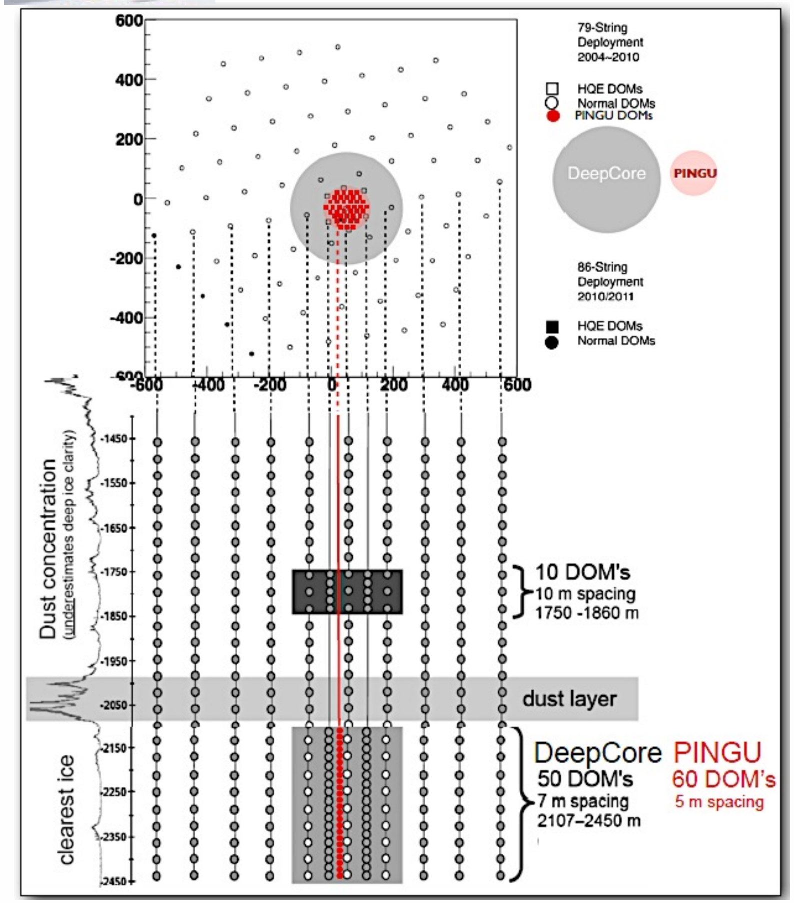
- high-energy sample (> 100 GeV)
- constrains syst. uncertainties
- oscillation signature expected in low-energy sample 20 – 100 GeV

no-oscillation hypothesis rejected at > 5σ
but ... not a high precision meas. of parameters yet!



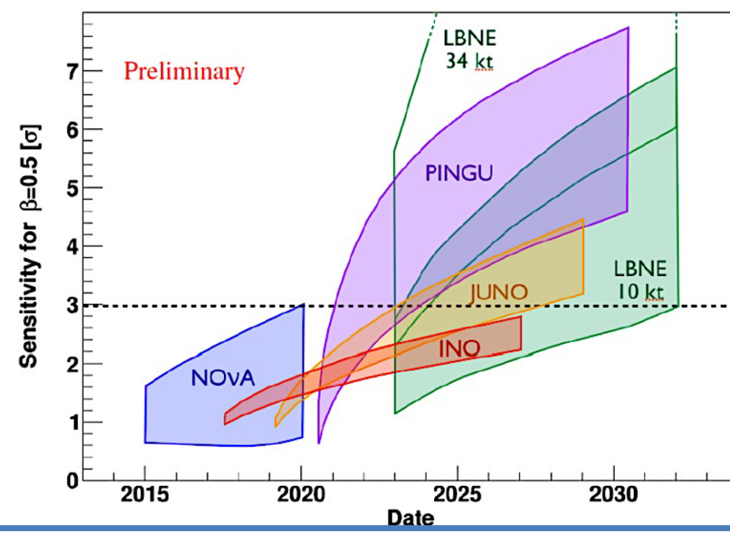
Low energy extension

PINGU The Precision IceCube Next Generation Upgrade



- neutrino mass hierarchy effects expected at <10 GeV – too low for DeepCore
- add 40 strings with 60 optical sensors each inside the DC

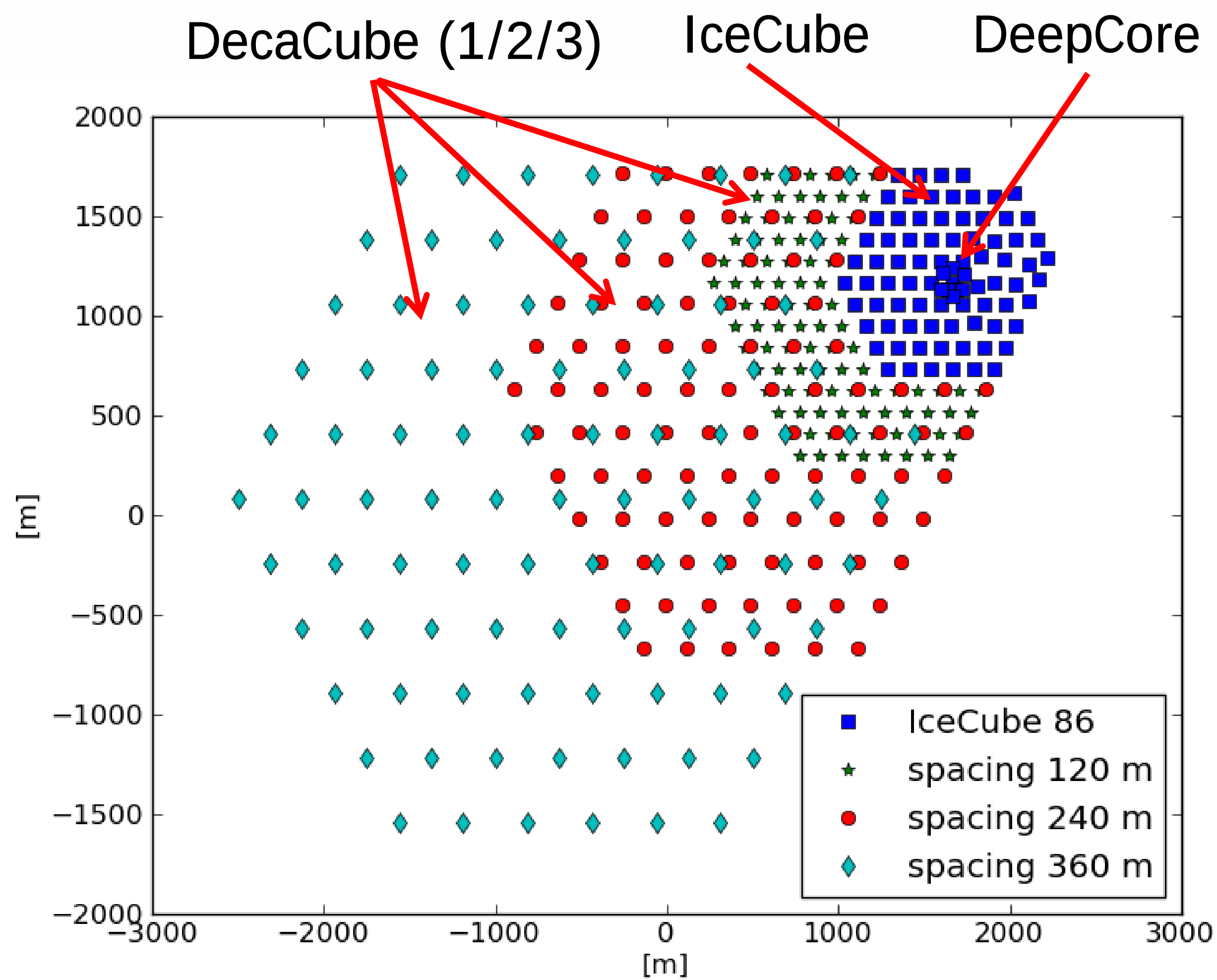
Preliminary: PINGU
can determine NMH with 3σ after ~3 yrs



PINGU LoI, arXiv:1401.2046

High-energy extension

increase in threshold not important
(in the region where atmospheric background dominates)



Effective volumes

Spacing 1 (120m):
IceCube (1 km^3)
+ 98 strings (1,3 km^3)
= 2.3 km^3

Spacing 2 (240m):
IceCube (1 km^3)
+ 99 strings (5,3 km^3)
= 6.3 km^3

Spacing 3 (360m):
IceCube (1 km^3)
+ 95 strings (11,6 km^3)
= **12.6 km^3**

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Summary and outlook

- IceCube has found the first high-energy neutrinos from extraterrestrial sources
- need to consolidate that observation with more data
- obvious next goal – try to identify the sources
- detector performs extremely well
- will be collecting data for at least 20 more years
- GRB limits are challenging the models
- all sky point source limits; WIMP limits; atm. μ and ν spectra
- cosmic ray spectra and anisotropies and m.m.
- extensions towards both lower and higher energies planned

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)
Inoue Foundation for Science, Japan
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)


”Somewhere, something incredible
is waiting to be known.” (C. Sagan)