Recent results from IceCube.

Detecting cosmic neutrinos and more

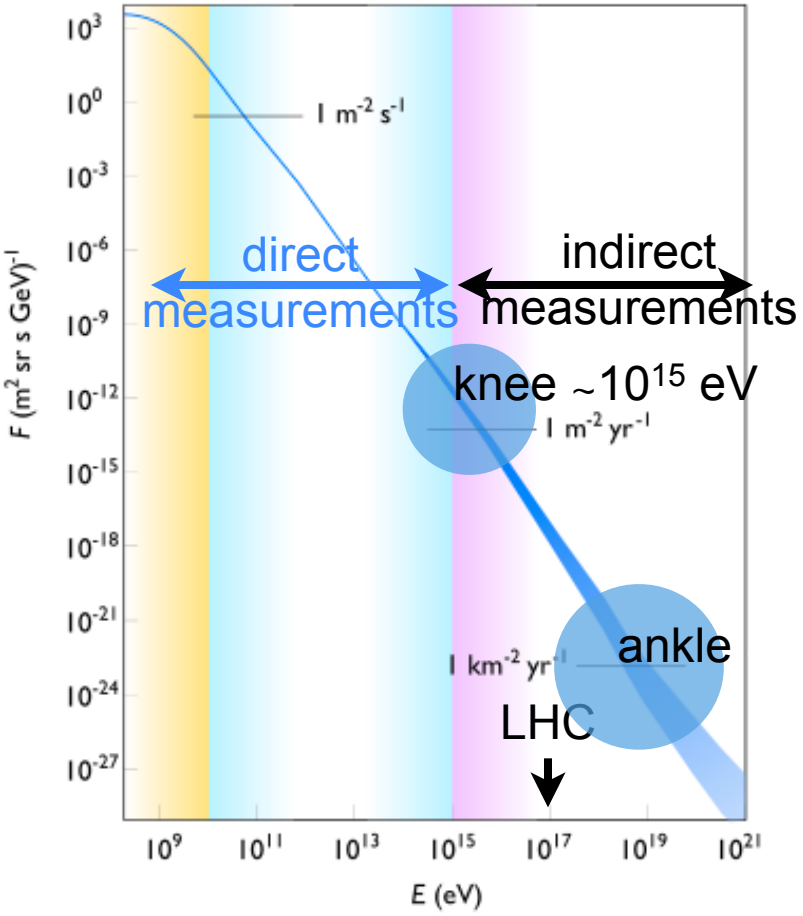
Elisa Bernardini
PRC 77, Astroparticle Neutrinos
Hamburg, 24 April 2014

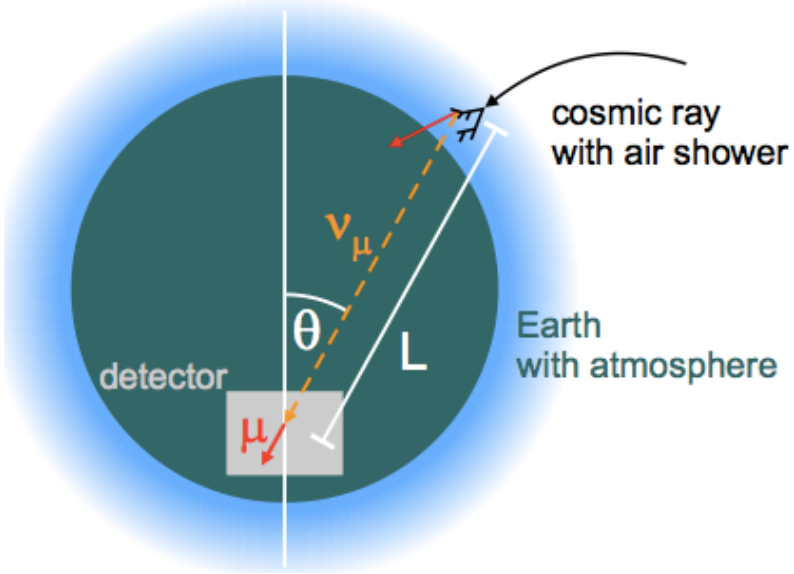
HELMHOLTZ ASSOCIATION

DESY

Seeking for the origin of Cosmic Rays … and more!

- Candidates for cosmic accelerators exist but understanding limited
- Unprecedented statistics of atmospheric neutrinos allows various searches of Physics Beyond the Standard Model





The IceCube scientific program and our role in it

- Neutrino astrophysics:
  - Probe the acceleration of Cosmic Rays
  - Individual astrophysical (point-like) sources
  - Transient phenomena (GRBs, AGN flares, Supernovae)
  - Diffuse cosmic flux

in this talk

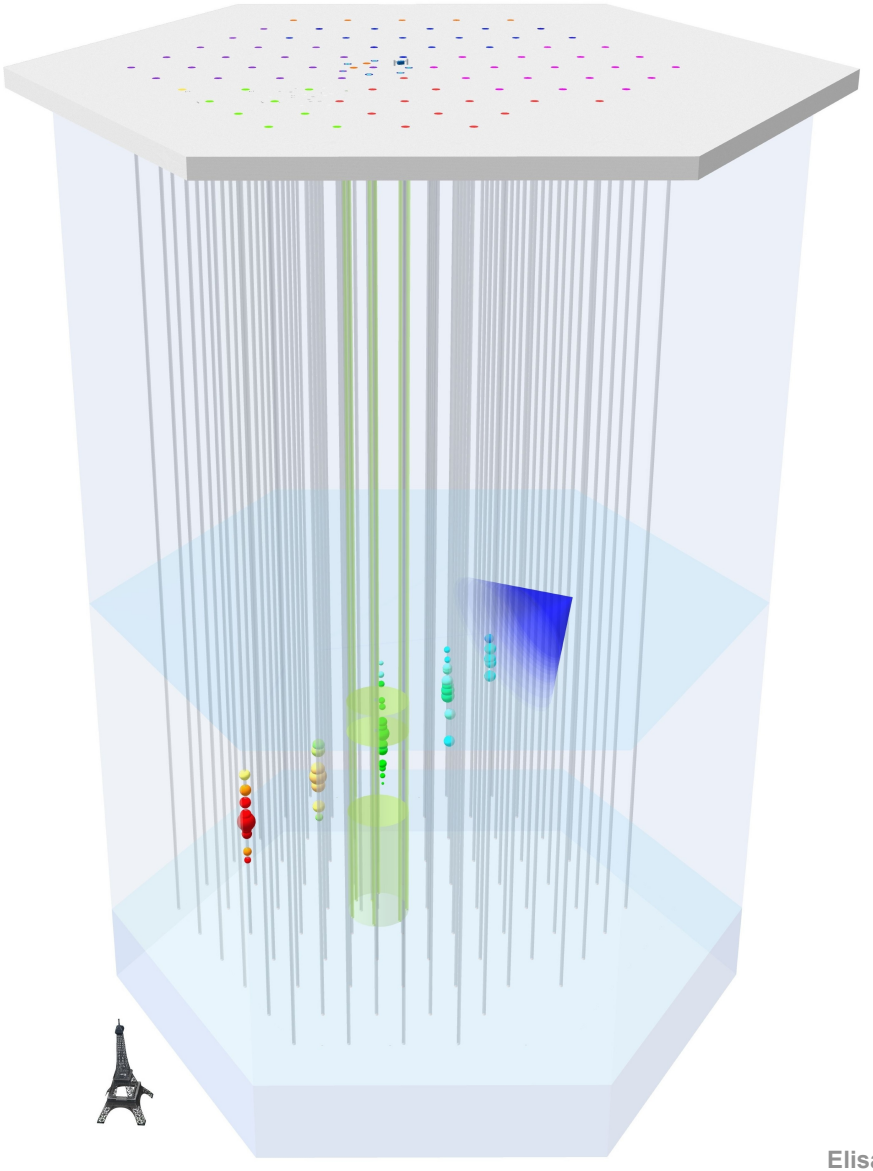
- Properties of Cosmic Rays (CR):
  - CR spectrum above the “knee” $O(10^{15}$ eV - 10^{18} eV)
  - CR composition
  - CR anisotropy

The IceCube scientific program and our role in it

- Dark Matter & Exotic particles:
  - WIMPs annihilation
  - Magnetic Monopoles
  - Sterile Neutrinos
  - Lorentz Invariance Violation
- Neutrino properties & particle physics:
  - Neutrino oscillation parameters
  - Charm production in atmosphere
  - High-energy cross-sections

in this talk

IceCube Observatory

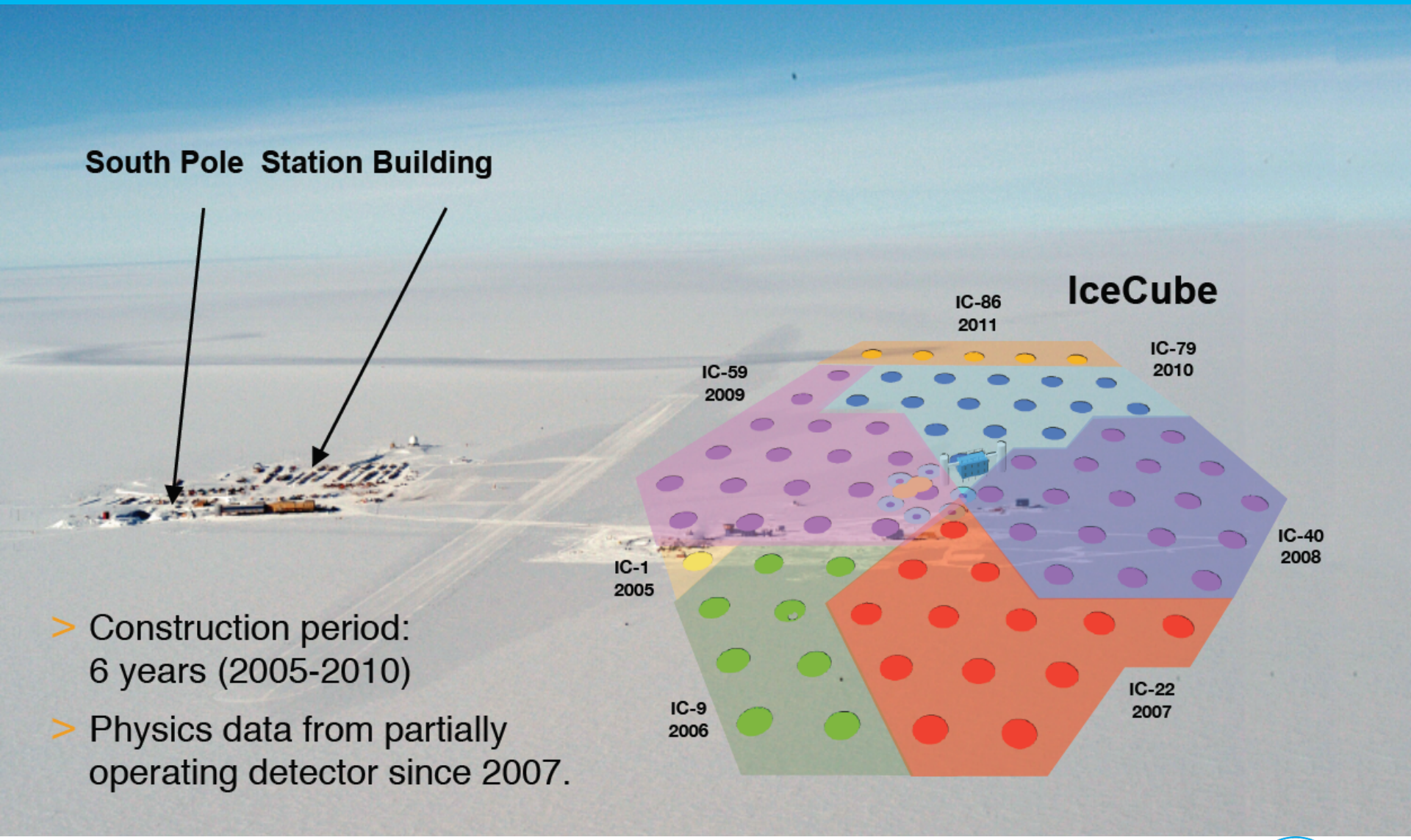


- 5160 sensors on 86 strings
- higher density DeepCore
- 1 km^3 sensitive volume
- ~98% of all sensors working after deployment
- failure rate <0.1% per year
- ~99% data taking efficiency

Our Role in IceCube

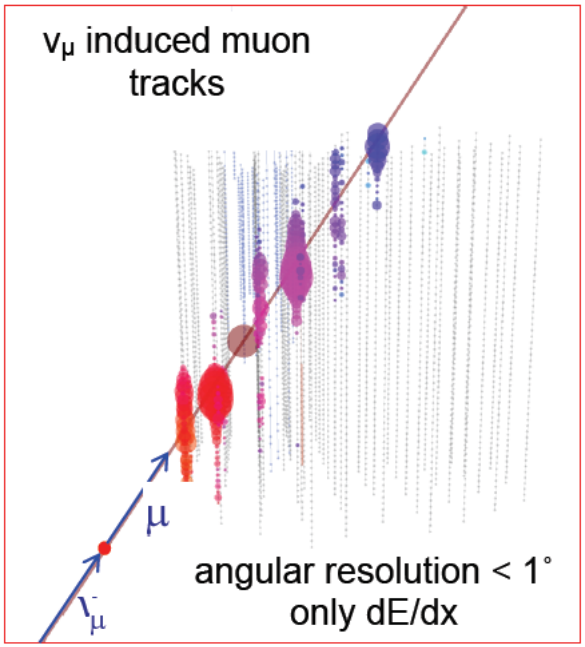
- Second largest group
- European TIER-1 datacenter
- 3.5 M€ investments for IceCube construction (out of 80 M€ total)
- 300 k€ / year for operations
- 13 FTE scientific personnel + 3 FTE support personnel for IceCube science and operations
- Currently 20 authors on IceCube publications

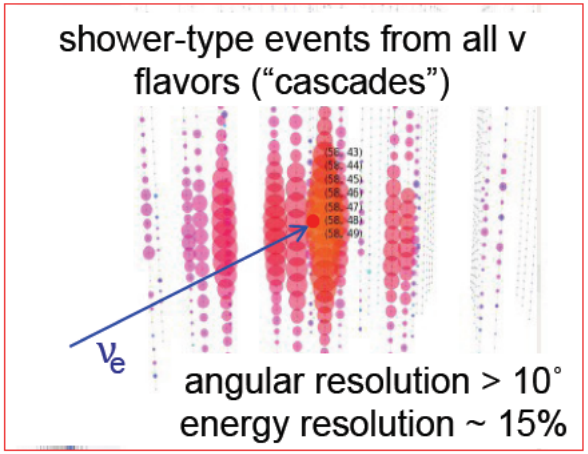
IceCube construction



- Construction period: 6 years (2005-2010)
- Physics data from partially operating detector since 2007.

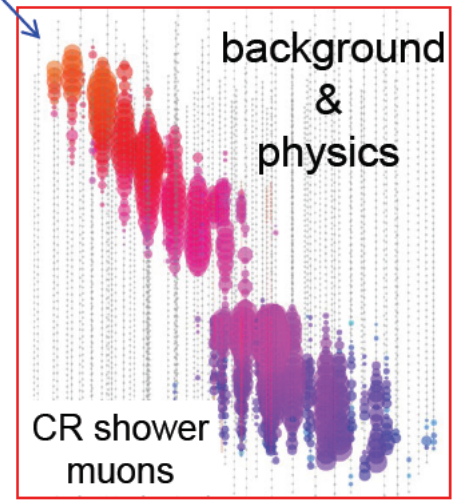
Event signatures in IceCube

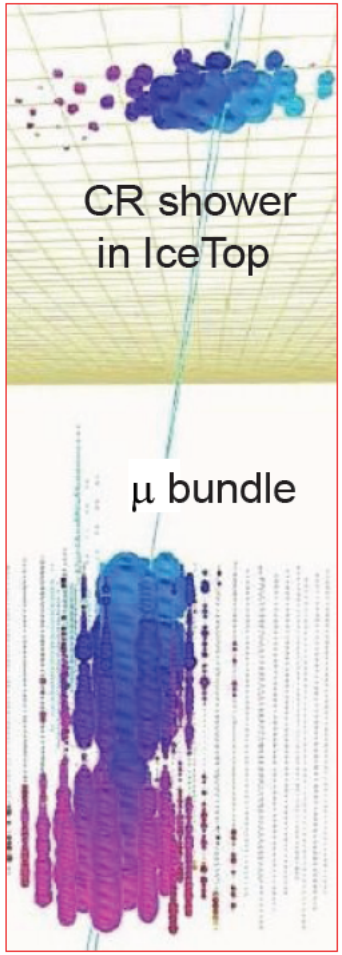




99.9999% of all events

μ

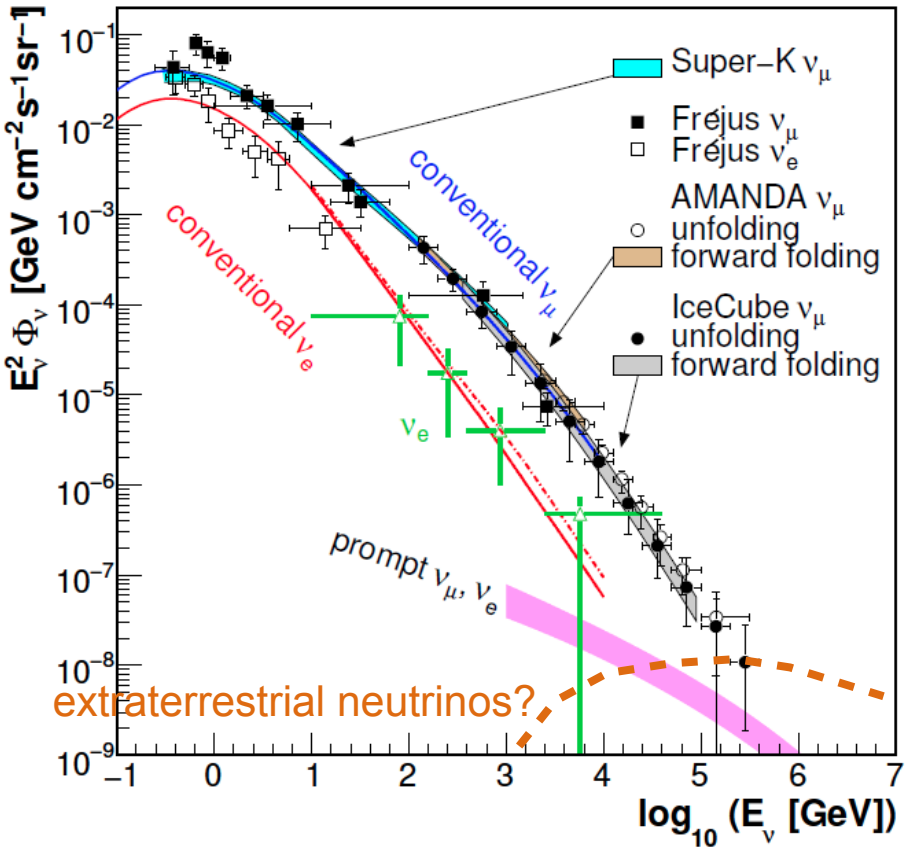


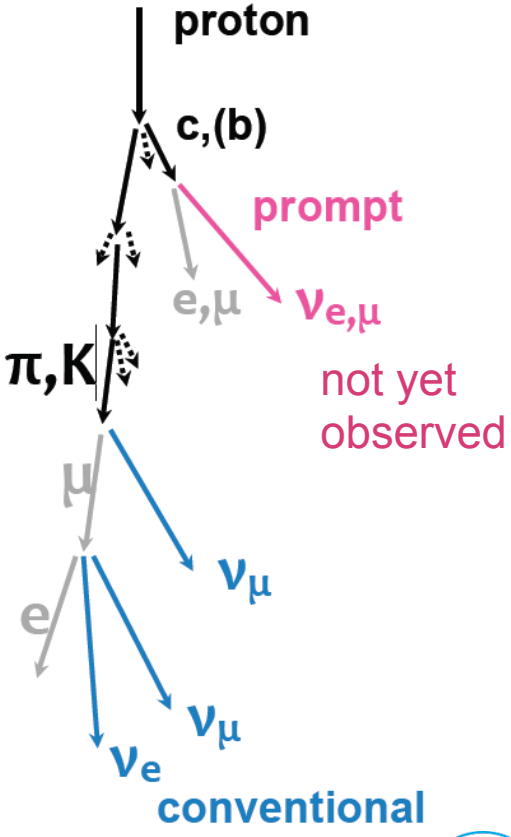


DESY

Search for astrophysical neutrinos

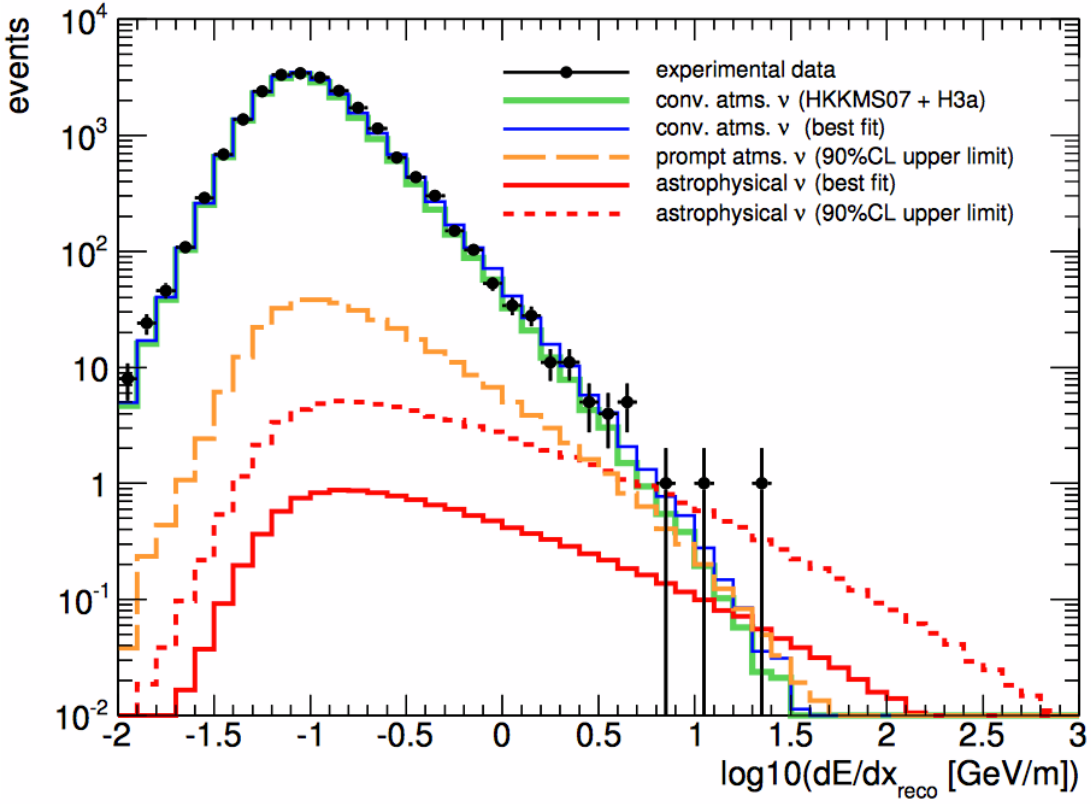
- Most neutrinos seen by neutrino telescopes are of atmospheric origin
- Atmospheric neutrinos are produced in CR air shower interactions





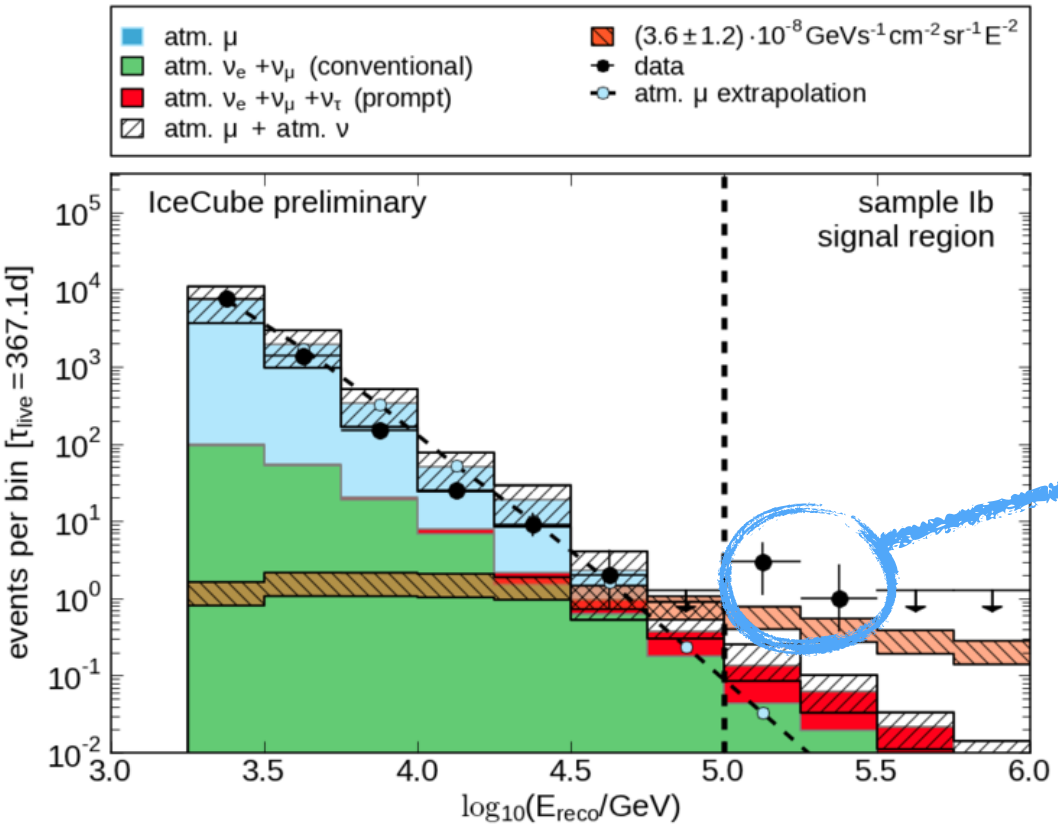
Diffuse neutrinos: through going muon neutrinos

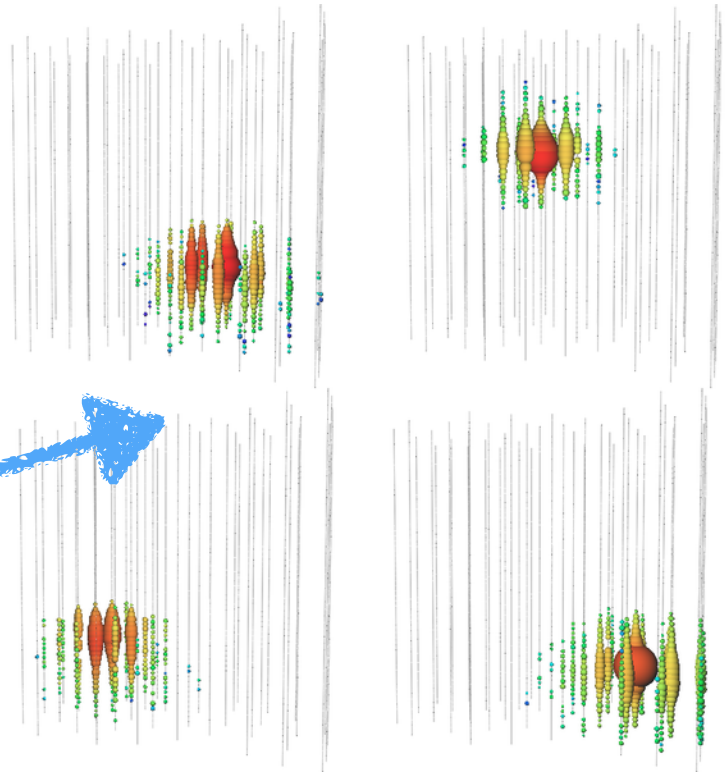
- Distinguish background and signal by energy and angular distribution
- Search for possible contributions of prompt atmospheric and astrophysical neutrinos
- One excess muon E ~ 200 TeV, significance 1.8 σ



Other indications: cascades (IC 40)

- 3 (+1 in control sample) cascades found > 100 TeV, muon background $0.04^{+0.06}_{-0.02}$, atmospheric neutrino background 0.21, significance 2.7 σ



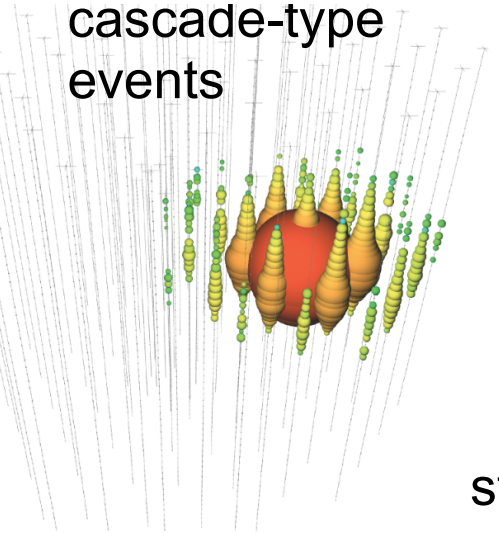


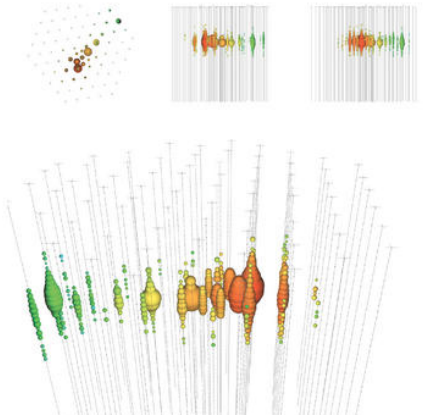
To appear in PRD (in press)

The breakthrough

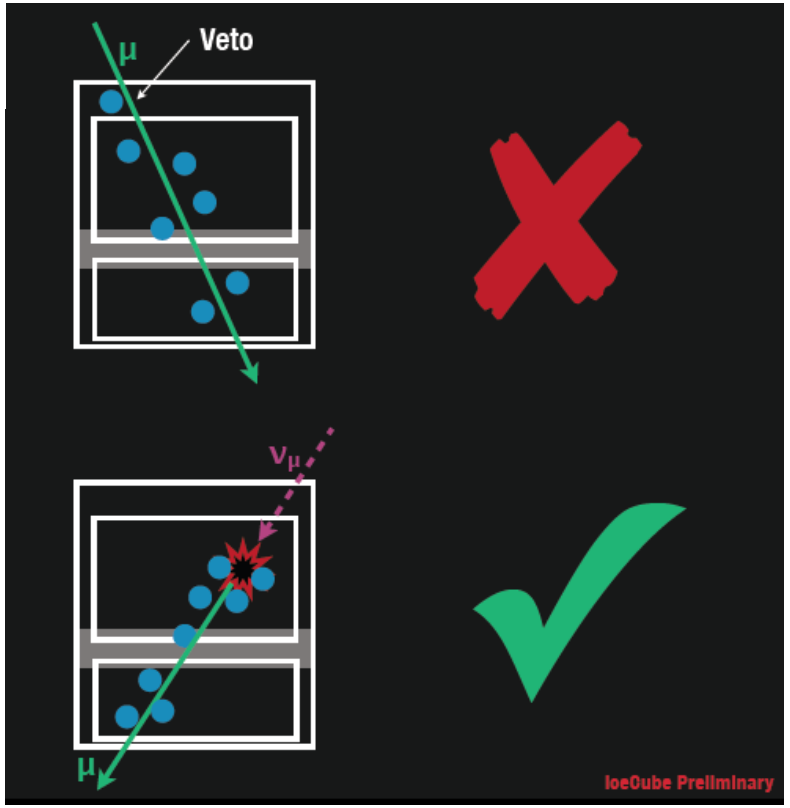
- Search for well reconstructed contained and semi-contained events
- Veto atmospheric muons and neutrinos
- Use data to measure background (inner veto layer)
- Energy threshold: ~ 30 TeV

cascade-type events



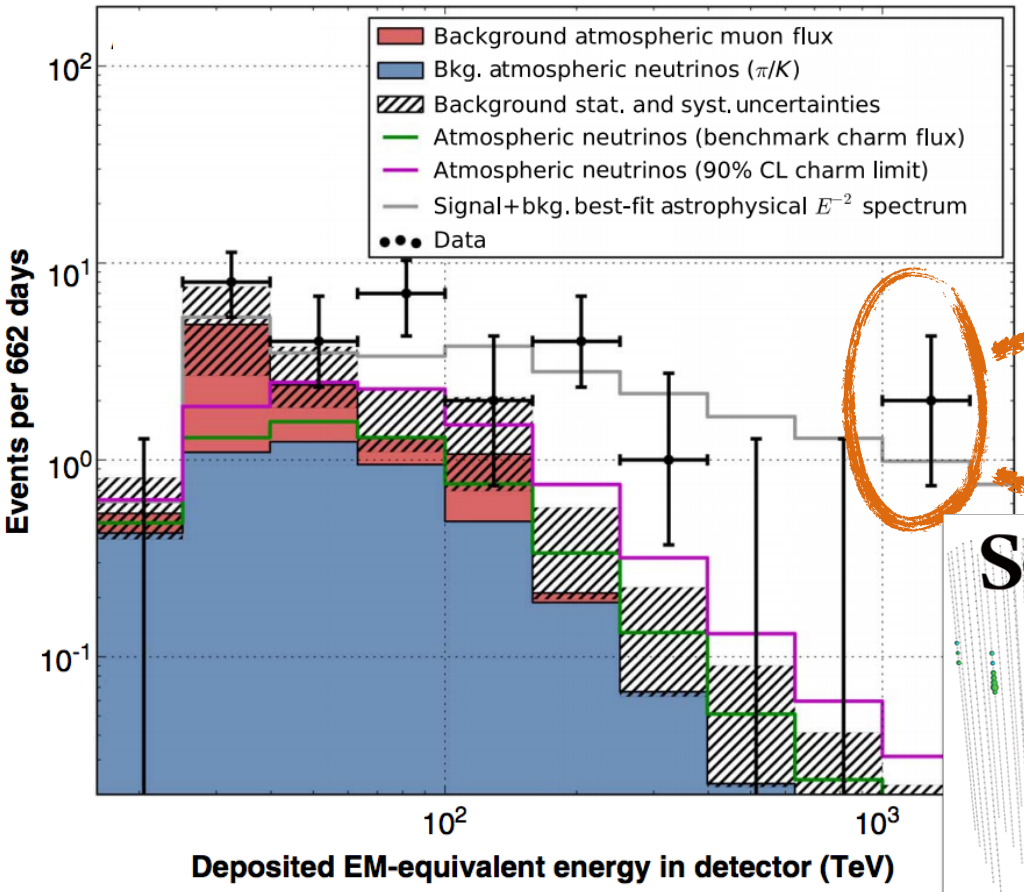


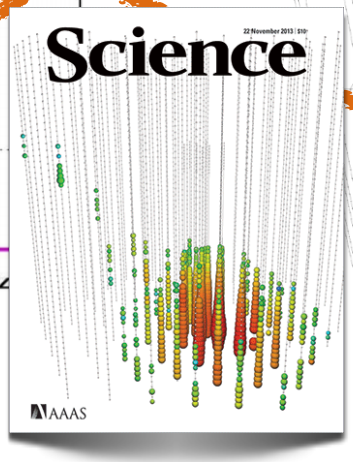
starting tracks

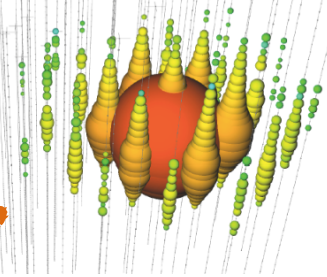


First clear evidence for extraterrestrial neutrinos (2013)

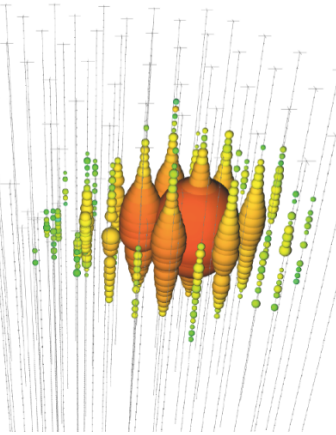
- 28 events found above 30 TeV, muon background $6.0^{+3.4}_{-3.4}$, atmospheric neutrino background $4.6^{+3.7}_{-1.2}$, significance 4.1 σ







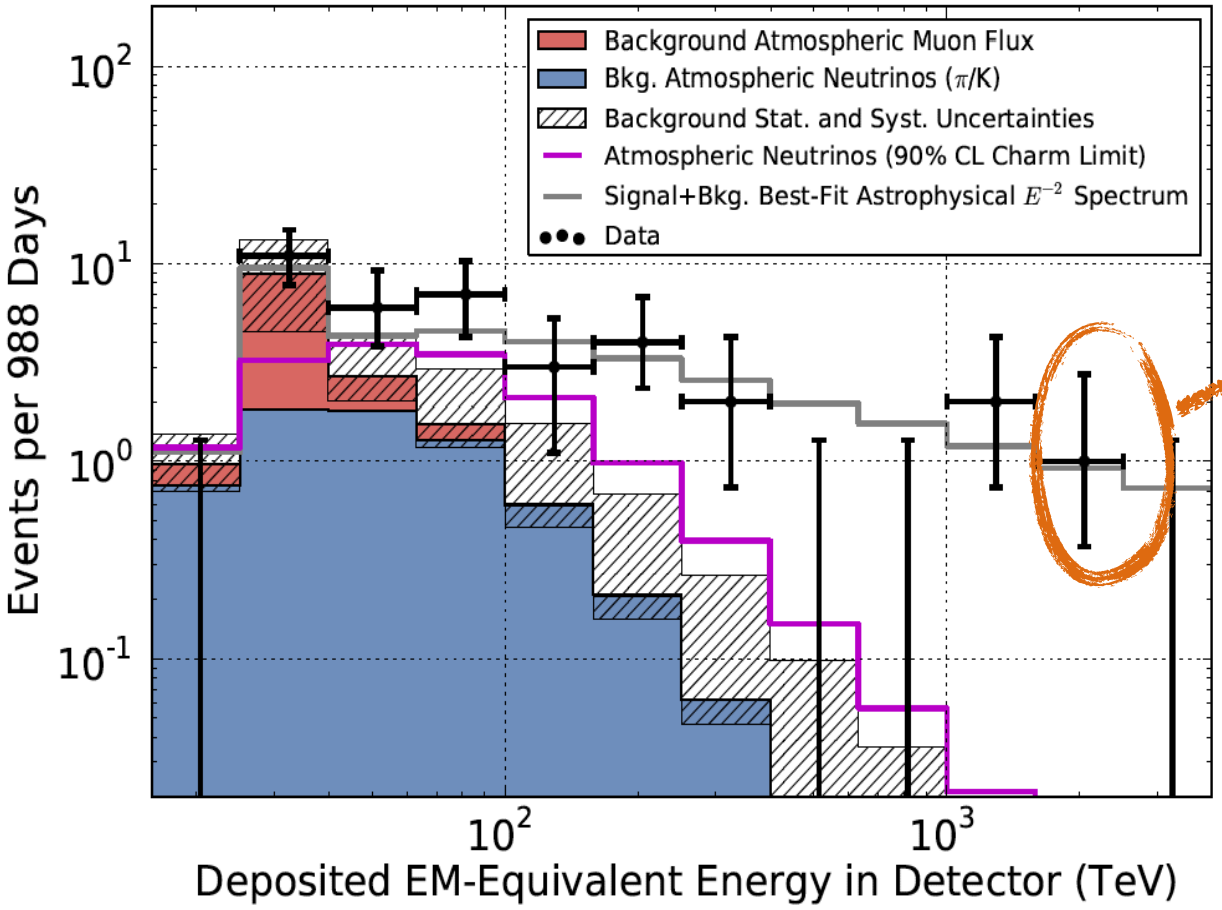
1.1 ± 0.17 PeV

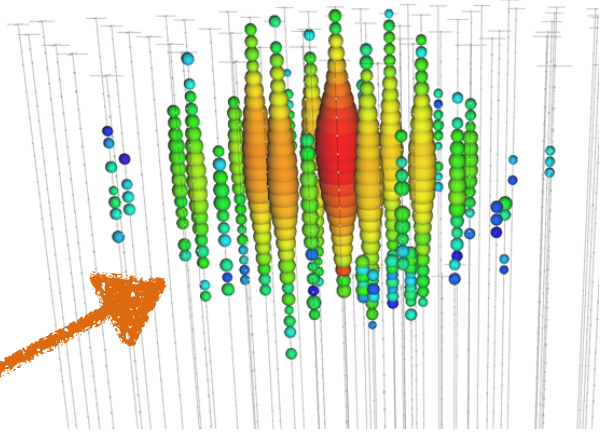


1.0 ± 0.15 PeV

The status today

- 37 events found, muon background $8.4^{+4.2}_{-4.2}$, atmospheric neutrino background $6.6^{+5.9}_{-1.6}$, significance 5.7 σ



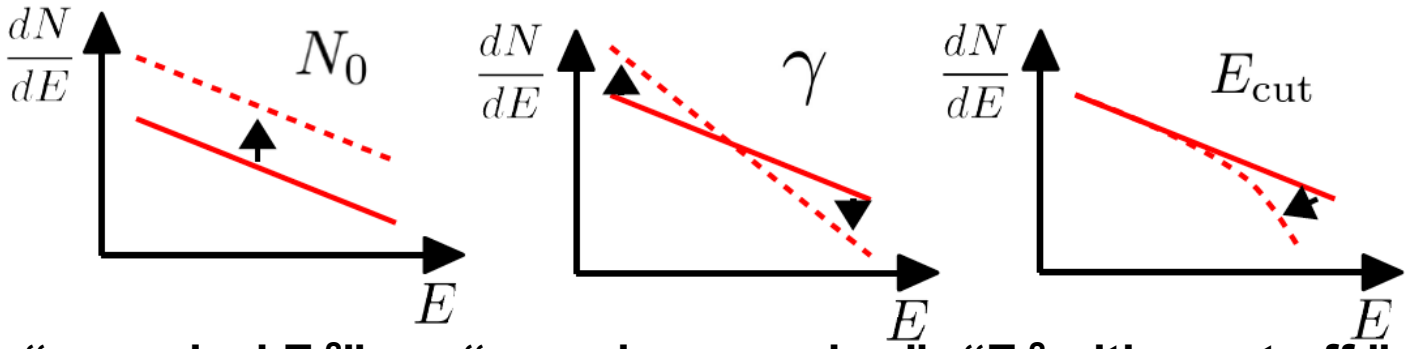


$2.0^{+0.26}_{-0.24}$ PeV

And now, taking all into account

- Do the individual analyses form a consistent picture?
- Are there spectral features different from E^{-2}?
- Global likelihood fit of total flux as a linear combination of:
  - Atmospheric μ from CORSIKA simulation / data
  - Atmospheric ν (conventional) from Honda et al. (2007) + Gaisser (2012)
  - Atmospheric ν (prompt) from Enberg et al. (2008) + Gaisser (2012)
  - Astrophysical ν: four hypotheses tested:

"BG-only"
(I)
+



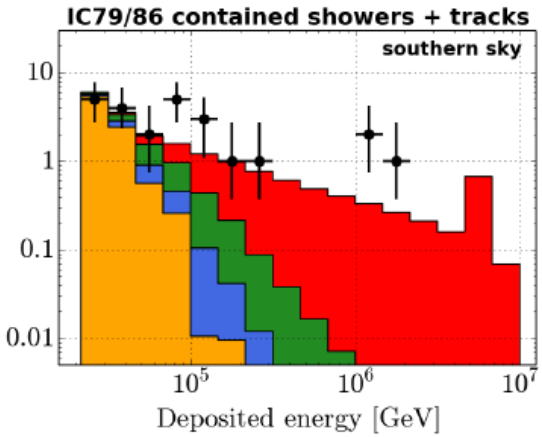
"canonical E^{-2}"
(II)

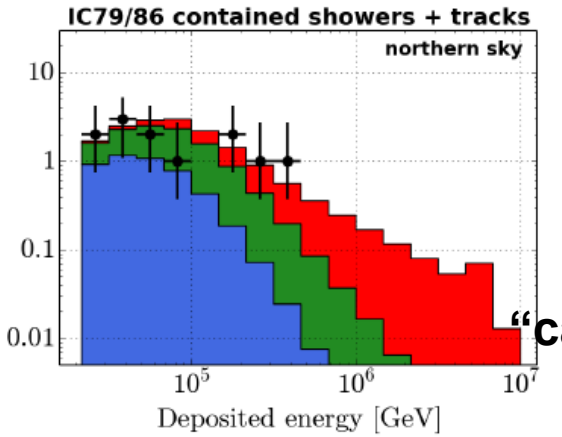
"generic power-law"
(III)

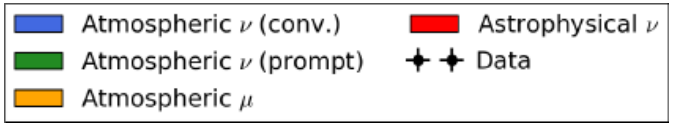
"E^{-2} with a cut-off "
(IV)

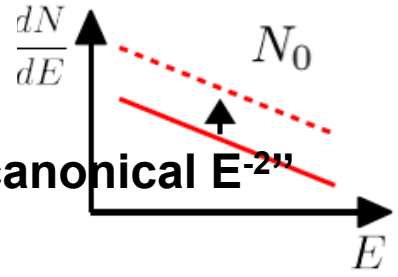
Global fit results

- Data best described with an astrophysical component with power-law spectrum (index $2.7^{+0.2}_{-0.2}$)

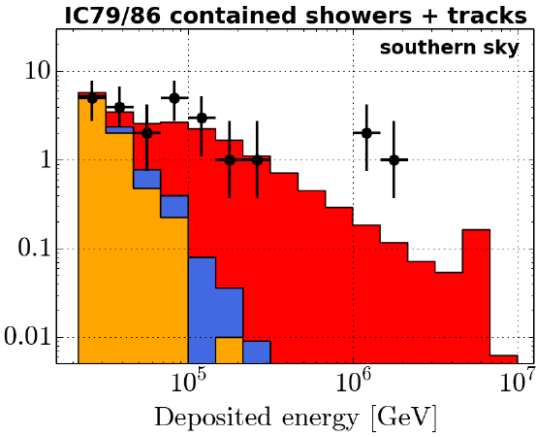


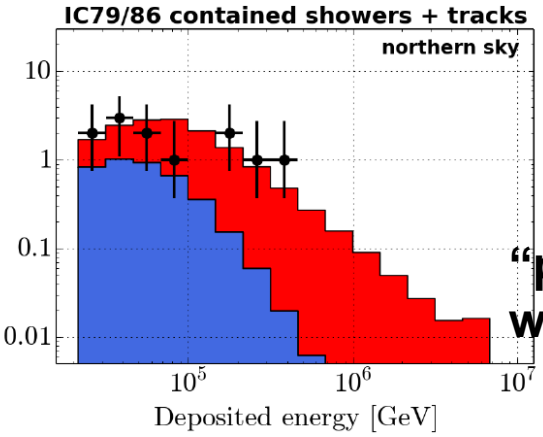


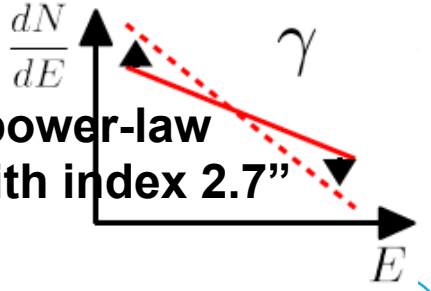




"canonical E^{-2}"



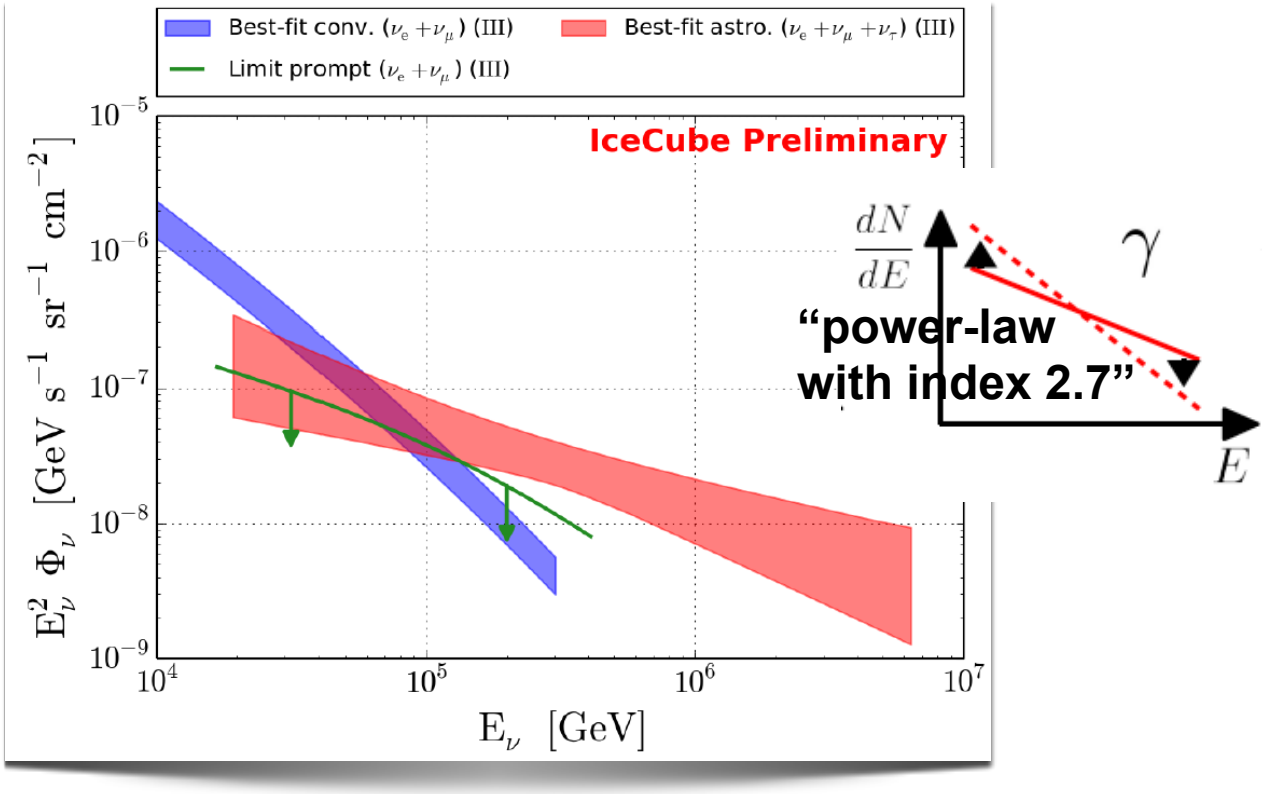




"power-law with index 2.7"

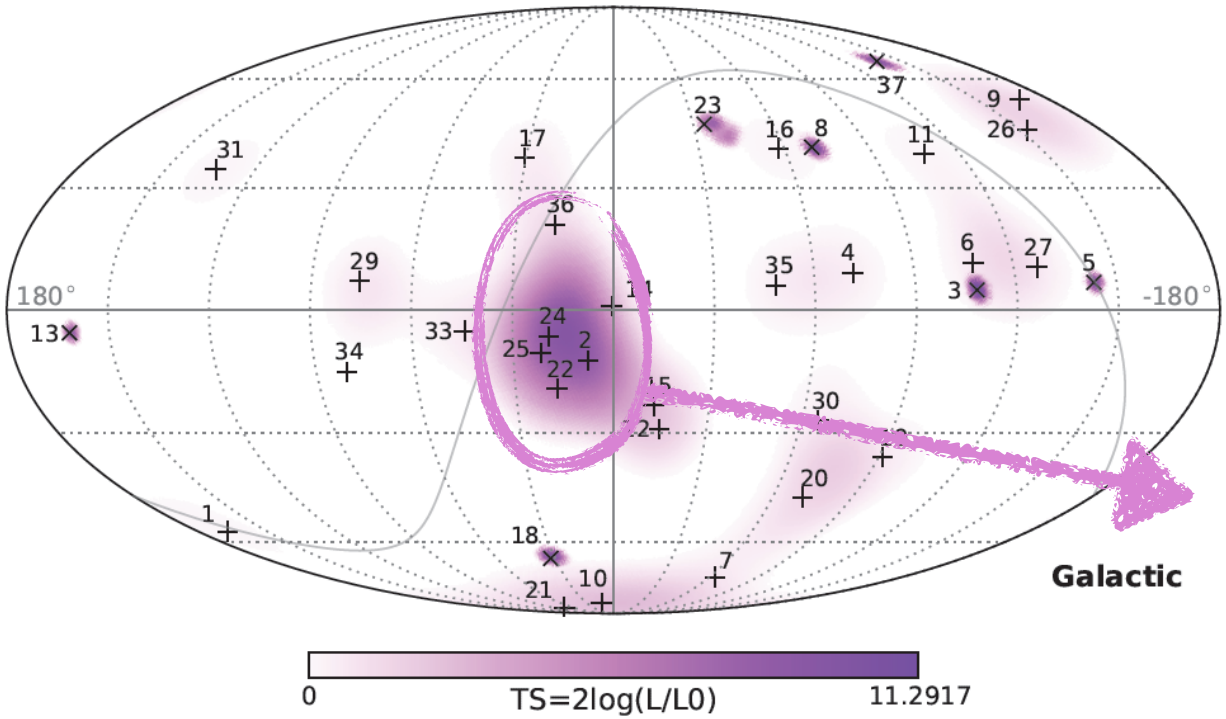
The consistent picture

- The prompt atmospheric neutrino flux is not constrained
- Best-fit power-law is preferred to the generic prediction of E^{-2} at 2.3 σ



Trying to pin point the sources: time integrated

- Cluster of a point source contribution above background using directional uncertainty map for each event
- Search for correlations with known gamma-ray sources



No statistically significance evidence of either clustering or correlations

28% of scrambled datasets yield a test statistic greater than or equal to this spot

Trying to pin point the sources: time dependent tests

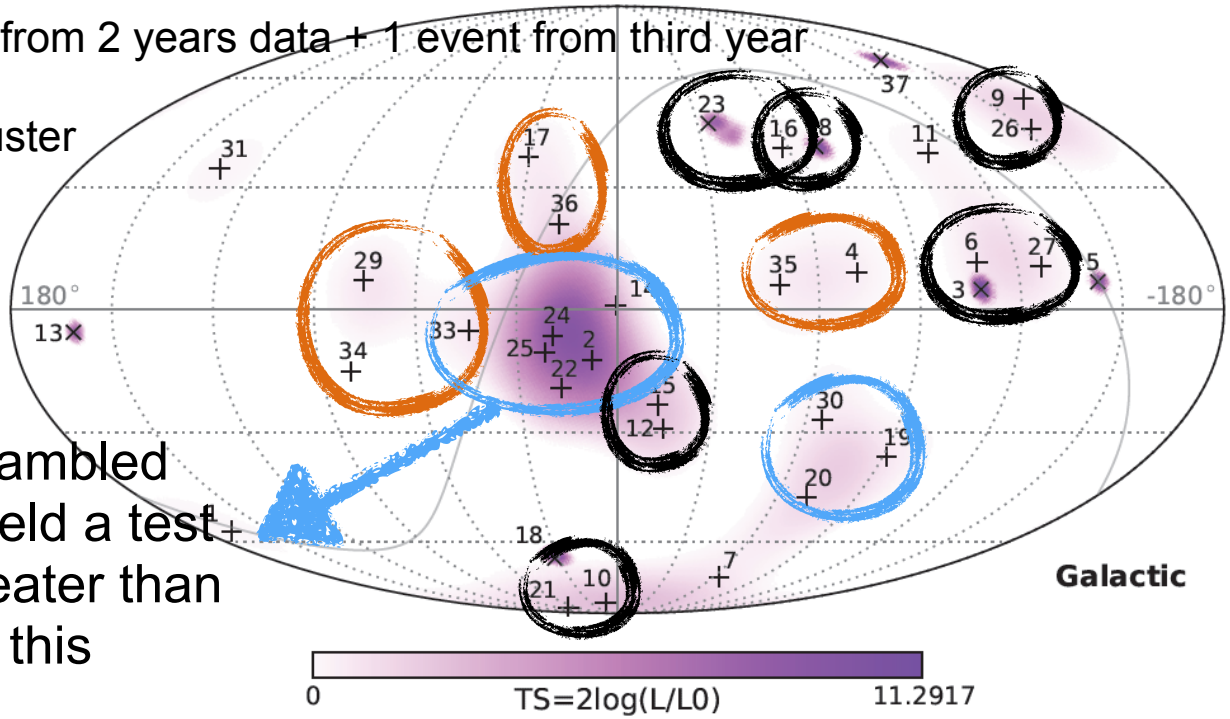
- Tests for most significant time sub-structures:
  - out of all 35 events (3 years)
  - within pre-defined space clusters

Cluster from 2 years data

Cluster from 2 years data + 1 event from third year

New cluster

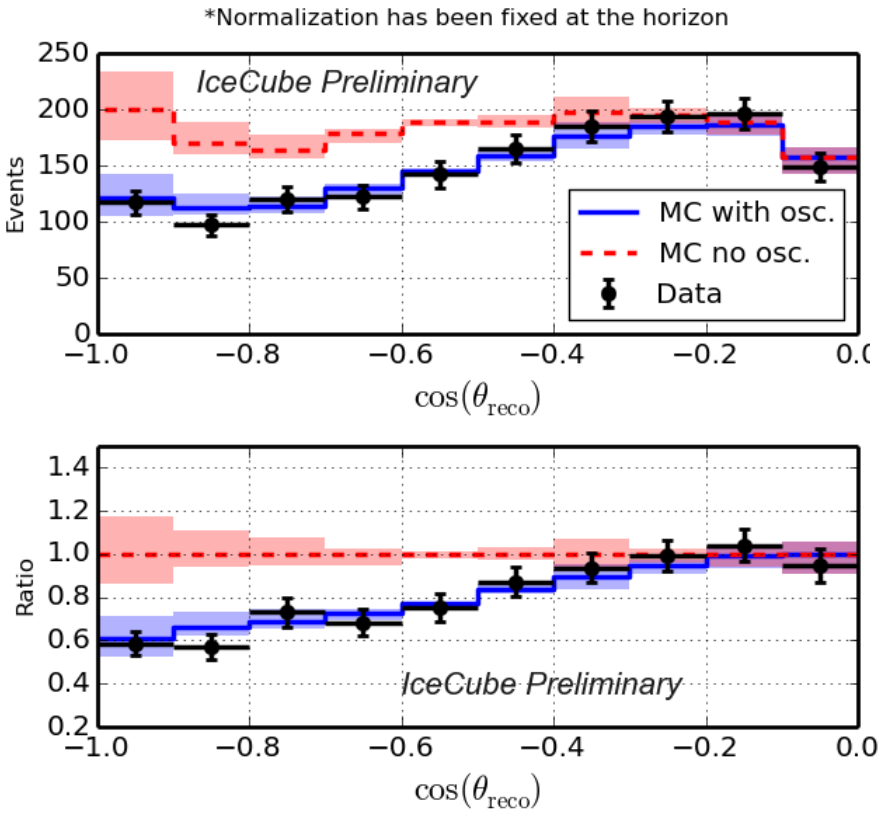
No statistically significance evidence for time structures

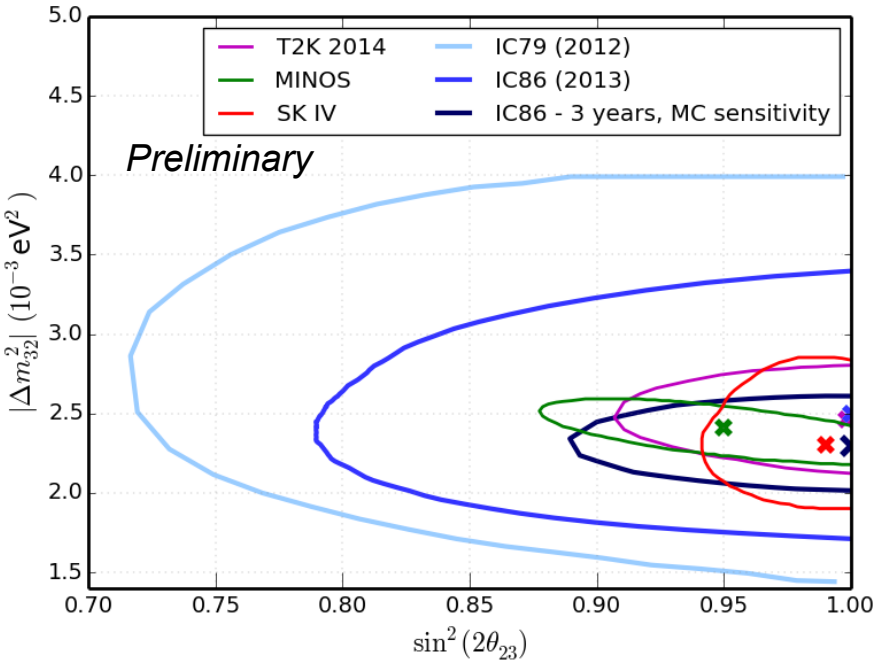


33% of scrambled datasets yield a test statistic greater than or equal to this cluster

Measurement of Neutrino Properties

- First high-significance determination of θ_{23} and Δm^2 with a high-energy neutrino telescope



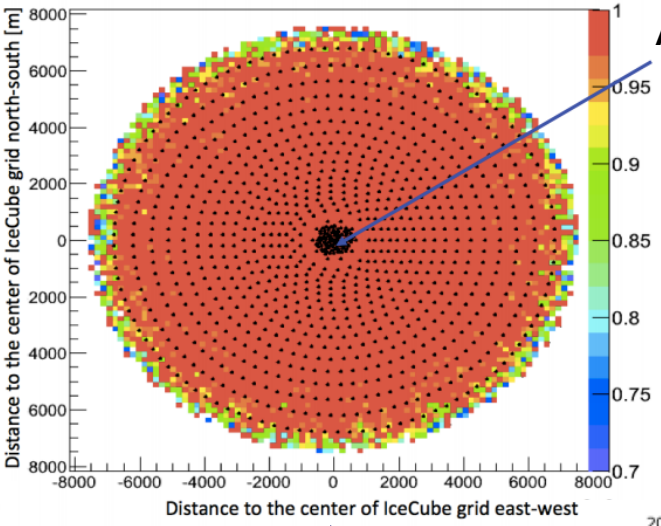


In progress, to be shown at Neutrino 2014

Beyond IceCube: A Future Multi-Purpose Research Infrastructure at South Pole

- **PINGU**
- Neutrino properties
  + in-ice DM detector
  + other…

Multi-km^2 Surface Detector

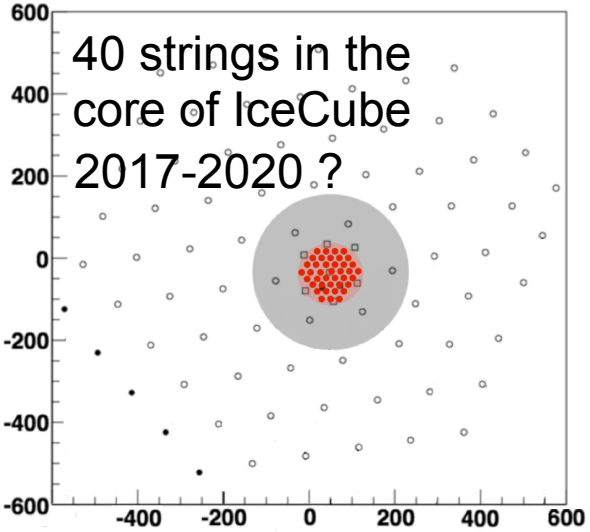


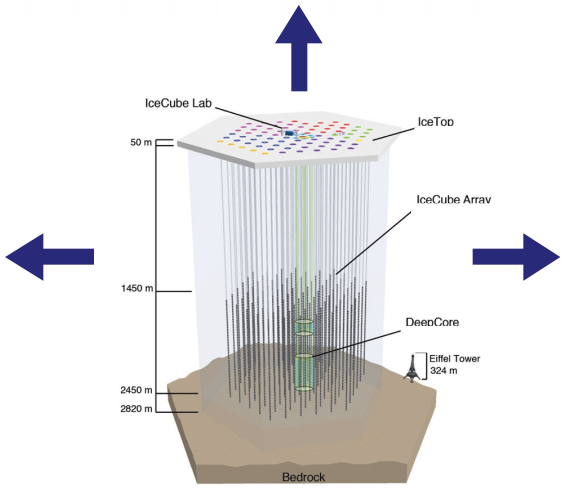
Atm. neutrino veto
CR physics

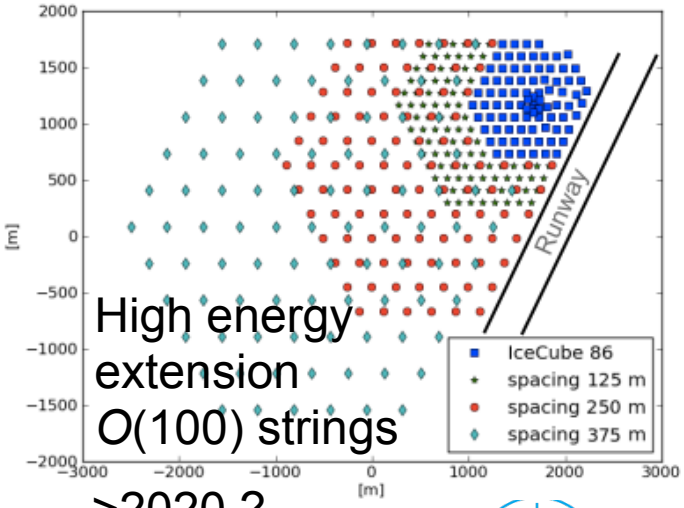
O(1000) tanks
> 2017 ?

Multi-km^3 Neutrino Telescope

Neutrino astronomy







High energy extension
O(100) strings
>2020 ?

Summary and (long term) perspectives

- 2013: First clear evidence for extraterrestrial neutrinos
- First high-significance determination of θ_{23} and Δm^2

Science Goals for IceCube 2014 - 2019

- Neutrino astronomy:
  - Study the properties of the extraterrestrial neutrinos & search for individual sources
  - Constrain CR production and acceleration models
- Neutrino properties:
  - Improvement on θ_{23}, Δm^2 constraints with DeepCore & search for sterile neutrinos
- CR and Beyond-the-Standard Model Physics:
  - Measurement of the CR spectrum/composition/anisotropy from PeV to EeV
  - Improvement of limits on WIMP annihilation/scattering cross-section & exotic particles

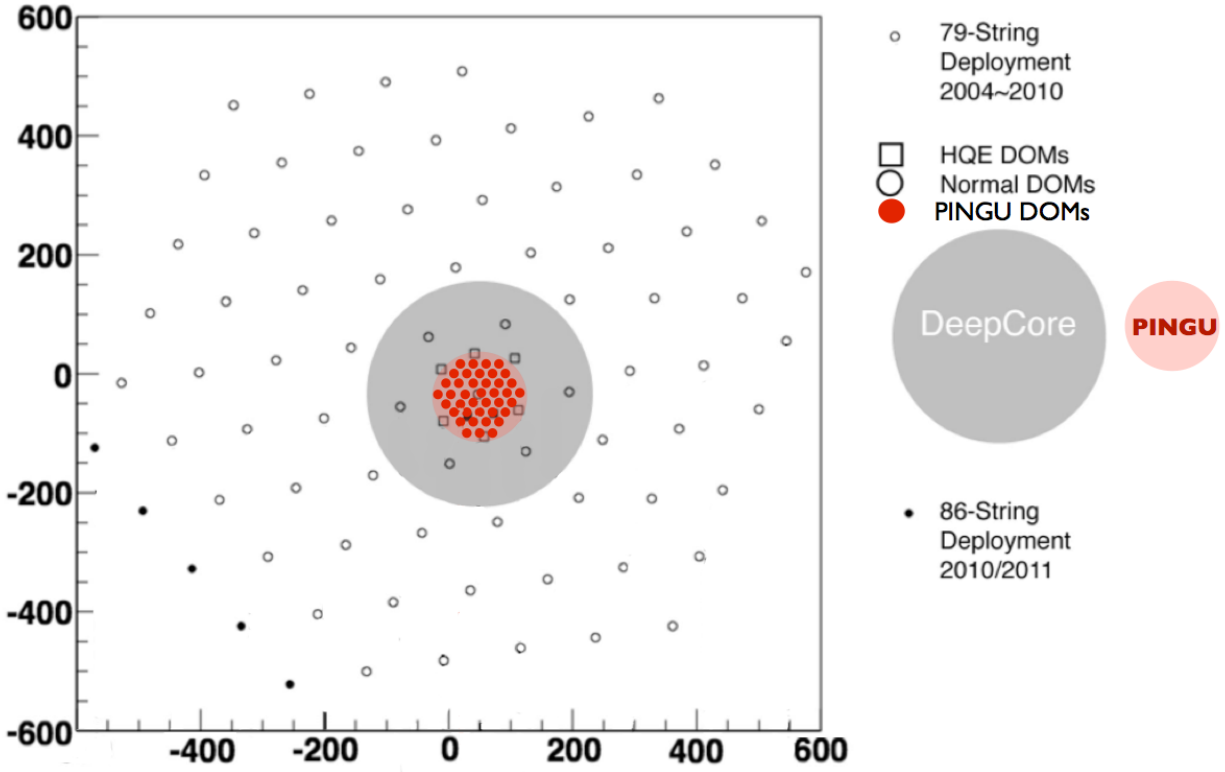
News at DESY

- W3 in experimental Astroparticle Physics (M. Kowalski) appointed
- Theory group extended towards Neutrino Astrophysics (W. Winter)

Extra slides

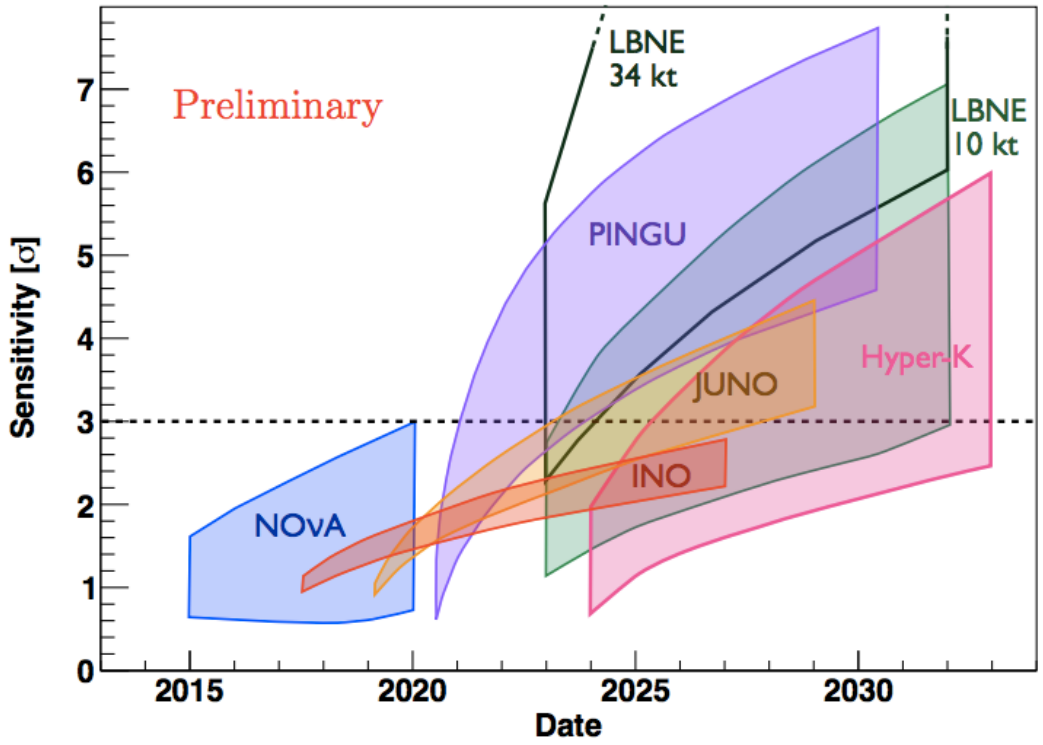
The Precision IceCube Next Generation Upgrade (PINGU)

- **40 new strings** in the core of IceCube
- **Measurement of neutrino mass hierarchy**
- + Precise measurement of θ_{23}, Δm^2
- + Greatly improved sensitivity for low-mass WIMPs
- + Earth tomography & improved SN detection



The Precision IceCube Next Generation Upgrade (PINGU)

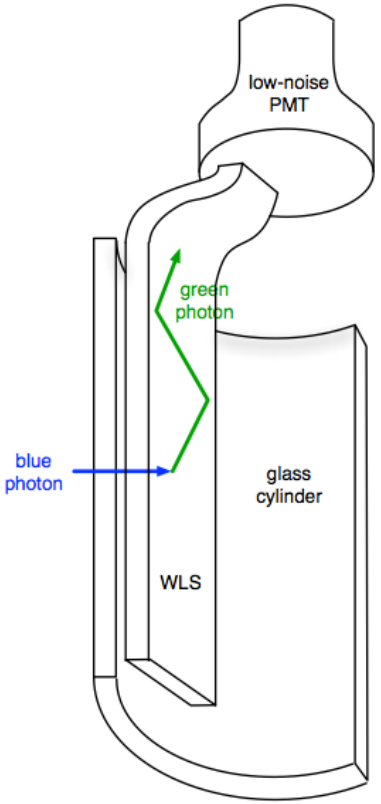
- Anticipated start of PINGU operation: >2020
- Mass hierarchy sensitivity: Reach **>3σ in 3.5 years**
- Complementary to reactor neutrino measurements (JUNO)

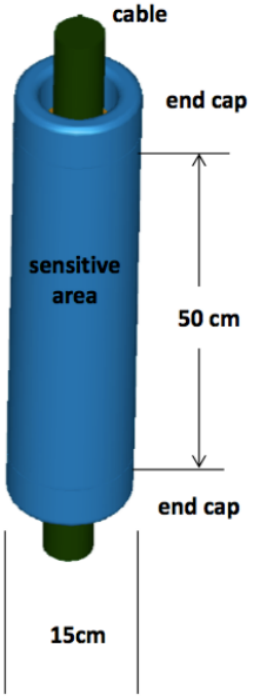


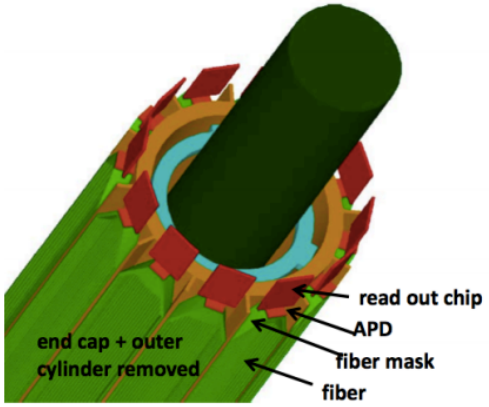
PINGU
Letter of Intent
arXiv:1401.2046

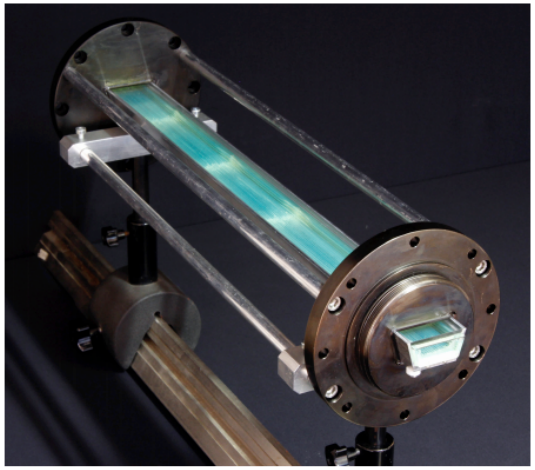
R&D activities at DESY

- Cylindrical photosensor designs using small PMT/ MPPC
- Wavelength shifter material to reduce costs for module & drilling







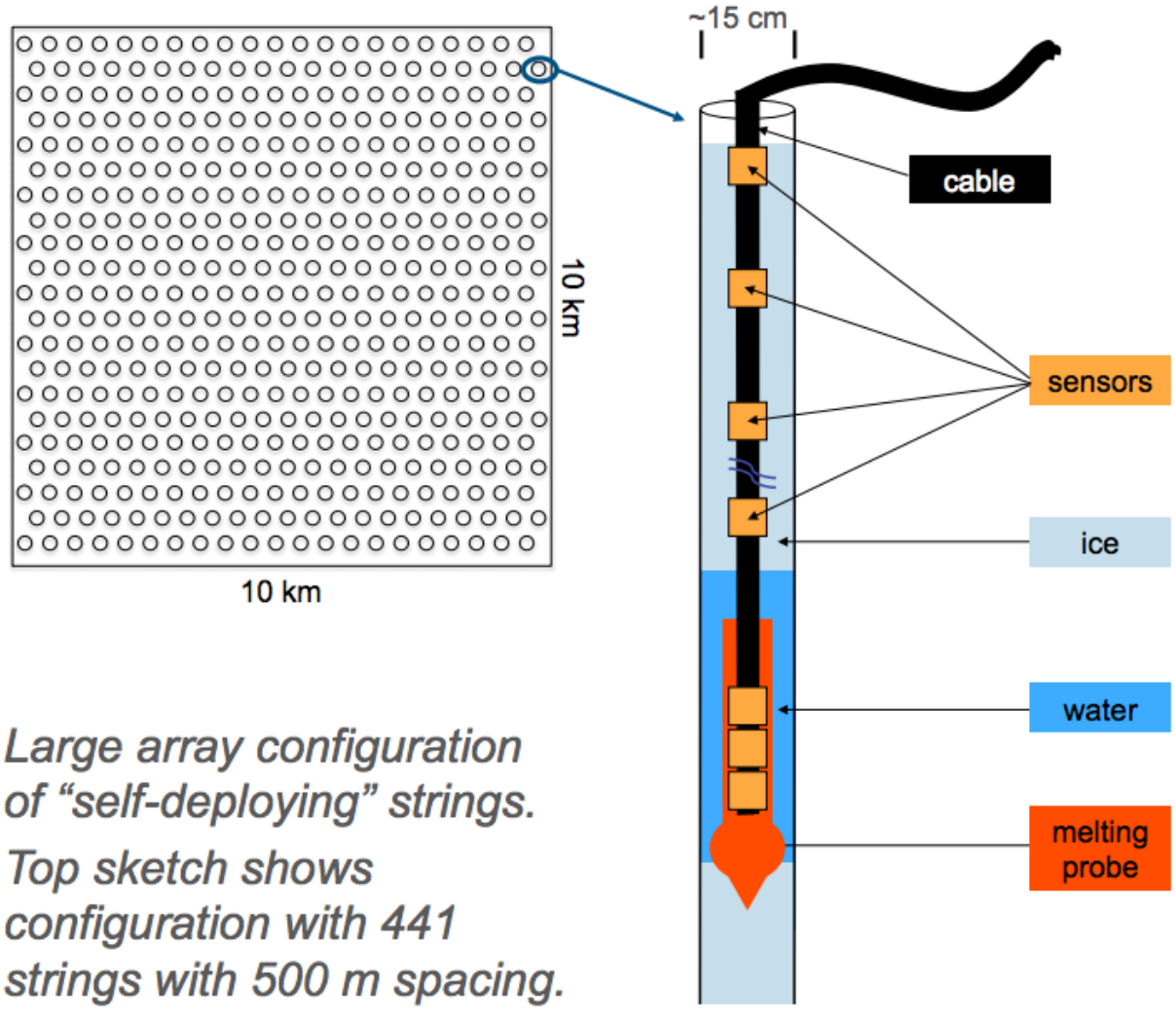


Schematic overview of ZOMBI (top).

ZOMBI test cell without PMTs (right).

R&D activities at DESY

- Alternative drilling technologies for large wide-spaced arrays

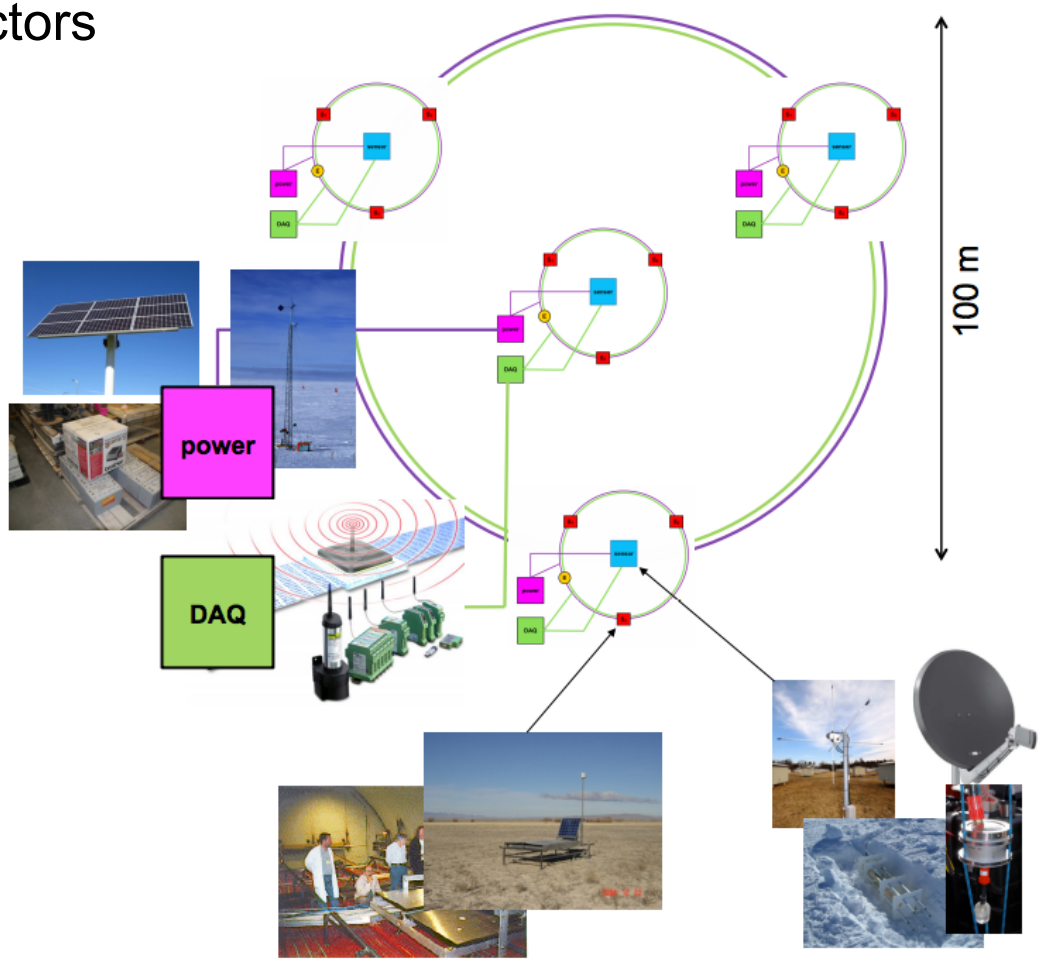


Large array configuration of "self-deploying" strings.

Top sketch shows configuration with 441 strings with 500 m spacing.

R&D activities at DESY

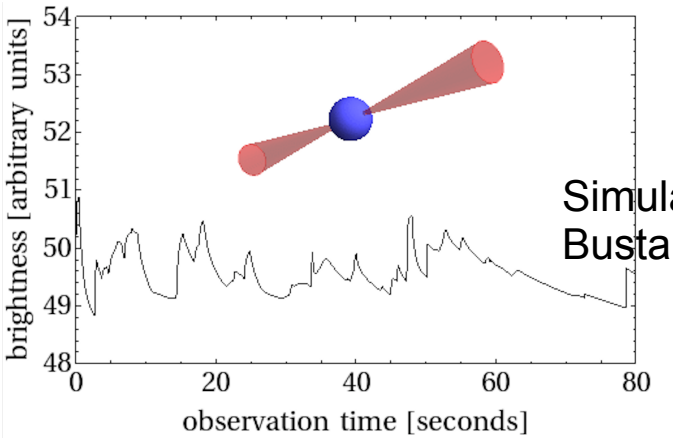
- Platform for in-situ tests of sensors, communication, power supply of surface detectors



Schematic overview of TAXI.

Theory: Perspectives for neutrino astronomy after recent discovery

- Origin of cosmic rays:
  - evidence from multi-messenger astronomy?
  - Heavy nuclei?
- Realistic/dynamical GRB models after IceCube results:
  - Light curve from first principles (collisions of shells)
  - Where are neutrinos, cosmic rays, gamma-rays produced?
  - What can be learned from future observations, e.g. CTA?
- Transport of the UHECRs, and role of the cosmogenic neutrino flux



Simulated light curve;
Bustamante, Baerwald, Winter, in preparation