

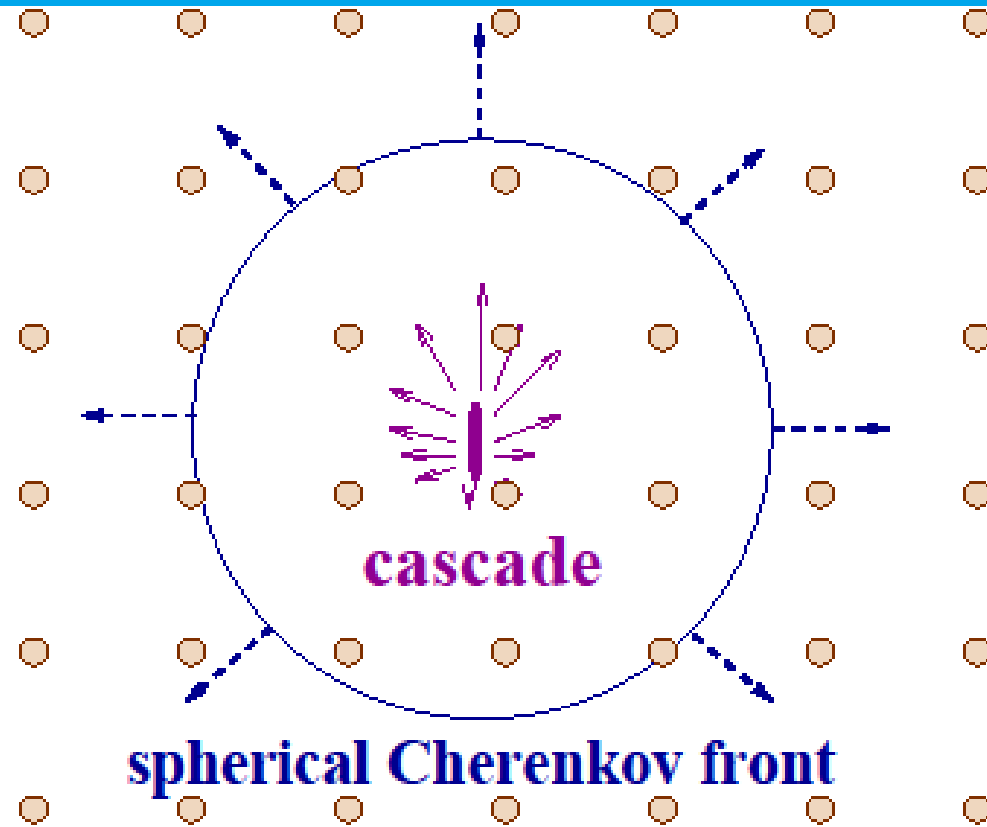
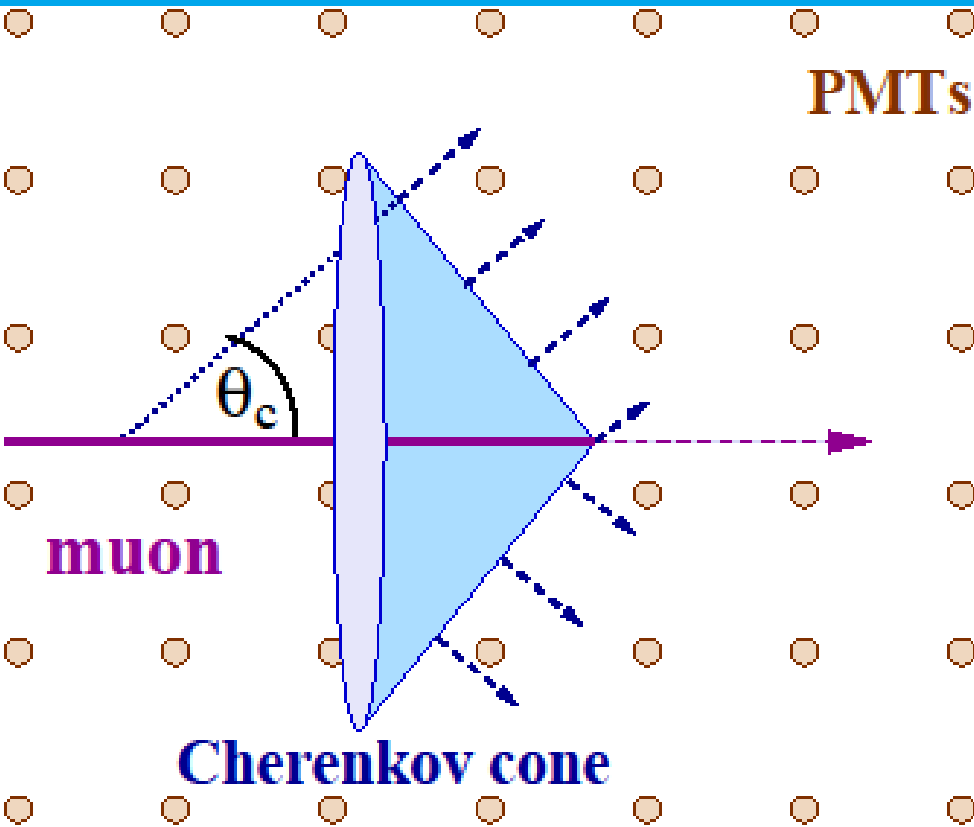
High-Energy Neutrino Astrophysics

Latest results and future prospects

C. Spiering, Moscow, August 22, 2013

DETECTION PRINCIPLE

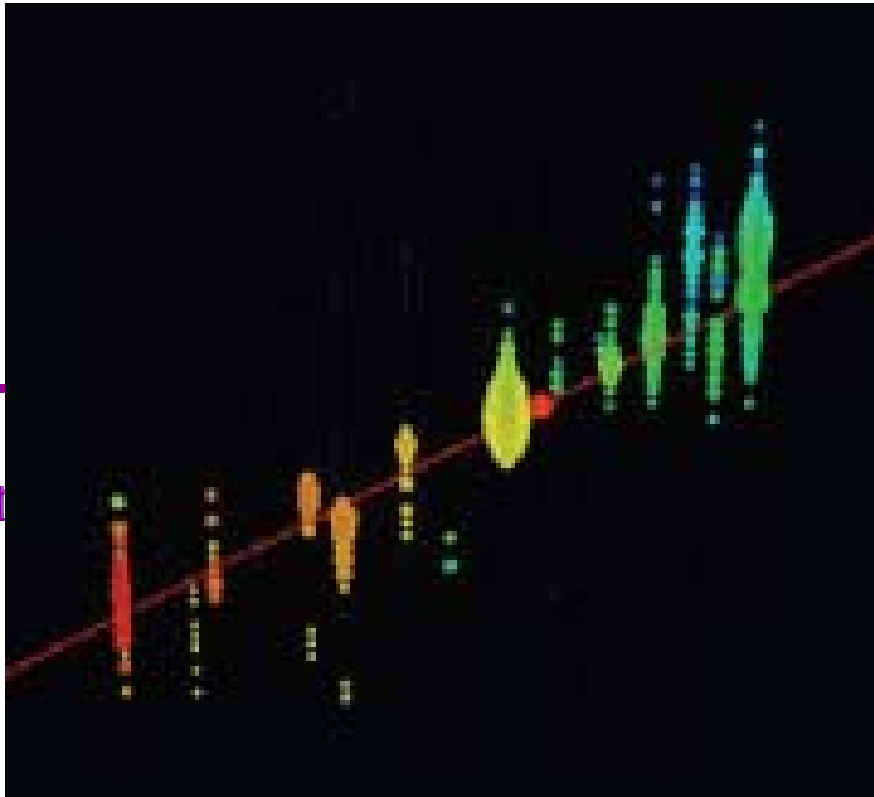
Detection Modes



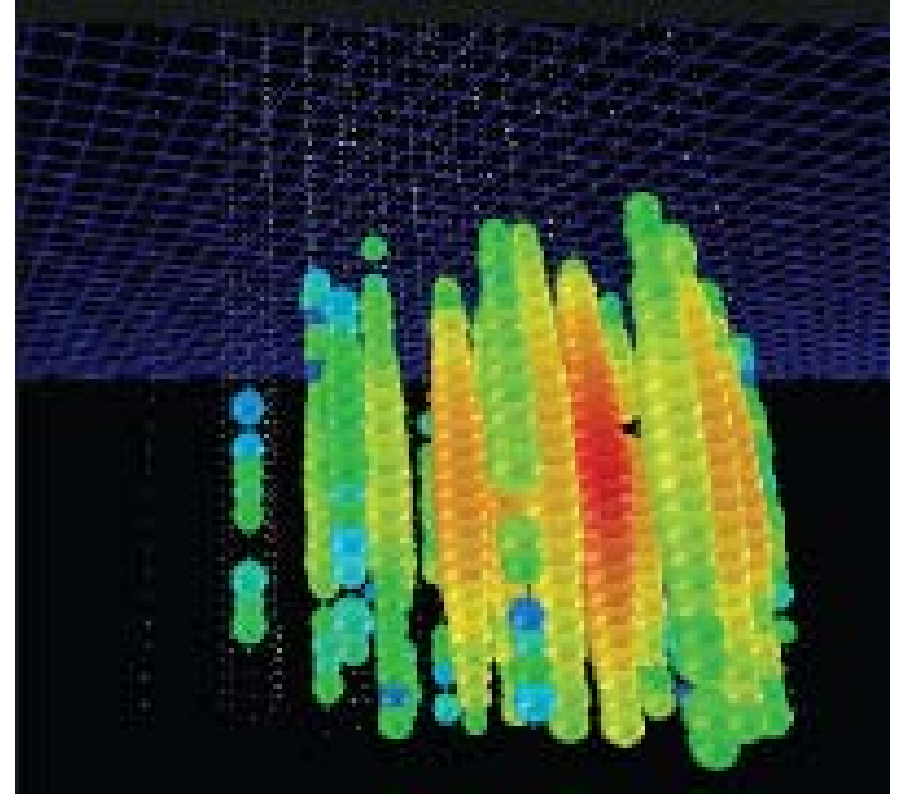
- Muon track from CC muon neutrino interactions
 - Angular resolution $< 1^\circ$
 - dE/dx resolution factor 2-3

- Cascade from CC electron/tau and NC all flavor interactions
 - Angular resolution 10° at 100 TeV
 - Energy resolution $\sim 15\%$

Detection Modes



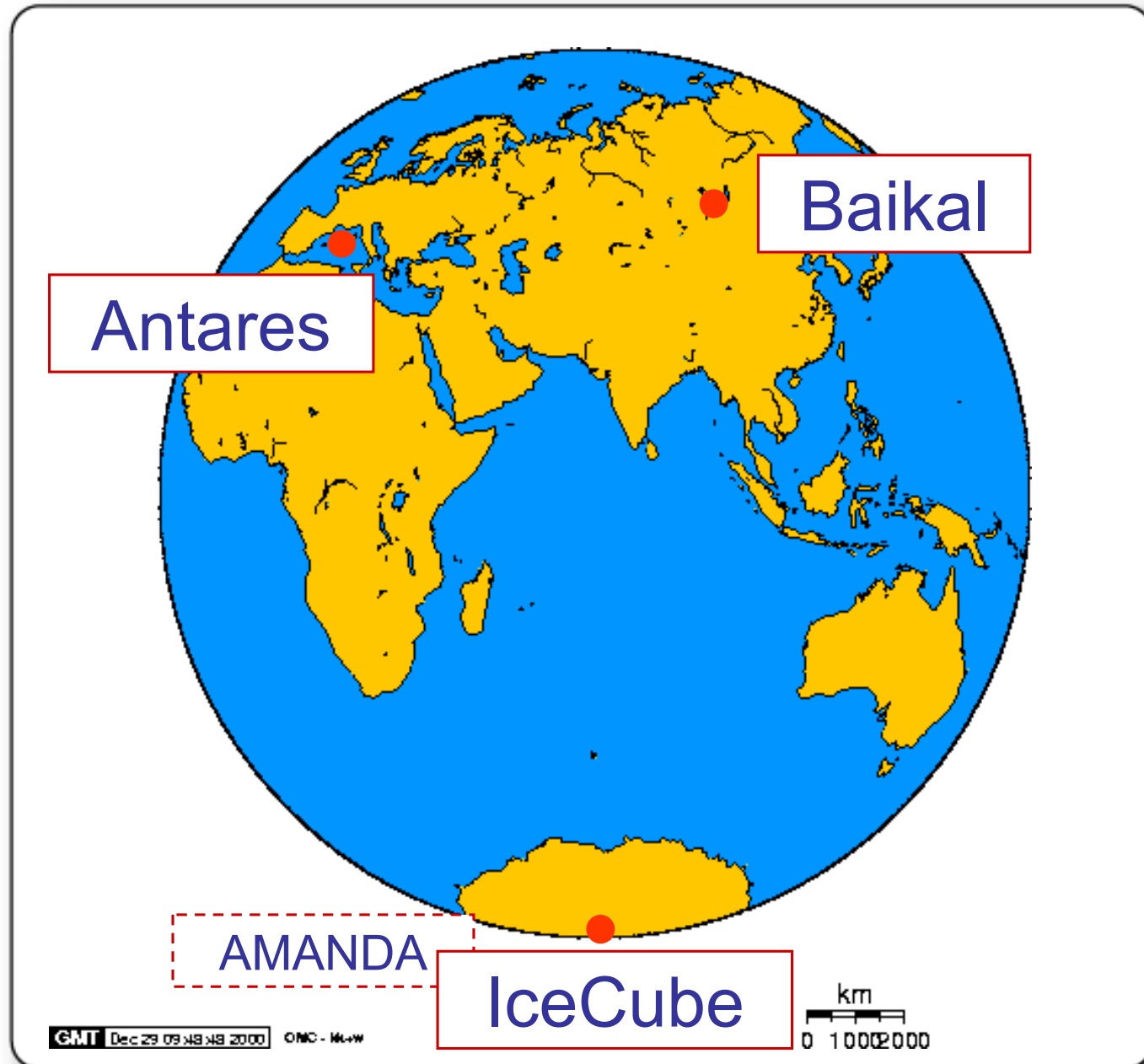
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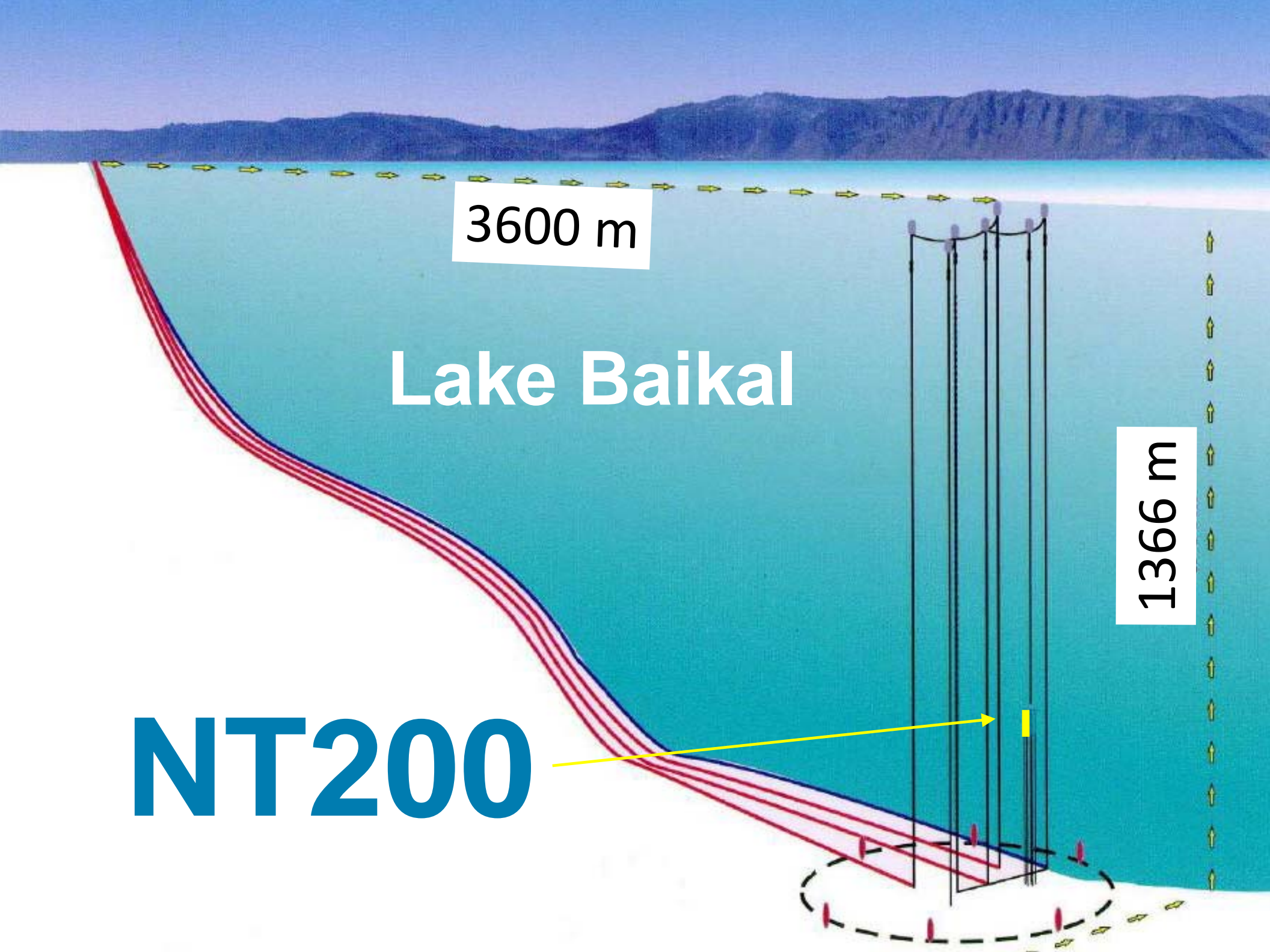


- Cascade from CC electron and NC all flavor interactions
 - Angular resolution 10° at 100 TeV
 - Energy resolution $\sim 15\%$

PRESENT DEVICES

Baikal – Antares - IceCube





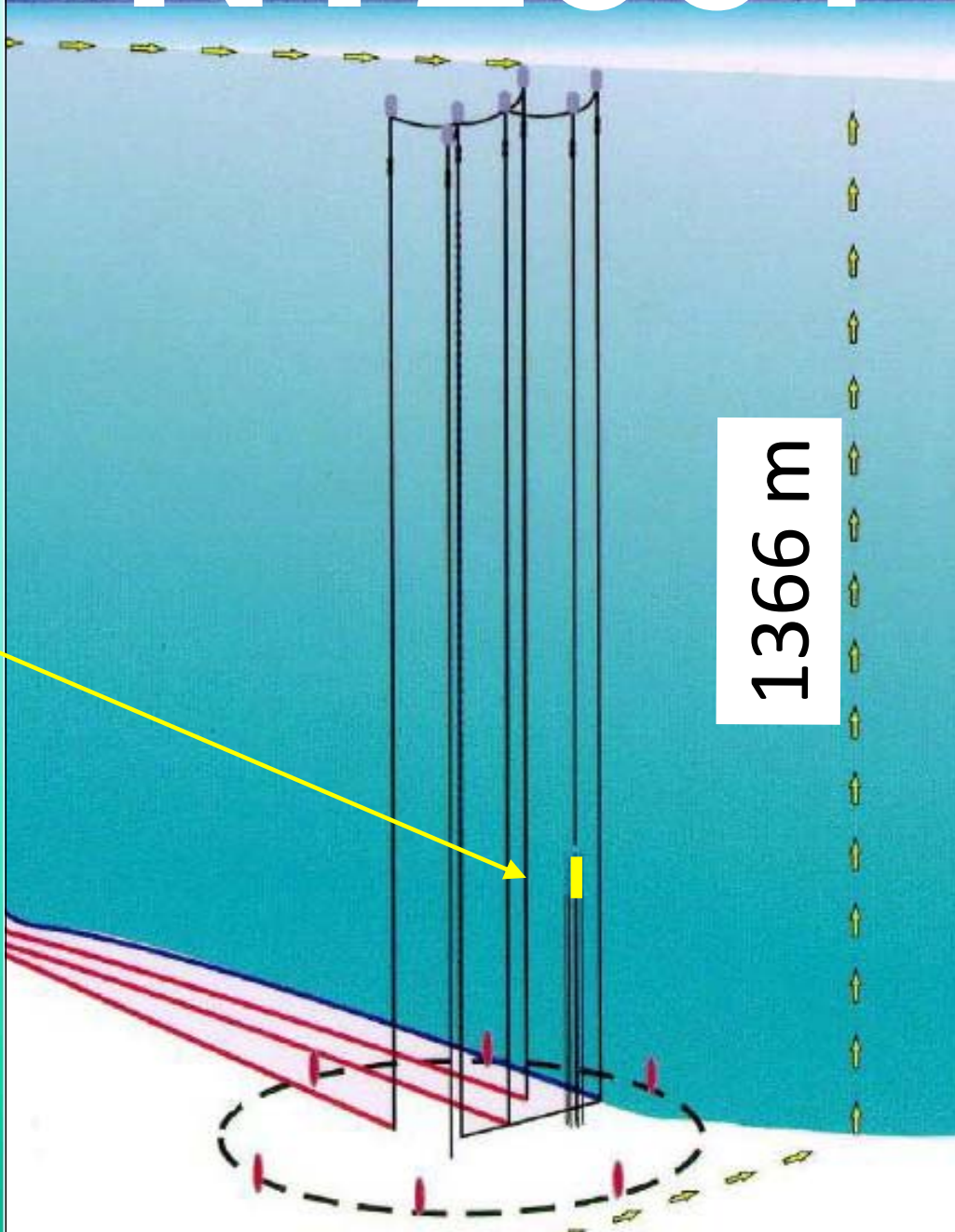
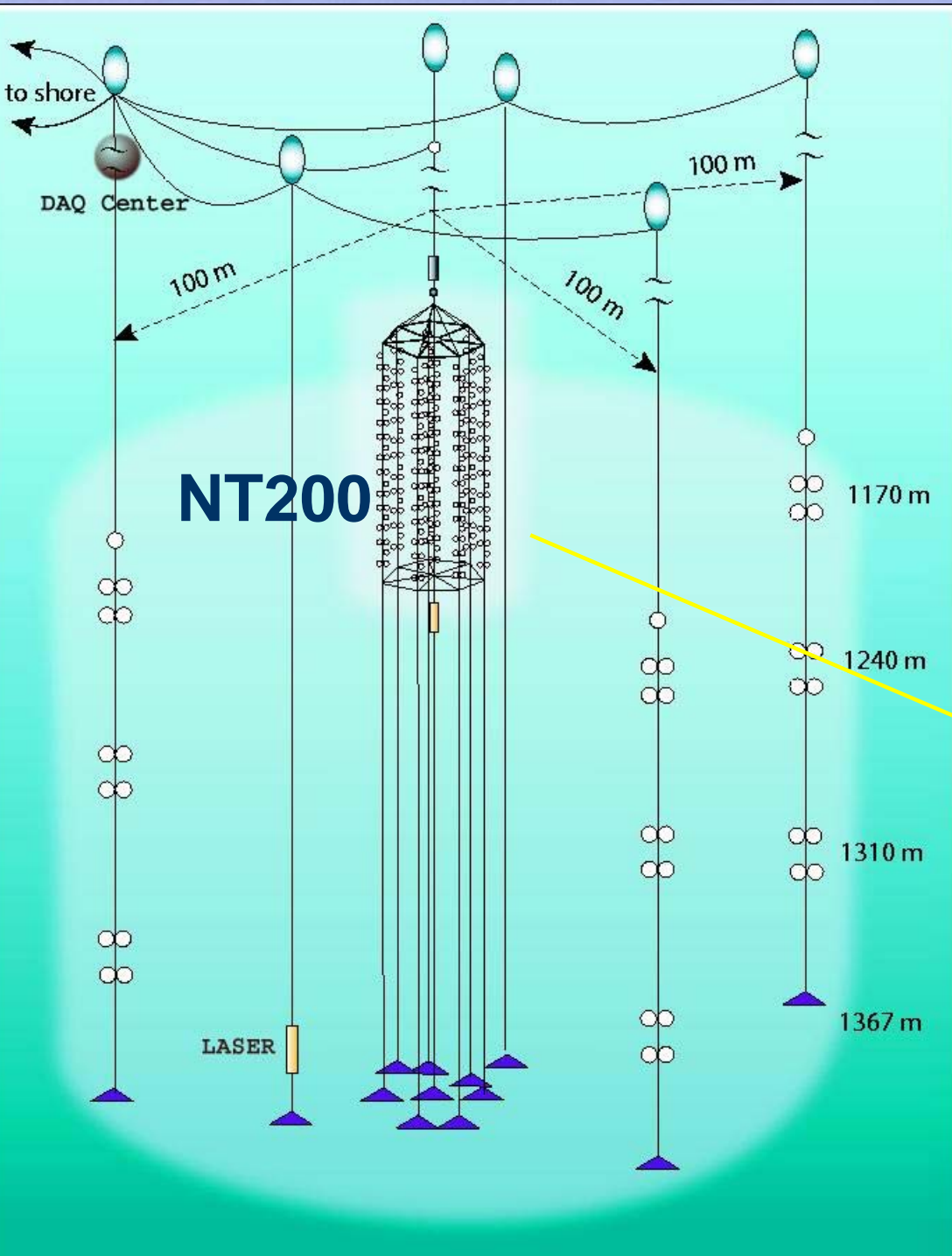
3600 m

Lake Baikal

1366 m

NT200

NT200+



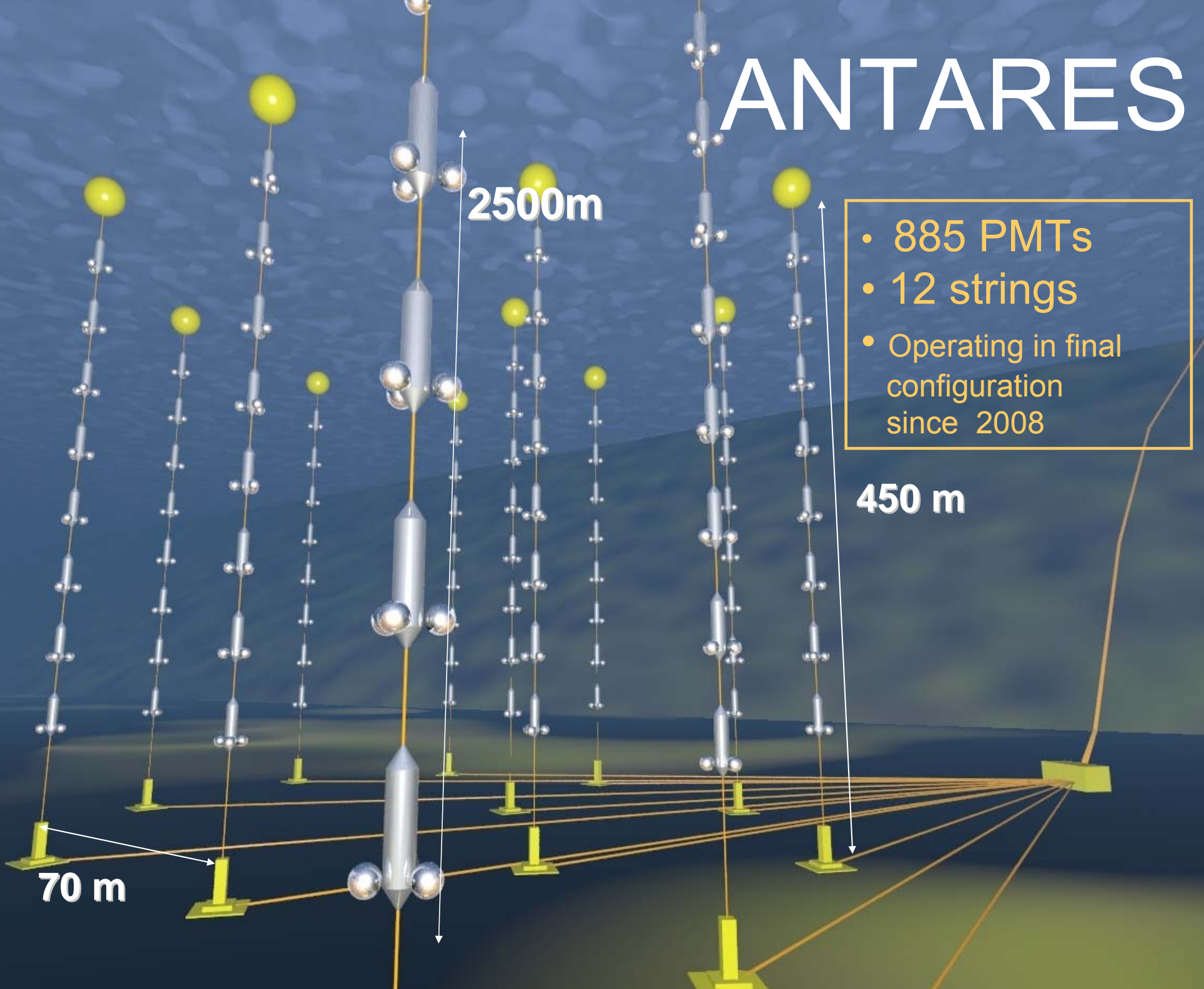
ANTARES

- 885 PMTs
- 12 strings
- Operating in final configuration since 2008

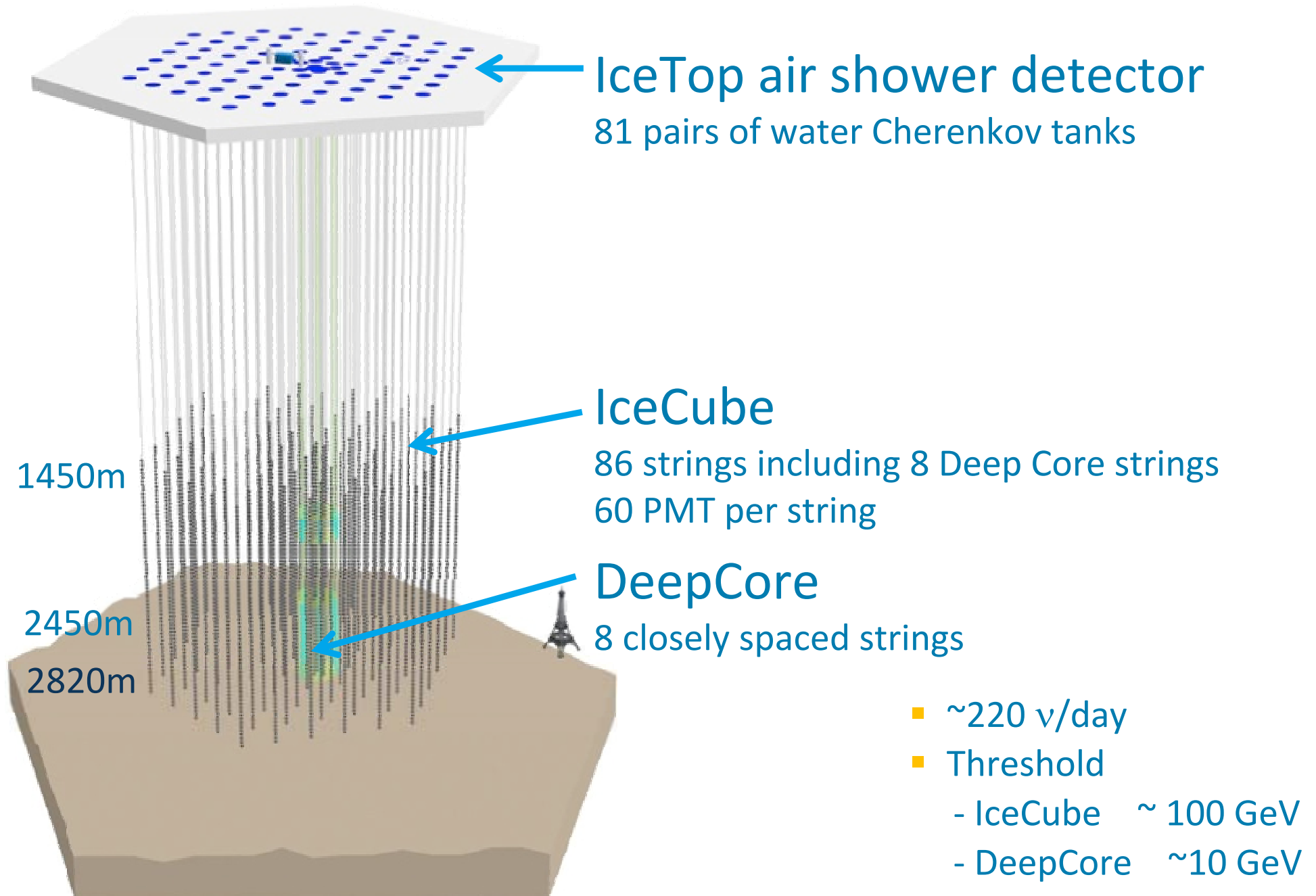
2500m

450 m

70 m

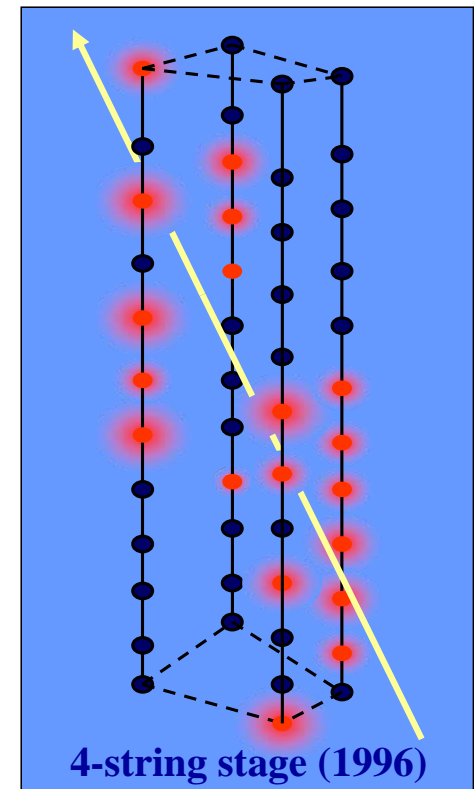


IceCube Neutrino Observatory



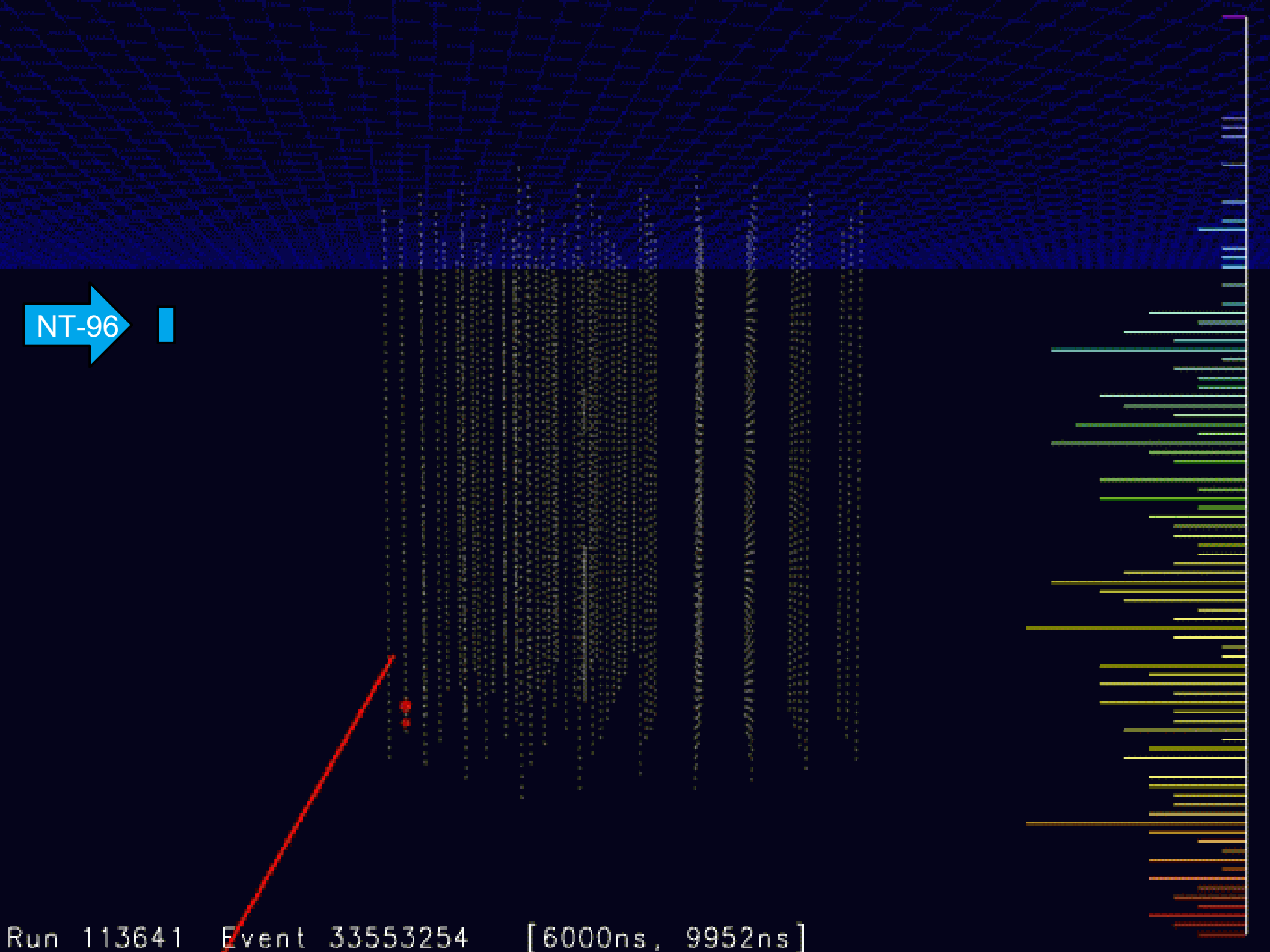
STUDY OF ATMOSPHERIC NEUTRINOS

Baikal 1996

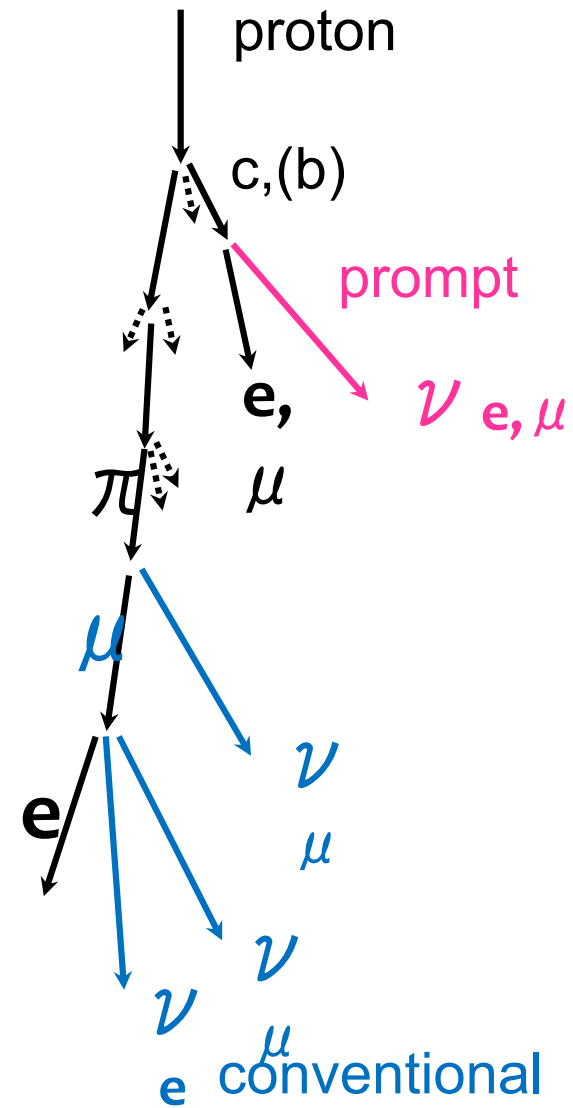
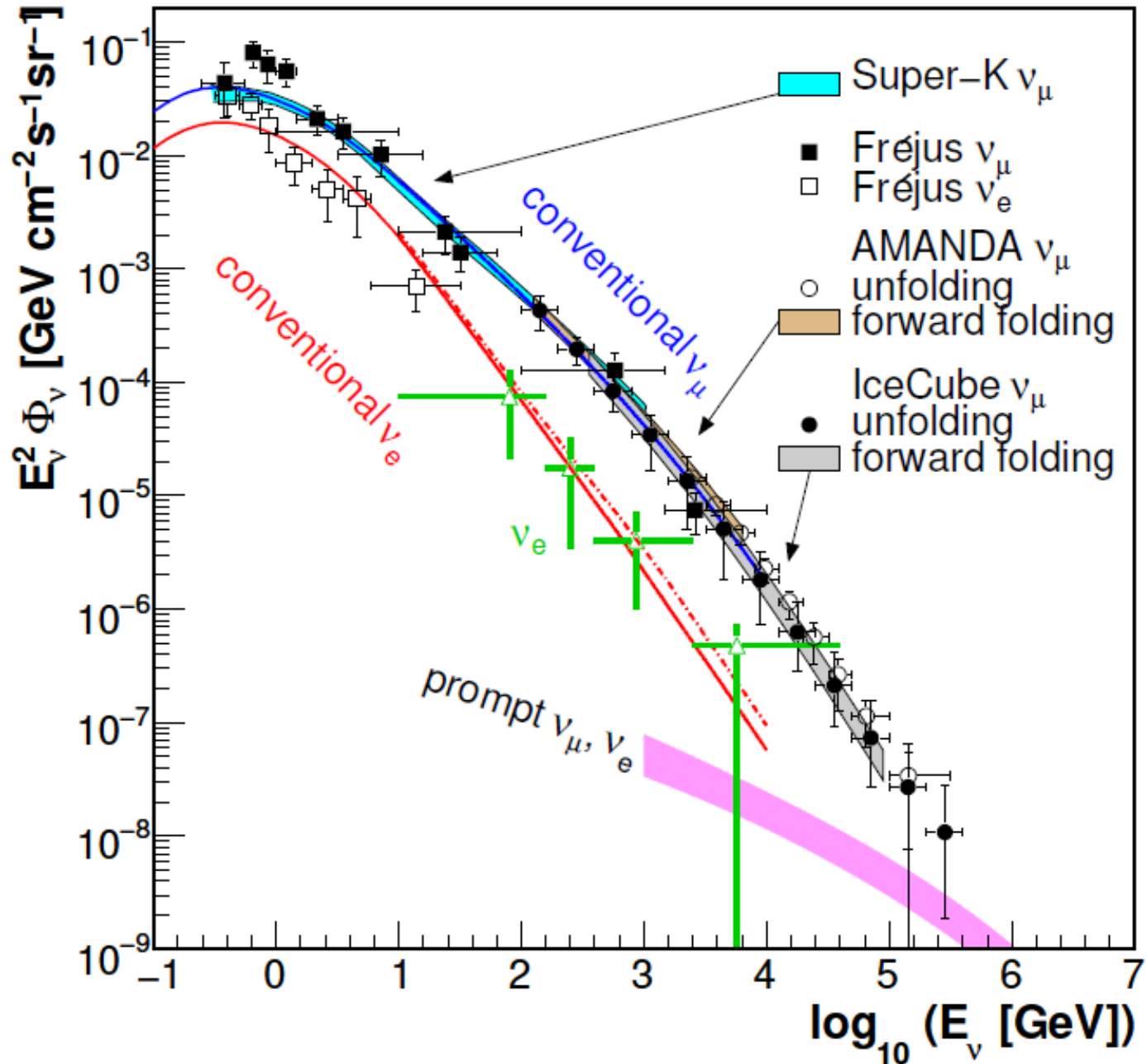


NT-96

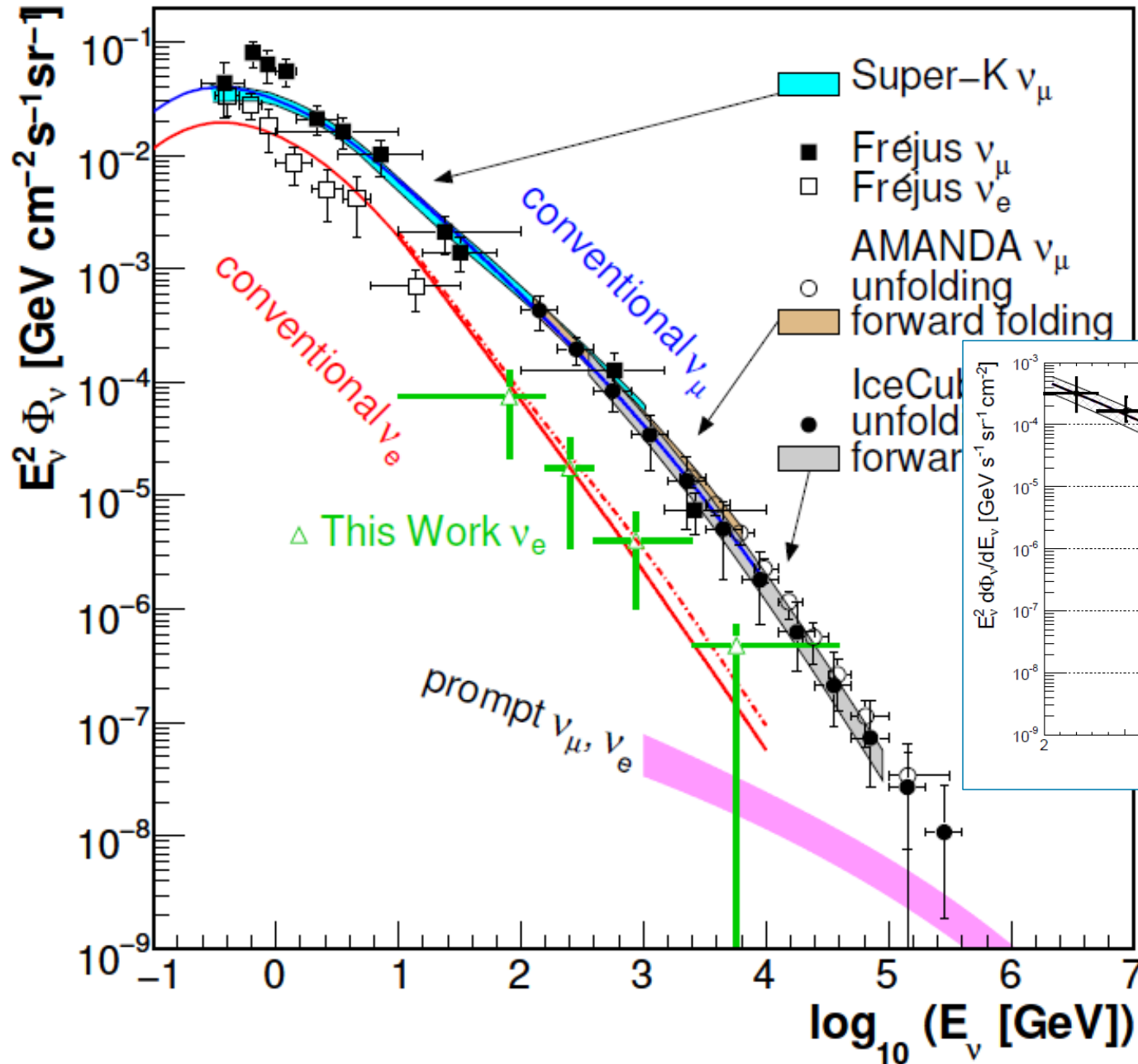
Run 113641 Event 33553254 [6000ns, 9952ns]



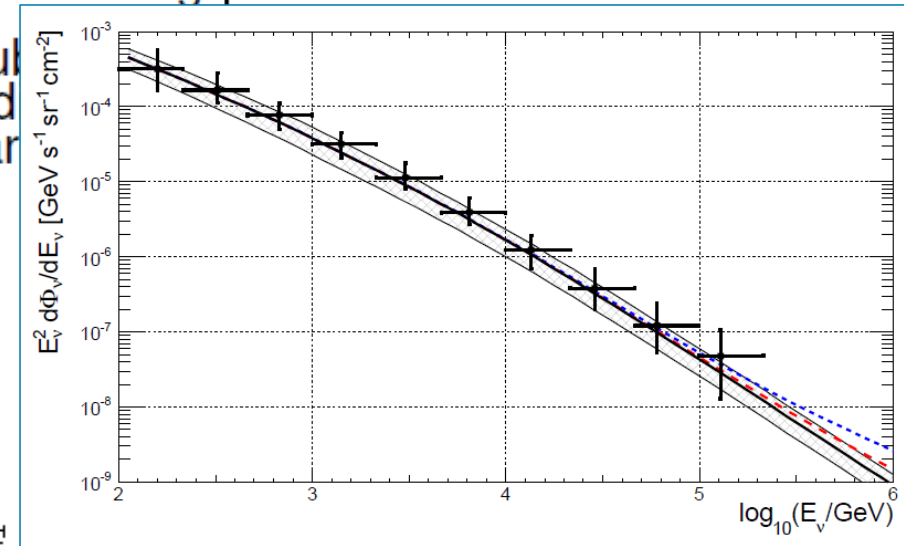
Atmospheric neutrinos in IceCube



Atmospheric neutrinos in IceCube ...



.. and ANTARES

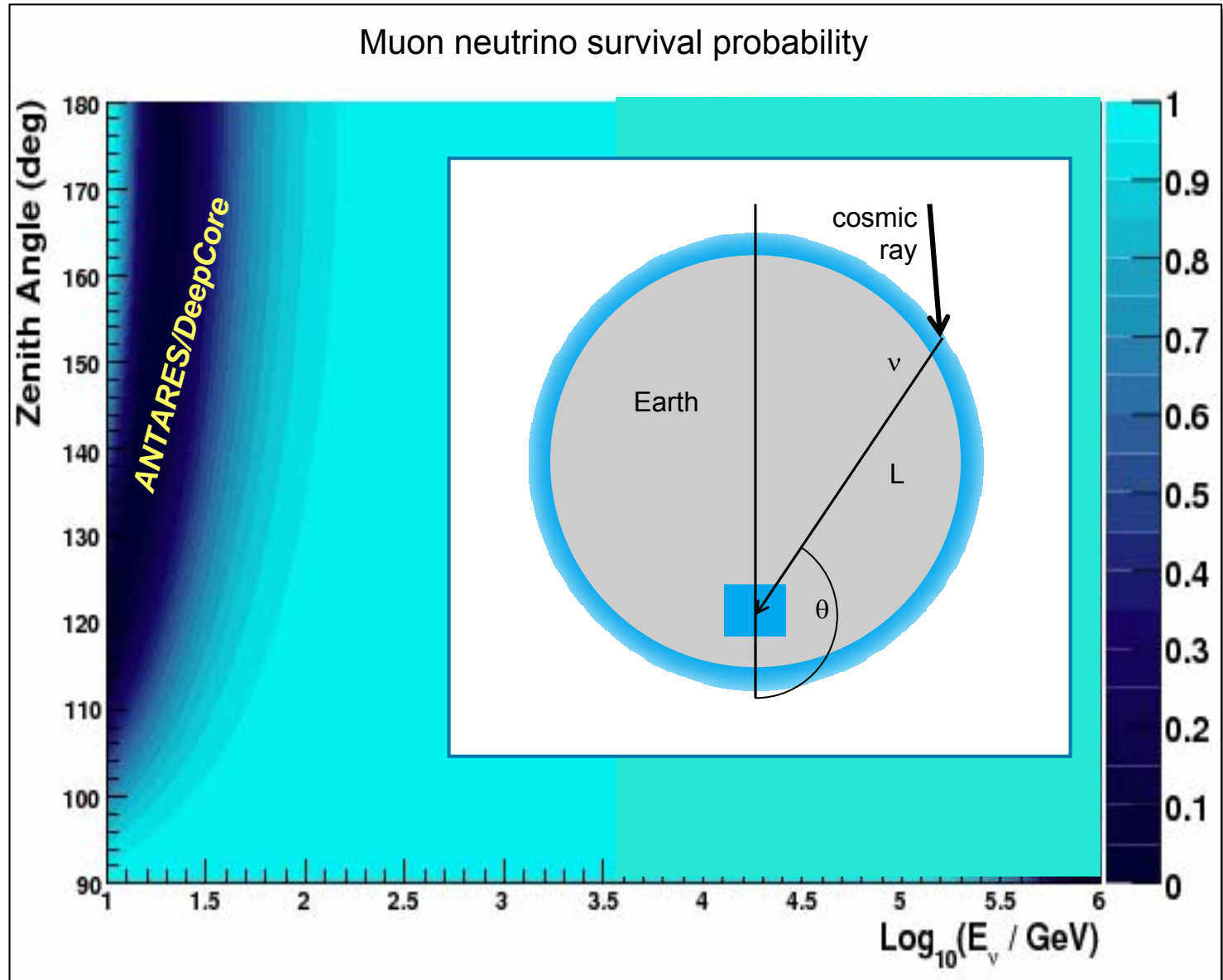


arXiv:1308.1599

Oscillations of atmospheric neutrinos

Vertically upward

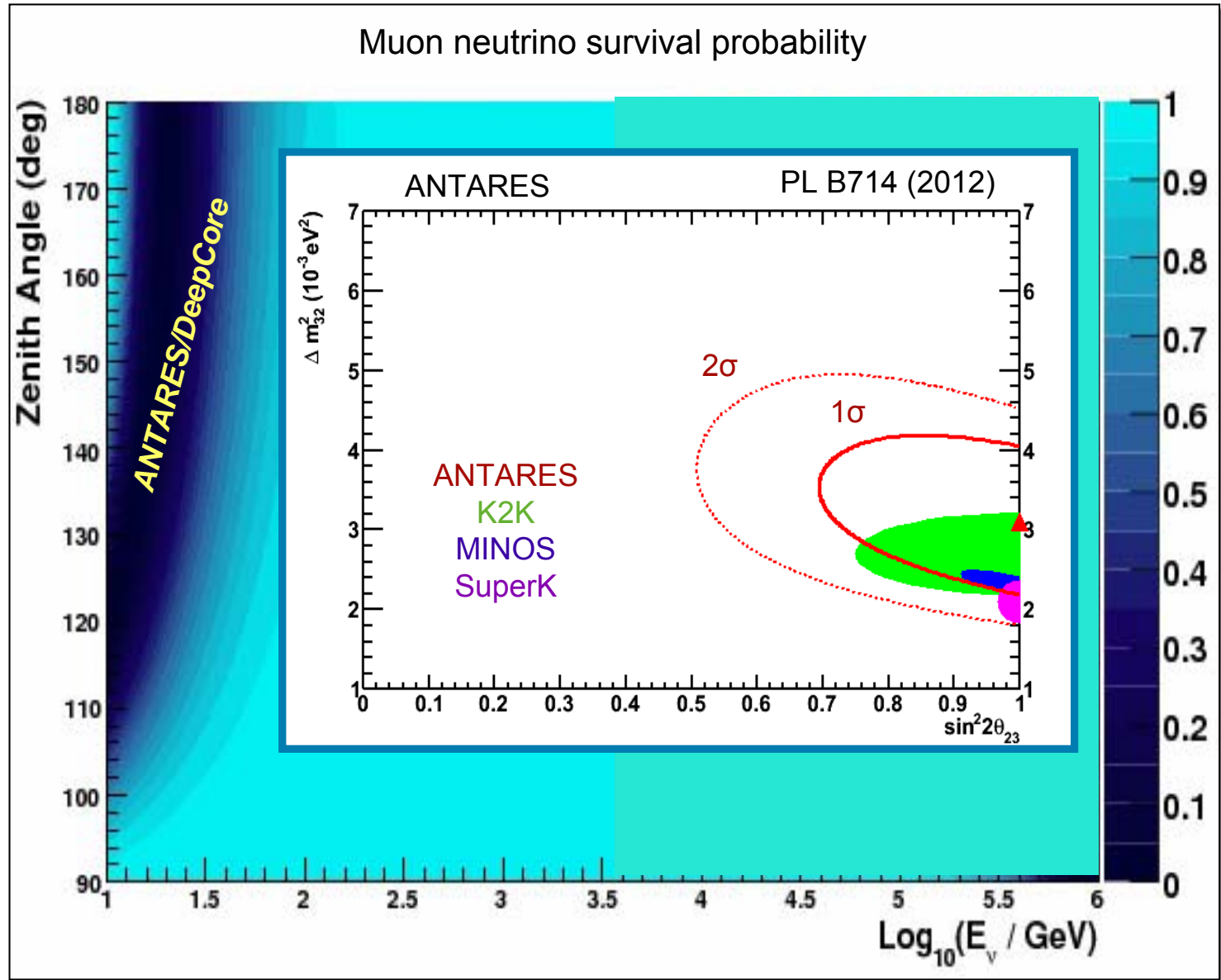
Horizontal



Oscillations of atmospheric neutrinos

Vertically upward

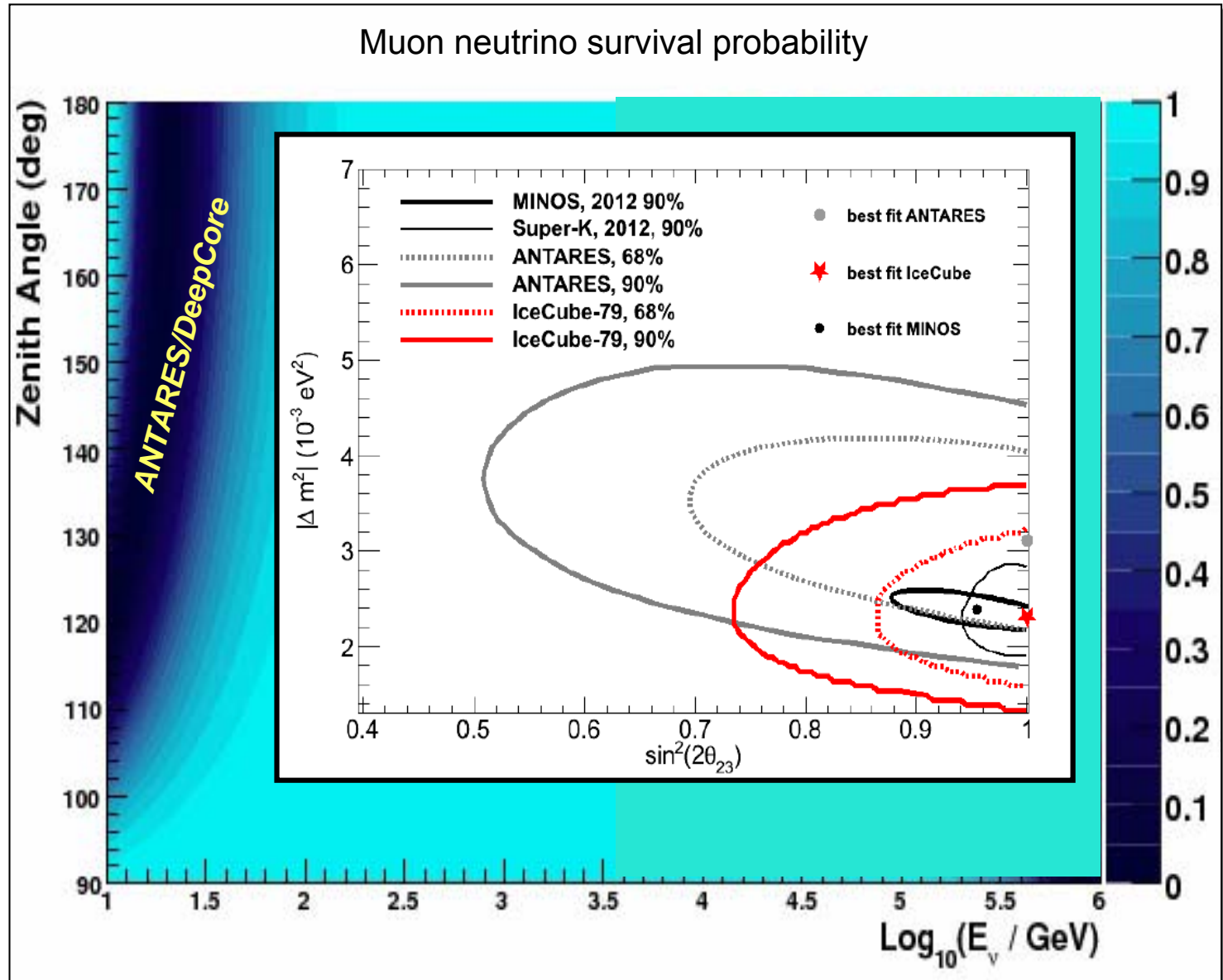
Horizontal



Oscillations of atmospheric neutrinos

Vertically upward

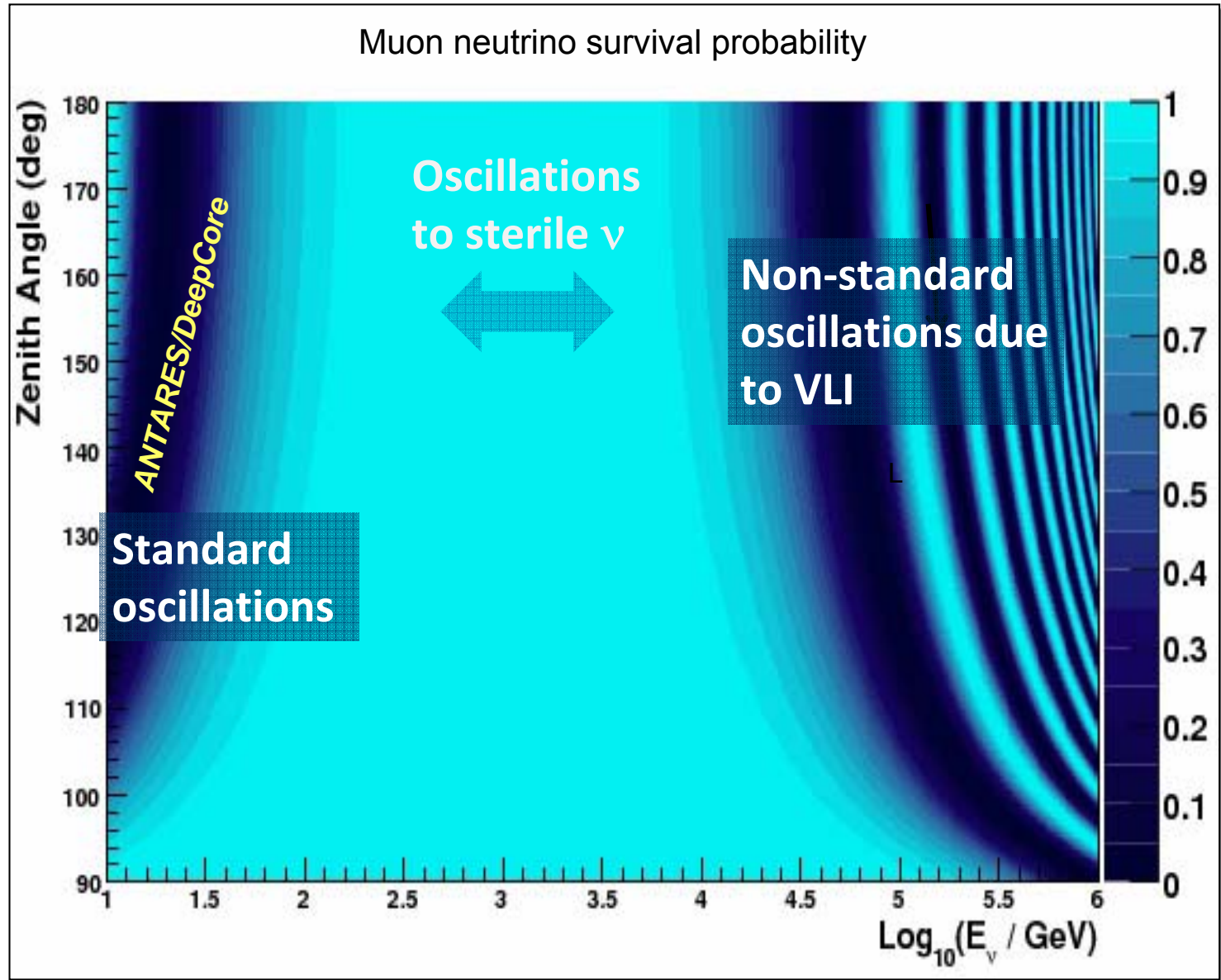
Horizontal



Oscillations of atmospheric neutrinos

Vertically upward

Horizontal



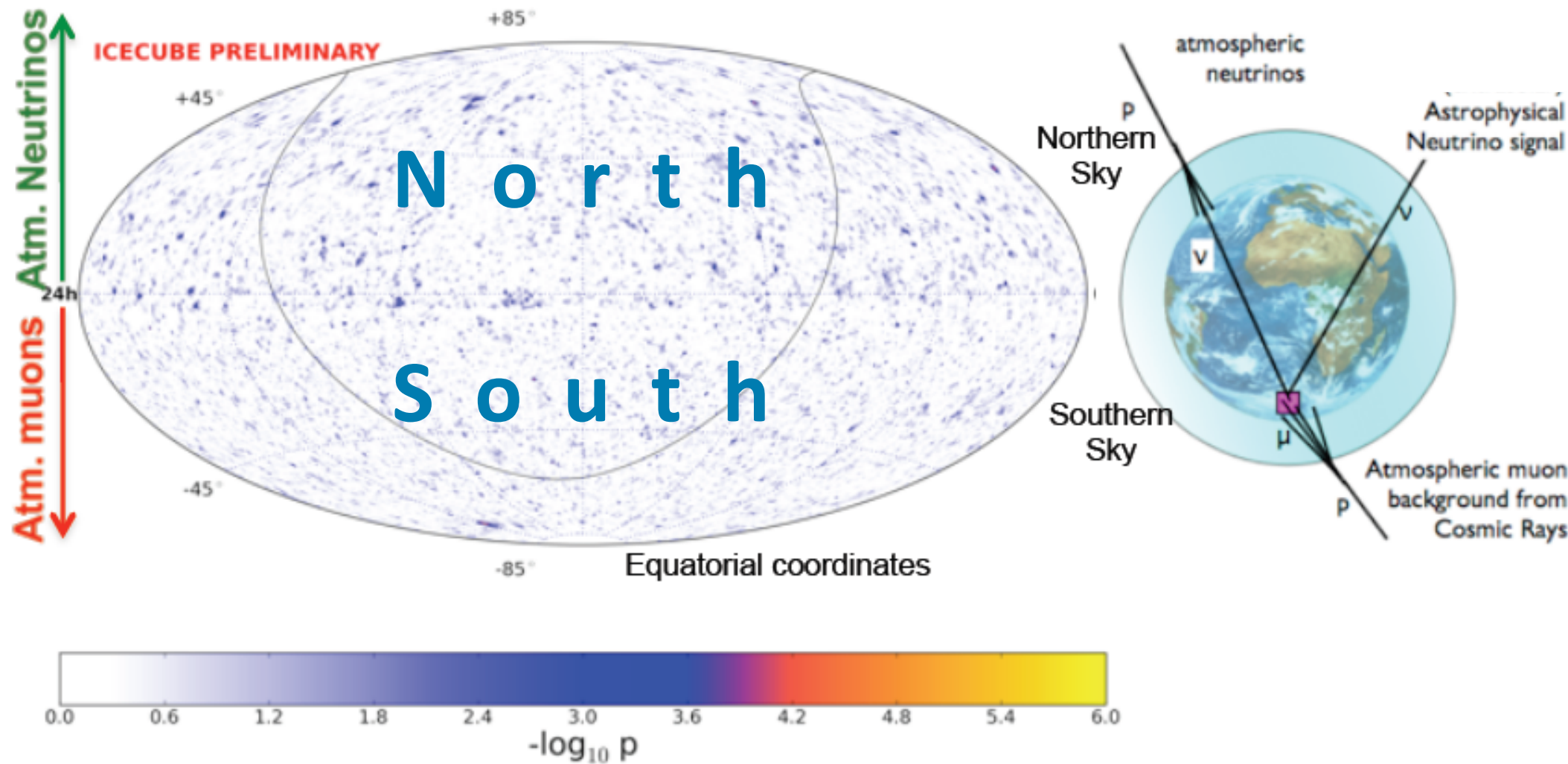
SEARCH FOR EXTRA-TERRESTRIAL NEUTRINOS

- Steady point sources
- Transient sources: GRB
- Diffuse flux

Point Source IceCube 4 years IC40/59/79/86

April 2011-March 2012

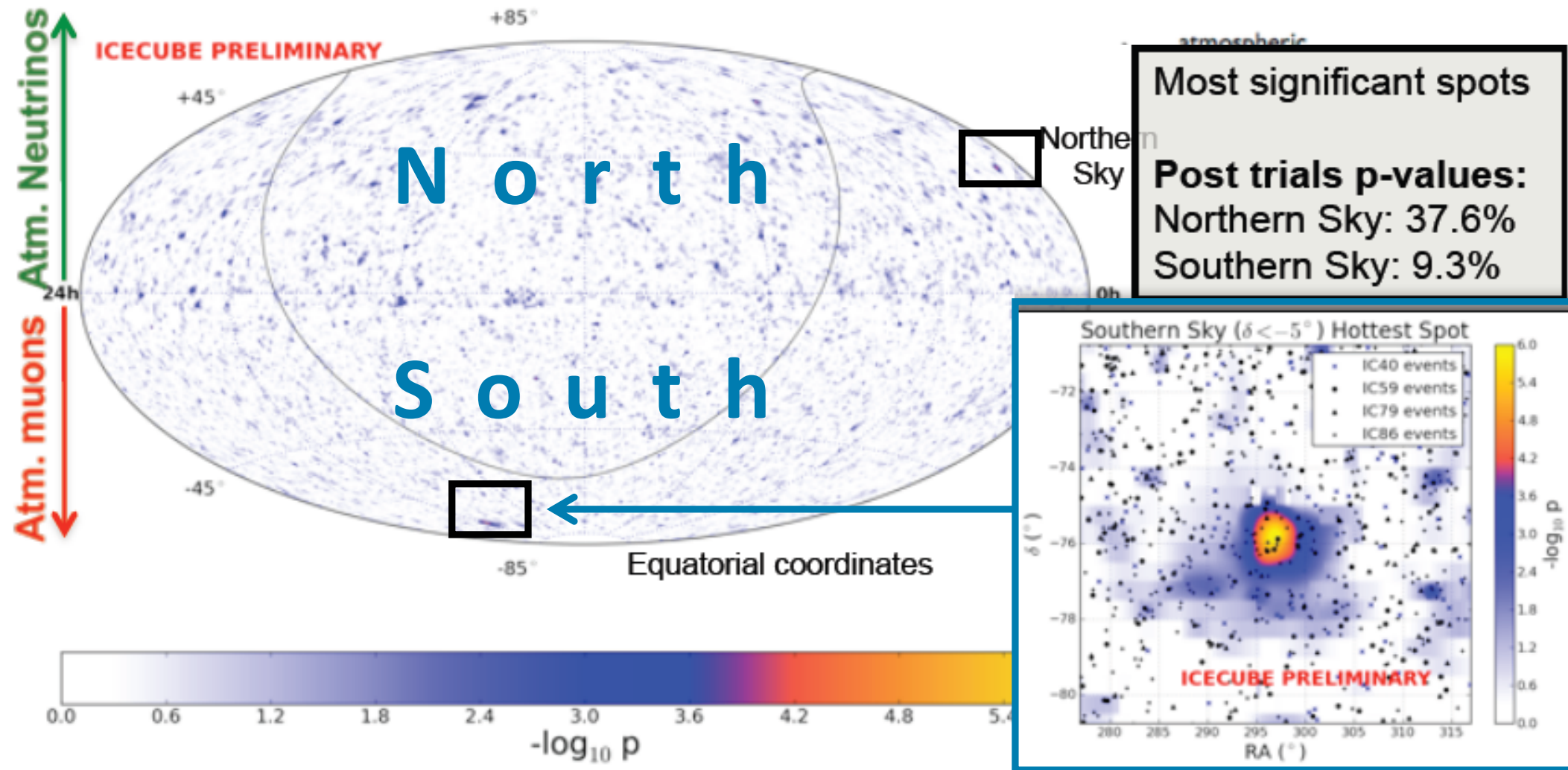
- 394,000 total events
 - 178k neutrino candidates in North, 216k atmospheric muons in South
- Livetime: 1371 days, including first year of completed detector



Point Source IceCube 4 years IC40/59/79/86

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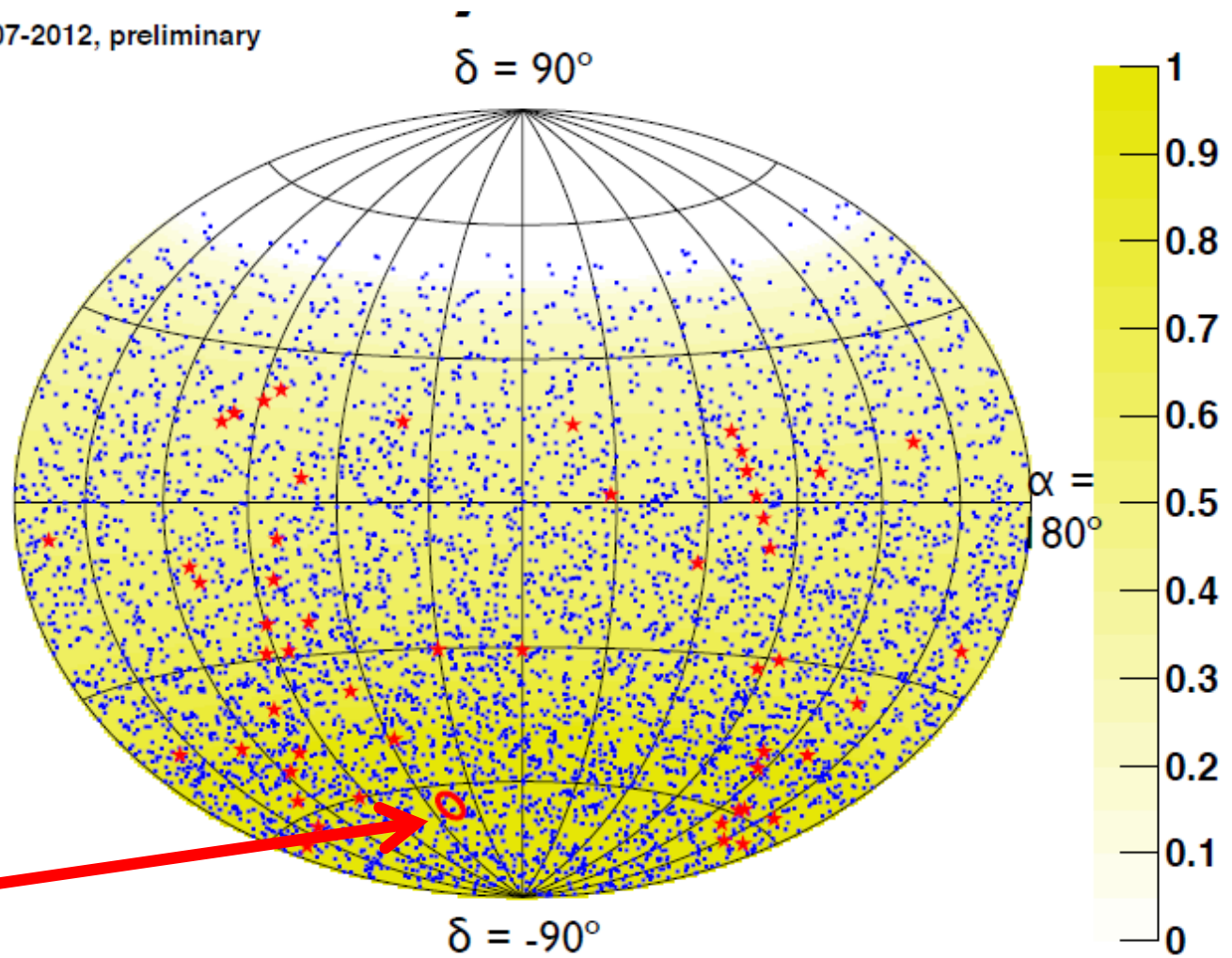
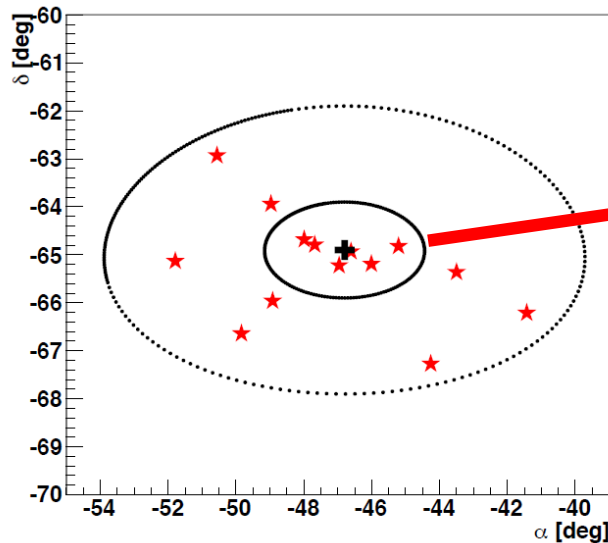
Antares 2007-2012, preliminary

- 5516 upward going events (90% purity)

- excess at $\alpha = -46.8^\circ$ $\delta = -64.9^\circ$

- p-value 2.1%

→ 2.3 σ

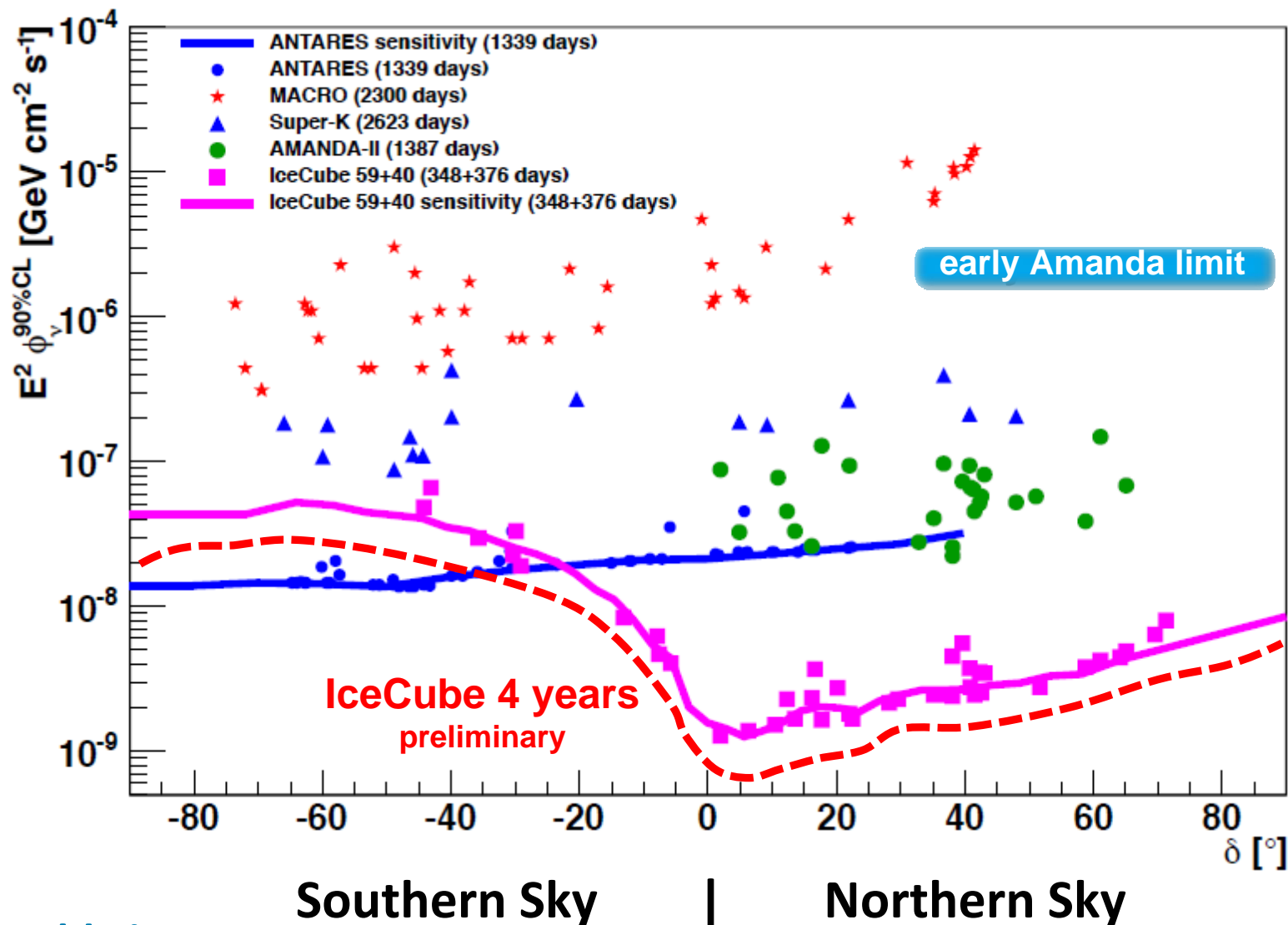


Limits for steady point sources

- Factor 1000 in 12 years
- No detections yet

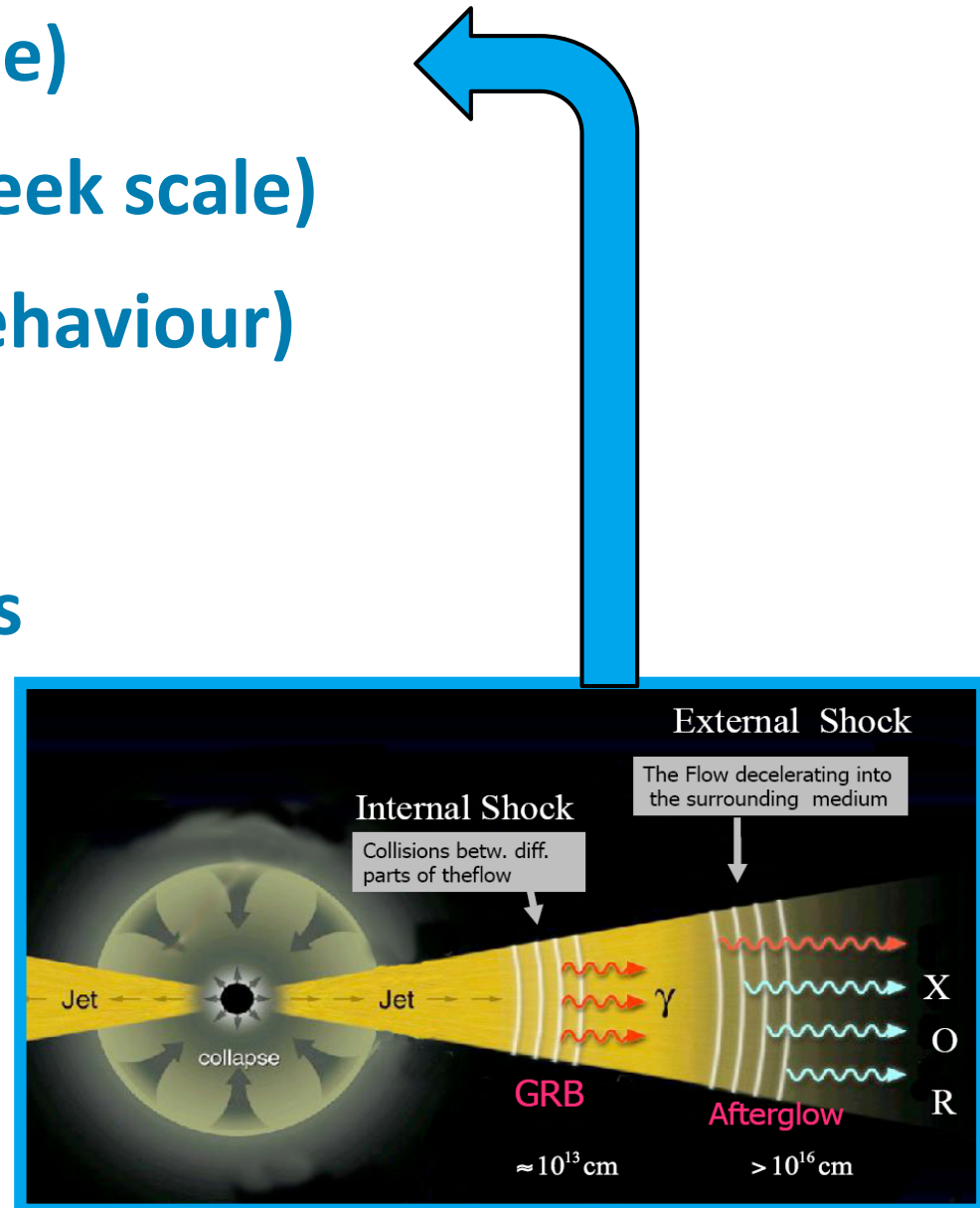
- Expect another factor 3 for IceCube in 2016

- KM3NeT/GVD would give ~ factor 50 w.r.t. Antares

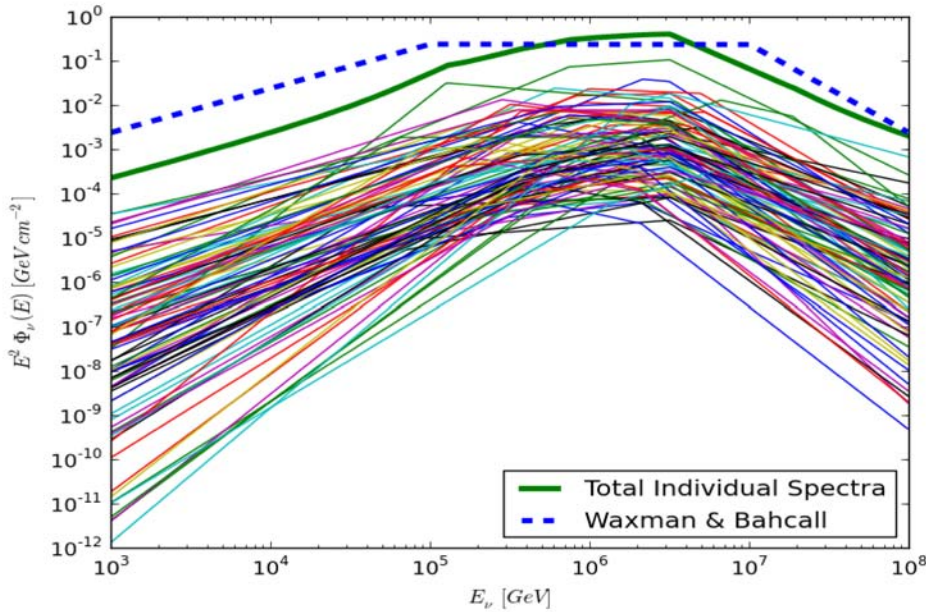


Transient Sources

- GRB (second to minute scale)
- AGN (Flares on hours to week scale)
- Binary systems (periodic behaviour)
- ANTARES and IceCube:
Various follow-up programs
($\nu \rightarrow \gamma$, $\nu \rightarrow \text{optical}$) and
common searches for
coincidences LIGO/VIRGO
ANTARES/IceCube
- IceCube: SN burst trigger



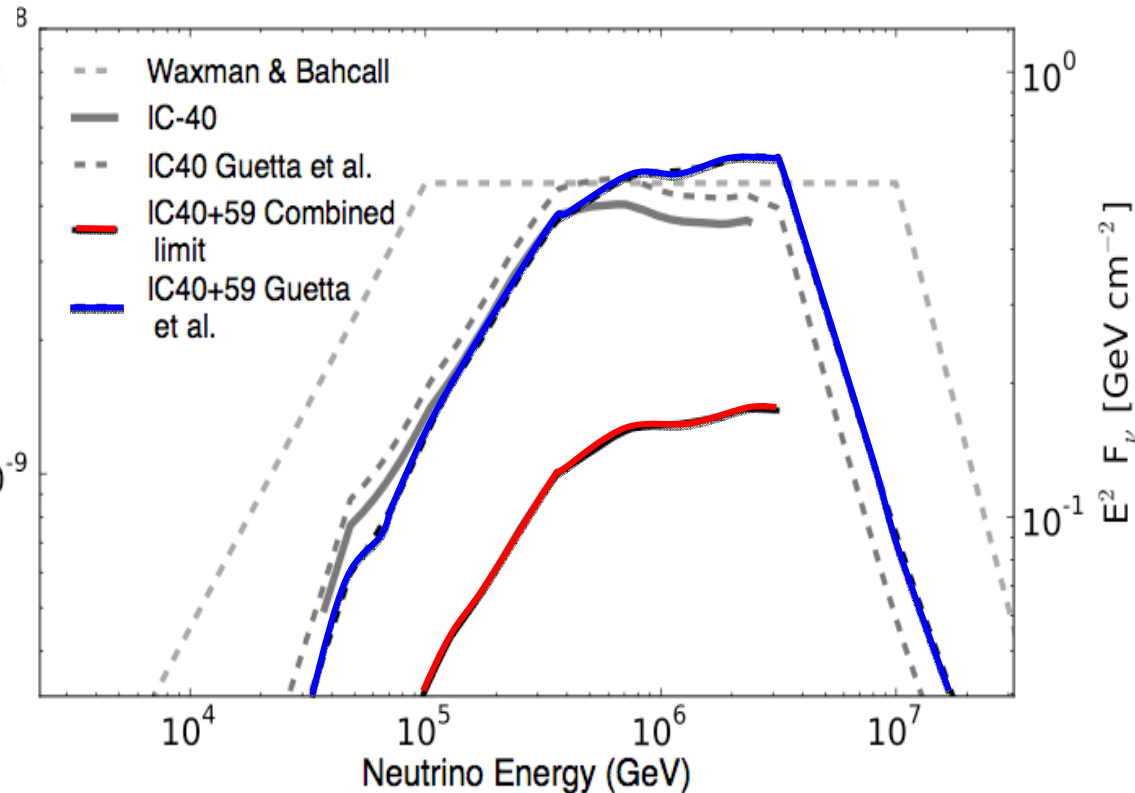
GRB Coincidence Search: IceCube



- 225 GRB at Northern sky (IC40 + IC59)
- No IceCube event in time and direction coincidence
- 8.4 coincidences expected (Guetta et. al)

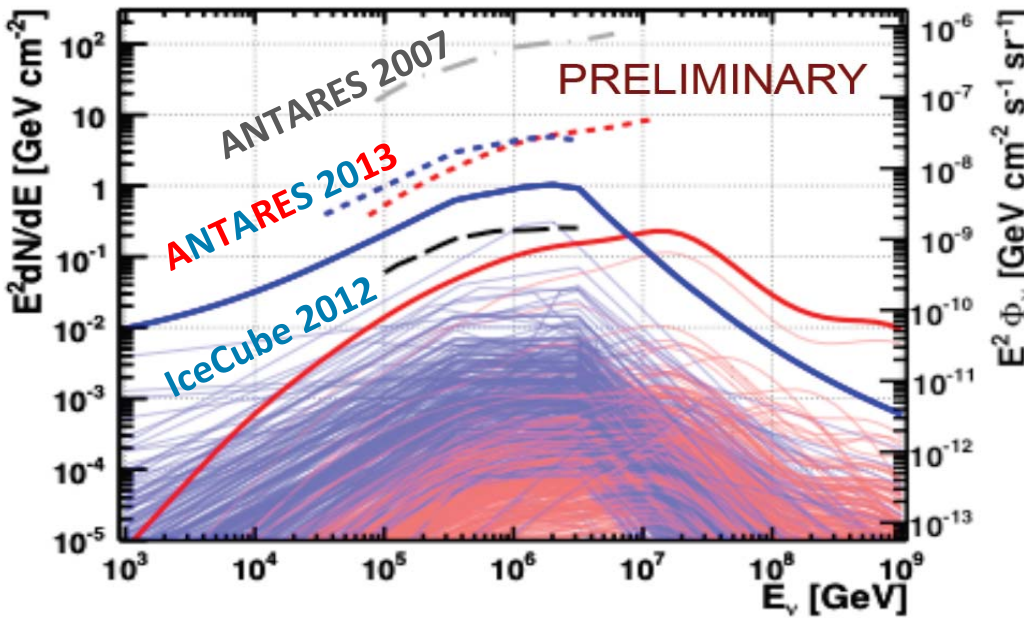
Standard fireball model à la Waxman or Guetta excluded with $> 3\sigma$ (Nature 484 (2012) 351)

Winter et al. have modeled the fireball numerically, using more realistic particle energy distributions, and got fluences less by nearly one order of magnitude !

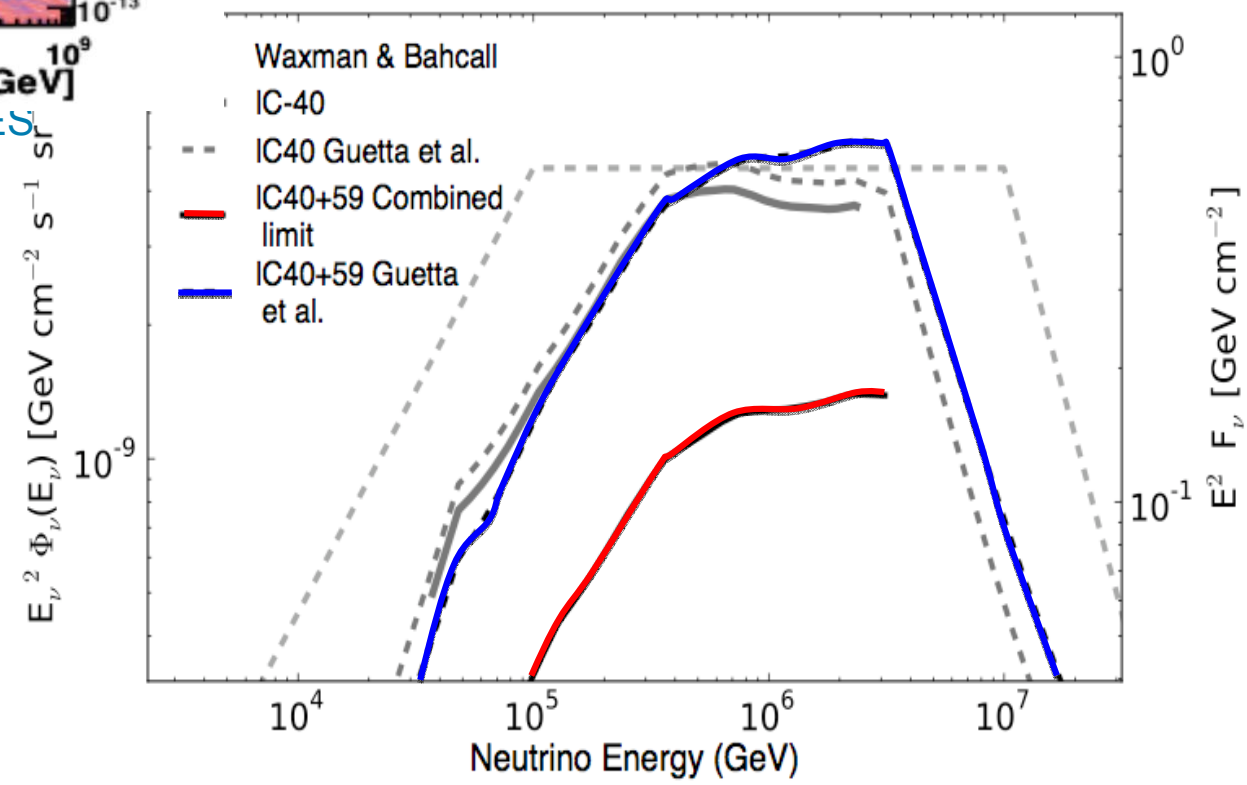


GRB Coincidence Search: ... and ANTARES

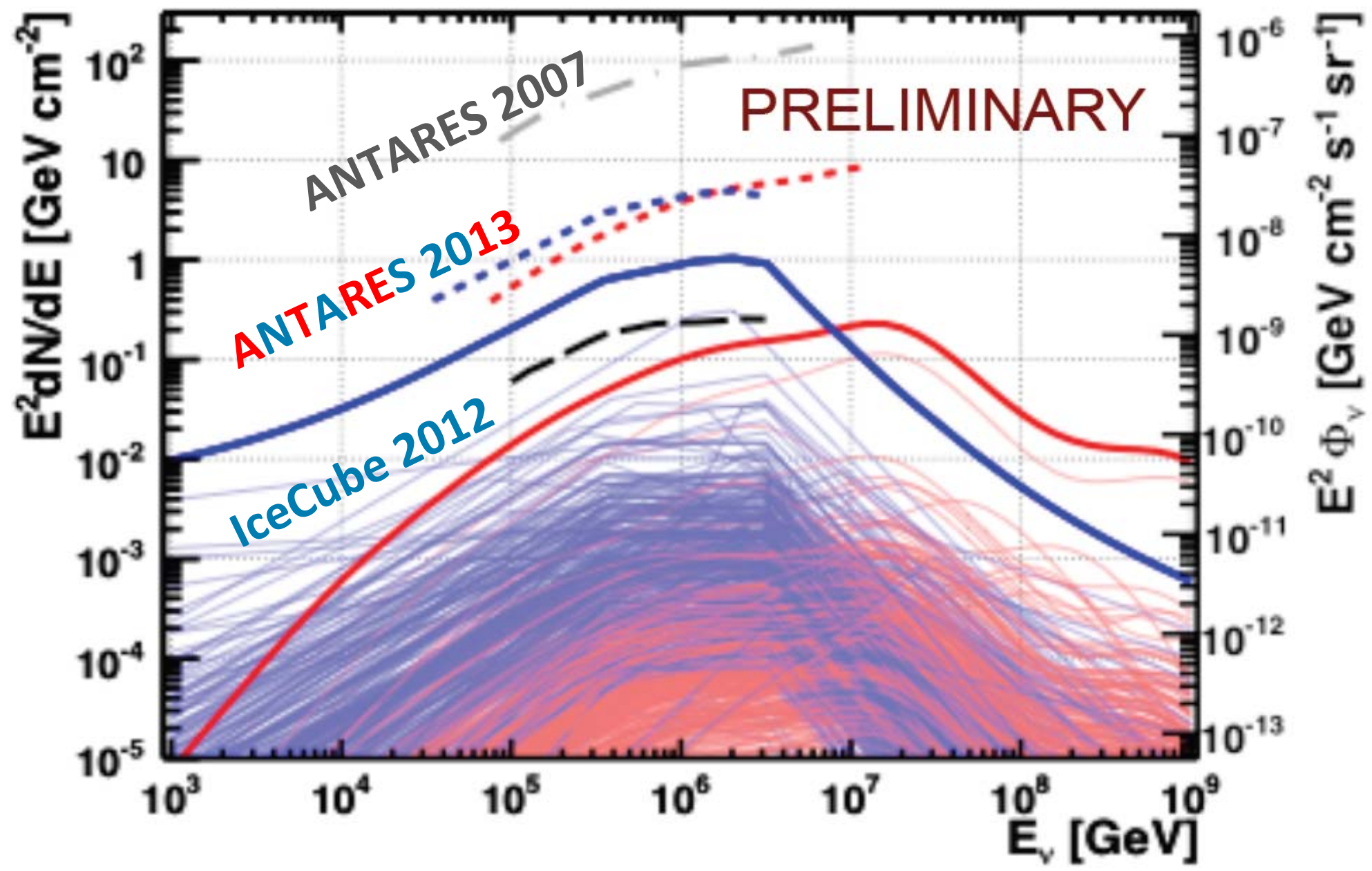
296 GRB at Southern sky
 No ANTARES event in time
 and direction coincidence
[arXiv:1307.0304](https://arxiv.org/abs/1307.0304)



- dashed grey
2007, 40 GRB
(JCAP 03 (2013) 06)
- Dotted blue/red: Antares 2013
- **dashed black**
IceCube 225 GRB
- Blue: Guetta et al. 2004
- Red: Hümmer et al, 2010

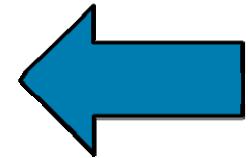
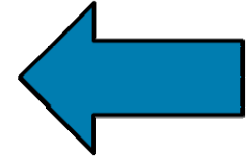
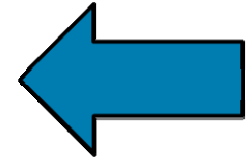


GRB Coincidence Search: ... and ANTARES

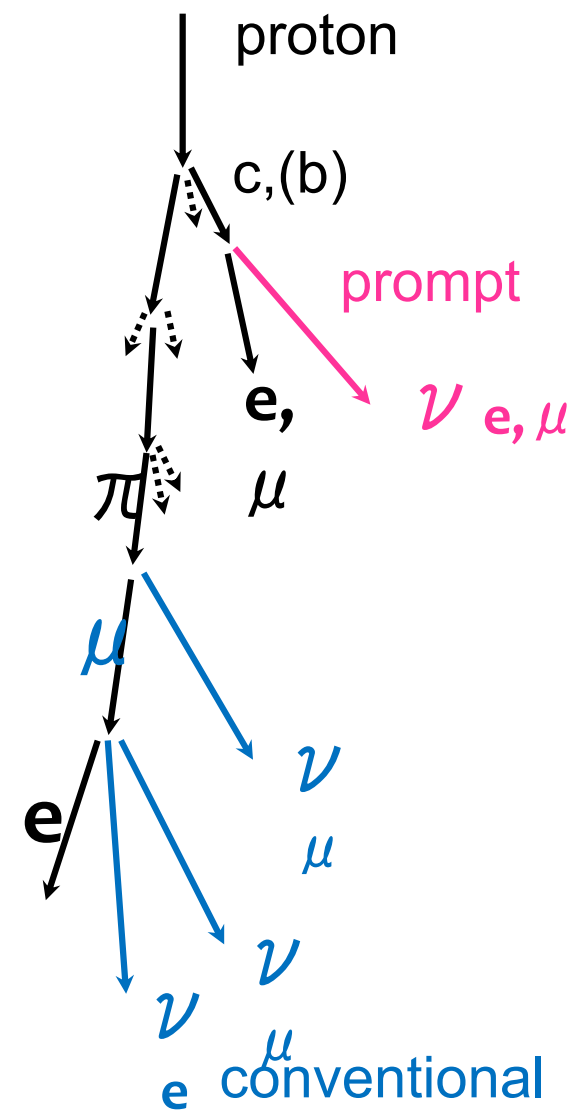
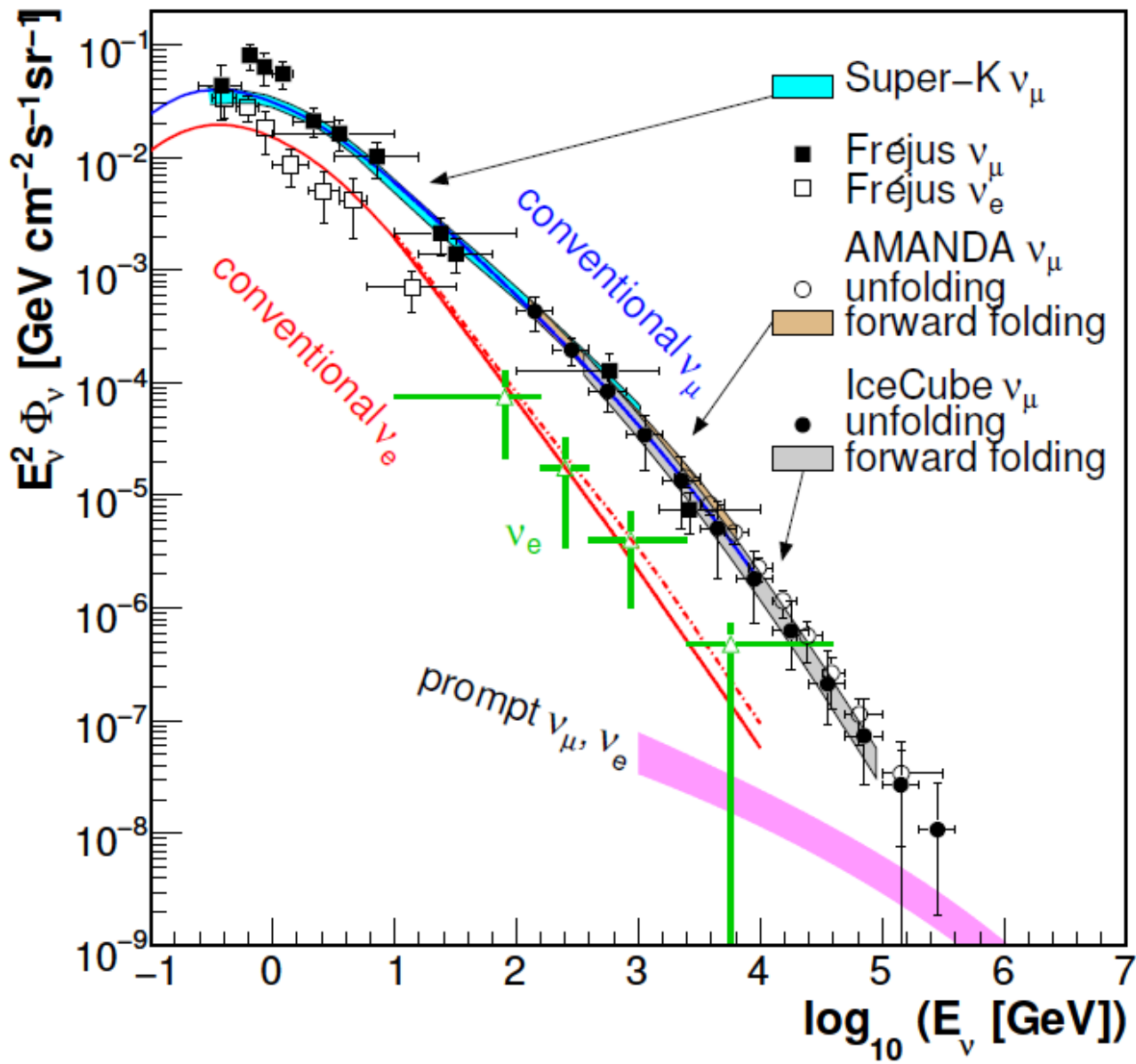


Diffuse extraterrestrial neutrino fluxes

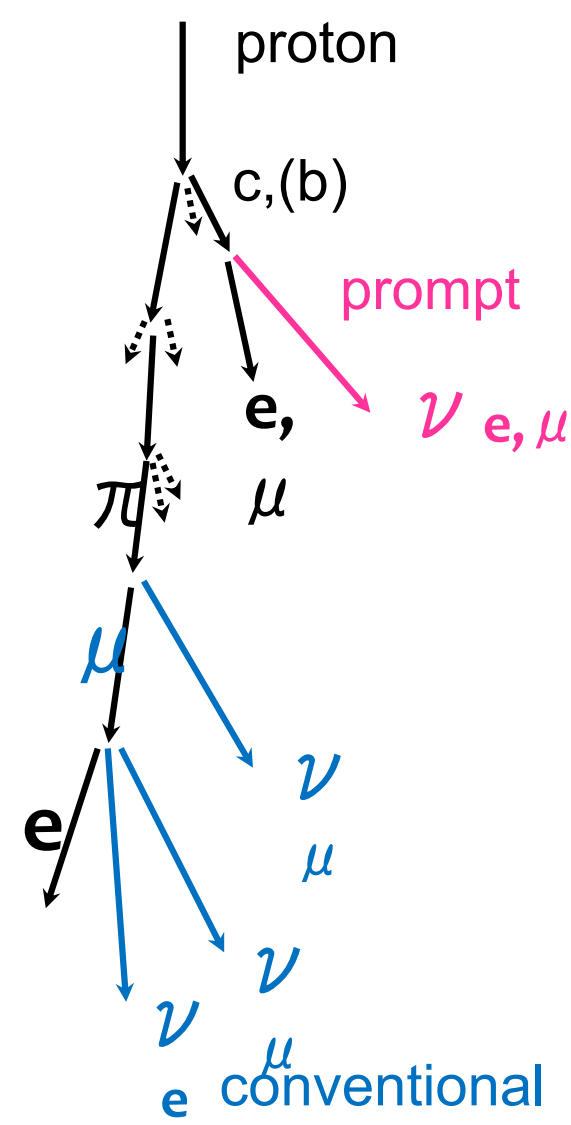
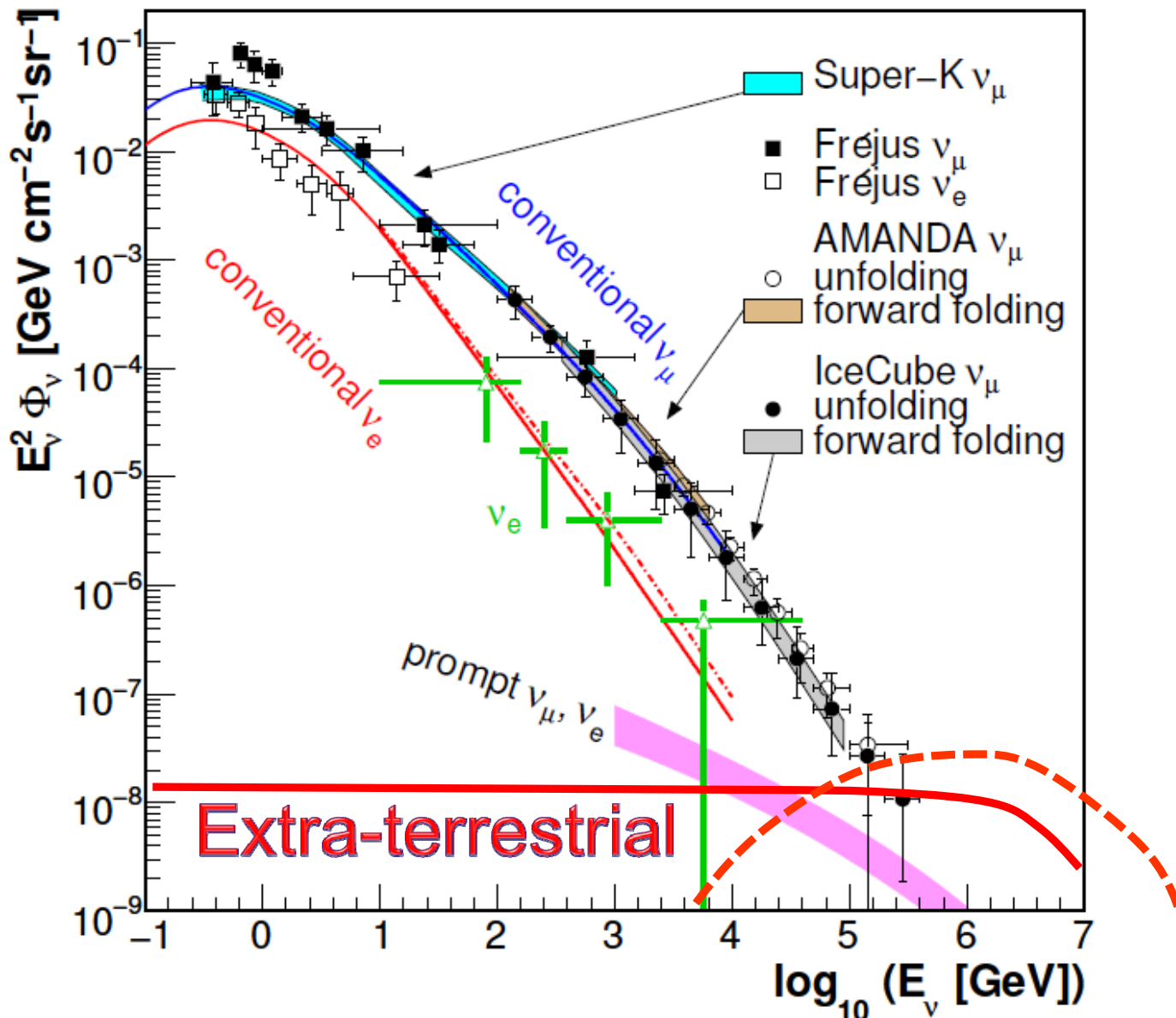
- **ANTARES, Amanda, IceCube:**
Upwards going muons
- **Amanda, IceCube: contained cascades**
- **Baikal, IceCube:**
Extremely high energies, all-sky
- **IceCube: galactic plane**
- **ANTARES: Fermi bubbles**



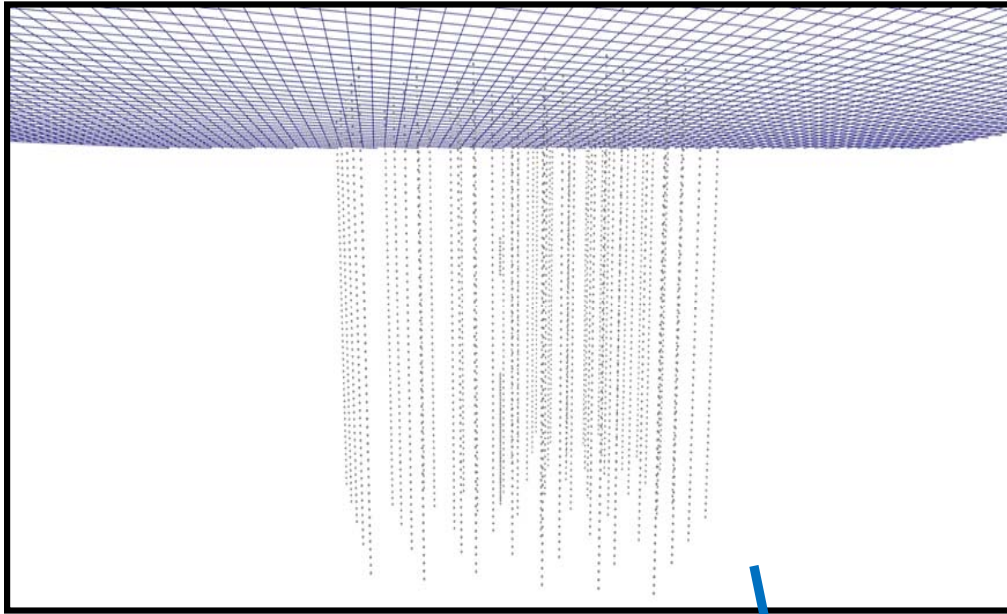
Search for an extraterrestrial diffuse ν flux



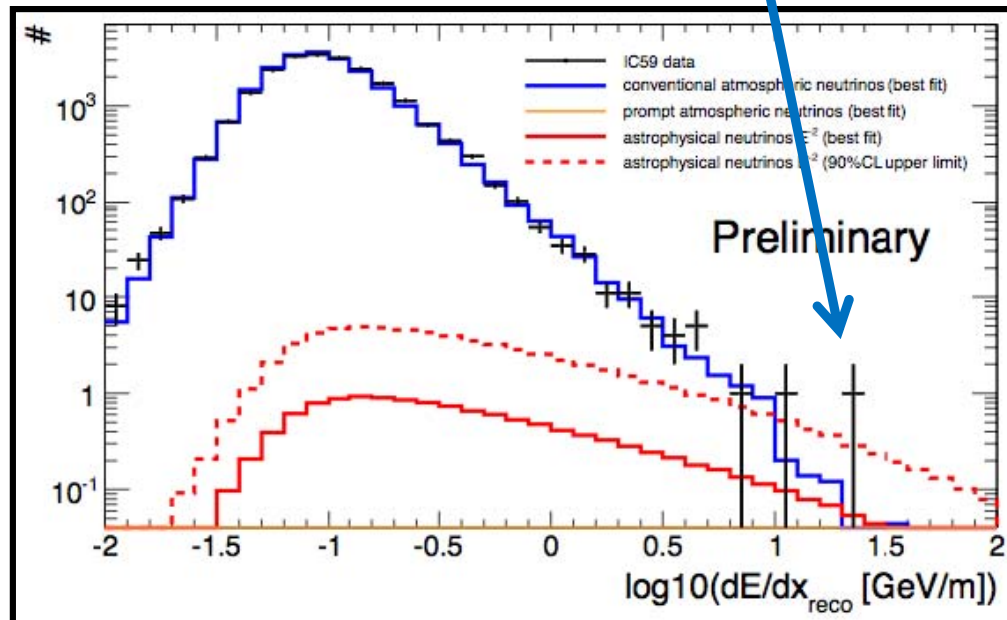
Search for an extraterrestrial diffuse ν flux



IceCube-59: upward muons

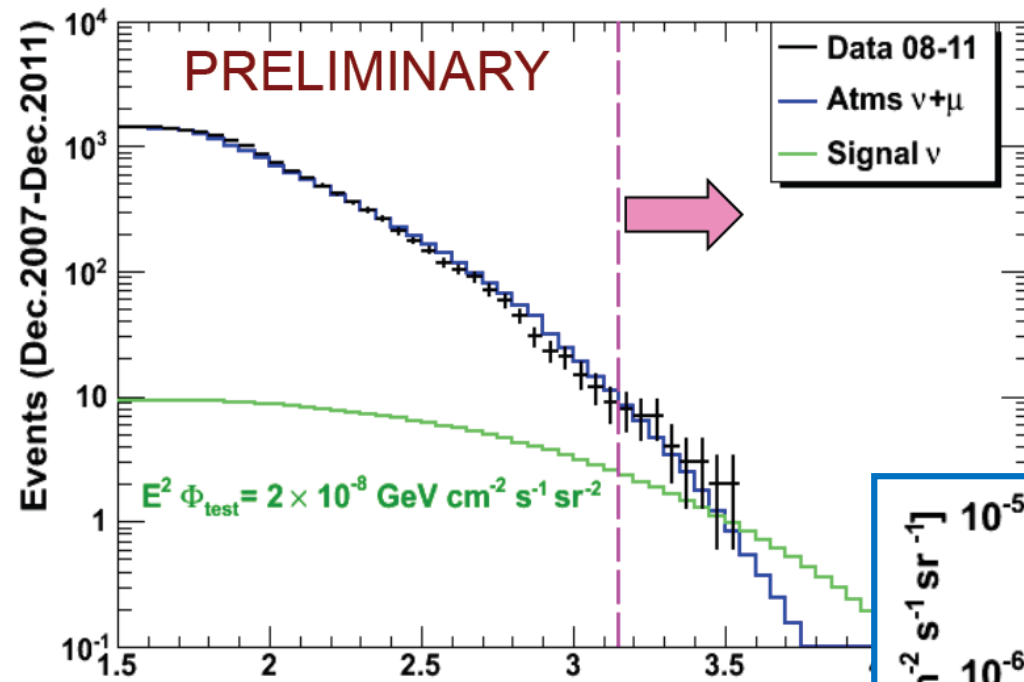


- A 200 TeV muon crossing IceCube
- The highest energy muon we have detected
- 1.8σ excess



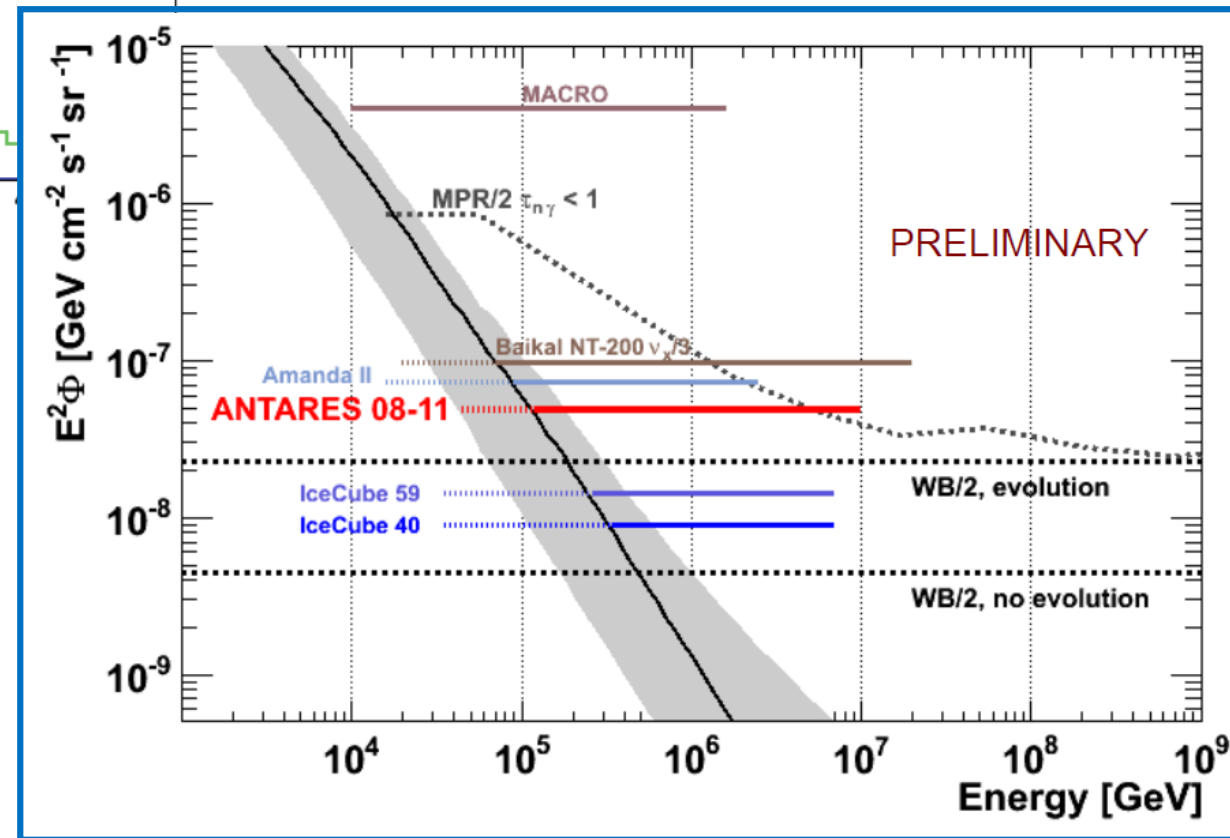
- IC-79 data coming soon !

Limits on diff. fluxes from upward muons



ANTARES 2008-2011

$$E^2 \Phi < 4.7 \times 10^{-8} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$$

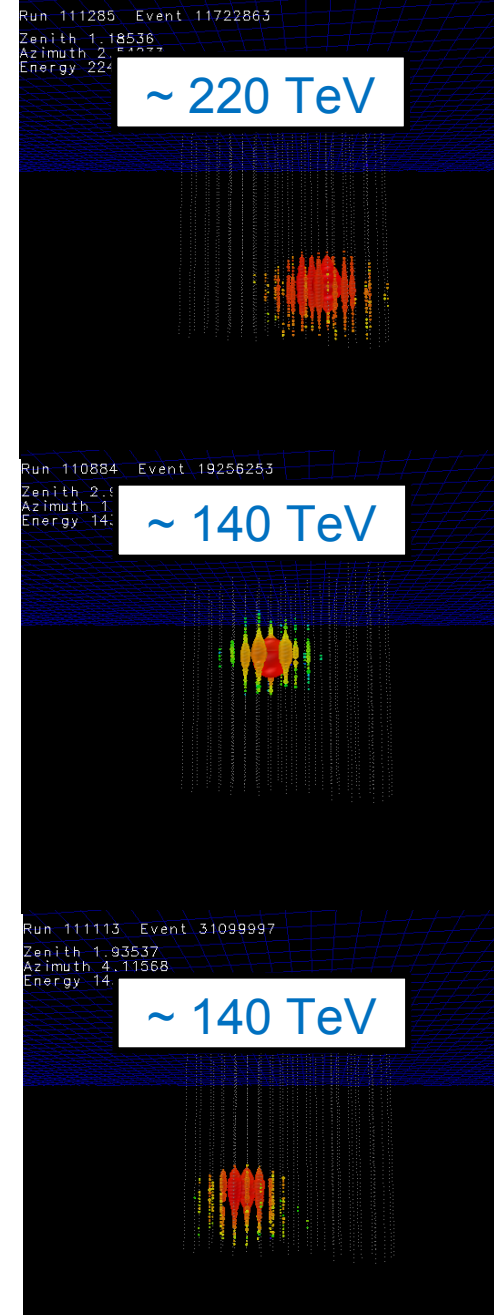
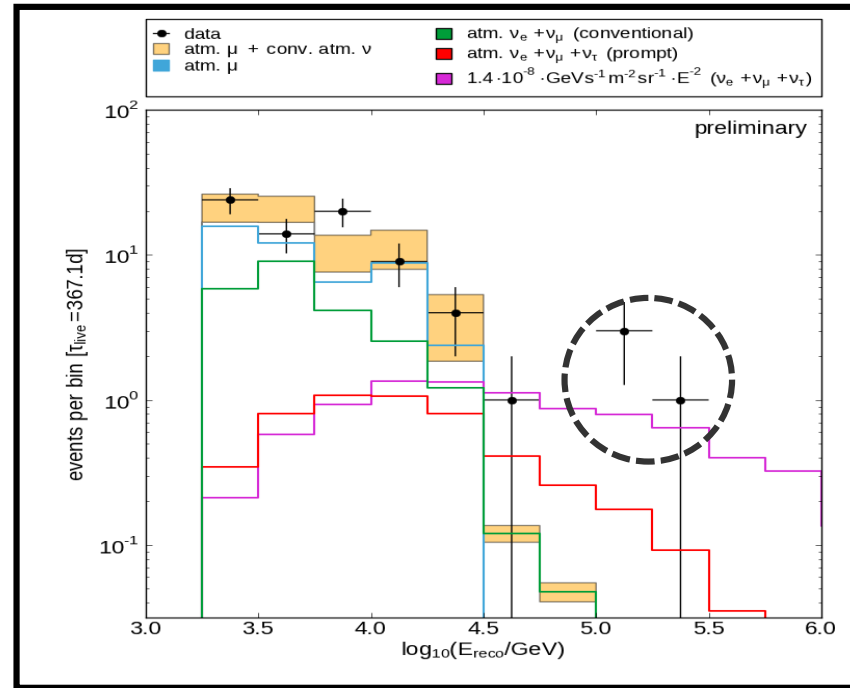


- Baikal NT-200
- AMANDA
- ANTARES
- IceCube 40, IceCube 59

IceCube contained cascades

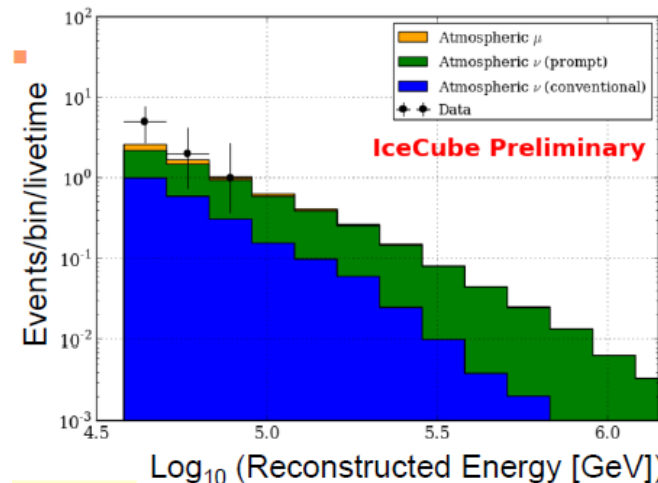
IceCube-40

3 cascade events
2.3 σ excess



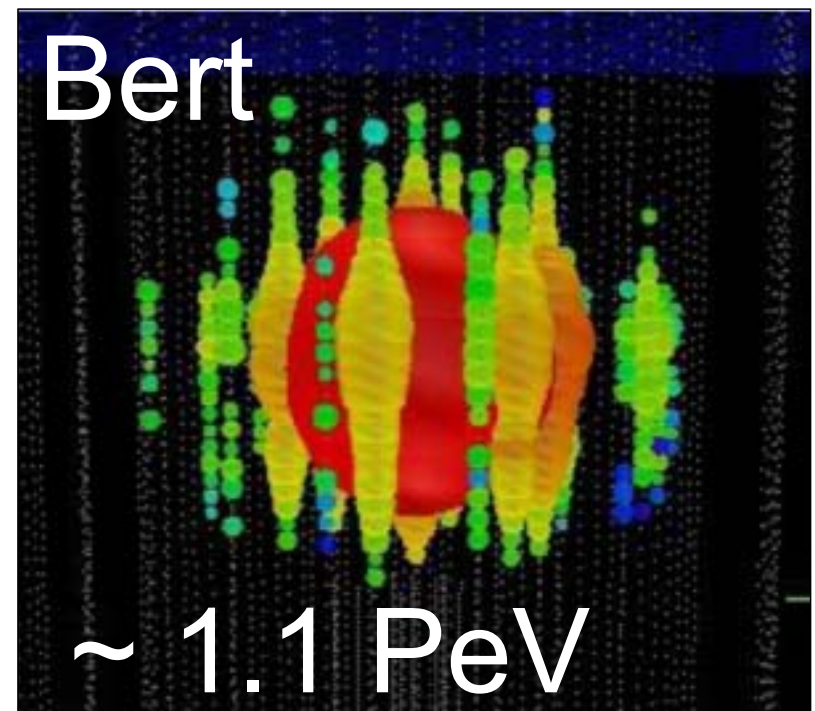
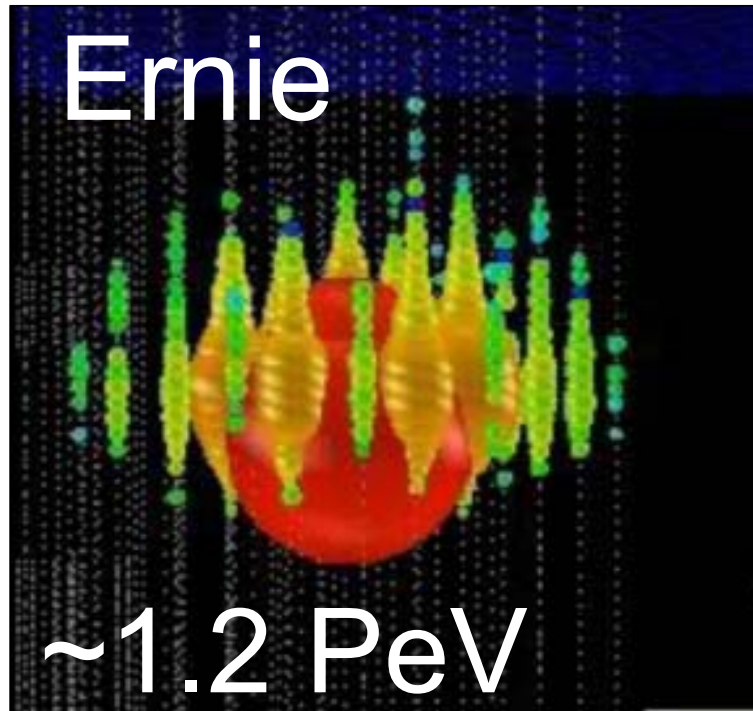
IceCube-59

Mild excess over
conventional
atm. neutrinos



Special Search for cosmogenic ν (Berezinsky Zatsepin)

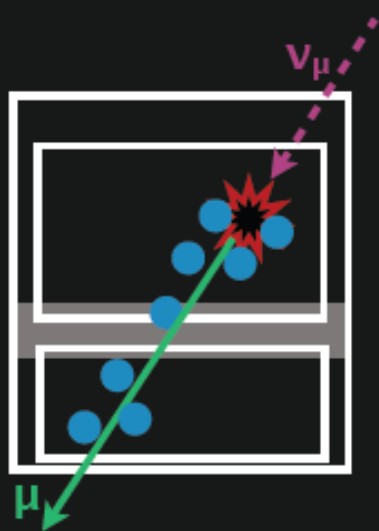
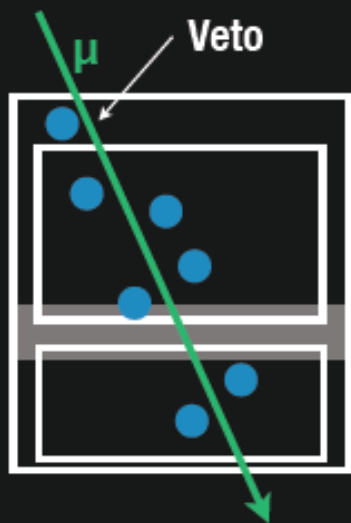
- IC79/IC86



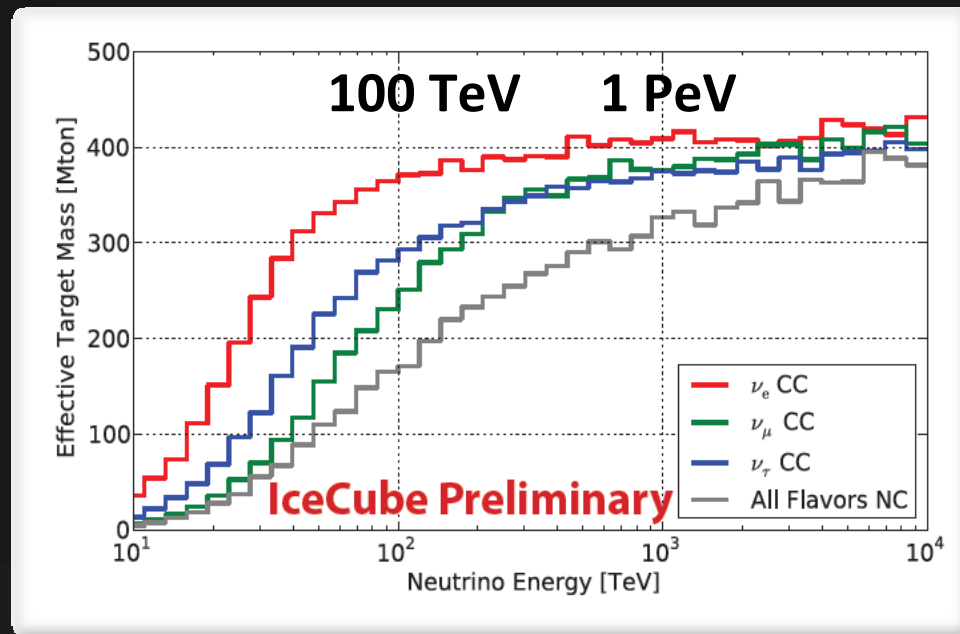
2.8σ

- Both downgoing
- Not from Glashow Resonance (which is at 6.3 PeV)
- Unbroken E^{-2} would have made 8-9 events at higher energy \rightarrow cut-off

High Energy Starting Event Analysis



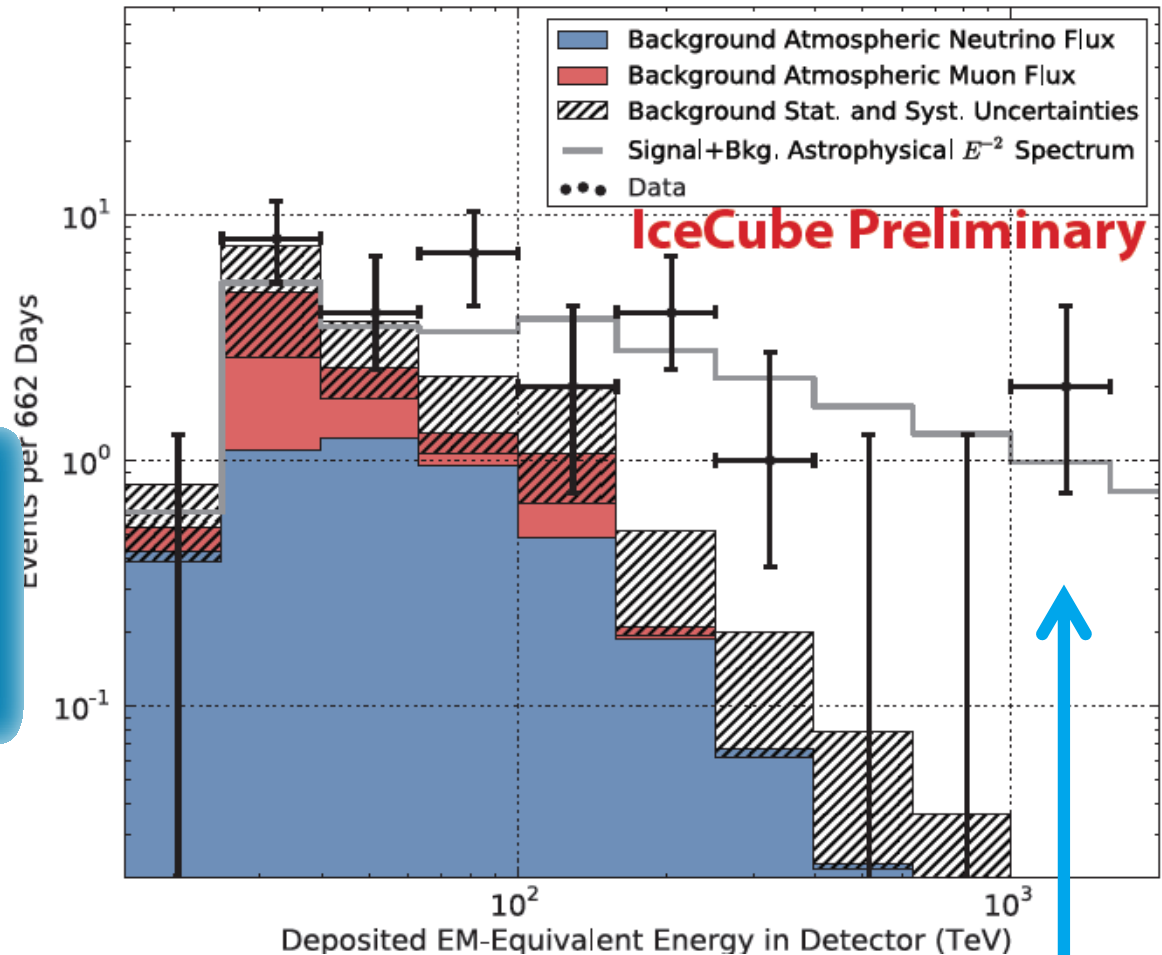
- Muon Veto
- $Q_{\text{tot}} > 6000$ photoelectrons
- 400 Mton eff. Volume
- Sensitive to all flavors above 60 TeV



HESE Results: Ernie & Bert + 26 additional events

- Significance of all 28 events: 4.1σ
- Background $10.6^{+5.0}_{-3.6}$

Results are consistent with previous analyses

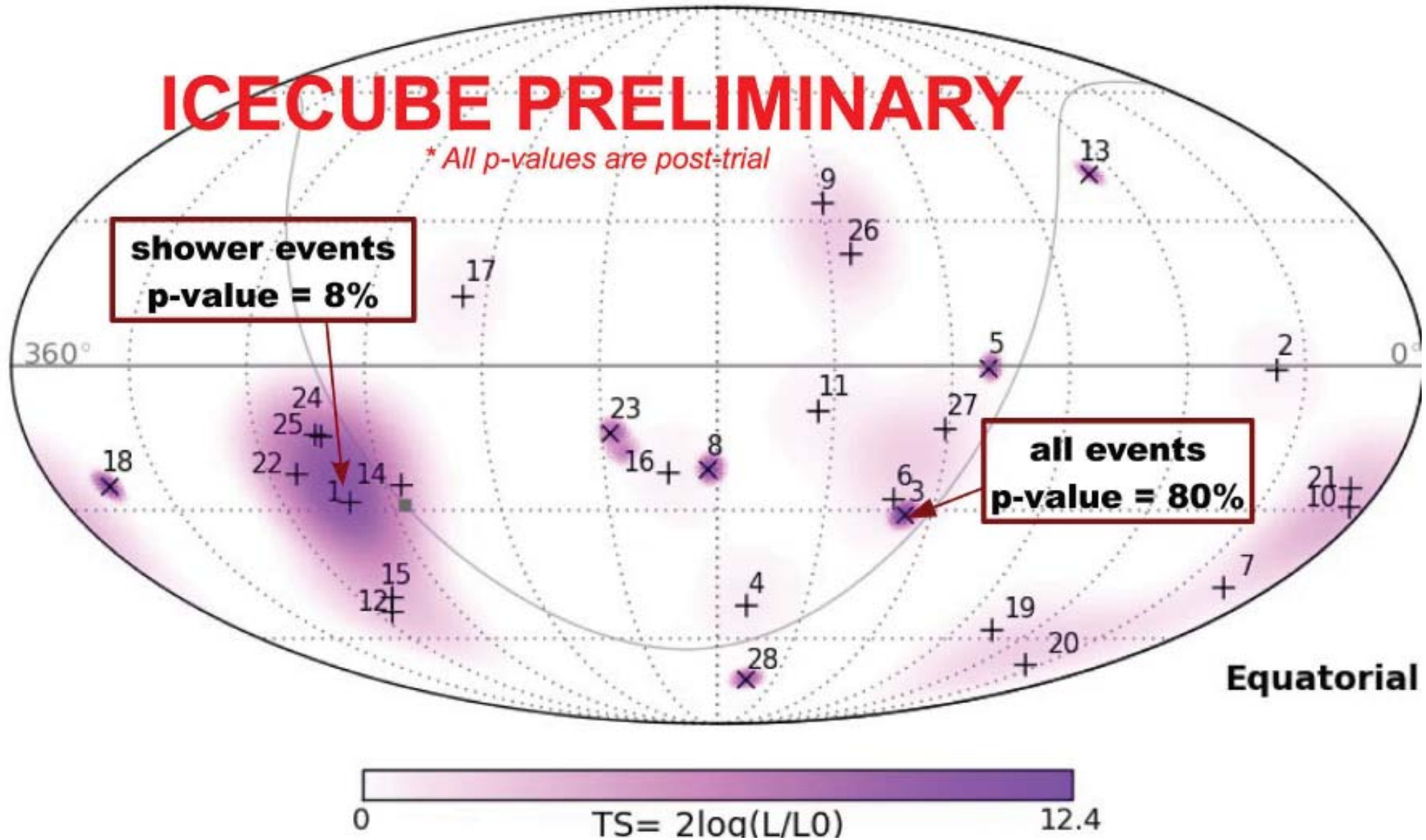


- Best fit for E^{-2} spectrum:
 $E^2\Phi = 4.8 \times 10^{-8} \text{ GeV cm}^2 \text{ s}^{-1} \text{ sr}^{-1}$
- Cut-off at 1.5-2 PeV

Ernie and Bert

HESE Skyplot:

Nothing significant !!!



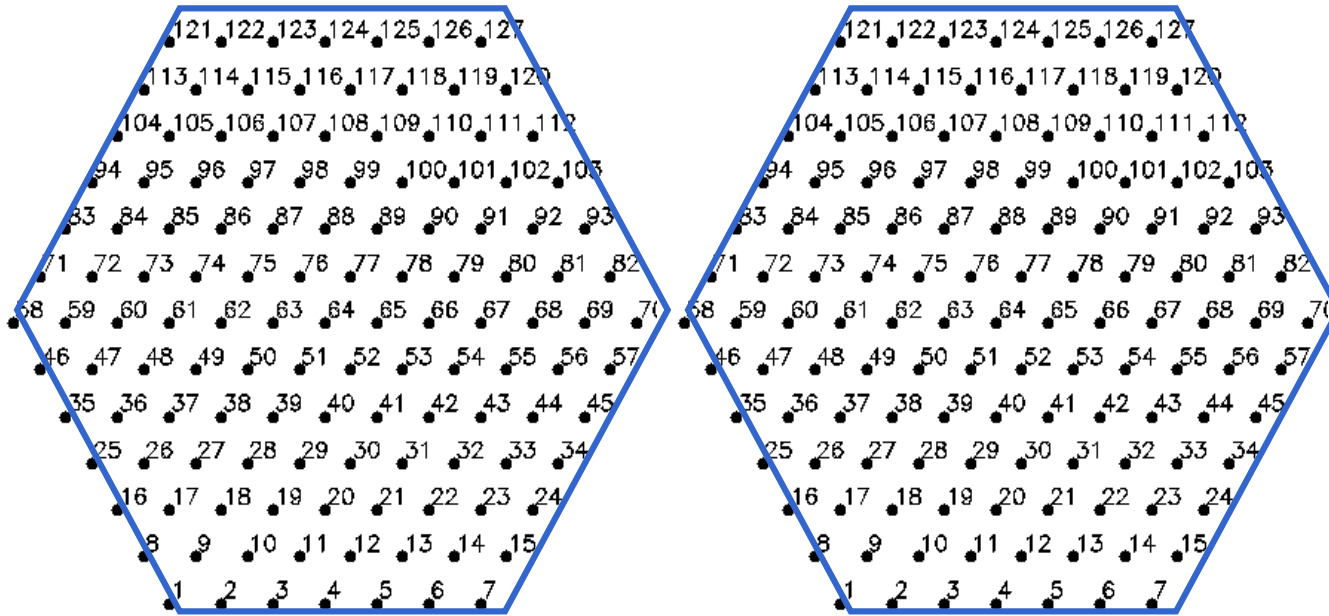
Looking Ahead

- One very high-energy event in the 10% „burn sample“ of 2012 data: BigBird
- Expect 2012 HESE results in fall 2013
- Also:
 - upgoing muon analysis IC79 (2010)
 - Cascade analysis IC79
 - Get the 5σ soon. But: do we understand systematic well enough?



THE FUTURE

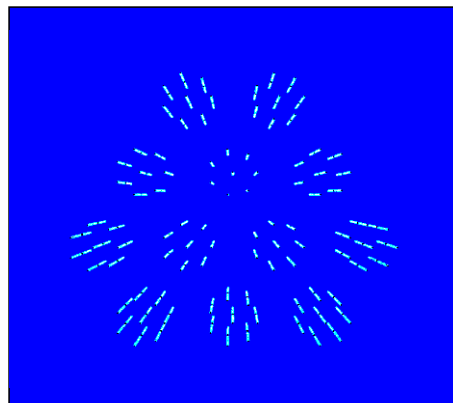
Water detectors



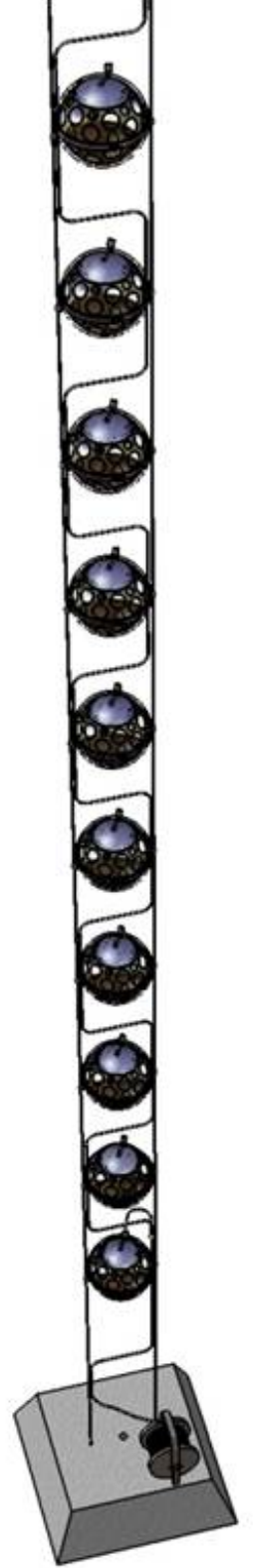
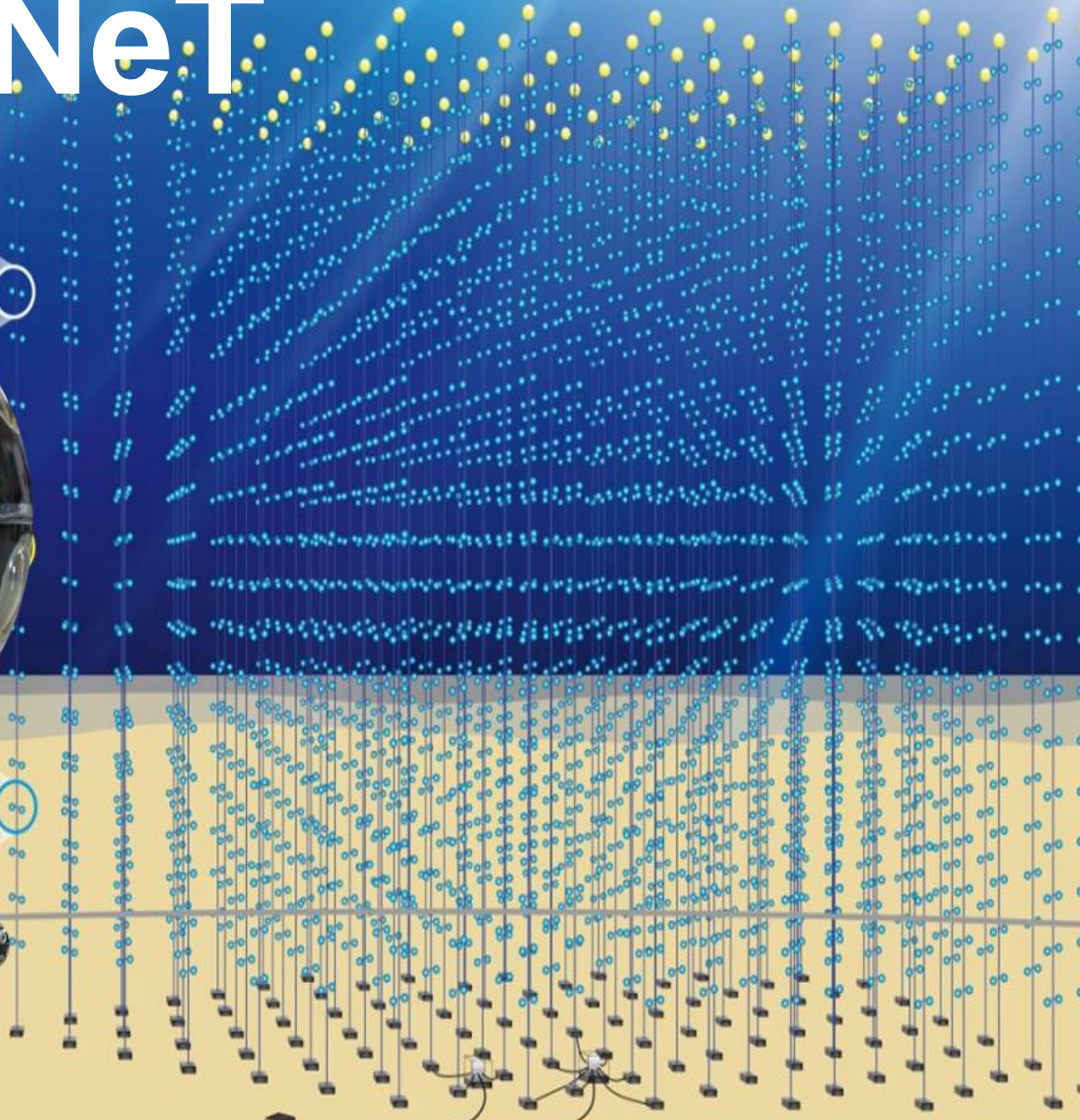
KM3NeT,
Mediterranean Sea,
several blocks à 1-2 km³
(altogether ~5 km³),
sensitive above 1 TeV

GVD, Lake Baikal, 0.5 km³ ... → 1.5 km³ ?

sensitive above 3 TeV



KM3NeT



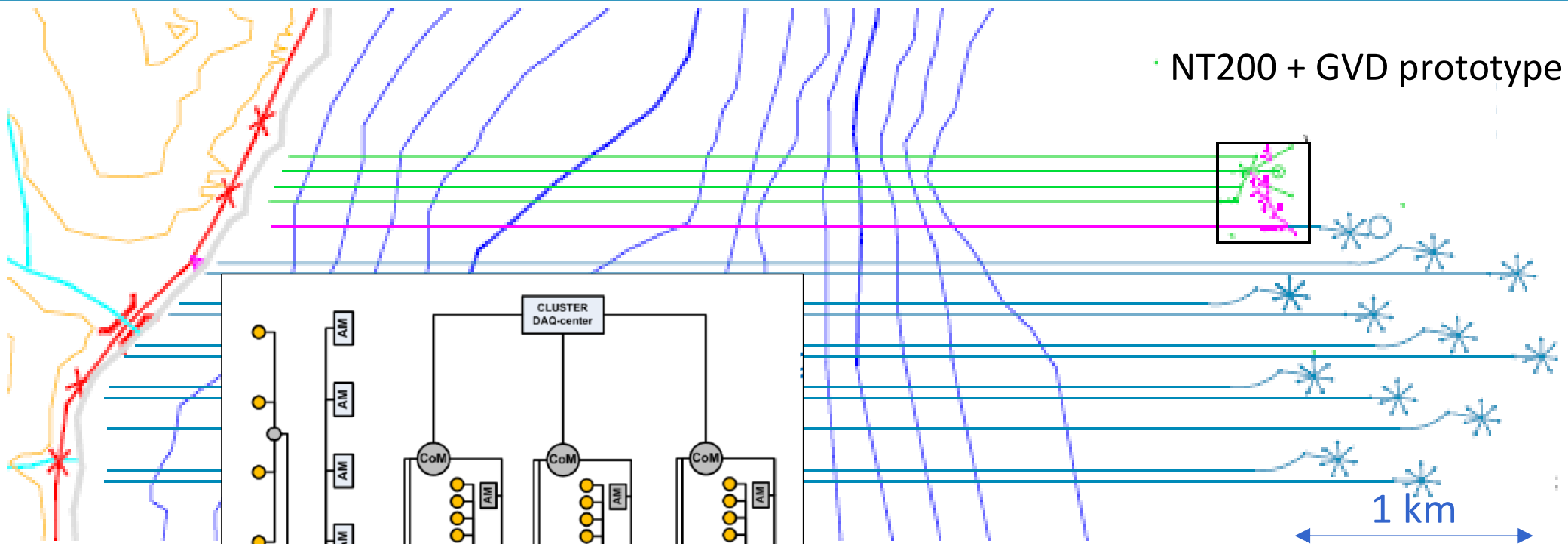
KM3NeT

Distributed infrastructure

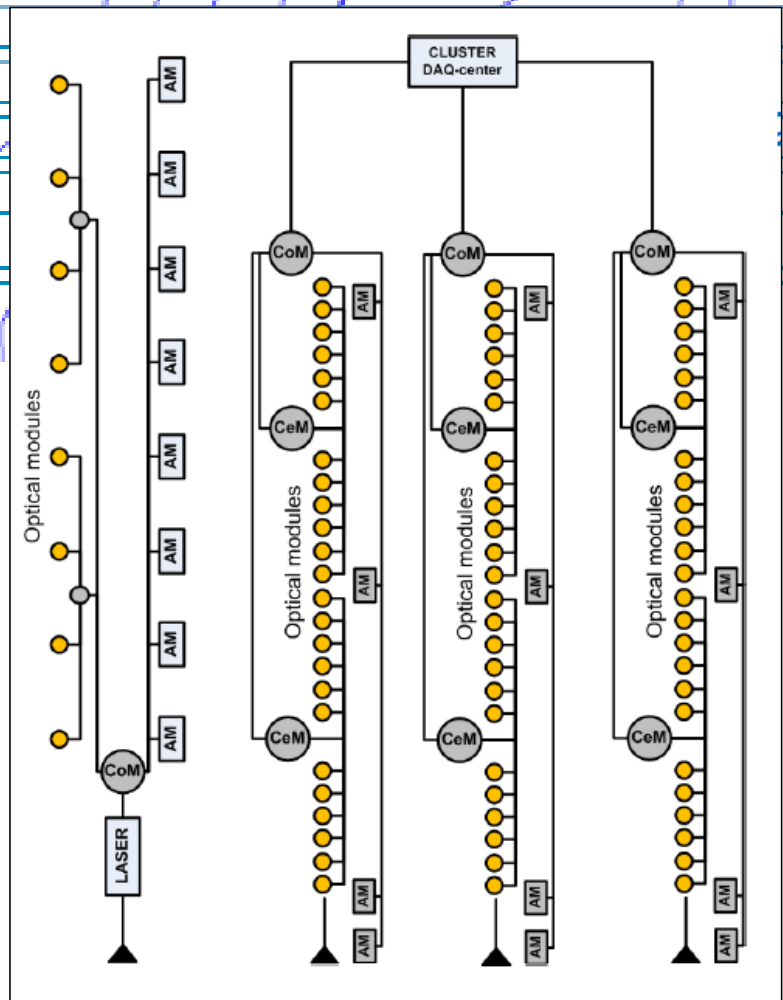
- KM3NeT-France (Toulon) ~2500m
- KM3NeT-Italy (Capo Passero) ~3400m
- KM3NeT-Greece (Pylos) ~4500m

**Until 2015: construction of
KM3NeT phase I detectors in France
and Italy (~40 M€)**

Gigaton Volume Detector (GVD) in Lake Baikal



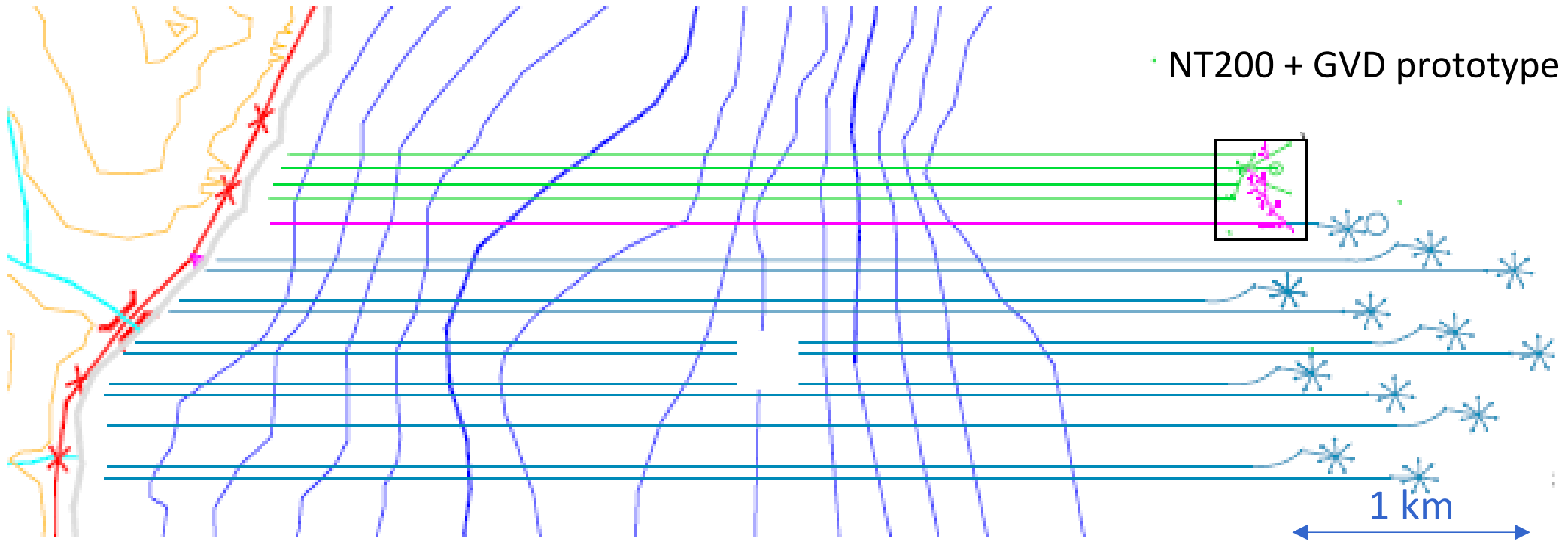
NT200 + GVD prototype



Engineering array April 2013

GVD

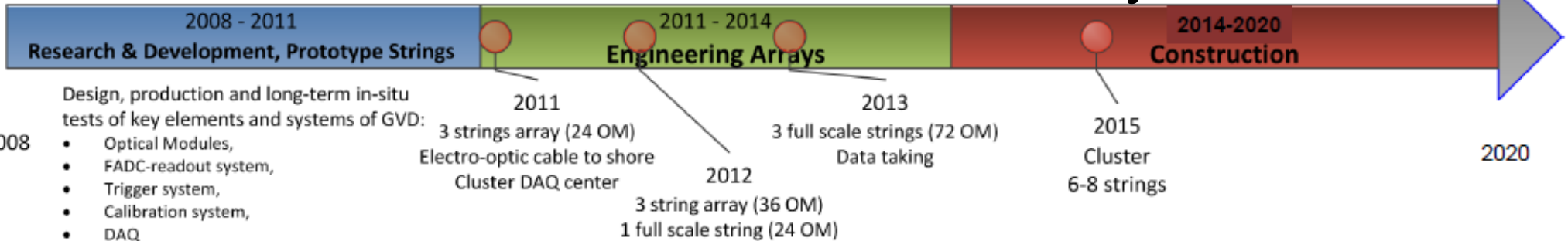
Gigaton Volume Detector (GVD) in Lake Baikal



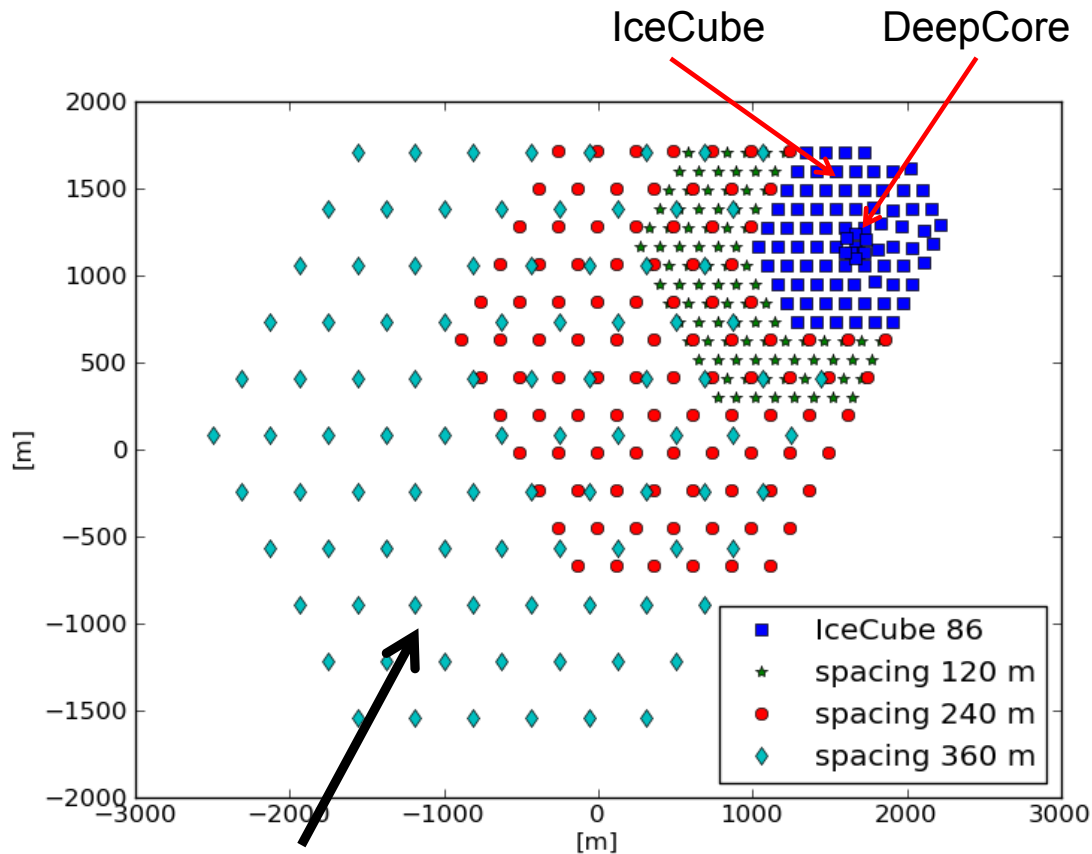
Project Timeline:

GVD

See talk of Zh. A. Djilkibaev

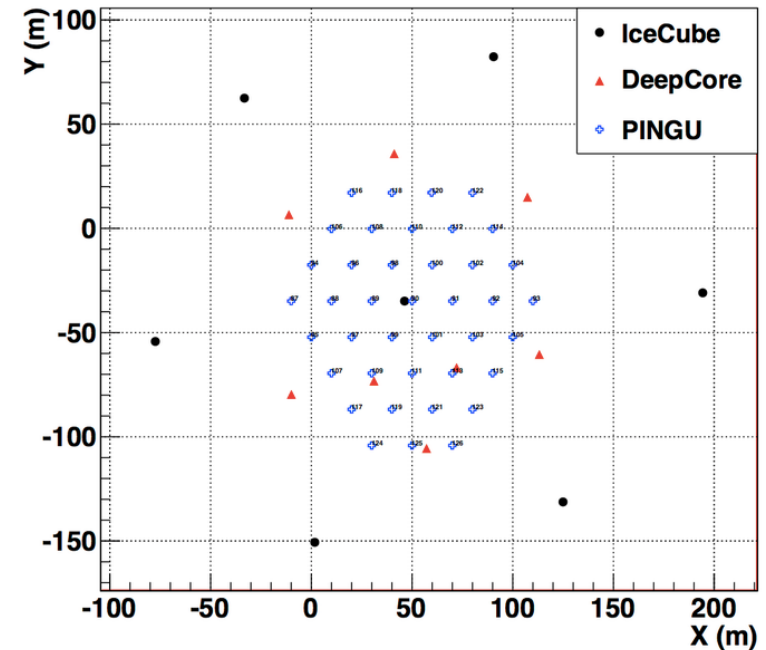


Options for IceCube Extensions



12,6 km³

Threshold for muons ~ 50 TeV,
gain eff. area for muons \sim factor 4,
gain for cascades \sim factor 10



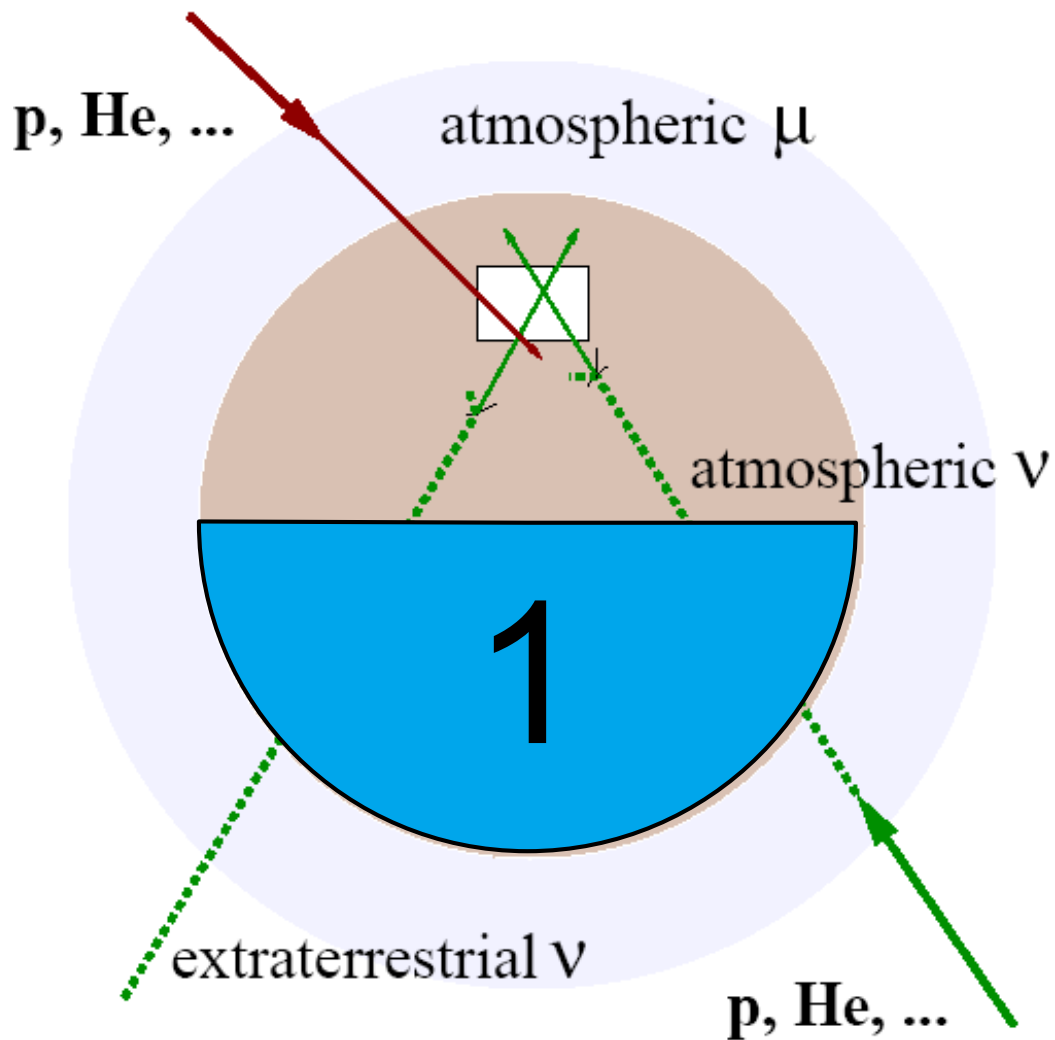
- **PINGU:**
low energy extension of DeepCore
- **Aim: Measure ν Mass Hierarchy**
- **Plan: deploy 2016/17 – 2019/20**
- **see talk of J. Brunner**

SUMMARY

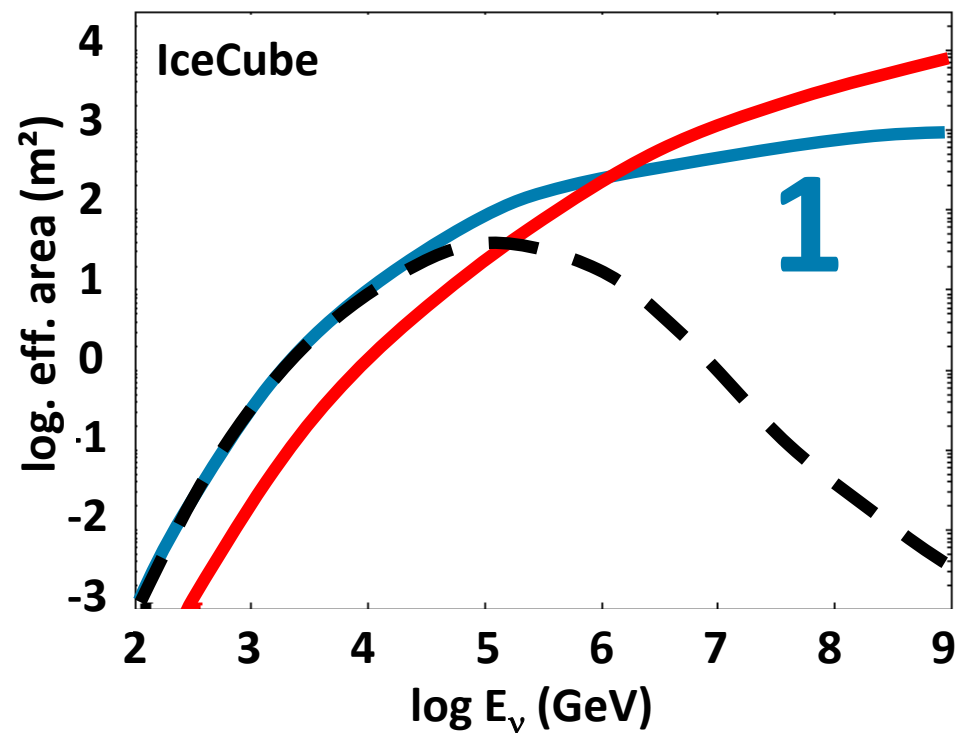
- Factor of 1000 improvement over last 12 years
- No indications of point sources yet
- Further factor 3 in sensitivity will bring us to the level of optimistic predictions for some SNR
- KM3NeT and GVD look to central part of the Galaxy and could eventually find point sources!
- Another option: IceCube++
- IceCube constrains models for GRB
- IceCube finds first strong indications for a diffuse flux of extraterrestrial high-energy neutrinos
- Light at the end of the tunnel or *Fata Morgana*?
- **The next months will give the answer!**

BACKUPS

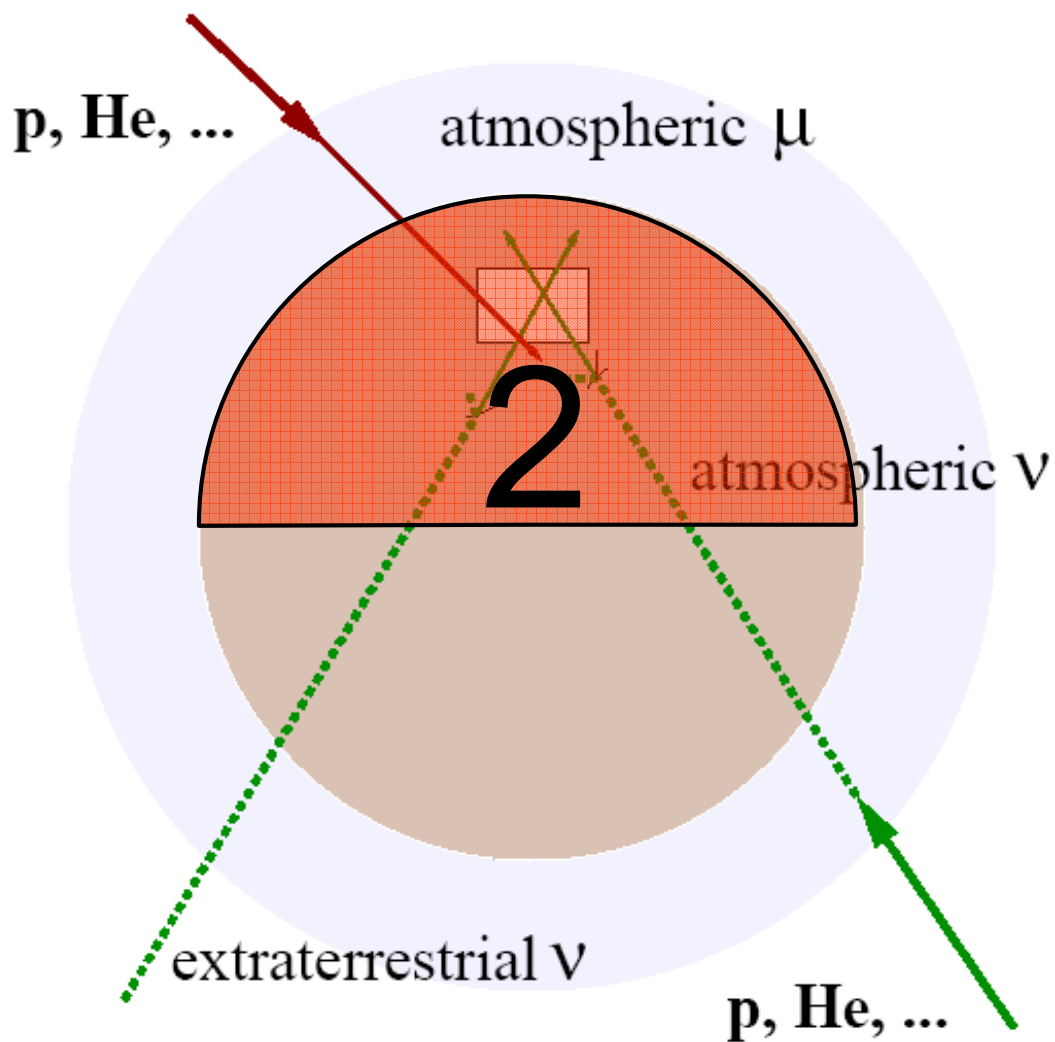
Effective Area



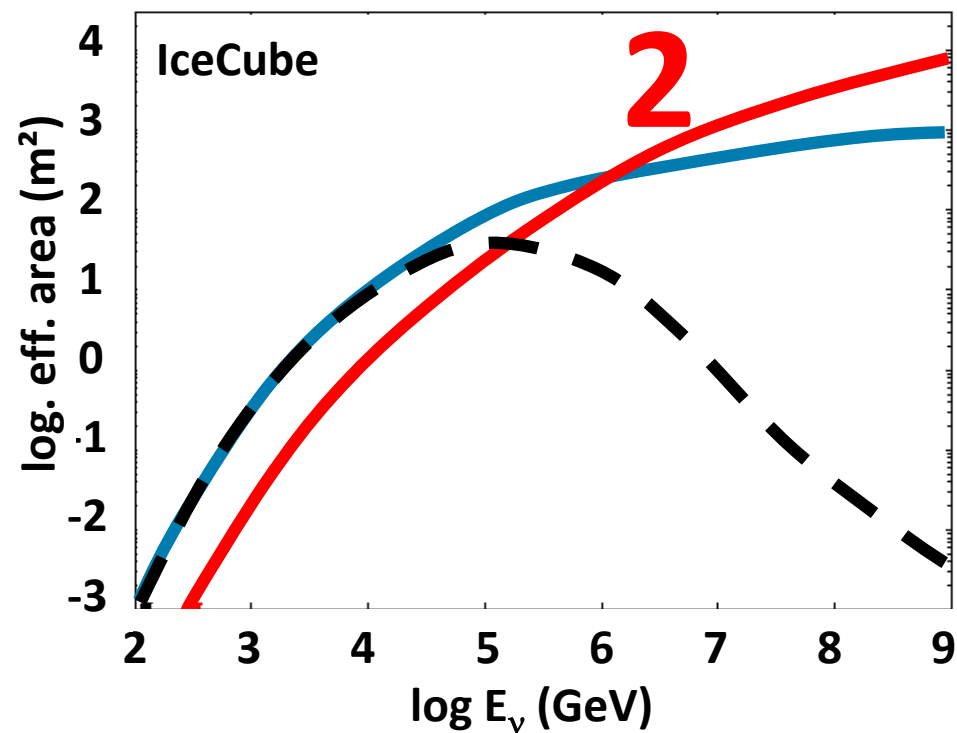
Effective area



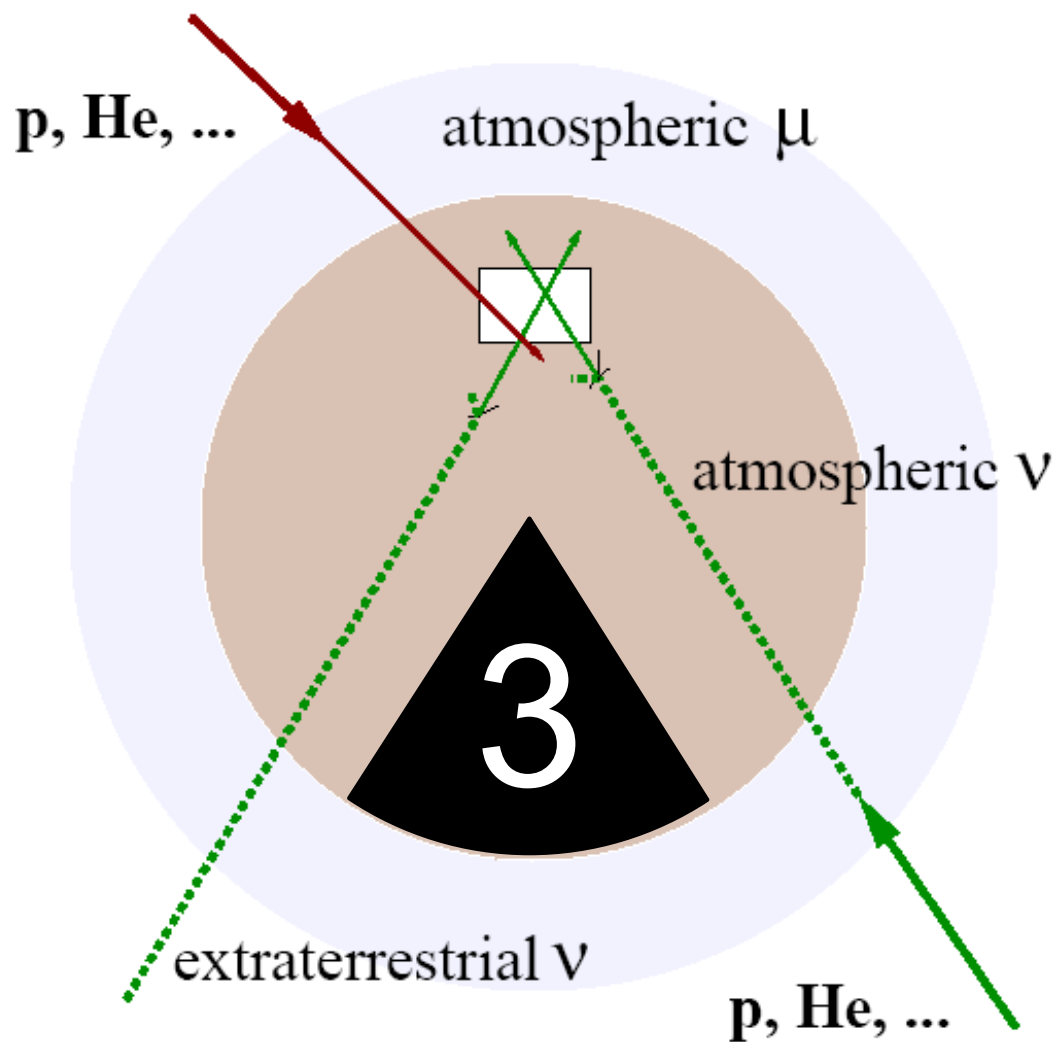
Effective Area



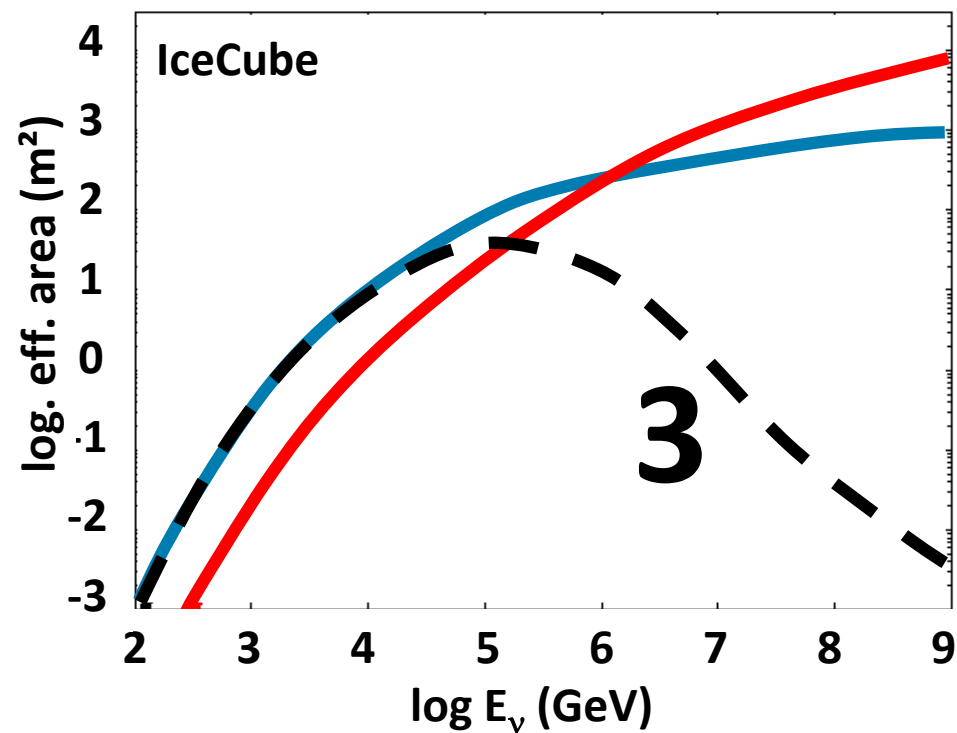
Effective area



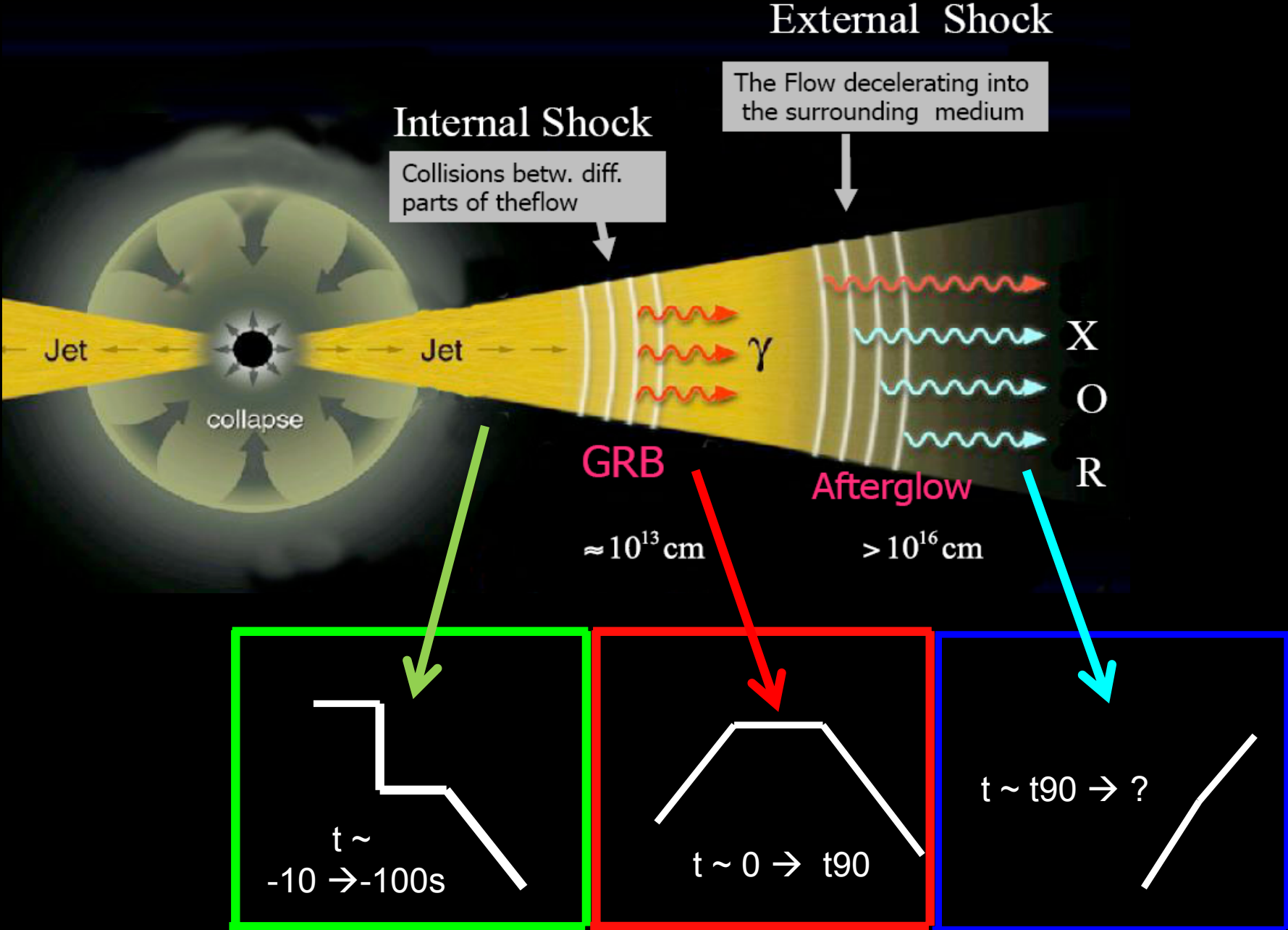
Effective Area



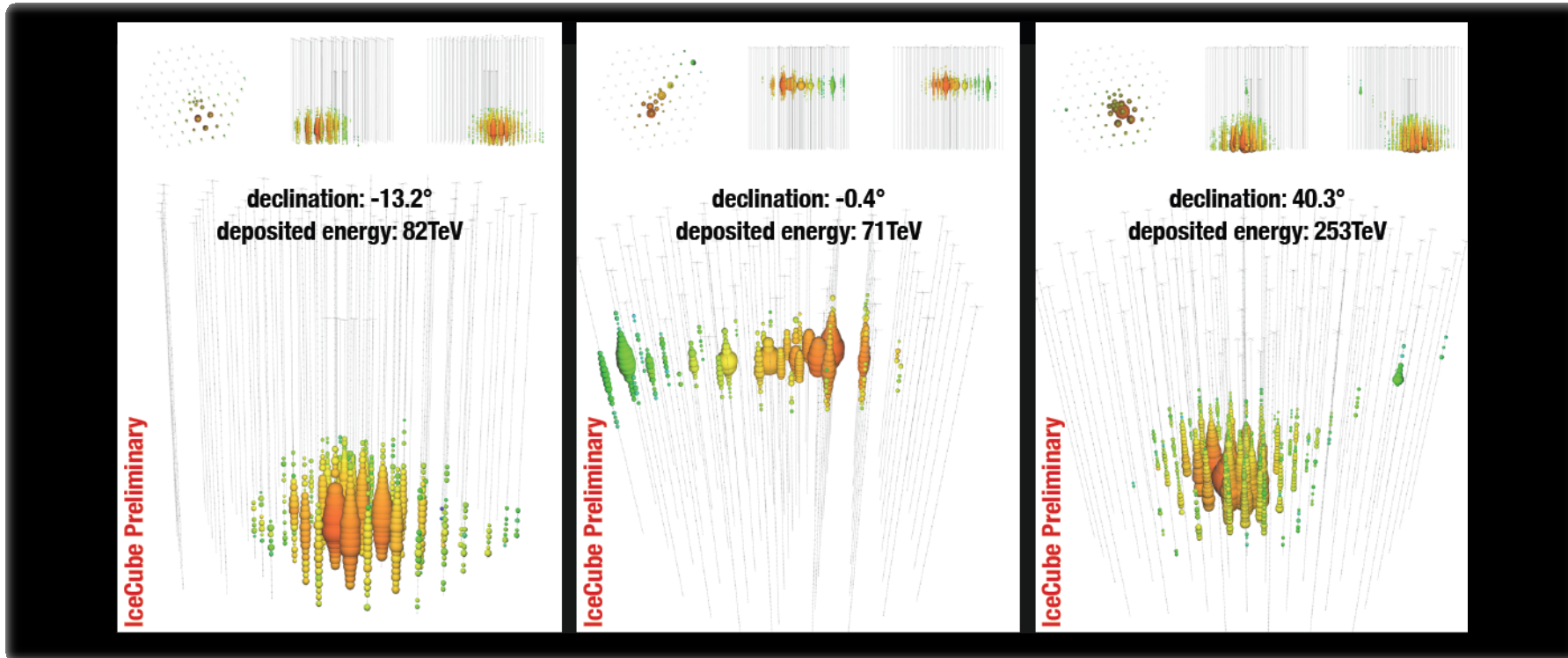
Effective area



Neutrinos from GRB

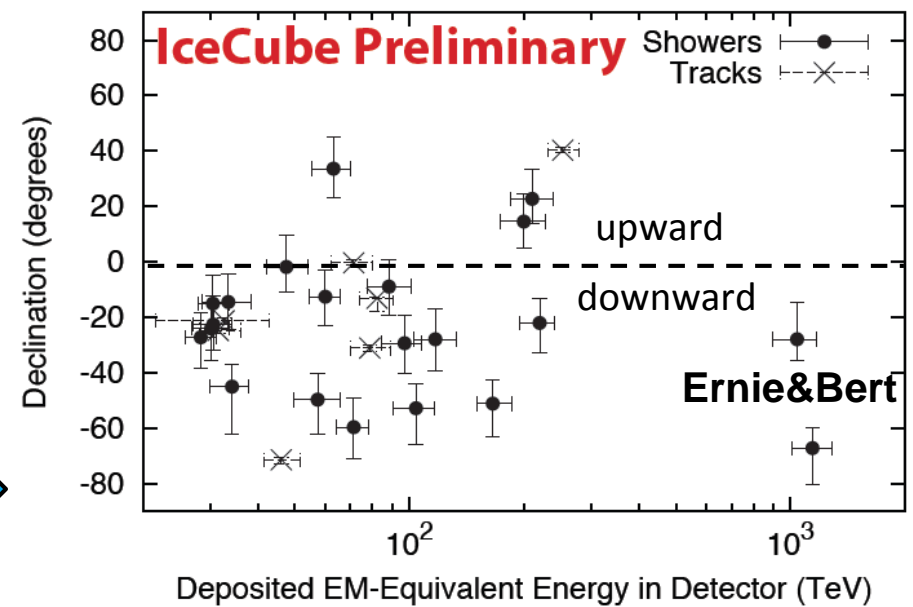


HESE results: 26 more events

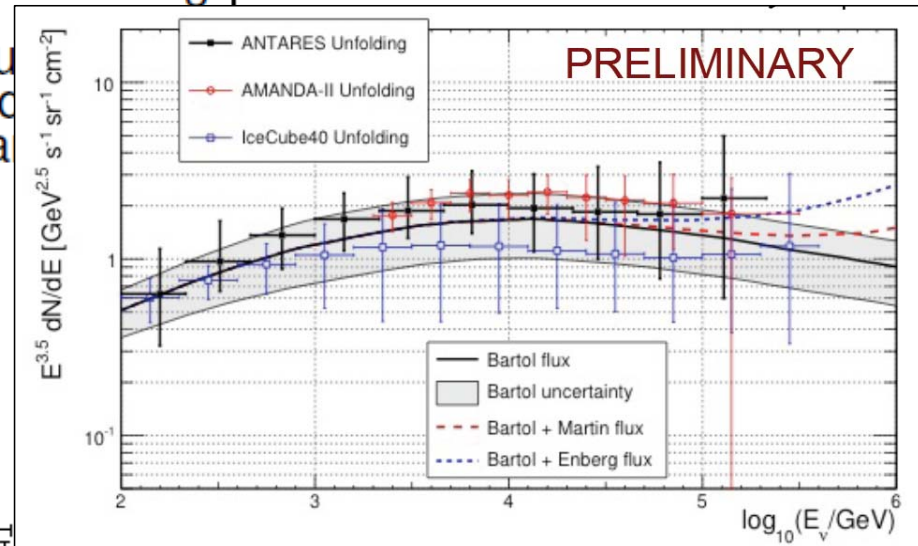
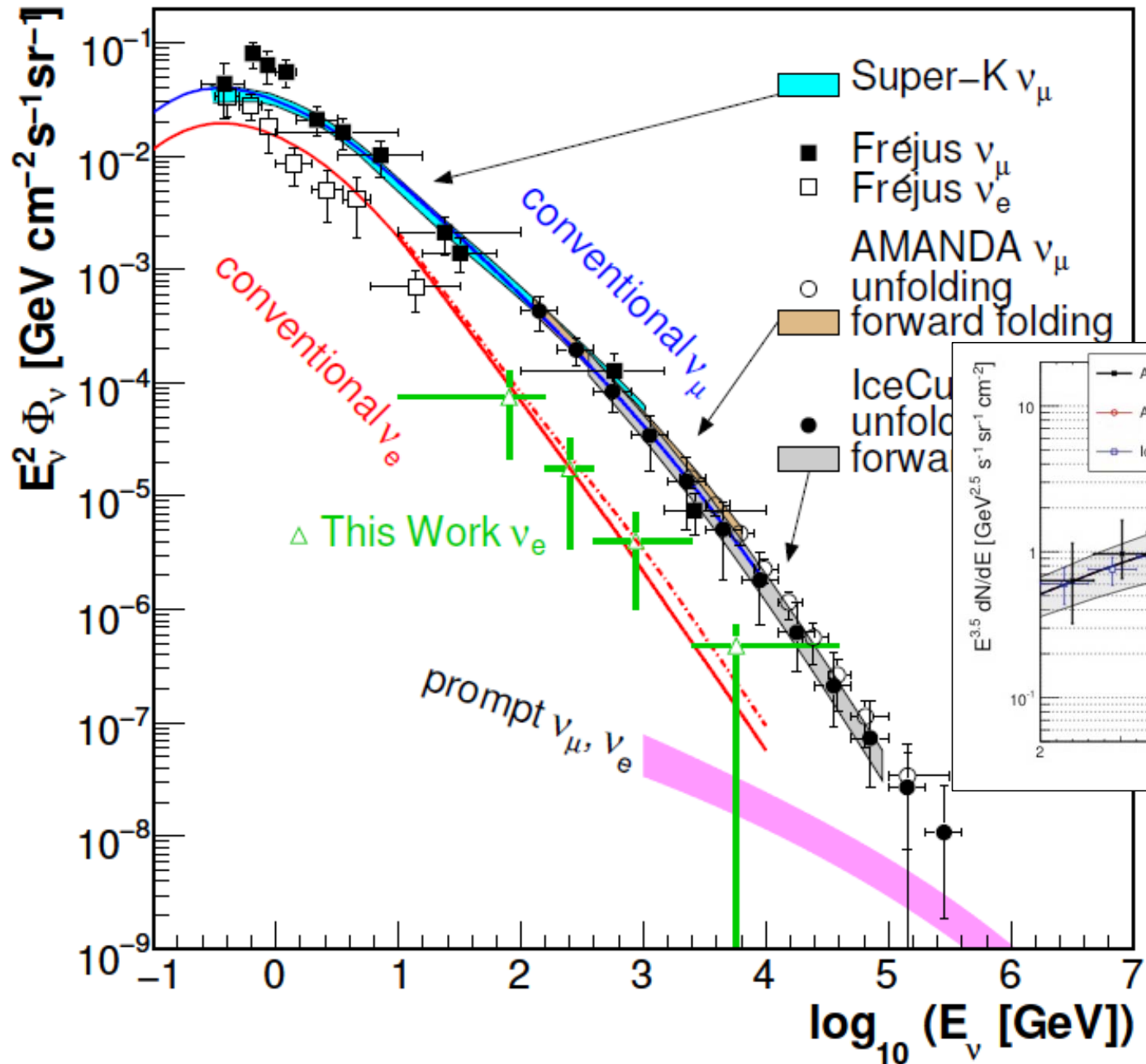


3 example events

Declination vs. deposited energy

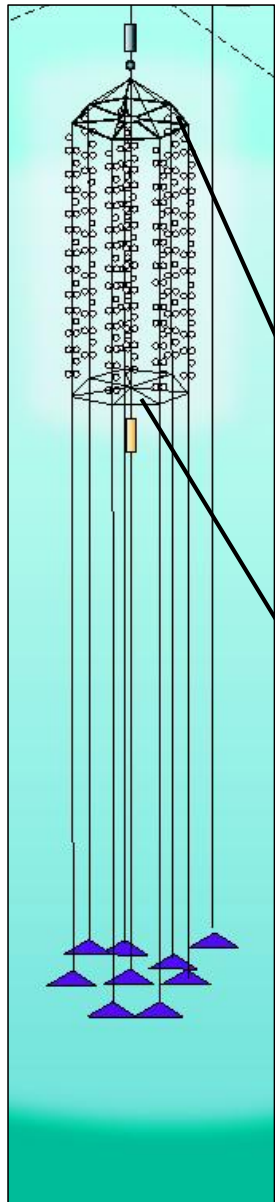


Atmospheric neutrinos: Charm component?



arXiv:1308.1599

Scales

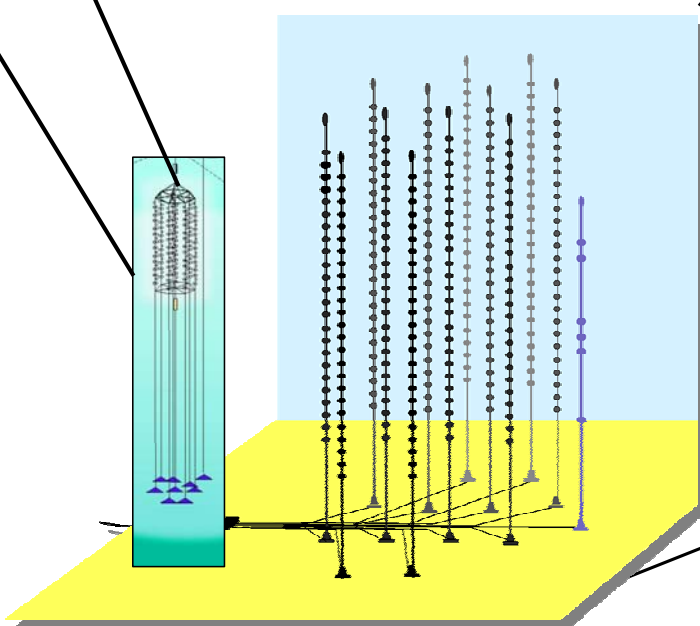


Baikal NT200

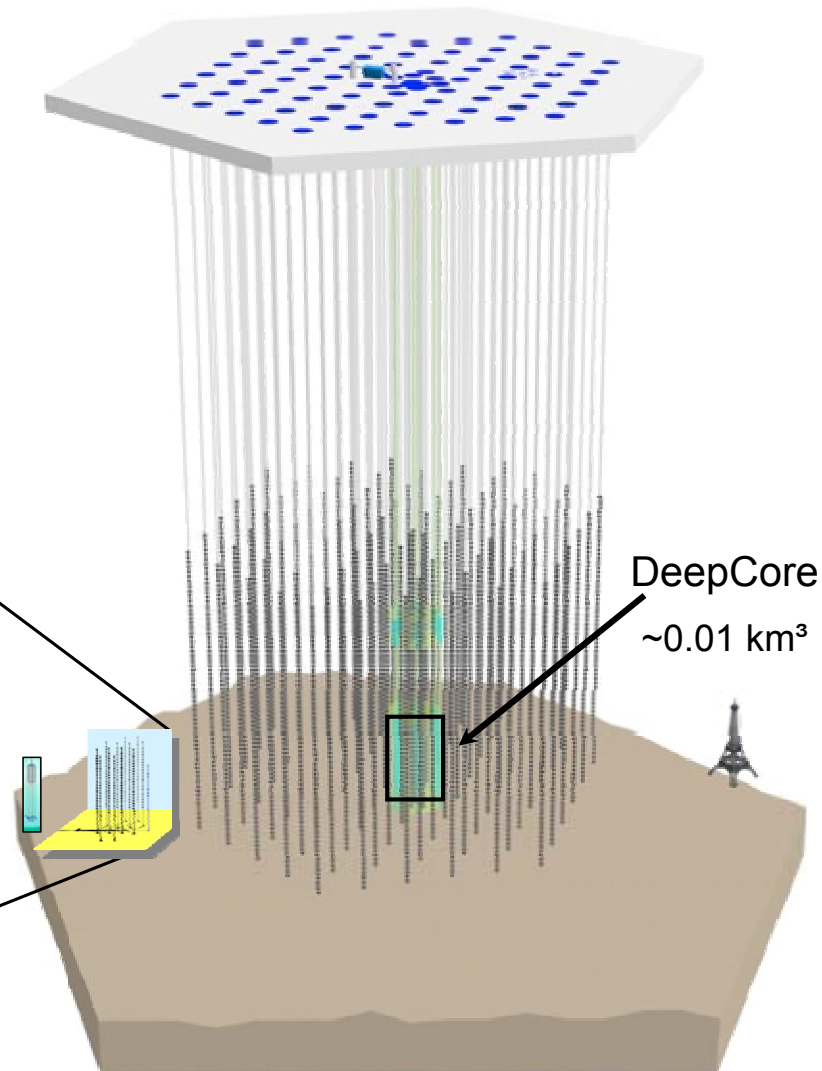
0.0001 km³

ANTARES

0.01 km³



IceCube 1 km³



DeepCore
~0.01 km³

Signal and Background

