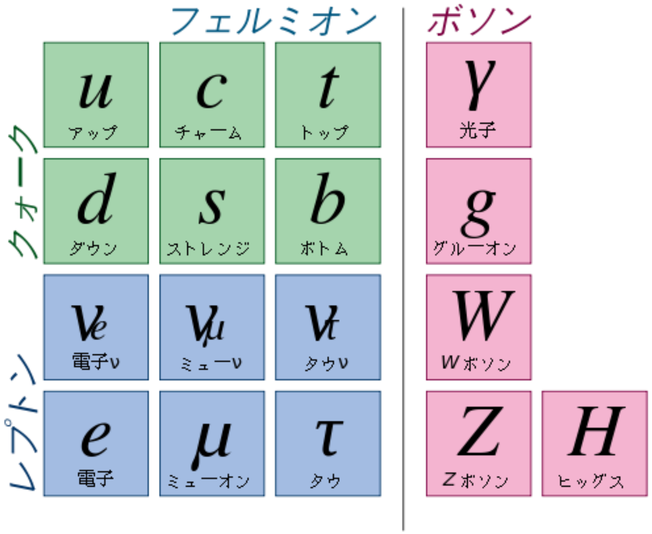
高エネルギーニュートリノ天文学の幕開け

千葉大学　間瀬圭一

■ ニュートリノって何？



素粒子の一つ。

β崩壊の課程で見つかった。

中性子 → 陽子 ＋ 電子

このままではエネルギー保存則が成り立たない！

$$E_n \neq E_p + E_e$$

Pauliの予言：中性子 → 陽子 ＋ 電子 ＋中性微子（1931年）

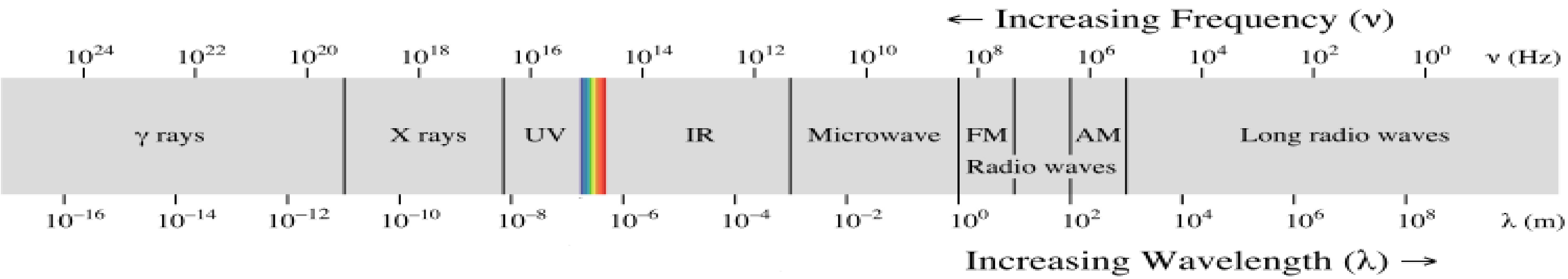
$$E_n = E_p + E_e + E_\nu$$

W. Pauli

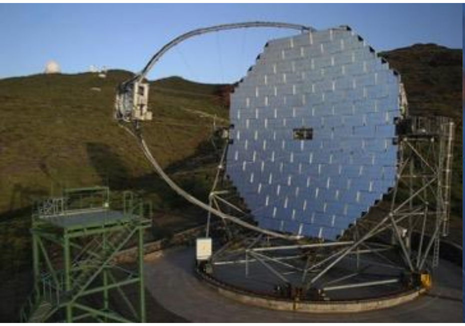
この中性微子がニュートリノ

ほとんど物質と相互作用しない。幽霊粒子。このため実験的に確かめられたのは1950年代。

■ 宇宙を見る目（光）

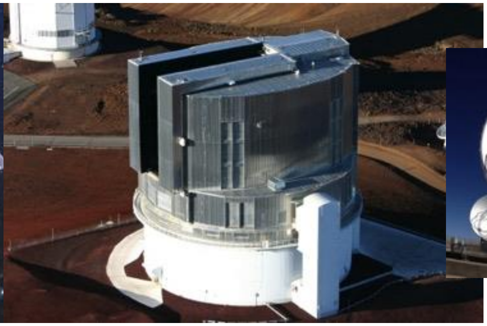


MAGIC望遠鏡



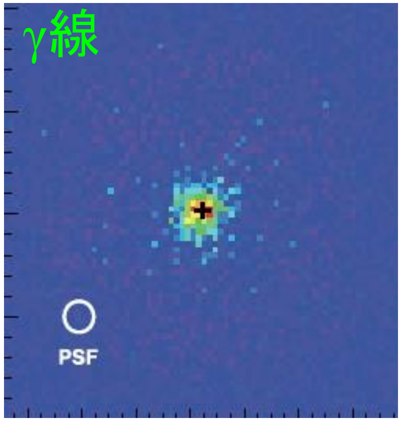
すざく衛星

すばる望遠鏡



ALMA望遠鏡

かに星雲



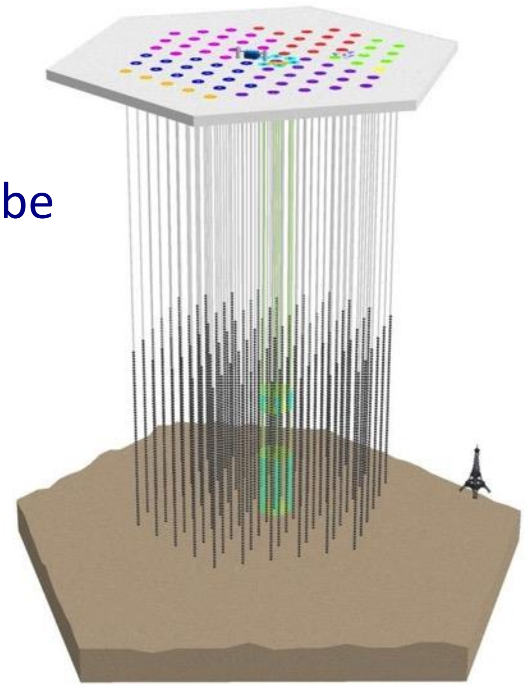
■ 宇宙を見る目(光以外)

- ✓ **ニュートリノ**
  - ✓ 弱い相互作用しかしないレプトン
  - ✓ 深宇宙からも届く

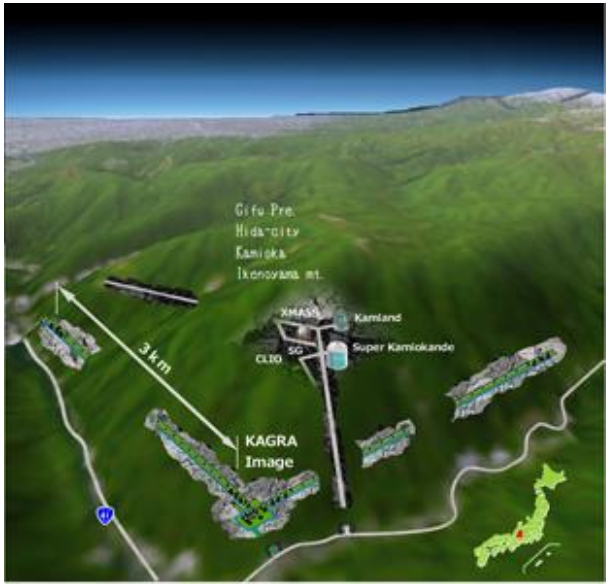
- ✓ **重力波**
  - ✓ 時空の歪みから発せられる波動

光以外の媒質を使うことで異なる物理現象を
調べることができる

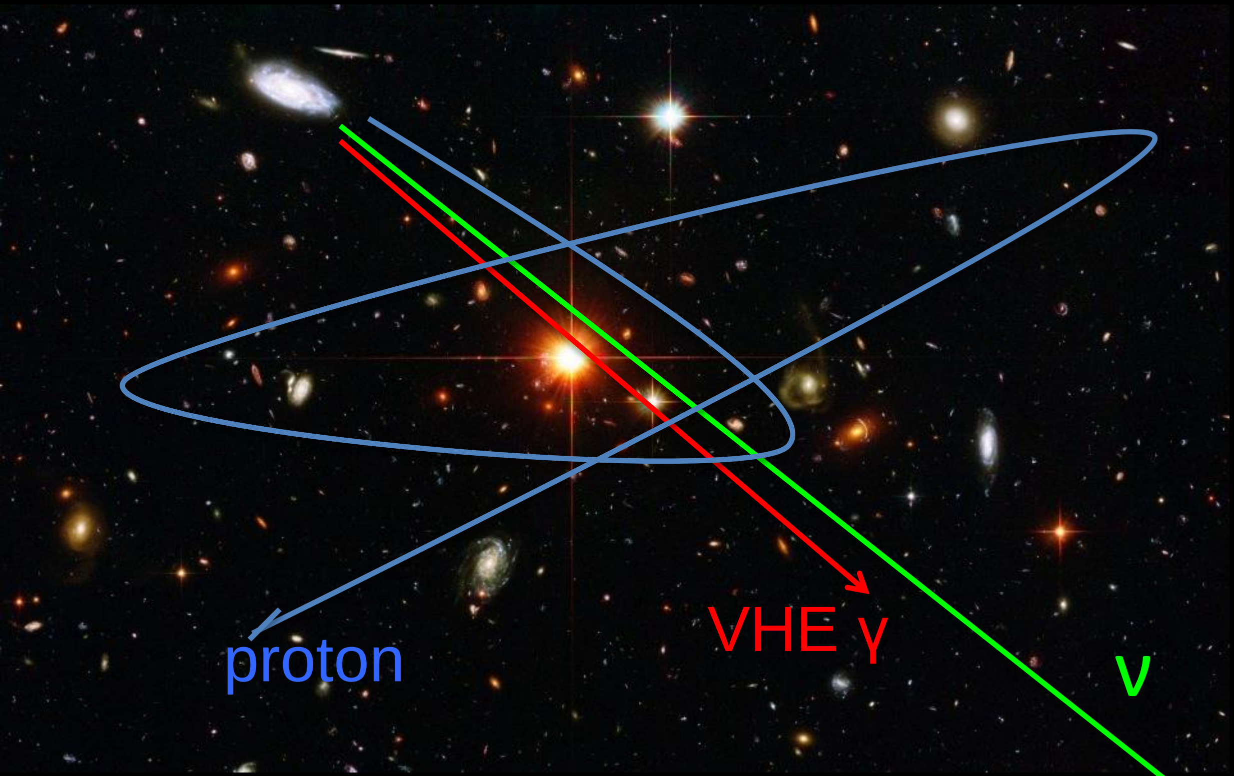
IceCube



KAGRA



■ Why neutrinos?



Neutrinos are rarely interacting particles

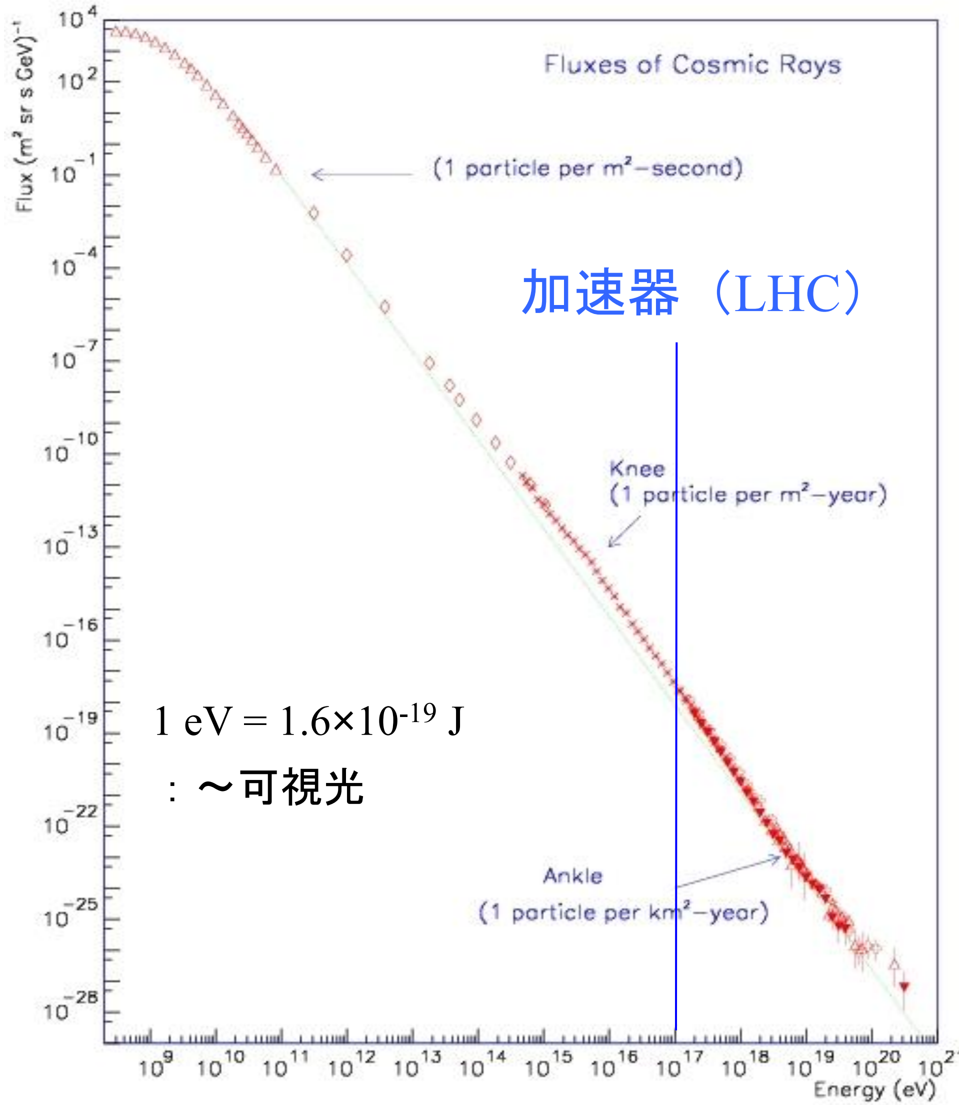
→ Deep Universe or/and inside objects

Produced through hadronic interactions

→ Cosmic ray origin

宇宙線

- 宇宙からの放射線の総称。現在では宇宙からの高エネルギー粒子の総称。（1912年発見）
- 10^9 eVから10^{20} eVまで幅広いエネルギースペクトラム
- 非常にありふれた粒子。我々の体を一秒間に数十発貫通。（二次宇宙線）
- 天体中で加速。
- 超高エネルギー（$>10^{18}$ eV）の起源は良く分かっていない。



Multi messengers

Neutrino production is closely related to production of **cosmic rays** and **gamma rays**

$$p + p\,(\gamma) \rightarrow \pi^{\pm} / \pi^{0} + anything$$

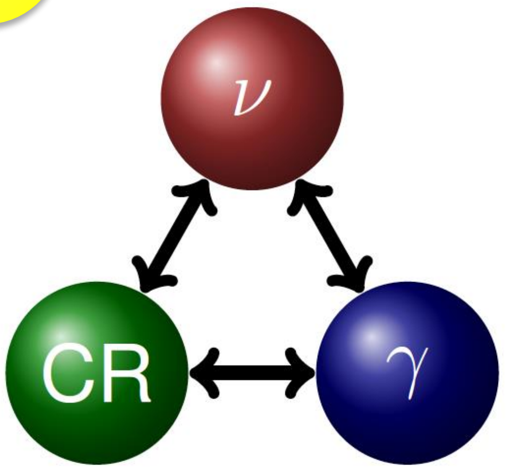
$$\pi^{+} \rightarrow \mu^{+} \nu_{\mu}$$

$$\mu^{+} \rightarrow e^{+} \nu_{e} \bar{\nu}_{\mu} \qquad E_{\nu_{\mu}} \approx E_{\nu_{e}} \approx E_{\bar{\nu}_{\mu}}$$

$$\pi^{0} \rightarrow 2\gamma$$

$$E_{\nu} \approx \frac{1}{20} E_{p} \qquad \Leftarrow \; E_{\pi} \approx \frac{1}{5} E_{p},\; E_{\nu} \approx \frac{1}{4} E_{\pi}$$

$$E_{\nu} \approx E_{\gamma}$$



©M. Ahlers

Neutrinos should be generated

The source of cosmic rays will be the neutrino source.

$$p + p(\gamma) \rightarrow \pi^{+} + anything \rightarrow \mu + \nu_{\mu}$$

Waxman-Bahcall limit

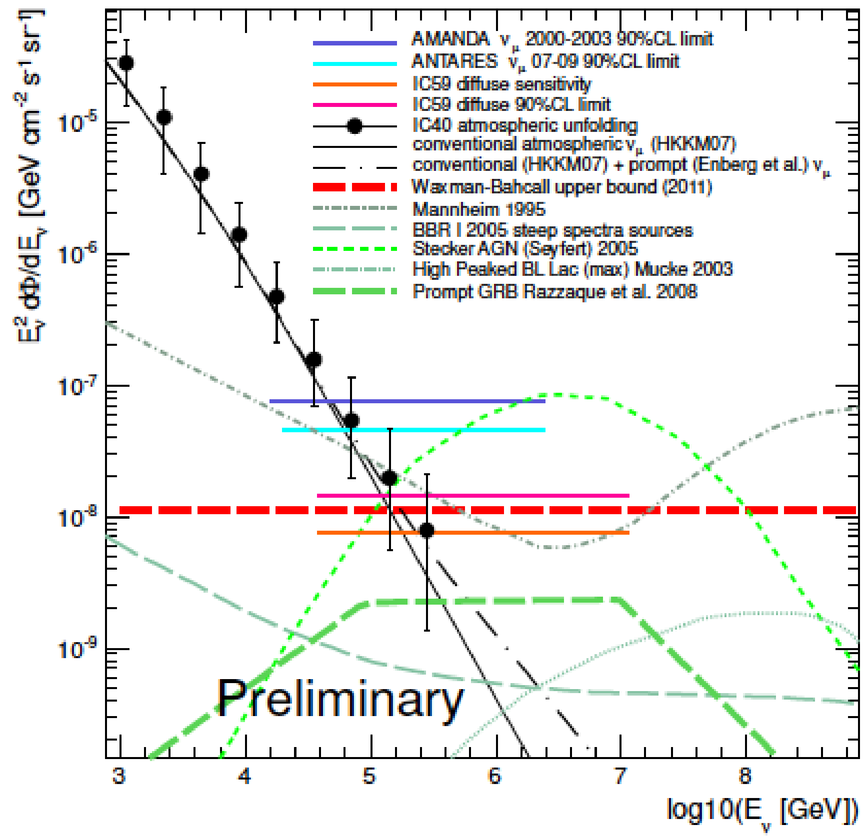
$$E_{\nu}^{2}\Phi_{\nu_{\mu}} = \frac{\varepsilon}{8}\xi_{Z} t_{H} \frac{c}{4\pi} E_{CR}^{2} \frac{d\dot{N}_{CR}}{dE_{CR}}$$

ε: fraction of energy going to neutrinos

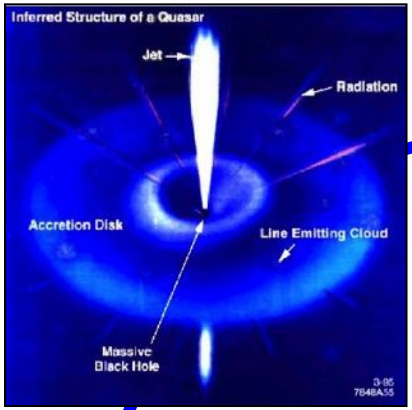
If ε=1, WB limit

$$E^{2}f = 10^{-8}\ GeV\, cm^{-2} s^{-1} sr^{-1}$$

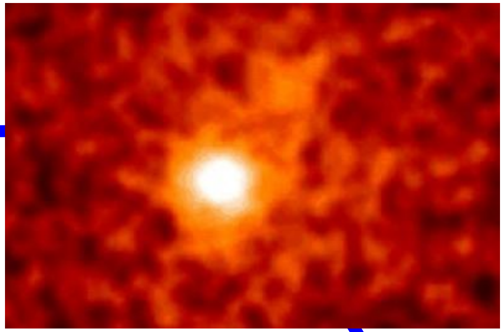
The sensitivity of 1 km^3 size detector is lower than WB limit.



■ Exploring the universe with neutrinos

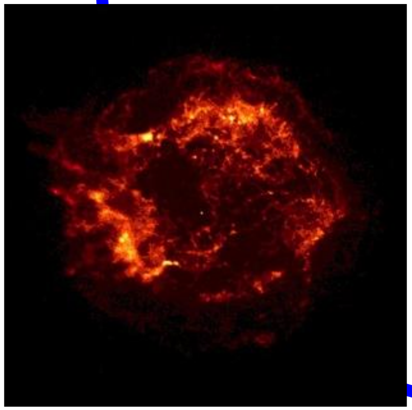


n AGNs

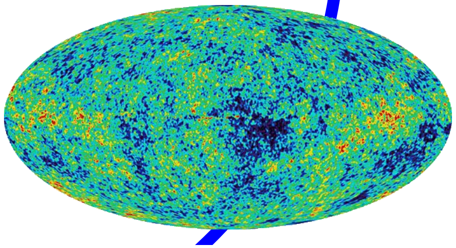


n GRBs

n Cosmic ray origin



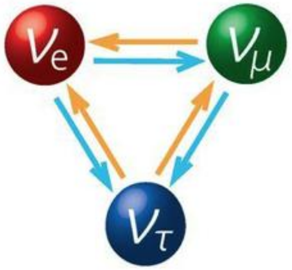
n Supernova



n Cosmogenic neutrinos

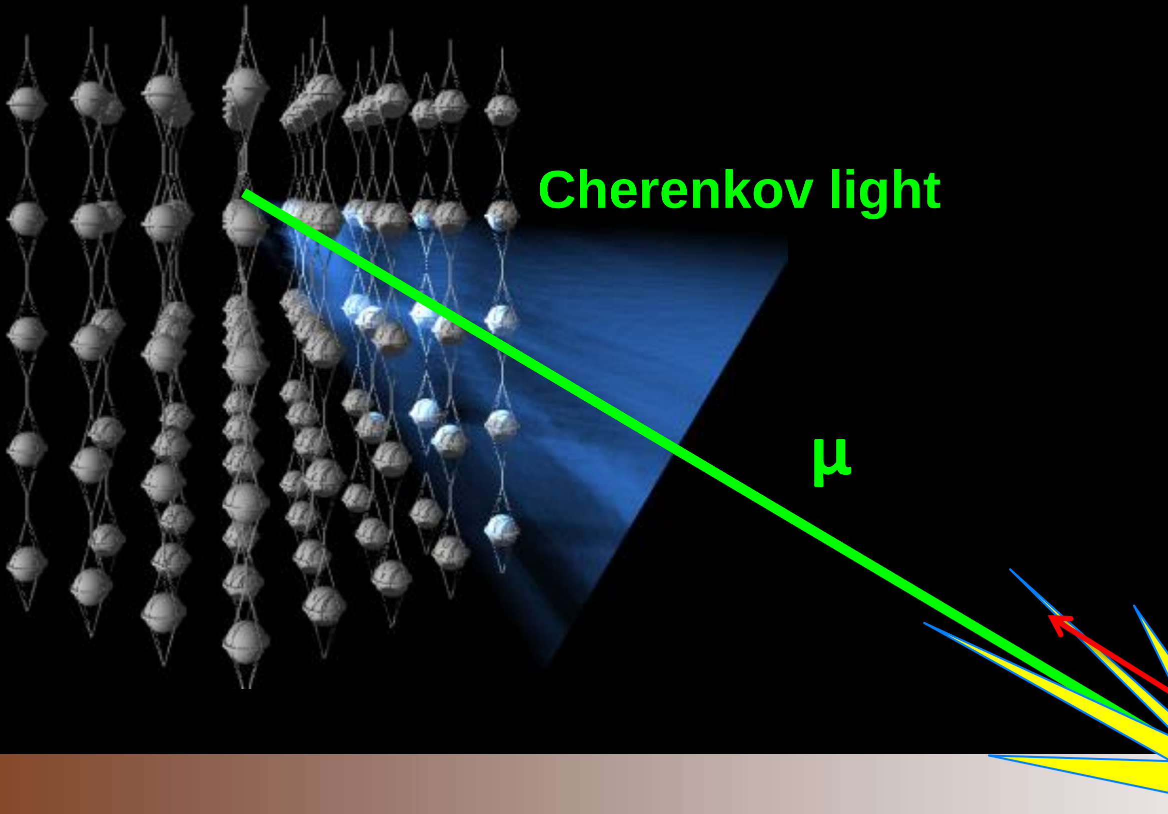
n Dark Matter

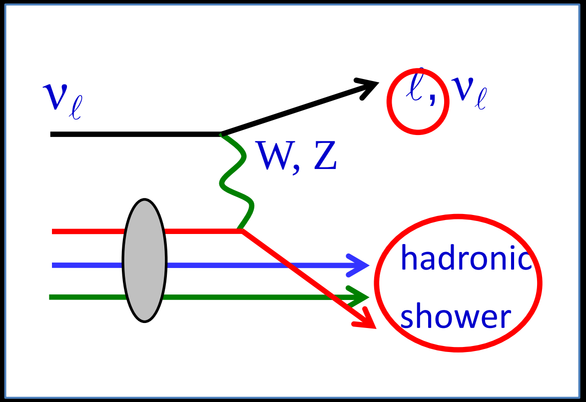
n Particle physics



n Neutrino oscillation

How do we detect neutrinos?

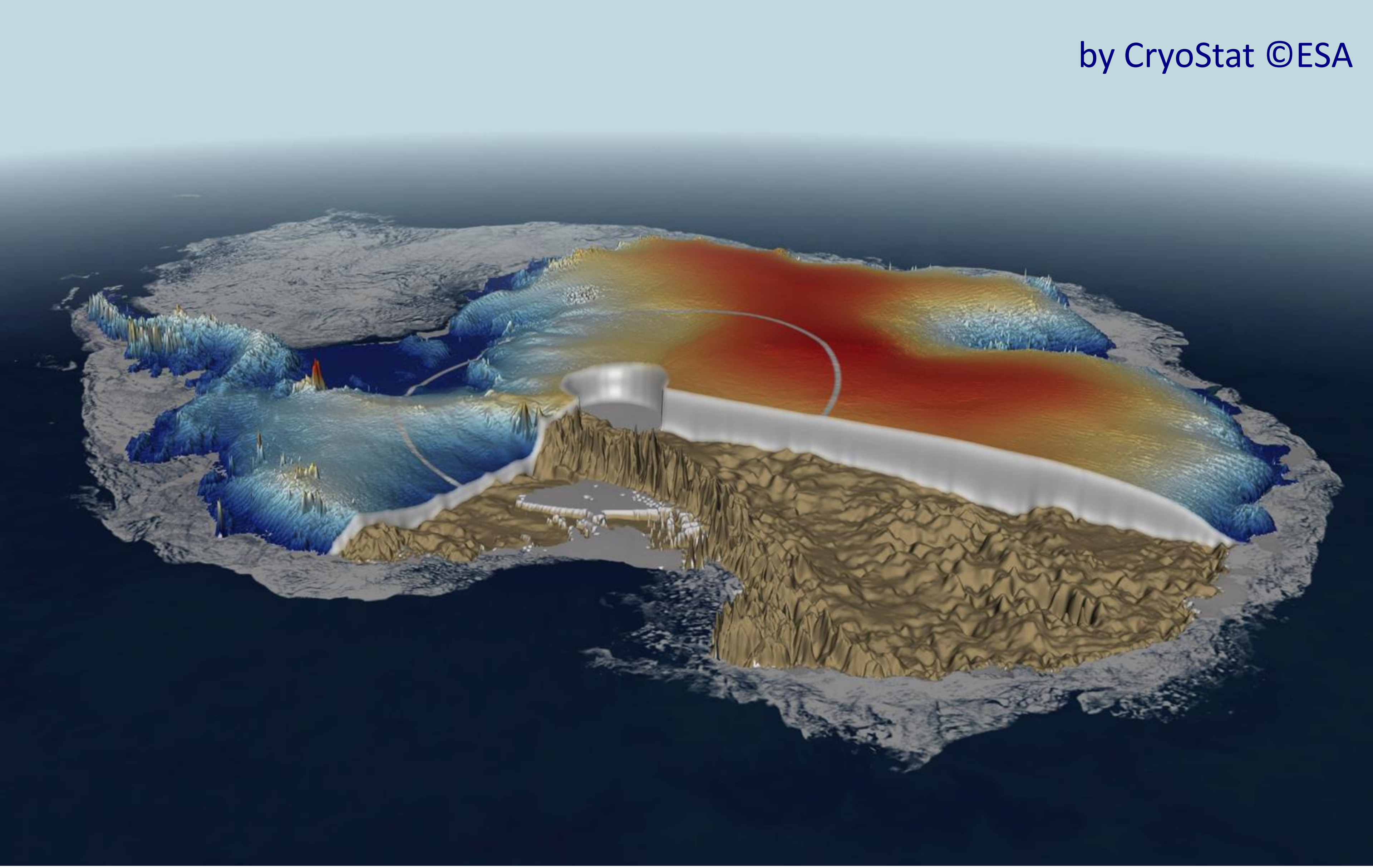




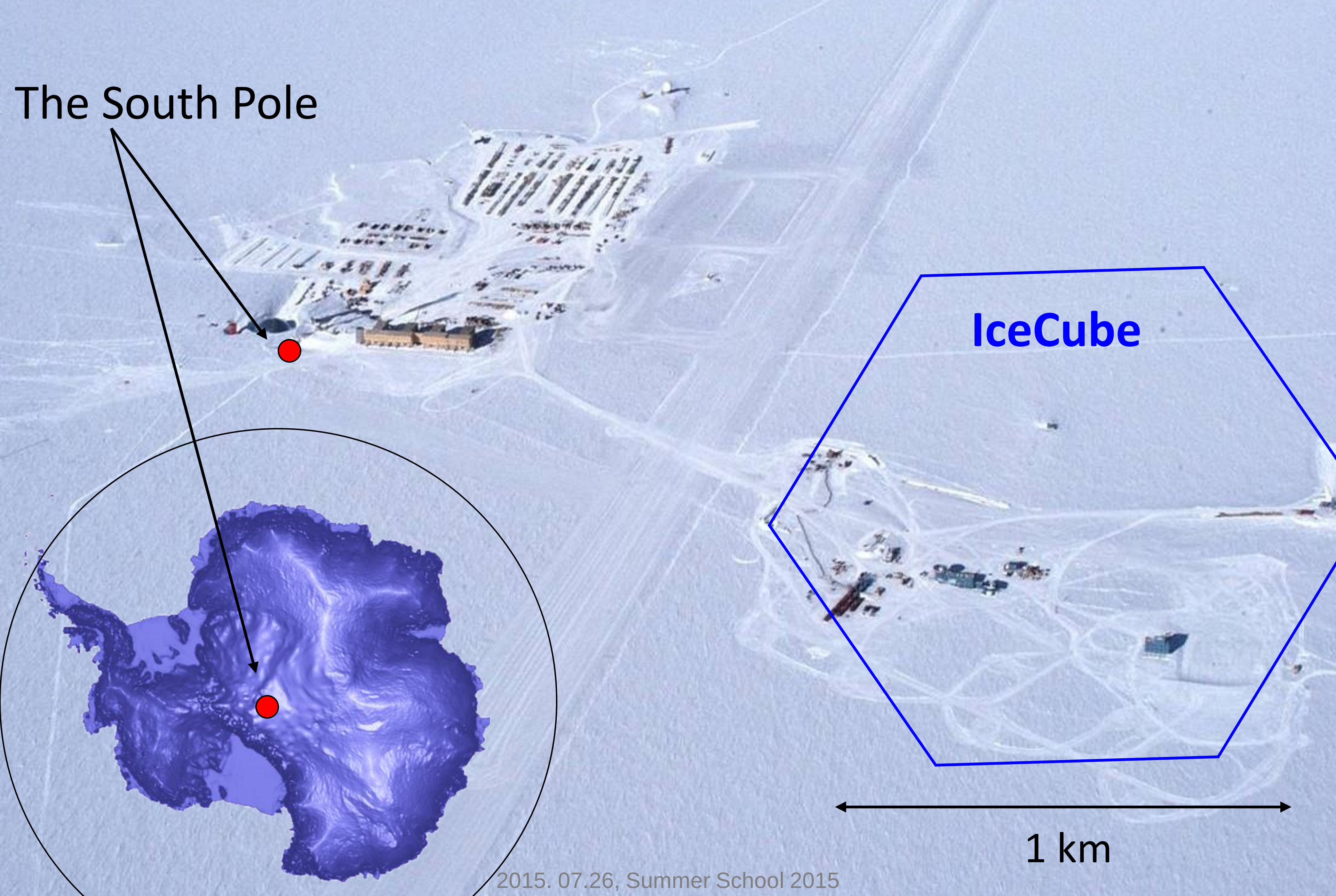
- Large volume for neutrinos to interact
- Transparent medium for light to propagate to photo-sensors

→ **Antarctica ice**

■ Part of our detector: Antarctica ice

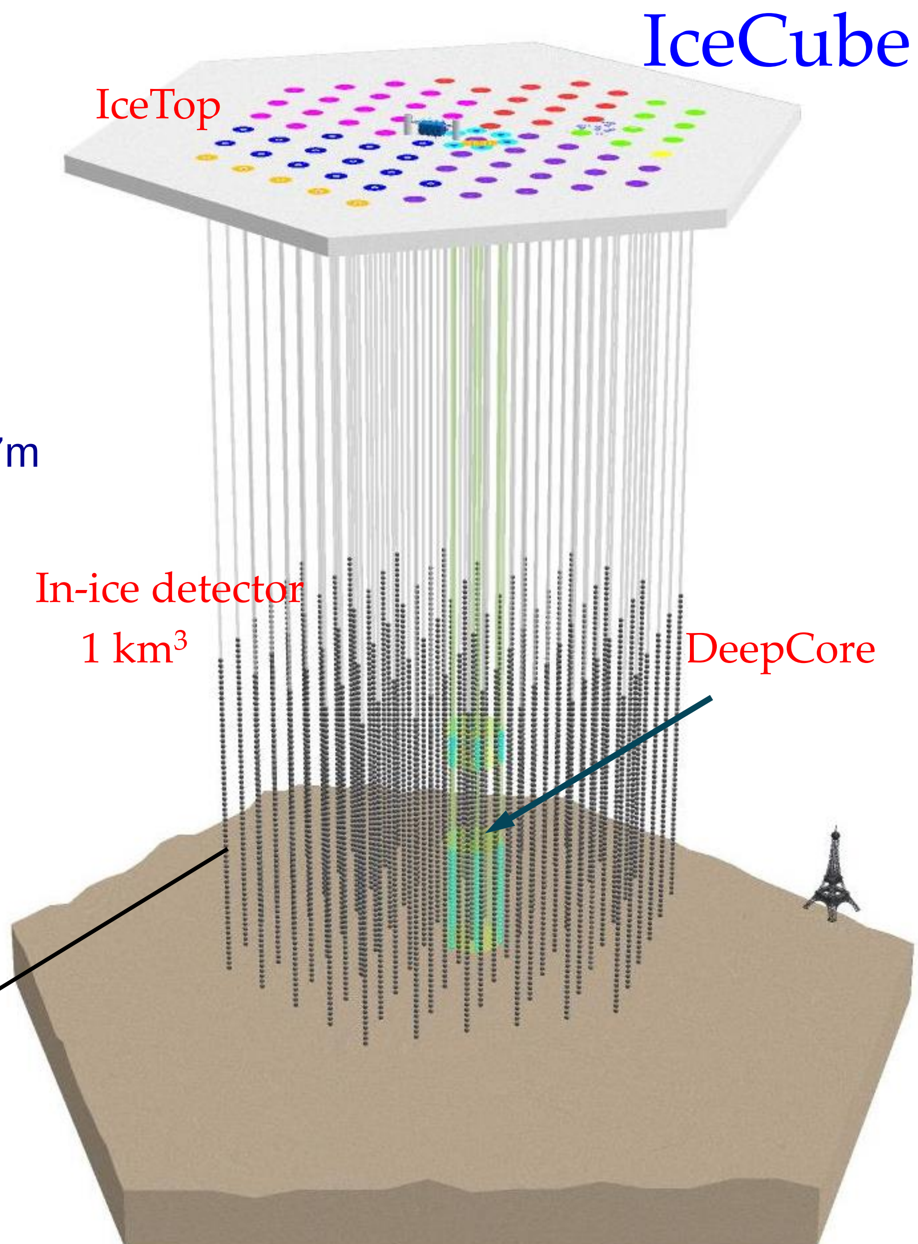


■ The IceCube detector at the South Pole

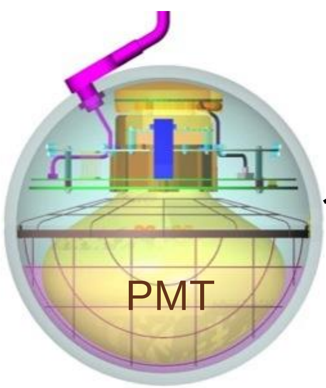


■ The IceCube detector

- ✧ Deployed in the Antarctica glacier
- ✧ In-ice + IceTop + DeepCore
- ✧ 86 strings (completed in 2010)
- ✧ ~ 5,000 photo-multiplier tubes (PMTs)
- ✧ Detector volume: ~ 1 km^3
- ✧ Detector spacing: horizontal 125m, vertical 17m
- ✧ ATWD 300MSPS
  3 different gains (x16, x2, x0.25)
- ✧ FADC for long duration pulse (6.4 μs)
- ✧ **Targets for cosmic high energy neutrinos**
  (mainly >~ 100 GeV)



Digital Optical Module (DOM)



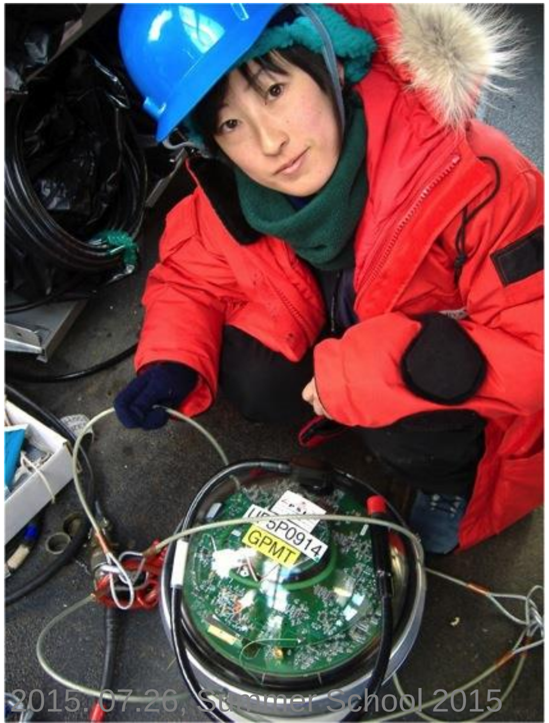
45 institutes and ~300 physicists

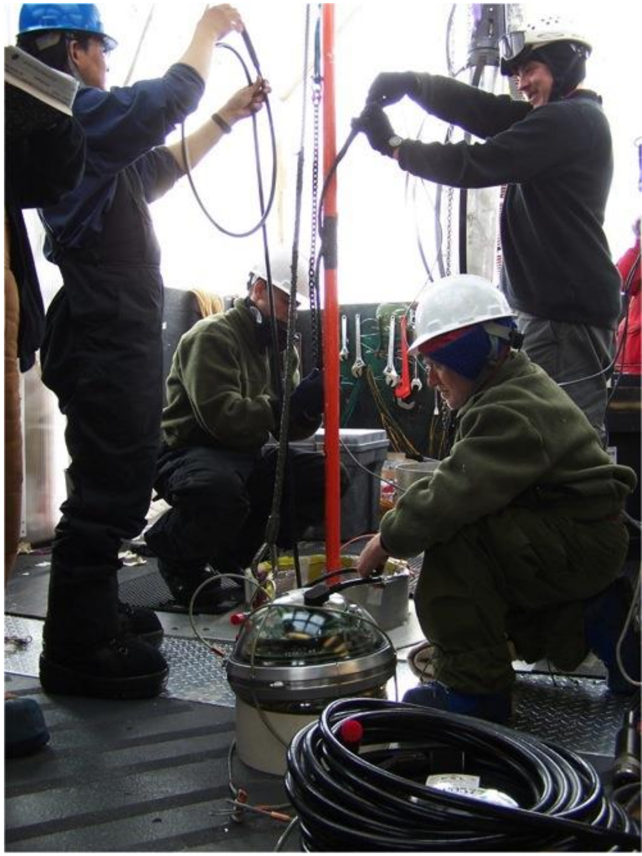
The IceCube Collaboration

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)
Japan Society for the Promotion of Science (JSPS)
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)

The deployment



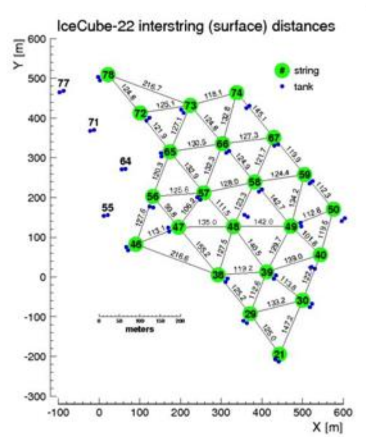


Use hot water to make a hole

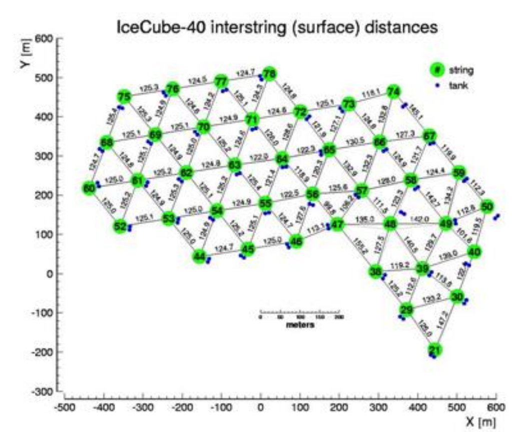
The construction

2004: project started
2006-2007: IC9
2007-2008: IC22
2008-2009: IC40
2009-2010: IC59
2010-2011: IC79
End of 2010: IceCube completed!
2011~: IC86

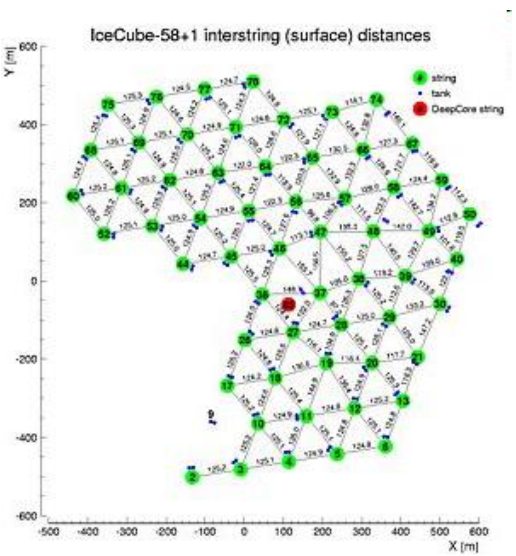
IC22 (2007-2008)



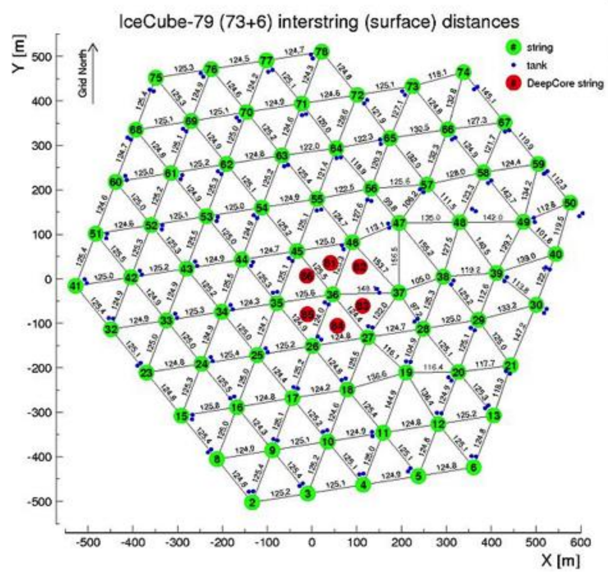
IC40 (2008-2009)



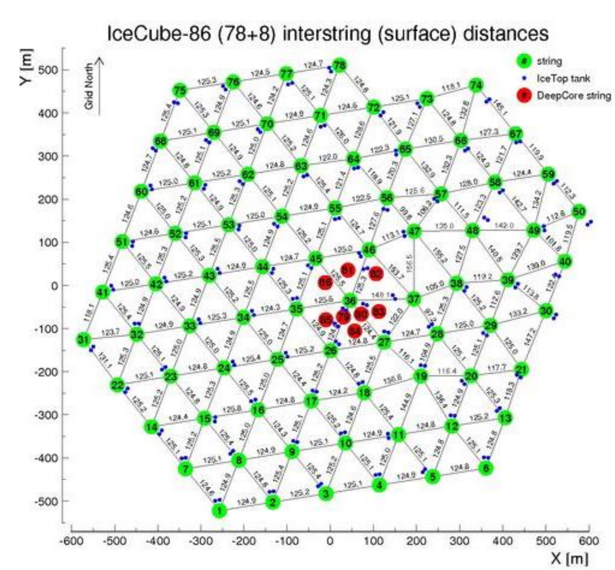
IC59 (2009-2010)



IC79 (2010-2011)



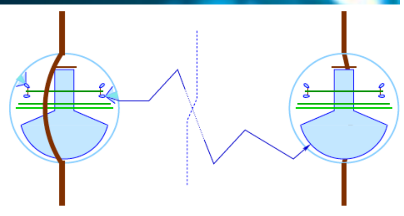
IC86 = complete IceCube (2011~)

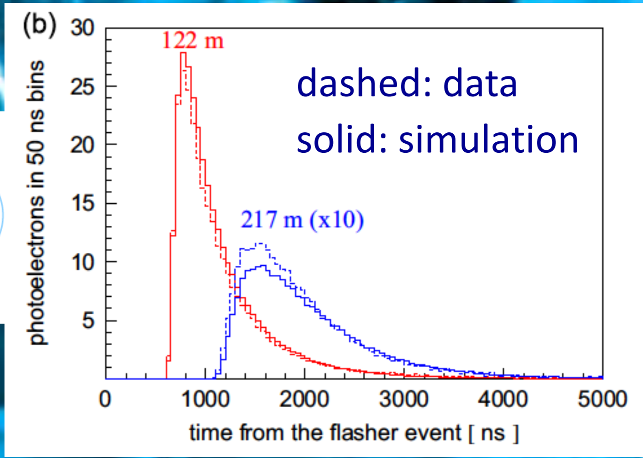


Calibration of our detector: ice

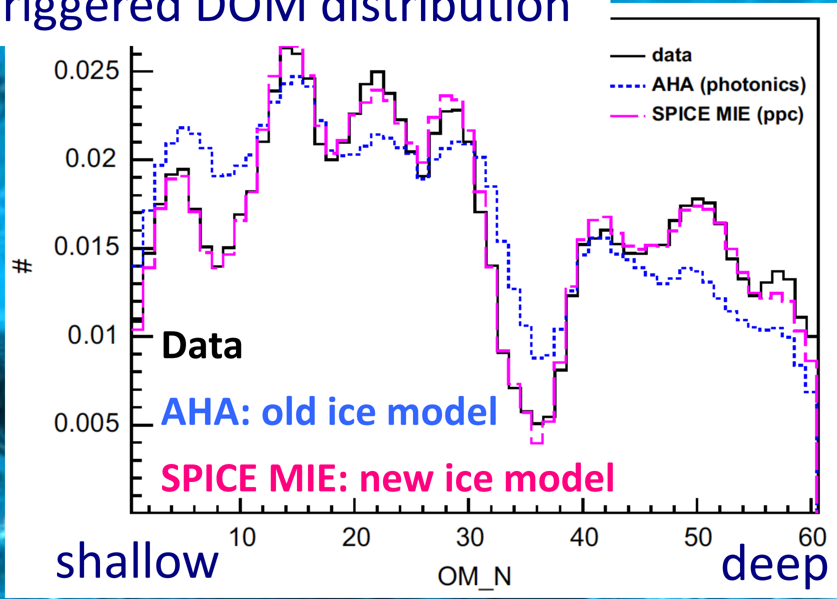
Ice properties calibrated by LEDs installed in DOMs

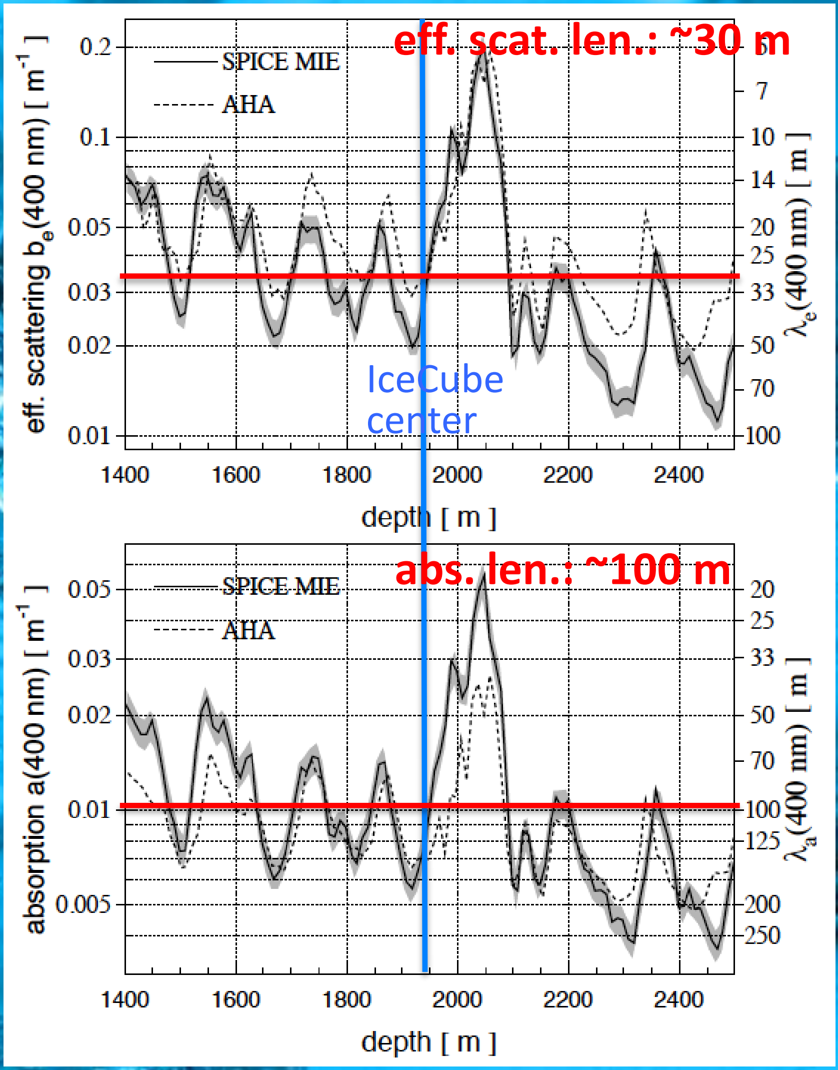
NIM A, 711, 73 (2013)





Triggered DOM distribution





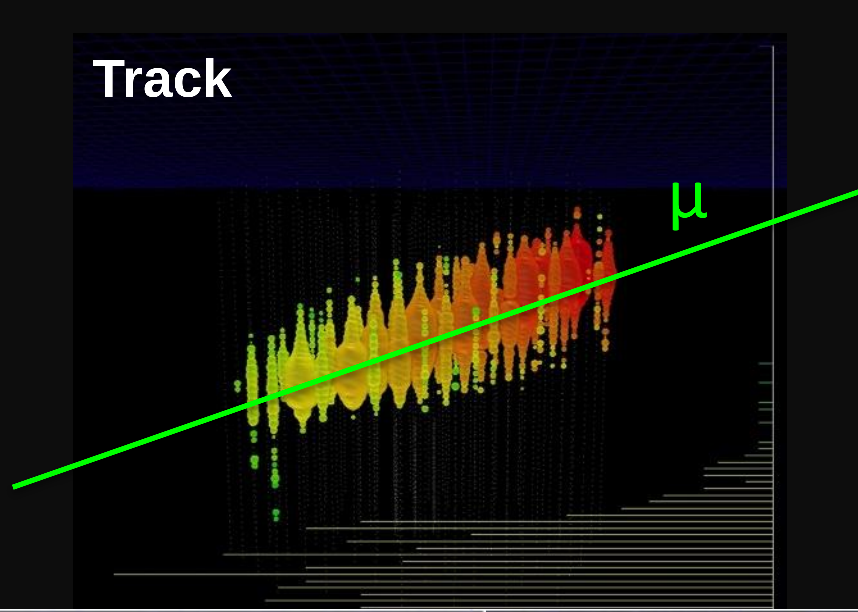
We understand the ice properties better!

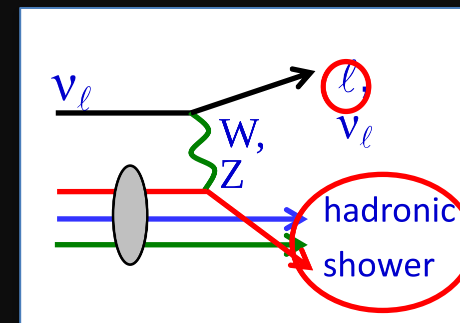
Particle identification

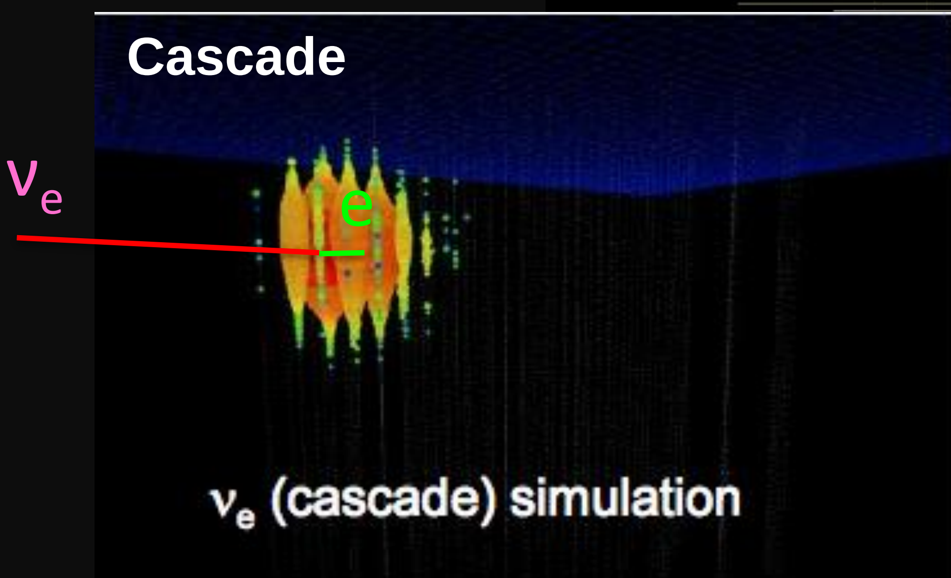
Angular resolution

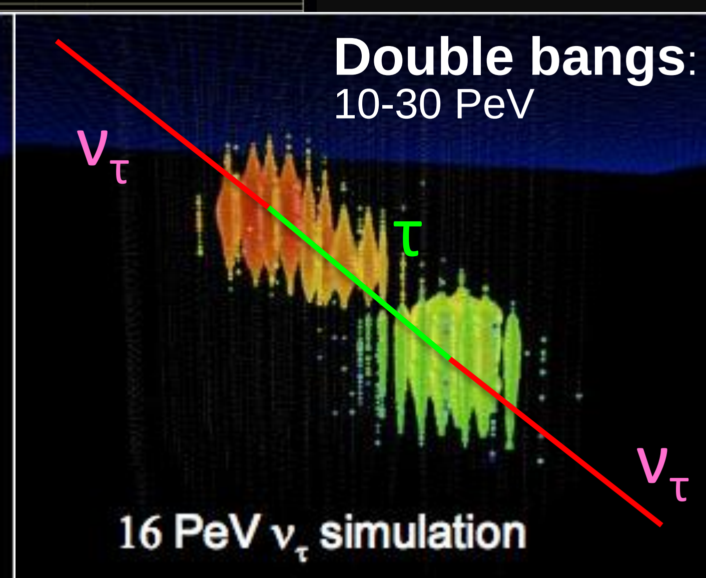
Tracks: ~1°

Cascades: ~10°









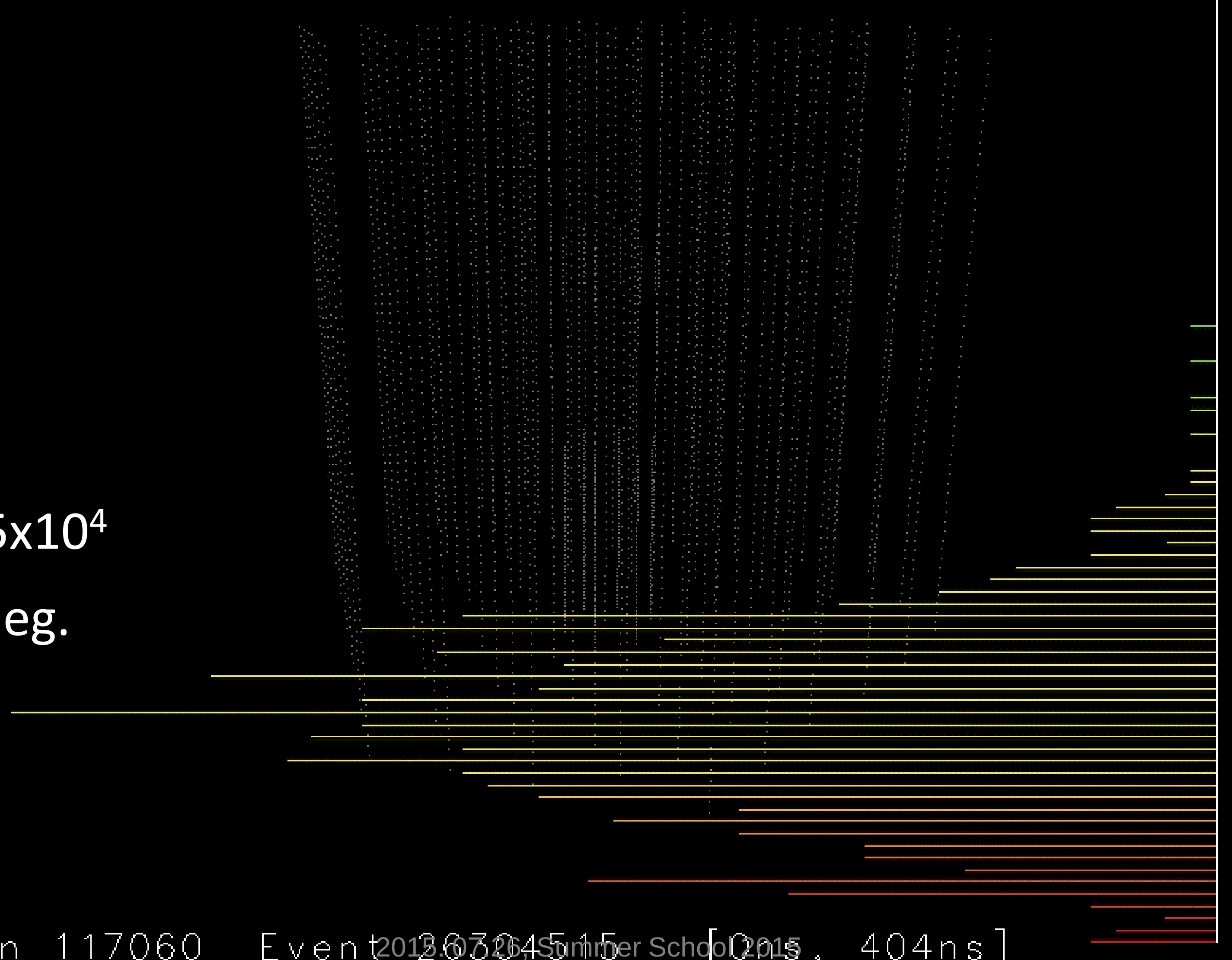
Note: neutral current events also generate cascades

Example of an event

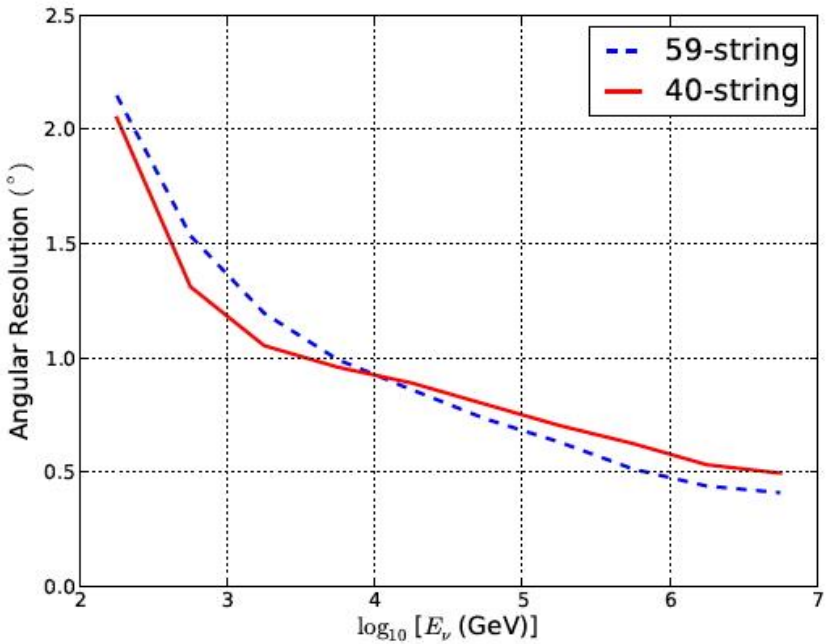
Observation data (IC-79 (IceCube with 79 strings))

NPE: 7.5×10^4

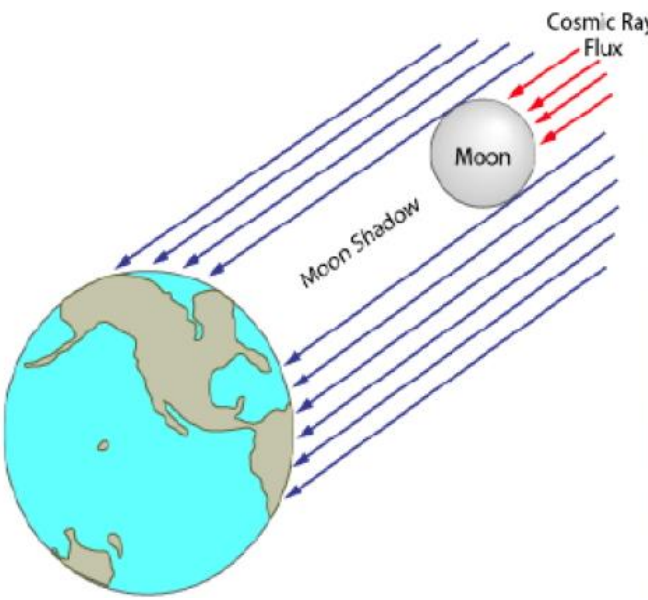
ZA: 70 deg.

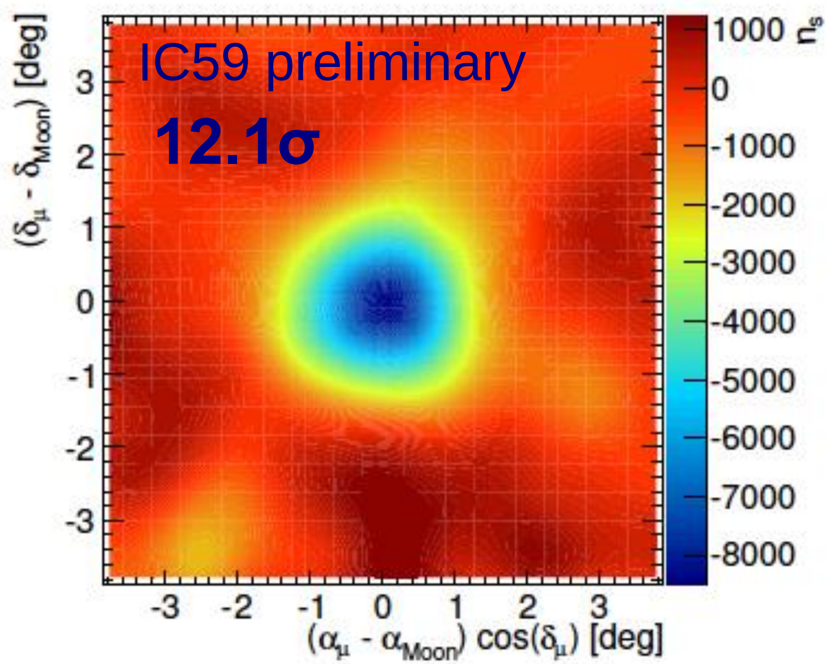


■ The angular resolution



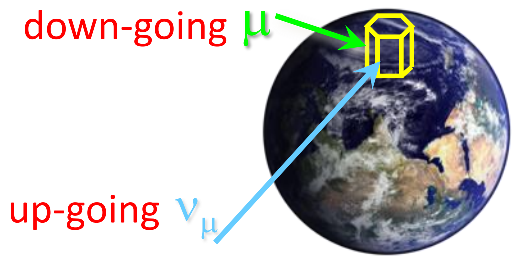
arXiv:1111.2741



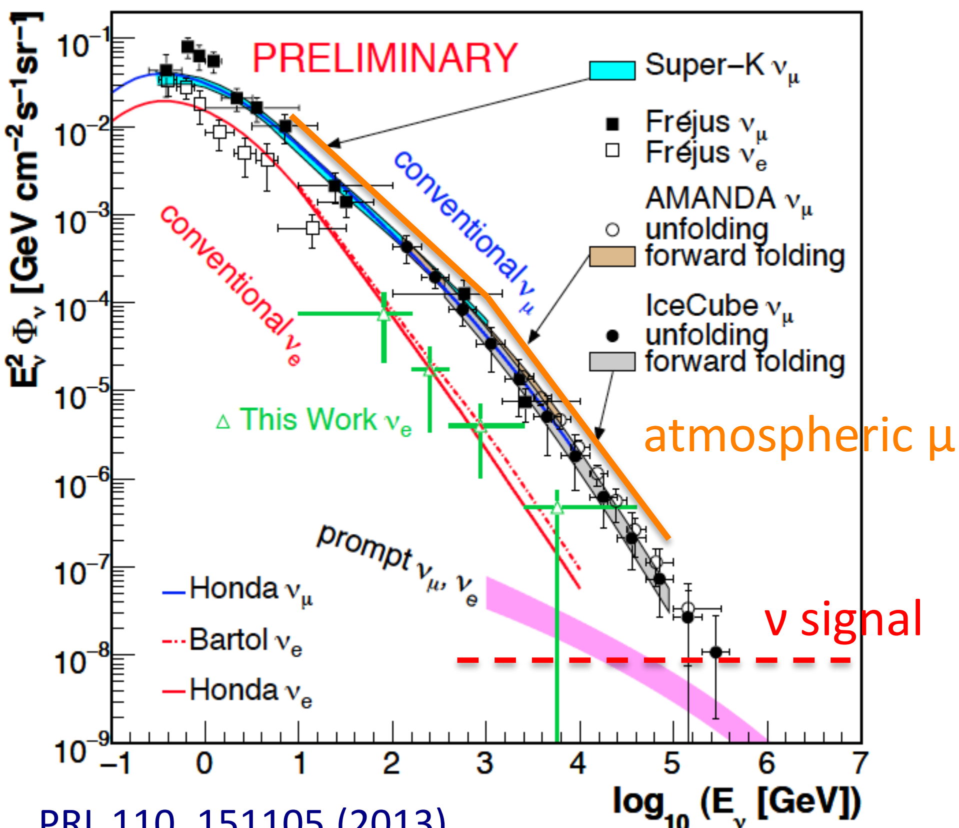


- Systematic angular shift < 0.2° (geomag. taken into account)
- Angular resolution < 1° (> 10 TeV)

■ Backgrounds

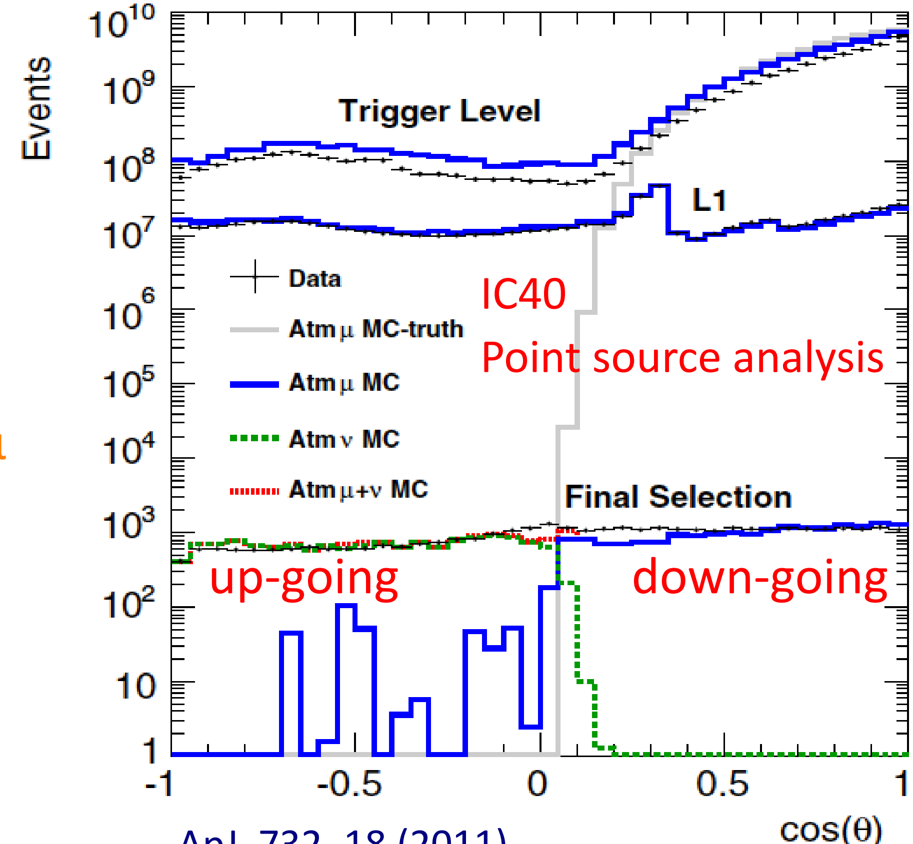


Energy spectra @ surface



PRL 110, 151105 (2013)

Zenith angle distribution @ detector



ApJ, 732, 18 (2011)

- Three main backgrounds: Atm μ, Atm ν, prompt ν (all CR originated)
- Essentially energy and zenith angle information used for signal searches

Point source search

Sensitive: > ~1 TeV

Search for muon neutrinos by using mainly the directions (energy info also used)

Test null hypothesis of no signal against one with signals

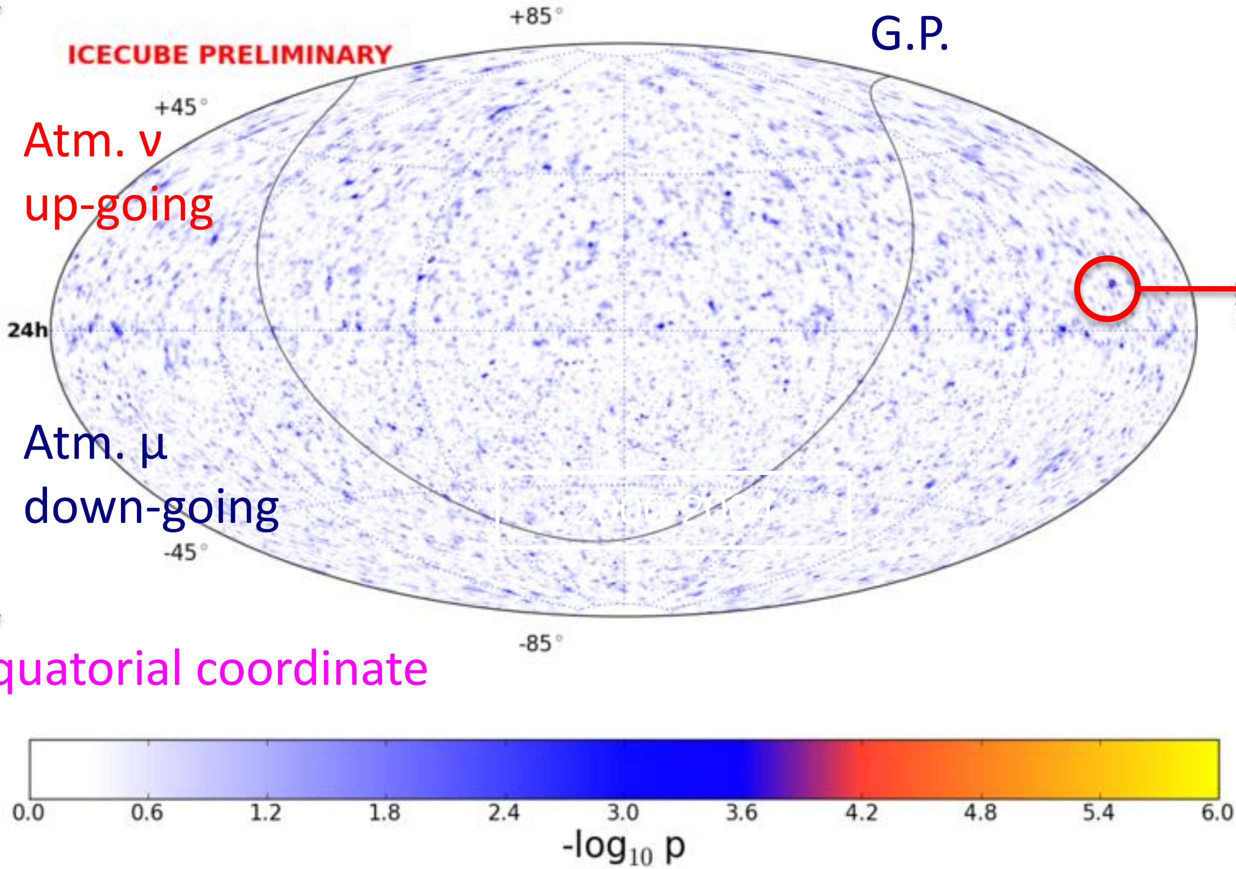
4-year data (IC40+IC59+IC79+IC86-I): 1371.7 days

178000 ν + 216000 μ

G.P.

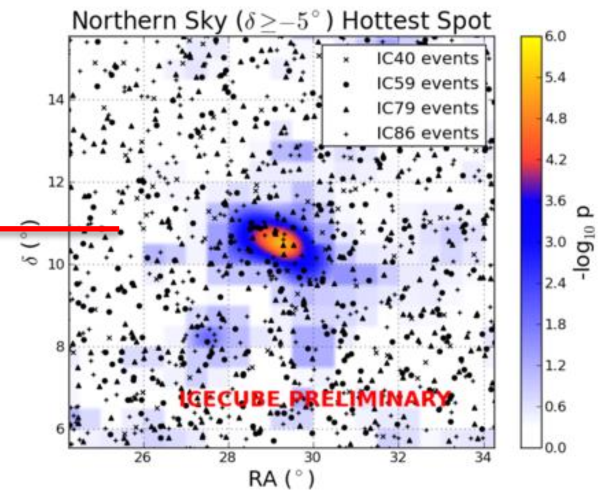
Atm. ν up-going

Atm. μ down-going



Equatorial coordinate

Hottest spot



post-trial after scrambling data

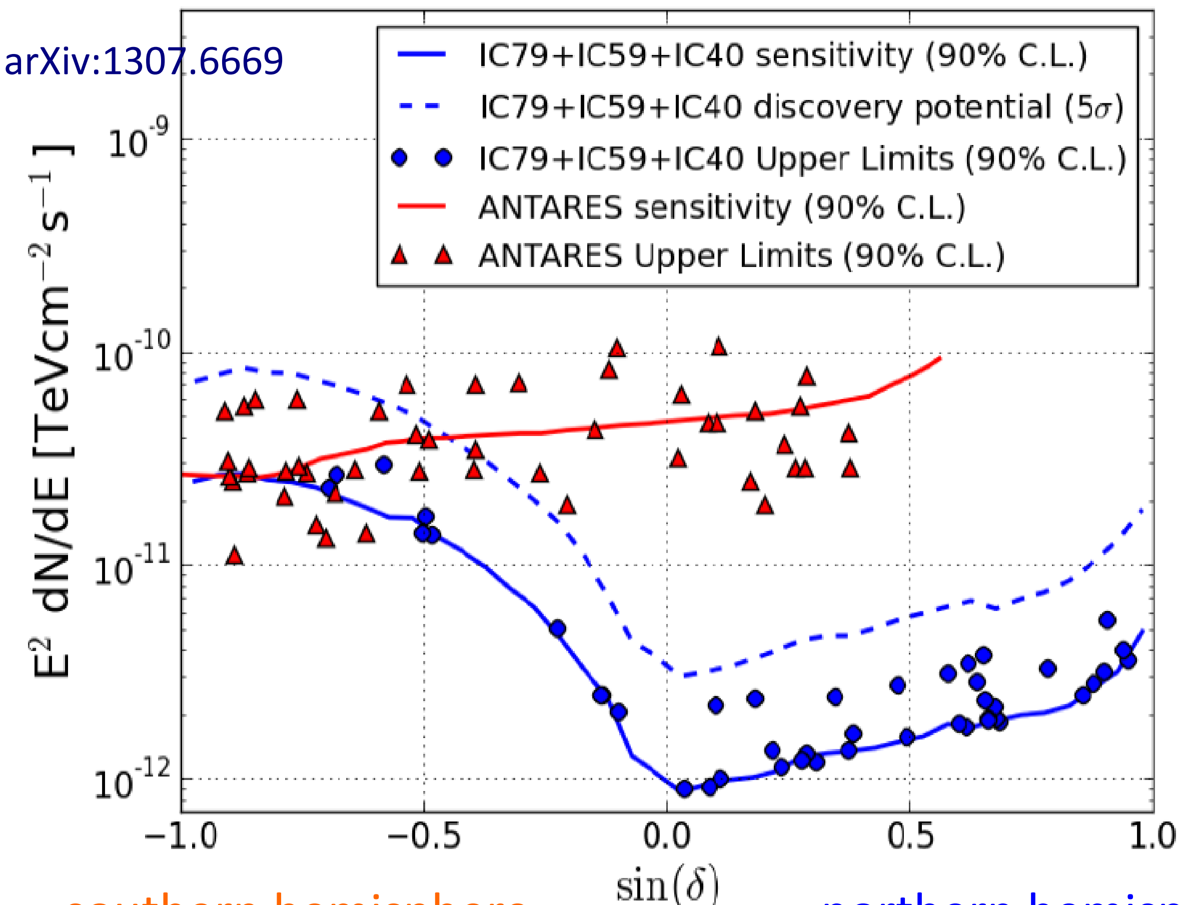
→ P-value: 22.6%

Not significant

Upper limit for selected sources

Most significant 44 sources are selected a priori to reduce the number of trials

The list was determined by a modeling producing neutrinos



southern hemisphere

northern hemisphere

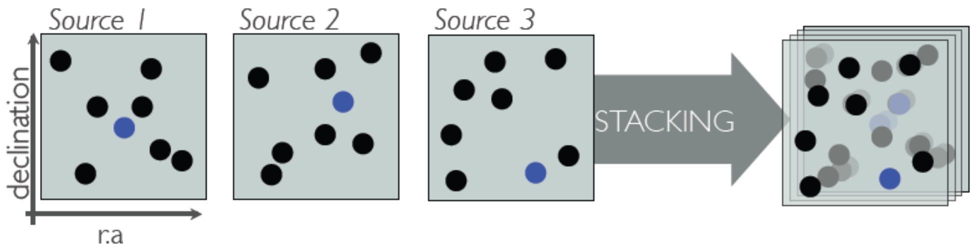
S5 0716+71
M82
1ES 1959+650
TYCHO
LSI 303
Cas A
1ES 2344+514
3C66A
H 1426+428
BL Lac
NGC 1275
Cyg OB2
Cyg X-3
Cyg A
Mrk 501
Mrk 421
4C 38.41
MGRO J2019+37
Cyg X-1
3C 123.0
W Comae
IC443
Crab Nebula
1ES 0229+200
Geminga
PKS 0235+164
3C 454.3
PKS 0528+134
M87
PKS 1502+106
MGRO J1908+06
HESS J0632+057
SS433
3C 273

3C279
QSO 2022-077
PKS 1406-076
QSO 1730-130
Sgr A*
PKS 1622-297
PKS 2155-304
PKS 1454-354
Cen A
PKS 0537-441

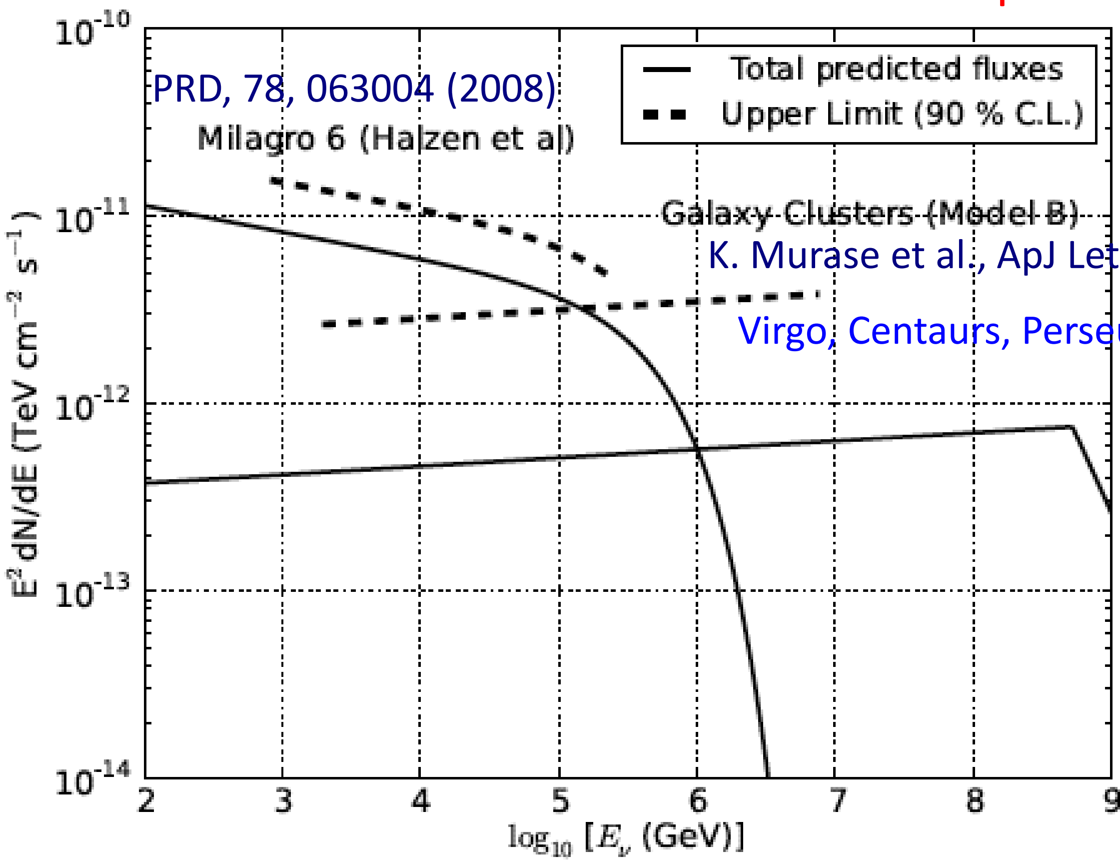
Stacking analysis

arXiv:1307.6669

Increase the ability by stacking a specific source class



Pp interactions



CRs generated inside virial radius of clusters

K. Murase et al., ApJ Let., 689, L105 (2008)

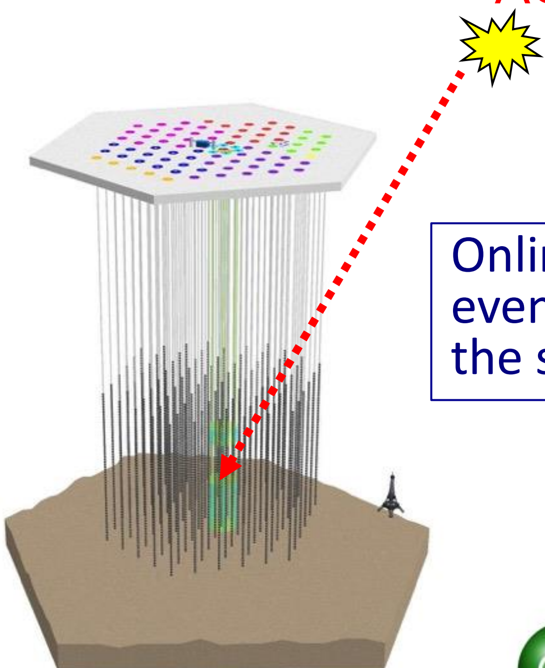
Virgo, Centaurs, Perseus, Coma, Ophiuchus

Close to model prediction

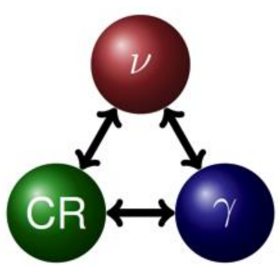
IceCube follow-up programs

- ✓ Send alerts to satellites/telescopes
- ✓ Multi messenger approach
- ✓ Few alerts per year

AGN/SN/GRB

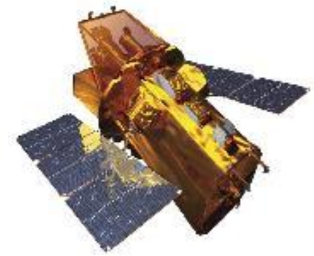


Online neutrino event selection at the south pole



Alert

Swift (X-ray)



PTF (optical)

ROTE (optical)

MAGIC (γ-ray)

VERITAS (γ-ray)

EHE online alert is coming

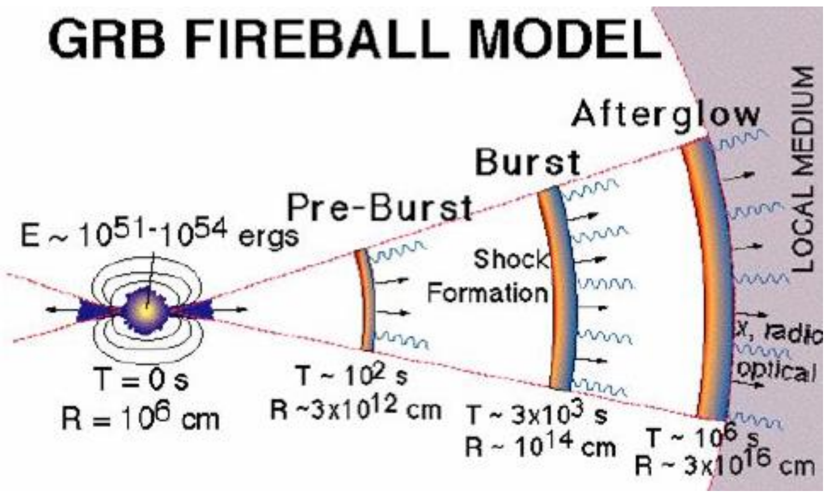
Search for neutrinos from GRBs

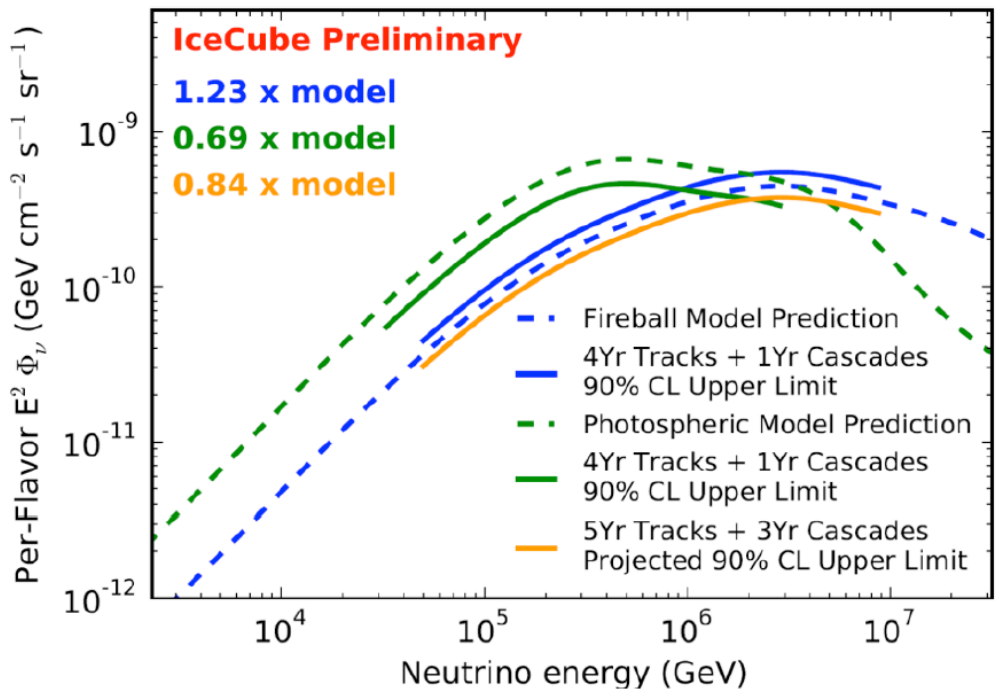
neutrino (ν_μ) searches by using the direction and the timing information of GRBs

→ Very low backgrounds

No significant neutrino signal → limits

- upgoing ν_μ track search – 506 bursts in 4yrs
- all-flavor cascade search – 257 bursts in 1yr





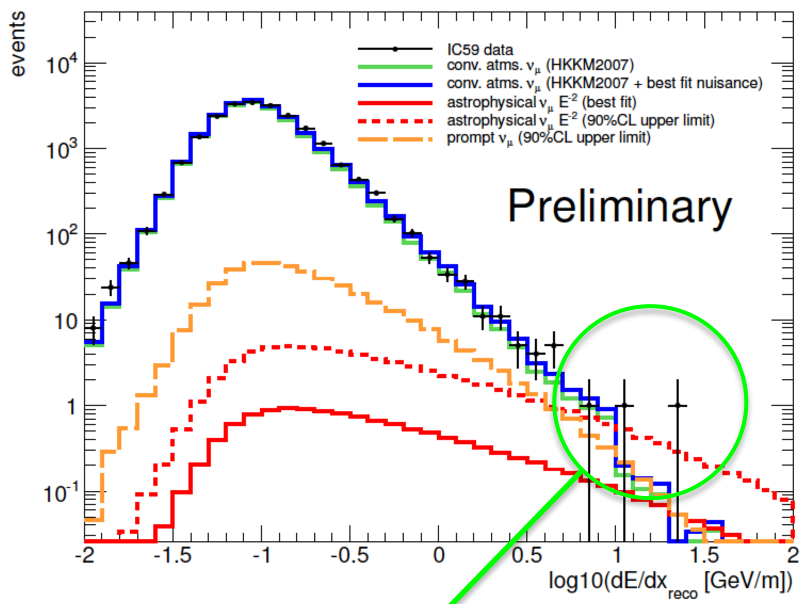
Close to constrain models

GRBs may not be the source of UHECRs

Diffuse neutrino search

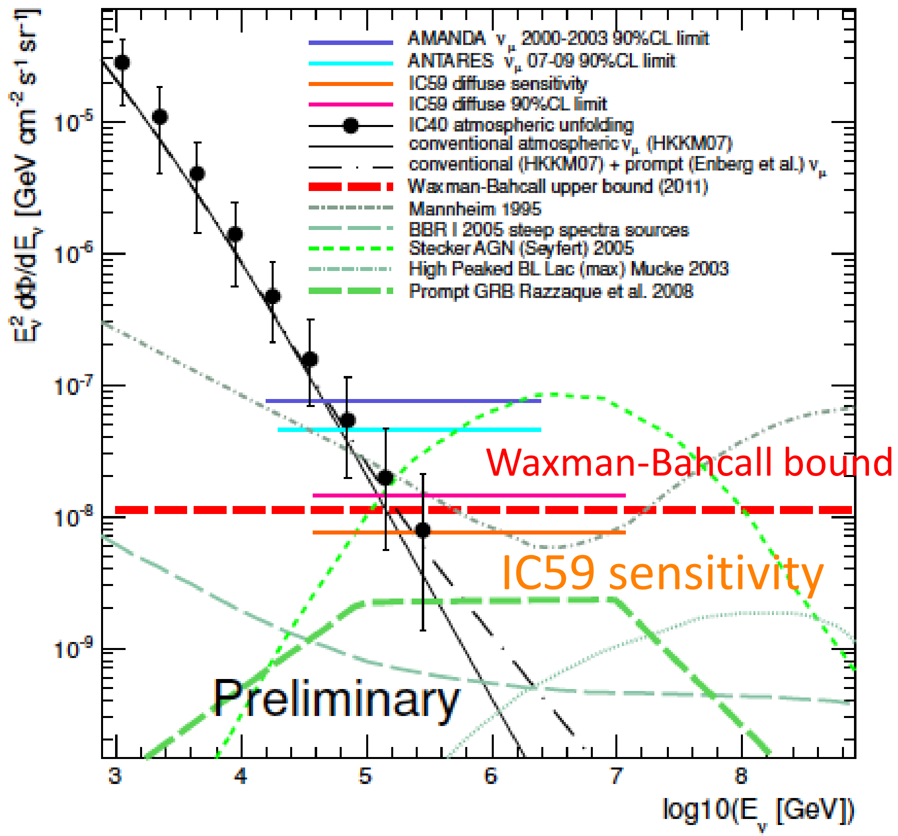
Idea to integrate weak neutrino flux
Search for diffuse muon neutrinos by using mainly energy information
Signal slope is harder than background slope

arXiv:1302.0127



Significance: 1.8σ

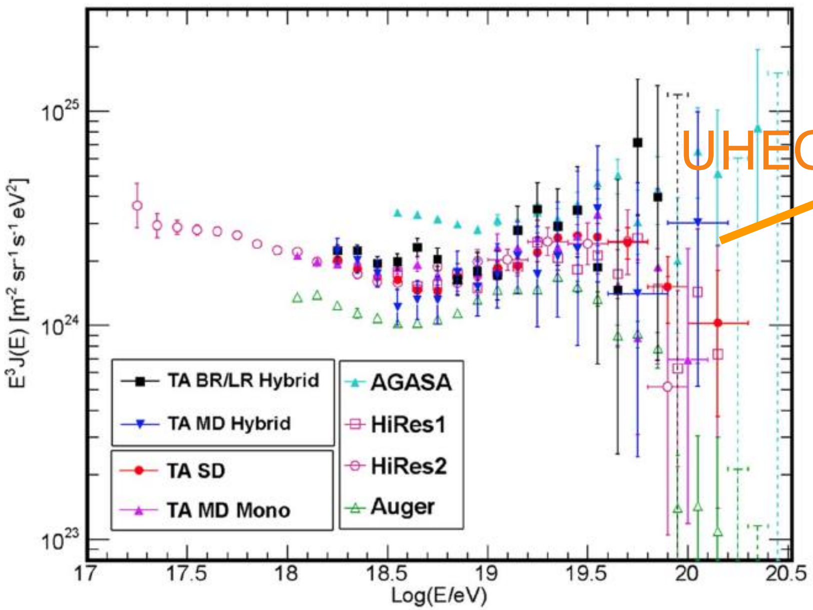
Sensitive: 30 TeV-10 PeV

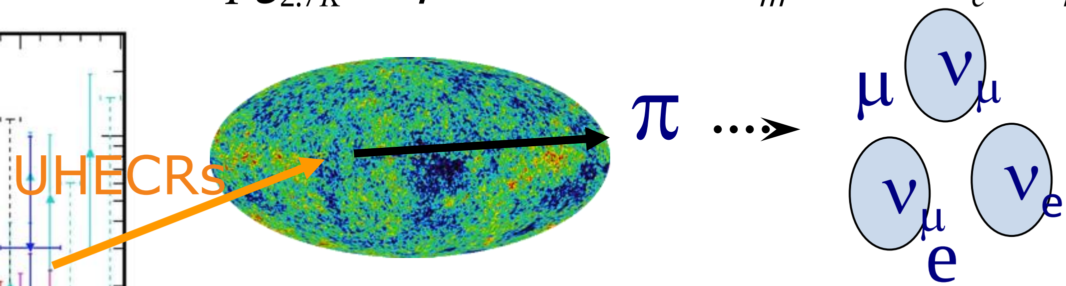


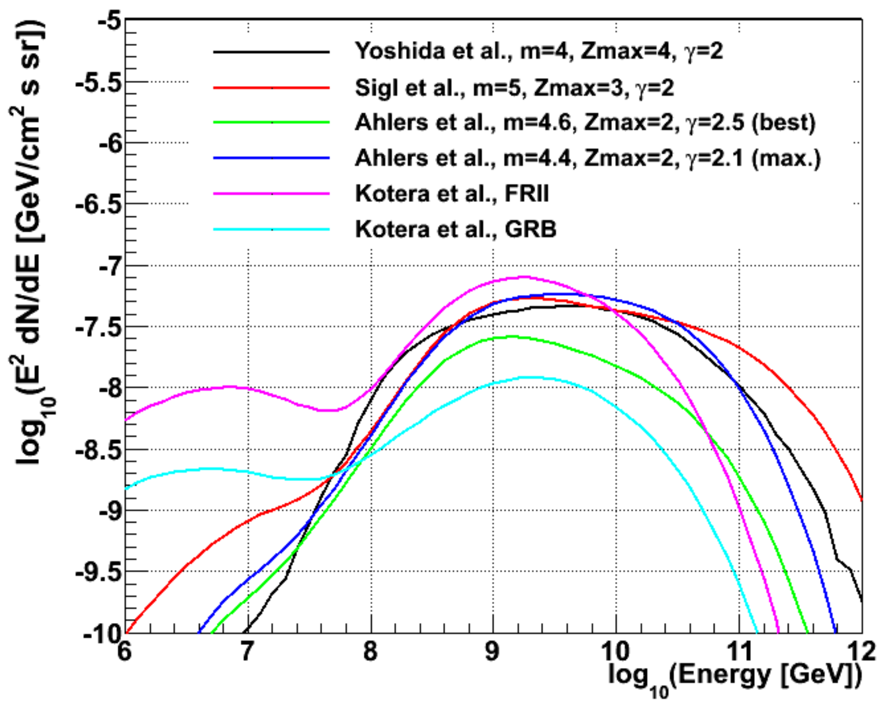
- Sensitivity is below Waxman-Bahcall bound
- Atmospheric neutrinos measured from 100 GeV - 300 TeV
  → Consistent with previous measurements

■ The extremely high energy (EHE) cosmogenic neutrino search

$$pg_{2.7K} \rightarrow p^{+} + X \rightarrow m^{+} + n_m \rightarrow e^{+} + n_e + \overline{n_m} + n_m$$







Shed light on the UHECR origin

- ✧ Source position
- ✧ Composition (proton/iron)?
- ✧ Source evolution / when the UHECR generation started

All flavor sensitive, Energy > 1 PeV

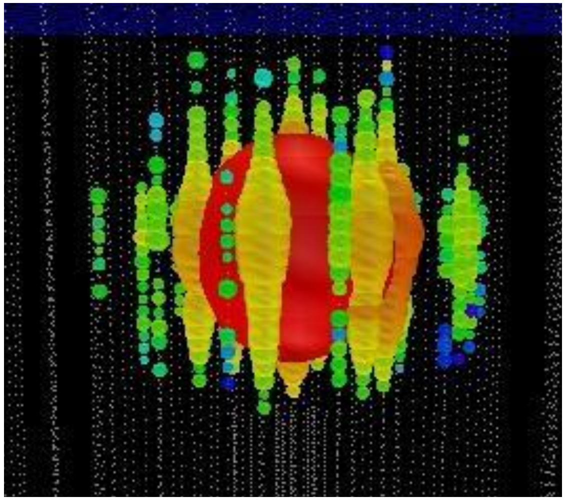
Two cascade like events found in 2011-2012 data

May, 2011 - May, 2012 (350.9 days), IC86 configuration

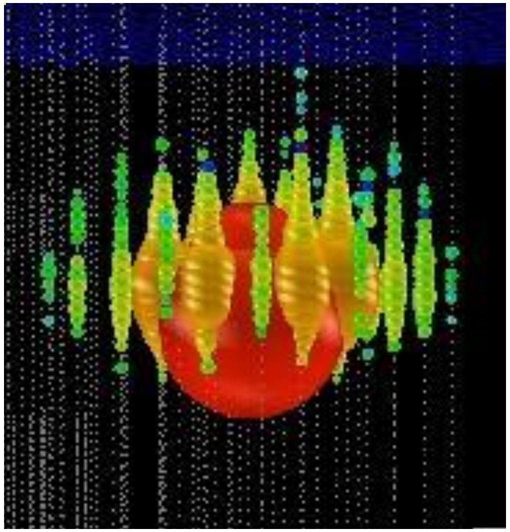
PRL 111, 021103 (2013)

Either CC interaction of ν_e or NC interaction of any flavor ν

"Bert"
Aug., 9th, 2011
Run 118545
-Event 63733662
NPE: 7.0×10^4
NDOM: 354
1.04 ± 0.16 PeV



"Ernie"
Jan, 3rd, 2012
Run 119316
-Event 36556705
NPE: 9.6×10^4
NDOM: 312
1.14 ± 0.17 PeV



	event rate in 615.9 days
Atmospheric muons	0.038 ± 0.004
conventional atmospheric neutrinos	0.012 ± 0.001
prompt neutrinos*	0.033 ± 0.001
total background	**0.082 ± 0.004**

* R. Enberg et al., PRD78, 043005 (2008)

Significance: 2.8σ

Highest energy neutrinos ever seen at that time!

The August event ("Bert")

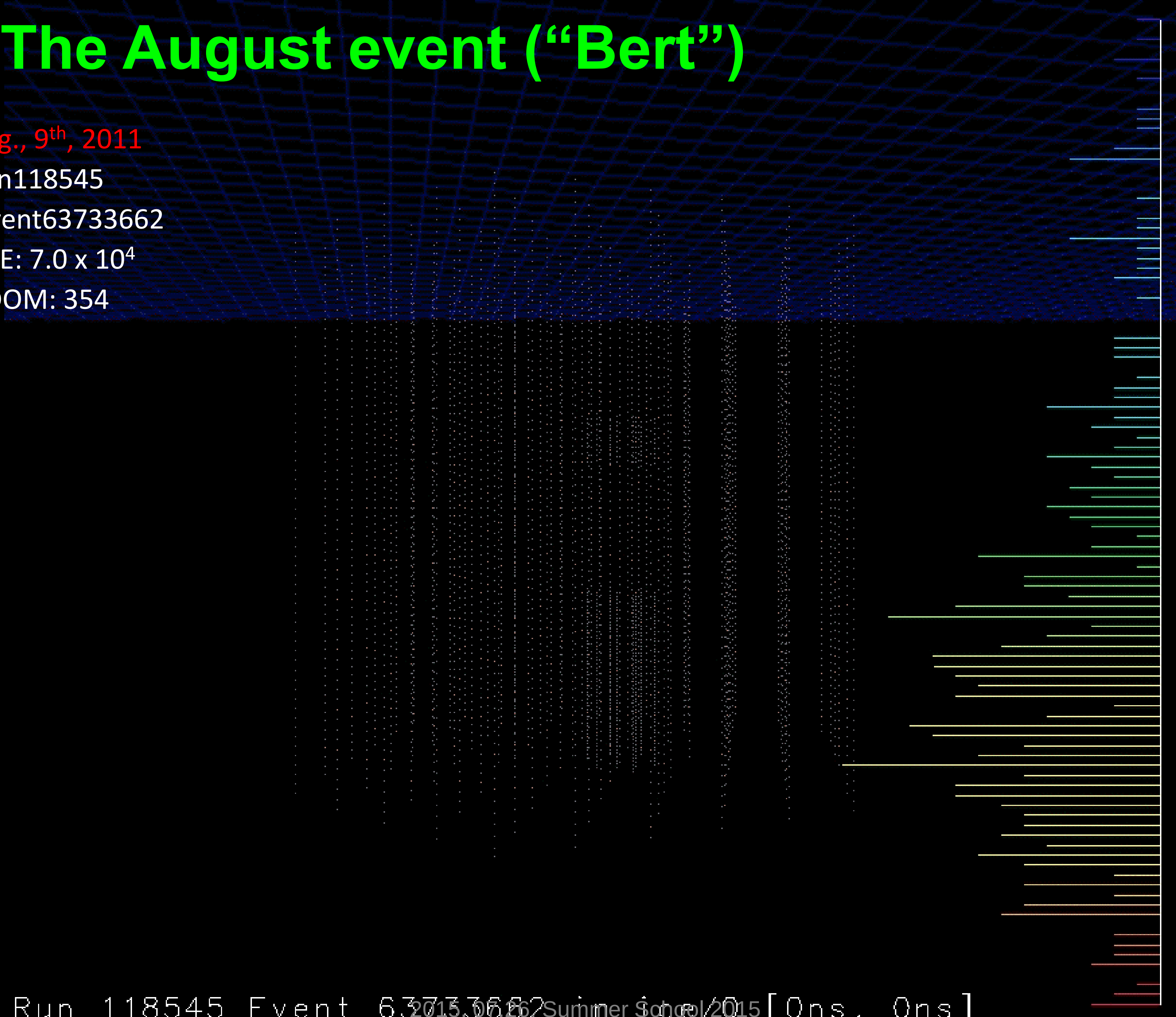
Aug., 9th, 2011

Run118545

-Event63733662

NPE: 7.0 x 10^4

NDOM: 354



The January event ("Ernie")

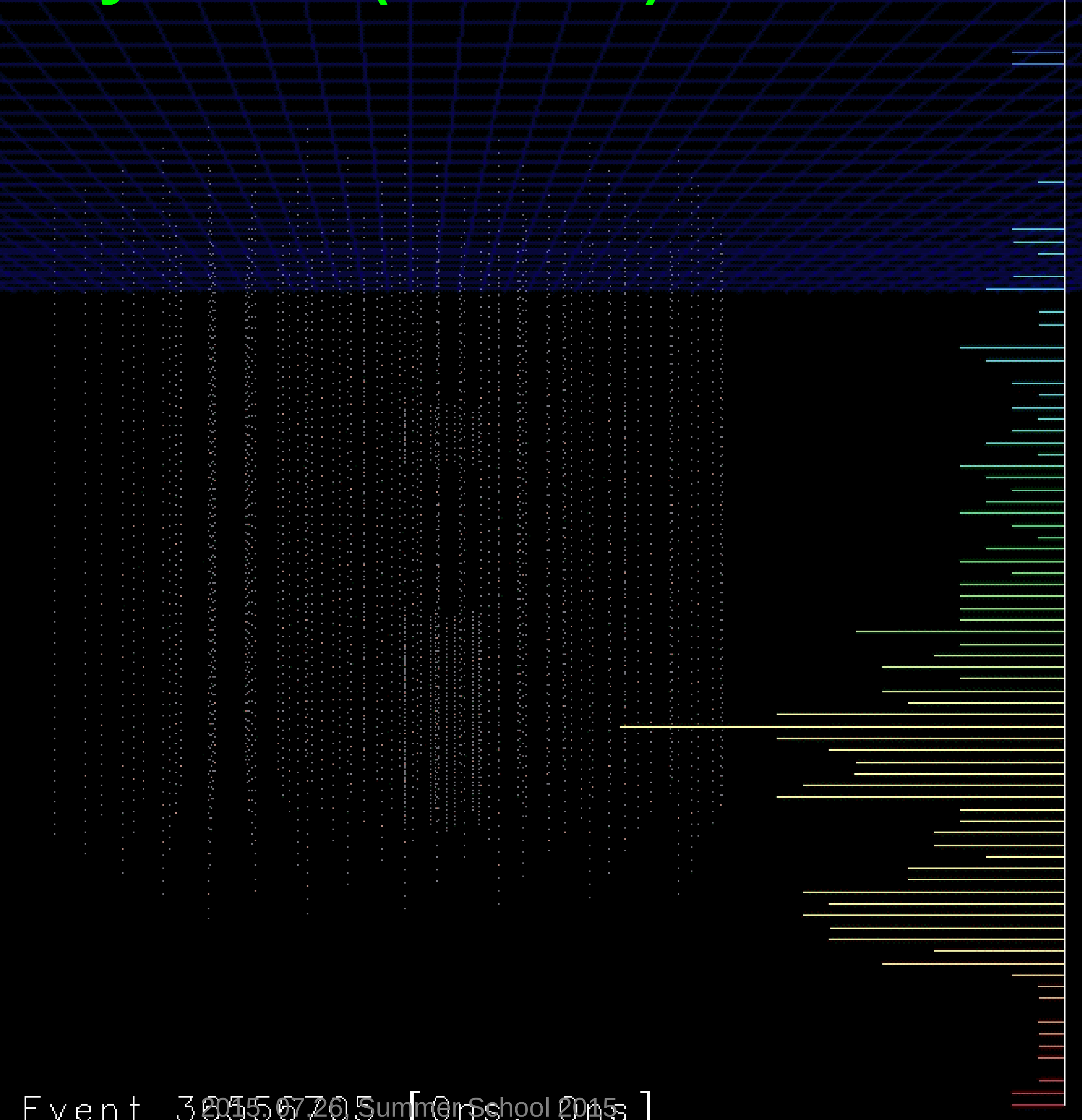
Jan, 3rd, 2012

Run119316

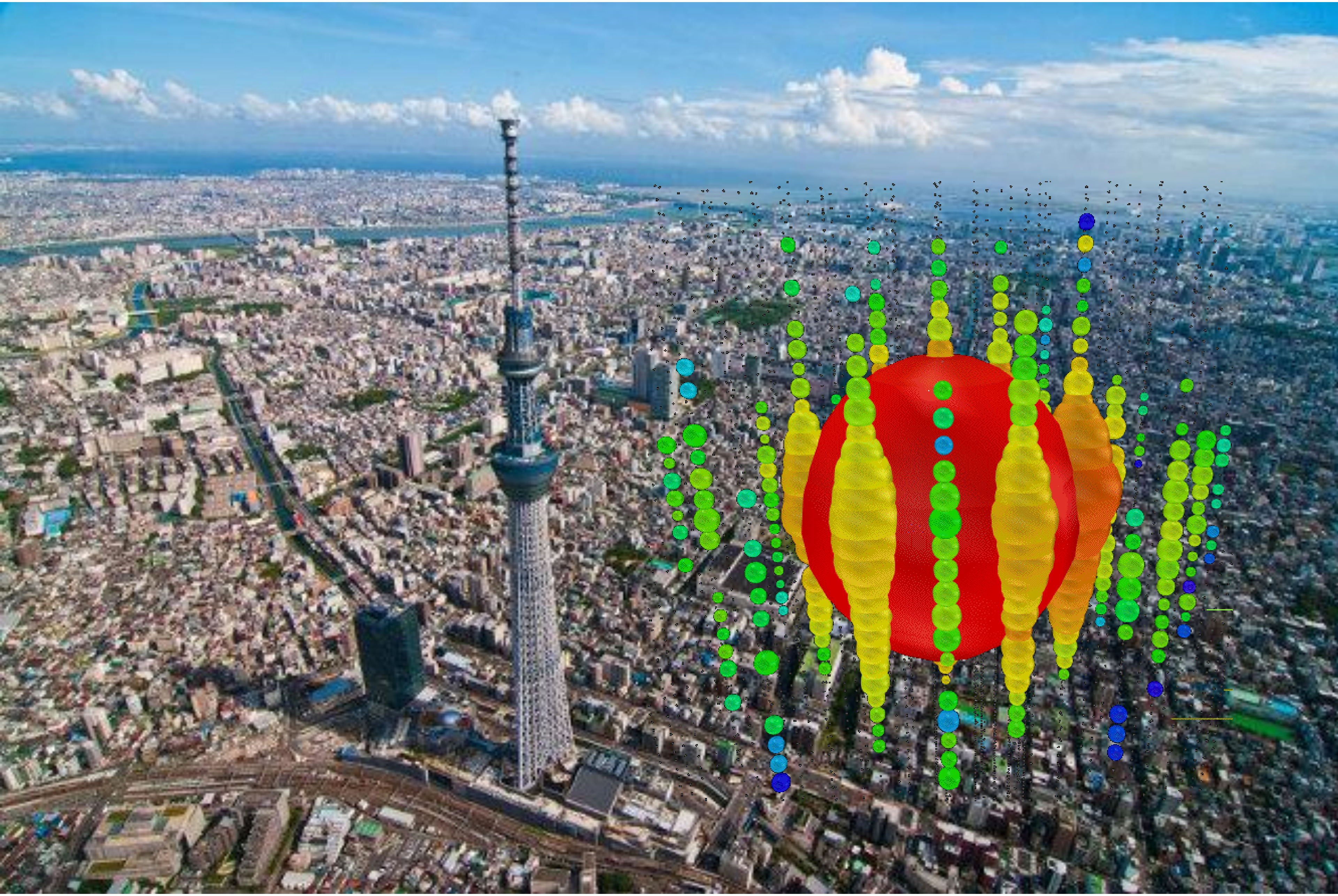
-Event36556705

NPE: 9.6 x 10^4

NDOM: 312



Bert visits Tokyo

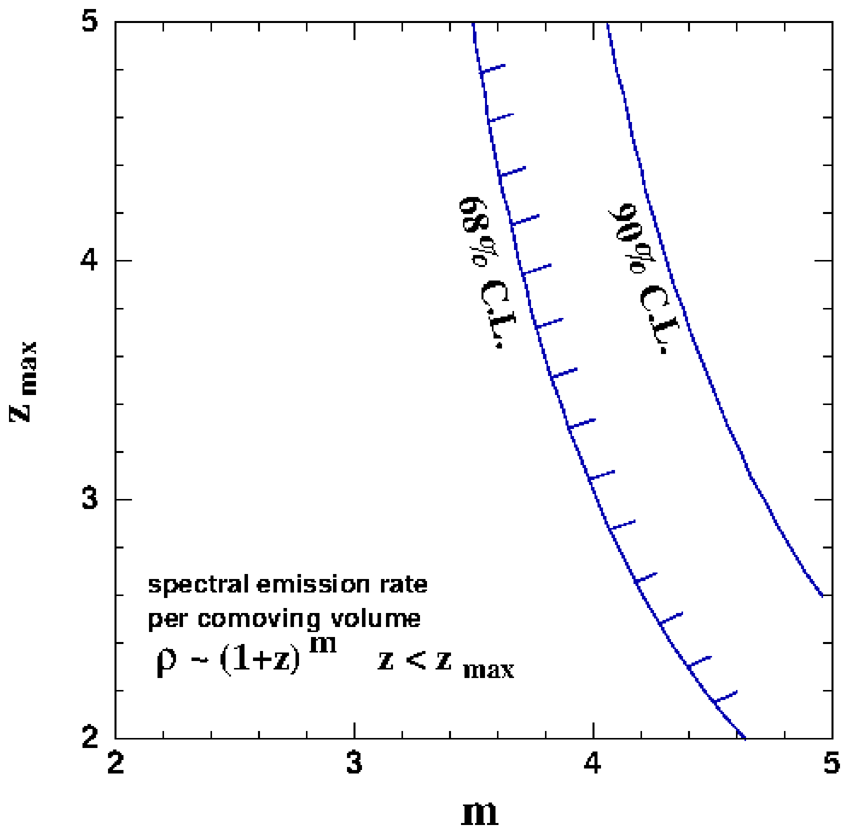


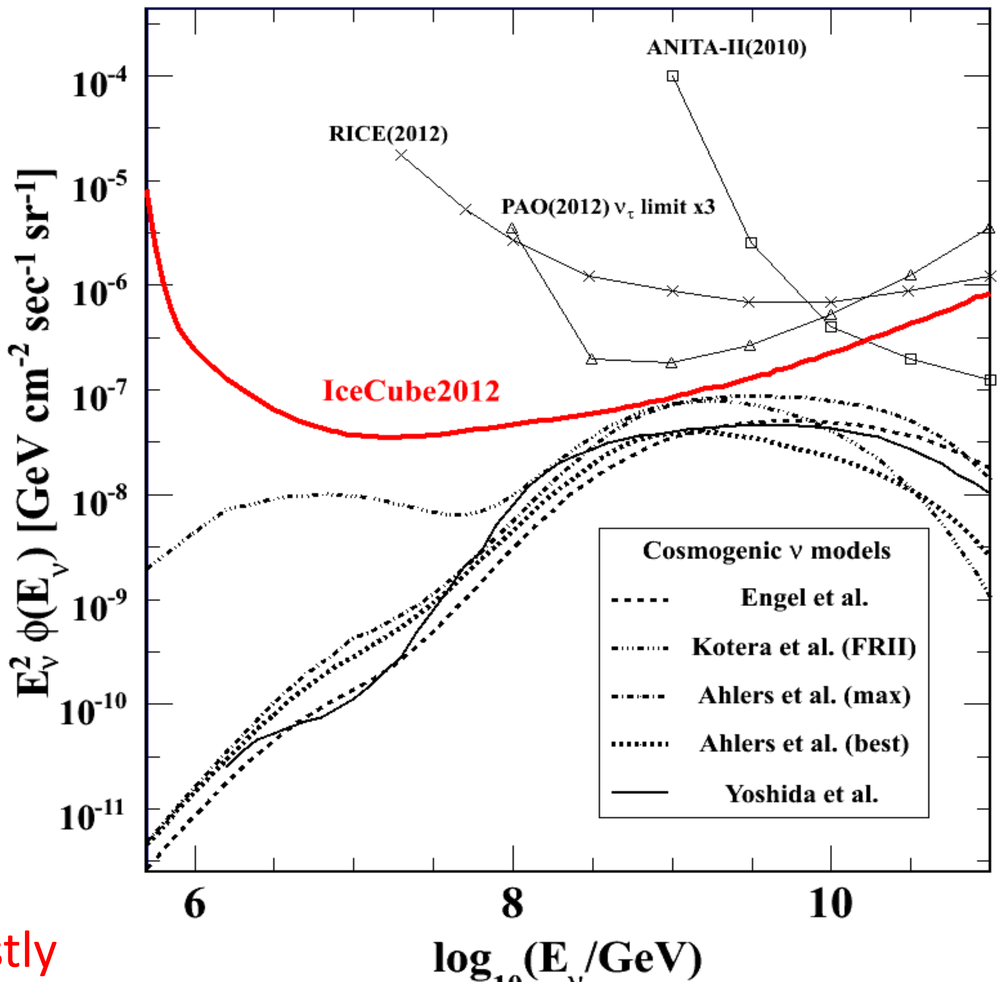
Limits

Energies of two PeV events are too low to be explained by cosmogenic neutrinos

No events observed above 100 PeV

PRD 88, 112008 (2013)



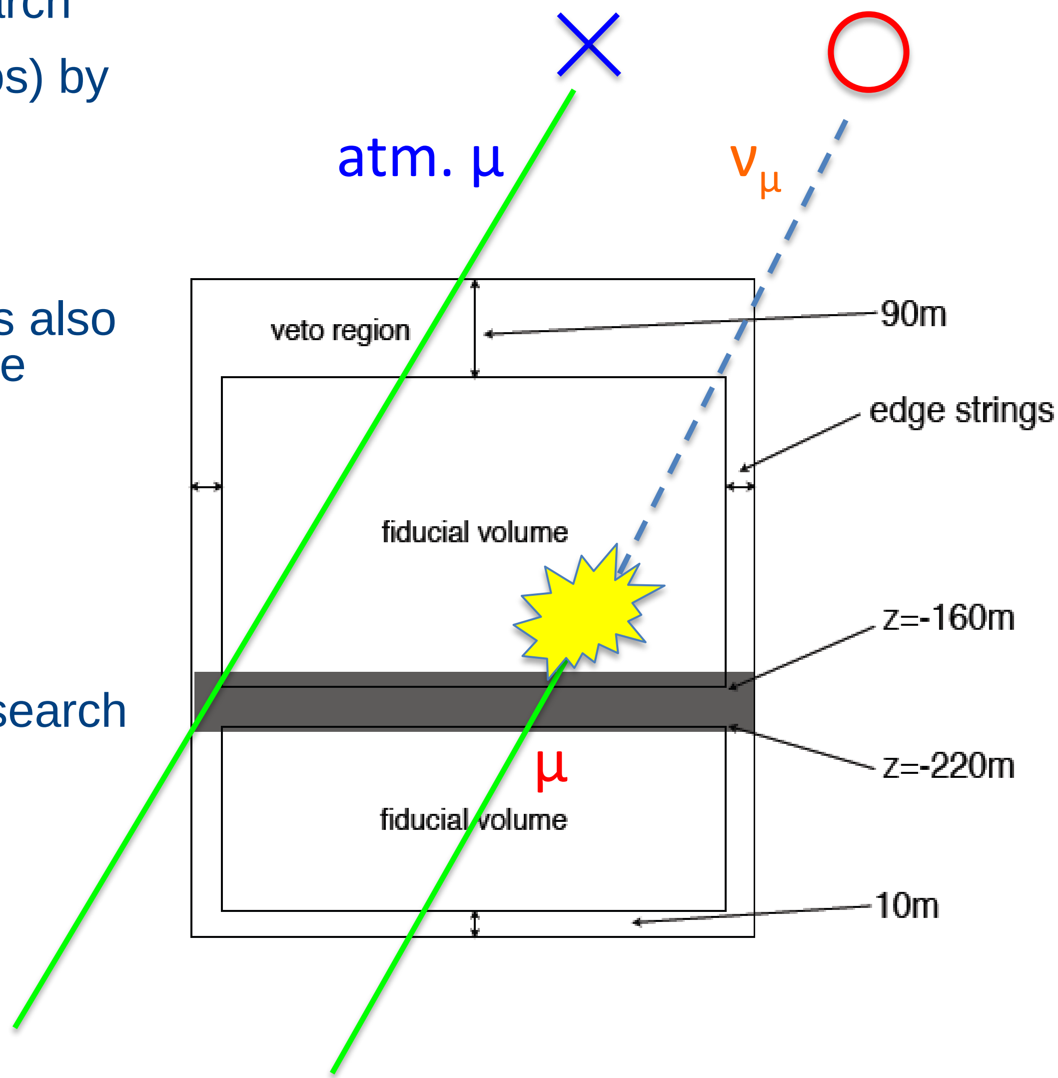


High evolution models (m>4) are mostly ruled out such as FR-II class of AGN

differential limit per one energy decade

High energy starting event search

- Follow-up of the EHE neutrino search
- Search contained events (neutrinos) by using outer layers as veto
- Atmospheric muon backgrounds reduced
- Atmospheric neutrino backgrounds also reduced as atmospheric muons are normally accompanied
- 420 Mton fiducial mass
- All flavor
- > 50 TeV
- 3 times better than EHE neutrino search @ 1 PeV



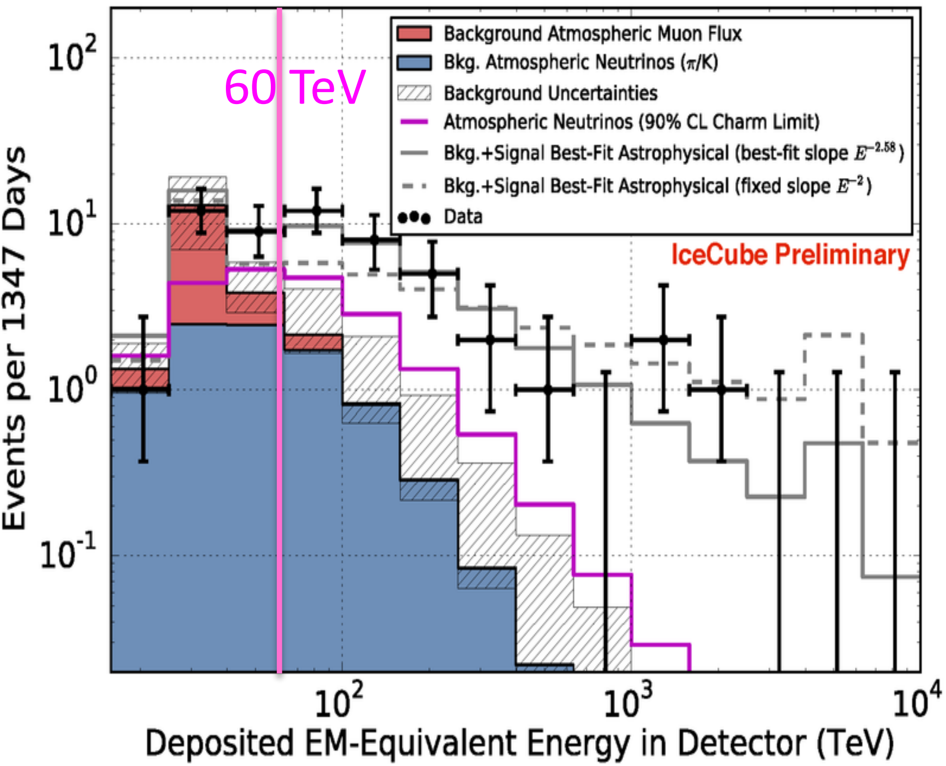
Deposited energy and zenith angle distributions

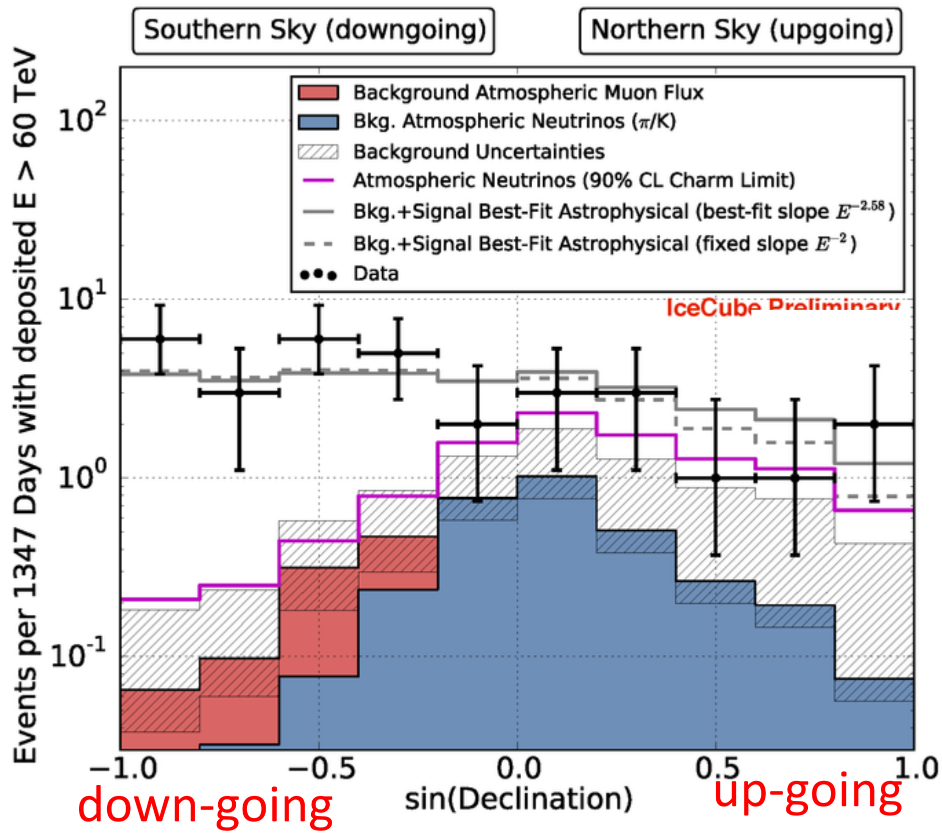
Other 54 events found! (39 cascades, 15 tracks) 4 year data

Significance: ~7σ

Expected BG: 21.6

E > 60 TeV





- Best fit: $E^{-2.58 \pm 0.25}$ (becomes softer, but consistent)
- $E^2\varphi = 0.84 \pm 0.3 \times 10^{-8}$ GeV/cm^2/s/sr (single flavors)

Sky map and the significance

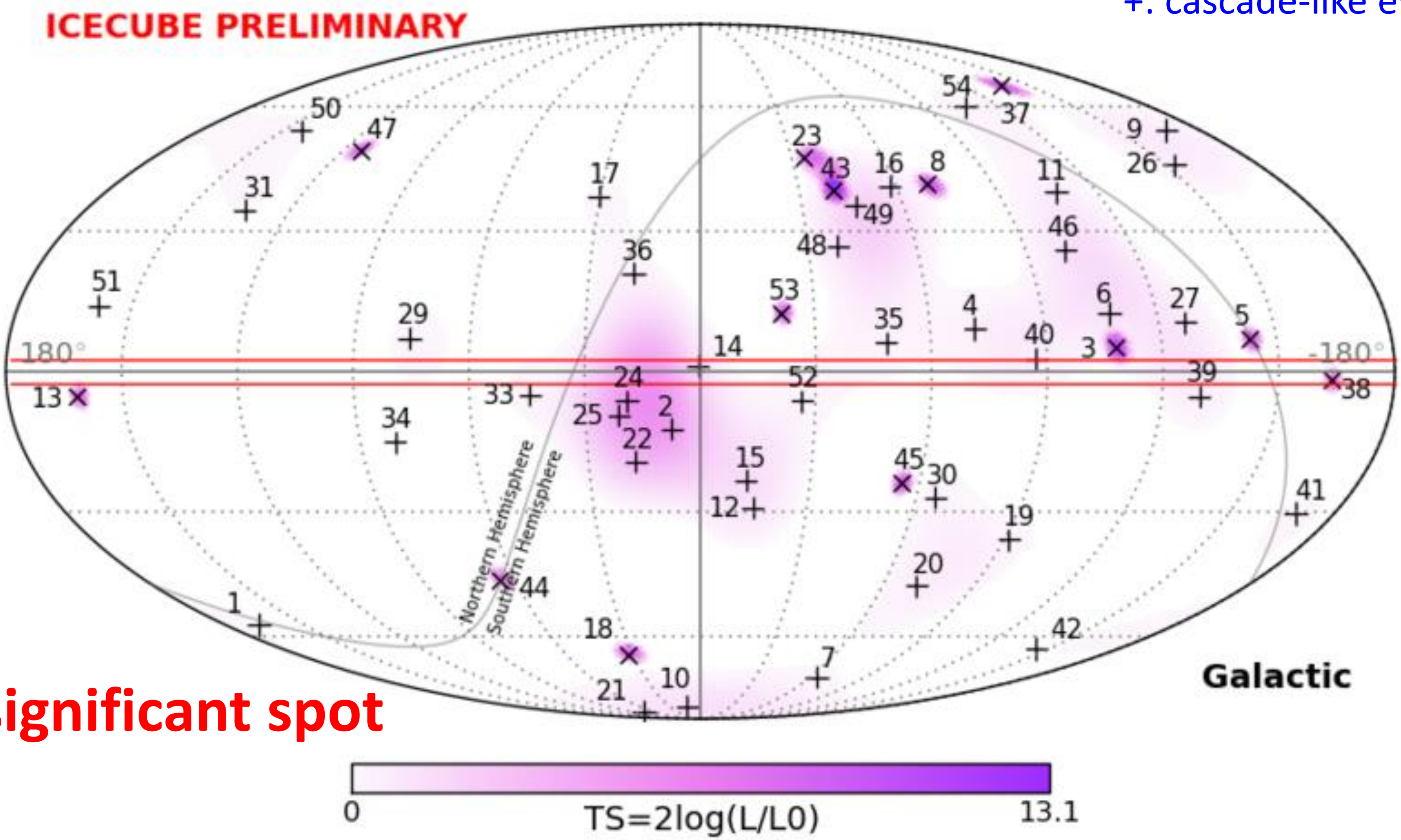
Test null hypothesis against the most likely

L0: null hypothesis

L: maximized likelihood

x: track-like events

+: cascade-like events

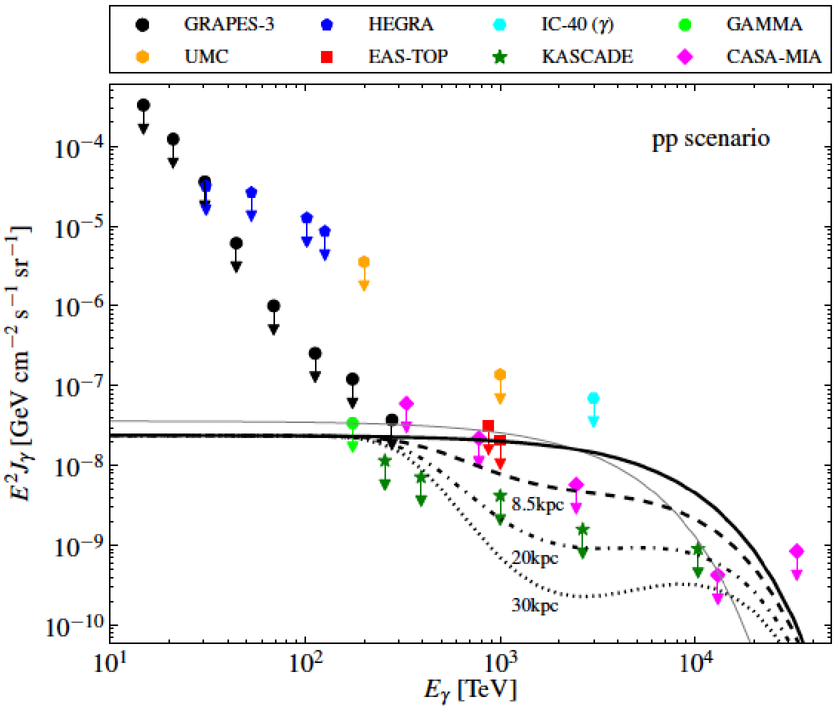


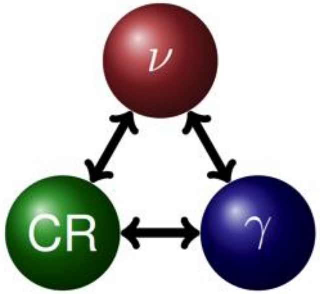
No significant spot

Galactic or extragalactic?

- ✓ Apparent concentration at the galactic center → not significant
- ✓ High latitude events → extragalactic

Gamma-ray flux expected from neutrino flux observed by IceCube





M. Ahlers and K. Murase, PRD, 90, 023010 (2014)

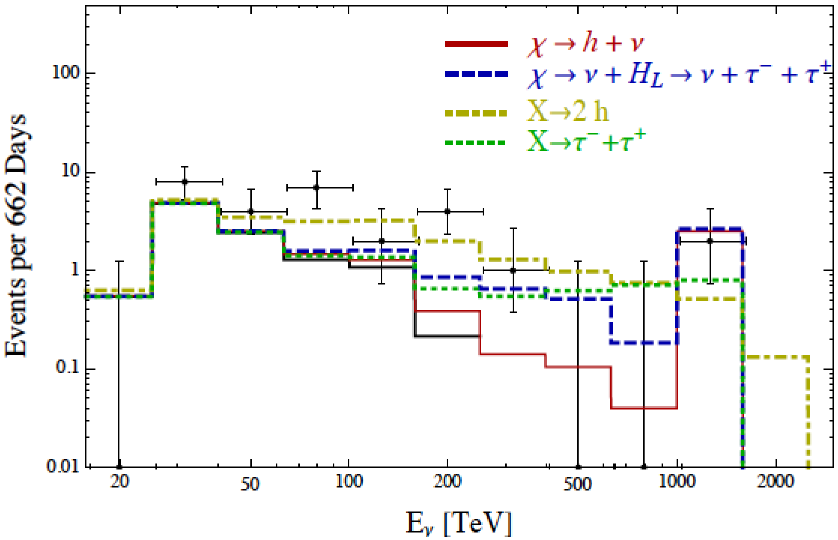
- ✓ Galactic hypothesis is disfavored, though half of the IceCube events are placed where other experiments can not observe
- ✓ Moreover, only 1 events out of 28 events is expected from the galactic plane
- ✓ Most of the events will be **extragalactic**

Dark matter origin?

Y. Bai, R. Lu and J. Salvaro,
arXiv: 1311.5864

- ✓ Expected energy distribution similar to observed (peak + continuum)
- ✓ Event rate from annihilation is too small
- ✓ Possibly decaying DM

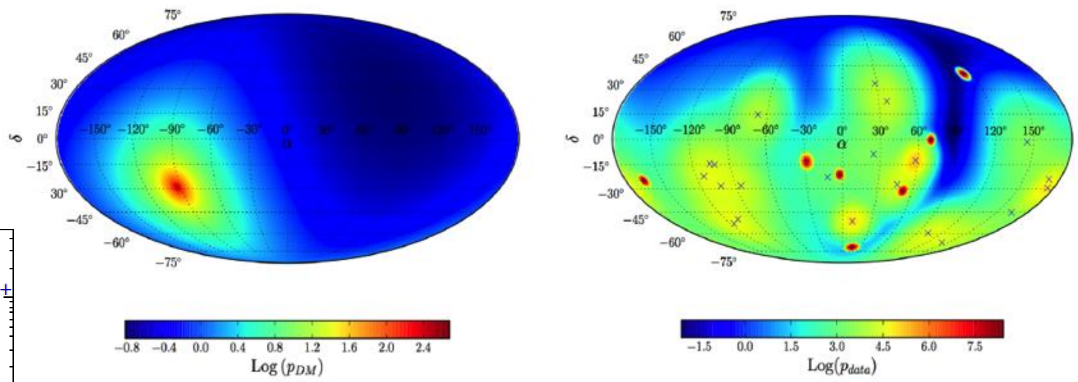
- ✓ DM alone can not explain the observation
- ✓ Best fit: DM + homogeneous BG



Equatorial coordinate

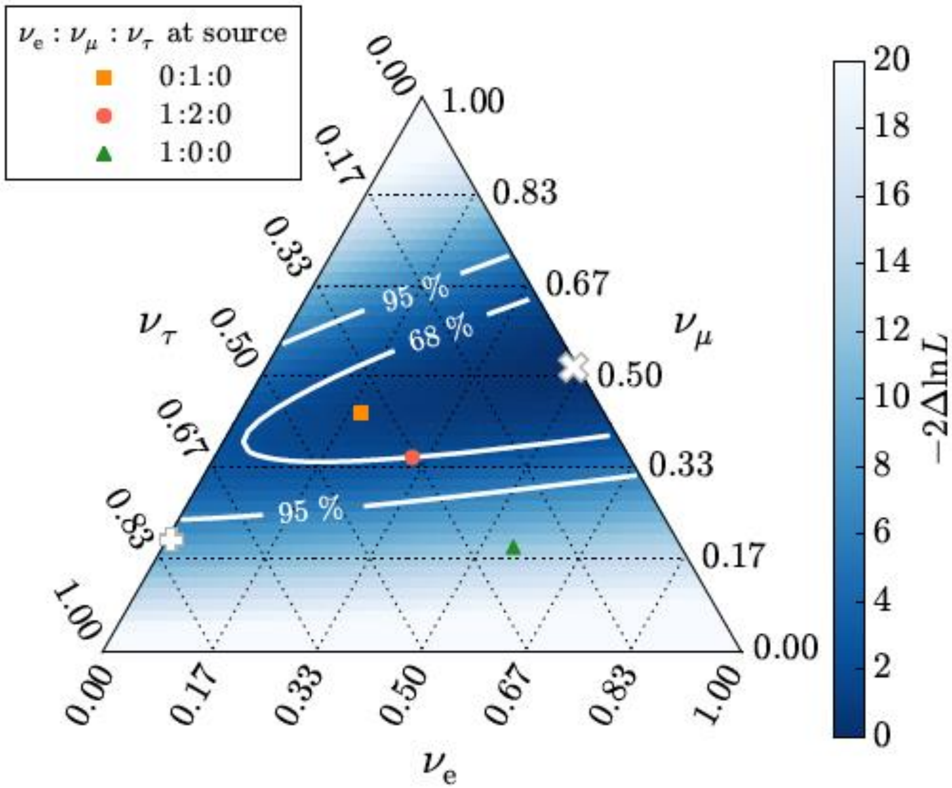
Einasto profile

Observed by IceCube



Neutrino flavor ratio

arXiv: 1507.03991



- ✓ Muon dumping

(muon lose energy due to a strong magnetic field or matter)

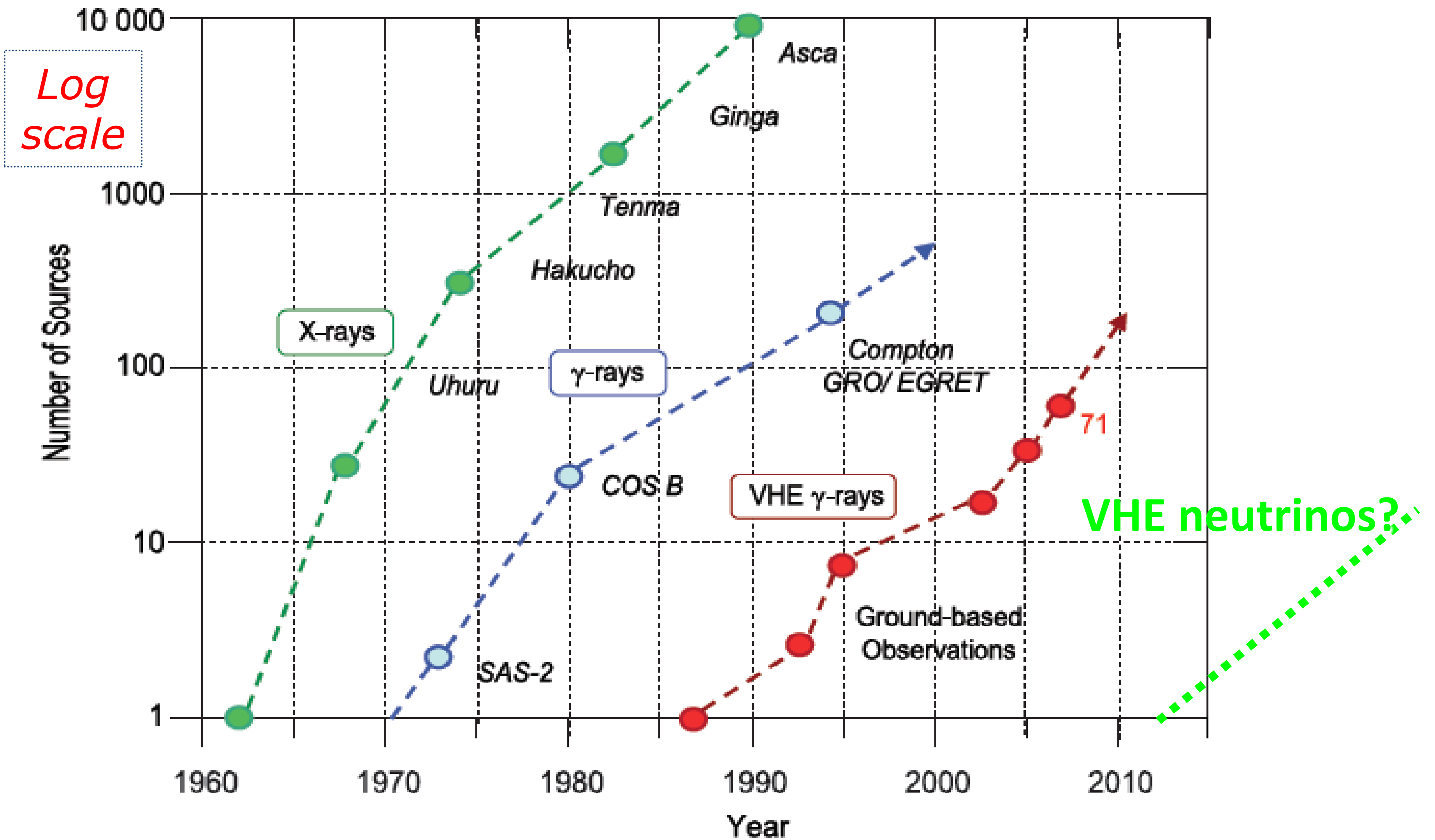
$\nu_e : \nu_\mu : \nu_\tau = 0 : 1 : 0$

- ✓ Neutron source

$\nu_e : \nu_\mu : \nu_\tau = 1 : 0 : 0$

Neutron source model rejected

How Kifune plot will be for VHE neutrinos?



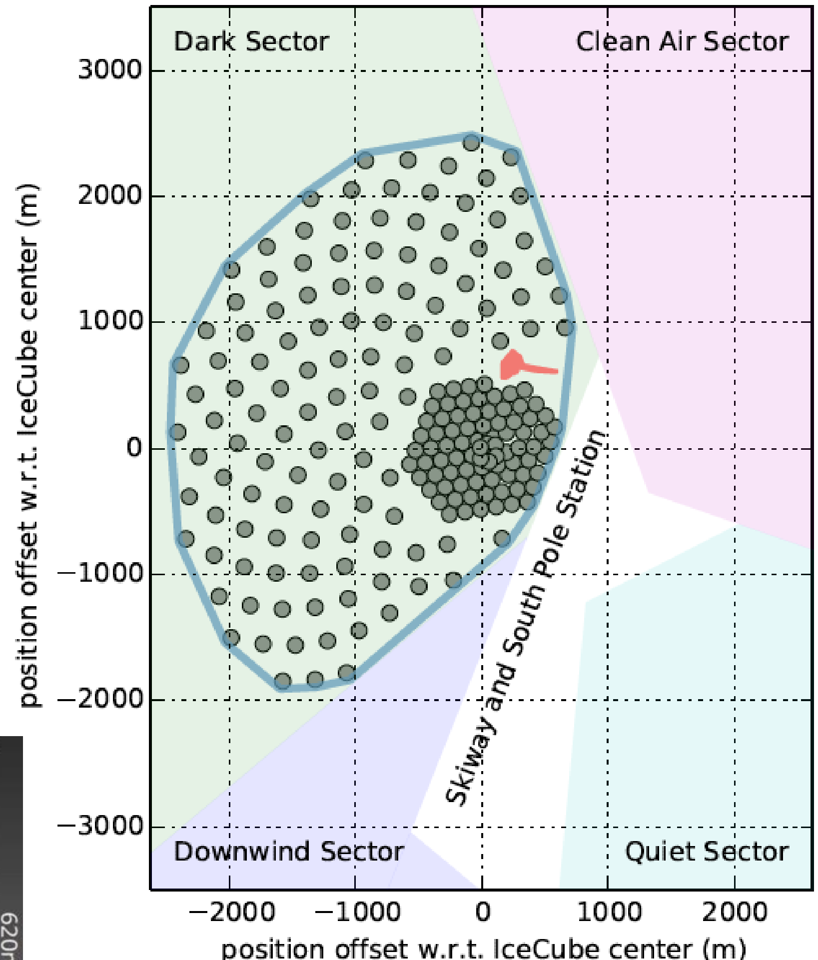
First detection is the most important!

High energy extension

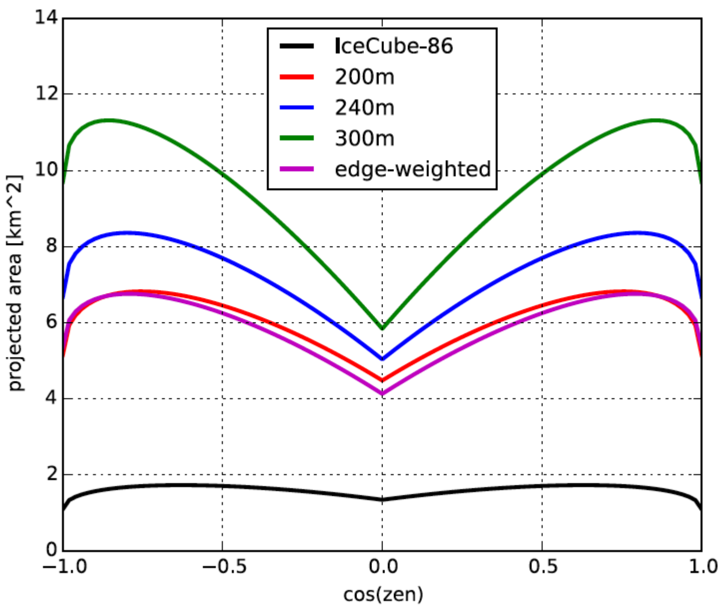
arXiv:1412.5106

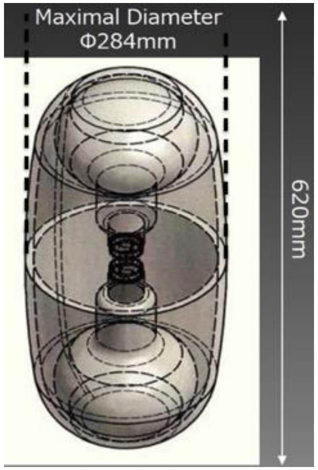
Increase the sensitivity at high energy (> 10 TeV)

- ✓ The optimization is on-going
- ✓ A possible new detector design
- ✓ Additional idea to extend surface tanks for veto



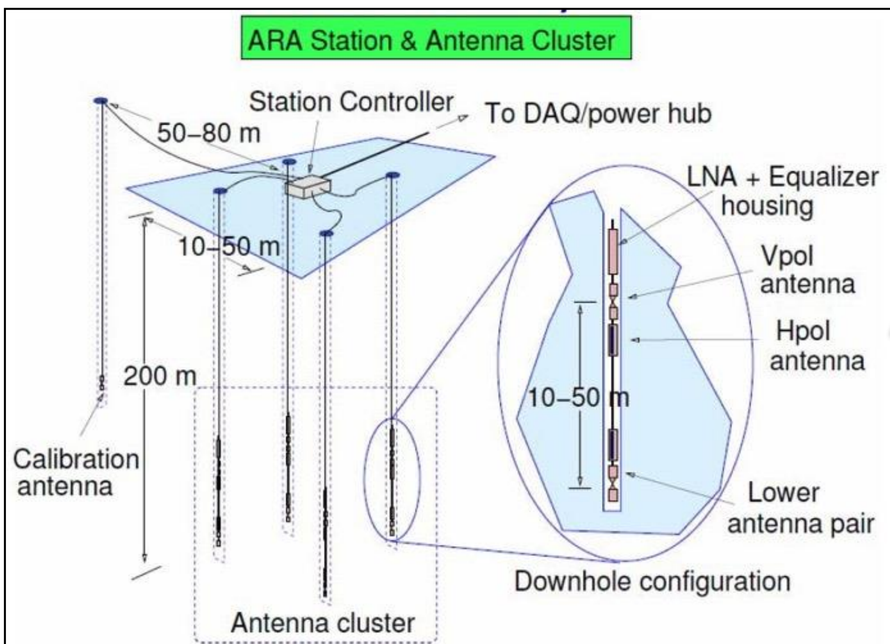
~120 new strings

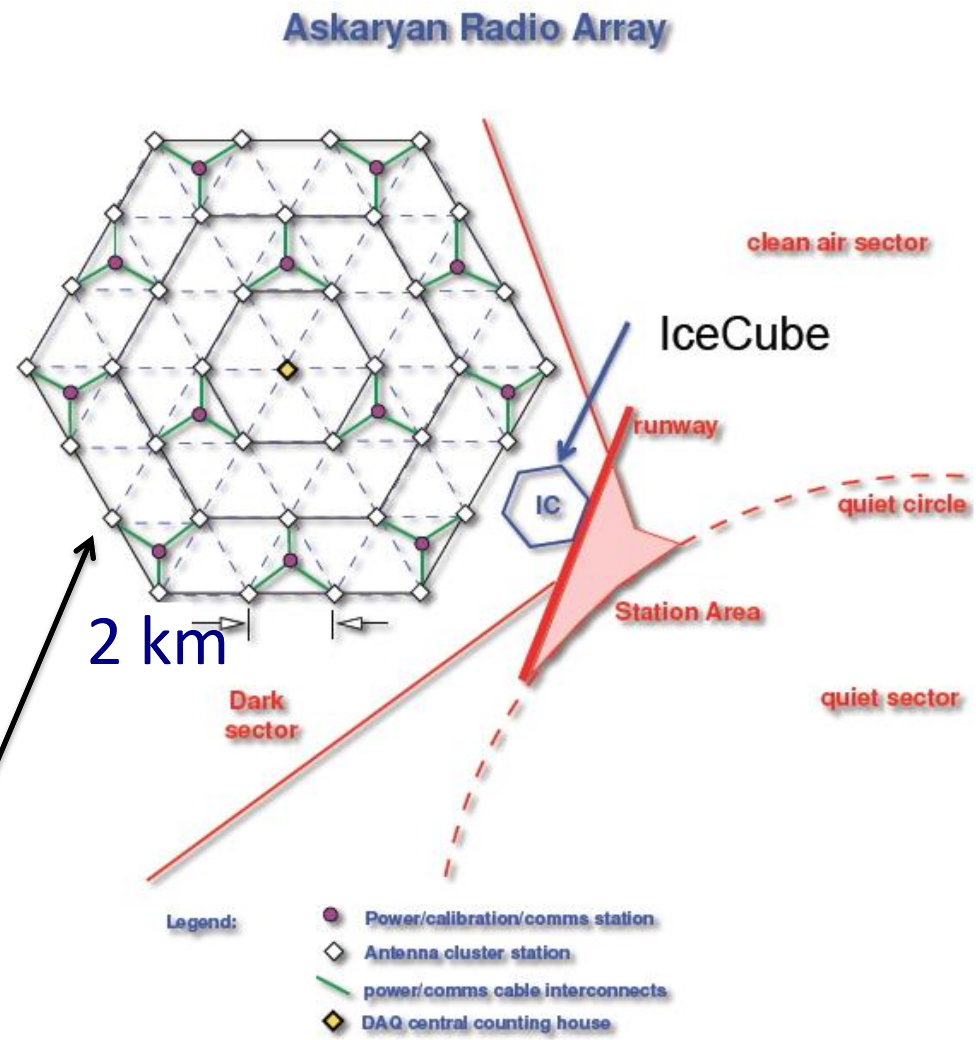




Askaryan Radio Array (ARA)

- Designed to observes high energy neutrinos above 10 PeV
- 37 stations (3 stations deployed so far)
- Each station has 4 strings of 200m depth
- Each string has 2 Vpol + 2Hpol broadband antennas (~200–800 MHz)
- Total surface area ~100 km^2



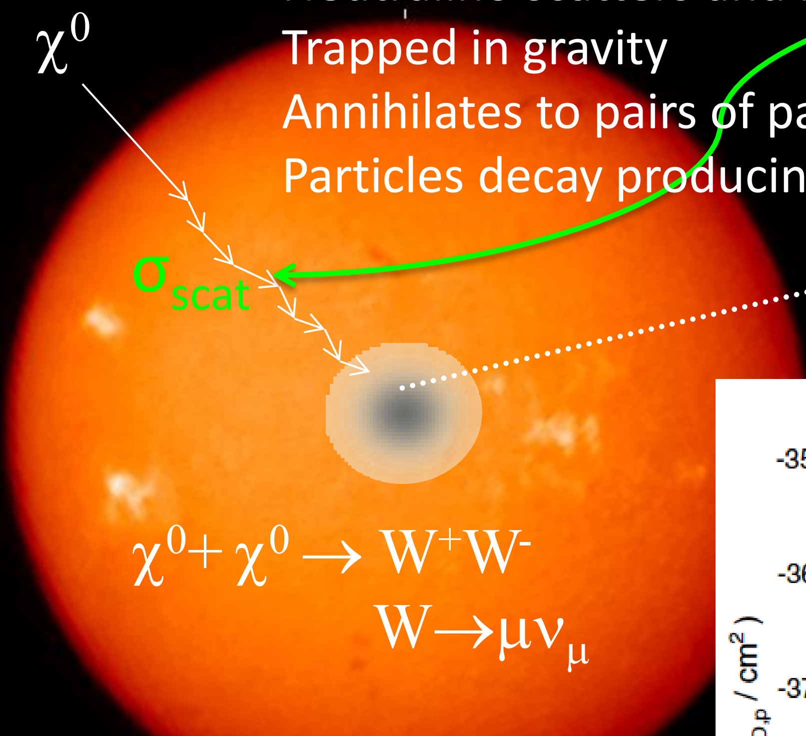


Astroparticle Physics **35** (2012) 457–477

❑ Dark matter search from Sun

observes muon neutrinos

Neutralino scatters and loses energy
Trapped in gravity
Annihilates to pairs of particles
Particles decay producing ν

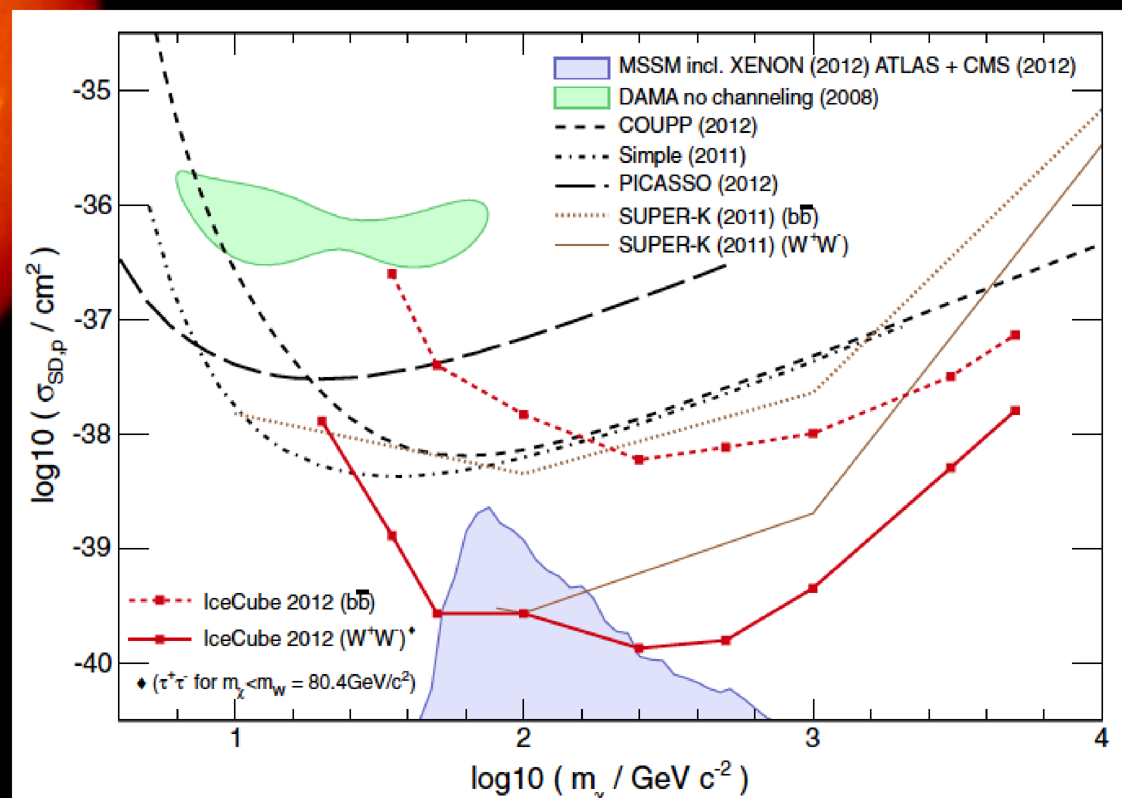


$\chi^0 + \chi^0 \rightarrow W^+W^-$
$W \rightarrow \mu\nu_\mu$

Branching ratio not perfectly known
$\chi^0 + \chi^0 \rightarrow W^+W^-$ (hard channel, typical)
$\chi^0 + \chi^0 \rightarrow b\bar{b}$ (soft channel, conservative)

χ^0: neutralino
Supersymetry particle
Mixture of super-partner of zino, photino, higgsino

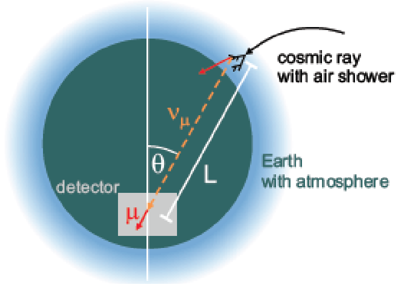
IC79 (317 days) PRL 110, 131302 (2013)

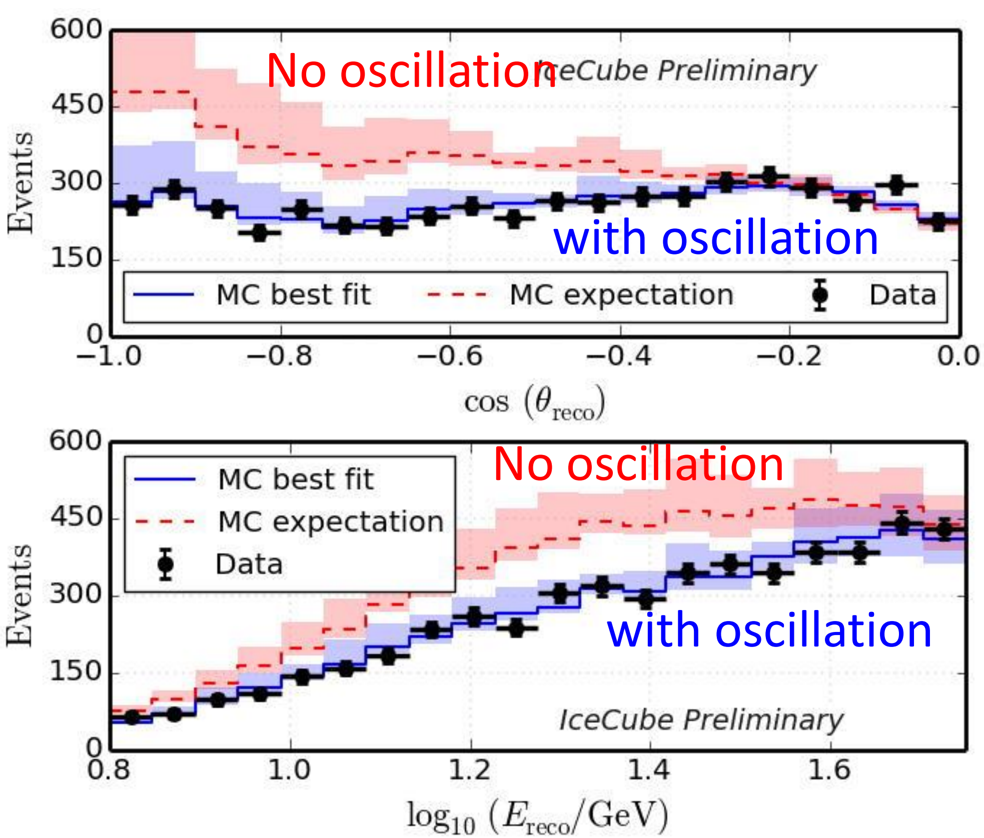


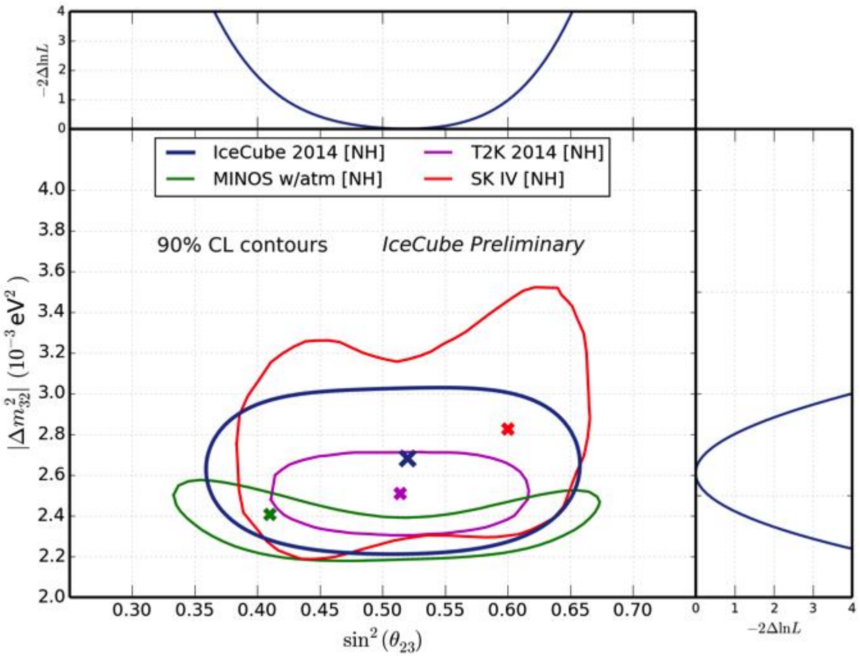
Atmospheric neutrino oscillation

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2(2\theta_{23})\sin^2(1.27\Delta m^2_{32} L/E)$$

- ✓ 3yr data (953 days)
- ✓ Competitive with other experiments







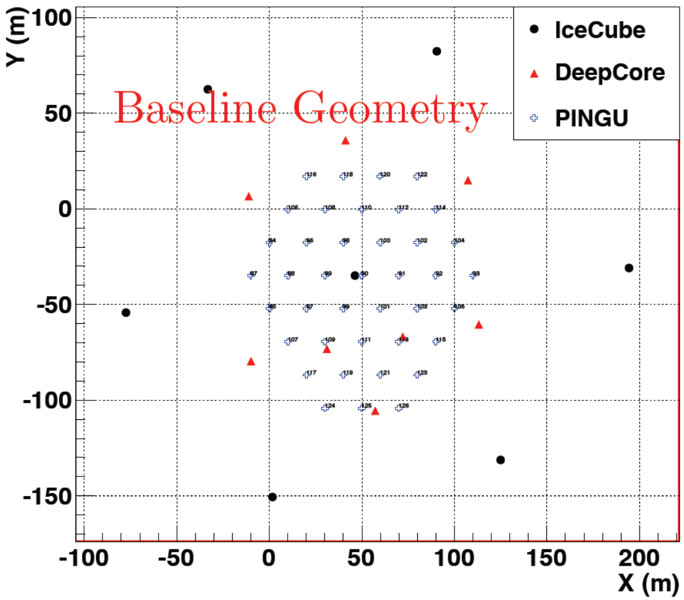
$$|\Delta m^2_{32}| = (2.72^{+0.19}_{-0.21}) \times 10^{-3}\ eV^2$$

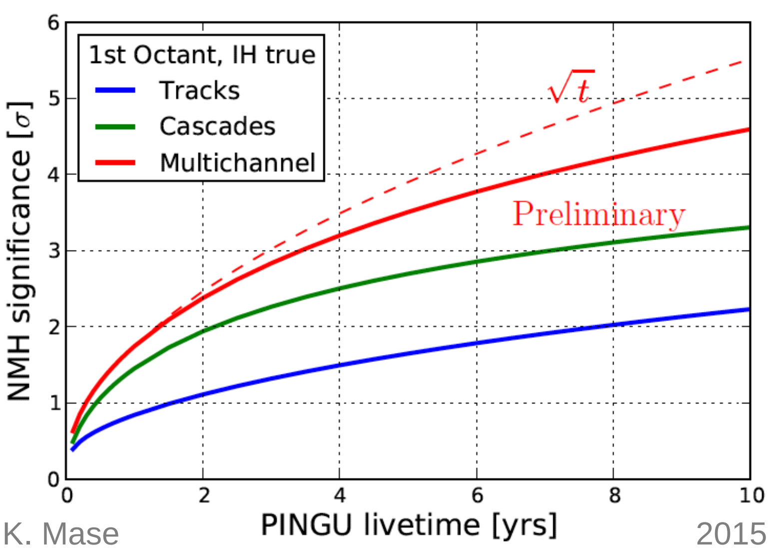
$$\sin^2\theta_{23} = 0.53^{+0.09}_{-0.12}\quad (NH)$$

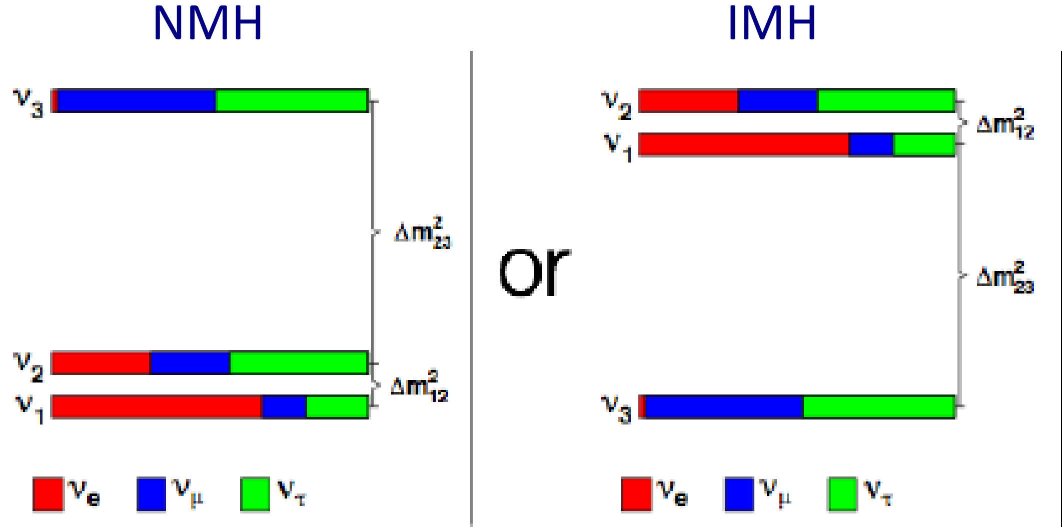
Precision IceCube Next Generation Upgrade (PINGU)

arXiv: 1401.2046

- ✓ High detector density (40 strings with 20 m spacing)
- ✓ Energy threshold: a few GeV
- ✓ Measures neutrino mass hierarchy
- ✓ Normal mass hierarchy (NMH) with 3 sigma after 3.5 years
- ✓ Resolutions: $\Delta E \sim 20\%$, $\Delta\theta \sim 10^{\circ}$ (depends on energy and flavor)







❑ Summary

- **Astrophysical neutrinos observed**
- **Gradual understanding of the observed events**
- Most events will be extragalactic
- Possible scenarios: AGNs, GRBs, DM etc.
- Can contribute to particle physics
- **More data and results are coming**
- **Future projects are being planed**

氷を掘ると宇宙が見える？