A new window to the Universe - Observation of Astrophysical Neutrinos with IceCube

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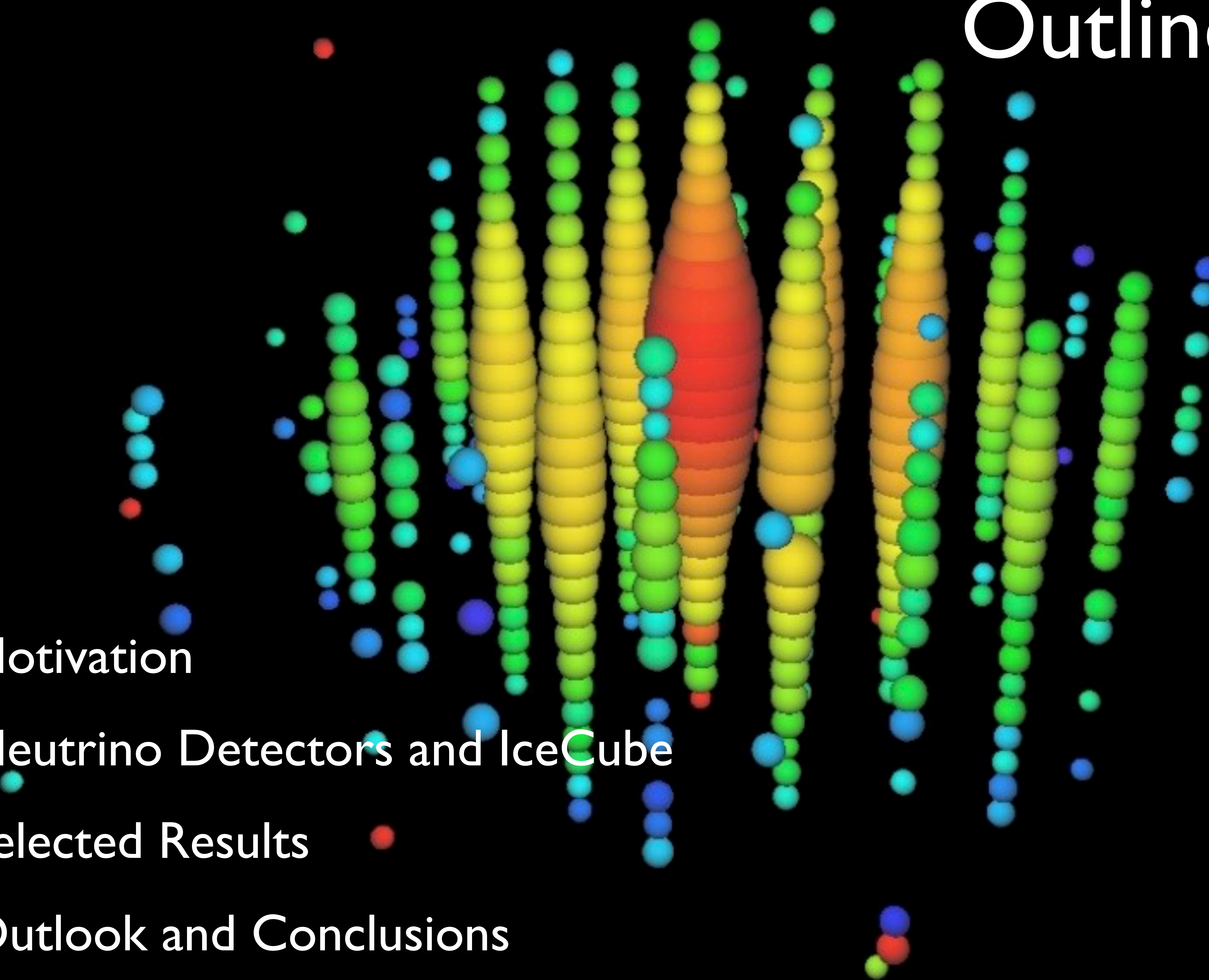
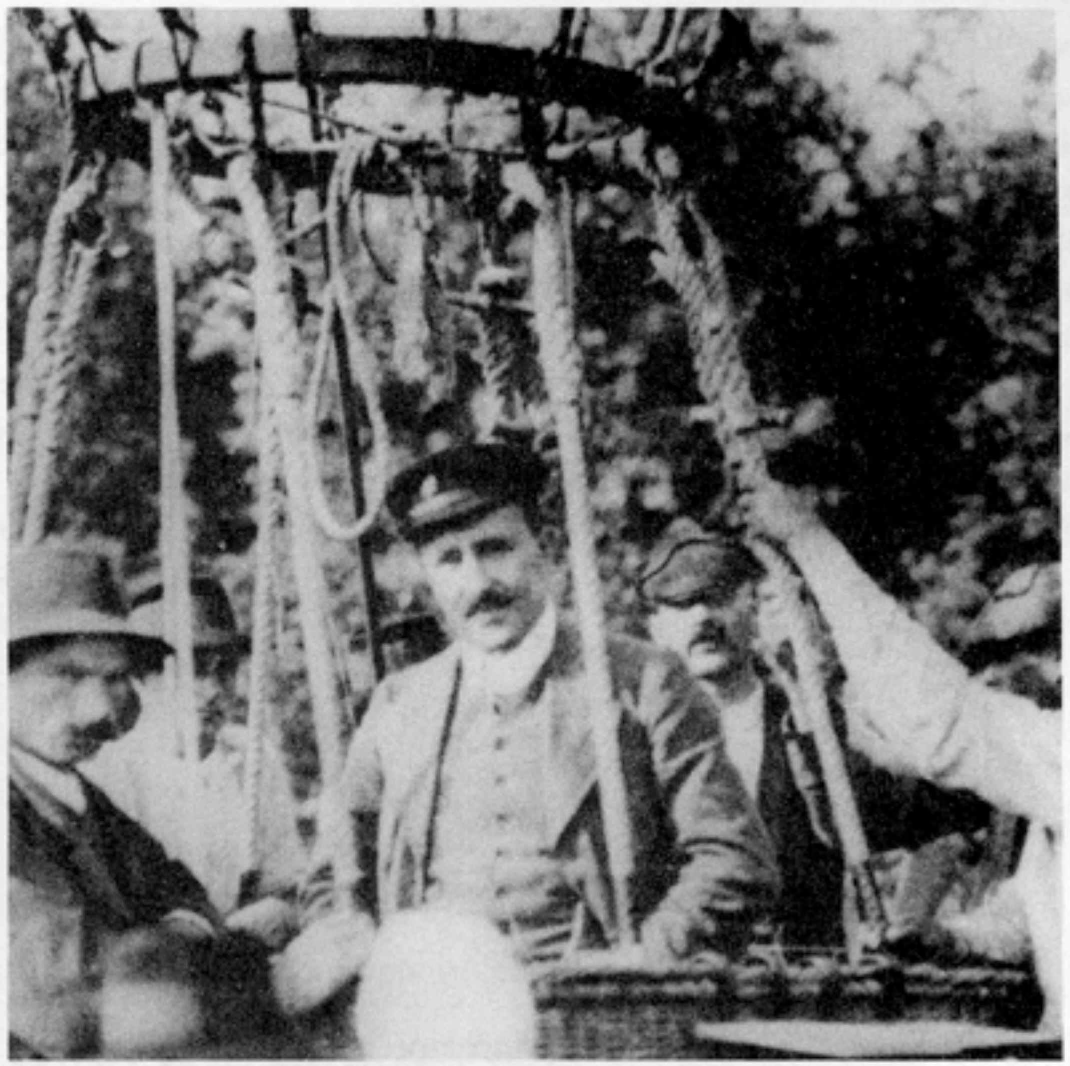
Outline



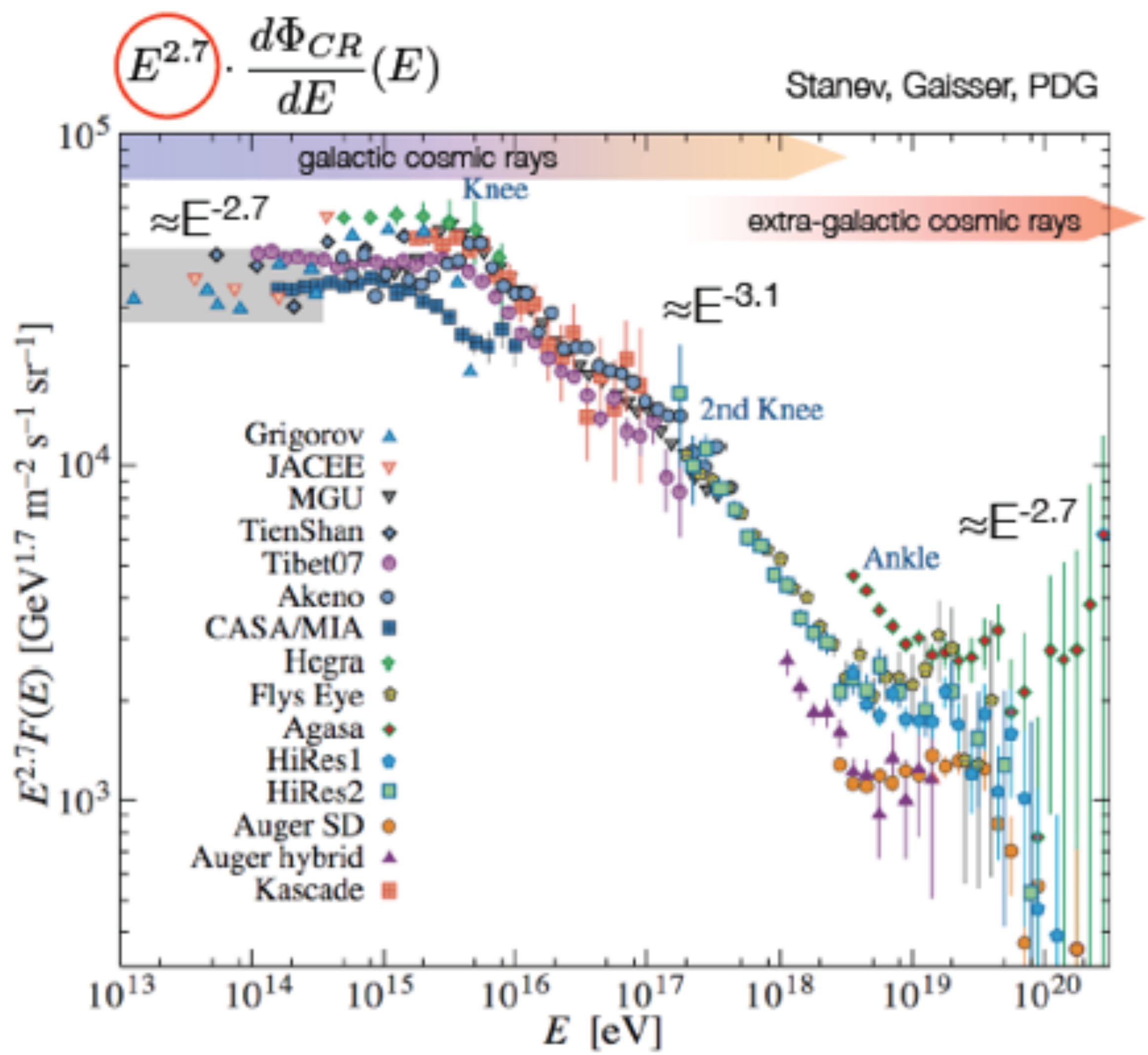
- Motivation
- Neutrino Detectors and IceCube
- Selected Results
- Outlook and Conclusions

High Energy Cosmic Ray Mystery



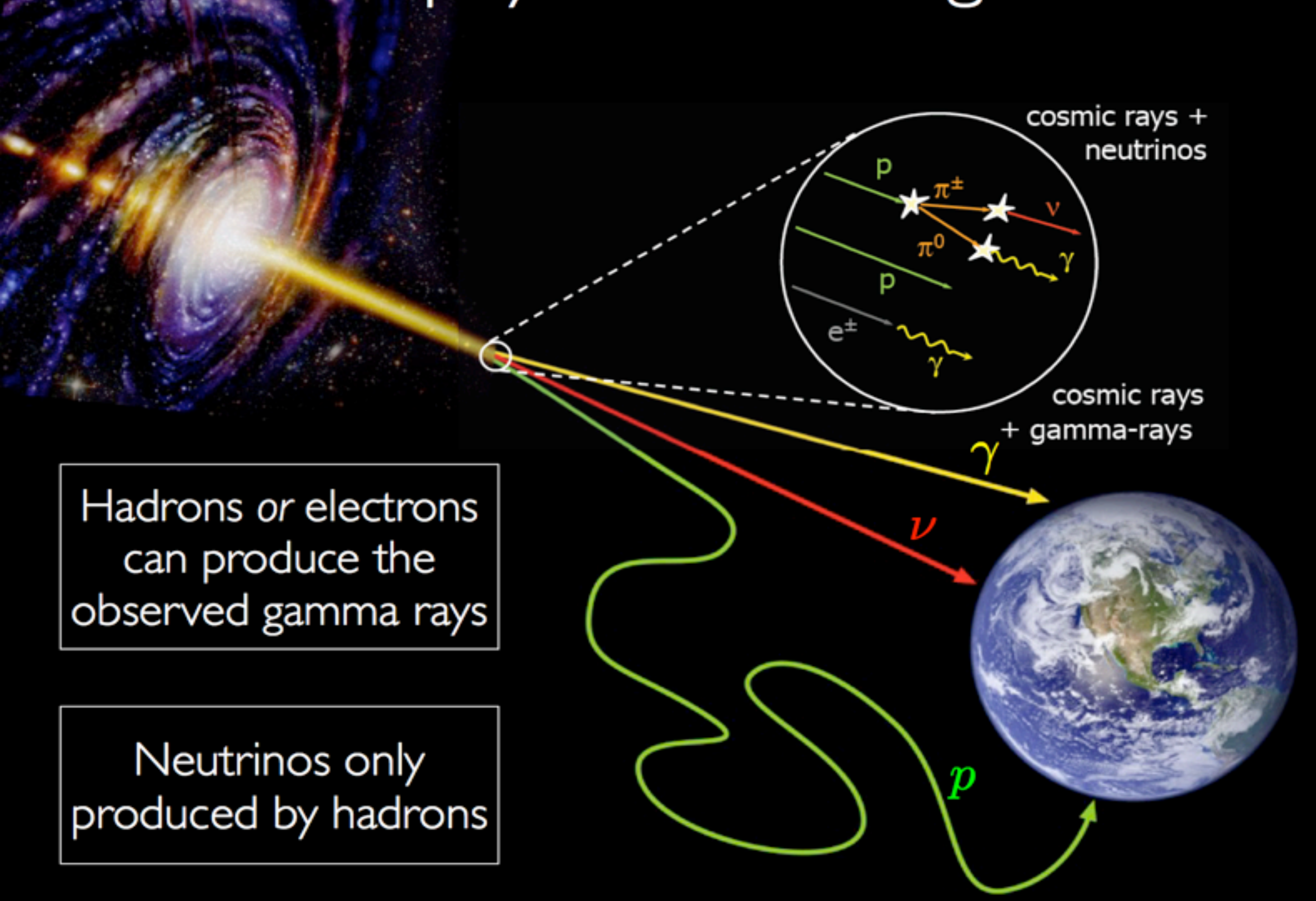
Courtesy ALPHONZ WEBER, FORDHAM UNIVERSITY

Victor Hess surrounded by Austrian peasants after landing from one of his ascensions a few weeks before his record breaking ascent in the Böhmen.



- Where are they coming from ?
- What cosmic sources accelerate these particles to energies in the EeV range ?

Astrophysical Messengers

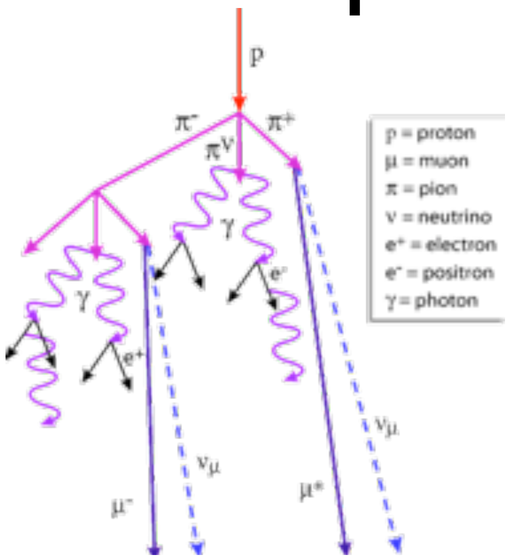


Hadrons *or* electrons can produce the observed gamma rays

Neutrinos only produced by hadrons

Sources of High Energy Neutrinos

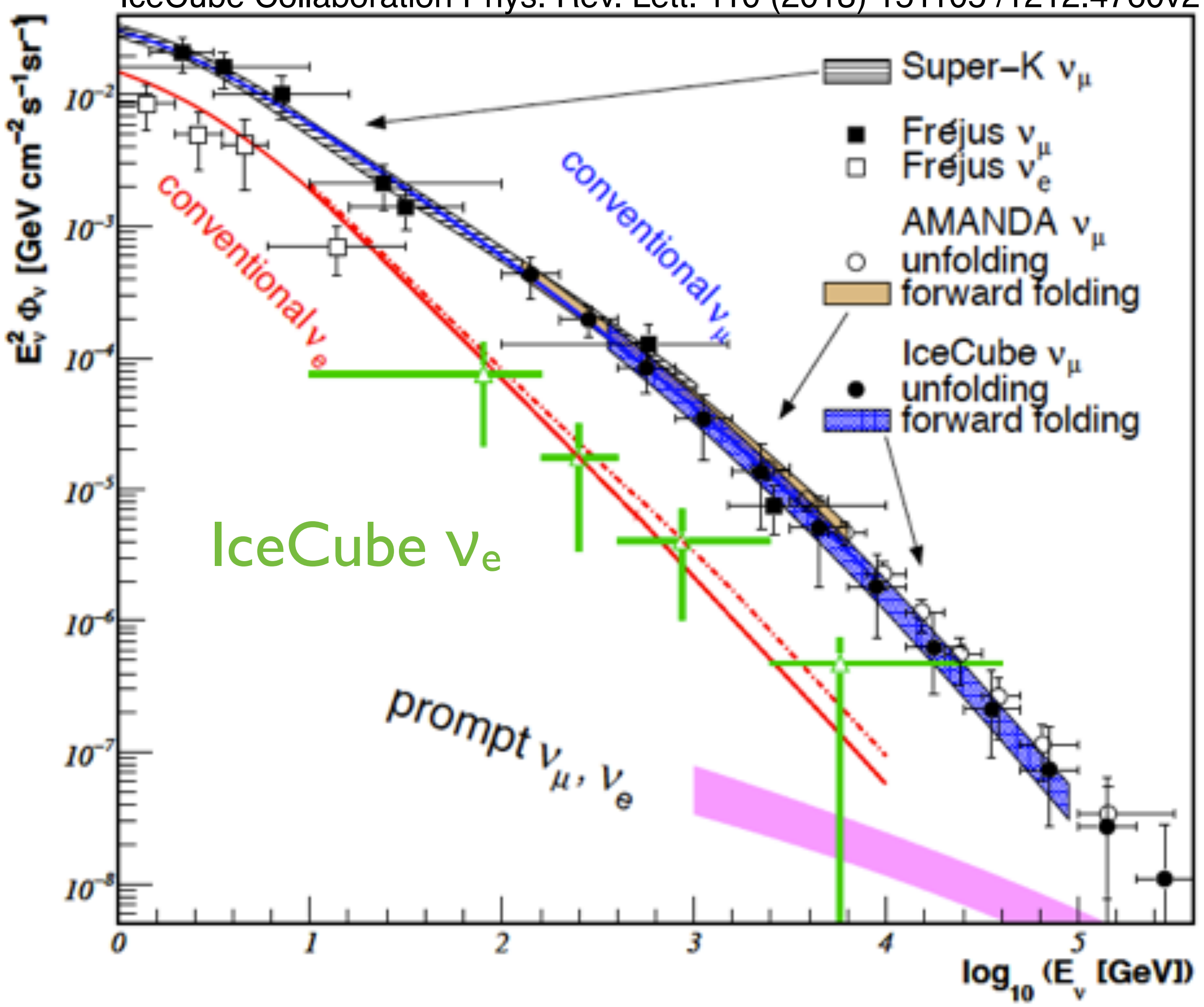
Atmospheric Neutrinos



Cosmic rays interact in the upper atmosphere:

$p + A \rightarrow \pi^{\pm} (K^{\pm})$ + other hadrons ... $\pi^{+} \rightarrow \mu^{+}\nu_{\mu} \rightarrow e^{+}\nu_{e}\nu_{\mu}\nu_{\mu}$

IceCube Collaboration Phys. Rev. Lett. 110 (2013) 151105 /1212.4760v2

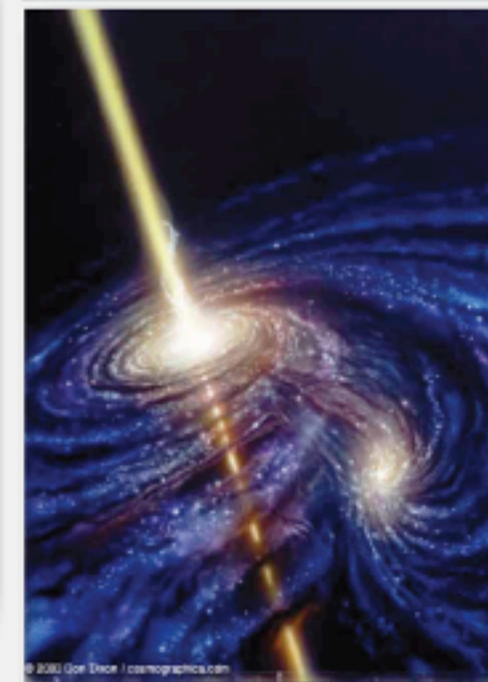


Astrophysical

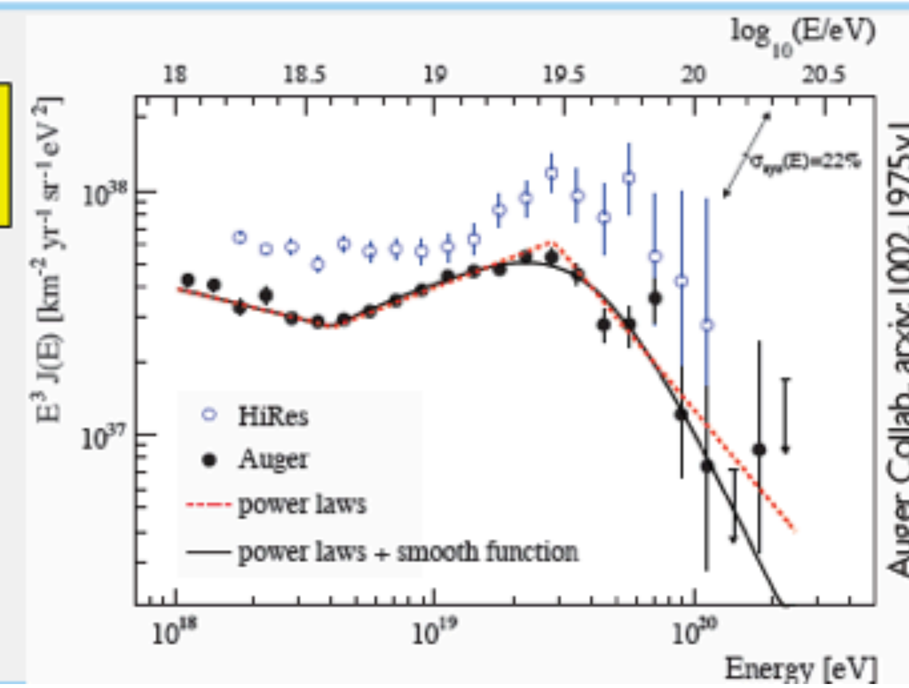
$p + (p,\gamma) \rightarrow \pi^{\pm} \rightarrow \nu$

Gamma-ray Bursts

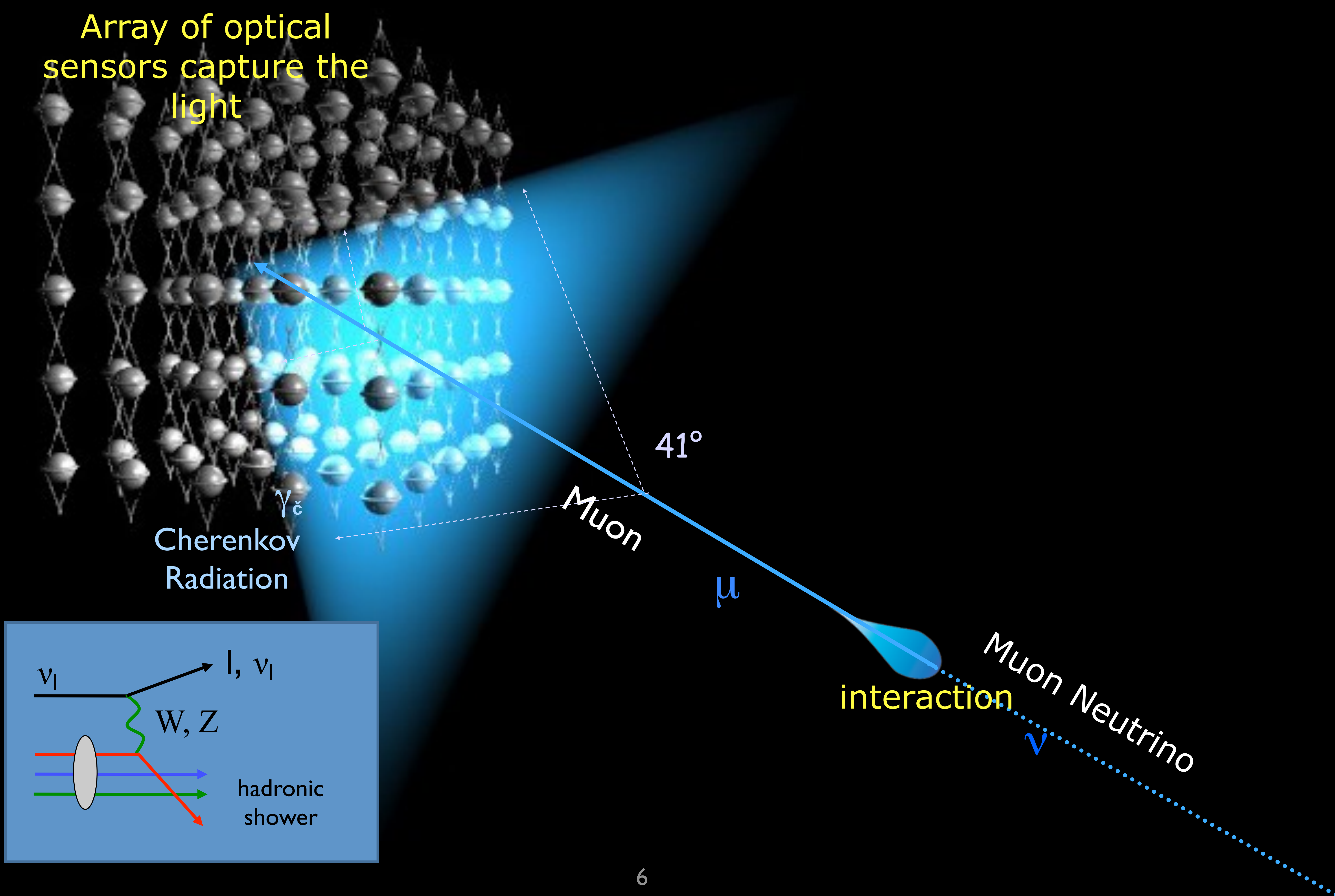
Active Galactic Nuclei

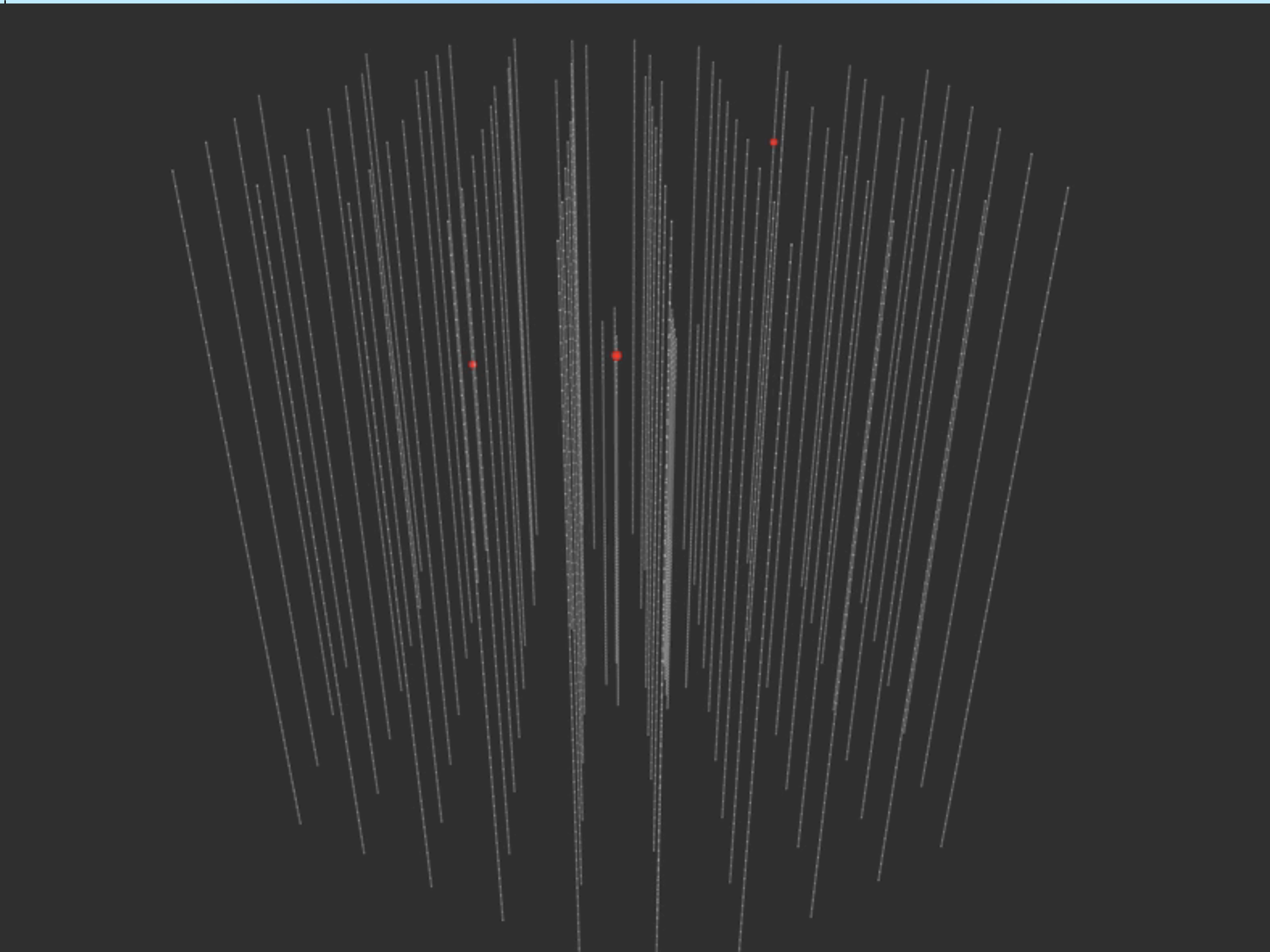


$p+\gamma_{3K} \rightarrow \Delta^{+}$ (GZK)



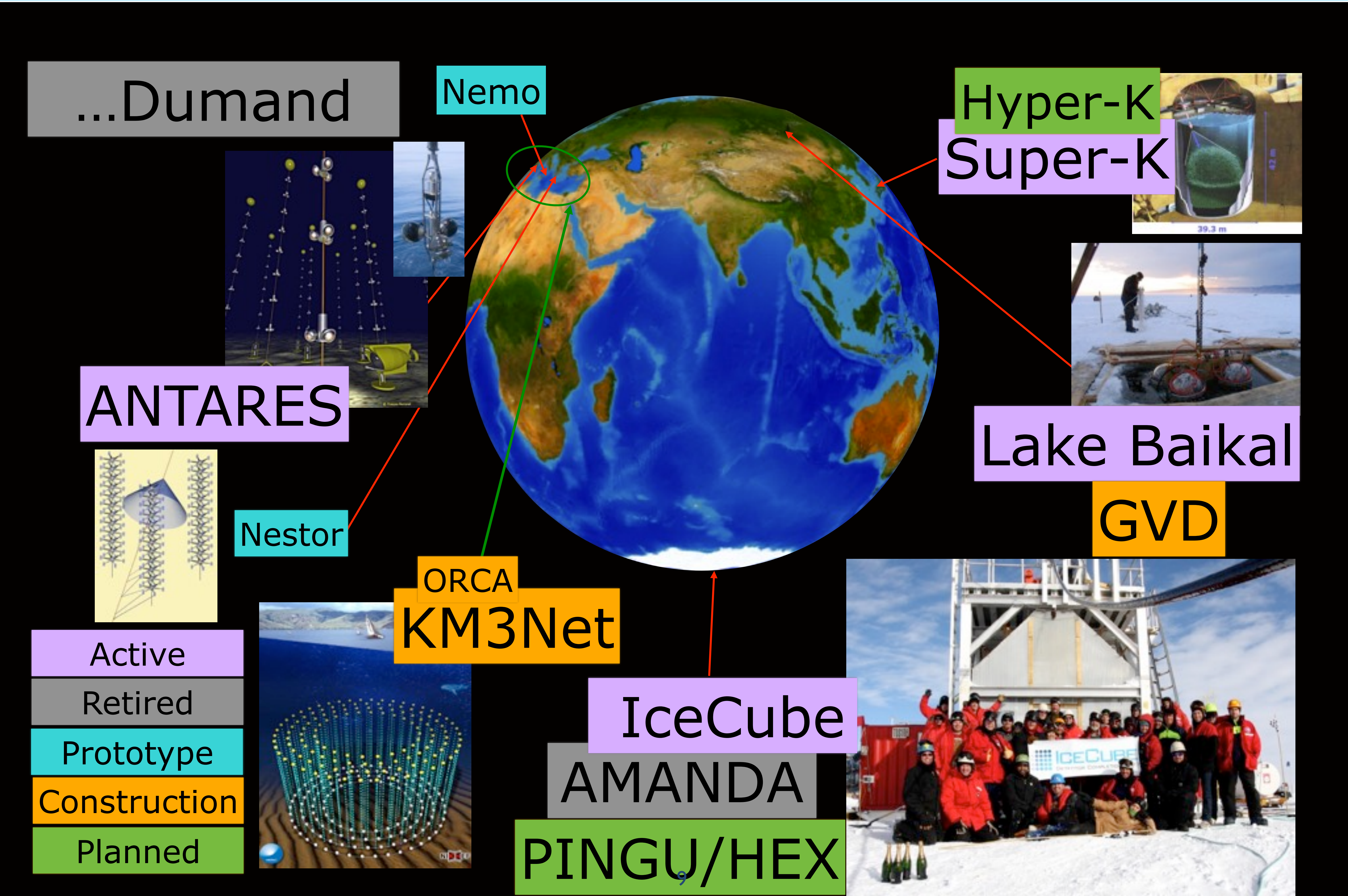
Principle of an optical Neutrino Telescope





Neutrino Telescopes

Neutrino Telescopes



The IceCube Neutrino Telescope

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SUNG KYUN KWAN UNIVERSITY (SKKU)

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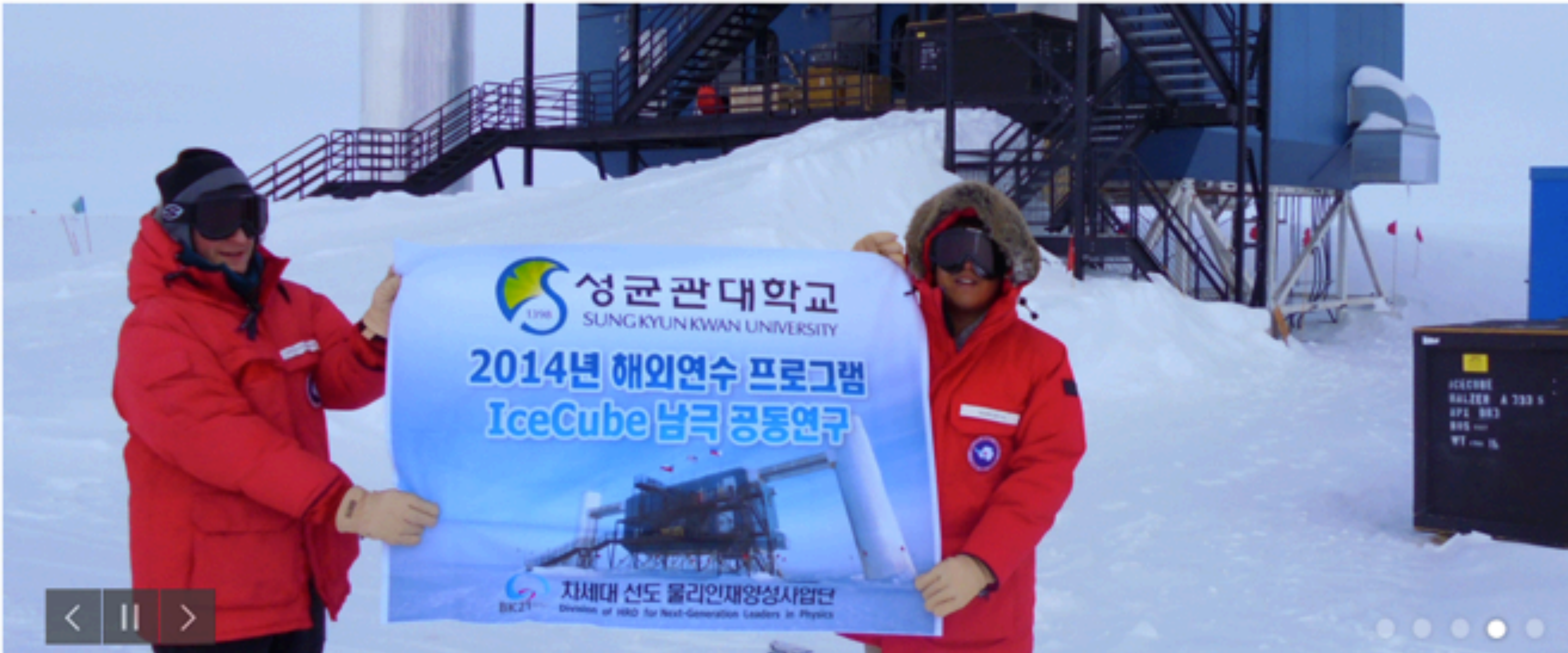

Brain Korea(BK) Project, Ice Cube Antartica Joint Reserch

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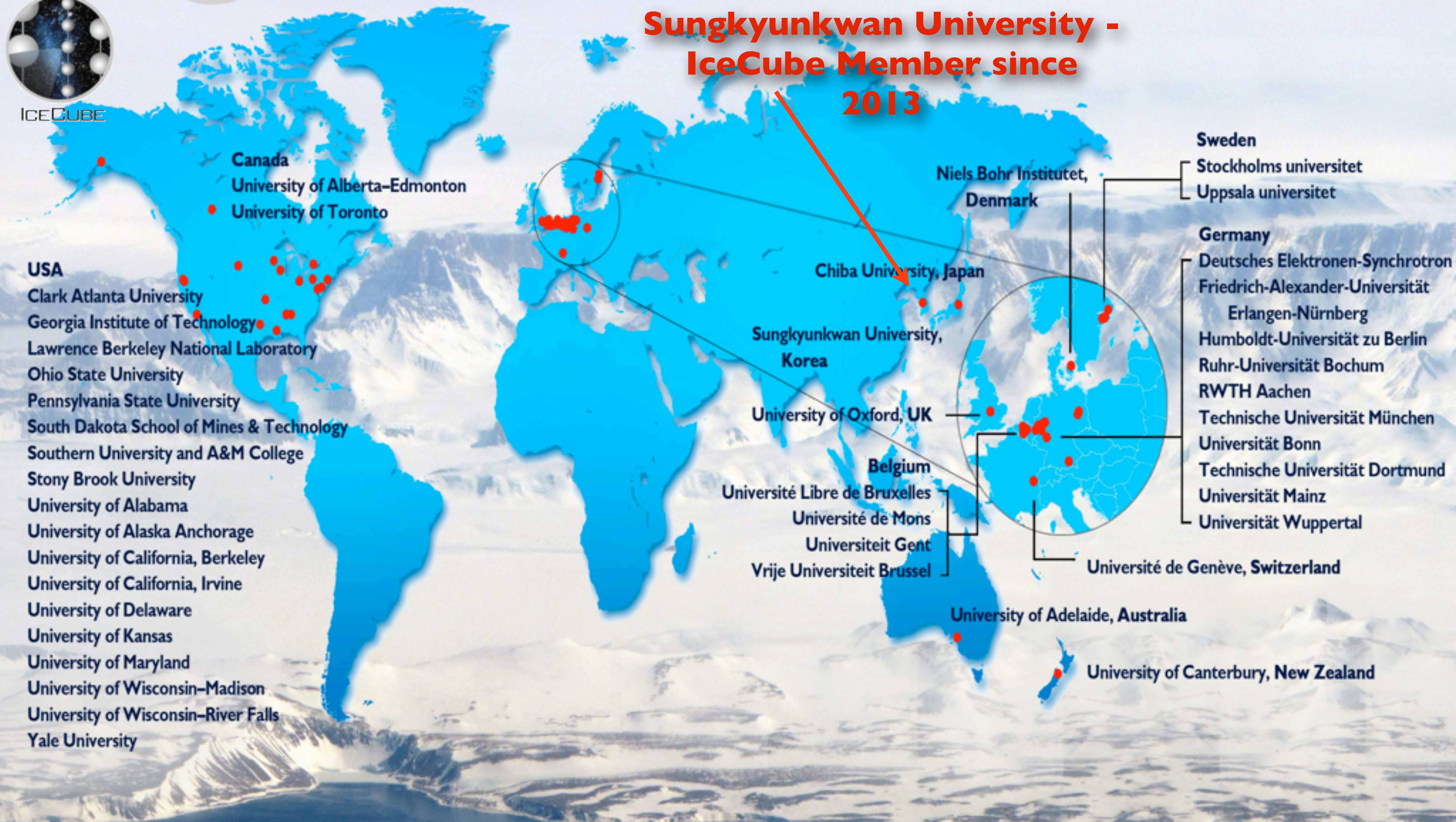
- Announcement to New International Students
- [Dormitory] 2015 Spring Myeongnyunhaksa Admi..

SKKU Reputation

SKKU News

Academics

Sungkyunkwan University - IceCube Member since 2013



Funding Agencies

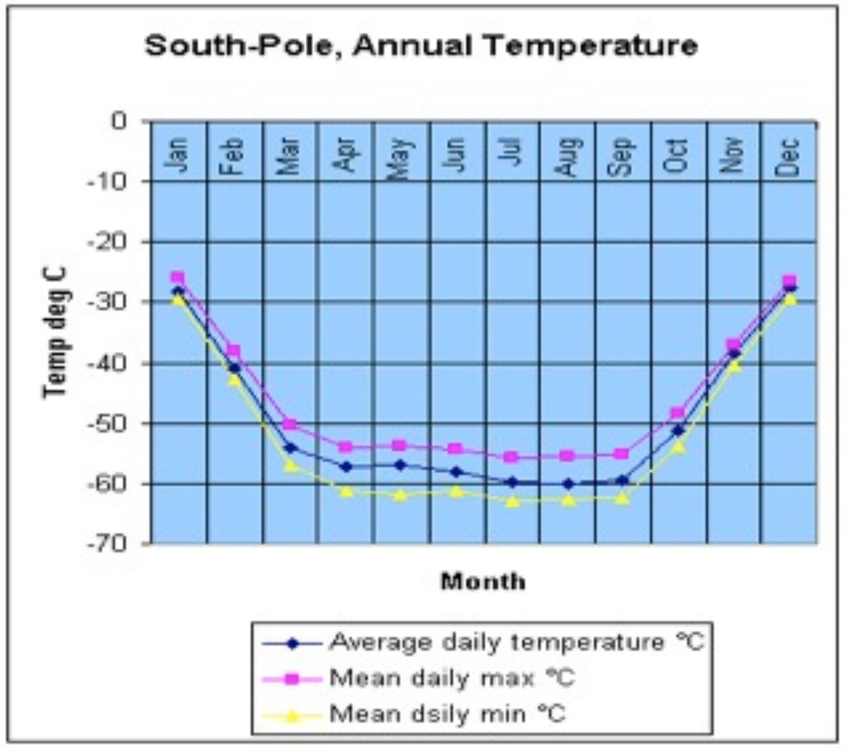
Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)
Federal Ministry of Education & Research (BMBF)
German Research Foundation (DFG)
Deutsches Elektronen-Synchrotron (DESY)
Japan Society for the Promotion of Science (JSPS)
Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)
National Research Foundation (NRF)

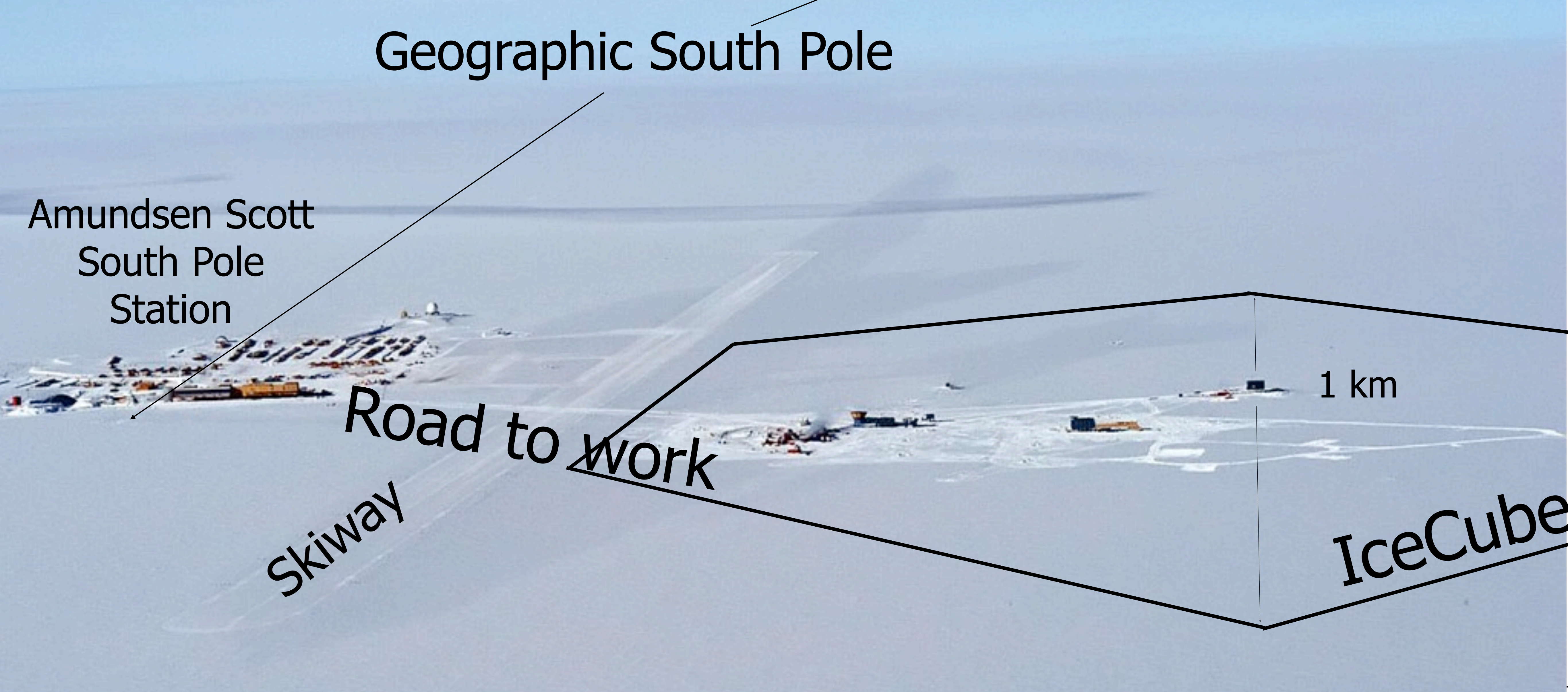

SOUTH
90°
2008


TEX

300 Club

Laboratory at the South Pole





The IceCube Neutrino Telescope

Gigaton Neutrino Detector at the Geographic South Pole

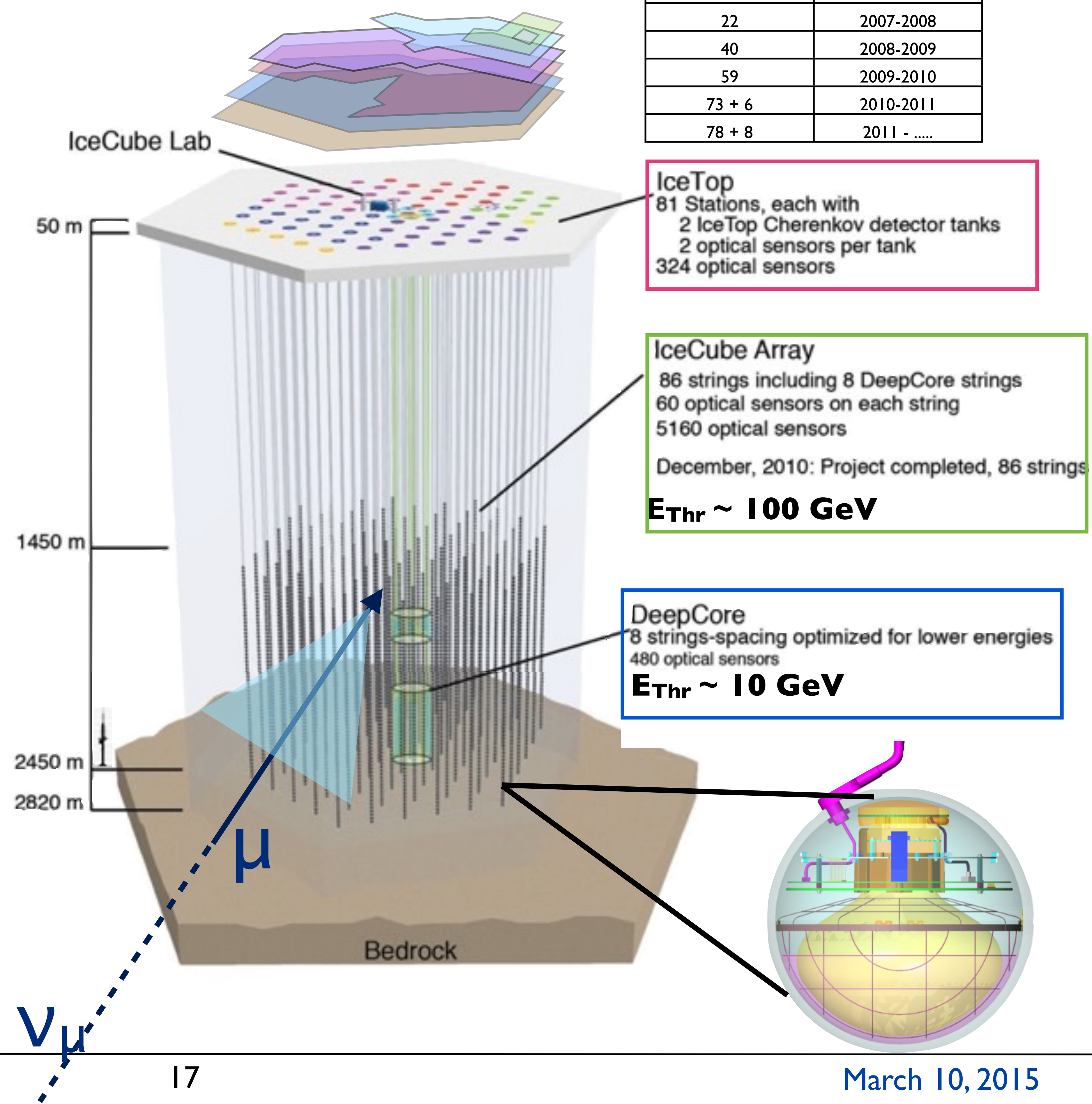
5160 Digital optical modules distributed over 86 strings

Completed in December 2010, start of data taking with full detector May 2011

Data acquired during the construction phase has been analyzed

Neutrinos are identified through Cherenkov light emission from secondary particles produced in the neutrino interaction with the ice

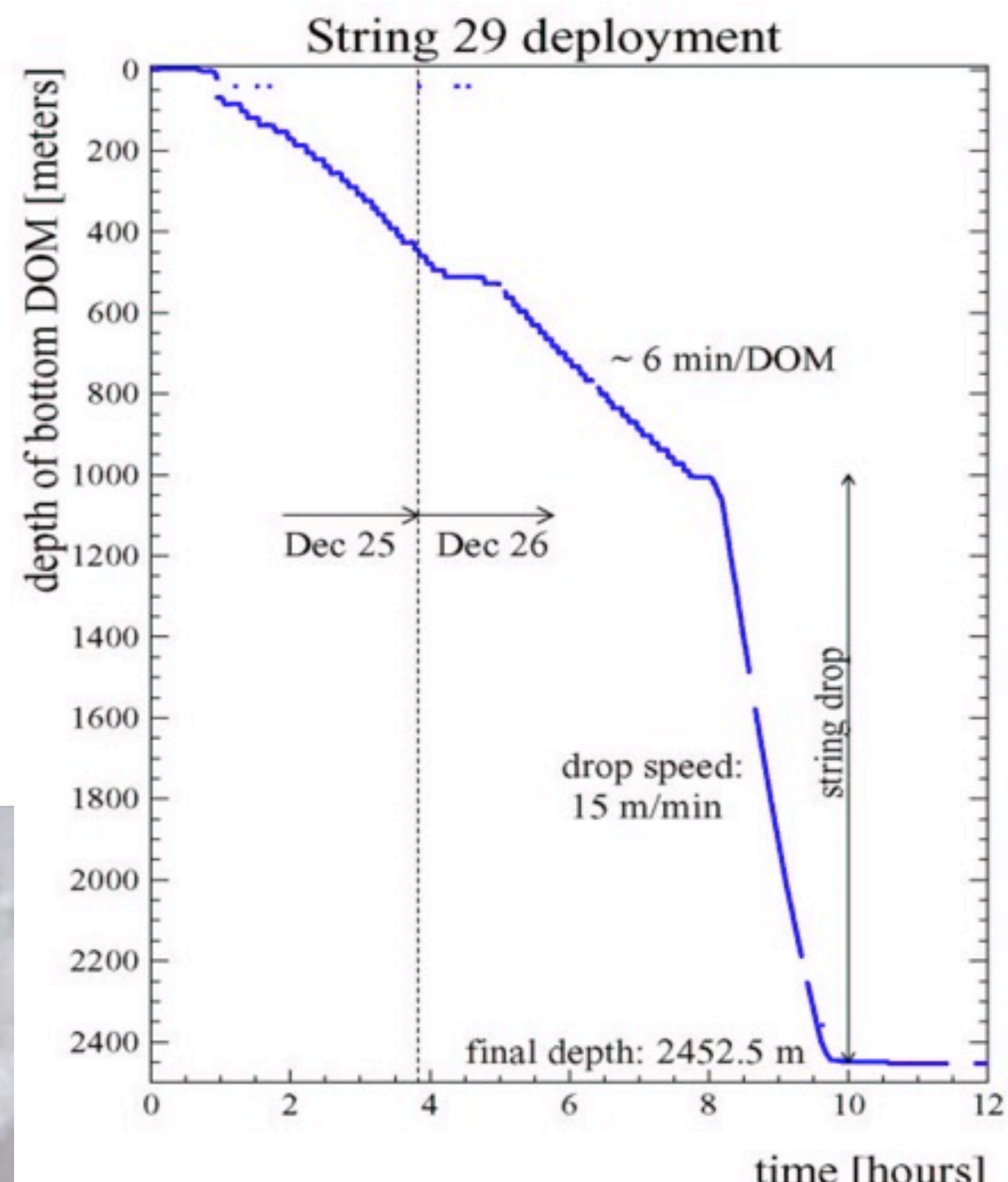
Strings	Dataset
1	2005-2006
9	2006-2007
22	2007-2008
40	2008-2009
59	2009-2010
73 + 6	2010-2011
78 + 8	2011 - .....



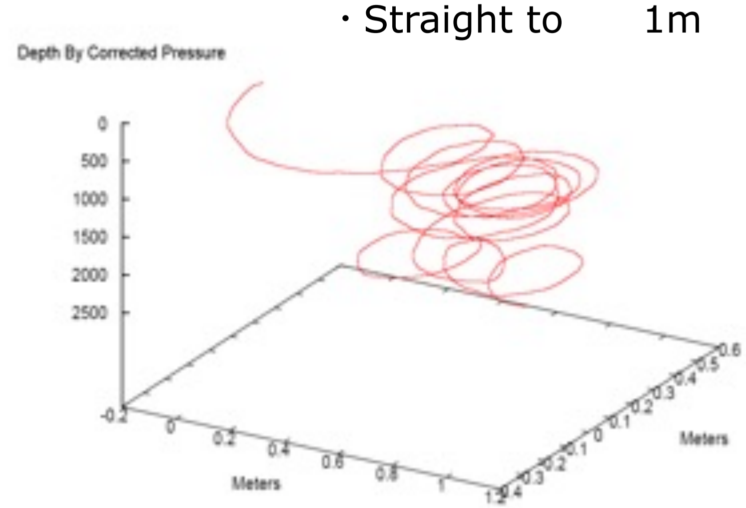
DOM @ SKKU

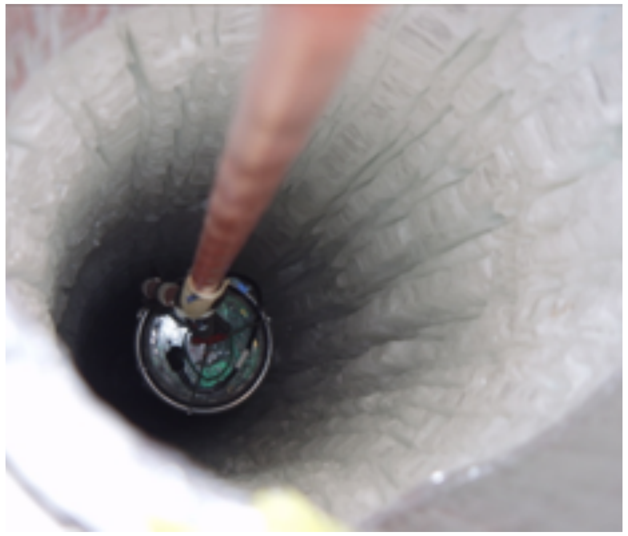
Photo: Ben Tibbets

Drilling & Deployment



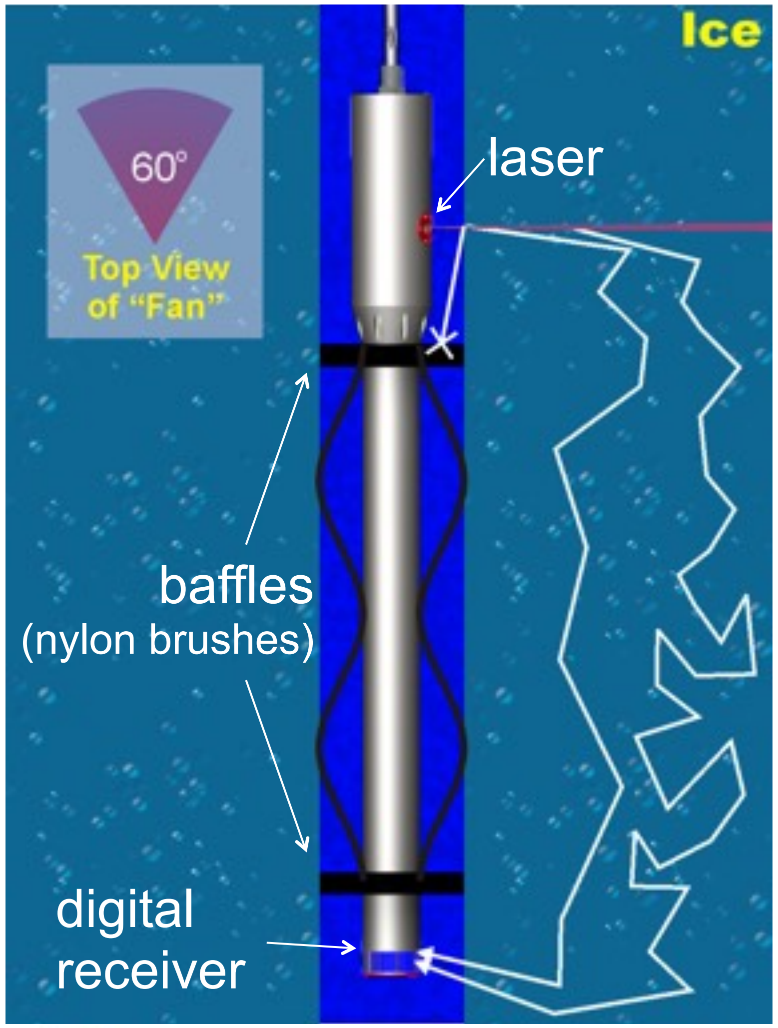
- Hole size ~60cm
- Depth ~2.5km
- Straight to 1m

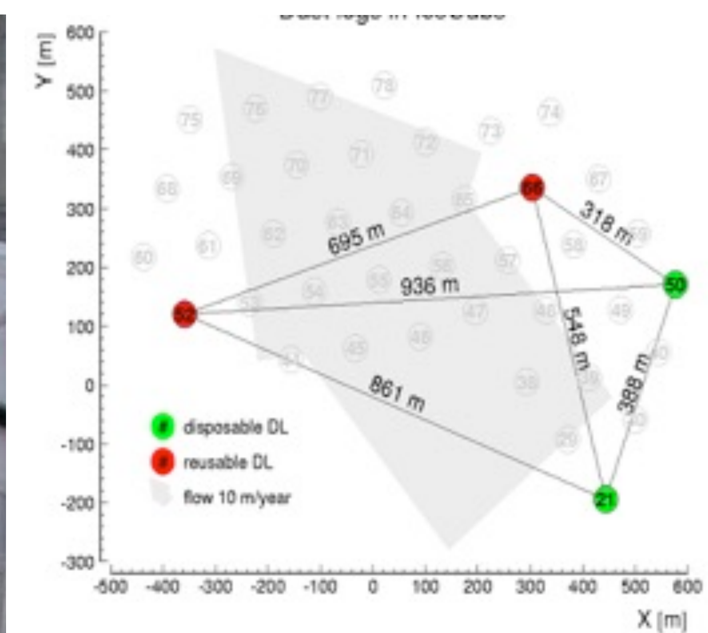


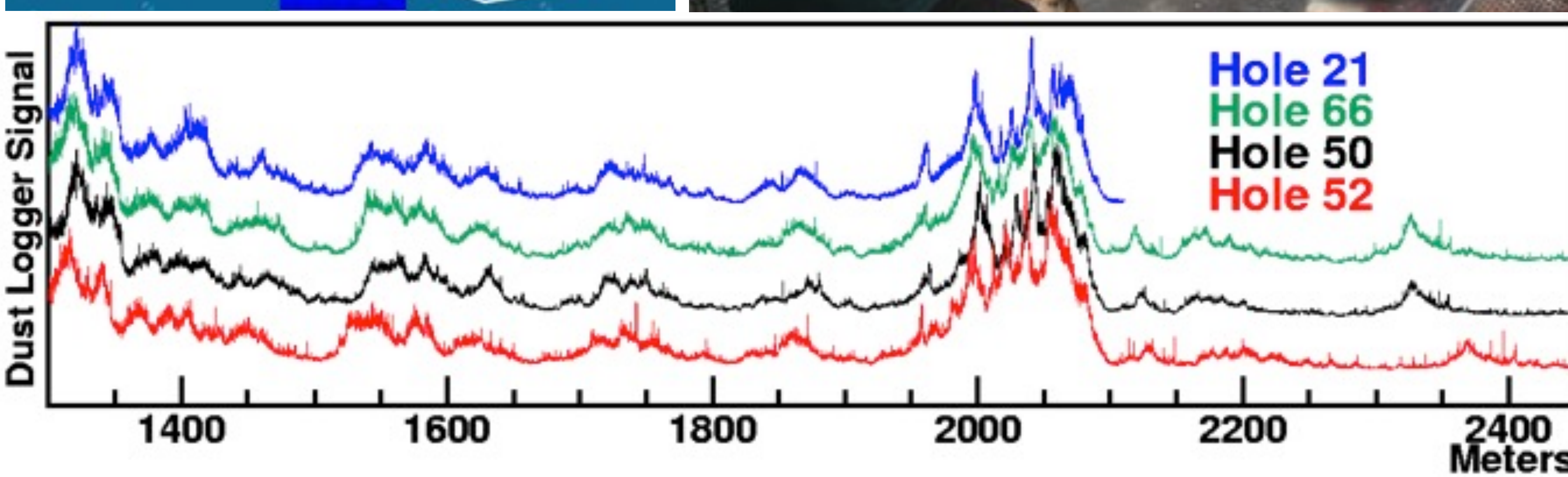


Drilling to 2500 m < 40h
String deployment ~ 12h

The Ice

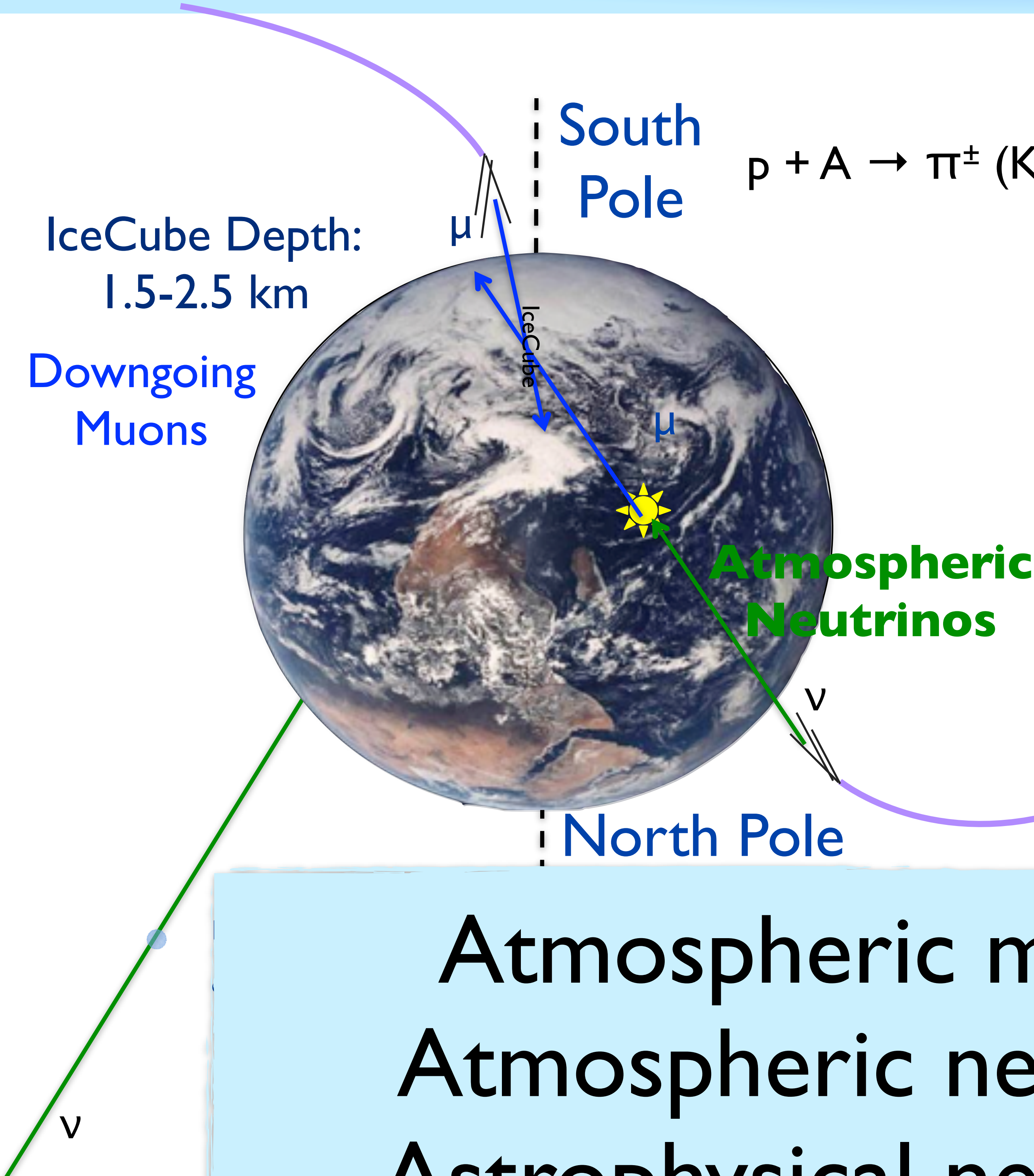






absorption length ~ 210m
scattering length ~20-40m

Signals in IceCube



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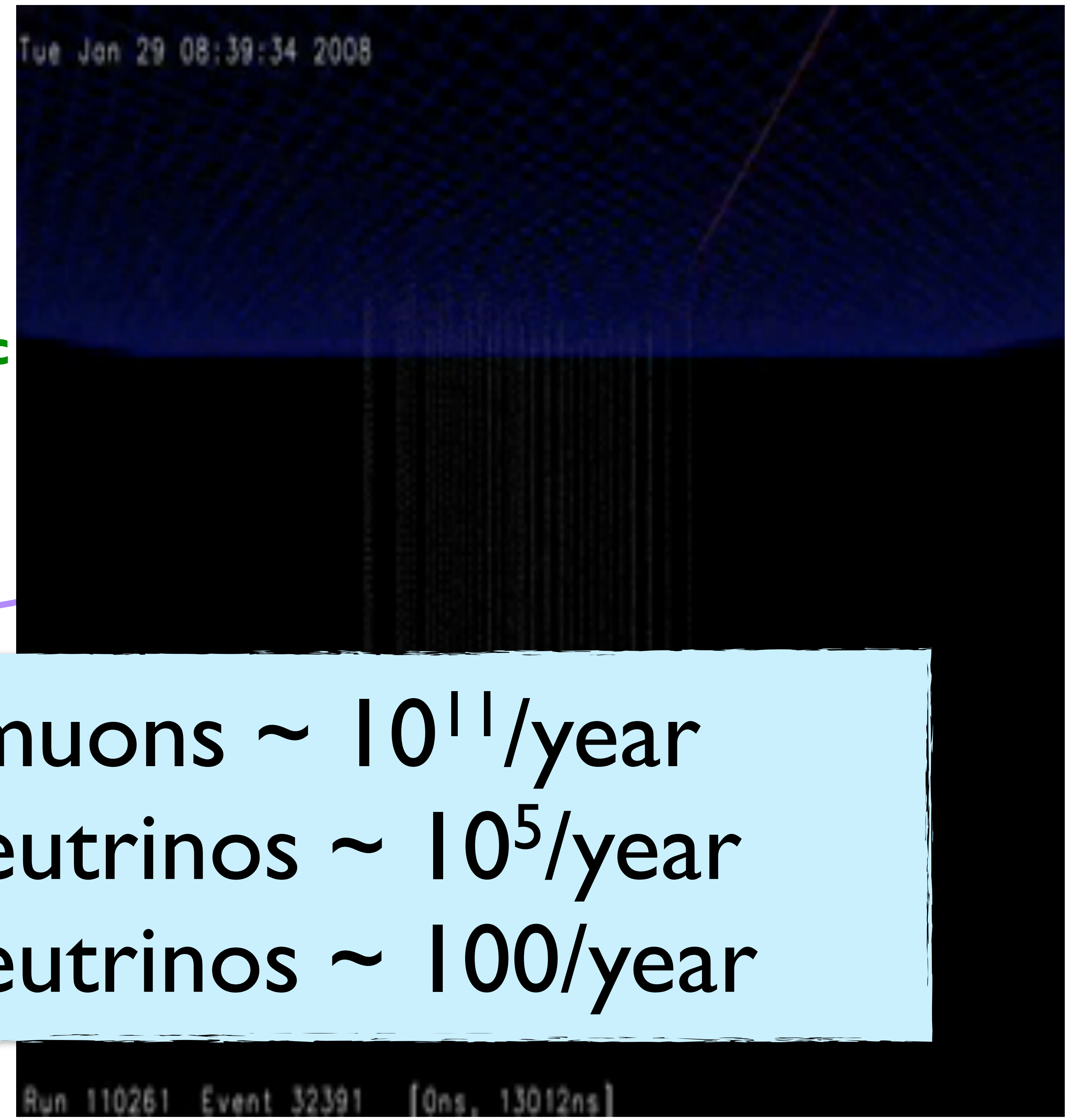


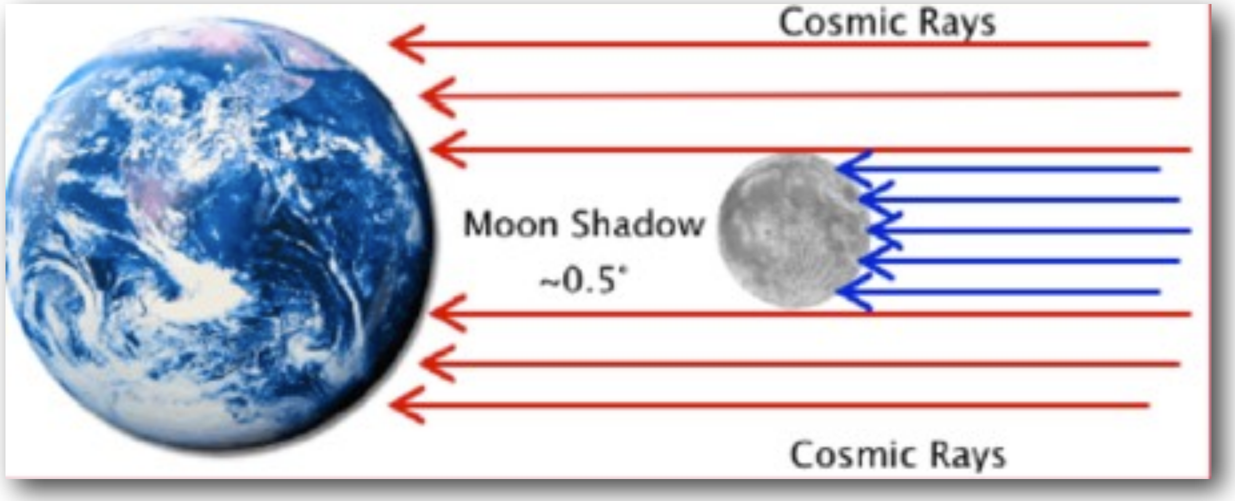
Atmospheric muons ~ 10^{11}/year
Atmospheric neutrinos ~ 10^{5}/year
Astrophysical neutrinos ~ 100/year

irreducible neutrino background to extra terrestrial neutrino fluxes

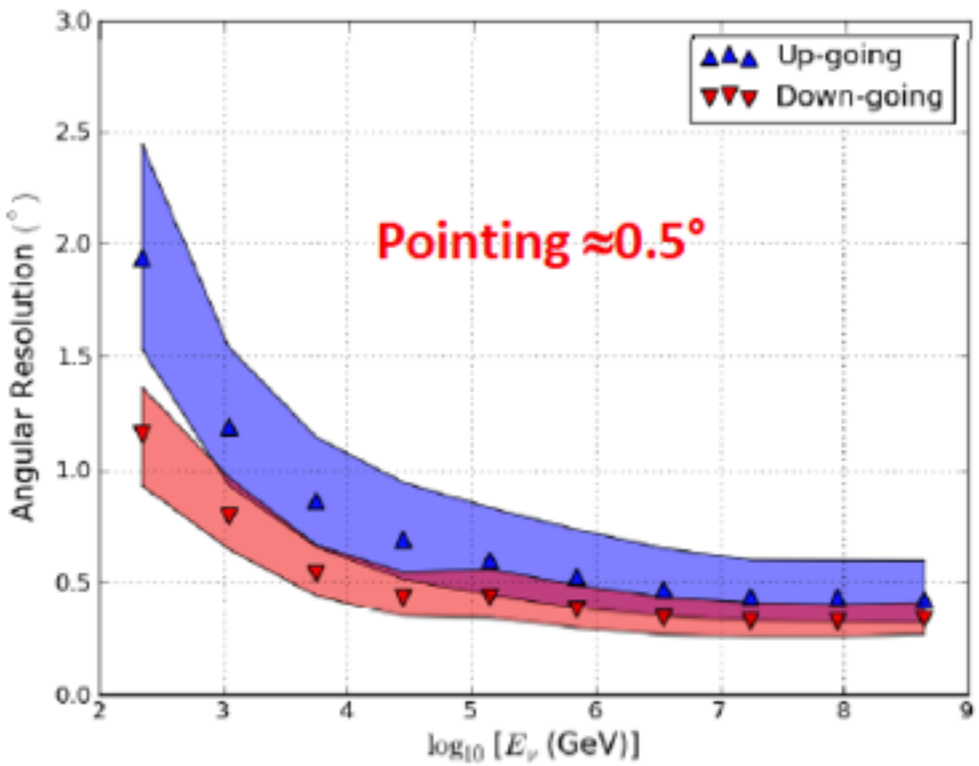
Calibration and Performance

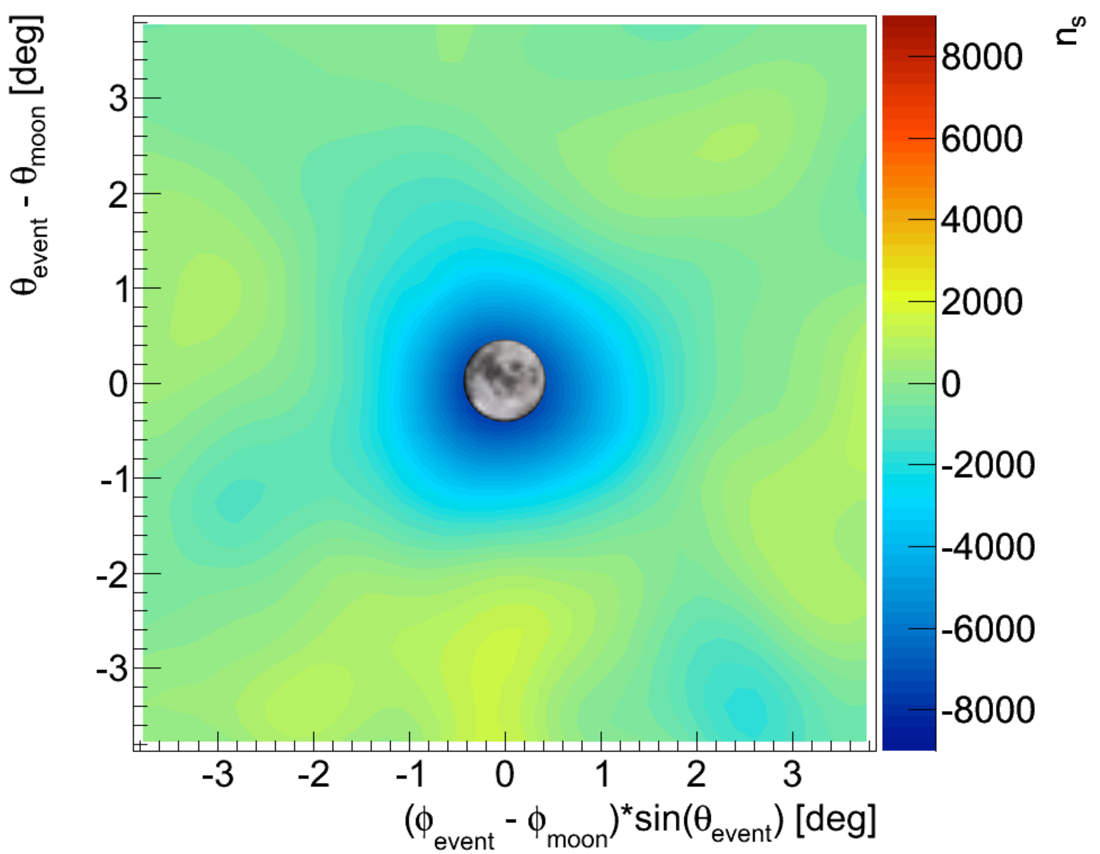
Physical Review D89 (2014) 102004

- Calibration Sources:
  - 12 LED flashers on each DOM
  - In-Ice Calibration Laser
  - Cosmic Rays
  - Moon Shadow
  - Atmospheric Neutrinos
  - Minimum-ionizing Muons



- Moon blocks cosmic rays - Observed muon deficit 14σ significance
  - systematic pointing error <0.1°

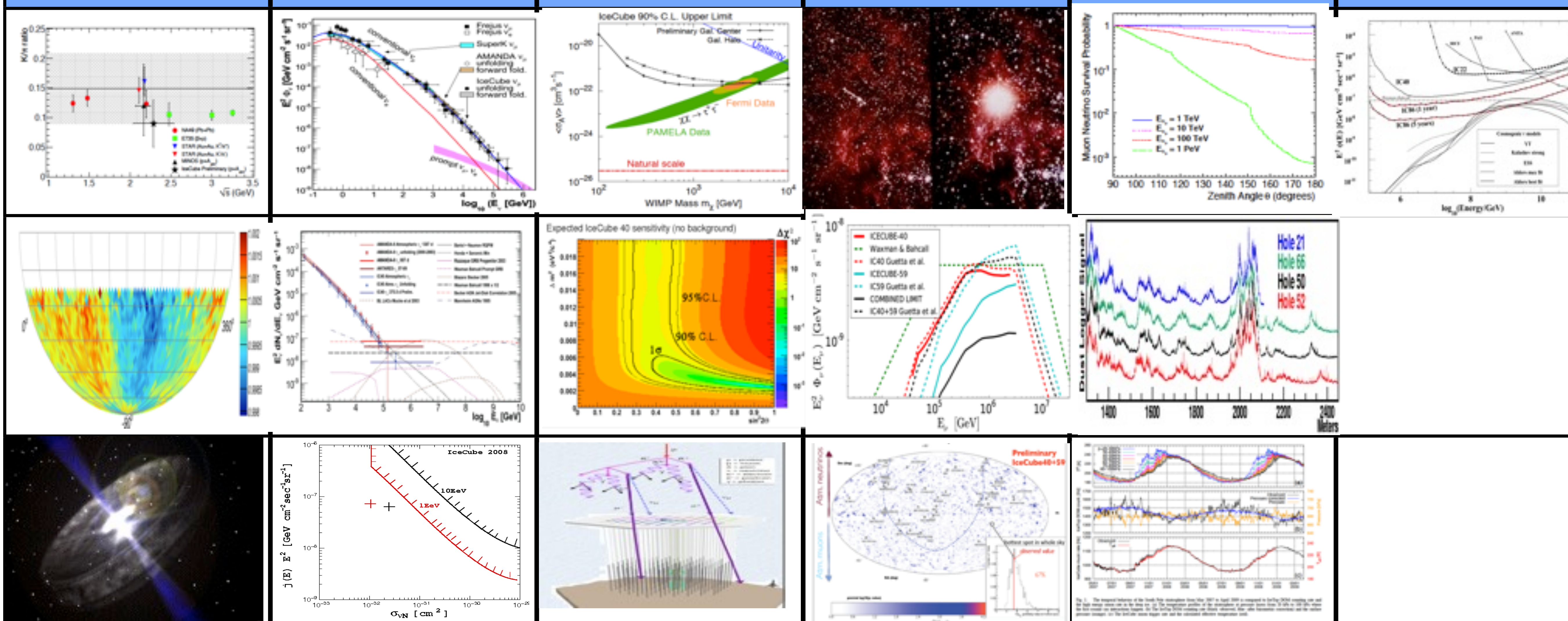




Physics Potential and Selected Results

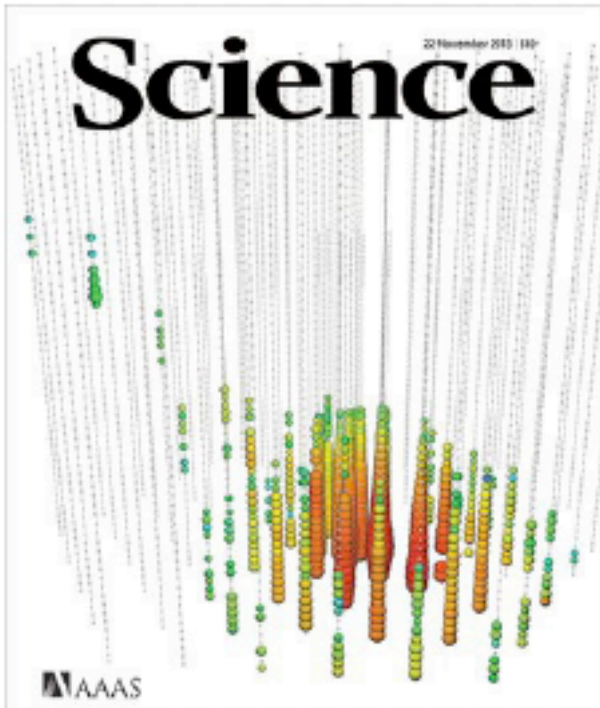
IceCube Science

Cosmic Rays	Atmospheric neutrinos	Particle Physics	Astronomy	Applied science	Cosmology



Very diverse science program, with neutrinos from 10GeV to EeV, and MeV burst neutrinos

Achievements



Recently detected High Energy Neutrinos of Astrophysical Origin

Science 342, 1242856 (2013)

Phy. Rev. Lett. 113, 101101 (2014)

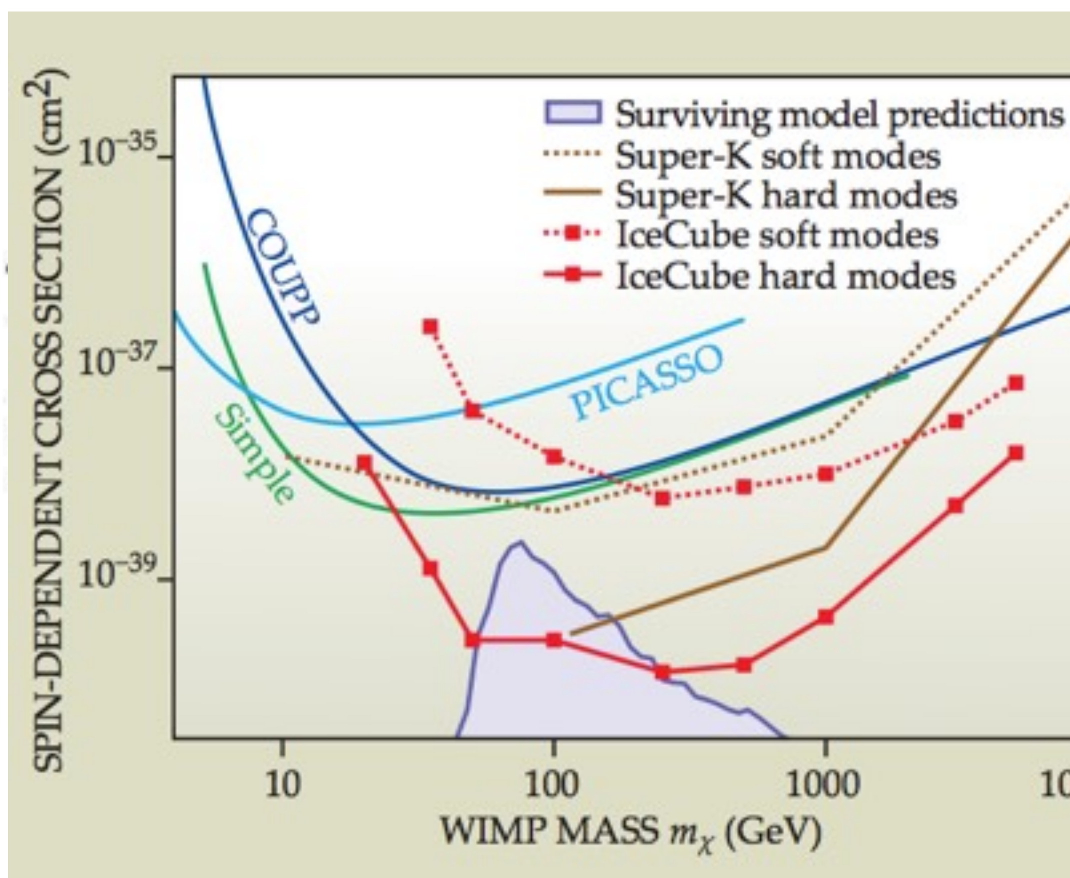
physicsworld
BREAKTHROUGH OF THE YEAR 2013

Physics World
Breakthrough of the Year 2013

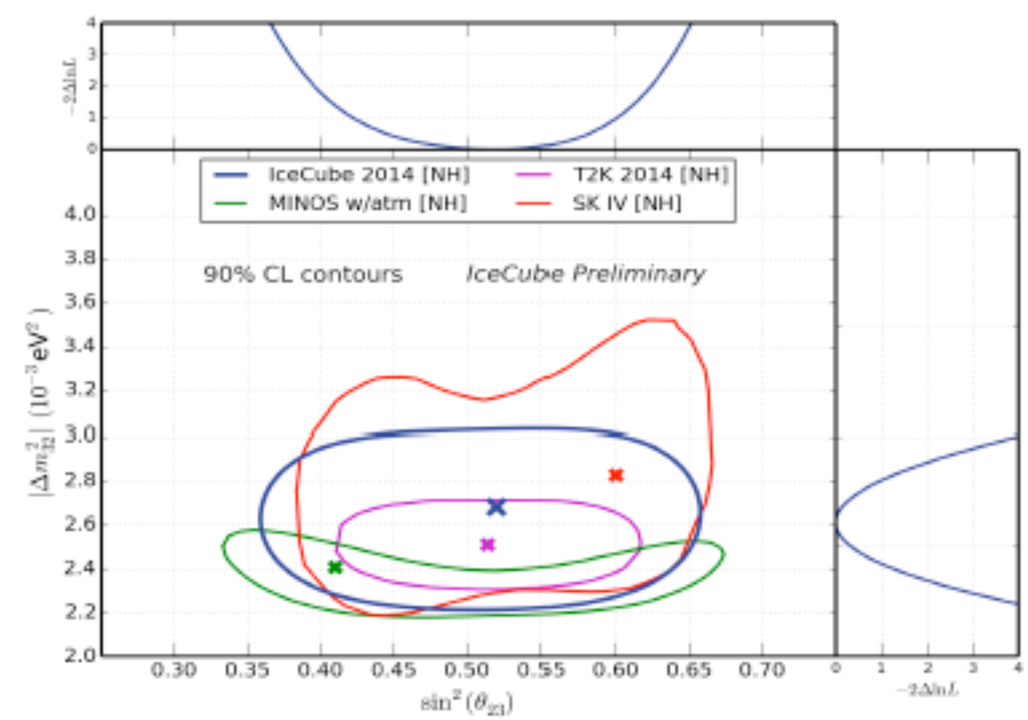
The *Physics World* Breakthrough of the Year is awarded for physics research published in 2013 and the decision is based on the following criteria:

- Fundamental importance of research
- Significant advance in knowledge
- Strong connection between theory and experiment
- General interest to all physicists

This is to certify that the *Physics World* Breakthrough of the Year has been given to
The IceCube South Pole Neutrino Observatory
for making the first observations of high-energy cosmic neutrinos

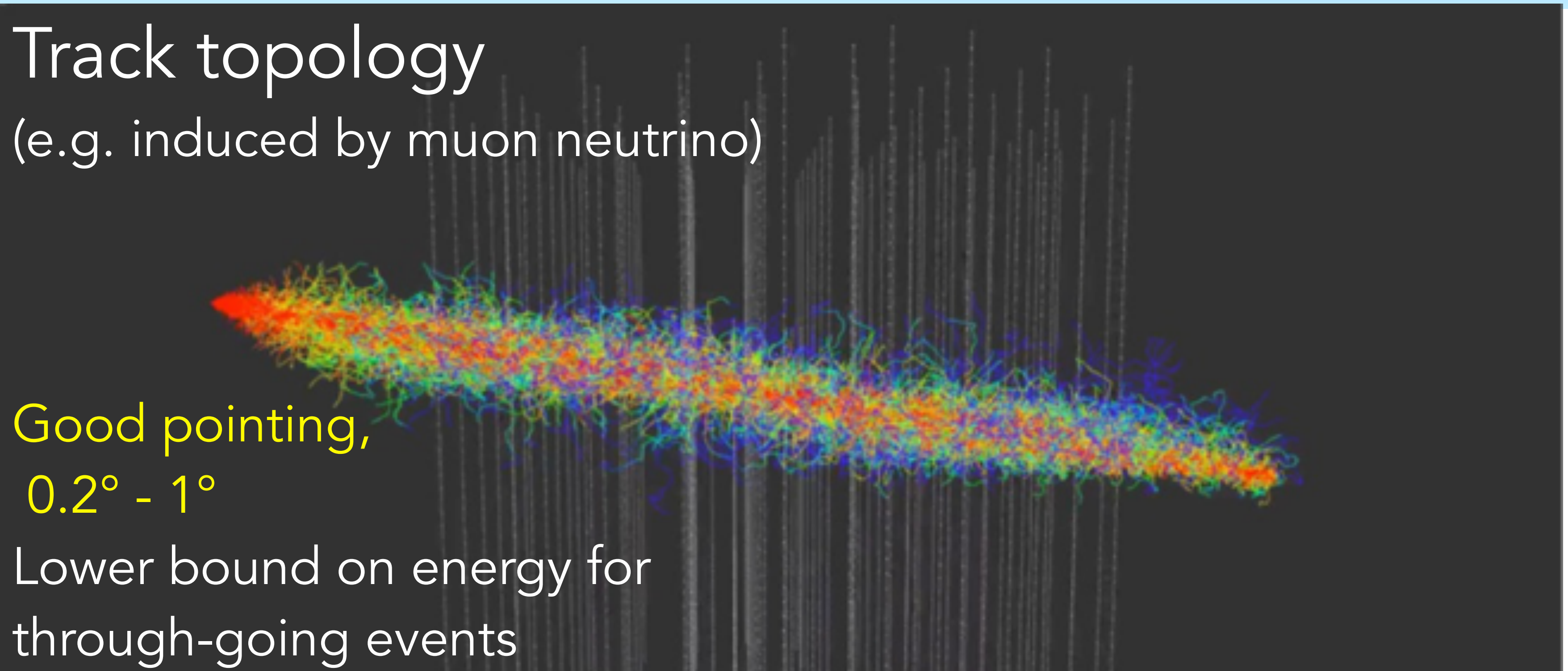


Phys. Today 66(5), 14 (2013)



IceCube Talk – Neutrino 2014

Event Topologies in IceCube

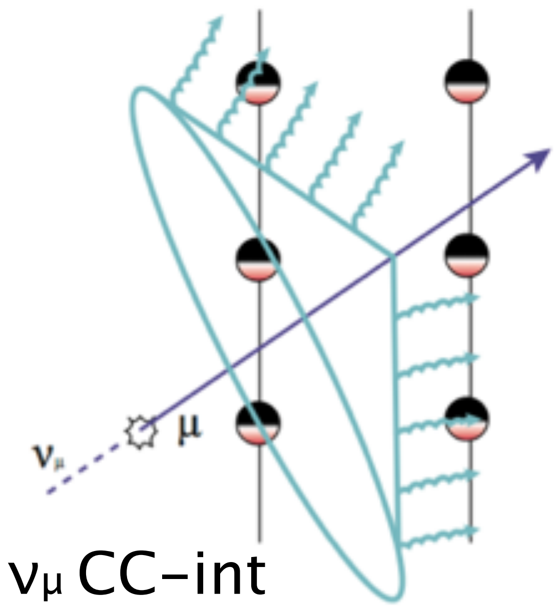


Track topology

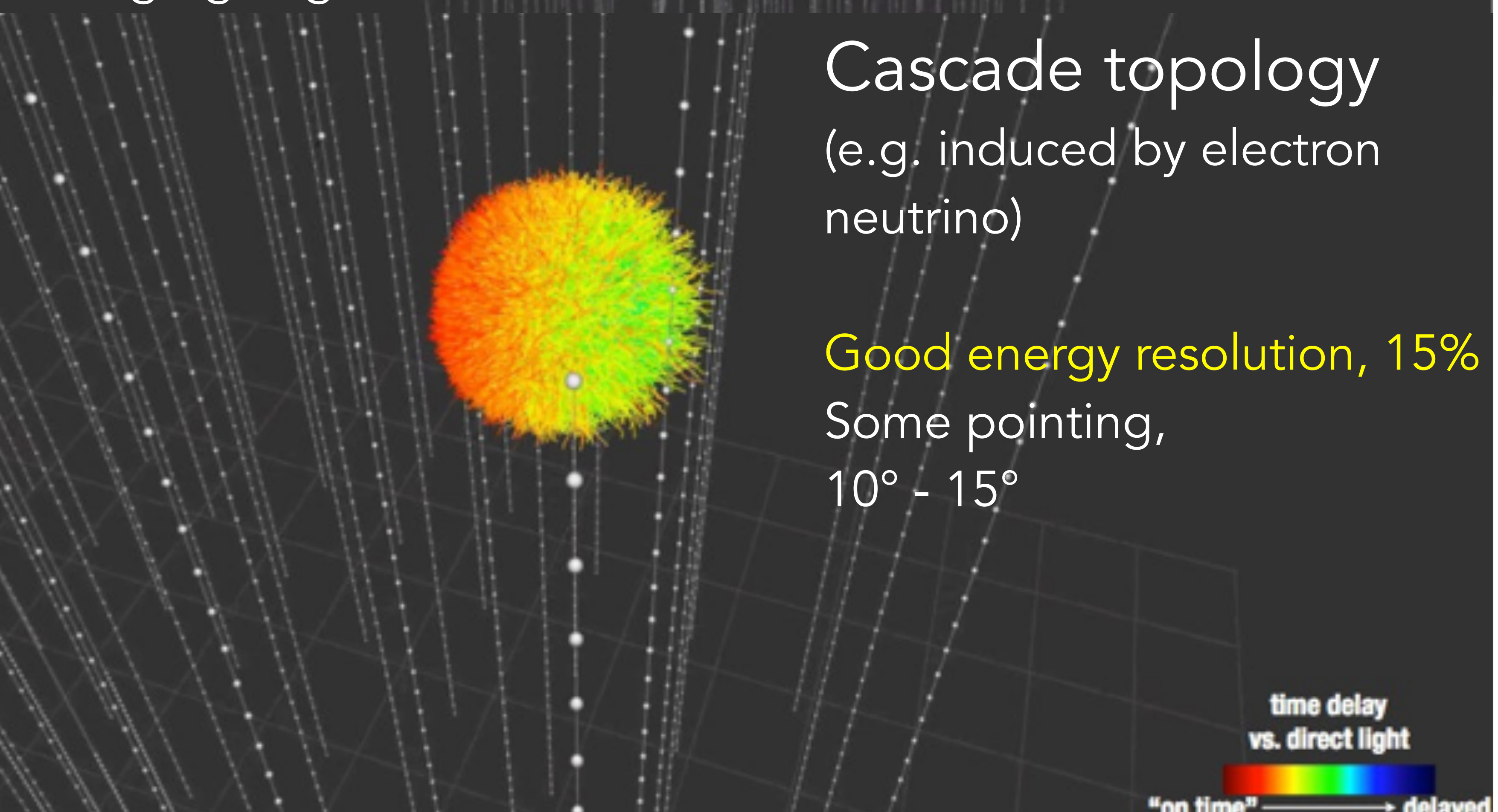
(e.g. induced by muon neutrino)

Good pointing,
0.2° - 1°

Lower bound on energy for through-going events



ν_μ CC–int

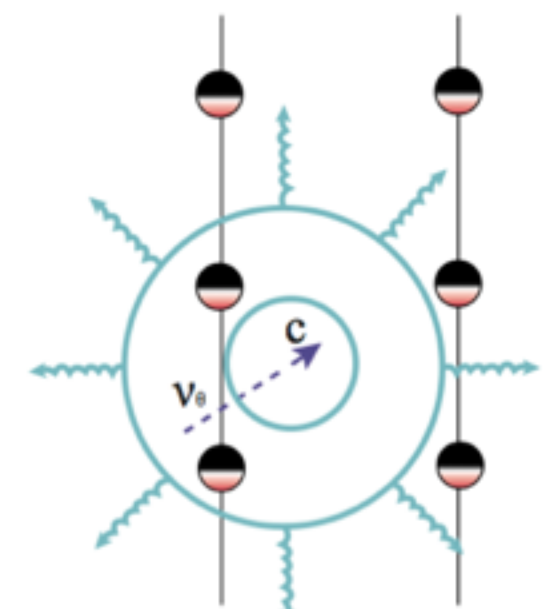


Cascade topology

(e.g. induced by electron neutrino)

Good energy resolution, 15%

Some pointing,
10° - 15°



ν_e ν_τ CC–int & ν_i NC–int

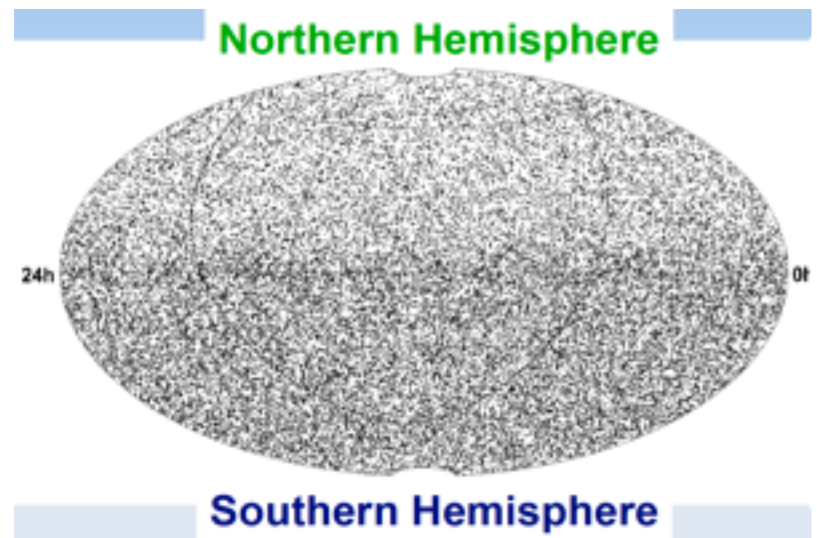
Astro-physical Neutrino Search

Finding Astrophysical Neutrinos

- How to overcome the large atmospheric neutrino background
- We need to rely on statistical methods to pick out neutrinos from this mess
  - Do neutrinos cluster anywhere in space, time, or arriving in coincidence with astronomical events or objects ?
  - Do we see any spectral features ?

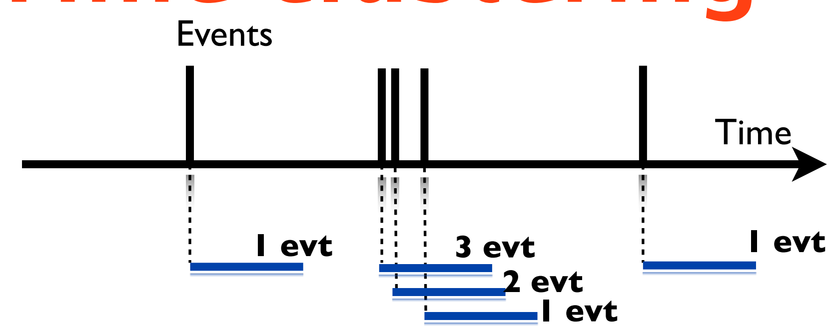
1. Point Source

single dominant source



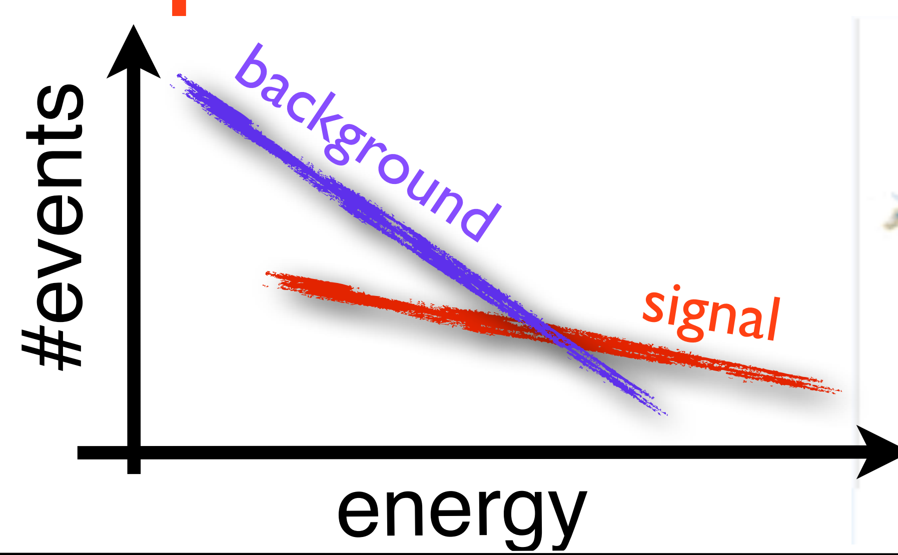
2. Time clustering

transient source



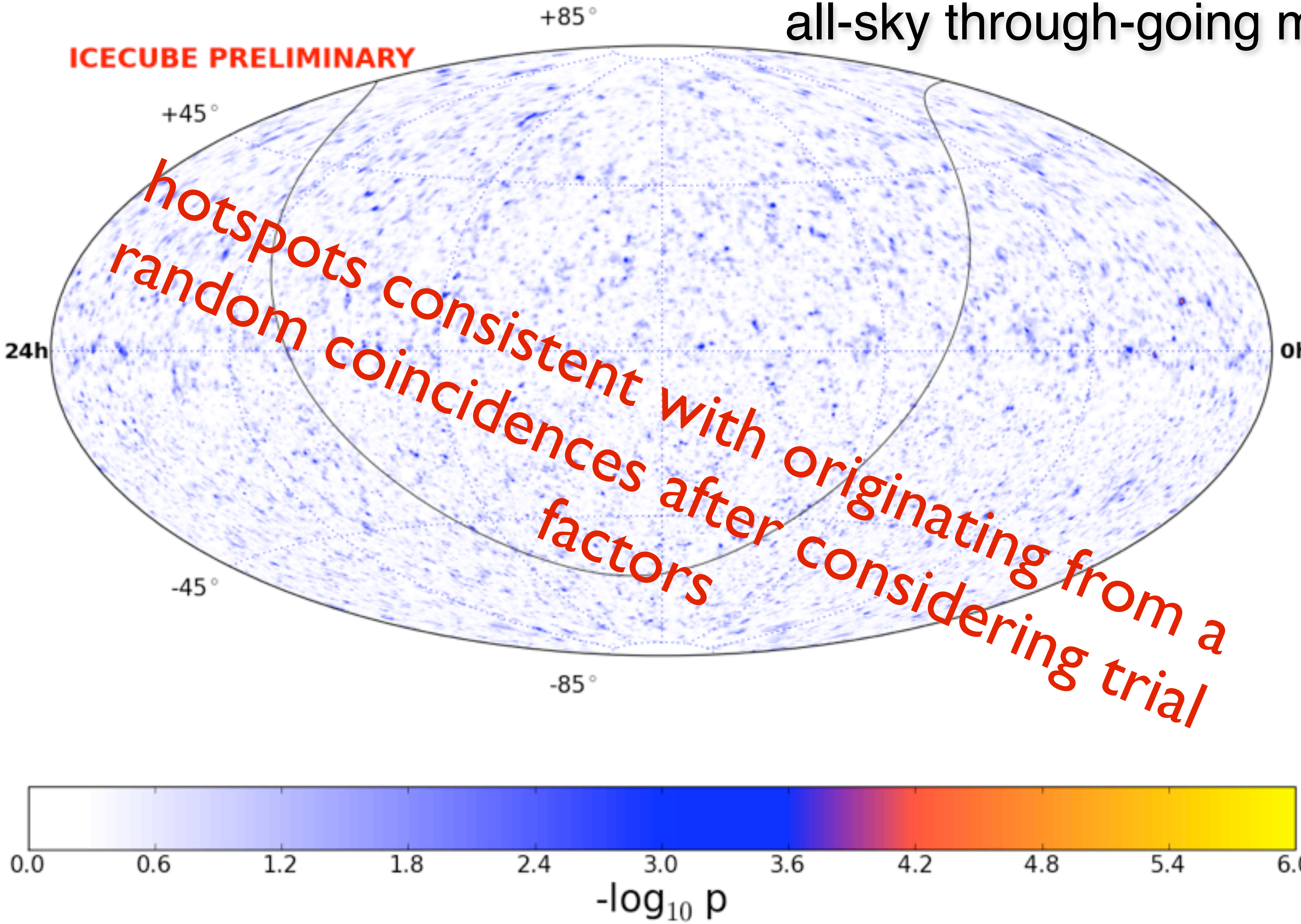
3. Spectral feature

cumulative flux

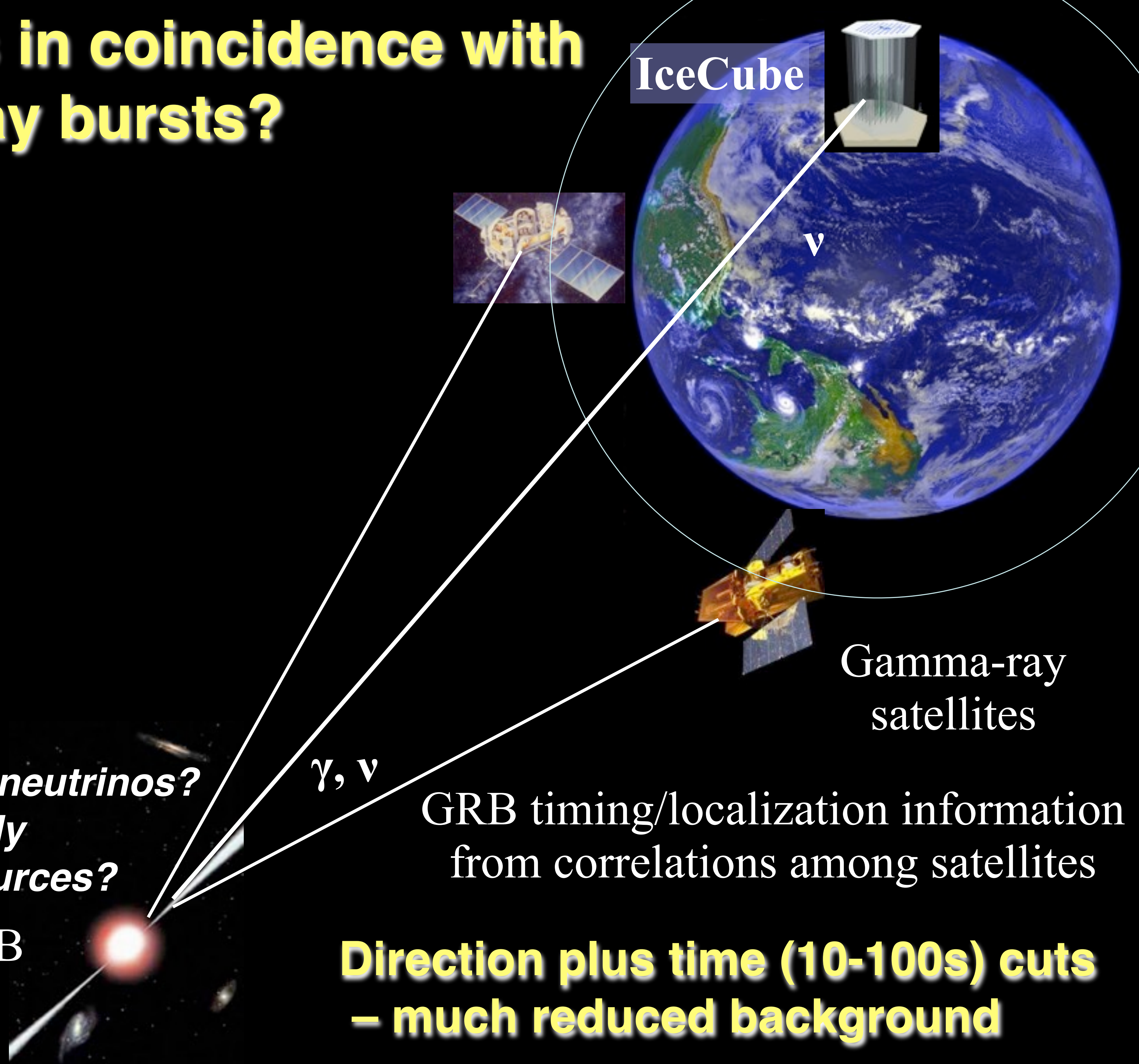


Point Source Search

IC40+59+79+86 significance:
all-sky through-going muons



Neutrinos in coincidence with gamma-ray bursts?



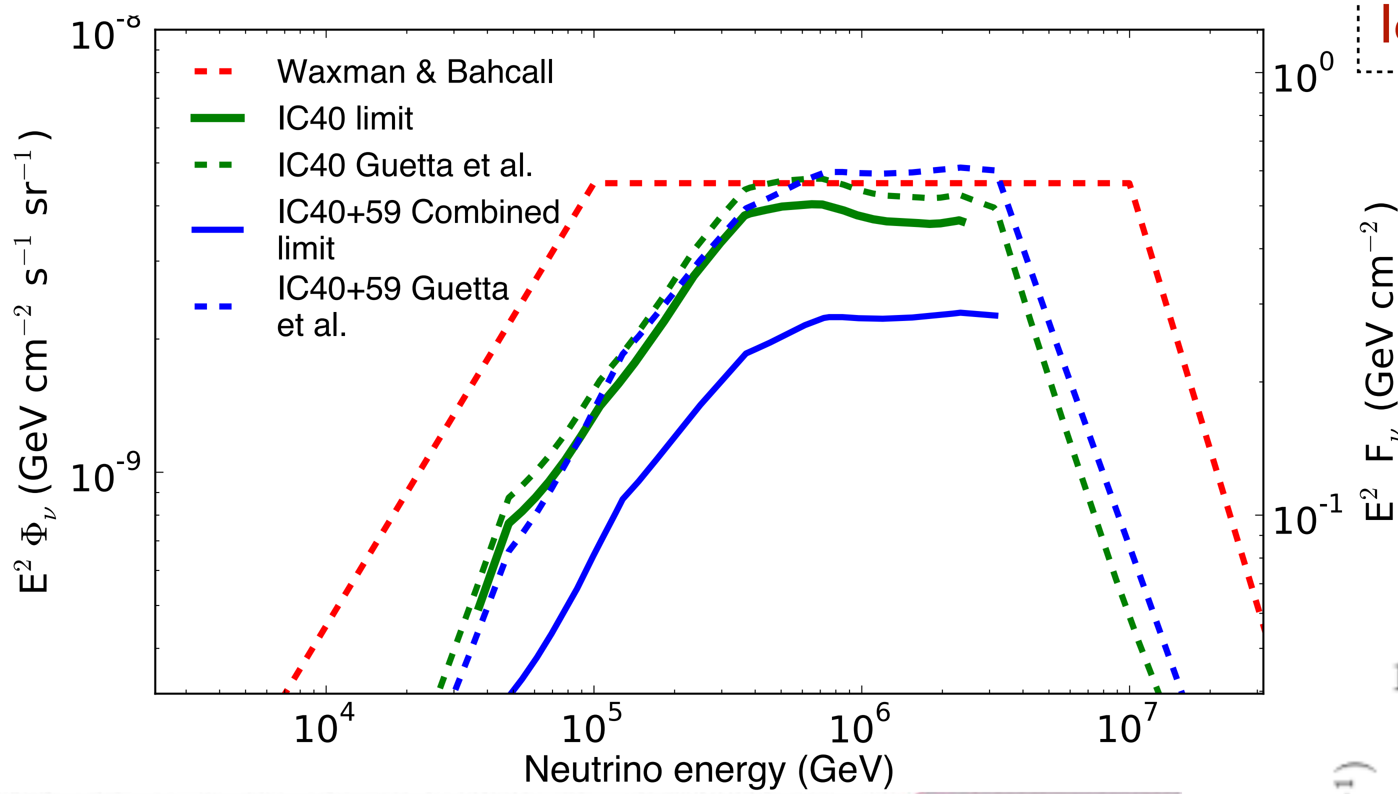
Where are the neutrinos? Are GRBs really cosmic ray sources?

GRB timing/localization information from correlations among satellites

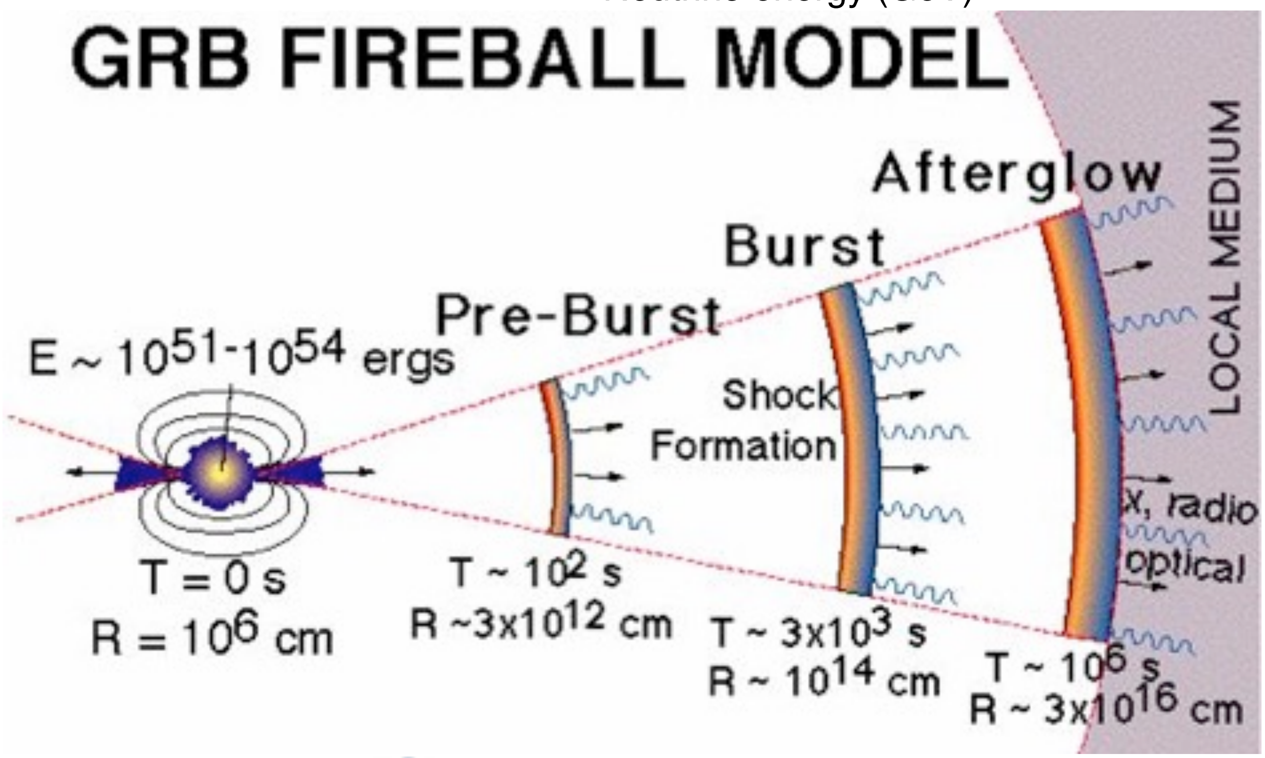
Direction plus time (10-100s) cuts – much reduced background

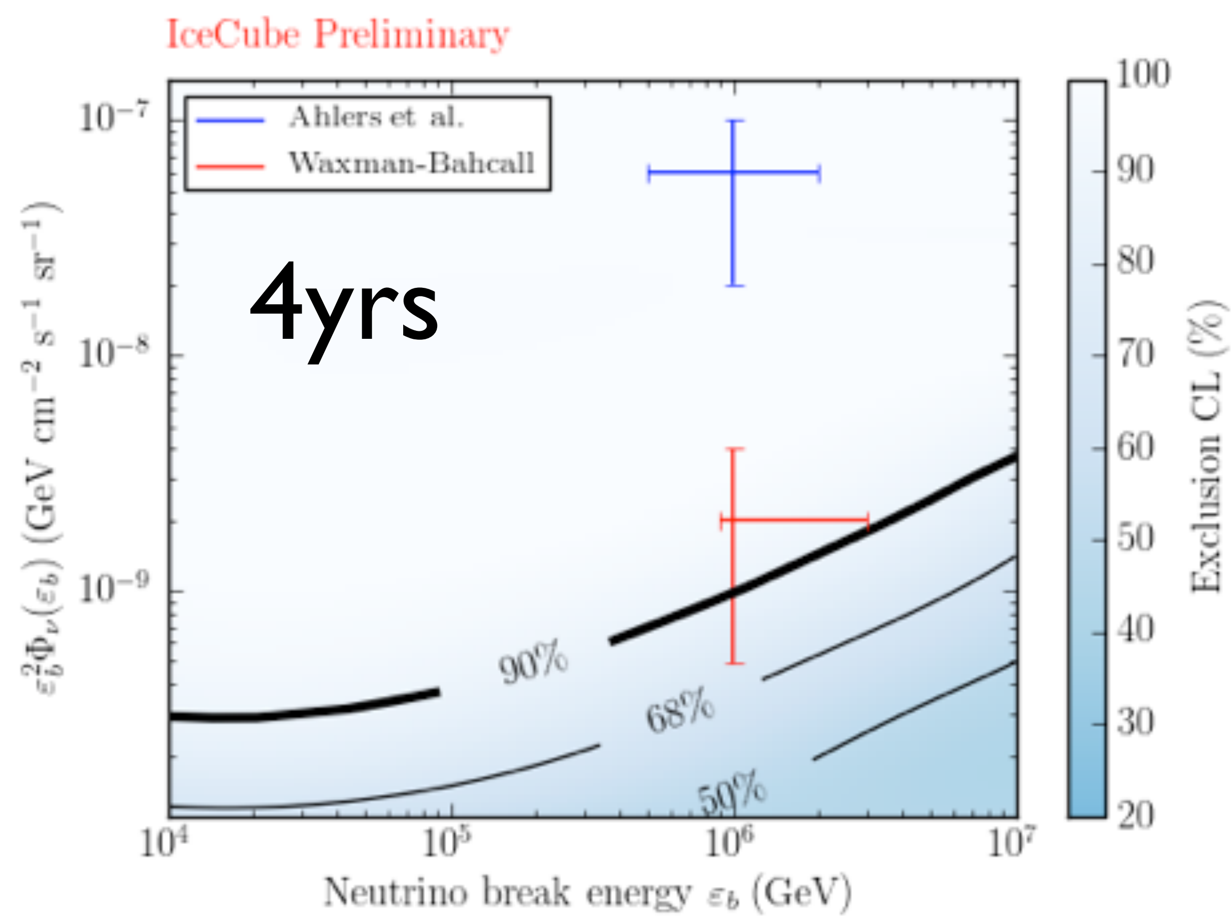
IC40 data **2008-2009** (117 GRBs in northern sky) and **IC59** data **2009-2010** (98 GRBs in the northern and 85 from southern sky) analyzed. **No coincidence found**

IceCube Collaboration - Nature Vol **484**, 351 (2012)



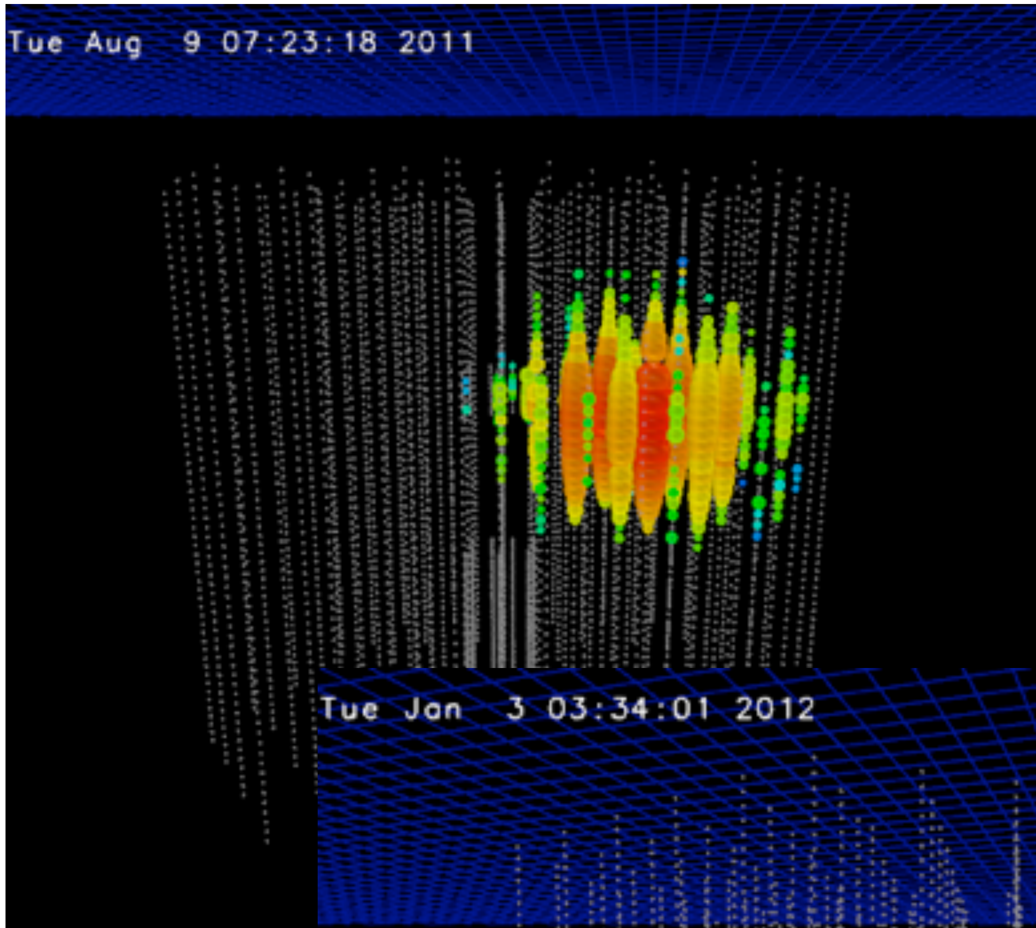
2yrs:
5.2 expected
0 seen

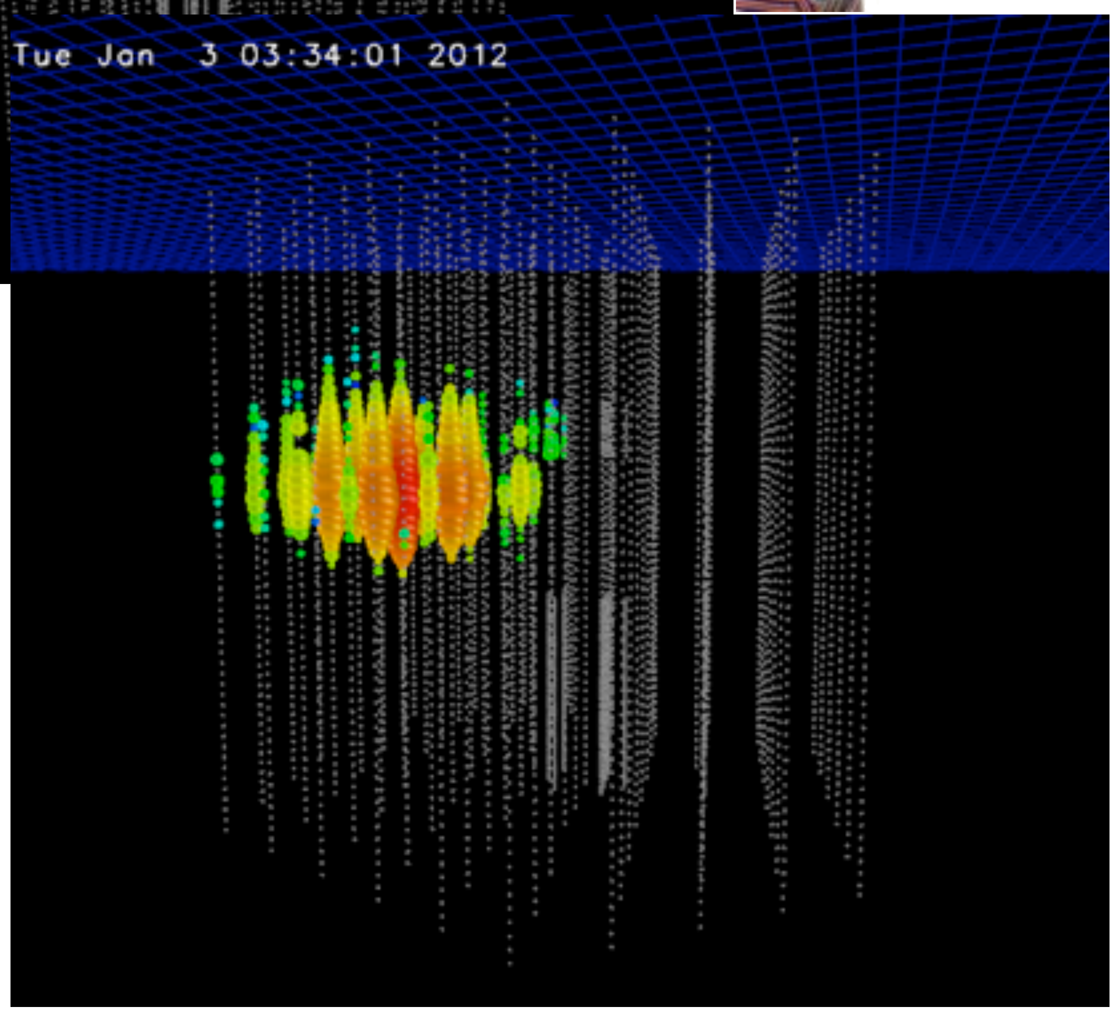




Search for highest energy neutrinos

IceCube Coll. Phys.Rev.Lett. 111 (2013) 021103 / arXiv 1304.5356

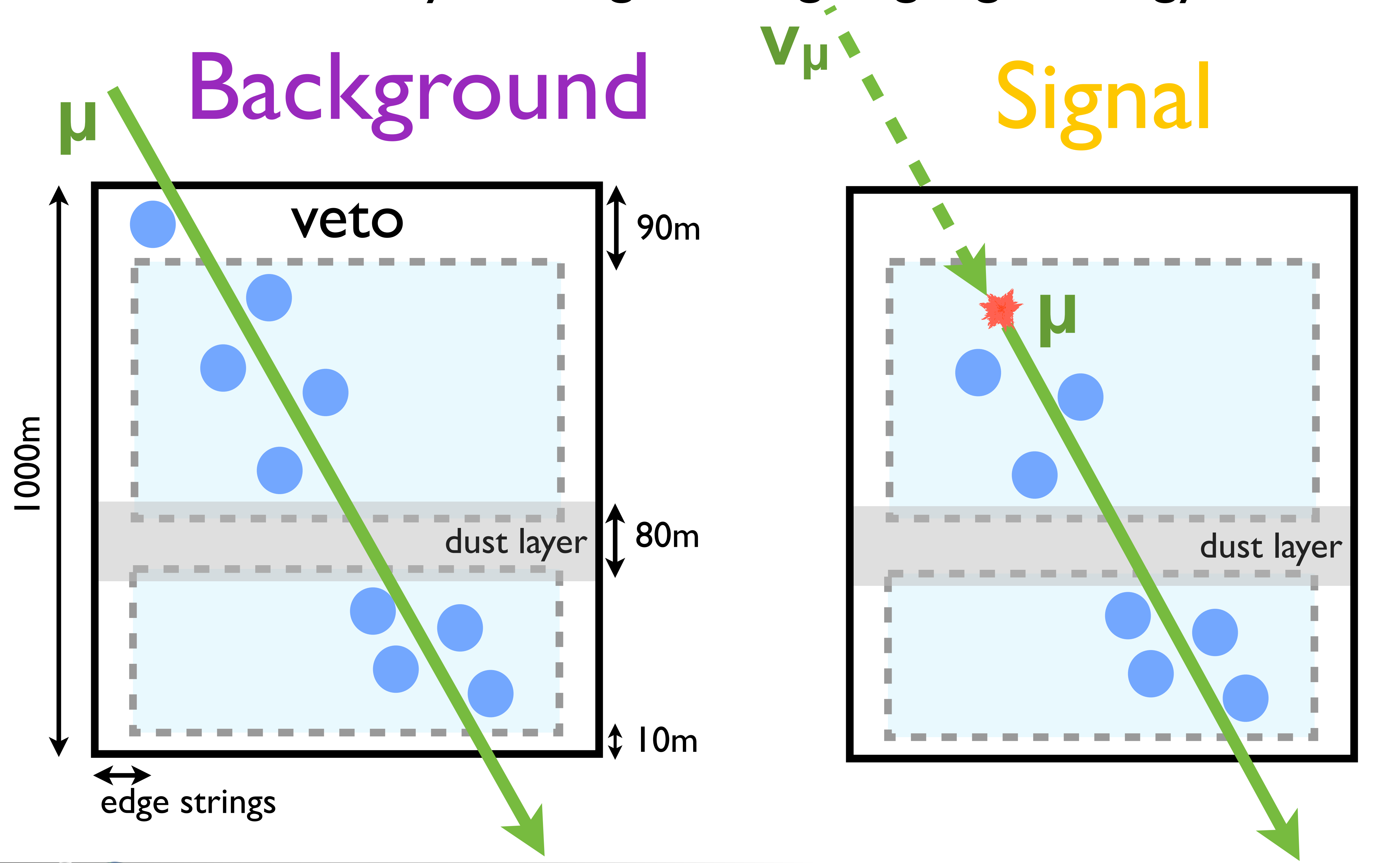




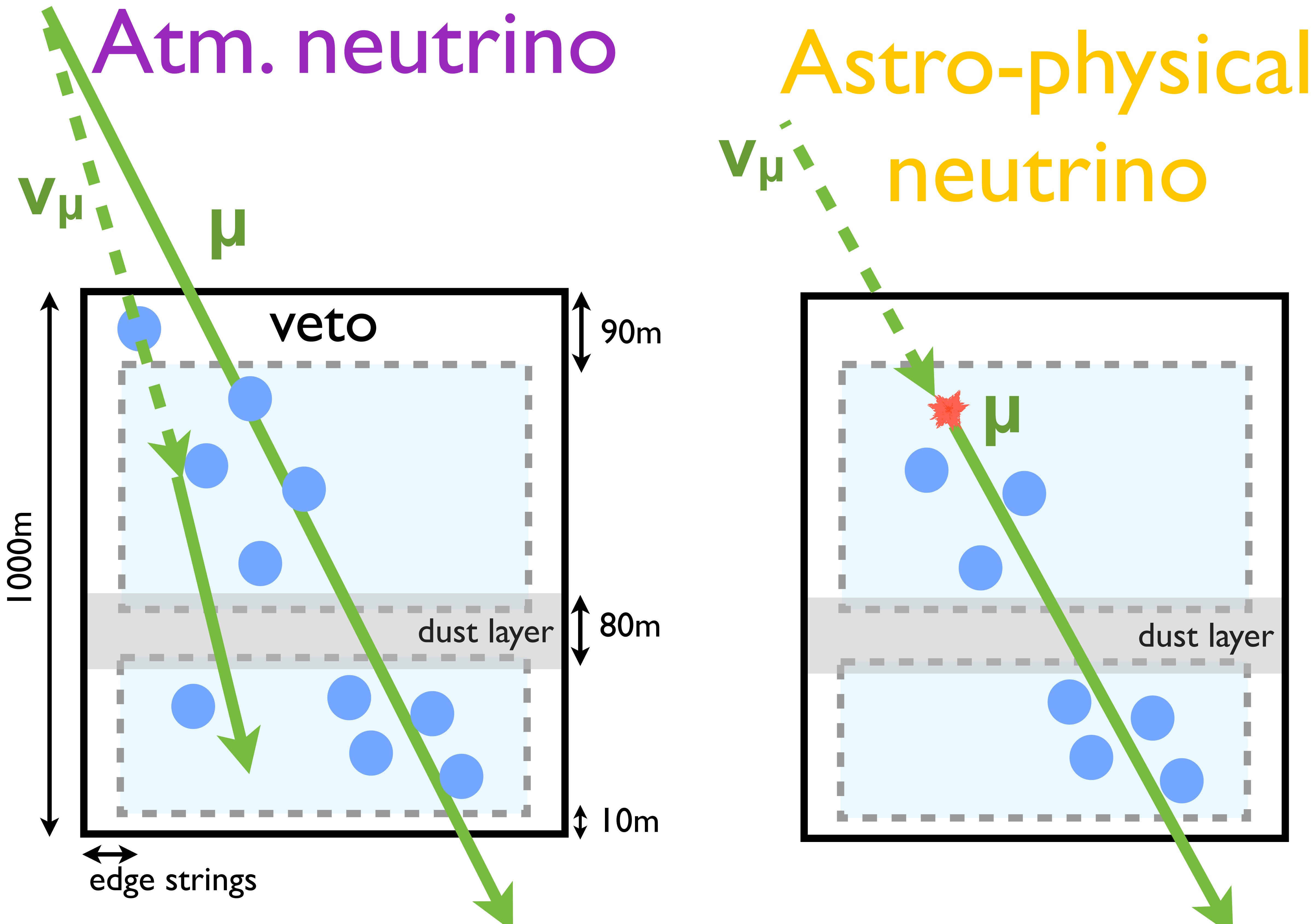
Dataset / Results
(670days of IC79/IC86 data)
expected 0.08 events
observed 2 events ($\rightarrow$ 2.7σ)

- Ernie ~1.15 PeV (~1.9 $\cdot 10^{-4}$J)
- Bert ~ 1.05 PeV (~1.7 $\cdot 10^{-4}$J)
- Energy is the visible energy of the cascade, could originate from NC event, ν_τ CC, or ν_e CC
- Angular resolution on cascade events at this energy ~10°
- Energy resolution is about 15% on the deposited energy

- Probe the energy region of about 30TeV to 1PeV, all flavors and all directions, by vetoing down-going high-energy muons



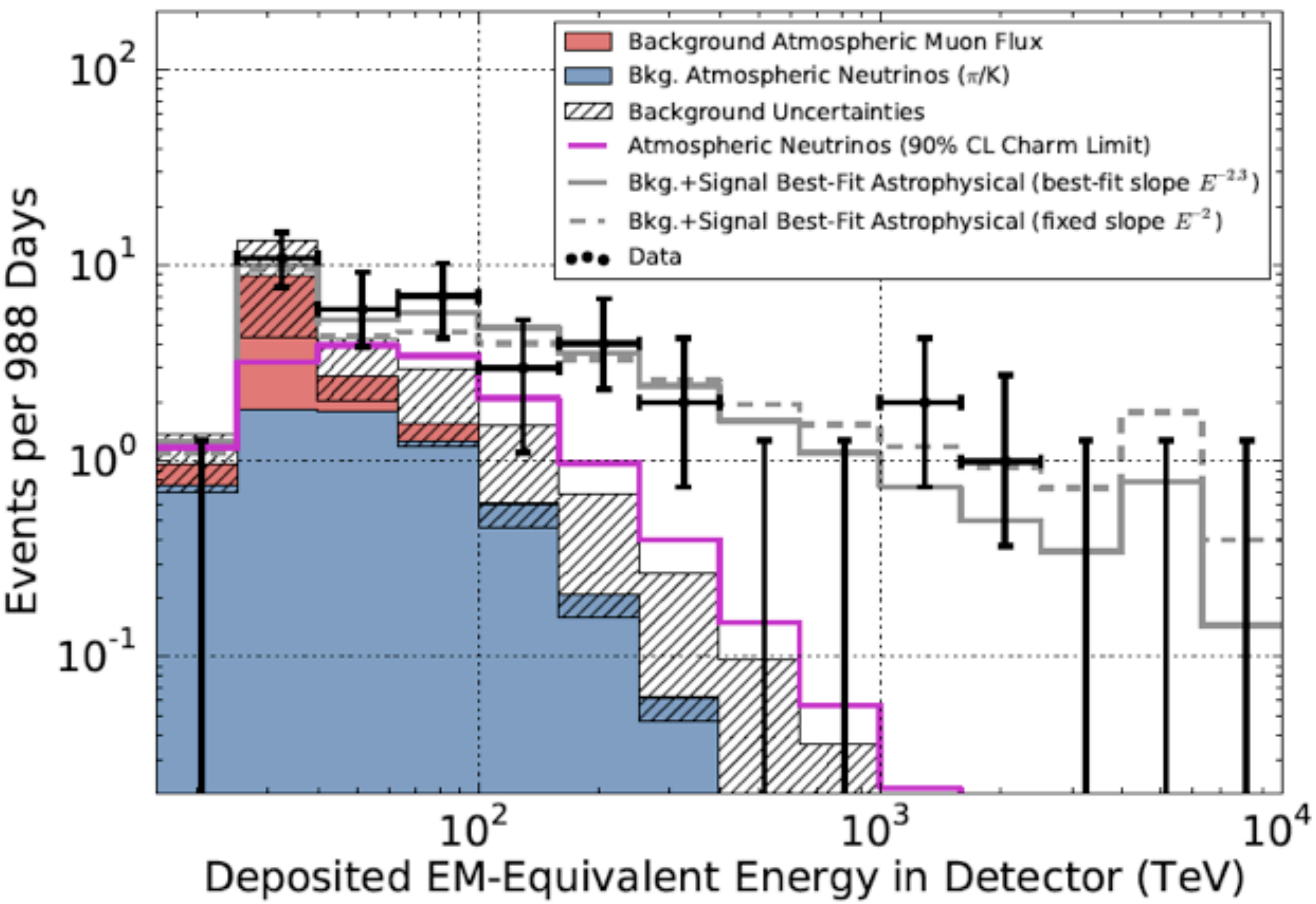
Veto and Self-veto



High-energy neutrino search

37 events (9 track-like, 28 showers) observed

Expectation from conventional atm. muons and neutrinos 15.0



IceCube Collaboration, *Science 342, 1242856 (2013)*,
IceCube Collaboration, *Phys. Rev. Lett 113, 101101 (2014)*

- Mesons including charm quarks in the atmosphere decay immediately to produce neutrinos, known as prompt neutrinos which are not observed yet.
- ERS, or Enberg et al. Phys. Rev. D 78, 043005 (2008) is used as a baseline prompt model
- Significance are based on the exact neutrino flux model, not including the uncertainty of the model.
- Atmospheric Bkg : CR Muon (8.4±4.2), Conv. Neutrino ($6.6^{+5.9}_{-1.6}$),
- Over 60 TeV < E < 2000 TeV, the spectrum consistent with E^{-2} or $E^{-2.3}$
- E^{-2} spectrum predicts too may neutrinos above ~2 PeV. So, a cutoff or steeper spectrum needed.

5.7 sigma rejection of atmospheric-only hypothesis

best fit flux: $E^2\Phi = 10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1}

Press coverage


〈이 기사는 2014년 01월 06일자 신문 23면에 게재되었습니다.〉

"한국 '세계적 리더' 될 좋은 기회"

기초과학 투자 의지 활발, 한국에 새 연구 터전 둥지.. 연구자-학생 영입해 연구

...르트 교수가 빙하 속 구형 디텍터를 활용해 중성미자를 검출

...운 시기다. 한국 과학계가 지금 이 새로운 분야

...수 있다."

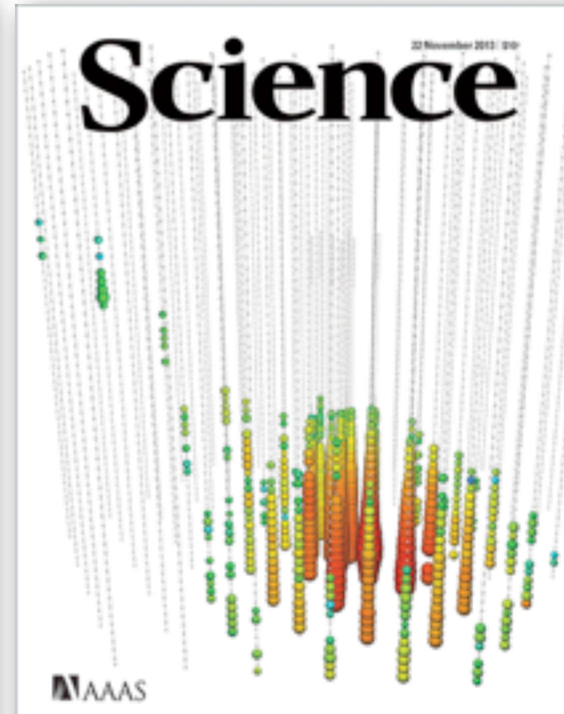

우주서 날라온 '유령입자' 뭔가봤더니

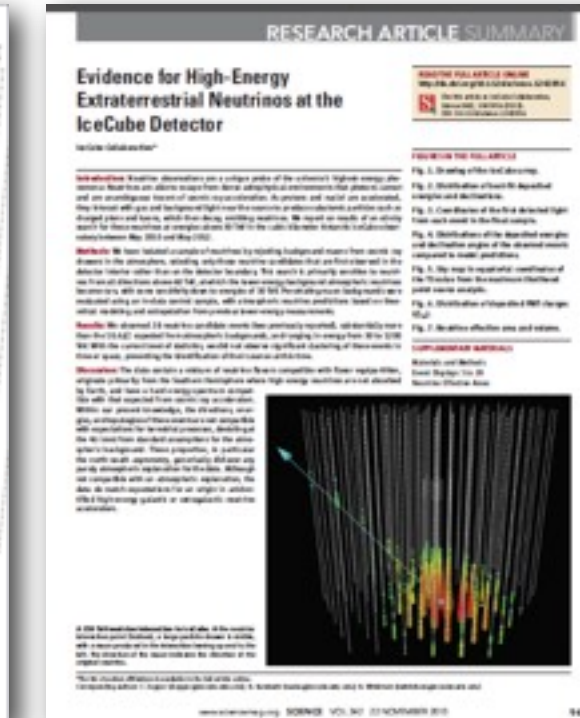
디지털타임스 | 기사입력 2013-11-24 20:51 | 최종수정 2013-11-25 11:33

아이스큐브 공동연구팀, 남극서 초고에너지 중성미자 최초로 포착

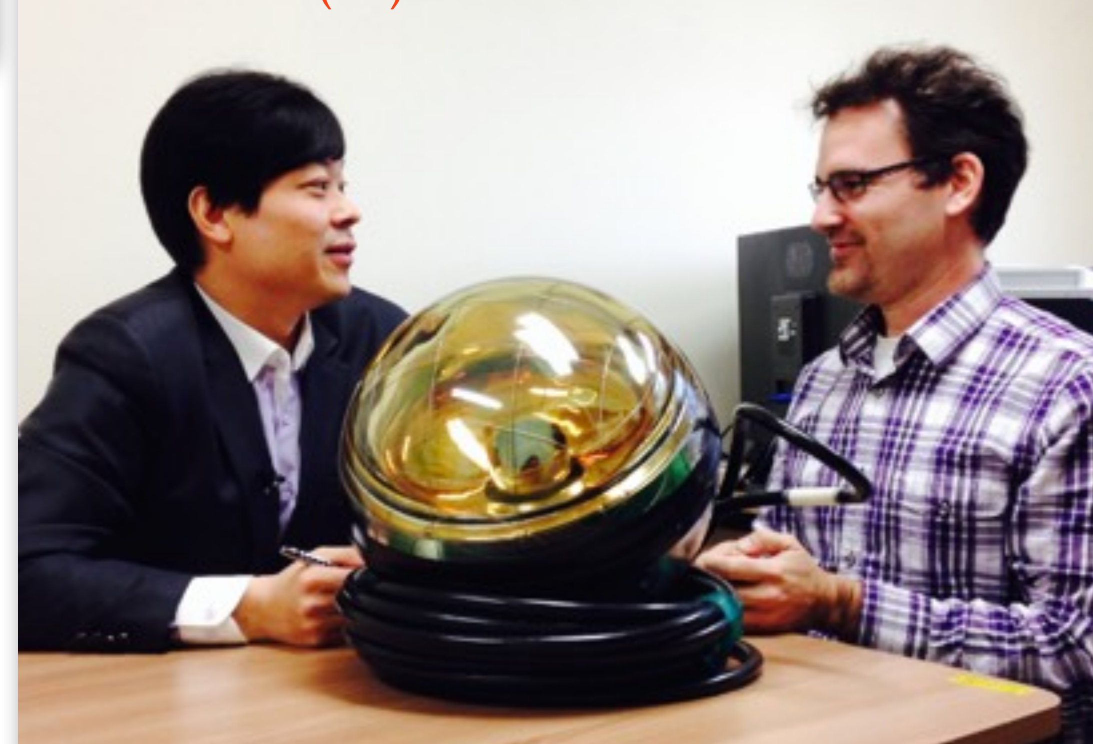
남극 얼음 깊이 설치된 연구장치에서 우주로부터 날아온 초고에너지 중성미자가 최초로 포착됐다.

세계 11개국 39개 기관 200여명의 연구자로 구성된 '아이스큐브' 국제공동 연구팀은 남극 얼음층에서 우주로부터 날아온 초고에너지 중성미자의 흔적을 최초로 포착, 세계적인 과학저널인 사이언스에 22일 발표했다. 국내에서는 카르스텐 로트 성균관대 물리학과 교수가 연구에 참여했다.

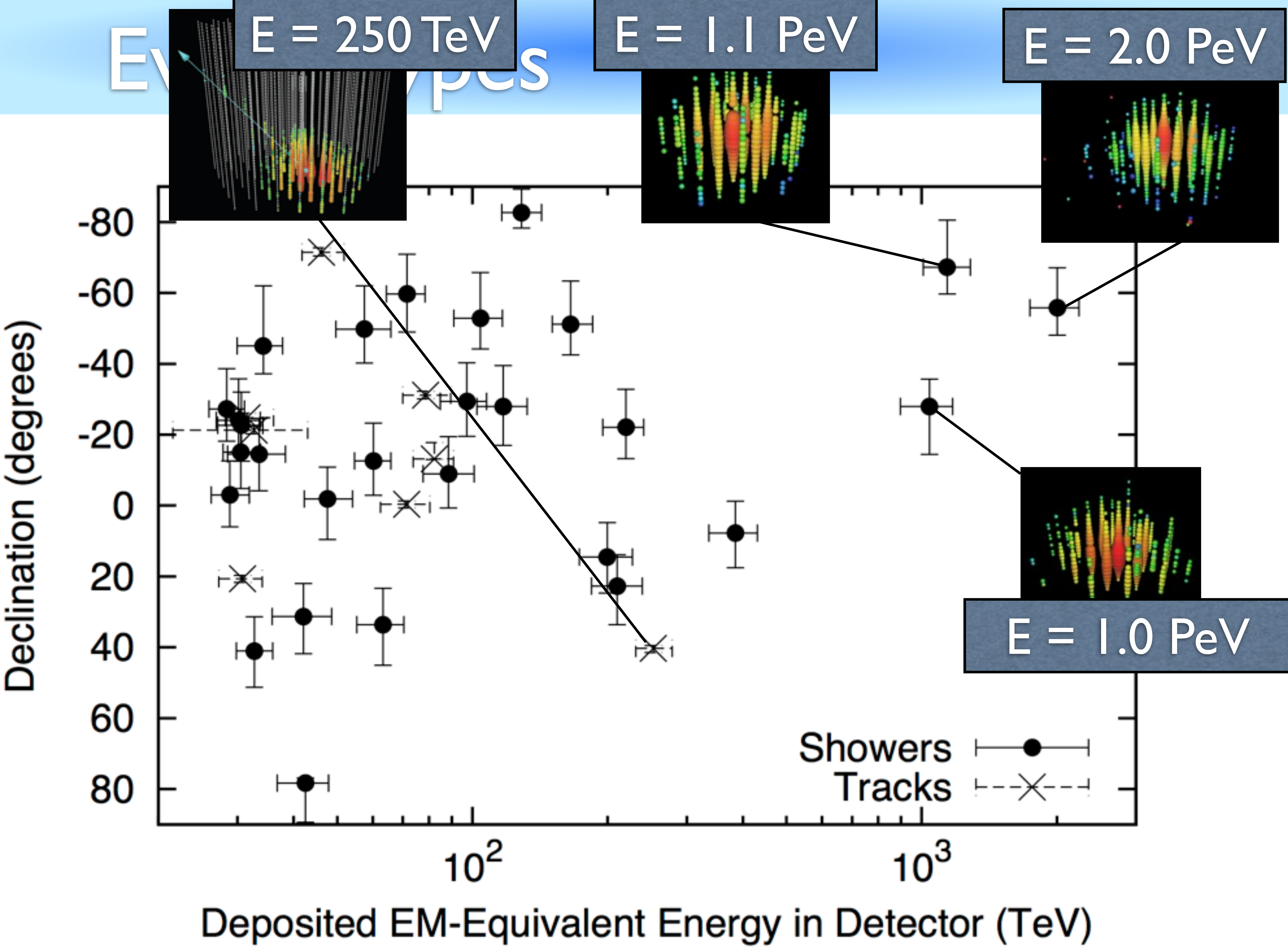




YTN Science (TV)

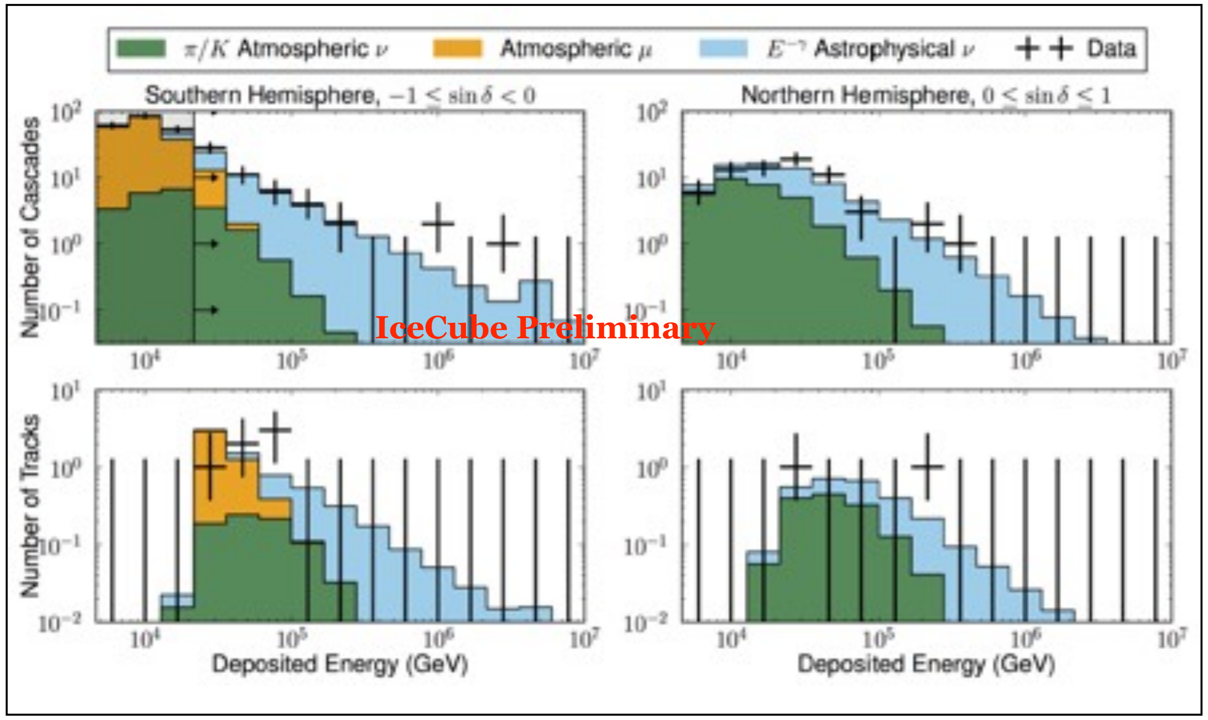


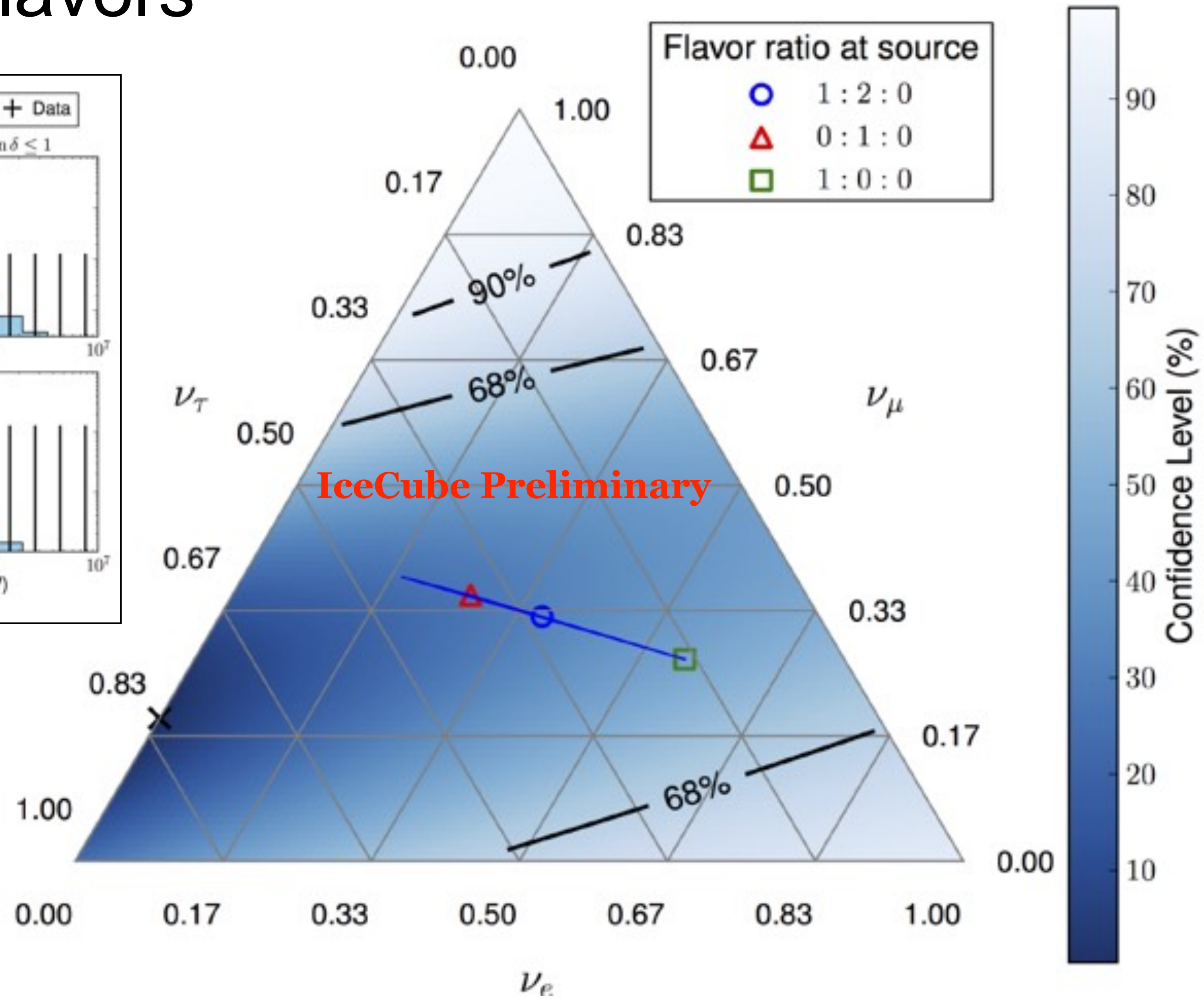
Ev ypes



E = 250 TeV
E = 1.1 PeV
E = 2.0 PeV
E = 1.0 PeV
Declination (degrees)
-80
-60
-40
-20
0
20
40
60
80
10^2
10^3
Deposited EM-Equivalent Energy in Detector (TeV)
Showers
Tracks

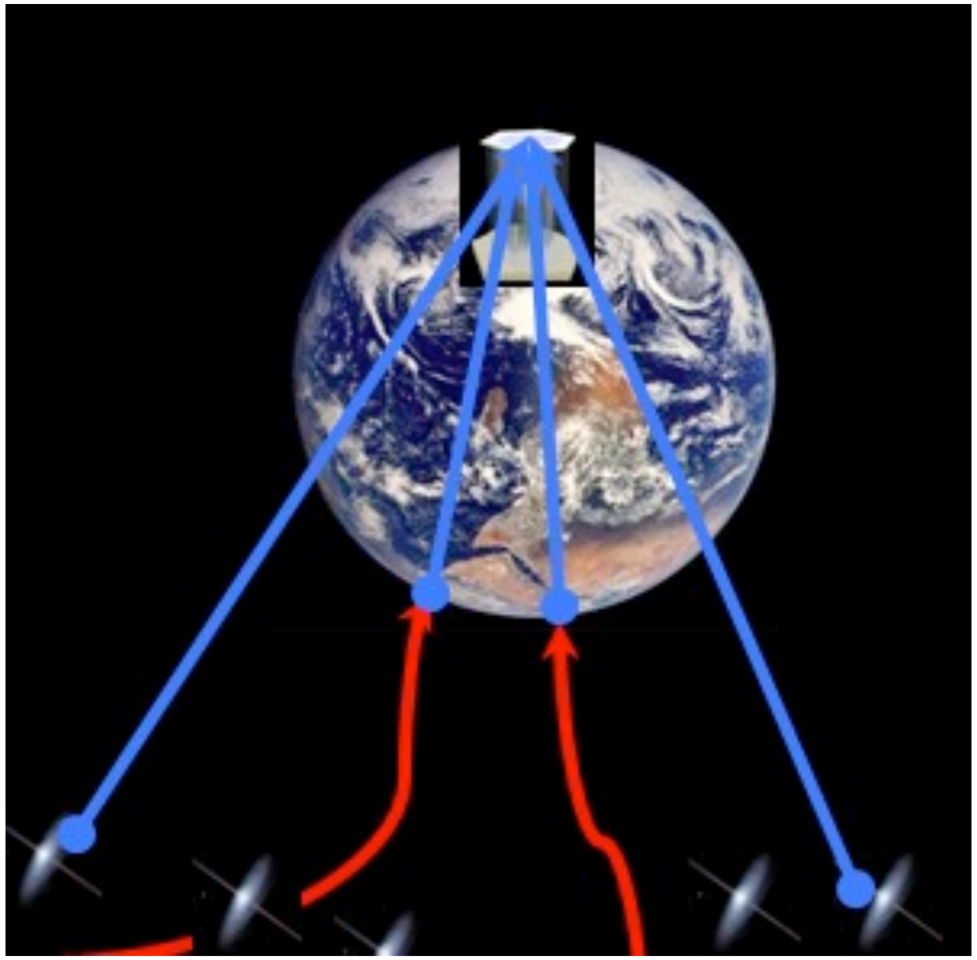
Floating Astrophysical Flavors

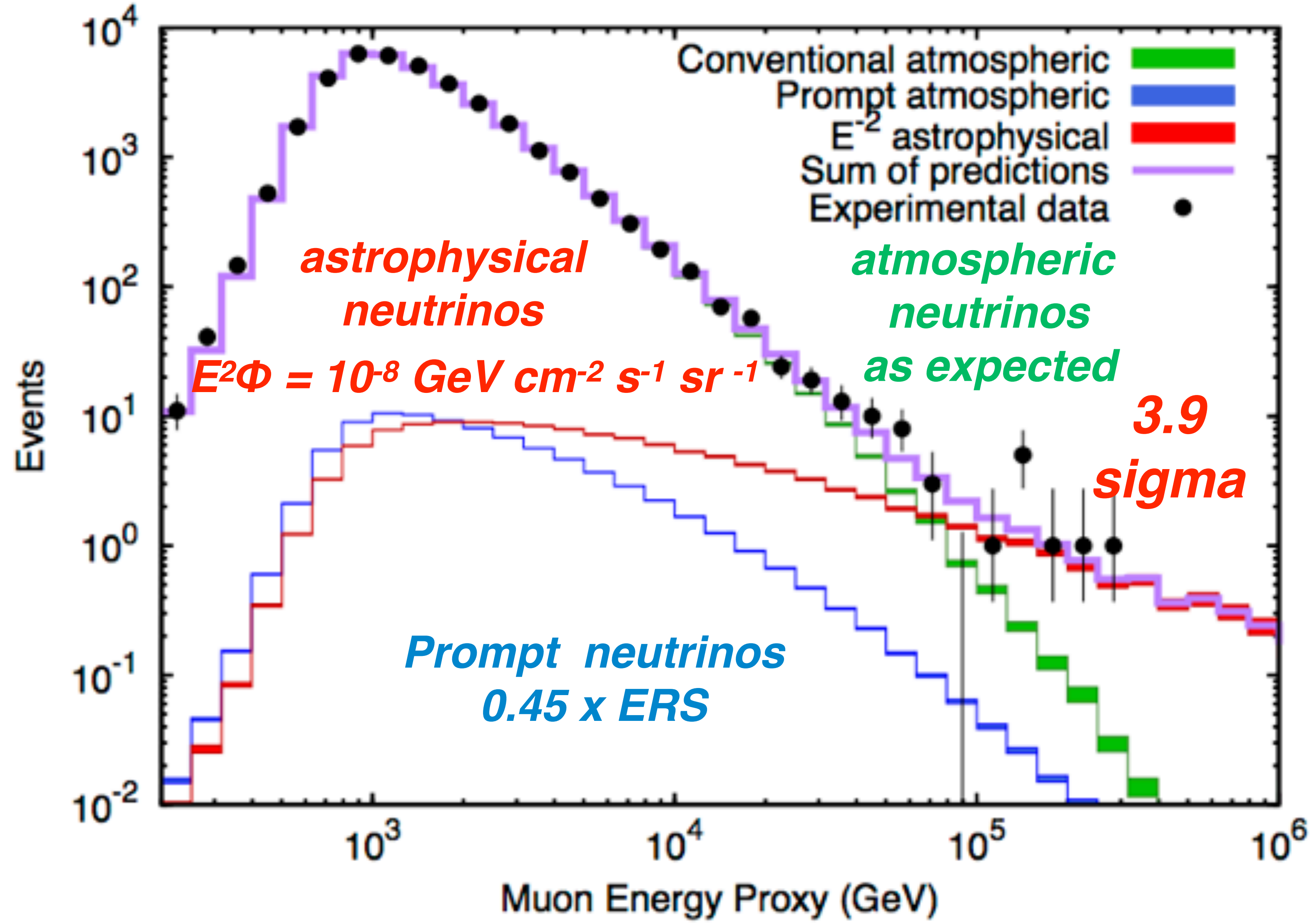


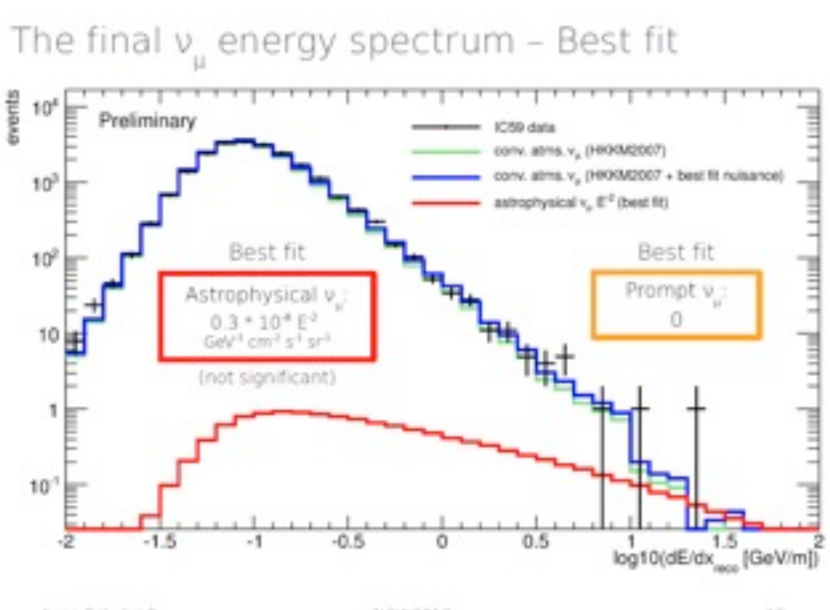


- Now allow the fraction of astrophysical neutrino flavor at surface
- Consistent with 1:1:1 and all possible source flavor compositions
- Pure ν_e on surface disfavored at 90% CL
- Pure ν_μ on surface disfavored at >99% CL

Up-going muon neutrino analysis





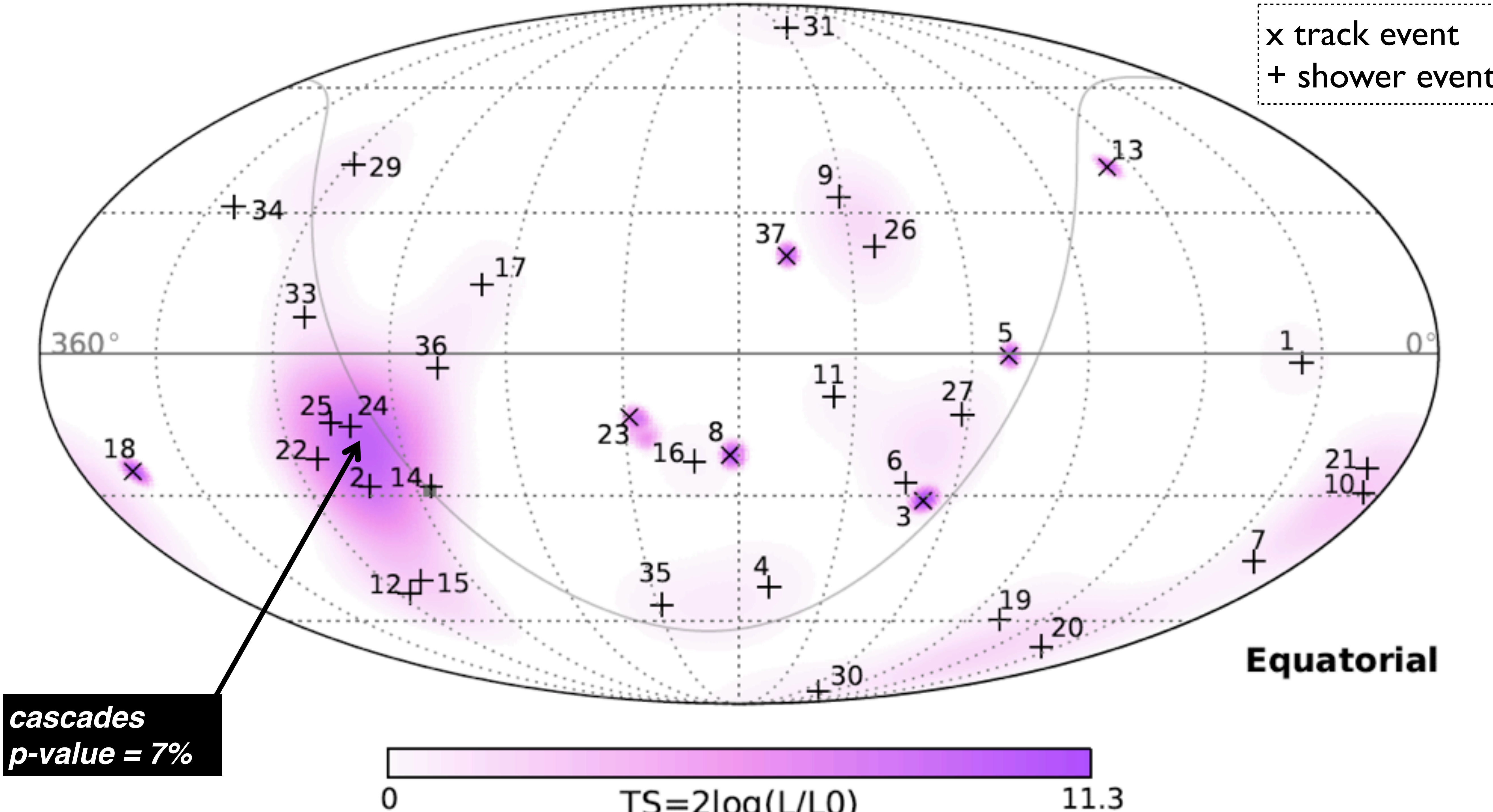


Hint from IC59 (1.8 sigma); now IC79/86-1 upgoing muon neutrinos give 3.9 sigma

Sources of the high-energy Neutrinos ?

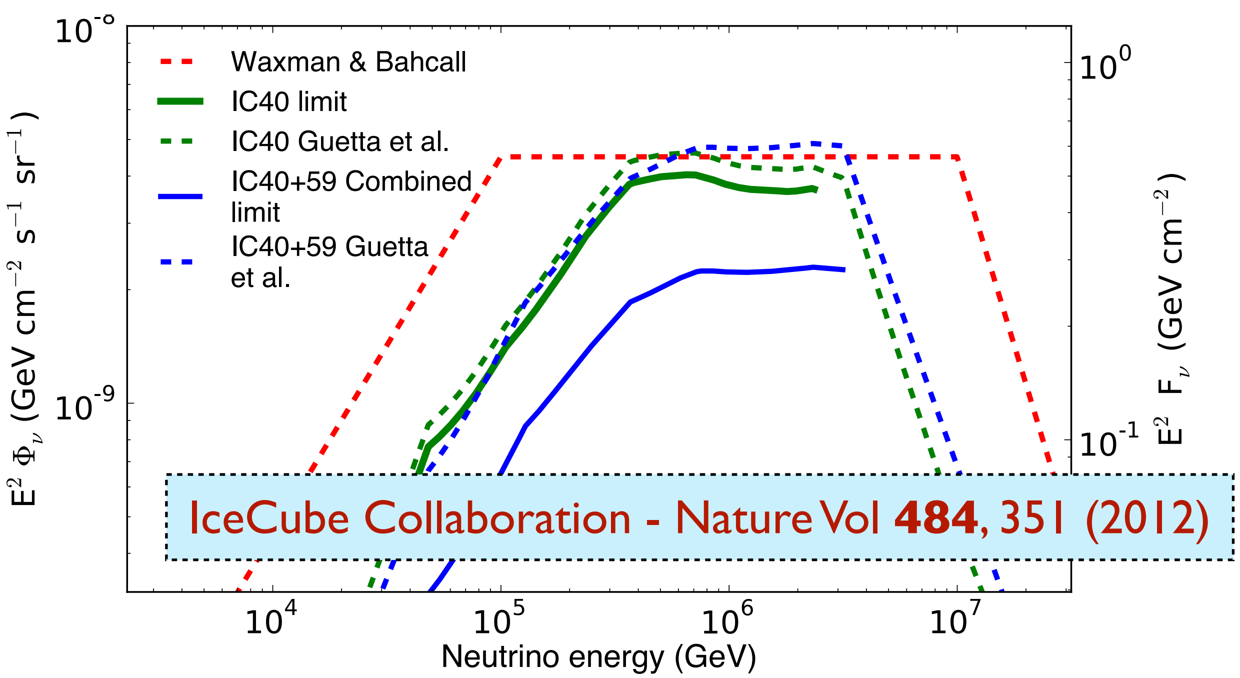
Clustering

IceCube Collaboration, *Science* 342, 1242856 (2013)



Extra Galactic

Gamma Ray Burst



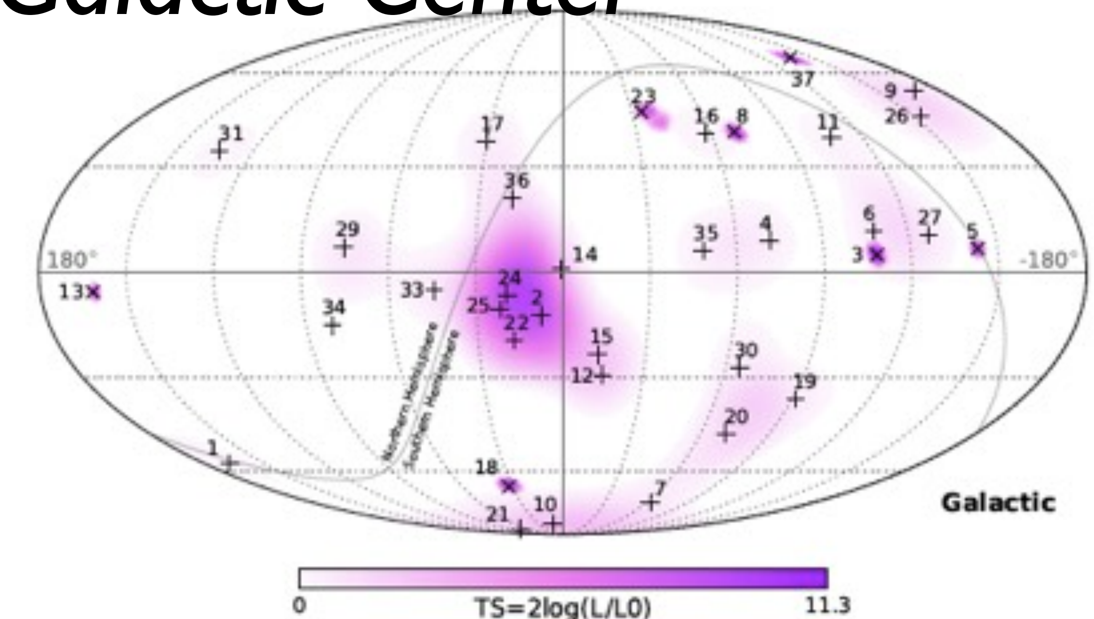
IceCube Collaboration - Nature Vol **484**, 351 (2012)

Active Galactic Nuclei / Starburst Galaxies

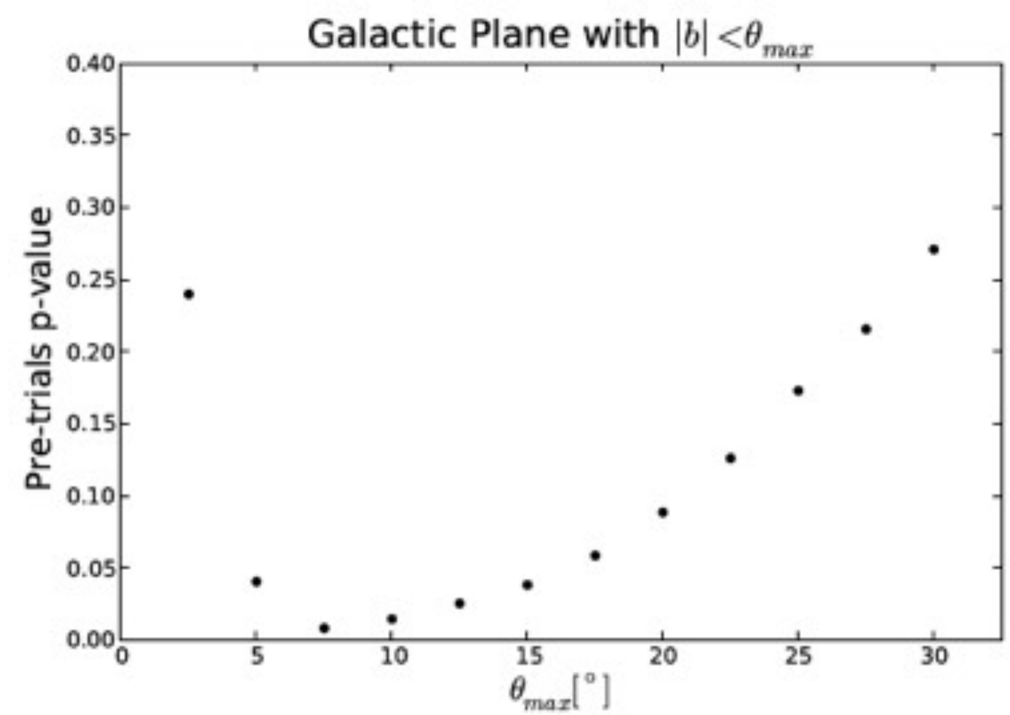
Starburst	M82	148.97	69.68	0.07	0.15
Radio	NGC 1275	49.95	41.51	0.0	–
Galaxies	Cyg A	299.87	40.73	0.9	0.03
	3C 123.0	69.27	29.67	0.0	–
	M87	187.71	12.39	0.0	–
	Cen A	201.37	-43.02	0.03	0.49

Galactic

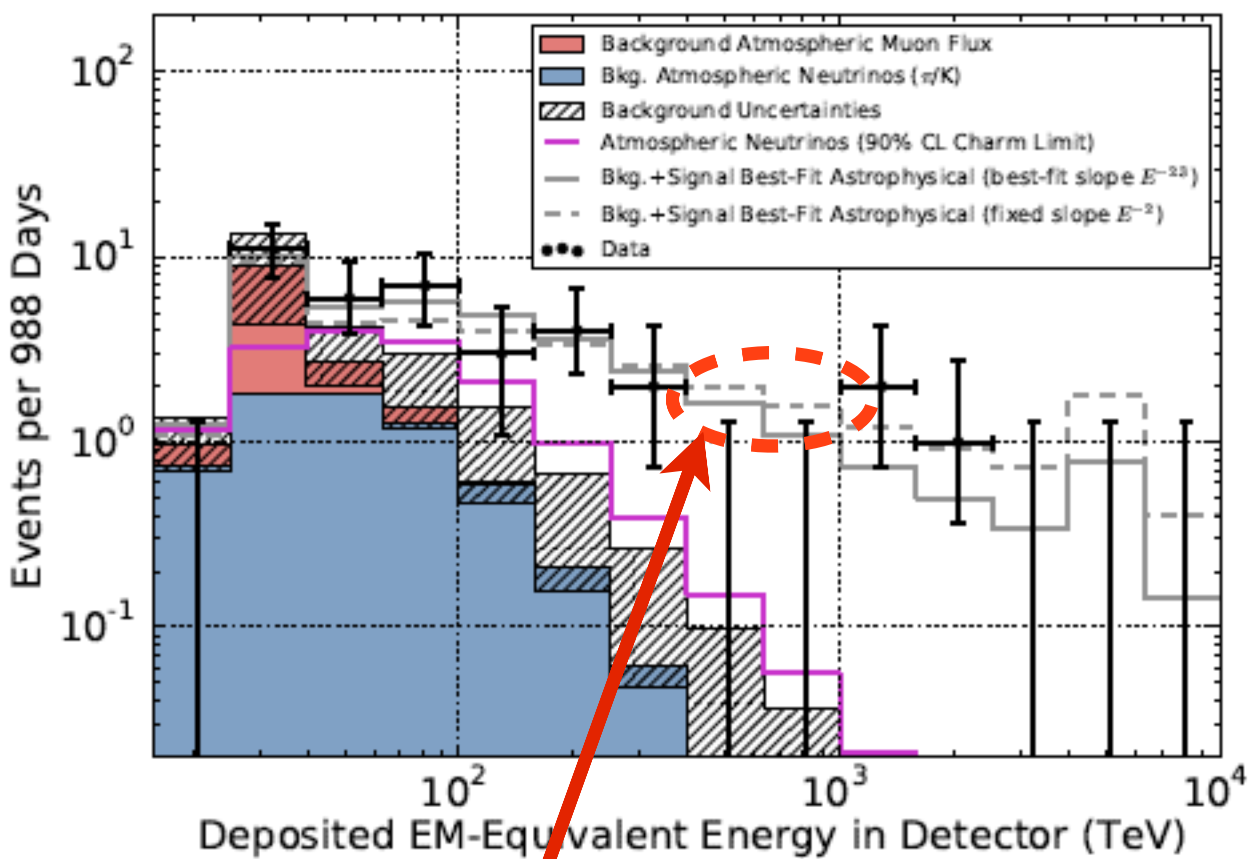
Galactic Center



Galactic Plane



PeV Neutrino Explanations



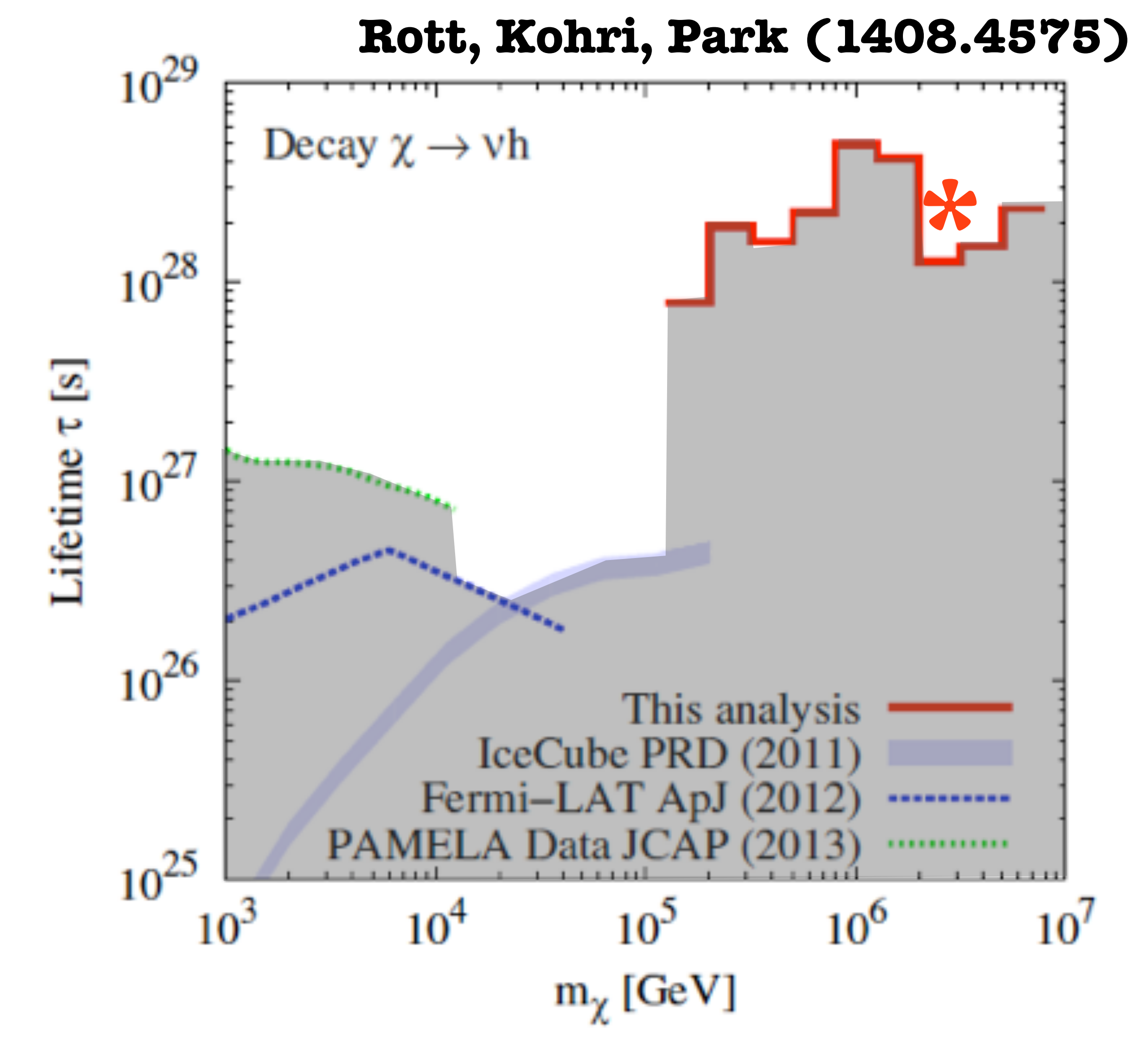
A gap larger than the one between 400 and 1000 TeV appears in 43% of realizations of the best-fit continuous spectrum.

- New IceCube data and color octet neutrino interpretation of the PeV energy events A.N. Akay, O. Cakir, Y.O. Gunaydin, U. Kaya, M. Sahin, S. Sultansoy. *arXiv:1409.5896*
- Mind the gap on Icecube: Cosmic neutrino spectrum and muon anomalous magnetic moment in the gauged L_{\mu} - L_{\tau} model Takeshi Araki, Fumihiro Kaneko, Yasufumi Konishi, Toshihiko Ota, Joe Sato, Takashi Shimomura. *arXiv:1409.4180*
- Galactic PeV neutrinos from dark matter annihilation Jesus Zavala Phys.Rev. D89 (2014) 123516 *arXiv:1404.2932*
- Color octet neutrino as the source of the IceCube PeV energy neutrino events A.N. Akay, U. Kaya, S. Sultansoy *arXiv:1402.1681*
- Geometric Compatibility of IceCube TeV-PeV Neutrino Excess and its Galactic Dark Matter Origin Yang Bai, Ran Lu, Jordi Salvado *arXiv:1311.5864*
- Superheavy Particle Origin of IceCube PeV Neutrino Events Vernon Barger, Wai-Yee Keung Phys.Lett. B727 (2013) 190-193 *arXiv:1305.6907*
- Neutrinos at IceCube from Heavy Decaying Dark Matter Brian Feldstein, Alexander Kusenko, Shigeki Matsumoto, Tsutomu T. Yanagida Phys.Rev. D88 (2013) 1, 015004 *arXiv:1303.7320*
- A. Esmaili and P. D. Serpico, Are IceCube neutrinos unveiling PeV-scale decaying dark matter?, JCAP 1311, 054 (2013) *arXiv: 1308.1105*
- ...

Heavy Dark Matter

- Heavy Decaying Dark Matter (example $\chi \rightarrow \nu h$)
- focus on most detectable feature (neutrino line)
- Backgrounds steeply falling with energy, highest energy events provide best sensitivity
- Continuum and spacial distribution could help identify a signal
- Bounds from Fermi-LAT and PAMELA derived from search for bb annihilation channel (dominant decay channel of Higgs).

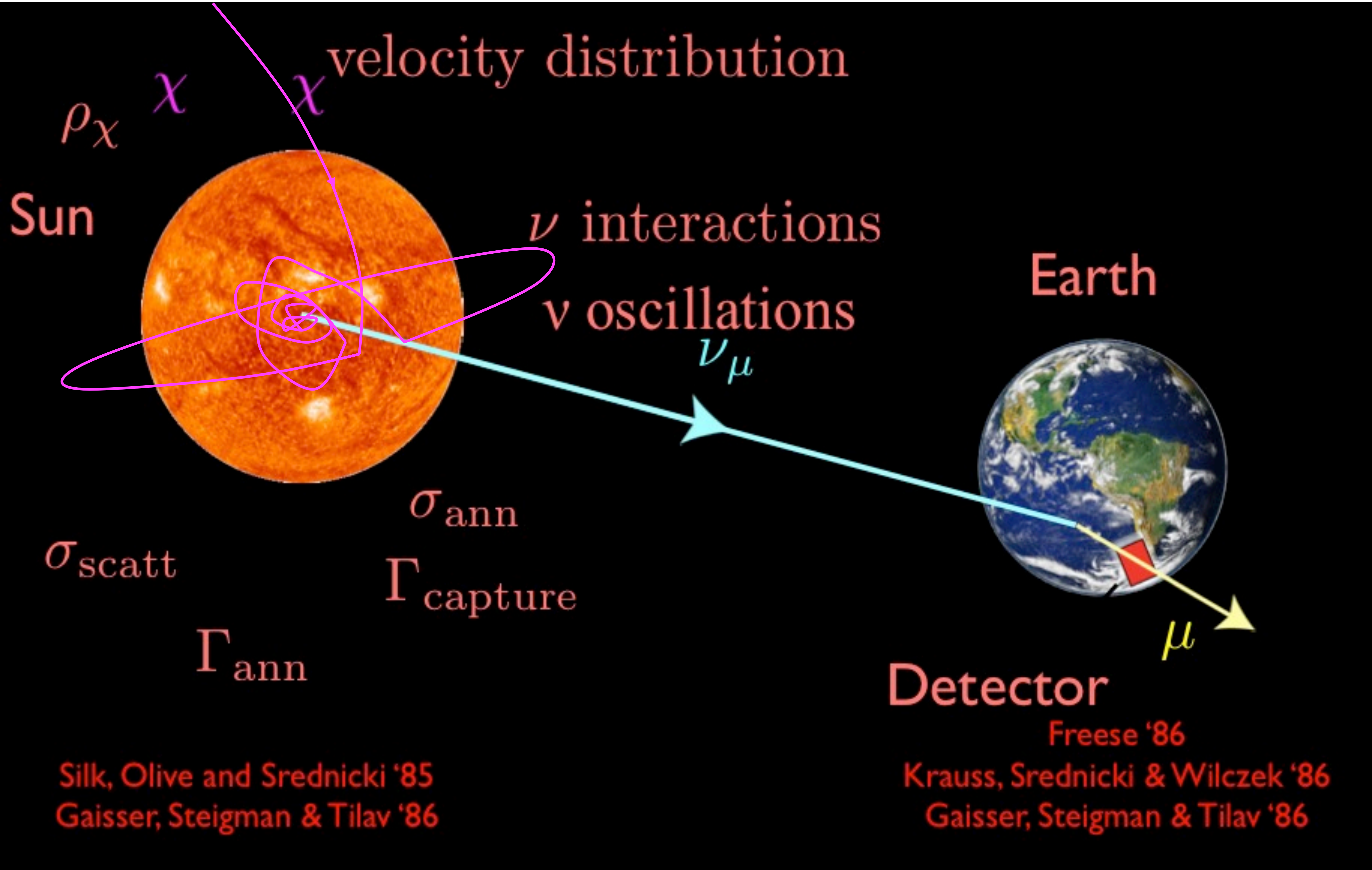
Bound on lifetime $\sim 10^{28}$s



<u>Heavy DM bounds with neutrinos, see also</u>
Murase and Beacom JCAP 1210 (2012) 043
Esmaili, Ibarra, and Perez JCAP 1211 (2012) 034

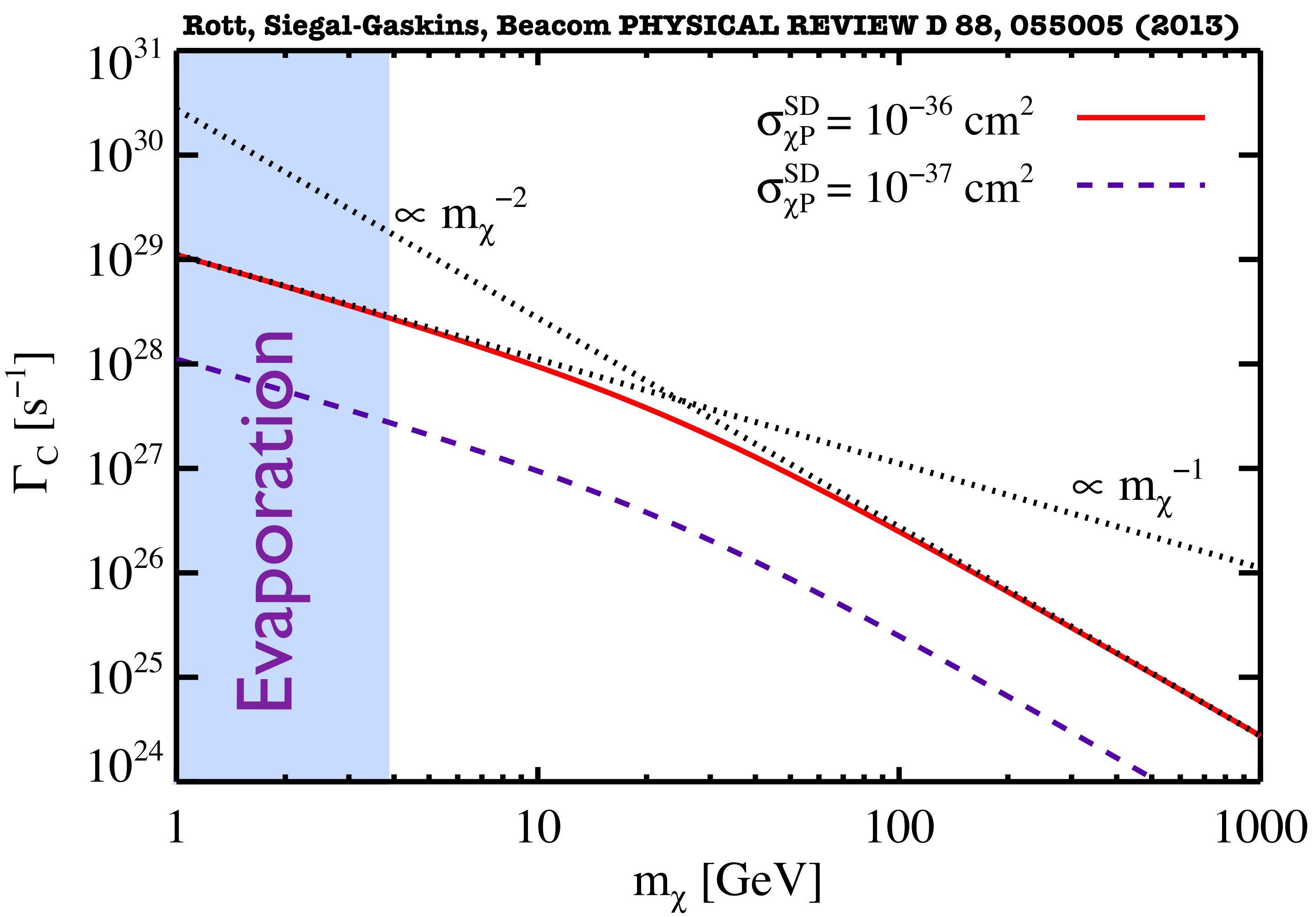
Hunt for Dark Matter with Neutrinos

Solar WIMP Signal



Solar WIMP Capture

- WIMPs can get gravitationally captured by the Sun
  - Capture rate, Γ_C ,depends on WIMP-nucleon scattering cross section
- Dark Matter accumulates and starts annihilating
  - → Only neutrinos can make it out
- Equilibrium: The capture rate regulates the annihilation rate ($\Gamma_A = \Gamma_C/2$)
  - The neutrino flux only depends on the WIMP-Nucleon scattering cross section



The capture rates scales as:

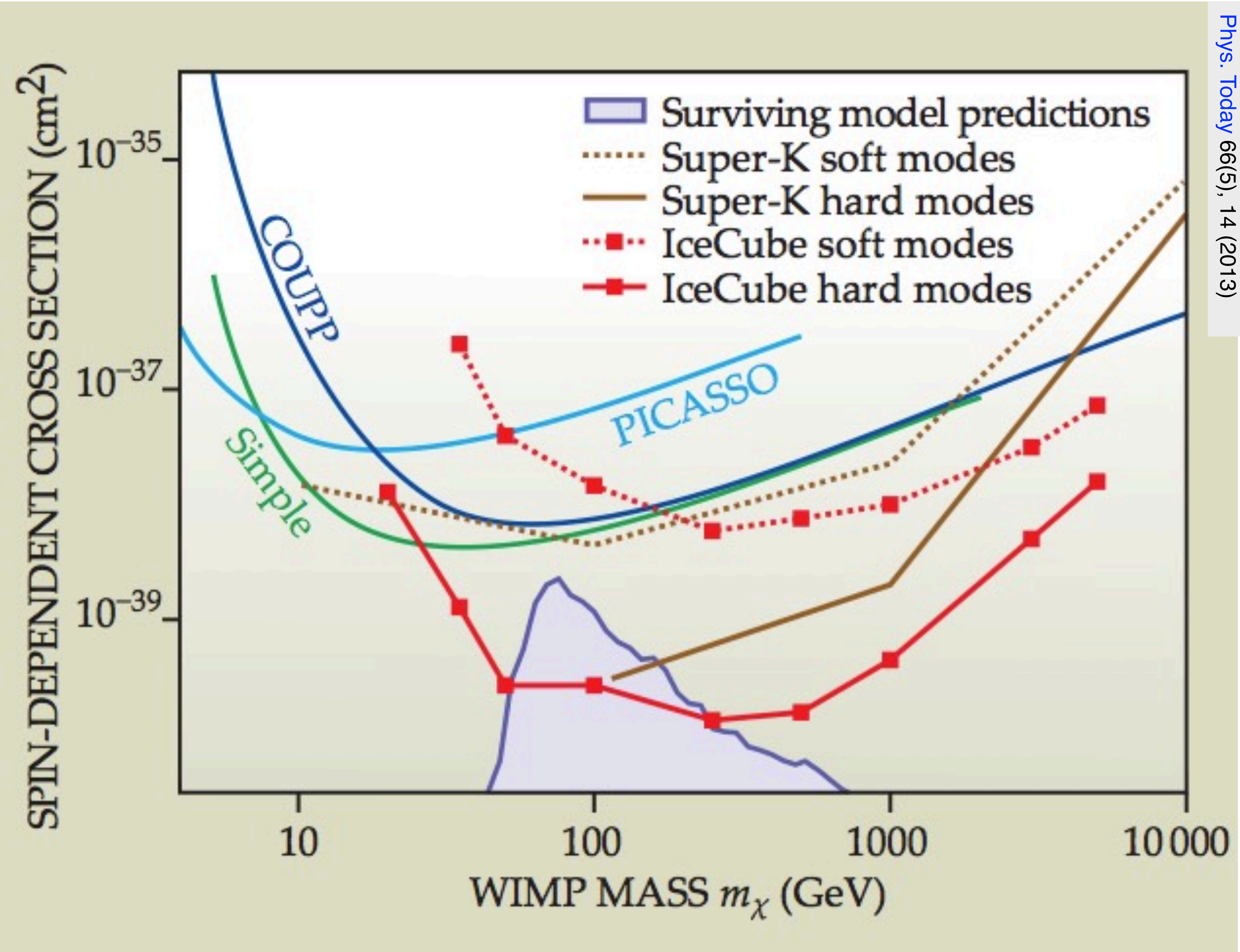
$\Gamma_C \sim \rho_\chi m_\chi^{-1} \sigma_A$ for $m_\chi \sim m_A$

$\Gamma_C \sim \rho_\chi m_\chi^{-2} \sigma_A$ for $m_\chi >> m_A$

number density + kinematic suppression

m_A - is the target mass

IceCube Result



Phys. Today 66(5), 14 (2013)

Neutrino bounds extremely competitive with Dark Matter direct detection

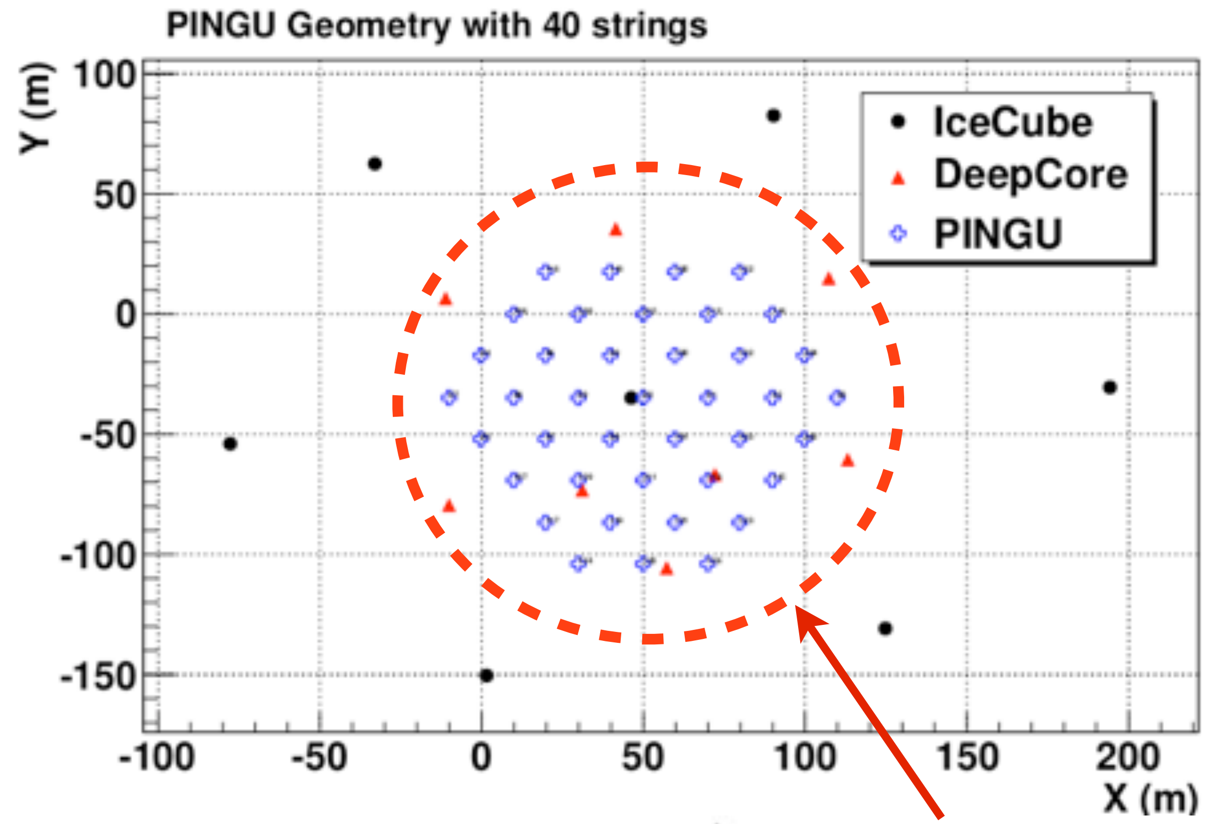
&

Can test models beyond the reach of LHC

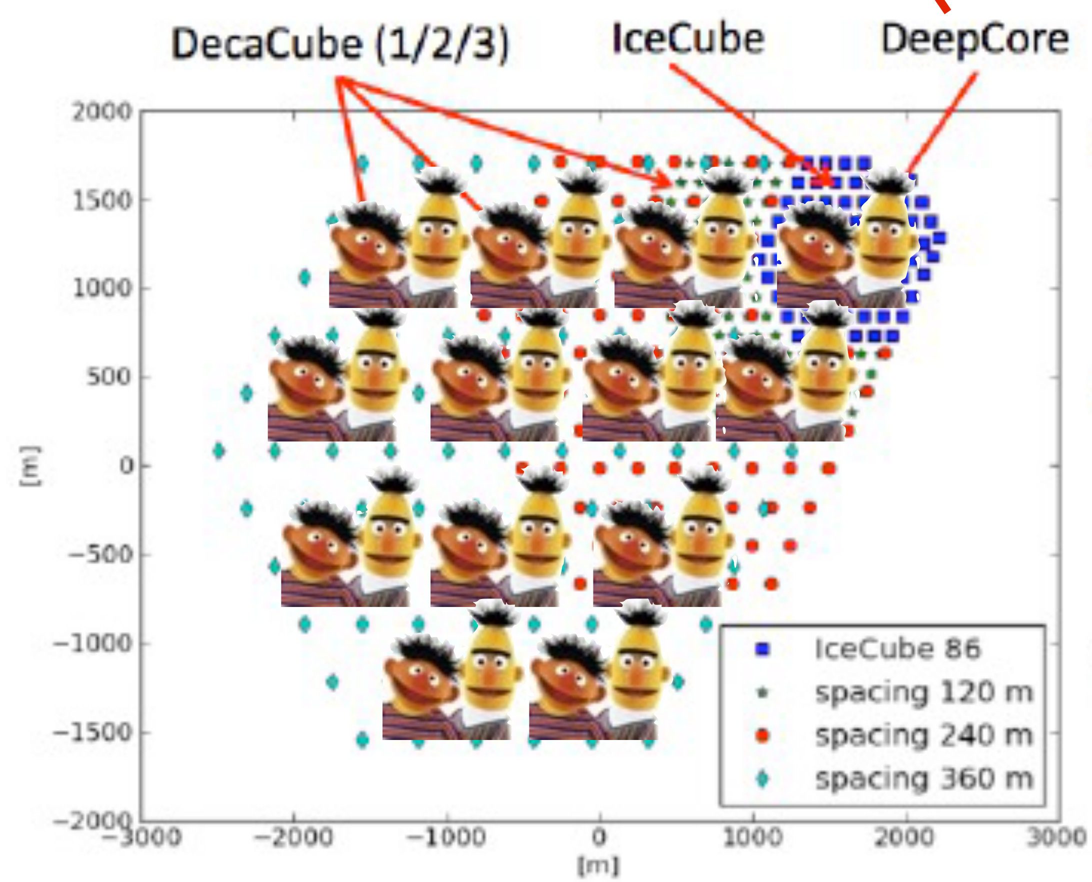
Future Plans

Future of IceCube

- Make it better
  - Precision detector with ~GeV threshold



- Make it bigger



Spacing 1 (120m):
IceCube (1 km^3)
+ 98 strings (1,3 km^3)
= 2,3 km^3

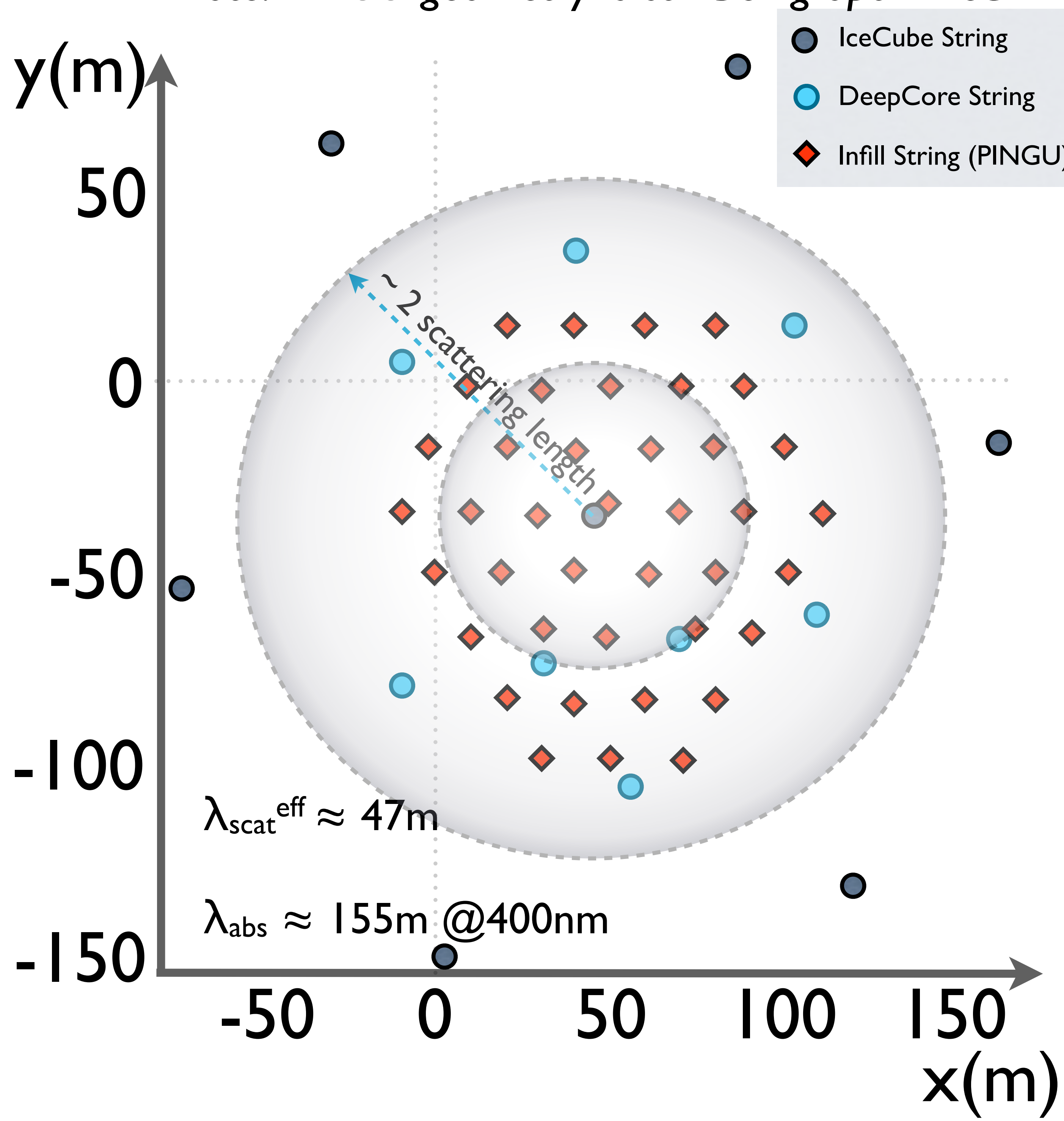
Spacing 2 (240m):
IceCube (1 km^3)
+ 99 strings (5,3 km^3)
= 6,3 km^3

Spacing 3 (360m):
IceCube (1 km^3)
+ 95 strings (11,6 km^3)
= 12,6 km^3

- PINGU upgrade plan
  - Instrument a volume of about 5MT with ~40 strings each containing 60-100 optical modules
  - Rely on well established drilling technology and photo sensors
  - Create platform for calibration program and test technologies for future detectors
- Physics Goals:
  - Precision measurements of neutrino oscillations (mass hierarchy, ...)
  - Test low mass dark matter models

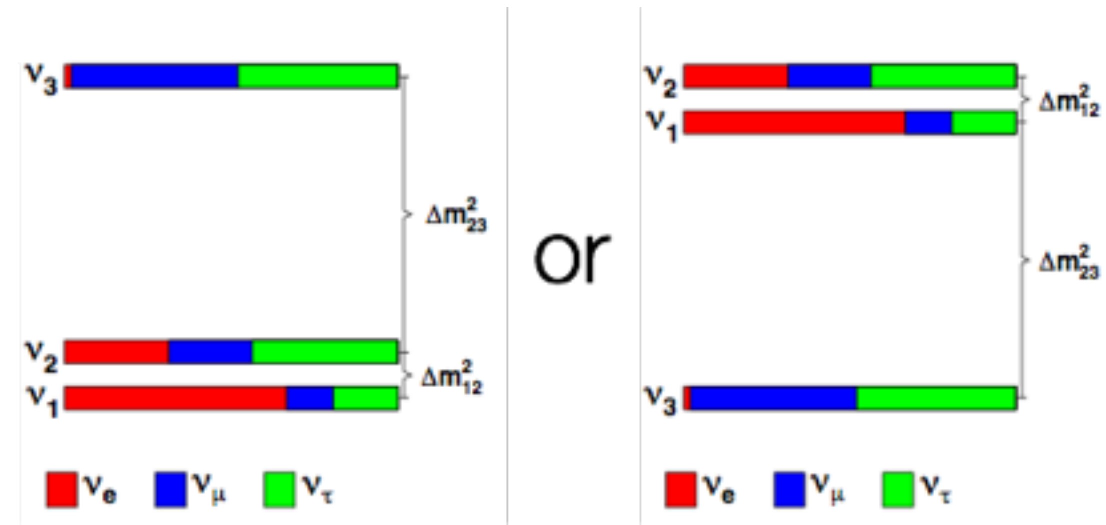
An example PINGU geometry (40 strings)

Note: PINGU geometry is still being optimized

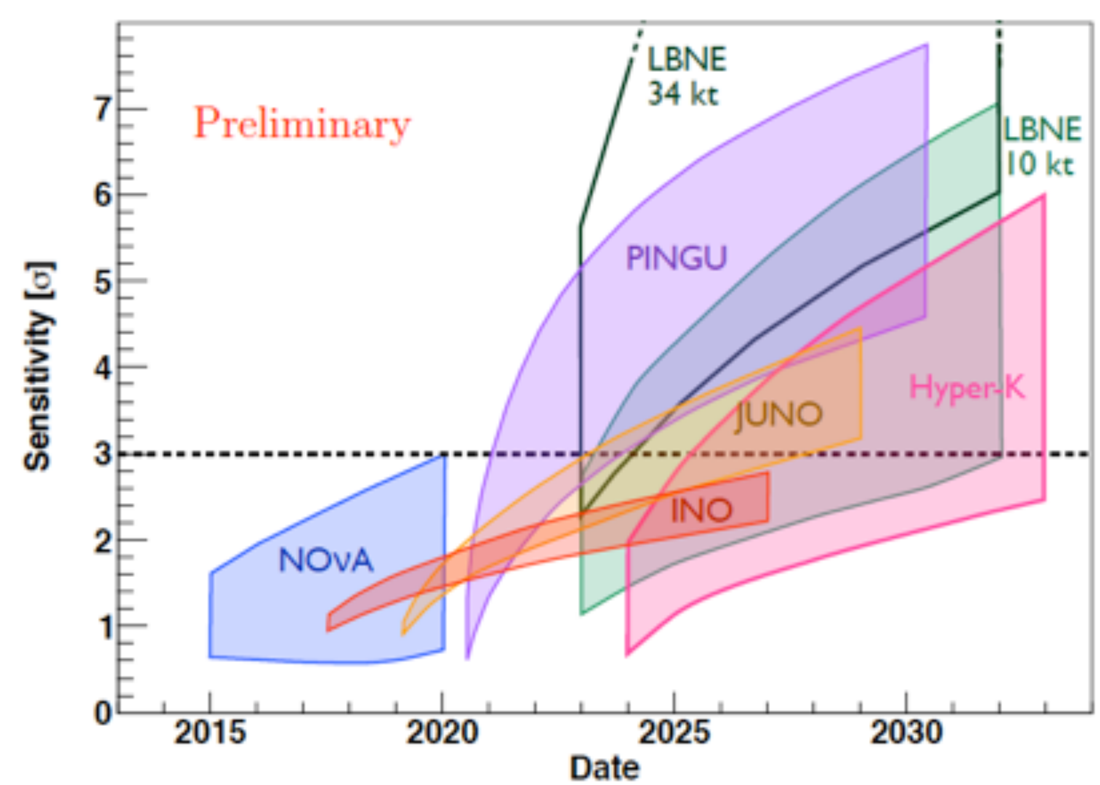


Advantages of PINGU

- Well-established detector and construction technology (low risk)
- Relatively low cost: ~$10M design/startup plus ~$1.25M per string
- Rapid schedule
- Quick accumulation of statistics once complete
- Provides a platform for more detailed calibration systems to reduce detector systematics
- Multipurpose detector: Neutrino Properties, Dark Matter, Supernovae, Galactic Neutrino Sources, Neutrino Tomography, ...
- Opportunity for R&D toward other future ic water Cherenkov detectors
- PINGU LOI released *arXiv:1401.2046*

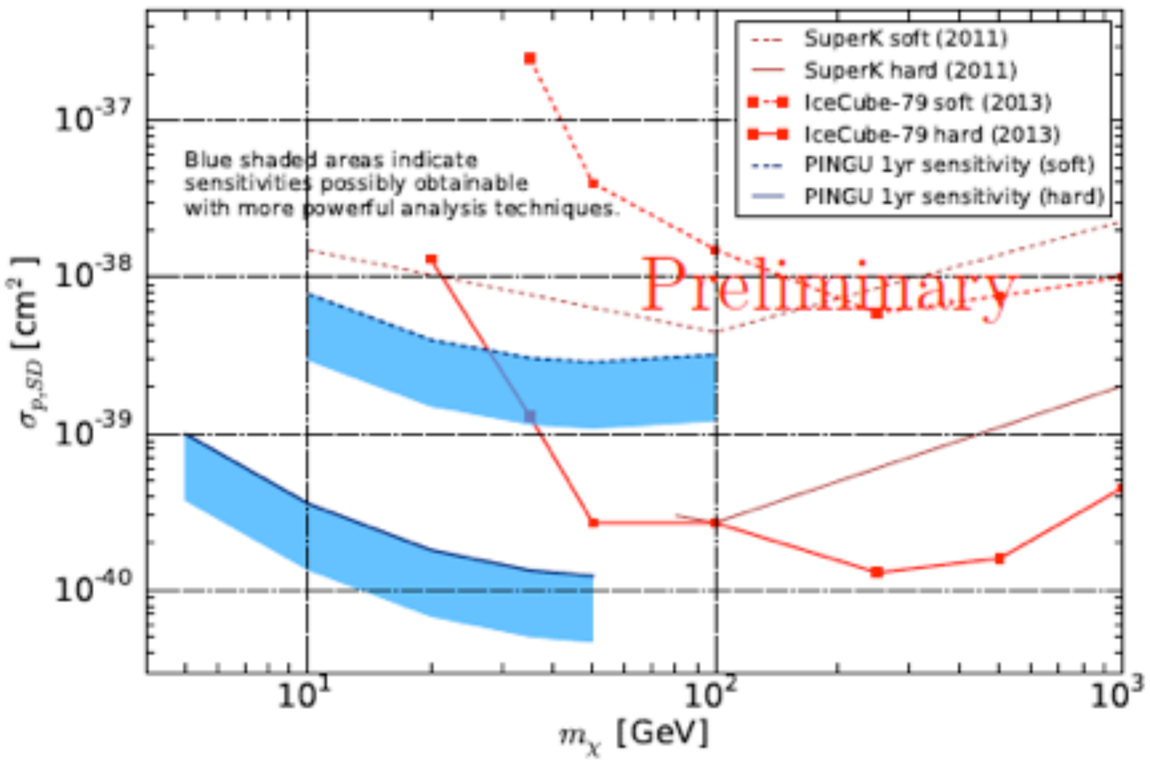


PINGU LOI



PINGU Multipurpose Experiment

Spin-dependent scattering



Tomography

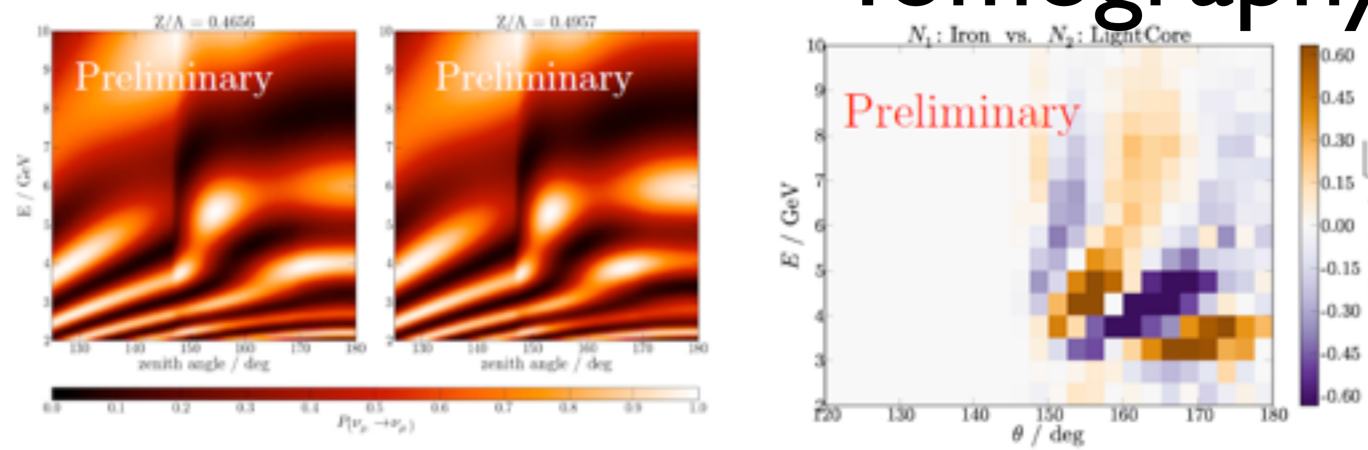
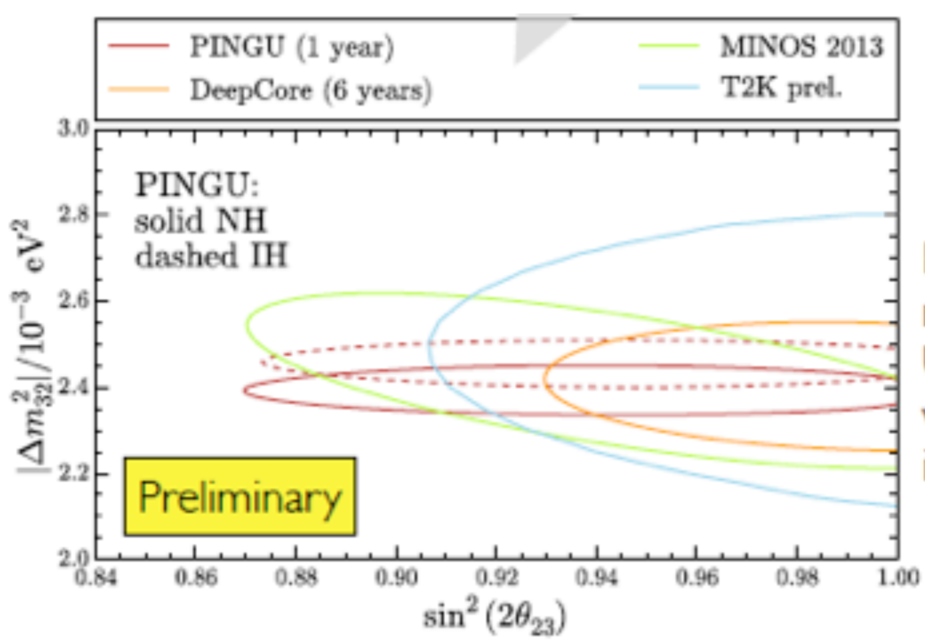


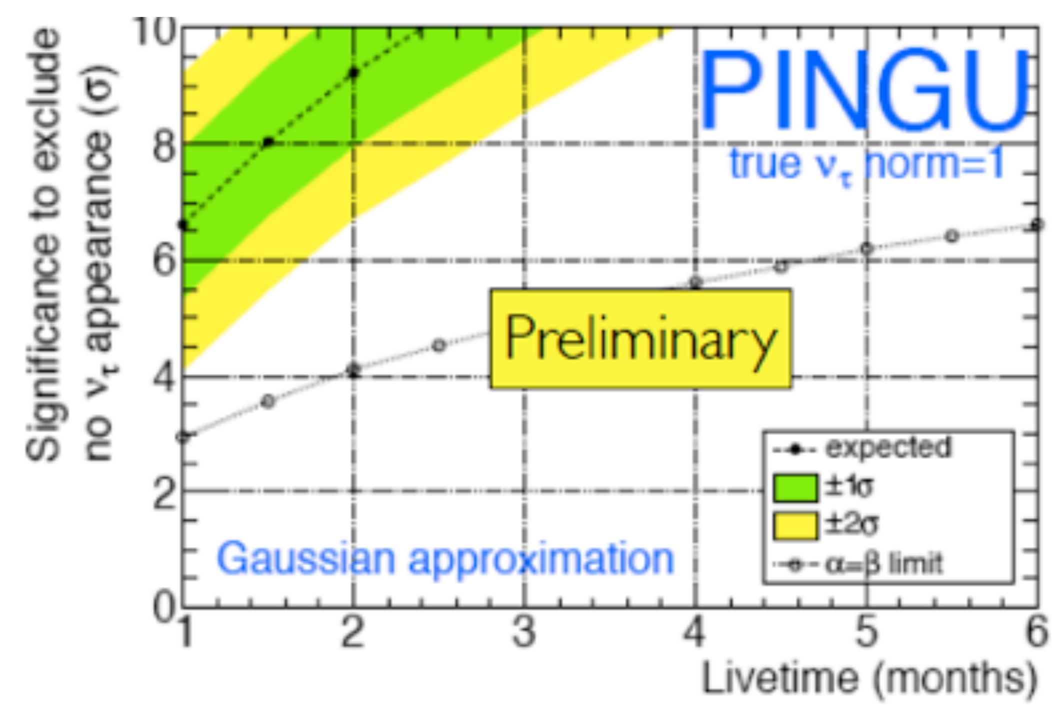
Figure 25: The impact of a changed core composition on the muon-neutrino survival probabilities is demonstrated by comparing the left most figure (pure iron core) and the middle figure (iron mixed with lighter elements). Signature of a pure iron Earth core with respect to a model assuming the same composition for mantle and core are shown on the right. The true neutrino energy and direction are shown for one year of data with 35% electron neutrino contamination.



Based on old reconstruction. Updated result will be much improved.

ν_μ disappearance: Highly competitive after 1 yr

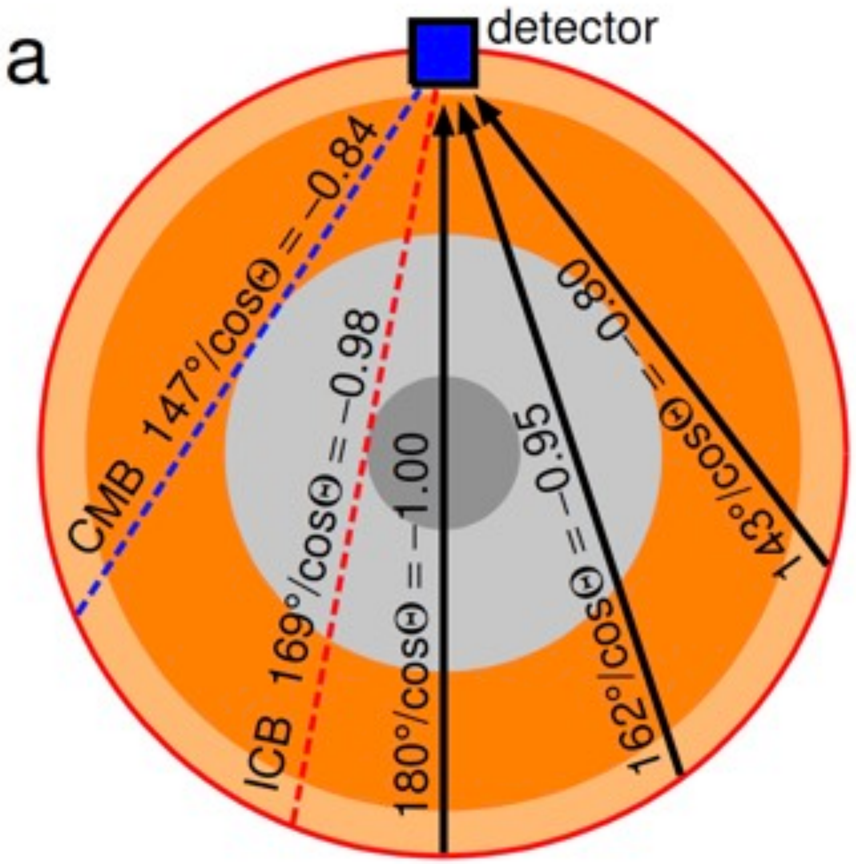
Also: See IceCube result, PRL 111, 081801 (2013)

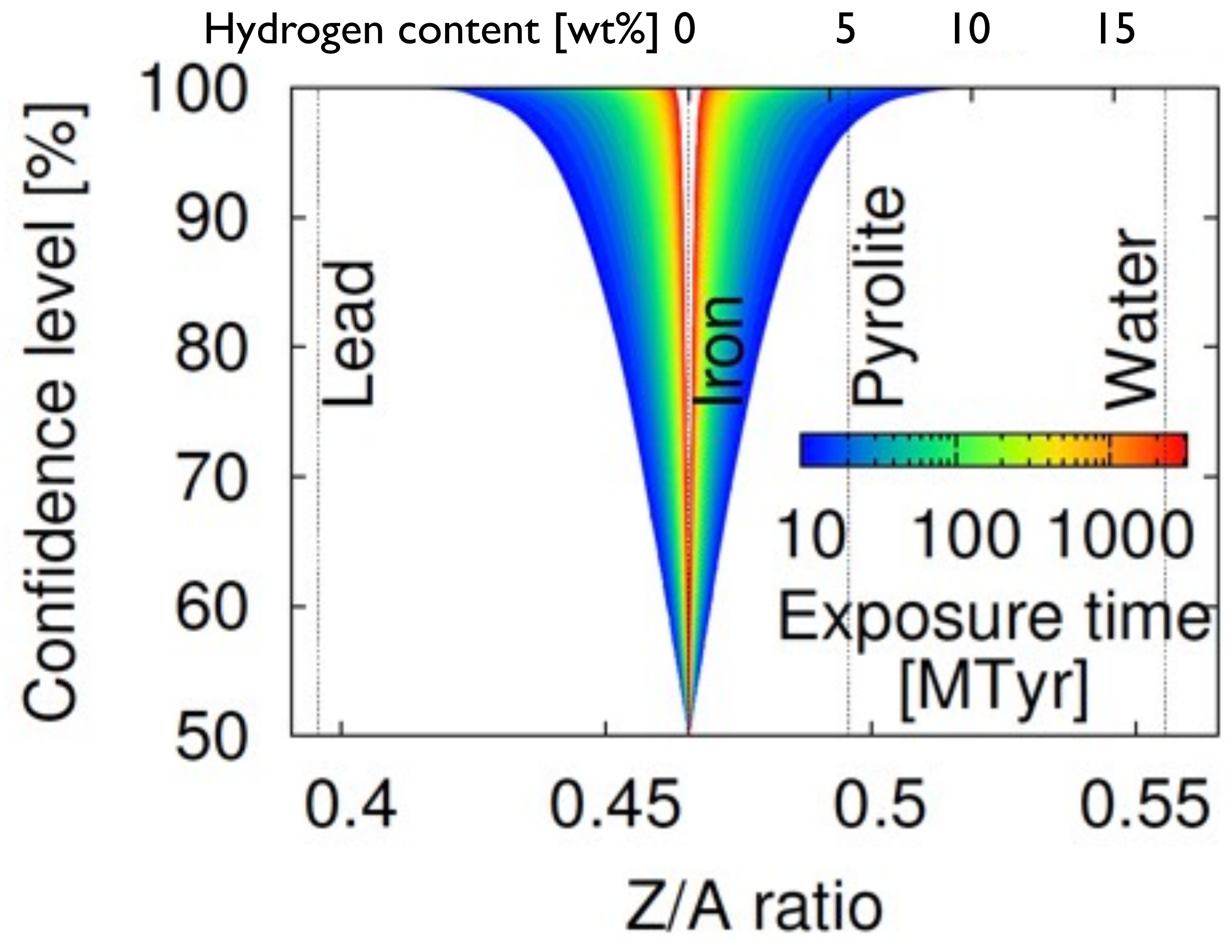


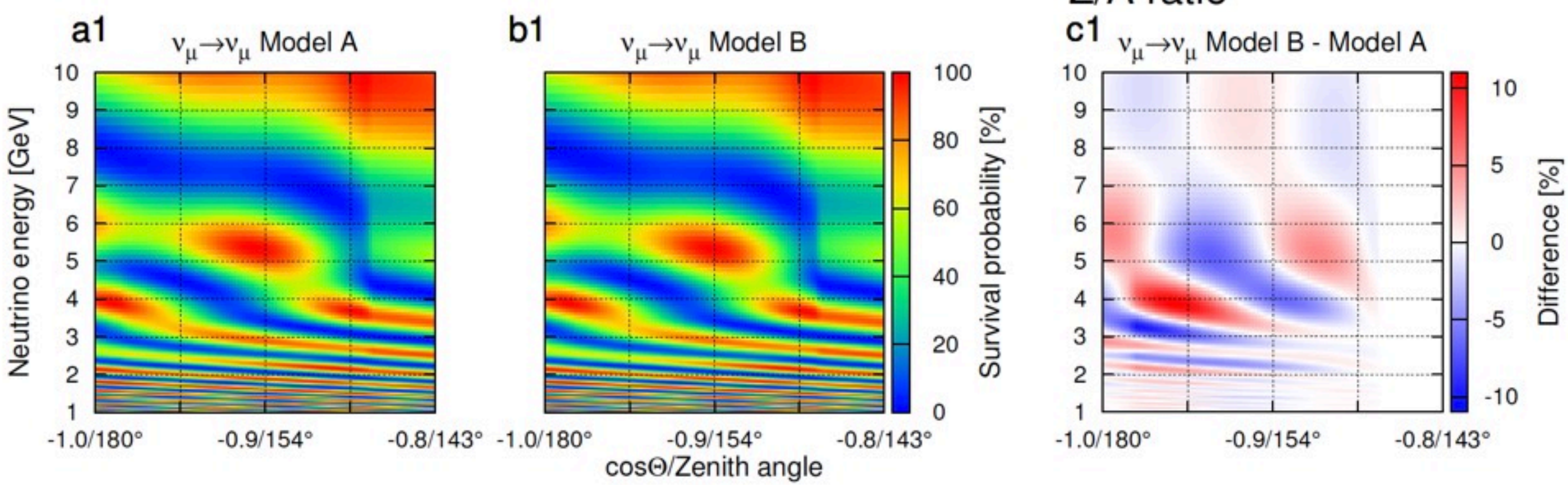
ν_τ appearance: Exclude null hypothesis at 5σ with ~1 month of data

Rott et al. e-print 1502.04930

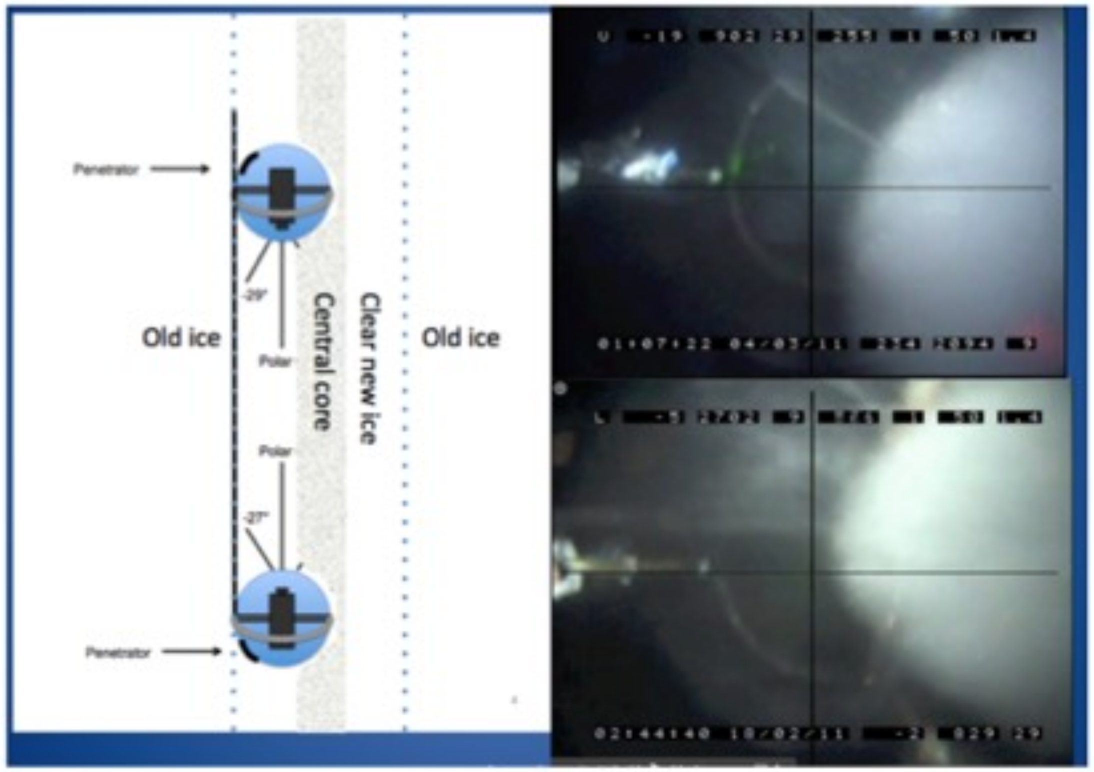
Neutrino Spectrometry

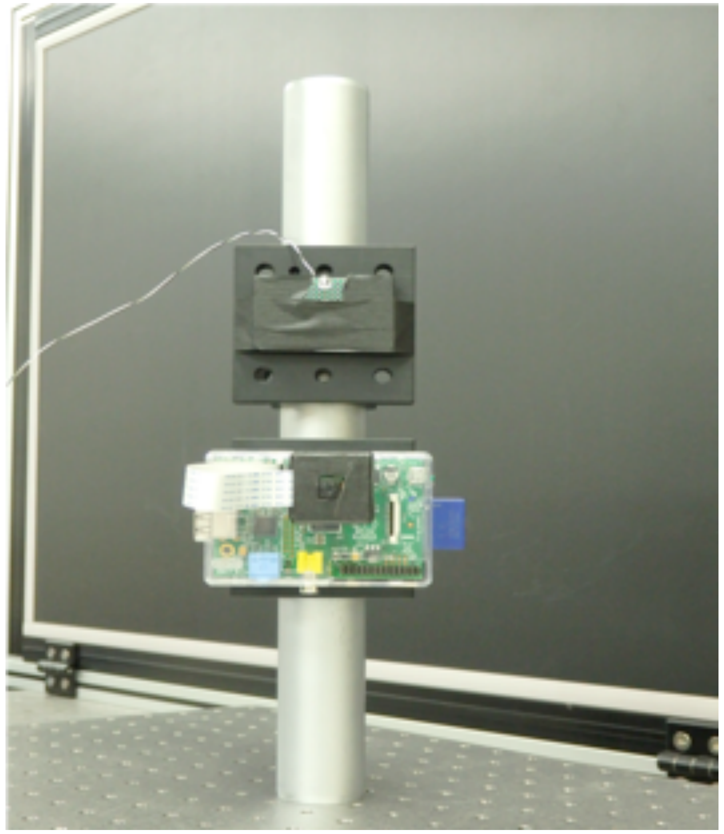






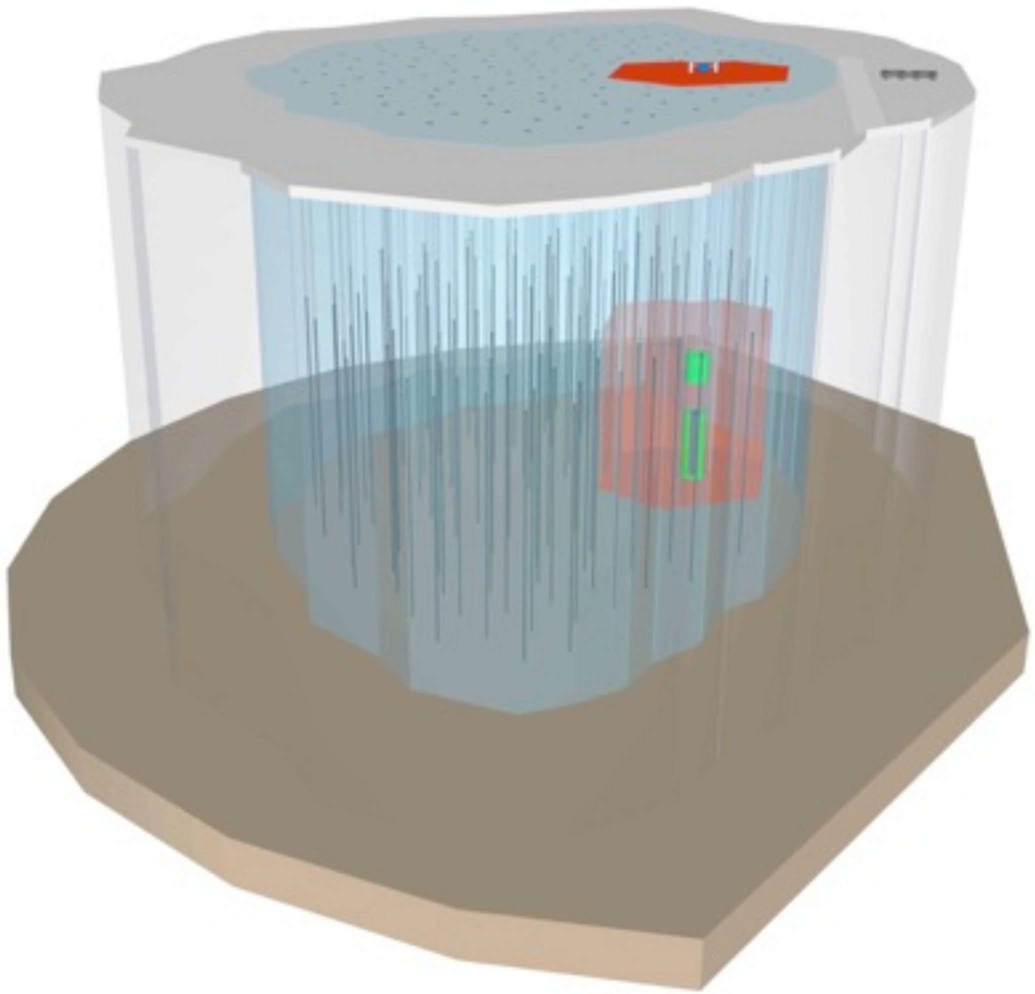
- Refrozen ice (hole ice) is a major source uncertainty
- There is good reason to expect that the situation for each sensor module can be rather different
  - Understand the ice conditions in the vicinity of every sensor
    - Where is the sensor with respect to the hole ice ?
    - Are there any impurities, cracks, bubbles, etc ...
    - Where is the cable located ?





Conclusions

- IceCube has reigned in a new era in astro-particle physics
  - What's the origin of the high-energy neutrino excess ?
  - Let's find out !
- Great prospect for future upgrades
  - PINGU in-fill aims at creating a large volume detector with a threshold of few GeV
  - High-energy extension for PeV neutrinos




Thanks !