IceCube and the Development of High-Energy Neutrino Astronomy

Naoko Kurahashi Neilson (Drexel University)
for the IceCube Collaboration

DBD16
November 9th, 2016
Osaka, Japam

IceCube and the Development of High-Energy Neutrino Astronomy

+ Neutrino Oscillations
+ WIMP Searches
+ Mass Hierarchy

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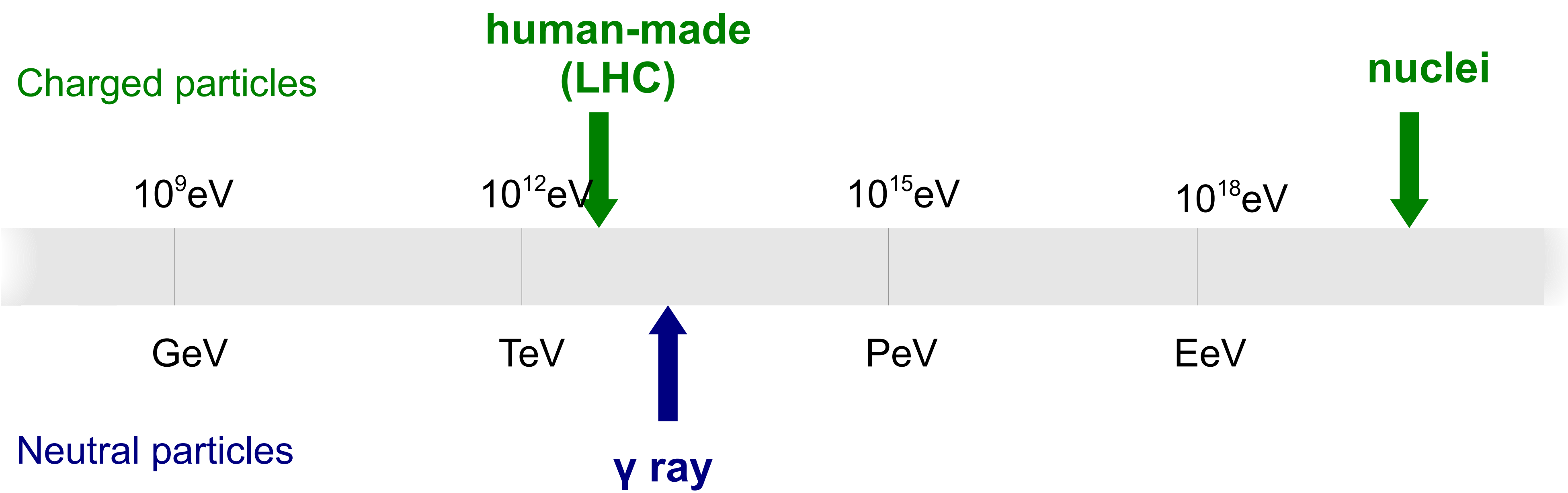
A high energy tale of the high energy tail
Highest energy particles observed

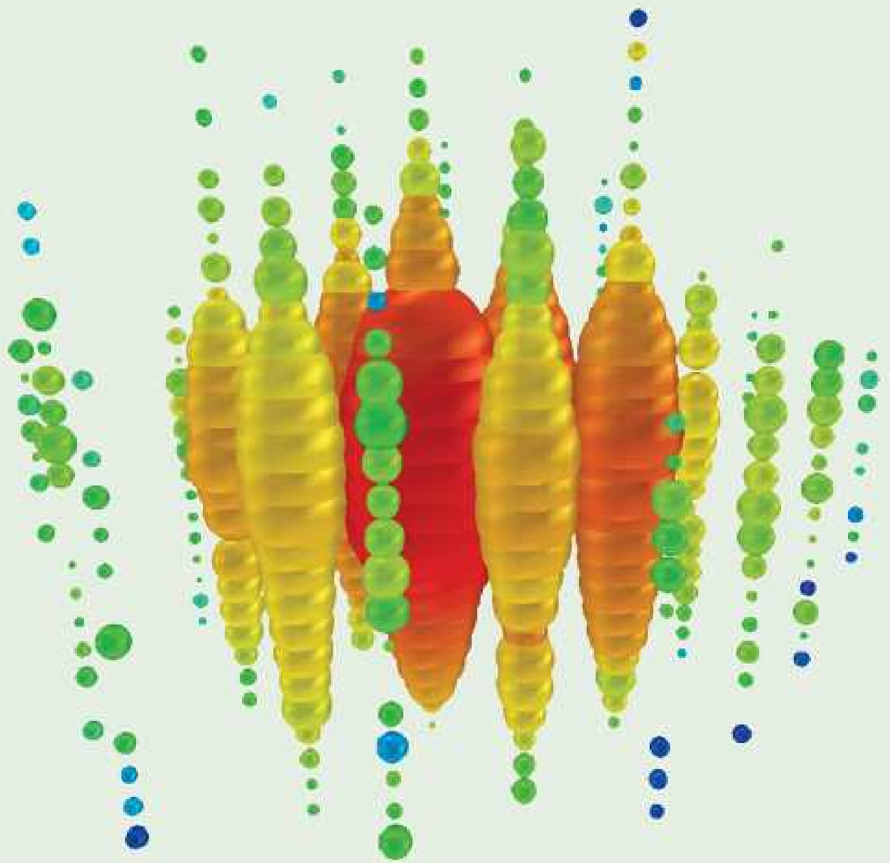


111

PHYSICAL REVIEW LETTERS™

PRL 111 (2), 020401–029902, 12 July 2013 (416 total pages)

Articles published week ending 12 JULY 2013



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Published by
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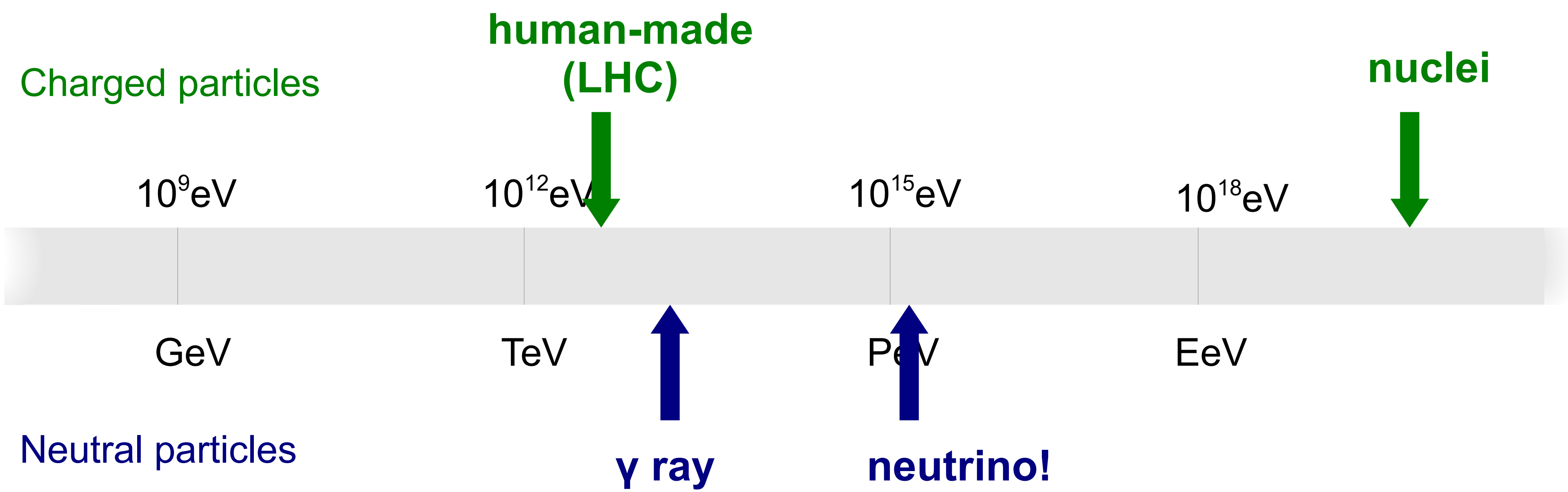
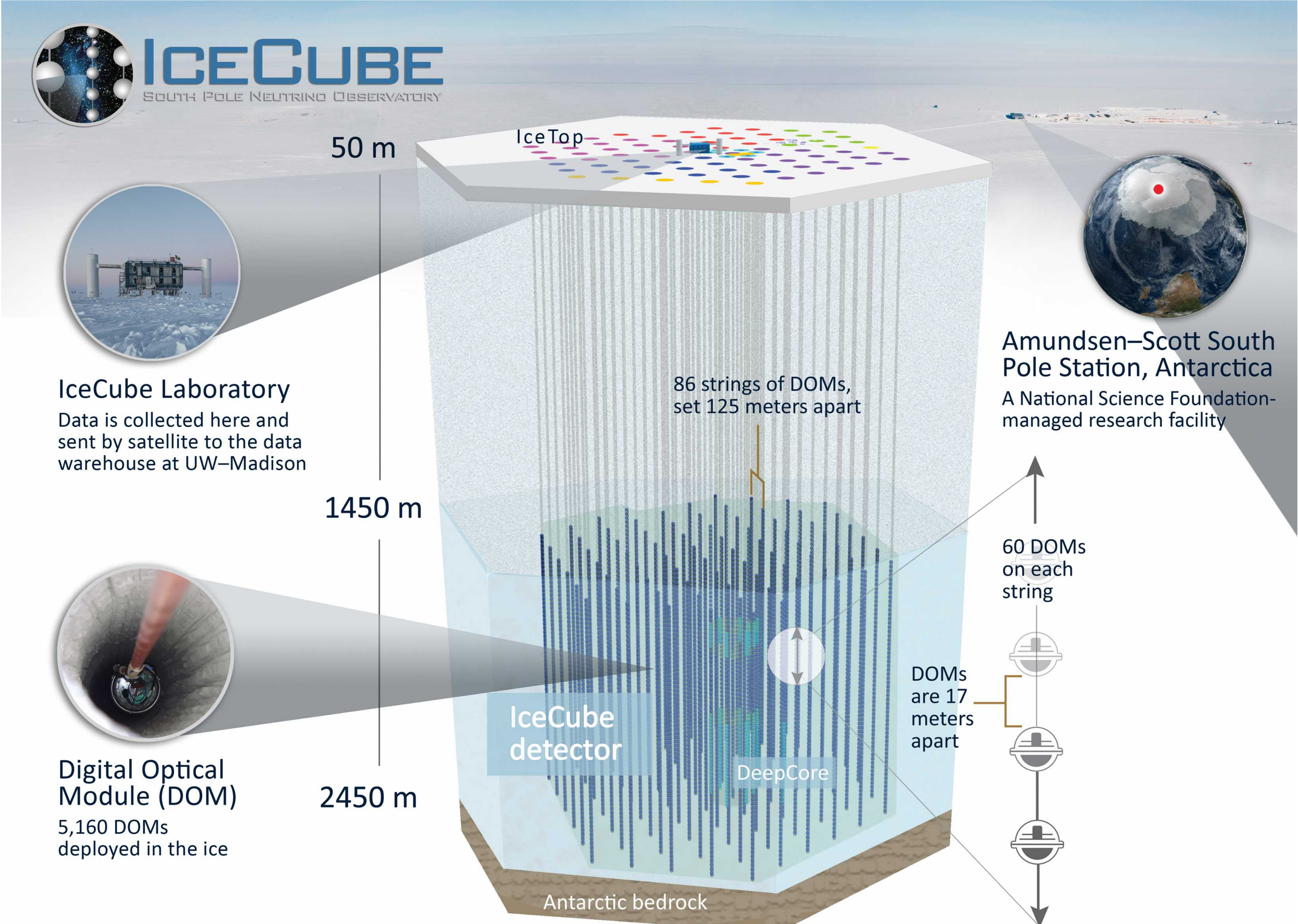
APS physics

Volume 111, Number 2

A high energy tale of the high energy tail
Highest energy particles observed

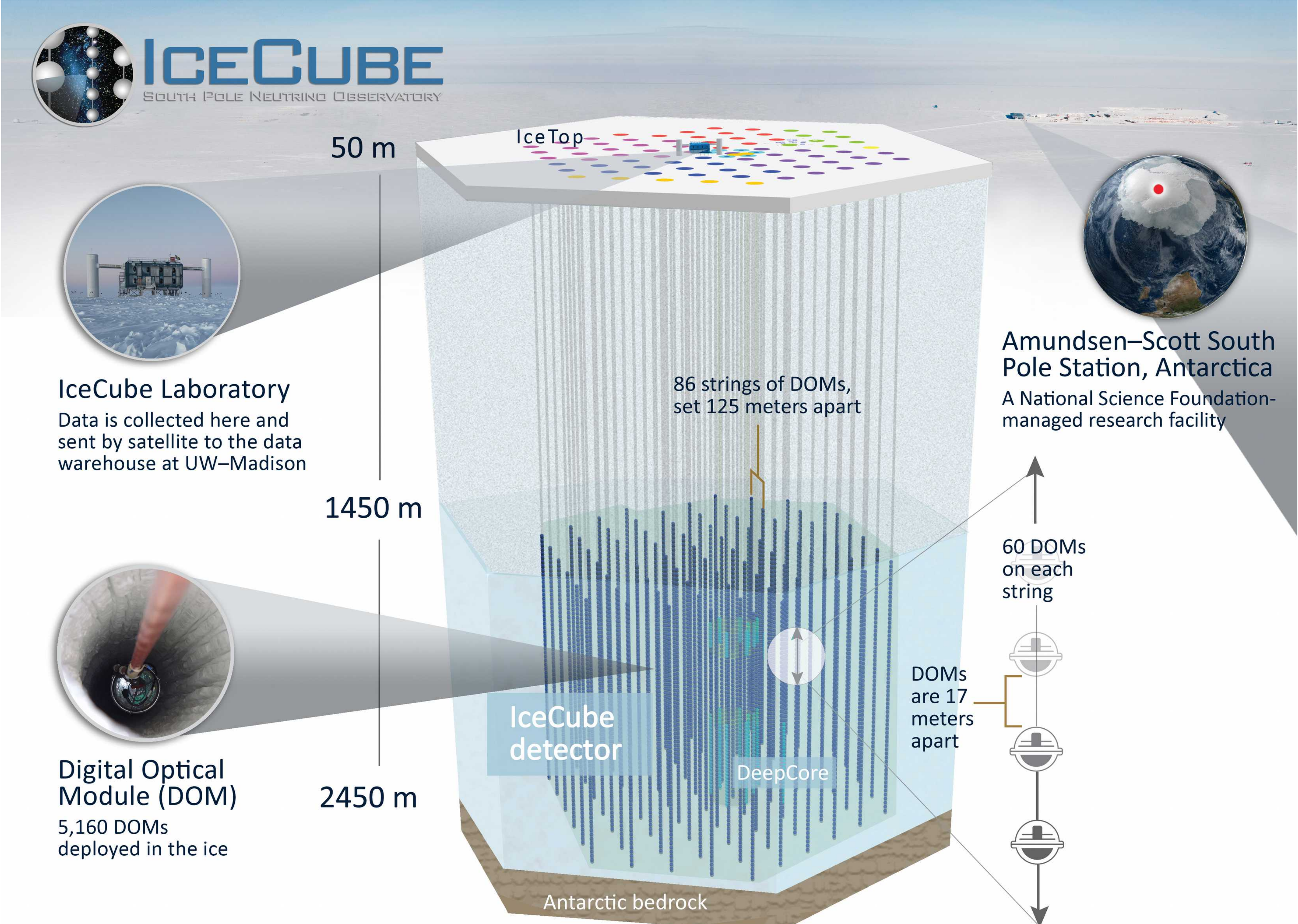


- What made such a high energy neutrino? Astronomy source? or...?
- Was it produced the same way we make man-made neutrino beams?
- We know where gamma-rays are produced in the universe, but cosmic rays?



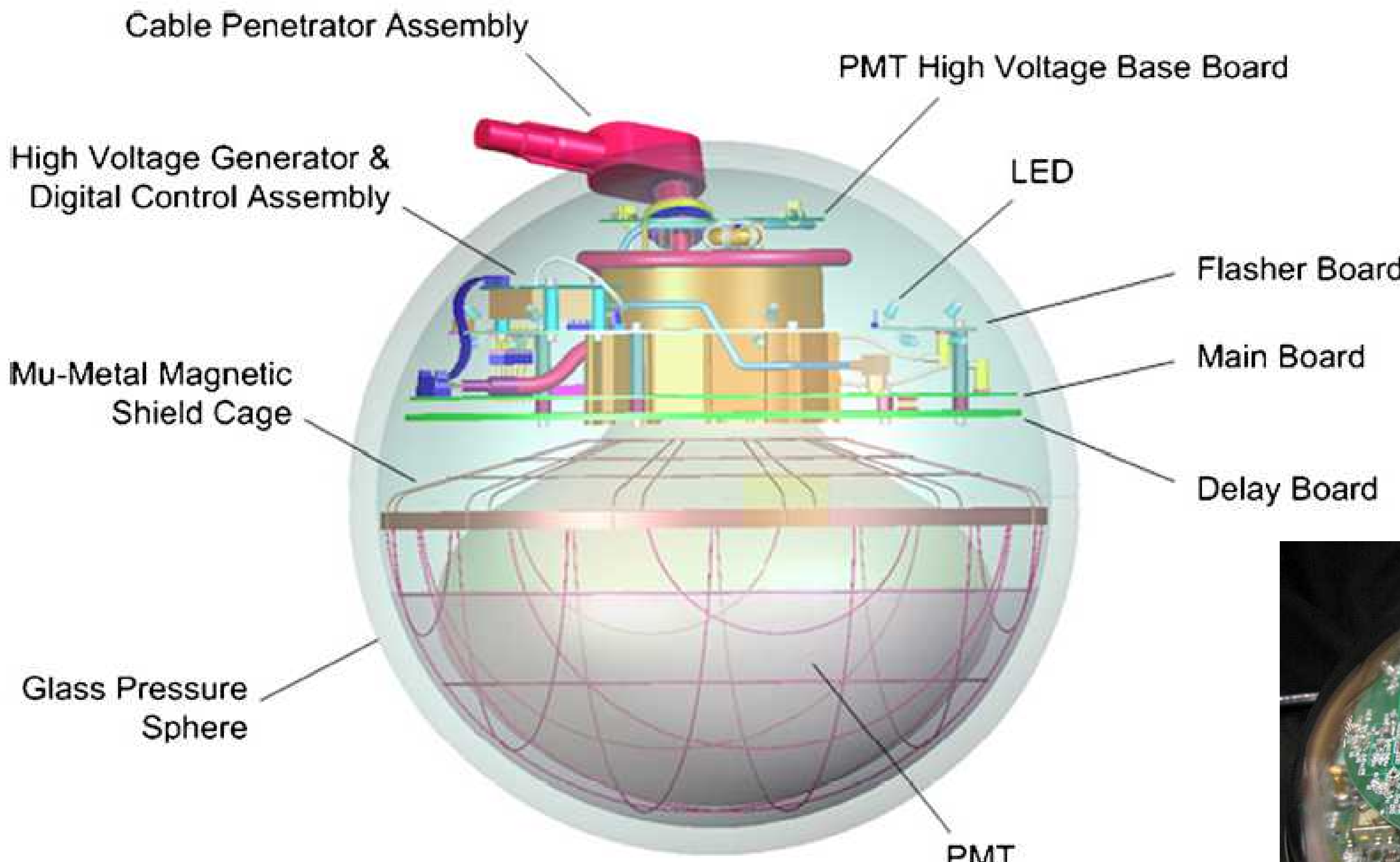
Completed in Dec 2010!

No pictures of inside a mine... instead a picture from close to the detector



Completed in Dec 2010!

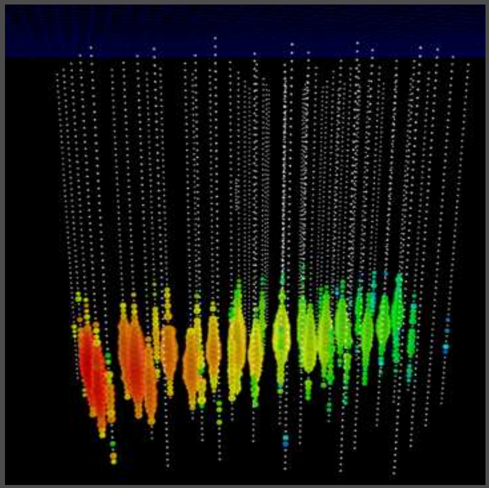
IceCube's Digital Optical Module (DOM)

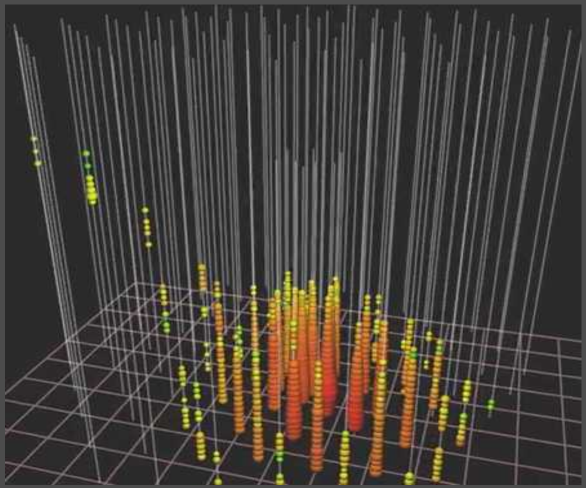


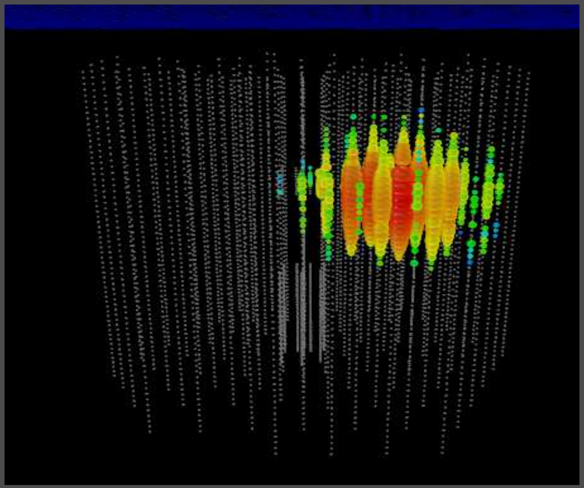
Topologies of different event types

Charge Current Muon Neutrinos

Charge Current Electron/Tau Neutrinos
All Neutral Current Neutrinos







$$\nu_e + N \to e + X$$

$$\nu_x + N \to \nu_x + X$$

$$\nu_\tau + N \to \tau + X$$

$$\nu_\mu + N \to \mu + X$$

hrough-going Track **Starting Track** **Shower**

~250 people for ~40 institutions

The IceCube Collaboration

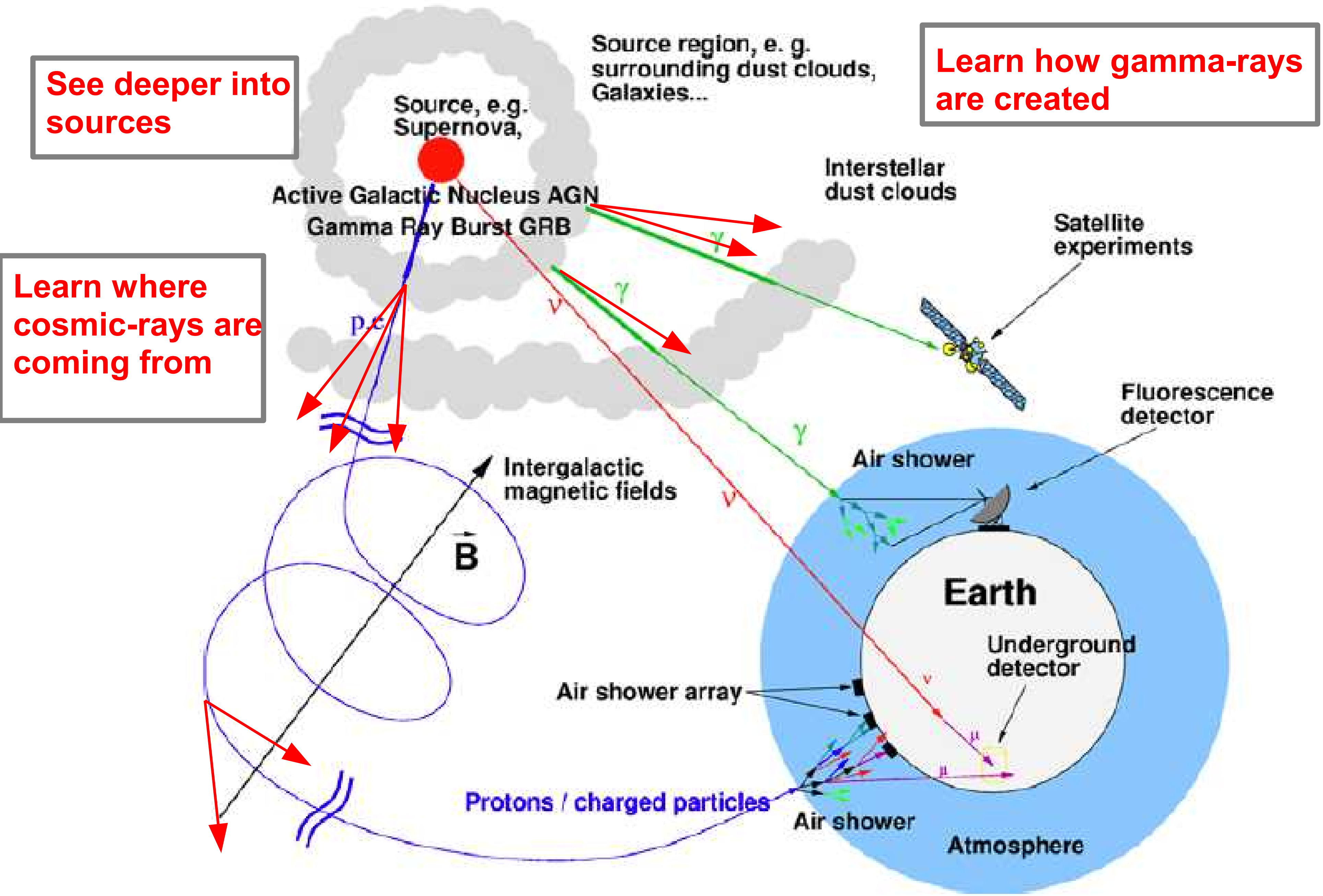
Funding Agencies

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)

IceCube Physics Programs

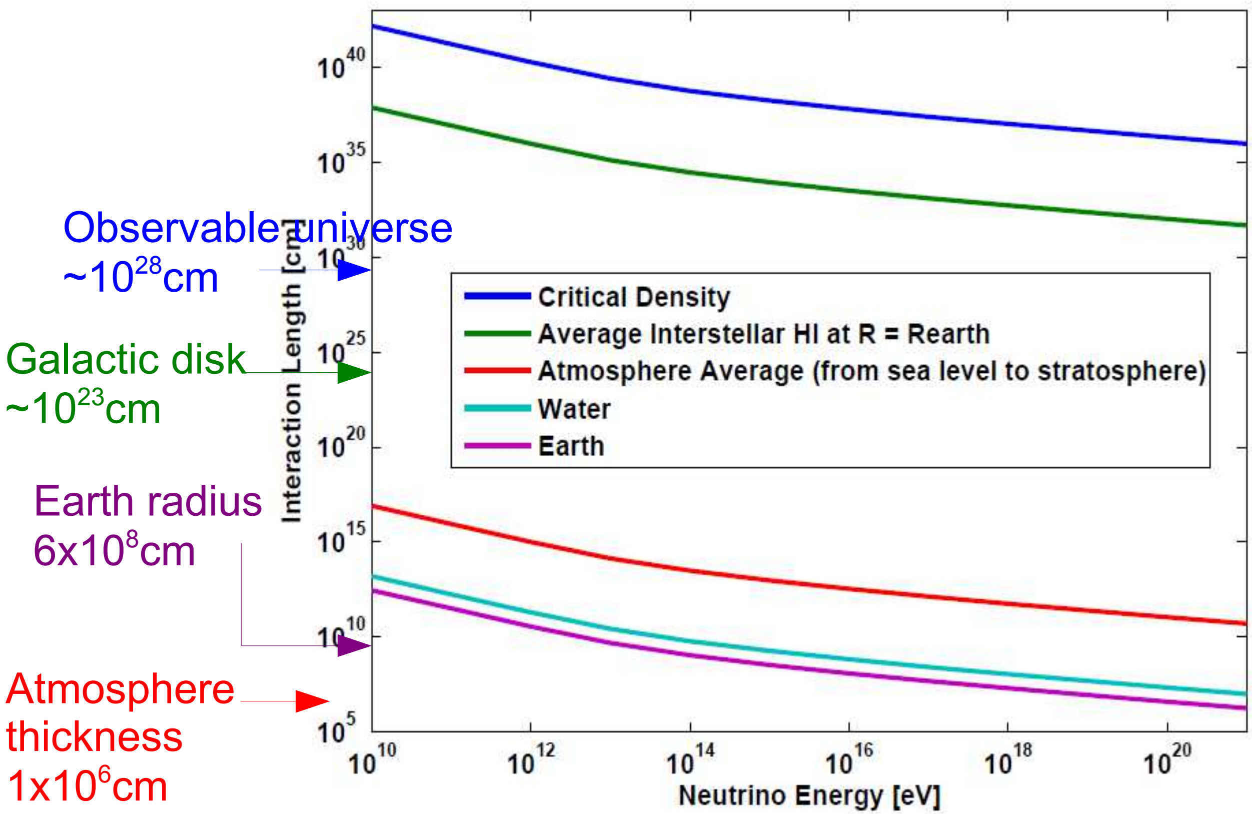
Cosmic Rays	Atmospheric neutrinos	Particle Physics	Astronomy	Applied science	Cosmology
Cosmic ray composition	Atmospheric neutrino spectrum	Dark Matter	Supernovae monitoring	Earth density profile	GZK neutrinos
Arrival directions	Charm production	Neutrino oscillations	Transient events, GRBs, AGNs	Glaciology	
Origin	neutrino cross sections	Neutrino velocities	Neutrino Point Sources	Atmospheric conditions	

Neutrino Astronomy – The Dream



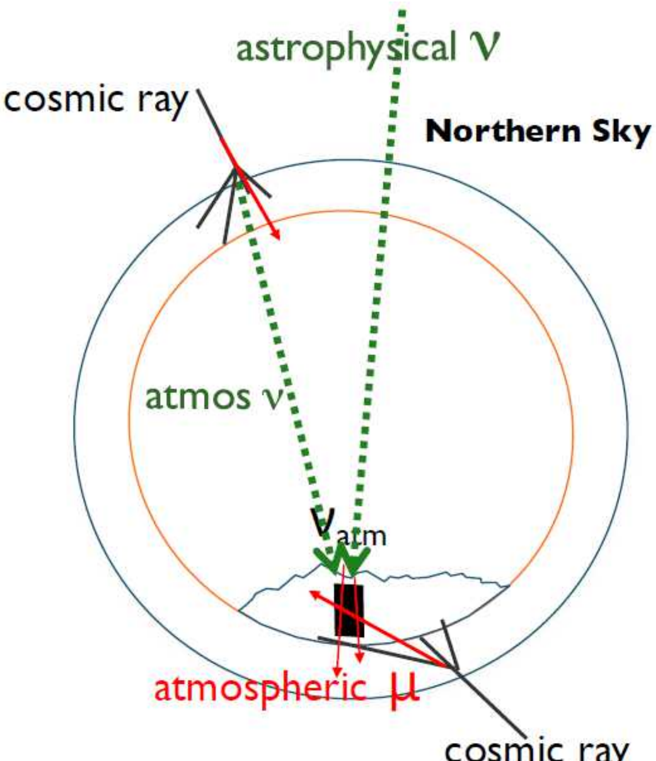
Neutrino Astronomy – The Reality

Issue 1: cross section



Cross section from **Gandhi et al., Phys. Rev. D 58 (1998) 093009**

Issue 2: backgrounds

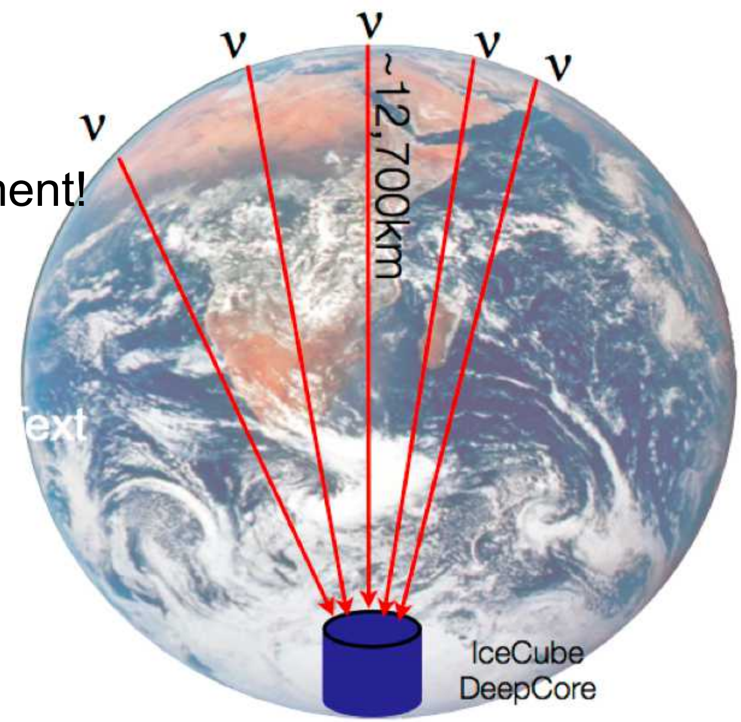


Oscillations: ν_μ Disappearance

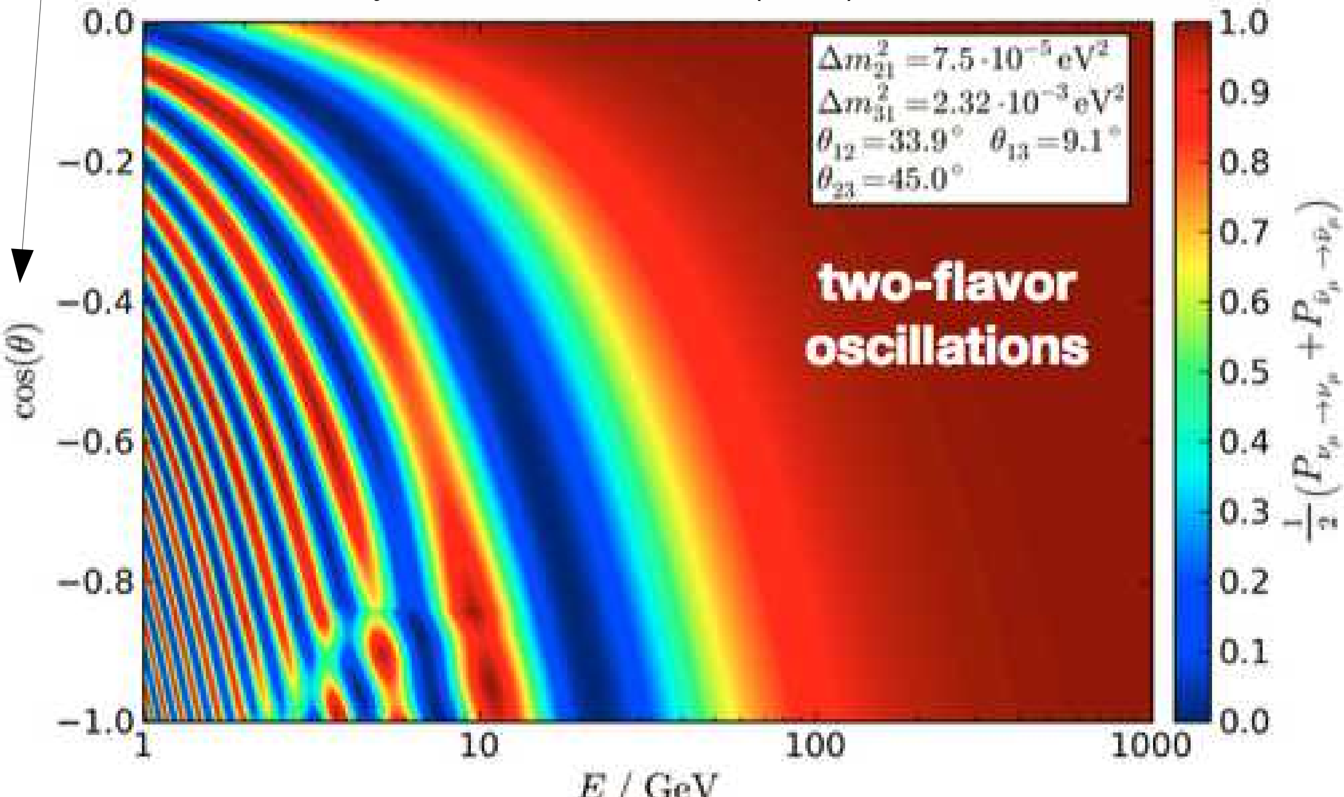
Atmospheric Neutrinos: One person's background is another person's signal

Angle of incidence
= baseline

Super-long baseline experiment!

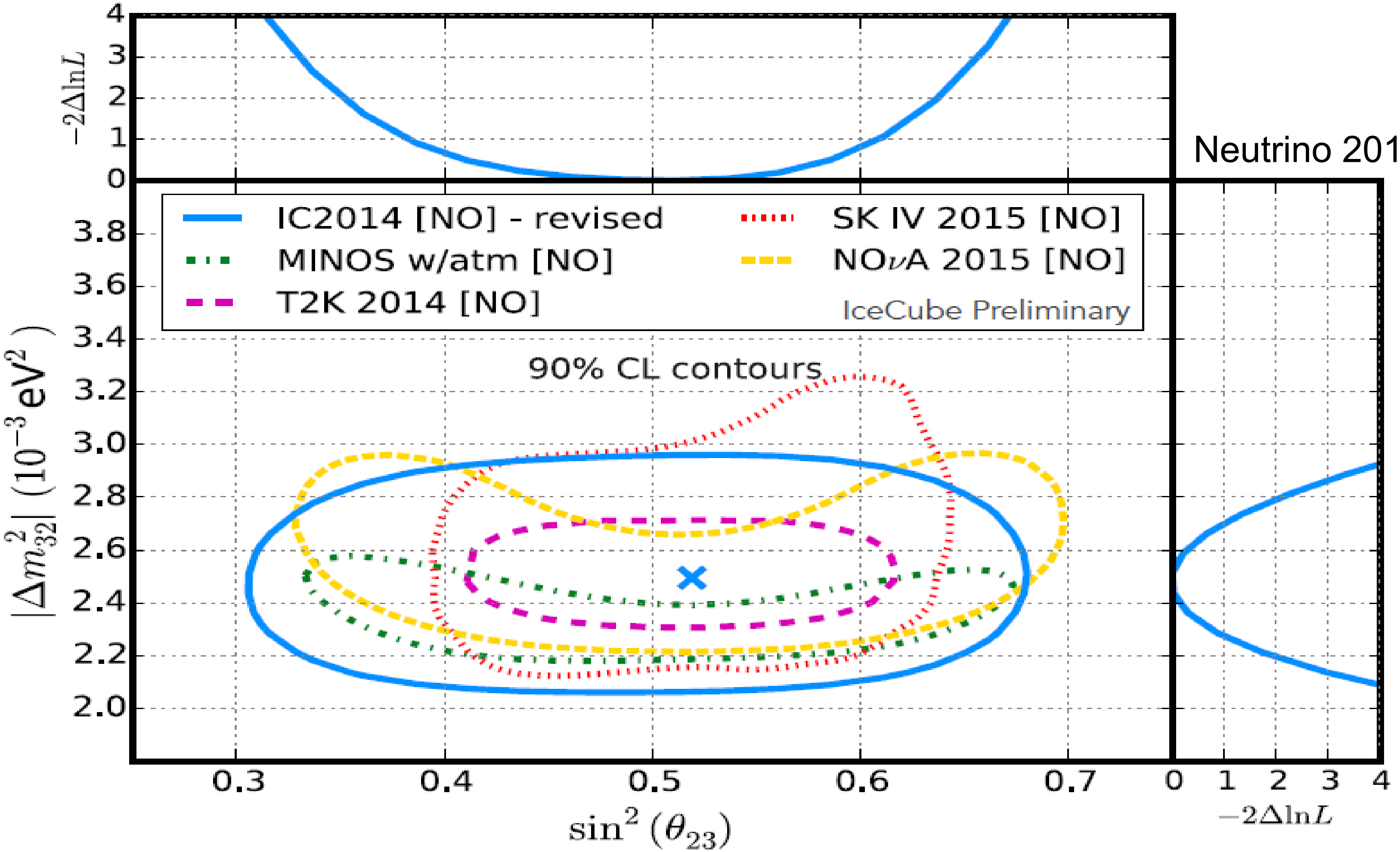


Phys. Rev. D 91, 072004 (2015)



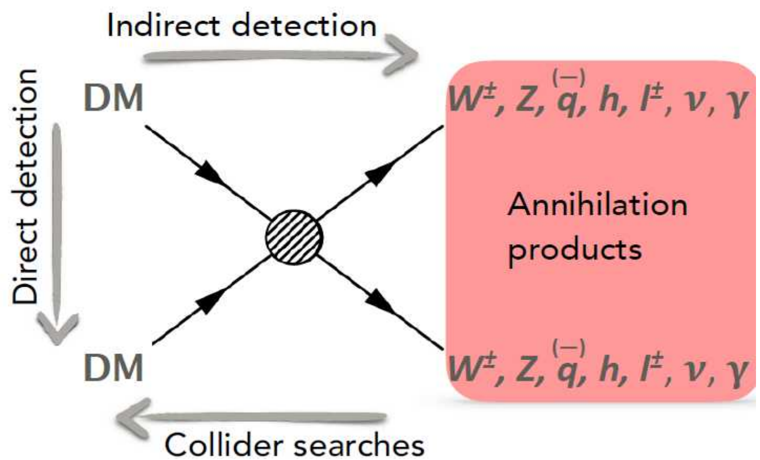
Oscillations: Numu Dissapearance

Oscillations results at 10 – 100 GeV!!



Neutrino 2016, IceCube

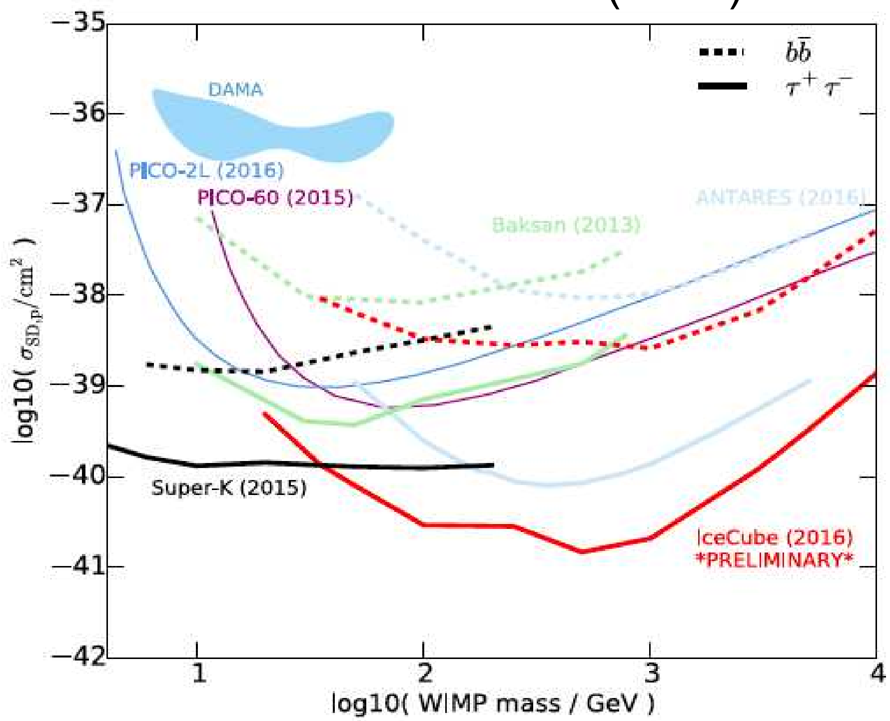
Indirect WIMP Searches:

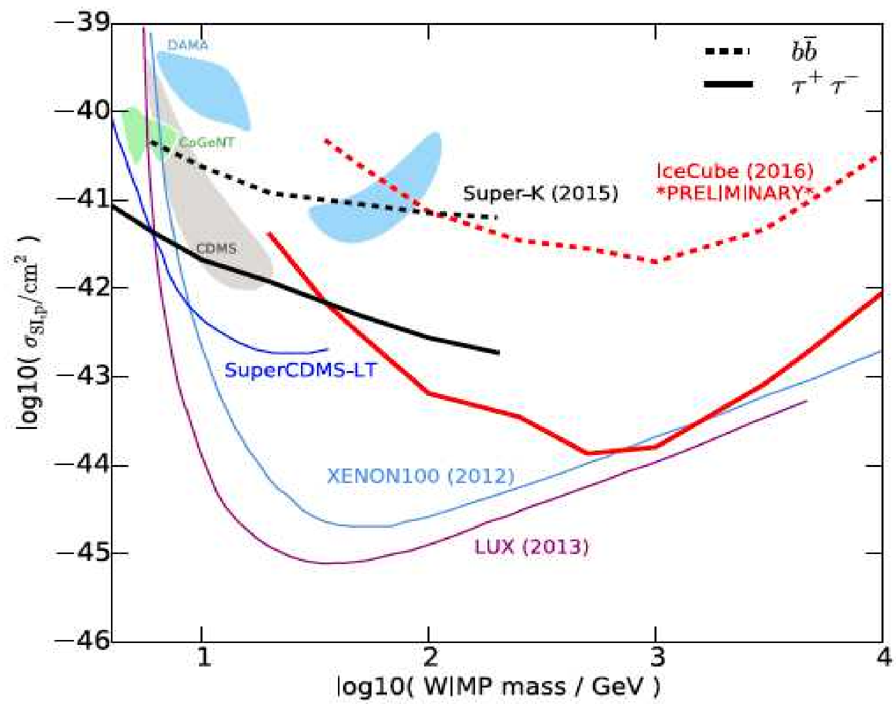


Solar WIMP Results

Assume annihilation into single state
Assume annihilation cross section $<\sigma v>_0 = 3 \times 10^{-26}\ cm^3\ s^{-1}$

JCAP 04 (2016) 022





Other things we do:

ICECUBE

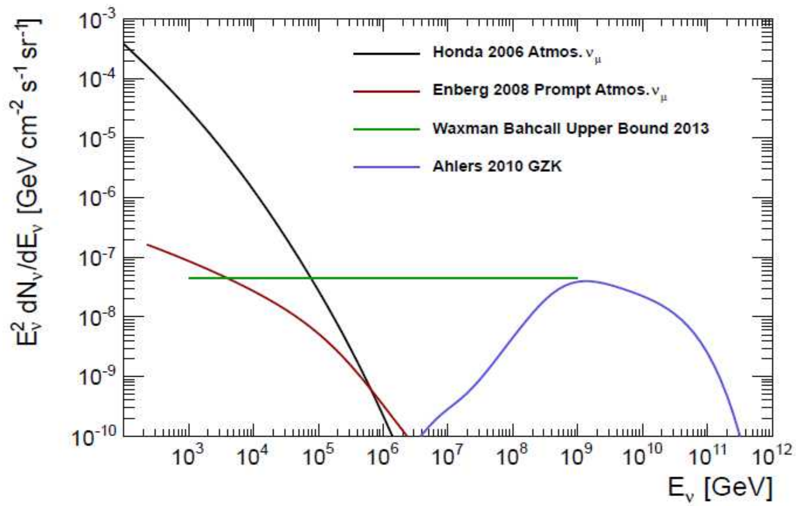
Sterile (3+1) Oscillation Searches
nu_tau Appearance
Non-Standard Interactions
Test on PMNS Unitarity

Galactic Halo WIMP Searches
Galactic Center WIMP Searches
Earth WIMP Searches

Two Ways to Probe Neutrino Astrophysics

Diffuse Analyses

Goal:
Resolve each spectral component in energy



Requirements:
- **Good energy proxy variable**
- **Good purity in data over statistical power (no events from component that's not fit)**
- **Accurate estimate of energy proxy error range**
- **Prior knowledge of characteristics of components helpful**

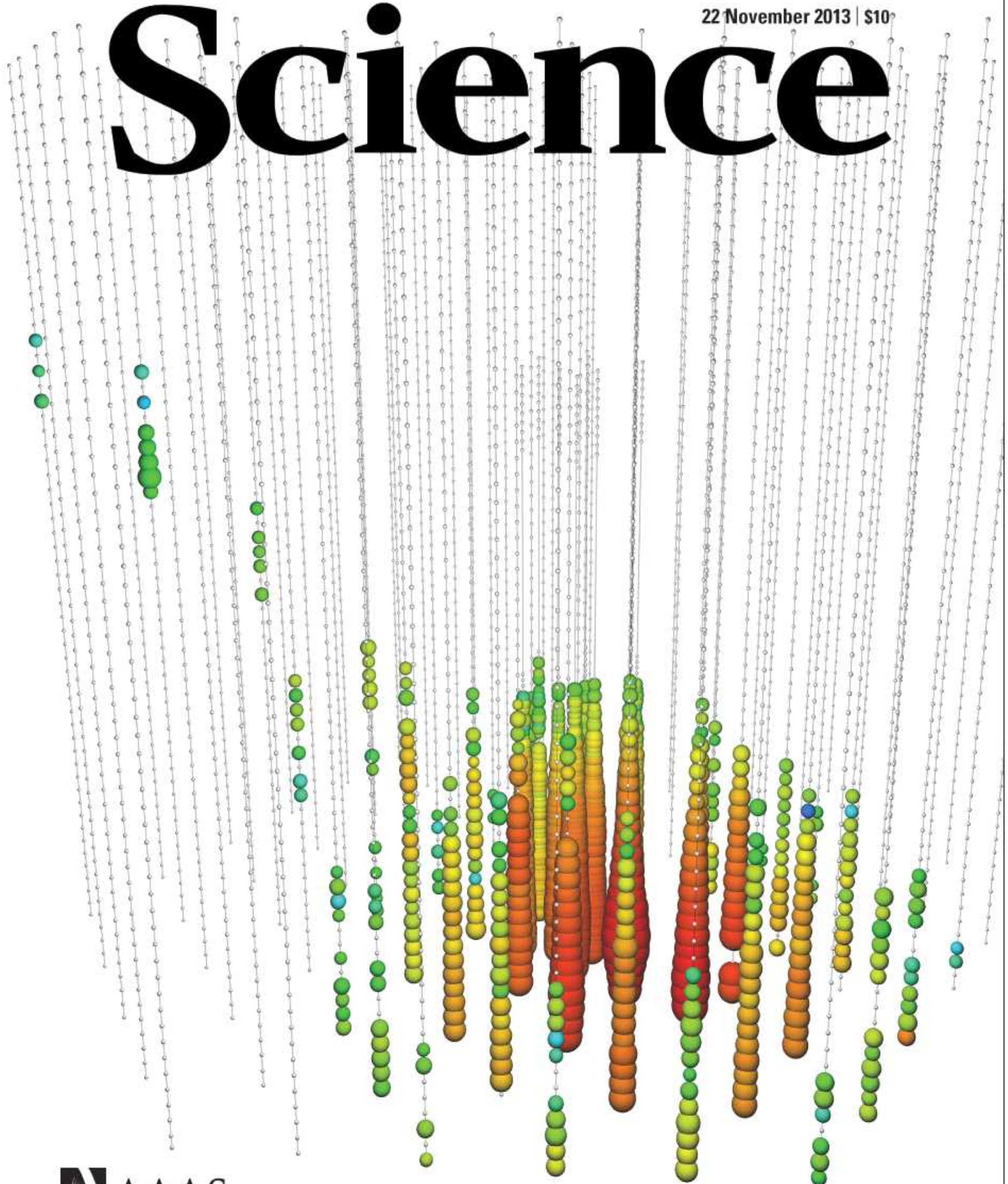
Point Source Analyses

Goal:
Resolve sources (clusterings) in space

Requirements:
- **Good angular resolution**
- **Good statistical power over purity (background is spatially uniform)**
- **Accurate estimate of angular error range**
- **Prior knowledge of potential source locations helpful**

Science

22 November 2013 | $10

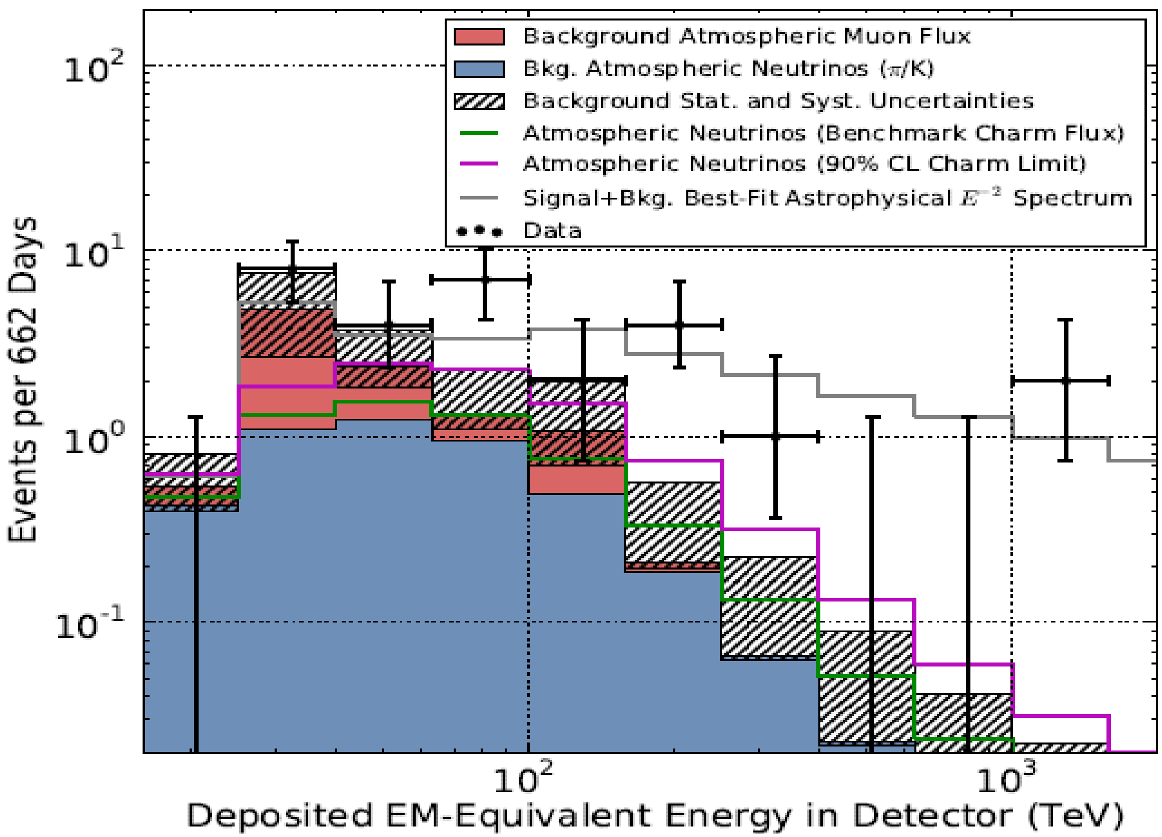


AAAS

Diffuse Analysis
IceCube's discovery analysis in 2013

2010-2012 (2 years of data)

Science 342, 1242856 (2013)

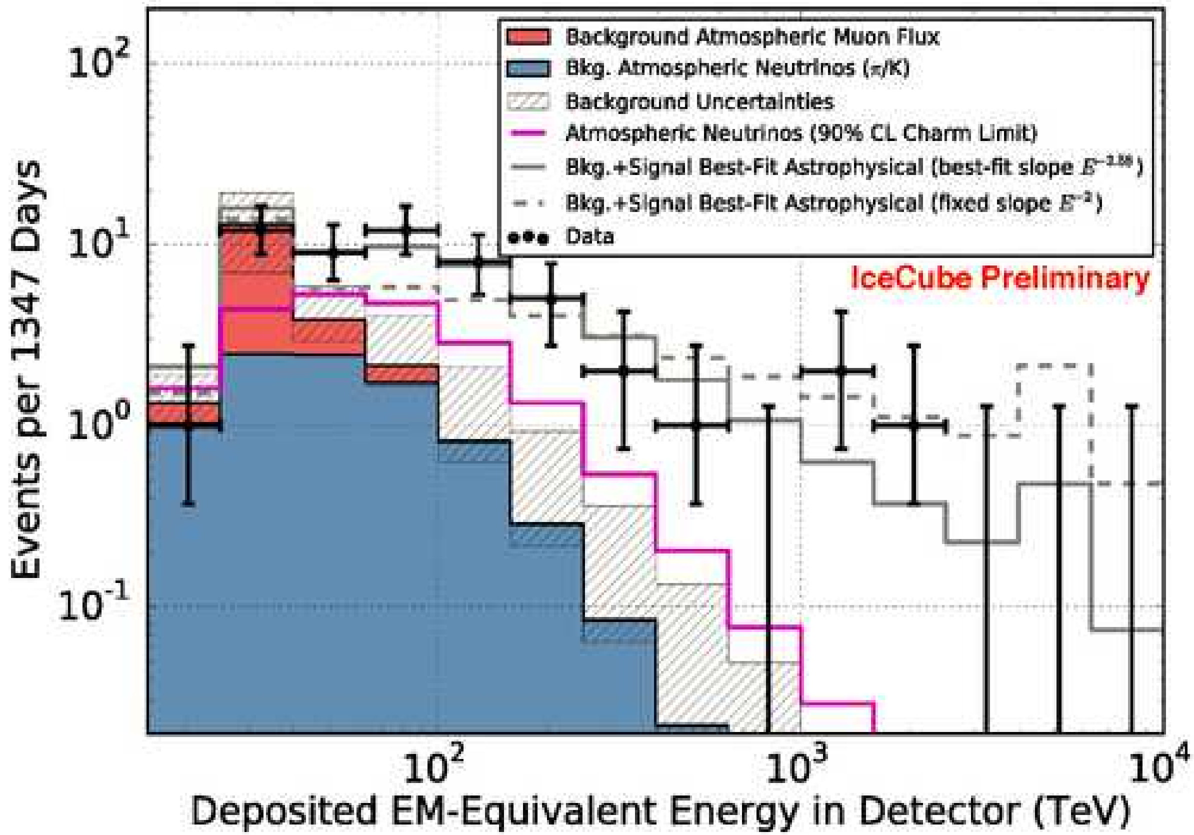


- Flux assuming E^{-2}: ~$1.2 \times 10^{-8} E^{-2}$ [/GeV/cm^2/s/sr]
- Best fit spectral index: -2.2

Diffuse Analysis
IceCube's discovery analysis in 2013

2010-2014 (4 years of data)

arXiv:1510.05223



- Flux assuming E^{-2}: ~$1.0 \times 10^{-8} E^{-2}$ [/GeV/cm^2/s/sr]
- Best fit spectral index: -2.6

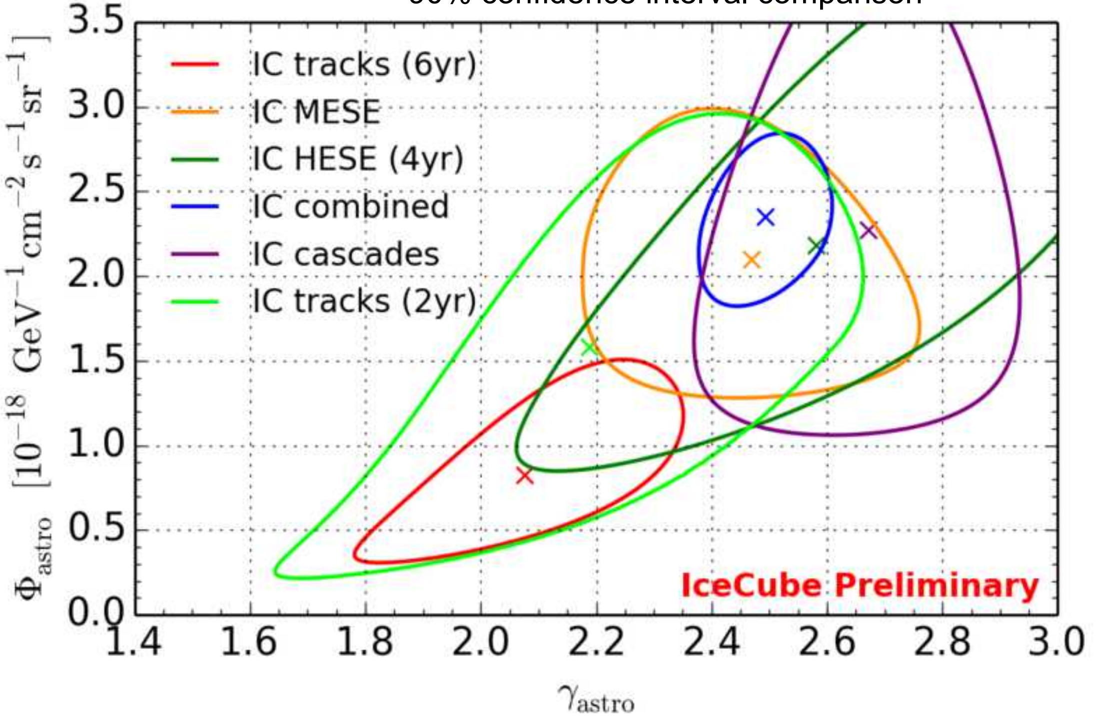
Diffuse Analyses Summary

- The universe emits high energy neutrinos
- Characterization in progress, but the whole picture is unclear for now

Assumptions:
- one flux for whole sky
- one spectral index
- same flux for each flavor

Some tensions imply.....
Break in the spectrum?
Spatially different flux?
Not 1:1:1?

90% confidence interval comparison

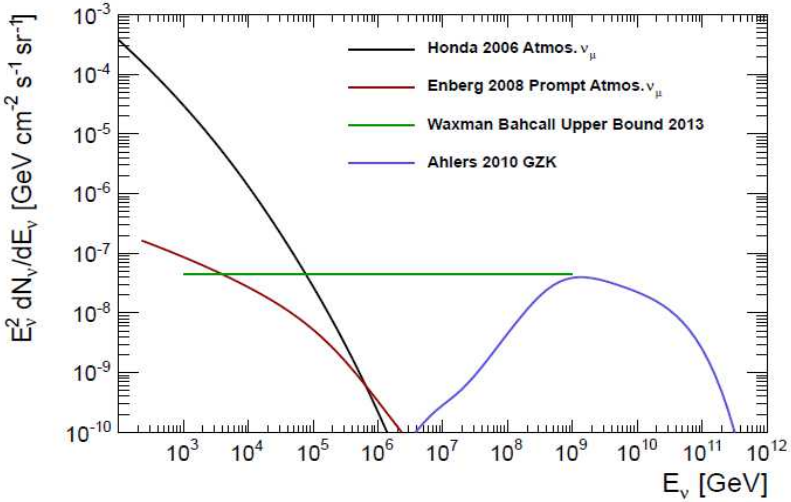


arXiv:1607.08006

Two Pronged Approach to Neutrino Astrophysics

Diffuse Analyses

Goal:
Resolve each spectral component in energy



Requirements:
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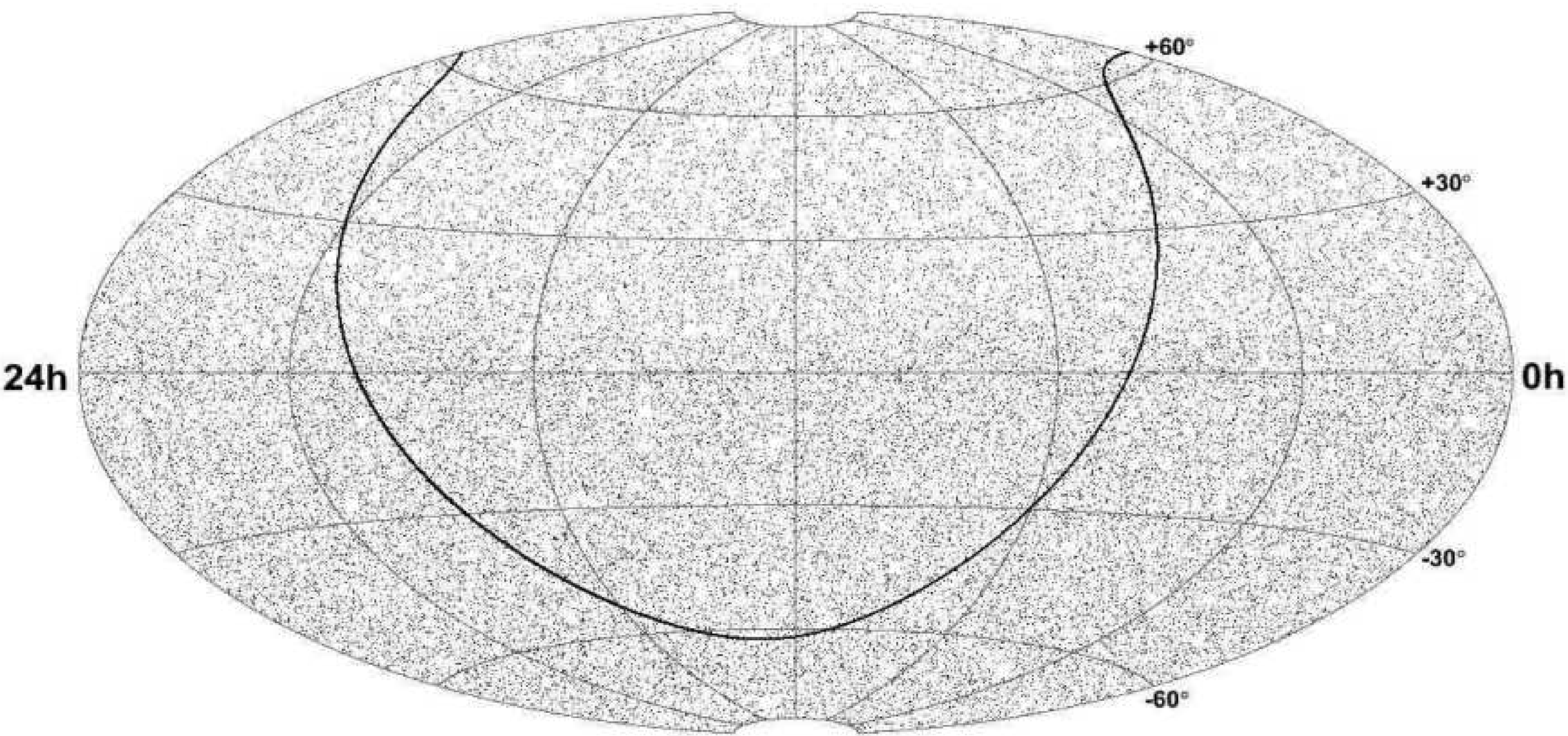
Point Source Analyses

Goal:
Resolve sources (clusterings) in space

Requirements:
- Good angular resolution
- Good statistical power over purity
  (background is spatially uniform)
- Accurate estimate of angular error range
- Prior knowledge of potential source locations helpful

Through-going tracks: Collect good angular resolution events

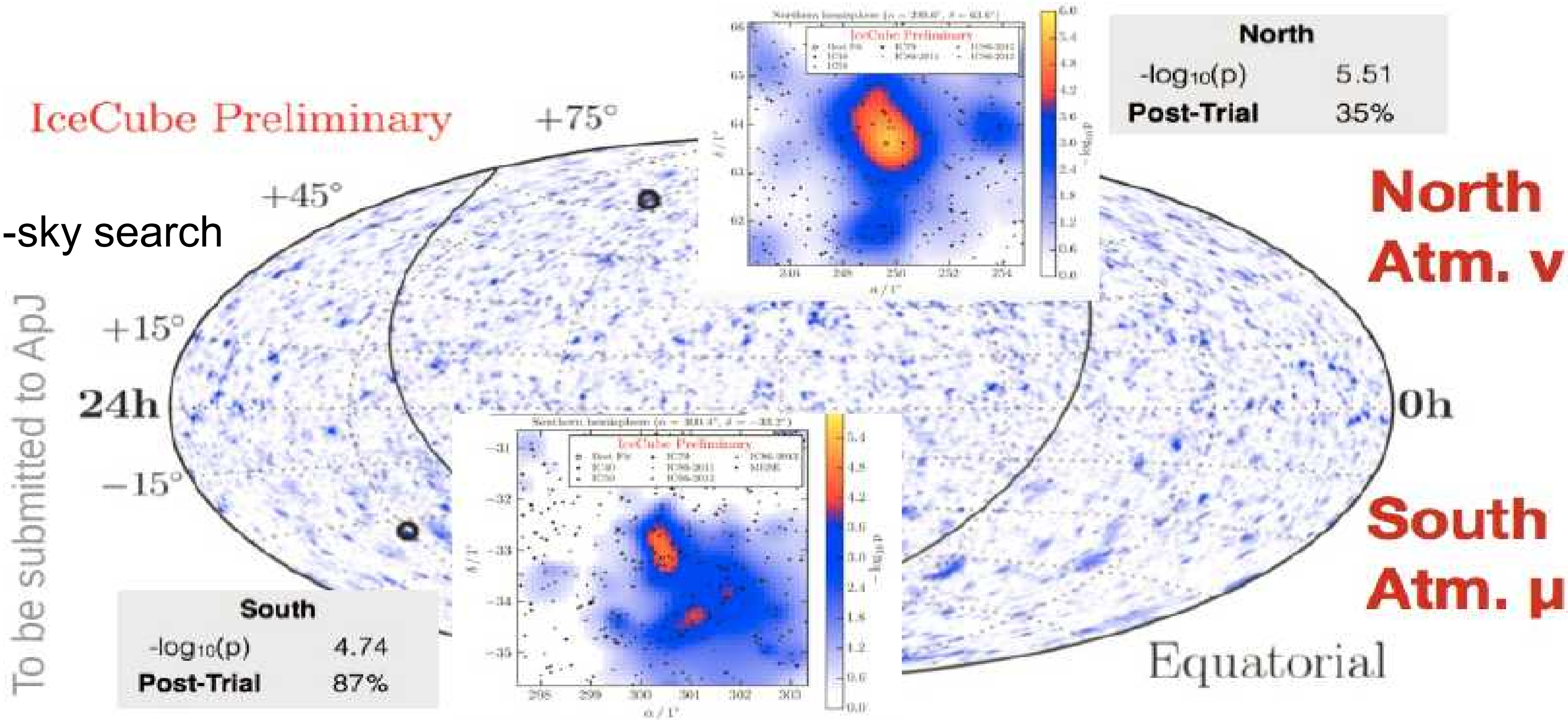
Equatorial coordinates



“2008” year Old Data (40-strings detector)
~37,000 events

Point Source Analysis 1
Search for cluster: all-sky and around known sources

All-sky search



Time-integrated unbinned search of hot spots in 7 years of data
(4-year version Astrophys.J. 796:109,2014)

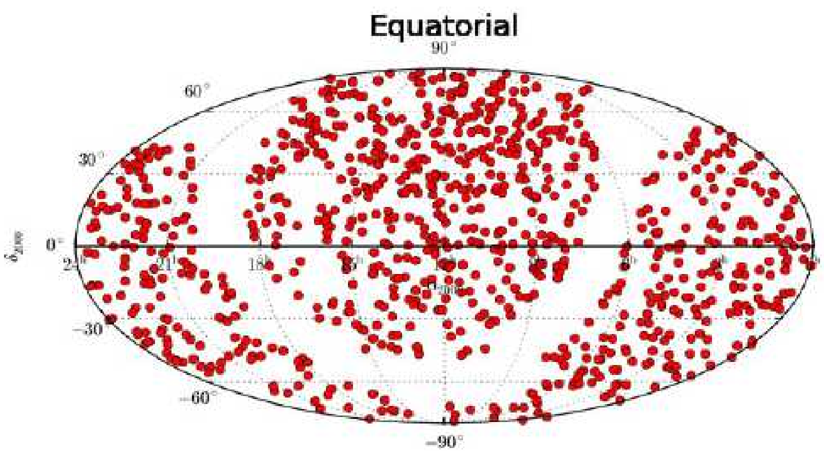
No indication of sources

Point Source Analysis 2
Test population of sources

Stacking of 862 Fermi 2LAC Blazars

Quasi-diffuse search (~10% of the sky at our angular resolution)

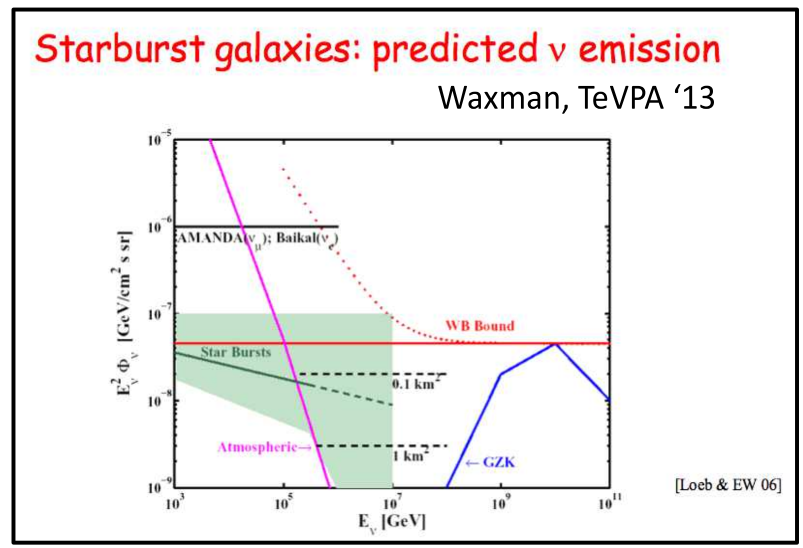
All Blazars in 2-LAC



IceCube Collab., arXiv:1410.1749 (2014)

Stacking of 127 nearby bright starburst galaxies

- Within $z < 0.03$
- F_{FIR}(60 micron) > 4 Jy
- F_{radio}(1.4 GHz) > 20 mJy



Astrophys.J. 796:10 (,2014)

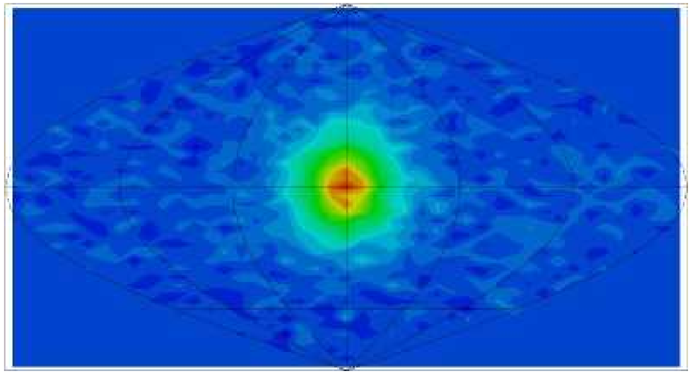
No indication of correlation → Tight limits set on source classes

Point Source Analyses conclusion

No TeV sources in neutrinos (yet)

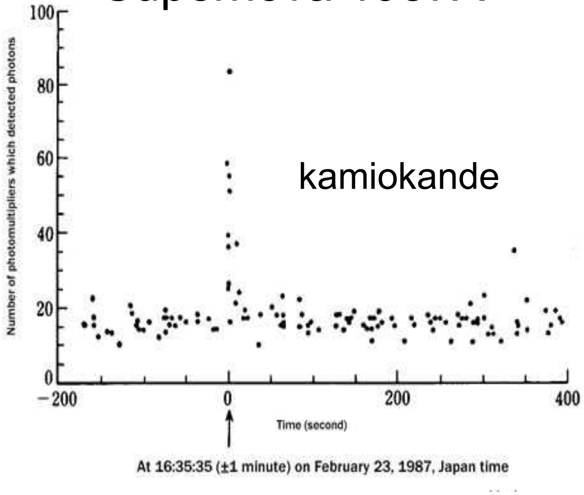
MeV neutrinos still lead in number of sources: 0 vs 2

The Sun



super-kamiokande

Supernova 1987A



*No direction, just timing

Universe emits high energy neutrinos... but tight limit on source category

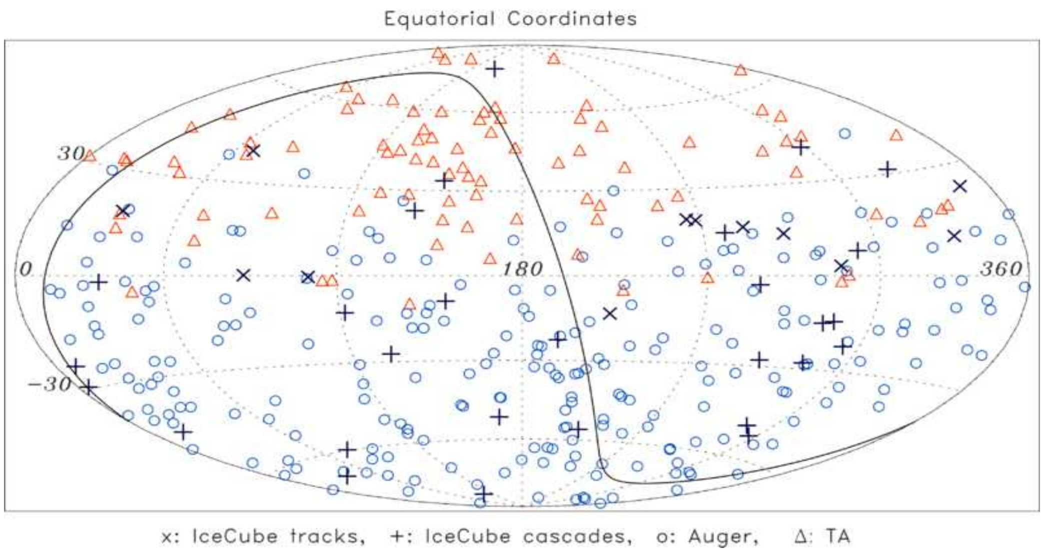
		Upper limit in diffuse flux	notes
Blazars		~ 17%	862 from Fermi 2nd AGN cat. Spectral index = -2.5
Nearby Starburst Galaxies		~ 8%	127 nearby Spectral index = -2
Galactic Sources	Young SNR	~ 5%	30 with no PWN or MC Spectral index = -2
	Young PWN	~ 3%	10 with no MC Spectral index = -2
Galactic Plane		~14%	Fermi Diffuse γ Spatial template Spectral index = -2.5 to -2.7
GRBs		~1%	506 bursts observed Spectral index = -2 to -2.7

Astrophys.J. 796:10 (2014), ApJ, 805, L5 (2015)

WHAT IS EMITTING NEUTRINOS?????

Multi-Messenger Astronomy (not only photons!)

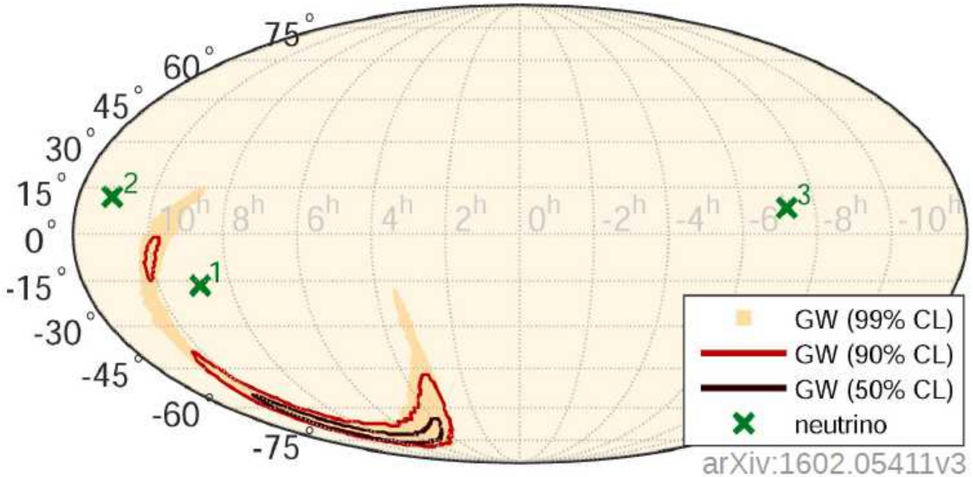
Ultra-high Energy Cosmic Rays



JCAP 1601 (2016) 01, 037

Correlation study with highest energy events from Auger and TA
No correlation beyond 3.3σ

Gravity Waves



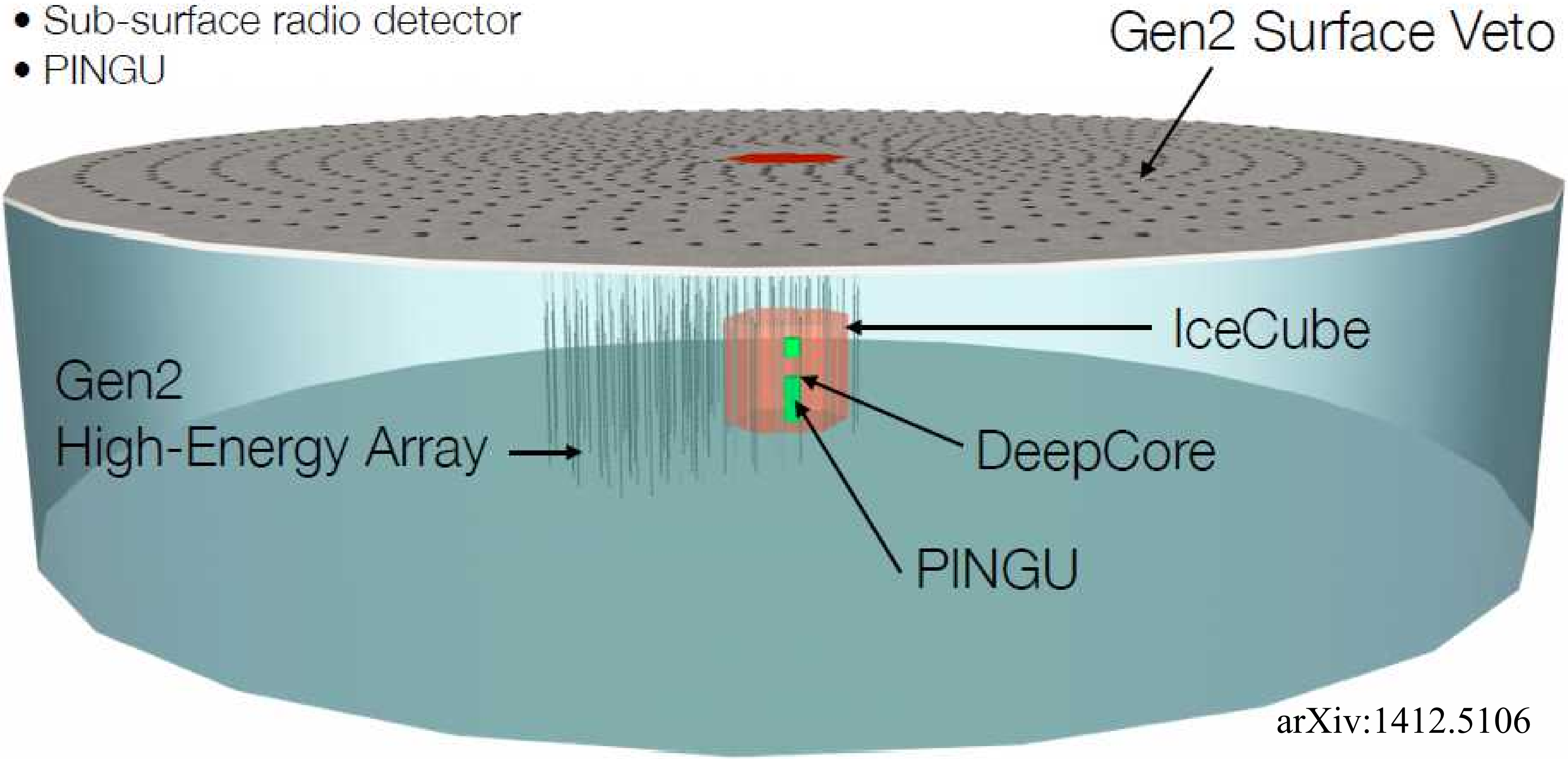
LIGO gravity signal and neutrino events within +/-500s

How can we increase our chances of neutrino discoveries <u>sooner</u>?

Factor of 10 doesn't seem like much until you realize how old you are in 10 years vs 100 years!

IceCube Gen2 – The next generation facility for neutrino physics and astronomy at the South Pole

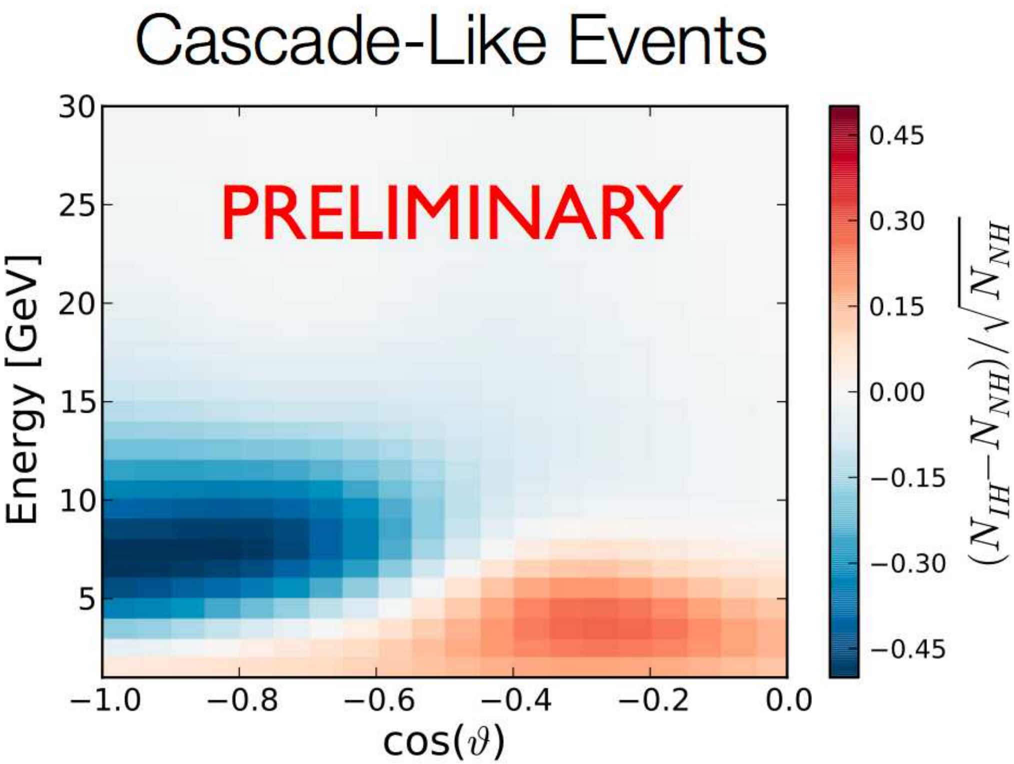
Multi-component observatory:
- Surface air shower detector
- Gen2 High-Energy Array
- Sub-surface radio detector
- PINGU

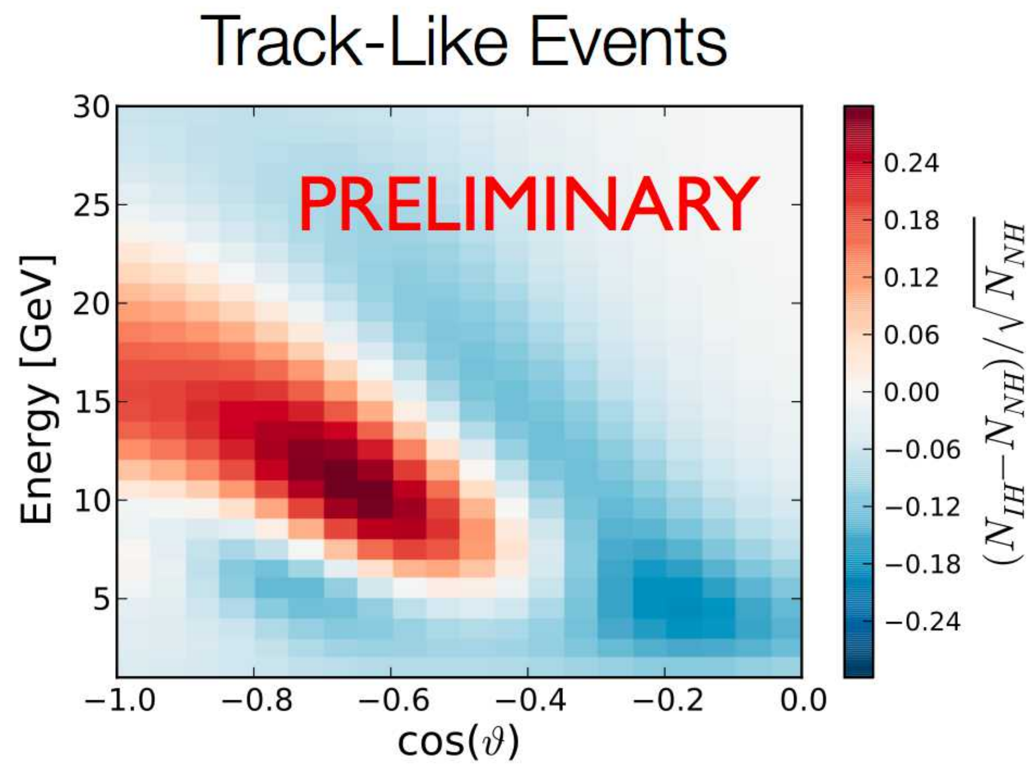


arXiv:1412.5106

Mass Hierarchy with PINGU

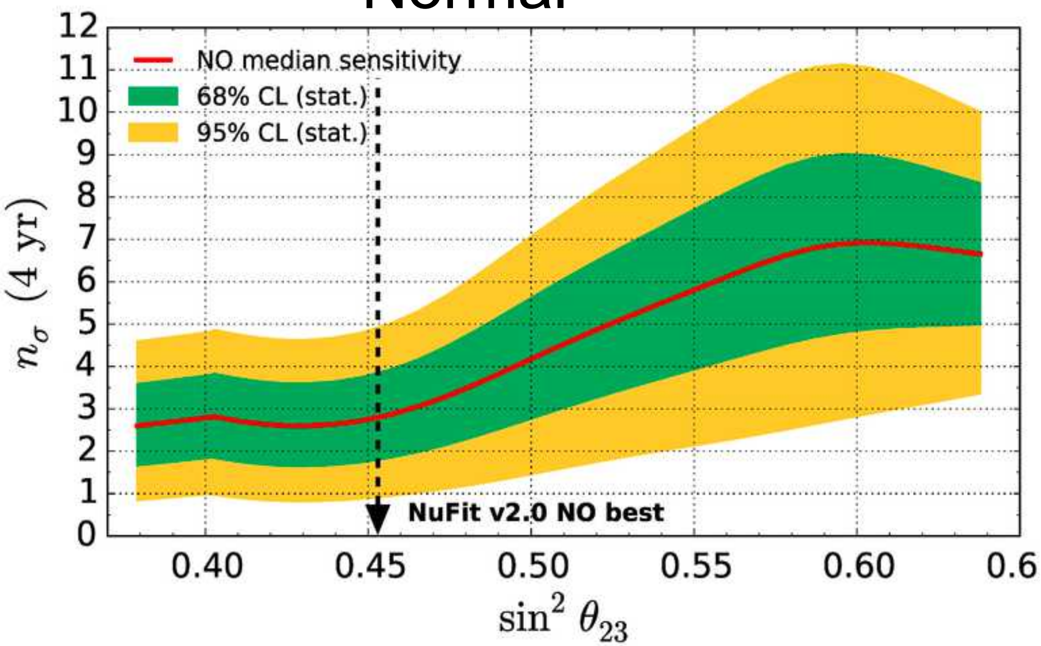
MSW effect on atmospheric neutrinos probe hierarchy



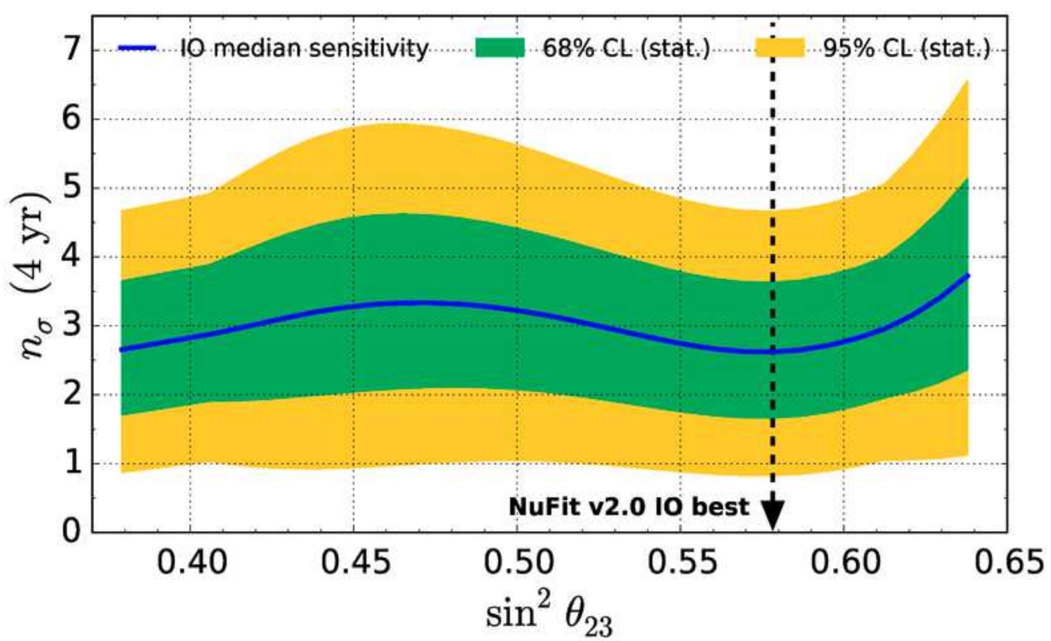


Mass Hierarchy with PINGU

Normal



Inverted



arXiv:1607.02671

Conclusions


Women Observing Stars, Ota Chou (1936)
Tokyo Modern Arts Museum

- IceCube has had great success so far, in astrophysics and particle physics

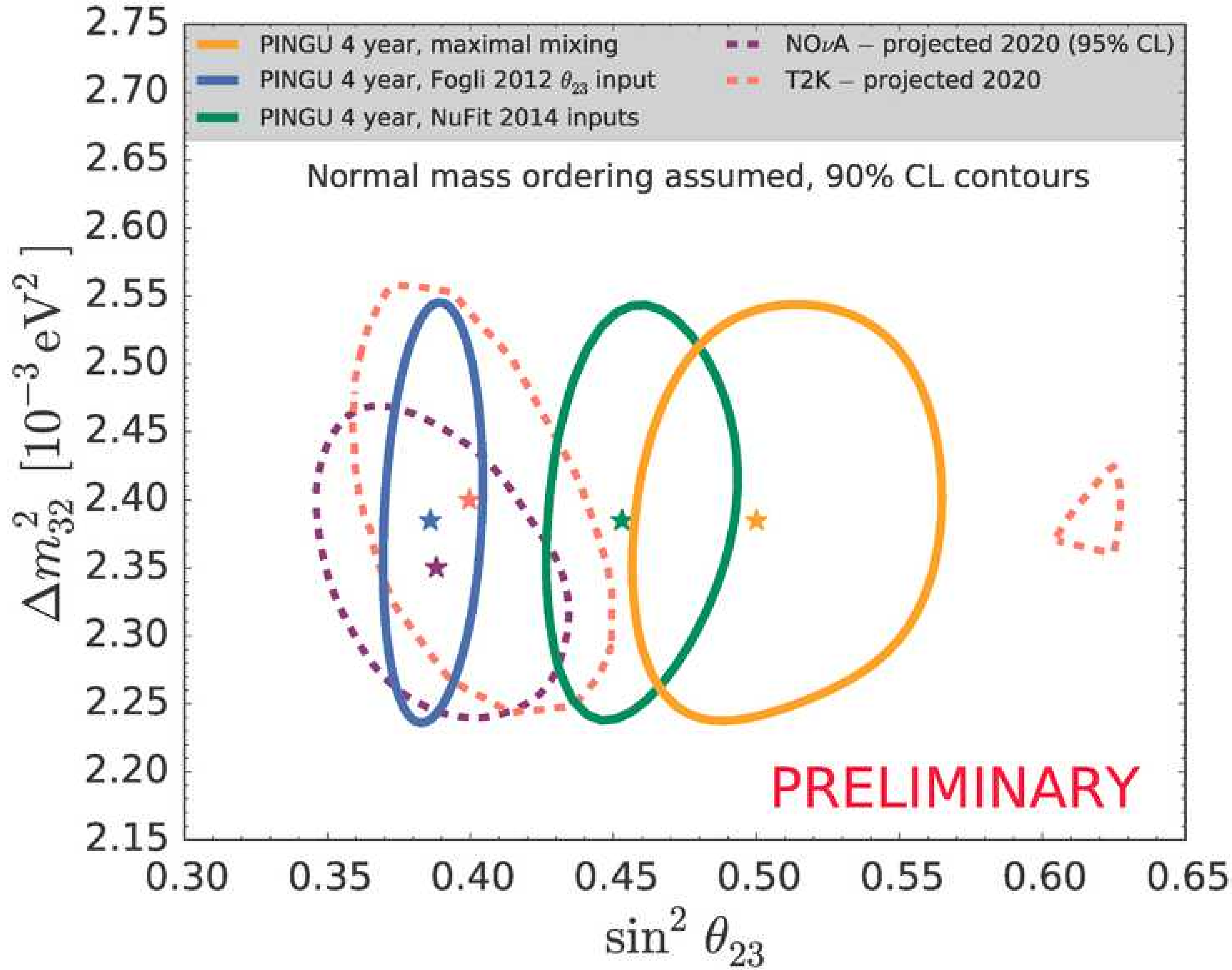
  → We are not a single purpose detector!

    - Neutrino astronomy a reality
    - Oscillation constraints using different baseline/energy
    - Indirect WIMP constraints using neutrinos

- We keep learning, and have plans to get us to discovery sooner on all topics

Backups

Oscillation with PINGU



Rapid Communication Example: April 27 2016

05:52:32
event seen in detector

05:53:53
automated GCN/AMON notice

23:24
manual recos give final location, error

16/04/28 22:38, Fermi LAT
GCN 19360, 5 unrelated blazars

16/04/29 12:24, HAWC
GCN 19361, no detection

16/04/29 15:55, MASTER
GCN 19362, no detection

16/04/29 21:08, Fermi GBM
GCN 19364, no detection

16/05/03 00:39, VERITAS
GCN 19377, no detection

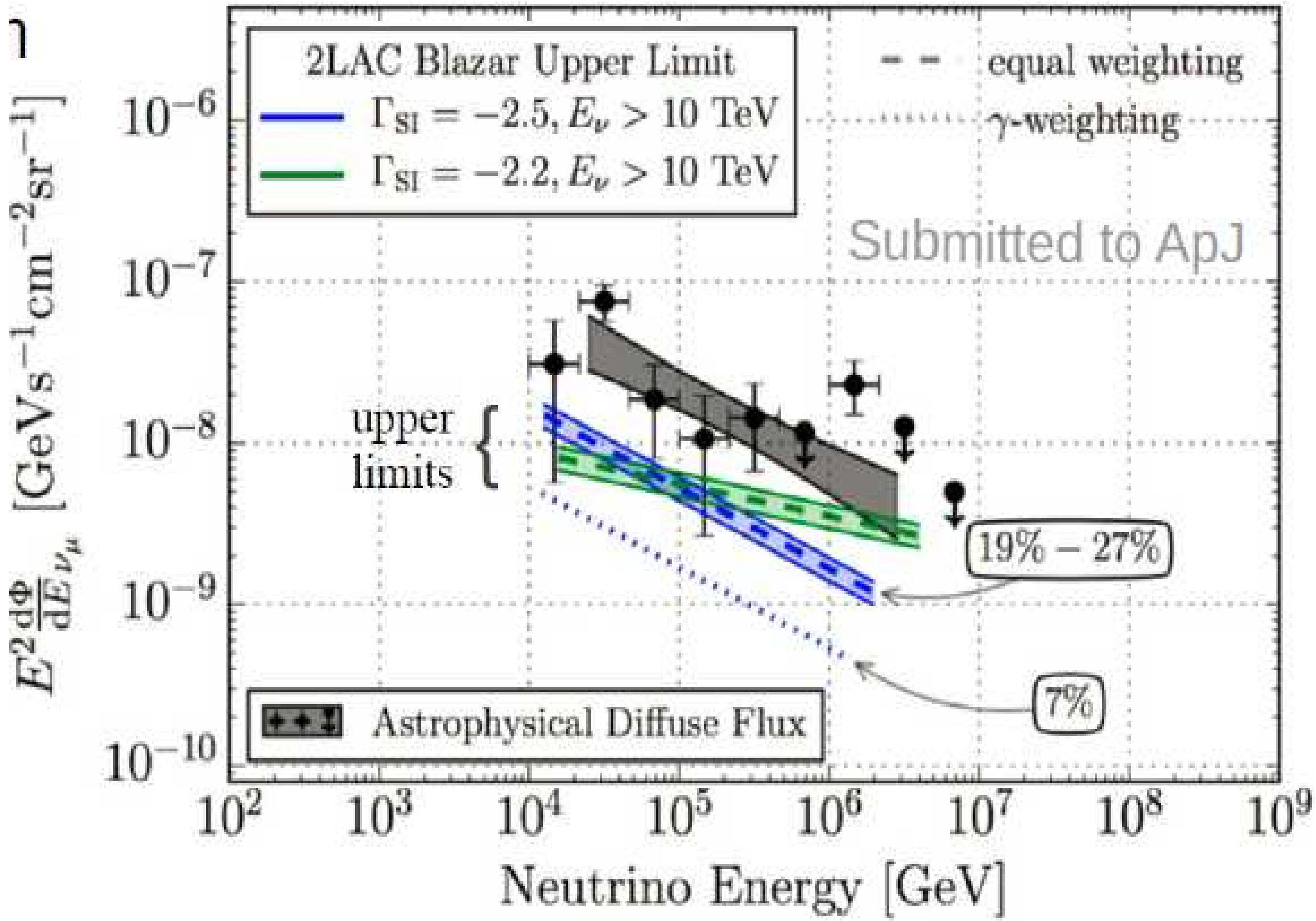
16/05/04 18:43, Pan-STARRS
GCN 19381,
24 faint transients, 8 known quasars, six old supernovas,
one new Ic SN candidate(PS16cgx)
at z~0.2 consistent with an explosion on April 27.,
no-correlated low-energy neutrinos found
in follow-up analysis

16/05/06 03:05, iPTF
GCN 19392, 3 transients, all AGN

16/05/12 18:05, Interplanetary Network
GCN 19426, no detection

16/05/13 13:02, FACT
GCN 19427,no detection

Putting diffuse and point source together



IceCube's Realtime Efforts

Individual MOU observatories:

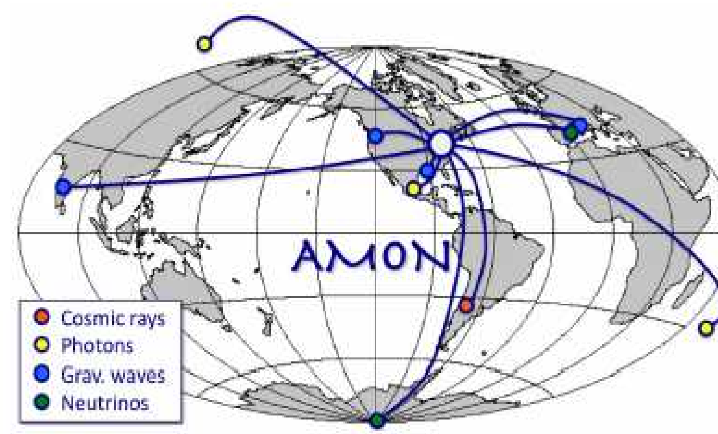
- Swift XRT
- Palomar Transient Factory
- Magic Gamma Ray Telescope
- VERITAS
- HAWC
- HESS
- LIGO/VIRGO
- Murchison Widefield Array

HAWC
High Altitude Water Cherenkov
Gamma-Ray Observatory

VERITAS

H.E.S.S.

Networks & public alerts:



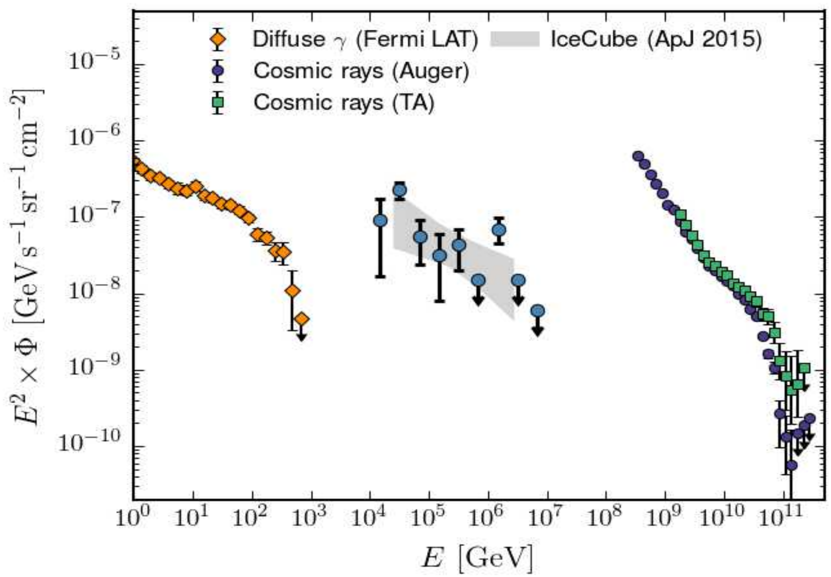
The Astrophysical Multimessenger Oberservatory Network:
FACT, VERITAS, MASTER,
LMT, ASAS-SN, LCOGT

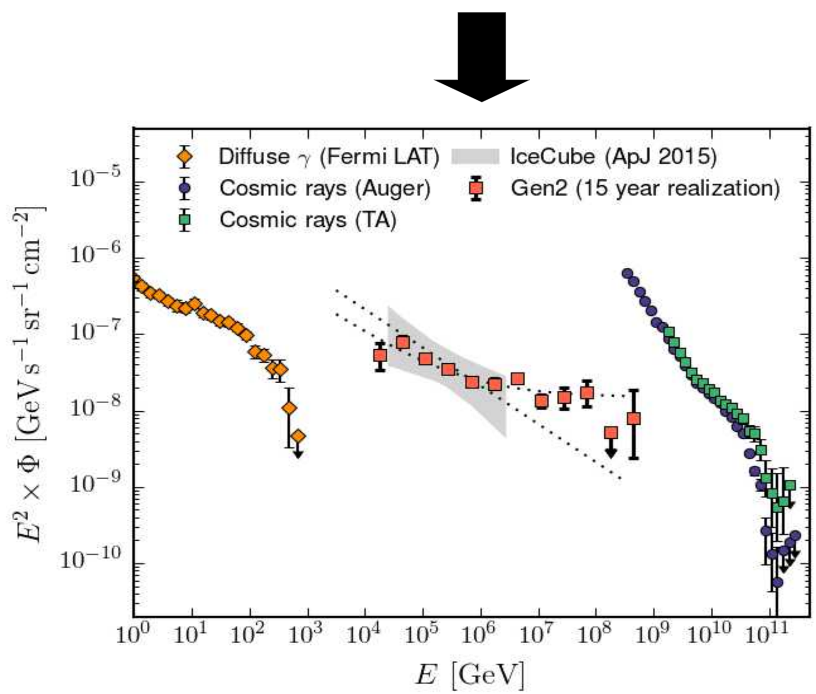
„The Astronomer's Telegram"

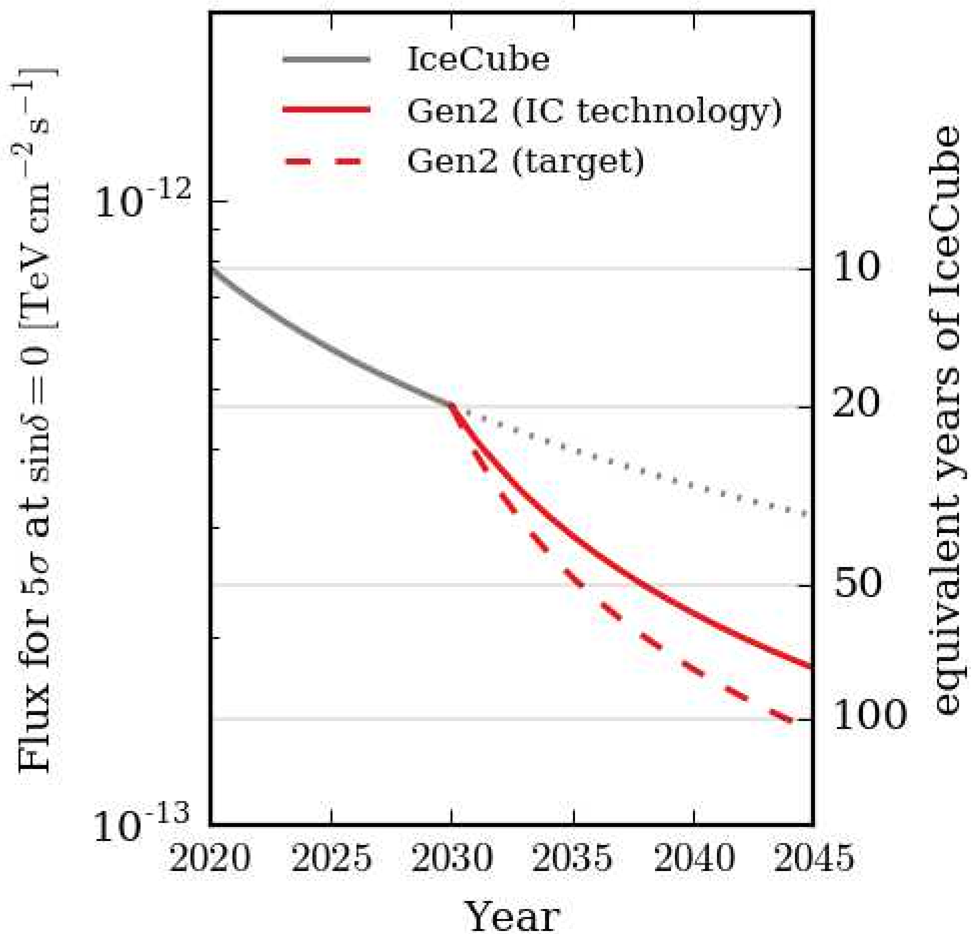
SNEWS

The **G**amma-ray **C**oordinates **N**etwork

Getting there sooner



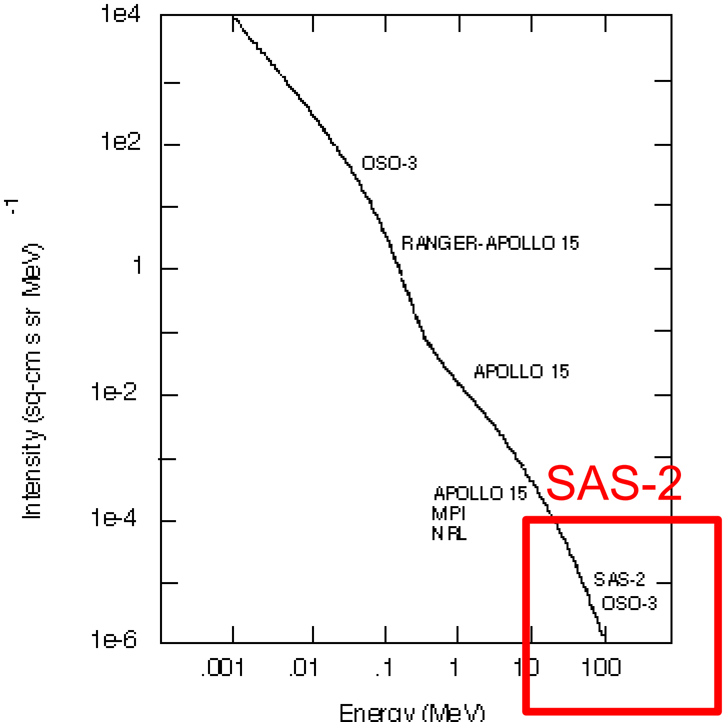




Historical Perspective: Gamma-ray Astronomy

Diffuse signal → first source → catalog!

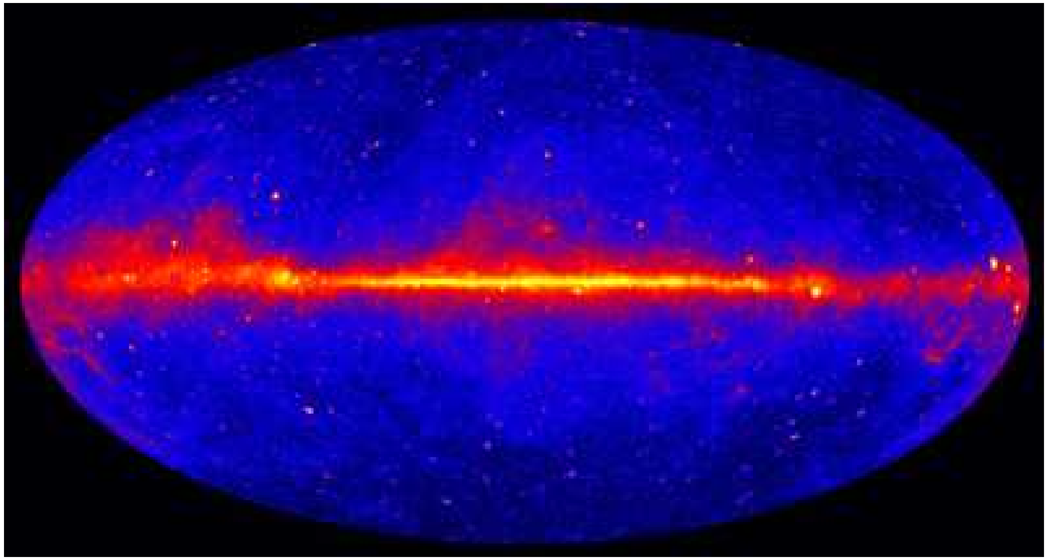
1970's



Diffuse celestial radiation

NOW

Fermi 5-year data

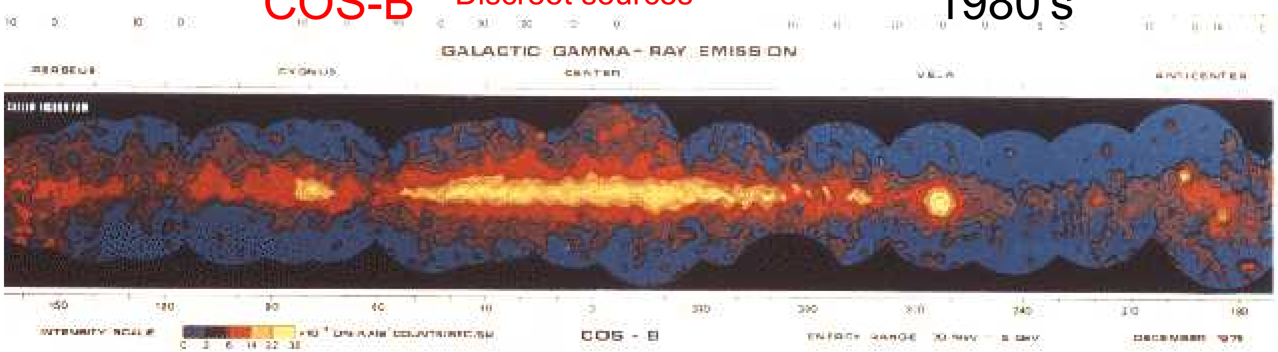


GSFC nasa.gov

COS-B

Discreet sources

1980's



GSFC nasa.gov

Historical Perspective: X-ray Astronomy

Diffuse signal → first source → catalog

(Sun detected in x-rays 1940's)

Diffuse emission and Scorpius X-1 1960's

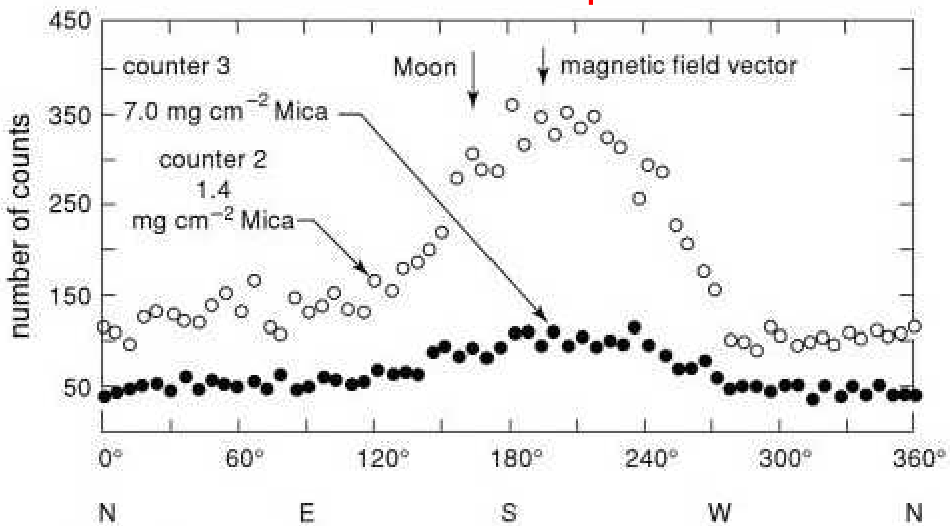
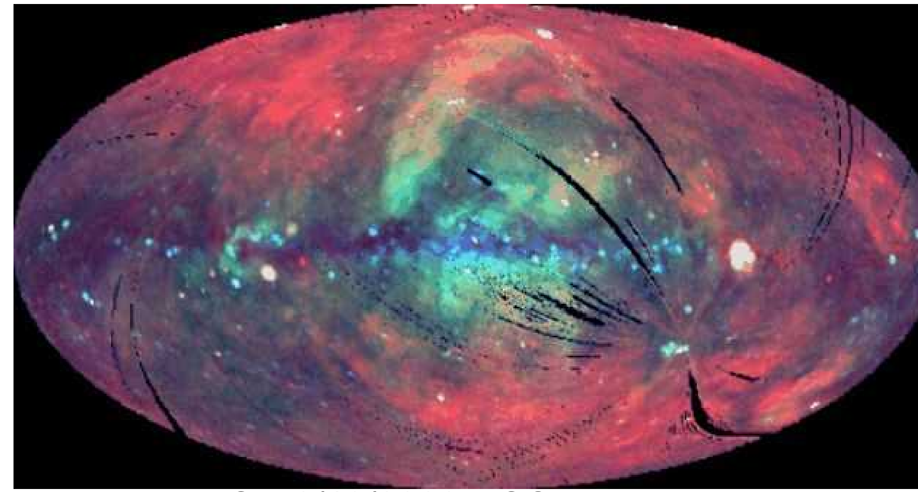
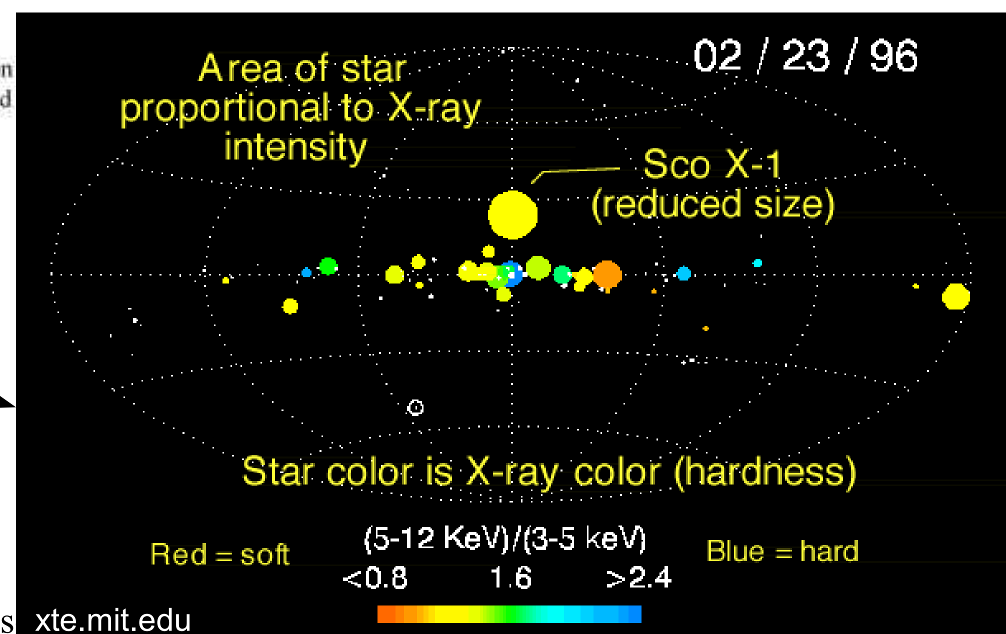


Figure 7.7: The discovery record of the X-ray source Sco X-1 and the X-ray background emission Giacconi and his colleagues in a rocket flight of June 1962. The prominent source was observed both detectors, as was the diffuse background emission (Giacconi *et al.*, 1962).

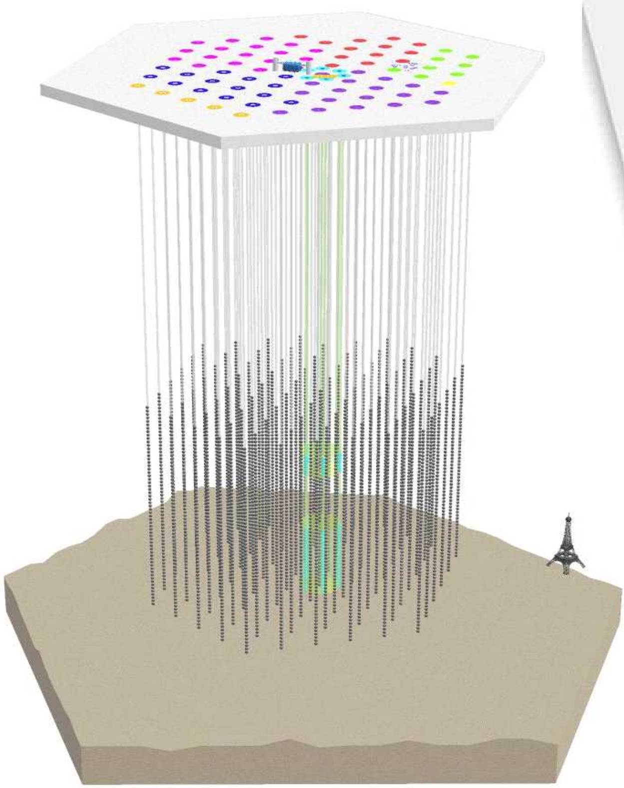
"The Cosmic Century" M. S. Longair

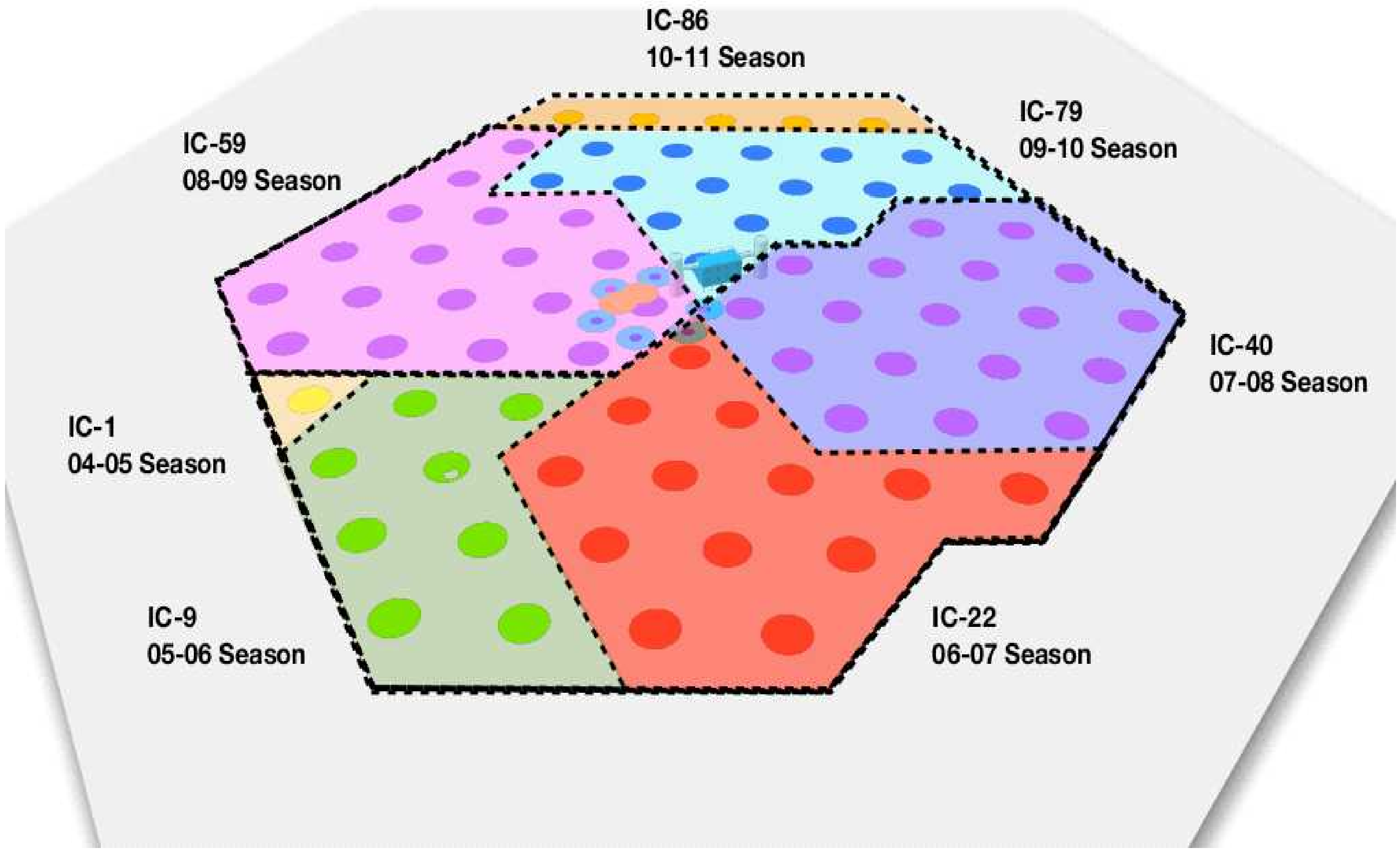


APOD 8/19/2000 ROSAT



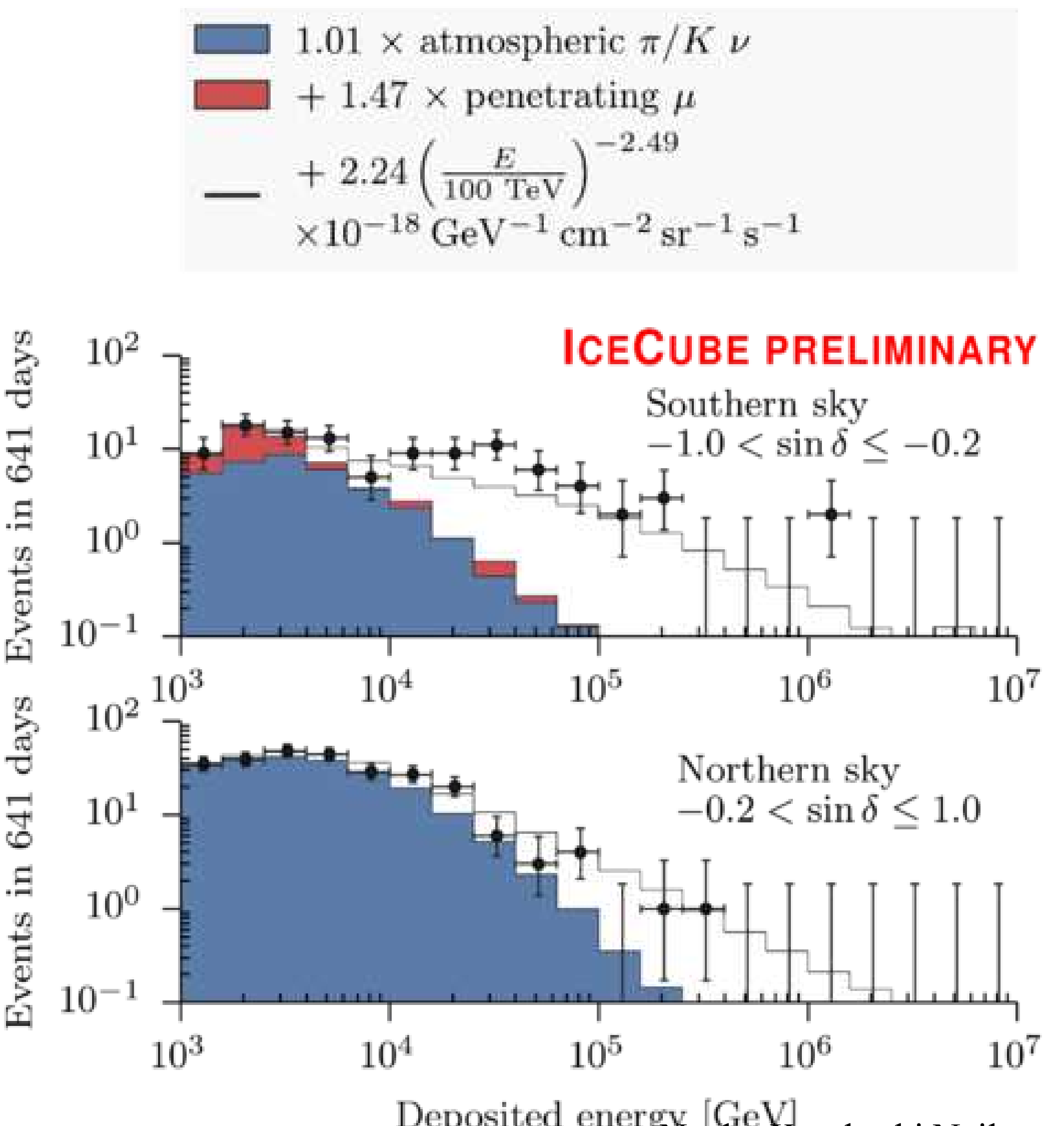
More IceCube Jargon





40-strings (IC-40), 376 days livetime, ~50% complete
59-strings (IC-59), 348 days livetime, ~50% complete
79-strings (IC-79), 333 days livetime, almost complete
86-strings (IC-86), 329 days livetime, complete

Diffuse Analysis 2
Updated veto to the discovery analysis



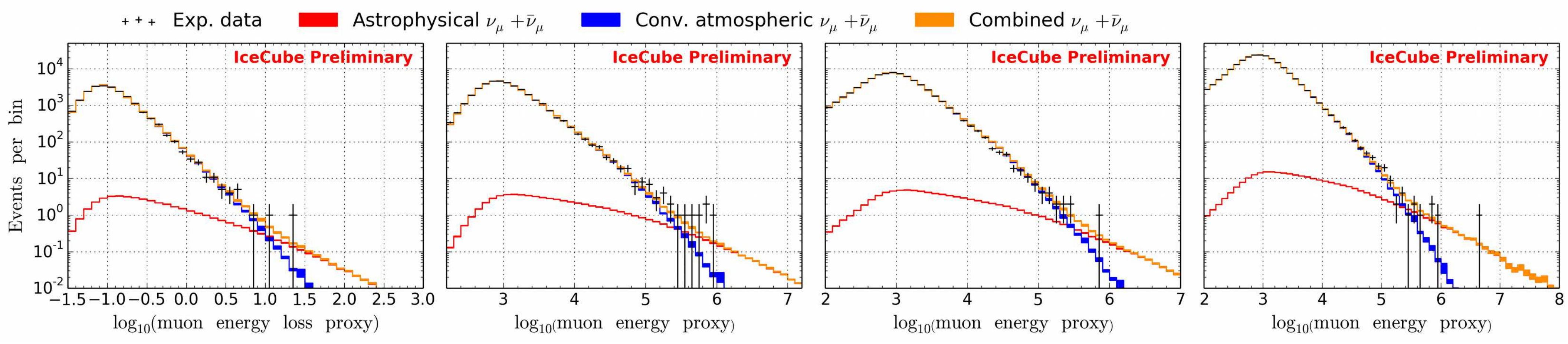
- Flux Level:~2.2 $(E/100GeV)^{-2.5}$ 10^{-8} [/GeV/cm^2/s/sr]
- Spectral index: -2.5

IceCube Collaboration (2015) Phys. Rev. D. 91

* This was for 2010-2012 data. Update to this analysis in the pipeline

Diffuse Analysis 3
A different approach: Only look below the horizon to avoid atmospheric muon background

arXiv:1607.08006



2009-2010 2010-2011 2011-2012 2011-2015

- Flux Level:~ 0.9 $(E/100\text{TeV})^{-2.13}$ 10^{-18} [/GeV/cm^2/s/sr]
- Spectral index: -2.1

IceCube backgrounds are atmospheric shower components

- Most charged π/K decay to μ rather than e
- ν produced in the same interaction, but lower cross section
  - Most common bkg: $\mu > \nu_\mu > \nu_e$ (Southern Hemisphere)
  - $\nu_\mu > \nu_e$ (Northern Hemisphere)
- At higher energy, meson lifetime is longer → more interact rather than decay
  - μ, ν Spectra softer than primary CR's
- At higher energies, charmed mesons produced
- Shorter lifetime, decay products are harder spectra than π/K decay → "prompt" flux