The background of the slide is a photograph of the IceCube detector on a large ice floe in Antarctica. The detector consists of a central blue control building with two tall, cylindrical support structures on either side. The ice is a deep blue color, and the sky is a pale, hazy blue. In the foreground, there is a 3D visualization of the detector's layout, showing a grid of vertical strings of colored spheres (red, orange, yellow, green, blue) representing the detector modules.

Neutrino Astronomy with IceCube and beyond

Marek Kowalski
HU Berlin & DESY

Neutrino 2016
London



ICECUBE

SOUTH POLE NEUTRINO OBSERVATORY



IceCube Laboratory
Data is collected here and sent by satellite to the data warehouse at UW-Madison



Digital Optical Module (DOM)
5,160 DOMs deployed in the ice

50 m

1450 m

2450 m

IceTop

86 strings of DOMs,
set 125 meters apart

IceCube
detector

DeepCore

DOMs
are 17
meters
apart

60 DOMs
on each
string

Antarctic bedrock



Amundsen-Scott South Pole Station, Antarctica
A National Science Foundation-managed research facility





ICECUBE
SOUTH POLE



IceCube Lab
Data is collect
sent by satell
warehouse a



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5 years
IceCube Detector Completion

Digital Optical
Module (DOM)
5,160 DOMs
deployed in the ice

2450

Antarctic bedrock



2007-08

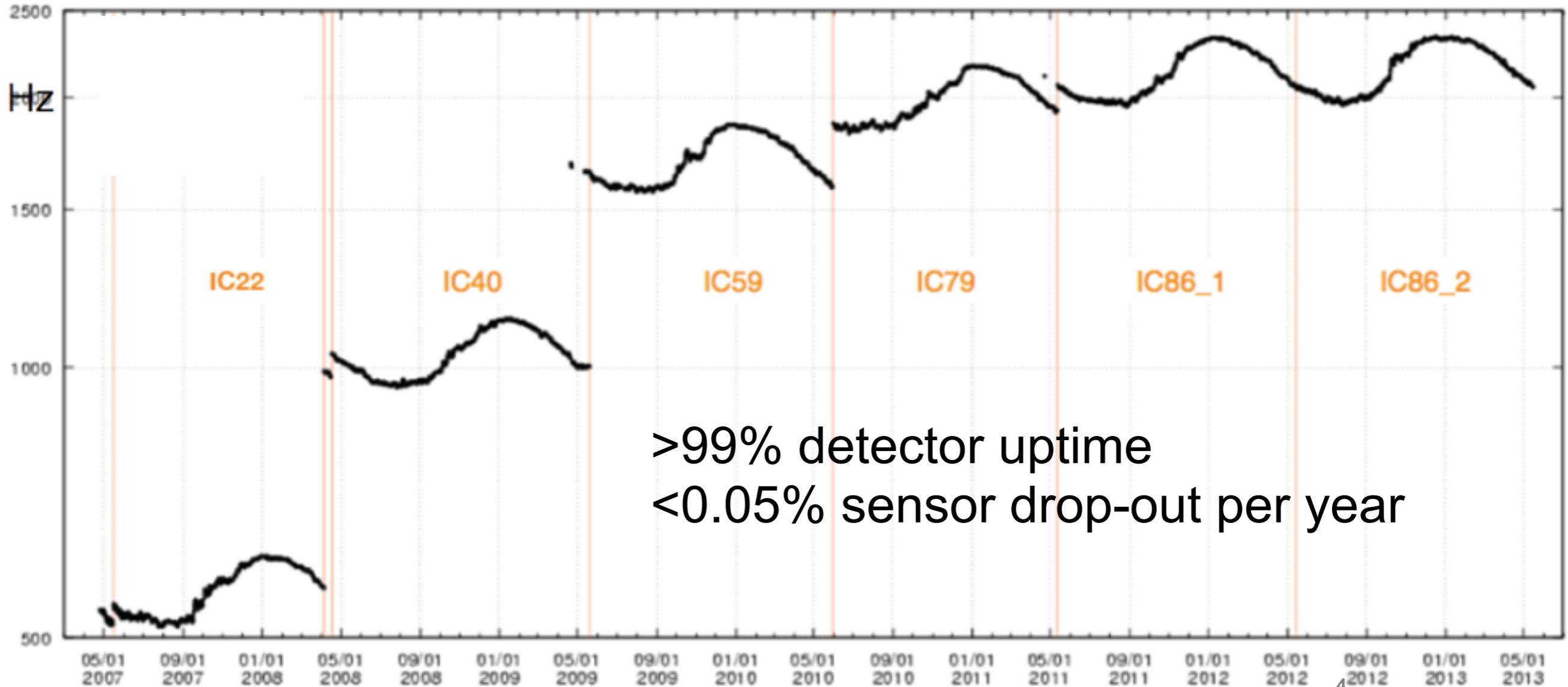
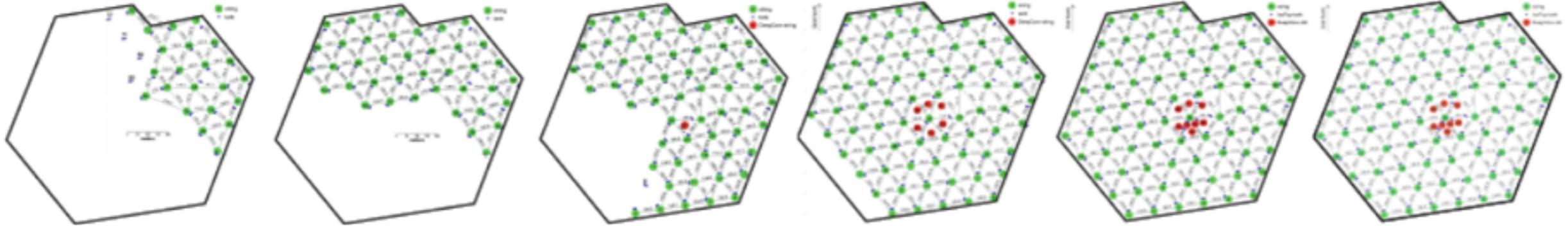
2008-09

2009-10

2010-11

2011-12

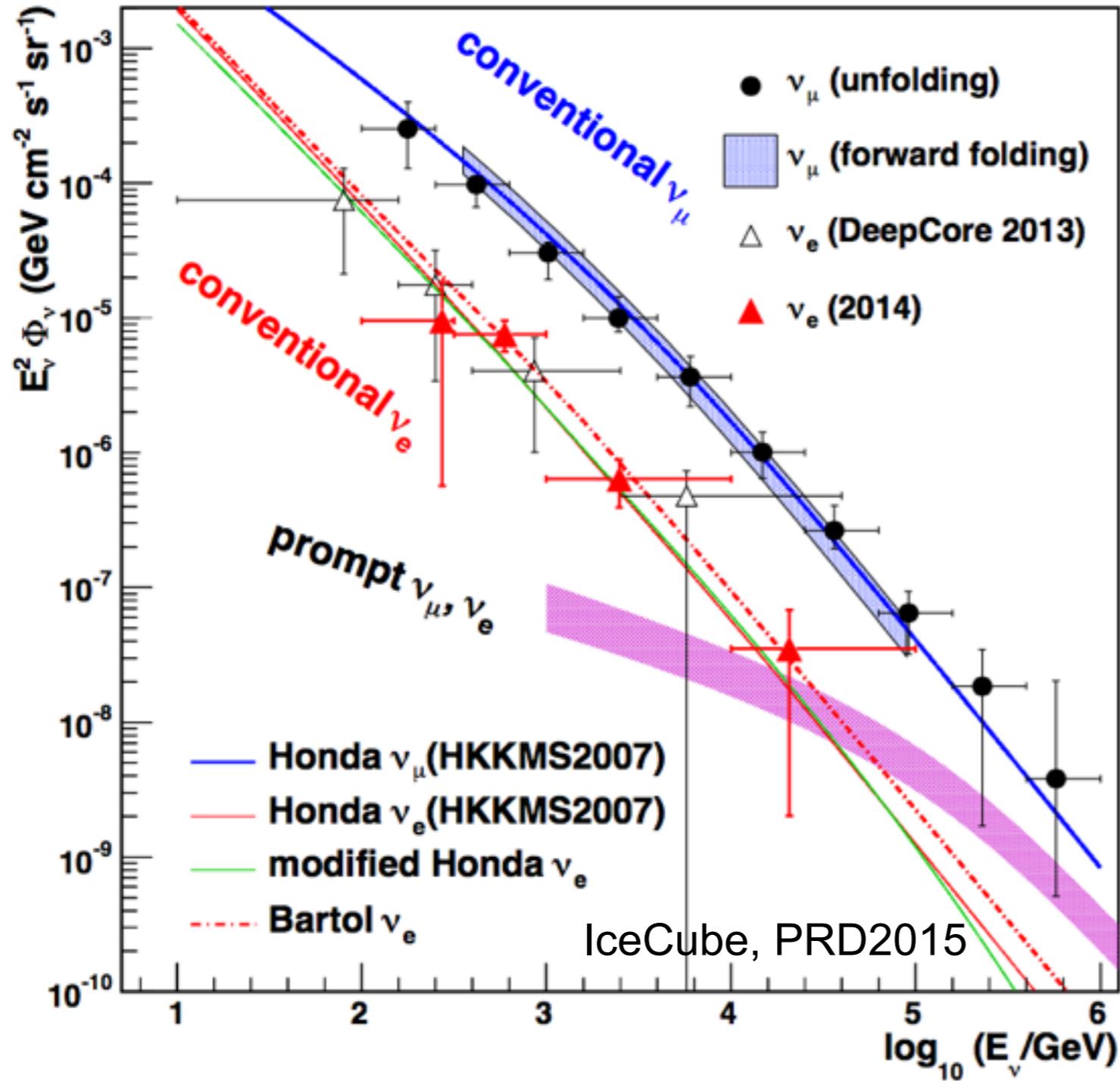
2012-13



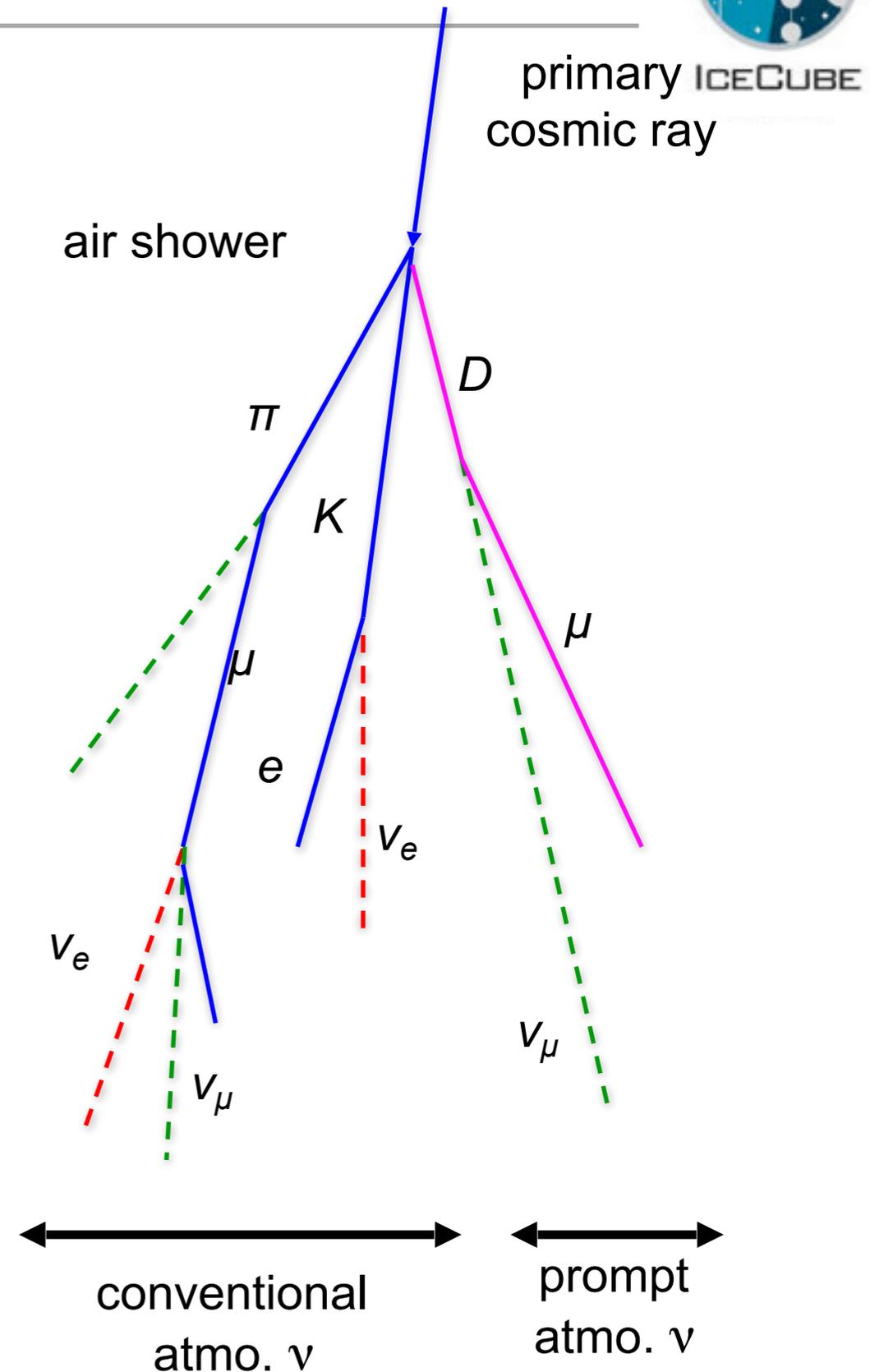
>99% detector uptime
<0.05% sensor drop-out per year



Atmospheric neutrinos

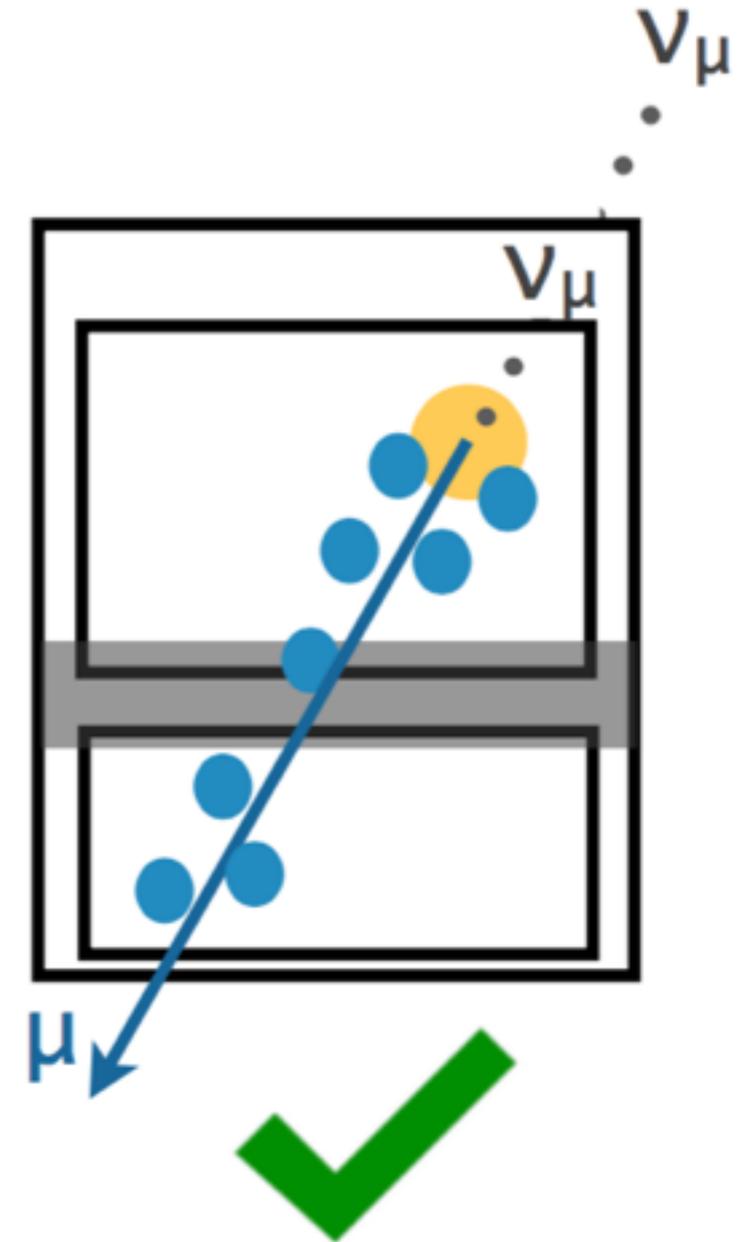
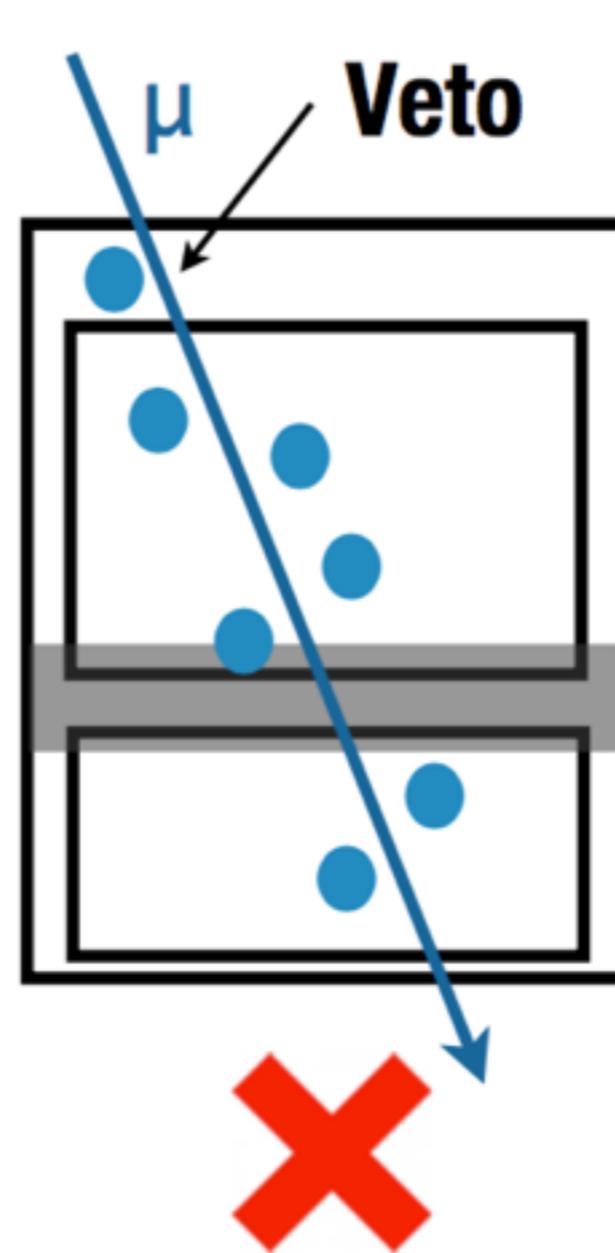
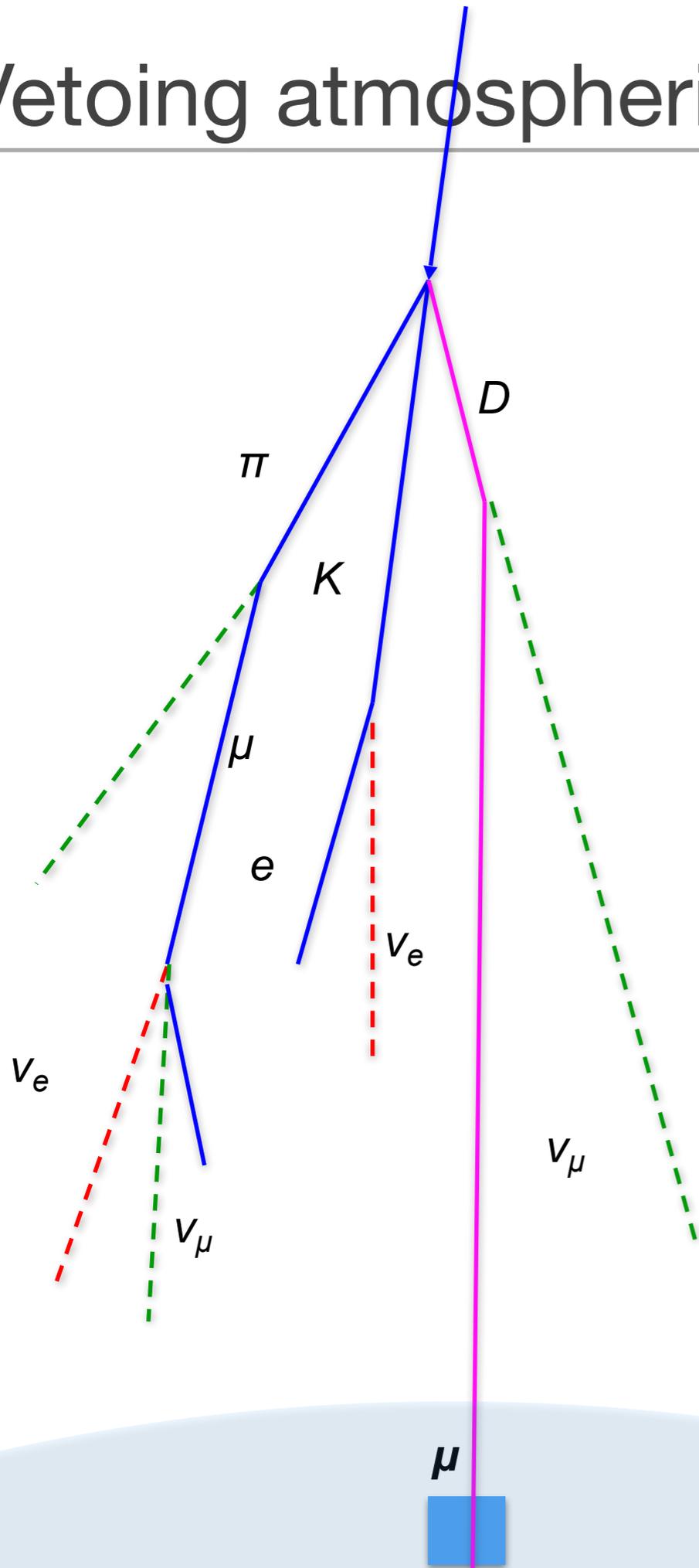


> 70.000 ν_μ / yr



Vetoing atmospheric muons & neutrinos

Schönert et al, 2009
Gaisser et al. 2014
IceCube, Science 2013

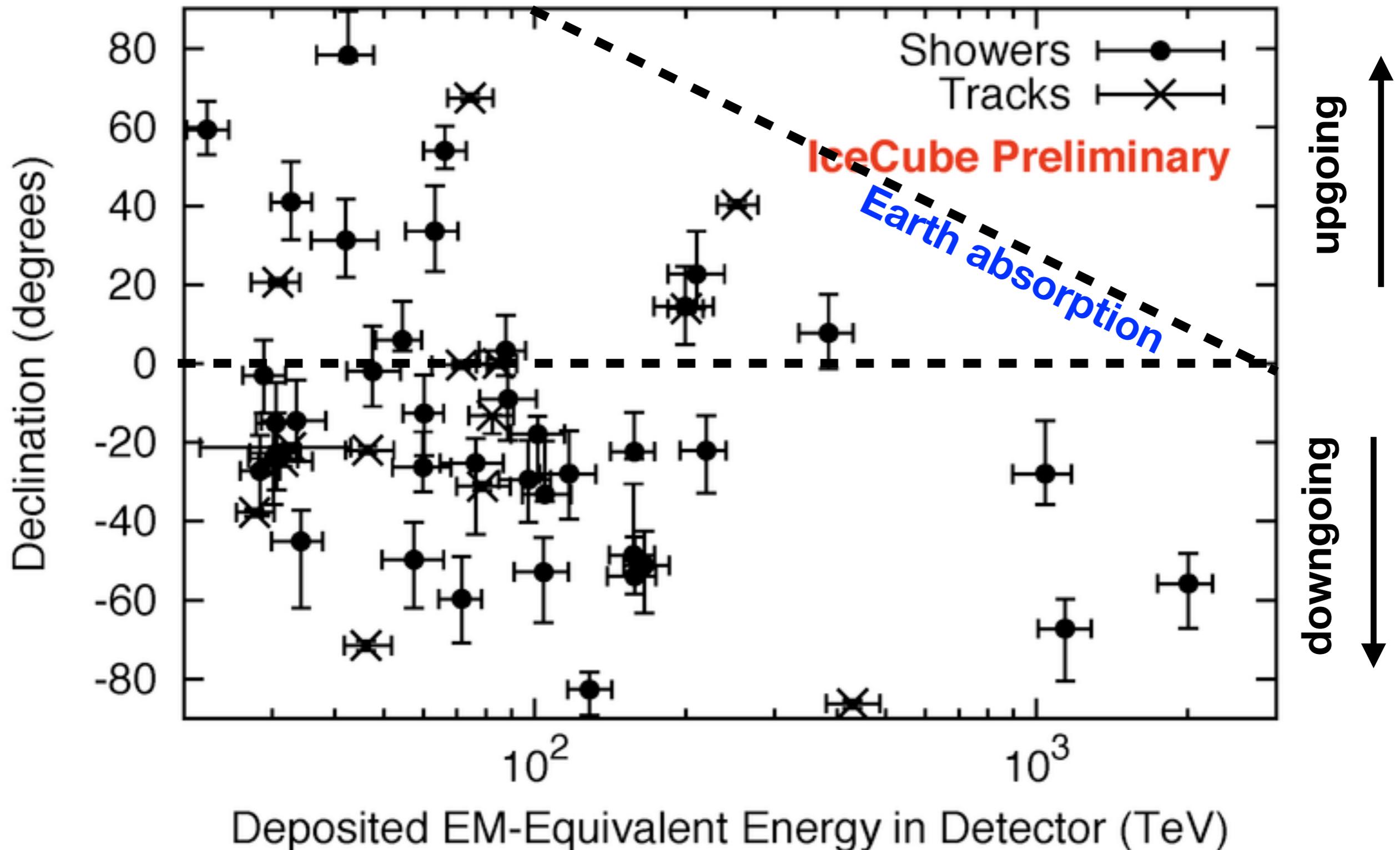


see also the poster by K. Jero (P2.012)

Astrophysical Neutrinos!



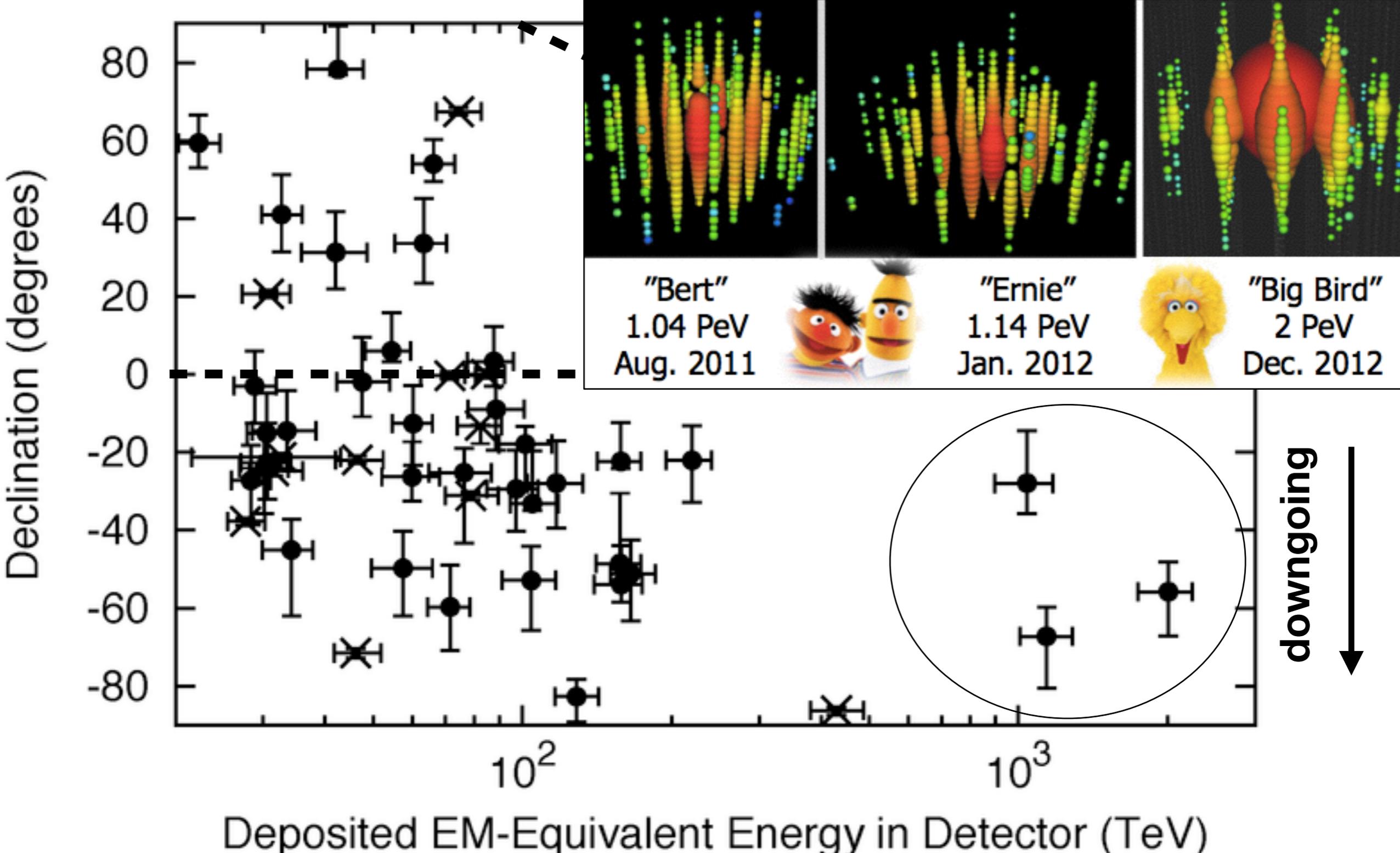
54 events observed with 20 ± 6 expected from atmosphere



Astrophysical Neutrinos!



54 events observed with 20 ± 6 expected from atmosphere

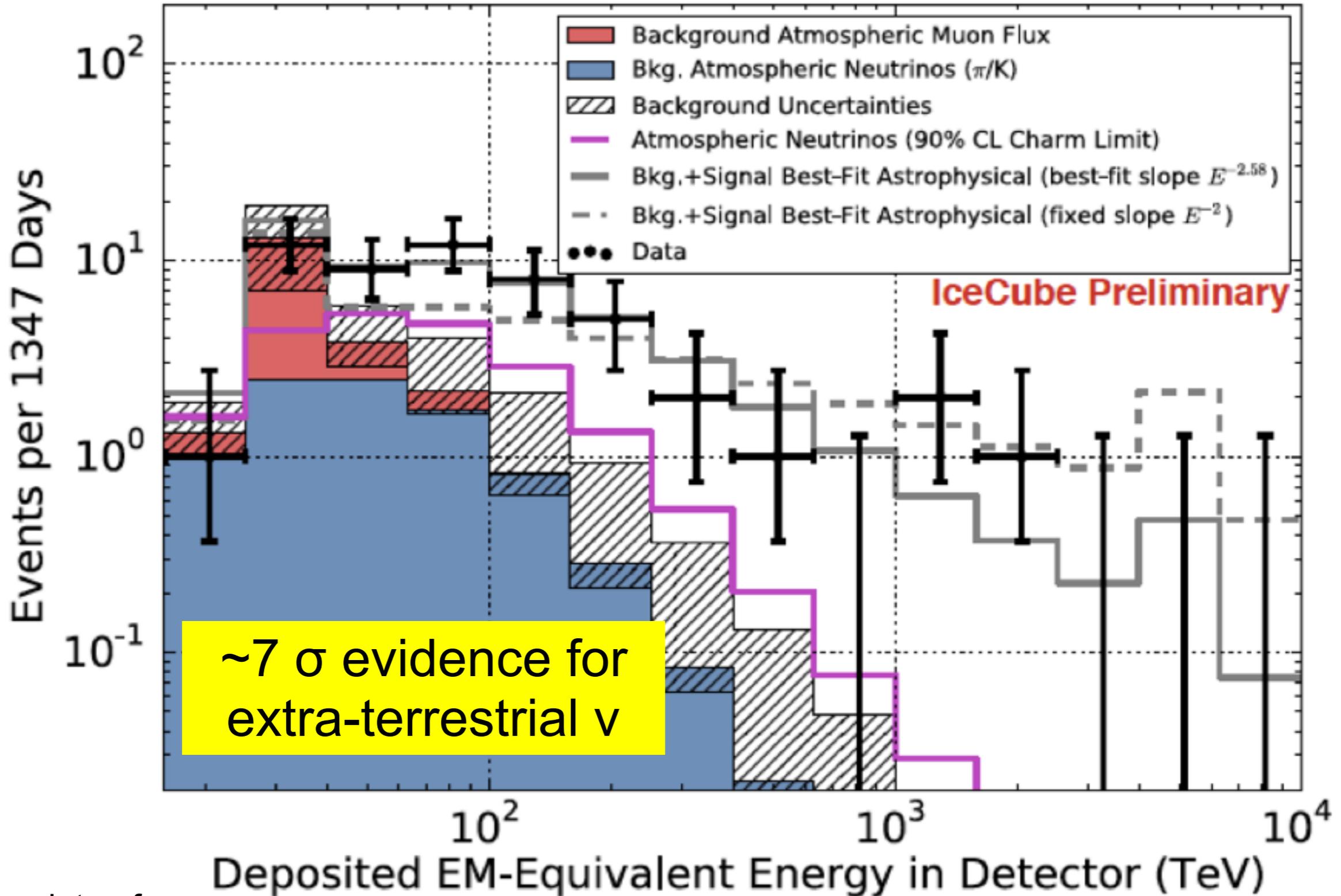




ICECUBE

Energy Spectrum

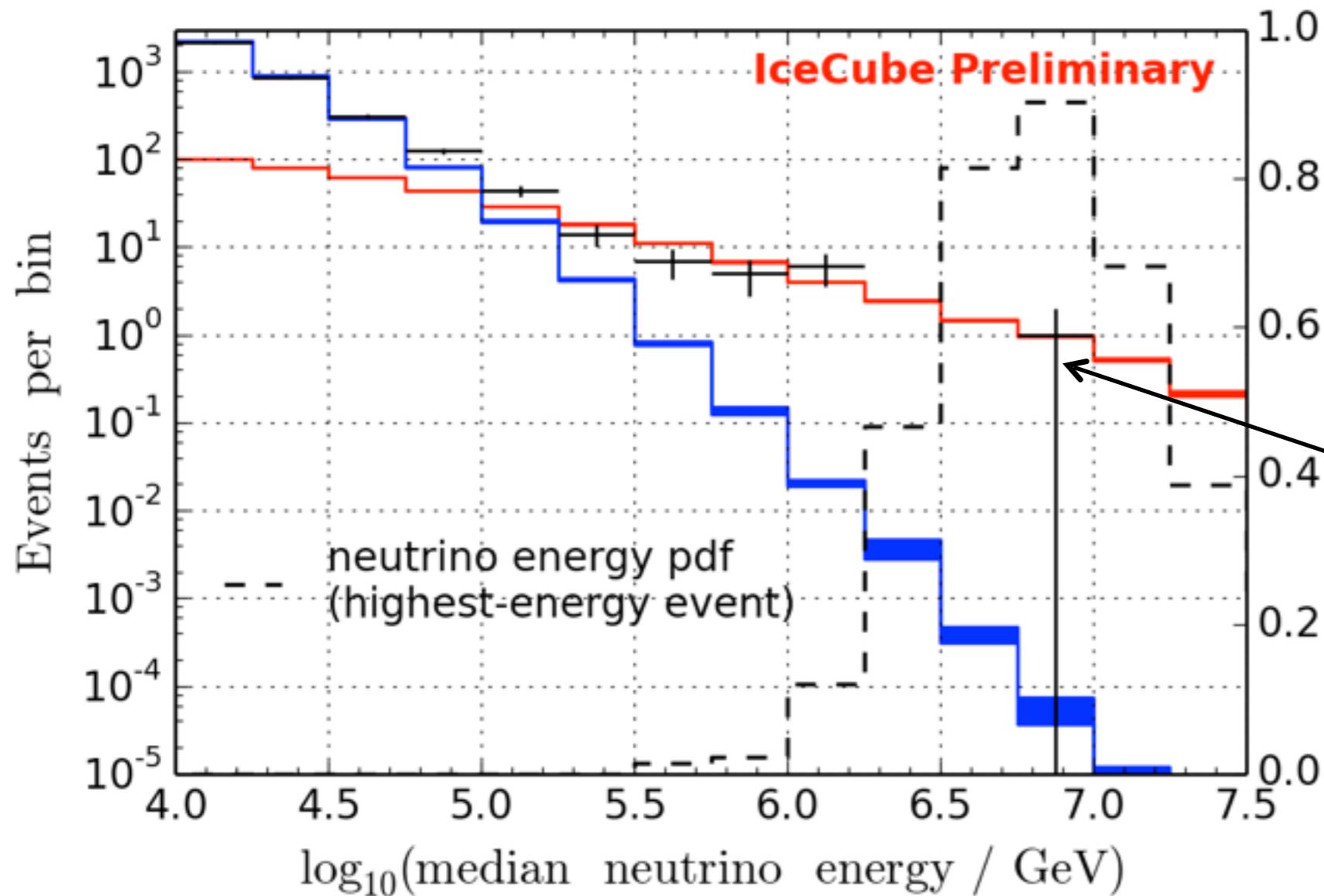
54 events observed with 20 ± 6 expected from atmosphere



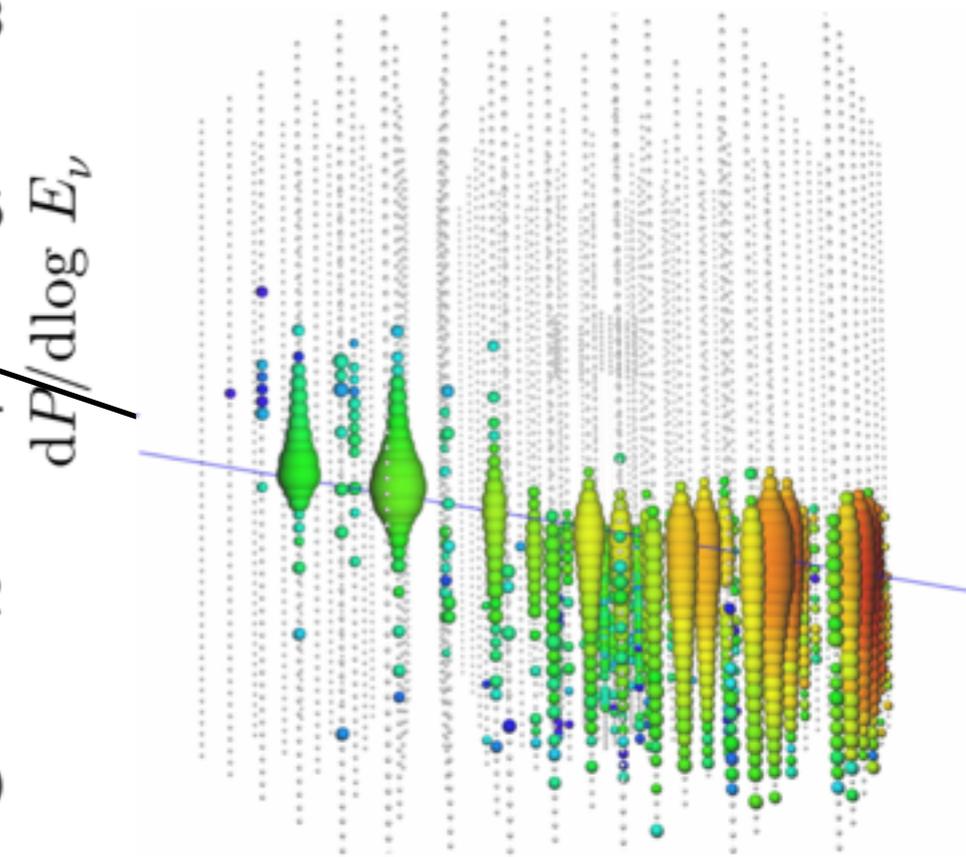
Through going muon tracks

unfolded data assuming unbroken best-fit power law

+++ Unfolding Conv. atmospheric $\nu_\mu + \bar{\nu}_\mu$
Astrophysical $\nu_\mu + \bar{\nu}_\mu$



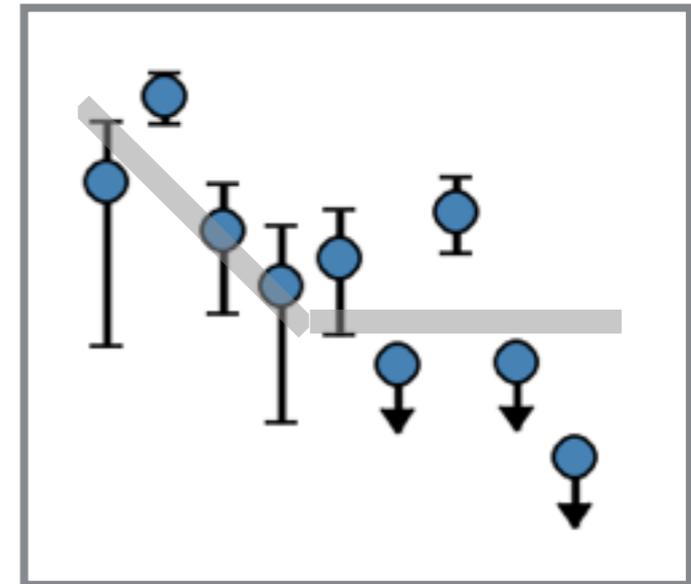
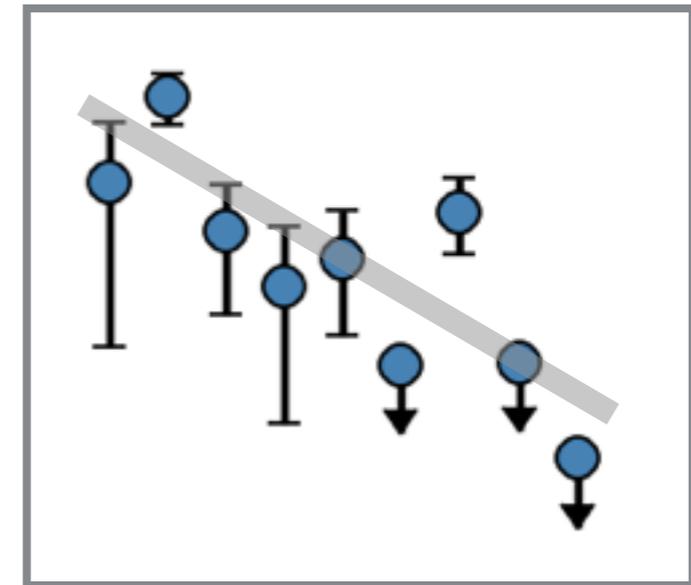
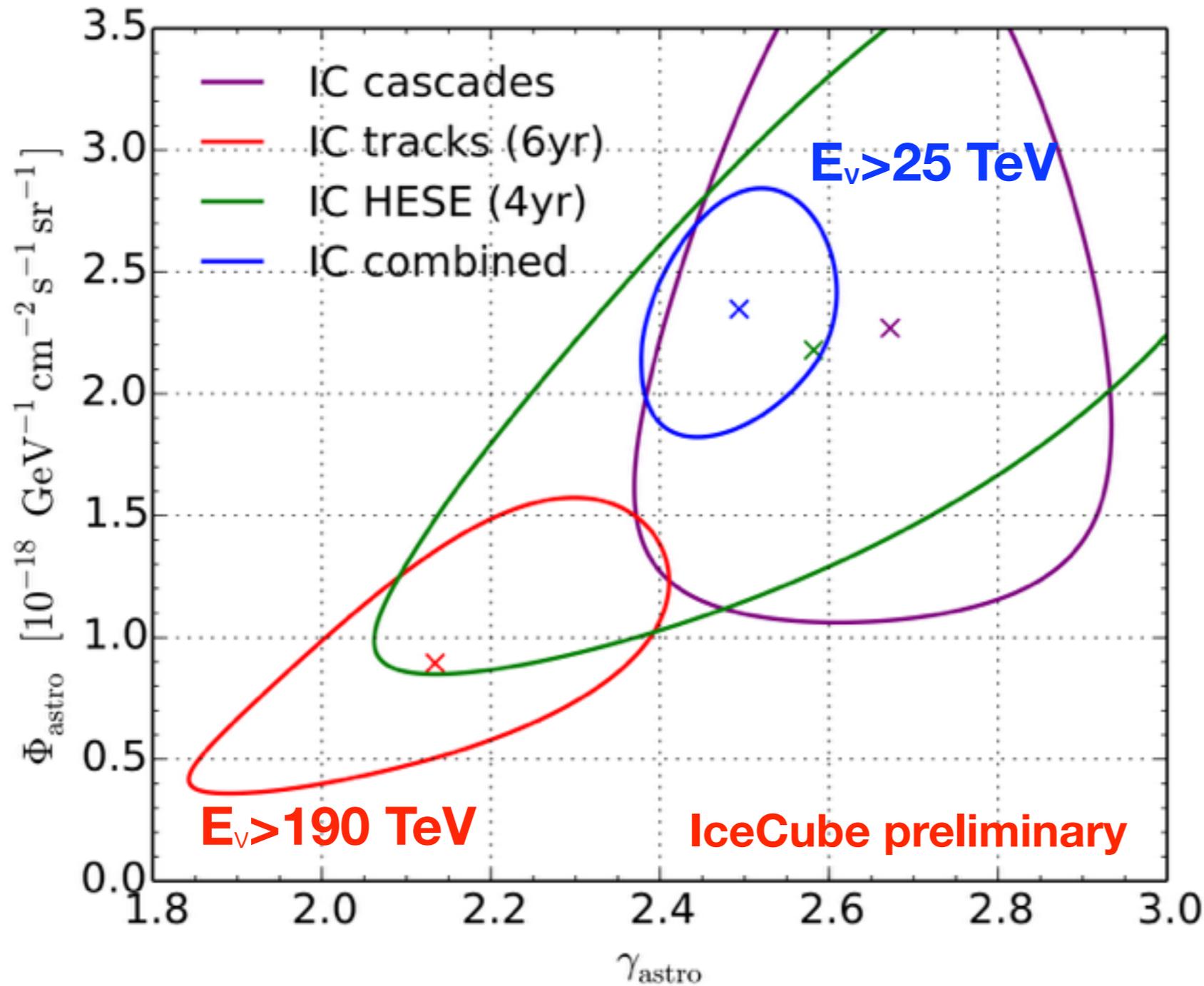
5.6 sigma detection of astrophysical neutrinos with through-going muons analysis



Deposited energy:
 $2.6 \pm 0.3 \text{ PeV}$



ICECUBE



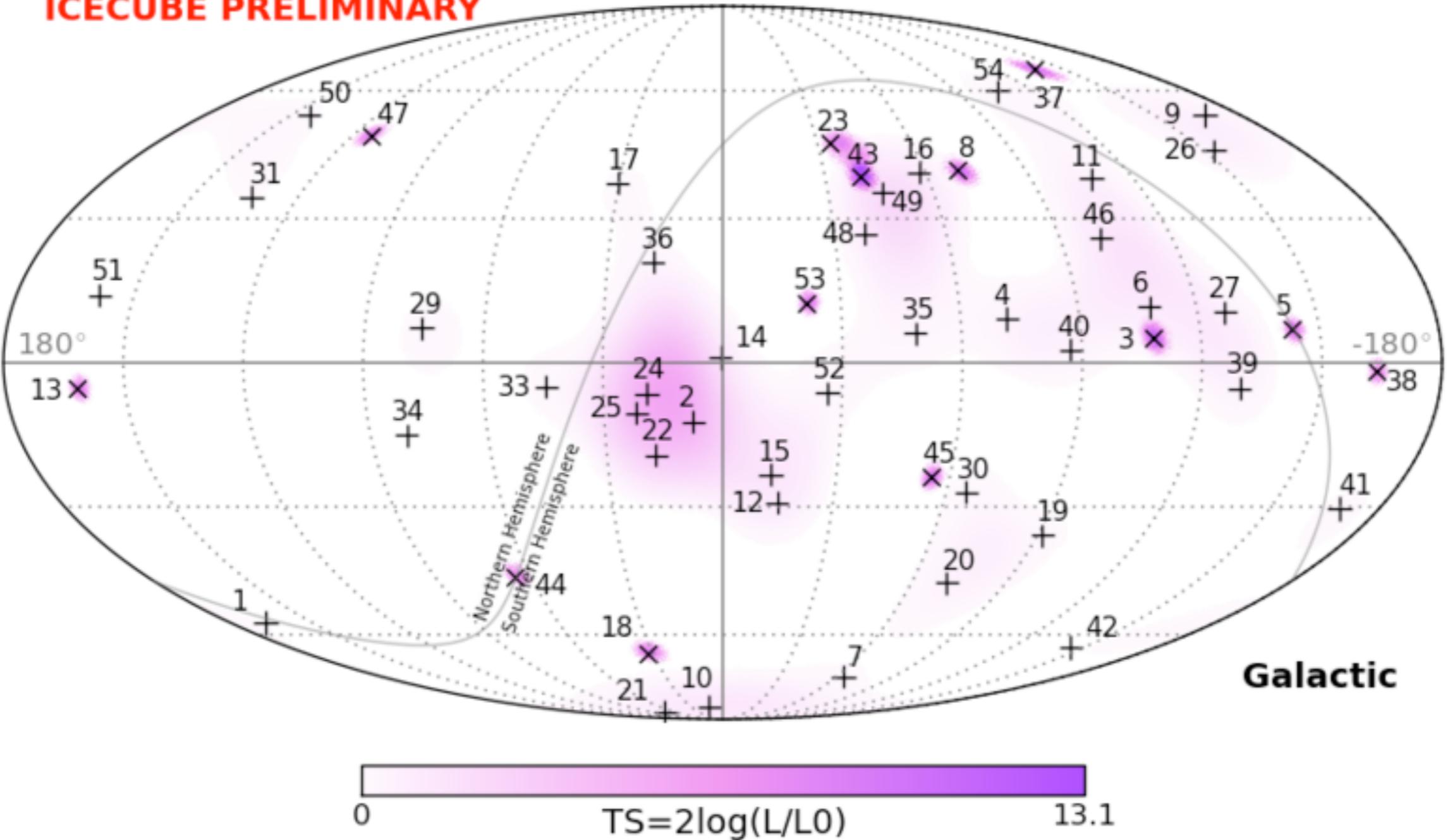
Combined spectral index: $\gamma = 2.50 \pm 0.09$
 High-energy tracks: $\gamma = 2.13 \pm 0.13$
 Prompt component < 1.06 x Enberg et al. (2008)

Are we seeing a spectral flattening of astrophysical neutrinos?

Sky map of 54 High Energy Starting Events



ICECUBE PRELIMINARY

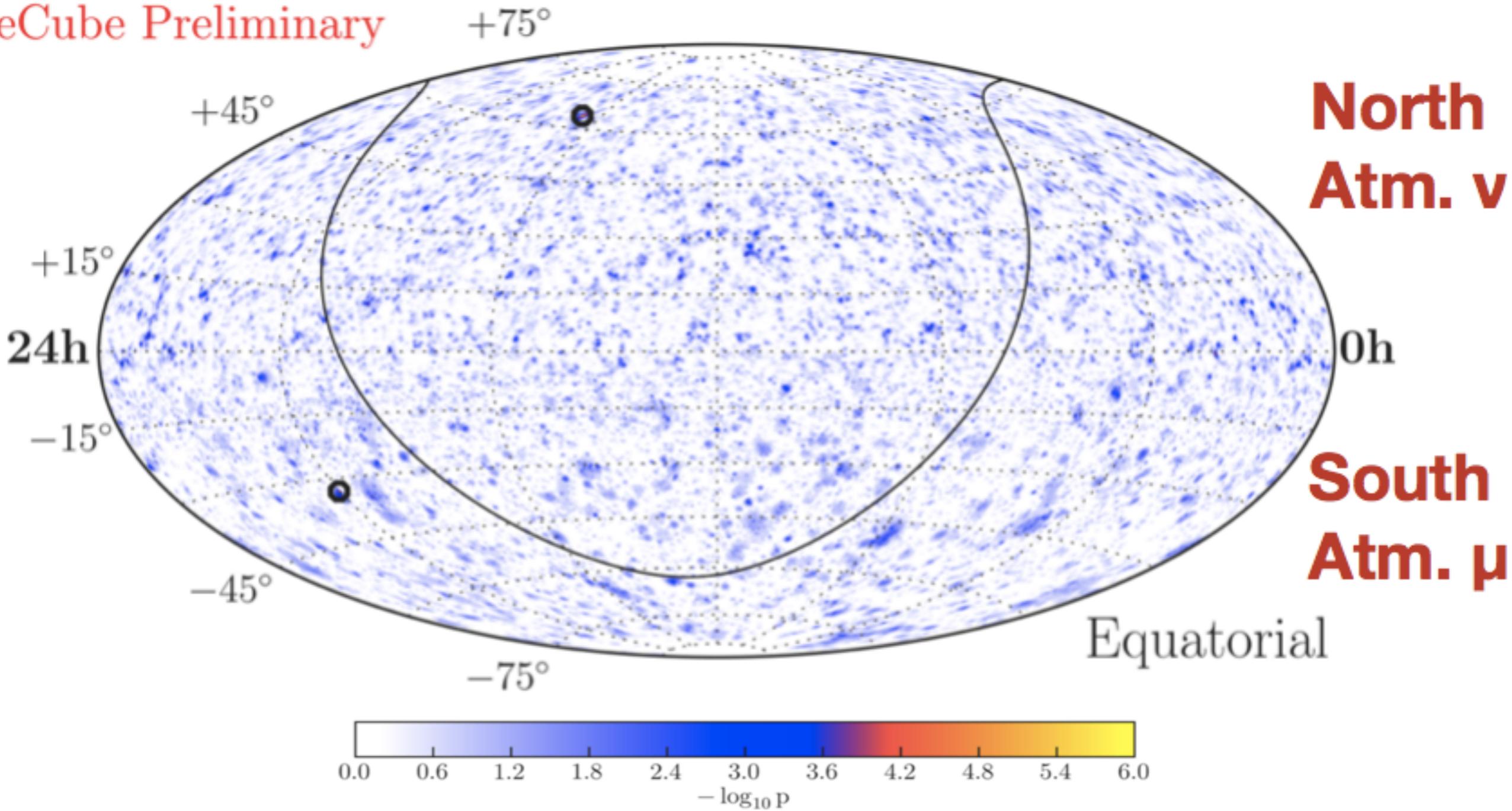


Largely isotropic \Rightarrow extragalactic origin!

Searching for point source in 7 years of data



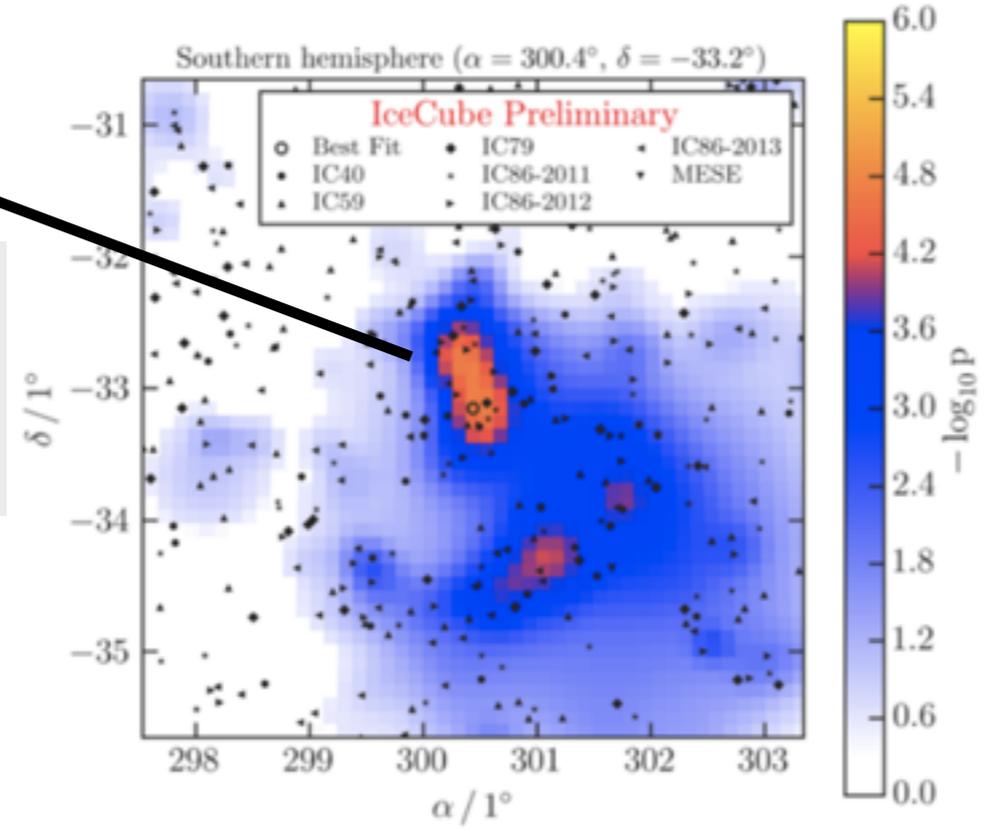
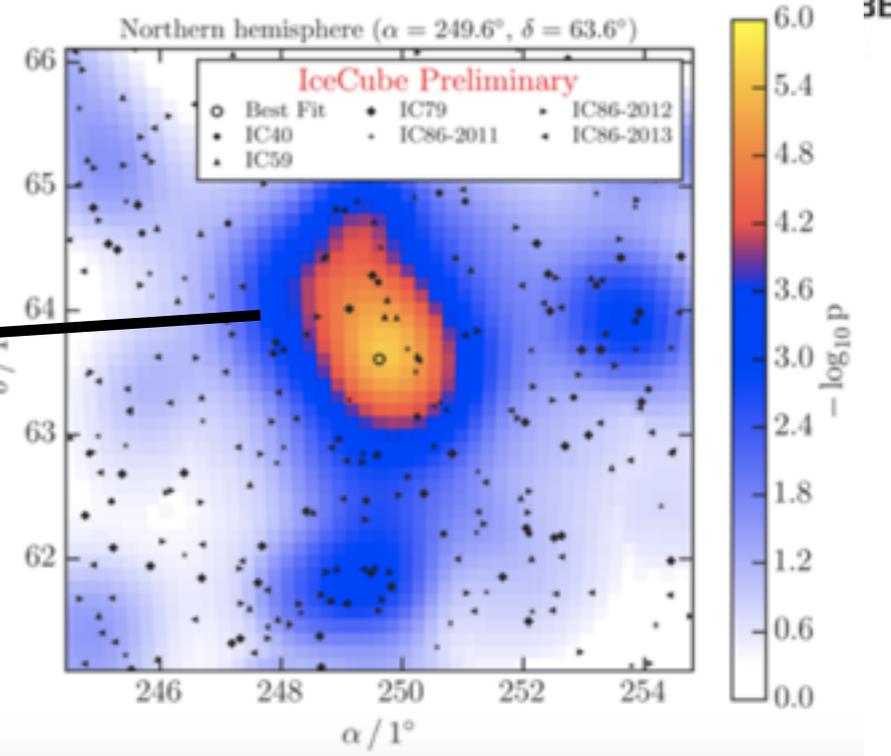
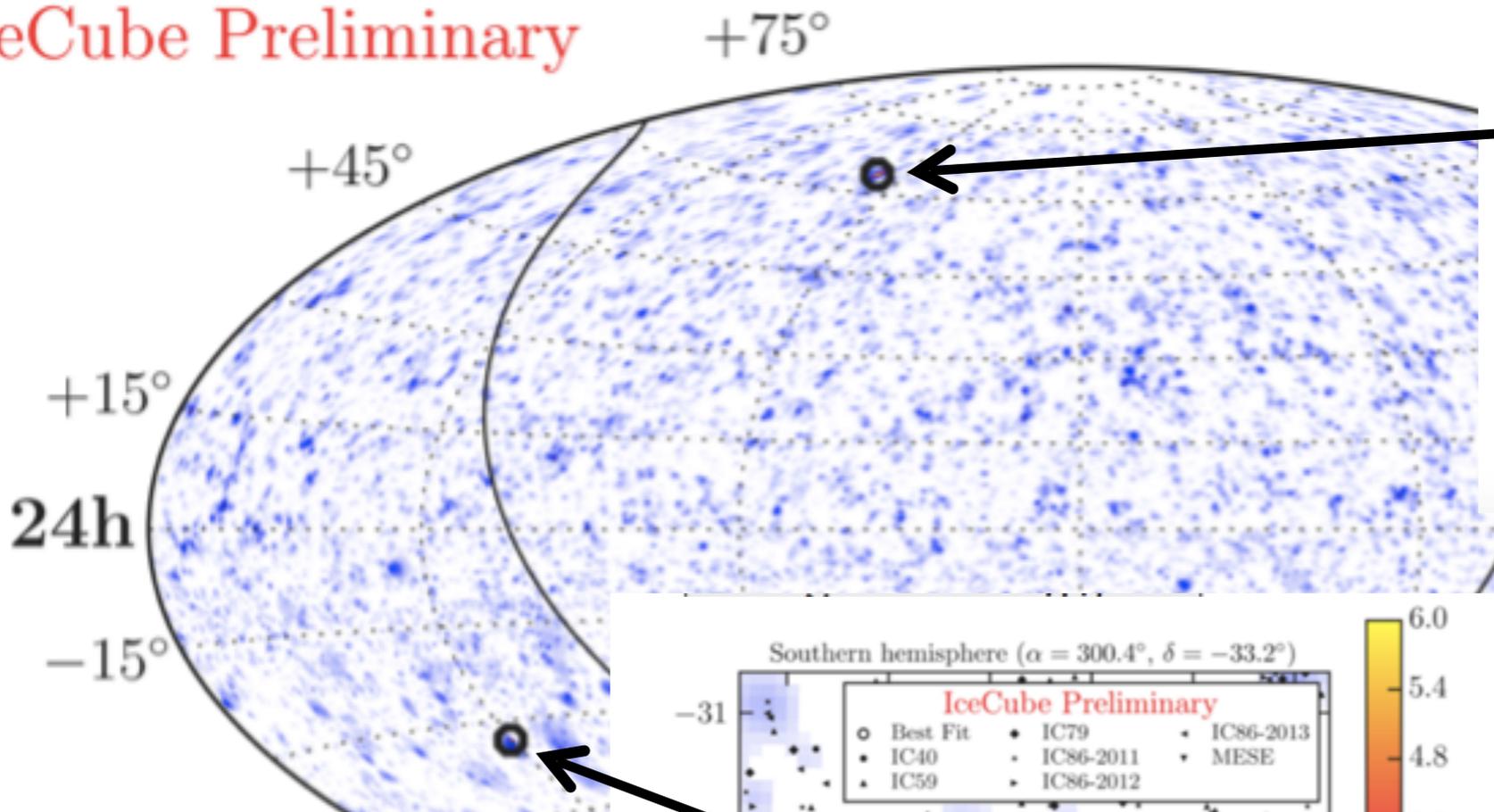
IceCube Preliminary



Searching for point source in 7 years of data



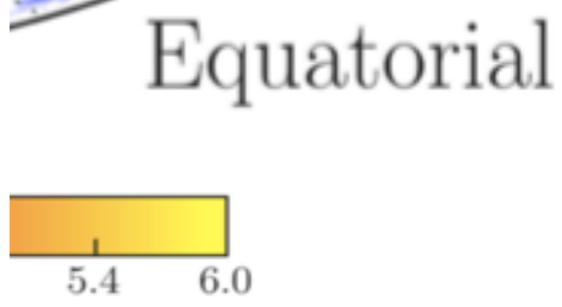
IceCube Preliminary



South	
$-\log_{10}(p)$	4.74
Post-Trial	87%

North	
$-\log_{10}(p)$	5.51
Post-Trial	35%

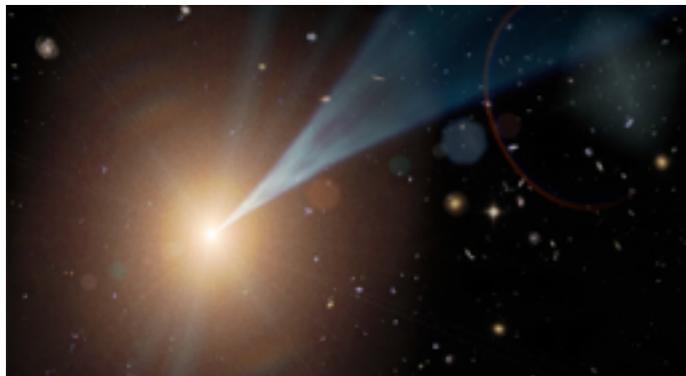
Atm. μ



Neutrinos from Blazars (Active Galactic Nuclei)

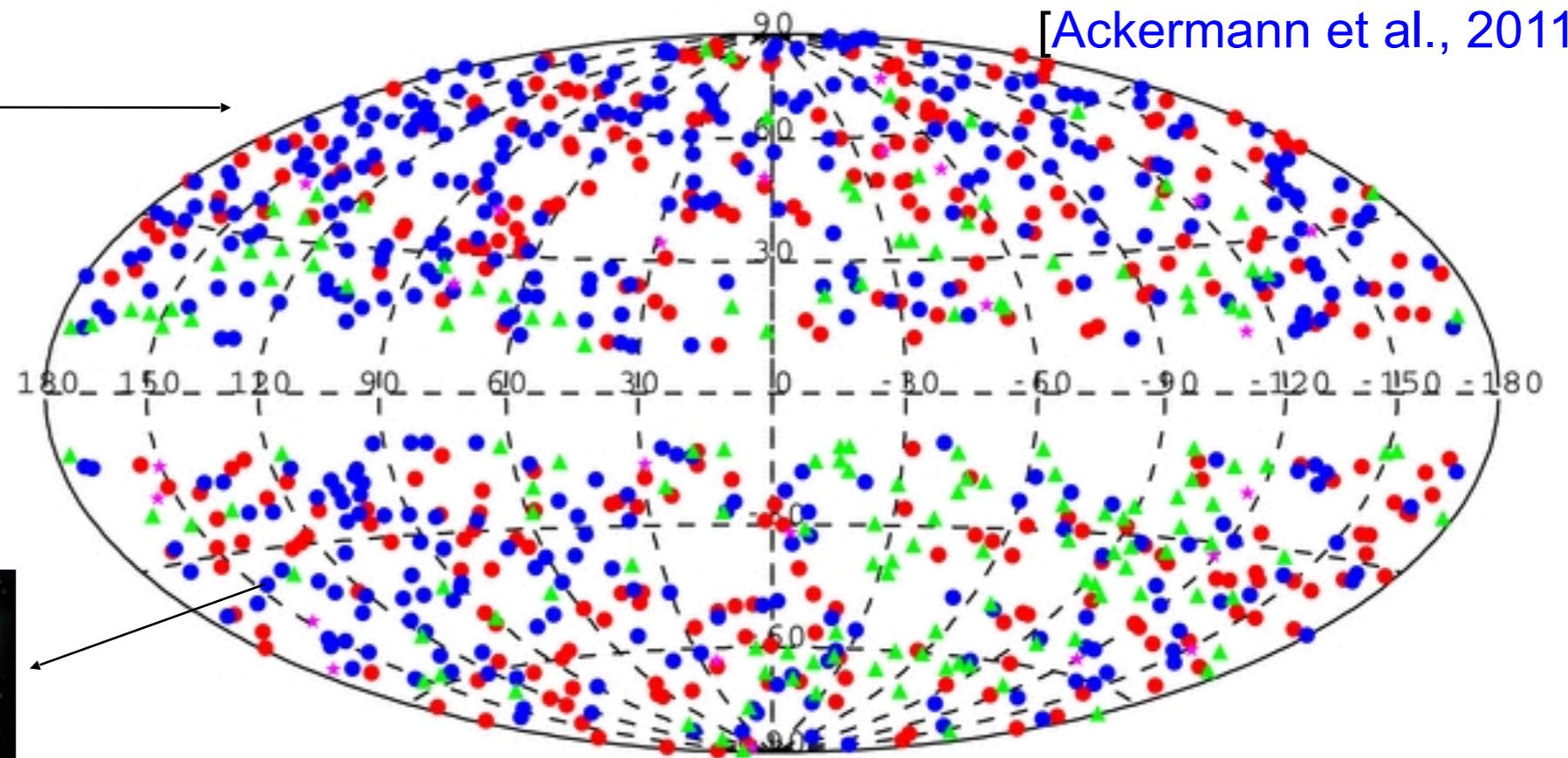


Total sources: ~ 900



FERMI-LAT AGN SKYMAP ($|b| > 10$)

[Ackermann et al., 2011]



● FSRQ

● BL-LAC

◆ Unknown Blazar

Look for faint **combined** neutrino emission from these sources



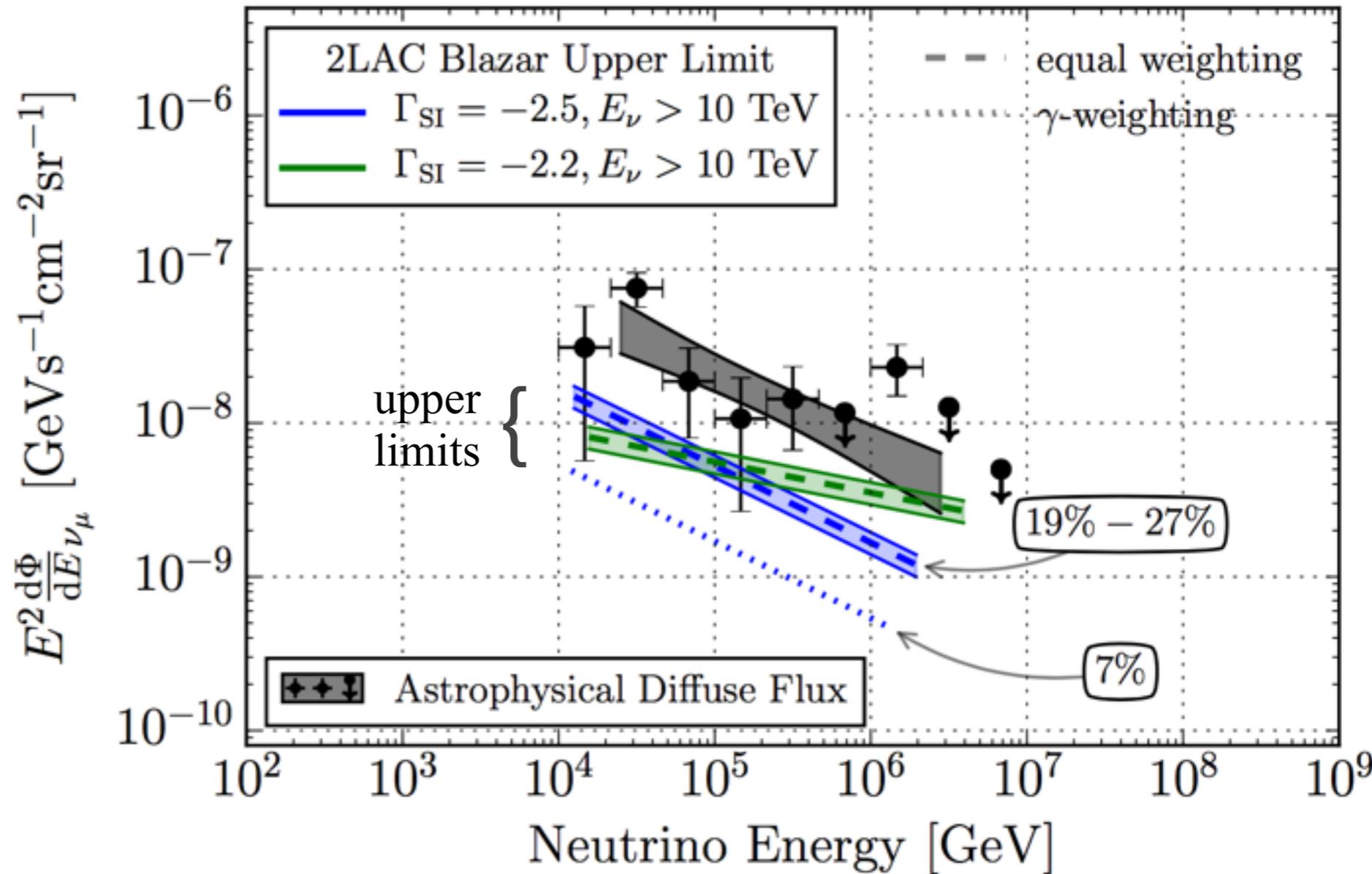
Neutrinos from Blazars (Active Galactic Nuclei)



Total sources: ~ 900



No correlation found:



< 30% of the astrophysical ν flux originates from Blazars

For more see talk by A. Franckowiak and poster by R. Maunu (P2.013)

The high-energy Universe: broader perspective

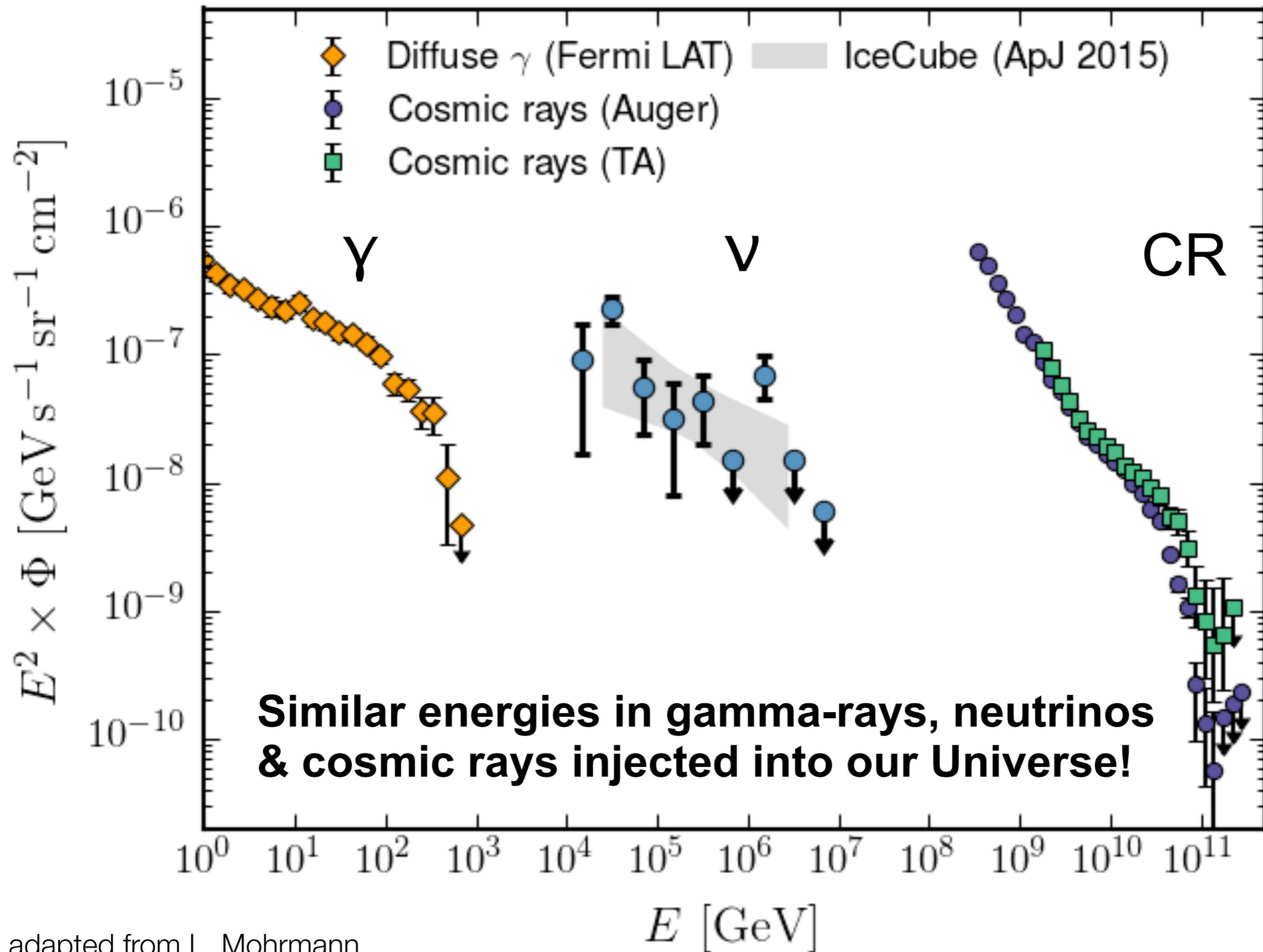


Fig. adapted from L. Mohrmann

The high-energy Universe: broader perspective

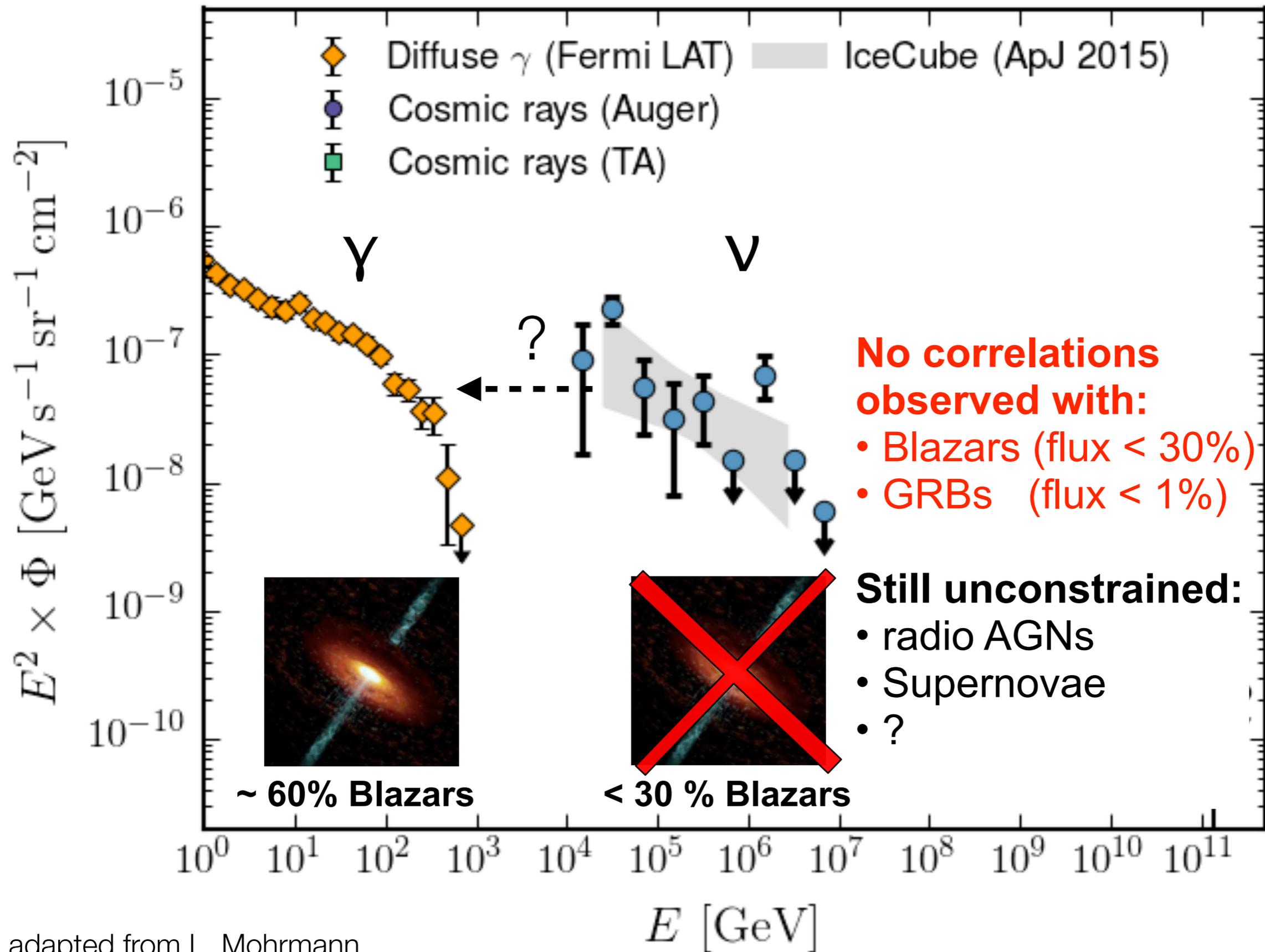
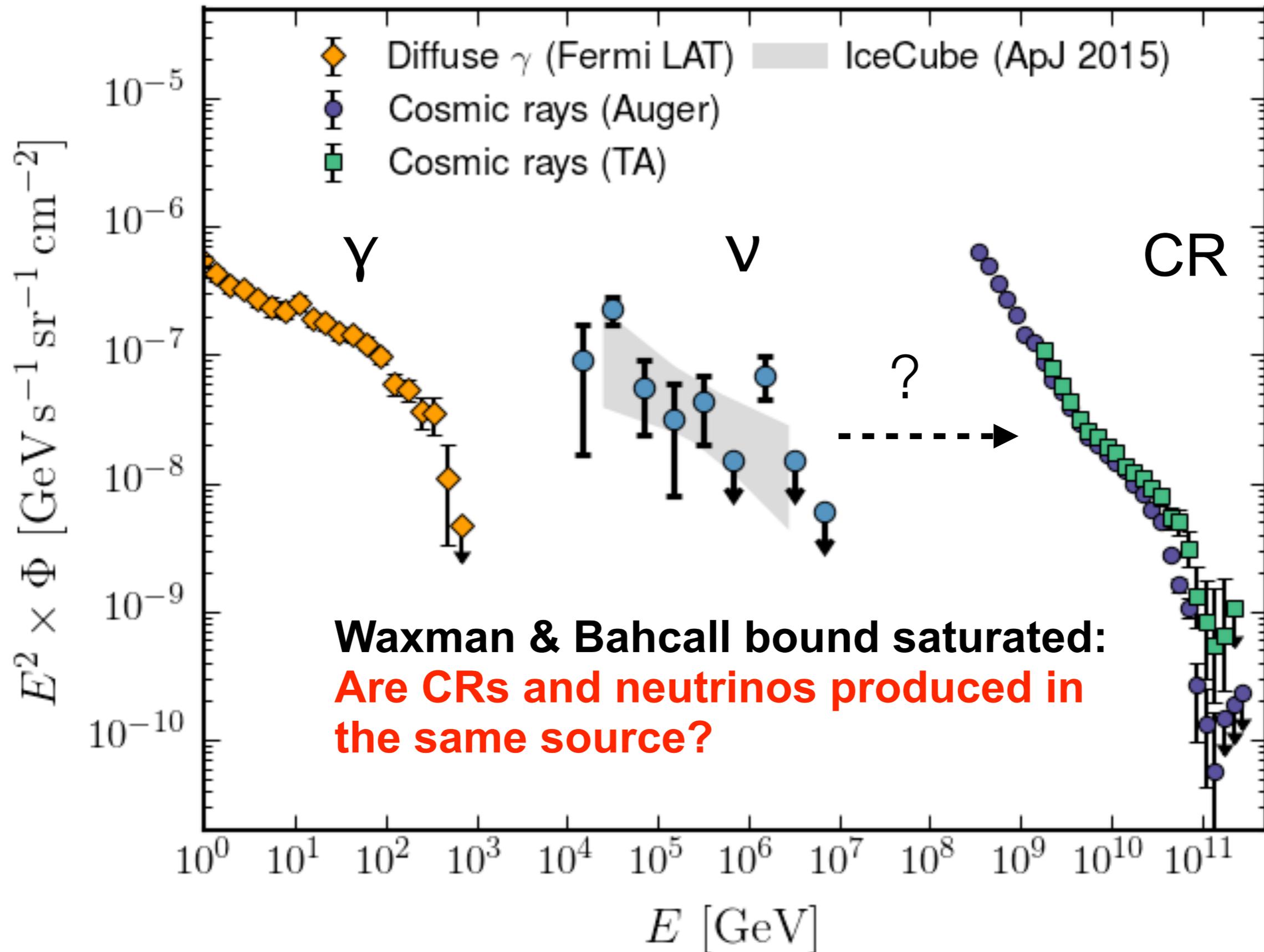


Fig. adapted from L. Mohrmann

The high-energy Universe: broader perspective

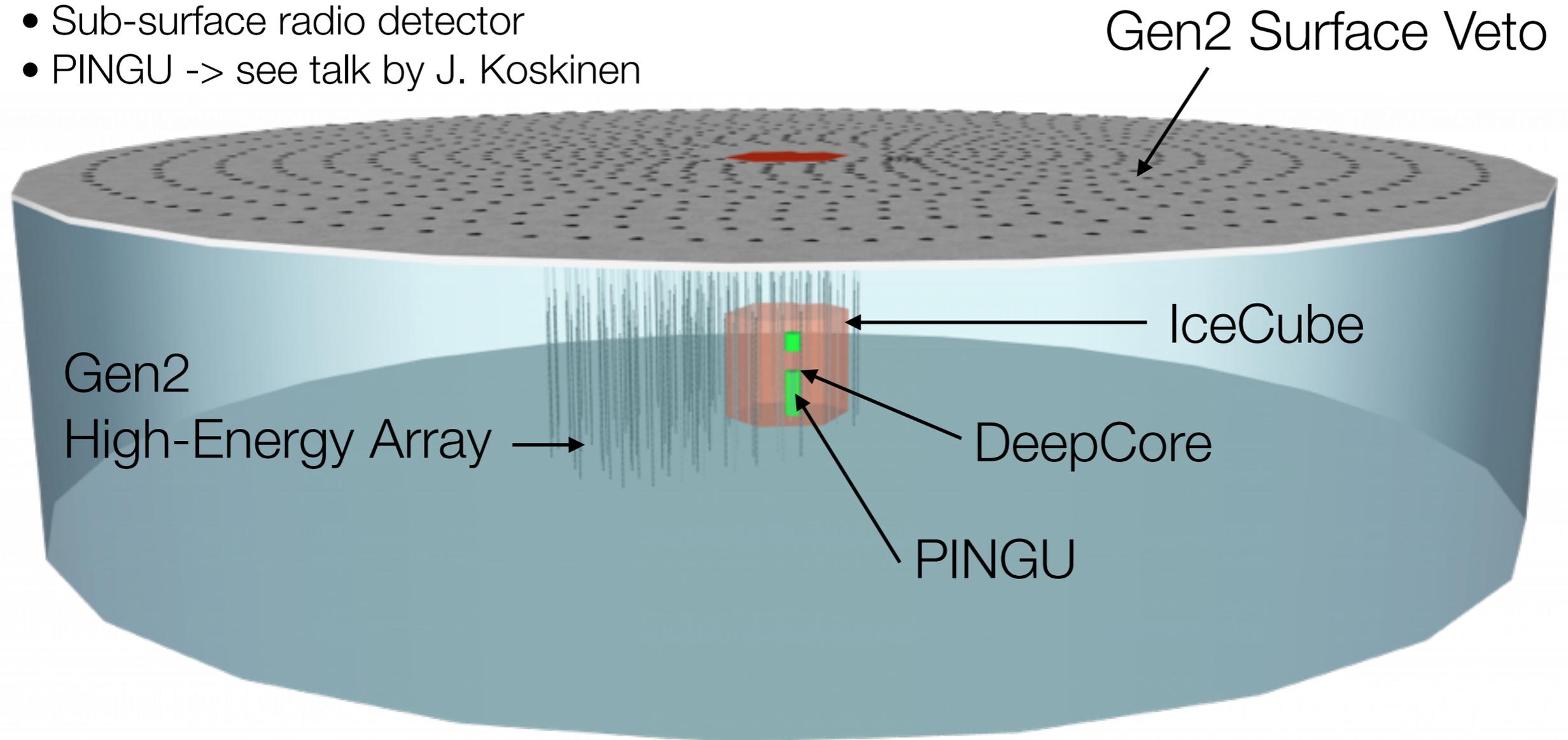




A wide band neutrino observatory (MeV – EeV) using several detection technologies – optical, radio, and surface veto – to maximize the science

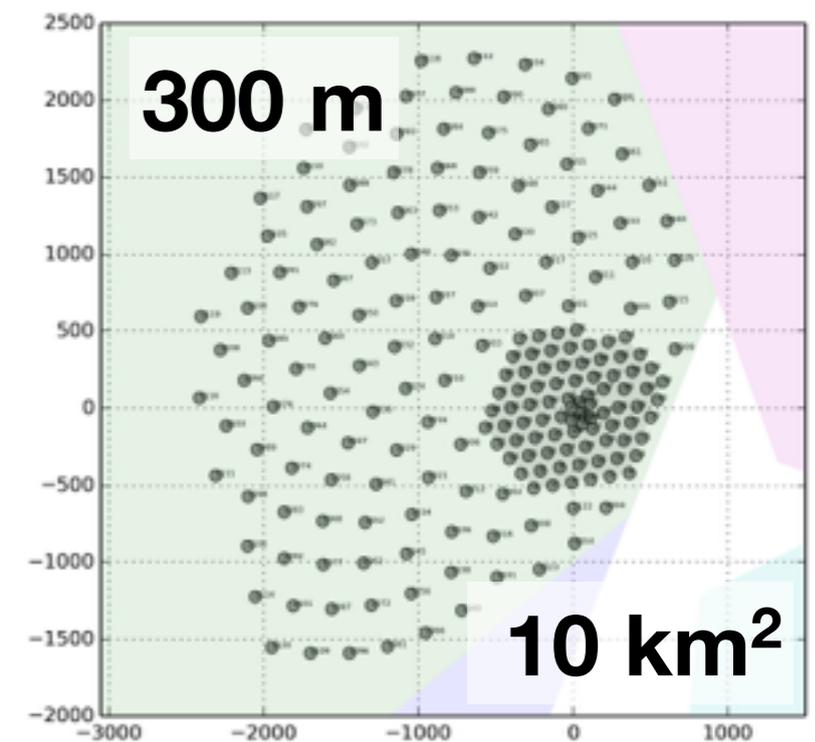
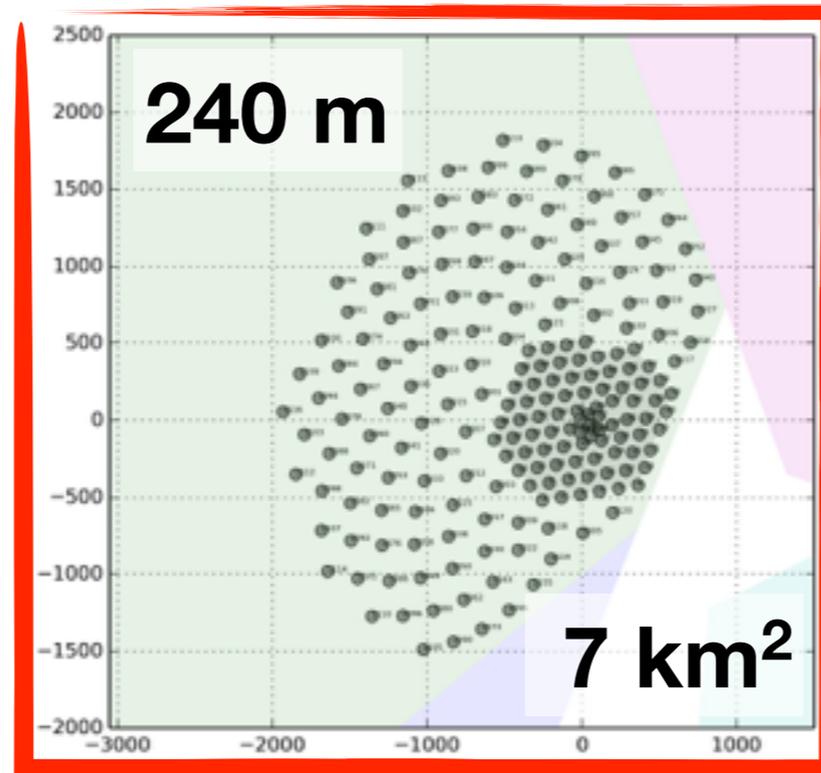
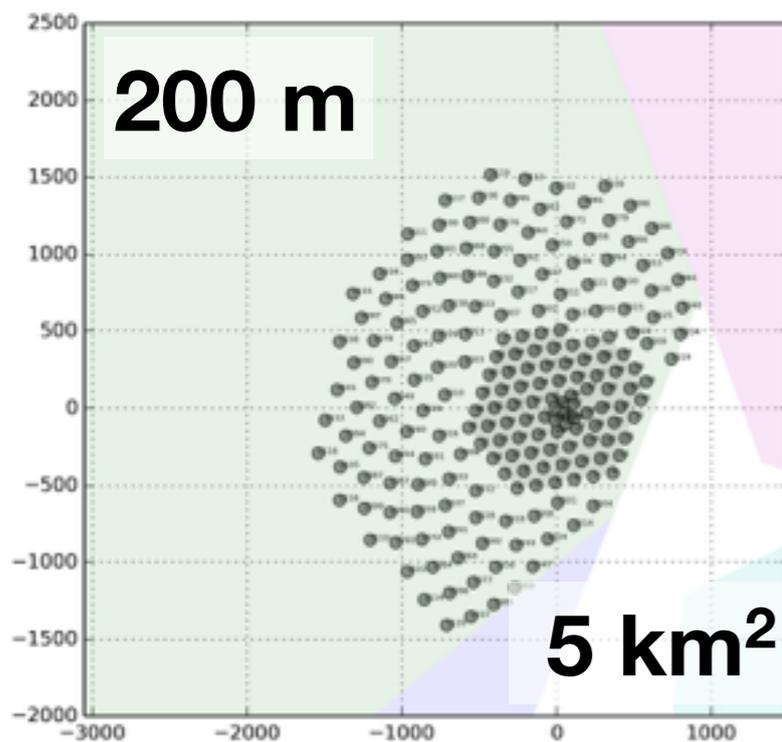
Multi-component observatory:

- Surface air shower detector
- Gen2 High-Energy Array
- Sub-surface radio detector
- PINGU -> see talk by J. Koskinen



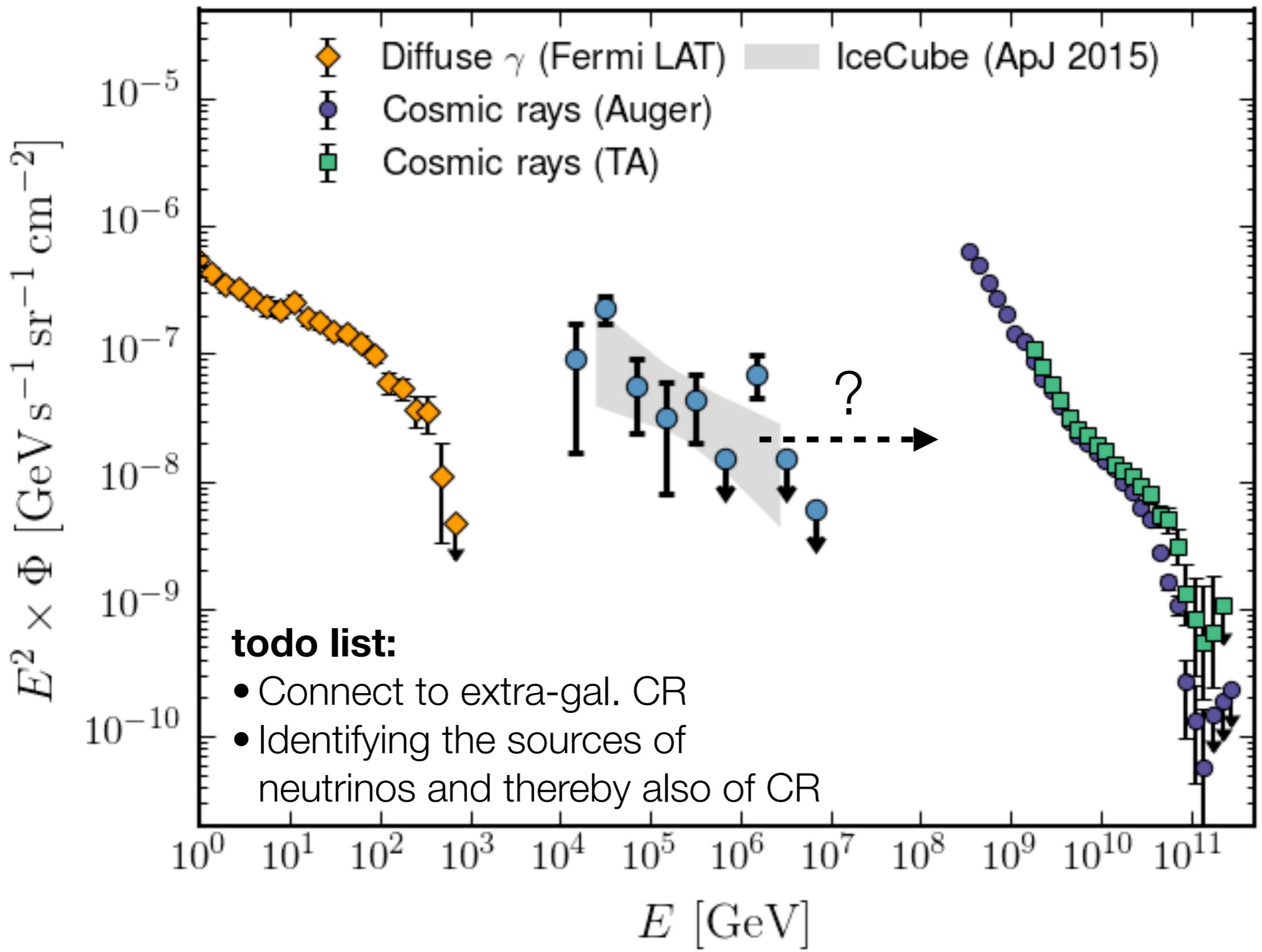
Geometry optimization

- Several layouts under evaluation
- Example: “Sunflower” geometry with different string spacings

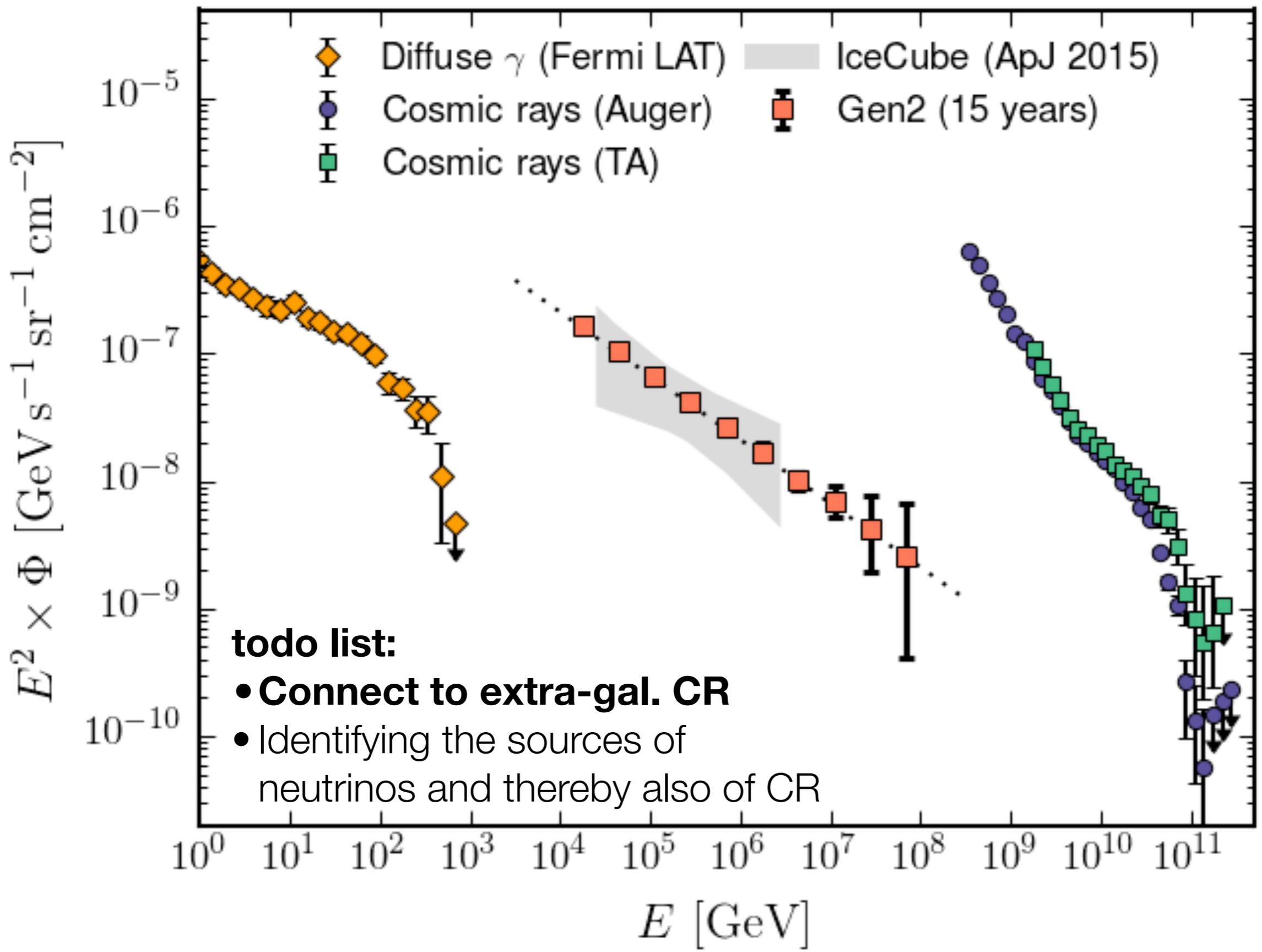


- ~120 new strings, 80 DOMs per string, instrumented over 1.25 km
- ~10 x IC volume for contained event analysis above 200 TeV

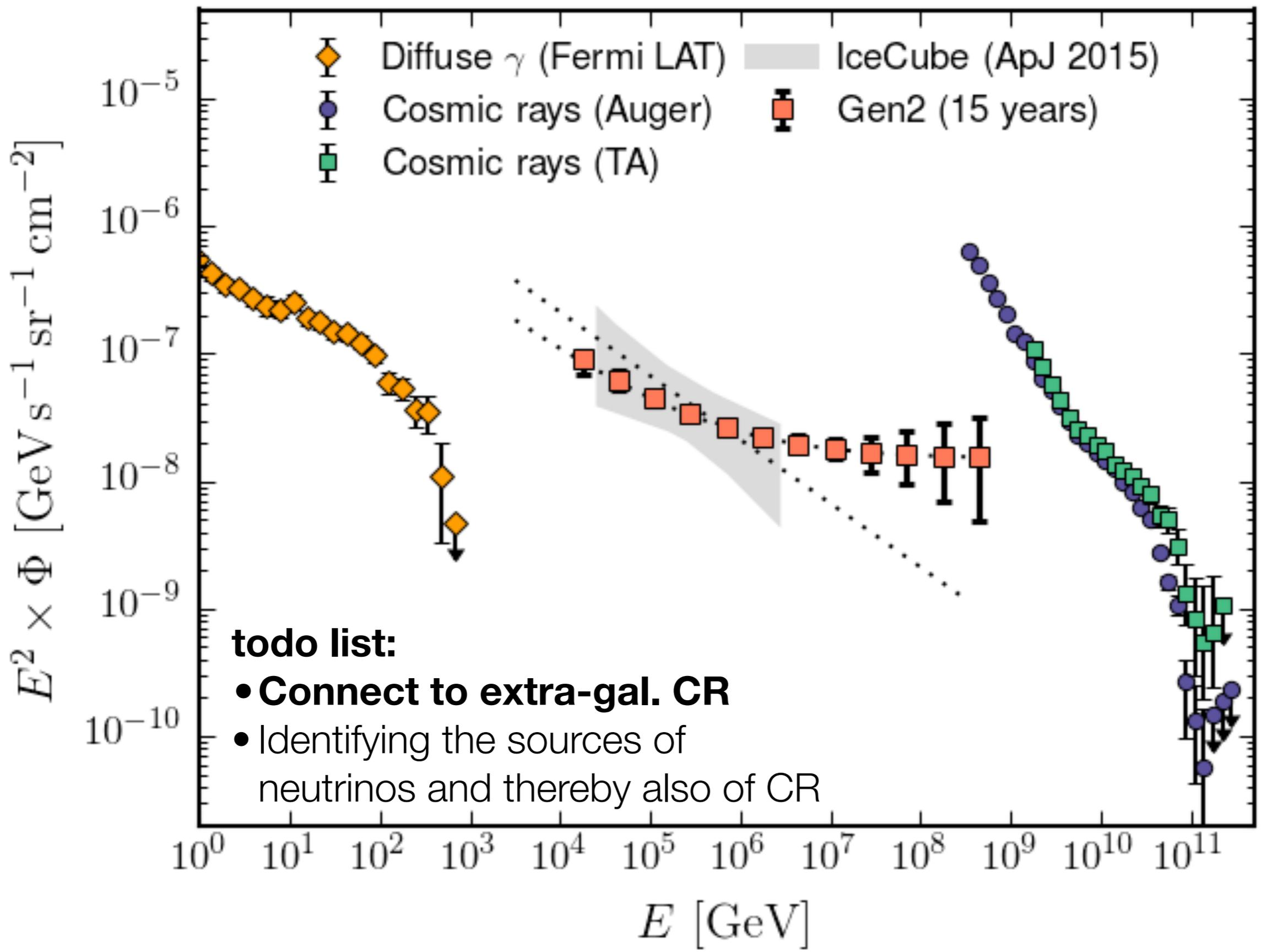
Resolving the mysteries of the UHE Universe



Resolving the mysteries of the UHE Universe



Resolving the mysteries of the UHE Universe



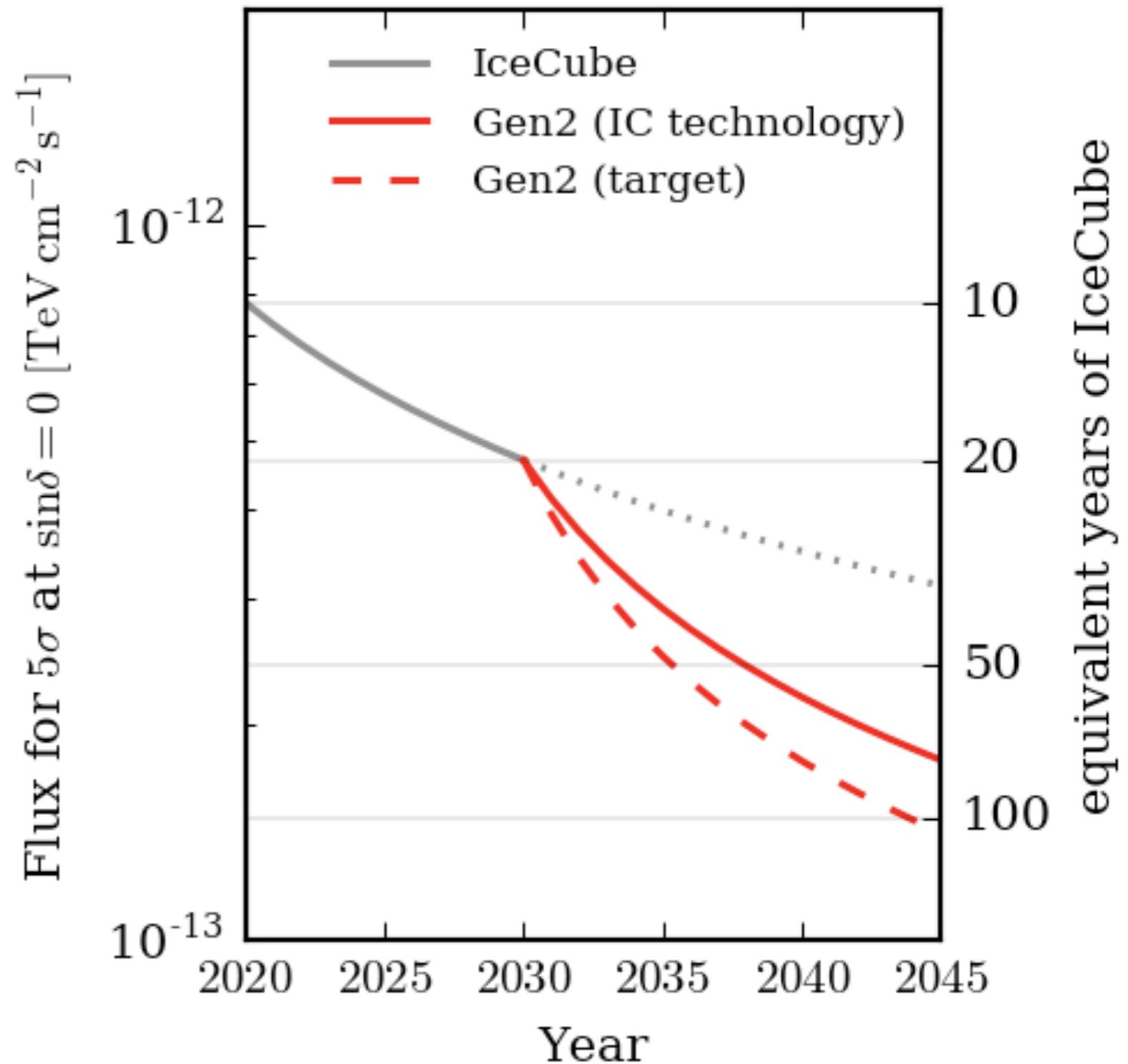
Point source sensitivity

- “Just a big IceCube” has ~three times the point source sensitivity
- Significant performance improvements expected from new sensors:



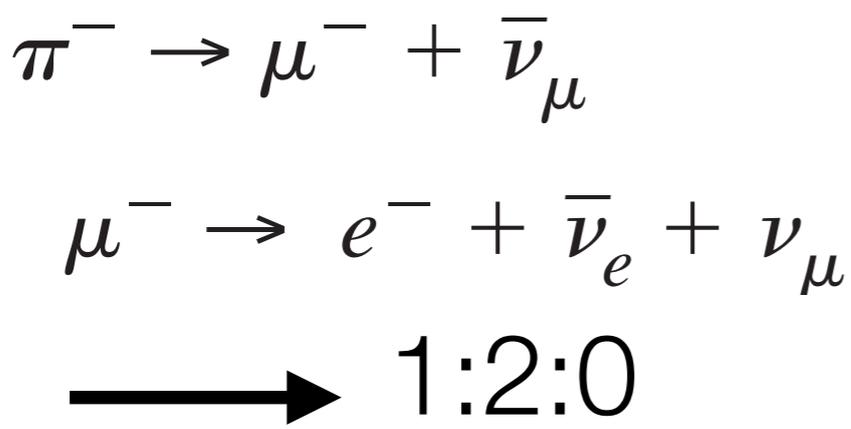
Sensitivity to all prospective source classes

Sensitivity to steady point sources

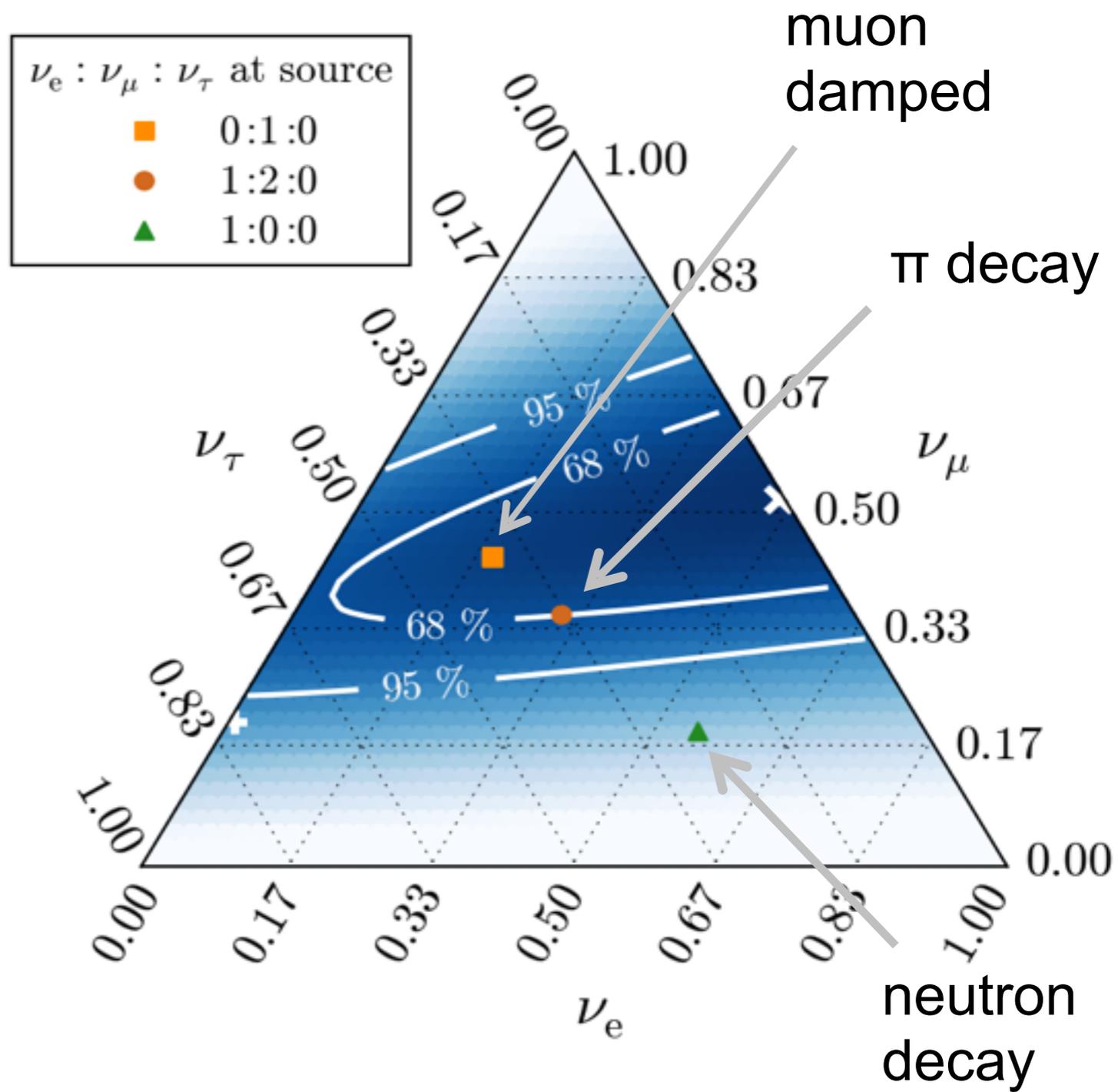


Flavor ratio constrain:

- conditions at source
e.g. magnetic fields
(e.g. Kashti & Waxman, PRL 1995)



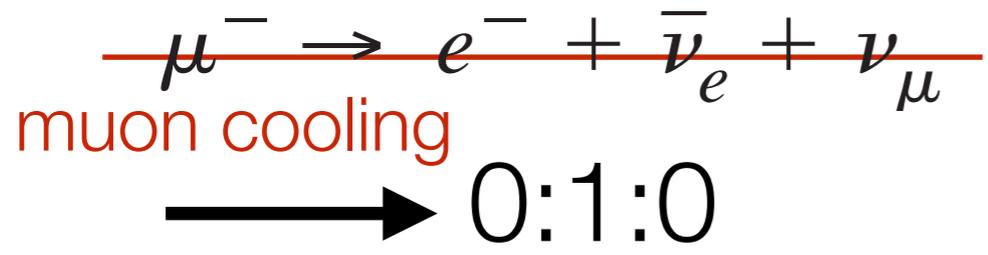
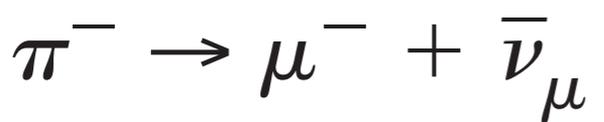
- neutrino physics, e.g. decay or new operators
(e.g. Argüelles et al., PRL 2015, Bustamante et al., PRL 2015)



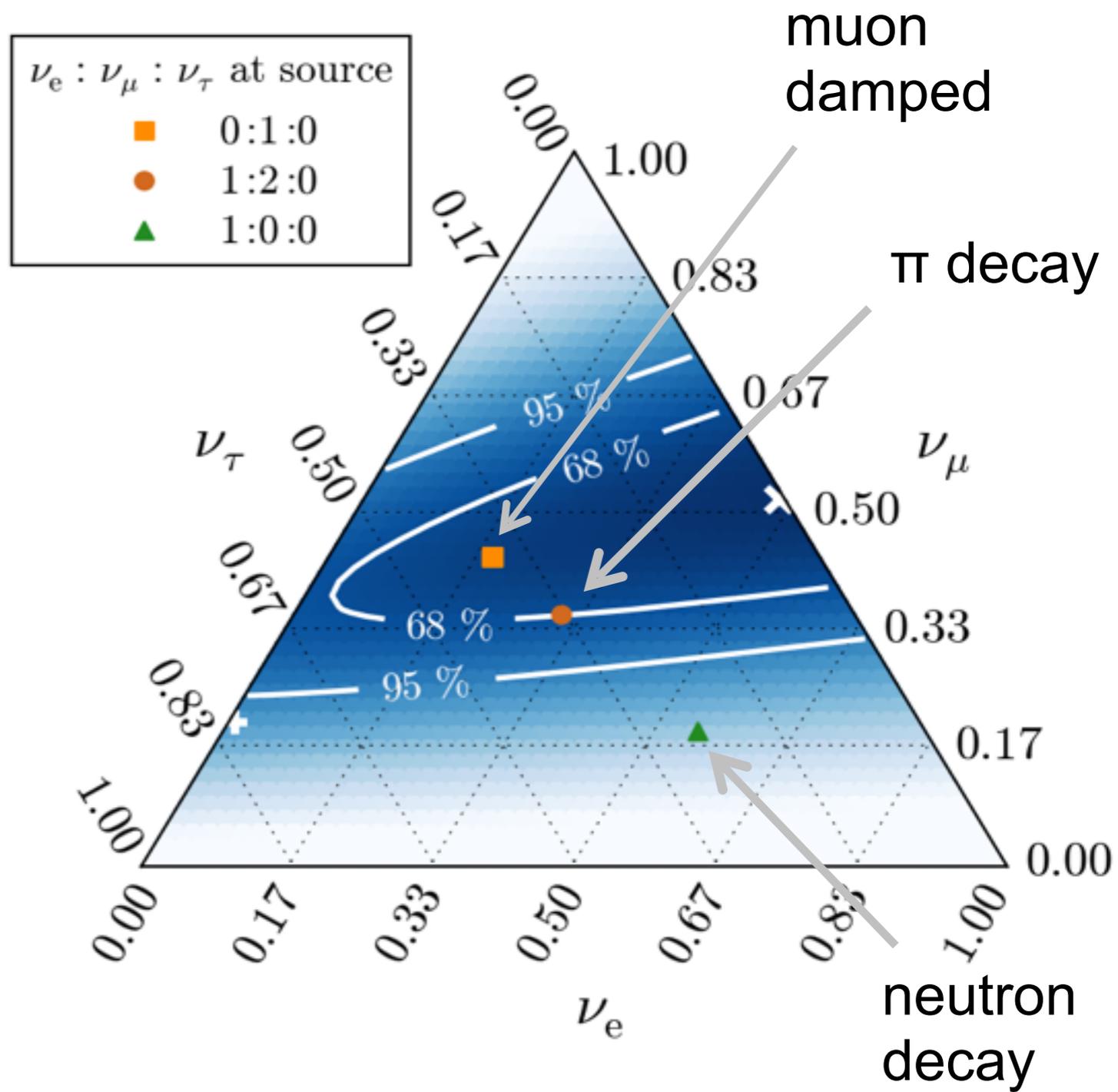
IceCube, ApJ 2015, see also PRL2015

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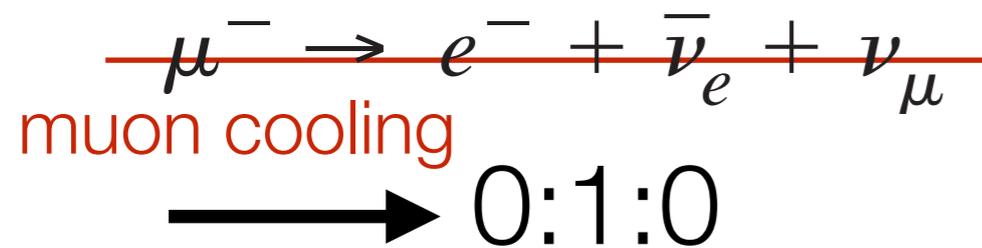
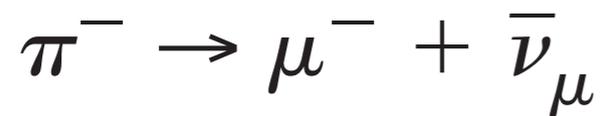
IceCube, ApJ 2015, see also PRL2015



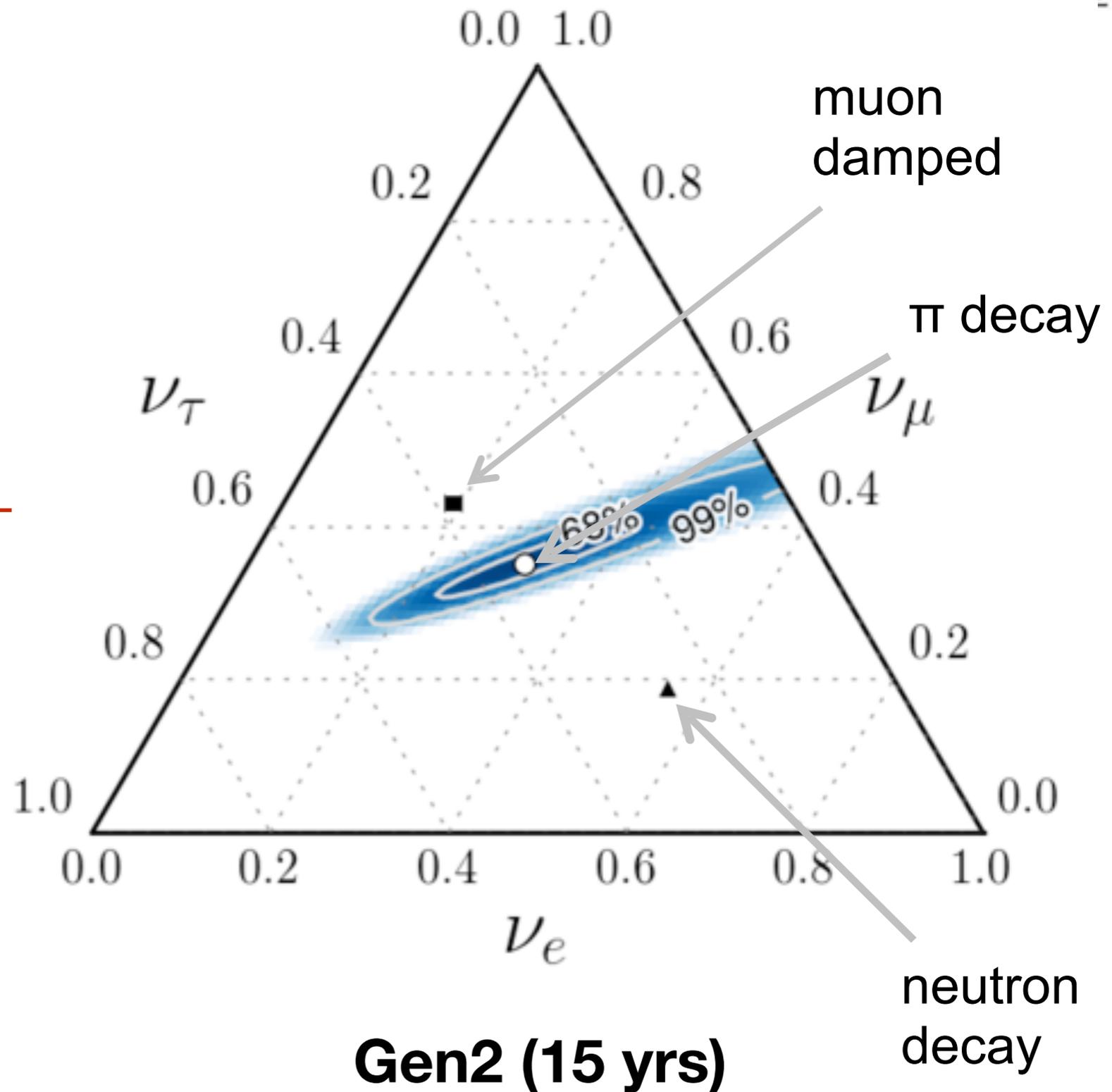
Flavor physics with astrophysical neutrinos

Flavor ratio constrain:

- conditions at source
e.g. magnetic fields
(e.g. Kashti & Waxman, PRL 1995)



- neutrino physics, e.g.
decay or new operators
(e.g. Argüelles et al., PRL 2015,
Bustamante et al., PRL 2015)



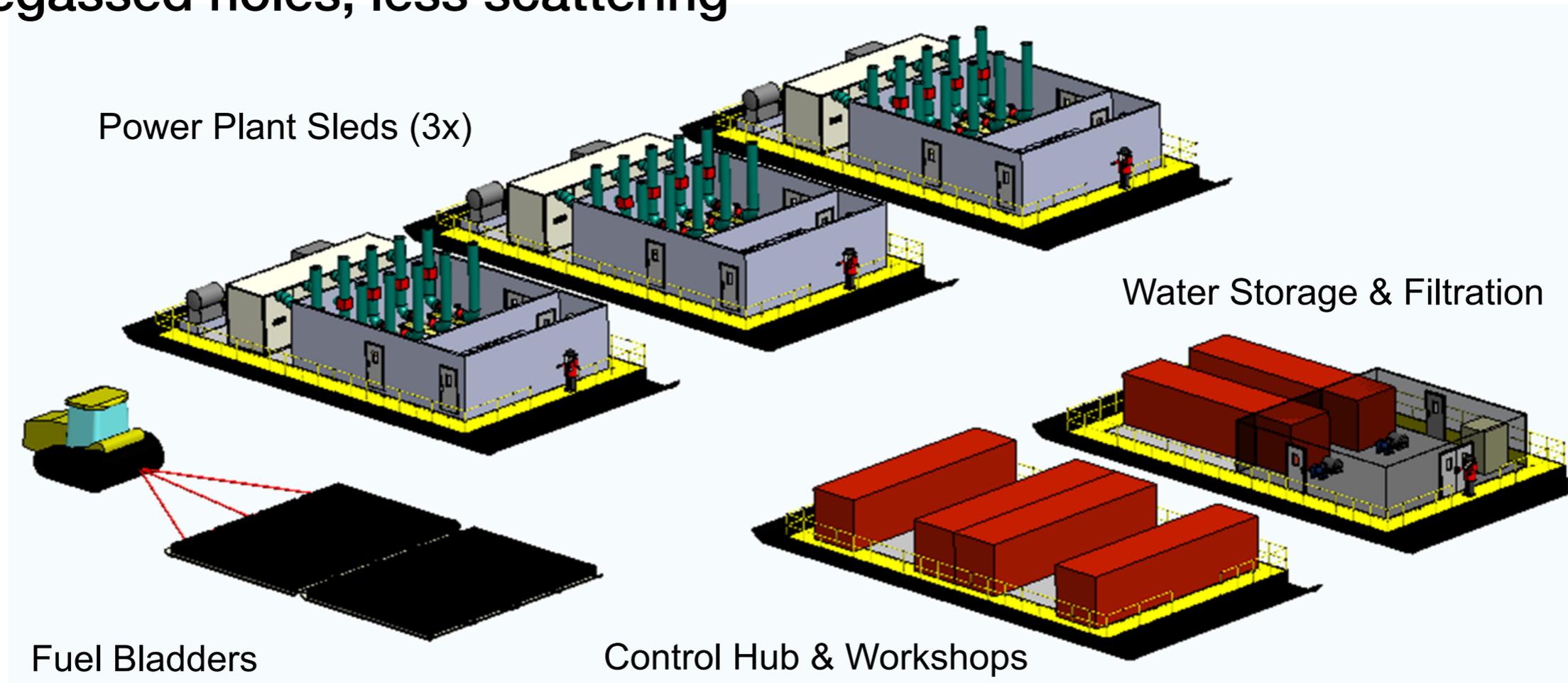
Simplified logistics & improved performance

Simplified logistics:

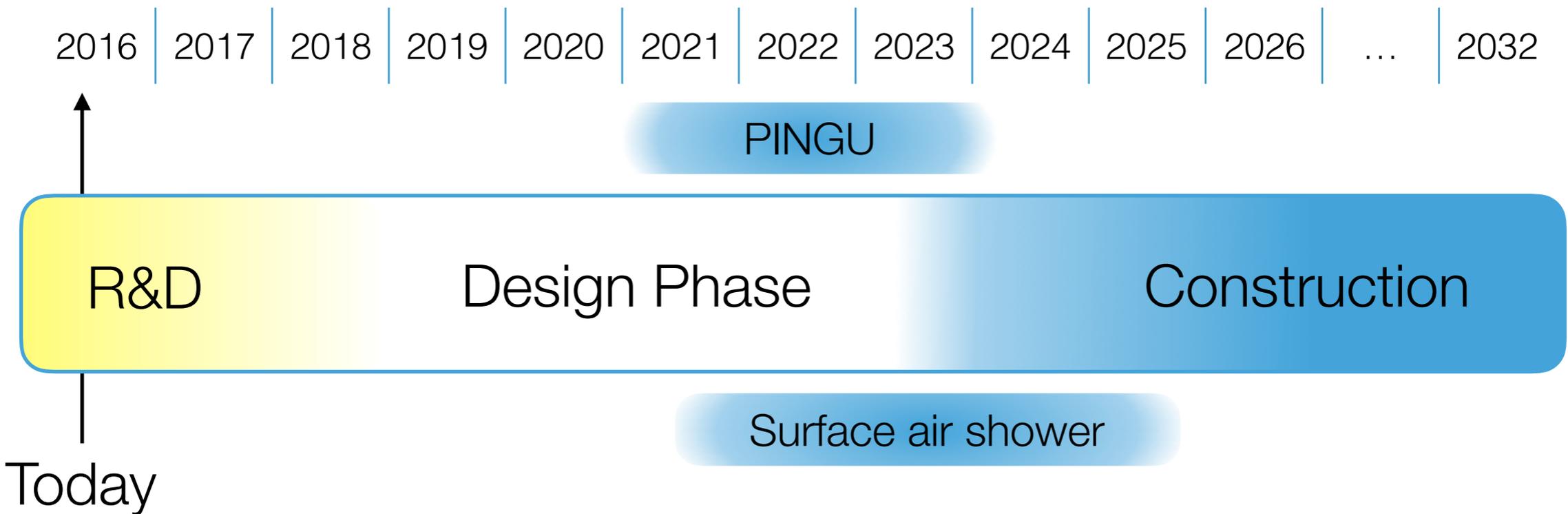
- ▶ Equipment and fuel delivered to Pole via single traverse instead of air
- ▶ Reduced logistical footprint at Pole; smaller crew

Improved performance:

- ▶ New sensors allow for narrower holes => large fuel savings
- ▶ Faster drilling
- ▶ Degassed holes, less scattering



Preliminary timeline



- ▶ Strong evidence of high-energy extra-terrestrial neutrinos in all channels, offering a unique view on the high-energy Universe
- ▶ Sources not yet resolved but appear to be of extra-galactic origin
- ▶ As old questions are answered, new ones emerge
- ▶ Planning for IceCube-Gen2 has started, optimized for neutrino astronomy in the next decades

New sensor designs for improved performance



mDOM



36

- Directional information
- More sensitive area per module

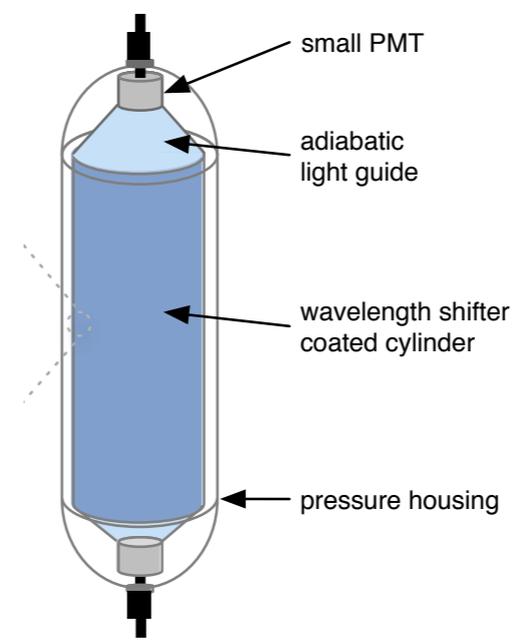
D-Egg



30

- Directional information
- More sensitive area per module
- Smaller geometry

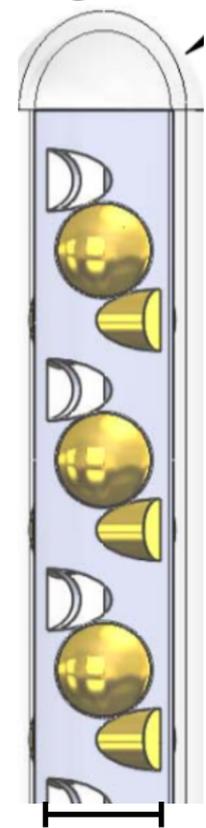
WOM



11

- more sensitive area per \$
- Small diameter
- Lower noise rate

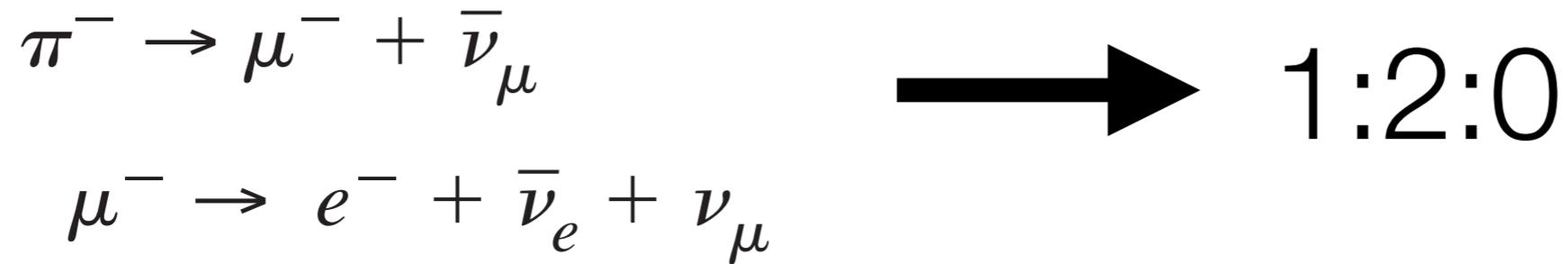
LOM



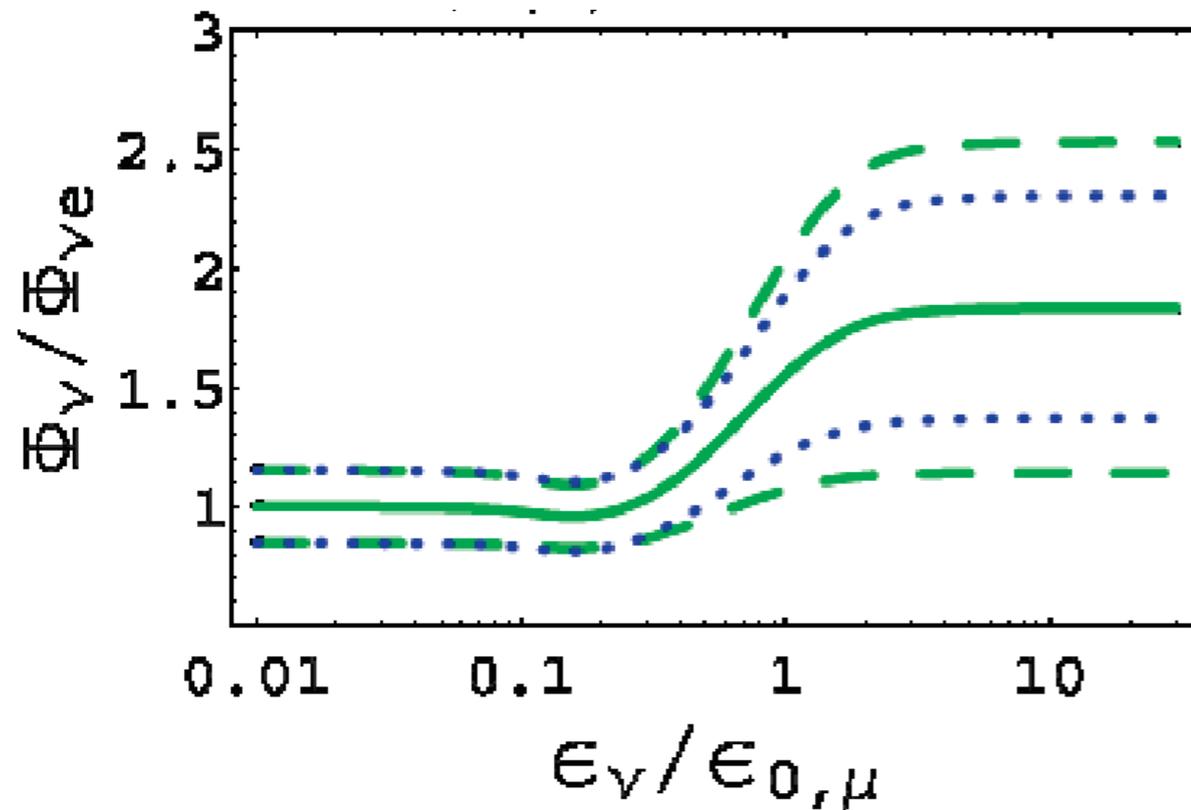
13

- Small diameter
- Directional info.
- More area per module

Science example: Probing neutrino production



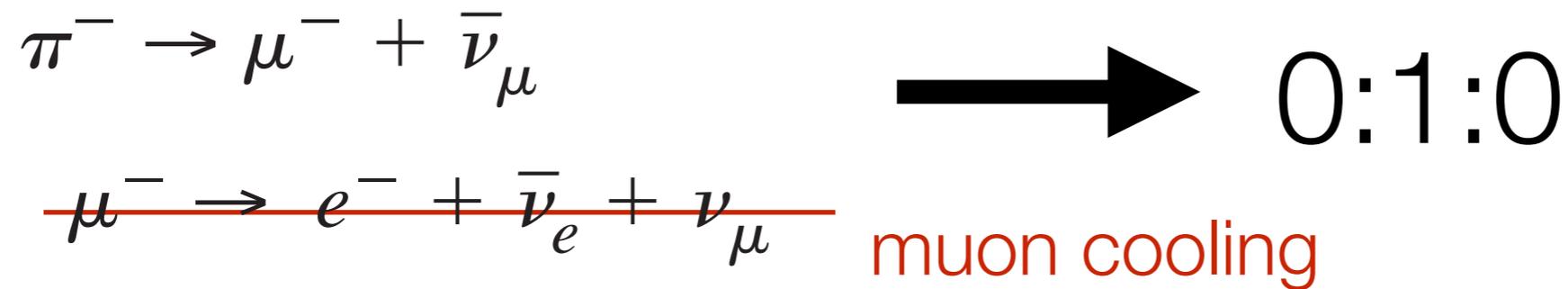
**15 yrs of
Gen2+IC**



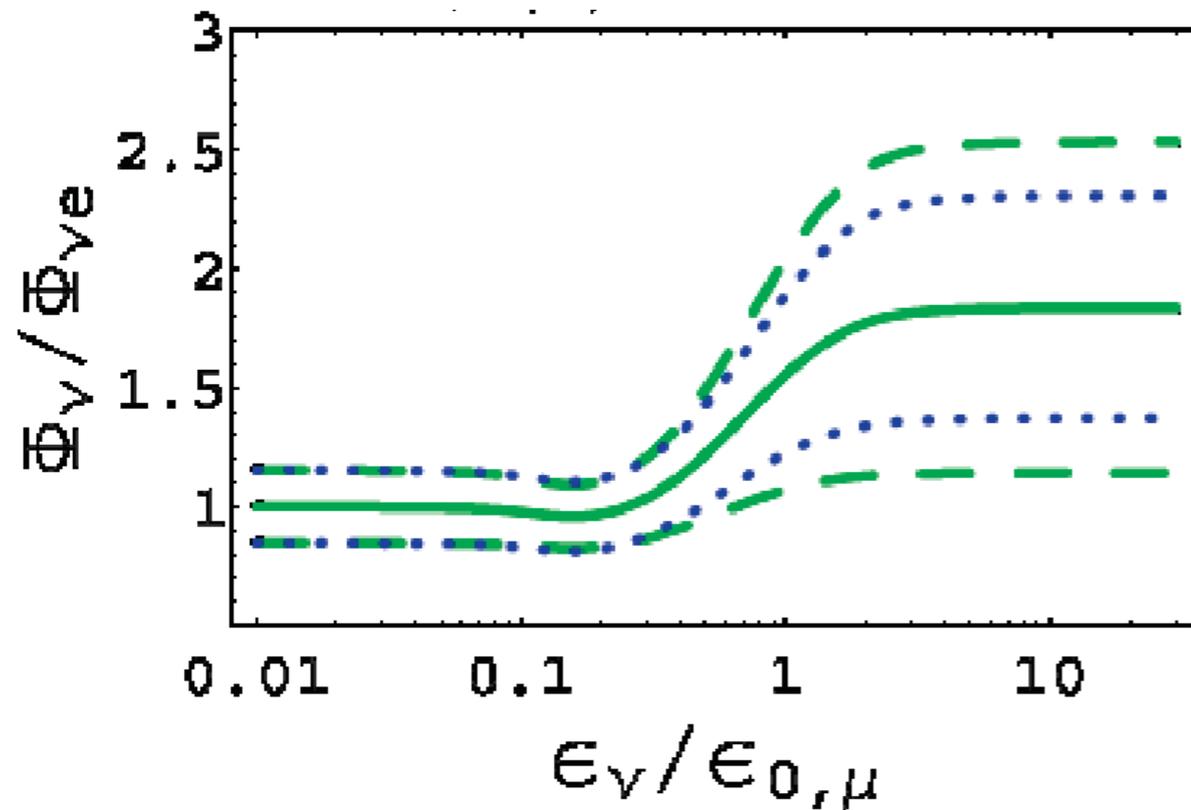
Kashti & Waxmann, PRL 95, 18110

**Flavor ratio constrains
conditions at the source
or entirely new physics
(e.g. Argüelles et al., PRL 2015)**

Science example: Probing neutrino production

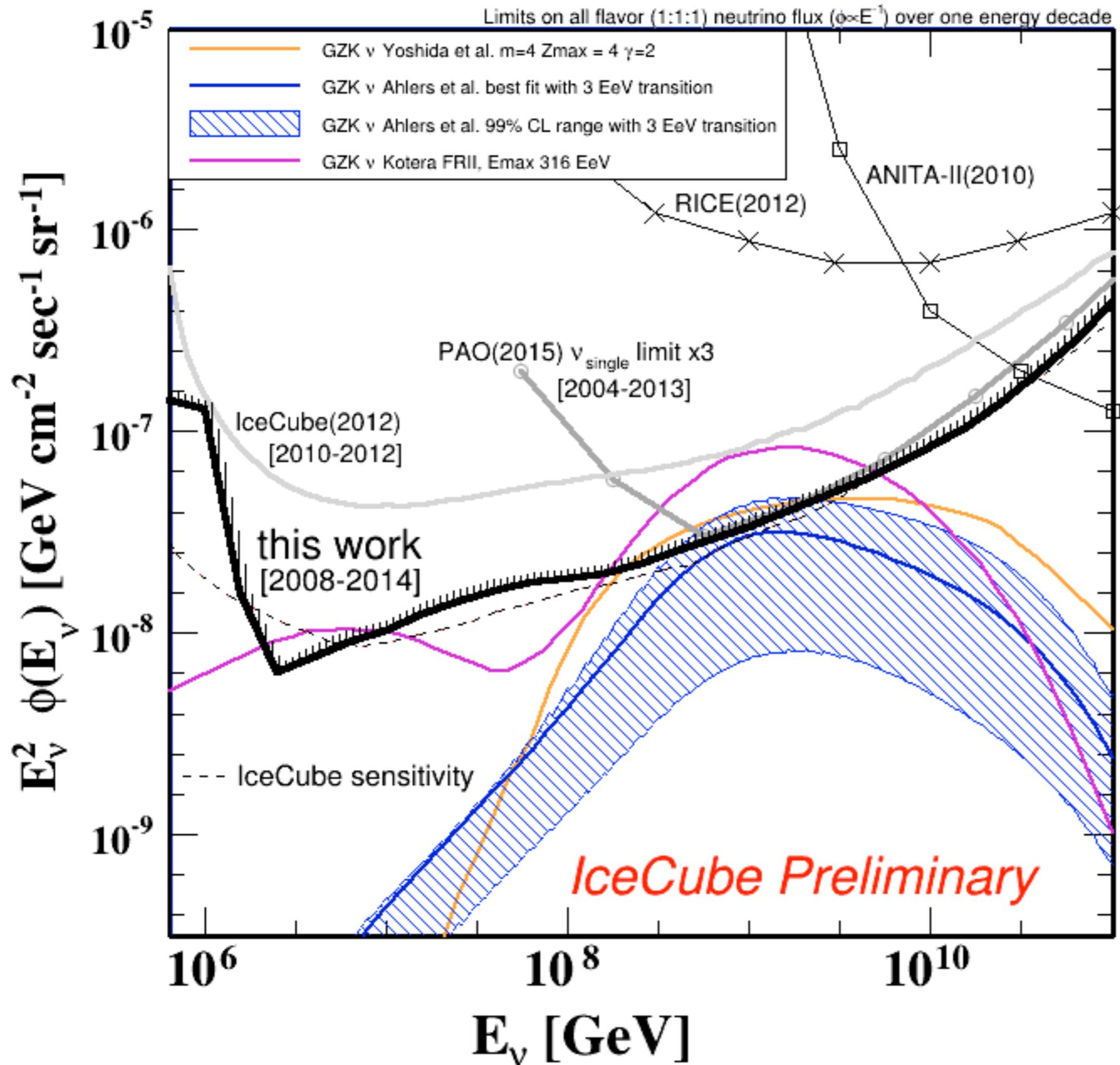


**15 yrs of
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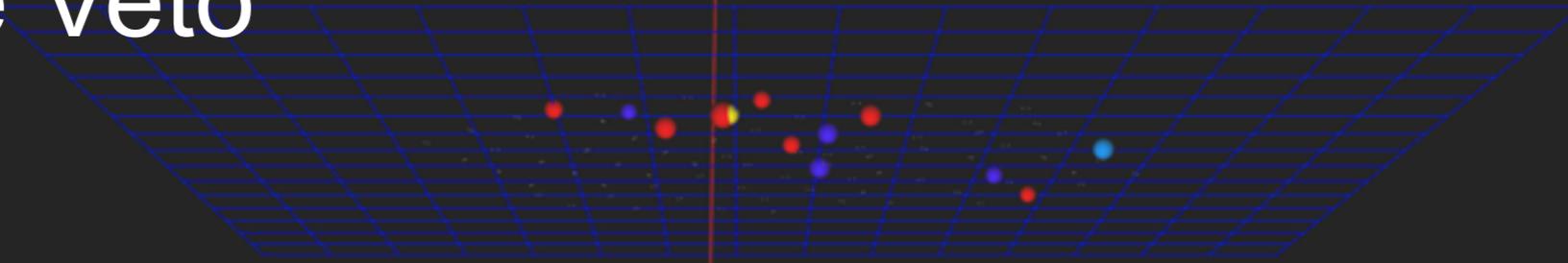


Kashti & Waxmann, PRL 95, 18110

**Flavor ratio constrains
conditions at the source
or entirely new physics
(e.g. Argüelles et al., PRL 2015)**



Surface Veto



cosmic neutrino
(detected 2014)

