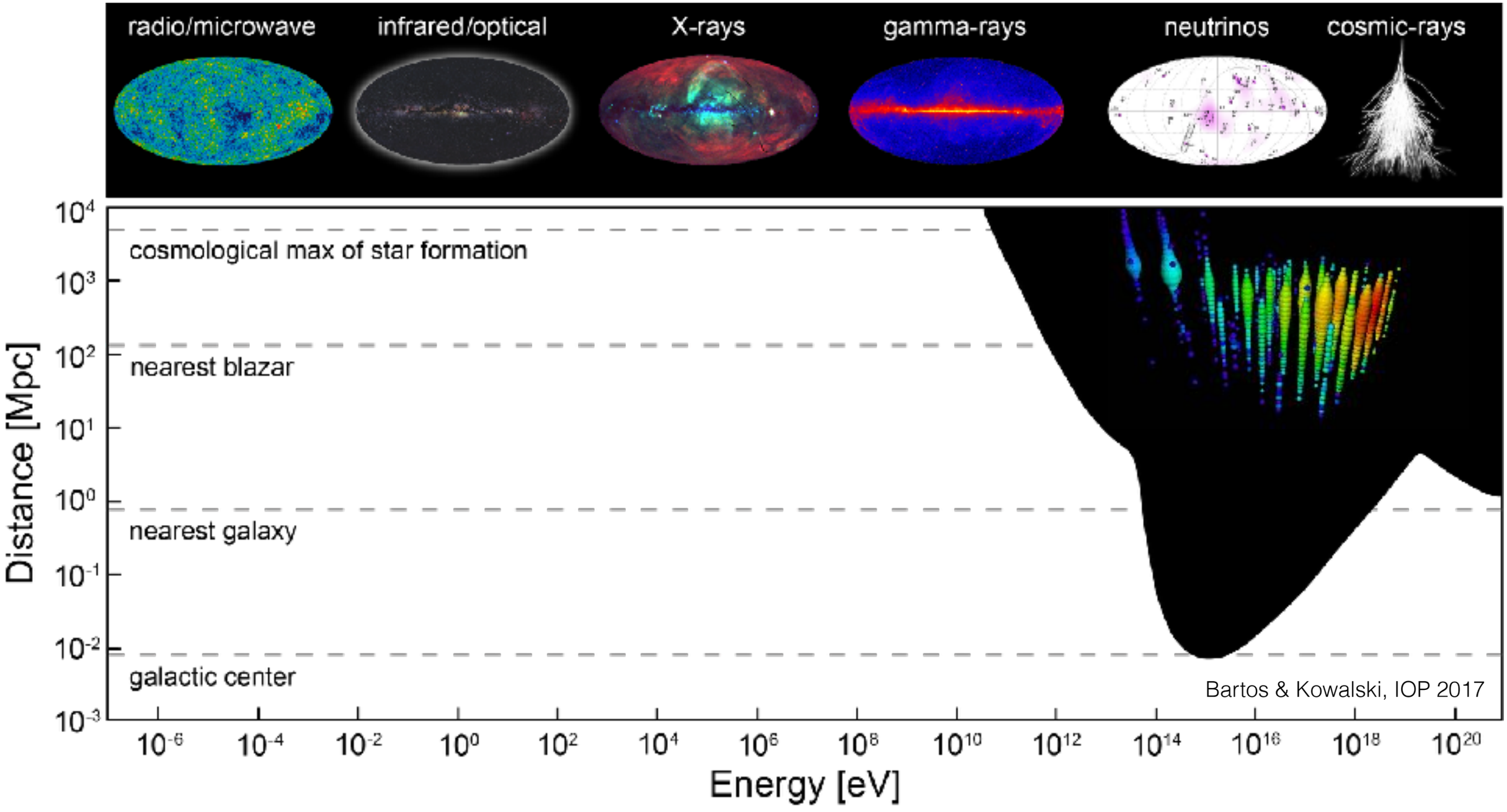
High-energy Neutrino Astronomy & IceCube

Marek Kowalski (DESY & Humboldt University Berlin)

SuGAR 2018, Brussels

Credit: M. Wolf/NSF

The promised land



The Universe is opaque to EM radiation for ¼ of the spectrum,
i.e. above 10-100 TeV where IceCube sees cosmic neutrinos.

IceCube

South Pole Neutrino Observatory

50 m

IceCube Laboratory

Data is collected here and sent by satellite to the data warehouse at UW–Madison

1450 m

Digital Optical Module (DOM)

5,160 DOMs deployed in the ice

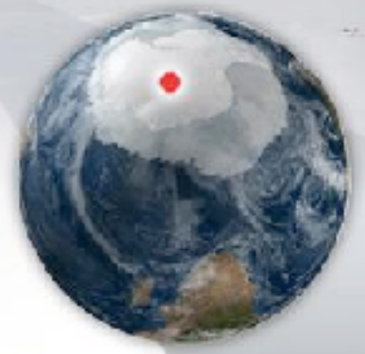
2450 m

86 strings of DOMs, set 125 meters apart

IceCube detector

DeepCore

Antarctic bedrock

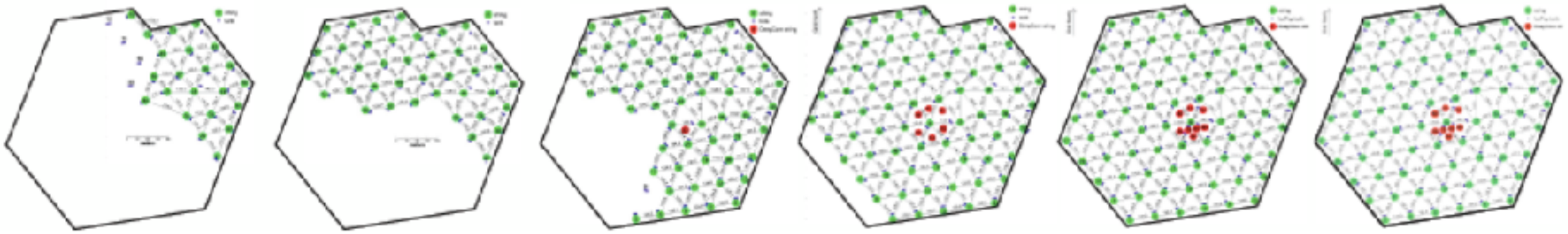


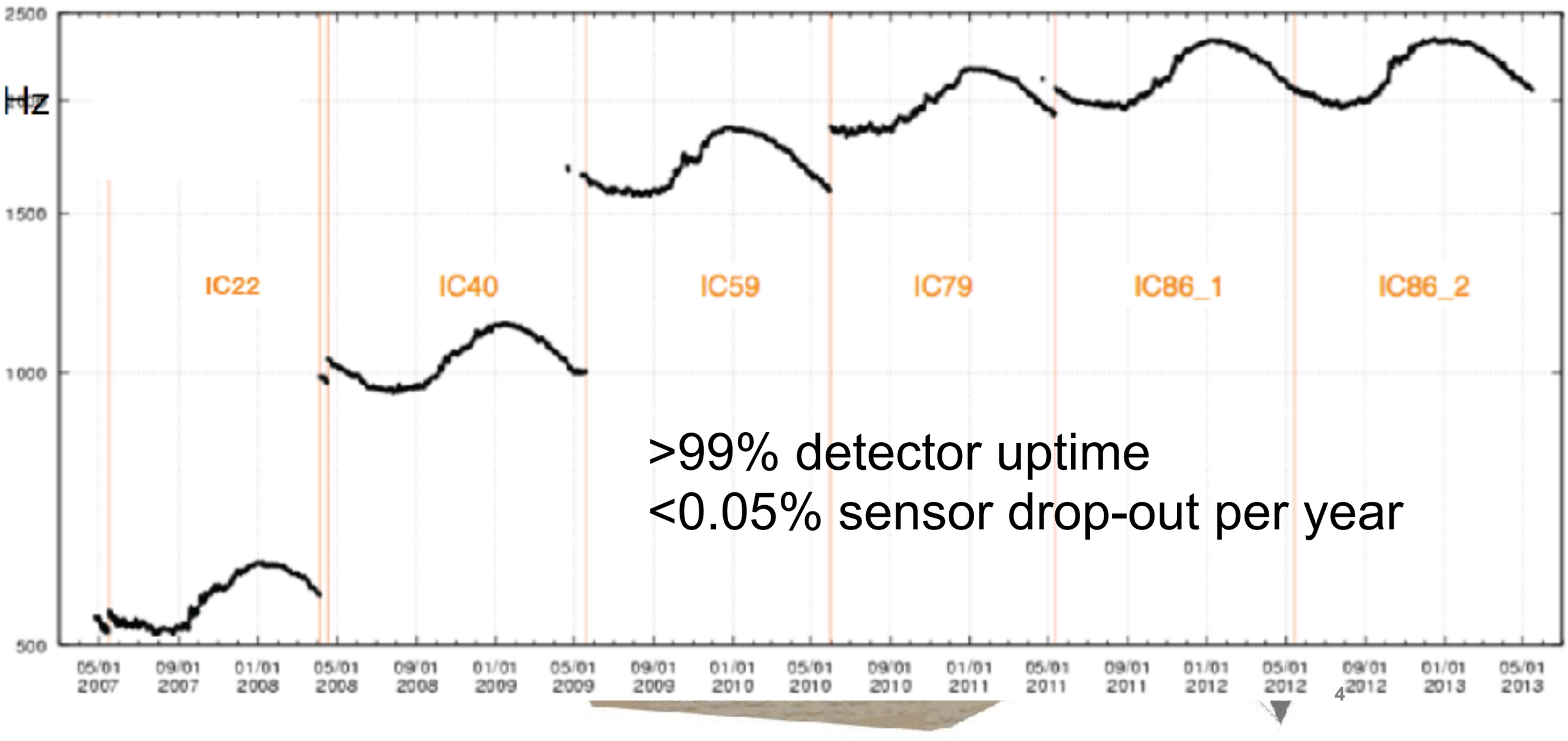
Amundsen–Scott South Pole Station, Antarctica

A National Science Foundation-managed research facility

60 DOMs on each string

DOMs are 17 meters apart

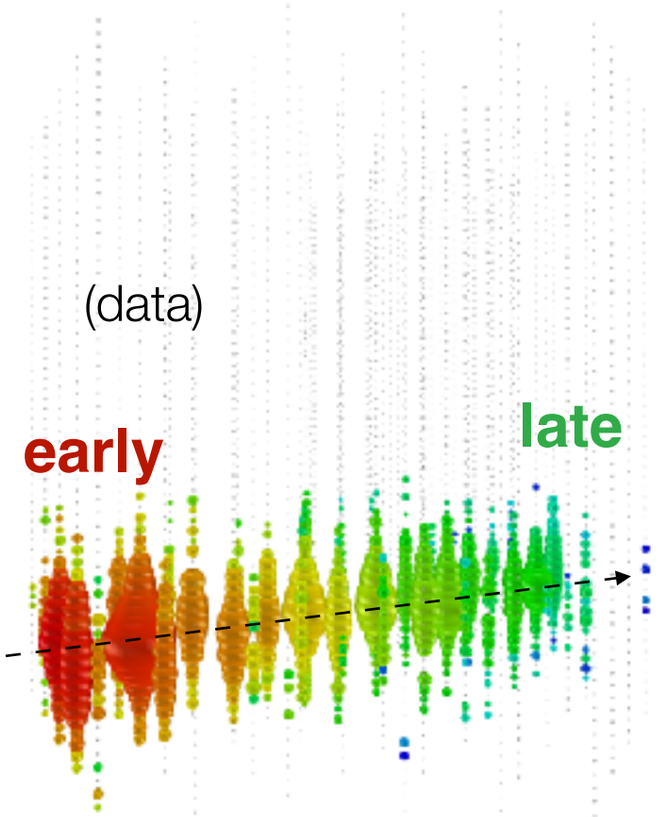




>99% detector uptime
<0.05% sensor drop-out per year

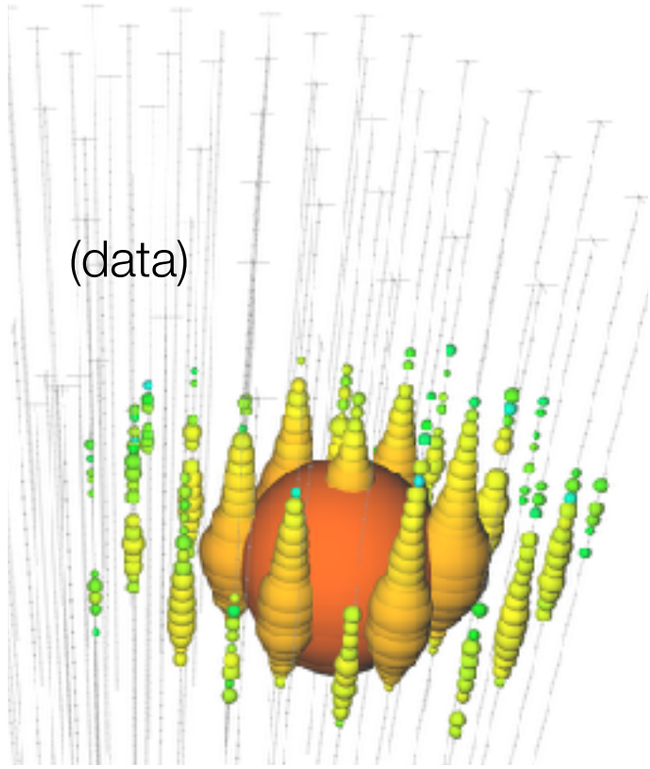
Neutrino event types

Charged-current ν_μ



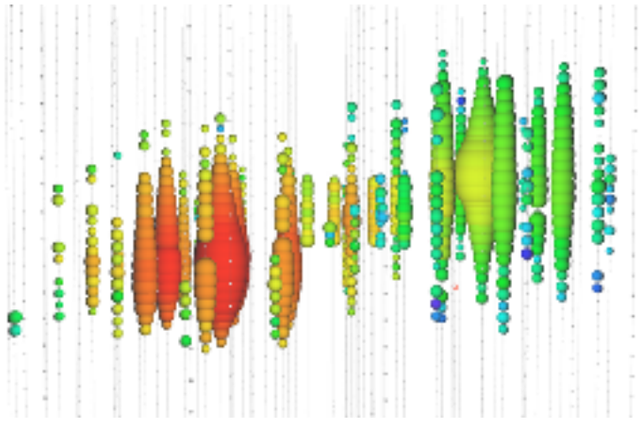
Up-going track

Neutral-current / ν_e



Isolated energy deposition (cascade) with no track

Charged-current ν_τ

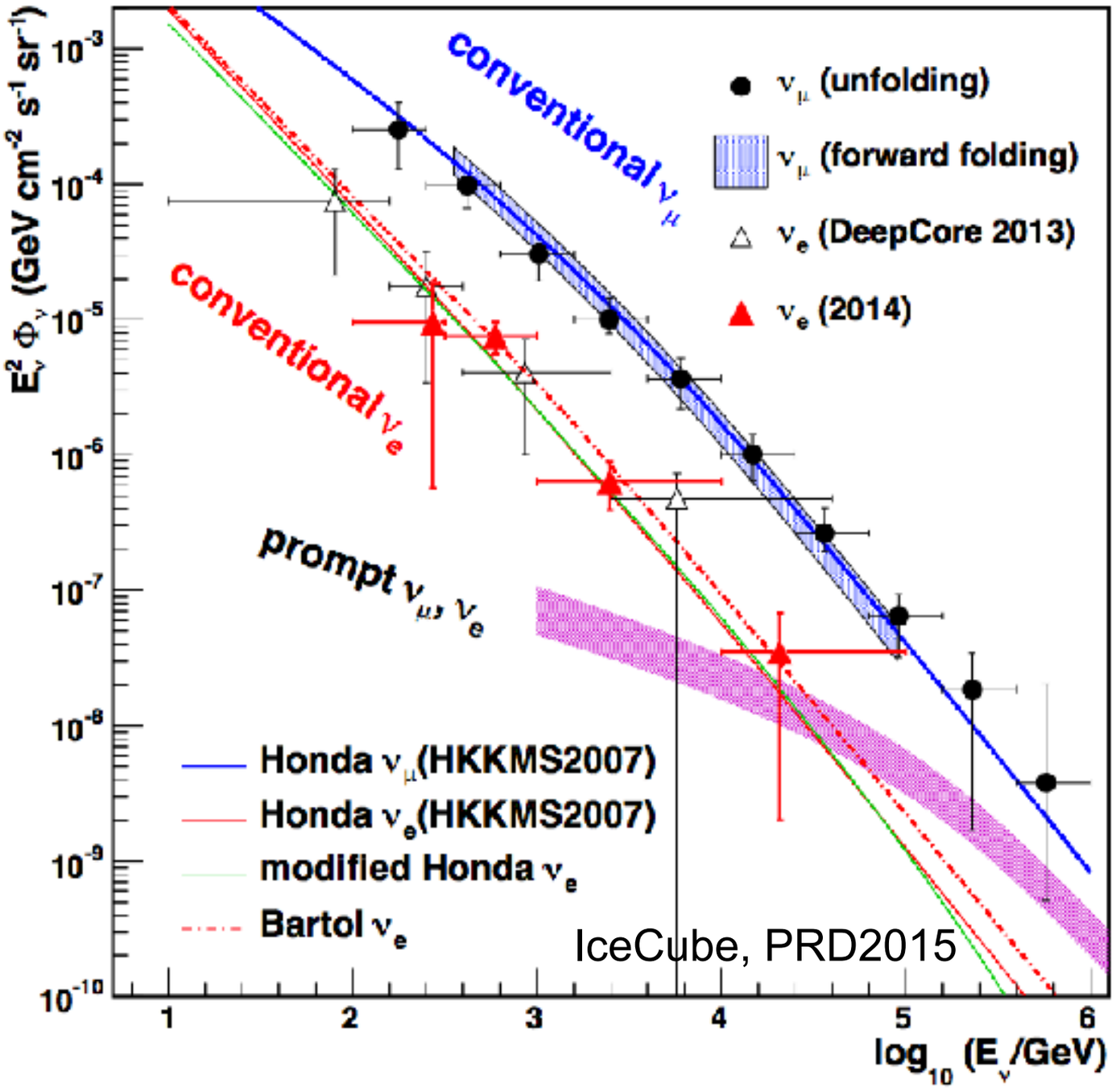


Double cascade

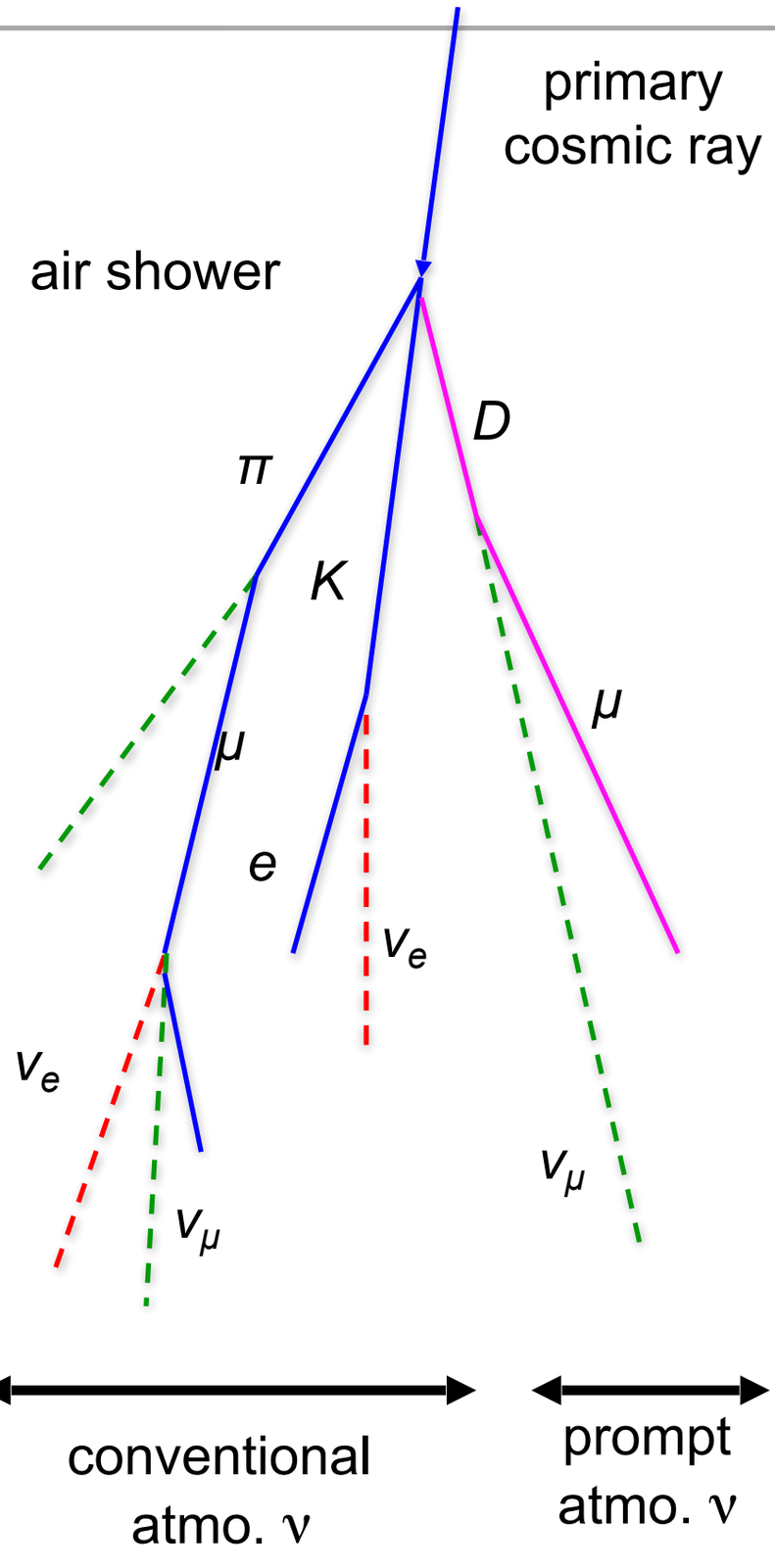
Atmospheric neutrinos & neutrino physics

Credit: M. Wolf/NSF

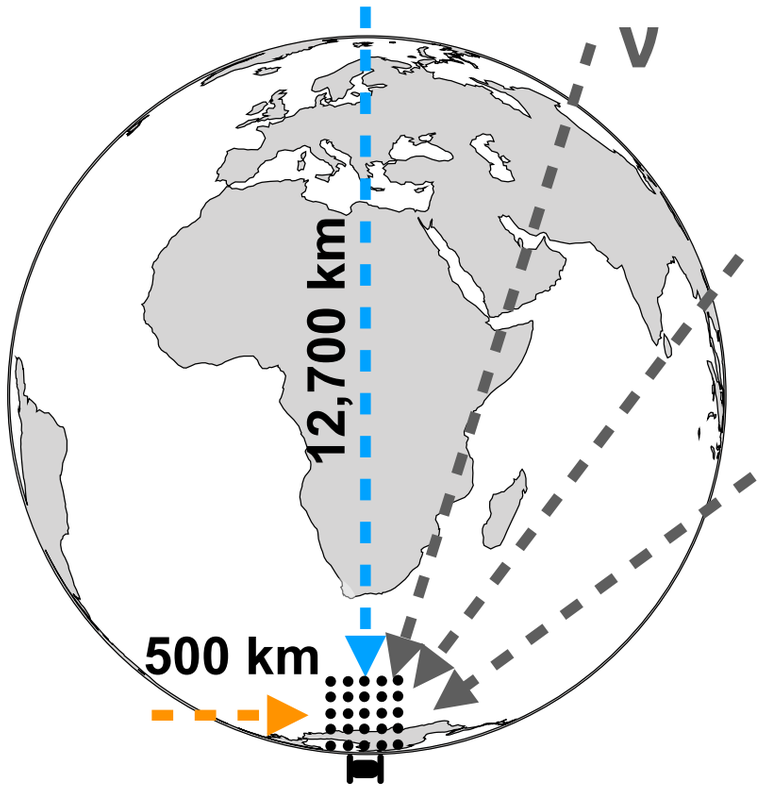
Atmospheric neutrinos



> 70.000 ν_μ / yr

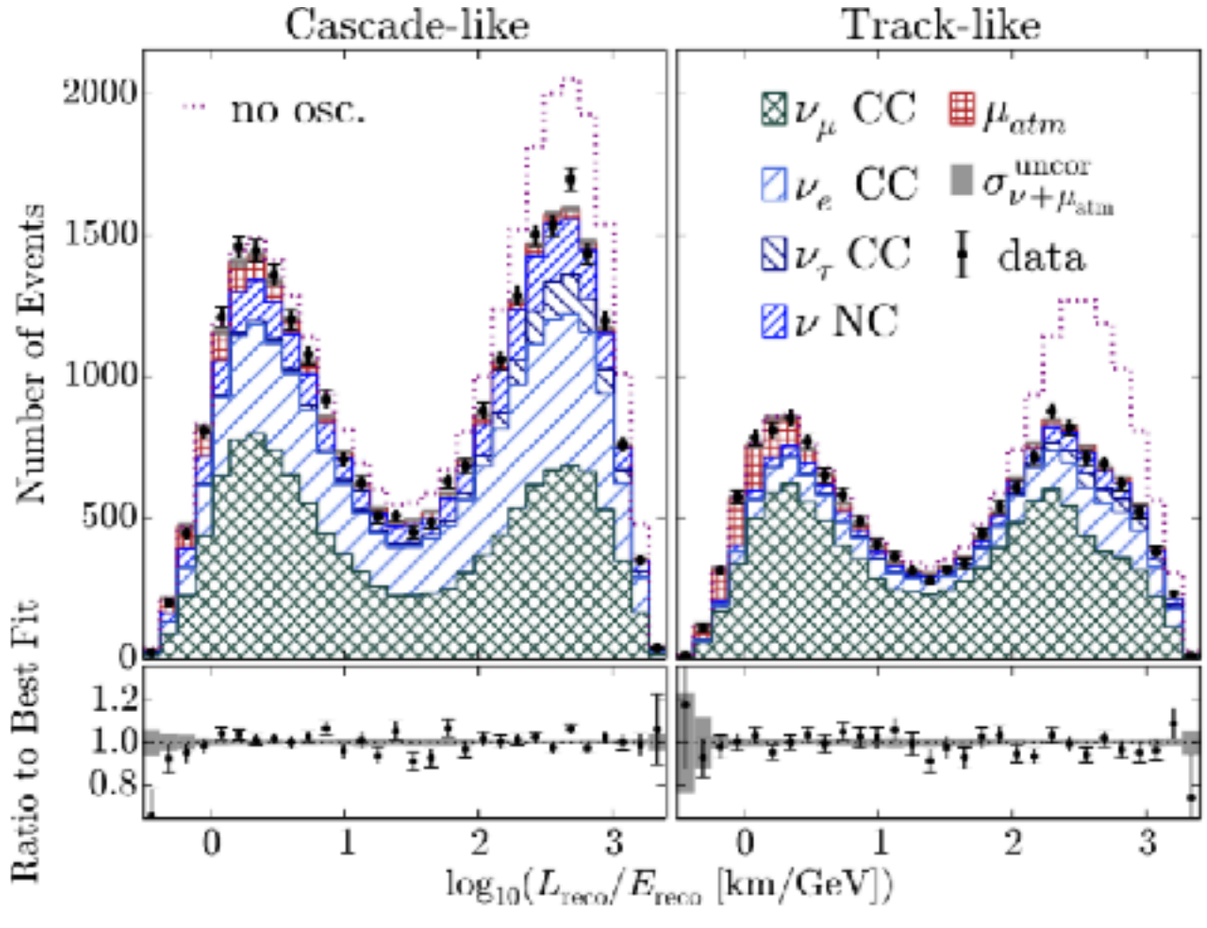


Exploiting atmospheric neutrinos for neutrino physics

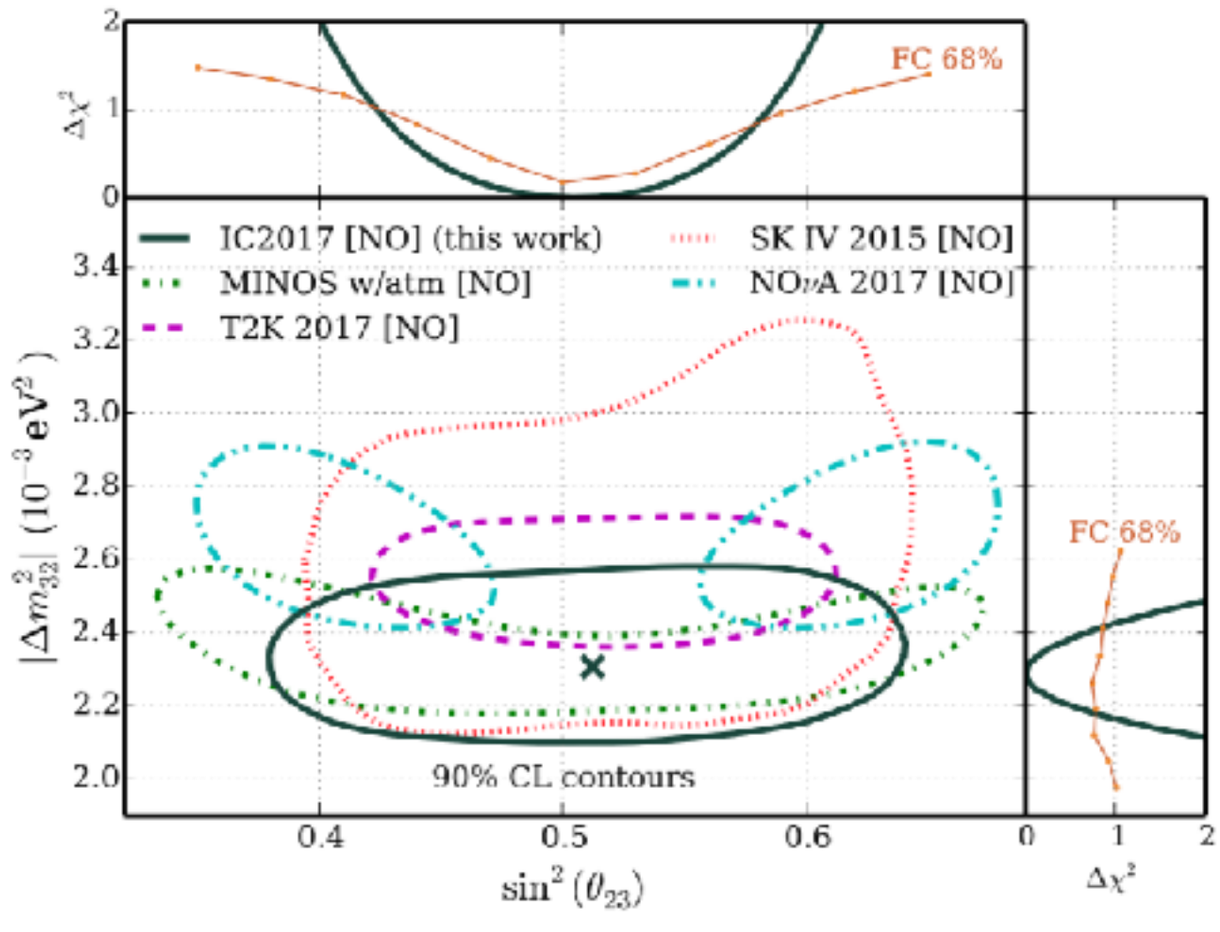


Neutrino oscillations

- IceCube / DeepCore probes mixing for multiple baselines and energies
- Measurements of neutrino mixing parameters competitive with dedicated neutrino beam experiments
- Strong constraints on sterile neutrinos



IceCube, PRL 2018 (arXiv:1707.07081)



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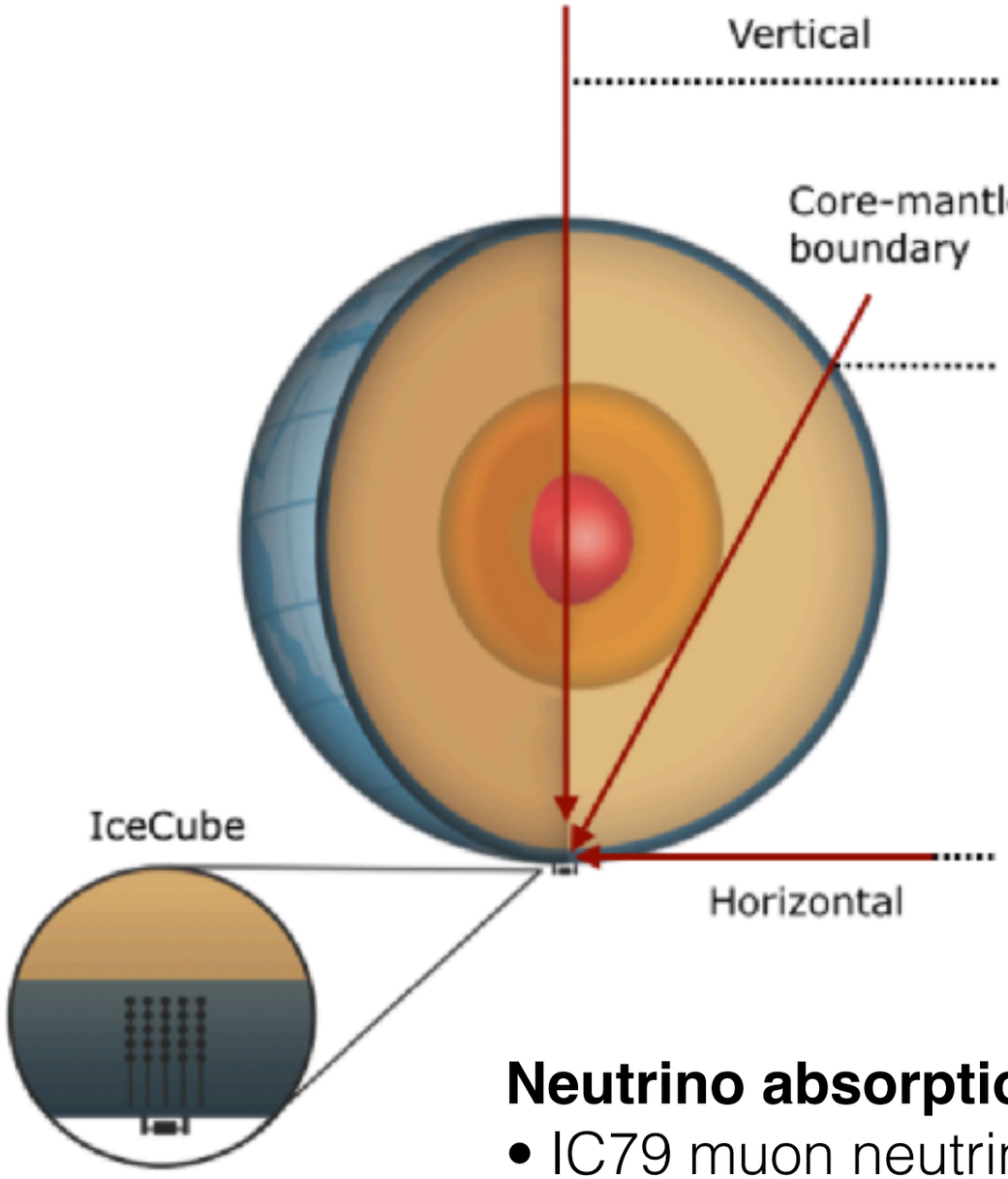
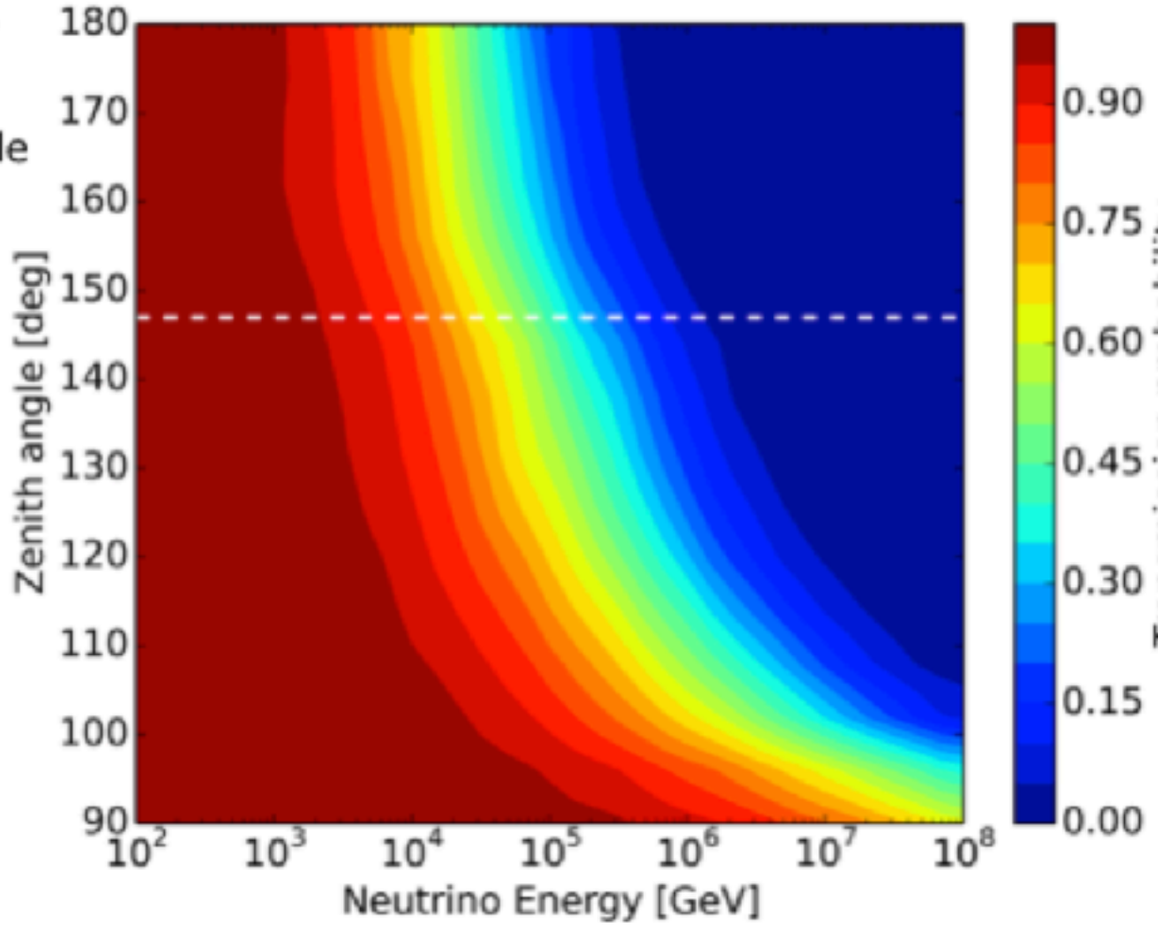


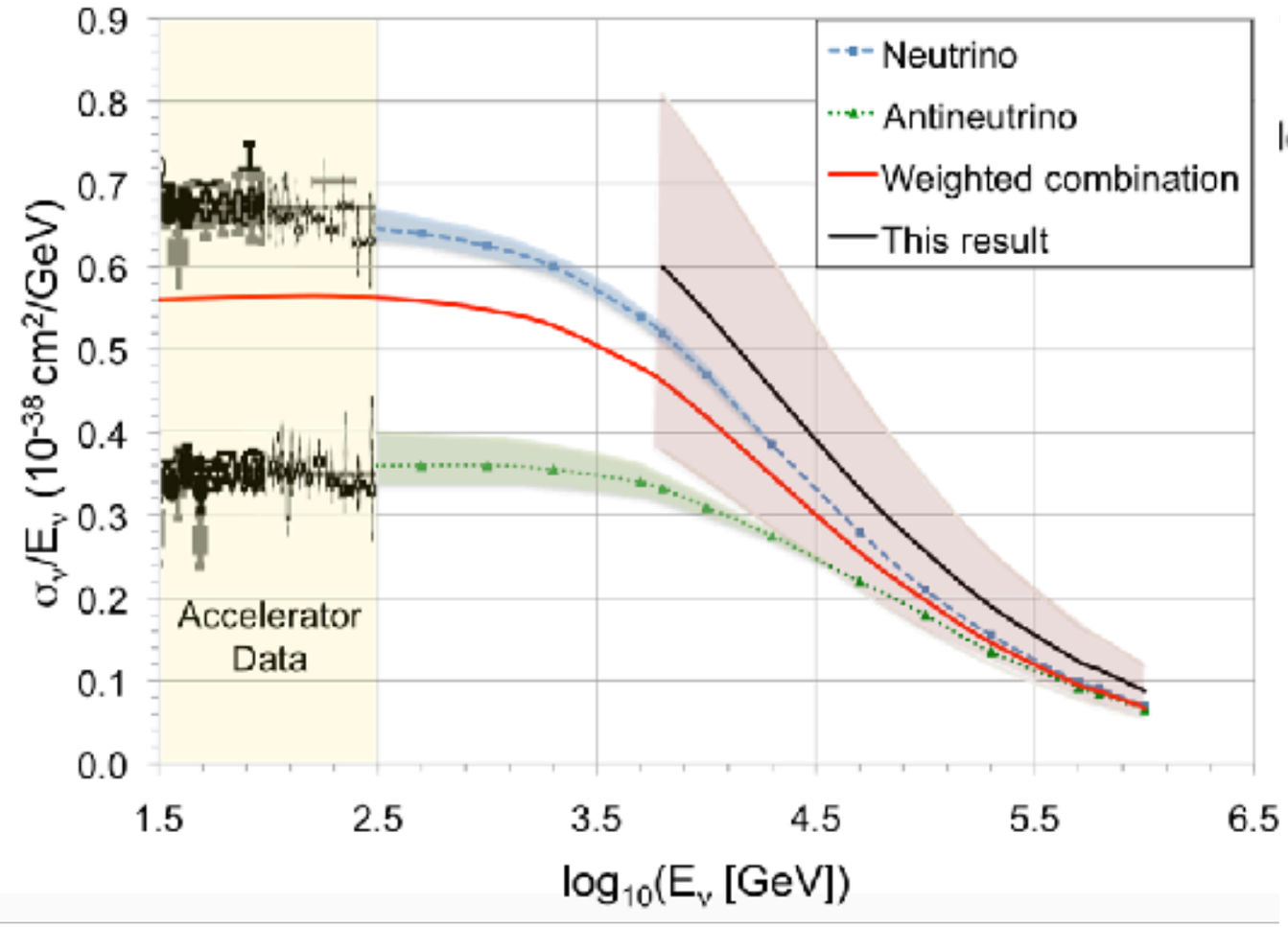


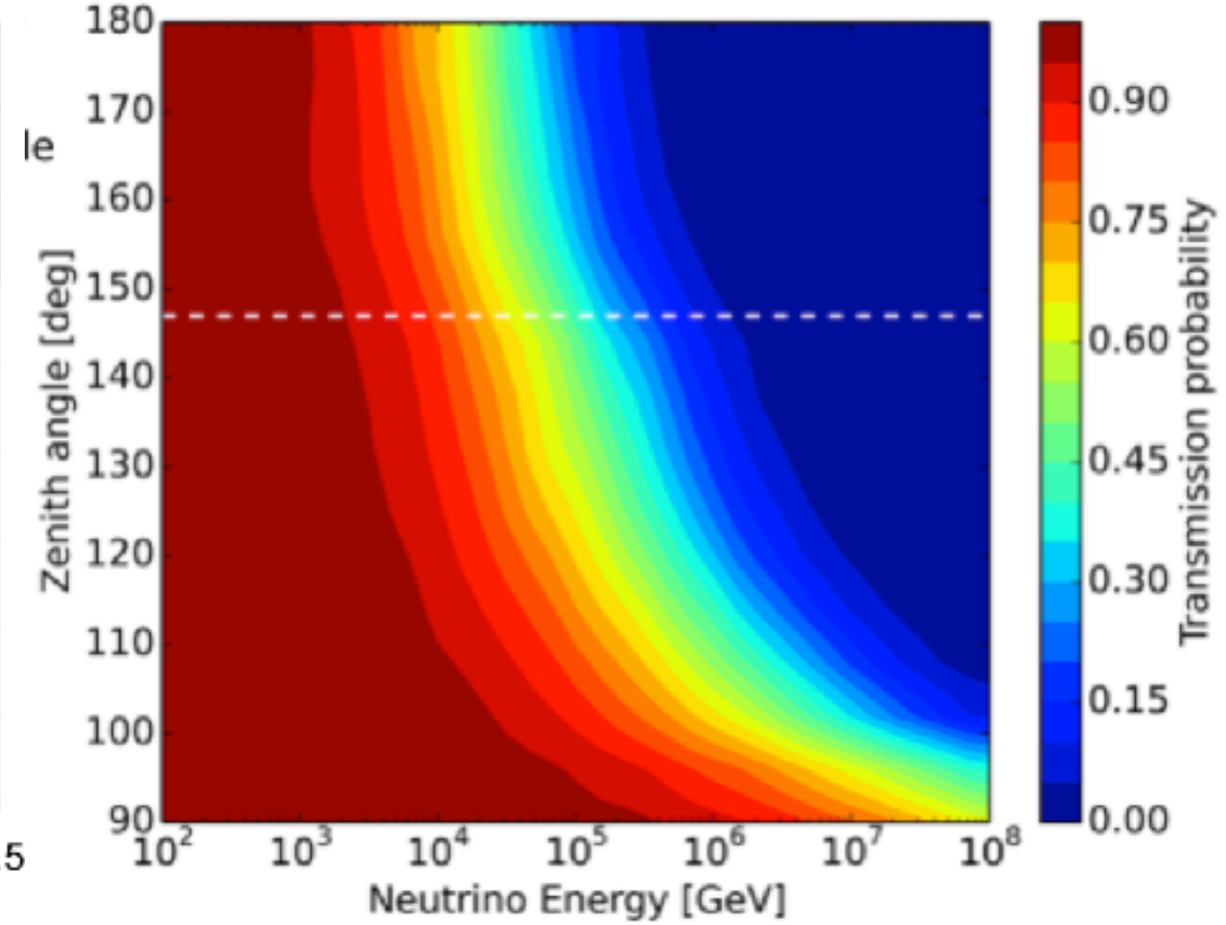
Neutrino absorption and x-section

- IC79 muon neutrino sample was used to study x-sections
- Astro. neutrino flux & spectra nuisance parameters in analysis

IceCube, Nature, 2017

Exploiting atmospheric neutrinos for neutrino physics





Neutrino absorption and x-section

- IC79 muon neutrino sample was used to study x-sections
- Astro. neutrino flux & spectra nuisance parameters in analysis
- x-section between 6.3 TeV and 980 TeV
  σ/σ_{SM}=1.30±0.20 (stat) ±0.41 (sys)

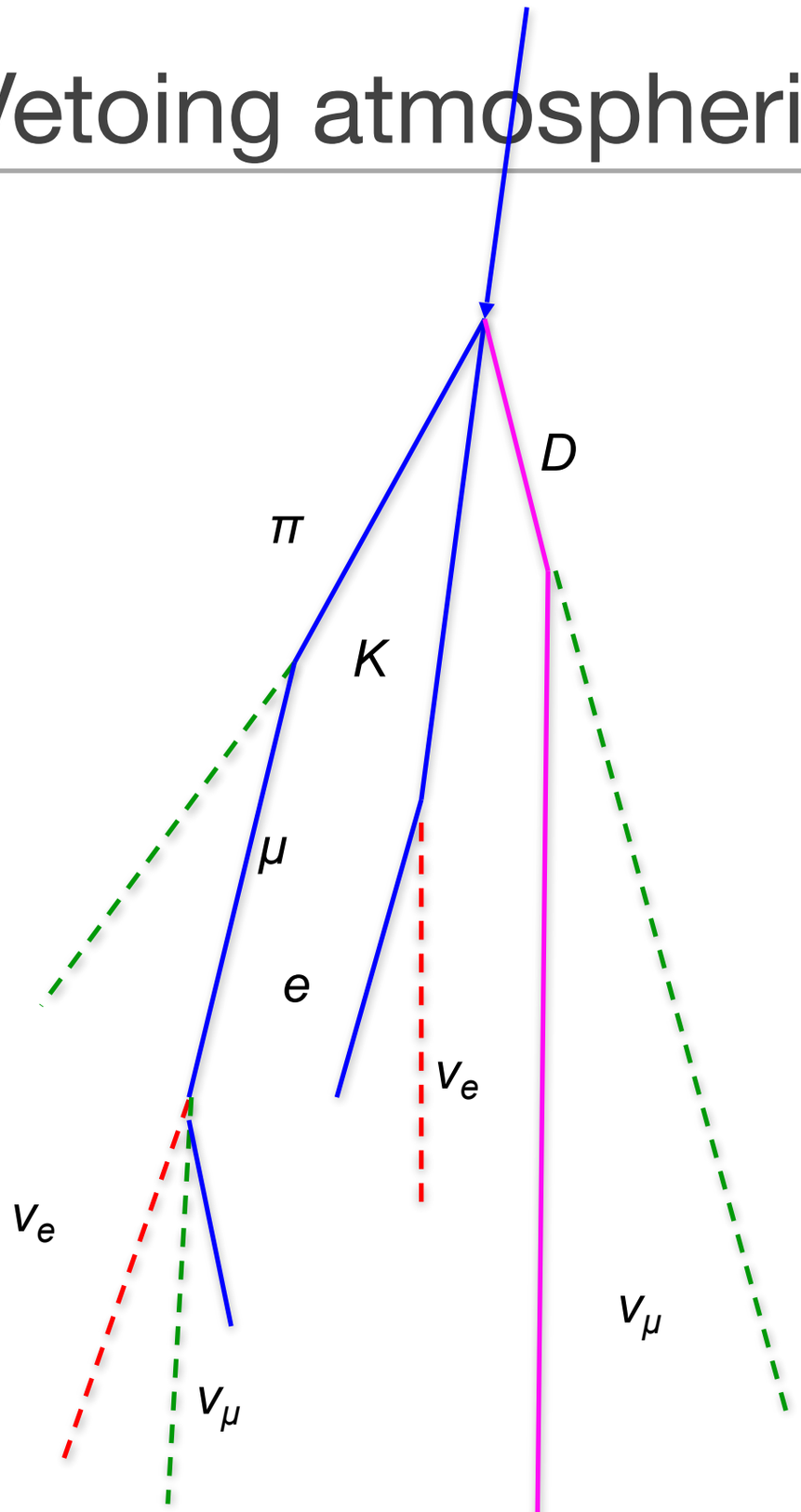
IceCube, Nature, 2017

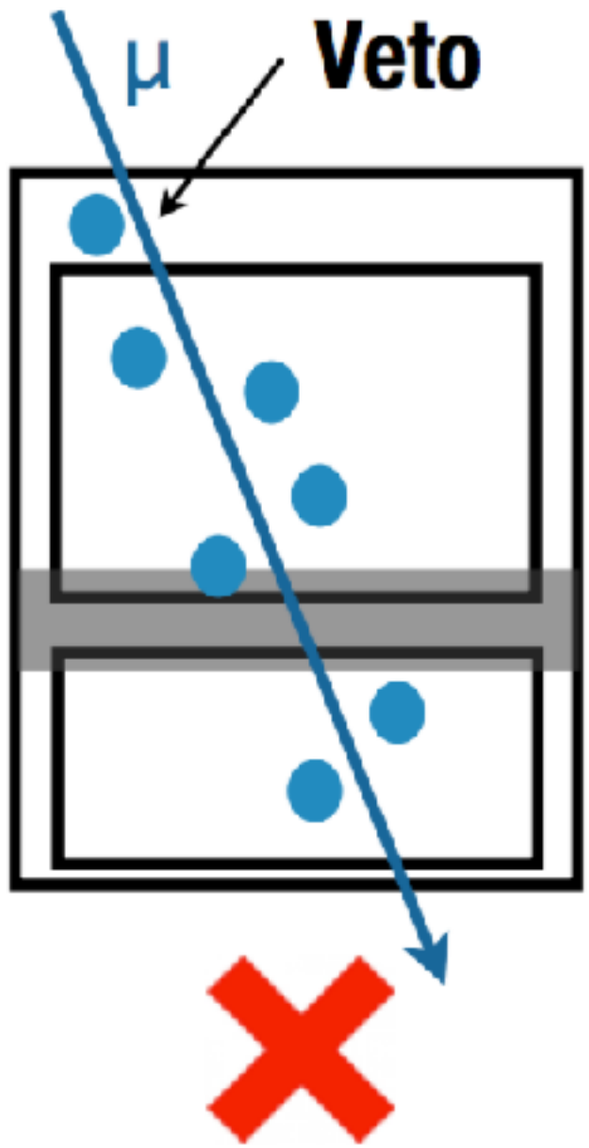
Astrophysical Neutrinos

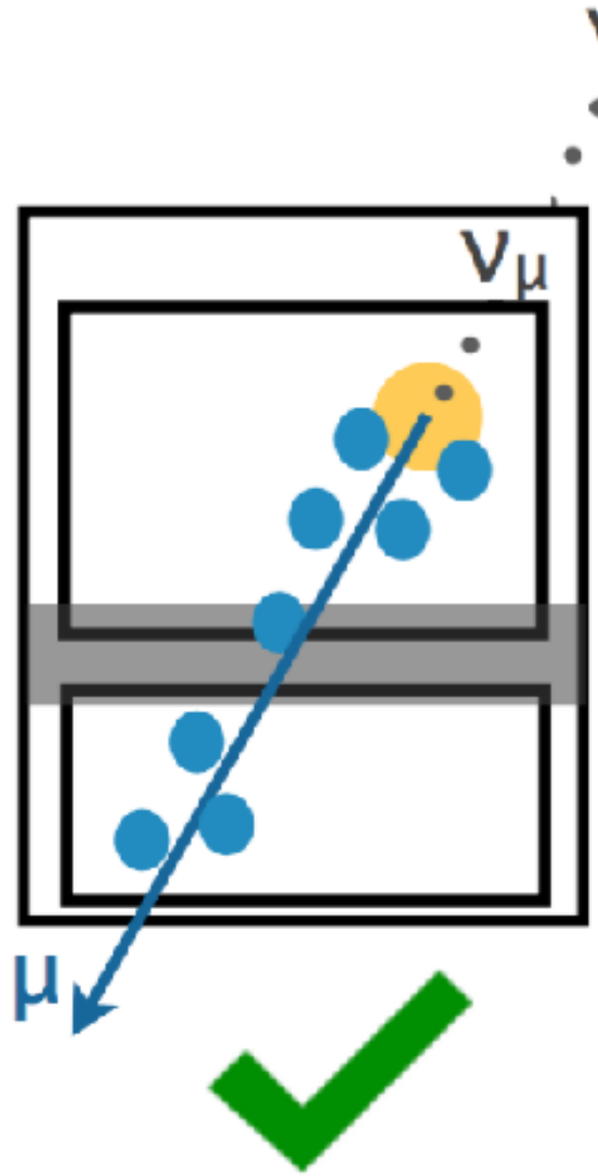
Credit: M. Wolf/NSF

Vetoing atmospheric muons & neutrinos

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

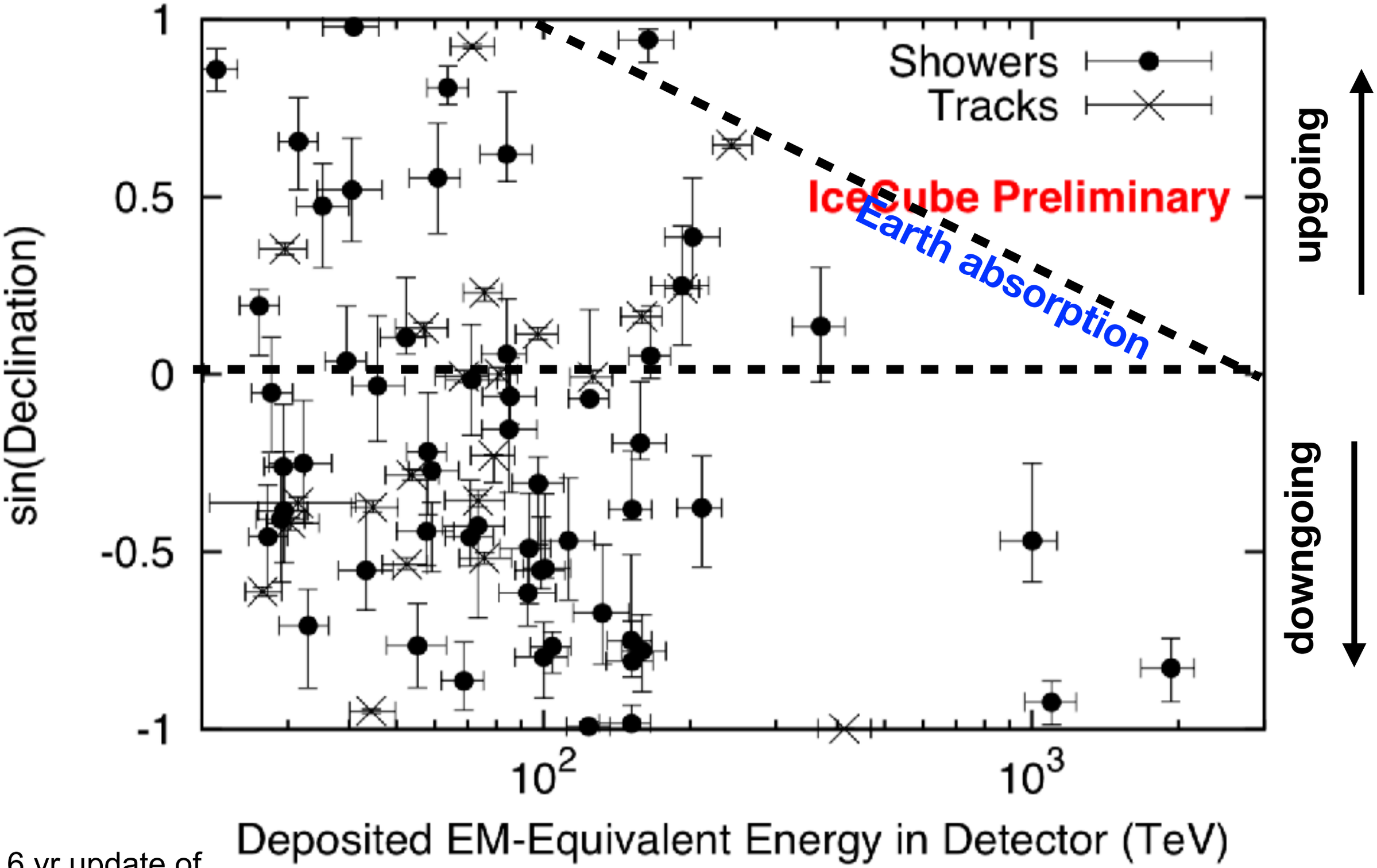






Astrophysical Neutrinos!

80 events observed with 25±7 expected from atmosphere



6 yr update of
PRL2014, Science 2013

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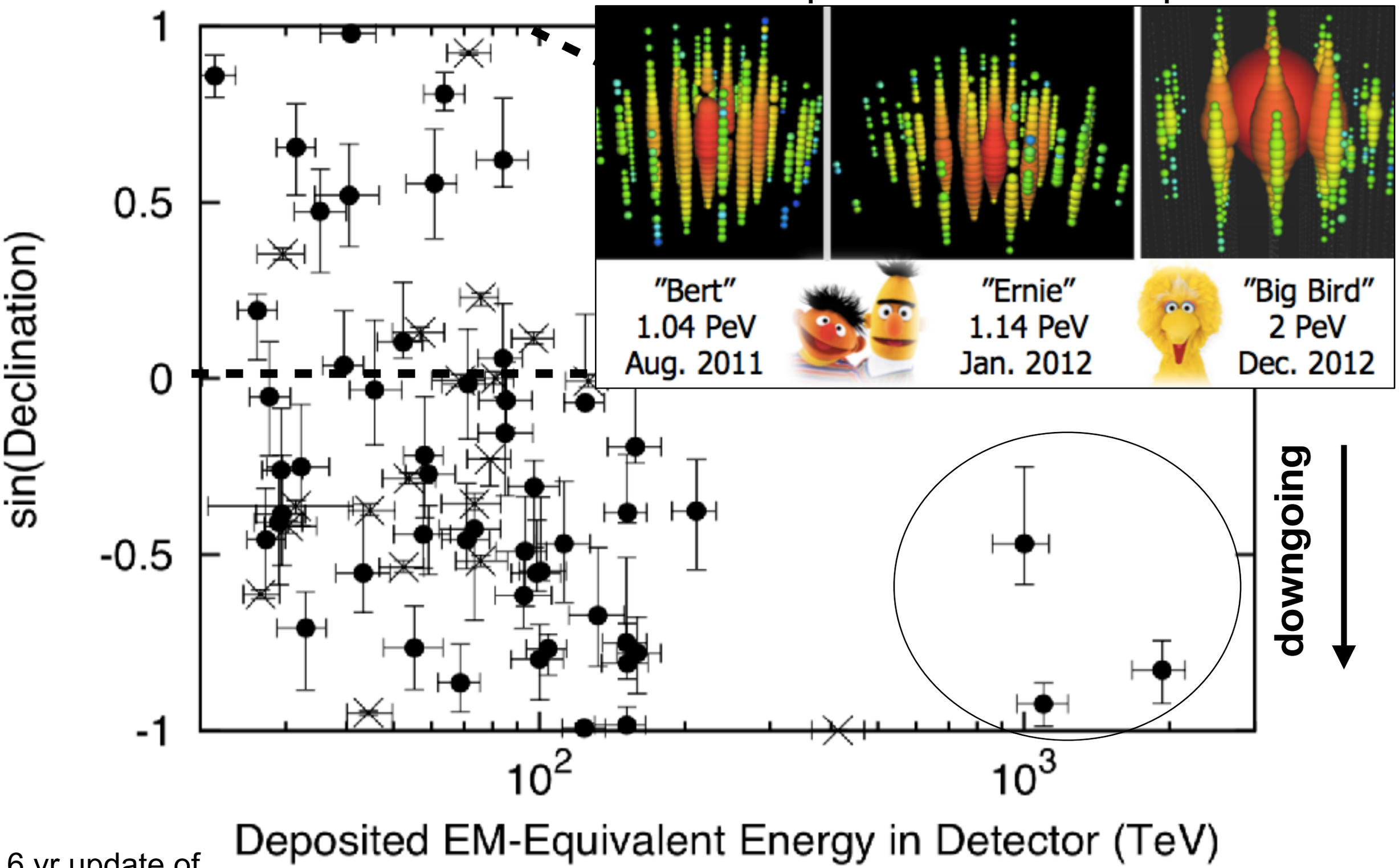

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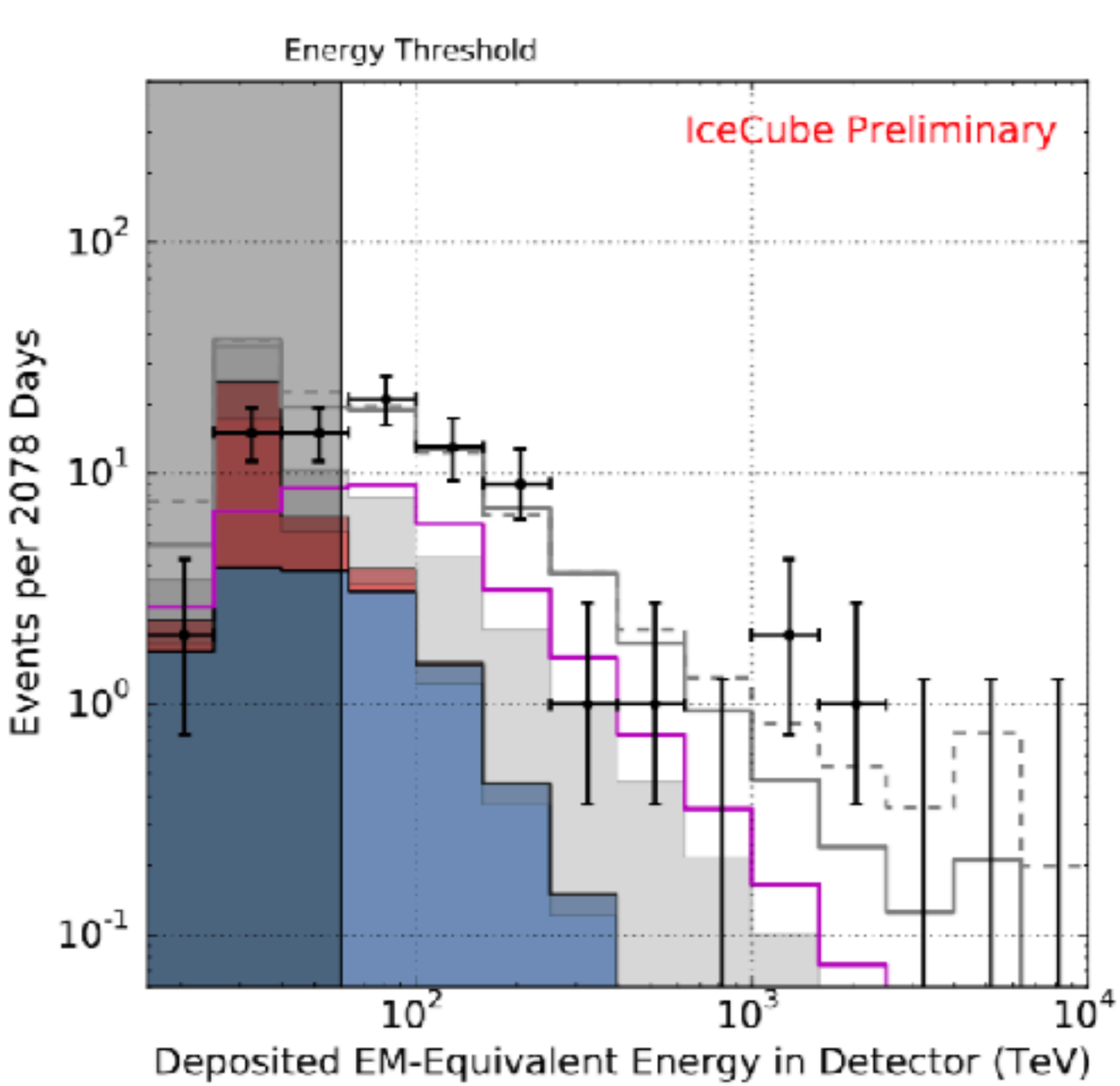
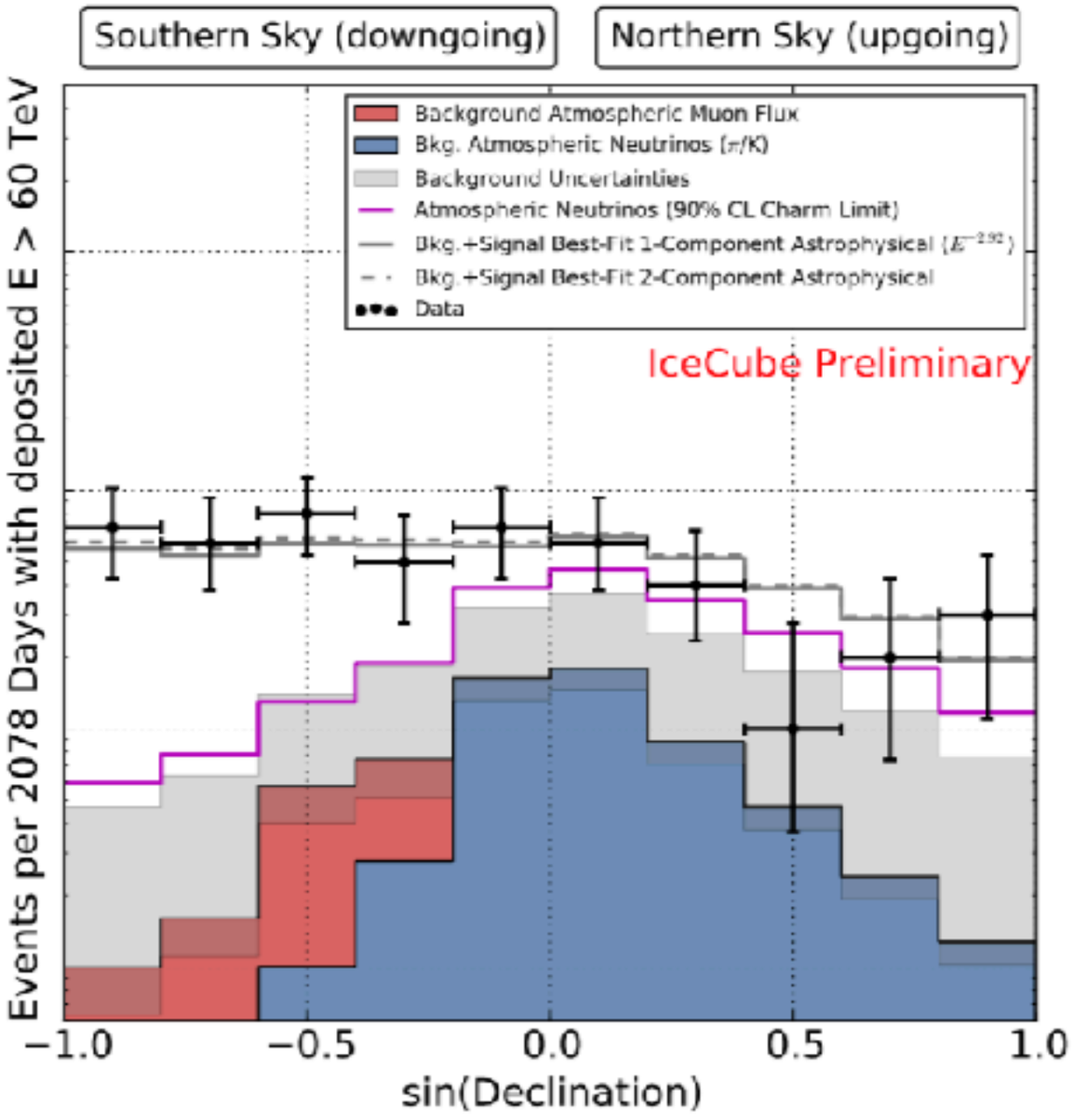
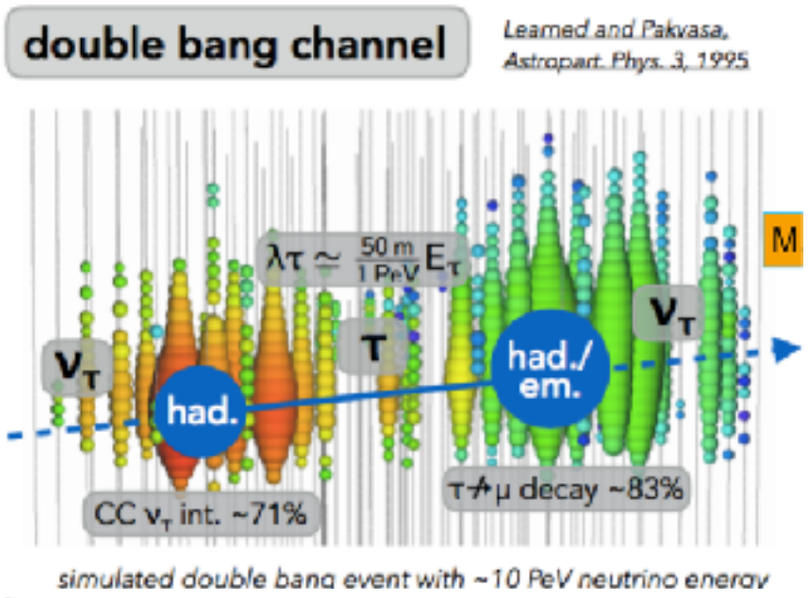




6 yr update of
PRL2014, Science 2013

Search for tau-neutrinos within the HESE sample



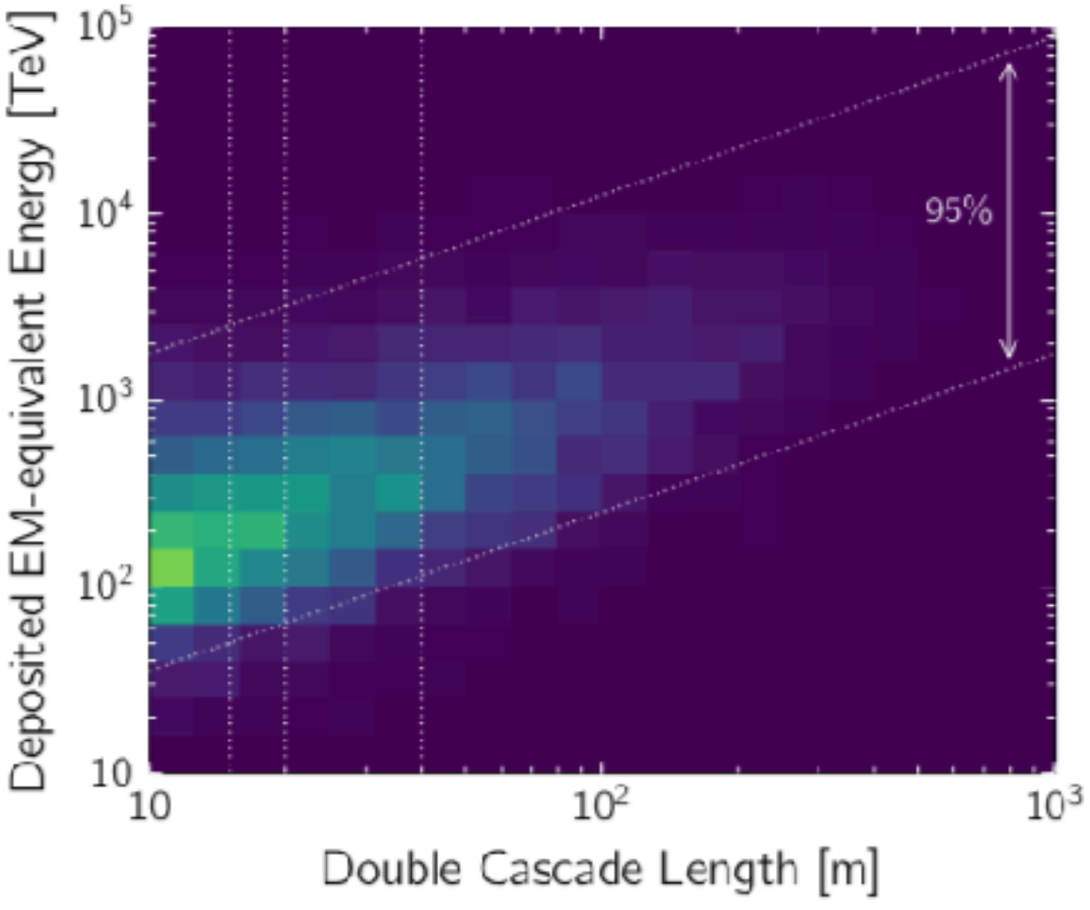
Sensitive to ~20m tau decay length

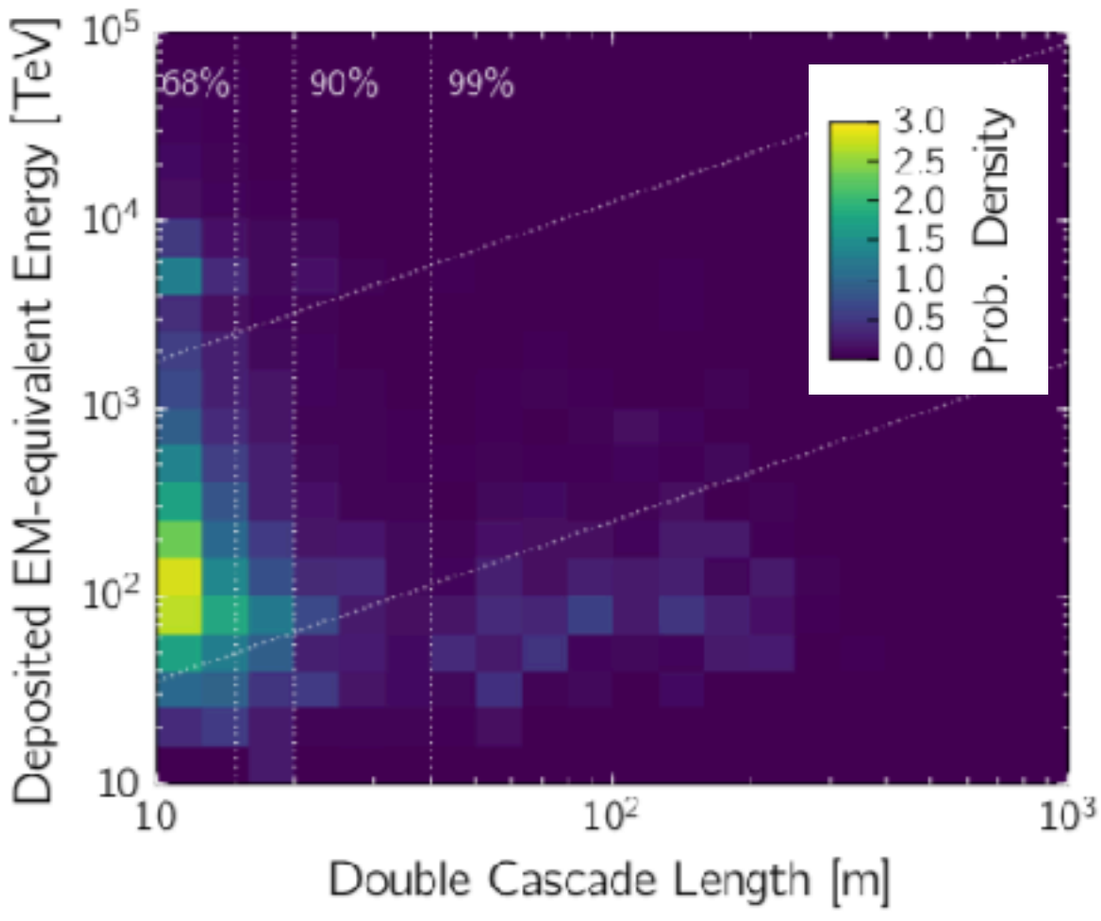
$\nu_e:\nu_\mu:\nu_\tau = 1:1:1$

Φ(E) diff. unfolding

$N_{sig} = 1.441^{+0.024}_{-0.018}$

$N_{bg} = 0.938^{+0.219}_{-0.092}$





IceCube, ICRC 2017

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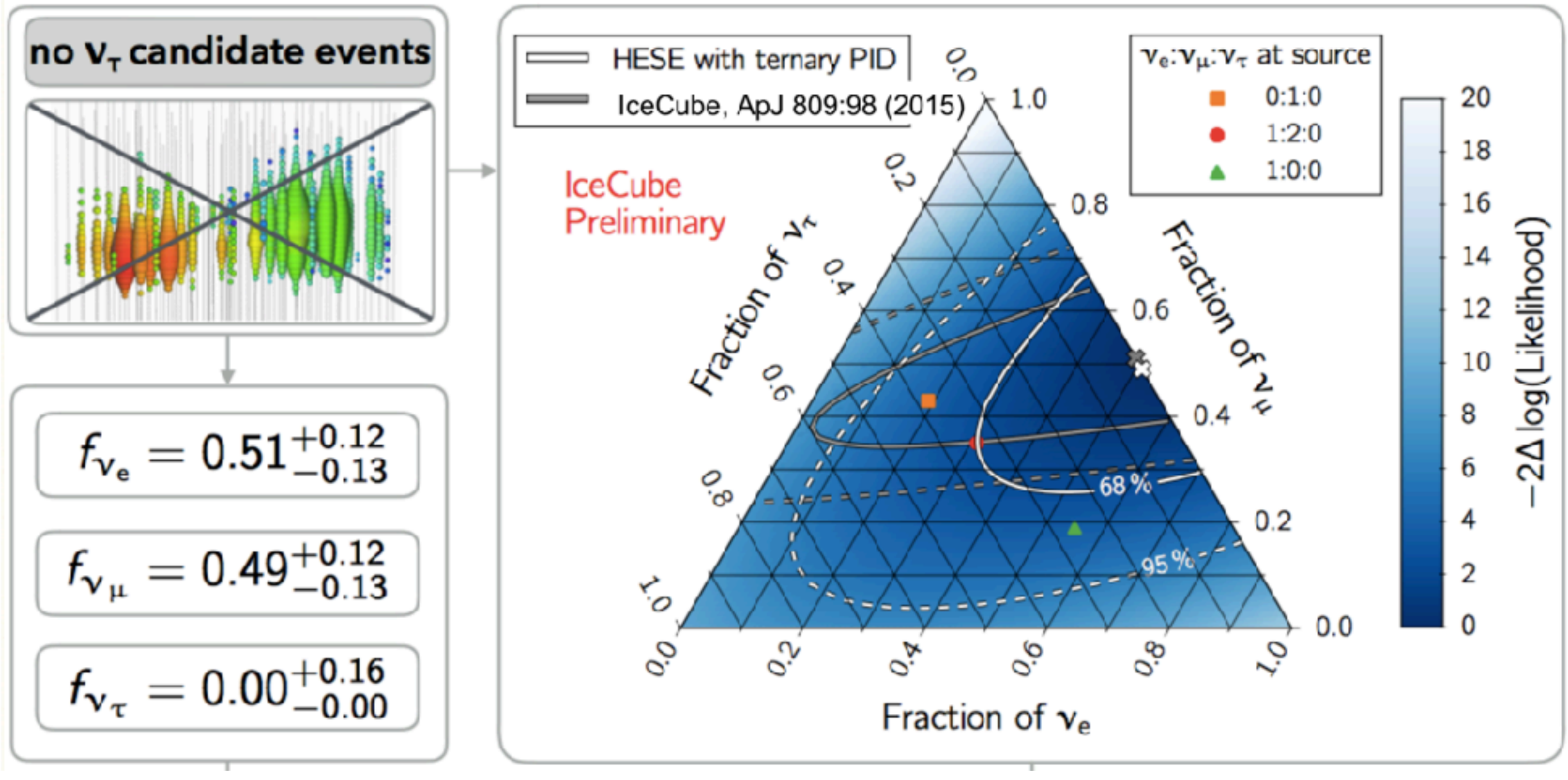
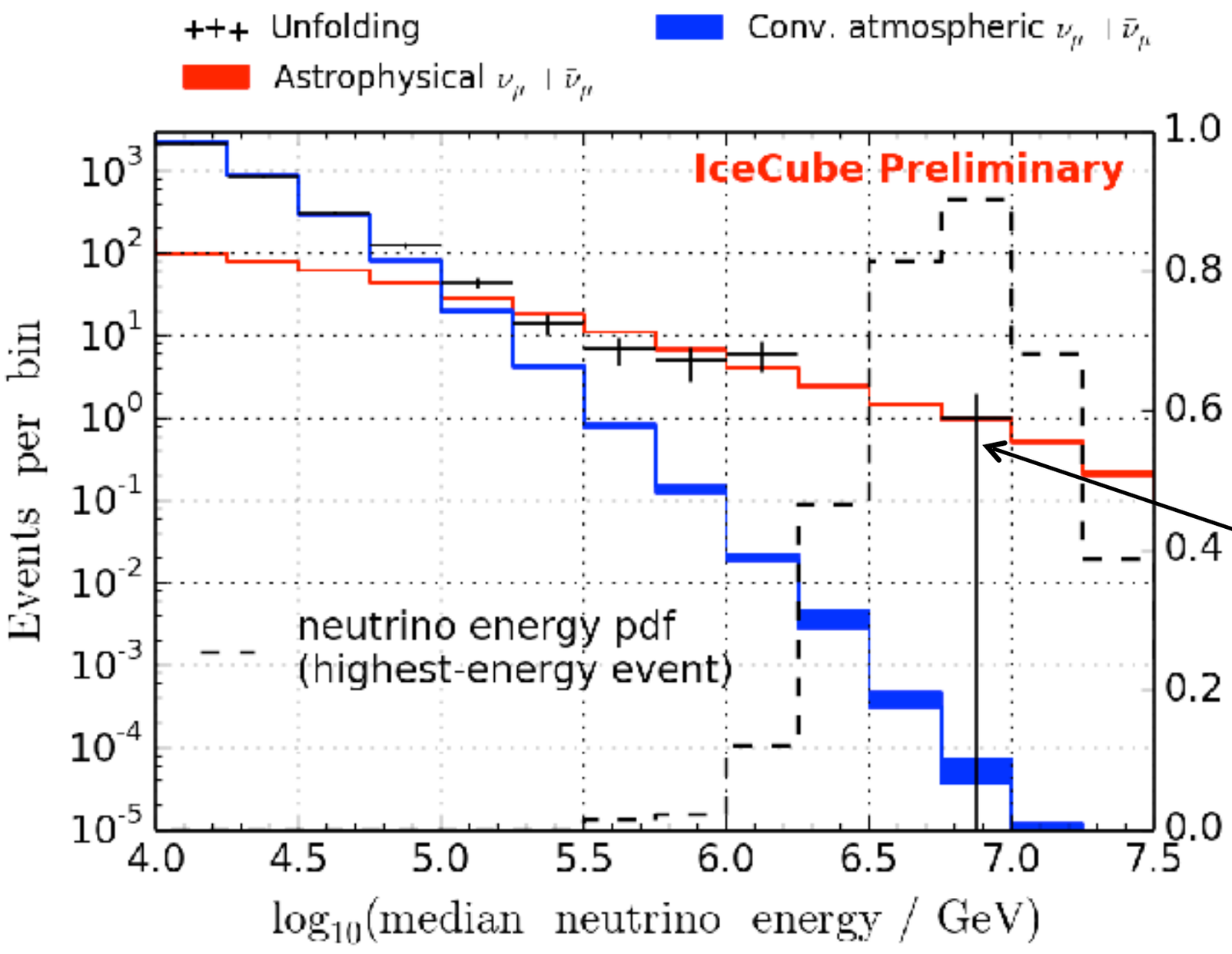


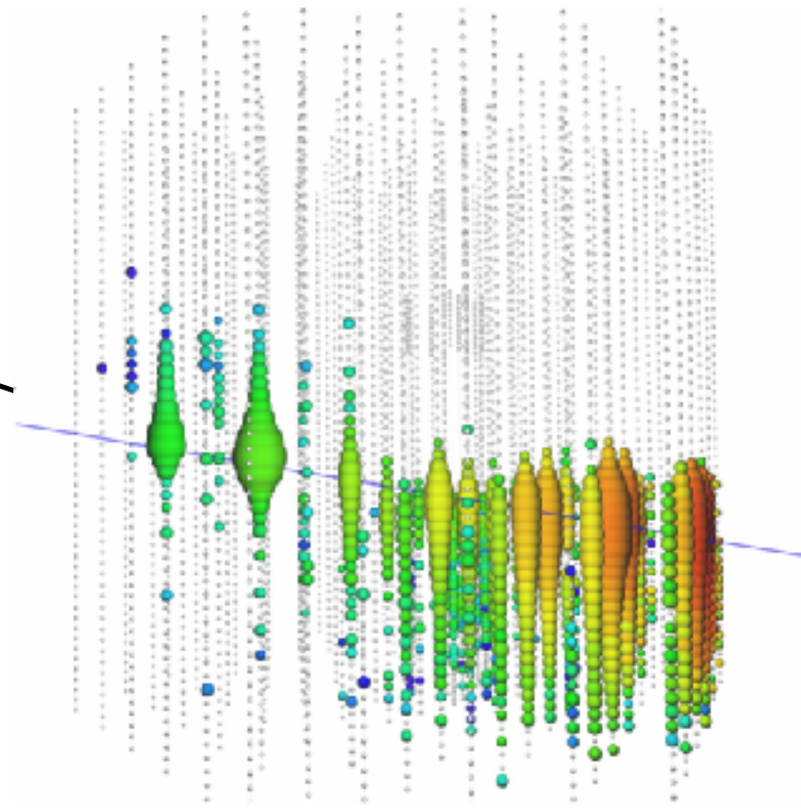
IceCube, ICRC 2017

Through going muon tracks

unfolded data assuming unbroken best-fit power law



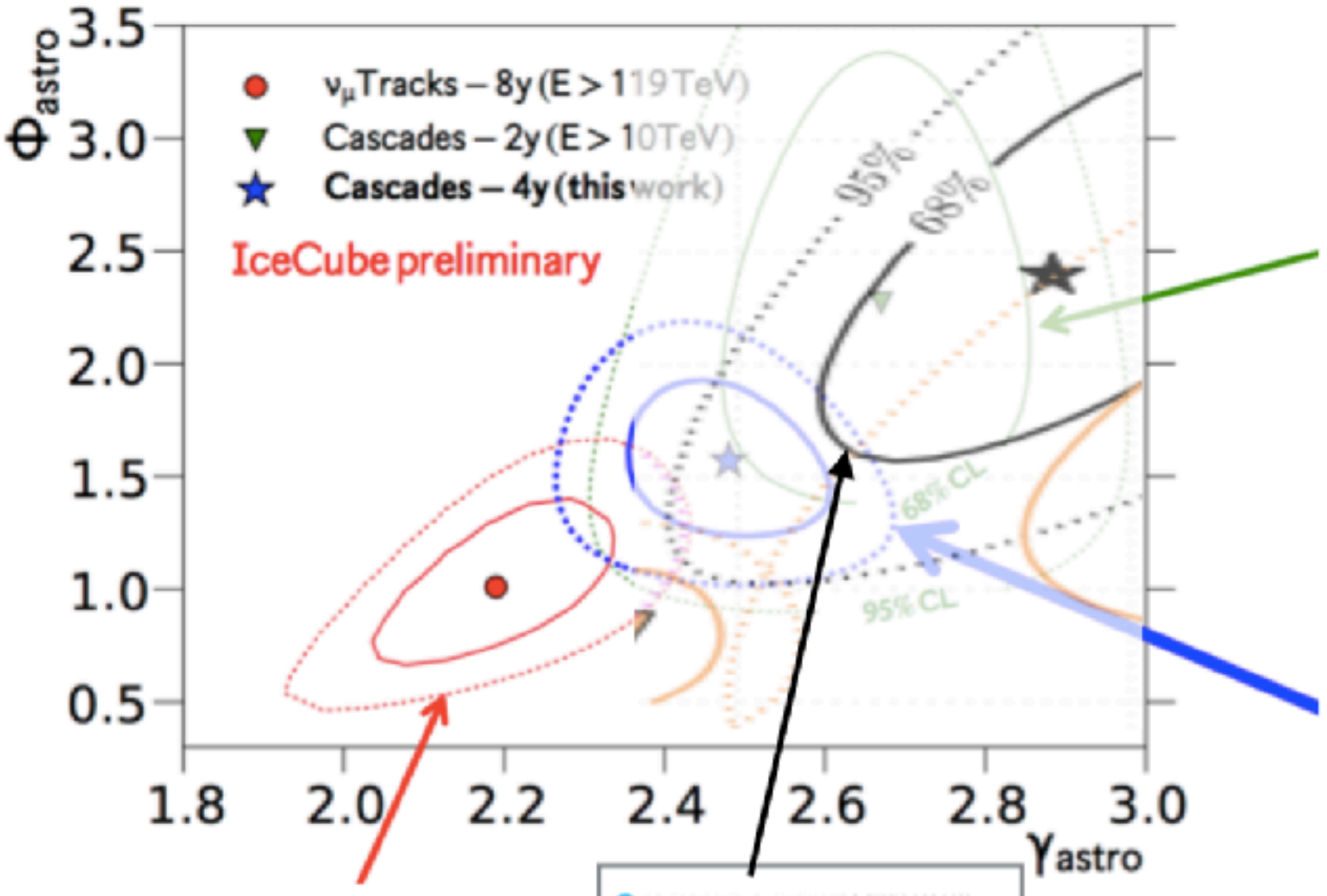
6.7 sigma detection of astrophysical neutrinos with through-going muons analysis

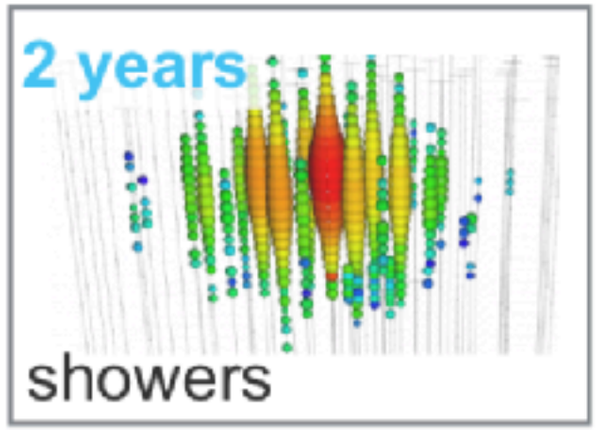


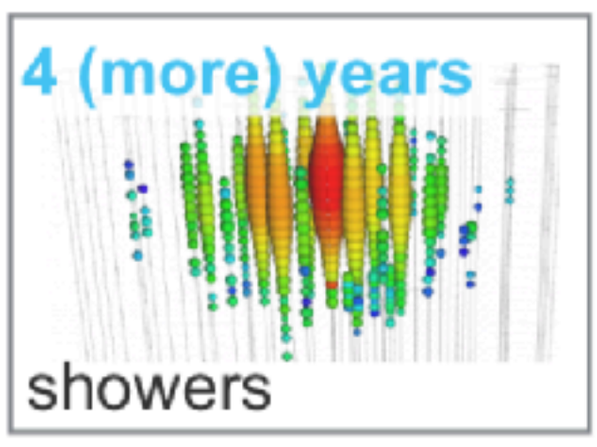
Deposited energy: 2.6±0.3 PeV

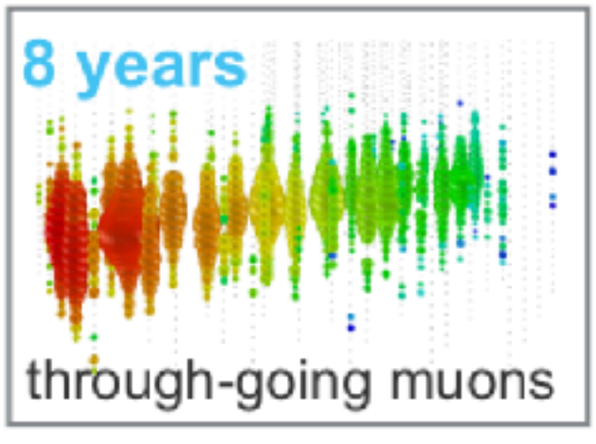
IceCube, ICRC 2017

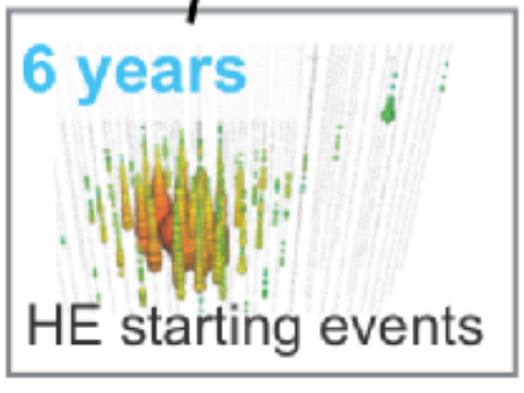
Spectra vs analyses











IceCube, ICRC 2017

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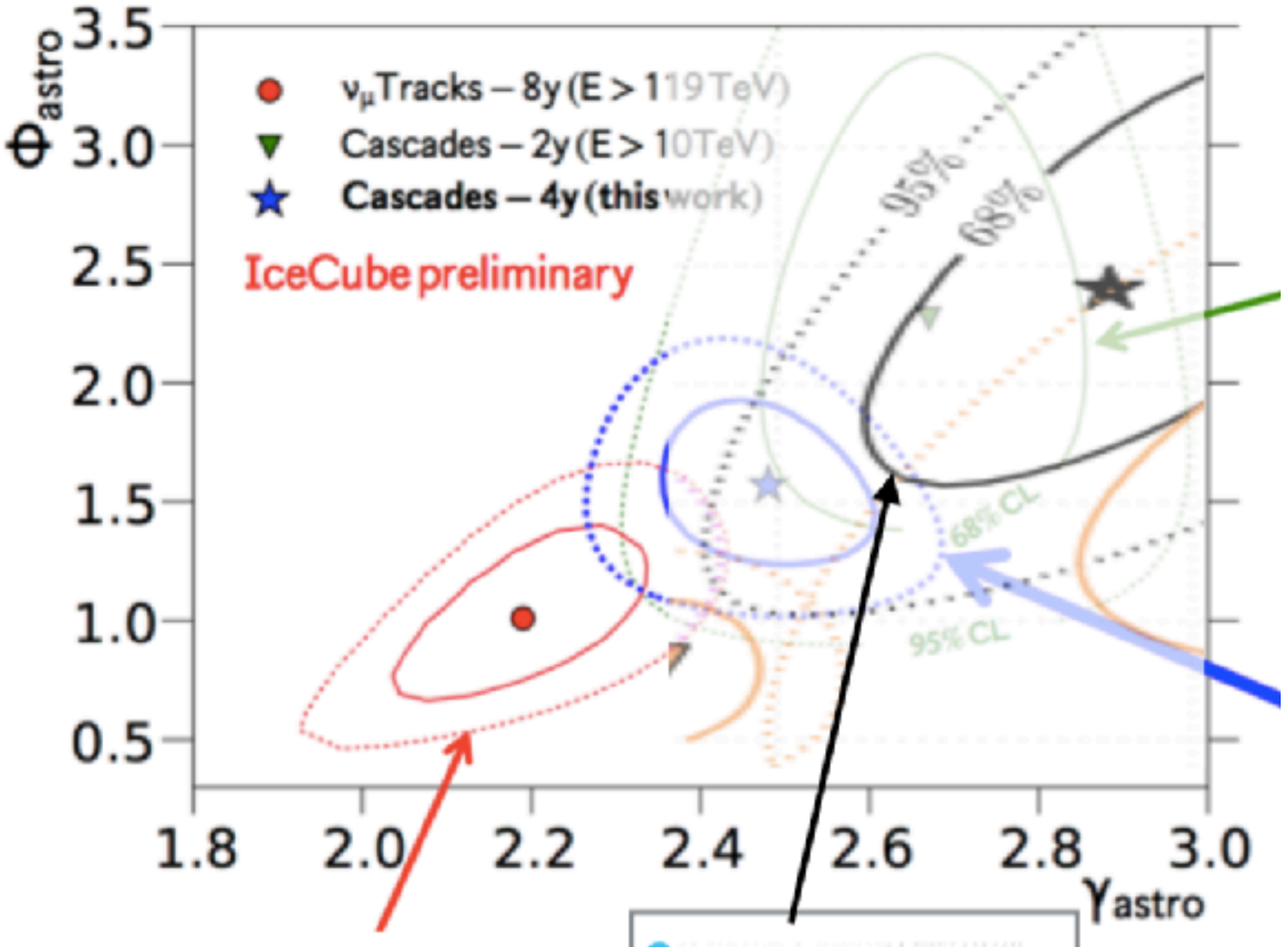
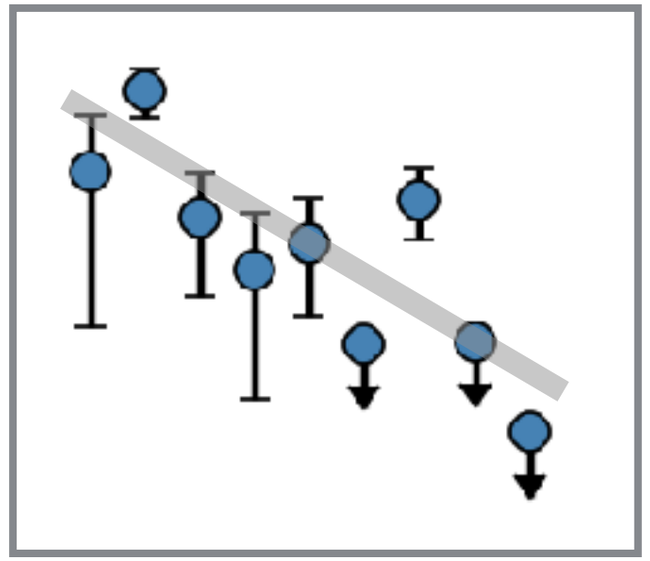
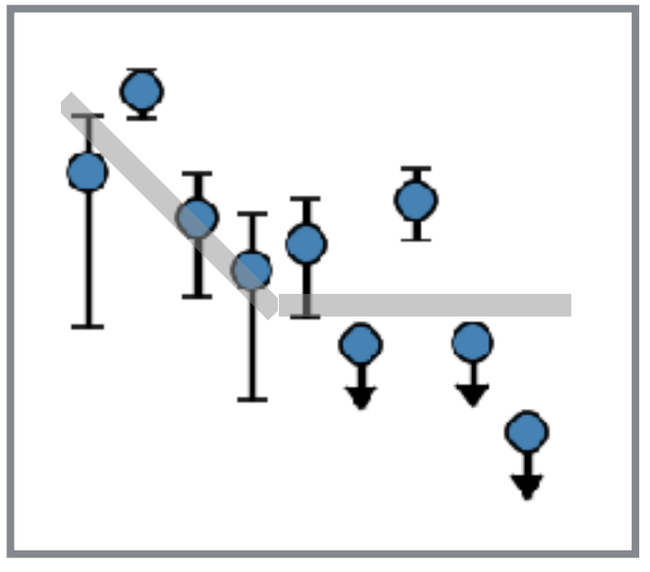
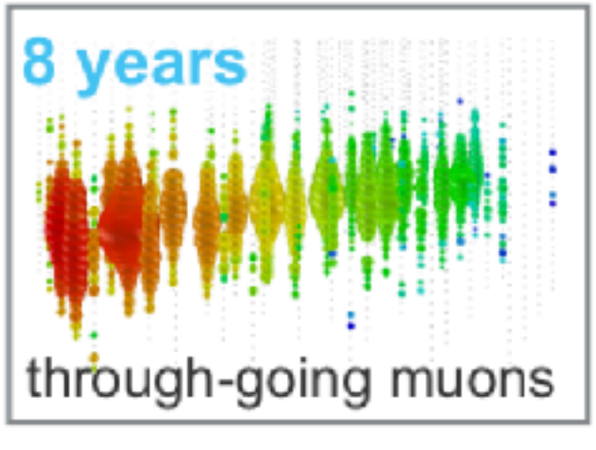
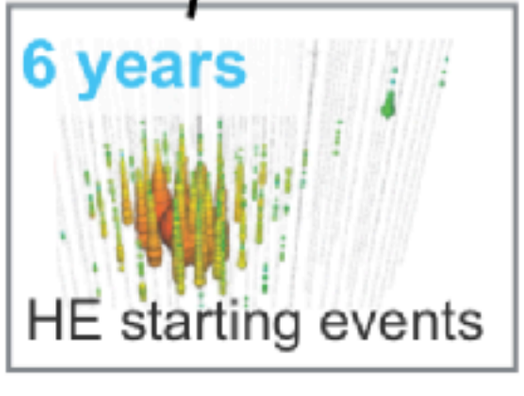




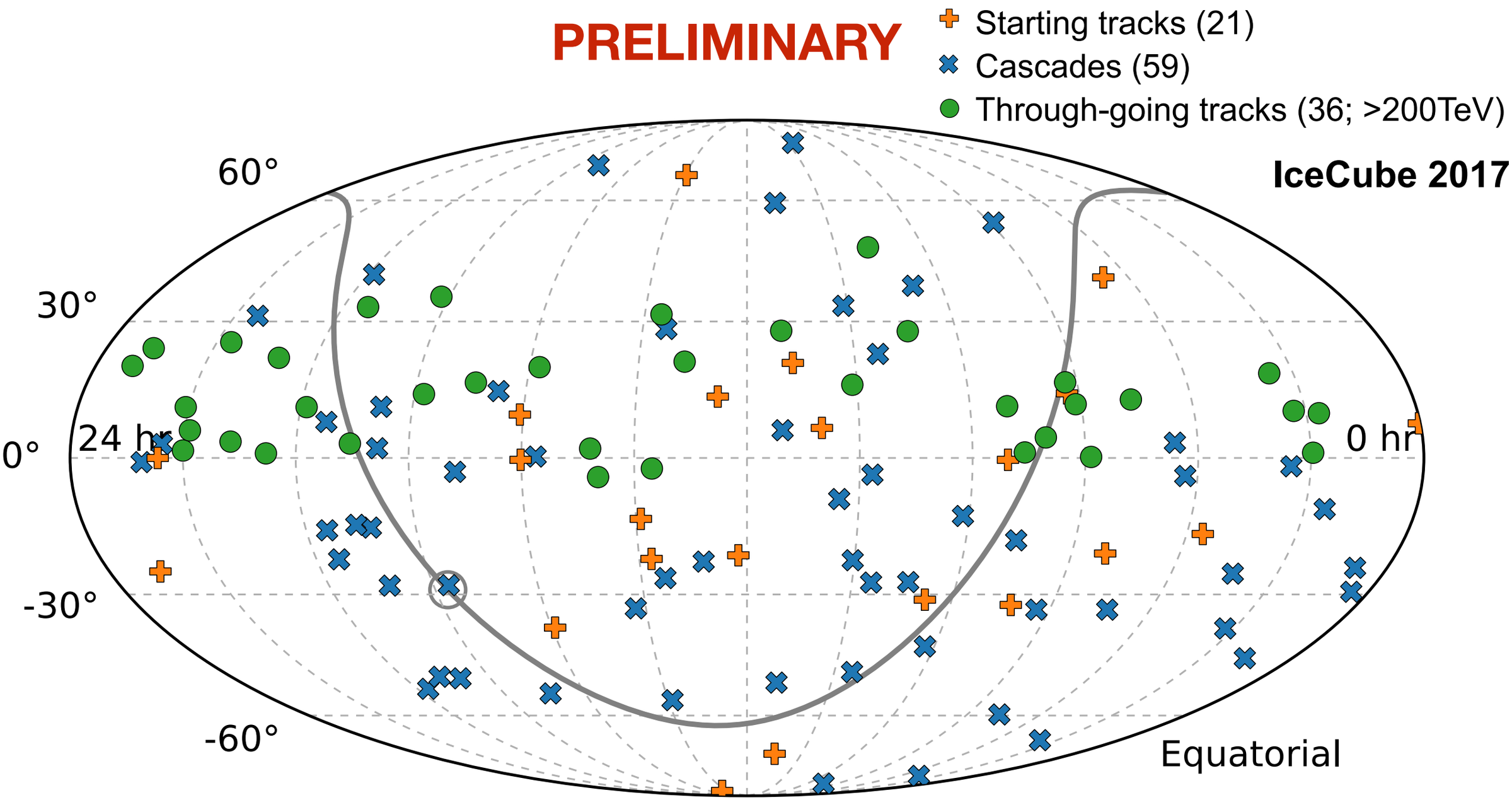






Are we seeing a spectral flattening of astrophysical neutrinos?

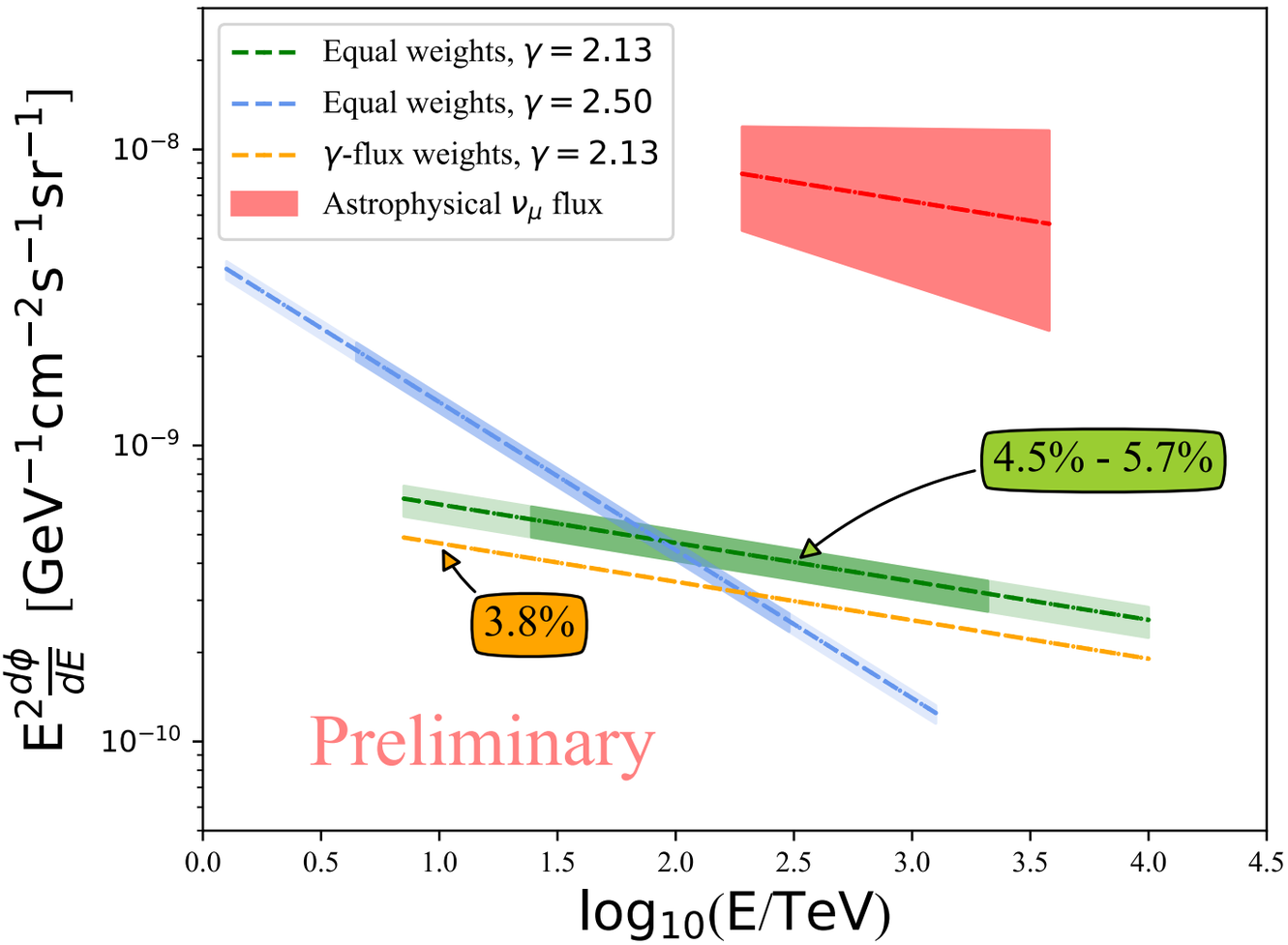
High-energy neutrinos on the sky observed by IceCube



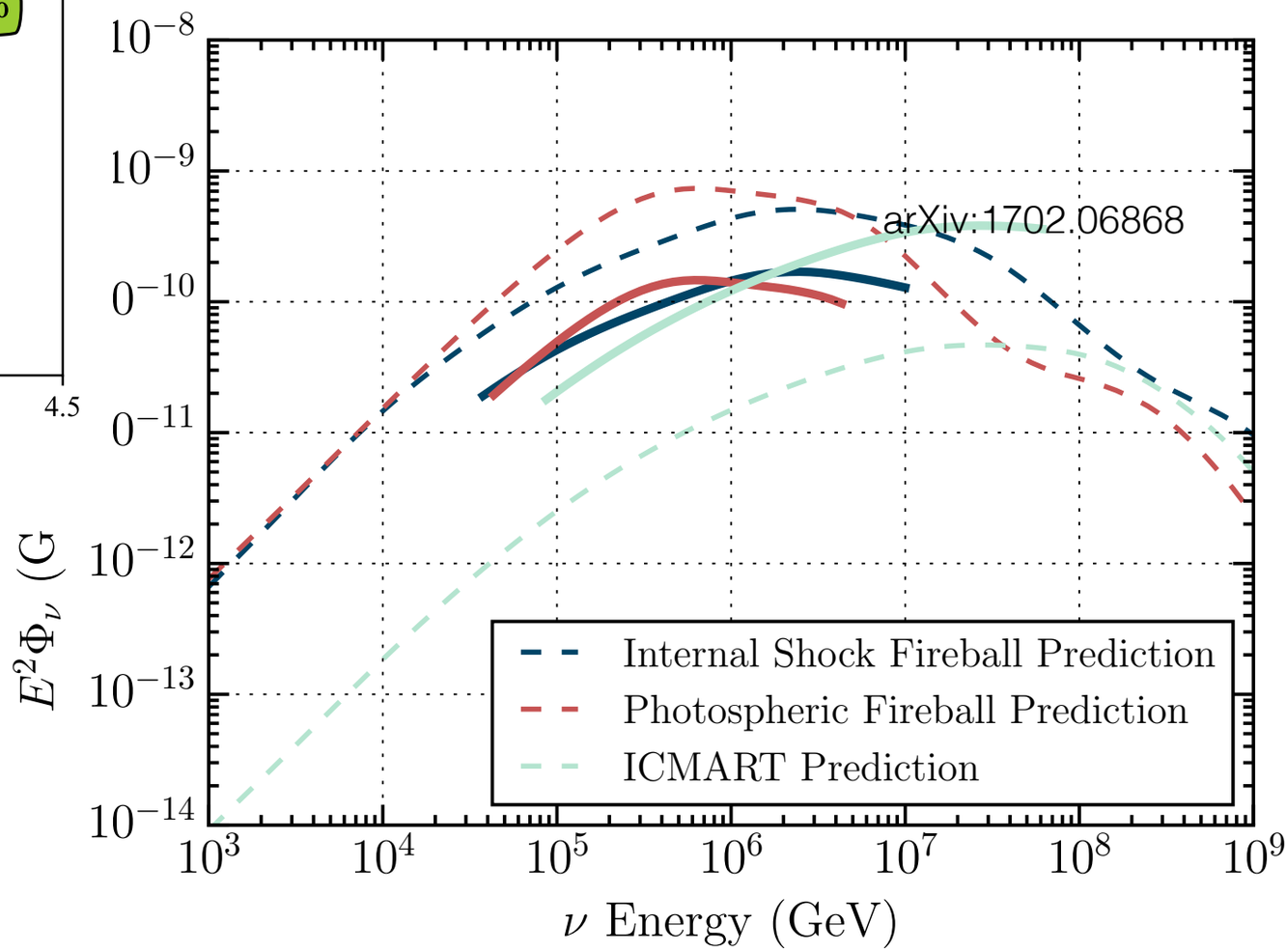
Event numbers: brightest point source vs all

$N_{ps} \sim 10^{-2}\ (n/10^{-7}\ Mpc^{-3})^{-1/3} \times N_{diff}$

High-energy neutrinos on the sky: Constraints on source candidates



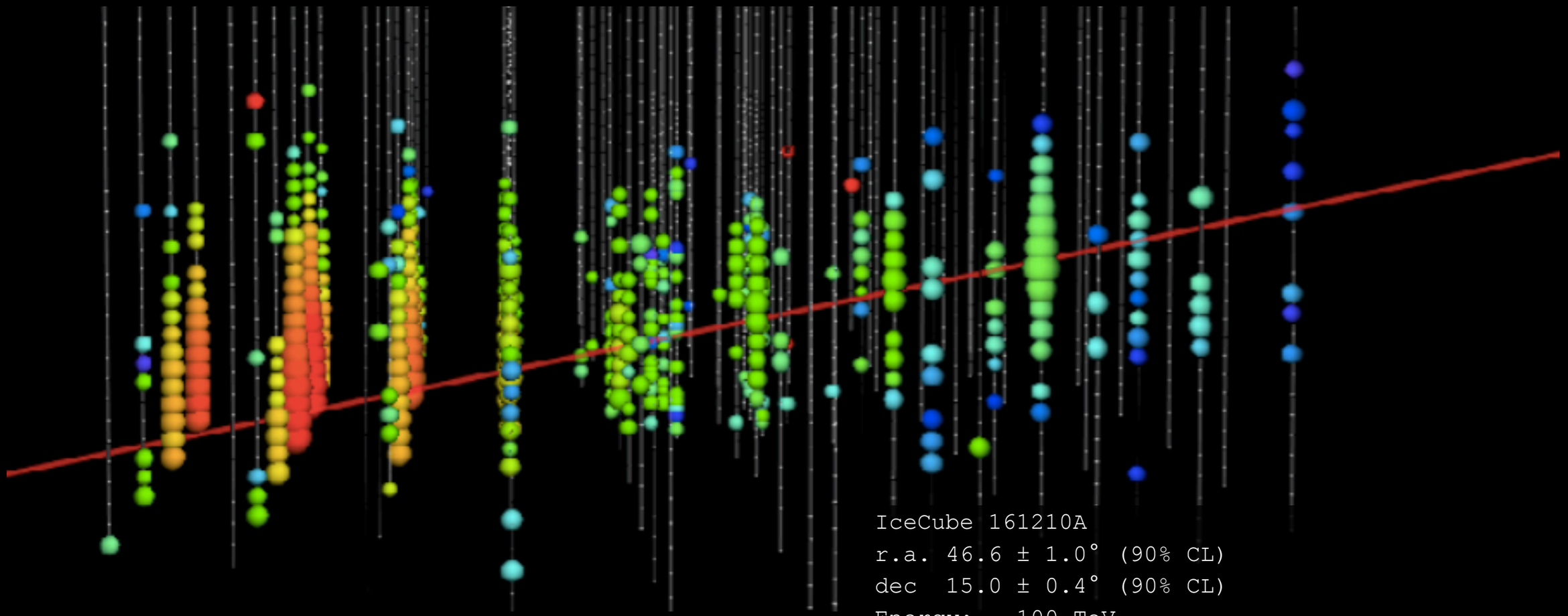
Blazars account for < 6% of the observed neutrino flux



Prompt emission from GRBs account for <1% of the observed neutrino flux.

Realtime alerts via GCN and AMON

Public alert stream running since April 2016 - 12 events so far

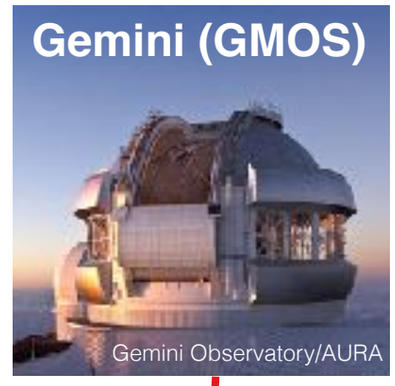


IceCube 161210A
r.a. 46.6 ± 1.0° (90% CL)
dec 15.0 ± 0.4° (90% CL)
Energy: ~ 100 TeV
Astrophysical signal probability: 49%
https://gcn.gsfc.nasa.gov/other/icecube_161210.gcn3

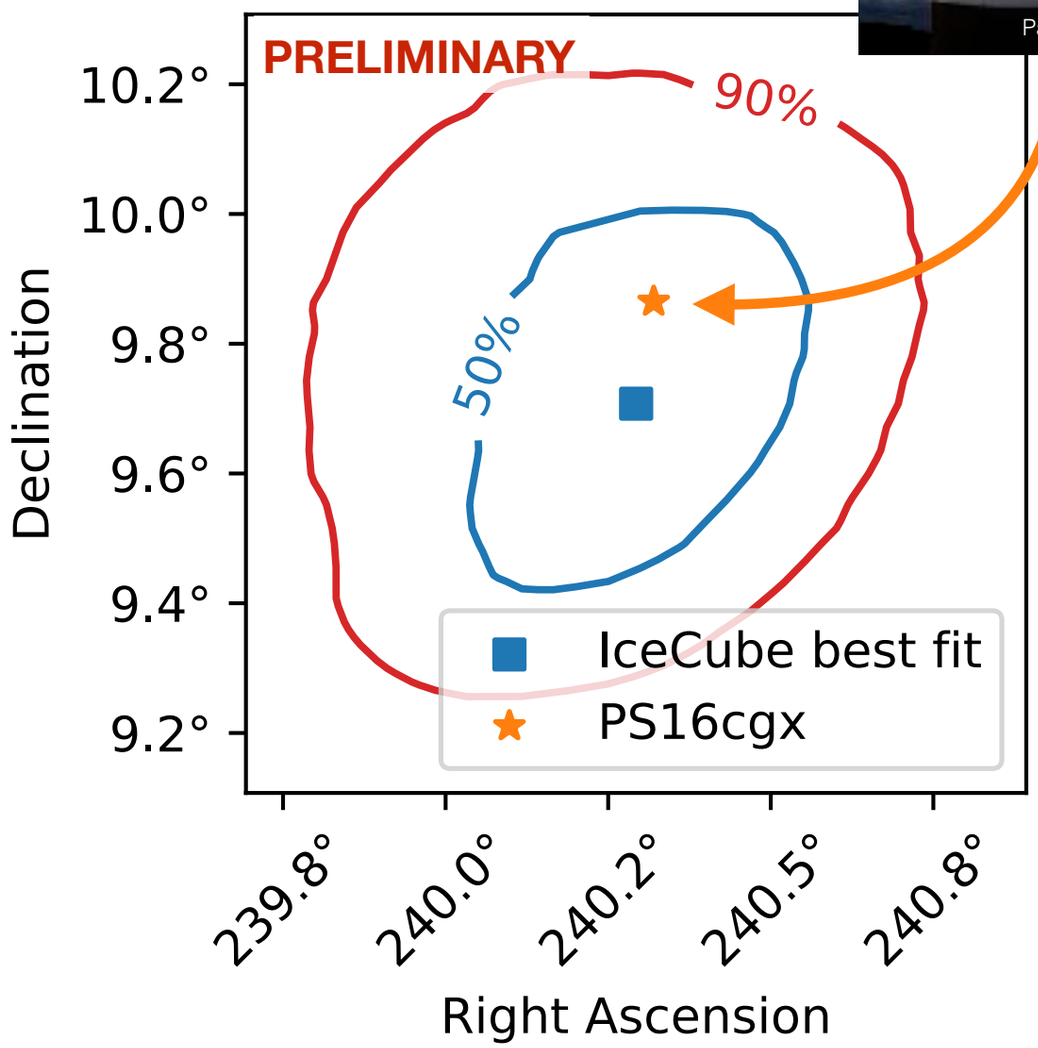
PS16cgx: a young supernova in the field of a HE starting neutrino

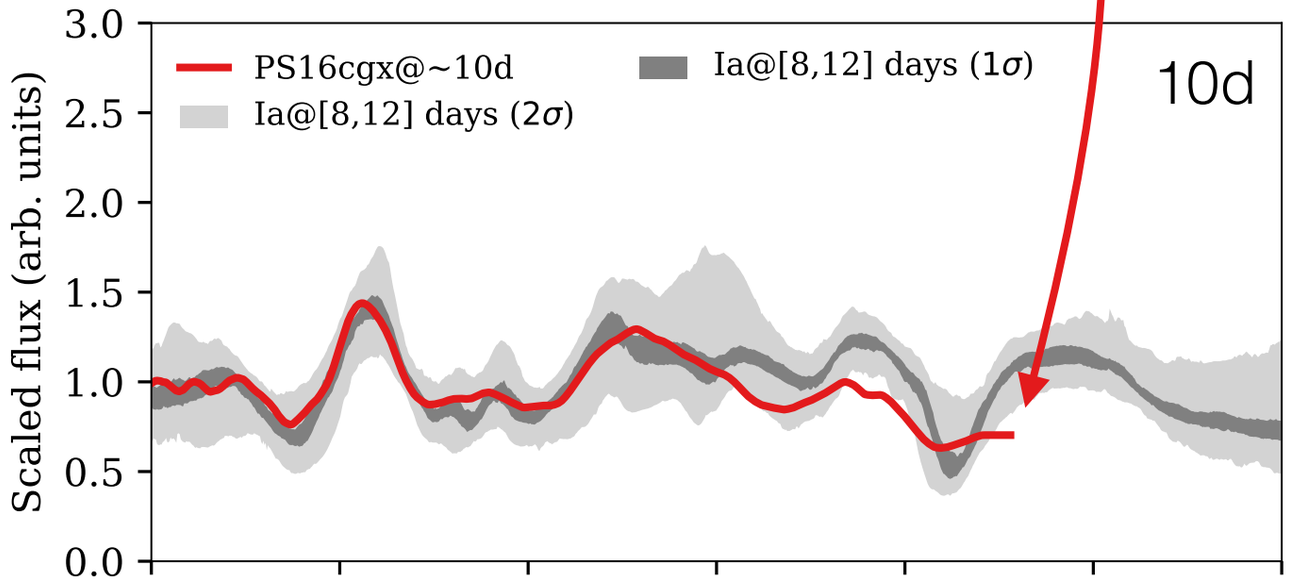
PanStarrs follow up of IceCube alert on 2016-04-27 and found a young supernova at z=0.3:

Light curve consistent with explosion days before neutrino alert



Optical spectroscopy
10, 20 days post-peak

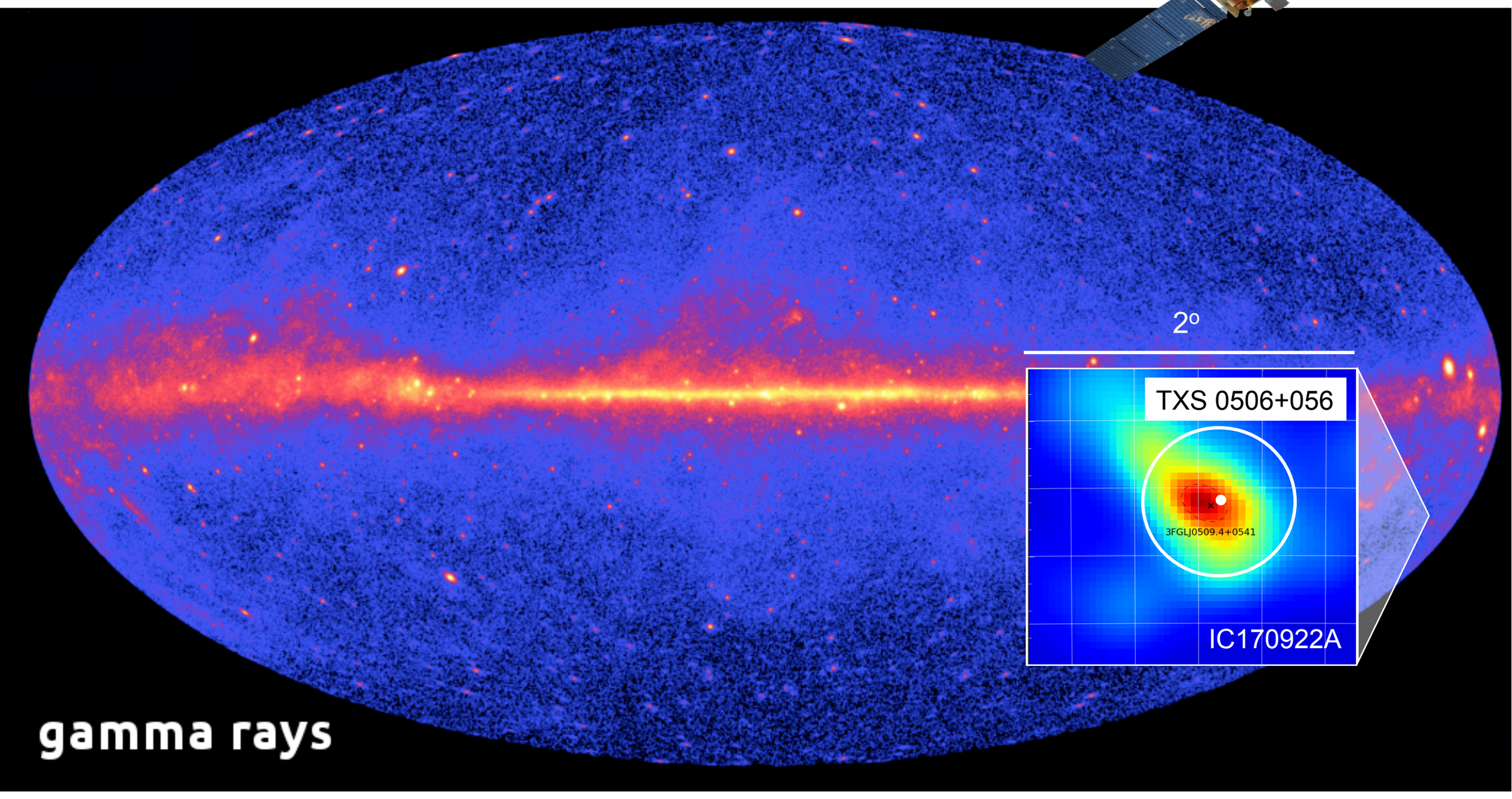




Features atypical for SNIa,
but not sufficient to exclude

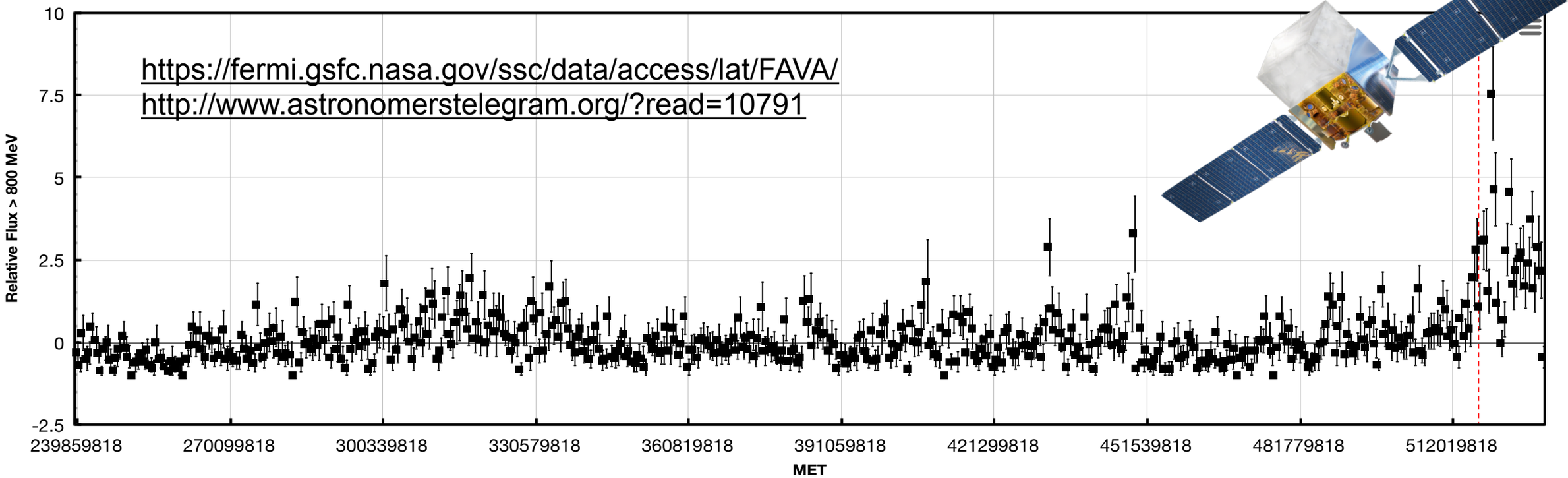
Chance probability { if **Ic** (associated with GRBs): **<1%**
if **Ia** (no HE neutrinos expected): **<10%**

IceCube 170922A: Alert coincident with flaring GeV-Blazar



https://fermi.gsfc.nasa.gov/ssc/data/access/lat/FAVA/
http://www.astronomerstelegram.org/?read=10791

IceCube 170922A: Alert coincident with flaring GeV-Blazar



- Neutrino coincident with **strong flare** observed by Fermi All-sky Variability Analysis (FAVA)
- Observations by **MAGIC** reveal emission at **>100 GeV**
- **Many more observatories involved,** detailed analysis ongoing

[Previous | Next | ADS]

First-time detection of VHE gamma rays by MAGIC from a direction consistent with the recent EHE neutrino event IceCube-170922A

ATel #10817; ***Razmik Mirzoyan for the MAGIC Collaboration***
on 4 Oct 2017; 17:17 UT
Credential Certification: Razmik Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de)

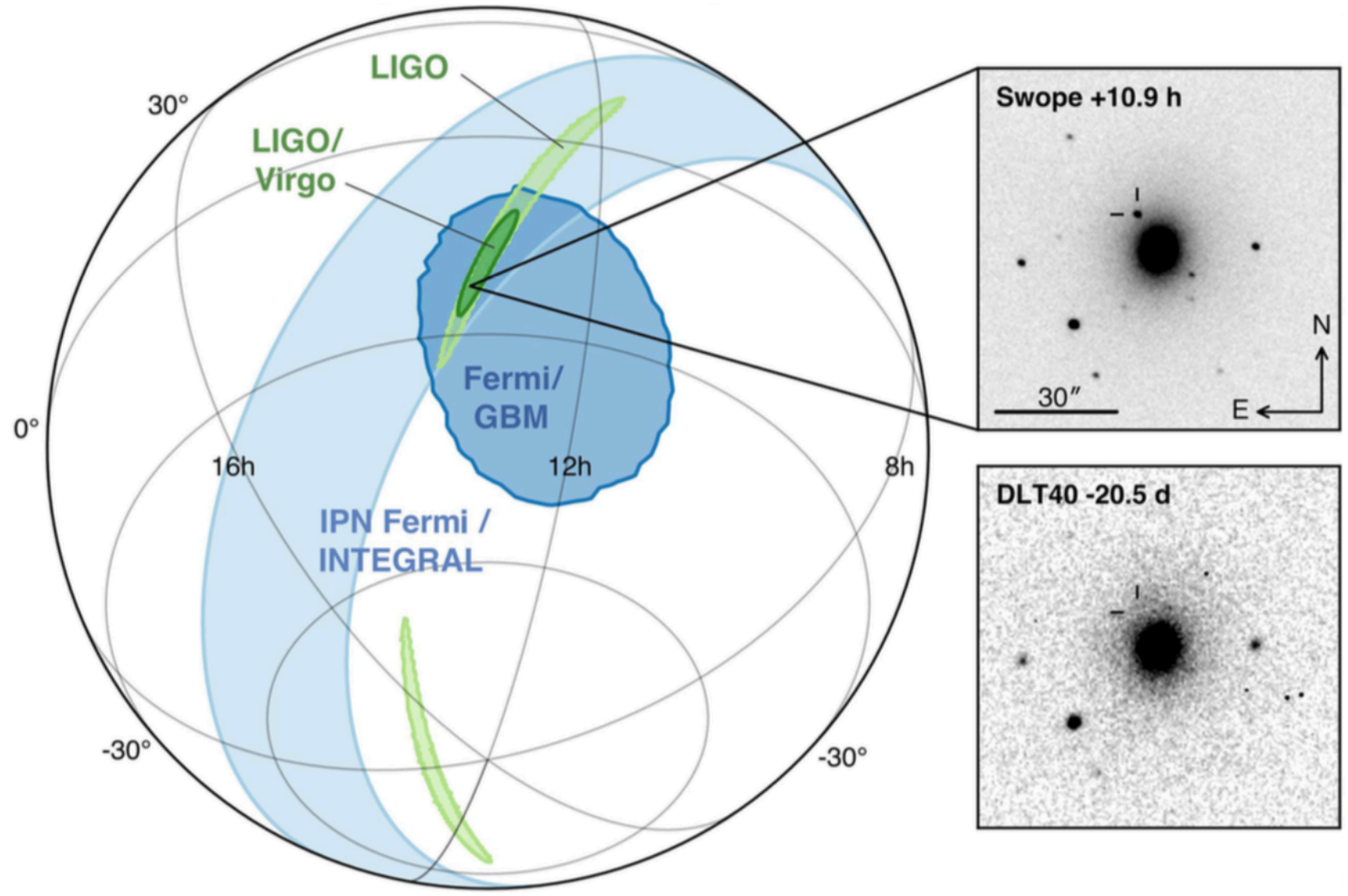
Subjects: Optical, Gamma Ray, >GeV, TeV, VHE, UHE, Neutrinos, AGN, Blazar

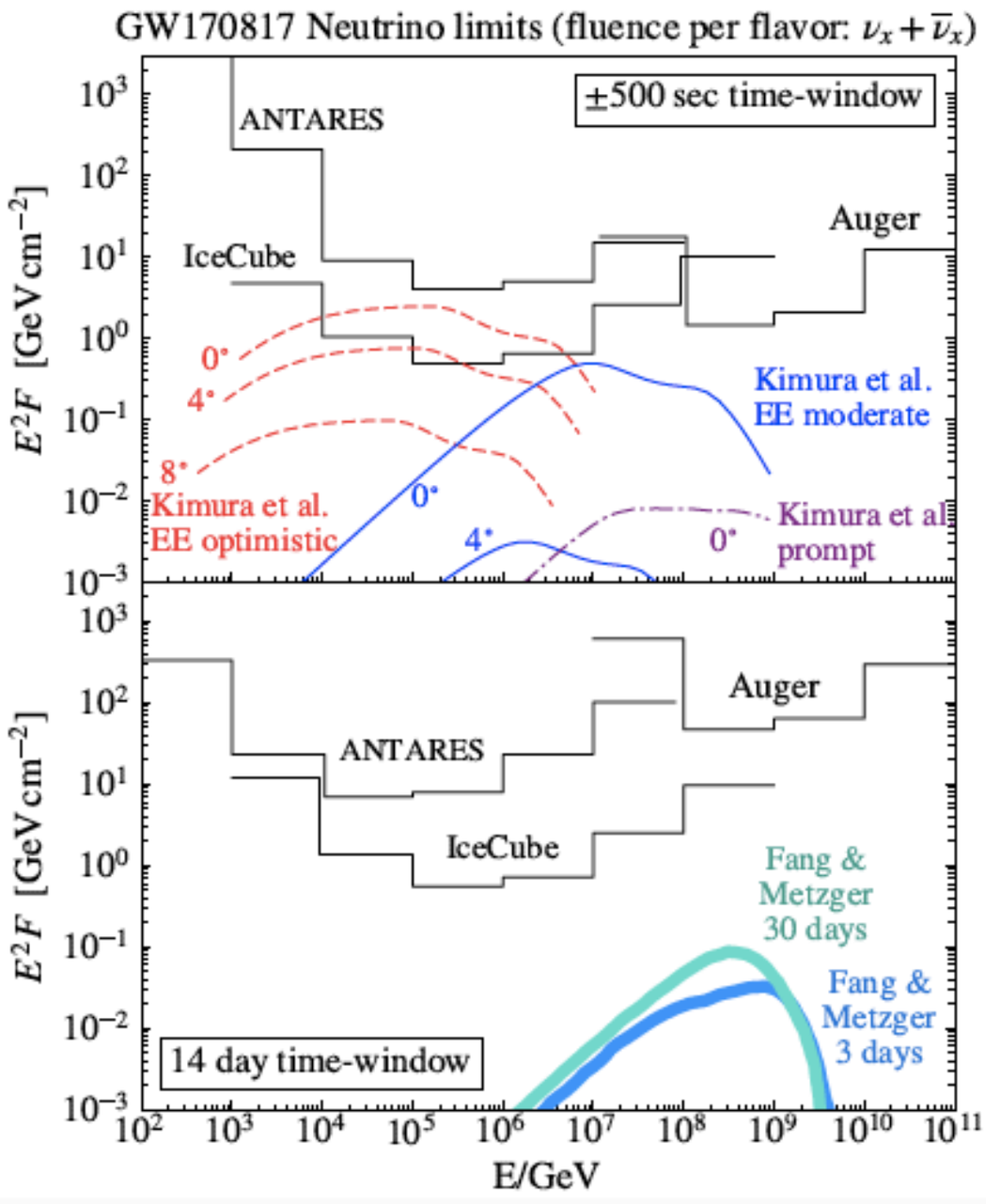
Referred to by ATel #: 10830, 10833, 10838, 10840, 10844, 10845, 10942

Tweet Recommend 448

After the IceCube neutrino event EHE 170922A detected on 22/09/2017 (GCN circular #21916), Fermi-LAT measured enhanced gamma-ray emission from the blazar TXS 0506+056 (05 09 25.96370, +05 41 35.3279 (J2000), [Lani et al., Astron. J., 139, 1695-1712 (2010)]), located 6 arcmin from the EHE 170922A estimated direction (ATel #10791). MAGIC observed this source under good weather conditions and a 5 sigma detection above 100 GeV was achieved after 12 h of observations from September 28th till October 3rd. This is the first time that VHE gamma rays are measured from a direction consistent with a detected neutrino event. Several follow up observations from other observatories have been reported in ATels: #10773, #10787, #10791, #10792, #10794, #10799, #10801, GCN: #21941, #21930, #21924, #21923, #21917, #21916. The MAGIC contact persons for these observations are R. Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de) E. Bernardini (elisa.bernardini@desy.de), K.Satalecka (konstancja.satalecka@desy.de). MAGIC is a system of two 17m-diameter Imaging Atmospheric Cherenkov Telescopes located at the Observatory Roque de los Muchachos on the Canary island La Palma, Spain, and designed to perform gamma-ray astronomy in the energy range from 50 GeV to greater than 50 TeV.

High energy emission from GW170817?





- Neutrino and gamma ray observatories have not seen a signal, consistent with off-axis short GRB scenario

Auger - ANTARES - IceCube joined publications, ApJ, 2017

The high-energy Universe: broader perspective

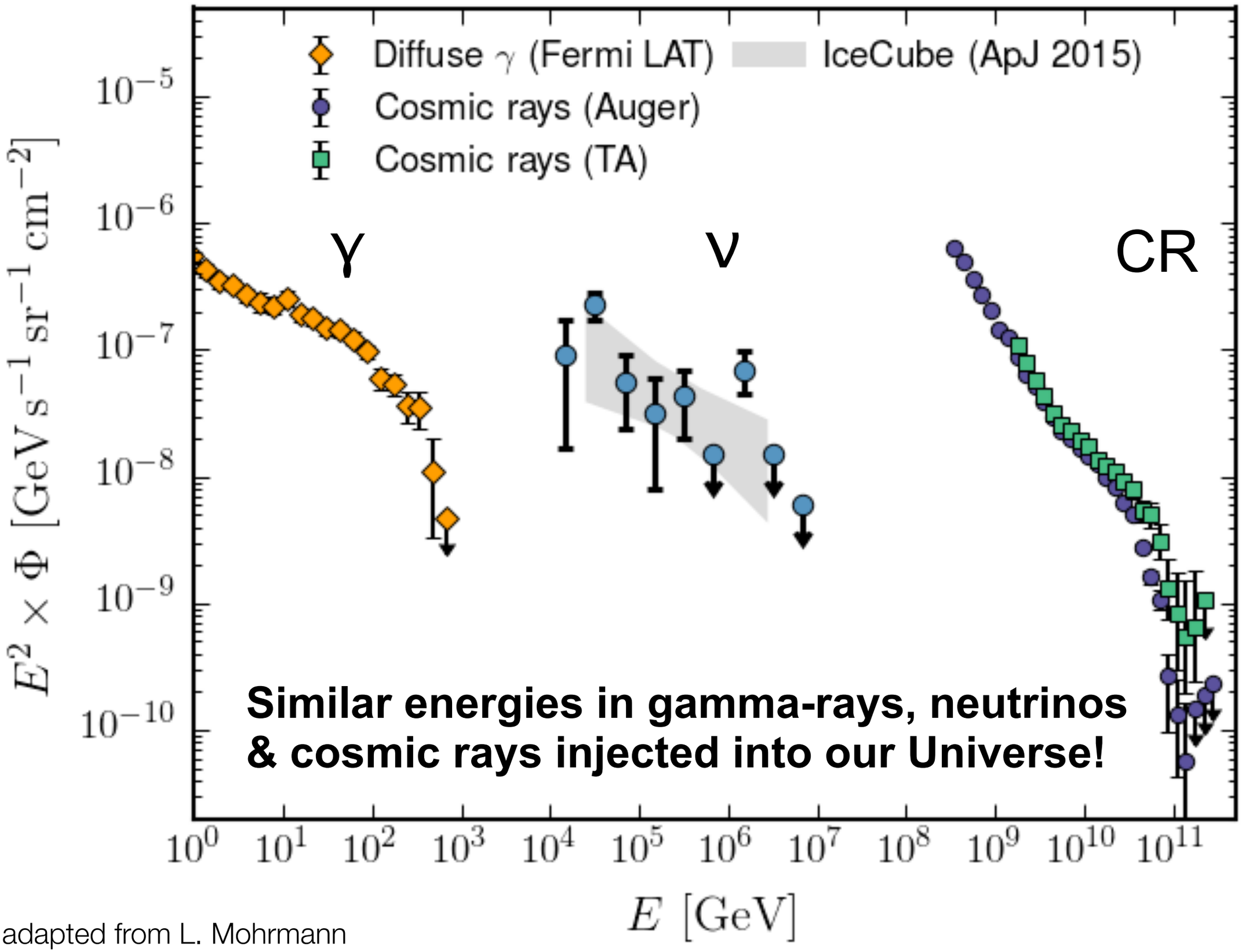


Fig. adapted from L. Mohrmann

The high-energy Universe: broader perspective

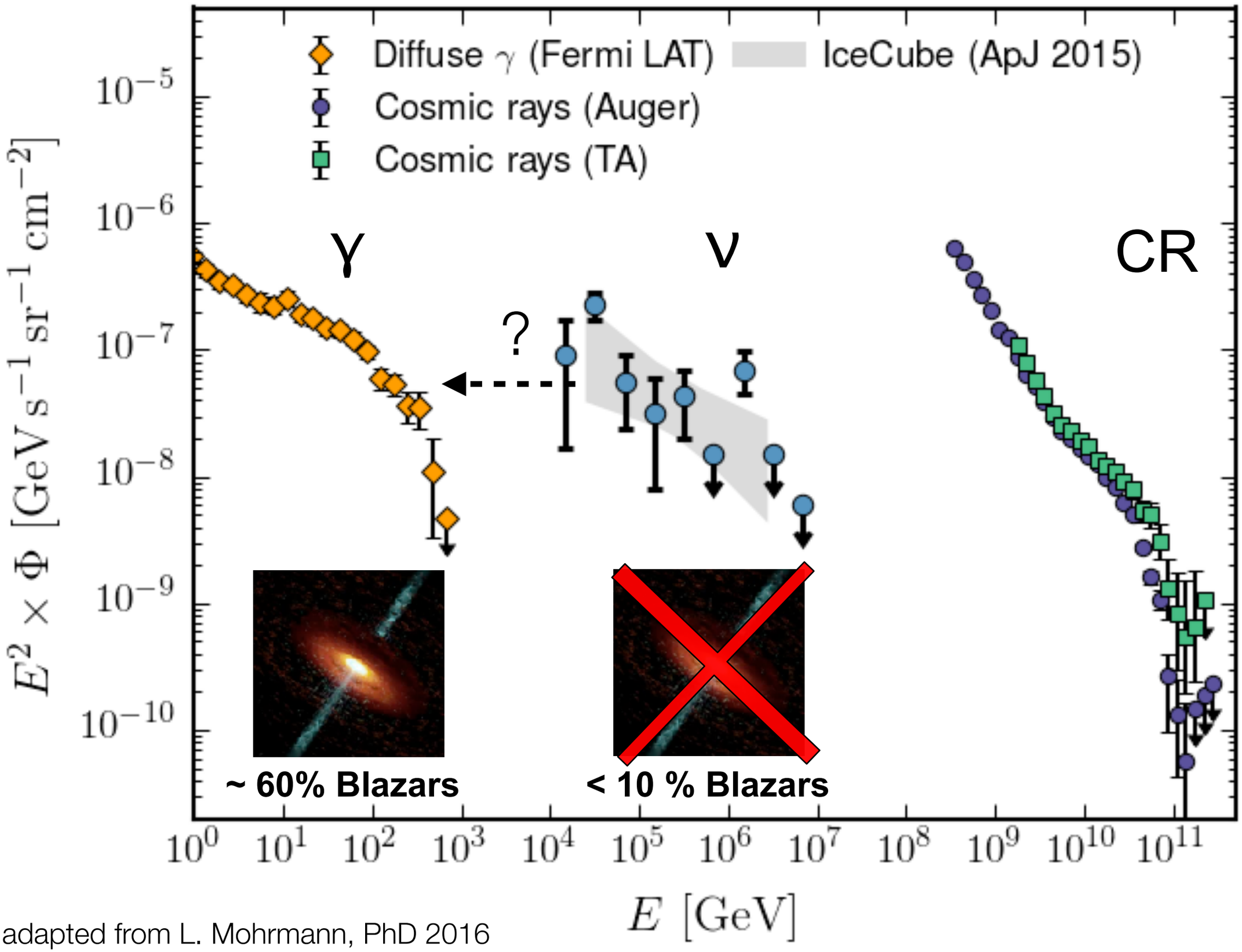
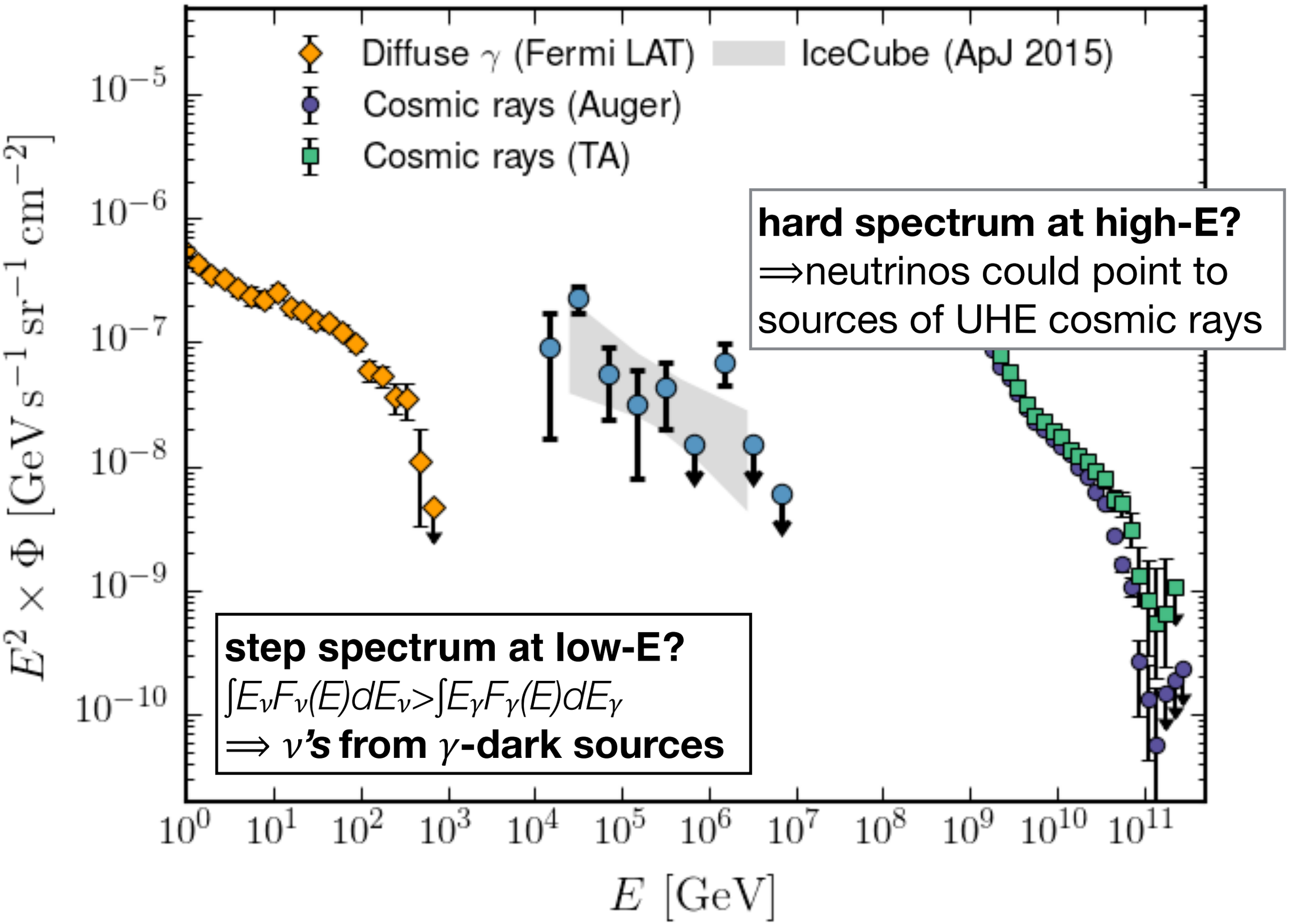


Fig. adapted from L. Mohrmann, PhD 2016

The high-energy Universe: broader perspective



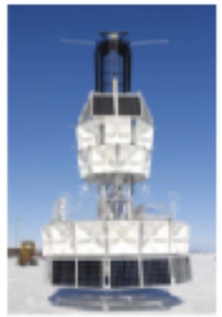
Preparing for the future

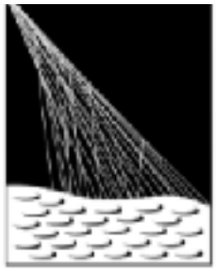
Credit: M. Wolf/NSF

Emerging tasks for high-energy neutrino astrophysics

- Resolve the sources of IceCube's high energy astrophysical neutrinos
- Identify the sources of the highest energy cosmic rays
- Decipher the production mechanisms of high energy cosmic particles
- Obtain a unique multi-messenger view into the explosion of stars and the evolution of stellar remnants
- Explore active galaxies and the very high-energy Universe when it was most active
- Study of galactic and extra galactic propagation of CR with neutrinos as tracers
- Test nuclear, neutrino and BSM physics

Future project overview



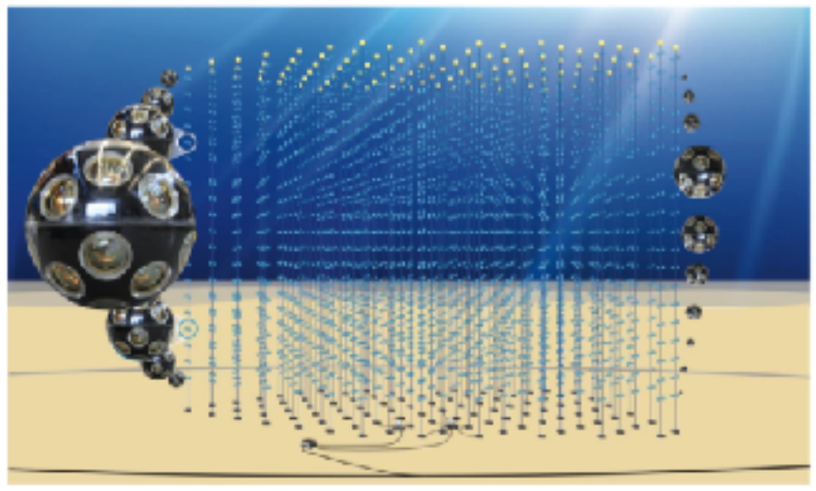


complementarity,
sensitivity to
neutrino sources
"~~precision~~ frontier"

Northern

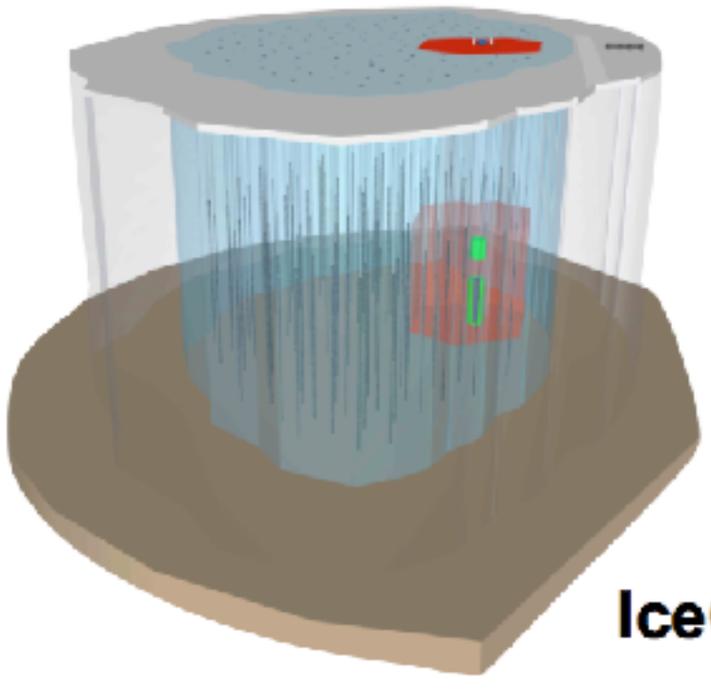
sensitivity at EeV
and beyond
"energy frontier"

Present neutrino detectors

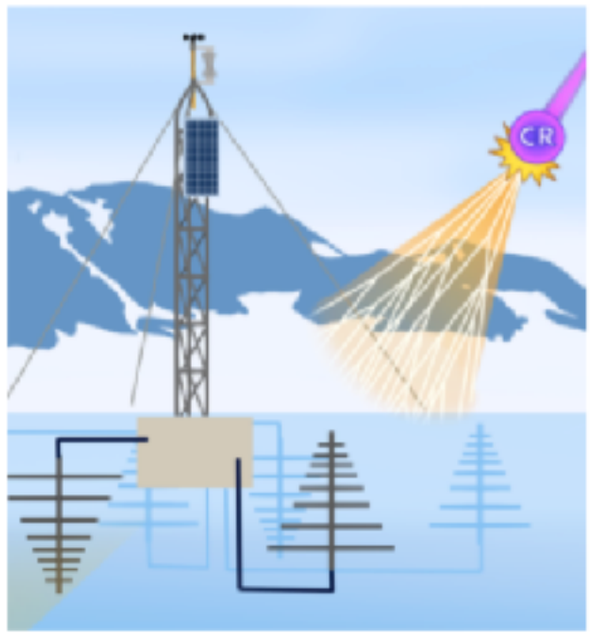


KM3NeT, GVD

sensitivity at
PeV energies
"intensity frontier"



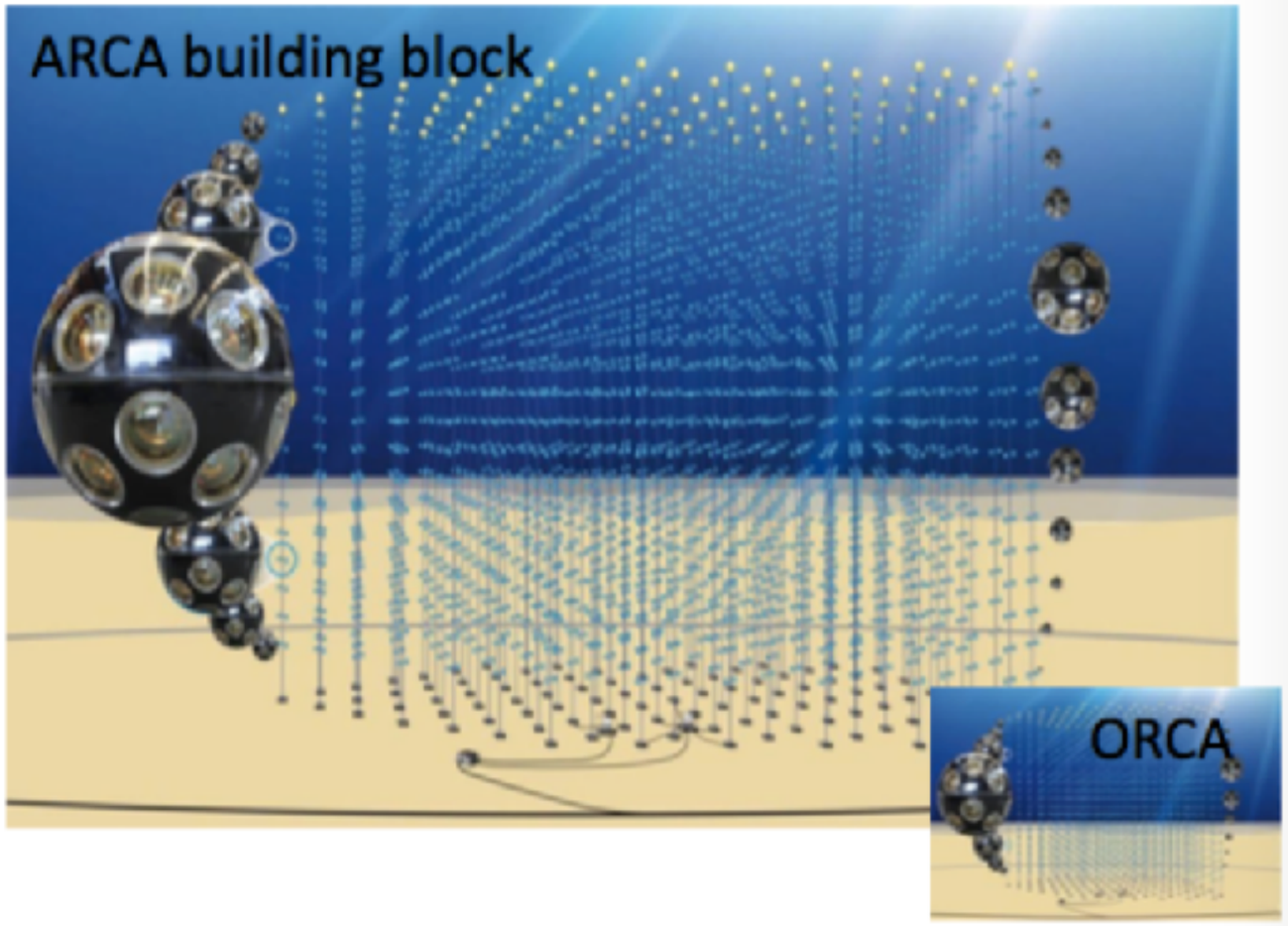
IceCube-Gen2



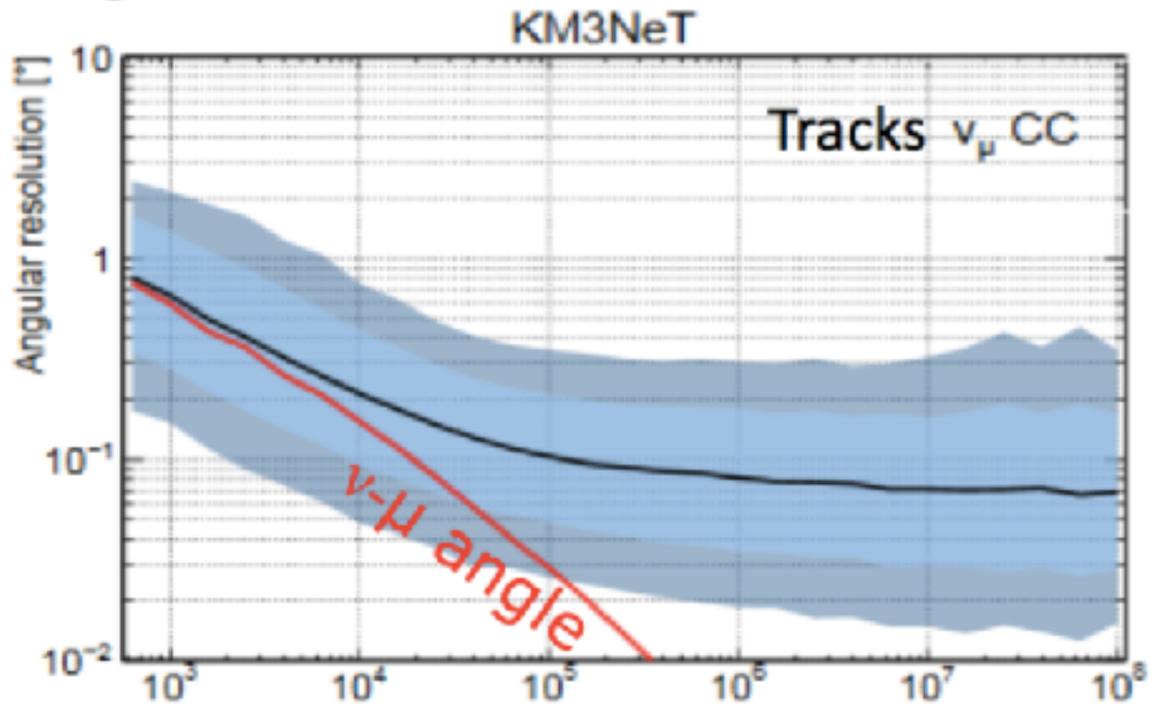
**ARA, ARIANNA,
EVA, GRAND**

credit: M. Ackermann

KM3NeT



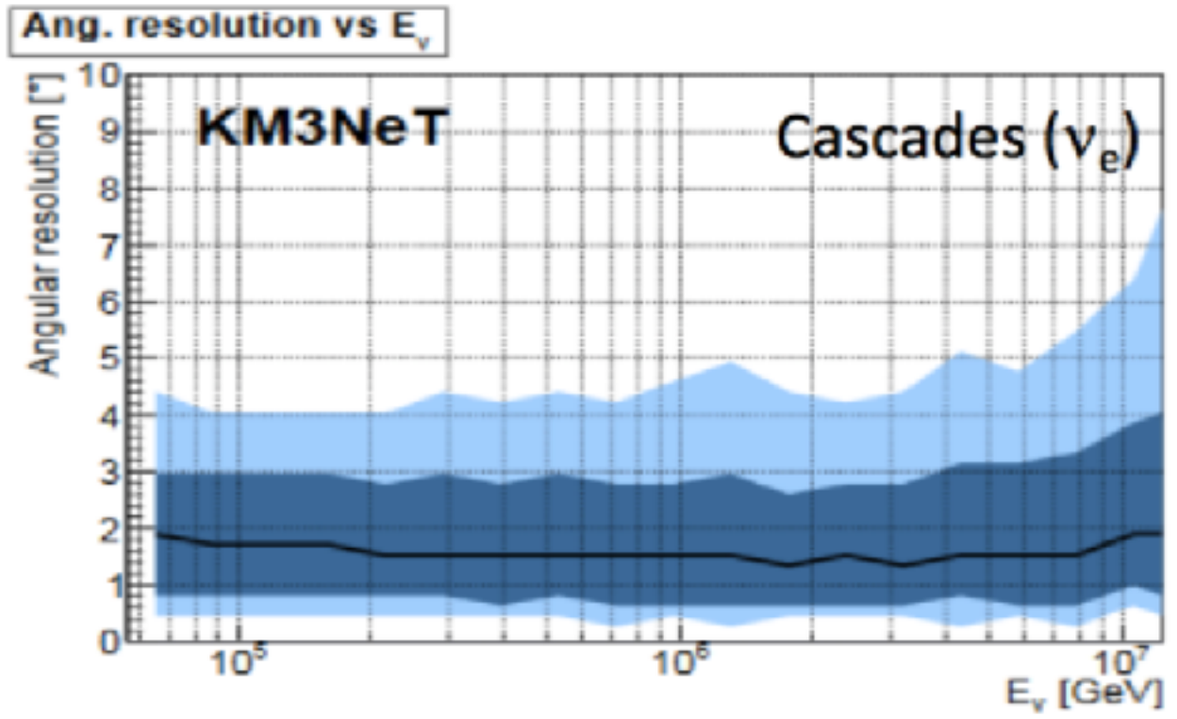
Opposite hemisphere to IC, similar energy range, but better angular resolution



KM3NeT 2.0 under construction

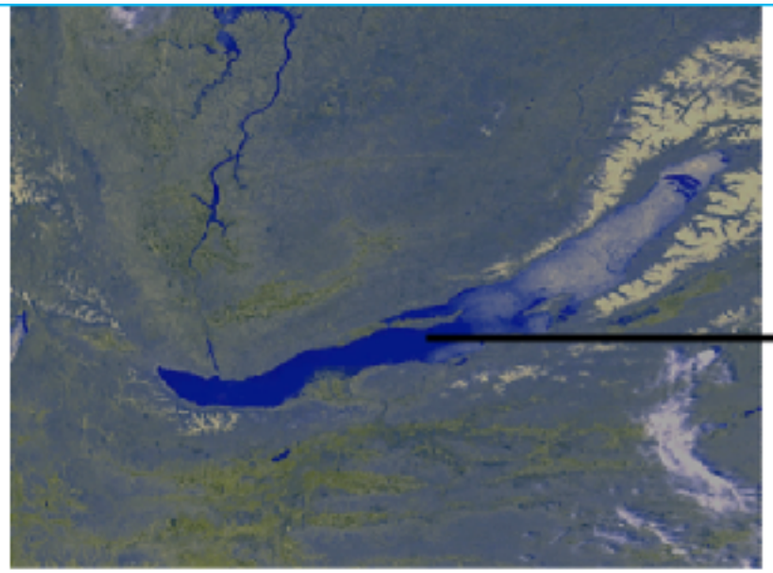
Two sub-arrays:

- **ARCA**: 2 sparse building blocks in Italy for cosmic neutrinos
- **ORCA**: 1 dense building block in France for oscillation

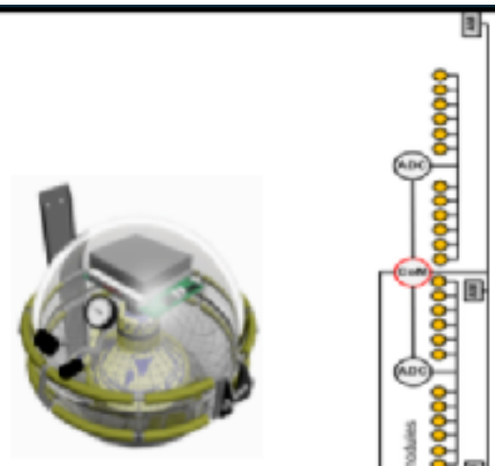


https://arxiv.org/abs/1601.07459

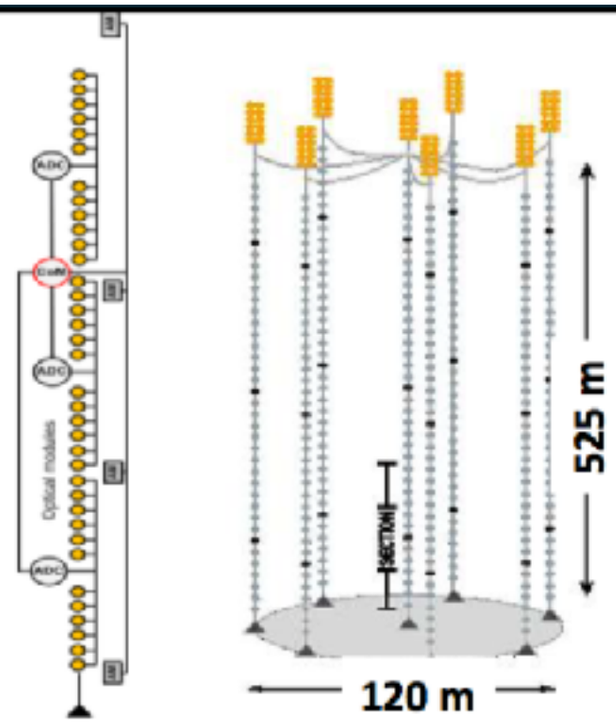
Giant Volume neutrino Detector (GVD)



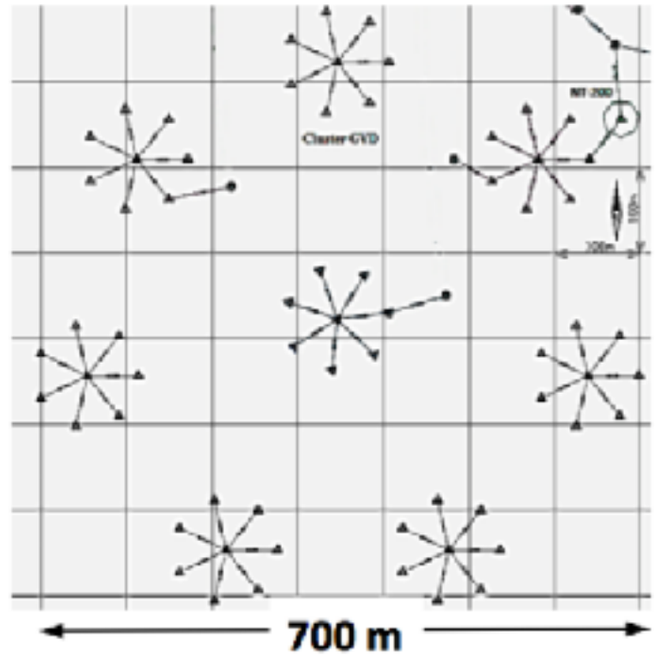
- Located at Lake Baikal
- 2 out of 8 clusters installed and operational



Optical module



String: 36 OMs Cluster: 8 strings



GVD-1: 8 clusters

	GVD-1	GVD-4
OMs	2304	10368
Clusters (8 Strings)	8	27
Depths, m	750 – 1275	600 – 1300
Eff. Volume (E_{SH} > 100 TeV)	0.4 km^3	1.5 km^3

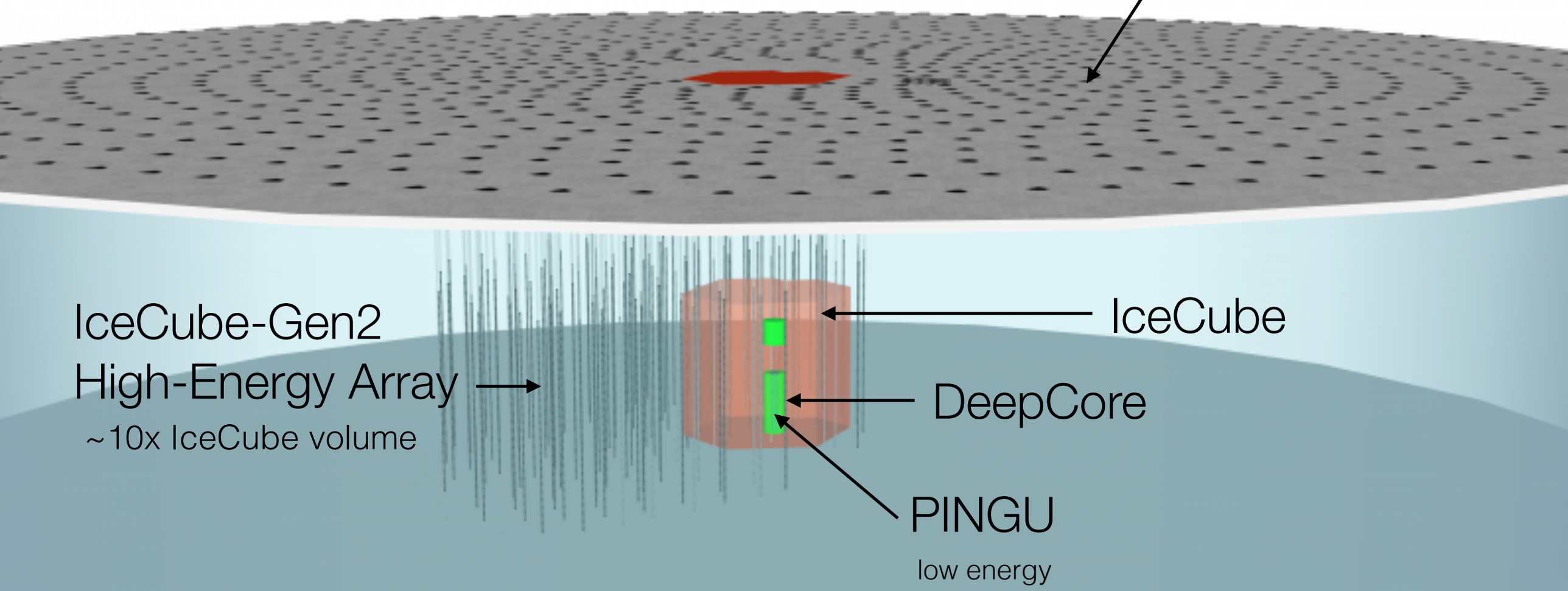
Directional resolution
Cascades: 3° – 5°
Muons: 0.25°

The IceCube-Gen2 facility

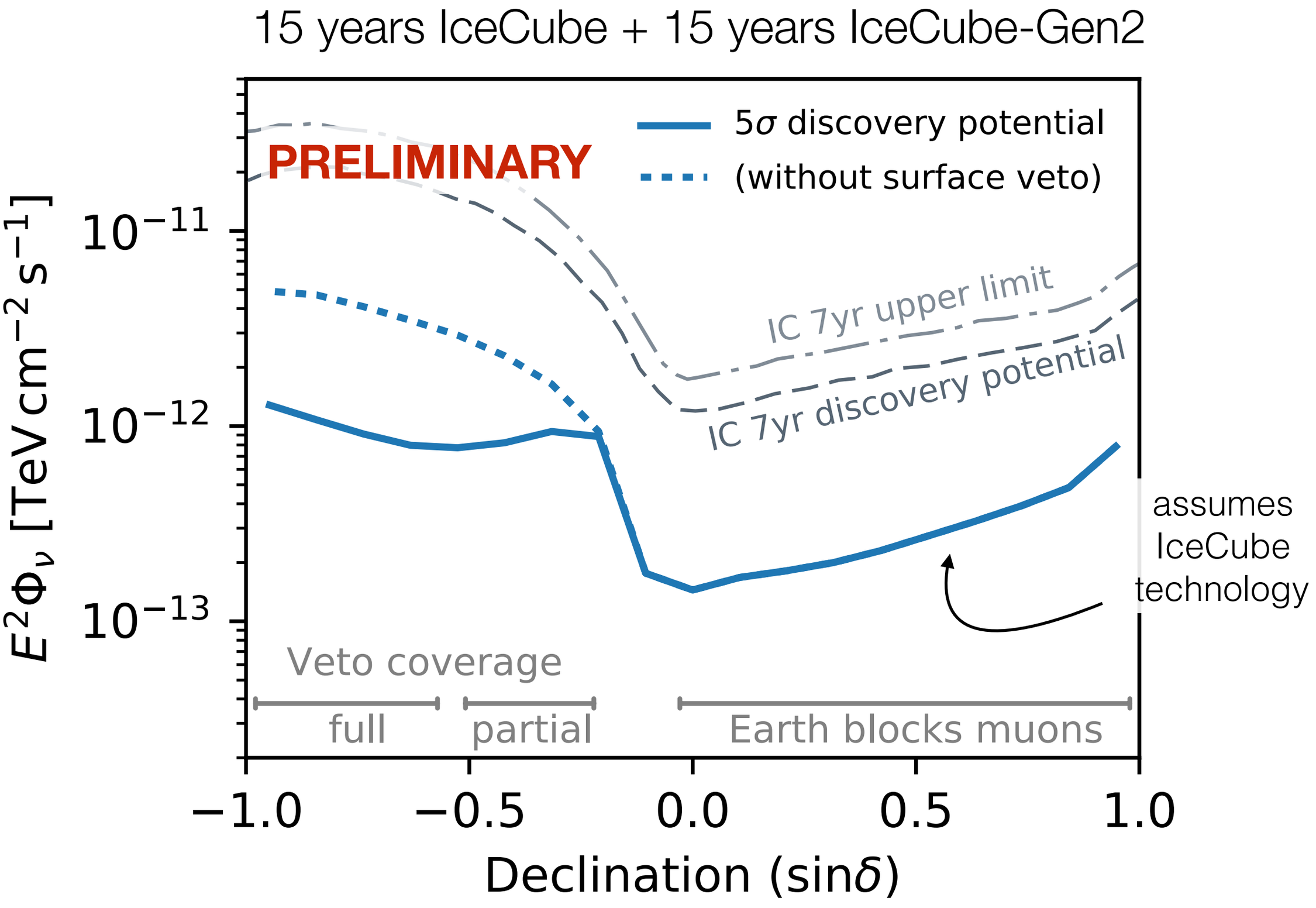
A wide band neutrino observatory (MeV – EeV) using several detection technologies – optical, radio, and surface veto – to maximize the science

Multi-component observatory:

- IceCube-Gen2 High-Energy Array
- Surface air shower detector
- Sub-surface radio detector
- PINGU



Identifying the sources of IceCube's neutrinos



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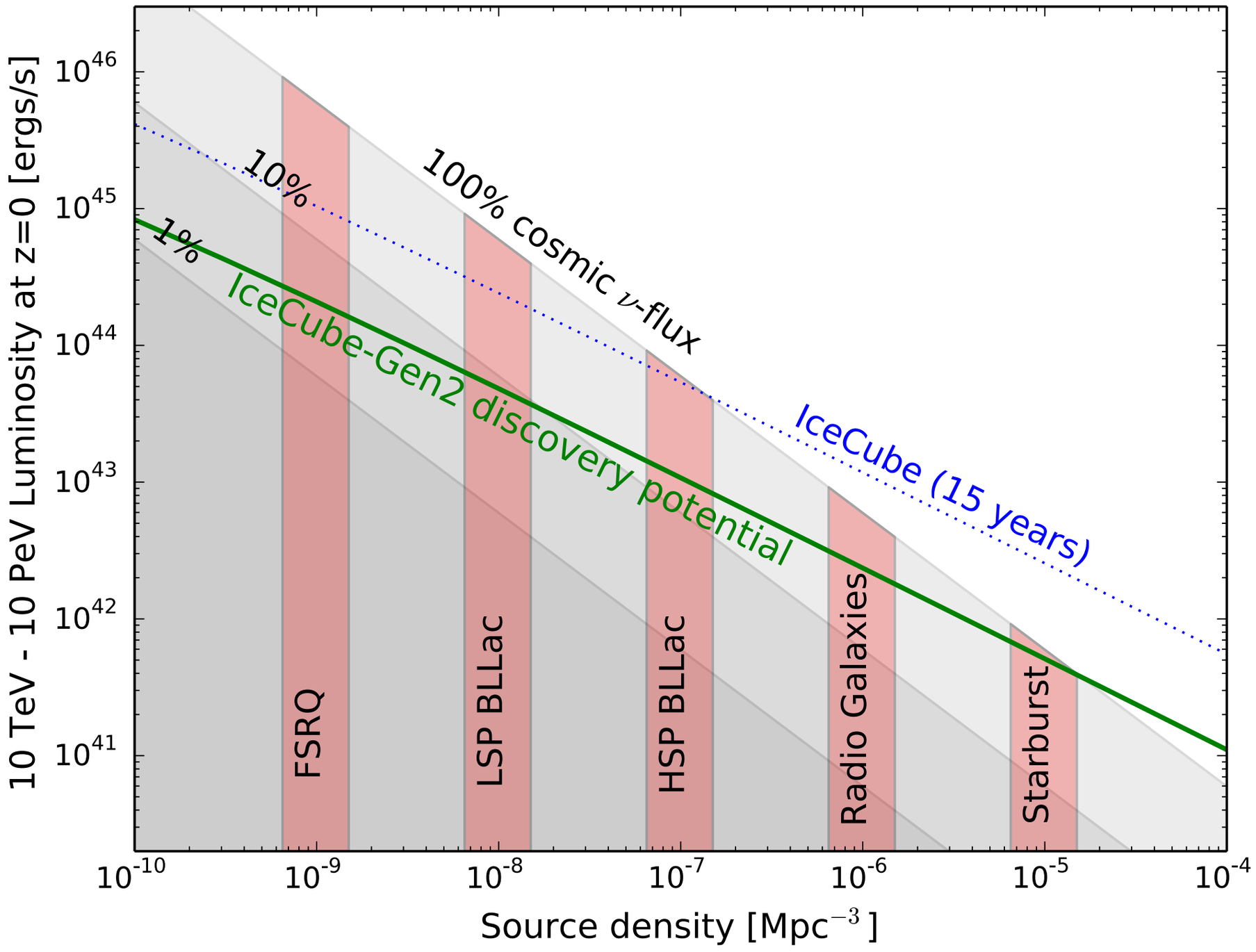
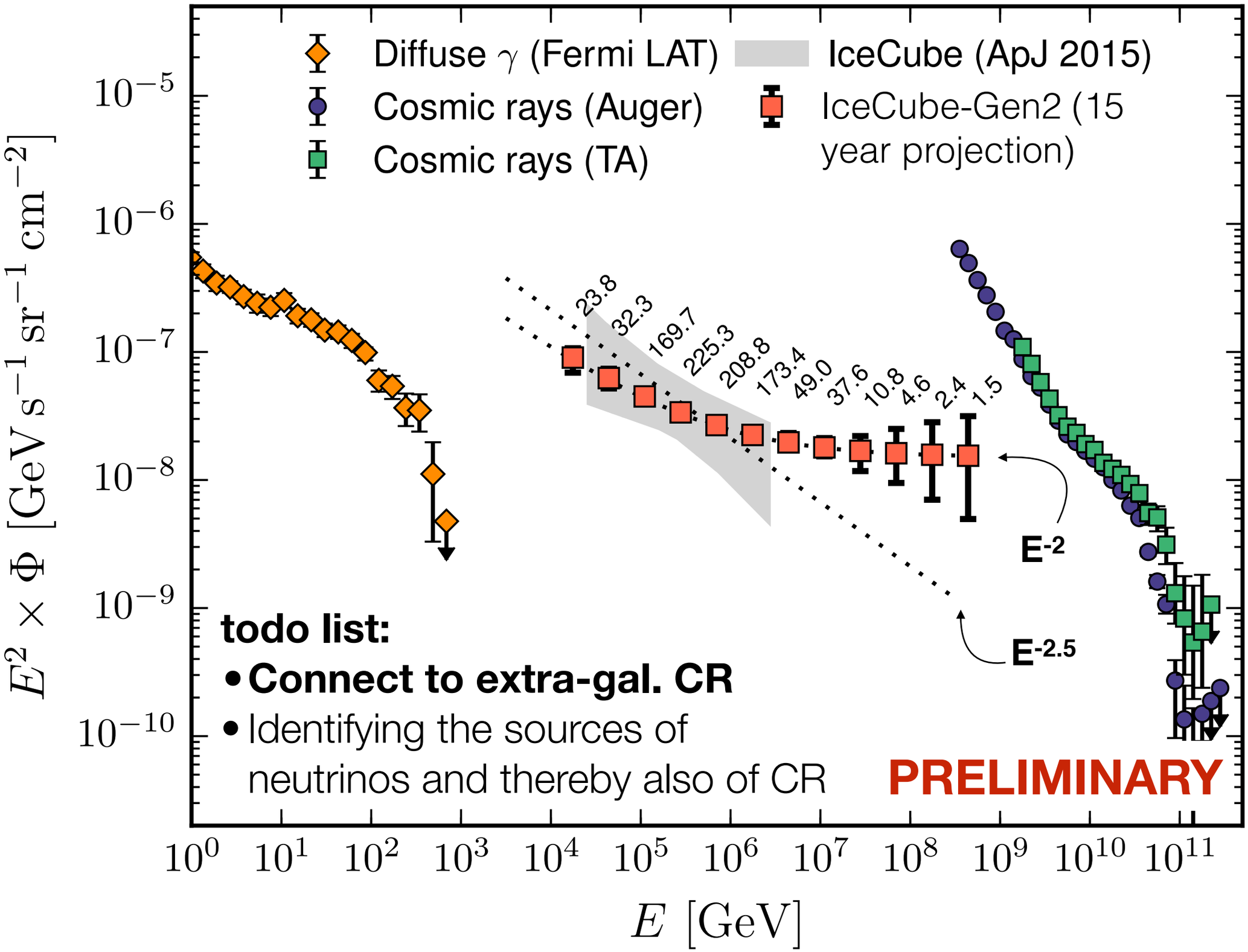


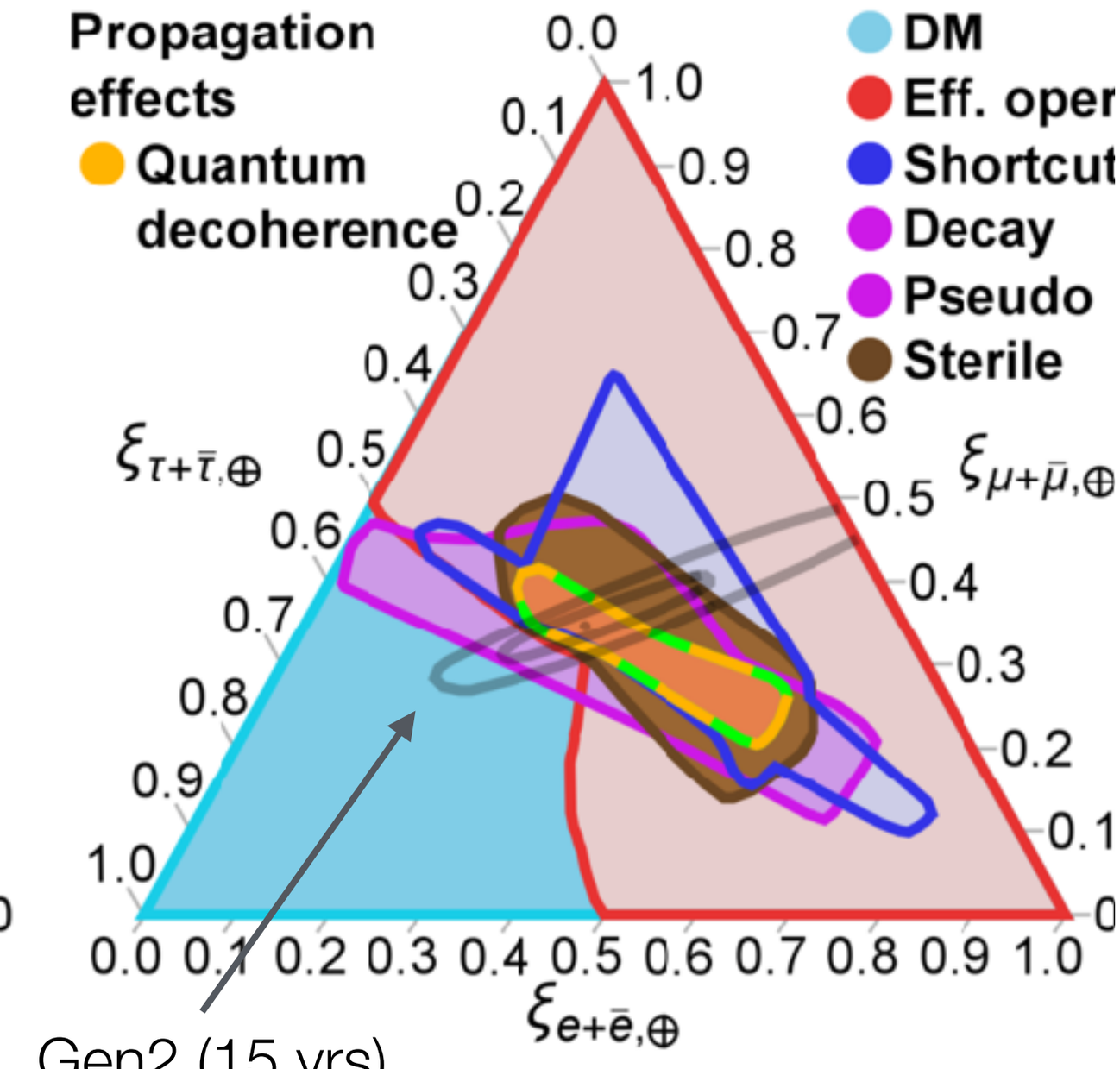
IC-Gen2 will have sufficient sensitivity to detect all reasonable source scenarios

*Sensitivity for source catalog search

Connecting HE neutrinos to UHE cosmic rays



Flavor triangle and BSM physics

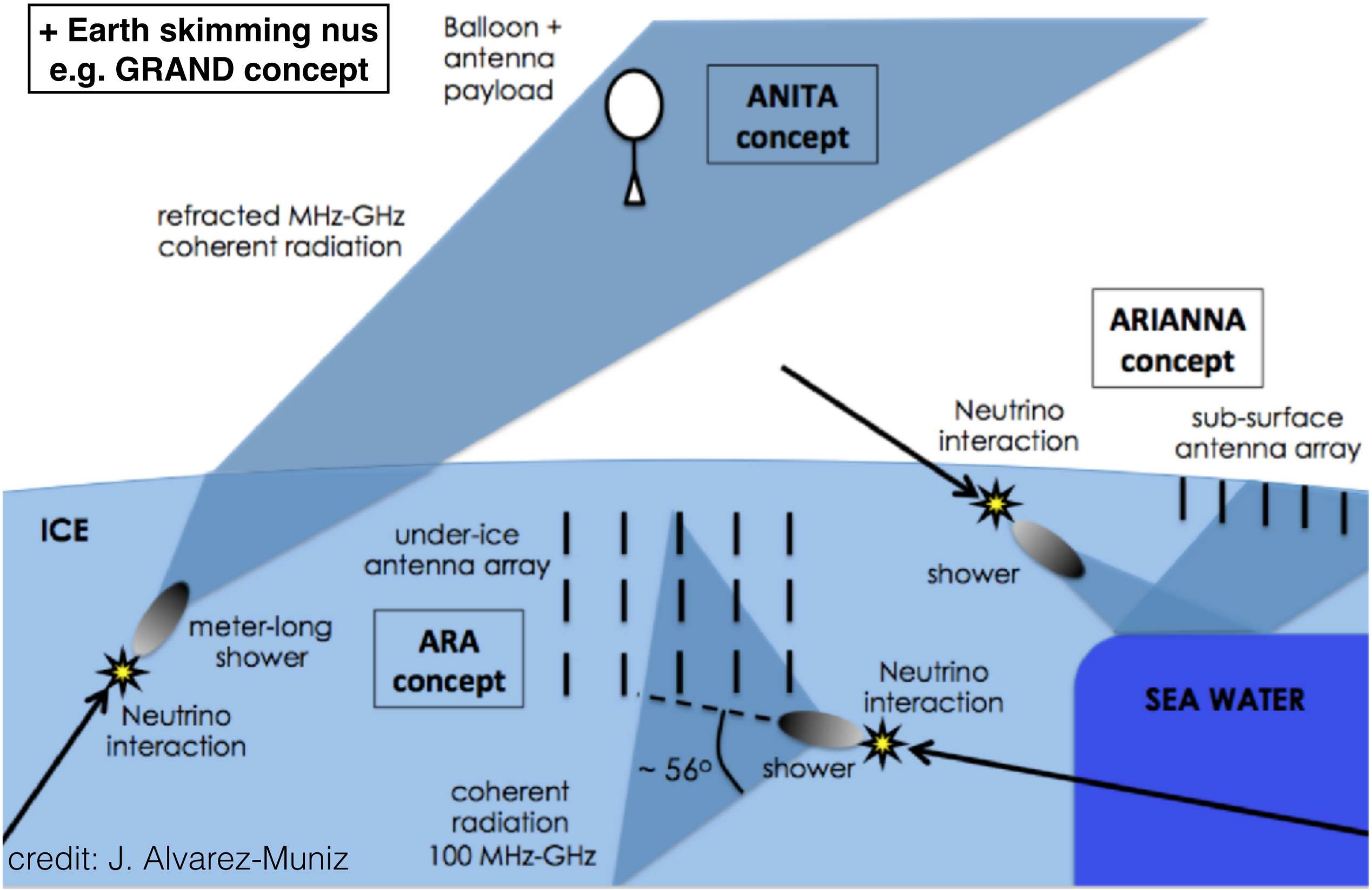


Gen2 (15 yrs)

Scenario	Exclusion by IceCube	Exclusion by IceCube-Gen2
Complete flavor triangle	42%	96%
Standard mixing	2%	73%
Non-standard neutrino production	17%	93%
NSI at production	5%	84%
Matter effetcs	0%	71%
Pseudo-Dirac neutrino	14%	85%
Decay	14%	85%
Quantum decoherence	2%	73%
Sterile neutrino	10%	86%
Effective operator	36%	94%
Interaction with DM	42%	96%
Shortcut through extra dimension	11%	80%
NSI in Earth matter	30%	92%
NSI at detection	11%	89%

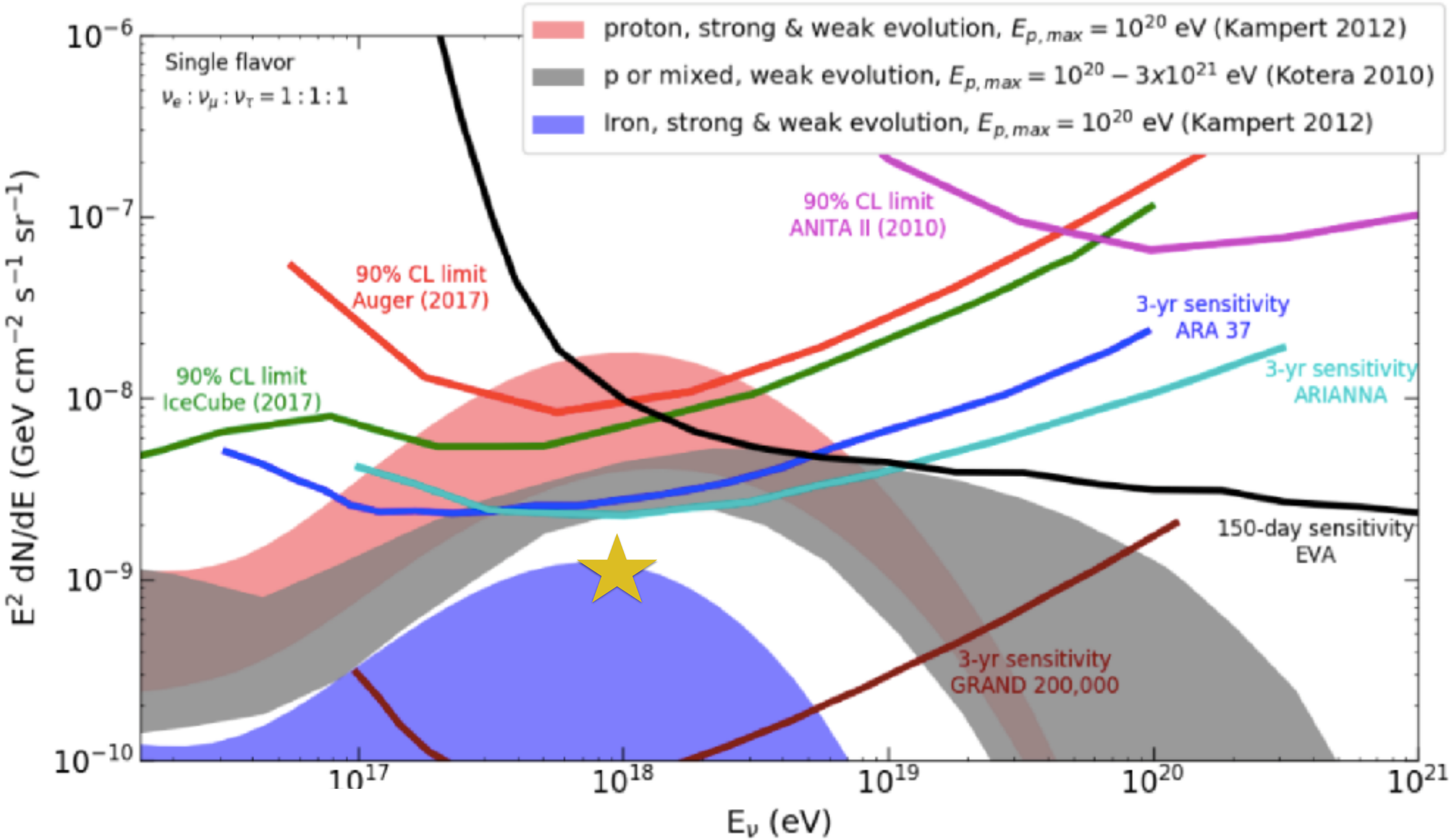
Rasmussen et al. (1707.07684)

Exploring the energy frontier with radio



credit: J. Alvarez-Muniz

Sensitivity of future radio detectors



Credit: J. Alvarez-Muniz

★ 10^{-9} GeV cm^{-2}s^{-1}sr^{-1} @10^{9} GeV benchmark point from Weizmann workshop 2017

Neutrino astronomy project timeline & Milestones

first Northern km^3-detector

IC upgrade (Gen2 Phase I)

20 years of IC; completion of IC-Gen2

… | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | … | 2031

IceCube Upgrade (7 string) — deployment

IC-Gen2

R&D / Design — Production — Deployment (8km^3)

KM3NeT

Prod. & Deployment — ARCA (2 blocks, 1.2km^3)

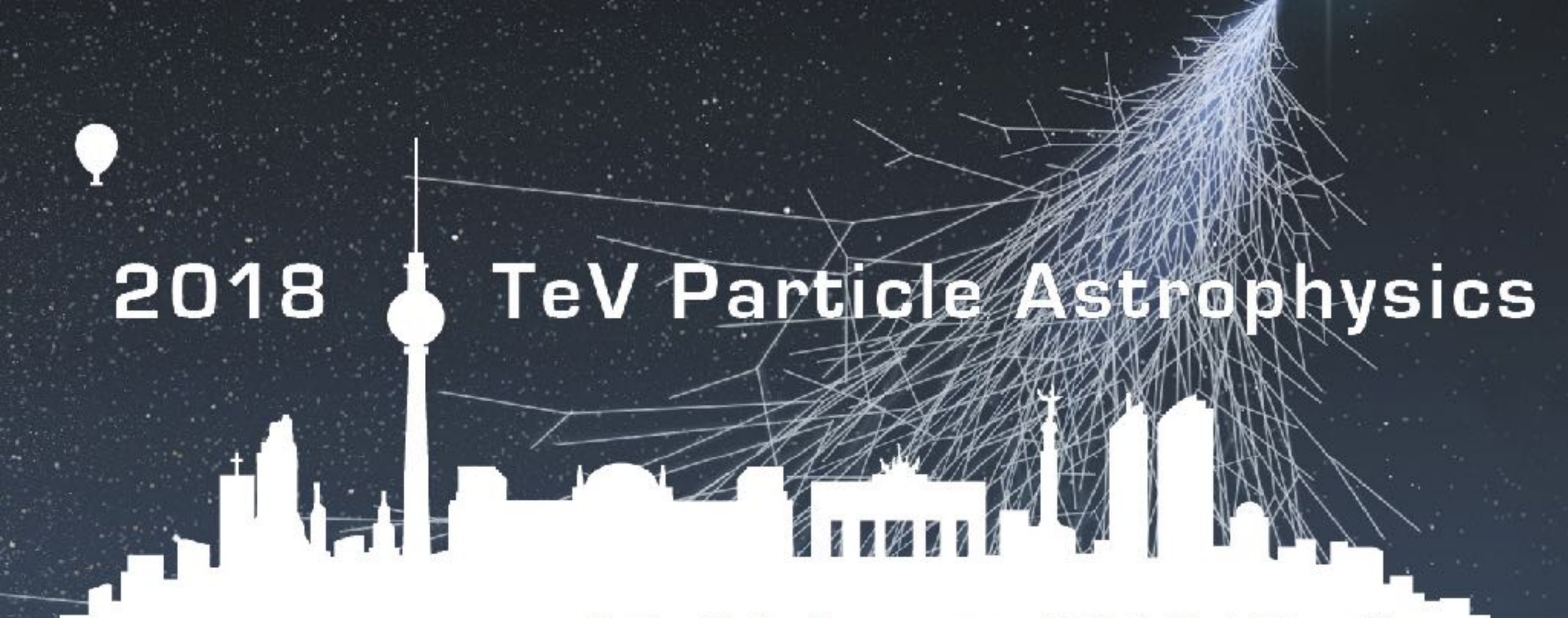
Prod. & Deploy — ORCA

GVD

Prod. & Deploy — (8 clusters, 0.4km^2)

Conclusions

- High-energy extra-galactic neutrinos observed, opening a unique view on the high-energy Universe
- Sources not yet resolved, new multi-messenger methods have the potential to provide the answer
- As old questions are answered, new ones emerge, i.e. the spectrum appears to be complex
- Construction and Planning of new projects underway to cover full sky and large energy range, optimized for neutrino astronomy in the next decades



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