HELMHOLTZ
ASSOCIATION

DESY

Summer Blot

PRC83 HAMBURG

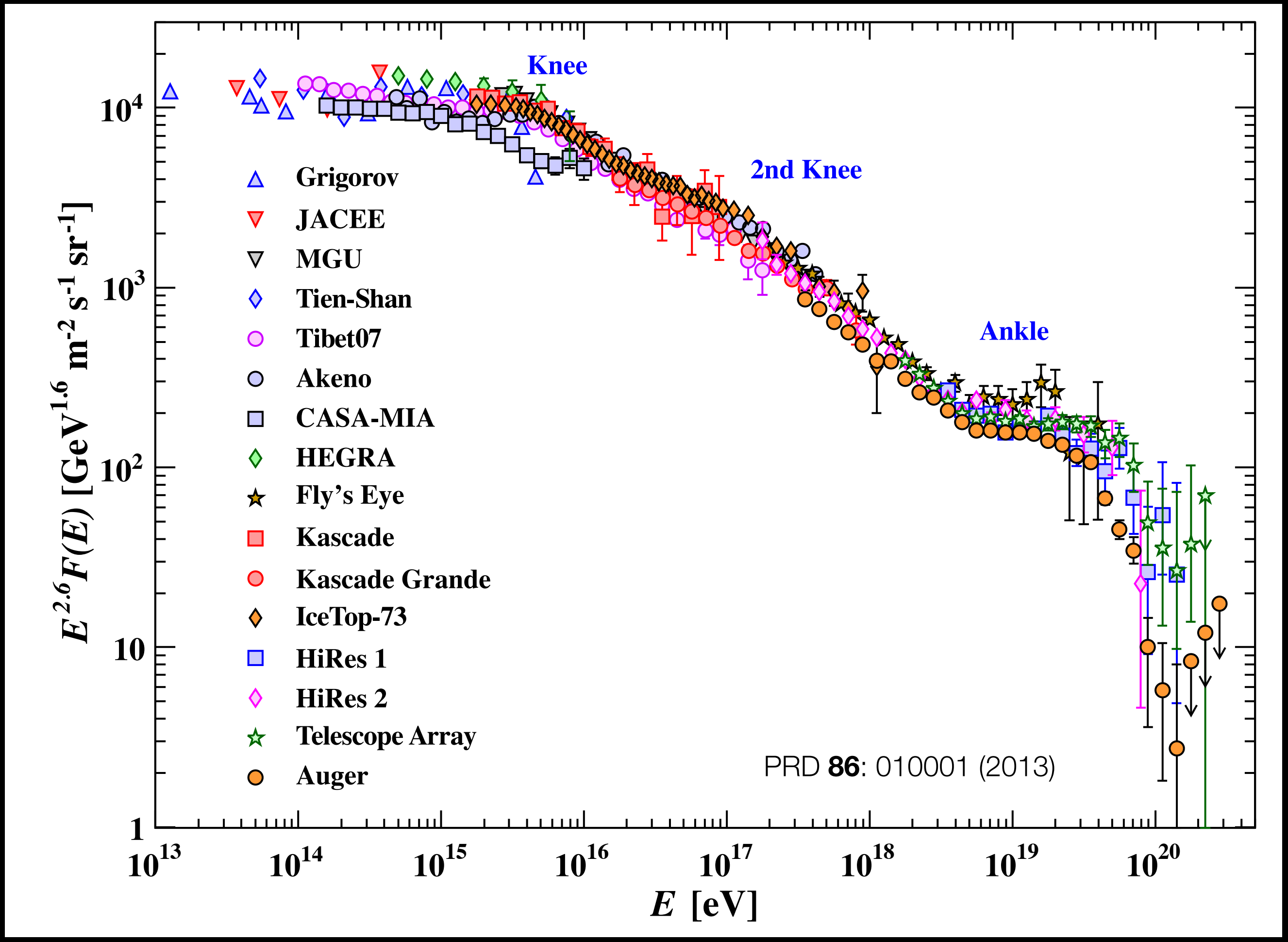
21.03.2017

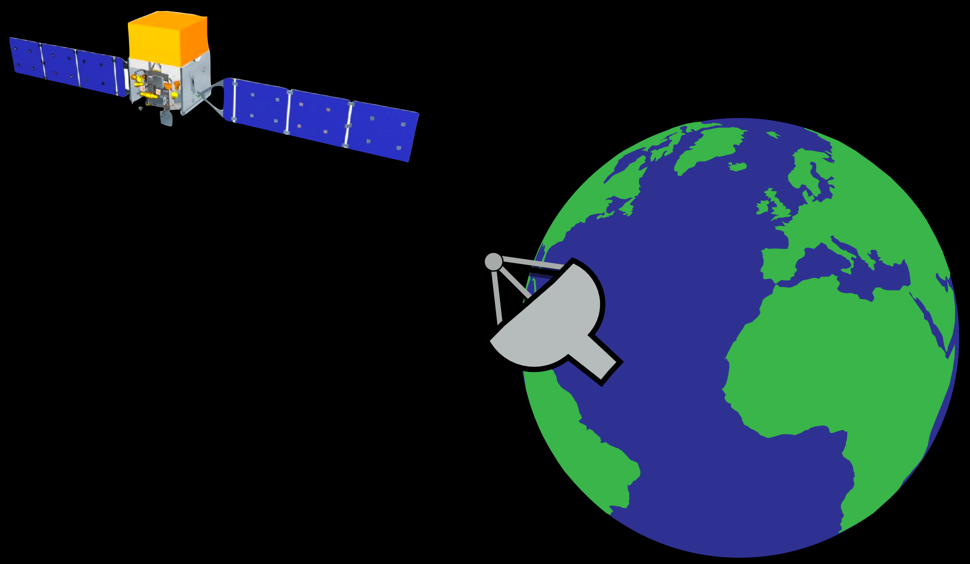
IceCube

Neutrino Astroparticle Physics

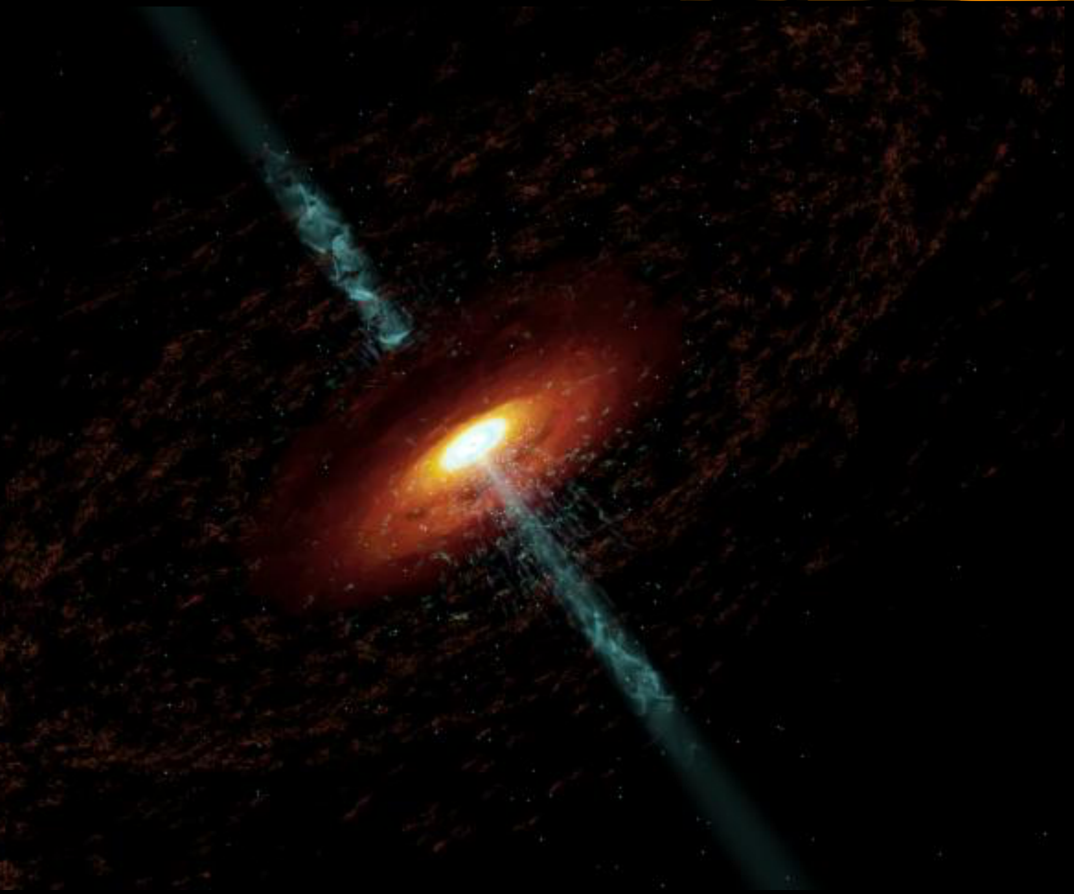
The origin of cosmic rays

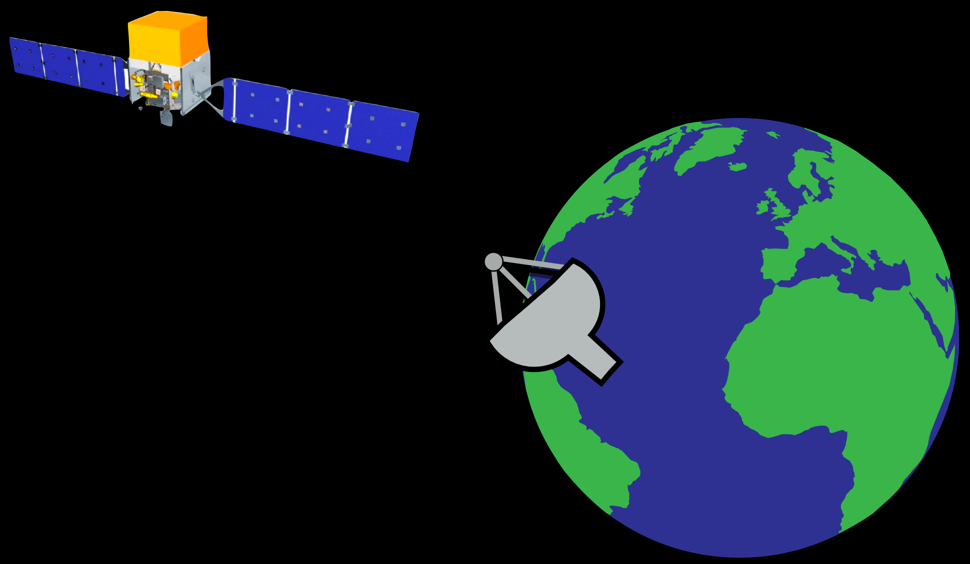
- Over the last century we have been measuring cosmic rays
- We have measured the spectrum and composition over a wide energy range
- But we don't know where they come from or understand the production/acceleration mechanisms





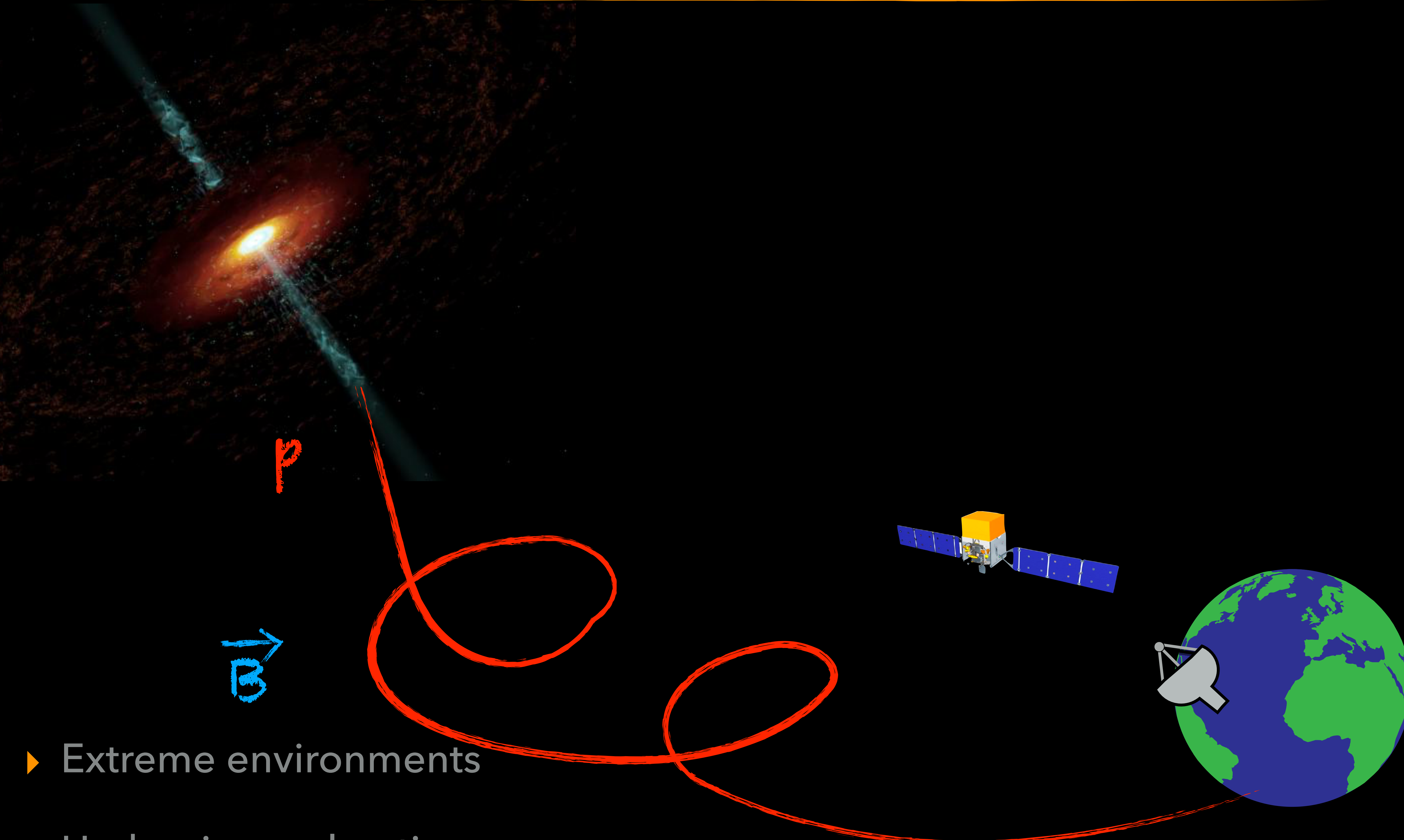
The origin of cosmic rays





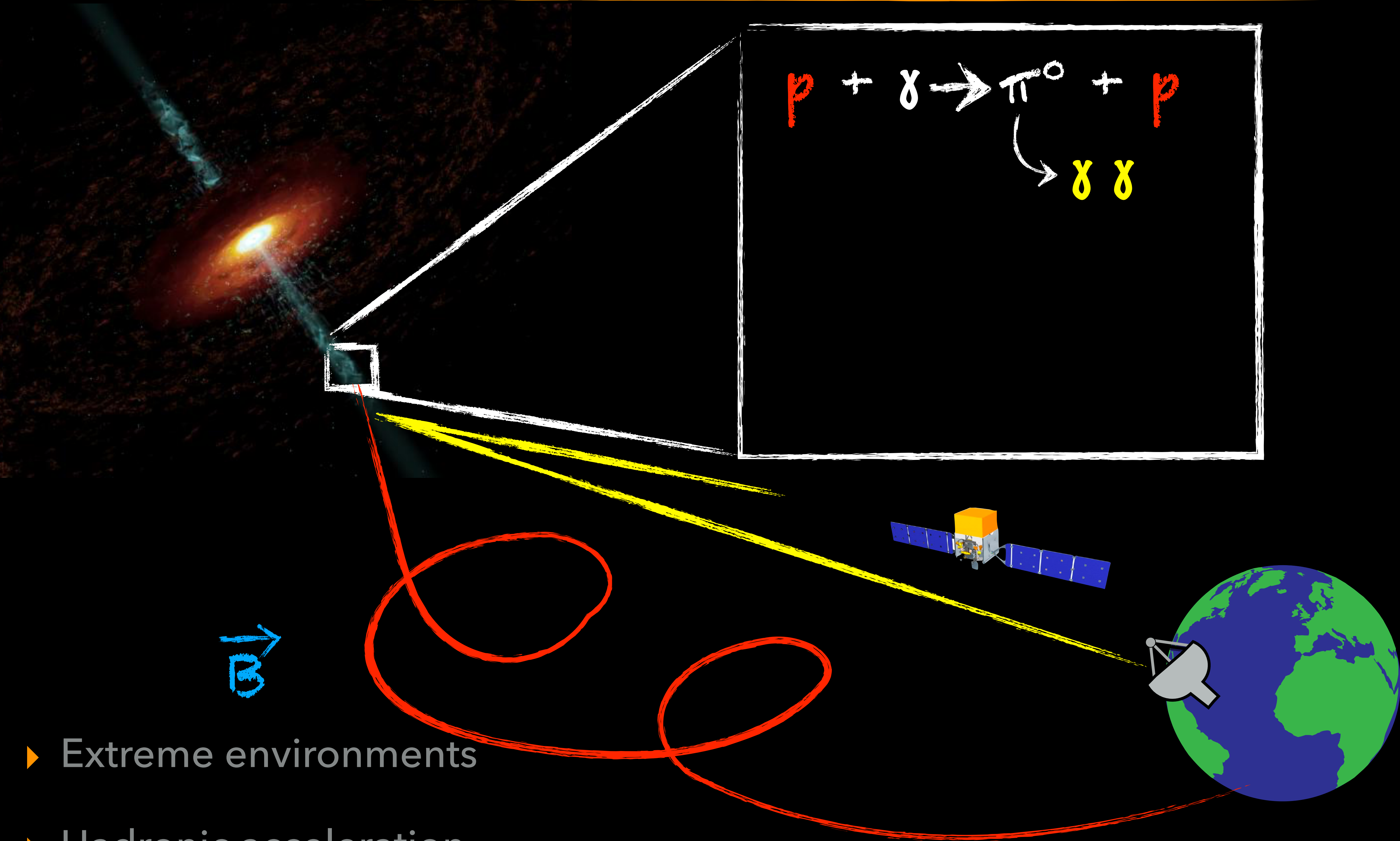
- Extreme environments

The origin of cosmic rays



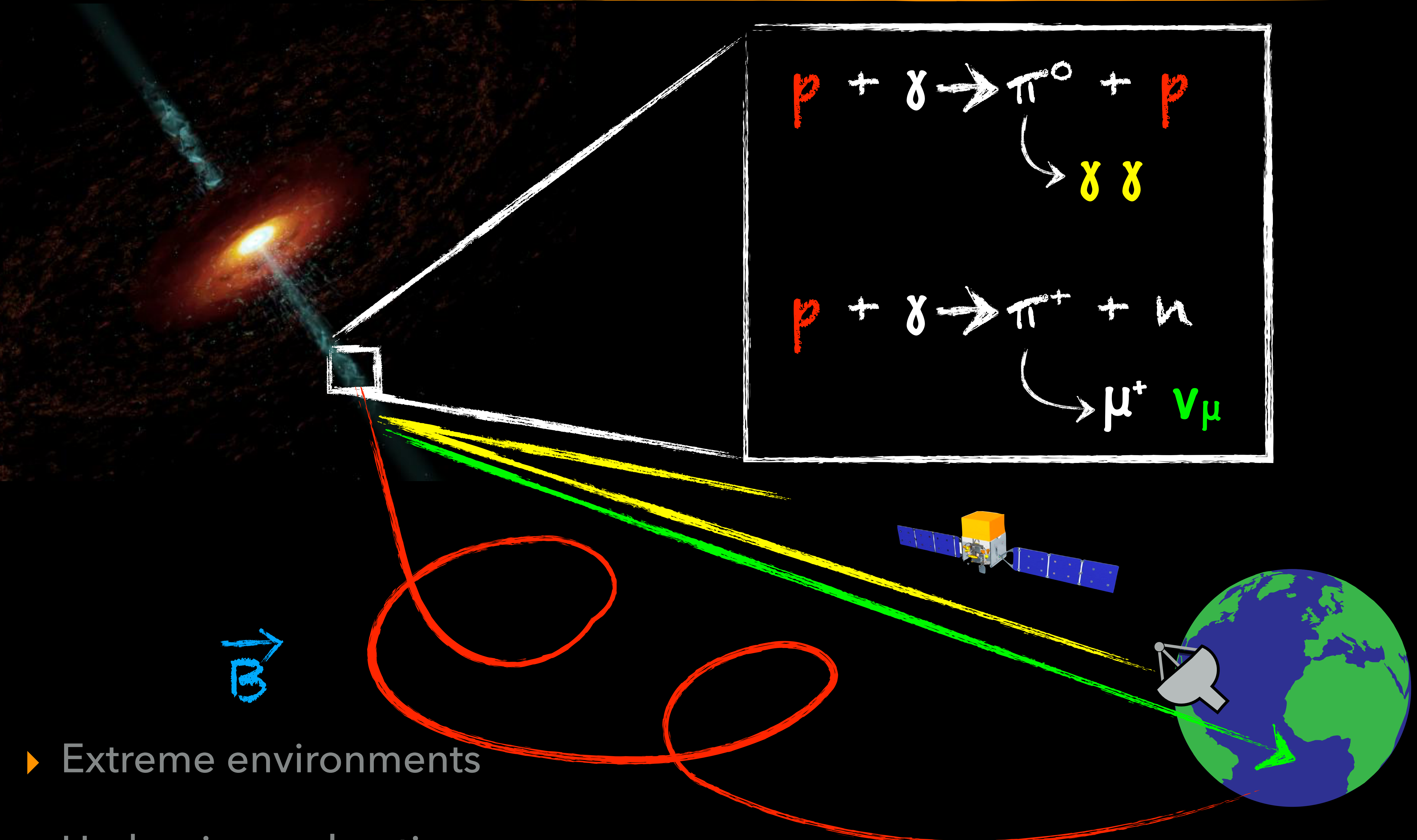
- Extreme environments
- Hadronic acceleration

The origin of cosmic rays



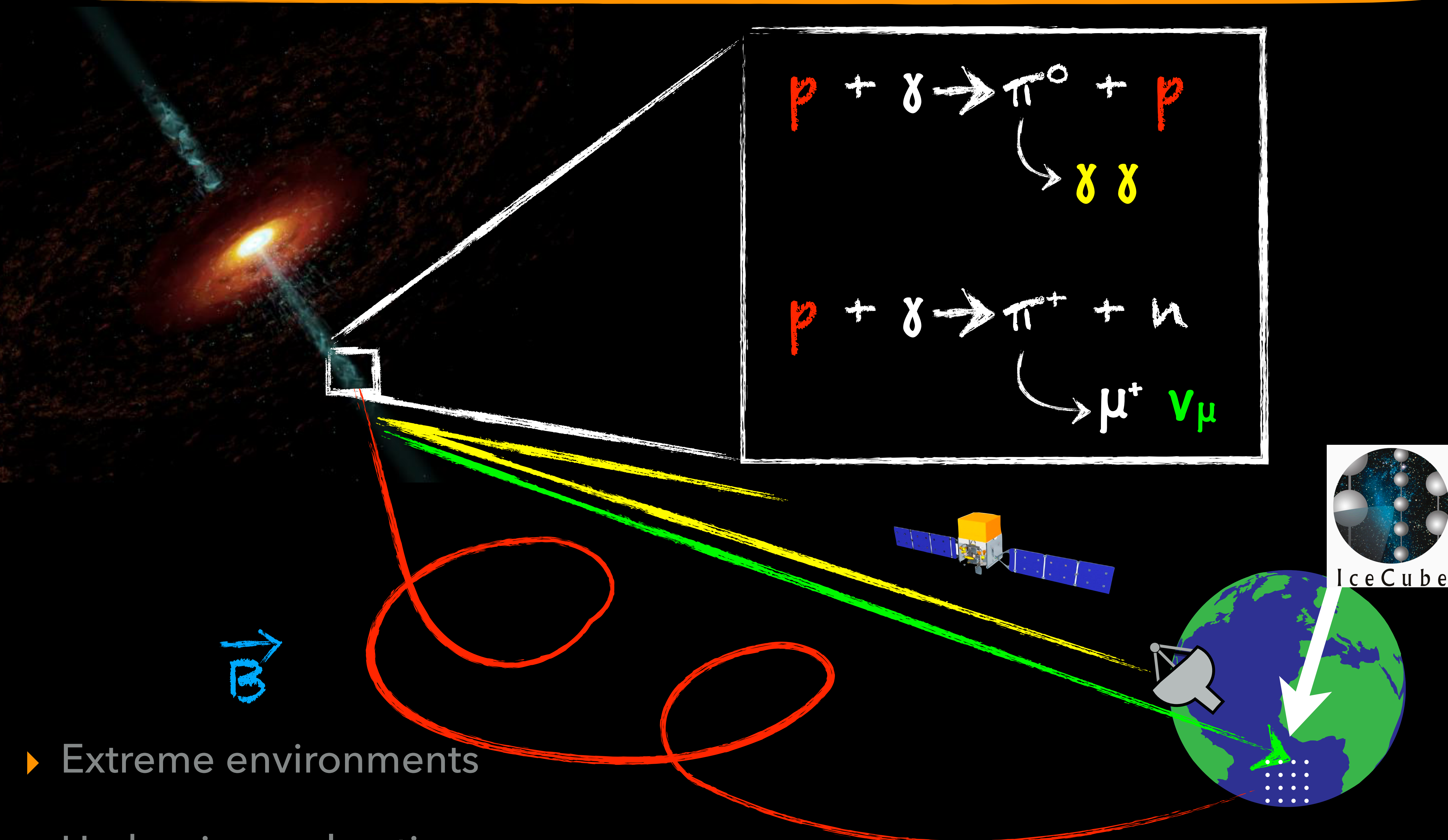
- Extreme environments
- Hadronic acceleration
- Interactions

The origin of cosmic rays



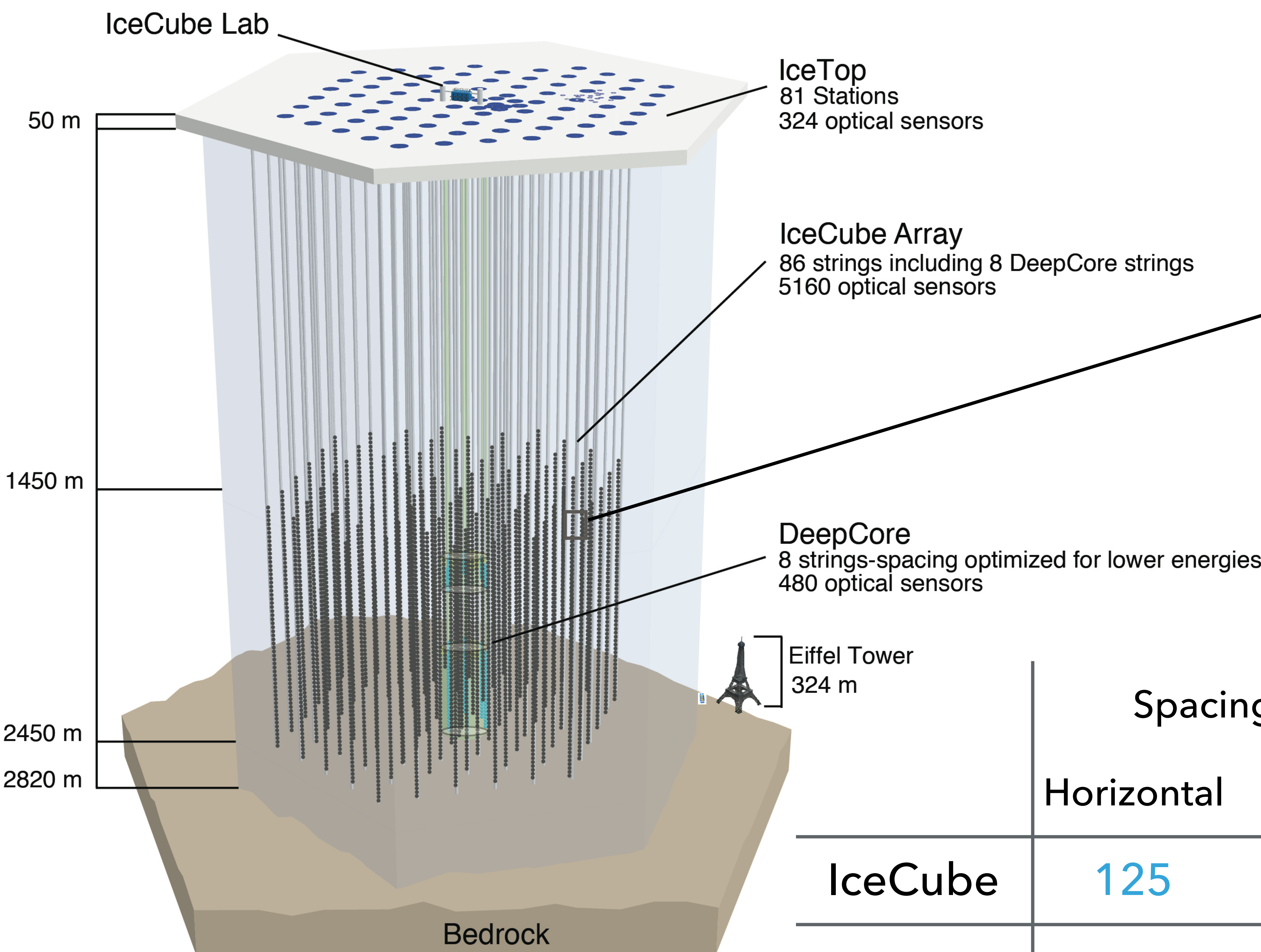
- Extreme environments
- Hadronic acceleration
- Interactions

The origin of cosmic rays



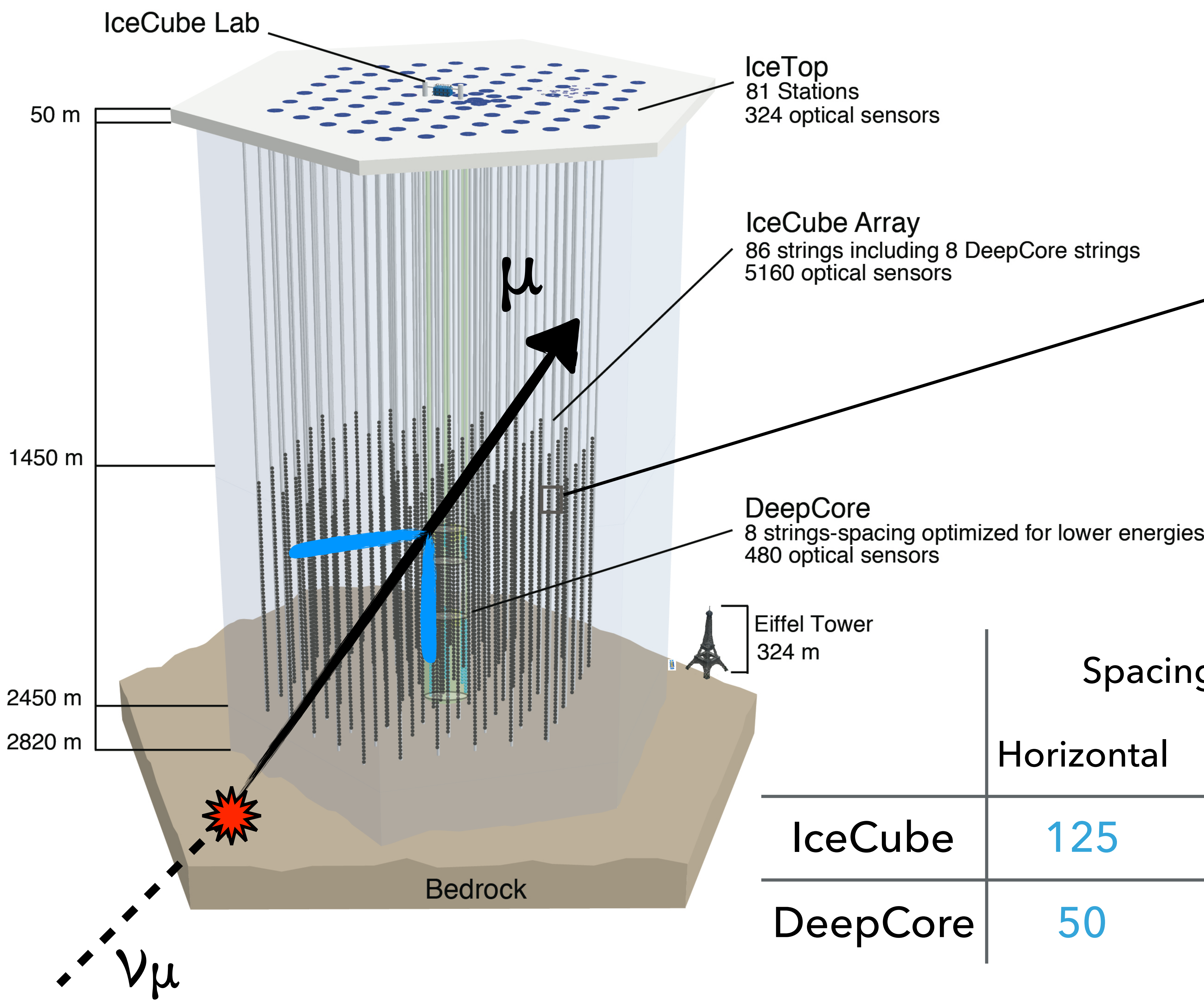
- Extreme environments
- Hadronic acceleration
- Interactions

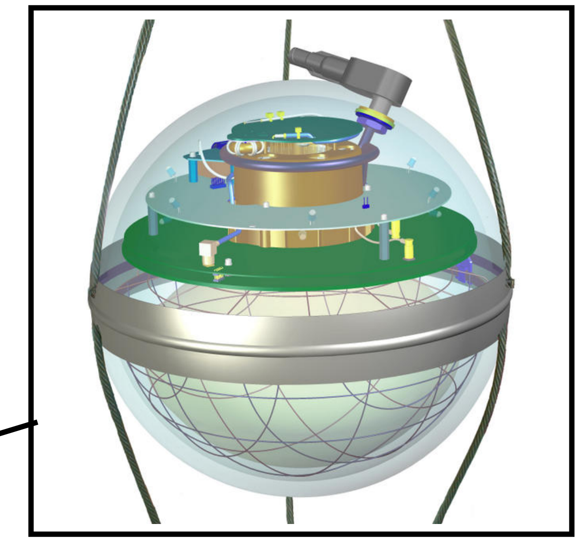
The IceCube Neutrino Observatory



	Spacing [m]		Energy threshold [GeV]
	Horizontal	Vertical	
IceCube	125	17	100
DeepCore	50	7	10

The IceCube Neutrino Observatory





	Spacing [m]		Energy threshold [GeV]
	Horizontal	Vertical	
IceCube	125	17	100
DeepCore	50	7	10

A global collaboration

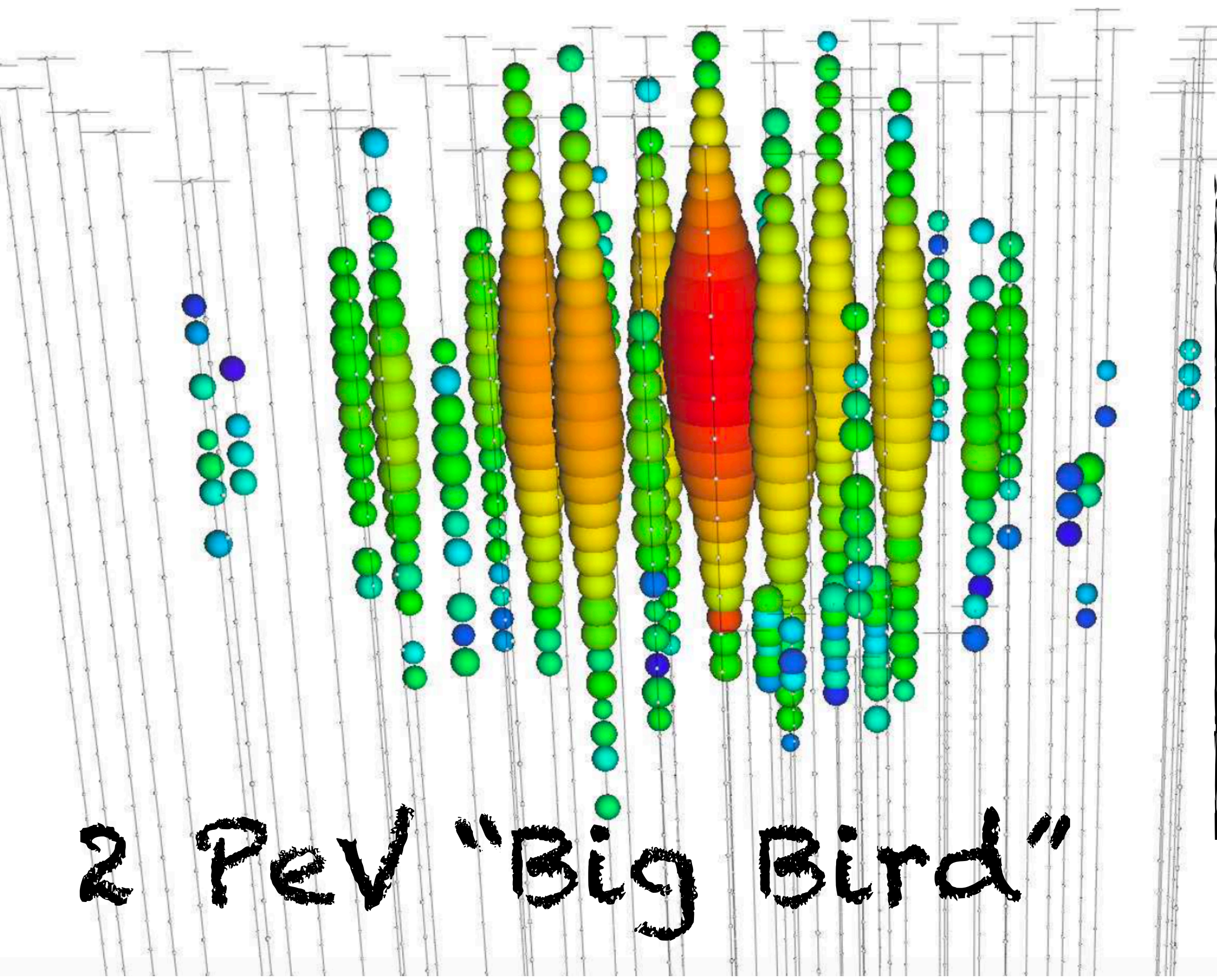
IceCube @ DESY

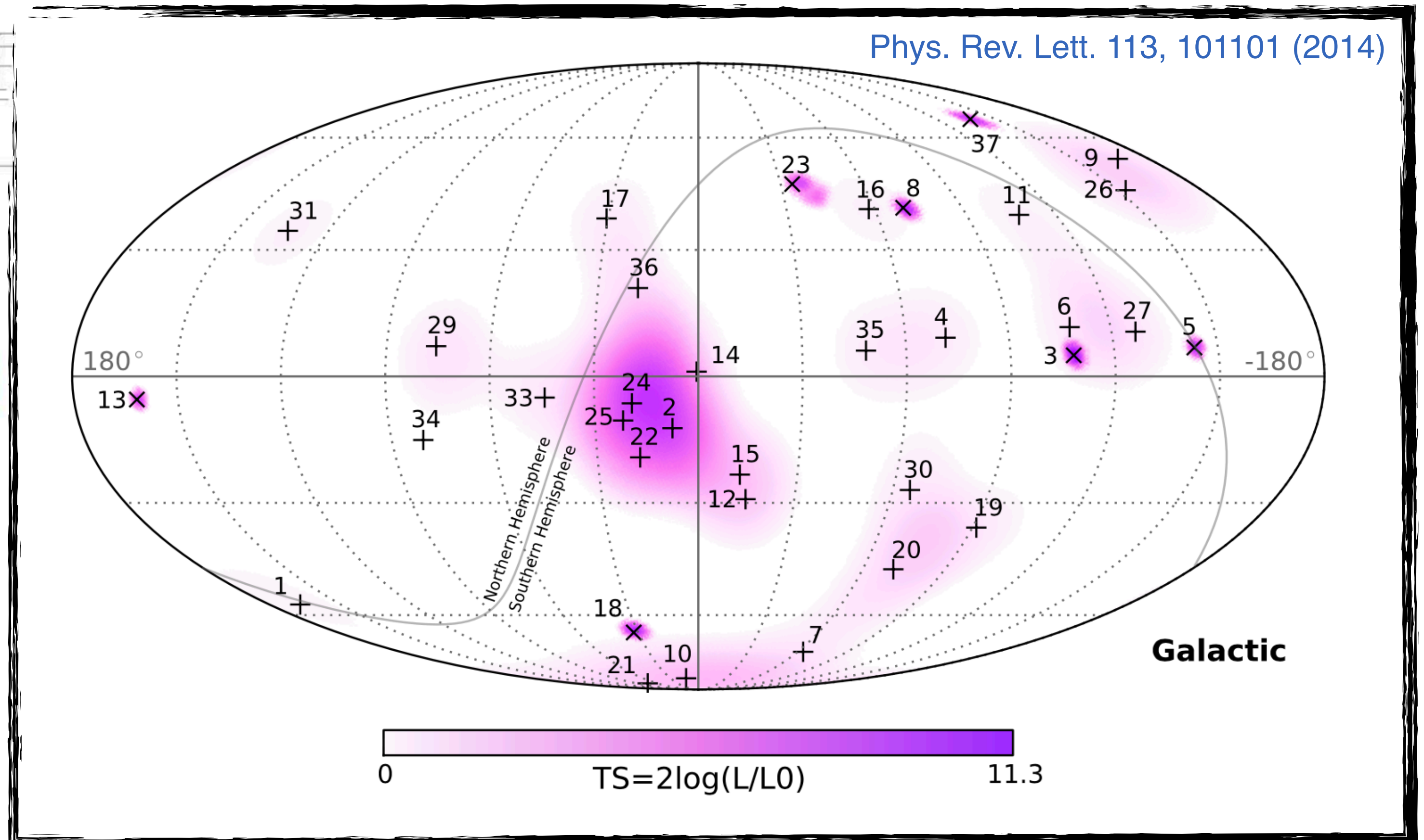
- **Origin and properties of cosmic neutrinos:** M. Ackermann, M. Usner, F. Bradascio, J. Stachurska, J. van Santen
- **Multi-messenger follow-up:** E. Bernardini, A. Franckowiak, T. Kintscher, M. Kowalski, K. Satalecka, A. Stasik, N. Strotjohann
- **Cosmic rays & IceTop upgrades:** T. Karg, S. Kunwar
- **Oscillations, sterile neutrinos:** S. Blot, A. Terliuk
- **Gen2 R&D/Sensitivity:** D. Hebecker, T. Karg, S. Kunwar, M. Kowalski, J. van Santen

5 permanent scientists, 4 postdocs, 8 PhD students

Detection of astrophysical neutrinos

- Astrophysical neutrinos detected
- No clustering of sources yet observed or correlation with any source catalogs so far
- Many other interesting things to do with these neutrinos…



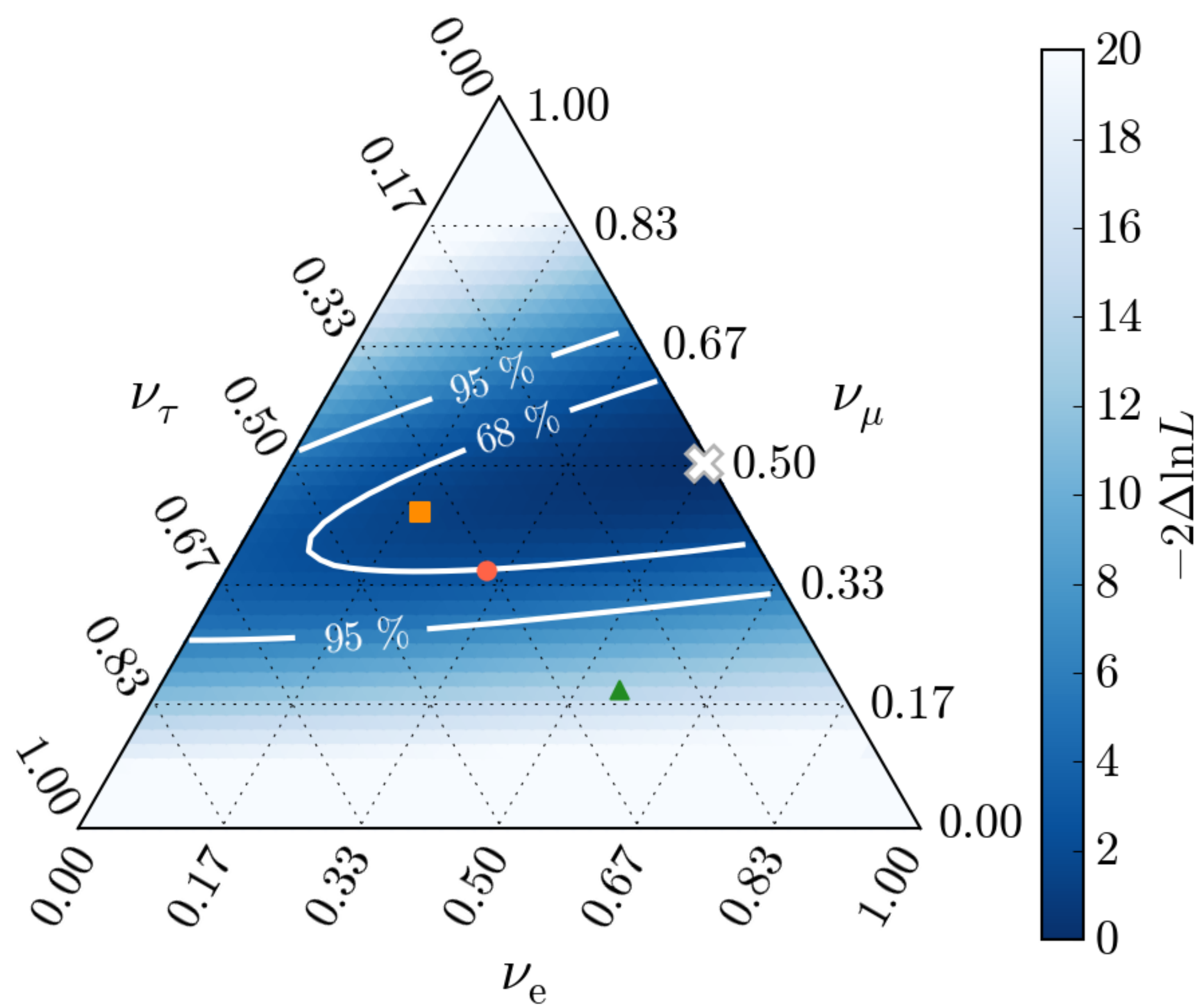


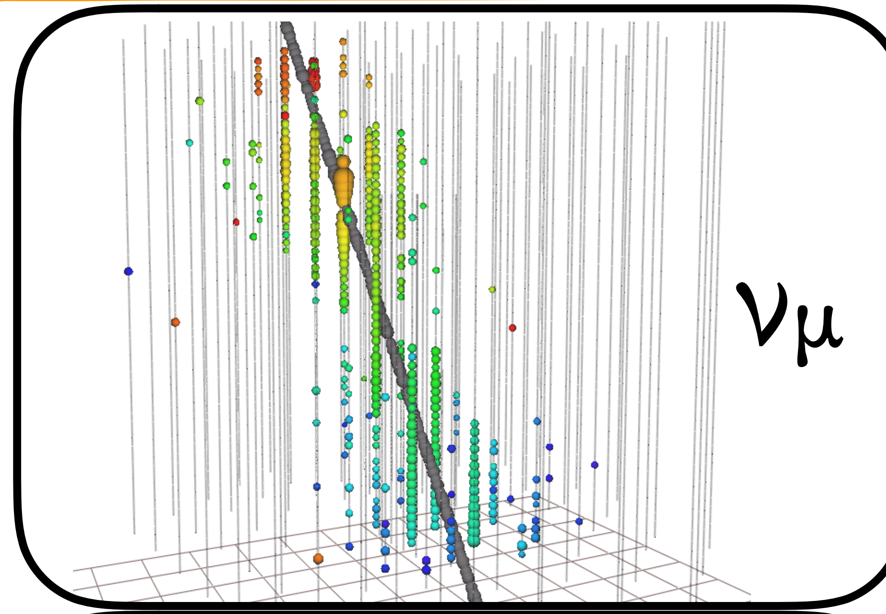
Flavour content of astrophysical neutrinos

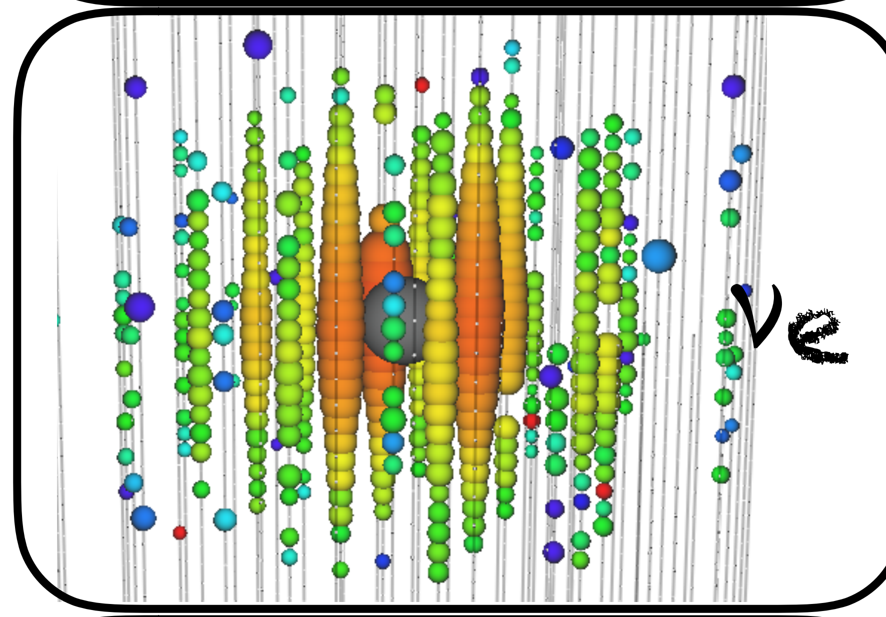
- Test neutrino production mechanisms

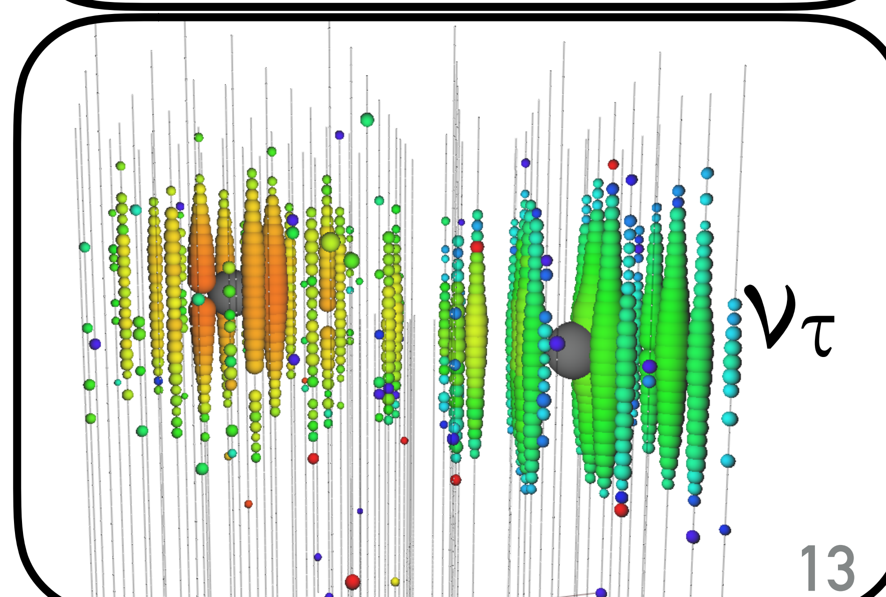
$\nu_e : \nu_\mu : \nu_\tau$ at source

■	0:1:0	Muon damping
●	1:2:0	Pion decay
▲	1:0:0	Neutron decay









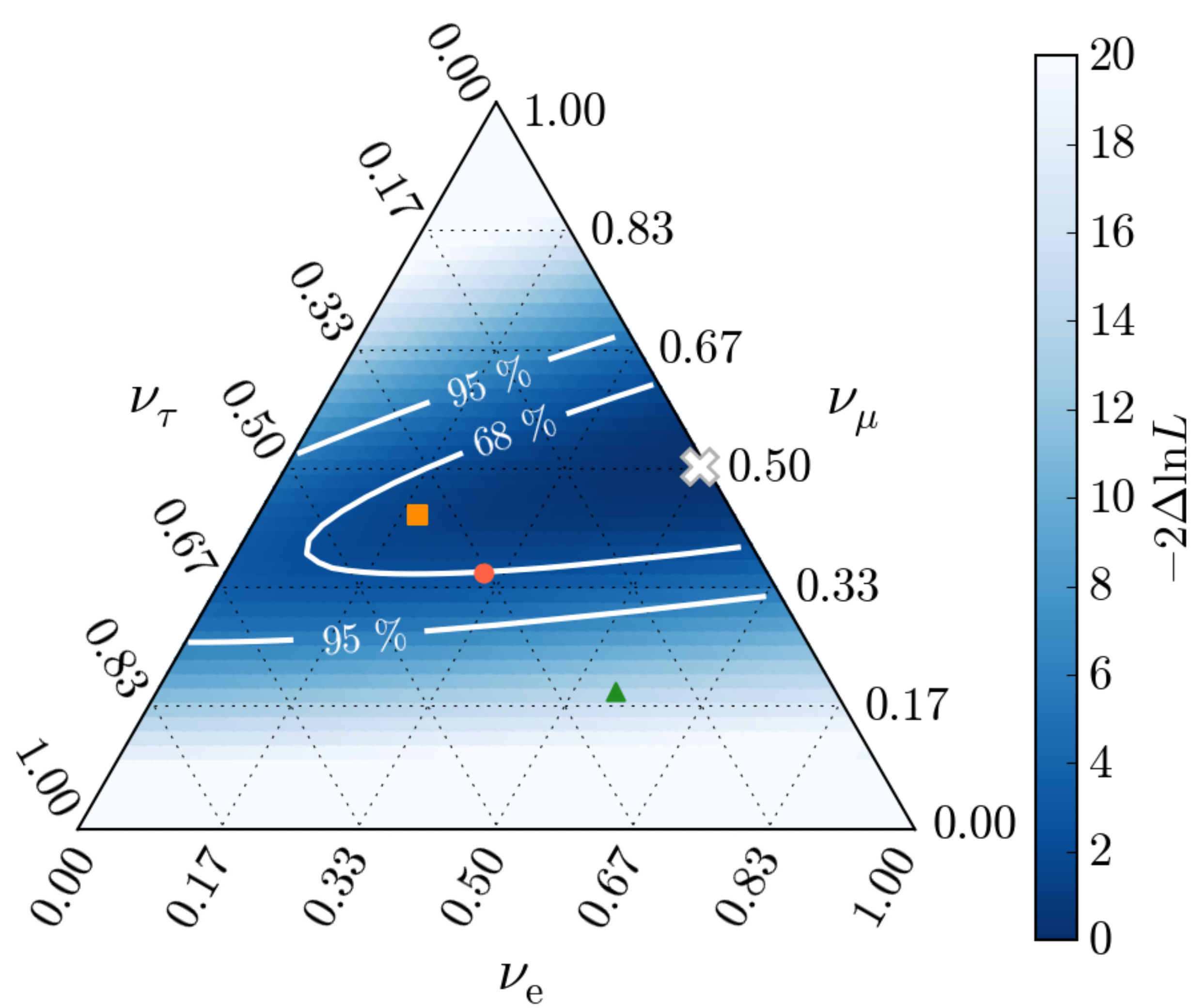
arXiv:1510.05223

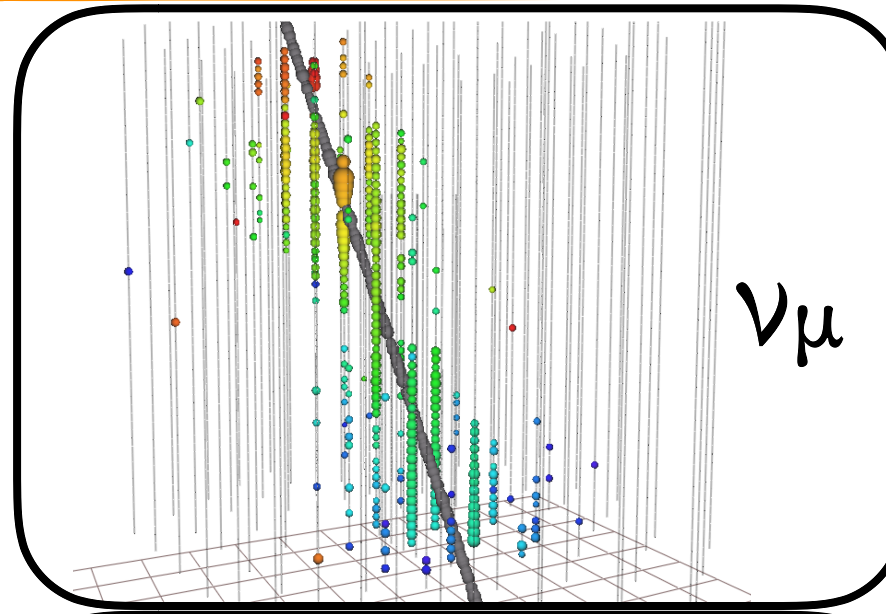
Flavour content of astrophysical neutrinos

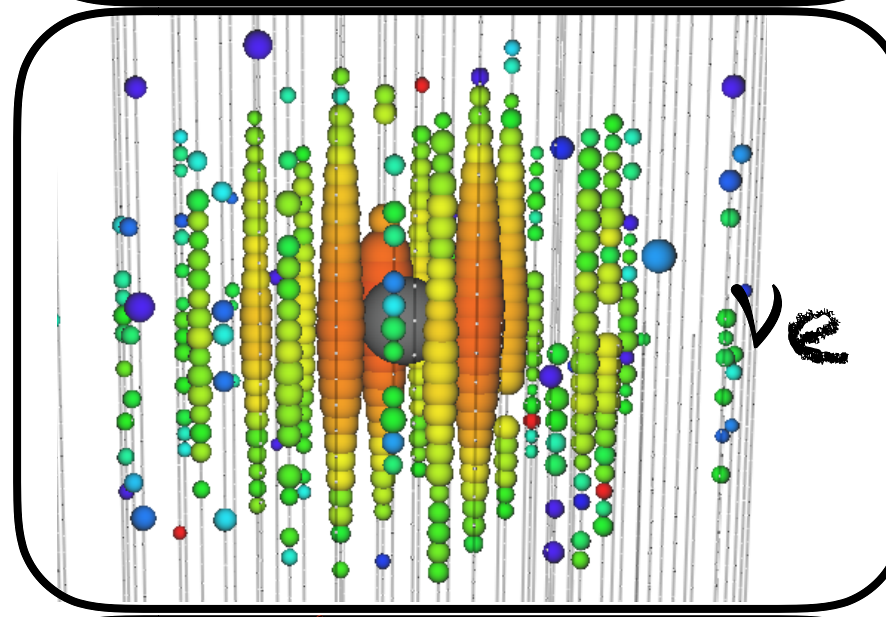
- Test neutrino production mechanisms

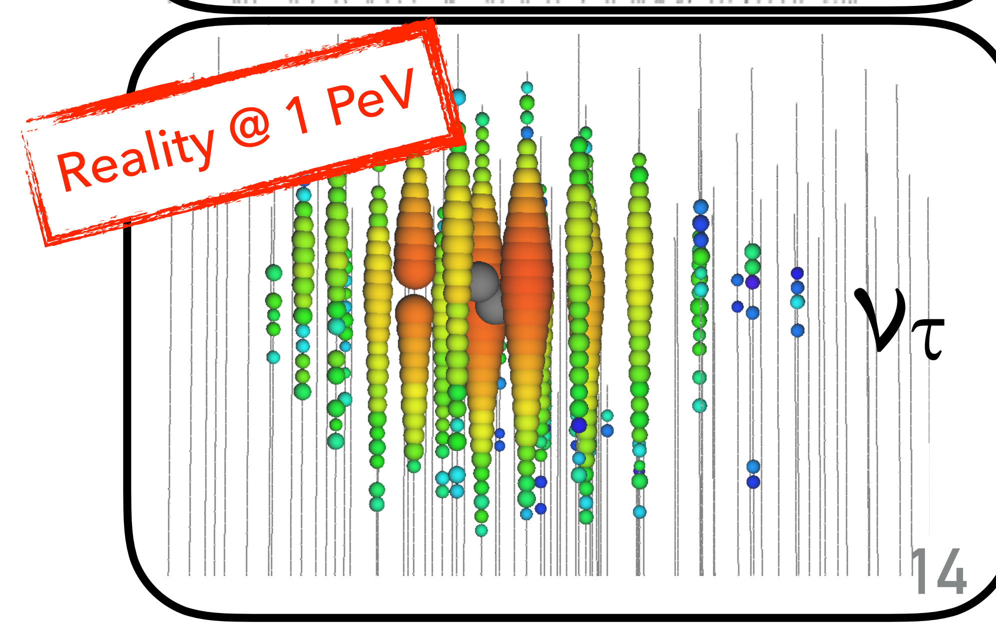
$\nu_e : \nu_\mu : \nu_\tau$ at source

■	0 : 1 : 0	Muon damping
●	1 : 2 : 0	Pion decay
▲	1 : 0 : 0	Neutron decay





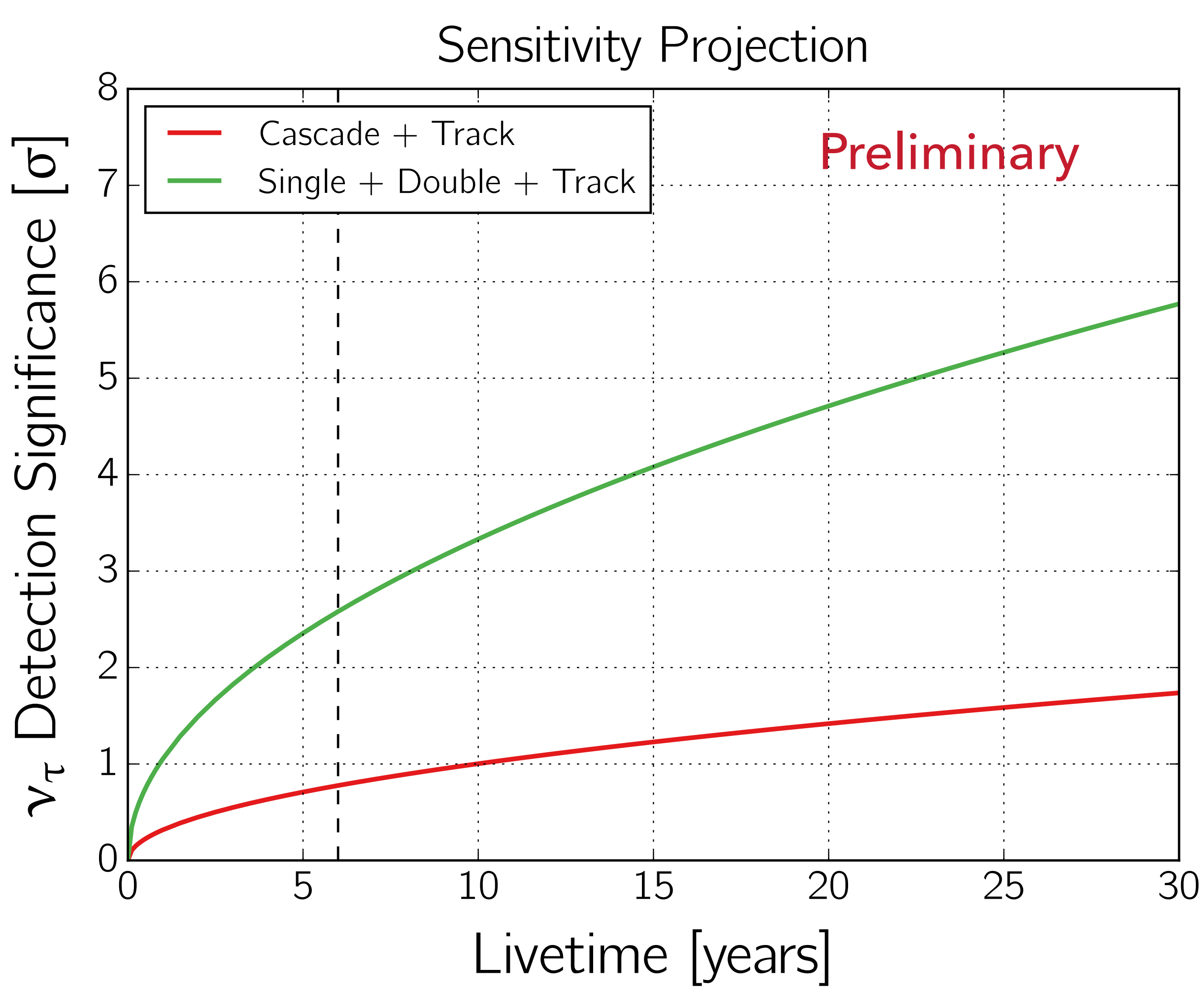


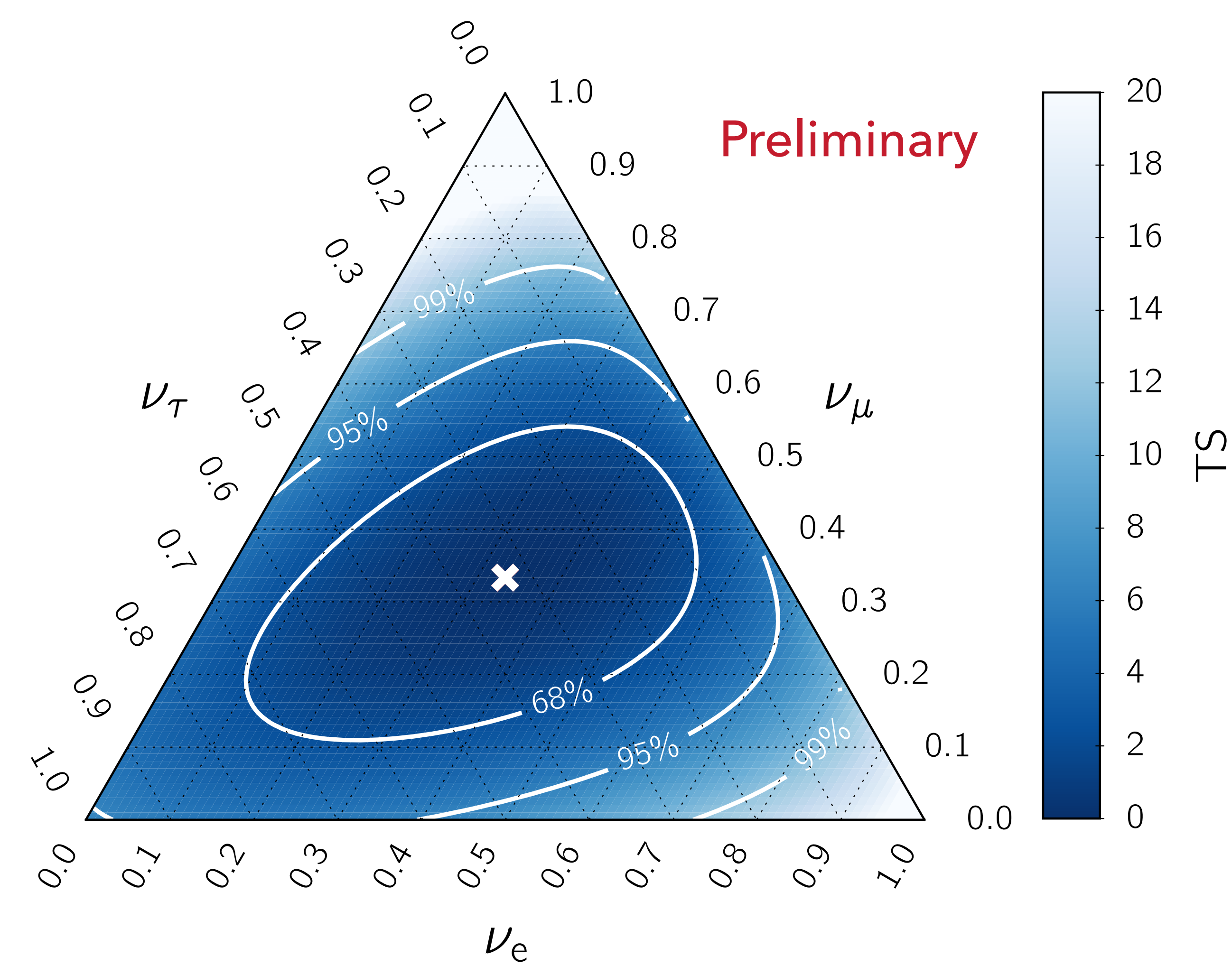


arXiv:1510.05223

Detection of Astrophysical Tau Neutrinos

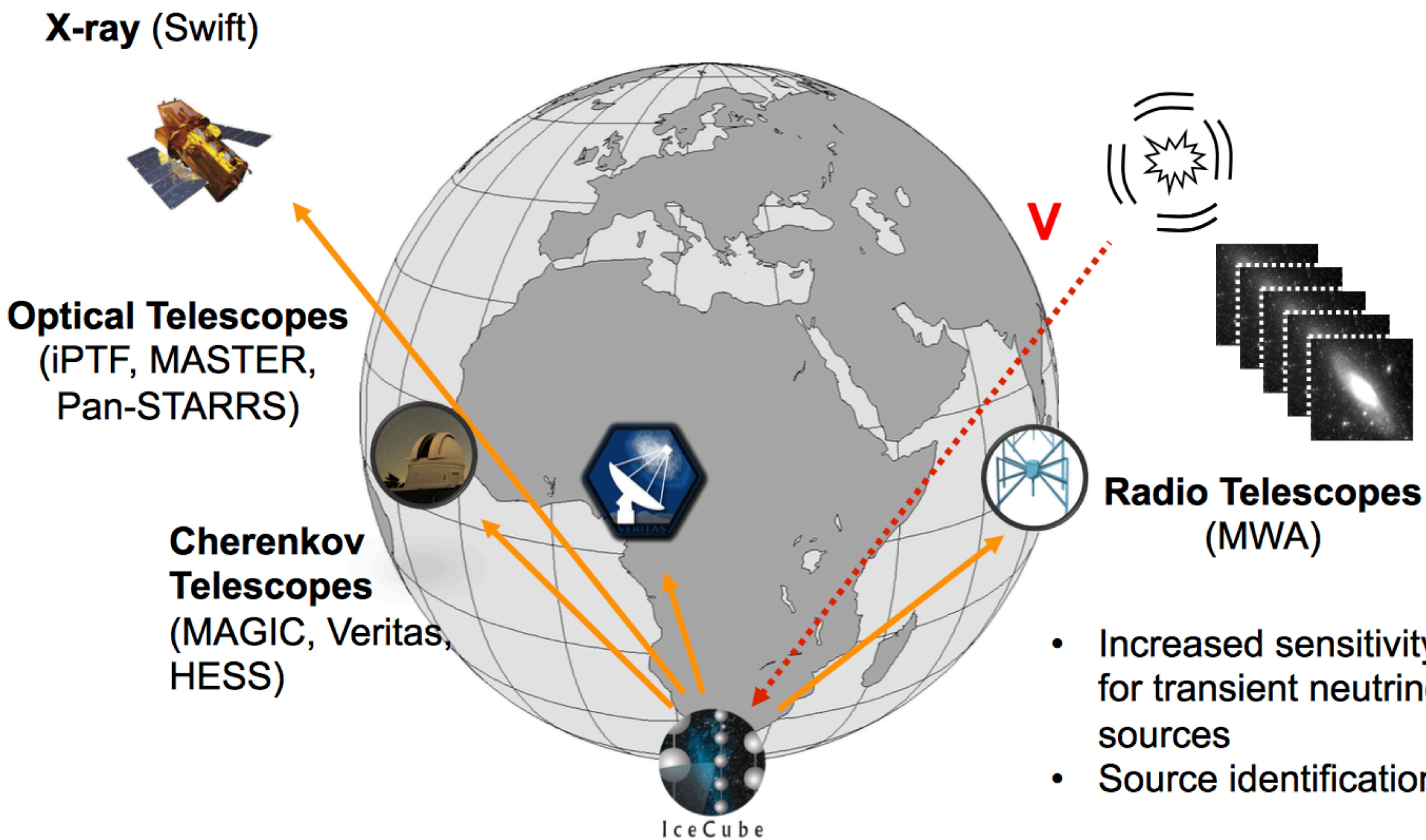
- New reconstruction method developed for ν_τ detection
- Rejection of "no ν_τ" at 2σ with 6 year data set
- Break degeneracy in flavour triangle





Assumes 1:1:1 underlying flavour content

Multi-messenger program

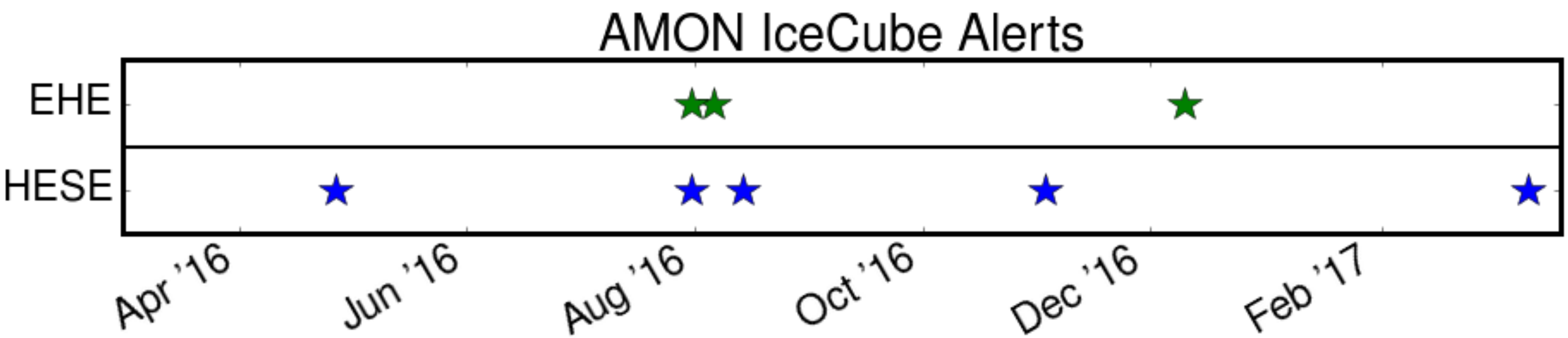


- Increased sensitivity for transient neutrino sources
- Source identification

Ackermann et al. arXiv:0709.2640
IceCube A&A 539, A60 (2012)
IceCube arXiv: 1610.01814

Realtime Alerts

- Public alert system for follow-up program running for ~1 year now
- Last alert just under 2 weeks ago
- Event selection/filters managed by DESY



Realtime Systems paper: https://arxiv.org/pdf/1612.06028.pdf

Multiplet paper: https://arxiv.org/pdf/1702.06131.pdf

DESY: E. Bernardini, A. Franckowiak, T. Kintscher, M. Kowalski, K. Satalecka, A. Stasik, N. Strotjohann

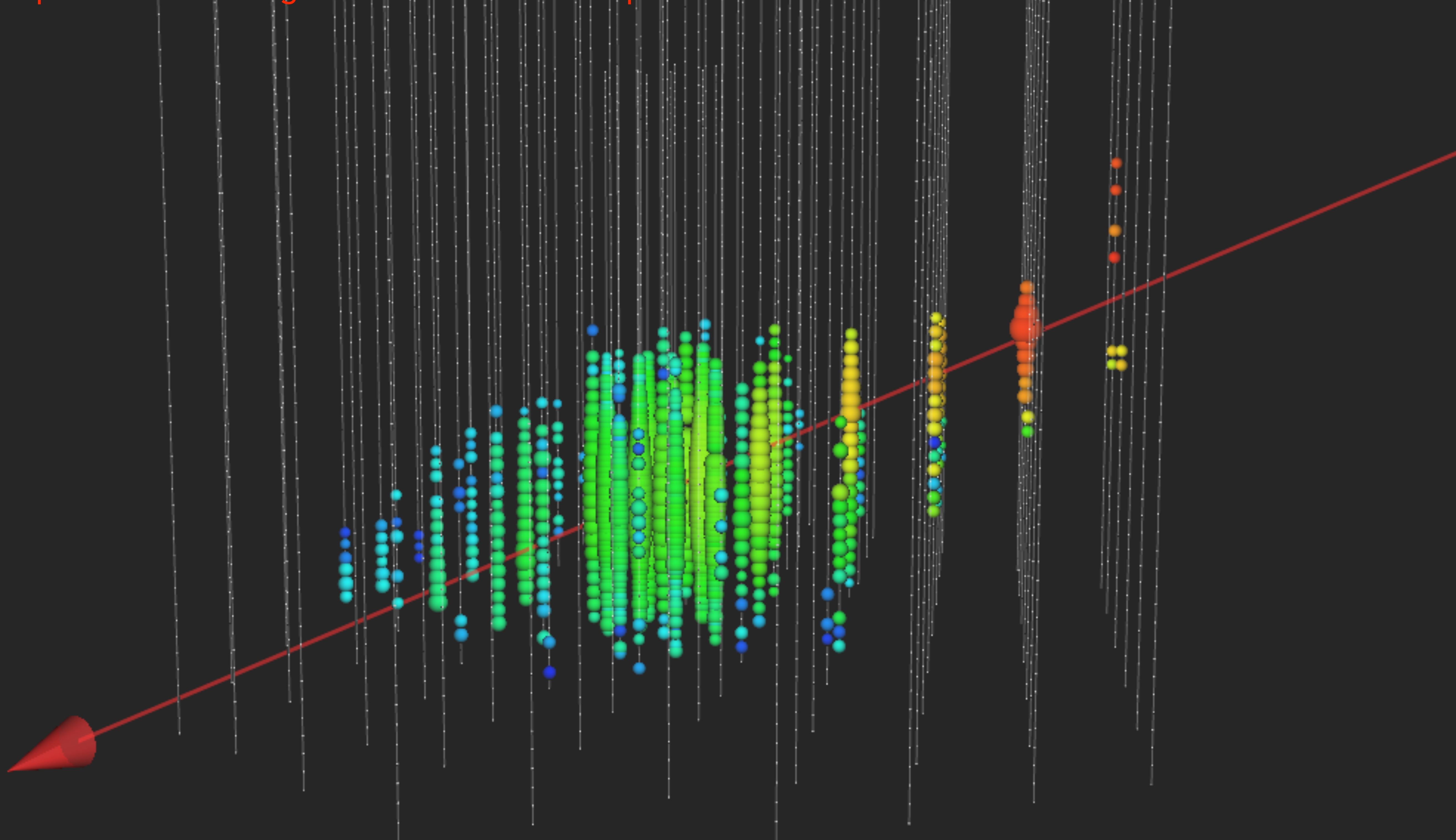
Date: 2017-03-12

Time: 13:49:39.8 UTC

RA: 305.15 deg (<+/- 0.5 ra uncertainty> deg 90% PSF containment) J2000

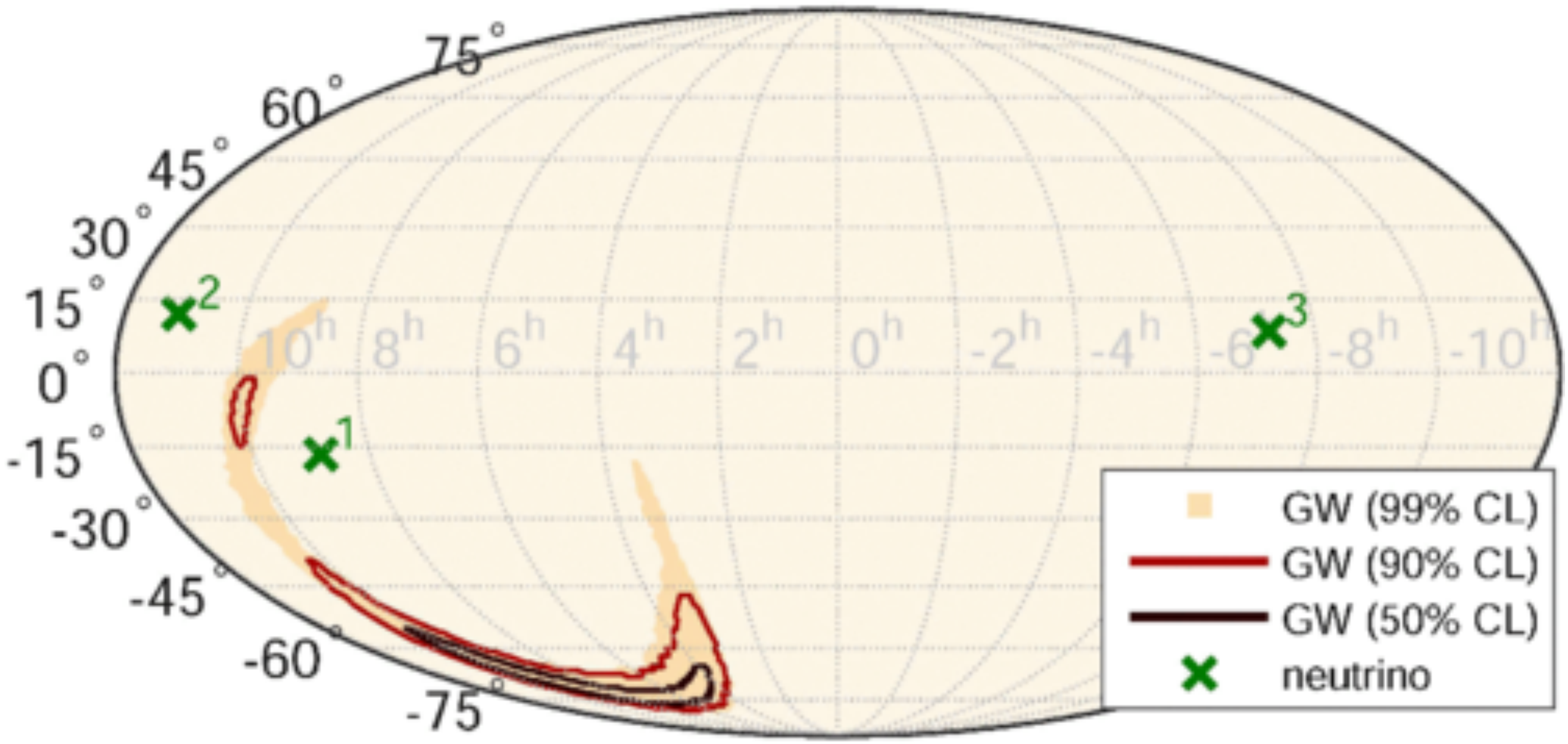
Dec: -26.61 deg (<+/- 0.5 dec uncertainty> deg 90% PSF containment) J2000

Additionally, after closer inspection of the event details, it shows signs of being consistent with rare atmospheric muon background events that are expected from the event selection



Multi-messenger program

- Also works vice versa
- Take alerts from other experiments and look for neutrinos



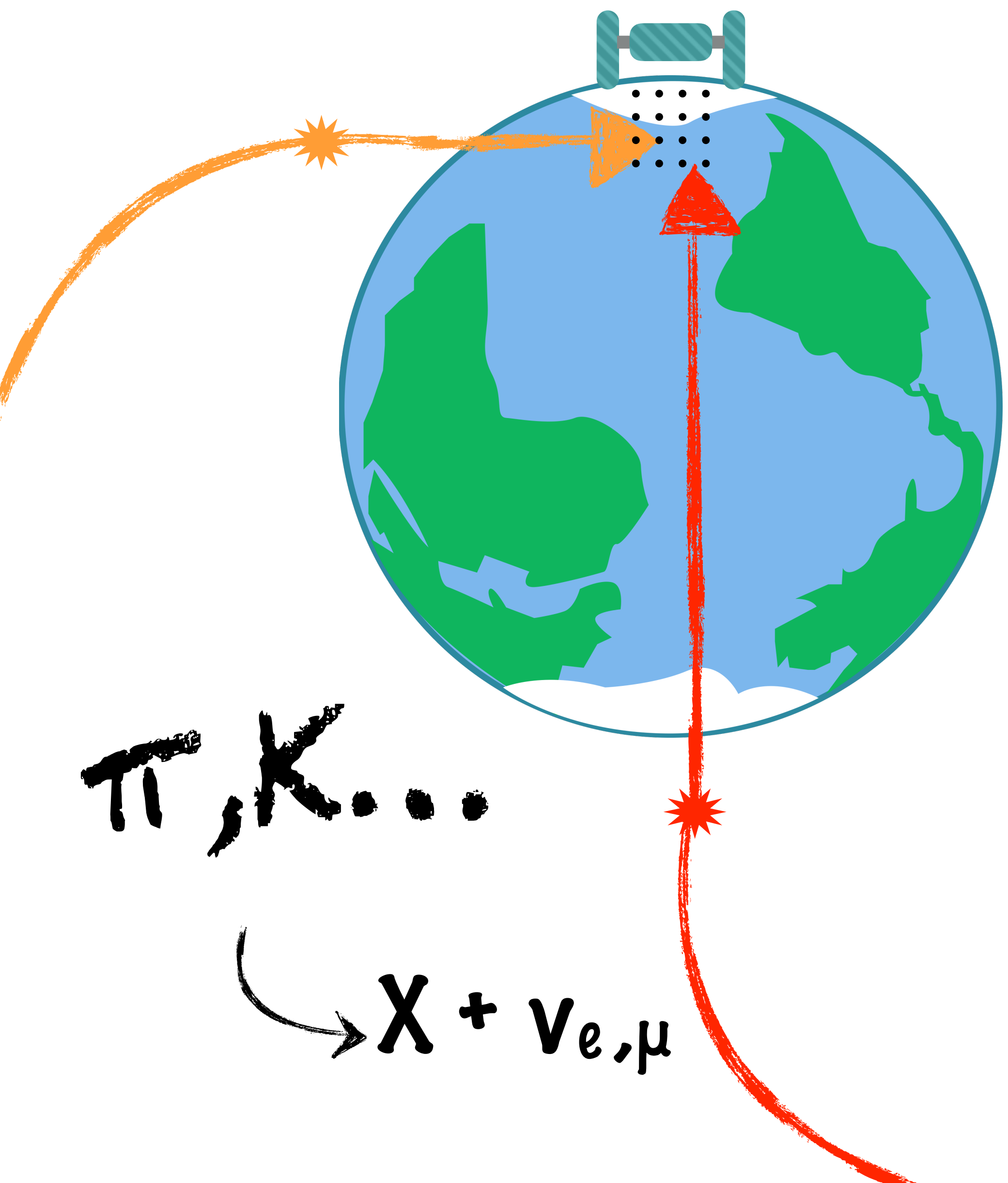
High-energy neutrino follow-up search of gravitational wave event GW150914 with ANTARES and IceCube

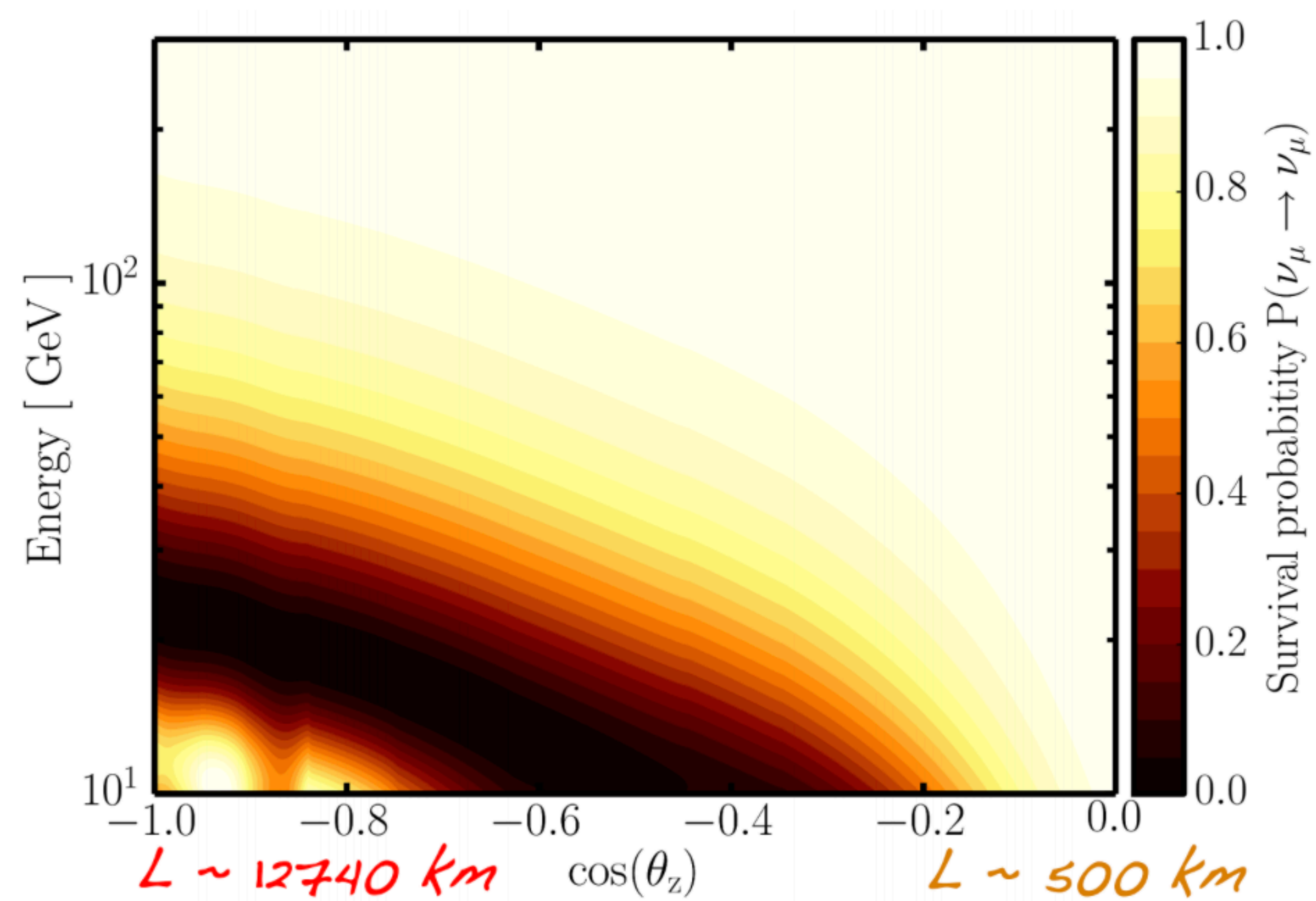
S. Adrián-Martínez et al. (Antares Collaboration, IceCube Collaboration, LIGO Scientific Collaboration, and Virgo Collaboration)
Phys. Rev. D **93**, 122010 – Published 23 June 2016

Recent highlights: Neutrino oscillations

- Use atmospheric neutrinos to measure neutrino oscillation
- Flavour eigenstate ≠ mass eigenstates & $m_1 \neq m_2 \neq m_3$:

$$\mathbf{P}_{\nu a \to \nu a} = \sin^2\theta_{23}\sin^2(\Delta m^2_{32}\mathbf{L} / 4\mathbf{E})$$





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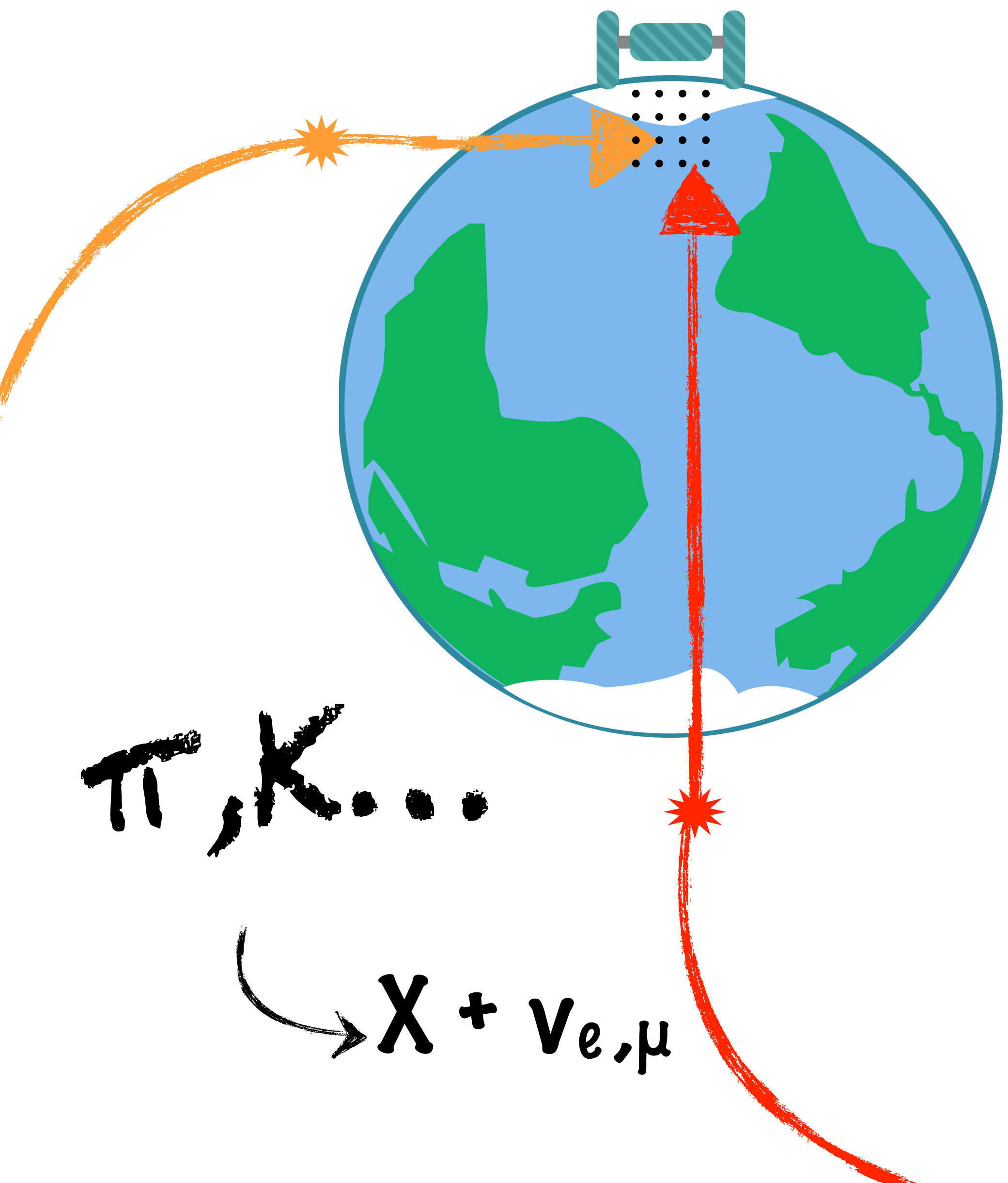
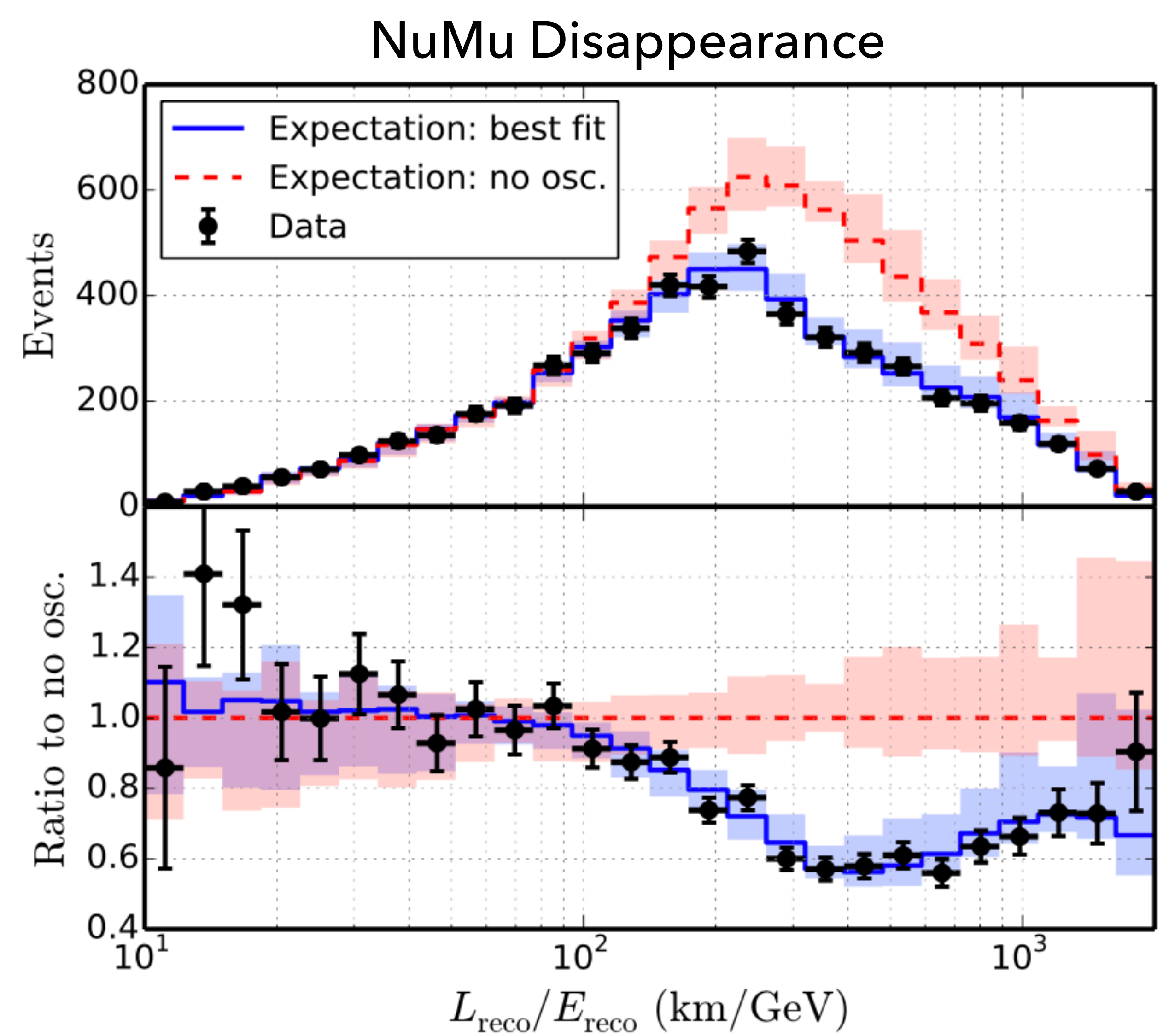
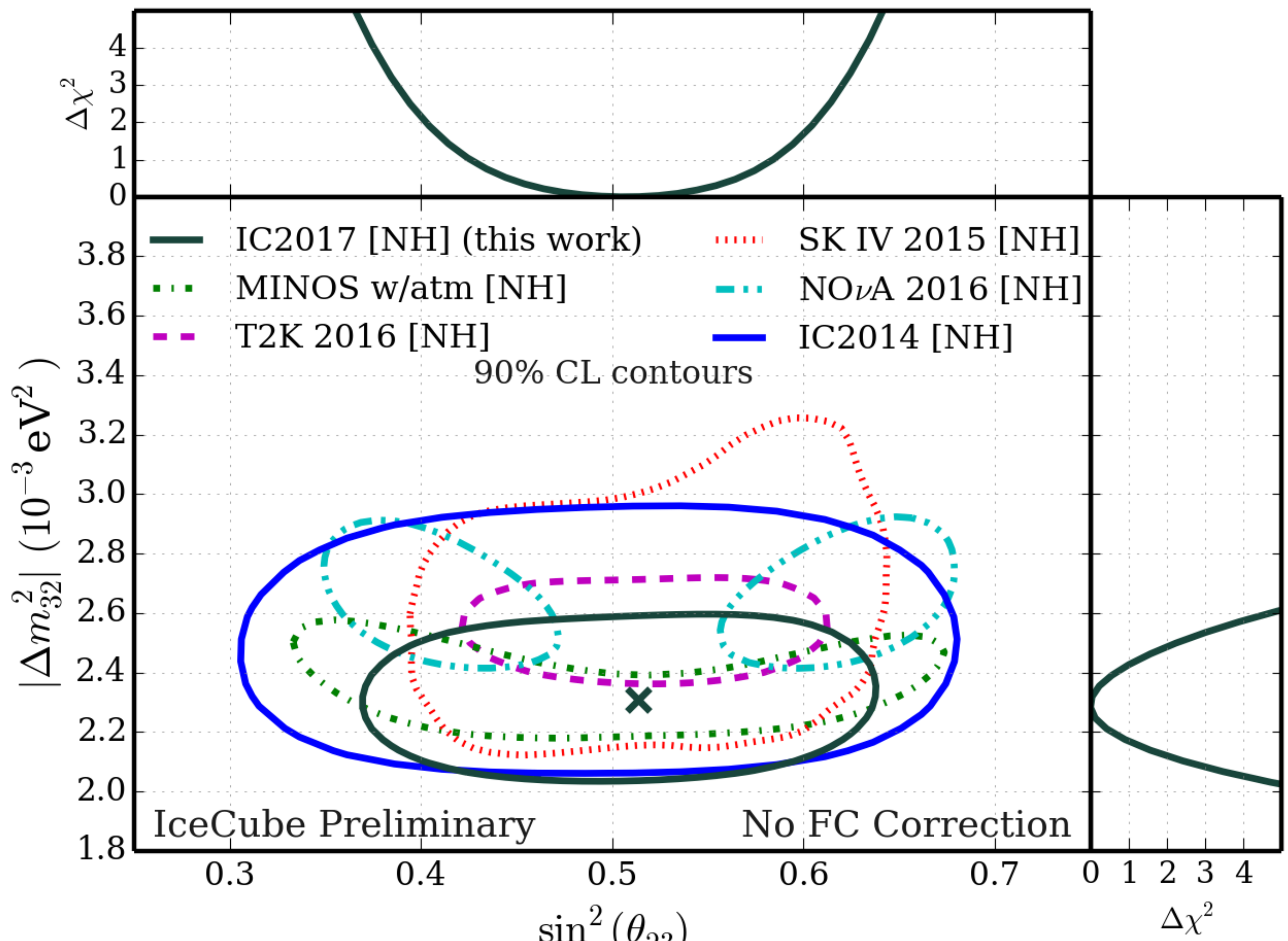




https://arxiv.org/pdf/1410.7227.pdf

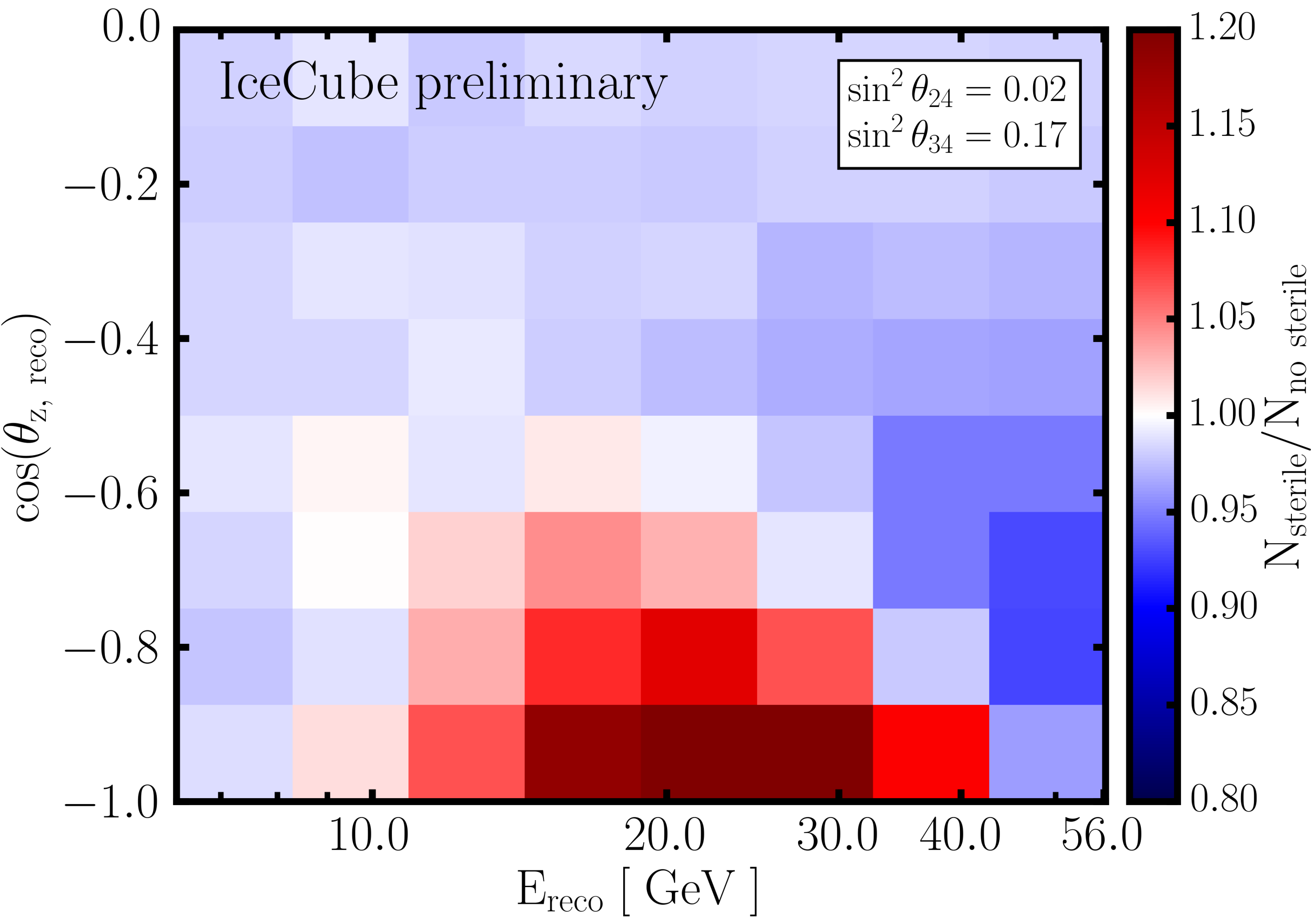
Recent highlights: Neutrino oscillations

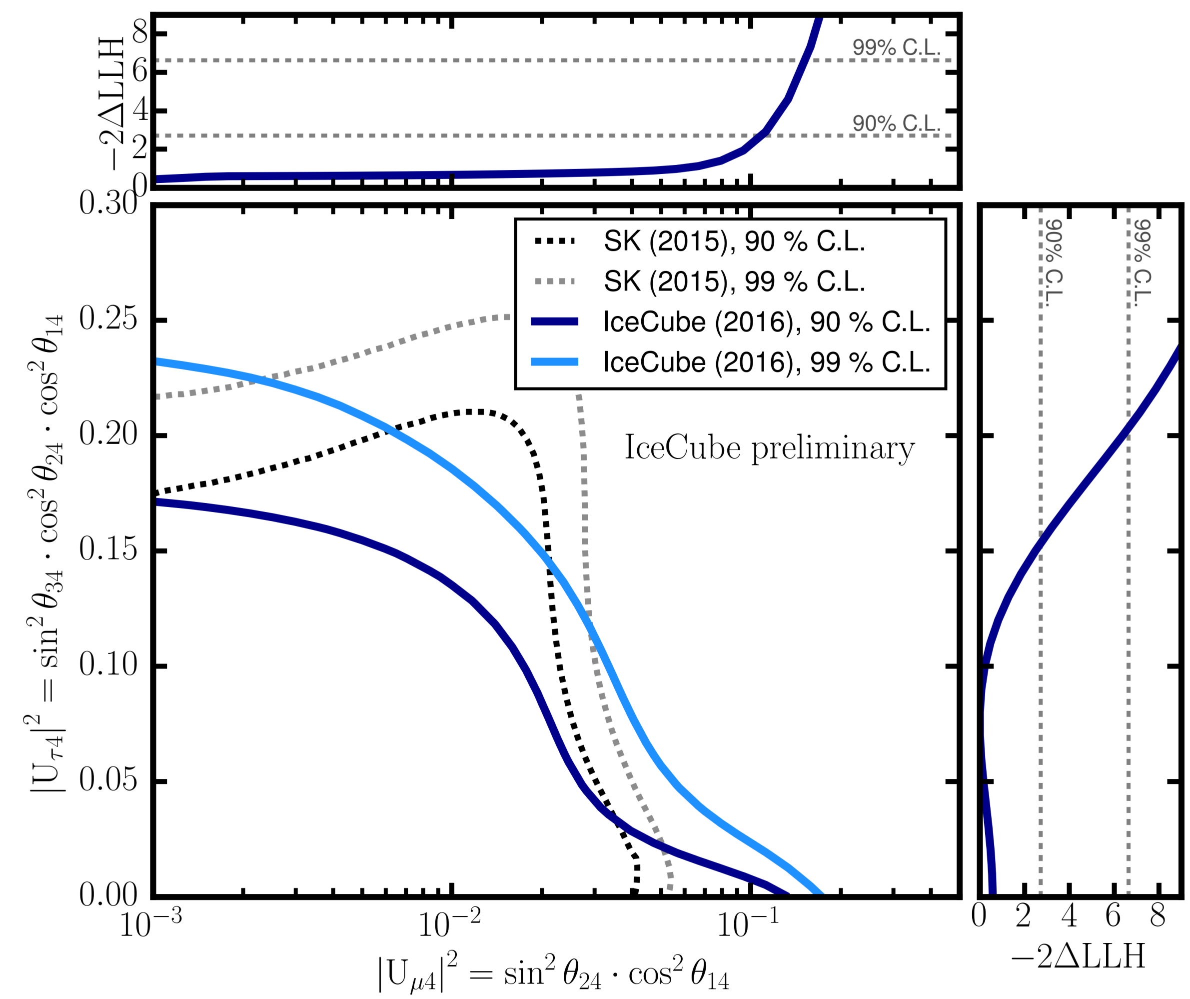
- Improvements to reconstruction and event selection lead to significant gains in oscillation measurements



Recent highlights: Neutrino oscillations

- Search for sterile neutrinos using 3 y of DeepCore data
- "Golden selection" with direct photons
- Results independent of the sterile neutrino mass splitting



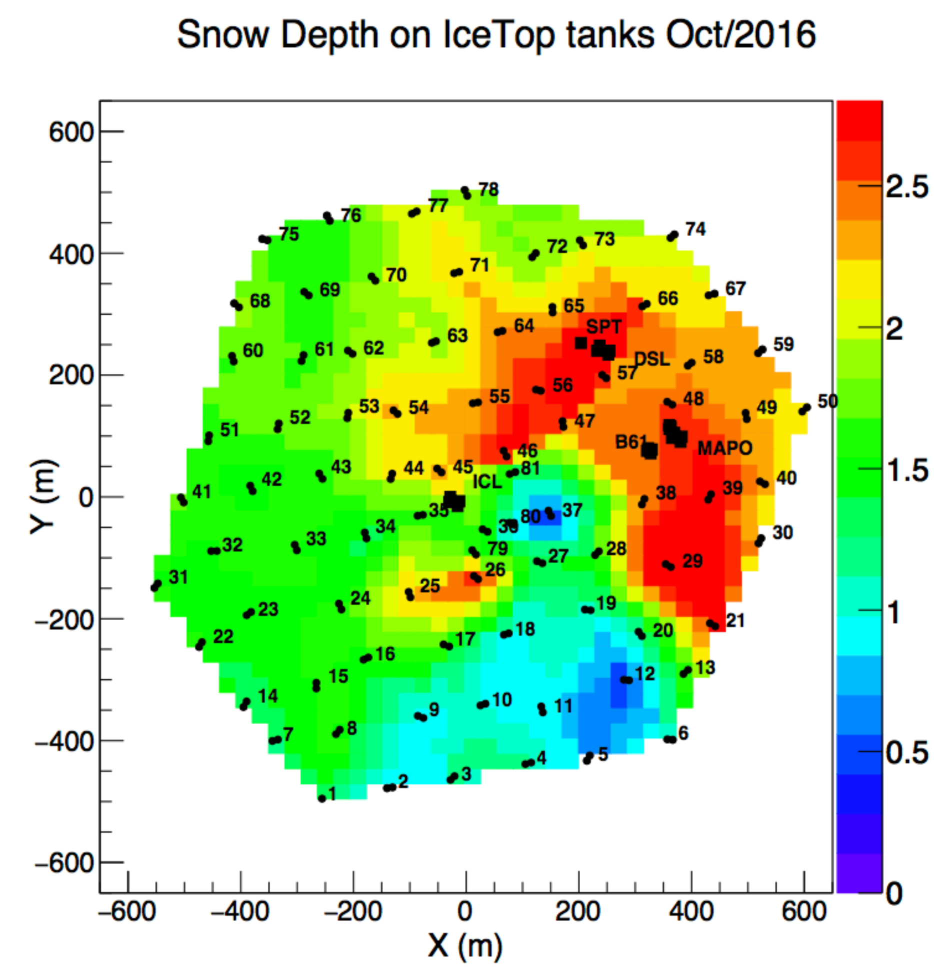


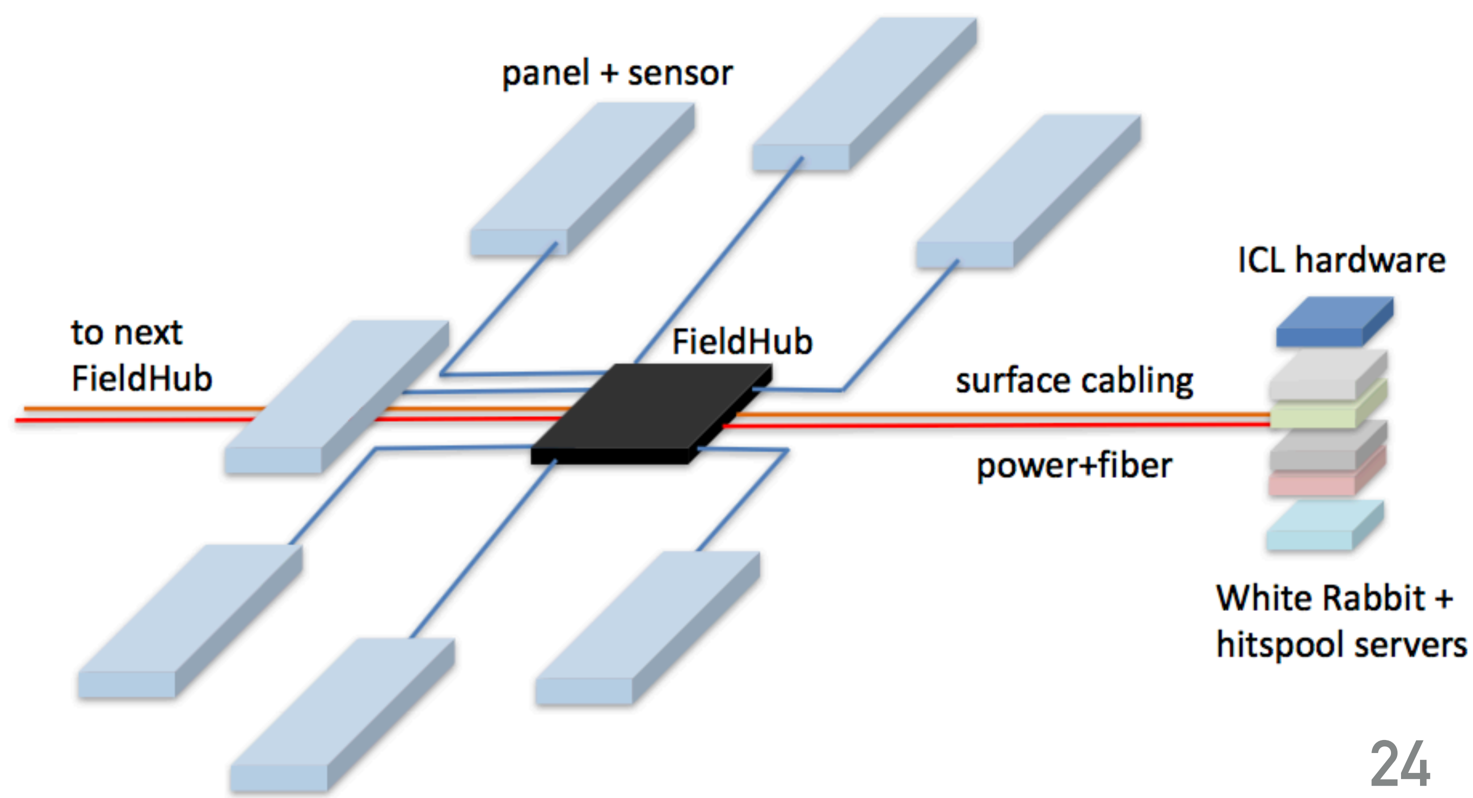
Submitted to PRD, https://arxiv.org/abs/1702.05160

DESY: S. Blot, A. Terliuk

IceTop Upgrade

- Snow build-up on IceTop reduces sensitivity for cosmic ray studies
- Deploy scintillator panels next season at south pole to calibrate out snow effects and improve energy reconstruction
- DESY developing DAQ

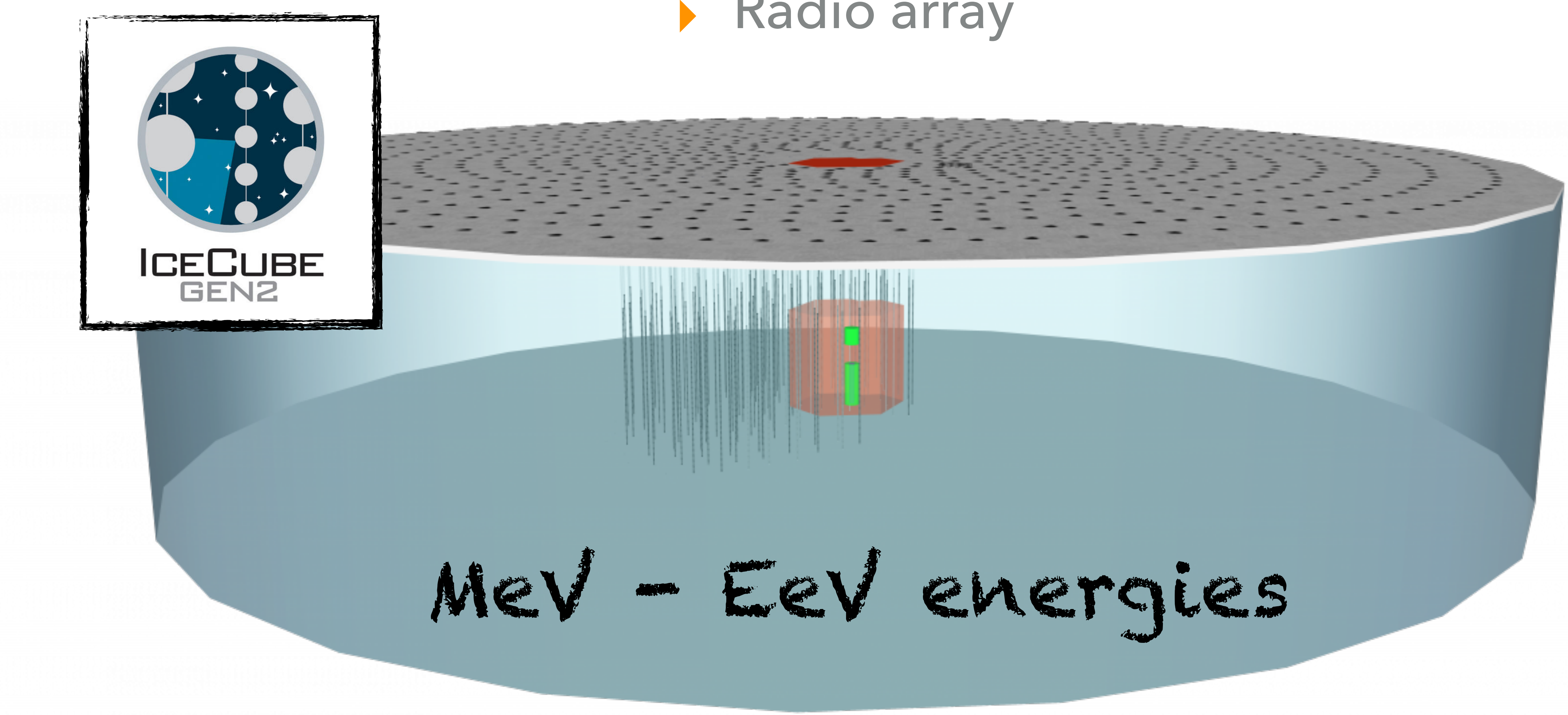




DESY: T. Karg, S. Kunwar

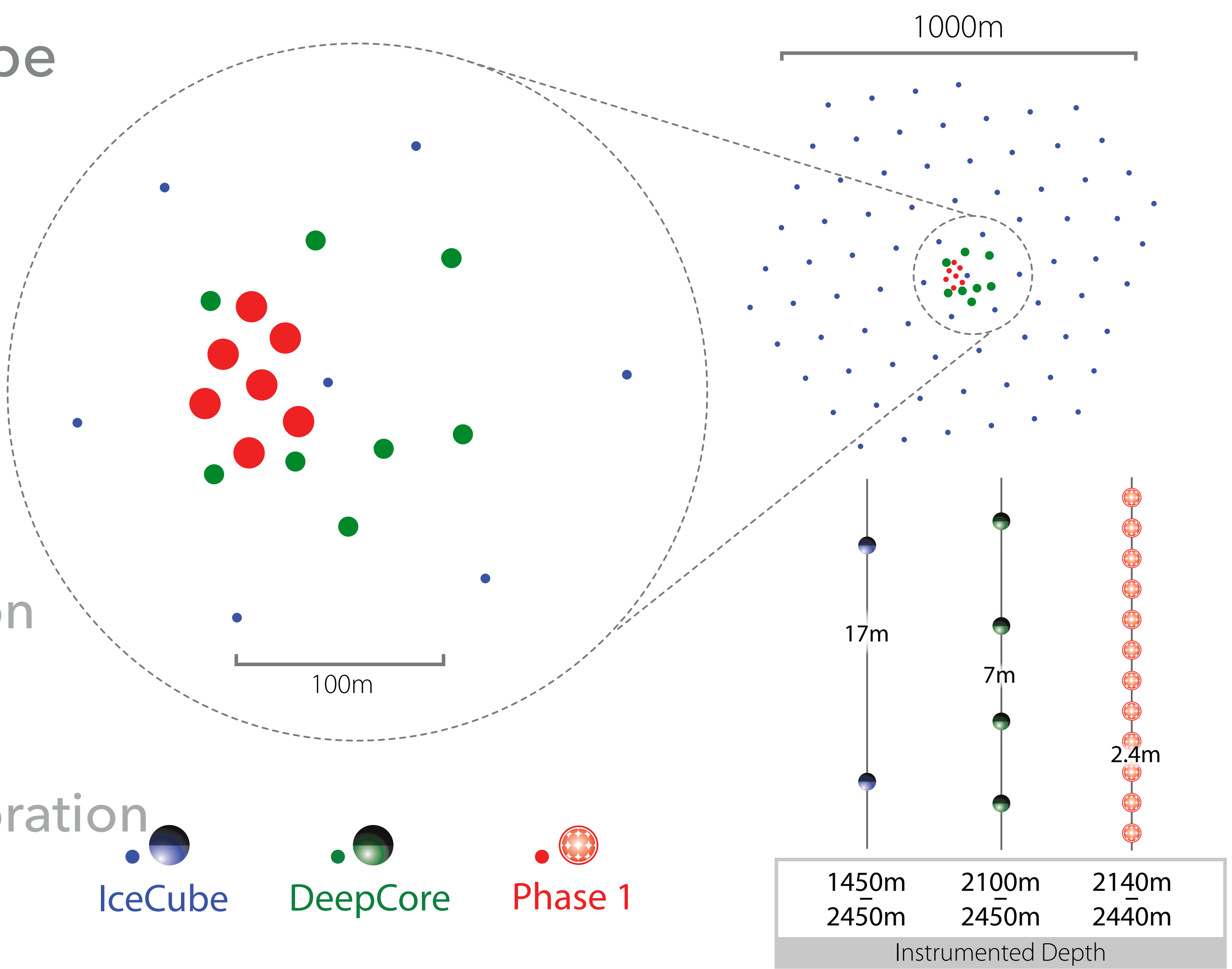
Upgrade to IceCube Gen2

- Goal:
  - 5x better sensitivity to detect point sources
  - 10x more statistics
- Larger instrumented volume
- Surface array for veto/air shower physics
- Denser center (PINGU) for precision neutrino physics
- Radio array



IceCube Gen2 – Phase 1

- First step towards IceCube Gen2 construction
- Three primary purposes
  - High impact neutrino physics
  - In-situ R&D of new photon sensor technologies
  - Deployment of new calibration devices



DESY:
(High energy) M. Kowalski, M. Ackermann, J. van Santen
(Low energy) A. Terliuk, S. Blot
(Hardware) D. Hebecker, T. Karg, S. Kunwar

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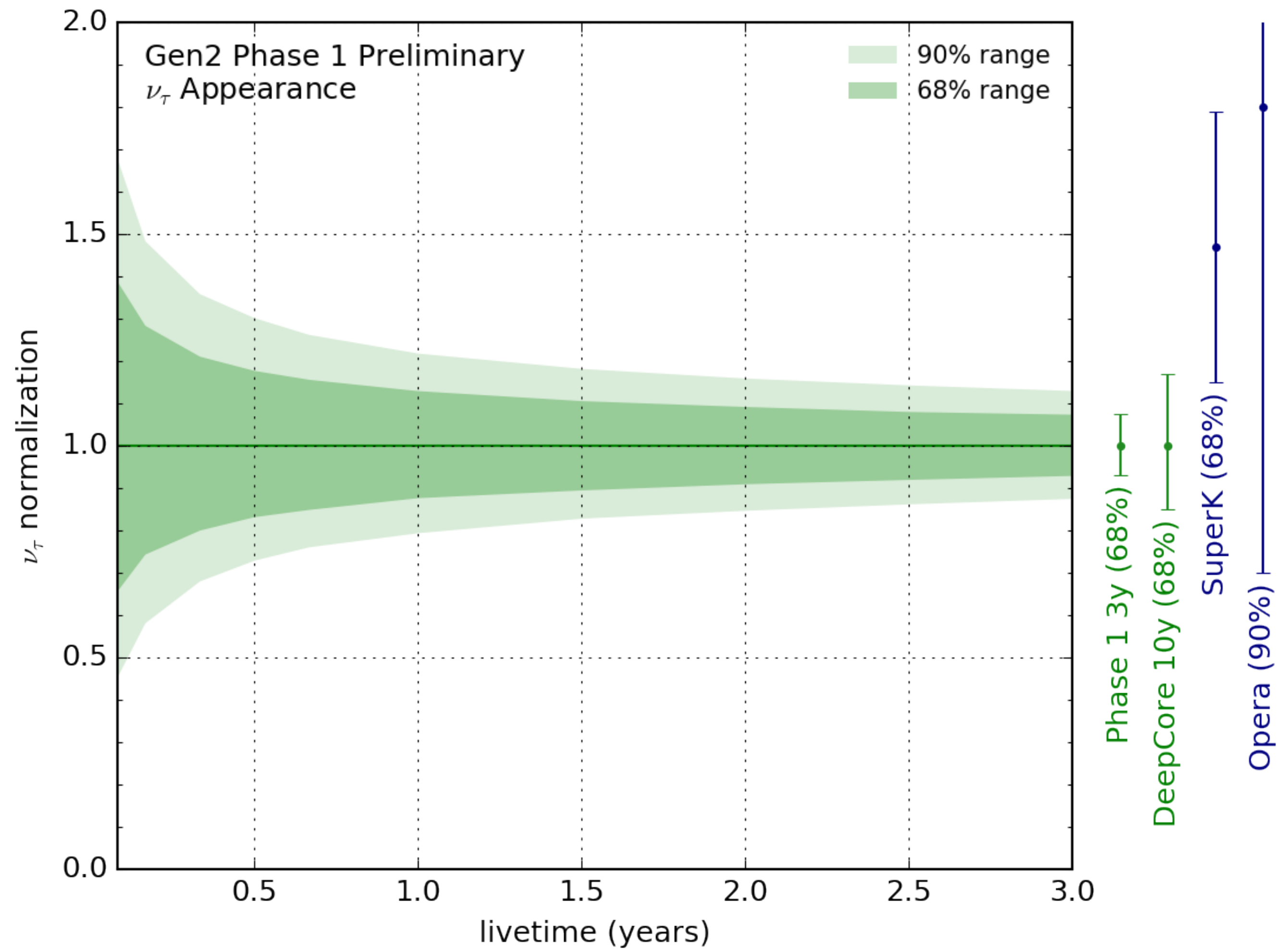

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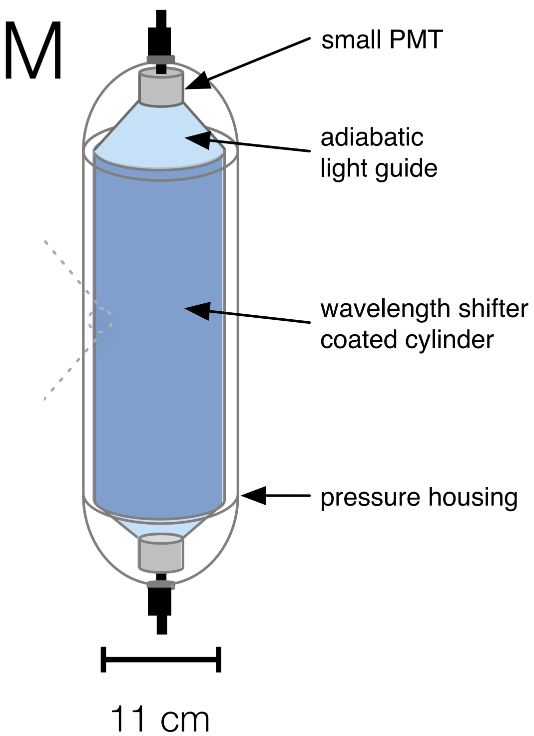
mDOM

- Directional information
- More sensitive area per module

WOM



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

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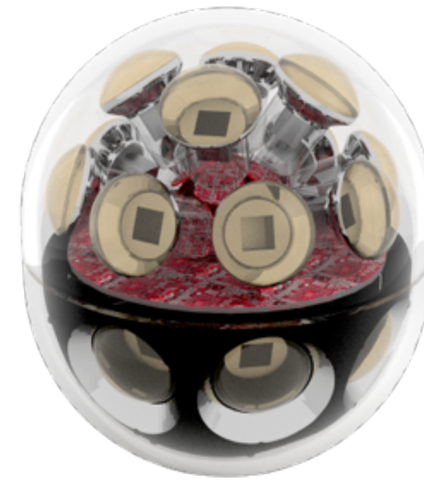
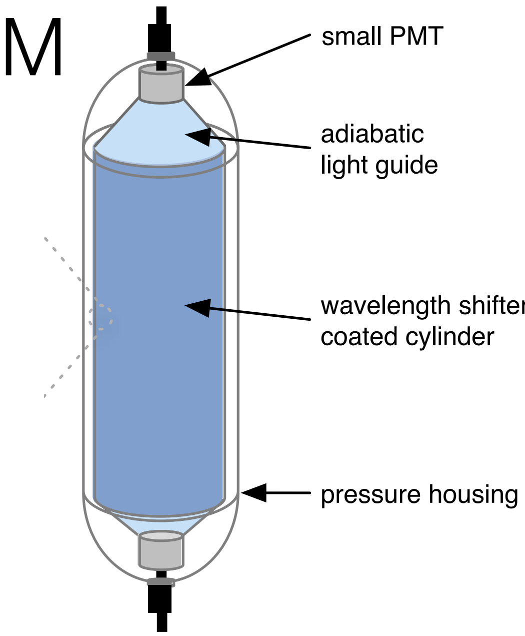


36 cm

- Directional information
- More sensitive area per module

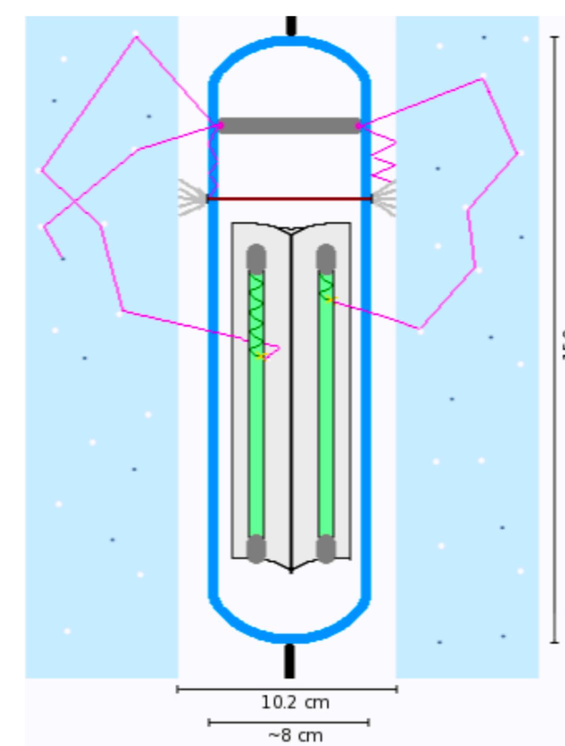
WOM



11 cm

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

- UV calibration device
- Development at DESY/ Humboldt U.



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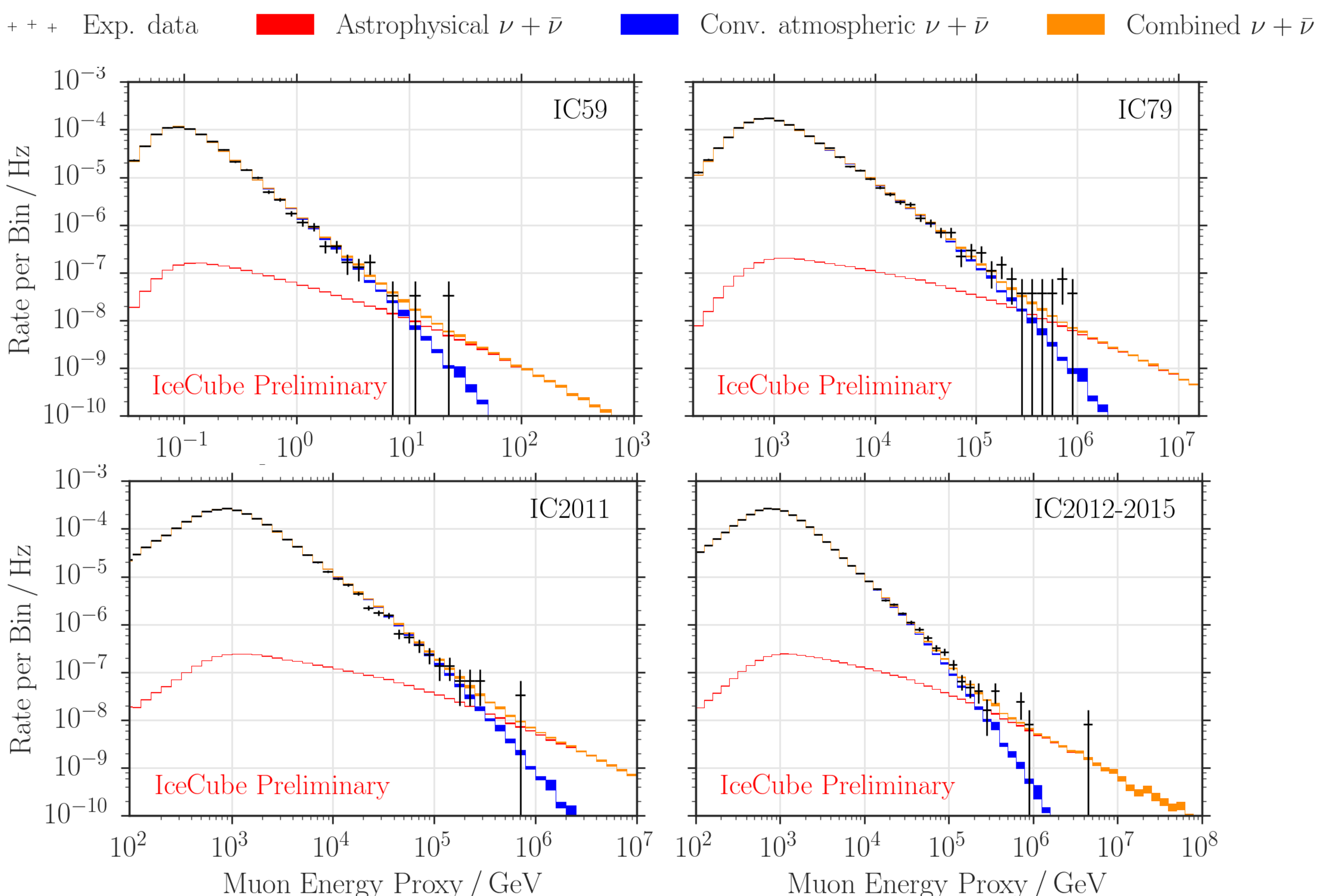
IceCube Neutrino Observatory is a great tool for
Neutrino AstroParticle Physics

With GeV - PeV neutrinos, making significant impact and
discoveries in various sub-fields

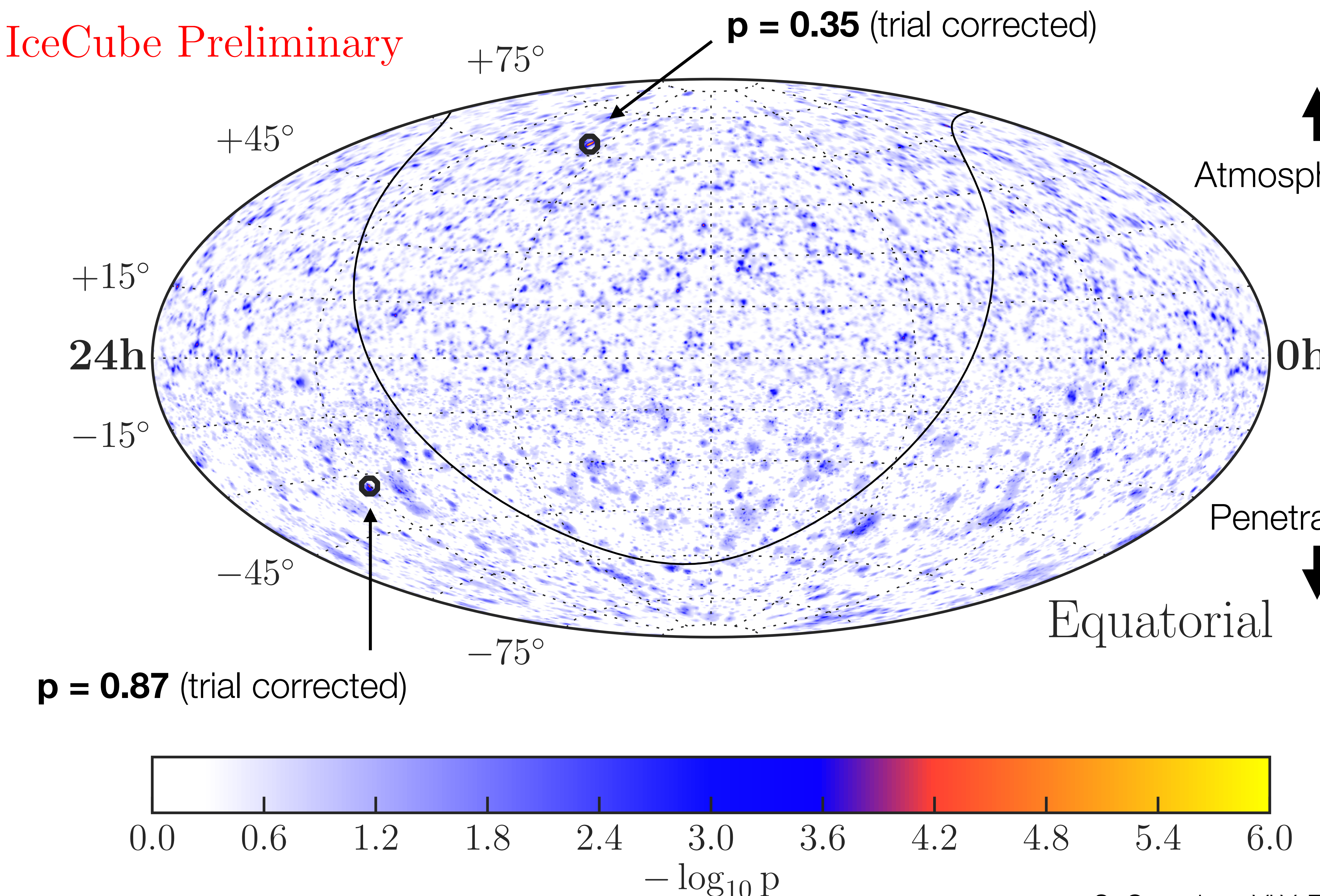
DESY scientists play a leading role in IceCube
operation/analysis and development of IceCube Gen2

BACKUPS

Astrophysical neutrino flux

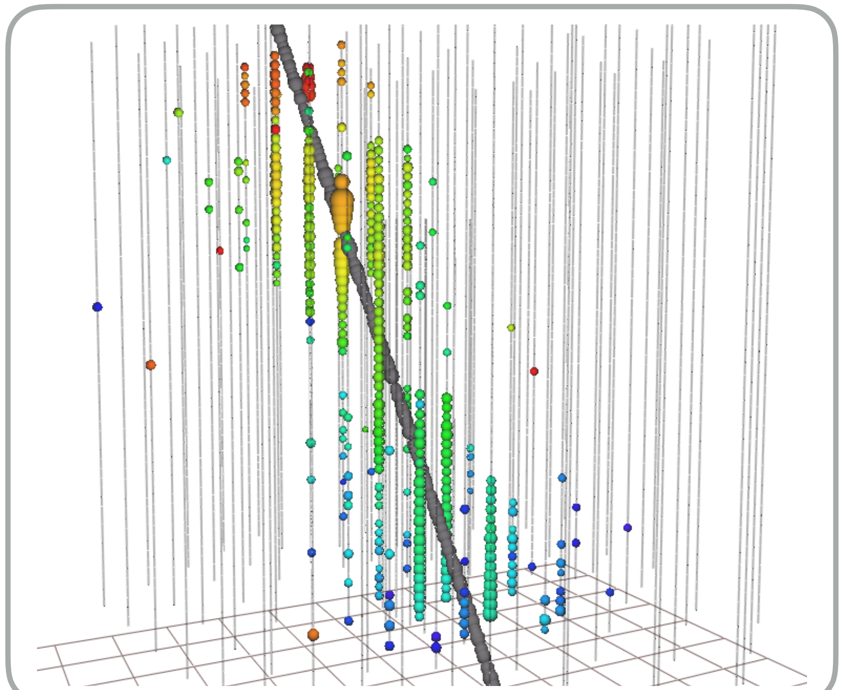
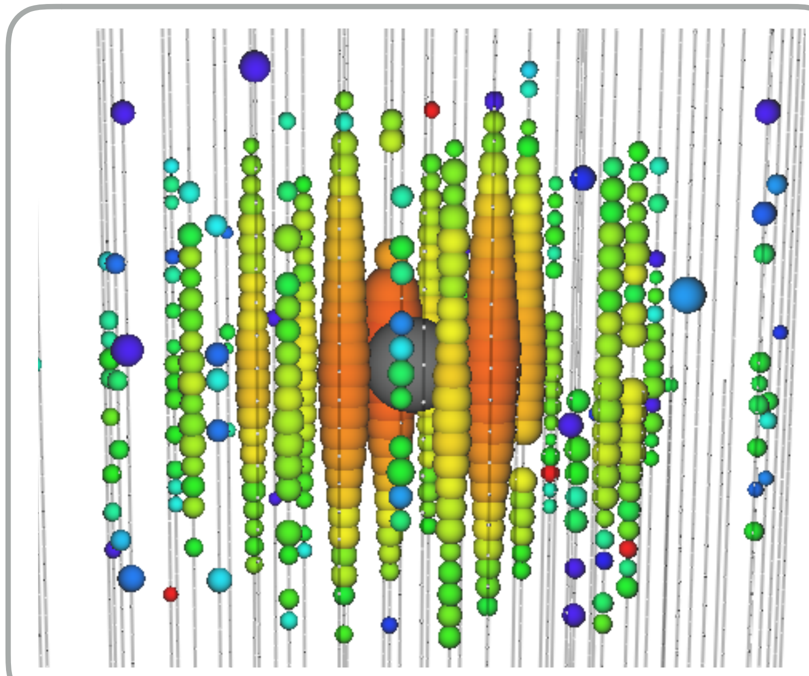
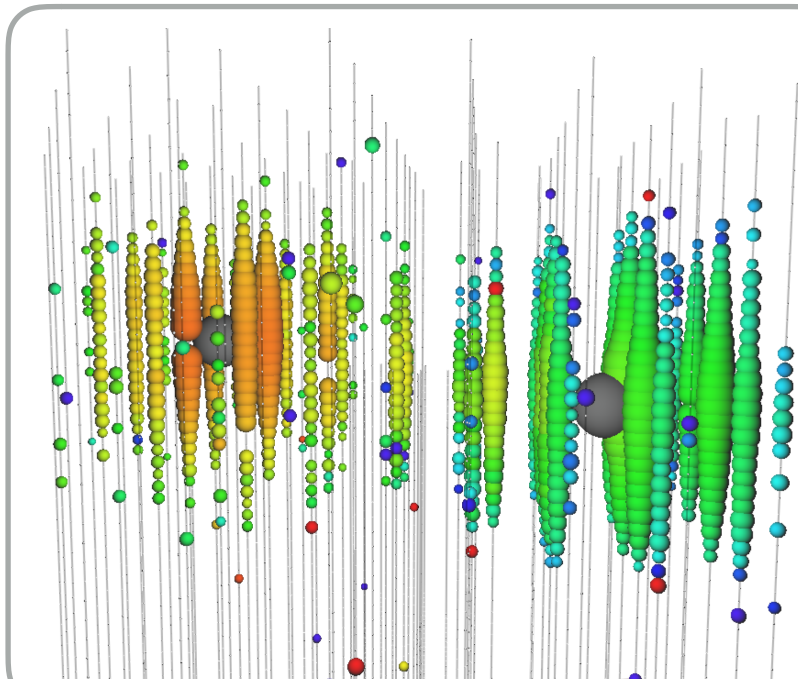


6-year steady point source search



S. Coenders, VLVνT 2015

event signatures

track	cascade	double bang
		
$\nu_\mu + N \rightarrow \mu + X$ atmospheric μ	$\nu_e + N \rightarrow e + X$ $\nu_f + N \rightarrow \nu_f + X$	$\nu_\tau + N \rightarrow \tau + X$ $\tau \rightarrow X + \nu_\tau$

why is the flavor ratio interesting?

$\nu_e:\nu_\mu:\nu_\tau$ at source

pion decay: 1:2:0

$\pi \rightarrow \mu + \nu_\mu$

$\mu \rightarrow e + \nu_e + \nu_\mu$

neutron decay: 1:0:0

$n \rightarrow p + e + \nu_e$

muon damping: 0:1:0

$\pi \rightarrow \mu + \nu_\mu$

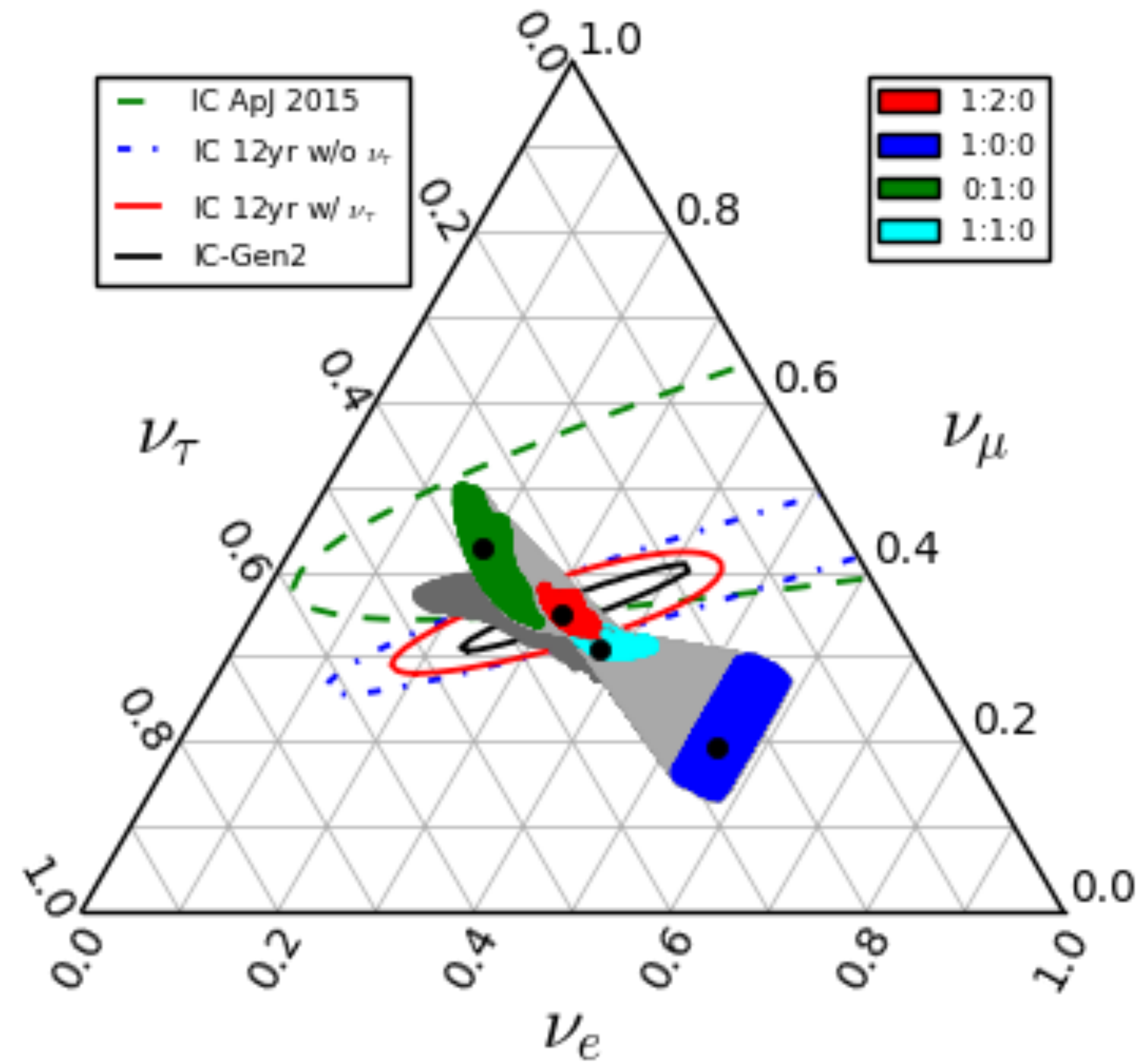
charm decay: 1:1:0

$X_c \rightarrow X + e + \nu_e$

$X_c \rightarrow X + \mu + \nu_\mu$

→ **cosmic baseline neutrino oscillations** →

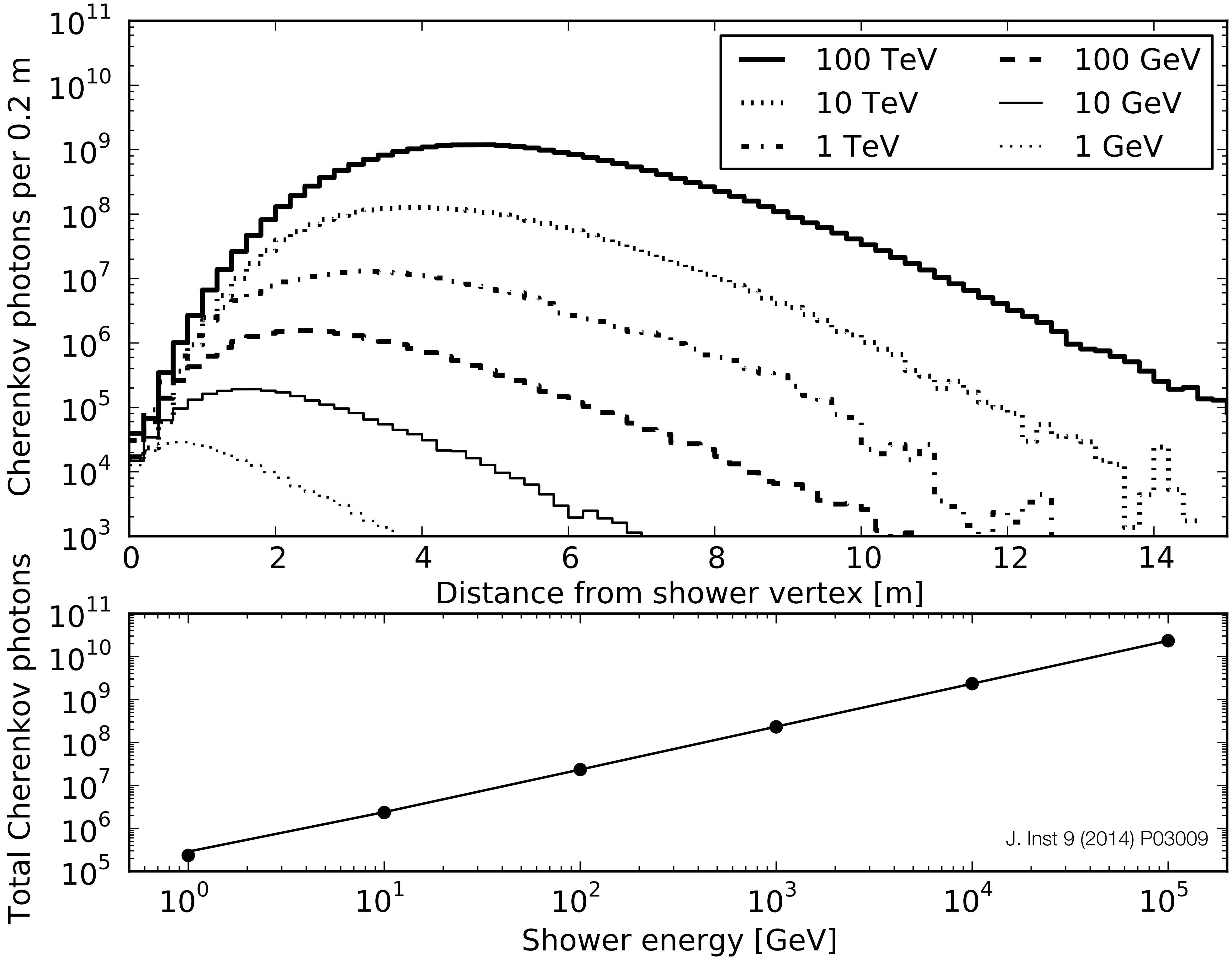
$\nu_e:\nu_\mu:\nu_\tau$ at Earth



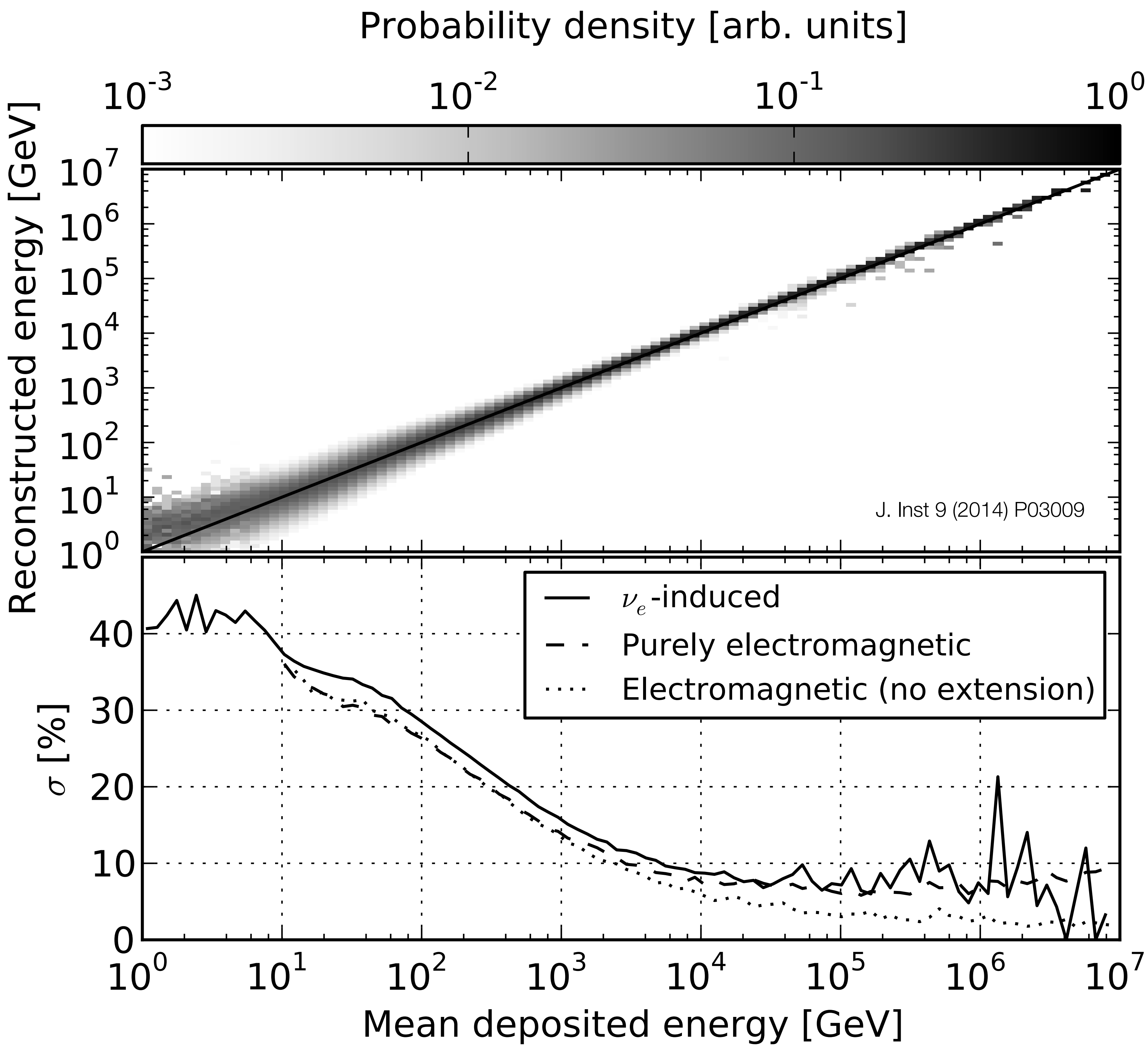
$0° < \delta_{CP} < 360°$

L. Lechner (TU Wien/DESY)

Cascade reconstruction: energy



Deposited-energy resolution for showers in IceCube



Detector paper

- **Summary of detector systems and operations is on the arXiv in December 2016, accepted by JINST**

The IceCube Neutrino Observatory: Instrumentation and Online Systems

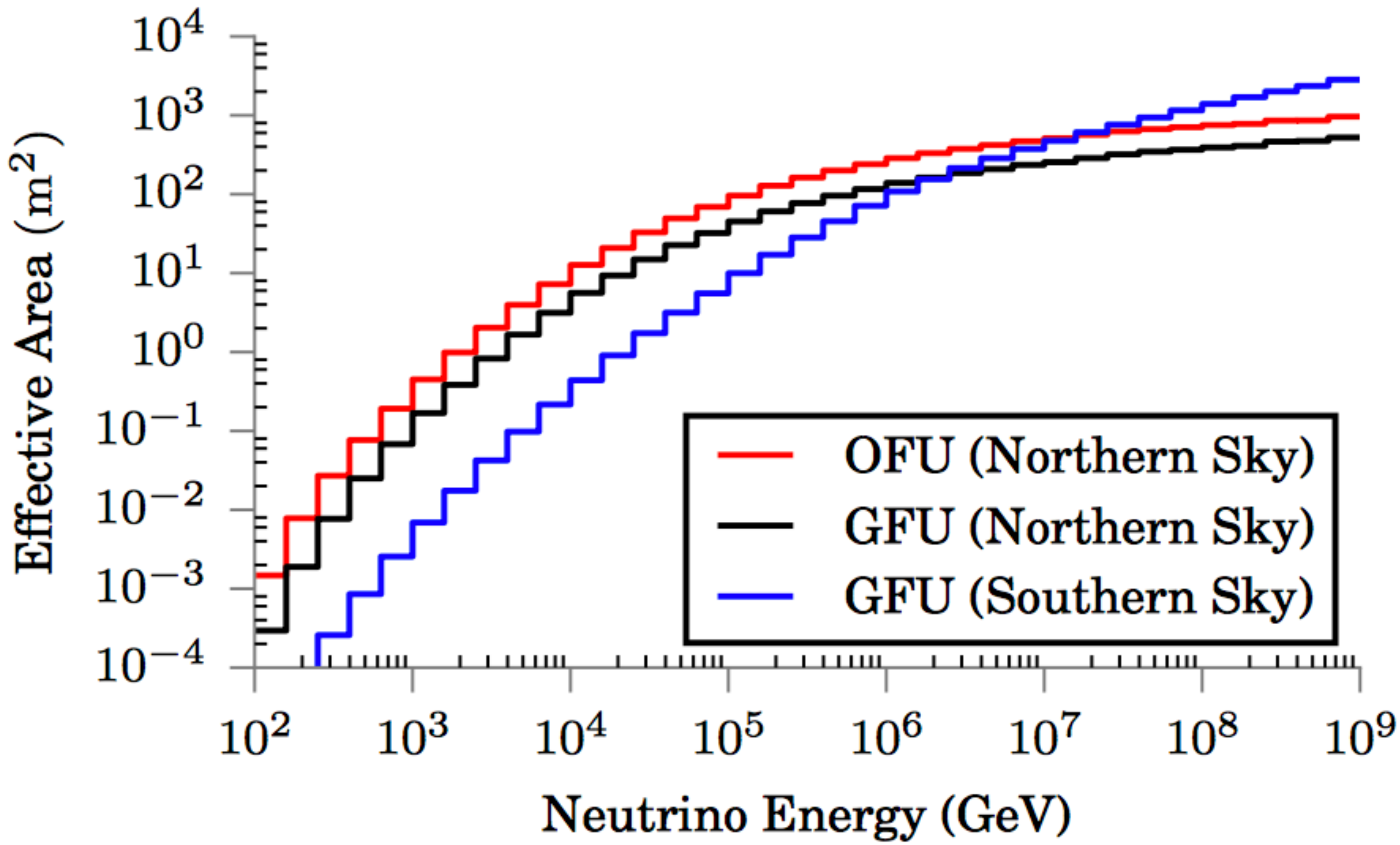
IceCube Collaboration: M. G. Aartsen, M. Ackermann, J. Adams, J. A. Aguilar, M. Ahlers, M. Ahrens, D. Altmann, K. Andeen, T. Anderson, I. Ansseau, G. Anton, M. Archinger, C. Argüelles, R. Auer, J. Auffenberg, S. Axani, J. Baccus, X. Bai, S. Barnet, S. W. Barwick, V. Baum, R. Bay, K. Beattie, J. J. Beatty, J. Becker Tjus, K.-H. Becker, T. Bendfelt, S. BenZvi, D. Berley, E. Bernardini, A. Bernhard, D. Z. Besson, G. Binder, D. Bindig, M. Bissok, E. Blaufuss, S. Blot, D. Boersma, C. Bohm, M. Börner, F. Bos, D. Bose, S. Böser, O. Botner, A. Bouchta, J. Braun, L. Brayeur, H.-P. Bretz, S. Bron, A. Burgman, C. Burreson, T. Carver, M. Casier, E. Cheung, D. Chirkin, A. Christov, K. Clark, L. Classen, S. Coenders, G. H. Collin, J. M. Conrad, D. F. Cowen, R. Cross, C. Day, M. Day, J. P. A. M. de André, et al. (286 additional authors not shown)

(Submitted on 15 Dec 2016)

The IceCube Neutrino Observatory is a cubic-kilometer-scale high-energy neutrino detector built into the ice at the South Pole. Construction of IceCube, the largest neutrino detector built to date, was completed in 2011 and enabled the discovery of high-energy astrophysical neutrinos. We describe here the design, production, and calibration of the IceCube digital optical module (DOM), the cable systems, computing hardware, and our methodology for drilling and deployment. We also describe the online triggering and data filtering systems that select candidate neutrino and cosmic ray events for analysis. Due to a rigorous pre-deployment protocol, 98.4% of the DOMs in the deep ice are operating and collecting data. IceCube routinely achieves a detector uptime of 99% by emphasizing software stability and monitoring. Detector operations have been stable since construction was completed, and the detector is expected to operate at least until the end of the next decade.

Comments: 83 pages, 50 figures; submitted to JINST
Subjects: **Instrumentation and Methods for Astrophysics (astro-ph.IM)**; Instrumentation and Detectors (physics.ins-det)
Cite as: arXiv:1612.05093 **[astro-ph.IM]**
(or arXiv:1612.05093v1 **[astro-ph.IM]** for this version)

Realtime Alerts

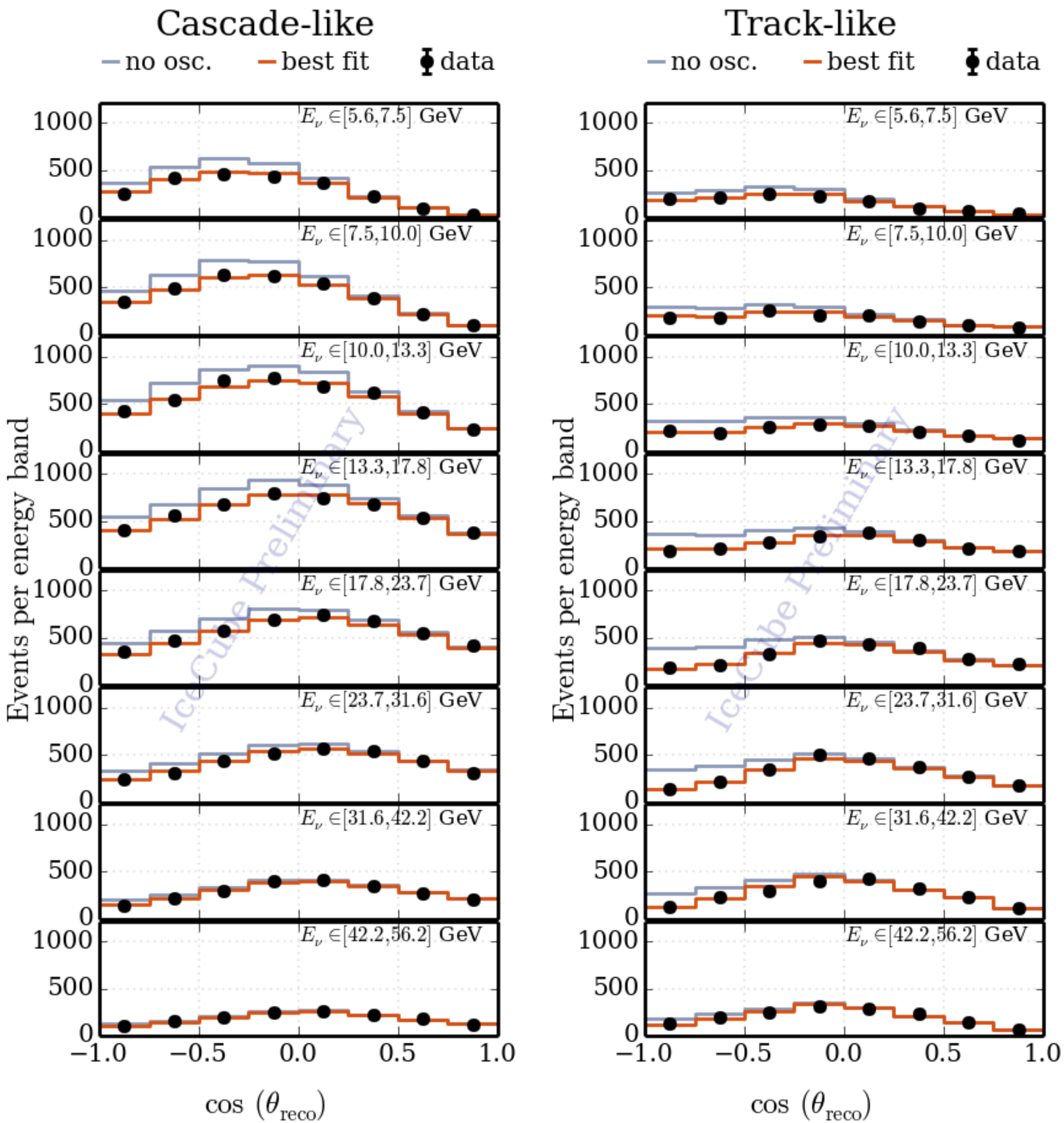


Updated numu disappearance

Tab A **Bestfit parameters obtained in θ_{23} and Δm^2_{32} analysis**

Parameter	Priors	NO	IO
Standard mixing parameters			
Δm^2_{32} (10^{-3} eV^2/c^4)	no prior	$2.31^{+0.12}_{-0.14}$	$-2.32^{+0.12}_{-0.13}$
$\sin^2\theta_{23}$	no prior	$0.51^{+0.08}_{-0.08}$	$0.51^{+0.08}_{-0.07}$
Atmospheric neutrino flux parameters			
$\Delta\gamma$ (spectral index change)	0.00±0.10	-0.02	-0.02
ν_e normalization	1.00±0.20	1.24	1.24
ν NC normalization	1.00±0.20	1.05	1.05
$\Delta(\nu/\bar{\nu})$, energy dependent (nubar_ratio)	0±1σ	-0.56	-0.60
$\Delta(\nu/\bar{\nu})$, zenith dependent (uphor_ratio)	0±1σ	-0.53	-0.55
Cross section parameters			
M_A (resonance) (GeV)	1.12±0.22	0.91	0.92
Detector parameters			
Hole ice scattering (p1)	0.020±0.010	0.022	0.022
Hole ice forward scattering (p2)	no prior	-0.76	-0.70
DOM efficiency (%)	100±10	103	103
Atmospheric μ background			
Atmospheric μ background contamination fraction (%)	no prior	5.2	5.2

Updated



Cascade-like
no osc.
best fit
data
Track-like
no osc.
best fit
data
Events per energy band
E_ν ∈[5.6,7.5] GeV
E_ν ∈[7.5,10.0] GeV
E_ν ∈[10.0,13.3] GeV
E_ν ∈[13.3,17.8] GeV
E_ν ∈[17.8,23.7] GeV
E_ν ∈[23.7,31.6] GeV
E_ν ∈[31.6,42.2] GeV
E_ν ∈[42.2,56.2] GeV
IceCube Preliminary
cos (θ_reco)

Multiplet

- Feb 17, 2016 observed 3 muon neutrino candidates within 100 s
- Expected from background (random coincidence) once every ~14 years
- Given lifetime of rollup-program, p=35%

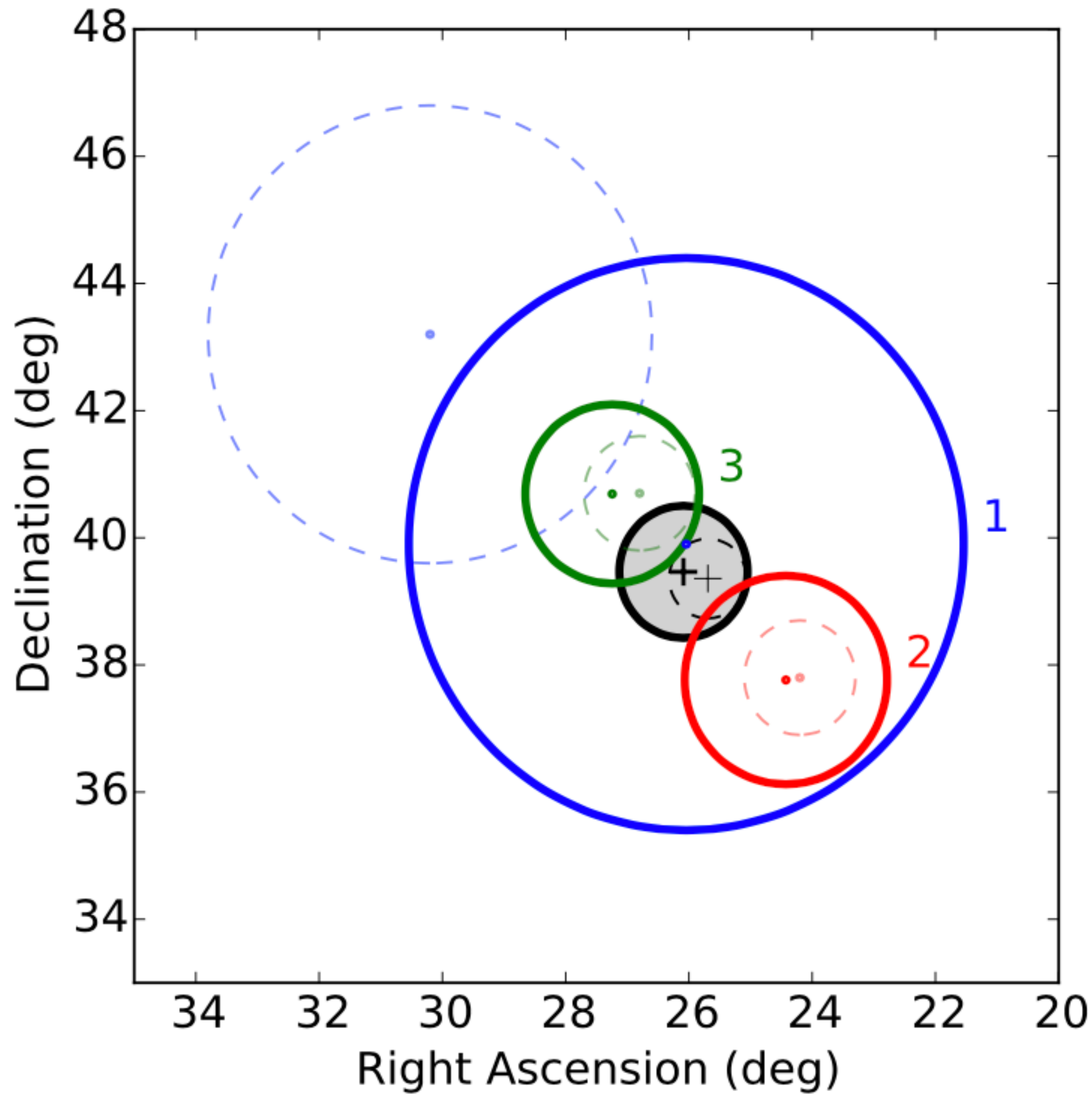
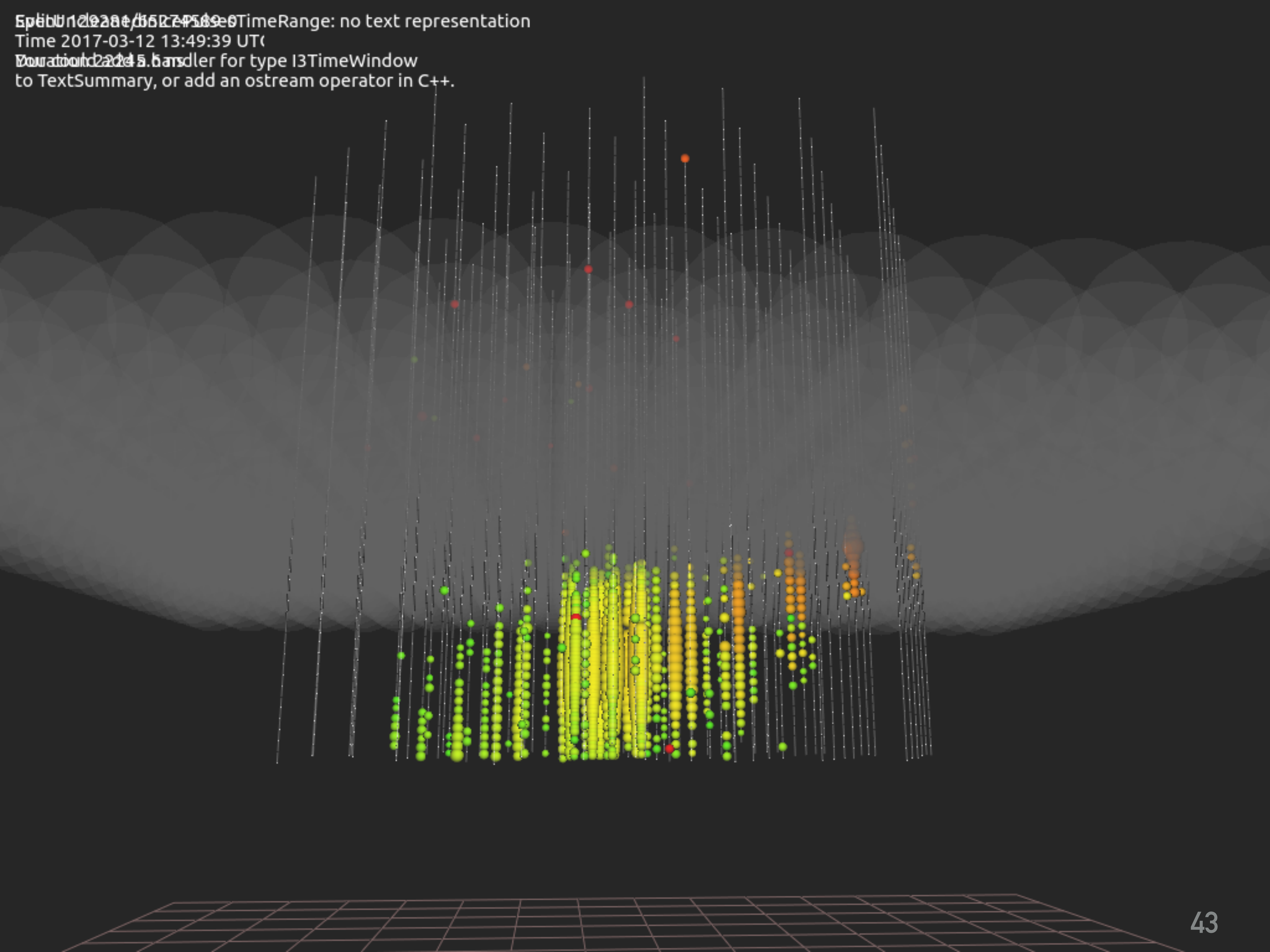


Fig. 1: Location of the three neutrino candidates in the triplet with their 50% error circles. The plus sign shows the combined direction and the shaded circle is the combined 50% error circle. The solid circles show the results of the MPE reconstruction which is as the default reconstruction in the following and the thin dashed circles correspond to the results of the Spline MPE reconstruction (compare Table 1).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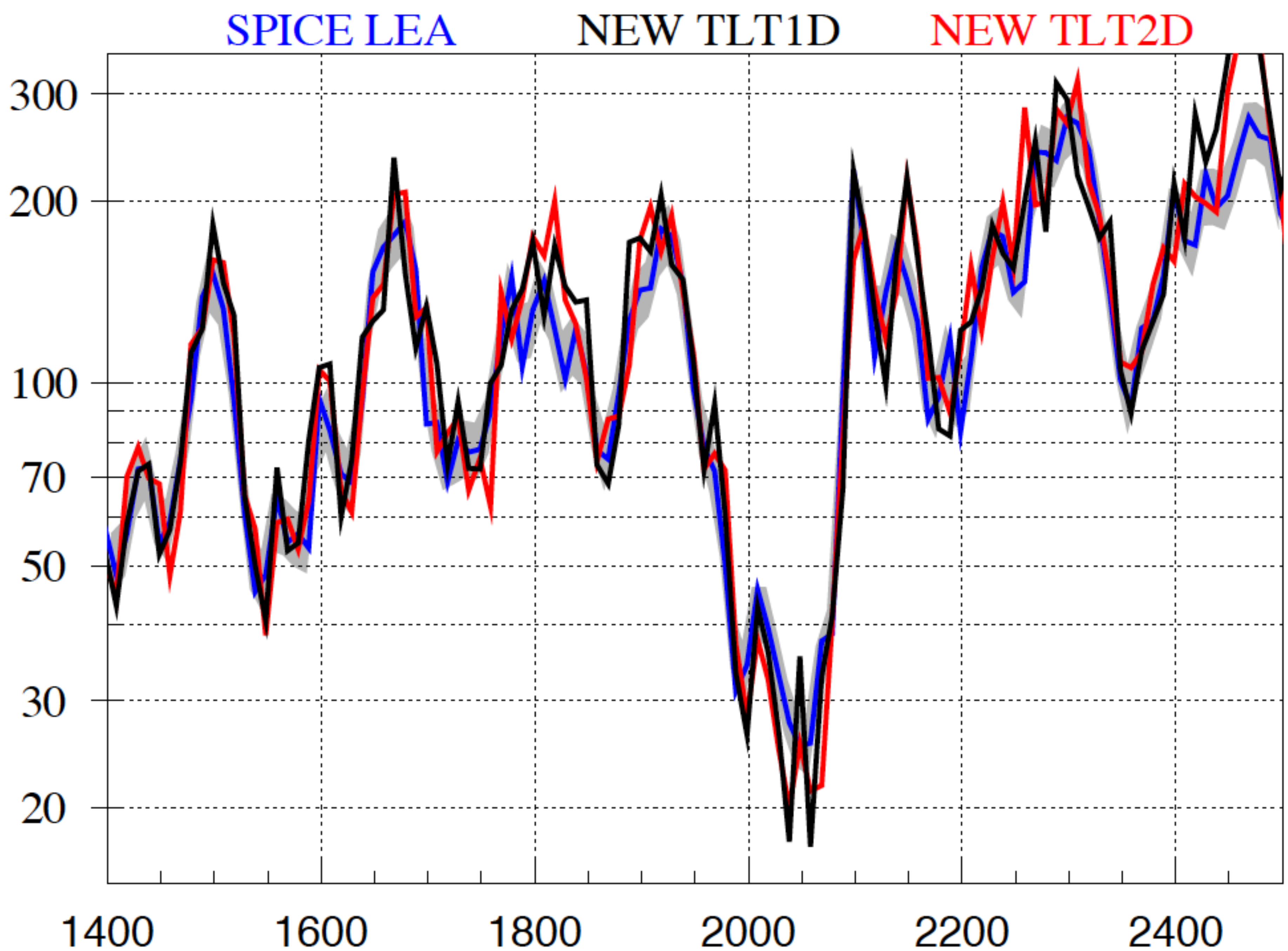
to TextSummary, or add an ostream operator in C++.



λa(400 nm) [m] vs. depth [m]

New optical module designs

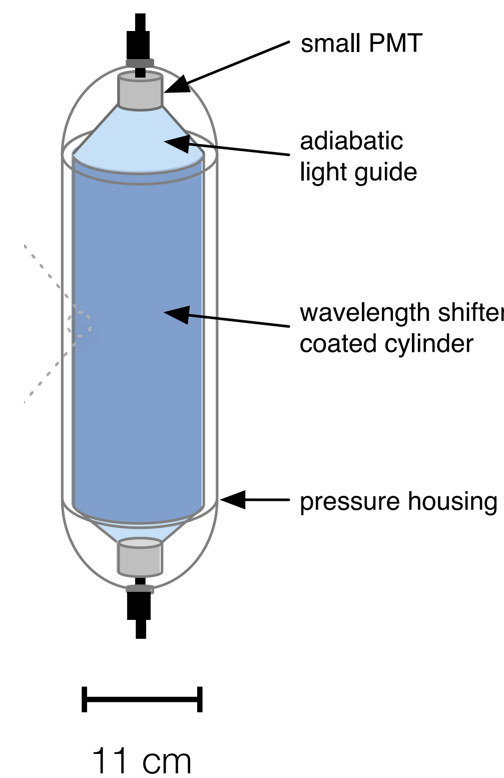
mDOM

- Directional information
- More sensitive area per module

D-Egg

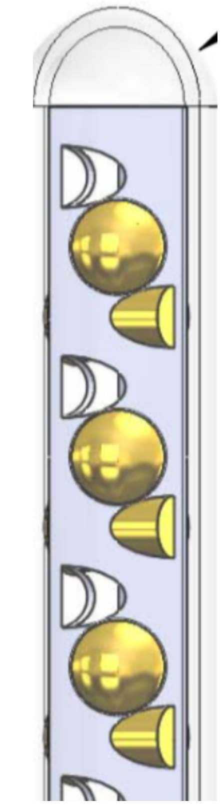
- Directional information
- More sensitive area per module
- Smaller geometry

WOM



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

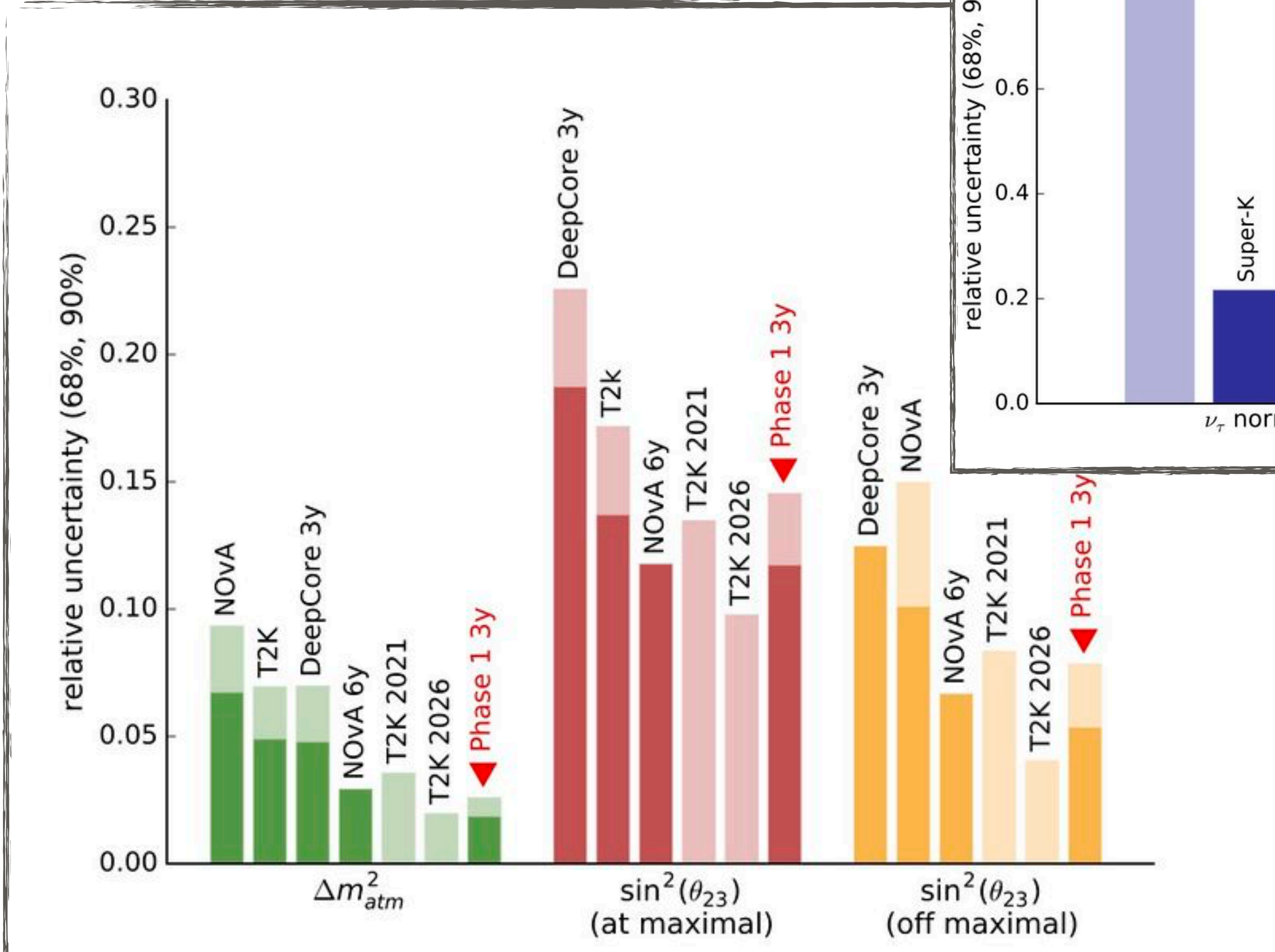
LOM

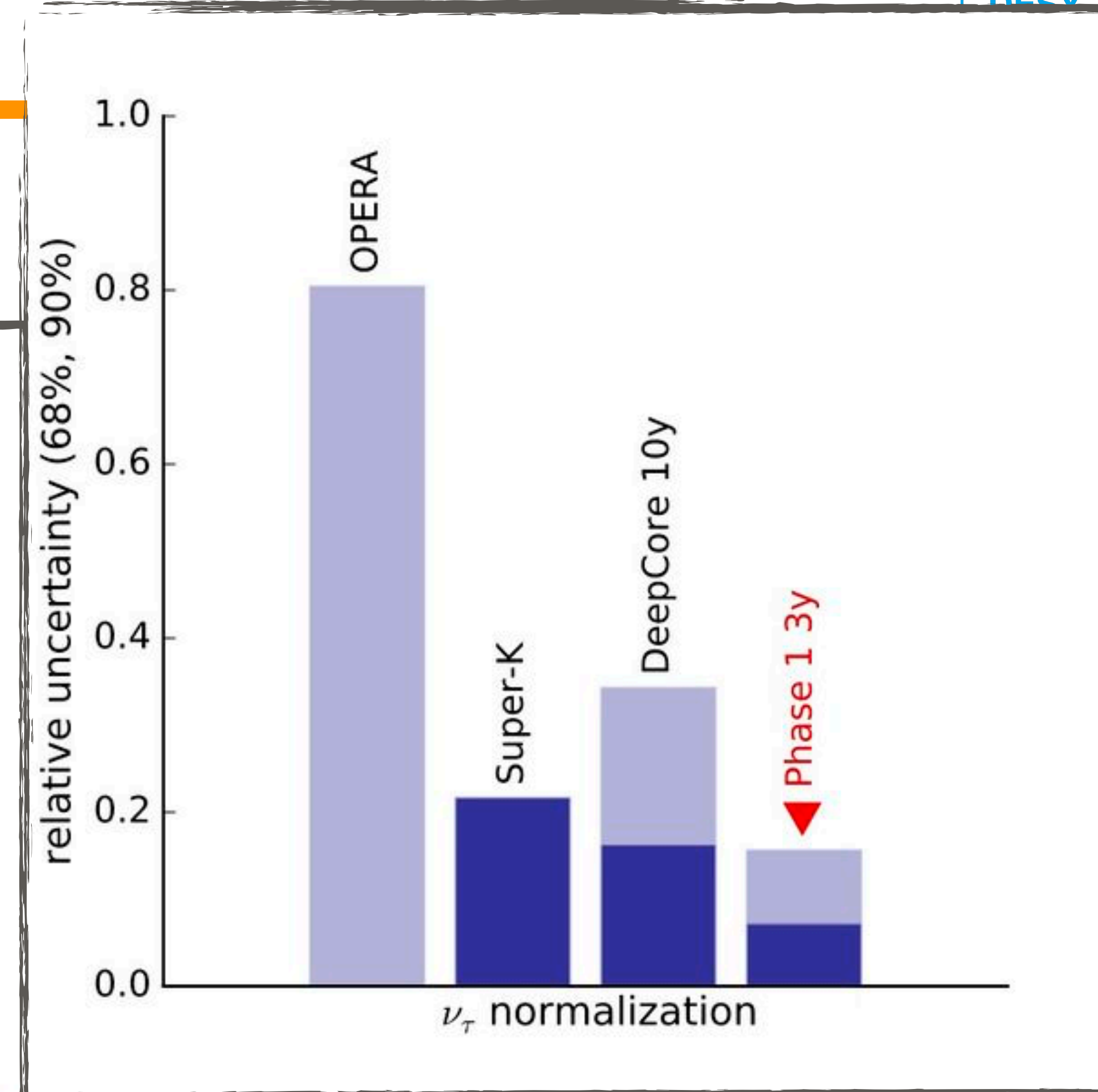


- Small diameter
- Directional info.
- More area per module

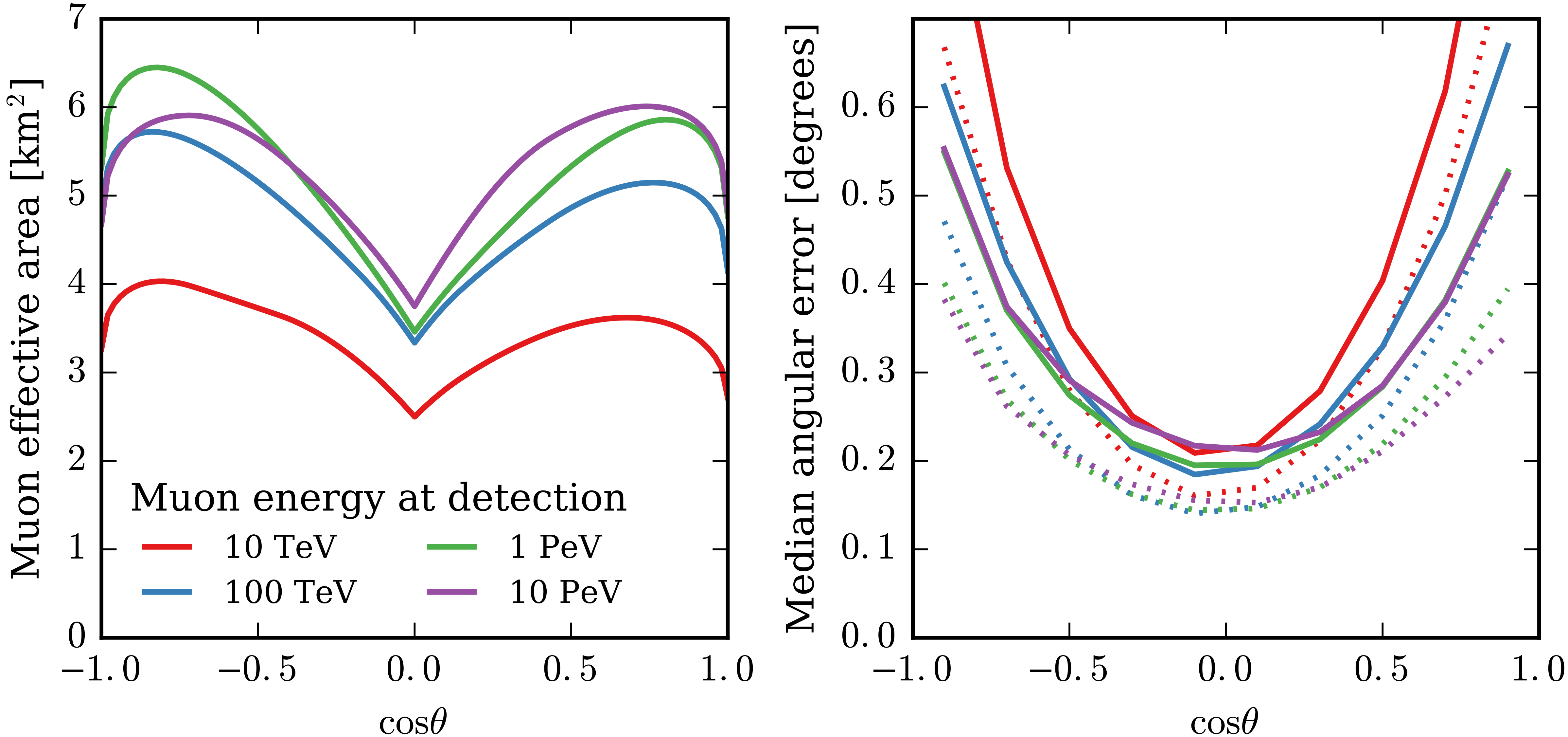
DESY: D. Hebecker, T. Karg, S. Kunwar, J. von Santen

IceCube Gen2-Phase1

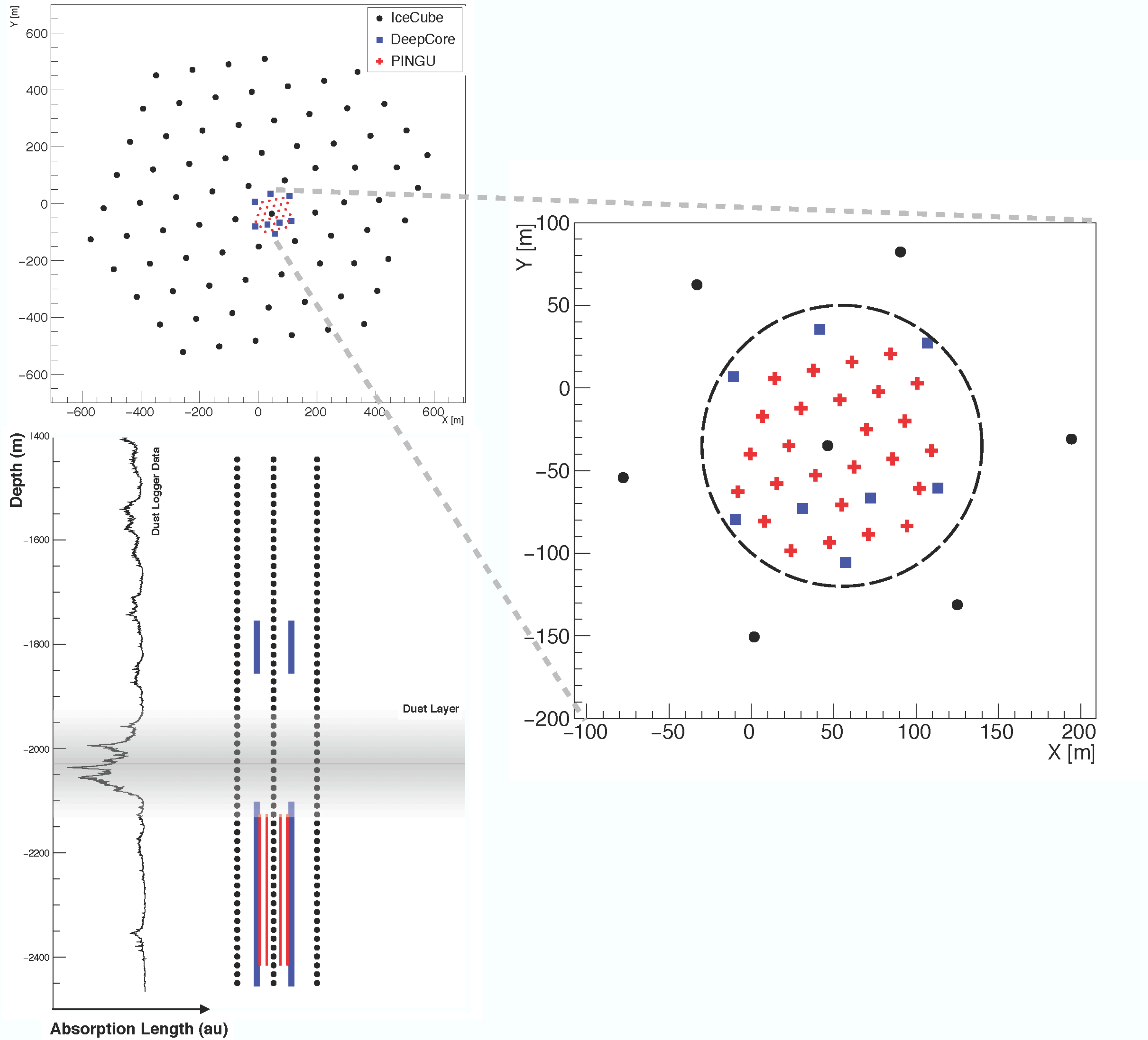




x2 photons

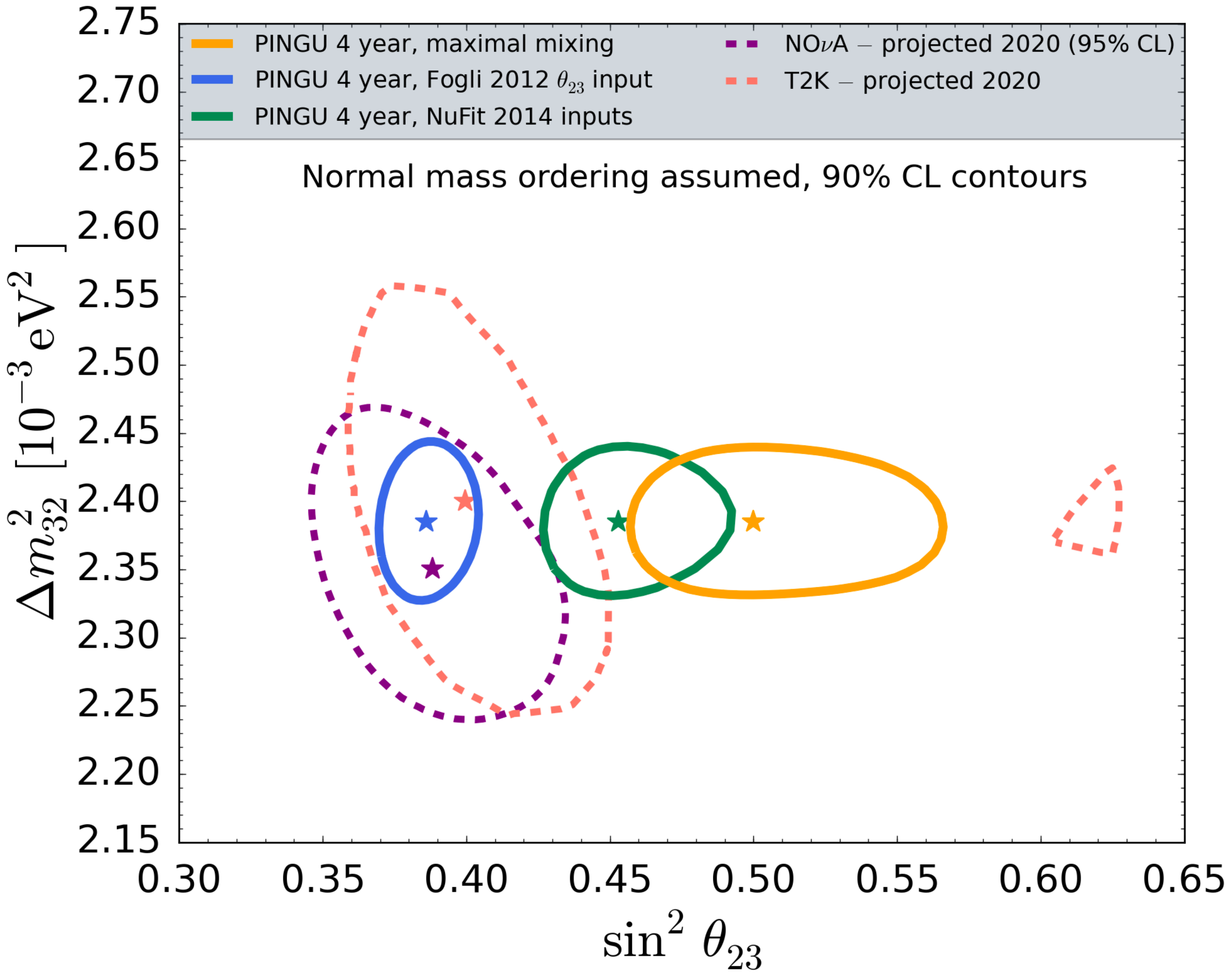

Muon effective area [km^2]
Muon energy at detection
10 TeV
100 TeV
1 PeV
10 PeV
Median angular error [degrees]
cosθ
cosθ

PINGU

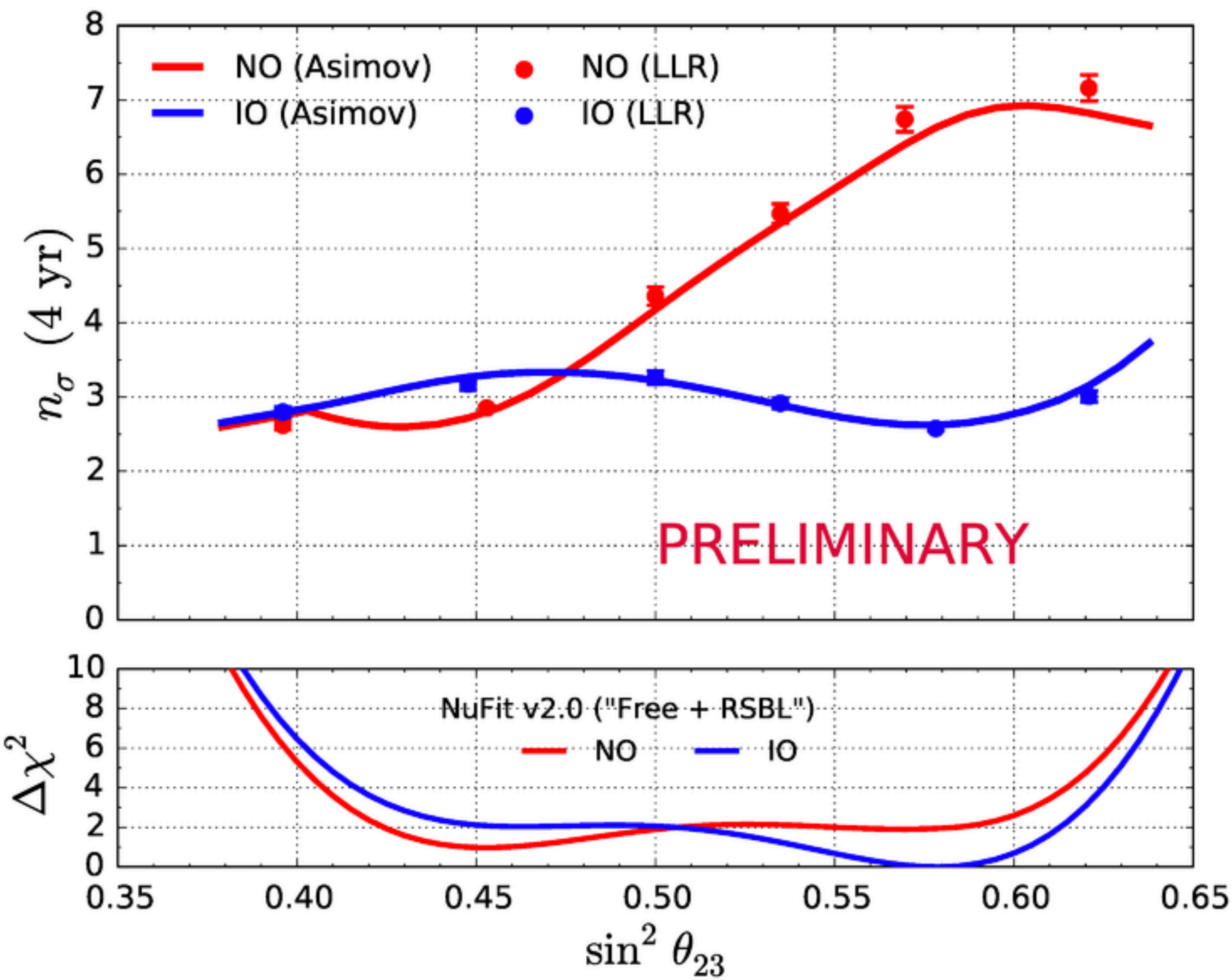


IceCube
DeepCore
PINGU
Y [m]
X [m]
Depth (m)
Dust Logger Data
Dust Layer
Absorption Length (au)

PINGU



PINGU 4 year, maximal mixing
PINGU 4 year, Fogli 2012 θ_{23} input
PINGU 4 year, NuFit 2014 inputs
NOνA – projected 2020 (95% CL)
T2K – projected 2020
Normal mass ordering assumed, 90% CL contours
Δm^2_{32} [10^{-3}eV^2]
2.75
2.70
2.65
2.60
2.55
2.50
2.45
2.40
2.35
2.30
2.25
2.20
2.15
0.30
0.35
0.40
0.45
0.50
0.55
0.60
0.65
$\sin^2\theta_{23}$



NO (Asimov)
IO (Asimov)
NO (LLR)
IO (LLR)
PRELIMINARY
n_σ (4 yr)
8
7
6
5
4
3
2
1
0
NuFit v2.0 ("Free + RSBL")
NO
IO
$\Delta\chi^2$
10
8
6
4
2
0
0.35
0.40
0.45
0.50
0.55
0.60
0.65
$\sin^2\theta_{23}$

Preliminary timeline