HIGH-ENERGY NEUTRINOS

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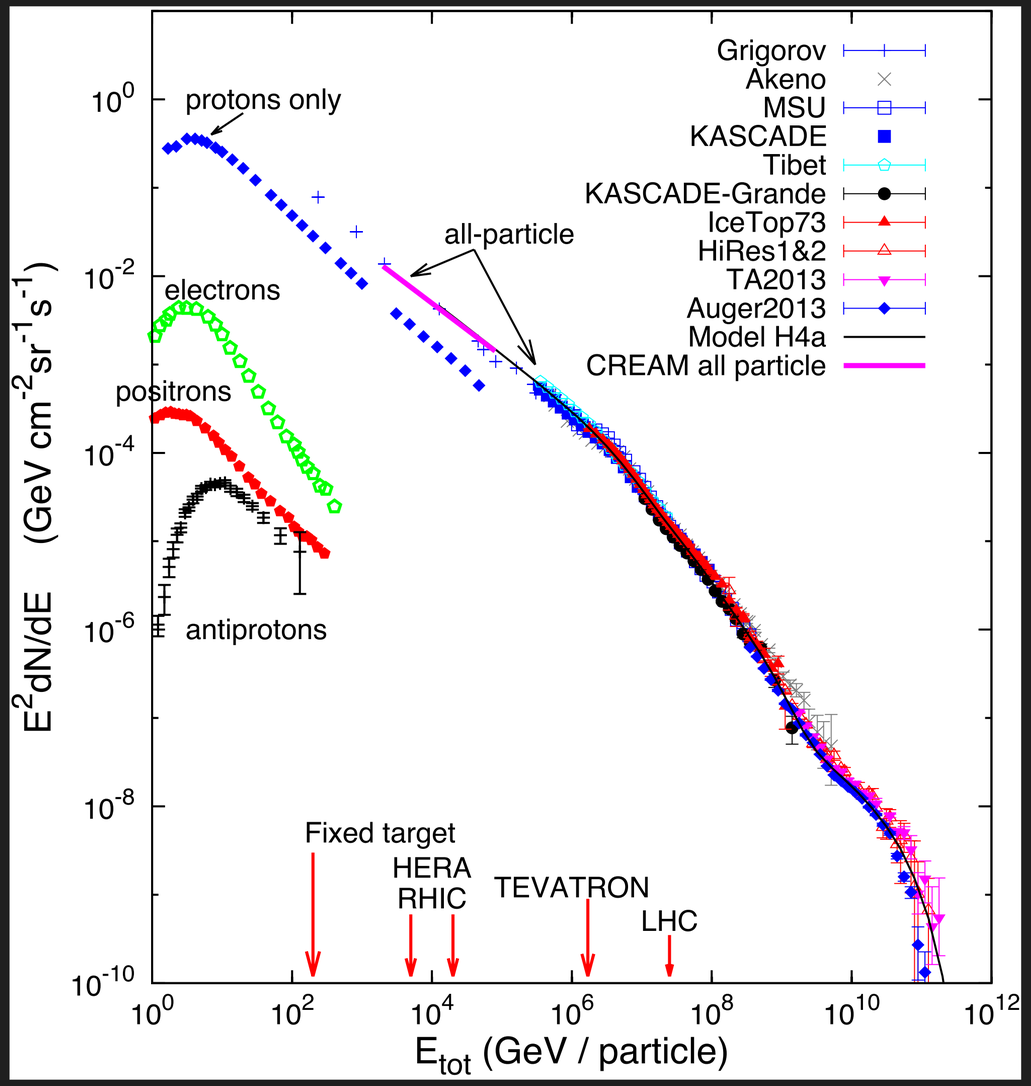
UNIVERSITY OF ALBERTA

COSMIC RAYS AND NEUTRINOS

Search for the sources of Cosmic Rays

COSMIC RAYS

where (and how) are they accelerated?



COSMIC RAYS

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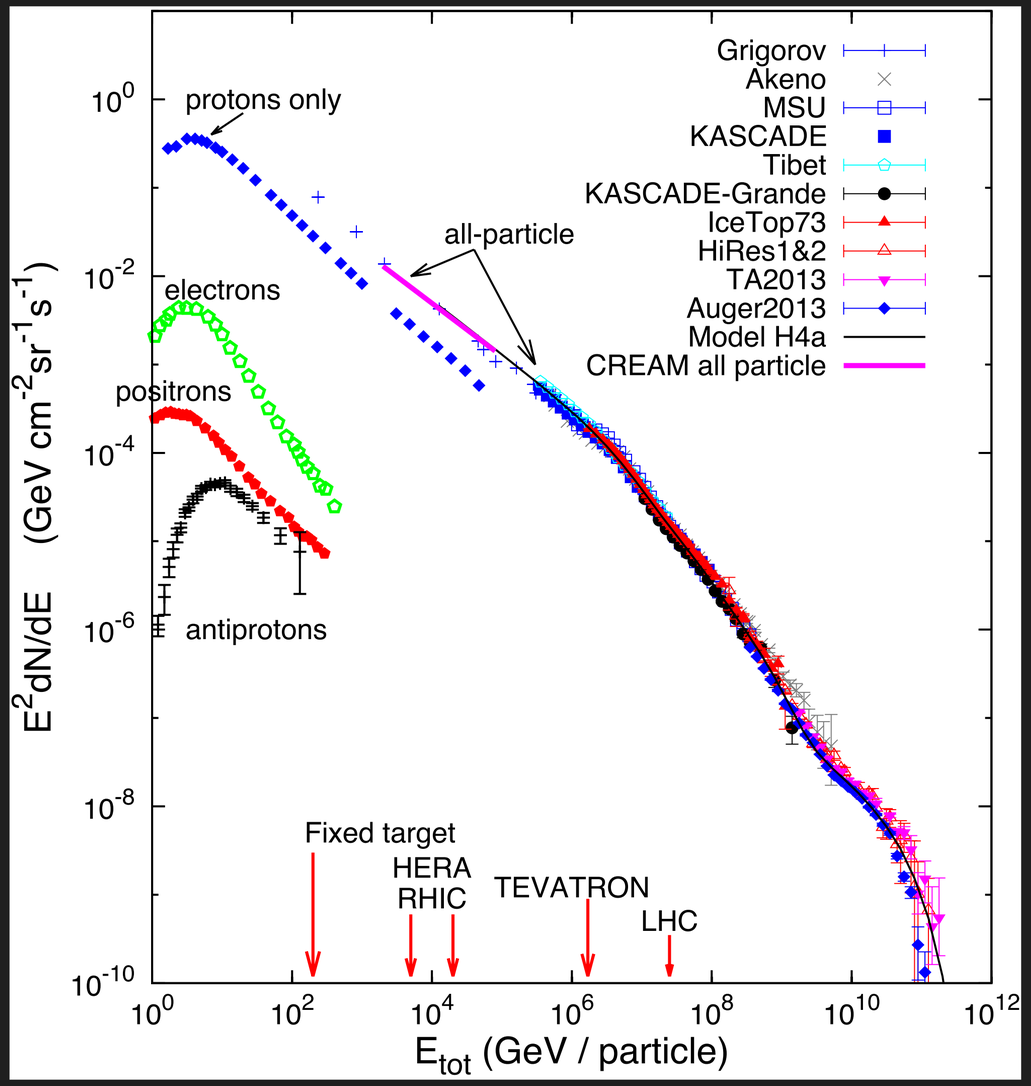
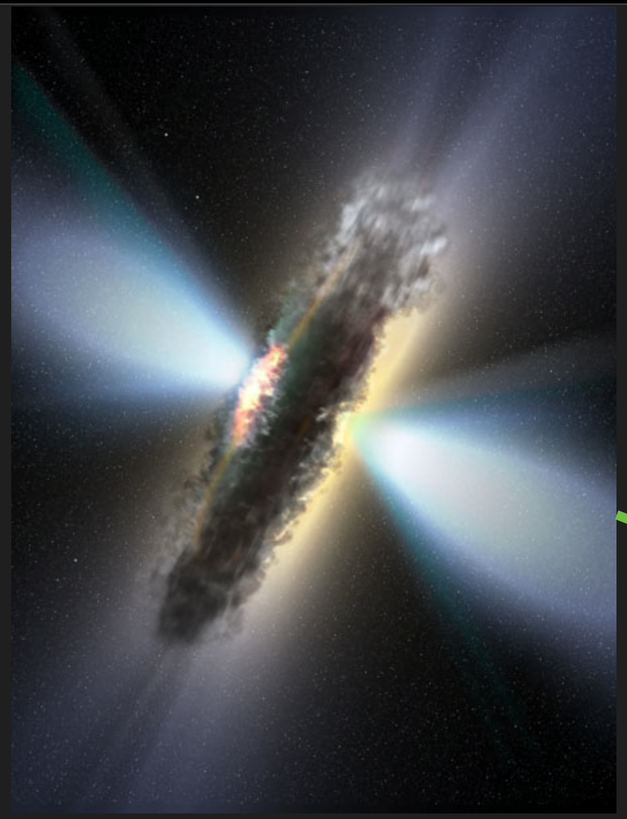


We know their energy spectrum over 11 orders of magnitude

Their sources (especially at the highest energies) are still mostly unknown

MULTI-MESSENGER ASTROPHYSICS WITH NEUTRINOS



- **Nuclei** can be deflected by magnetic fields

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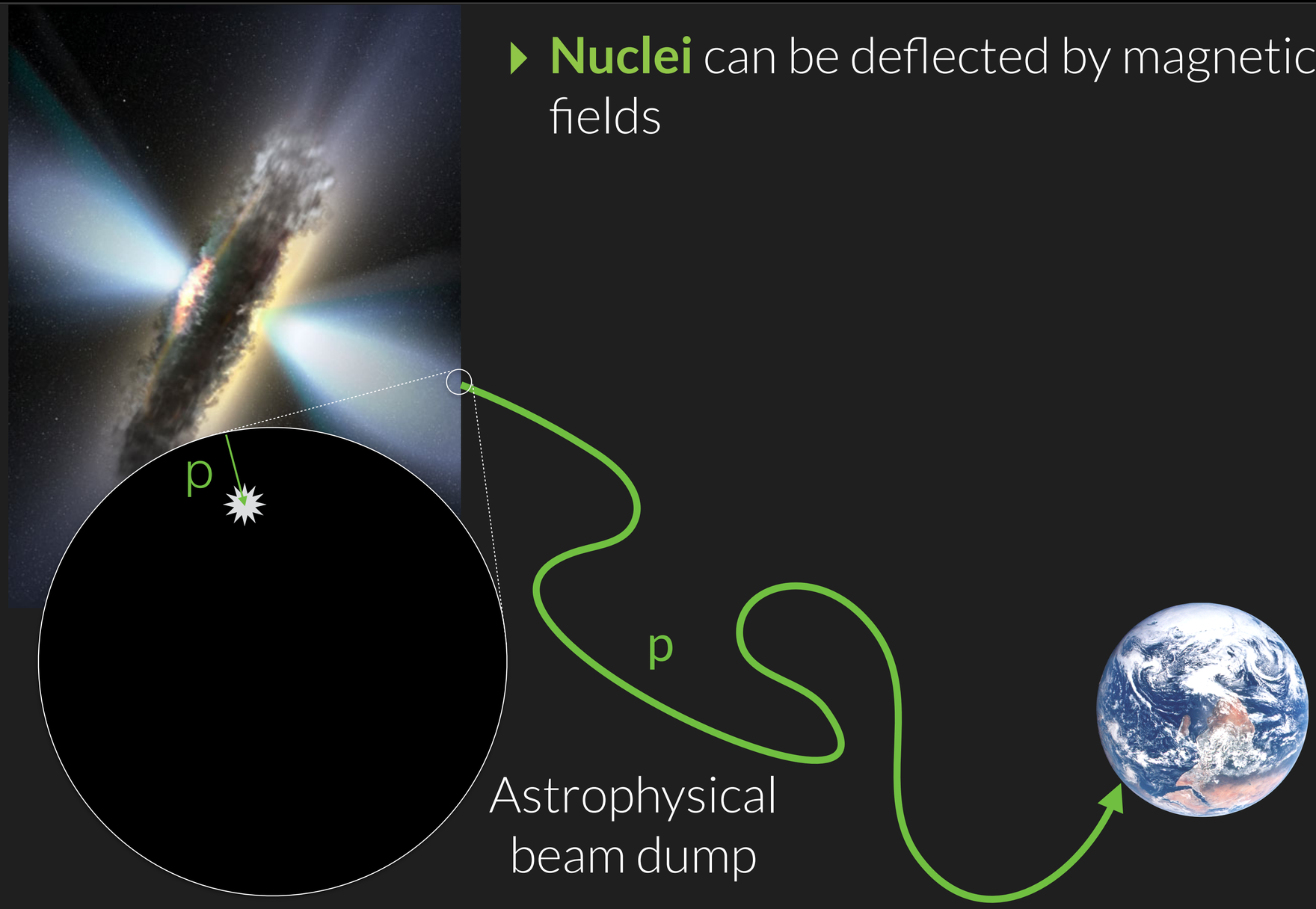

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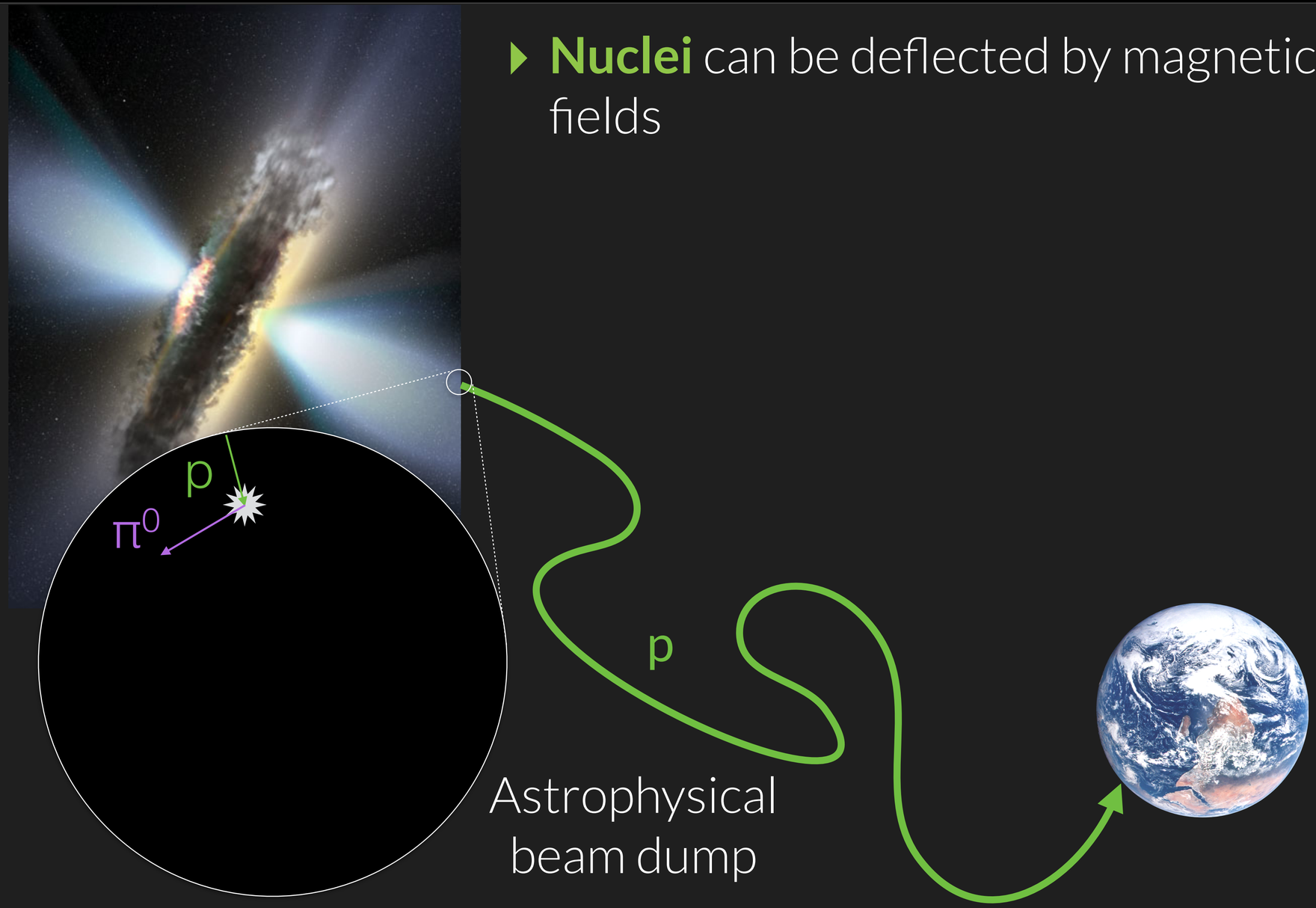

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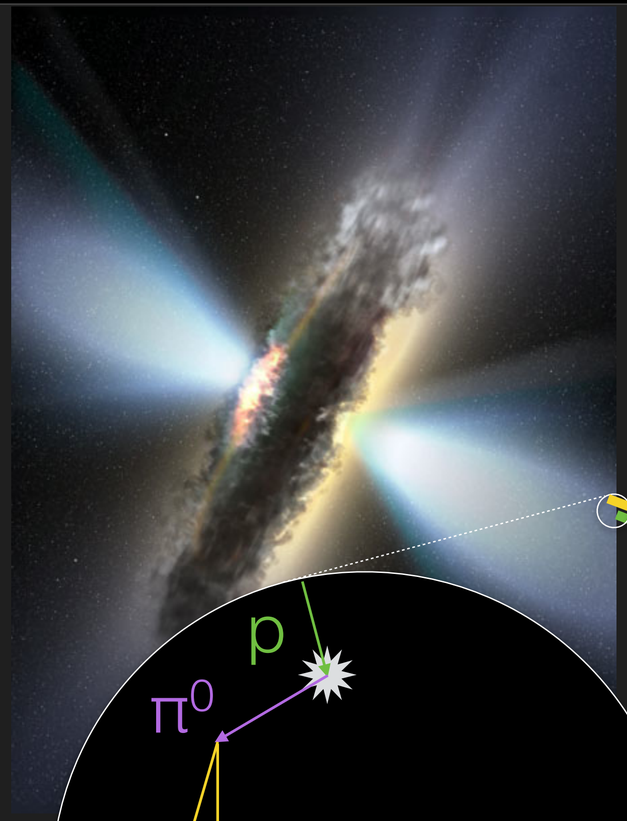
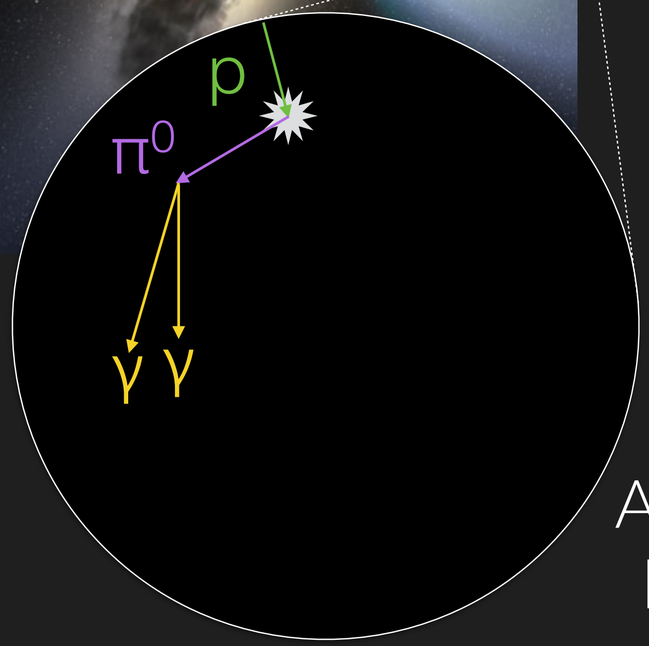
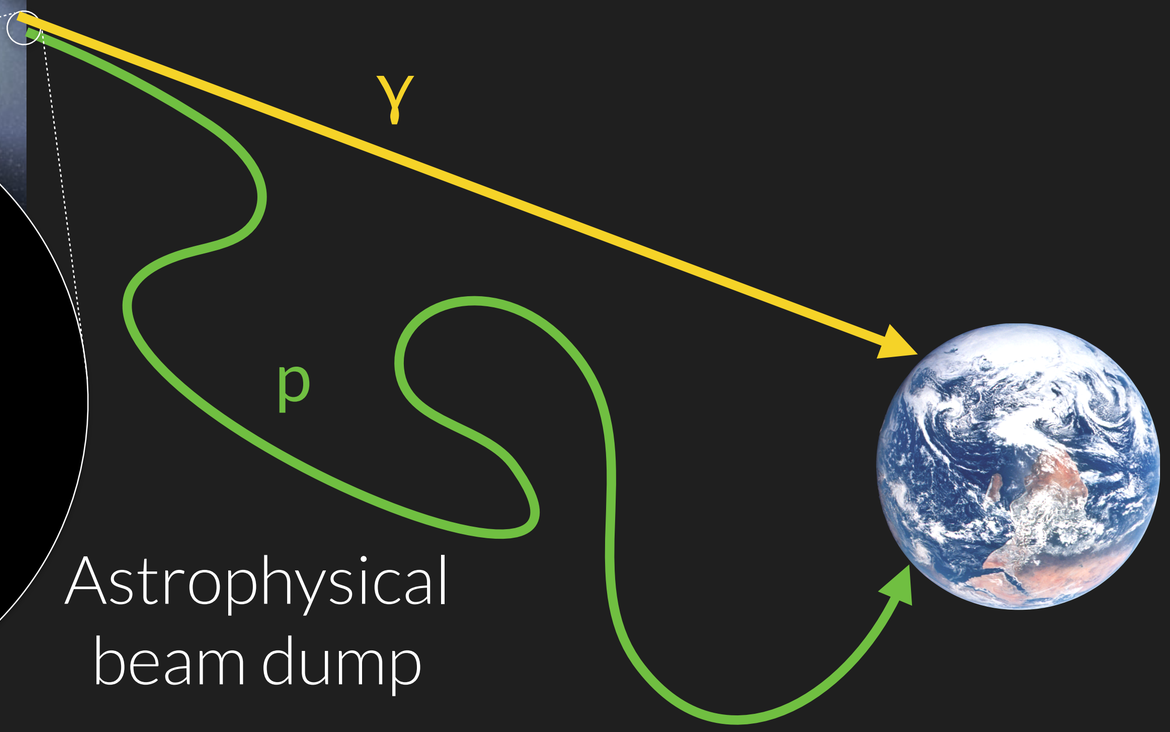


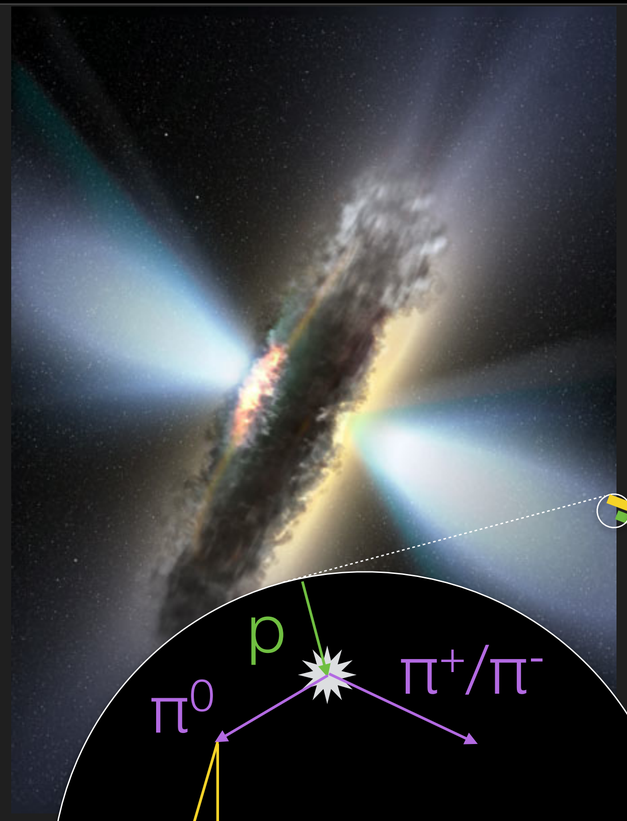
- **Nuclei** can be deflected by magnetic fields
- **Gamma rays** can be absorbed





Astrophysical beam dump

MULTI-MESSENGER ASTROPHYSICS WITH NEUTRINOS



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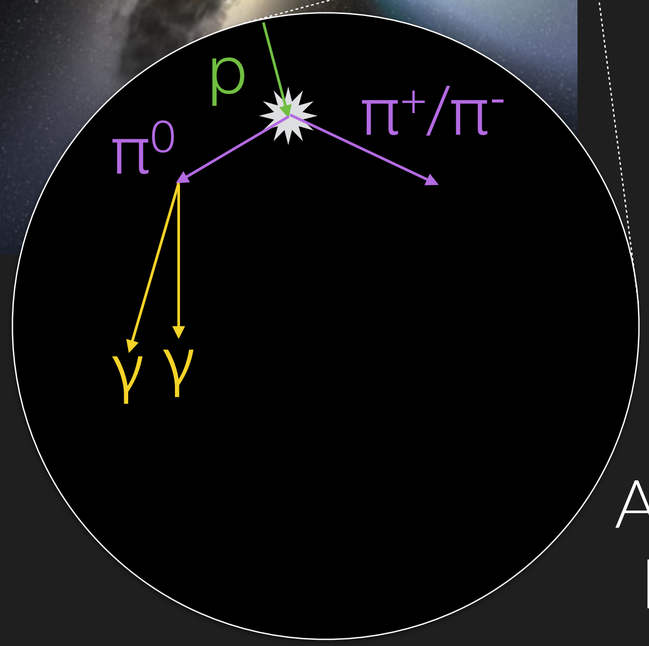

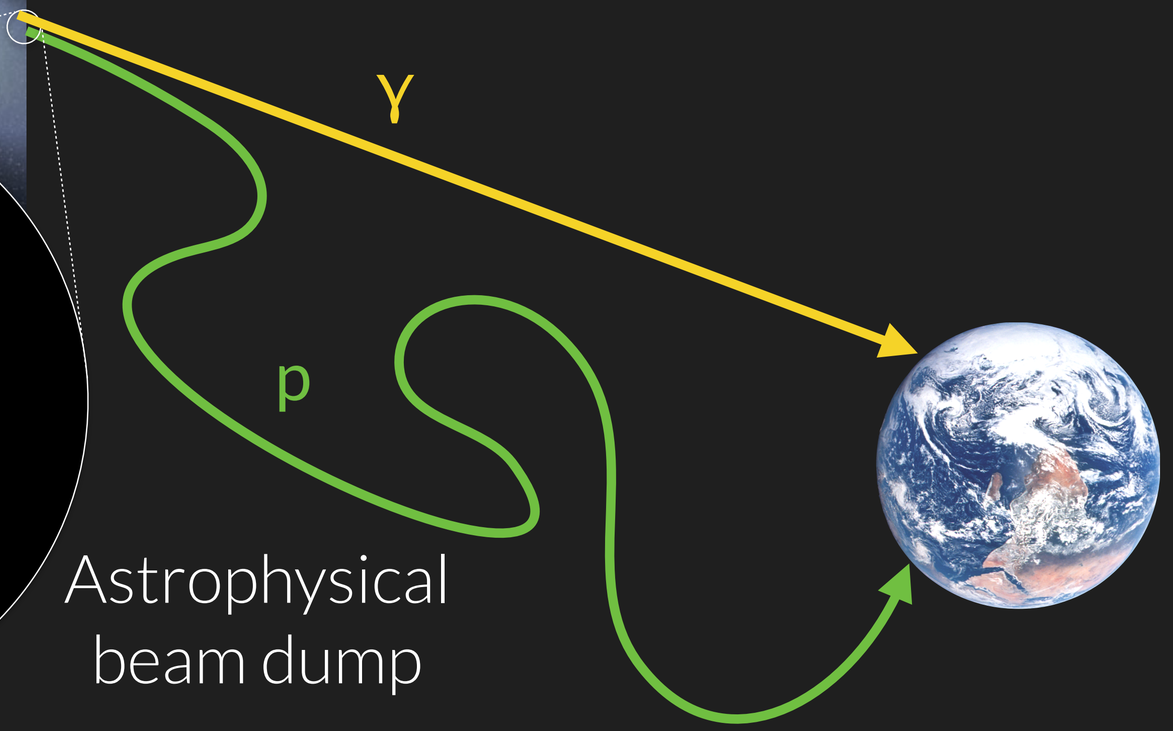

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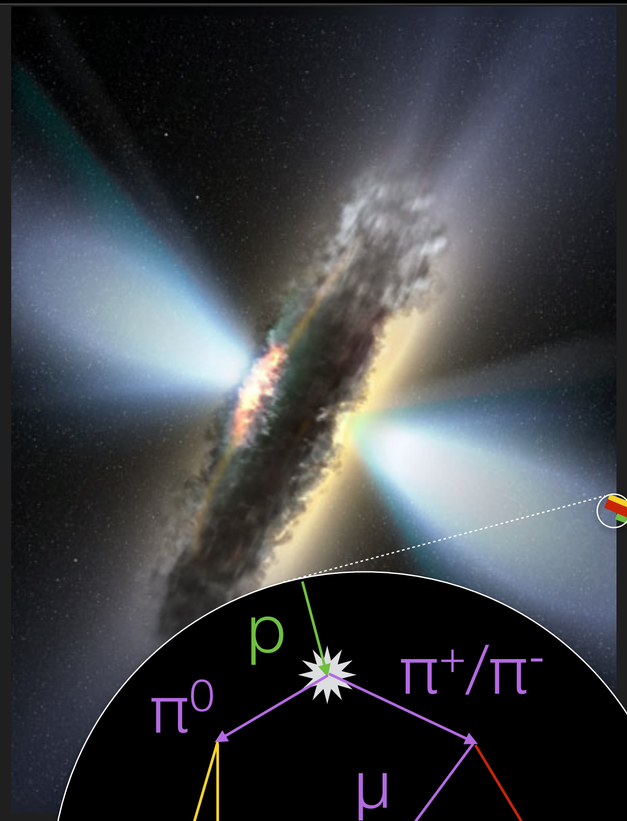
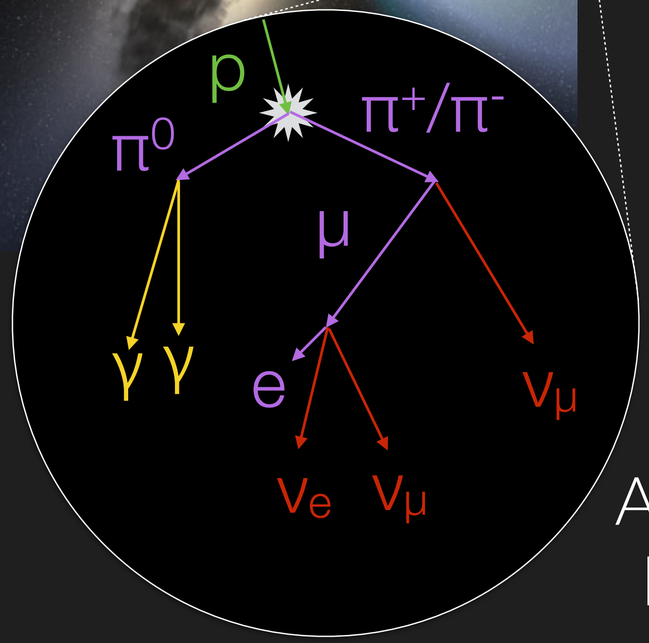
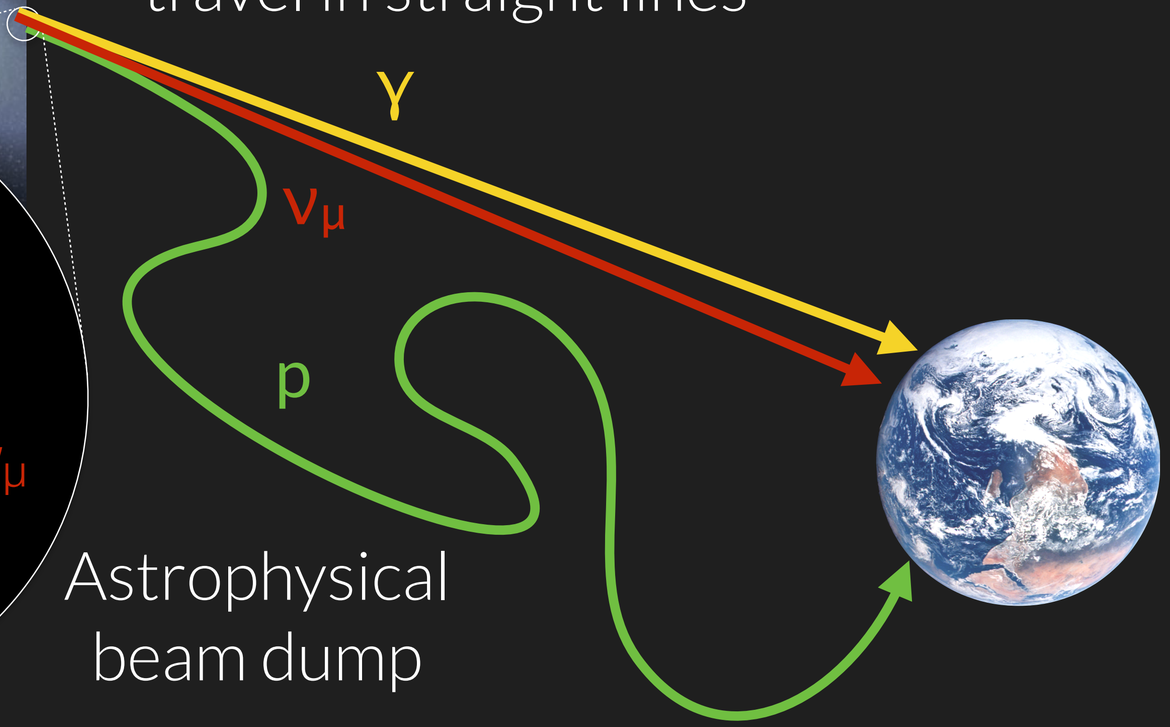


- **Nuclei** can be deflected by magnetic fields
- **Gamma rays** can be absorbed
- **Neutrinos** are difficult to stop and travel in straight lines

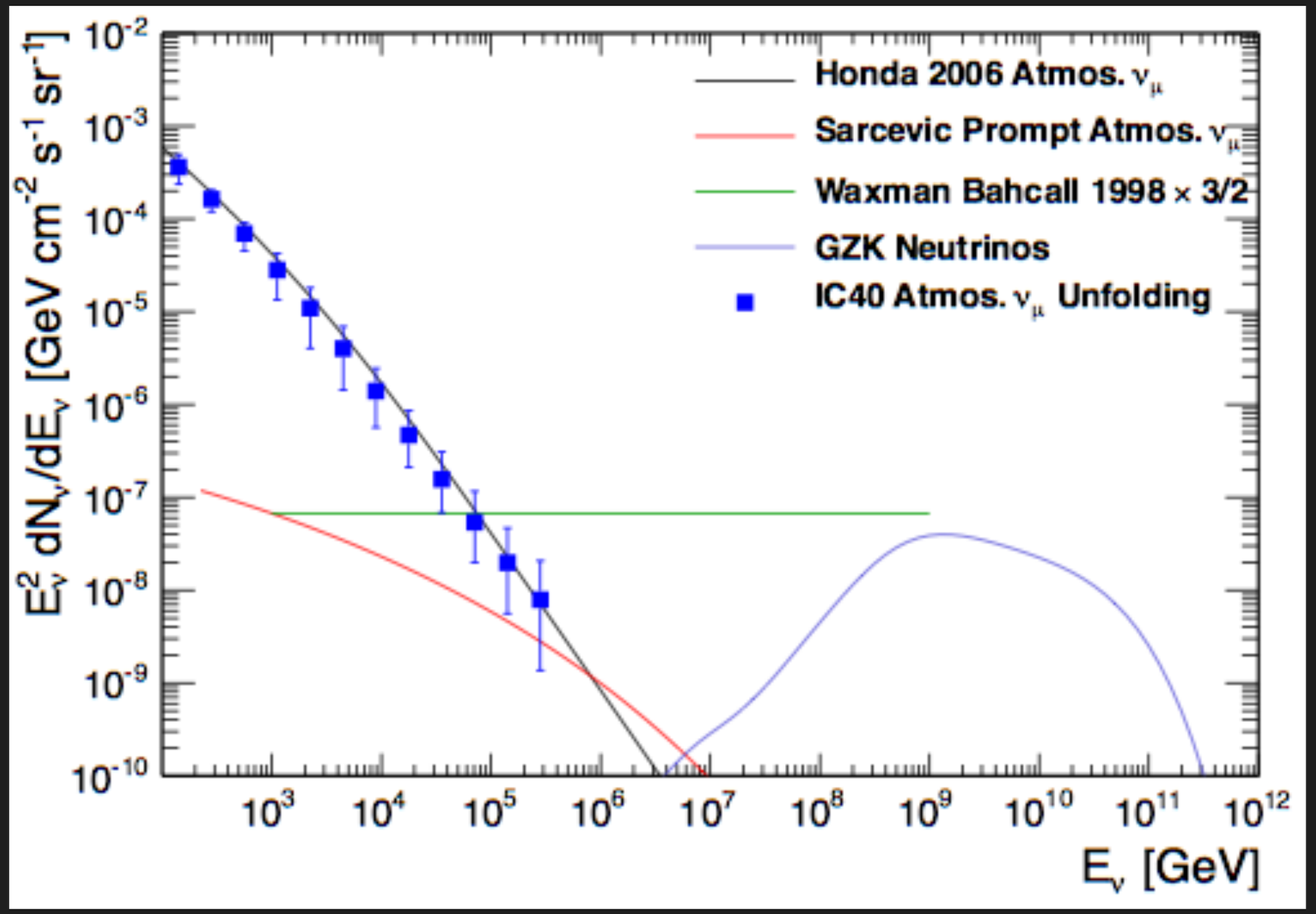




Astrophysical beam dump

NEUTRINOS ABOVE 1 TEV

sketch of the different expected neutrino flux components



NEUTRINOS ABOVE 1 TEV

sketch of the different expected neutrino flux components

ATMOSPHERIC NEUTRINOS (π/K)

dominant < 100 TeV

ATMOSPHERIC NEUTRINOS (CHARM)

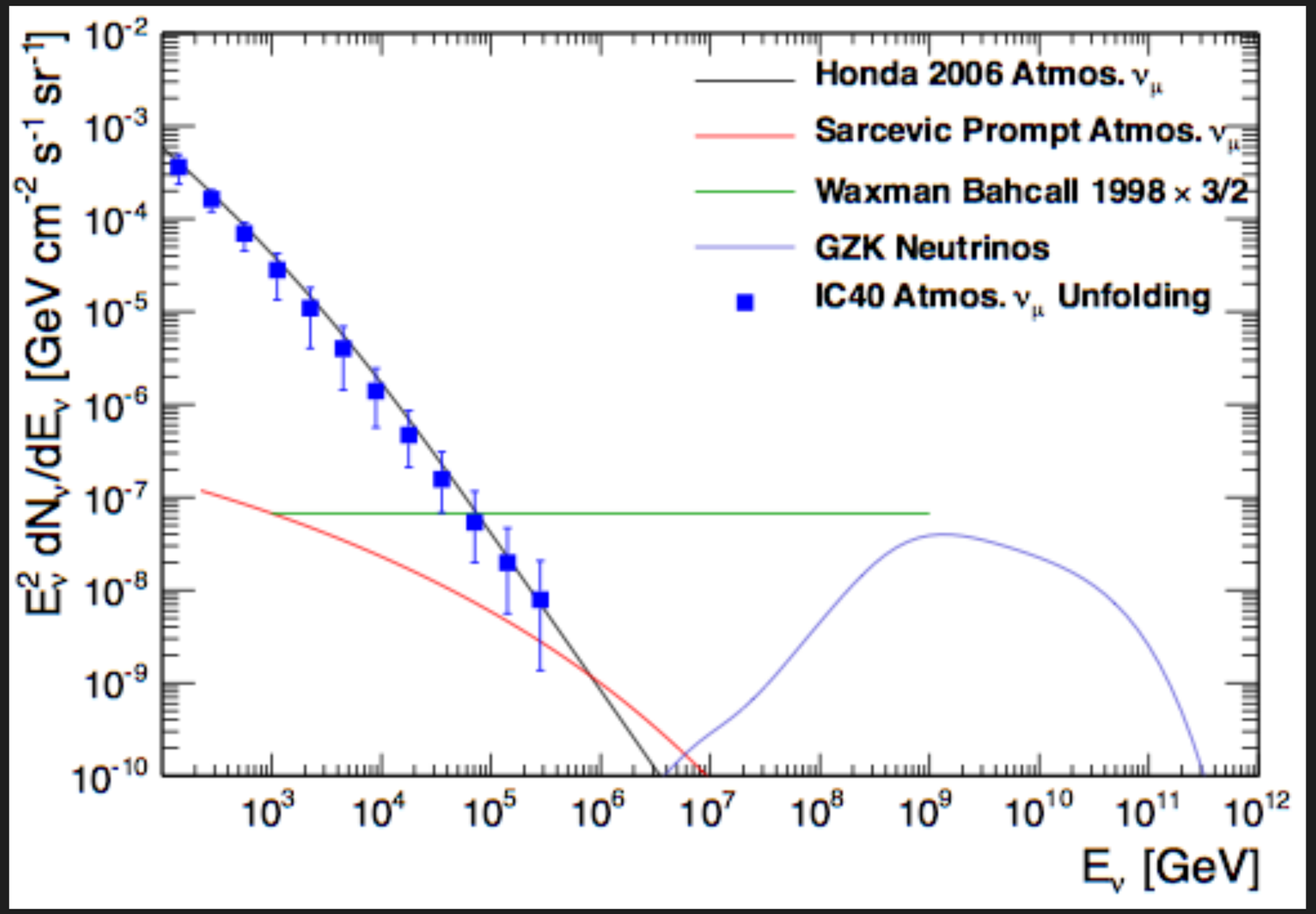
"prompt" ~ 100 TeV

ASTROPHYSICAL NEUTRINOS

maybe dominant > 100 TeV

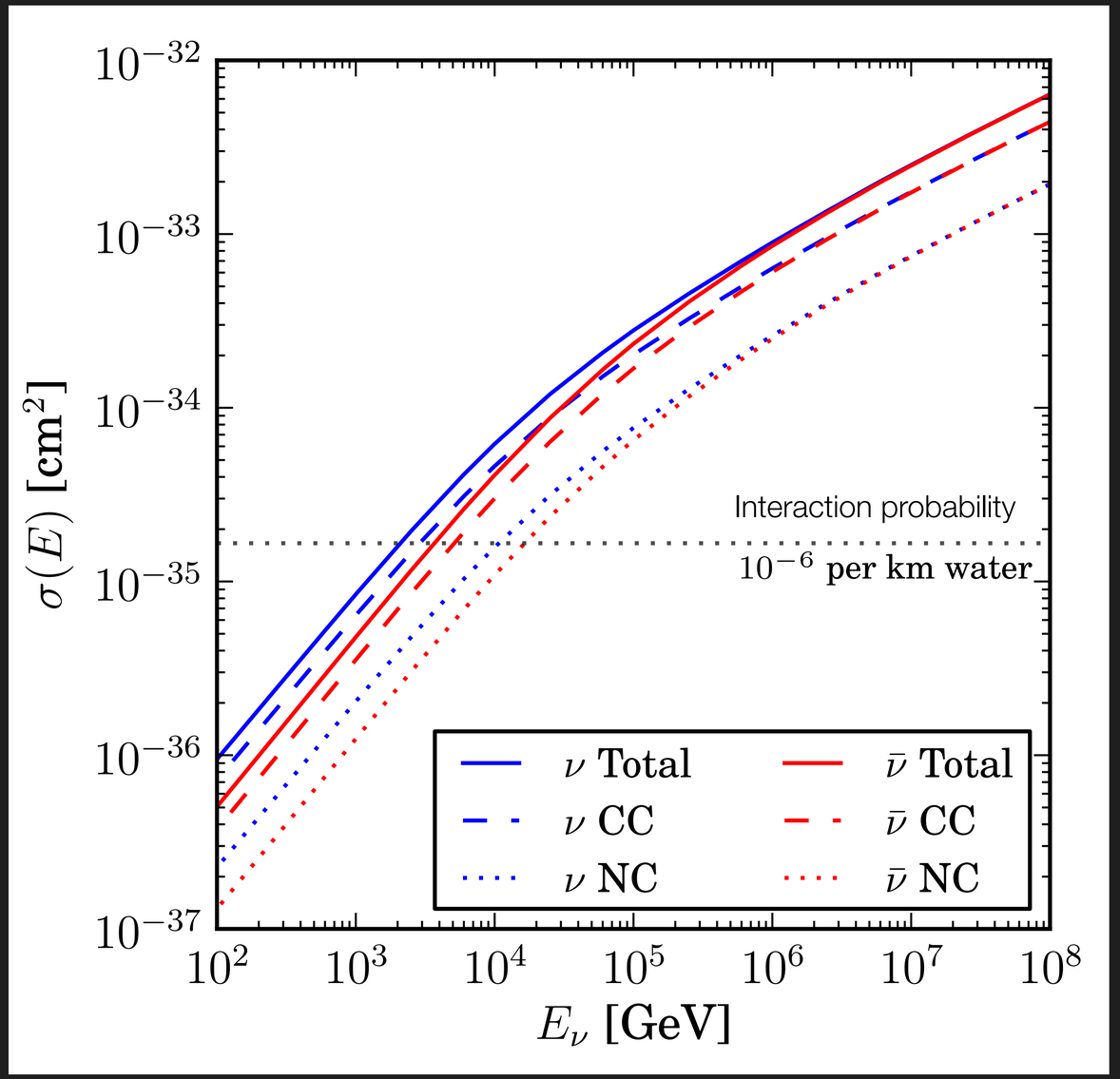
COSMOGENIC NEUTRINOS

$>10^6$ TeV



DETECTING TEV NEUTRINOS

Interaction cross-sections are very small



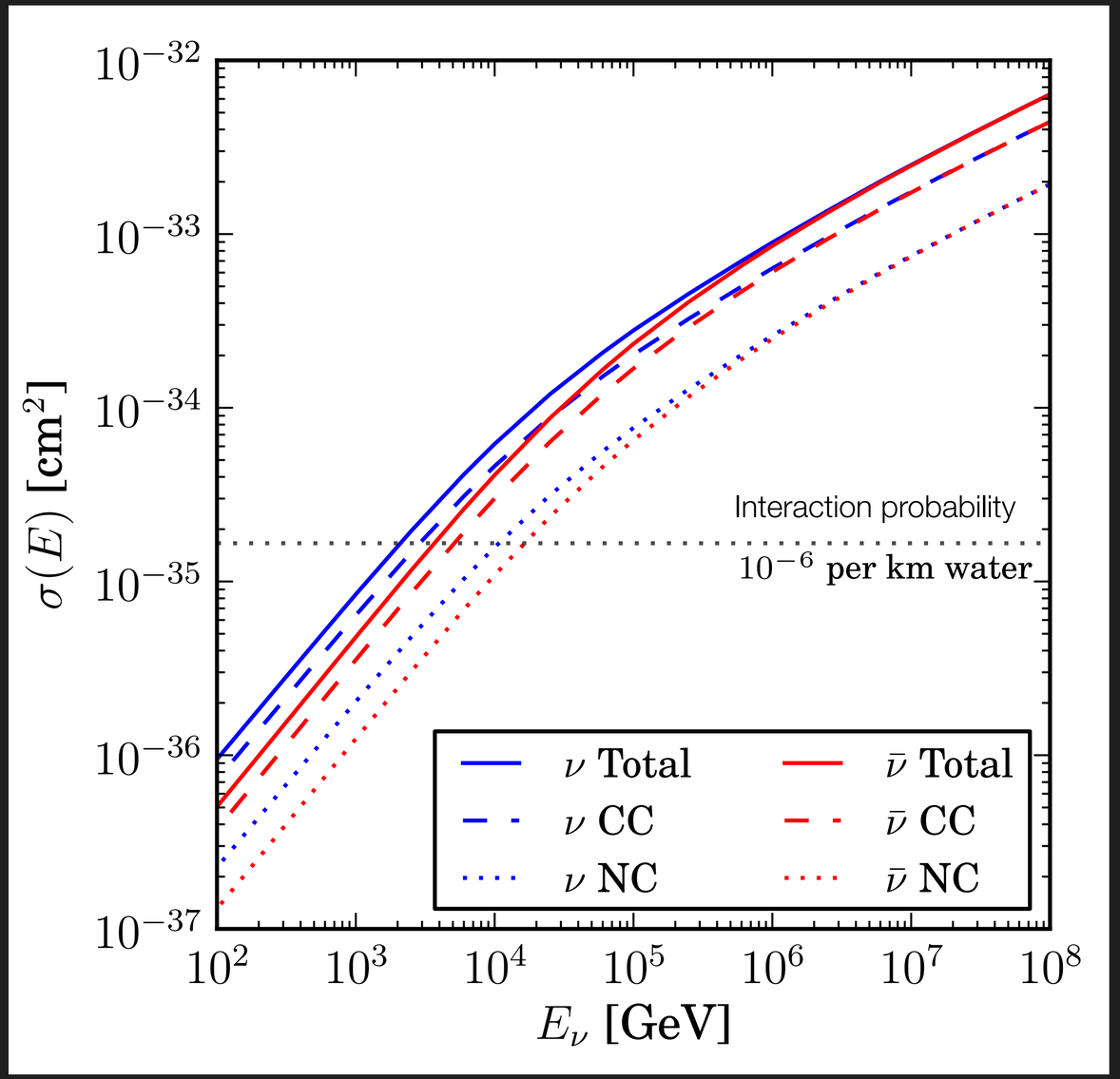
DETECTING TEV NEUTRINOS

Interaction cross-sections are very small

Benchmark astrophysical flux: O(10^5) per km^2 per year above 100 TeV

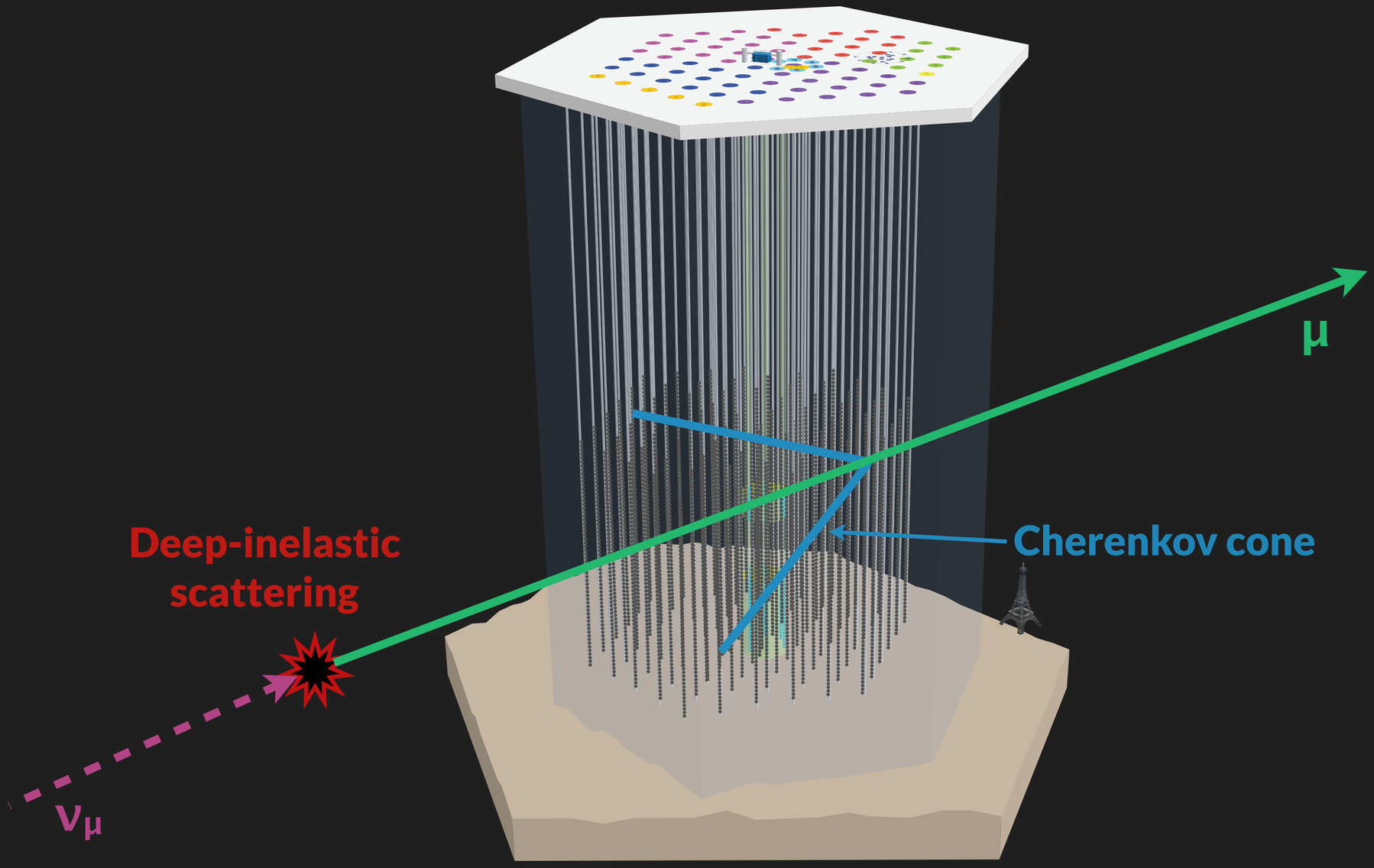
Need **km^3-scale** detectors!

Large volumes, use natural water or ice



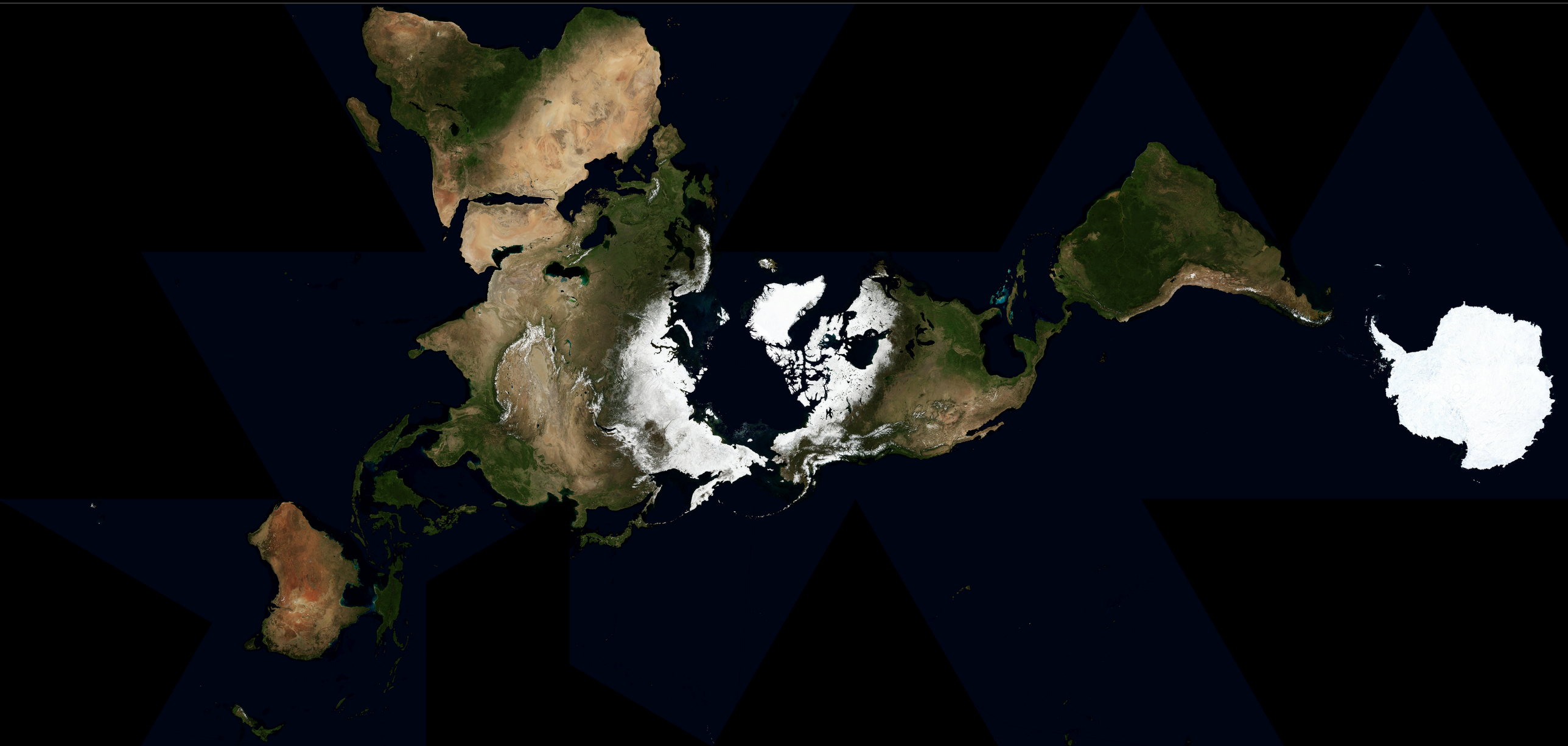
DETECTING NEUTRINOS

Neutrinos are detected by looking for Cherenkov radiation from secondary particles (muons, particle showers)



NEUTRINO TELESCOPE SITES

deep natural sites with water/ice (deep sea, lakes, glaciers)



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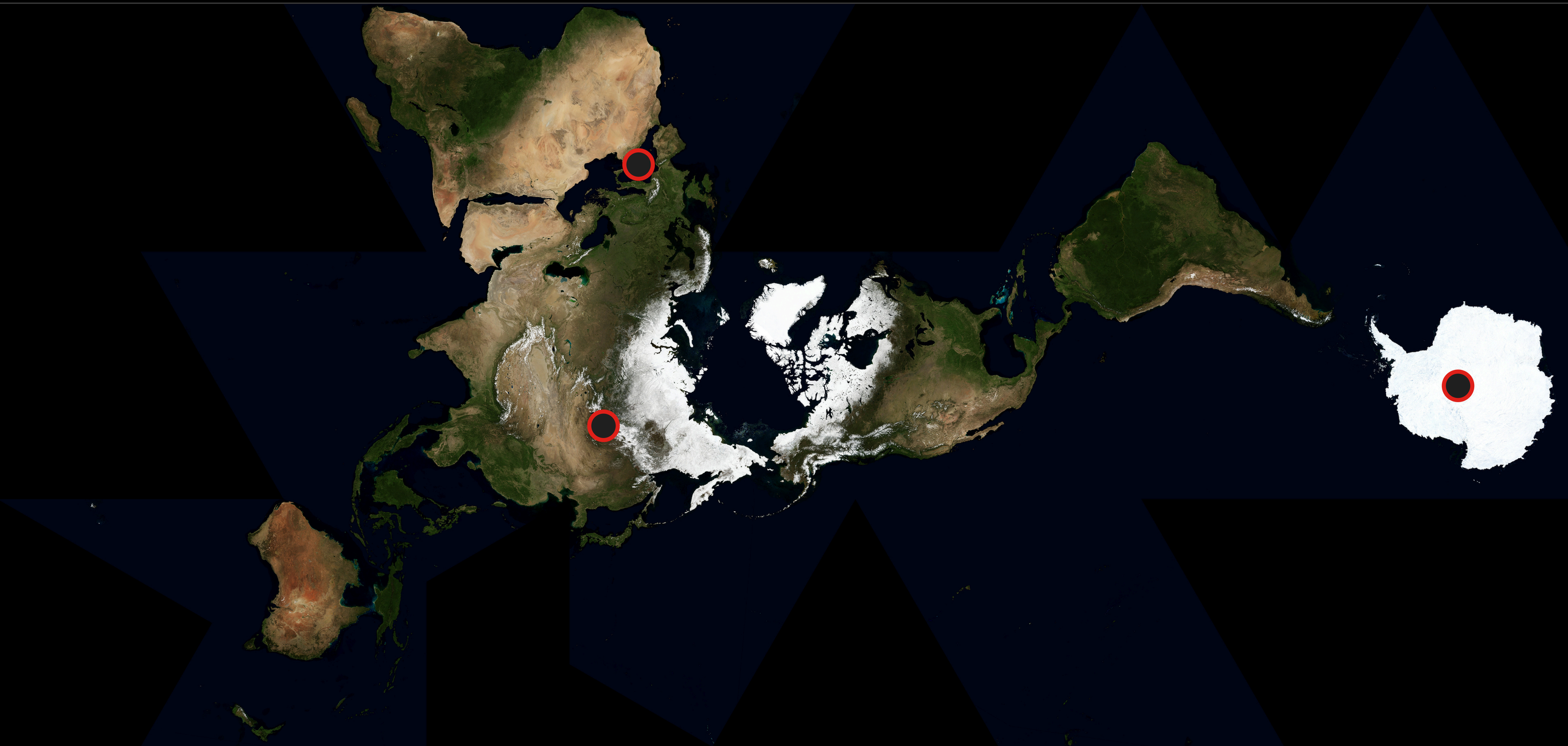

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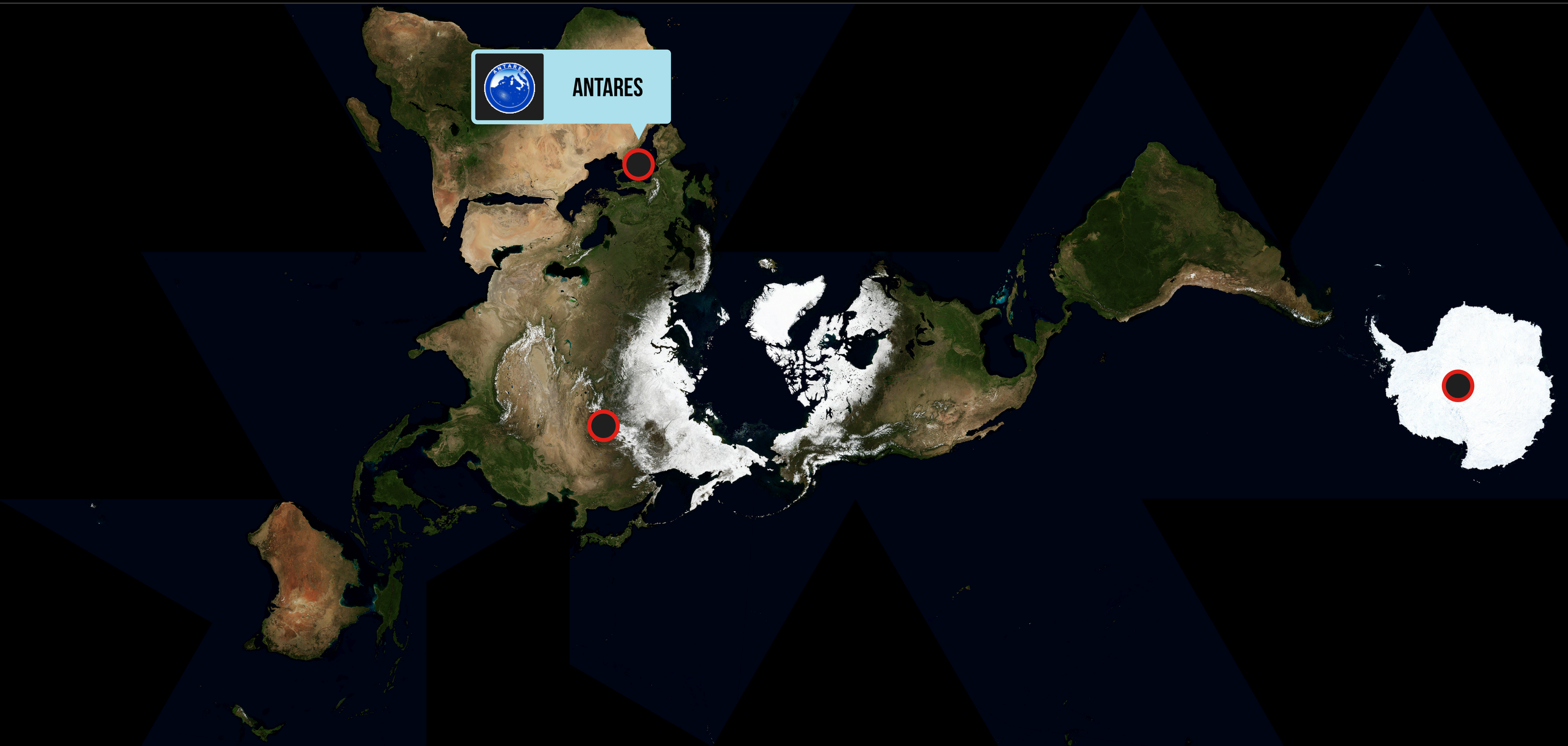

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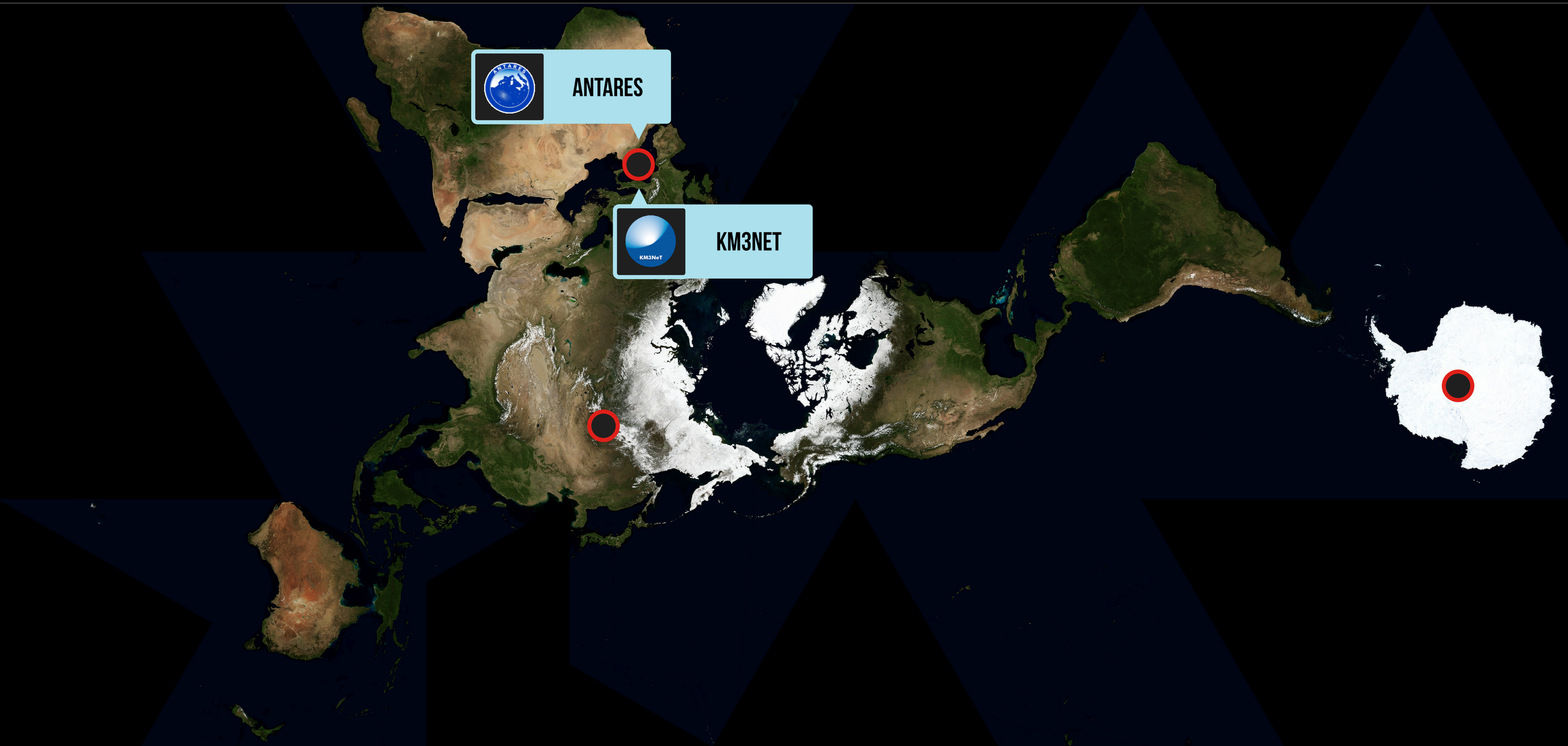

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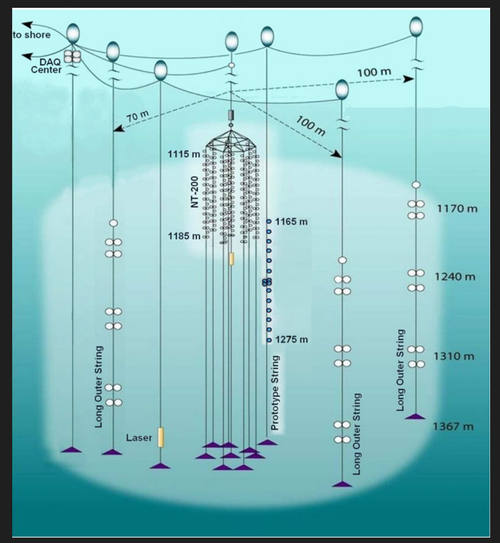
THE WORLD'S NEUTRINO TELESCOPES

lakes, sea, glaciers

NT-200+

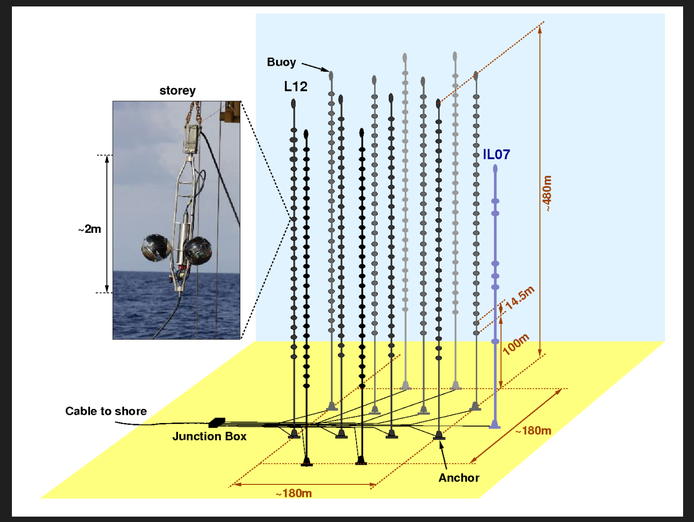


Lake Baikal

1/2000 km^3

228 PMTs

Antares

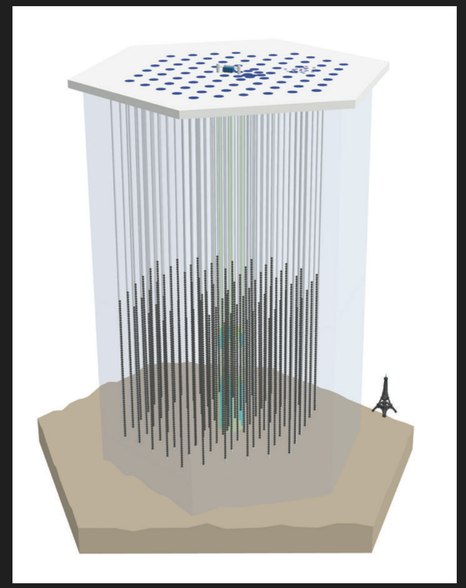


Mediterranean Sea

1/100 km^3

885 PMTs

IceCube



South Pole glacier

1 km^3

5160 PMTs

Larger, sparser → higher energies

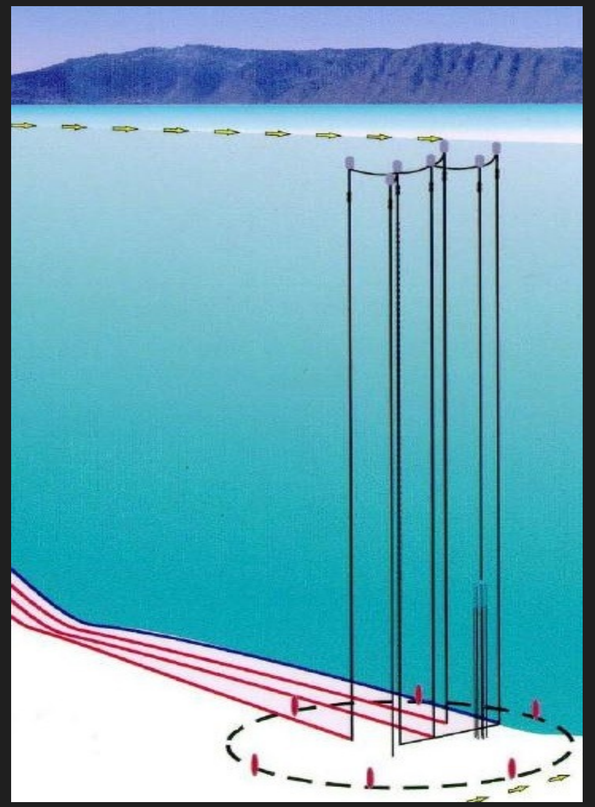
Lake Baikal

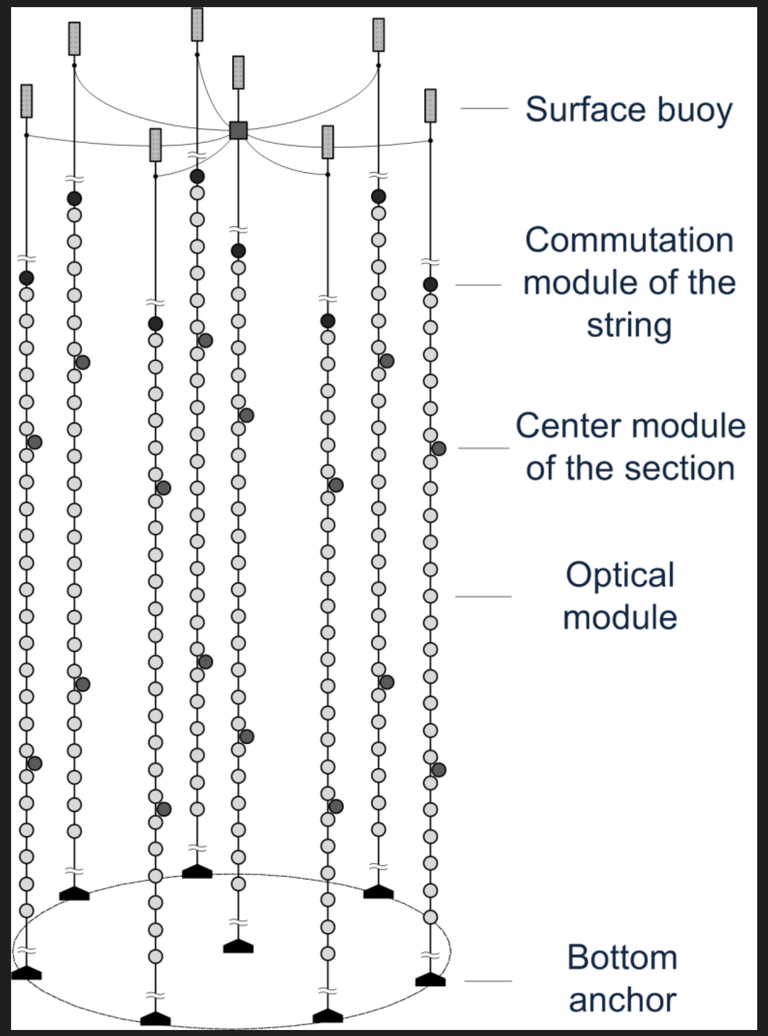
BAIKAL / BAIKAL-GVD

Neutrino telescope deployed in Lake Baikal

First cluster of the gigaton detector deployed in April 2015

Plan: 8-12 such arrays

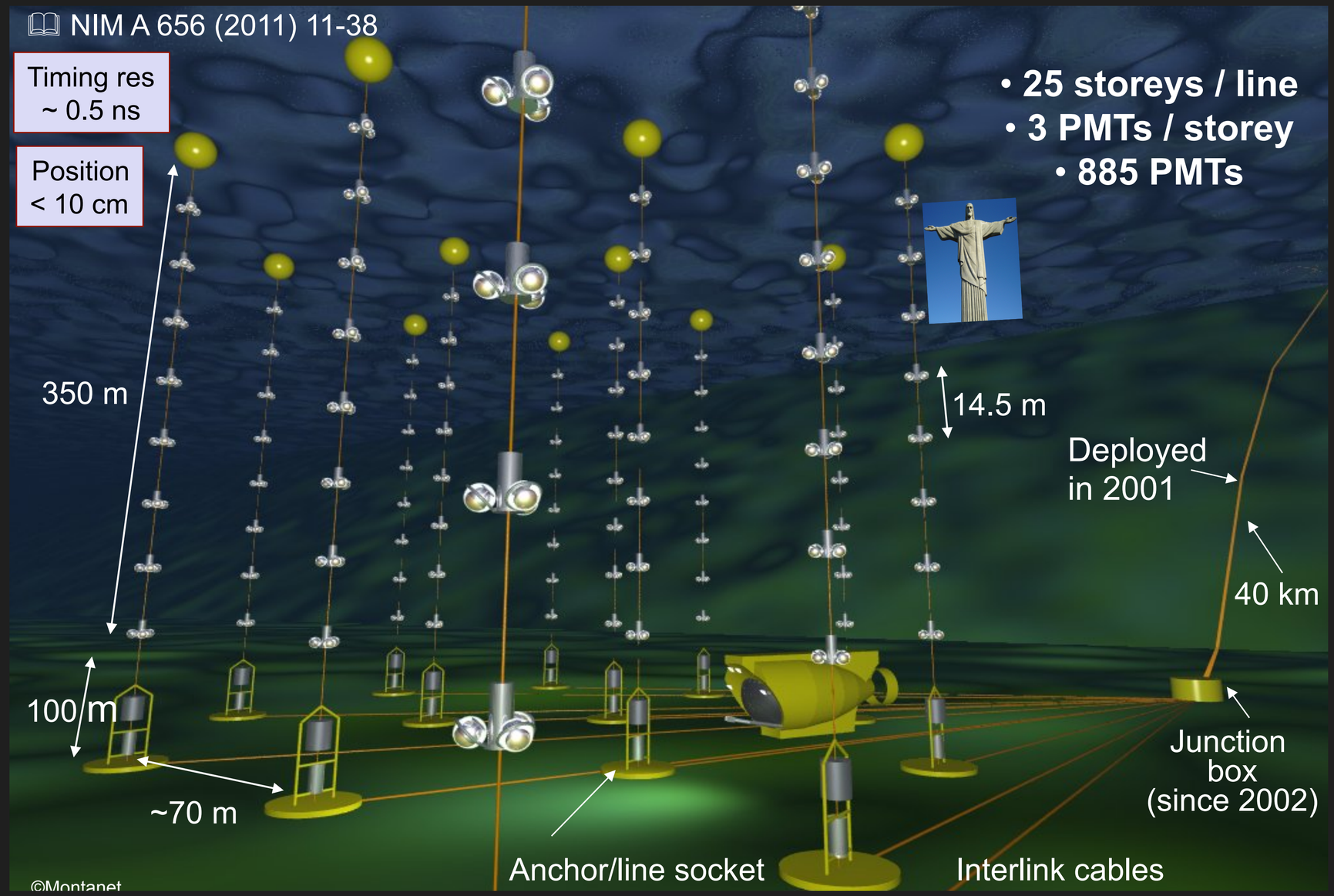


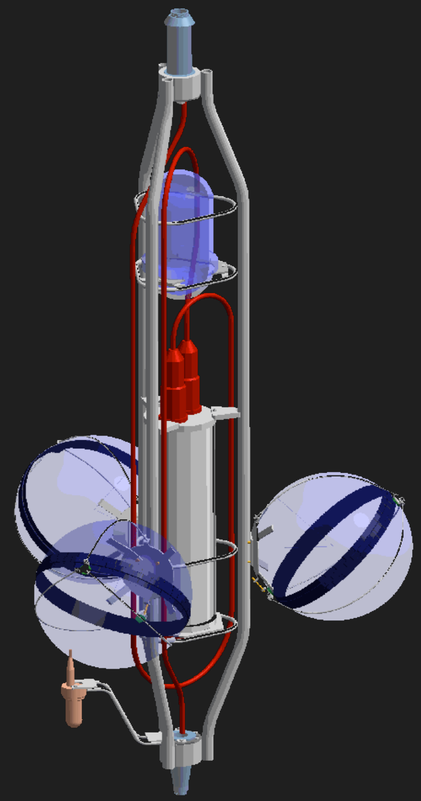



Mediterranean Sea

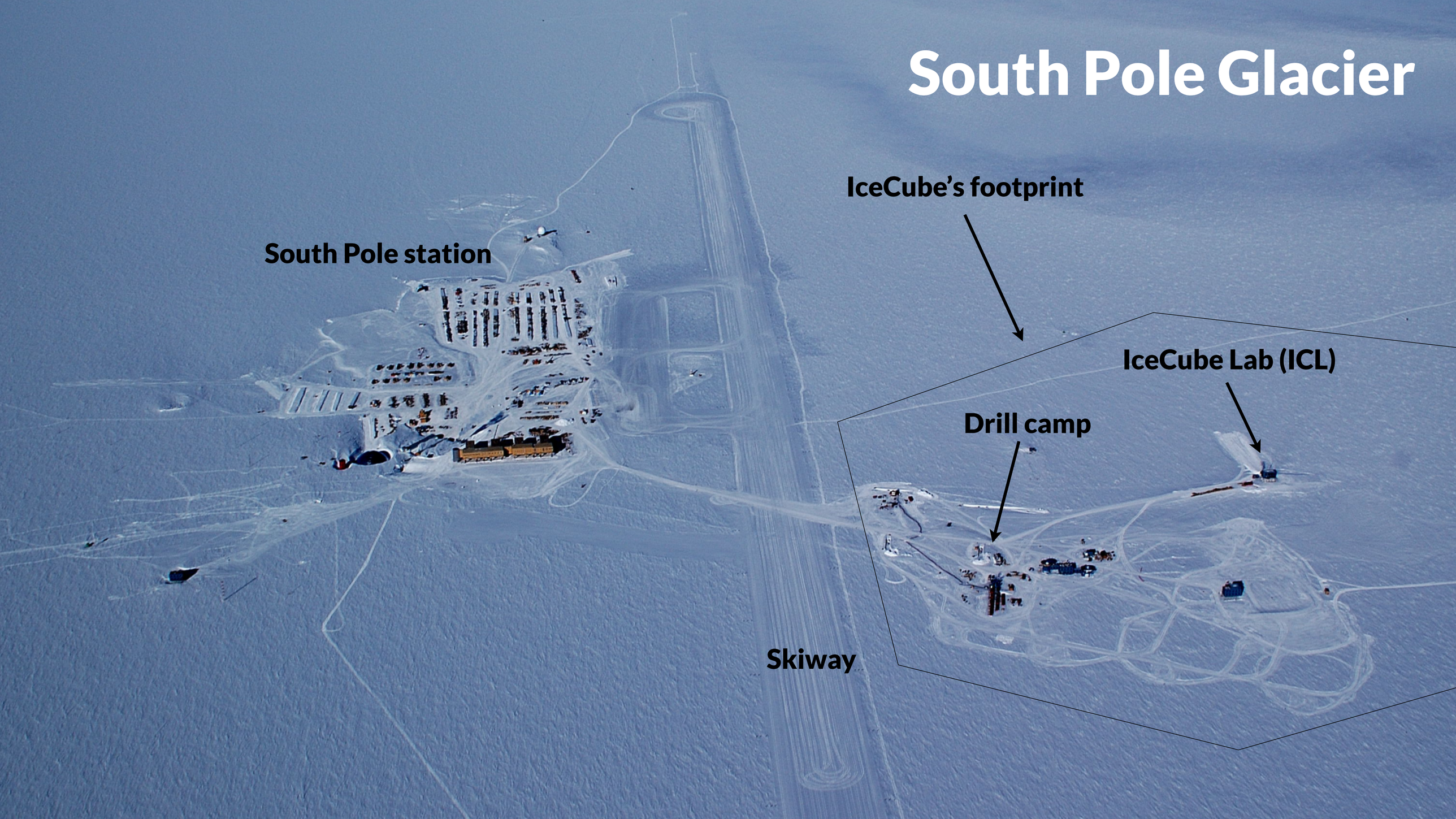
THE ANTARES NEUTRINO TELESCOPE

In the Mediterranean Sea near Toulon, France





“storey” with 3 OMs


South Pole Glacier
IceCube's footprint
South Pole station
IceCube Lab (ICL)
Drill camp
Skiway

THE ICECUBE NEUTRINO OBSERVATORY

Deployed in the deep glacial ice at the South Pole

5160 PMTs

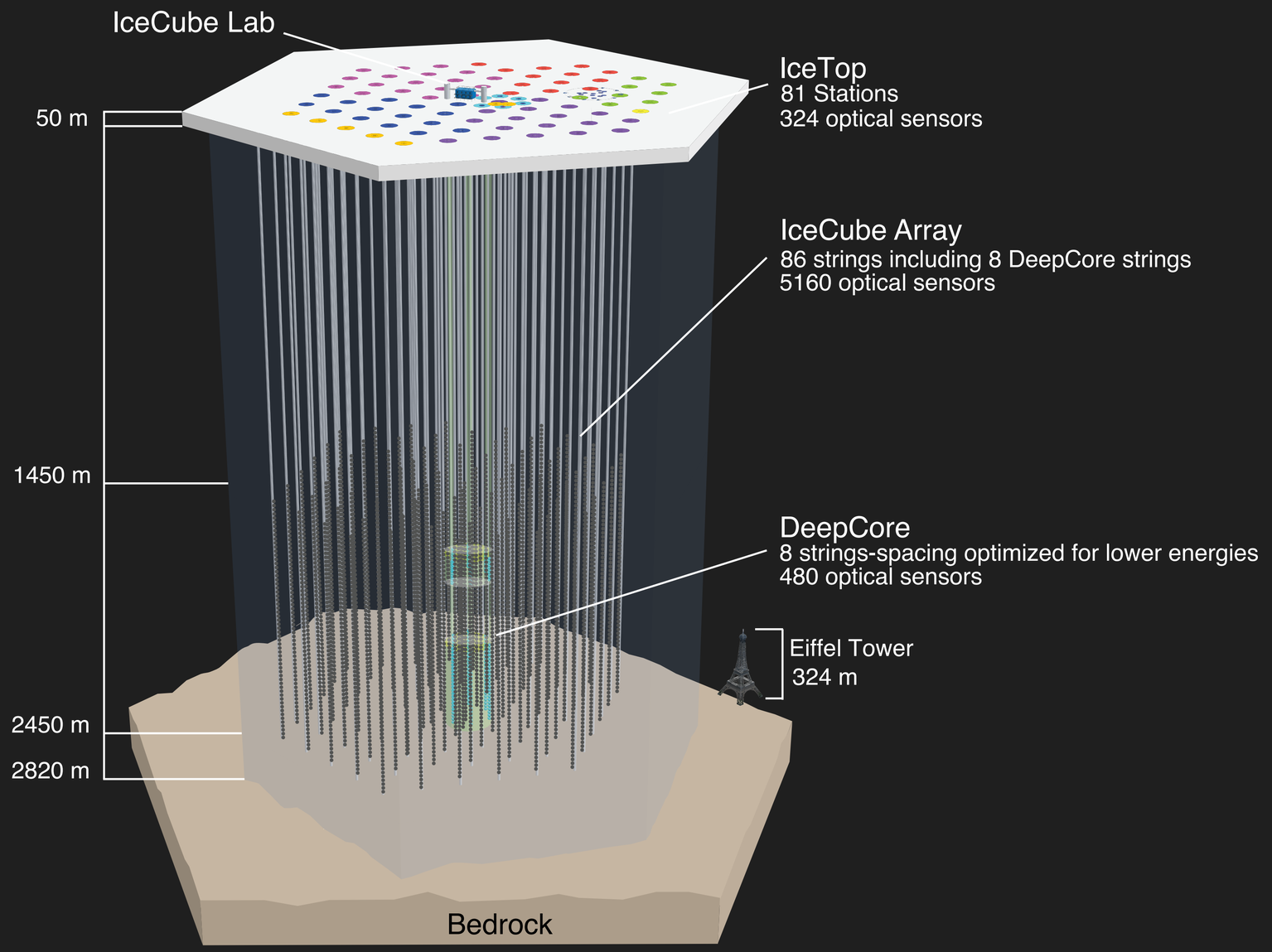
1 km^3 volume

86 strings

17 m vertical spacing

125 m string spacing

Completed **2010**

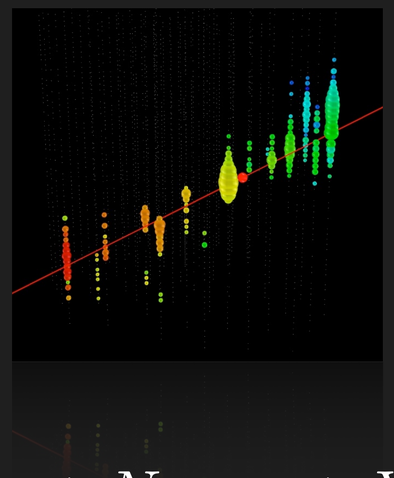


NEUTRINO EVENT SIGNATURES

Signatures of signal events

time

CC Muon Neutrino

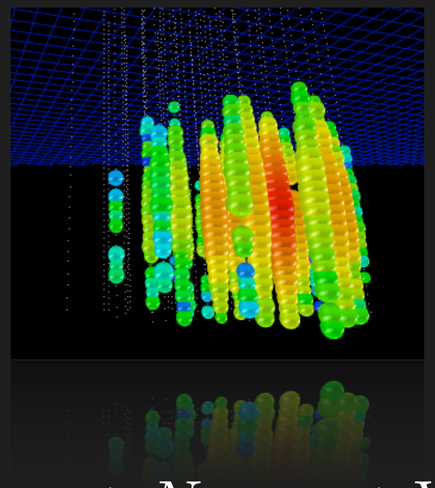


$$\nu_\mu + N \rightarrow \mu + X$$

track (data)

factor of ≈ 2 energy resolution
< 1° angular resolution at high energies

Neutral Current / Electron Neutrino



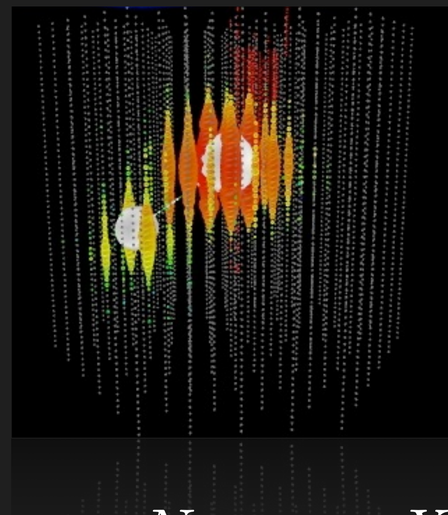
$$\nu_e + N \rightarrow e + X$$

$$\nu_x + N \rightarrow \nu_x + X$$

cascade (data)

≈ ±15% deposited energy resolution
≈ 10° angular resolution (in IceCube)
(at energies ≳ 100 TeV)

CC Tau Neutrino



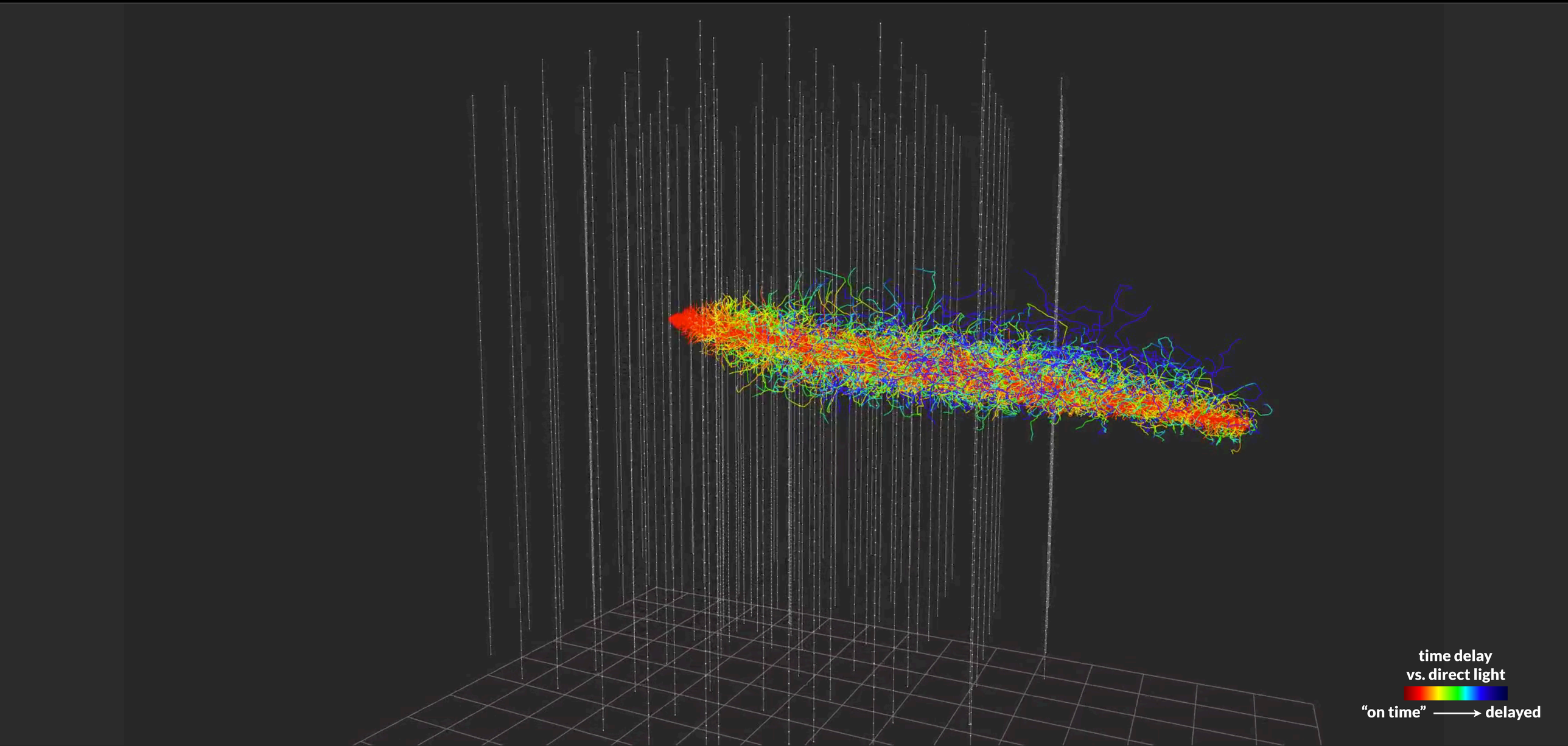
$$\nu_\tau + N \rightarrow \tau + X$$

“double-bang” (≳10PeV) and other signatures (simulation)

(not observed yet: τ decay length is 50 m/PeV)

DETECTION PRINCIPLE (MUON IN ICE)

Neutrinos are detected by looking for Cherenkov radiation from secondary particles



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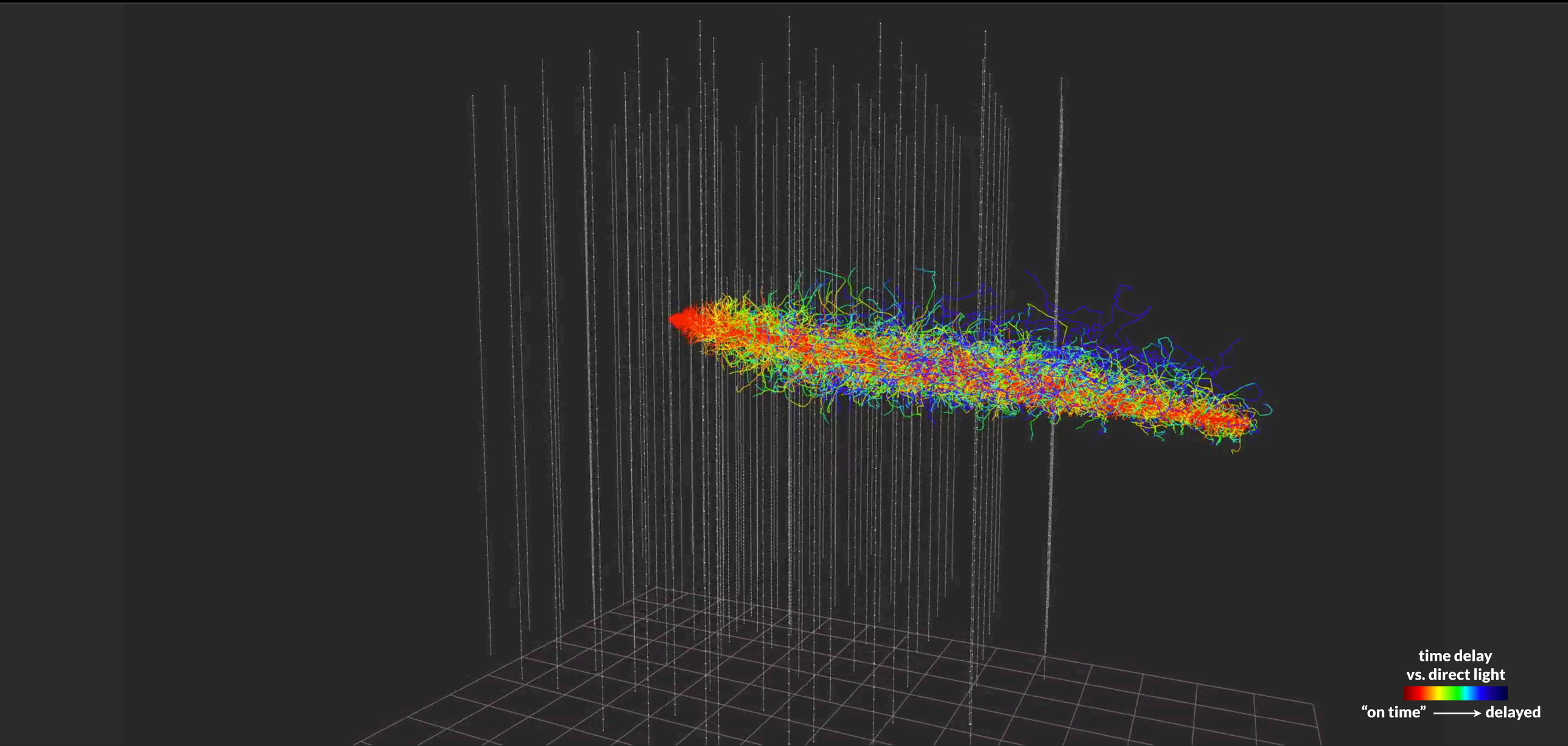

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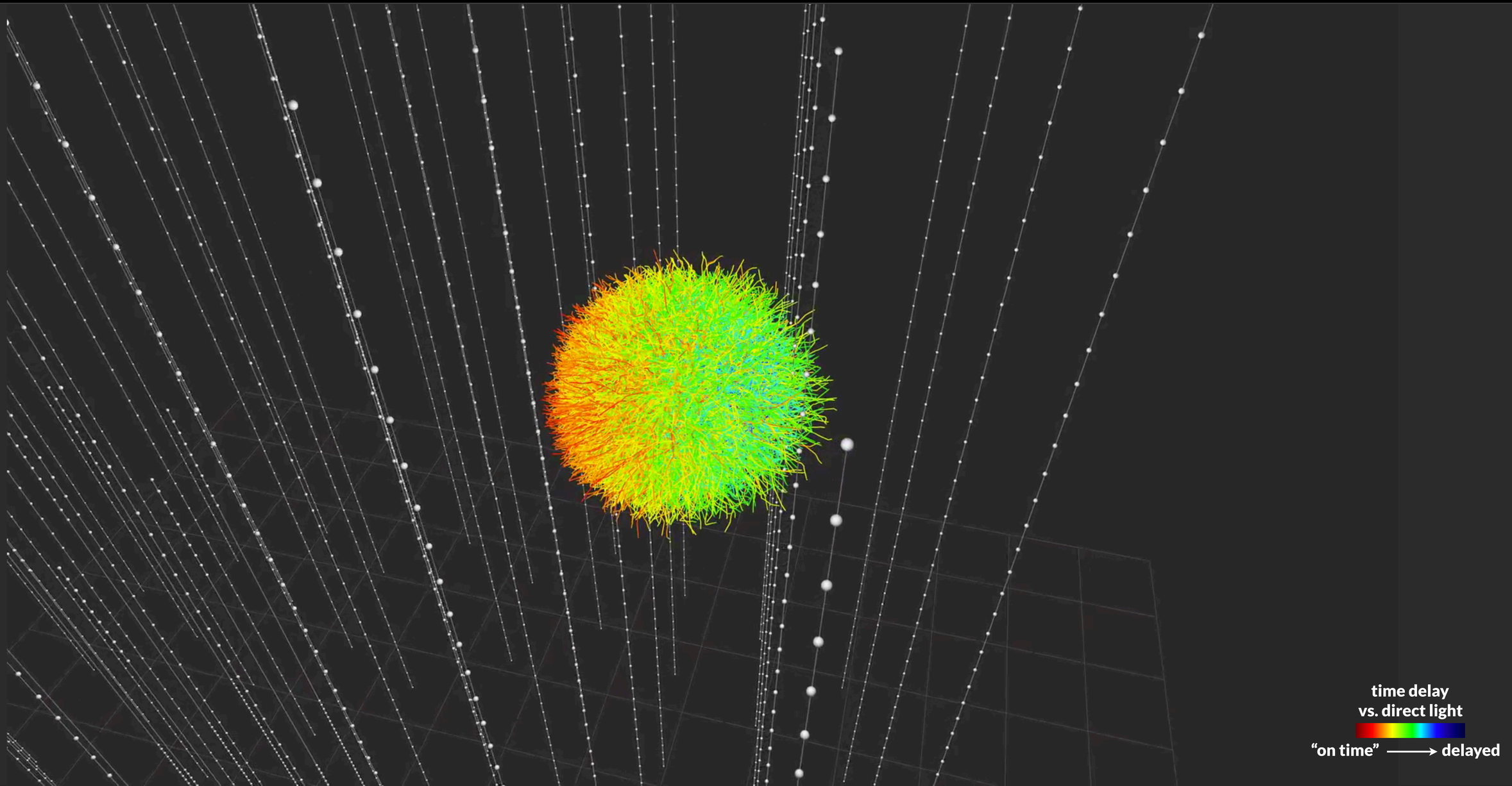

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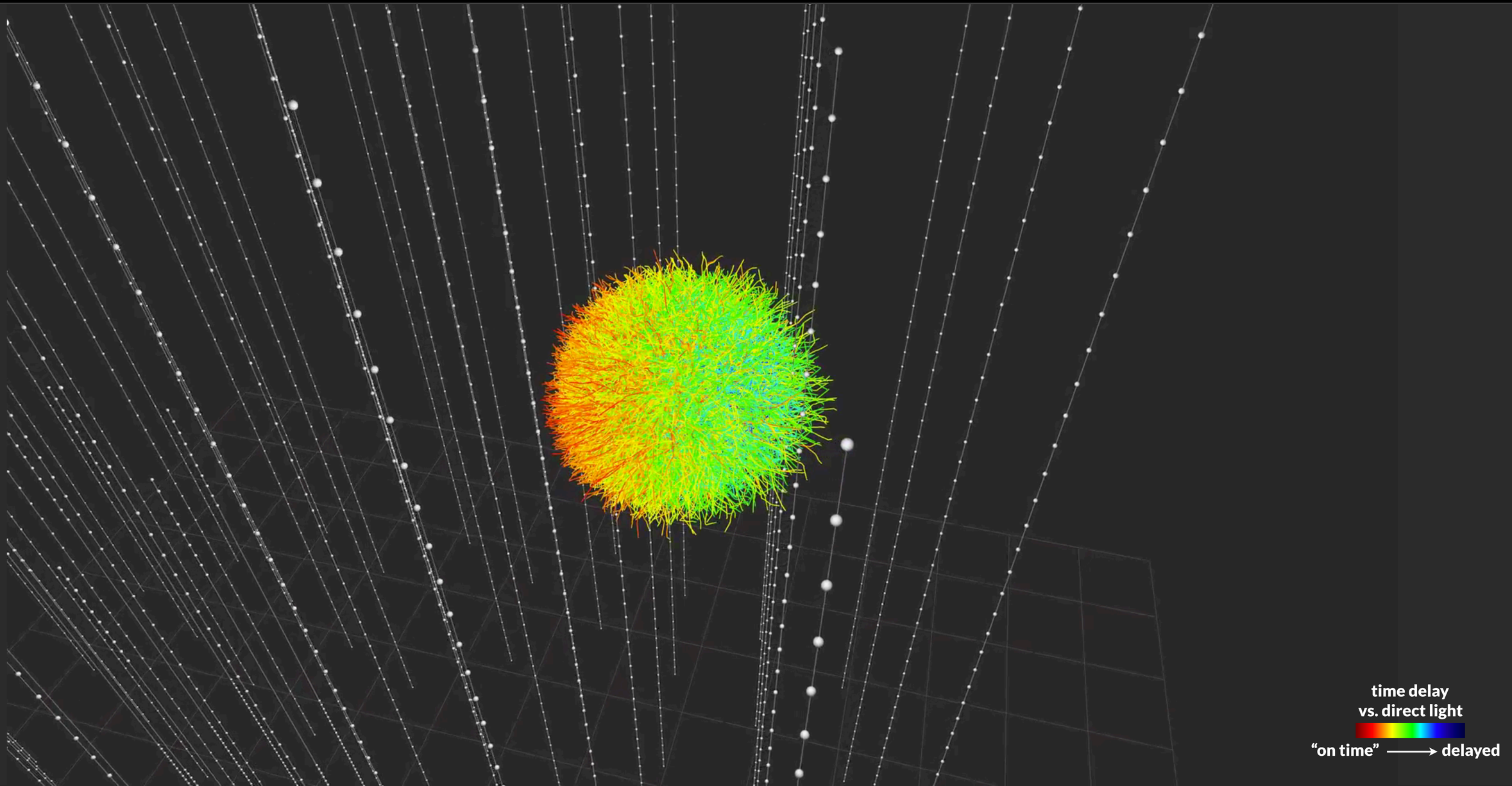
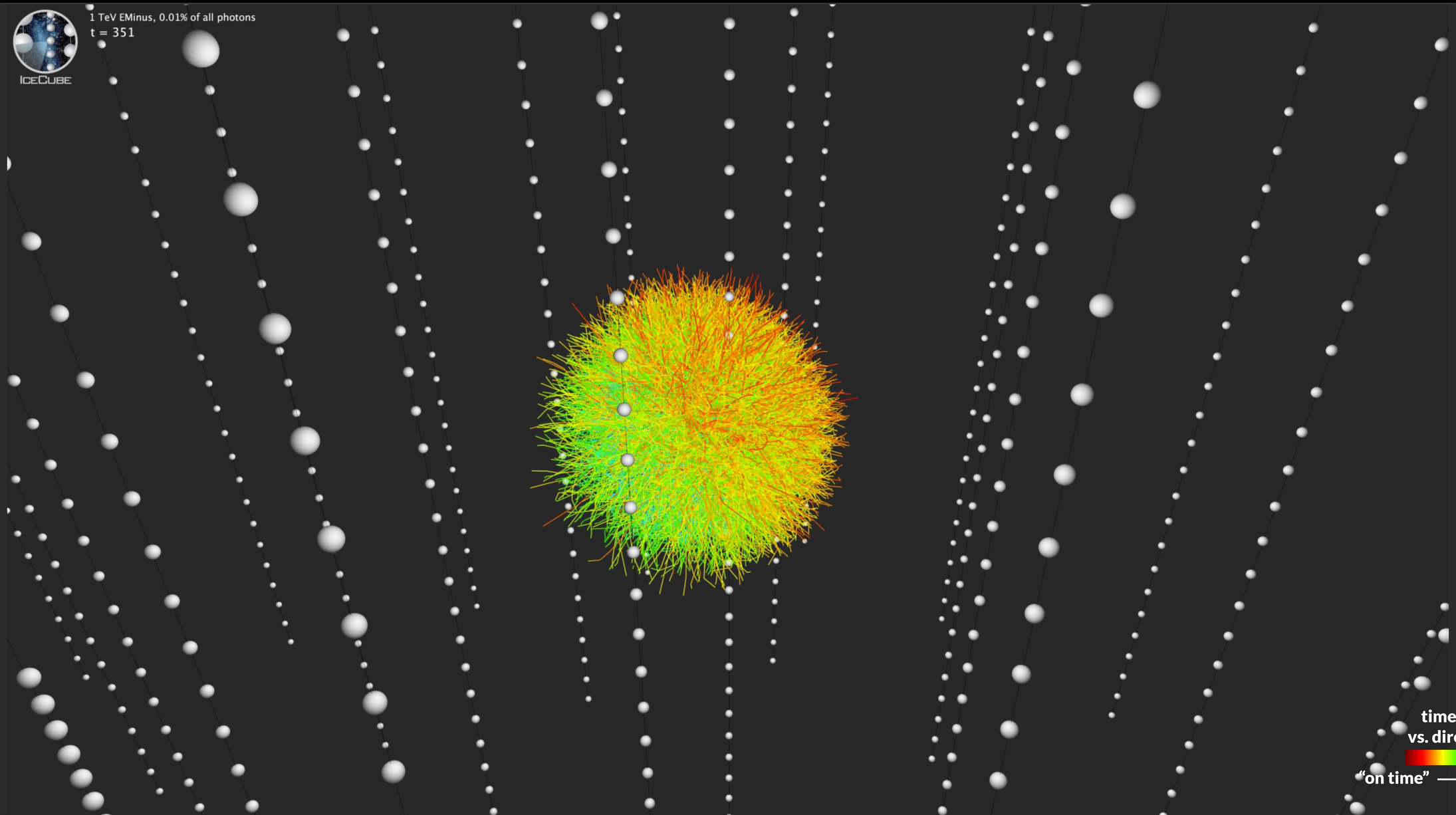


DETECTION PRINCIPLE (CASCADE IN ICE)

Another Shower



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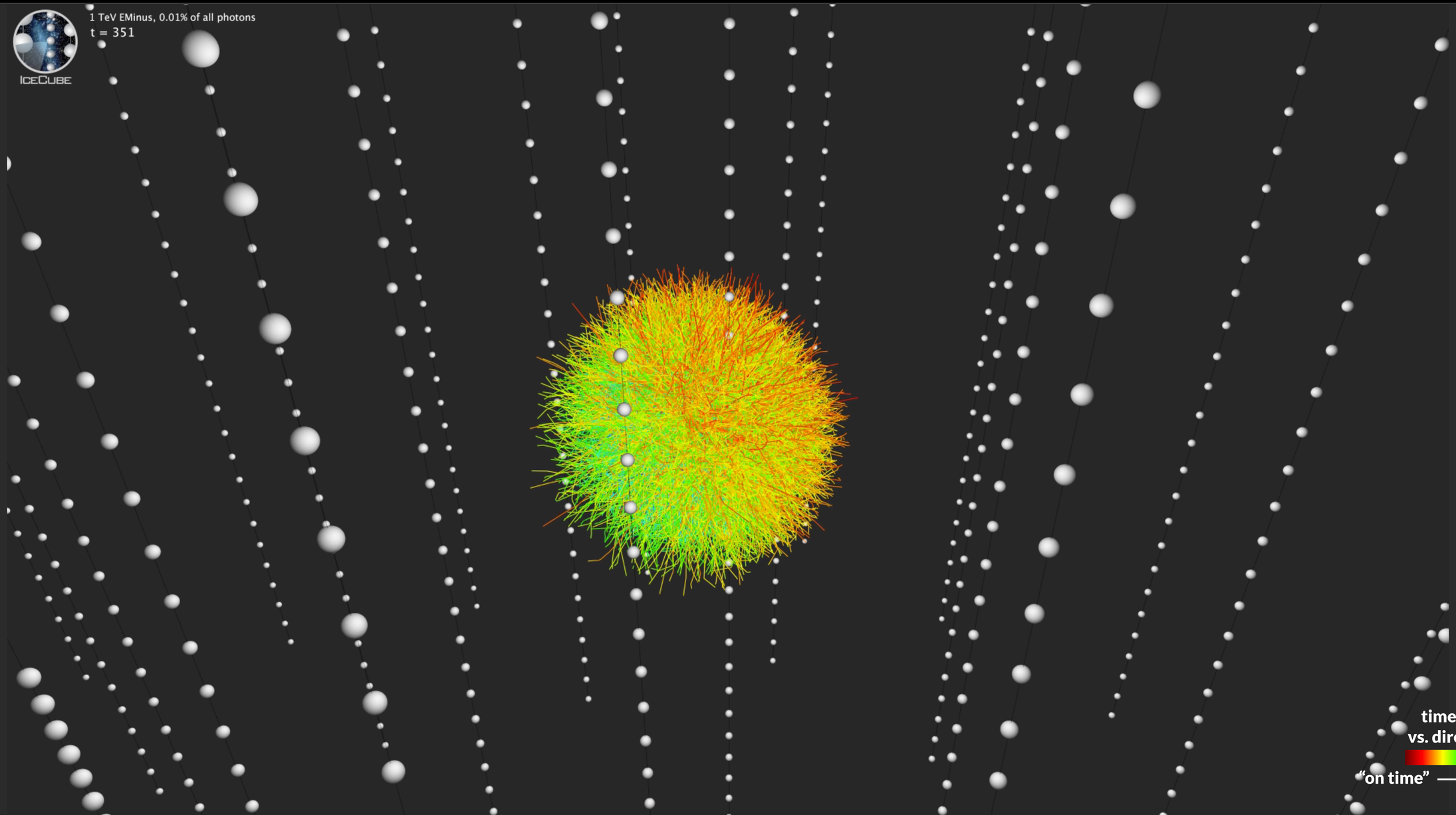
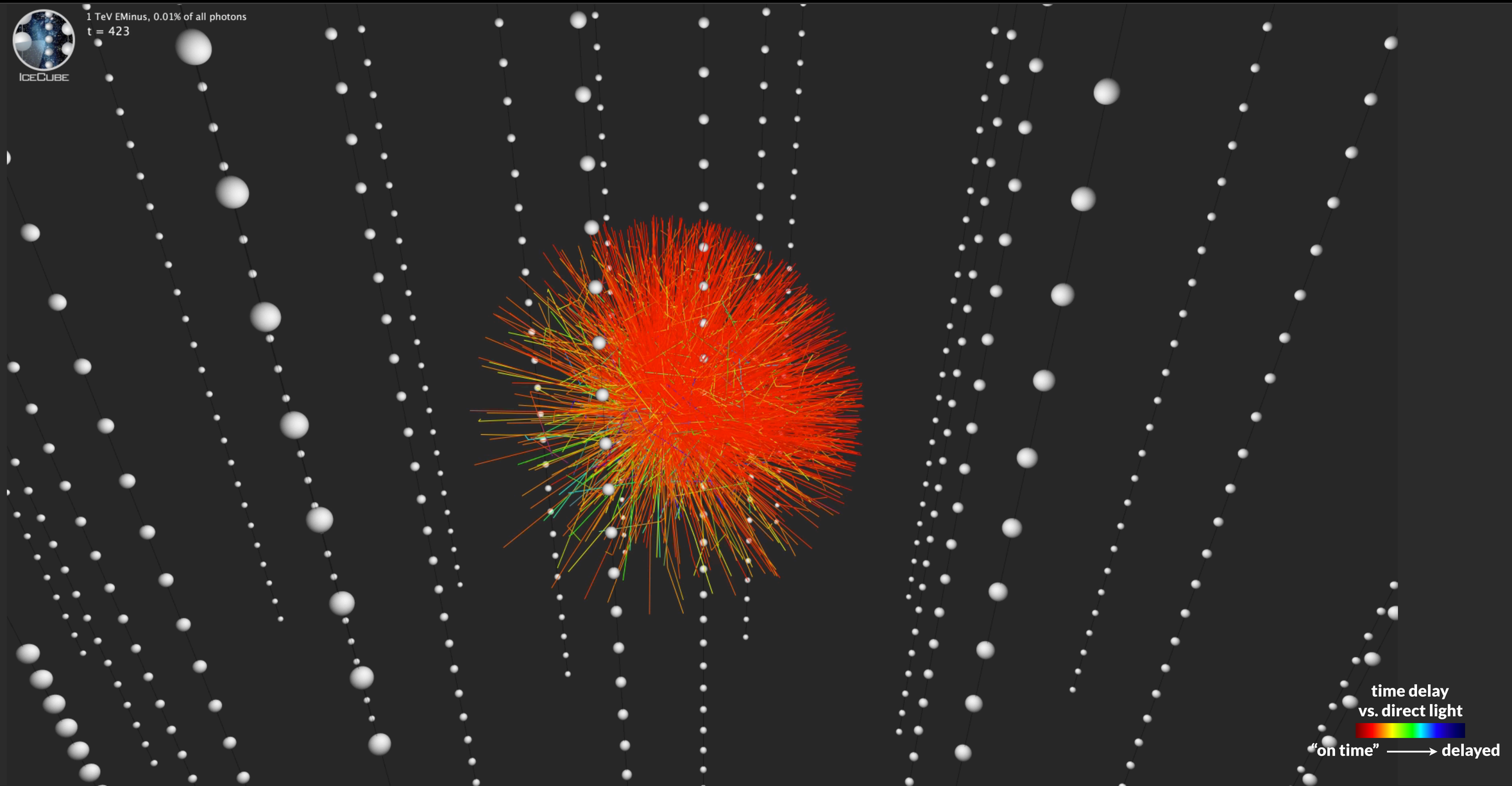


DETECTION PRINCIPLE (CASCADE IN WATER)

This is how it would look in sea water (KM3NeT/ANTARES)



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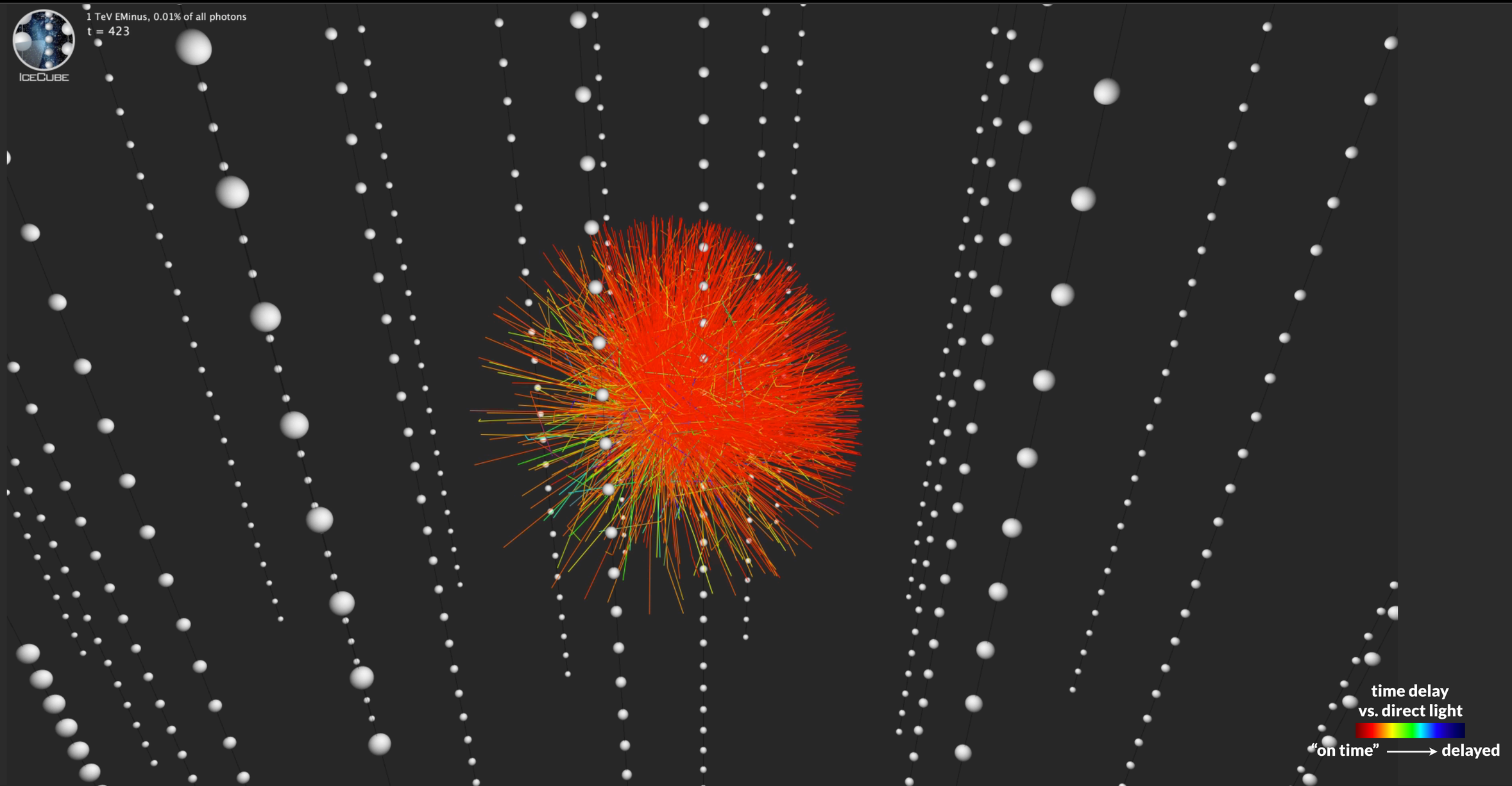
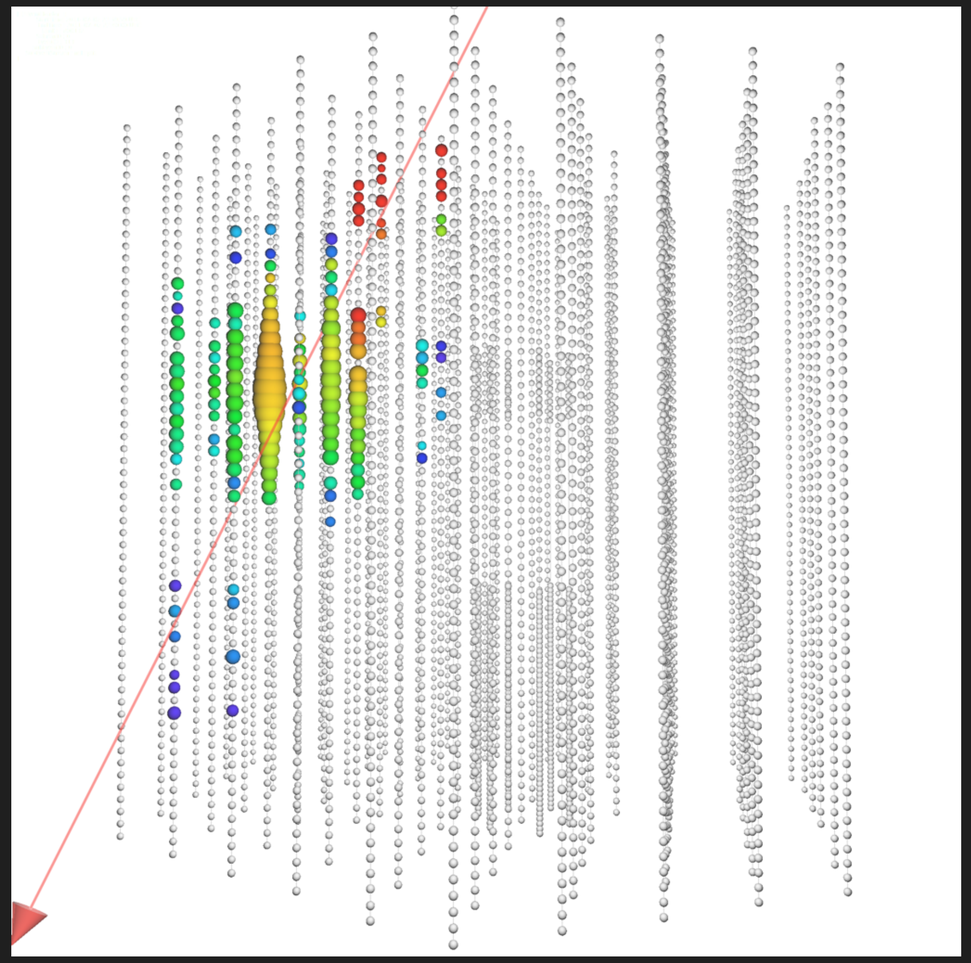
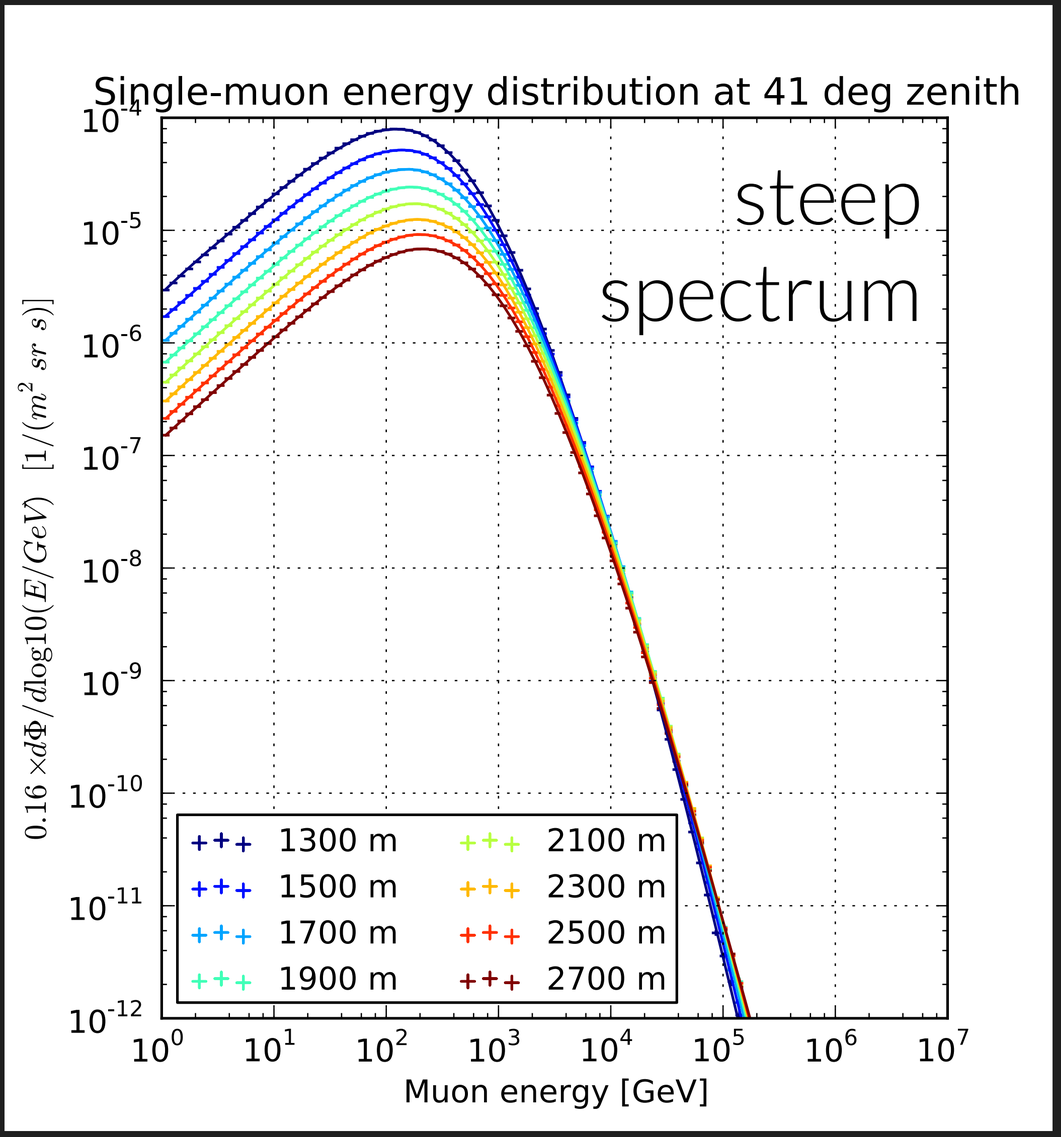


BACKGROUND: PENETRATING MUONS



100 TeV single muon



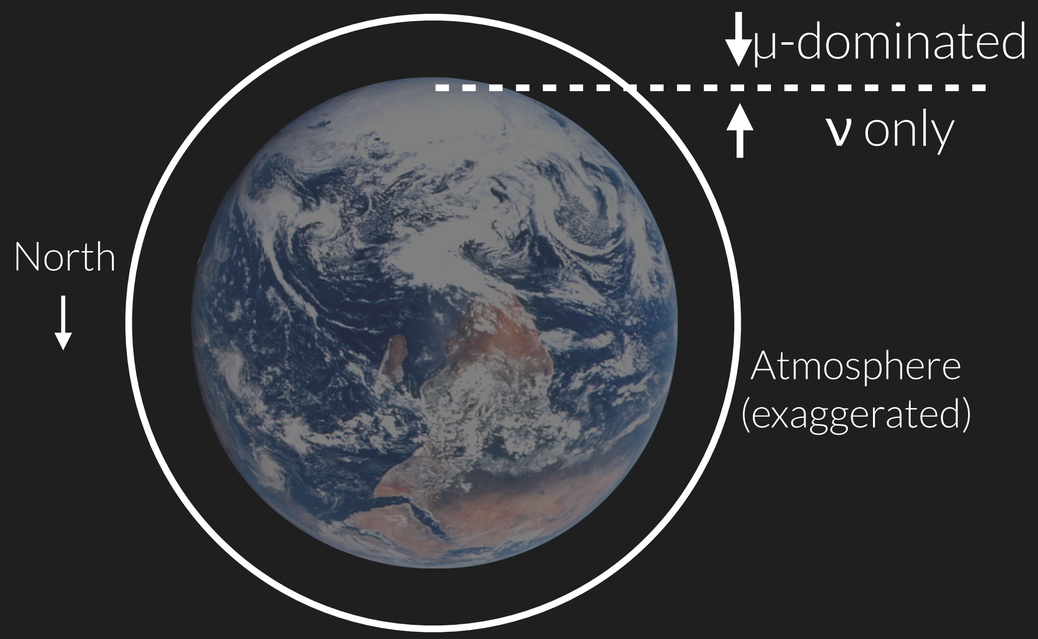
ISOLATING NEUTRINO EVENTS

two strategies

ISOLATING NEUTRINO EVENTS

two strategies

Up-going tracks



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two strategies

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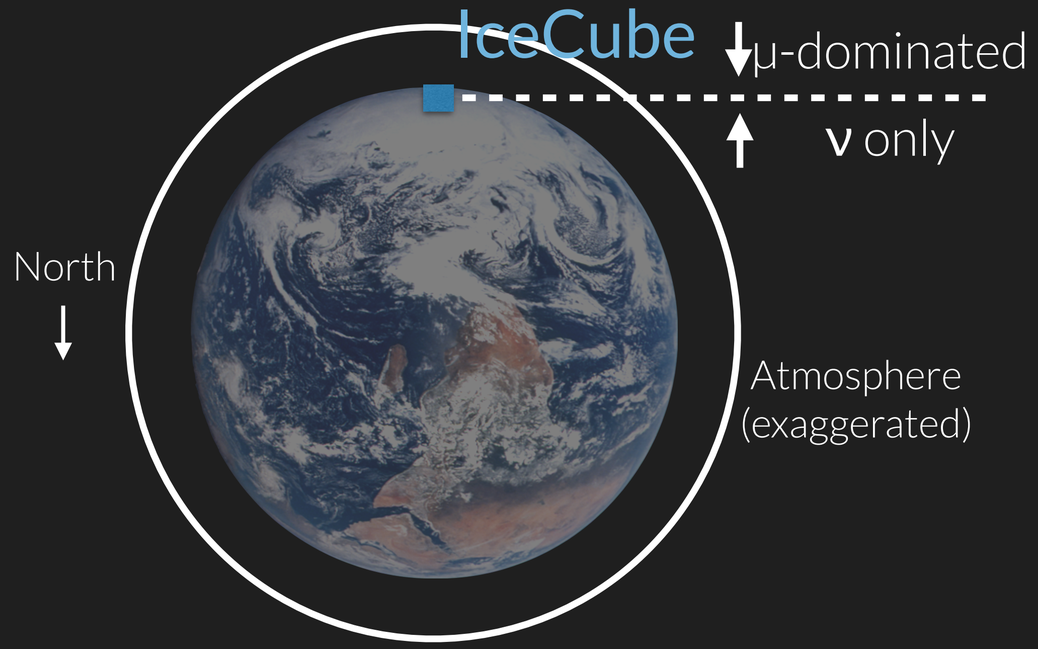

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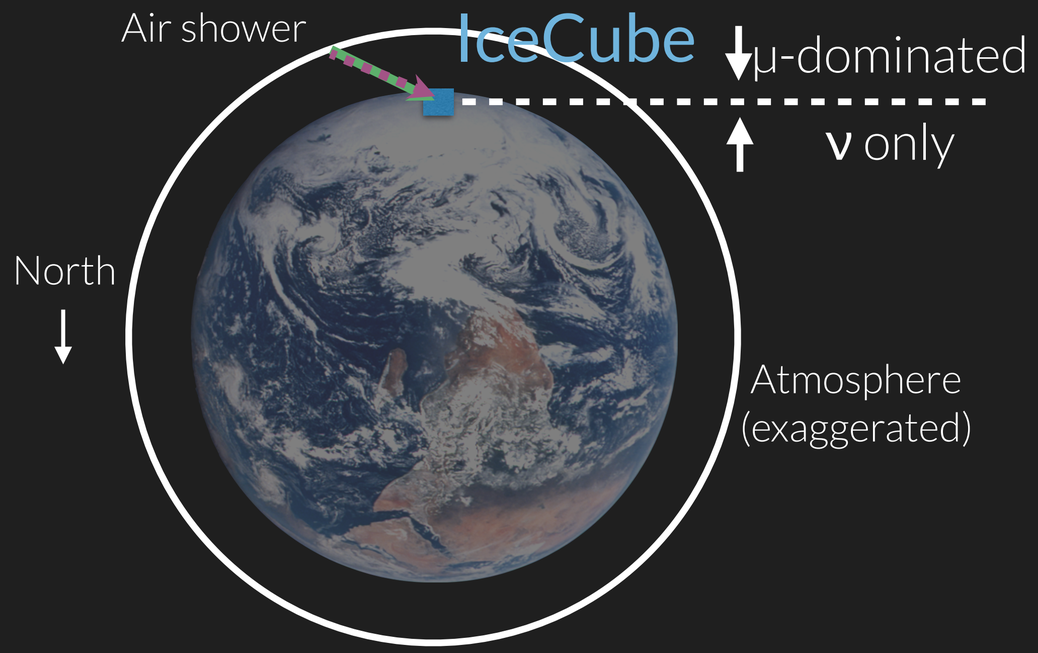

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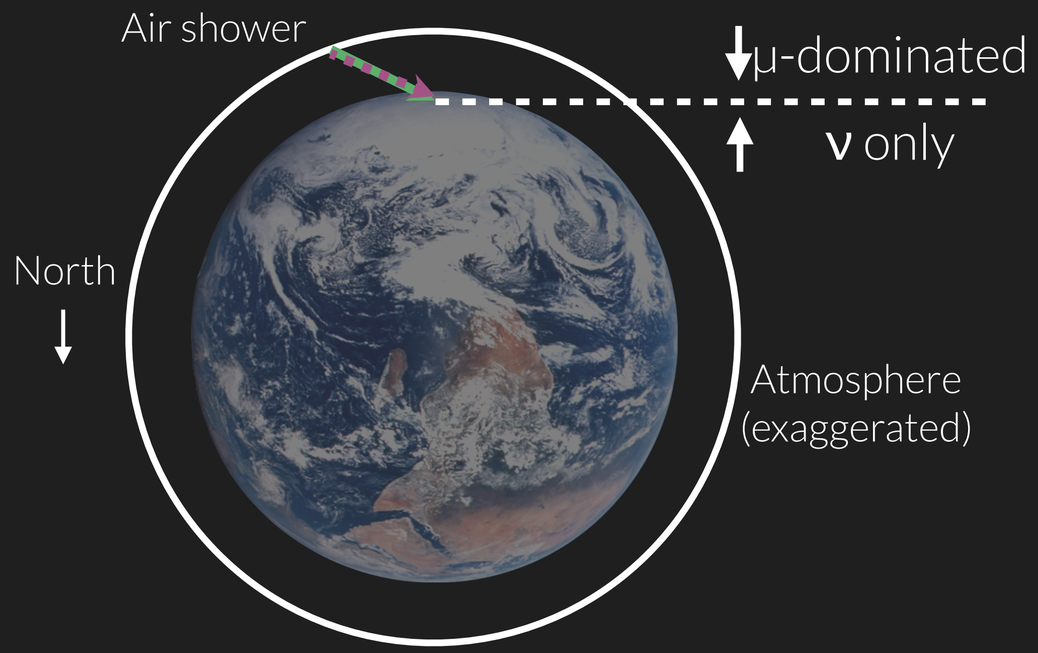

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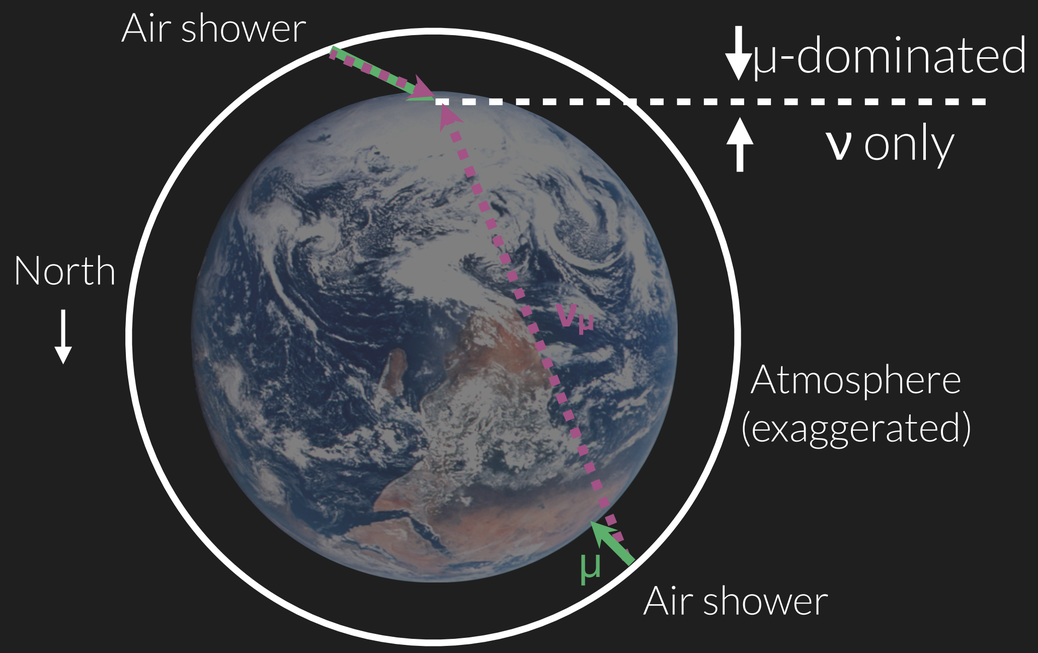
two strategies

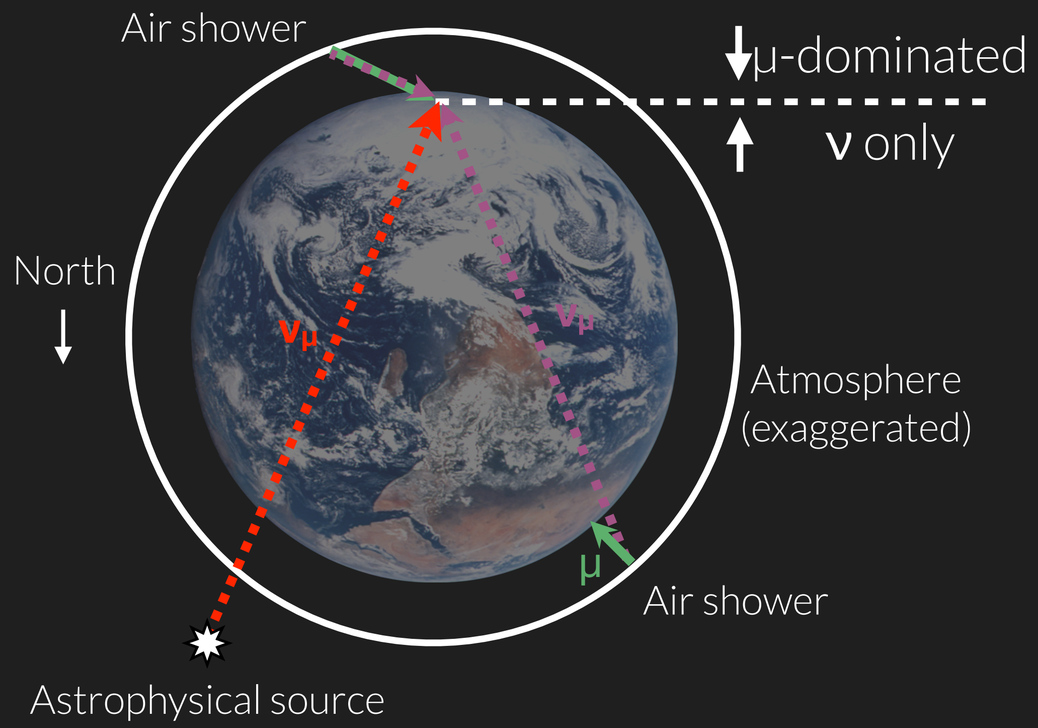
Up-going tracks



ISOLATING NEUTRINO EVENTS

two strategies

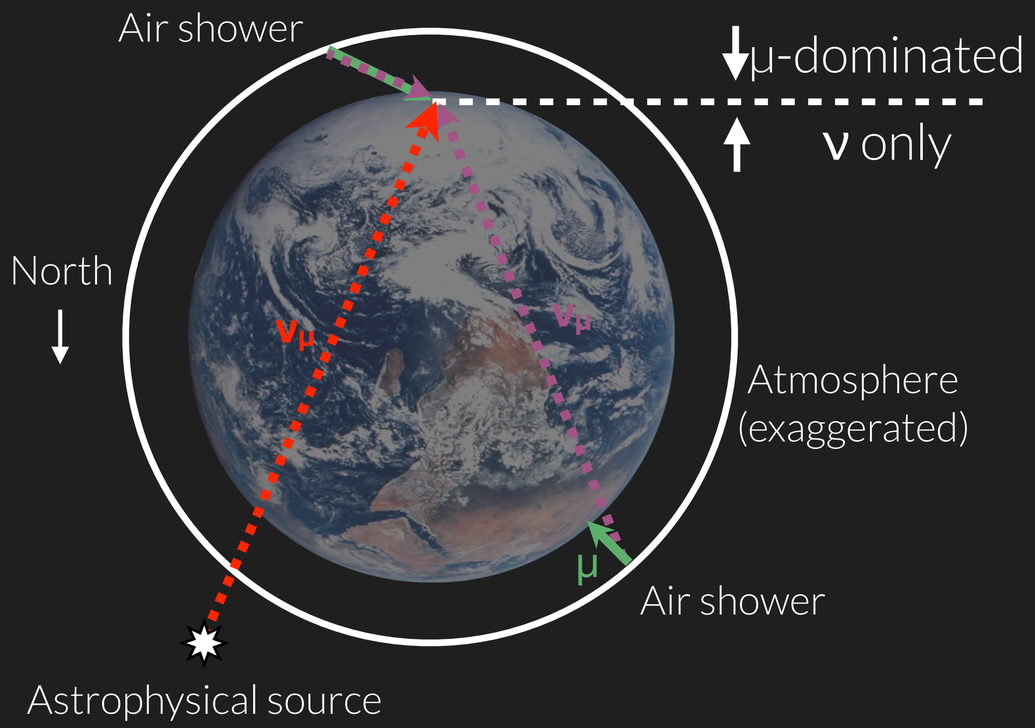
Up-going tracks



ISOLATING NEUTRINO EVENTS

two strategies

Up-going tracks



Earth stops penetrating muons

Effective volume larger than detector

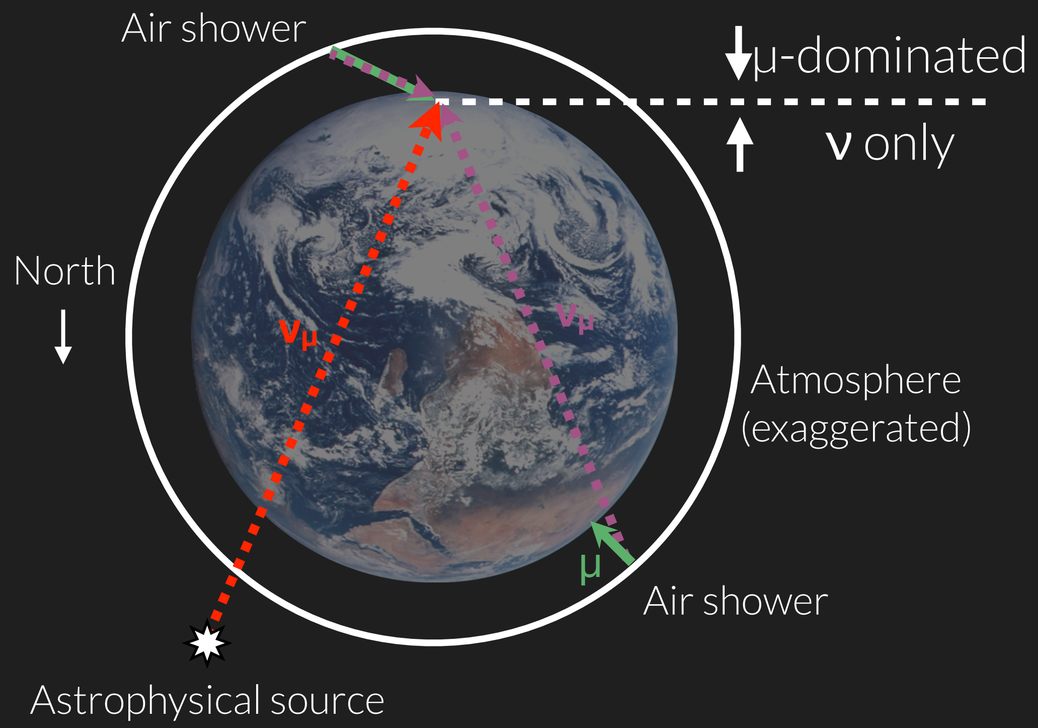
Sensitive to ν_μ only

Sensitive to “half” the sky

ISOLATING NEUTRINO EVENTS

two strategies

Up-going tracks



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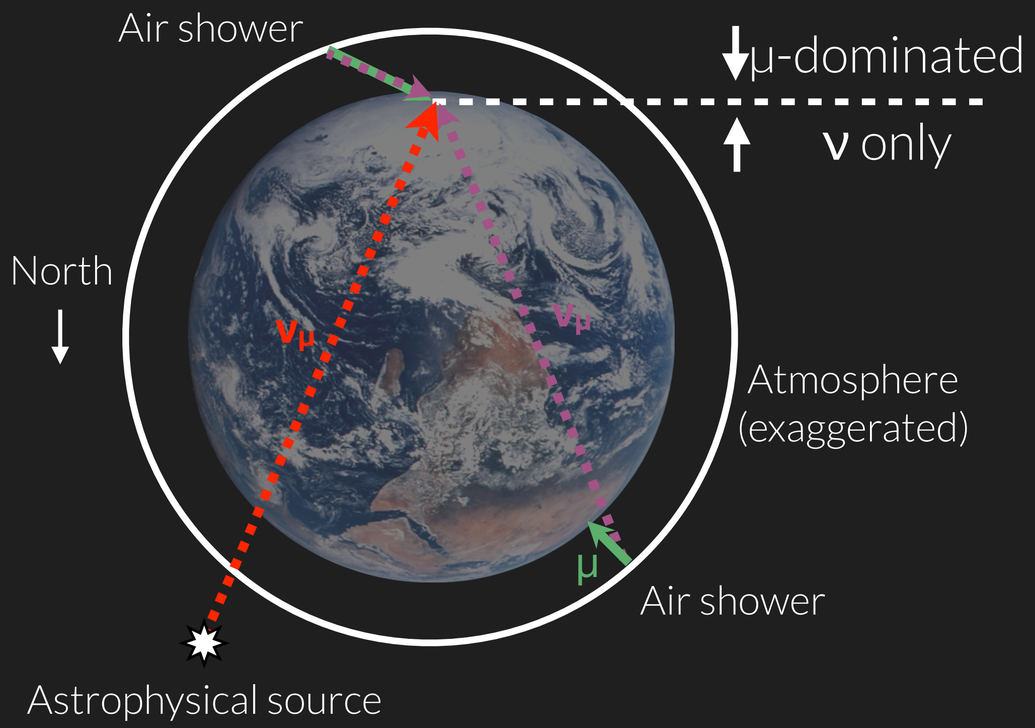
Active veto

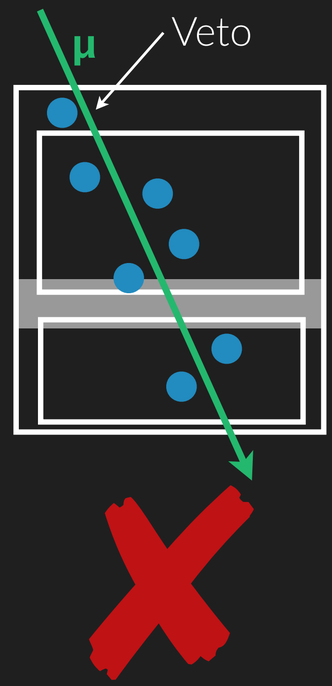
ISOLATING NEUTRINO EVENTS

two strategies

Up-going tracks



Active veto



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ISOLATING NEUTRINO EVENTS

two strategies

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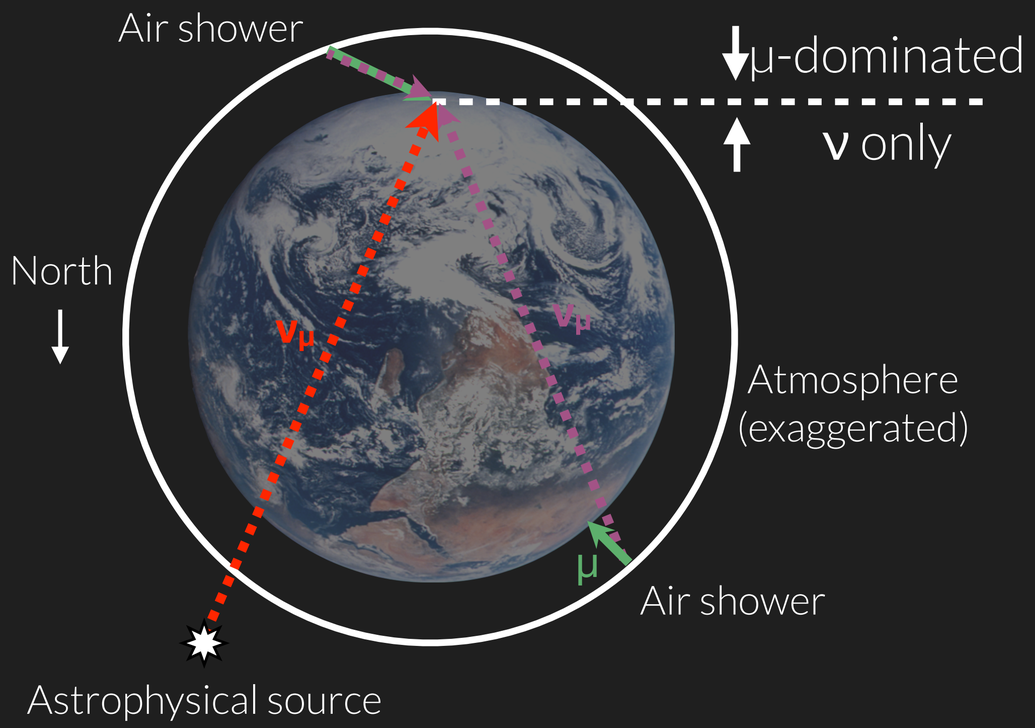

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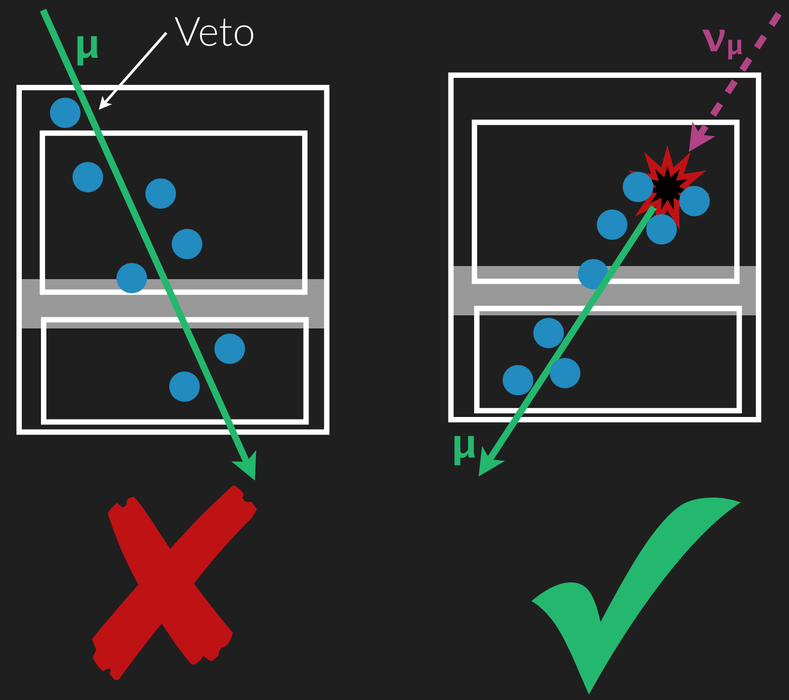
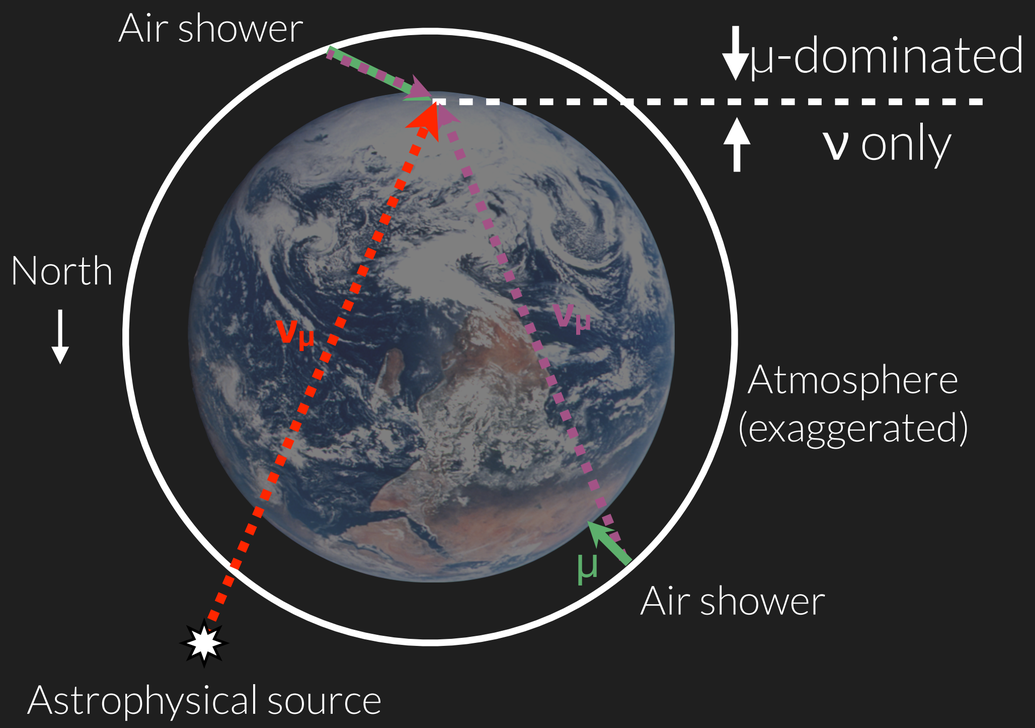


ISOLATING NEUTRINO EVENTS

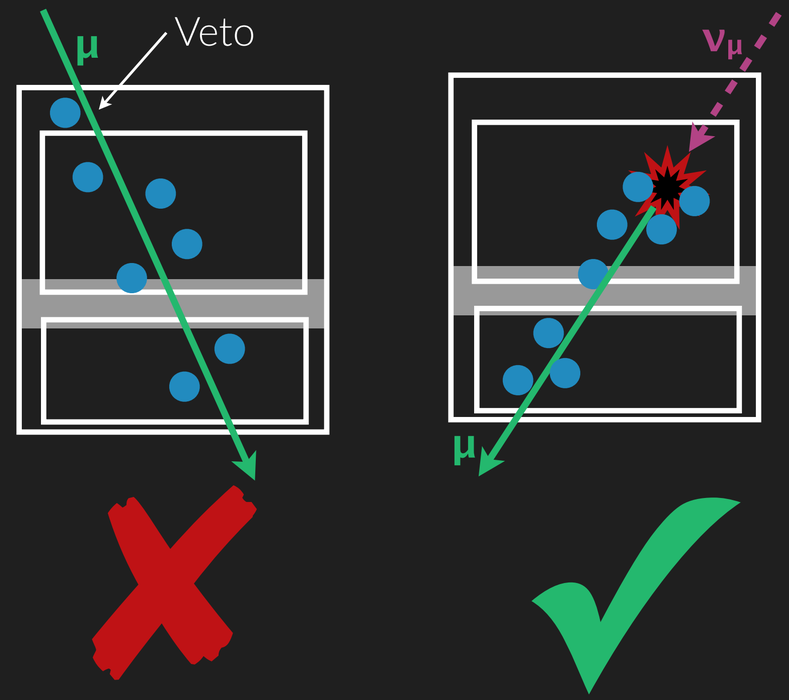
two strategies

Up-going tracks



Earth stops penetrating muons
Effective volume larger than detector
Sensitive to ν_μ only
Sensitive to "half" the sky

Active veto



Veto detects penetrating muons
Effective volume smaller than detector
Sensitive to all flavors
Sensitive to the entire sky

CALIBRATION

Various calibration devices/methods to control detector systematics (example: IceCube)

LED flashers on each DOM

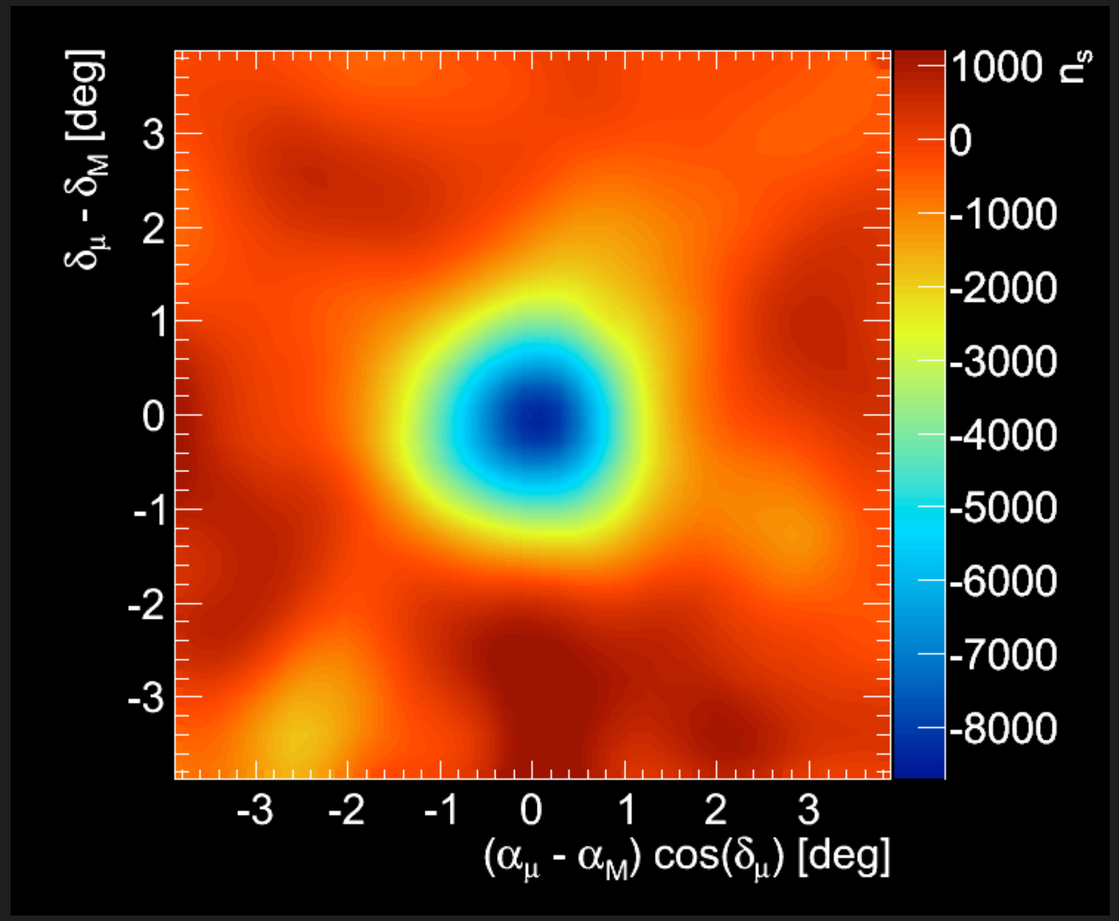
In-ice calibration **laser**

Cosmic ray **energy spectrum**

Moon shadow

Atmospheric neutrino energy spectrum

Minimum-ionizing muons



Moon Shadow in Cosmic Rays
Muons in IceCube (59 strings)

THE (VERY) HIGH-ENERGY TAIL

Update of the high-energy astrophysical flux discovery analysis

WHAT DID ICECUBE FIND? (6 YEARS)

82 events in 2078 days

80(+2) events observed!

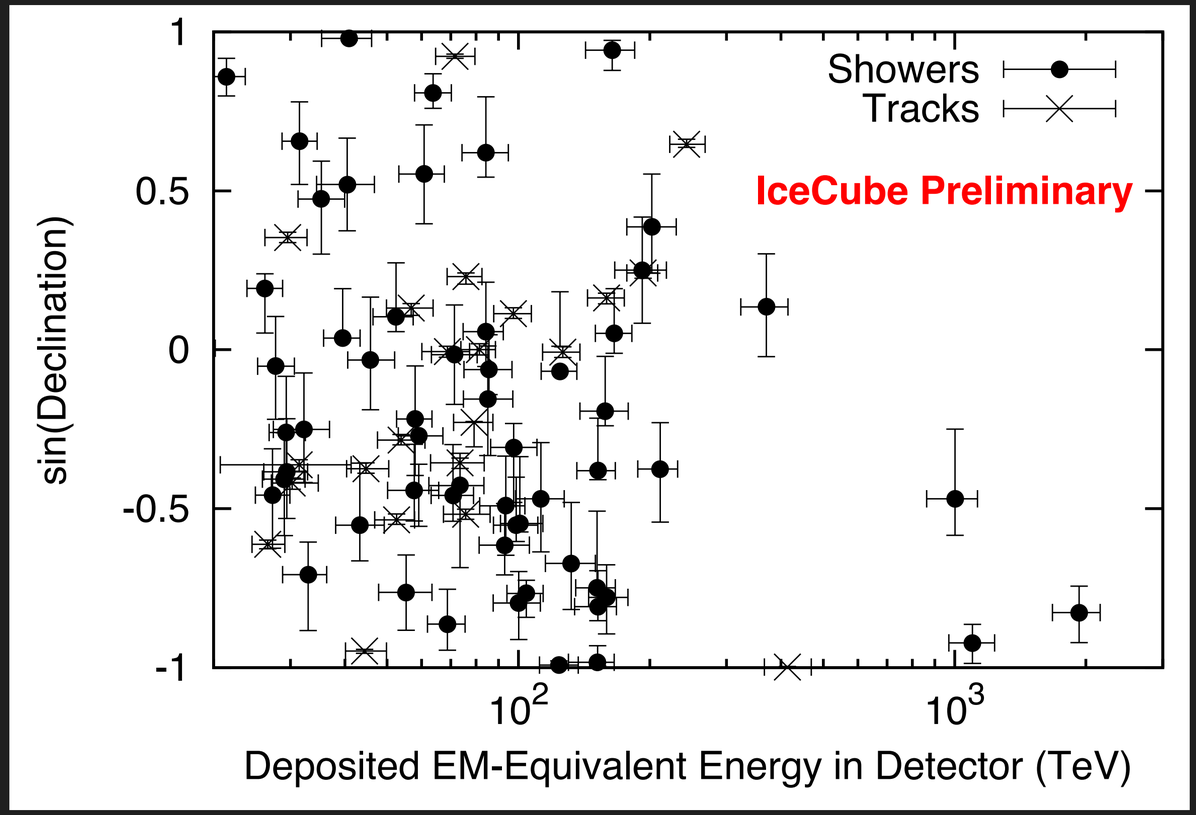
Estimated background:

$15.6^{+11.4}_{-3.9}$ atm. neutrinos

25.2±7.3 atm. muons

Two of them are an obvious (but expected) background:

coincident muons from two CR air showers



We updated the **cross-section model** (now “CSMS”) -> expected ~25% decrease in best-fit normalization

ENERGY SPECTRUM (6 YEARS)

energy deposited in the detector (lower limit on neutrino energy)

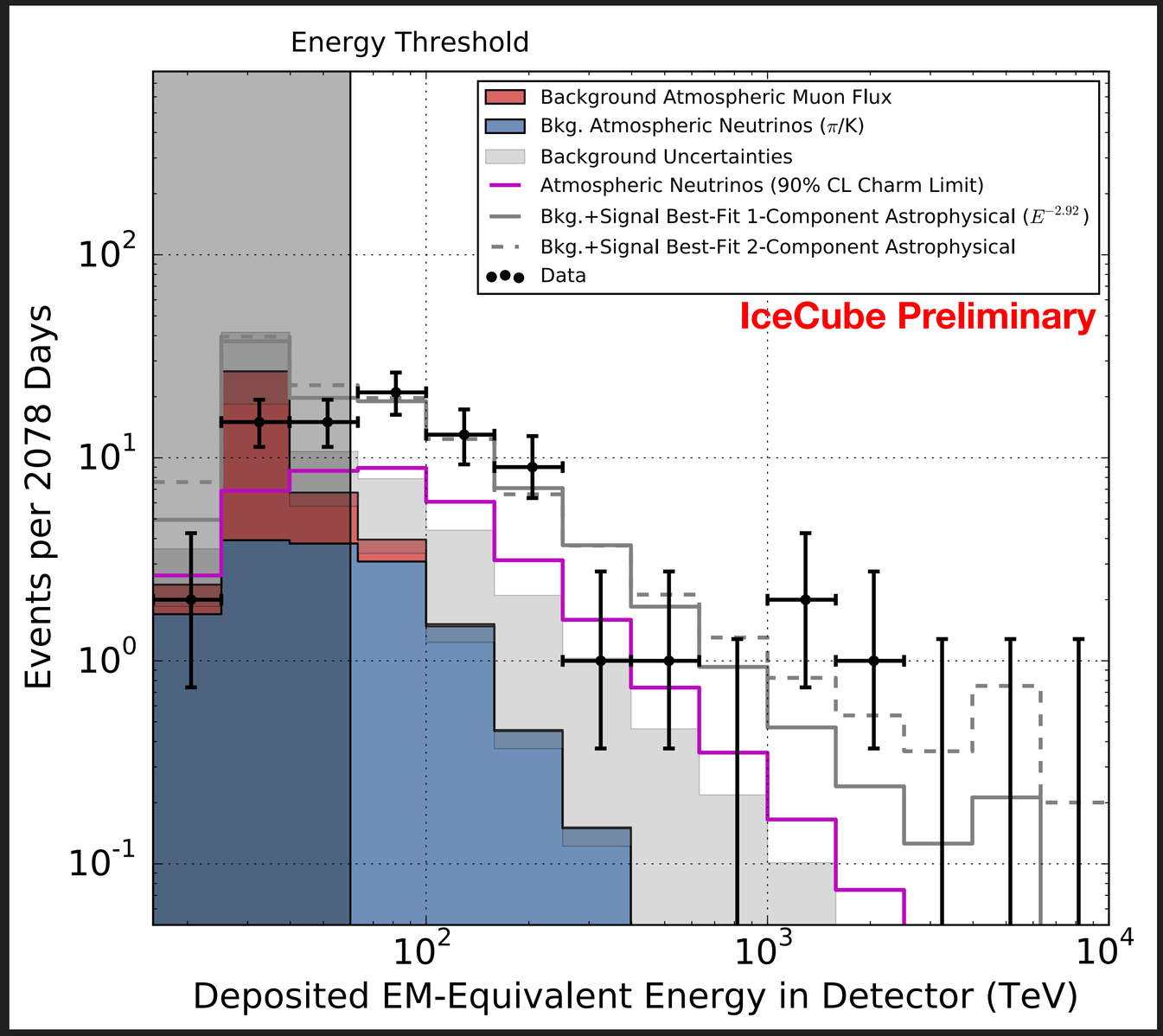
Compatible with benchmark single power-law model.

Things might be more complicated, but this is not the analysis to decide that.

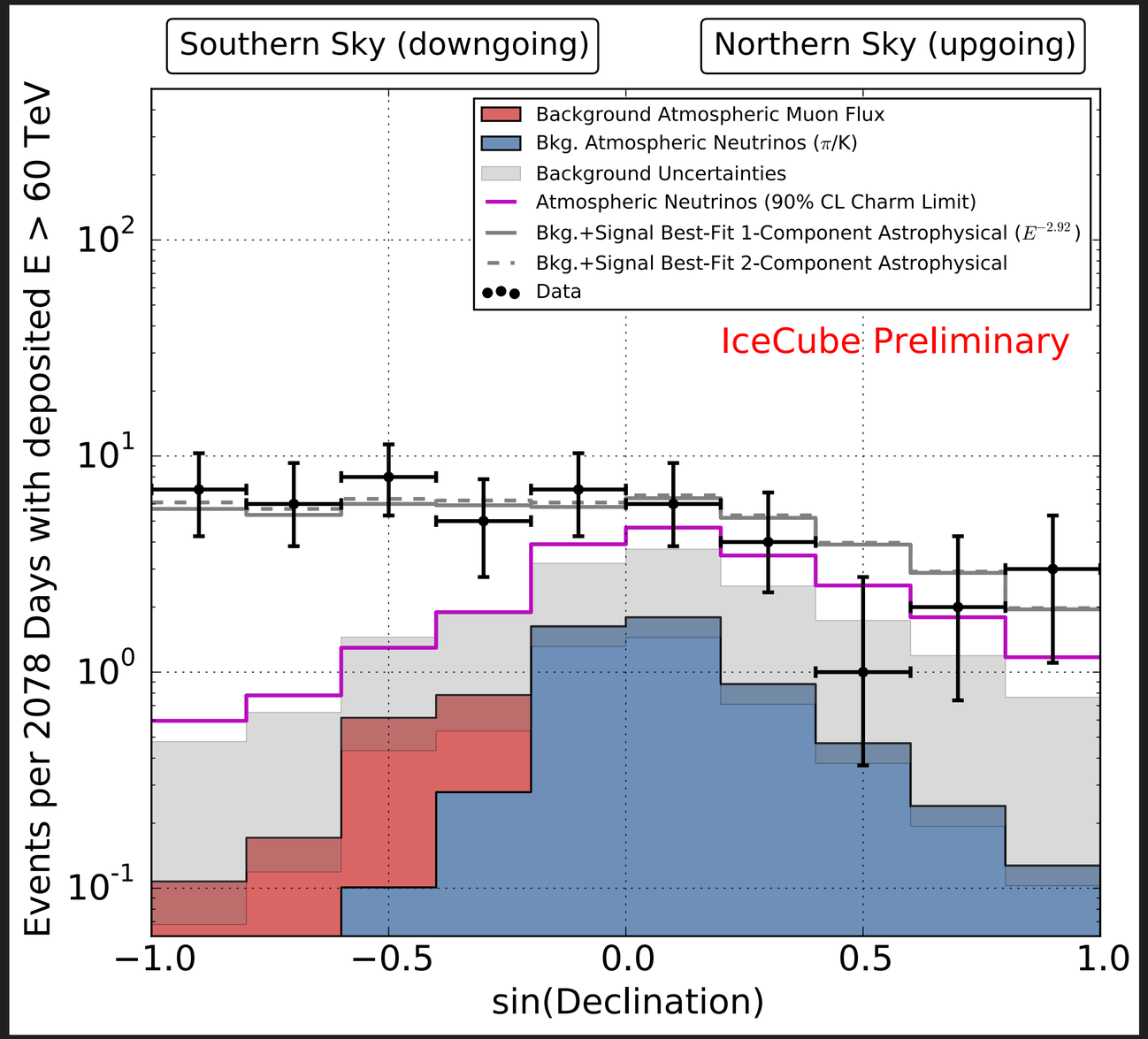
Best fit spectral index ($E^{-\gamma}$):

$\gamma = -2.92^{+0.33}_{-0.29}$

$E^2\Phi = 2.46 \pm 0.8 \times 10^{-8} \times (E / 100\text{TeV})^{-0.92}$ GeV cm^{-2} s^{-1} sr^{-1}

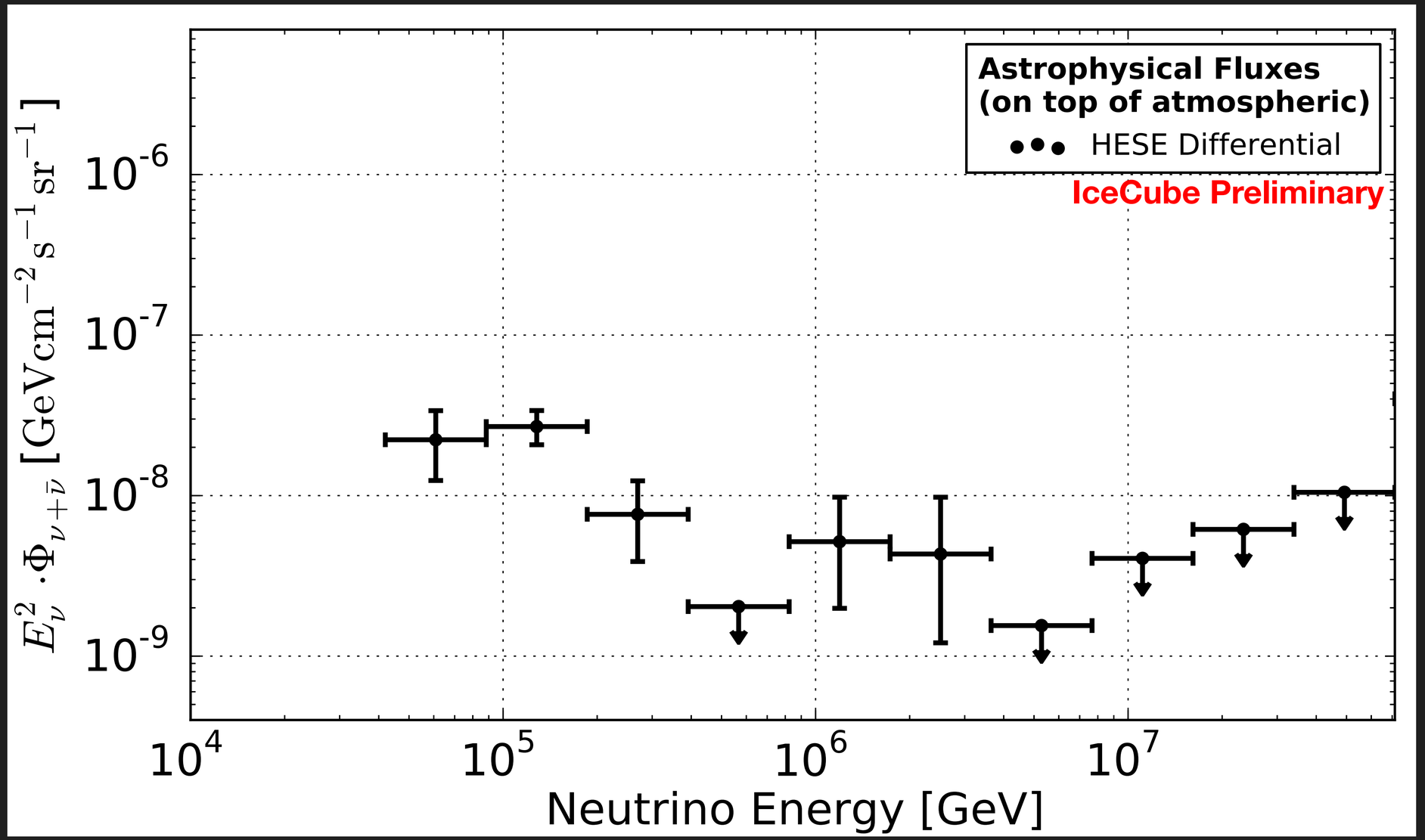


ZENITH DISTRIBUTION (6 YEARS)



UNFOLDING TO NEUTRINO ENERGY

Fit for an arbitrary spectrum + background components (with priors) - 6 years



assumption: 1:1:1 flavor ratio, 1:1 neutrino:anti-neutrino

UNFOLDING TO NEUTRINO ENERGY

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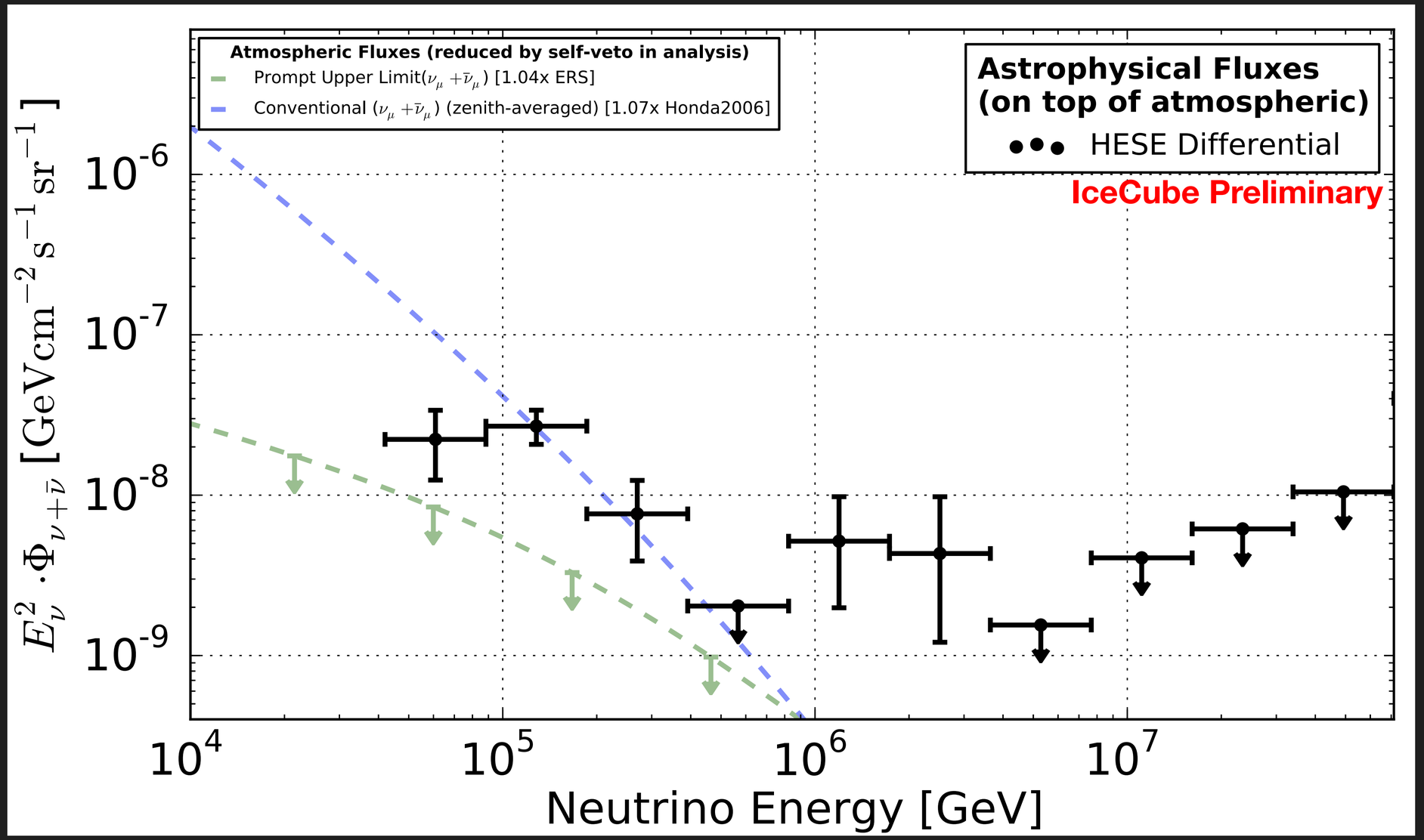

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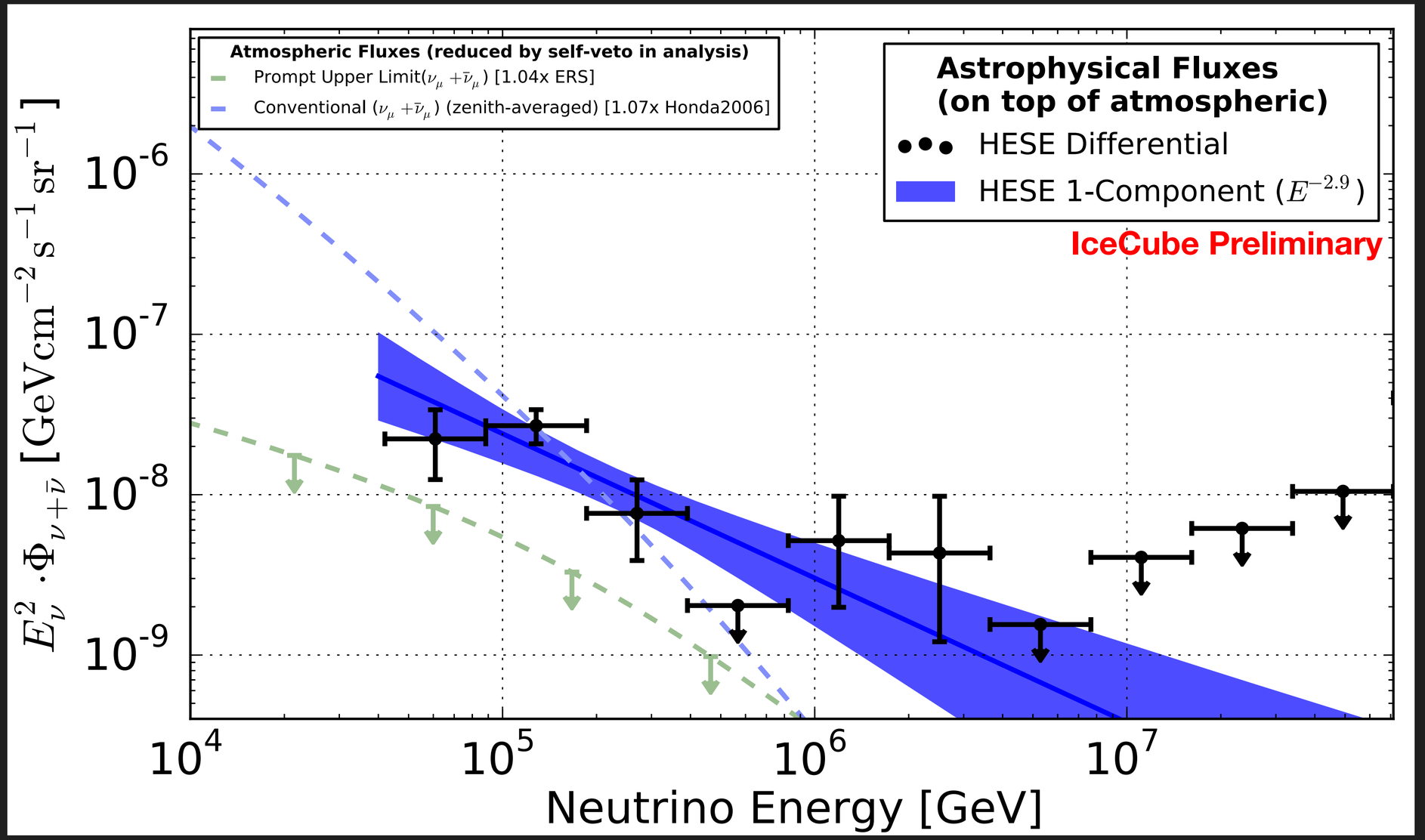
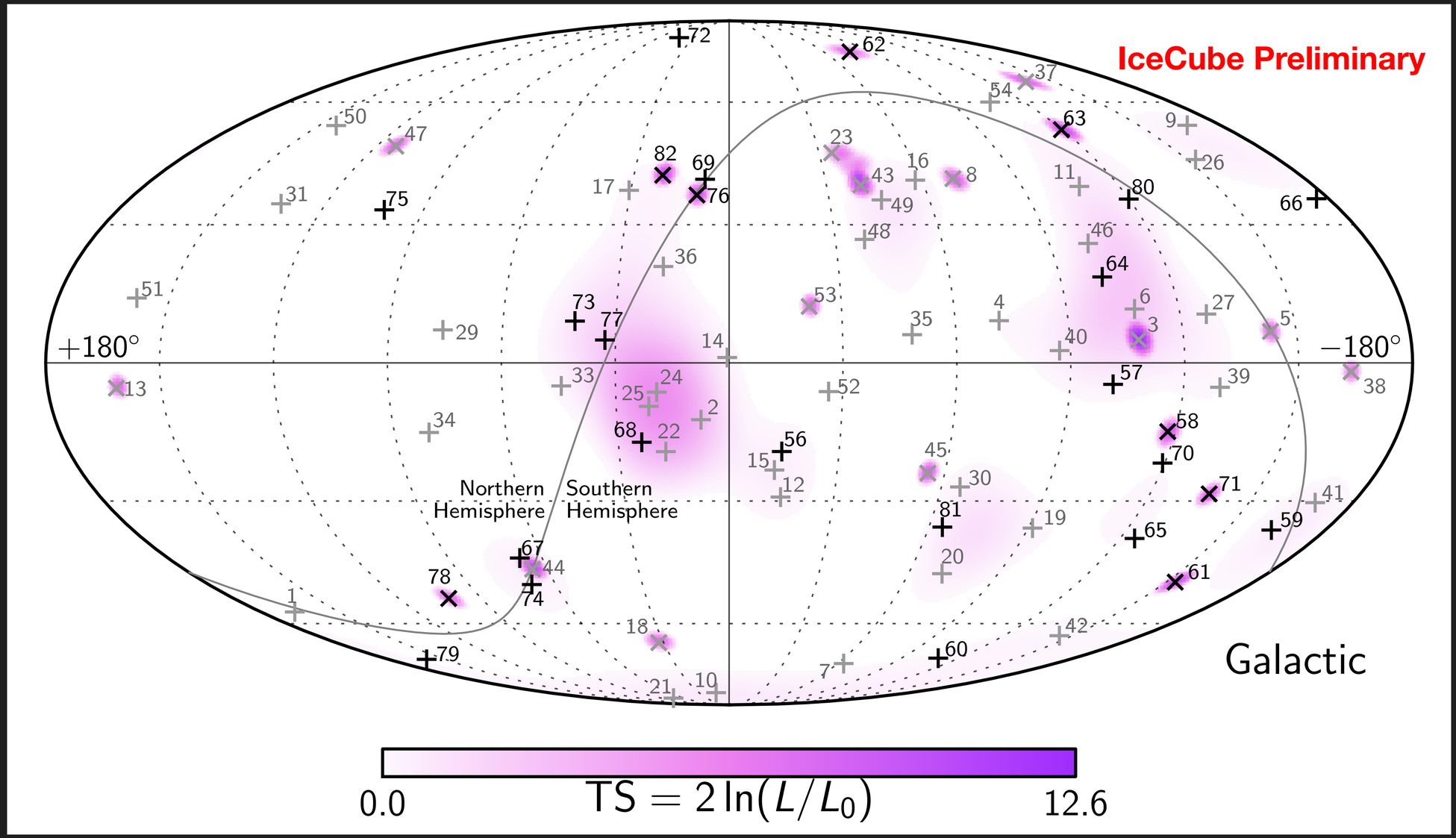


assumption: 1:1:1 flavor ratio, 1:1 neutrino:anti-neutrino

SKYMAP / CLUSTERING

No significant clustering observed (six years)



(all p-values are post-trial)

SKYMAP / CLUSTERING

No significant clustering observed

Analyzed with a variant of the standard PS method (w/o energy) (i.e. scrambling in RA)

Significance (p-value): **77%** (not significant)

Other searches (multi-cluster, galactic plane, time clustering, GRB correlations) not significant either

UPGOING MUONS

Highest-energy neutrino-induced muon

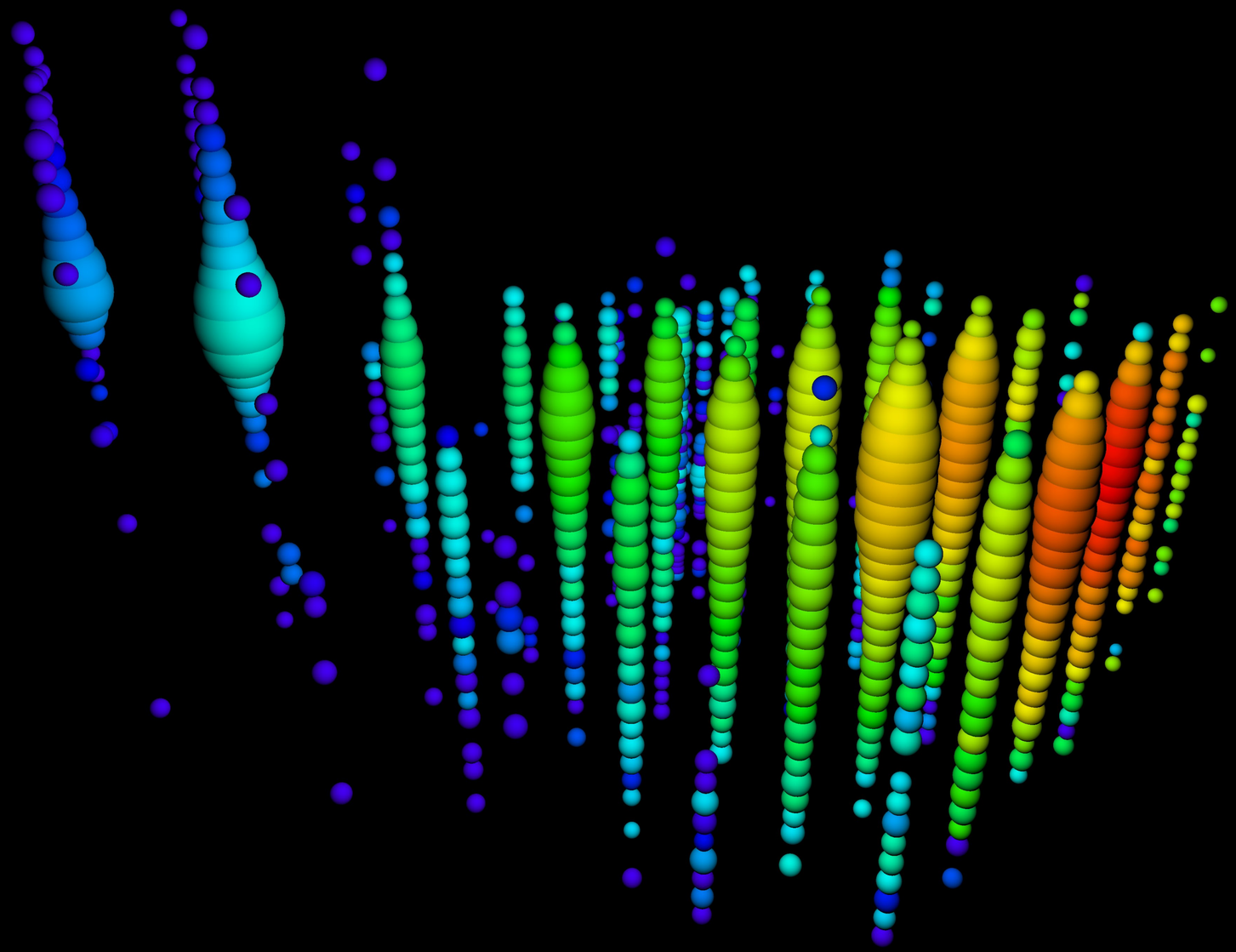
up-going
(i.e. not a CR muon)

deposited energy:
2.6±0.3 PeV
neutrino energy:
8.7 PeV (median)

date: June 11, 2014

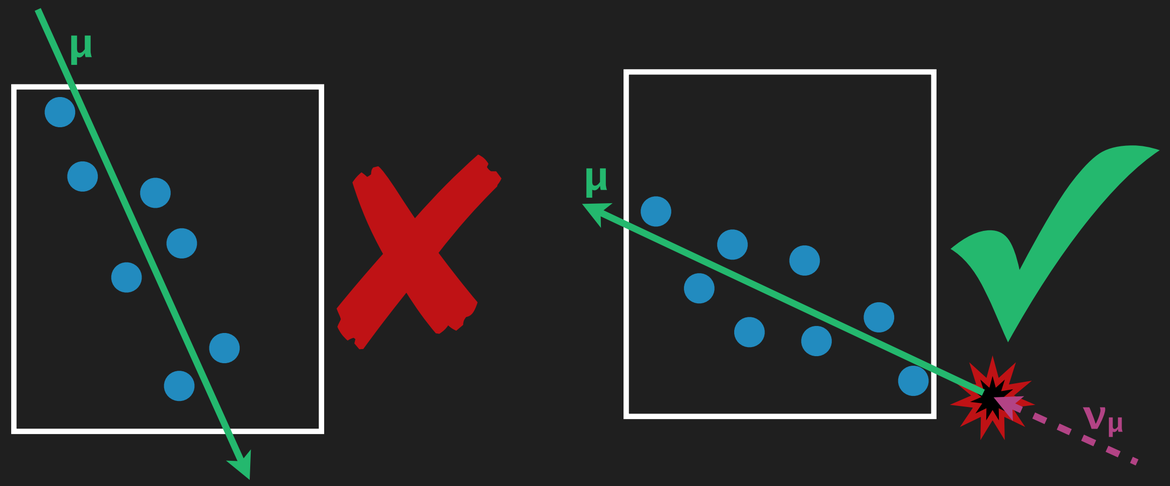
direction:
11.48° dec / 110.34° RA

ApJ 833 (2016) no.1, 3



UPGOING MUONS - SPECTRAL COMPONENTS

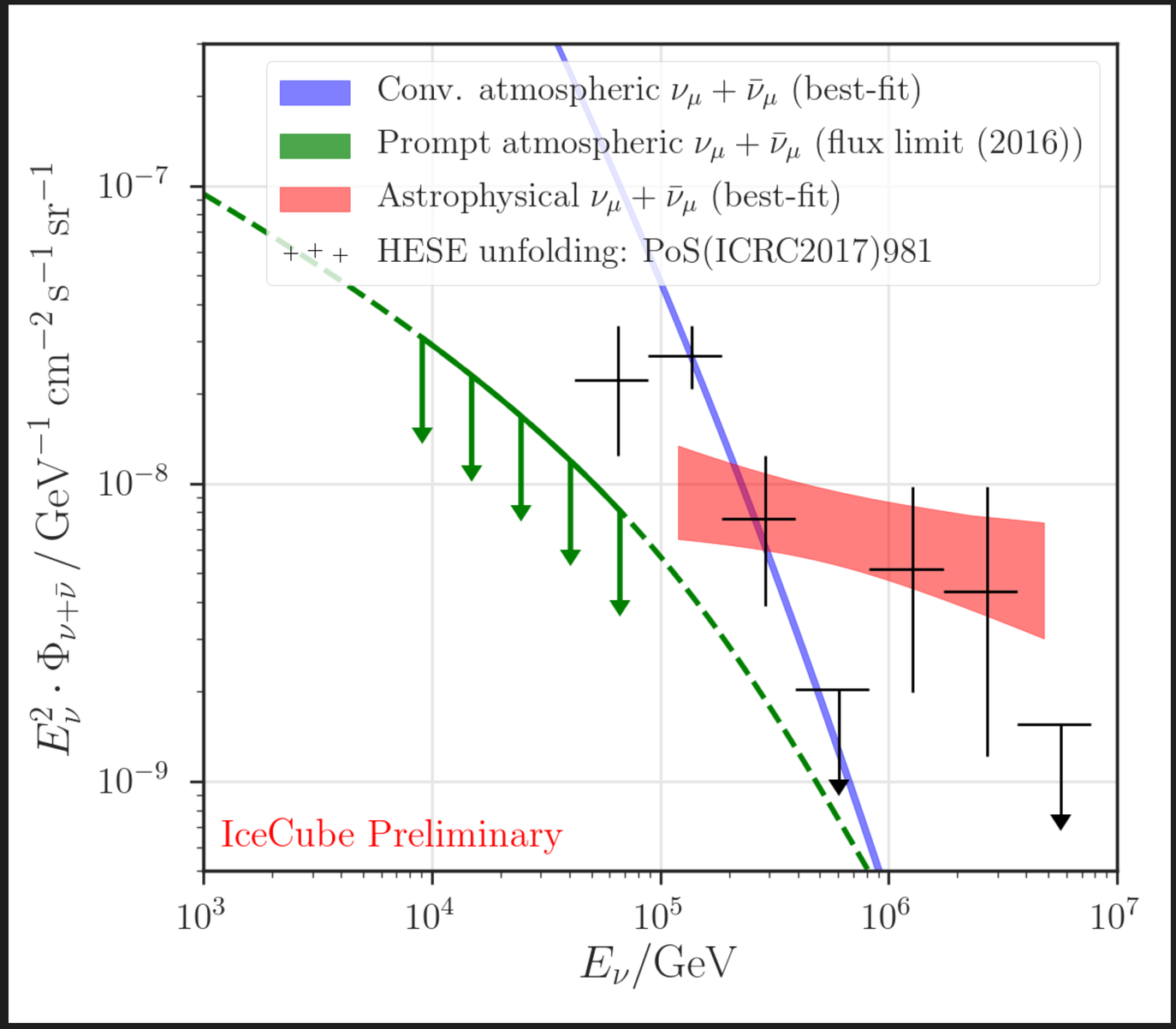
Eight years of data (from C. Haack | ICRC2017)



Selected horizontal and up-going muon tracks

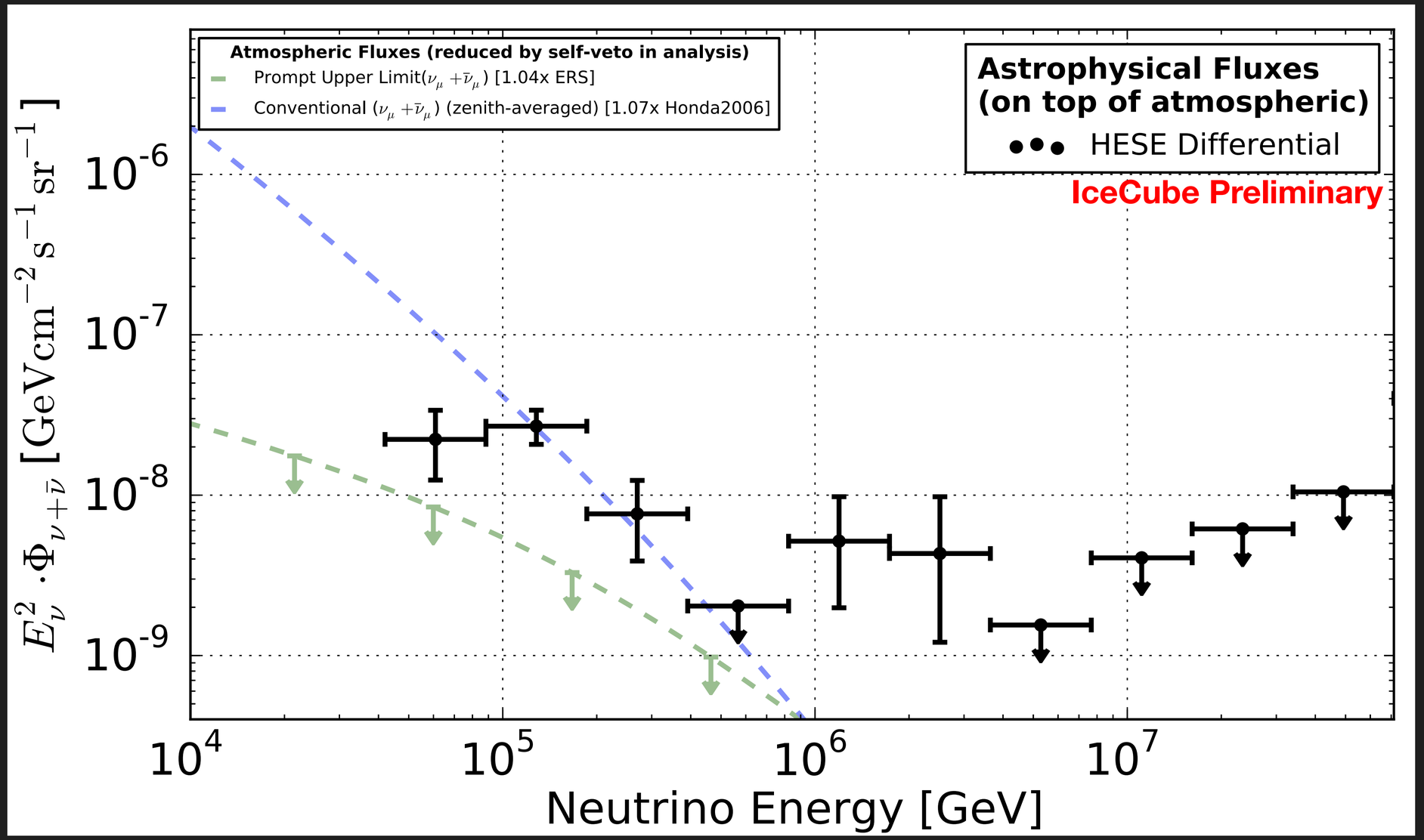
Sensitive to astrophysical neutrinos above ~120 TeV

power-law index: 2.19±0.10
prompt component fits to zero



UNFOLDING TO NEUTRINO ENERGY

Fit for an arbitrary spectrum + background components (with priors) - 6 years



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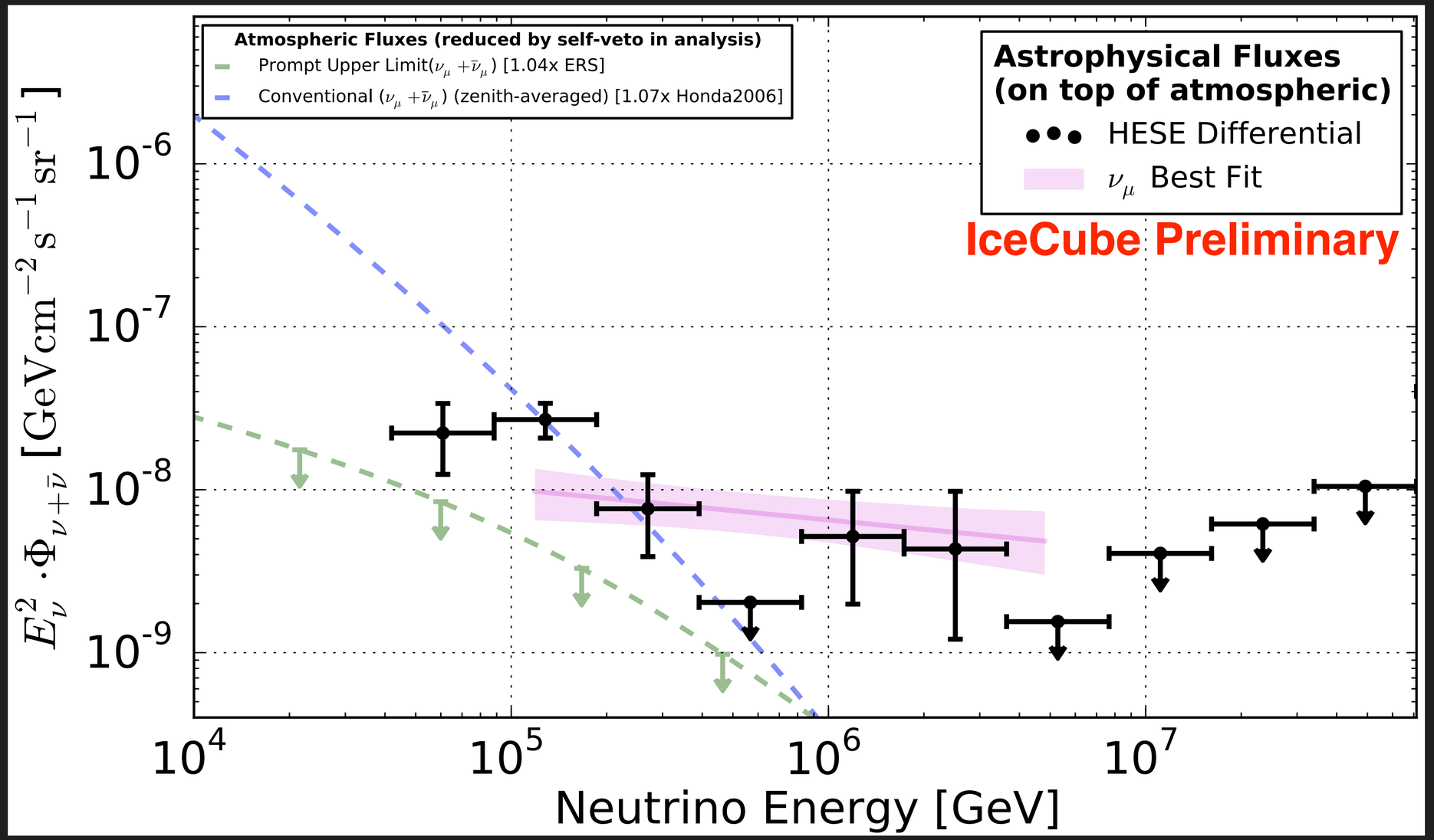

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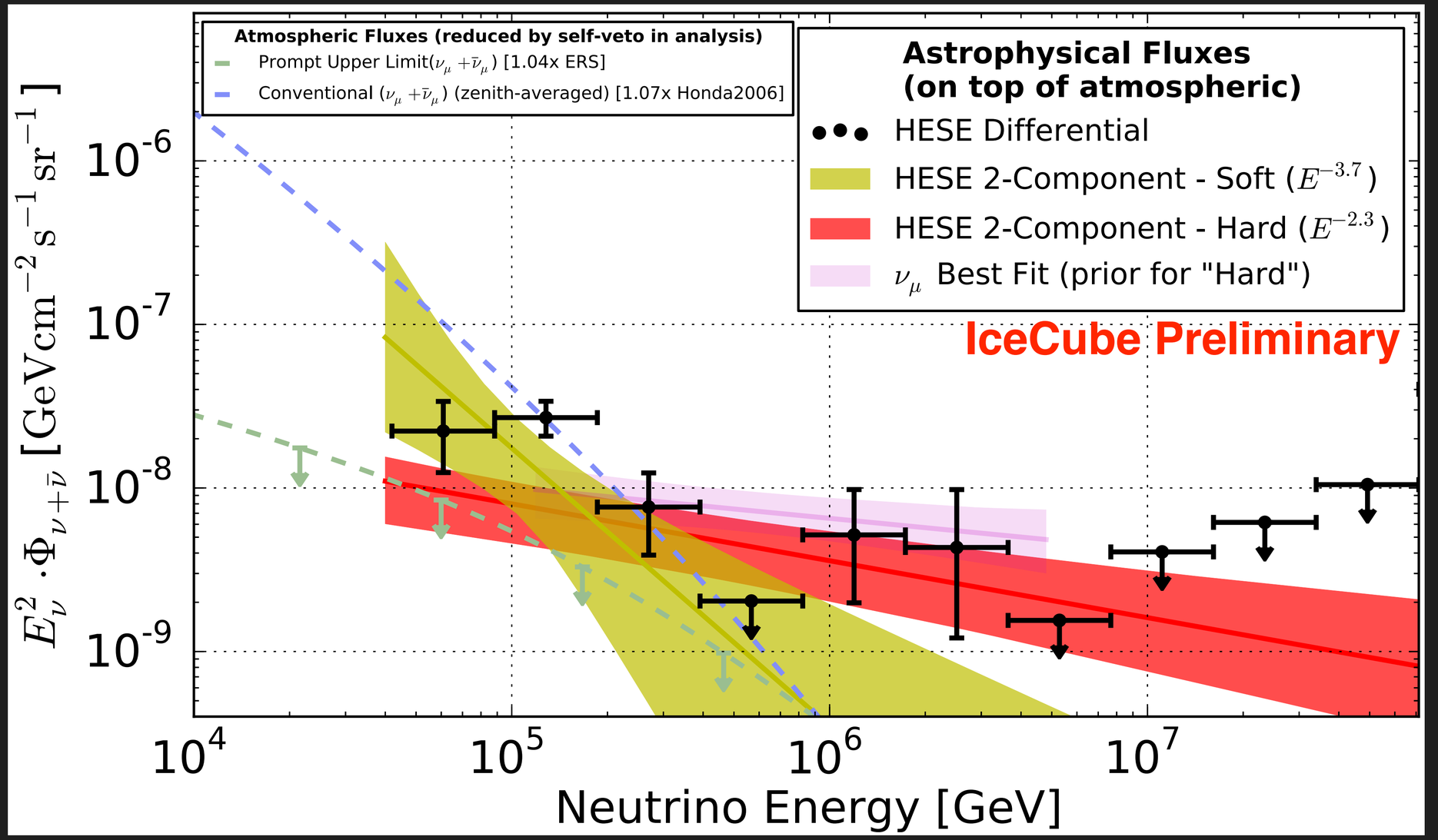

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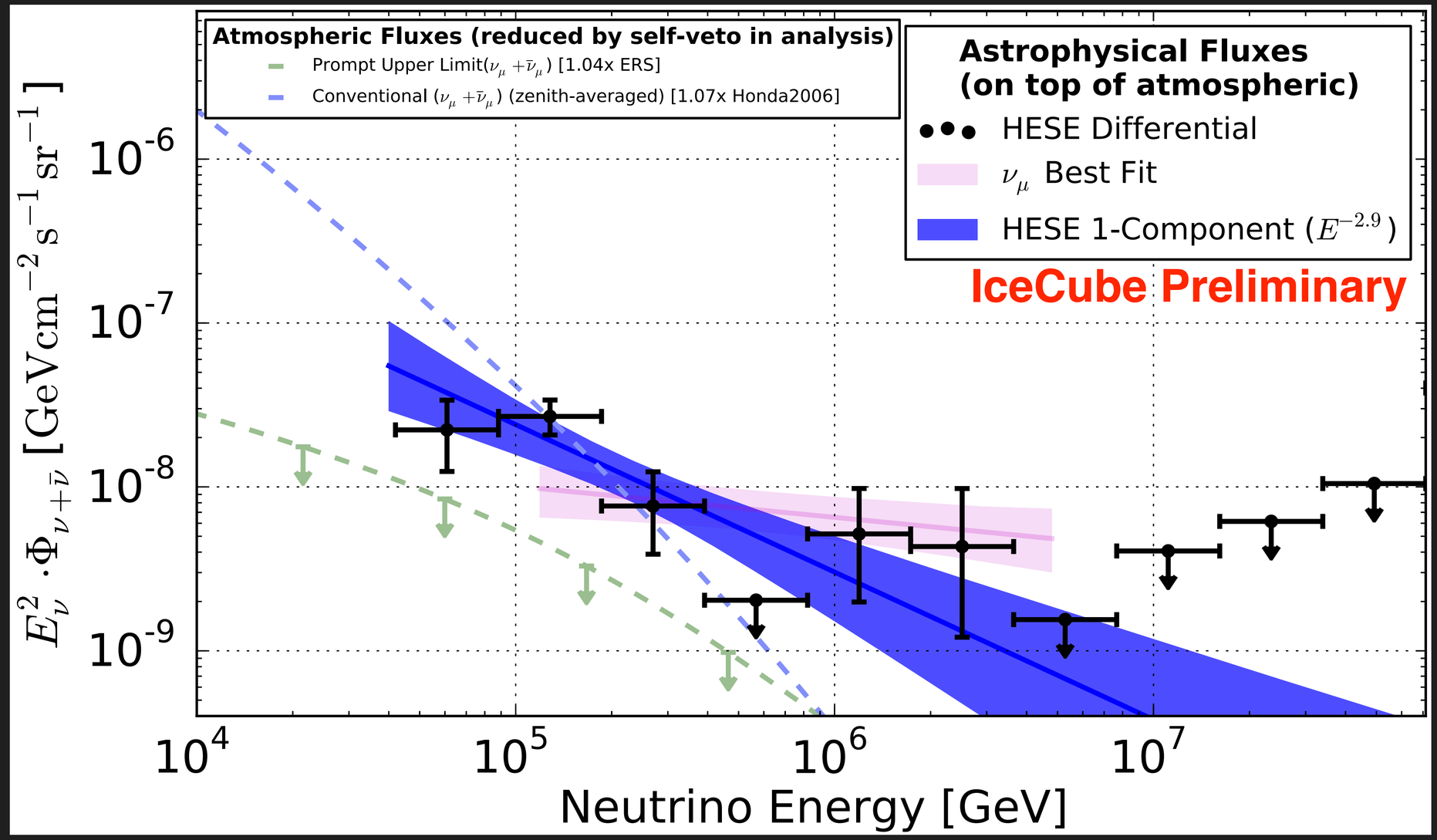


This data sample is not able to discriminate between a 1-component and a 2-component model

NO EVIDENCE FOR 2 COMPONENTS IN THIS ANALYSIS

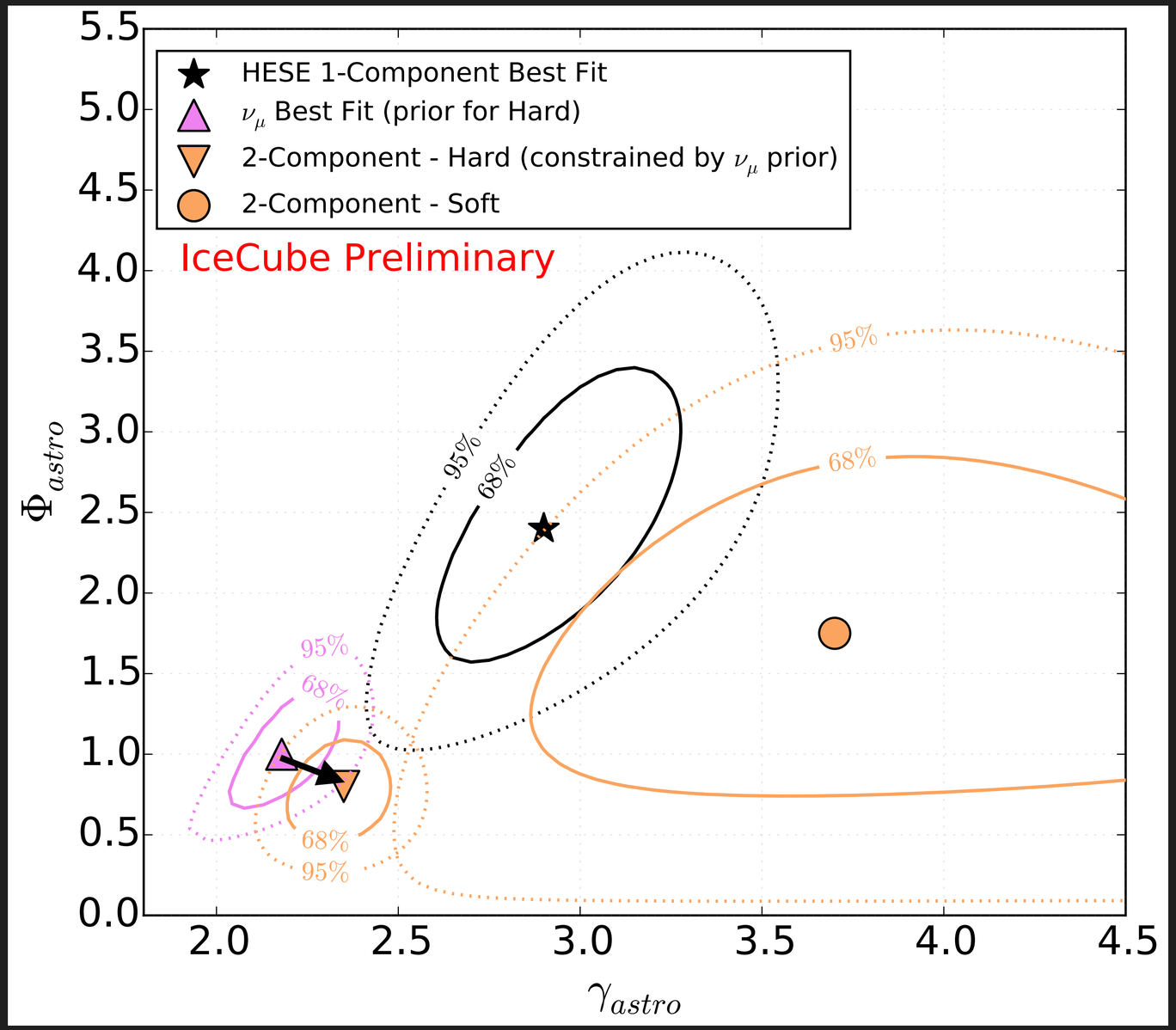
We are not able to make statements about the spectral shape with this analysis - stay tuned for future selections/analyses

Best-fit normalization Φ_{astro} at 100 TeV vs. astrophysical index γ_{astro}

1-component power-law in **black**

2-component assumption in **orange** - with a prior on the hard component from the muon neutrino analysis

This data sample **can not discriminate** between a 1-component and a 2-component model

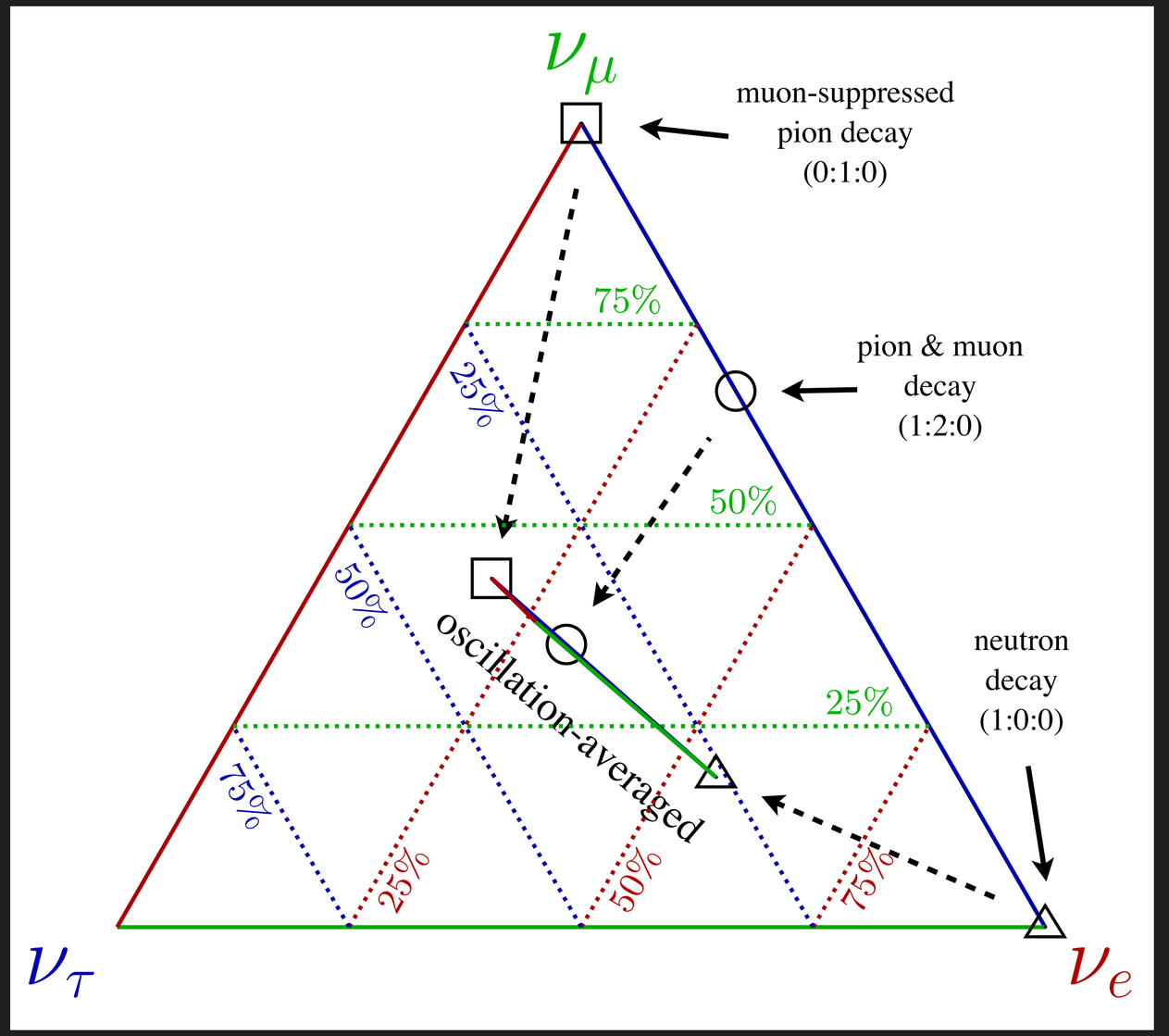


FLAVOR COMPOSITION

Flavor ratio at Earth contains information about source ratio after oscillations en route to Earth

For standard oscillations, only a small region of flavor ratios is allowed at Earth

	at source			at Earth		
	ν_e	ν_μ	ν_τ	ν_e	ν_μ	ν_τ
pion decay	1	2	0	1	1	1
muon-damped	0	1	0	0.2	0.39	0.39
neutron decay	1	0	0	0.56	0.22	0.22



GLOBAL FIT OF ICECUBE ANALYSES

interesting results such as flavor ratio

fit for flavor ratio, spectral shape and cutoff

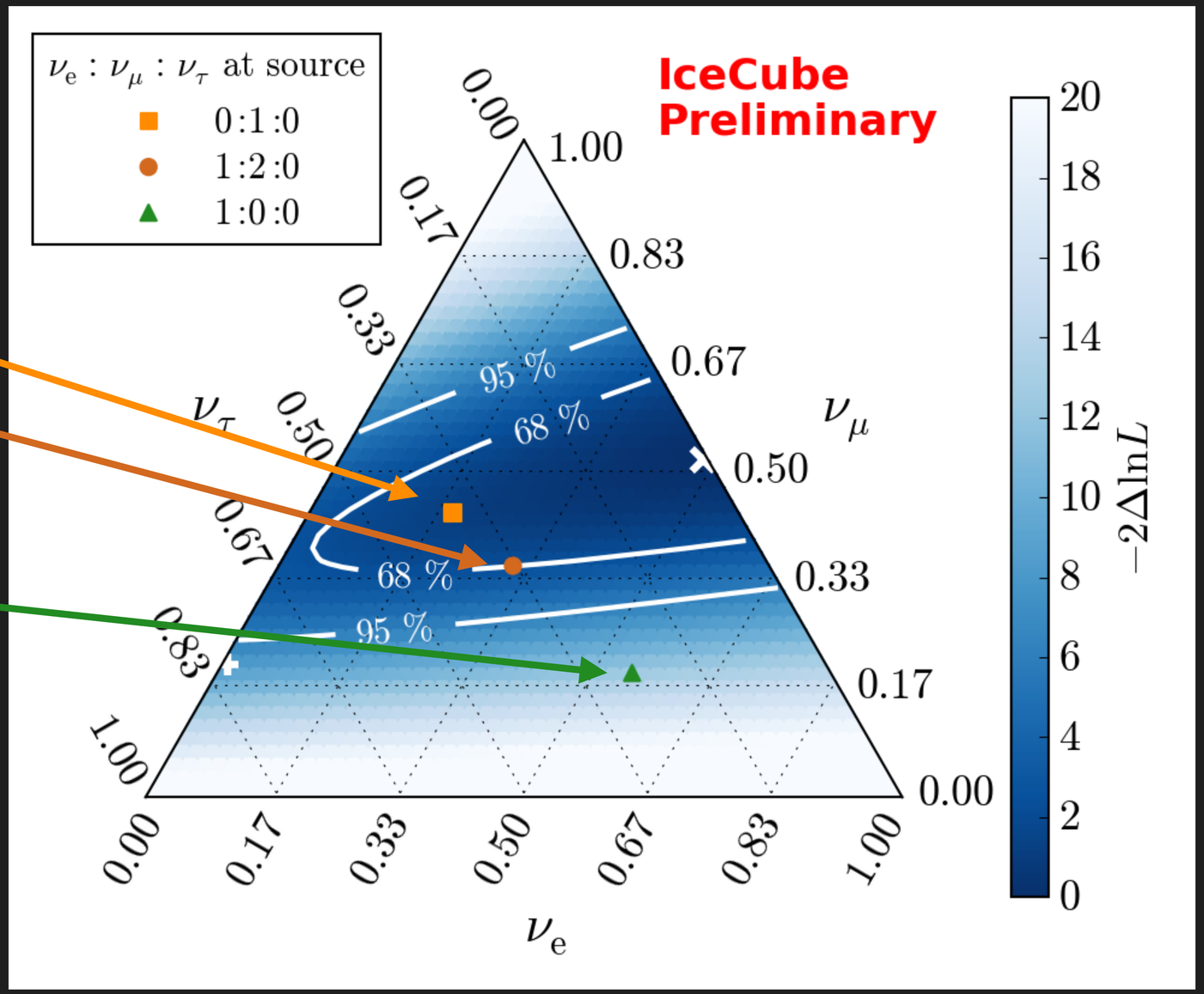
muon-damped (0:1:0)

pion decay (1:2:0)

→ compatible

neutron decay (1:0:0)

→ excluded at 3.7σ

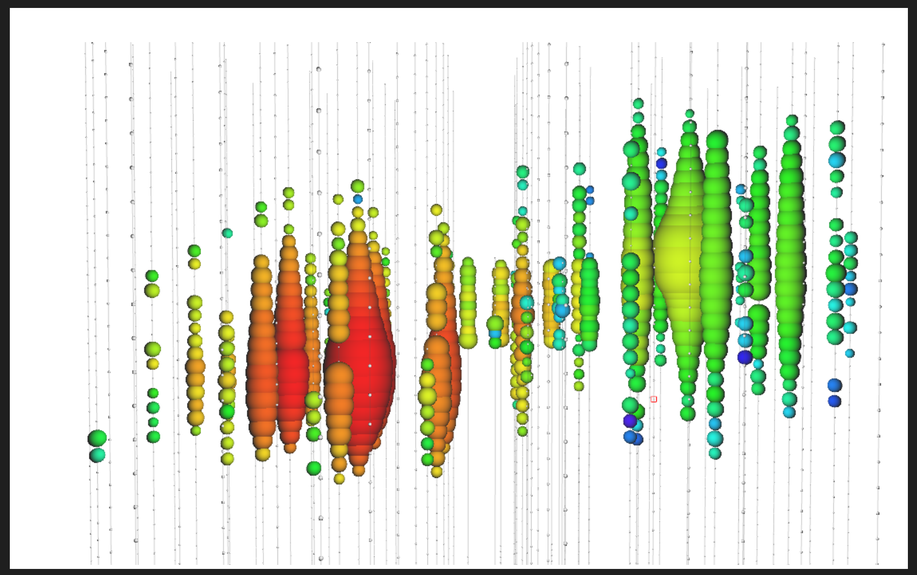


ApJ 809, 98 (2015)/
PoS(ICRC2015)1066

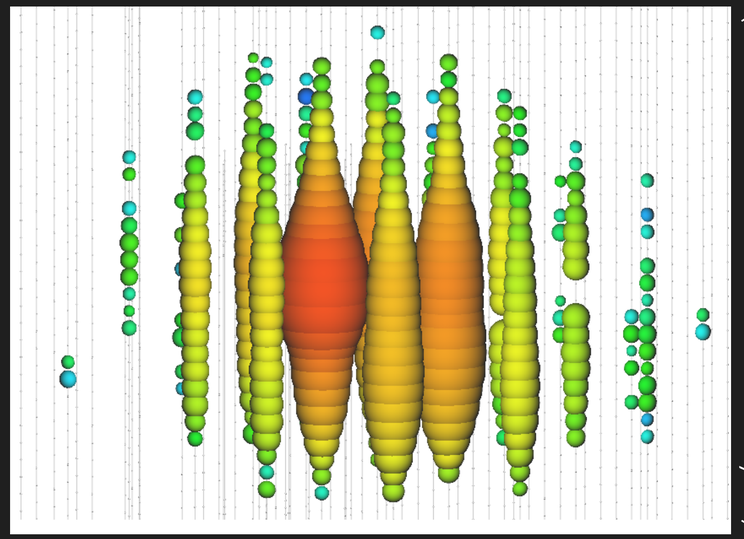
TAU NEUTRINOS

should see the first taus soon

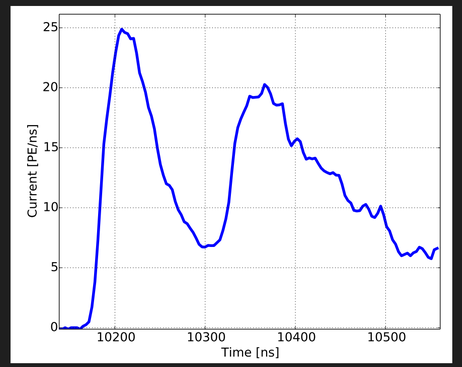
should be able to identify a “double-bang” signature above ~PeV - not observed yet!

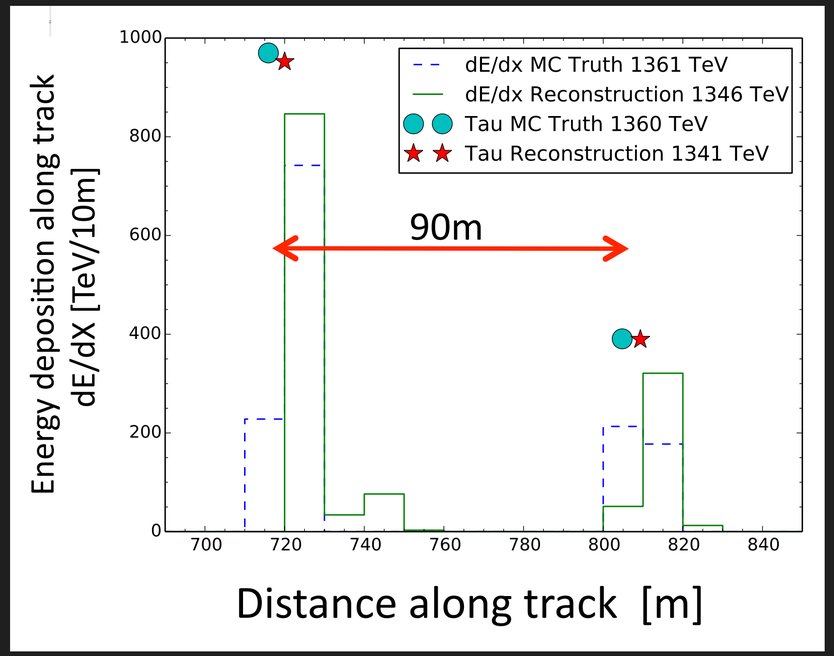


event with longer decay length



simulated event, 1.36PeV (no data event identified yet)



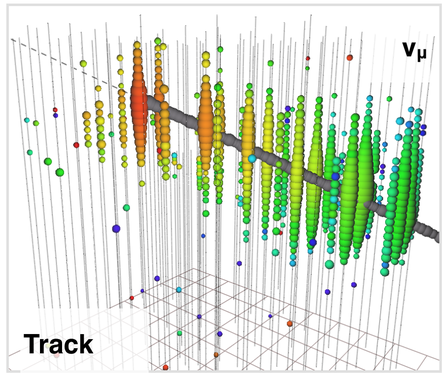


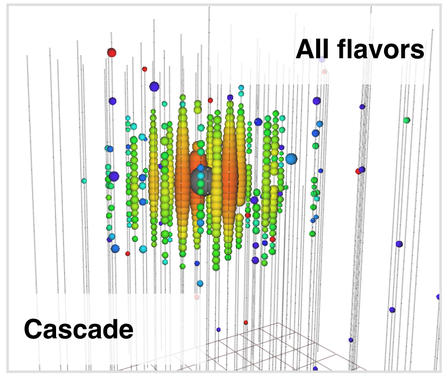
at lower energies identification is more challenging - IceCube just set new limits!

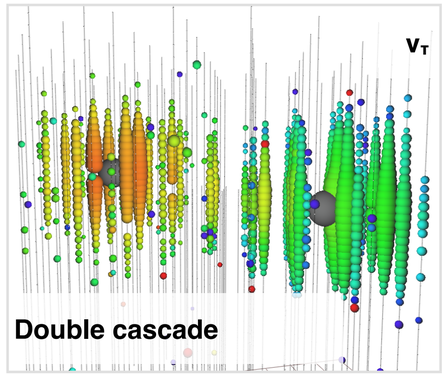
TAU NEUTRINO SEARCHES WITH STARTING EVENTS

update of global fit in progress

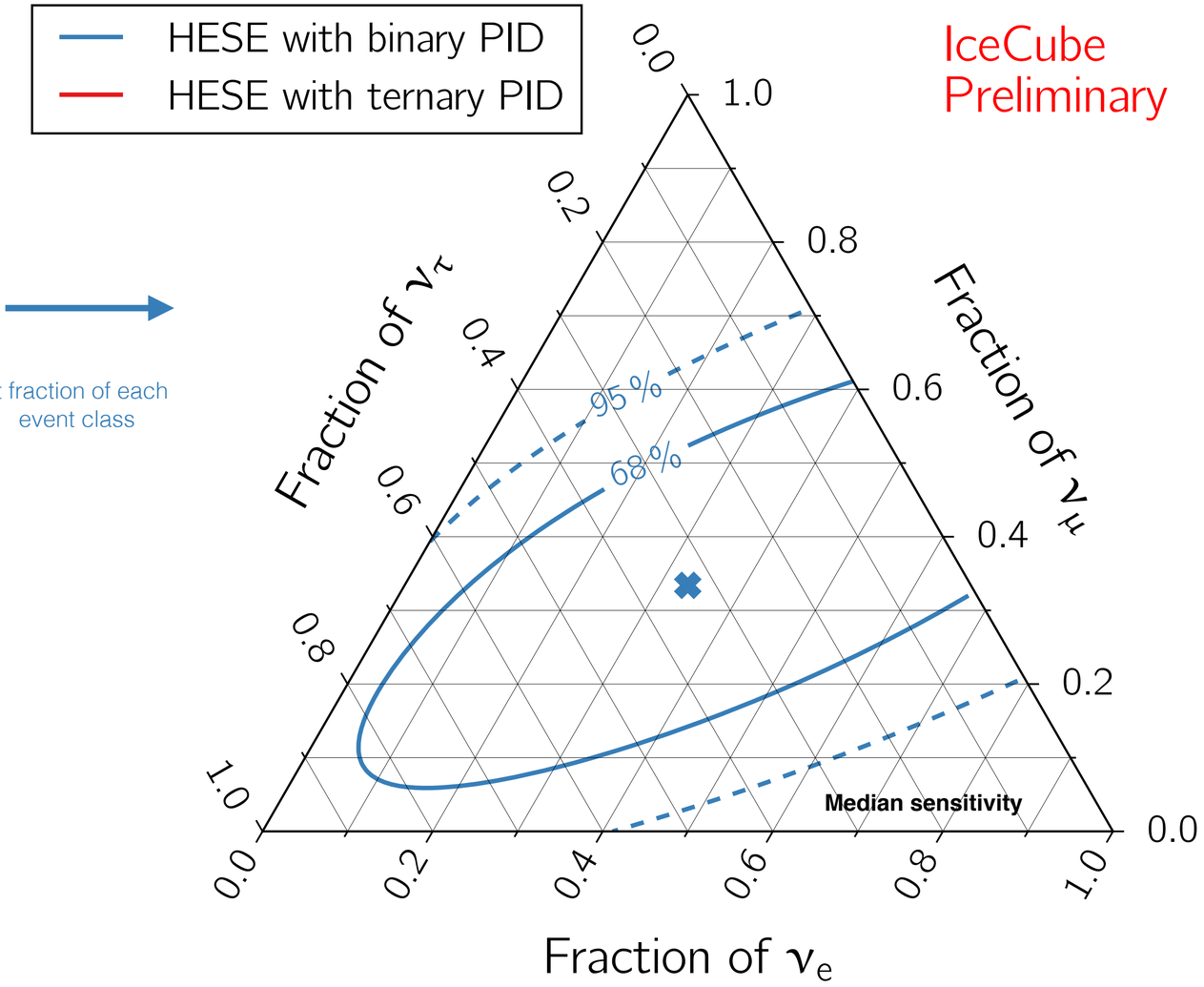
PoS(ICRC2017) 974







fit fraction of each event class



TAU NEUTRINO SEARCHES WITH STARTING EVENTS

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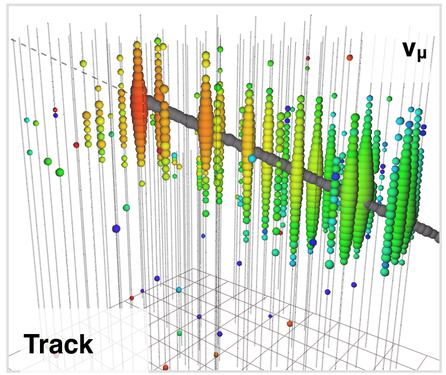
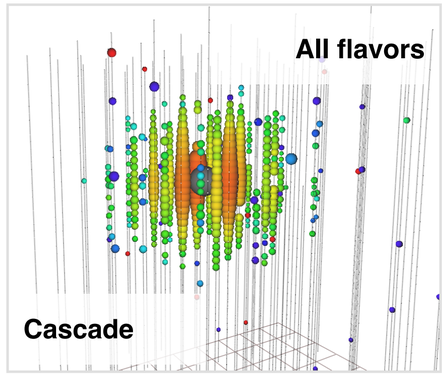
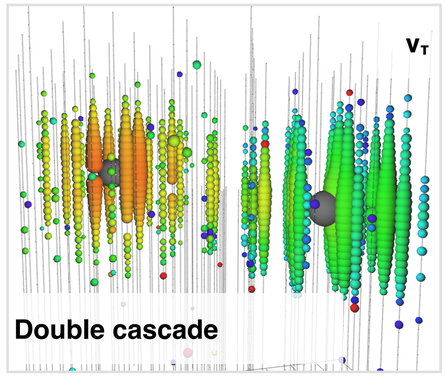
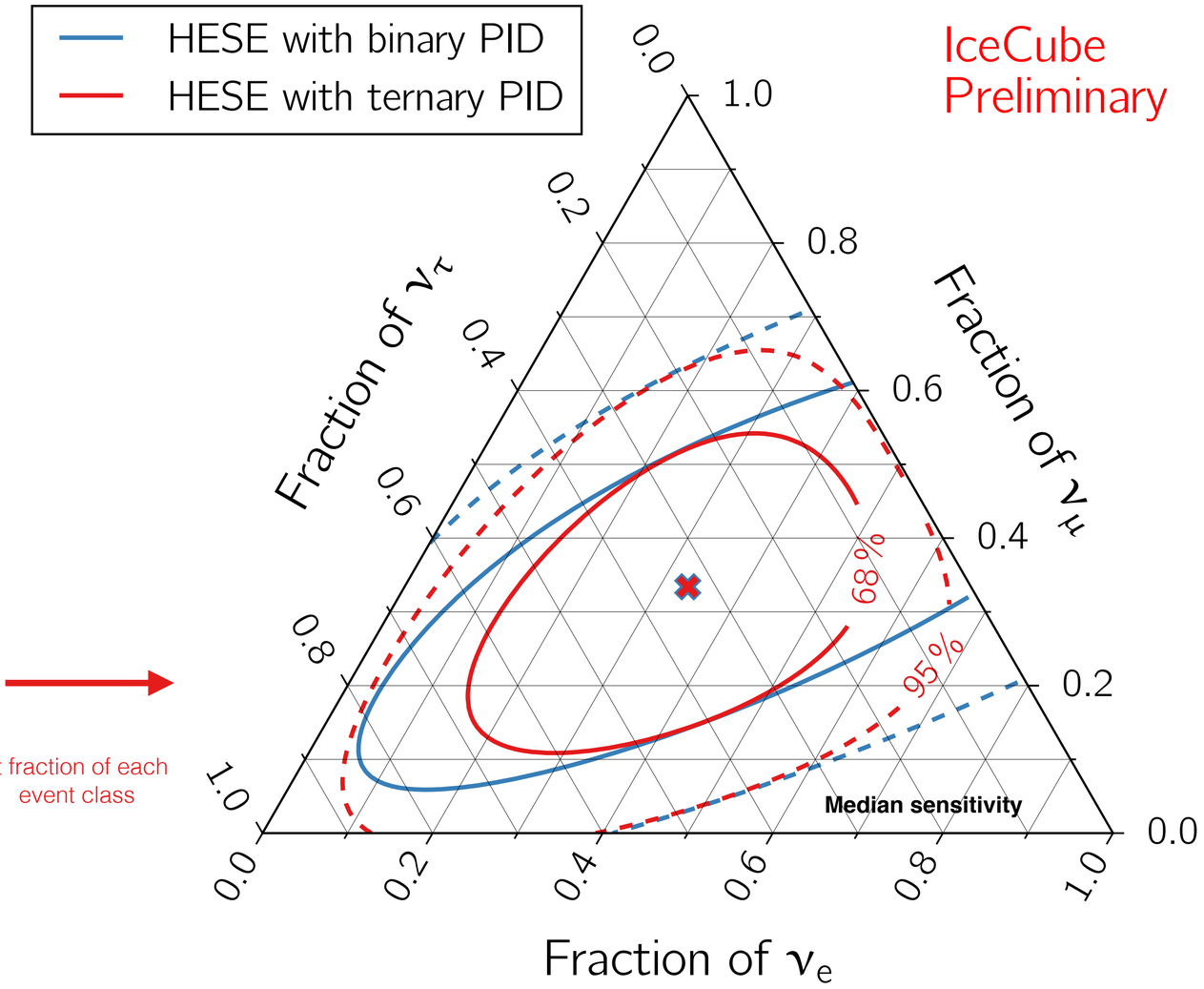
PoS(ICRC2017) 974







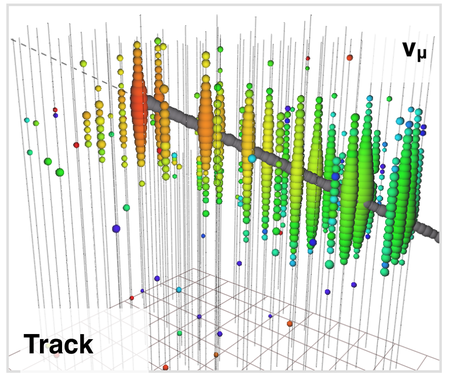
fit fraction of each event class

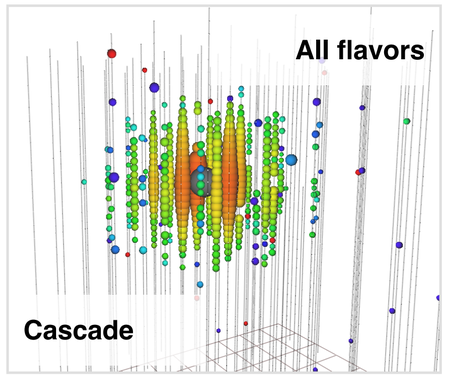


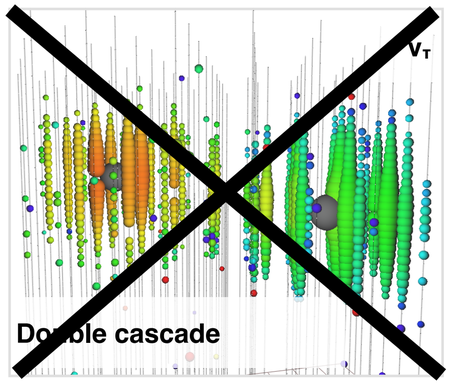
TAU NEUTRINO SEARCHES WITH STARTING EVENTS

update of global fit in progress

PoS(ICRC2017) 974

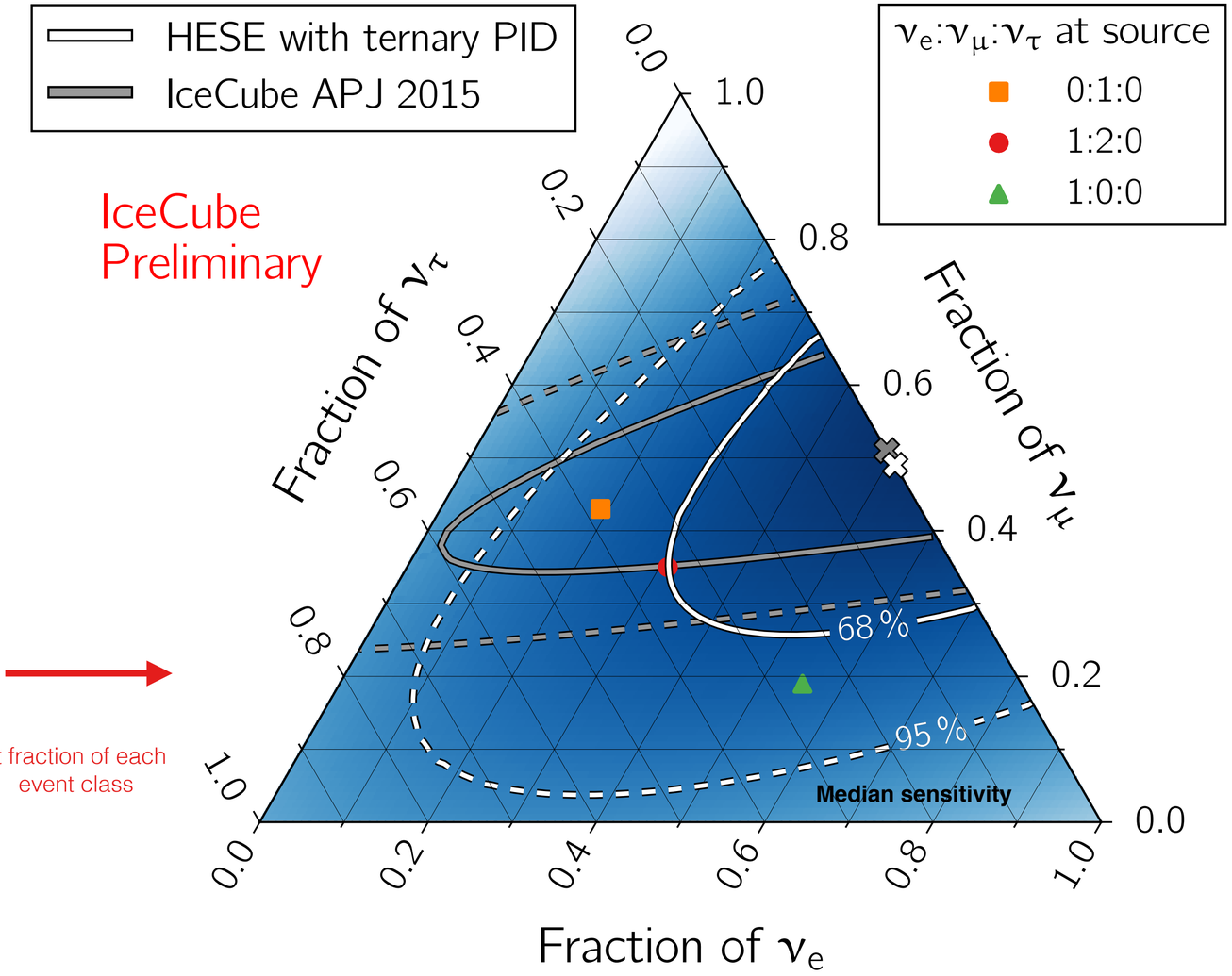






no ν_τ candidates observed

fit fraction of each event class

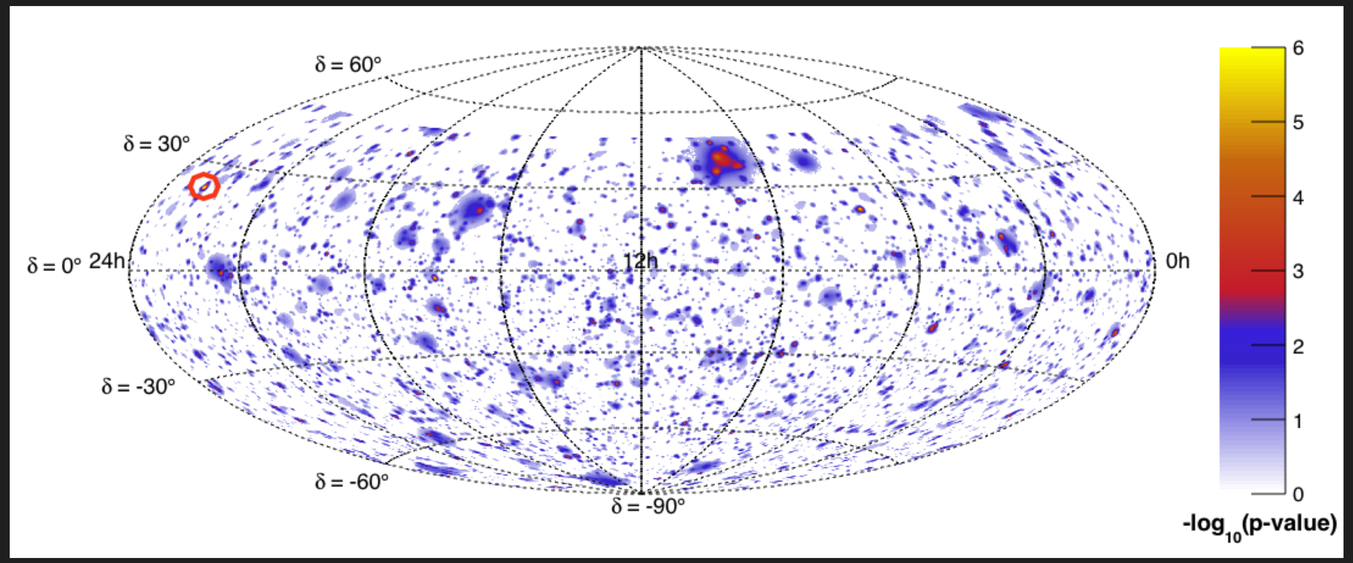


update of global fit in progress

Lack of ν_τ candidates compatible with statistical fluctuation

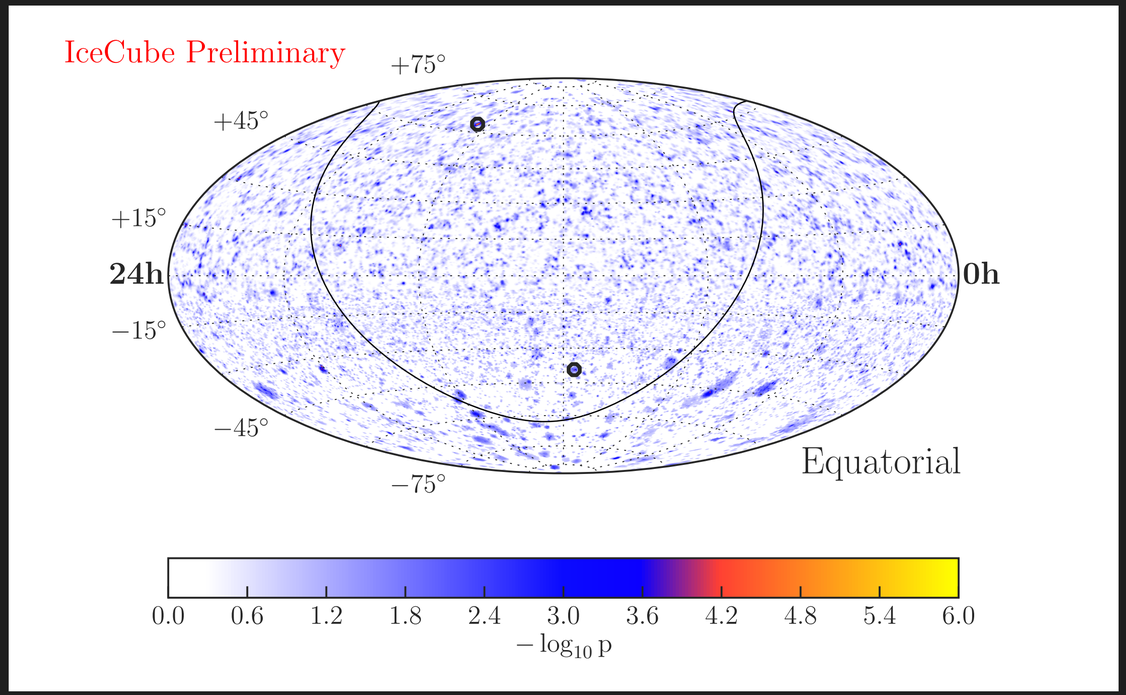
WHERE ARE THE SOURCES?

There is still no evidence for point sources of high-energy neutrinos.



arXiv:1706.01857

ANTARES all-flavour search (~6 years):
~1.9σ chance probability (post-trial)



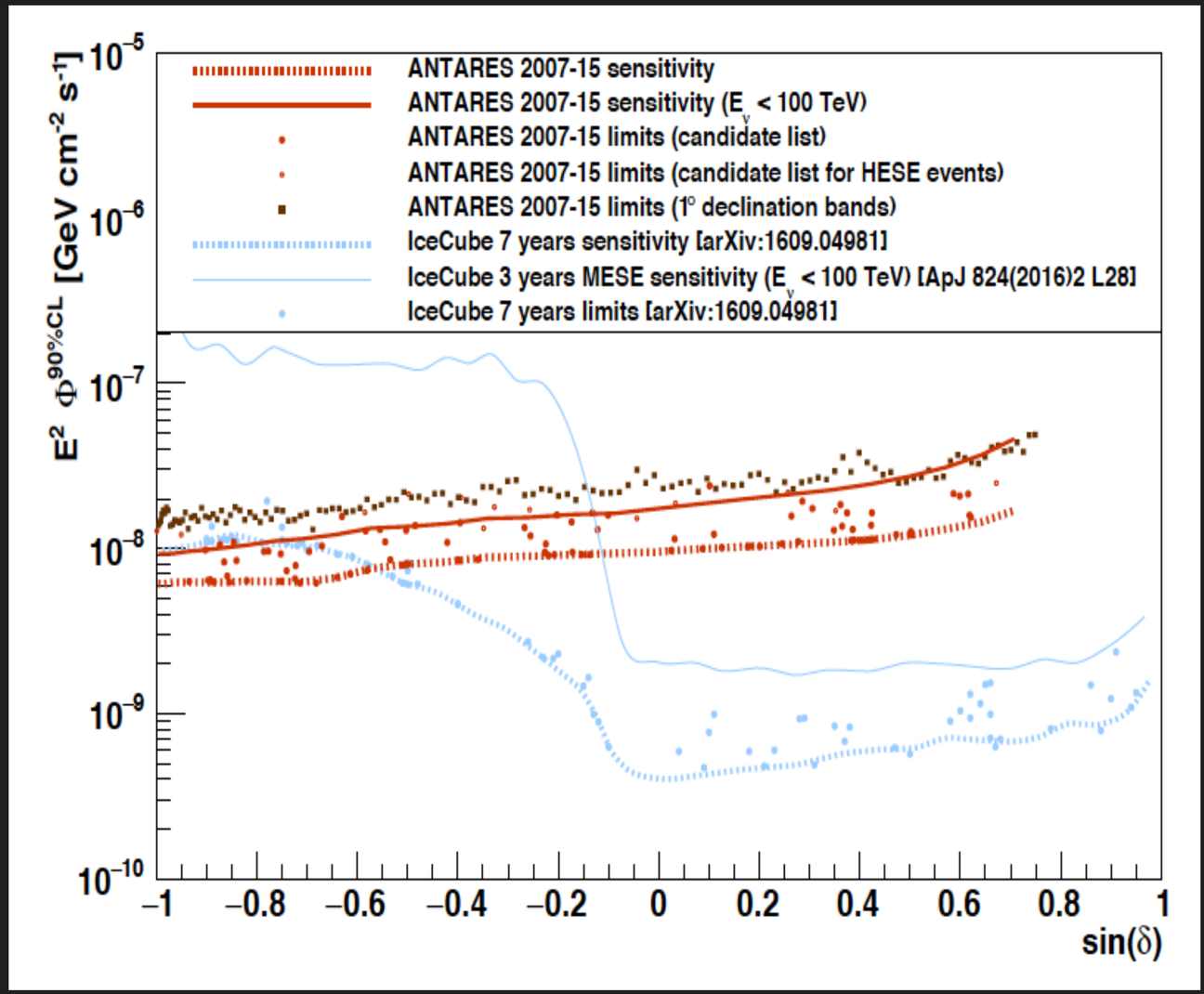
IceCube 6-year though-going muon point source search
Northern-sky muons: **44%** chance probability
> PeV southern-sky muons: **38%**

ApJ 835 (2017) 2, 151

CONSTRAINTS ON POINT SOURCES

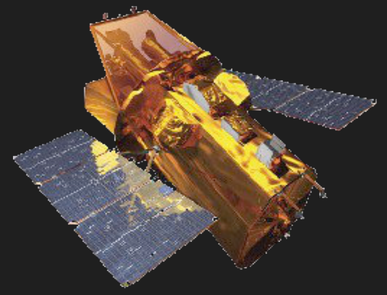
ANTARES can observe the southern sky through the Earth
→ lower threshold, better sensitivity in the south

IceCube has a larger effective area
→ more events, better sensitivity in the north



ALERTS/FOLLOW-UPS

we try to alert other experiments as soon as we see an interesting event



SN/GRB/…

ν

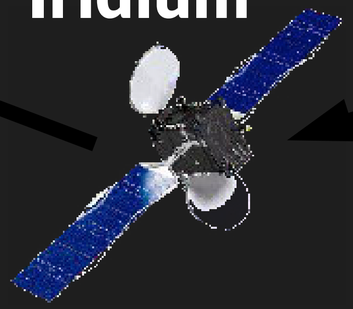
IceCube

PTF (optical)

Swift (X-Ray)

"The North"

Iridium



Veritas/
H.E.S.S./
MAGIC/…

(similar for ANTARES)

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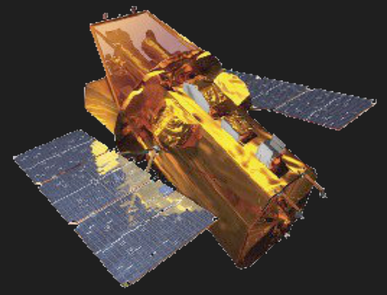

SN/GRB/…

ν

see D. Cowen's talk on Friday!

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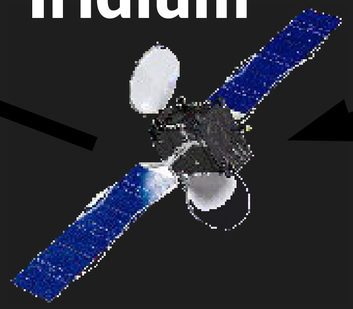


IceCube

Veritas/
H.E.S.S./
MAGIC/…

(similar for ANTARES)

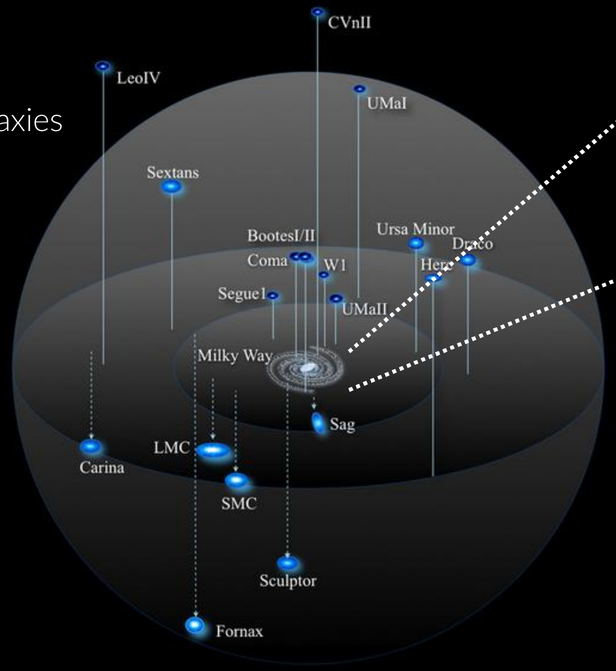
DARK MATTER

(High-Energy) Neutrino Signals from the Sun, the Galactic Center, Halo and more!

INDIRECT DARK MATTER SEARCHES

Look at objects where dark matter might have accumulated gravitationally over the evolution of the Universe

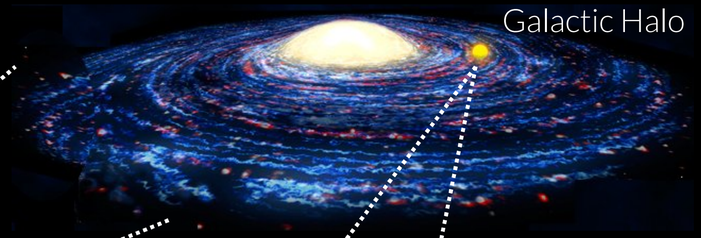
Clusters of Galaxies



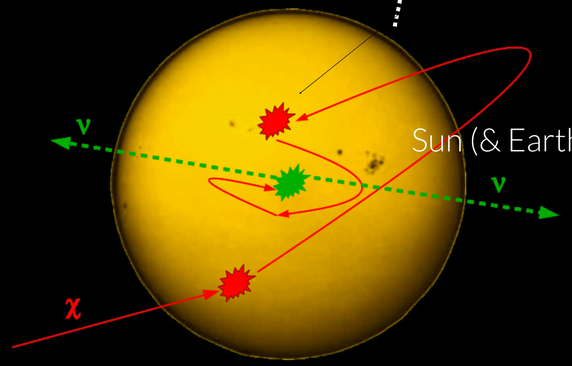
Dwarf spheroidal galaxies

Galactic Center

Galactic Halo

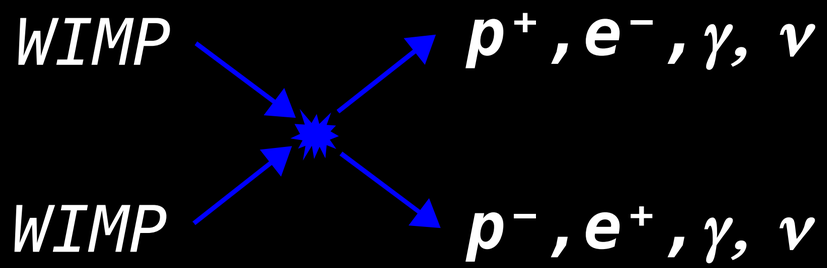


accumulate due to WIMP-proton elastic scattering



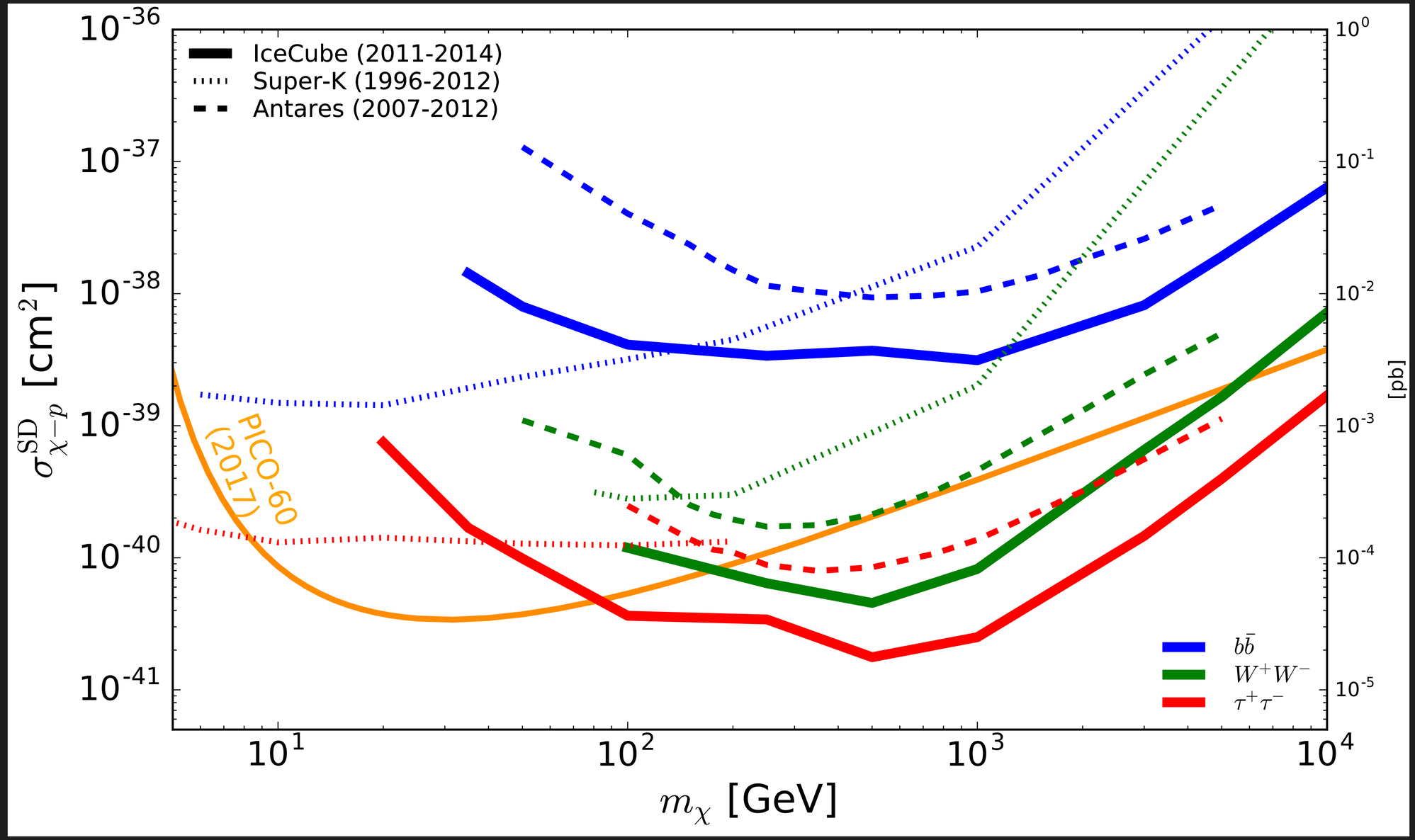
Sun (& Earth)

MSSM - neutralino



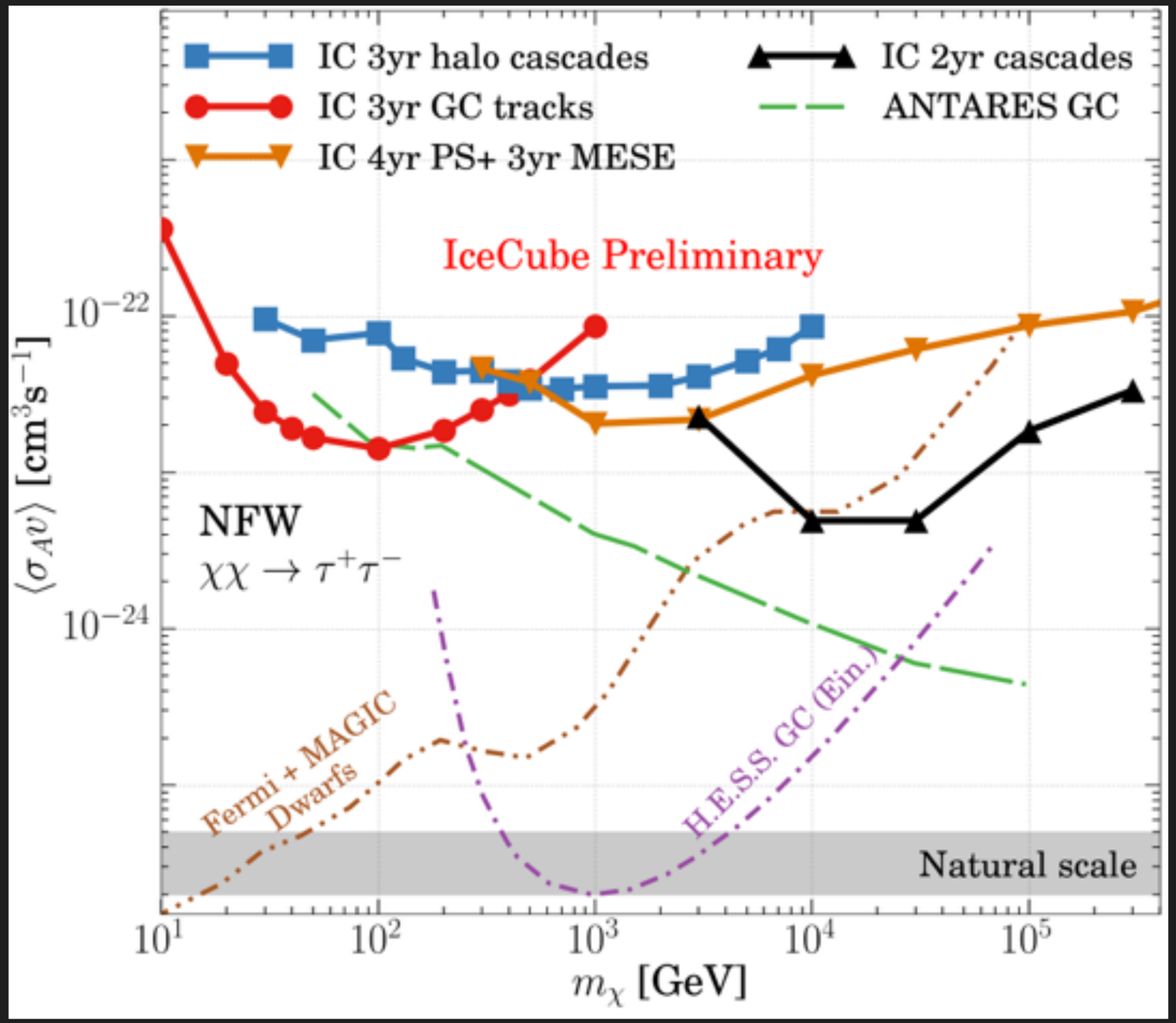
SOLAR WIMP RESULTS - ICECUBE AND ANTARES

(from M. Medici's talk)



GALACTIC - ICECUBE AND ANTARES

(from M. Medici's talk)



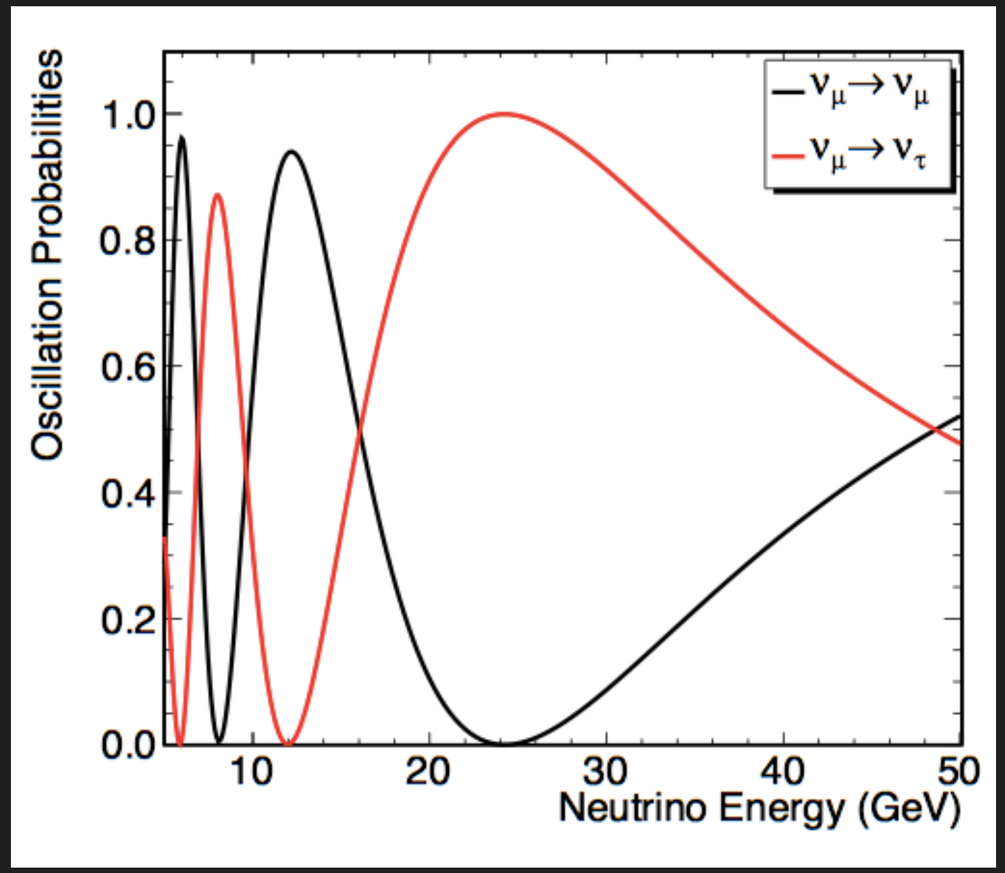
NEUTRINO OSCILLATIONS

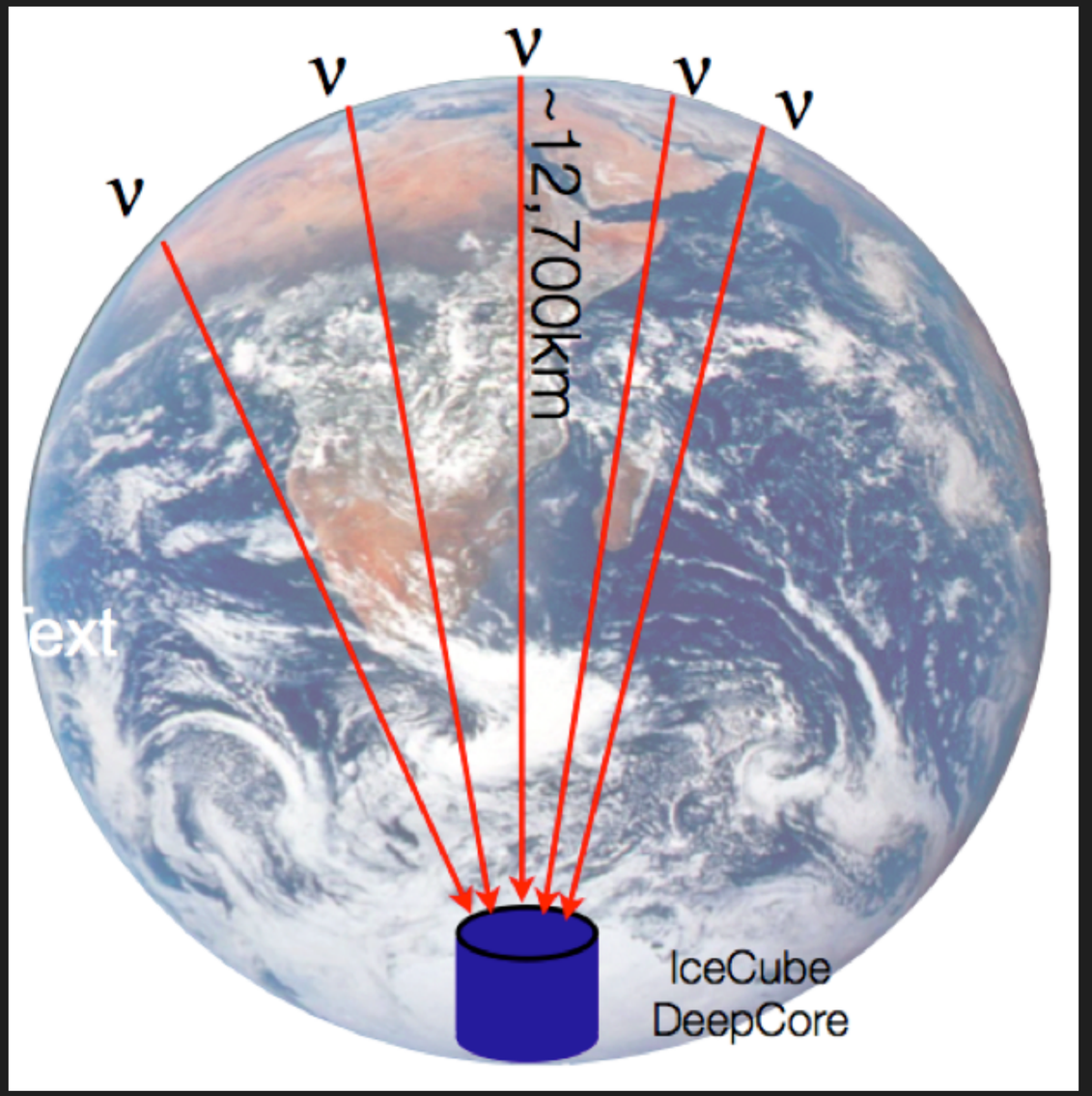
Using the atmospheric neutrino
“background” to study neutrino physics

NEUTRINO OSCILLATIONS WITH ATMOSPHERIC NEUTRINOS

neutrino oscillations through Earth's diameter are accessible by IceCube/DeepCore

First oscillation maximum at 24 GeV, accessible with DeepCore





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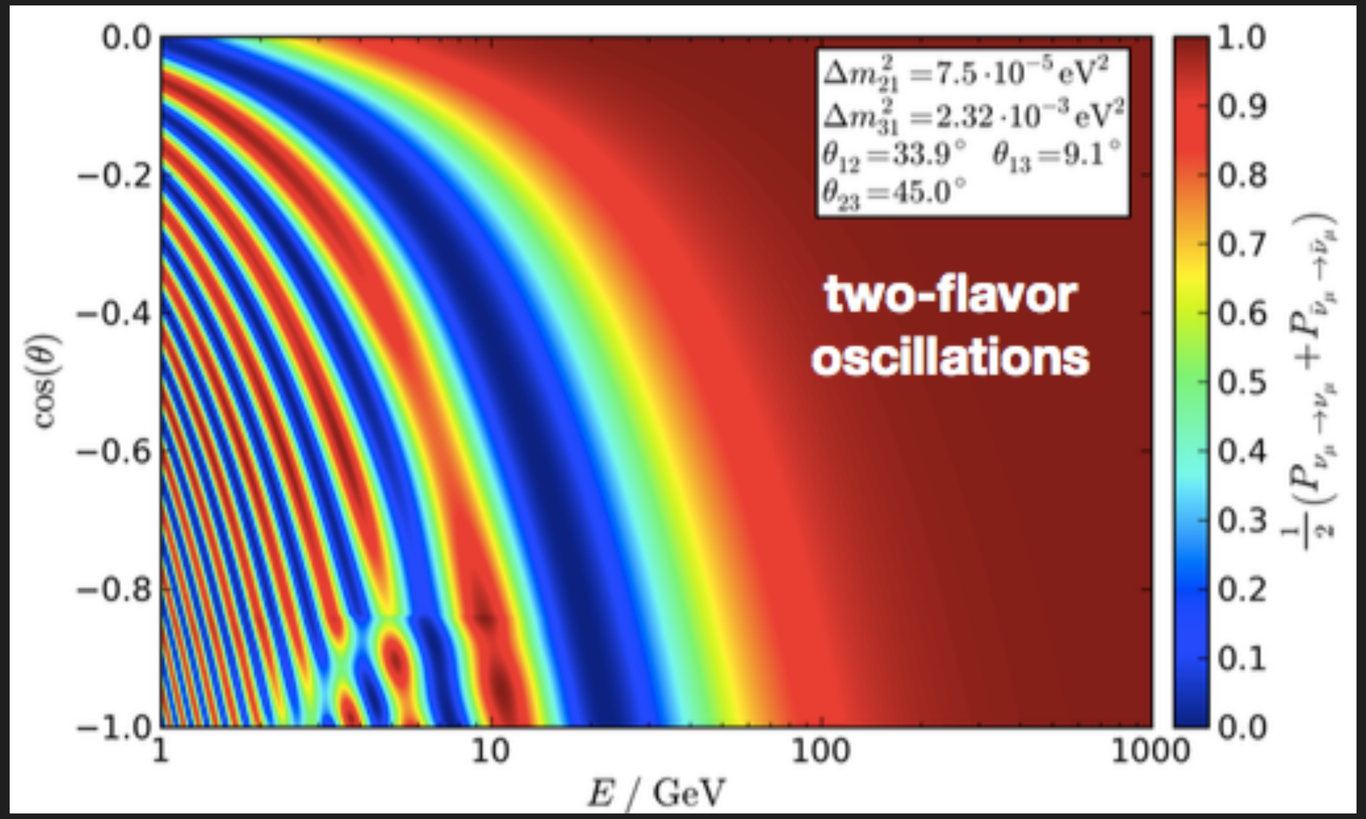
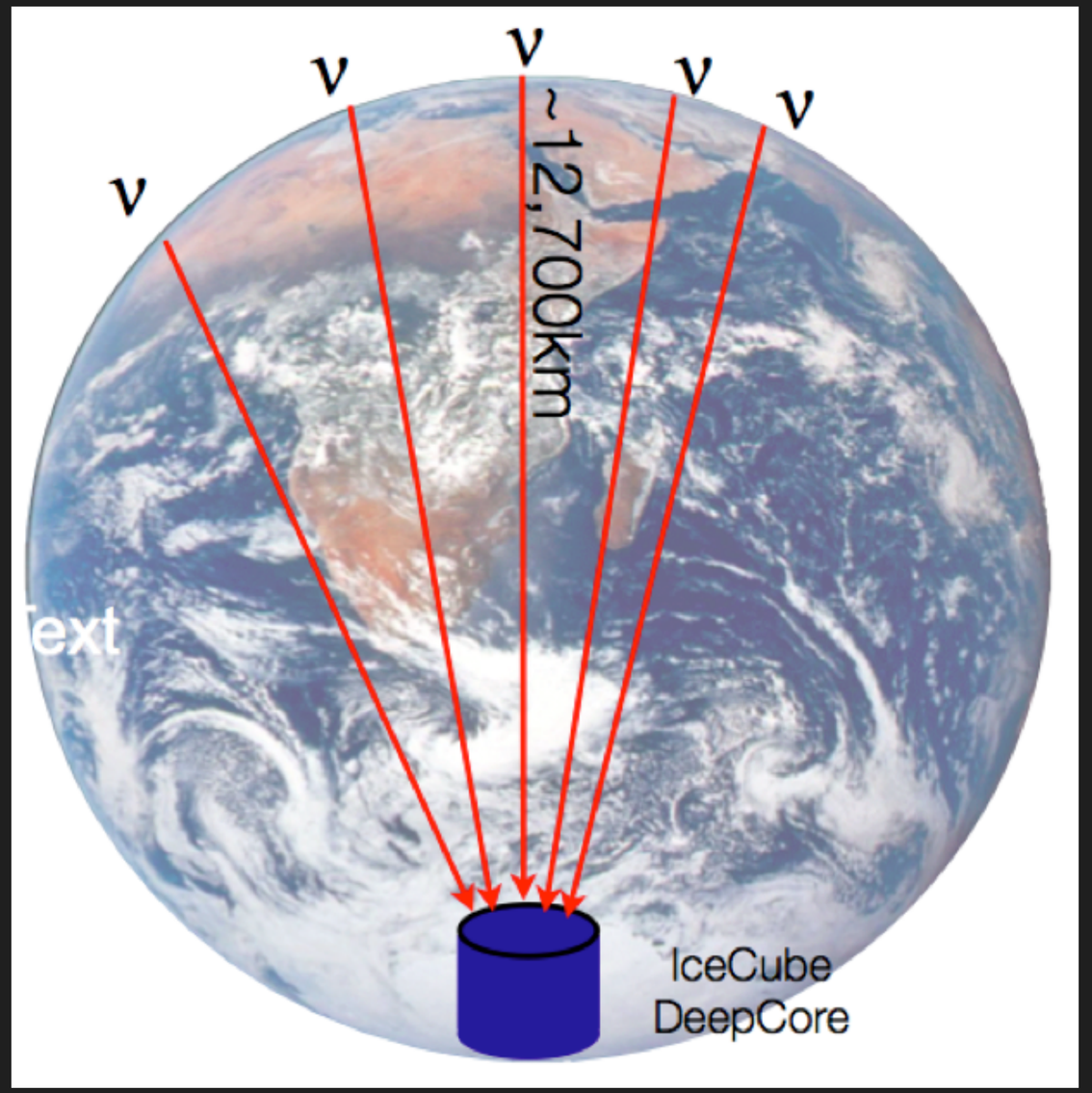
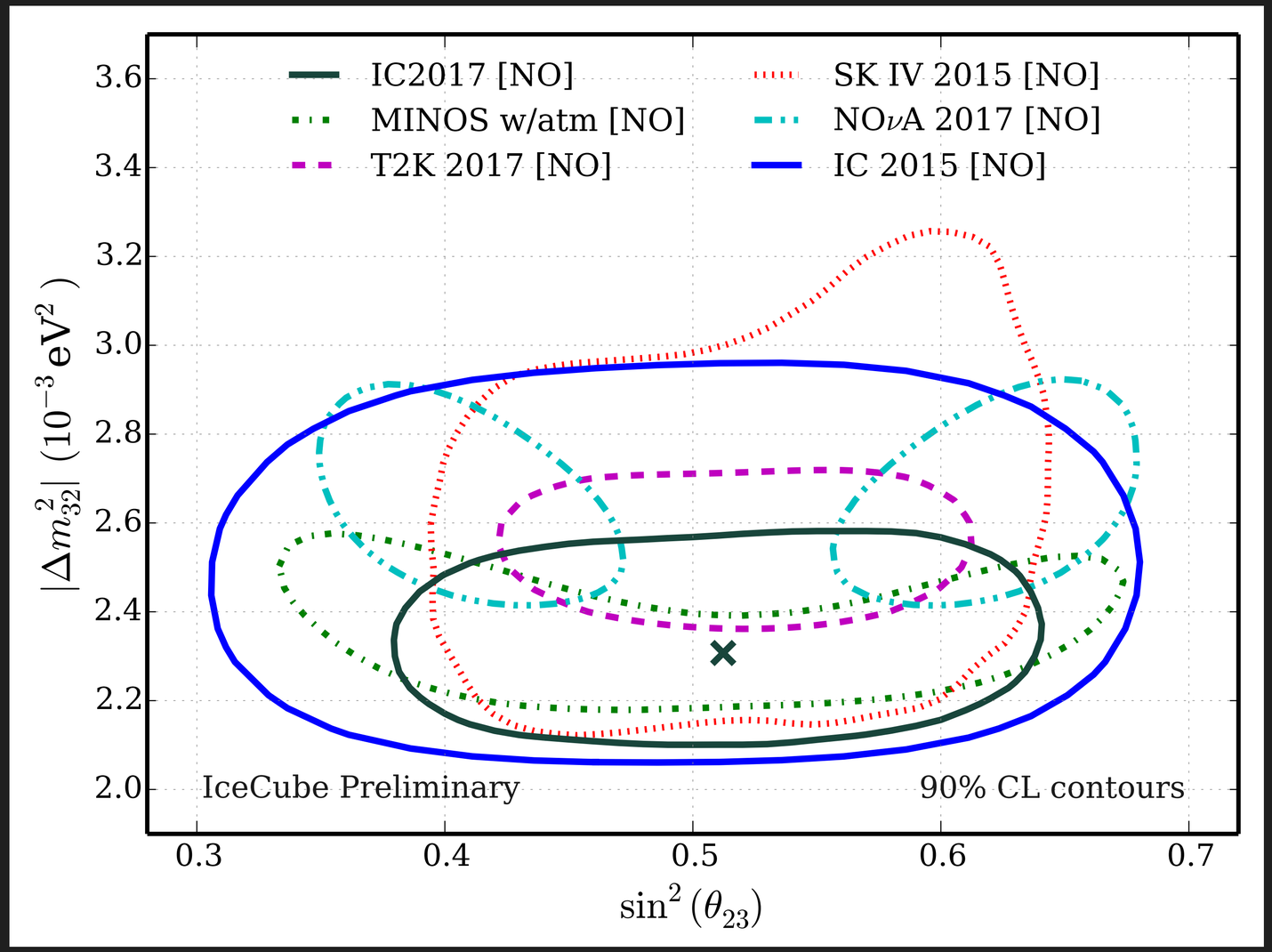
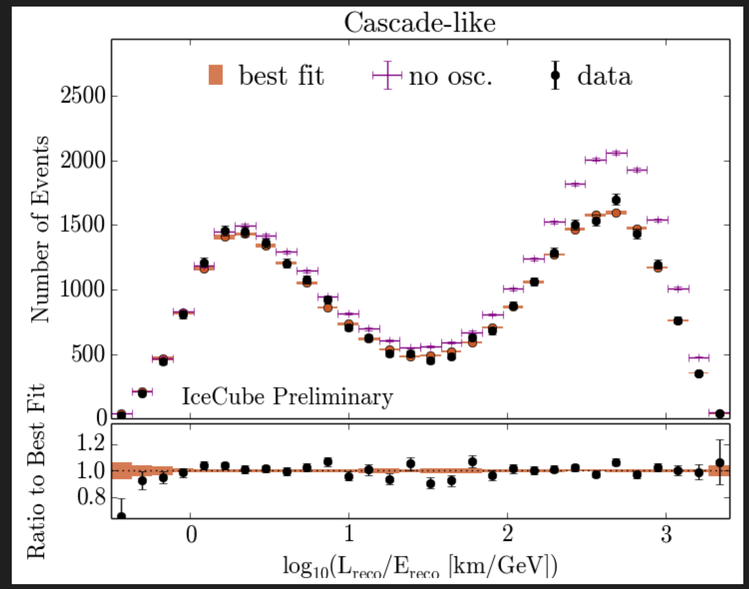


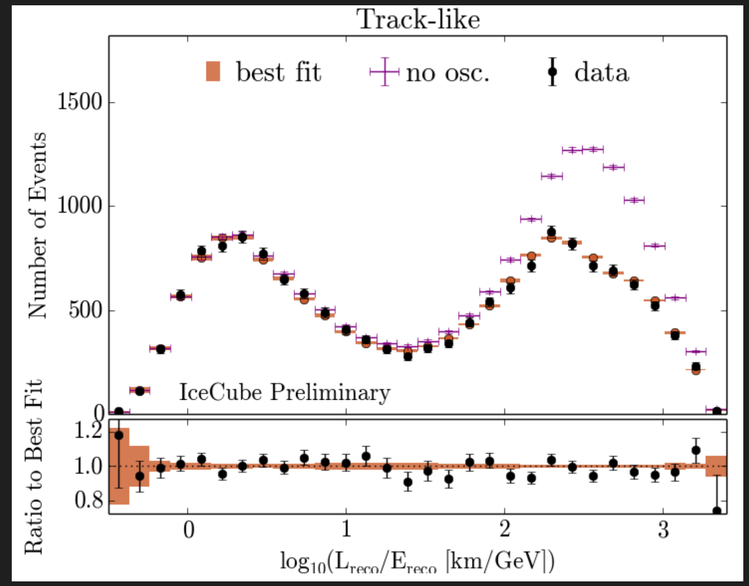


3-YEAR MUON DISAPPEARANCE STUDY

3 years of data (2011-2014, 953 days) - competitive with other experiments







arXiv:1707.07081

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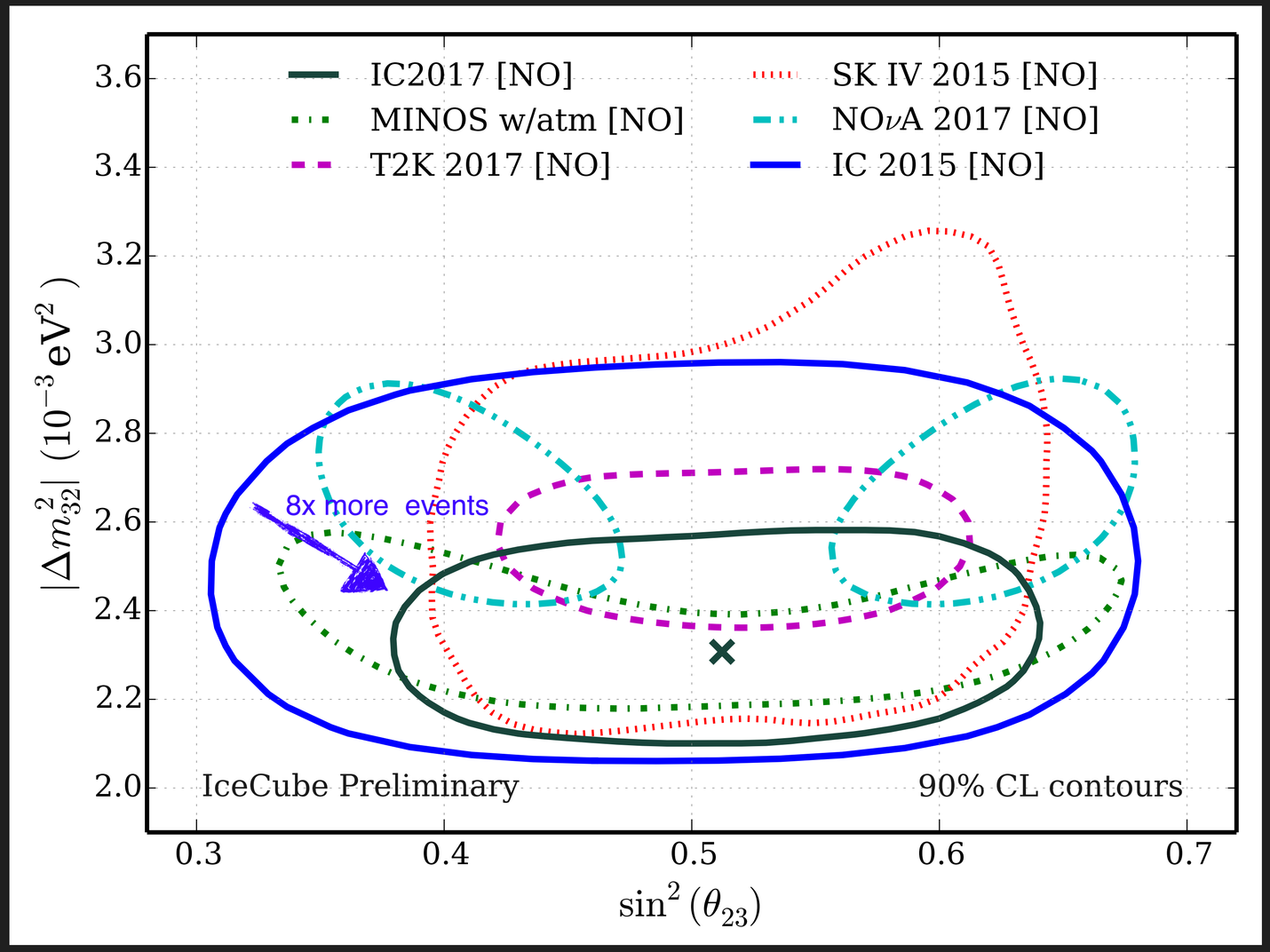
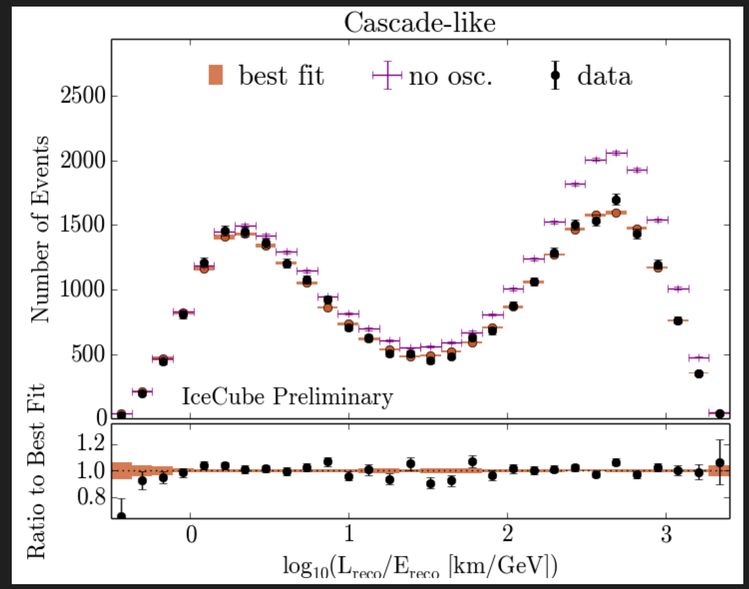
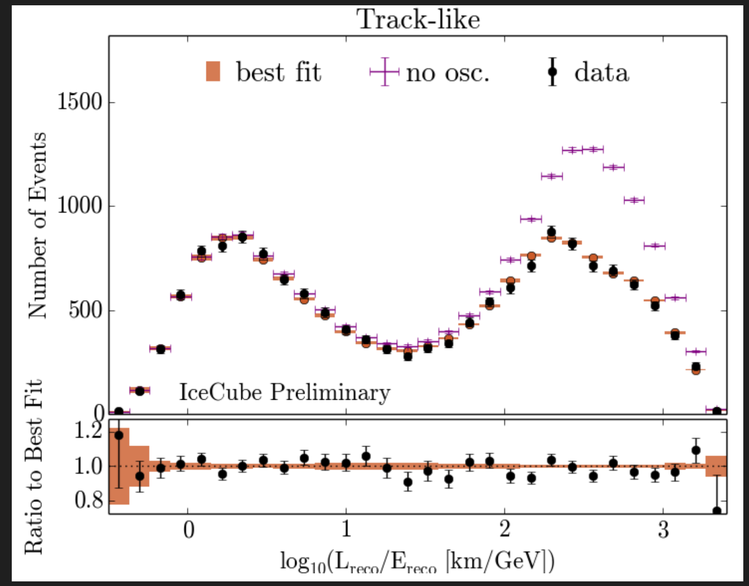






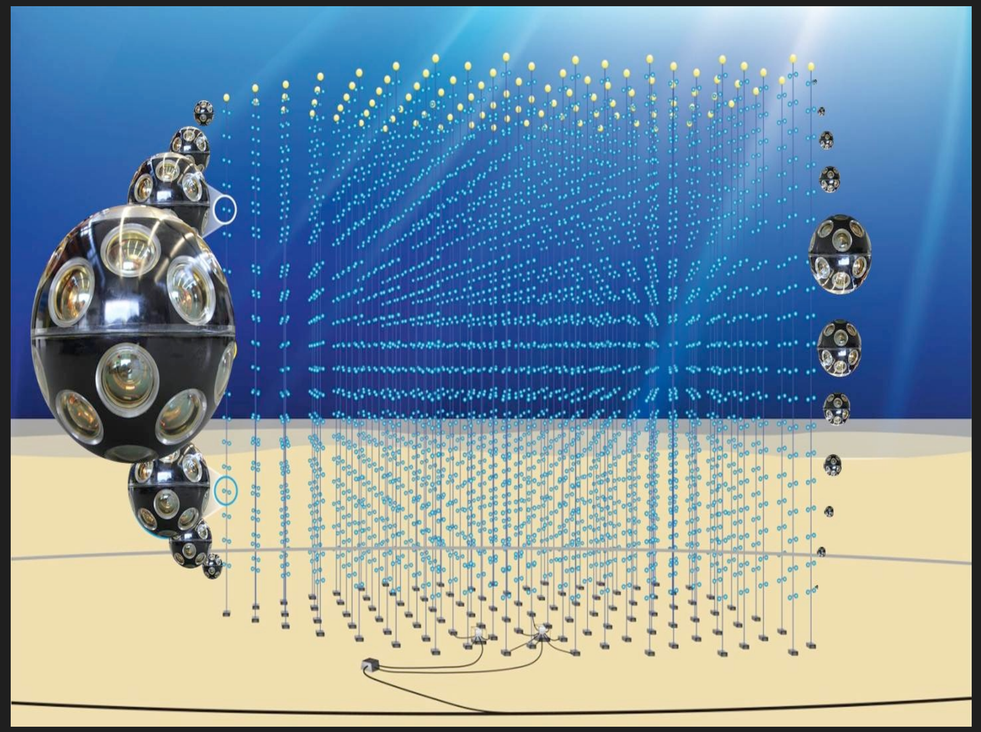
arXiv:1707.07081

THE FUTURE

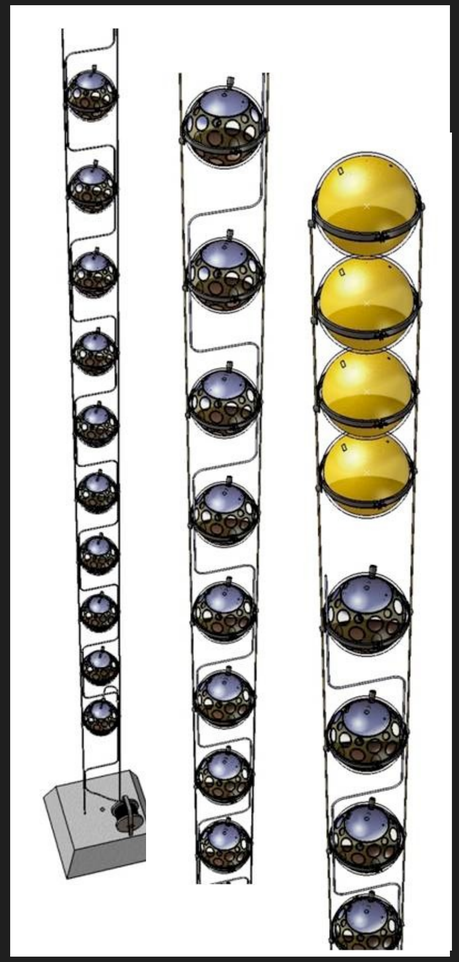
Extending the sensitivity to higher energies, new hemispheres

THE KM3NET NEUTRINO TELESCOPE

Multi-site installation in the Mediterranean Sea (France, Italy), instrumented in "building blocks", started construction



KM3NeT "building block"



string with OMs

Multi-PMT digital optical module ("DOM")

THE KM3NET NEUTRINO TELESCOPE

Multi-site installation in the Mediterranean Sea (France, Italy), instrumented in "building blocks", started construction

31 x 3" PMTs
Hamamatsu, ETL, HZC

Light collection ring
20–40% gain in PC for free

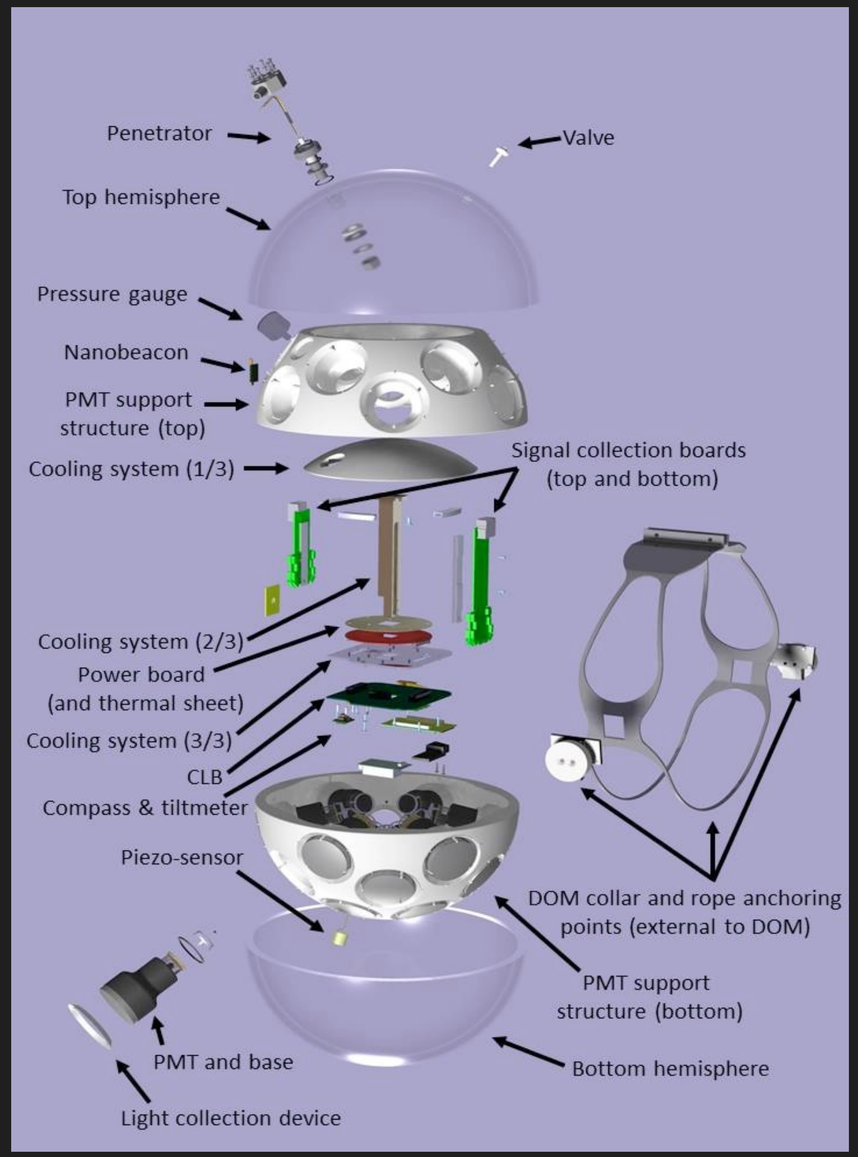
Low power
< 10 W / DOM

FPGA readout
sub-ns time stamping
time over threshold

Calibration
LED & acoustic piezo

Optical fibre data transmission
DWDM with 80 wavelengths
Gb/s readout

multiPMT optical module



KM3NET: ARCA AND ORCA

two different building blocks

ARCA: "Astrophysical Research with Cosmic in the Abyss"

Study astrophysical neutrino fluxes at **E > 100 GeV**

2 "blocks" at the **Italian** site (2 strings deployed)

ORCA: "Oscillations Research with Cosmics in the Abyss"

Resolve the neutrino mass hierarchy (**1 GeV < E < 100 GeV**)

1 "block" at the **French** site (2 strings ready to be deployed)

KM3NET CONSTRUCTION

first two strings have been deployed!

KM3NET CONSTRUCTION

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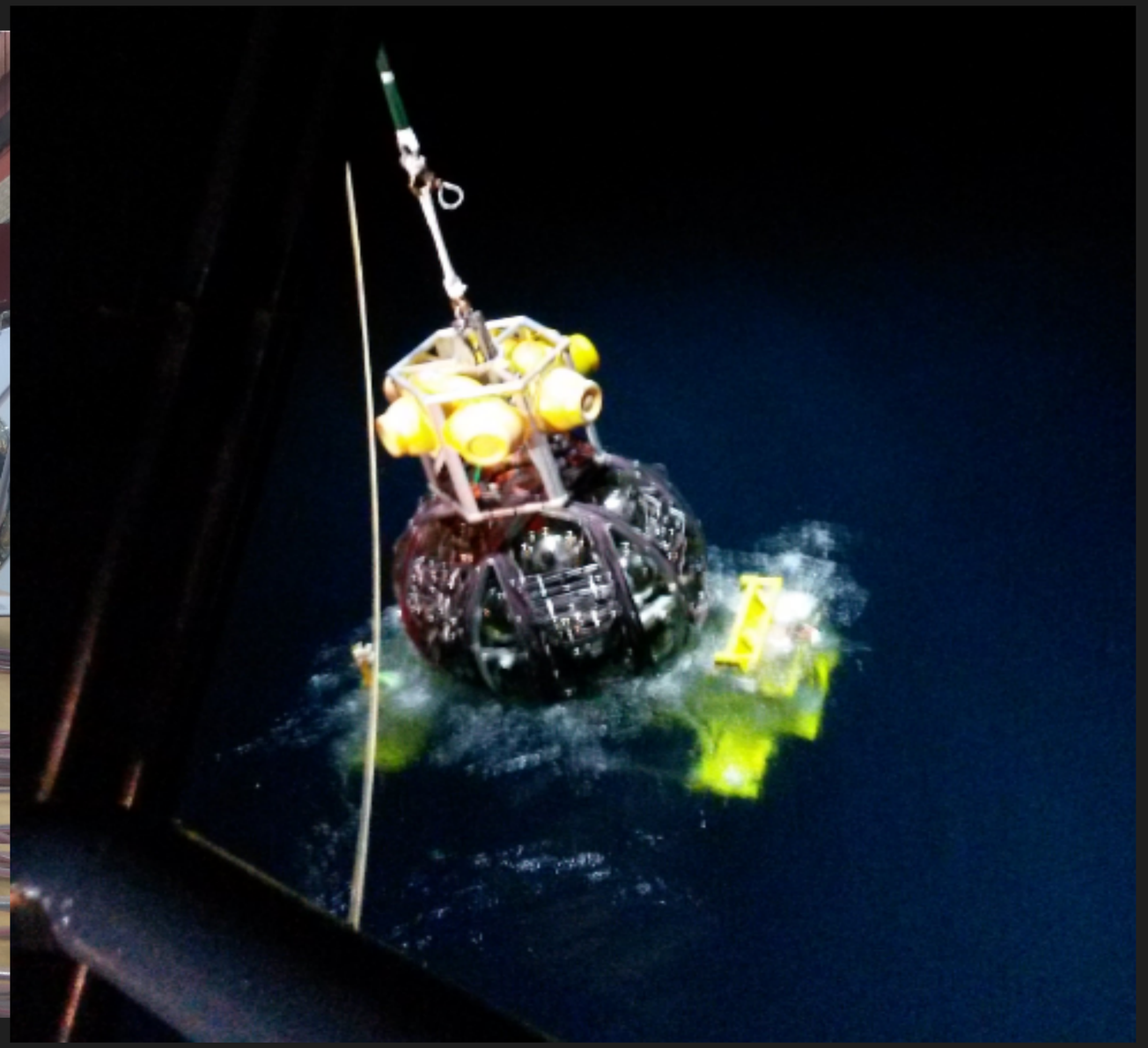

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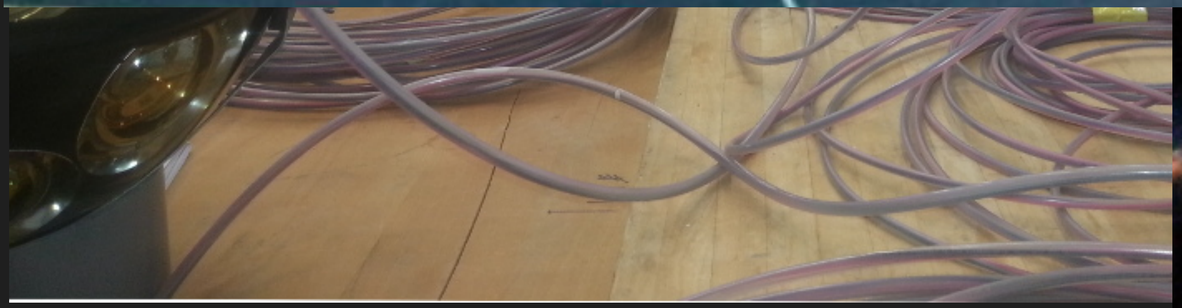
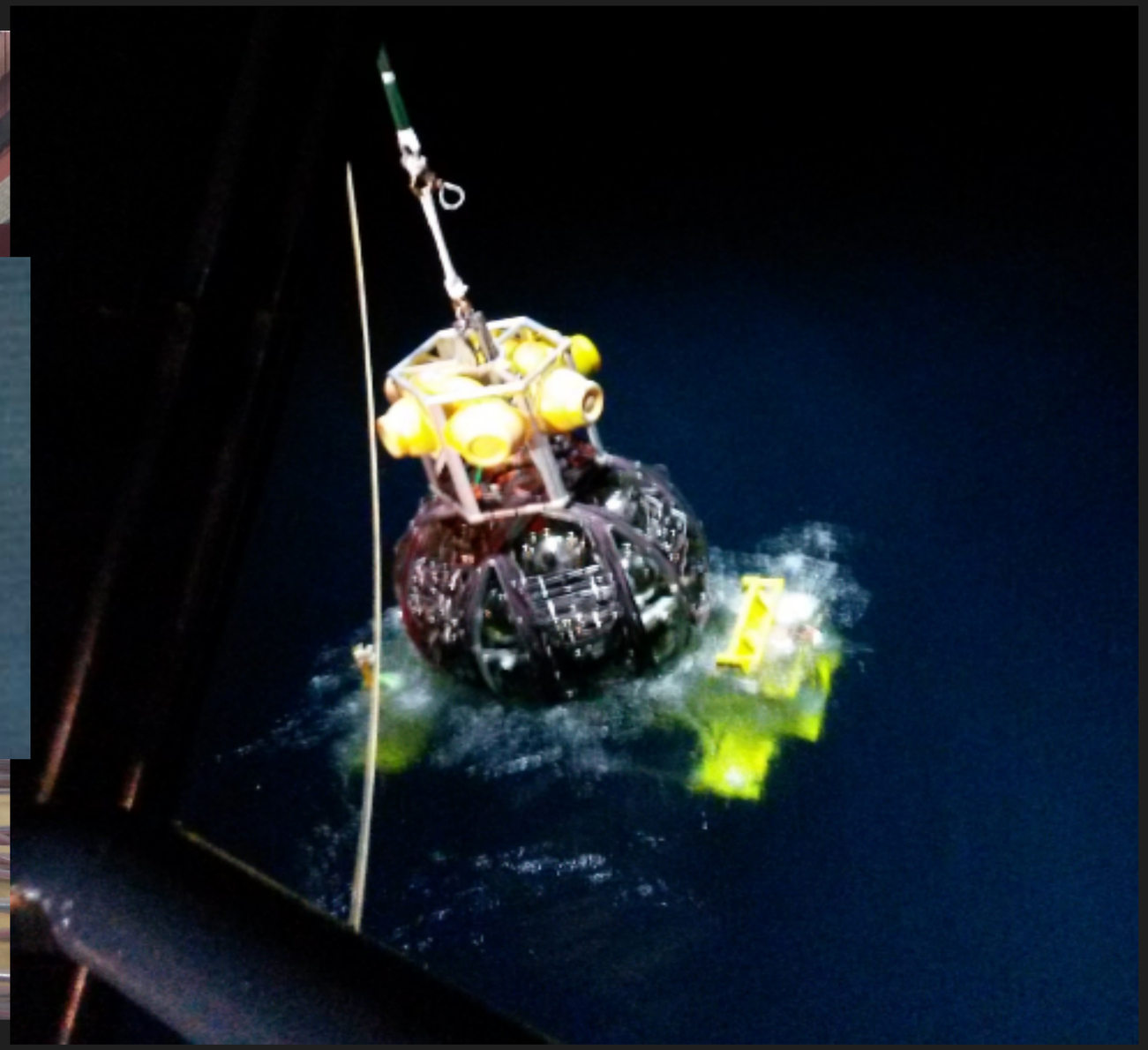


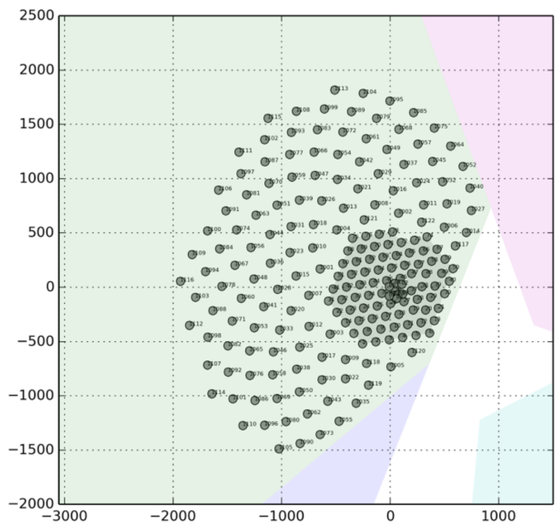


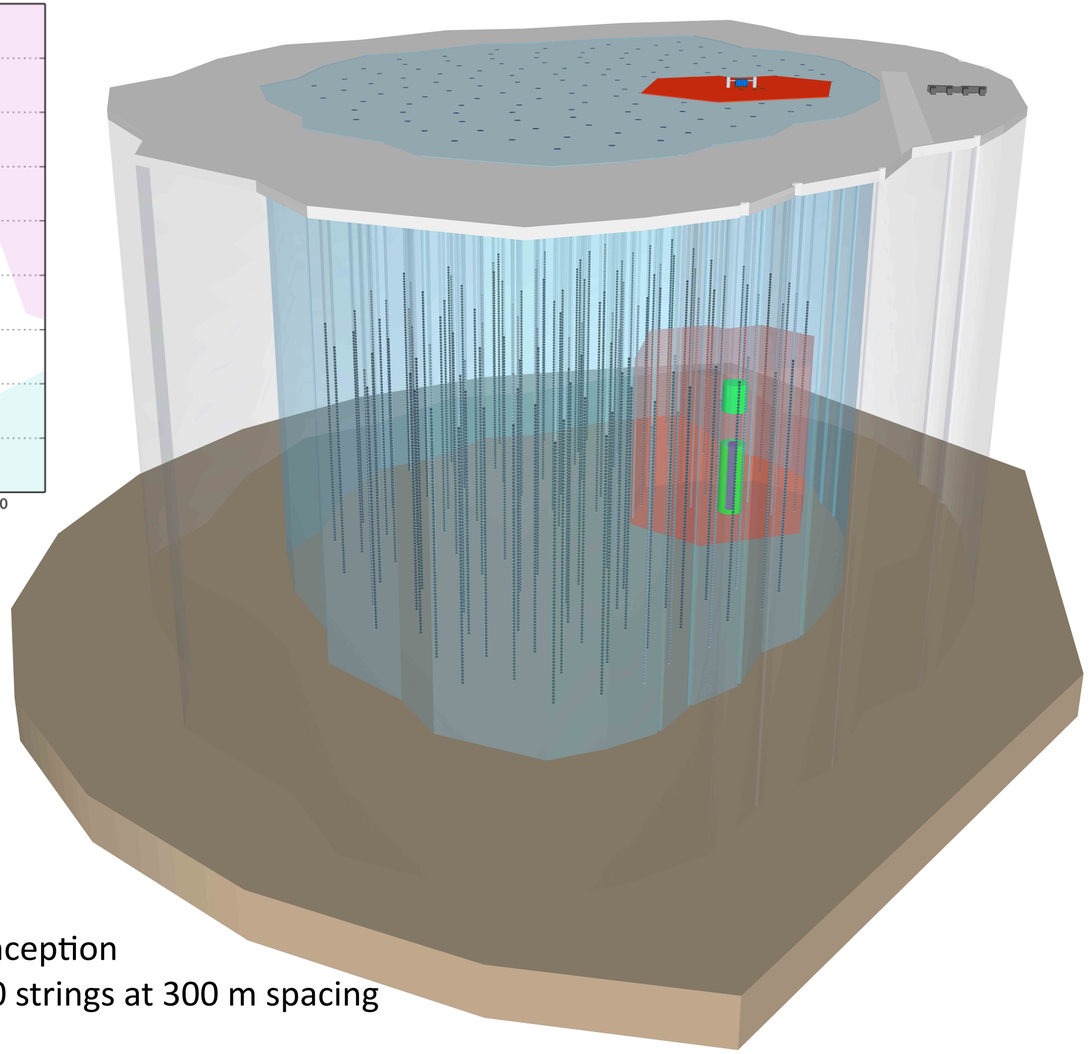
ICECUBE-GEN2: HIGH-ENERGY

IceCube has provided an amazing sample of events, but is still limited by the small number of events

few 10's of astrophysical neutrinos per year

The IceCube-Gen2 High-Energy Array will instrument a significantly larger volume (~10km^3)





Artist conception
Here: 120 strings at 300 m spacing

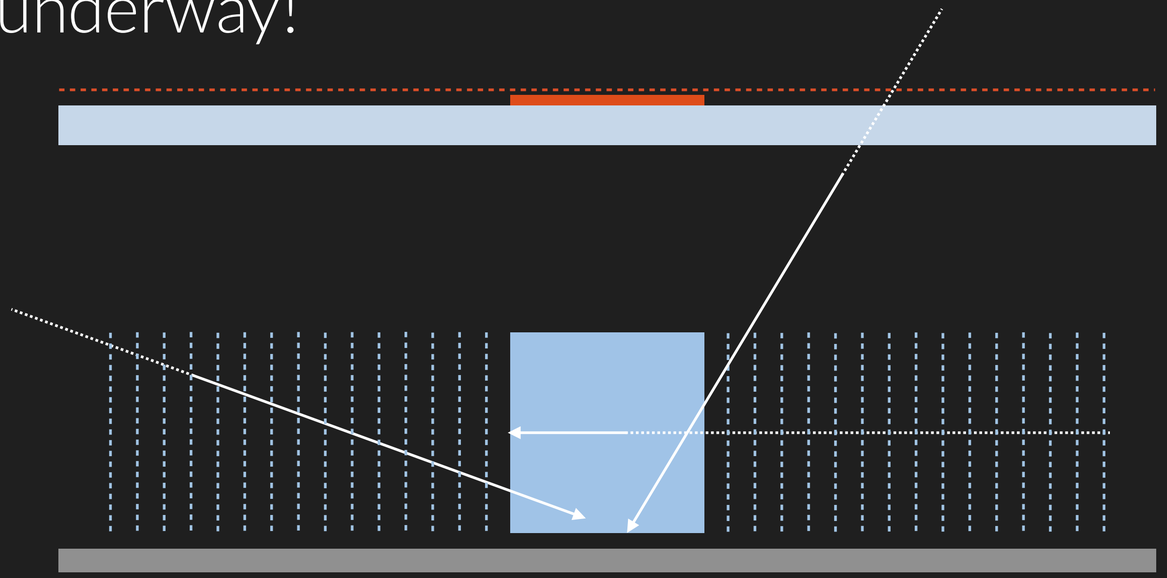
ICECUBE-GEN2: SURFACE VETO

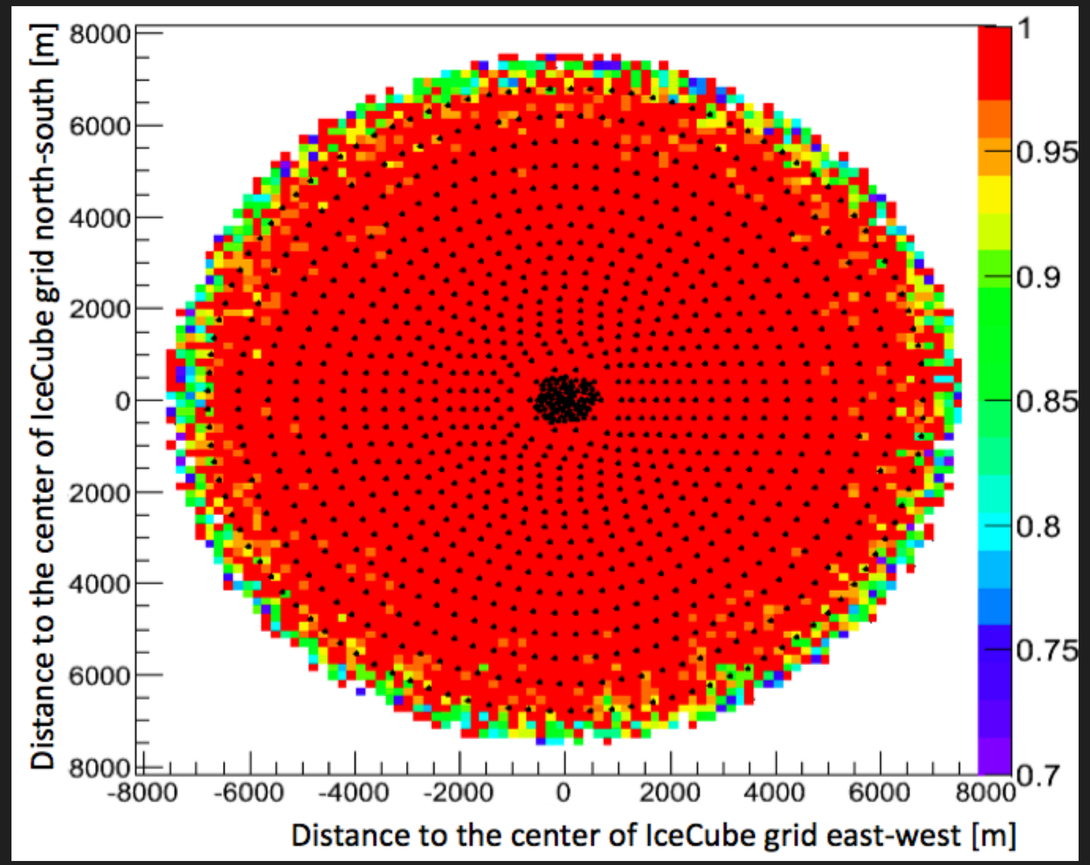
R&D for a surface array

similar to the current “IceTop” surface array (or alternative technology) - CR physics and veto neutrinos from CR air showers at the ice surface

increase volume for starting tracks

R&D is underway!





ICECUBE-GEN2: PINGU

measuring the mass hierarchy using atmospheric neutrinos

cover energies down to a **few GeV**

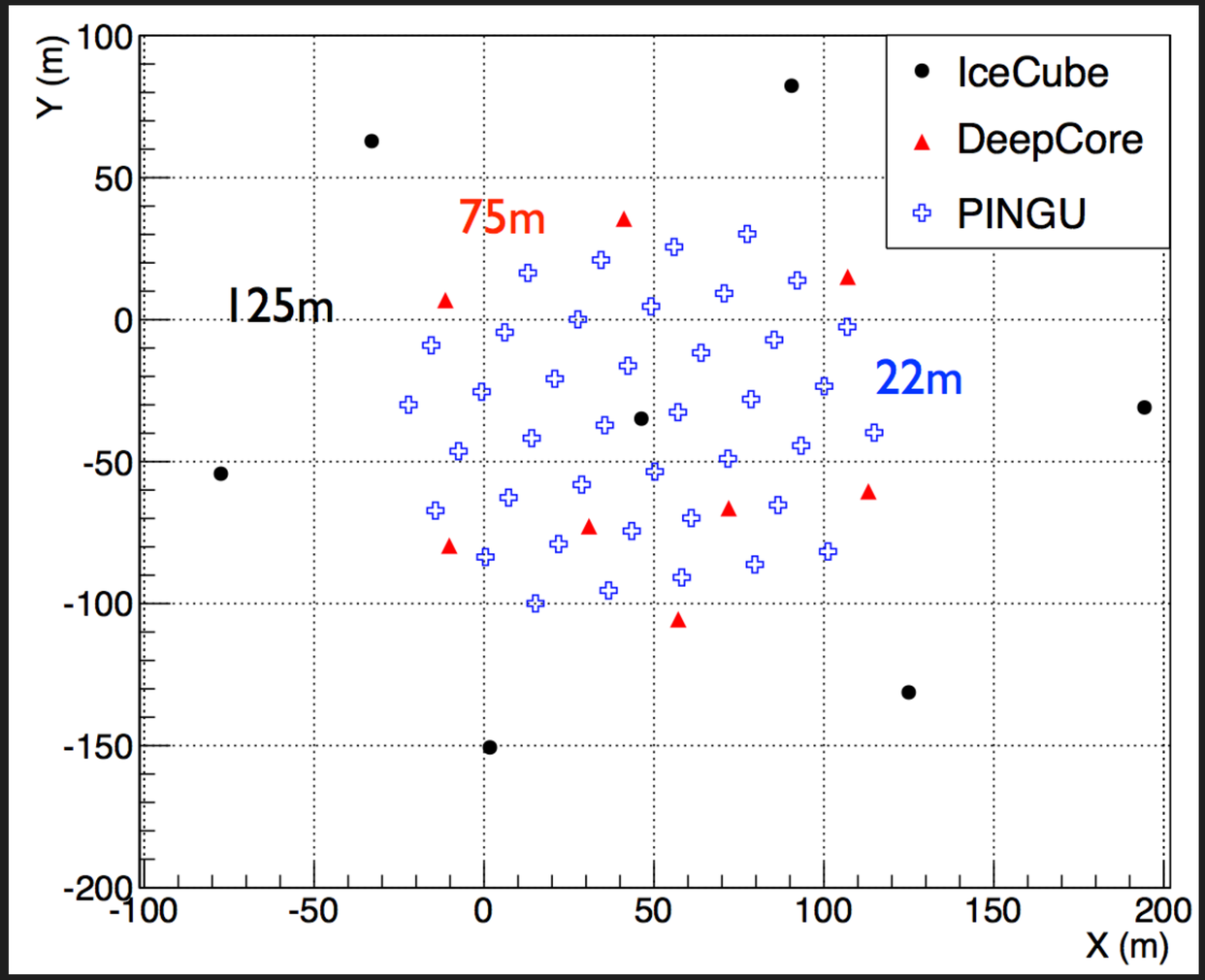
add **40** strings to IceCube/DeepCore

22m string spacing

2m DOM spacing

use the difference in MSW effect for ν and anti-ν

combine with difference in ν and anti-ν cross-section



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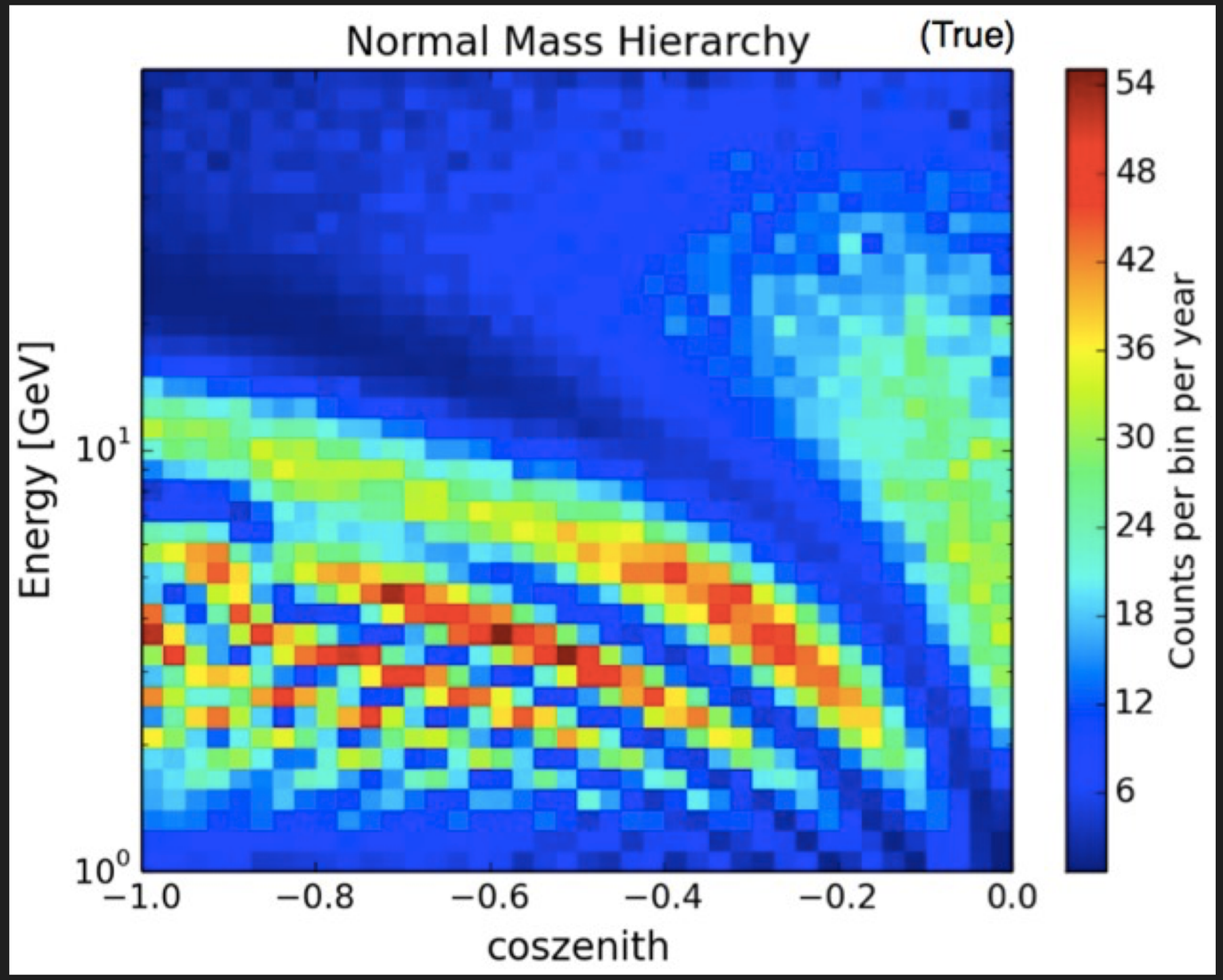

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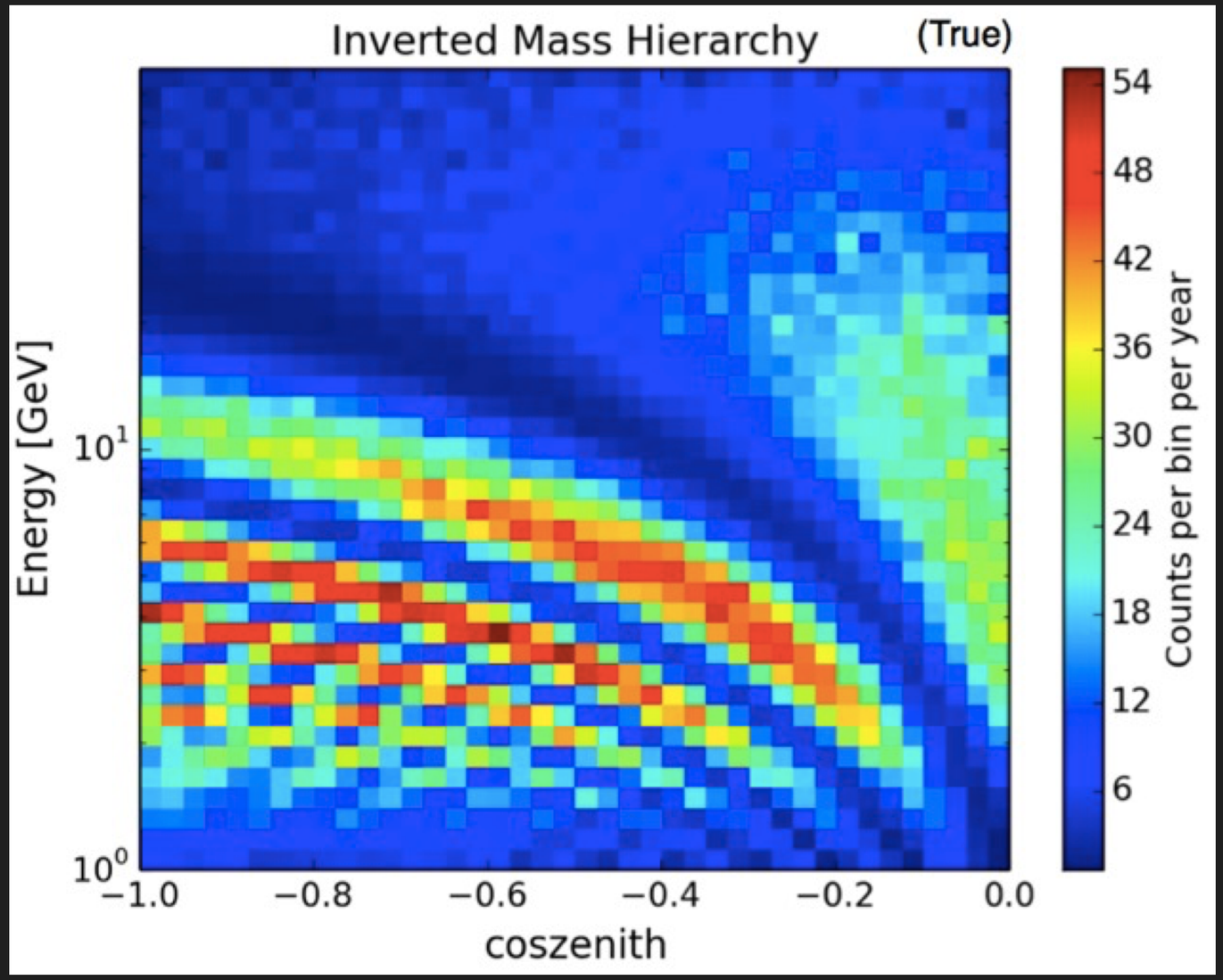

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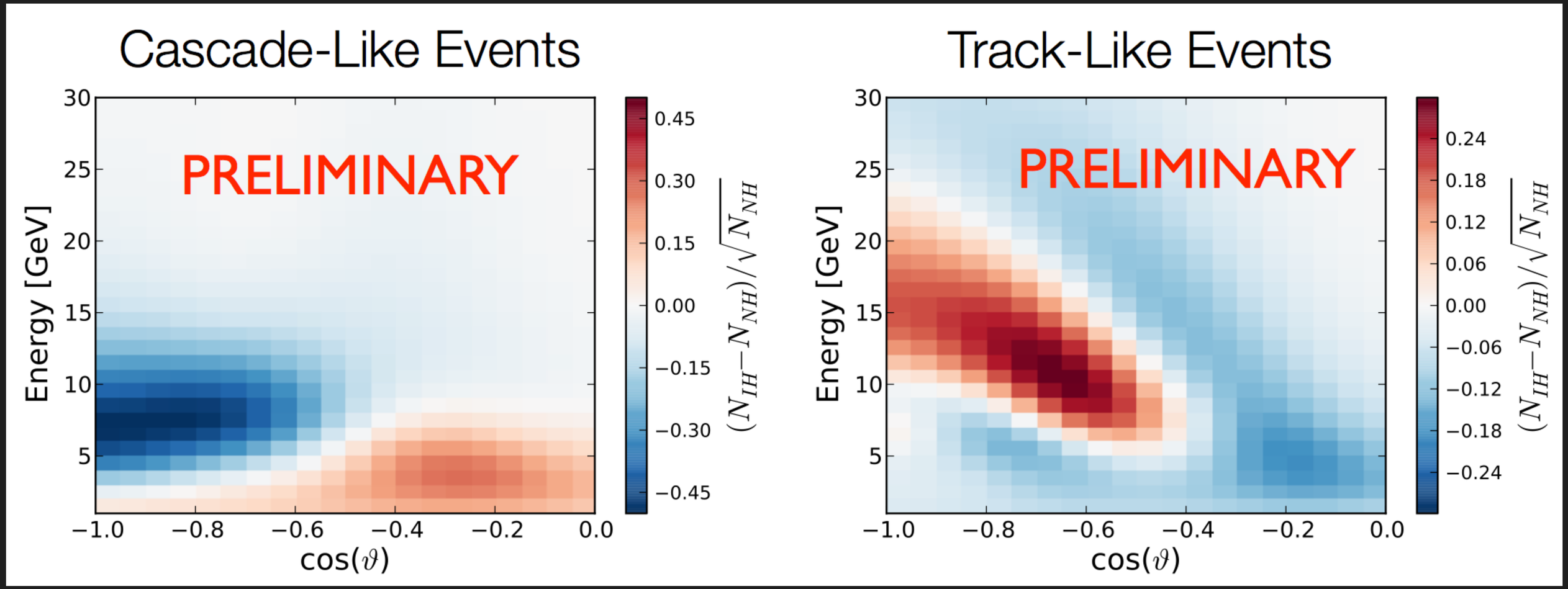


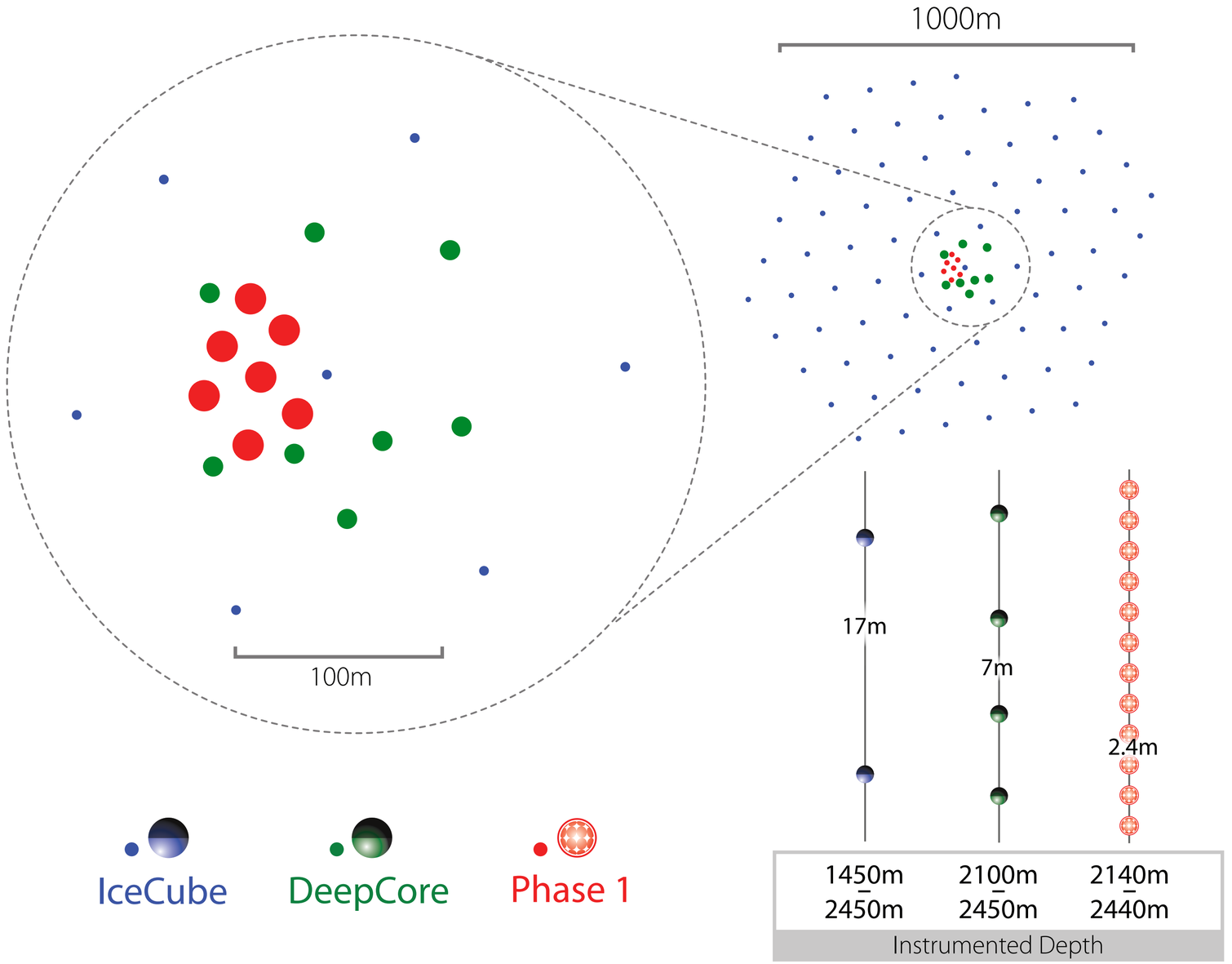
ICECUBE-GEN2: PHASE 1

Science goals:

ν_μ disappearance

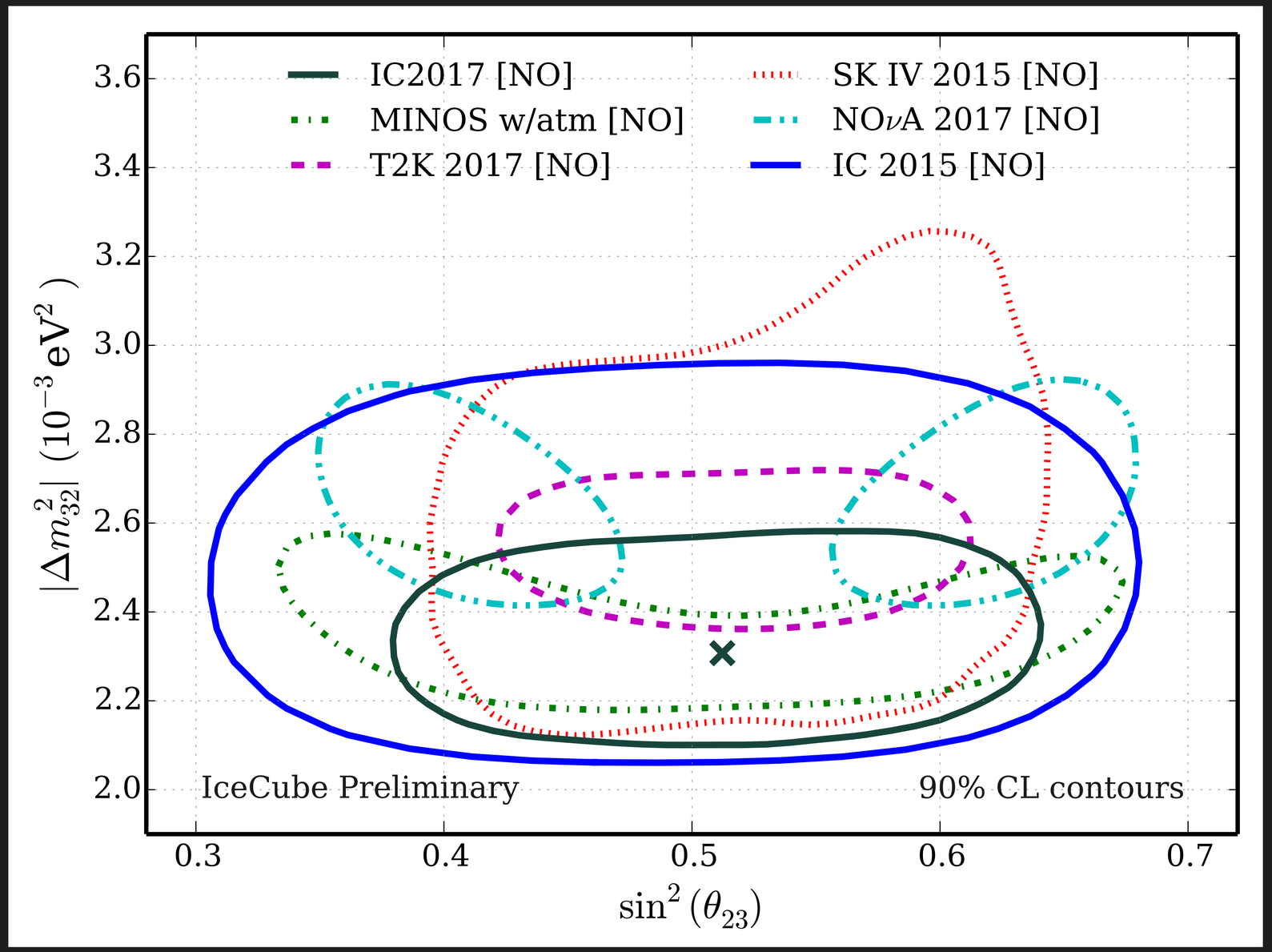
ν_τ appearance

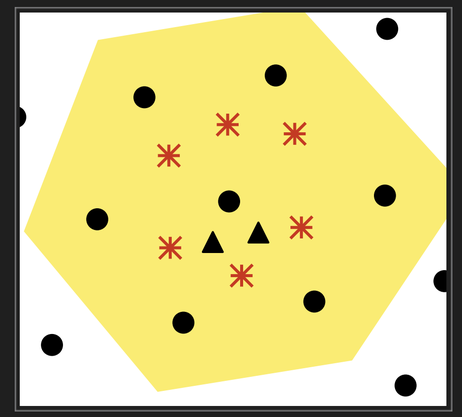
precise calibration of IceCube **optical properties** and **DOM response**



ICECUBE-GEN2: PHASE 1

precision muon neutrino disappearance



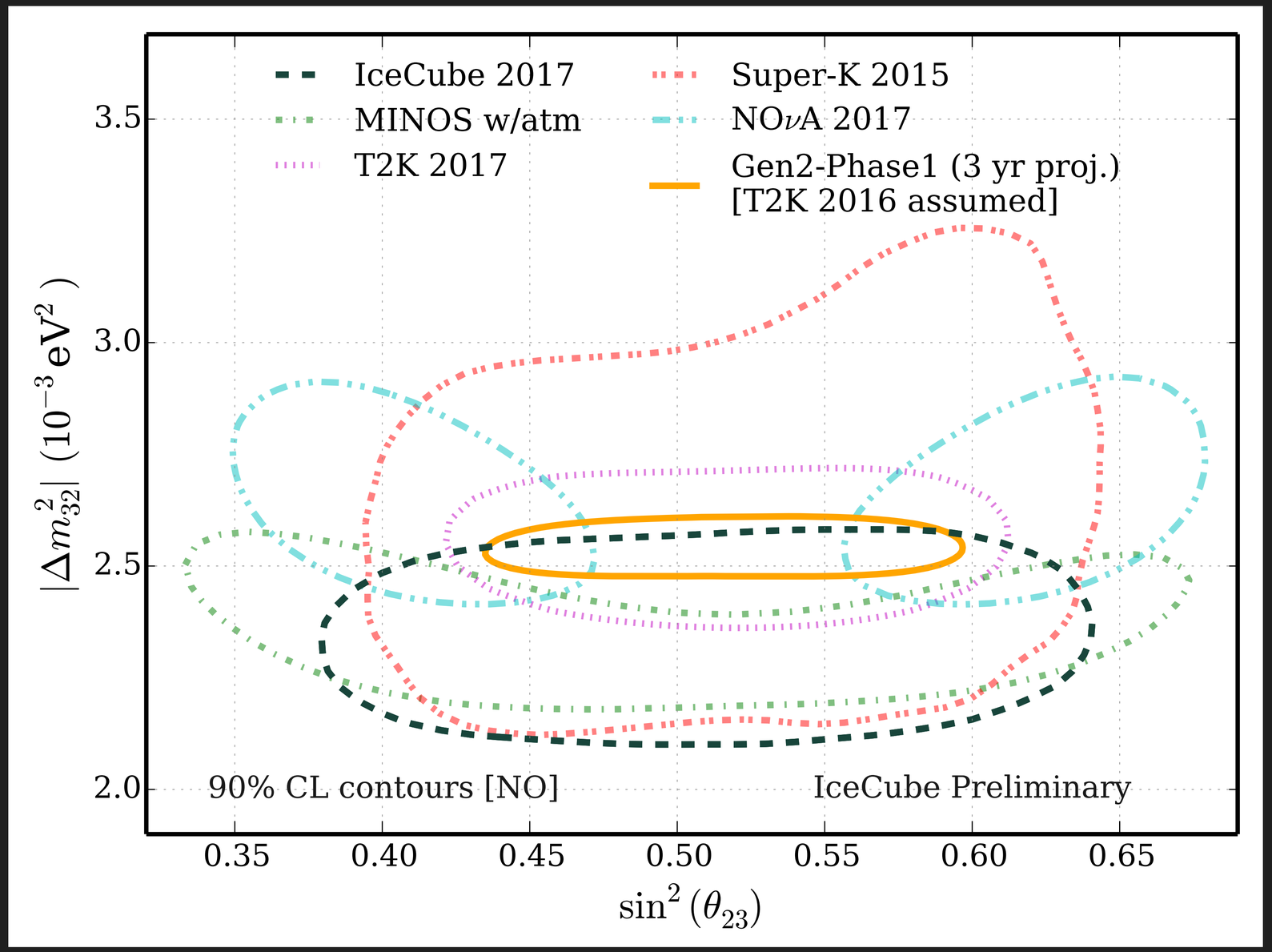


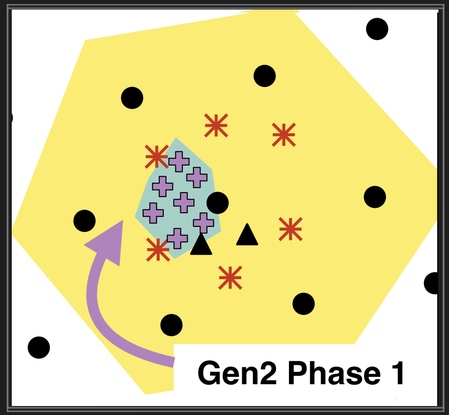
IceCube DeepCore: 3 years

Precision significantly improved over DeepCore

ICECUBE-GEN2: PHASE 1

precision muon neutrino disappearance



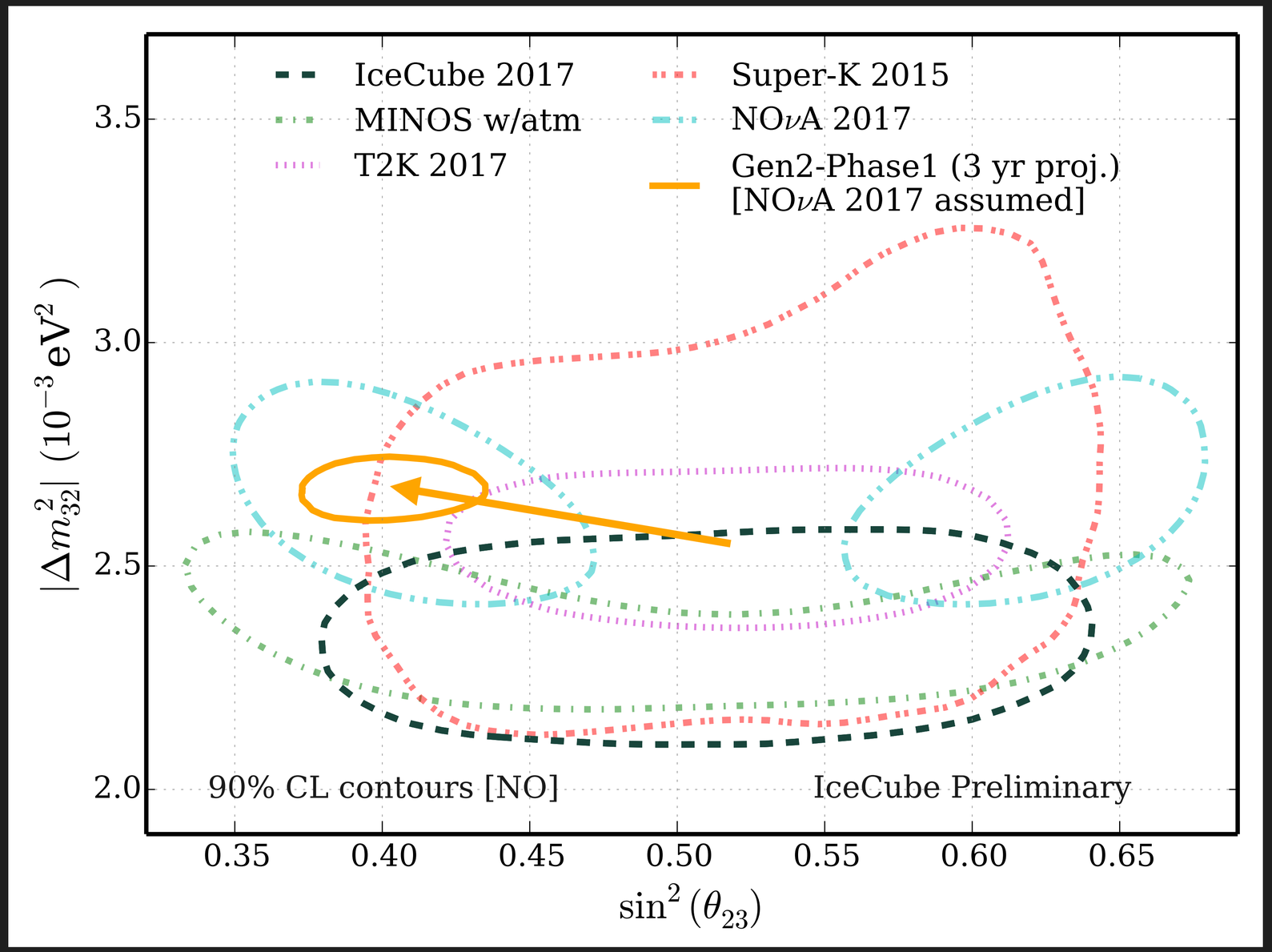


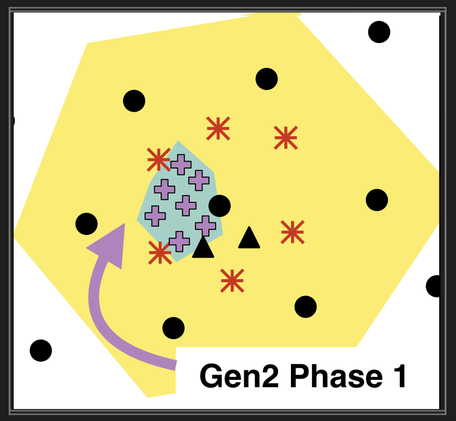
Gen2 Phase 3 years

Precision significantly improved over DeepCore

ICECUBE-GEN2: PHASE 1

precision muon neutrino disappearance



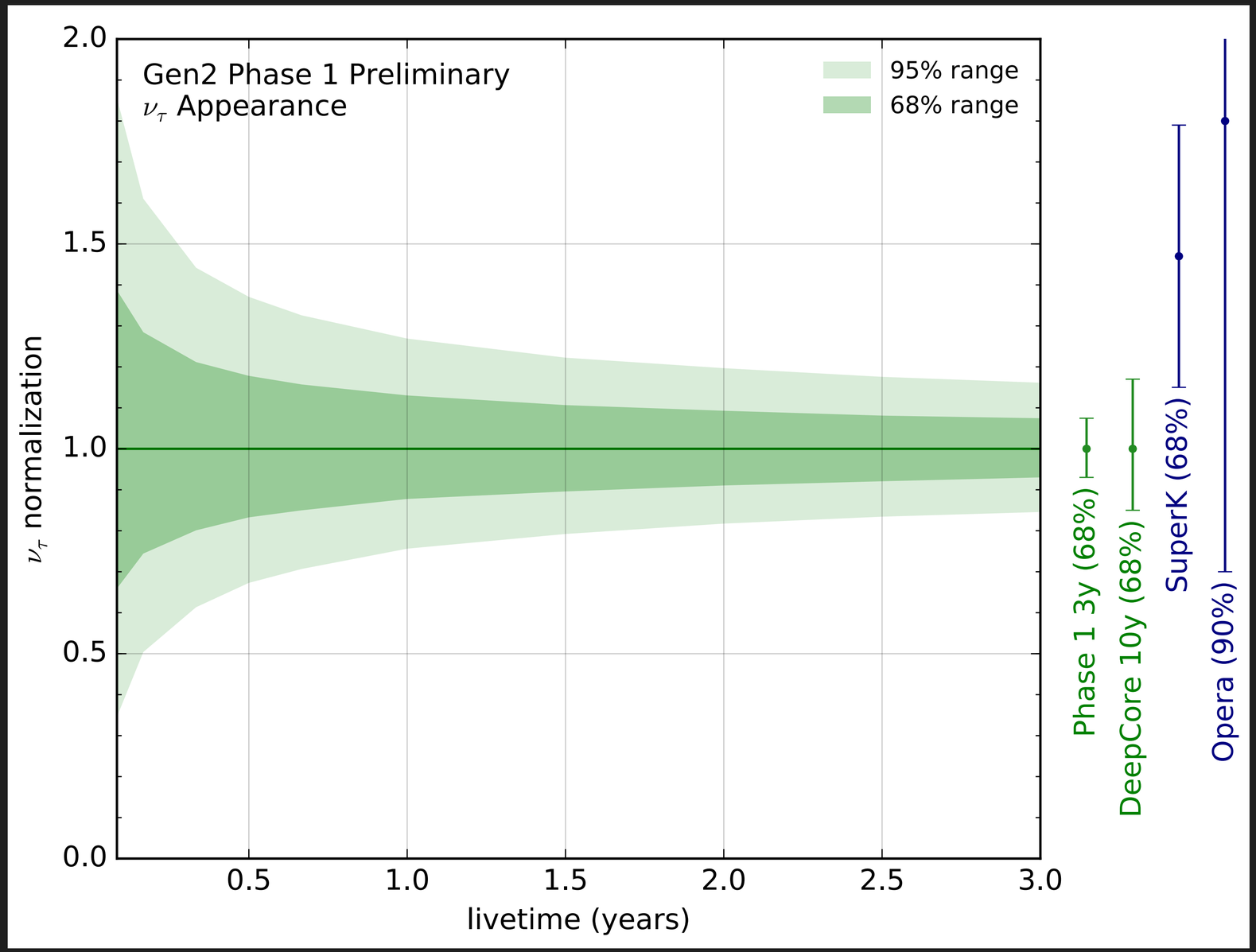


Gen2 Phase 3 years

Precision significantly improved over DeepCore

ICECUBE-GEN2: PHASE 1

tau neutrino appearance



Phase 1 can provide best measurement of ν_τ appearance to date

ICECUBE-GEN2: PHASE 1

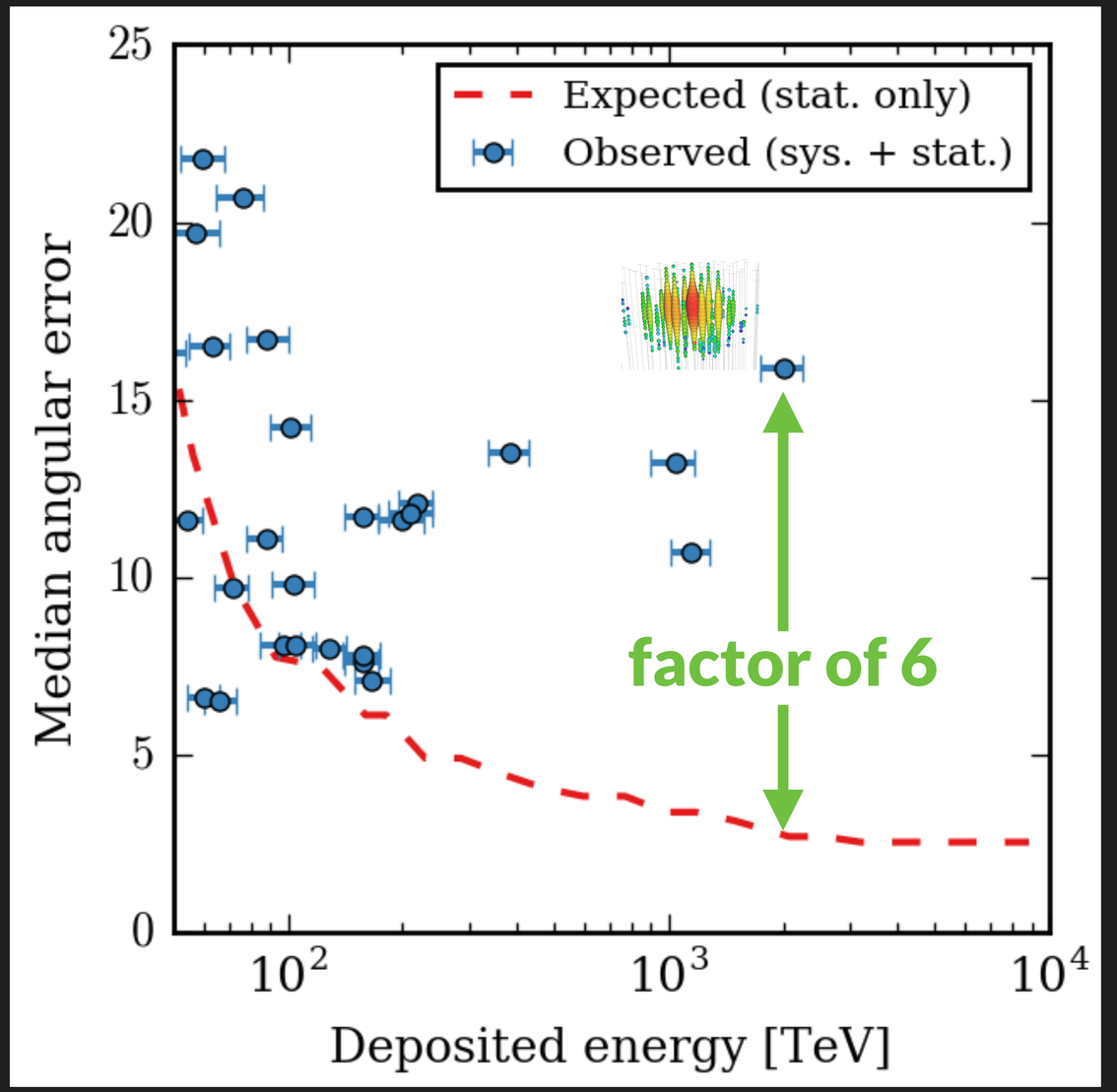
enhancing IceCube high-energy science through better calibration

New **calibration devices** inside IceCube enhance HE science

reconstructions, tau flavor identification

New calibration boosts the entire IceCube data set (> 10 yrs)

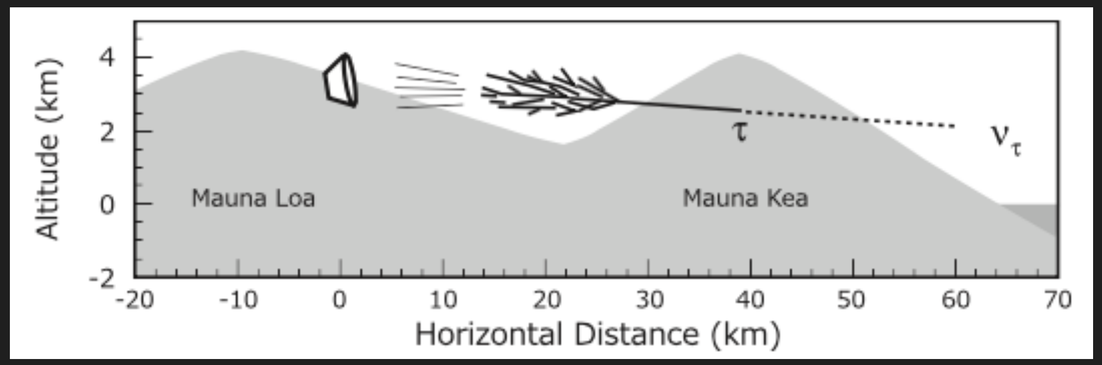
POCAM being deployed at Lake Baikal



angular reco. systematics limited

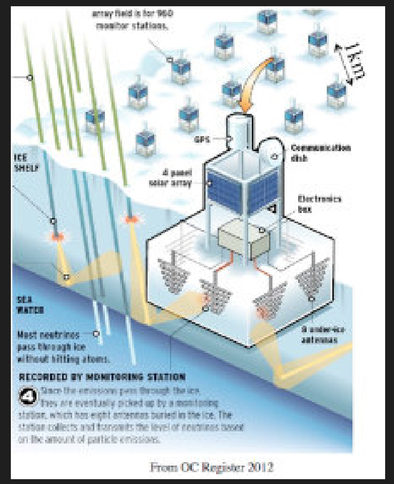
MORE DETECTORS / METHODS

non-water detectors | radio detectors

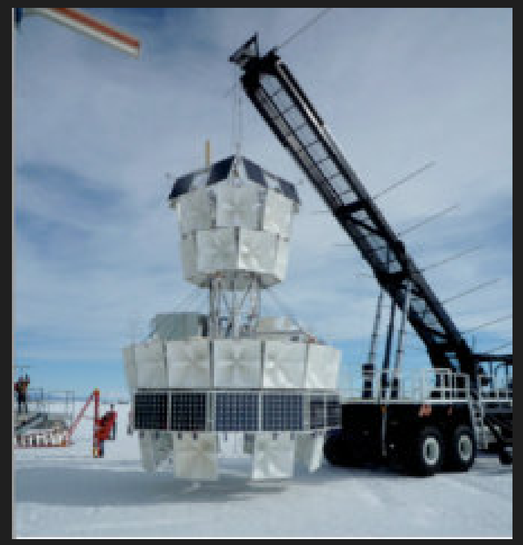


earth skimming tau Cherenkov shower detection (arXiv:1202.5656) - can be deployed on land!

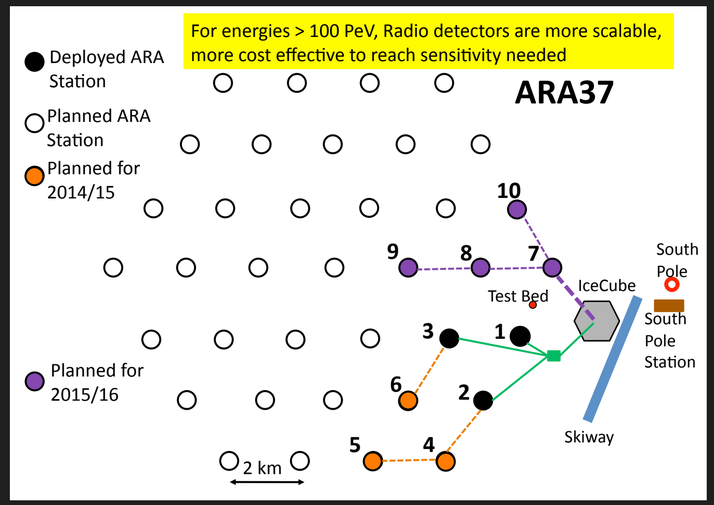
radio detectors for energy range above ~10 PeV (Askaryan effect)



ARIANNA



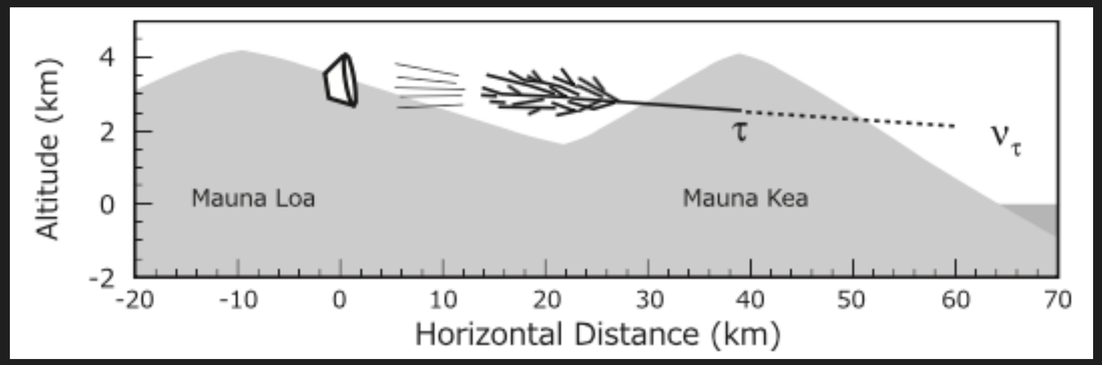
ANITA



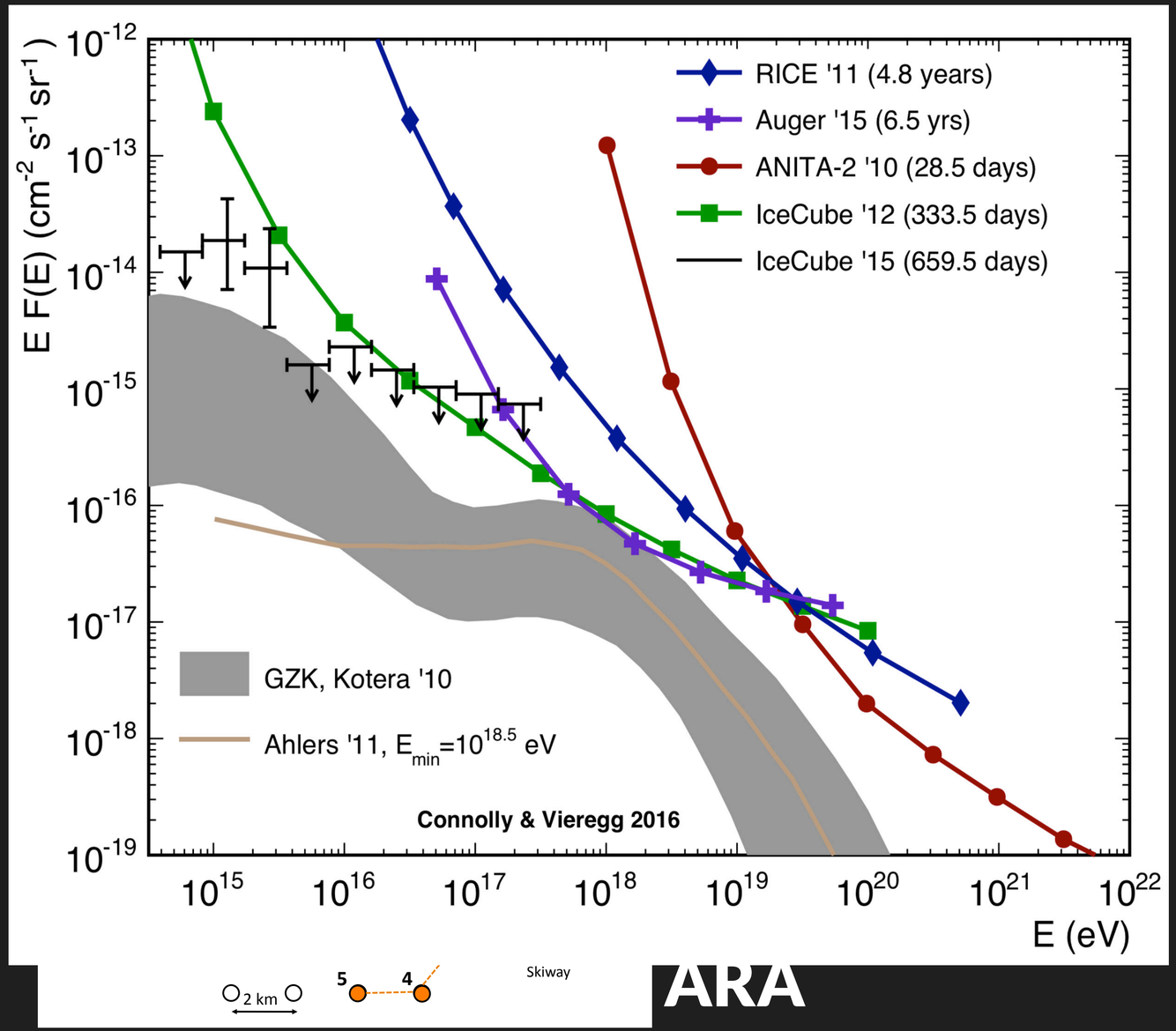
ARA

MORE DETECTORS / METHODS

non-water detectors | radio detectors

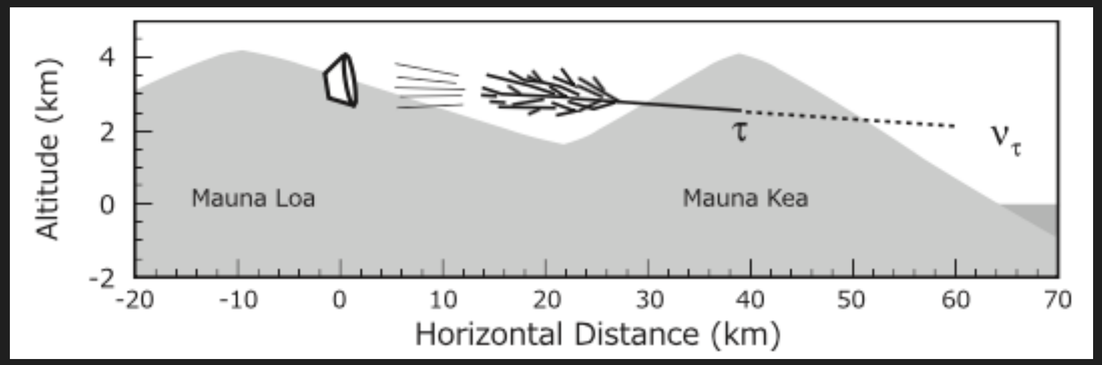


earth skimming tau Cherenkov shower detection (arXiv:1202.5656) - can be deployed on land!



MORE DETECTORS / METHODS

non-water detectors | radio detectors



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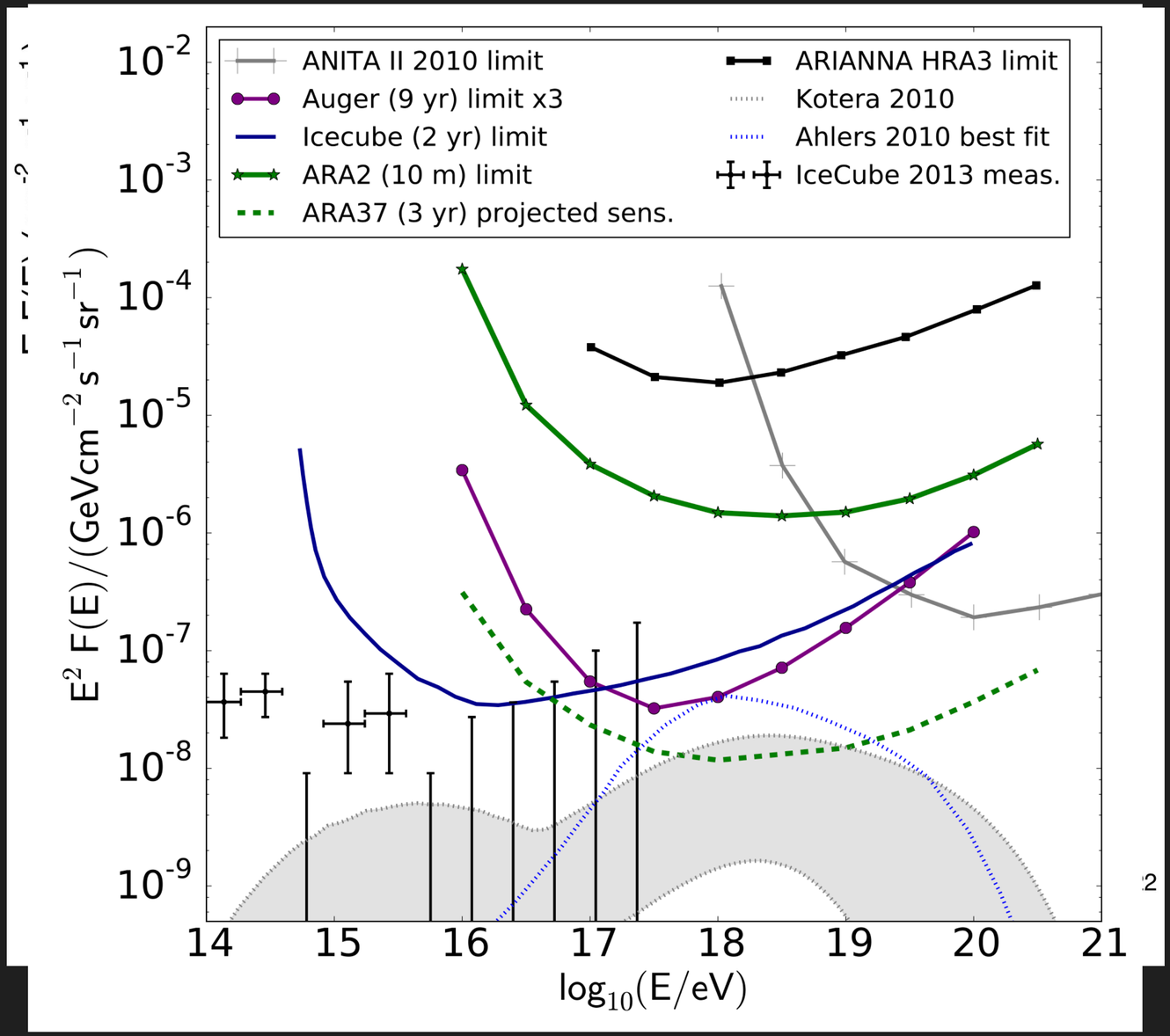

CONCLUSIONS

and summary

I could only cover a very small subset of topics…

We are studying the detailed properties of the flux of astrophysical neutrinos and are looking for its sources

In addition we are using atmospheric neutrinos to study neutrino physics (oscillations!)

Had to omit many other results (CR composition, searches for neutrinos from GRBs, …)

More data is being taken and analyses are ongoing

We are looking at future projects - KM3NeT and IceCube-Gen2

most photographs/timelapse: M. Wolf/NSF
https://www.flickr.com/photos/135762220@N06/

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THANK YOU!