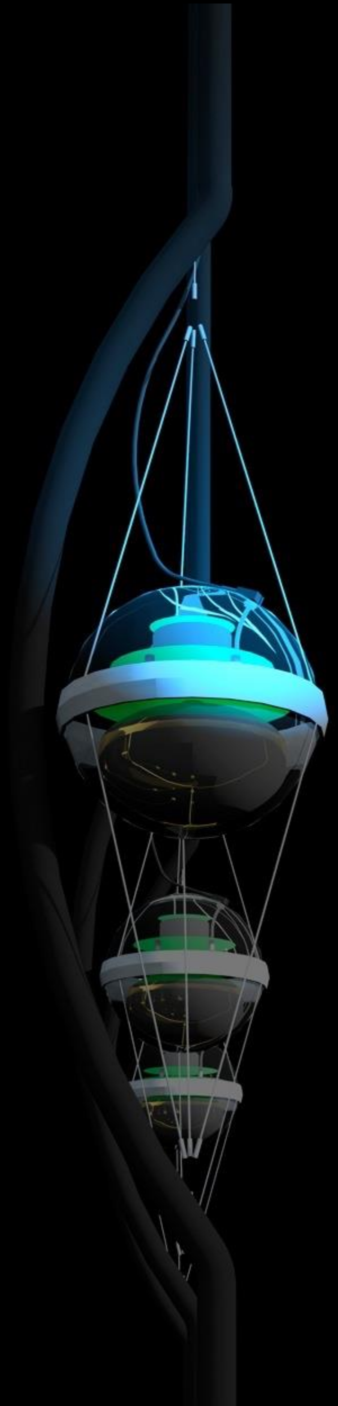
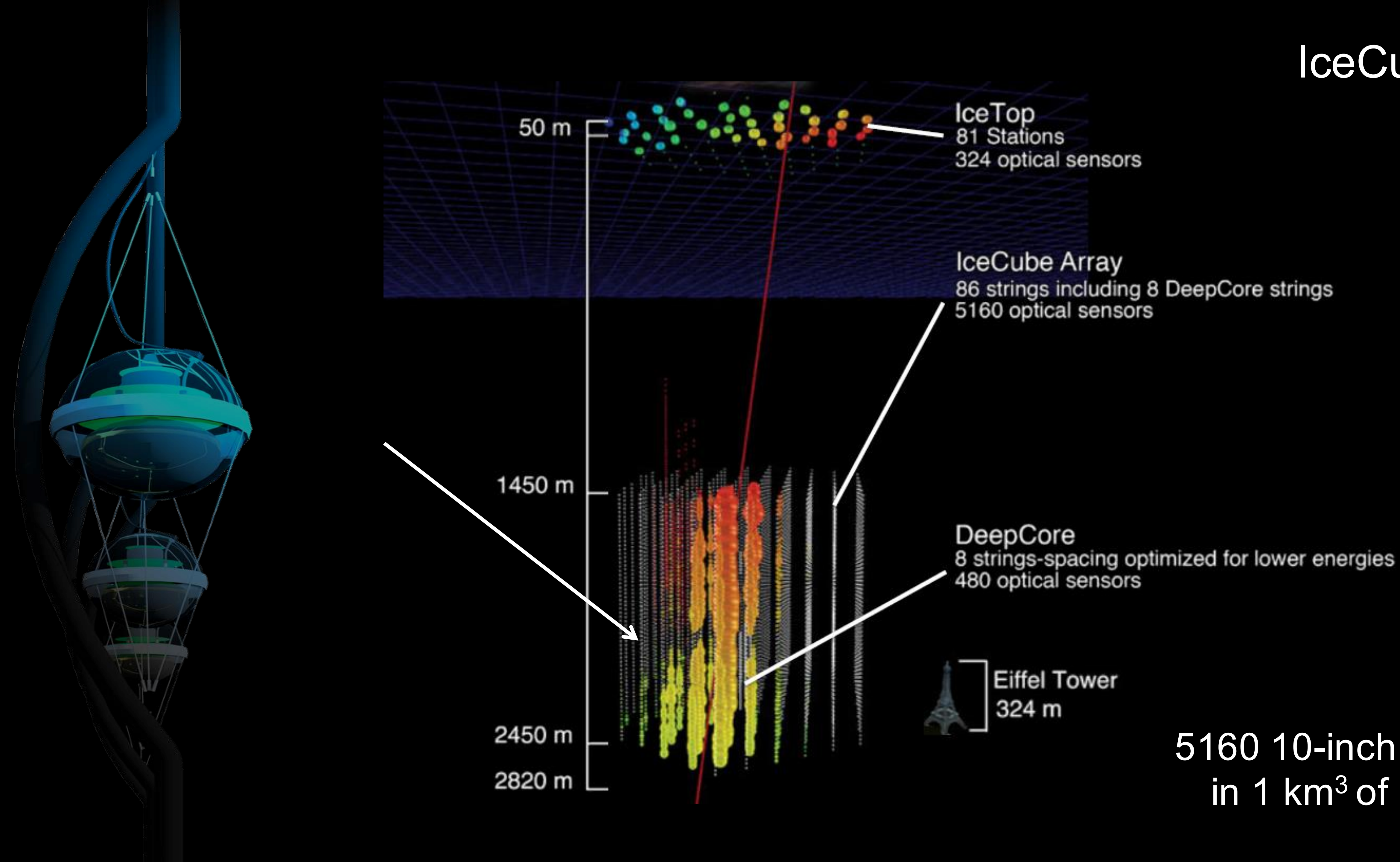


IceCube: beyond neutrino astronomy

francis halzen

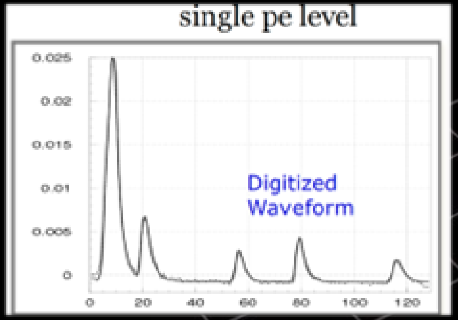
- natural Antarctic ice as a Cherenkov detector
- neutrino physics: from GeV to PeV
- detecting the next Galactic supernova explosion
- search for dark matter
- beyond the Standard Model physics: quantum decoherence, sterile neutrinos, neutrino cross sections, …
- cosmic ray physics

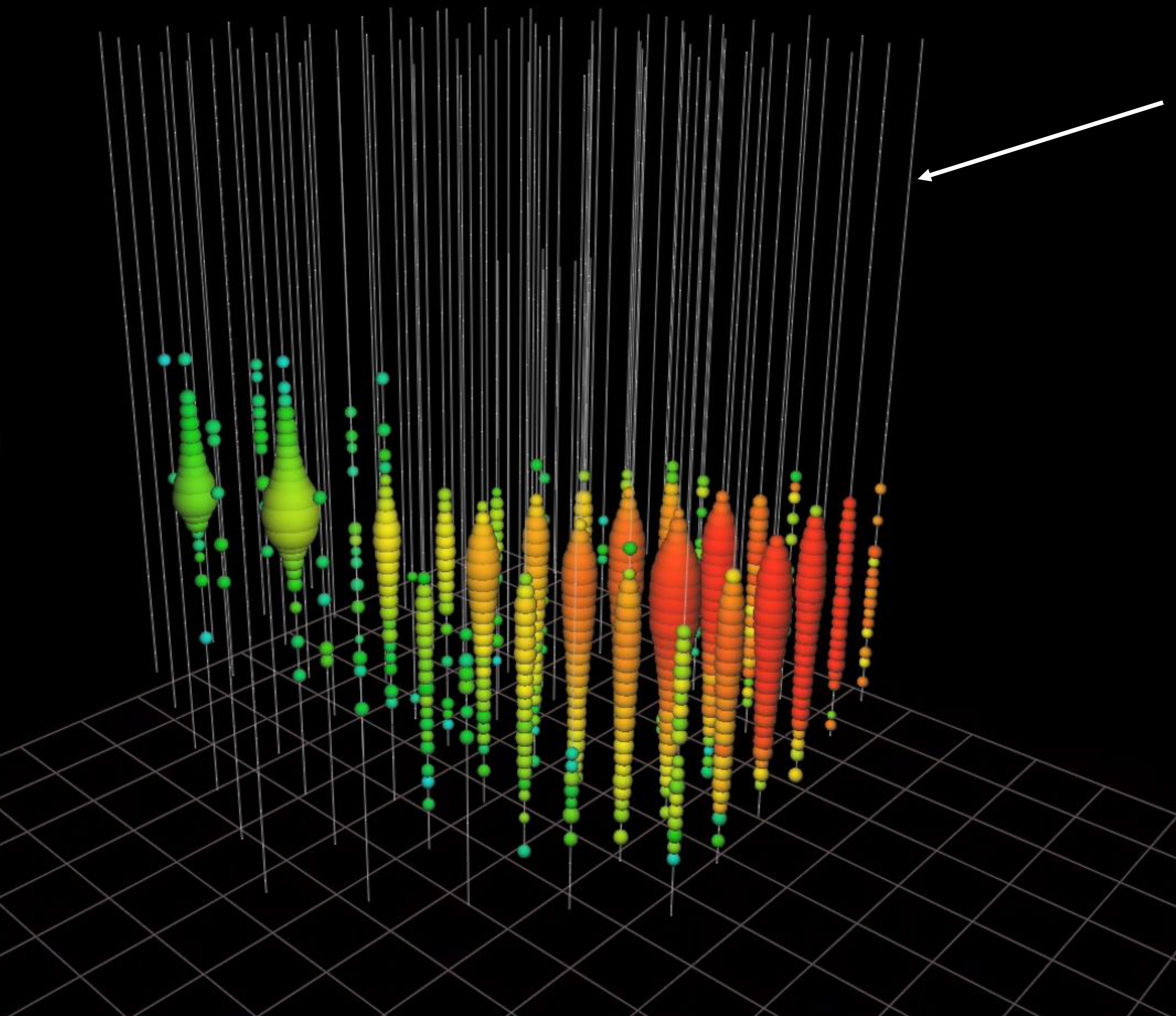
IceCube

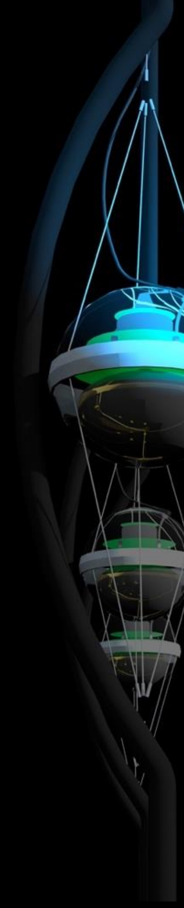


5160 10-inch PMs
in 1 km^3 of ice

1 km^3 of Antarctic ice instrumented with 5160 PMT (10inch) below 1450m

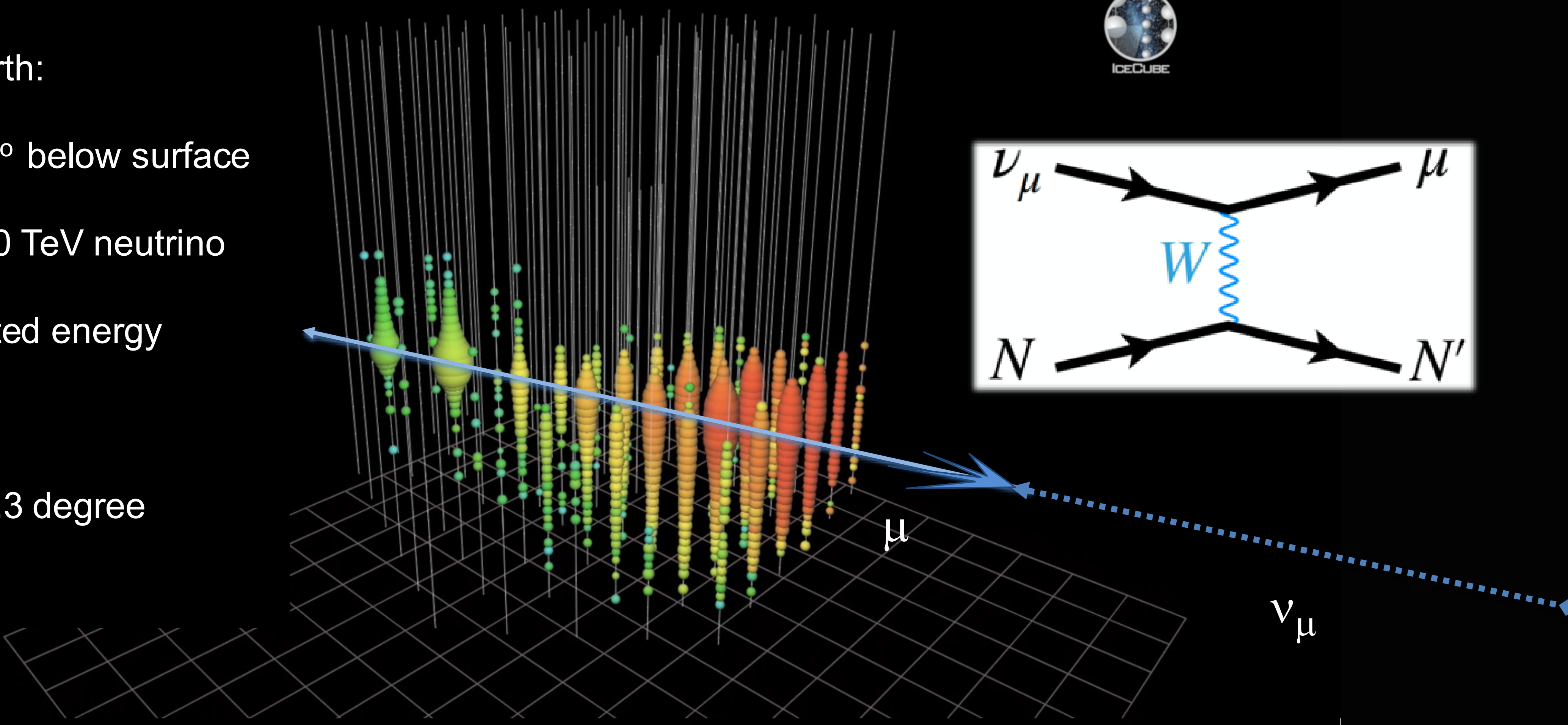


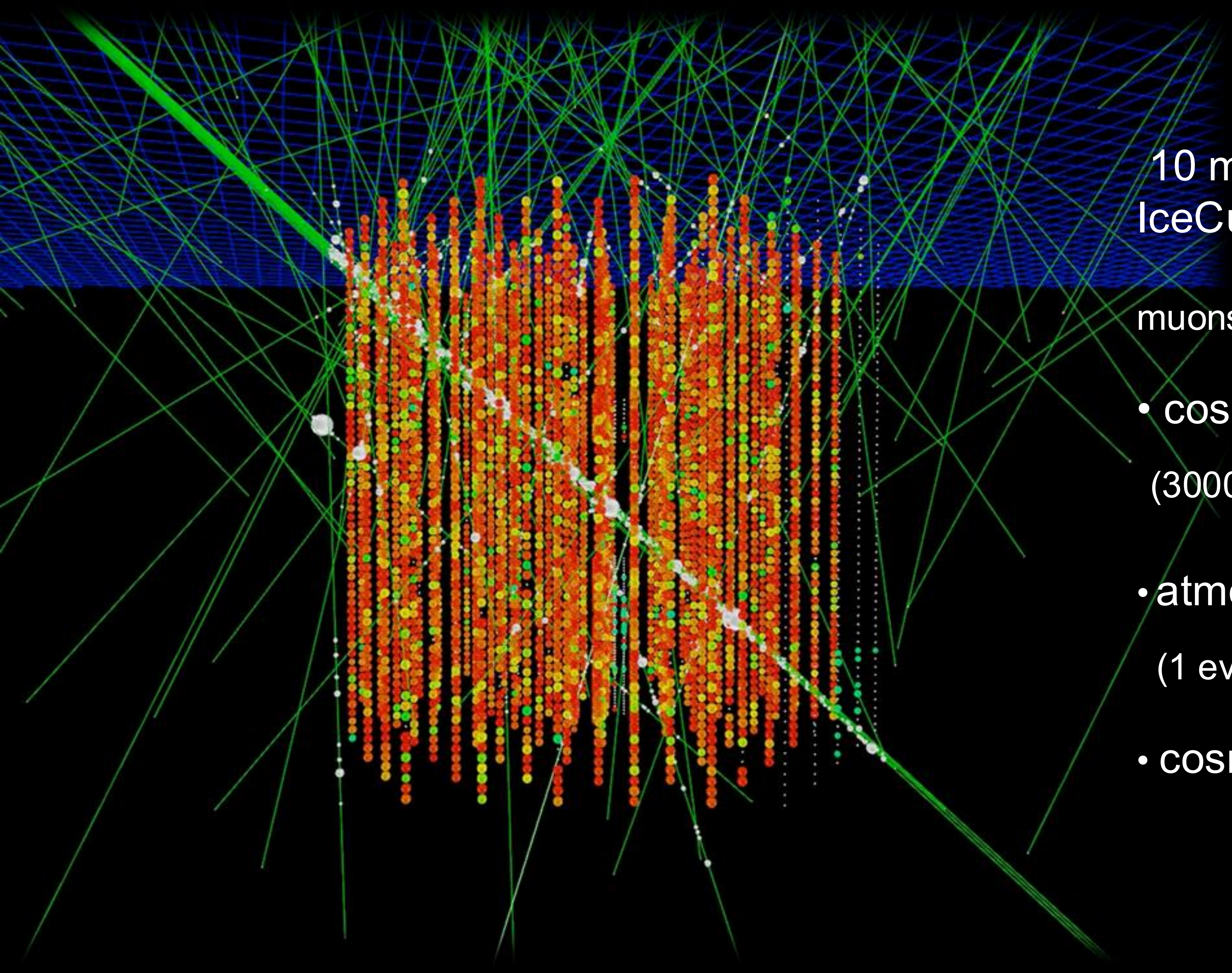




Look through the Earth:

- upgoing muon 11° below surface
- produced by 8,700 TeV neutrino
- 2,600 TeV deposited energy
- not atmospheric
- reconstructed < 0.3 degree
- astronomy





10 msec movie of IceCube taking data

muons detected per year

- cosmic ray muons ~ 10^{11}

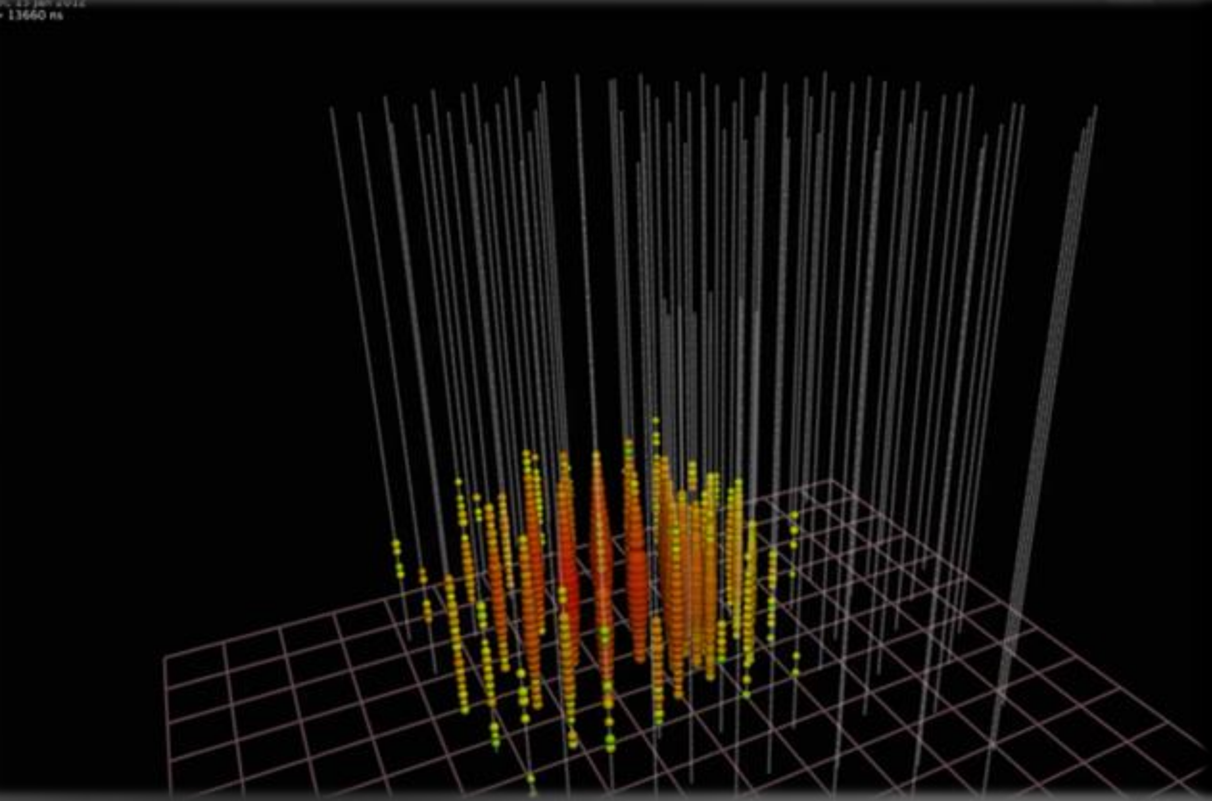
(3000 per second)

- atmospheric neutrinos ~ 10^5

(1 every 5 minutes)

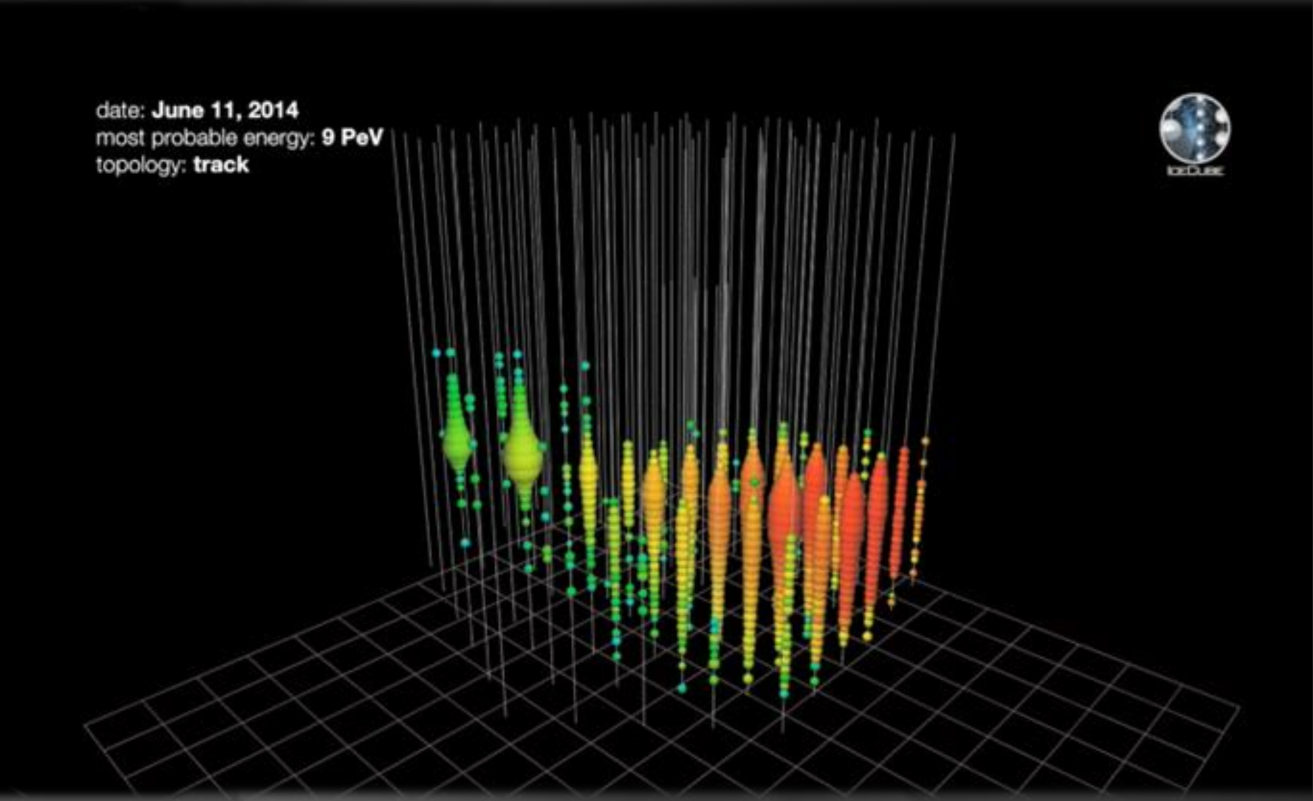
- cosmic neutrinos ~ 200

neutrinos interacting
inside the detector



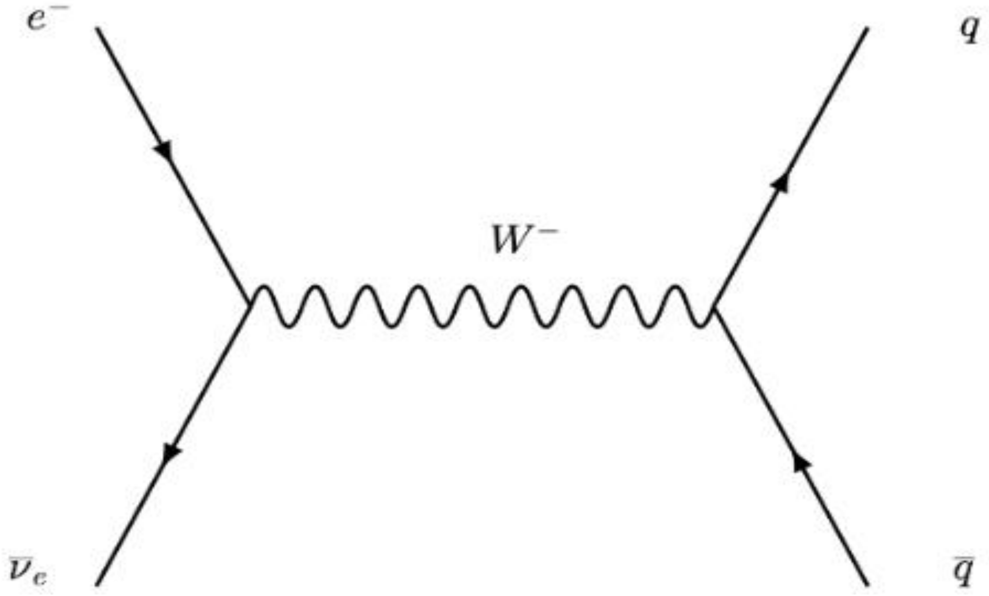
superior total energy
measurement
to 10%, all flavors, all sky

muon neutrinos
filtered by the Earth



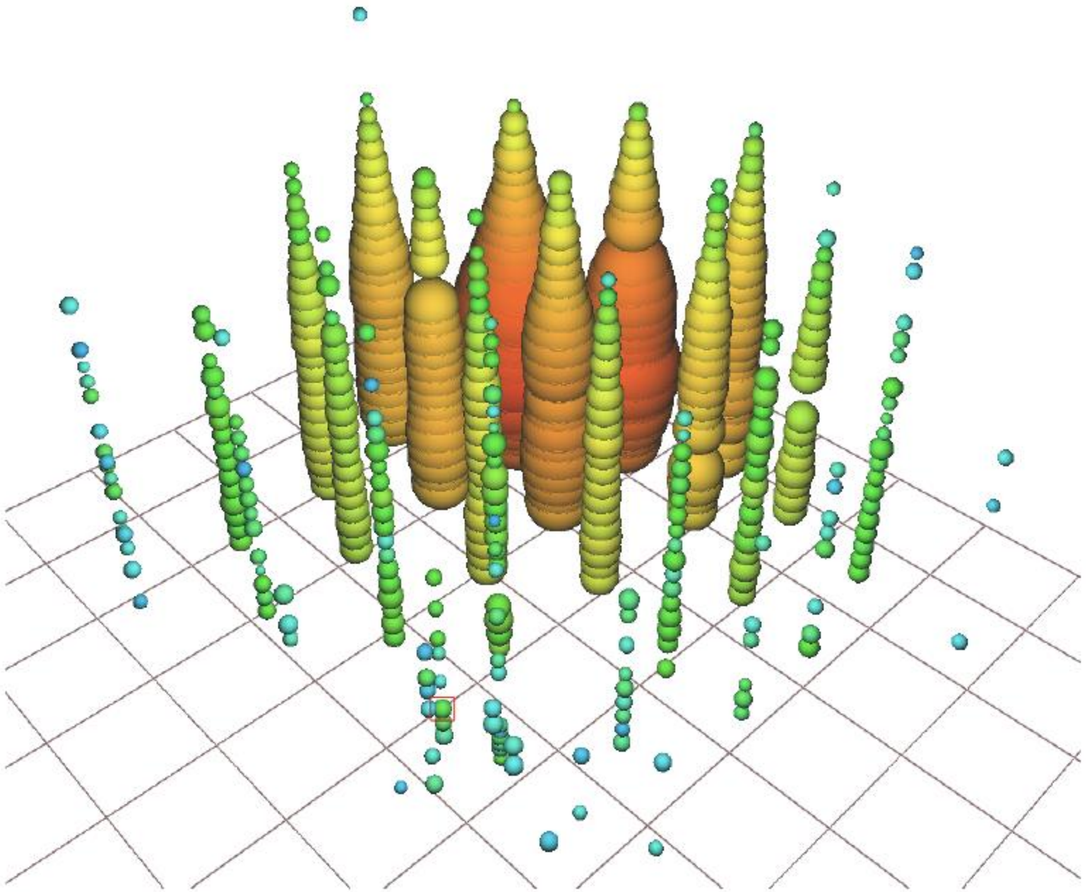
superior angular resolution < 0.3°
including systematics

Glashow resonance event with energy 6.3 PeV

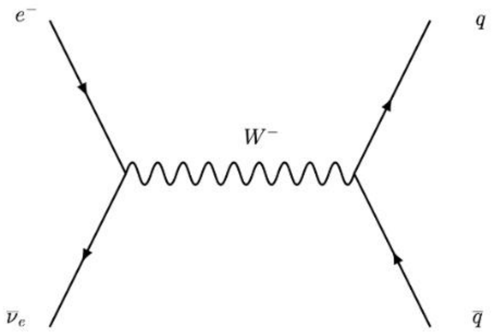


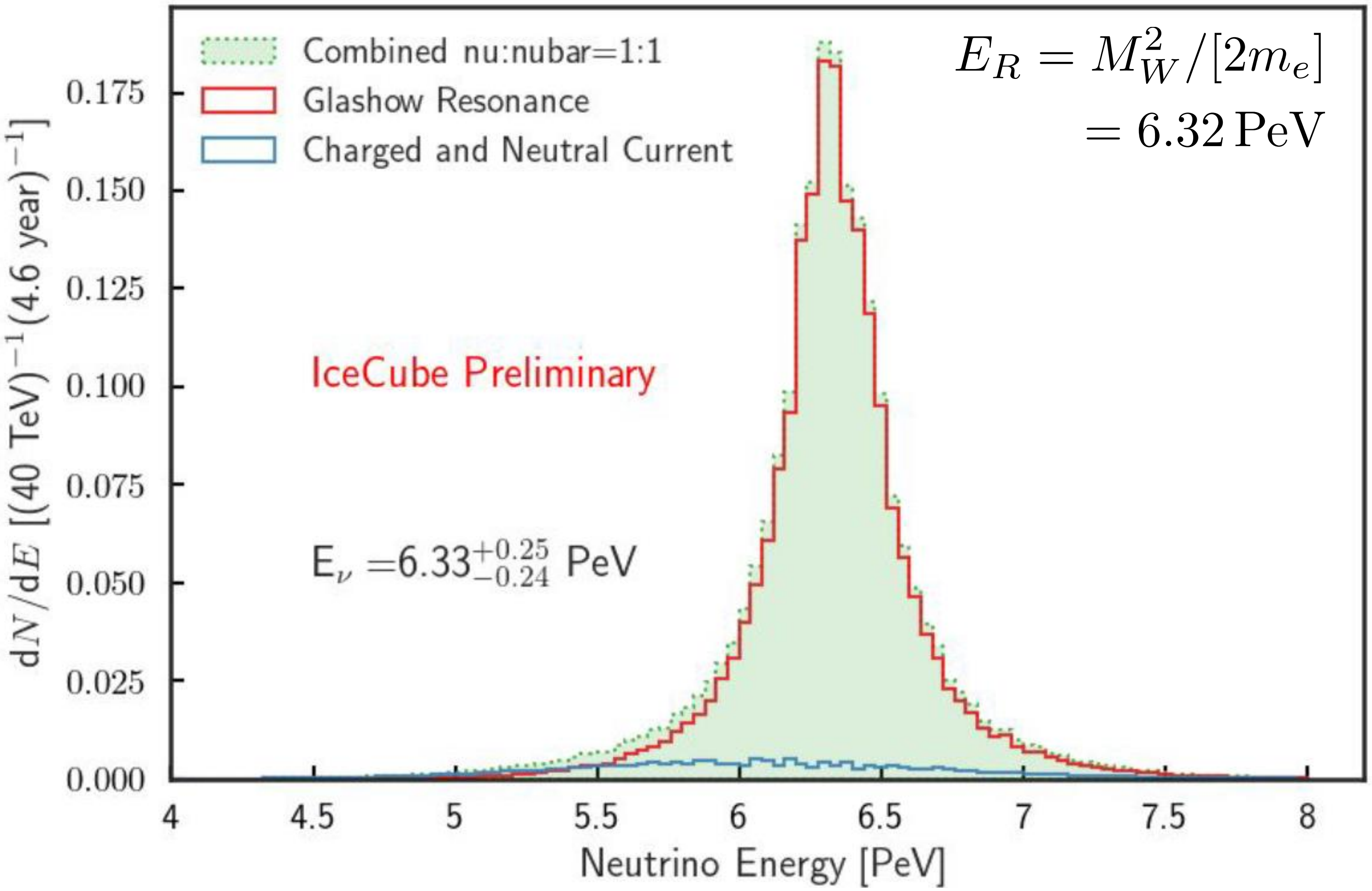
$$E_R = M_W^2/[2m_e] = 6.32\,\mathrm{PeV}$$

resonant production of a weak intermediate boson by an anti-electron neutrino interacting with an atomic electron



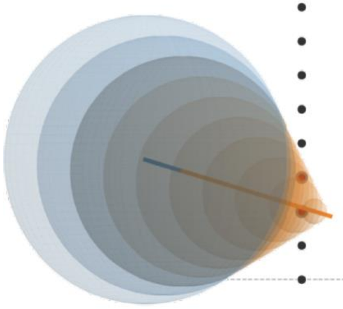
- energy measurement understood
- shower consistent with the hadronic decay of a weak intermediate boson W
- identification of anti-electron neutrino



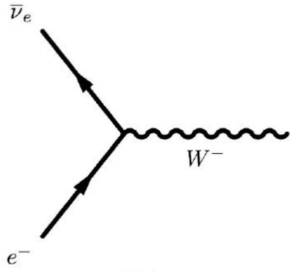


First hint of W boson resonance in data (Glashow resonance)

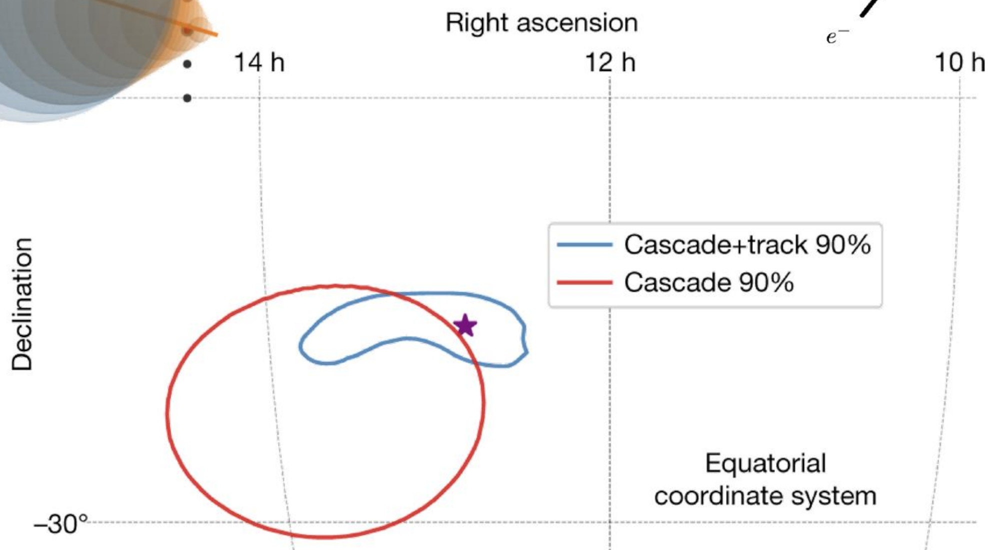
Nature **591,** 220–224 (2021)

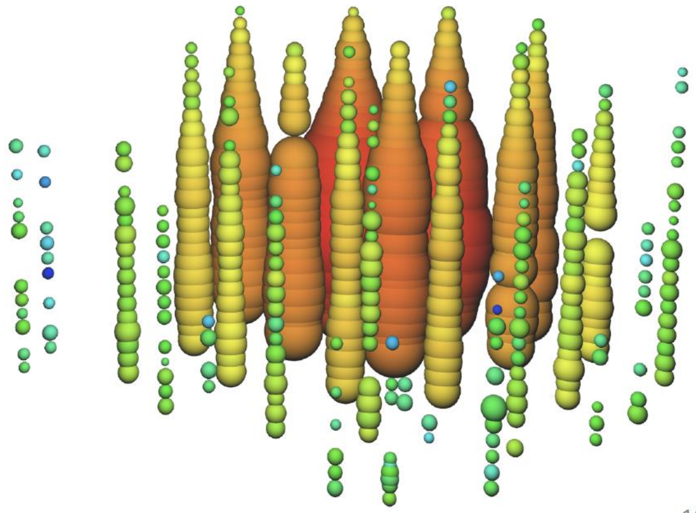


$$E_R = M_W^2/(2m_e) = 6.32\mathrm{PeV}$$

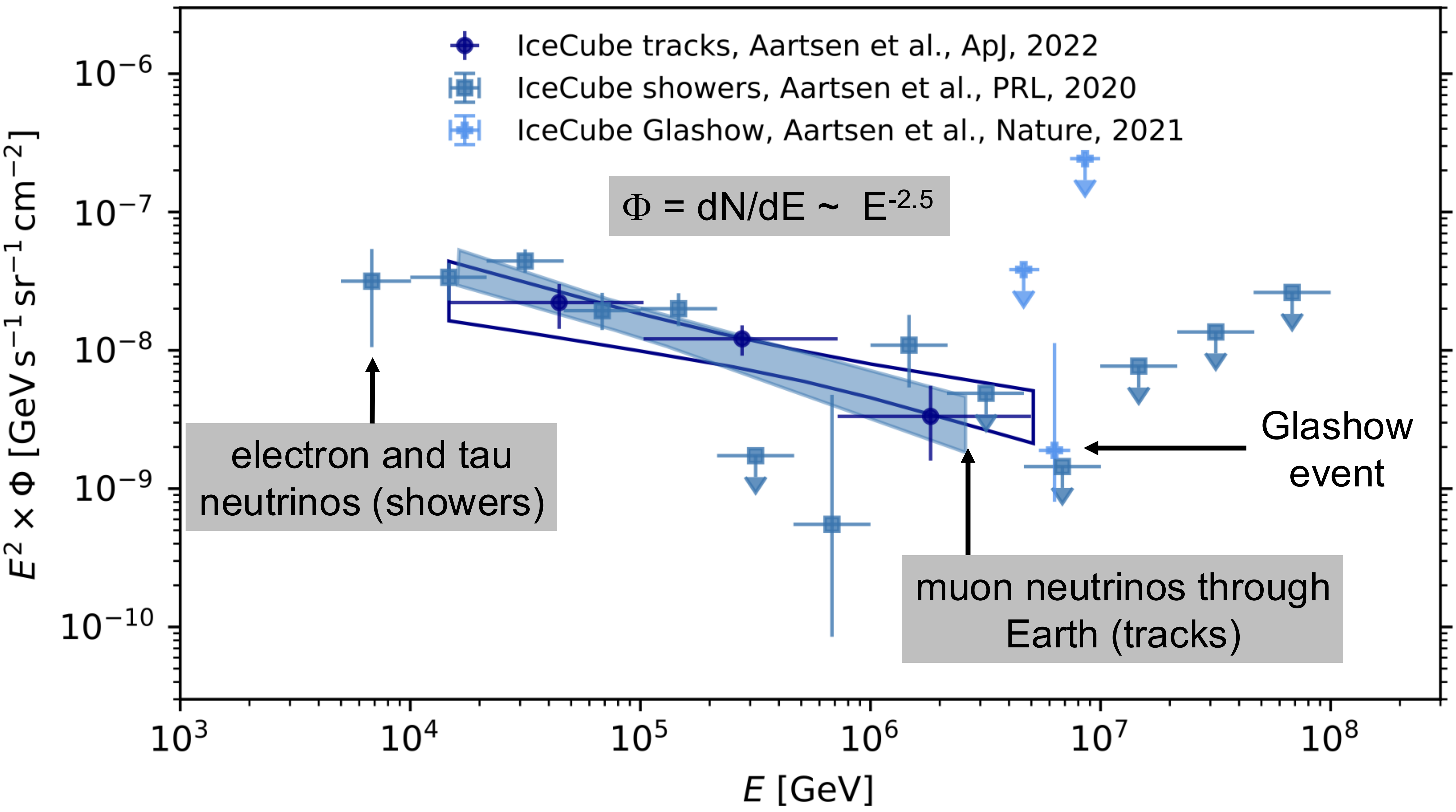


By measuring nu/nubar -> probe source environment directly (magnetic field, pp/pgamma)





Identified muonic component from the hadronic shower
angular uncertainty contour shrinks by a factor of 5 with hybrid reco

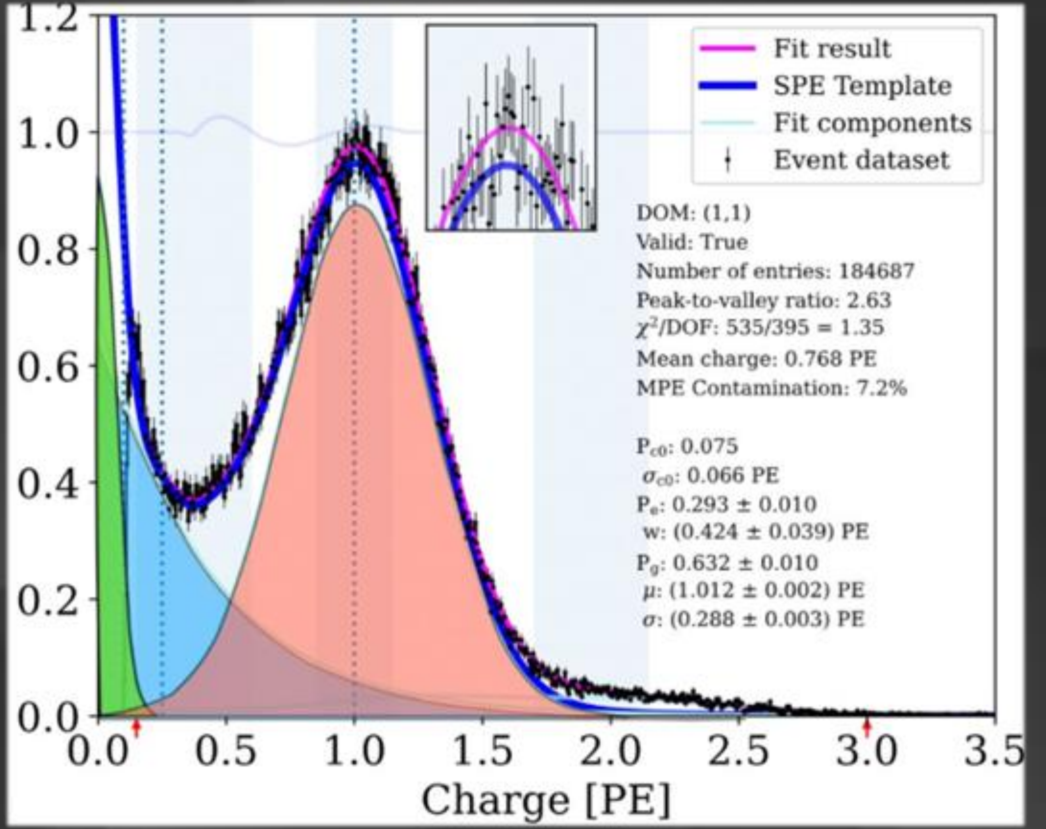

IceCube tracks, Aartsen et al., ApJ, 2022
IceCube showers, Aartsen et al., PRL, 2020
IceCube Glashow, Aartsen et al., Nature, 2021
Φ = dN/dE ~ E-2.5
electron and tau neutrinos (showers)
Glashow event
muon neutrinos through Earth (tracks)
E² × Φ [GeV s⁻¹ sr⁻¹ cm⁻²]
E [GeV]
10⁻⁶
10⁻⁷
10⁻⁸
10⁻⁹
10⁻¹⁰
10³
10⁴
10⁵
10⁶
10⁷
10⁸

after 10 years: interesting fluctuations or neutrino sources?

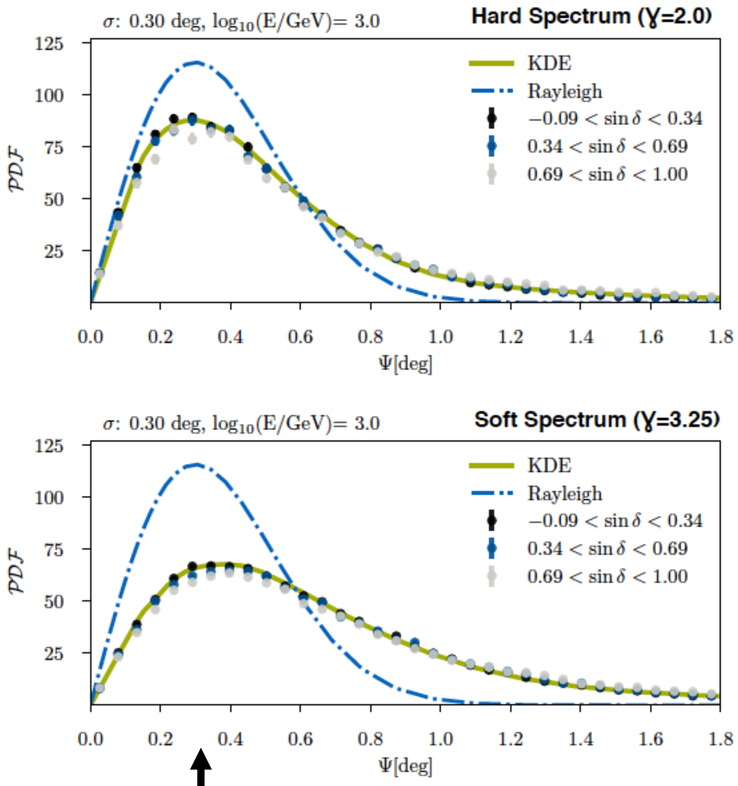
→ crash program to upgrade the performance of IceCube

- improved detector geometry
- each photomultiplier calibrated individually
- improved characterization of the optics of the ice
- improved muon angular resolution and energy reconstruction using **machine learning**
- *point spread function consistent with simulation or, we were partially blind*
- *…*

applied to 10 years of archival data (pass 2), data unblinded



- point spread function consistent with simulation
- insensitive to systematics

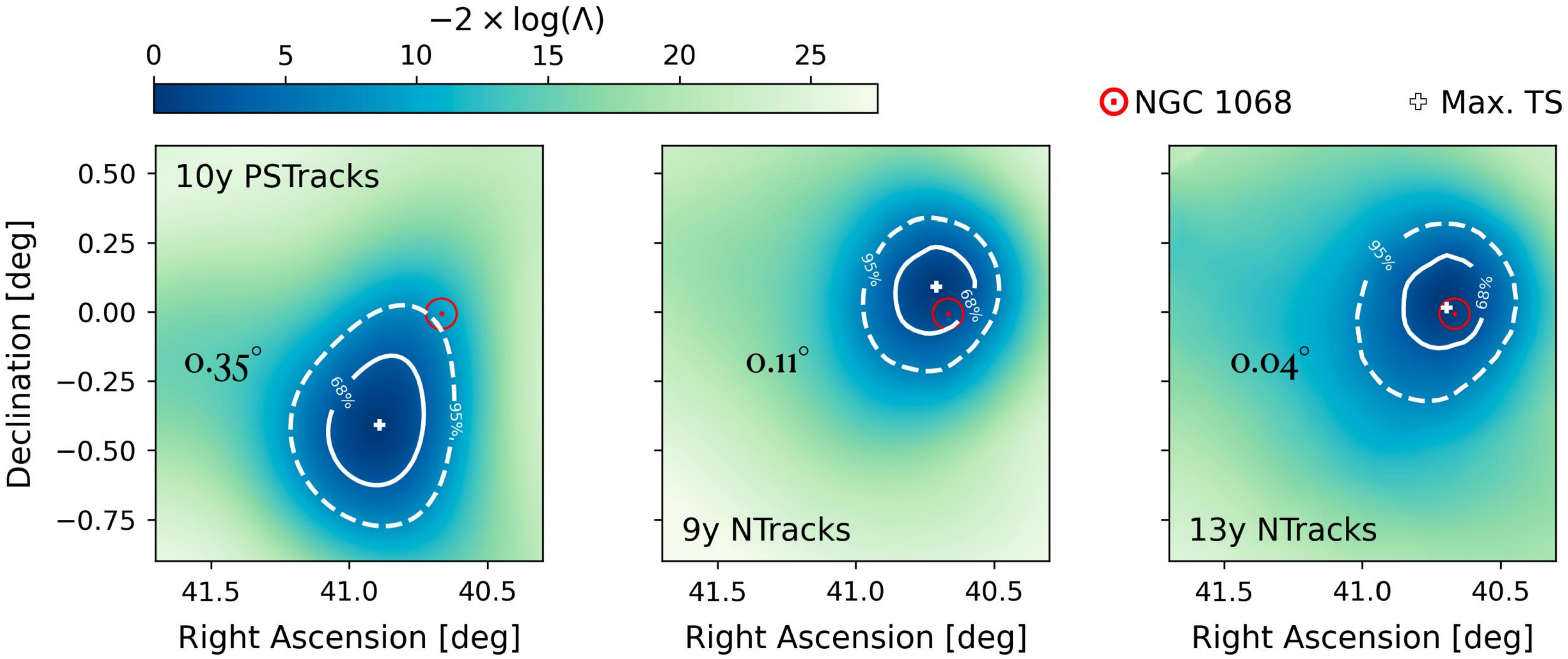


muon direction

- Rayleigh (1D-projection of 2D Gauss) doesn't describe our Monte Carlo accurately → Tails are suppressed
- The distribution depends on the spectral index!
- Effect mainly visible at < 10 TeV energies where the kinematic angle between neutrino and muon matters
- **Solution:** Obtain a numerical representation of the γ-dependent spatial term from MC simulation (for example using KDEs)

$$\frac{1}{2\pi\sigma^2}e^{-\frac{\psi^2}{2\sigma^2}} \rightarrow \mathcal{S}\left(\psi\,|\,\sigma,\, E_\mu,\, \gamma\right)$$

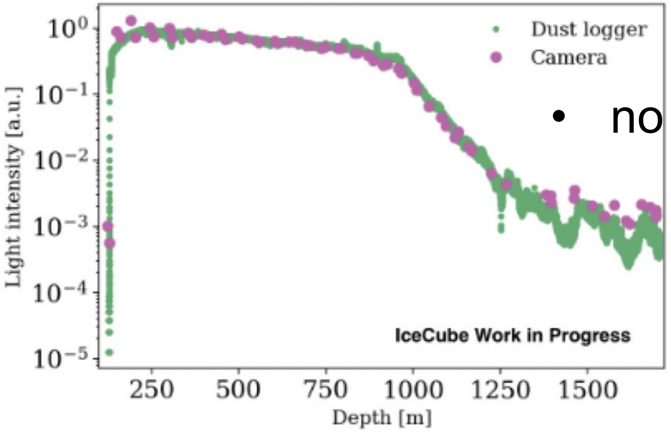
0.35 deg → 0.1 deg → 0.04 deg



NGC 1068 comes into focus

ice: step by step

- hole ice ?

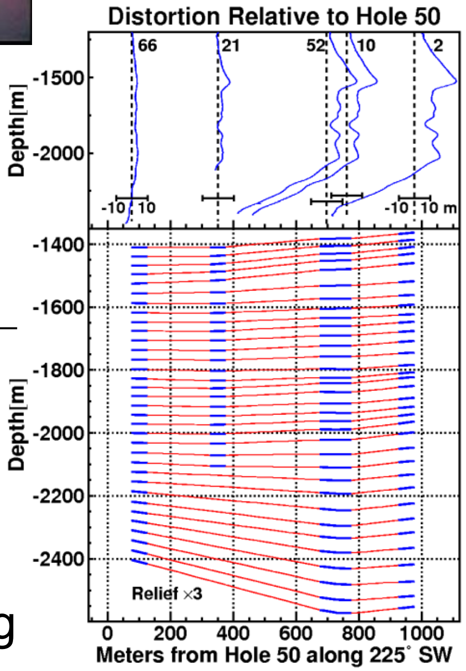


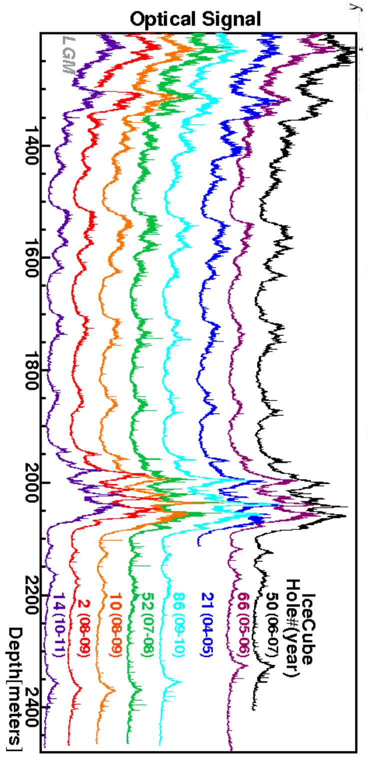
- no air bubbles/hydrates below 1350 m

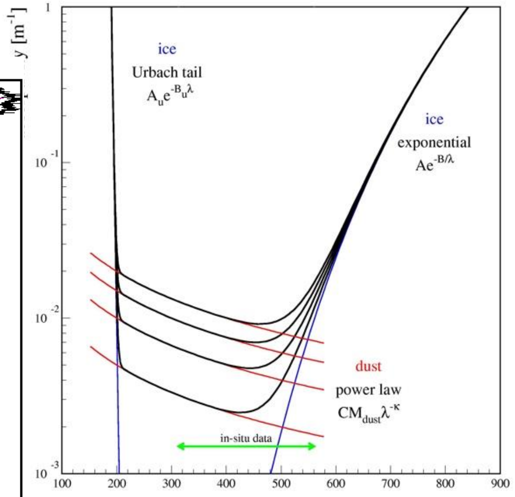
- > 100 m absorption length limited by dust

- ice layers

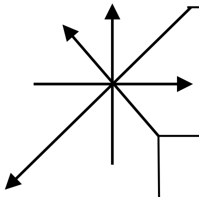
- tilted ice layers







- birefringence

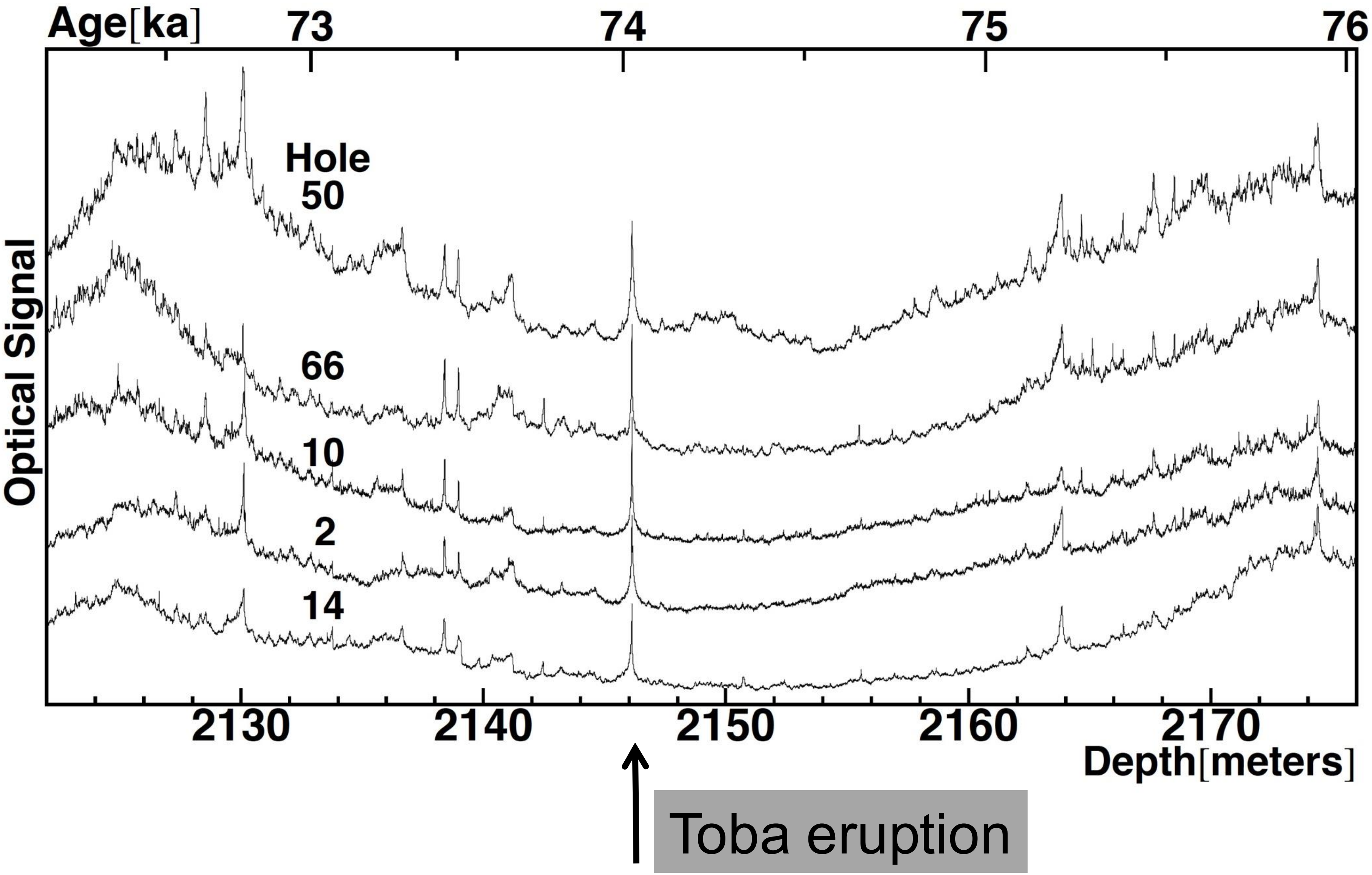


Ice Layer tilt direction
225° SW

Ice flow direction
41° NW

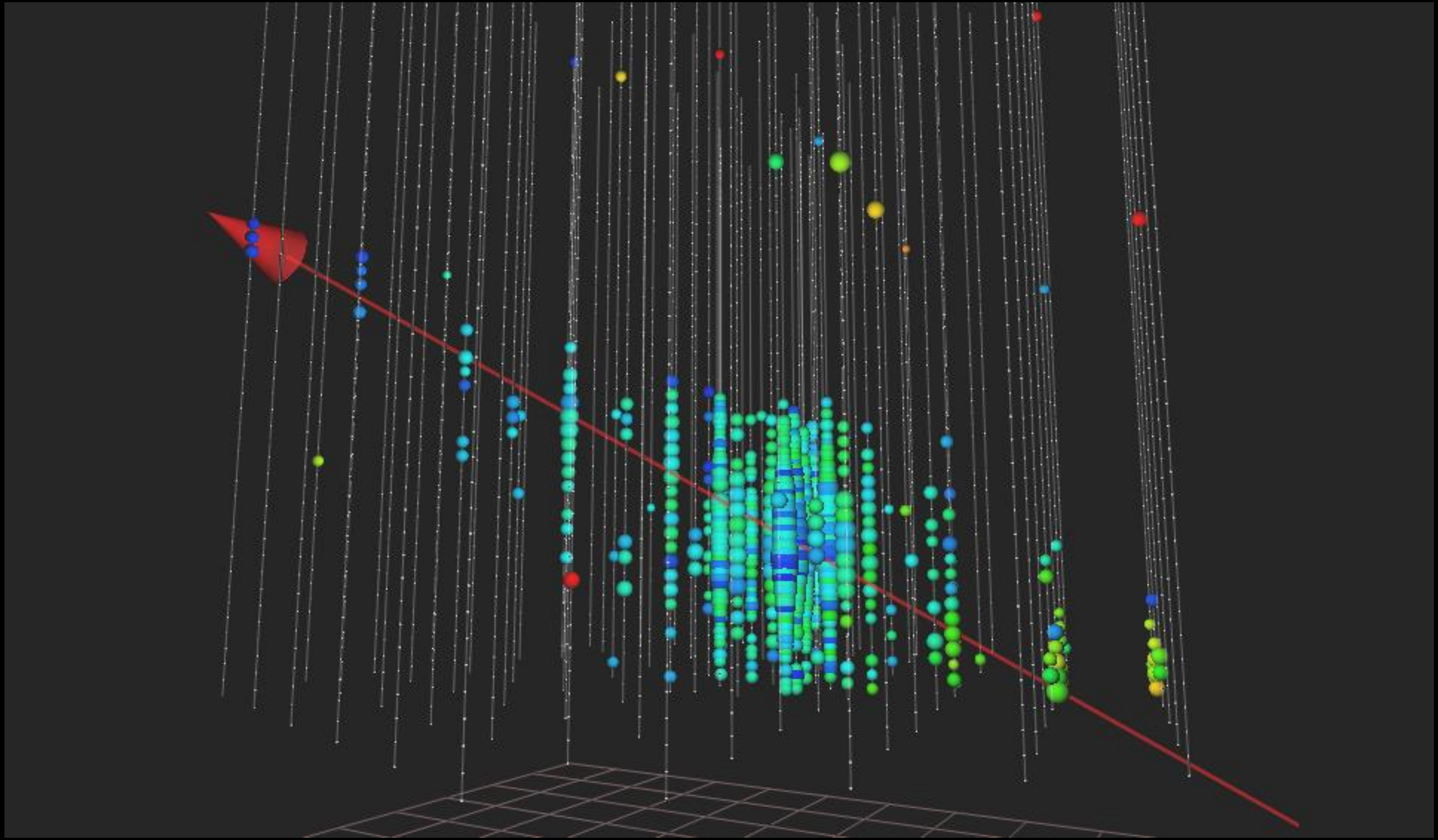
- anisotropy
~8% less scattering
41° NW

we are limited by computing, not the optics of the ice

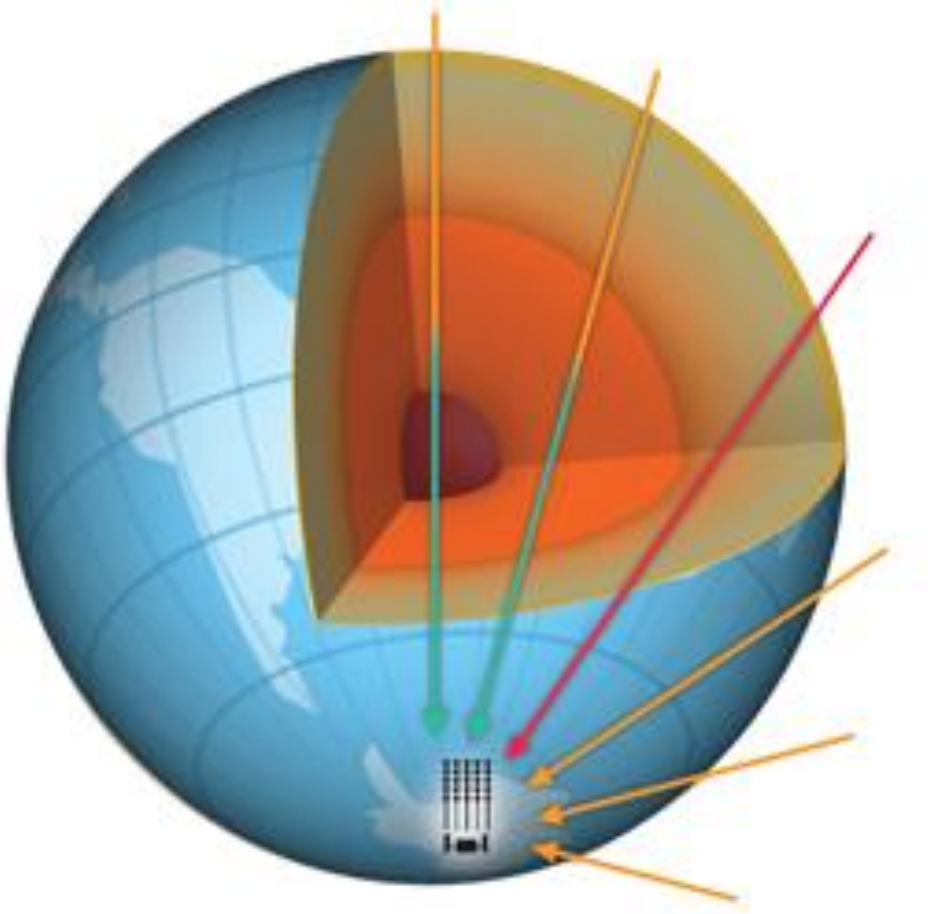


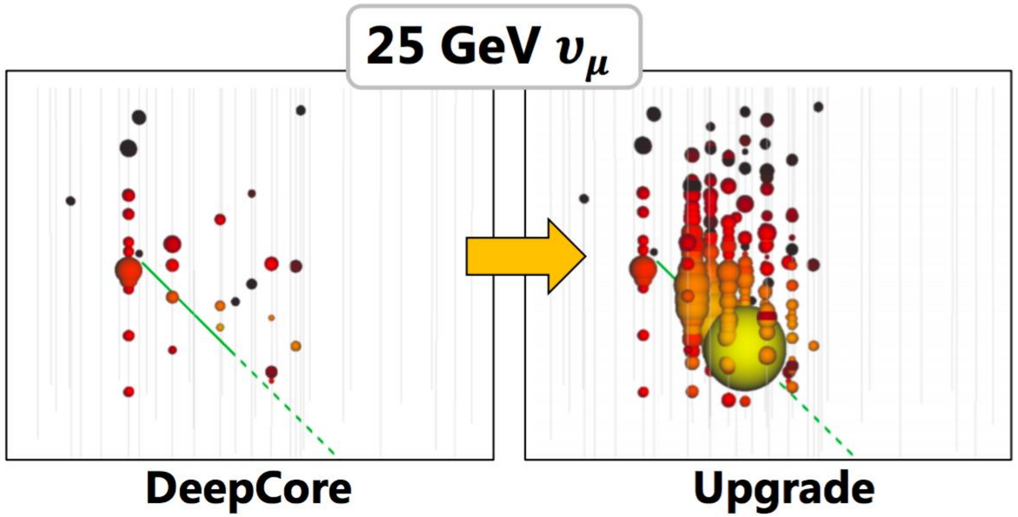
Toba eruption

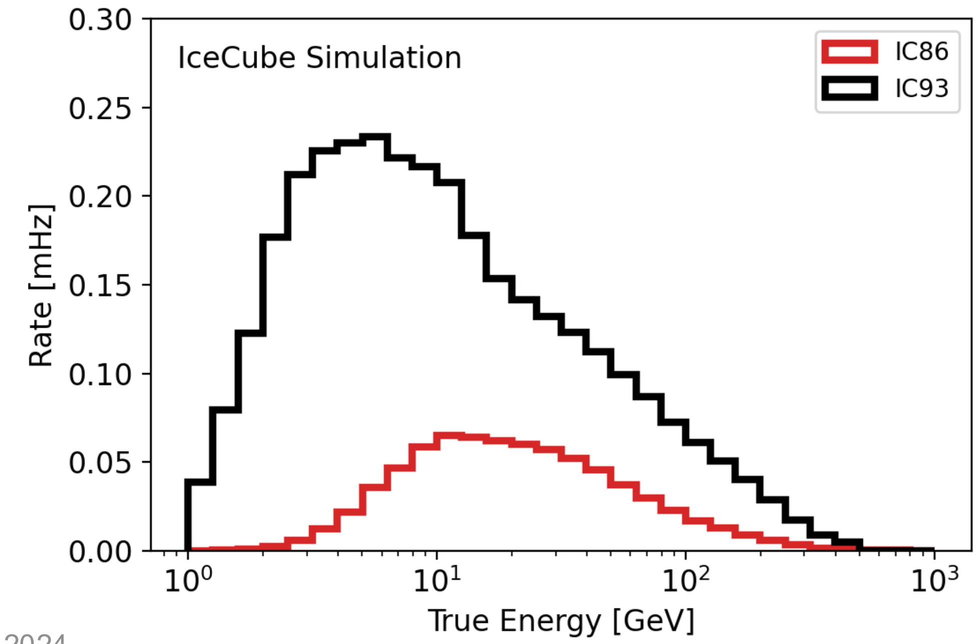
IceCube and DeepCore



IceCube Upgrade Physics: Oscillation

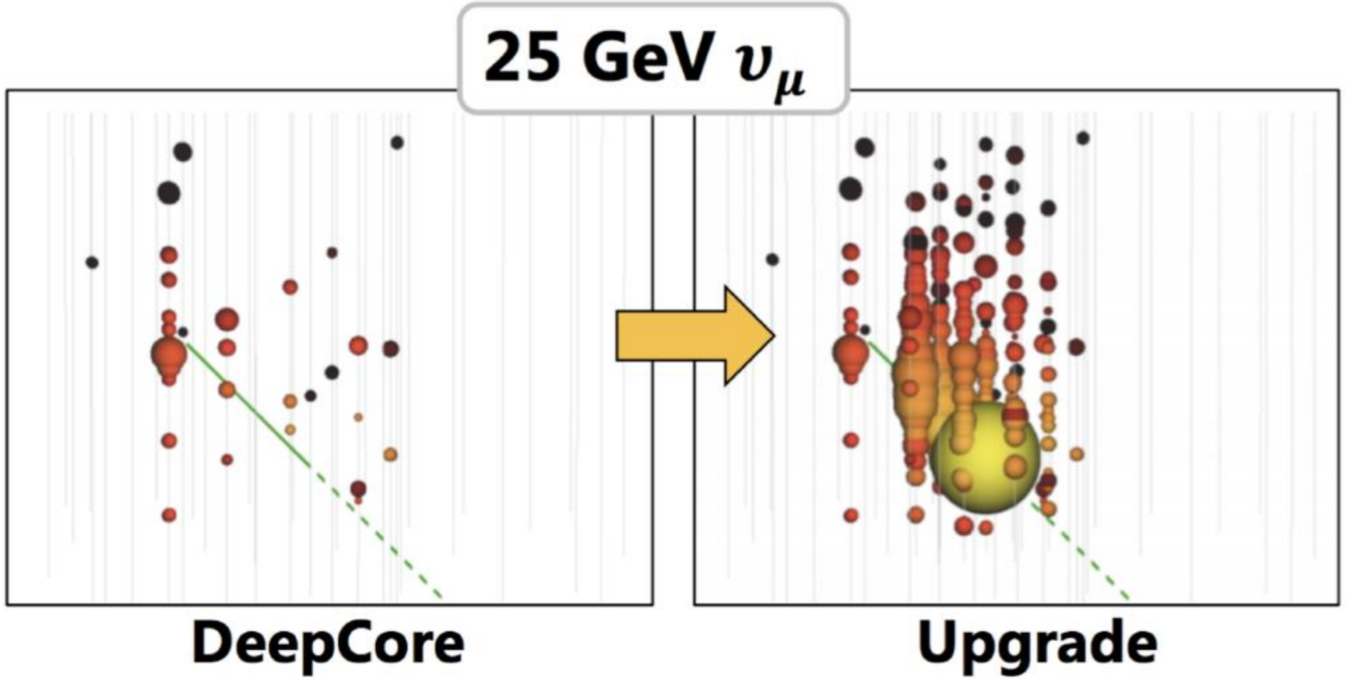






Dense instrumentation, short baselines and high photocathode area will yield very large atmospheric neutrino statistics at low energies compared to IceCube DeepCore

Low energy neutrinos in the Upgrade



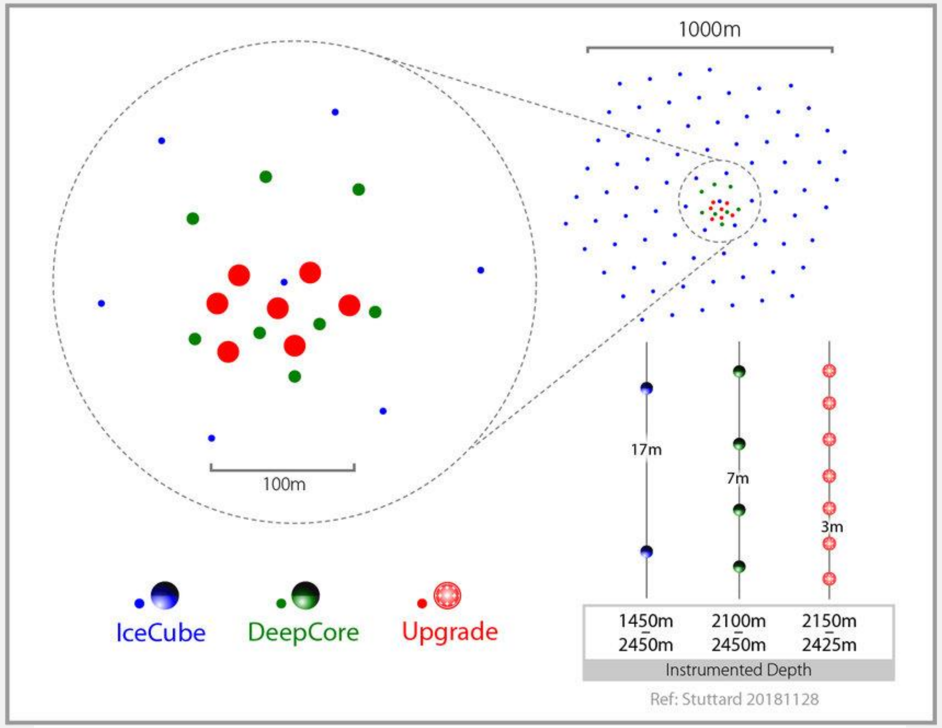
IceCube Overview

- IceCube
  - DeepCore
  - IceTop
- Upgrade
- IceCube-Gen2
  - Full

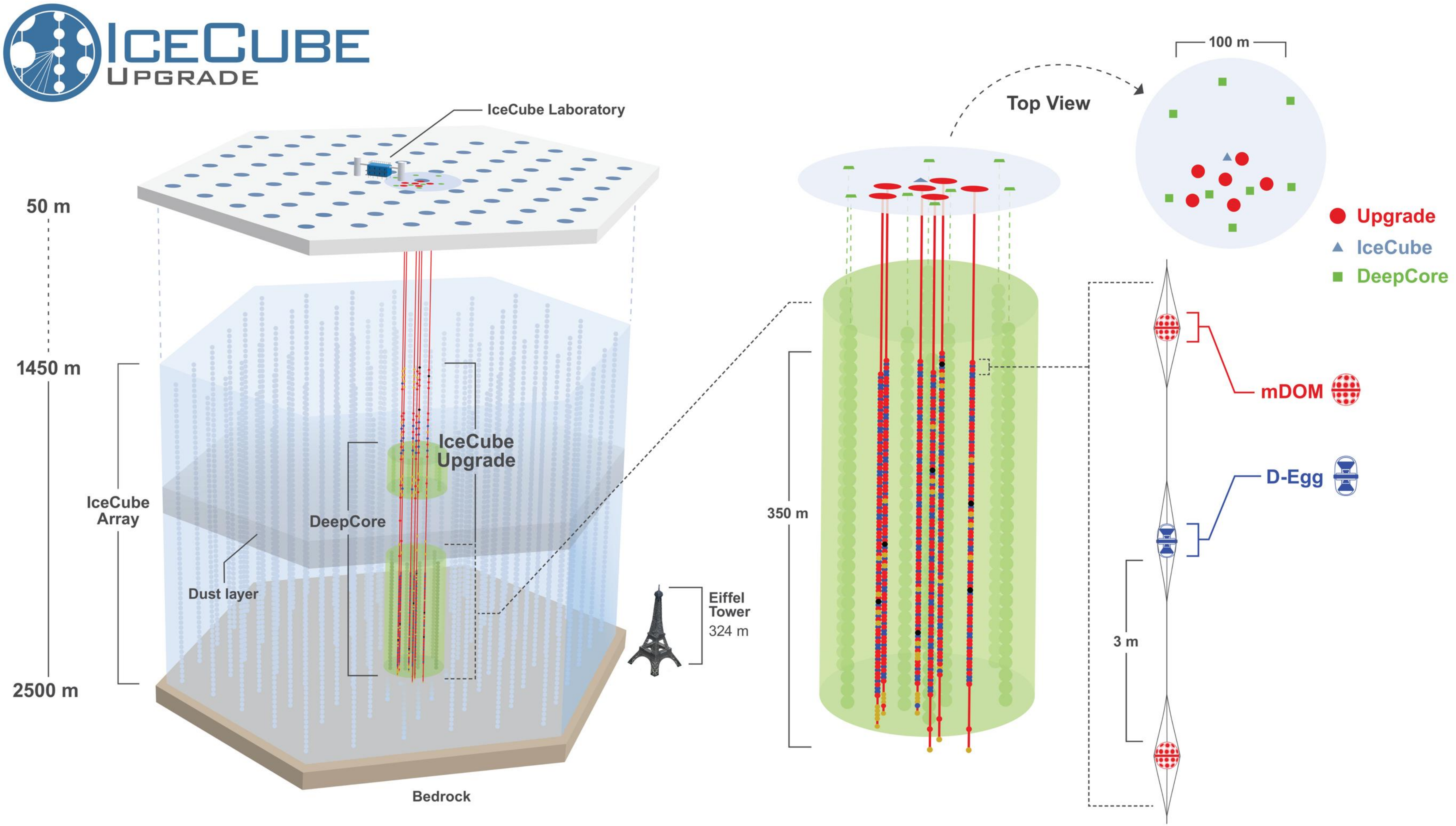
Done & Delivering

Underway

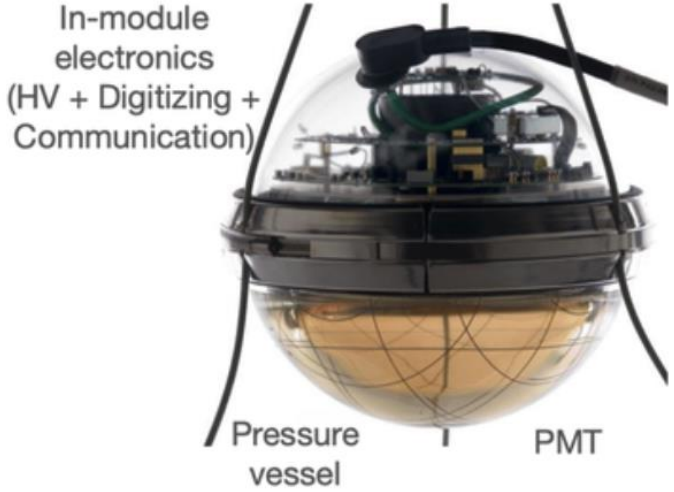
Astro2020 Review Preliminary Design in Preparation



- 10 megaton volume
- string spacing : 125m → 35m → 22m
- module spacing: 17m → 7m → 3 m

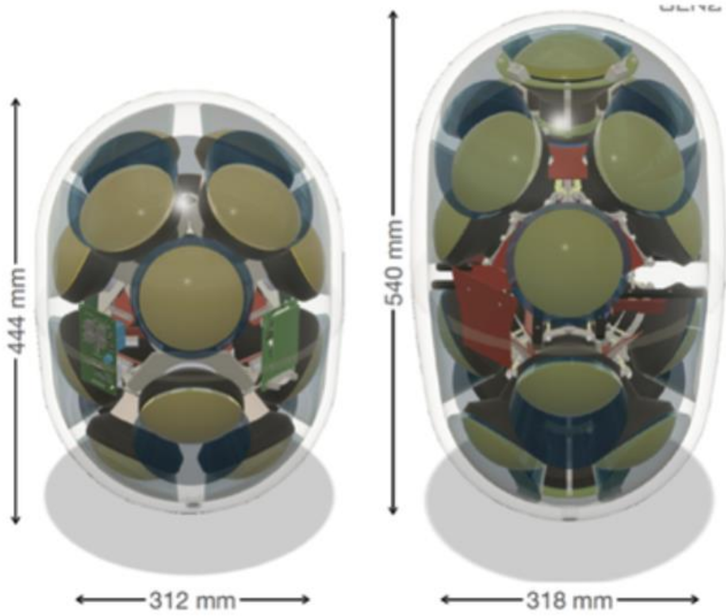

IceCube Upgrade
IceCube Laboratory
Top View
100 m
Upgrade
IceCube
DeepCore
50 m
1450 m
2500 m
IceCube Array
IceCube Upgrade
DeepCore
Dust layer
Eiffel Tower
324 m
Bedrock
350 m
mDOM
D-Egg
3 m

IceCube Digital Optical Module (DOM)



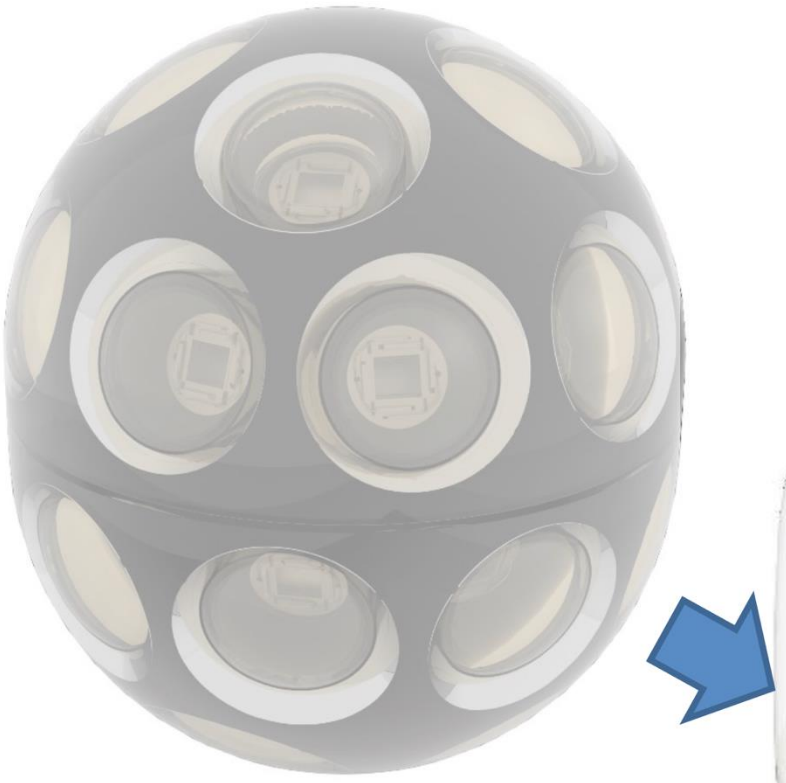

mDOM

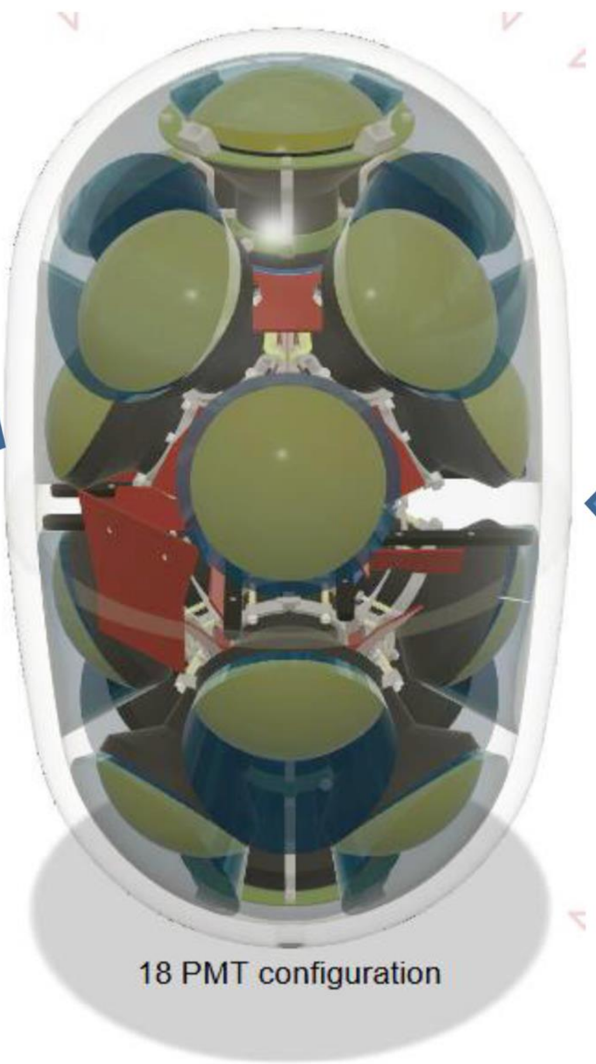

D-Egg



16 PMT option

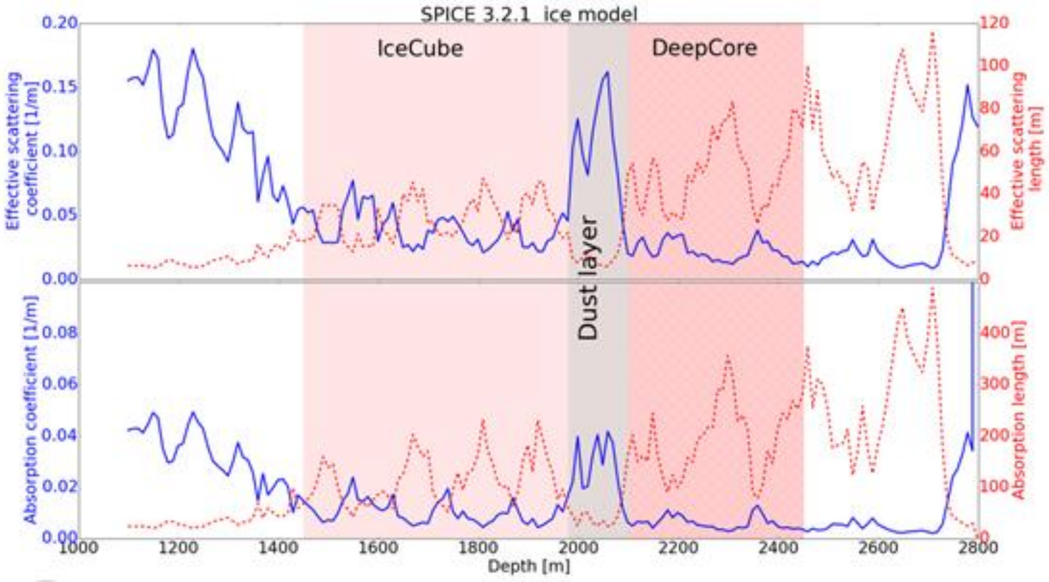
18 PMT option



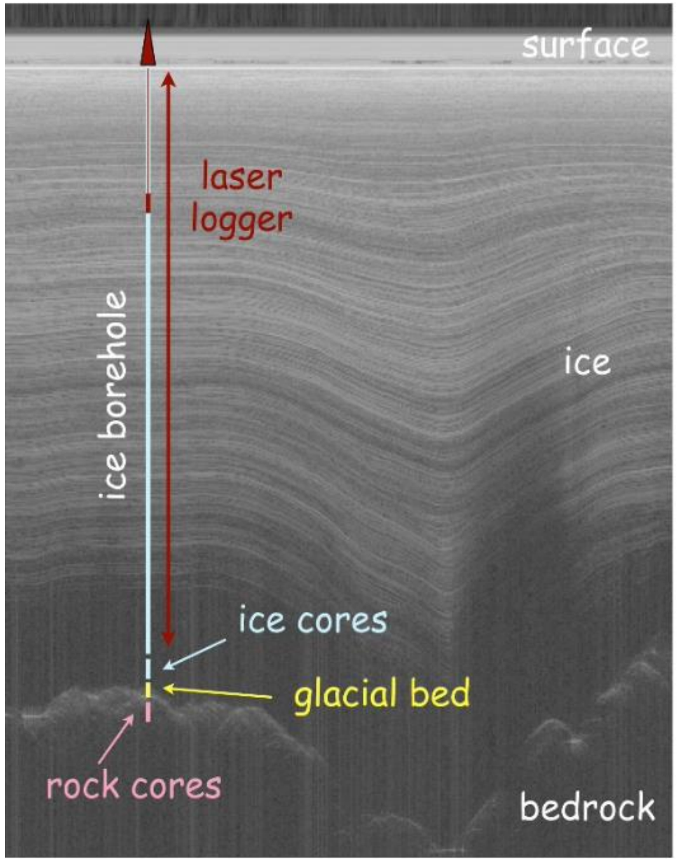


towards IceCube-Gen2

The ice model: Calibration in the Upgrade



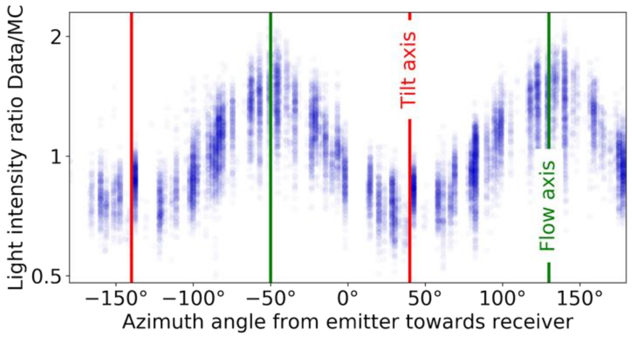
Depth dependent concentration of dust in undisturbed "bulk ice"

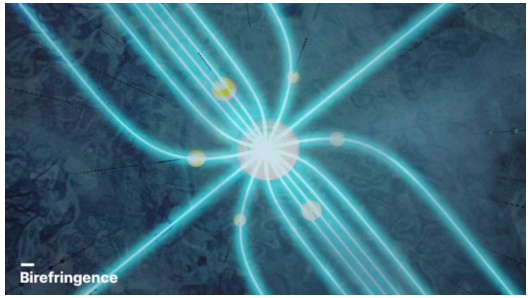


Dust layers not horizontal

Bubbles in refrozen "hole ice"

We have made tremendous progress in understanding the ice, but simulation round trip tests indicate that the ice model can still be improved

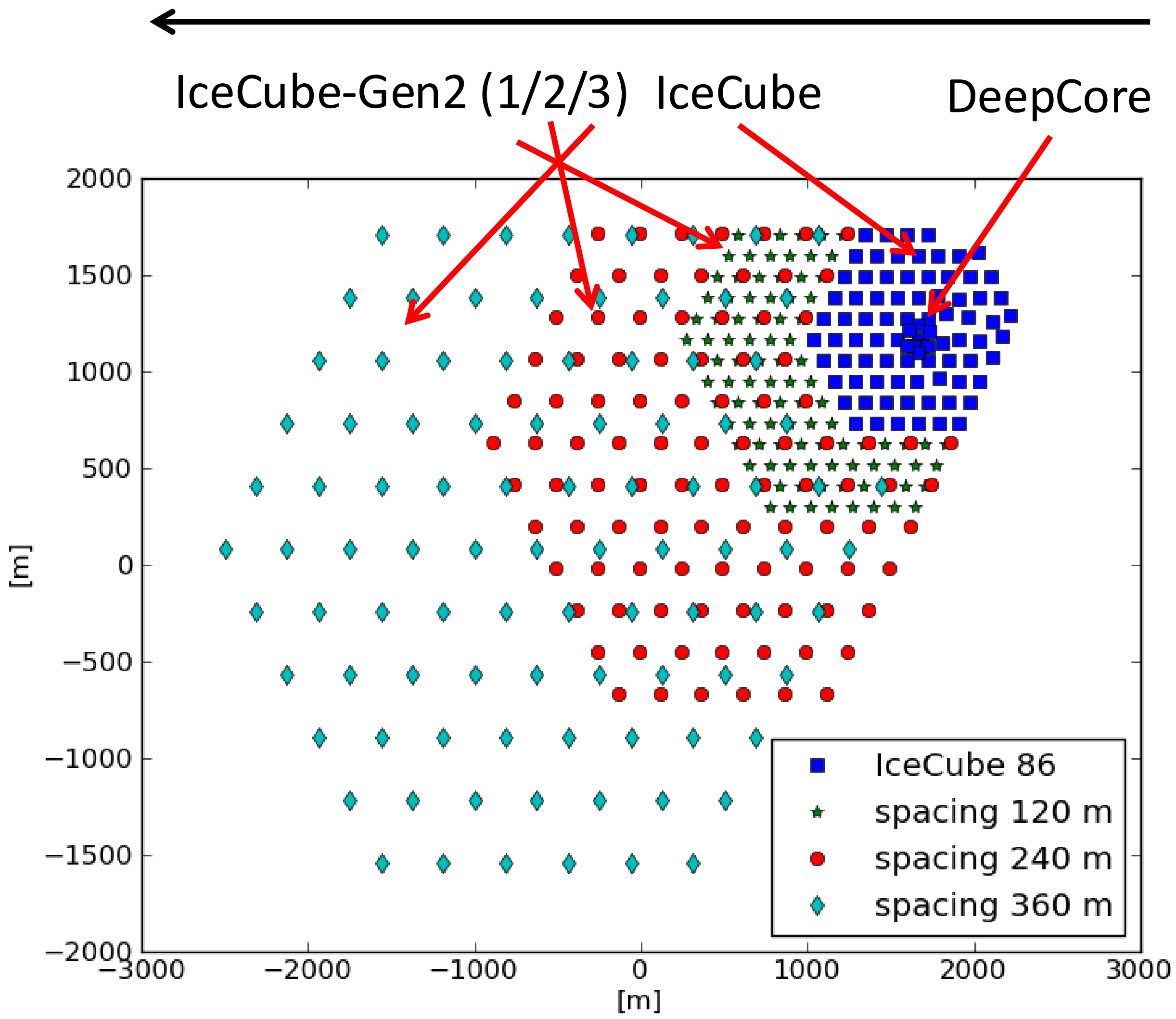




Anisotropic scattering due to birefringent ice crystals

measured optical properties → twice the string spacing

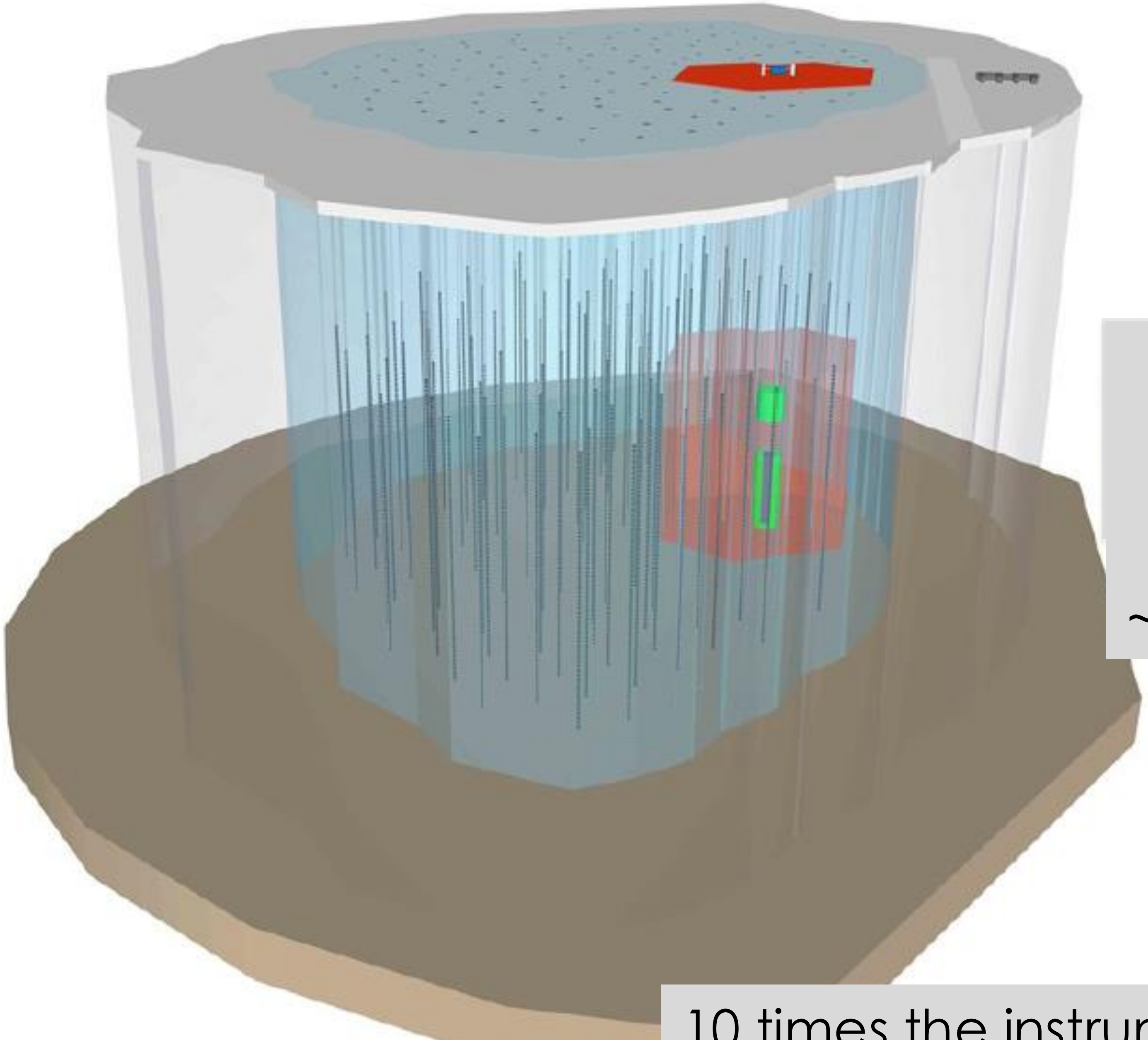
(increase in threshold not important: only eliminates energies where the atmospheric background dominates)



Spacing 1 (120m):
IceCube (1 km^3)
+ 98 strings (1,3 km^3)
= 2,3 km^3

Spacing 2 (240m):
IceCube (1 km^3)
+ 99 strings (5,3 km^3)
= 6,3 km^3

Spacing 3 (360m):
IceCube (1 km^3)
+ 95 strings (11,6 km^3)
= 12,6 km^3



120 strings
depth 1.35 to
2.7 km
80 DOM/string
~250 m spacing

10 times the instrumented volume
for the same budget as IceCube

10 PeV

10 TeV
120 strings
1350-1600m
80 modules

100 GeV

1 GeV

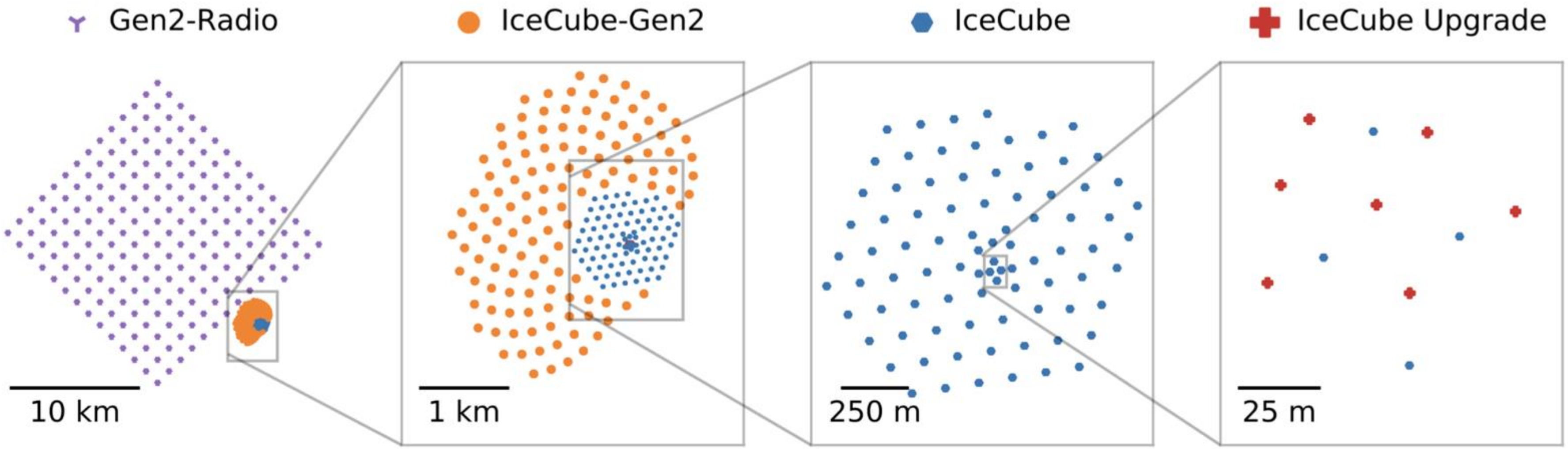
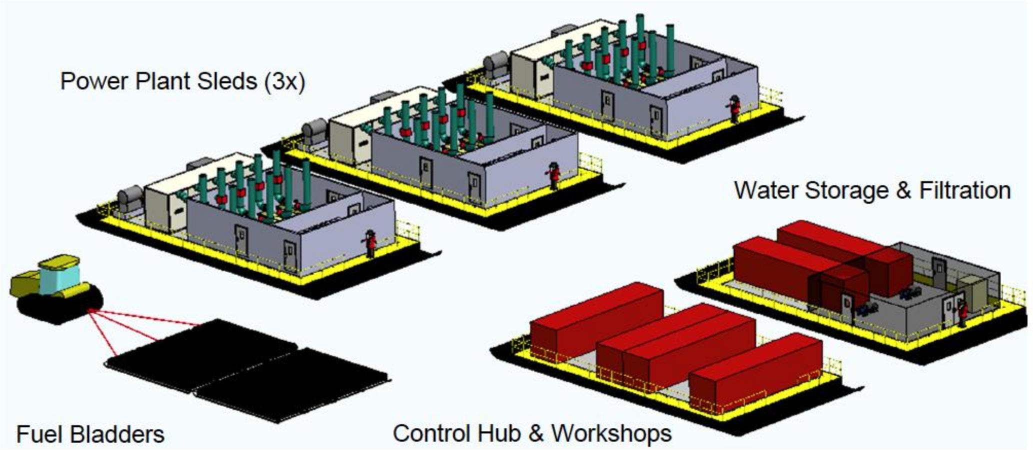
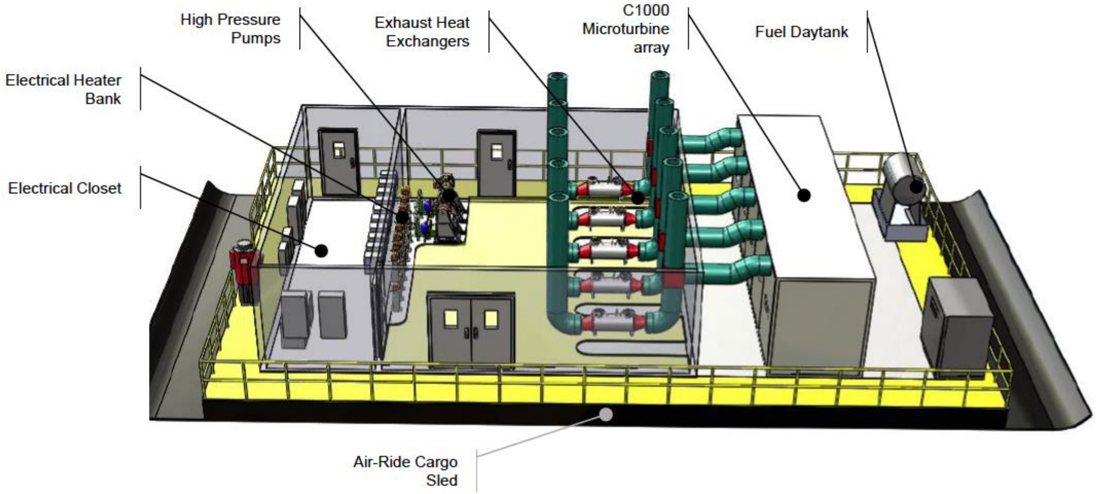


Figure 10: Exploded top-view of the full IceCube-Gen2 observatory. Far left shows the radio array, composed of individual stations resulting in a more than 500 km^2 instrumented area, relative to the Gen2 optical deep ice array and the existing IceCube detector.



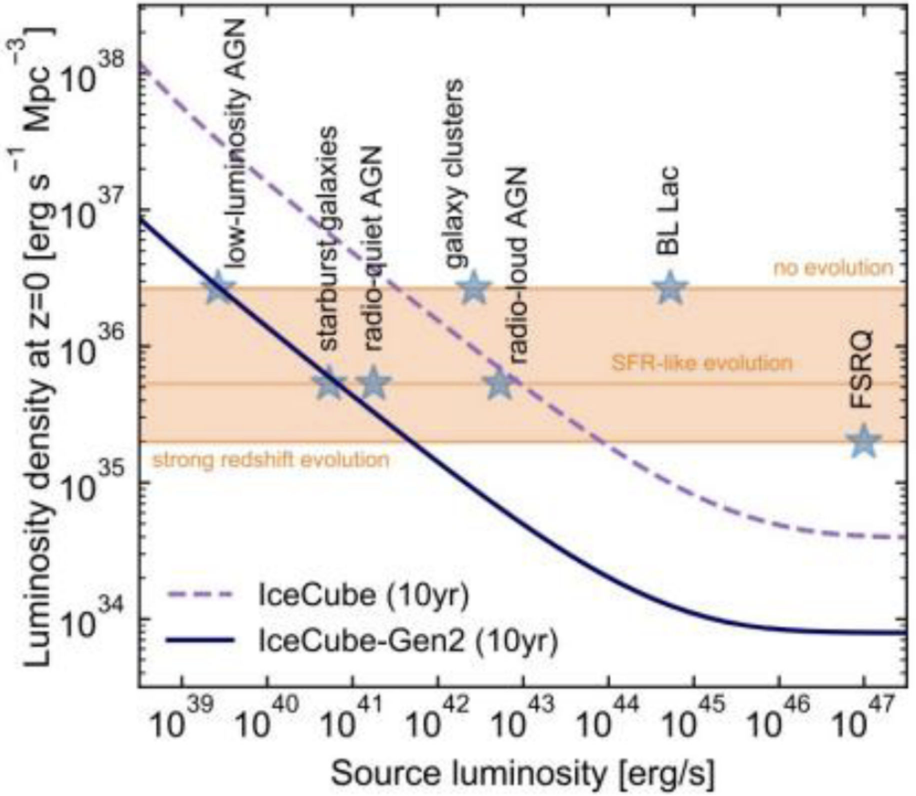


- Next-generation Enhanced Hot Water Drill
  - reduced footprint
  - smaller crew
- Transport equipment and fuel using South Pole Traverse
  - fewer flights needed
- May also reduce hole diameter
  - reduced fuel usage

Number of flights

LC 130 aircraft

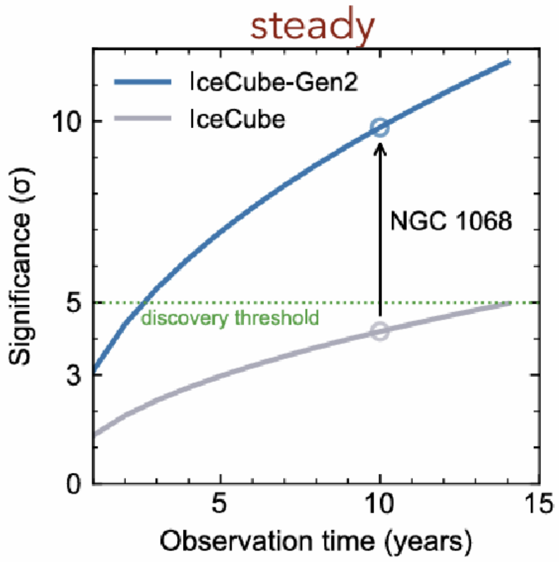
resolving the neutrino sky from TeV to EeV energy

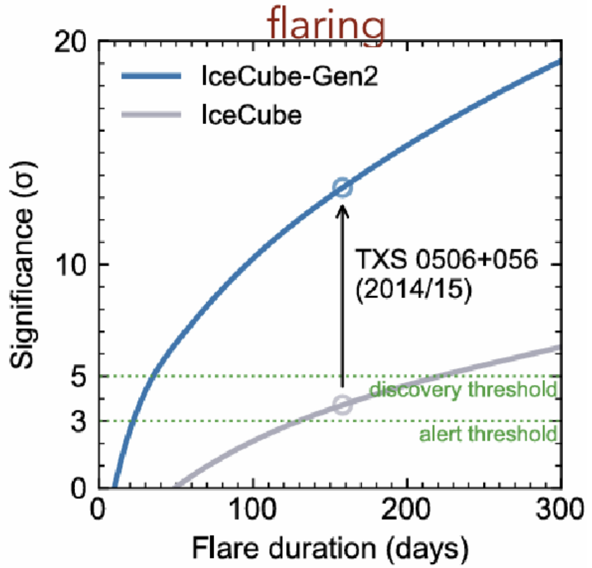


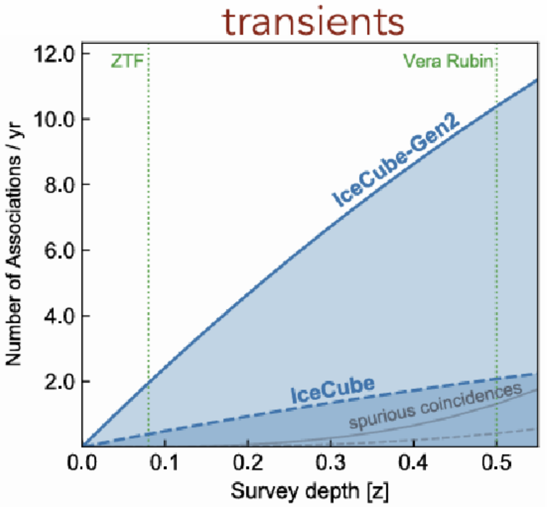
IceCube-Gen2 vs IceCube:

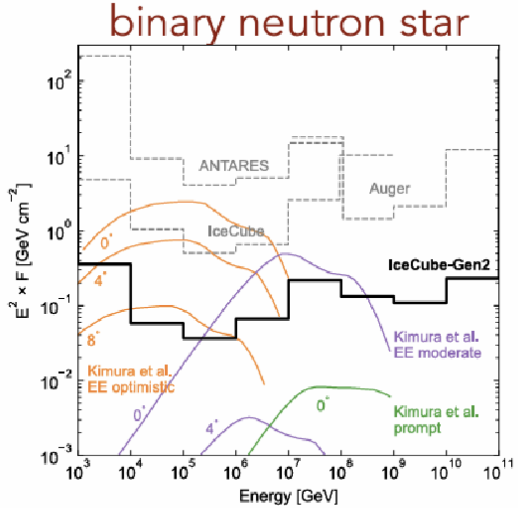
- 5 x point source sensitivity
- 10 x number of sources

IceCube-Gen2 will probe the leading source classes producing the diffuse neutrino flux

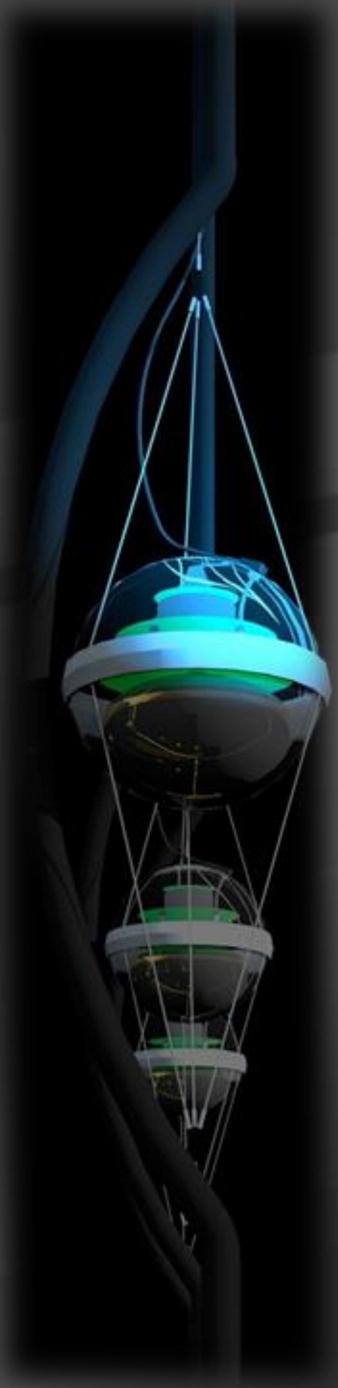








Technical Design Report - Part I



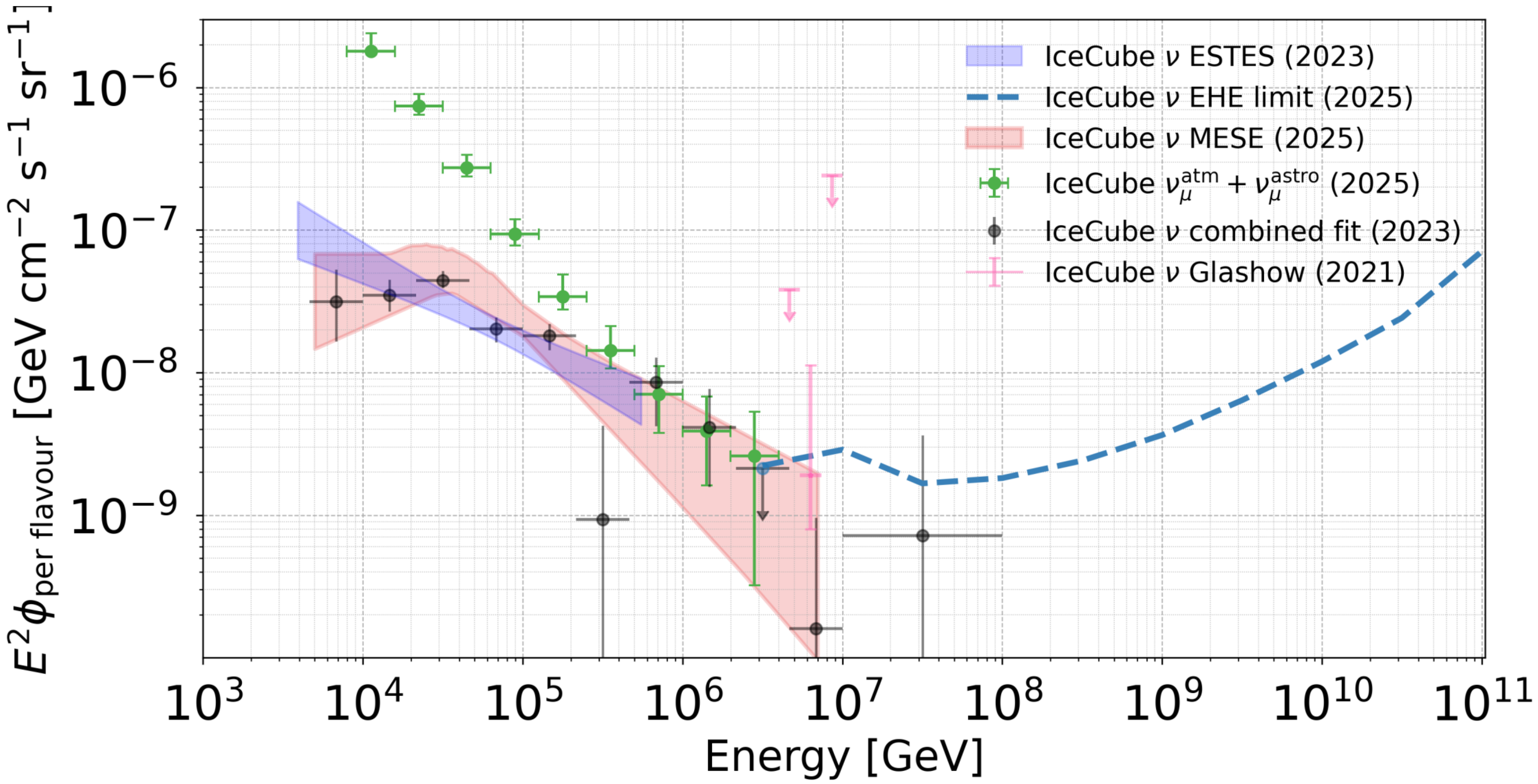
IceCube: beyond neutrino astronomy

Francis Halzen

- natural Antarctic ice as a Cherenkov detector
- neutrino physics: from GeV to PeV
- detecting the next Galactic supernova explosion
- search for dark matter
- beyond the Standard Model physics: quantum decoherence, sterile neutrinos, neutrino cross sections, …
- cosmic ray physics

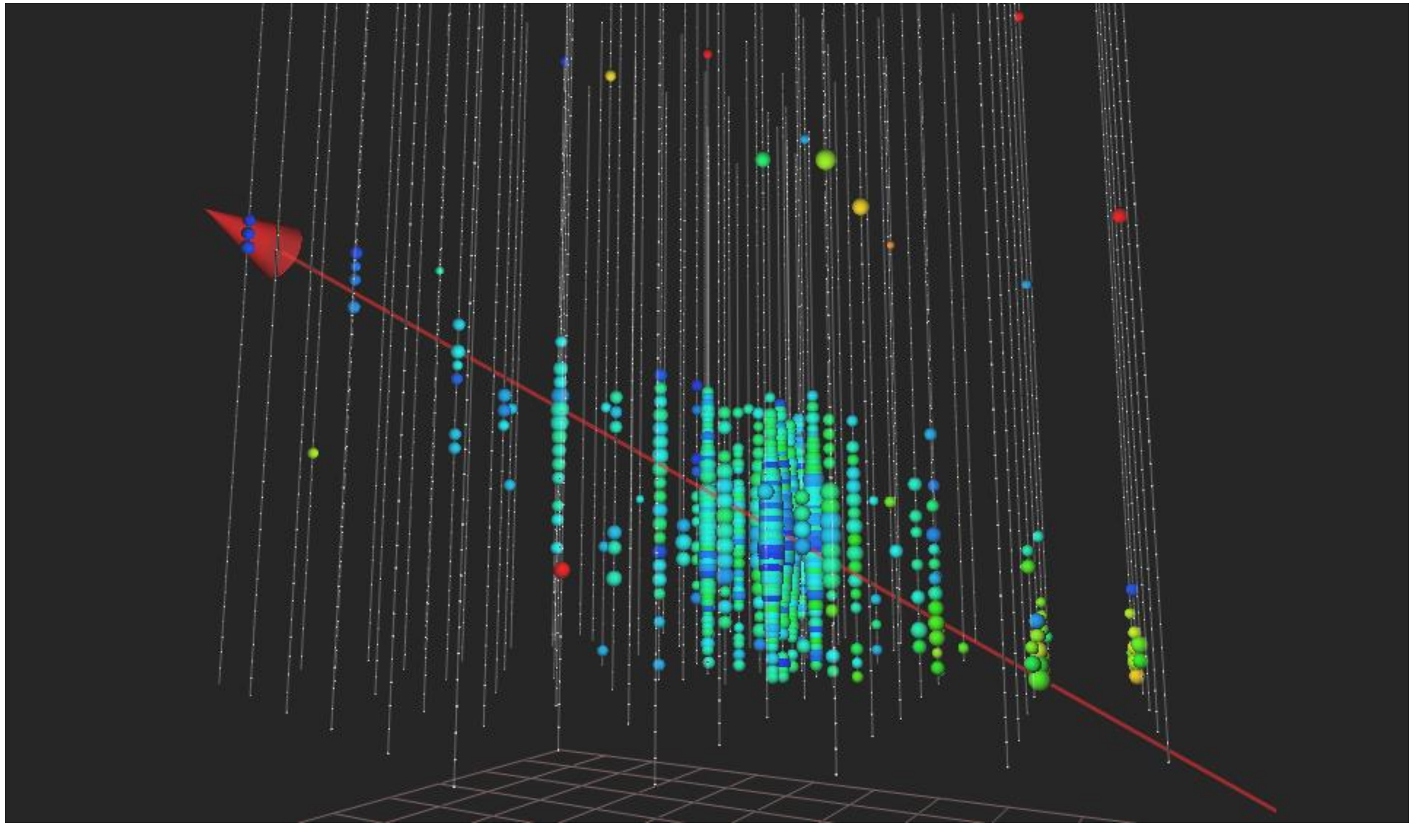
IceCube.wisc.edu

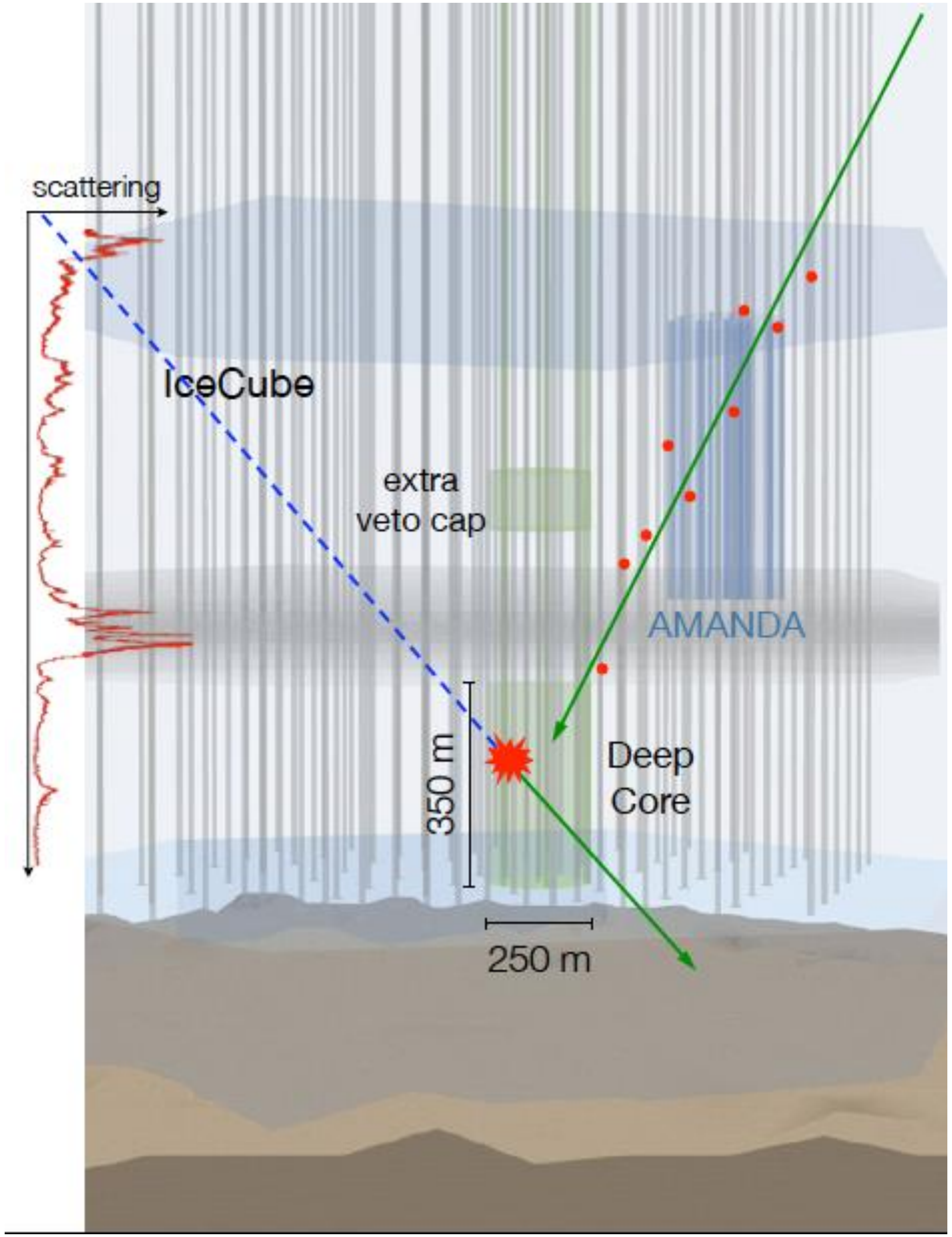
natural neutrino beams: the atmosphere and the cosmos



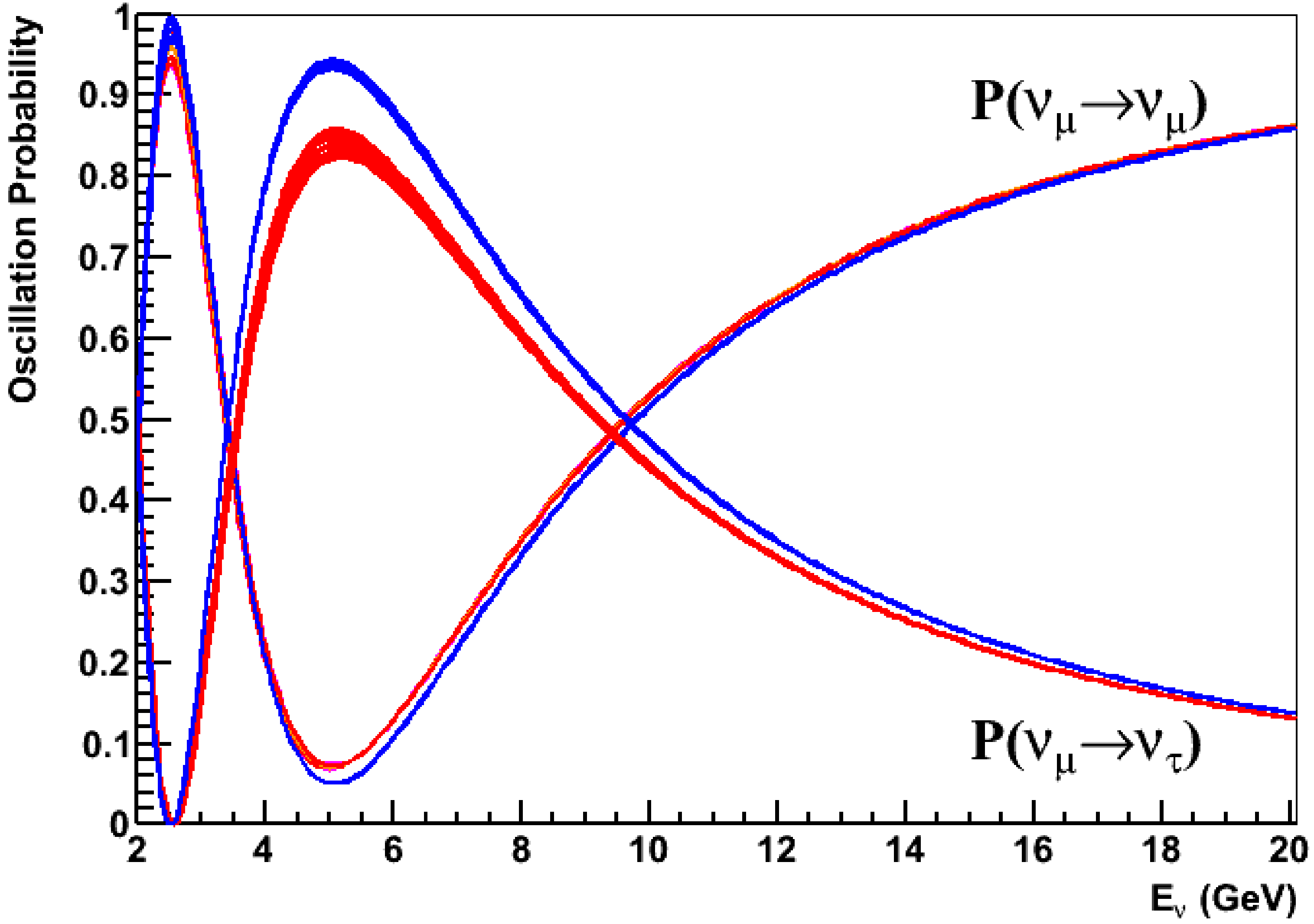
one million atmospheric neutrinos:

- 2 megaton detector (statistics)
- near 25 GeV energy nearly all muon neutrinos reappear as tau neutrinos. We measure both.
- IceCube veto: puts DeepCore at an effective depth well below SNOLAB



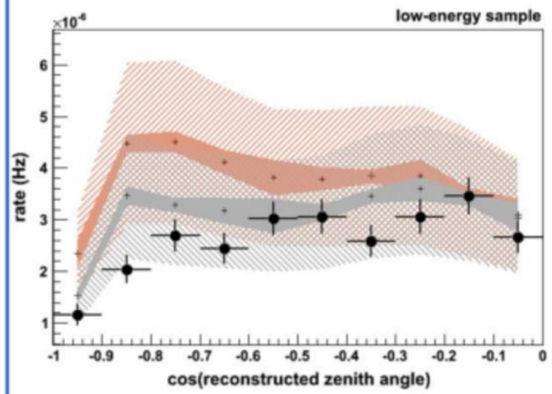


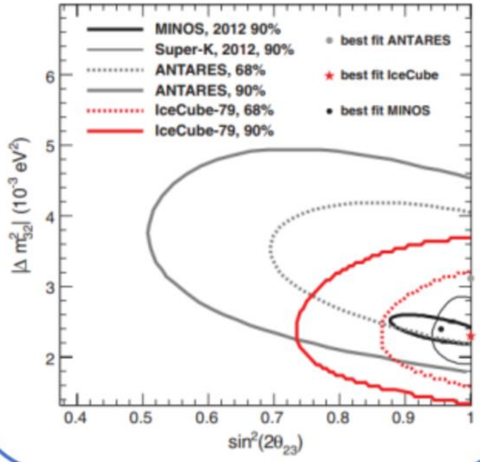
- oscillations at 10 GeV energy and above
- oscillation parameters measured in a new energy range.



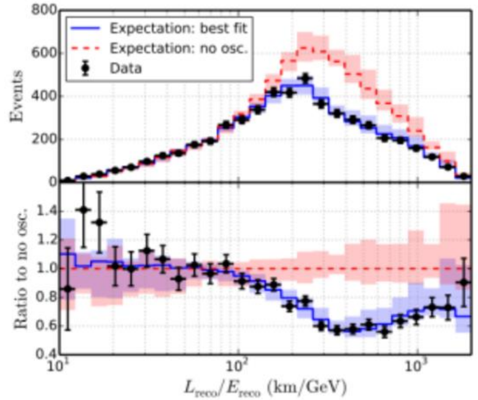
Atmospheric oscillations progression

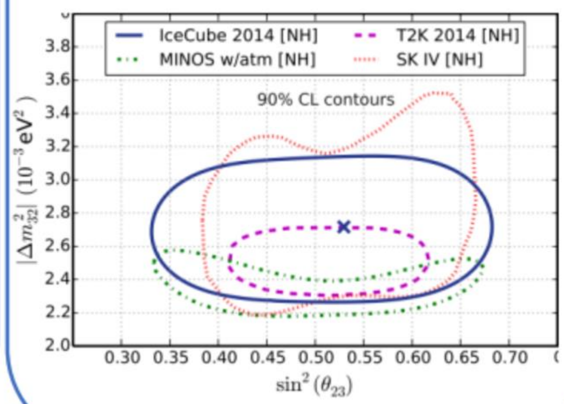
IceCube, PRL 111, 081801 (2013)
700 events



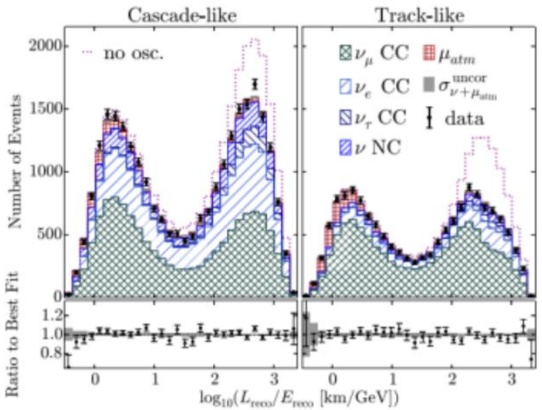


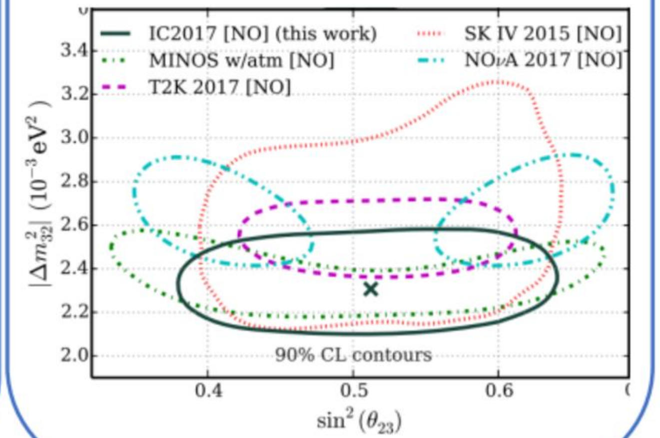
IceCube, PRD 91, 072004 (2015)
~5k events



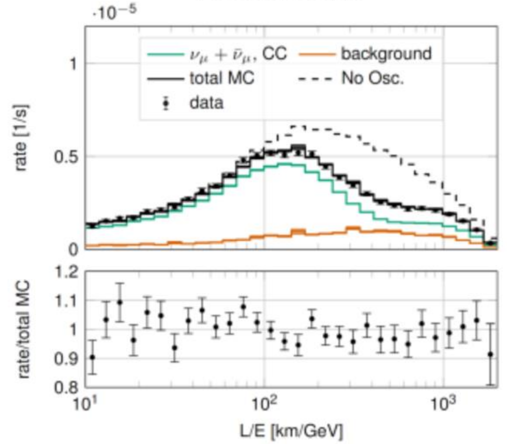


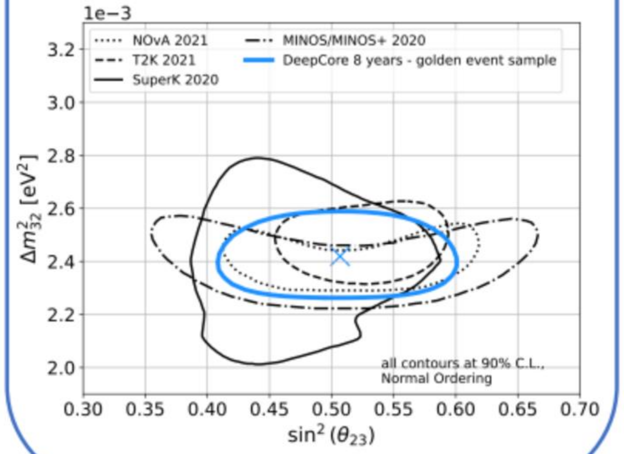
IceCube, PRL 120, 071801 (2018)
~35k events



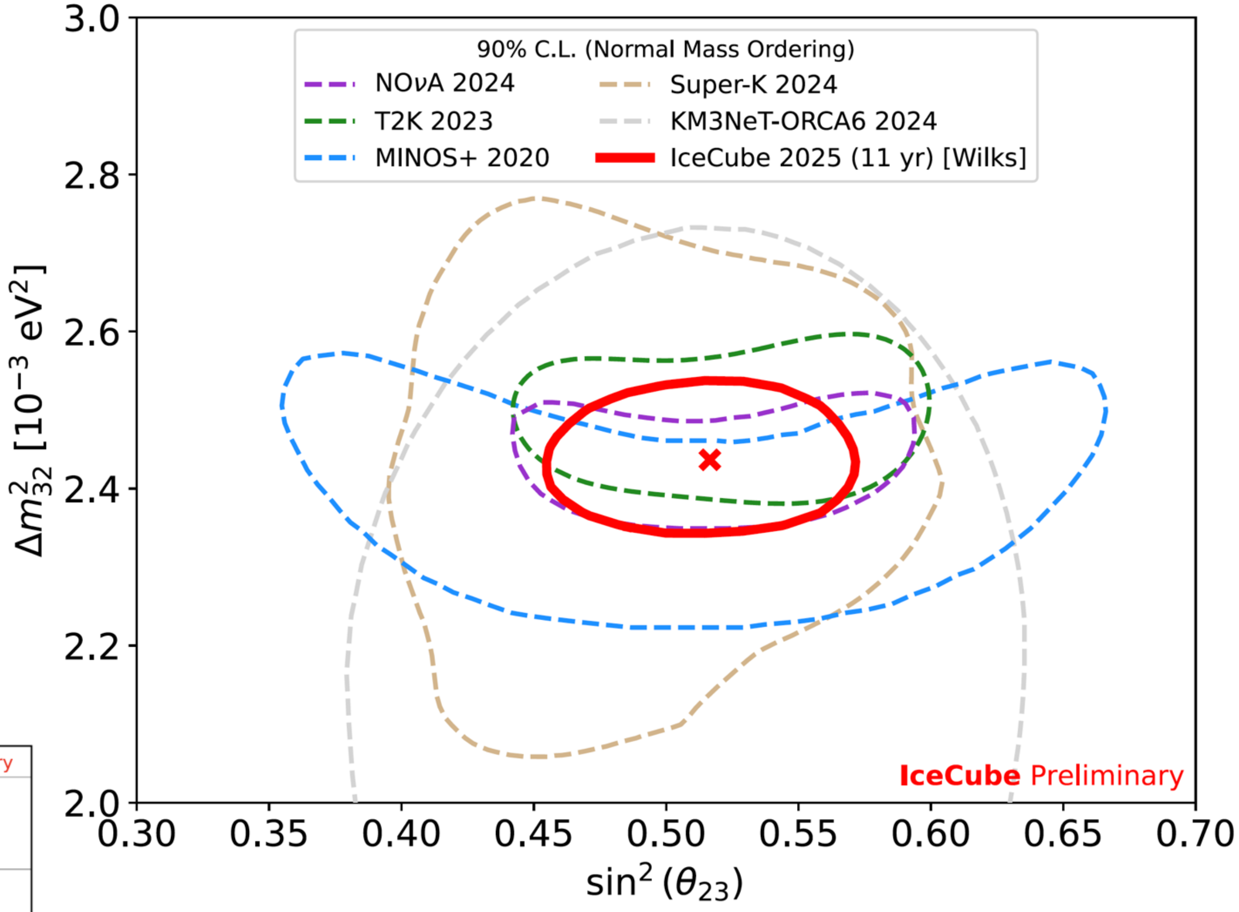


IceCube, PRD 108, 012014 (2023)
~22k events

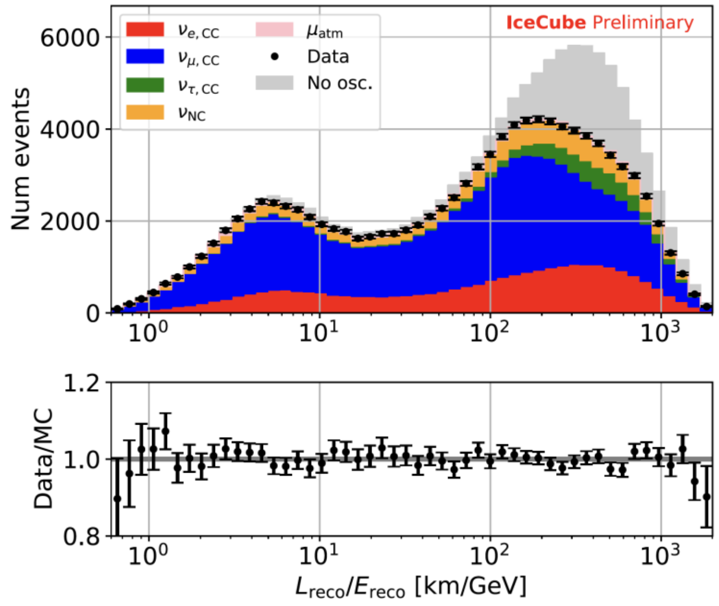


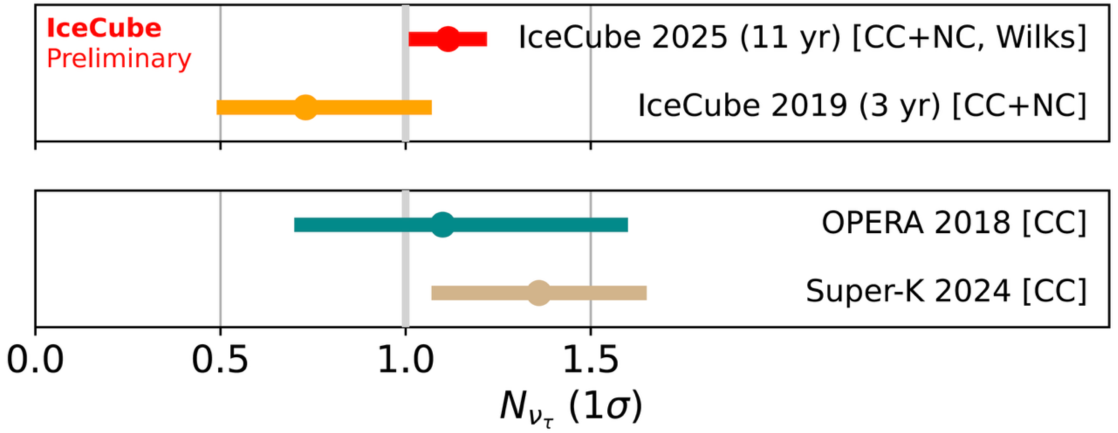


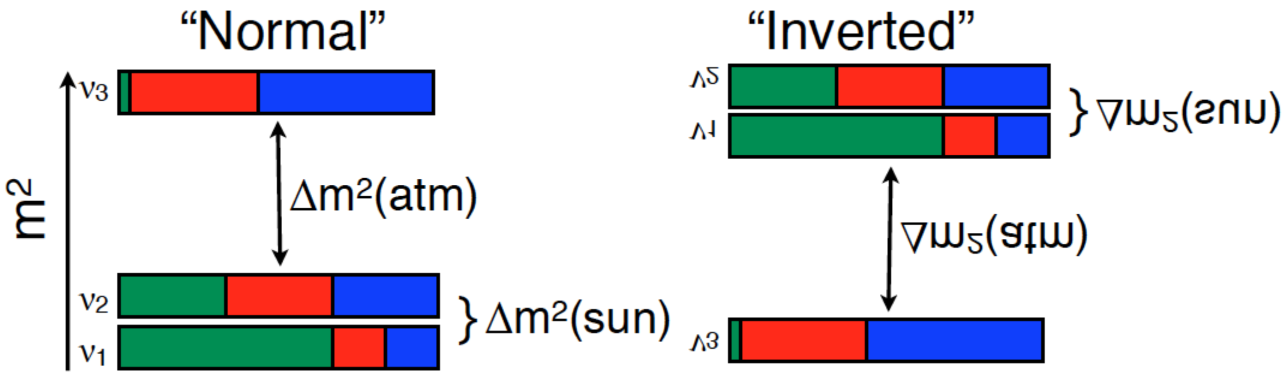
- fit both the atmospheric flux and the oscillation parameters
- blind analysis

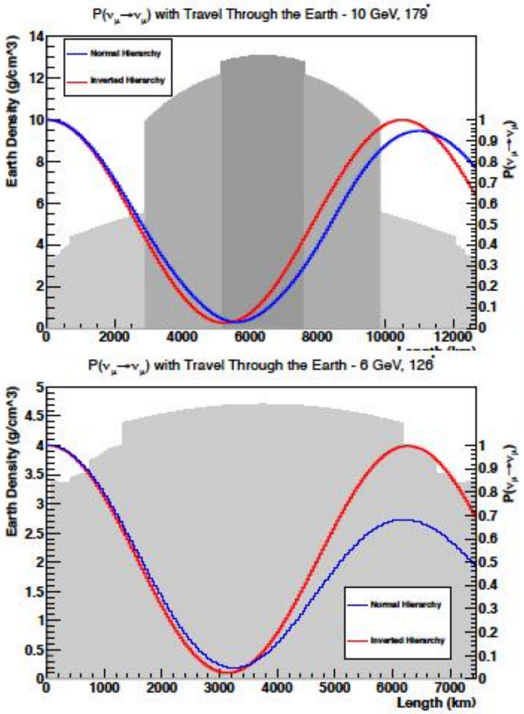


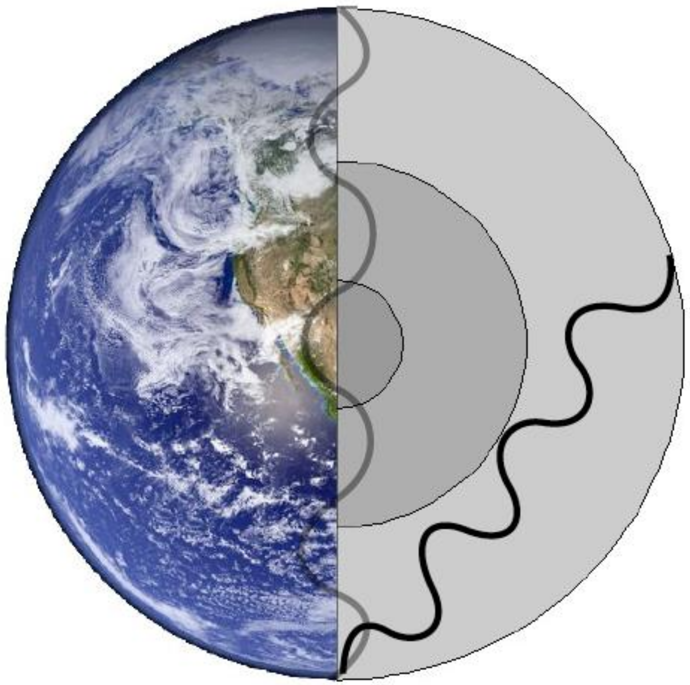
- Broad coverage of L/E phase-space
  - Baselines ranging from ~200km to ~12700km
  - Reconstructed energies from 5 GeV - 100 GeV











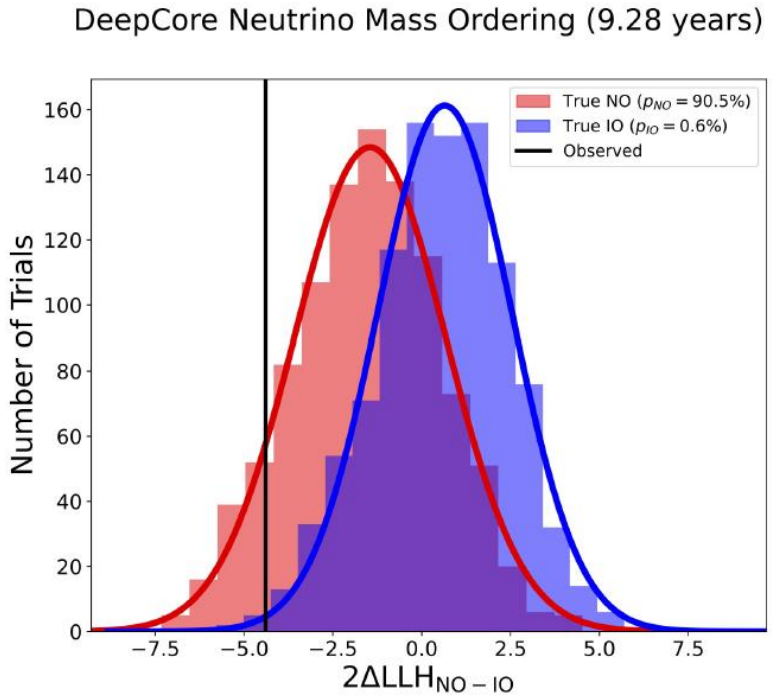
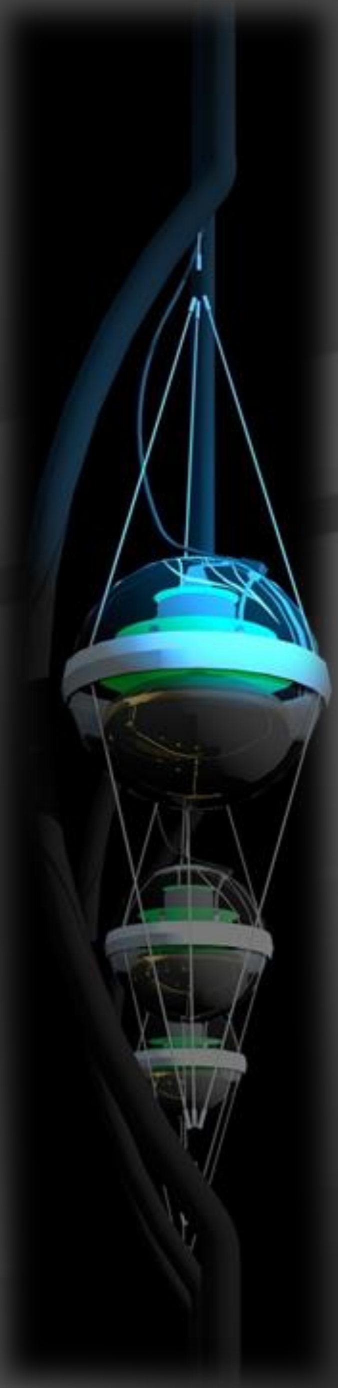


Figure 8.2: Results of the NMO analysis using 9.28 years of IceCube DeepCore data. The analysis observes a preference for the normal ordering over the inverted ordering at $2\Delta LLH_{\text{NO-IO}} = -4.398$, leading to a disfavoring of the inverted ordering at a 93.7% exclusion level, or 1.86σ.

Maria Prado UW-Madison thesis

	3-Year DeepCore	9.28-Year DeepCore (this work)
Observed $2\Delta LLH_{\text{NO-IO}}$	-0.738	-4.398
p_{IO}	15.7%	0.6%
p_{NO}	71.1%	90.5%
CL_s	53.3%	6.3%

Table 8.2: Comparison between the 3-year DeepCore NMO results [40] and this work. Clear improvement in the robustness of the results can be observed, where a much stronger preference for the normal ordering is now found.



IceCube: beyond neutrino astronomy

Francis Halzen

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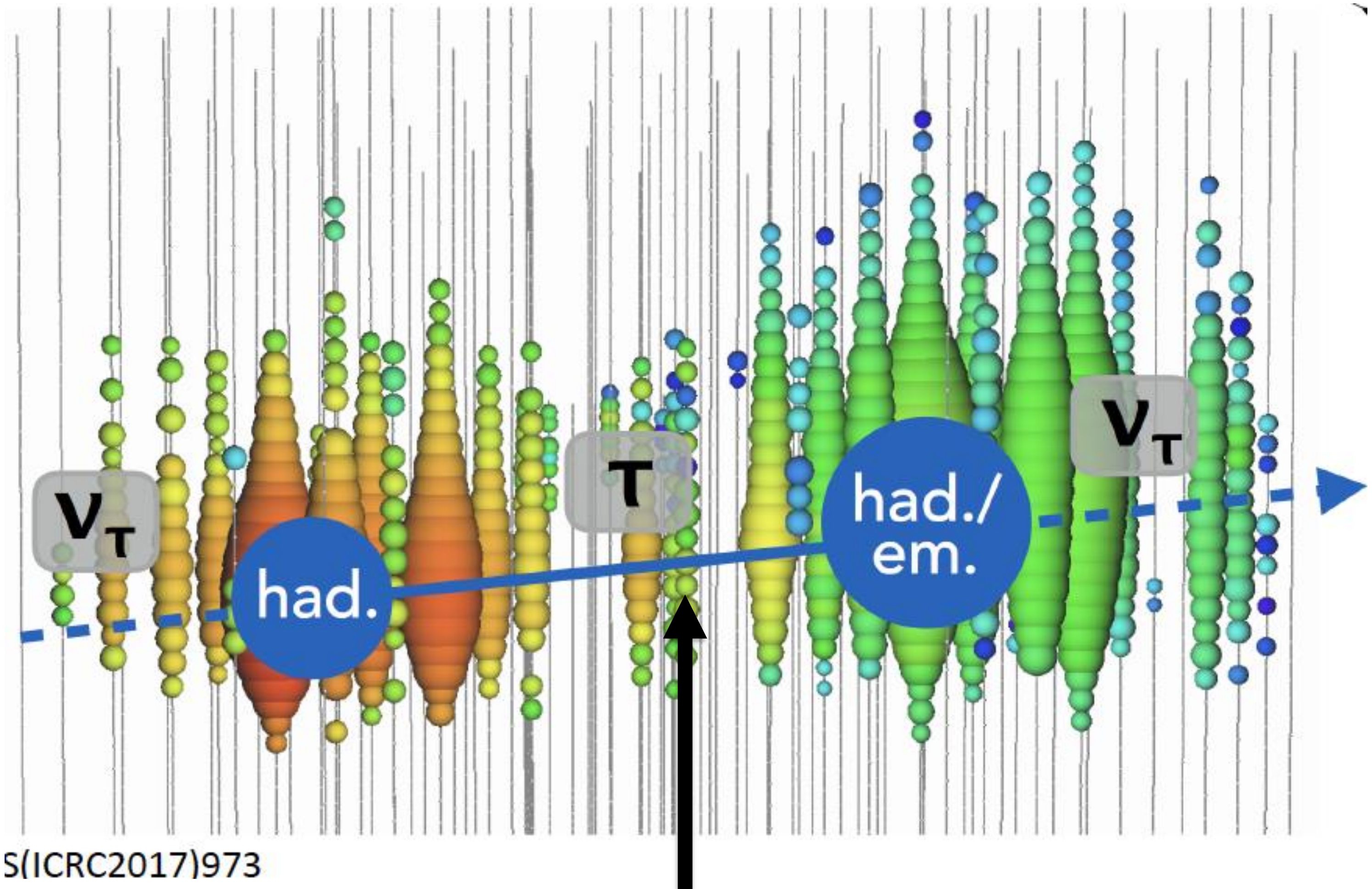
- detecting the next Galactic supernova explosion
- search for dark matter
- beyond the Standard Model physics: quantum decoherence, sterile neutrinos, neutrino cross sections, …
- cosmic ray physics

IceCube.wisc.edu

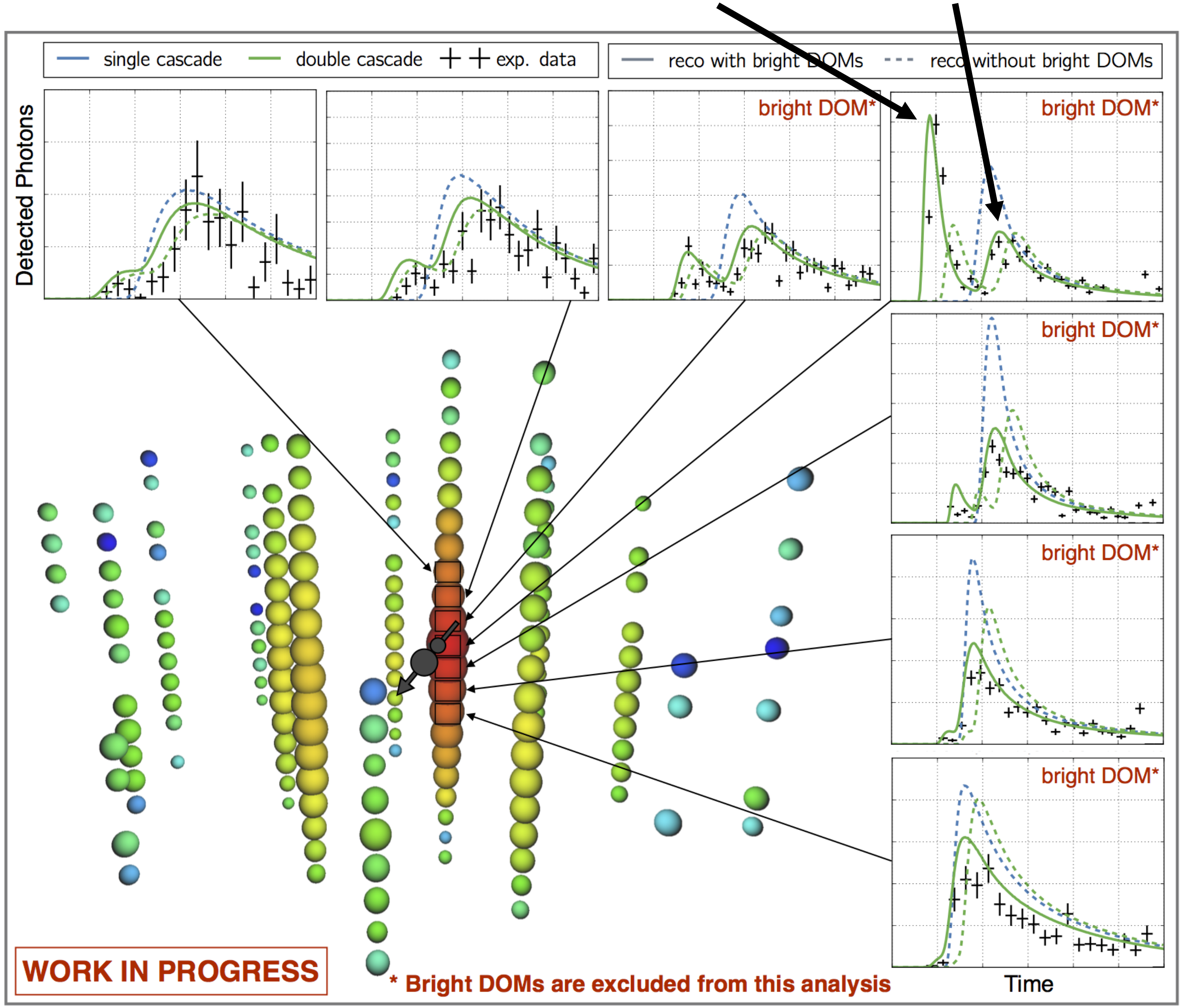
tau neutrino production and decay

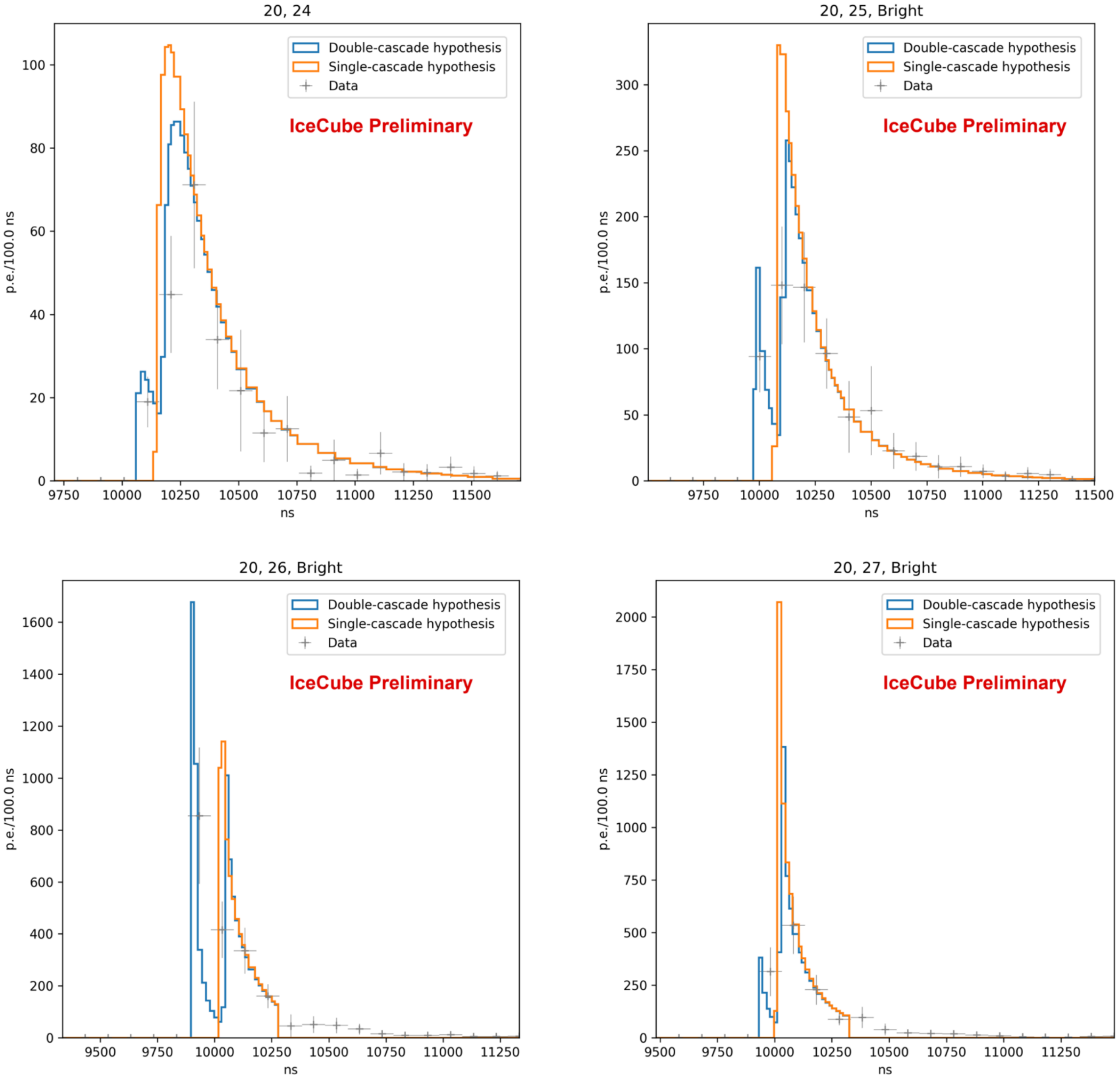


tau decay length:
$\gamma c\tau$ = 50m per PeV

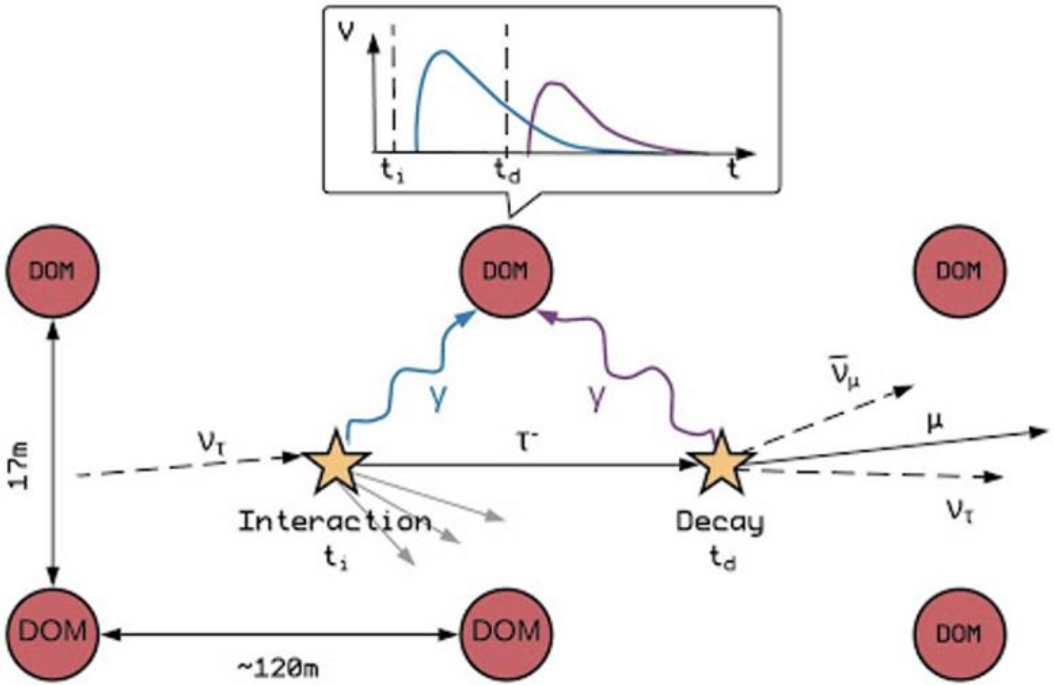
a cosmic tau neutrino with 17m lifetime

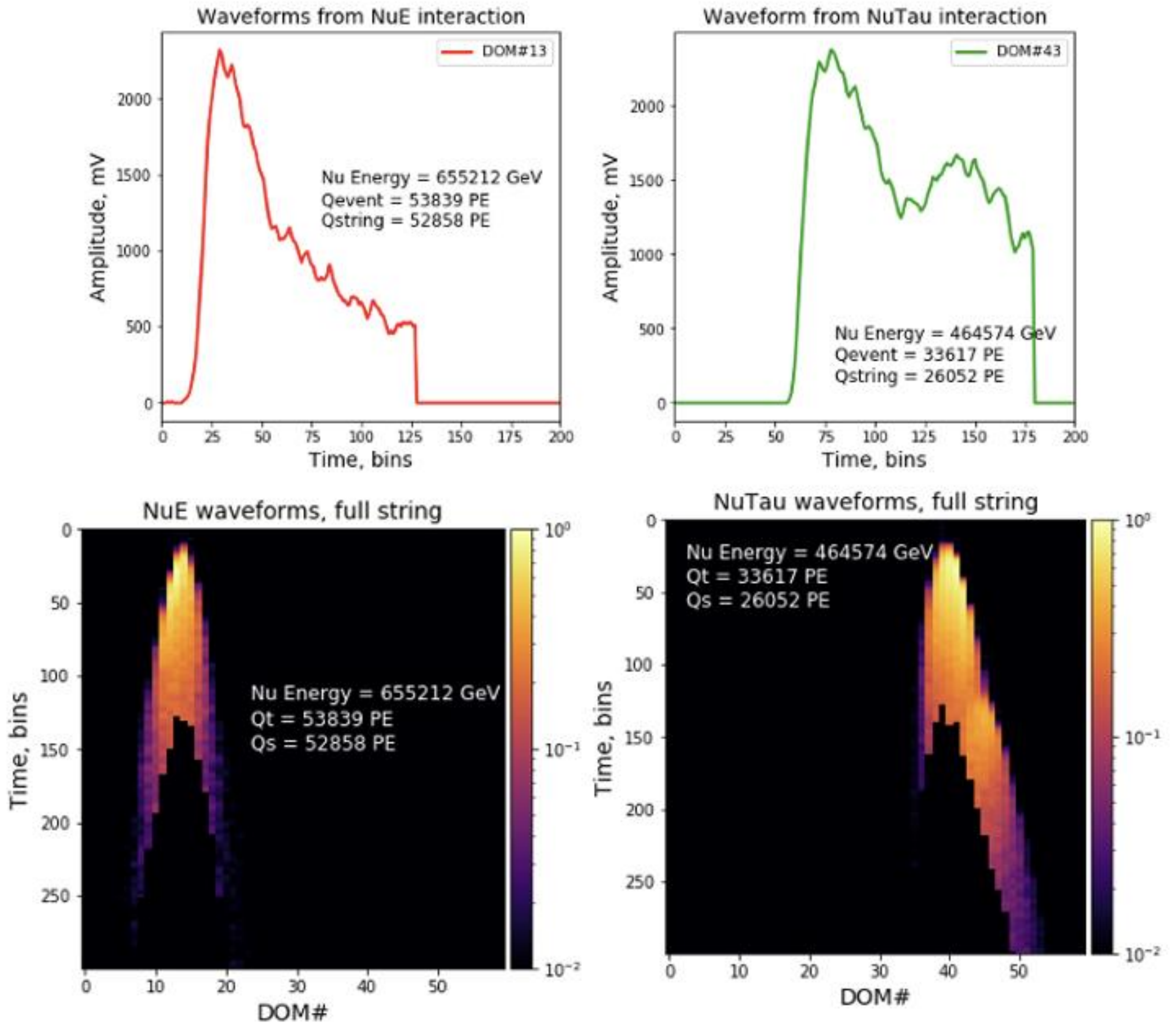
light from nutau interaction and tau decay



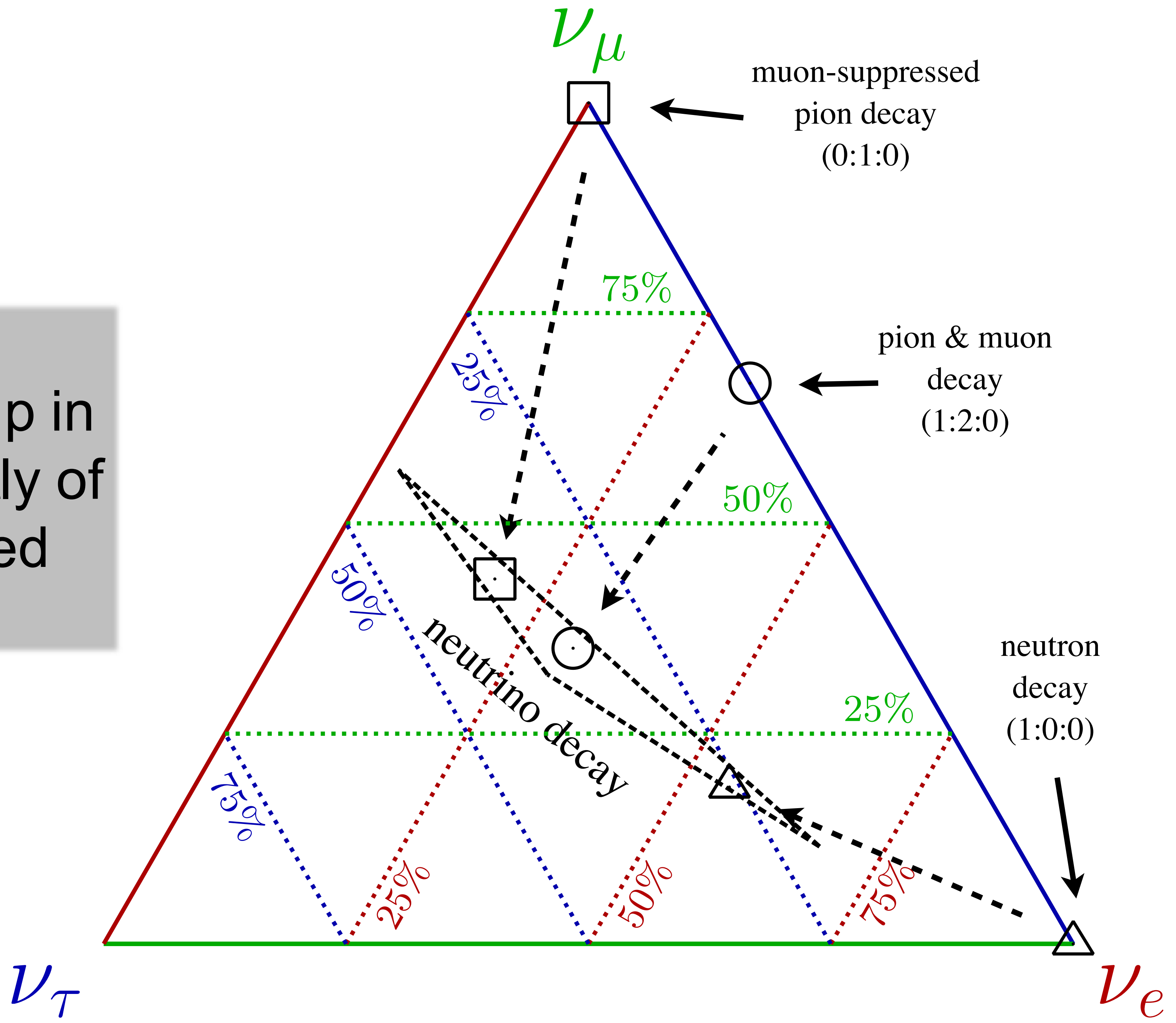

20, 24
Double-cascade hypothesis
Single-cascade hypothesis
Data
IceCube Preliminary
p.e./100.0 ns
ns
20, 25, Bright
Double-cascade hypothesis
Single-cascade hypothesis
Data
IceCube Preliminary
p.e./100.0 ns
ns
20, 26, Bright
Double-cascade hypothesis
Single-cascade hypothesis
Data
IceCube Preliminary
p.e./100.0 ns
ns
20, 27, Bright
Double-cascade hypothesis
Single-cascade hypothesis
Data
IceCube Preliminary
p.e./100.0 ns
ns

- double bang events: 8 predicted on a background of 1 and 7 observed
- each nutau event is an extragalactic neutrinos search

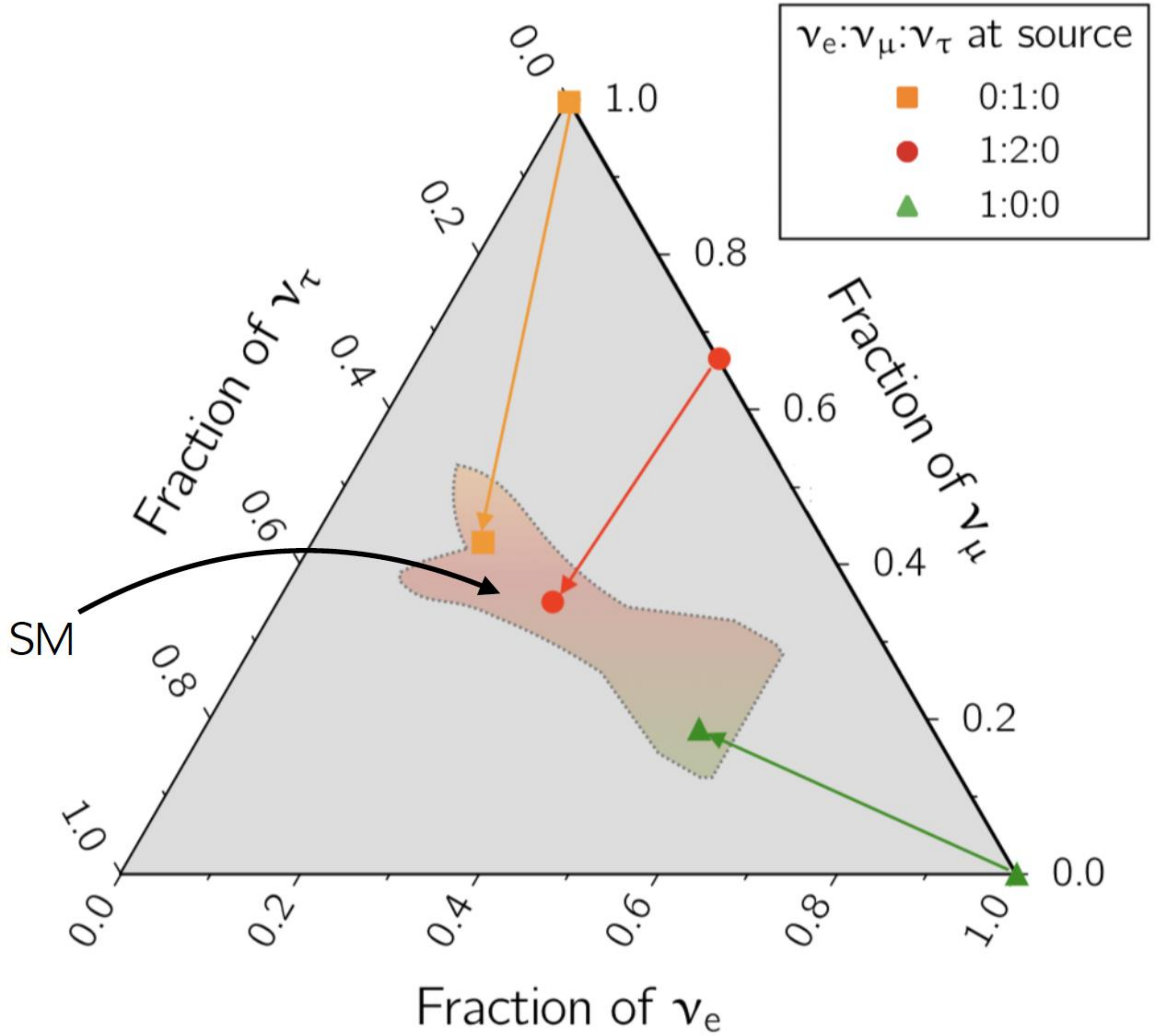


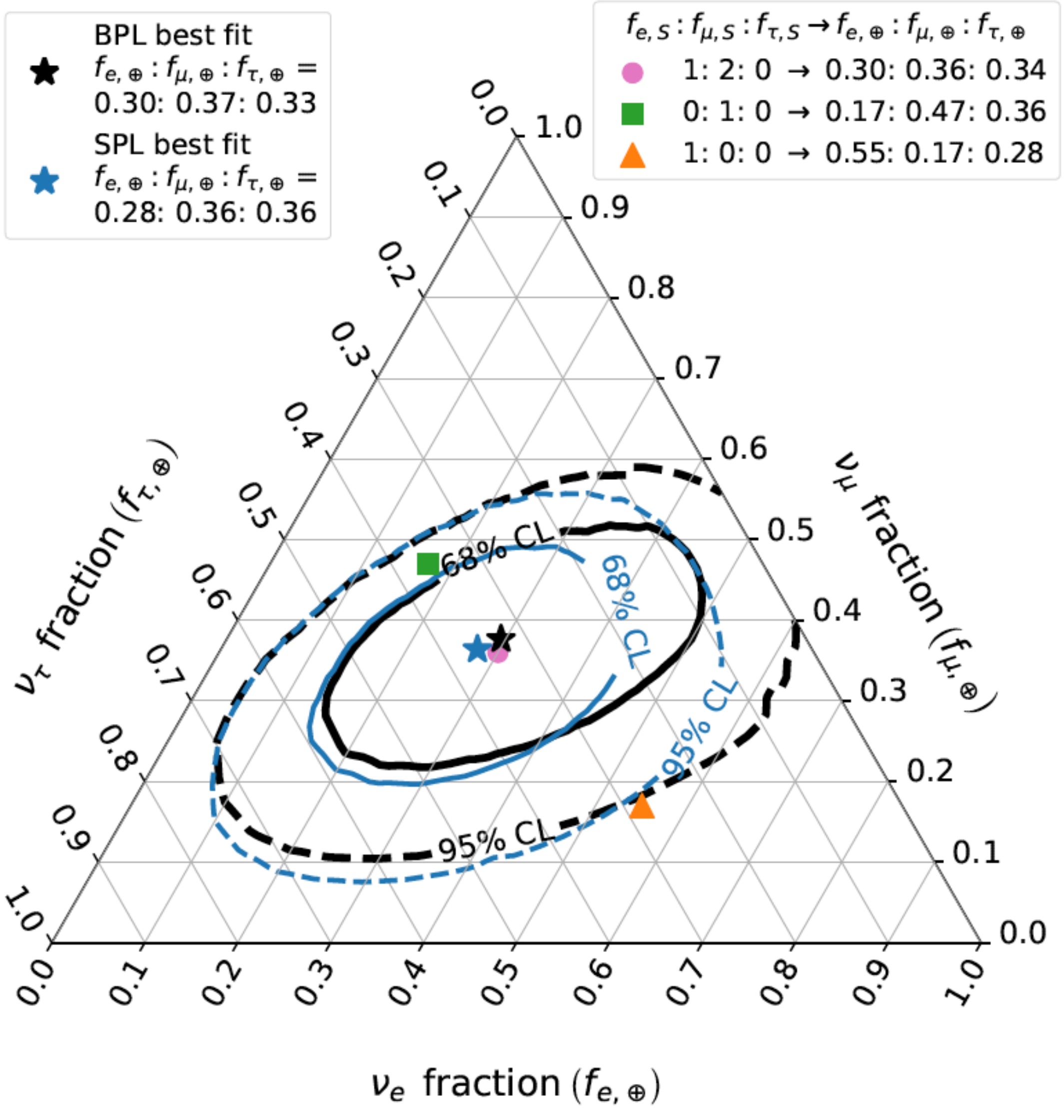


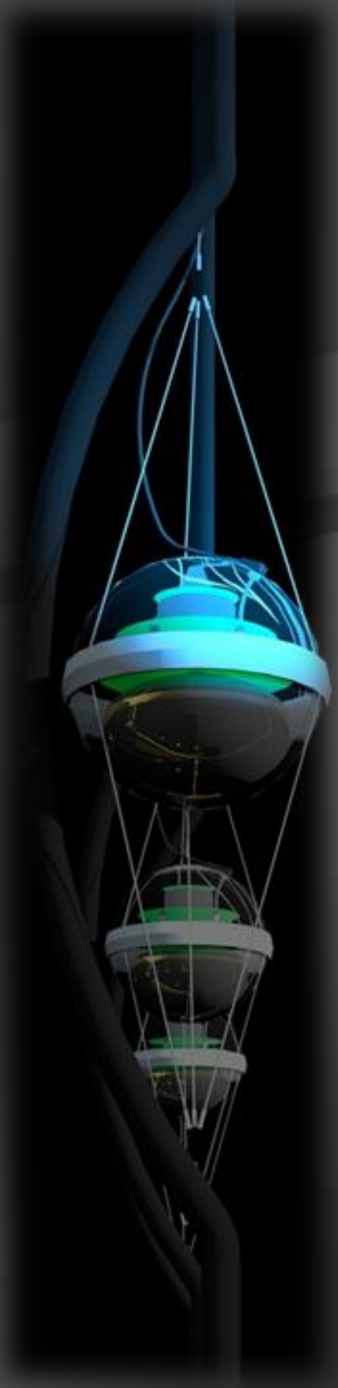
new physics ?
3-neutrino model ends up in the triangle independently of the initial flavors produced by cosmic accelerators



oscillations of PeV neutrinos over cosmic distances to 1:1:1







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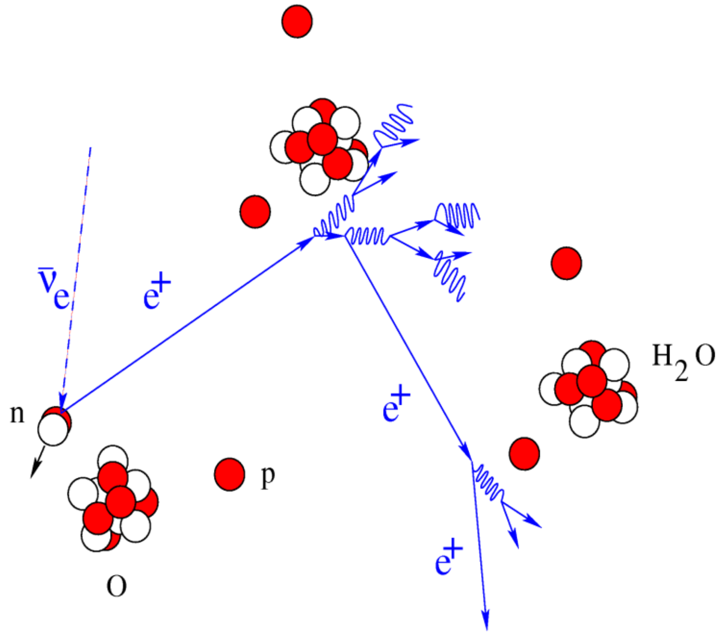
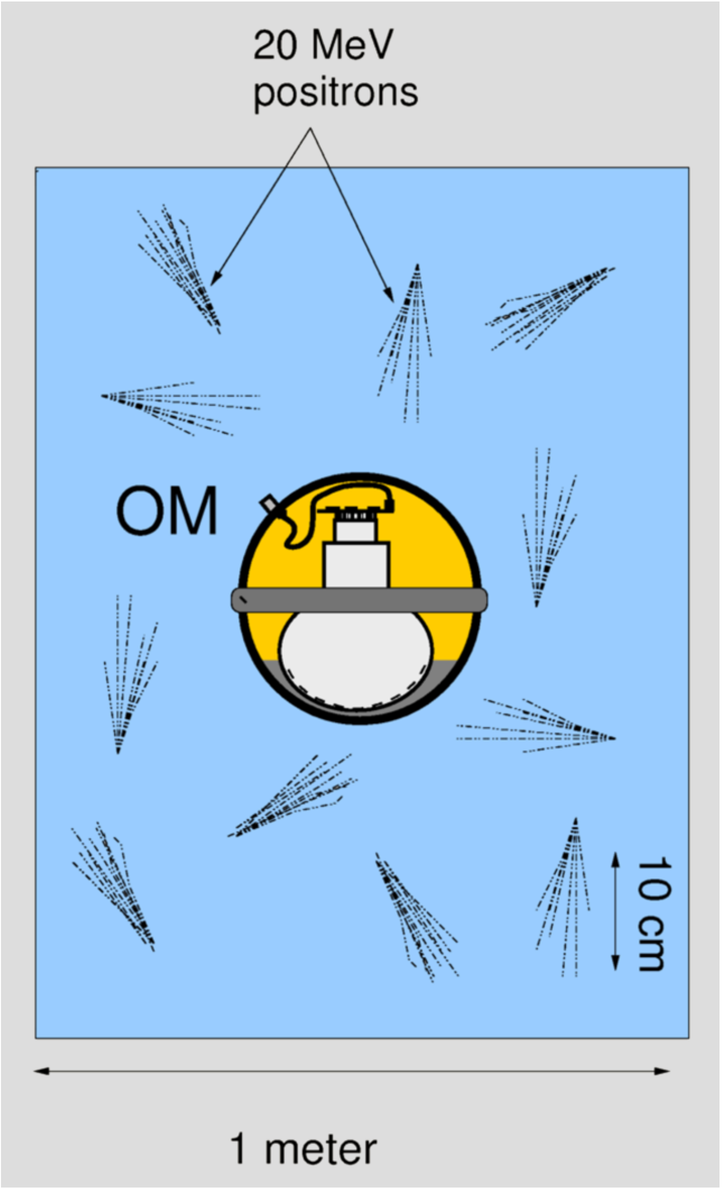
supernova burst: light from $\bar{\nu}_e + p \rightarrow n + e^+$

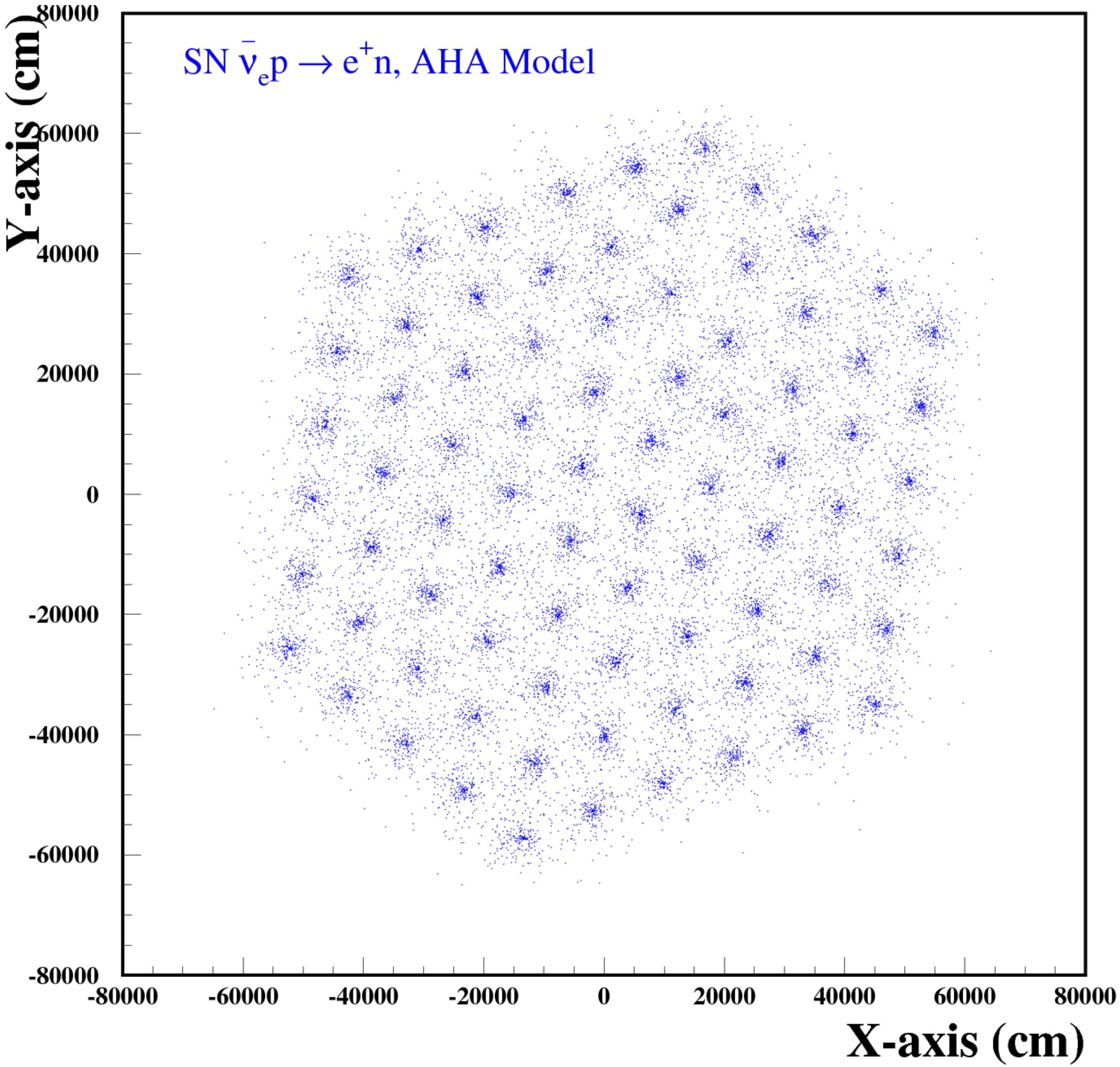
- ☞ PMT noise low (280 Hz)
- ☞ detect correlated rate increase on top of PMT noise when supernova neutrinos pass through the detector

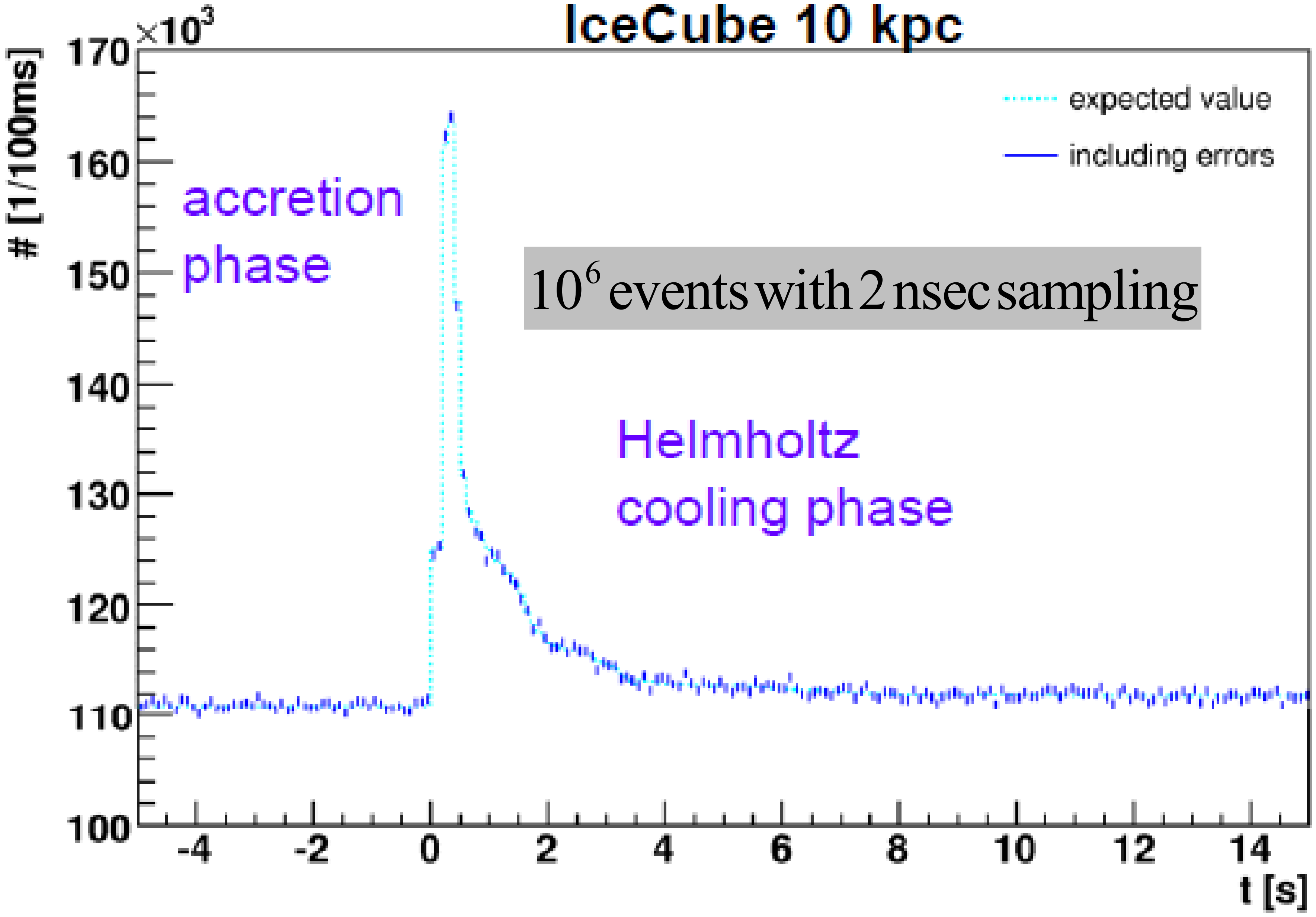




starting points of neutrino showers from supernova neutrinos

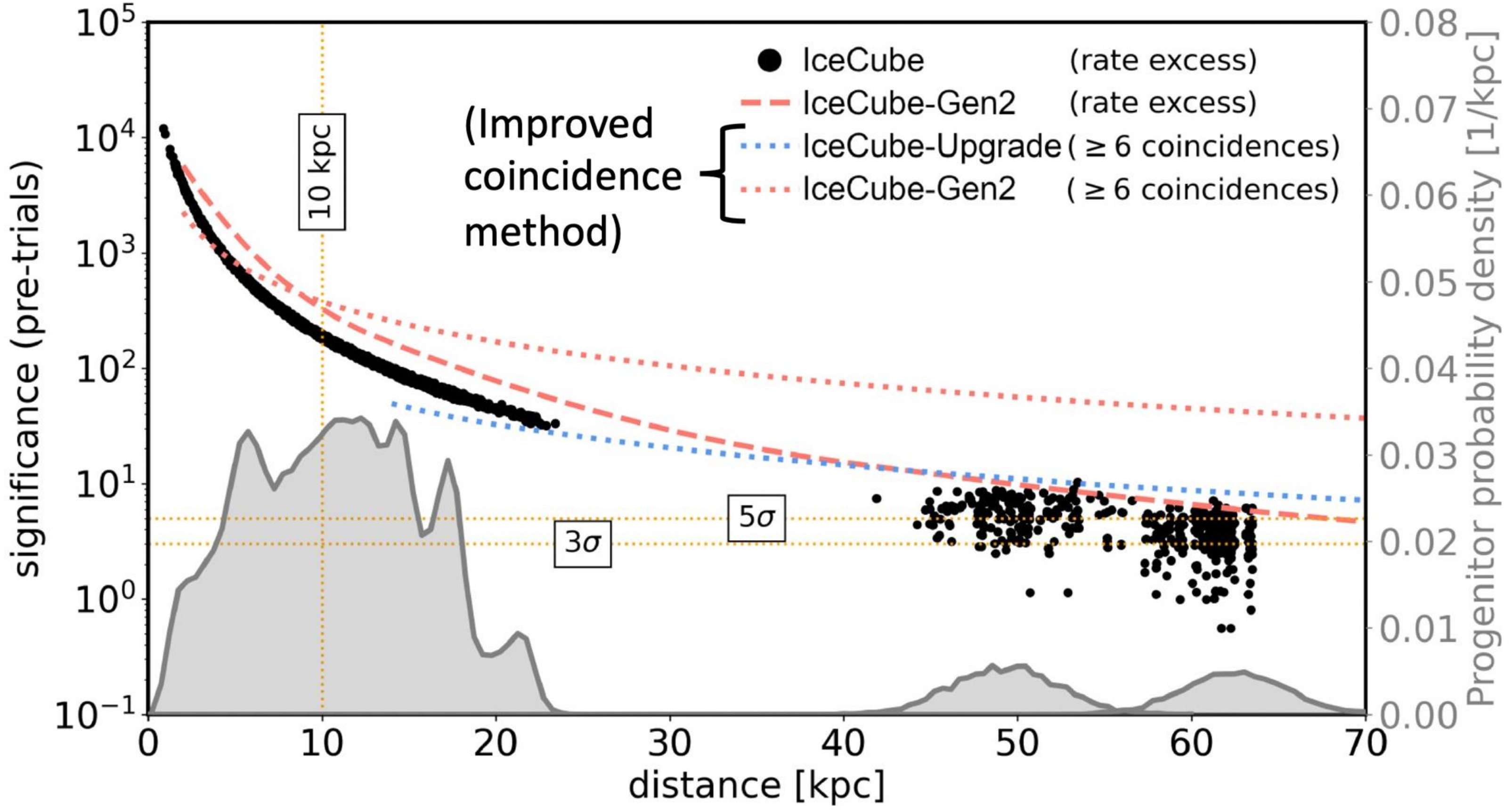
- equivalent detection volume of a 2 megaton SuperK-style detector
- 1 million events from 10 kpc
- neutronization electron neutrinos
- energy measurement from two-photon correlation



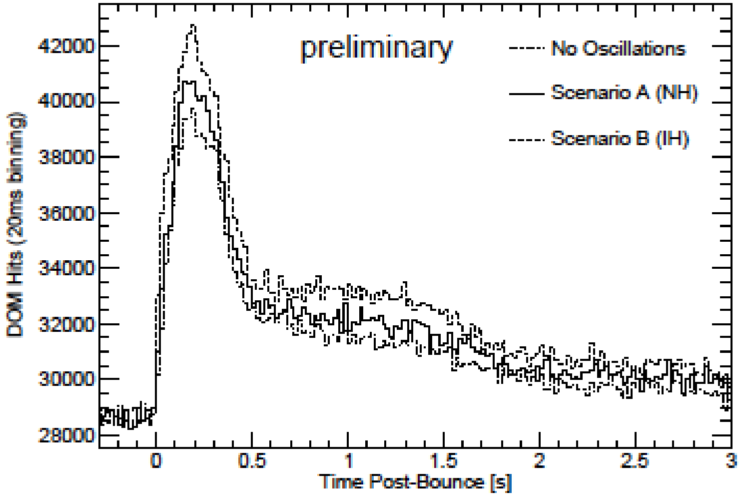

IceCube 10 kpc
$\times 10^3$
[1/100ms]
t [s]
expected value
including errors
accretion phase
Helmholtz cooling phase
10^6 events with 2 nsec sampling

MeV neutrinos in the Upgrade and Gen2

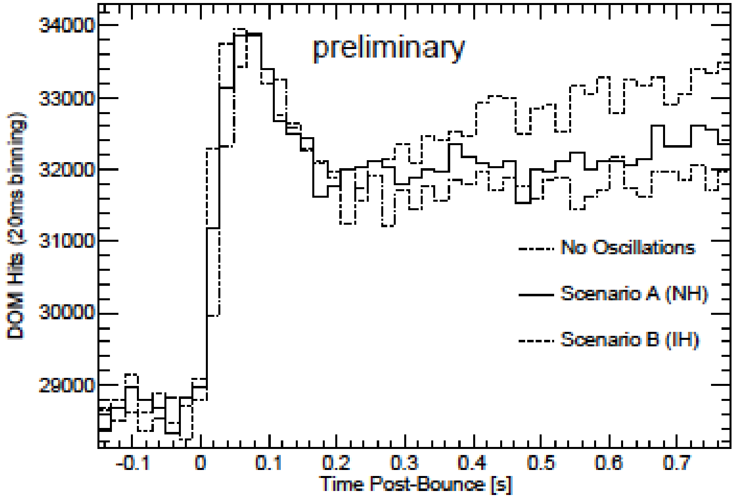
Require coincidences between nearby phototubes to reduce noise



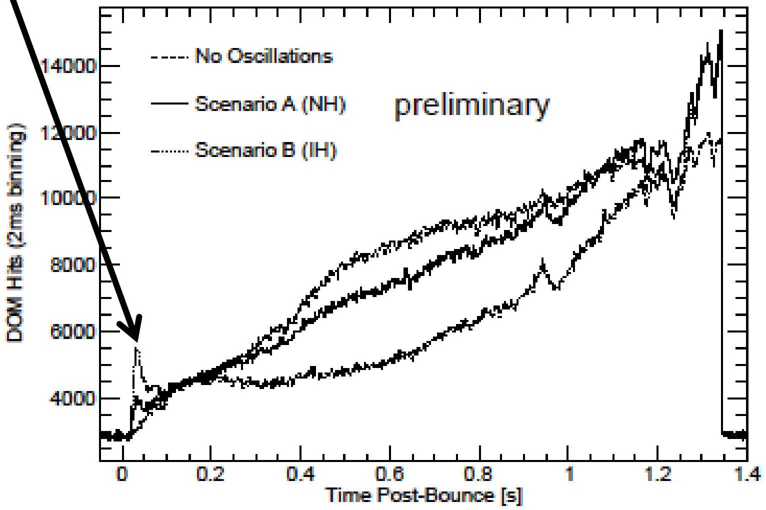
Livermore



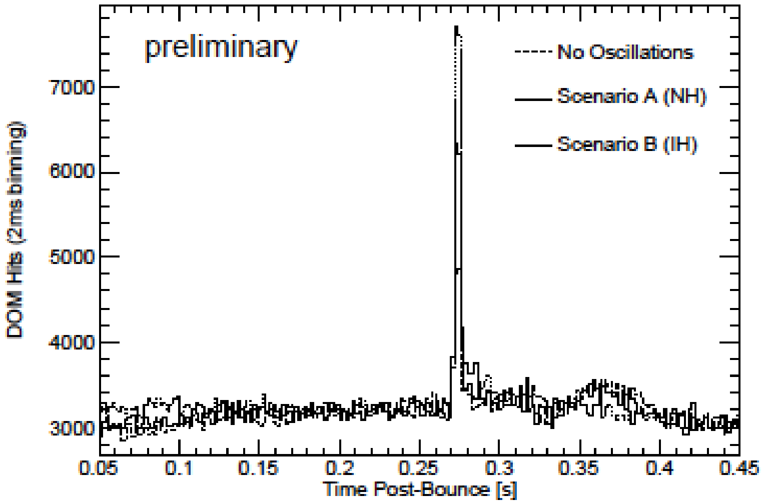
Garching



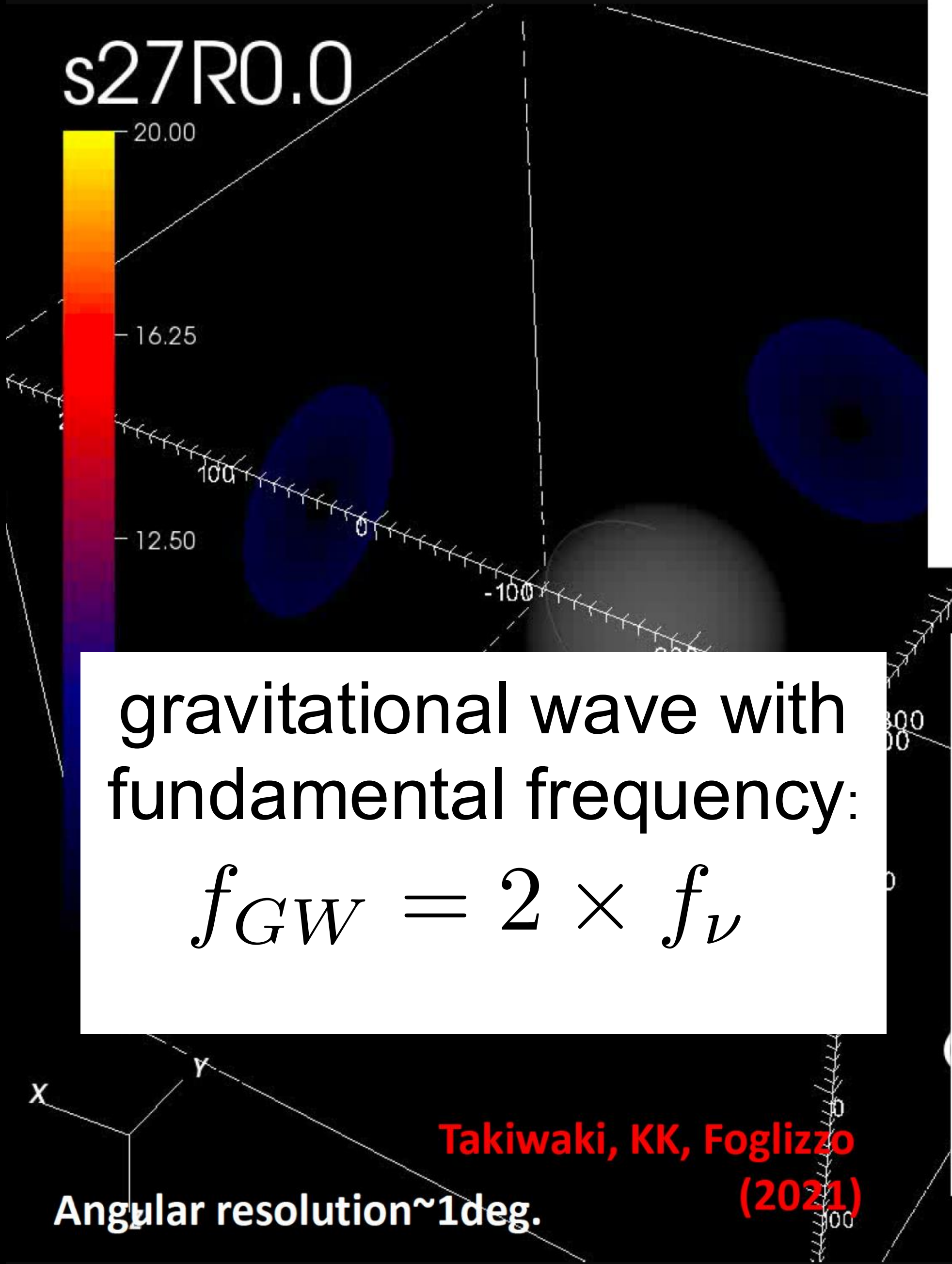
quark star



black hole



27 M_{sun} progenitor (WH07)

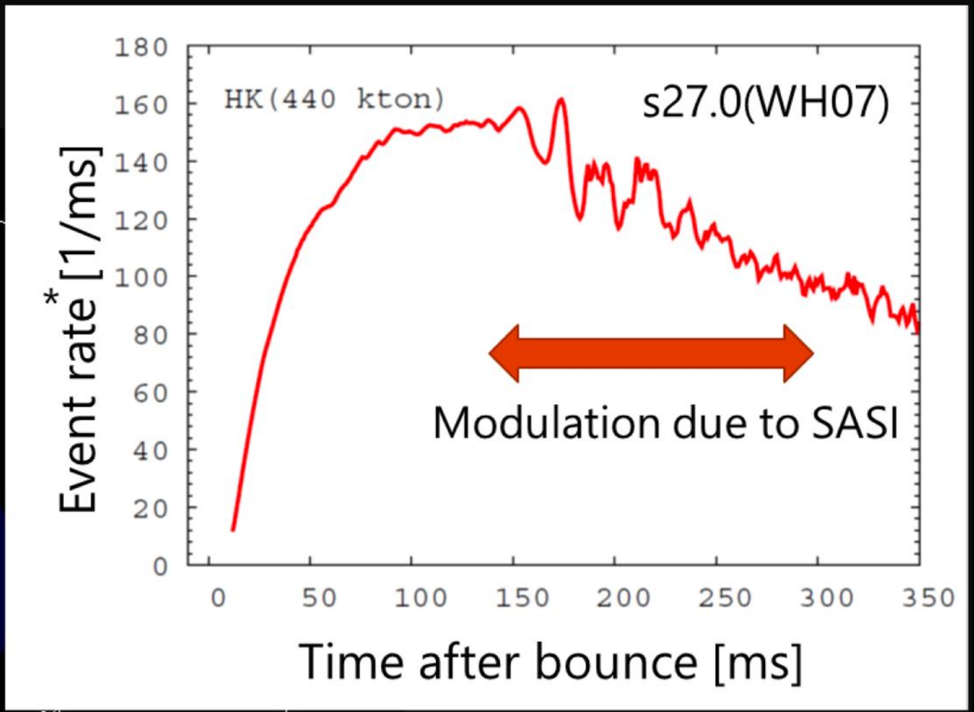


gravitational wave with fundamental frequency:

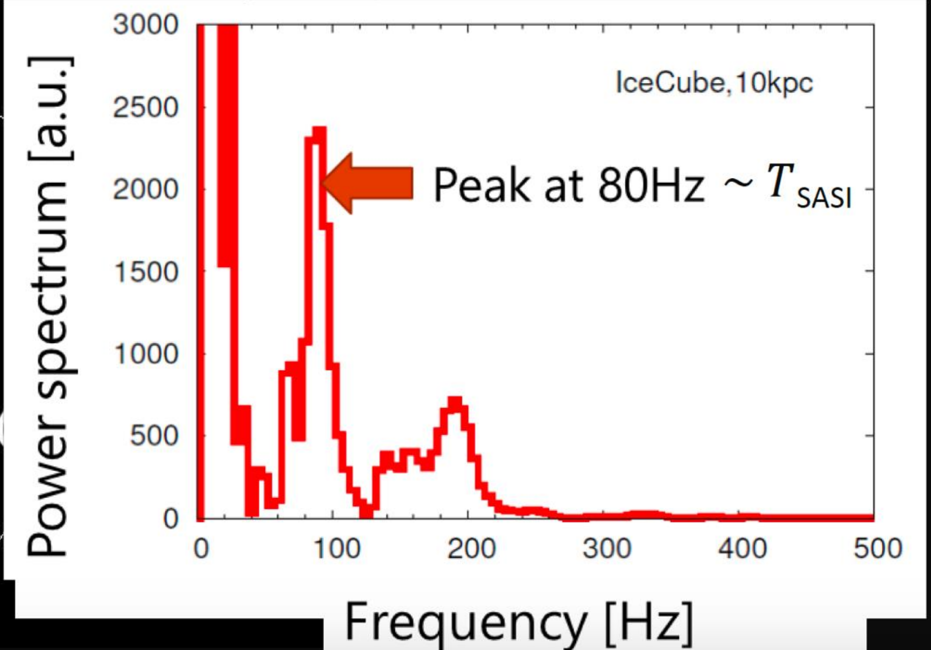
$$f_{GW} = 2 \times f_{\nu}$$

Takiwaki, KK, Foglizzo (2021)

Angular resolution~1deg.

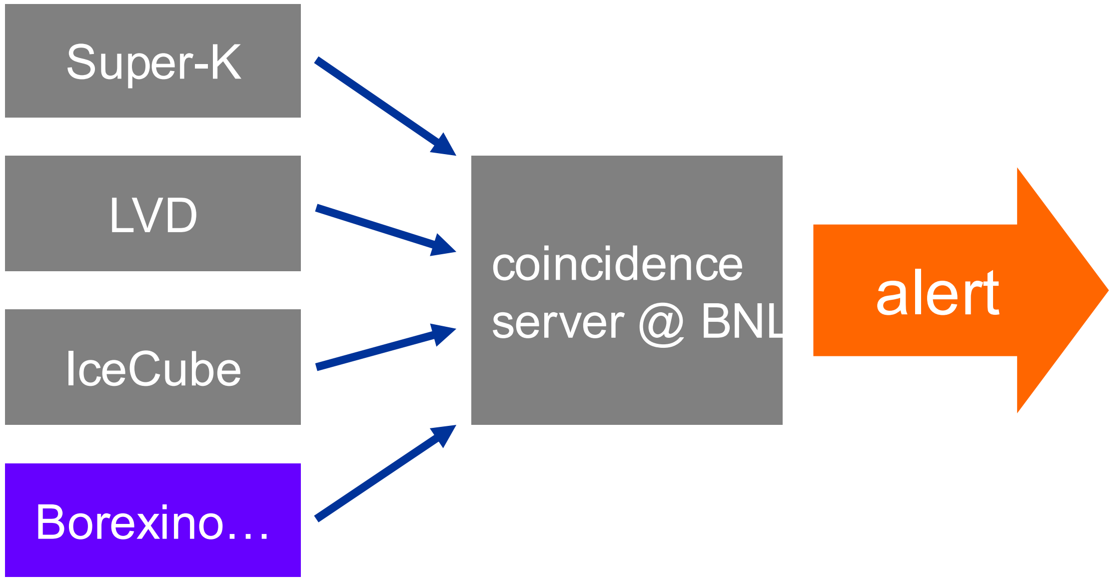


(consistent with Tamborra et al. (2013,2014))



Participation in SNEWS

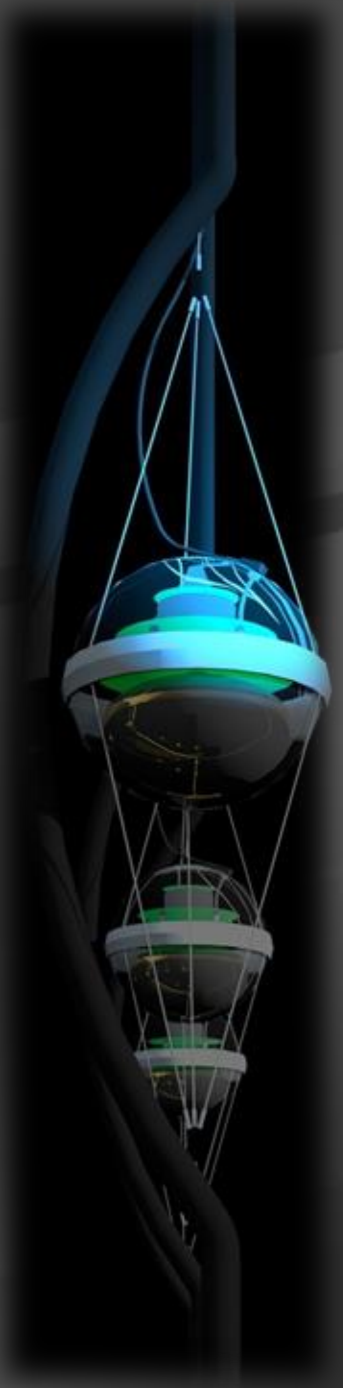
…several hours advanced notice to astronomers …



received iridium messages (last 4 weeks)

message type	time (UTC)	time delay to reception (seconds)	needed modem dial attempts
missing test message(s)			
test	Mon Jul 10 08:19:38 2006	224	1
test	Sun Jul 9 11:15:12 2006	218	1
test	Sat Jul 8 11:15:12 2006	208	1
test	Fri Jul 7 11:15:12 2006	208	1
test	Thu Jul 6 11:15:11 2006	214	1
test	Thu Jul 6 11:09:05 2006	205	1
missing test message(s)			
test	Mon Jul 3 09:45:12 2006	195	1
sn	Sun Jul 2 11:17:12 2006	445	1
	signal strength is [8.716532e+00 ± 1.325448e+00] Hz analysis timebase is [4] sec, active channels are [476], χ^2 is [5.421858e+02]		
test	Sun Jul 2 09:45:11 2006	196	1
test	Sat Jul 1 09:45:12 2006	195	1
test	Fri Jun 30 09:45:12 2006	185	1
test	Thu Jun 29 09:45:12 2006	181	1
sn	Wed Jun 28 11:20:29 2006	448	1
	signal strength is [7.296678e+00 ± 8.447978e-01] Hz analysis timebase is [10] sec, active channels are [474], χ^2 is [5.770201e+02]		
test	Wed Jun 28 09:45:12 2006	185	1
test	Tue Jun 27 09:45:12 2006	175	1
test	Mon Jun 26 09:45:12 2006	175	1
test	Sun Jun 25 09:45:12 2006	176	1
sn	Sun Jun 25 02:15:47 2006	571	2
	signal strength is [9.946102e+00 ± 1.333087e+00] Hz analysis timebase is [4] sec, active channels are [475], χ^2 is [5.061309e+02]		
test	Sat Jun 24 09:45:12 2006	165	1
test	Fri Jun 23 09:45:12 2006	165	1
test	Fri Jun 23 09:26:21 2006	170	1
test	Fri Jun 23 08:59:13 2006	732	10
test	Thu Jun 22 10:33:23 2006	162	1
test	Thu Jun 22 09:45:12 2006	160	1
test	Thu Jun 22 09:38:29 2006	163	1
test	Thu Jun 22 09:27:30 2006	167	1
test	Thu Jun 22 08:45:12 2006	173	1
missing test message(s)			
test	Tue Jun 20 09:30:12 2006	154	1

http://snews.bnl.gov astro-ph/0406214



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IceCube targets for dark matter annihilation

Sun

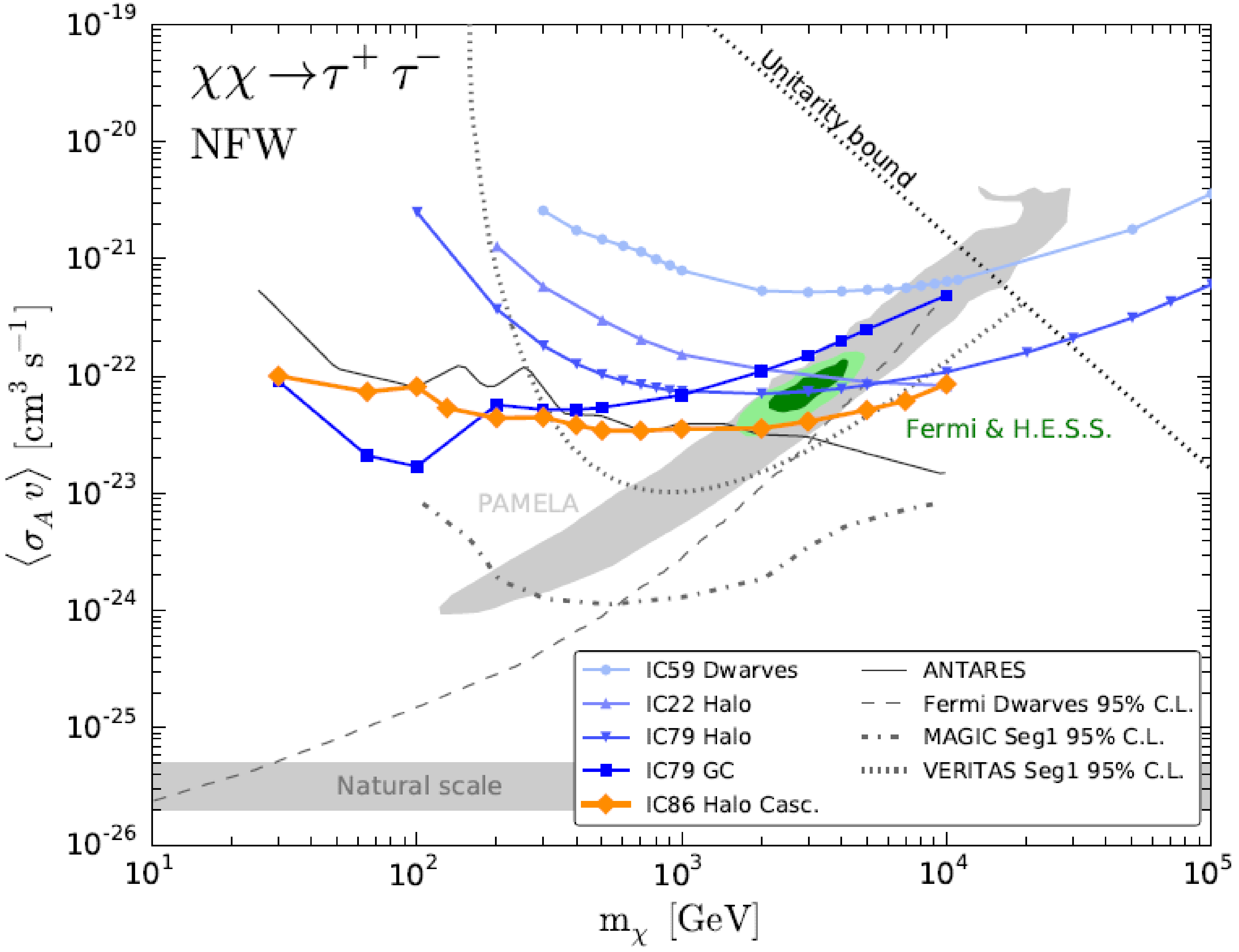
Galactic Centre

Dwarf galaxies

Earth

Galactic Halo

Galaxy clusters

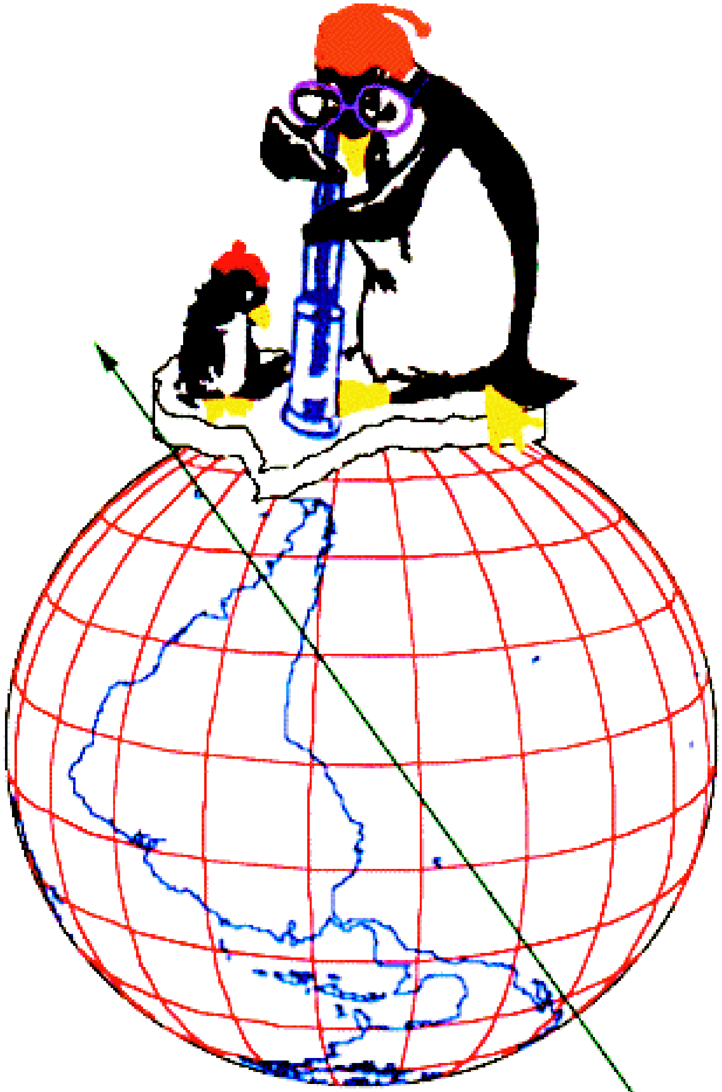


$\chi\chi \rightarrow \tau^+ \tau^-$
NFW
Unitarity bound
Fermi & H.E.S.S.
PAMELA
Natural scale
IC59 Dwarves
IC22 Halo
IC79 Halo
IC79 GC
IC86 Halo Casc.
ANTARES
Fermi Dwarves 95% C.L.
MAGIC Seg1 95% C.L.
VERITAS Seg1 95% C.L.
$\langle \sigma_A v \rangle$ [cm^3 s^{-1}]
m_χ [GeV]

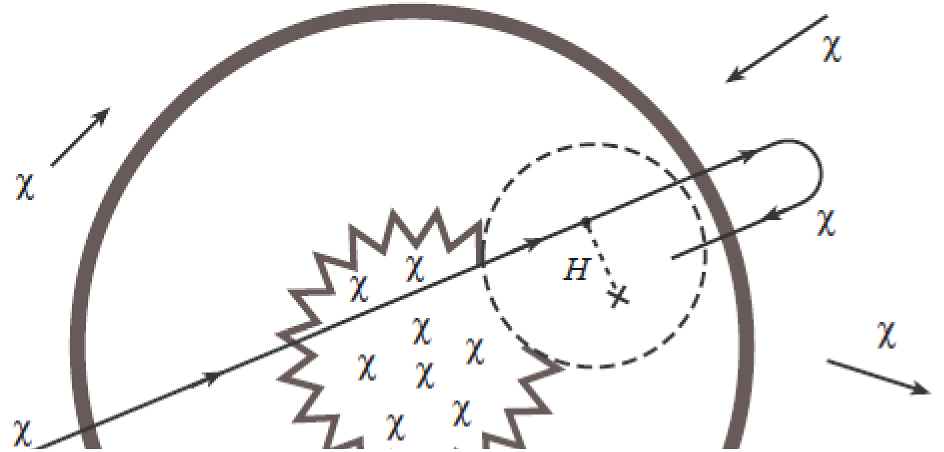
1992 Cline meeting at UCLA


The Economist
FEBRUARY 29TH–MARCH 6TH 1992

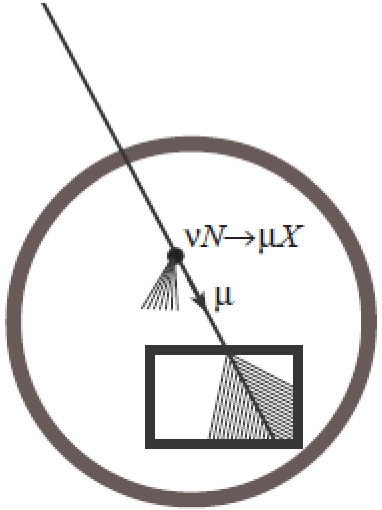
FLAWED SUPERFUND	pages 18 and 80
CALIFORNIA'S WOMEN	page 32
MULTI-MEDIA MADNESS	pages 17 and 73
ANTARCTIC SCIENCE	pages 91-93



AMANDA



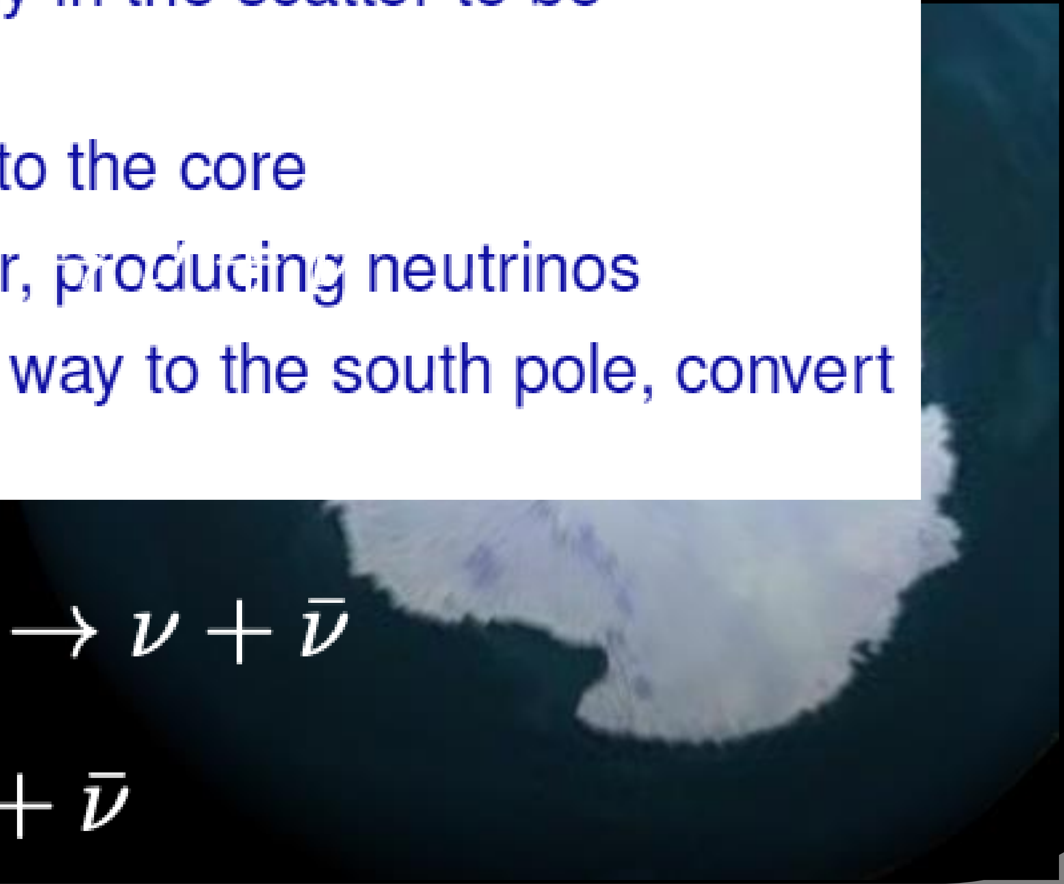
$$C^{\odot} \approx 3.35 \times 10^{20}\,\mathrm{sec}^{-1} \left(\frac{\rho_{\rm local}}{0.3\,\mathrm{GeV/cm^3}}\right)\left(\frac{270\,\mathrm{km/s}}{\bar{v}_{\rm local}}\right)^3 \left(\frac{100\,\mathrm{GeV}}{m_\chi}\right)^2 \times \left(\frac{\sigma_{\chi\mathrm{H,SD}} + \sigma_{\chi\mathrm{H,SI}} + 0.07\,\sigma_{\chi\mathrm{He,SI}} + 0.0005\,S(m_\chi/m_{\rm O})\,\sigma_{\chi\mathrm{O,SI}}}{10^{-6}\,\mathrm{pb}}\right).$$



supersymmetry on the back of an envelope
arXiv 9404252

WIMP Capture and Annihilation

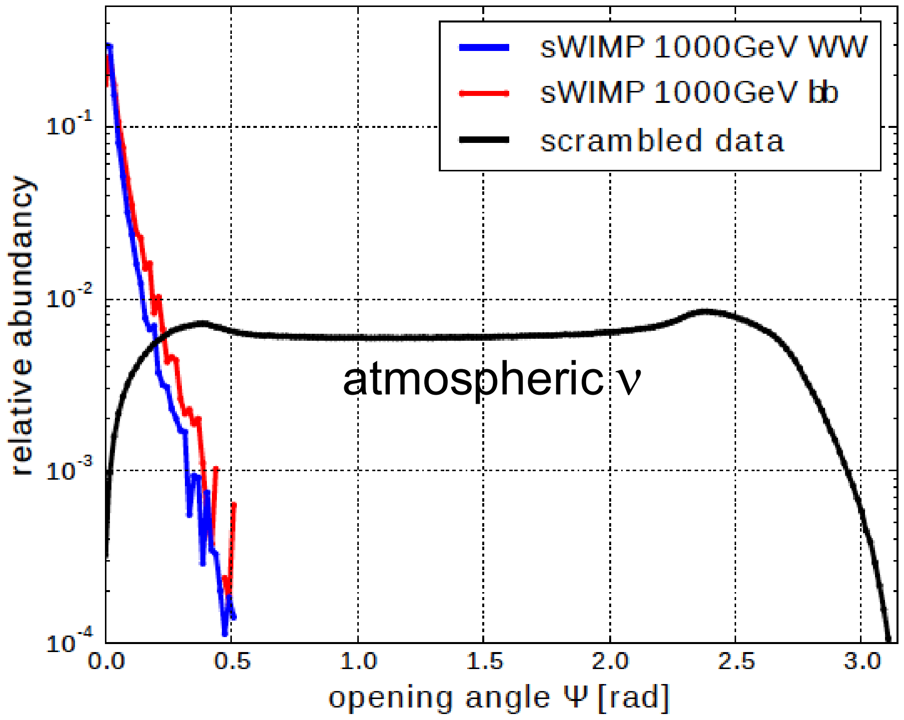
1. Halo WIMPs scatter on nuclei in the Sun
2. Some lose enough energy in the scatter to be gravitationally bound
3. Scatter some more, sink to the core
4. Annihilate with each other, producing neutrinos
5. Propagate+oscillate their way to the south pole, convert into muons in the ice



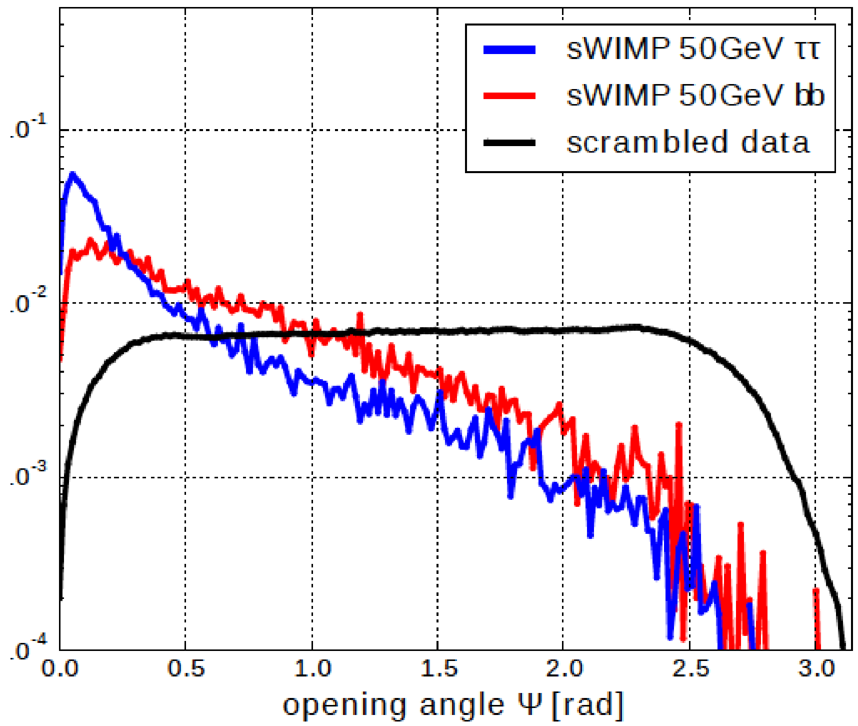
$$\chi + \bar{\chi} \rightarrow W^{+} + W^{-} \rightarrow \nu + \bar{\nu}$$

$$\rightarrow \tau + \bar{\tau} \rightarrow \nu + \bar{\nu}$$

sun



$$m_\chi = 1\,\mathrm{TeV}$$

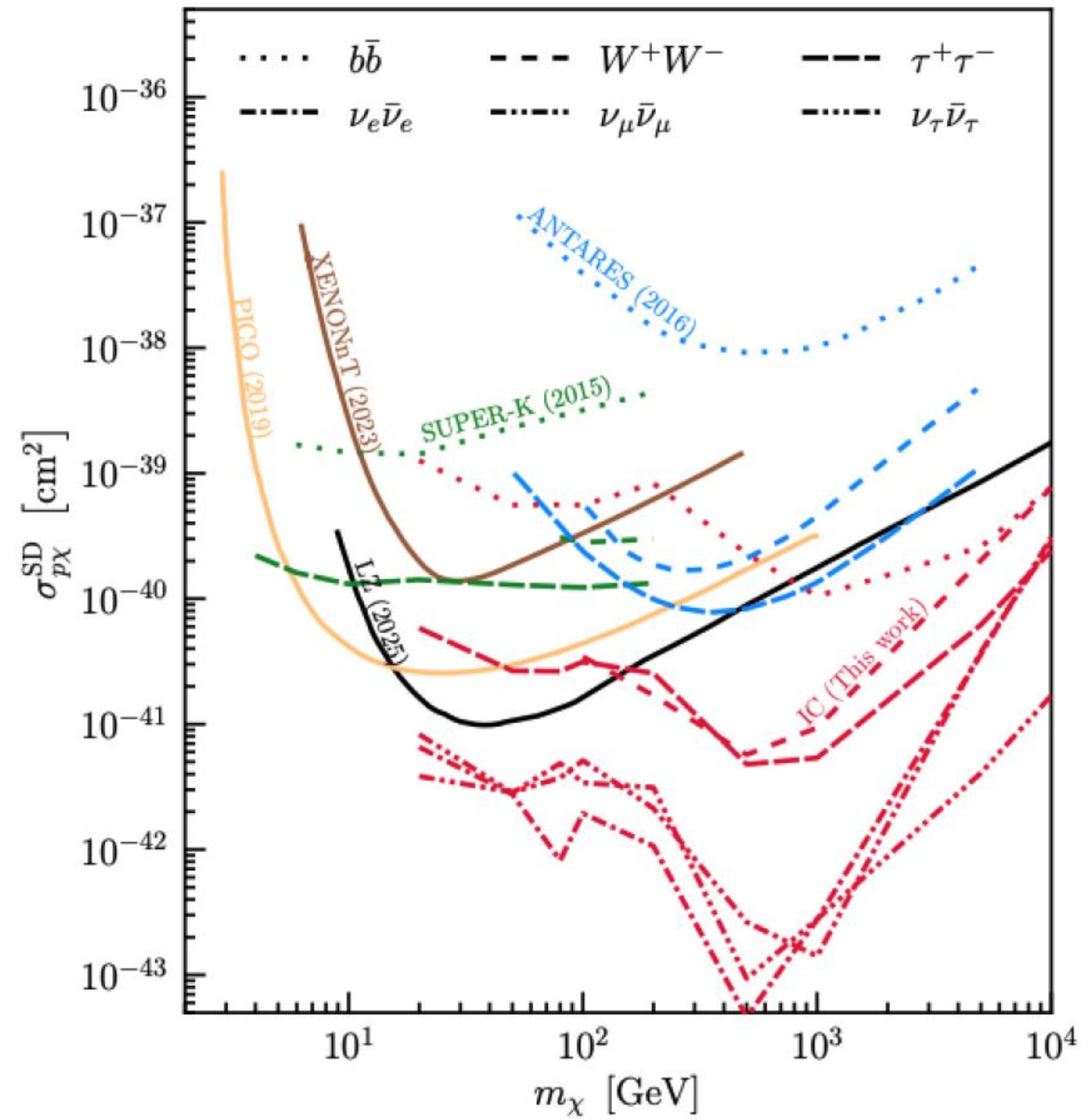


$$m_\chi = 50\,\mathrm{GeV}$$

detection is a smoking gun

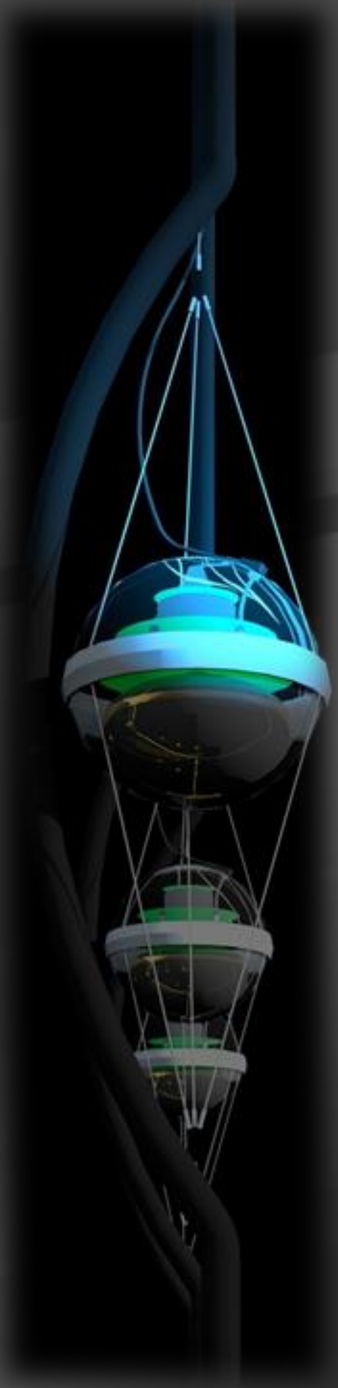
- indirect rates are dictated by the interaction cross section of WIMPS with hydrogen.
  → no unknown astrophysics

- in the neutrino case there is a direct connection between theory and observation and the background is understood.



$b\bar{b}$
W^+W^-
$\tau^+\tau^-$
$\nu_e\bar{\nu}_e$
$\nu_\mu\bar{\nu}_\mu$
$\nu_\tau\bar{\nu}_\tau$
ANTARES (2016)
XENONnT (2023)
PICO (2019)
SUPER-K (2015)
LZ (2025)
IC (This work)
10^{-36}
10^{-37}
10^{-38}
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
$\sigma_{p\chi}^{\mathrm{SD}}$ [cm^2]
10^1
10^2
10^3
10^4
m_χ [GeV]

DM-Ice Prototype Detector



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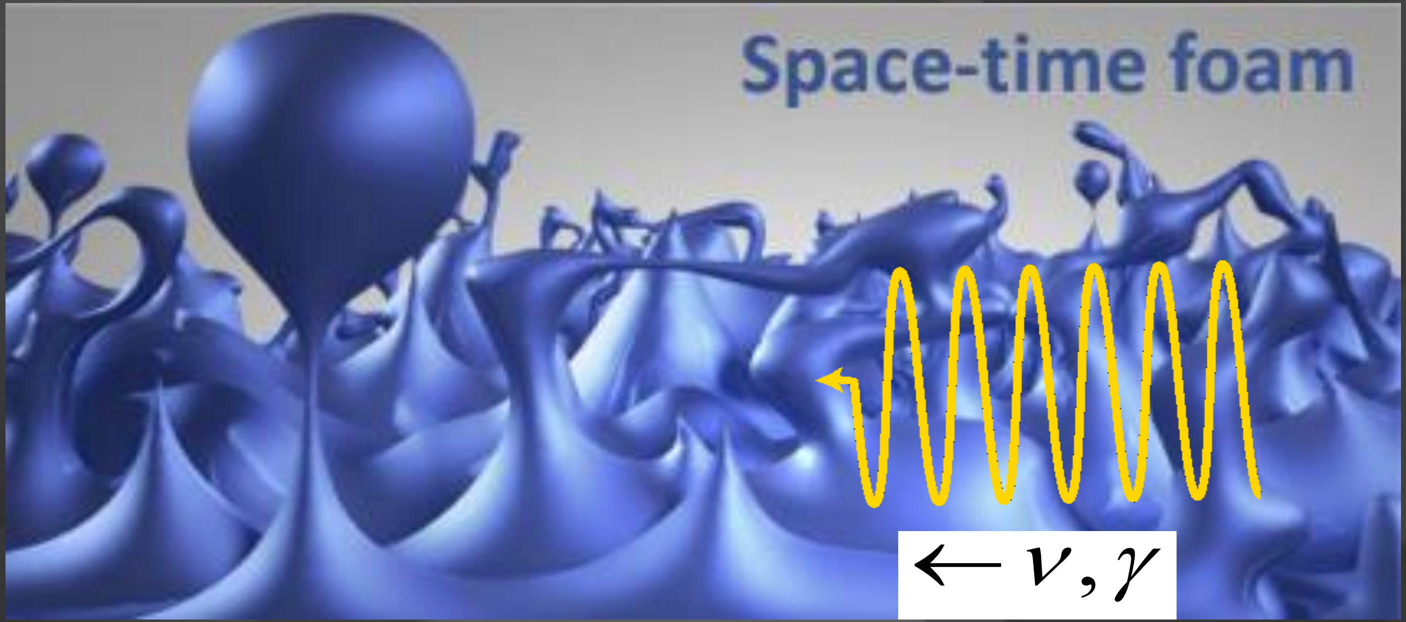
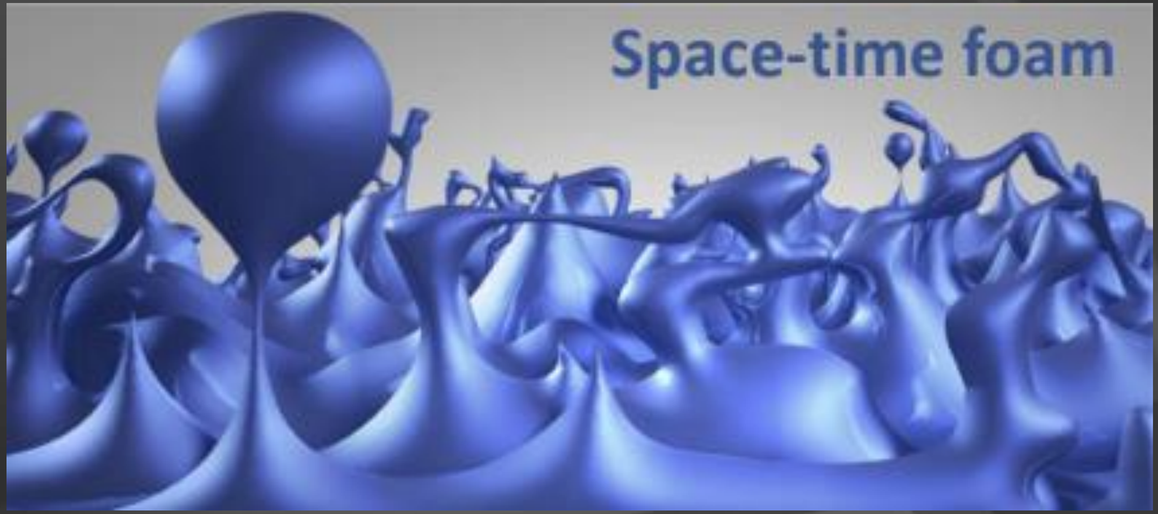


- quantized space: quantum fluctuations of space-time when geometry is activated

- oscillations as interferometer sensing quantum fluctuations

$$E^2 = p^2 + m^2 \pm E^2 \left(\frac{E}{M_{QG}}\right)^n \pm \ldots$$



$$E^2 = p^2 + m^2 \pm E^2 \left(\frac{E}{M_{QG}}\right)^n \pm \ldots$$

so far standard oscillations prevail over decoherence reaching $M_{QG} > M_{Planck}$

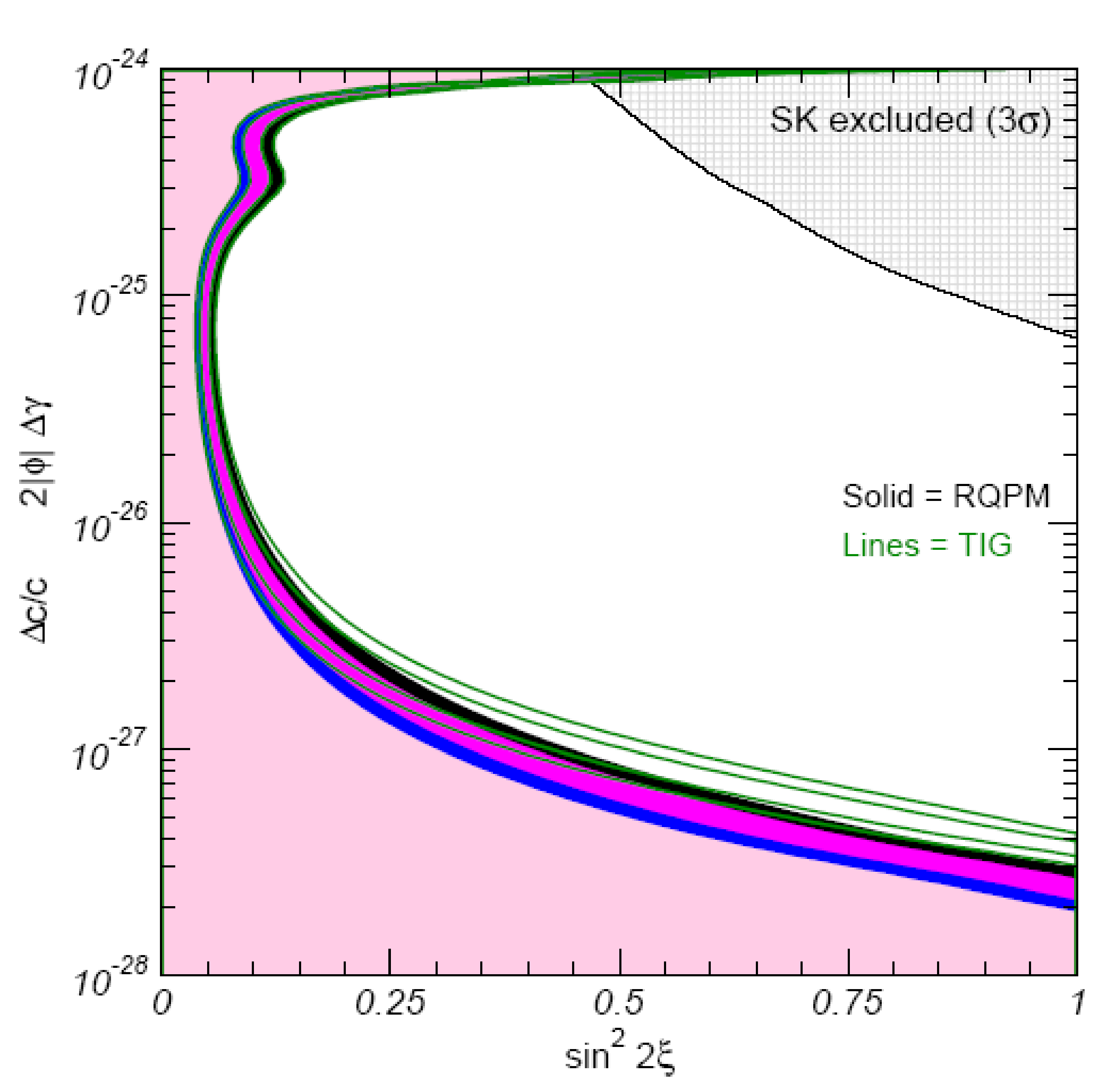
- the effects are small but become observable for high energies and long distances
- speed of neutrinos depends on their energy, like photons in a crystal
- modification to dispersion relation leads to an energy dependent speed of light
- for some coefficients IceCube yields world-best limits with atmospheric neutrinos

[2308.00105 [hep-ex]]

IceCube

tests
• equivalence principle and
• Lorentz invariance

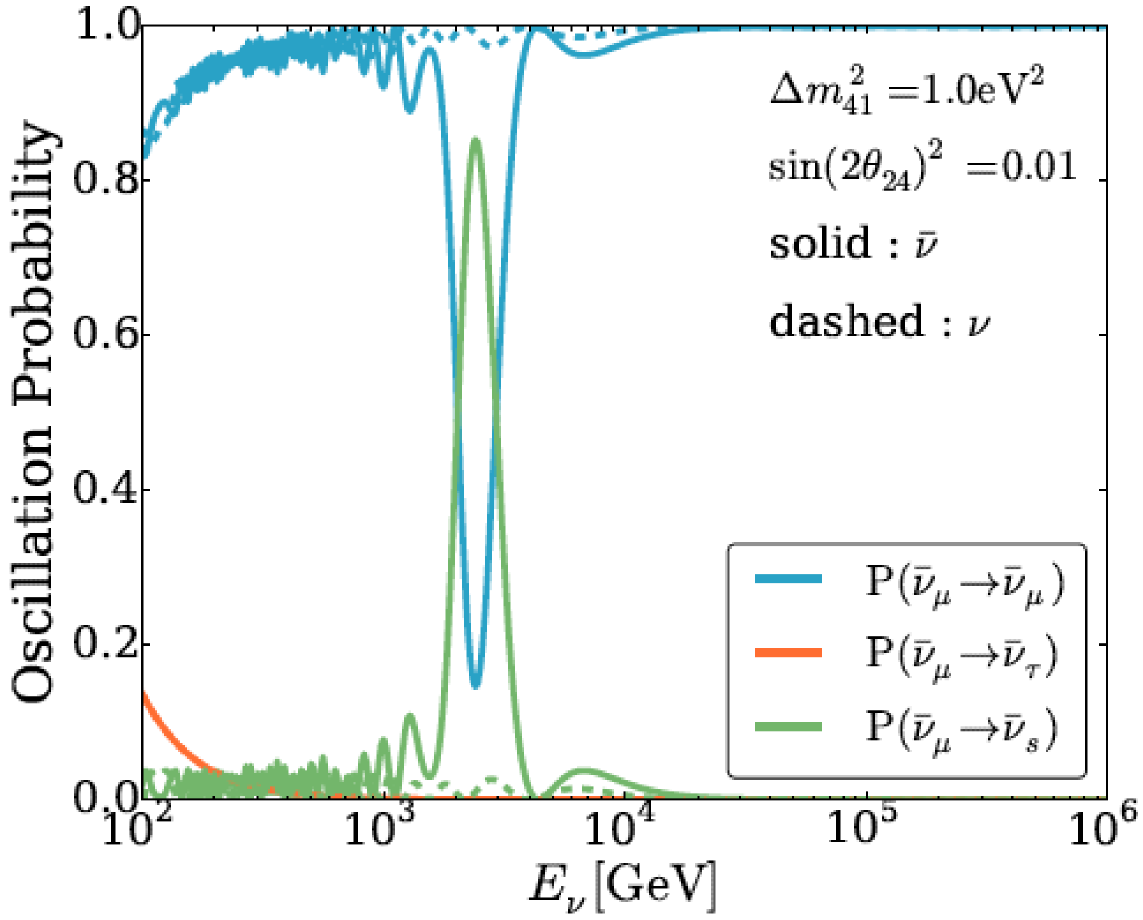
...general relativity will not last 200 years...
M. Turner

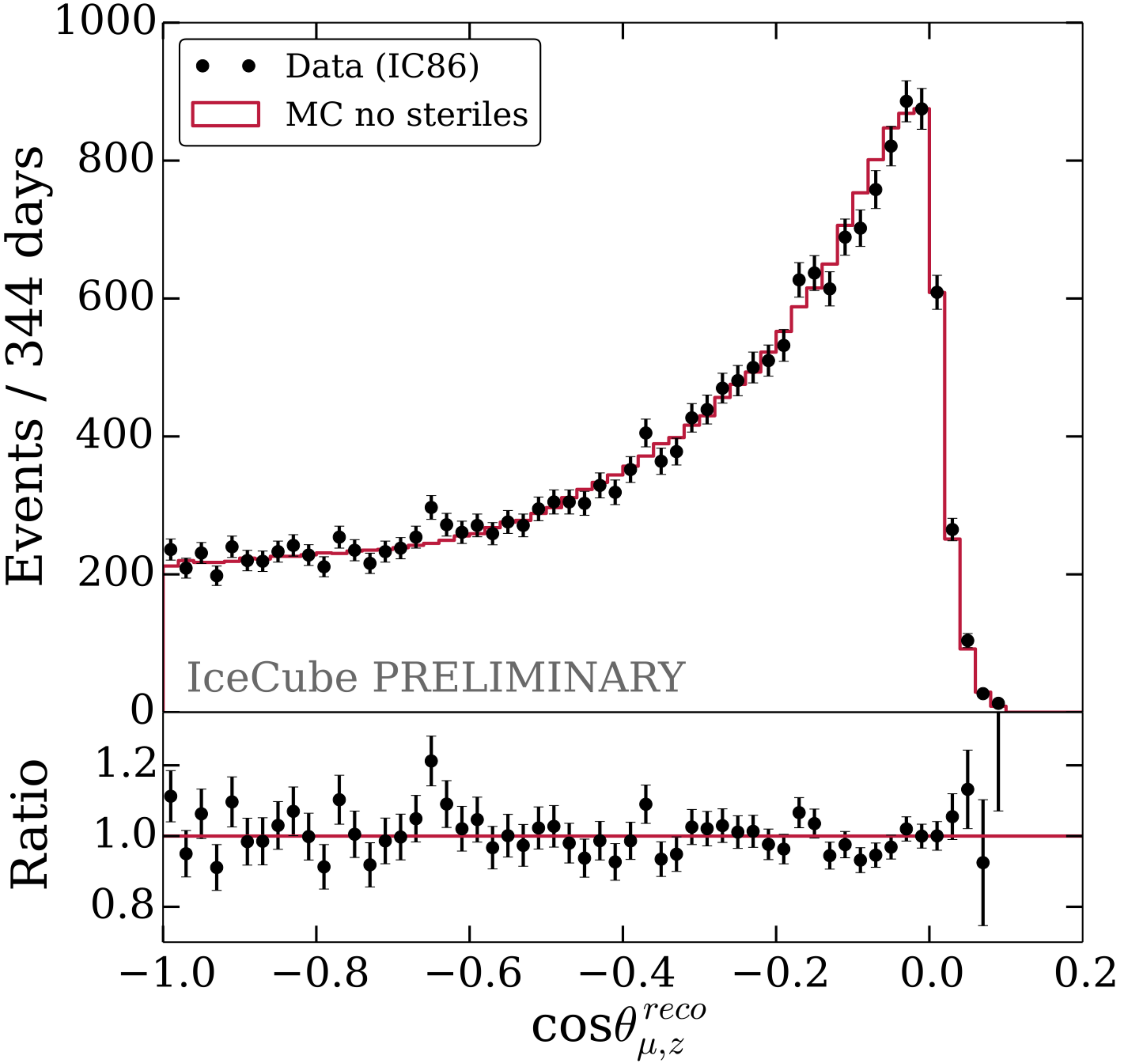


eV sterile neutrino → Earth MSW resonance for TeV neutrinos

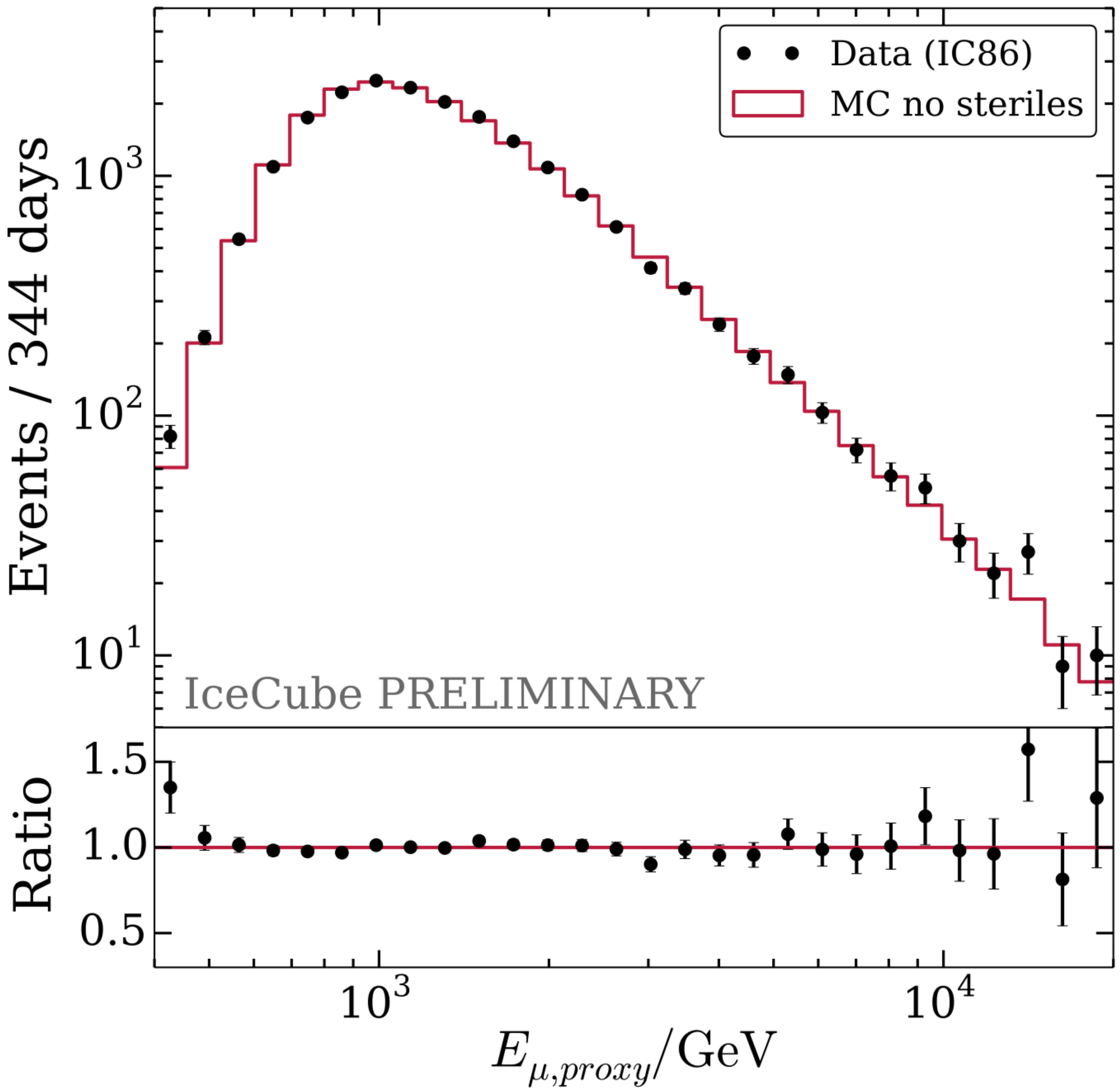
In the **Earth** for sterile neutrino $\Delta m^2 = O(1eV^2)$ the MSW effect happens when

$$E_\nu = \frac{\Delta m^2 \cos 2\theta}{2\sqrt{2} G_F N} \sim O(TeV)$$



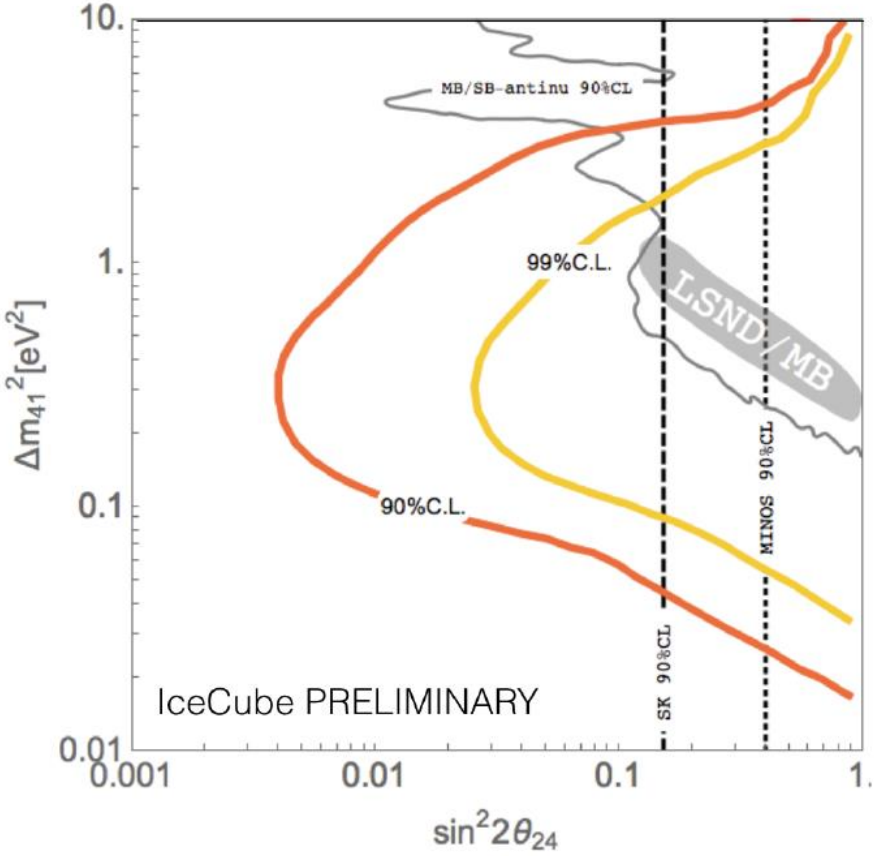


Data (IC86)
MC no steriles
IceCube PRELIMINARY
Events / 344 days
Ratio
0
200
400
600
800
1000
0.8
1.0
1.2
−1.0
−0.8
−0.6
−0.4
−0.2
0.0
0.2
$\cos\theta_{\mu,z}^{reco}$

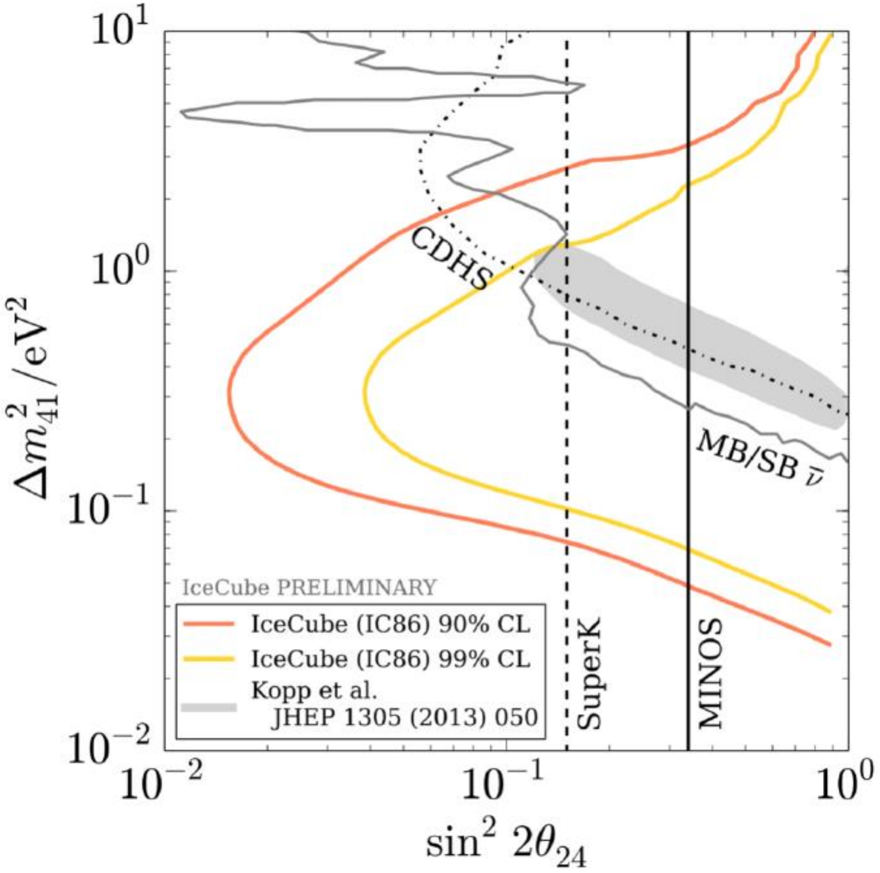


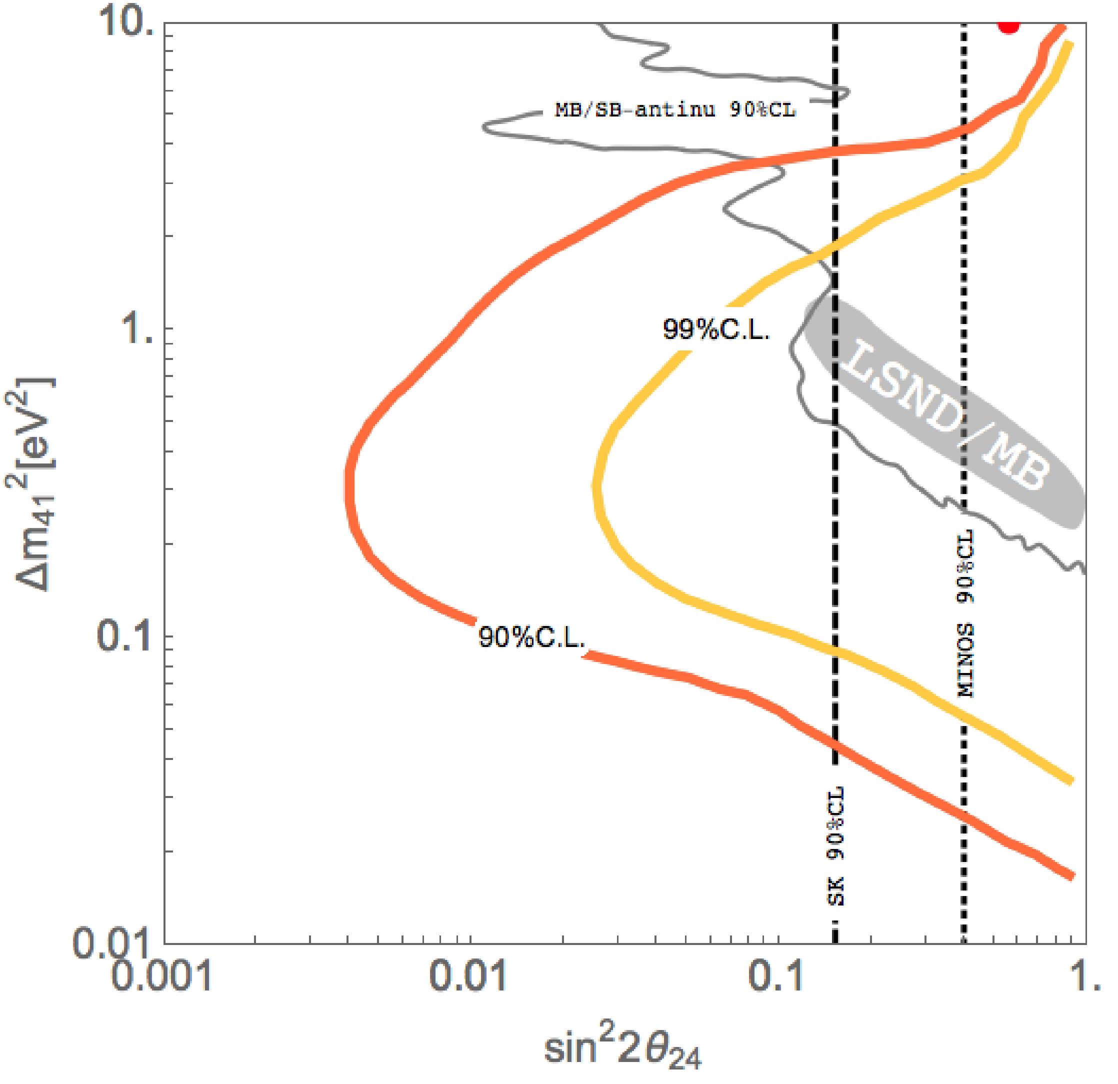
Data (IC86)
MC no steriles
Events / 344 days
10^3
10^2
10^1
IceCube PRELIMINARY
Ratio
1.5
1.0
0.5
10^3
10^4
$E_{\mu,proxy}$/GeV

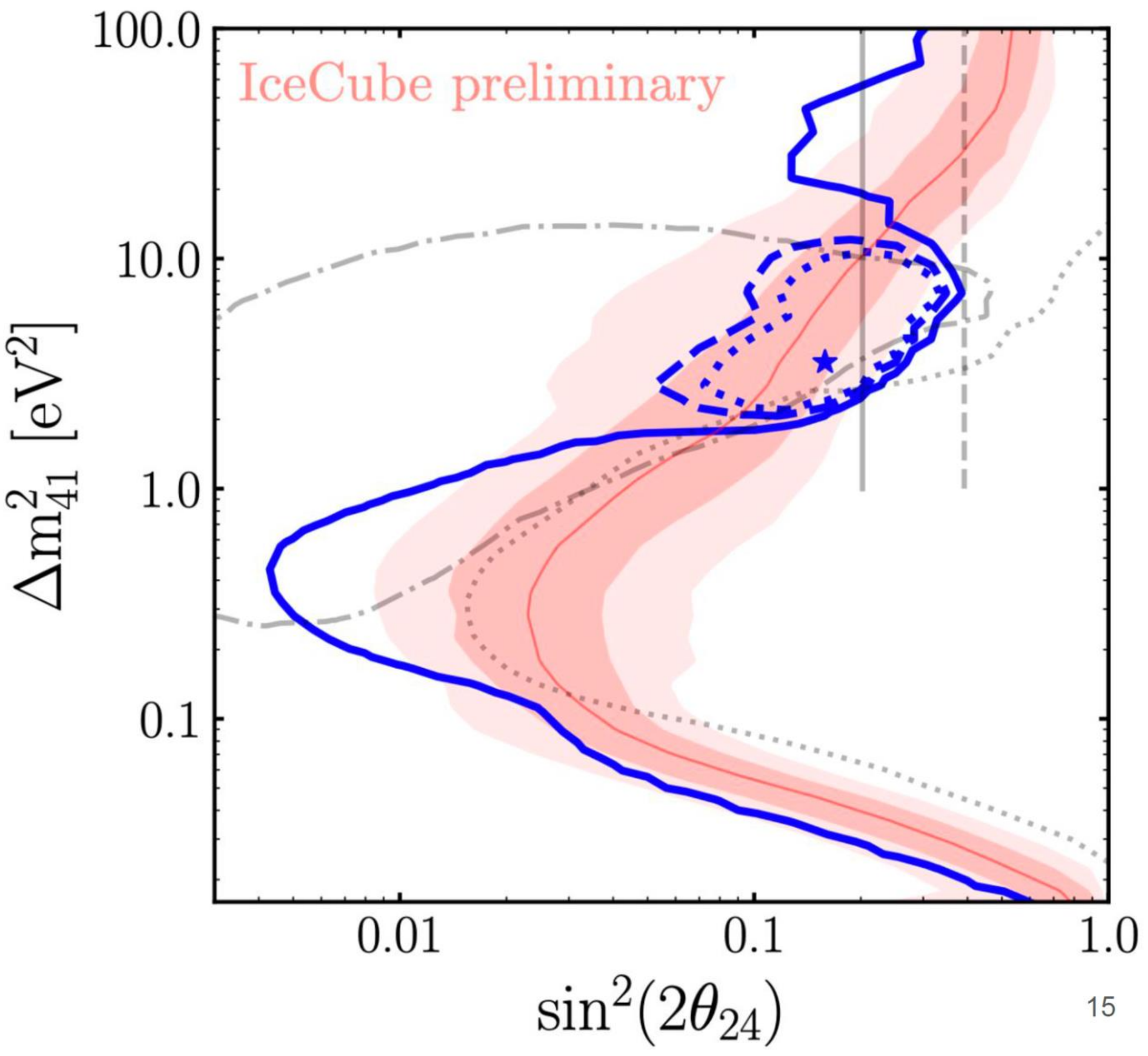
SHAPE



SHAPE+RATE

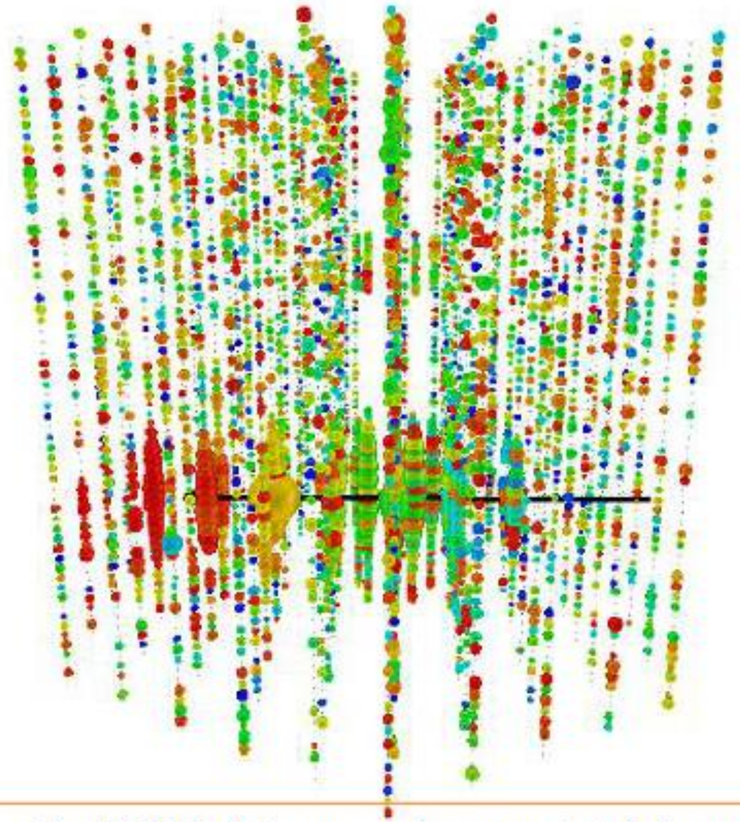



10.
1.
0.1
0.01
0.001
0.01
0.1
1.
$\Delta m_{41}{}^2[\mathrm{eV}^2]$
$\sin^2 2\theta_{24}$
MB/SB-antinu 90%CL
99%C.L.
90%C.L.
LSND/MB
SK 90%CL
MINOS 90%CL

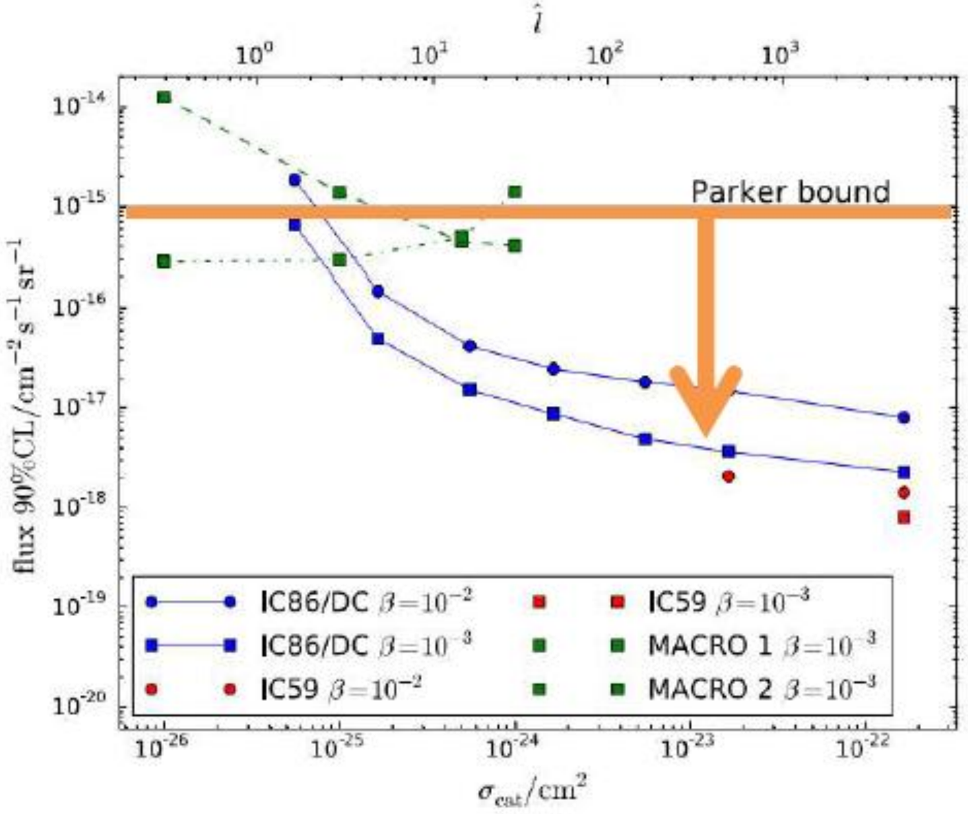

IceCube preliminary
100.0
10.0
1.0
0.1
0.01
0.1
1.0
Δm^2_{41} [eV^2]
$\sin^2(2\theta_{24})$

GUT monopoles

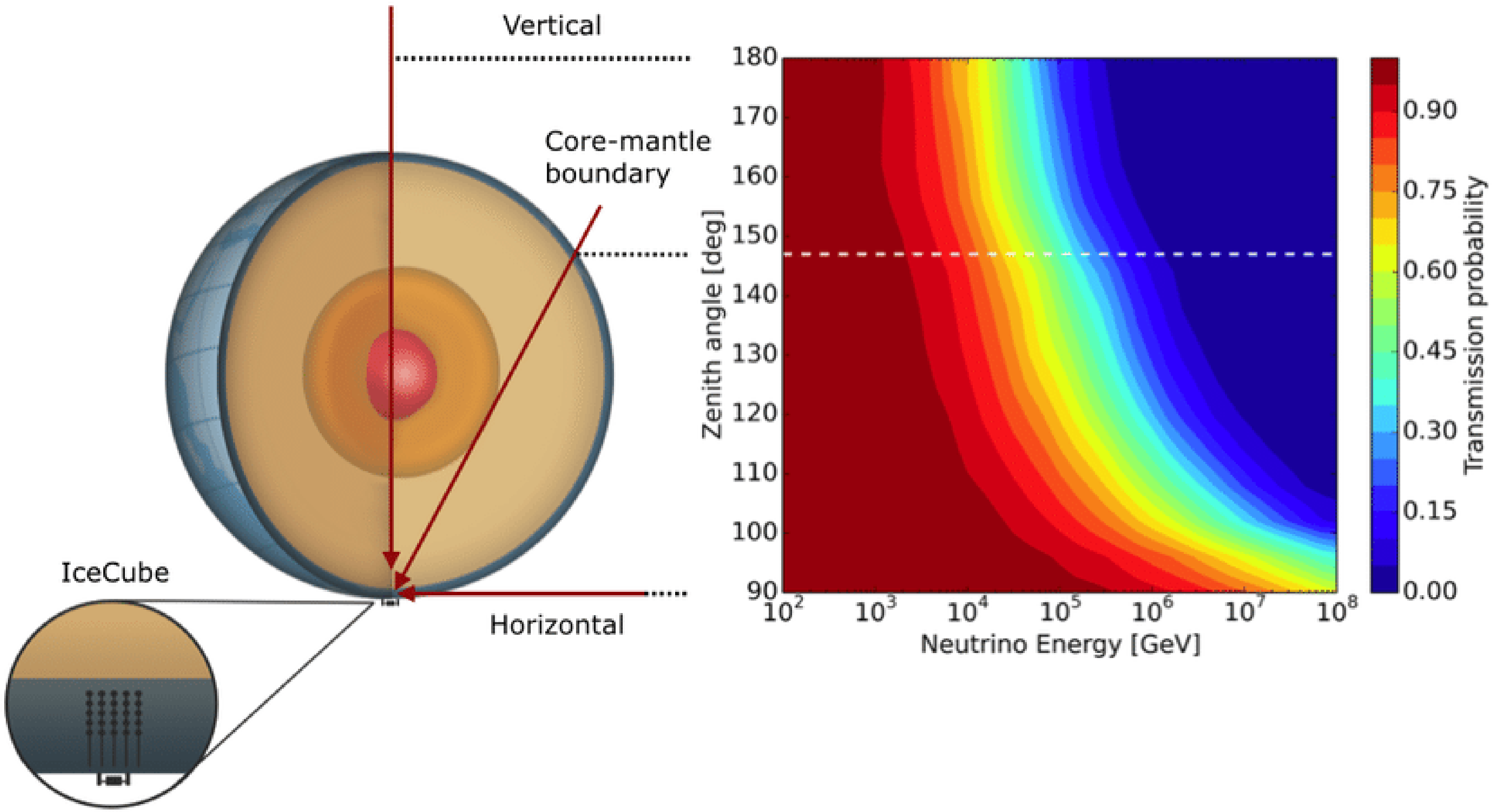
Example: slowly moving magnetic monopole catalyzing proton decay:



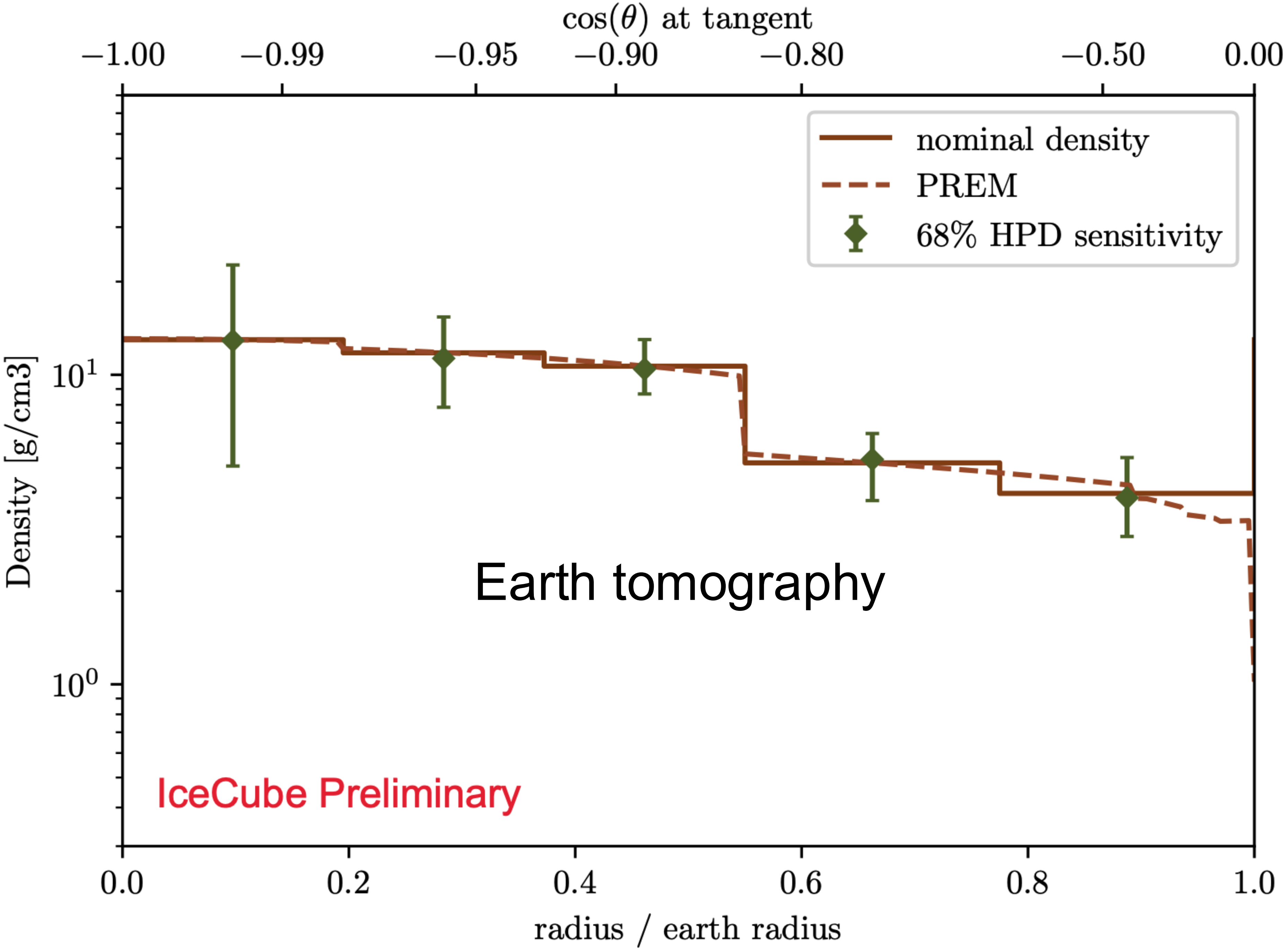
v ~ c/1000, 10 ms data, special trigger
Strong signal above integrated noise

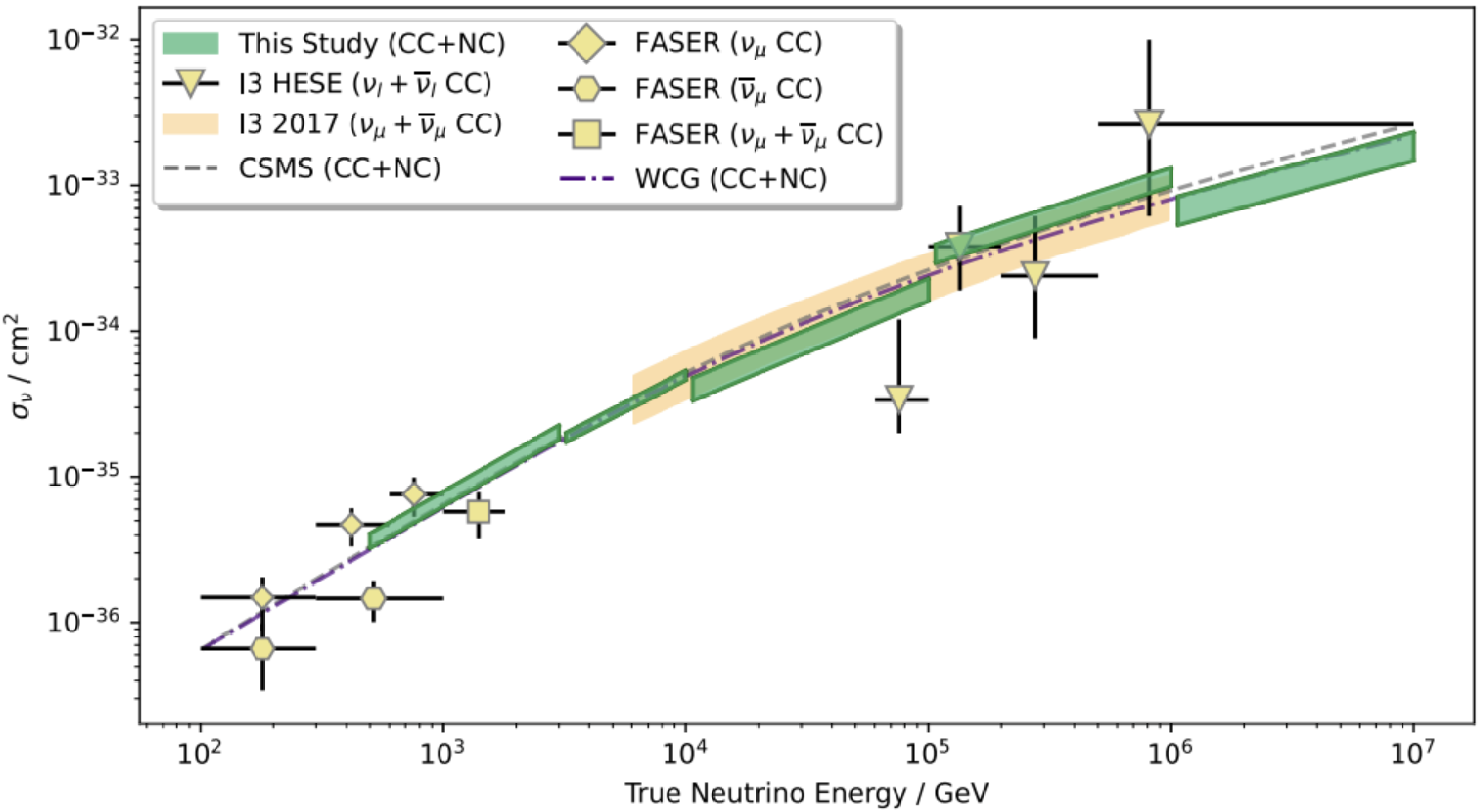


EPJC 74, 7 (cover print)

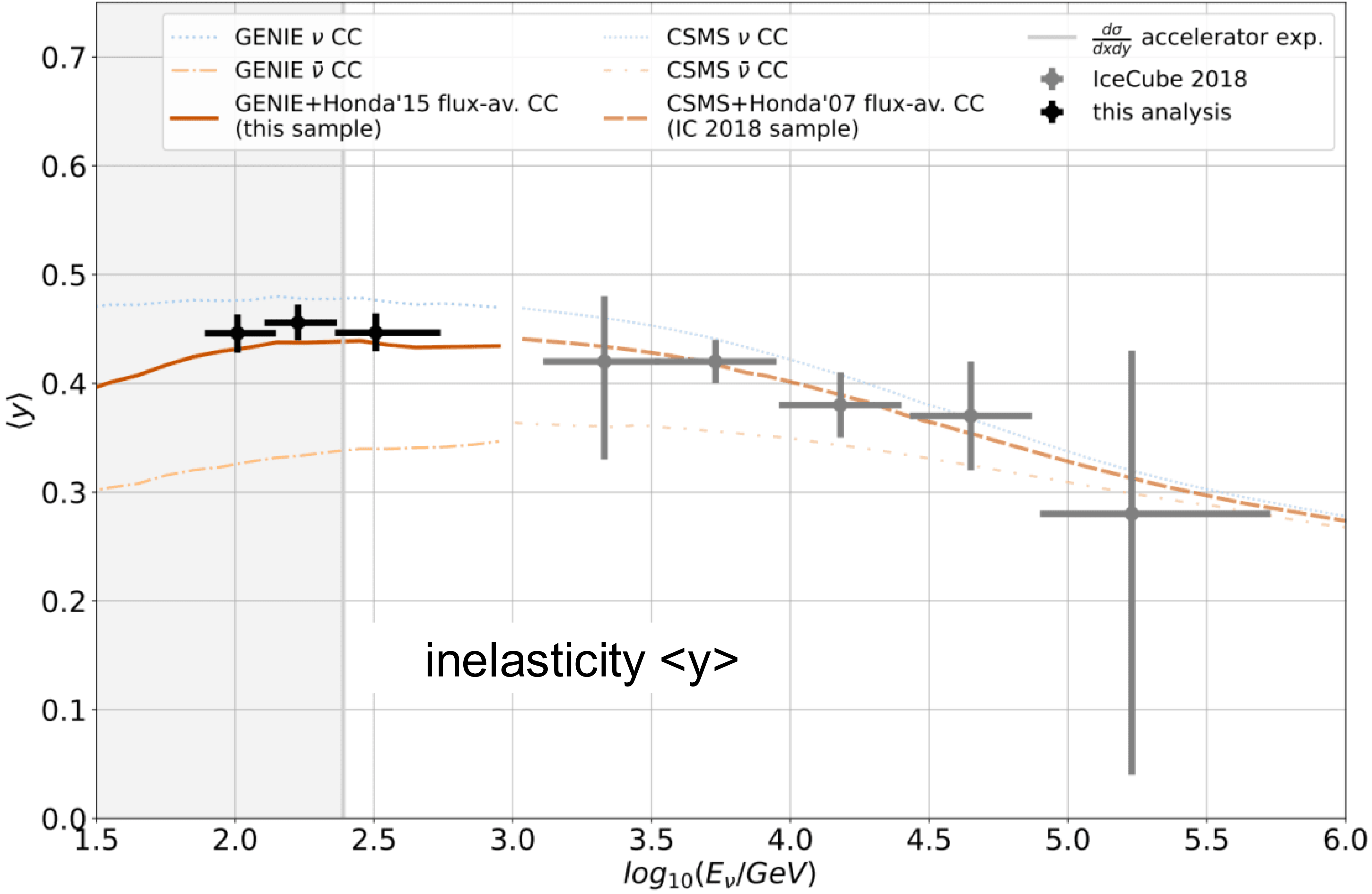


absorption length of a neutrino is 12,500 km at 70 TeV

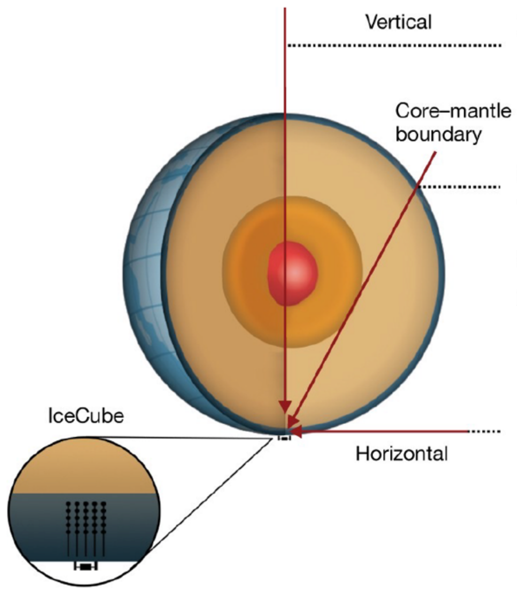

cos(θ) at tangent
−1.00
−0.99
−0.95
−0.90
−0.80
−0.50
0.00
nominal density
PREM
68% HPD sensitivity
Density [g/cm3]
10^1
10^0
Earth tomography
IceCube Preliminary
0.0
0.2
0.4
0.6
0.8
1.0
radius / earth radius

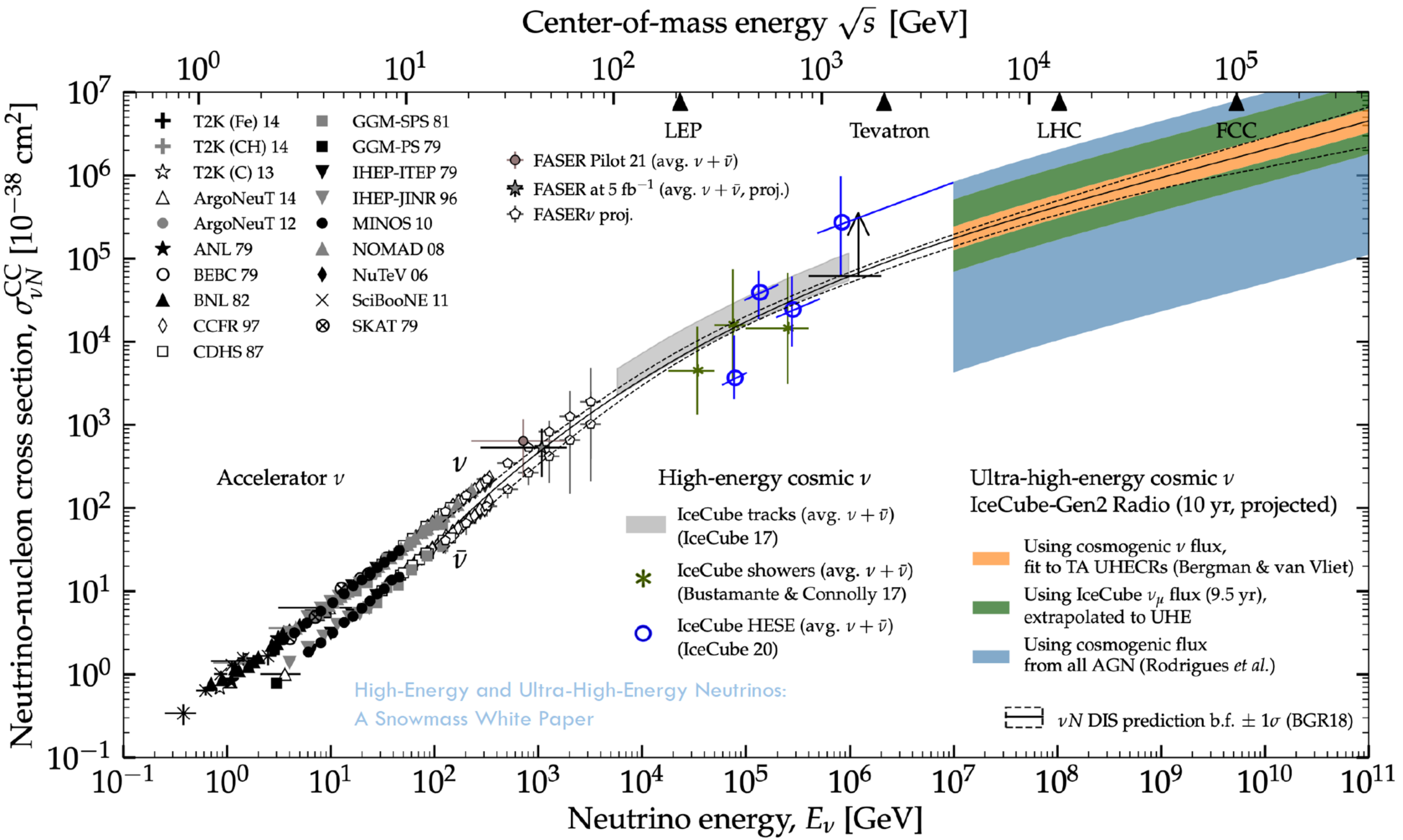


This Study (CC+NC)
I3 HESE ($\nu_l + \overline{\nu}_l$ CC)
I3 2017 ($\nu_\mu + \overline{\nu}_\mu$ CC)
CSMS (CC+NC)
FASER (ν_μ CC)
FASER ($\overline{\nu}_\mu$ CC)
FASER ($\nu_\mu + \overline{\nu}_\mu$ CC)
WCG (CC+NC)
10^{-32}
10^{-33}
10^{-34}
10^{-35}
10^{-36}
σ_ν / cm^2
10^2
10^3
10^4
10^5
10^6
10^7
True Neutrino Energy / GeV

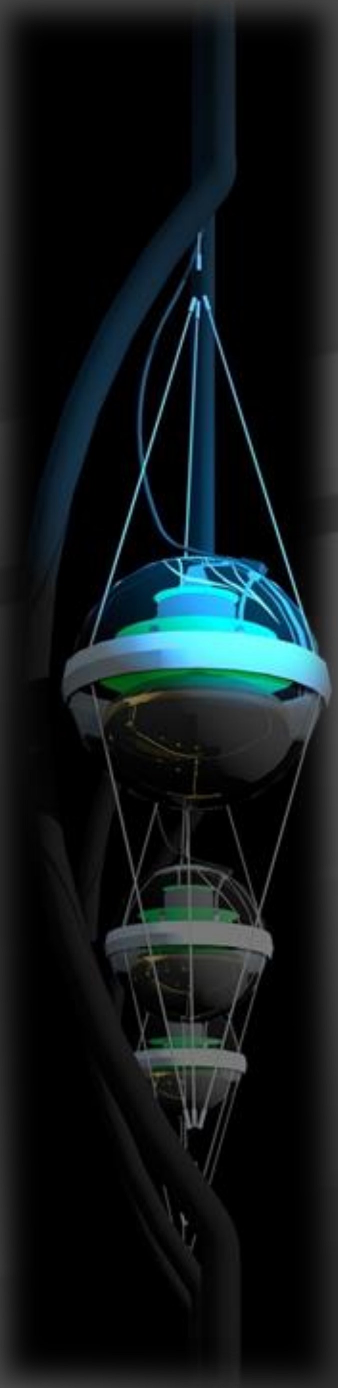

GENIE ν CC
GENIE ν̄ CC
GENIE+Honda'15 flux-av. CC (this sample)
CSMS ν CC
CSMS ν̄ CC
CSMS+Honda'07 flux-av. CC (IC 2018 sample)
$\frac{d\sigma}{dxdy}$ accelerator exp.
IceCube 2018
this analysis
inelasticity <y>
⟨y⟩
$log_{10}(E_\nu/GeV)$
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
6.0

CROSS SECTION WITH EARTH AS THE TARGET





Extending x-section measurements to energies beyond Earth-based accelerators

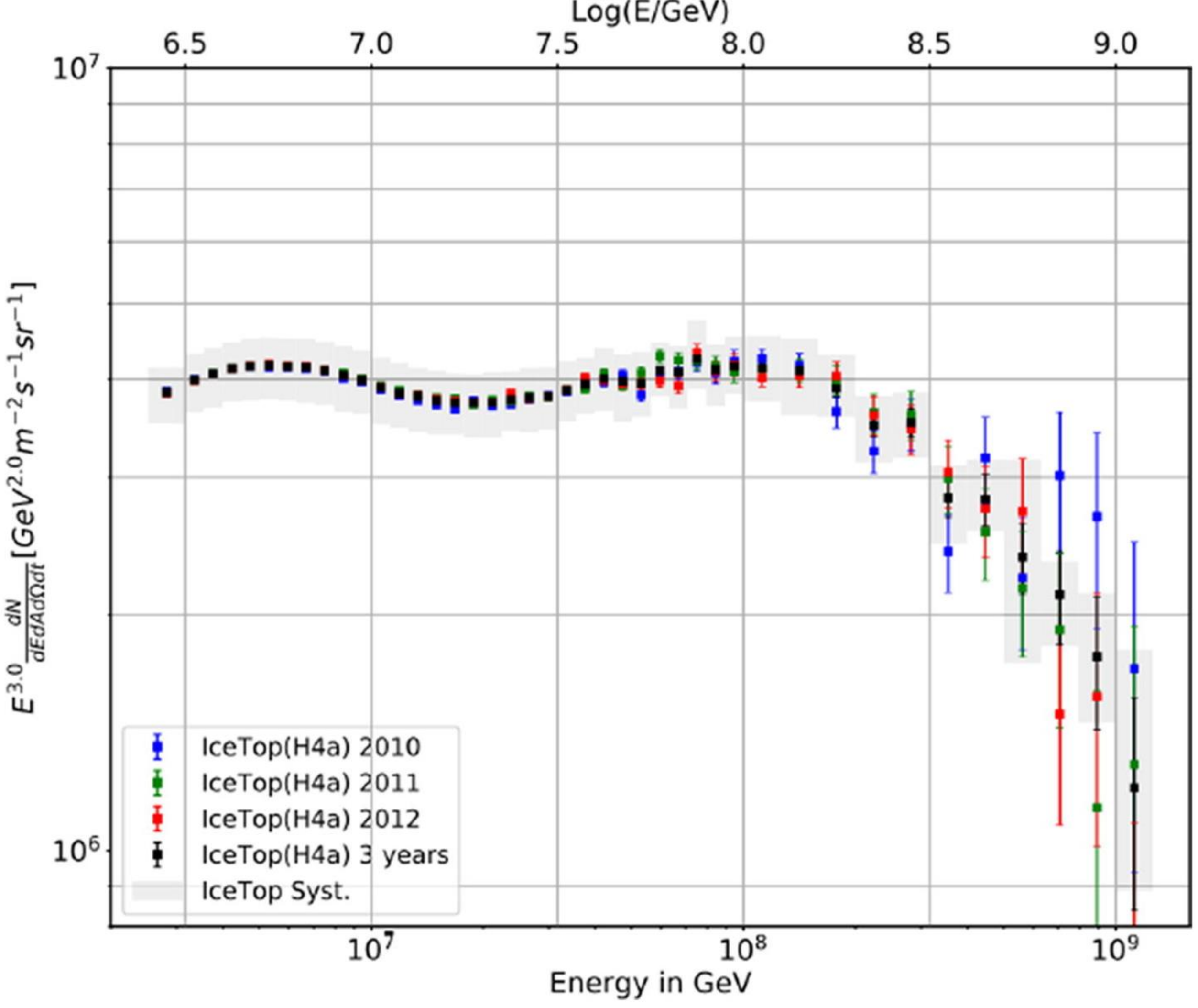


IceCube: beyond neutrino astronomy

Francis Halzen

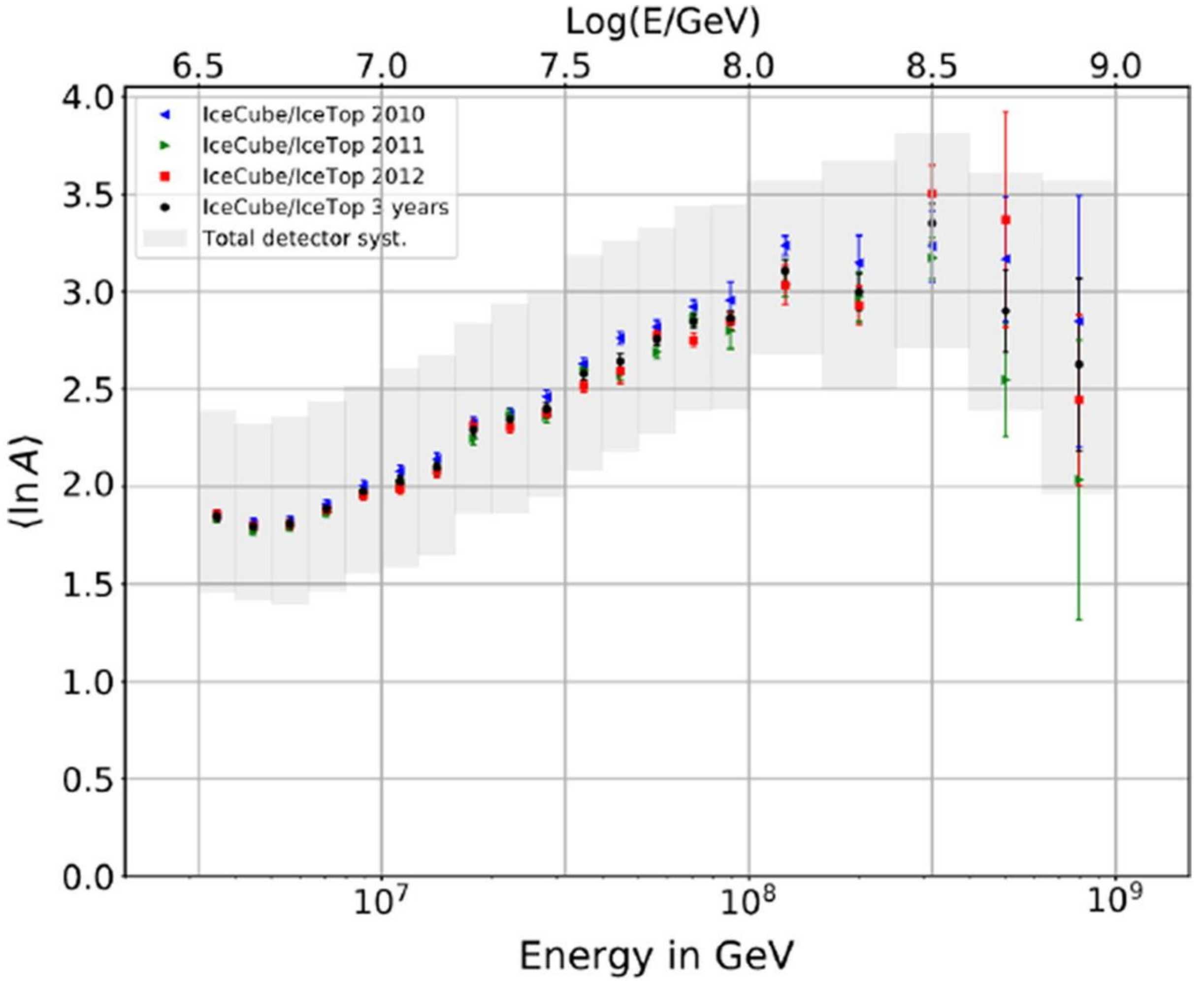
- natural Antarctic ice as a Cherenkov detector
- neutrino physics: from GeV to PeV
- detecting the next Galactic supernova explosion
- search for dark matter
- beyond the Standard Model physics: quantum decoherence, sterile neutrinos, neutrino cross sections, …
- cosmic ray physics

IceCube.wisc.edu

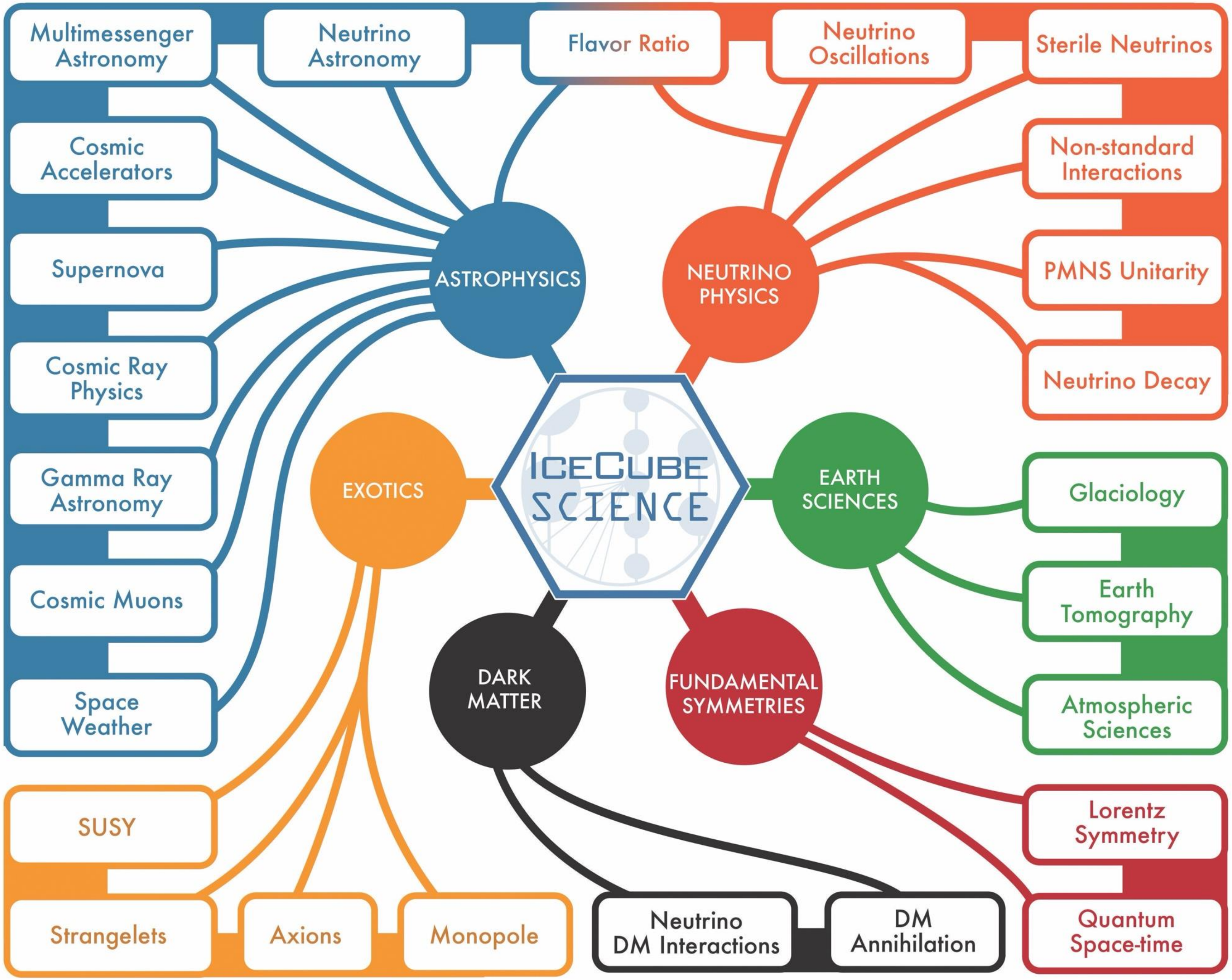


Log(E/GeV)
6.5
7.0
7.5
8.0
8.5
9.0
10^7
10^6
$E^{3.0}\frac{dN}{dEdAd\Omega dt}[GeV^{2.0}m^{-2}s^{-1}sr^{-1}]$
IceTop(H4a) 2010
IceTop(H4a) 2011
IceTop(H4a) 2012
IceTop(H4a) 3 years
IceTop Syst.
10^7
10^8
10^9
Energy in GeV

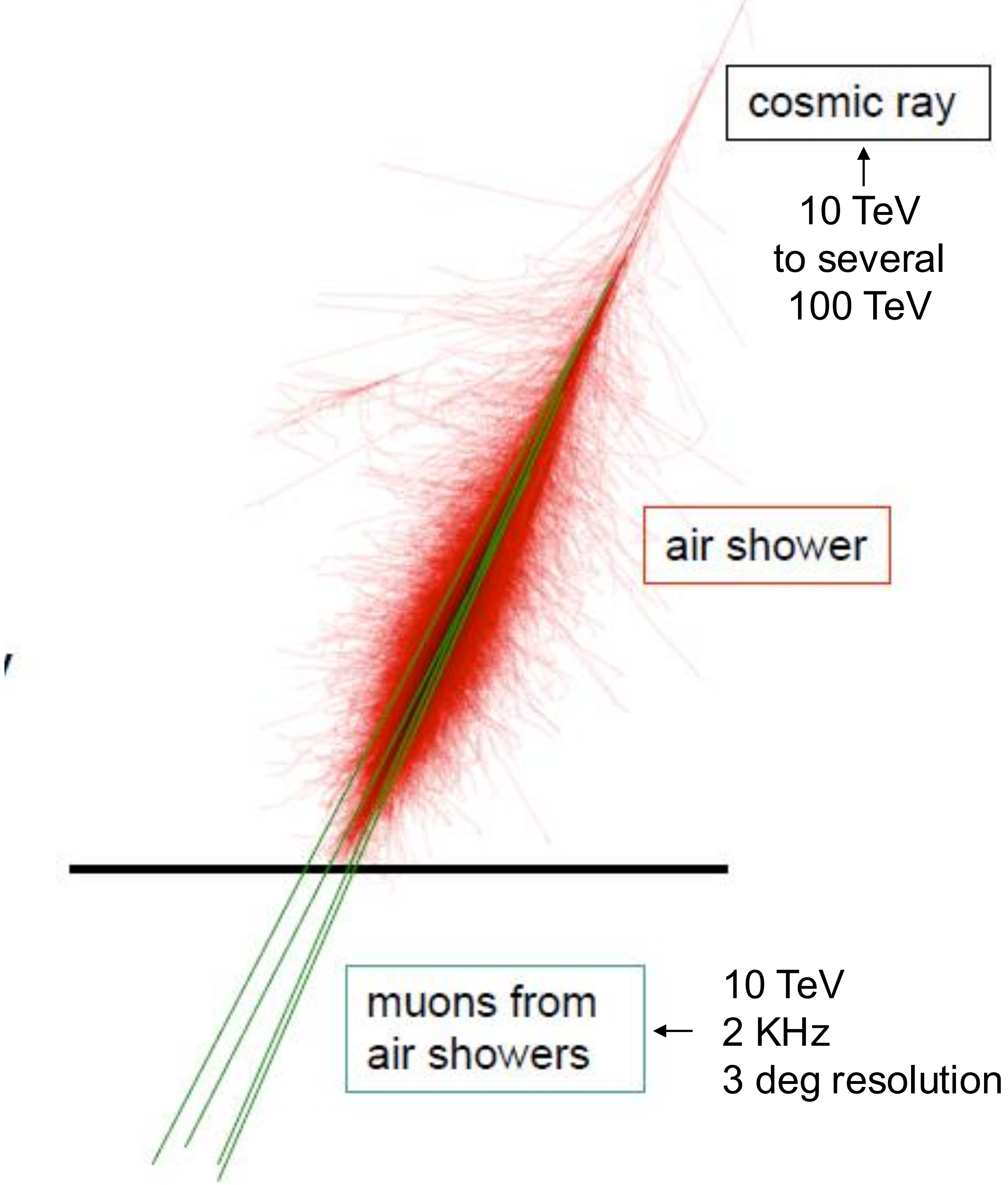
IceTop



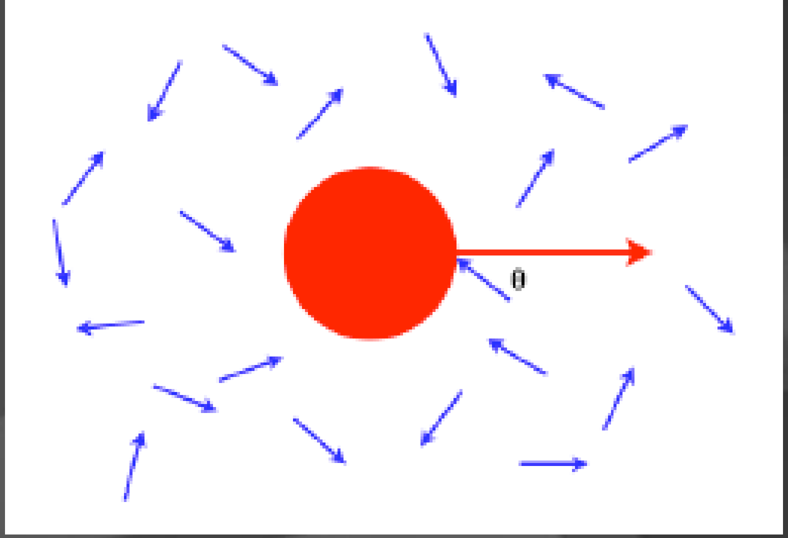
Log(E/GeV)
6.5
7.0
7.5
8.0
8.5
9.0
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
$\langle \ln A \rangle$
IceCube/IceTop 2010
IceCube/IceTop 2011
IceCube/IceTop 2012
IceCube/IceTop 3 years
Total detector syst.
10^7
10^8
10^9
Energy in GeV


ICECUBE SCIENCE
ASTROPHYSICS
Multimessenger Astronomy
Neutrino Astronomy
Cosmic Accelerators
Supernova
Cosmic Ray Physics
Gamma Ray Astronomy
Cosmic Muons
Space Weather
Flavor Ratio
NEUTRINO PHYSICS
Neutrino Oscillations
Sterile Neutrinos
Non-standard Interactions
PMNS Unitarity
Neutrino Decay
EARTH SCIENCES
Glaciology
Earth Tomography
Atmospheric Sciences
FUNDAMENTAL SYMMETRIES
Lorentz Symmetry
Quantum Space-time
DARK MATTER
Neutrino DM Interactions
DM Annihilation
EXOTICS
SUSY
Strangelets
Axions
Monopole

cosmic rays in IceCube



- galactic
- not solar
- highest energies approach the "knee"
- gyroradius < 1 pc in microgauss field
- closest sources > 100 pc

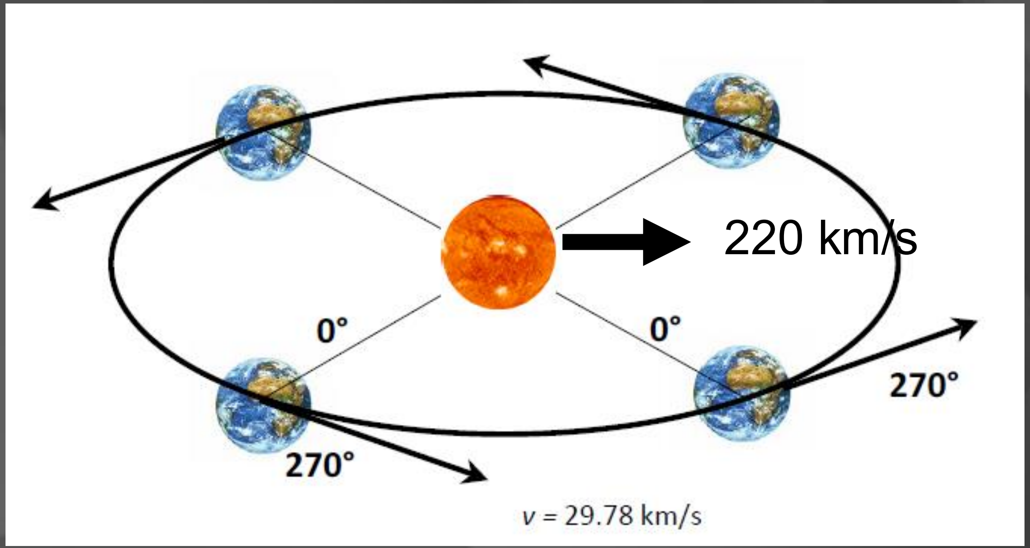


dipole anisotropies

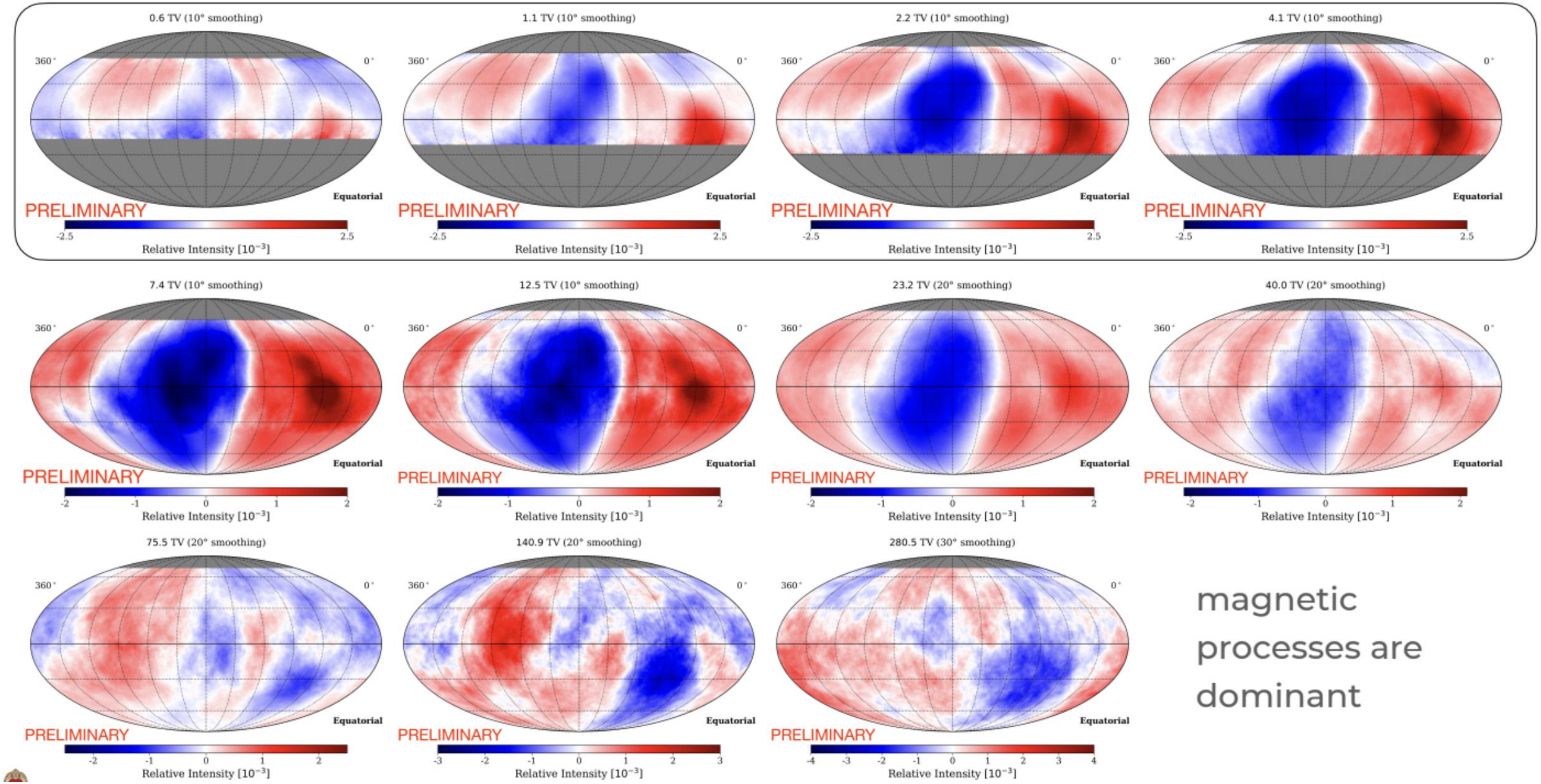
motion of the Earth in the frame of the cosmic rays?

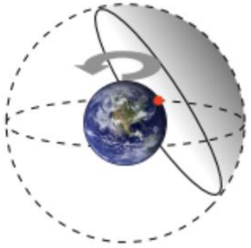
- solar dipole: motion of the Earth around the sun

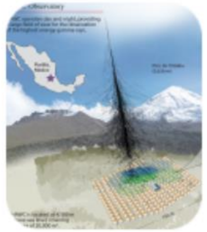
- motion of the Sun relative to the Galaxy (Compton-Getting)

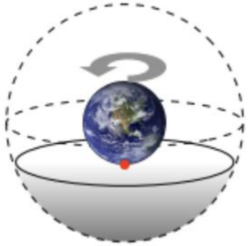


HAWC & IceCube - PoS(ICRC2025)244 & arXiv:2507.07070

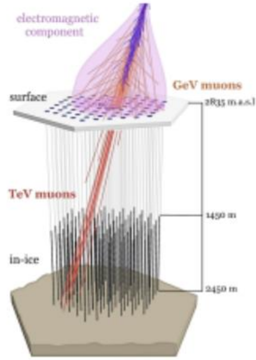




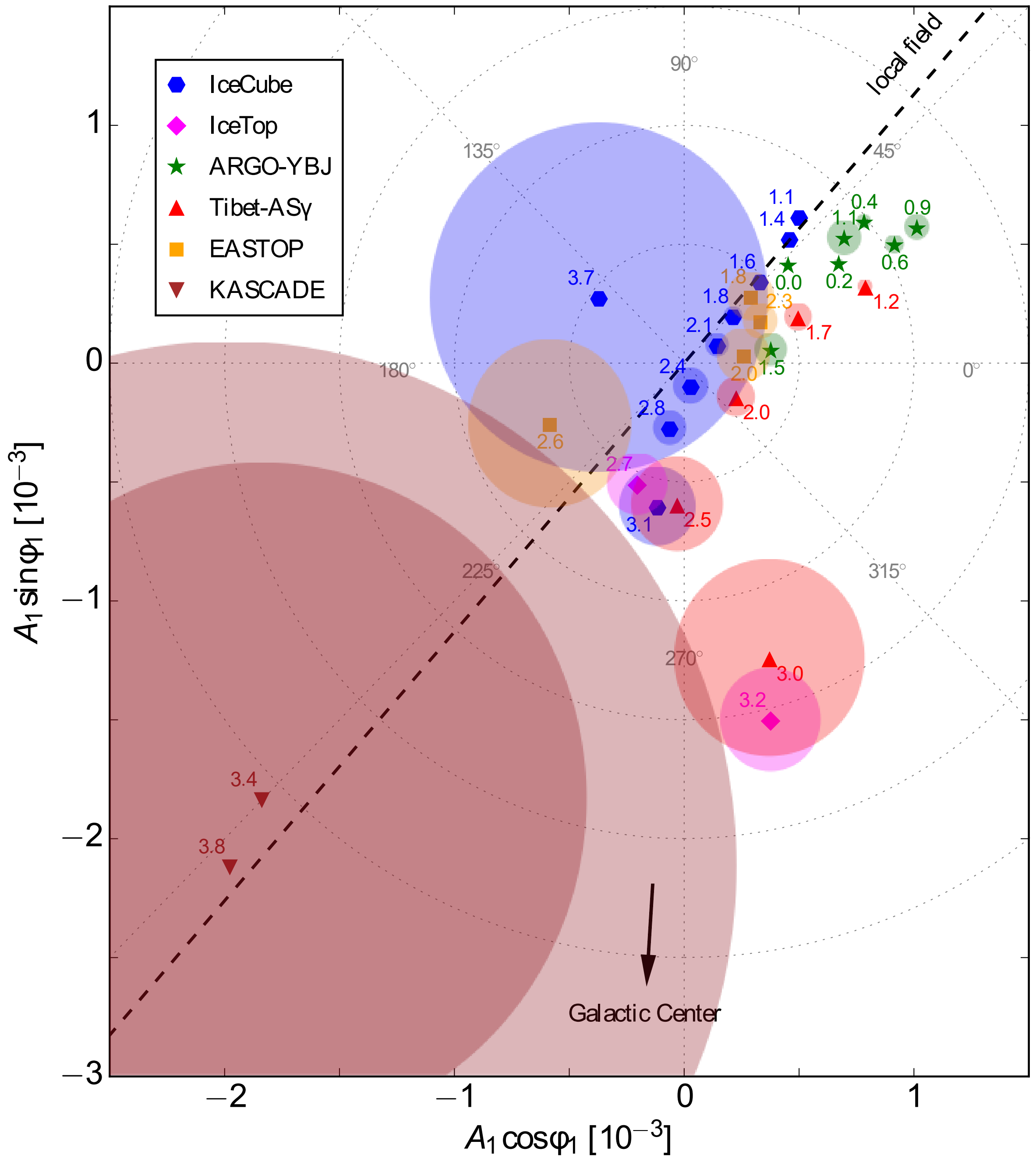


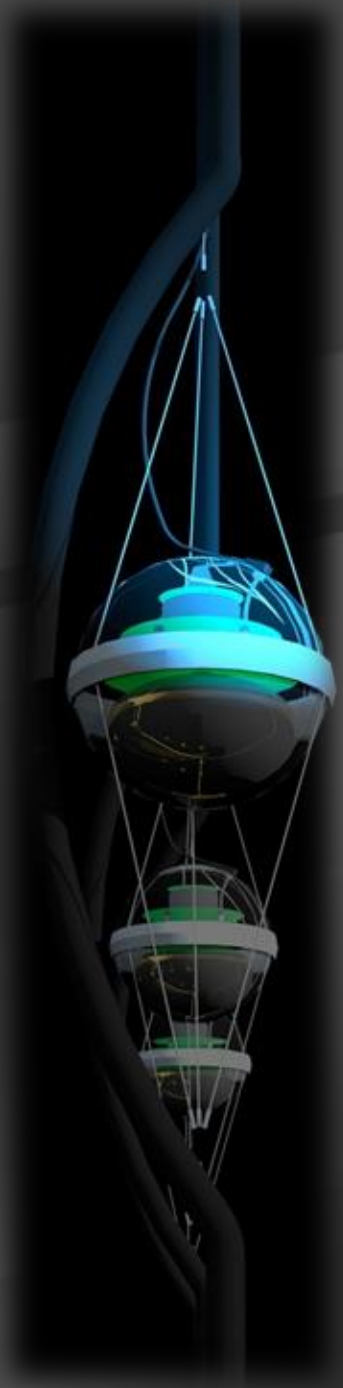


magnetic processes are dominant



dipole rotates from the direction of the local magnetic field at TeV energy to the direction of the Galactic center at PeV energy possibly reflecting nearby Galactic cosmic ray sources





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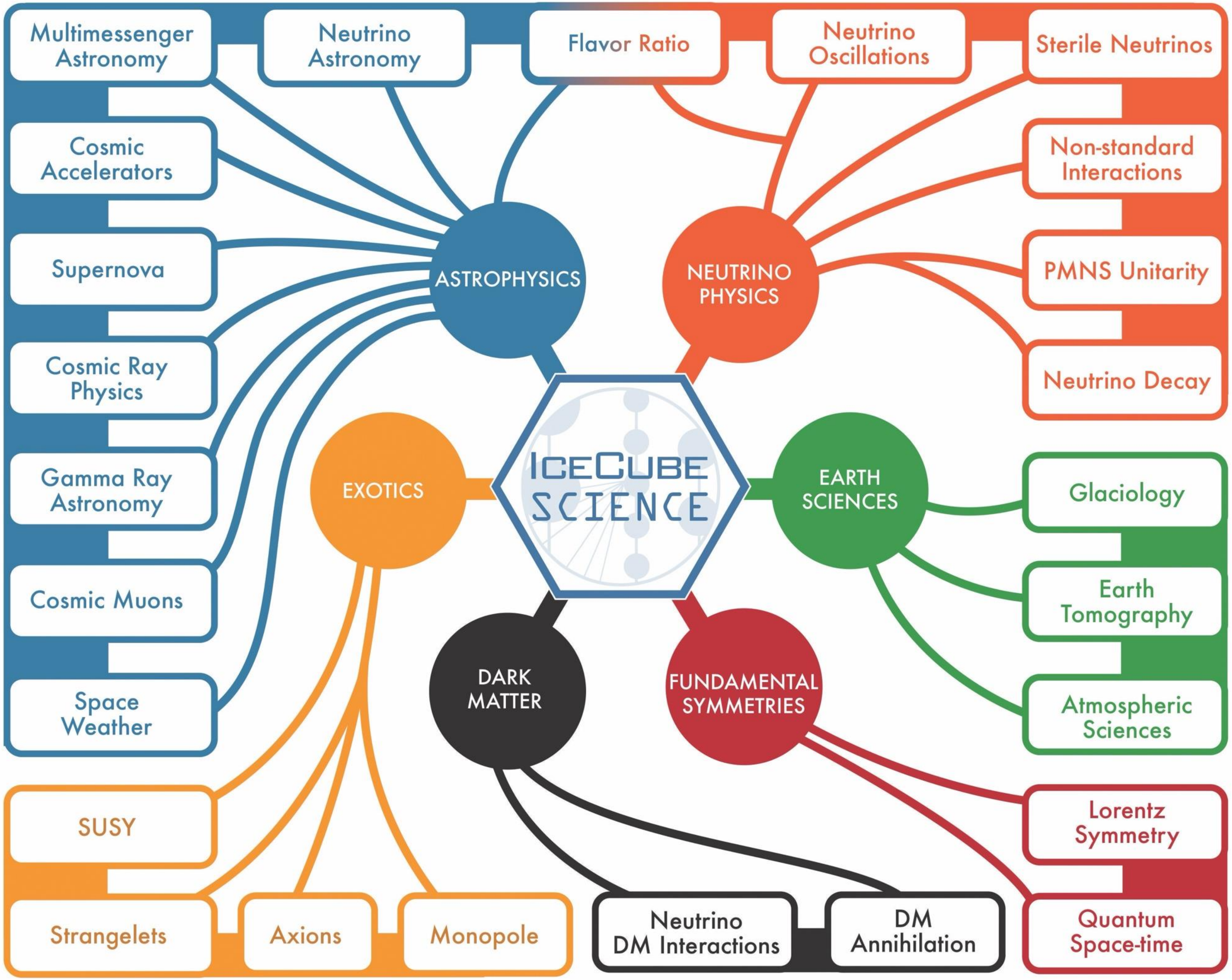
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Axions
Monopole

THE ICECUBE COLLABORATION

THE ICECUBE COLLABORATION

ALIA 1

1

TED KINGDOM 1

UNITED STATES 25

ICECUBE
South Pole Neutrino Observatory