Current and future neutrino experiments with tomography potential

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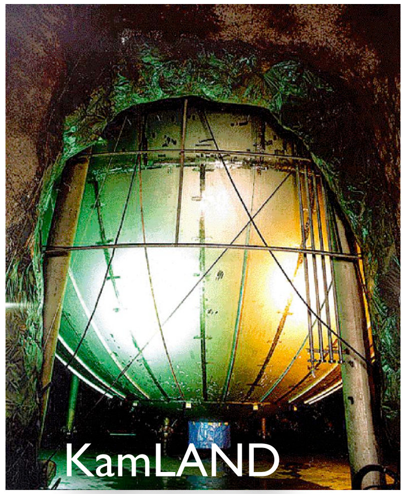
Outline

- Motivation
- Neutrino Oscillation Tomography
- Understanding sensitivities with a generic neutrino detector
- Neutrino Experiments Status
- Summary / Outlook

- What can neutrino detectors do for Solid Earth Science ?
  - **Muon Radiography**
    - Atm. airshower muon absorption
  - **Geo-neutrinos**
    - Low-energy neutrino detection from nuclear decays
  - **Neutrino absorption tomography**
    - Atmospheric air shower high-energy neutrino absorption
  - **Neutrino oscillation tomography**
    - Atmospheric air shower neutrino oscillations

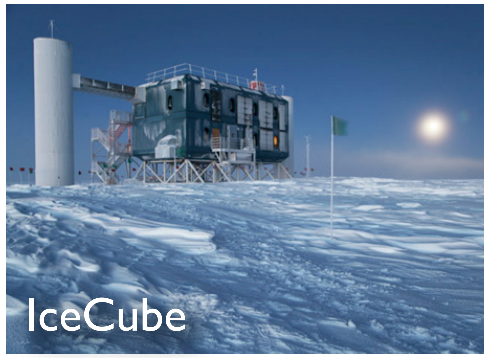
Geo-neutrinos

U and Th geo-ν

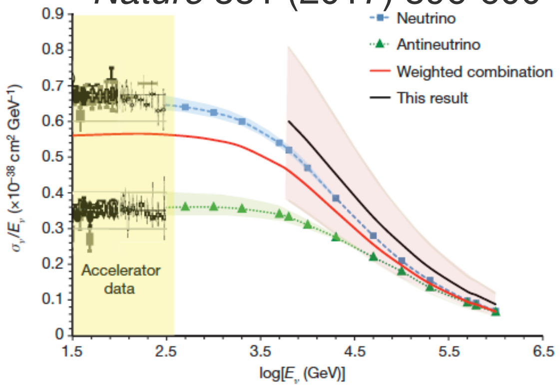


Nature Geoscience; Volume: 4, 647–651 (2011)

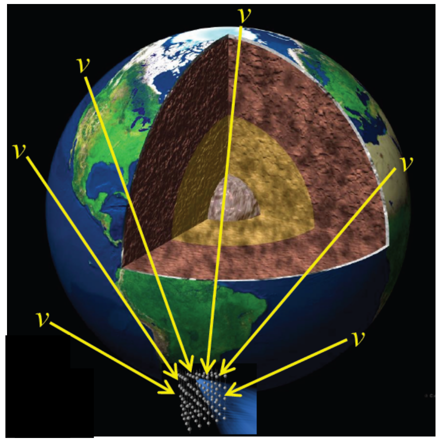
Neutrino absorption tomography

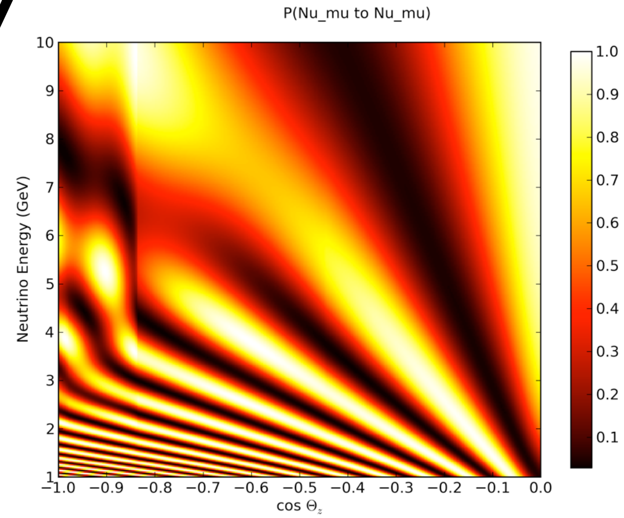


IceCube Collaboration
Nature 551 (2017) 596-600



Neutrino oscillation tomography



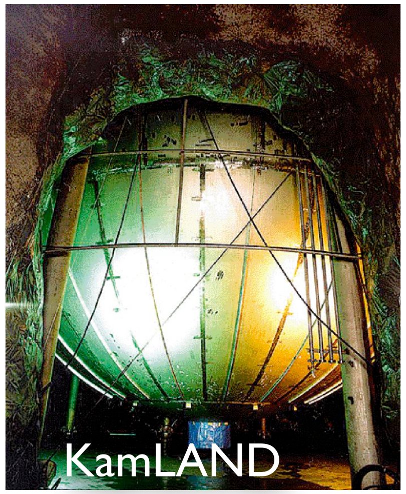


Motivation (Particle Physics ⇐ Earth Science)

- What can neutrino detectors do for Solid Earth Science ?
  - **Muon Radiography**
    - Atm. airshower muon absorption
  - **Geo-neutrinos**
    - Low-energy neutrino detection from nuclear decays
  - **Neutrino absorption tomography**
    - Atmospheric air shower high-energy neutrino absorption
  - **Neutrino oscillation tomography**
    - Atmospheric air shower neutrino oscillations

Geo-neutrinos

U and Th geo-ν



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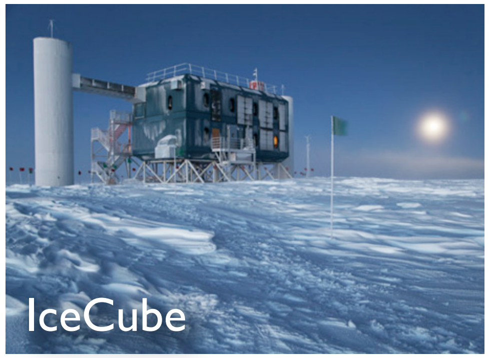
Neutrino absorption tomography



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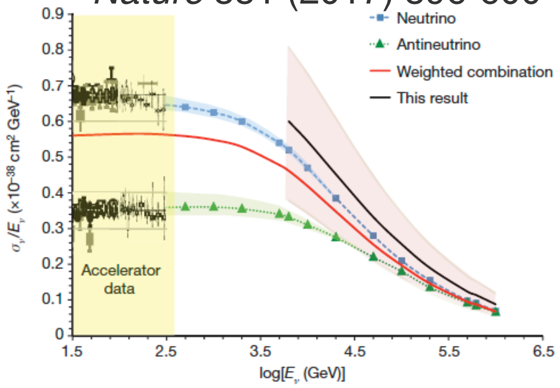
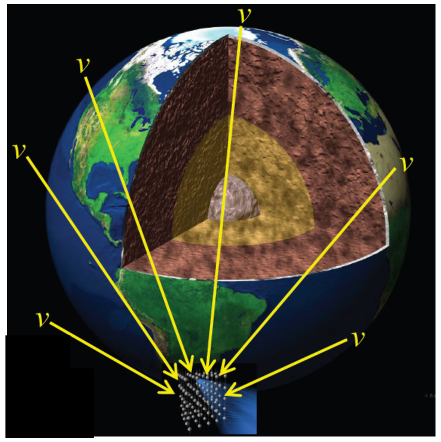
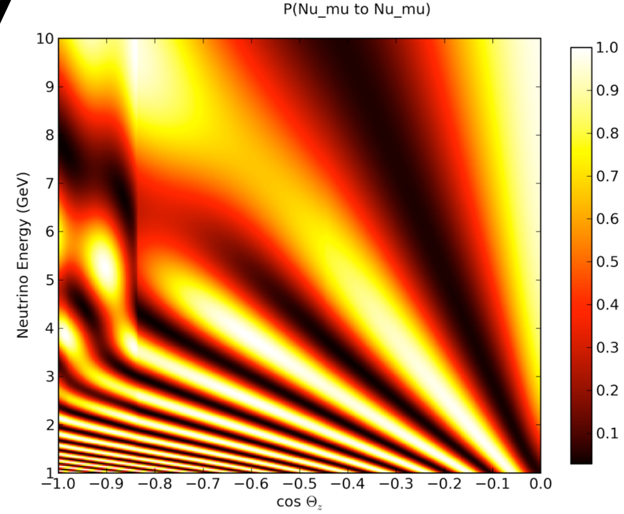


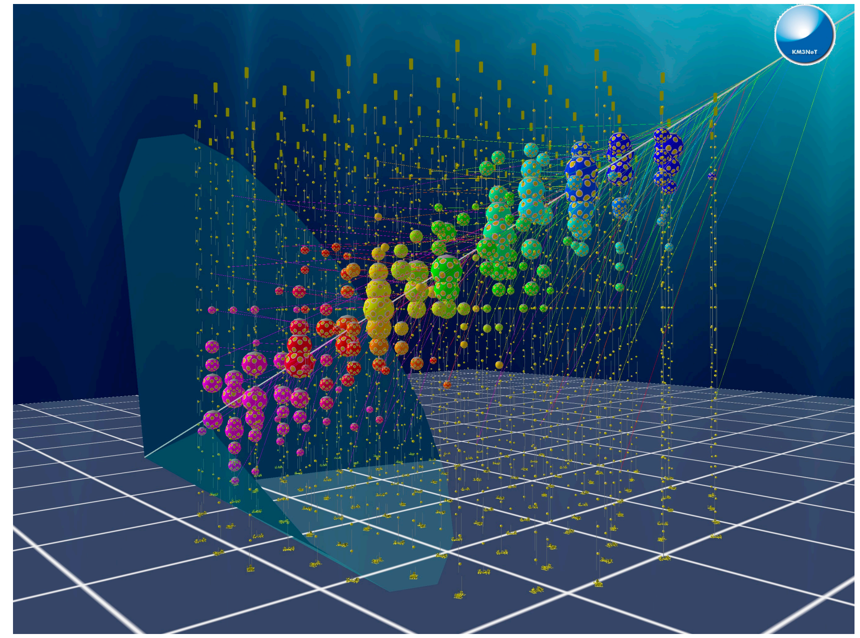
Neutrino oscillation tomography



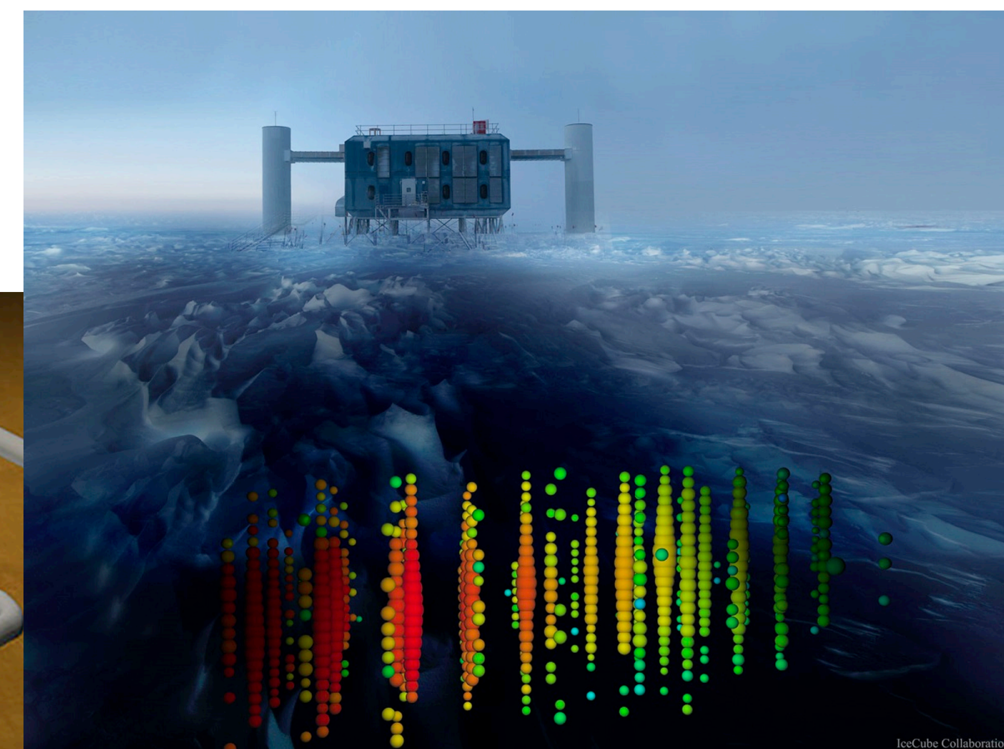


Motivation - Neutrino Oscillation Tomography

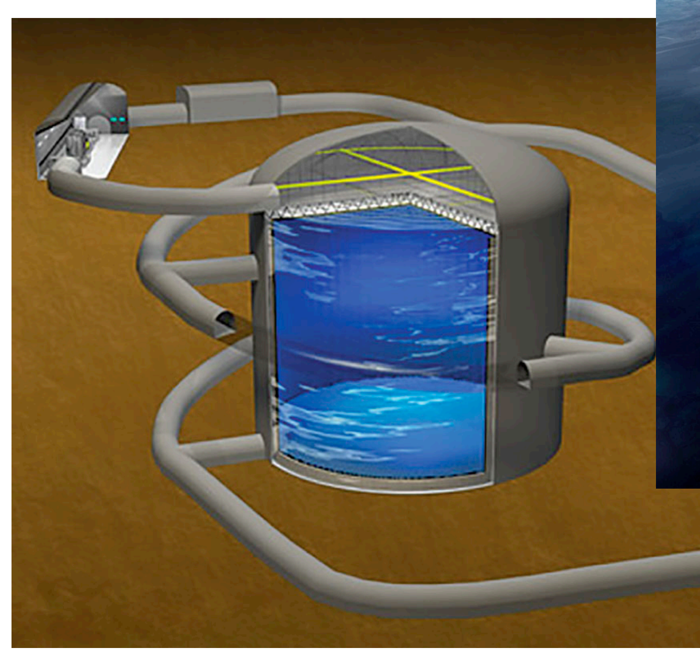
- New Method to understand inner Earth
  - Inner Earth Composition
    - Light elements in the outer core ?
    - Understand the Geodynamo
  - Lower mantle density and anisotropy
- Apply neutrino physics to Earth Science



https://www.km3net.org/

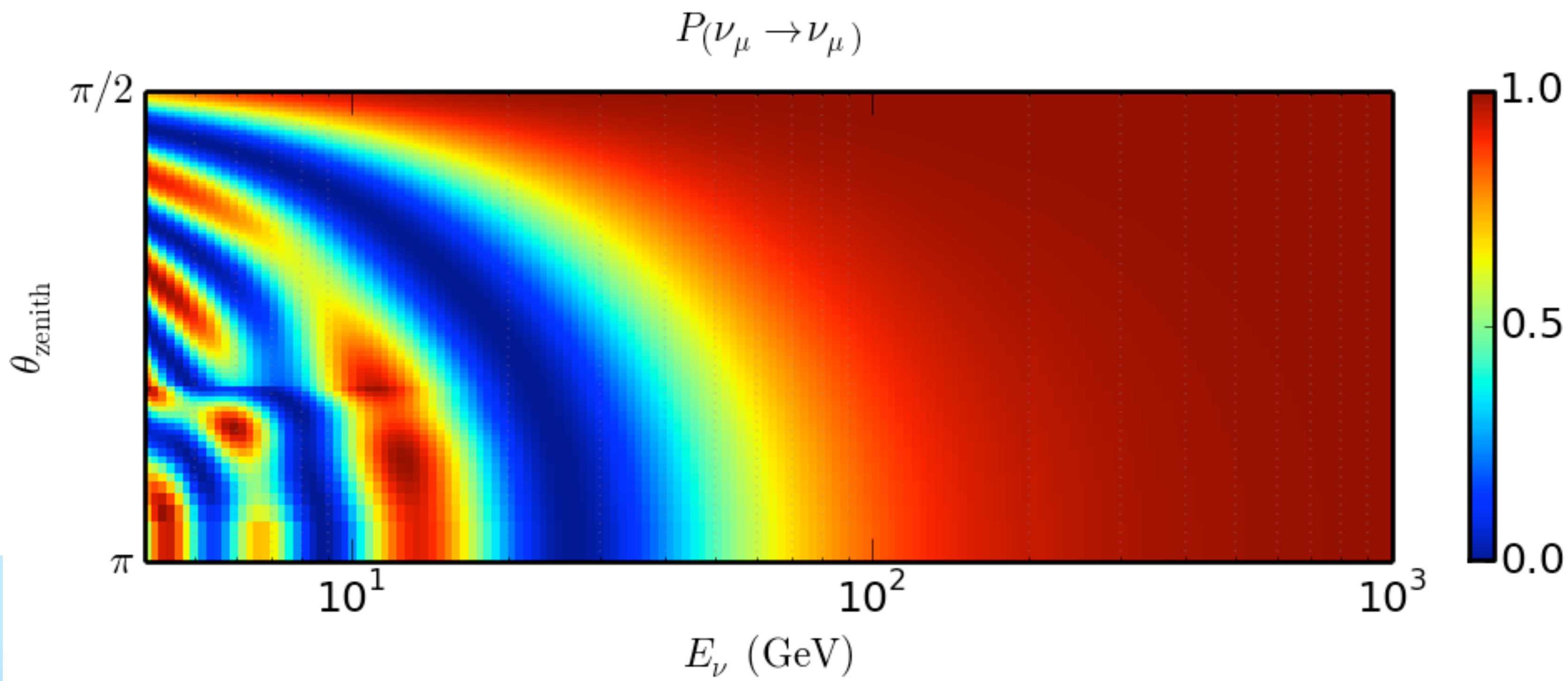


http://icecube.wisc.edu



http://www.hyper-k.org/

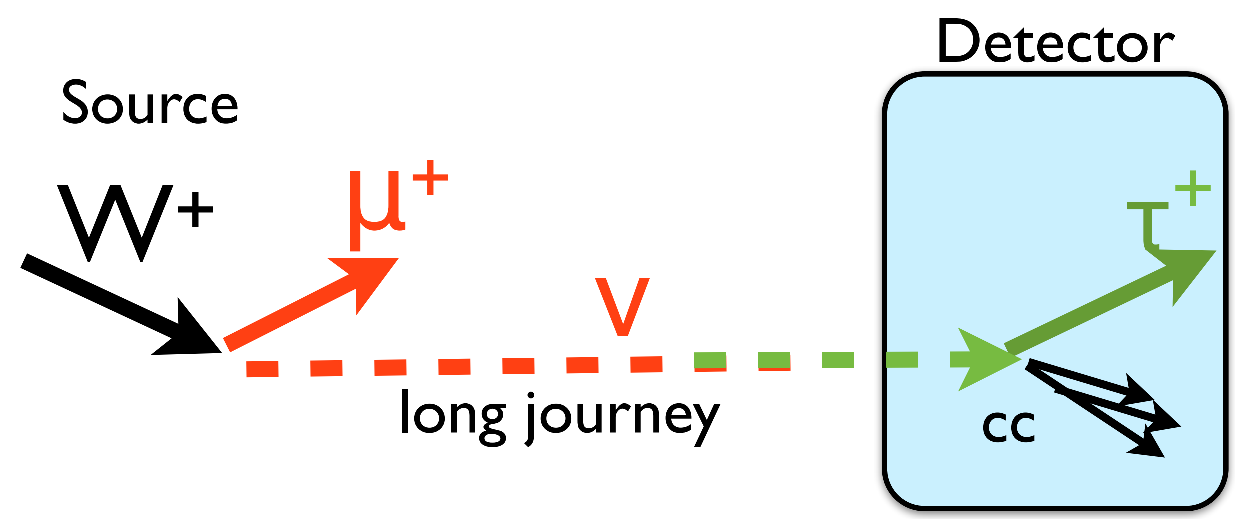
Motivation - Neutrino Oscillation Tomography and understanding general detector sensitivity

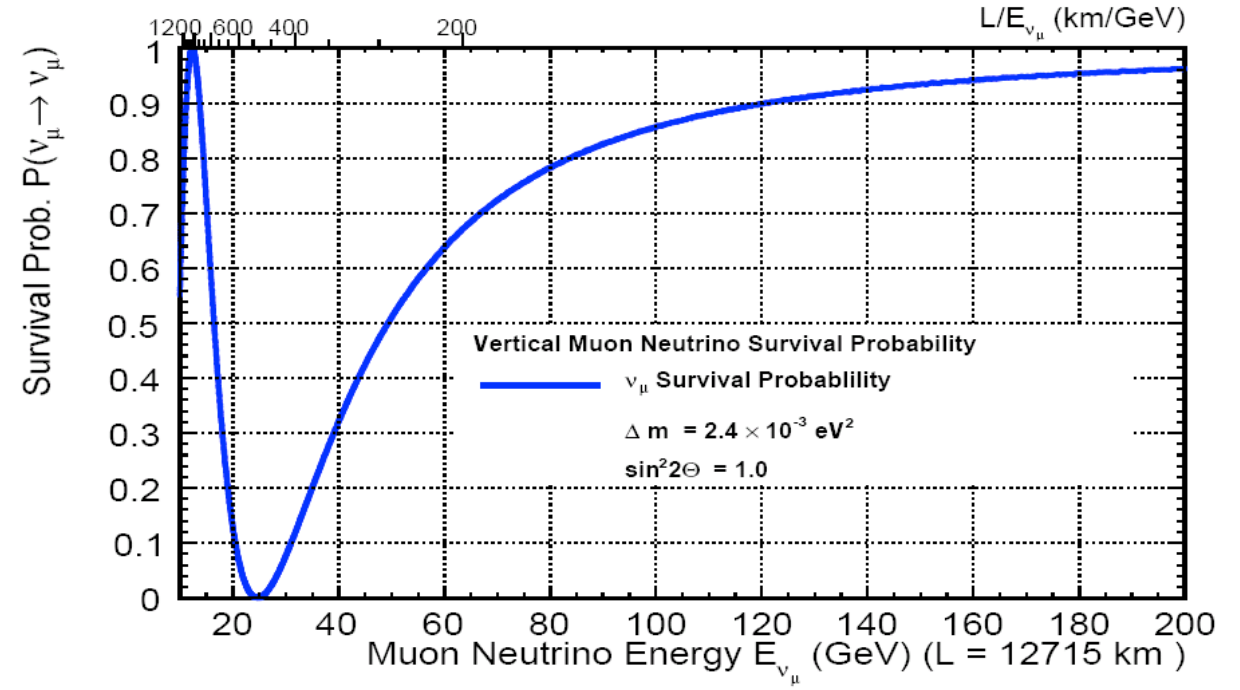


Neutrino Oscillations

Neutrino Oscillations Basics

- Neutrinos come in three different flavors: ν_e, ν_μ, ν_τ
- A neutrino created as one flavor can change into a different flavor
- This phenomenon (neutrino oscillations) depends on the energy of the neutrino and the distance traveled
- It further depends on the "potential" the neutrino travels through





$$P(\nu_\alpha \to \nu_\beta) = 4\sin^2\theta\cos^2\theta\sin^2\left(\frac{\Delta m_{ij}^2 L}{4E}\right)$$

oscillation probability

oscillation parameters

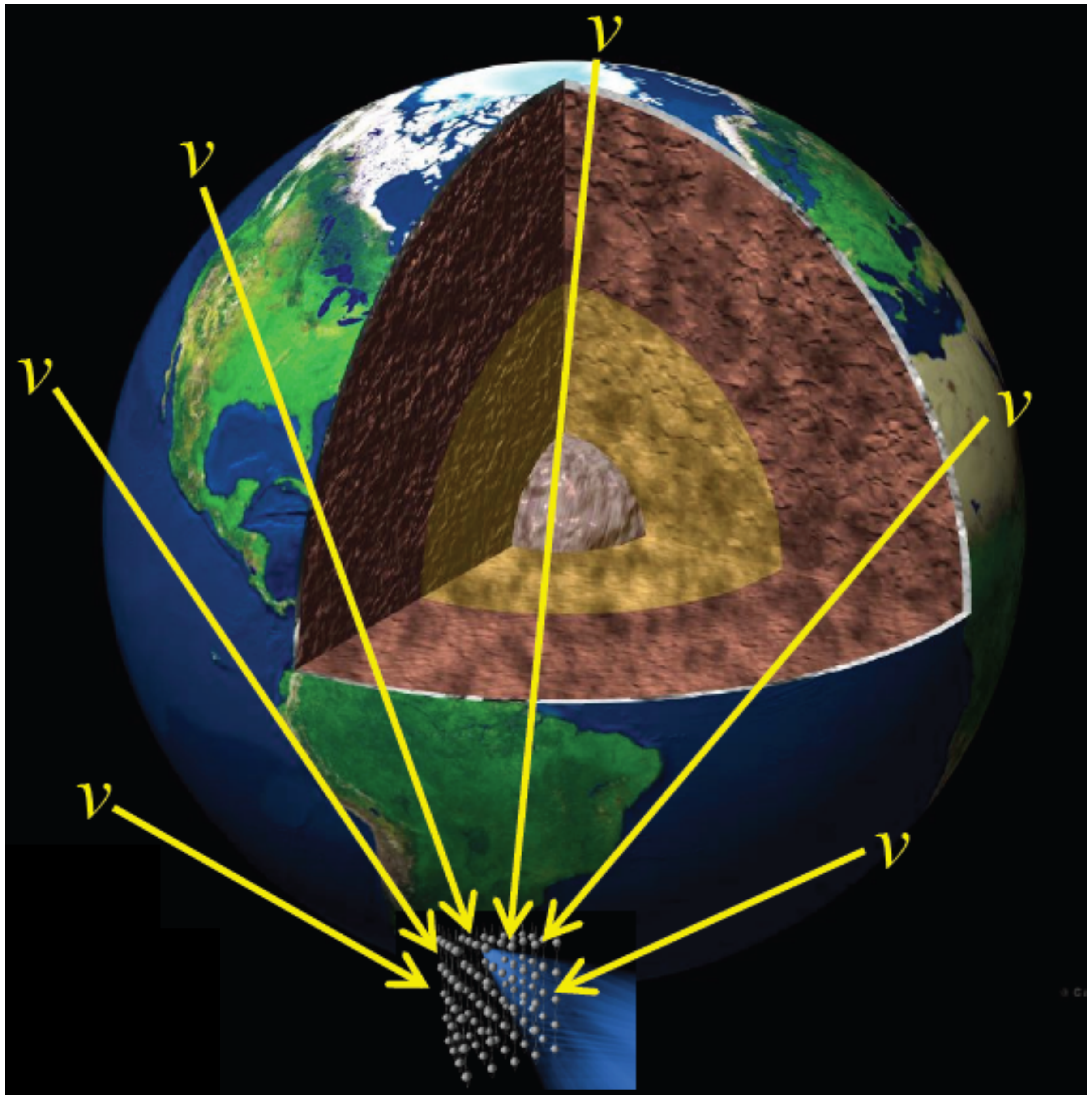
energy

distance

Neutrino Oscillation Tomography

Motivation - Methodology

- The Earth **matter density** profile can be determined from **seismic measurements**
- Matter induced **neutrino oscillation** effects however dependent on the **electron density**
- Given a matter density profile the "average" composition (or **Z**/**A**) along the neutrino path can be determined using neutrino signals (Oscillation tomography)



Electron density in core
Y_c=electron/nucleons

corresponding zenith angles for boundaries
inner core $\theta_\nu < 169°$ ($\cos\theta_\nu < -0.98$)
outer core $\theta_\nu < 147°$ ($\cos\theta_\nu < -0.84$)

Z/A ratios

Element		Z	A	Z/A
Hydrogen	H	1	1.008	0.9921
Carbon	C	6	12.011	0.4995
Oxygen	O	8	15.999	0.5
Magnesium	Mg	12	24.305	0.4937
Silicon	Si	14	28.085	0.4985
Sulfur	S	16	32.06	0.4991
Iron	Fe	26	55.845	0.4656
Nickel	Ni	28	58.693	0.4771

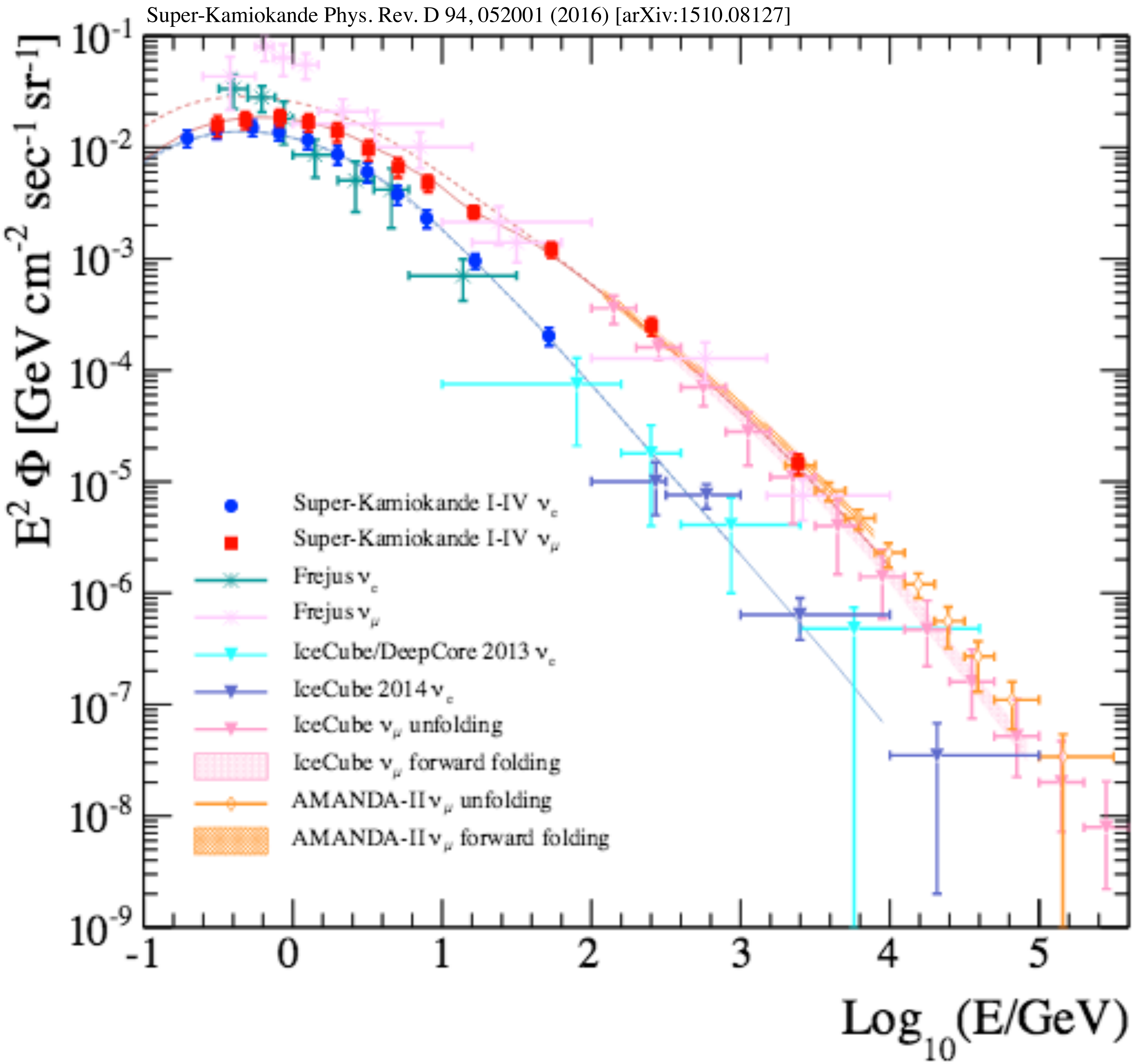
Z - Atomic Number **A** - Atomic Mass

- Z/A ratios

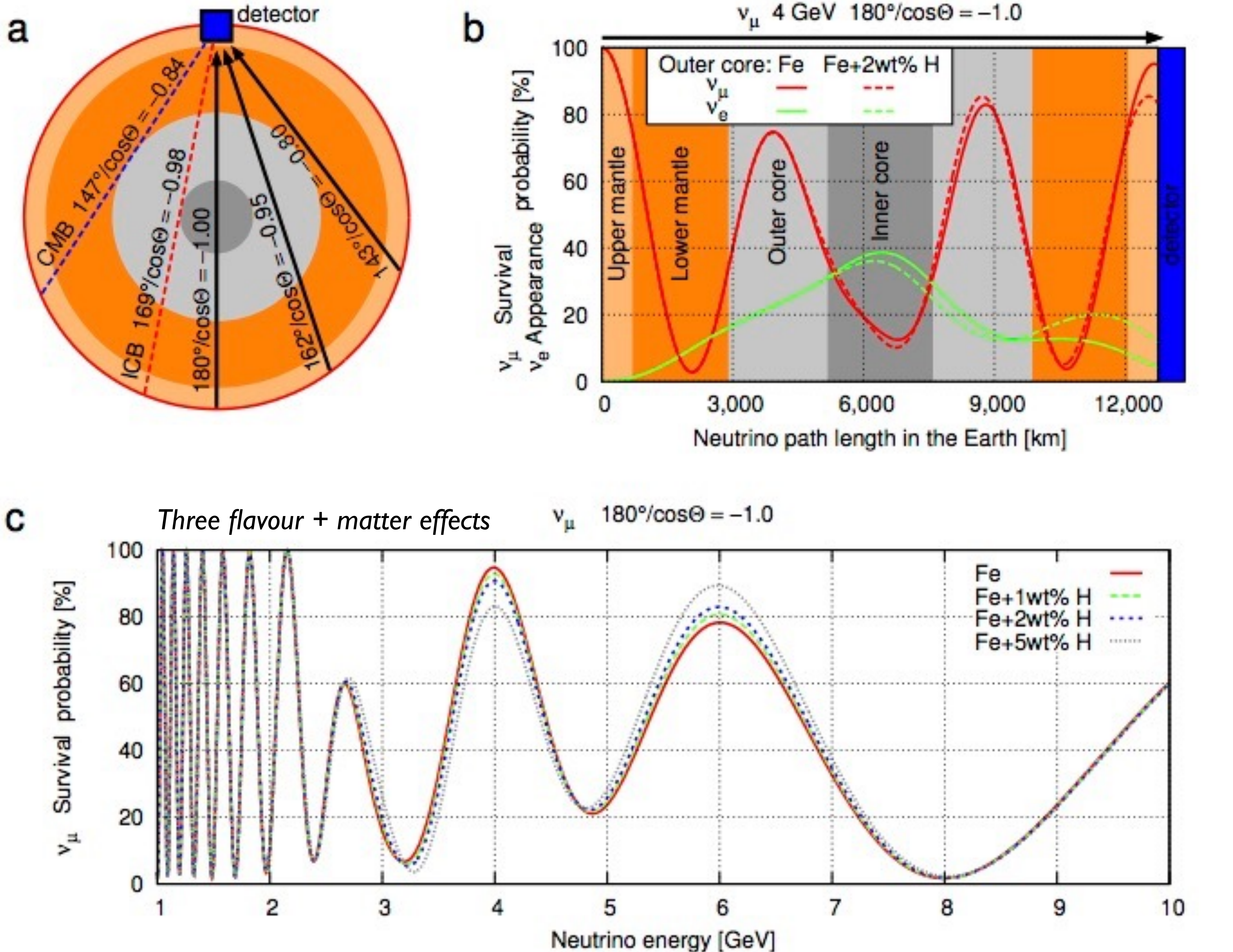
Atmospheric Neutrinos

Atmospheric neutrinos are a **natural** steady **source of muon and electron neutrinos** at the energy range relevant for neutrino oscillation tomography

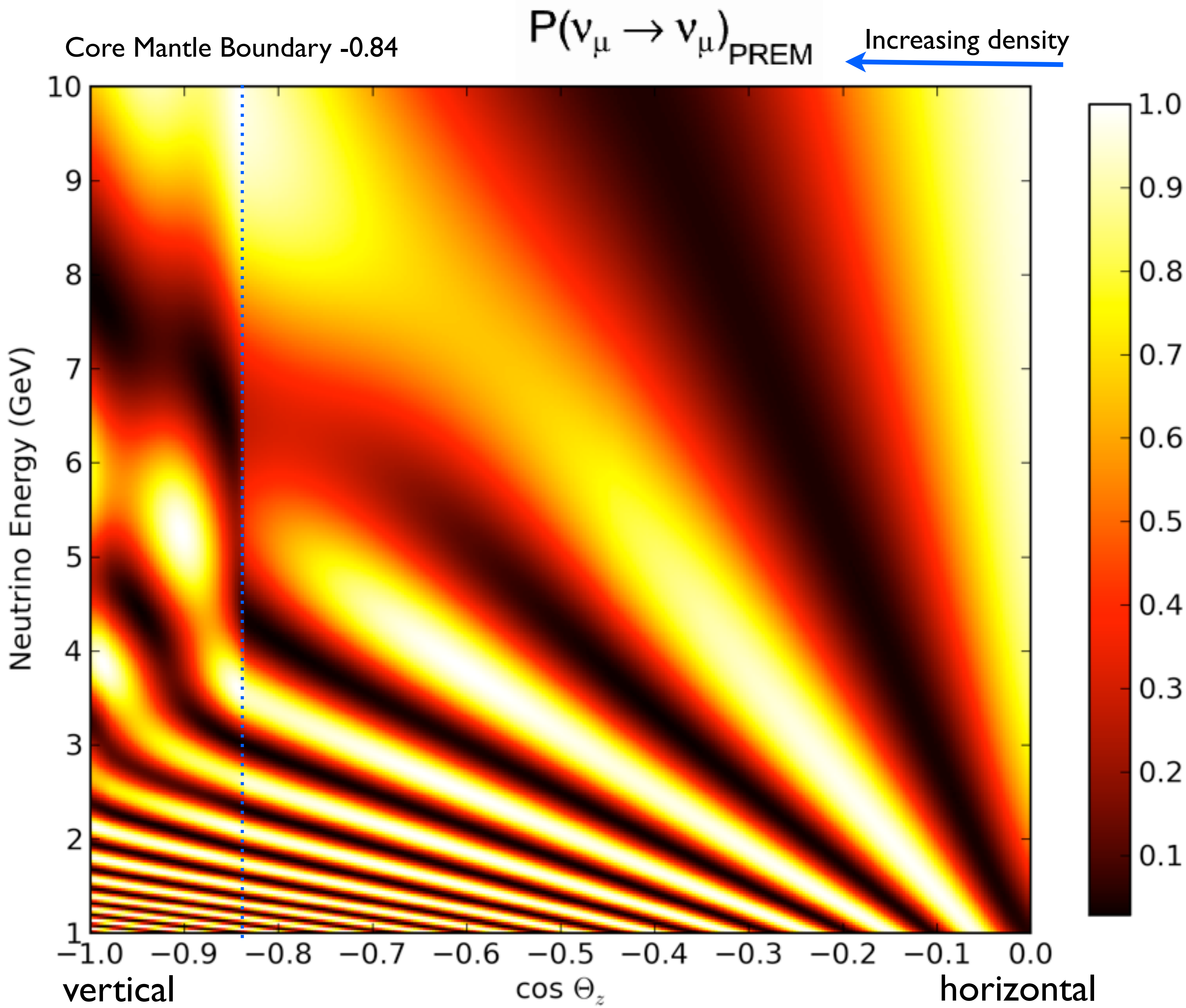
- p + A → $\pi^{\pm}$ ($K^{\pm}$) + other hadrons
  - $\pi^+ \rightarrow \mu^+ \nu_\mu \rightarrow e^+ \nu_e \nu_\mu \nu_\mu$



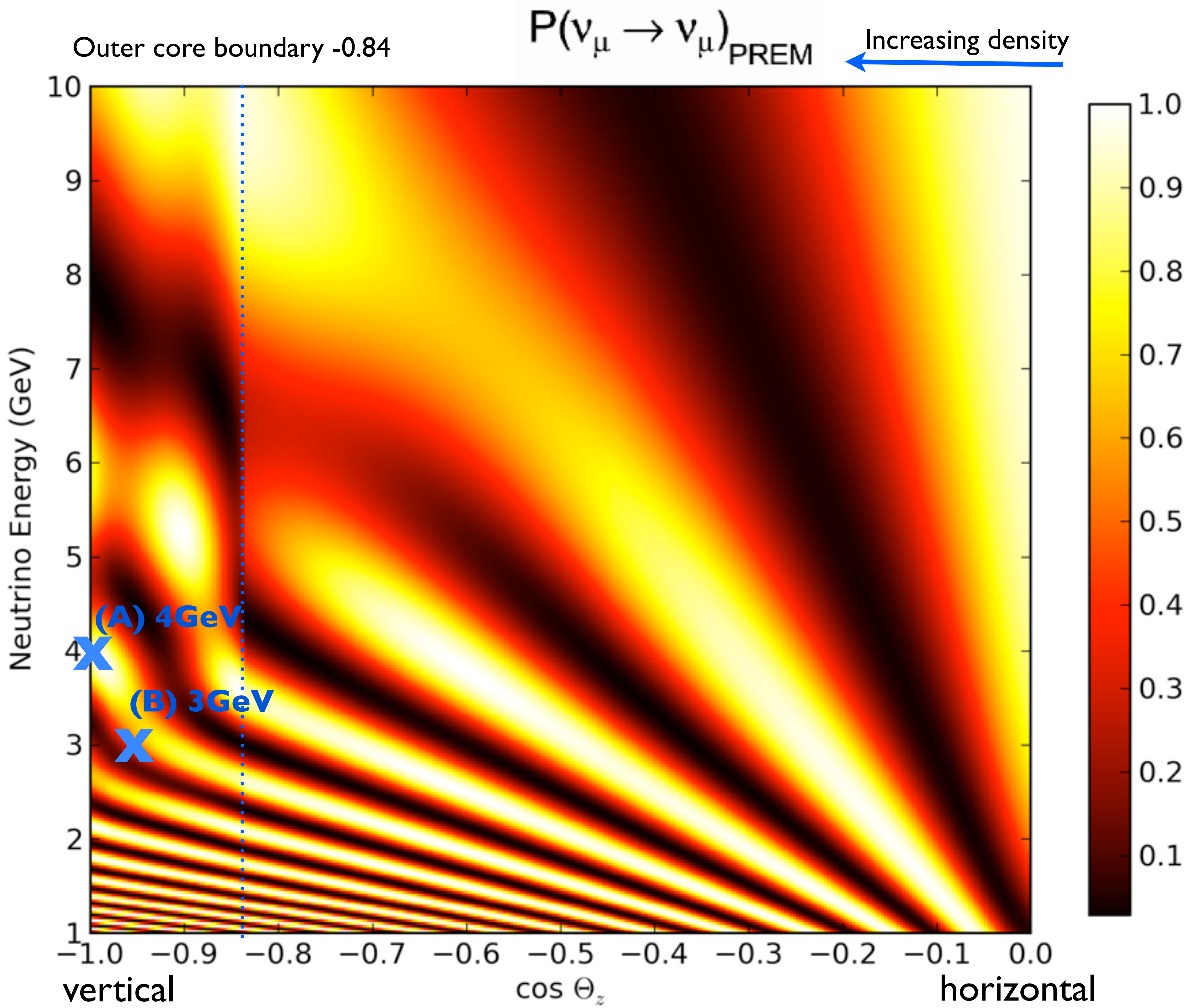
Rott & Taketa 2015



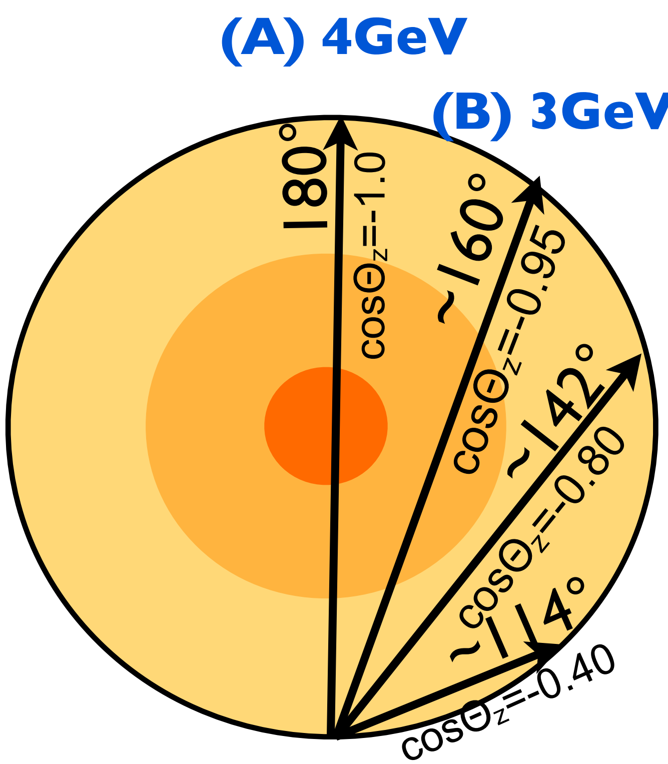
Oscillograms



How to read an oscillograms



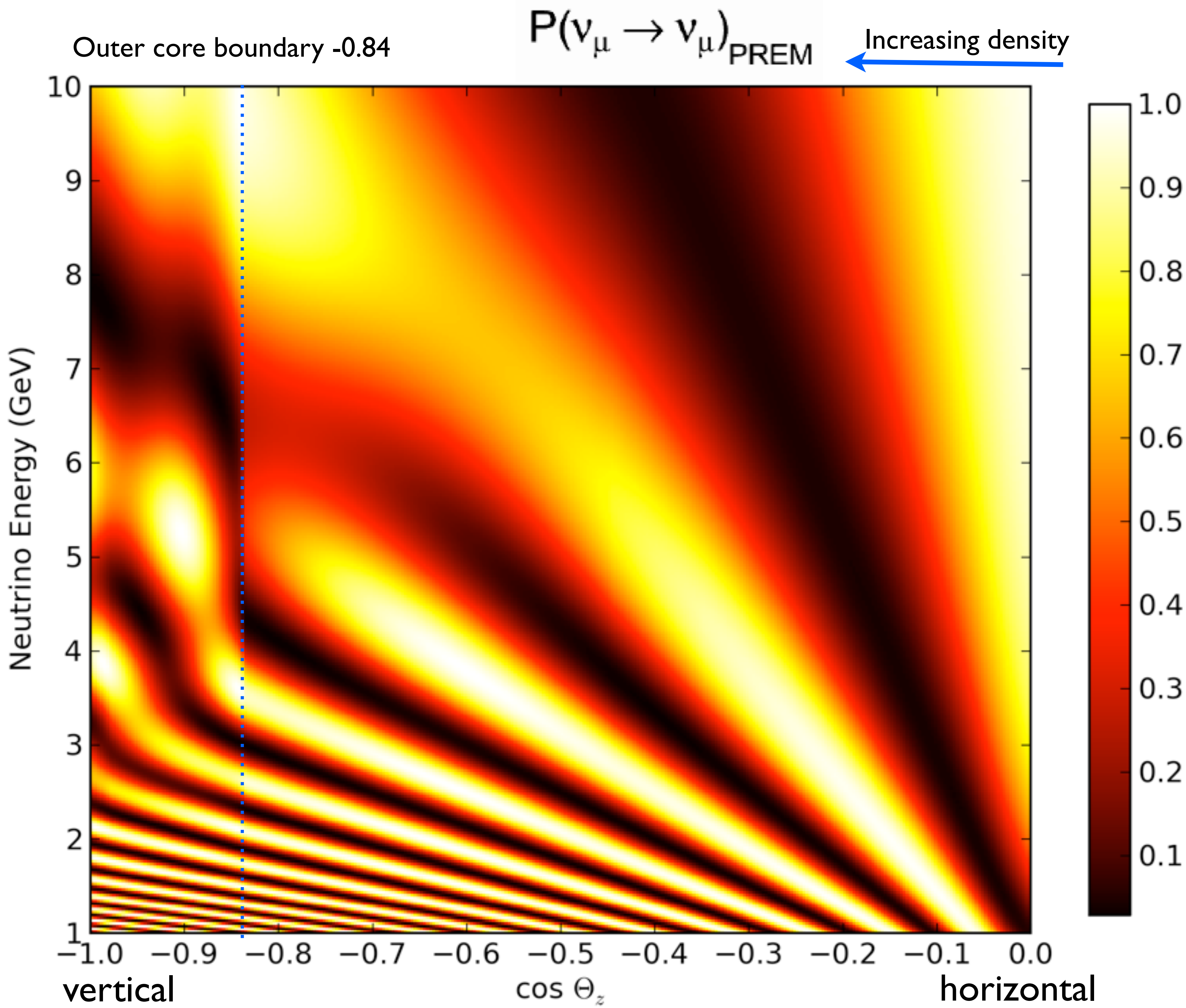
An example ...



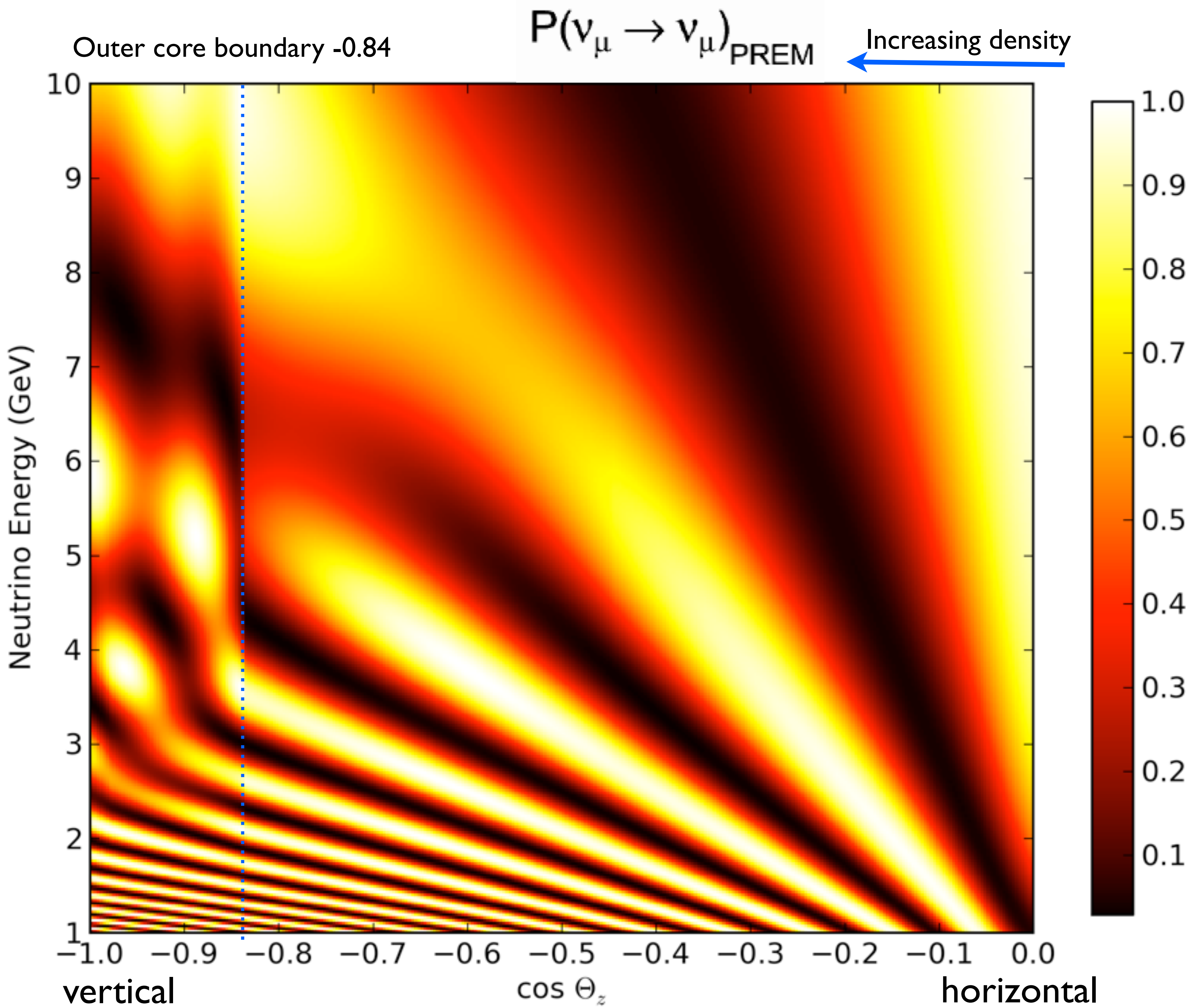
A muon neutrino created at **(A)** with energy 4GeV has a ~**90%** chance to be detected as such after traversing the Earth

A muon neutrino created at **(B)** with energy 3GeV has a ~**40%** chance to be detected as such after traversing the Earth

Oscillogram ("normal" electron density)



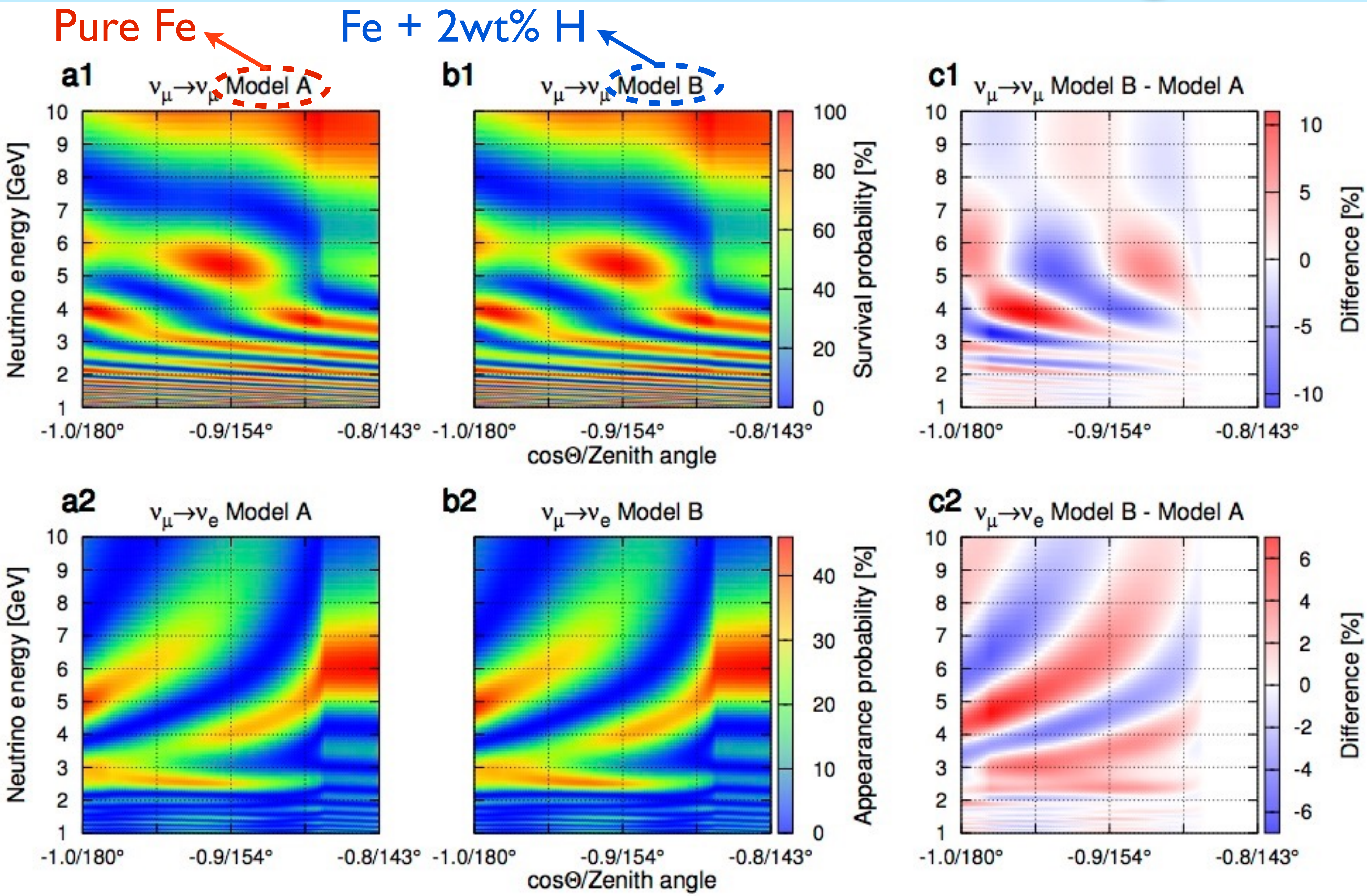
Oscillogram (enhance electron density)



Change Earth core electron density by 10% to visualize change in survival probability

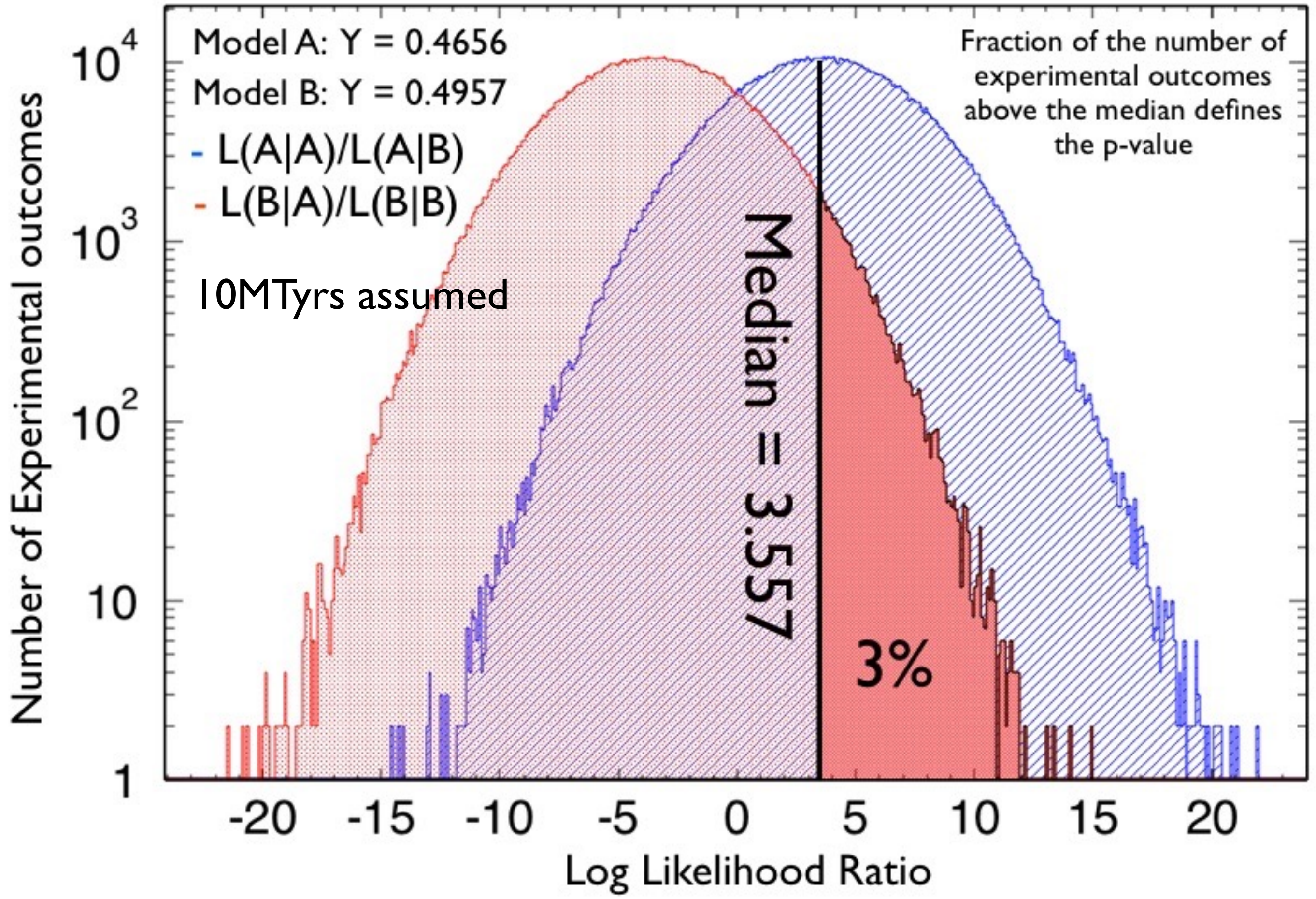
Most significant changes are seen in an energy range of **2-10GeV** and for neutrinos passing through the core region(**cosθ < -0.84**)

Oscillograms

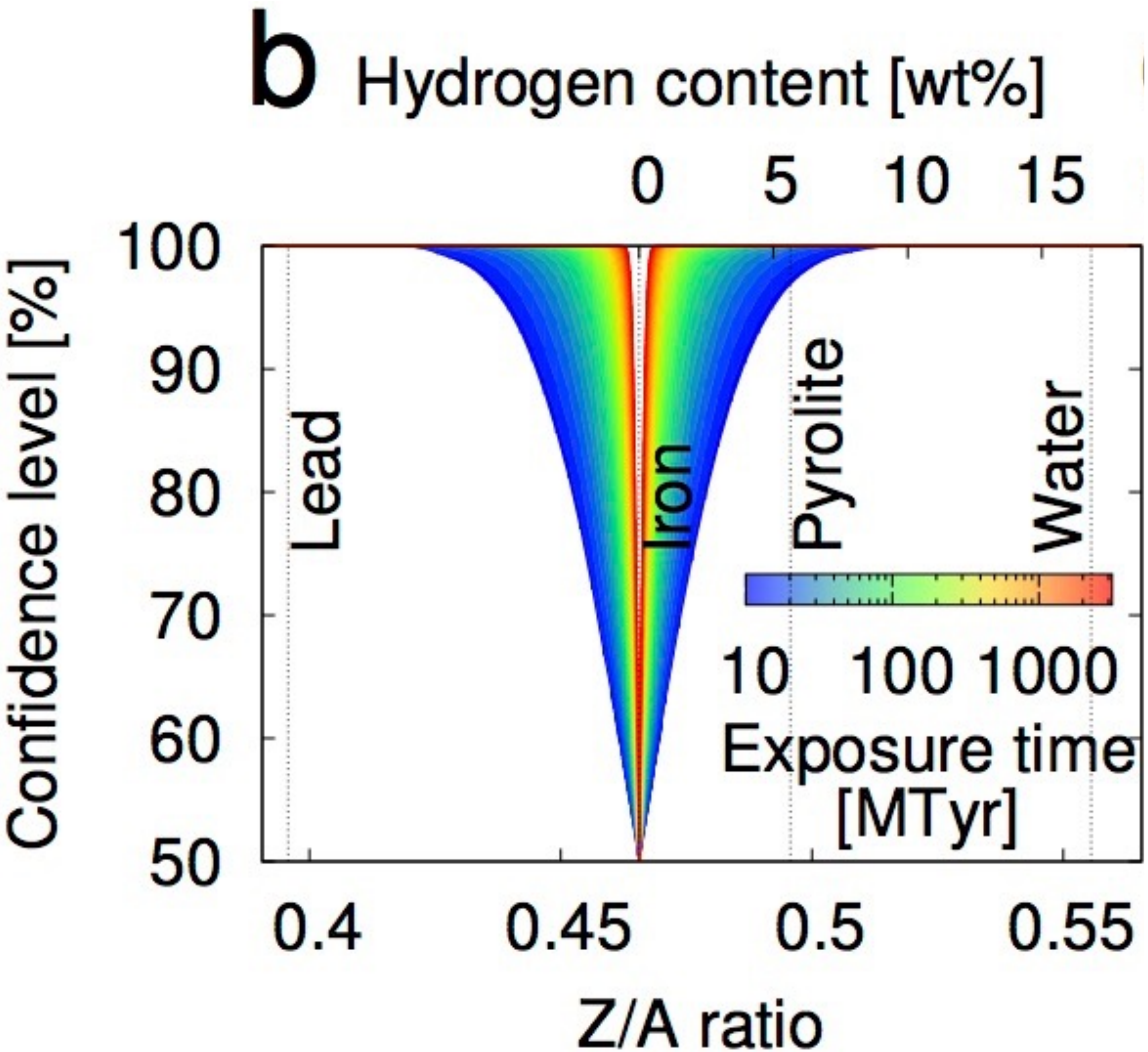


Statistical Method

- Generate template for expected number of events and their distribution in energy and zenith angle for two different outer core composition models (Model A and Model B)
- Assume one composition and calculate likelihood with respect to A and B and take ratio
- Perform pseudo experiments
- Distribution tells us the probability to distinguish the two models if the measurement were to be done



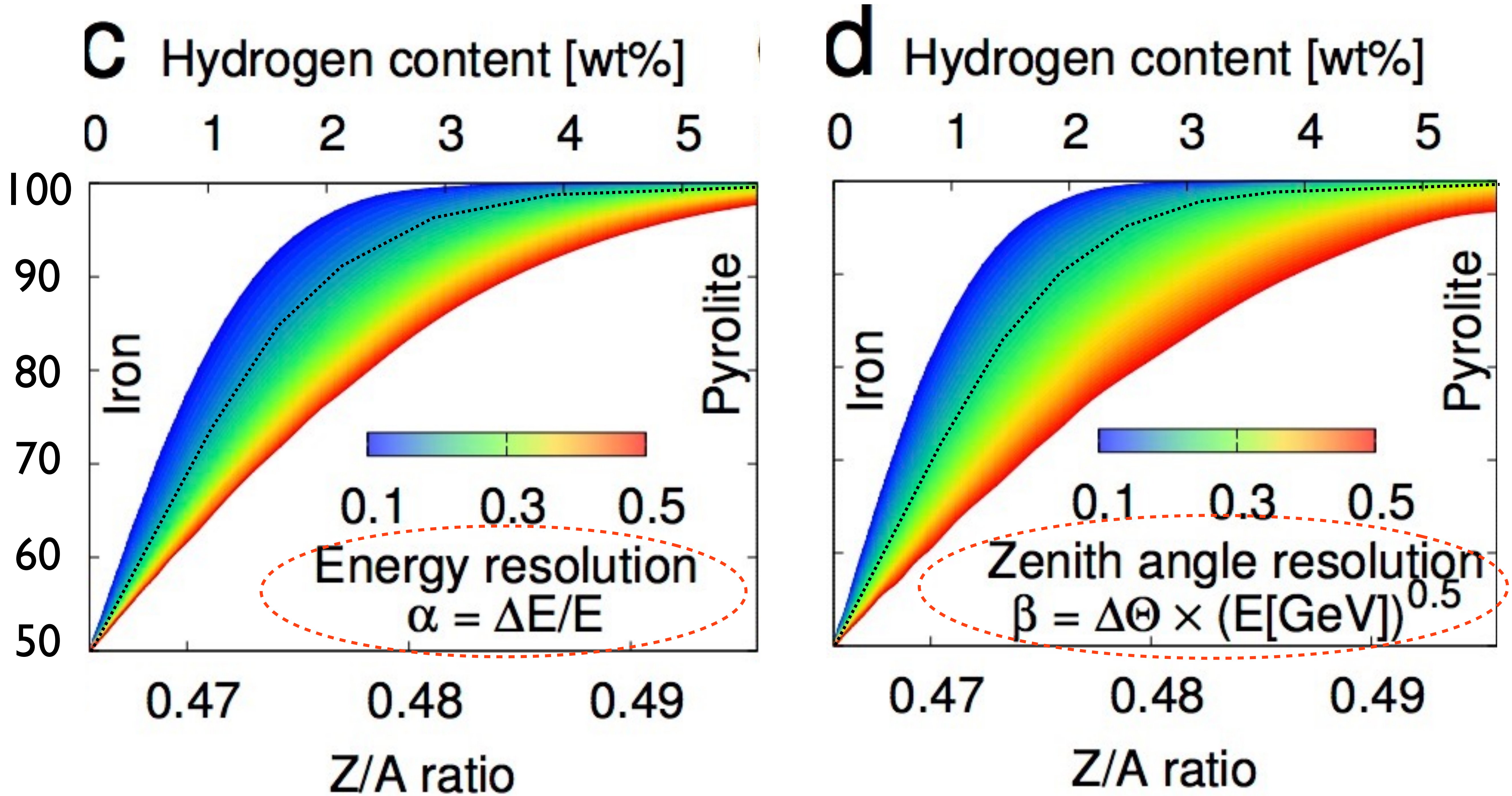
Sensitivity



- 10MTyrs of a PINGU-like data:
- Probe ~2-4wt% hydrogen
- Reject extreme core composition models

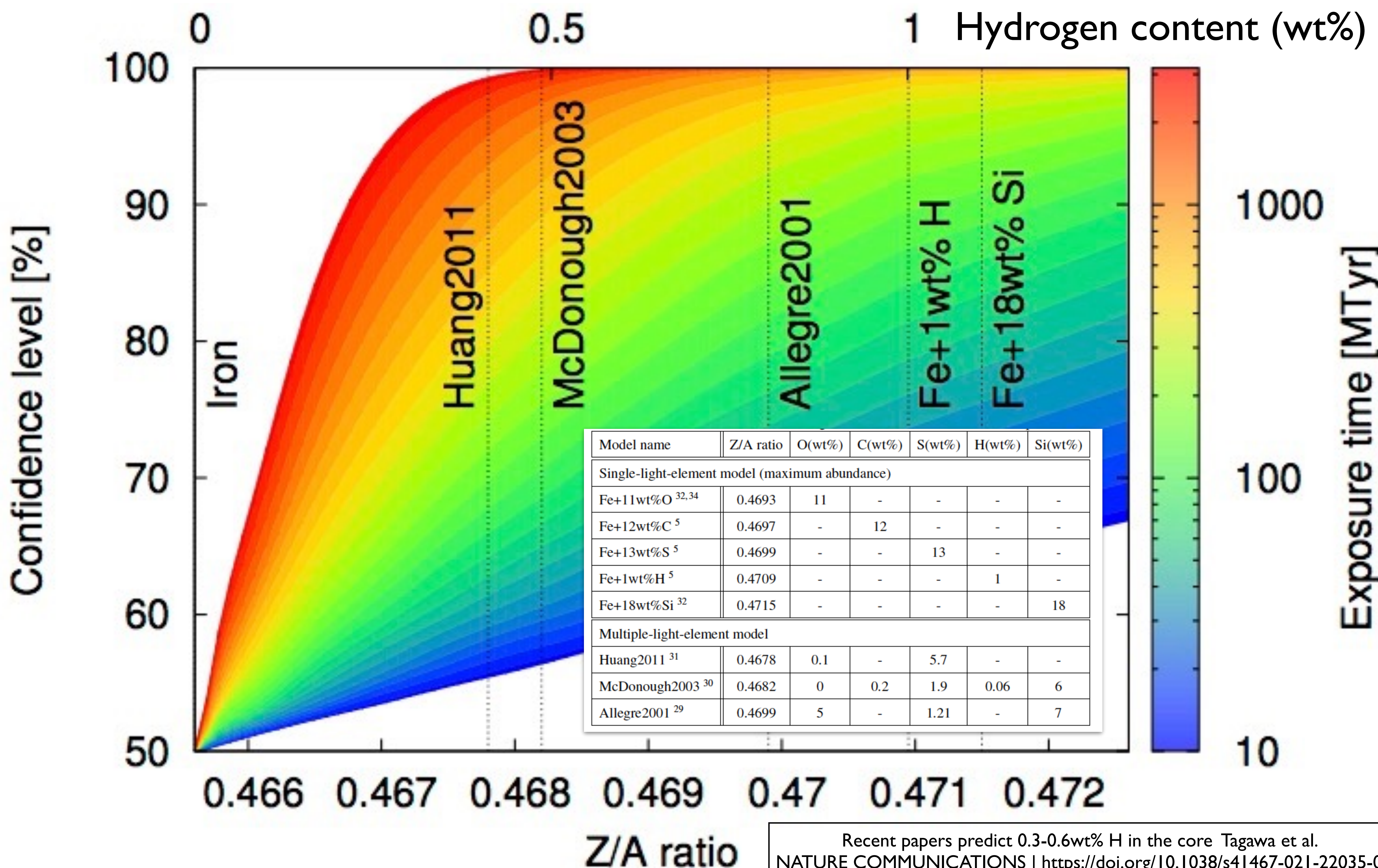
How can we increase sensitivity ?

- Dependence on the angular resolution and energy resolution
  - Assuming 30MTyrs



Rott & Taketa 2015

Distinguishing Outer core models



Model name	Z/A ratio	O(wt%)	C(wt%)	S(wt%)	H(wt%)	Si(wt%)
Single-light-element model (maximum abundance)						
Fe+11wt%O [32,34]	0.4693	11	-	-	-	-
Fe+12wt%C [5]	0.4697	-	12	-	-	-
Fe+13wt%S [5]	0.4699	-	-	13	-	-
Fe+1wt%H [5]	0.4709	-	-	-	1	-
Fe+18wt%Si [32]	0.4715	-	-	-	-	18
Multiple-light-element model						
Huang2011 [31]	0.4678	0.1	-	5.7	-	-
McDonough2003 [30]	0.4682	0	0.2	1.9	0.06	6
Allegre2001 [29]	0.4699	5	-	1.21	-	7

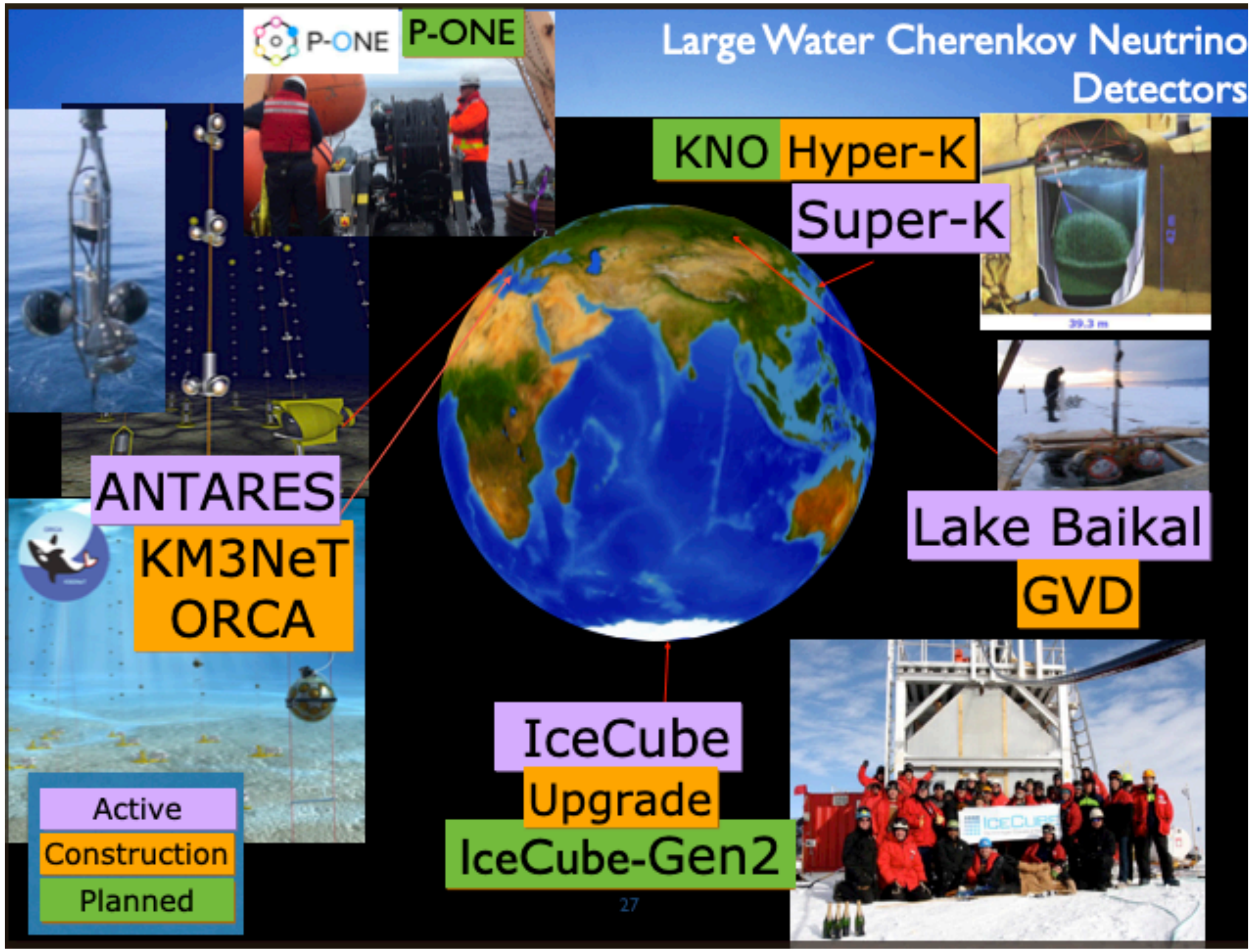
Recent papers predict 0.3-0.6wt% H in the core Tagawa et al.
NATURE COMMUNICATIONS | https://doi.org/10.1038/s41467-021-22035-0

Neutrino Source and Detectors

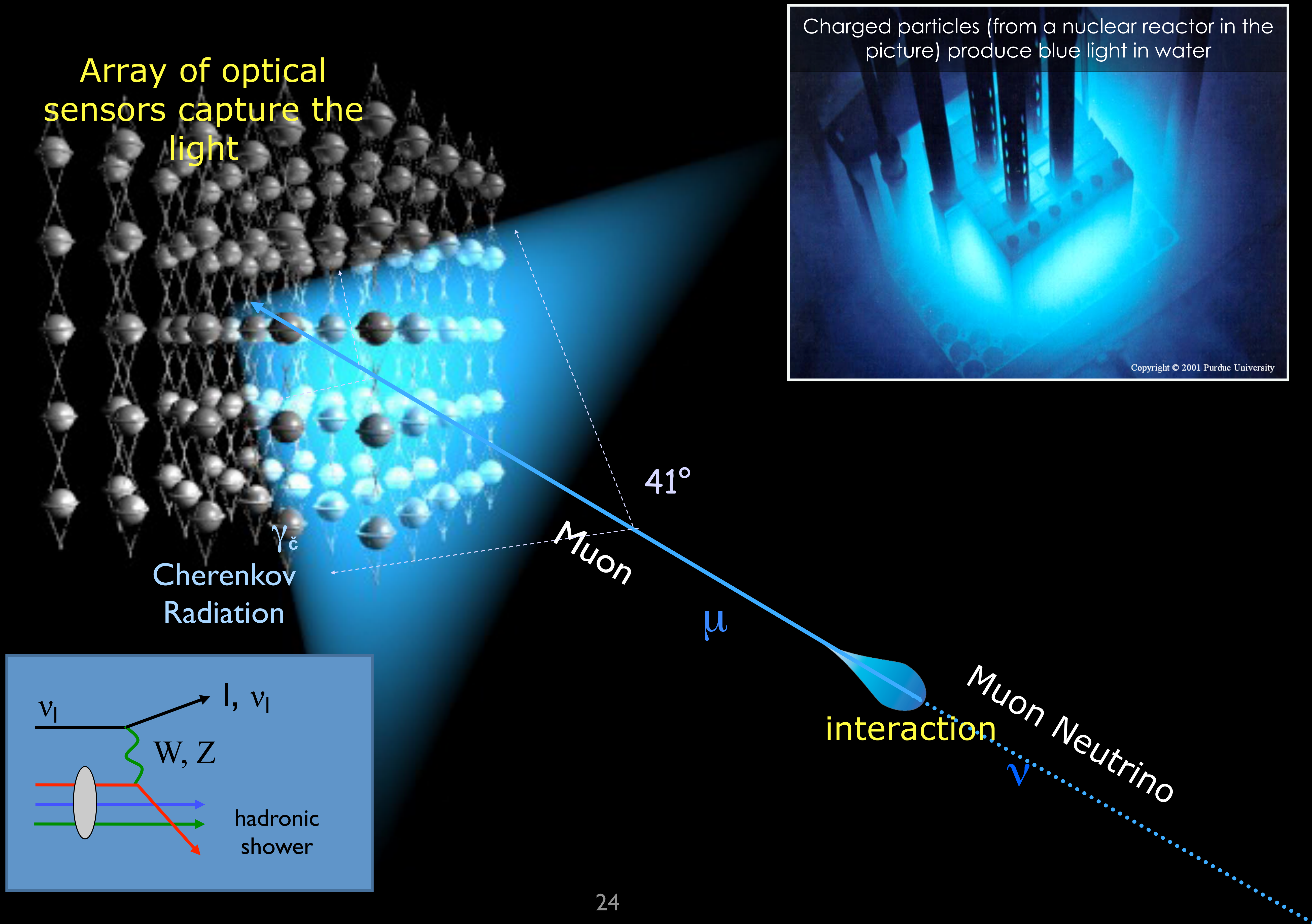
Atmospheric neutrinos are a **natural** steady **source of muon and electron neutrinos** at the energy range relevant for neutrino oscillation tomography

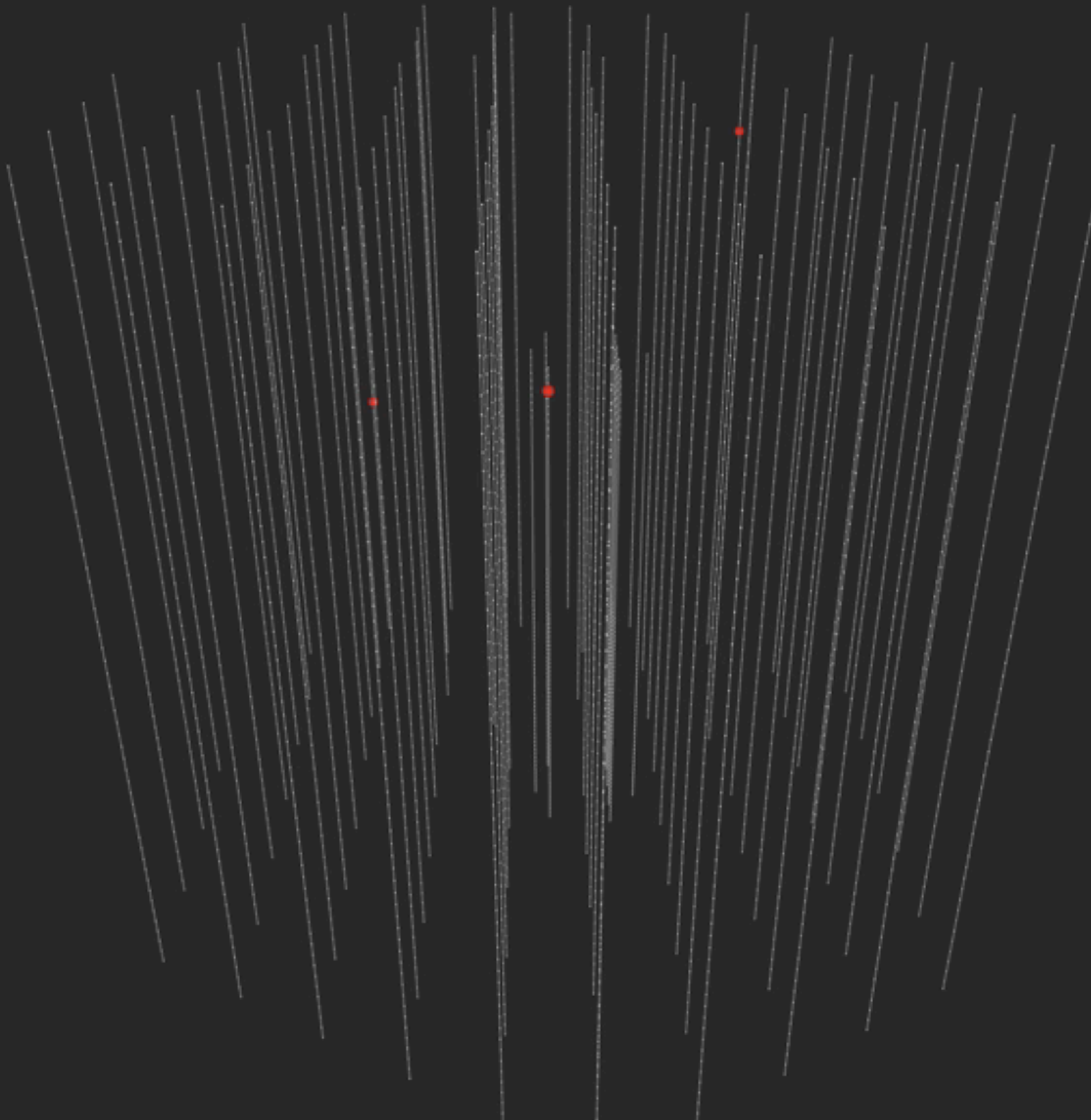
- $p + A \rightarrow \pi^\pm (K^\pm)$ + other hadrons
  - $\pi^+ \rightarrow \mu^+ \nu_\mu \rightarrow e^+ \nu_e \nu_\mu \nu_\mu$

- Detector requirements for neutrino oscillation tomography
  - **good energy resolution** ⇒ fully contained events, good optical coverage
  - **good angular resolution** ⇒ precise timing, good optical coverage
  - **large volume** ⇒ acquire high statistics neutrino sample

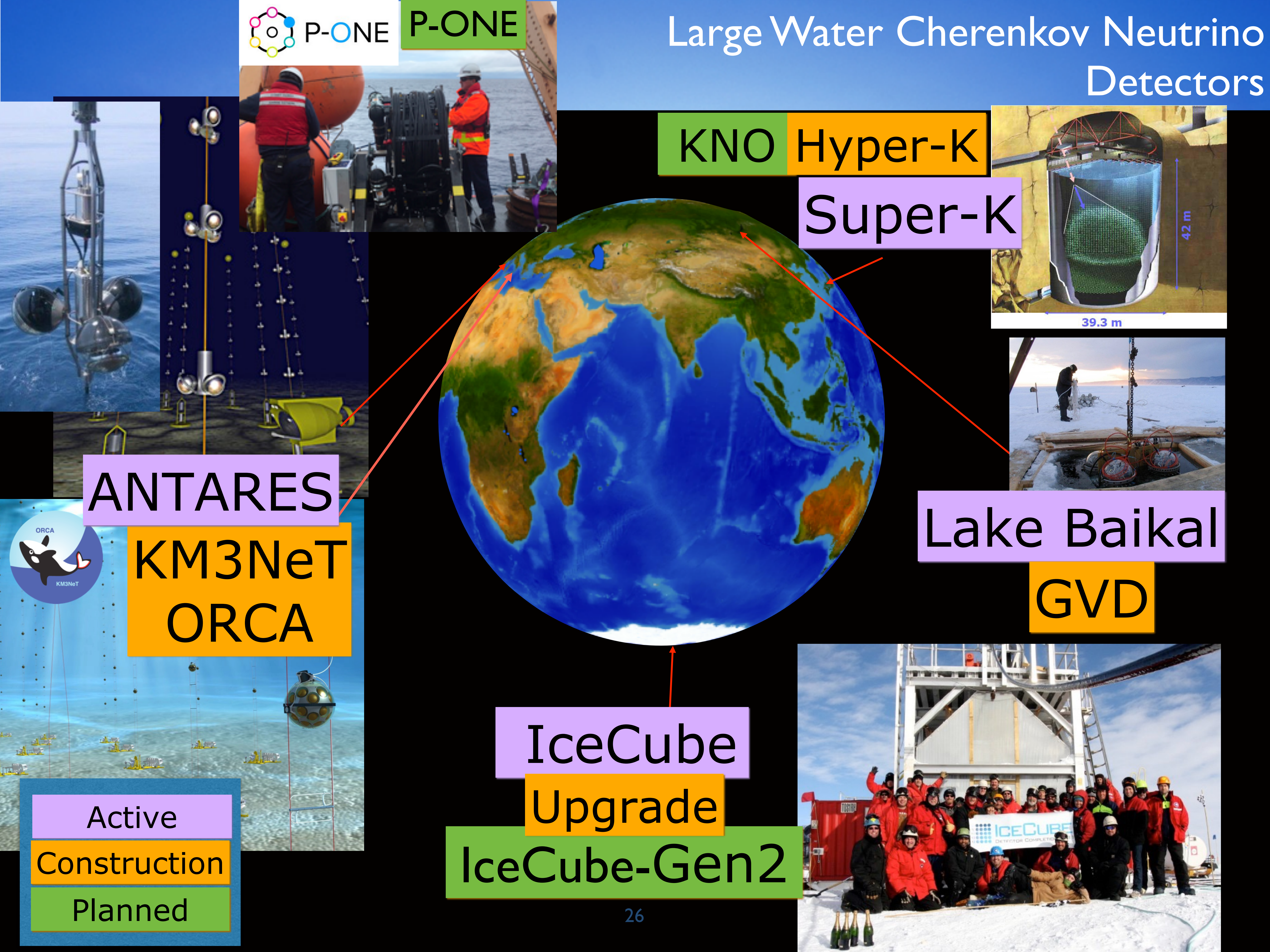


Principle of an optical Neutrino Telescope

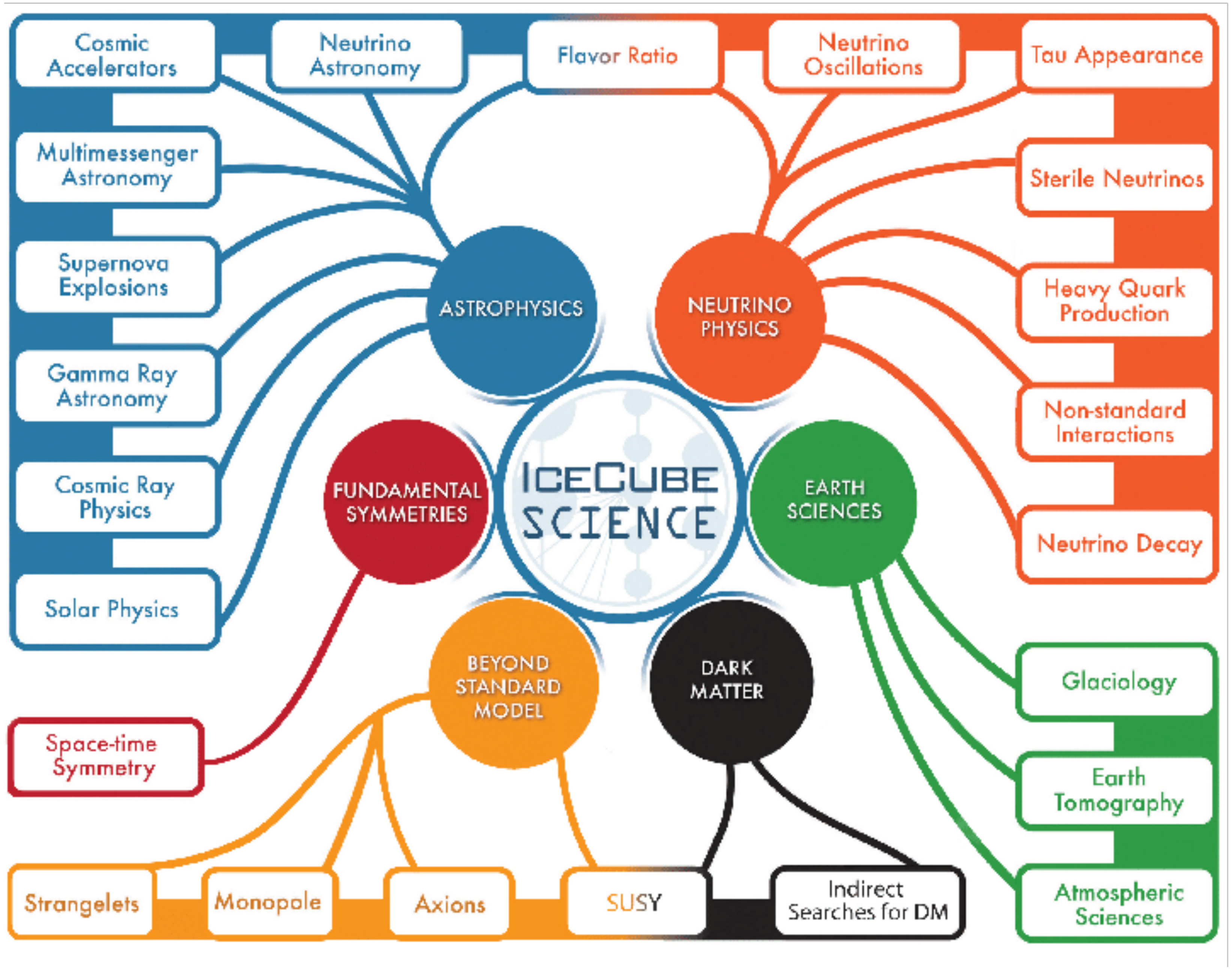




Large Water Cherenkov Neutrino Detectors

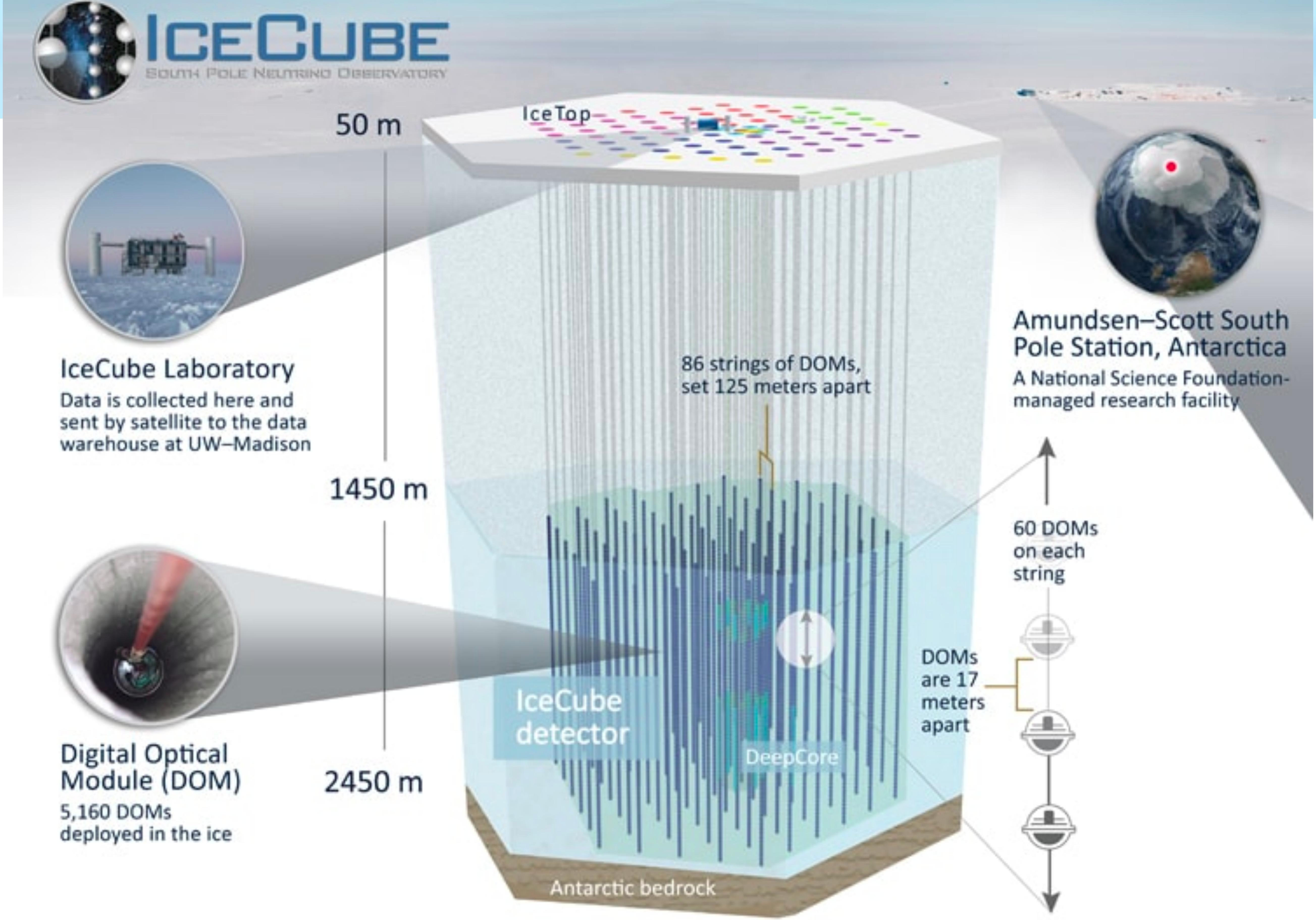


Neutrino Telescope Science



- Intrinsic to neutrino telescopes to enable extremely diverse scientific programs !
    - Example IceCube -Very diverse science program, with neutrinos from 10GeV to EeV, and MeV burst neutrinos

Neutrino Experiments (large volume water/ice Cherenkov detector)



see talk by Sanjib K Agarwalla

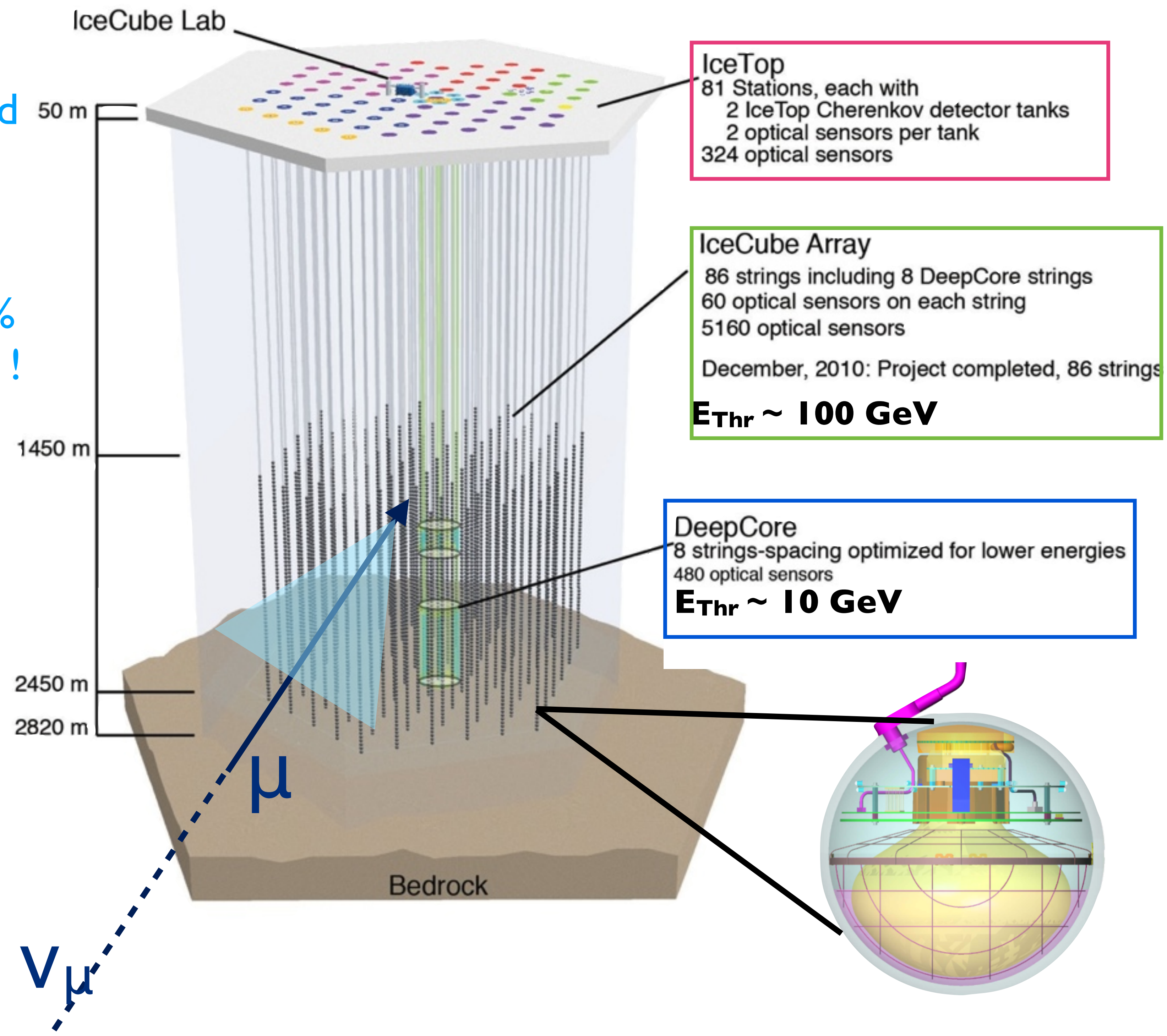
The IceCube Neutrino Telescope

- Gigaton Neutrino Detector at the Geographic South Pole
- 5160 Digital optical modules distributed over 86 strings
- Completed in December 2010
- Extremely stable: >99% uptime and 98% of sensor modules in perfect condition !
- Neutrinos are identified through Cherenkov light emission from secondary particles produced in the neutrino interaction with the ice

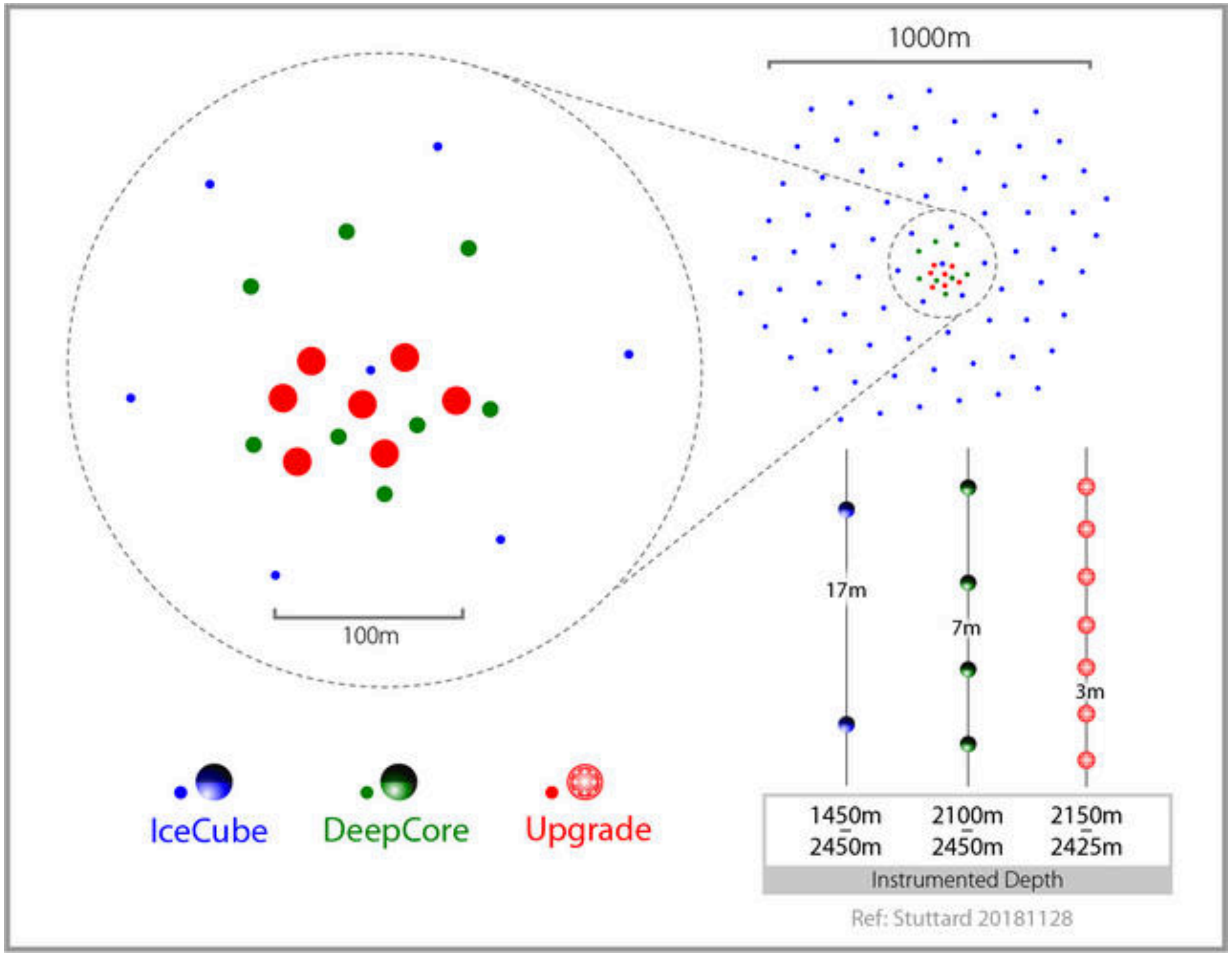

〈이 기사는 2014년 01월 06일자 신문 23면에 게재되었습니다.〉

"한국 '세계적 리더' 될 좋은 기회"

기초과학 투자 의지 활발, 한국에 새 연구 터전 둥지.. 연구자·학생 영입해 연구

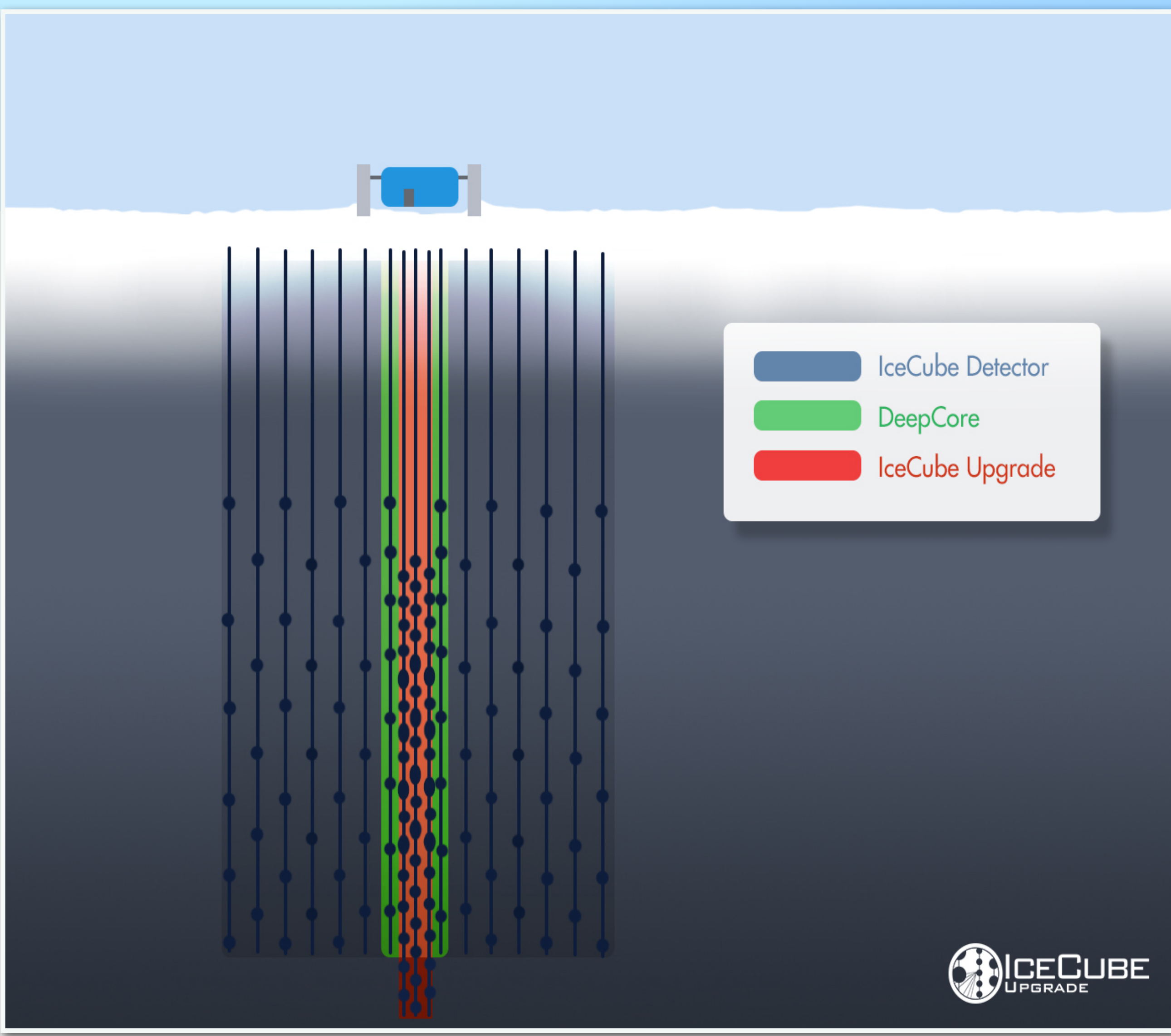


IceCube Upgrade



- 7 new, high-precision strings in the central, densely instrumented region. Funded, installation in 2025.
- Benefits: New detector technologies. Better low energy reconstruction. Improved flavor identification. Precise calibration of detector medium

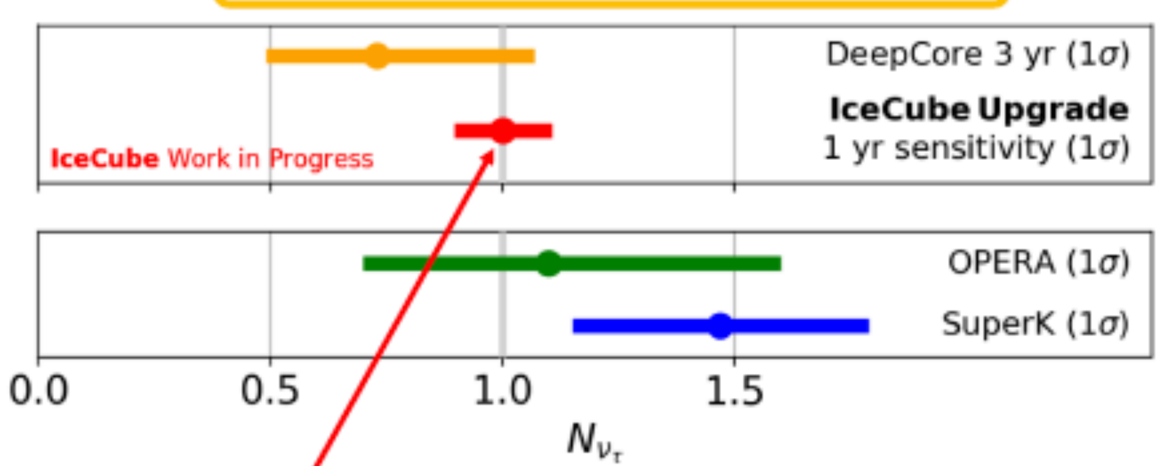
IceCube Upgrade



Science goals and objectives

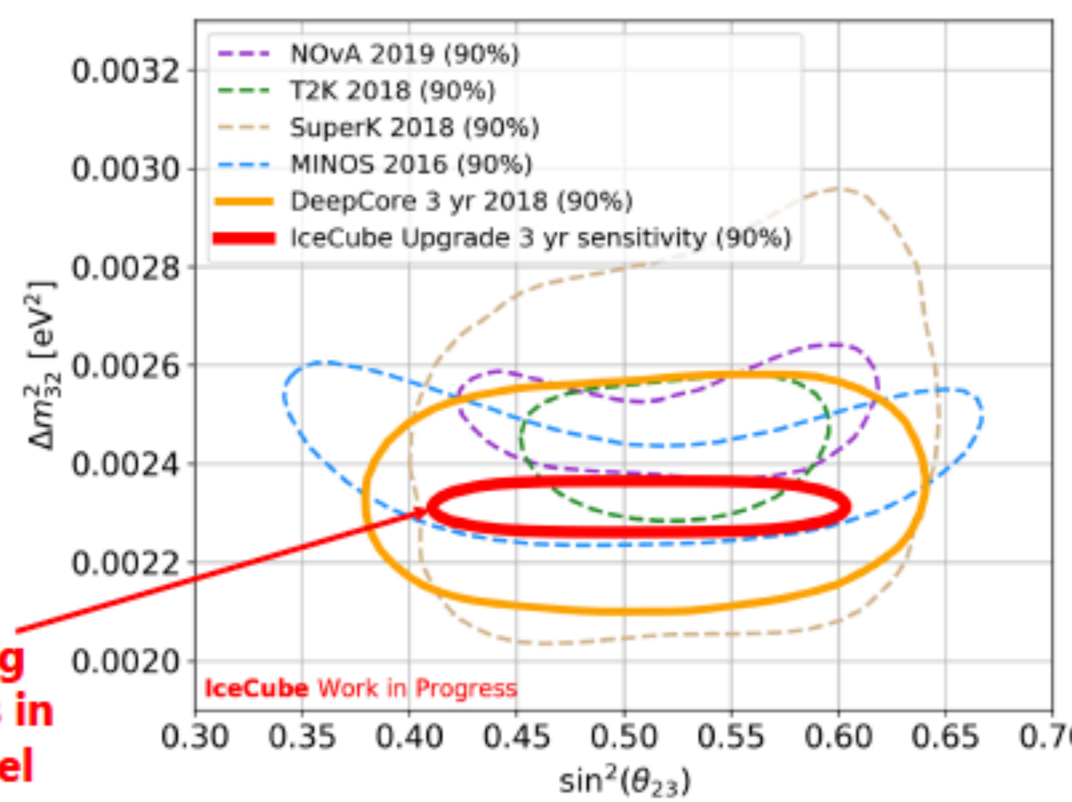
- Tau neutrino appearance - Test unitarity of the PMNS matrix
- Recalibration campaign - Retroactively apply improved ice-model to archival data (since 2010)

υ_τ appearance sensitivity (1 yr)



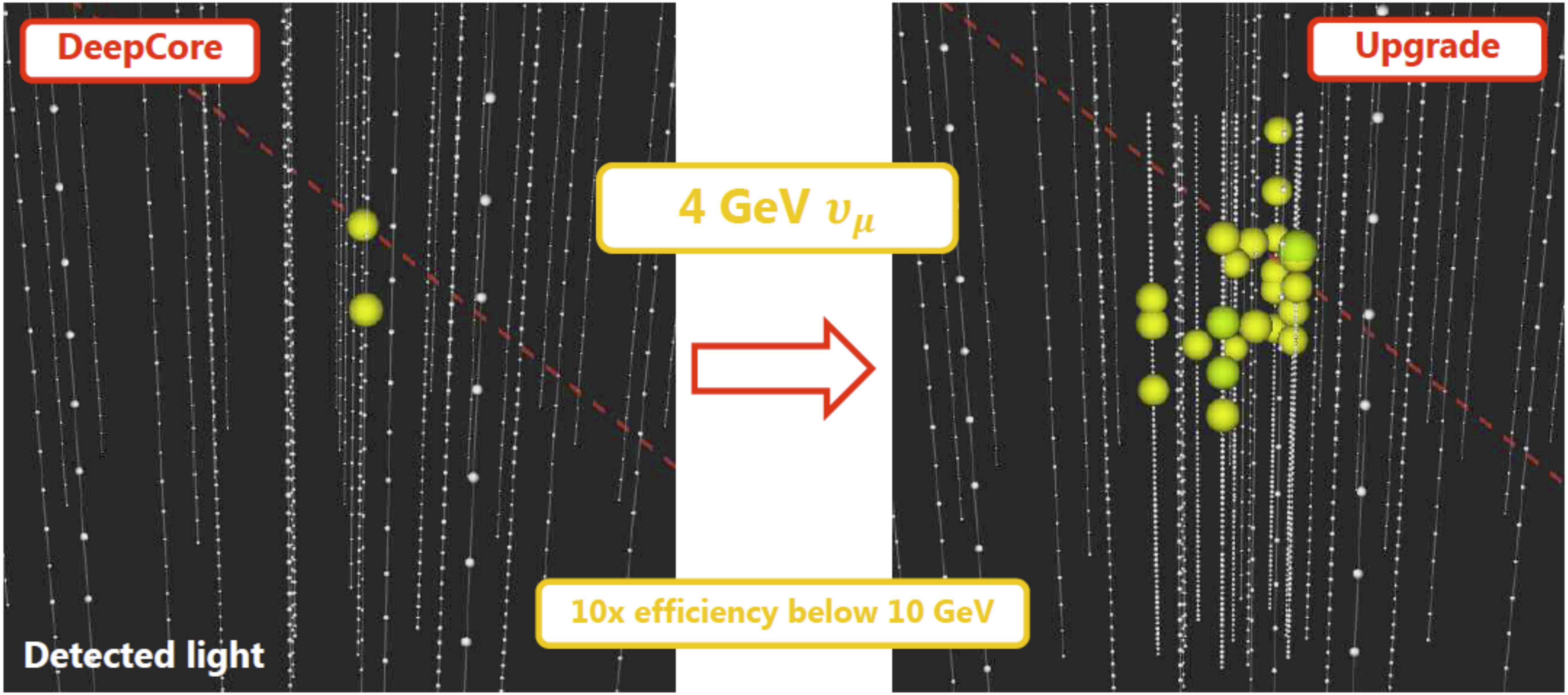
10% precision after 1 year
(6% after 3 years)

υ_μ disappearance sensitivity (3 yr)

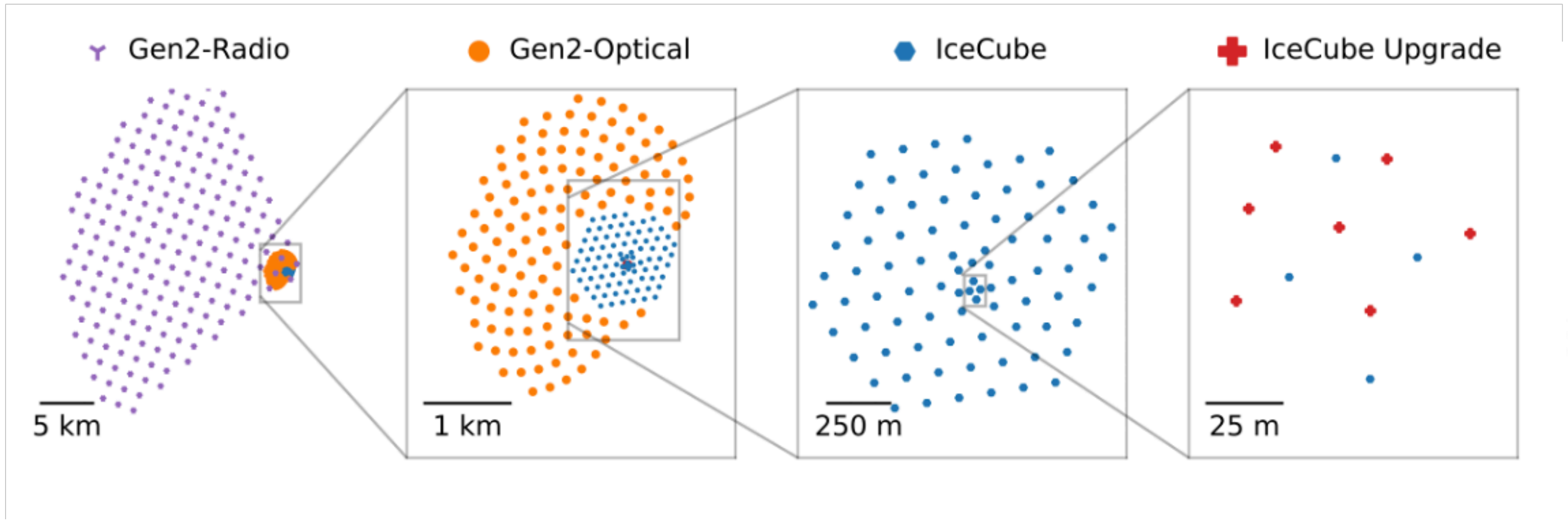


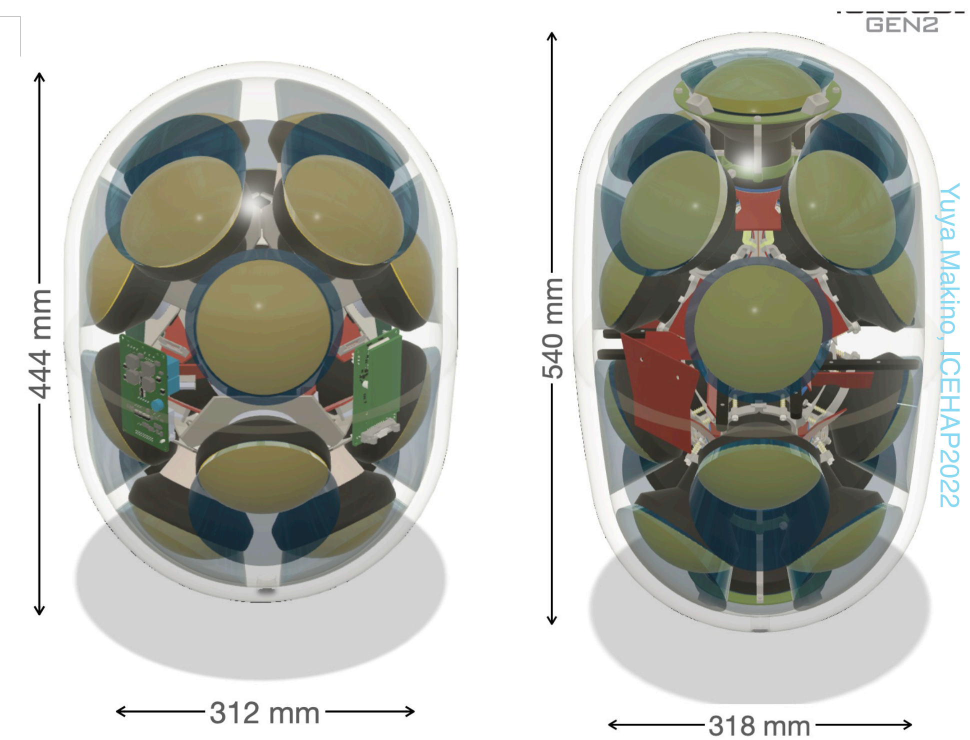
Competitive with long baseline experiments in disappearance channel

Improved light-collection for low-energy events



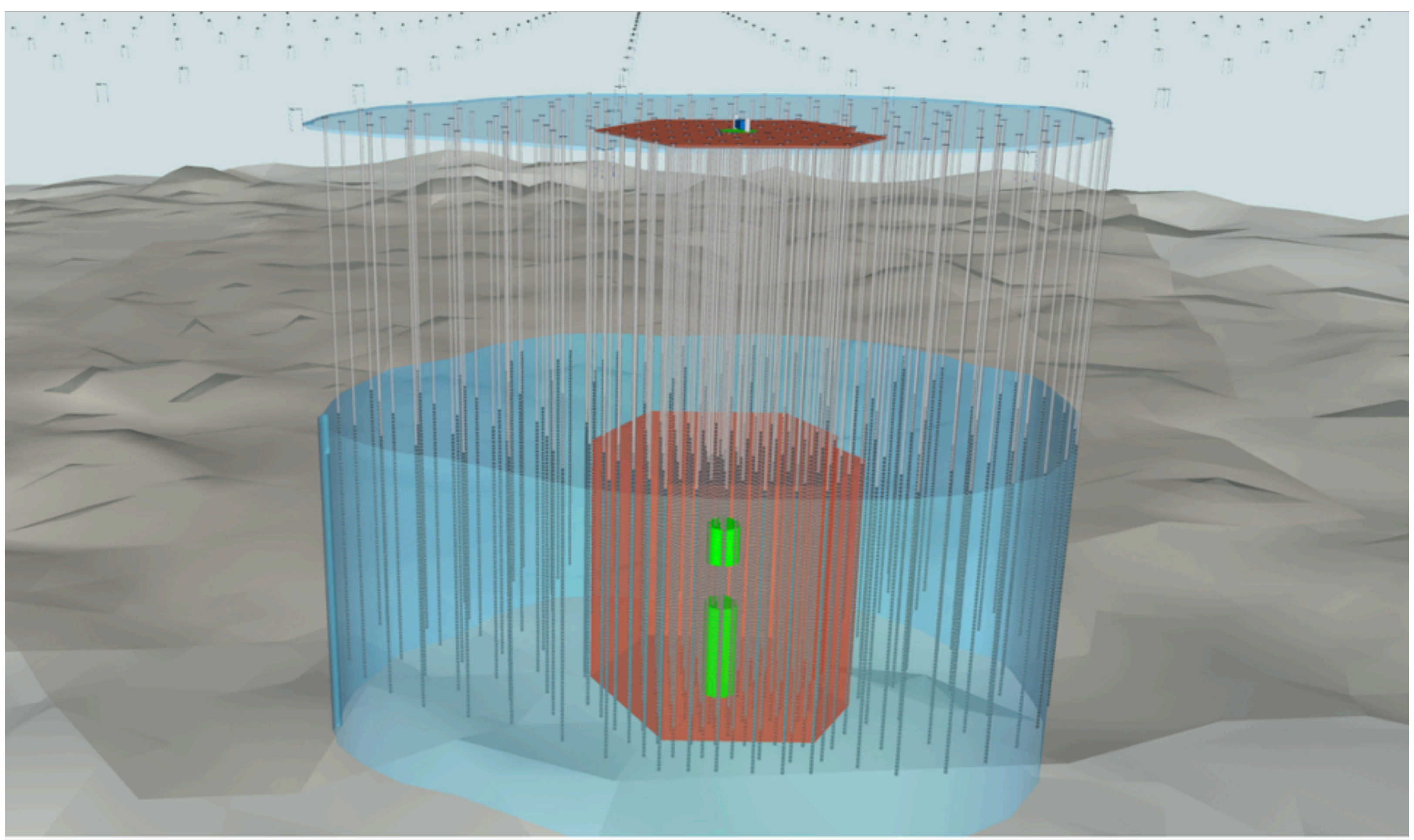
IceCube-Gen2



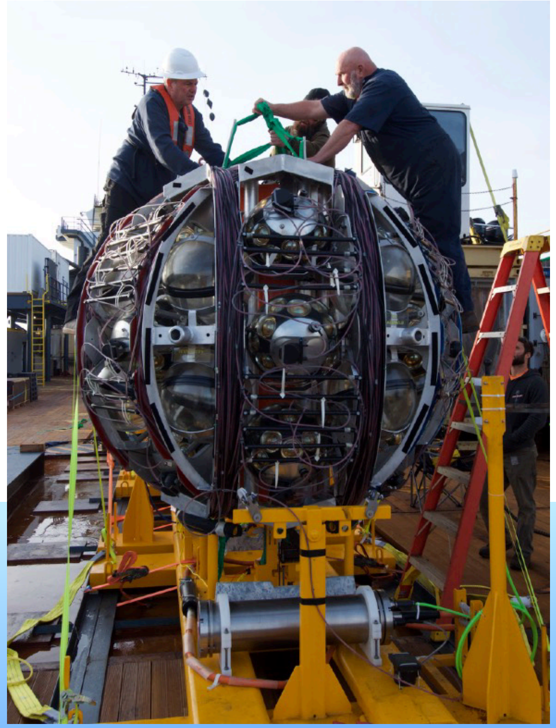


16 PMT option

18 PMT option



- Technical design report (TDR) ready soon
- Baseline design 120 additional optical strings, 240m string spacing following Fibonacci sequence (Sunflower geometry)
- Radio component to target at UHE



KM3NeT / ORCA (Oscillation Research with Cosmics in the Abyss)

see talk by Veronique Van Elewyck

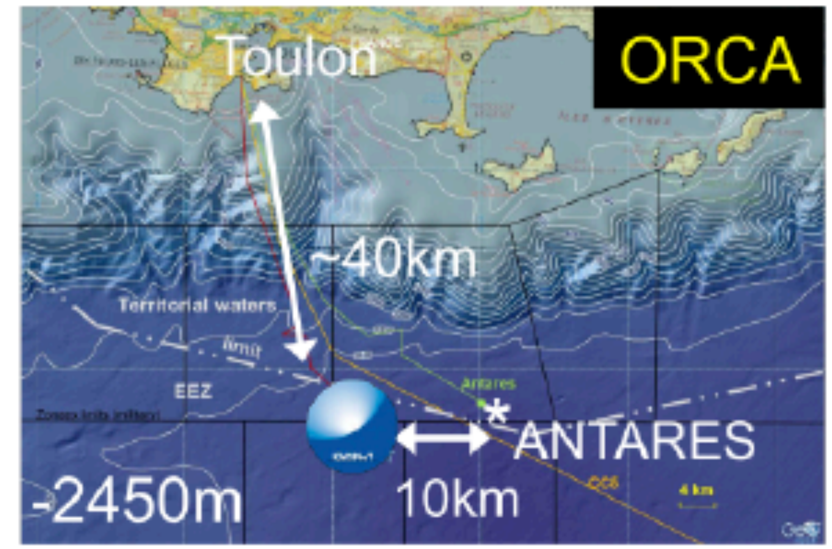
KM3NeT

Km3Net

KM3NeT: ARCA & ORCA

ARCA → TeV-PeV neutrino astronomy

ORCA → neutrino mass ordering with few-GeV atmospheric neutrinos

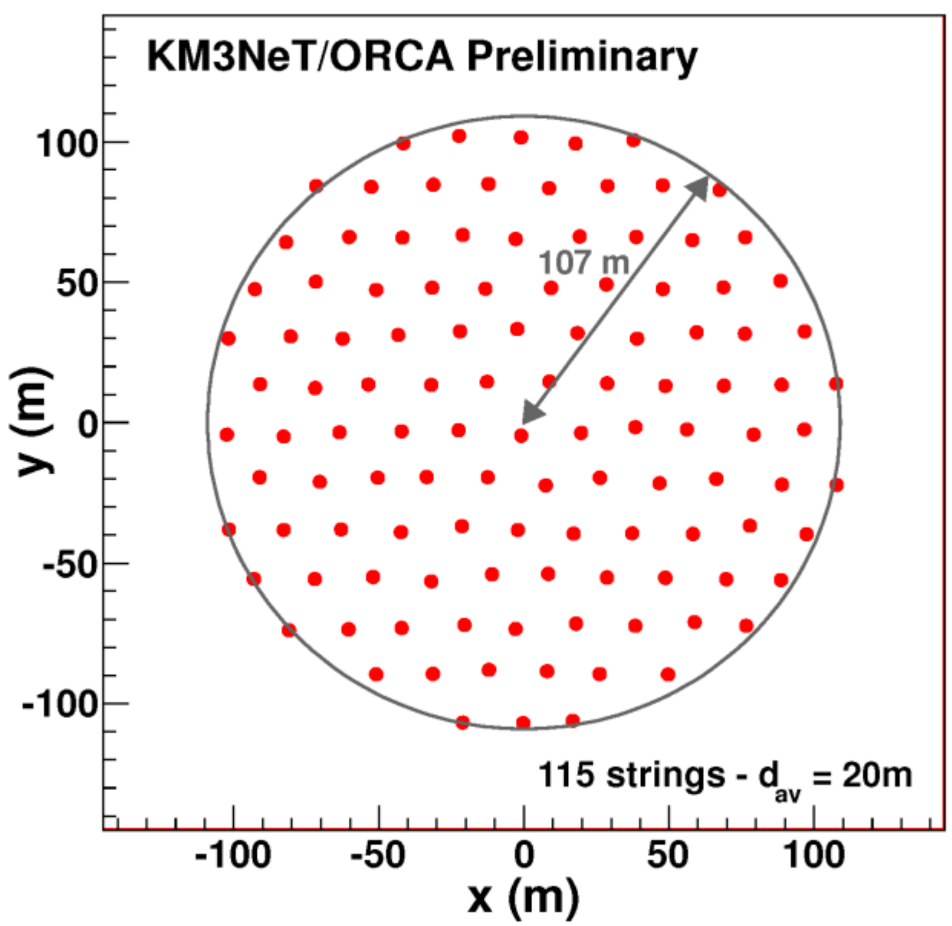


ORCA: Oscillation **R**esearch with **C**osmics in the **A**byss

ARCA: Astroparticle **R**esearch with **C**osmics in the **A**byss

ORCA

- ORCA (Oscillation Research with Cosmics in the Abyss)
  - anchored on the seabed off the shore of Toulon (France)
  - Volume of 7 Mton of seawater
  - 115 vertical strings (20m horizontal spacing)
  - 18 modules per with 9m vertical separation



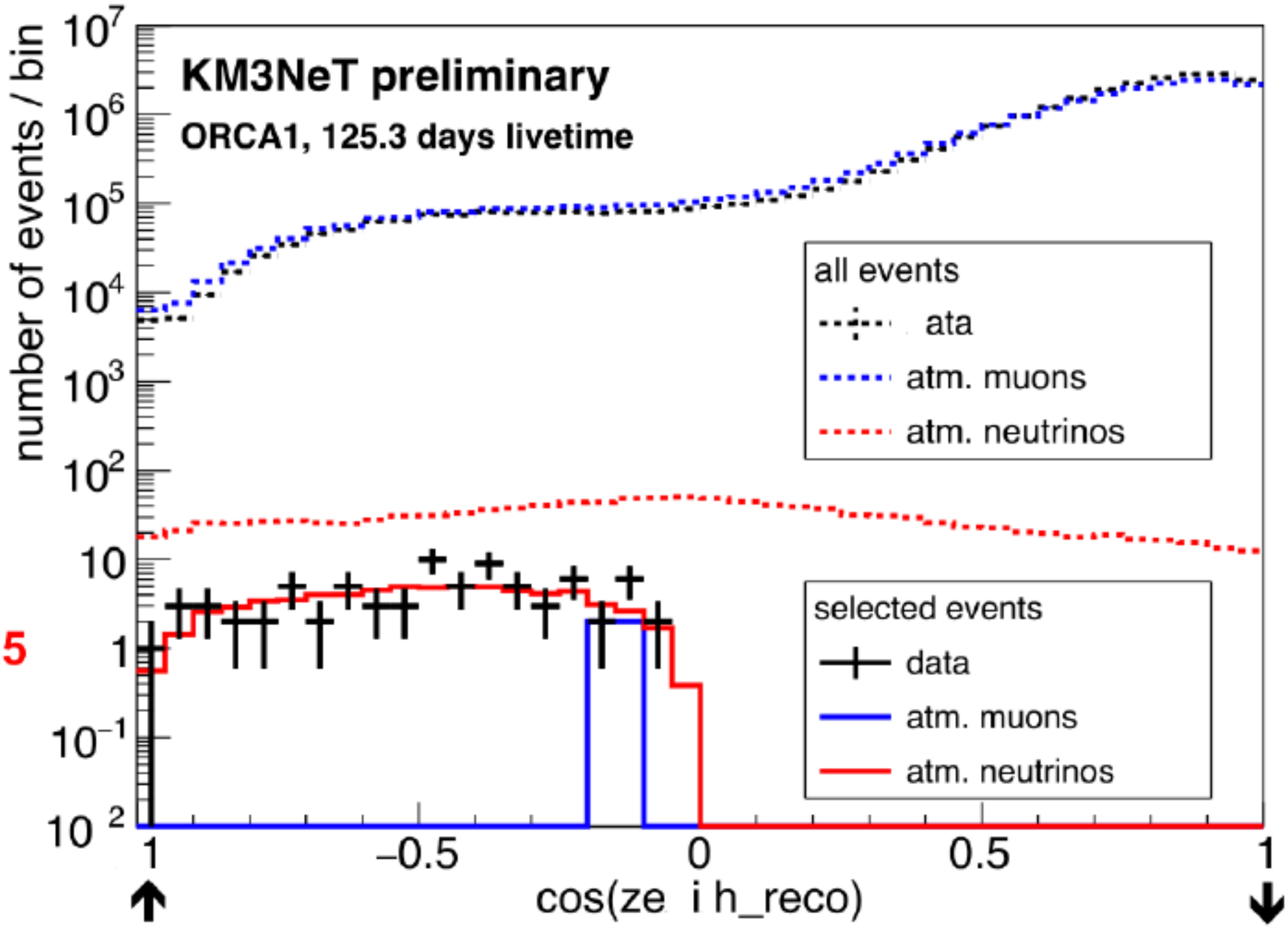
- 31 3-inch PMTs in 17-inch glass spher (cathode area ~3x10-inch PMTs)
- Front-end electronics, digitisation, optical signal → glass fibre
- Single penetrator
- Advantages:
  - Increased photocathode area
  - 1-vs-2 photo-electron separation → better detection of coincidences
  - Directionality
  - Cost / photocathode area
  - Minimal number of penetrations → reduced risk

KM3NeT (status Fall 2022)

Km3Net

- ANTARES completed construction in 2008
  - ~2500m deep, 12 Vertical lines, each 350m high
  - Decommissioned May 2022
- KM3NET:
  - ORCA: 2500 m deep, 20m string spacing, 10 detection unites running
  - ARCA: 3500m deep, 90m string spacing, 19 detection units successfully deployed

Neutrinos !



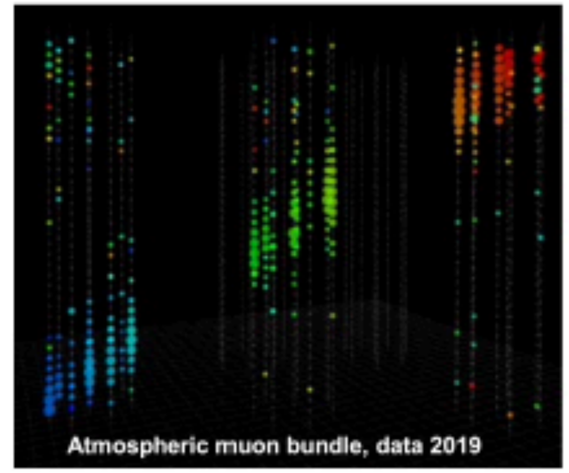
Data: 77

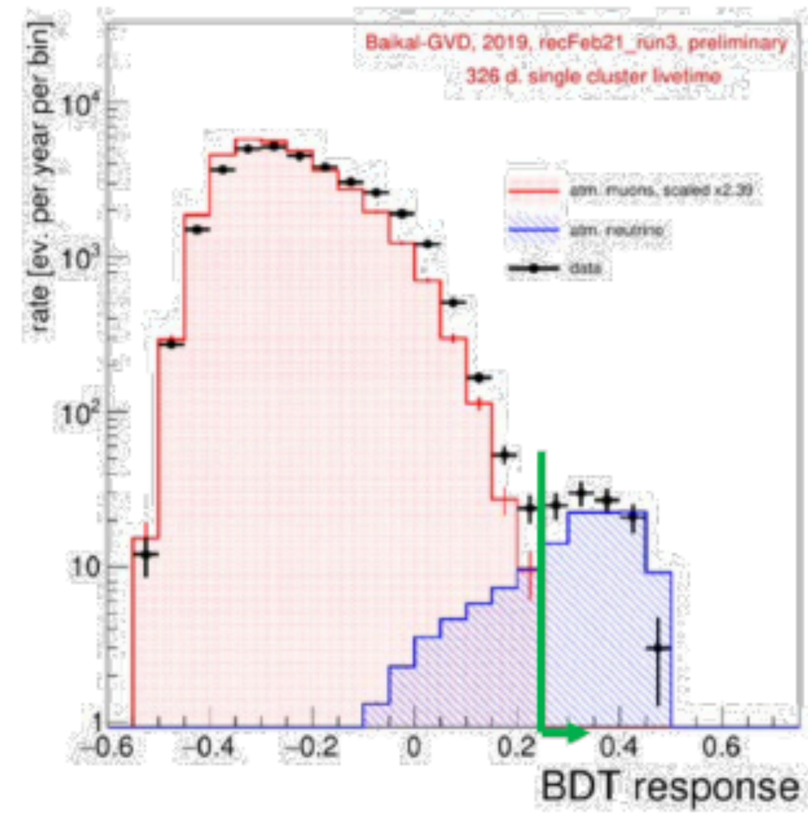
ν MC: 67.5

μ MC: 4

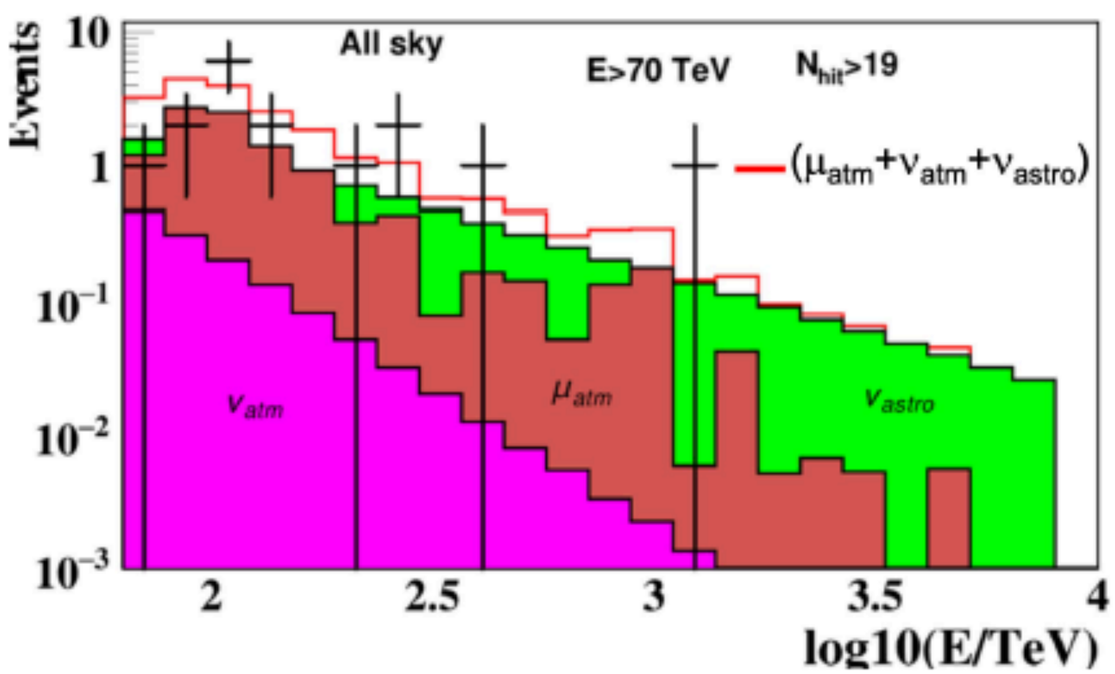
Baikal-GVD

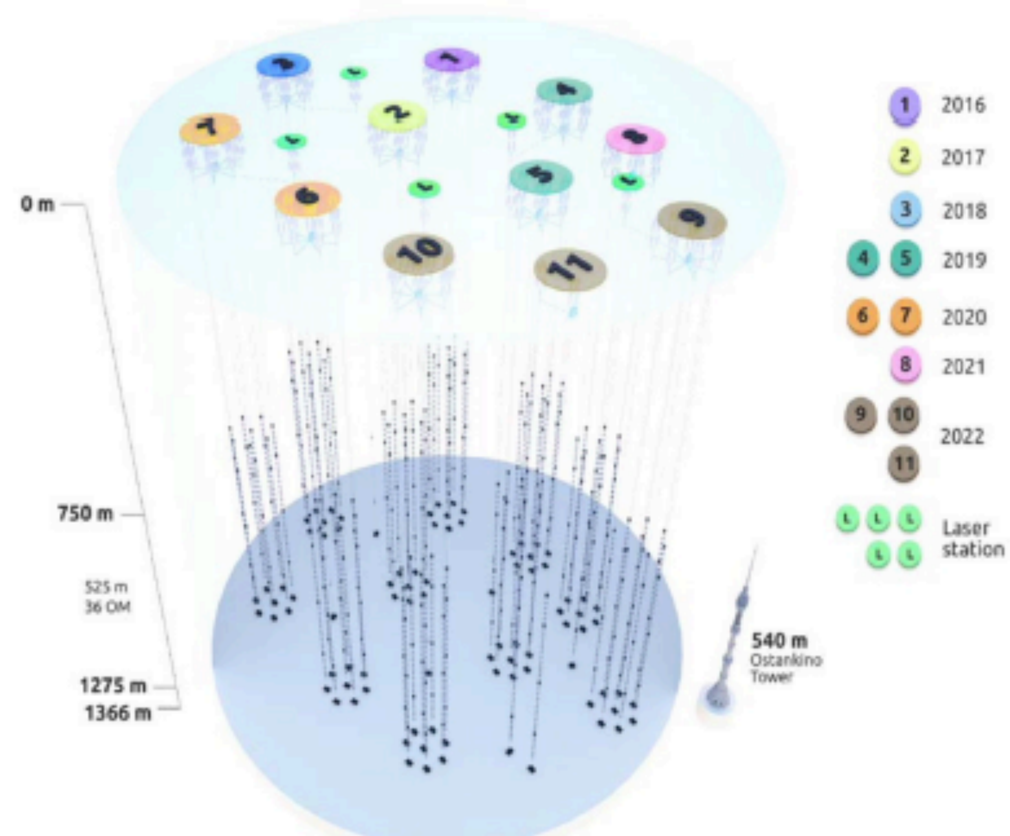
BAIKAL-GVD

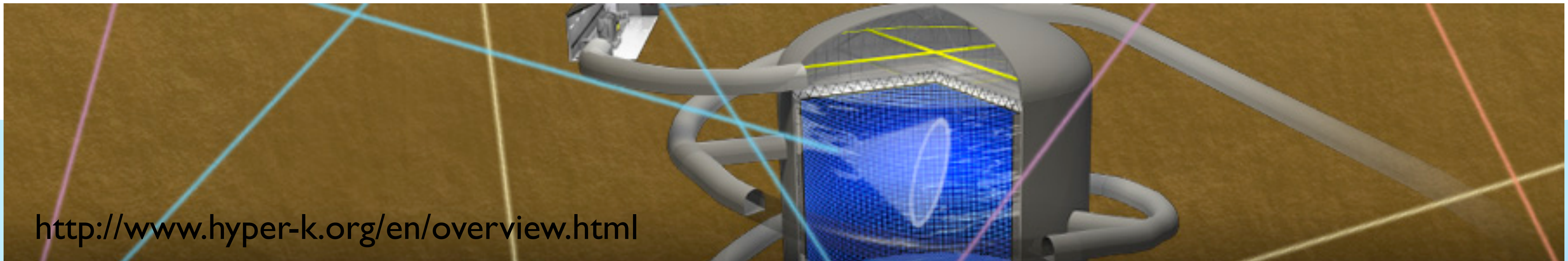




- 2022: Successfully deployed 10 clusters, 5 laser stations
- Each cluster has 288 OMs and depth 750-1275m
- 2025/2026 – ~ 1km3 GVD with total of 16-18 clusters
- 2022-2024 – "Conceptual Design Report" for next generation neutrino telescope in Lake Baikal



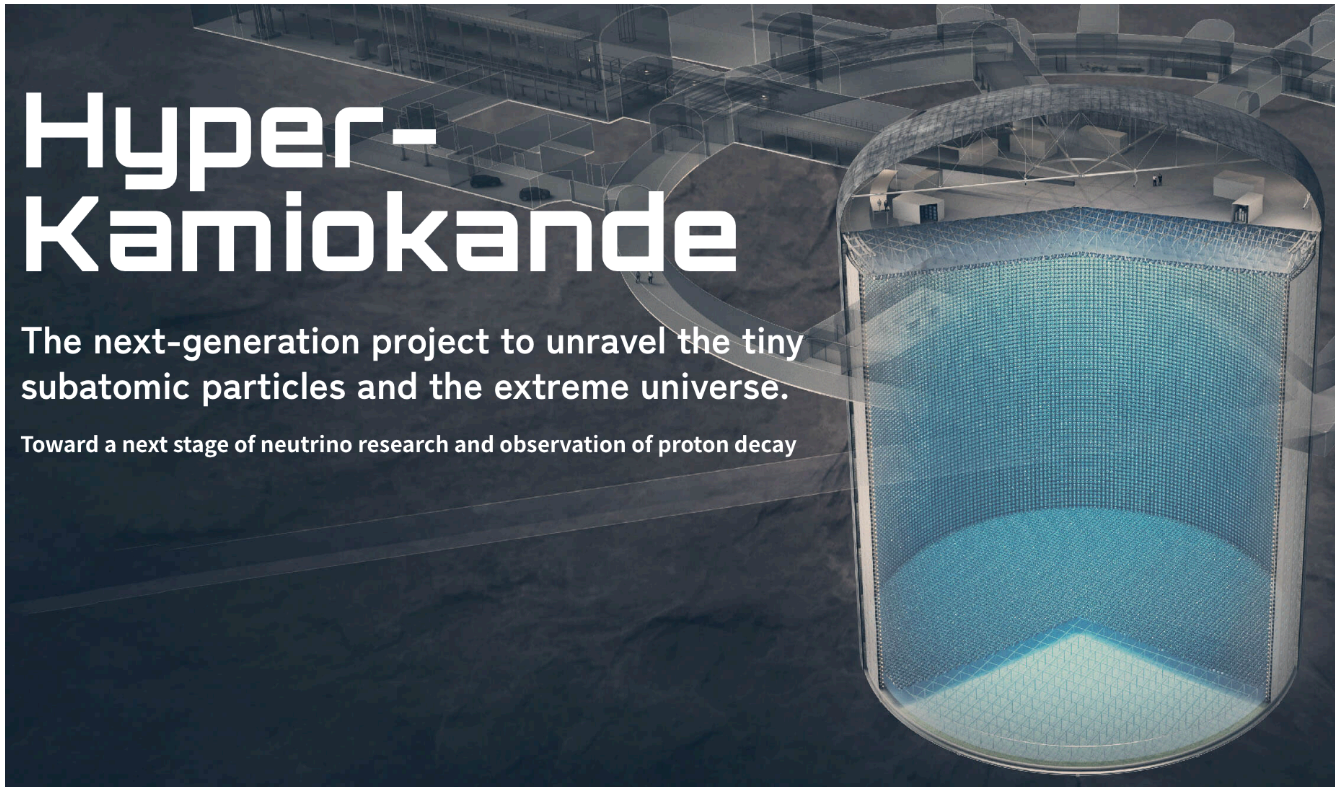


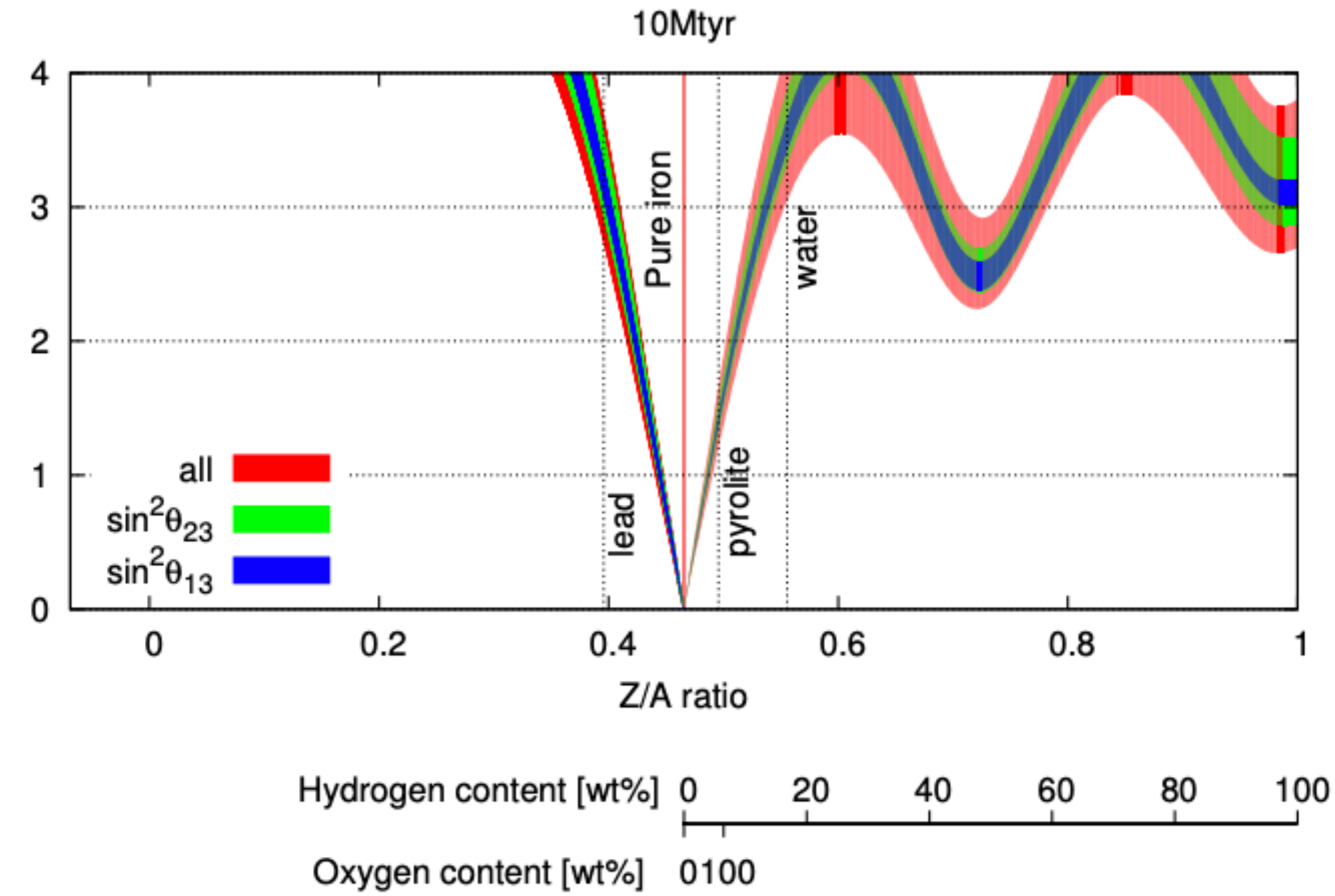


Hyper-Kamiokande

see talk by Andrew Santos

Hyper-Kamiokande





https://lib-extopc.kek.jp/preprints/PDF/2016/1627/1627021.pdf

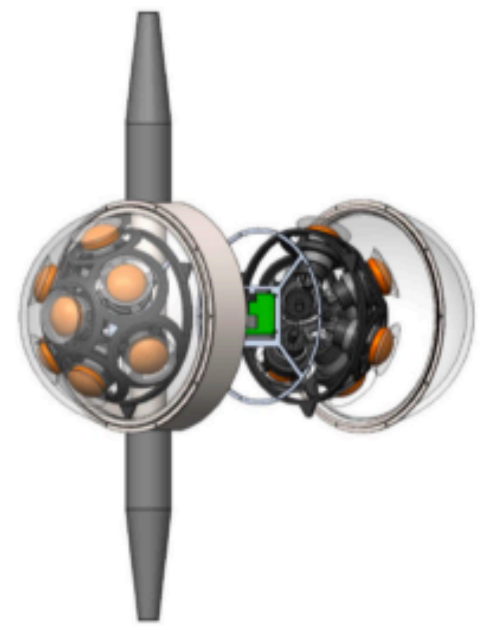
Hyper-K under construction, completion in 2027

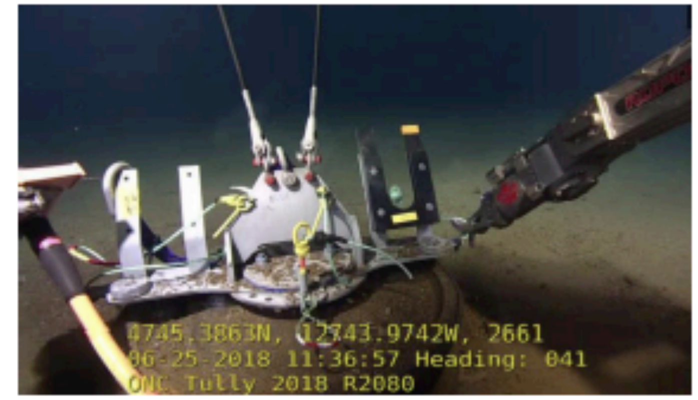
Possibility of second tank in Korea could double the fiducial volume
PTEP 2018 (2018) 6, 063C01, Prog Theor Exp Phys (2018)

Proposed detectors

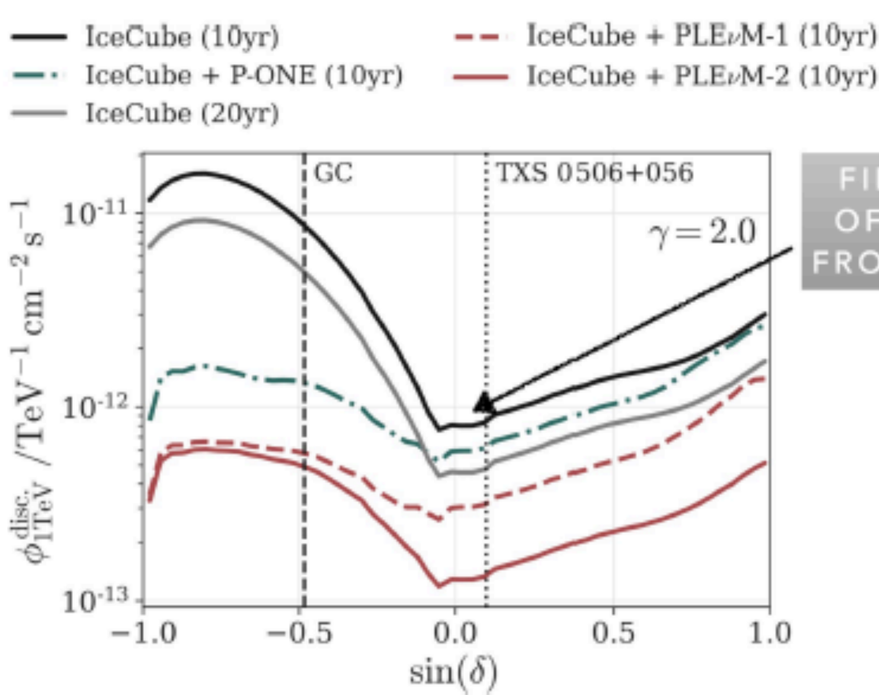
P-ONE

P-ONE

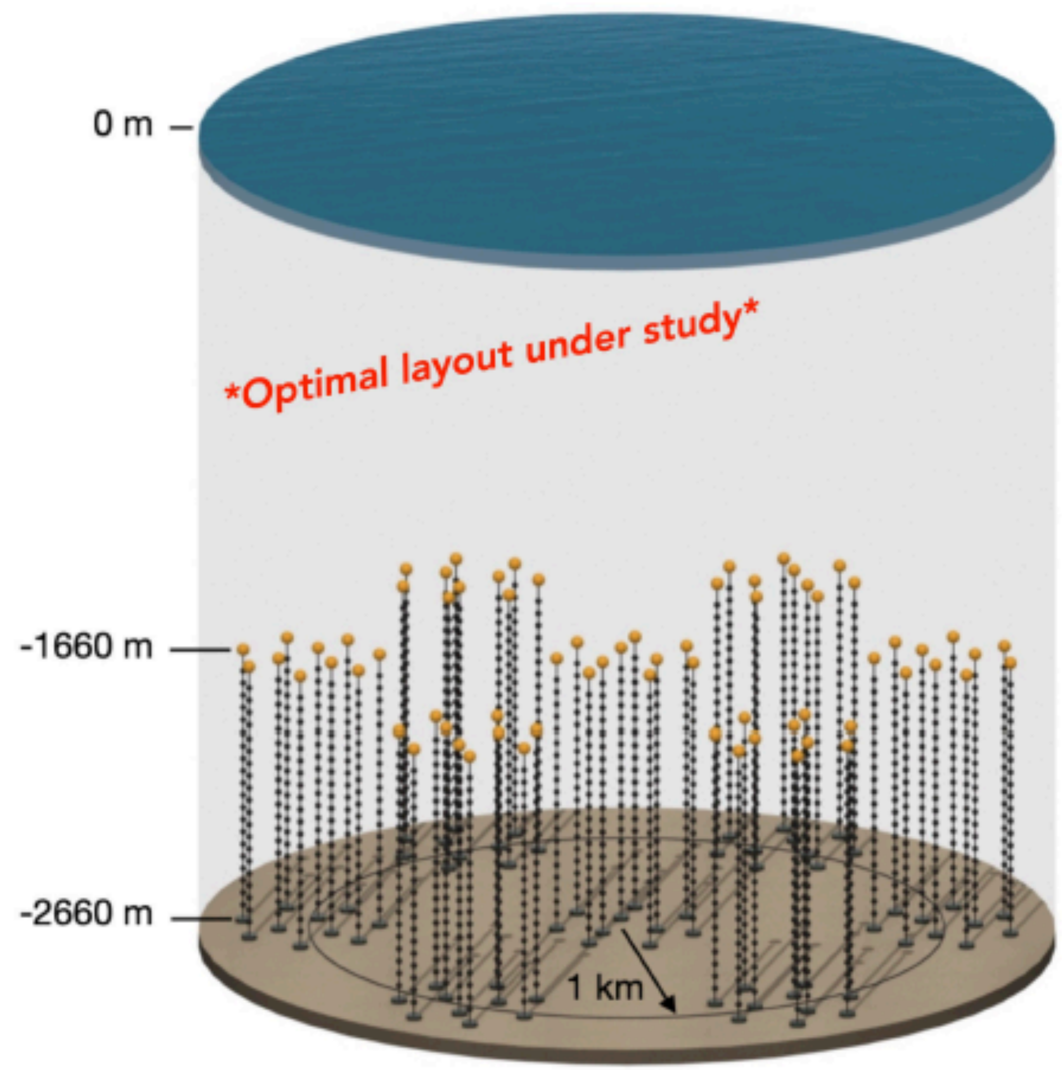




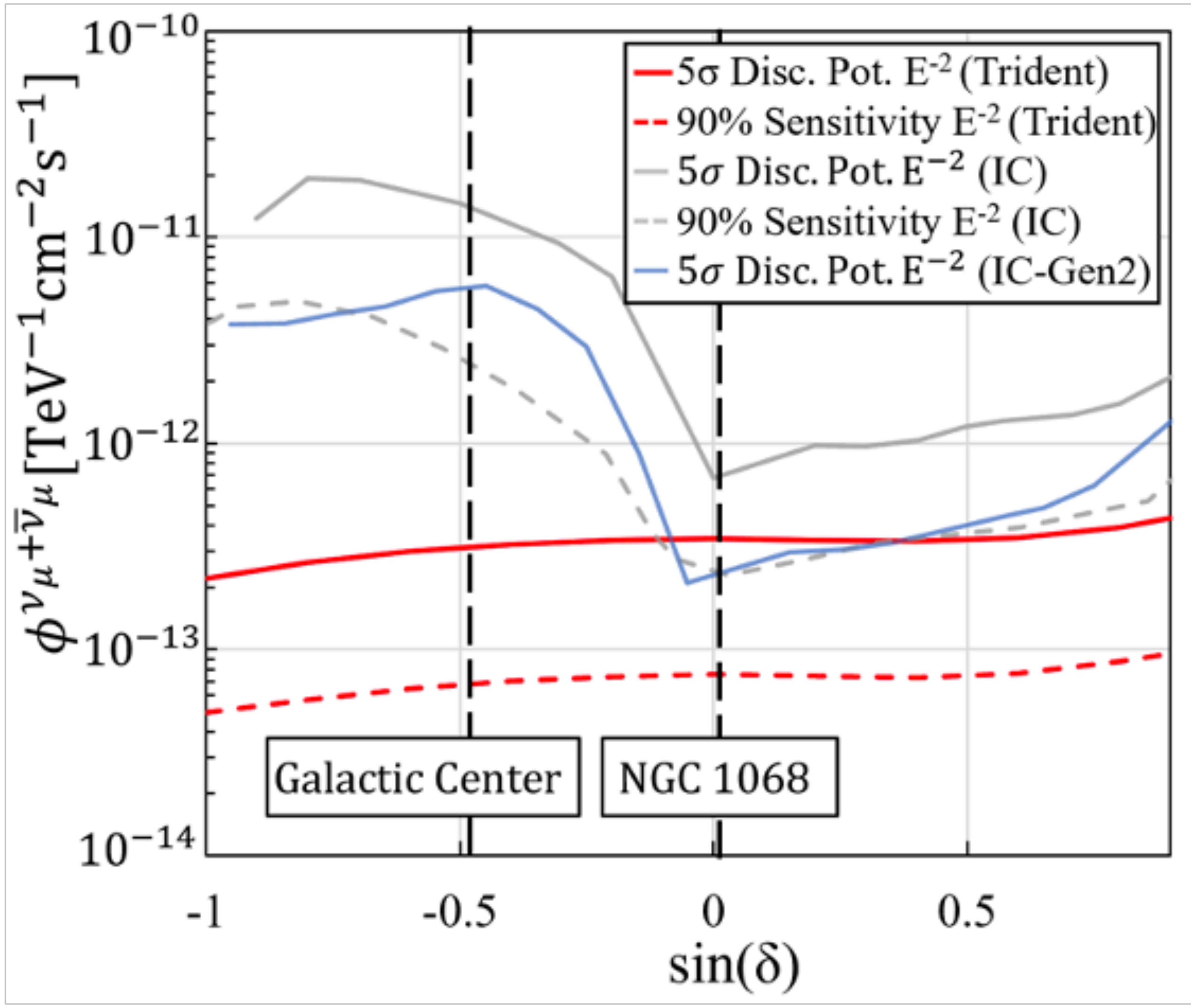
P-ONE Collaboration, Nature Astronomy (2020)

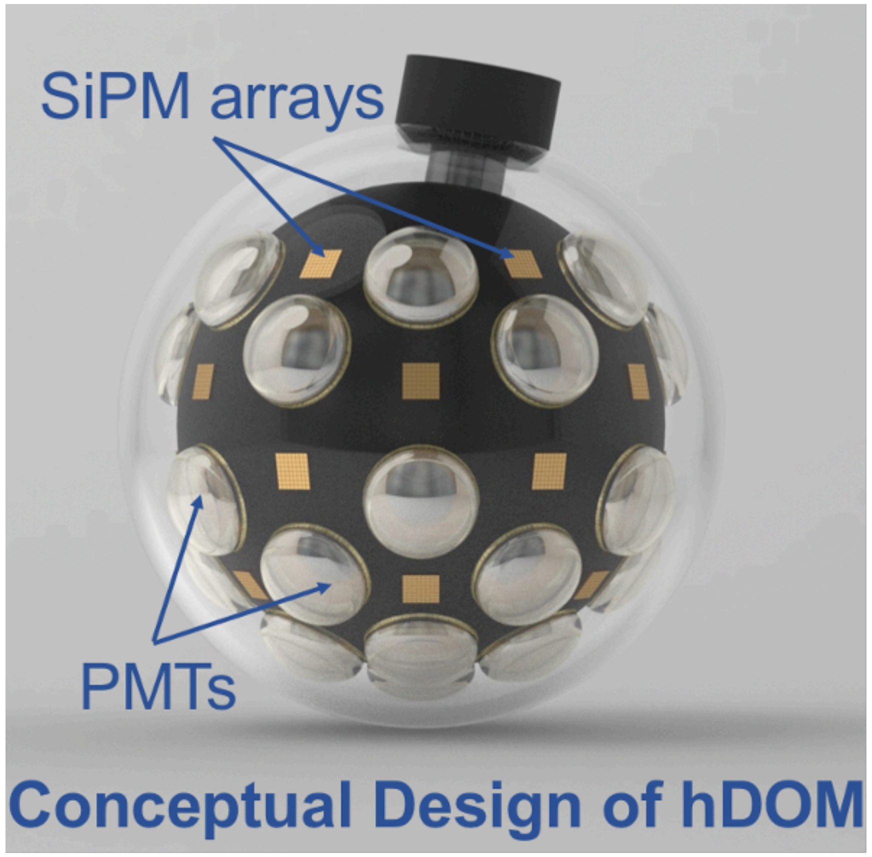


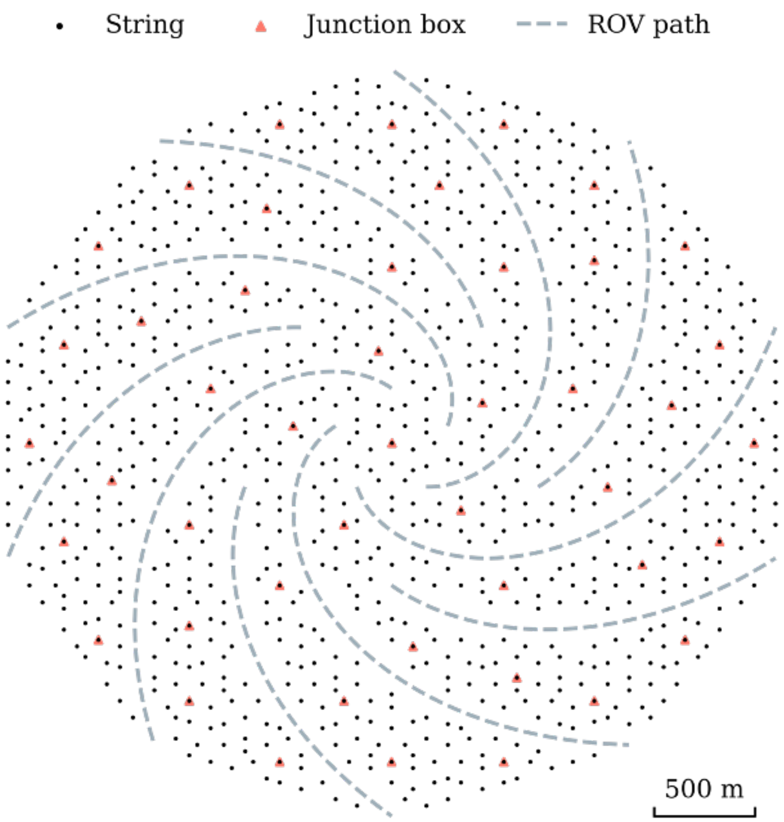
FIRST HINTS OF SOURCES FROM ICECUBE



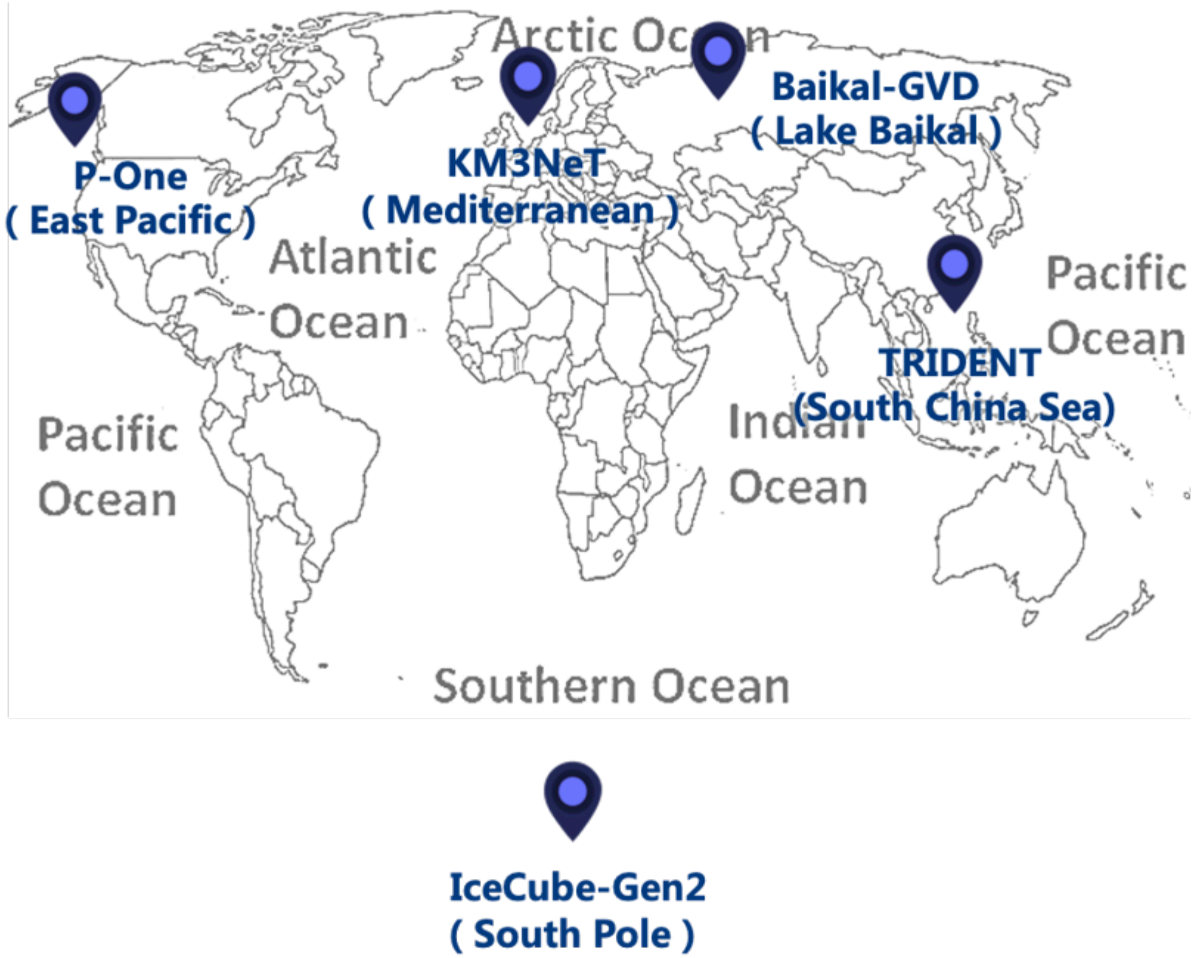
- Envisioned full detector:
  - 1211 strings
  - 30 hDOM per string
  - 7.5 km^3
  - 3475m depth at South China Sea
  - Underwater robots for deployment and maintain the detector

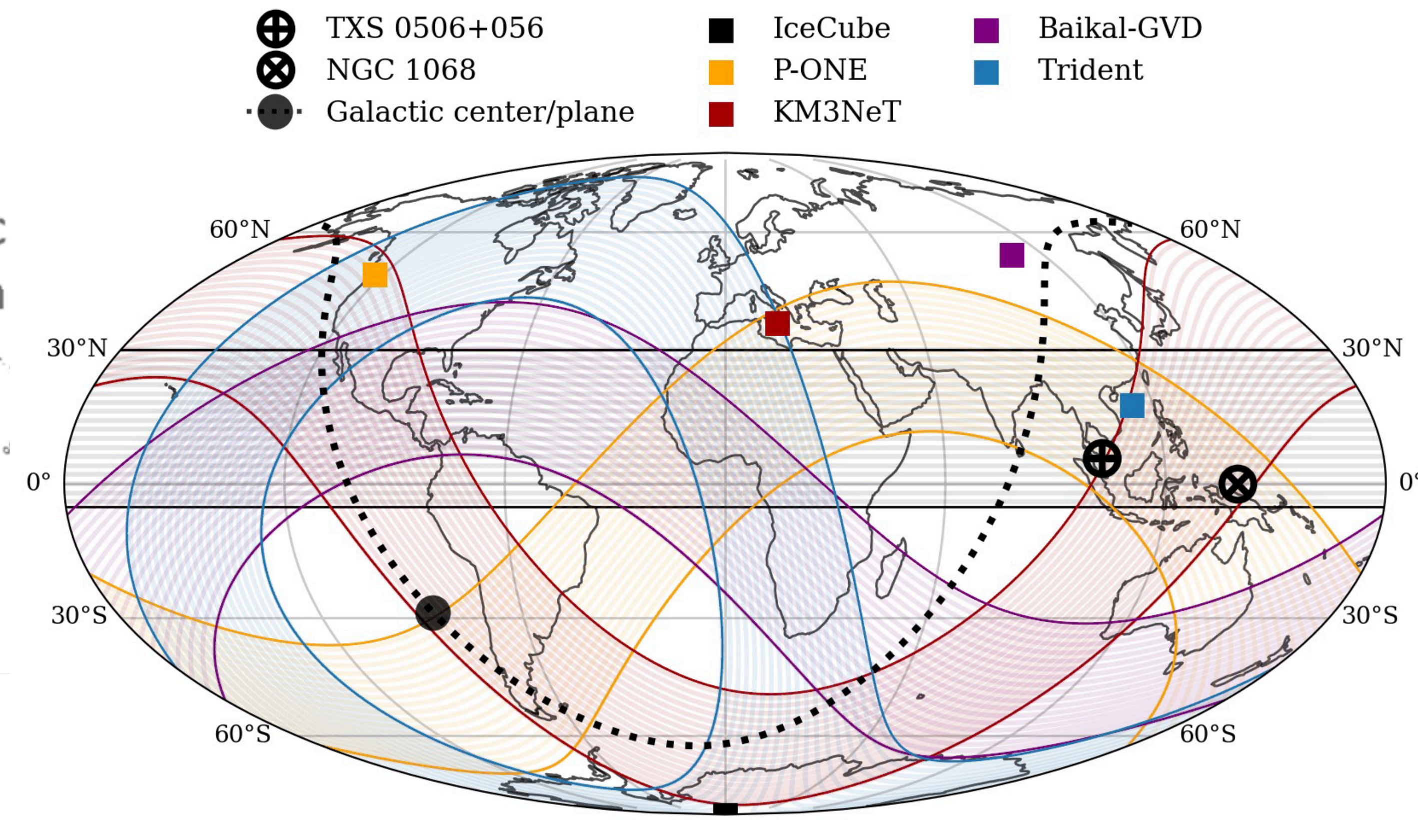






Future Neutrino Telescope Network





- Attempts on-going to coordinate efforts among the neutrino telescope community
  - GNN
  - Future Neutrino Telescope Network

Neutrino Oscillation Tomography Road Ahead

Goals

(1) Demonstrate feasibility of neutrino oscillation tomography →

(2) Perform first neutrino oscillation tomography measurement →

(3) Distinguish specific Earth composition models via oscillation tomography →

Detectors

- Now
  - Feasibility of very large volume neutrino detectors has been demonstrated (IceCube, ...)
  - High-precision neutrino detectors demonstrated (Super-K, ...)
- Near future
  - ~1MT detectors with 2-10GeV neutrino sensitivity (Upgrade, ORCA, Hyper-K, Baikal-GVD (?) ...)
- More distant future
  - >>10MT detector with 2-10GeV neutrino sensitivity (new detector, augmented PINGU or ORCA)

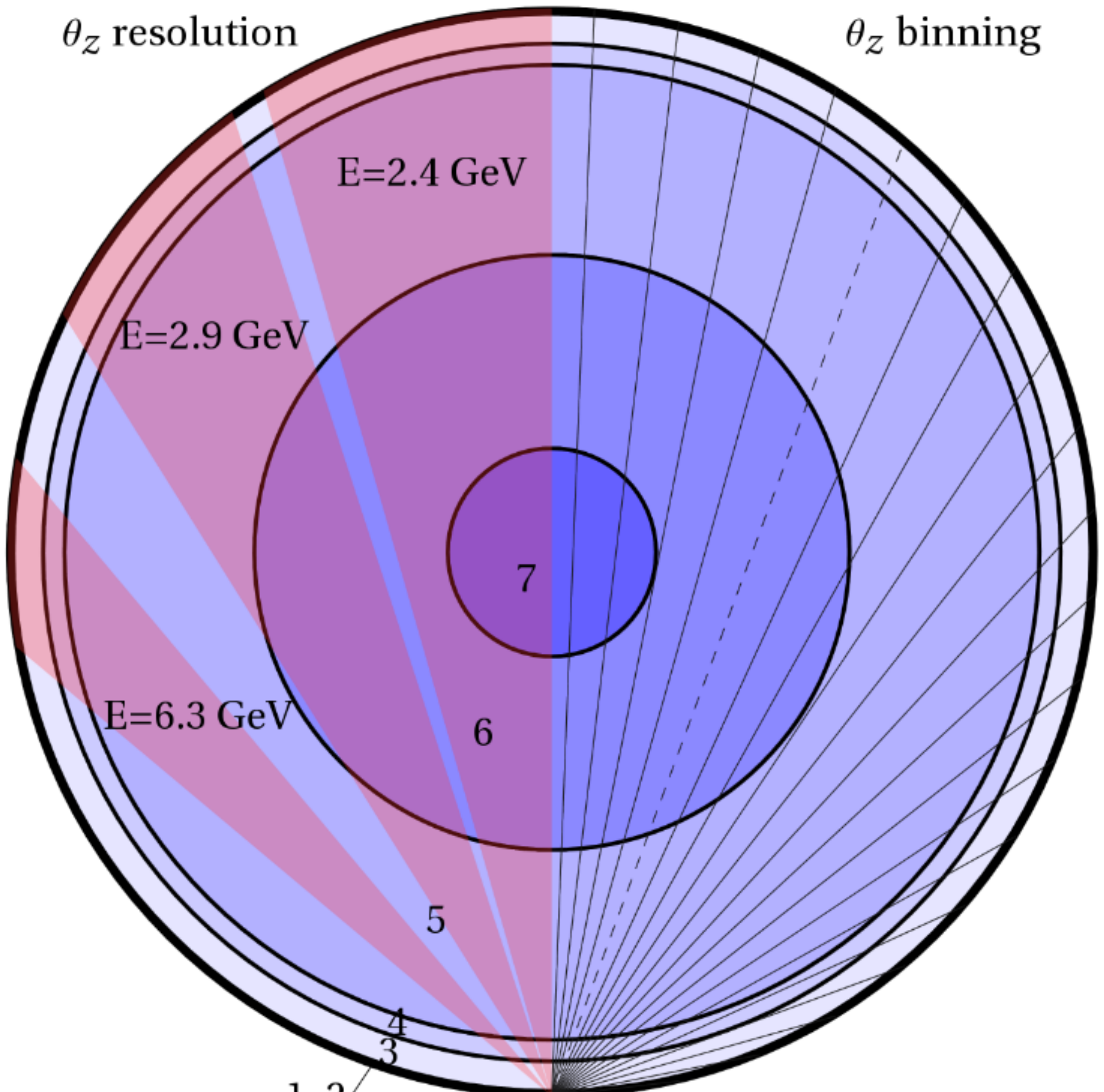
Conclusions

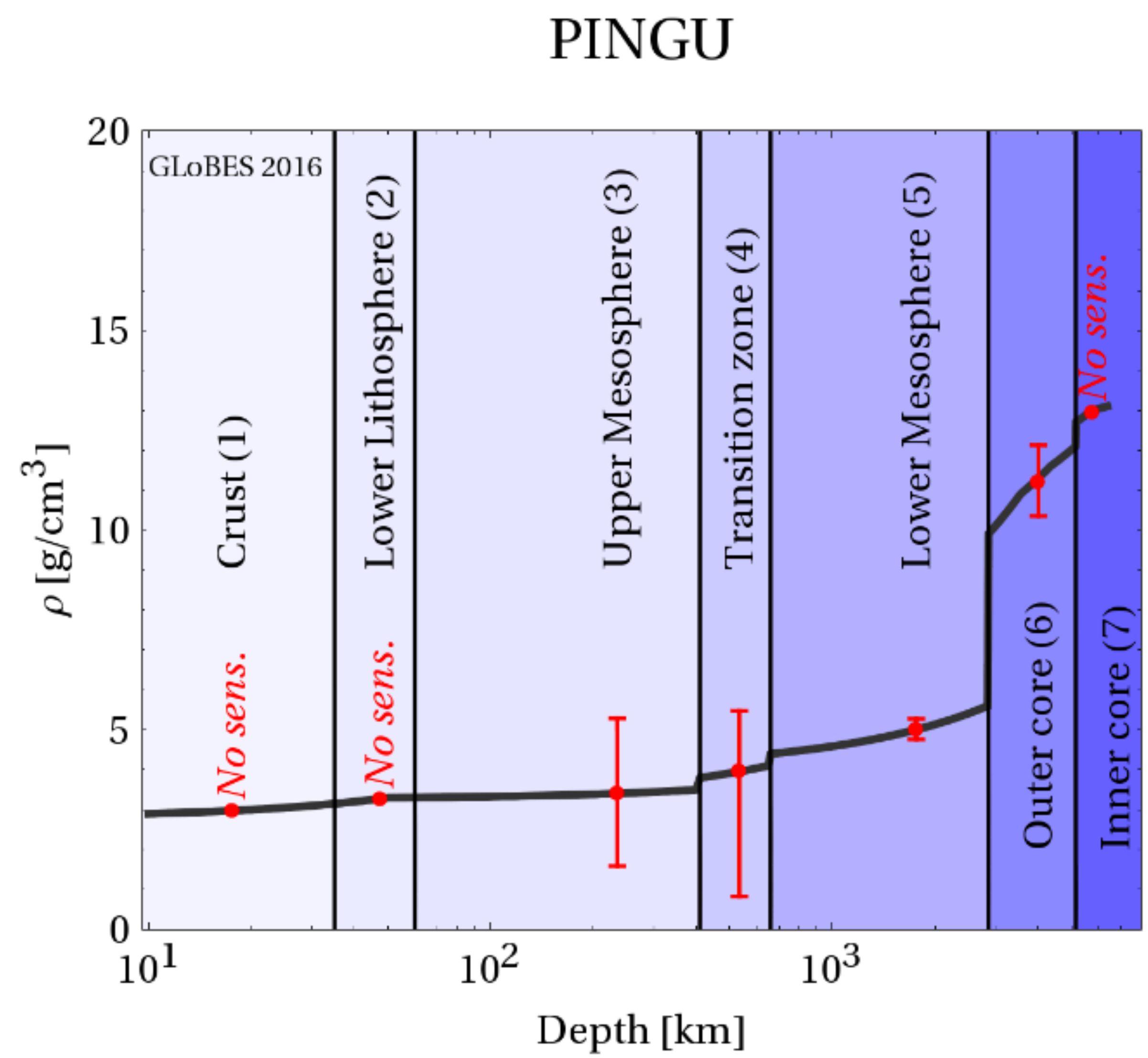
- Neutrino oscillation tomography is a novel method to better understand the Earth interior
  - Measure the Earth interior composition
    - Extremely sensitivity to hydrogen
  - Sensitivity to lower mantle density / LLSVP
- IceCube Upgrade/Hyper-K/ORCA will be able to put first experimental constrains on the Earth Core water content within first few years of operations (given normal mass hierarchy)
- The next-generation of detectors / dedicated experiments offer the long-term prospect to distinguish specific core models
  - very large - high statistics sample
  - good energy resolution and angular resolutions

Density measurement

W.Winter Nucl.Phys. B908 (2016) 250-267

Density measurements





Excellent sensitivities to the lower mantle density and give a robust lower bound on the outer core density

PINGU and ORCA can provide complementary information due to different locations. Seismic measurements show irregular wave propagation zones in the lower mantle

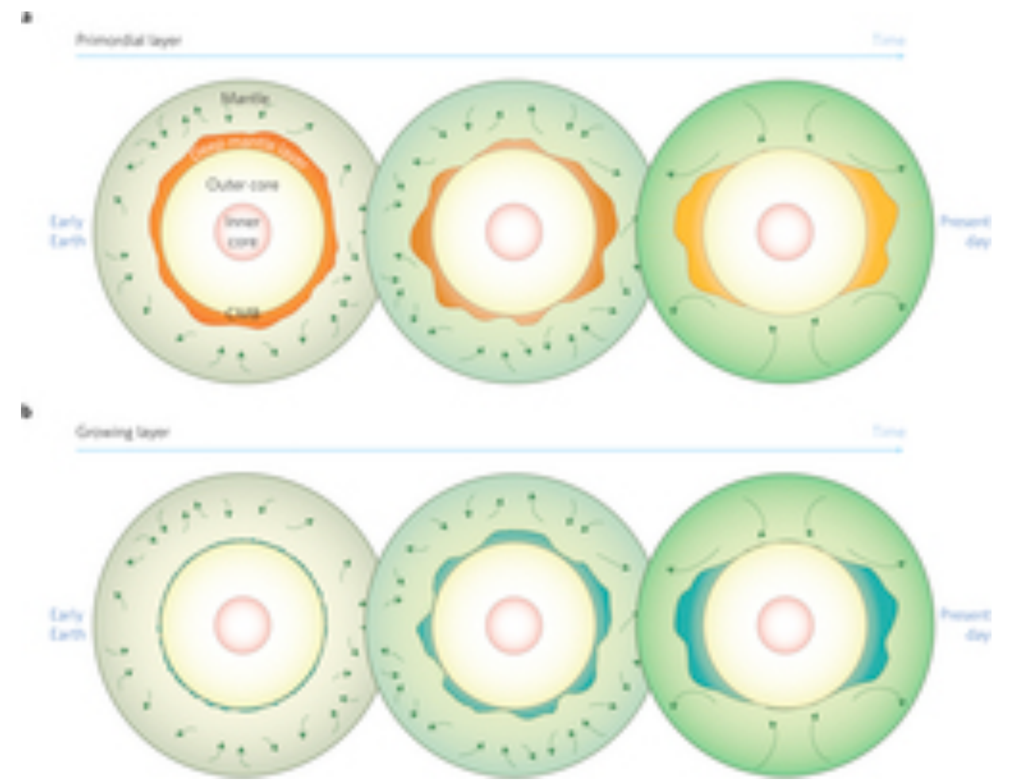
Percentage errors achievable with 10 years of data

Layer	PINGU NO	PINGU IO	ORCA NO	ORCA IO
Crust (1)	No sens.	No sens.	No sens.	No sens.
Lower Lithosphere (2)	No sens.	No sens.	No sens.	No sens.
Upper Mesosphere (3)	-53.4/+55.0	No sens.	-51.2/+53.4	-69.1/+52.2
Transition zone (4)	-79.2/+38.3	No sens./+72.2	-61.2/+35.6	-52.7/+45.8
Lower Mesosphere (5)	-5.0/+5.2	-10.5/+11.6	-4.0/+4.0	-4.7/+4.8
Outer core (6)	-7.6/+8.2	-40.2/No sens.	-5.4/+6.0	-6.5/+7.1
Inner core (7)	No sens.	No sens.	-60.8/+32.9	No sens.

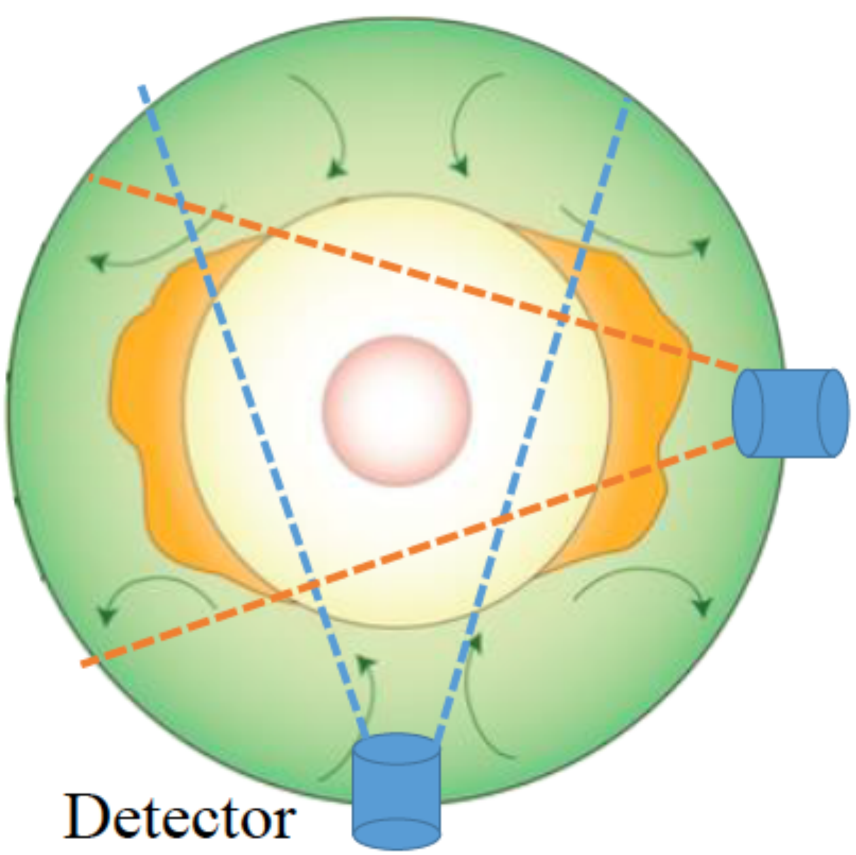
http://www.nature.com/ngeo/journal/v9/n7/pdf/ngeo2733.pdf

Lower mantle

- Continent-sized anomalous zones with low seismic velocity at the base of Earth's mantle
- Large low shear velocity provinces (LLSVP) up to 1,200km above CMB



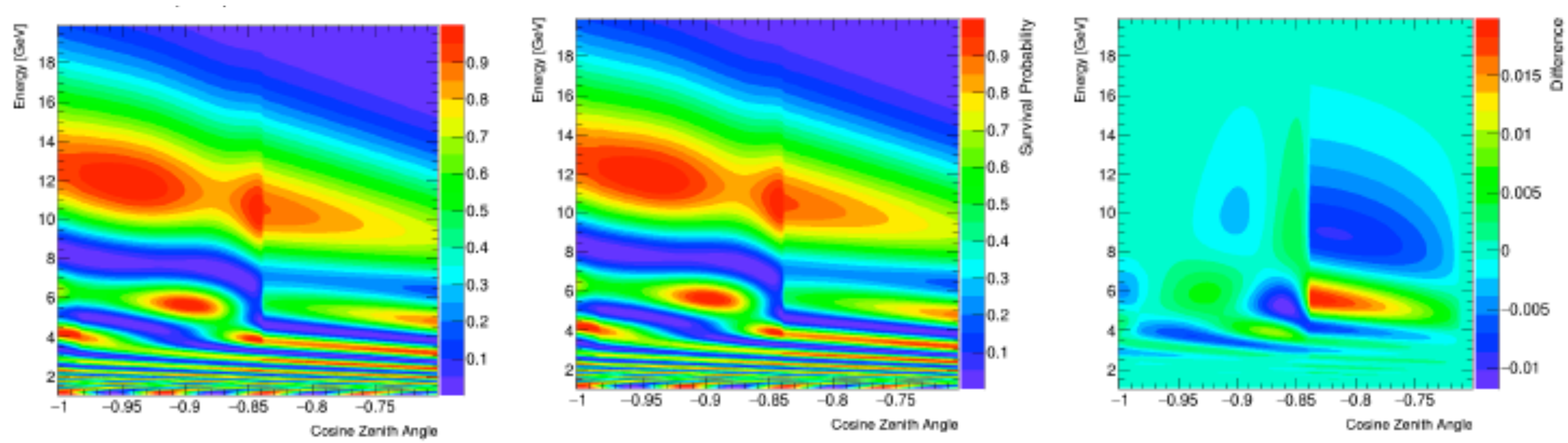
Anisotropic lower mantle



Detector

Muon neutrino survival probability

Z/A=0.4957 Z/A=0.5007 Difference



- Tomography with multiple detectors

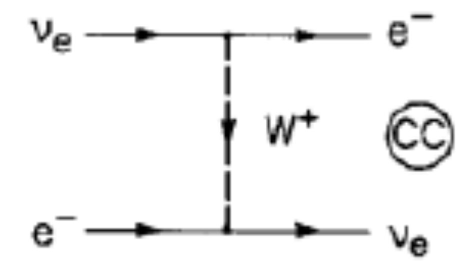
Neutrino Oscillations in Matter

slide from Walter Winter

- Oscillation probabilities in

vacuum: $$P_{\alpha\alpha} = 1 - \sin^2 2\theta \, \sin^2 \frac{\Delta m^2 L}{4E}$$

matter: $$P_{\alpha\alpha} = 1 - \sin^2 2\tilde{\theta} \, \sin^2 \frac{\Delta \tilde{m}^2 L}{4E}$$



(Wolfenstein, 1978; Mikheyev, Smirnov, 1985)

$$\Delta\tilde{m}^2 \; = \; \xi \cdot \Delta m^2, \quad \sin 2\tilde{\theta} = \frac{\sin 2\theta}{\xi},$$

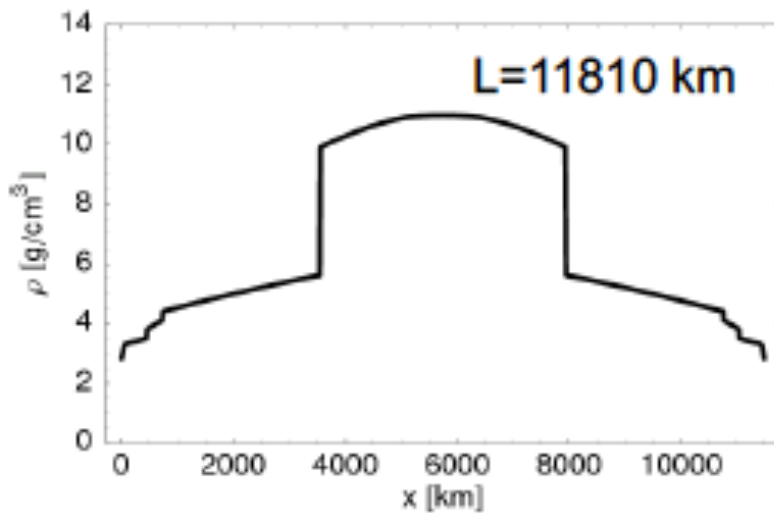
$$\xi \; \equiv \; \sqrt{\sin^2 2\theta + \left(\cos 2\theta - \hat{A}\right)^2},$$

$$\hat{A} \; = \; \frac{2EV}{\Delta m^2} = \frac{\pm 2\sqrt{2} E \, G_F \, n_e}{\Delta m^2}$$

⇨ **MO**

Resonance energy (from $\hat{A} \rightarrow \cos 2\theta$):

$$E_{\mathrm{res}} \, [\mathrm{GeV}] \sim 13\,200 \; \cos 2\theta \, \frac{\Delta m^2 \, [\mathrm{eV}^2]}{\rho \, [\mathrm{g/cm^3}]}$$

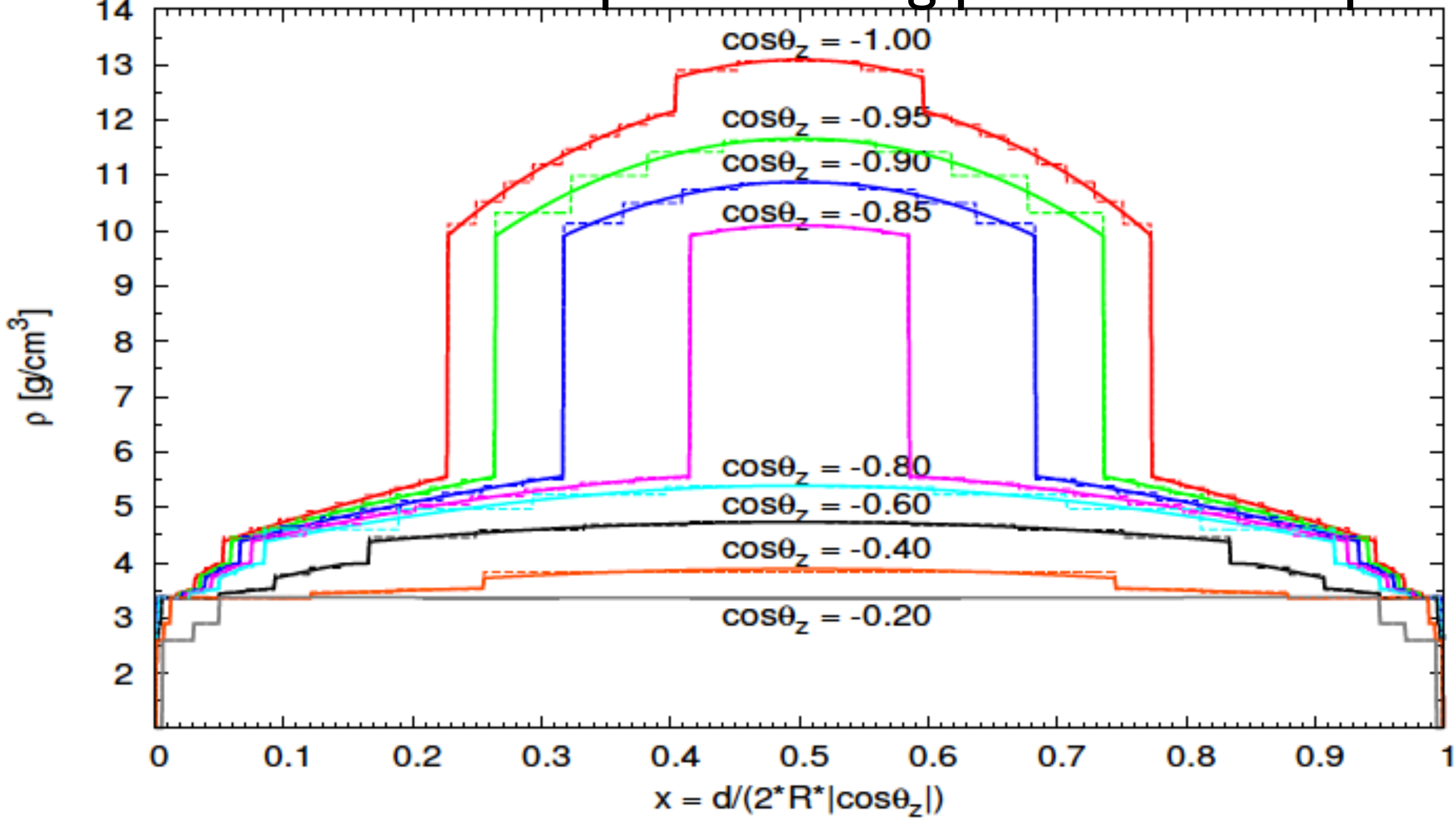


For ν_μ appearance, Δm_{31}^2:
- $\rho \sim 4.7$ g/cm³ (Earth's mantle): $E_{res} \sim 6.4$ GeV
- $\rho \sim 10.8$ g/cm³ (Earth's outer core): $E_{res} \sim 2.8$ GeV

Walter Winter | PANE 2018 | 31.05.2018 | Page 10

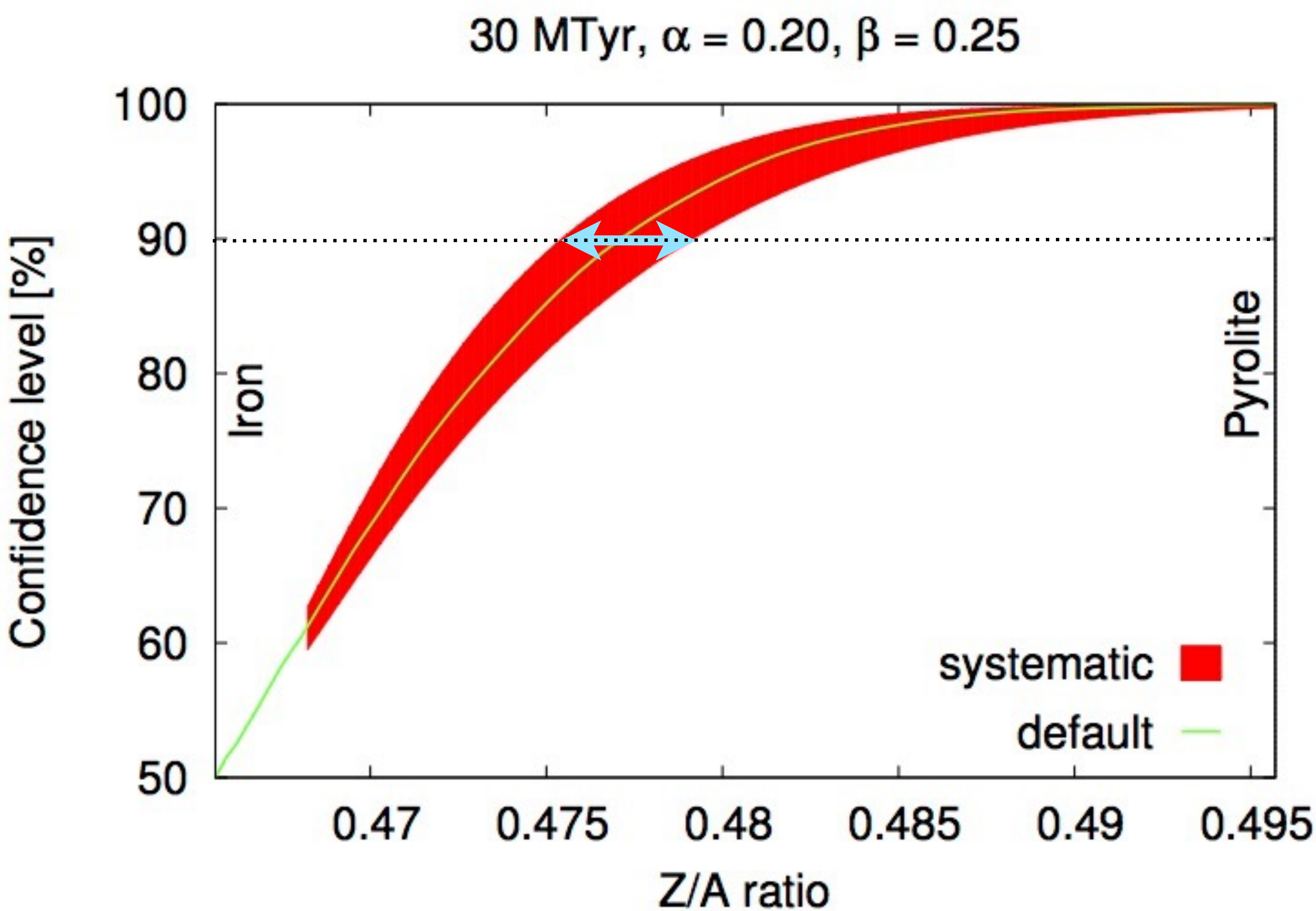
Thank you !

https://arxiv.org/pdf/1309.3176.pdf



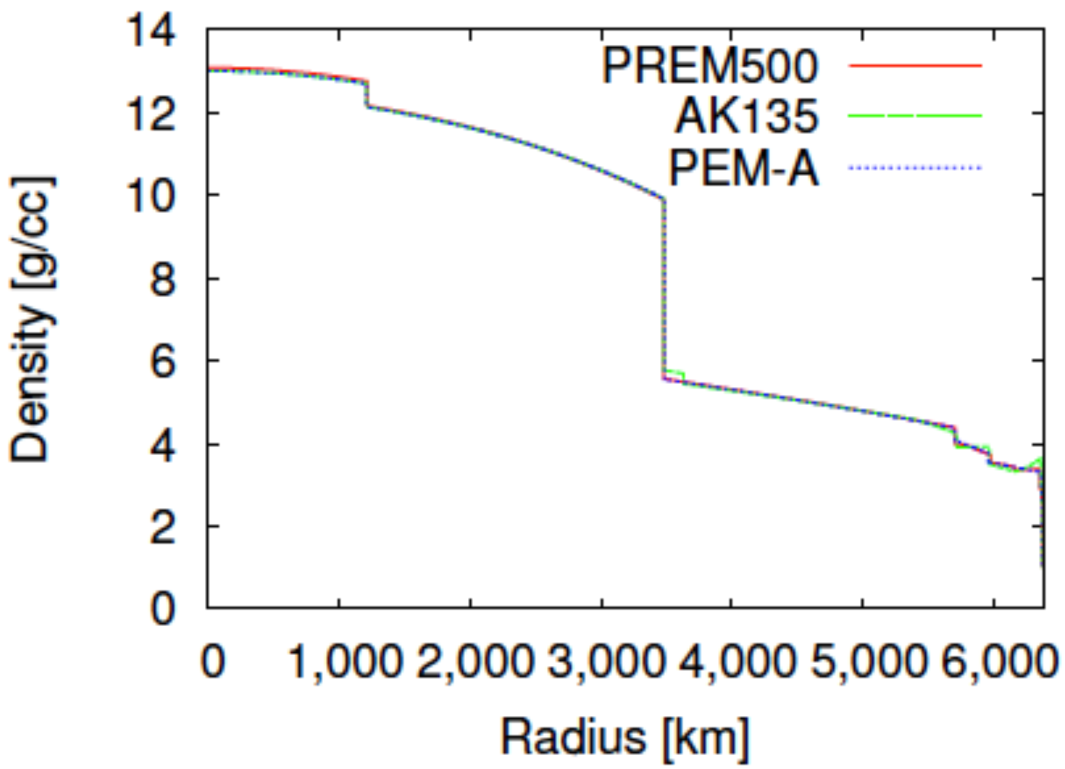
Rott & Taketa 2015

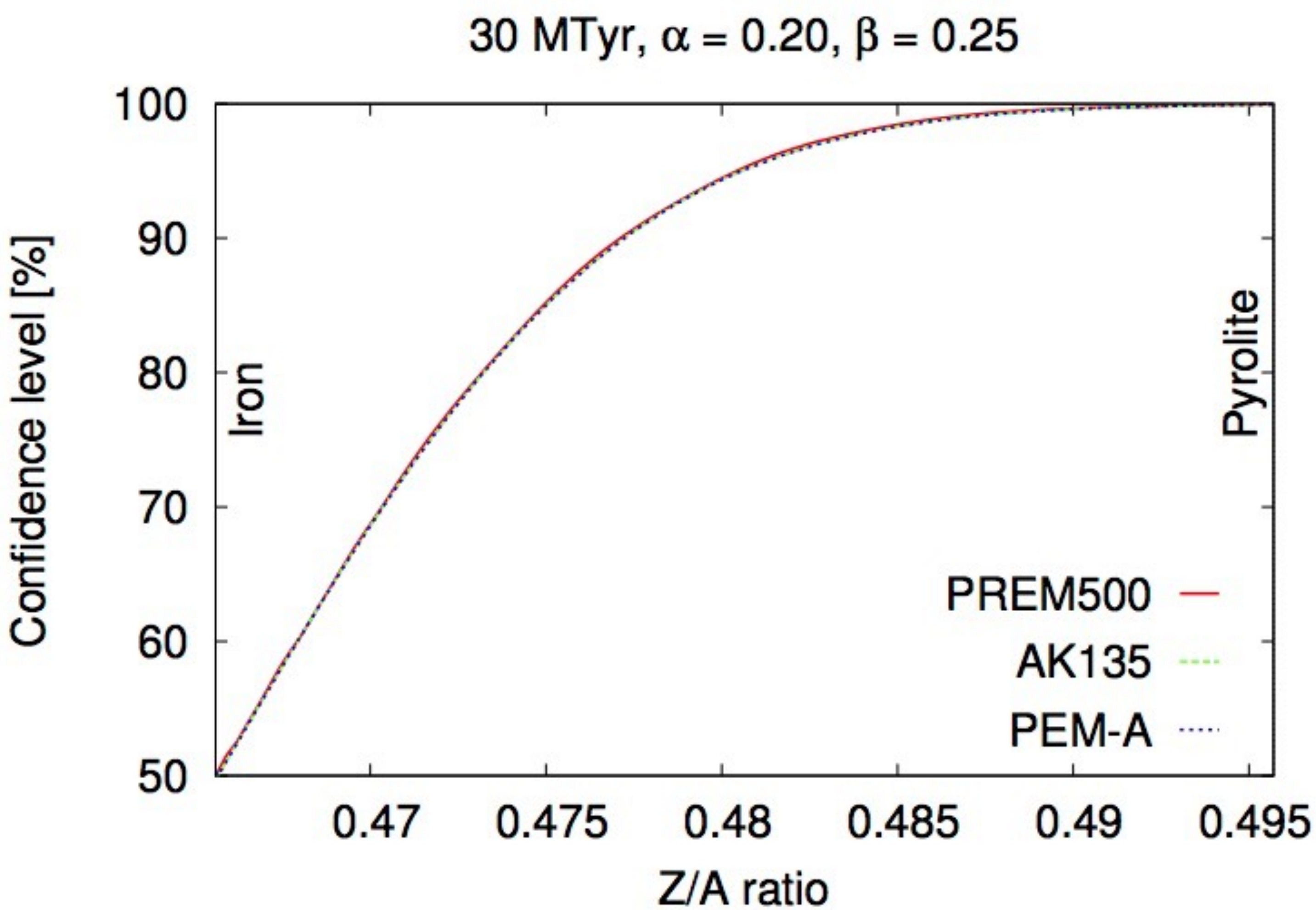
Uncertainty due to mixing parameters

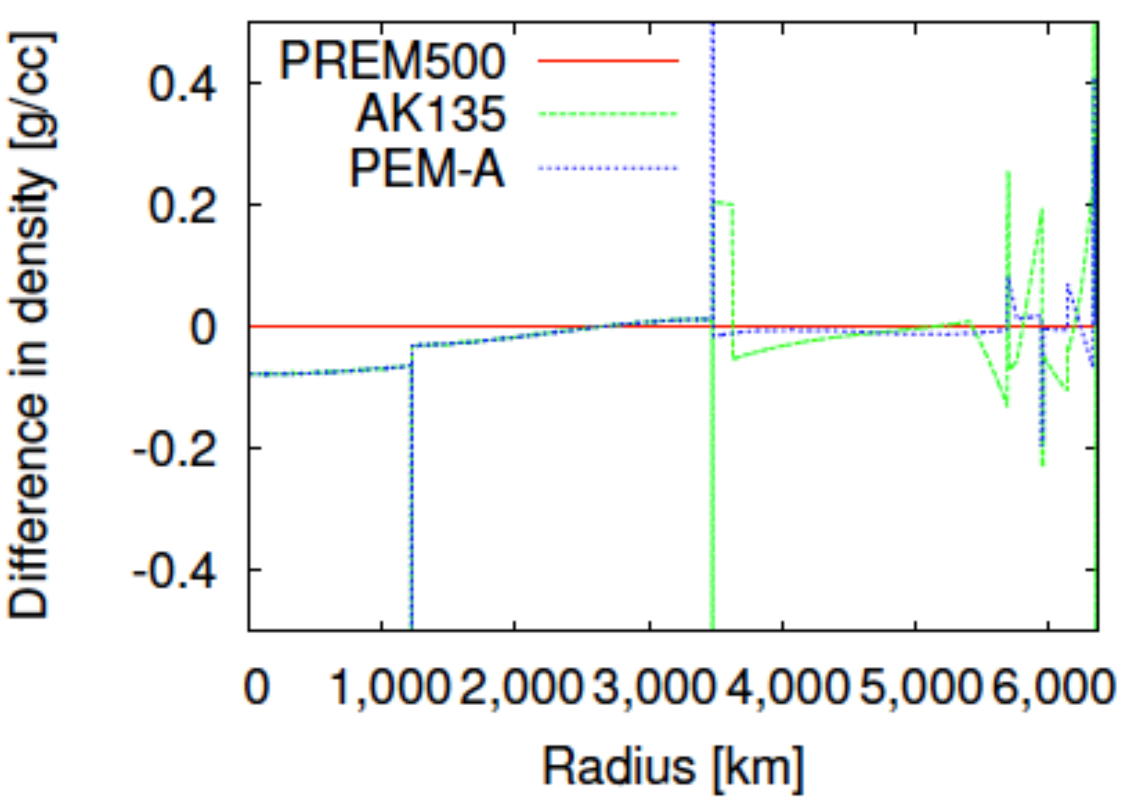


Use the best fit oscillation parameters and their uncertainties of:
Capozzi, F. et al. Status of three-neutrino oscillation parameters, circa 2013. Physical Review D 89, 093018 (2014).

Uncertainty due to Earth model







Uncertainty due to the Earth mass density profile is negligible

PREM500 - Dziewonski, A. & Anderson, D. Preliminary reference Earth model. Physics of the Earth and Planetary Interiors 25, 297–356 (1981).
AK135 - Kennett, B., Engdahl, E. & Buland, R. Constraints on seismic velocities in the earth from travel times. Geophysical Journal International 122, 108–124 (1995).
PREM-A - Dziewonski, A., Hales, A. & Lapwood, E. Parametrically simple earth models consistent with geophysical data. Physics of the Earth and Planetary Interiors 10, 12–48 (1975).