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Atmospheric neutrino oscillations

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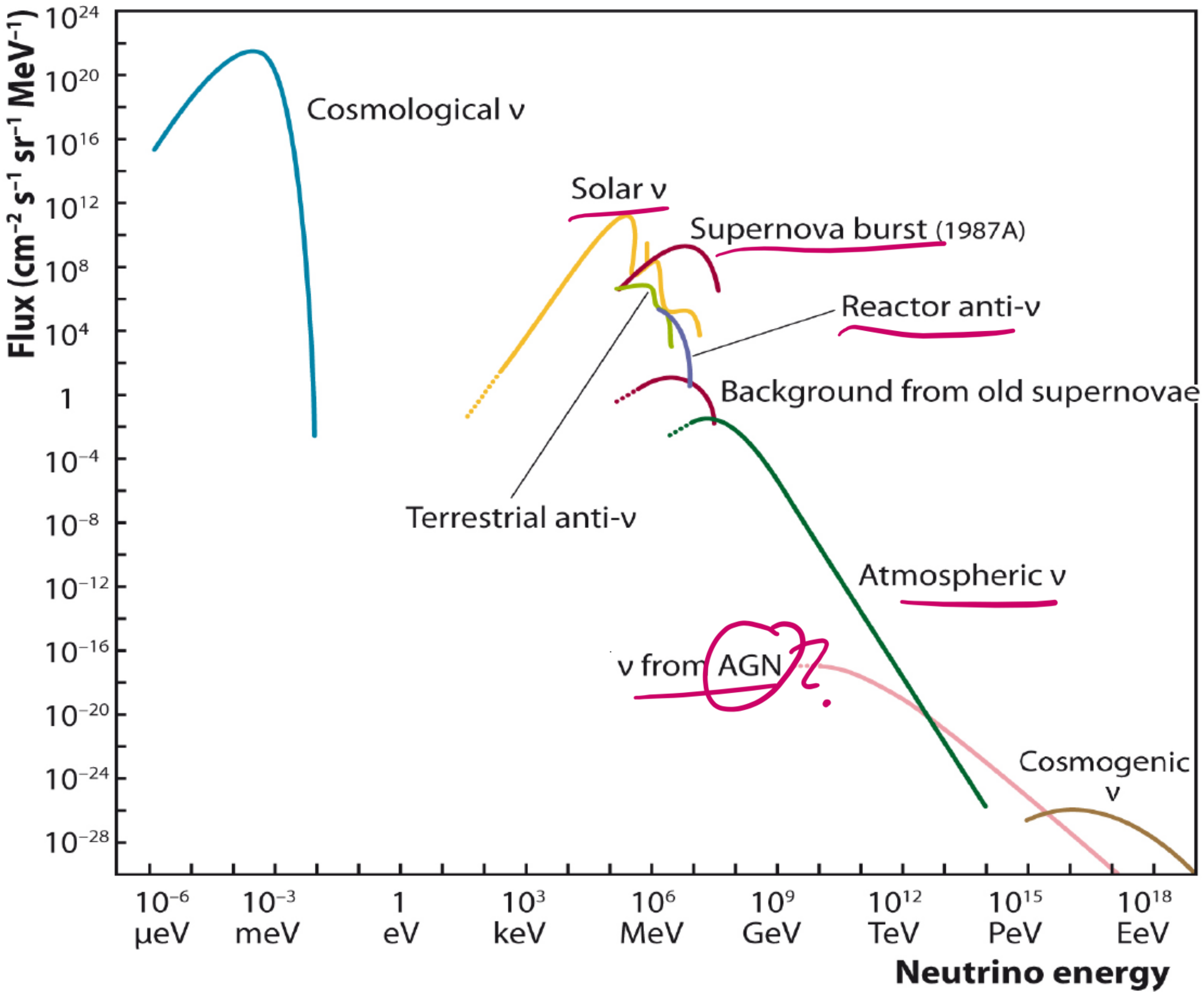
Astroparticle School 2024

Obertrubach-Bärnfels

J. Yang, WIPAC

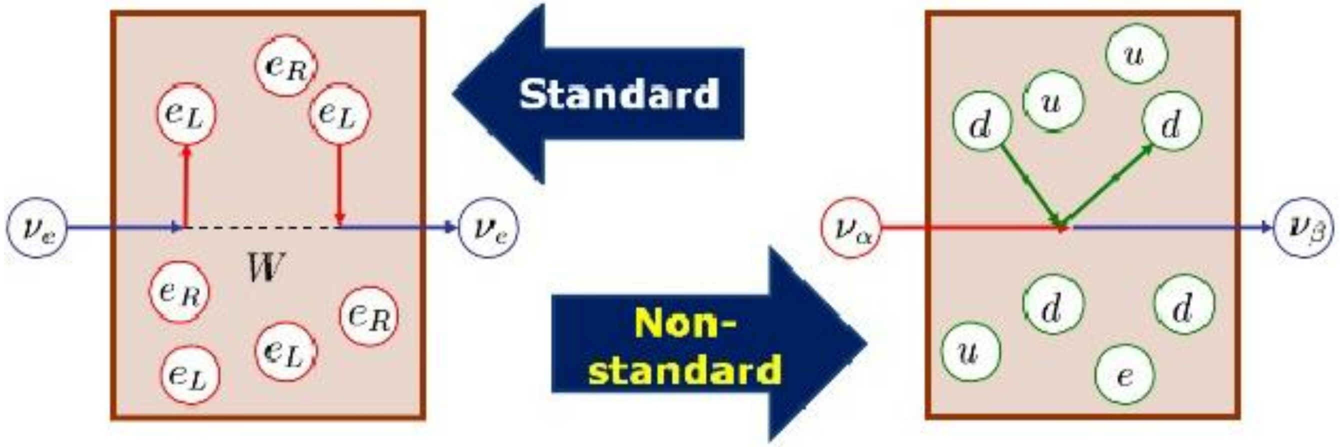
neutrinos as probes

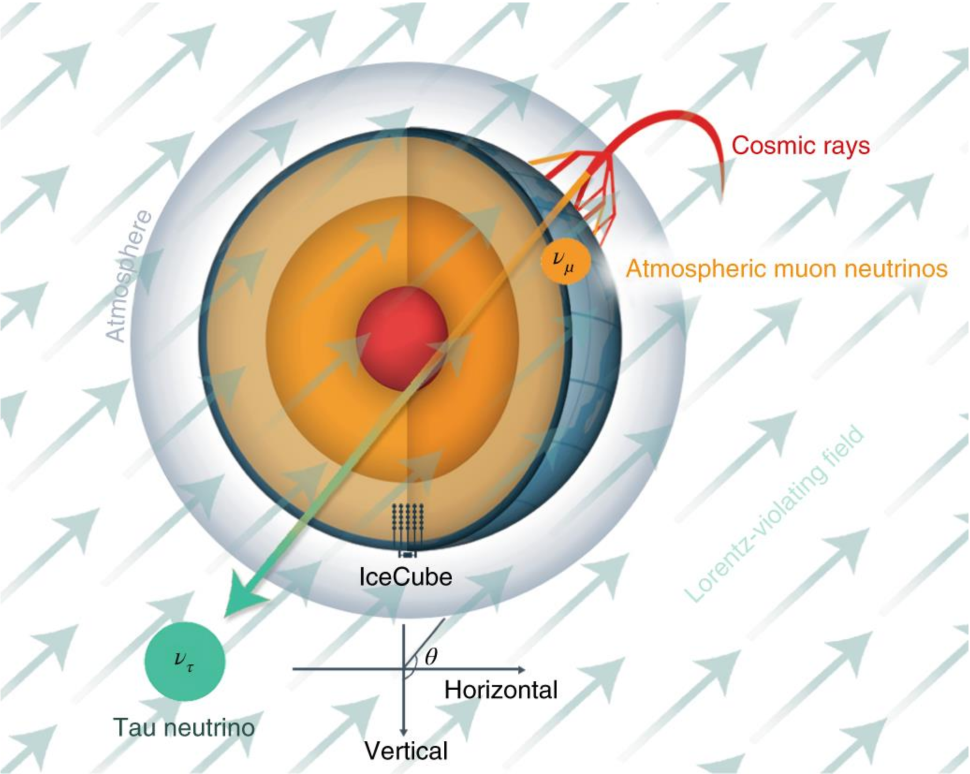
neutrino sources



searching for exotic physics with ν

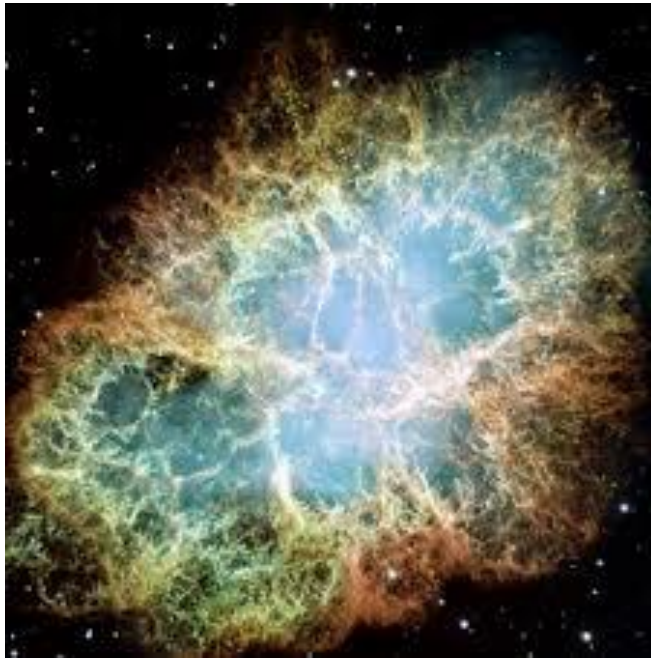
non-standard interactions



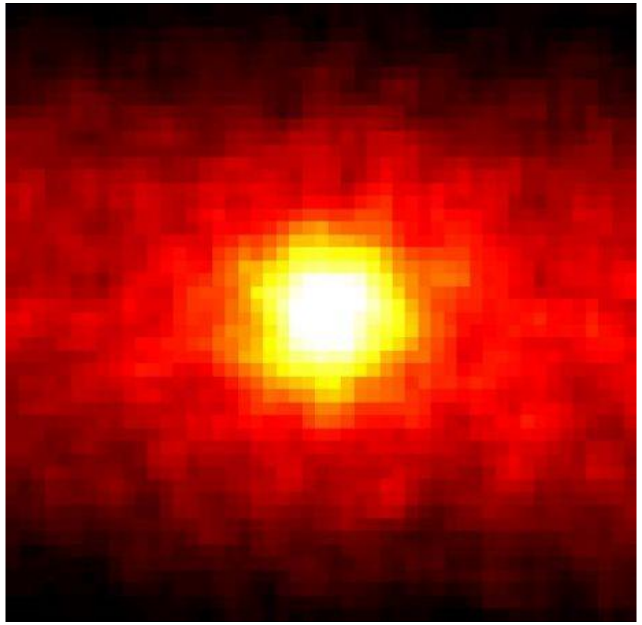


Lorentz invariance violation

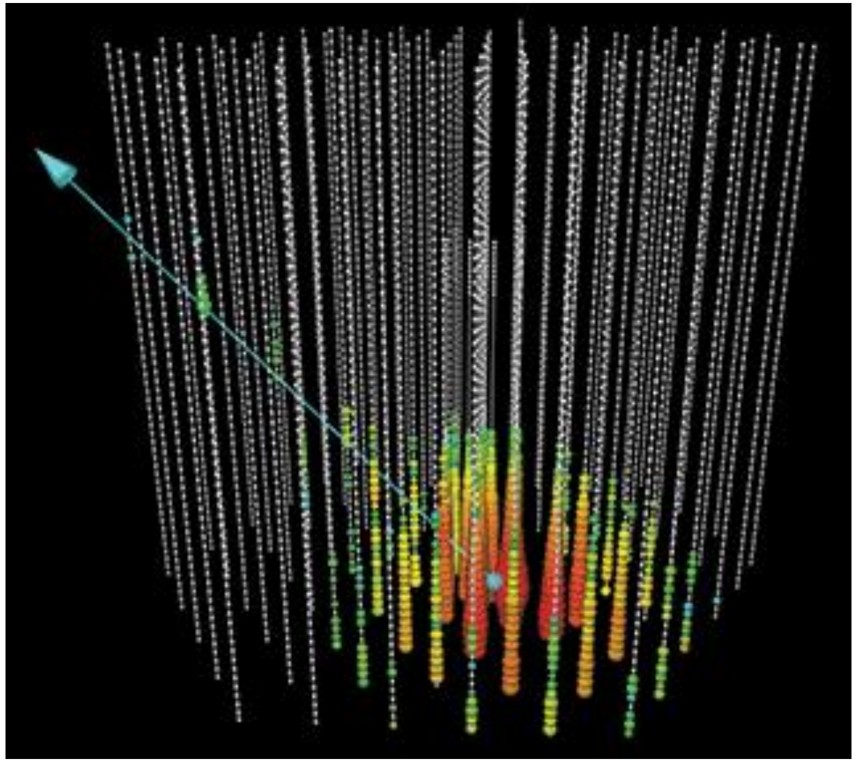
studying astrophysical objects



supernova neutrinos



solar neutrinos



HE neutrinos from violent sources

outline

-historical context

-modeling atmospheric neutrinos

-detection technology

-motivation & recent results

-future experiments

atmospheric neutrino origins

A lot of the material borrowed from

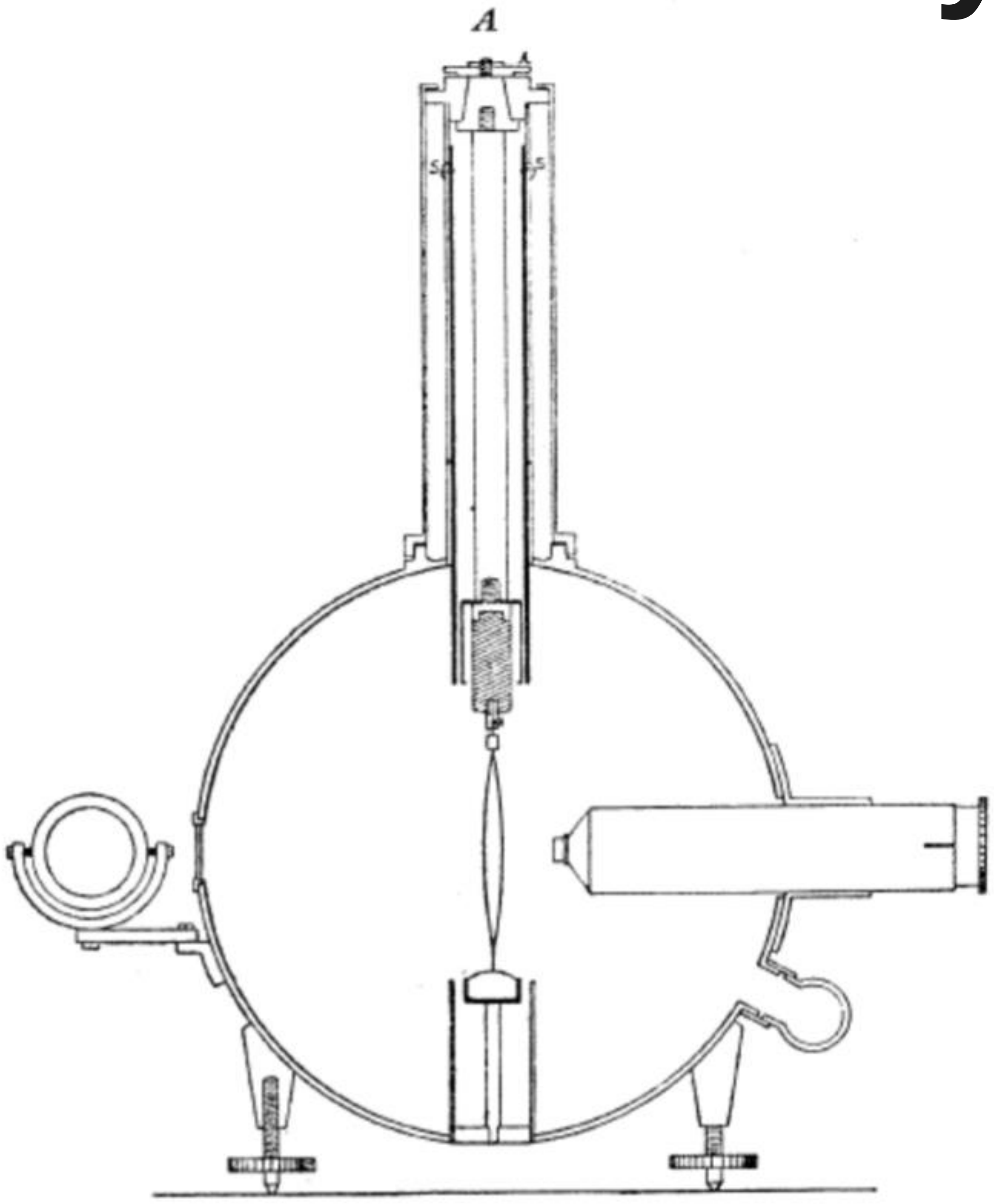
- P. Lipari's talk at neutrino history conference
- Horeandel, Early cosmic-ray work published in German
- Bertolotti, Celestial Messengers

it starts with radioactivity

-phenomenon of radioactivity discovered in late 1800’s

-electroscopes were used to study levels of radioactivity

-they would spontaneously discharge, why?



a source outside Earth?

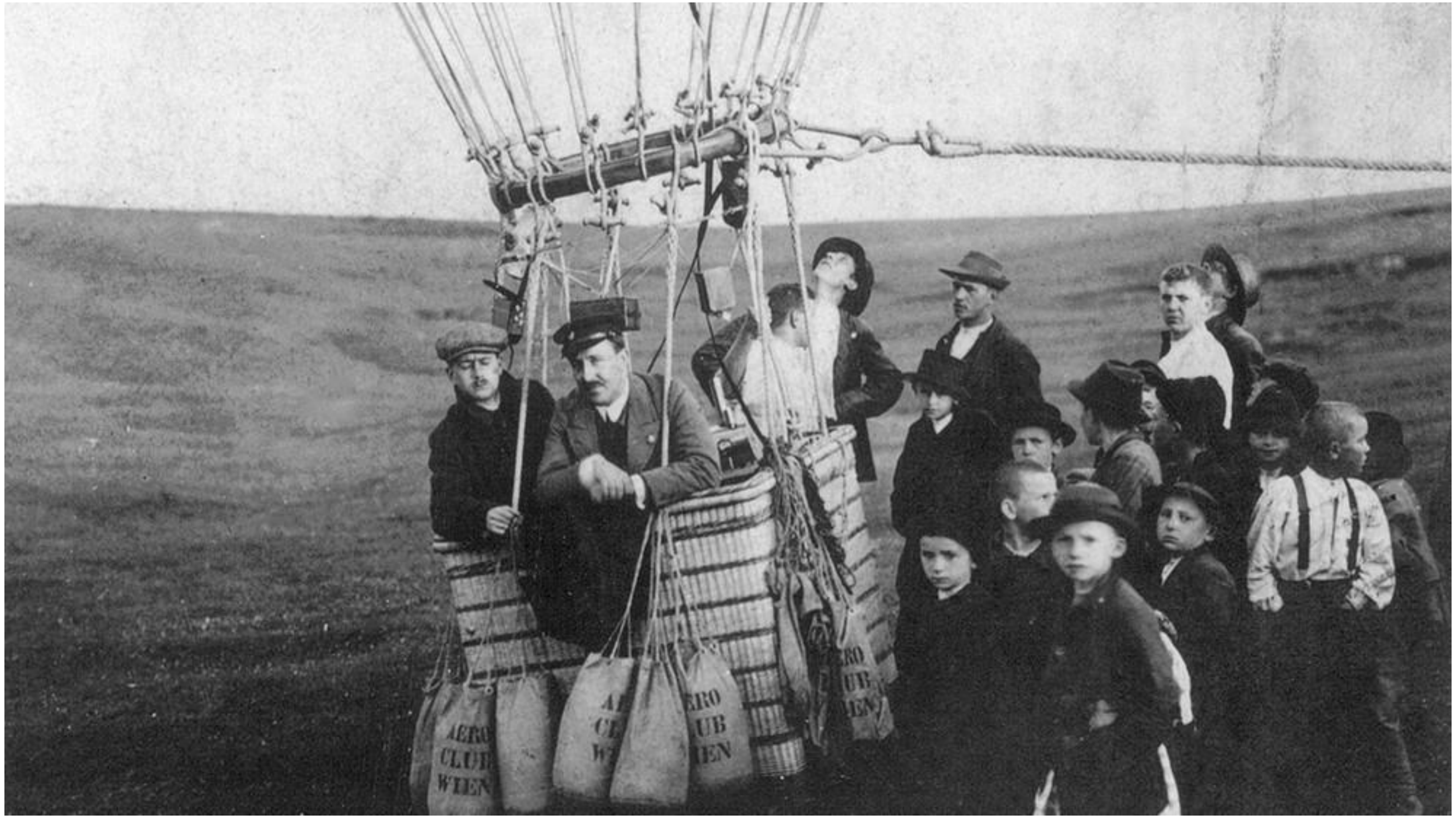
-could radioactivity have **non-terrestrial** origin?

-in 1910 Theodor Wulf went up the Eiffel Tower (300m) and measured less radiation than on the ground, but **more than expected**

adventurous experiments

-Viktor Hess made multiple balloon flights in 1912

-Going up to 5km elevation



adventurous experiments

Tabelle der Mittelwerte.

Mittlere Höhe über dem Erdboden m	Beobachtete Strahlung in Ionen pro ccm und sec.			
	Apparat 1	Apparat 2	Apparat 3	
	Q_1	Q_2	Q_3 (reduziert)	Q_3 (nicht reduziert)
0	16,3 (18)	11,8 (20)	19,6 (9)	19,7 (9)
bis 200	15,4 (13)	11,1 (12)	19,1 (8)	18,5 (8)
200—500	15,5 (6)	10,4 (6)	18,8 (5)	17,7 (5)
500—1000	15,6 (3)	10,3 (4)	20,8 (2)	18,5 (2)
1000—2000	15,9 (7)	12,1 (8)	22,2 (4)	18,7 (4)
2000—3000	17,3 (1)	13,3 (1)	31,2 (1)	22,5 (1)
3000—4000	19,8 (1)	16,5 (1)	35,2 (1)	21,8 (1)
4000—5200	34,4 (2)	27,2 (2)	—	—

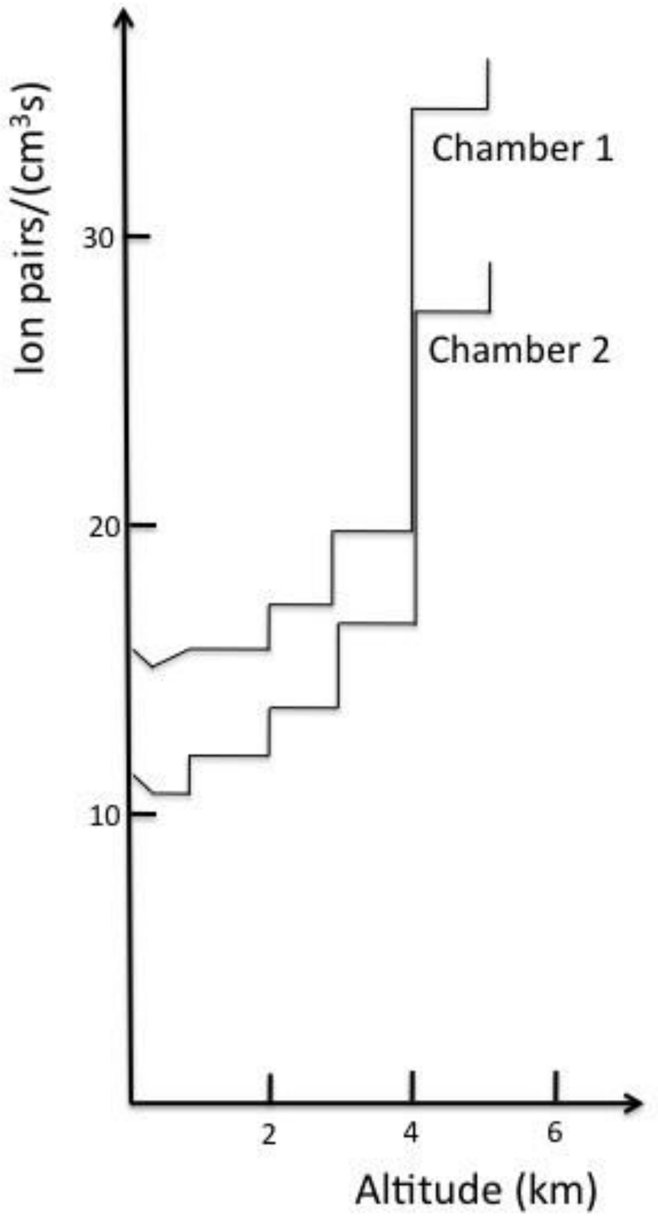
Hess, V.F., 1912, Phys.. Z, 13 1084.

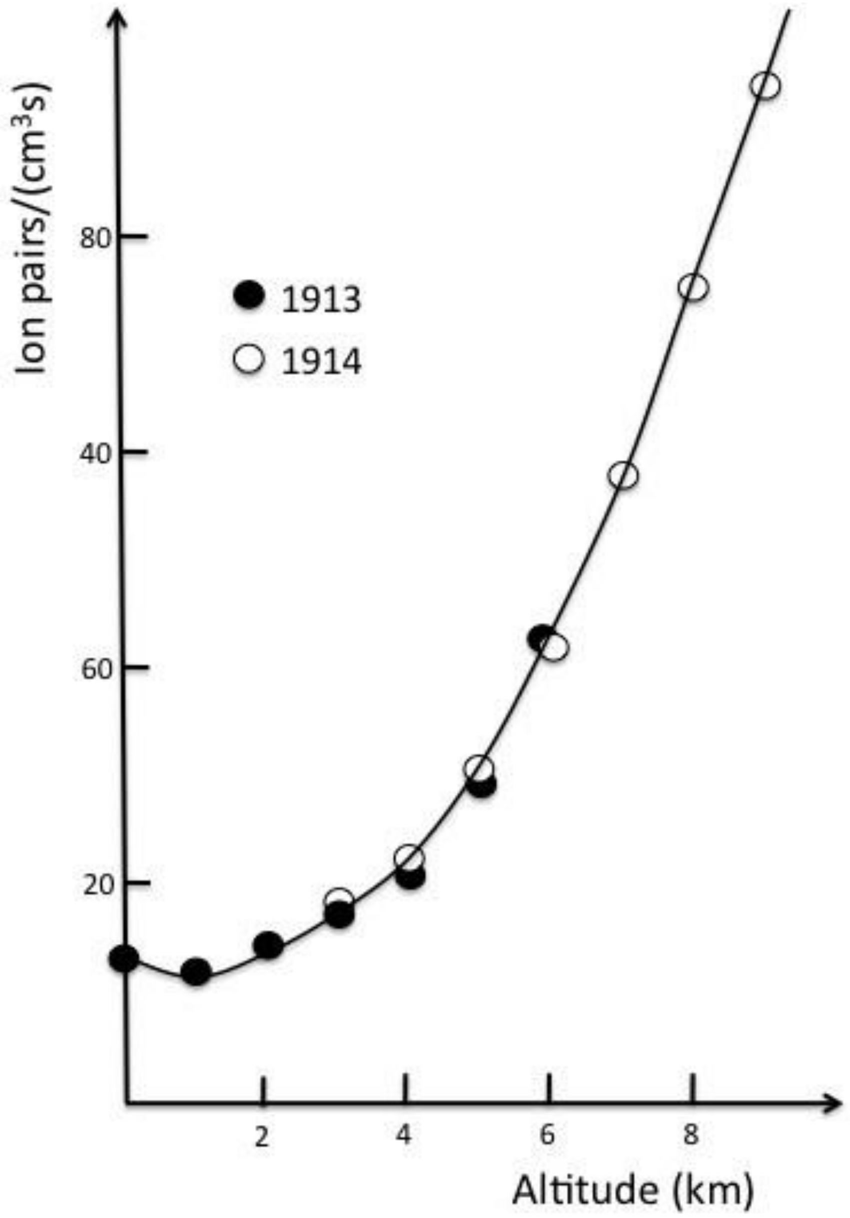
coming from the cosmos

-there's a dip, then a sharp rise in radiation levels

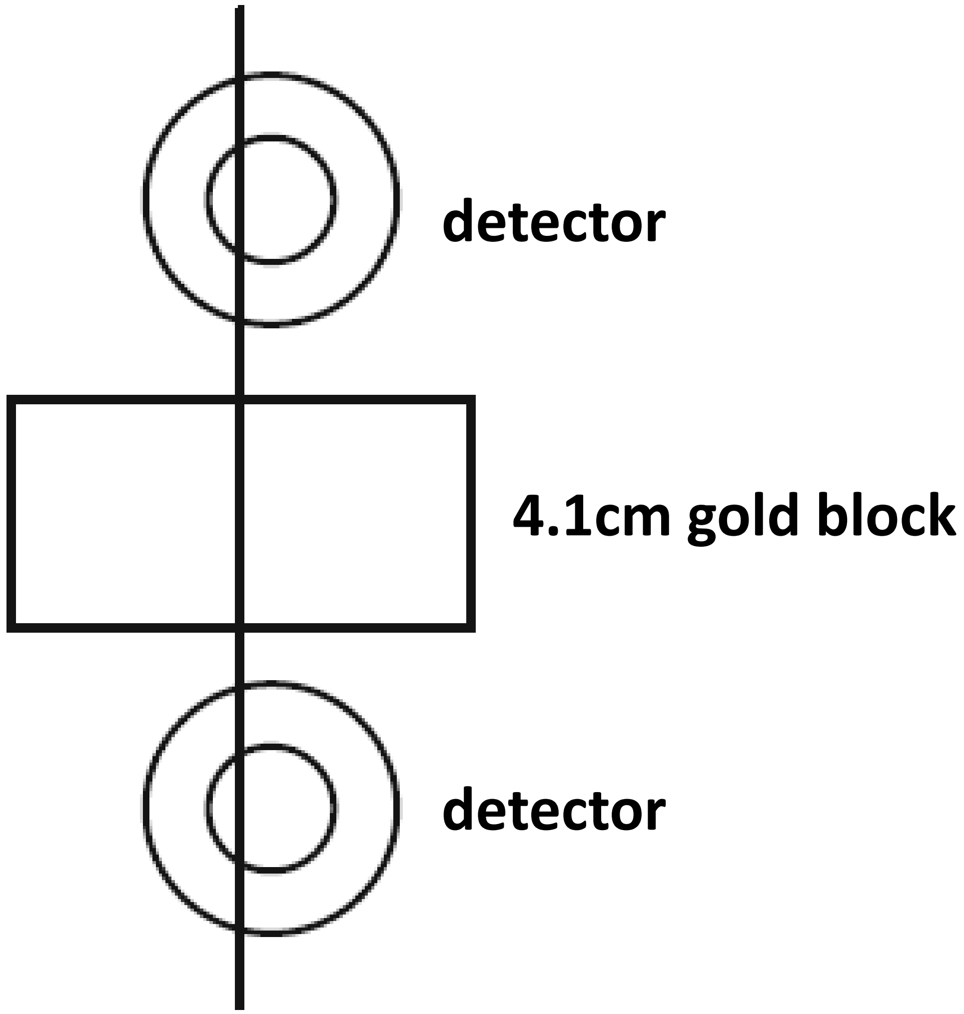
-Kolhörster confirmed the measurements shortly afterwards

-non-terrestrial radiation exists: cosmic rays





identifying the radiation



76% of particles passing through

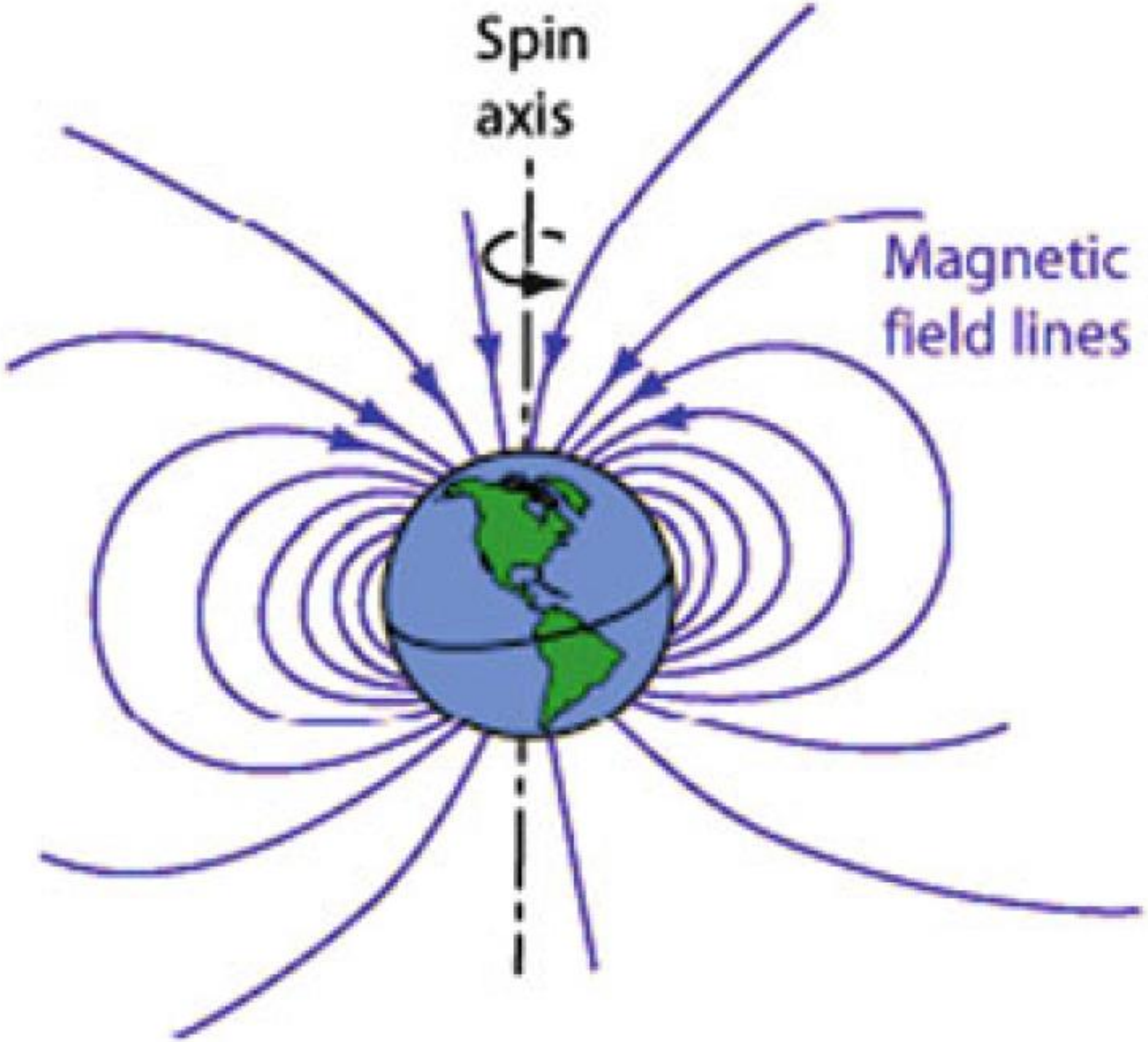
-but what is it? first believed to be gamma rays

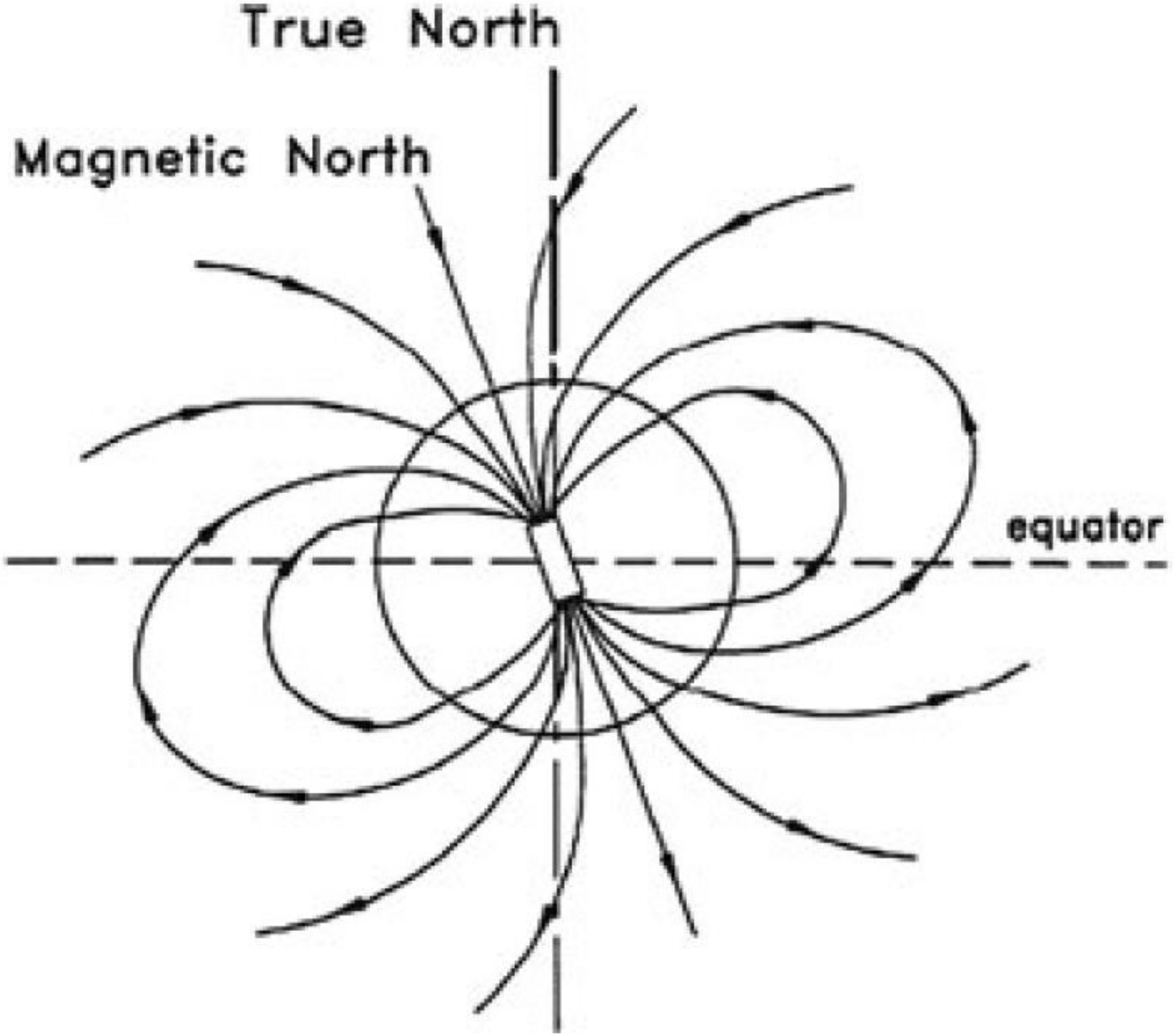
-but in 1928-1929 Bothe & Kolhoerster showed the radiation to be very penetrating

-first peek at muons (at that time not known)

-what about the primary radiation?

Earth has a magnetic field

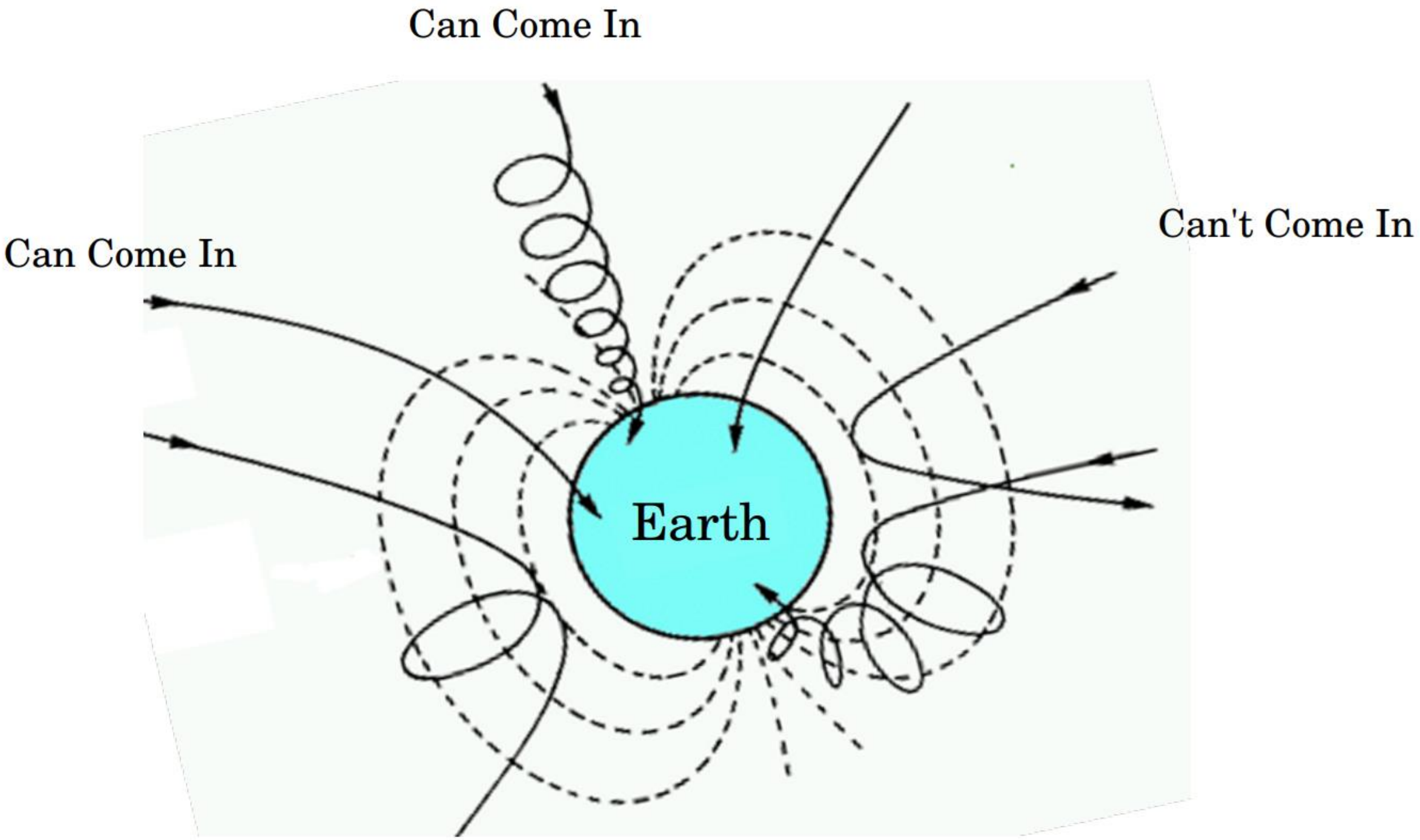


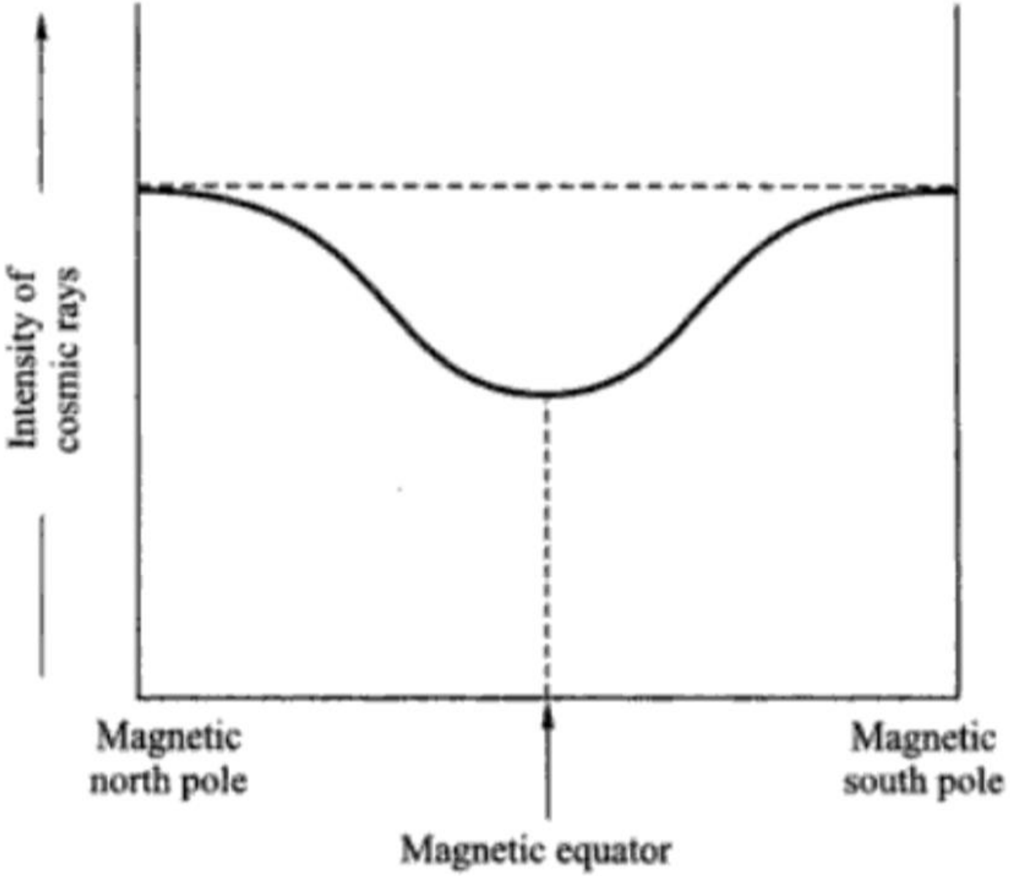


identifying primary CRs

-intensity of cosmic rays is smaller at the equator

-B-field deflecting them → they are charged!



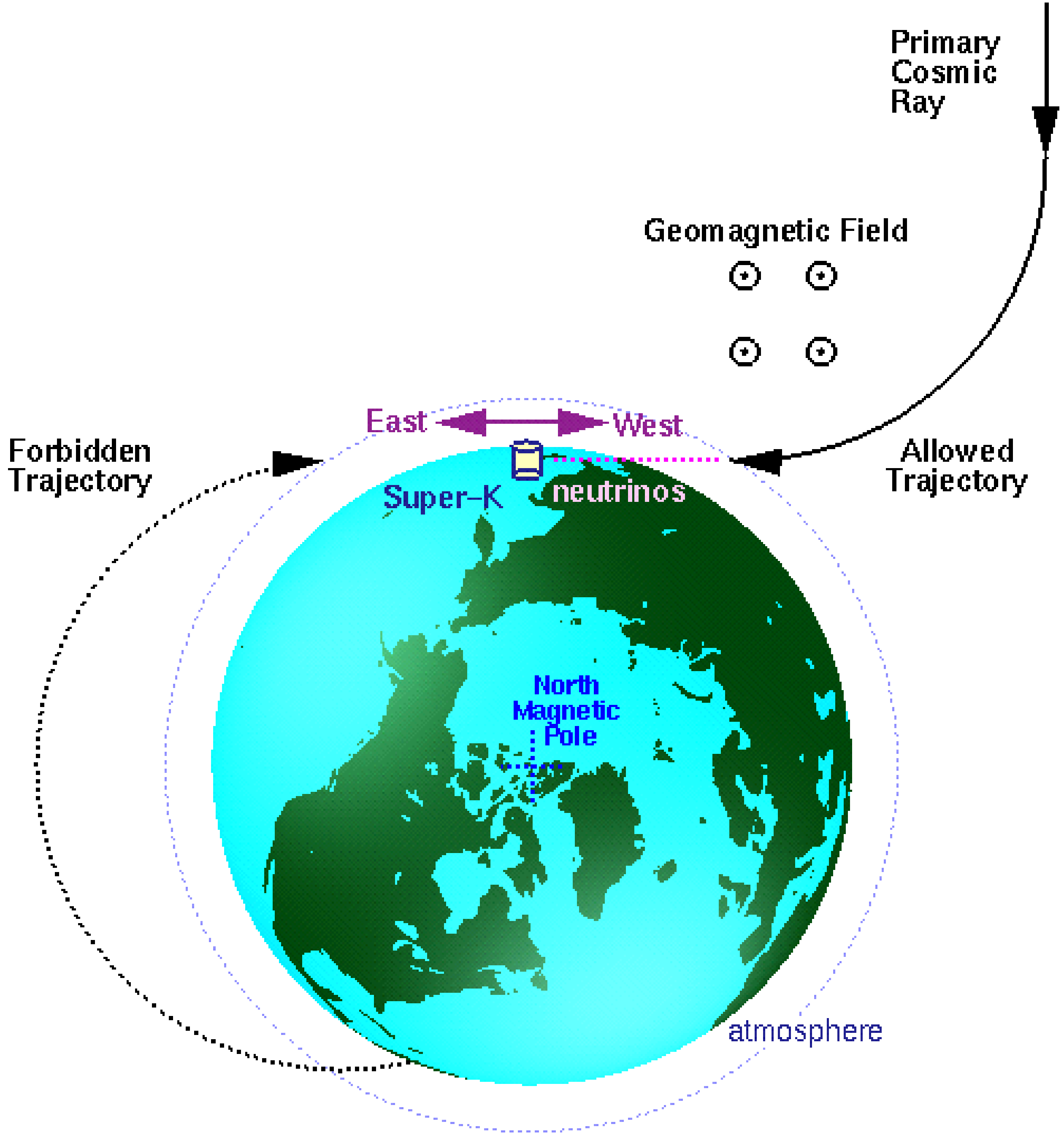


positively charged CRs

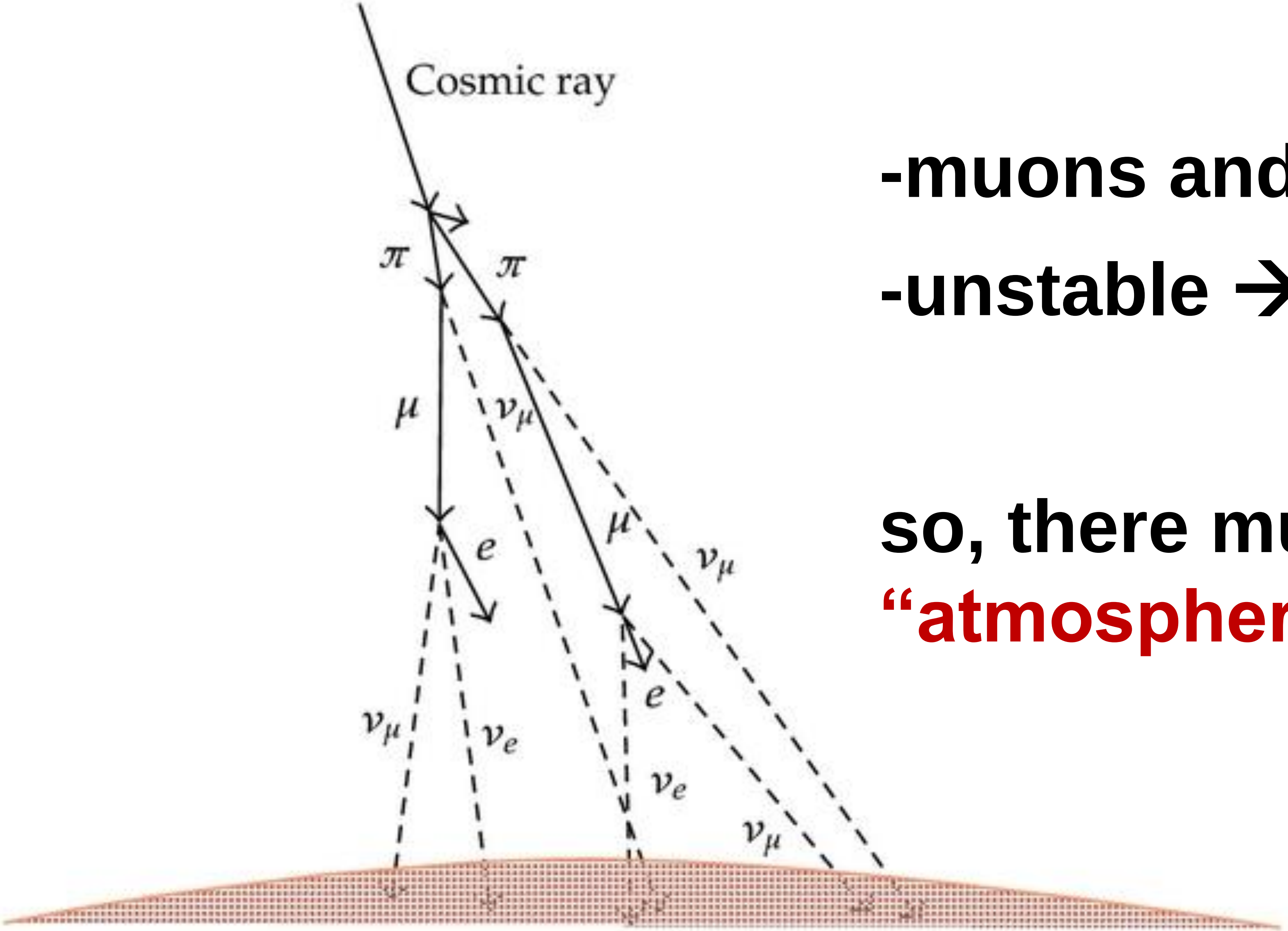
-in 1930 Rossi proposed a charge-induced asymmetry in arrival directions

-Earth shadows trajectories → more particles from west compared to east

-most CRs are positively charged → protons & nuclei



consequences of CR interactions



-muons and pions are produced

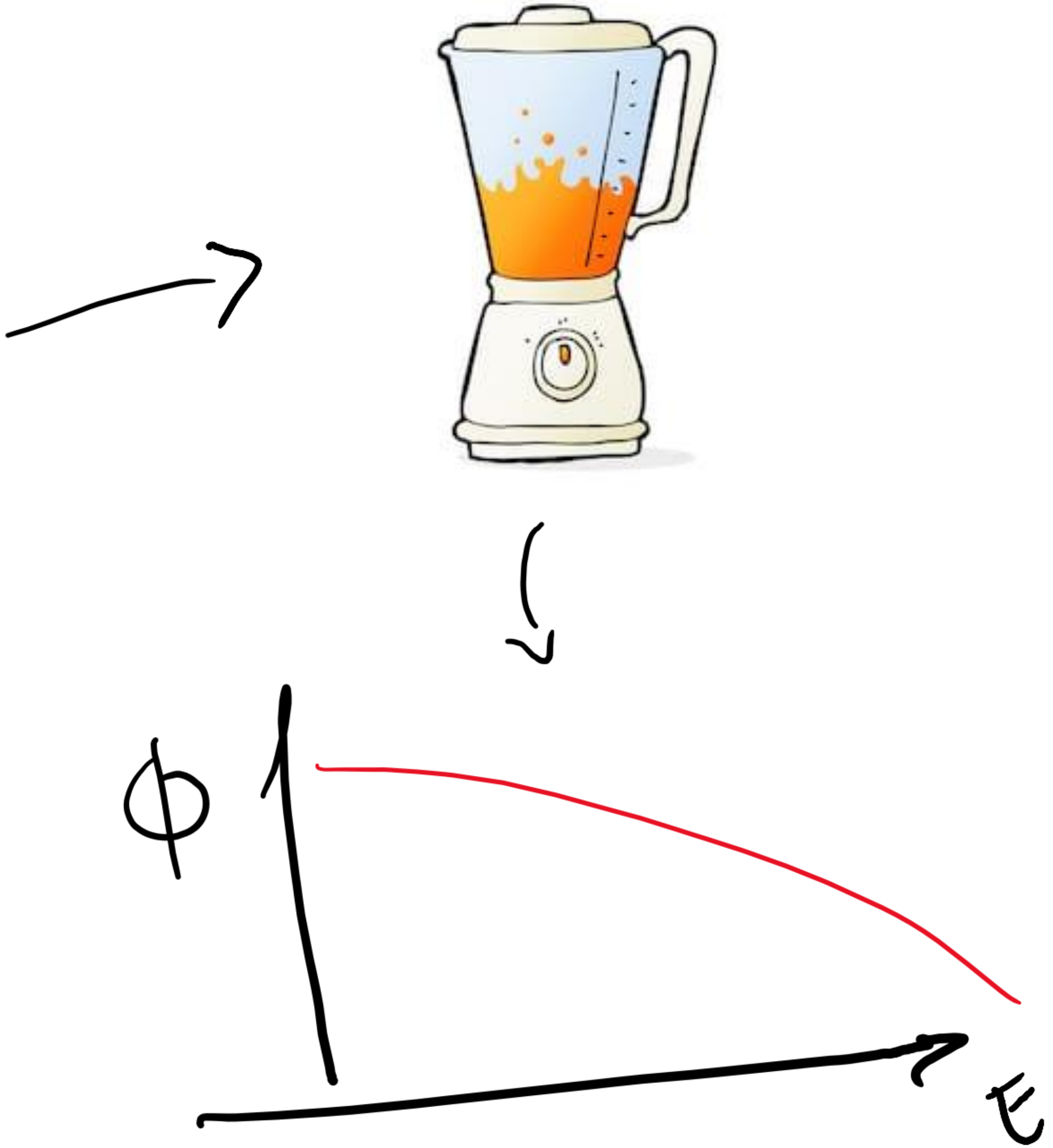
-unstable → decay → neutrinos

so, there must be an "atmospheric neutrino" flux

modeling the atmospheric neutrino flux

calculation needs

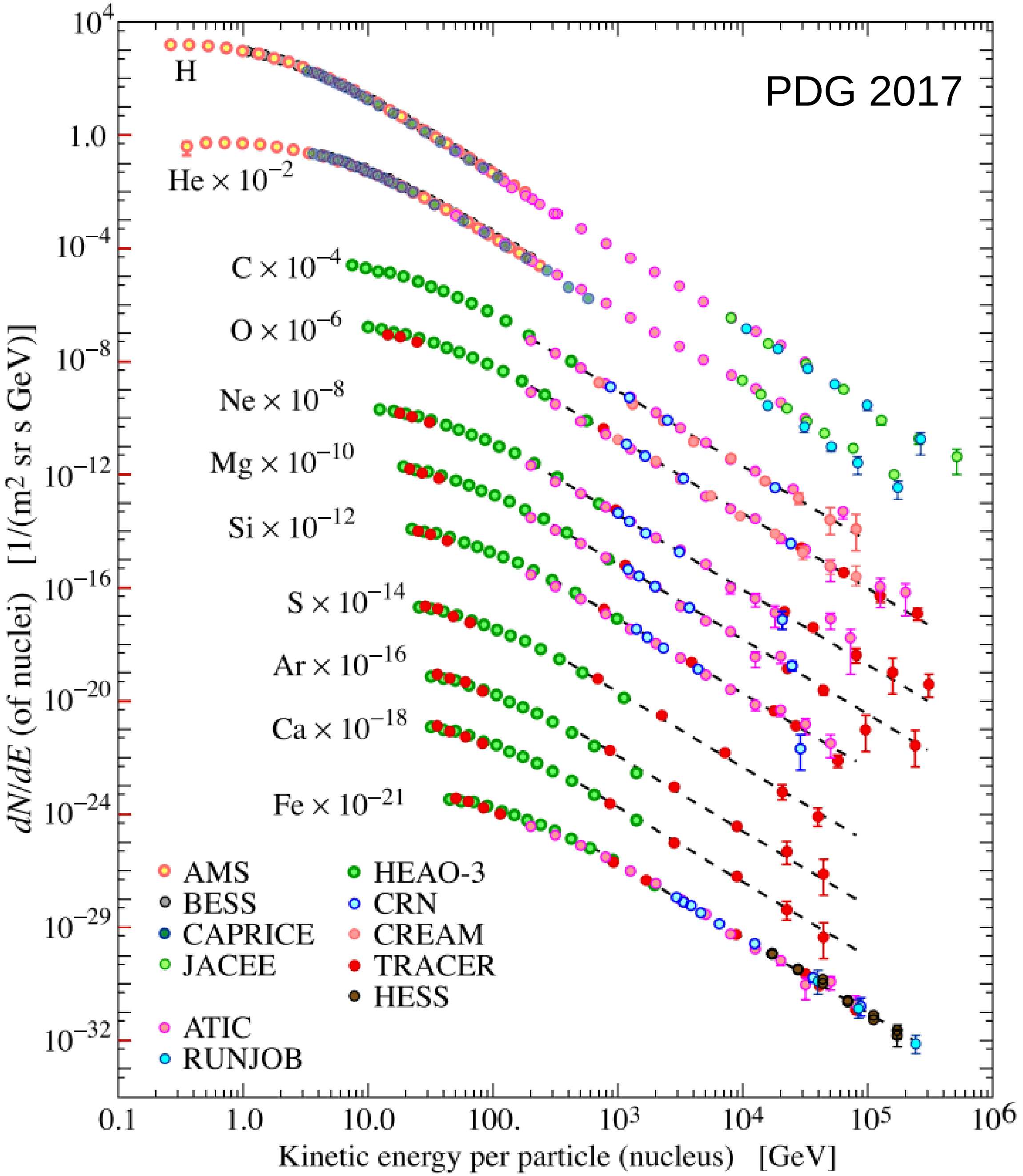
- **-cosmic ray flux**
- **-atmospheric density**
- **-hadronic interactions**
- **-model of weak decays**



cosmic ray flux

-many **new measurements** in last years

-extreme precision from **AMS-II, CALET and DAMPE**

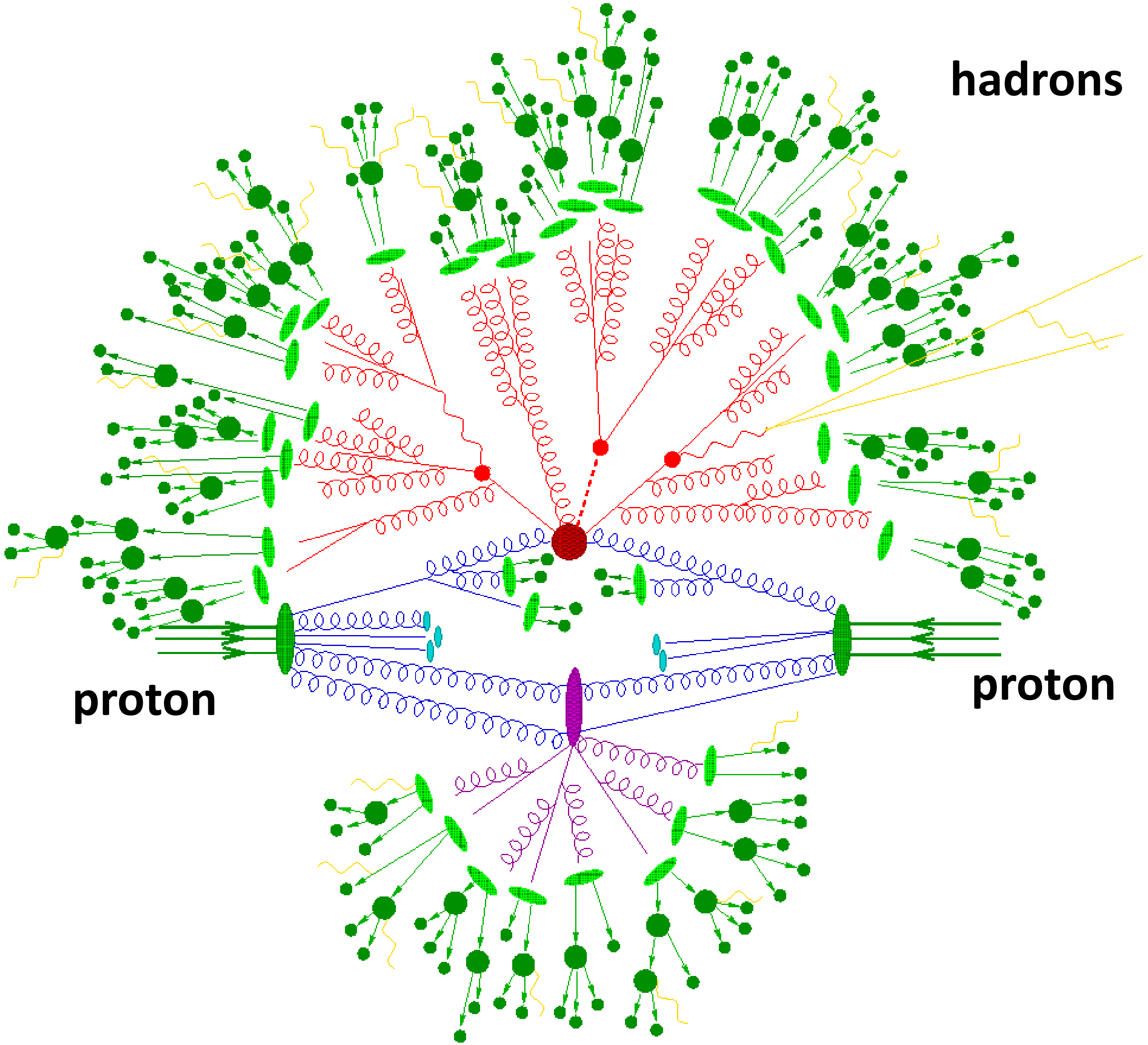


hadronic interactions

-messy interactions

-no full first-principle calculations

-use MC generators that mix phenomenology and calculations



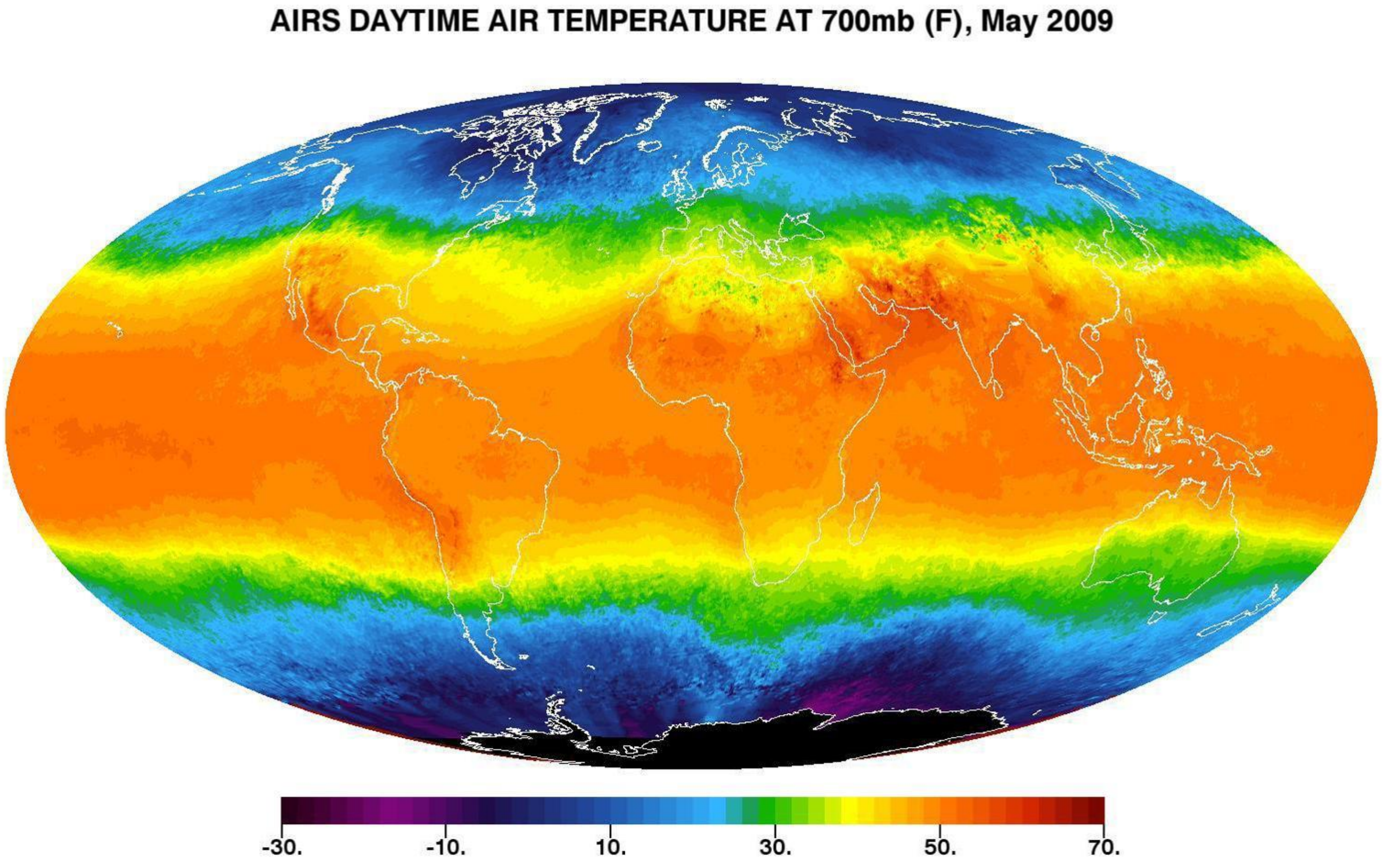
atmospheric density

-model or direct measurement

-using satellite data

AIRS

NRLMSIS-E-00



computation scheme options

a) analytically approx. cascade equations

b) numerically solving the equations

$$\frac{\mathrm{d}\Phi_h(E,X)}{\mathrm{d}X} = -\frac{\Phi_h(E,X)}{\lambda_{\mathrm{int},h}(E)} \quad \text{Interactions with air}$$

$$-\frac{\Phi_h(E,X)}{\lambda_{\mathrm{dec},h}(E,X)} \quad \text{Decays}$$

$$-\frac{\partial}{\partial E}(\mu(E)\Phi_h(E,X)) \quad \text{Continuous losses}$$

$$+\sum_k \int_E^\infty \mathrm{d}E_k \frac{\mathrm{d}N_{k(E_k)\to h(E)}}{\mathrm{d}E} \frac{\Phi_k(E_k,X)}{\lambda_{\mathrm{int},k}(E_k)} \quad \text{Re-injection from interactions}$$

$$+\sum_k \int_E^\infty \mathrm{d}E_k \frac{\mathrm{d}N^{\mathrm{dec}}_{k(E_k)\to h(E)}}{\mathrm{d}E} \frac{\Phi_k(E_k,X)}{\lambda_{\mathrm{dec},k}(E_k,X)} \quad \text{Re-injection from decays}$$

See A. Fedynitch's talk at ISAPP 2018
for a more complete discussion

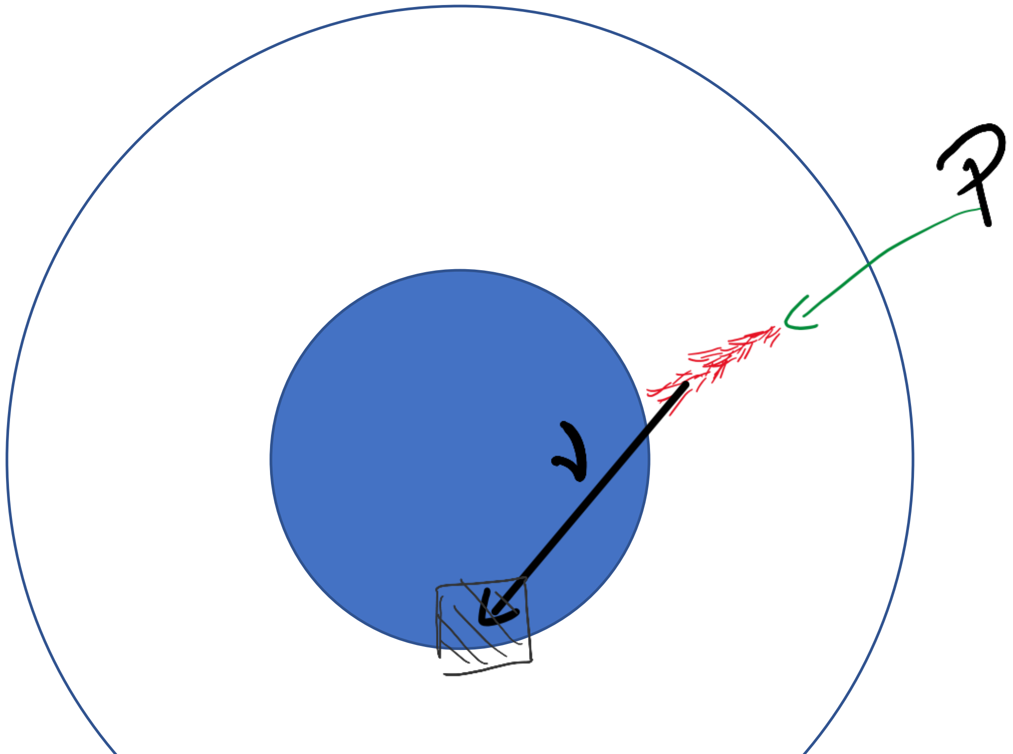
$$X(h_0) = \int_0^{h_0} \mathrm{d}\ell\ \rho_{\mathrm{air}}(\ell)$$

computation scheme options

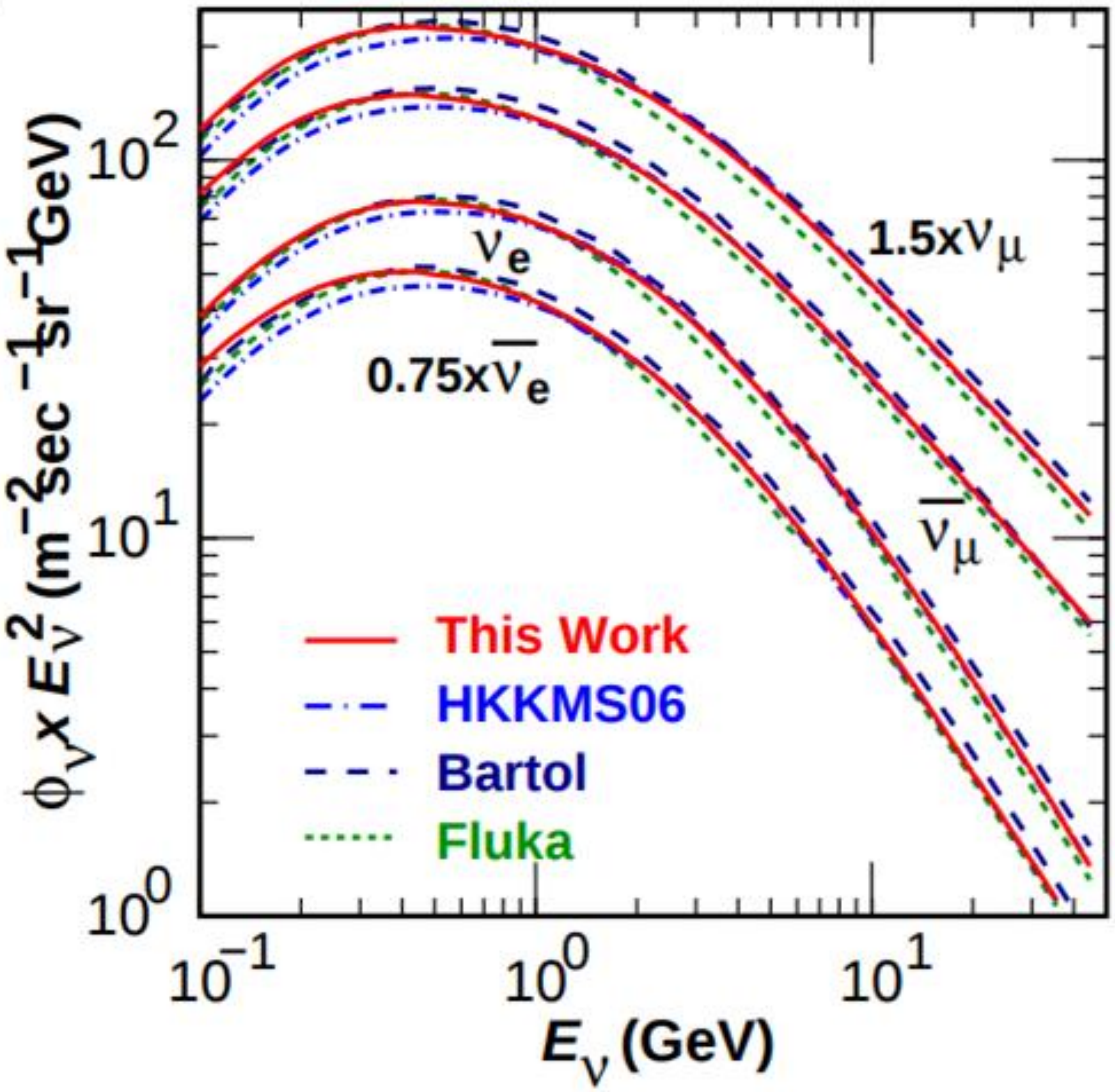
a) analytically approx. cascade equations

b) numerically solving the equations

c) MC of CR injected far from Earth



predicted flux



M. Honda et al., Phys. Rev. D70, 043008 (2004)

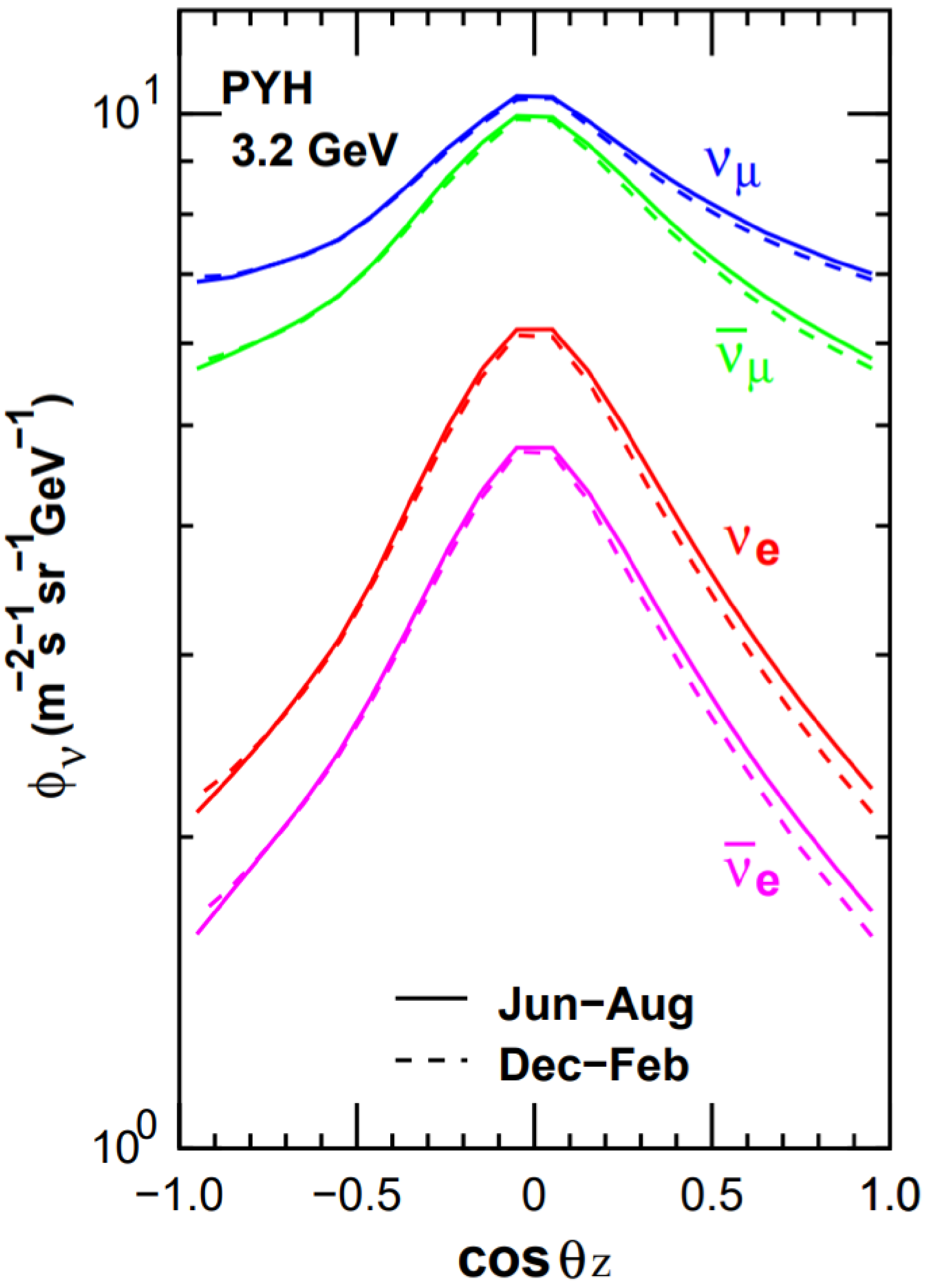
-covers a wide energy range

-contains four different particles

-dominated by muon neutrinos

-approximately top/down symmetric

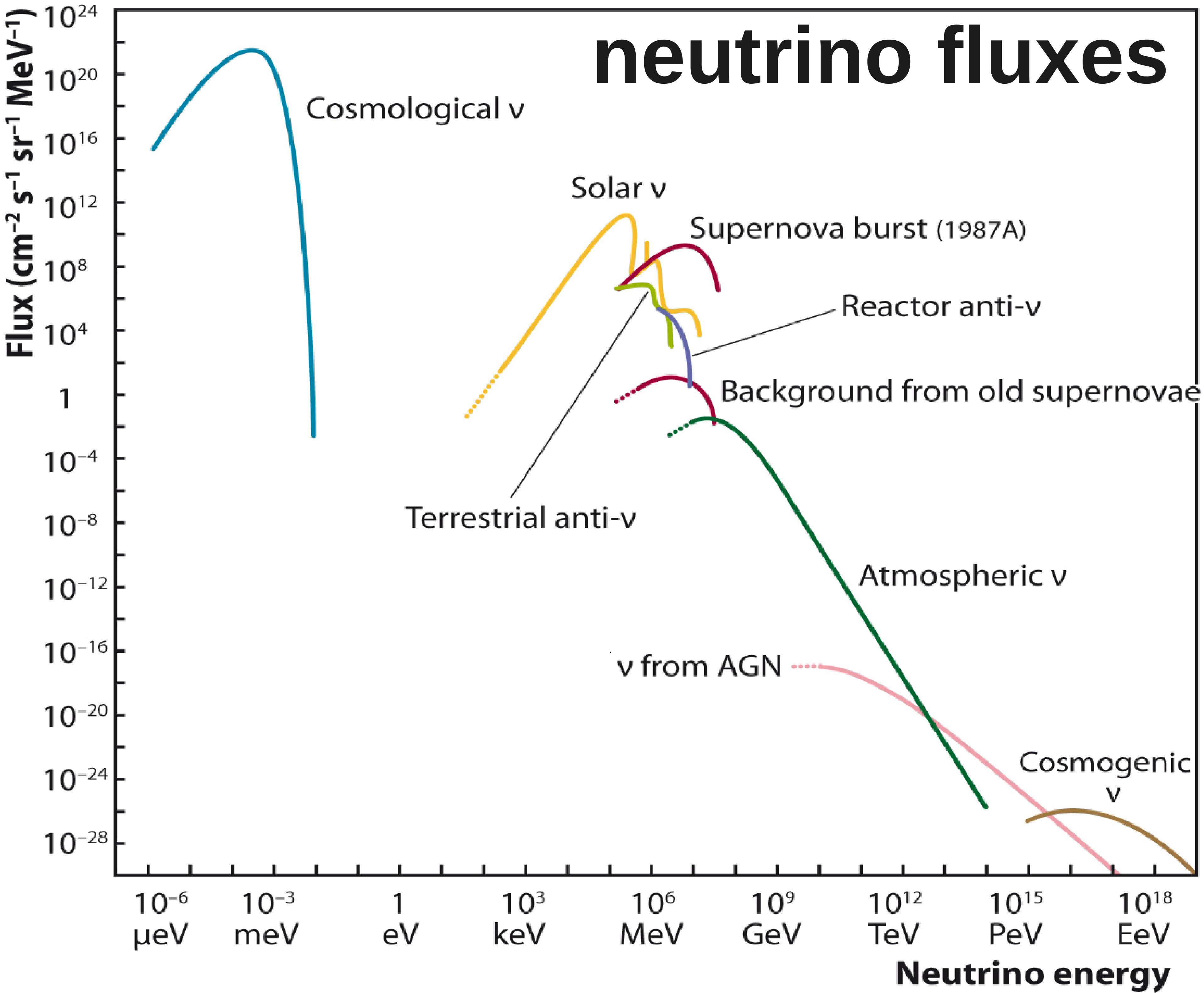
predicted flux



M. Honda et al., Phys. Rev. D70, 043008 (2004)

- -covers a **wide energy** range
- -contains **four** different particles
- -dominated by **muon** neutrinos
- -approximately top/down **symmetric**

neutrino fluxes

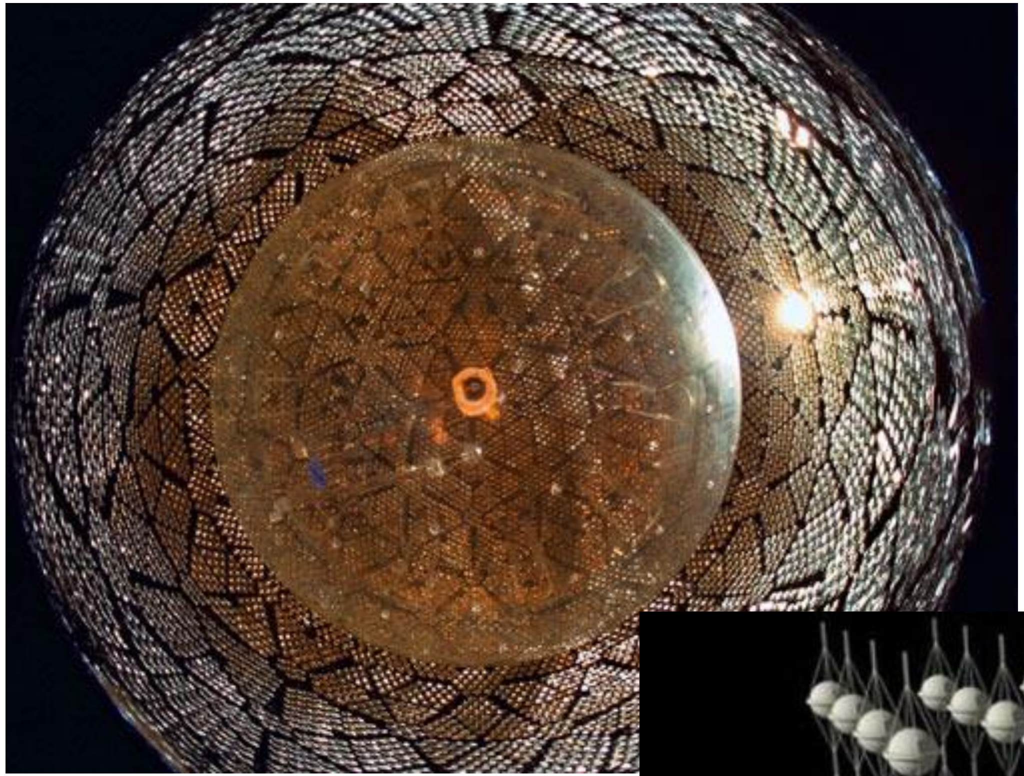


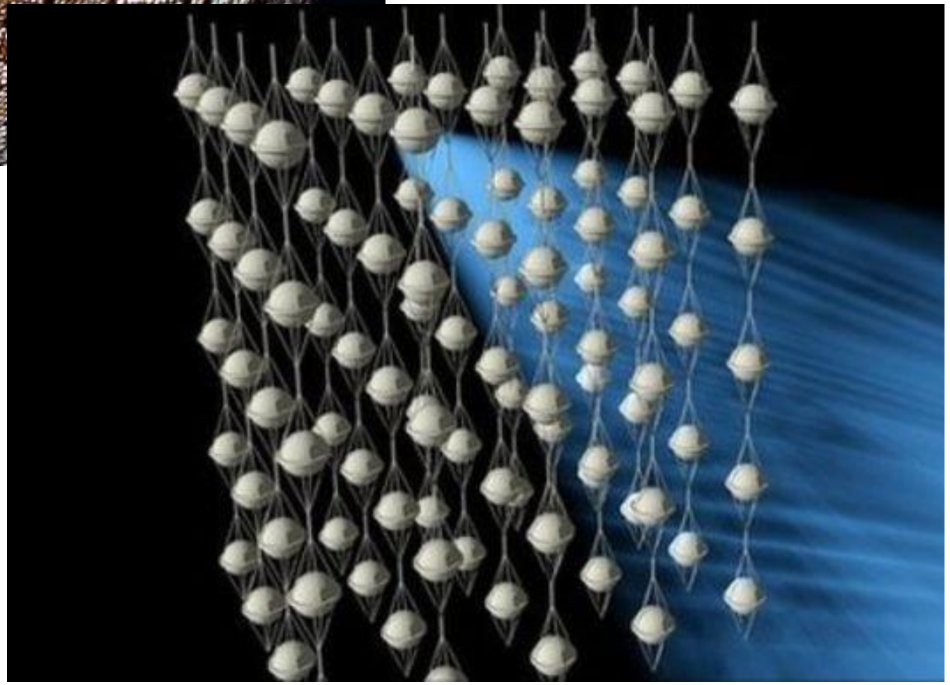
atmospheric neutrino detection

first ideas

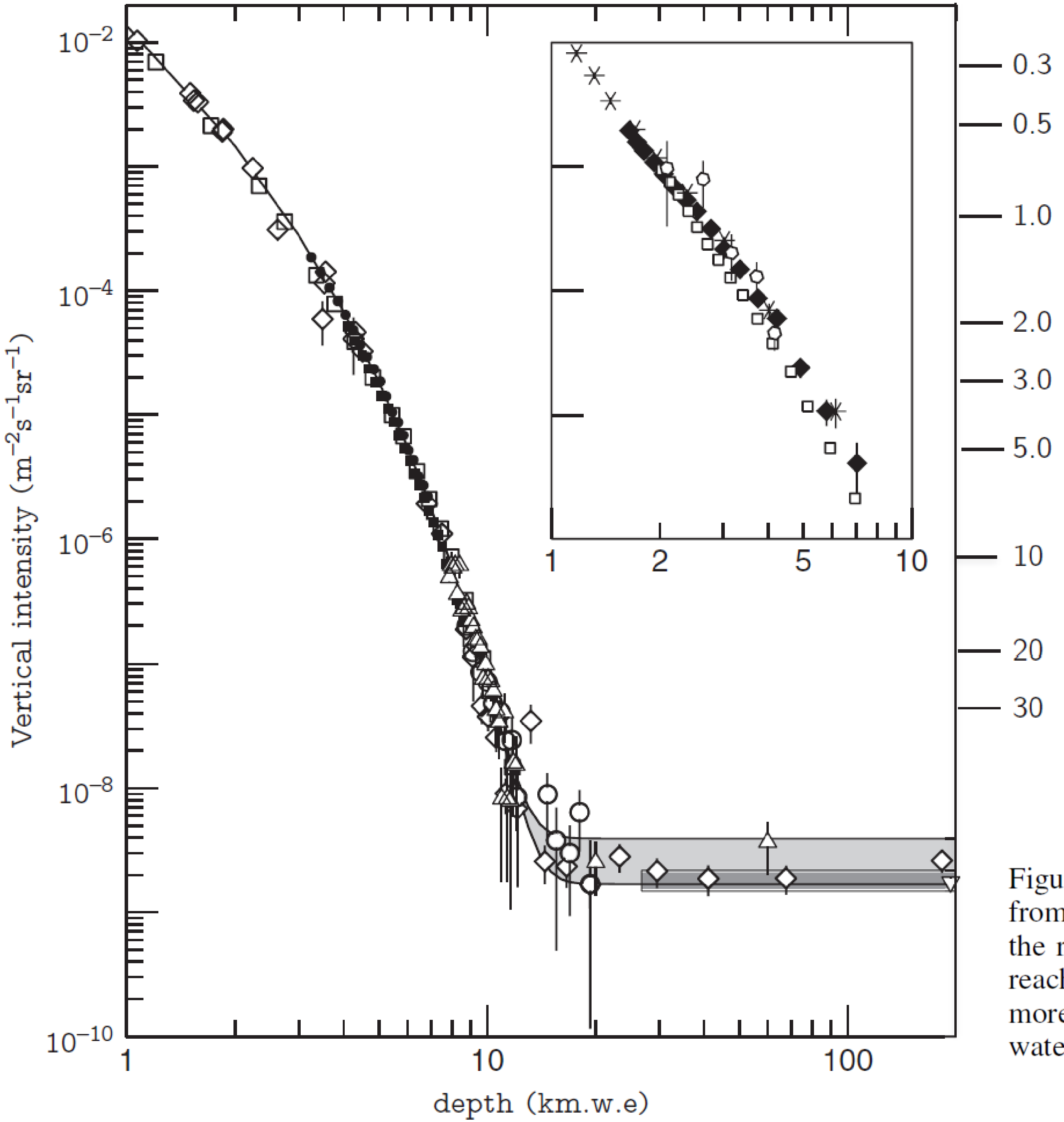
-Greisen (1960) proposed a volume of water surrounded by Cherenkov counters

-Markov (1960) proposed installing detectors deep in a lake or the sea





first ideas



key point:
deep underground
to avoid muon background

Figure 8.2 Relation between muon intensity and depth underground, adapted from Review of Particle Physics [10]. The left axis is the vertical intensity, while the right axis shows the minimum muon energy (TeV) at production needed to reach the depth corresponding to a given intensity. At depths of 10 km.w.e. and more neutrino-induced muons dominate. The inset shows measurements made in water or ice.

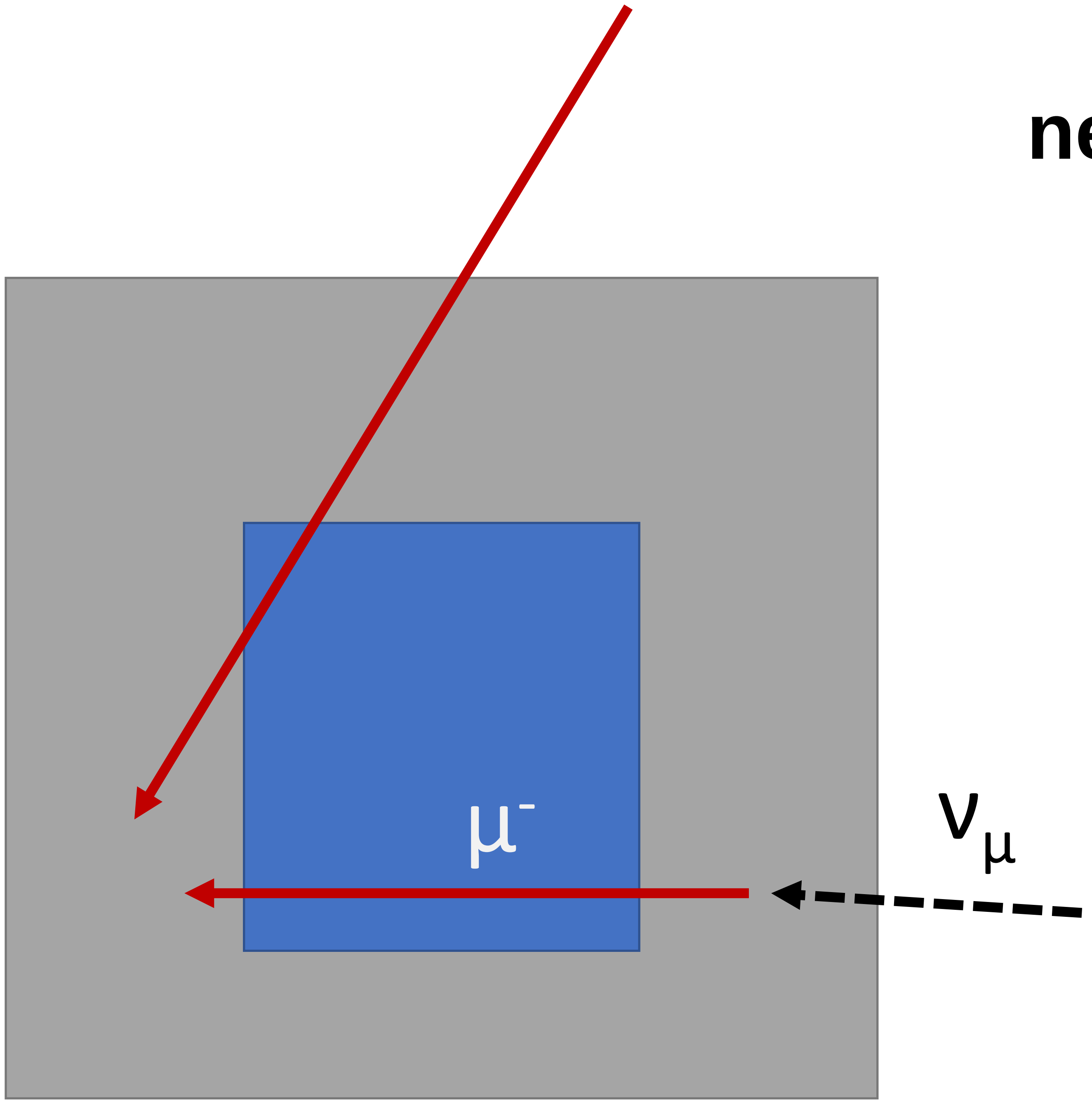
Gaisser, Cosmic Rays and Particle Physics (2016)

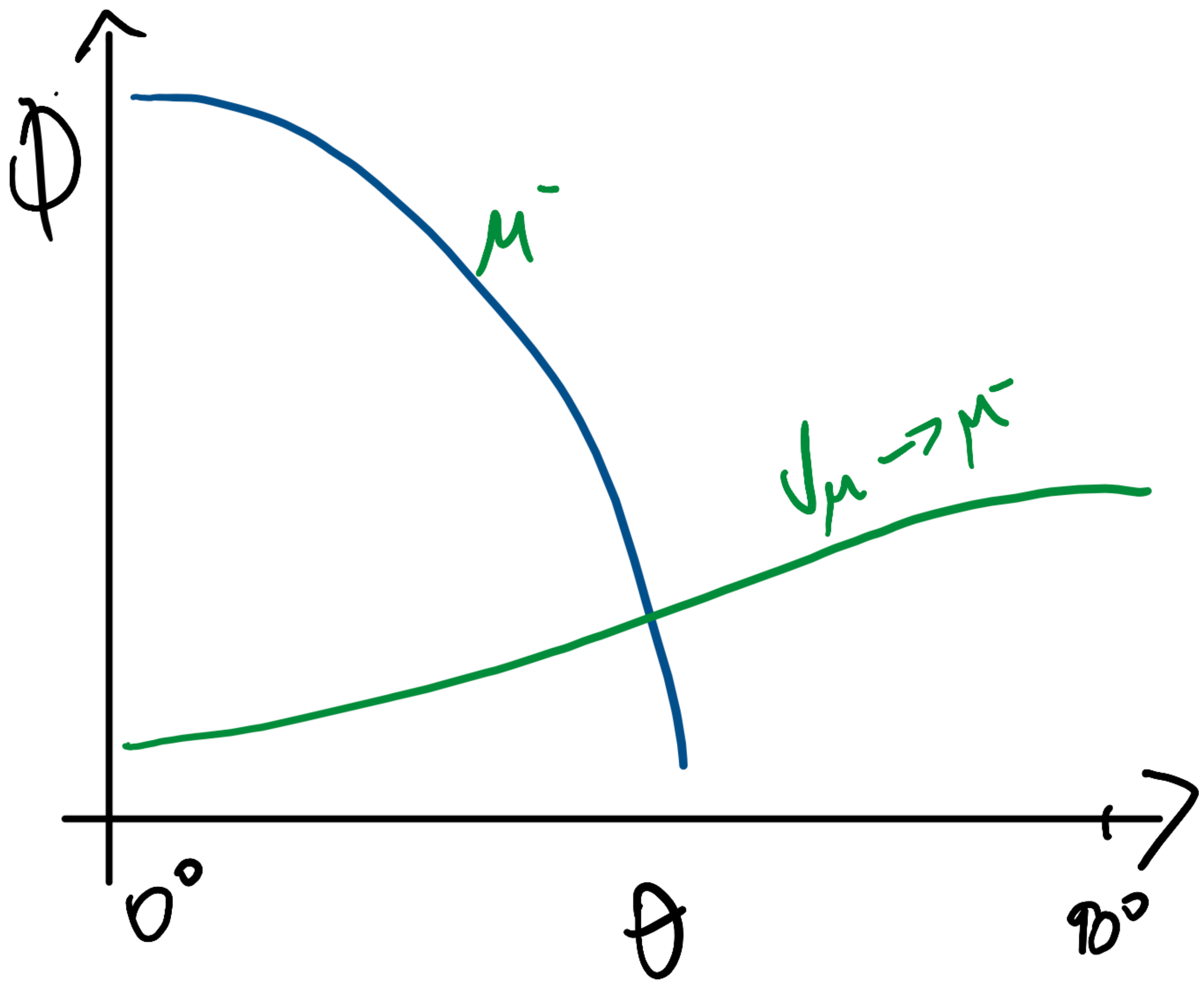
discovery of atmospheric neutrinos (1965-68)

Kolar Gold Fields detector

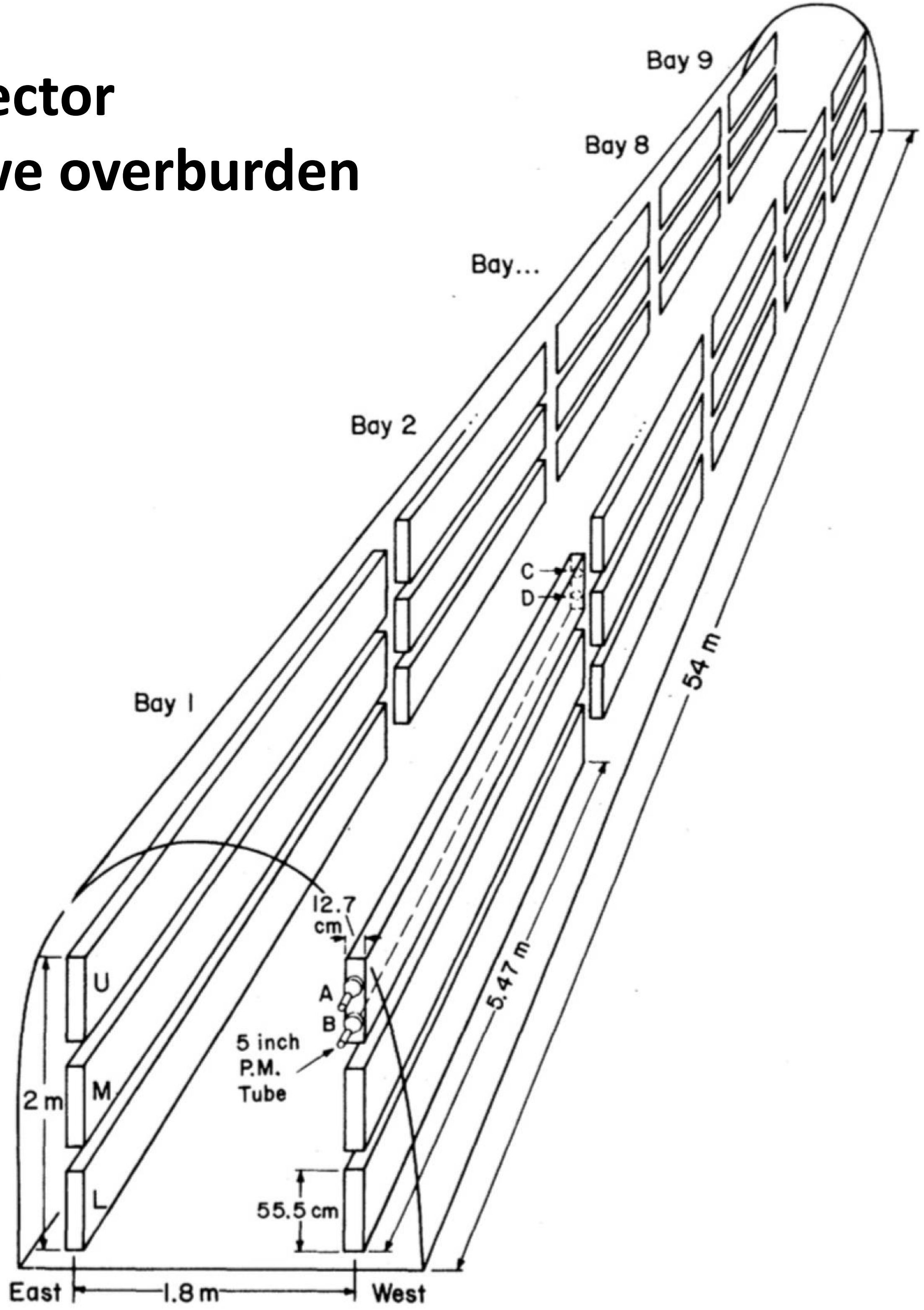
Case Western Irvine/South Africa Neutrino Detector

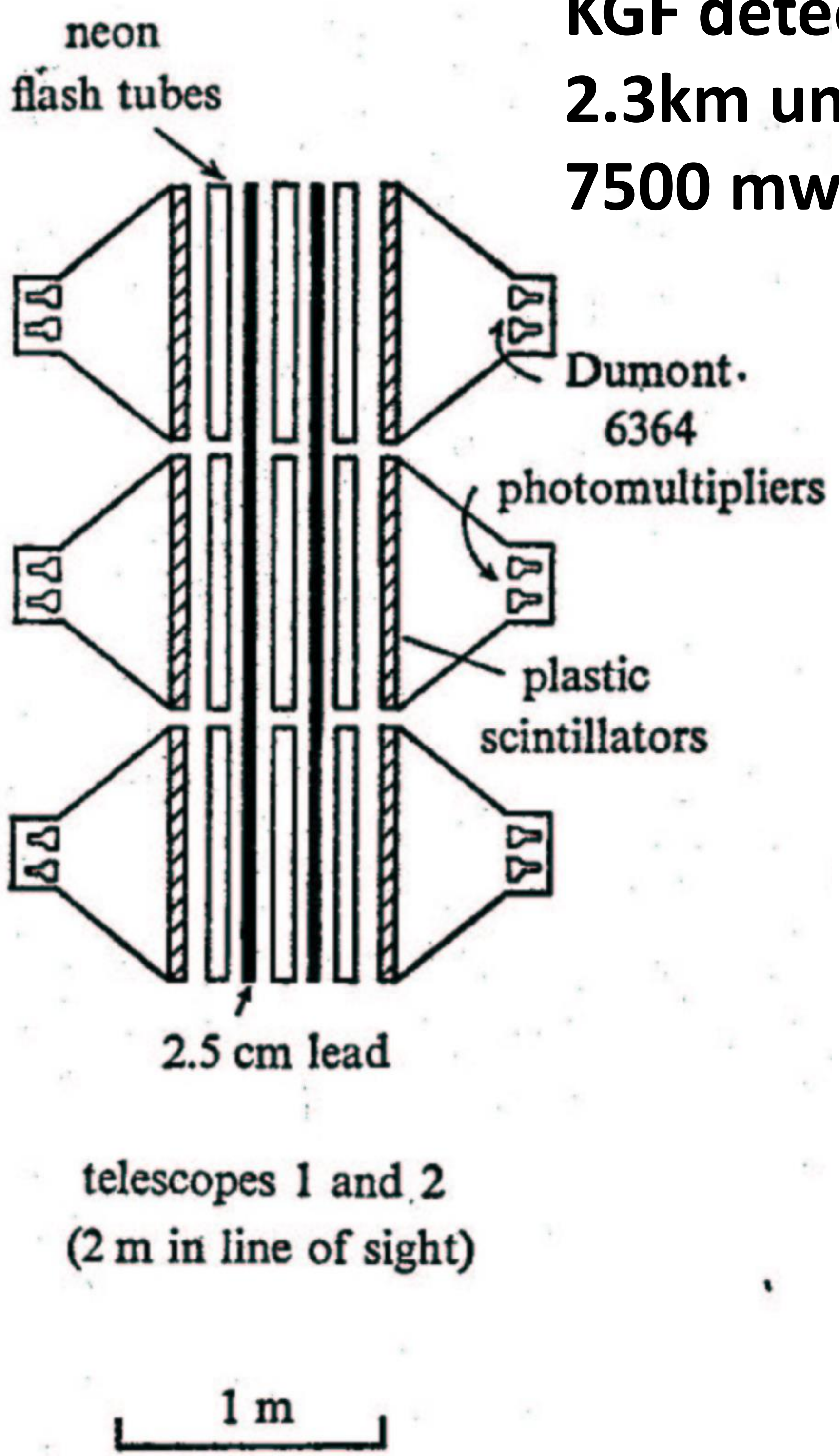
neutrino-induced muons





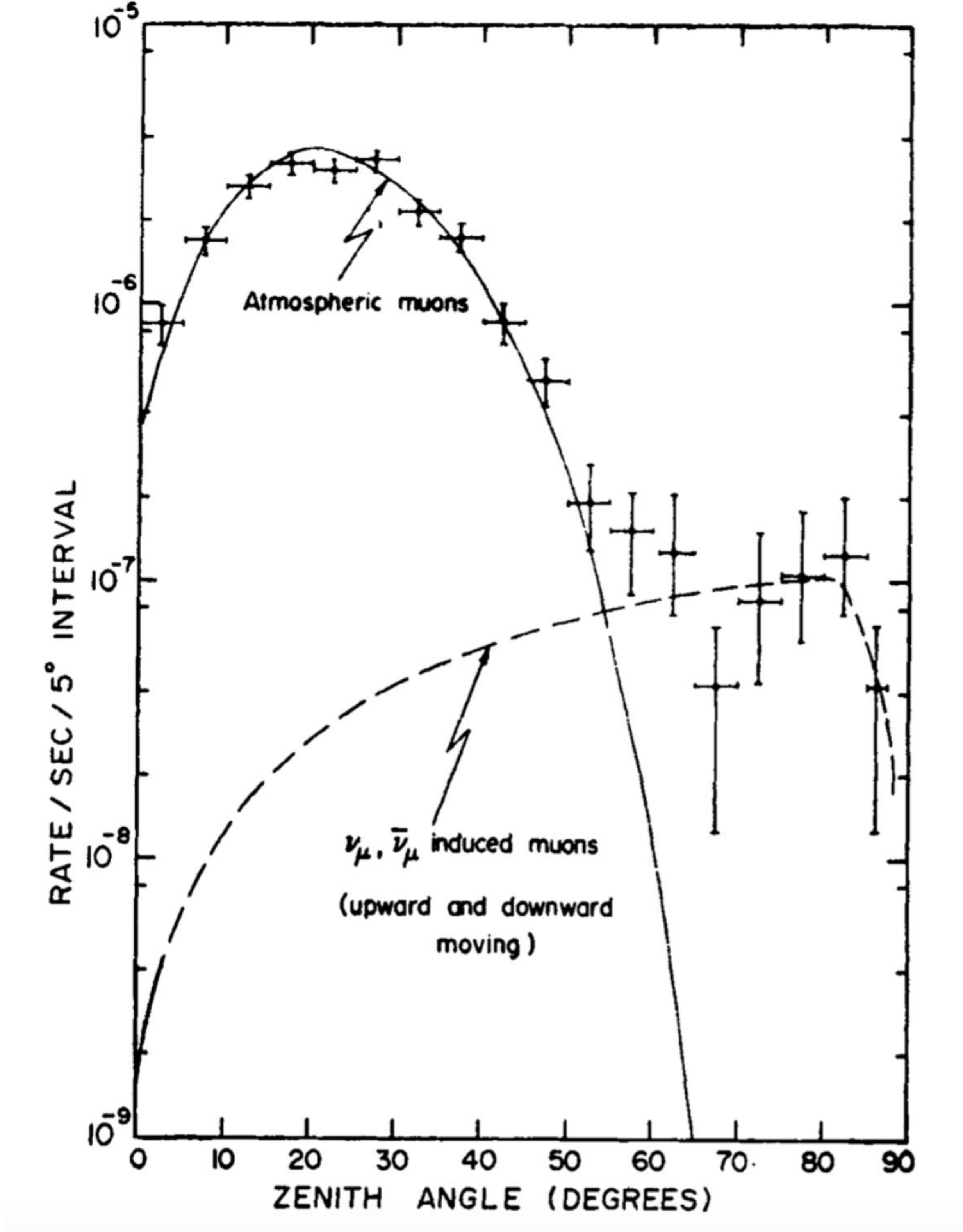
CWI detector
8800 mwe overburden

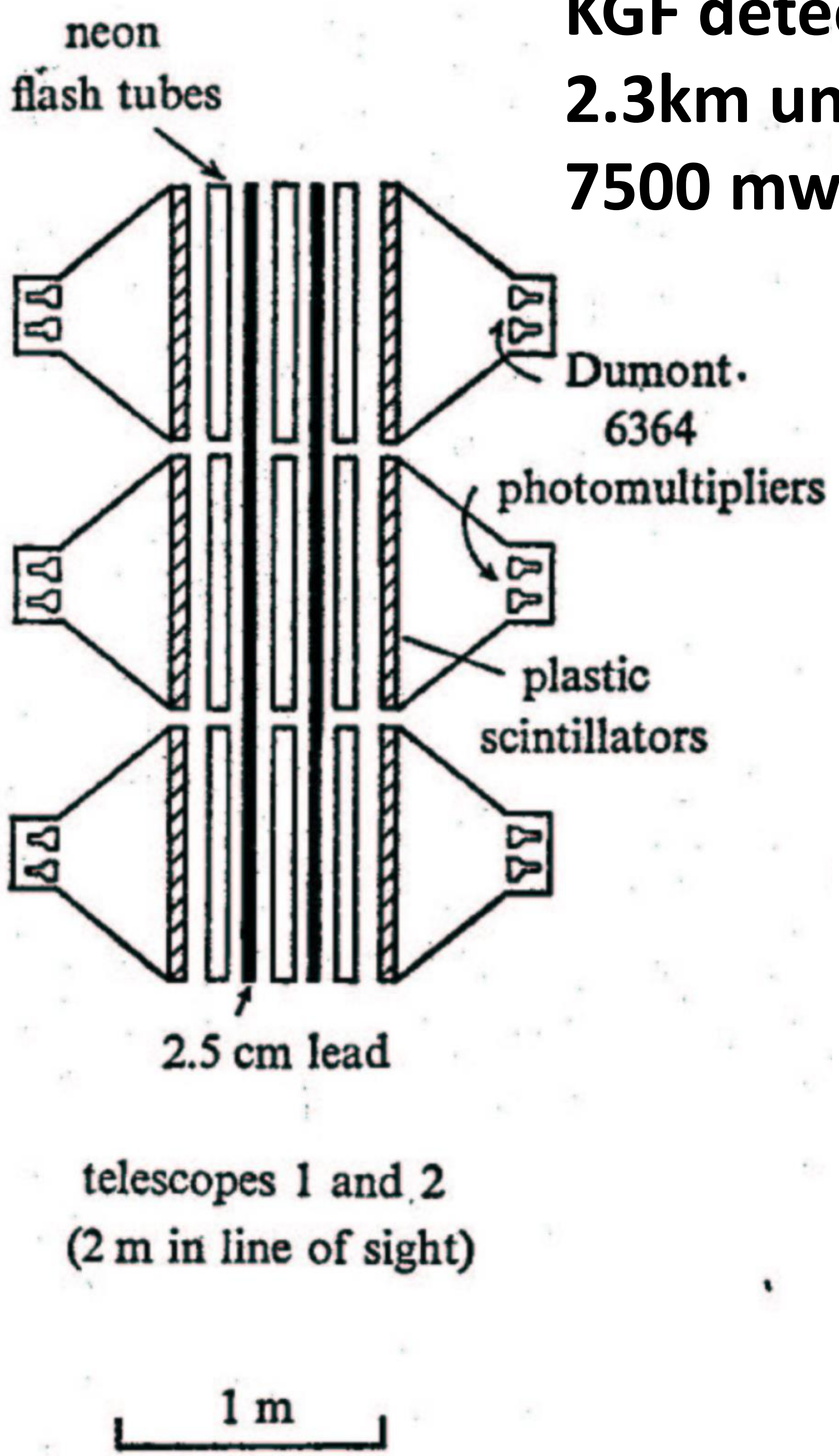




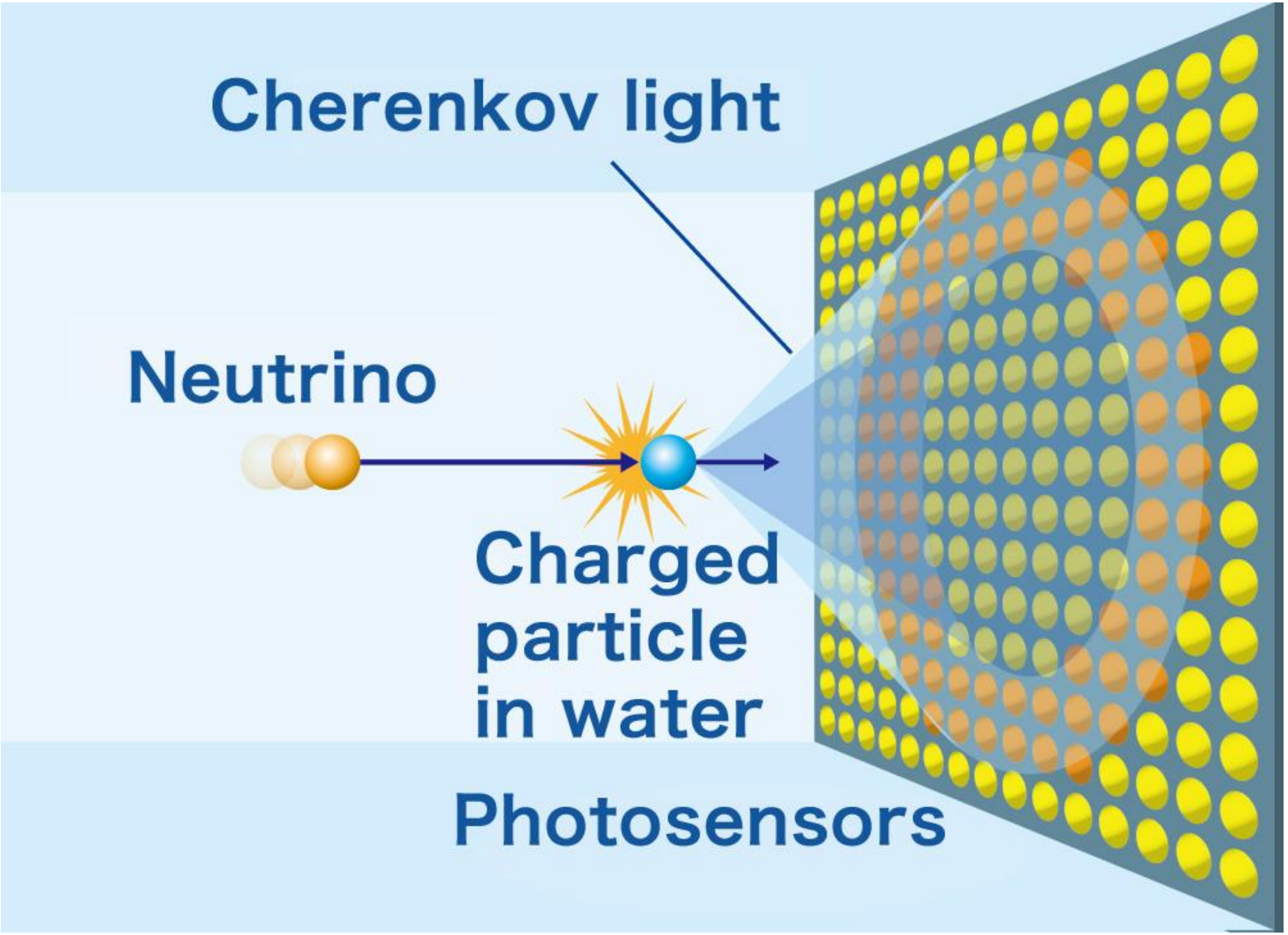
KGF detector
2.3km under rock
7500 mwe

KGF detector
2.3km under rock
7500 mwe





Cherenkov detectors



tracking calorimeters

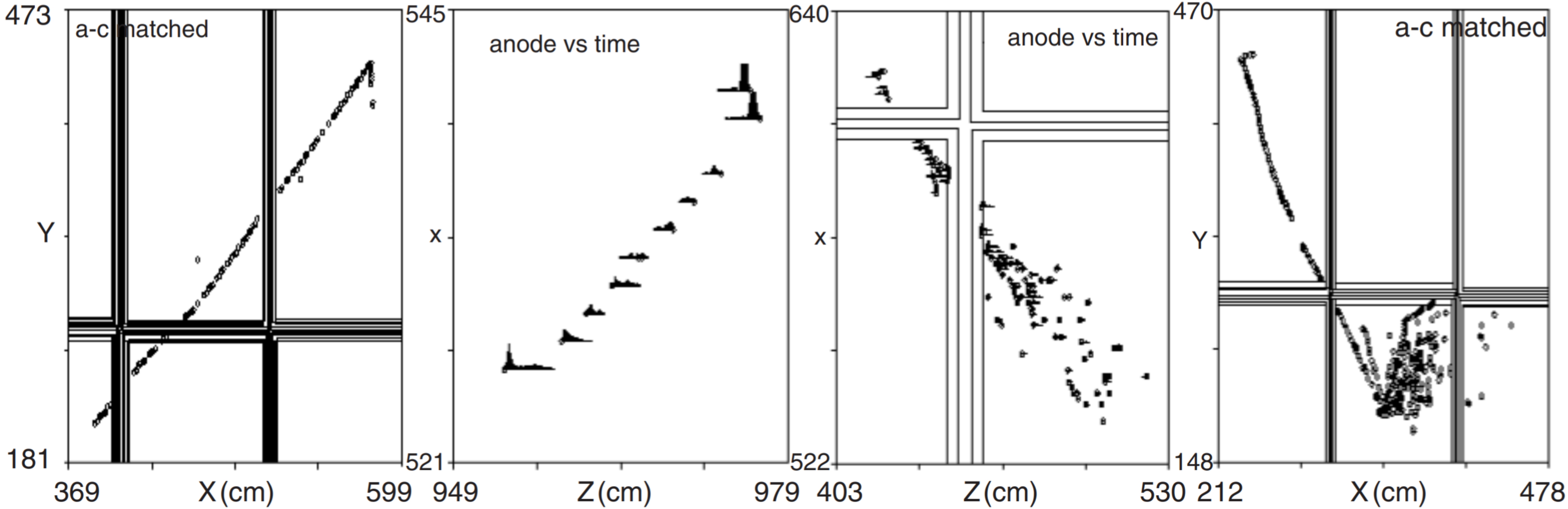
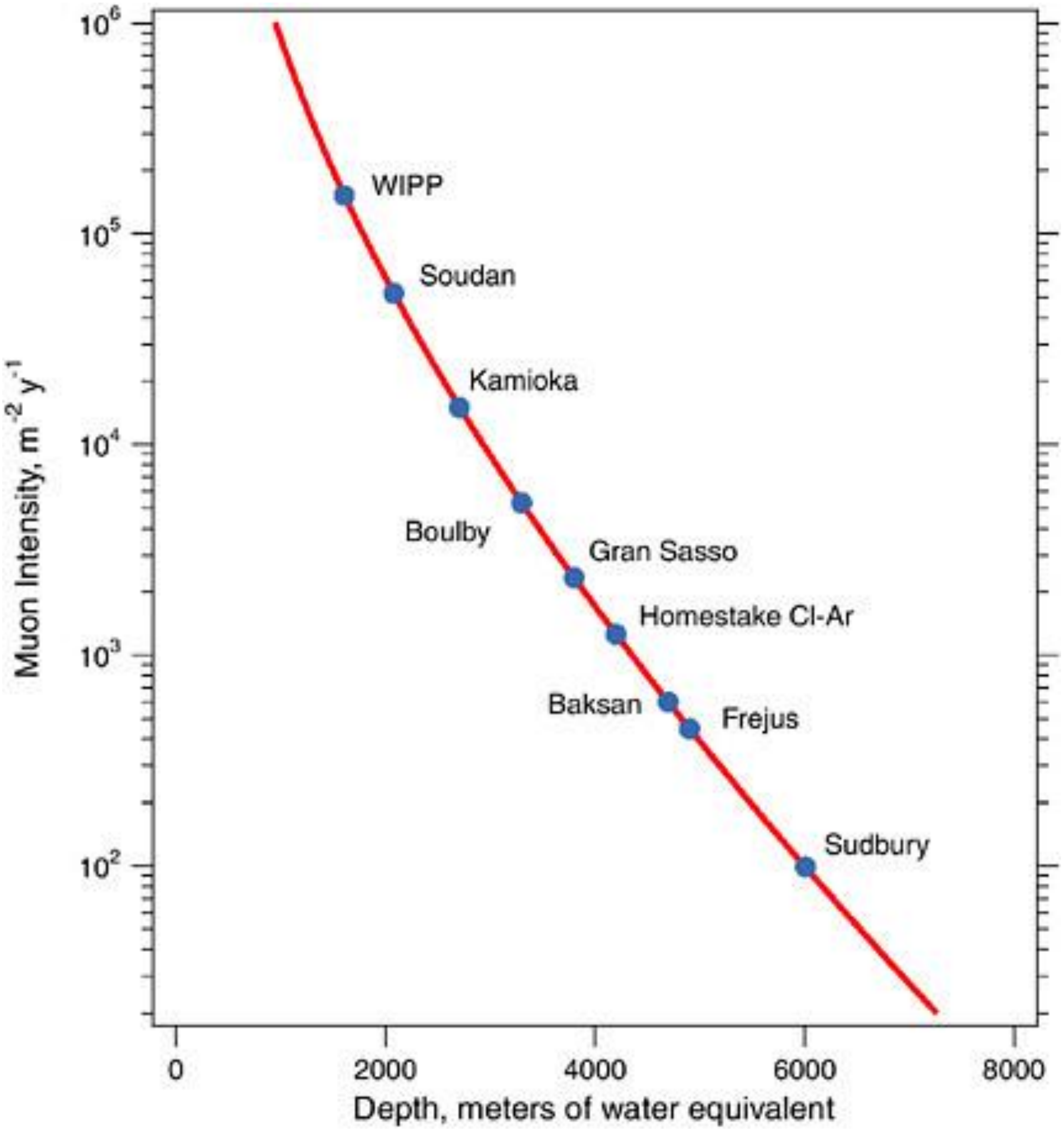


Figure 9. Example event displays from the Soudan-2 detector, showing the long track from a muon and a shorter, more heavily ionizing track from a recoil proton.

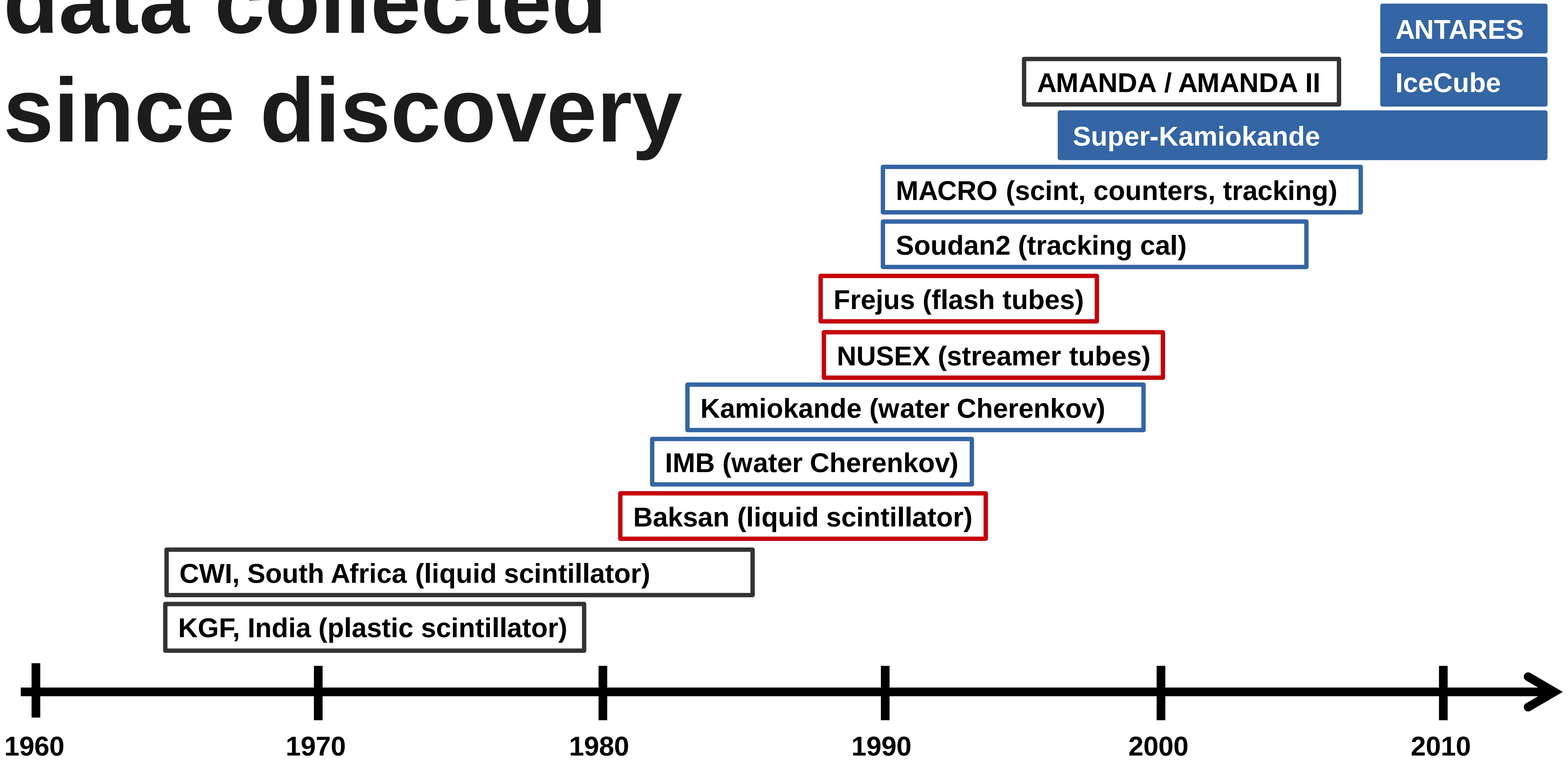
Kajita, New Journal of Physics 6 (2004) 194



again:

go **deep underground**

data collected since discovery



*take dates with caution – list is incomplete

on the early experiments

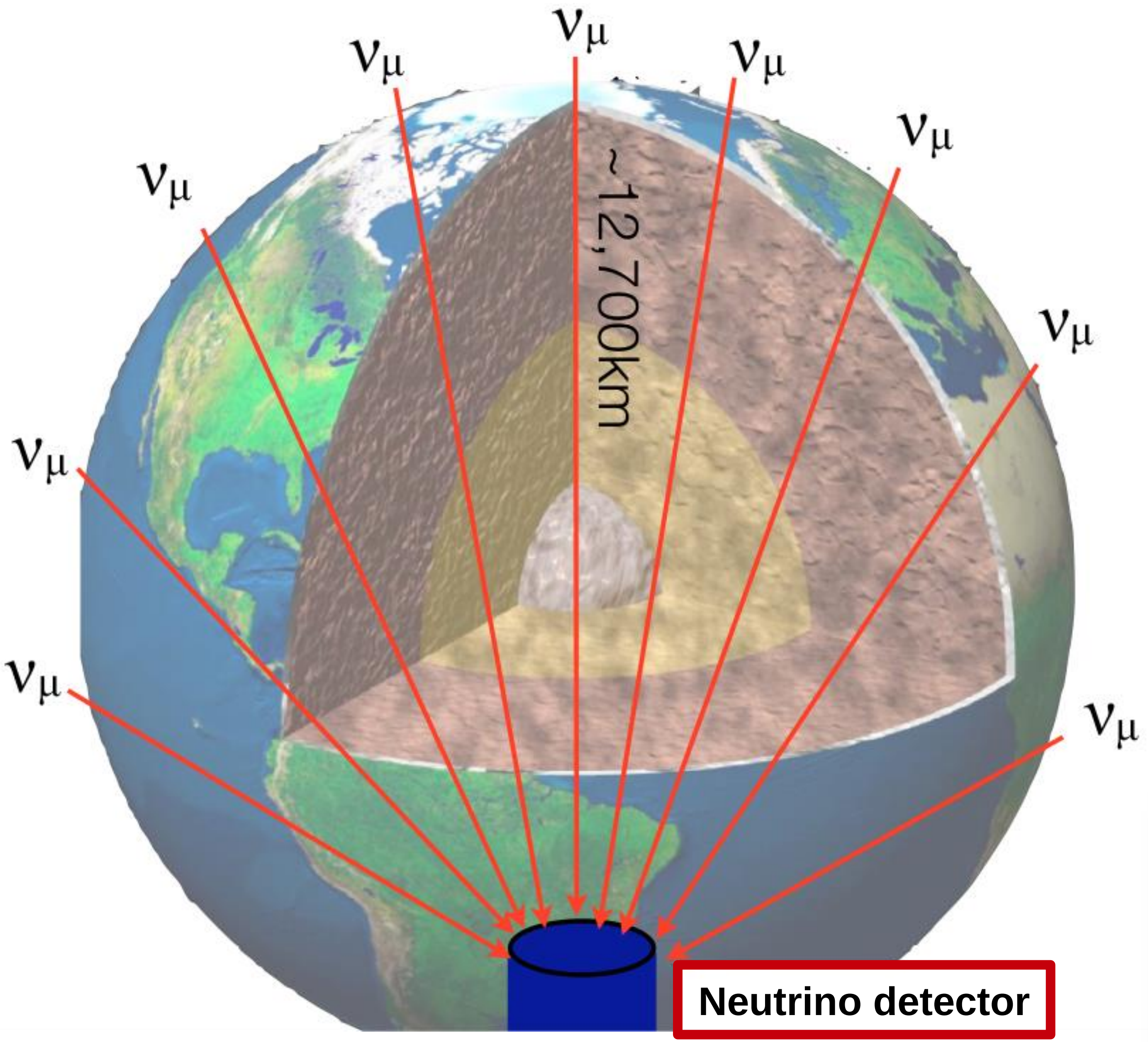
-motivated by the search for proton decay

-atmospheric neutrinos were not the goal

-but now we know a little more

physics motivation

why atmospherics?



Borrowed from T. DeYoung

direction → baseline

~10km - ~12,700km

different e^- density along paths

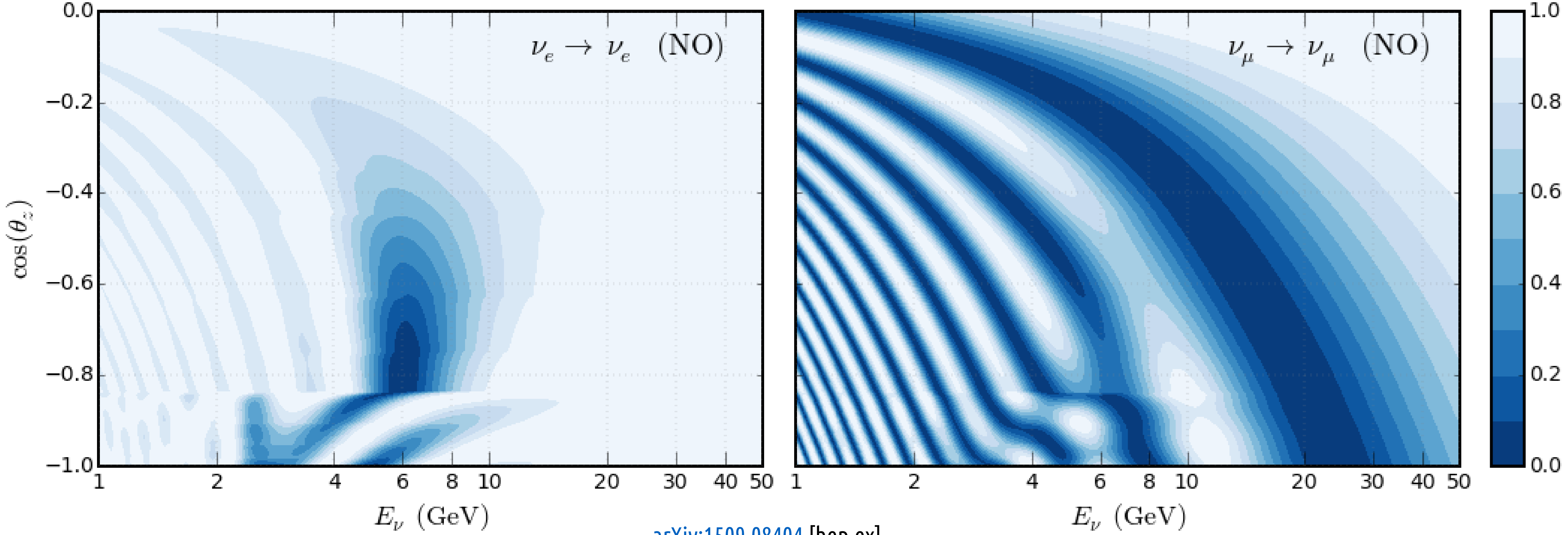
$$|\Delta m^2_{\text{large}}| \gg |\Delta m^2_{\text{small}}|$$

Relevant mass-splitting

$$P^{2\nu}_{\nu_\alpha \to \nu_\beta}(L, E) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2}{4E}L\right)$$

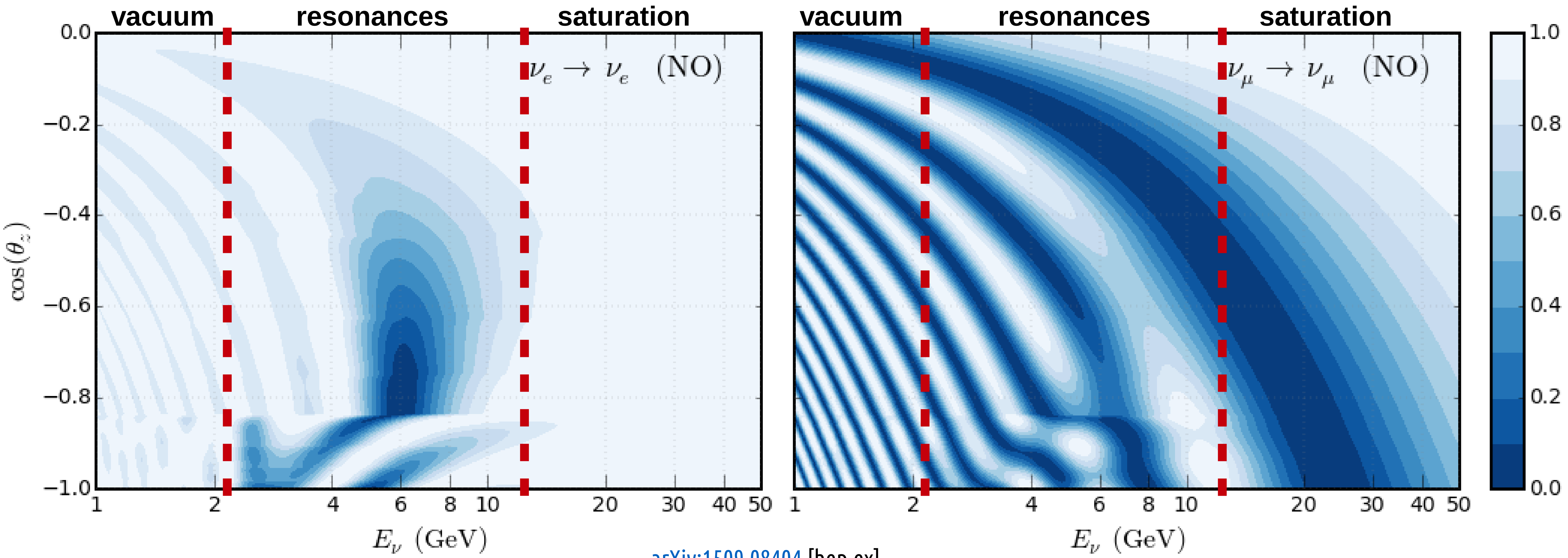
effective mixing angle

survival probabilities



arXiv:1509.08404 [hep-ex]

survival probabilities

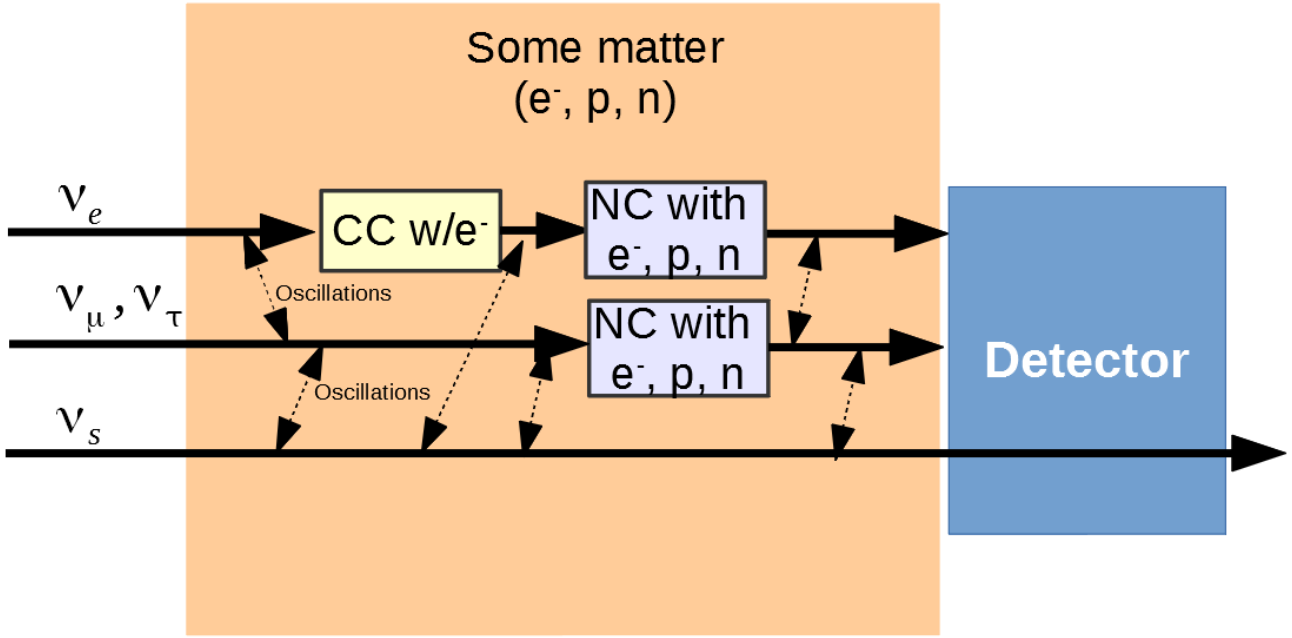


arXiv:1509.08404 [hep-ex]

vacuum: $|\Delta m^2_{32}|$ θ_{23} θ_{13} **resonance:** Δm^2_{32} **saturation:** $|\Delta m^2_{32}|$ θ_{23}

ν_τ appearance

exotic possibilities

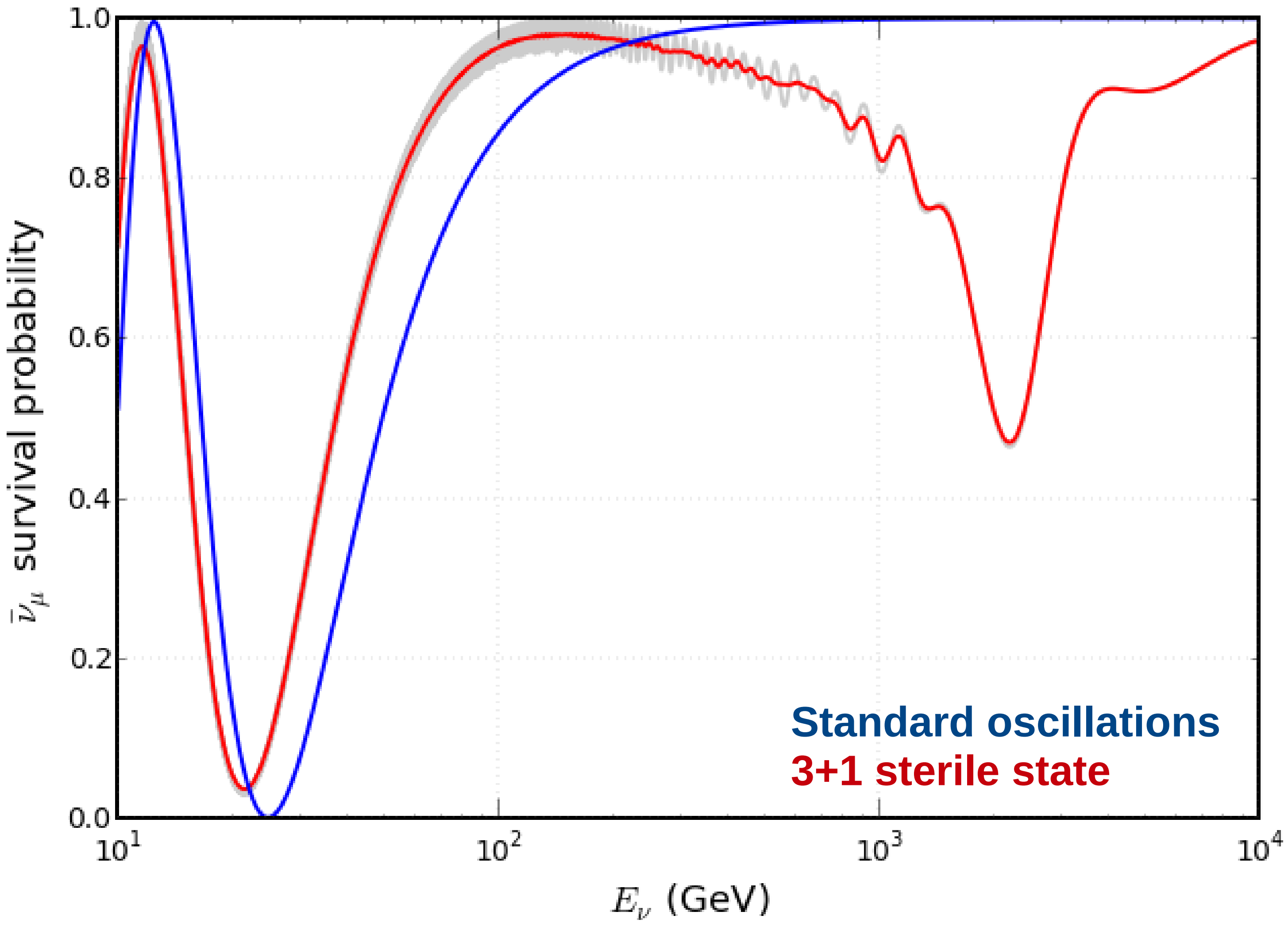


$$\tan 2\theta_M = \frac{\tan 2\theta}{1 - \frac{A_{CC}}{\Delta m^2 \cos 2\theta}}.$$

sterile neutrinos

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{bmatrix}$$

exotic possibilities



for cosθ = -1 (crossing all of the Earth)

sterile neutrinos

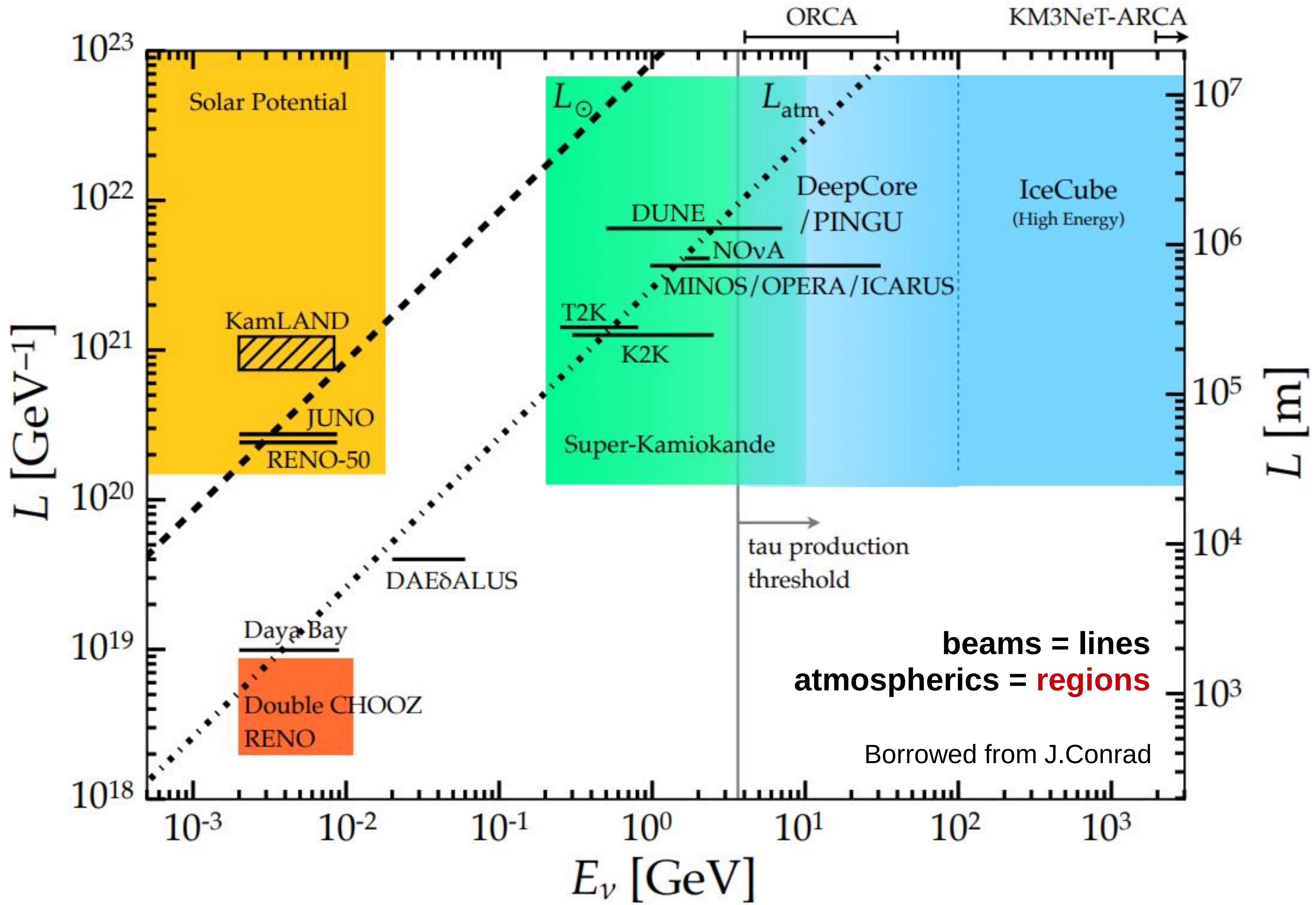
-modify std. osc. effect

-add osc. at E ~ TeV

$$\sin^2\left(\frac{\Delta m^2}{4E}L\right)$$

- modify $P(\nu_{\mu} \rightarrow \nu_{\mu})$

wide baseline, energy range

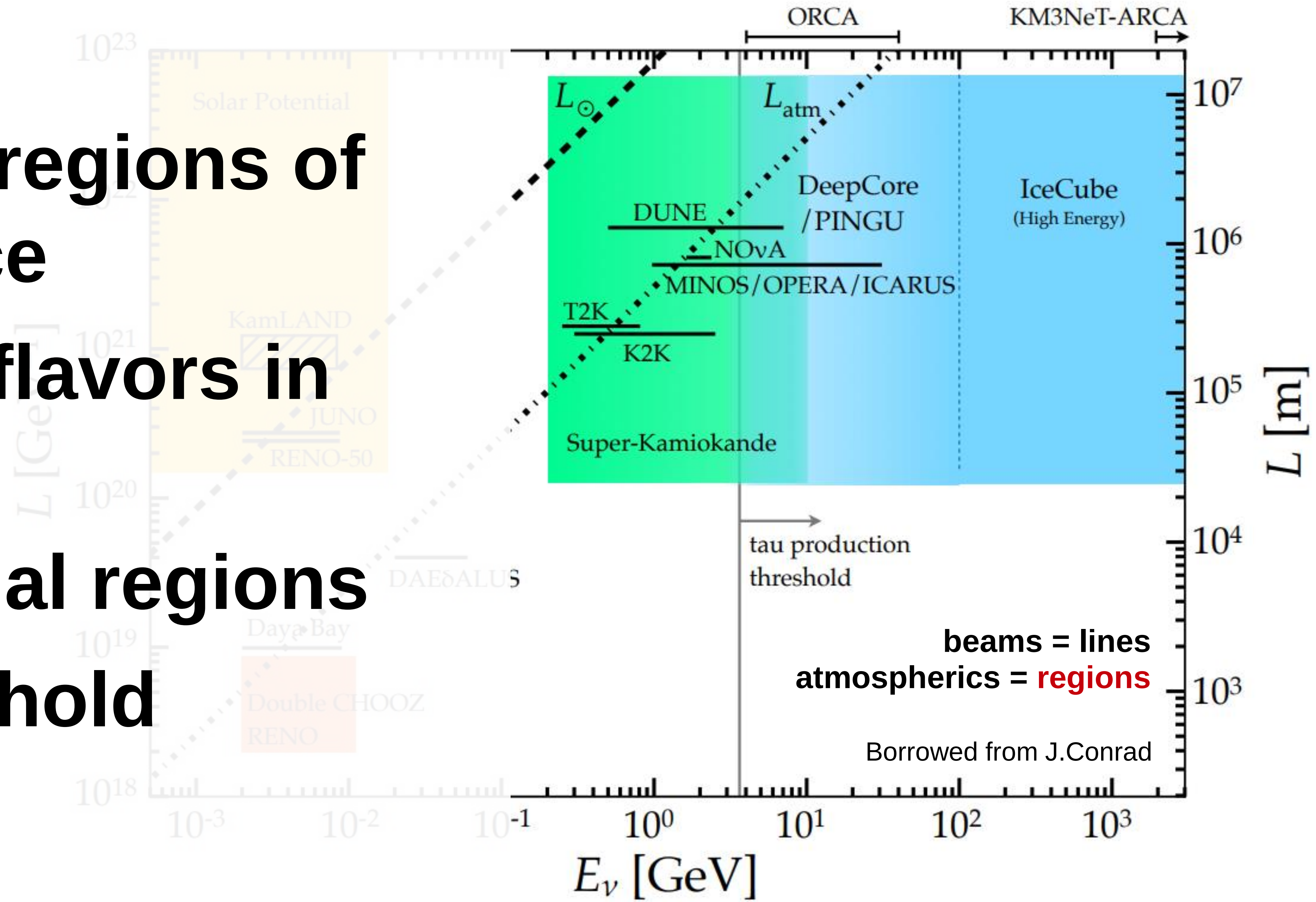


beams = lines
atmospherics = regions

Borrowed from J.Conrad

wide baseline, energy range

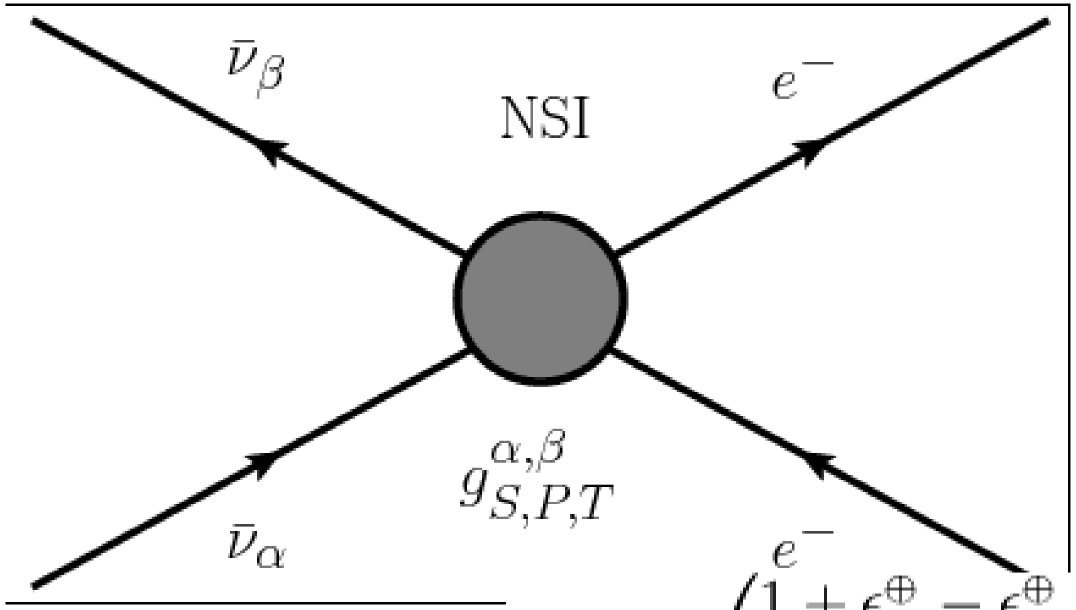
- -large **L&E** regions of phase space
- -2 **ν, anti-ν** flavors in "beam"
- -on/off signal regions
- -**E > τ** threshold



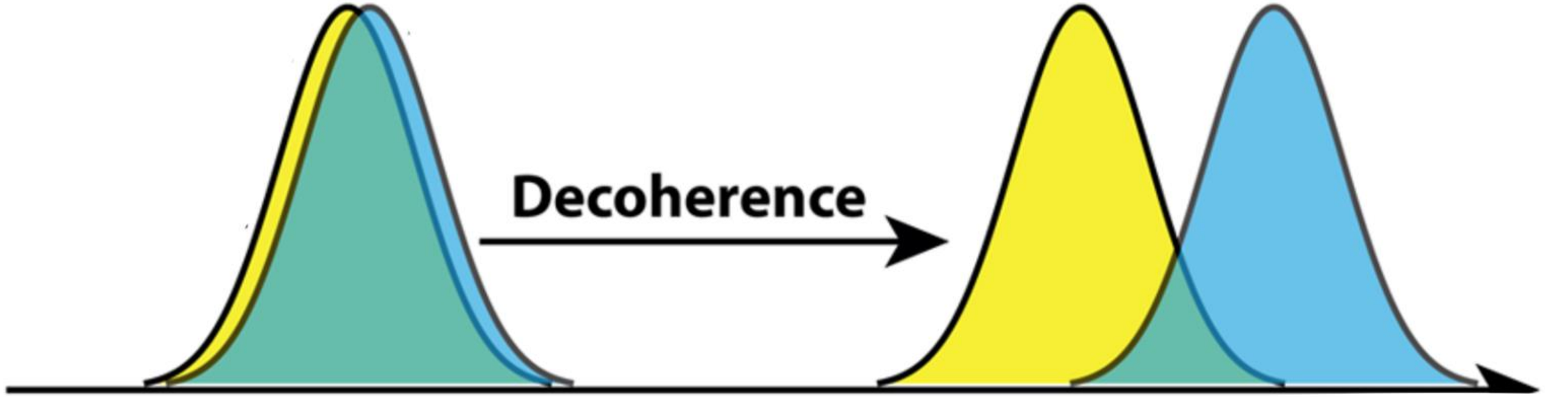
and the off-signal regions?

-used to probe **exotic** possibilities

-all show as **distortions** in the spectrum

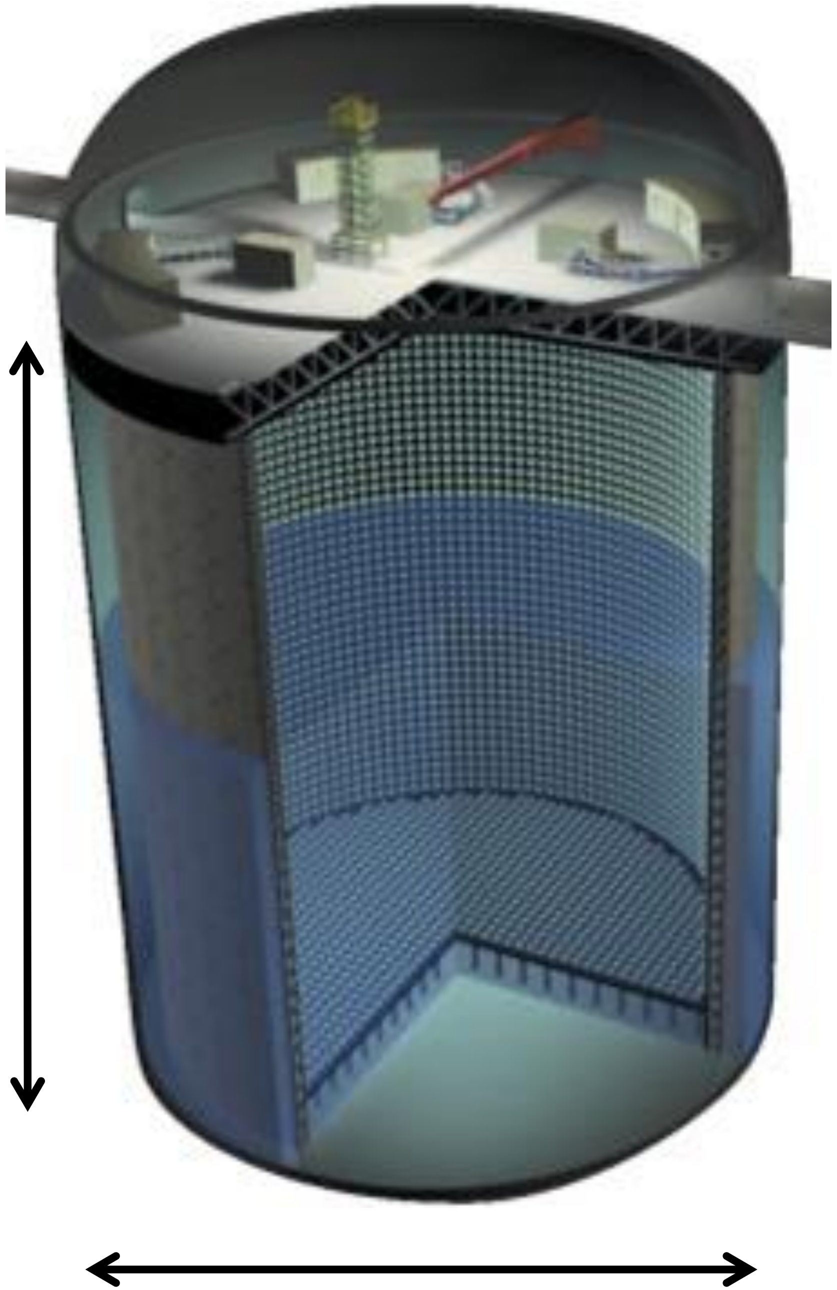


$$H_{\text{mat}} = \begin{pmatrix} 1+\epsilon^{\oplus}_{ee}-\epsilon^{\oplus}_{\mu\mu} & \epsilon^{\oplus}_{e\mu} & \epsilon^{\oplus}_{e\tau} \\ \epsilon^{\oplus *}_{e\mu} & 0 & \epsilon_{\mu\tau} \\ \epsilon^{\oplus *}_{e\tau} & \epsilon^{\oplus *}_{\mu\tau} & \epsilon^{\oplus}_{\tau\tau}-\epsilon^{\oplus}_{\mu\mu} \end{pmatrix}.$$

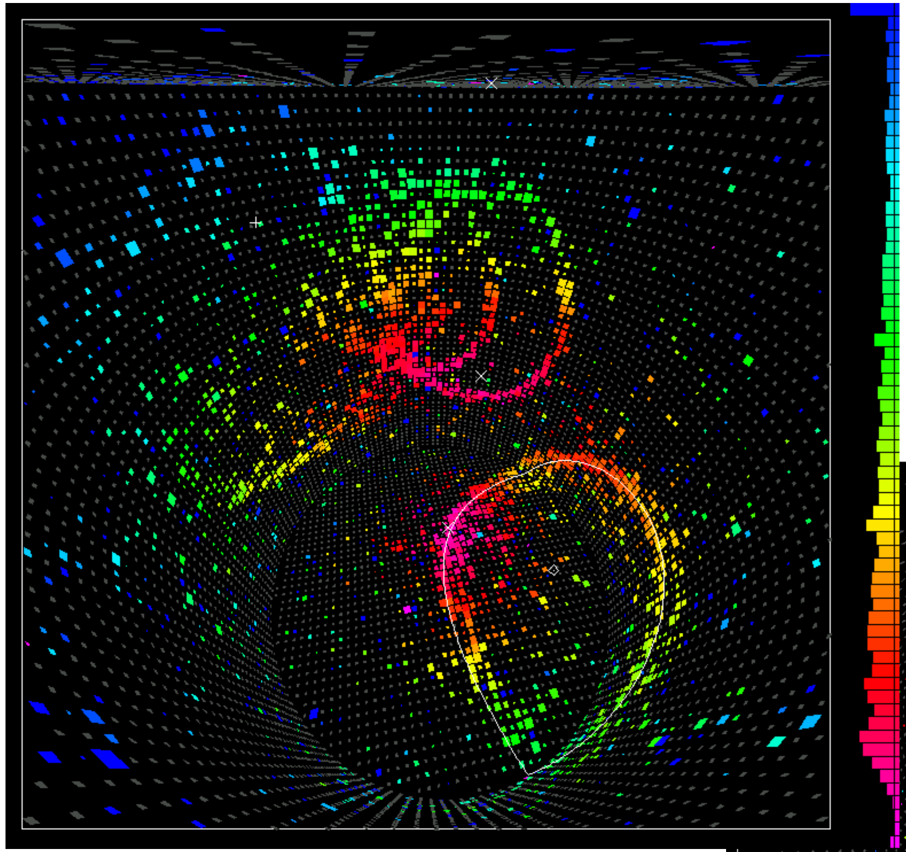


recent atmospheric neutrino measurements

Super-Kamiokande

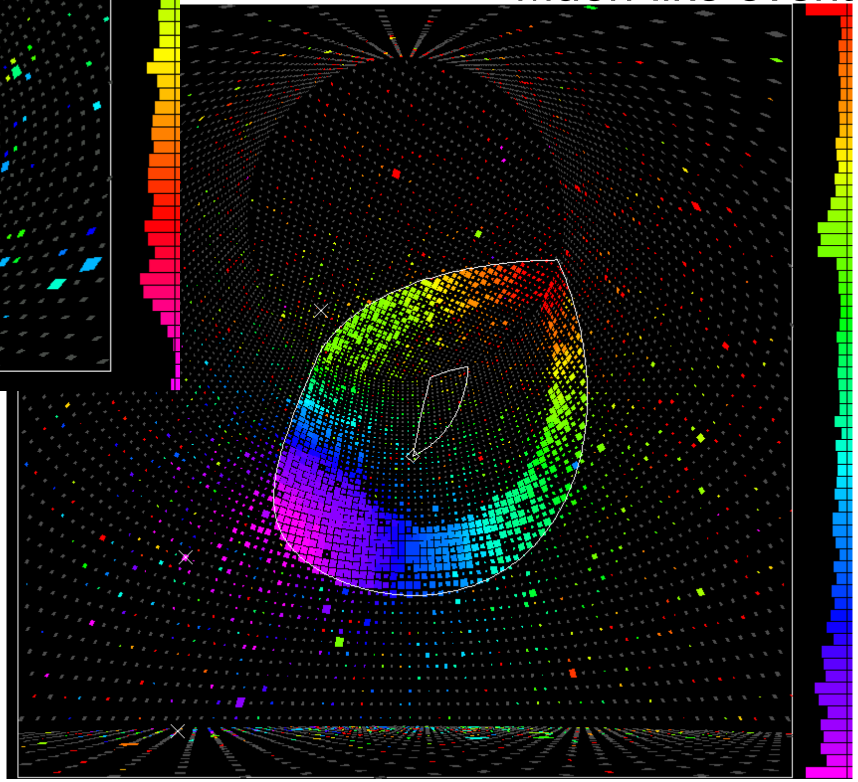


~40m



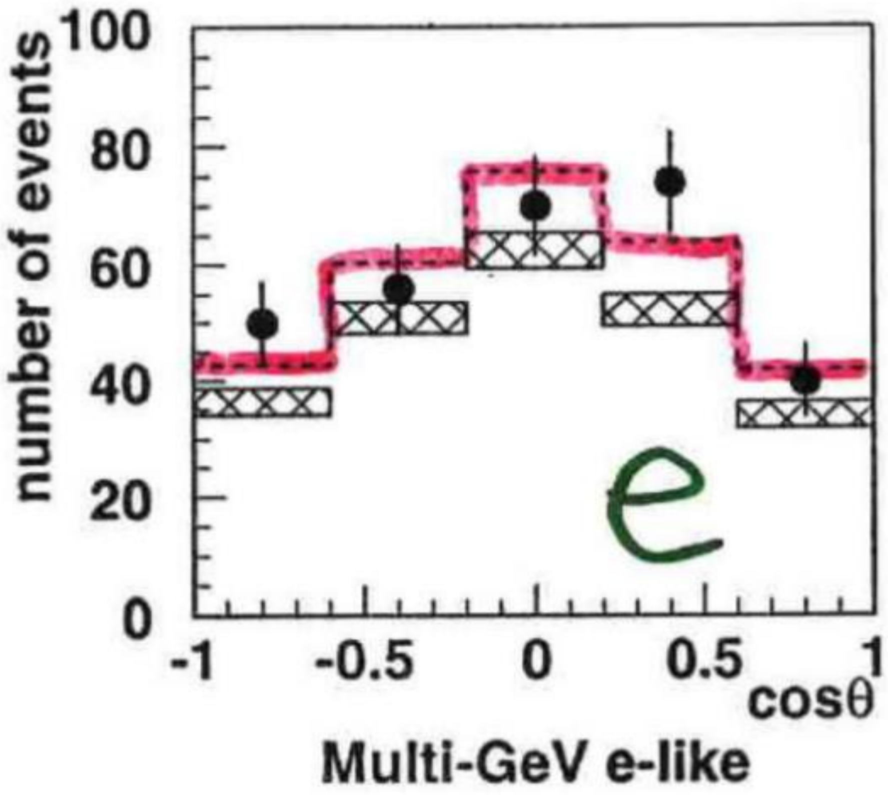
Two-gamma-like event

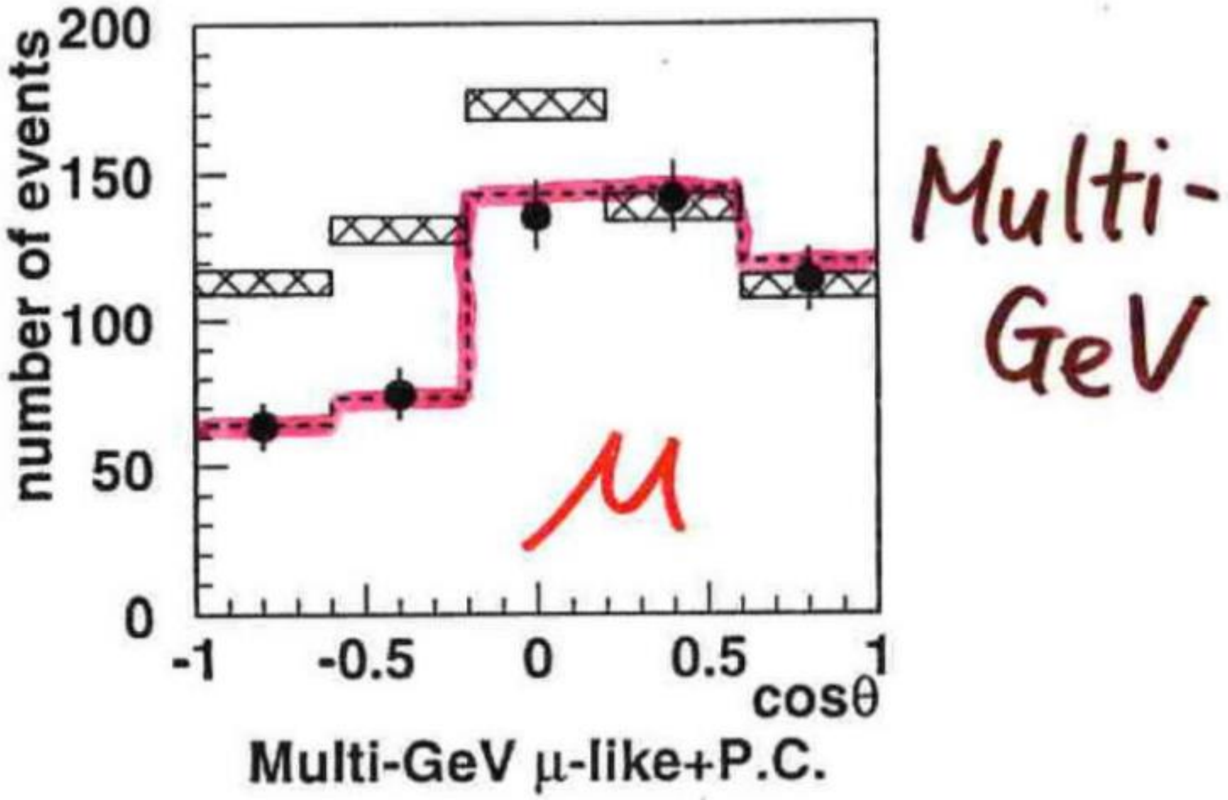
Muon-like event



http://www.ps.uci.edu/~tomba/sk/tscan/pictures.html

Super-Kamiokande



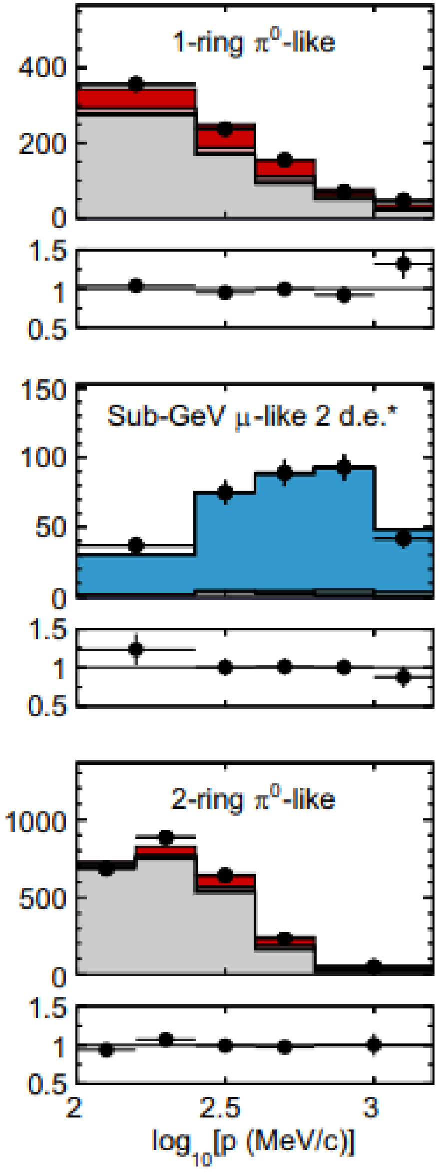


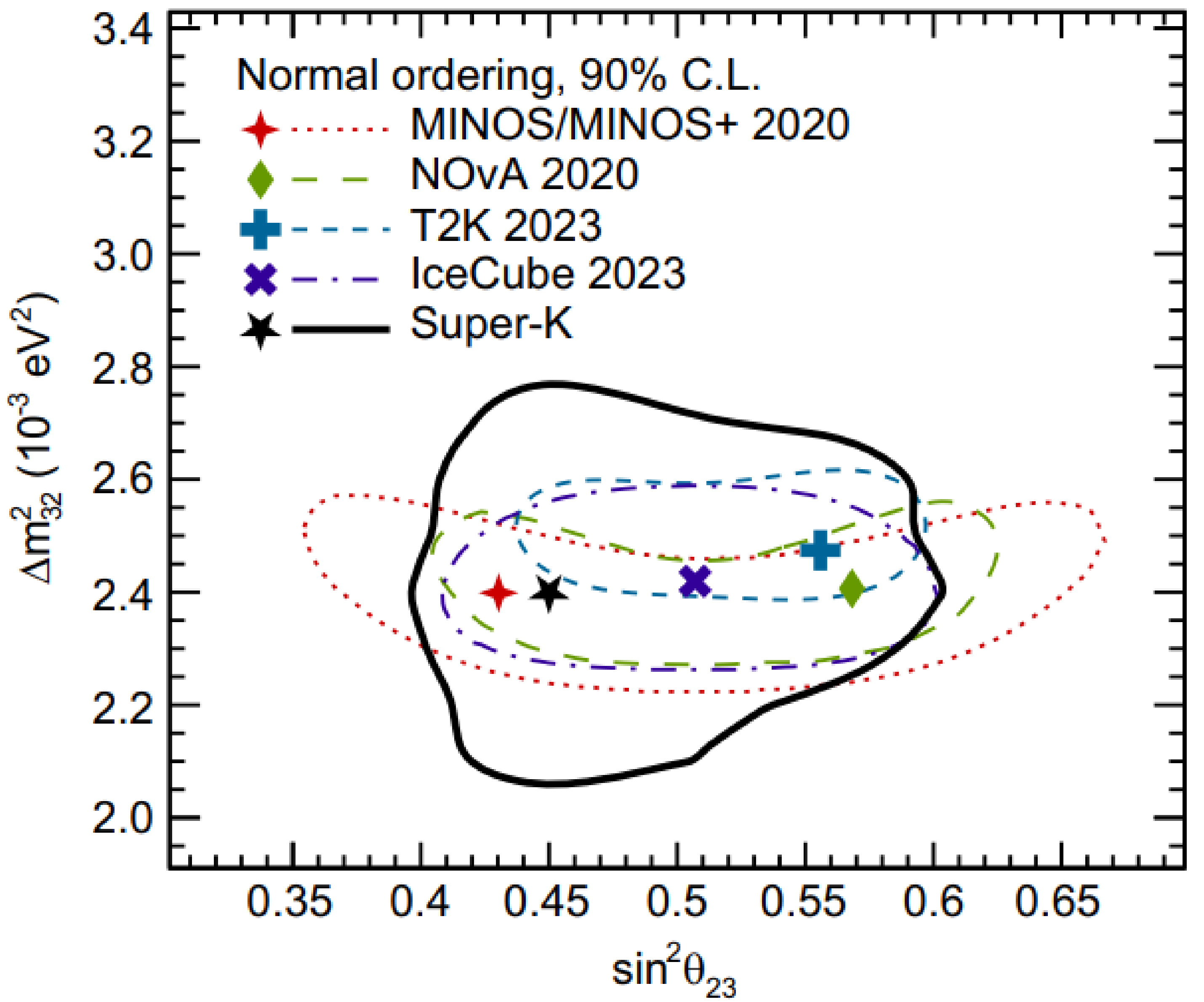
from Neutrino'98 presentation

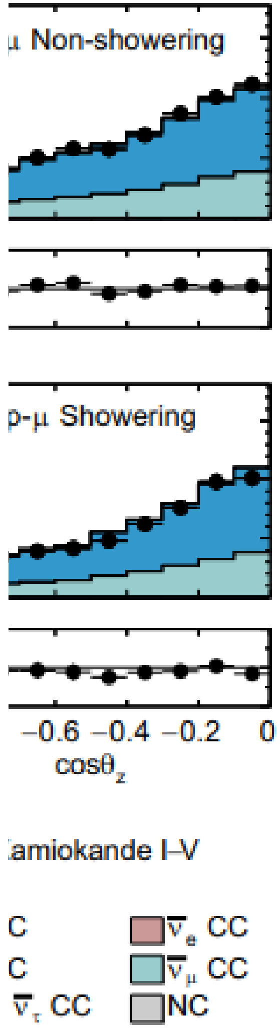
Super-Kamiokande

Standard oscillations

Phys. Rev. D 109 07214 (2024)



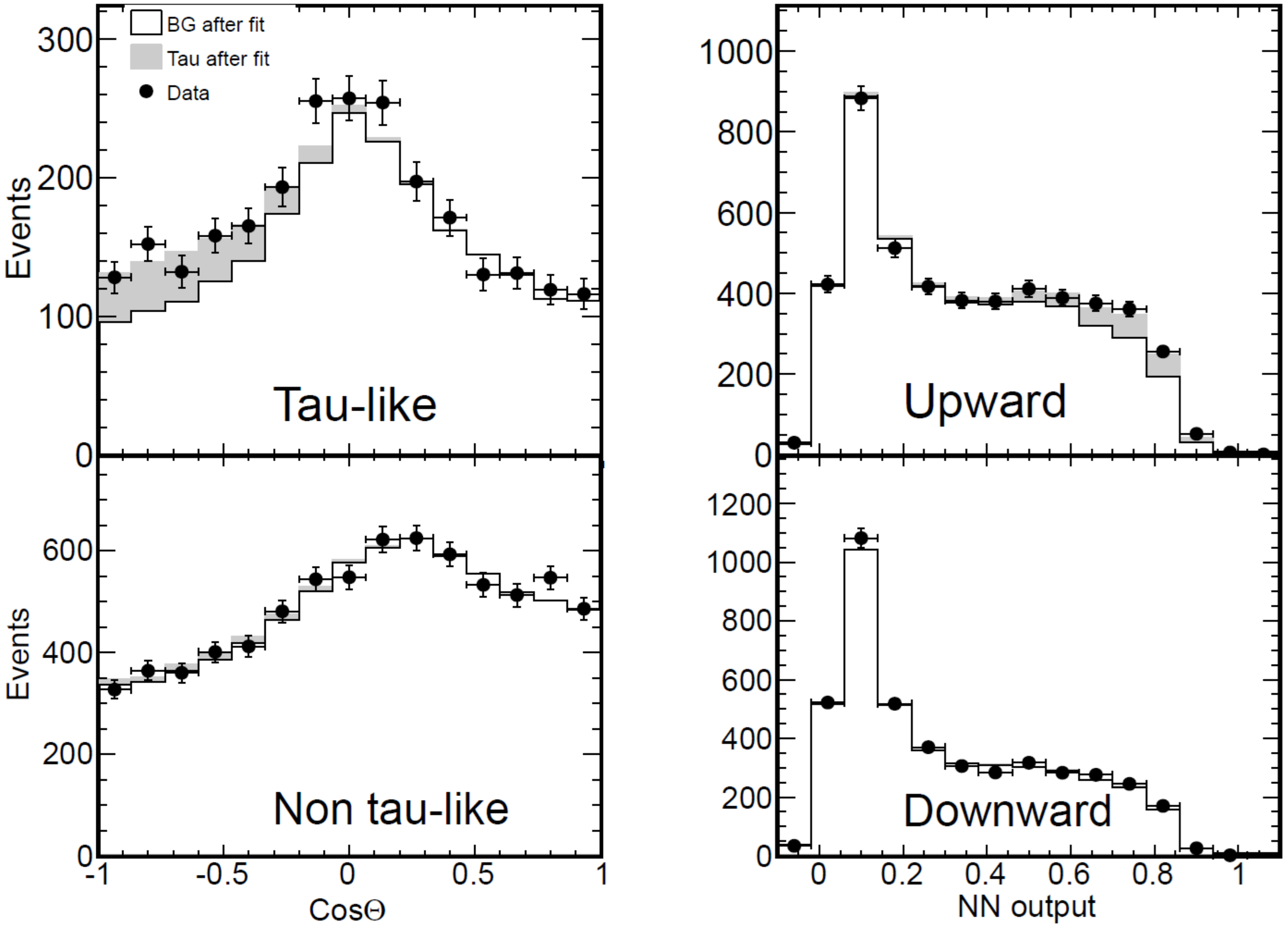




Super-Kamiokande

NuTau appearance

Phys. Rev. D 98, 052006 (2018)

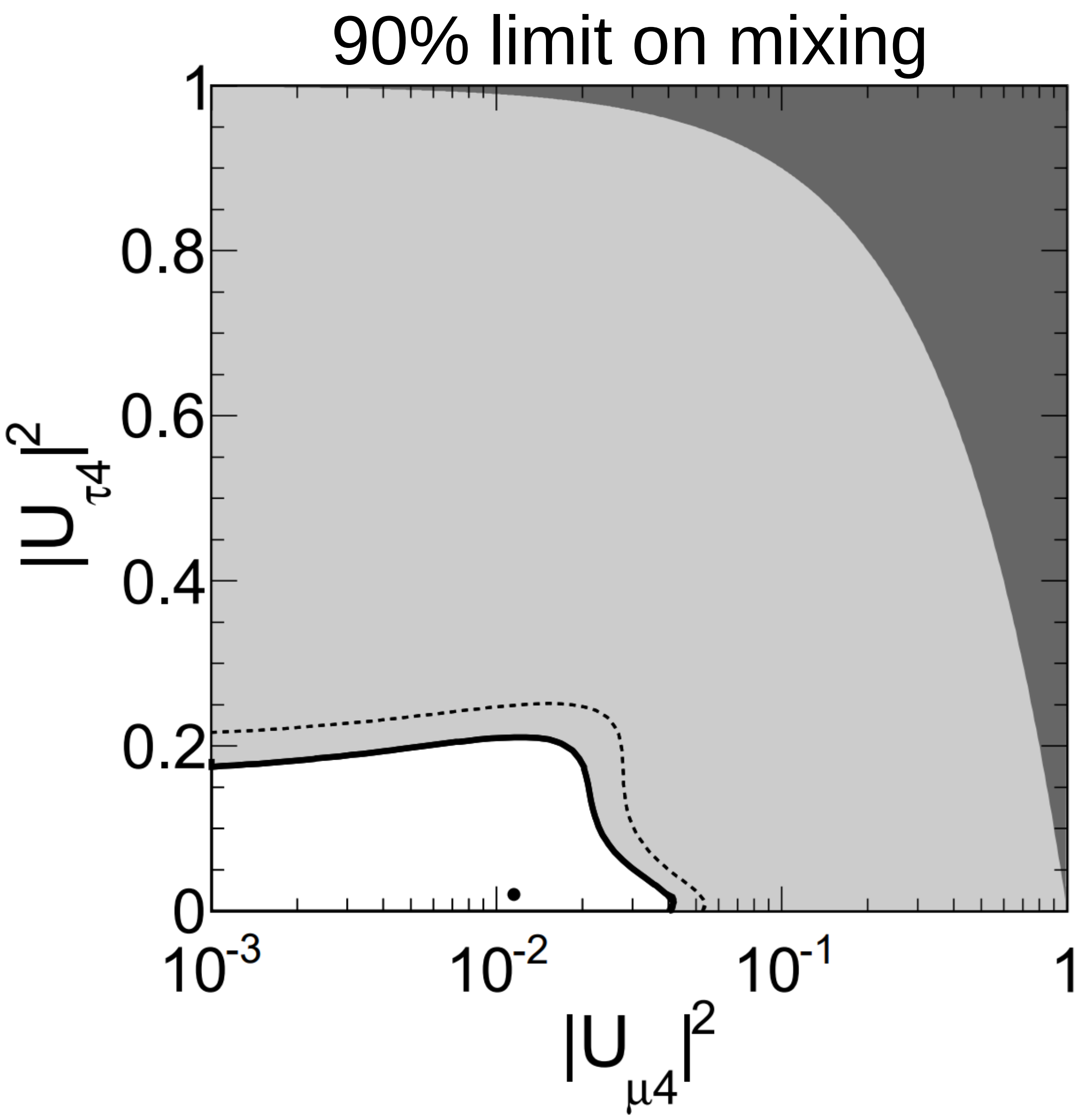


4.6σ evidence for NuTau appearance

Super-Kamiokande

Sterile neutrinos

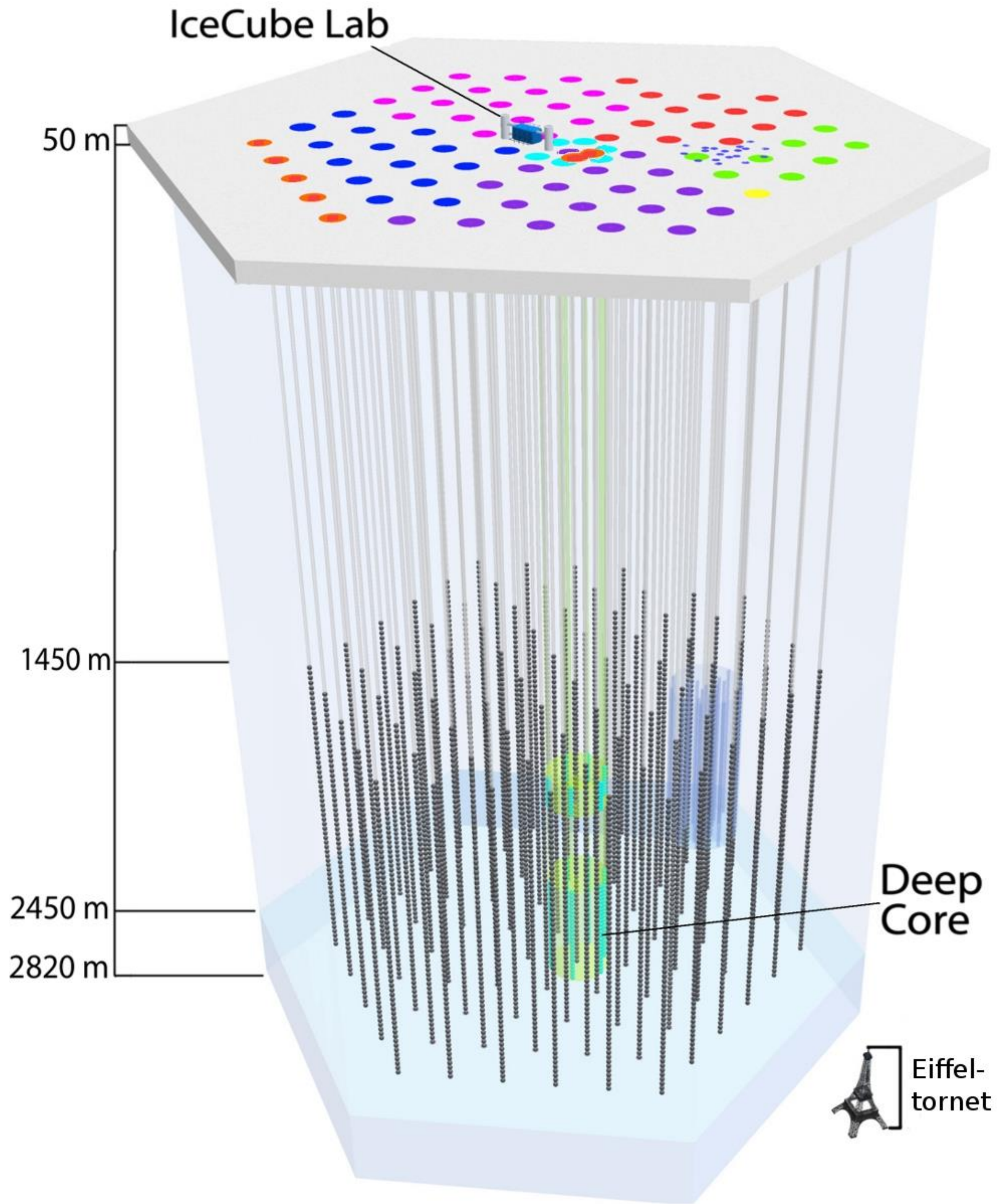
Phys. Rev. D 91, 052019 (2015)

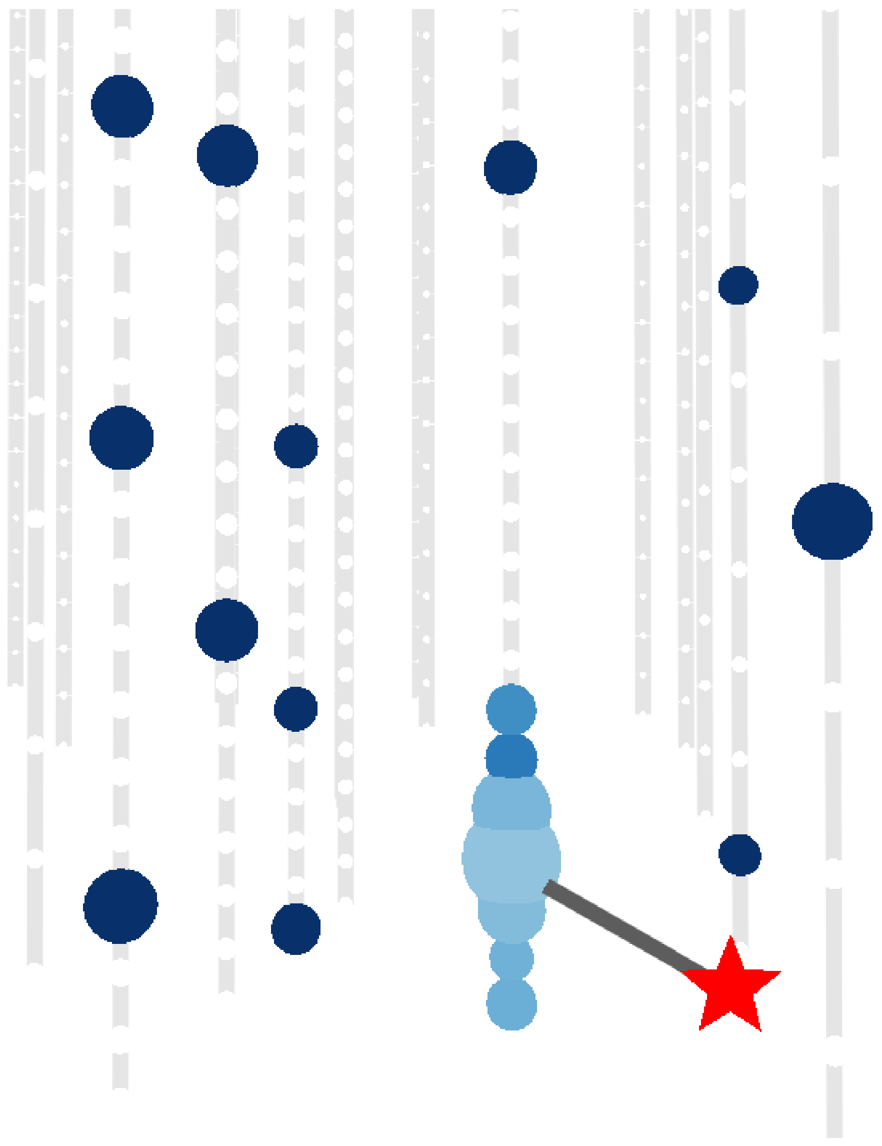


$$\mathbf{U} \equiv \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

- **search for spectral distortions due to steriles**
- **sensitive to $\nu_\mu \leftrightarrow \nu_\tau$ mix**

IceCube DeepCore



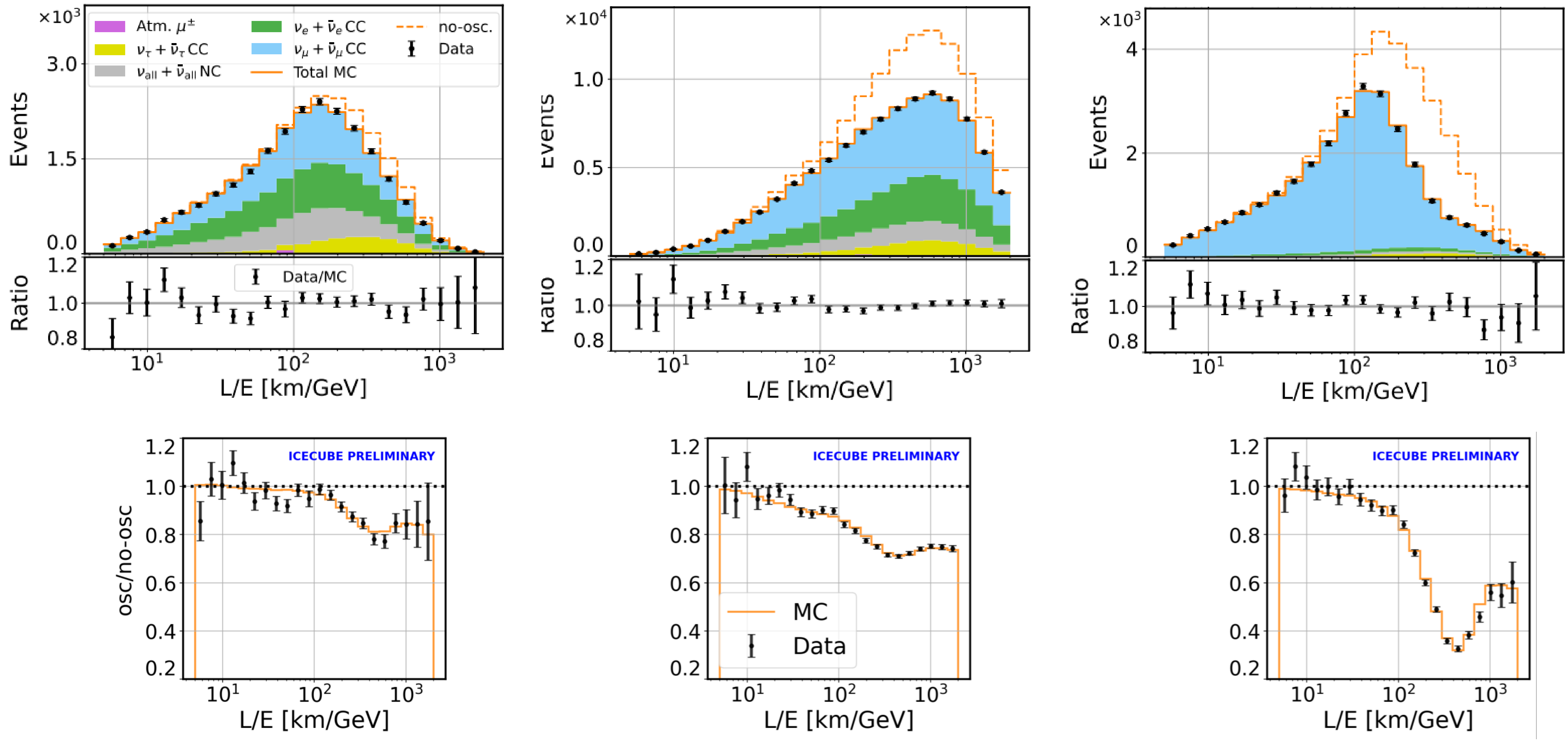


12 GeV ν_μ interaction

8 GeV track (R~40m) + 4 GeV cascade

IceCube DeepCore

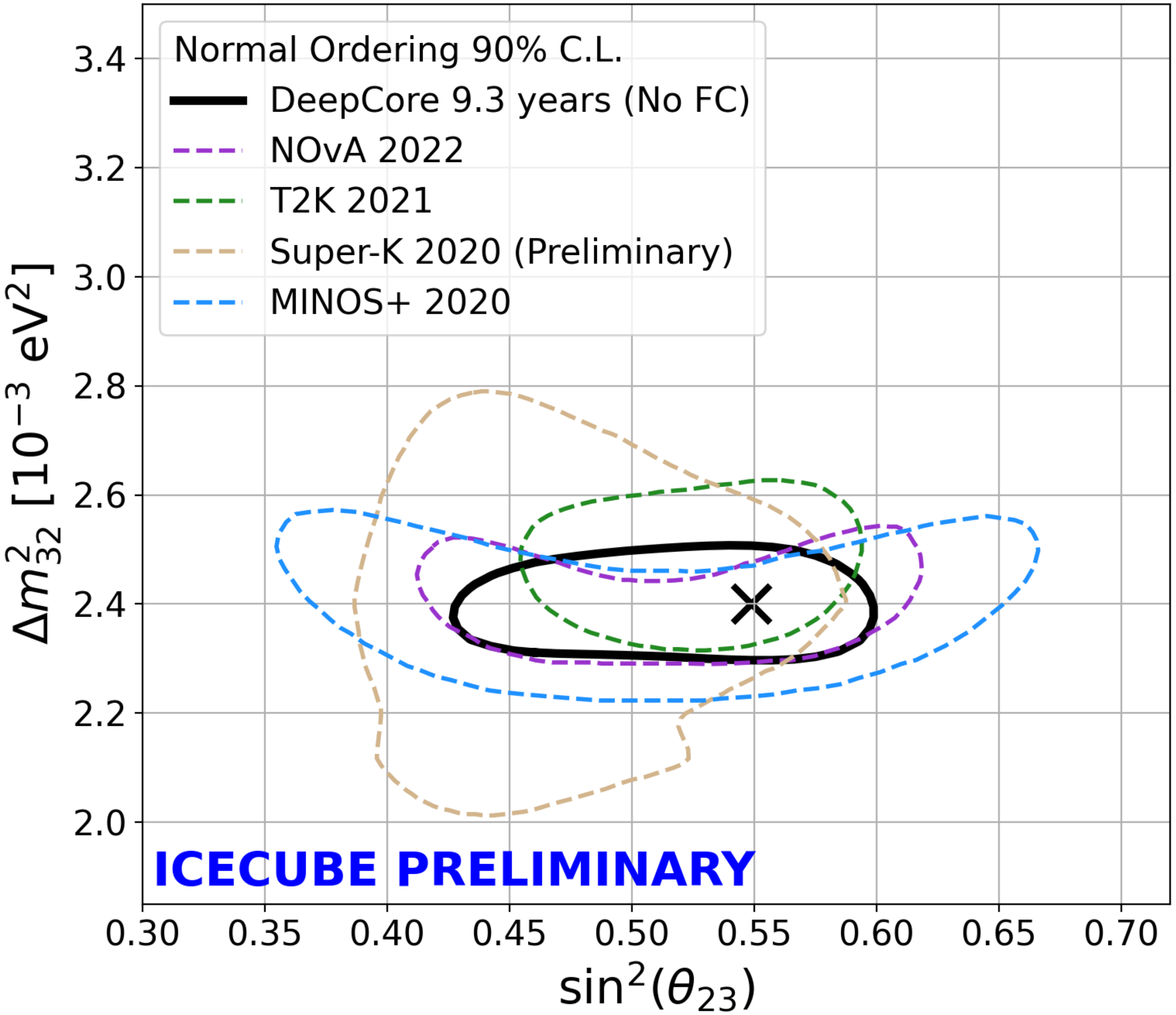
Standard oscillations (2024)



IceCube DeepCore

Standard oscillations (2024)

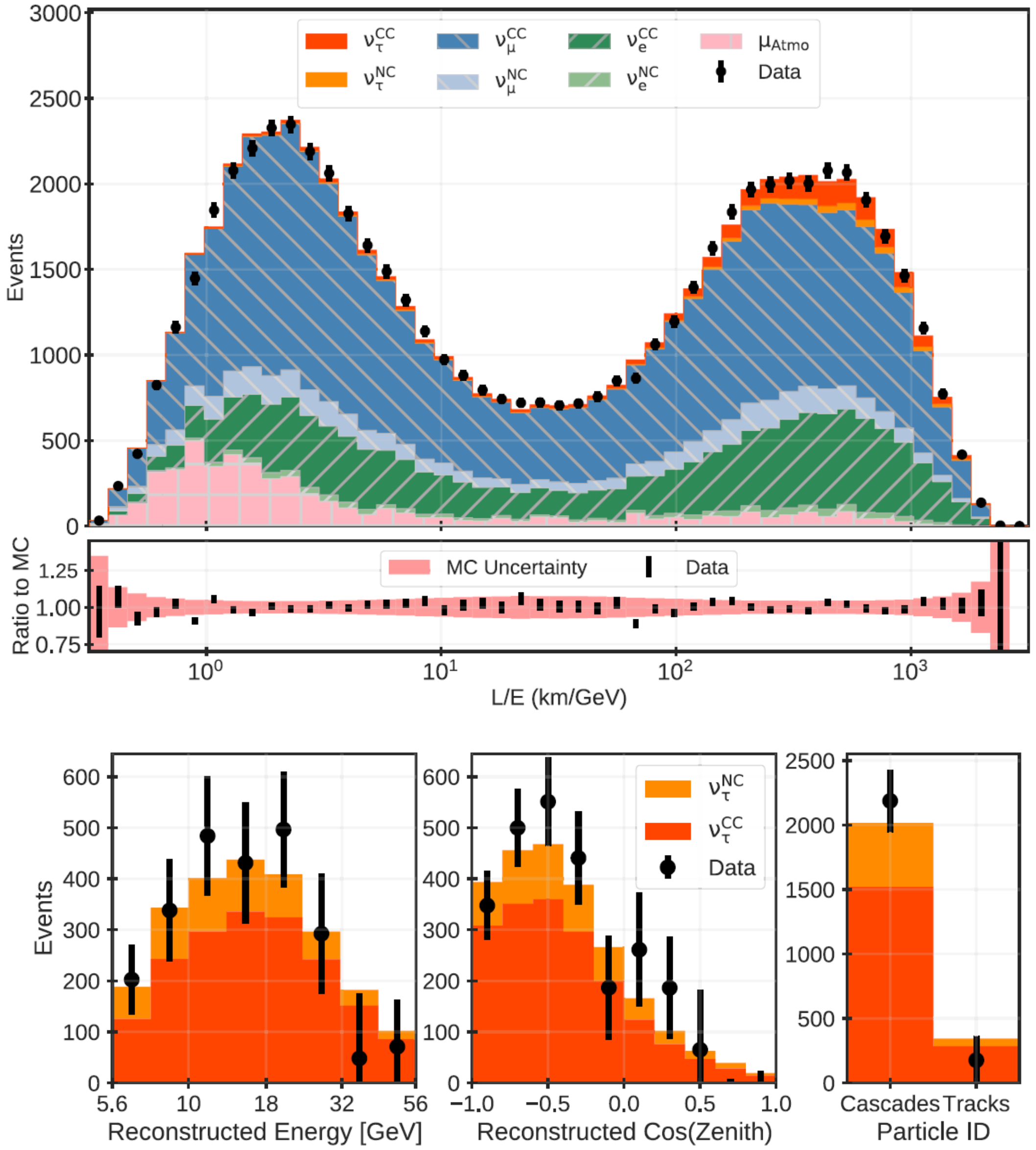
arXiv:2405.02163 [hep-ex]

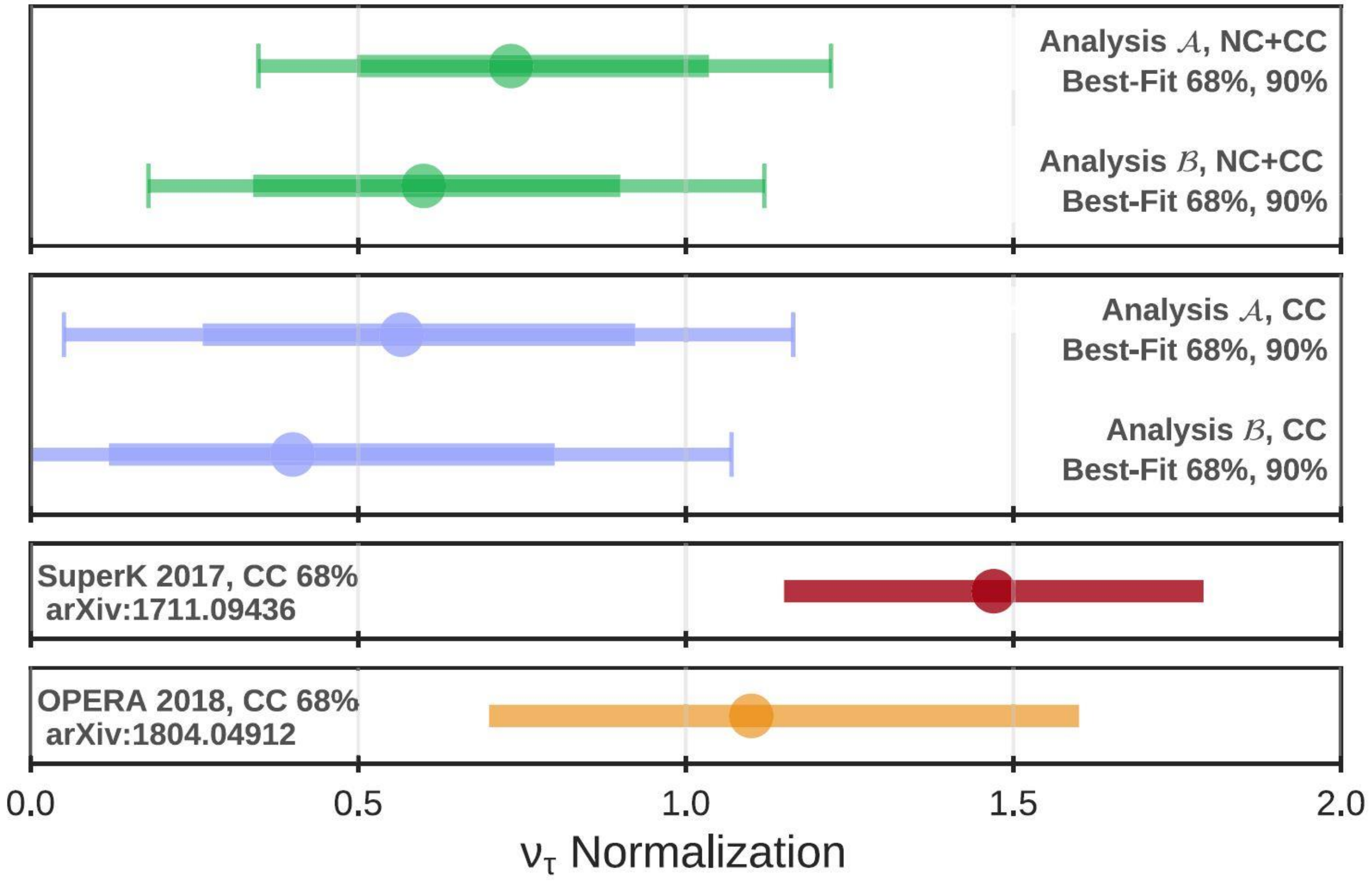


IceCube DeepCore

NuTau appearance

Phys. Rev. D 99, 032007 (2019)





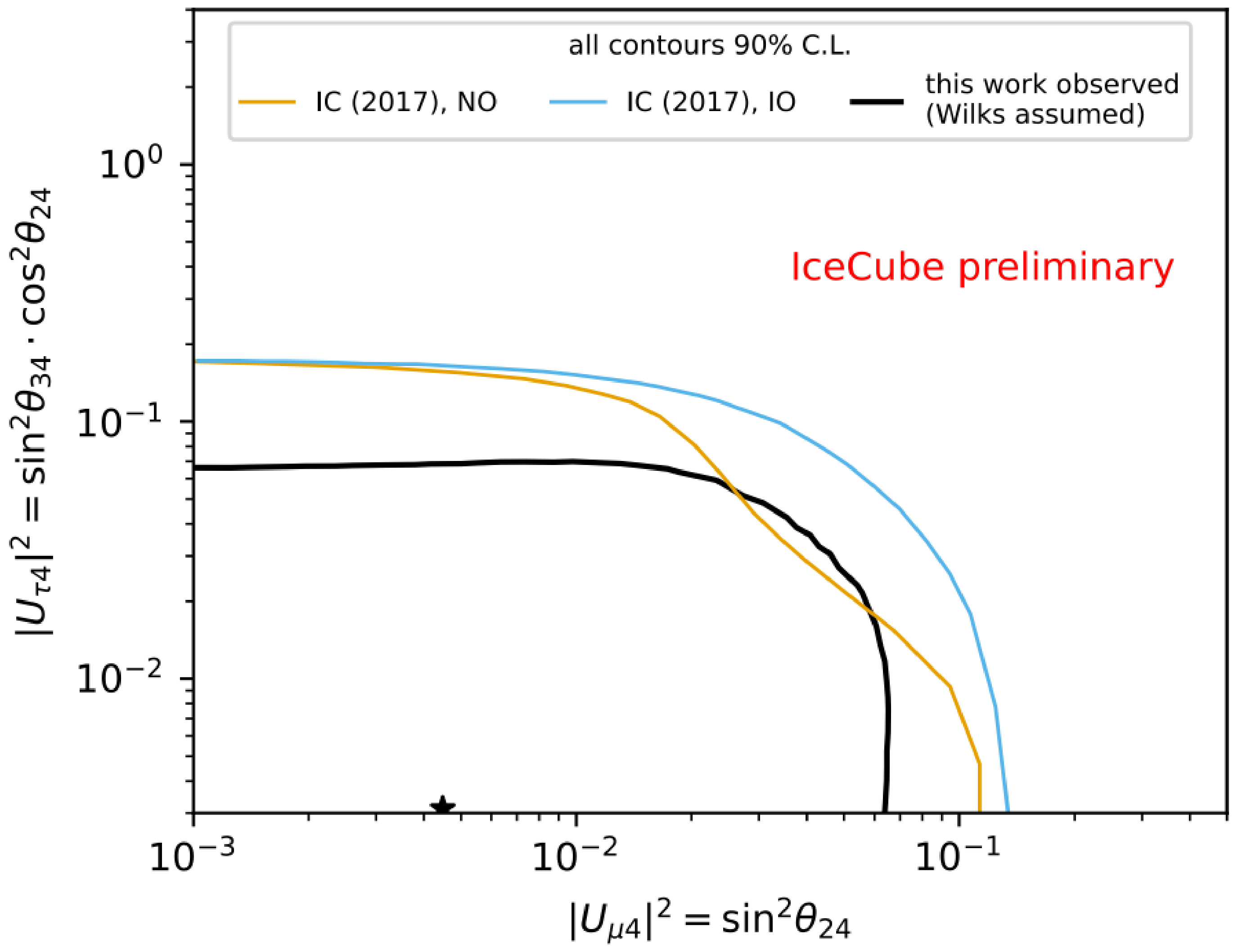
IceCube DeepCore

Sterile neutrinos

arXiv:2407.01314 (2024)

$$\mathbf{U} \equiv \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

-there is no preference for a sterile neutrino state mixing at "low" E



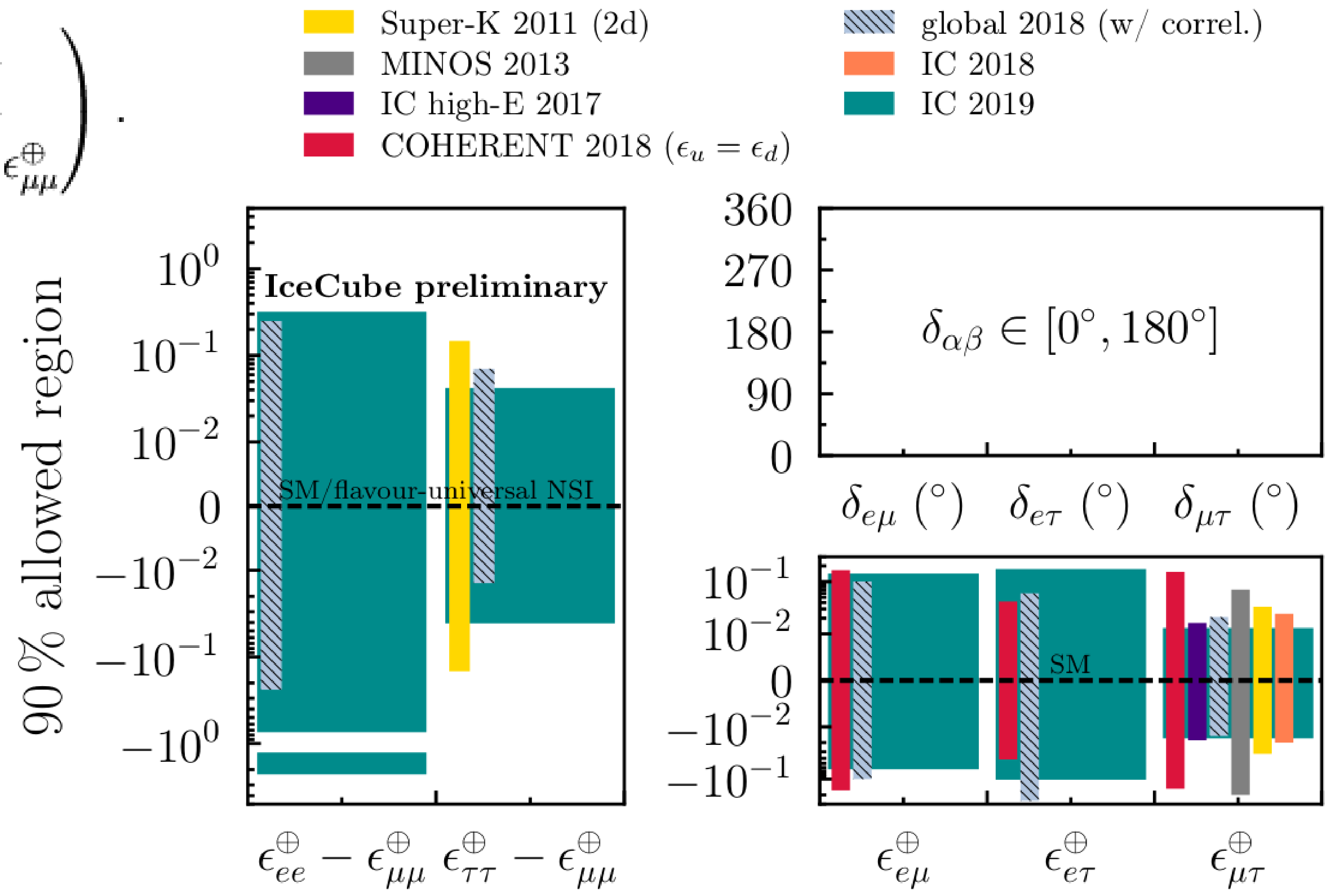
IceCube DeepCore

Non-standard interactions

Phys. Rev. D104 (2021) 072006

$$H_{\text{mat}} = \begin{pmatrix} 1 + \epsilon^{\oplus}_{ee} - \epsilon^{\oplus}_{\mu\mu} & \epsilon^{\oplus}_{e\mu} & \epsilon^{\oplus}_{e\tau} \\ \epsilon^{\oplus *}_{e\mu} & 0 & \epsilon_{\mu\tau} \\ \epsilon^{\oplus *}_{e\tau} & \epsilon^{\oplus *}_{\mu\tau} & \epsilon^{\oplus}_{\tau\tau} - \epsilon^{\oplus}_{\mu\mu} \end{pmatrix}.$$

-there is no preference for additional NSIs



IceCube (high energy)

Sterile neutrinos

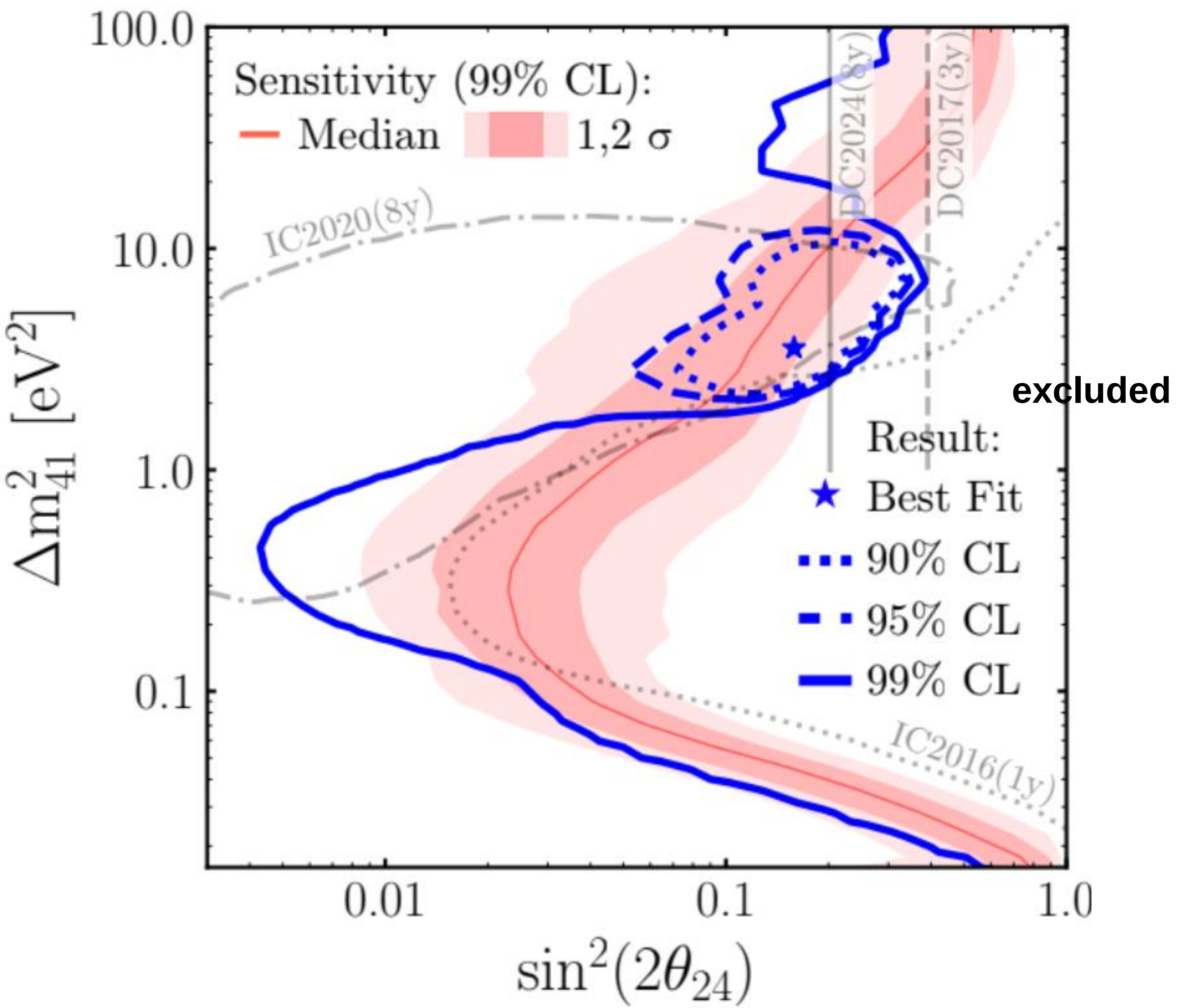
arXiv:2405.08070 (2024)

E_{nu} ~ TeVs

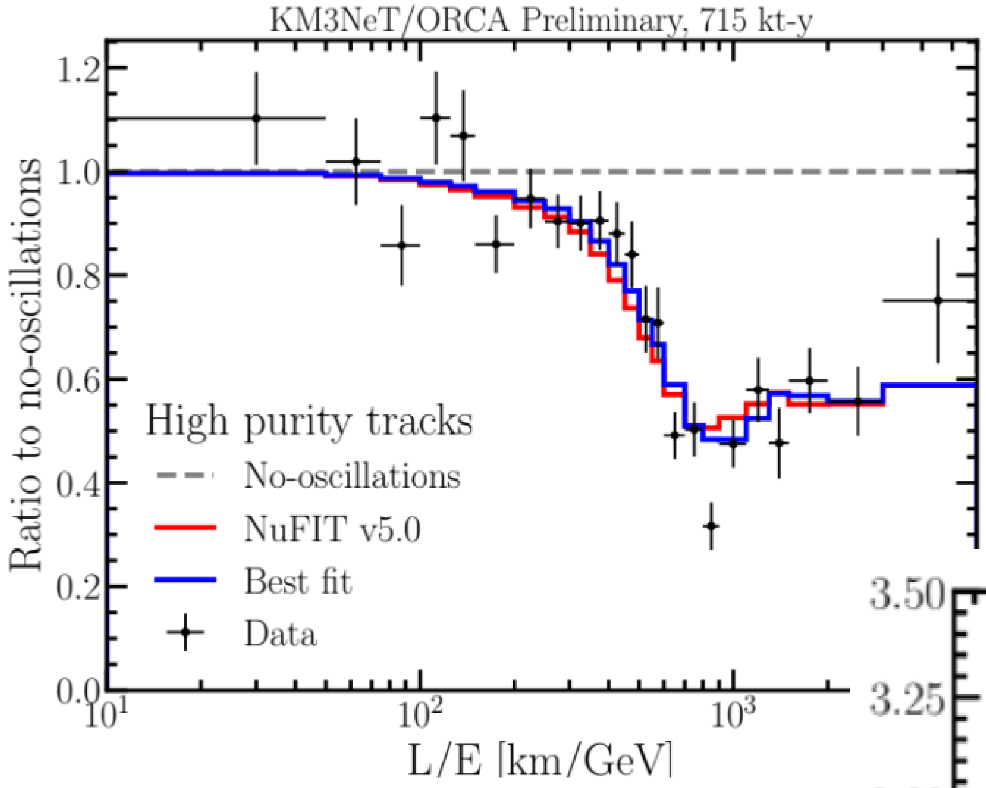
$$\mathbf{U} \equiv \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

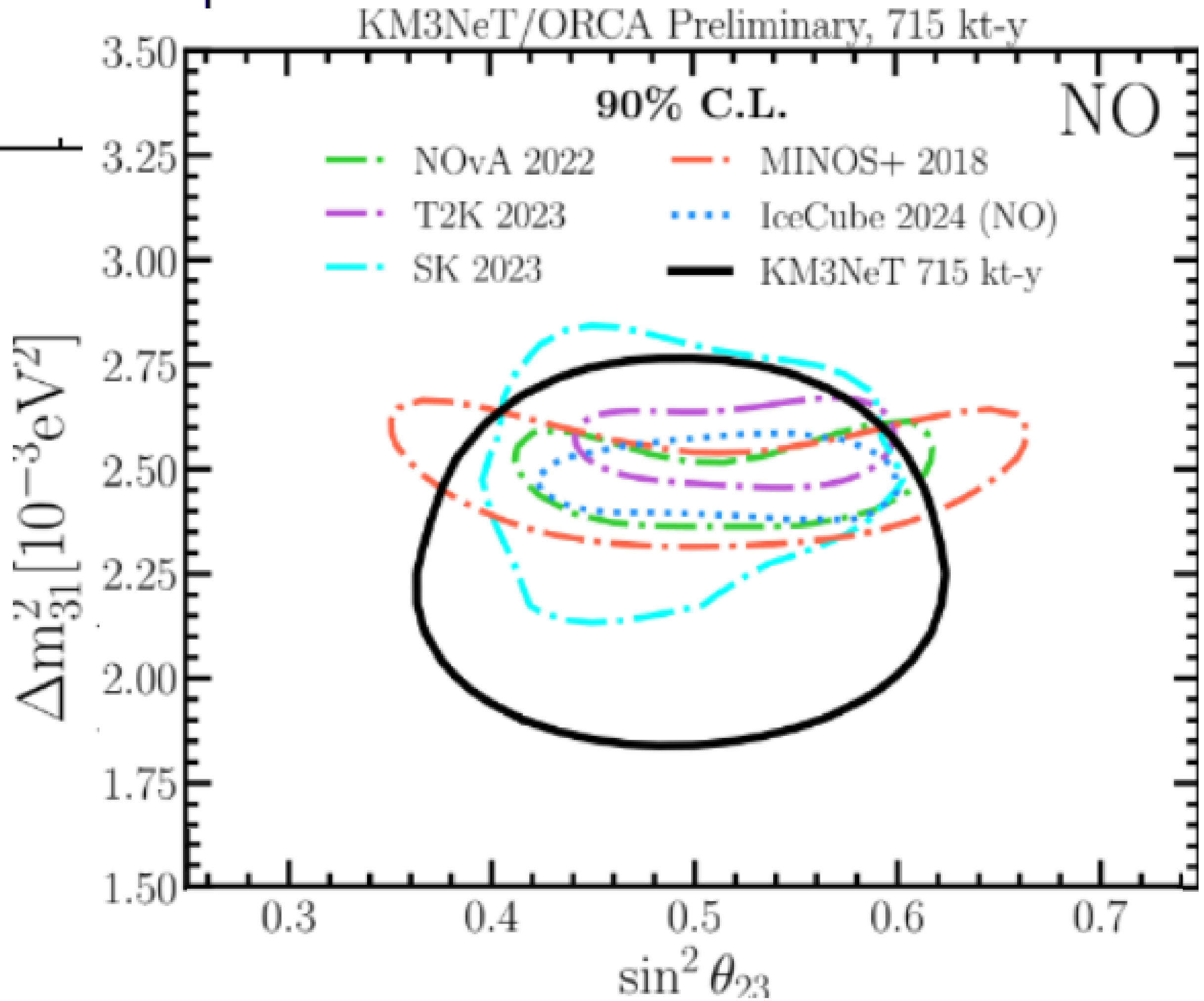
$$|U_{\mu4}|^2 = \sin^2\theta_{24},$$

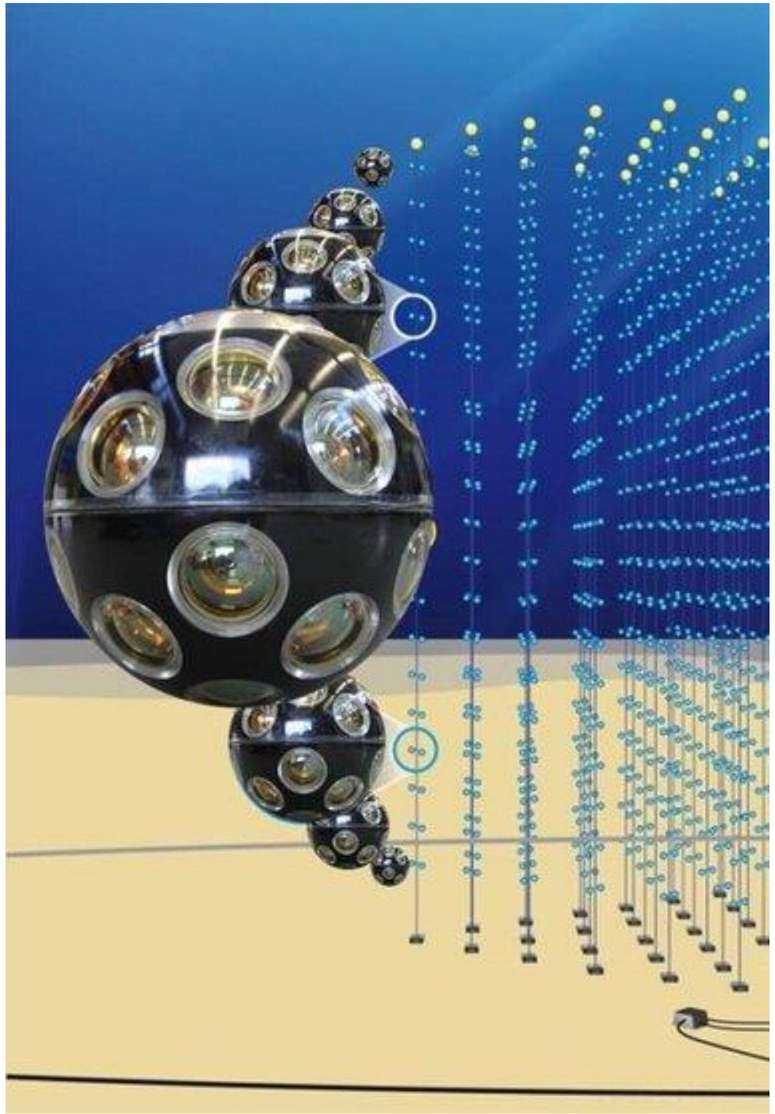
$$|U_{\tau4}|^2 = \cos^2\theta_{24} \cdot \sin^2\theta_{34}.$$



KM3NeT-ORCA
water Cherenkov

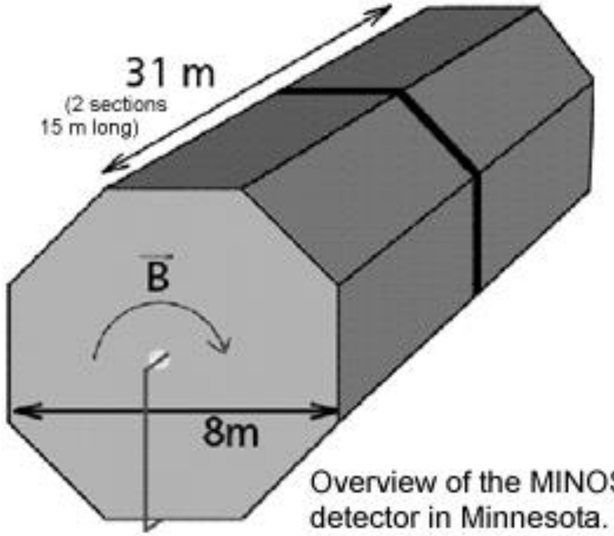






Standard oscillations
ORCA with 6 lines
Presented at Neutrino 2024

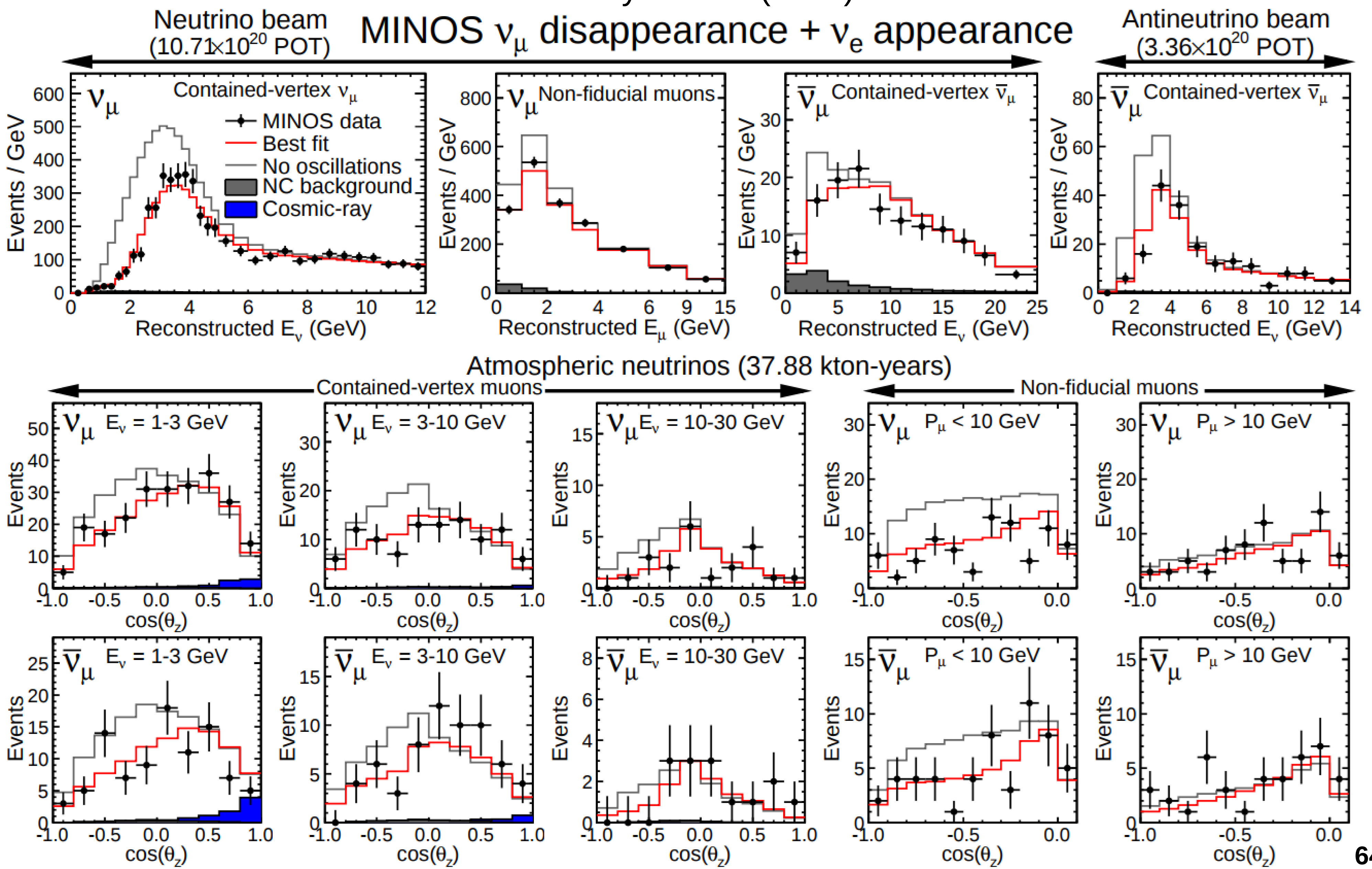
MINOS
magnetized steel & scintillator calorimeter



Overview of the MINOS detector in Minnesota.

***measurement is dominated by beam data**

Nucl.Phys. B908 (2016) 130-150



towards the future

main interests

-precision measurements

-neutrino mass ordering

- Earth tomography

-CP-violation in leptons*

… bigger, better, denser experiments

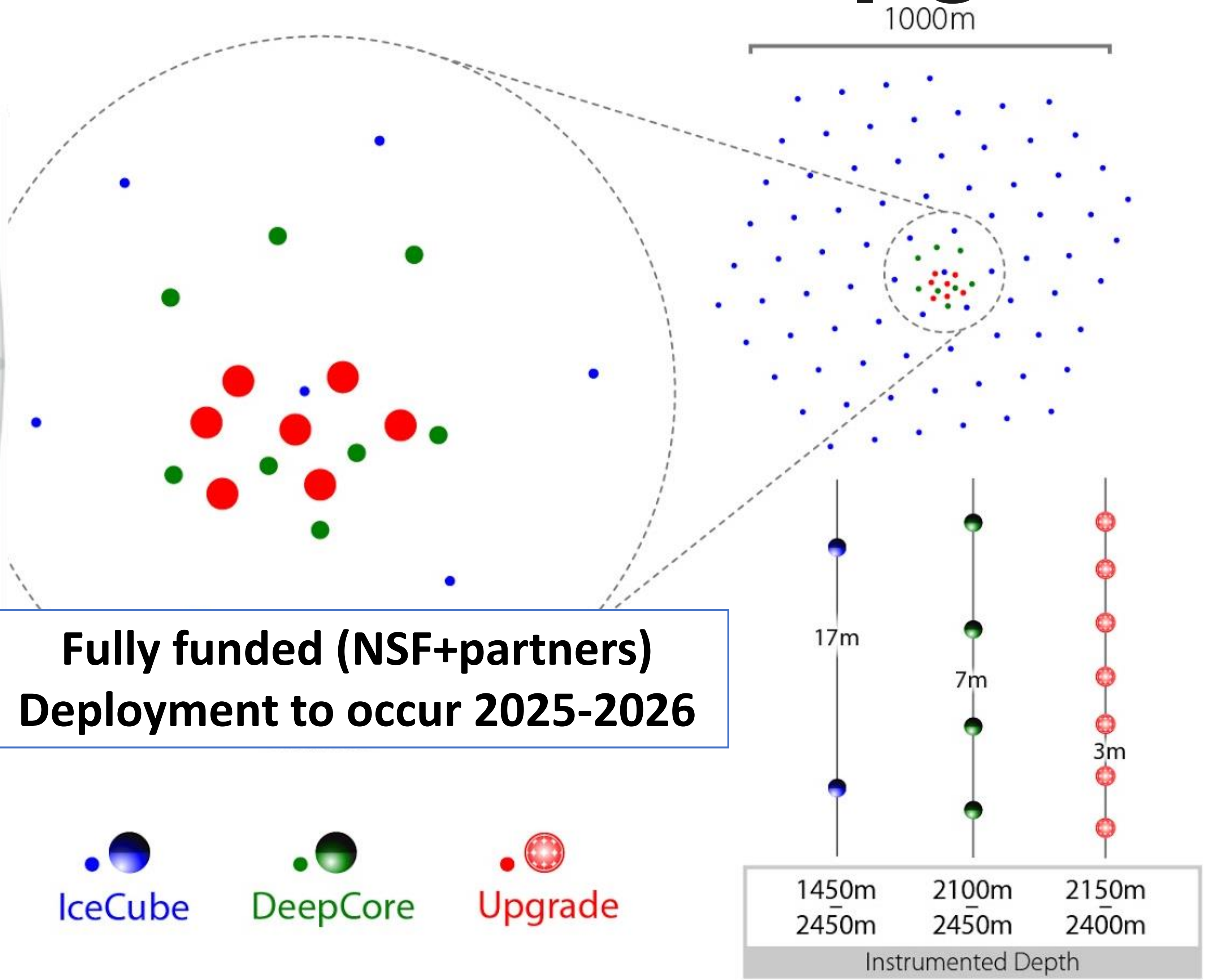
Hyper-Kamiokande

-8x Super-Kamiokande's FV / tank

-260kt mass / tank

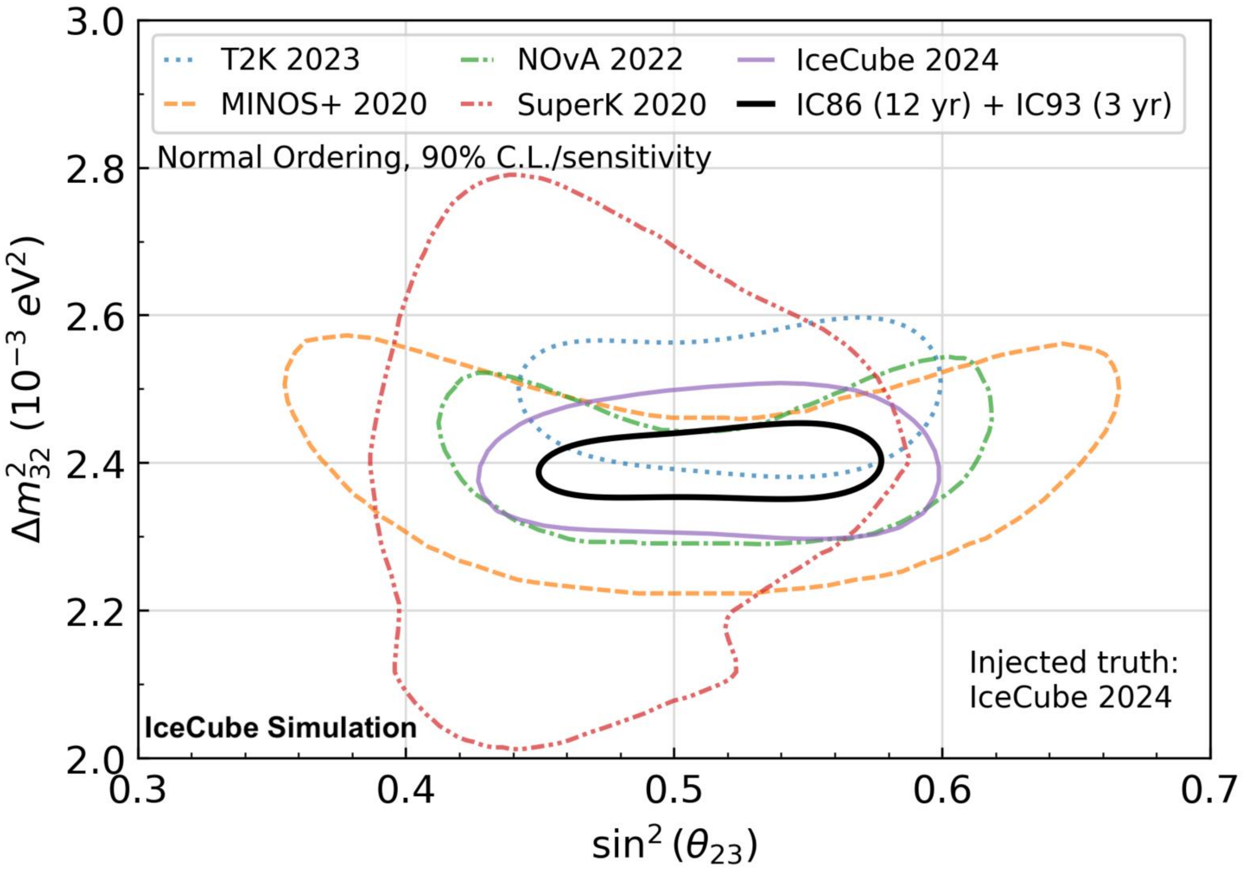
-atmospheric+beam nus

the IceCube upgrade



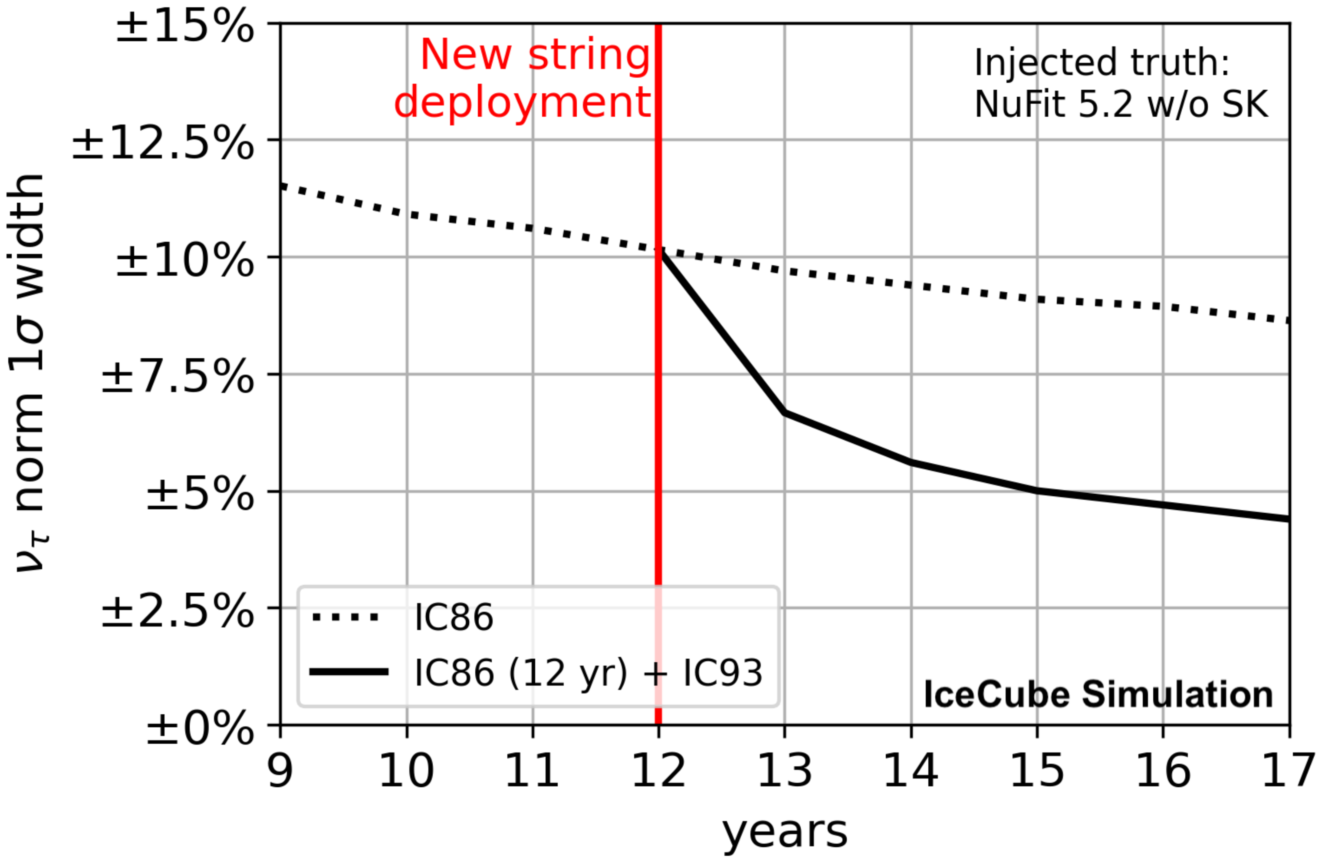
Fully funded (NSF+partners)
Deployment to occur 2025-2026

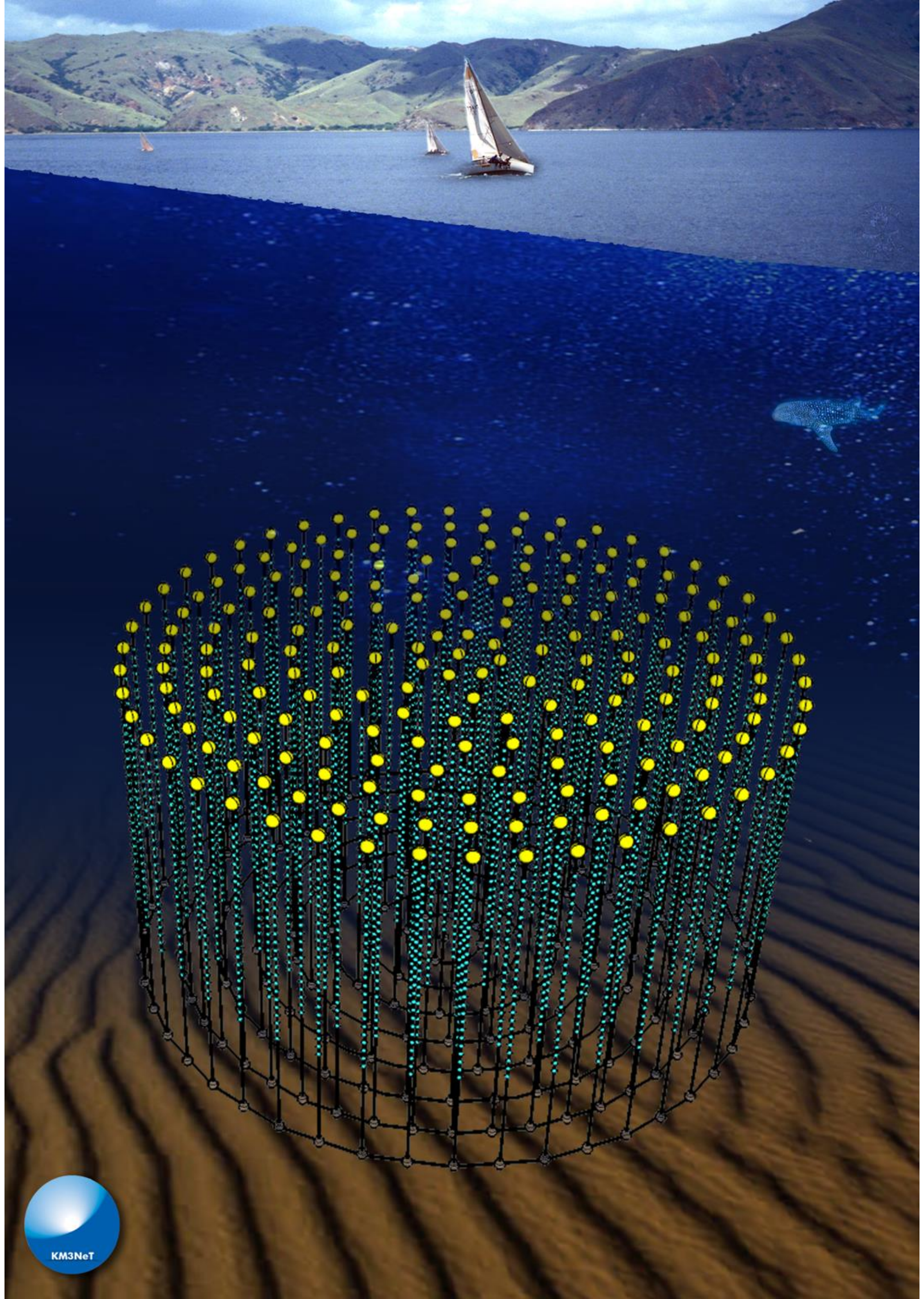
the IceCube upgrade

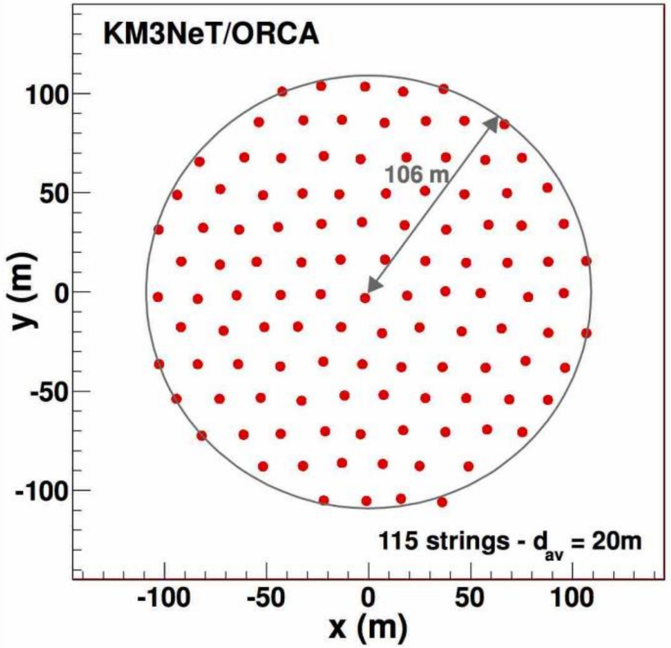


osc. parameters

nutau appearance



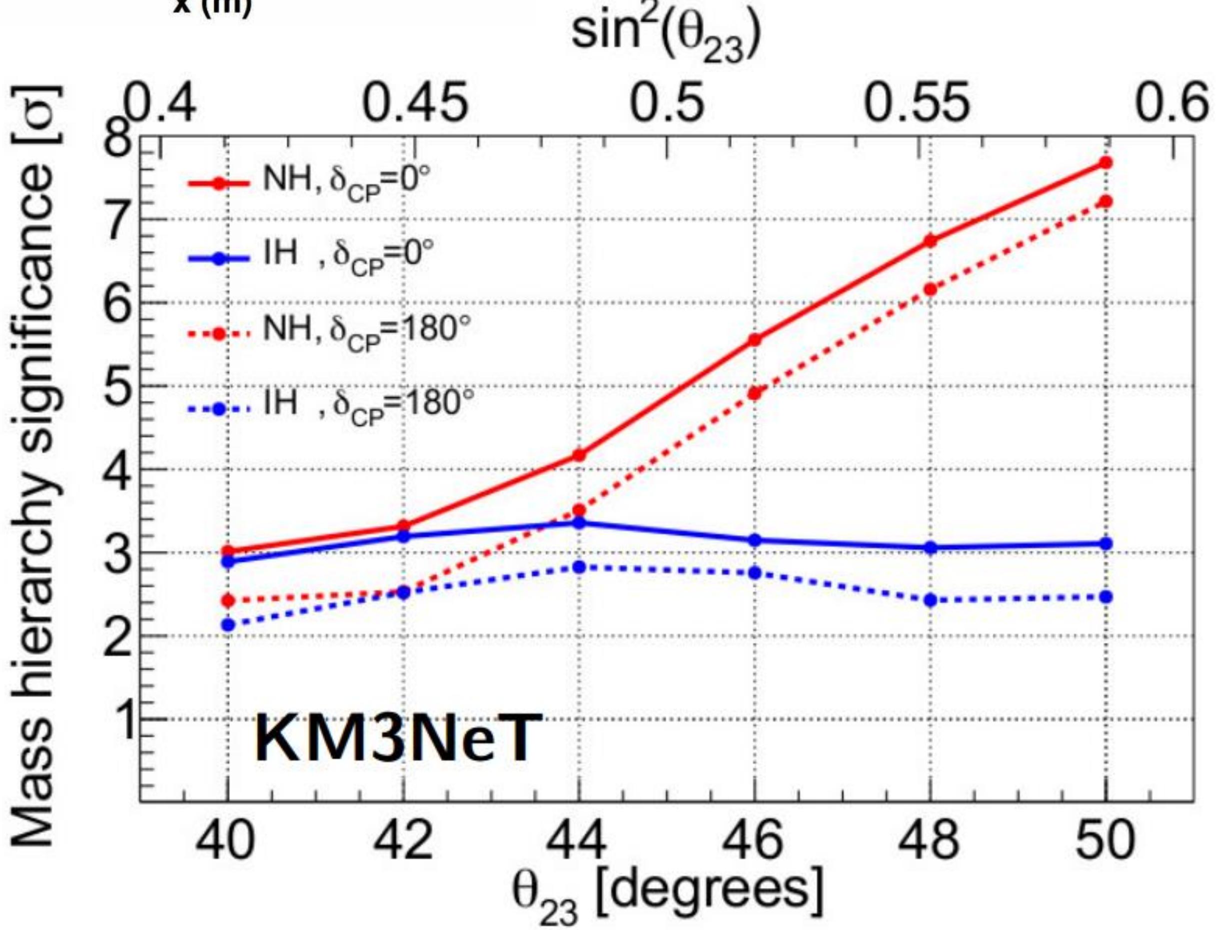




ORCA

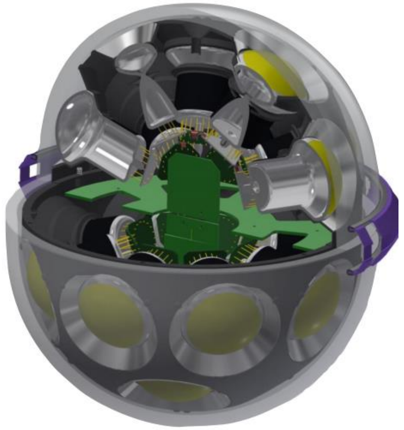
mass ordering (3y)

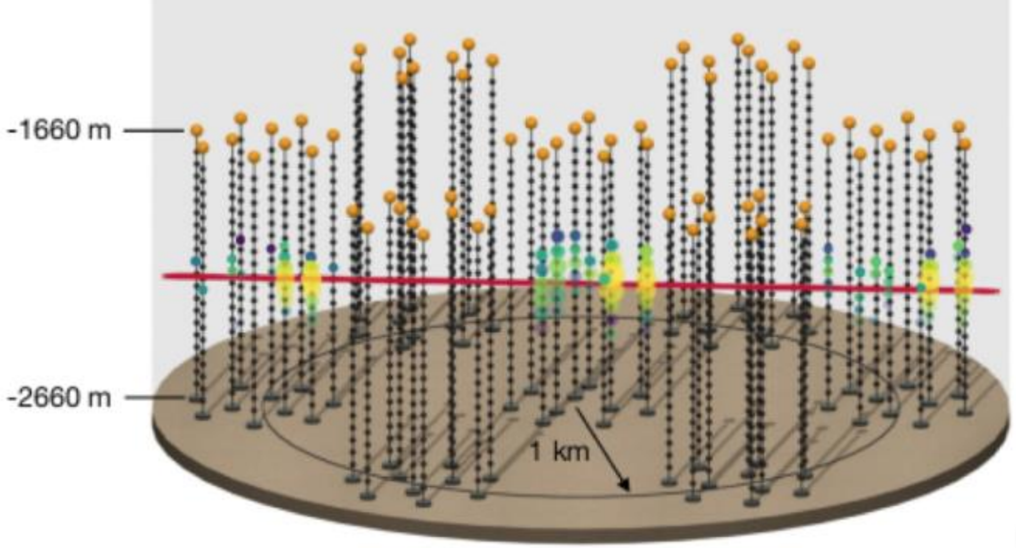
J.Phys. G43 (2016) no.8, 084001



P-ONE:
the Pacific Ocean Neutrino Explorer

-IceCube-like array
-Off the coast of Vancouver island
-Funding for first *demonstrator* secured





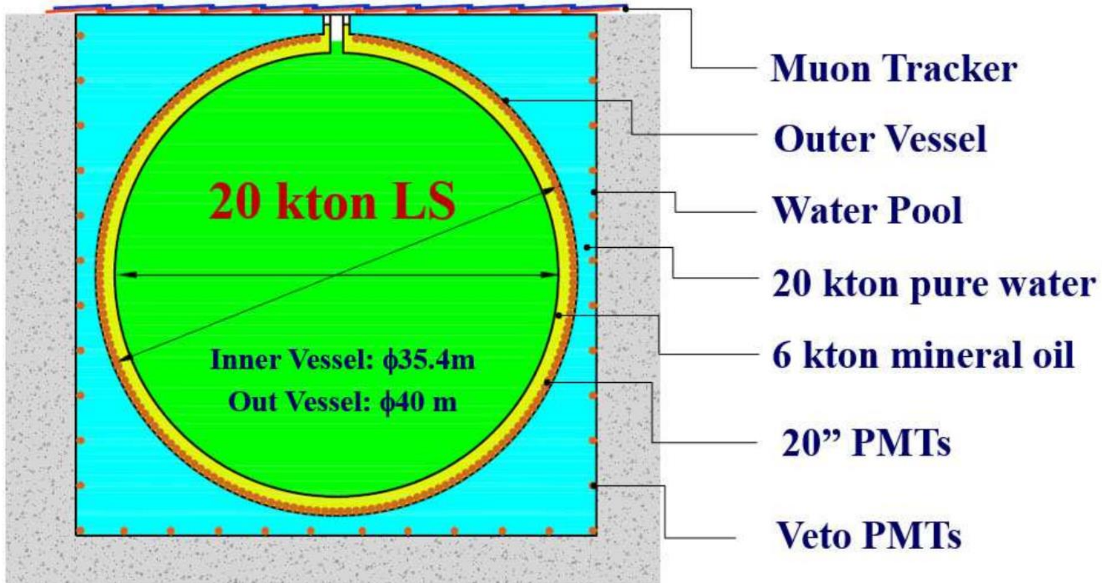
other experiments

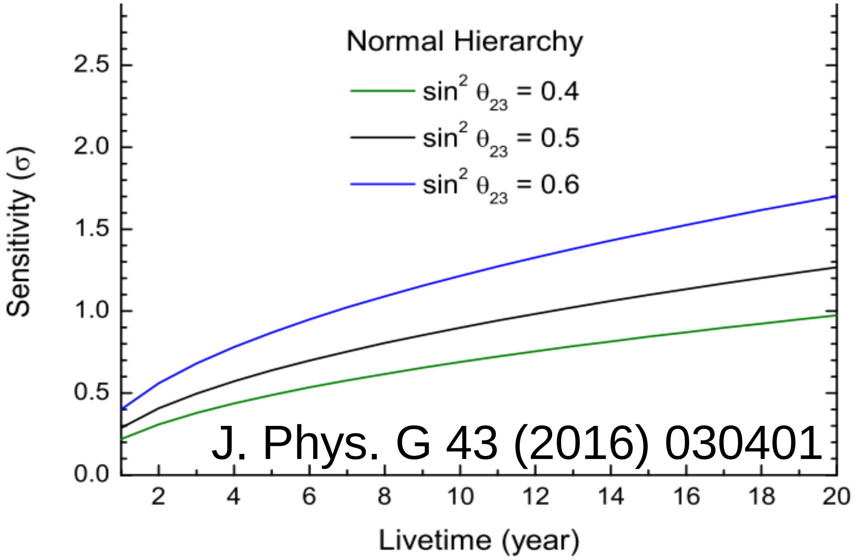
atmospheric ν are a secondary measurement

mass ordering sensitivity from atm. ν only

JUNO

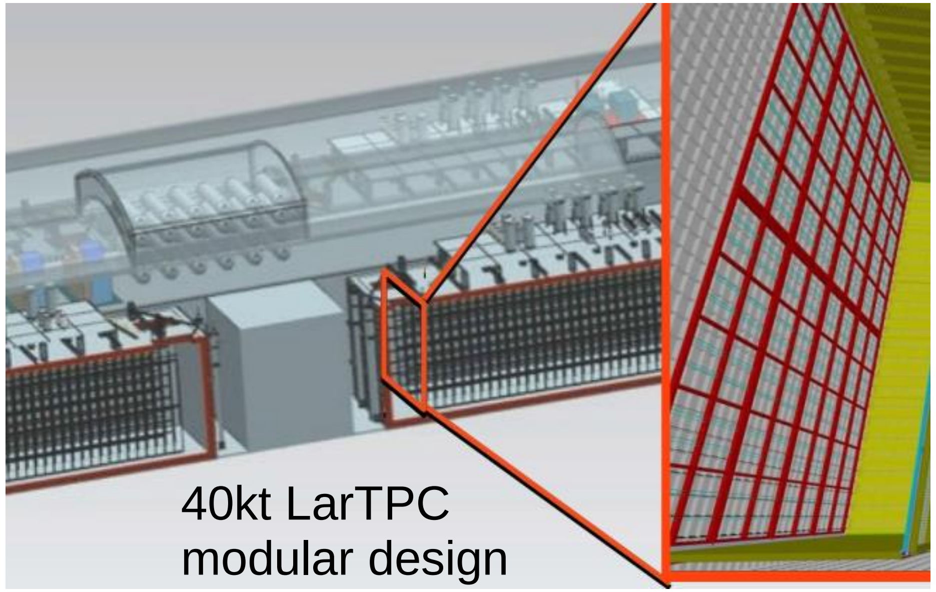
mass ordering from reactor neutrinos

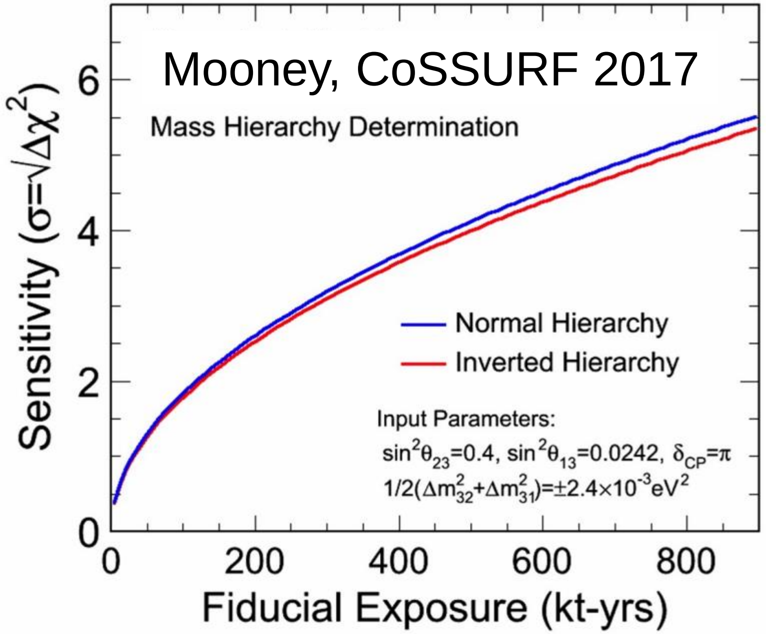




DUNE

CP violation from beam neutrinos





final words

summary & outlook

-atm. nus are an invaluable tool for neutrino physics

-very large & unique phase space in L/E, flavor

-experiments producing well understood, reliable results

-next generation measurements tough, but possible

-renewed efforts to model & understand atm nus ongoing

-more data, new software, workshops in last years