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Atmospheric Neutrino Experiments

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J. Yang, WIPAC

outline

- historical context
- modeling atmospheric neutrinos
- detection technology
- motivation & recent results
- future experiments

atmospheric neutrino origins

A lot of the material borrowed from

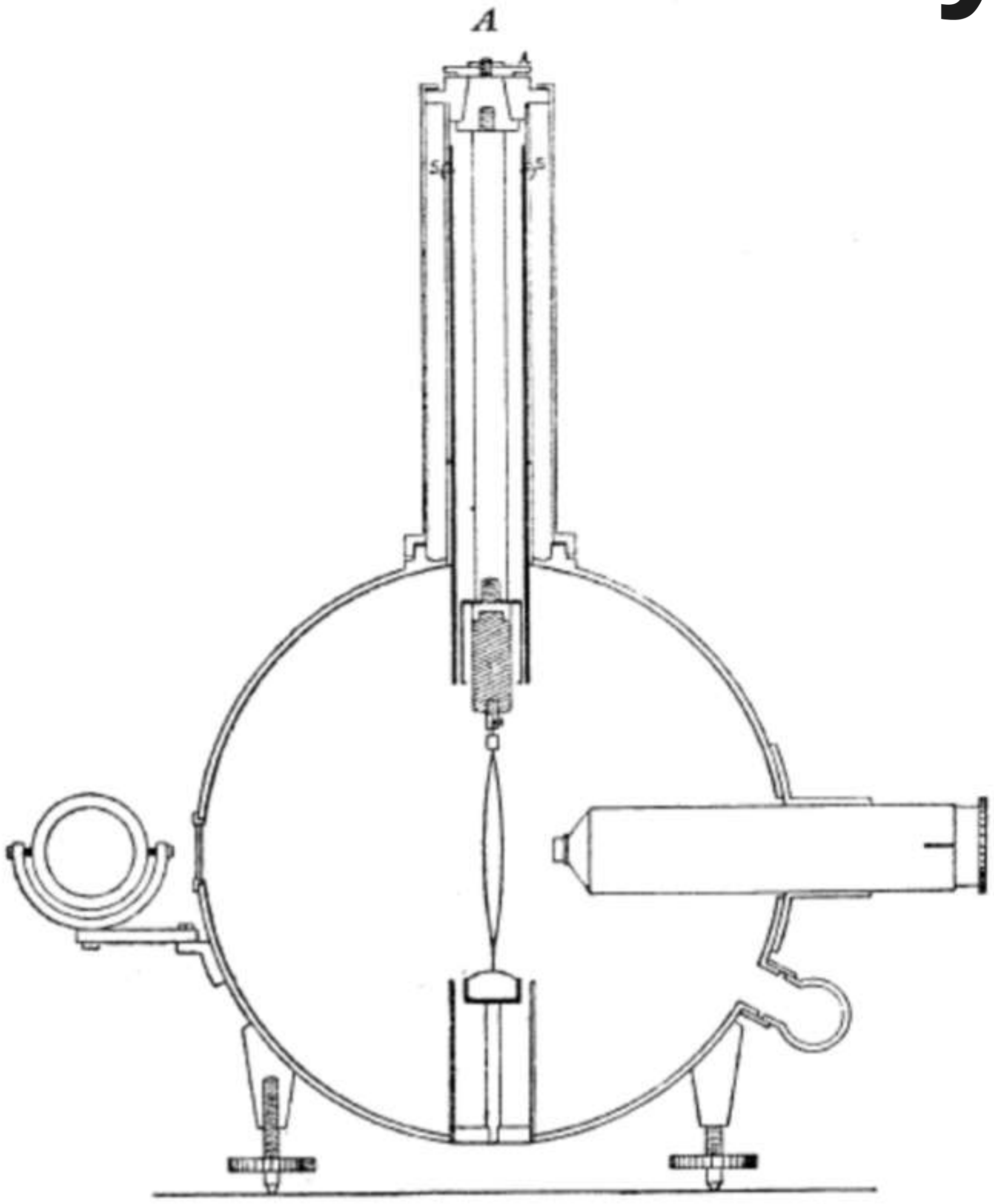
- P. Lipari’s talk at neutrino history conference
- Horeandel, Early cosmic-ray work published in German
- Bertolotti, Celestial Messengers

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?



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?

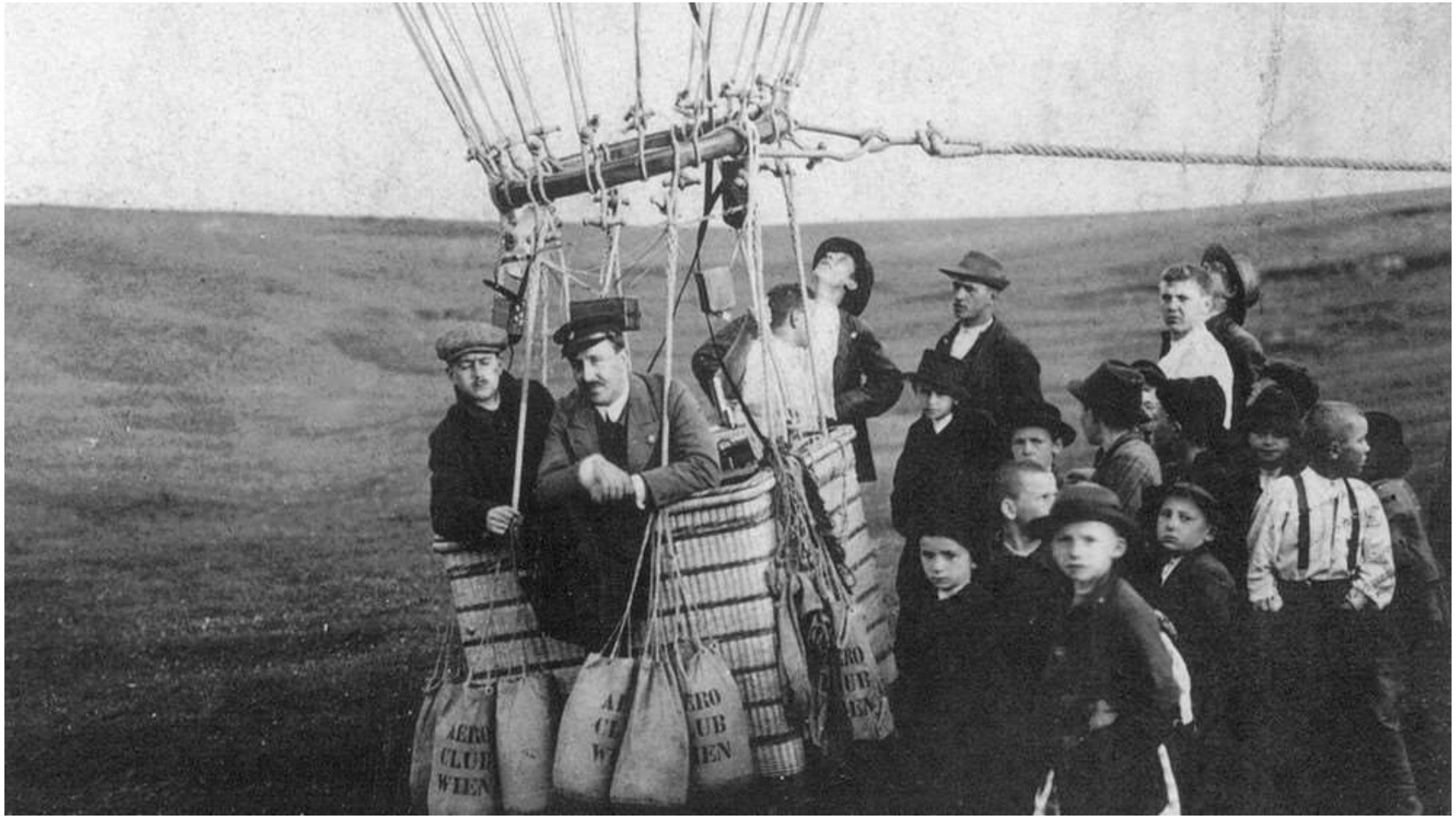
-could radioactivity have non-terrestrial origin?

-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

Physik. Zeitschr. XIII, 1912. Hess, Durchdringende Strahlung bei sieben Freiballonfahrten. 1089

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)	—	—

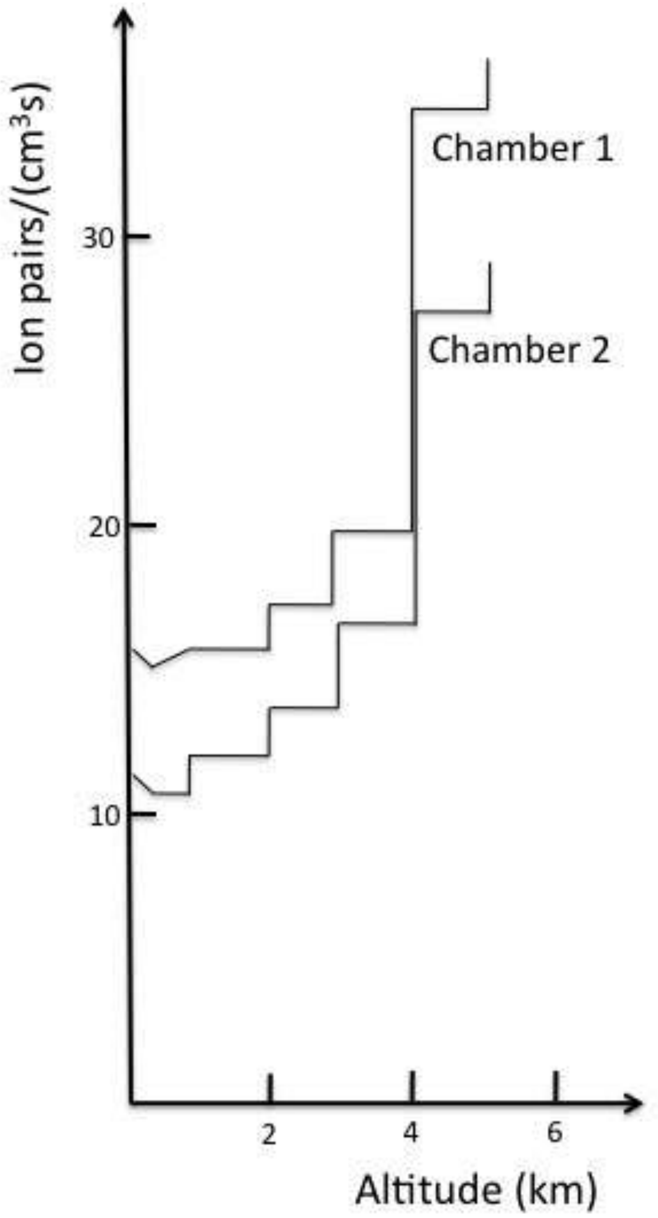
Hess, V.F., 1912, Phys.. Z, 13 1084.

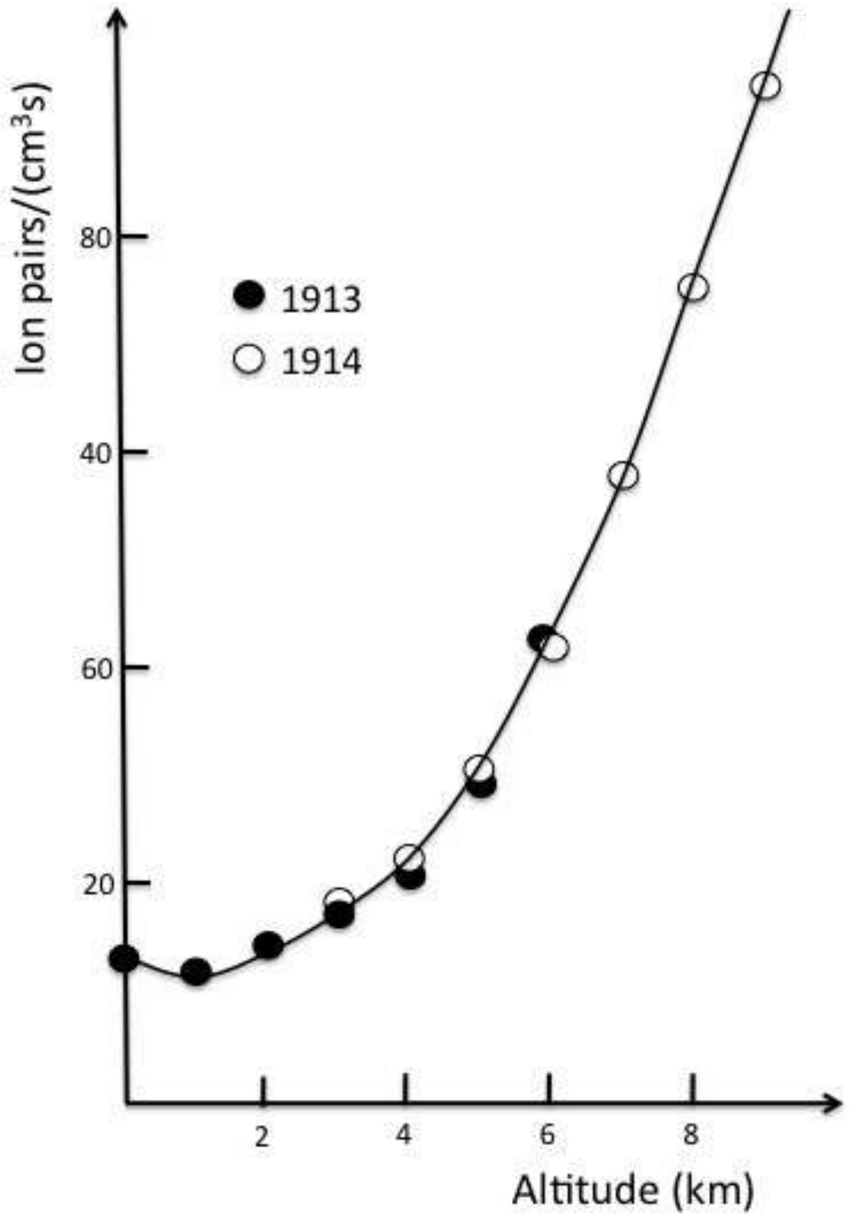
coming from the cosmos

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

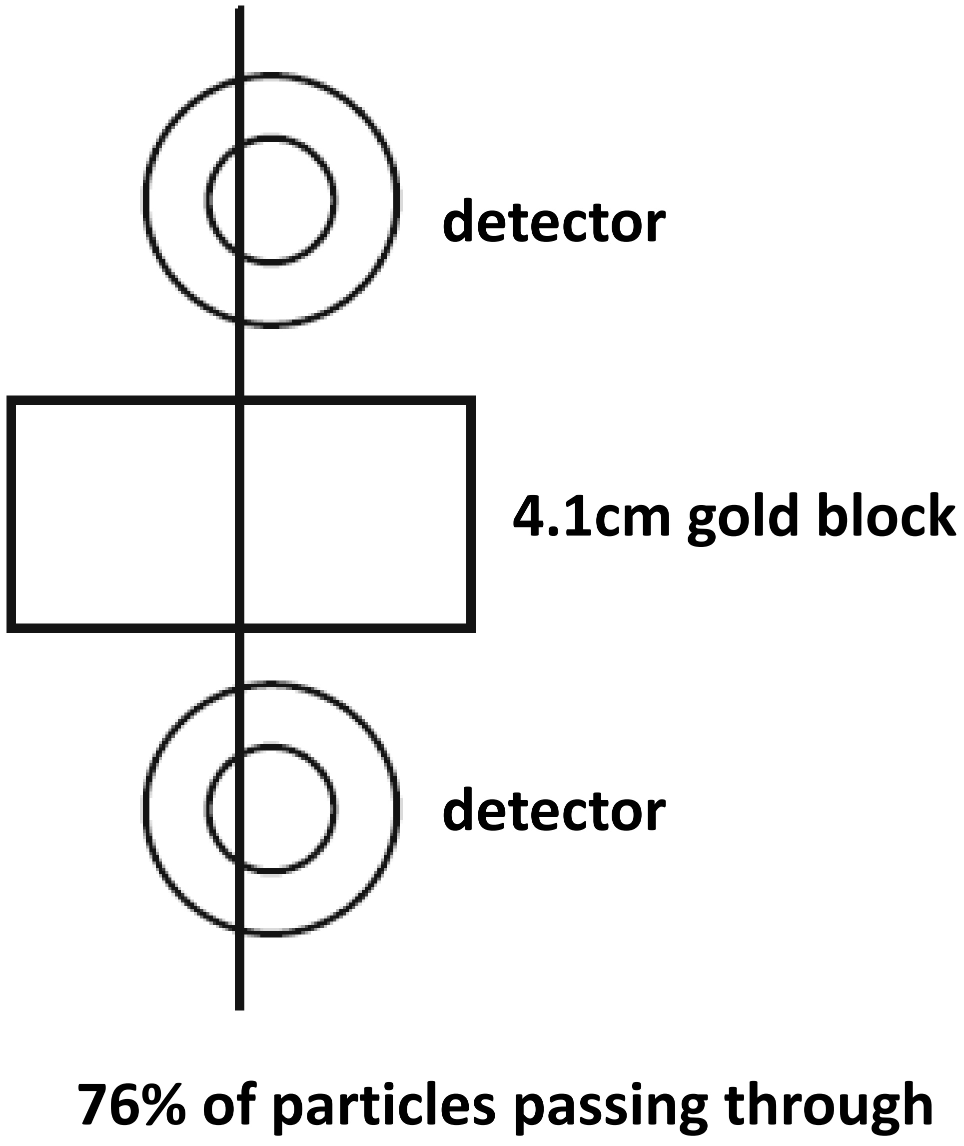
-Kolhörster confirmed the measurements shortly afterwards

-non-terrestrial radiation exists: cosmic rays





identifying the radiation



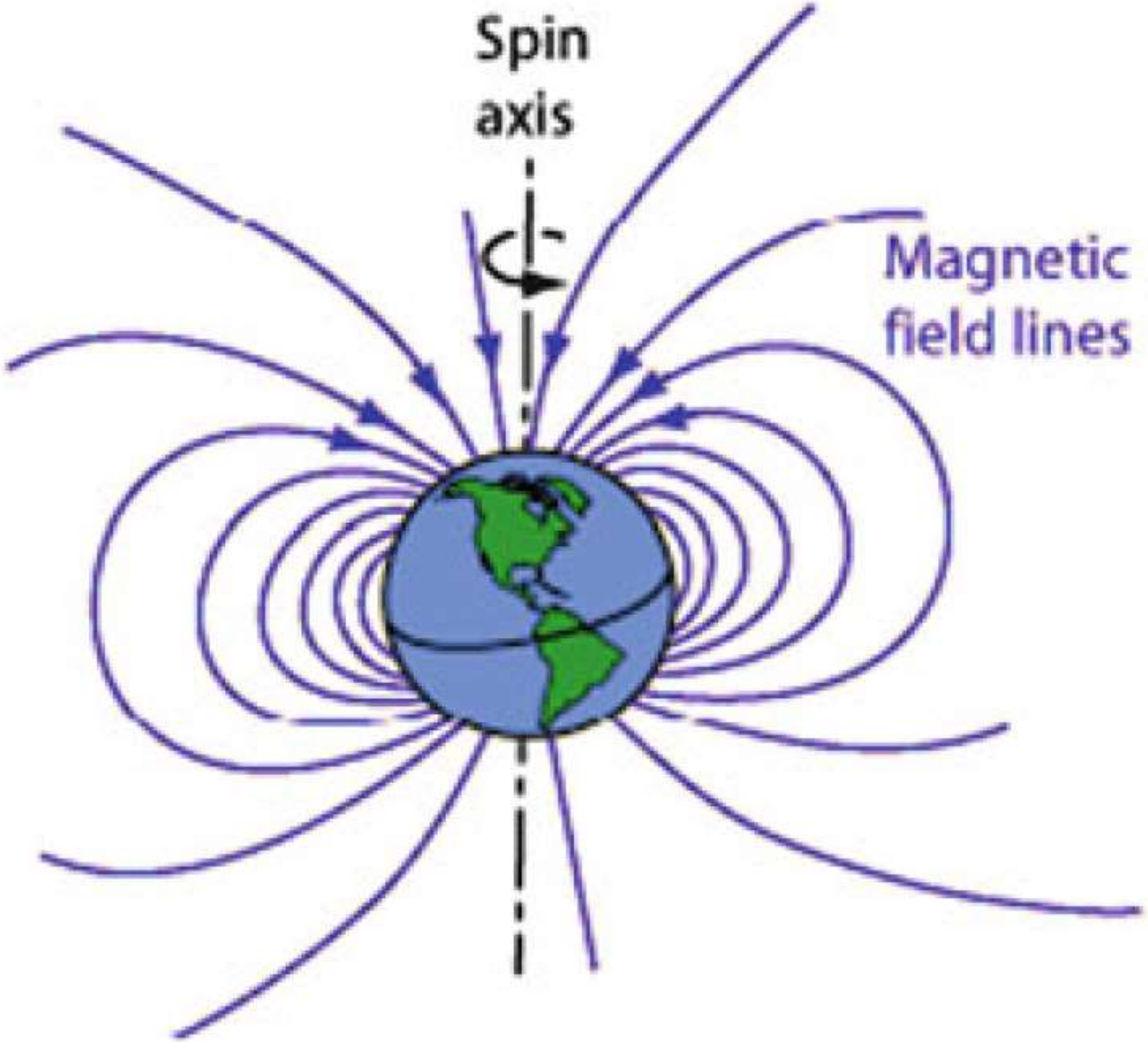
-but what is it? first believed to be **gamma rays**

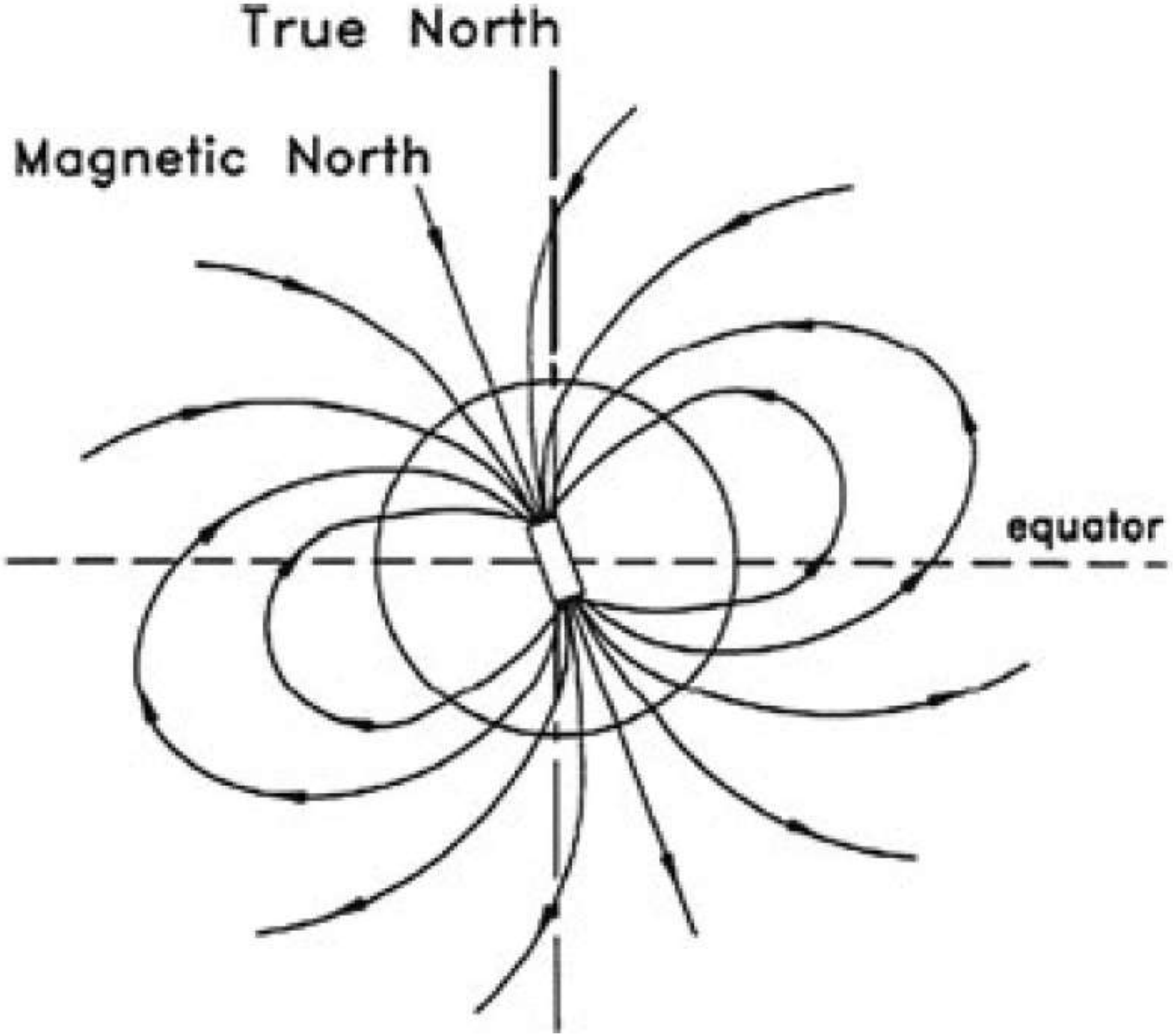
-but in 1928-1929 Bothe & Kolhoerster showed the radiation to be **very penetrating**

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

-what about the **primary** radiation?

Earth has a magnetic field

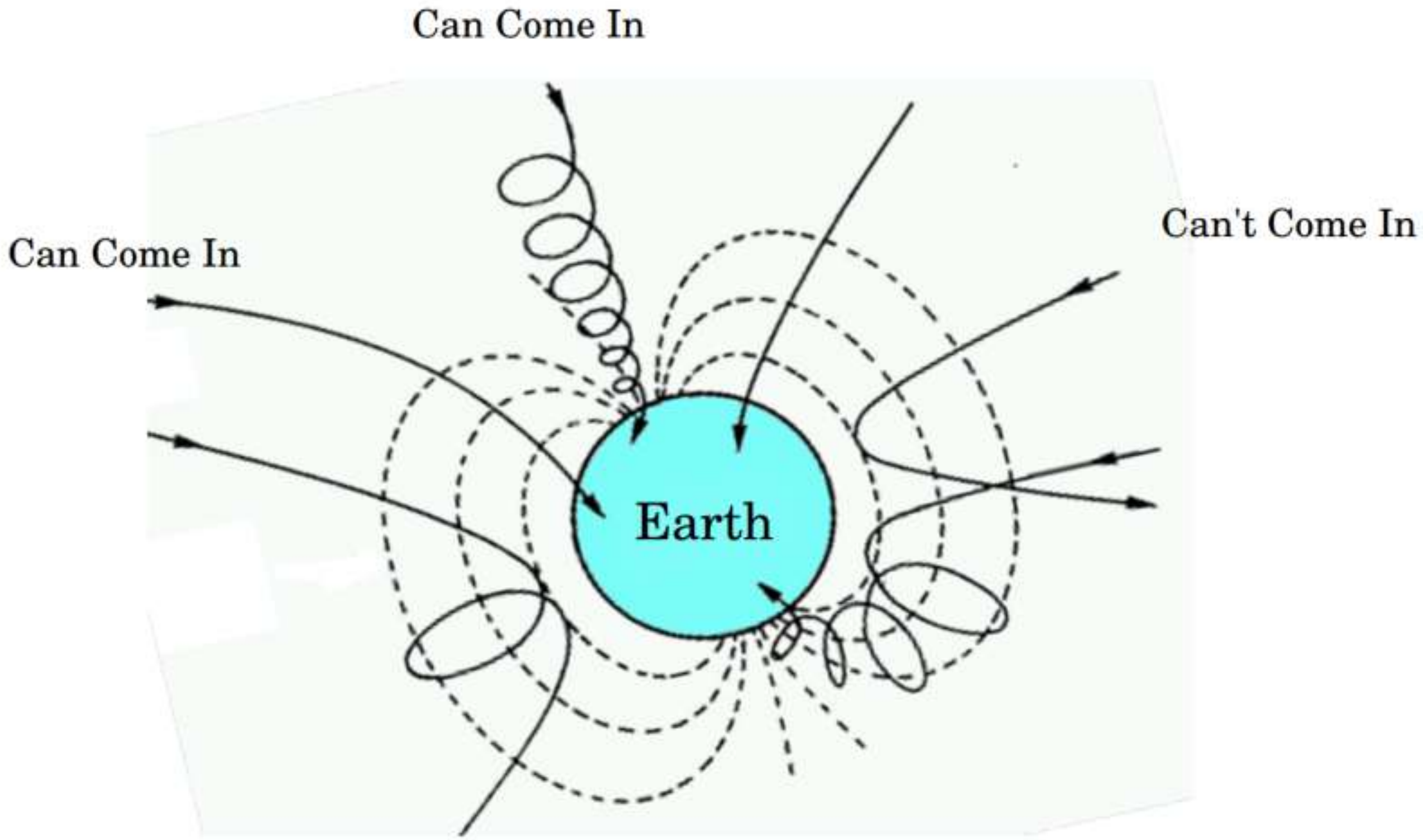


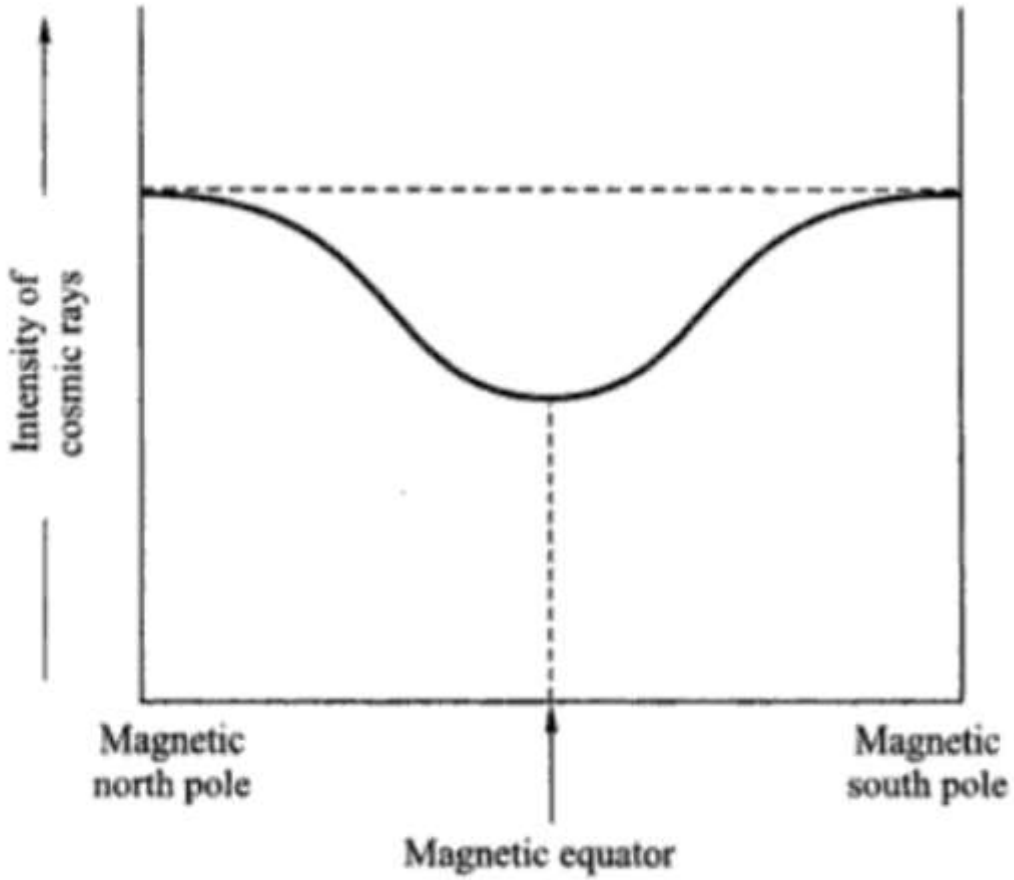


identifying primary CRs

-intensity of cosmic rays is smaller at the equator

-B-field deflecting them → they are charged!



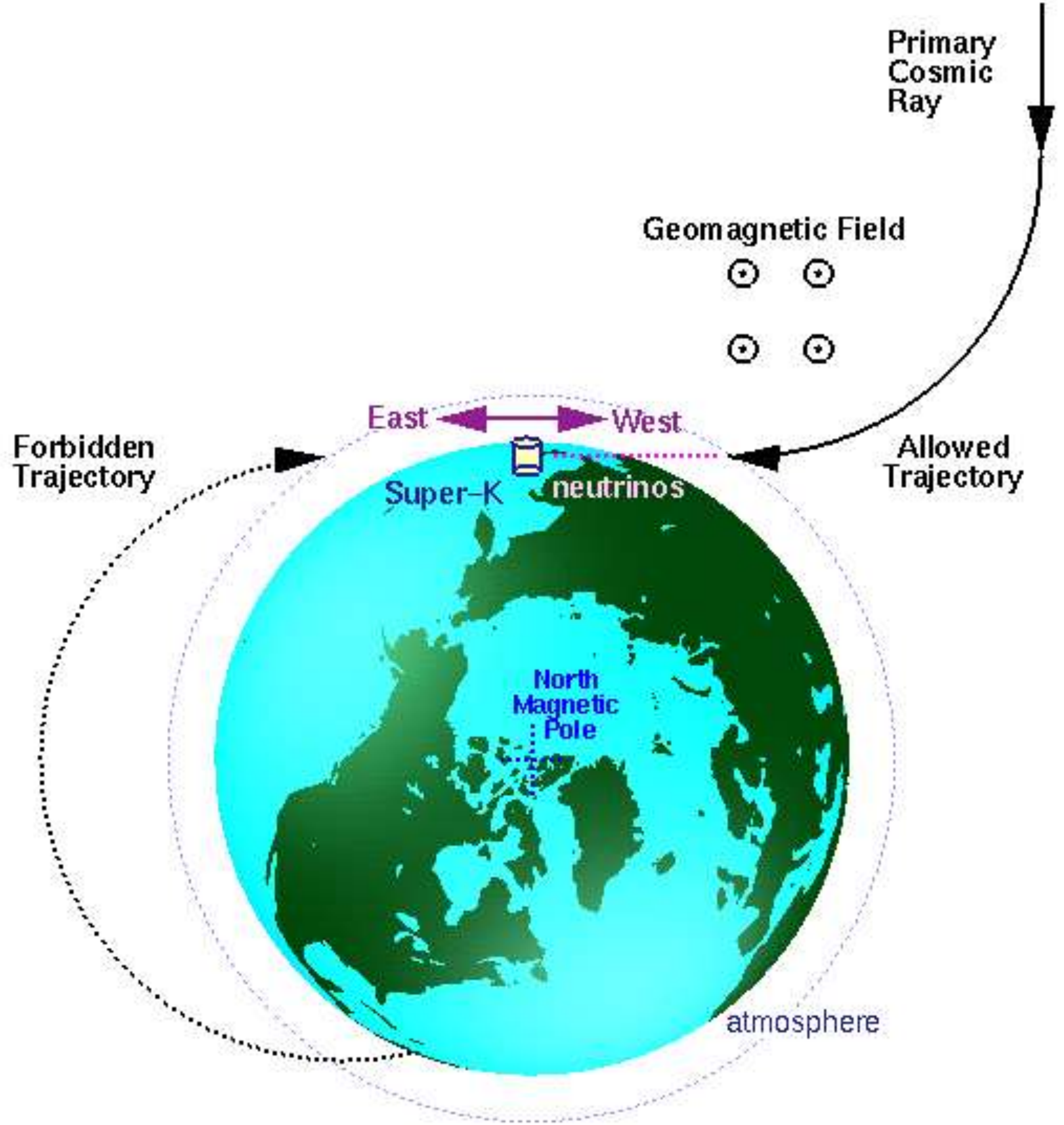


positively charged CRs

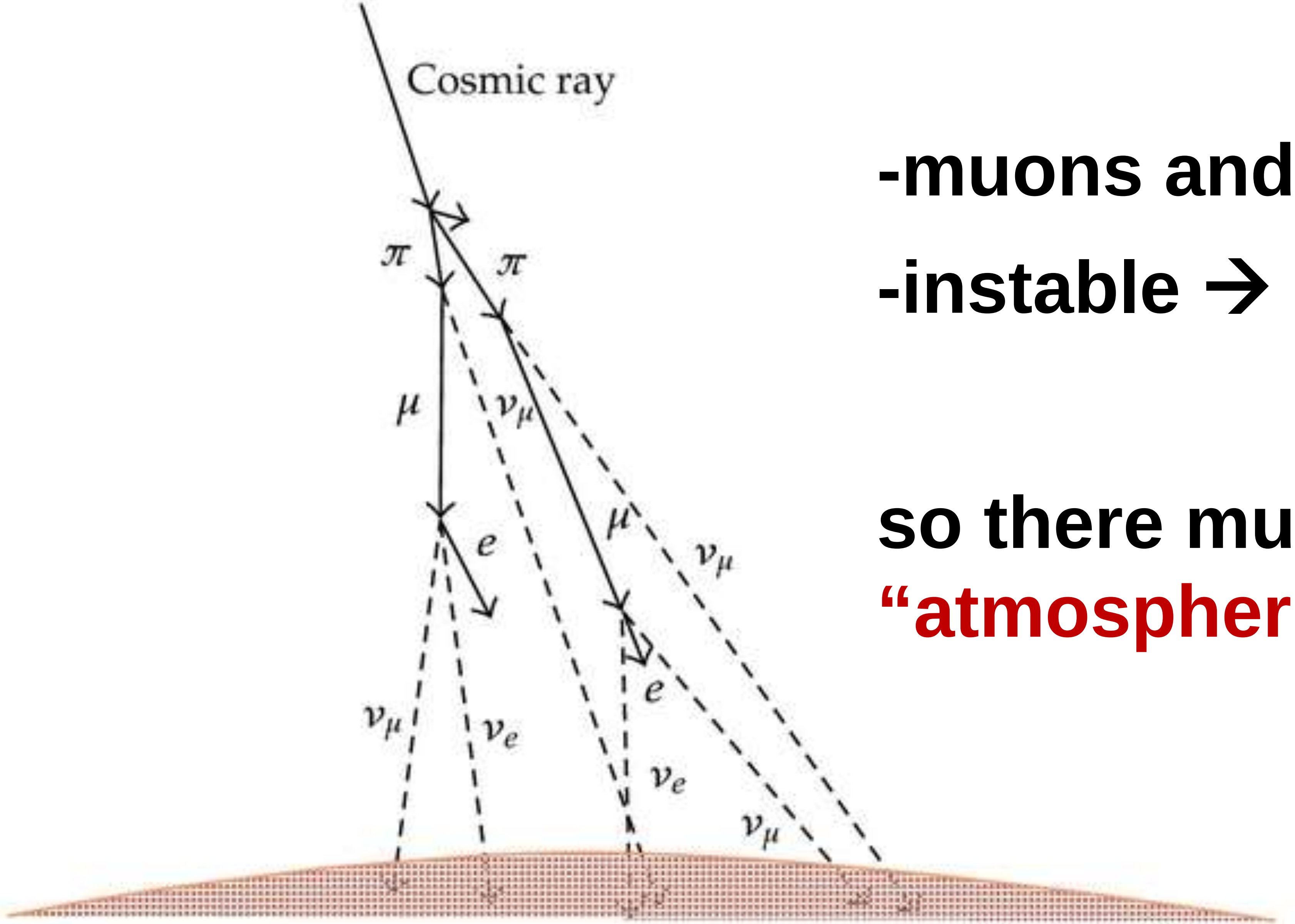
-in 1930 Rossi proposed a charge-induced asymmetry in arrival directions

-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

-instable → decay → neutrinos

so there must be an
"atmospheric neutrino" flux

modeling the atmospheric neutrino flux

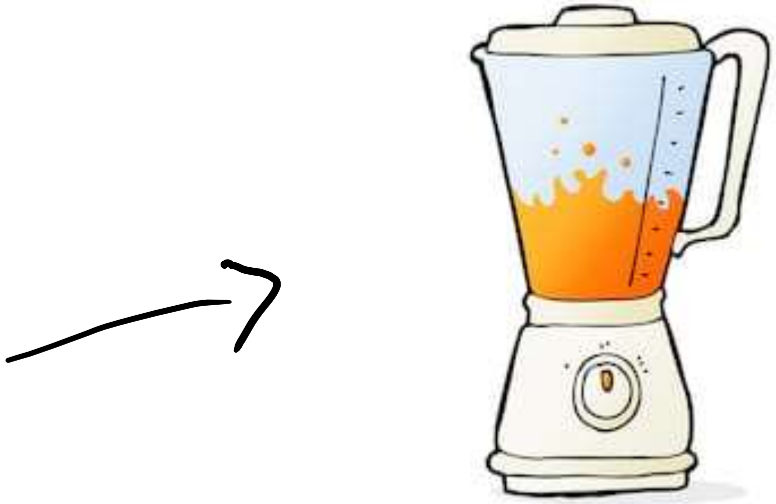
calculation needs

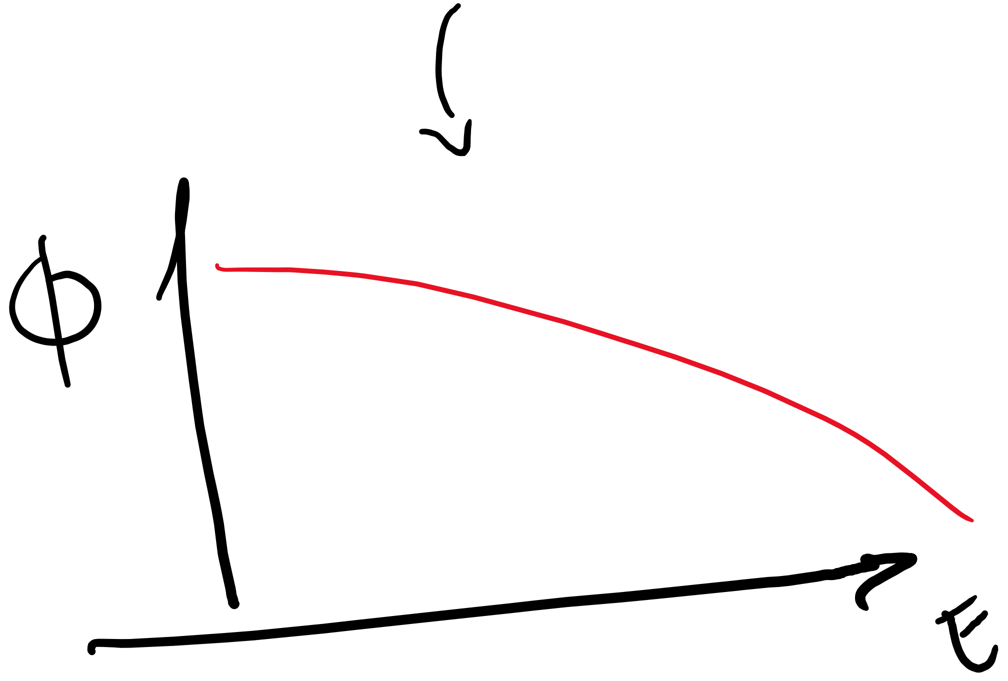
-**cosmic ray** flux

-atmospheric **density**

-hadronic **interactions**

-model of weak **decays**

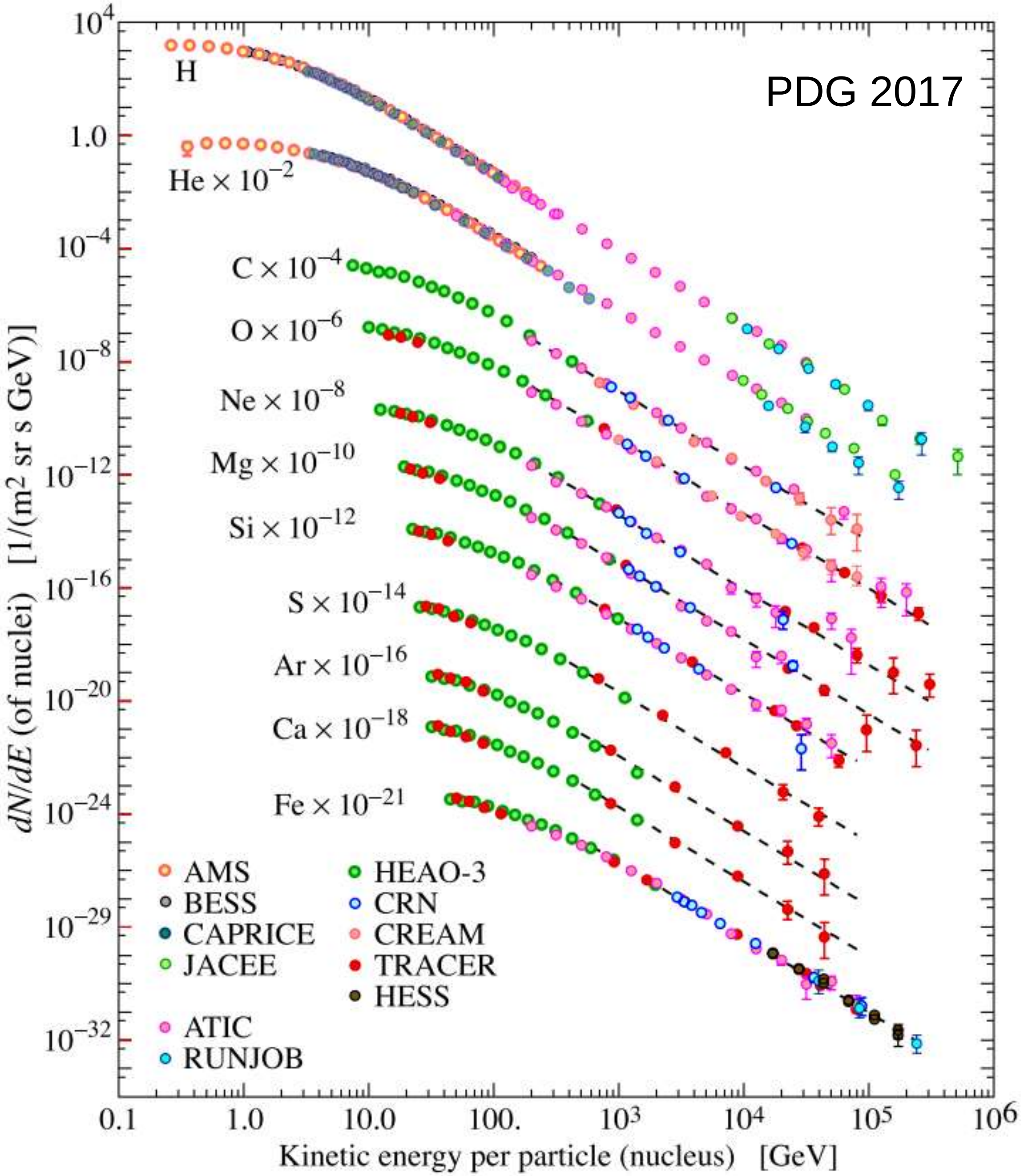




cosmic ray flux

-many **new measurements** in last years

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

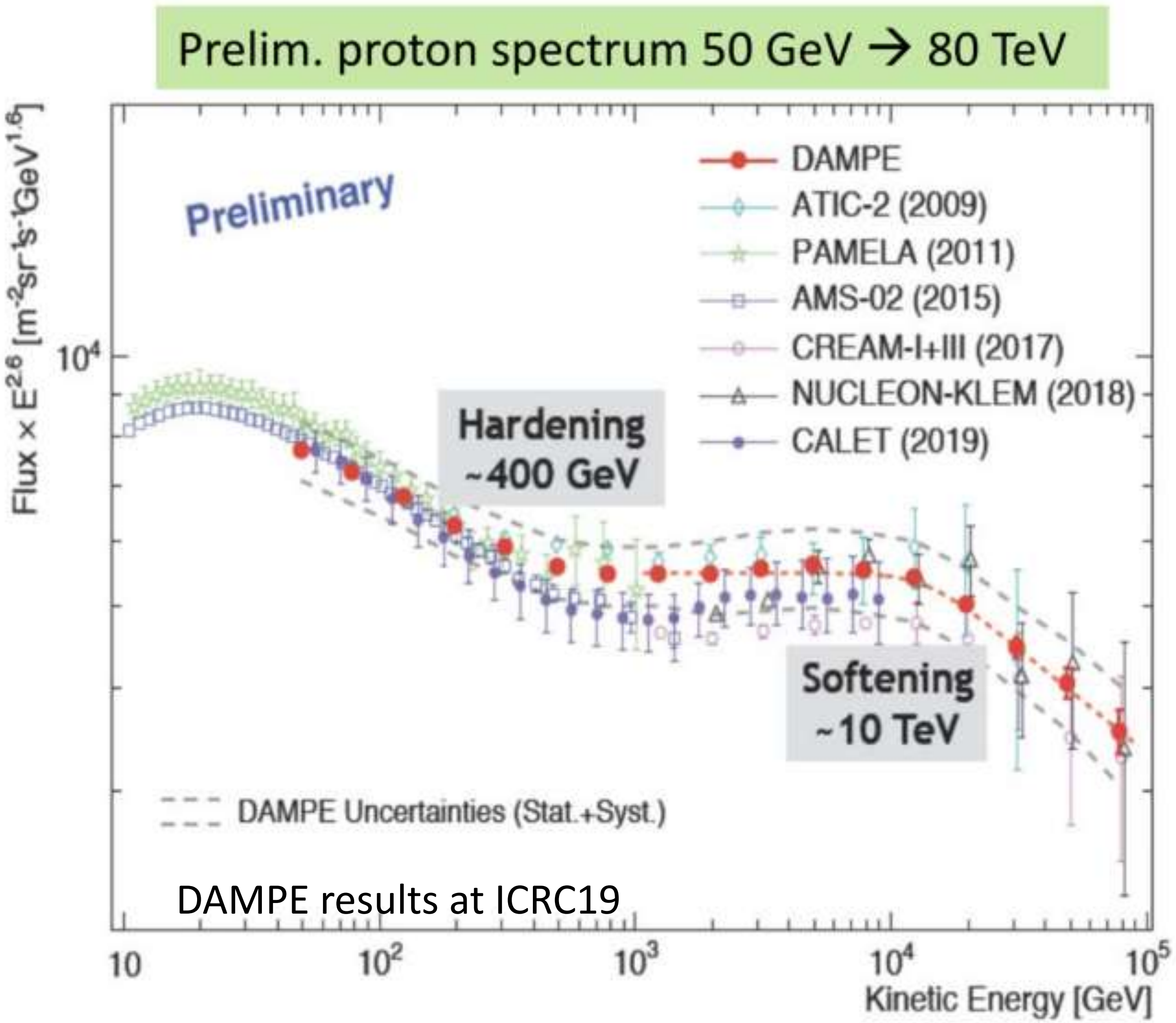


cosmic ray flux

-many **new measurements** in last years

-extreme precision from AMS-II, CALET and DAMPE

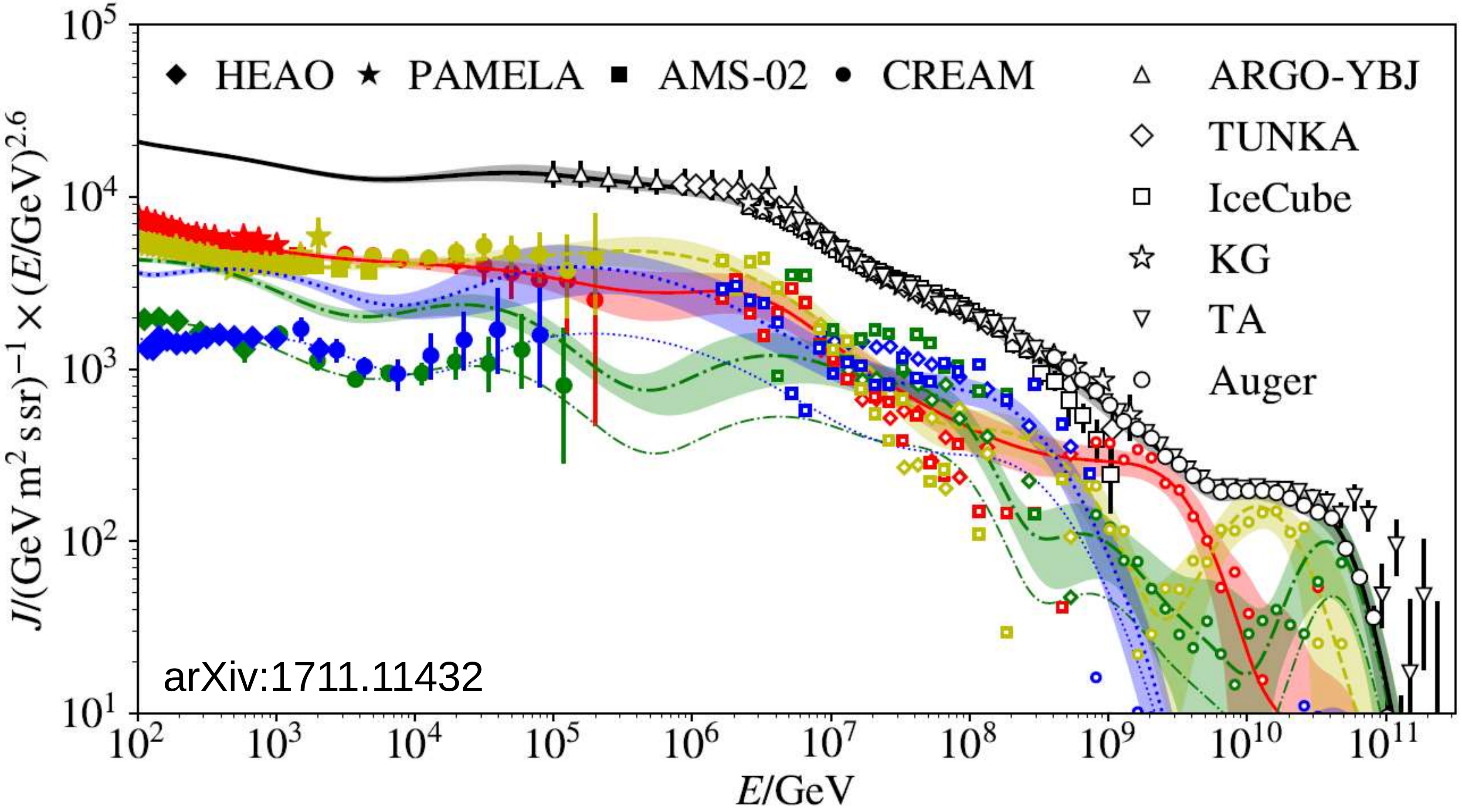
-systematics limited?



cosmic ray flux

a new way to model

- -standard model: power law primary fluxes
- -new approach:
  global fit to data

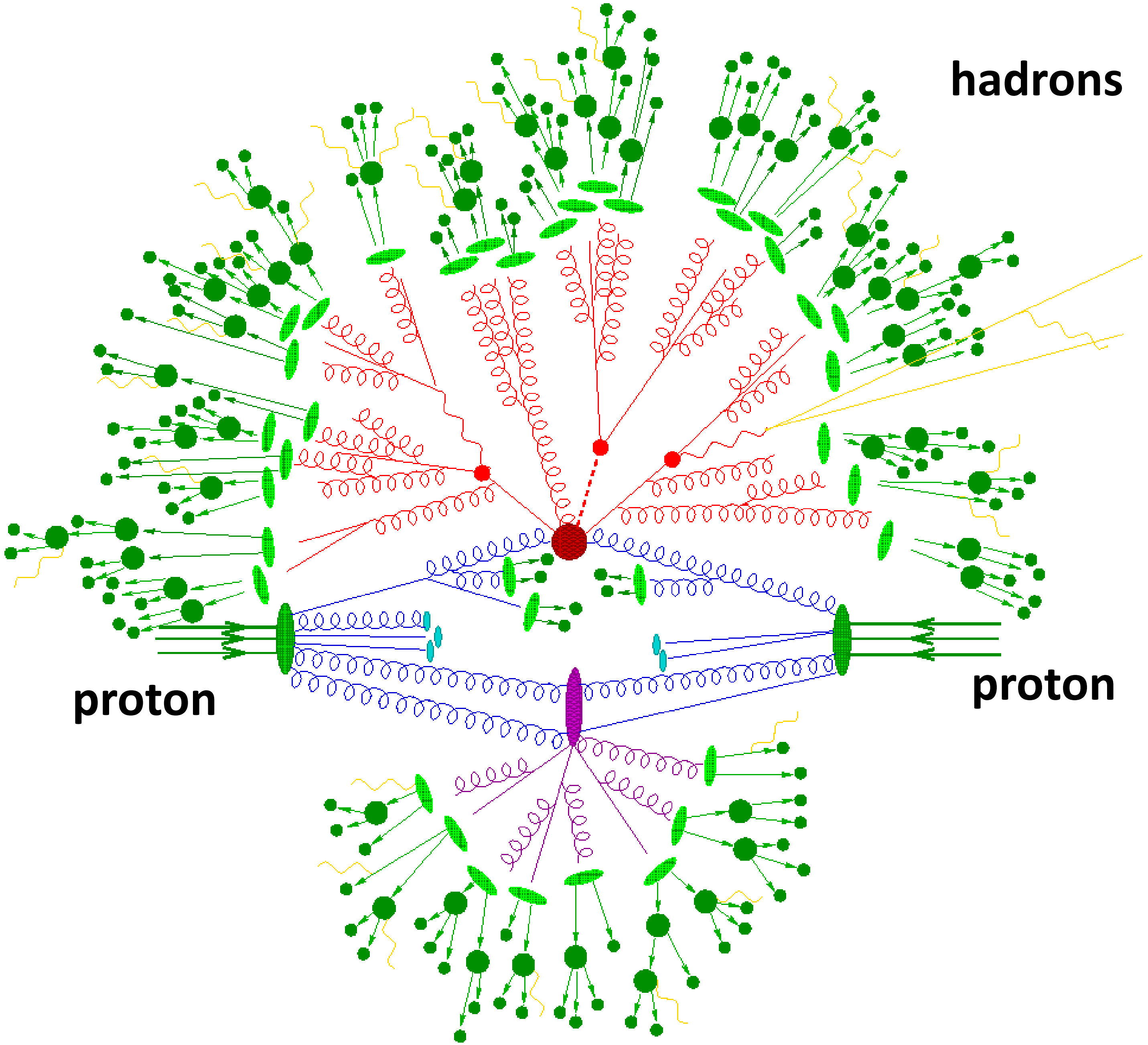


hadronic interactions

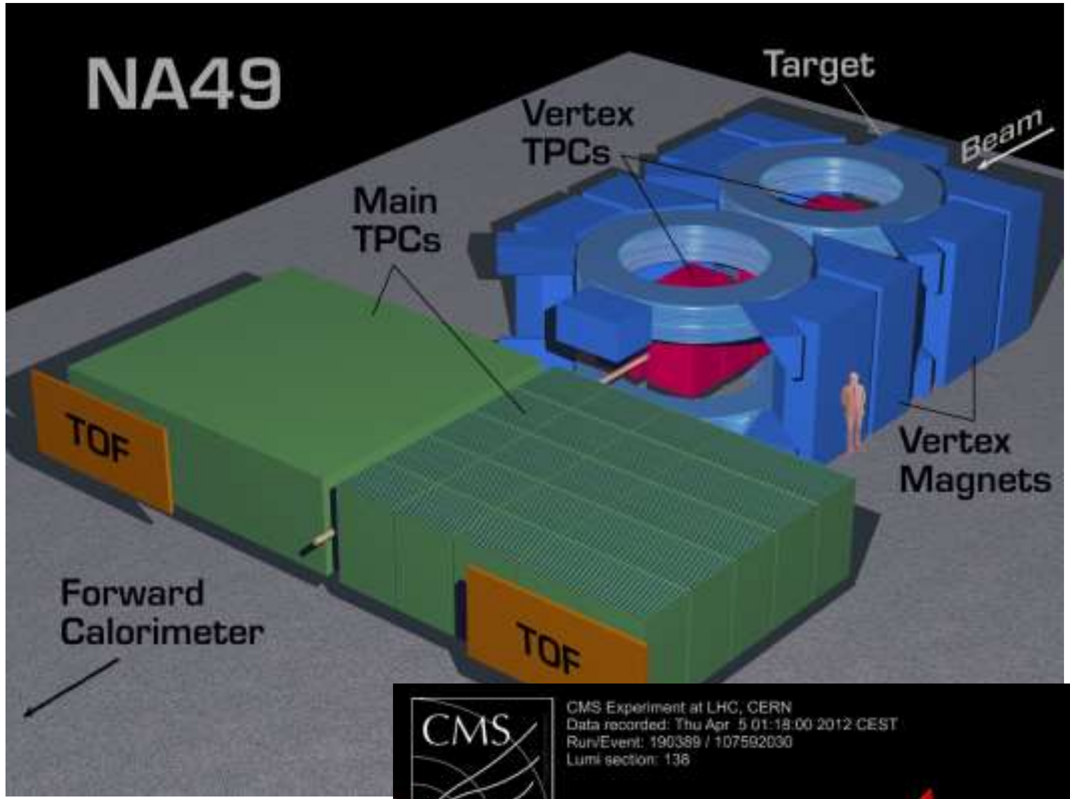
-**messy** interactions

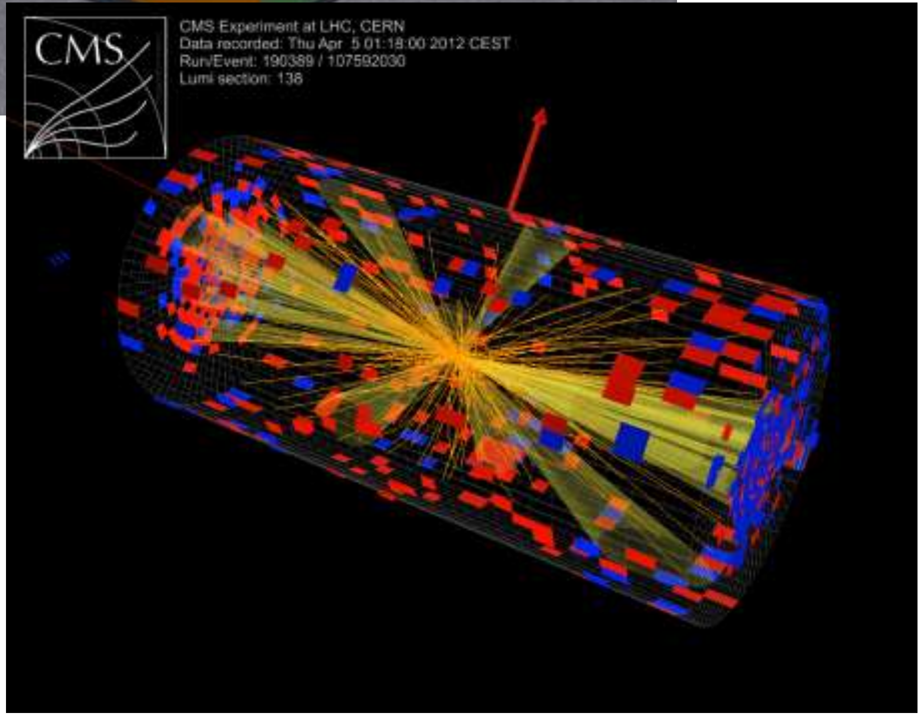
-no full first-principle calculations

-use MC generators that **mix** phenomenology and calculations



hadronic interactions



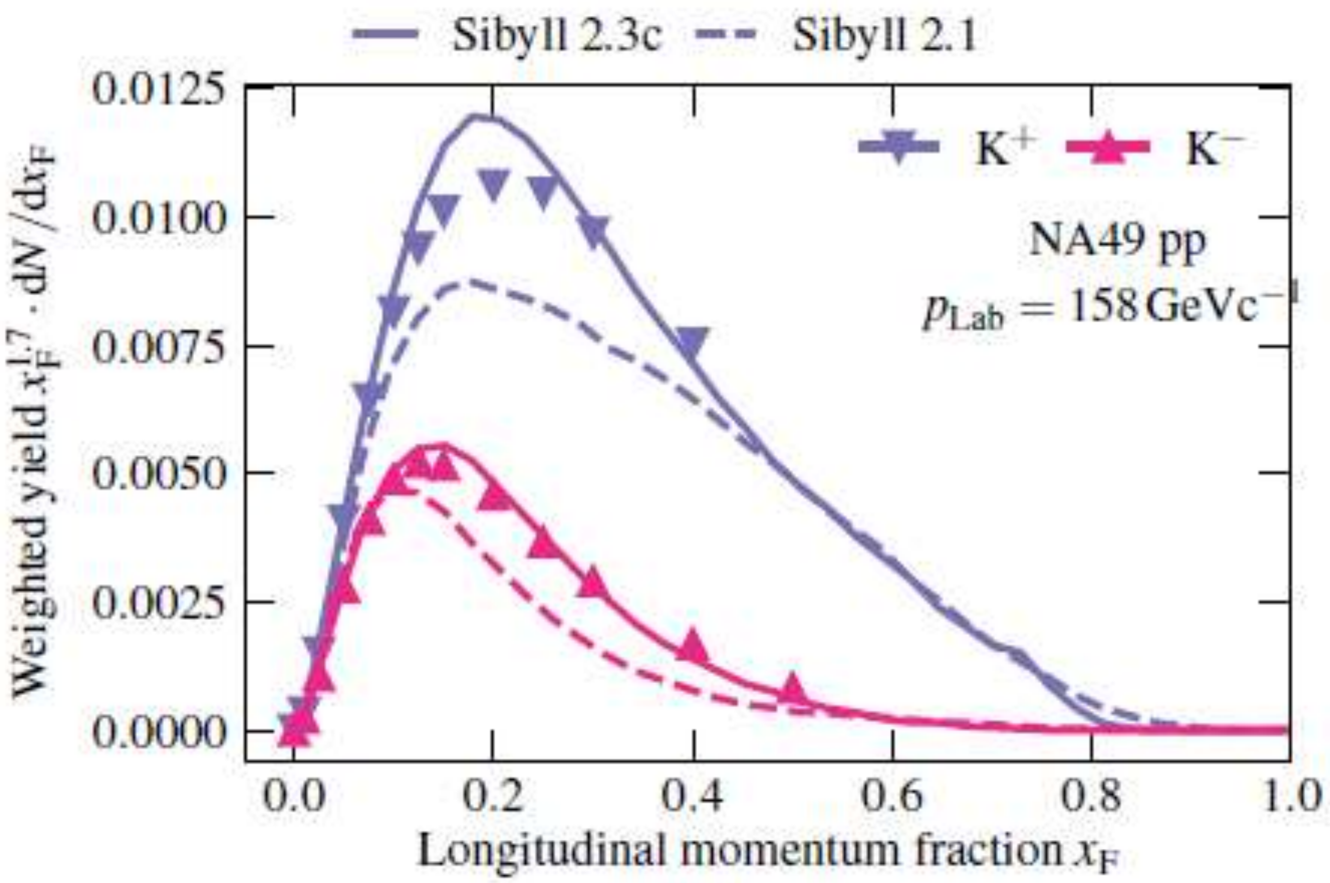


-MC generators **tuned** to data

-using fixed target experiments, colliders

-**extrapolate** in regions without data

hadronic interactions



-MC generators **tuned** to data

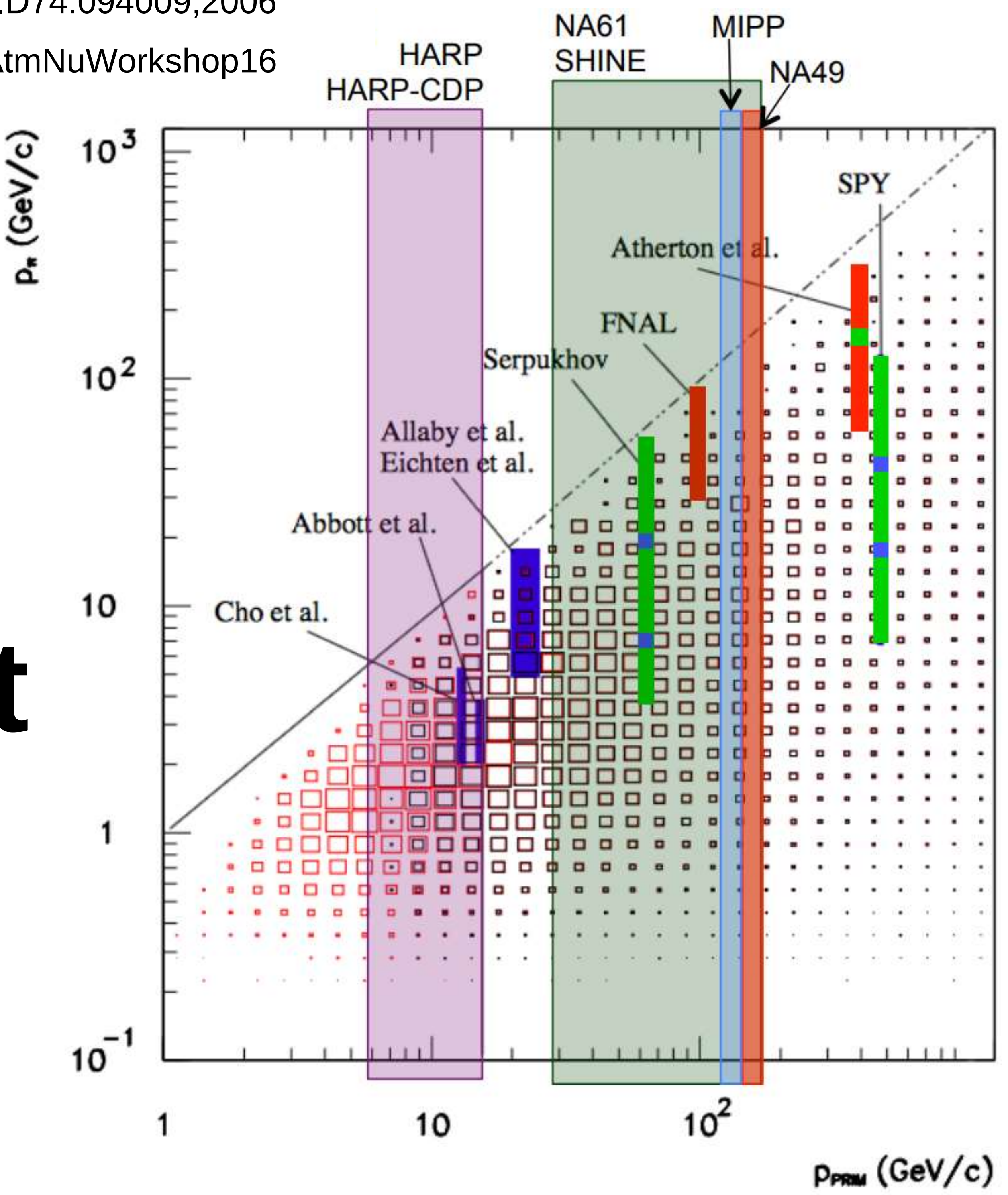
-using fixed target experiments, colliders

-**extrapolate** in regions without data

Updated from Phys.Rev.D74:094009,2006

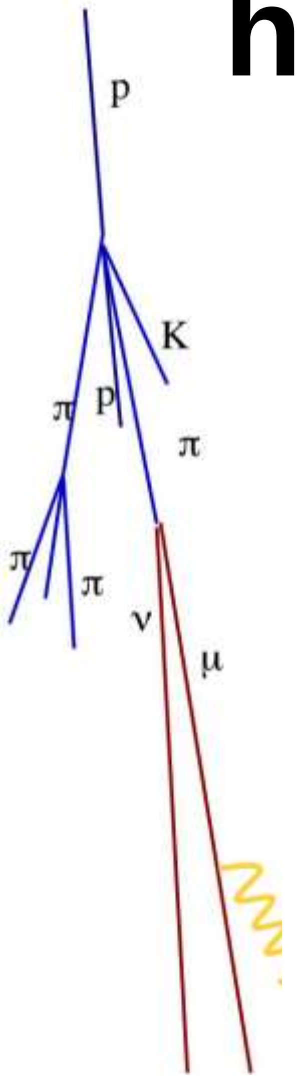
Barr, AtmNuWorkshop16

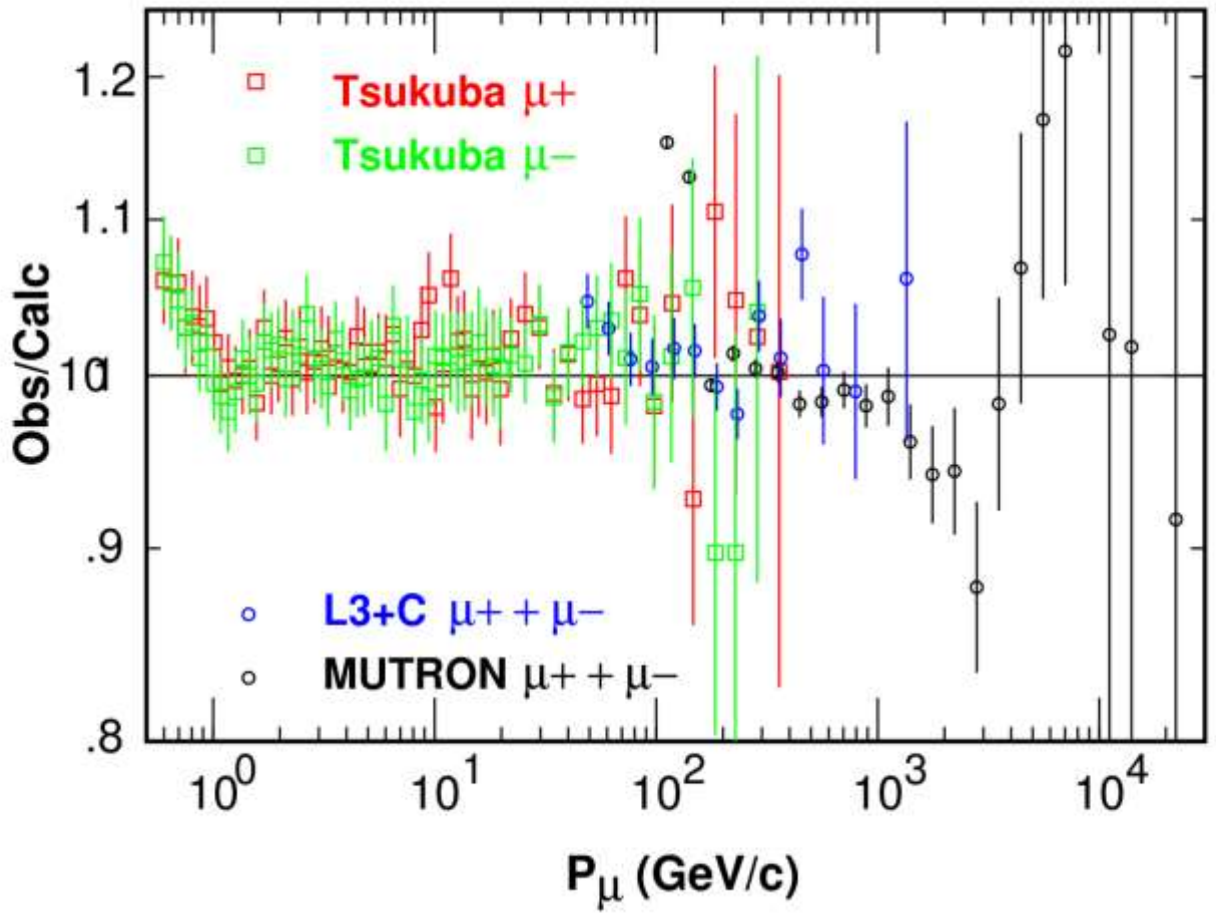
experimental **coverage** increasing but still limited



hadronic model calibration

-use **cosmic muon** data to calibrate hadronic int. models → **nu flux**





Honda, PANE2018
Muon flux comparison after
tuning hadronic interaction models

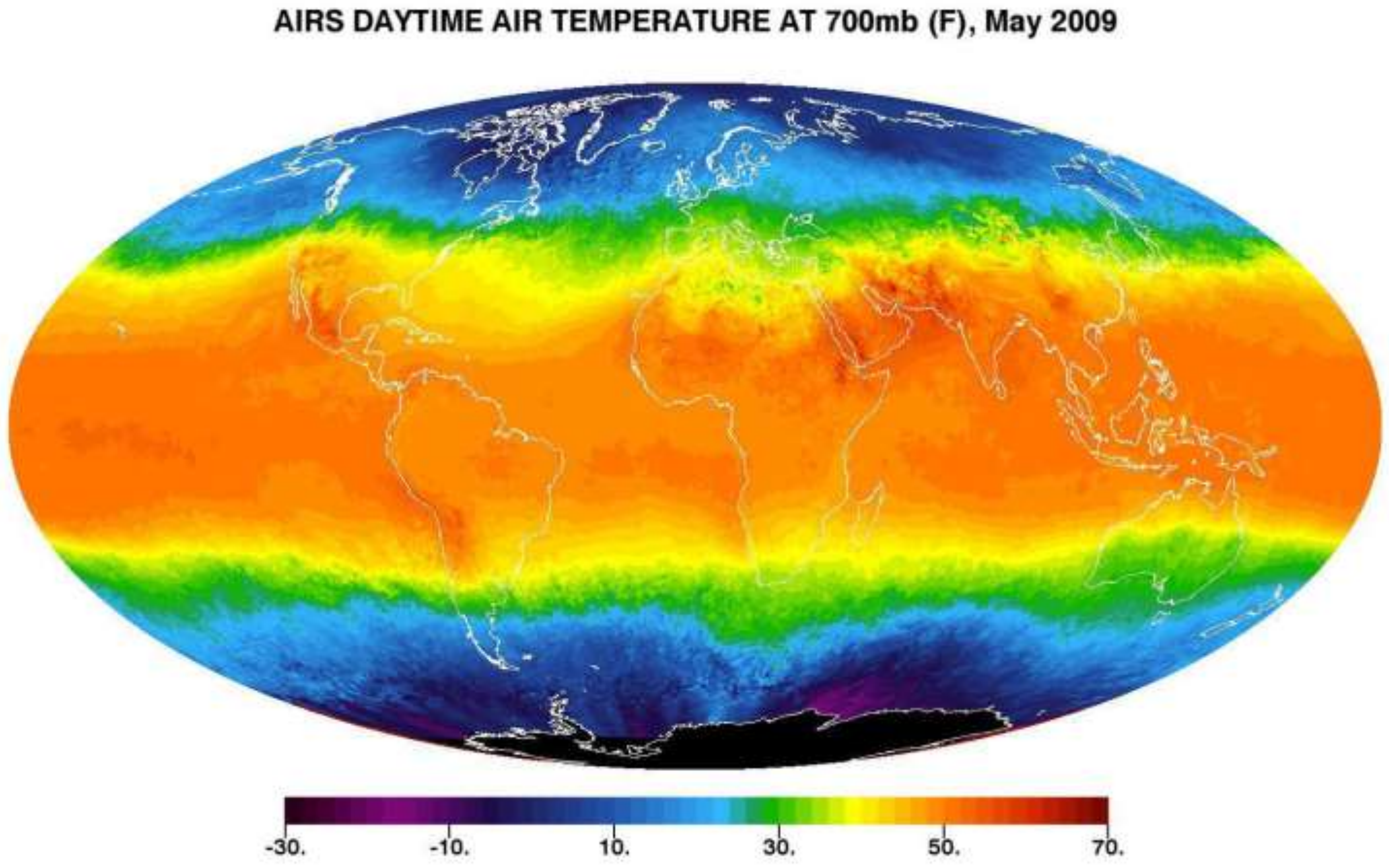
atmospheric density

-model or direct measurement

-using satellite data

AIRS

NRLMSIS-E-00



computation scheme options

a) analytically approx. cascade equations

b) numerically solving the equations

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

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

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

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

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

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

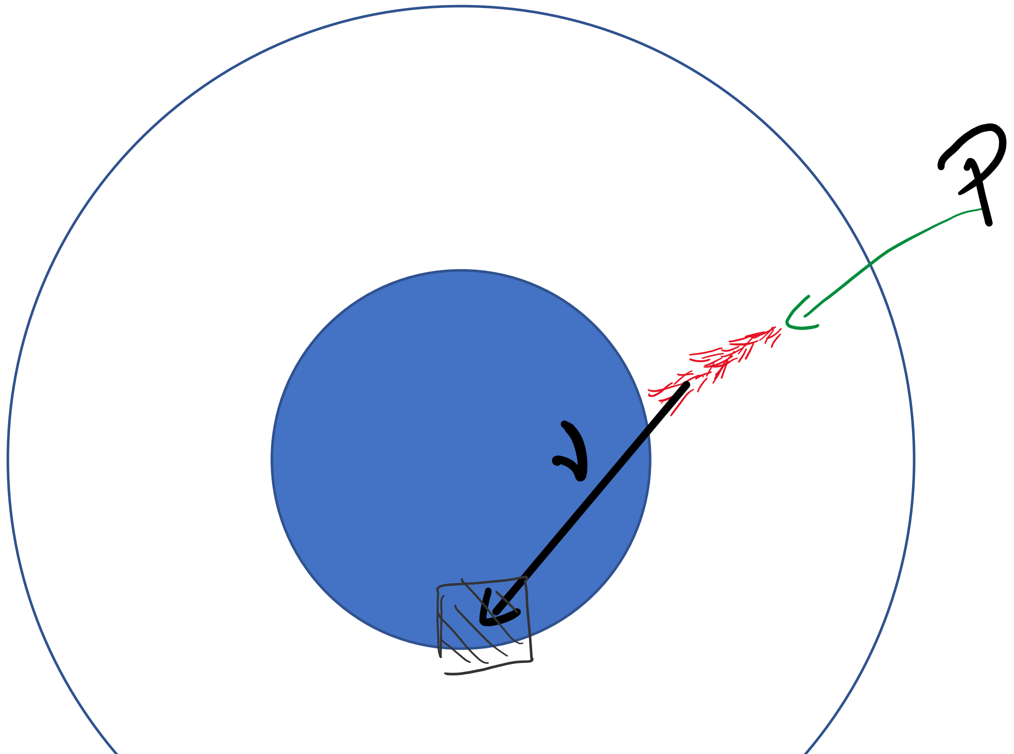
$$X(h_0) = \int_0^{h_0} \mathrm{d}\ell \; \rho_{\mathrm{air}}(\ell)$$

computation scheme options

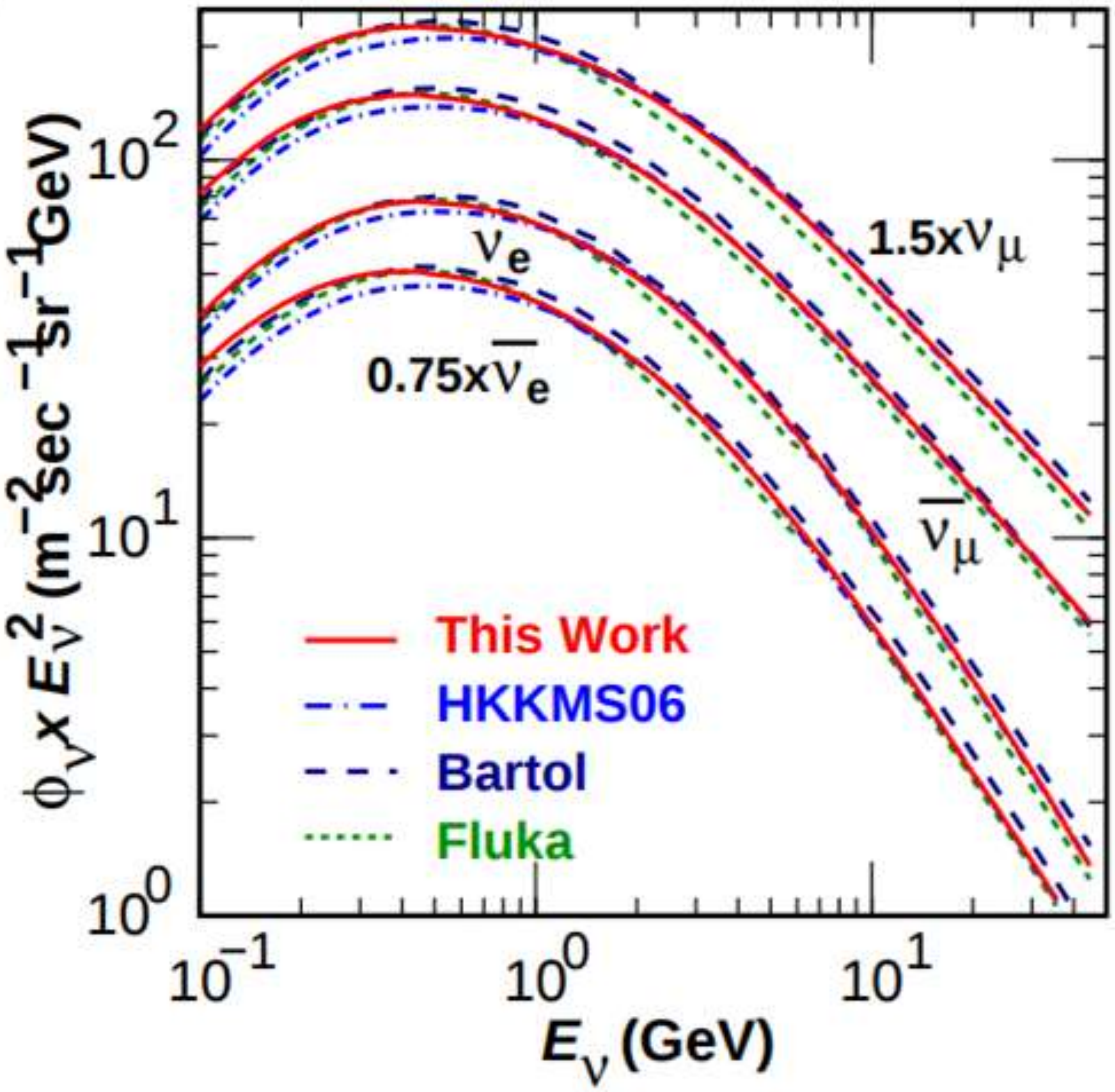
a) analytically approx. cascade equations

b) numerically solving the equations

c) MC of CR injected far from Earth



predicted flux



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

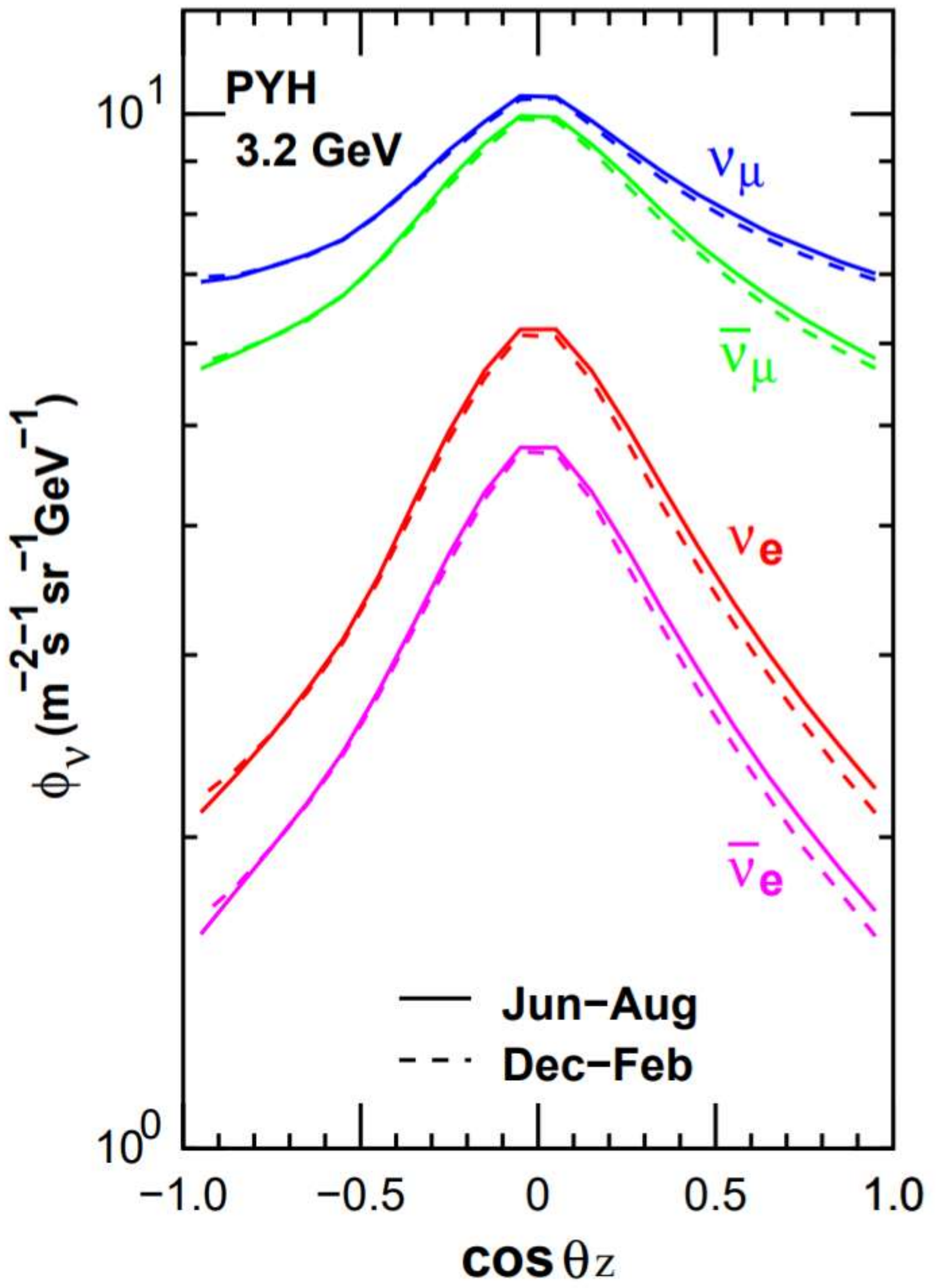
-covers a **wide energy** range

-contains **four** different particles

-dominated by **muon** neutrinos

-approximately top/down **symmetric**

predicted flux



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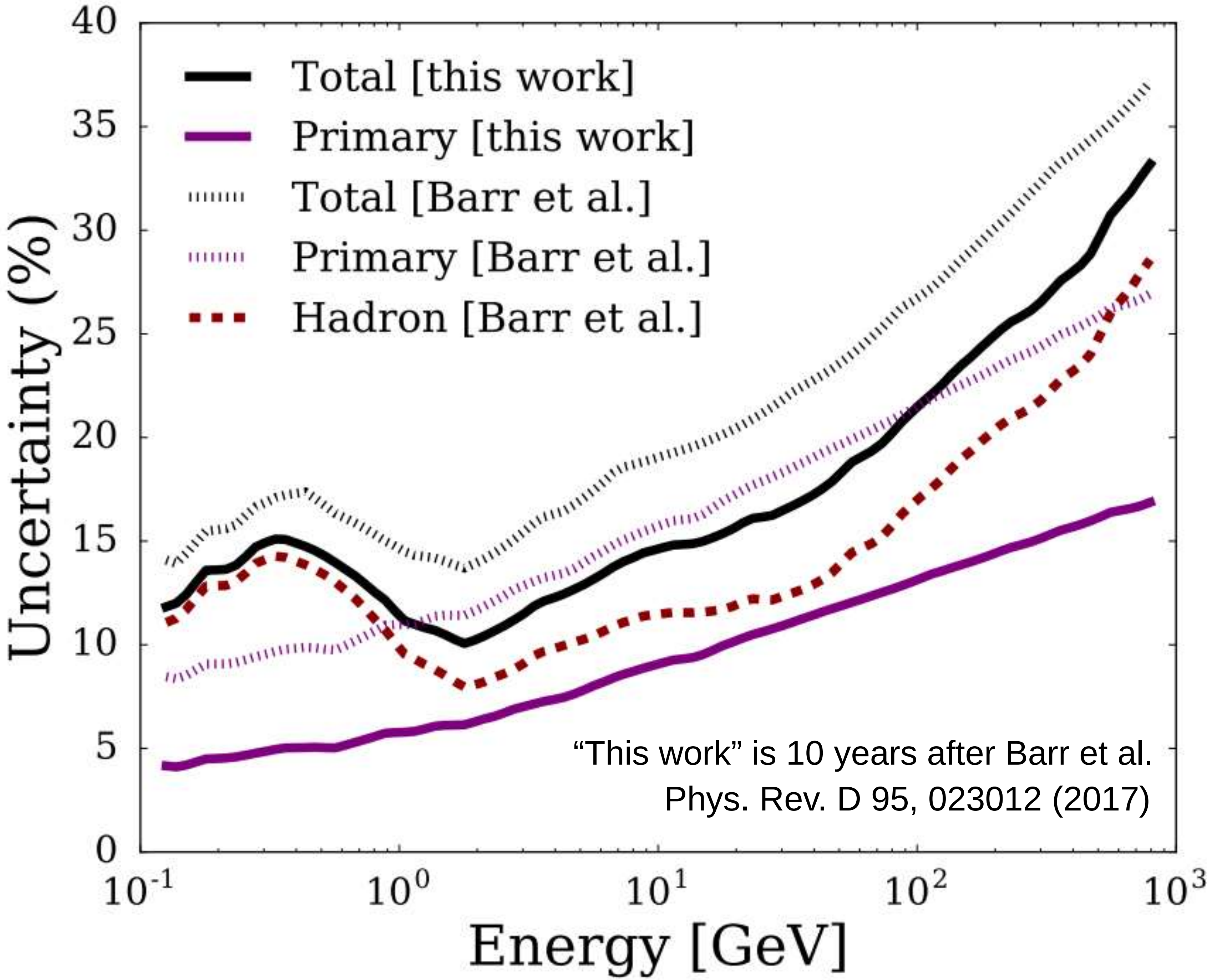
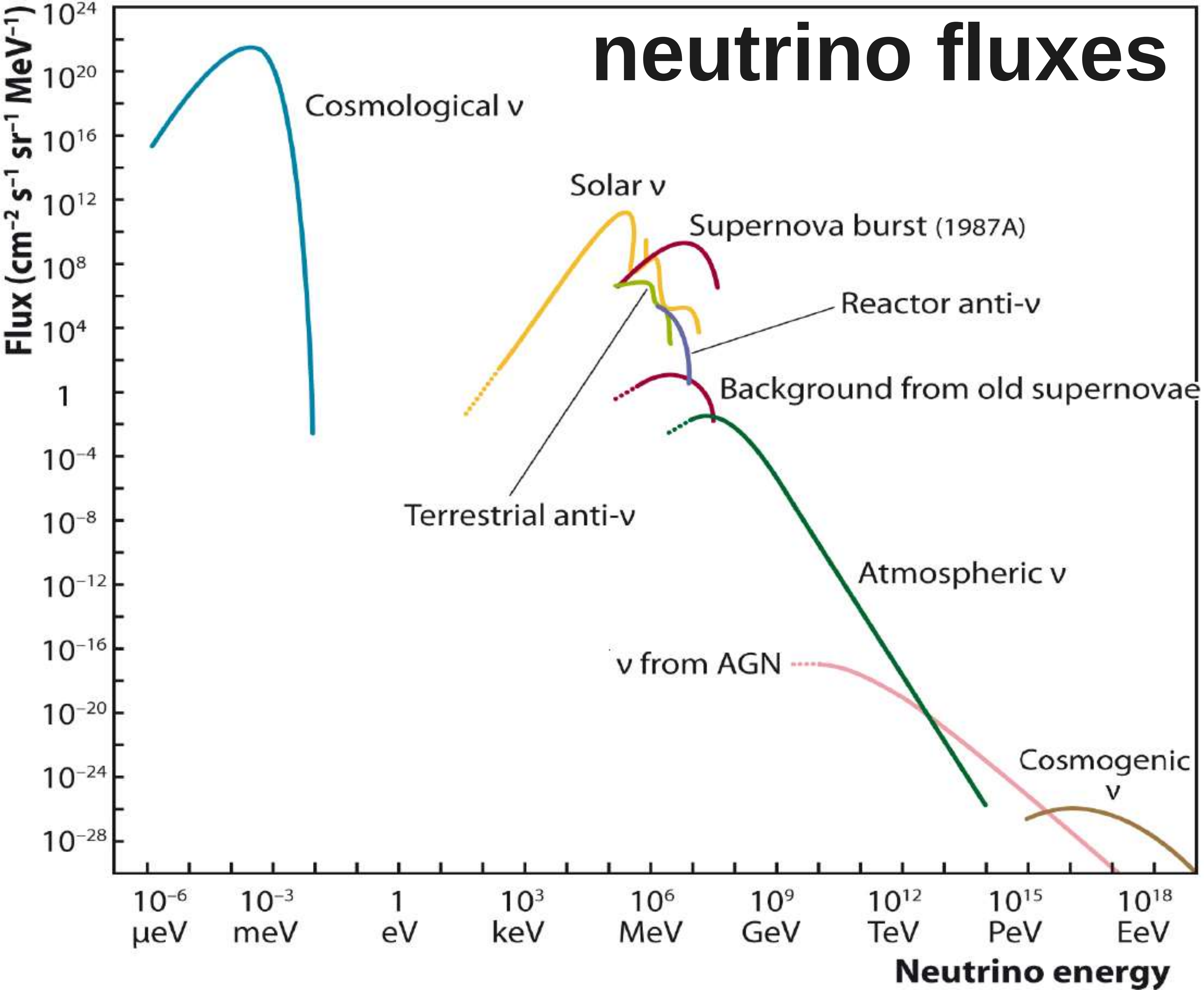
flux uncertainties

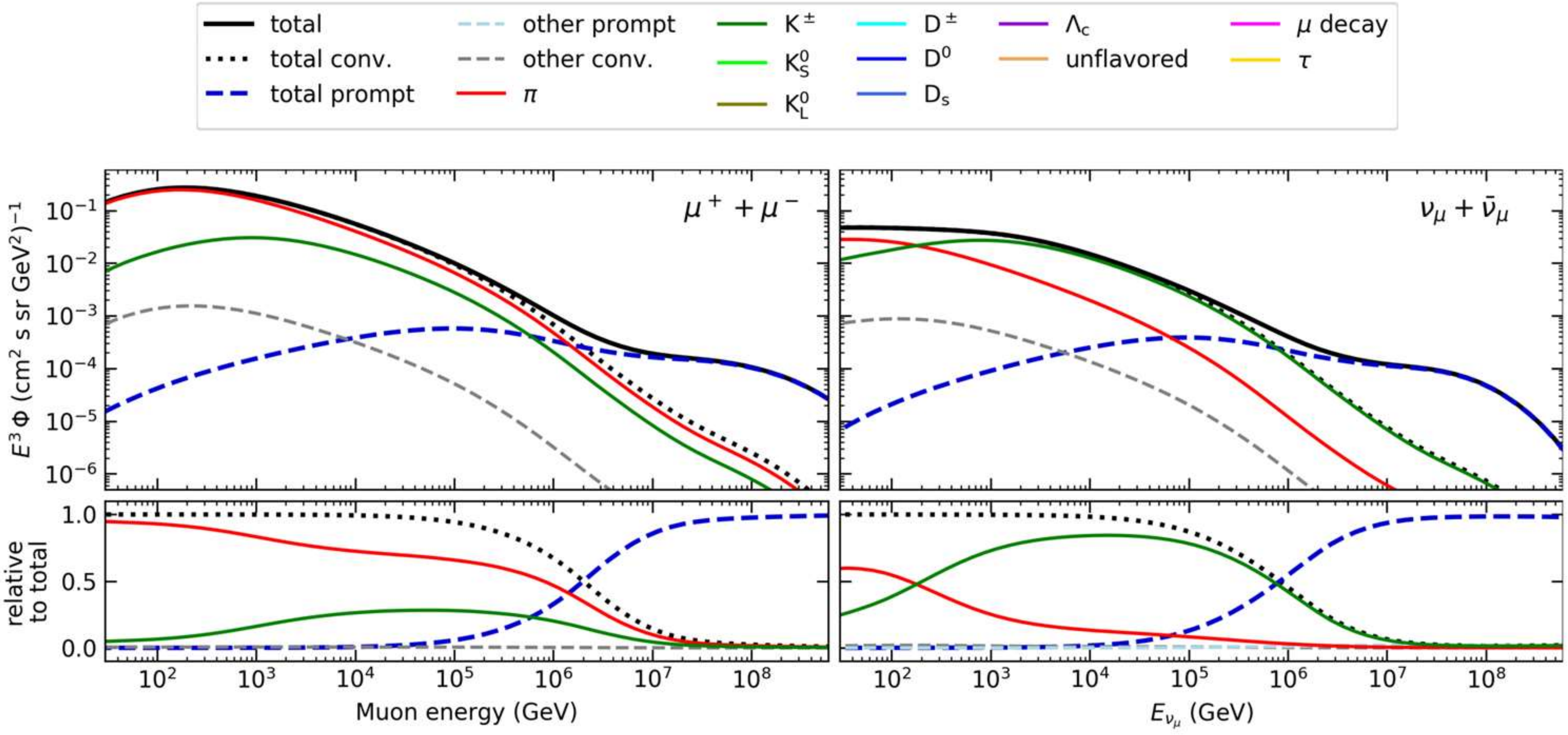


"This work" is 10 years after Barr et al.
Phys. Rev. D 95, 023012 (2017)

neutrino fluxes



flux by parent meson



A. Fedynitch, PANE2018

atmospheric neutrino flux

improvements from last decade

-better input measurements

-CR and had. int. errors reduced

-uncertainties under scrutiny

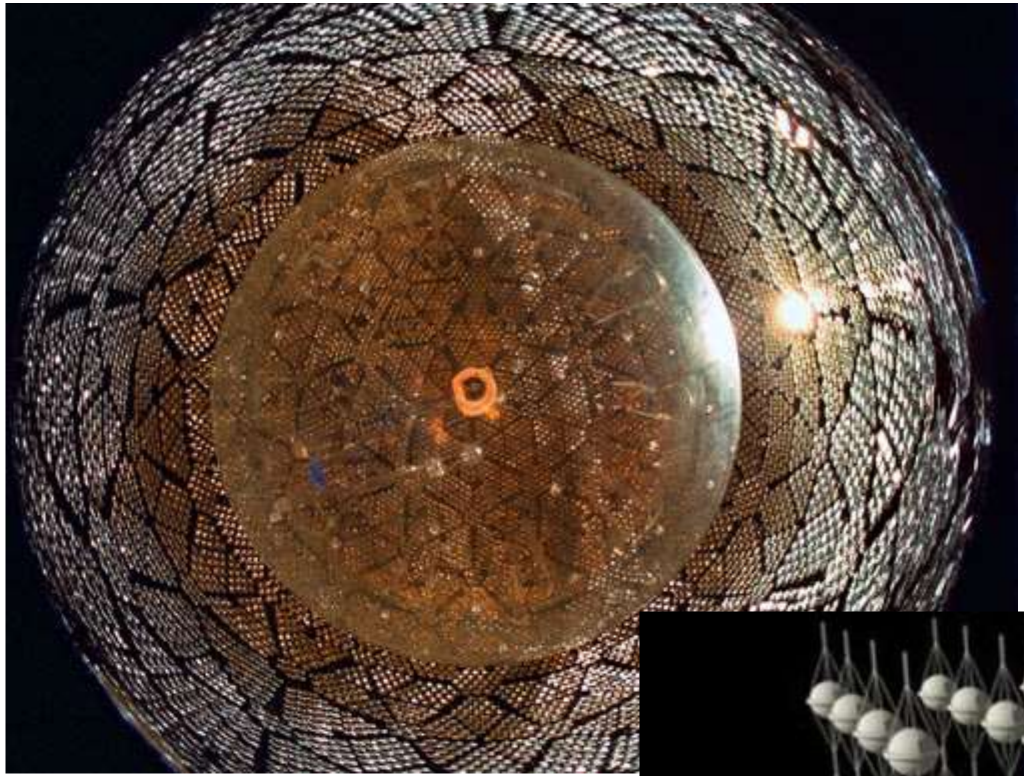
-renewed efforts & tools

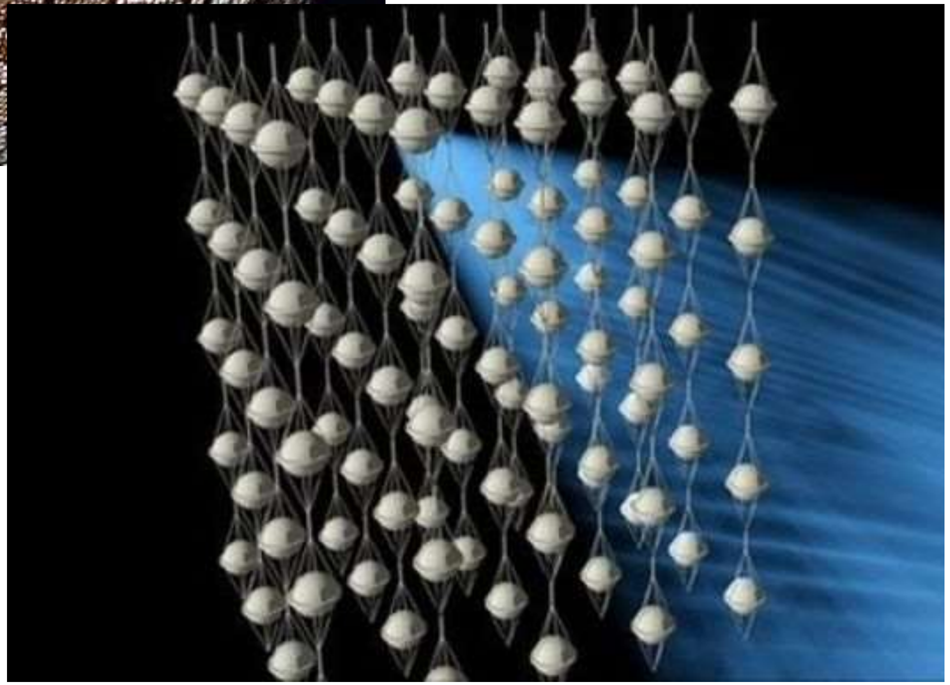
atmospheric neutrino detection

first ideas

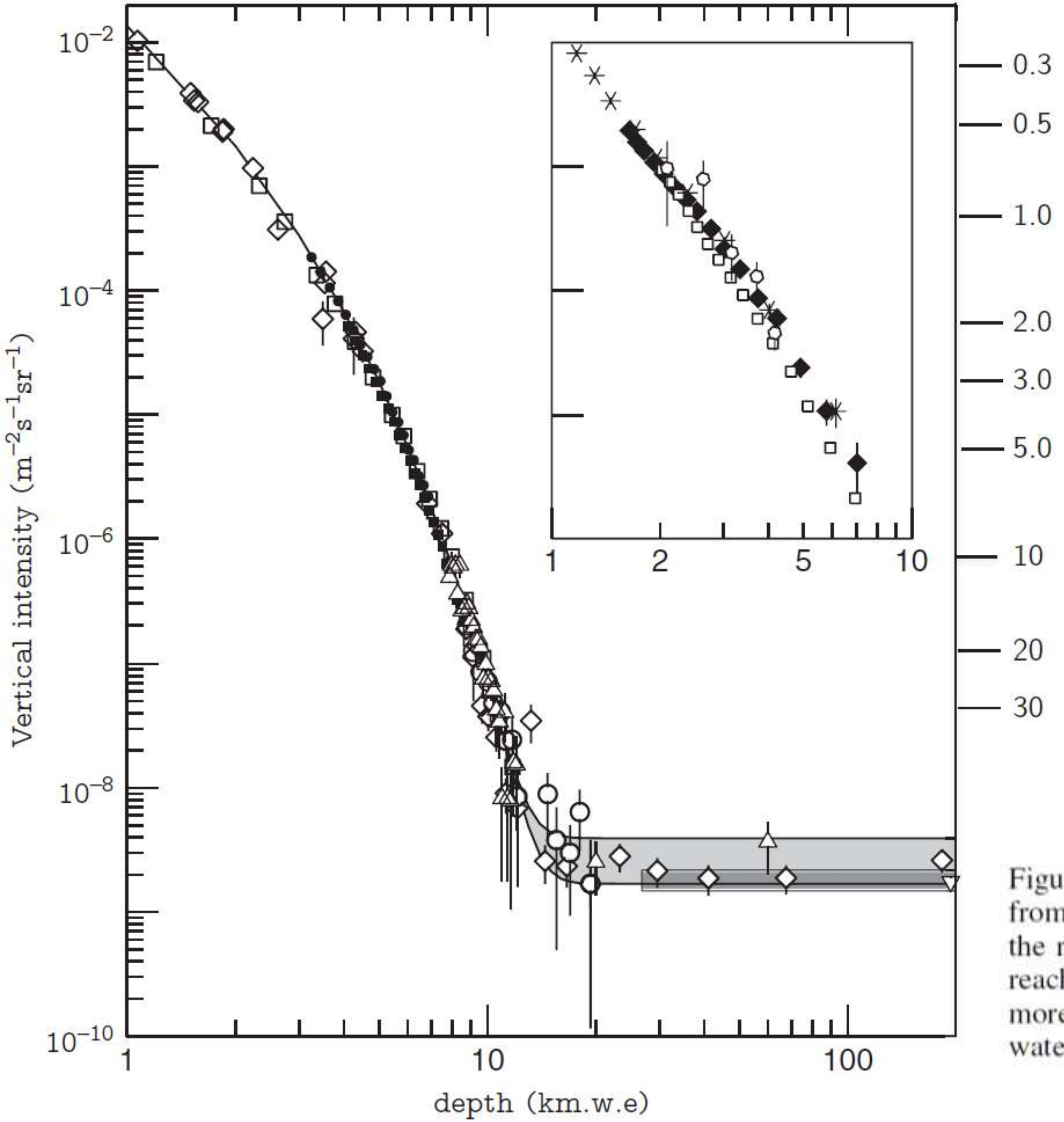
-Greisen (1960) proposed a volume of water surrounded by Cherenkov counters

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





first ideas

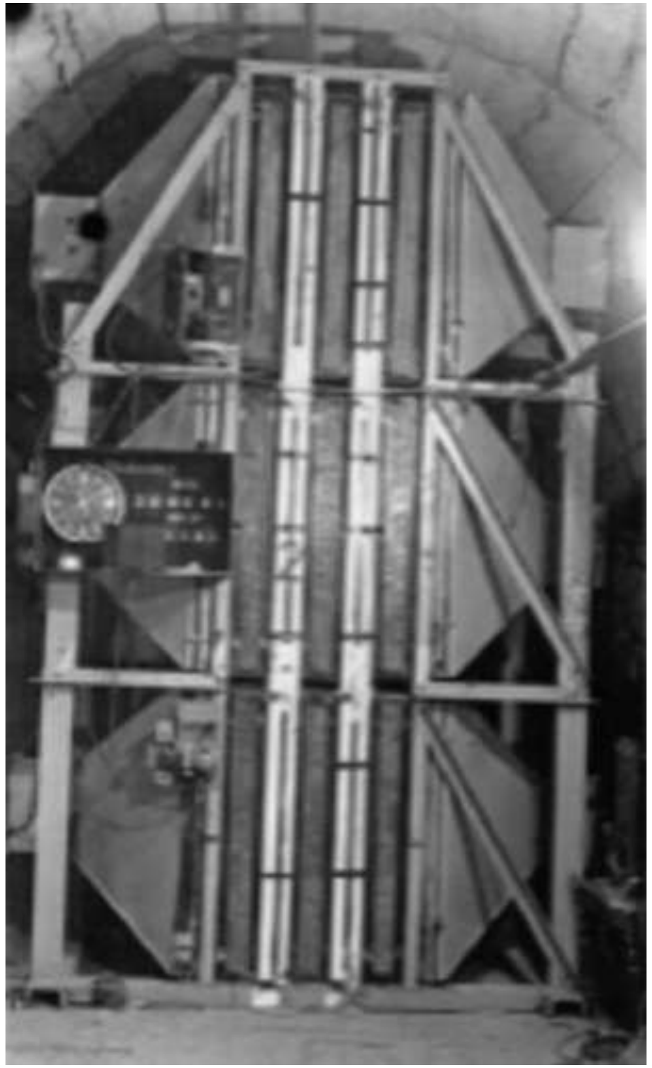


key point:
deep underground
to avoid muon background

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.

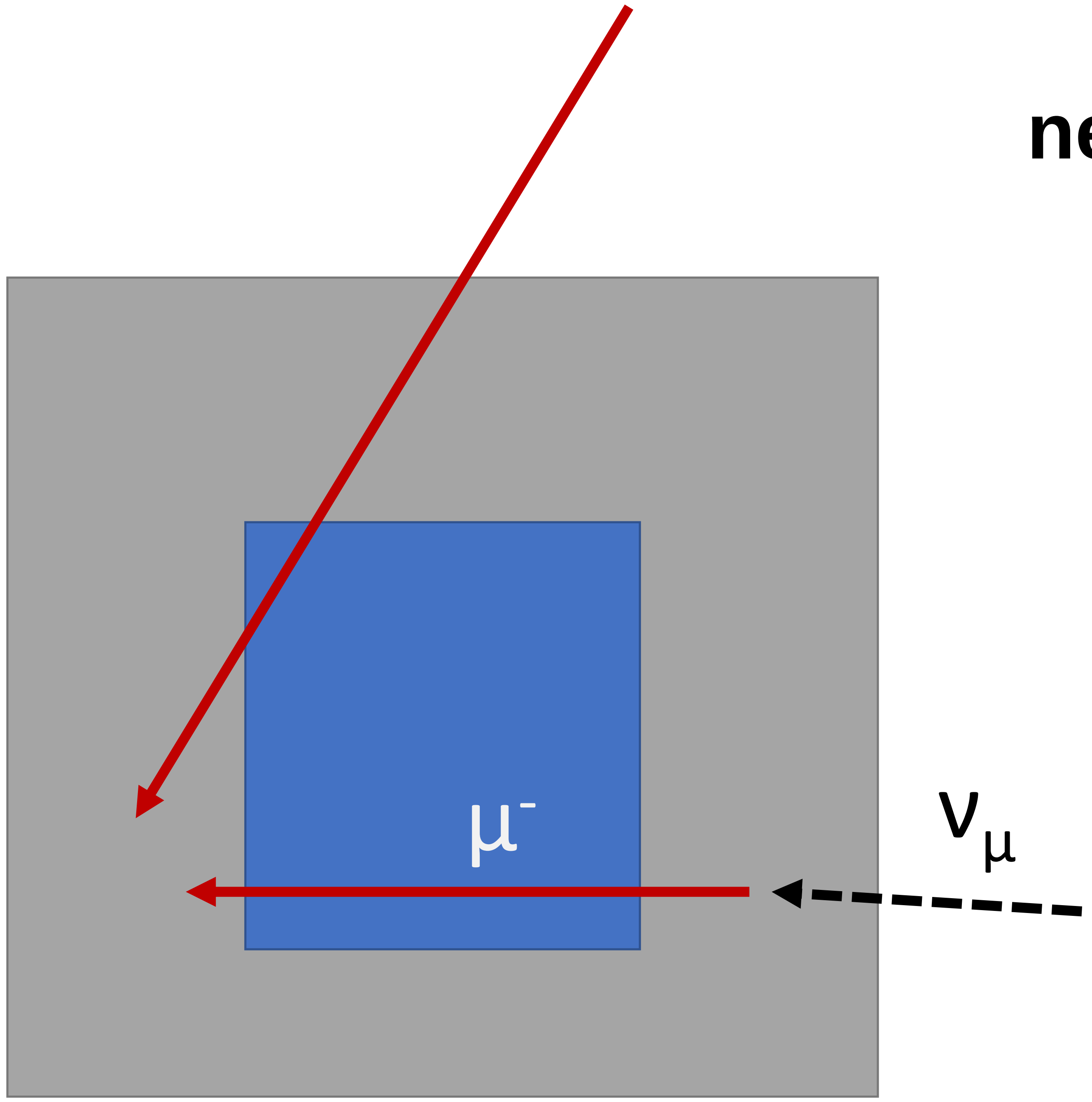
Gaisser, Cosmic Rays and Particle Physics (2016)

discovery of atmospheric neutrinos (1965-68)

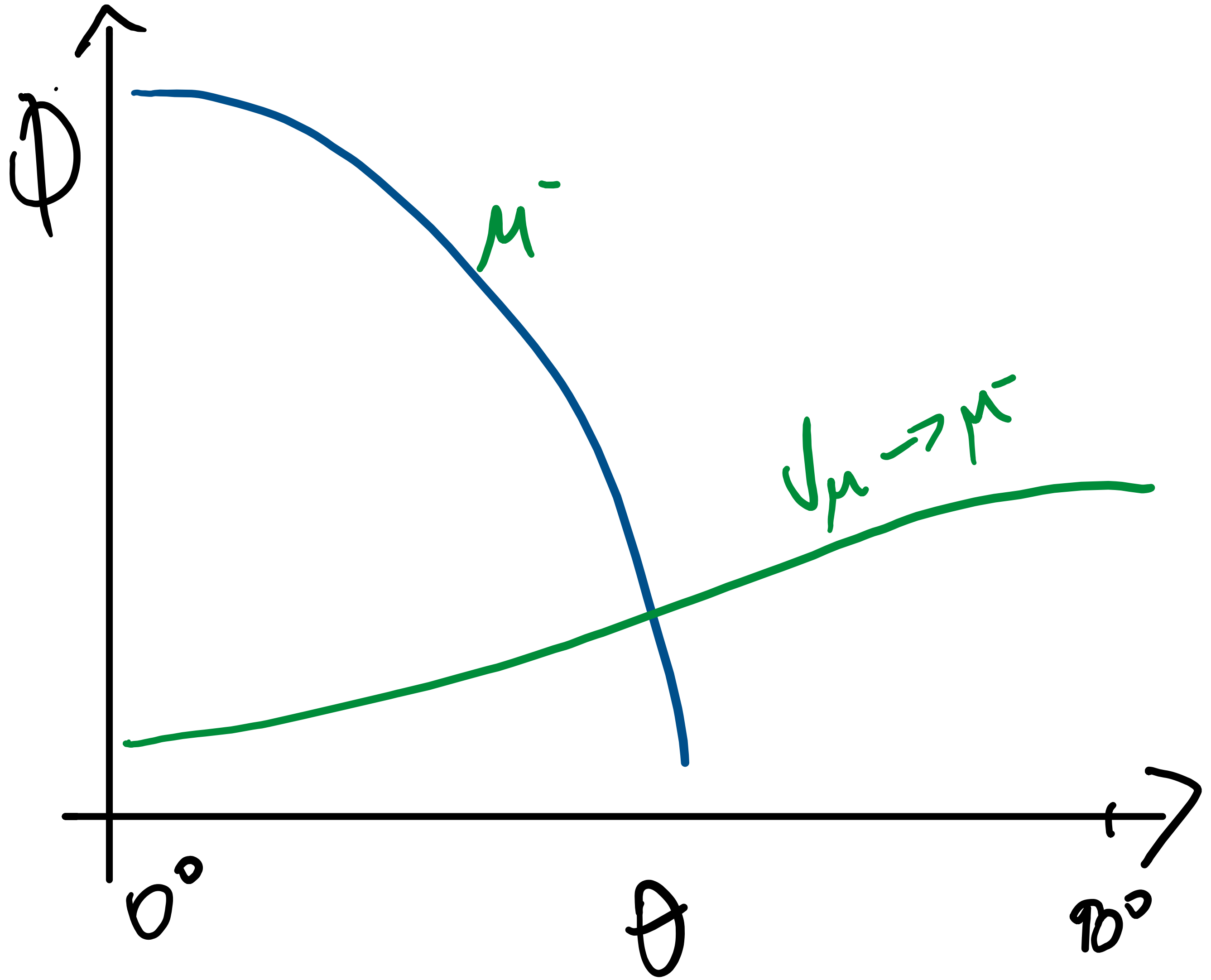


Kolar Gold Fields detector

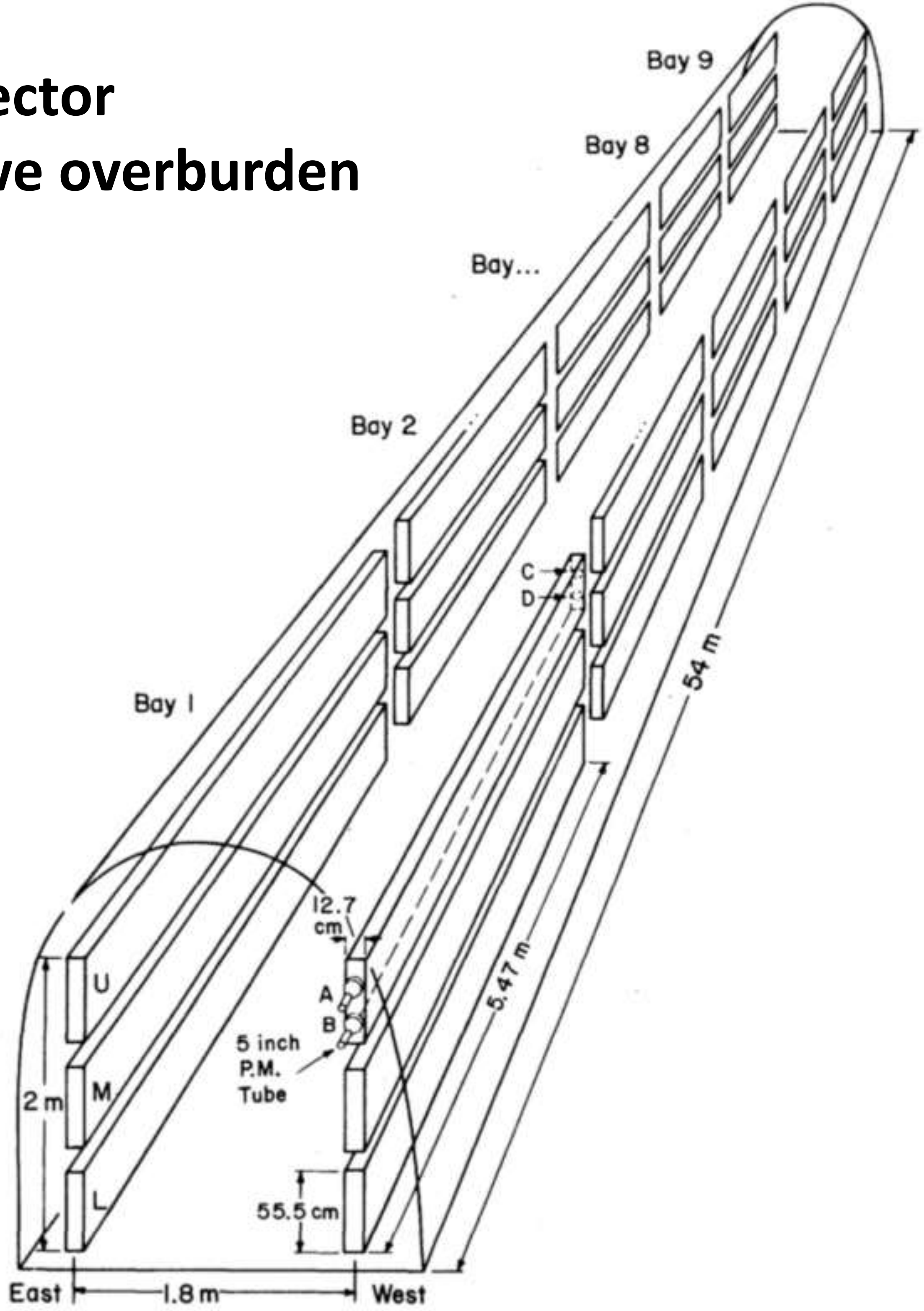
Case Western Irvine/South Africa Neutrino Detector



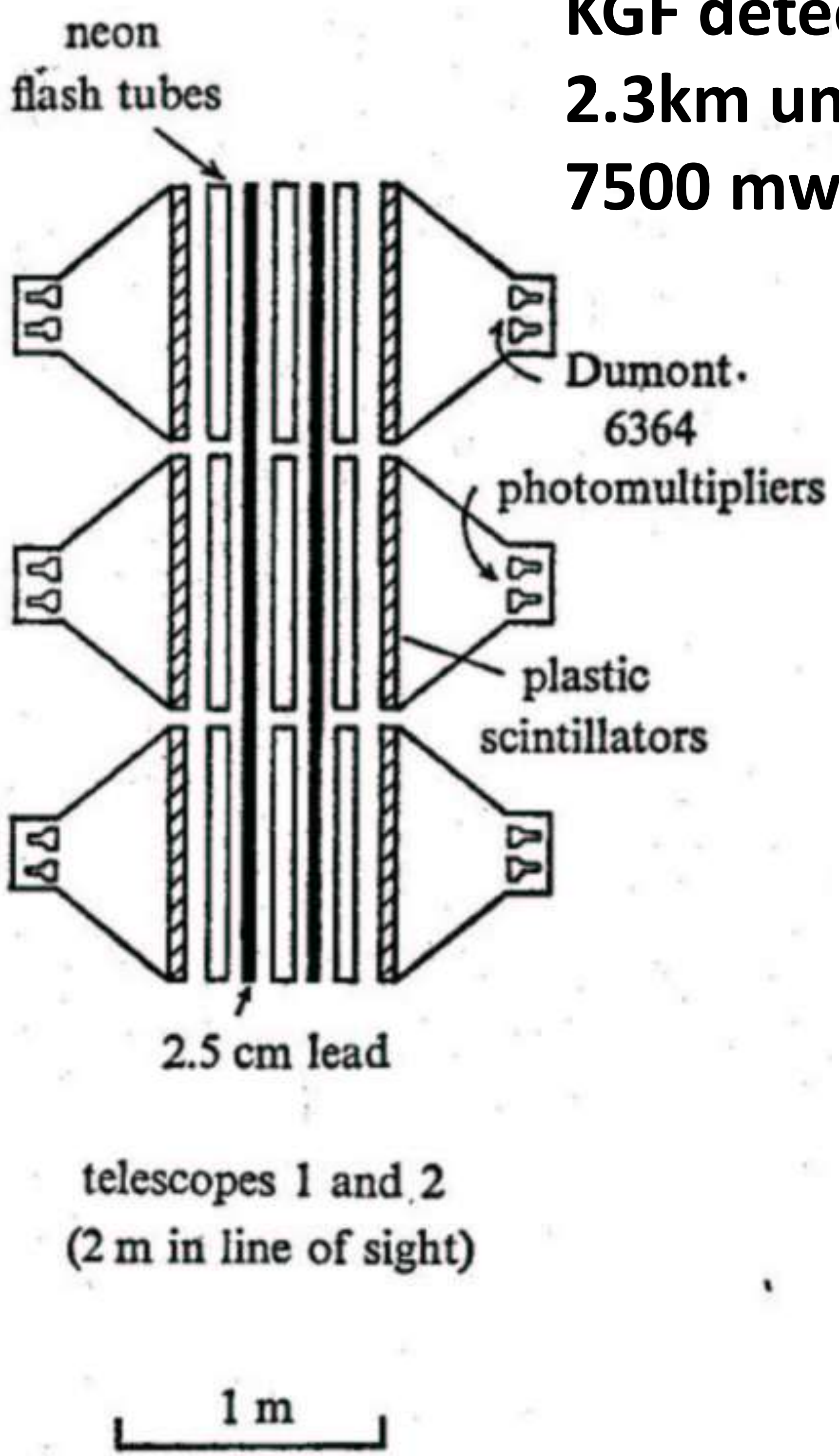
neutrino-induced muons

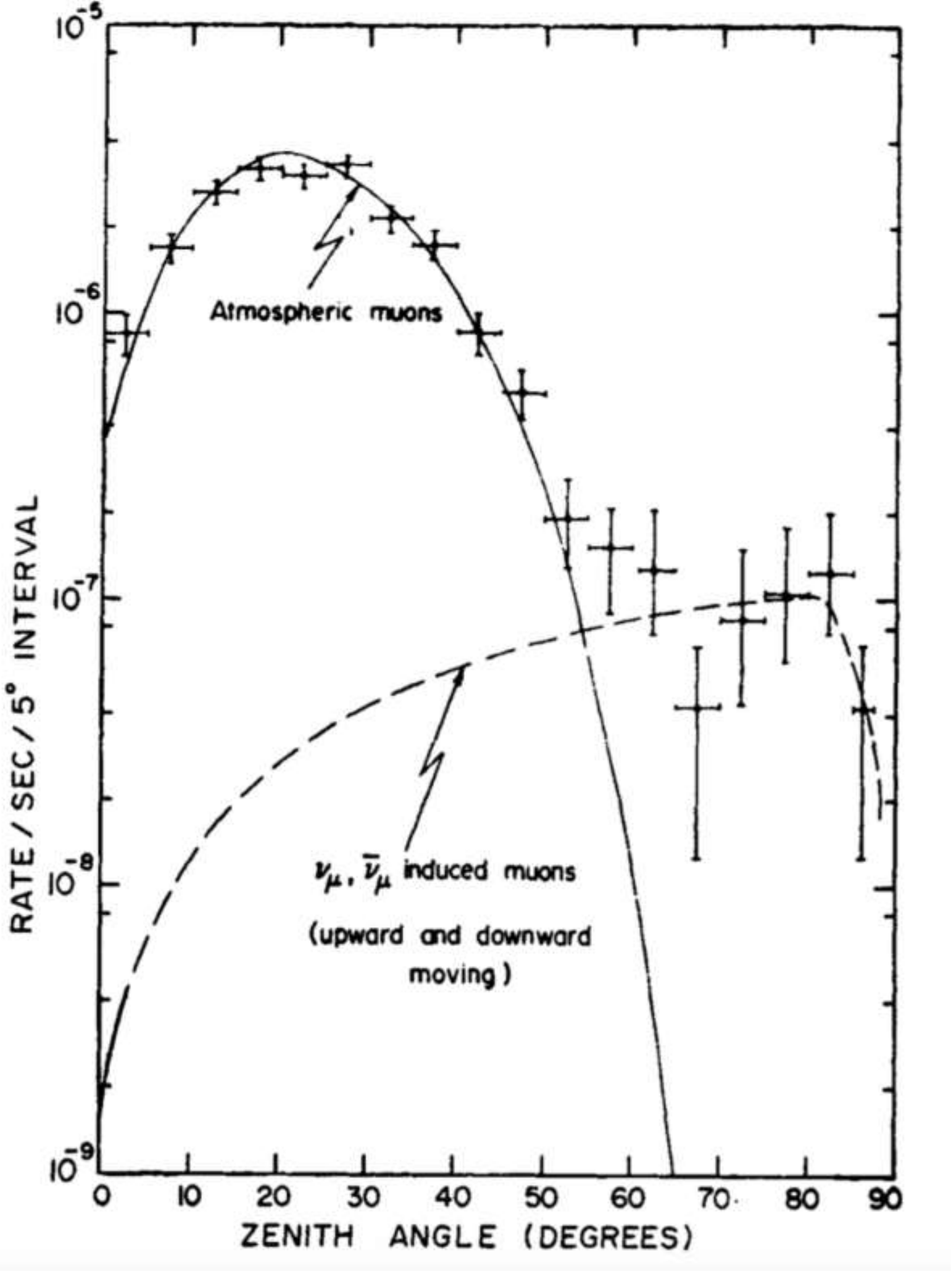


CWI detector
8800 mwe overburden



KGF detector
2.3km under rock
7500 mwe





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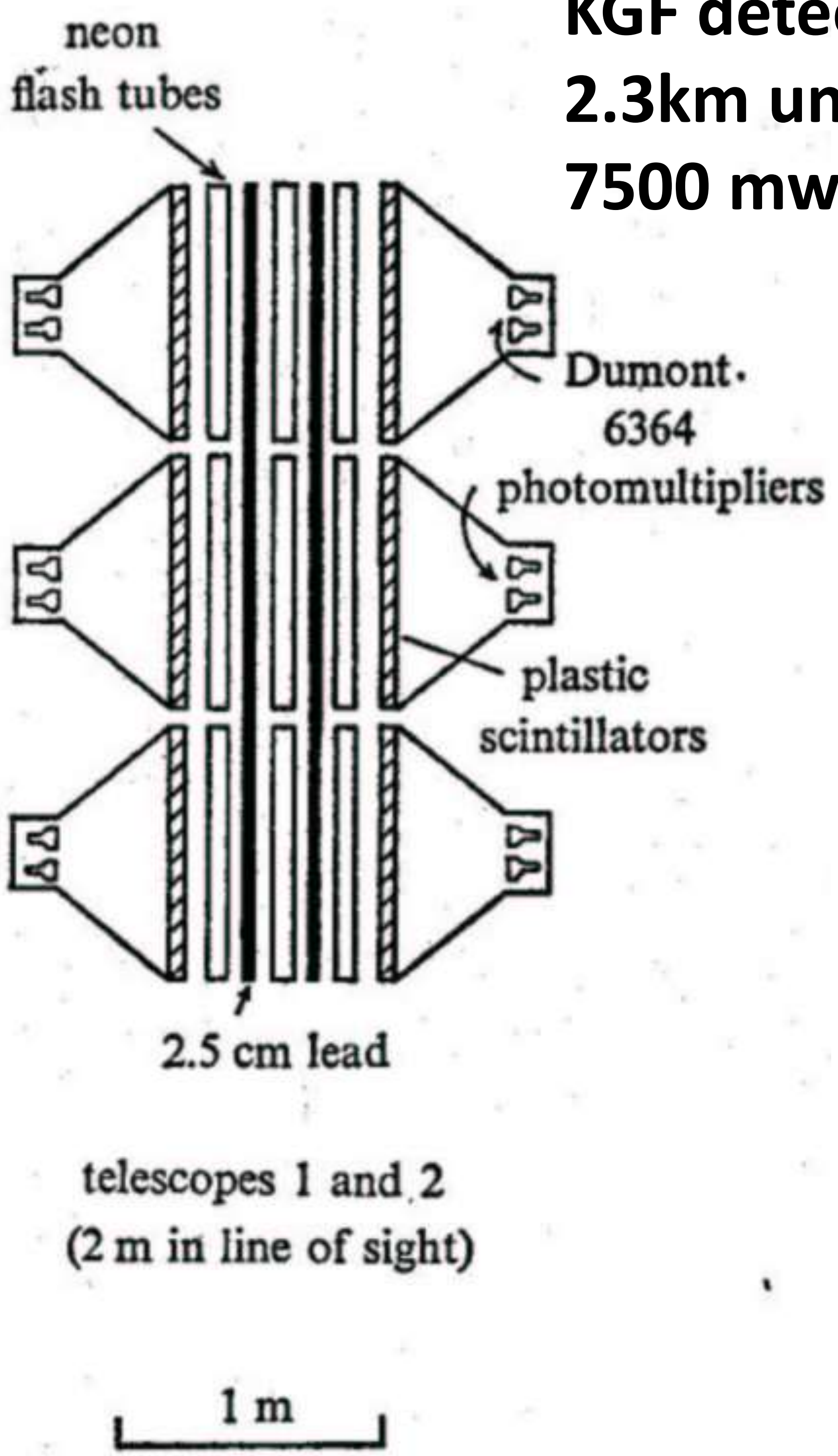
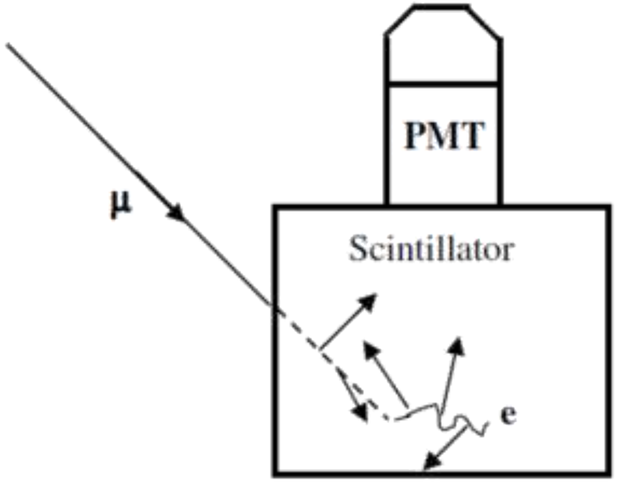
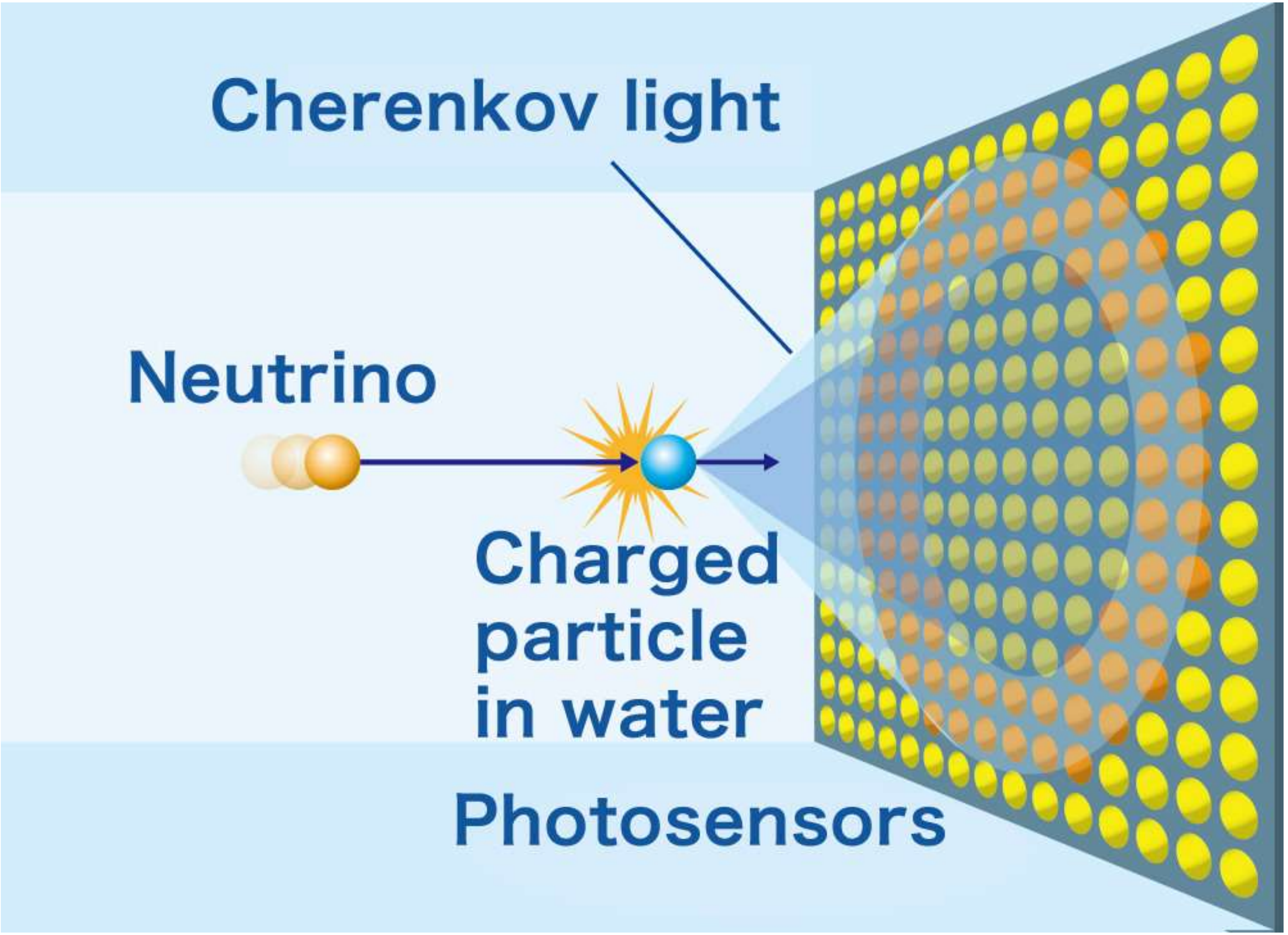


scintillator detectors



Cherenkov detectors



tracking calorimeters

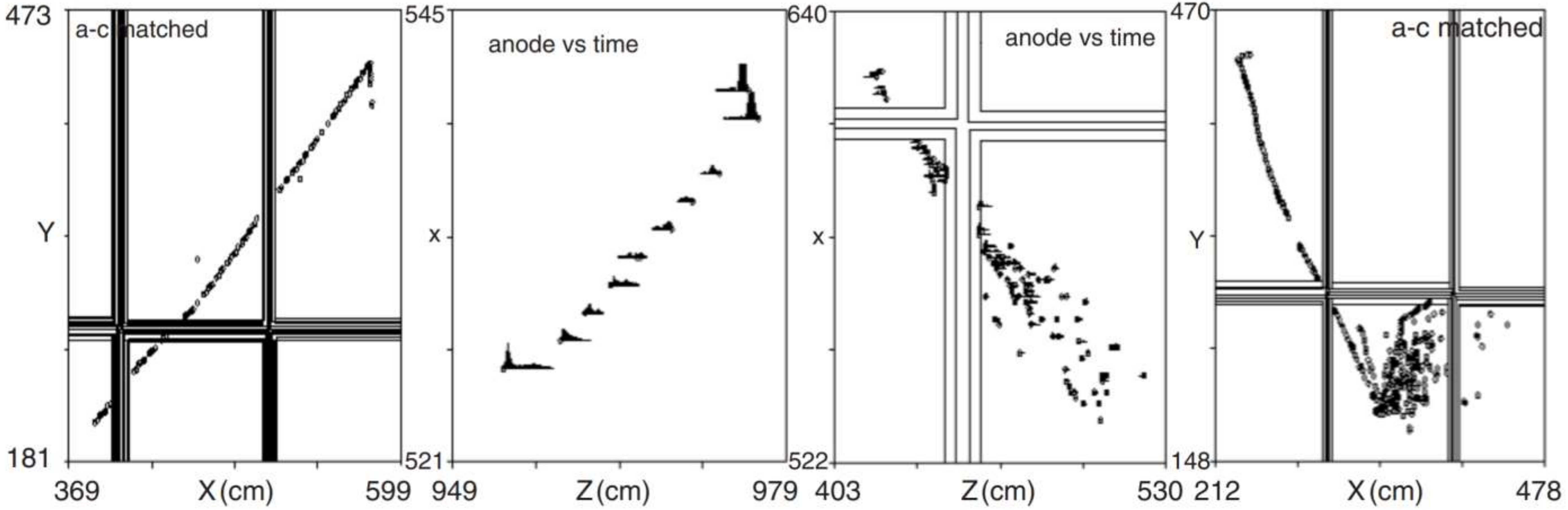
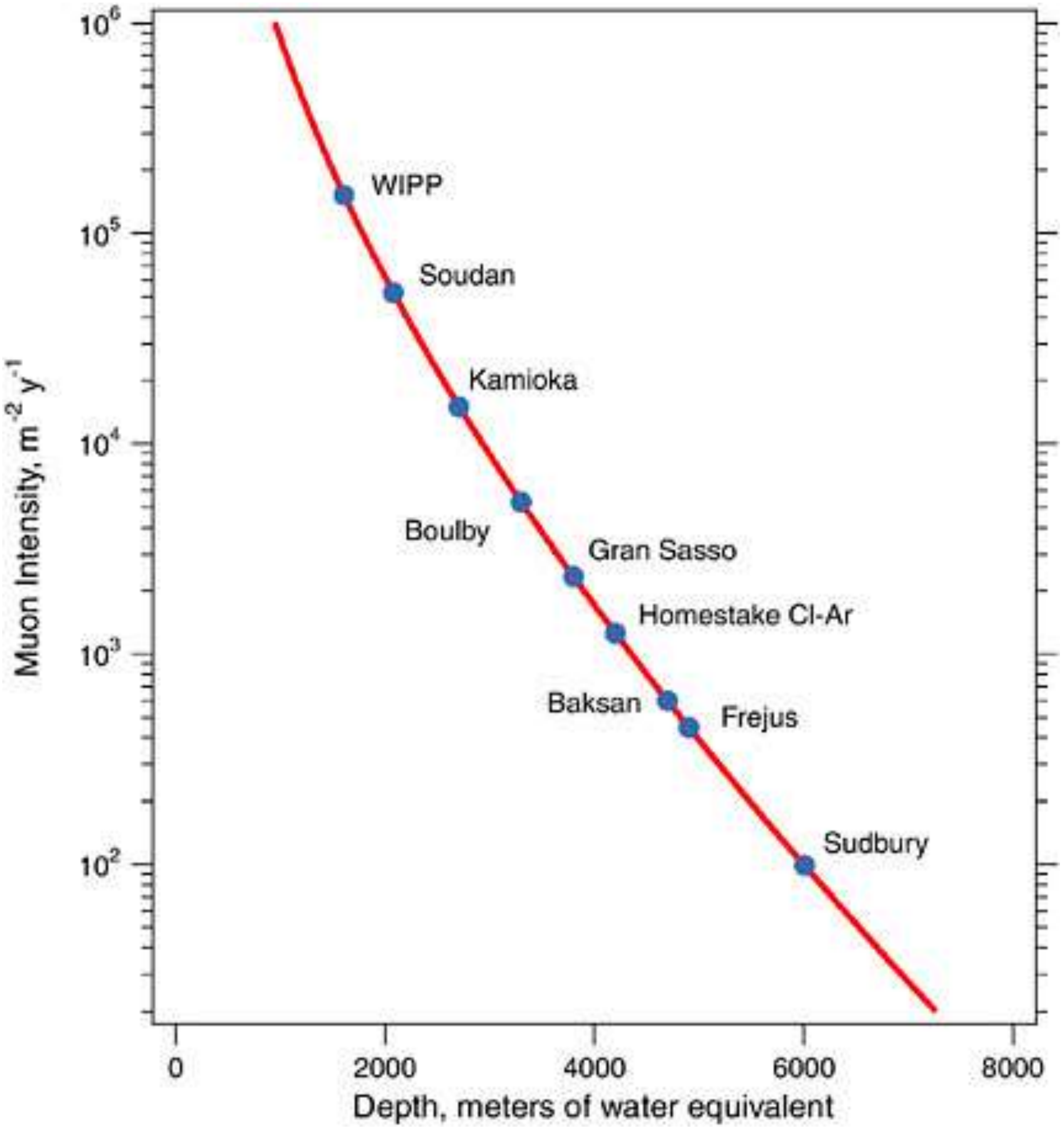


Figure 9. Example event displays from the Soudan-2 detector, showing the long track from a muon and a shorter, more heavily ionizing track from a recoil proton.

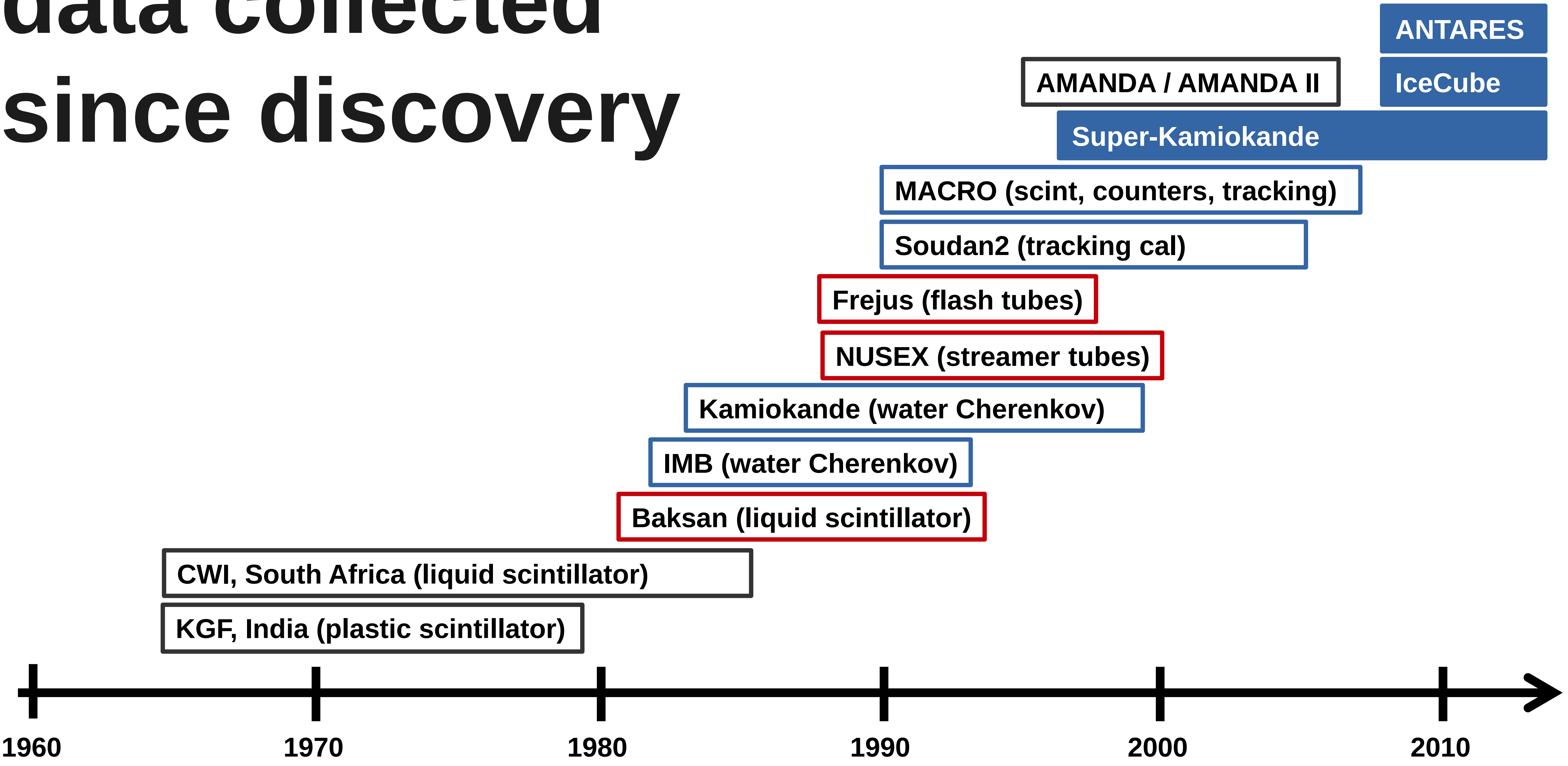
Kajita, New Journal of Physics 6 (2004) 194



again:

go deep underground

data collected since discovery



*take dates with caution – list is incomplete

on the early experiments

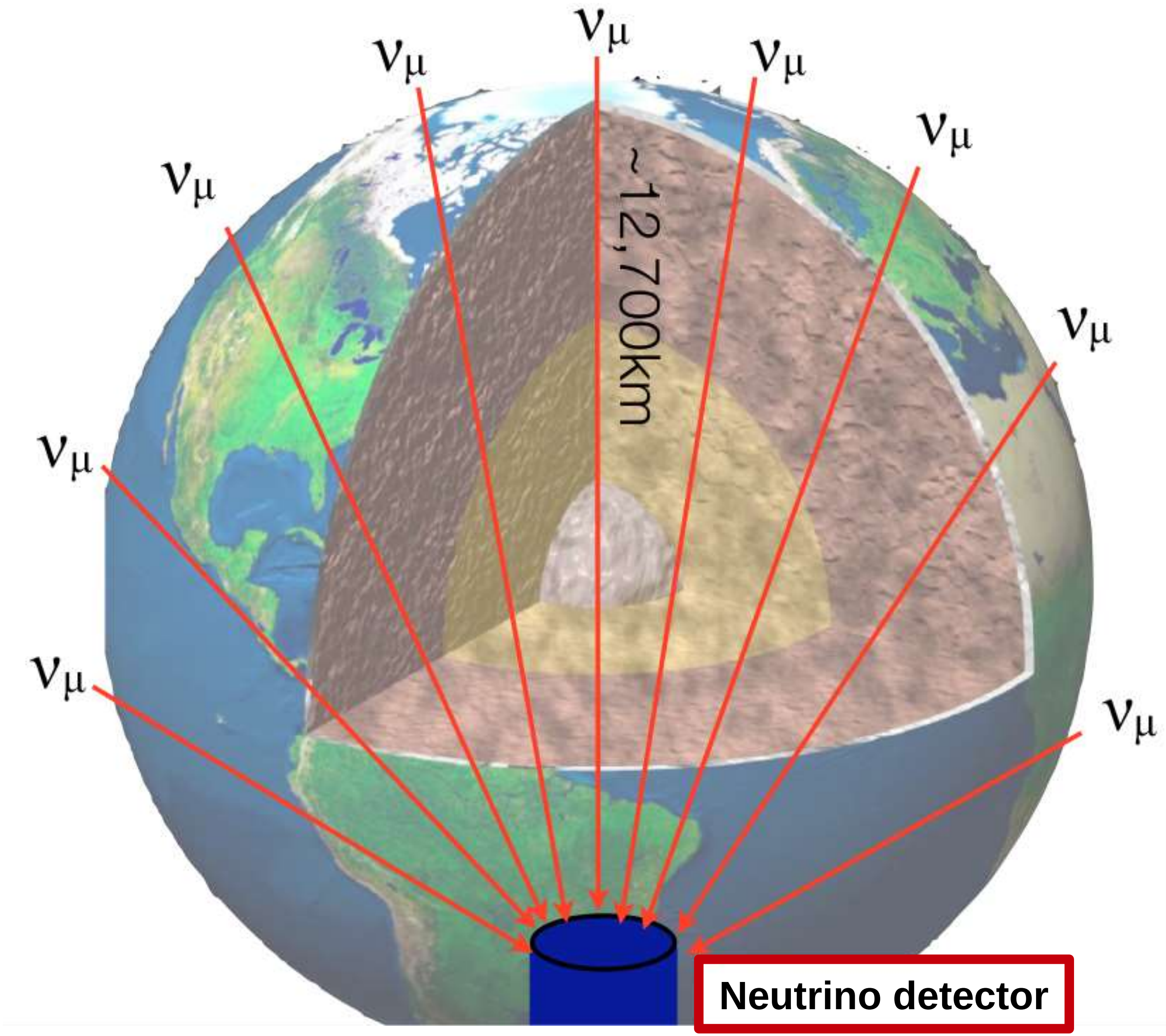
-motivated by the search for **proton decay**

-atmospheric neutrinos were **not the goal**

-but now we know a **little more**

physics motivation

why atmospherics?

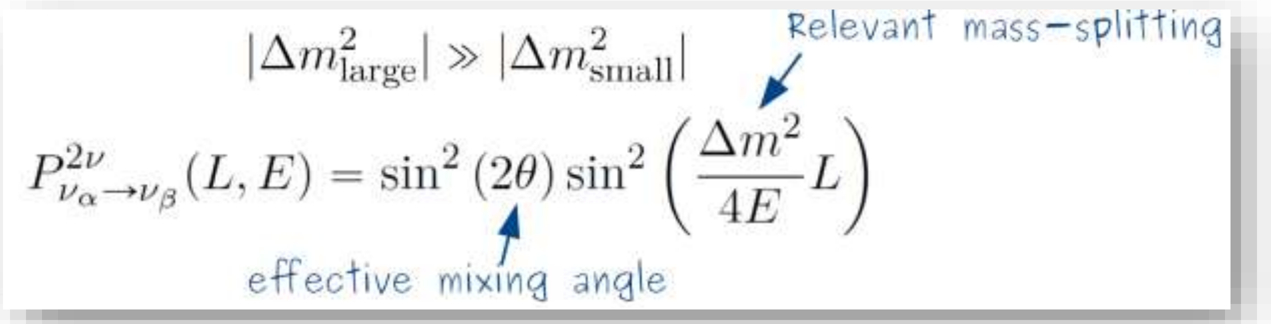


Borrowed from T. DeYoung

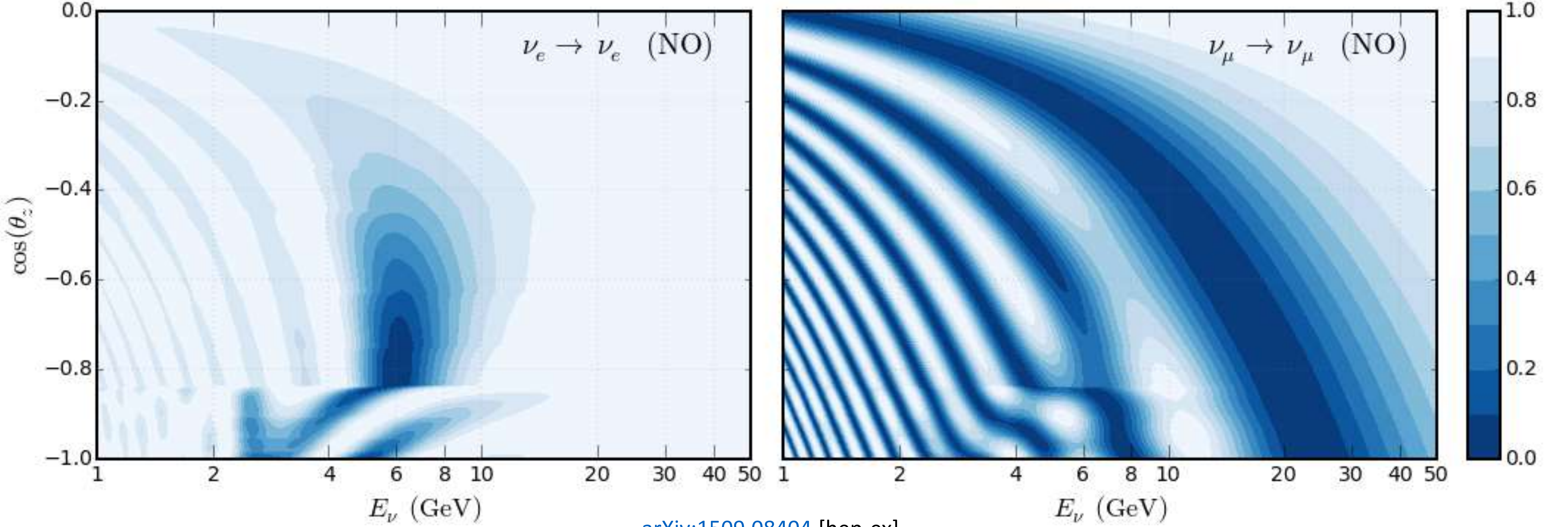
direction → baseline

~10km - ~12,700km

different e^- density along paths

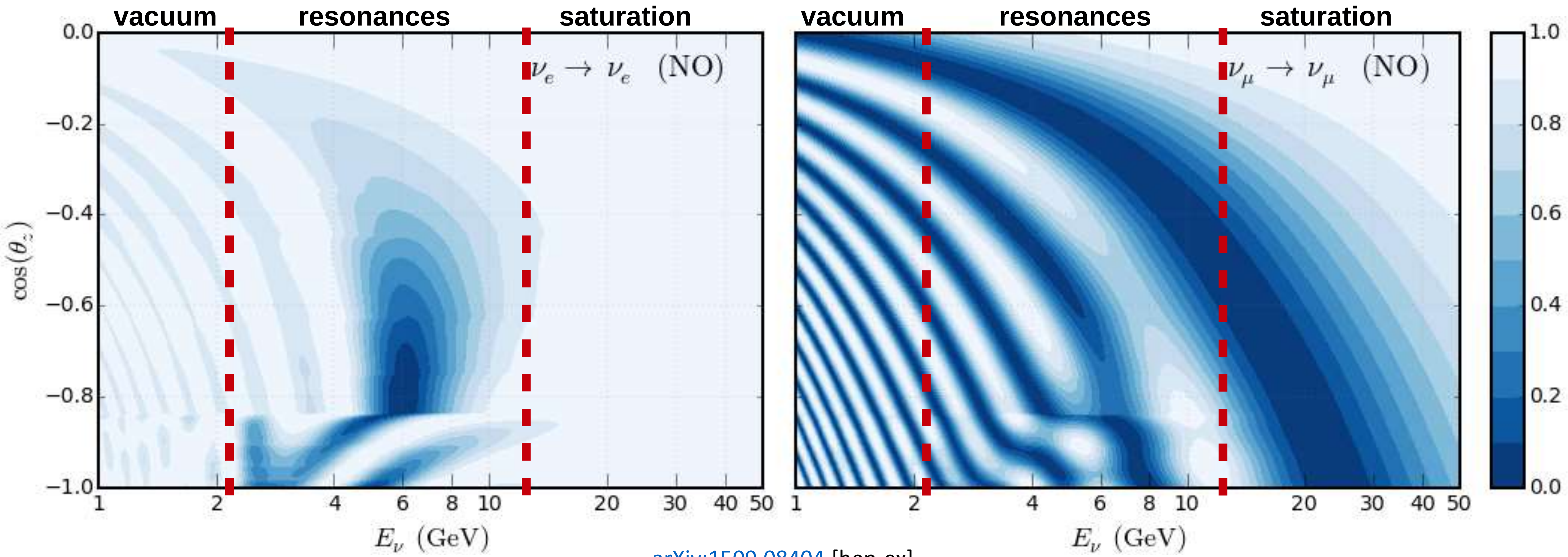


survival probabilities



arXiv:1509.08404 [hep-ex]

survival probabilities

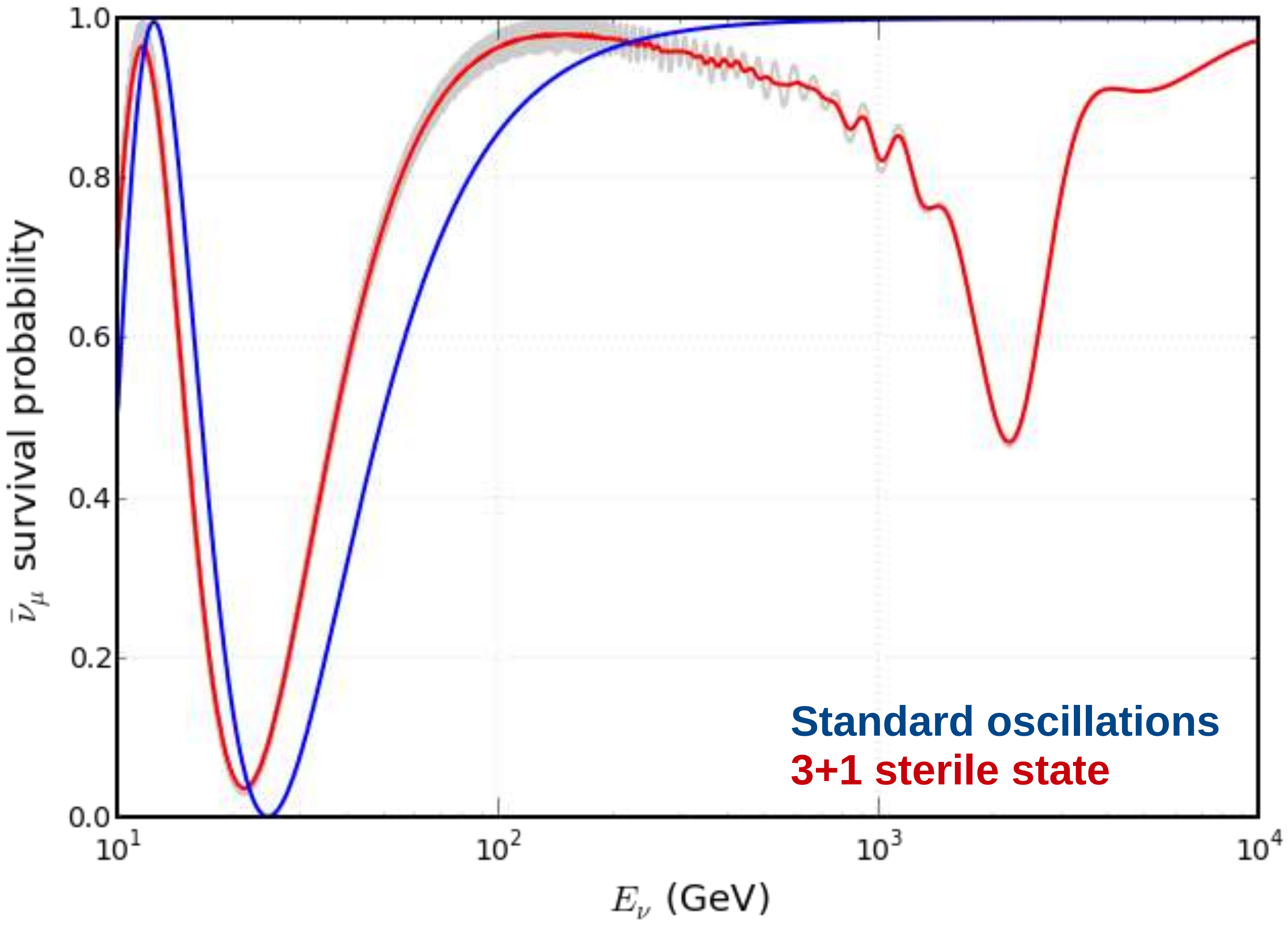


arXiv:1509.08404 [hep-ex]

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



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

sterile neutrinos

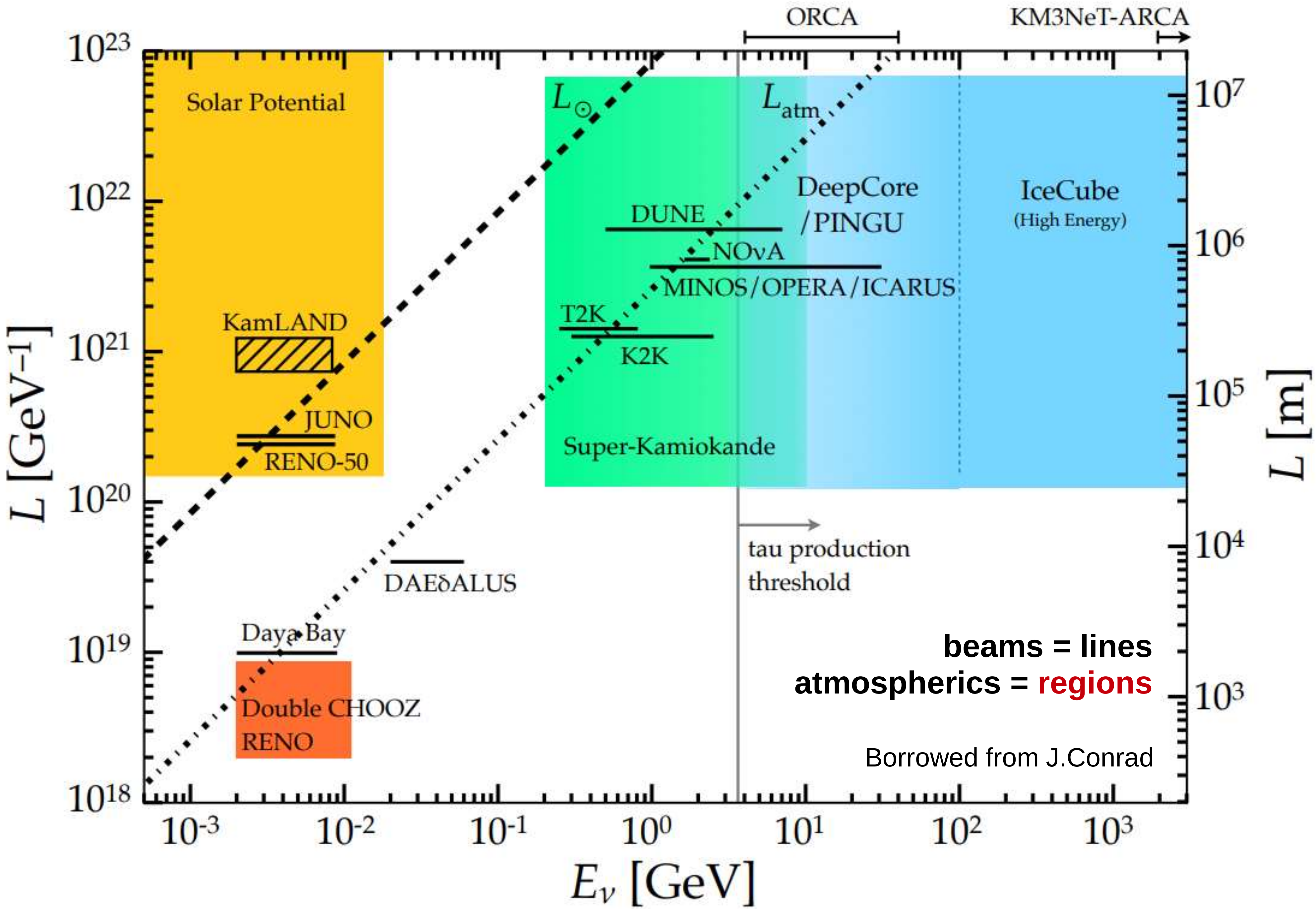
-modify std. osc. effect

-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

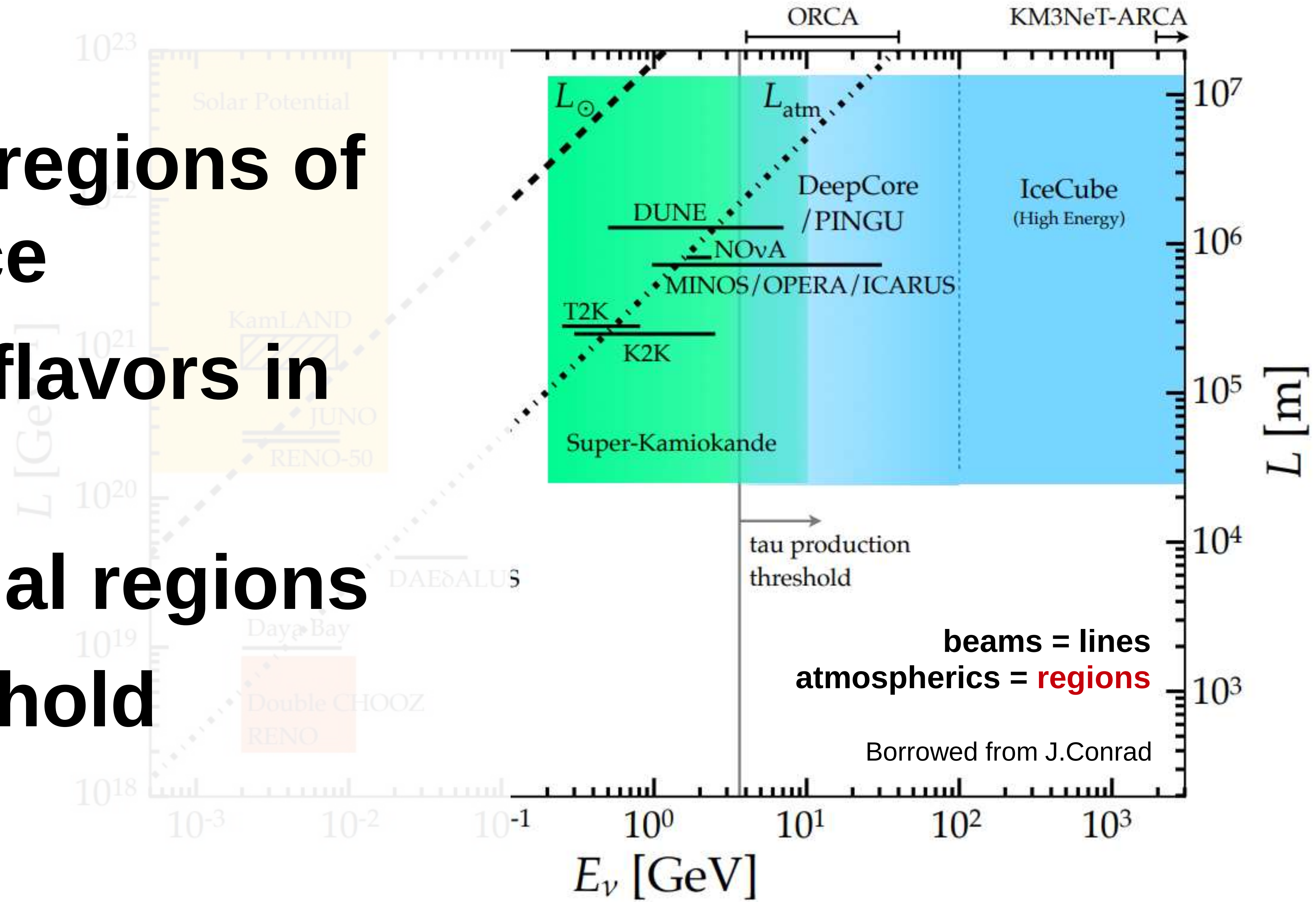
wide baseline, energy range

-large L&E regions of phase space

-2 ν, anti-ν flavors in "beam"

-on/off signal regions

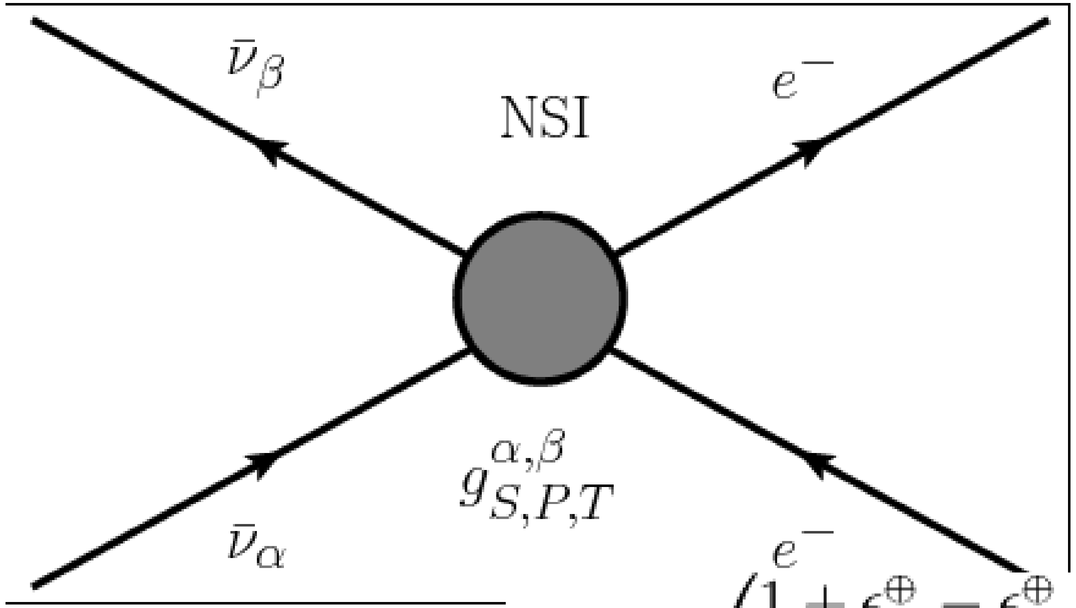
-E > τ threshold



and the off-signal regions?

-used to probe **exotic** possibilities

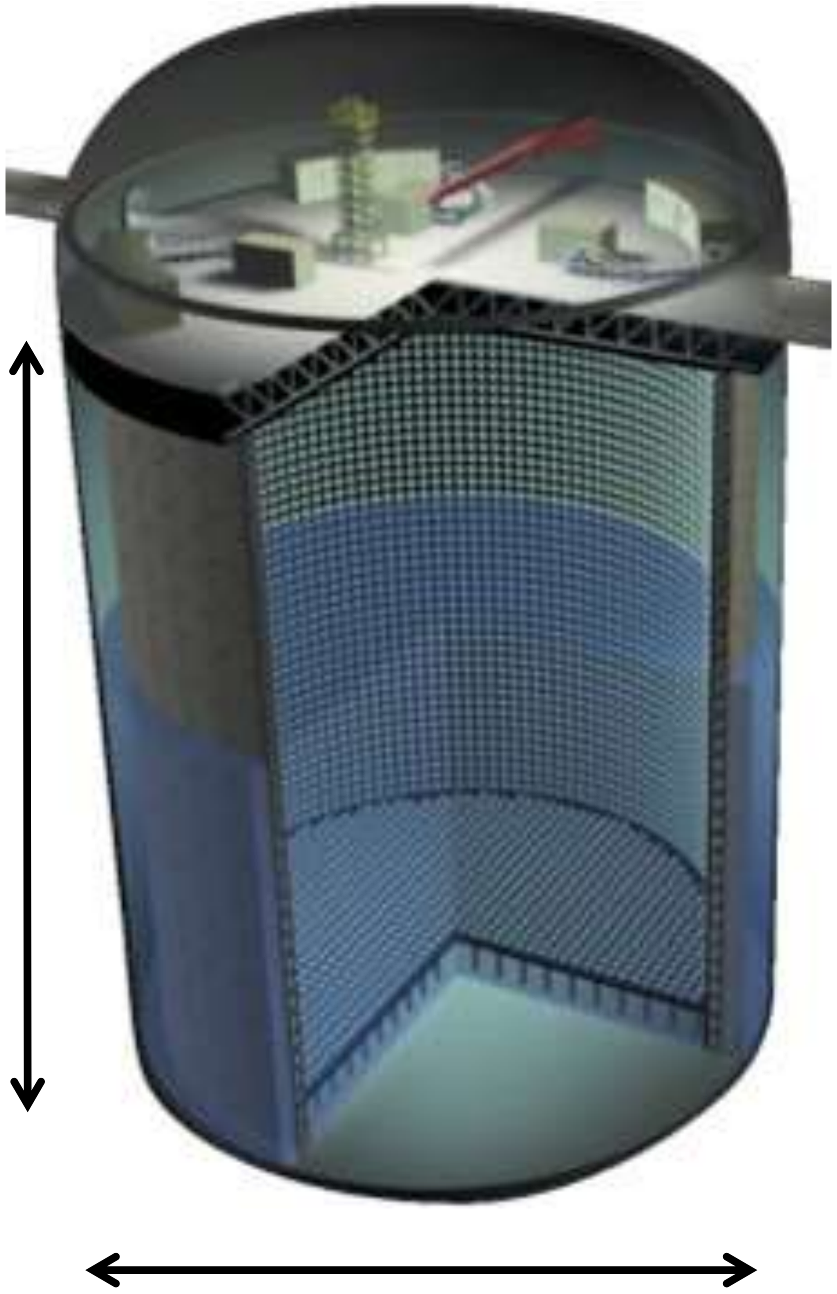
-all show as **distortions** in the spectrum

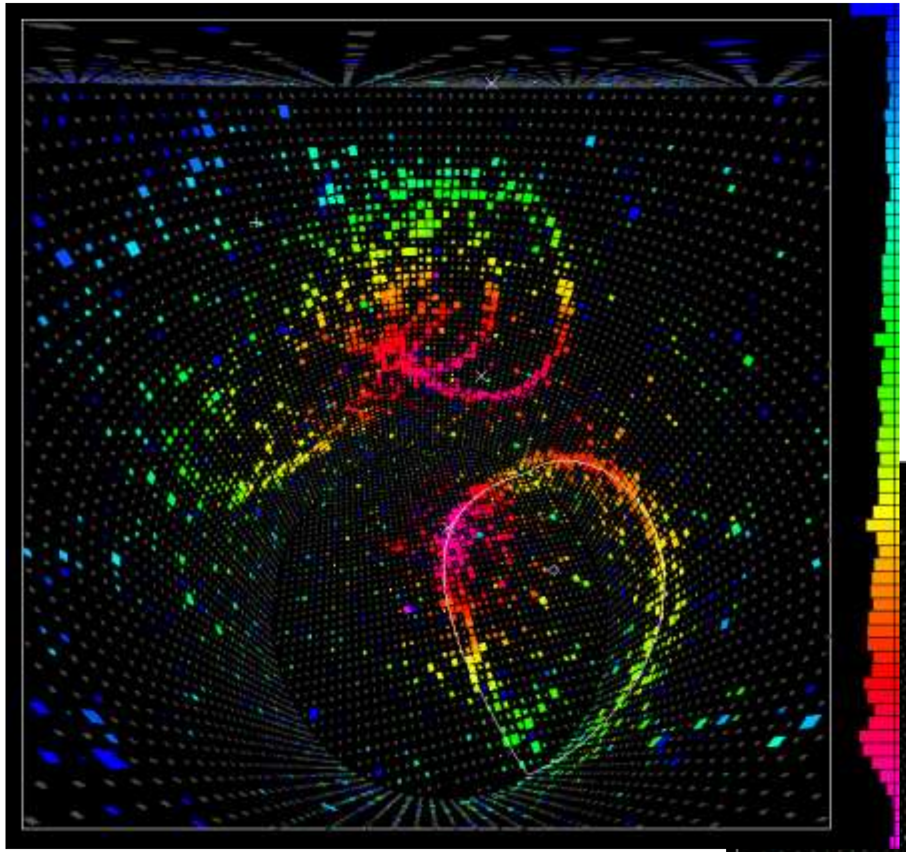


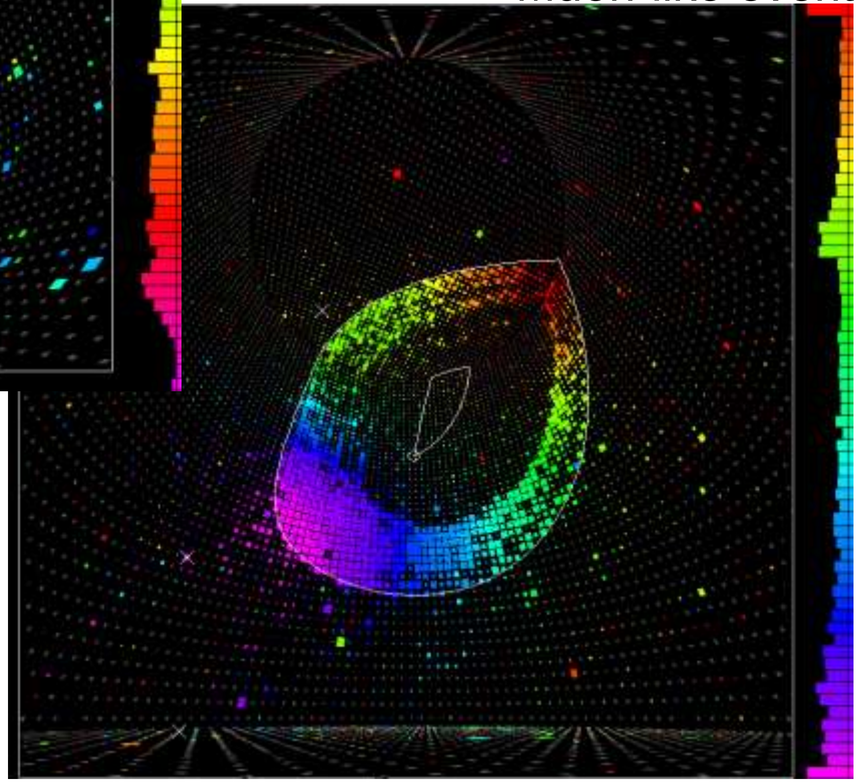
$$H_{\mathrm{mat}} = \begin{pmatrix} 1+\epsilon^{\oplus}_{ee}-\epsilon^{\oplus}_{\mu\mu} & \epsilon^{\oplus}_{e\mu} & \epsilon^{\oplus}_{e\tau} \\ \epsilon^{\oplus *}_{e\mu} & 0 & \epsilon_{\mu\tau} \\ \epsilon^{\oplus *}_{e\tau} & \epsilon^{\oplus *}_{\mu\tau} & \epsilon^{\oplus}_{\tau\tau}-\epsilon^{\oplus}_{\mu\mu}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

recent atmospheric neutrino measurements

Super-Kamiokande

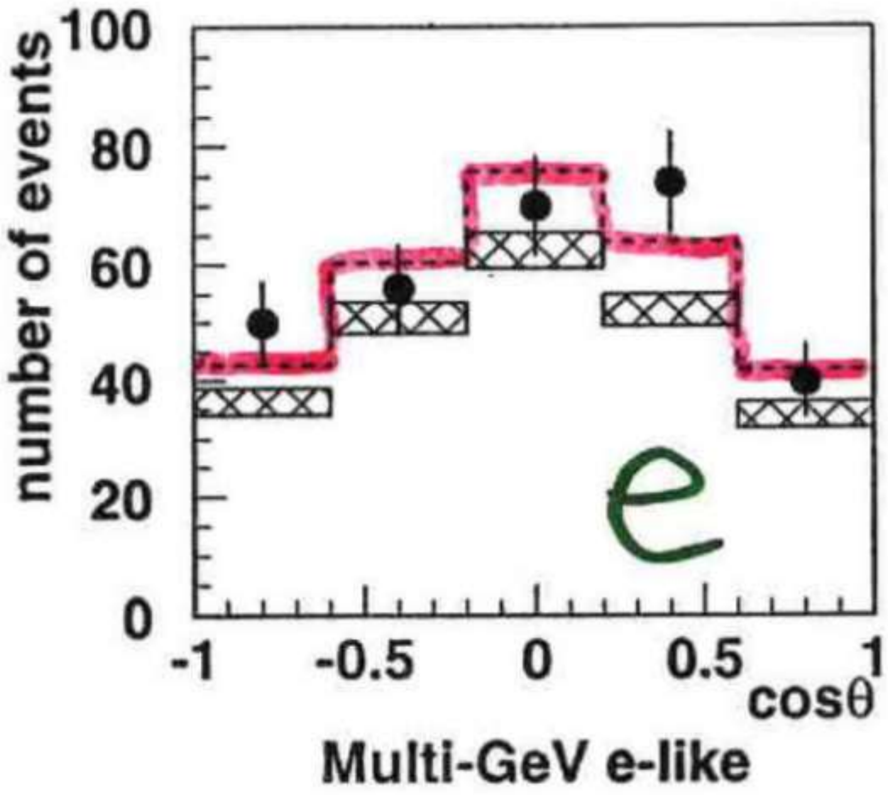


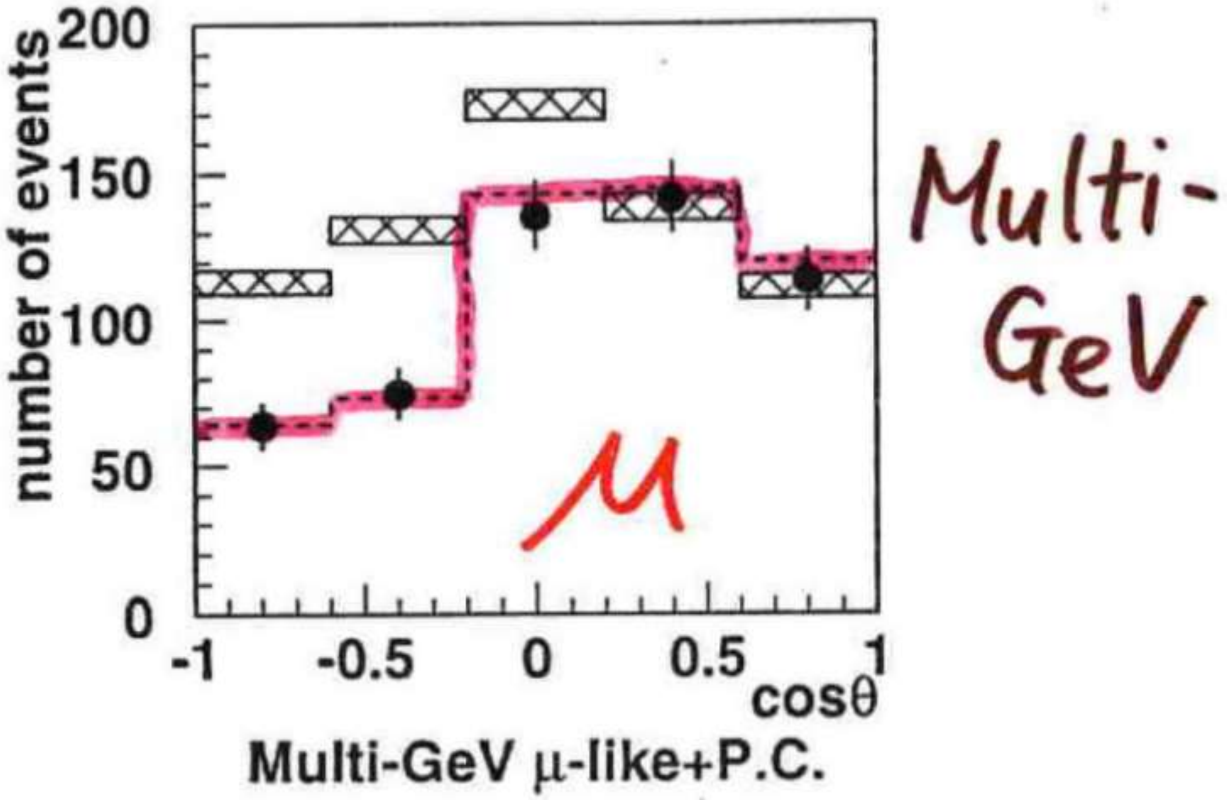

Two-gamma-like event

Muon-like event


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

Super-Kamiokande



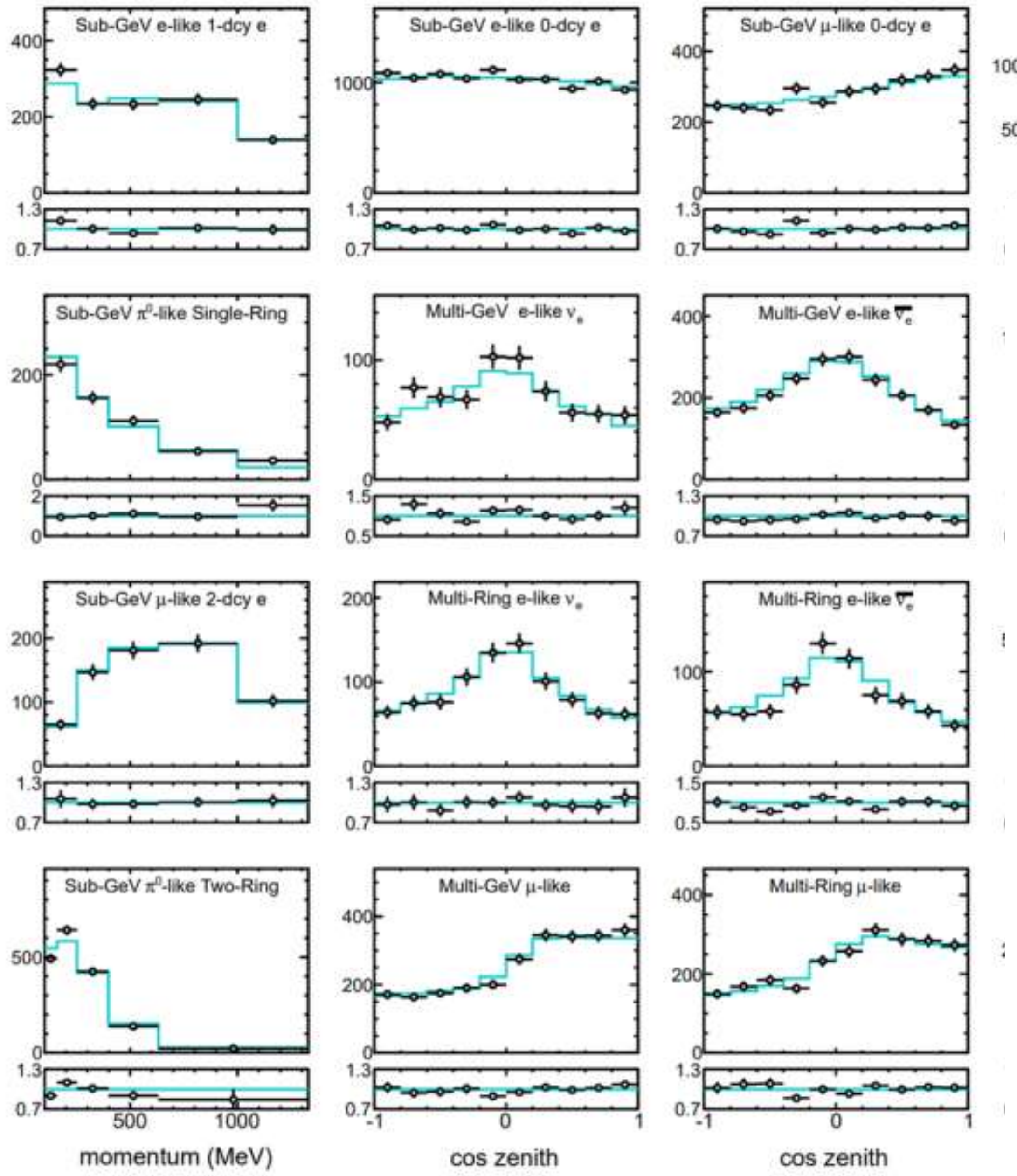


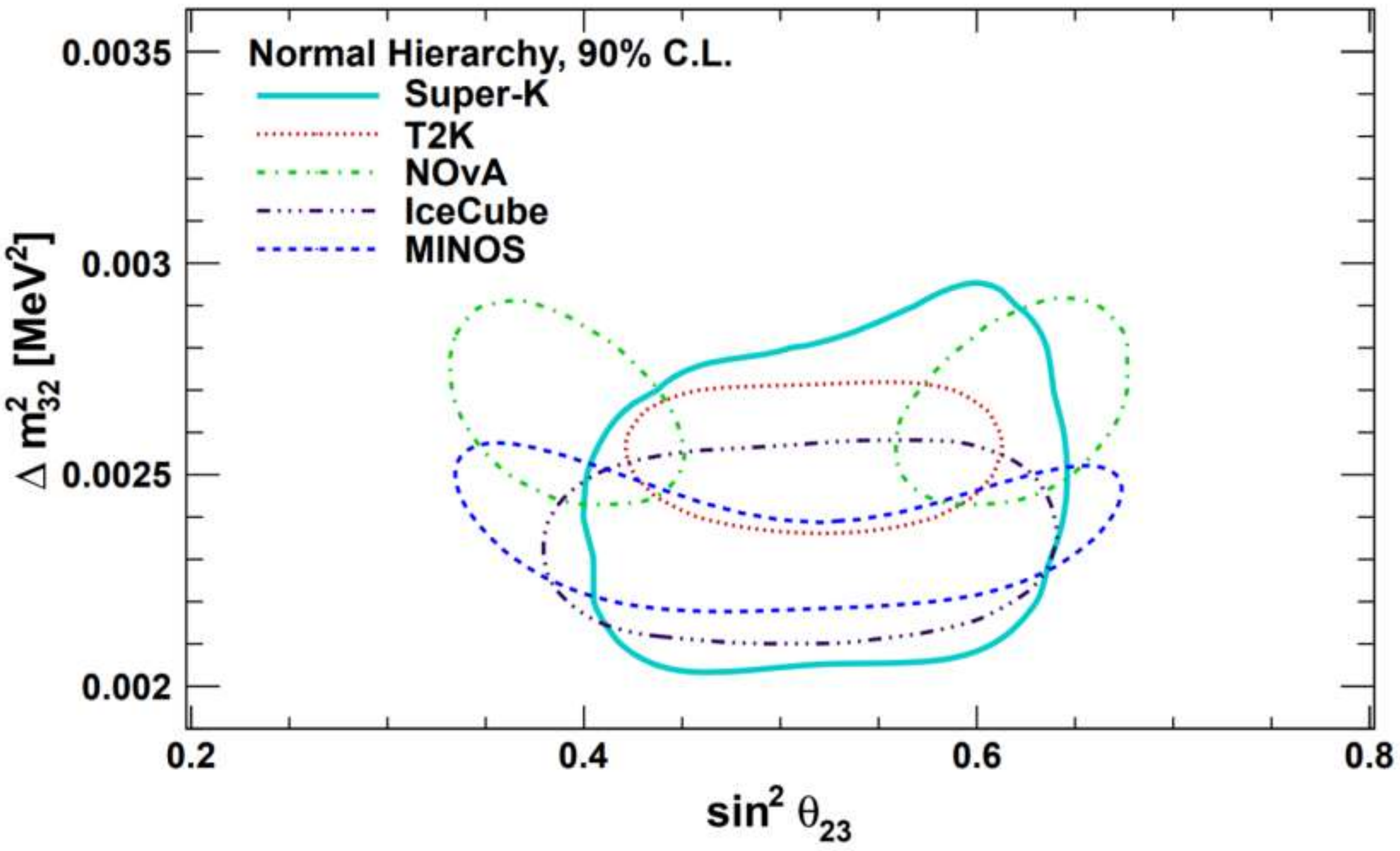
from Neutrino'98 presentation

Super-Kamiokande

Standard oscillations

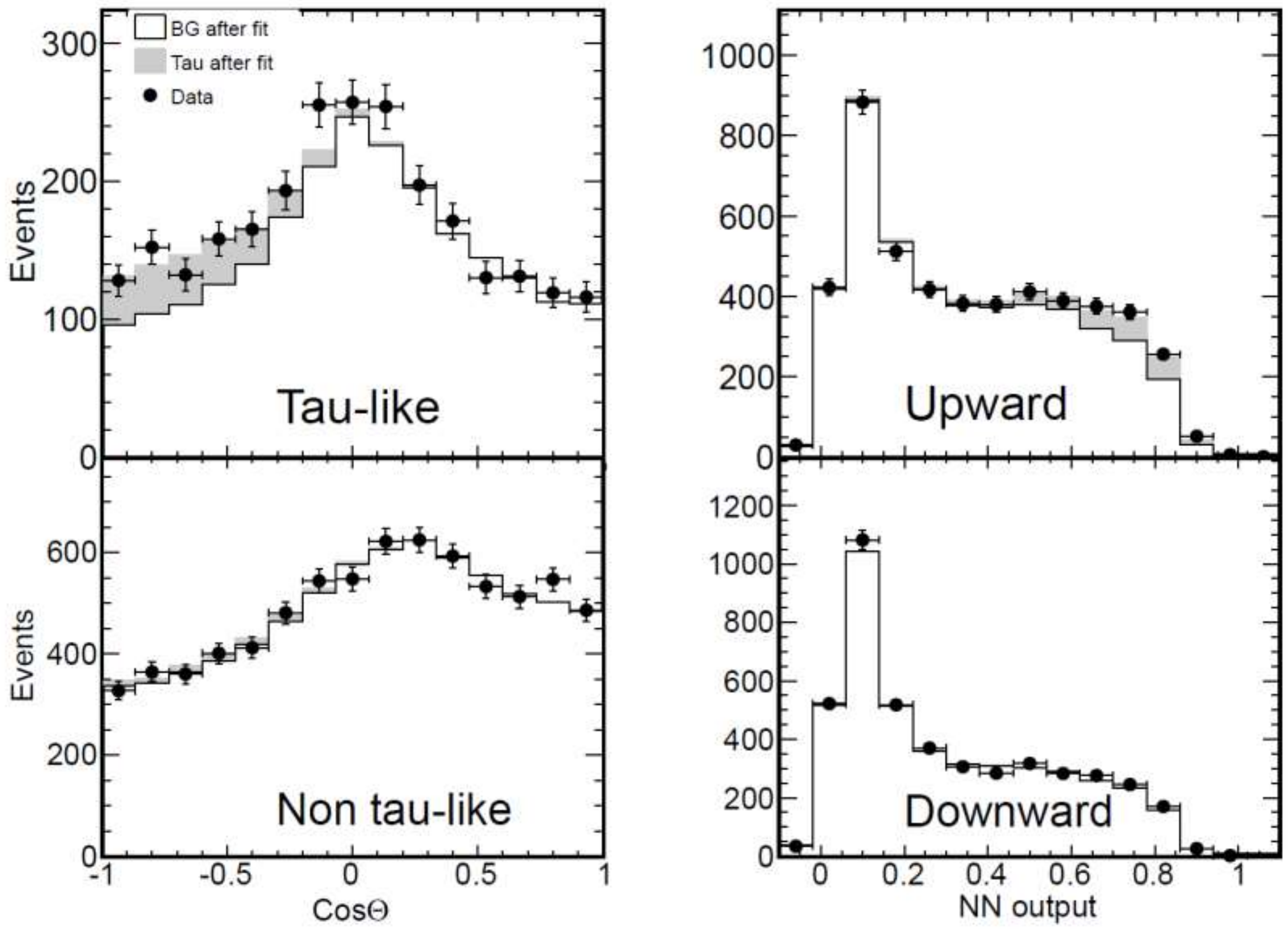
Phys. Rev. D 97, 072001 (2018)





Super-Kamiokande

NuTau appearance
Phys. Rev. D 98, 052006 (2018)



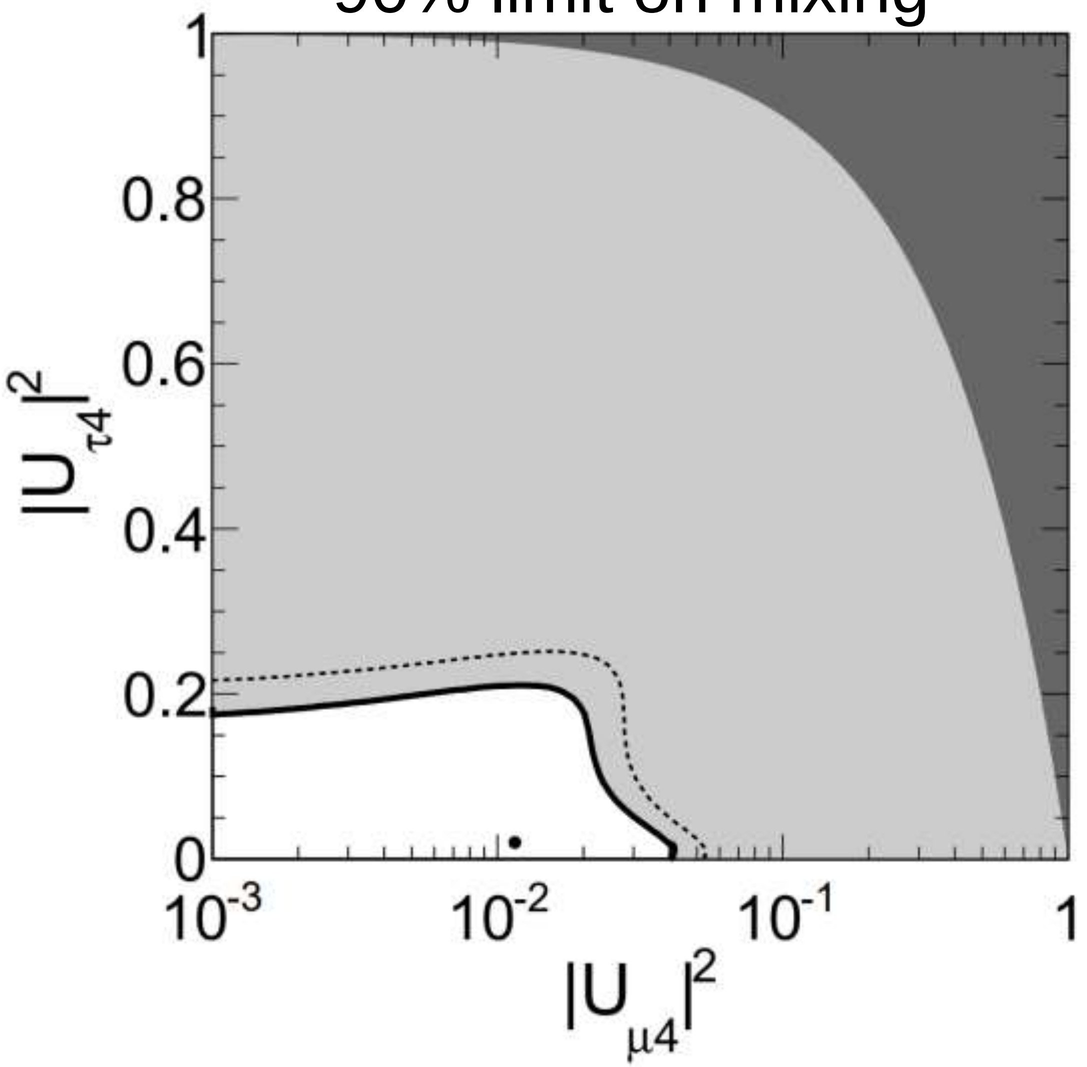
4.6σ evidence for NuTau appearance

Super-Kamiokande

Sterile neutrinos

Phys. Rev. D 91, 052019 (2015)

90% limit on mixing



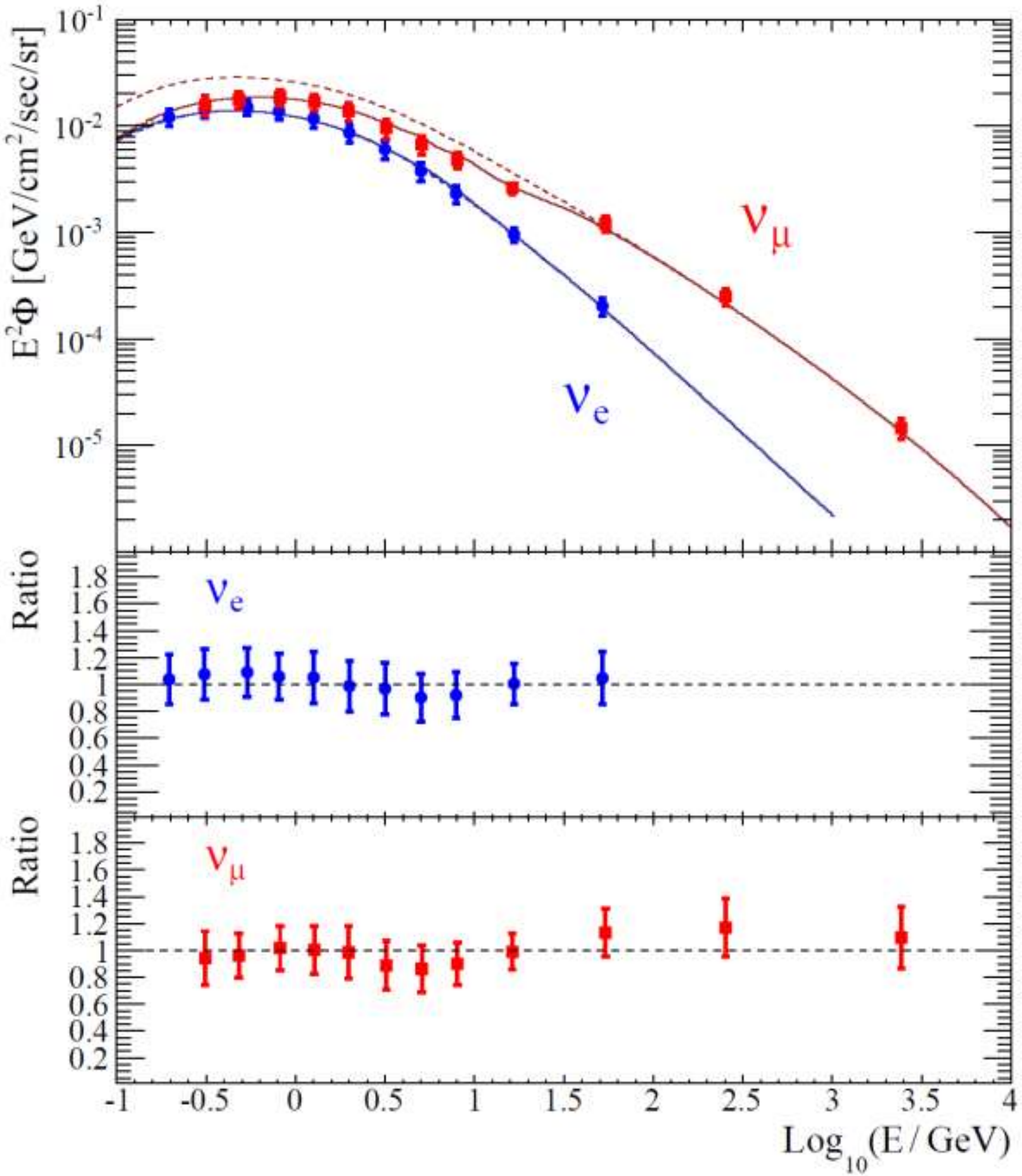
$$\mathbf{U} \equiv \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

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

Super-Kamiokande

Flux unfolding

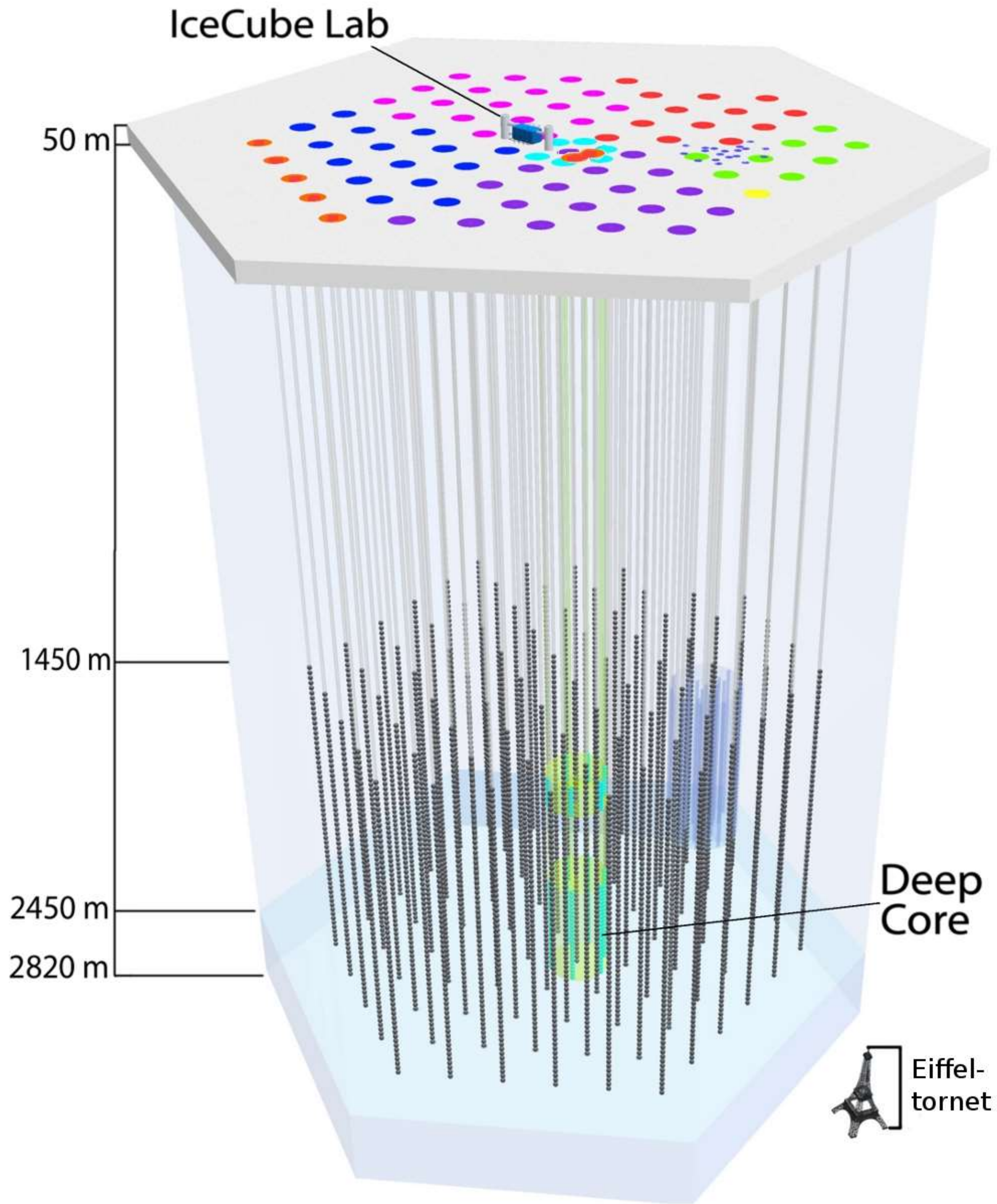
Phys. Rev. D 94, 052001 (2016)

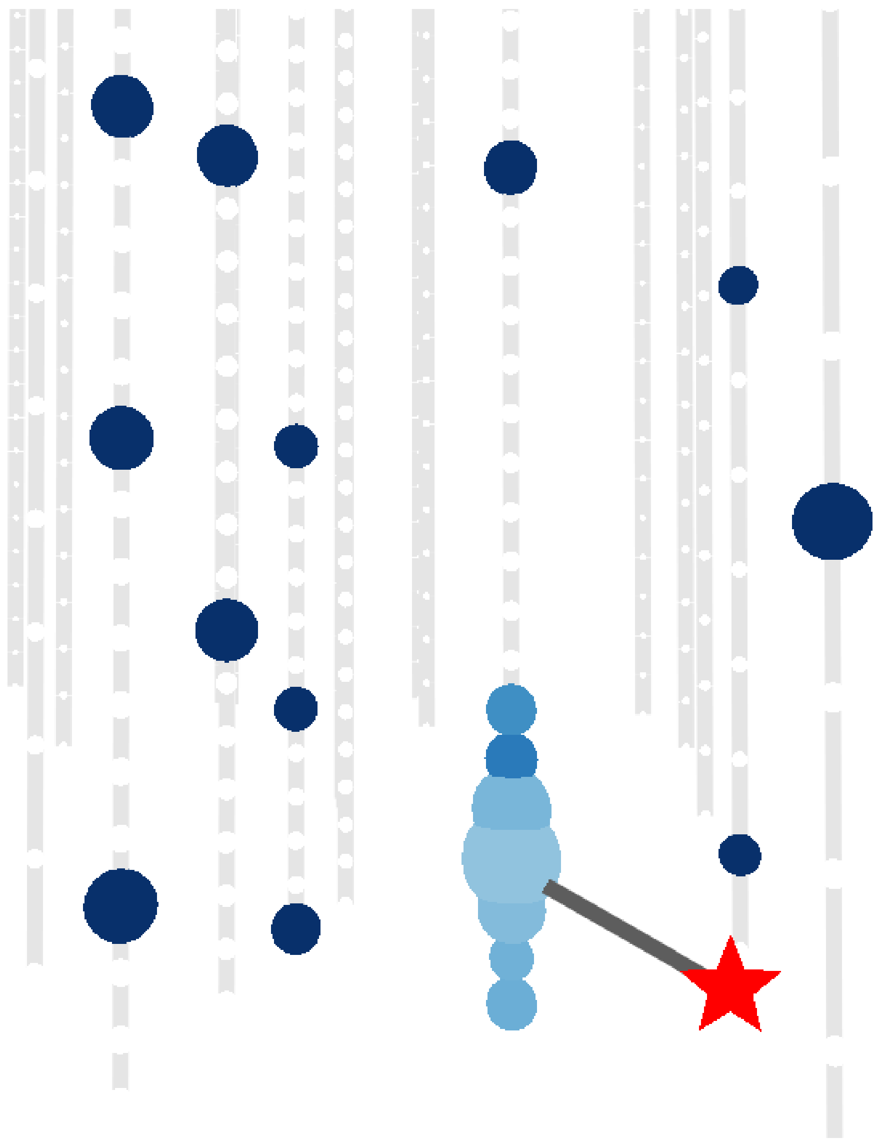


- direct measurement of total fluxes

- unfolding with special attention to low-energies

IceCube DeepCore



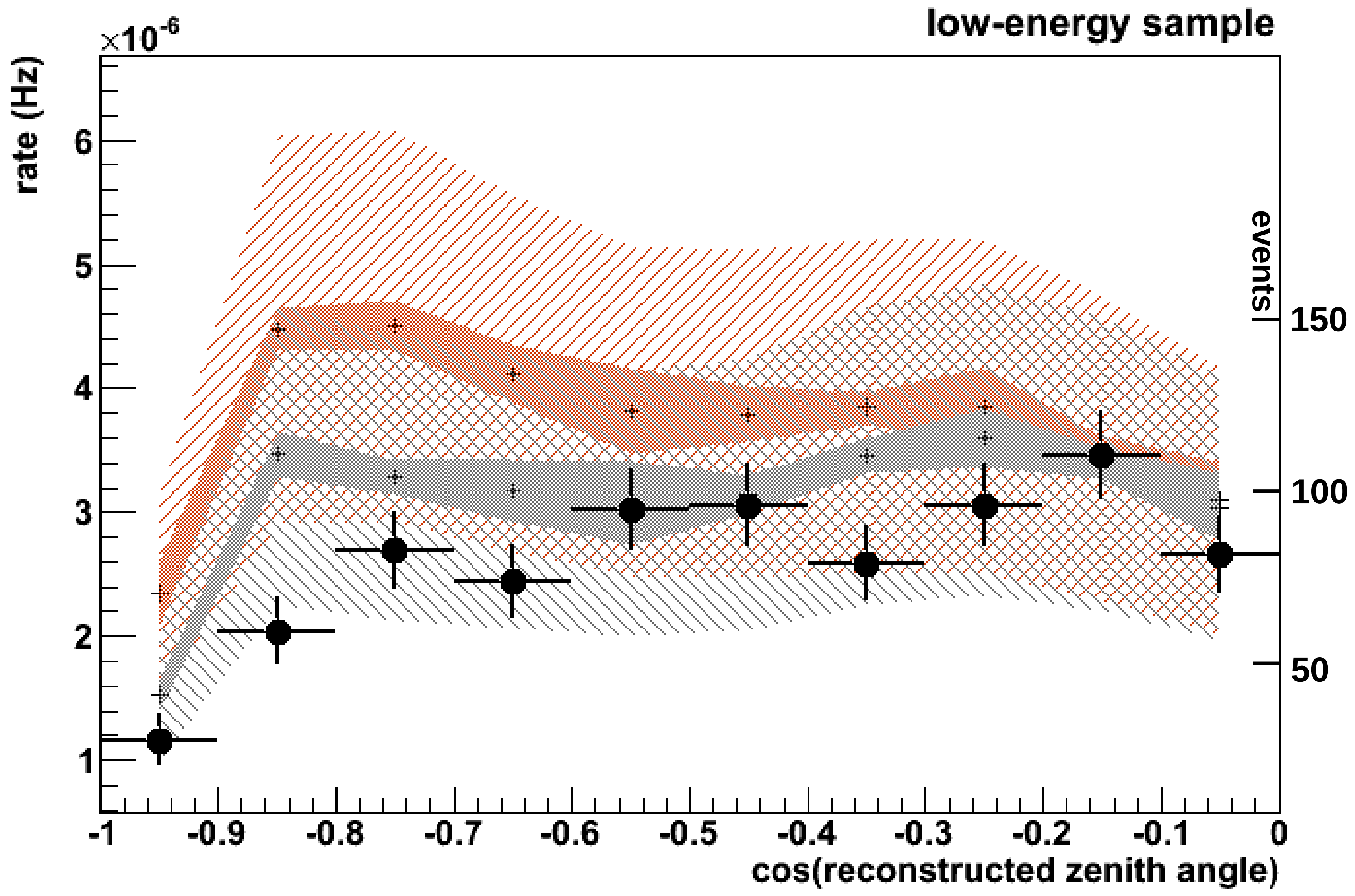


12 GeV ν_μ interaction

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

IceCube DeepCore

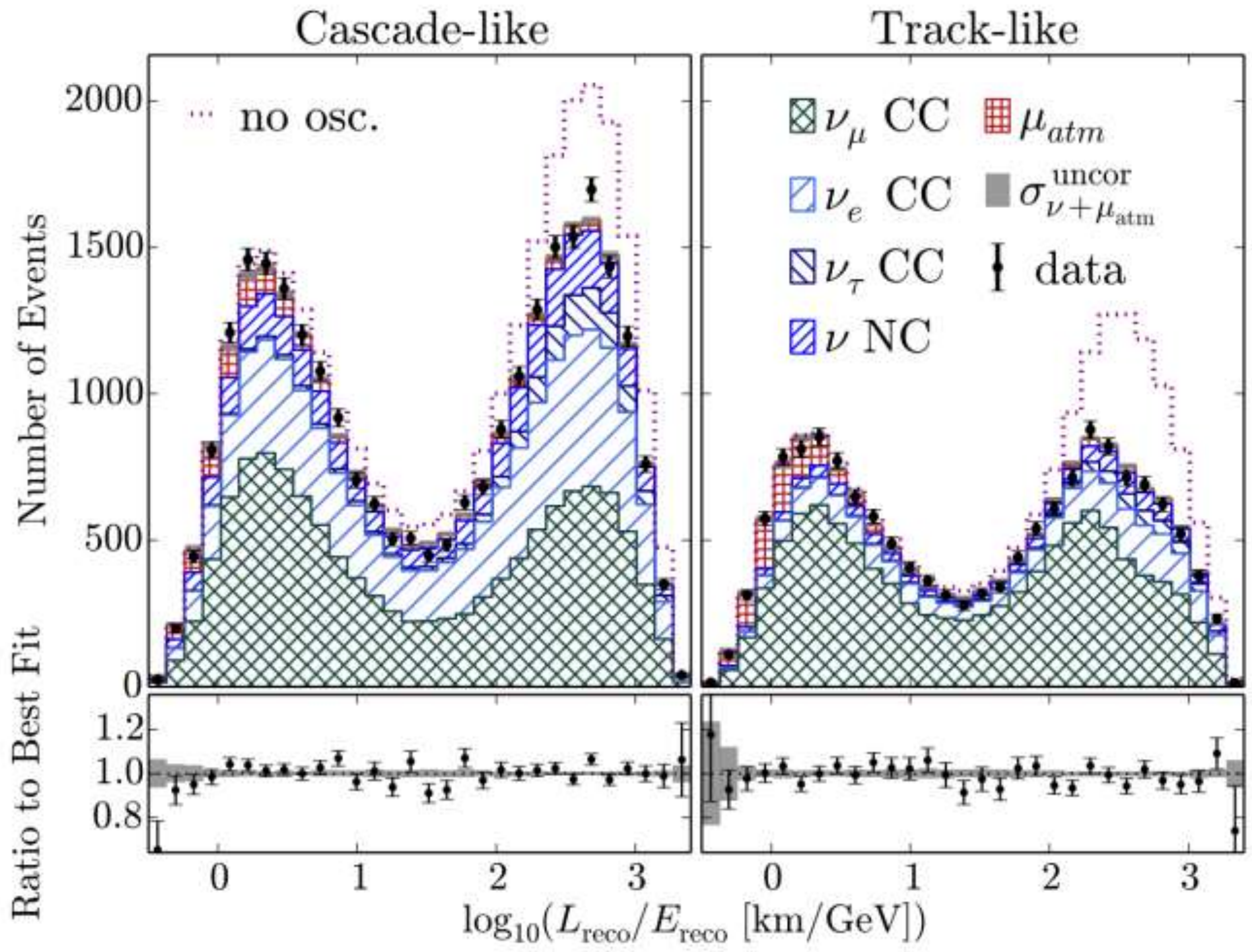
first publication on oscillations in 2013

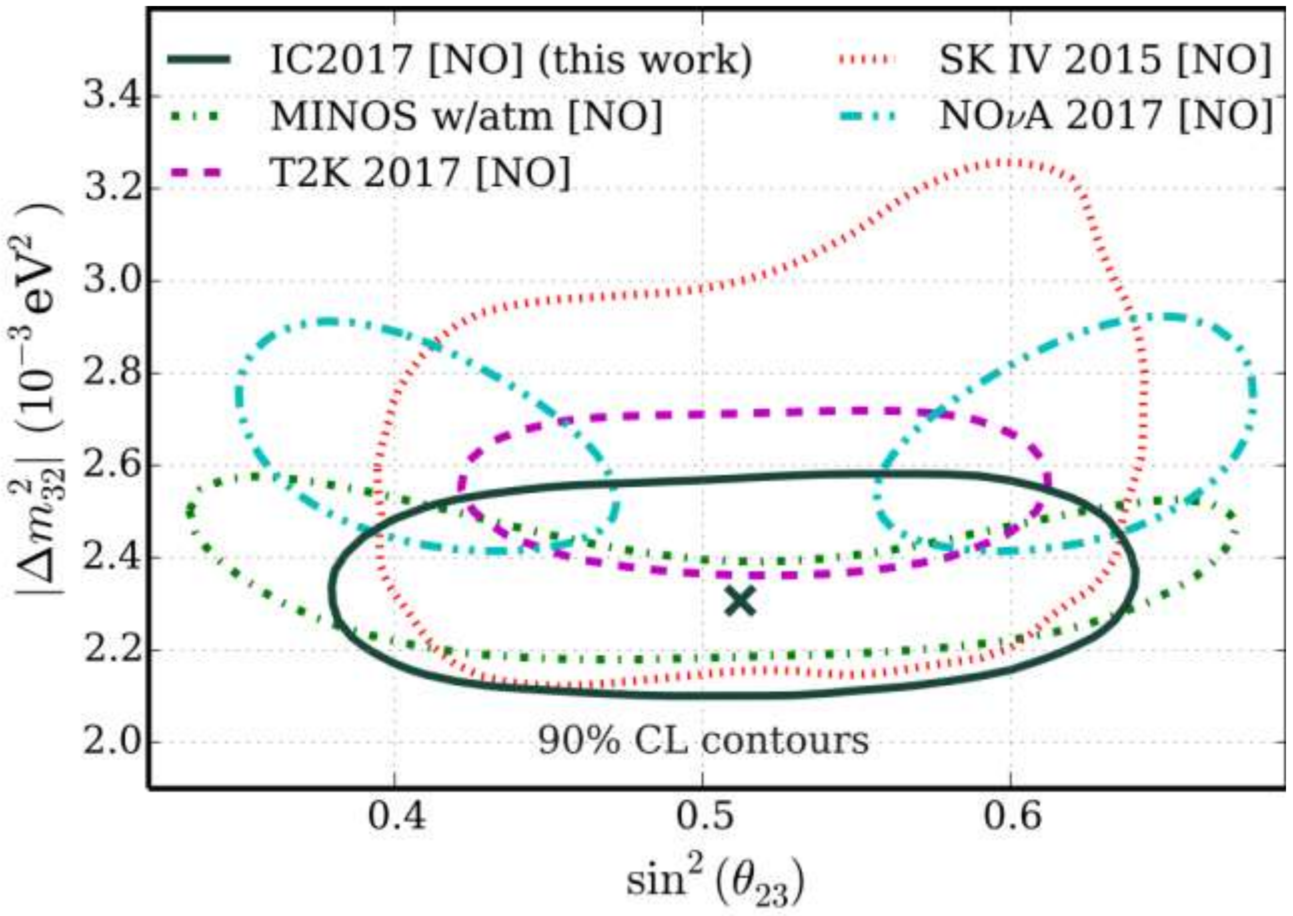


IceCube DeepCore

Standard oscillations

Phys. Rev. Lett. 120, 071801 (2018)

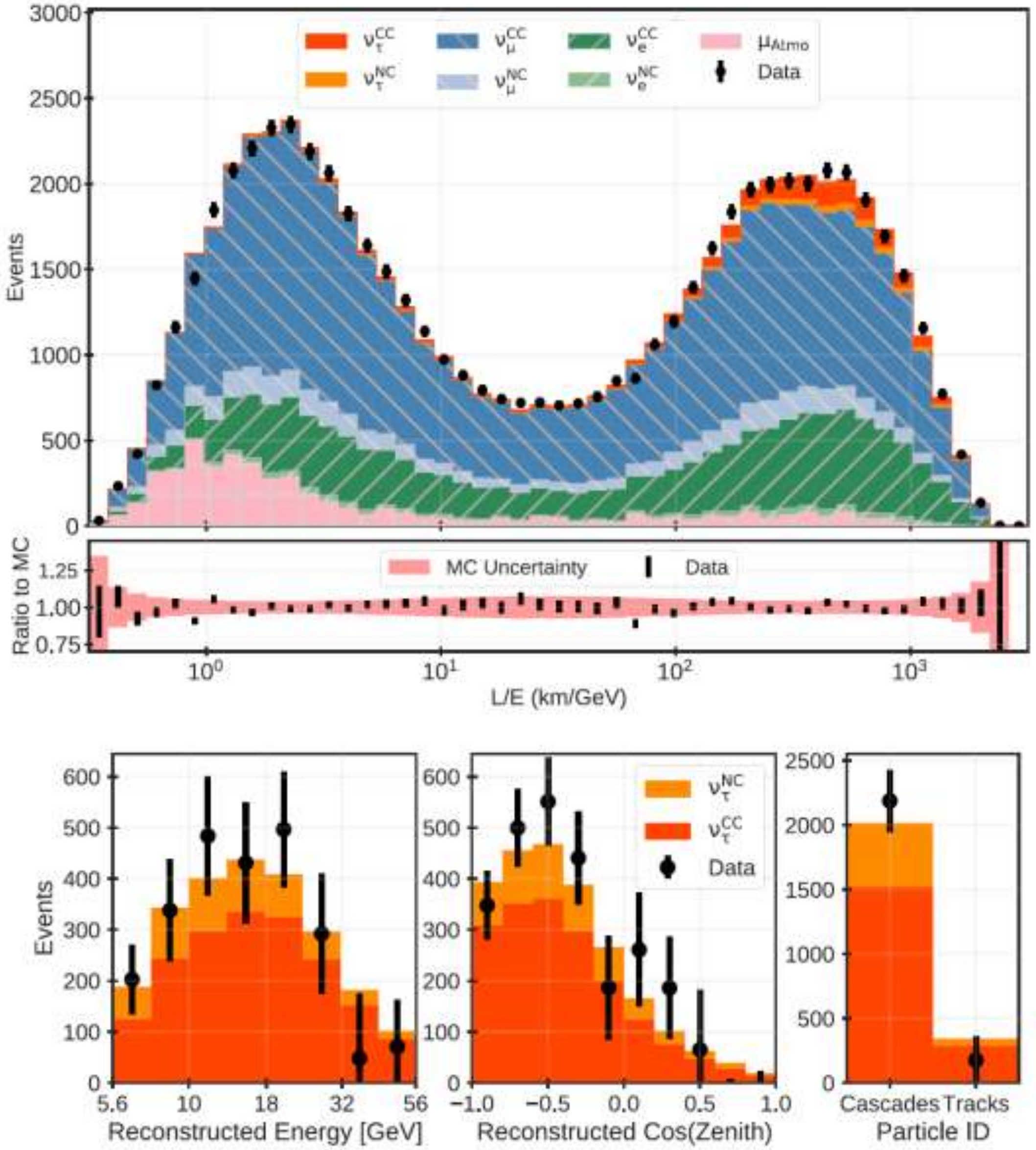


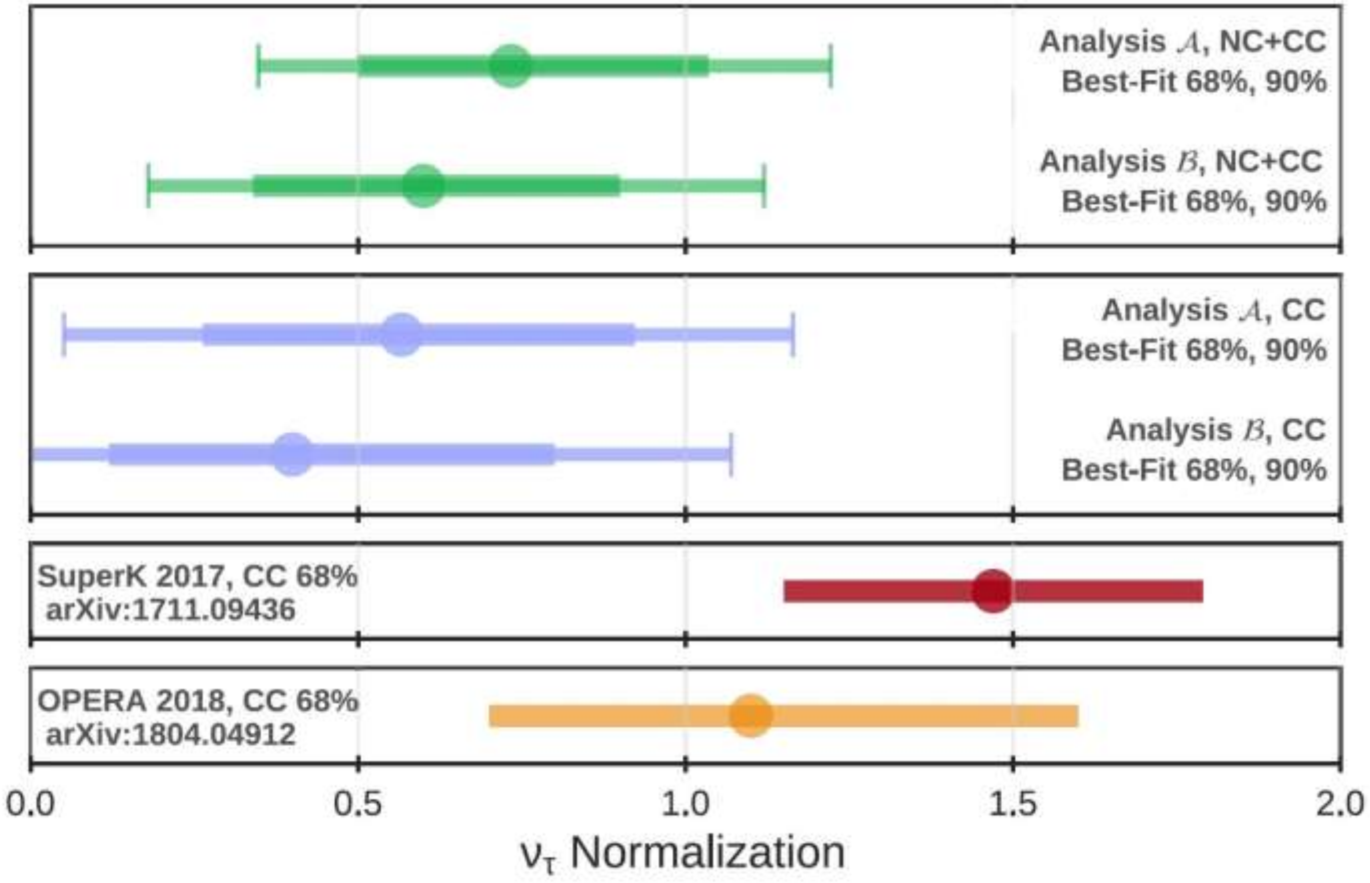


IceCube DeepCore

NuTau appearance

Phys. Rev. D 99, 032007 (2019)





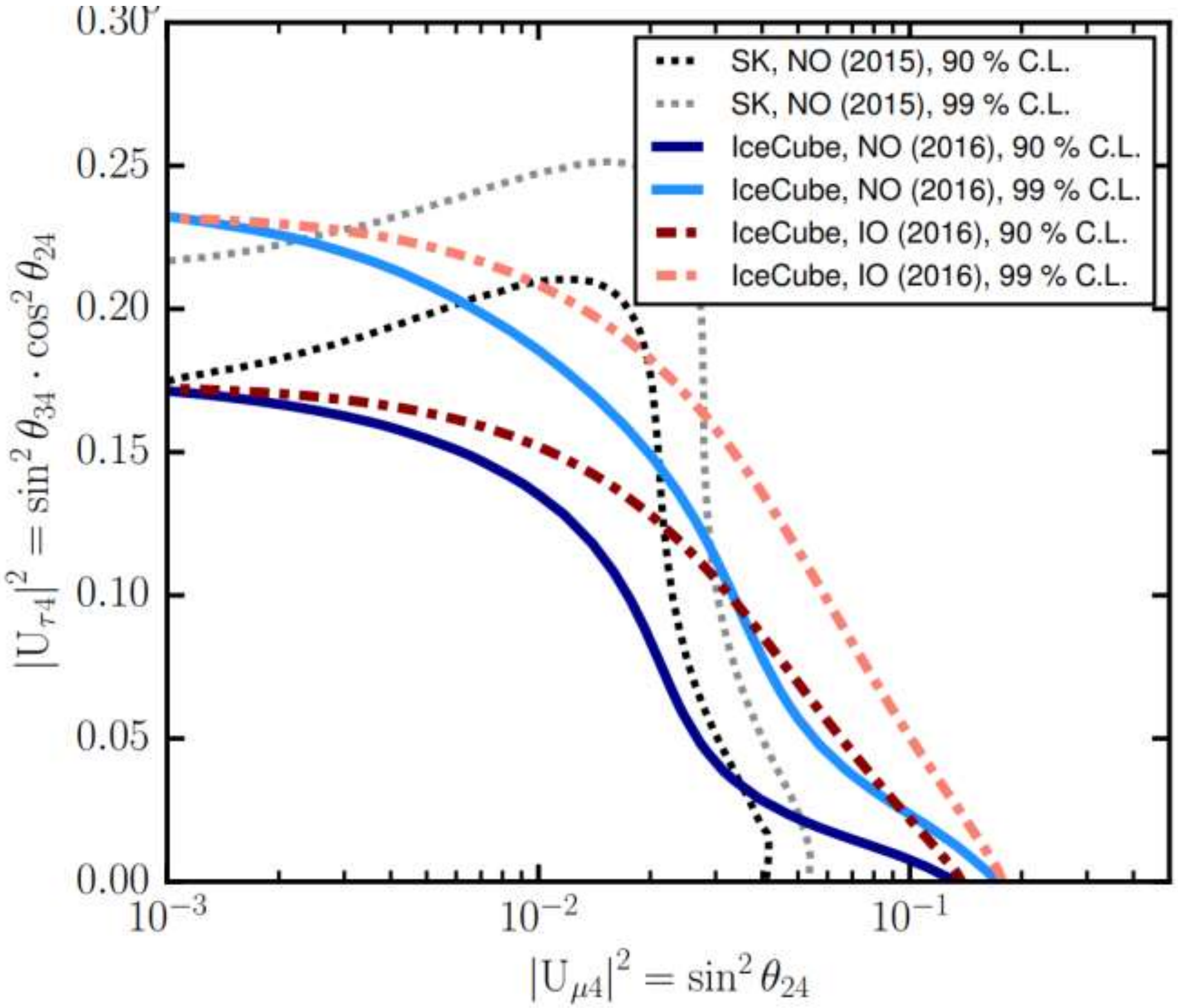
IceCube DeepCore

Sterile neutrinos

Phys. Rev. D 95, 112002 (2017)

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

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



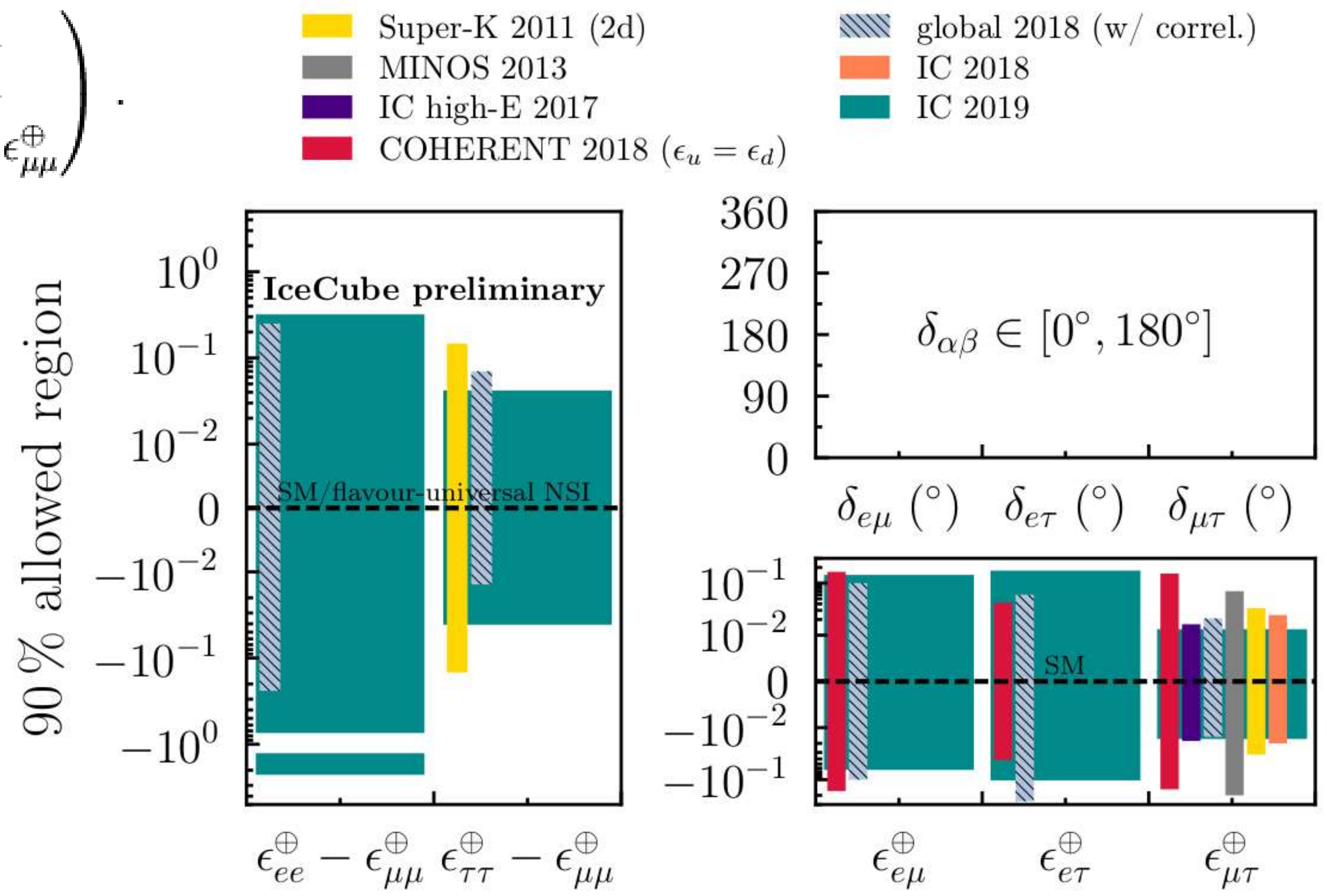
IceCube DeepCore

Non-standard interactions

In preparation

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

-there is no preference for additional NSIs



IceCube (high energy)

Sterile neutrinos

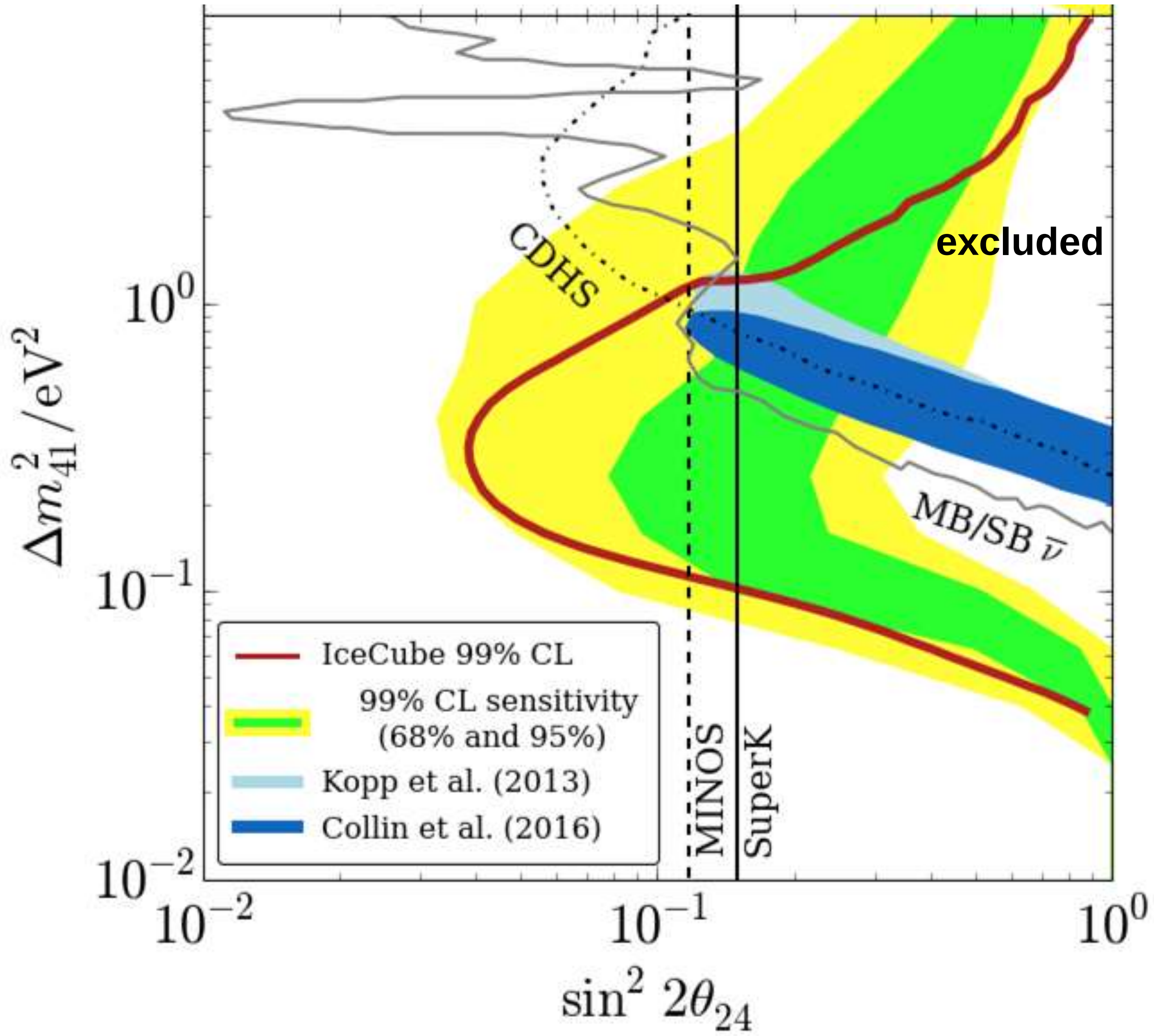
Phys. Rev. Lett. 117, 071801 (2016)

E_{nu} ~ TeVs

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

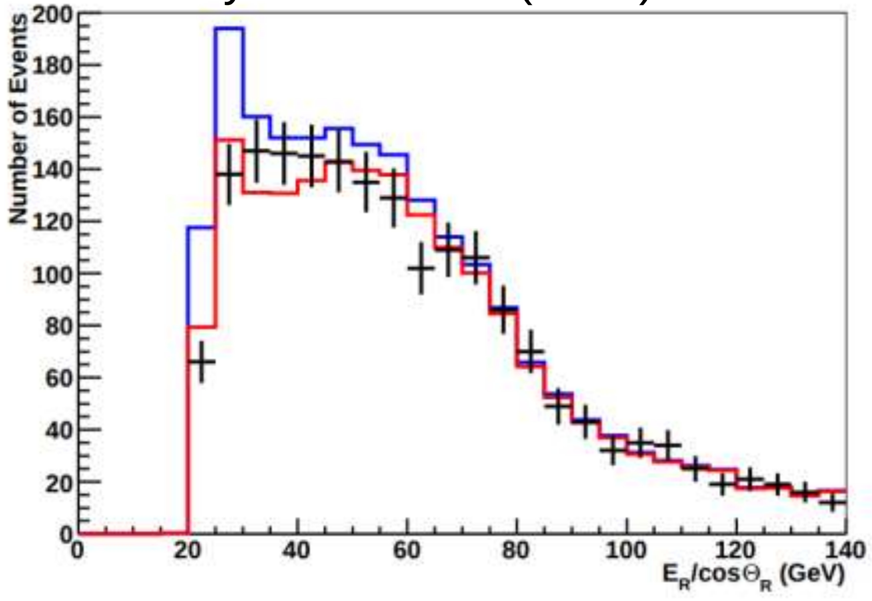
$$|U_{\mu 4}|^2 = \sin^2\theta_{24},$$

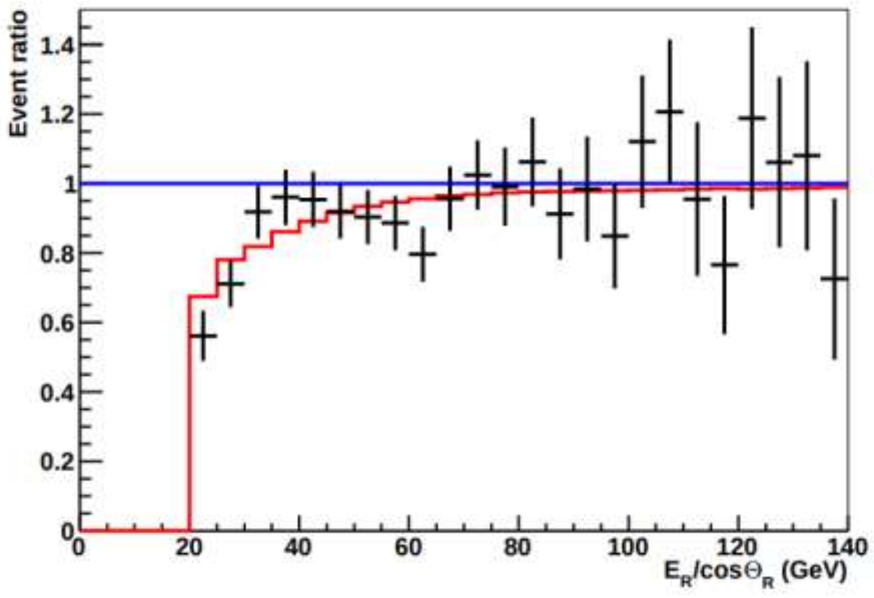
$$|U_{\tau 4}|^2 = \cos^2\theta_{24}\cdot\sin^2\theta_{34}.$$

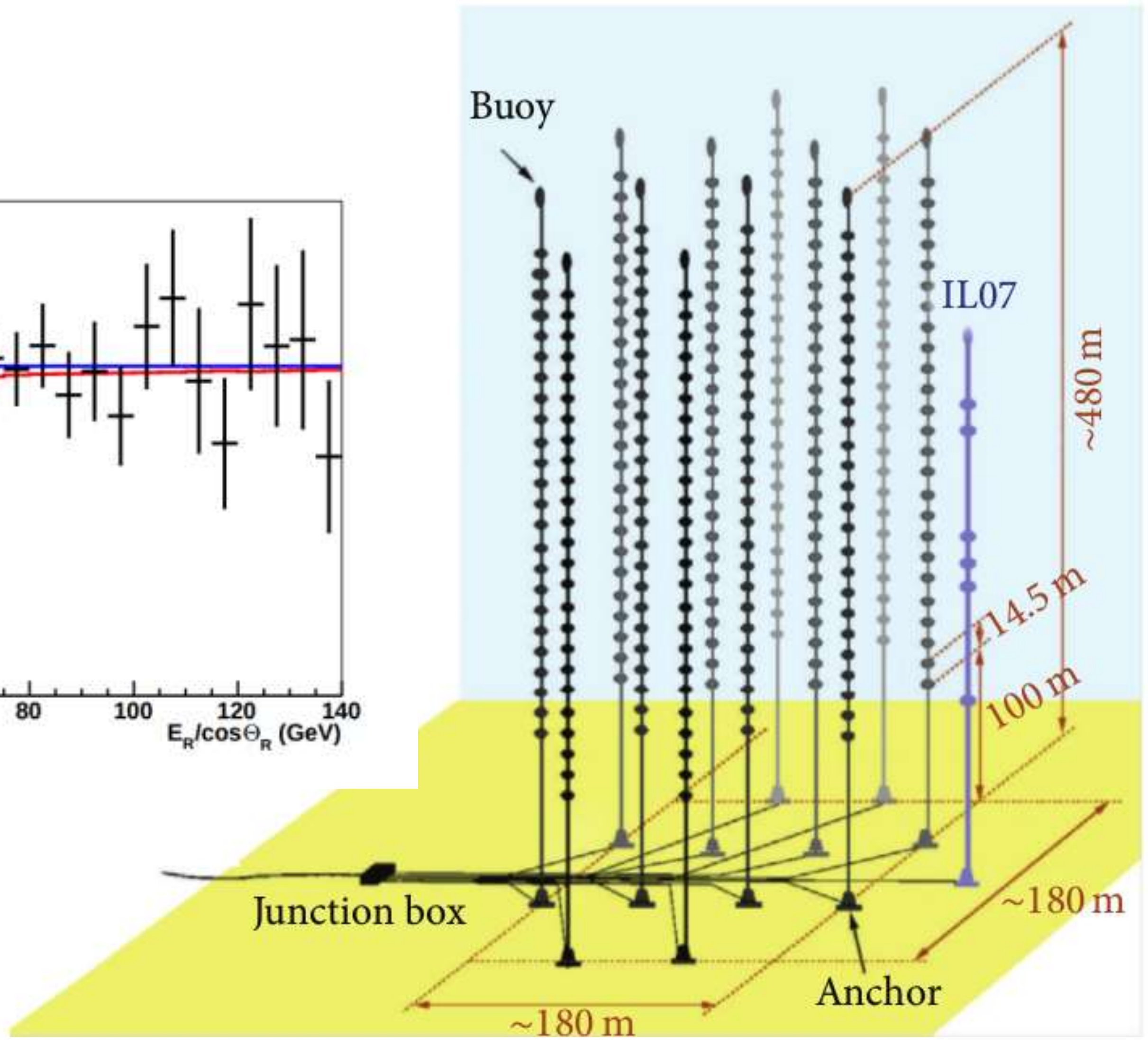


ANTARES
water Cherenkov

Phys.Lett. B714 (2012)

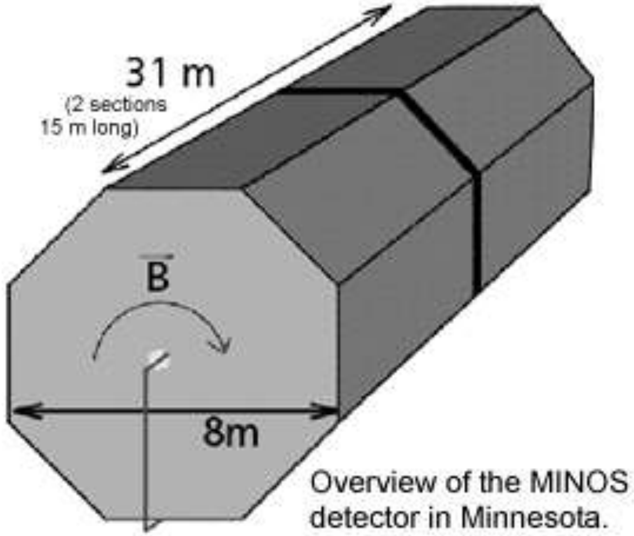


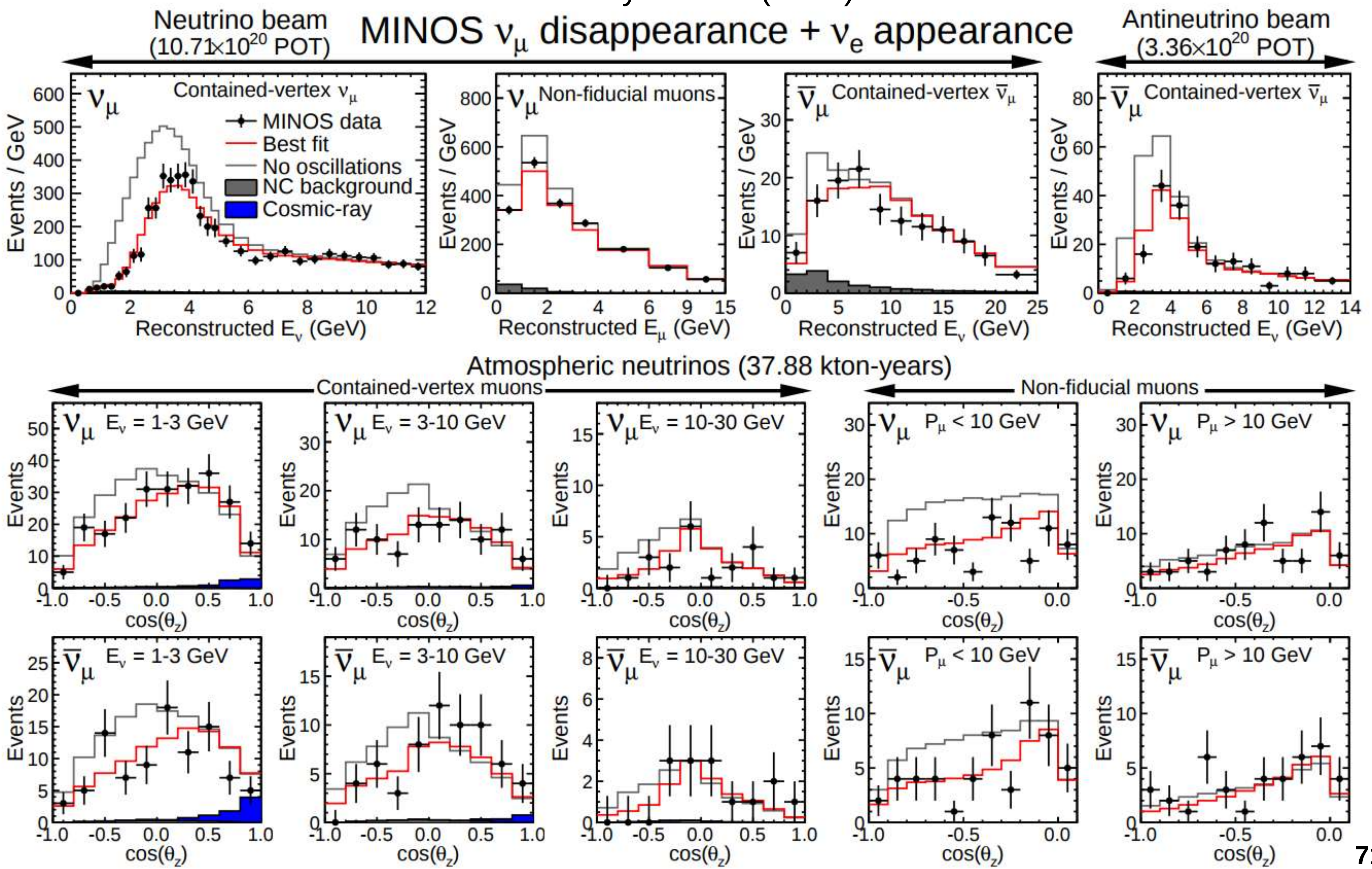




MINOS
magnetized steel & scintillator calorimeter

Nucl.Phys. B908 (2016) 130-150





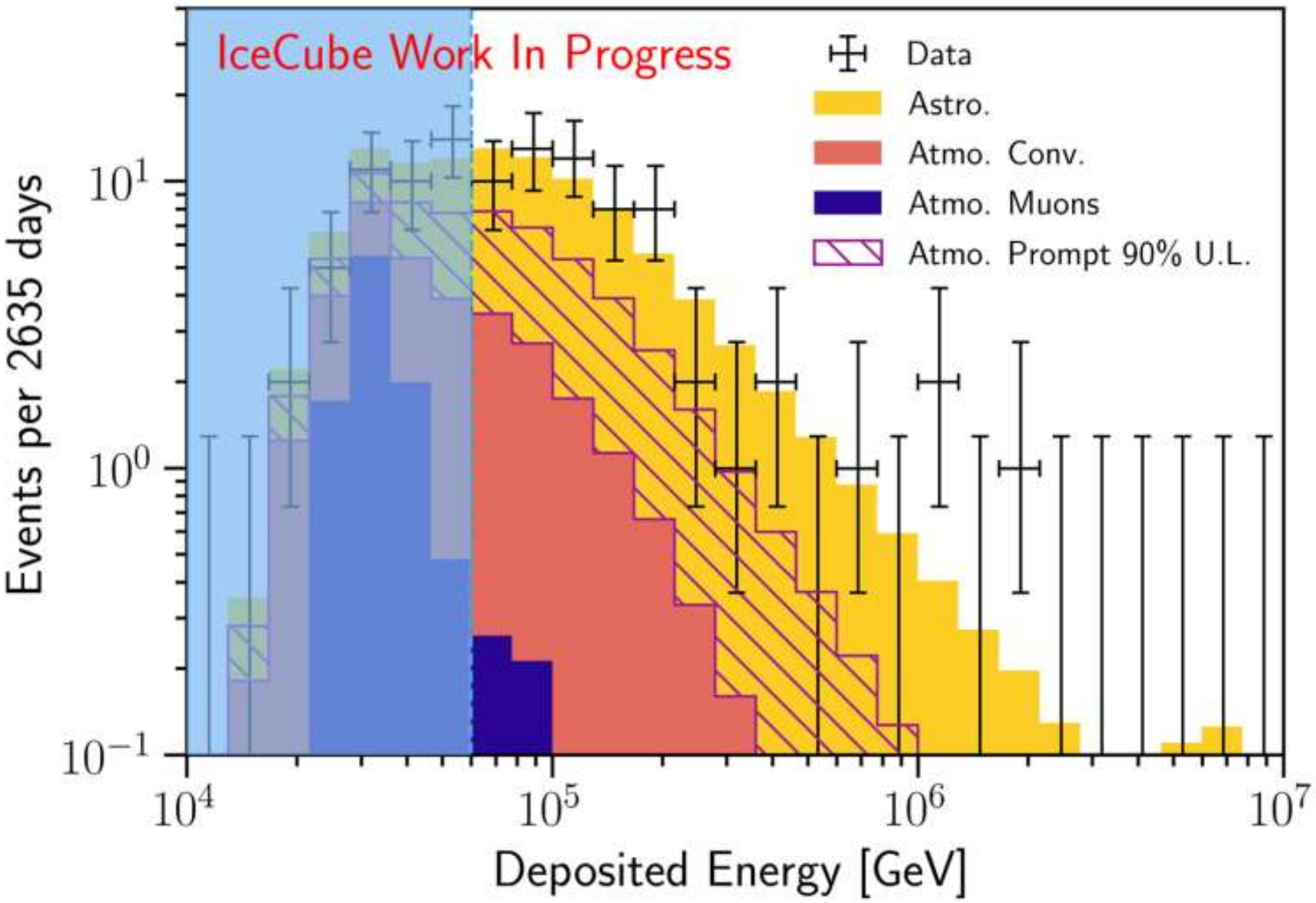
*measurement is dominated by beam data

cosmic neutrinos in telescopes

See results from IceCube, ANTARES and future projections

atmospherics are background for cosmic searches

neutrinos from charmed mesons very uncertain



towards the future

main interests

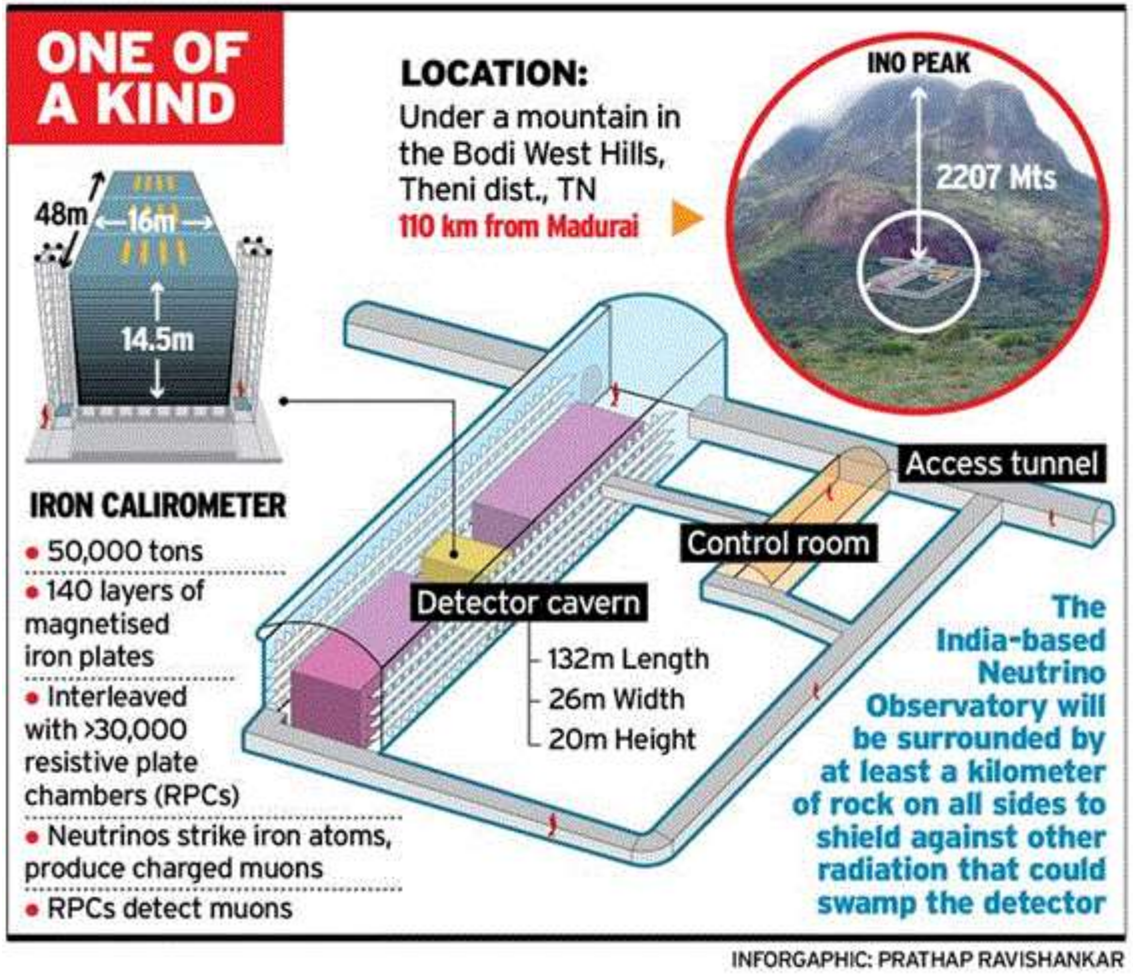
-precision measurements

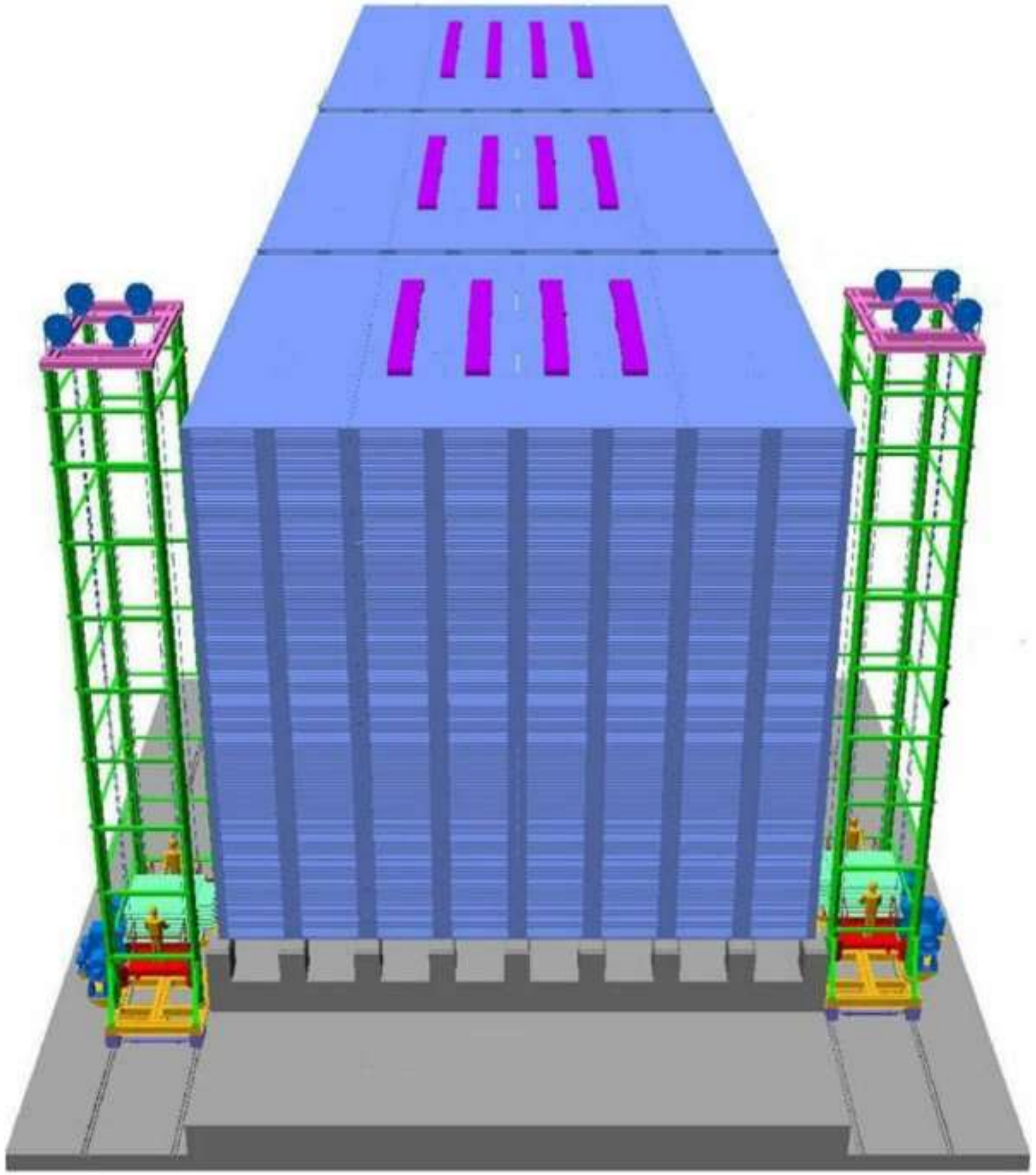
-neutrino mass ordering

-CP-violation in leptons*

… bigger, better, denser experiments

INO

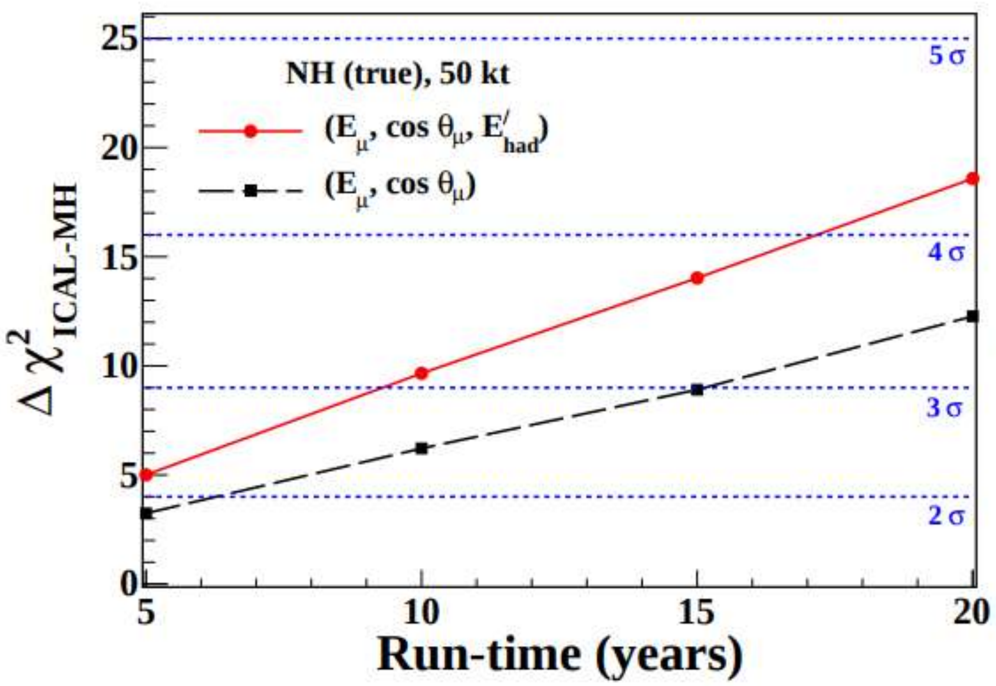


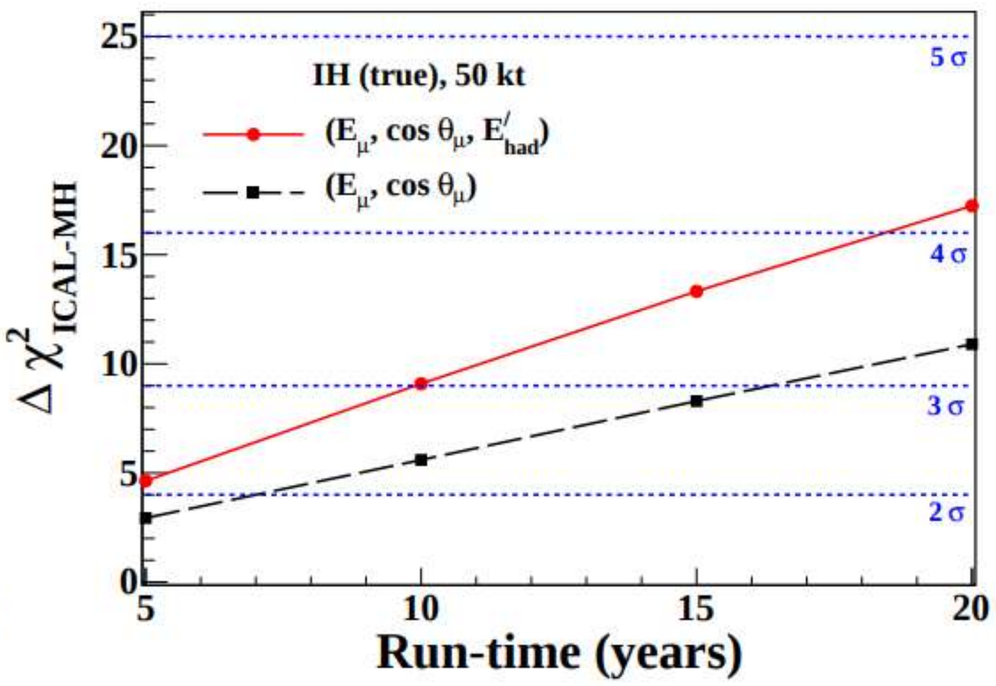


-individual particle **tracking**

-**charge** identification

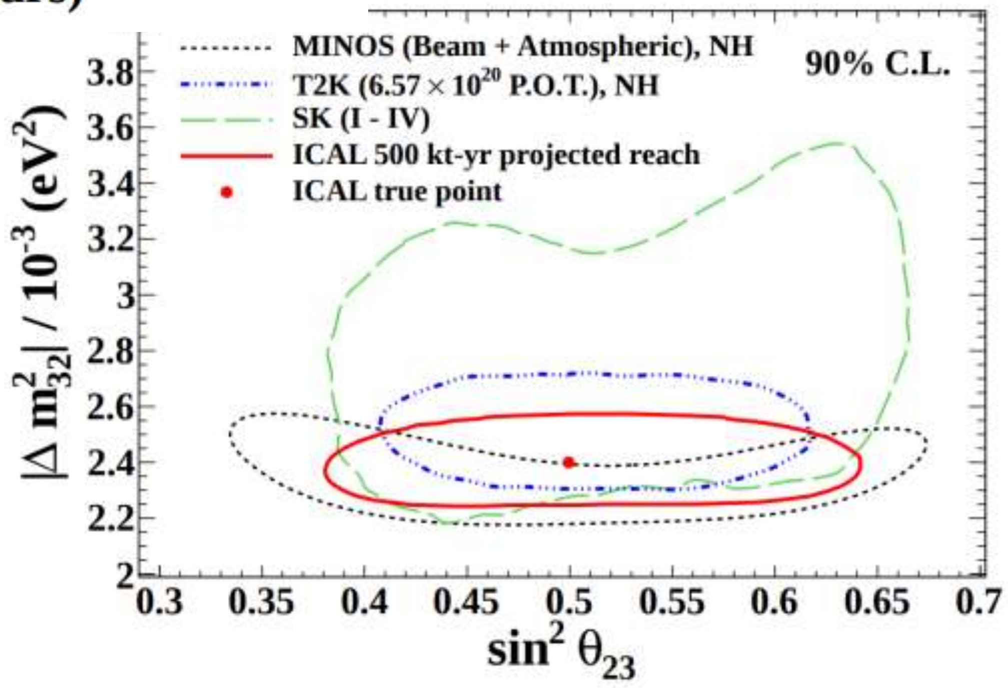
INO





mass ordering

arXiv:1406.3689 [hep-ph]



oscillation parameters after 10 years of run-time

Hyper-Kamiokande

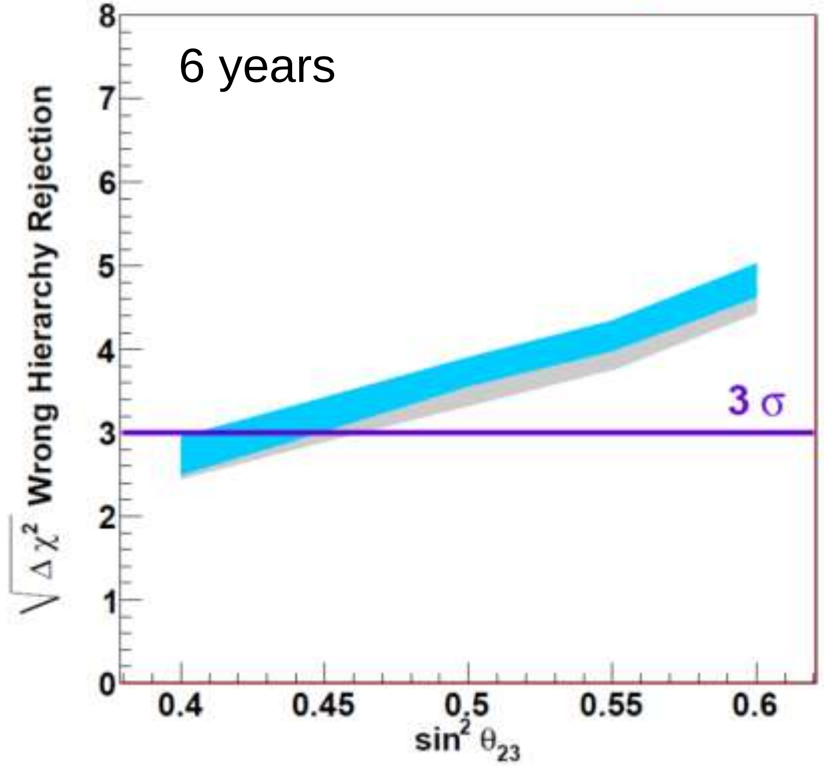
-8x Super-Kamiokande's FV / tank

-260kt mass / tank

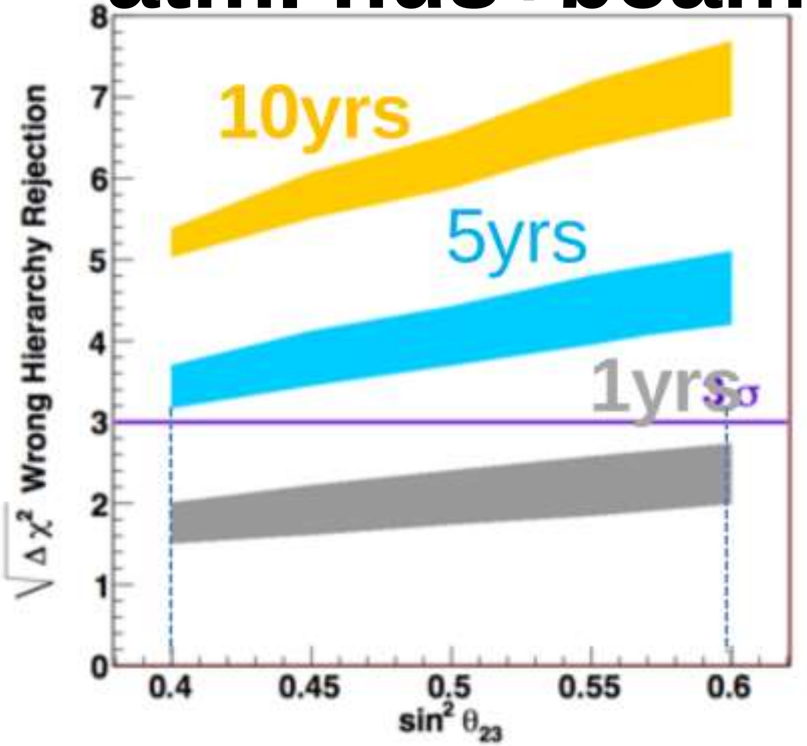
-atmospheric+beam nus

Hyper-Kamiokande (one tank)

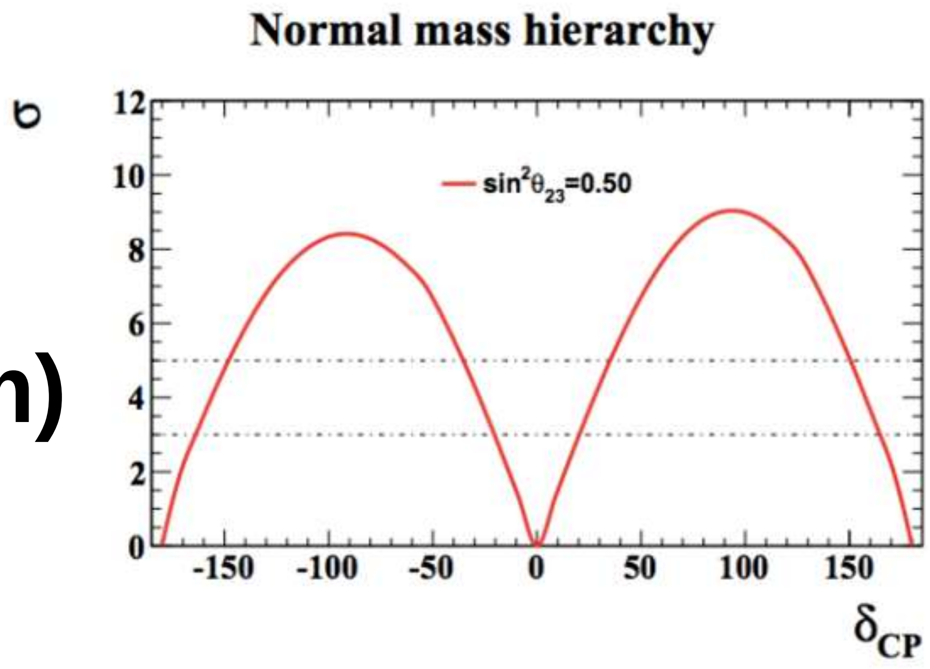
atm. nus



atm. nus+beam

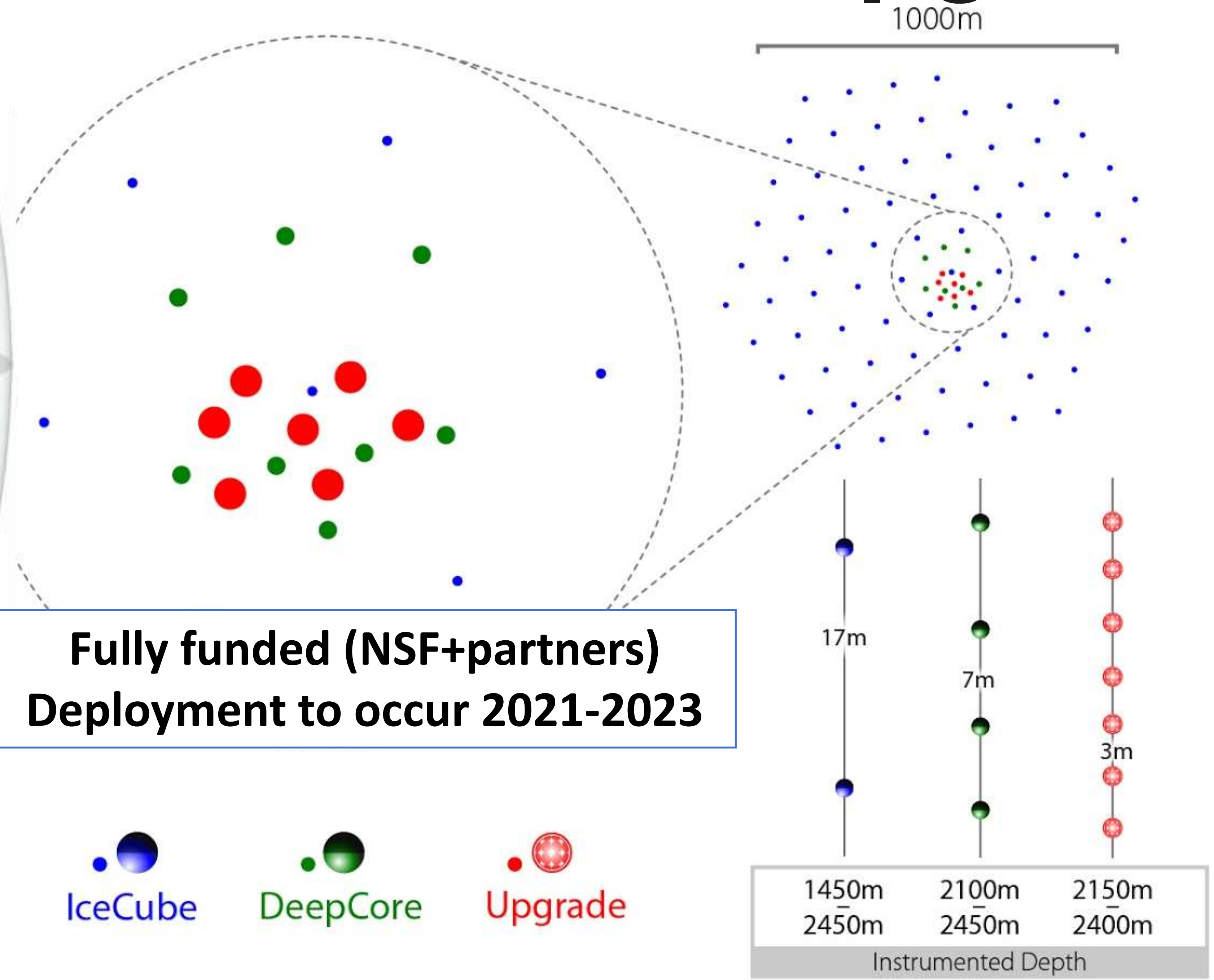


CP-violation after 10 years (beam)



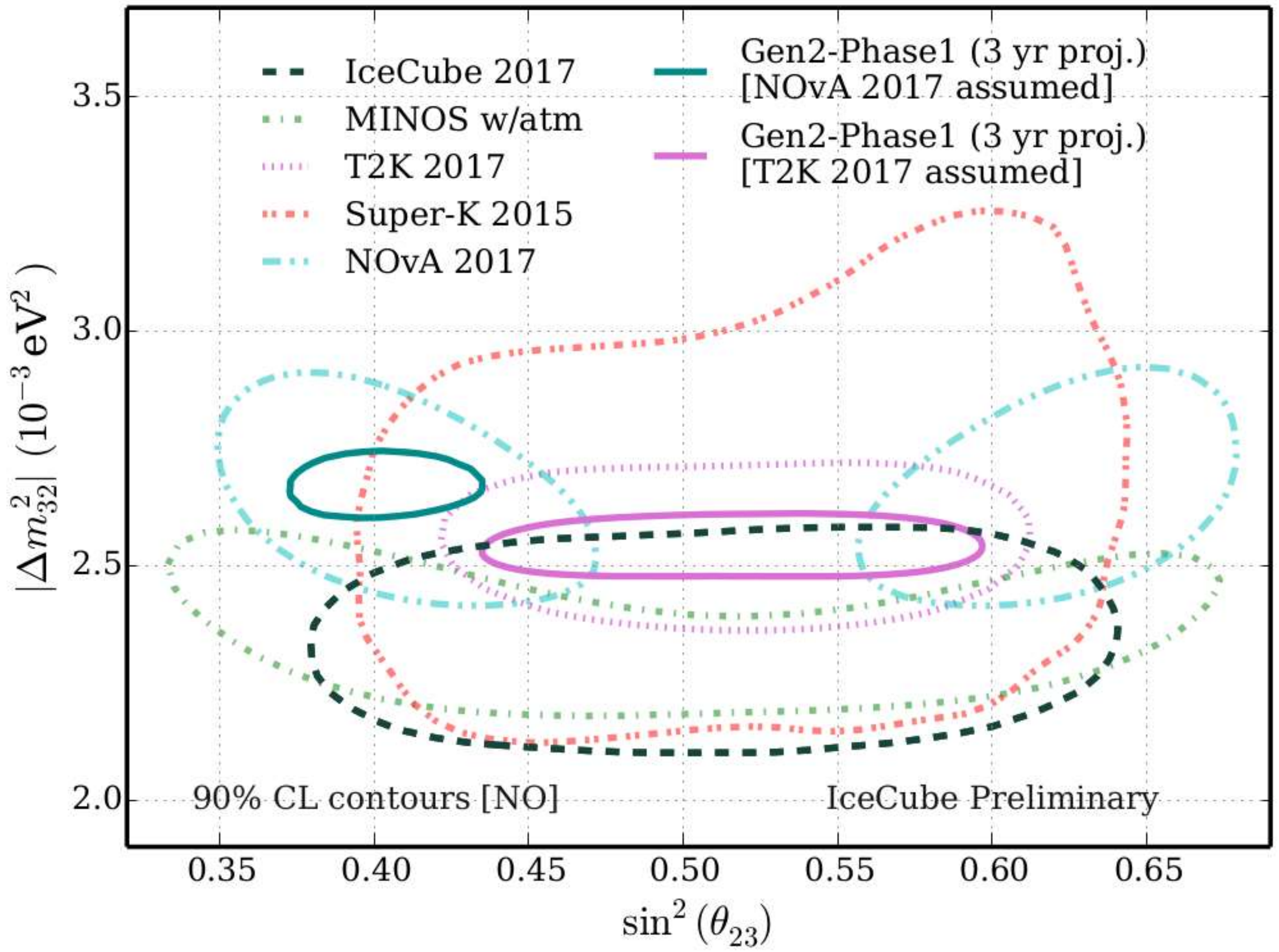
Zsoldos, ICRC2017

the IceCube upgrade



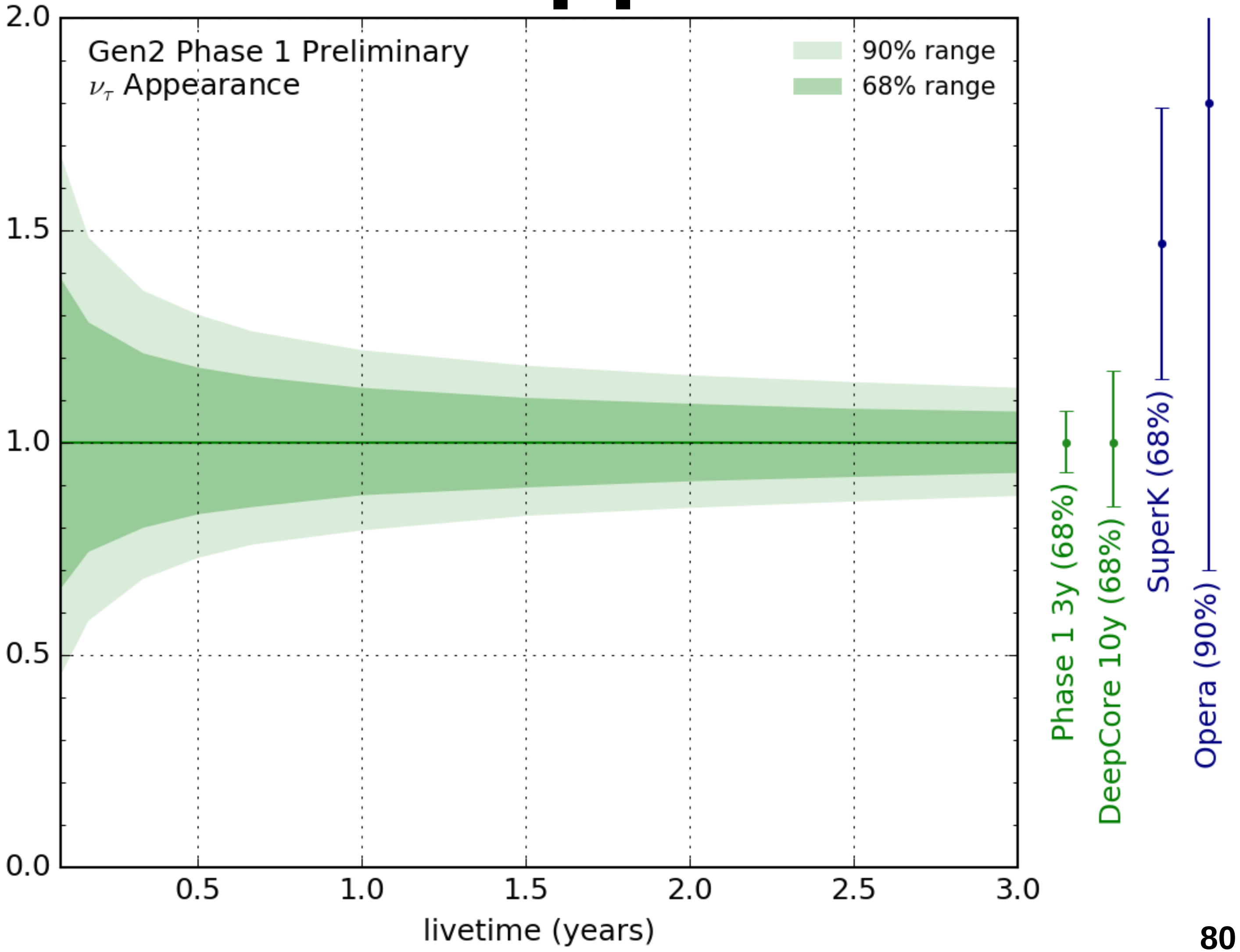
Fully funded (NSF+partners)
Deployment to occur 2021-2023

the IceCube upgrade

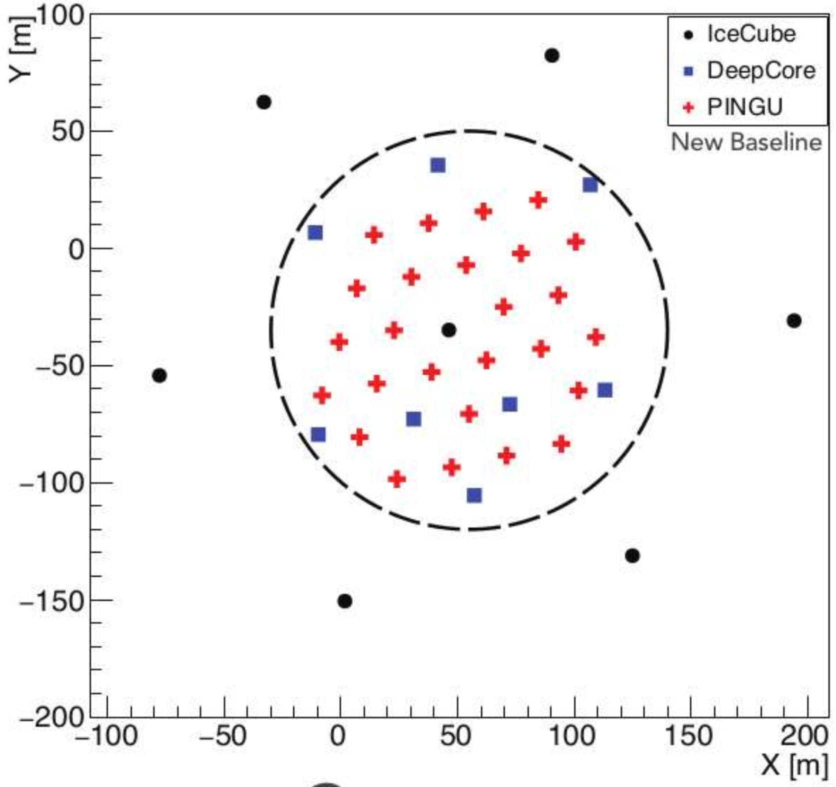


osc. parameters

nutau appearance



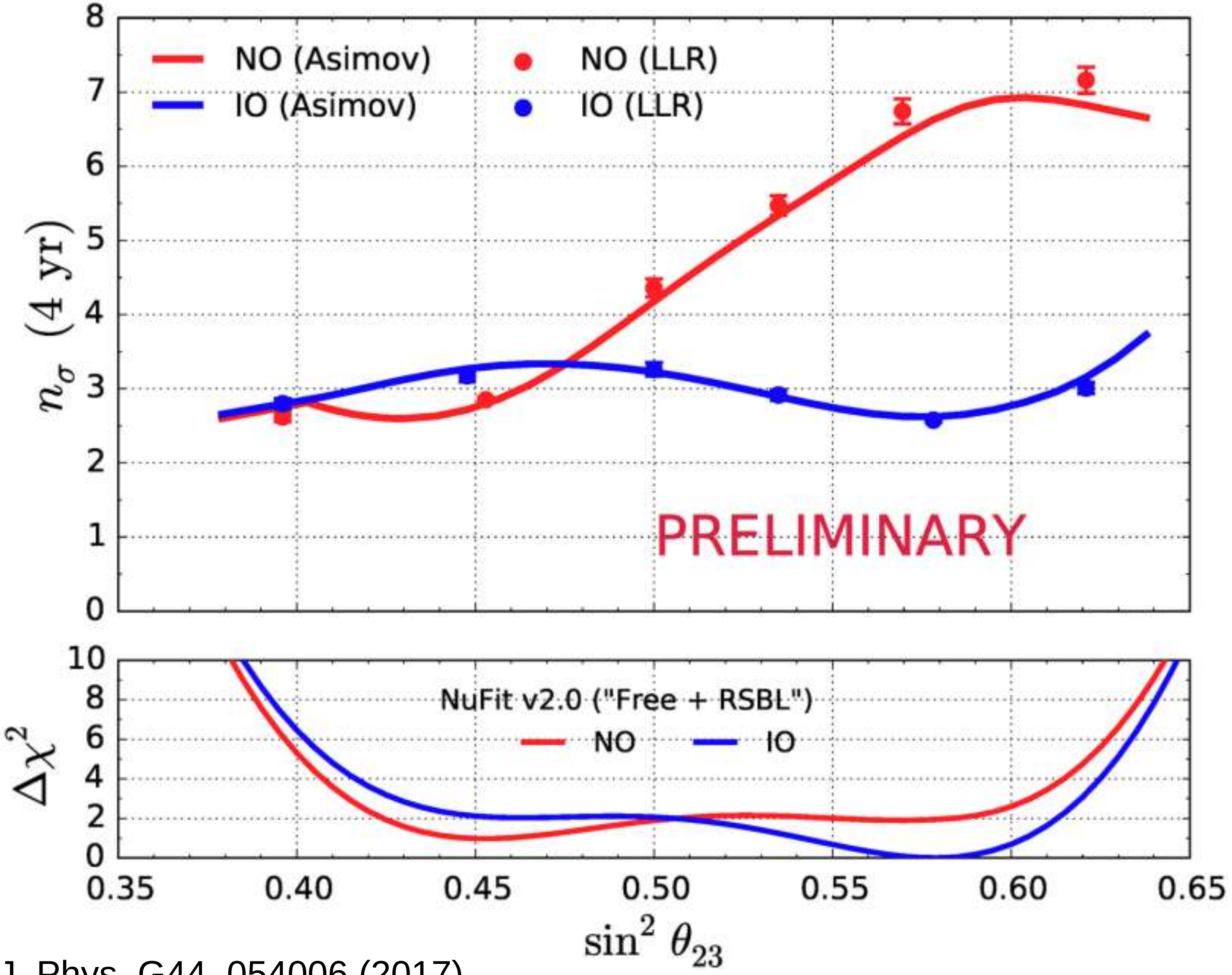
PINGU



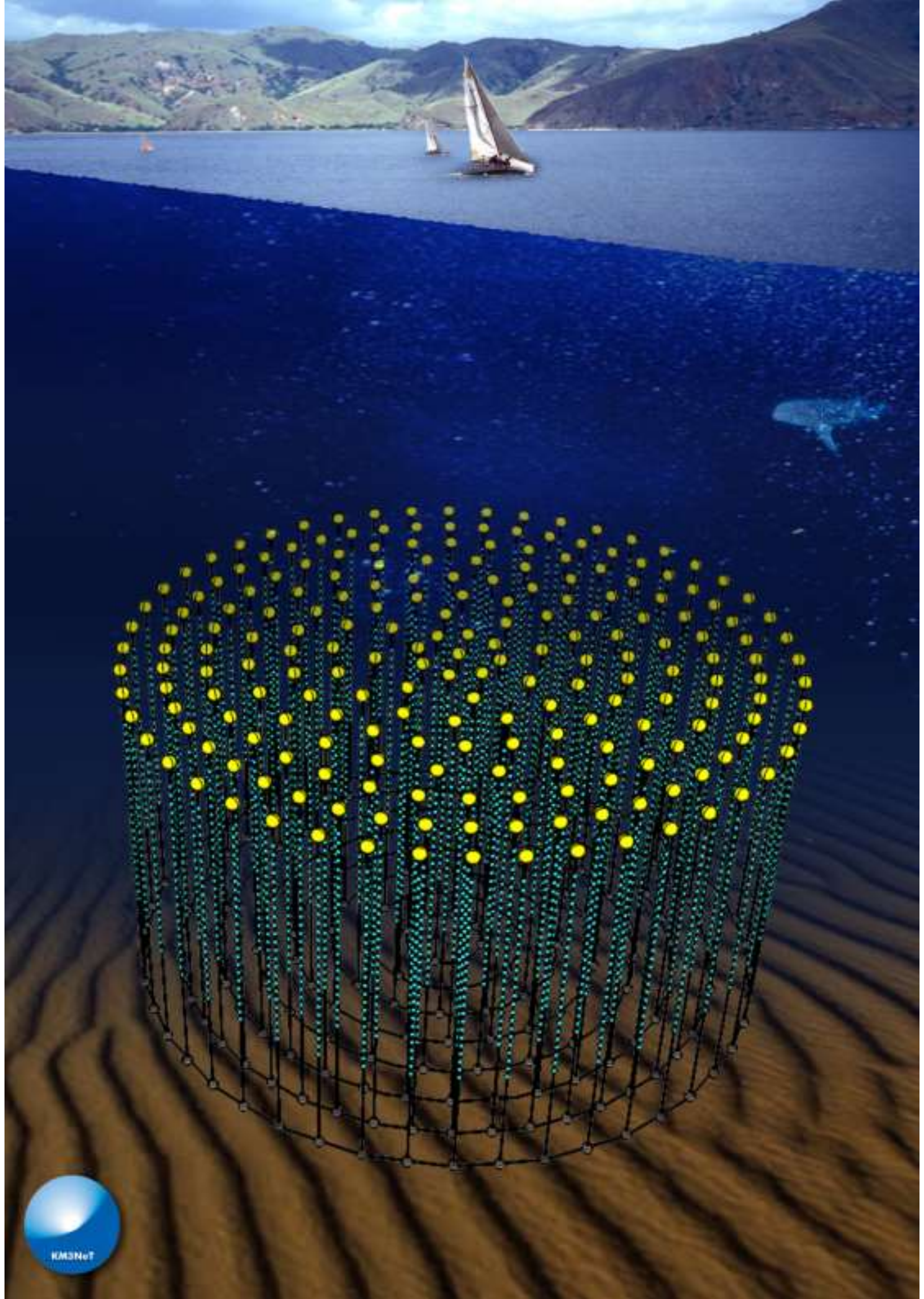
Current

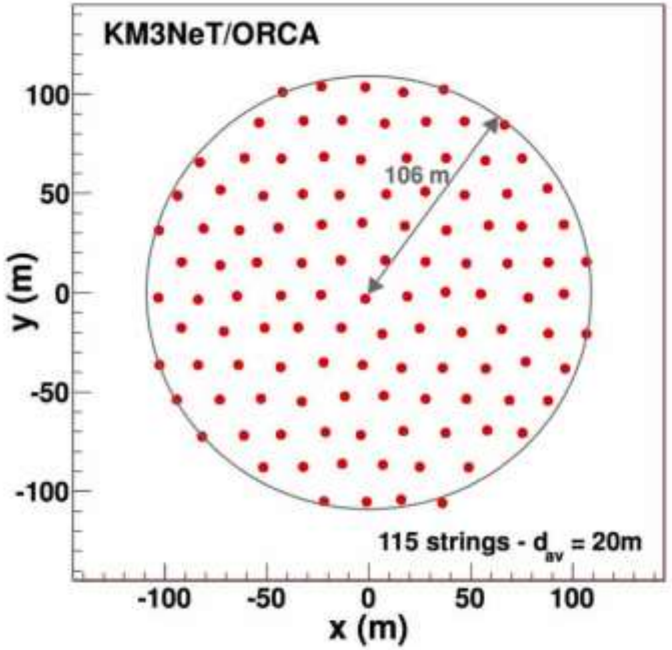
26 strings
192 DOMs/string
1.5 m DOM-DOM spacing

mass ordering



J. Phys. G44, 054006 (2017)

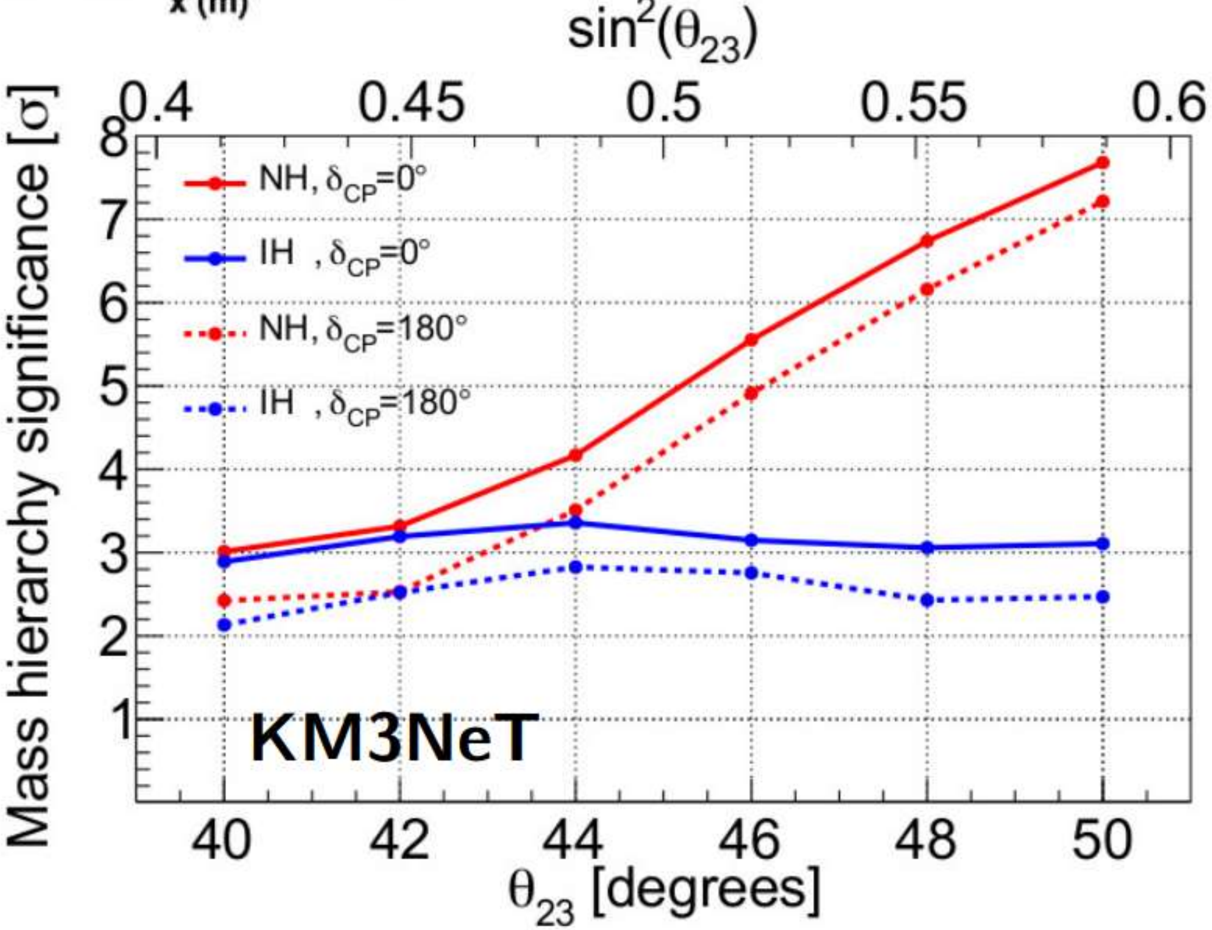




ORCA

mass ordering (3y)

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



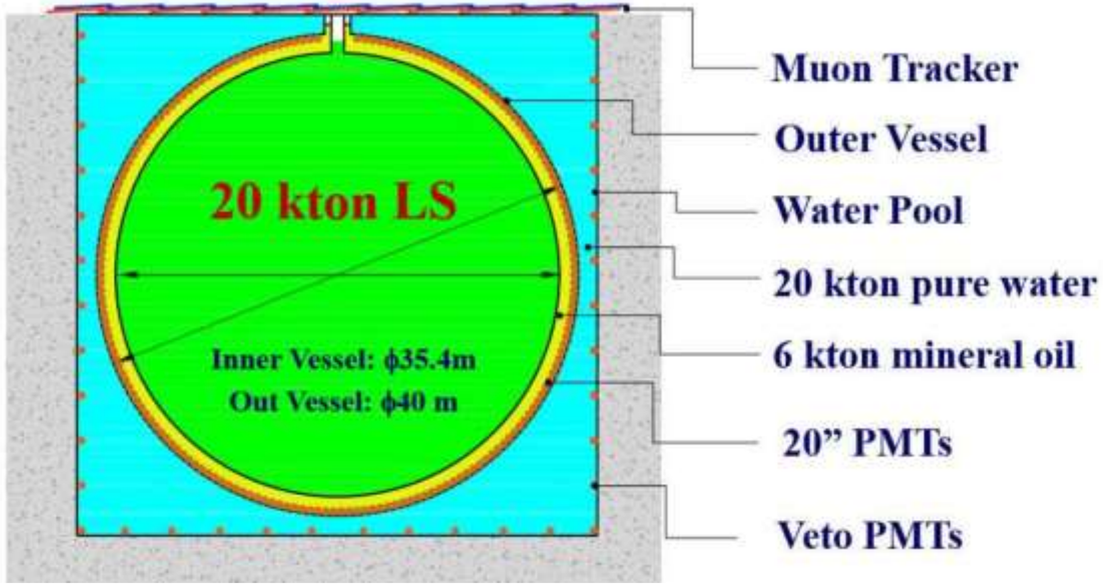
other experiments

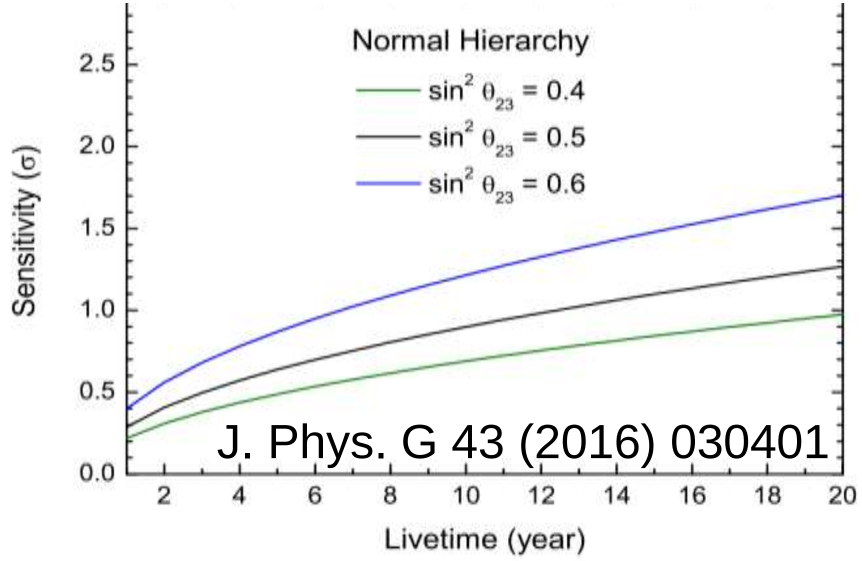
atmospheric ν are a secondary measurement

mass ordering sensitivity from atm. ν only

JUNO

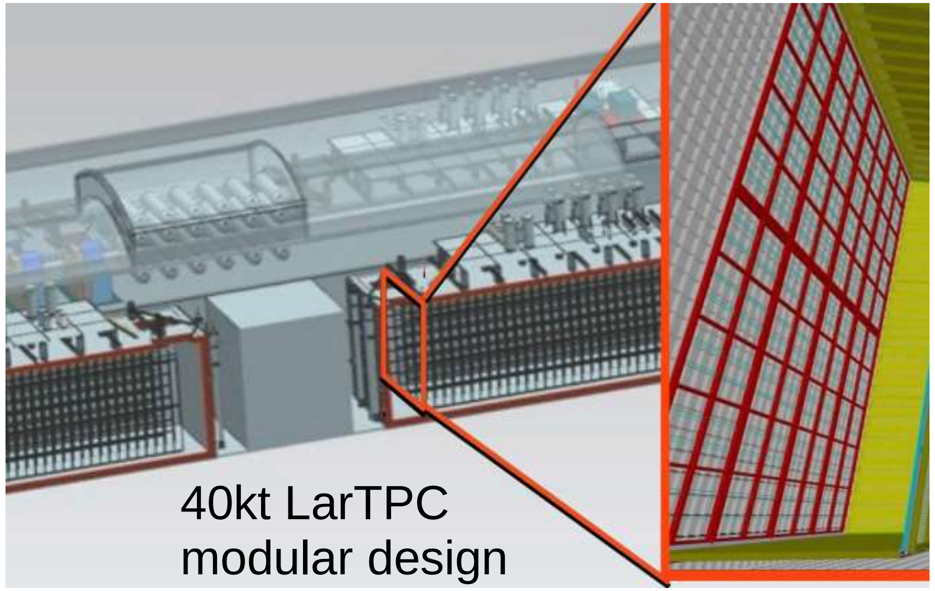
mass ordering from reactor neutrinos

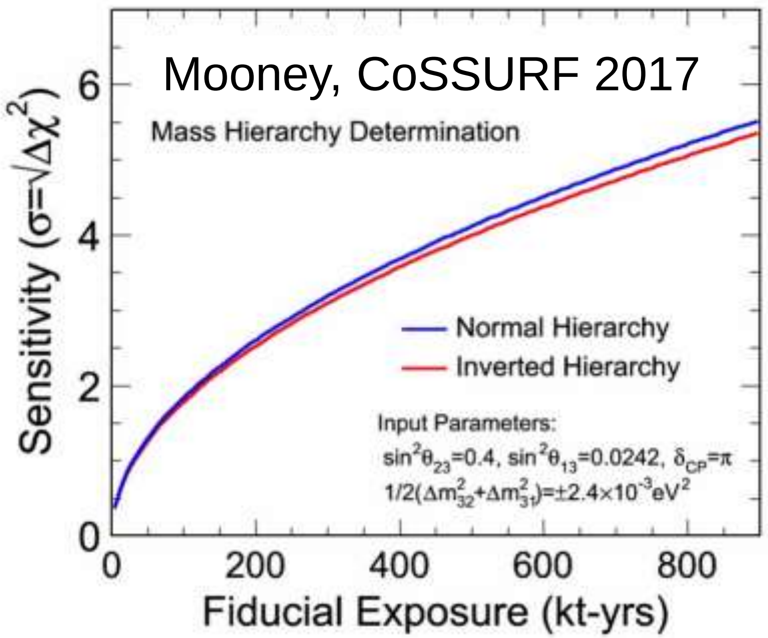




DUNE

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

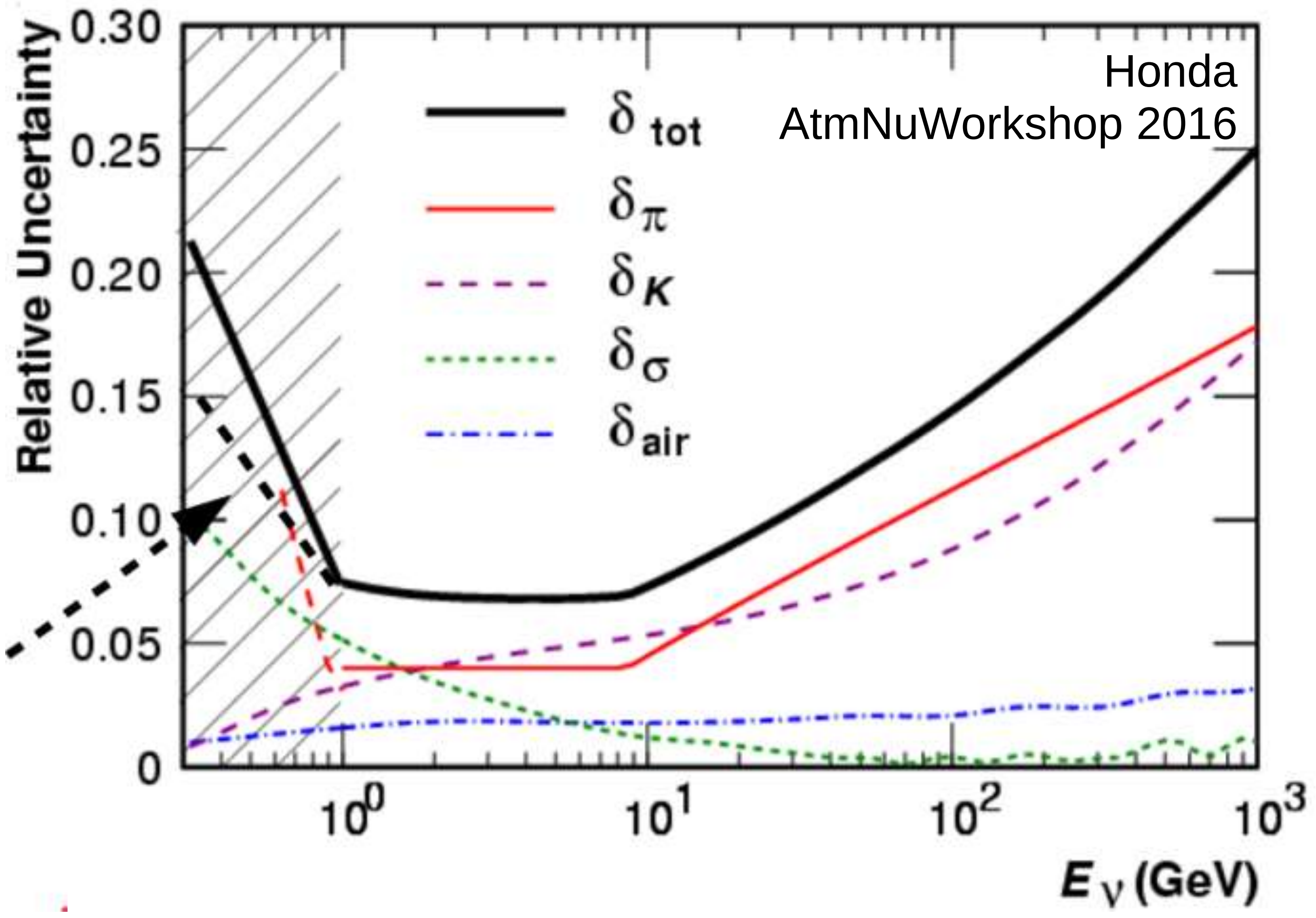
-renewed efforts to model & understand atm nus ongoing

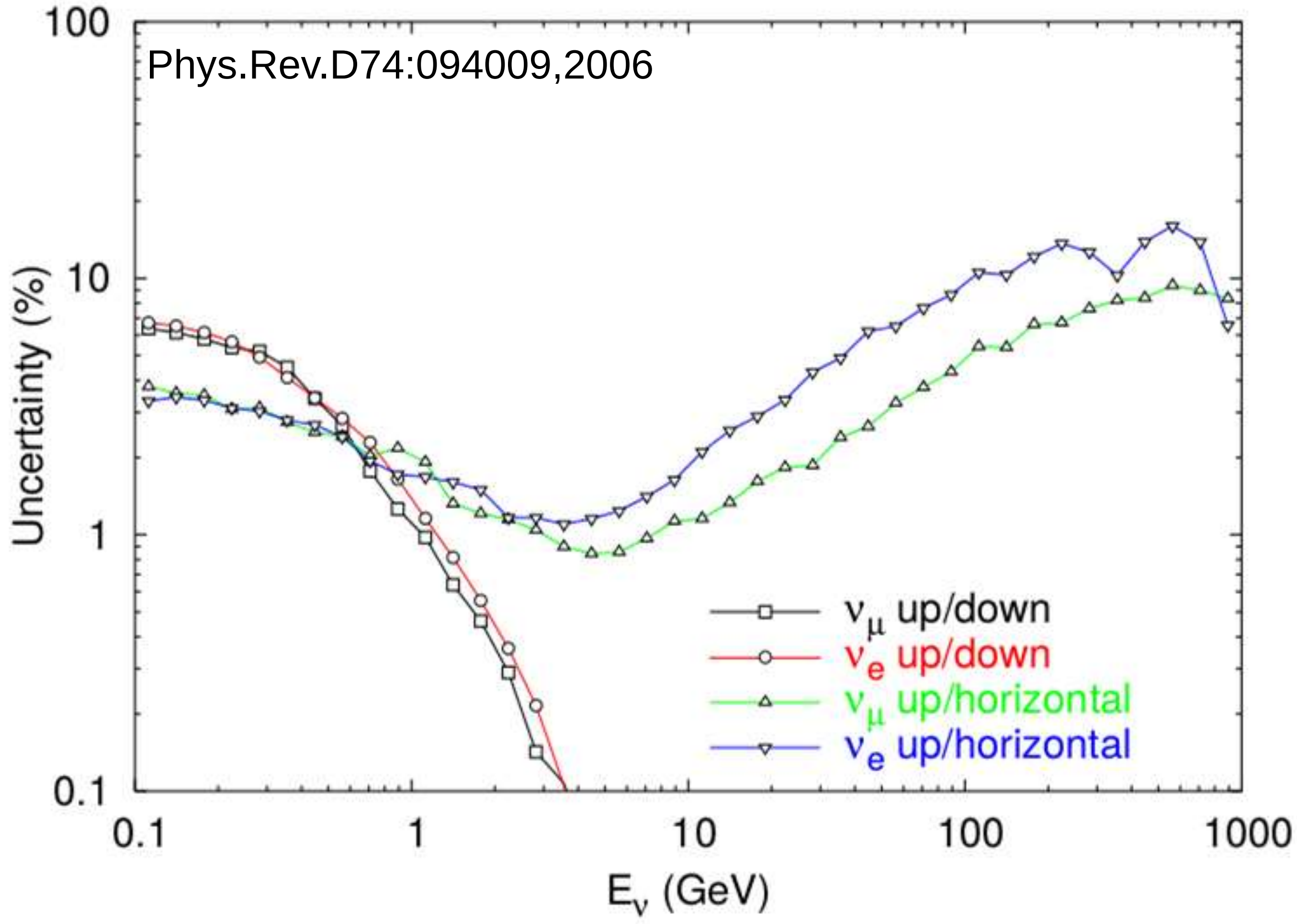
-more data, new software, workshops in last years

backup

atmospheric neutrino flux

-and its uncertainties





the math of oscillations

in Nature 3 neutrinos have been observed

matrix described by 4 parameters: θ_{12}, θ_{13}, θ_{23}, δ

$$U_{\text{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & e^{-i\delta} s_{13} \\ 0 & 1 & 0 \\ e^{i\delta} s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

(Possible Majorana phases ignored)

two unique mass splittings with a hierarchy

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

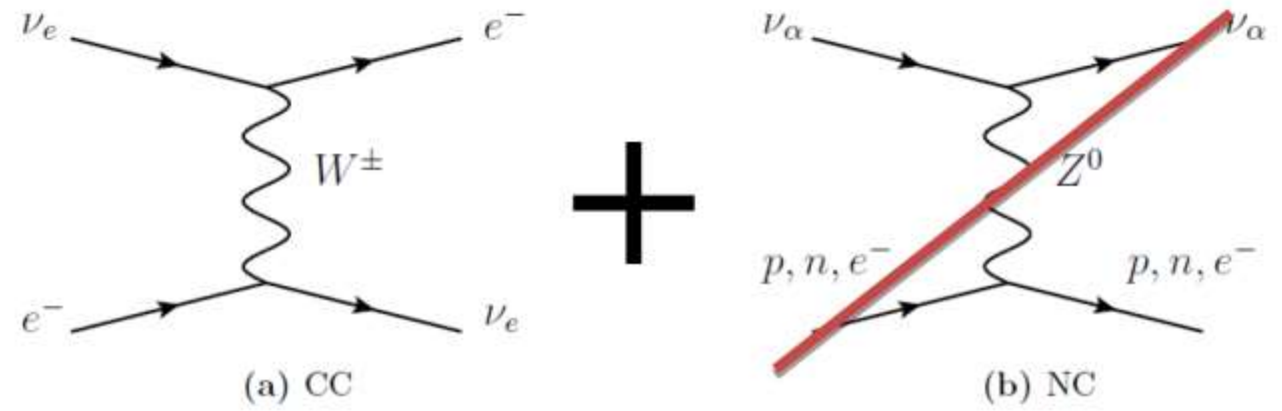
Relevant mass-splitting

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

effective mixing angle

meutrinos crossing matter

scattering processes in ordinary matter



$$\mathcal{H}_0 \to \mathcal{H} = \mathcal{H}_0 + V(n_e) \qquad V(n_e) = \pm\sqrt{2}\, G_F\, n_e(x)\, \beta,$$

recycling the formalism: effective parameters in matter

in constant electron density:

$$\Delta m_M^2 = \sqrt{(\Delta m^2 \cos 2\theta - A_{\rm CC})^2 + (\Delta m^2 \sin 2\theta)^2}\,,$$

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

$$A = \pm 2\sqrt{2}\, E\, G_F\, n_e.$$

*See Phys.Rev.D64:053003,2001 for a full derivation

matter effects in oscillations

MSW resonance and saturation, a local effect

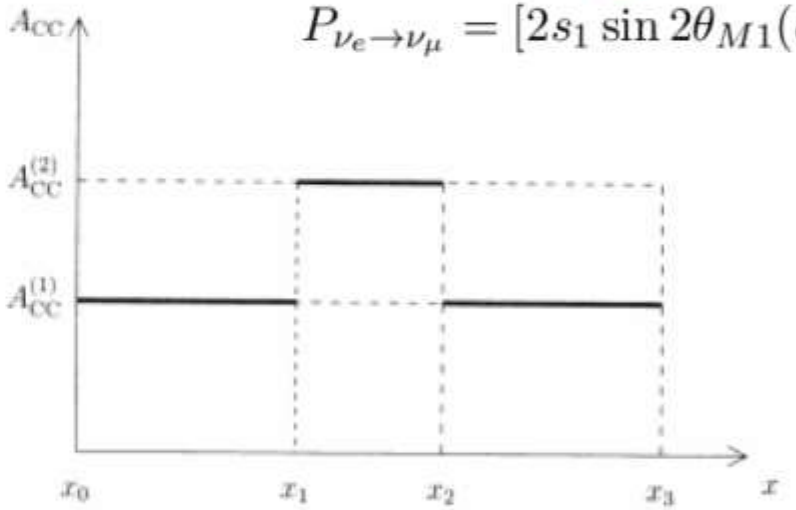
if $A_{\mathrm{R}} = \Delta m^2_{31}\cos(2\theta_{13}).$ → $\tan(2\theta^M_{13}) = \dfrac{\tan(2\theta_{13})}{1 - \dfrac{A}{\Delta m^2_{31}\cos(2\theta_{13})}}$ (goes to zero) → $\theta^{\mathrm{M}}_{13} = \dfrac{\pi}{4}$ maximal (resonance)

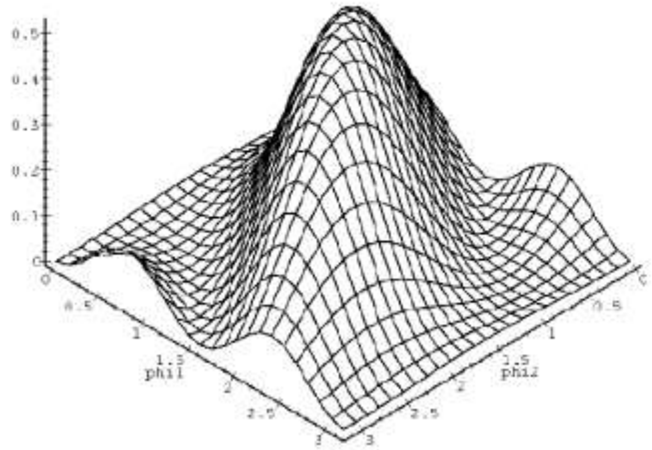
if $|A_{\mathrm{R}}| \gg \Delta m^2_{31}\cos(2\theta_{13}).$ → $\tan(2\theta^M_{13}) = \dfrac{\tan(2\theta_{13})}{1 - \dfrac{A}{\Delta m^2_{31}\cos(2\theta_{13})}}$ (becomes large) → $\theta^{\mathrm{M}}_{13} = \dfrac{\pi}{2}$ no mixing (saturation)

---

parametric resonance, a global effect

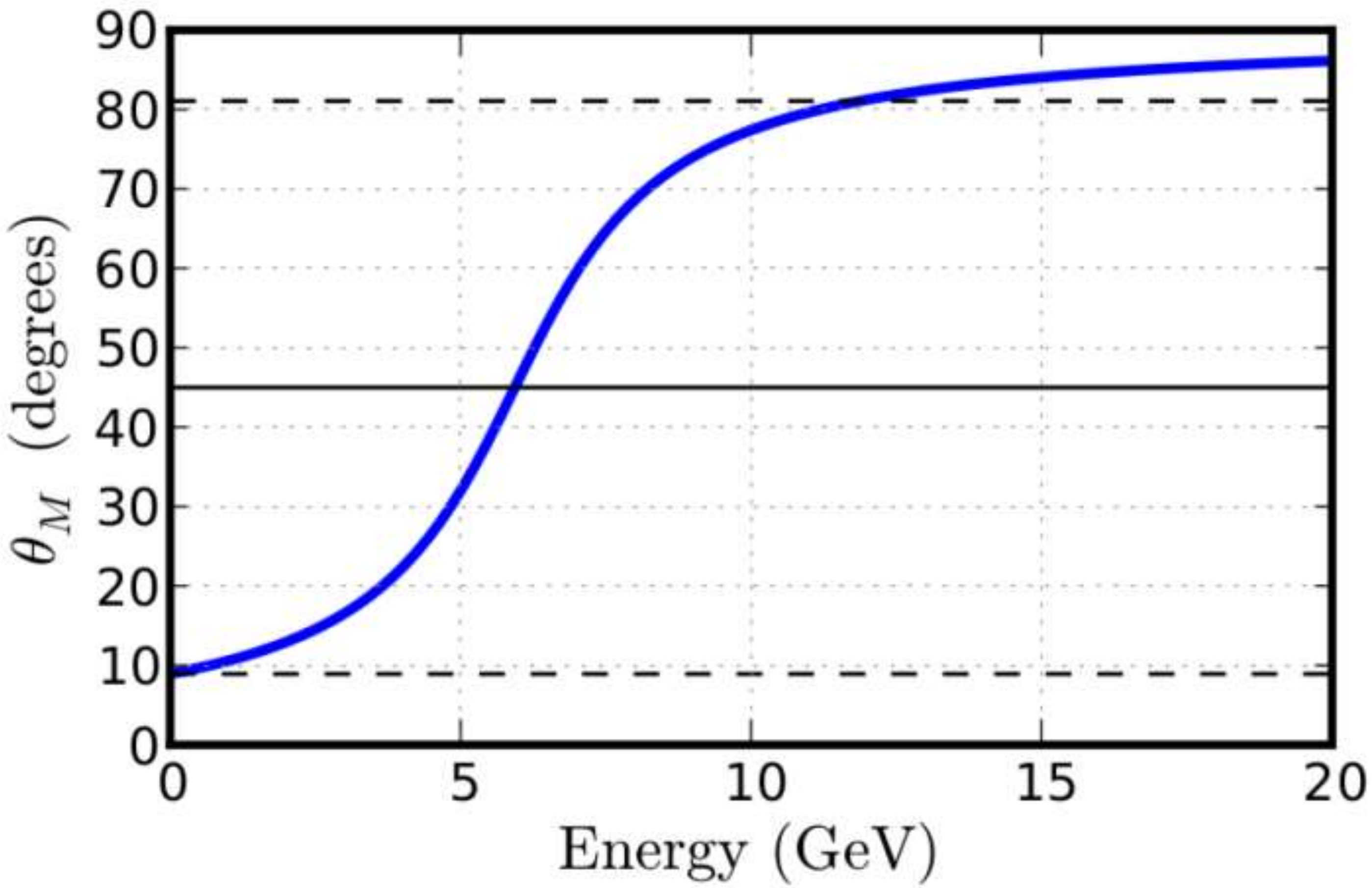
$$P_{\nu_e\to\nu_\mu} = [2s_1\sin 2\theta_{M1}(c_1c_2 - s_1s_2\cos 2(\theta_{M1} - \theta_{M2})) + s_2\sin(2\theta_{M2})]^2$$





saturation effect in θ_{13}

Figure 3.4: Effective θ_{13} as a function of neutrino energy for an electron number density of 2.5 (blue). Dashed black lines show the value of θ_{13} for vacuum, from 4.1, and its complement ($\pi/2 - \theta_{13}$). The solid black line indicates maximal mixing. Calculated using Eq. 3.45.

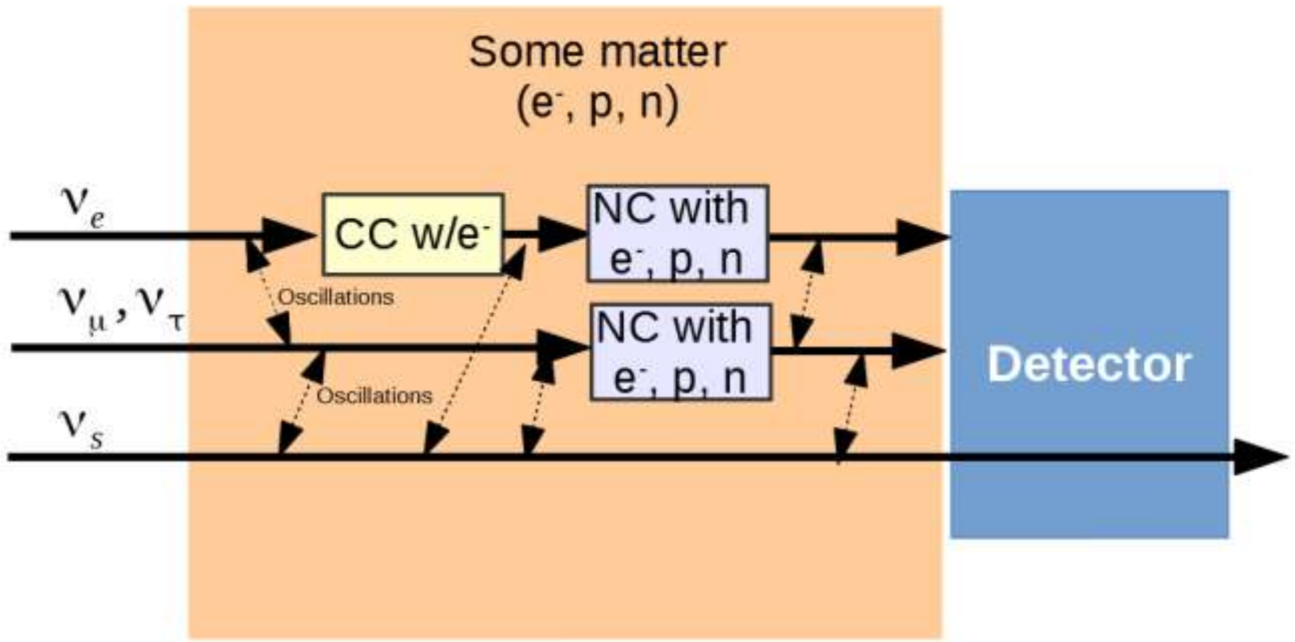


And sterile neutrinos? They also fit

Possibility: Additional neutrino state that doesn't couple to W/Z

- New state mixes with known ones
- Ex: 3+1 → +3 mixing angles +1 phase

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



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

what about sterile neutrinos?

idea: additional neutrino that does not couple to W/Z

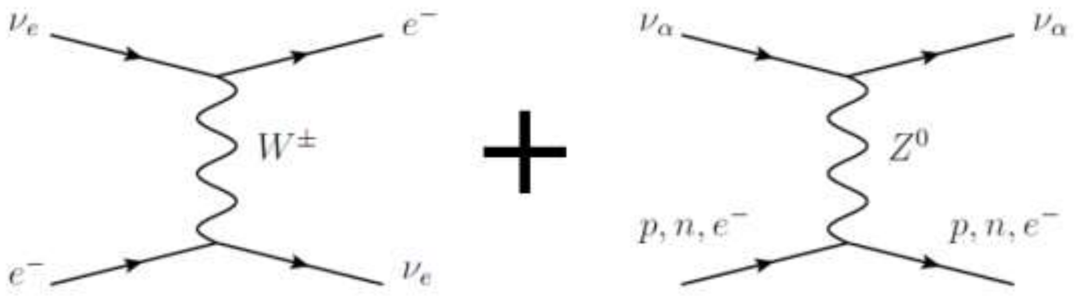
new state mixes with known flavor states

ex: 3+1 → +3 mixing angles, +1 phase

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

matter effects are different

NC interactions no longer global



(a) CC (b) NC

new mixing angles can undergo resonances

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

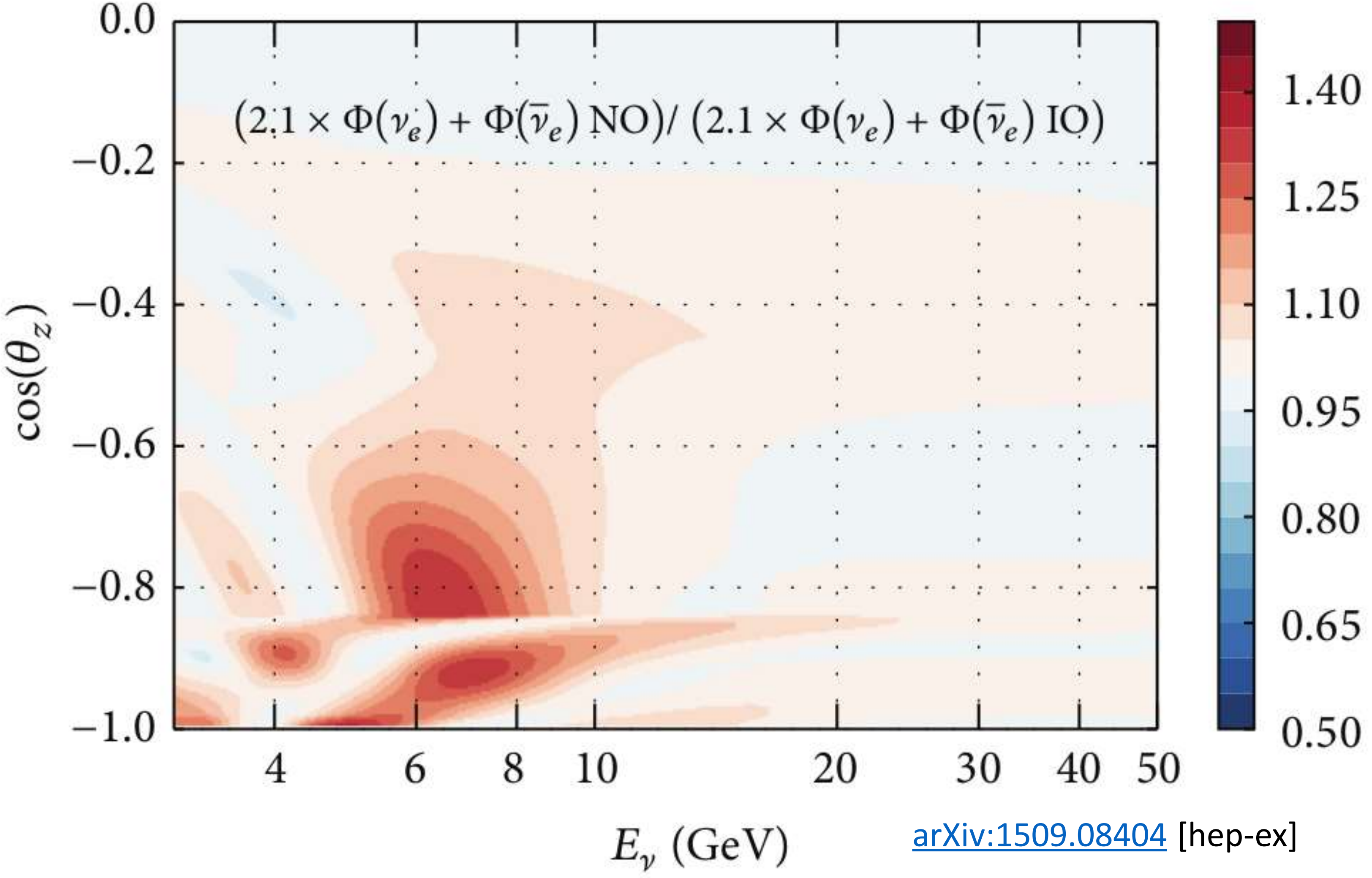
VLVNTs vs beam experiments

TABLE 1: Qualitative comparison of experiments measuring the atmospheric neutrino oscillation parameters. The table is divided into detector and flux characteristics. Note that the far detector of T2K is Super-Kamiokande but uses accelerator neutrinos. Detector performances taken from [4, 9, 38, 43, 49, 83, 95]. Expected neutrino events quoted from published results of ν_μ disappearance at analysis level (note that for VLVNTs this number can vary significantly depending on the studied range in energy, zenith angle, and topology). COH refers to coherent pion production. For details on the other interaction channels and energy ranges see Figure 8.

	Parameter	VLVNT		SK	MINOS, T2K, and NOvA
		ANTARES	DeepCore		
Detector (far)	Instrumentation density (m^{-3})	9.1×10^{-5} OMs	2.3×10^{-5} DOMs	0.2 OMs	15 channels
	Detection principle	Cherenkov light over tens of meters		Cherenkov rings	Trackers/calorimeters
	E_ν resolution	50% ± 22%	25% at 20 GeV	3% at 1 GeV	10–15% at 10 GeV
	θ_ν resolution	3° at 20 GeV	8° at 20 GeV	2-3°	—
	Particle ID capabilities	Muon/no muon in interaction		e, μ, π (rings)	Individual particles, charge
Neutrino flux	Source of neutrinos	Atmosphere: mix of $\nu_e, \bar{\nu}_e, \nu_\mu$, and $\bar{\nu}_\mu$			Accelerator: $\nu_\mu/\bar{\nu}_\mu$ modes
	Baseline	10–12700 km			300–800 km
	Flux determination	Atm. ν models, self-fit		+top/down ratios	Near/far detector
	Energy range	10–100 GeV		Few MeV–few GeV	Few GeV
	Main interaction channel	DIS		QE	QE, RES, COH, and DIS
	ν events expected with osc.	530	1800	2000	30 (T2K), 900 (MINOS)
	and without osc. (per year)	660	2300	2300	120 (T2K), 1050 (MINOS)

arXiv:1509.08404 [hep-ex]

NMO



arXiv:1509.08404 [hep-ex]

FIGURE 5: Expected interaction rate of electron neutrinos and antineutrinos predicted by a NO over the rate predicted assuming an IO. Using the oscillation parameters in [3]. Because of the flux ratio $\nu_\mu/\bar{\nu}_\mu$ and the cross section difference, estimated to be 2.1 times larger for neutrinos than antineutrinos, more electron neutrino interactions are expected for a NO.