Propriétés des neutrinos: vers une physique de precision

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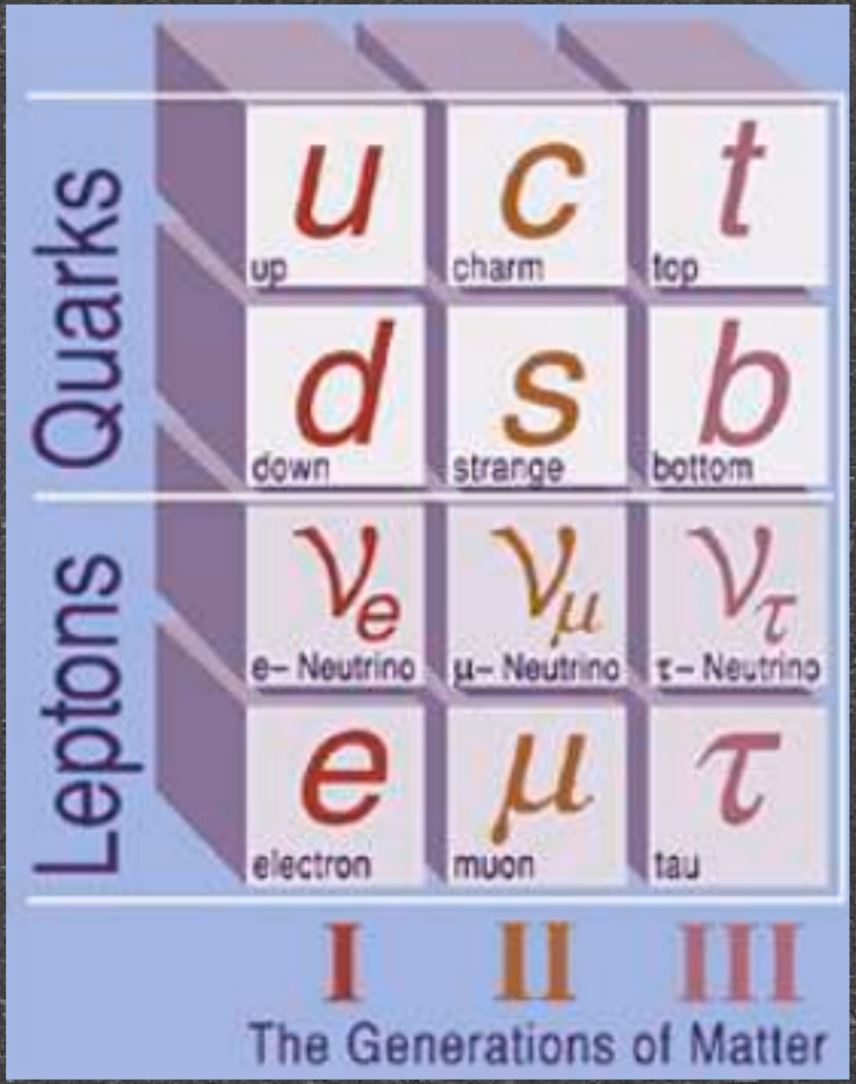
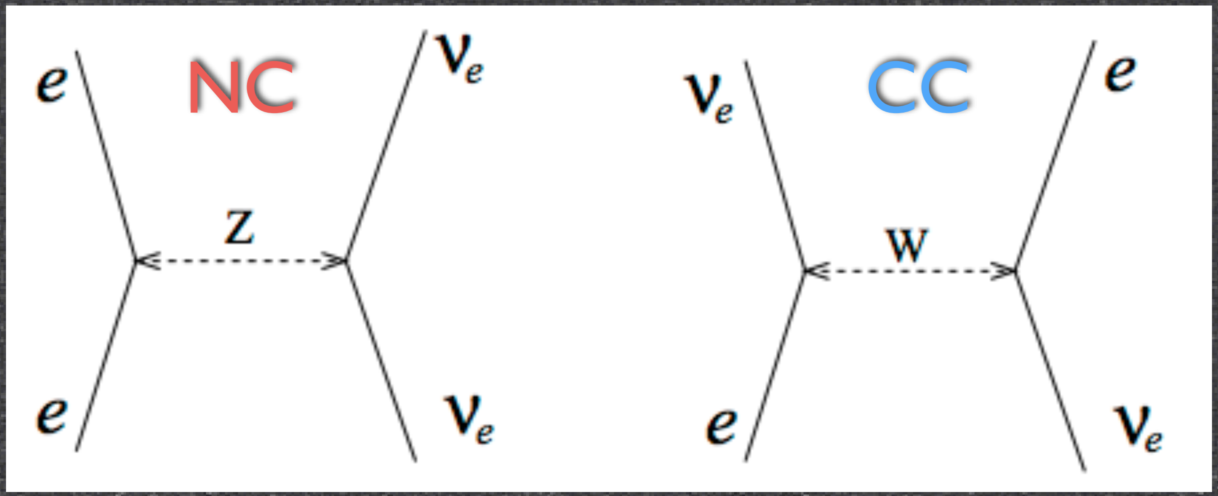
SFP - 21/07/2017

Neutrinos in the SM





They interact only through weak interactions → Neutral current (Z-boson) or Charged current (W-boson)

Neutrinos are standard model particles → neutral cousin of the electron and of the other charged leptons

In the Standard Model neutrinos are massless particles → current limit on the sum of the neutrino masses ~1 eV → order of magnitudes lighter than the other fermions

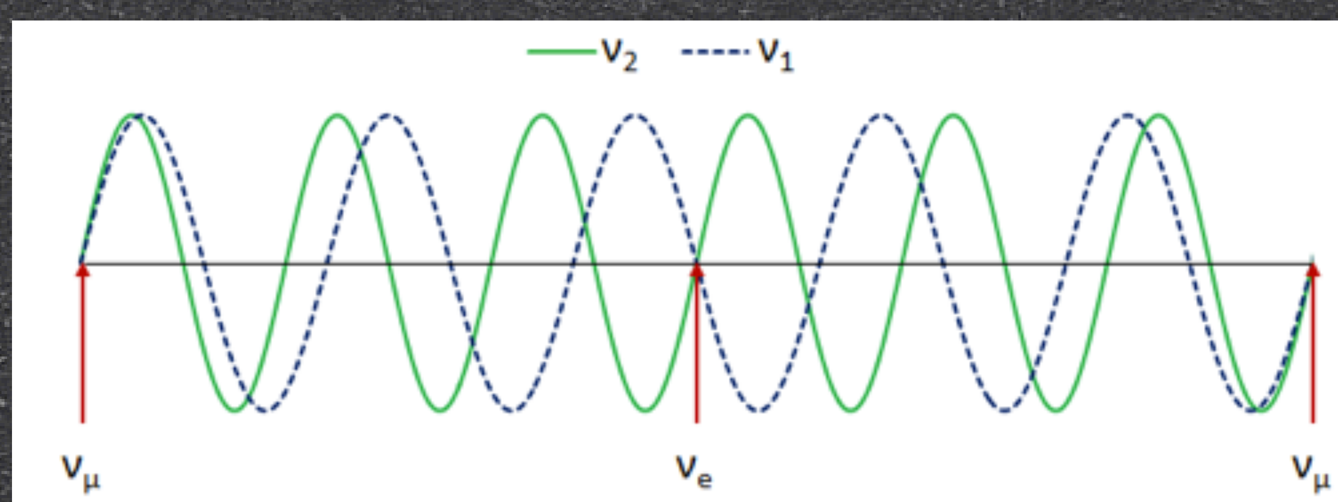
Neutrinos oscillations and Nobel Prize

- **2015 Nobel prize in physics was awarded for the discovery of neutrinos oscillations → SuperKamiokande (1998) and SNO (2001)**

"***pour la découverte des oscillations des neutrinos, ce qui montre que les neutrinos ont une masse***"

A. McDonald T. Kajita

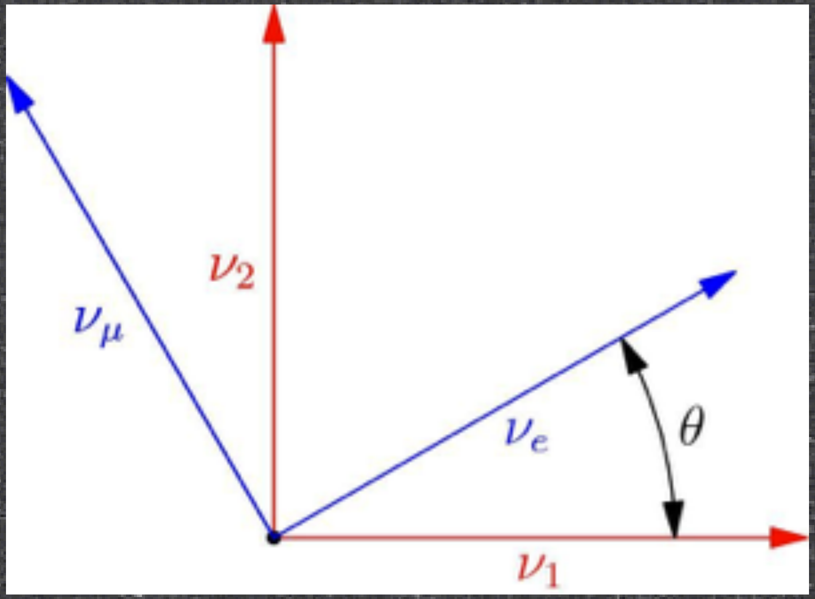
- **Neutrinos are produced in flavor eigenstates (ν_e, ν_μ)**
- **The flavor is a quantum mechanical state combination of 2 different mass states**
- **Conversely a neutrino in a definite mass state must be a mixture of 2 flavor (ν_e, ν_μ)**
- **While propagating the two waves interfere with each other → at a distance L the original ν_μ can be detected as ν_e**



Mixing angles and Δm^2

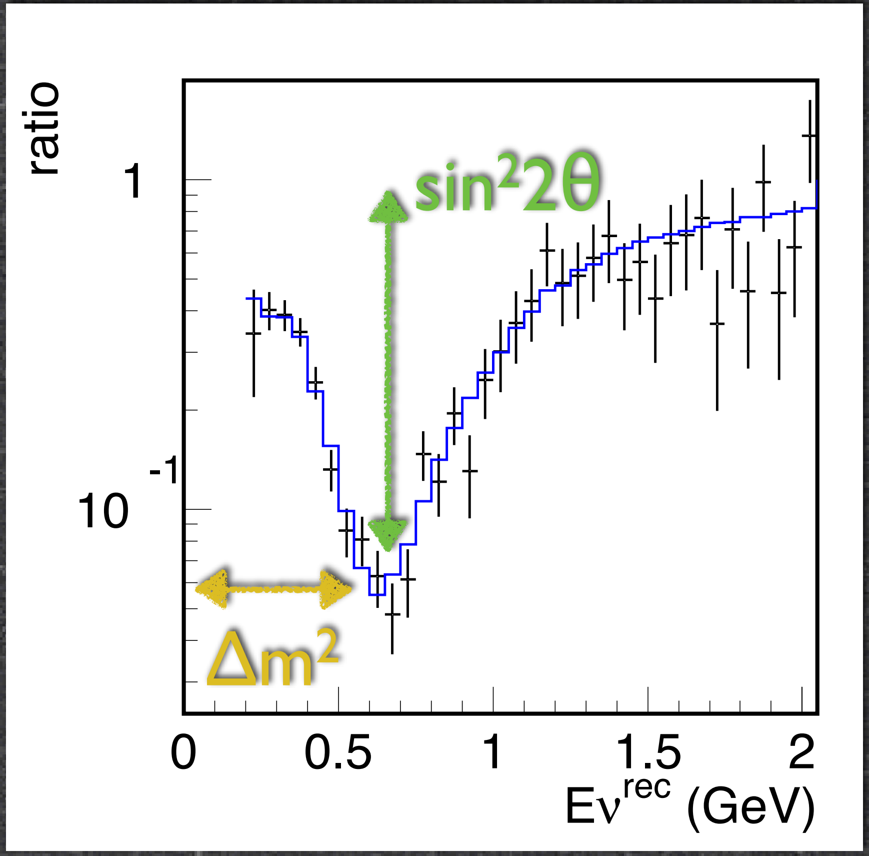
- In the 2 flavor case neutrino oscillations can be described by a rotation matrix with one mixing angle

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$



$$P(\nu_e \to \nu_\mu) = \sin^2(2\theta)\sin^2(\Delta m^2_{12} L/E)$$

- Baseline L is fixed
- Neutrino energy E can be reconstructed in the experiment
- Observing the oscillation pattern allow to determine the mixing angle θ and the mass difference Δm^2 (not the absolute mass)

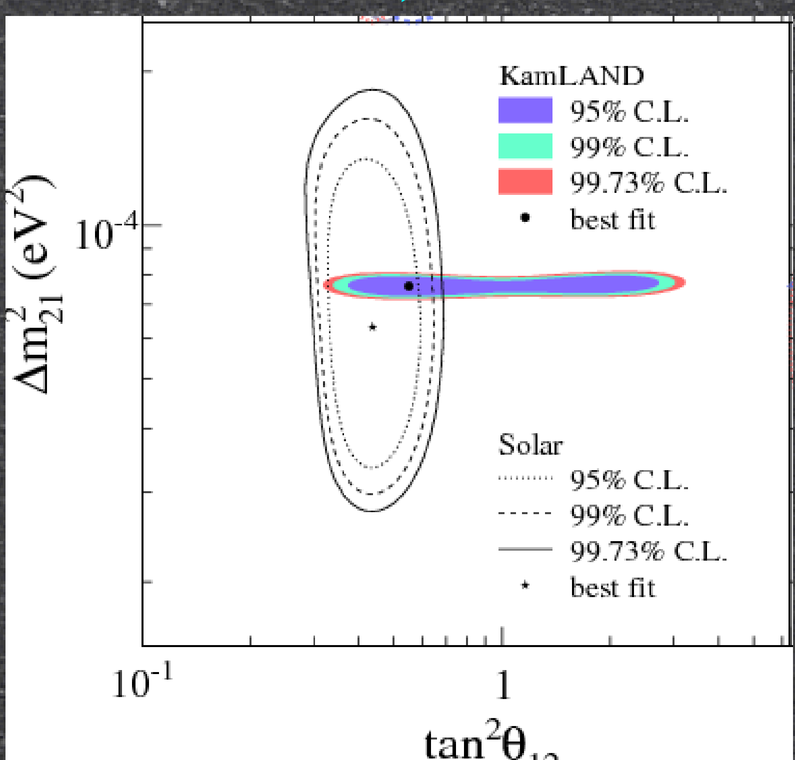


3 flavor neutrino mixing: PMNS matrix

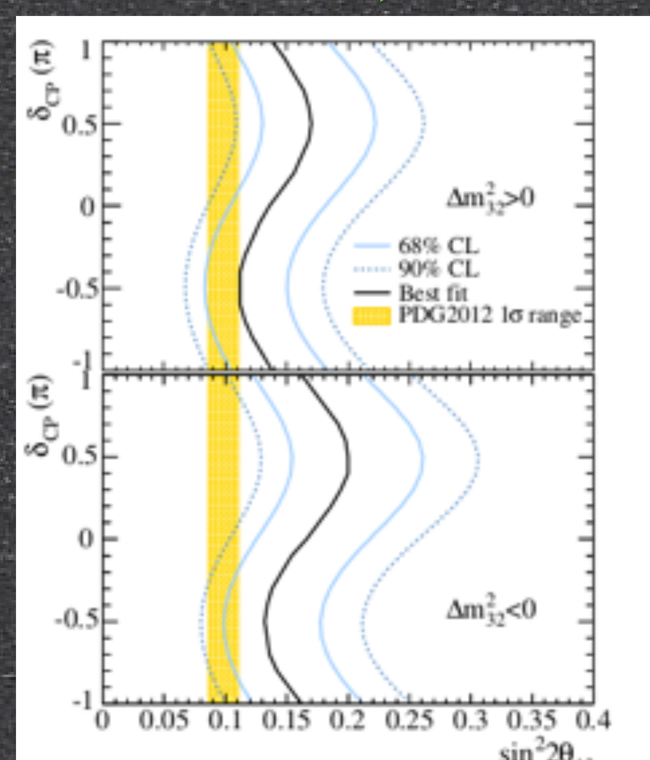
$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=\begin{pmatrix}cos\theta_{12} & sin\theta_{12} & 0\\ -sin\theta_{12} & cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}cos\theta_{13} & 0 & sin\theta_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -sin\theta_{13}e^{i\delta} & 0 & cos\theta_{13}\end{pmatrix}\begin{pmatrix}1 & 0 & 0\\ 0 & cos\theta_{23} & sin\theta_{23}\\ 0 & -sin\theta_{23} & cos\theta_{23}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

- 3 mixing angles
- 2 independent mass differences
- 1 CP violation phase

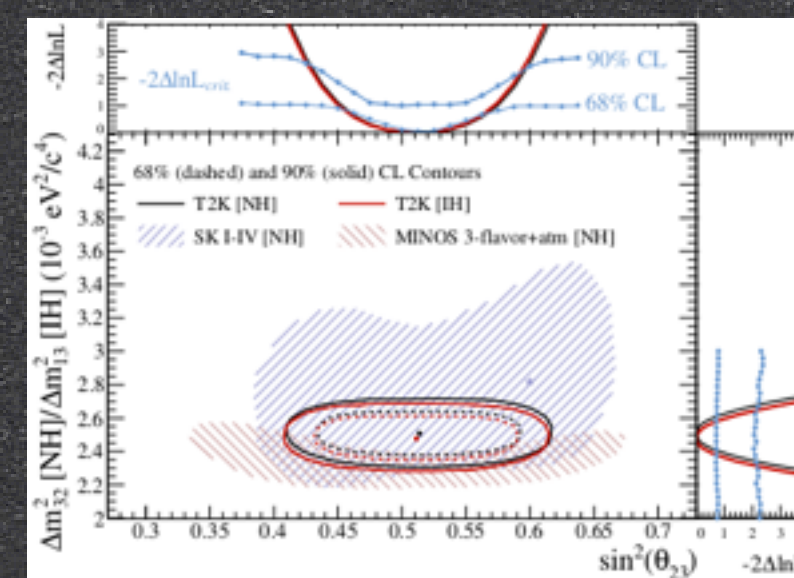
Solar (SNO, KamLand)
→ θ_{12}, Δm_{12}



Interference (Daya Bay, T2K)
→ θ_{13}, δ_{CP}

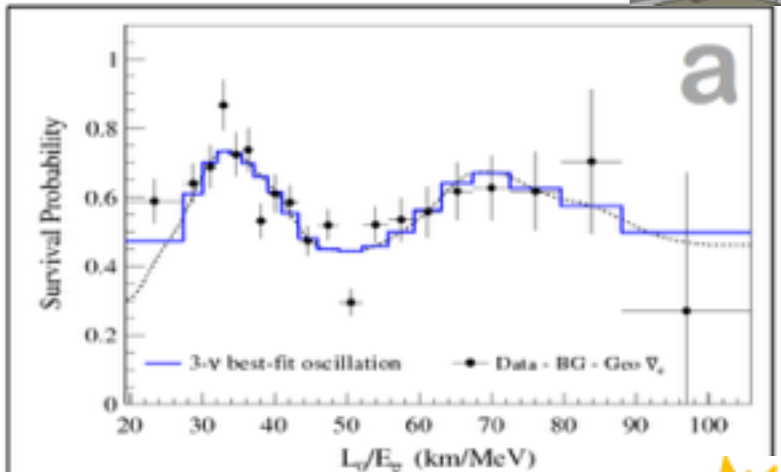


Atmospheric (SK, K2K, Minos, T2K)
→ θ_{23}, Δm_{32}

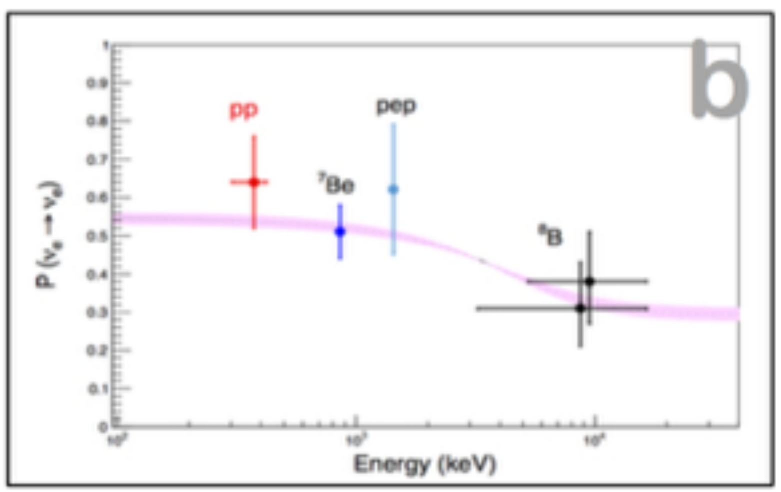


Neutrino oscillations

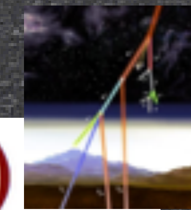
e→e (δm^2 , θ_{12})

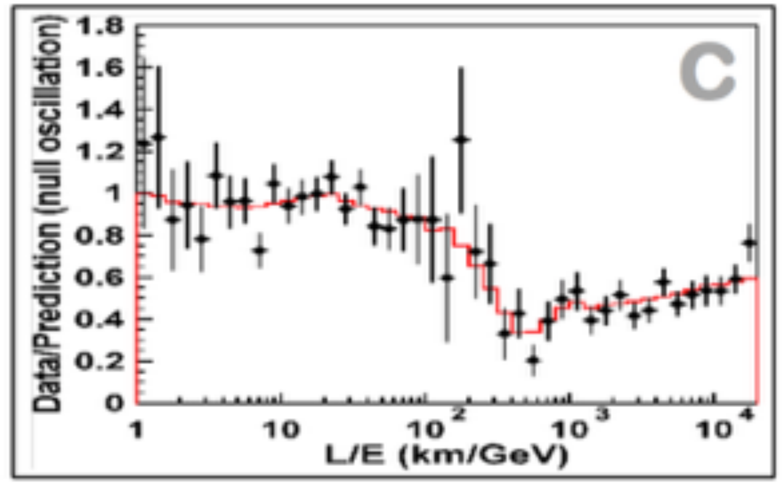


e→e (δm^2 , θ_{12})

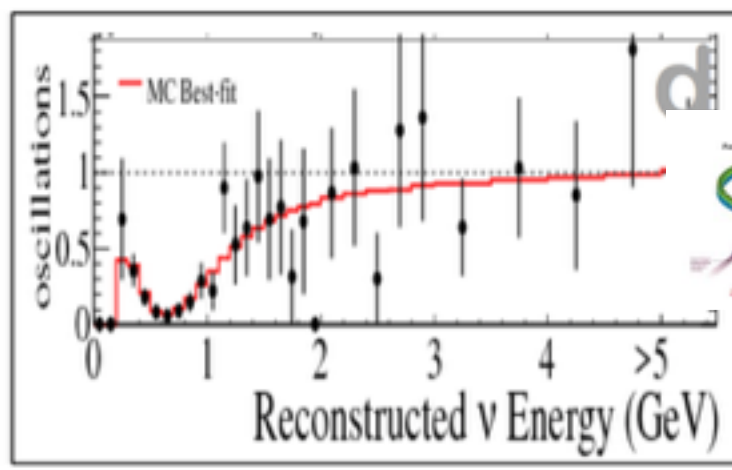


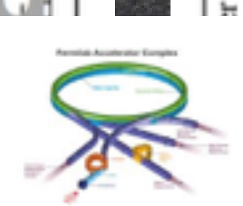
μ→μ (Δm^2 , θ_{23})



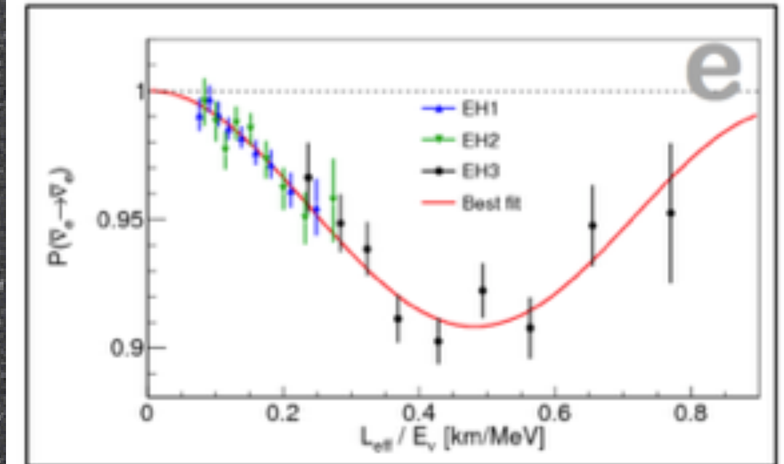


μ→μ (Δm^2 , θ_{23})

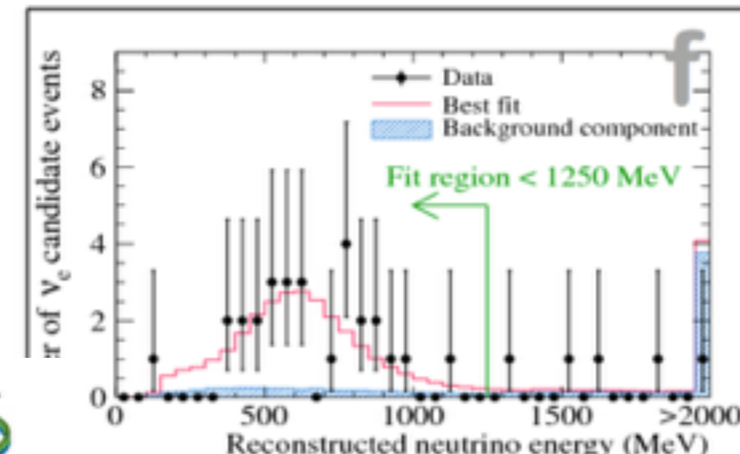




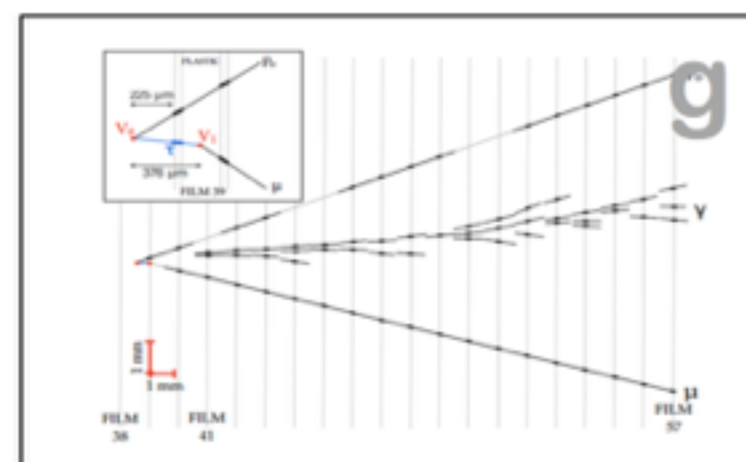
e→e (Δm^2 , θ_{13})



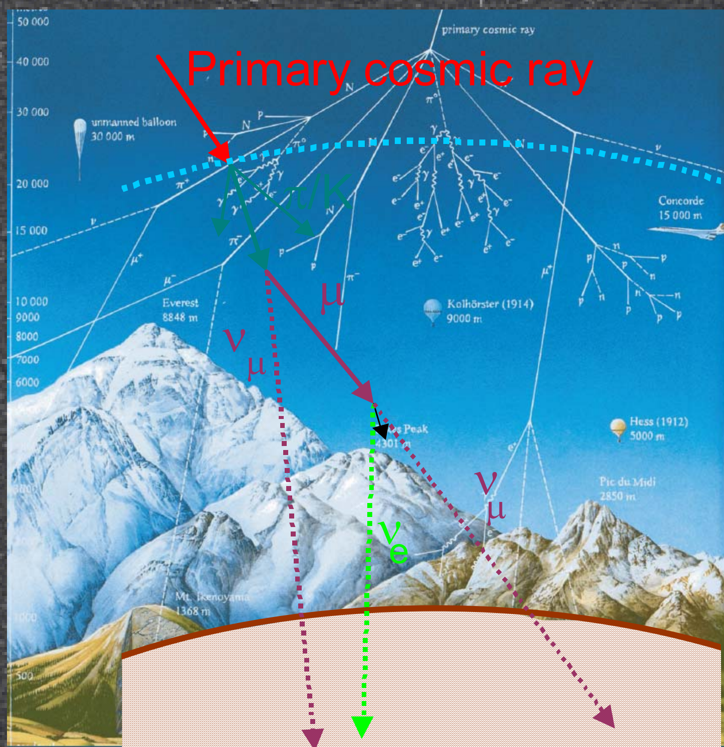
μ→e (Δm^2 , θ_{13} , θ_{23})

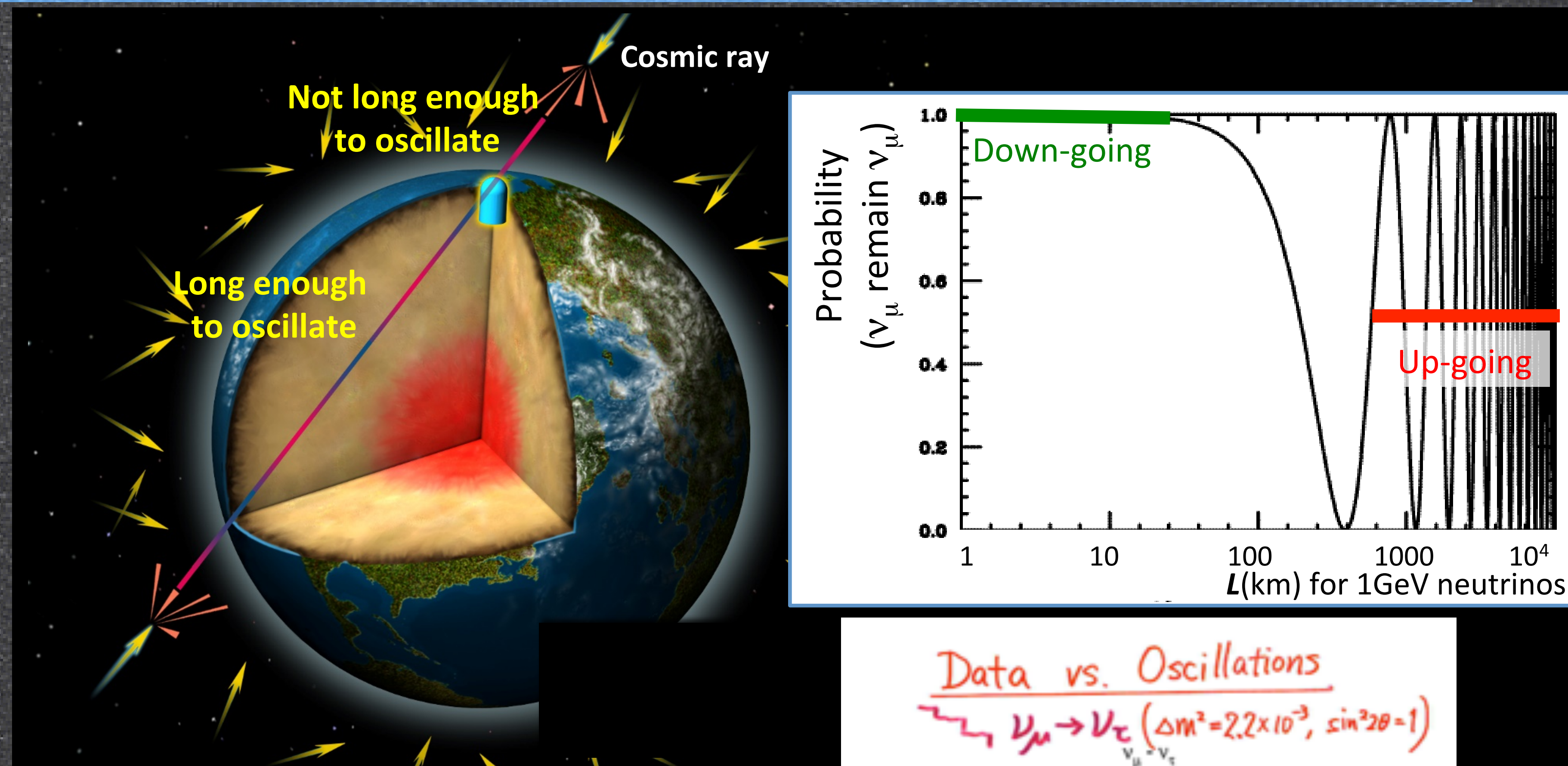


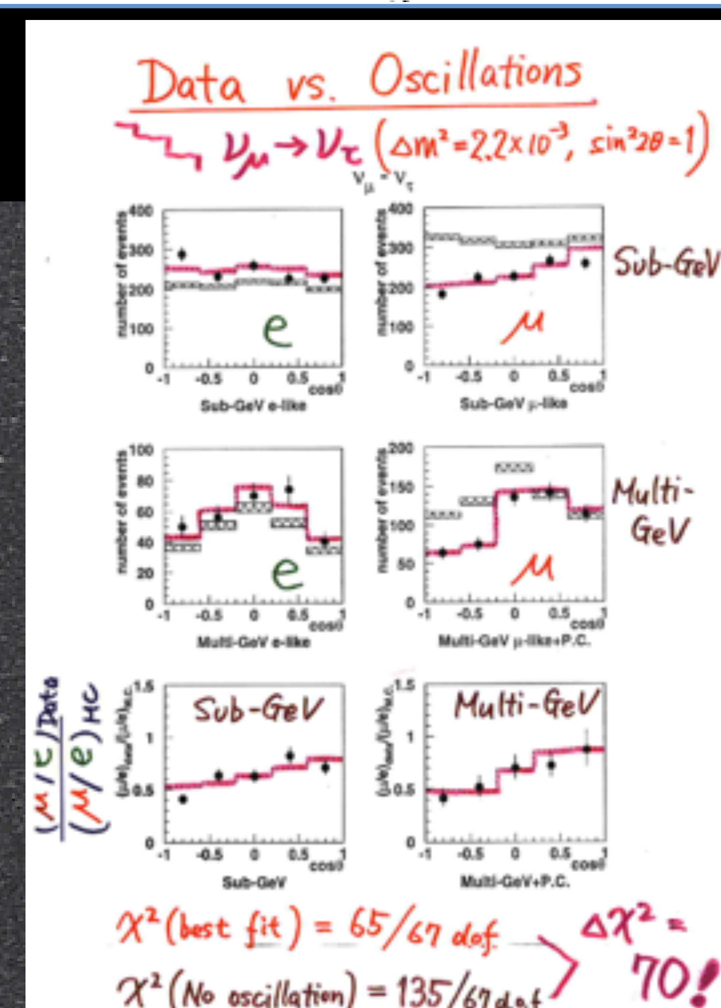
μ→τ (Δm^2 , θ_{23})



1998: Super-Kamiokande

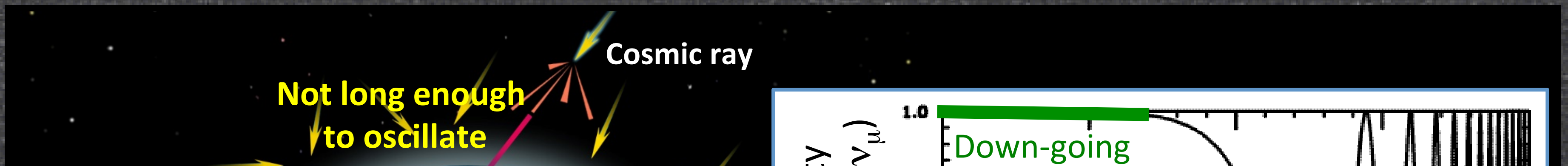


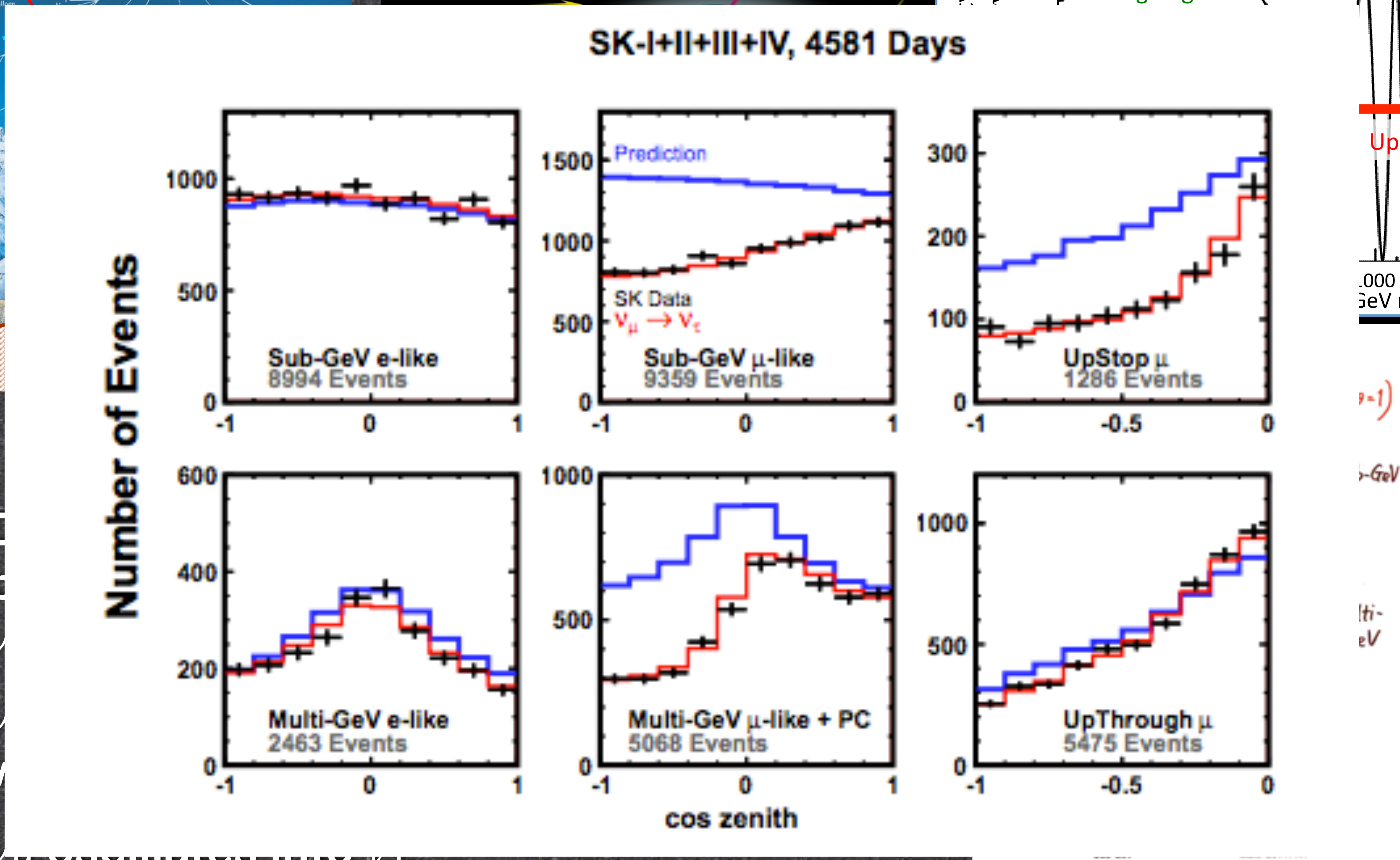


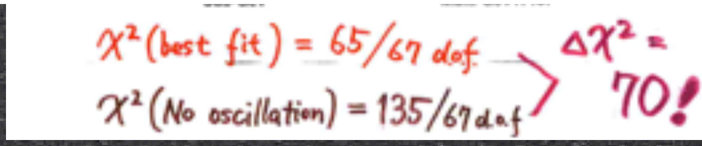


- Discovery of neutrino oscillations
- Water Cherenkov detector able to distinguish muons produced by ν_μ from electrons produced by ν_e
- ν_μ from downstream ($\cos(\theta)<1$) disappear while ν_e are as expected
- ν_μ oscillates into ν_τ

Super-Kamiokande







- ν_μ oscillates into ν_τ

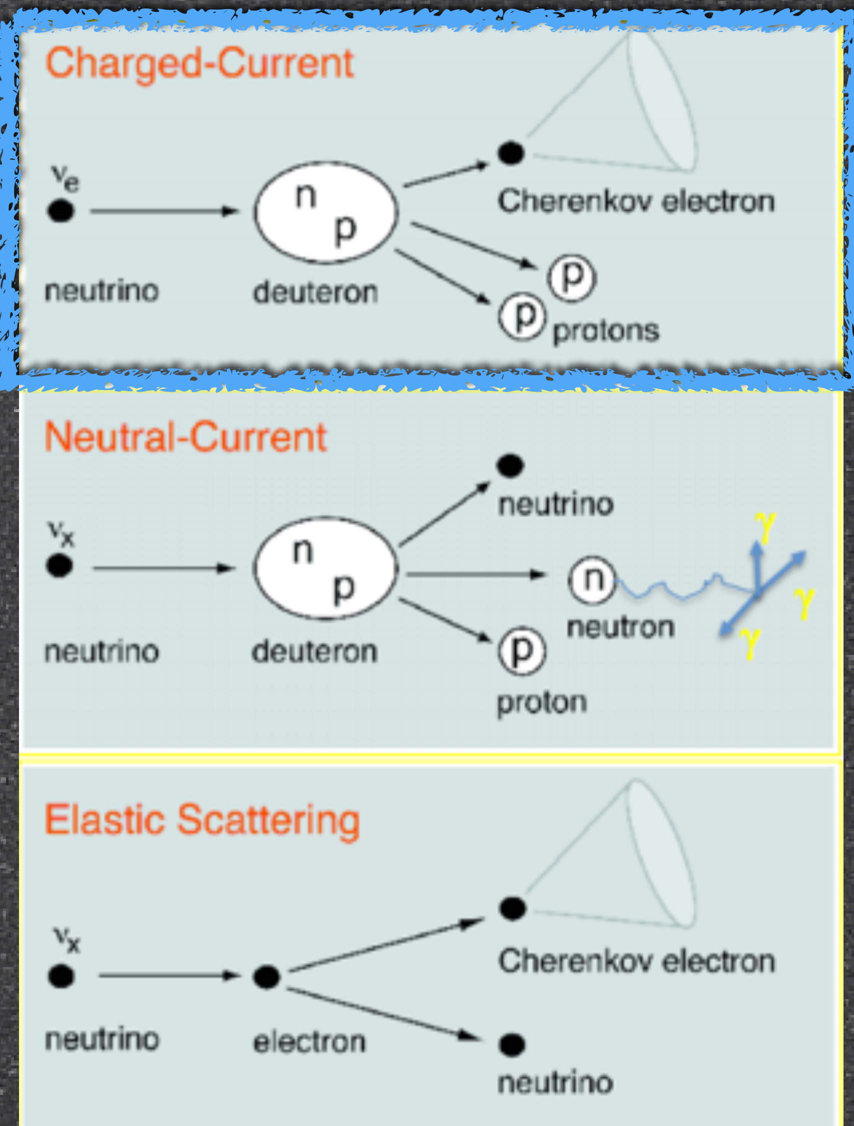
2001: SNO

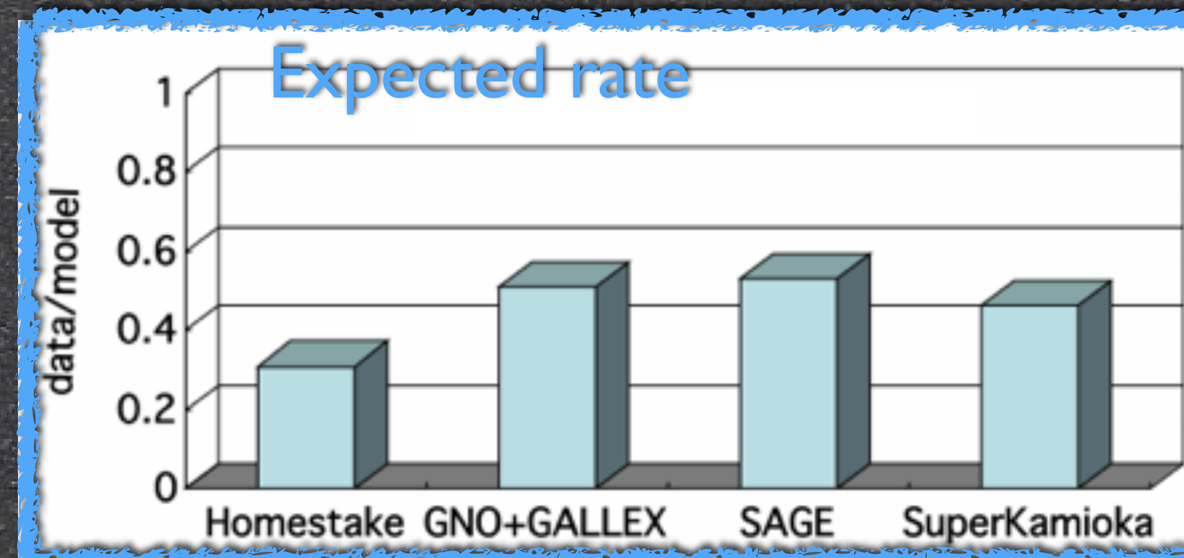
- ν_e are produced in the Sun and their flux can be precisely computed → since 1960s experiments on Earth observed a deficit of ν_e charged current interactions (ν_e → e)

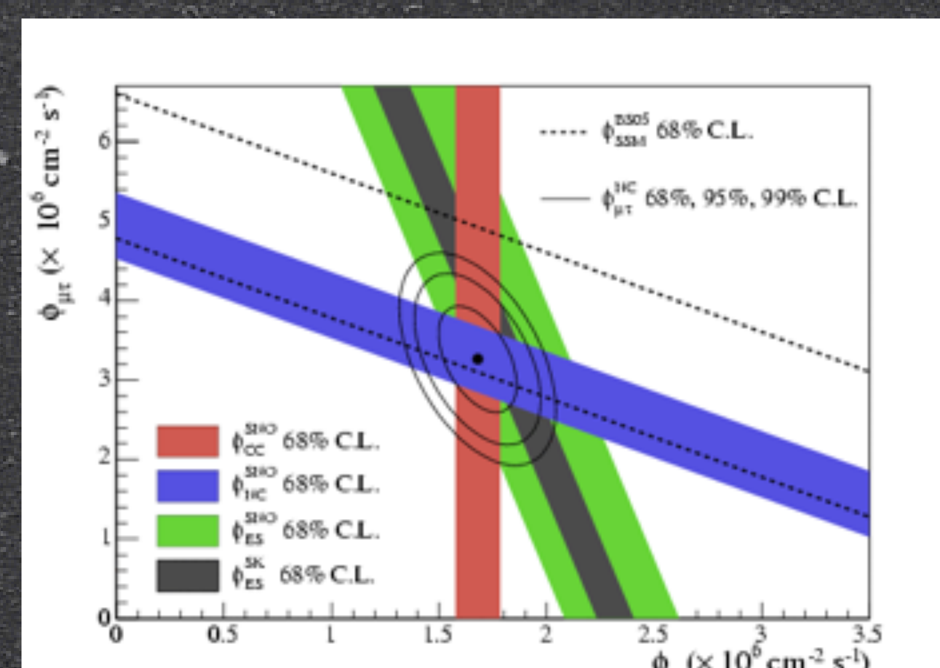
CC → sensitive only to νe flux

NC → sensitive to total ν flux

ES → $\Phi(\nu e) \sim 6(\Phi\nu_\mu + \Phi\nu_\tau)$







$$P_{ee} = \frac{\phi_e}{\phi_e + \phi_\mu + \phi_\tau} = \frac{\phi_{CC}}{\phi_{NC}}$$

How to measure θ_{13}

- Until 2011 the last mixing angle θ_{13} was unknown

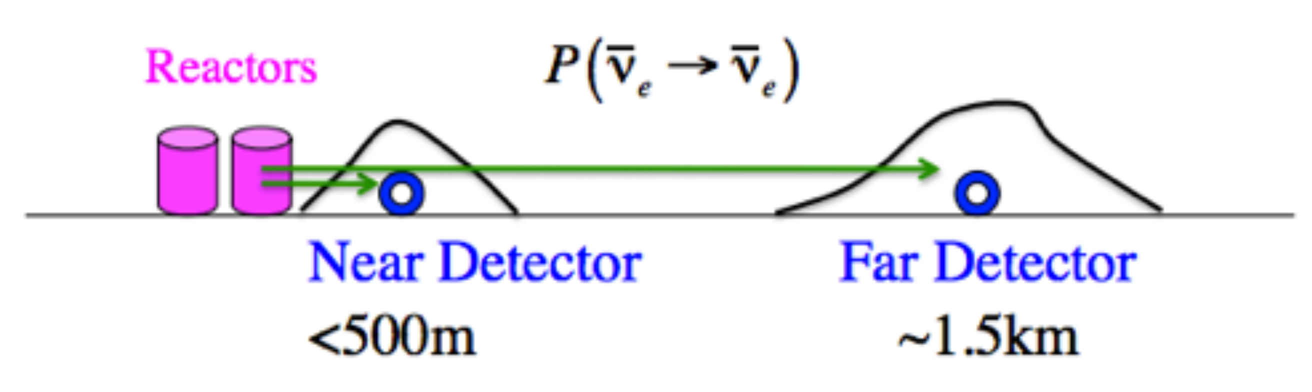
Reactors (DChooz, RENO, Daya Bay)

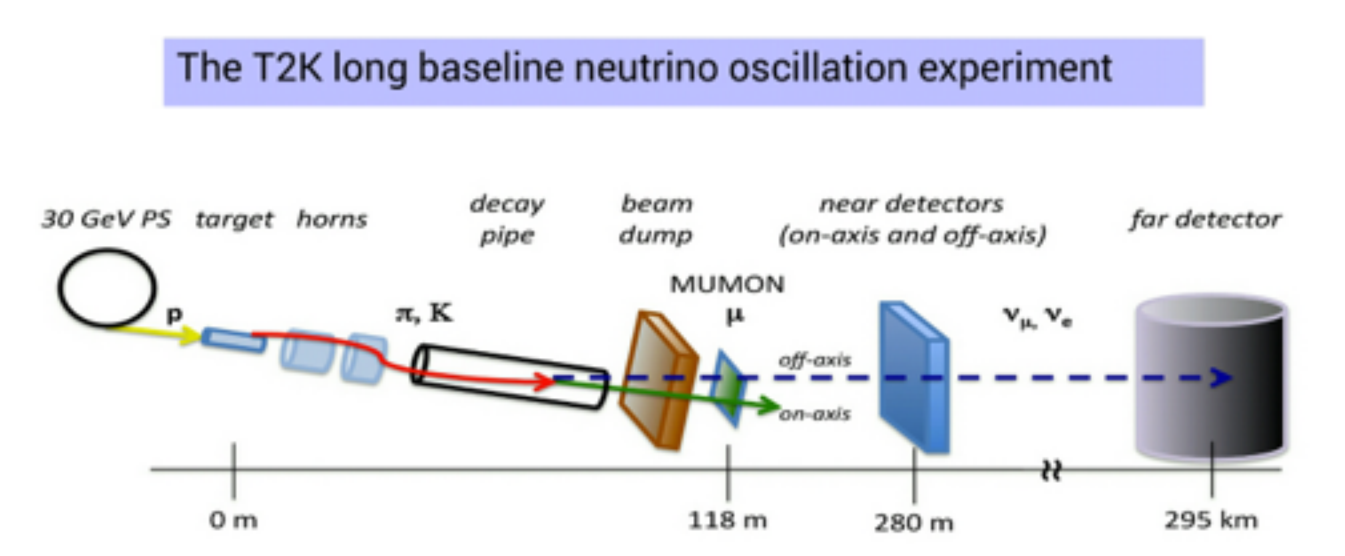
✓ Disappearance of $\bar{\nu}_e$ $P(\bar{\nu}_e \to \bar{\nu}_e)$
✓ $\bar{\nu}_e$ produced in nuclear reactors
  ✓ Neutrino energy few MeV
  ✓ Distance L ~ 1 km

✓ Signature: disappearance of the $\bar{\nu}_e$ produced in the reactor → depends on θ_{13}

Accelerators (T2K, Nova):

✓ Appearance experiment: $P(\nu_\mu \to \nu_e)$
✓ ν_μ neutrino beam
  ✓ Neutrino energy ~1 GeV
  ✓ Distance L >~ 300 km
✓ Signature: ν_e appearance in ν_μ beam
✓ Degeneracy of θ_{13}, δ_{CP}, sign of Δm^2





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  - ✓ Neutrino energy few MeV
  - ✓ Distance L ~ 1 km
- ✓ Signature: disappearance of the $\bar{\nu}_e$ produced in the reactor → depends on θ_{13}

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - sin^2 2\theta_{13} sin^2\Delta_{13} - cos^4\theta_{13} sin^2 2\theta_{12} sin^2\Delta_{12}$$

Simple dependence on θ_{13} (and Δm_{31}^2

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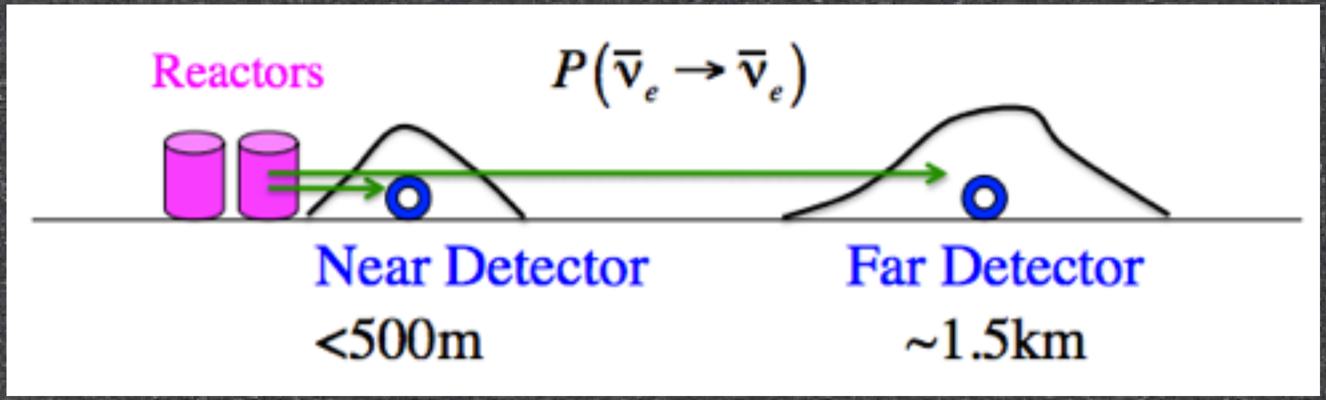
1st order → θ_{13}

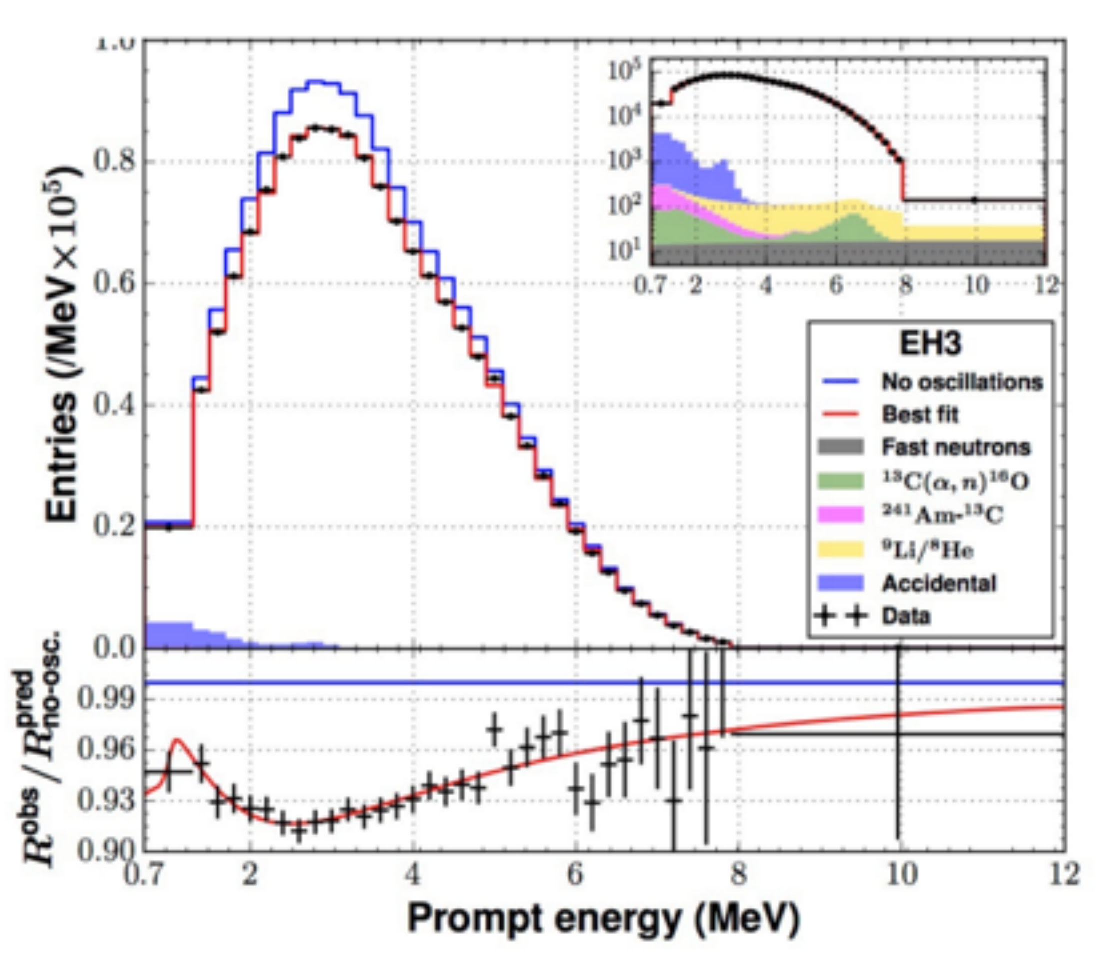
$$P(\nu_\mu \to \nu_e) \sim \sin^2\theta_{23} \frac{sin^2 2\theta_{13}}{(\hat{A}-1)^2} \sin^2((\hat{A}-1)\Delta)$$
$$+ \alpha \frac{8 J_{CP}}{\hat{A}(1-\hat{A})} \sin(\Delta) \sin(\hat{A}\Delta) \sin((1-\hat{A})\Delta)$$
$$+ \alpha \frac{8 I_{CP}}{\hat{A}(1-\hat{A})} \cos(\Delta) \sin(\hat{A}\Delta) \sin((1-\hat{A})\Delta)$$
$$\alpha^2 \frac{cos^2\theta_{23} \sin^2\theta_{12}}{\hat{A}^2} \sin^2(\hat{A}\Delta)$$

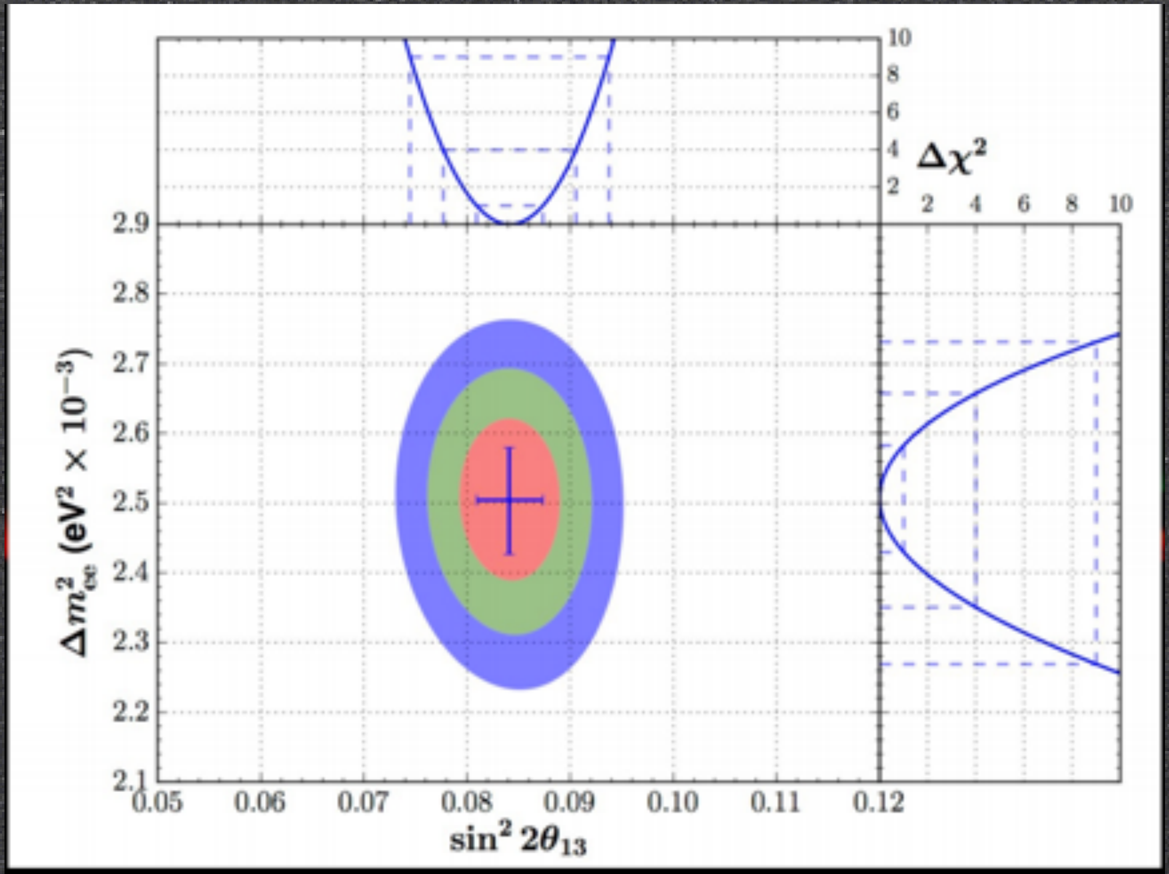
J_{CP} → CPV term
A depends on the sign of Δm^2

$\Delta = \Delta m_{32}^2 L/4E$ $\alpha = |\Delta m_{32}^2|/|\Delta m_{21}^2|$ ~1/30

θ_{13} measurement with reactors





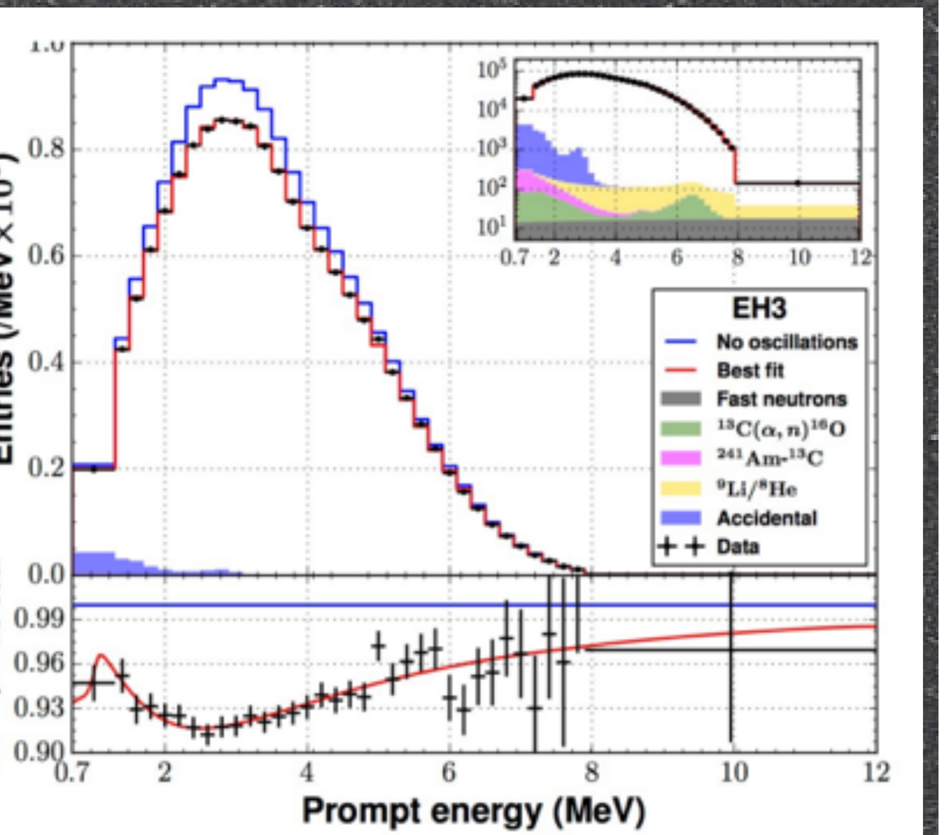


$\sin^2(2\theta_{13}) = 0.0841 \pm 0.0027(stat) \pm 0.0019(syst)$

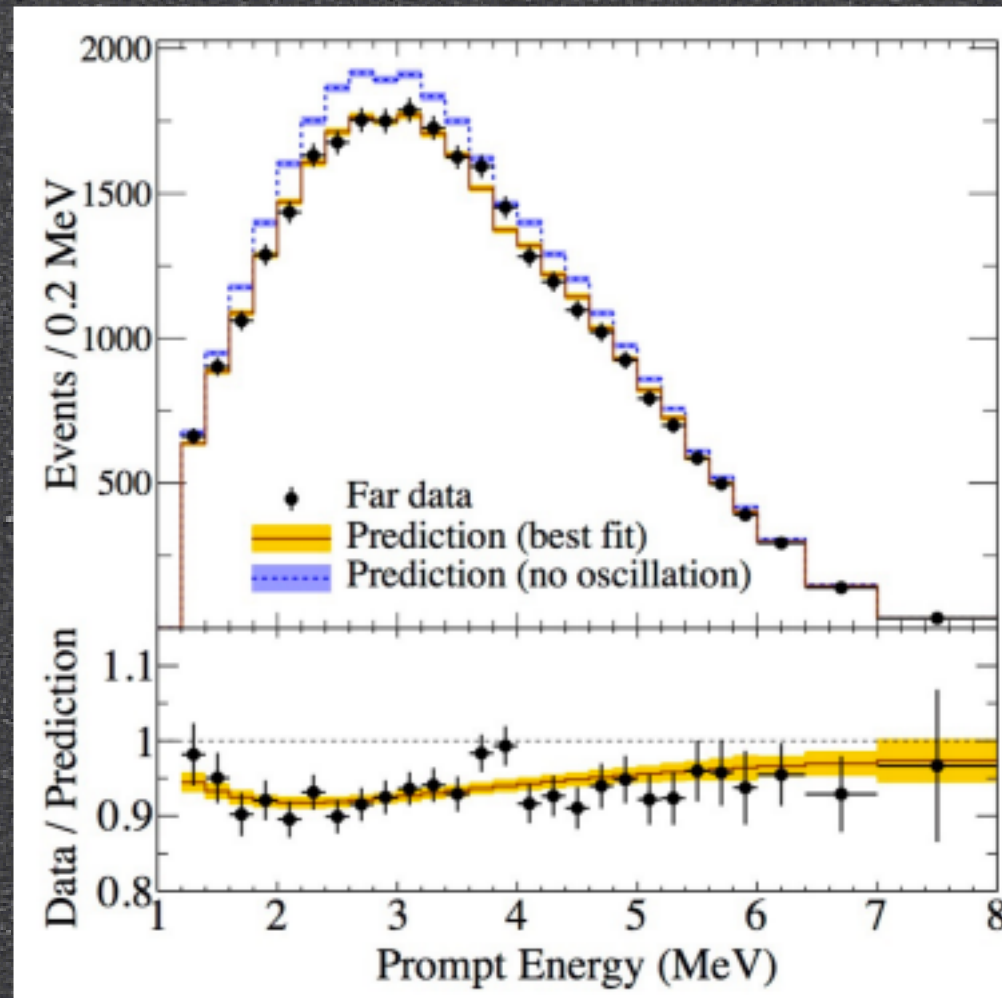
- **Daya Bay: set of near and far detectors → precise measurement of θ_{13} from ν_e disappearance**

Daya Bay, RENO and Double Chooz

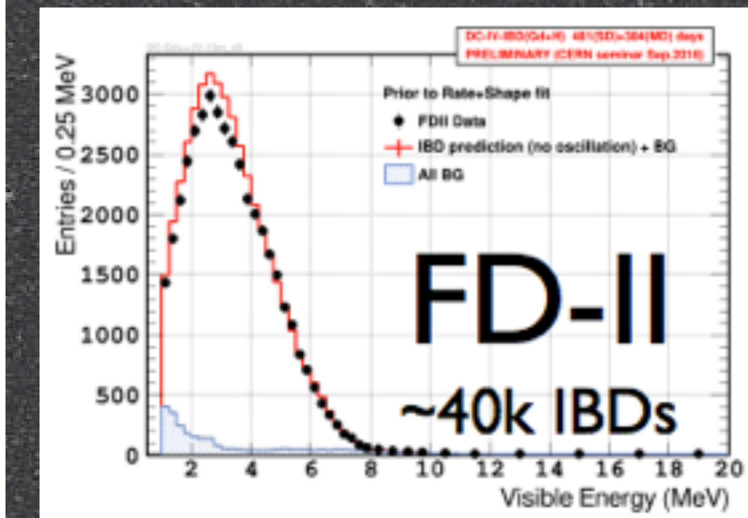
Daya Bay

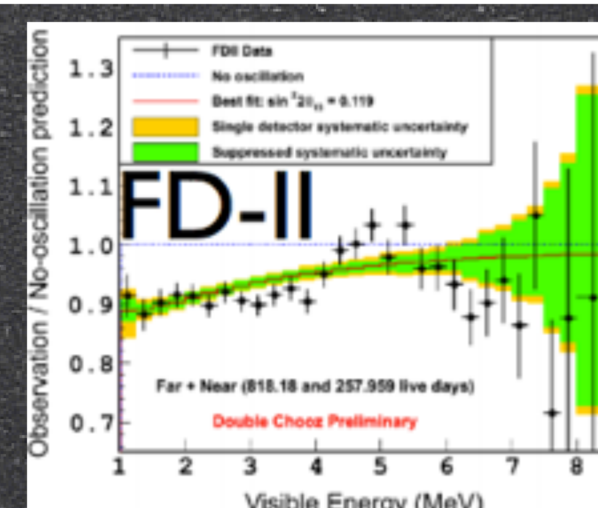


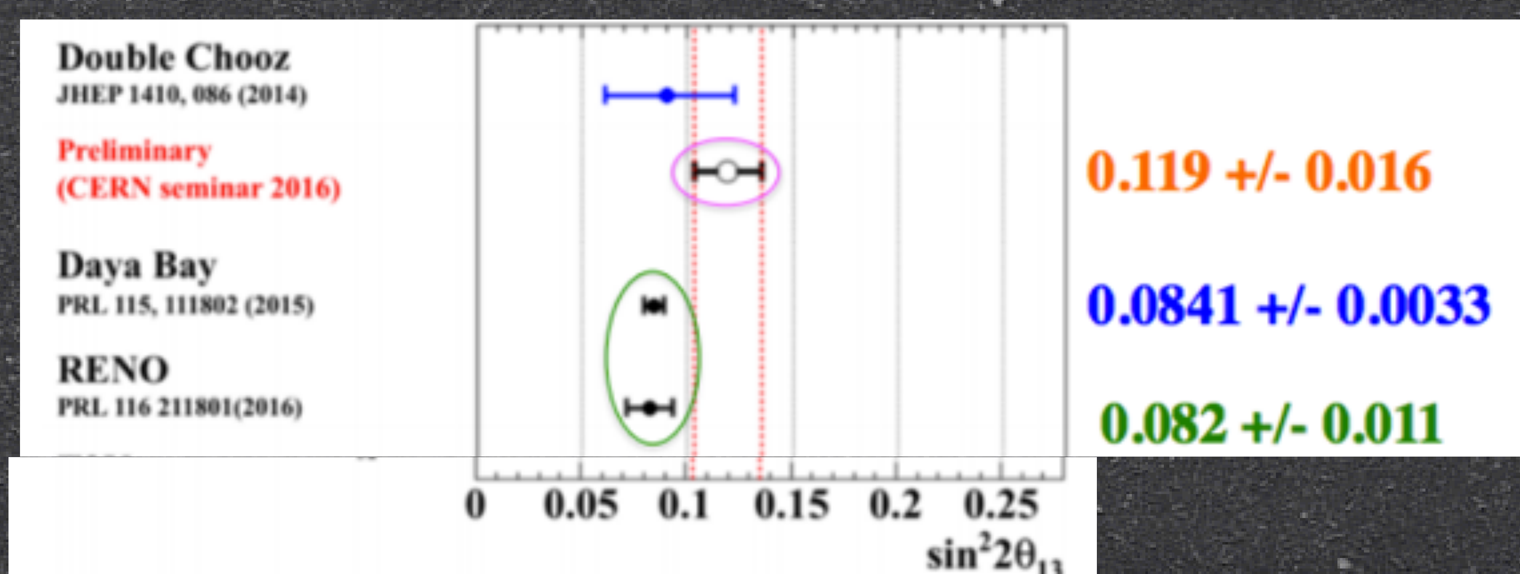
RENO



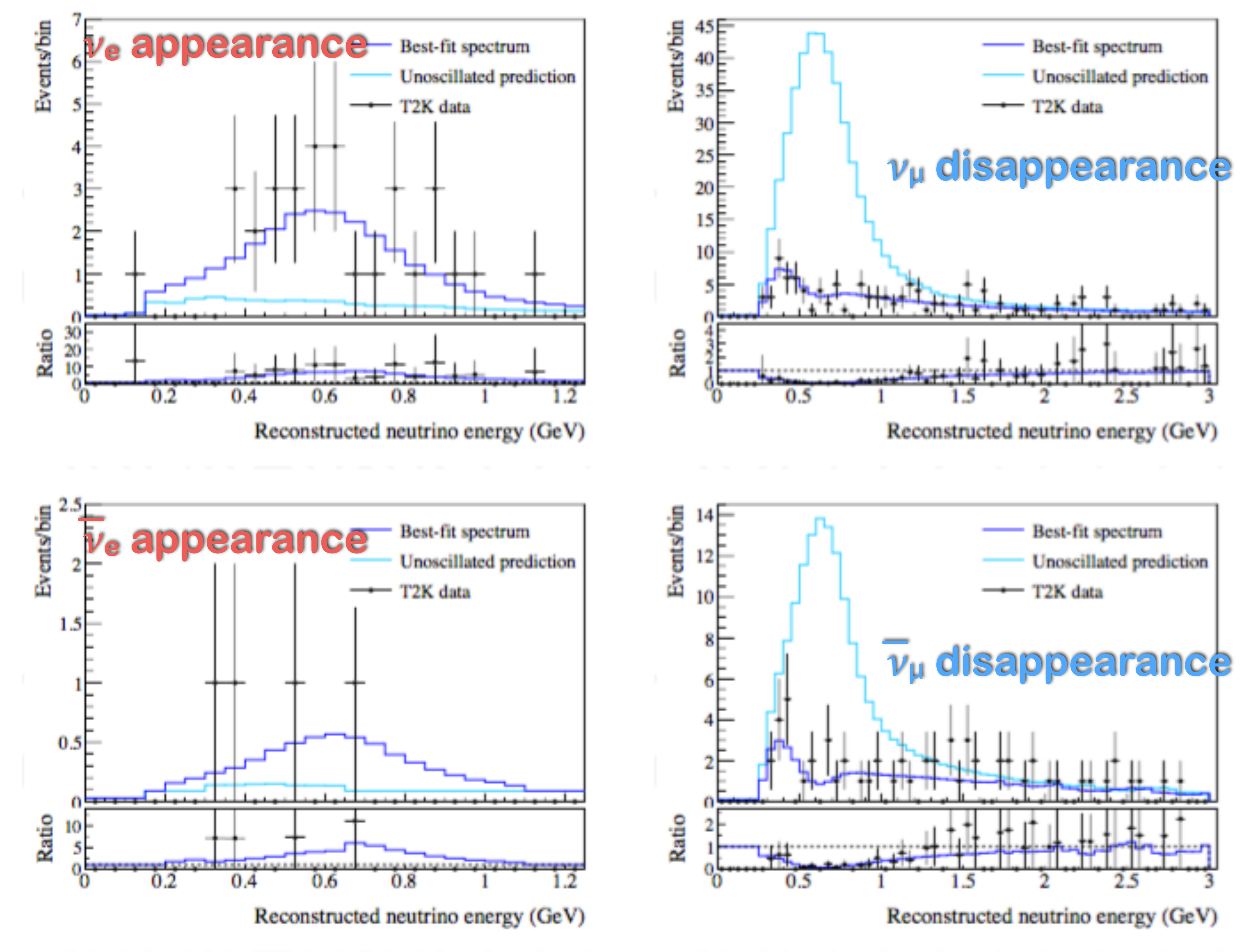
Double Chooz





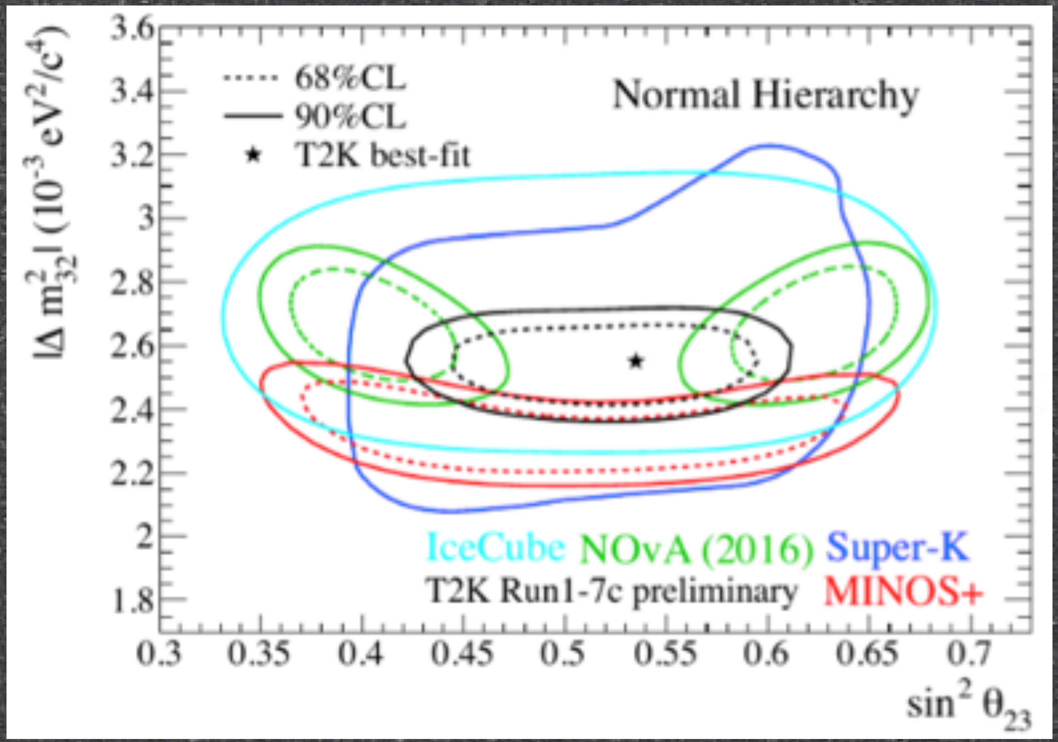


T2K: appearance and disappearance



ν_μ disappearance (T2K and NOVA)

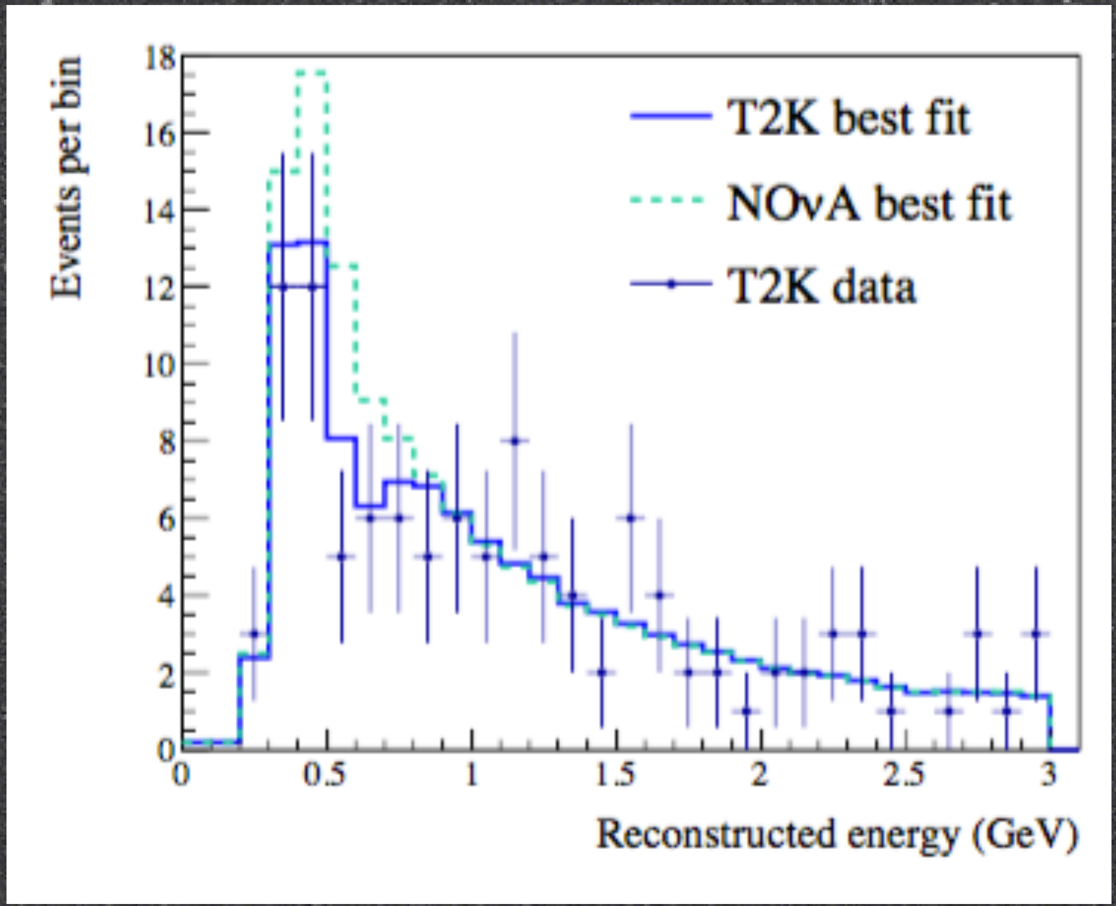
- ν_μ disappearance is sensitive to Δm^2_{32} (position of the oscillation dip) and $\sin^2(\theta_{23})$ (amplitude of the dip)



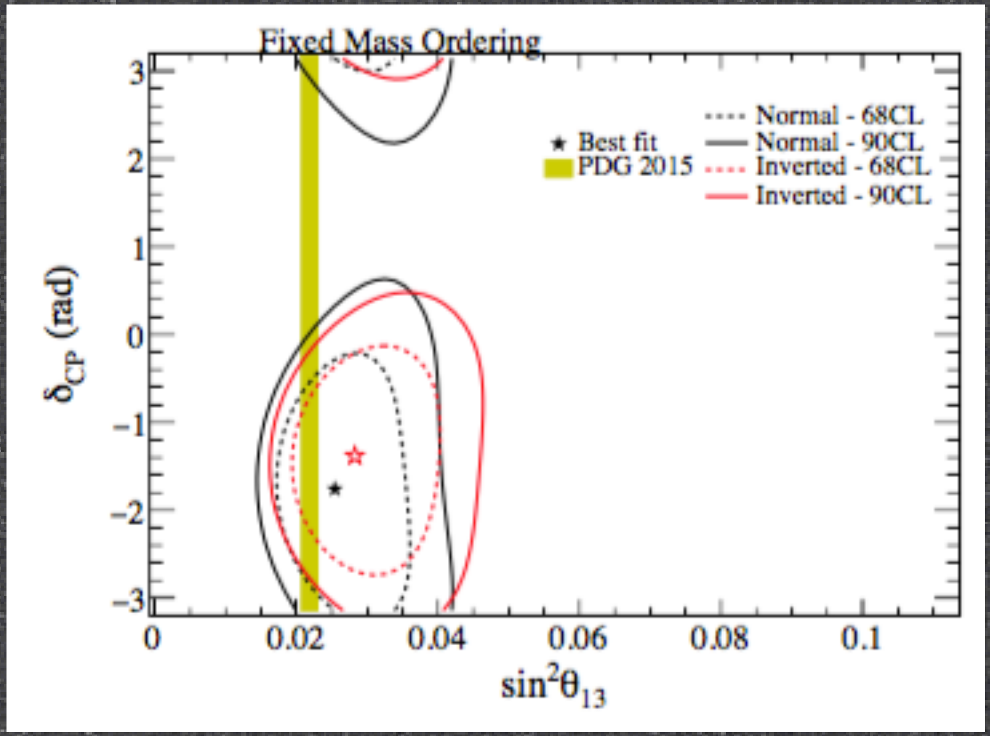
T2K prefers maximal mixing
NOνA excludes maximal mixing at 2.6σ

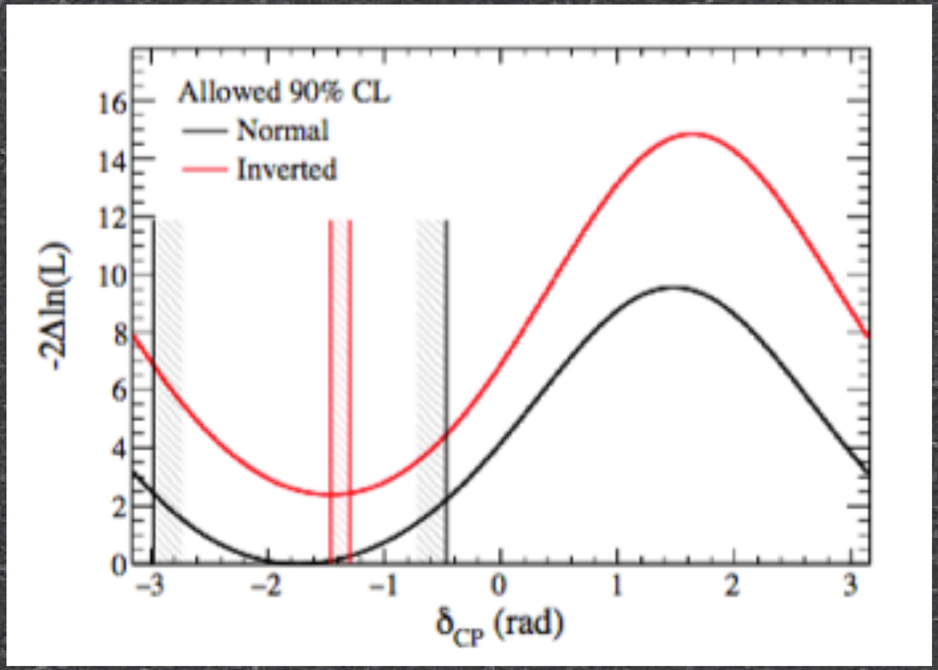
T2K data with NOνA best fit

More data will help!



T2K: CP violation results (δ_{CP})





- By comparing neutrinos and antineutrinos T2K is sensitive to δCP
- Adding reactor constraints on θ_{13} CP conservation is excluded at 90% CL

	$\delta_{CP}=-\pi/2$	δCP=0	$\delta_{CP}=\pi/2$	$\delta_{CP}=\pi$	Data
νe	28.7	24.2	19.6	24.2	32
$\bar{\nu} e$	6.0	6.9	7.7	6.8	4
$\nu\mu$	136.1	135.8	136.0	136.4	135
$\bar{\nu}\mu$	64.4	64.2	64.4	64.5	66

Open questions

- One of the main open problems in our understanding of the Universe is the matter-antimatter asymmetry

$$\eta = \frac{n_B - n_{\bar{B}}}{\gamma} = (6.21 \pm 0.16) \times 10^{-10}$$

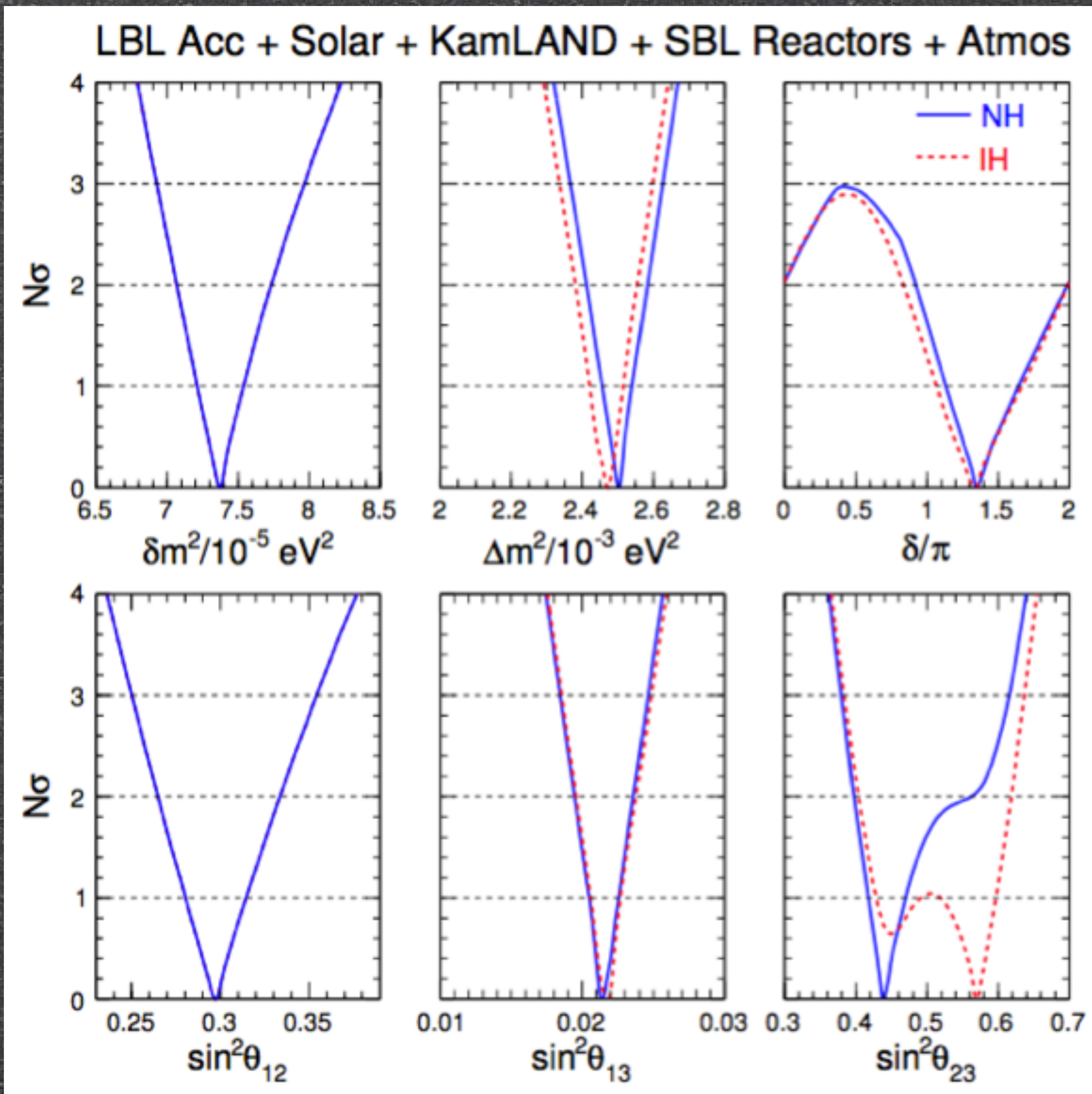
$$Y_B = \frac{n_B - n_{\bar{B}}}{s} = (8.75 \pm 0.23) \times 10^{-11}$$

$$\frac{n_{\bar{B}}}{n_B} < 10^{-6}$$

3 Sakharov's conditions:
- baryon number violation
- C and CP violation
- deviation from thermal equilibrium dynamics

- The measured CP violation in the quark sector is to small to generate the observed asymmetry → Asymmetry can be generated by the leptons → Leptogenesis
- CP violation in the leptonic sector is one of the conditions necessary for the leptogenesis → observation of CP violation in neutrinos might be behind the corner!

Global picture and unknowns

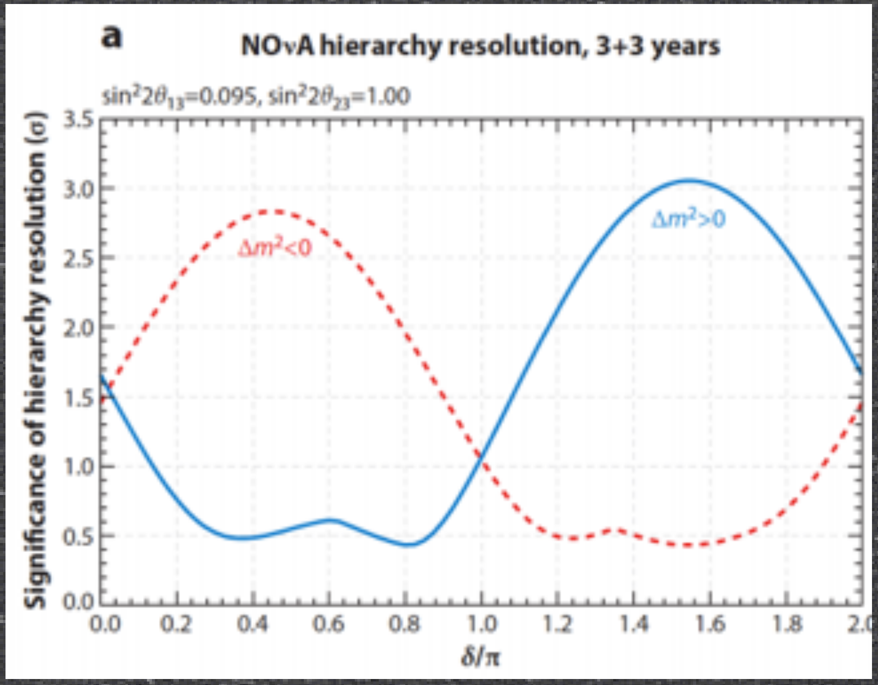


In the last 20 years the 2 mass squared differences and the 3 mixing angles have been measured

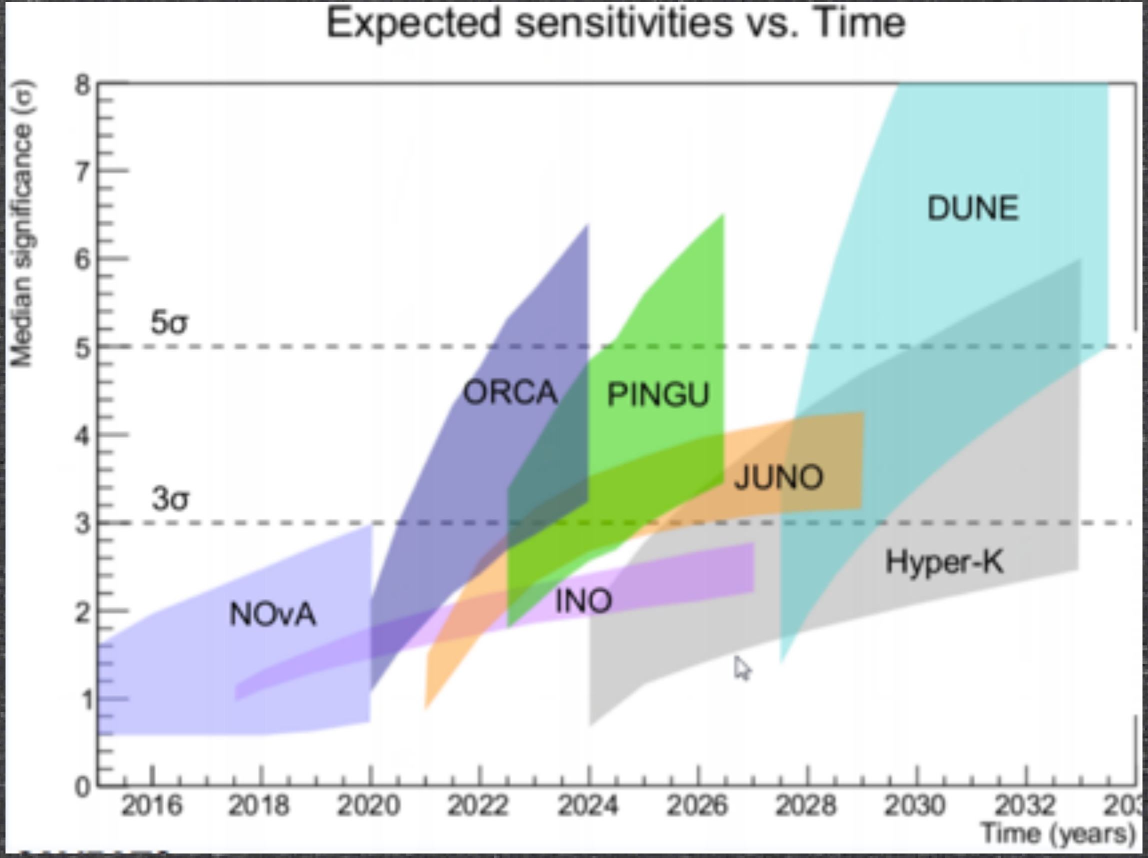
3 open questions:
δ_{CP}: hints (~2σ) that it might be different from zero
Mass ordering: $\nu 3 > \nu 2 > \nu 1$ (NH) or $\nu 2 > \nu 1 > \nu 3$ (IH) ?
θ_{23}: maximal?

Mass ordering measurements

- Mass ordering is accessible to different experiments using different techniques: accelerators (NOVA, DUNE, HK), reactors (JUNO) or atmospheric neutrinos (ORCA, PINGU)



NOνA can reach 3σ in 2020 if lucky (need a “good” value of δ_{CP})



ORCA and PINGU → sensitivity depends on θ23 and on systematics

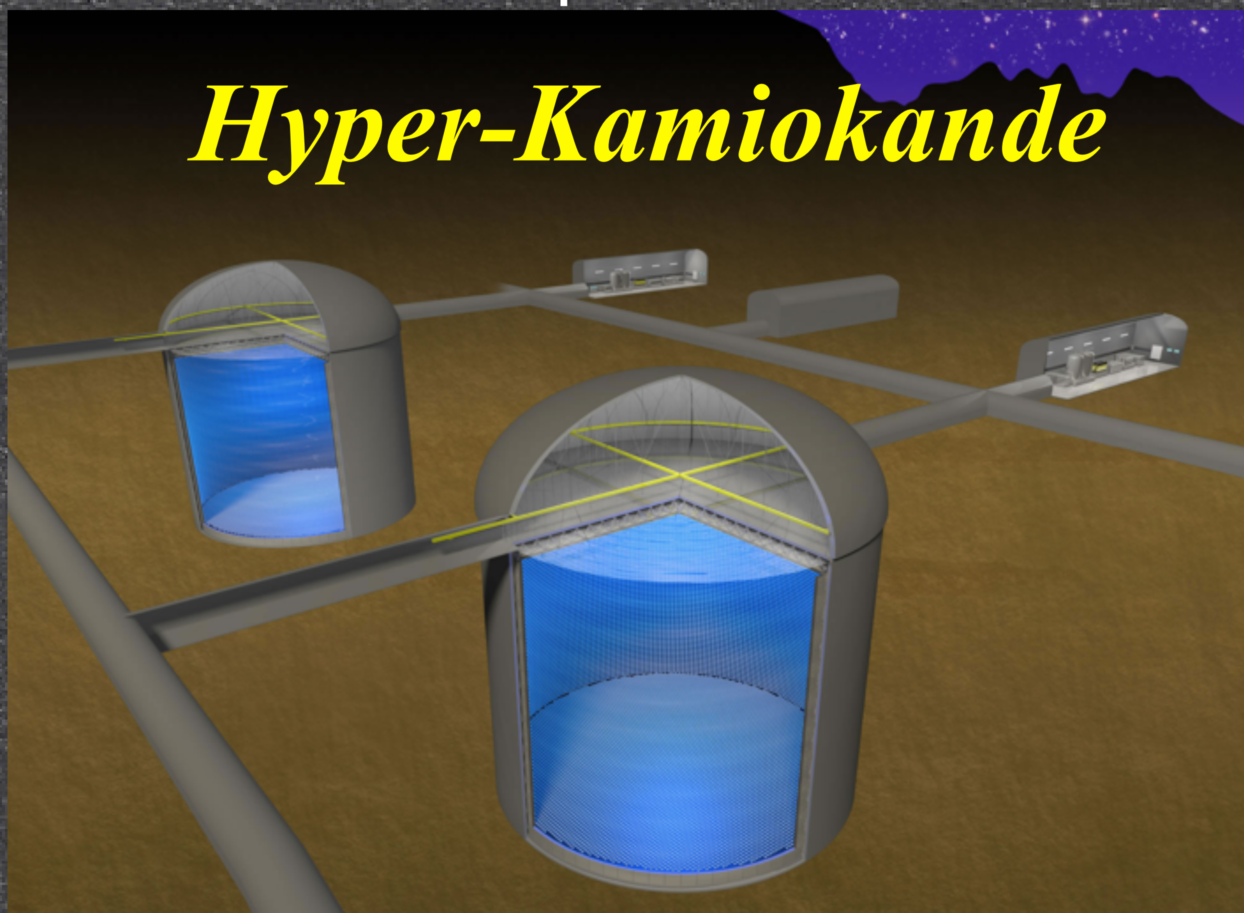
JUNO → sensitivity depends on energy resolution

DUNE → very long baseline, large matter effects → will measure MO but not before 2026

δ_{CP} and future long-baselines

- **Best chance to measure δ_{CP} is with accelerators**

T2K + T2K phase-II + HK

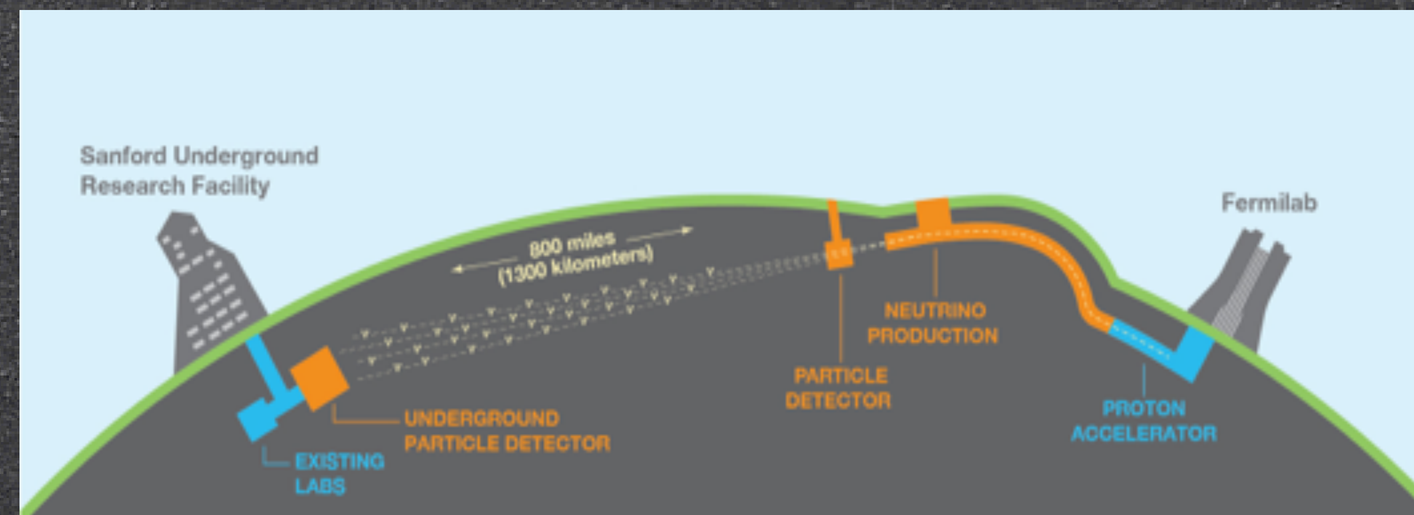


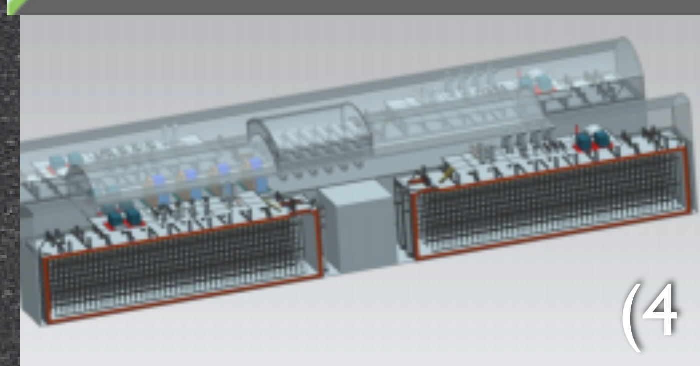
Hyper-K Design Report (7E21 POT for nu and 20E21 POT for anti-nu)

		signal		BG						Total
		$\nu_\mu \to \nu_e$	$\overline{\nu}_\mu \to \overline{\nu}_e$	ν_μ CC	$\overline{\nu}_\mu$ CC	ν_e CC	$\overline{\nu}_e$ CC	NC	BG Total	
ν mode	Events	2300	21	10	0	347	15	188	560	2880
	Eff.(%)	63.6	47.3	0.1	0.0	24.5	12.6	1.4	1.6	—
$\bar{\nu}$ mode	Events	289	1656	3	3	142	302	274	724	2669
	Eff. (%)	45.0	70.8	0.03	0.02	13.5	30.8	1.6	1.6	—

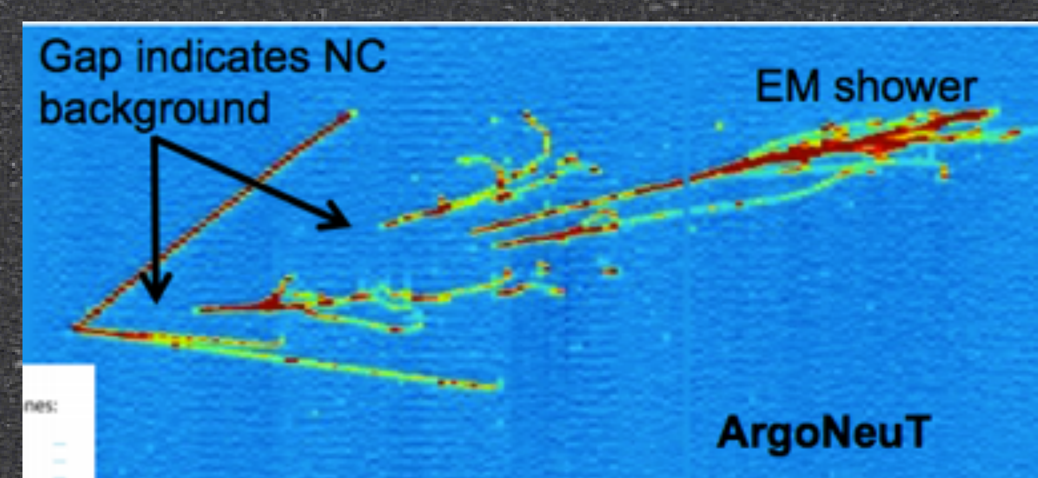
assuming δ_{CP}=0

NOνA and DUNE





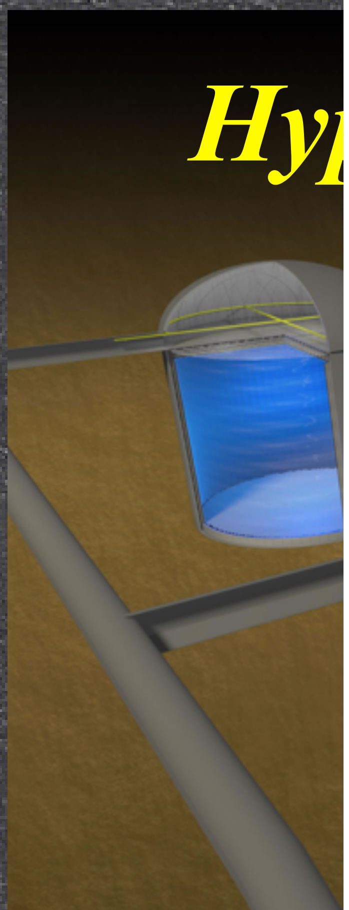
40 kT Liquid Argon detector
(4 modules, 10 kton each)

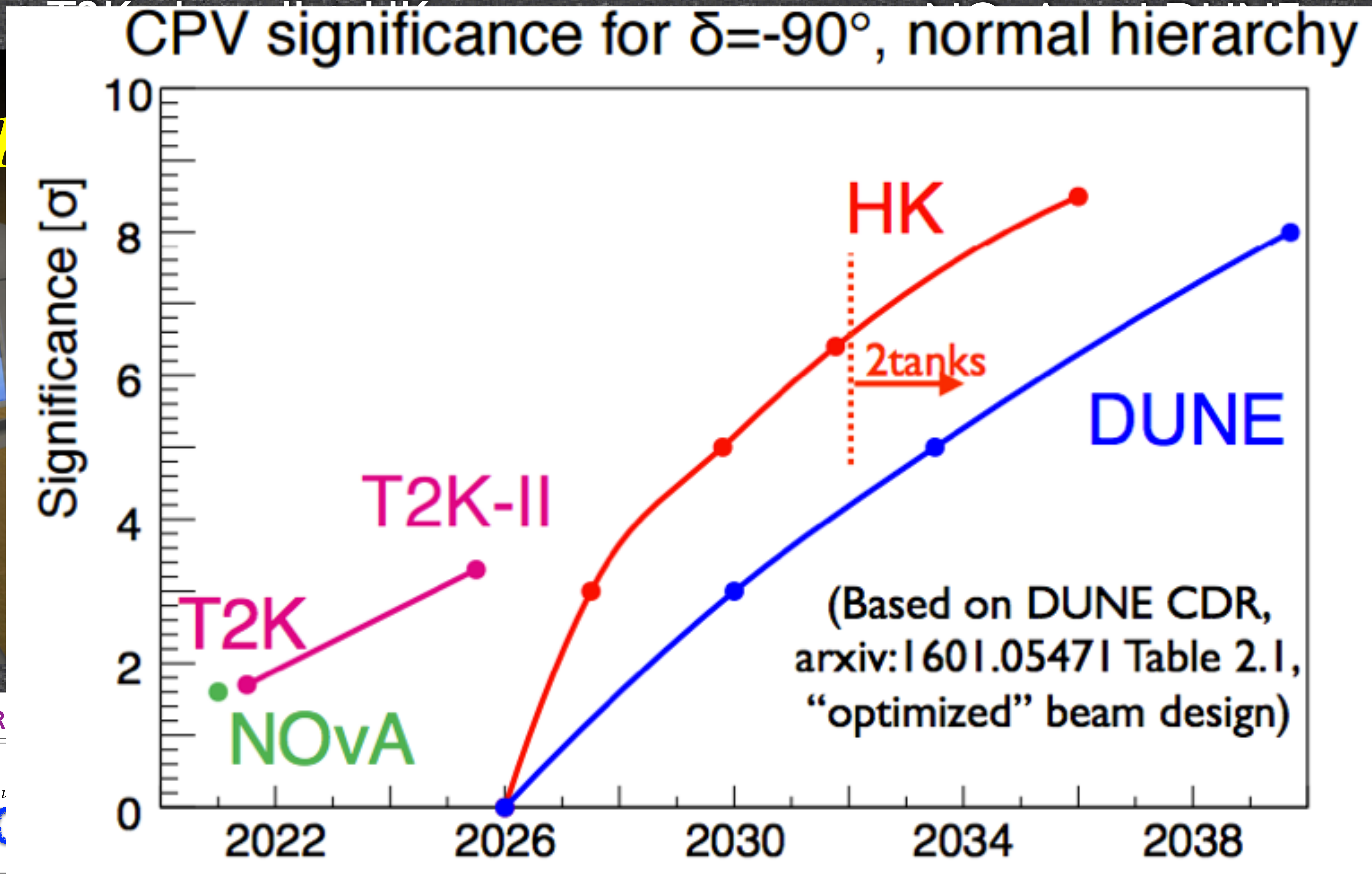


δCP and future long-baselines

- δCP can only be measured by accelerator experiments

T2K



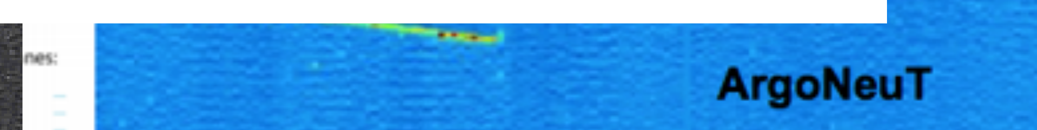


Argon
r
ton each)

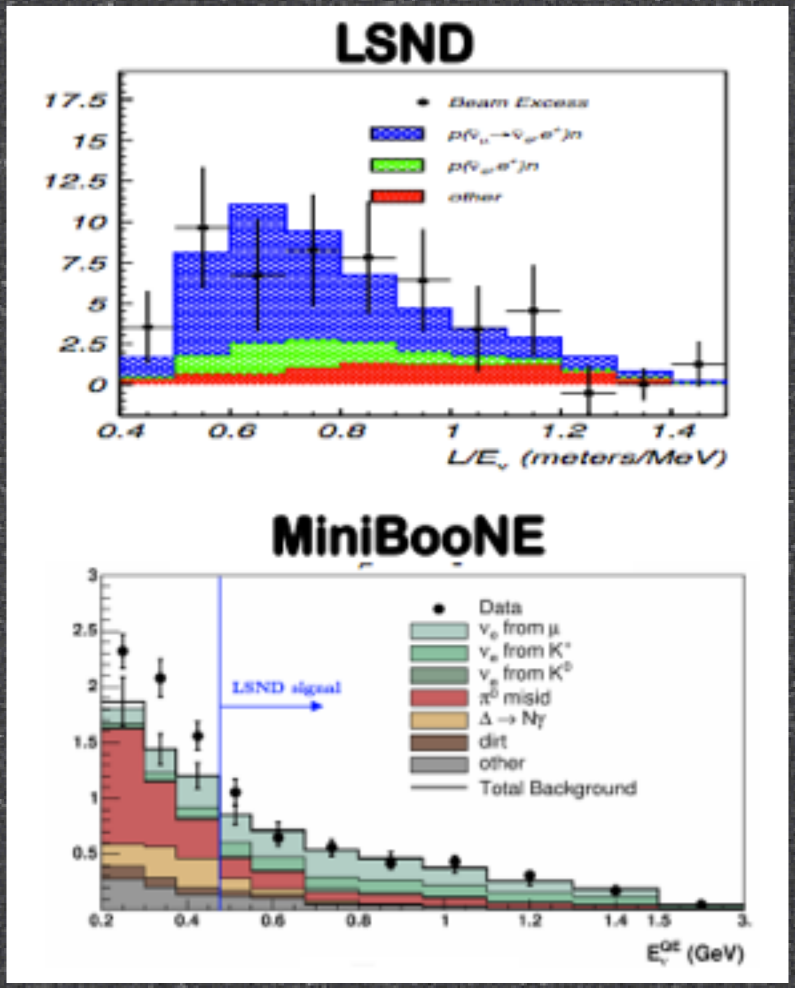
Hyper-K Design R

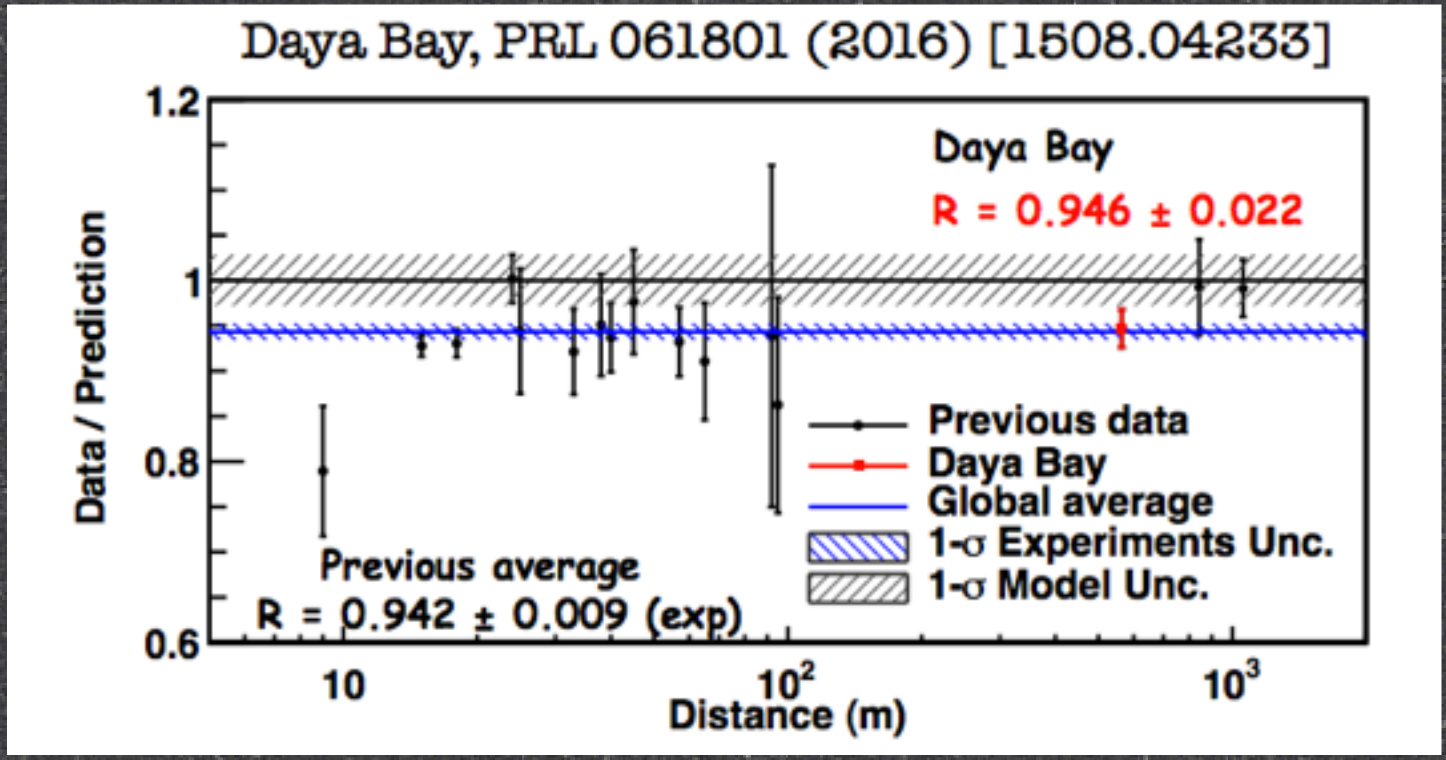
ν mode	Events									
	Eff.(%)									
$\bar{\nu}$ mode	Events									
	Eff. (%)	45.0	70.8	0.03	0.02	13.5	30.8	1.6	1.6	—

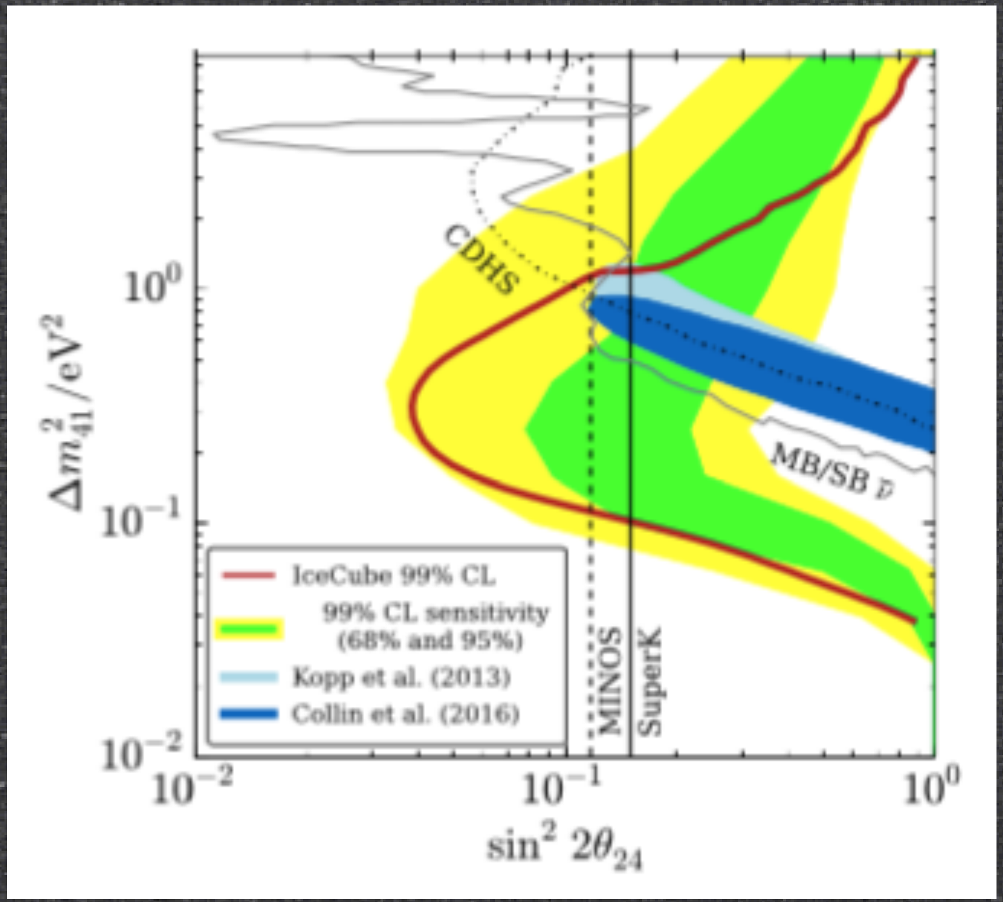
assuming δ_{CP}=0



Anomalies







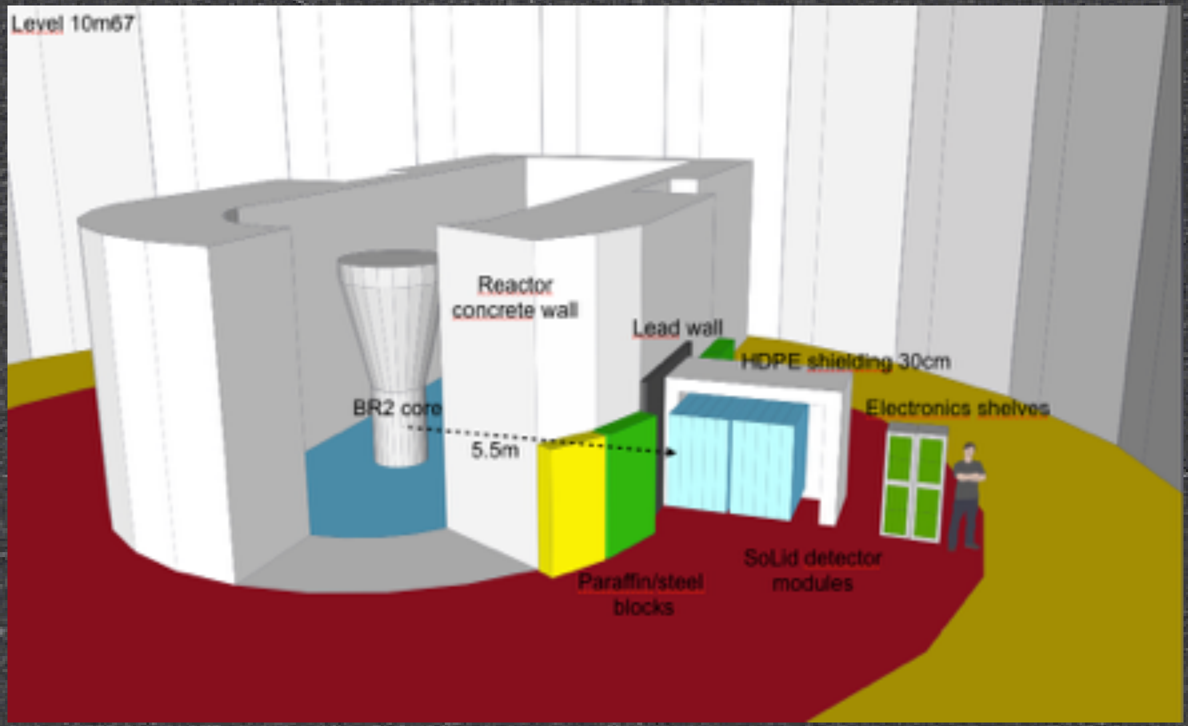
- Anomalies observed in ν_e disappearance (reactor) and ν_e appearance (LSND, MiniBooNE)
- Might be explained with the existence of an additional state (3+1 model)
- No observations of ν_μ disappearance → difficult to reconcile everything in a single framework

Sterile neutrinos

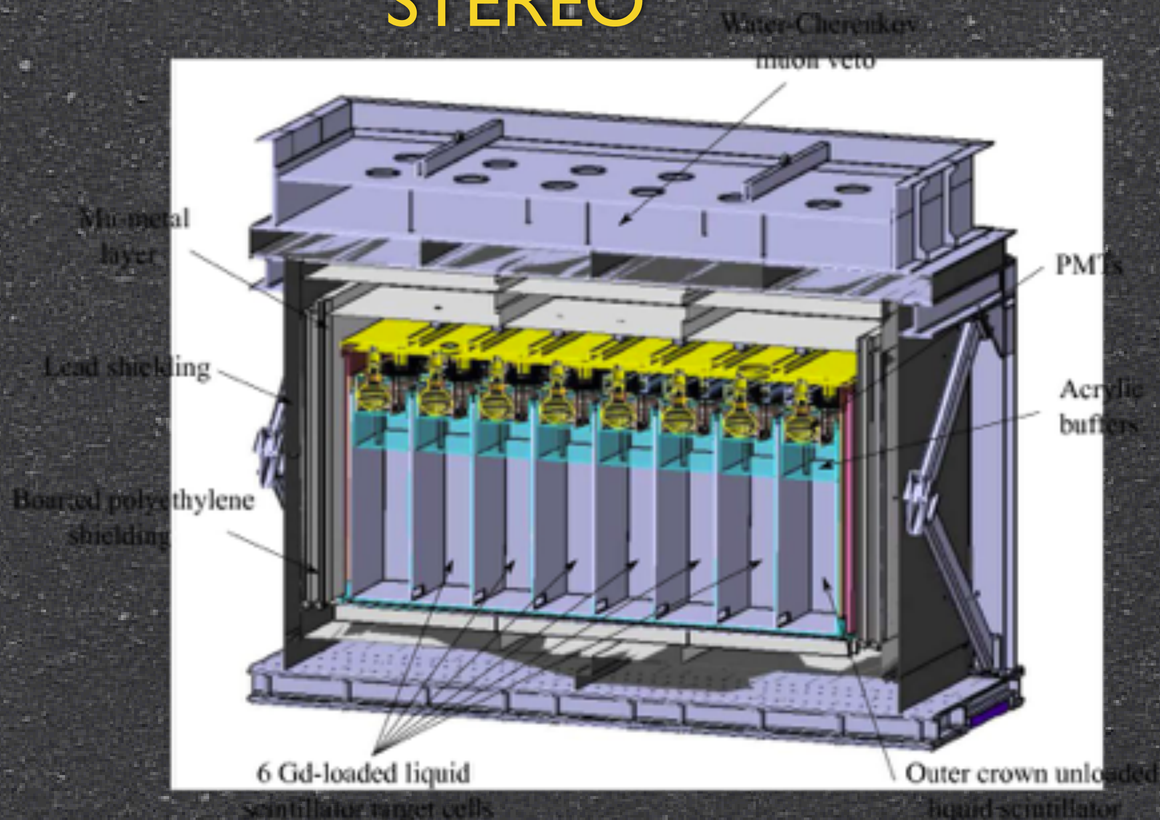
See Nathalie's talk for more details on cosmology and sterile neutrinos

- Several experiments set to investigate these anomalies in the next years and will hopefully give a firm answer
  - Discovery or exclusion of sterile neutrinos at the eV scale
  - Program of short baseline at Fermilab to investigate $\nu\mu$ disappearance and νe appearance
  - Reactors and sources for the νe disappearance

SOLID



STEREO



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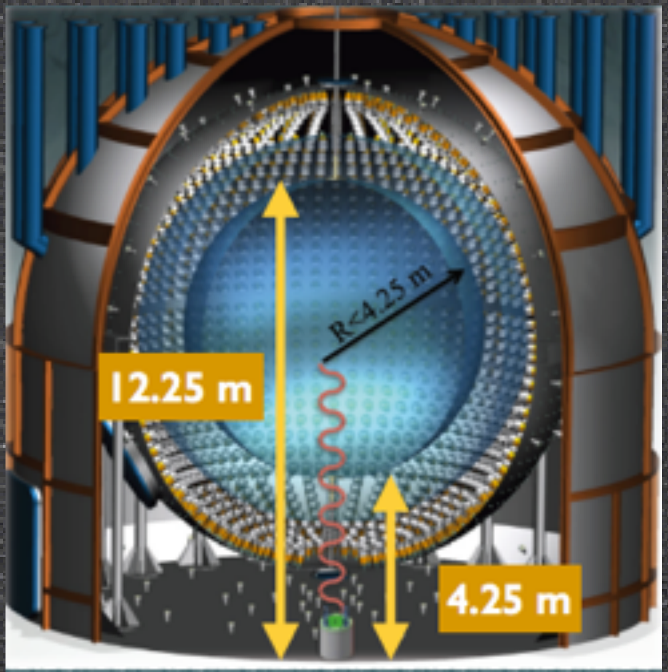
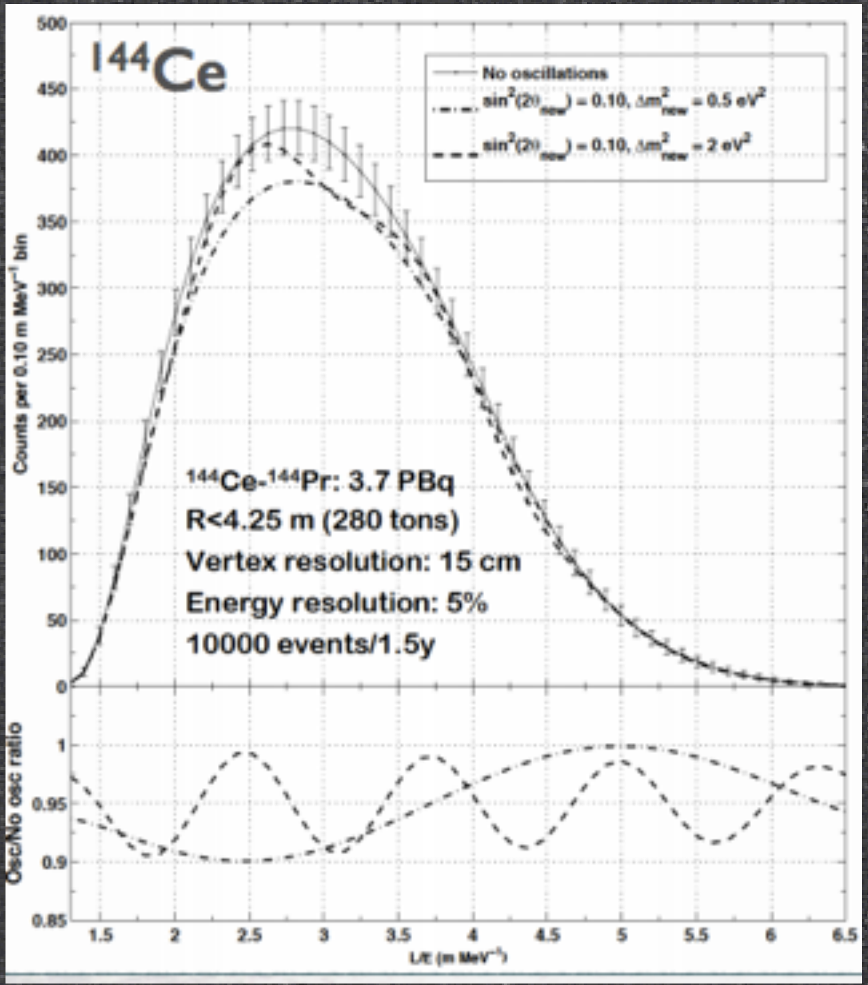
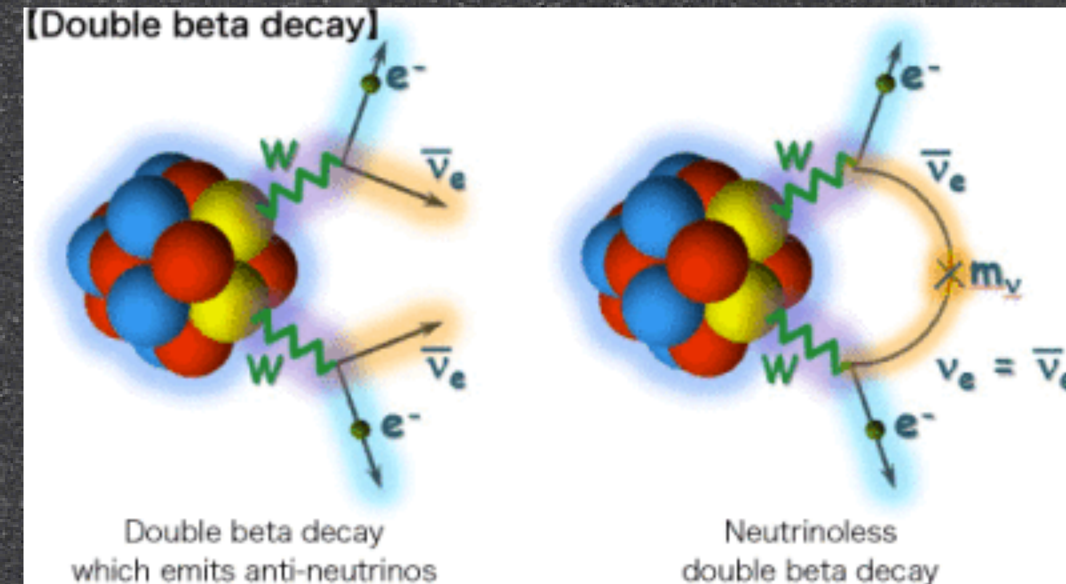
SOX ^{144}Ce $\overline{\nu}_e$ source close to Borexino → start beginning of 2018

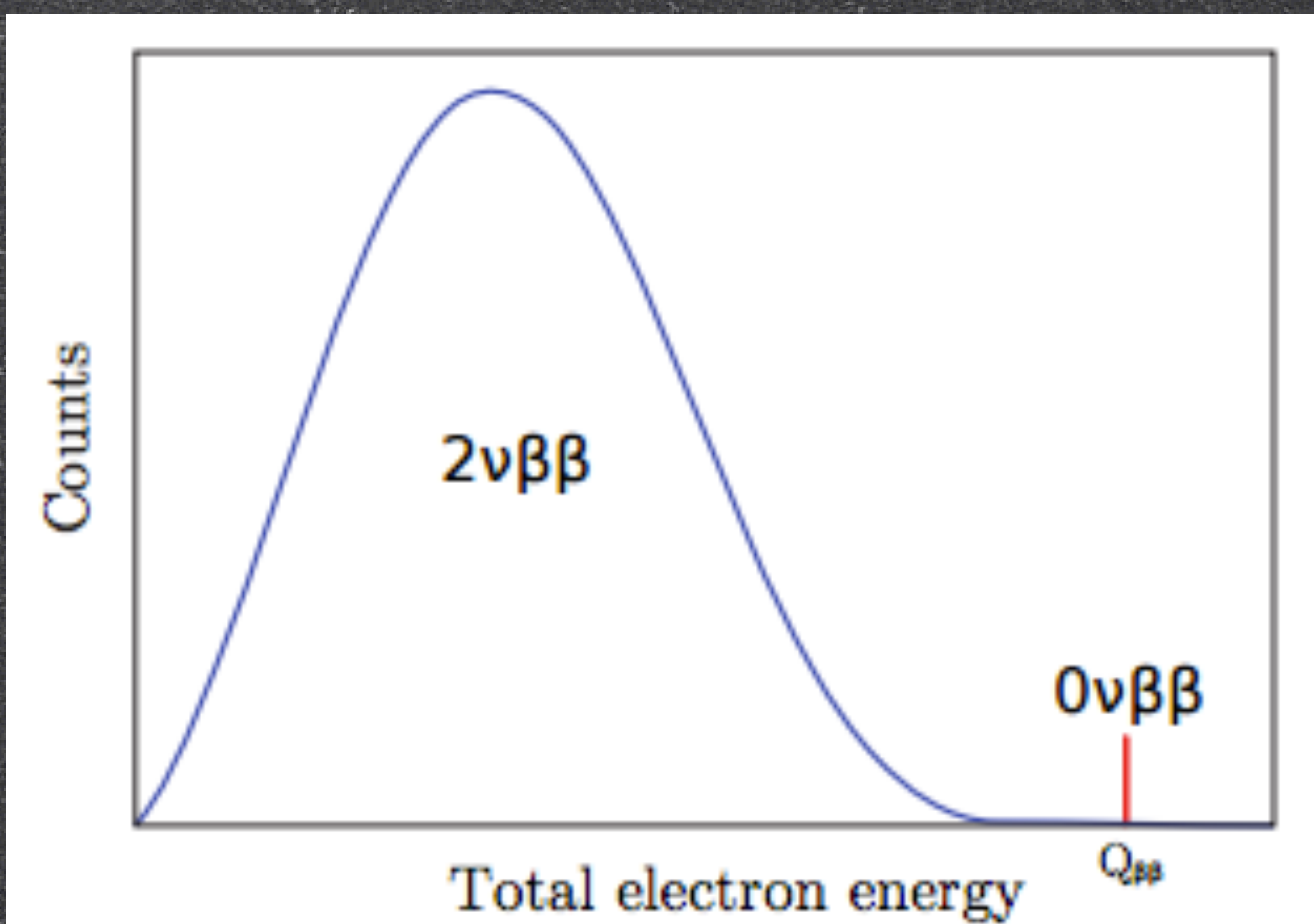


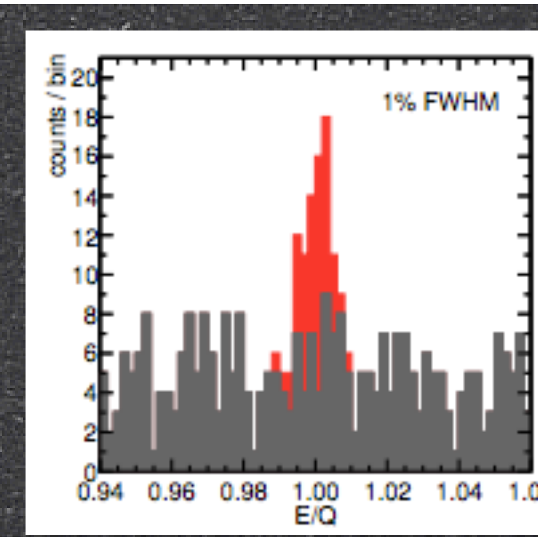


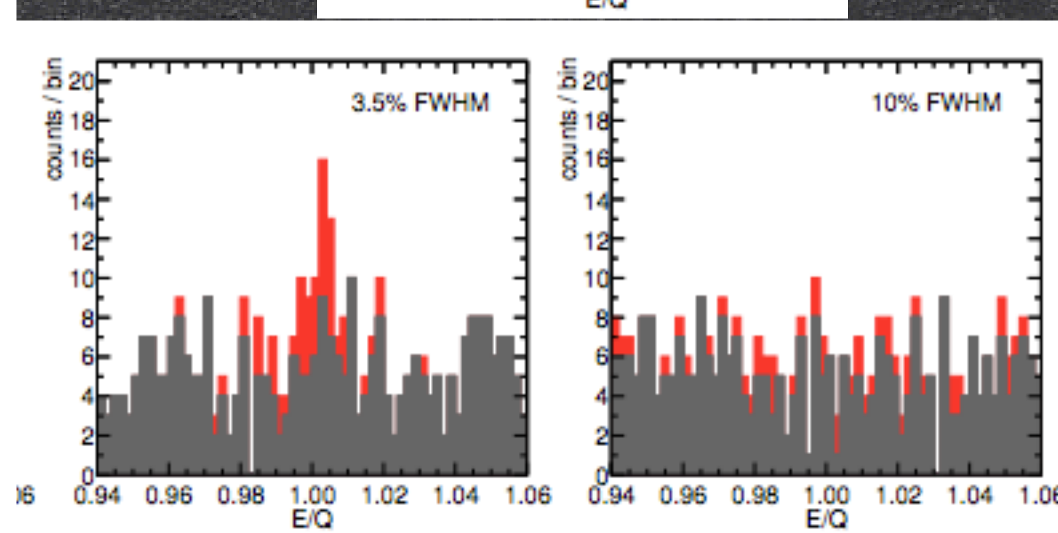
Double β decay without neutrinos

- Neutrinos are the only fermions that can be Majorana particles → $\nu = \bar{\nu}$
- If neutrinos are Majorana particles then it is possible to have a double β-decay without emission of neutrinos



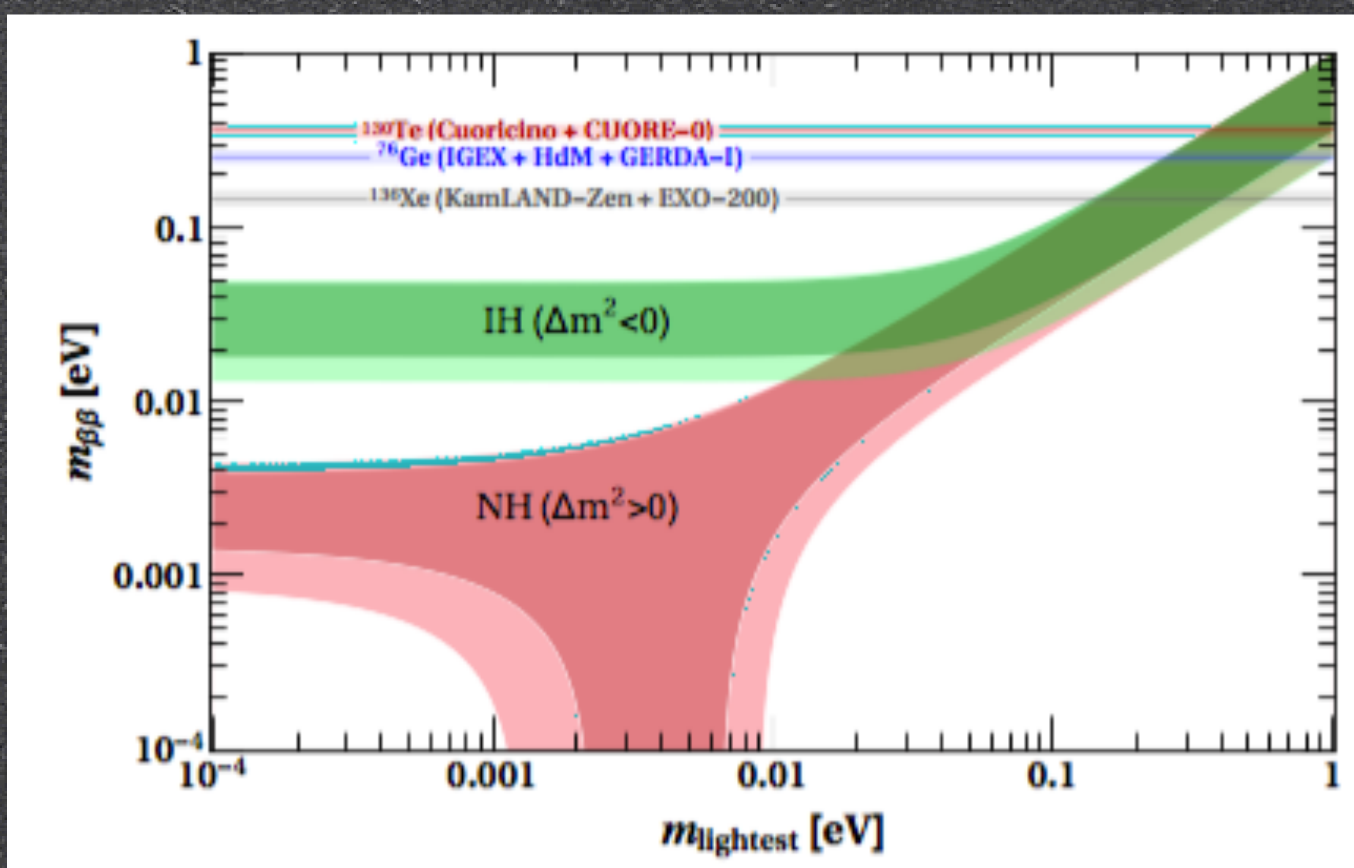


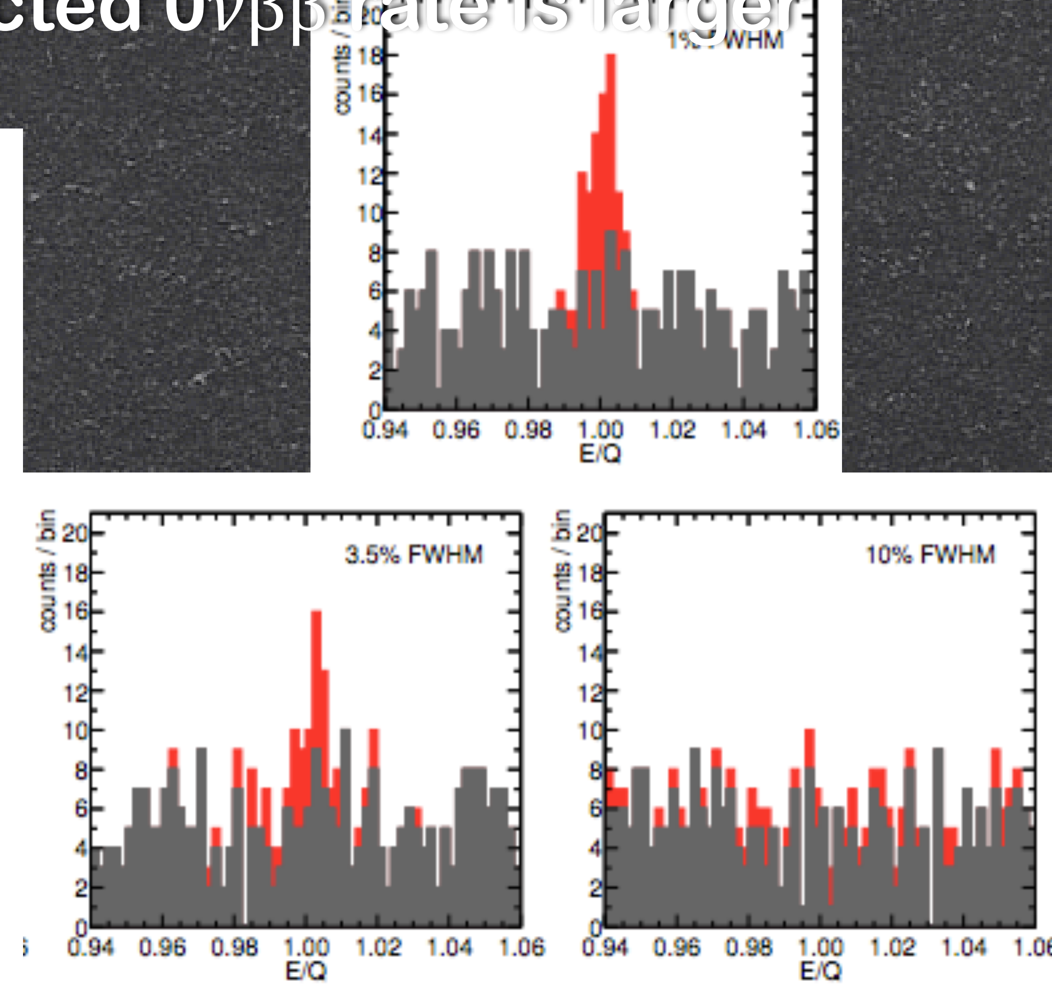




0νββ and 2νββ

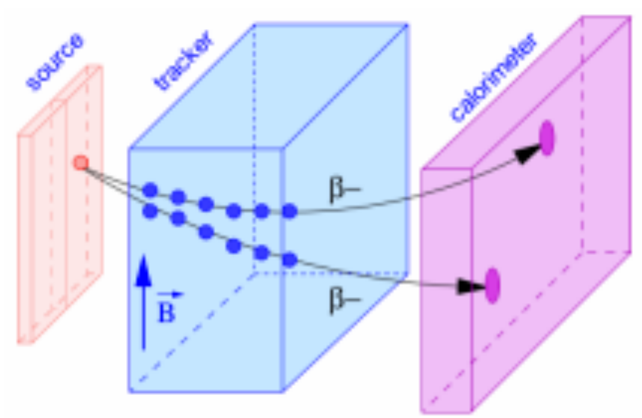
- Need to use isotopes for which single β decay is forbidden
- Need high Q-value for the 0νββ to reduce radioactivity bcg
  - Main background due to 2νββ
- The expected rate of 0νββ depends on the absolute mass of neutrinos (unknown) and the ordering
  - If inverted hierarchy the expected 0νββ rate is larger



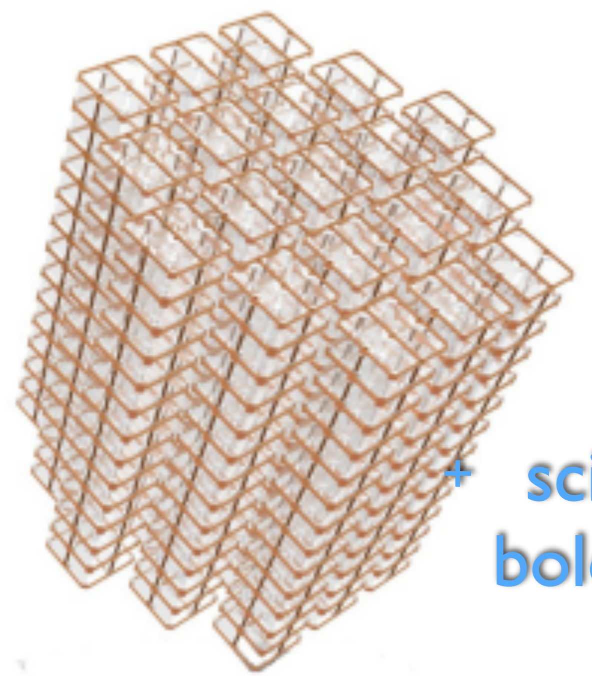


Different techniques

Tracking

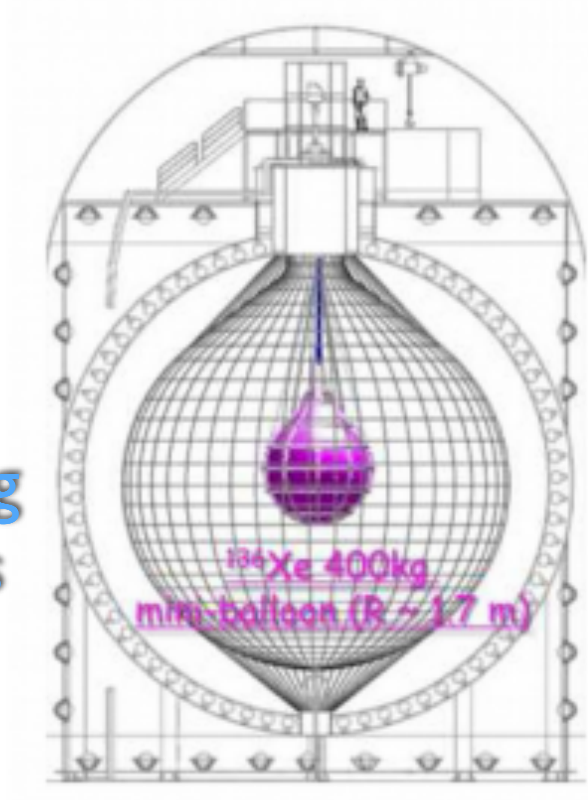


Bolometers



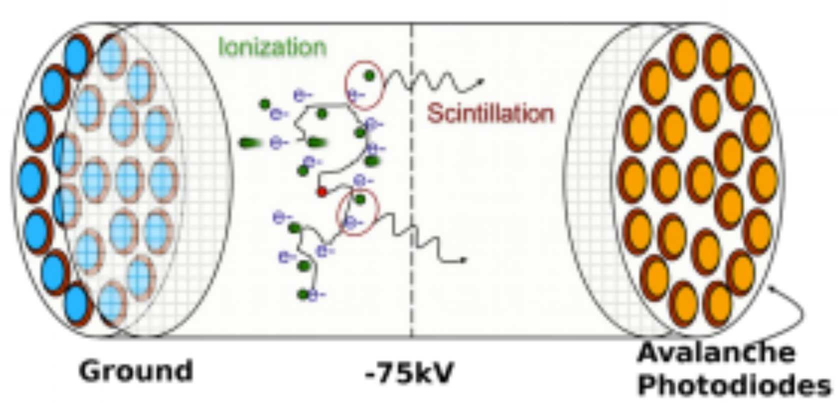
+ scintillating bolometers

Loaded liquid scintillators



Ge diodes

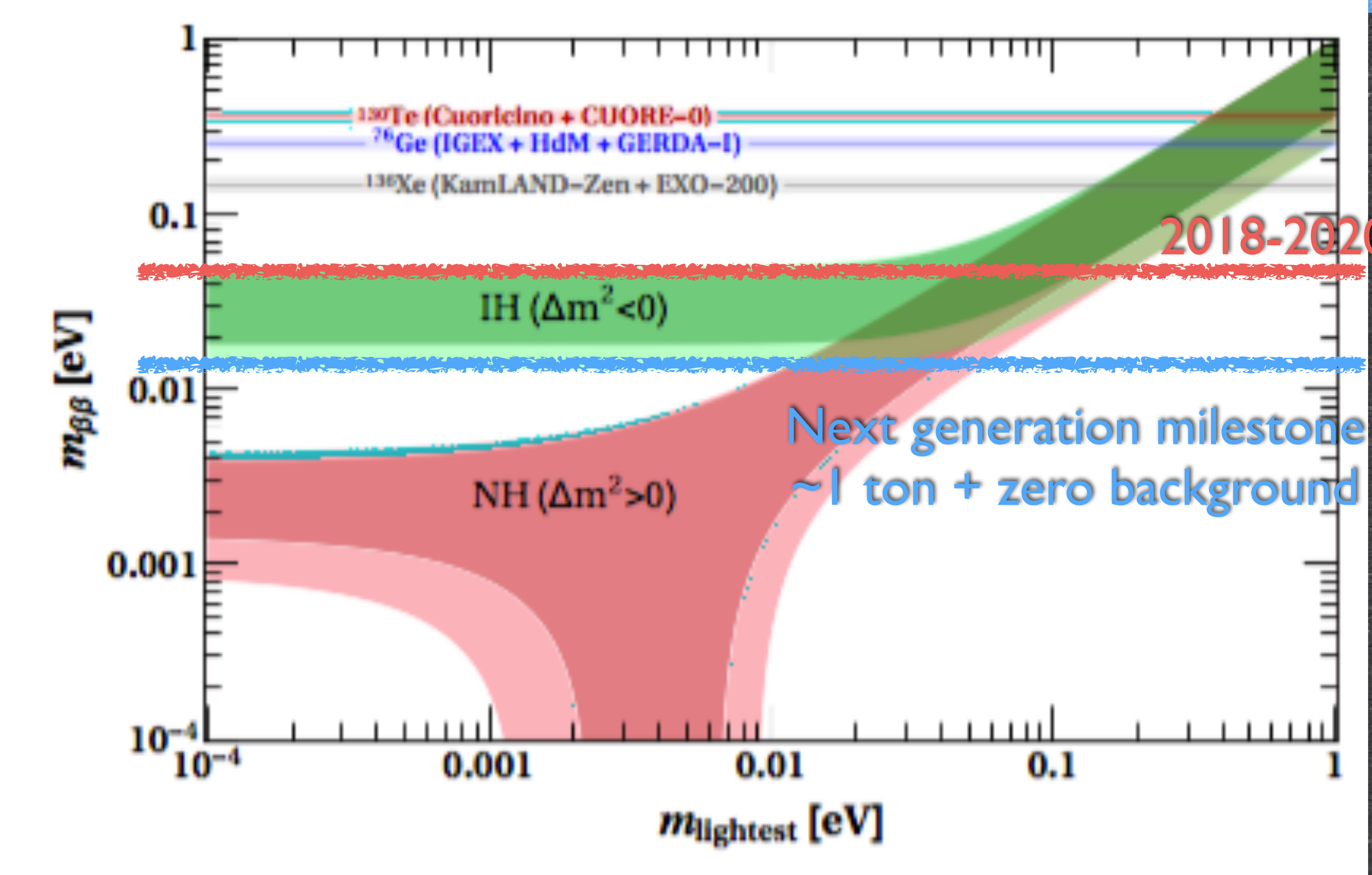
Liquid and gaseous Xe TPC



Desired features

- Good energy resolution
- Low background
- Scalability to large masses
- Possibility to investigate different isotopes with the same technique
- Event topology reconstruction

The path towards the observation



- By 2018 we will start investigating the IH region
- Goal of next generation experiments will be to investigate the IH region → lot of R&D is needed
- The way beyond → (?) R&D and R&D

Conclusions

- Neutrinos are fundamental particles in the SM but we still need to learn a lot about them!
- Neutrino oscillations are nowadays well established (Nobel prize in 2015) → only indication of physics beyond the SM
  - All mixing angles have been measured
  - The discovery of CP violation in the leptonic sector might be (almost) behind the corner
  - Precision tests of the PMNS paradigm will be performed by current and next generation of experiments (HK and DUNE for CP violation, + many others for the mass ordering)
  - Anomalies will lead to discover/rule out sterile neutrinos
- The nature of neutrinos is still unknown
  - Might be Dirac or Majorana particles → The observation of $0\nu\beta\beta$ would mean that neutrinos are Majorana particles