Experimental neutrino physics: status and prospects*

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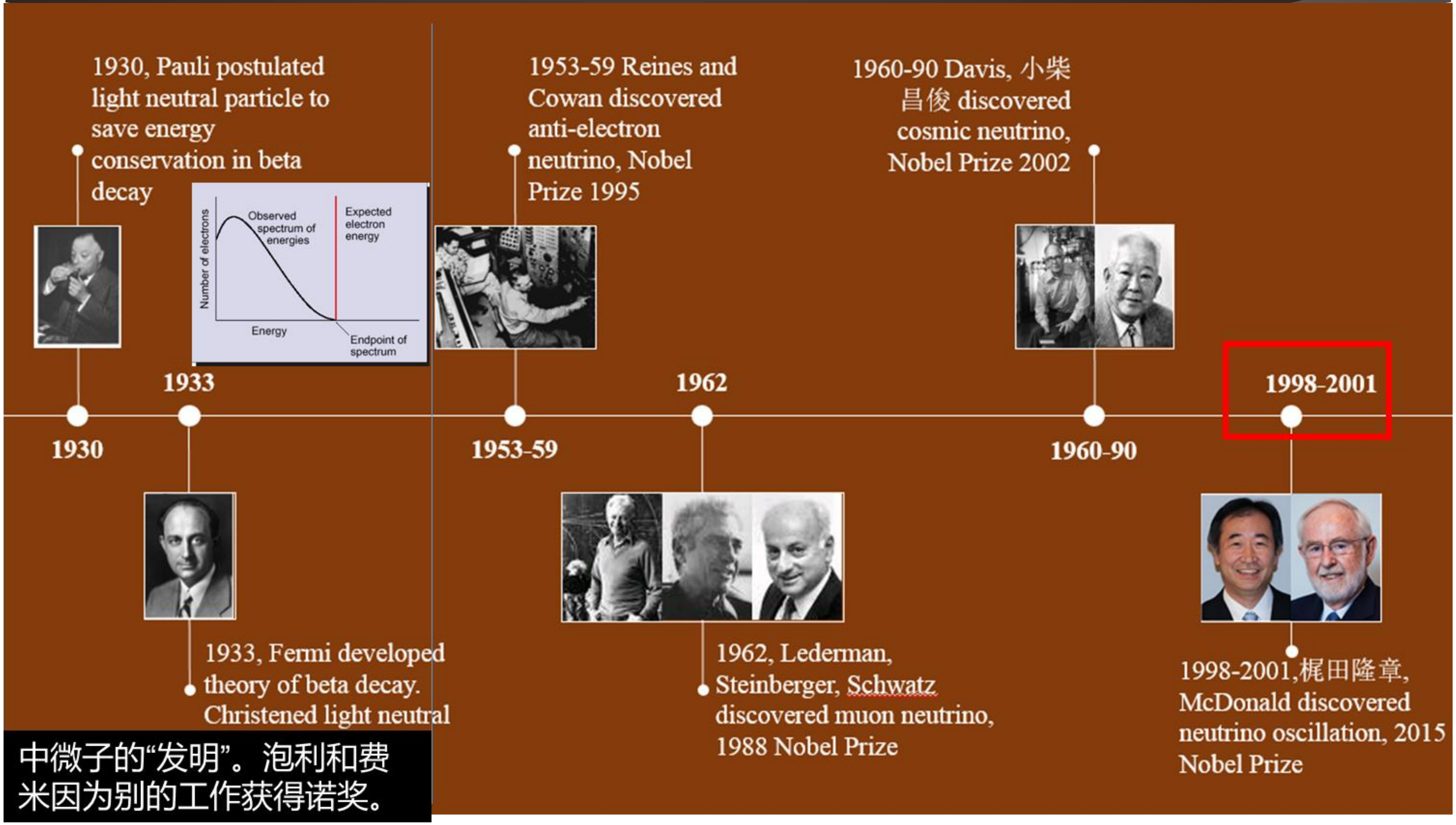
* Materials heavily based on experimental talks given at Neutrino 2016

Neutrinos: glories in the past century



1930, Pauli postulated light neutral particle to save energy conservation in beta decay

1933, Fermi developed theory of beta decay. Christened light neutral

1953-59 Reines and Cowan discovered anti-electron neutrino, Nobel Prize 1995

1962, Lederman, Steinberger, Schwatz discovered muon neutrino, 1988 Nobel Prize

1960-90 Davis, 小柴昌俊 discovered cosmic neutrino, Nobel Prize 2002

1998-2001,梶田隆章, McDonald discovered neutrino oscillation, 2015 Nobel Prize

中微子的“发明”。泡利和费米因为别的工作获得诺奖。

Flavor physics in leptons

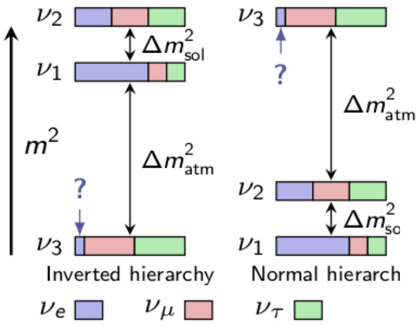
$$-\mathcal{L}_{\mathrm{cc}} = \frac{g}{\sqrt{2}} \Bigg[\overline{\begin{pmatrix} e & \mu & \tau \end{pmatrix}_{\mathrm{L}}} \gamma^{\mu} \overset{\boxed{\text{PMNS matrix}}}{\overset{\downarrow}{U}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}_{\mathrm{L}} W_{\mu}^{-}$$

$$+ \overline{\begin{pmatrix} u & c & t \end{pmatrix}_{\mathrm{L}}} \gamma^{\mu} \underset{\boxed{\text{CKM matrix}}}{\underset{\uparrow}{V}} \begin{pmatrix} d \\ s \\ b \end{pmatrix}_{\mathrm{L}} W_{\mu}^{+} \Bigg] + \mathrm{h.c.}$$

Neutrino mixing

Transformation from mass to weak eigenstates

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



$\Delta m^2_{\mathrm{atm}} = 2.4\times10^{-3}$ eV^2

$\Delta m^2_{\mathrm{sol}} \sim 7.6\times10^{-5}$ eV^2

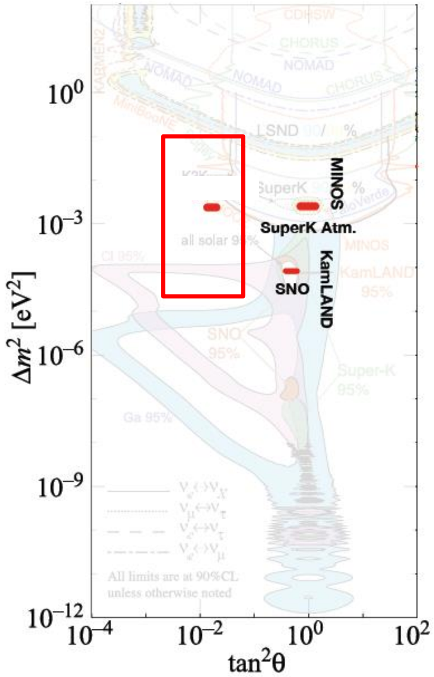
Solar: $\theta_{12}\sim32°$ Atmospheric: $\theta_{23}\sim45°$

$$U_{PMNS} = \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}$$

$$\times \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$\theta_{13}\sim9°$

δ: CP Violation Phase

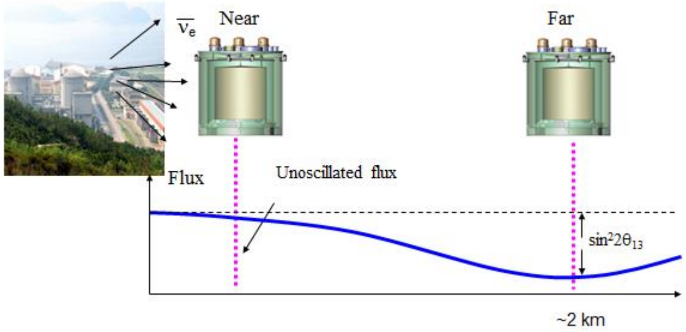


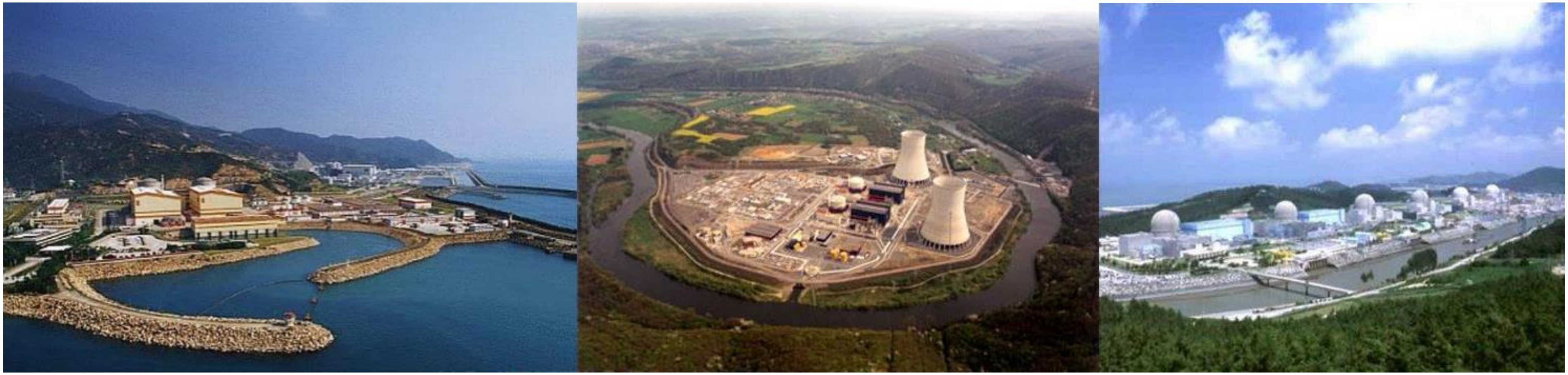
The last mixing angles θ_{13}

$$P(\nu_e \to \nu_e) = 1 - \boxed{\sin^2 2\theta_{13}}\left(\cos^2\theta_{12}\boxed{\sin^2\Delta_{31}} + \sin^2\theta_{12}\boxed{\sin^2\Delta_{32}}\right) - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{12}$$

$$\Delta_{ij} = \frac{\Delta m_{ij}^{\ 2} L}{4E_\nu}$$

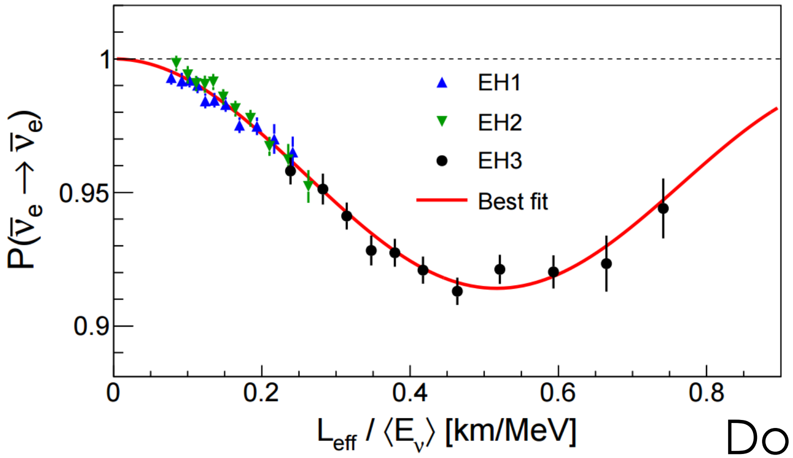
$\Delta m_{31}^2 = 2.4\times10^{-3}\ \mathrm{eV}^2$, reactor neutrino $E\nu \sim 4$ MeV, $L = 2$ km



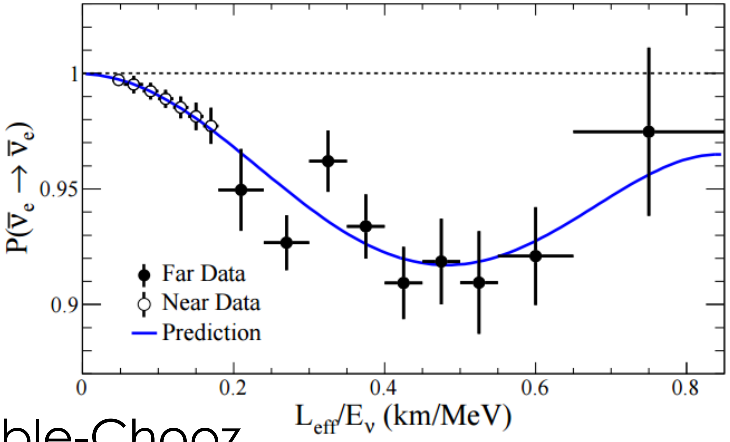


All three experiments with multiple detector

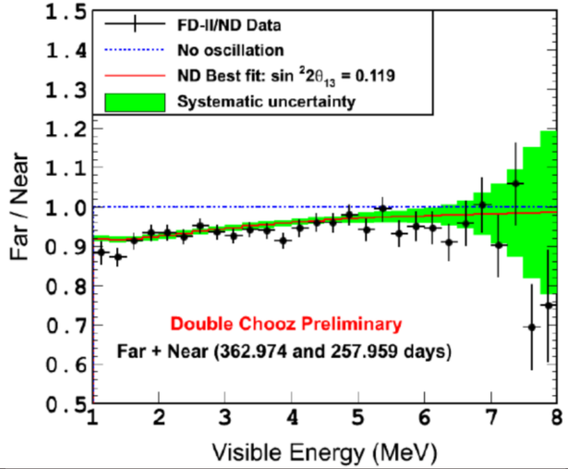
Daya Bay (arXiv:1610.04802)



RENO (arXiv:1610.04326)

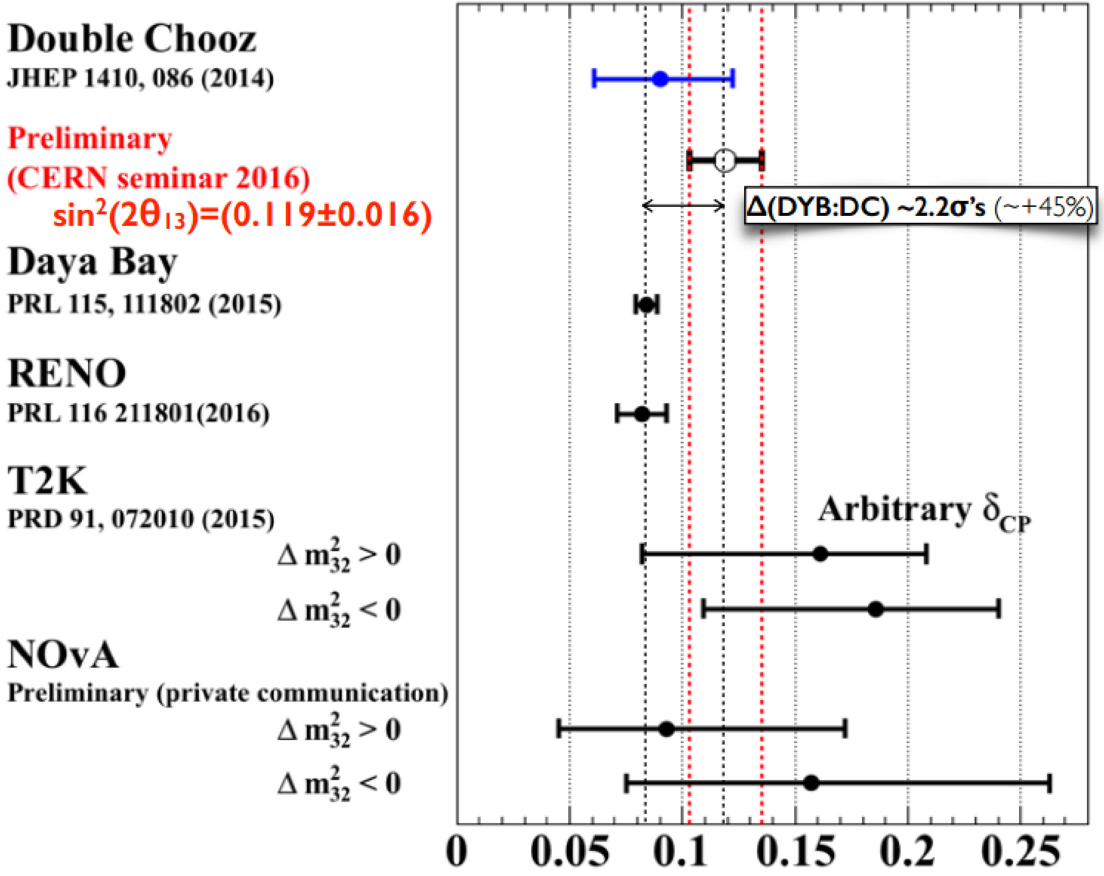


Double-Chooz



CERN seminar,
Sep. 2016

Impressive world data on θ_{13}



A. Cabrera, DC release talk, 09-20-2016

Daya Bay, RENO, and Double Chooz are now sitting together (first meeting Oct 2016) and discussing combined analysis

Open questions

- ~~What's the last mixing angle θ_{13}?~~
- What is the mass ordering of neutrinos?
- What's the absolute energy scale of the neutrinos?
- Is neutrino Majorana particle?
- Is there CP violation in the lepton sector?
- Are neutrino flavor > 3?

Open questions

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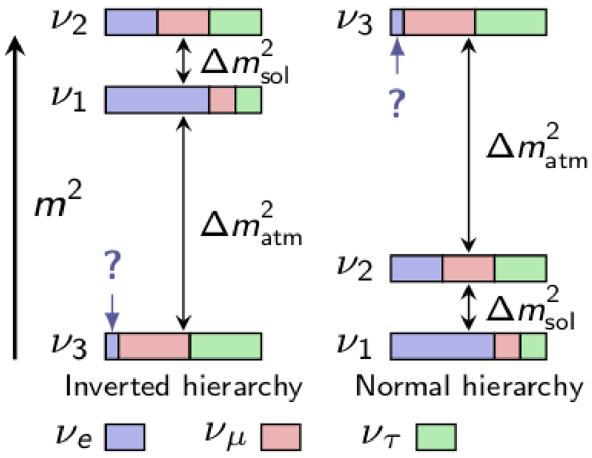
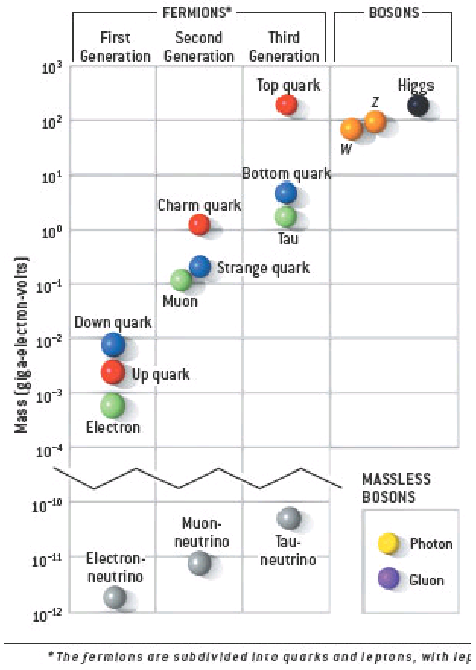
Mass hierarchy?

- $|\Delta m_{31}^2| = 2.4\times10^{-3}\ \mathrm{eV}^2$, $\Delta m_{21}^2 = 7.5\times10^{-5}\ \mathrm{eV}^2$
- Mass hierarchy:

  Is m_1 the lightest (normal) or m_3 the lightest (inverted)?
- Can loosely translate to: is electron neutrino the lightest?





Connection with flavor models

- Consequences for $M_\nu = U_{\mathrm{PMNS}}\, M_\nu^{\mathrm{diag}}\, U_{\mathrm{PMNS}}^T$ (to leading order)

$$M_\nu \simeq \begin{pmatrix} \varepsilon & \varepsilon & \varepsilon \\ \varepsilon & 1 & 1 \\ \varepsilon & 1 & 1 \end{pmatrix}$$

Hierarchy: normal

$$M_\nu \simeq \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 1 \\ 0 & 1 & 1 \end{pmatrix}$$

Hierarchy: inverted

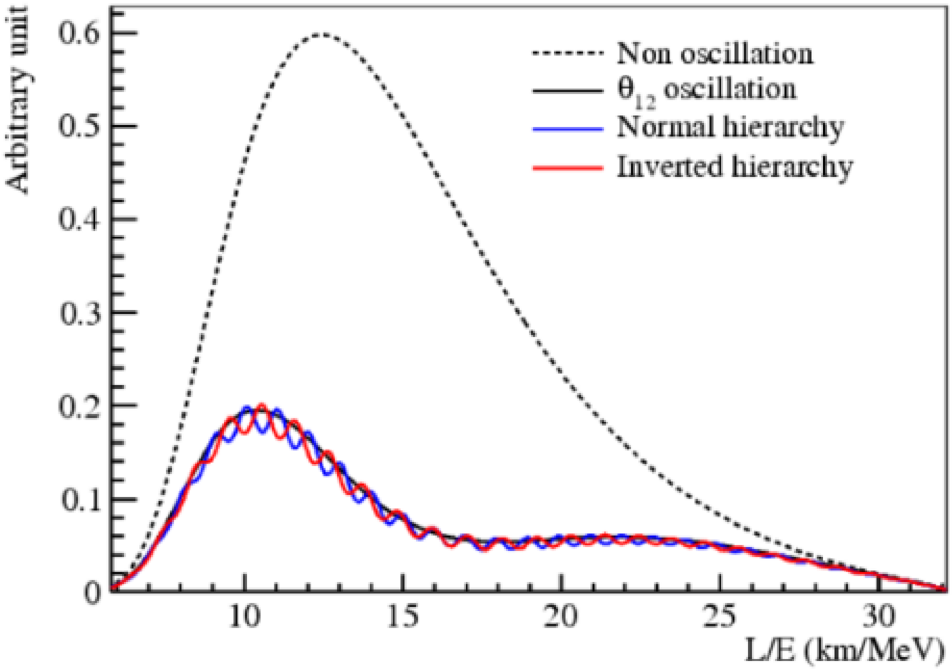
$$M_\nu \simeq \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Degenerate case

- **Very different structure of neutrino mass matrix!**
  Model discriminator (flavor models)

JUNO experiment

$$P(\nu_e \to \nu_e) = 1 - \boxed{\sin^2 2\theta_{13}}(\cos^2\theta_{12}\boxed{\sin^2\Delta_{31}} + \sin^2\theta_{12}\boxed{\sin^2\Delta_{32}}) - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{12}$$

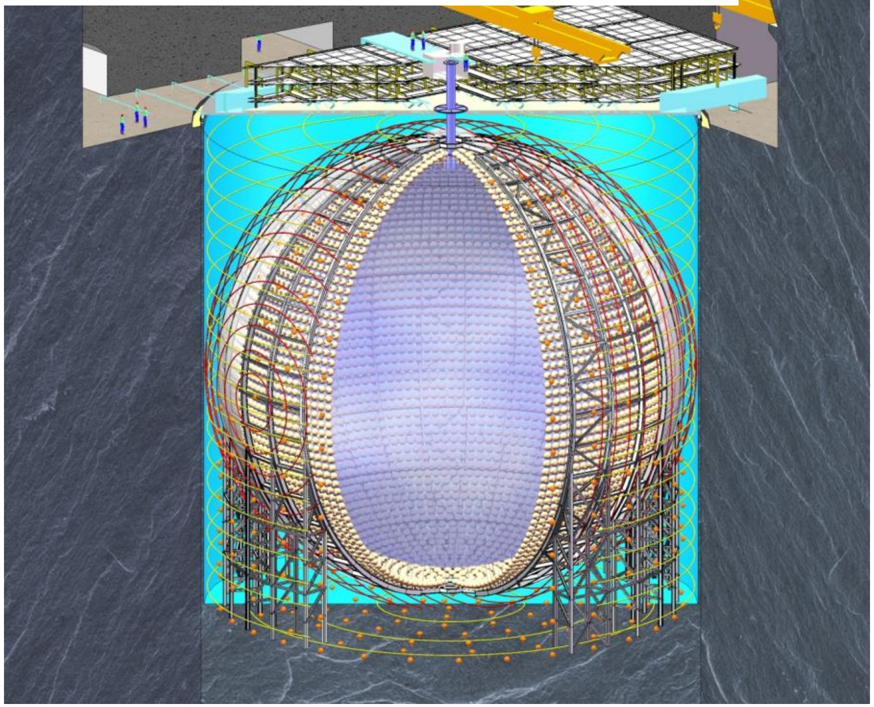


- 20k-ton multi-purpose LS detector
- Construction phase: 2013-2020
- 66 institutes, 444 collaborators

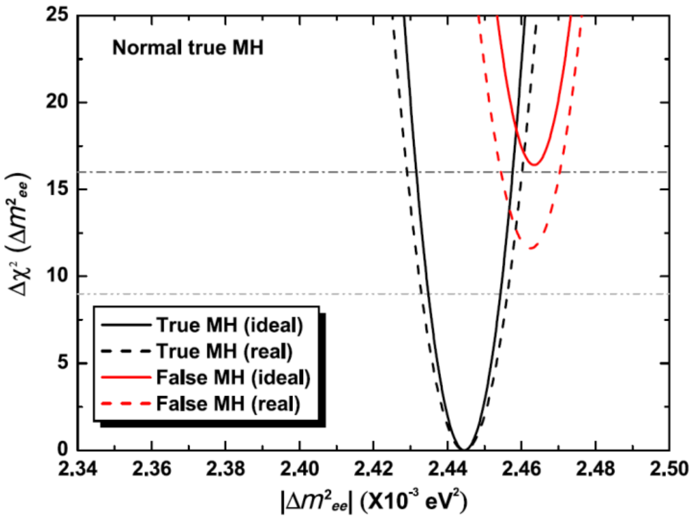
JUNO experiment

Schedule:

Civil preparation：2013-2014
Civil construction：2014-2017
Detector component production：2016-2017
Detector assembly & installation：2018-2019
Filling & data taking：2020

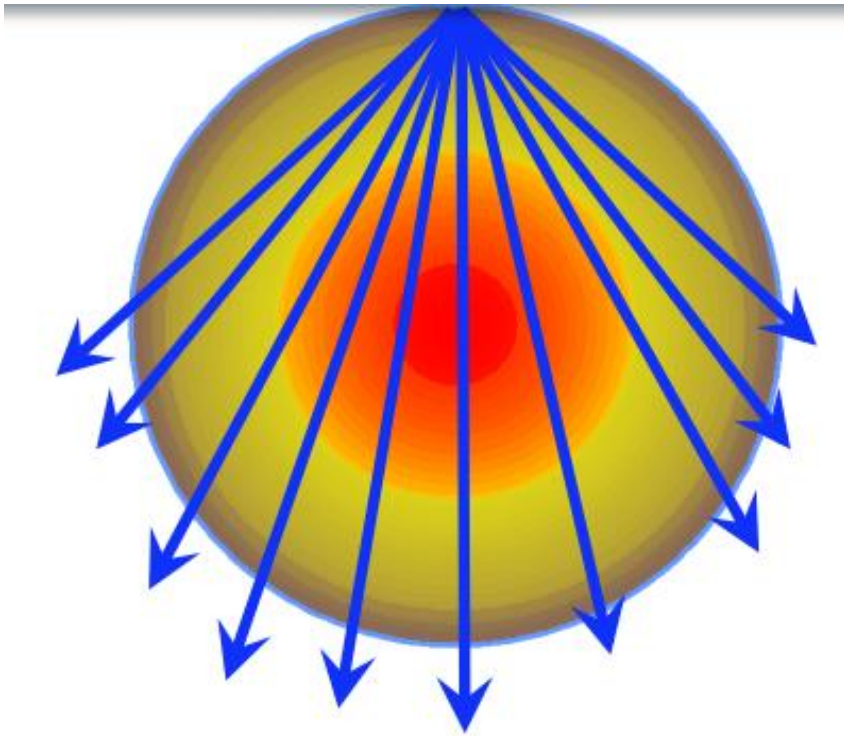


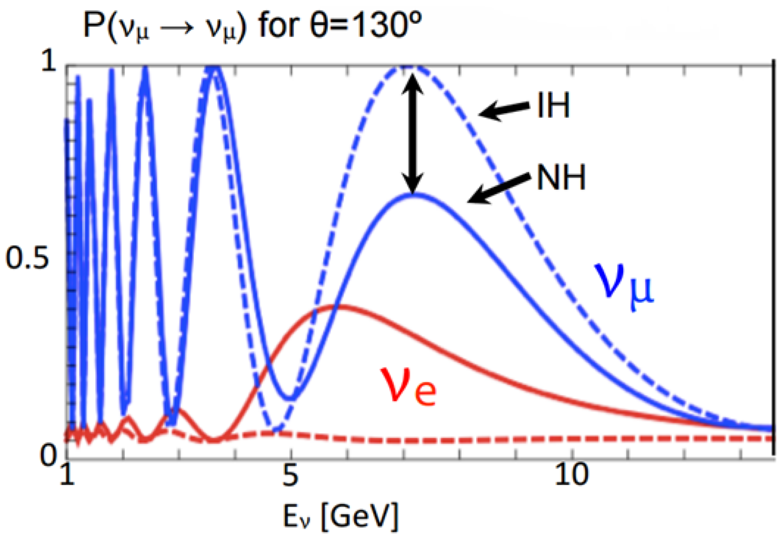
- 27-36 GW reactor power, 20k ton LS detector
- **3%/√E** energy resolution, **<1%** energy scale uncertainty
- >3σ (4σ) 6-years MH determination JUNO-alone (JUNO+accelerator exps)



Atmospheric neutrino experiments

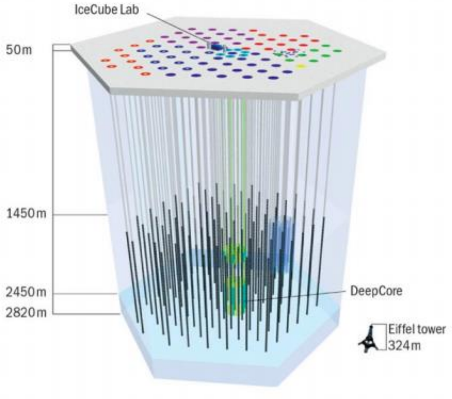
- Wide range of baselines and energy
- Oscillation pattern altered by the matter effects
- Tracking and energy reconstruction important

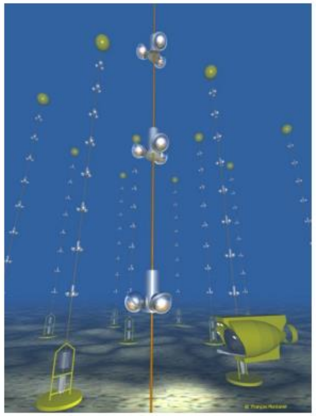




Atmospheric neutrino experiments

IceCube





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INO

PINGU

Precision IceCube Next Generation Upgrade

- Denser array
- Low energy threshold ~ 1-3 GeV

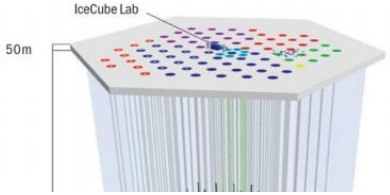
ORCA

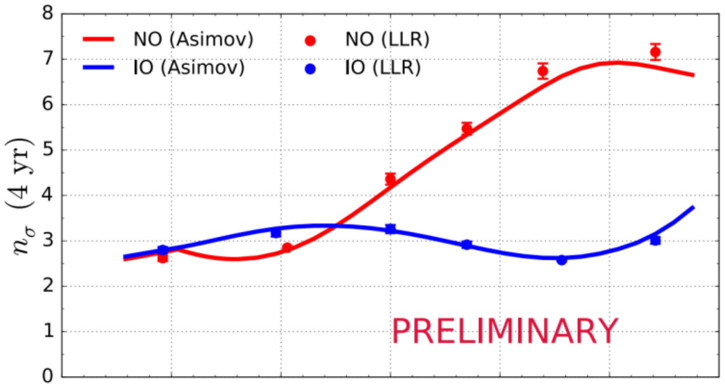
KM3NeT

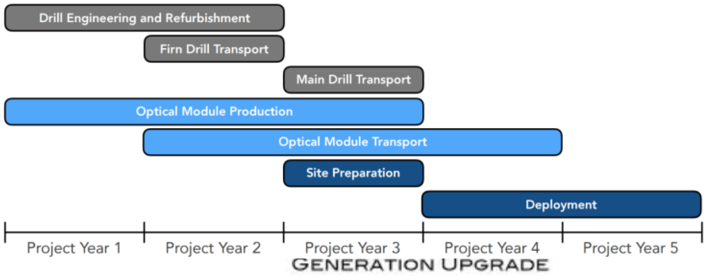
Oscillation Research with Cosmics with the Abyss

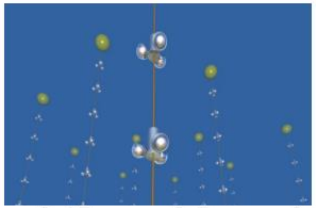
ORCA

Atmospheric neutrino experiments









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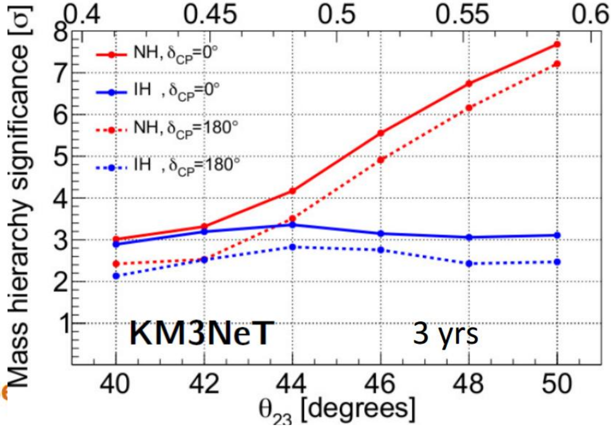
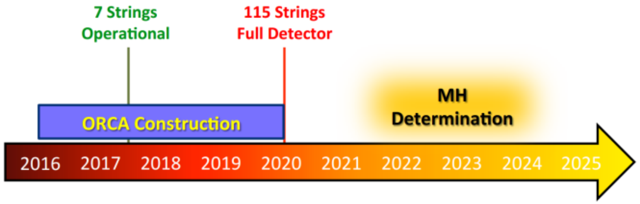
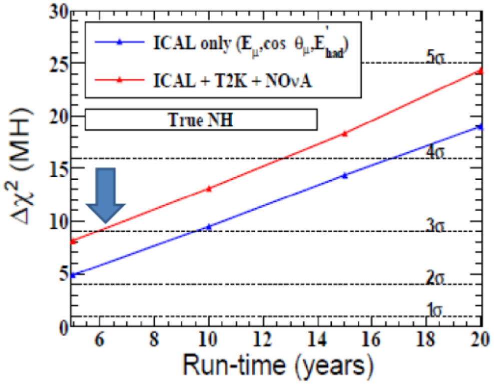
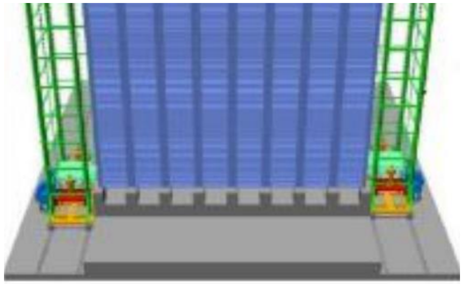




Cosmics with the Abyss

INO





Open questions

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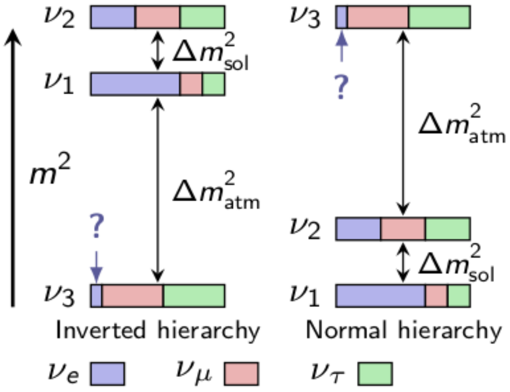
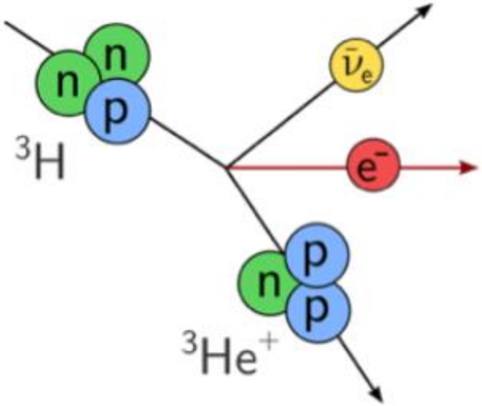
Effective electron neutrino mass

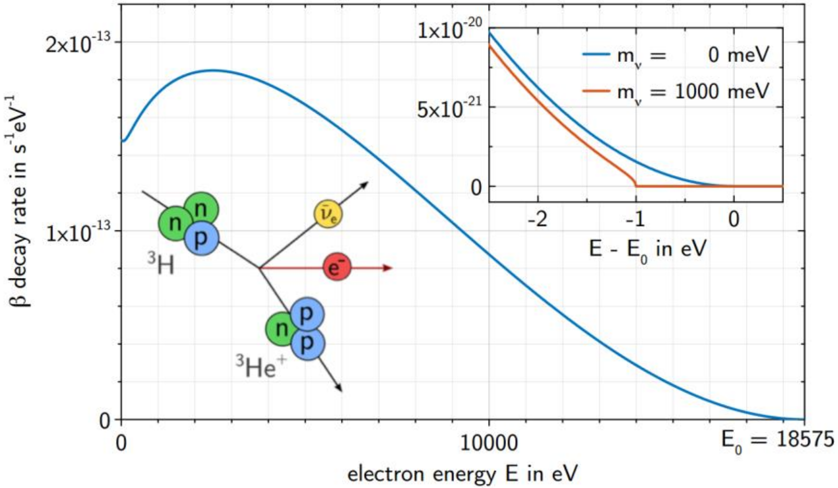


$\Sigma m_\nu > 58\ mV$ $\Sigma m_\nu > 100\ mV$

$$\langle m \rangle_e \equiv \sqrt{\sum_i \left(m_i^2 |U_{ei}|^2\right)}$$

Even the lightest mass eigenstate is zero, the effective flavor mass is non-zero

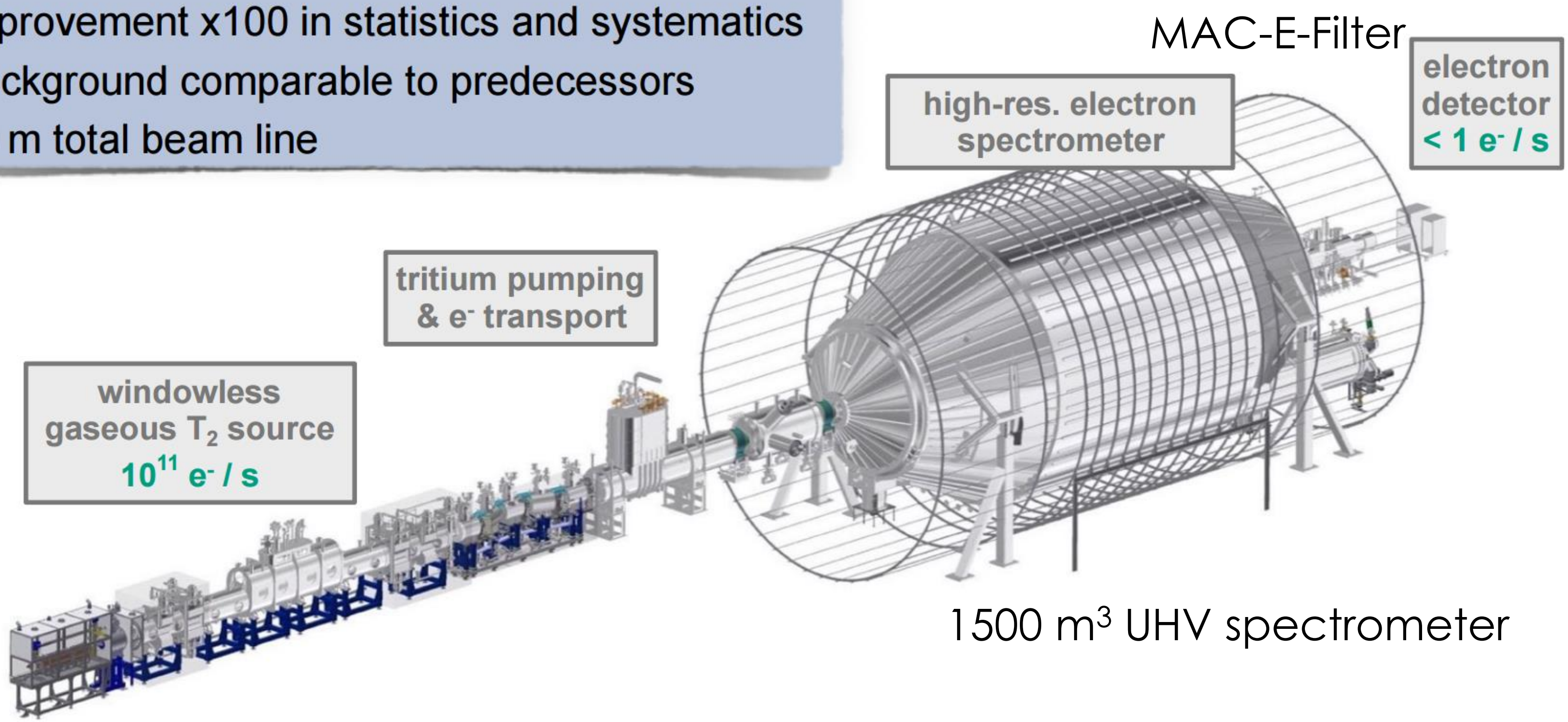




KATRIN experiment

Sensitivity: 2 eV ➜ 0.2 eV

- Improvement x100 in statistics and systematics
- Background comparable to predecessors
- 70 m total beam line



MAC-E-Filter

high-res. electron spectrometer

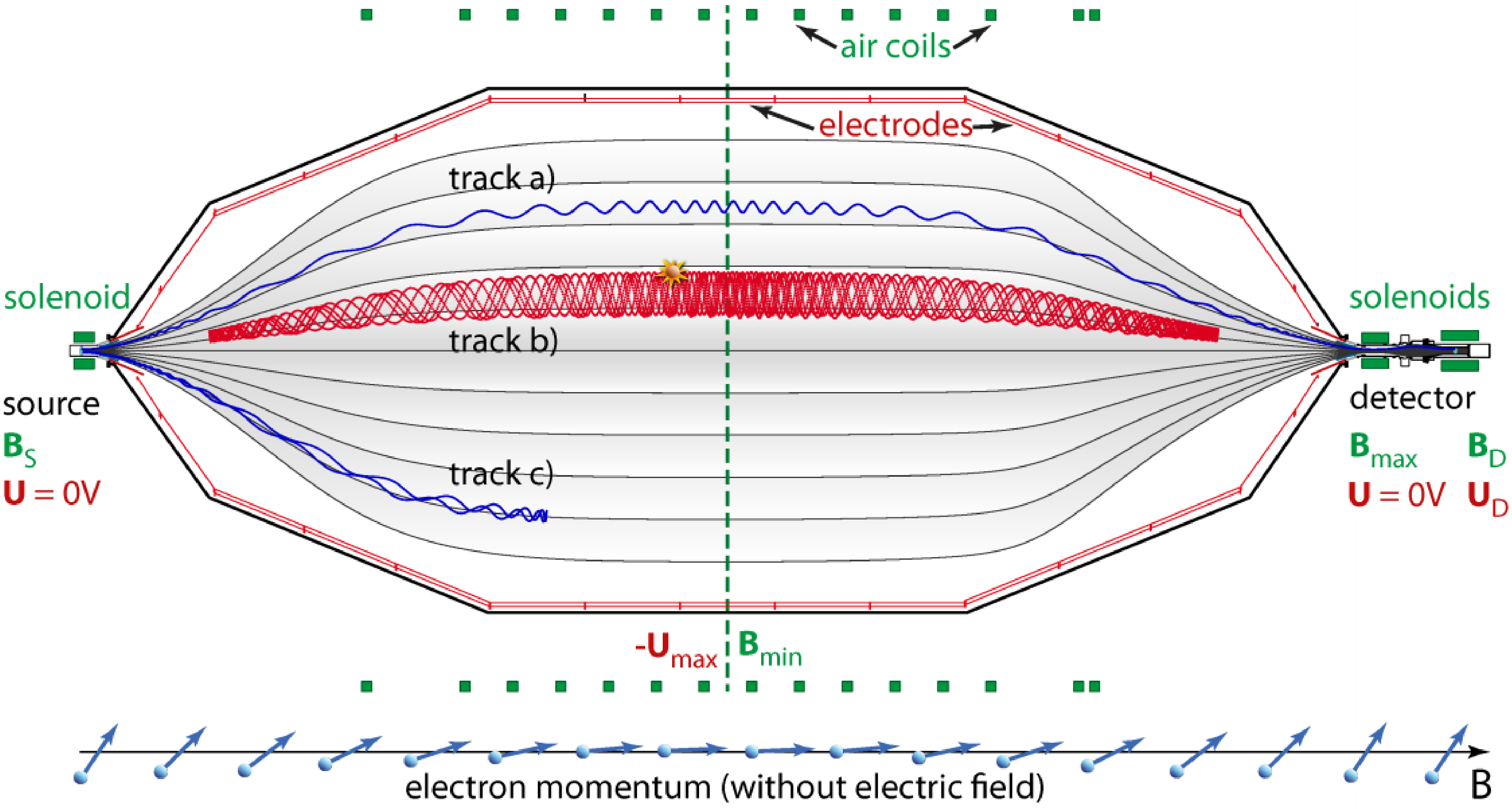
electron detector $< 1\ e^- / s$

tritium pumping & e^- transport

windowless gaseous T_2 source $10^{11}\ e^- / s$

1500 m^3 UHV spectrometer

MAC-E-Filter


air coils
electrodes
track a)
track b)
track c)
solenoid
source
B_S
$U = 0V$
solenoids
detector
B_{max}
B_D
$U = 0V$
U_D
$-U_{max}$
B_{min}
electron momentum (without electric field)
B

KATRIN Experiment

KATRIN
Karlsruhe
Tritium
Neutrino
Experiment

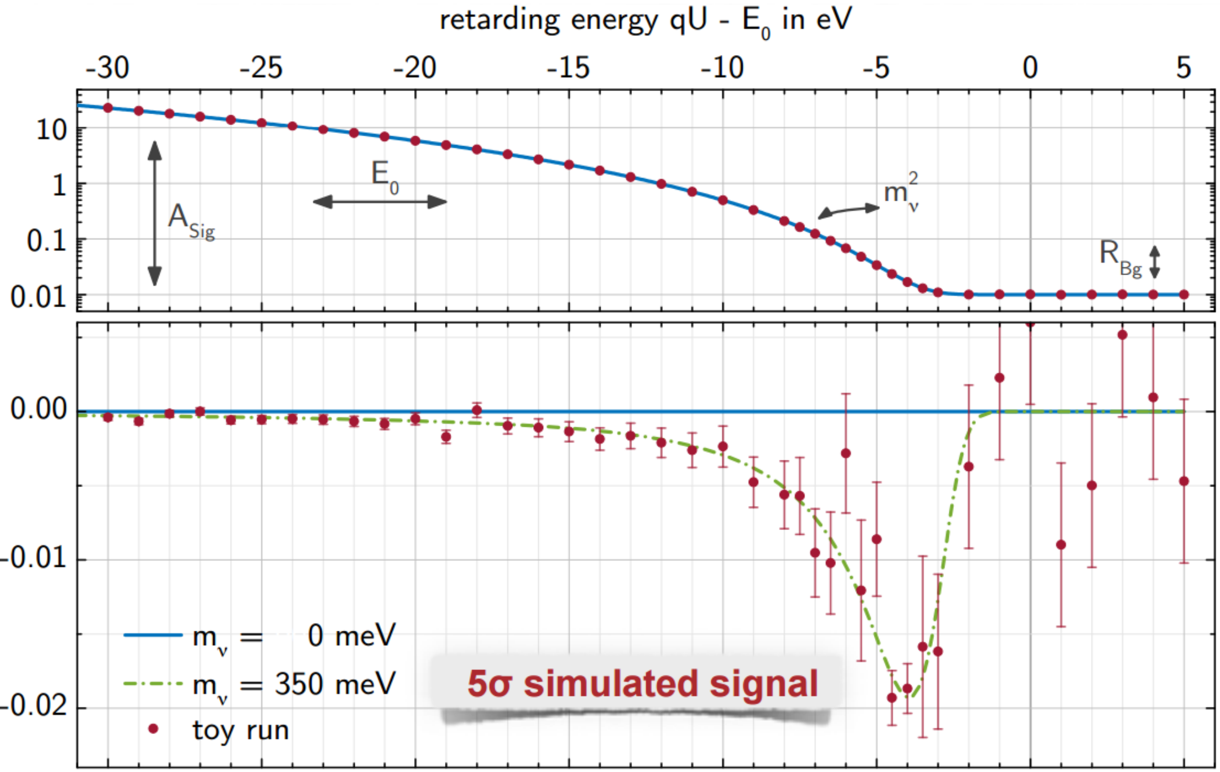
Source and transport systems

- Test of source beamtube cooling system
- Completion of closed tritium loops
- Cold commissioning of full source beamline: first with D2(T2)

Full system integration

- Final commissioning of spectrometer & detector section
- "First light" planned for autumn 2016
- **First tritium data in 2017**

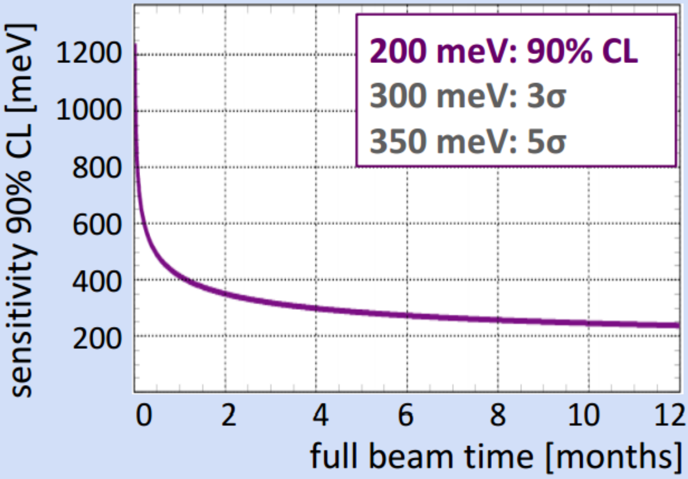
Projection



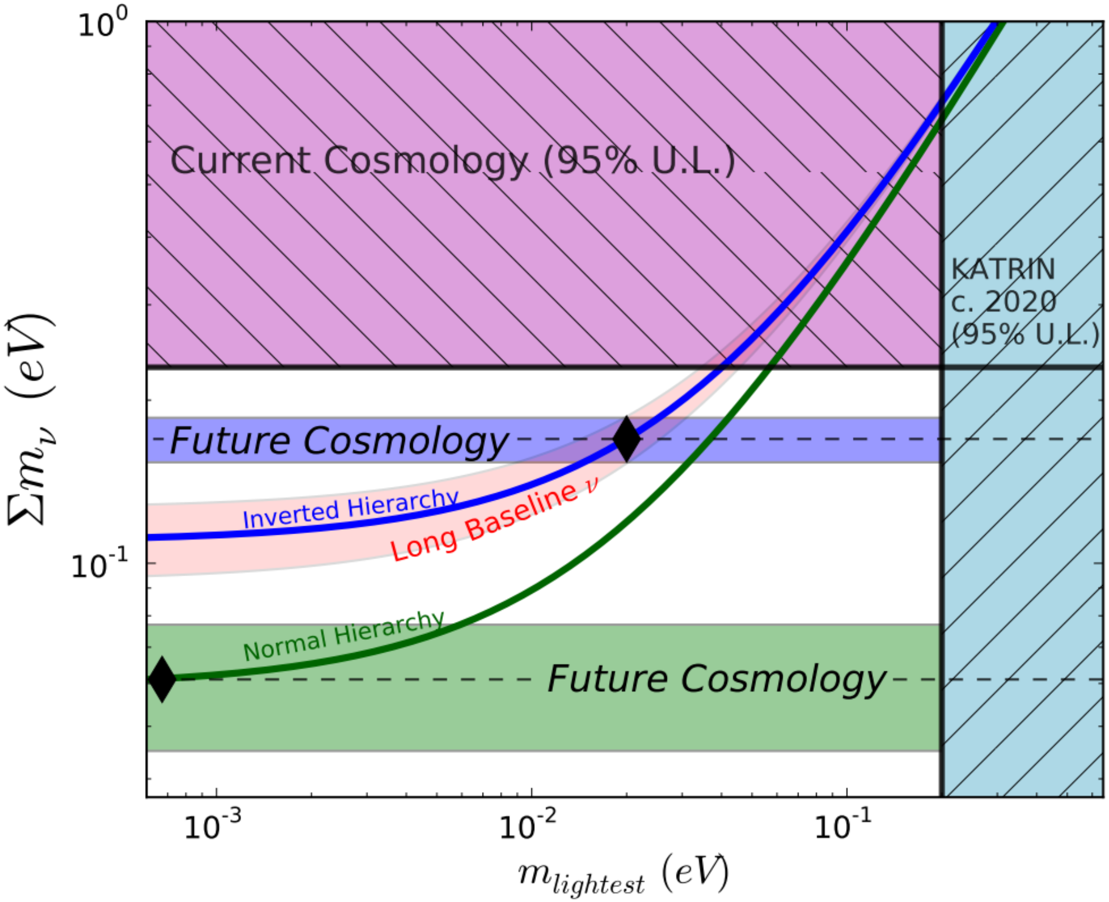
5σ simulated signal

3 yrs (5 cal. yrs) to balance statistics and systematics

at design parameters:



Interplay with cosmology



arXiv: 1309.5383
Future cosmology combing number of surveys leading to uncertainty of 16 meV!

- Gravitational lensing in CMB
- Baryon acoustic oscillation
- Weak lensing of the galaxy

Open questions

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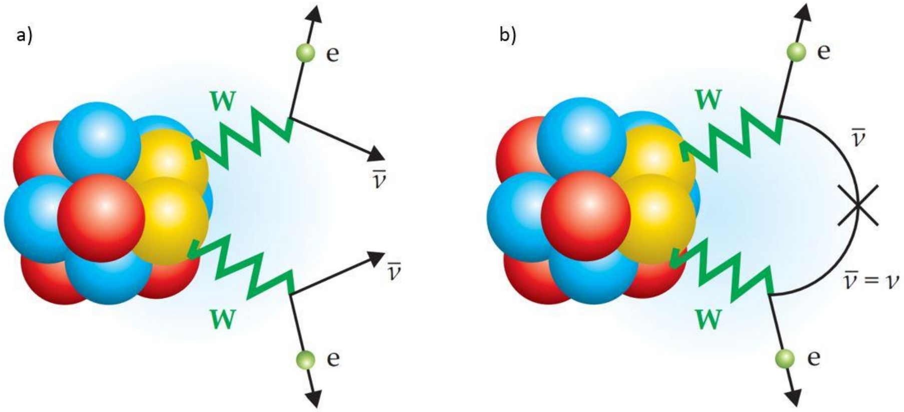
Majorana particles

Majorana mass term:

$$m_R \overline{\nu_R^{C}} \nu_R$$

- Majorana, 1937
- Can be tested via neutrinoless double β decay, W. Furry, 1939

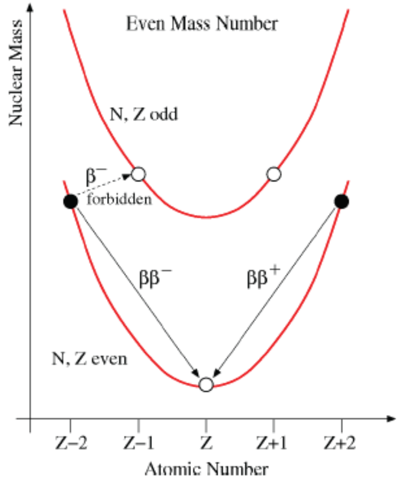
Neutrinoless double beta decay

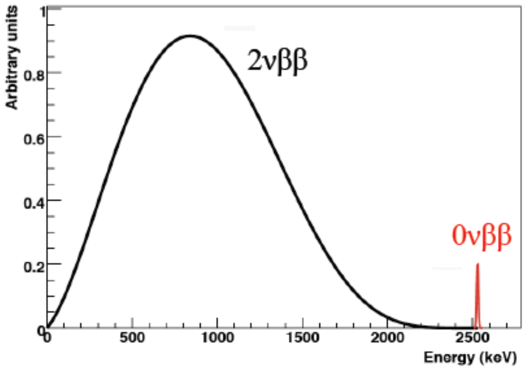


- Neutrinoless double beta decay
  - The nature of neutrinos, Dirac or Majorana
  - lepton number violation
- Extremely rare events T > 10^{24} year.

$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}(Q,Z)\ |M^{0\nu}|^2\ \frac{|\langle m_{\beta\beta}\rangle|^2}{m_e^2}$$

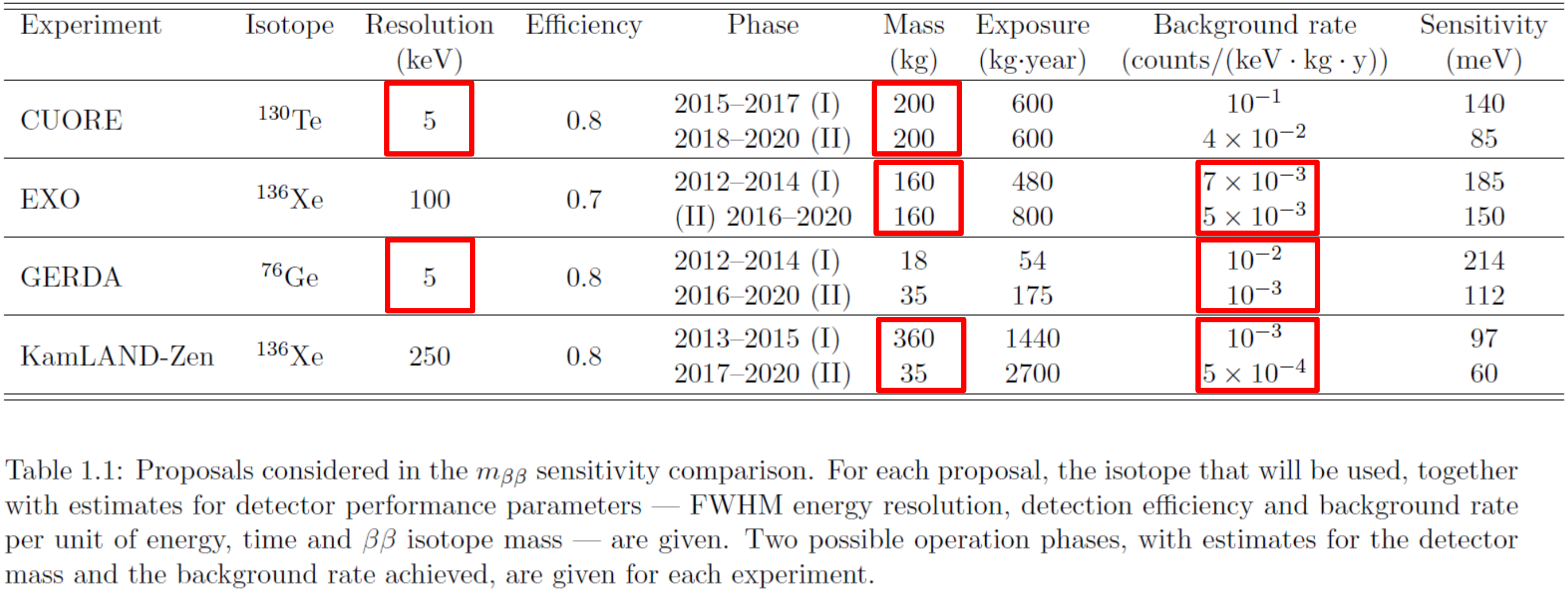
$$m_{\beta\beta} \equiv \left|\sum_{i=1}^{3} U_{ei}^2\, m_i\right| .$$





Sum of electrons energy

Front runners



Experiment	Isotope	Resolution (keV)	Efficiency	Phase	Mass (kg)	Exposure (kg·year)	Background rate (counts/(keV · kg · y))	Sensitivity (meV)
CUORE	^{130}Te	5	0.8	2015–2017 (I)	200	600	10^{-1}	140
				2018–2020 (II)	200	600	4×10^{-2}	85
EXO	^{136}Xe	100	0.7	2012–2014 (I)	160	480	7×10^{-3}	185
				(II) 2016–2020	160	800	5×10^{-3}	150
GERDA	^{76}Ge	5	0.8	2012–2014 (I)	18	54	10^{-2}	214
				2016–2020 (II)	35	175	10^{-3}	112
KamLAND-Zen	^{136}Xe	250	0.8	2013–2015 (I)	360	1440	10^{-3}	97
				2017–2020 (II)	35	2700	5×10^{-4}	60

Table 1.1: Proposals considered in the $m_{\beta\beta}$ sensitivity comparison. For each proposal, the isotope that will be used, together with estimates for detector performance parameters — FWHM energy resolution, detection efficiency and background rate per unit of energy, time and $\beta\beta$ isotope mass — are given. Two possible operation phases, with estimates for the detector mass and the background rate achieved, are given for each experiment.

Front runners

Experiment	Isotope	Resolution (keV)	Efficiency	Phase	Mass (kg)	Exposure (kg·year)	Background rate (counts/(keV · kg · y))	Sensitivity (meV)
				2015–2017 (I)	200	600	10^{-1}	140
				2018–2020 (II)	200	600	4×10^{-2}	85

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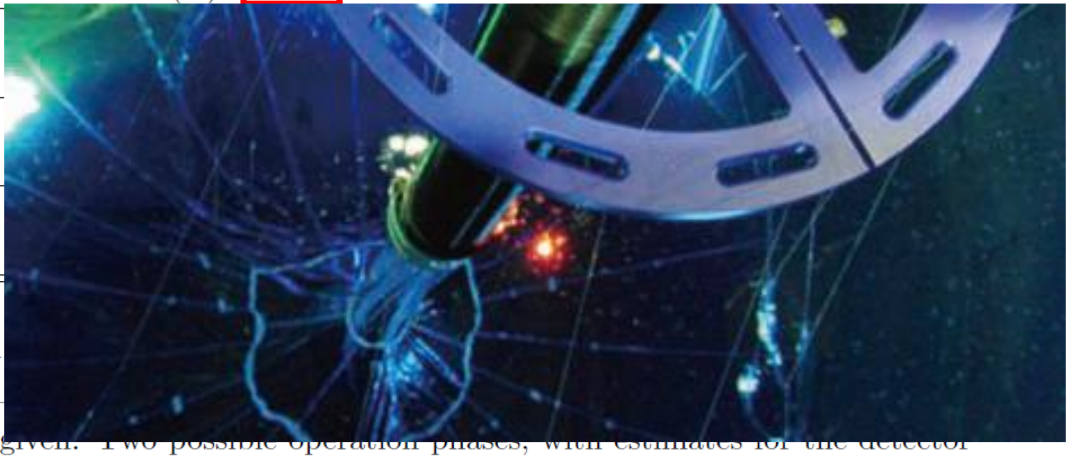
s –

e given. Two possible operation phases, with estimates for the detector

for each experiment.

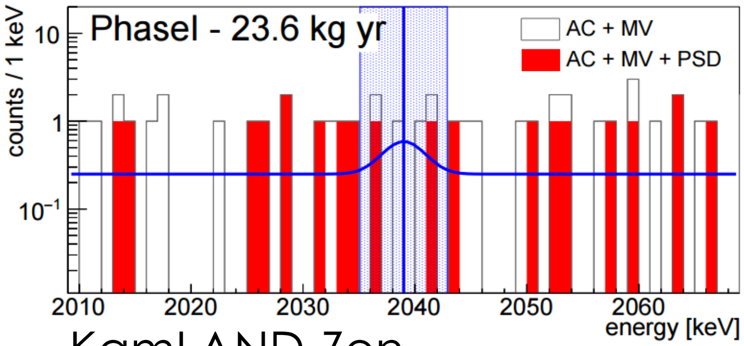


GERDA, ^{76}Ge

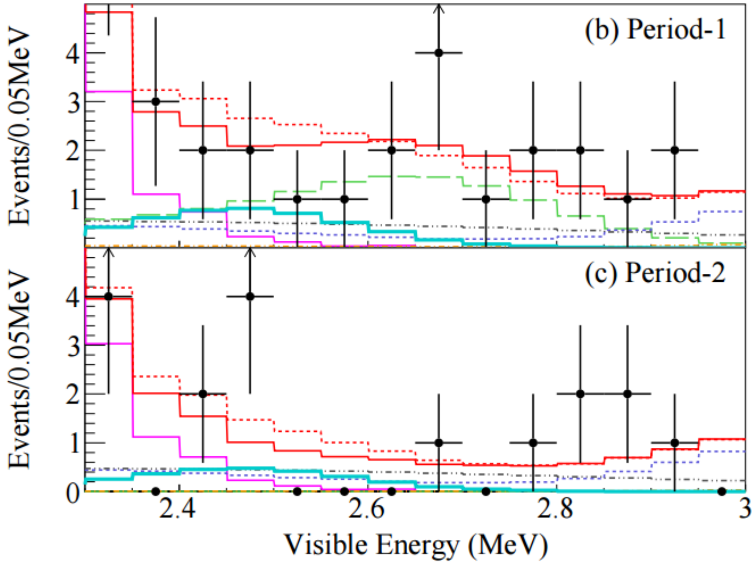
KamLAND-Zen, ^{136}Xe

Constraints from non-discovery

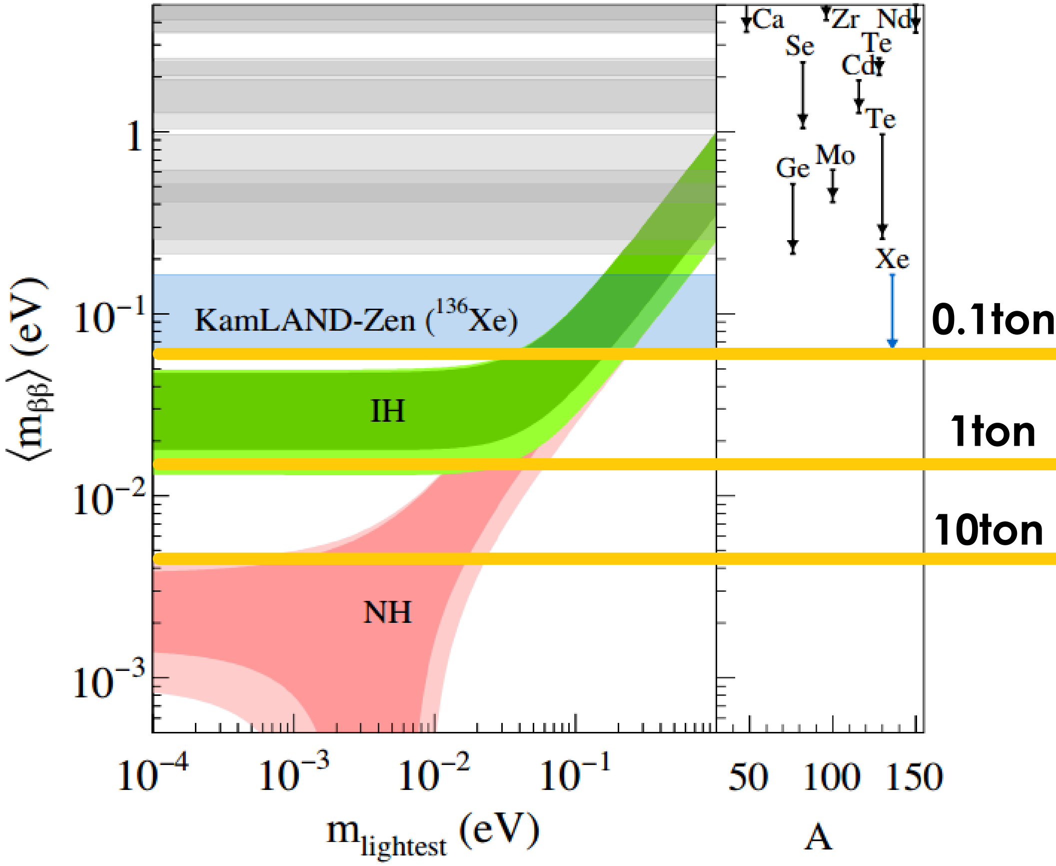
GERDA Phase-I



KamLAND-Zen



Phys. Rev. Lett. 117, 082503 (2016)



0.1ton

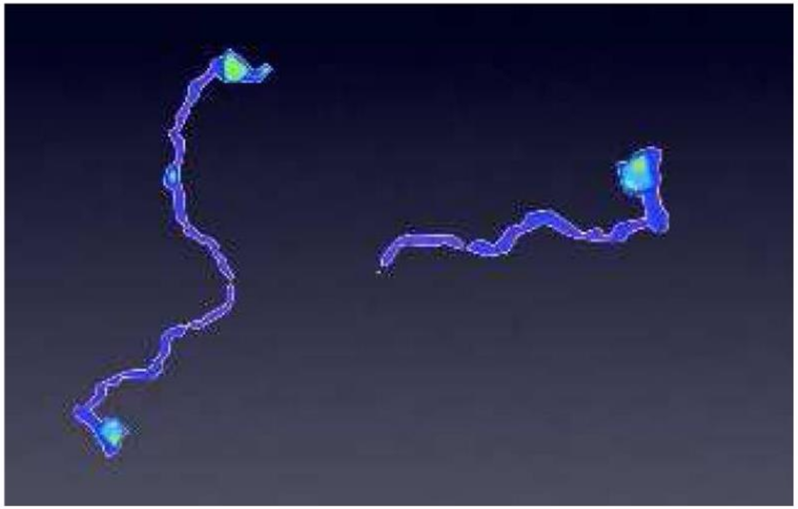
1ton

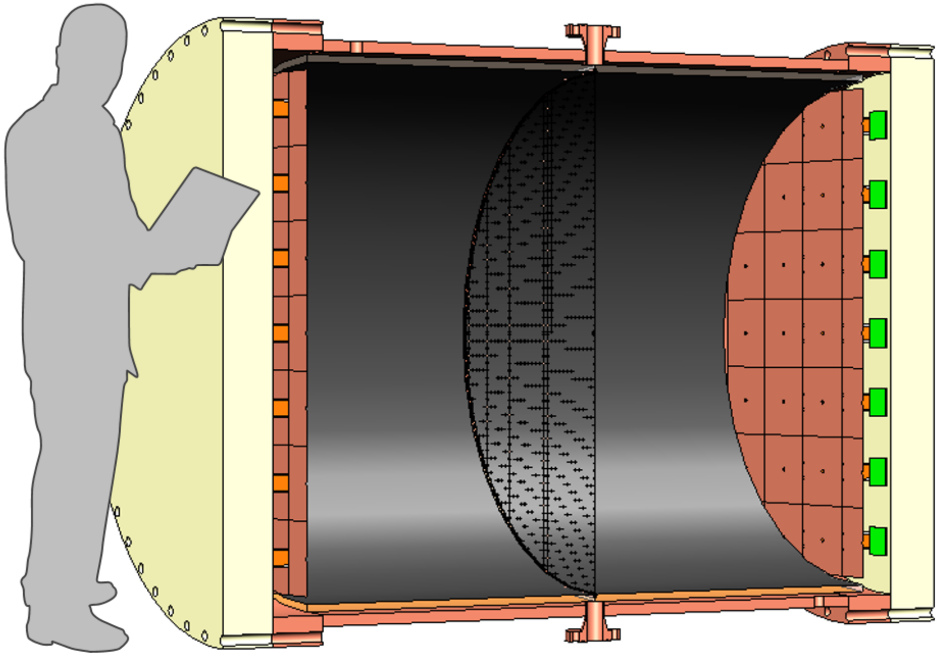
10ton

Gaseous ^{136}Xe

PANDA X

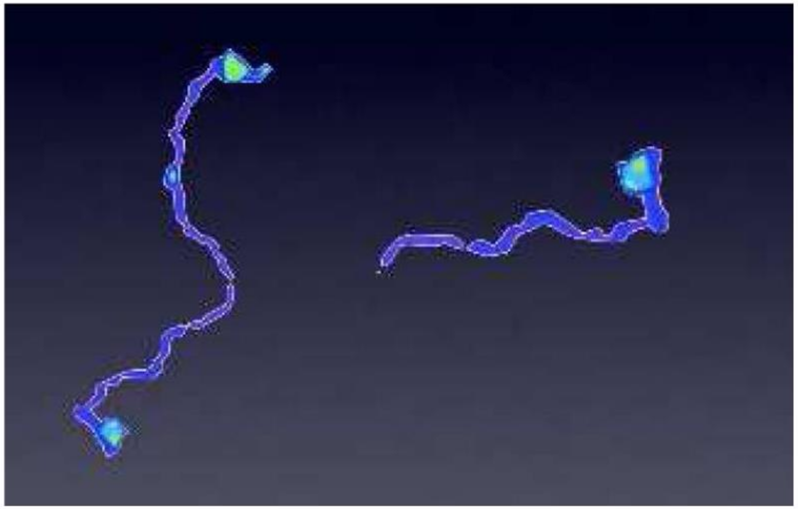
Tracking: smoking guy for discovery



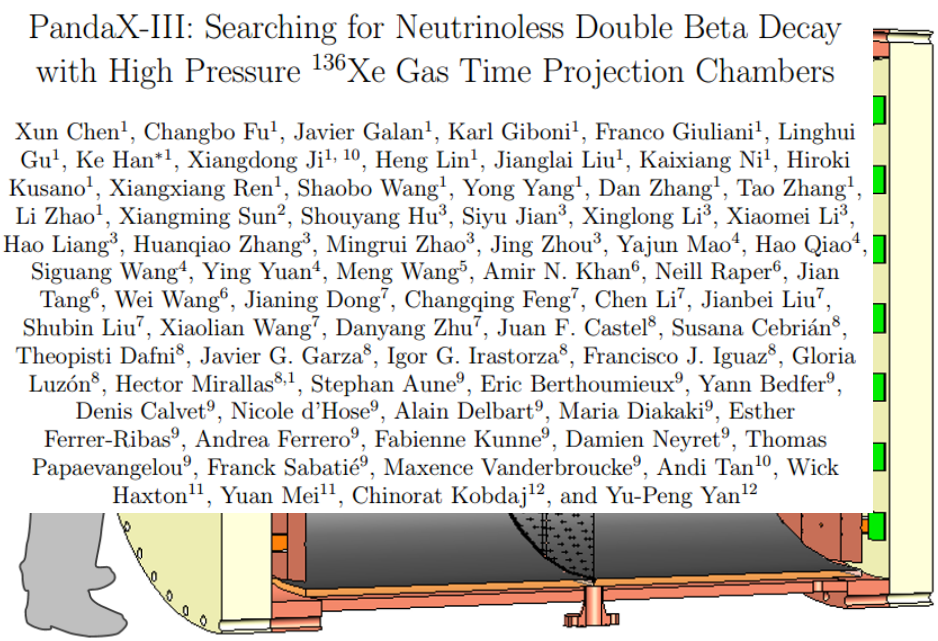


Gaseous ^{136}Xe

Tracking: smoking guy for discovery



arXiv:1610.08883



PandaX-III: Searching for Neutrinoless Double Beta Decay with High Pressure ^{136}Xe Gas Time Projection Chambers

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Open questions

- ~~What’s the last mixing angle θ_{13}?~~
- What is the mass ordering of neutrinos?
- What’s the absolute energy scale of the neutrinos?
- Is neutrino Majorana particle?
- Is there CP violation in the lepton sector?
- Are neutrino flavor > 3?

Long baseline neutrino experiments

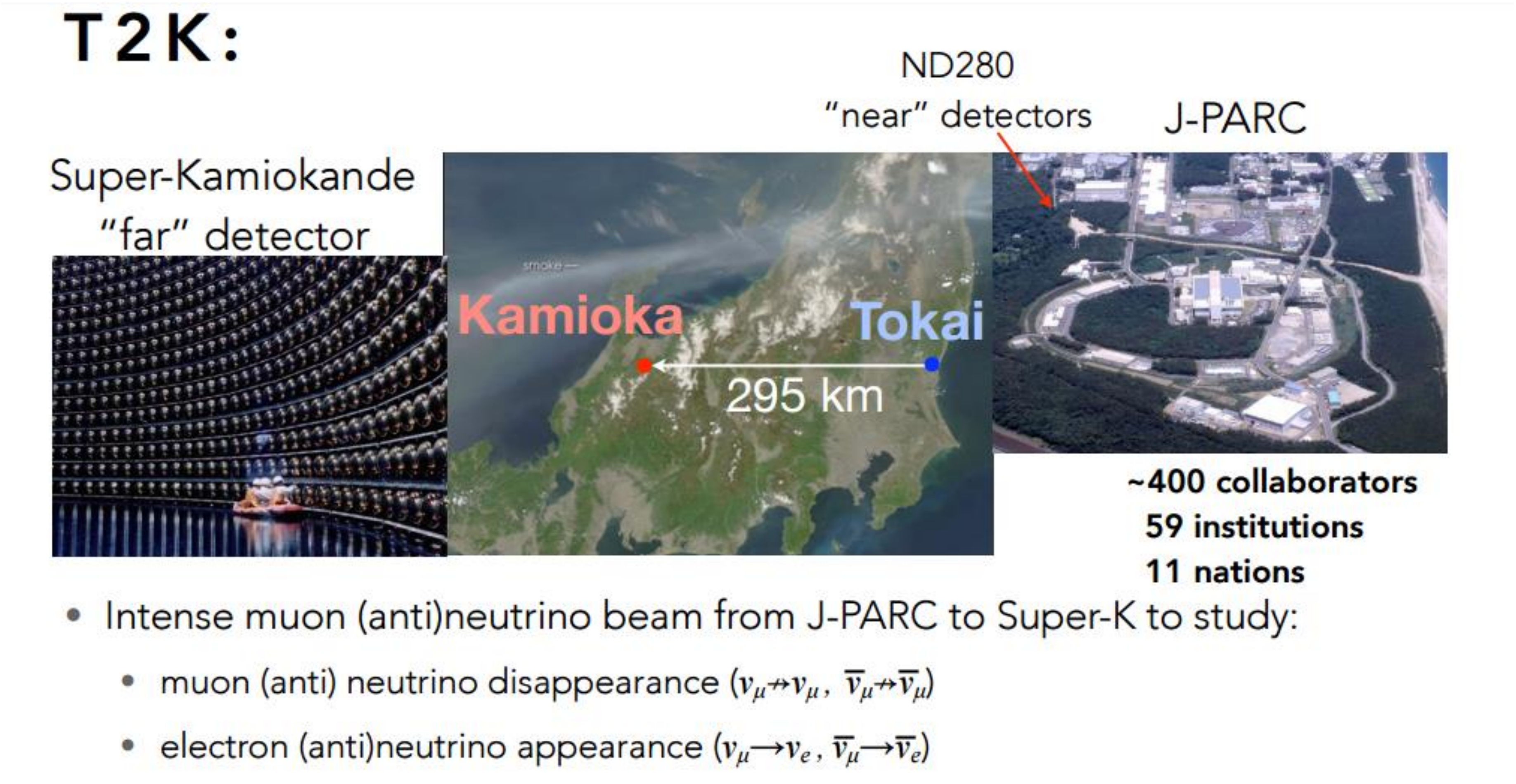
$$
\begin{aligned}
P(\nu_\mu \to \nu_e) \;\sim\; & \boxed{\sin^2 2\theta_{13}} \times \boxed{\sin^2 \theta_{23}} && \times \boxed{\frac{\sin^2[(1-x)\Delta]}{(1-x)^2}} \\
& \boxed{-\alpha \sin\delta} \times \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} && \times \sin\Delta \, \frac{\sin[x\Delta]}{x} \, \frac{\sin[(1-x)\Delta]}{(1-x)} \\
& +\alpha \cos\delta \times \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} && \times \cos\Delta \, \frac{\sin[x\Delta]}{x} \, \frac{\sin[(1-x)\Delta]}{(1-x)} \\
& +\mathcal{O}(\alpha^2)
\end{aligned}
$$

$$
\alpha = \left| \frac{\Delta m^2_{21}}{\Delta m^2_{31}} \right| \sim \frac{1}{30} \qquad \Delta \equiv \frac{\Delta m^2_{31} L}{4E} \qquad \boxed{x \equiv \frac{2\sqrt{2} G_F N_e E}{\Delta m^2_{31}}}
$$

M. Freund, Phys.Rev. D64 (2001) 053003

- $\sin^2 2\theta_{13}$ dependence of leading term
- θ_{23} dependence of leading term: "octant" dependence (θ_{23}=/>/<45°?)
- CP odd phase δ: asymmetry of probabilities $P(\nu_\mu \to \nu_e) \neq P(\bar{\nu}_\mu \to \bar{\nu}_e)$ if $\sin\delta \neq 0$
- Matter effect through x: ν_e ($\bar{\nu}_e$) enhanced in normal (inverted) hierarchy

T2K



T2K:

Super-Kamiokande
"far" detector

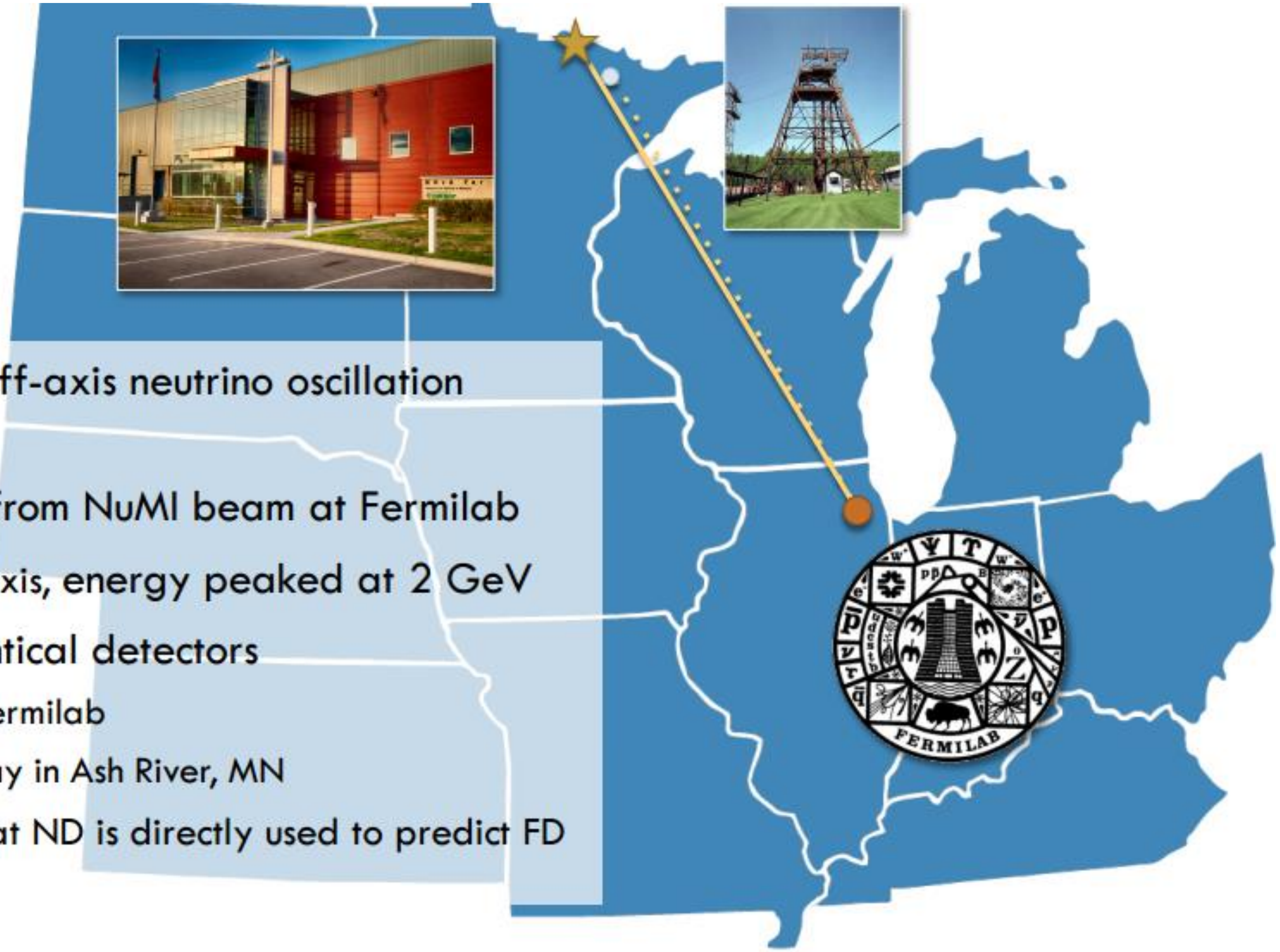
ND280
"near" detectors

J-PARC

~400 collaborators
59 institutions
11 nations

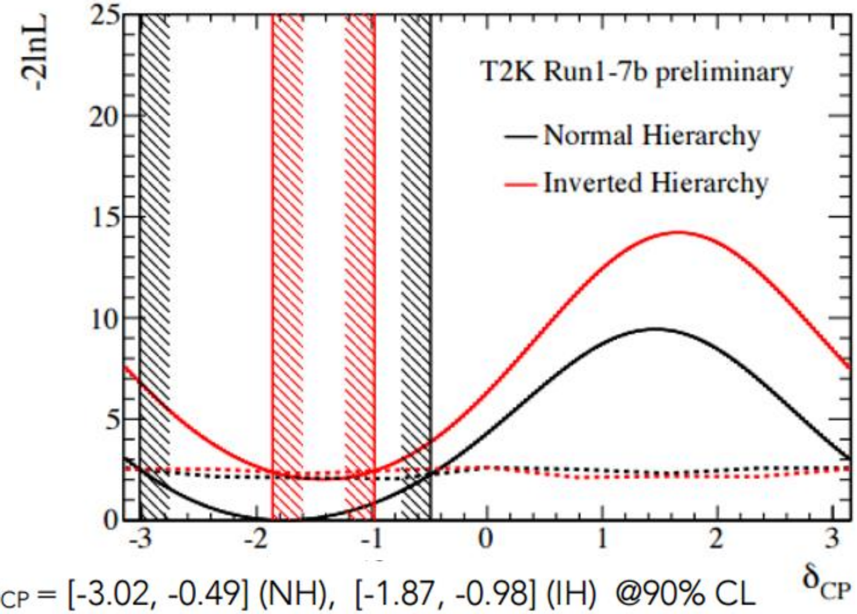
- Intense muon (anti)neutrino beam from J-PARC to Super-K to study:
  - muon (anti) neutrino disappearance ($\nu_\mu \nrightarrow \nu_\mu$, $\bar{\nu}_\mu \nrightarrow \bar{\nu}_\mu$)
  - electron (anti)neutrino appearance ($\nu_\mu \rightarrow \nu_e$, $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$)

NOvA

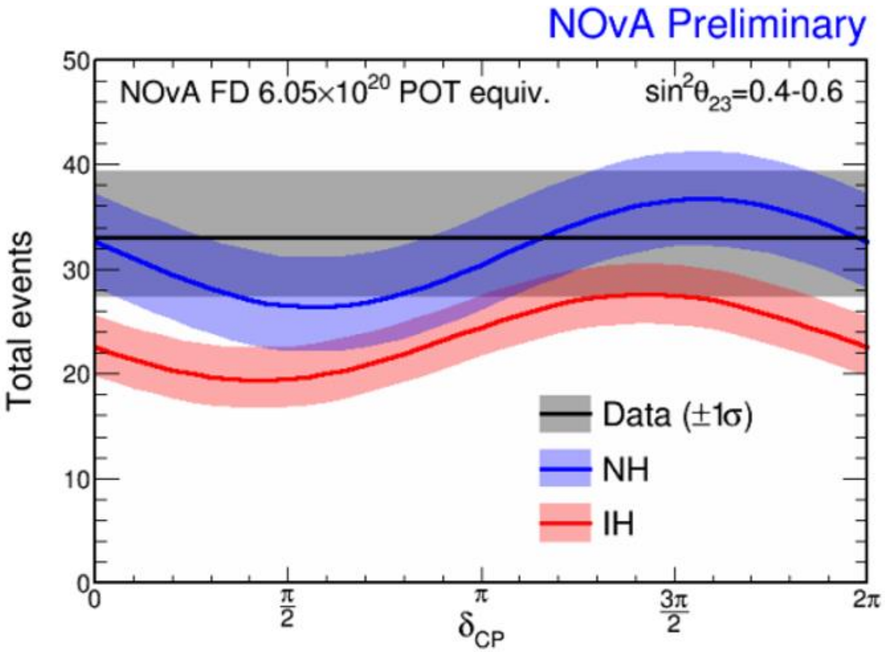


- Long-baseline, off-axis neutrino oscillation experiment
- Study neutrinos from NuMI beam at Fermilab
- At 14 mrad off-axis, energy peaked at 2 GeV
- Functionally identical detectors
  - ND on site at Fermilab
  - FD 810 km away in Ash River, MN
  - Measurement at ND is directly used to predict FD

CP violation angle



δ_{CP} = [-3.02, -0.49] (NH), [-1.87, -0.98] (IH) @90% CL

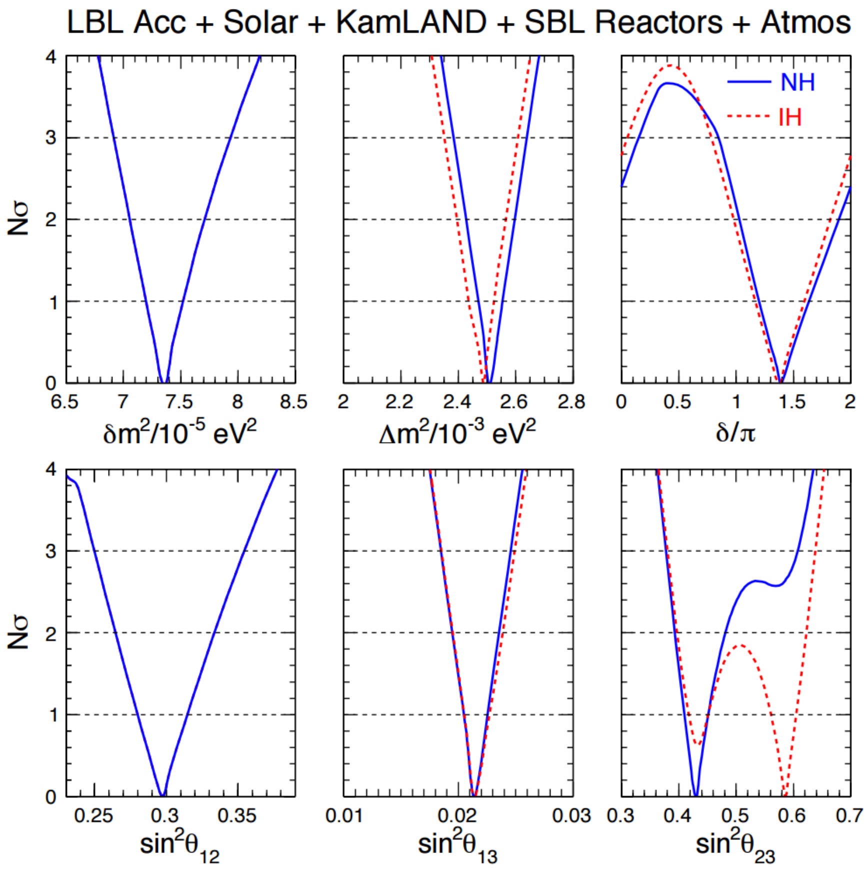


- Global best fit Normal Hierarchy

$$\delta_{CP} = 1.49\pi$$
$$\sin^2(\theta_{23}) = 0.40$$

- best fit IH-NH, $\Delta\chi^2$=0.47

Hints from global fits



A. Marrone, Neutrino 2016

CP phase trend:

- $\delta \sim 1.4\,\pi$ at best fit
- CP-conserving cases $(\delta = 0, \pi)$ disfavored at $\sim 2\sigma$ level or more
- Significant fraction of the $[0,\pi]$ range disfavored at $>3\sigma$

θ_{23} trend:

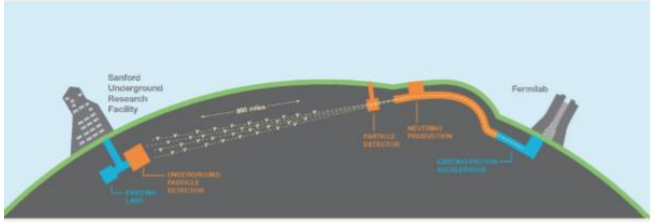
- maximal mixing disfavored at about $\sim 2\sigma$ level
- best-fit octant flips with mass ordering

$$\Delta\chi^2_{\mathrm{IO-NO}} = 3.1$$

inverted ordering slightly disfavored

Next generation of mega detectors moving fast

4x17kT LAr detectors



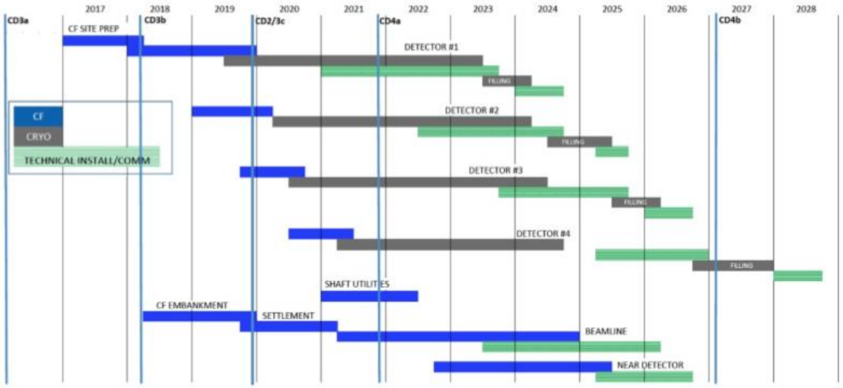
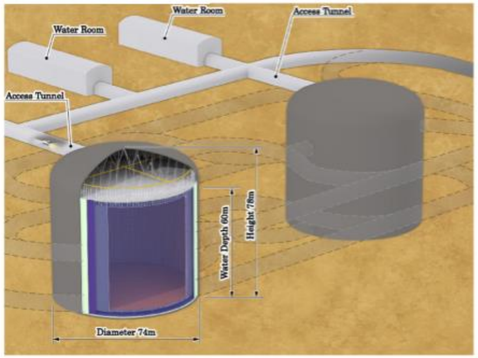
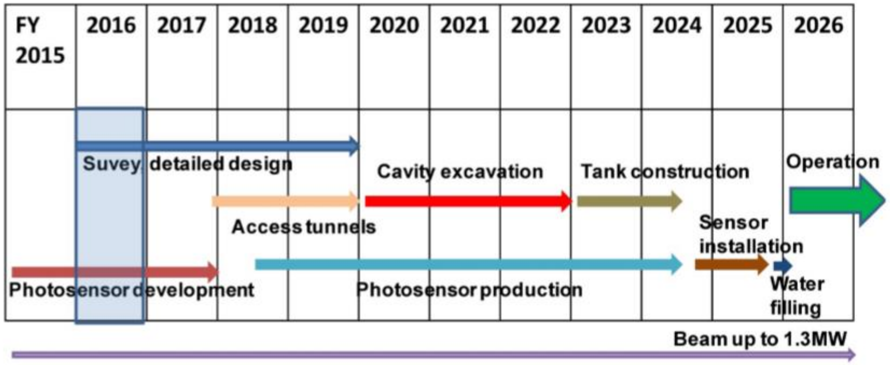


Figure 1.1: High-level

dule

500kton water detector





Open questions

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- What is the mass ordering of neutrinos?
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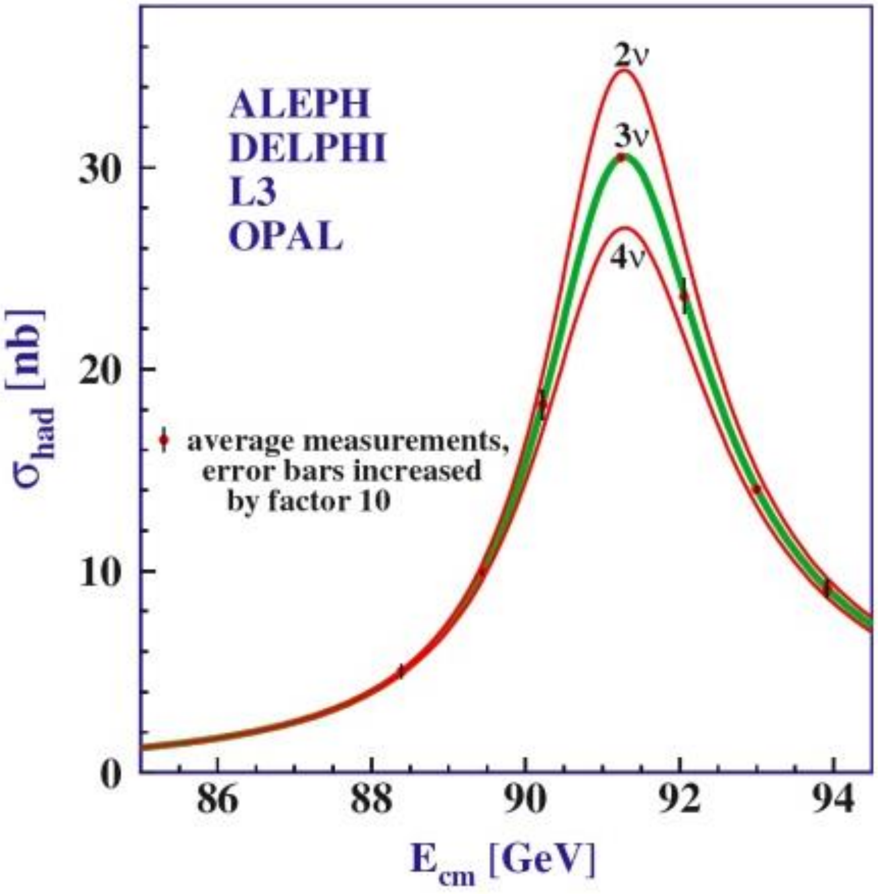
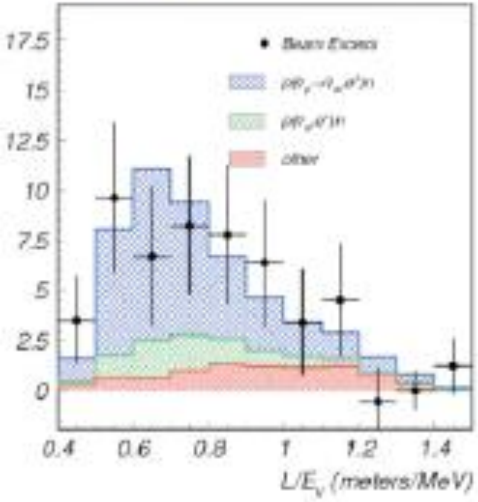
Number of active neutrino flavors



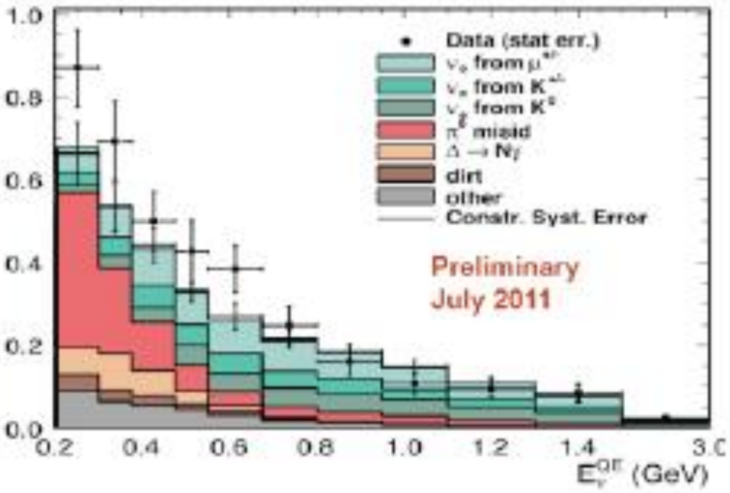
- A heavier type which can be heavier than Z
- Or a type of neutrino that DOES NOT participate in weak interactions ("sterile")
  - However, they can still "mix" with regular ones (quantum mechanics still works)

Anomalies

LSND

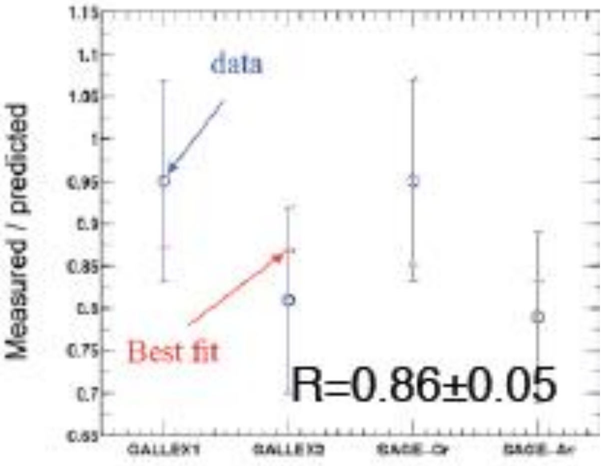


MiniBoone



Preliminary
July 2011

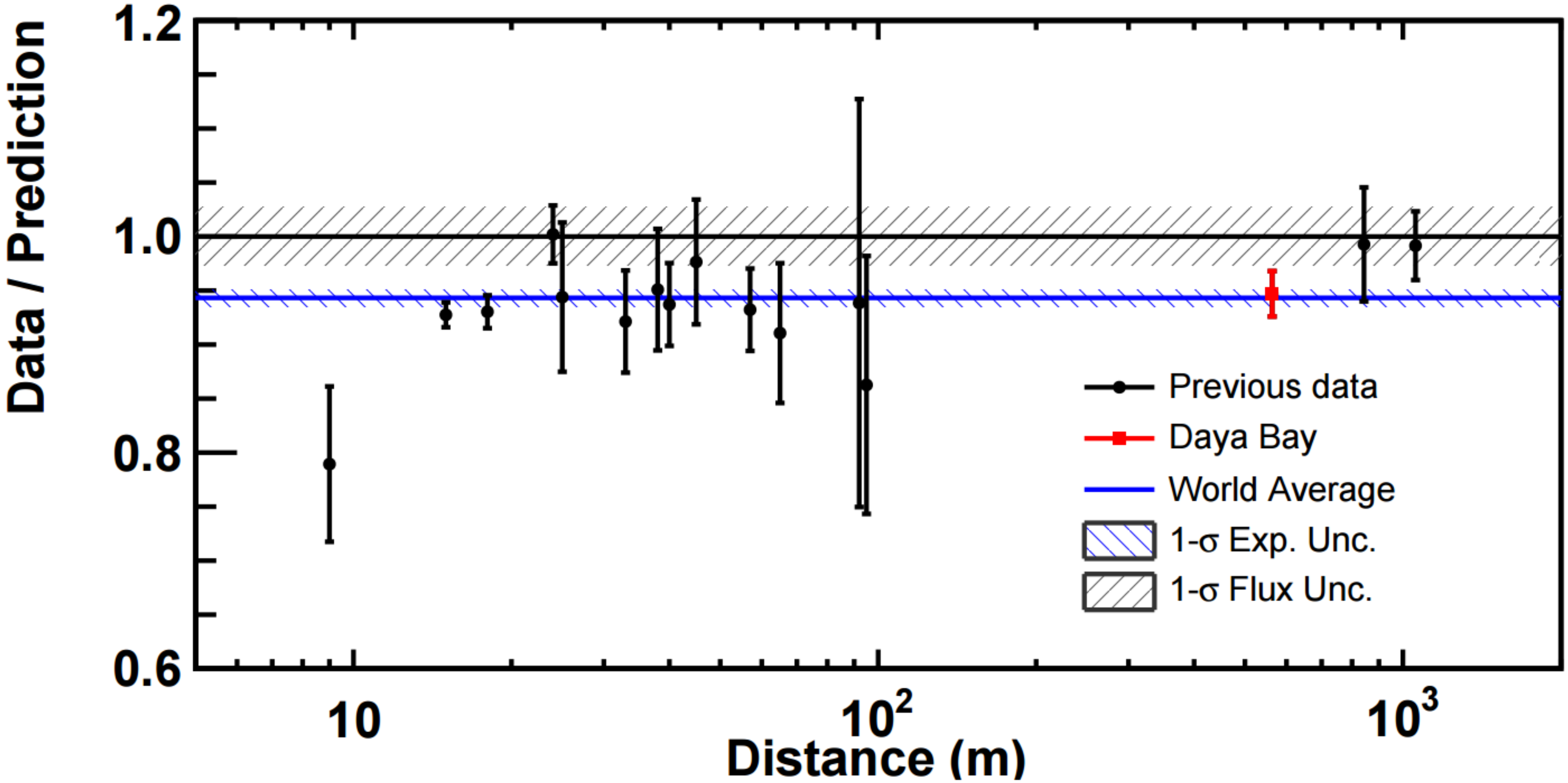
Ga Anomaly



R=0.86±0.05

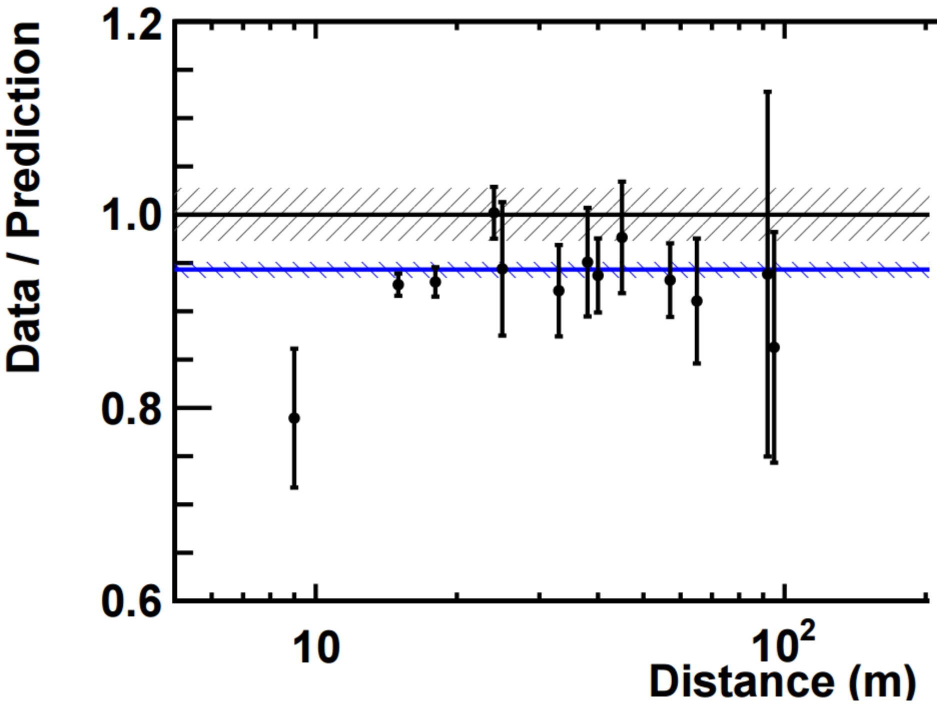
Anomalies

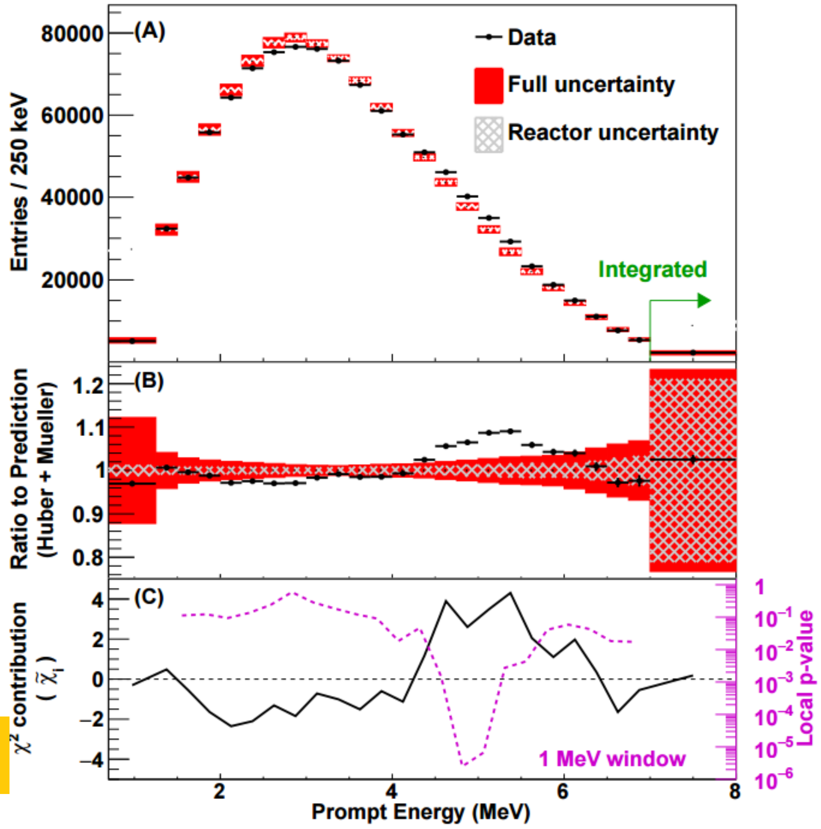
arXiv:1607.05378



Anomalies

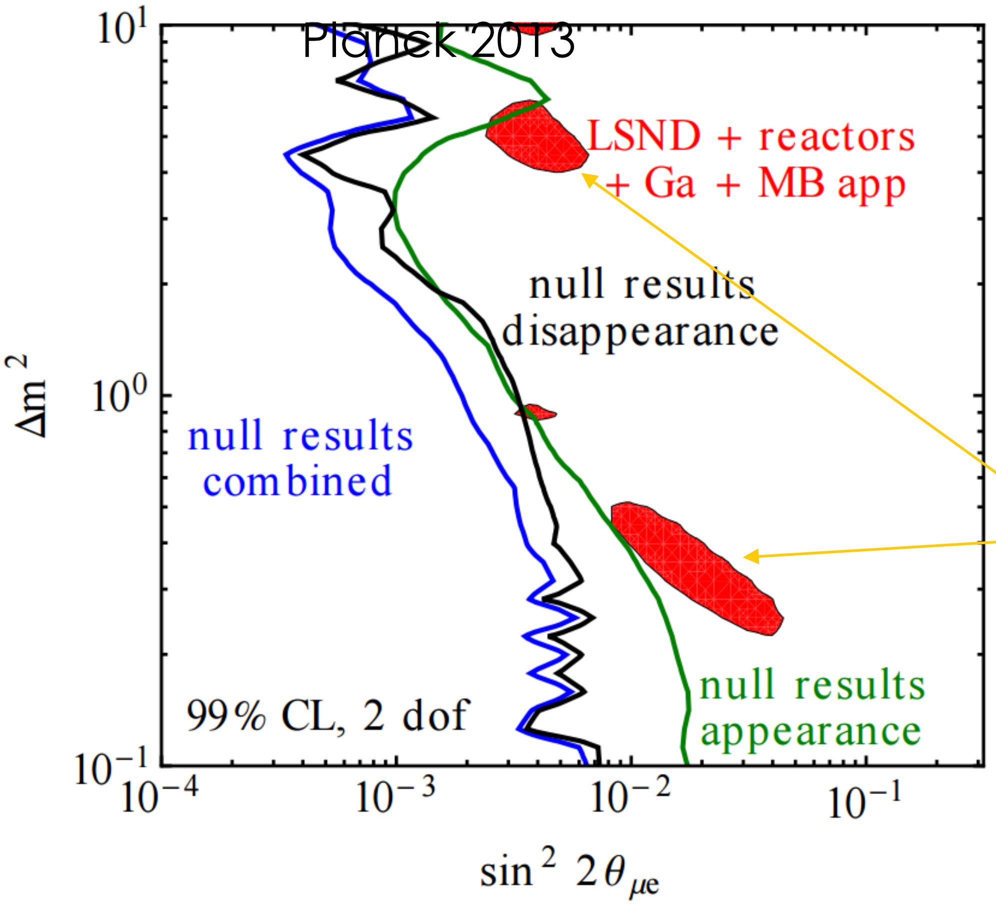
arXiv:1607.05378





Reactor flux model might be unreliable …

Global situation

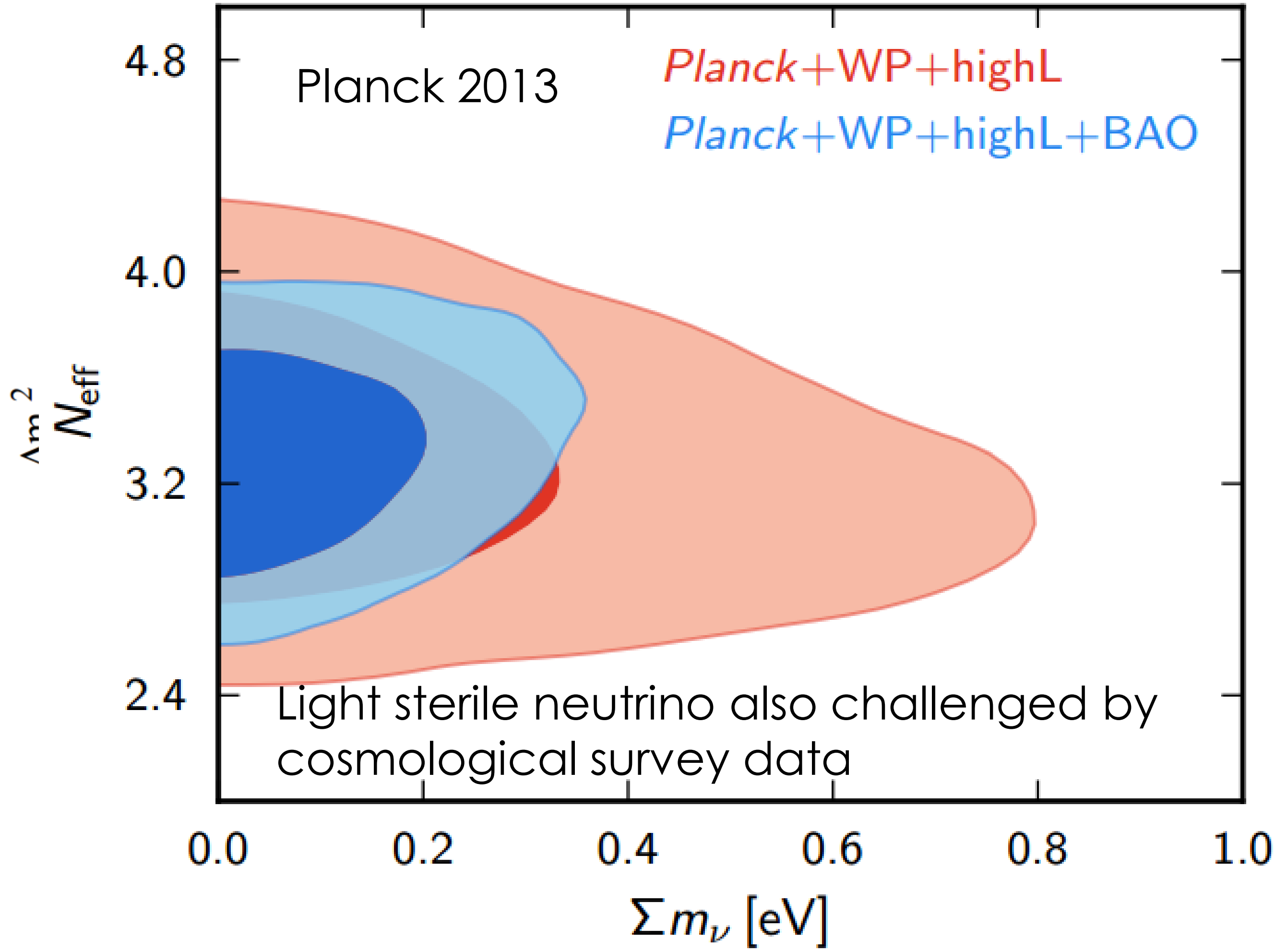


Kopp et al., arXiv: 1303.3011

3+1 model

- Large $\Delta m^2 > 0.1$ eV^2
- Already in conflict with combination with all null results

Global situation



Light sterile neutrino also challenged by cosmological survey data

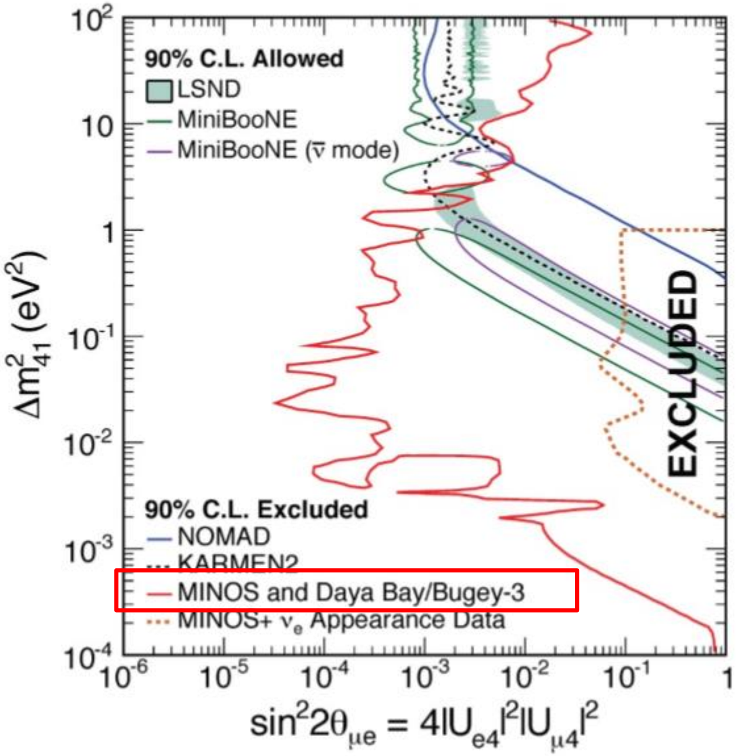
Xiv: 1303.3011

odel

m^2 > 0.1 eV^2
in conflict
mbination
ull results

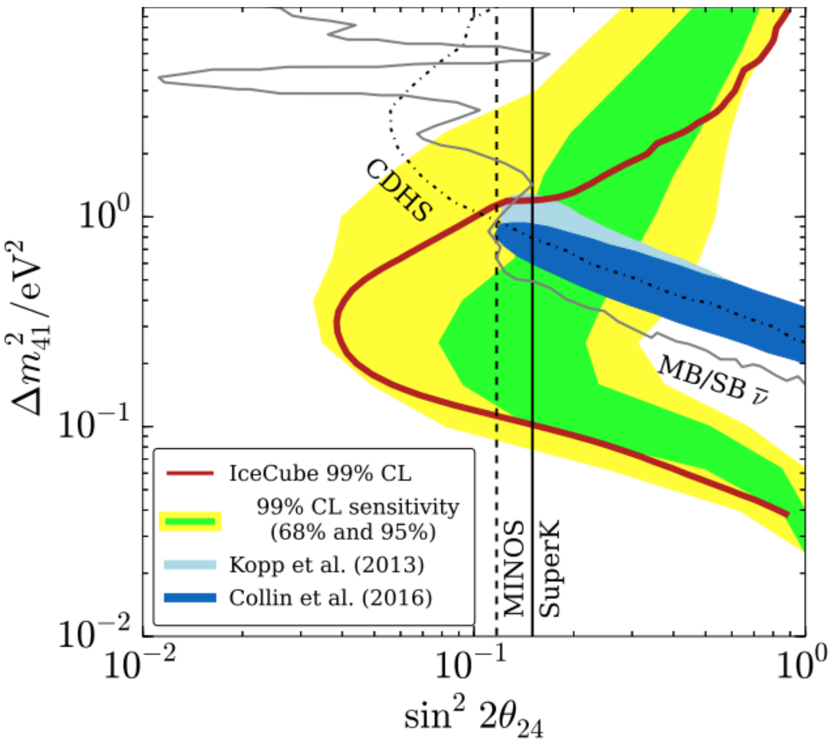
New null results

Phys. Rev. Lett. 117, 151801 (2016)



Combination of e and μ disappearance to lead to an unambiguous constraint on electron appearance

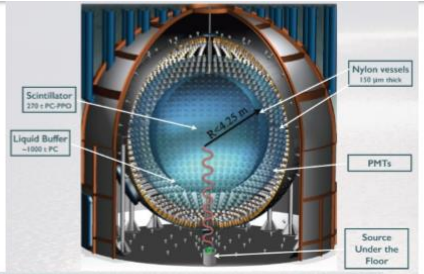
Phys. Rev. Lett. 117, 071801 (2016)

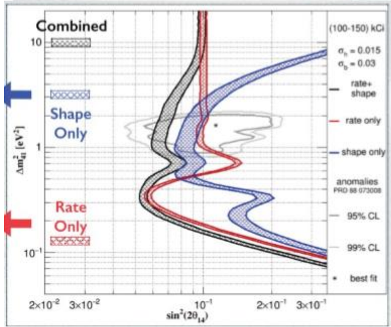


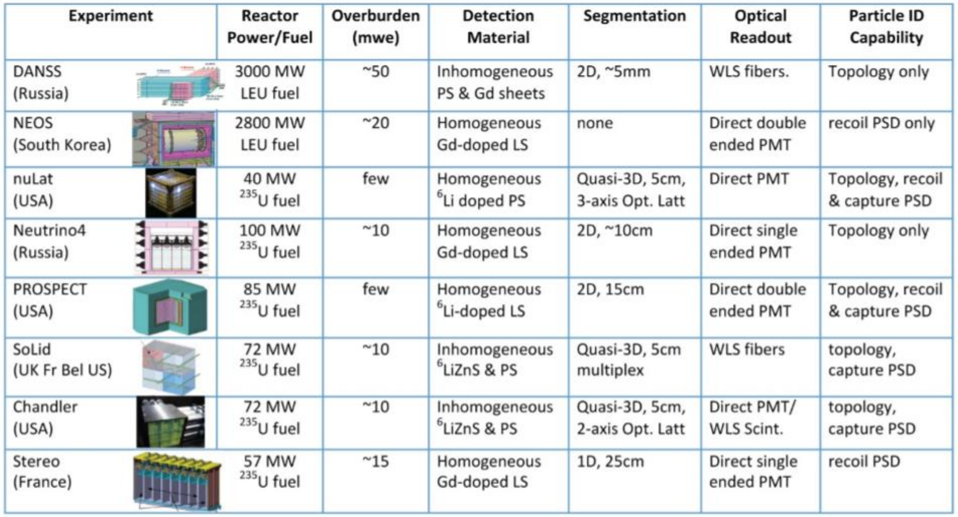
Icecube 320 GeV – 20 TeV μ disappearance

A zoo of new sterile hunters

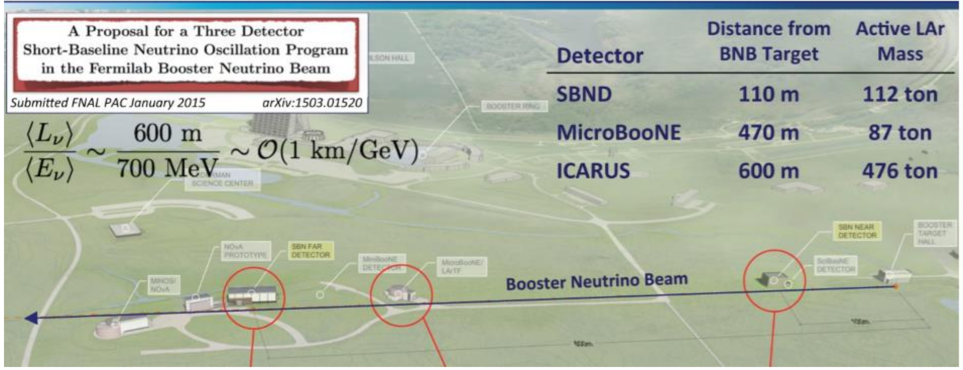
- **Strong neutrino source @ Borexino**
- **Short baseline reactors**
- **Short baseline accelerator**
- **Definitive to the parameter space $\Delta m^2 \sim 0.1$ eV^2 & above**







Experiment	Reactor Power/Fuel	Overburden (mwe)	Detection Material	Segmentation	Optical Readout	Particle ID Capability
DANSS (Russia)	3000 MW LEU fuel	~50	Inhomogeneous PS & Gd sheets	2D, ~5mm	WLS fibers.	Topology only
NEOS (South Korea)	2800 MW LEU fuel	~20	Homogeneous Gd-doped LS	none	Direct double ended PMT	recoil PSD only
nuLat (USA)	40 MW ^{235}U fuel	few	Homogeneous ^{6}Li doped PS	Quasi-3D, 5cm, 3-axis Opt. Latt	Direct PMT	Topology, recoil & capture PSD
Neutrino4 (Russia)	100 MW ^{235}U fuel	~10	Homogeneous Gd-doped LS	2D, ~10cm	Direct single ended PMT	Topology only
PROSPECT (USA)	85 MW ^{235}U fuel	few	Homogeneous ^{6}Li-doped LS	2D, 15cm	Direct double ended PMT	Topology, recoil & capture PSD
SoLid (UK Fr Bel US)	72 MW ^{235}U fuel	~10	Inhomogeneous ^{6}LiZnS & PS	Quasi-3D, 5cm multiplex	WLS fibers	topology, capture PSD
Chandler (USA)	72 MW ^{235}U fuel	~10	Inhomogeneous ^{6}LiZnS & PS	Quasi-3D, 5cm, 2-axis Opt. Latt	Direct PMT/ WLS Scint.	topology, capture PSD
Stereo (France)	57 MW ^{235}U fuel	~15	Homogeneous Gd-doped LS	1D, 25cm	Direct single ended PMT	recoil PSD

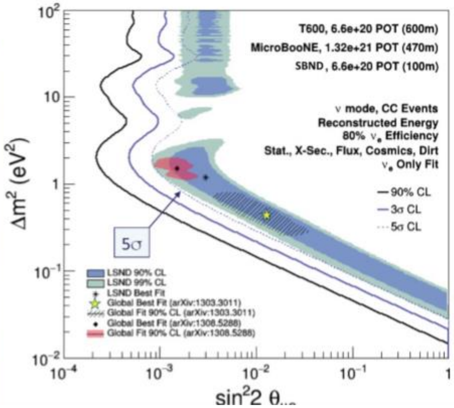


A Proposal for a Three Detector
Short-Baseline Neutrino Oscillation Program
in the Fermilab Booster Neutrino Beam

Submitted FNAL PAC January 2015 *arXiv:1503.01520*

$$\frac{\langle L_\nu \rangle}{\langle E_\nu \rangle} \sim \frac{600\ \mathrm{m}}{700\ \mathrm{MeV}} \sim \mathcal{O}(1\ \mathrm{km/GeV})$$

Detector	Distance from BNB Target	Active LAr Mass
SBND	110 m	112 ton
MicroBooNE	470 m	87 ton
ICARUS	600 m	476 ton



Summary and outlook

- Multiple experimental probes are strategically answering the key questions in neutrino physics
- A somewhat surprise: first implication of leptonic CP violating from world data
- In the next ten years,
  - Precision unitarity tests up to 1% precision
  - firm answer on CP
  - mass hierarchy determined
  - absolute mass to <0.2 eV
  - Majorana neutrino may be discovered if neutrino mass order is inverted
- Unexpected surprise may still be ahead!