



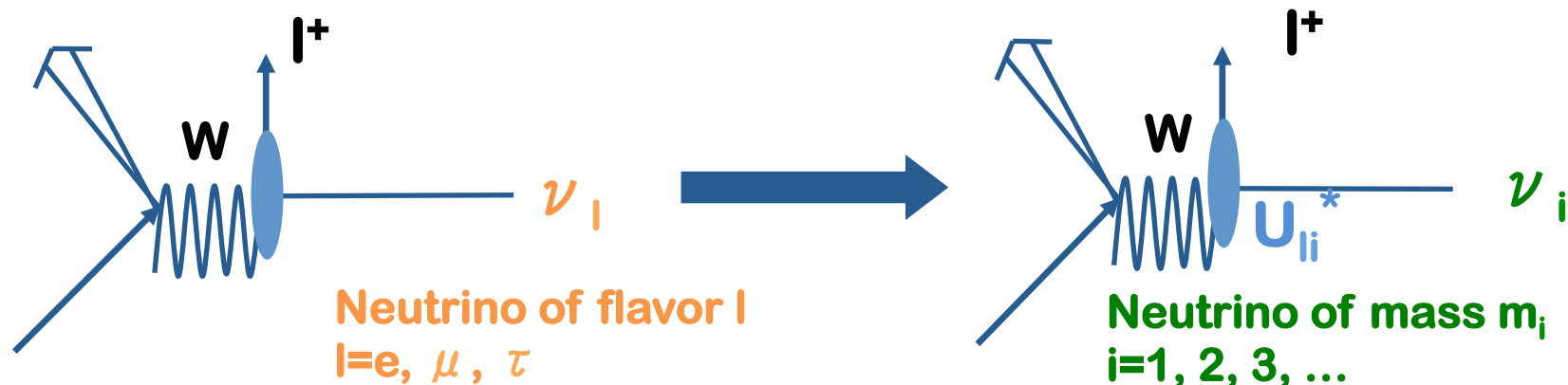
Neutrinos: Experimental Review

Chalonge Workshop
Meudon, June 06th 2012

Thierry Lasserre
CEA-Saclay

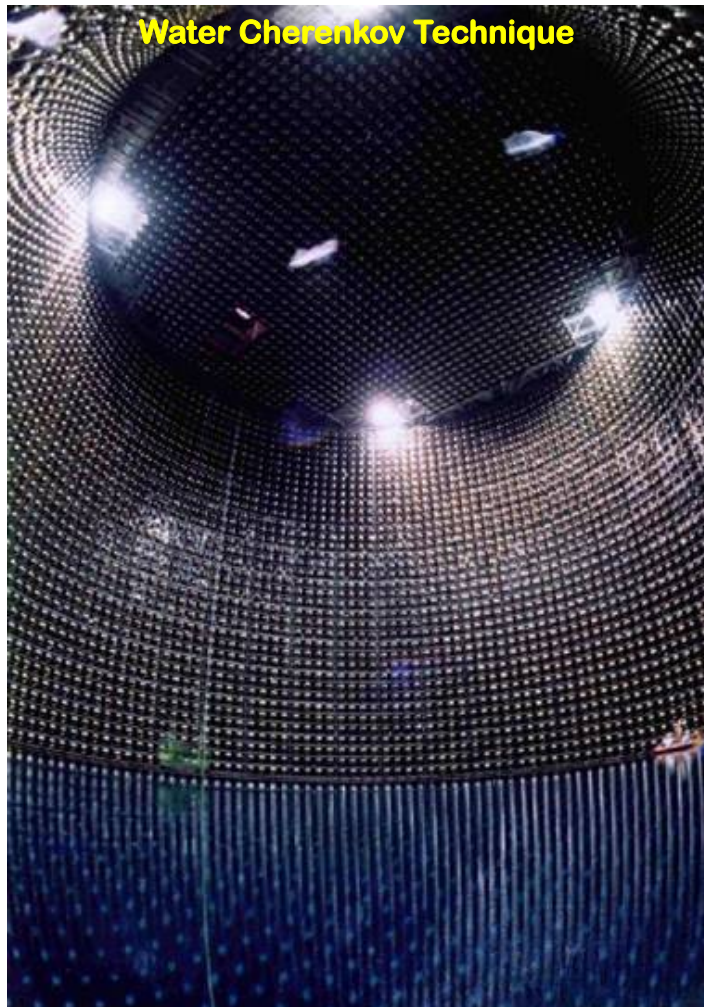
Established Neutrino Physics

- 3 types, spin $\frac{1}{2}$, neutral, left handed, $\sigma(1 \text{ MeV}) \approx 10^{-45-43} \text{ cm}^2$
- Neutrinos have tiny masses and mix: $0.04 \text{ eV} < m_\nu < \approx 1 \text{ eV}$
- Two views on W decay:



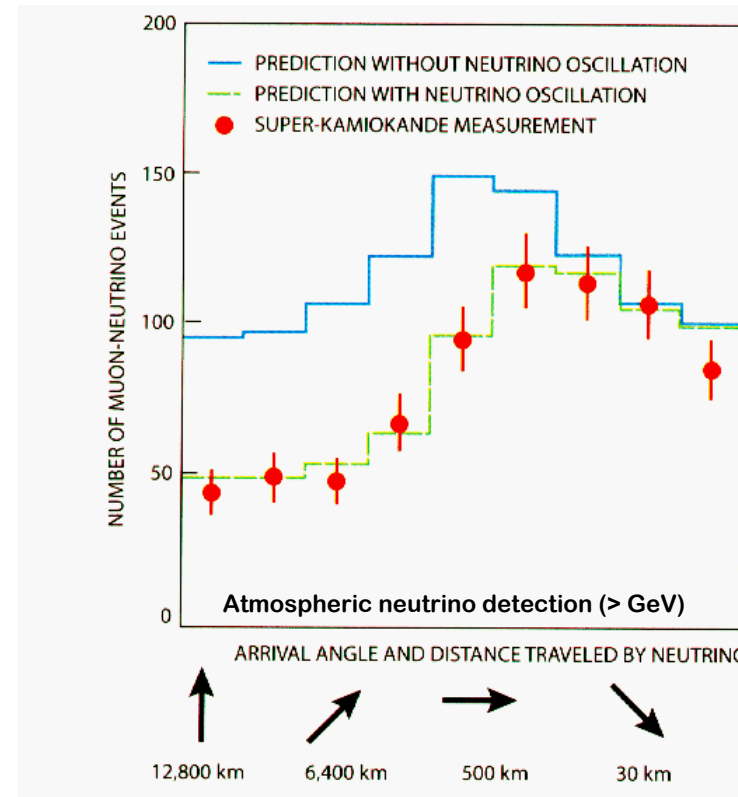
- PMNS matrix U relates mass & flavor: $|\nu_i\rangle = \sum U_{\alpha i} |\nu_\alpha\rangle$
- A compelling evidence of physics Beyond the Standard Model

SuperKamiokande Breakthrough (1998)



50 kt of pure water, 12 000 PMTs
Good E-resolution
e/μ discrimination at low energy

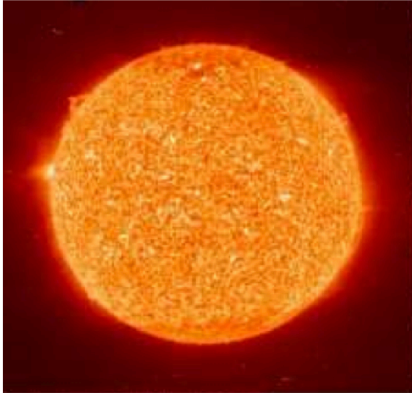
$$\frac{\Phi^{\text{Atm}}_{\nu_{\mu}}(\text{up})}{\Phi^{\text{Atm}}_{\nu_{\mu}}(\text{down})} = 0.54 \pm 0.04$$



**Neutrino do have mass
and they mix (oscillation)**

Neutrino Oscillation: Established

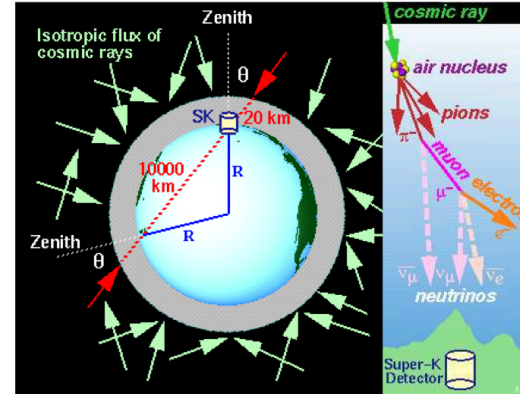
sun



reactors



atmosphere



accelerators



Homestake, SAGE, GALLEX
SuperK, SNO, Borexino

KamLAND, CHOOZ

SuperKamiokande

K2K, MINOS, T2K

- $\nu_\mu \rightarrow \nu_\tau$ or $\text{anti-}\nu_\mu \rightarrow \text{anti-}\nu_\tau$:
- $\nu_e \rightarrow \nu_{\mu, \tau}$:
- $\text{anti-}\nu_e \rightarrow \text{anti-}\nu_{\text{other}}$:
- $(\text{anti-})\nu_\mu \rightarrow (\text{anti-})\nu_{\text{other}}$:
- $\nu_\mu \rightarrow \nu_e$:

atmospheric & beam experiments

solar experiments

reactor experiments

atmospheric & beam experiments

beam experiments

$$P(\bar{\nu}_x \rightarrow \bar{\nu}_x) = 1 - \sin^2(2\theta_i) \sin\left(1.27 \frac{\Delta m_i^2 (\text{eV}^2) L (\text{m})}{E (\text{MeV})}\right)$$

3 ν Oscillation Formalism

PMNS mixing matrix

$$U = \begin{matrix} \text{Atmospheric} \\ \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \end{matrix} \times \begin{matrix} \text{Cross-Mixing} \\ \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \end{matrix} \times \begin{matrix} \text{Solar} \\ \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \end{matrix} \times \begin{matrix} \text{Majorana CP phases} \\ \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix} \end{matrix}$$

θ_{23} : “atm.” mixing angle θ_{13} θ_{12} : “solar” mixing angle

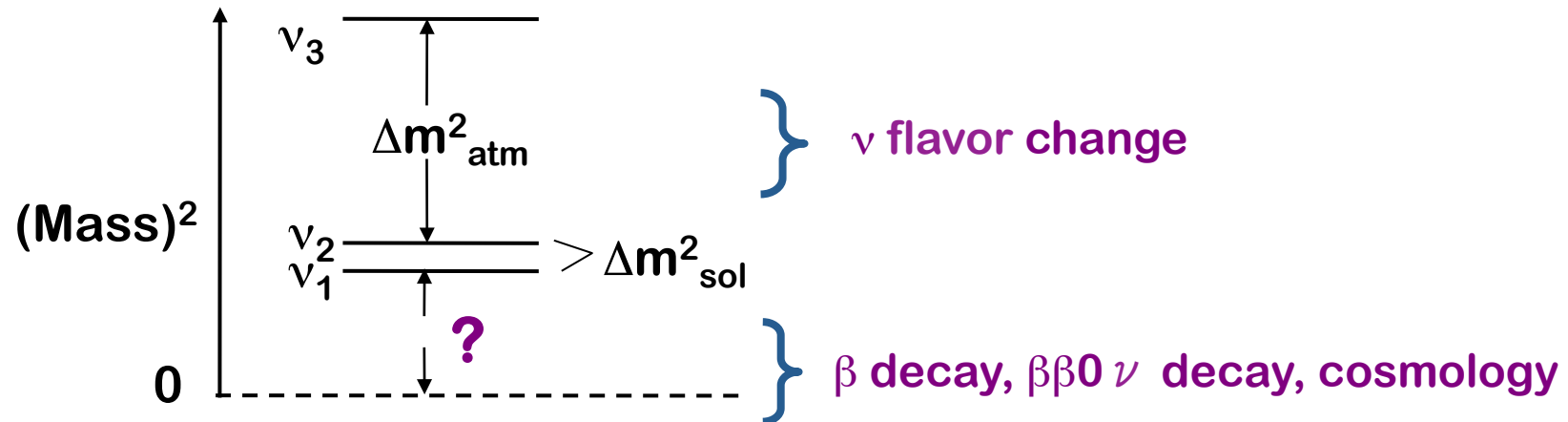
δ Dirac CP violating phase

2 Majorana phases
(L violating processes)

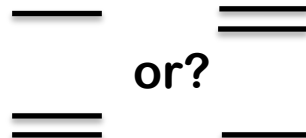
- 3 masses m_1, m_2, m_3 : $\Delta m_{\text{sol}}^2 = m_2^2 - m_1^2$ & $\Delta m_{\text{atm}}^2 = |m_3^2 - m_1^2|$
- 3-flavour effects are suppressed since: $\Delta m_{\text{sol}}^2 \ll \Delta m_{\text{atm}}^2$ (1/30) & $\theta_{13} \ll 1$

Open questions

- What are the masses of the mass eigenstates ν_i ?



- Is the spectral pattern



$\bar{\nu}$ behavior in matter, $\beta\beta 0 \nu$

- Is there any conserved Lepton Number (Dirac or Majorana neutrino) ? $\beta\beta 0 \nu$

- Precise measurements of the leptonic mixing matrix?
- Do the behavior of ν violate CP?
- Is leptonic CP responsible for the matter-antimatter asymmetry?

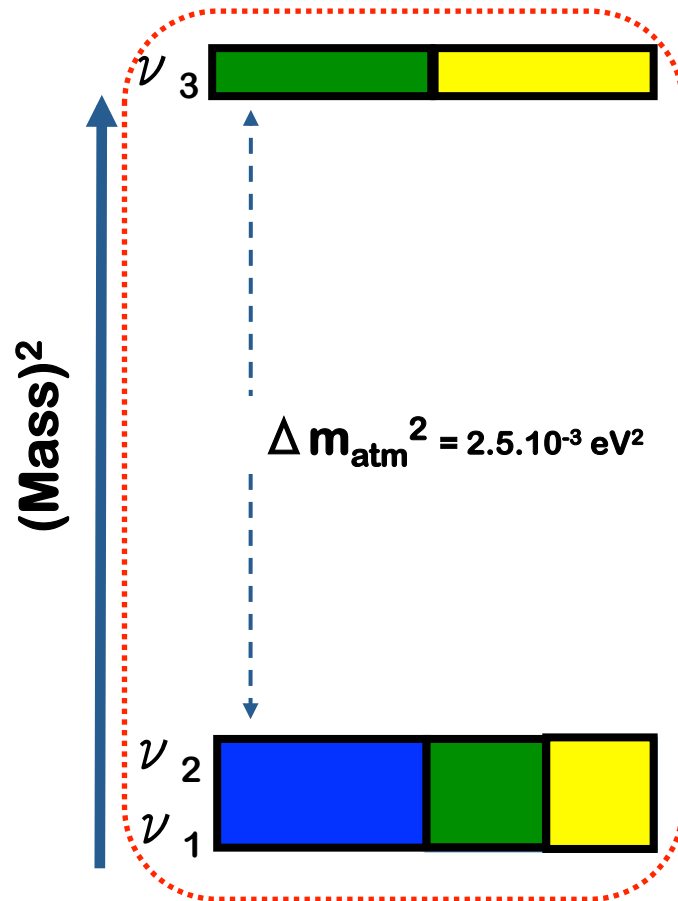
ν flavor change

- Are there additional (sterile) neutrino states ν flavor change, Cosmology

Question 1)

What are the leptonic mixing parameters?

Δm^2_{31} & θ_{23}



$$\Delta m^2 (\text{eV}^2) \sim L(\text{km}) / E(\text{MeV})$$

Atmospheric:

- $L \sim 10^4 \text{ km}$ & $E \sim 1\text{-}30 \text{ GeV}$

Reactors:

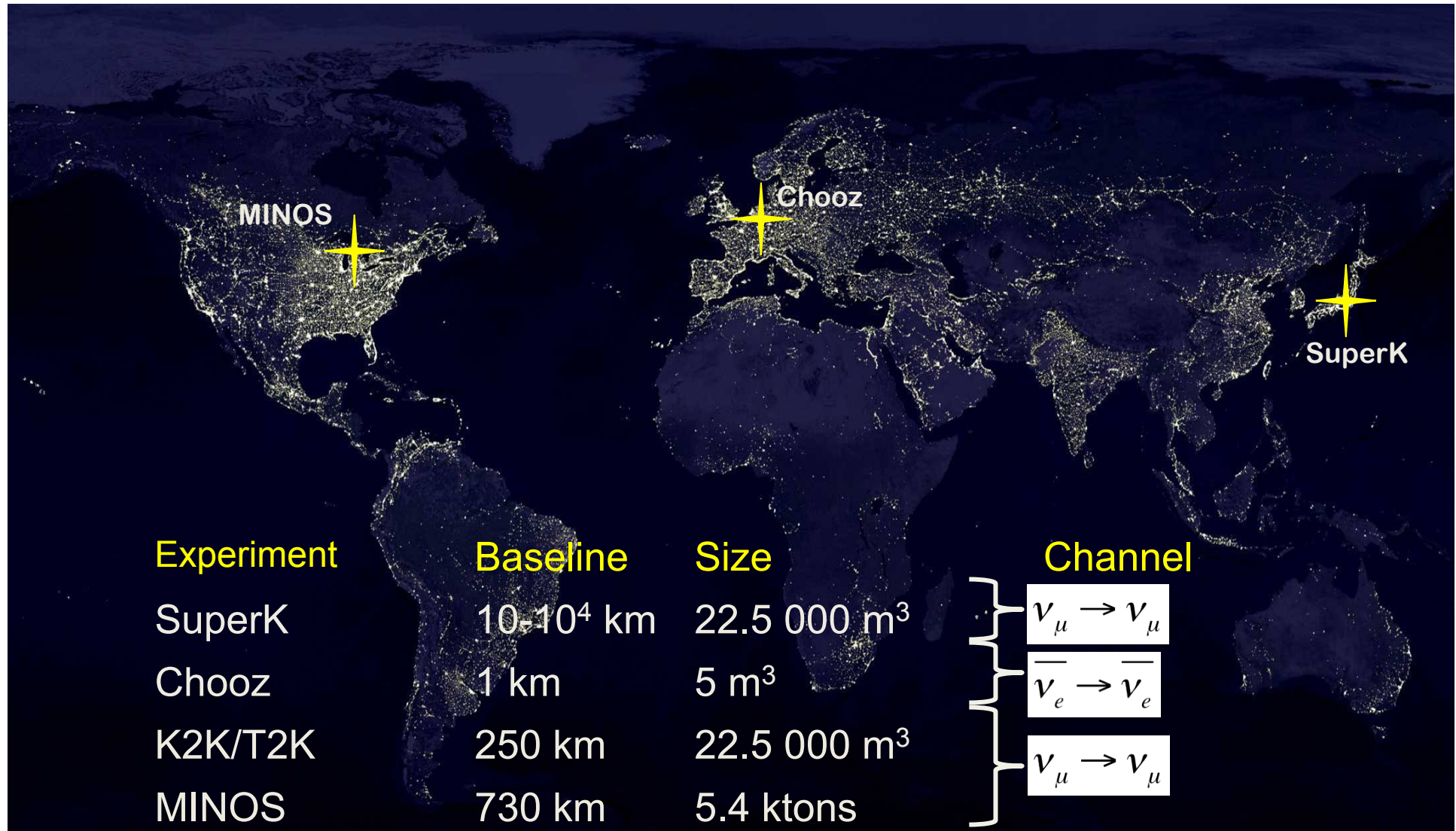
- $L \sim 1 \text{ km}$ & $E \sim 3 \text{ MeV}$

Accelerators:

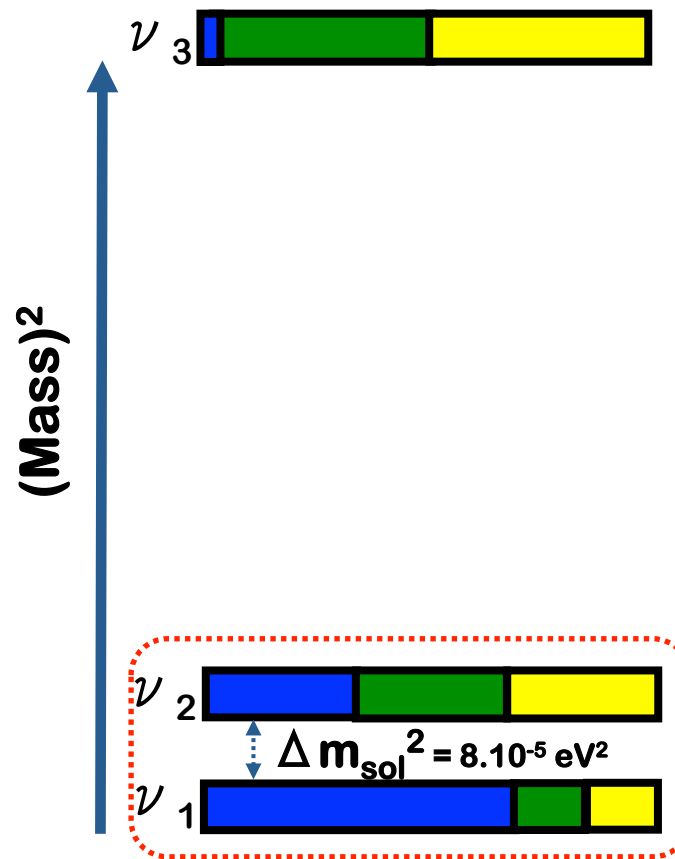
- $L \sim 1000 \text{ km}$ & $E \sim 3 \text{ GeV}$

$$\nu_e \quad \boxed{\text{blue}} \quad |U_{ei}|^2 \quad \nu_\mu \quad \boxed{\text{green}} \quad |U_{\mu i}|^2 \quad \nu_\tau \quad \boxed{\text{yellow}} \quad |U_{\tau i}|^2$$

Atmospheric/Beam Experiments



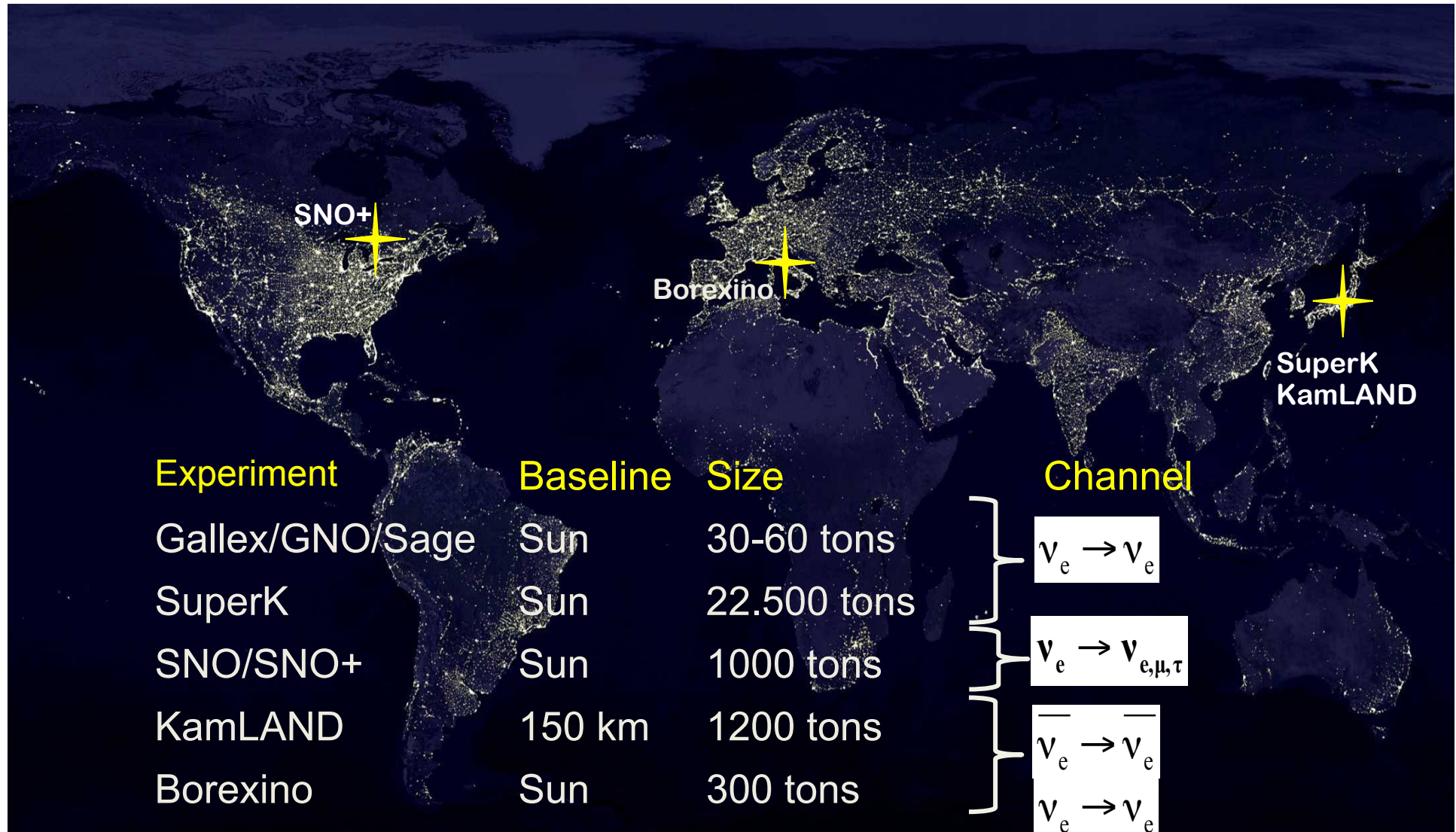
Δm^2_{21} & θ_{12}



$L \sim 100 \text{ km}$ & $E \sim \text{MeV}$
Or MSW 'flavor transition'

$$\nu_e \quad \boxed{\text{blue}} \quad |U_{ei}|^2 \quad \nu_\mu \quad \boxed{\text{green}} \quad |U_{\mu i}|^2 \quad \nu_\tau \quad \boxed{\text{yellow}} \quad |U_{\tau i}|^2$$

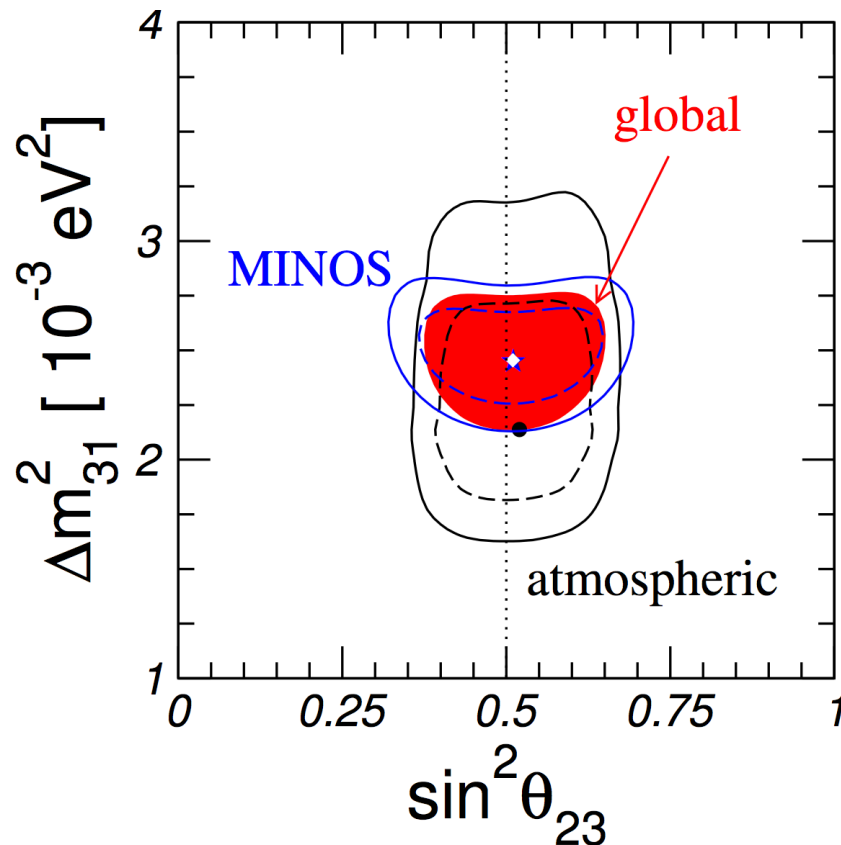
Solar / Reactor Experiments



Leading Order Oscillation Picture

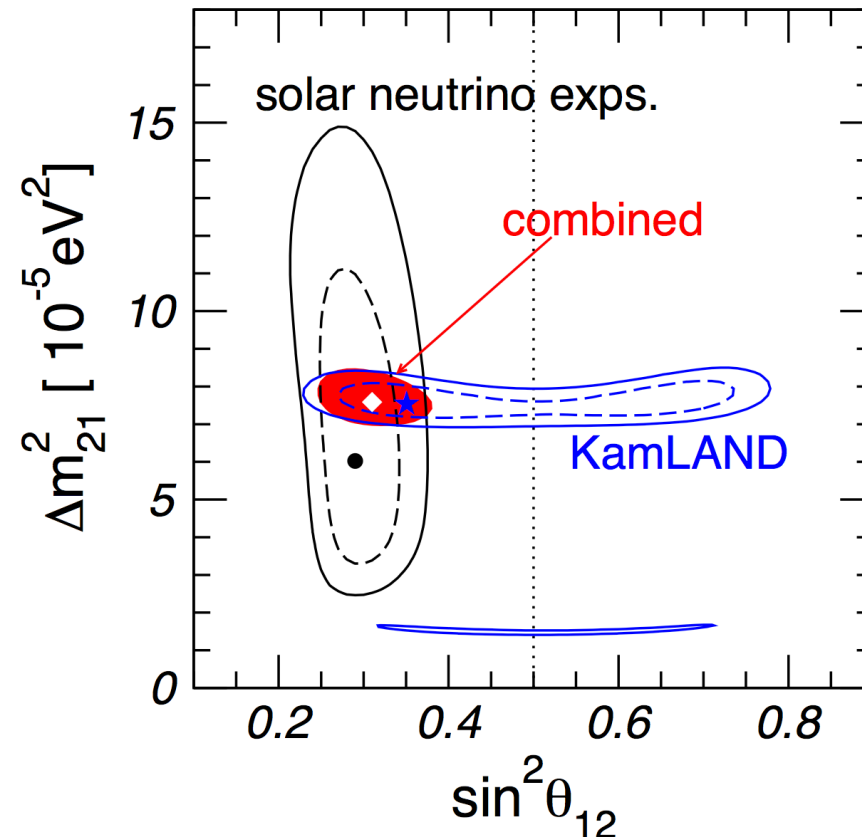
Atmospheric Oscillation

- $\nu_\mu \rightarrow \nu_\tau$
- $\Delta m^2 \approx 10^{-3} \text{ eV}^2$
- $\sin^2(\theta) \approx 0.5$

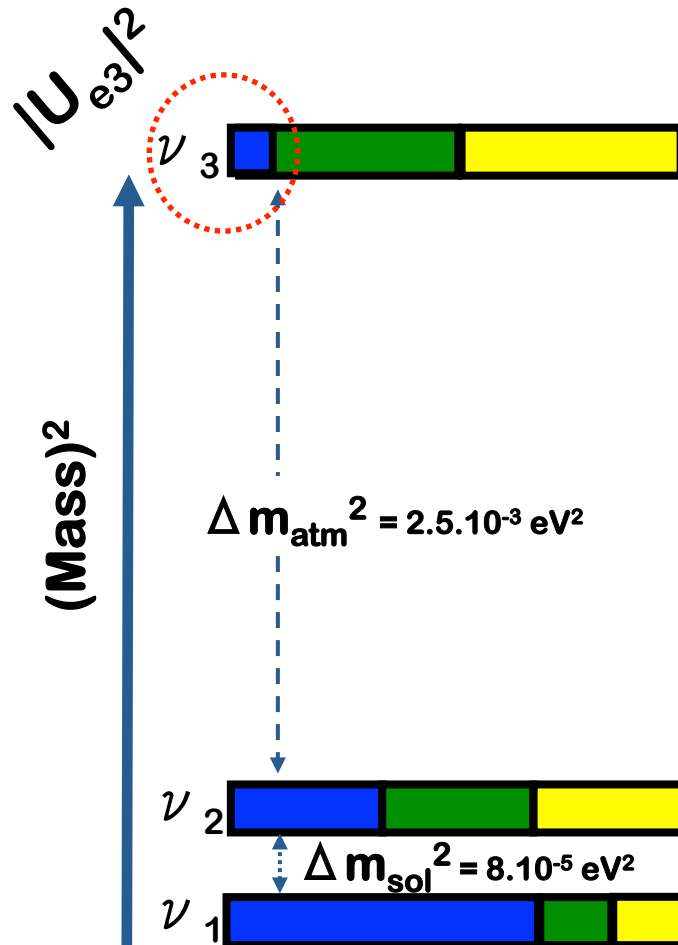


Solar Oscillation

- $\nu_e \rightarrow \nu_{\mu, \tau}$
- $\Delta m^2 \approx 10^{-4} \text{ eV}^2$
- $\sin^2(\theta) \approx 0.3$



θ_{13}



$$\nu_e \quad \boxed{\text{blue}} \quad |U_{ei}|^2 \quad \nu_\mu \quad \boxed{\text{green}} \quad |U_{\mu i}|^2 \quad \nu_\tau \quad \boxed{\text{yellow}} \quad |U_{\tau i}|^2$$

▪ Need to connect the ν_e flavour with the isolated neutrino (Δm_{atm}^2)

▪ L~1 km, E~MeV

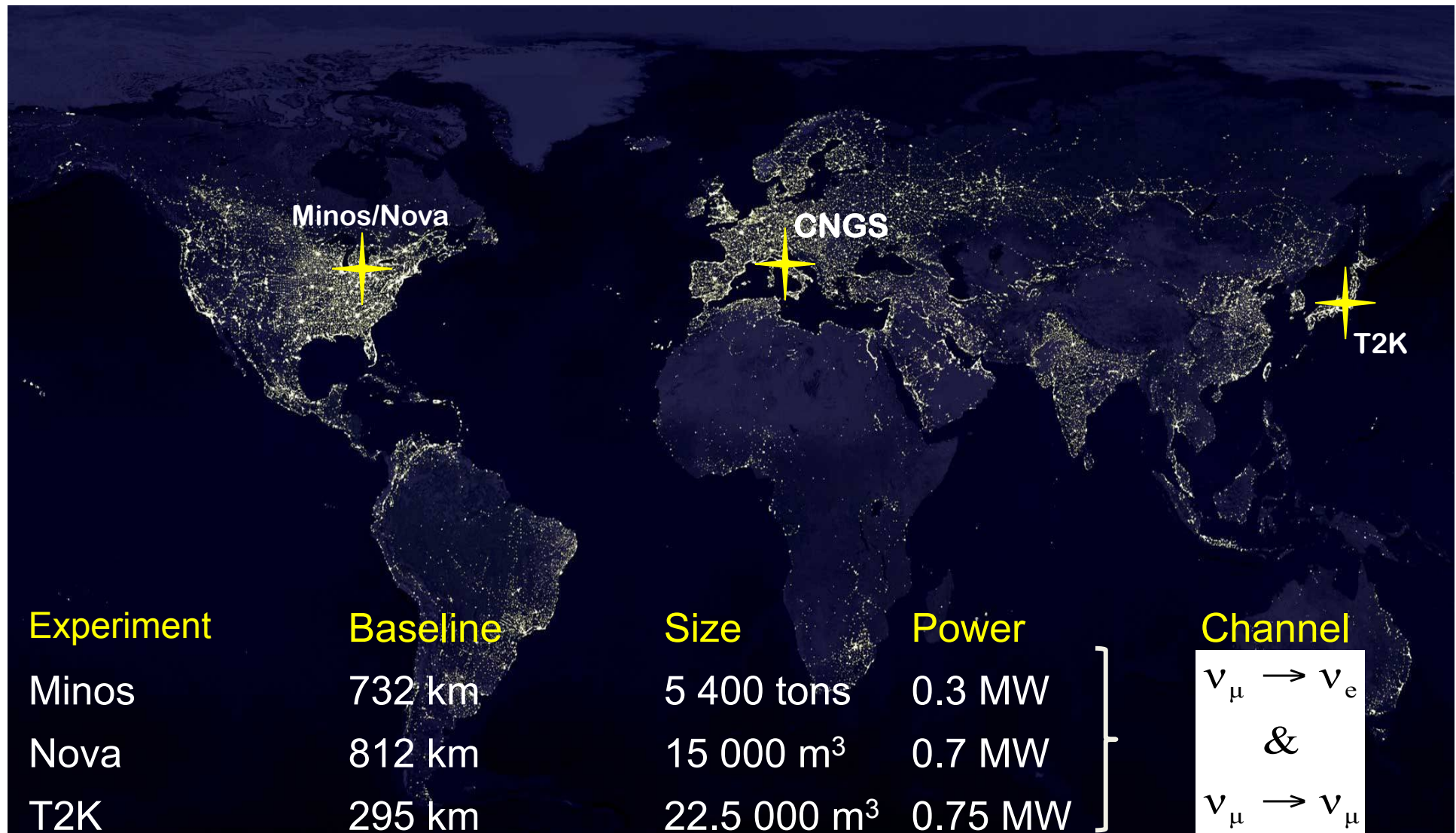
- disappearance expt. @reactor
- θ_{13} only $\rightarrow$ 'clean'

▪ L~1000 km, E~GeV

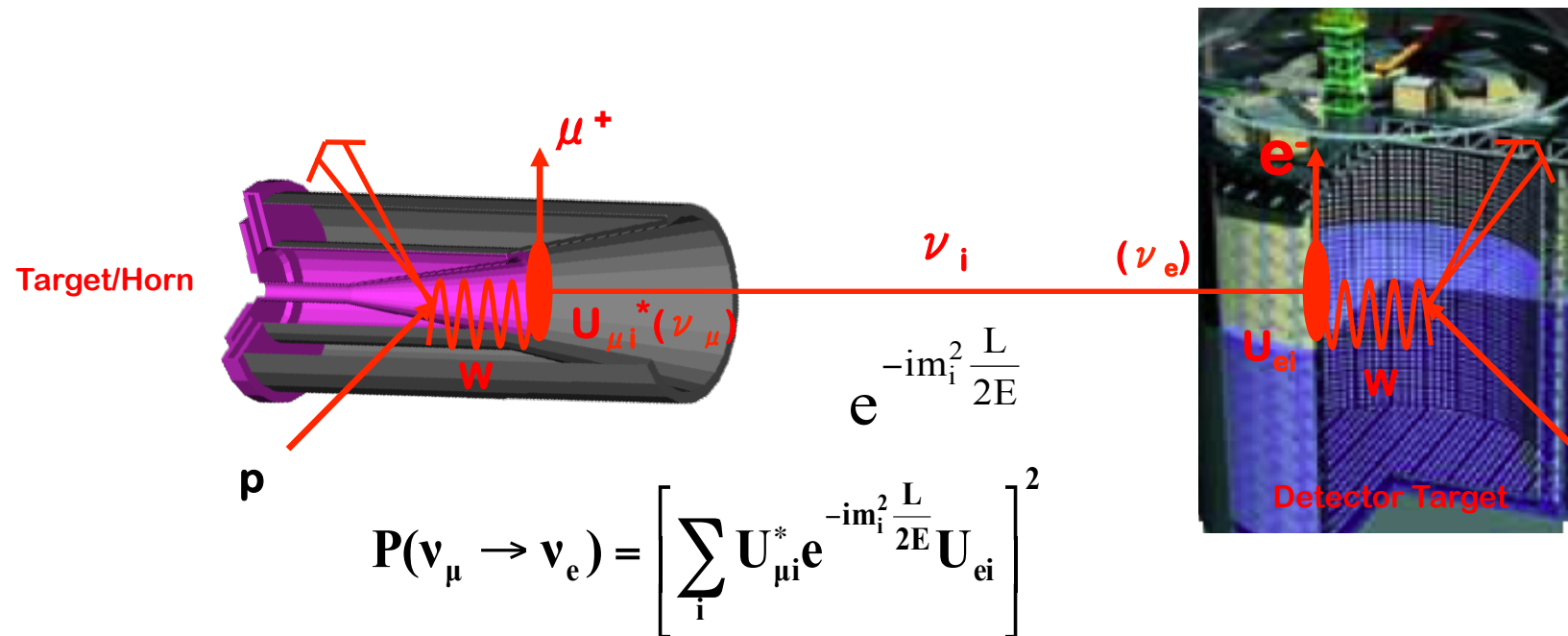
- accelerator experiments
- appearance expt. @Beam
- (θ_{13} , NH/IH, δ_{CP})
 $\rightarrow$ correlations & degeneracies

$\rightarrow$ Complementary projects

Beam Neutrino Experiments



ν -Beam: Oscillation Physics

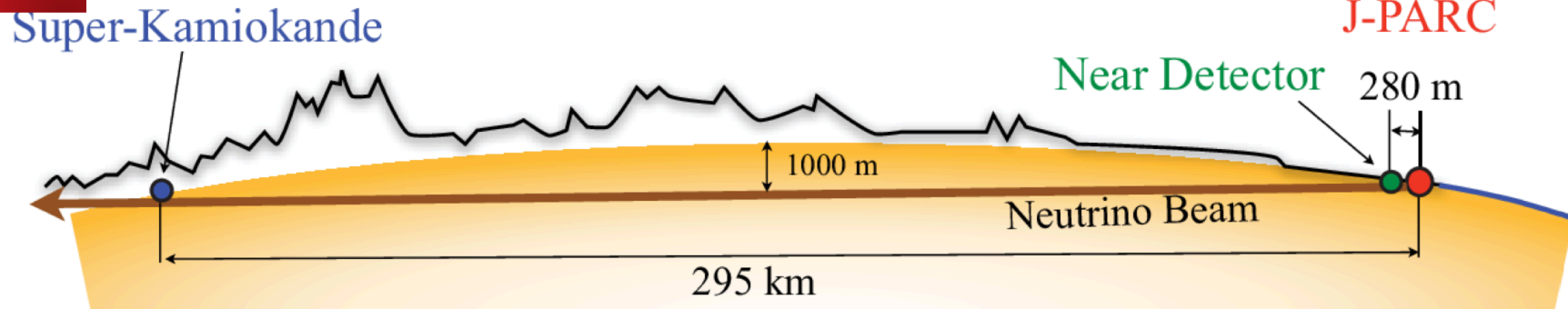


- Complex oscillation formula
 - depends on $\sin^2(2\theta_{13})$, Δm_{31}^2 , $\text{sign}(\Delta m_{31}^2)$, δ
- $\gg$ MeV muon antineutrinos → appearance experiments
 - $\sin^2(2\theta_{13})$ measurement depends on δ -CP
- $\gg$ MeV neutrinos + $\gg 100$ km baseline → matter effects
 - $\sin^2(2\theta_{13})$ measurement independent of $\text{sign}(\Delta m_{13}^2)$

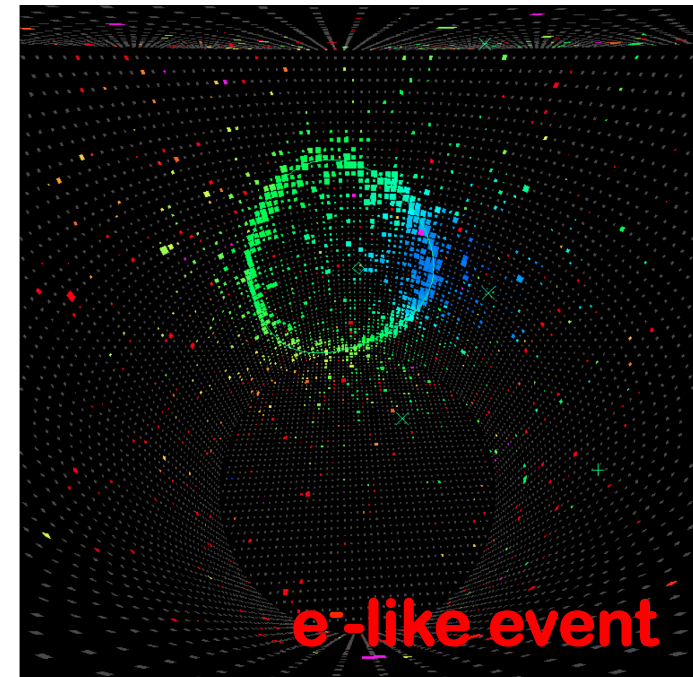
Very sensitive
to apparition

Correlation &
degeneracies

T2K (Tokai to Kamioka) @JPARK

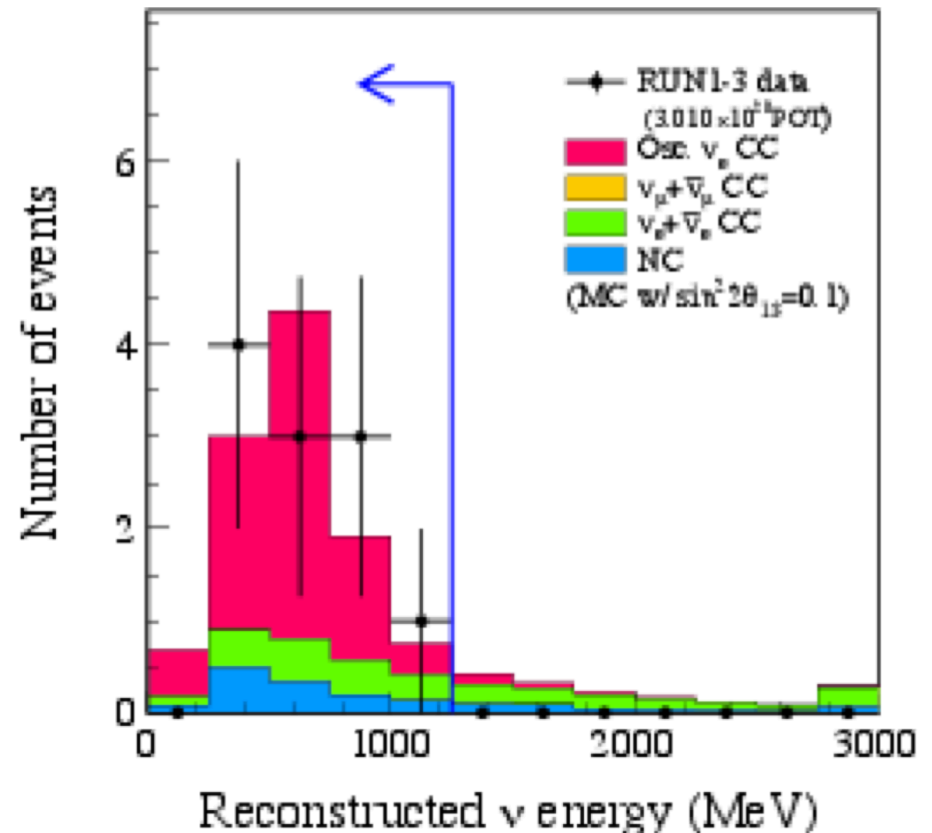


- **Channel:** $\nu_{\mu} \rightarrow \nu_e$ (1st goal: search for non-zero θ_{13} , beam contamination, NC- $1\pi_0$)
- **Channel:** $\nu_{\mu} \rightarrow \nu_{\mu}$ ($\sin^2 2\theta_{23}$ @ 1% & Δm^2_{23} @ 2%, single pion production)
- **Detection, CCQE:** $\nu_l + n \rightarrow p + l^-$ ($l=e, \mu$)
- **Beam Setup:**
 - Off-axis beam (2.5°), ramping to 750 kW...
 - Quasi-monochromatic ν_{μ} beam (400 MeV)
 - Small intrinsic ν_e contamination
 - Reduced high-E non-CCQE backgrounds
- **Far Detector at 295 km:**
 - Super Kamiokande (50 kt)
- **Near Detector at 280 m:**
 - On & Off-Axis detectors (Ingrid & ND280)

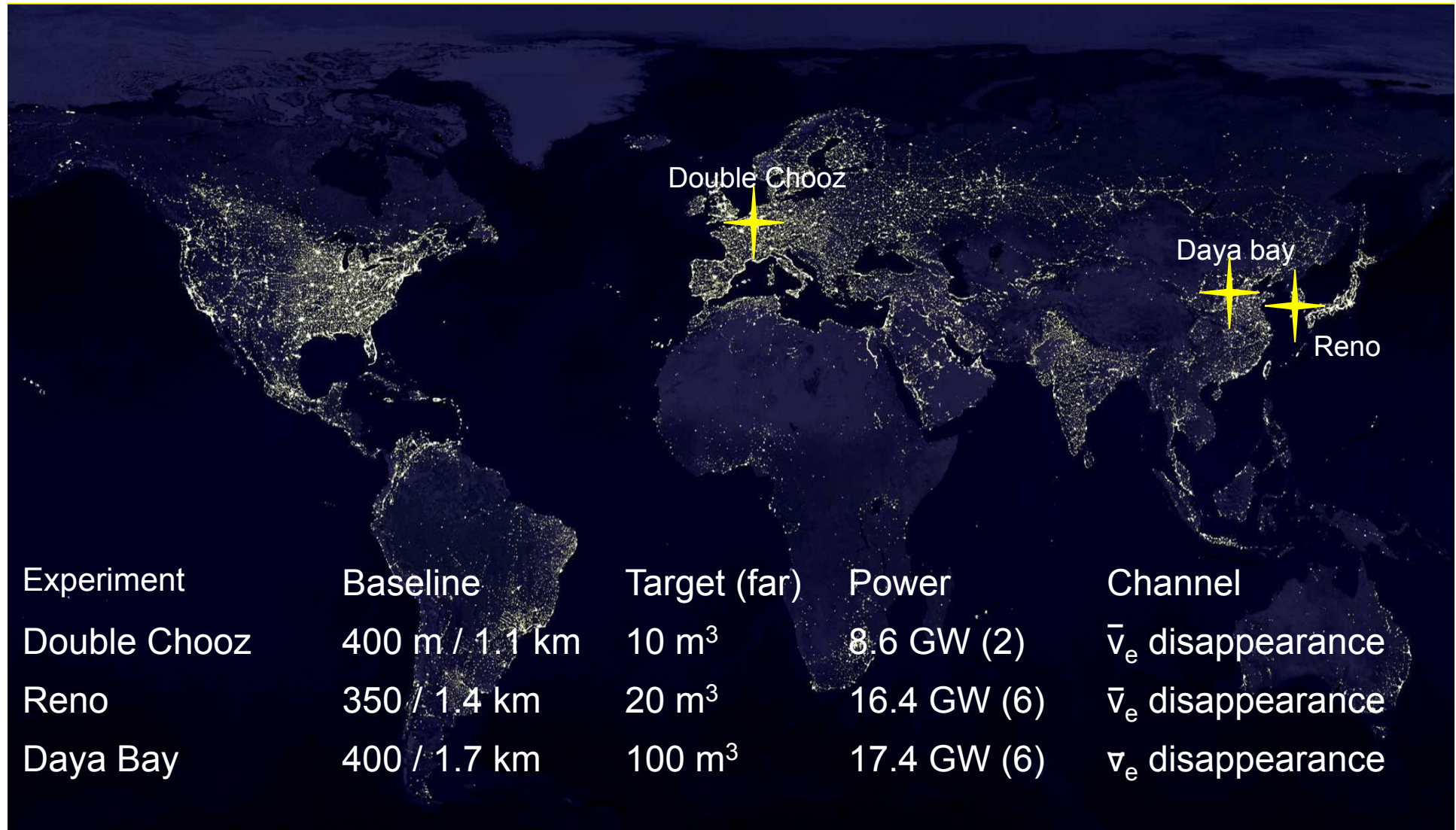


Latest T2K results on θ_{13}

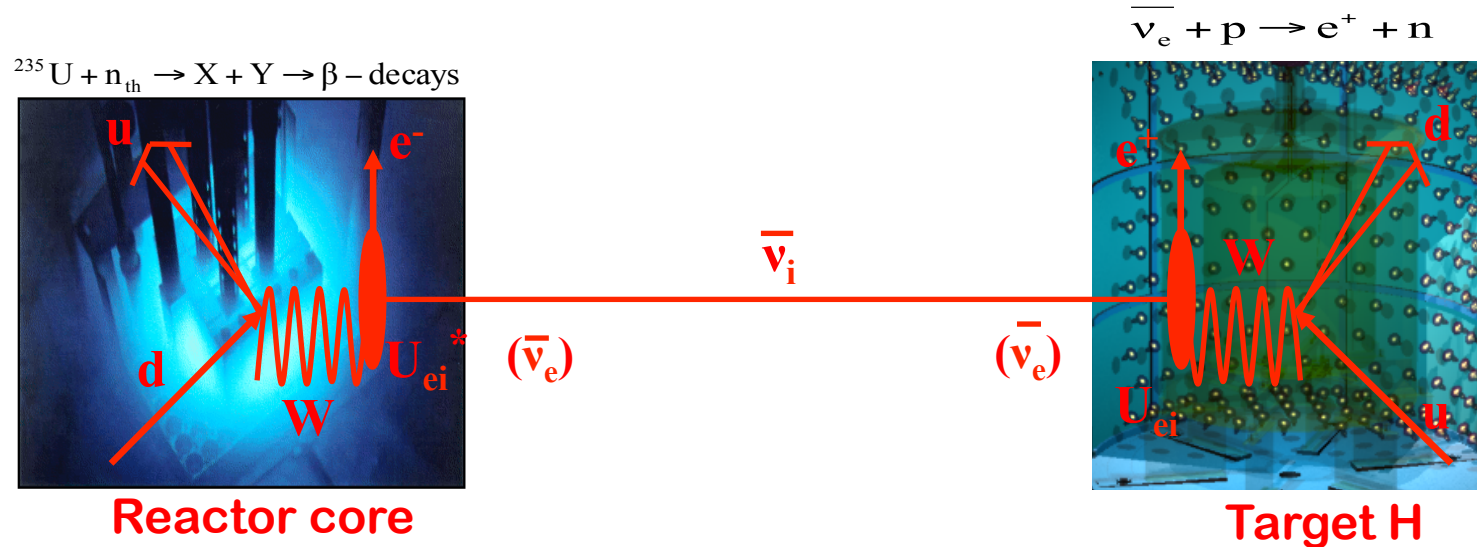
- New results on $\nu_{\mu} \rightarrow \nu_e$ based on **3×10^{20} pot** (4% exposure's goal)
- Expected **Background: 3.22 ± 0.43**
 - intrinsic ν_e contamination
 - π^0 from NC interactions
- **11 candidate events** :
Indication of ν_e appearance
- Under $\theta_{13}=0$ hypothesis,
 $P(\text{obs} > 11 \text{ events}) = 0.08\%$ (3.2σ)
- Next Goals:
 - Still limited by stat!
 - Achieve 5σ in 2013 (8×10^{20} pot)
 - Upgrade JPARC (**7.5×10^{21} pot in 2021**)



Reactor Neutrino Experiments



Reactor: Oscillation Physics



$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2(2\theta_{13}) \left[\sin^2 \left(1.27 \frac{\Delta m_{\text{atm}}^2 (\text{eV}^2) L (\text{m})}{E (\text{MeV})} \right) + O\left(\frac{\Delta m_{\text{sol}}^2}{\Delta m_{\text{atm}}^2}\right) \right]$$

- Simple oscillation formula

→ depends $\sin^2(2\theta_{13})$ & Δm_{atm}^2 , weakly on Δm_{sol}^2

- MeV electron antineutrinos → disappearance experiment

→ $\sin^2(2\theta_{13})$ measurement independent of $\delta\text{-CP}$

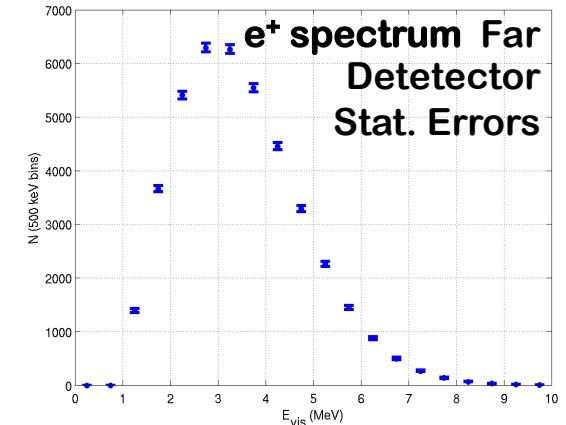
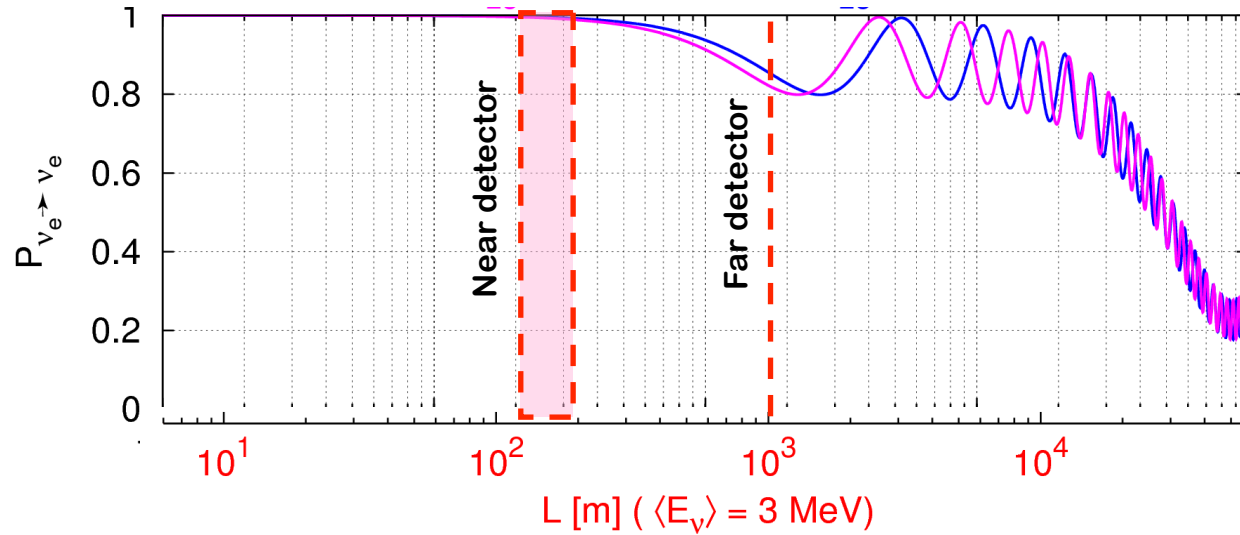
- MeV neutrinos + 1 km baseline → no matter effects $O[10^{-4}]$

→ $\sin^2(2\theta_{13})$ measurement independent of $\text{sign}(\Delta m_{13}^2)$

'clean'
information
on θ_{13}

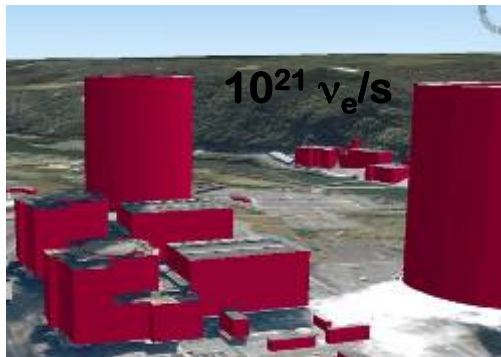
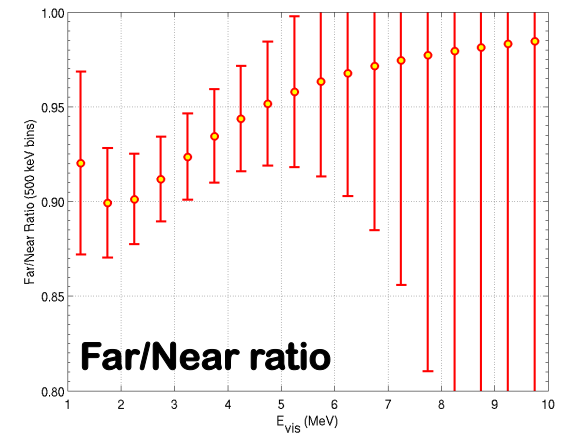
Experimental Concept

$$P(\nu_e \rightarrow \nu_e) = 1 - \sin^2(2\theta_{13}) \sin^2(\Delta m_{31}^2 L / 4E)$$

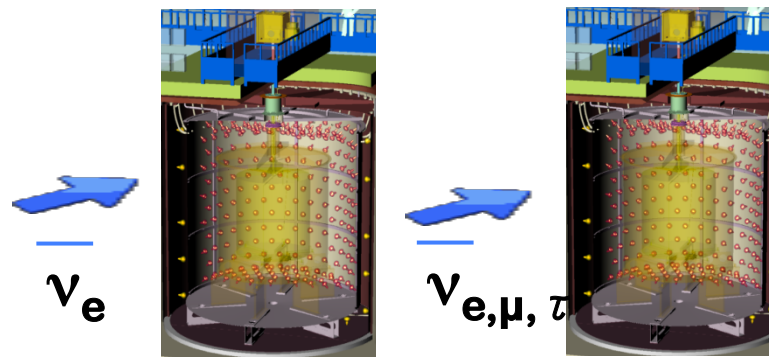


$$\Delta m_{\text{atm}}^2 = 3.0 \cdot 10^{-3} \text{ eV}^2$$

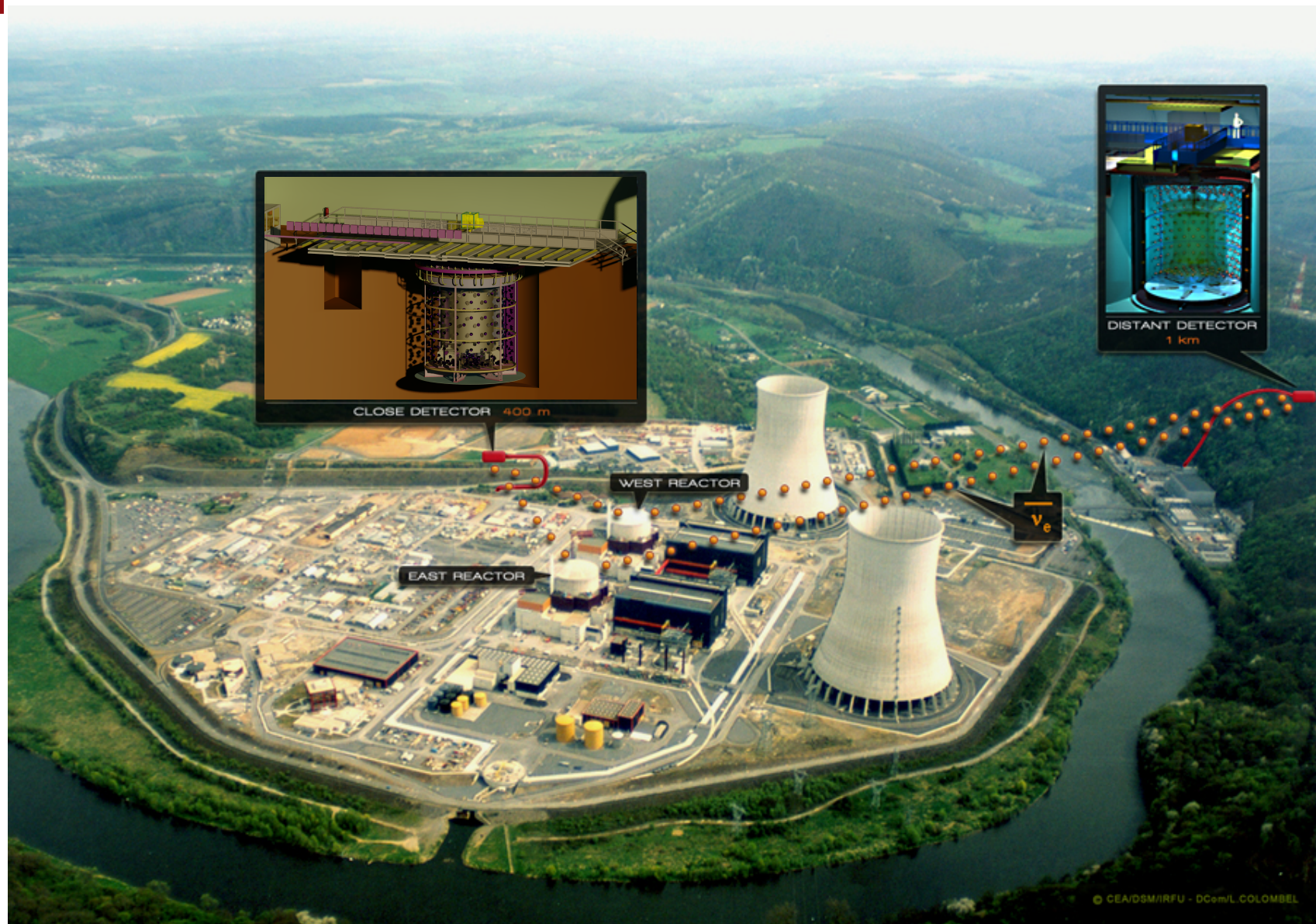
$$\sin^2(2\theta_{13}) = 0.12$$



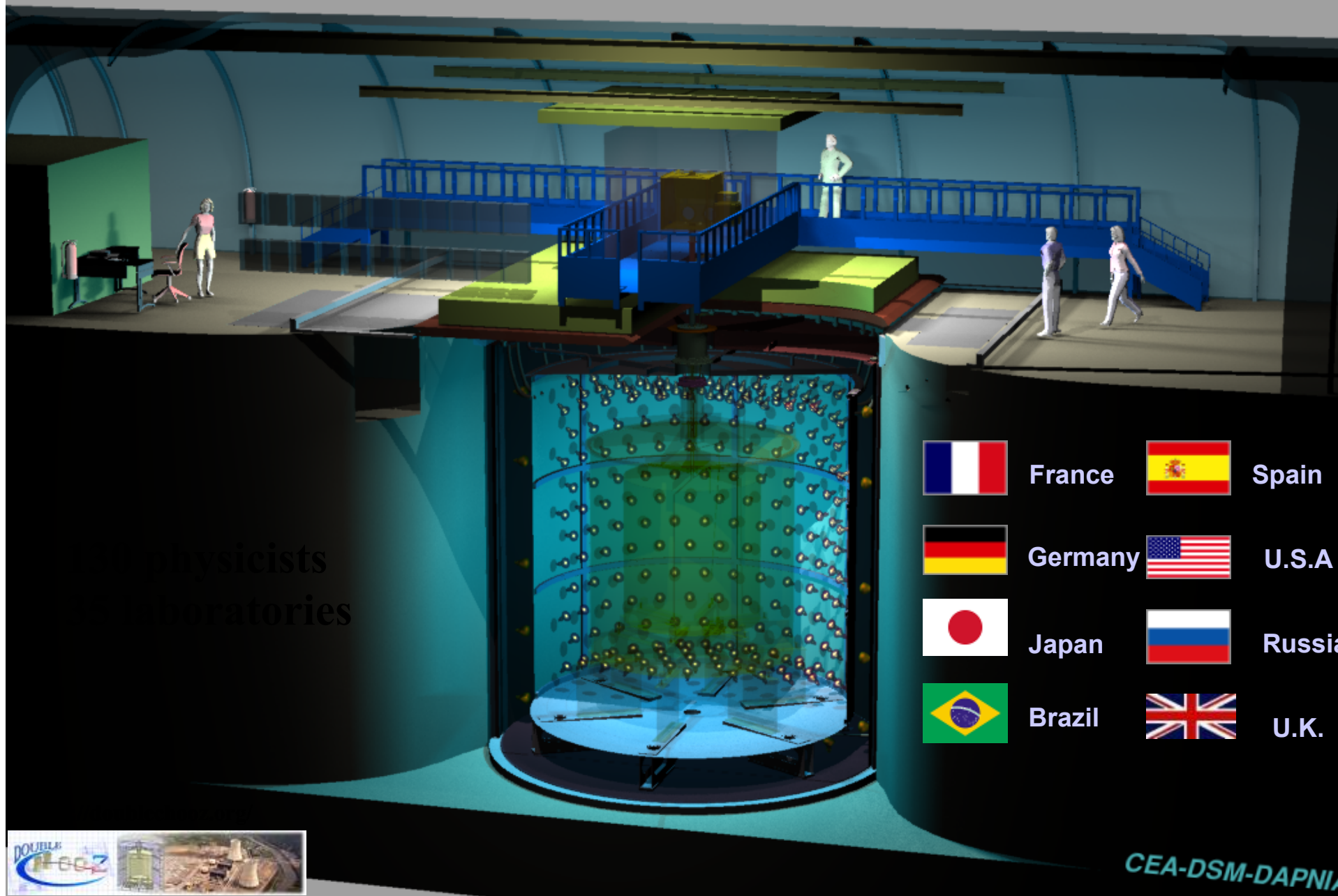
Chooz Nuclear Power Station
2 cores of 4.3 GW_{th} each



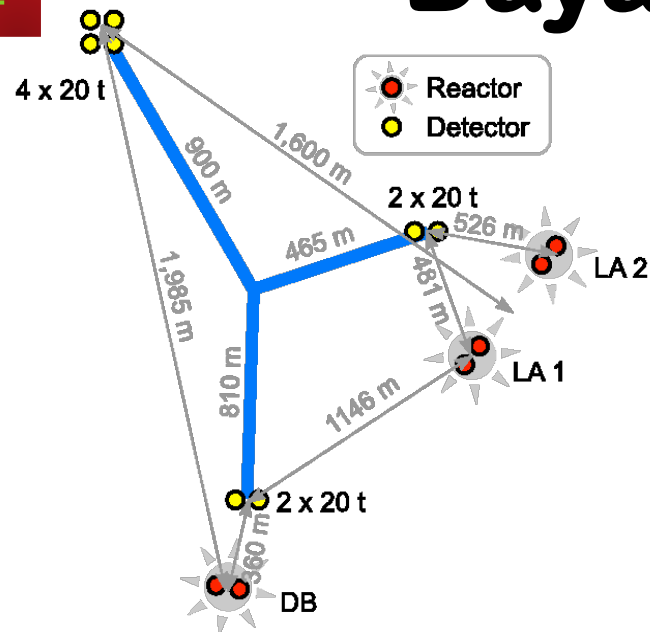
Double Chooz: Site



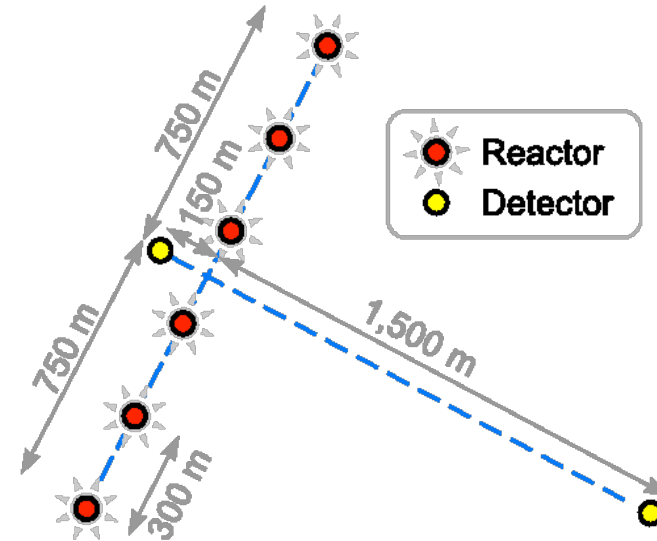
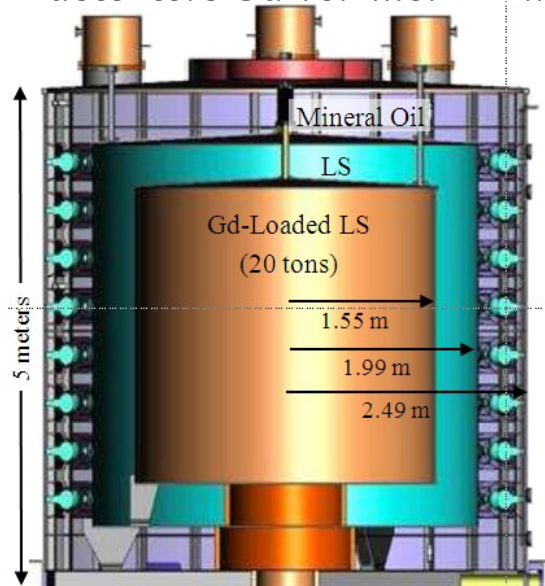
Double Chooz



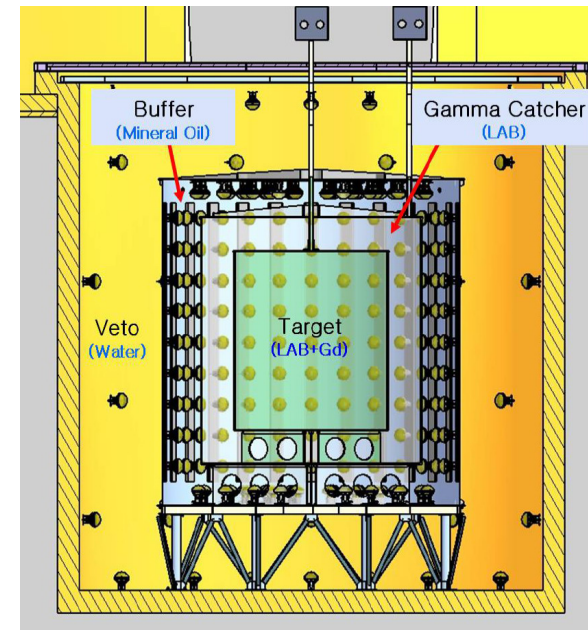
Daya Bay and Reno



8 detectors Gd-volume: 200 m³

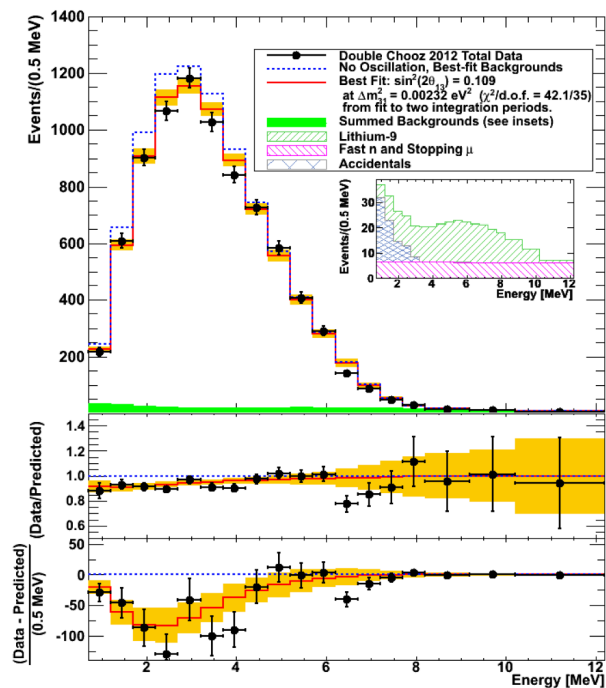


2 detectors, Gd-volume: 40 m³



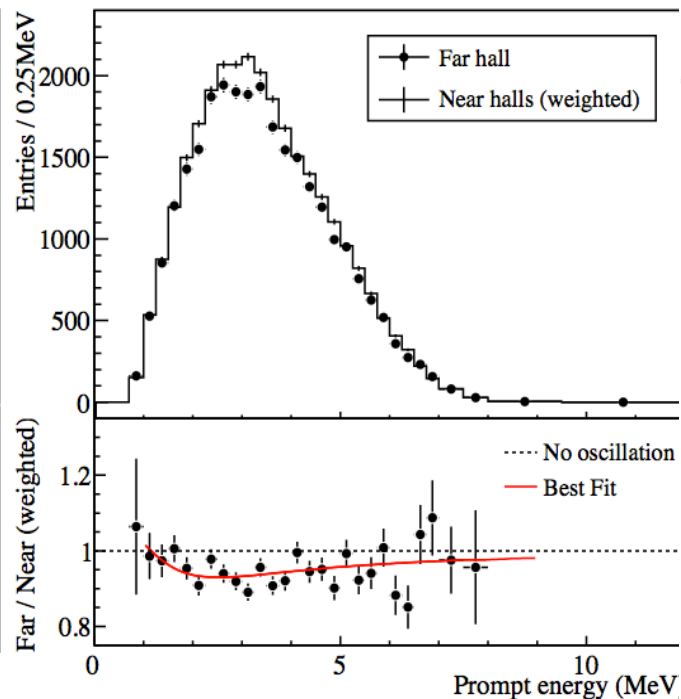
Reactor Results

Double Chooz (Oct. 2011)



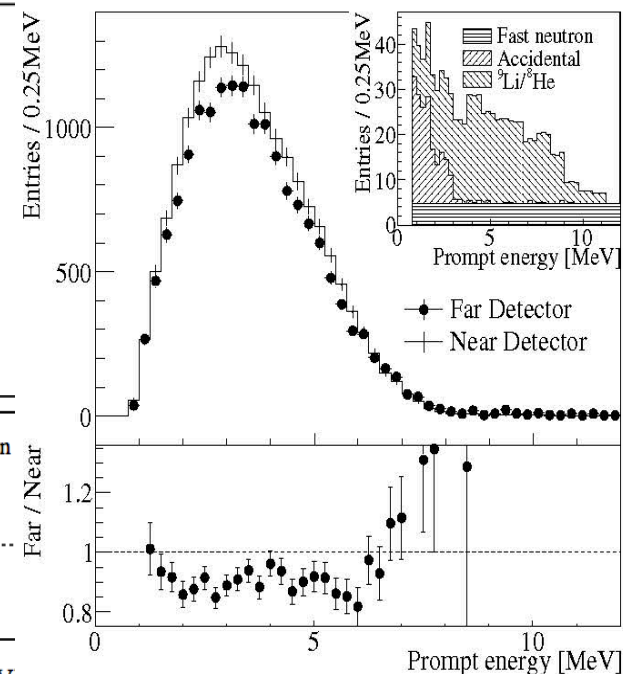
Rate+shape analysis
BG constraints with
reactor off-off data

Daya Bay (March 2012)



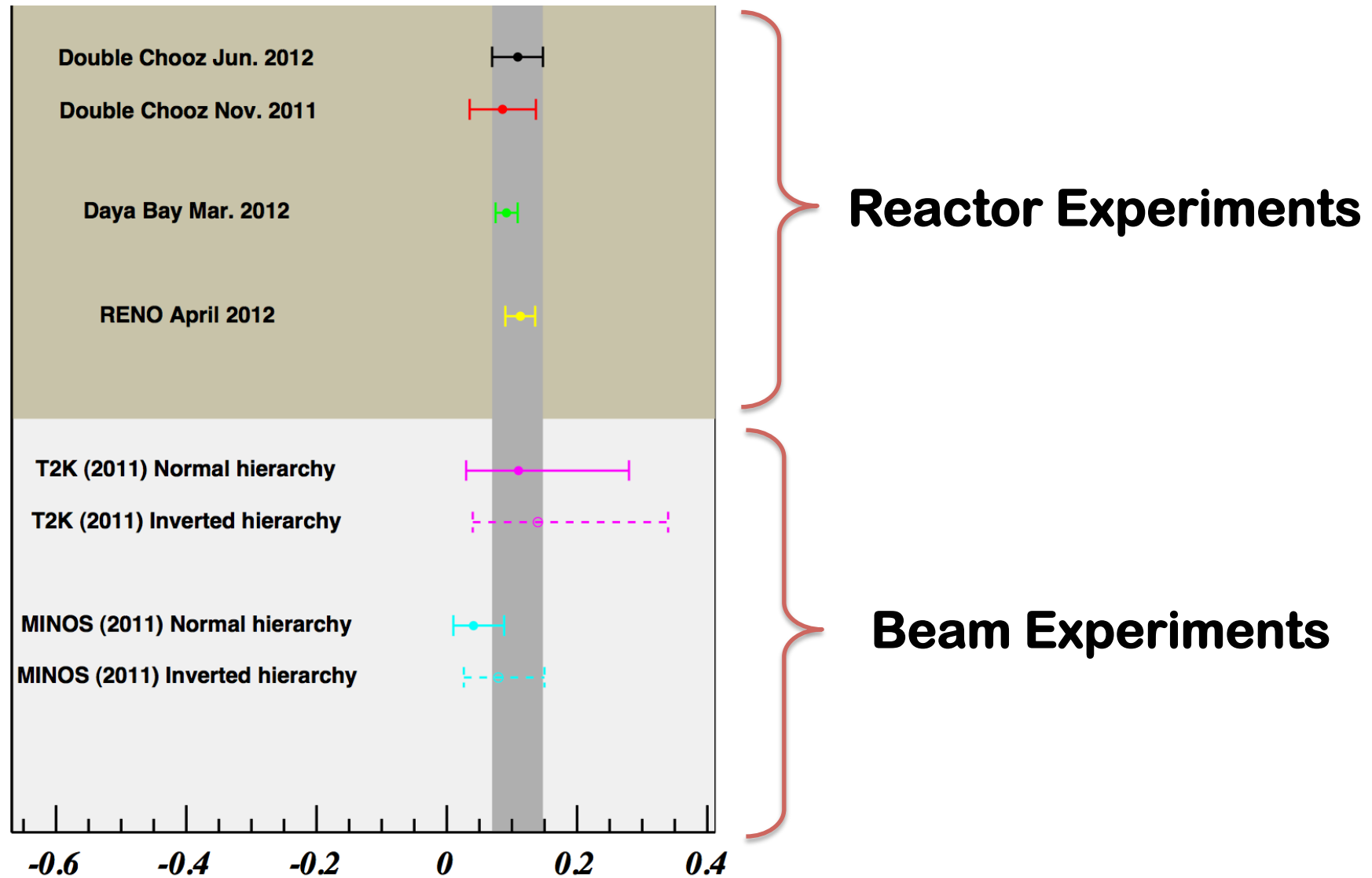
Leading precision
now 15% error
But still rate only analysis
Most accurate measurement

RENO (April 2012)

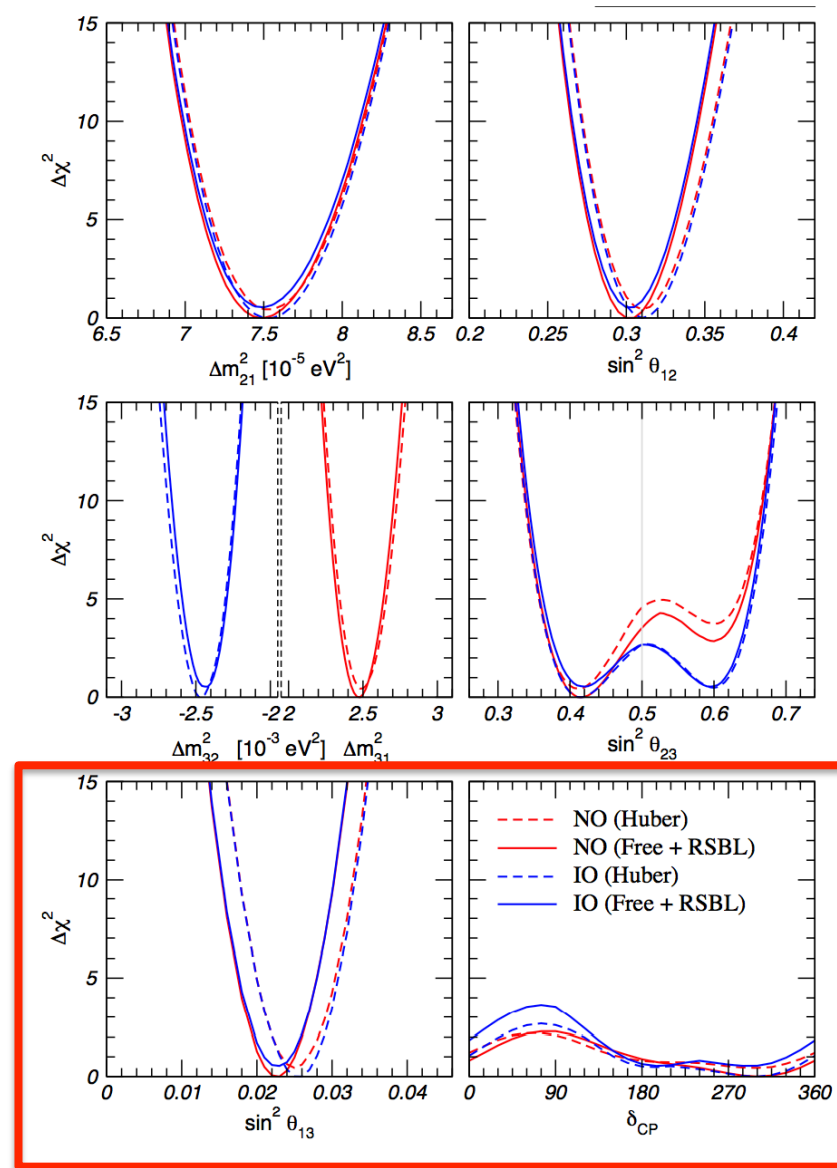
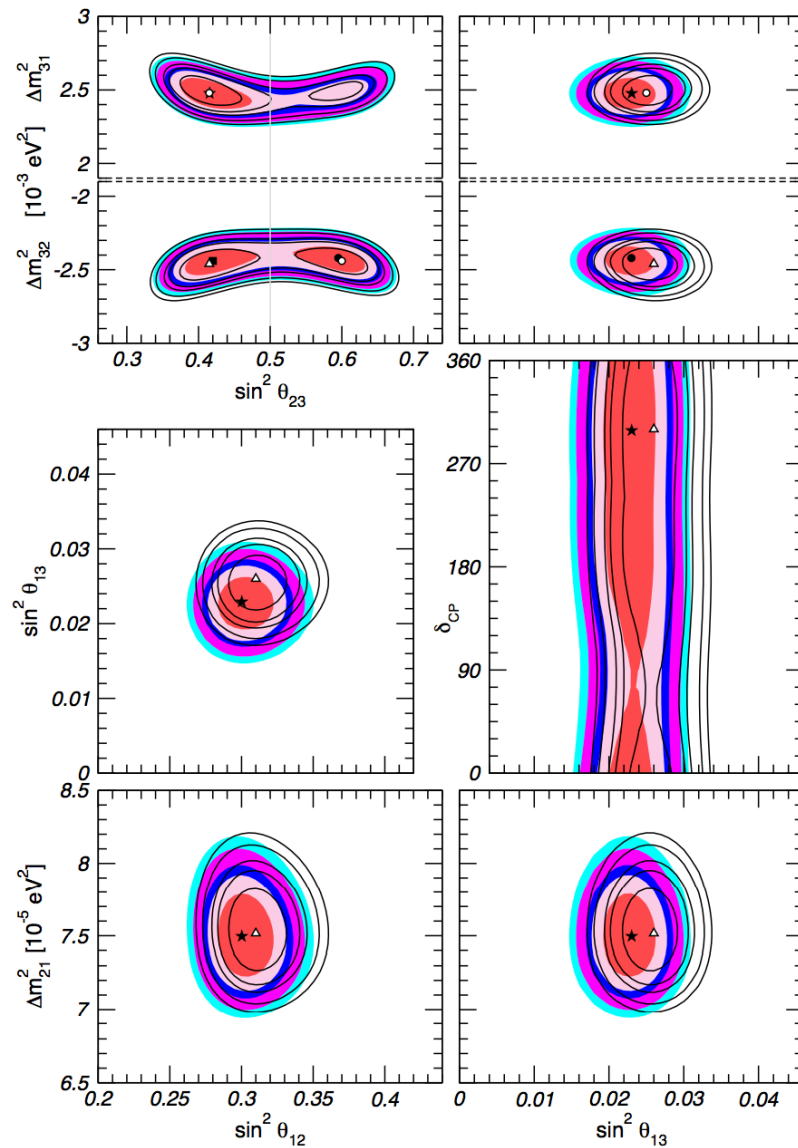


Rate only measurement
Concerns on the analysis

Summary of the θ_{13} Results



Global Fit (NuFit 2012)



First 'constraint' on δ

Question 2)

What is the spectral
mass pattern ?

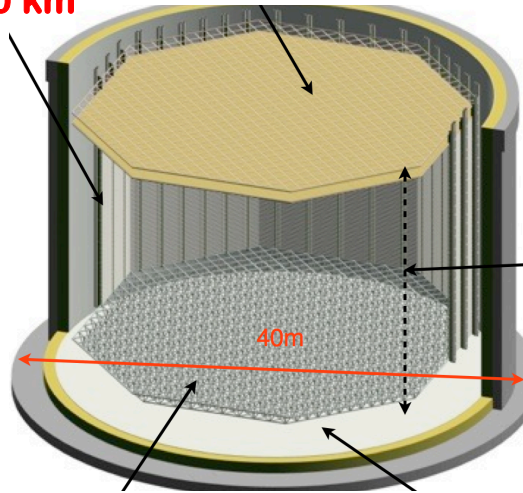
Skipped

Question 3)

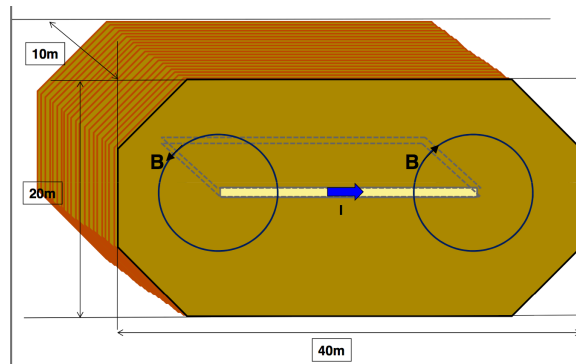
Do the behavior of
 ν violate CP?

MH & CPV: long term projects

L=2300 km



**LBNO (Europe, underground)
20-100 kt LAr +
Magnetic Spectrometer**

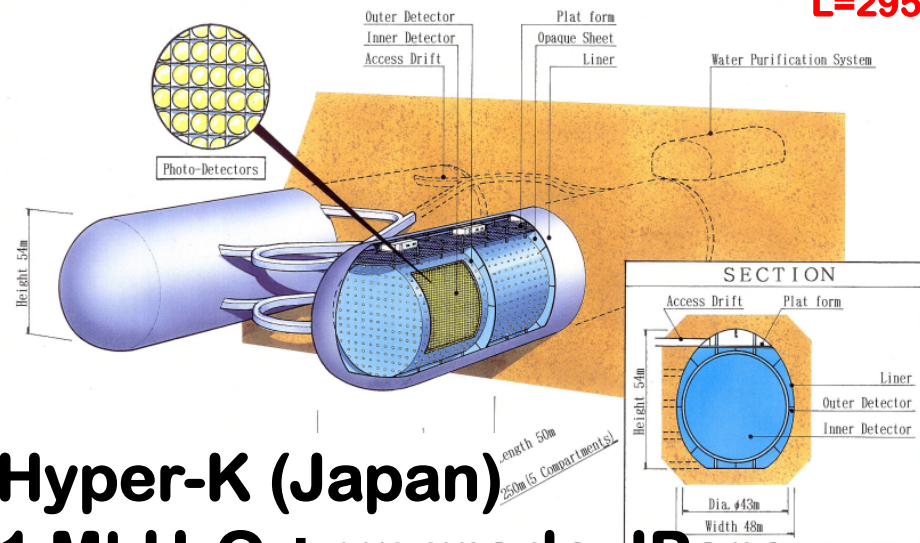


L=1300 km



**LBNE (US)
10 kt LAr
(surface)**

L=295km



**Hyper-K (Japan)
1 Mt H₂O + upgrade JParc**

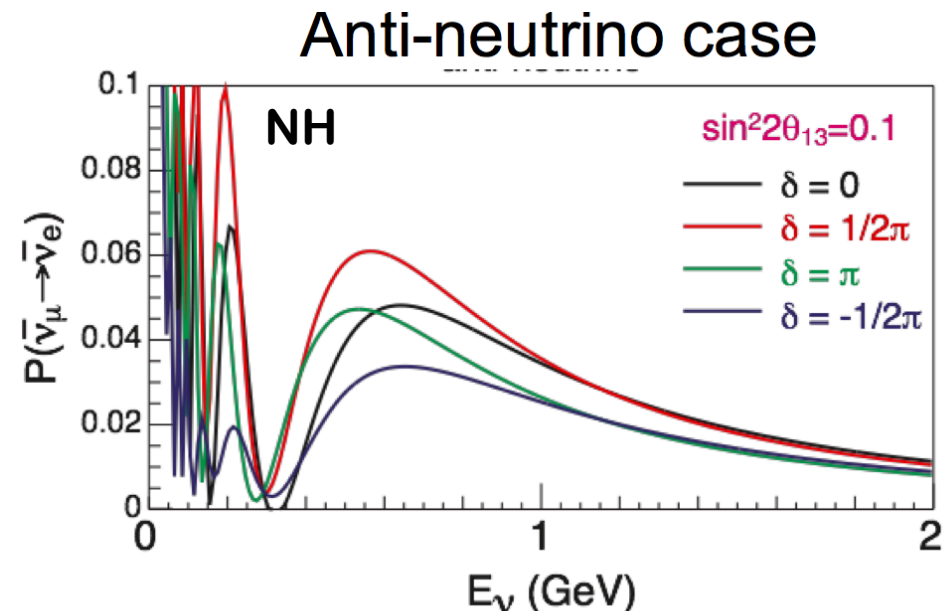
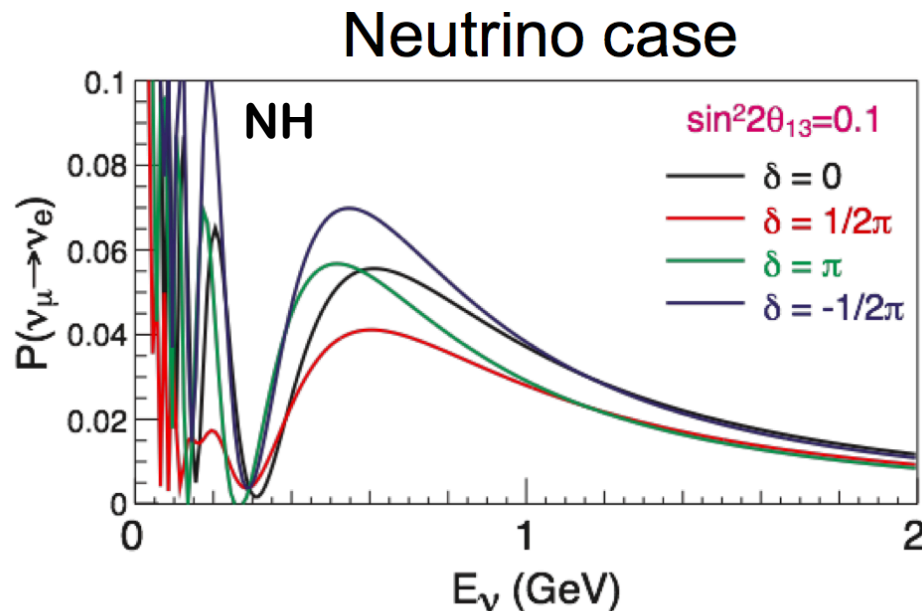
Towards CP-violation Search

$$\left. \begin{aligned} P(\nu_{\mathbf{e}} \rightarrow \nu_{\mathbf{\mu}}) &= |A|^2 + |S|^2 + 2 A S \sin \delta \\ P(\bar{\nu}_{\mathbf{e}} \rightarrow \bar{\nu}_{\mathbf{\mu}}) &= |A|^2 + |S|^2 - 2 A S \sin \delta \end{aligned} \right\} A_{\text{CP}} \propto \frac{P(\nu_{\mathbf{e}} \rightarrow \nu_{\mathbf{\mu}}) - P(\bar{\nu}_{\mathbf{e}} \rightarrow \bar{\nu}_{\mathbf{\mu}})}{P(\nu_{\mathbf{e}} \rightarrow \nu_{\mathbf{\mu}}) + P(\bar{\nu}_{\mathbf{e}} \rightarrow \bar{\nu}_{\mathbf{\mu}})}$$

$$A_{\text{CP}} = \frac{2 A S \sin \delta}{|A|^2 + |S|^2} = \frac{\sin(\Delta m_{12}^2 L/4E) \sin \theta_{12} \sin \theta_{13} \sin \delta}{\sin^2 2\theta_{13} + \text{solar term...}}$$

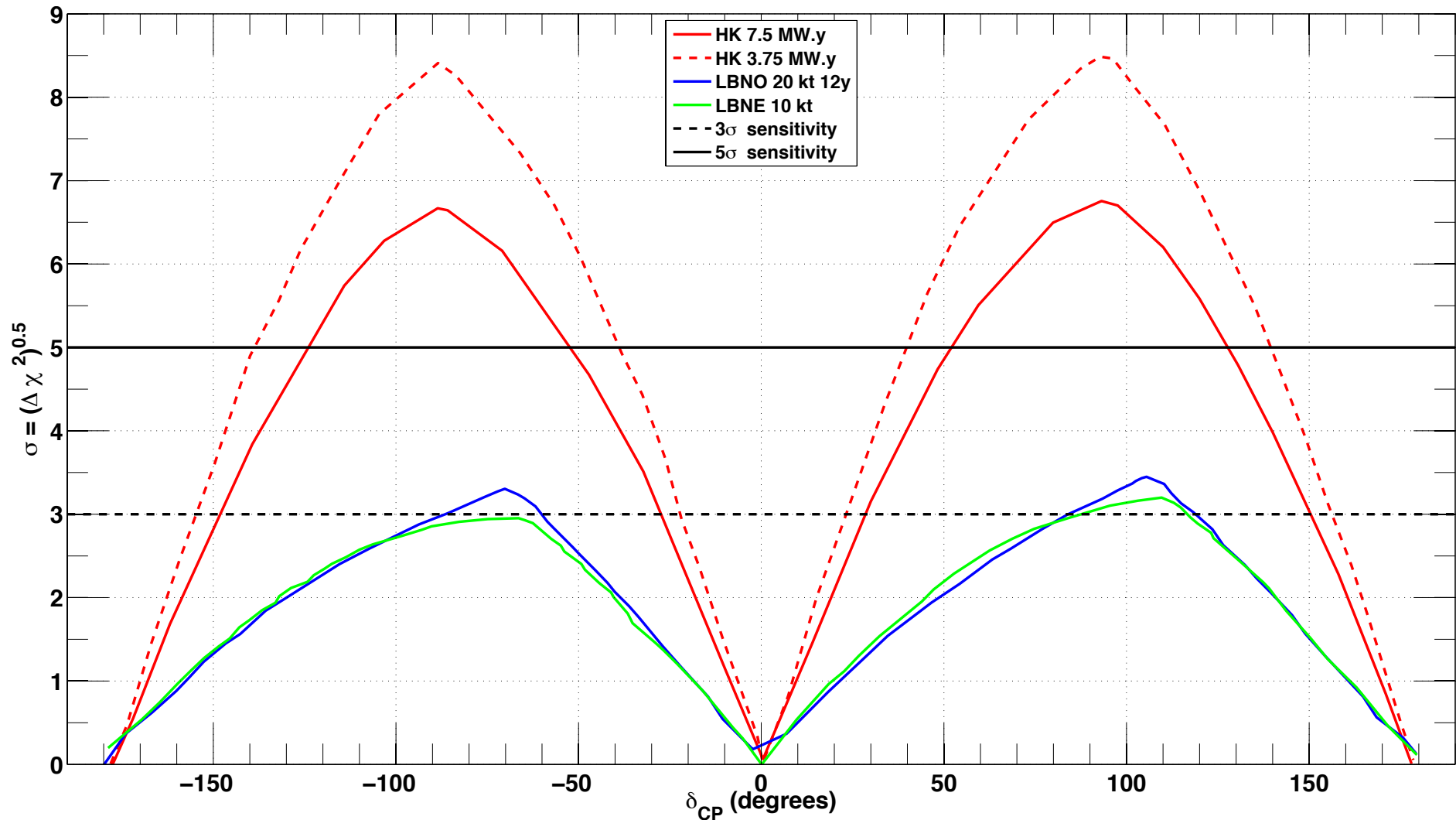
HK: CPV signal ($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$)

- Identity CC ν_e events
- Comparison between $P(\nu_\mu \rightarrow \nu_e)$ & $P(\text{anti-}\nu_\mu \rightarrow \text{anti-}\nu_e)$
 - Up to 25% difference expected
- Need statistics $\rightarrow$ **1 Mt H_2O for HK (x25 SK)**



LBNO(E), HK: CPV Sensitivity

Rejection of the null hypothesis for different CP values

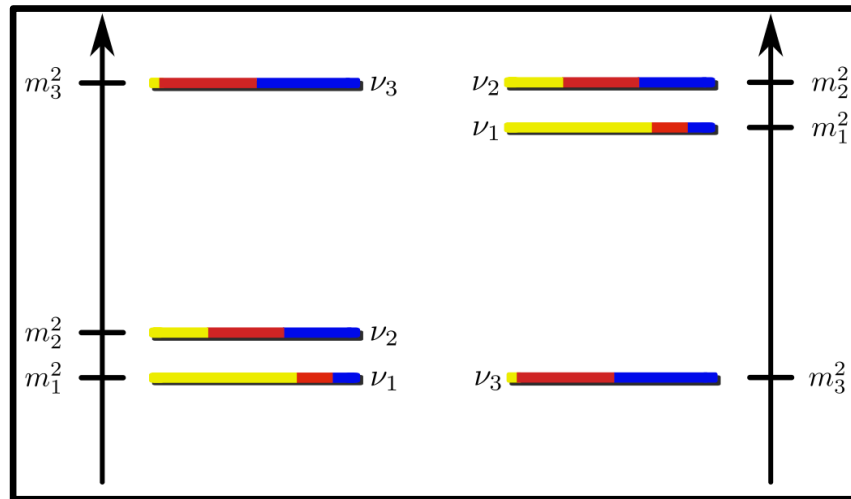


Question 4)

What are the masses of the mass eigenstates ?

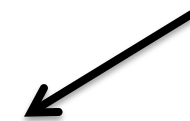
Neutrino Mass Scale

What is the ν Mass Hierarchy?



V_1 V_2 V_3

What set the ν Mass Scale?

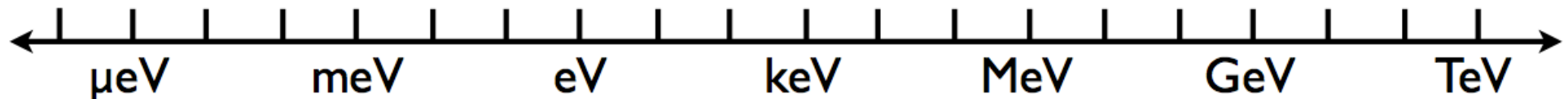


◇ Au

d s b

u c t

e μ τ





Finding the Neutrino Mass Scale

- **Astrophysics**
 - Supernovae, from 1987A $m < 23\text{eV}$
- **Cosmology**
 - CMB+ Large Scale Structures +... - $\sum m_i < 0.6 - 2\text{ eV}$
- **Fermion Decays**
 - μ , τ decays - relatively poor sensitivity
 - β decay
 - $\beta\beta$ decay
- **Neutrino Oscillations**
 - No absolute scale but only square of mass differences

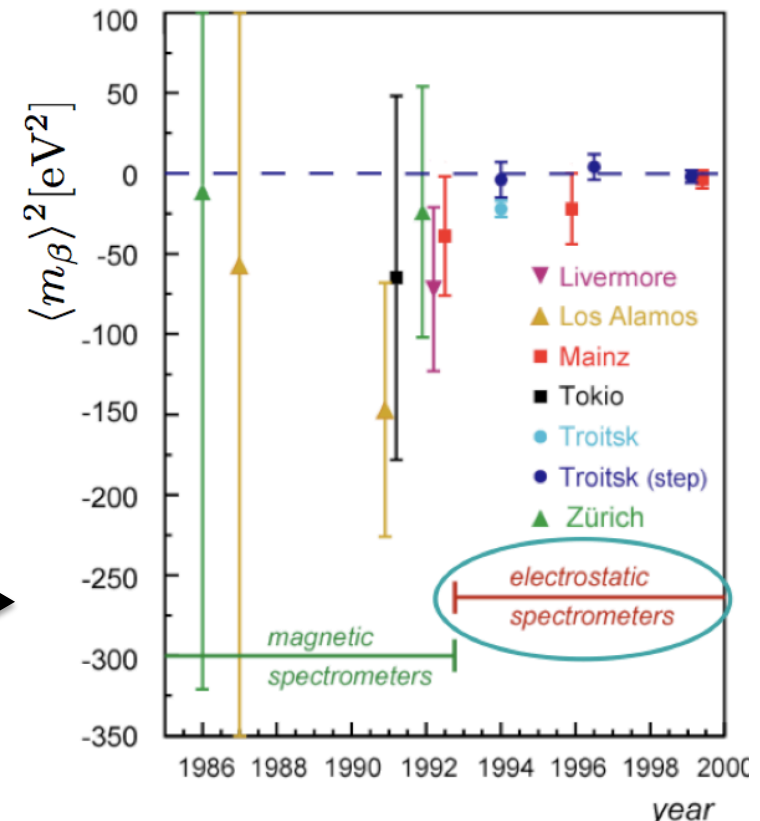
Beta Decay

- **β^- Decay:** ${}_Z^AX \rightarrow {}_{Z+1}^AX + e^- + \bar{\nu}_e$
- **Energy spectrum shape depends on ν mass**
 - Based on kinematics and energy conservation
 - Weak dependence on theory
 - Sensitive to incoherent sum:

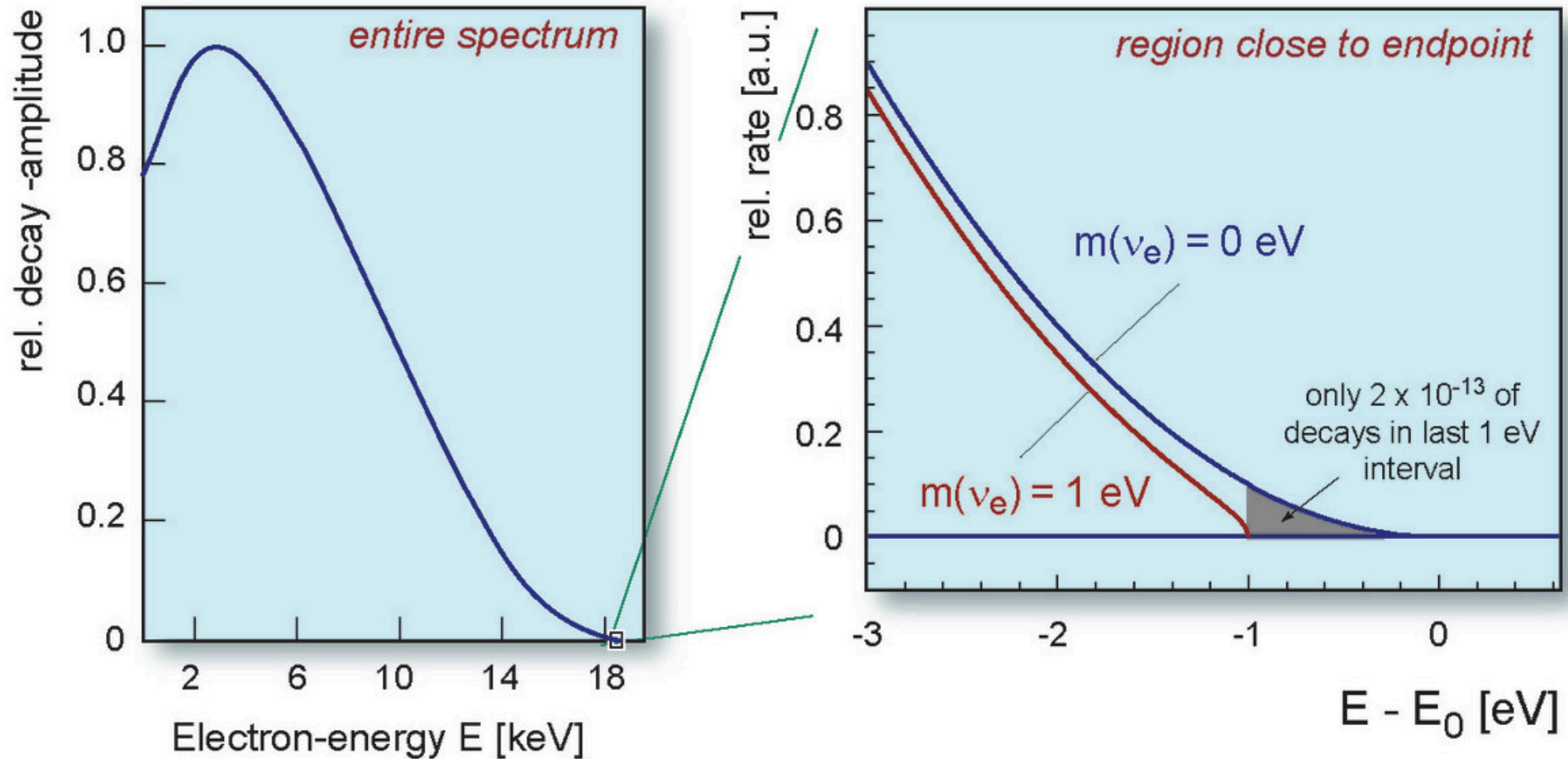
$$\langle m_\beta \rangle = \sqrt{\sum_{1,2,3,..} |U_{ei}|^2 m_i^2}$$

- **Best constraint by Mainz & Troitsk Experiments**

- $\langle m_\beta \rangle < 2.2 \text{ eV}$

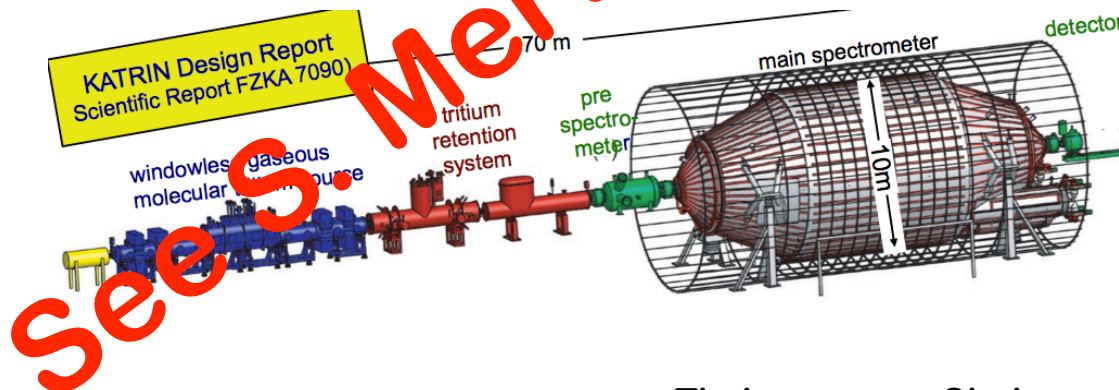


Absolute Mass From Beta decay



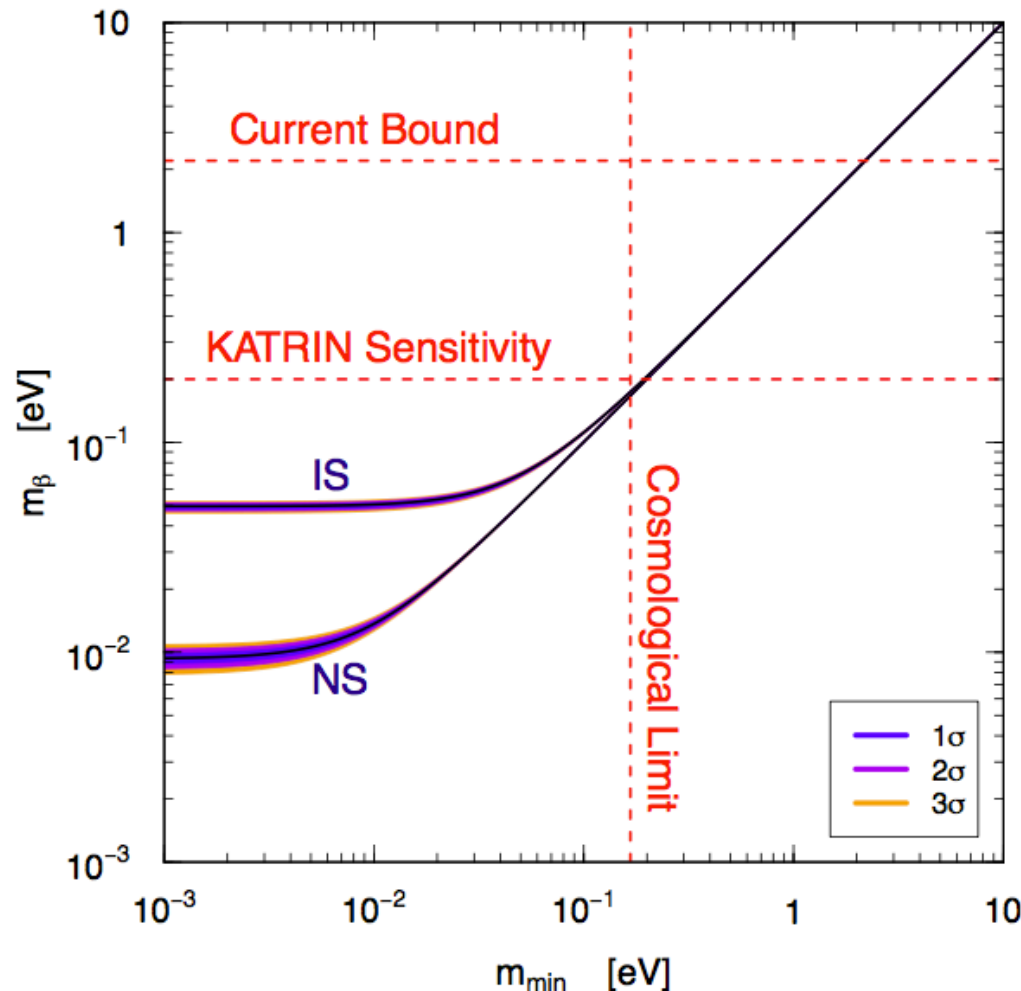
Beta Decay: KATRIN

- Measure both shape and energy of e^- in the last few eV below the Tritium beta decay endpoint energy
- Detector:
 - Gaseous Tritium Source (^3H decay, $t_{1/2} = 12.3$ y, $Q = 18.57$ keV)
 - 10 m diameter Magnetic Spectrometer (MAC-E Filter)
- Status: commissioning detector components. Data in 2015
- 90% C.L sensitivity : 0.2 eV



Prospects of Beta Decay (β)

Direct Measurement of the mass scale but no experimental prospect to disentangle NH & IH



- $\langle m_\beta \rangle = \sqrt{\sum_{1,2,3,\dots} |U_{ei}|^2 m_i^2}$

- **Degenerate:** $\langle m_\beta \rangle = m_\nu$

- **IH:** $\langle m_\beta \rangle = \Delta m_{\text{atm}}^2$

- **NH:** $\langle m_\beta \rangle$ can be $\ll \Delta m_{\text{atm}}^2$

Question 4)

Is there a conserved
Lepton Number? Eq.
Dirac or Majorana ν ?

Double Beta Decay ($\beta\beta$)

- Second-order process only detectable if first-order β decay is energetically forbidden

- **2ν :** ${}^A_Z X \rightarrow {}^A_{Z+2} X + 2e^- + 2\bar{\nu}_e$ (detected)

- $\Delta L=0$

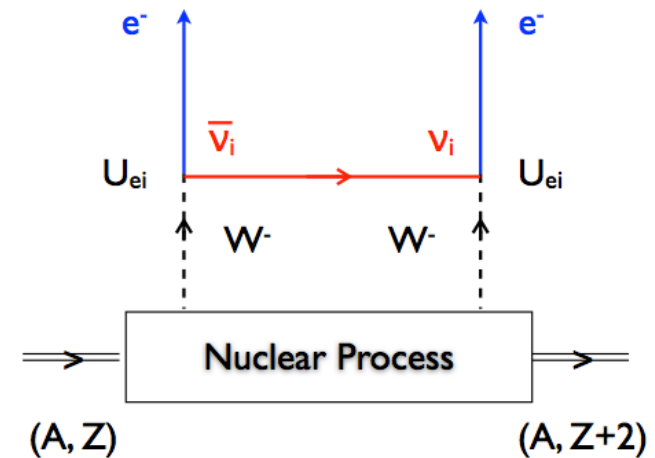
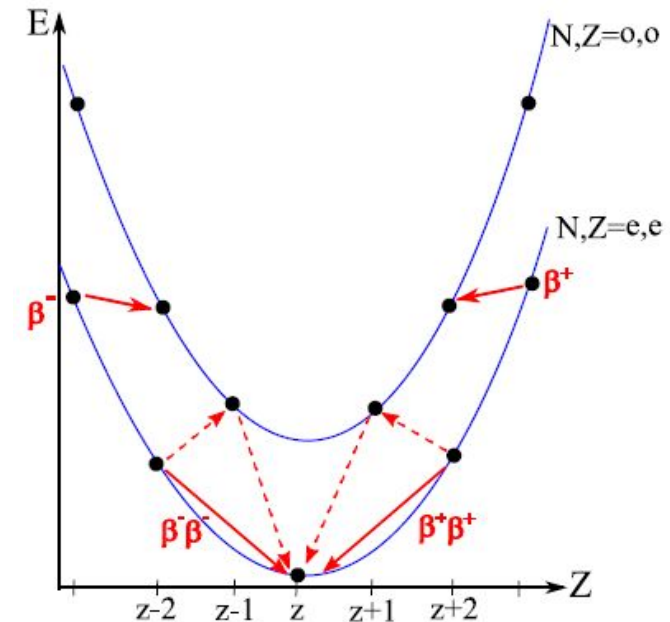
- $(T_{1/2}^{2\nu})^{-1} = G_{2\nu} |M_{2\nu}|^2 \approx 10^{18-21} \text{ y}$

- **0ν :** ${}^A_Z X \rightarrow {}^A_{Z+2} X + 2e^-$ (not yet seen)

- $\Delta L=2$ – Majorana Neutrino

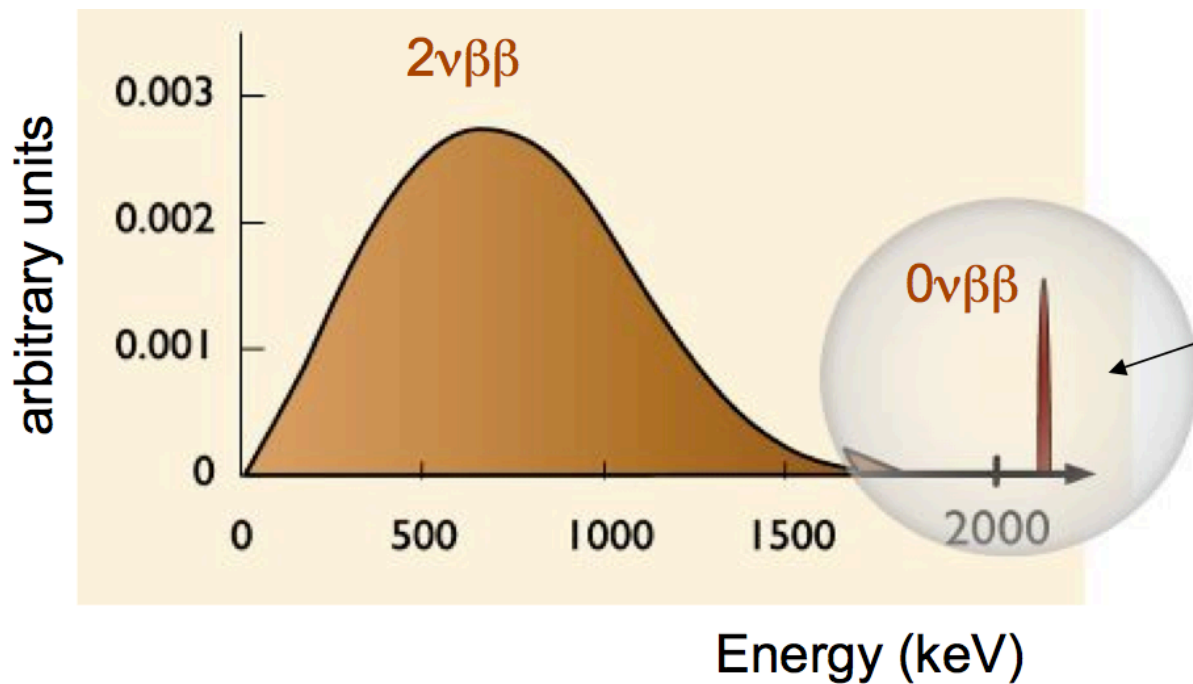
- $(T_{1/2}^{0\nu})^{-1} = G_{0\nu} |M_{0\nu}|^2 |m_{\beta\beta}|^2$

- **$\beta\beta$ mass:** $\langle m_{\beta\beta} \rangle = \left| \sum_{1,2,3,..} U_{ei}^2 m_i \right|$



2ν0β: experimental signature

- Peak at $Q = E_{e1} + E_{e2} - 2m_e \rightarrow$ Calo (Gerda, MJ, Kam-Zen)
- Two electrons from same vertex $\rightarrow$ Tracking (Super Nemo)
- Production of grand-daughter isotope $\rightarrow$ EXO



[Candidates with $Q > 2$ MeV]

Candidate	Q [MeV]	%Abund
$^{48}\text{Ca} \rightarrow ^{48}\text{Ti}$	4.271	0.187
$^{76}\text{Ge} \rightarrow ^{76}\text{Se}$	2.040	7.8
$^{82}\text{Se} \rightarrow ^{82}\text{Kr}$	2.995	9.2
$^{96}\text{Zr} \rightarrow ^{96}\text{Mo}$	3.350	2.8
$^{100}\text{Mo} \rightarrow ^{100}\text{Ru}$	3.034	9.6
$^{110}\text{Pd} \rightarrow ^{110}\text{Cd}$	2.013	11.8
$^{116}\text{Cd} \rightarrow ^{116}\text{Sn}$	2.802	7.5
$^{124}\text{Sn} \rightarrow ^{124}\text{Te}$	2.228	5.64
$^{130}\text{Te} \rightarrow ^{130}\text{Xe}$	2.530	34.5
$^{136}\text{Xe} \rightarrow ^{136}\text{Ba}$	2.479	8.9
$^{150}\text{Nd} \rightarrow ^{150}\text{Sm}$	3.367	5.6

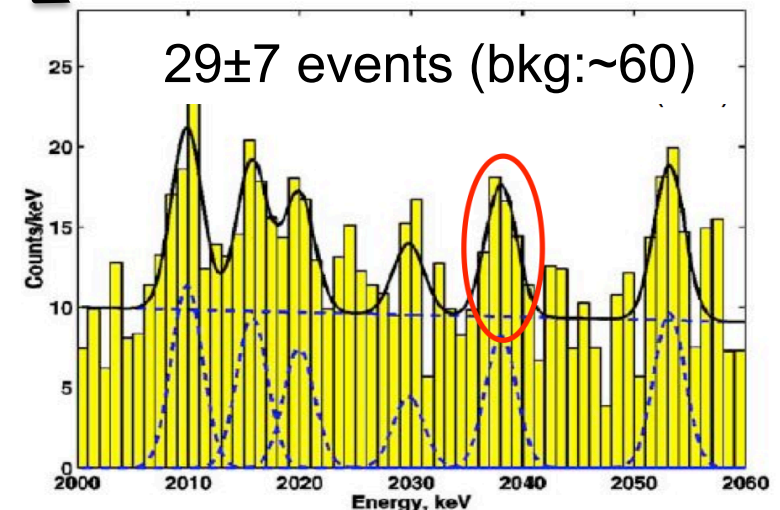
$$T_{1/2}^{0\nu} \propto \epsilon \frac{a}{A} \sqrt{\frac{Mt}{b\Delta E}}$$

Diagram showing the factors influencing the half-life $T_{1/2}^{0\nu}$:

- Detector Efficiency (ϵ)
- Isotopic Fraction (a)
- Atomic Mass (A)
- Detector Mass (M)
- Running Time (t)
- Background Rate (b)
- Detector Resolution (ΔE)

Claim of $0\nu 2\beta$ in Ge

- Part of the Heidelberg-Moscow Coll.
 - 72 kg.year – Bkg 0.1/(kg.y.keV)
- A Majorana ν at large mass scale?
 - Claim of evidence at 4.2σ
 - $T_{1/2} = [0.7-4.2] \times 10^{25} \text{ y}$ (3σ)
 - $|m_{\beta\beta}| = [0.17-0.45] \text{ eV}$ (90% CL)
 - Analysis controversial
- **Benchmark for current projects**
 - Need $O(10^2 \text{ kg.y})$
 - Need background reduction x10

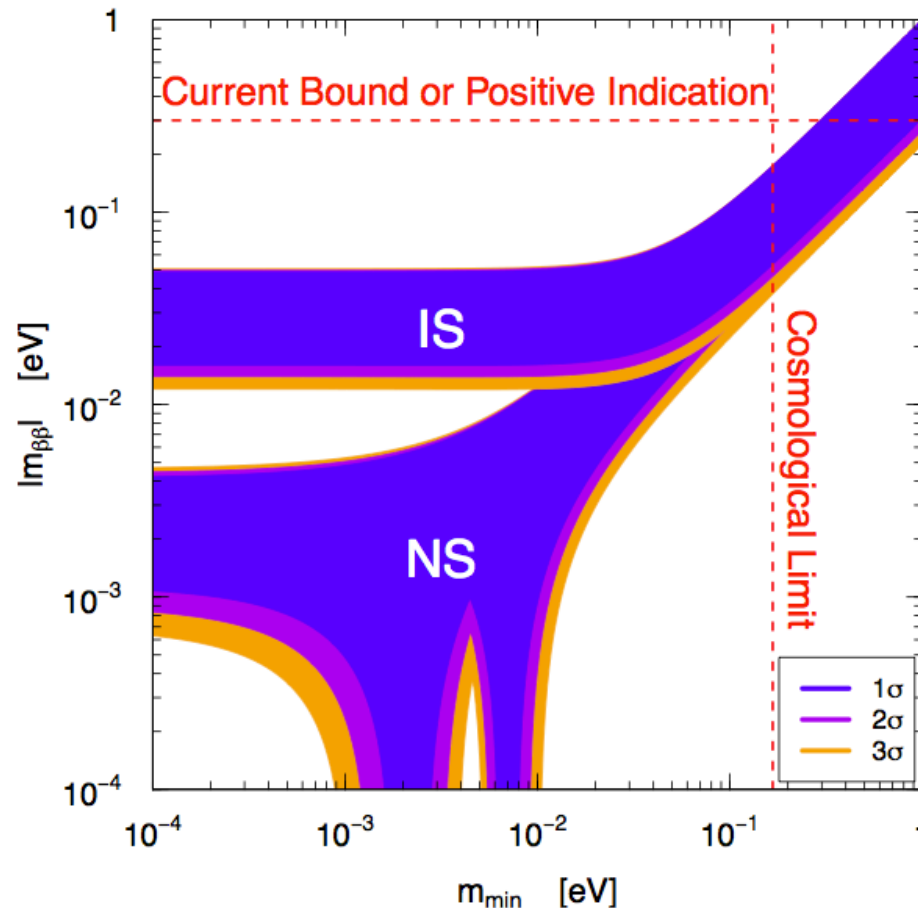


Overview of experiments

Isotope	Experiment	Technique	Mass	Enriched	$Q_{\beta\beta}$ [MeV]	Start/Stage
^{130}Te	Cuoricino	TeO_2 bolometers	40.7kg	No	2.6	Done
$^{82}\text{Se}, ^{100}\text{Mo}$	NEMO-3	tracko-calo	0.9kg/6.9kg	Yes	3.37	Done
^{76}Ge	GERDA	Ge diodes in LN_2	34.3kg	86%	2.04	2009
^{136}Xe	EXO-200	LXe [tracking]	150kg	80%	2.47	2010
^{136}Xe	KamLAND	Isotope in LS	400kg	90%	2.47	2012
^{130}Te	CUORE	TeO_2 bolometers	204kg	No	2.53	2014
^{150}Nd	SNO+	Isotope in LS	56kg	No/50%	3.37	2014
^{76}Ge	Majorana	Ge diodes	30-60kg	86%	2.04	2015
$^{82}\text{Se}, ^{150}\text{Nd}$	SuperNEMO	tracko-calo	100kg	Yes	3.37	2014
^{100}Mo	MOON	tracking	1t	No	3.03	Prototype
^{116}Cd	COBRA	CdZnTe semicond	?	No	2.80	Prototype
^{48}Ca	CANDLES	CaF_2 cryst in LS	few t	No	4.27	Prototype

Prospect of $\beta\beta 0\nu$

- 1- Test the ^{76}Ge Claim – $m_{\beta\beta} \approx 100 \text{ meV} \rightarrow$ ongoing
- 2- Test the IH scheme - $m_{\beta\beta} \approx 10 \text{ meV}$
- 3- Need new ideas / technology - $m_{\beta\beta} \approx 1 \text{ meV} ?$



■ $\beta\beta 0\nu$ implications

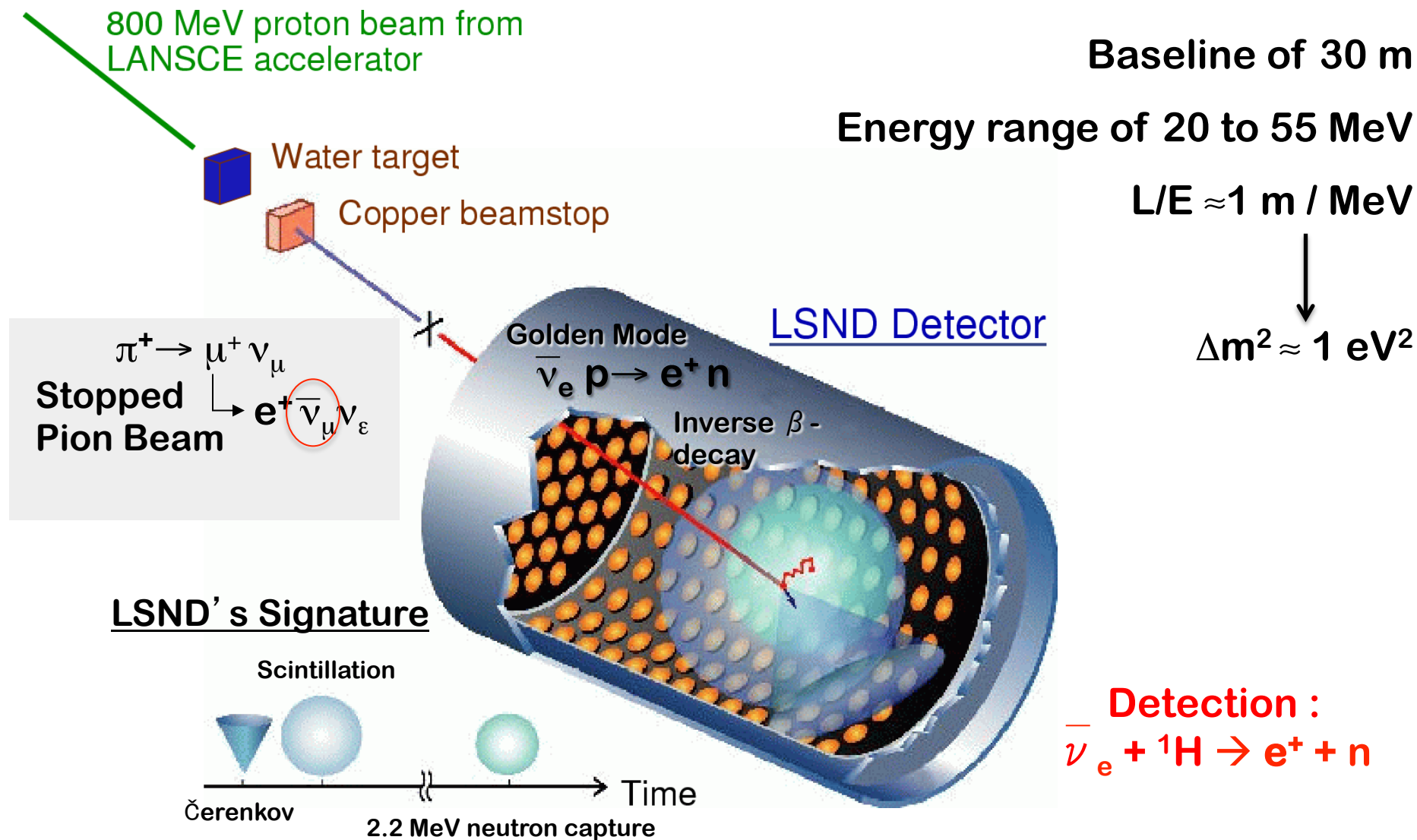
- ν = Majorana
- L number violation
- Credit to See-Saw mass generation mechanisms

Question 5)

Are there additional (sterile) ν states?

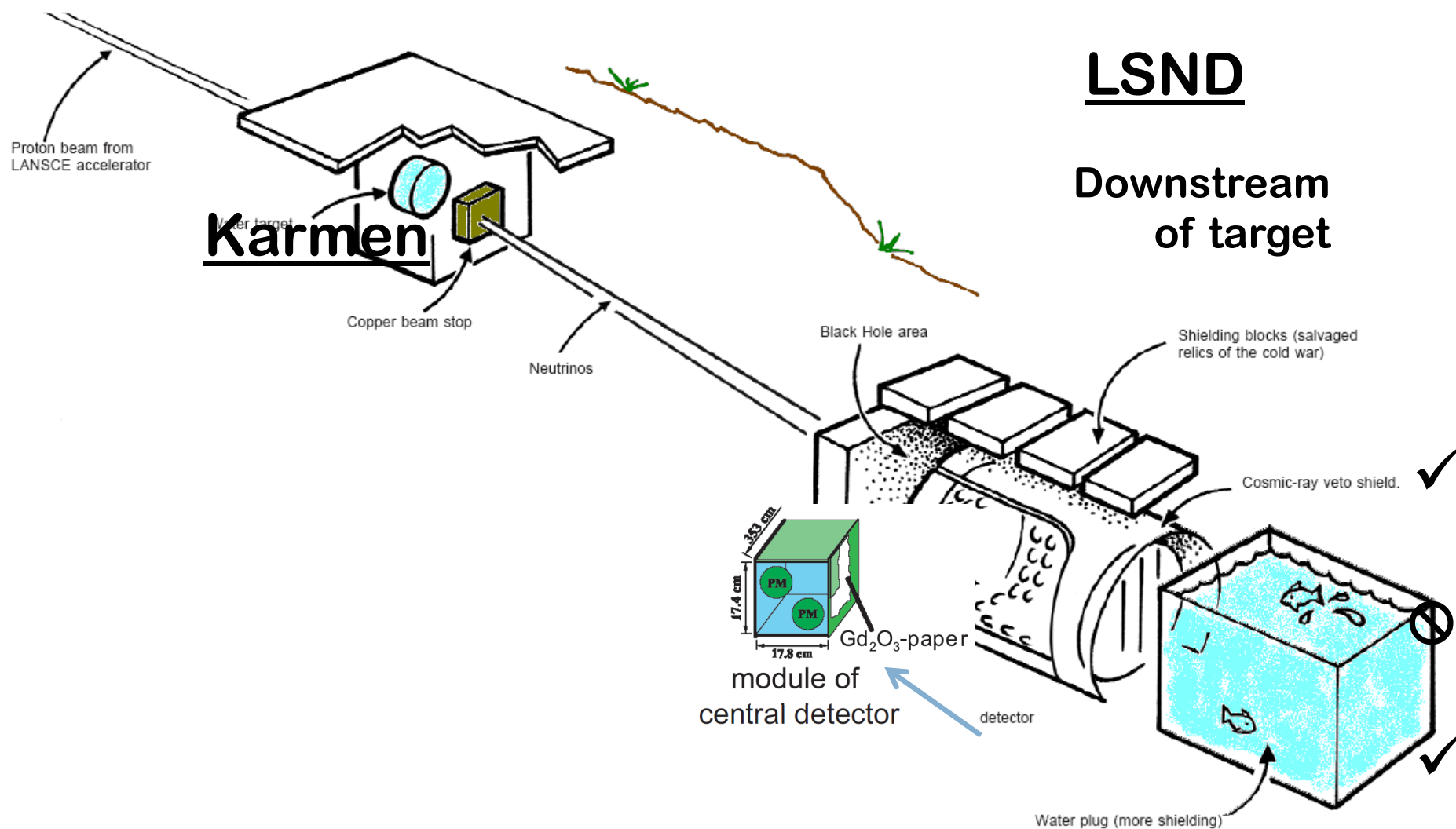
A bunch of Neutrino Anomalies

LSND (Los Alamos, 1993-98)



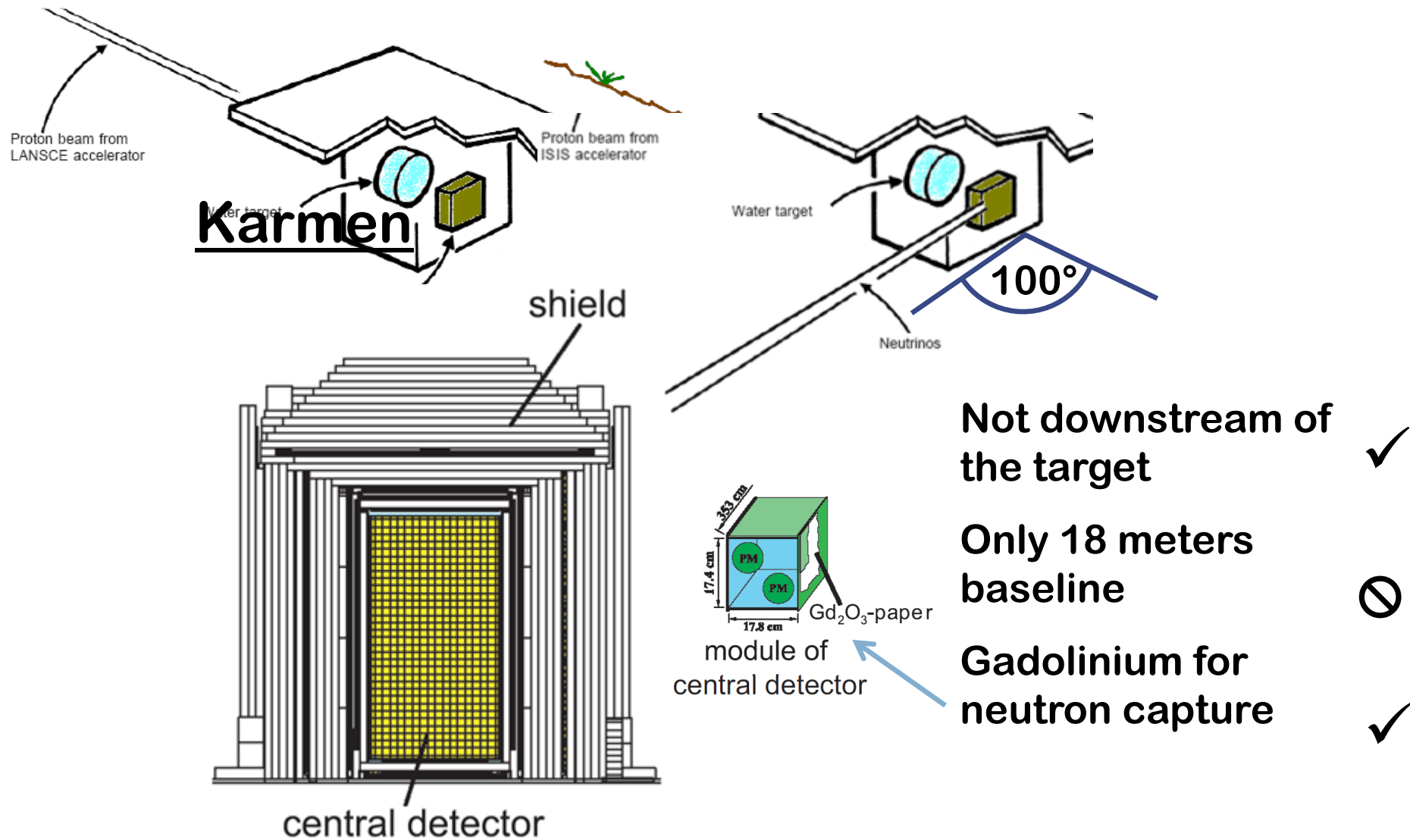
Karmen (stopped π^+ beam)

Oscillation not confirmed – exclude part of LSND



Karmen (stopped π^+ beam)

Oscillation not confirmed – exclude part of LSND



LSND

- 1st results published in PRL 75 (1995)

- Channel:** $\text{anti-}\nu_{\mu} \rightarrow \text{anti-}\nu_e$

- Detection :** $\text{anti-}\nu_e + {}^1\text{H} \rightarrow e^+ + n$

- Baseline:** 30 m

- Energy:** $20 < E \text{ (MeV)} < 200$

- Status:**

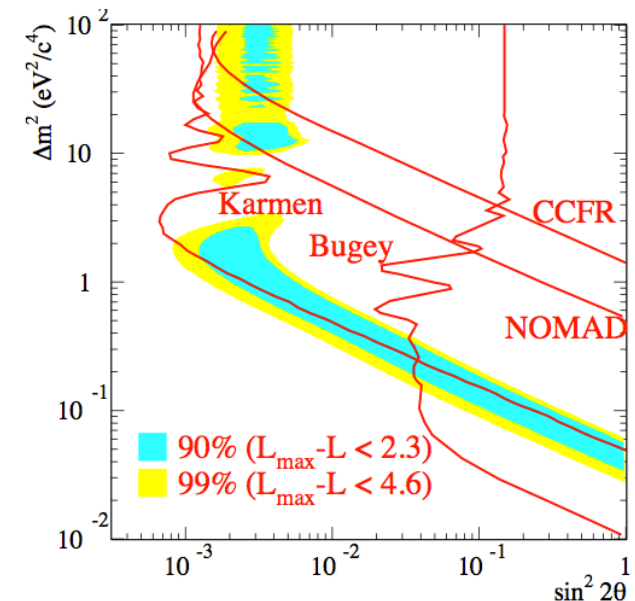
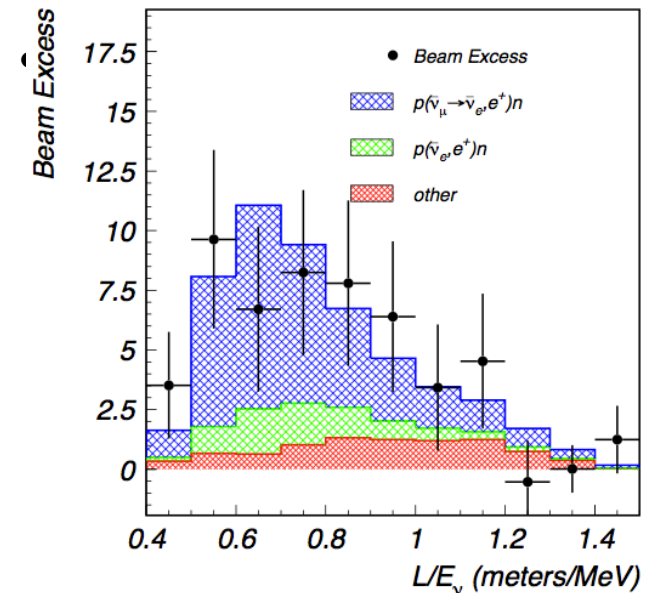
- anti- ν_e excess observed
 $\rightarrow 32.2 \pm 9.4 \pm 2.3 \text{ (} 3.8\sigma \text{)}$

- not confirmed by Karmen

- Oscillation parameters:**

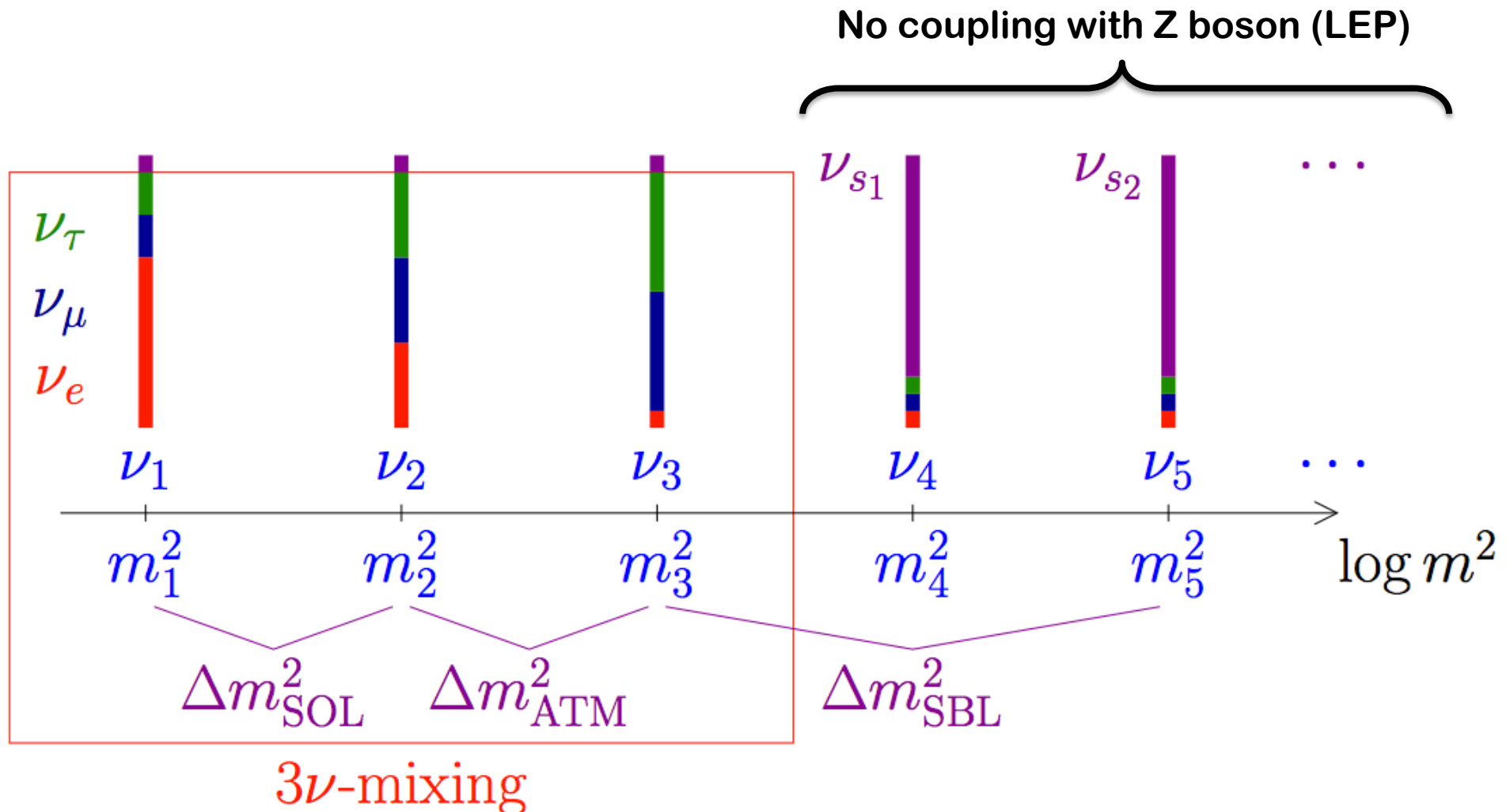
- $\Delta m^2 \gg 0.2 \text{ eV}^2 \gg \Delta m_{\text{atm}}^2$

- Require a 4th neutrino state



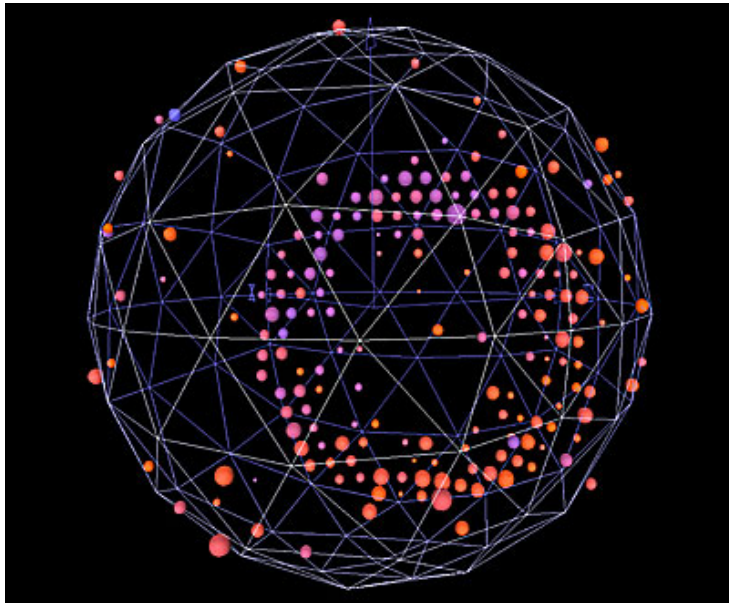
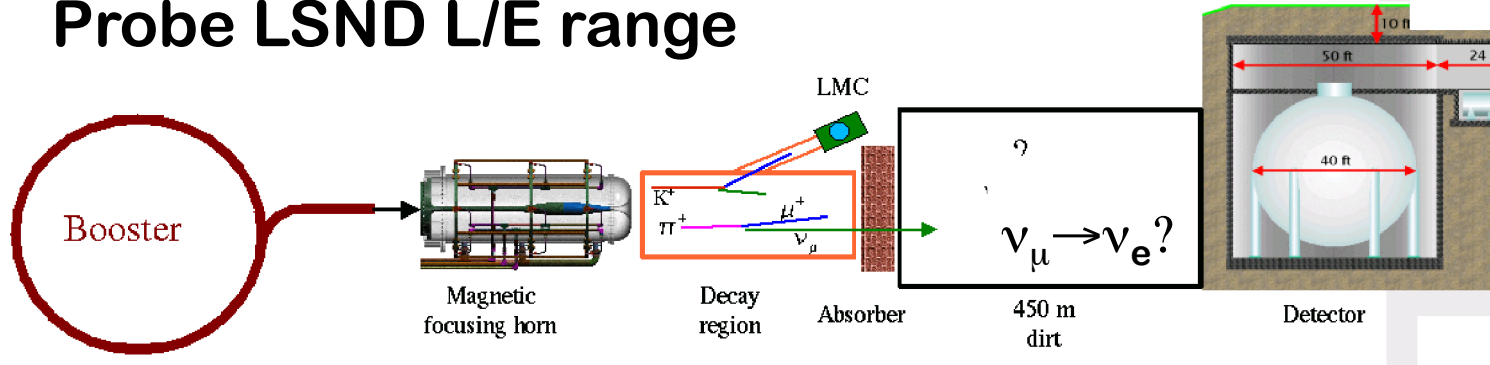
Adding Sterile Neutrinos

Introduce a light ν_R in SM, No SM interactions mixing with active ν 's



The MiniBooNE Experiment

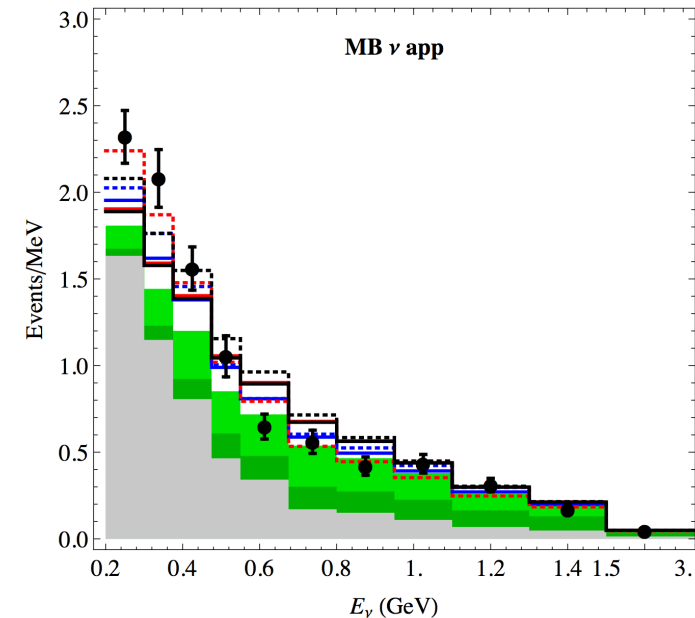
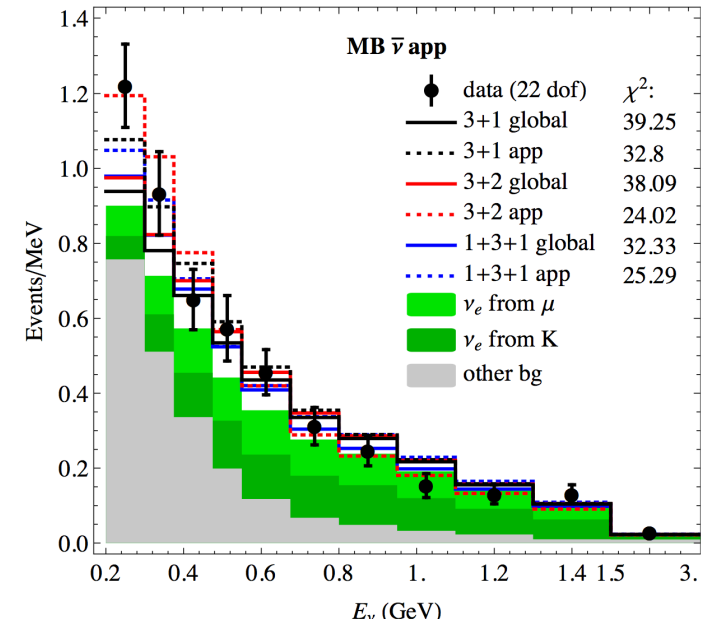
Primary goal: look for ν_e appearance in a ν_μ beam
Probe LSND L/E range



- Cherenkov + scintillation
- π^+ (π^-) decay in flight beam
- $L/E \approx 1 \text{ m / MeV}$
 - Baseline: 500 m
 - $\langle E \rangle 500 \text{ MeV}$
- Started in 2002

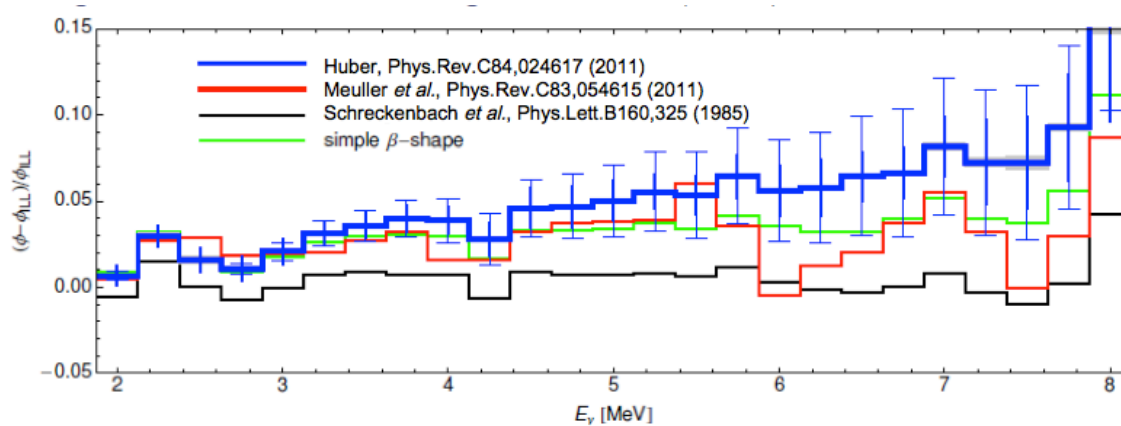
Miniboone Results (FNAL)

- Results published from 20107-12
- **Channel:** $(\text{anti-})\nu_{\mu} \rightarrow (\text{anti-})\nu_e$
- **Detection:** $\nu_e (p)n \rightarrow e p (\text{CCQE})$
- **Baseline:** 541 m
- **Energy:**
 - 200 < E (MeV) < 3000
- **Status:**
 - Excess of event at low energy
 - 3.8σ
 - 4th neutrino?
 - Backgrounds issue?



The Reactor Anomaly

- i) **V_{emission}**: Improved reactor neutrino spectra $\rightarrow$ +3.5%



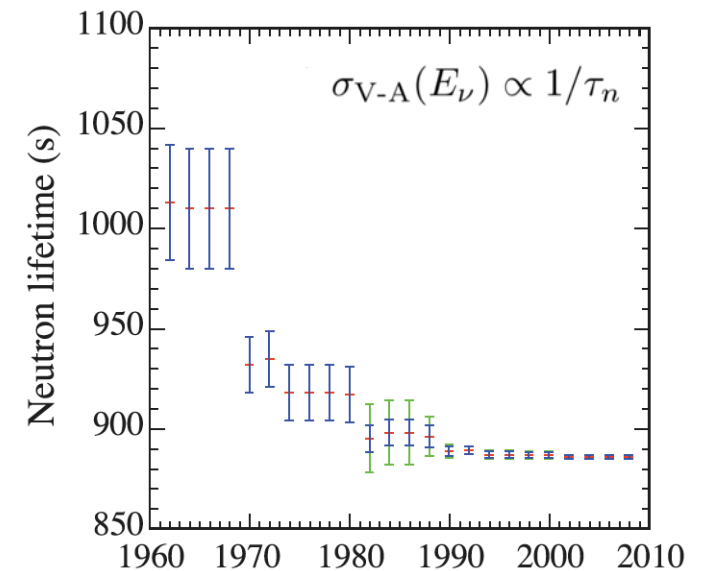
PRC83, 054615 (2011)

PRC84, 024617 (2011)

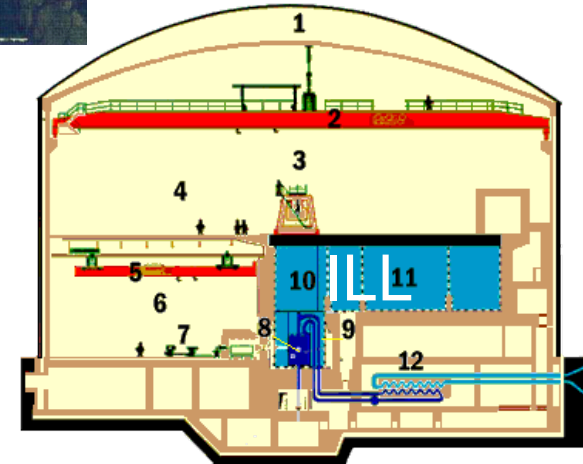
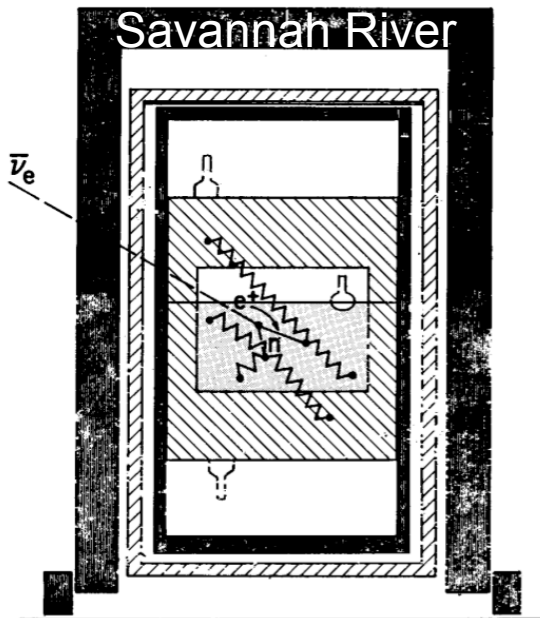
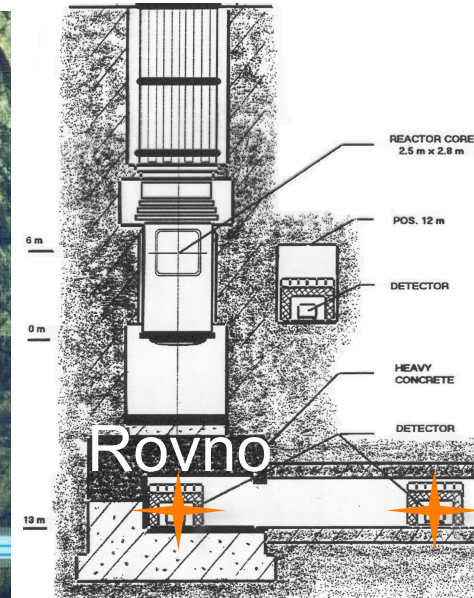
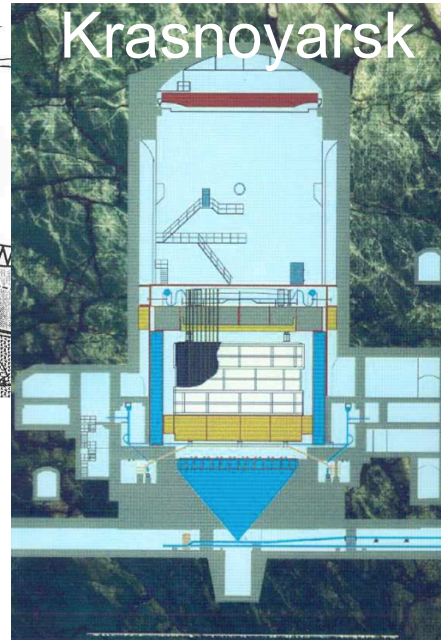
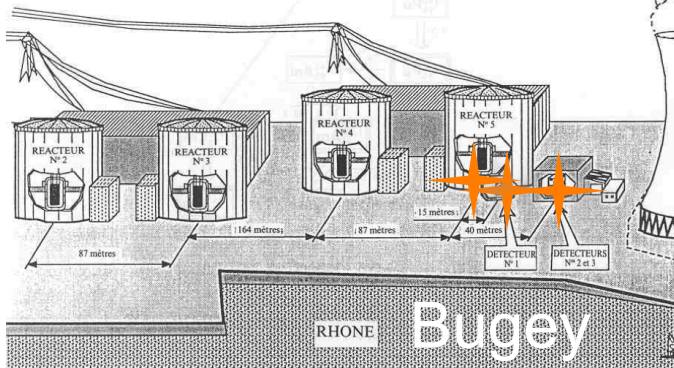
- ii) **V_{detection}**: Reevaluation of σ_{IBD} $\rightarrow$ +1%
Evolution of the neutron life time

- iii) **V_{detection}**: Accounting for long-lived isotopes accumulating in reactors $\rightarrow$ +1%

PRD 83, 073006 (2011)

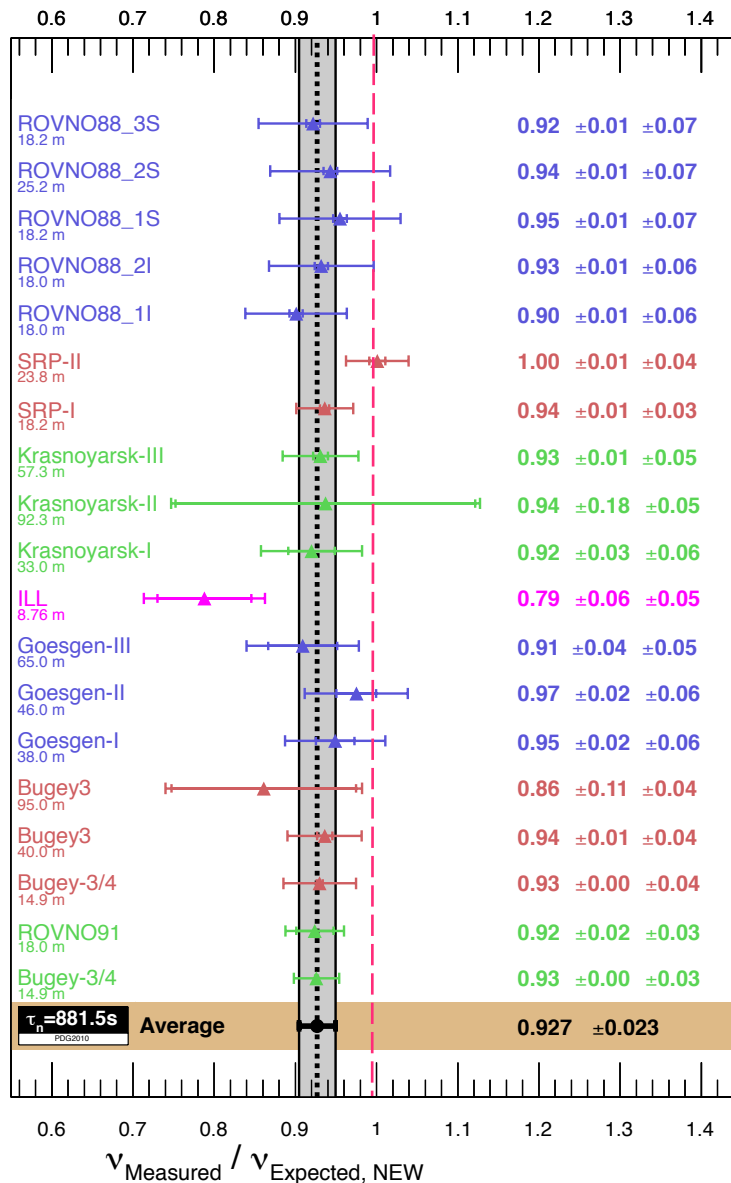


19 Experimental Results below 100m



Measured cross sections / fission taken at their face values

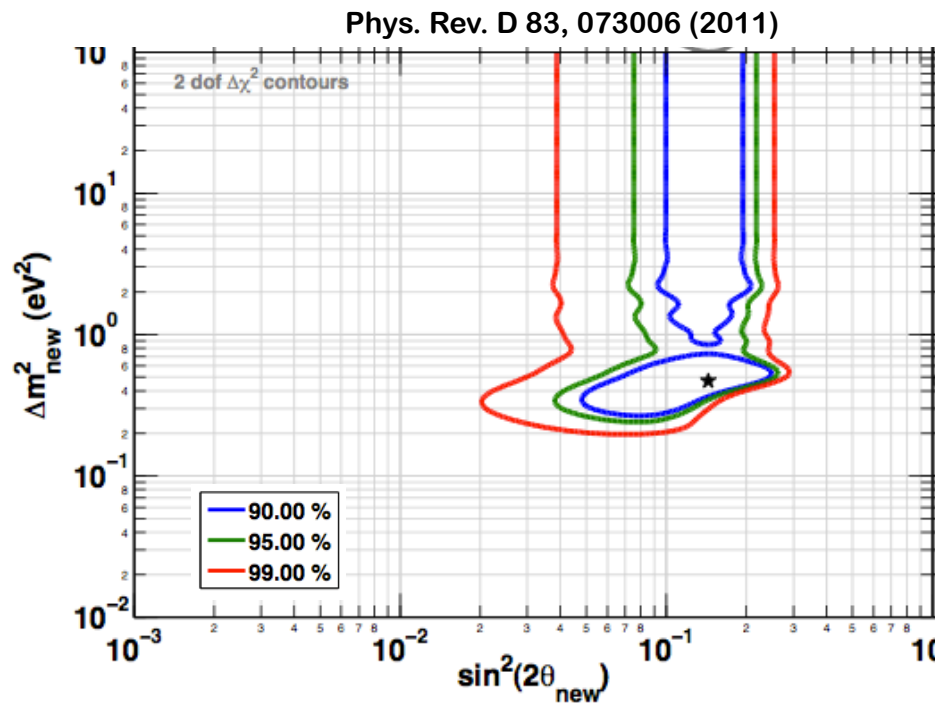
The reactor anomaly



- 19 experiments reanalyzed
PRD 83, 073006 (2011)
- **7% deficit wrt the new prediction**
 - $\approx 3\%$: reevaluation of emitted flux
 - $\approx 3\%$: reevaluation of
 - IDB cross section revision
 - Accounting for off eq. effect
- **99.7 % C.L. deviation from unity**
- **Artifact or new physics?**

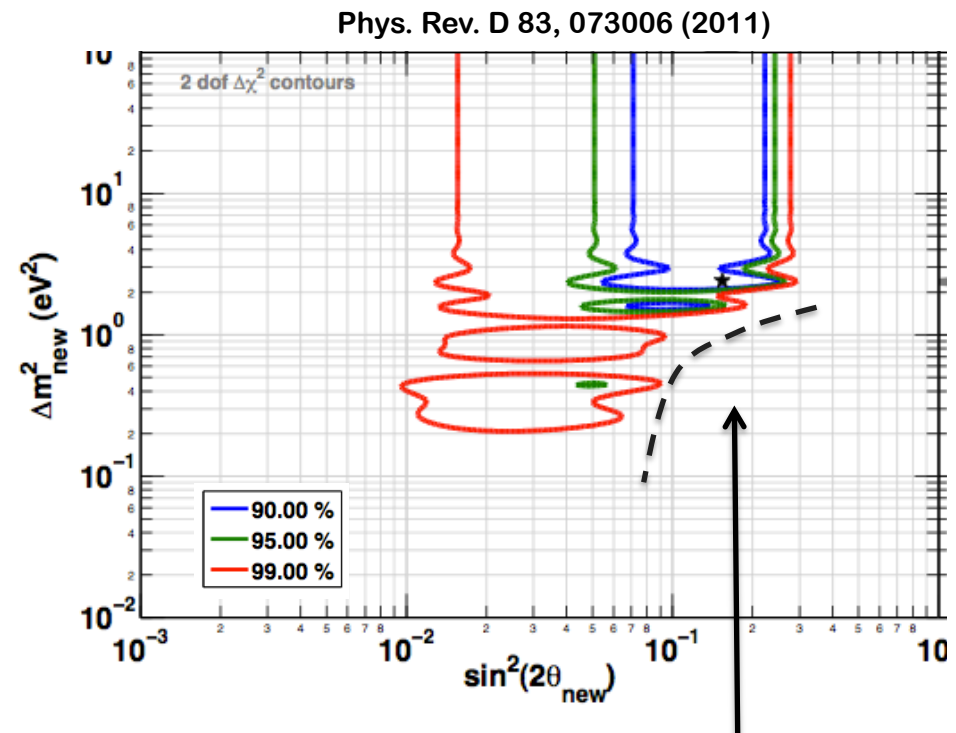
The 4th neutrino hypothesis

Rate Only Analysis



- Best Fit at $\Delta m^2_{\text{new}} \approx \text{few } 0.1 \text{ eV}^2$

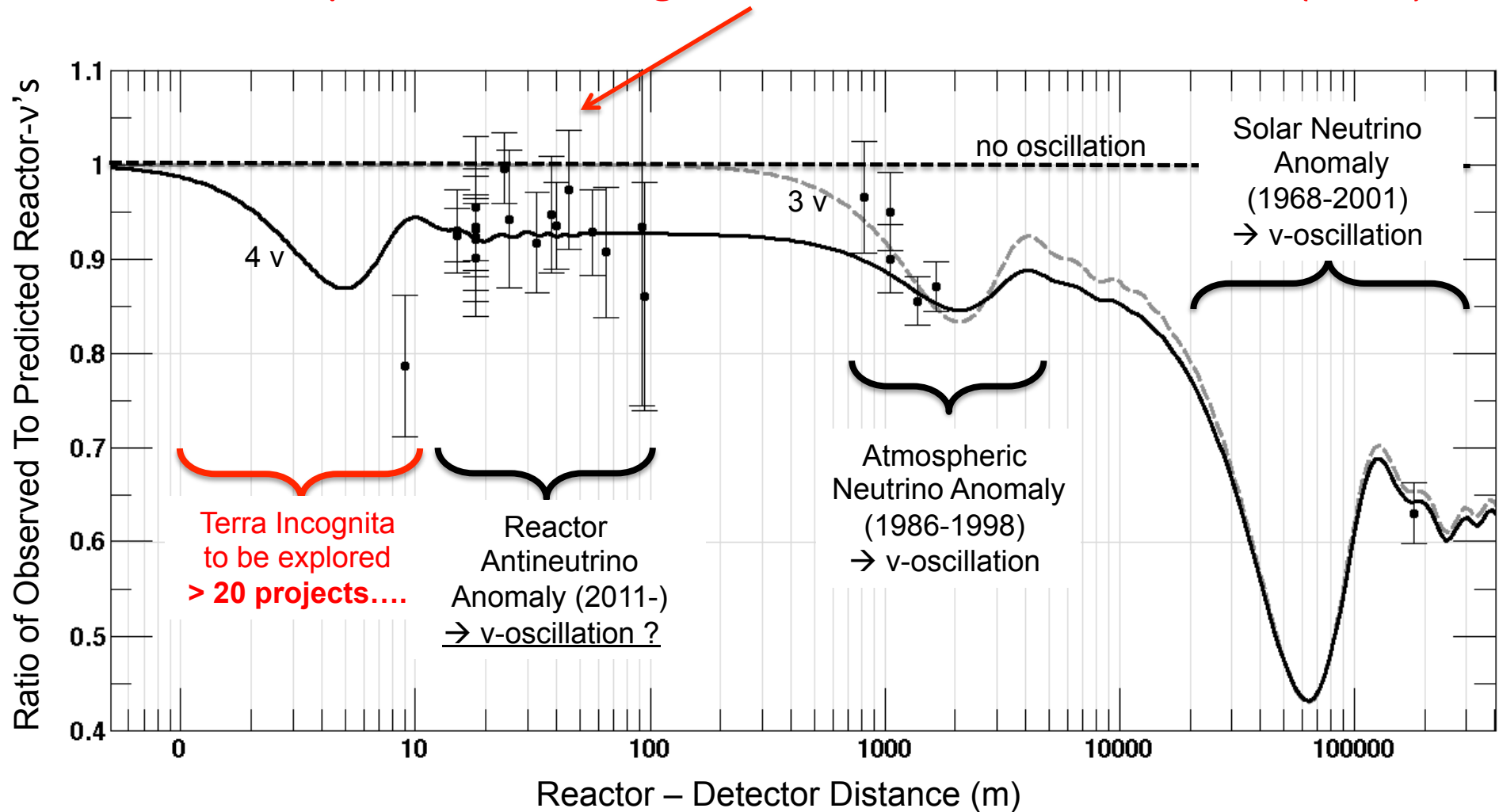
Rate + Shape Analysis



- Bugey-3 40m/15m E_{spectrum} ratio
→ No energy spectrum distortion
→ large PWR core extension
- Best Fit at $\Delta m^2_{\text{new}} > 1 \text{ eV}^2$

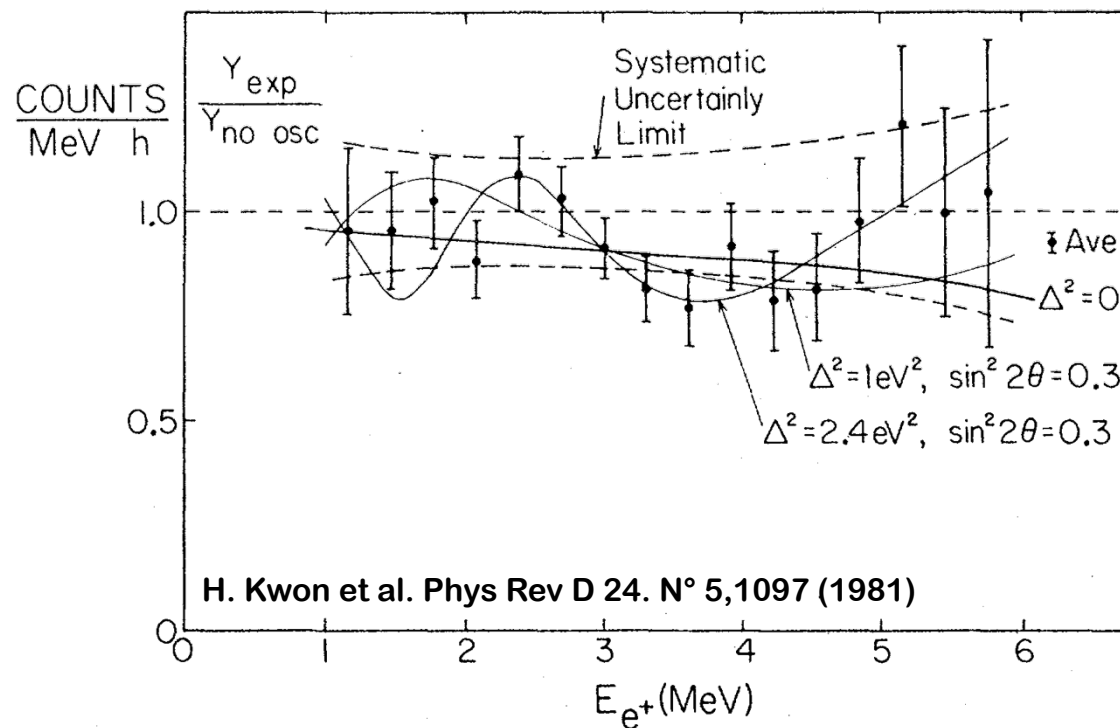
The Reactor Anomaly

- Observed/predicted averaged event ratio: $R=0.927\pm0.023$ (3.0σ)



Puzzling 1981 ILL v-experiment

- Reactor at ILL with almost pure ^{235}U , with compact core
- **Detector 8.8 m from a COMPACT core**
- Reanalysis in 1995 to account for overestimation of flux at ILL reactor by 10%... Affects the rate only but **20% deficit!**



- Large errors, but a striking pattern is seen by eye ?

The Gallium Neutrino Anomaly

- Test of solar neutrino detectors
GALLEX and SAGE (ν_e 's)

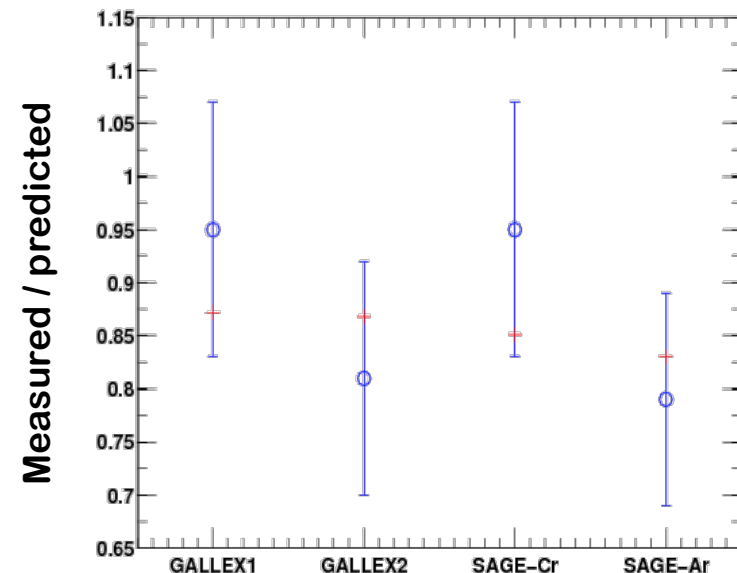
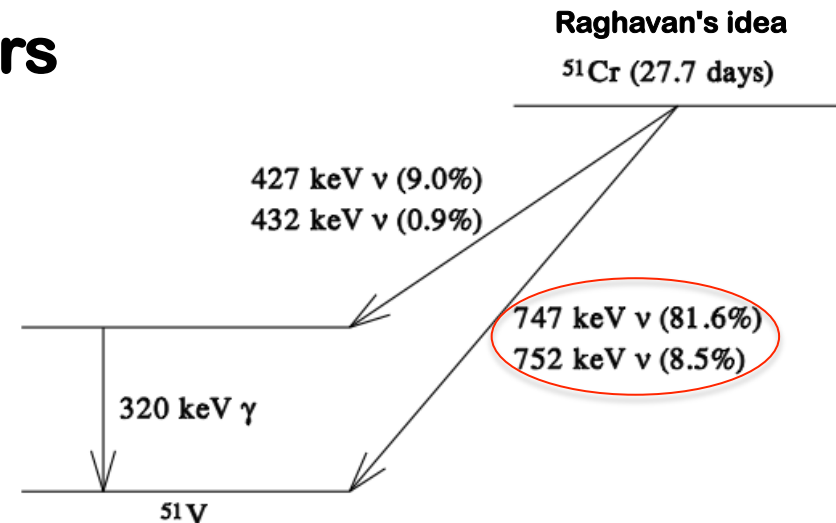
- $E \approx \text{MeV}$, Baseline range $\approx \text{few m}$

- 4 calibration runs
 $\approx 1\text{-}2 \text{ MCi EC } \nu_e$ emitters

- Gallex
 - ^{51}Cr source (750 keV)
- Sage
 - ^{51}Cr & ^{37}Ar (810 keV)

- **Deficit observed**

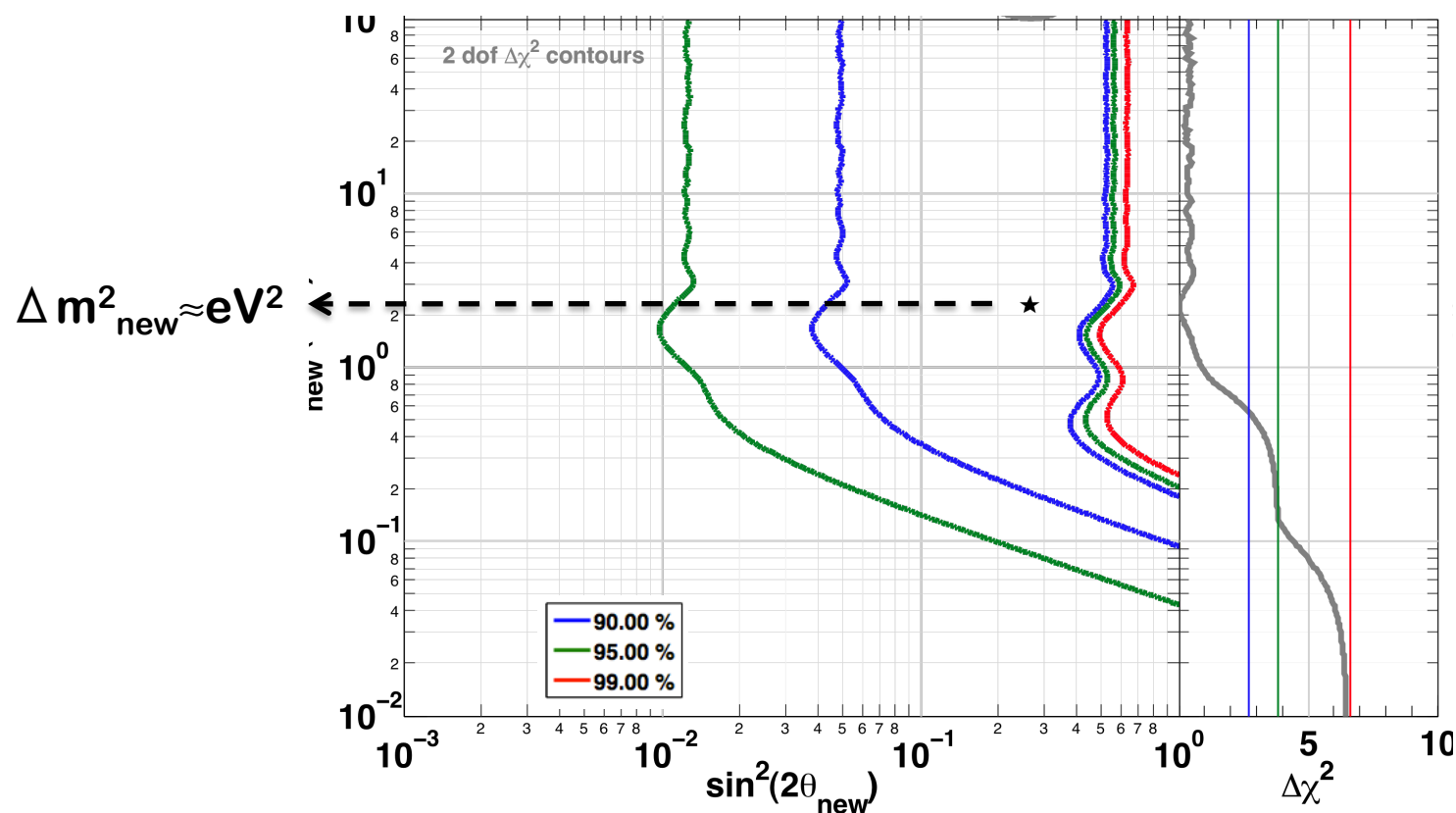
- $R_{\text{obs/pred}} = 0.86 \pm 0.05$ (σ_{Bahcall})
- $R_{\text{obs/pred}} = 0.76 \pm 0.085$ (σ_{Haxton})



The Gallium Neutrino Anomaly

Fit to ν_e disappearance hypothesis (3+1)

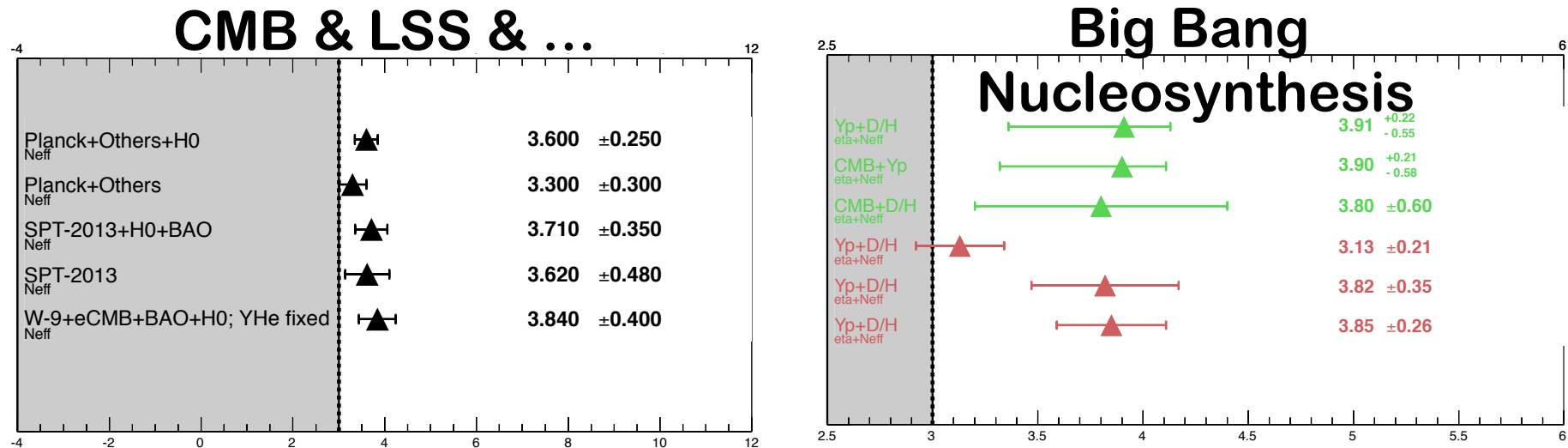
$$\begin{pmatrix} \nu_e \\ \nu_s \end{pmatrix} = \begin{pmatrix} \cos \theta_{\text{new}} & \sin \theta_{\text{new}} \\ -\sin \theta_{\text{new}} & \cos \theta_{\text{new}} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_{\text{new}} \end{pmatrix}, \quad P_{ee} = 1 - \sin^2(2\theta_{\text{new}}) \sin^2\left(\frac{\Delta m_{\text{new}}^2 L}{E}\right)$$



No-oscillation hypothesis disfavored at 2.7σ (PRC 83 065504, 2011)

Number of ν 's From Cosmology

Universe Expansion Rate $H^2 \approx (\rho_Y + \rho_\nu) - \rho_Y$ given by CMB data



- WMAP + other observables consistent with 3 and 4
- Planck favors 3.3, but consistent with 4
- Strong cosmological bounds, but model dependent

Anomalies & 4th Neutrino

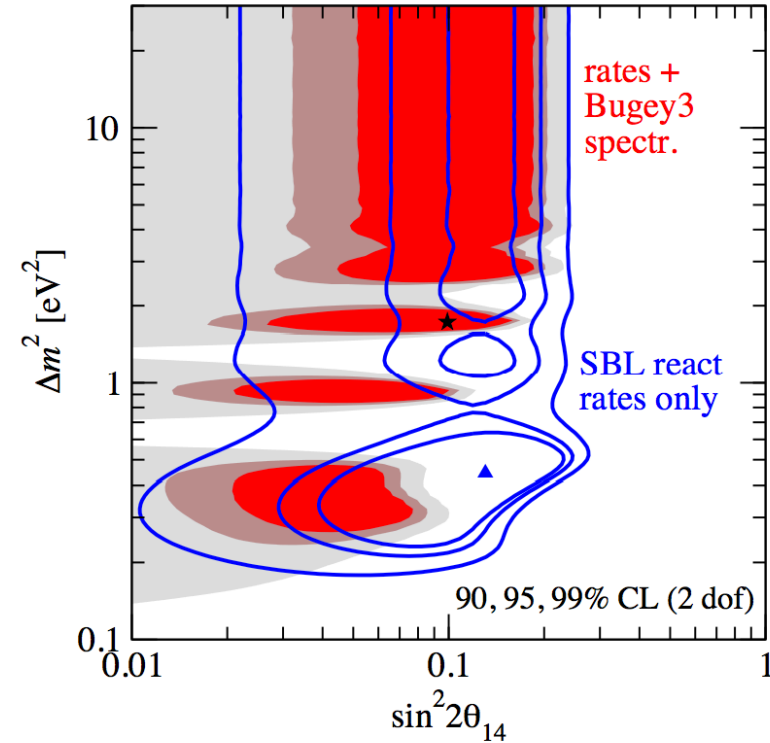
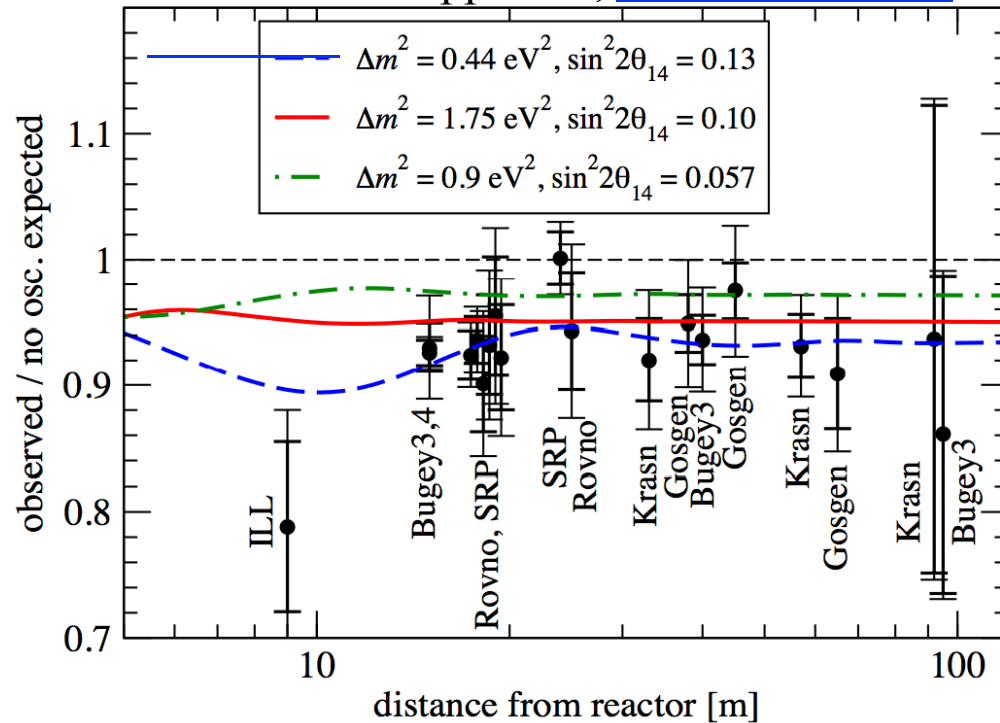
Anomaly	Source	Type	Sensitivity to Oscillation	Channel	Significance
LSND	Decay-at-Rest	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	$\frac{\text{Total Rate}}{\text{Energy}}$	CC	3.8 σ
MiniBoone	Short baseline	$\nu_\mu \rightarrow \nu_e$	$\frac{\text{Total Rate}}{\text{Energy}}$	CC	3.8 σ
Gallium	Electron Capture	ν_e dis.	$\frac{\text{Total Rate}}{\text{Energy}}$	CC	2.7 σ
Reactor	Beta-decay	$\bar{\nu}_e$ dis.	$\frac{\text{Total Rate}}{\text{Energy}}$	CC	3.0 σ
Cosmology	Big-Bang	All	Number of ν , N_{eff}	$N_{\text{eff}} = 3$ or 4 allowed	

could be interpreted by an existing eV² 4th neutrino state?

Global Picture

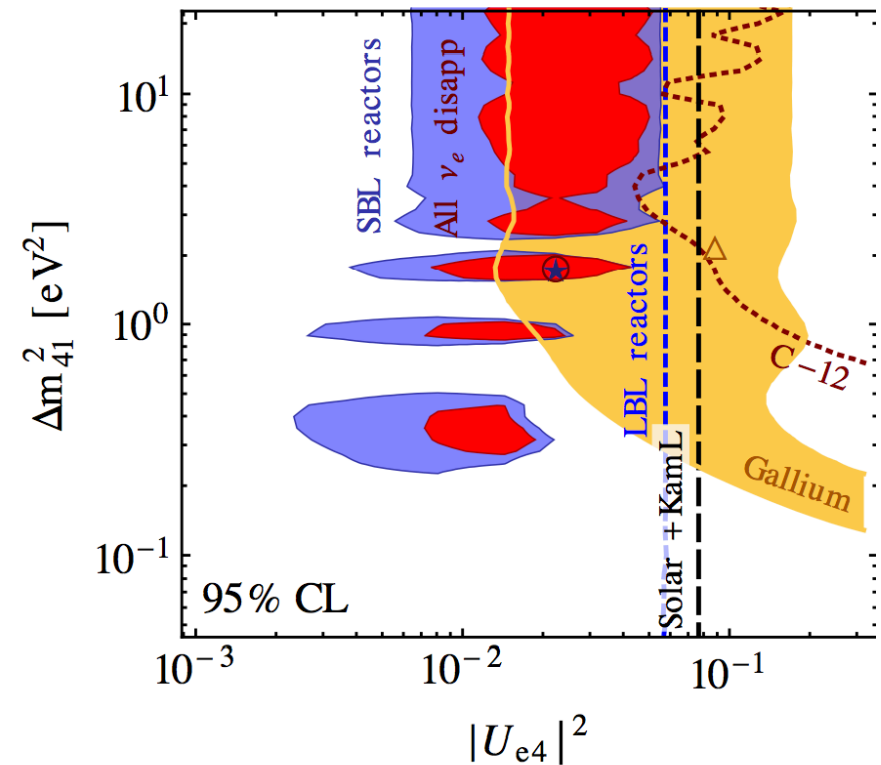
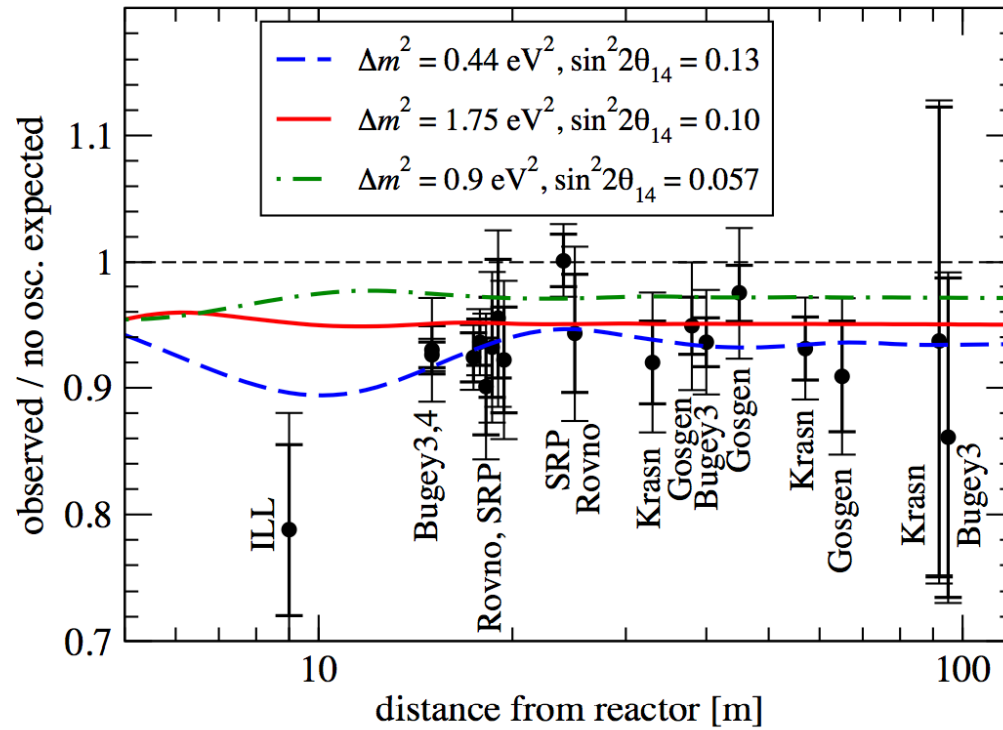
$\bar{\nu}_e$ disappearance (3+1 scenario)

J. Kopp et al., [arXiv:1303.3011](https://arxiv.org/abs/1303.3011)



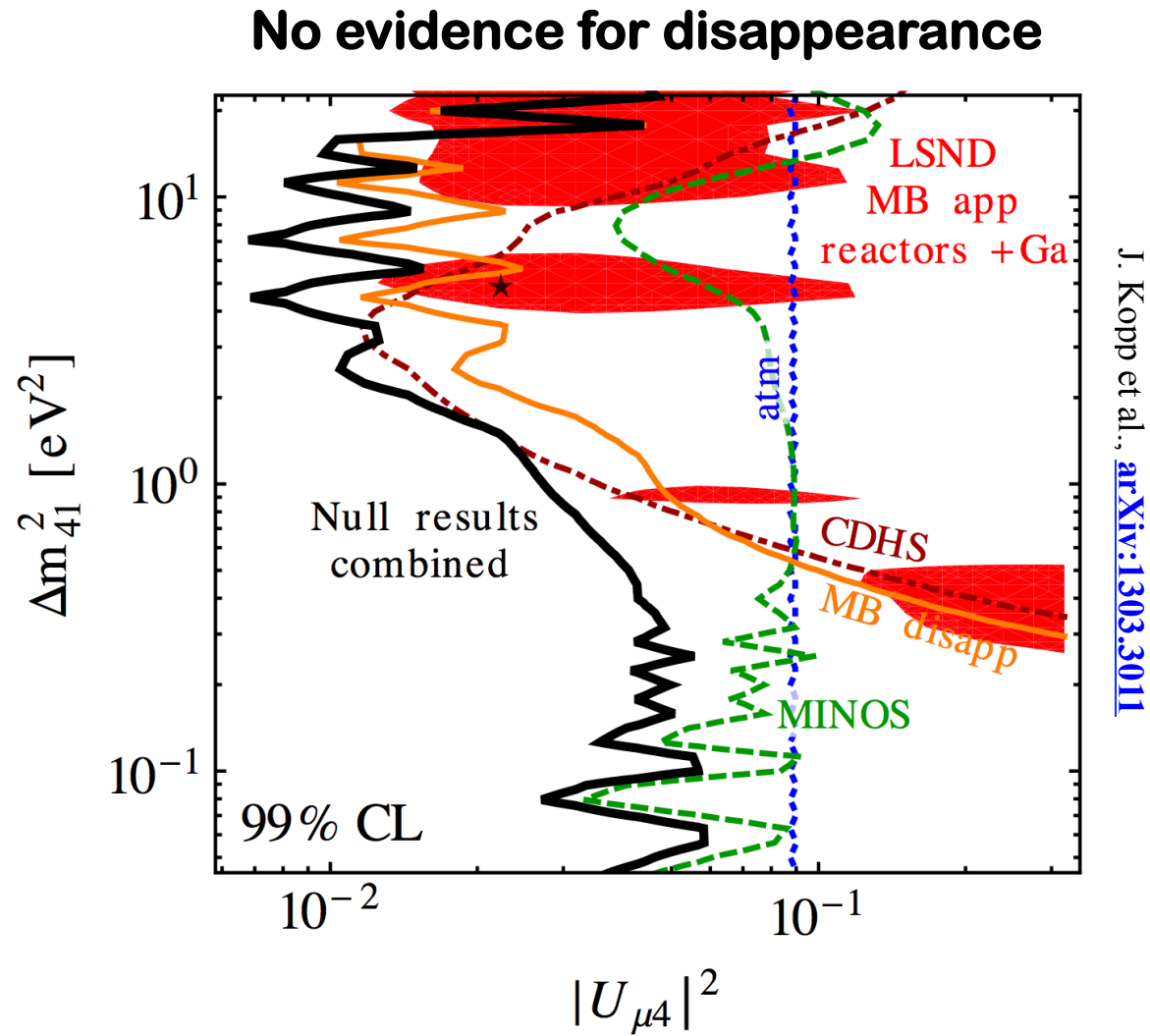
	$\sin^2 2\theta_{14}$	Δm_{41}^2 [eV ²]	$\chi^2_{\min}/\text{dof}$ (GOF)	$\Delta\chi^2_{\text{no osc}}/\text{dof}$ (CL)
SBL rates only	0.13	0.44	11.5/17 (83%)	11.4/2 (99.7%)
SBL incl. Bugey3 spectr.	0.10	1.75	58.3/74 (91%)	9.0/2 (98.9%)

$\bar{\nu}_e$ disappearance (3+1 scenario)

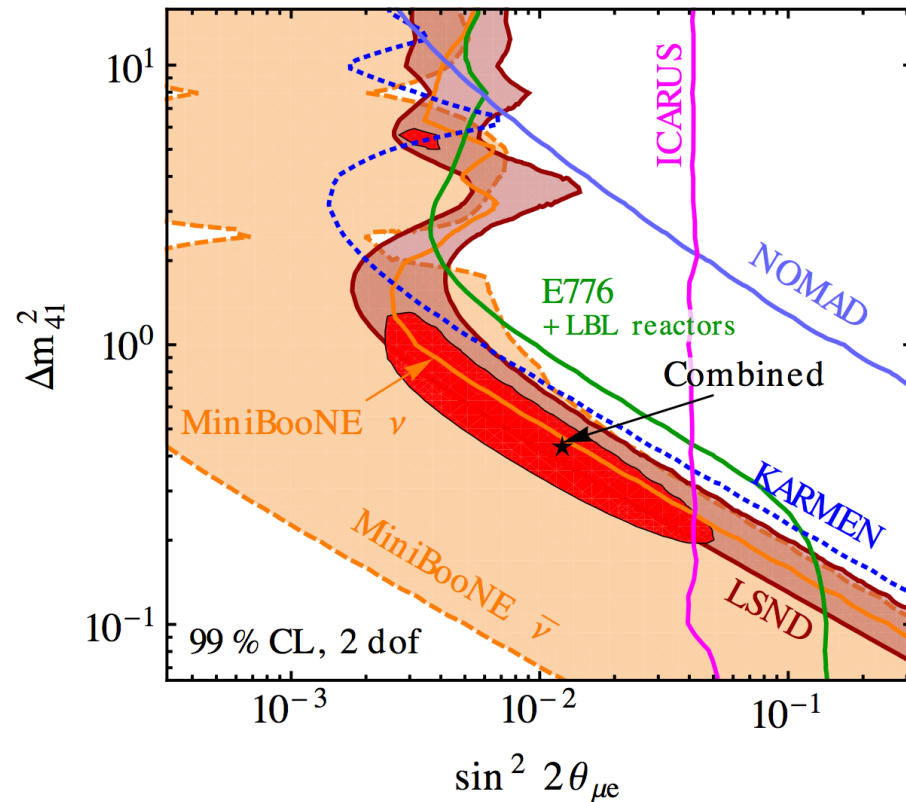


J. Kopp et al., arXiv:1303.3011	$\sin^2 2\theta_{14}$	Δm_{41}^2 [eV ²]	$\chi_{\min}^2/\text{dof}$ (GOF)	$\Delta\chi_{\text{no osc}}^2/\text{dof}$ (CL)
SBL rates only	0.13	0.44	11.5/17 (83%)	11.4/2 (99.7%)
SBL incl. Bugey3 spect.	0.10	1.75	58.3/74 (91%)	9.0/2 (98.9%)
SBL + Gallium	0.11	1.80	64.0/78 (87%)	14.0/2 (99.9%)
global ν_e disapp.	0.09	1.78	403.3/427 (79%)	12.6/2 (99.8%)

$\bar{\nu}_\mu$ disappearance (3+1 scenario)



$\bar{\nu}_e$ appearance (3+1, 3+2 scenarios)



J. Kopp et al., [arXiv:1303.3011](https://arxiv.org/abs/1303.3011)

	χ^2_{3+1}/dof	χ^2_{3+2}/dof	$\chi^2_{1+3+1}/\text{dof}$
LSND	11.0/11	8.6/11	7.5/11
MiniB ν	19.3/11	10.6/11	9.1/11
MiniB $\bar{\nu}$	10.7/11	9.6/11	12.7/11
E776	32.4/24	29.2/24	31.3/24
KARMEN	9.8/9	8.6/9	9.0/9
NOMAD	0.0/1	0.0/1	0.0/1
ICARUS	2.0/1	2.3/1	1.5/1
Combined	87.9/66	72.7/63	74.6/63

- Global fit to all appearance data is consistent
- Improvement of the fit by adding 2 sterile neutrinos

Appearance / Disappearance Coupling

- Electron disappearance channel

- $P_{ee} = 1 - \sin^2 2\theta_{ee} \sin^2 \frac{\Delta m_{41}^2}{4E}$ & $\sin^2 2\theta_{ee} = |U_{e4}|^2 (1 - |U_{e4}|^2)$

- Muon disappearance channel

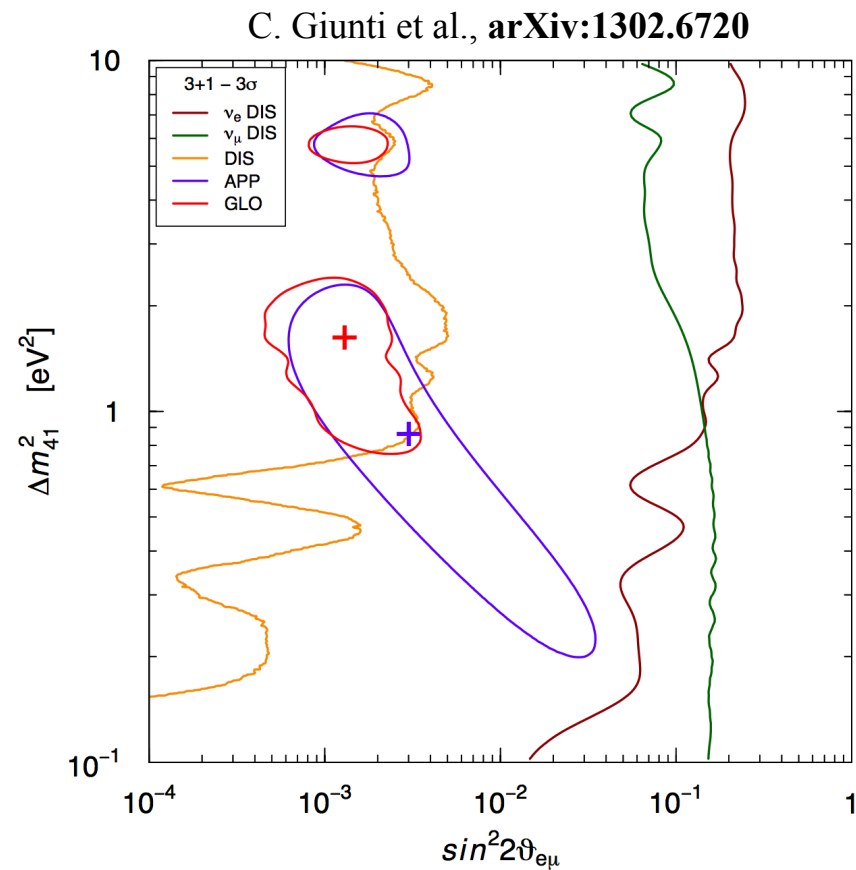
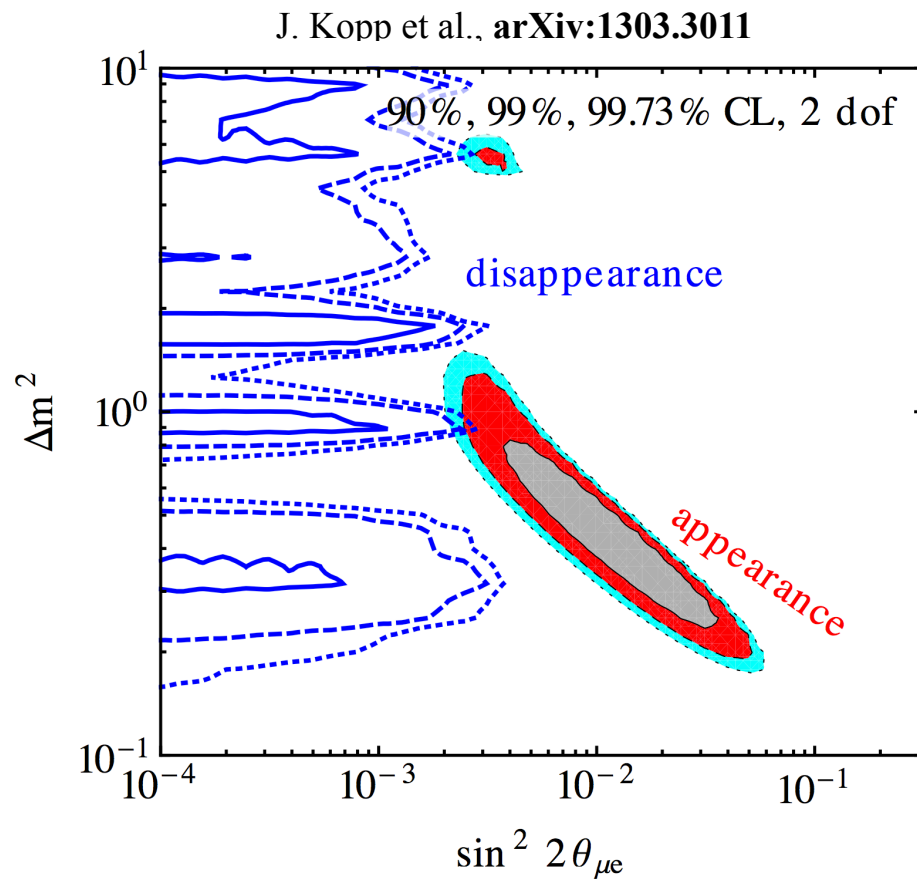
- $P_{\mu\mu} = 1 - \sin^2 2\theta_{\mu\mu} \sin^2 \frac{\Delta m_{41}^2}{4E}$ & $\sin^2 2\theta_{\mu\mu} = |U_{\mu 4}|^2 (1 - |U_{\mu 4}|^2)$

- Electron appearance channel

- $P_{\mu e} = 4 \sin^2 2\theta_{\mu e} \sin^2 \frac{\Delta m_{41}^2}{4E}$ & $\sin^2 2\theta_{\mu e} \approx \frac{1}{4} \sin^2 2\theta_{ee} \sin^2 2\theta_{\mu\mu}$

$\nu_\mu \rightarrow \nu_e$ appearance required both ν_μ & ν_e disappearance

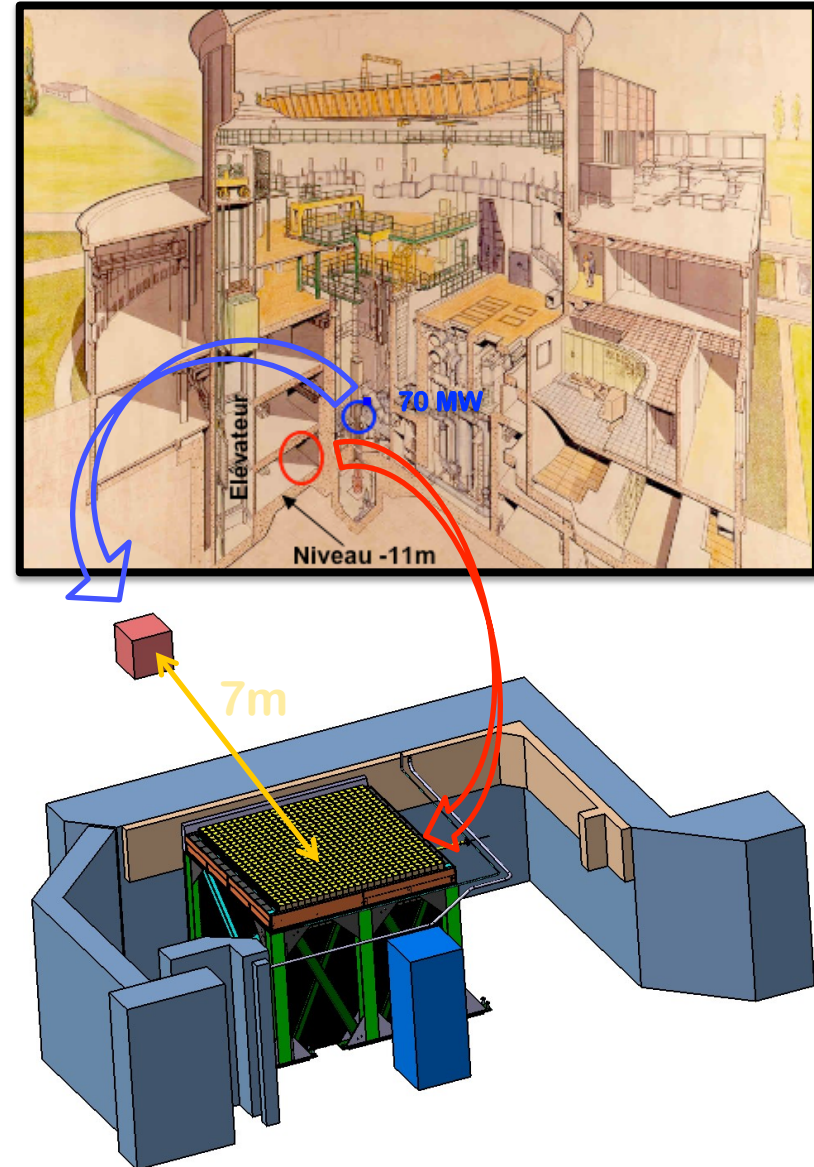
Appearance / disappearance tension



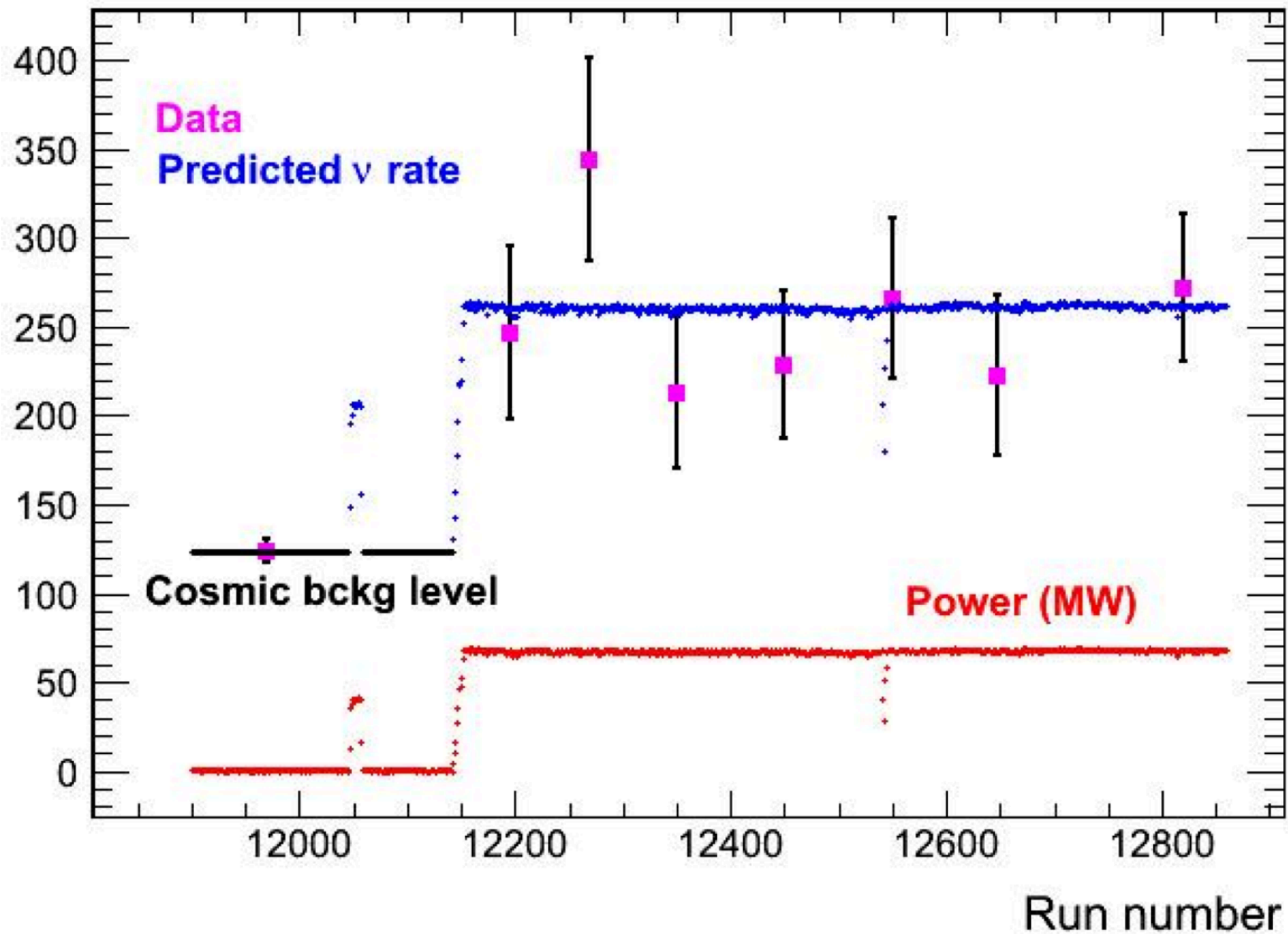
Testing the eV-scale Sterile Neutrino Hypothesis

@Reactor: Nucifer

- **Osiris research reactor**
 - At Saclay, France
 - 70 MW, 20% ^{235}U
 - **Compact**: 60x60x60 cm³
- Detector designed for reactor monitoring studies
 - 850 kg Gd-loaded liquid scintillator
 - 350 int. expected / day
- But modest oscillation detection capabilities:
 - Short baseline: only **7 m**
 - Target: $h = 70 \text{ cm}$, $\Phi = 1.2 \text{ m}$



@Reactor: Nucifer



With Anti-neutrino generator

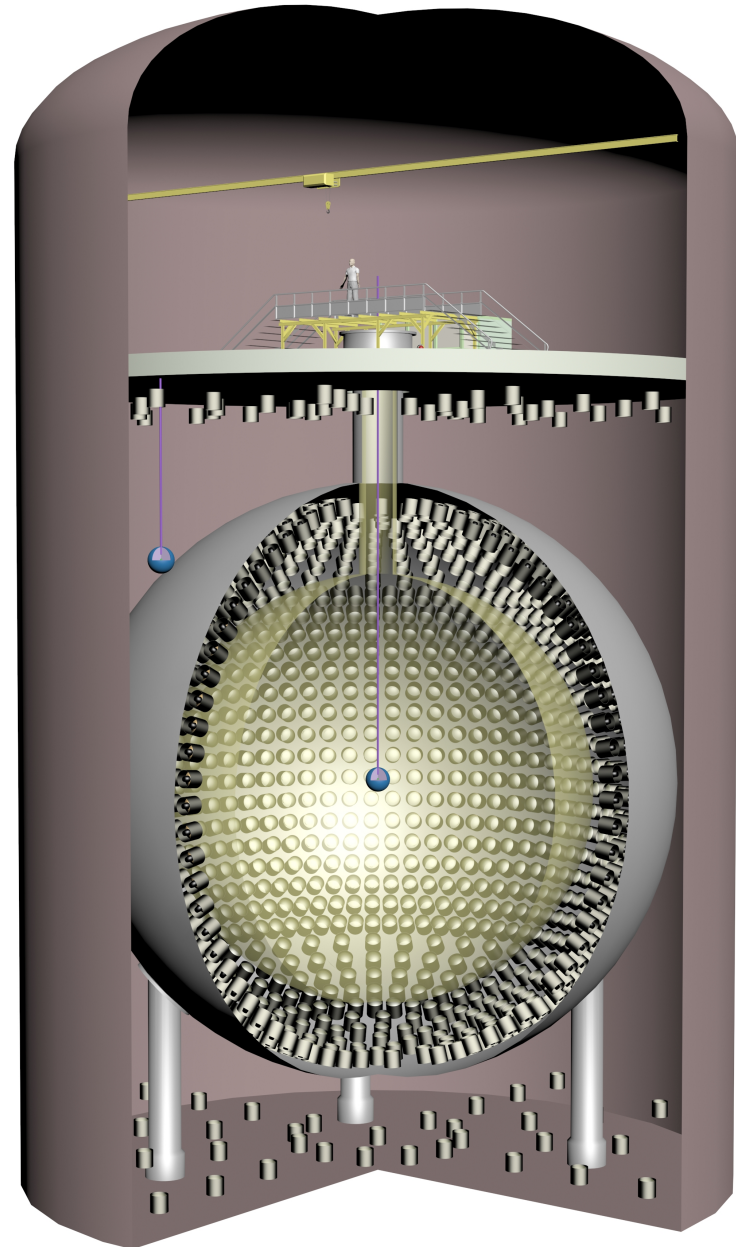
- Place the $\bar{\nu}$ -emitter inside or close to existing detectors
 - Very short Baseline (few m)
 - Low Background

i) $\bar{\nu}$ -source at center

$$\frac{dN_{\bar{\nu}}}{dR} \propto \left[1 - \sin^2(2\theta) \sin^2 \left(1.27 \frac{\Delta m^2 R}{\langle E \rangle} \right) \right]$$

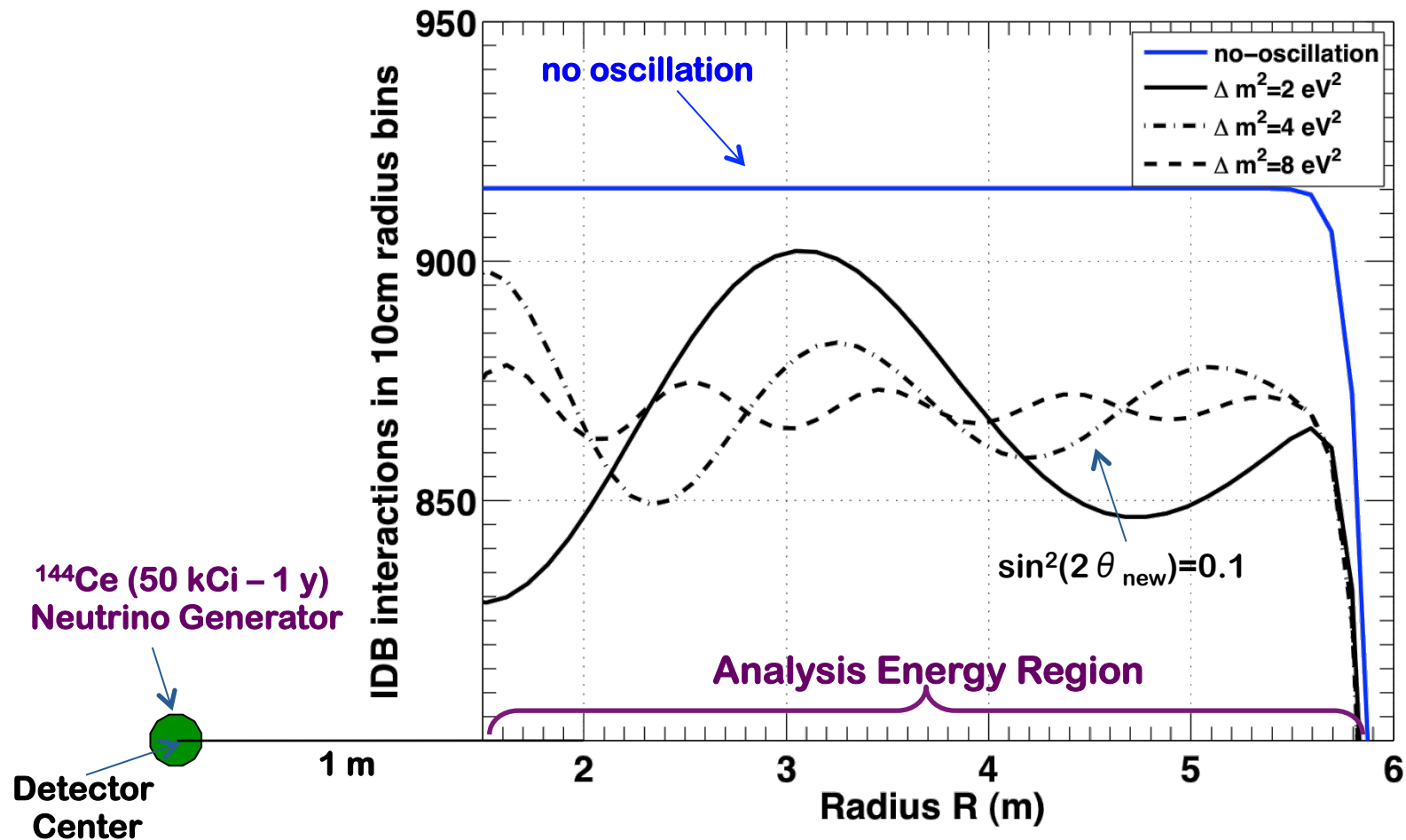
ii) $\bar{\nu}$ -source Outside LS

- Specific oscillation pattern analytically computable



Unambiguous Proof of $\nu_e \rightarrow \nu_s$ Oscillation

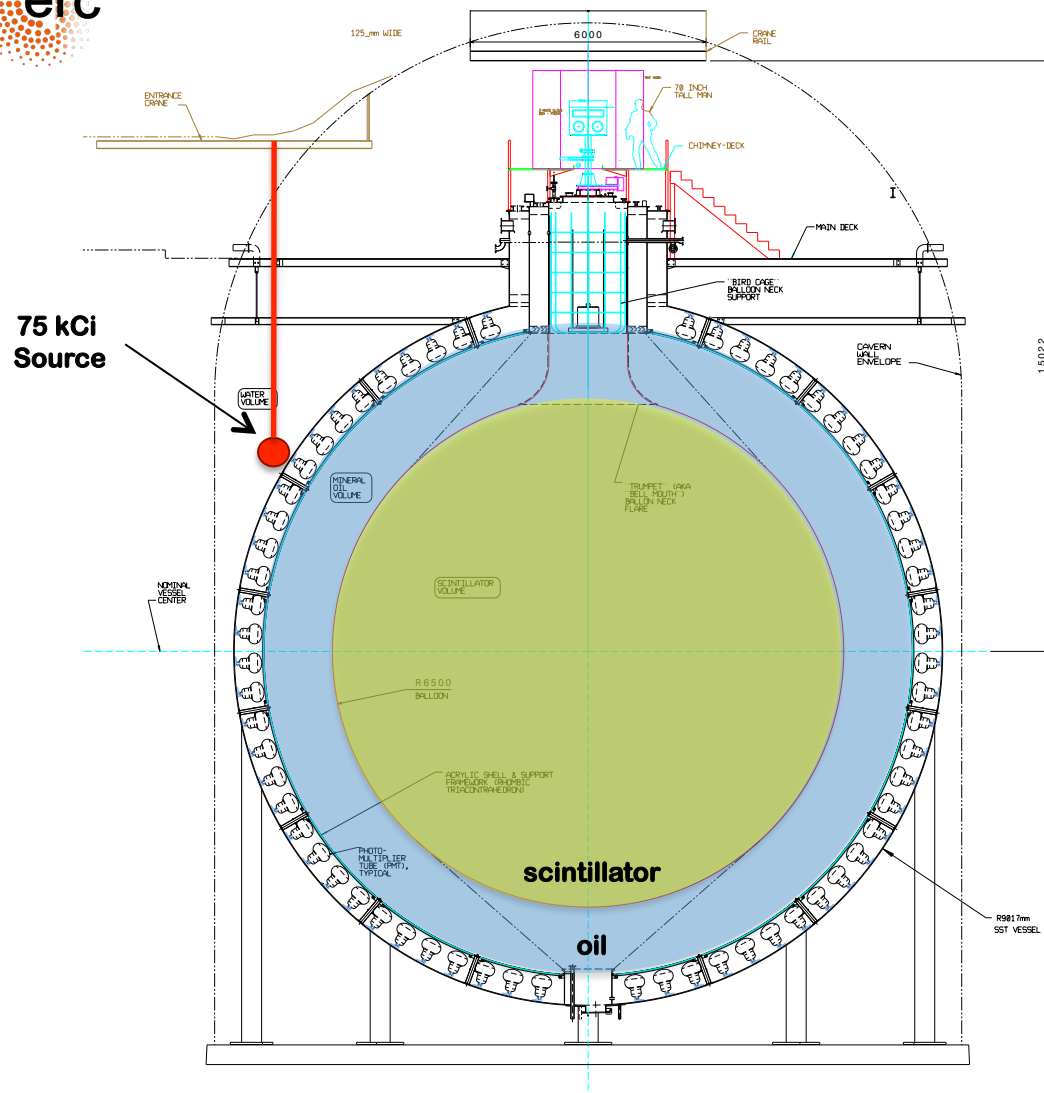
$$\frac{dN}{dR}(R,t) \propto \frac{A(t)}{4\pi R^2} \times \langle \sigma \rangle \times N_p \times \cancel{4\pi R^2} \times P_{ee}\left(\frac{\Delta m^2 R}{\langle E \rangle}\right)$$



CELAND Phase 1: 2015 in KamLAND

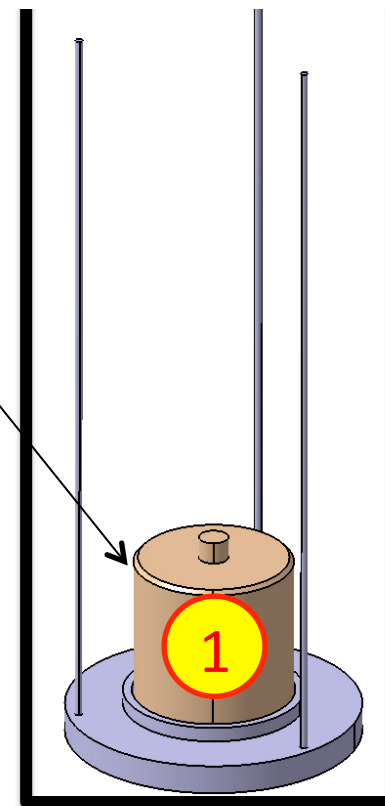


erc



Source @2.5 m away from LS
75 kCi & 6 months of data taking

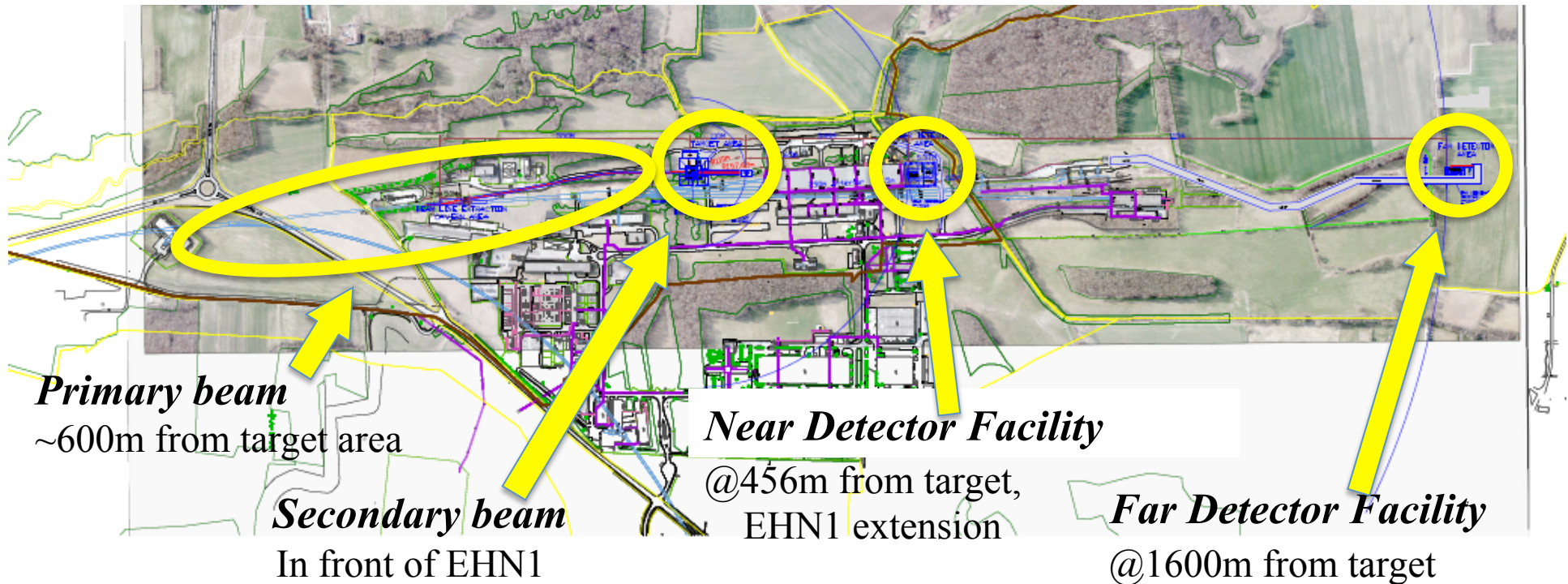
tungsten alloy,
54 cm
 $d=18.5 \text{ g/cm}^3$



SS structure to isolate the source from
the OD Water (no contamination risk)

@Accelerator (CERN)

- **Concept** ($L/E \approx \text{km/GeV} \rightarrow \text{eV-scale } 4^{\text{th}} \nu$)
 - Move T600 (2 x 300 tons) from LNGS to CERN, 2013/14
 - New T150 (150 tons)
 - New magnetized muon spectrometers (Opera's techno)
 - New neutrino beam on the SPS (on-axis, few GeV, fast extraction, $4.5 \cdot 10^{19}$ pot/y, neutrinos & antineutrino runs, start 2016/7?, under review)



Many Projects: Overview

Experiment Type	Appearance / Disappearance	Oscillation Channel	Projects
Reactor	Disappearance	$\bar{\nu}_e \rightarrow \bar{\nu}_e$	Nucifer, Stéréo, Scraam, Neutrino-4, DANSS, Poséidon, MARS, ...
Radioactive Source	Disappearance	$\bar{\nu}_e \rightarrow \bar{\nu}_e$ $\nu_e \rightarrow \nu_e$	CeLAND, SOX (Cr & Ce), Sage2, SNO+, LENS-s
Cyclotron	Disappearance	$\bar{\nu}_e \rightarrow \bar{\nu}_e$	IsoDAR
Pion / Kaon Decay-at-Rest	Apparition & Disappearance	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ $\nu_e \rightarrow \nu_e$	OscSNS, CLEAR, DAEδALUS, KDAR
Pion Decay-in-Flight (Beam)	Appearance & Disappearance	$\nu_\mu \rightarrow \nu_e$ $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ $\nu_\mu \rightarrow \nu_\mu$ $\nu_e \rightarrow \nu_e$	MINOS+, MicroBooNE, LAr1kton+MicroBooNE, Icarus/Nessie@CERN
Low-E Neutrino Factory	Appearance & Disappearance	$\nu_e \rightarrow \nu_\mu$ $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$ $\nu_\mu \rightarrow \nu_\mu$ $\bar{\nu}_e \rightarrow \bar{\nu}_e$	vSTORM@Fermilab

Conclusion (1/2)

- **Neutrinos mix and oscillate.** A lot's of momentum to understand the neutrino mixing properties ! Neutrino $\neq$ Quark mixing

$$U_{\text{CKM}} = \begin{bmatrix} 1 & 0.2 & 0.001 \\ 0.2 & 1 & 0.01 \\ 0.001 & 0.01 & 1 \end{bmatrix}$$

$$U_{\text{PMNS}} = \begin{bmatrix} 0.8 & 0.5 & 0.16 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{bmatrix}$$

- Large undergoing program towards the measurement of **neutrino masses** (KATRIN, GERDA, EXO/KamLAND-Zen...)
 - Two mixing angles and mass splitting measured
 - **NEW: θ_{13} measured (DC/DB/RENO/T2K)**
- Lot's of prospects for Mass Hierarchy determination
- Open the way for CP violation measurements (LBNE, LBNO, HK)

Conclusion (2/2)

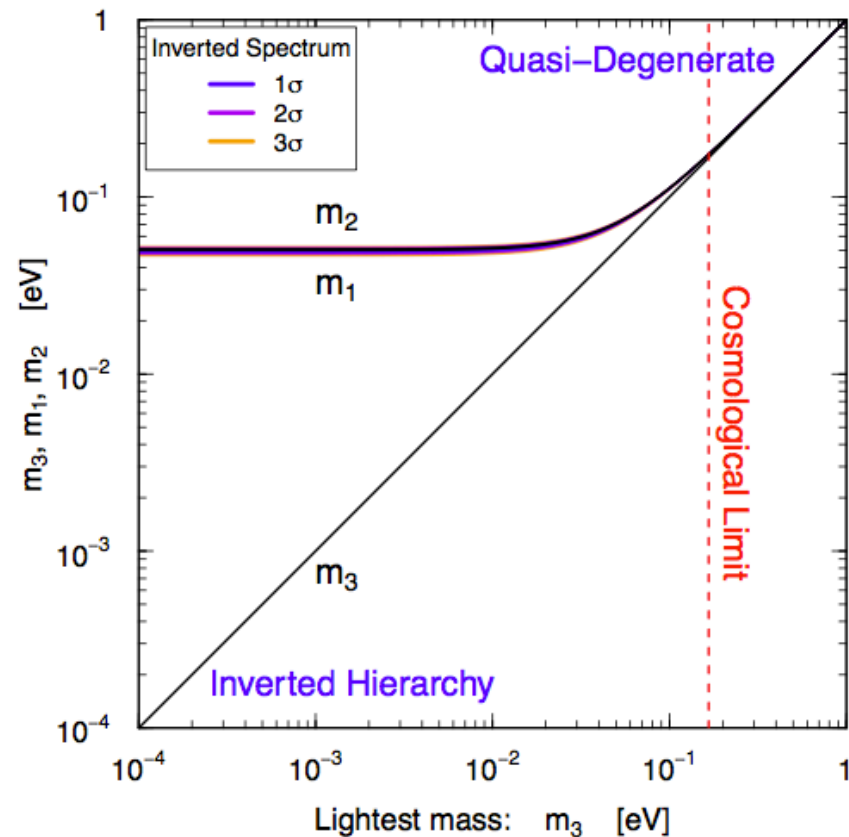
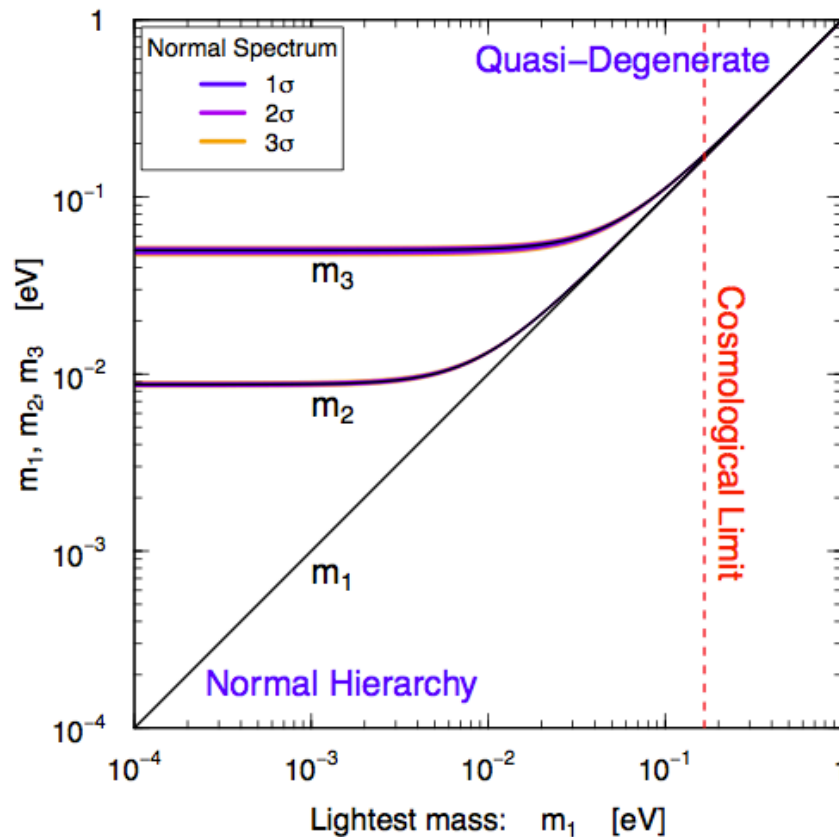
- **A bunch of anomalies calling for clarification:**
 - LSND (ν_s , $\Delta m^2 \approx \text{eV}^2$?) & Miniboone ?
 - Gallium Anomaly (ν_s , $\Delta m^2 \approx \text{eV}^2$?)
 - Reactor Anomaly (ν_s , $\Delta m^2 \approx \text{eV}^2$?)
- Hint in favor of sterile neutrinos is compatible with cosmological data (CMB, LSS, BBN), though ≈ 1 eV-scale mass is a too heavy
- Bunch of 2 to 3 σ effects but cannot be ignored...
- **Need for new conclusive short baseline experiments, more than 20 projects studied**

Additional Slides

Two mass hierarchies allowed

$$\text{NH} \begin{cases} m_3 = \sqrt{m_1^2 + m_{\text{atm}}^2} \\ m_2 = \sqrt{m_1^2 + m_{\text{solar}}^2} \\ m_1 \end{cases}$$

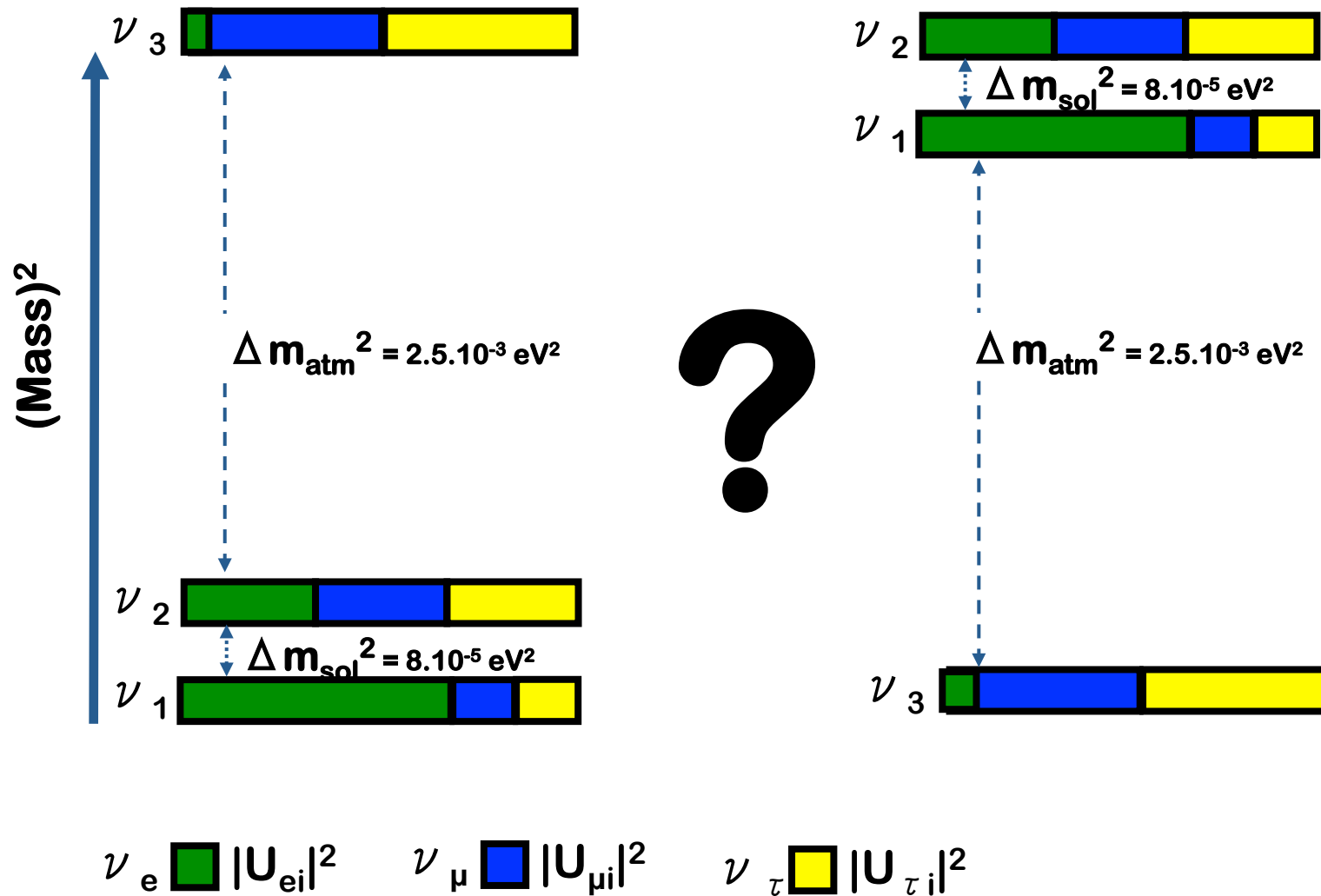
$$\text{IH} \begin{cases} m_1 \approx \sqrt{m_3^2 + m_{\text{atm}}^2} \\ m_2 = \sqrt{m_3^2 + m_{\text{atm}}^2} \\ m_3 \end{cases}$$



Question 2)

**What is the spectral
mass pattern ?**

Sign of Δm^2_{31}



MH: middle term projects

2012: Large θ_{13} open the door to new initiatives:

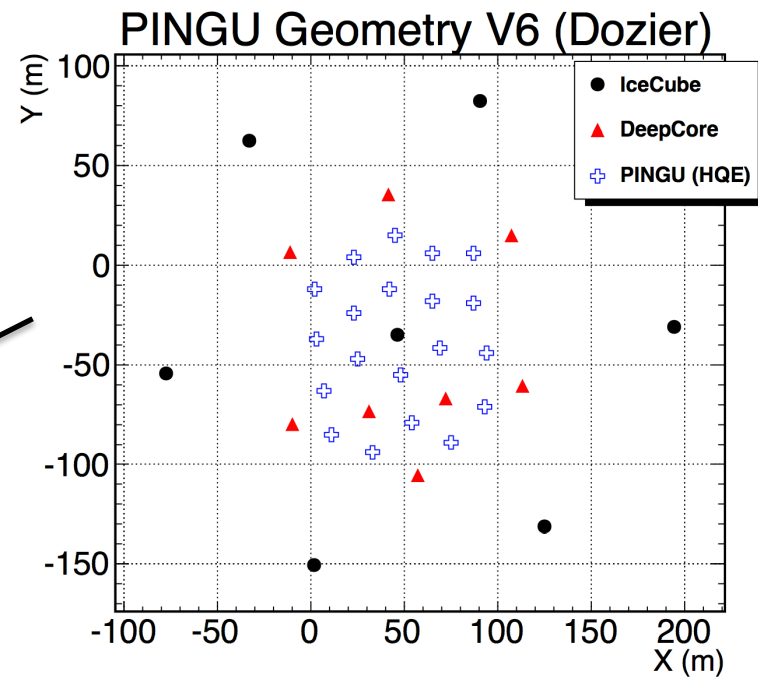
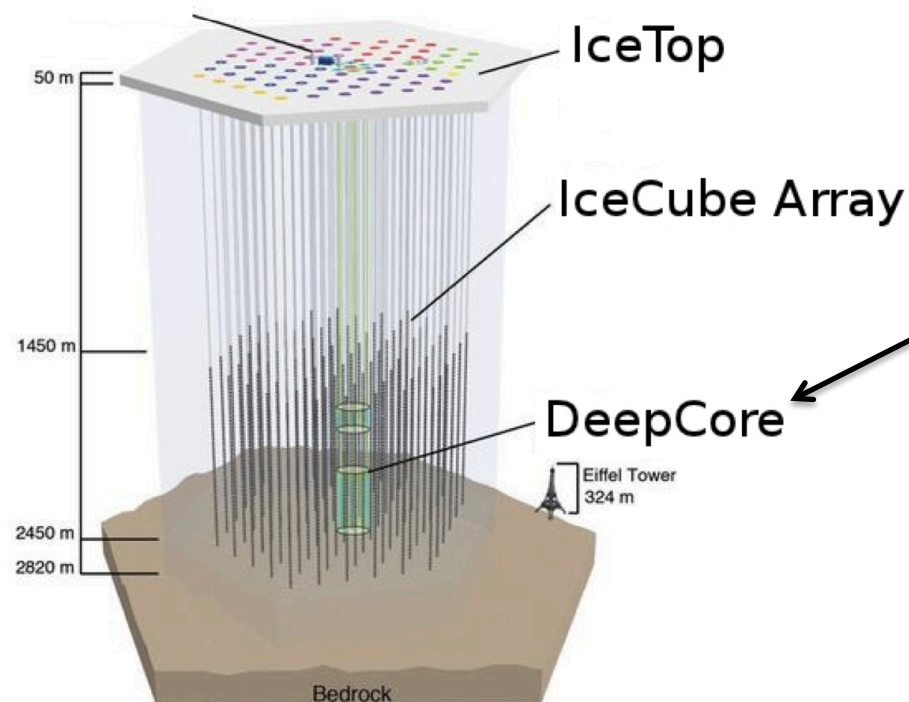
- **Atmospheric neutrino L/E measurement**
 - Pingu (Ice-Cube) & Orca (KM3net)
 - **50 kt scale reactor experiment at 55 km**
 - Daya-Bay II
 - **Atmospheric neutrino in magnetized detector**
 - INO
 - **Beam of Neutrinos in Matter**
-
- **Prospects: results before 2020 ?**

IceCube Neutrino Telescope

Existing: 1 km³ antarctic ice instrumented with 5160 PMTs
+ **Deep Core** 20 strings to reduce threshold

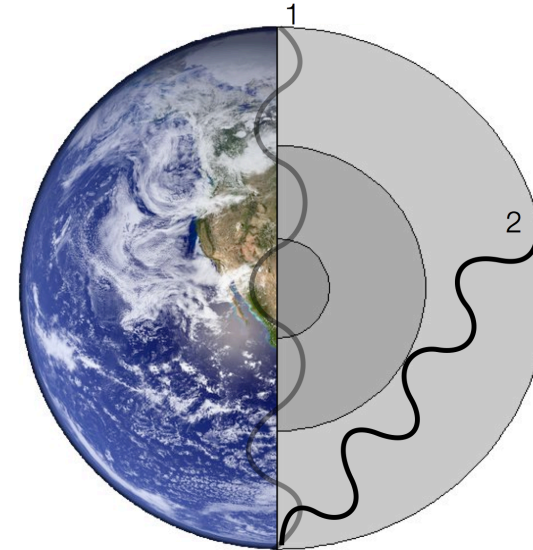
Next: **PinGU** → Add 20 strings within DeepCore

IceCube Lab

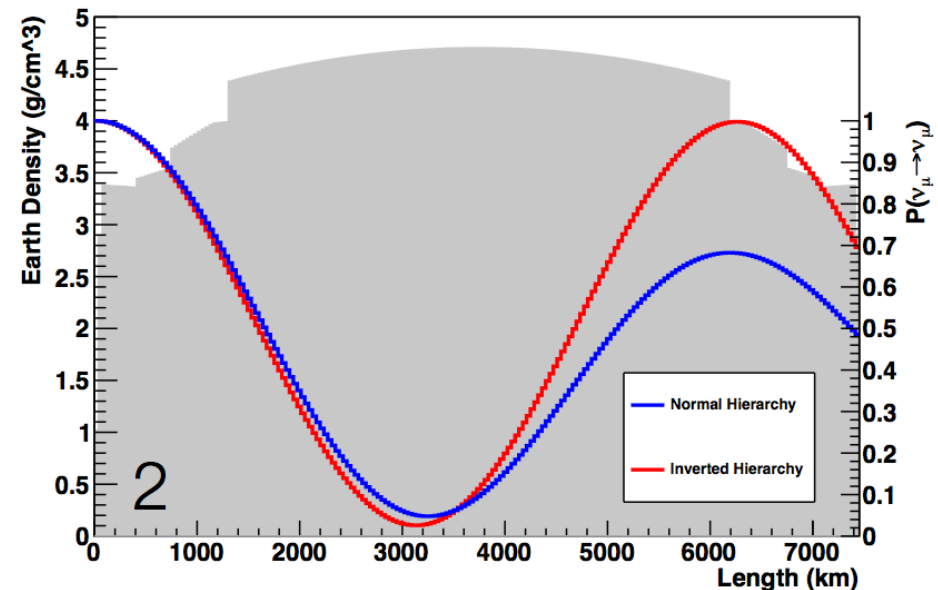


MH with PINGU (& ORCA)

- Lower Threshold to few GeV
 - Fine mesh string array
- Keep Megaton volume
- Matter Effects:
 - IH/NH has up to a 20% difference in oscillation probability for specific energies and zenith angles
- Promising but sensitivity under study...
- Deployment by 2018
- Similar project in the Mediterranean see (Orca)

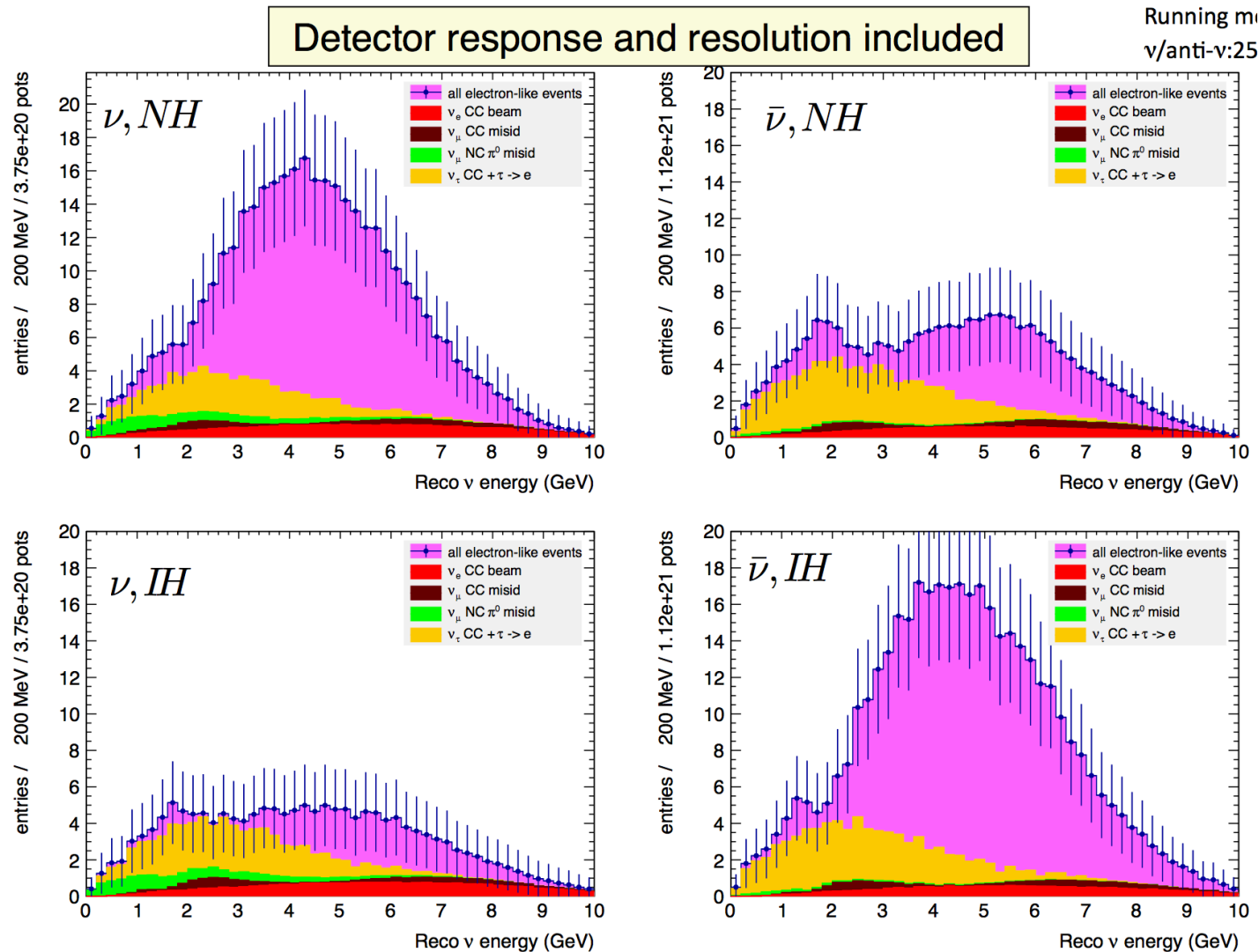


$P(\nu_\mu \rightarrow \nu_\mu)$ with Travel Through the Earth - 6 GeV, 126



LBNO: Mass Hierarchy ($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$)

Excellent prospect – Earliest schedule for 5σ : 2026 (start + 3 years)



Question 4)

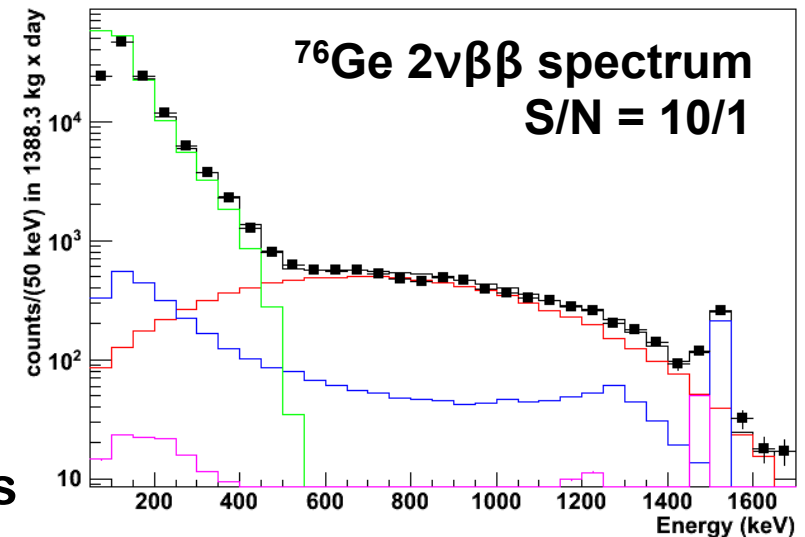
**Is there a conserved
Lepton Number? Eq.
Dirac or Majorana ν ?**

Overview of experiments

Isotope	Experiment	Technique	Mass	Enriched	$Q_{\beta\beta}$ [MeV]	Start/Stage
^{130}Te	Cuoricino	TeO_2 bolometers	40.7kg	No	2.6	Done
$^{82}\text{Se}, ^{100}\text{Mo}$	NEMO-3	tracko-calo	0.9kg/6.9kg	Yes	3.37	Done
^{76}Ge	GERDA	Ge diodes in LN_2	34.3kg	86%	2.04	2009
^{136}Xe	EXO-200	LXe [tracking]	150kg	80%	2.47	2010
^{136}Xe	KamLAND	Isotope in LS	400kg	90%	2.47	2012
^{130}Te	CUORE	TeO_2 bolometers	204kg	No	2.53	2014
^{150}Nd	SNO+	Isotope in LS	56kg	No/50%	3.37	2014
^{76}Ge	Majorana	Ge diodes	30-60kg	86%	2.04	2015
$^{82}\text{Se}, ^{150}\text{Nd}$	SuperNEMO	tracko-calo	100kg	Yes	3.37	2014
^{100}Mo	MOON	tracking	1t	No	3.03	Prototype
^{116}Cd	COBRA	CdZnTe semicond	?	No	2.80	Prototype
^{48}Ca	CANDLES	CaF_2 cryst in LS	few t	No	4.27	Prototype

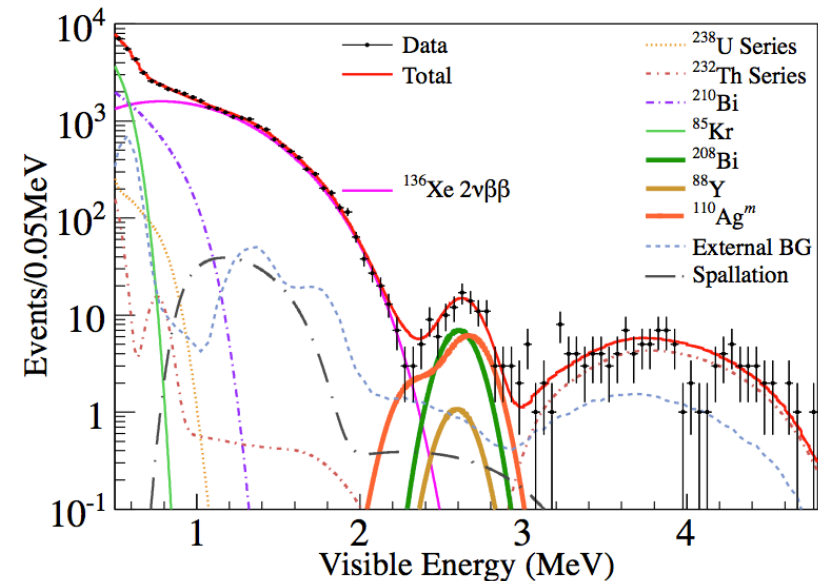
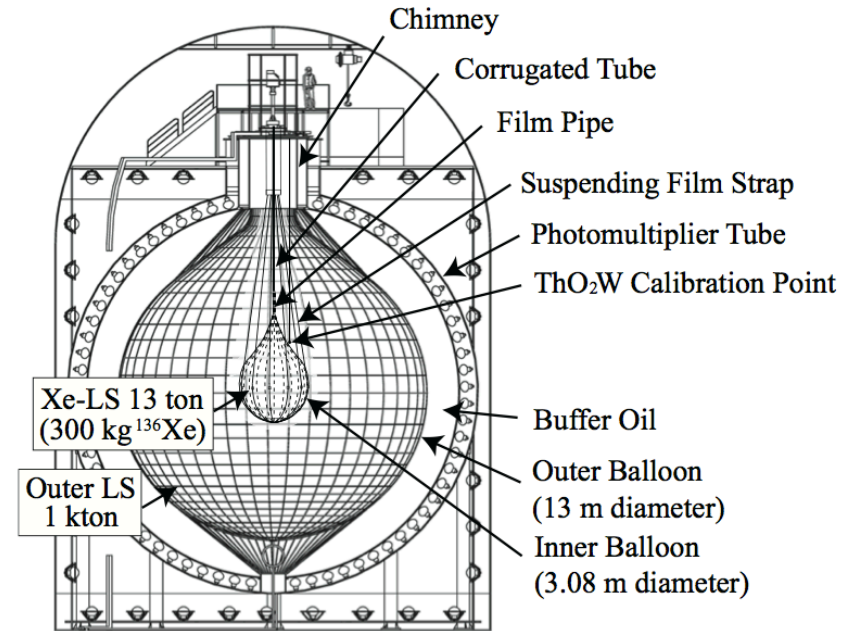
GERDA at LNGS

- **Target: ^{76}Ge**
 - Low $2\nu\beta\beta$ rate ($T_{1/2}=1.4\times 10^{21}$ y)
 - High $Q_{\beta\beta}$ value (2039 keV)
- **Detector: high purity ^{76}Ge -diodes (source & detector) immersed in LAr as shielding and coolant**
- **Status (Phase 1):**
 - Data taking since end 2011
 - Bkg: $0.017+0.009-0.005/(\text{keV}\cdot\text{kg}\cdot\text{y})$
→ Factor 10 bkg reduction wrt HDM
- **Future (Phase 2):**
 - Factor 10 bkg reduction by LAr scintillation and novel HP-Ge detectors



KamLAND-Zen at Kamioka

- KamLAND LS detector
- Liquid ^{136}Xe (92%) in balloon
- 77.6 day x 129 kg of ^{136}Xe
- $2\nu 2\beta$
 - $T_{1/2} = (2.38 \pm 0.14) \times 10^{21}$ yr
 - Consistent with EXO
- $0\nu 2\beta$
 - $T_{1/2} > 5.7 \times 10^{24}$ yr (90% CL)
 - But Fukushima Contamination
- Upgrade plan:
 - 1 ton ^{136}Xe
 - KamLAND upgrade



EXO-200 at WIPP

- 200 kg liquid enriched ^{136}Xe
- TPC (energy and position)
- Data taking since may 2011
 - 32.5 kg-yr
 - Bkg: $1.5 \times 10^{-3} \text{ kg}^{-1}\text{yr}^{-1}\text{keV}^{-1}$
- $2\nu 2\beta$ (2011)
 - $T_{1/2} = (2.11 \pm 0.21) \times 10^{21} \text{ yr}$
- $0\nu 2\beta$ (2012)
 - $T_{1/2} > 1.6 \times 10^{25} \text{ yr}$ (90% CL)
 - $|m_{\beta\beta}| < 140\text{--}380 \text{ meV}$
- Prospect: Barium tagging

