Neutrinos: Experimental Review

SILAFAE 2012

Sao Paulo, December 13th 2012

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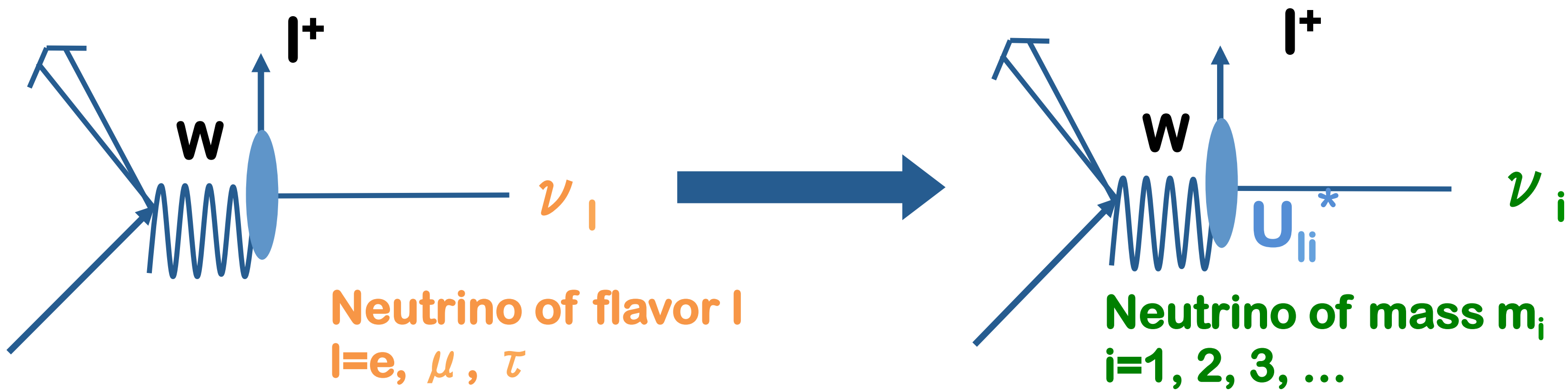
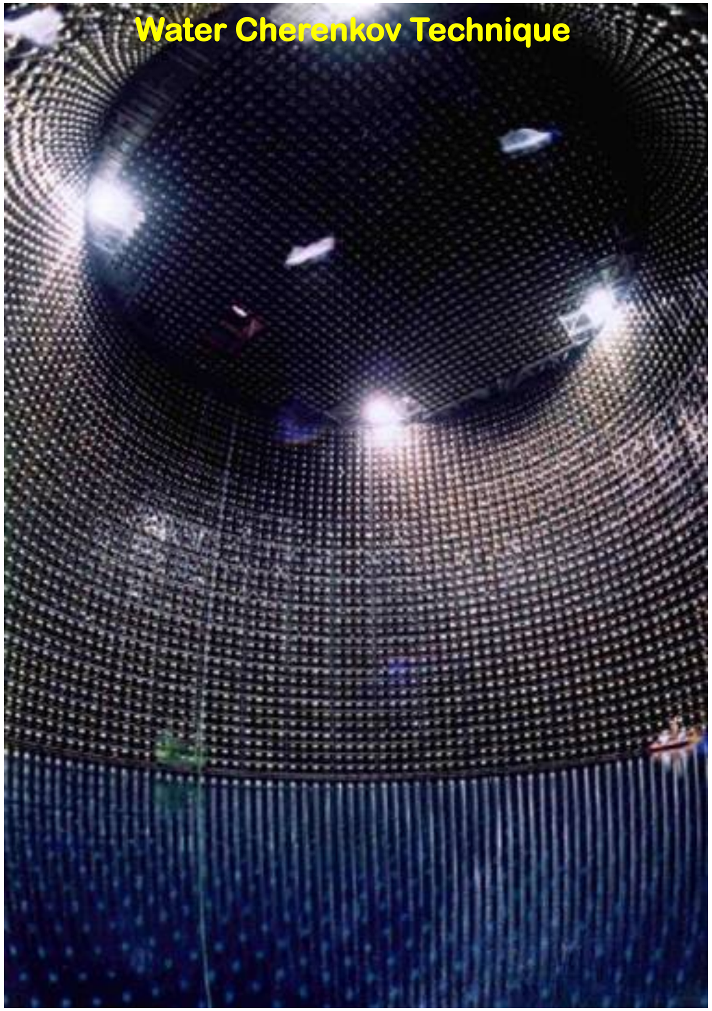
Established Neutrino Physics

- 3 types, spin ½, 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:



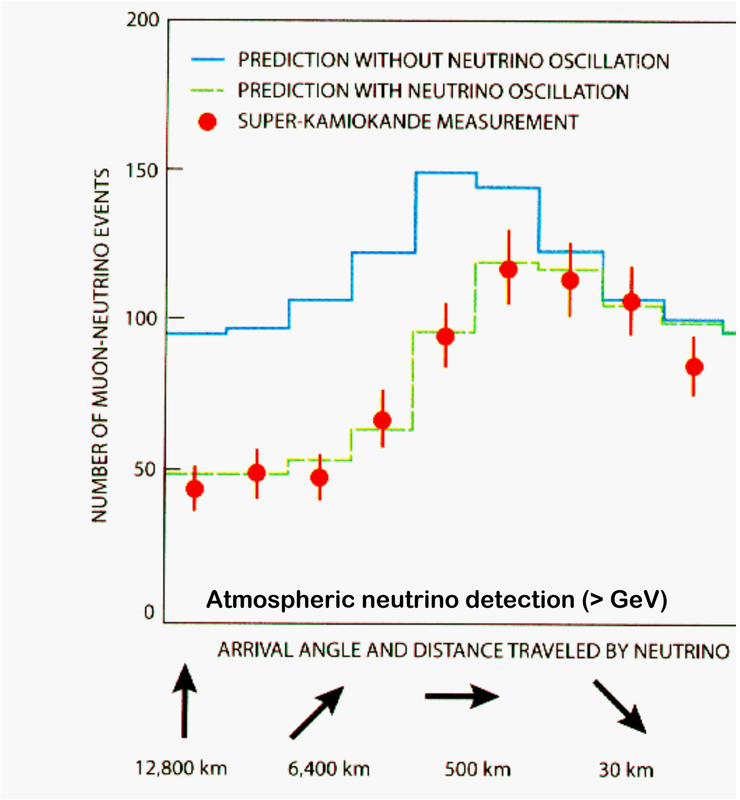
- PMNS matrix U relates mass & flavor: $|\nu_i\rangle = \Sigma\, U_{\alpha i}\, |\nu_\alpha\rangle$
- A compelling evidence of physics Beyond the Standard Model

SuperKamiokande Breaktrough (1998)



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

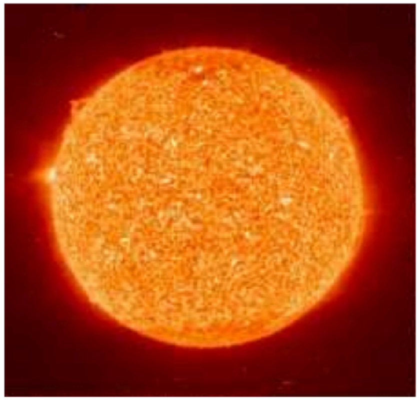
$$\Phi^{Atm}{}_{\nu_\mu}(up) \Big/ \Phi^{Atm}{}_{\nu_\mu}(down) = 0.54 \pm 0.04$$

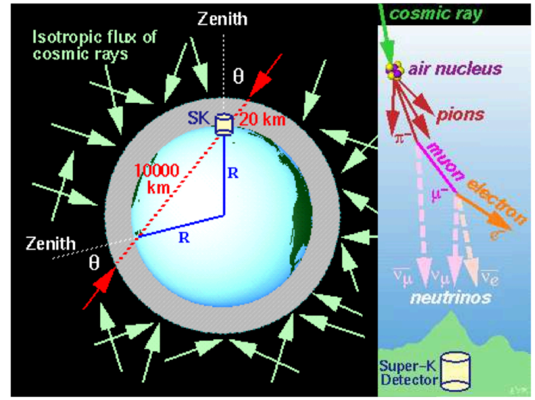


Neutrino do have mass and they mix (oscillation)

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 anti-$\nu_\mu \rightarrow$ anti-ν_τ : **atmospheric & beam experiments**
- $\nu_e \rightarrow \nu_{\mu,\tau}$: **solar experiments**
- anti-$\nu_e \rightarrow$ anti-ν_{other} : **reactor experiments**
- (anti-)$\nu_\mu \rightarrow$ (anti-)ν_{other} : **atmospheric & beam experiments**
- $\nu_\mu \rightarrow \nu_e$: **beam experiments**

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

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3 ν Oscillation Formalism

PMNS mixing matrix

Atmospheric — Cross-Mixing — Solar — Majorana ~~CP~~ phases

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \times \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \times \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

θ_{23} : "atm." mixing angle — θ_{13} — θ_{12} : "solar" mixing angle

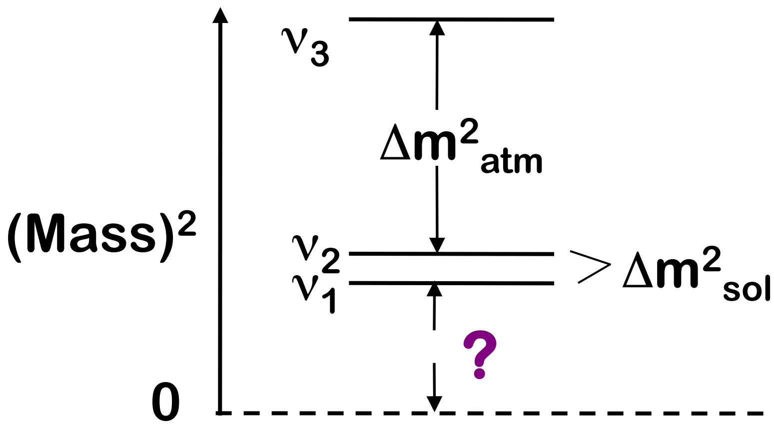
δ Dirac CP violating phase

2 Majorana phases (L violating processes)

- 3 masses m_1, m_2, m_3 : $\Delta m^2_{sol} = m^2_2 - m^2_1 \;\&\; \Delta m^2_{atm} = |m^2_3 - m^2_1|$
- 3-flavour effects are suppressed since: $\Delta m^2_{sol} << \Delta m^2_{atm}\ (1/30)\ \&\ \theta_{13} << 1$

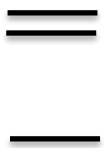
Open questions

- What are the masses of the mass eigenstates ν_i?



} ν flavor change

} β decay, $\beta\beta0\nu$ decay, cosmology

- Is the spectral pattern  or?  $\overset{(-)}{\nu}$ behavior in matter, $\beta\beta0\nu$

- Is there any conserved Lepton Number (Dirac or Majorana neutrino) ? $\beta\beta0\nu$

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

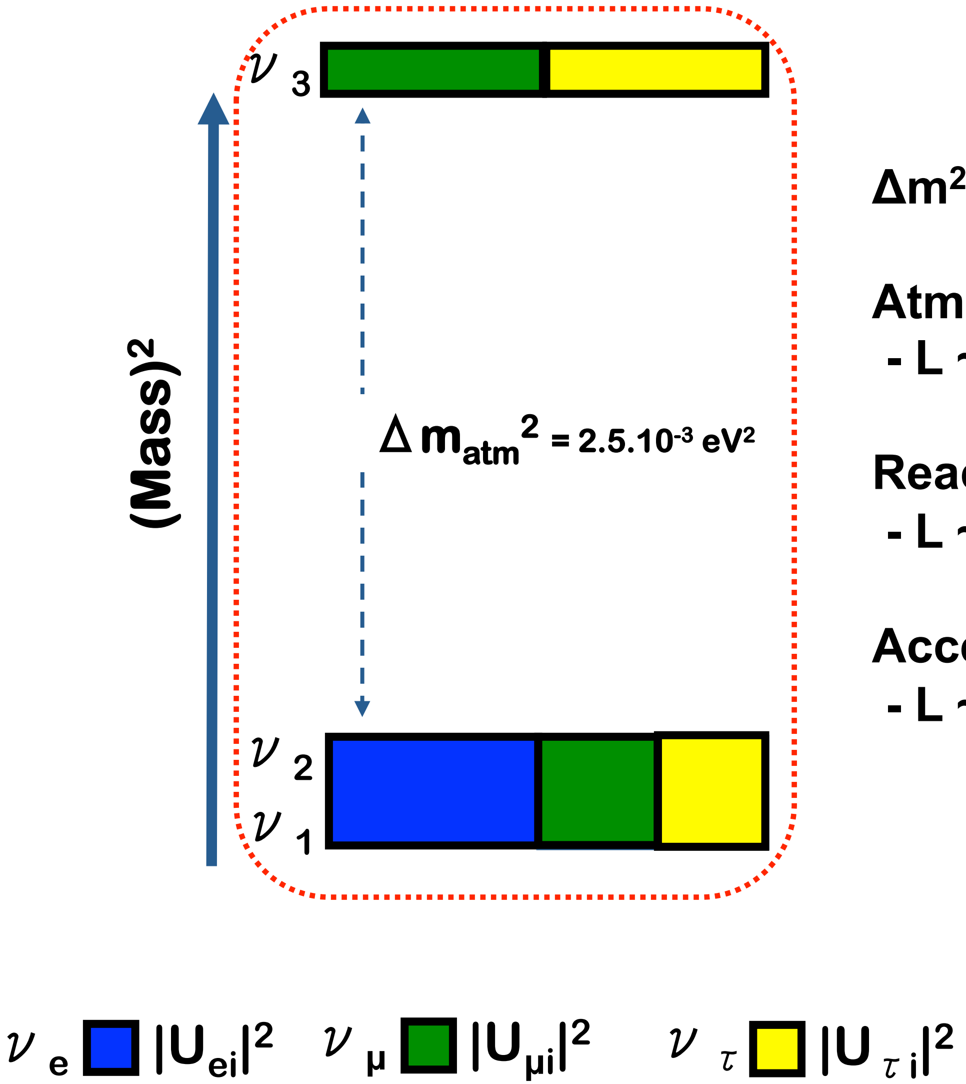
} ν flavor change

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

Question 1)

What are the leptonic mixing parameters?

Δm^2_{31} & θ_{23}



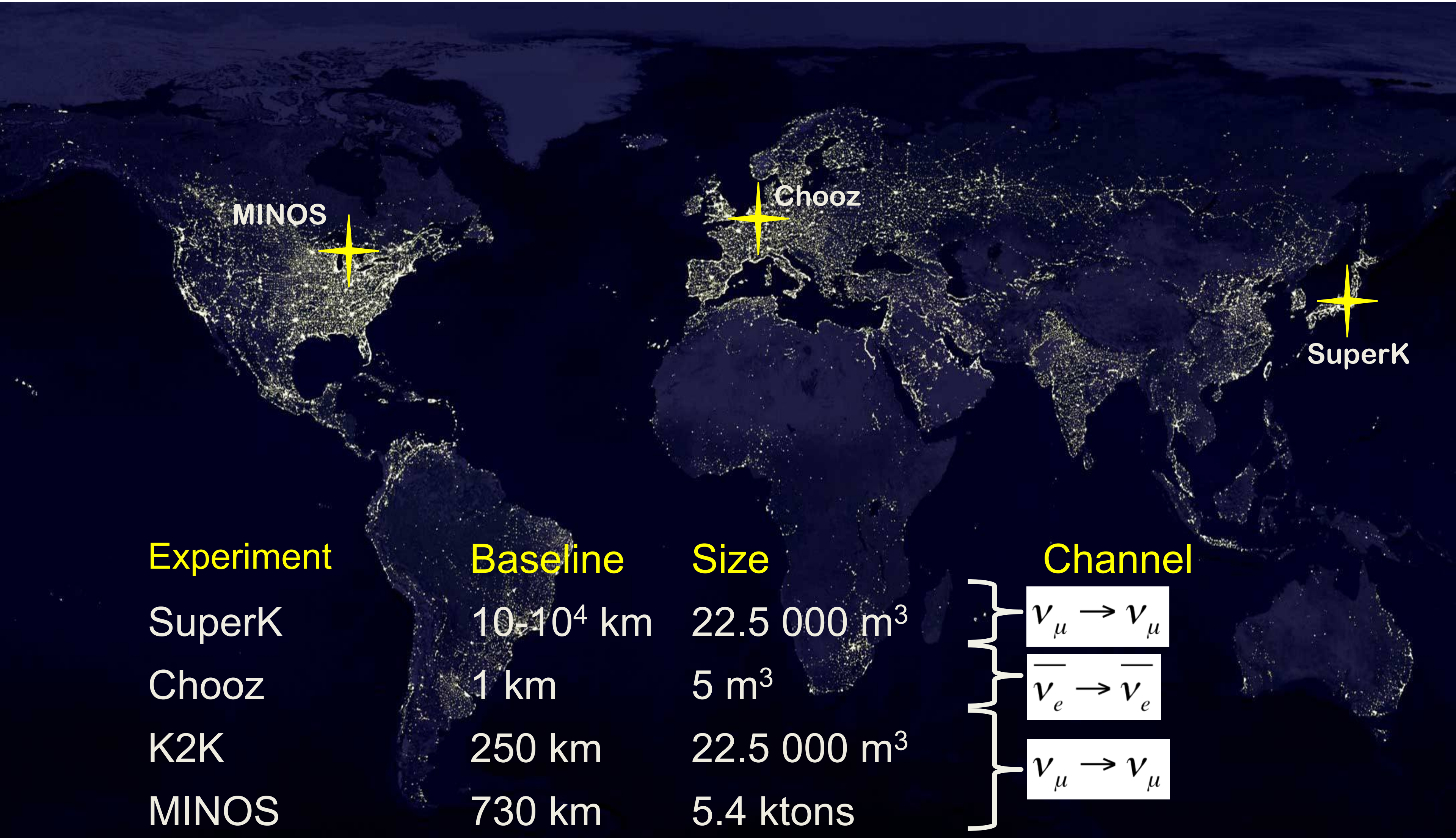
$\Delta m^2 \sim L / E$

Atmospheric:
- $L \sim 10^4$ km & $E \sim$ 1-30 GeV

Reactors:
- $L \sim 1$ km & $E \sim 3$ MeV

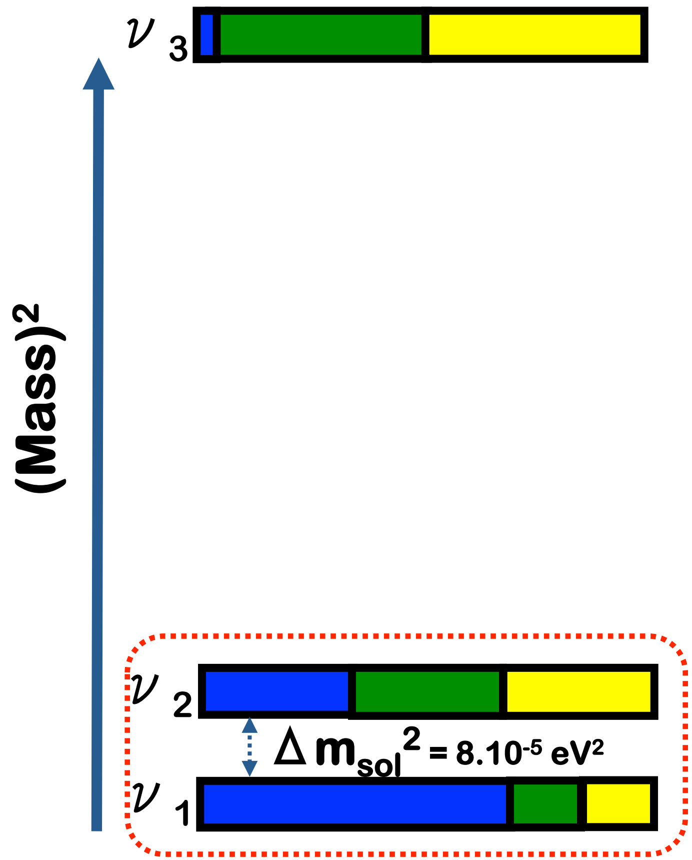
Accelerators:
- $L \sim 1000$ km & $E \sim 3$ GeV

Addressing Atmospheric Sector



Experiment	Baseline	Size	Channel
SuperK	$10\text{-}10^4$ km	22.5 000 m^3	$\nu_\mu \rightarrow \nu_\mu$
Chooz	1 km	5 m^3	$\overline{\nu}_e \rightarrow \overline{\nu}_e$
K2K	250 km	22.5 000 m^3	$\nu_\mu \rightarrow \nu_\mu$
MINOS	730 km	5.4 ktons	$\nu_\mu \rightarrow \nu_\mu$

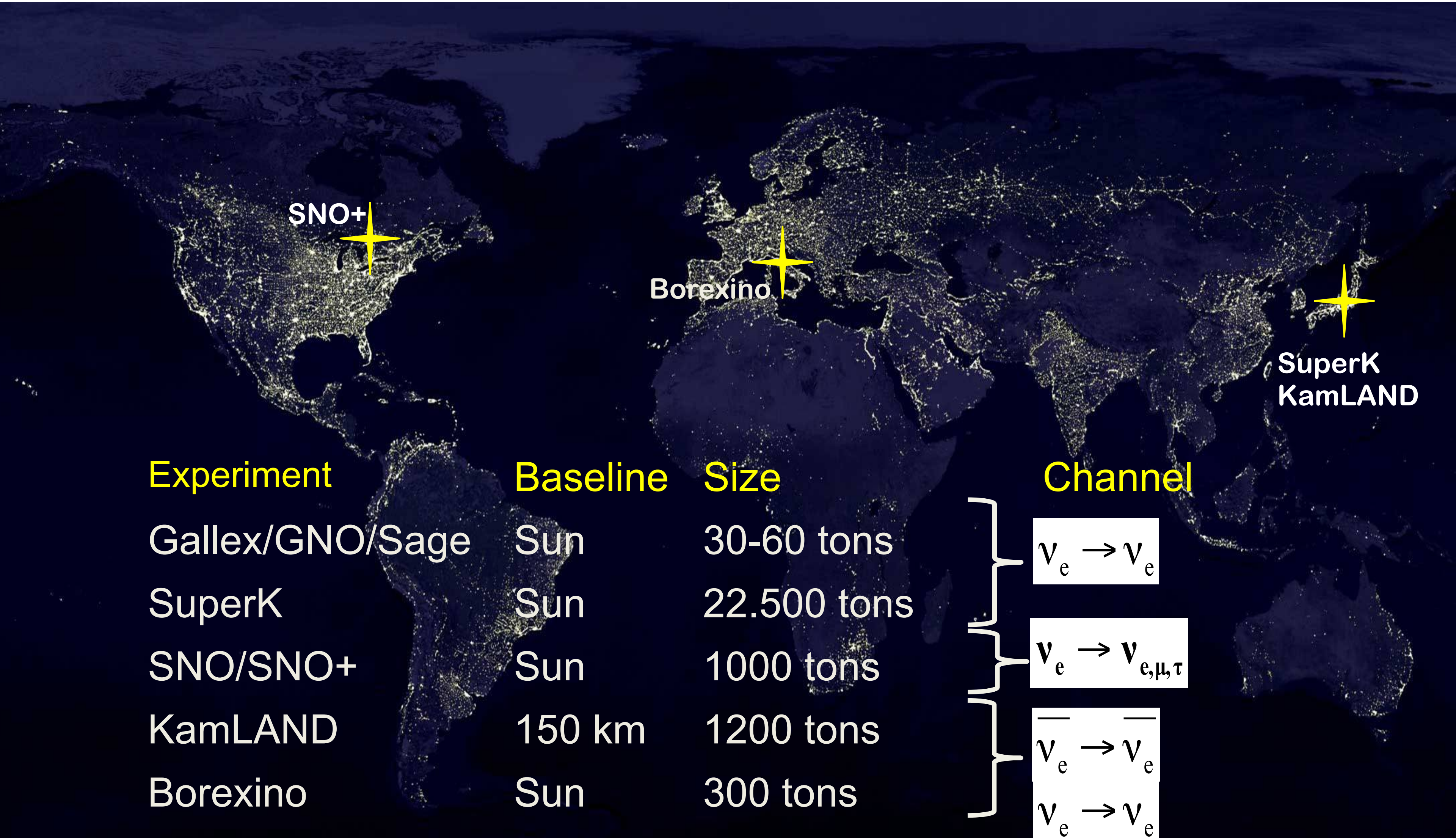
Δm^2_{21} & θ_{12}



L~100 km & E~MeV
Or MSW 'flavor transition'

ν_e $|U_{ei}|^2$ ν_μ $|U_{\mu i}|^2$ ν_τ $|U_{\tau i}|^2$

Addressing Solar Sector



Experiment	Baseline	Size
Gallex/GNO/Sage	Sun	30-60 tons
SuperK	Sun	22.500 tons
SNO/SNO+	Sun	1000 tons
KamLAND	150 km	1200 tons
Borexino	Sun	300 tons

Channel

- Gallex/GNO/Sage, SuperK: $\nu_e \rightarrow \nu_e$
- SuperK, SNO/SNO+: $\nu_e \rightarrow \nu_{e,\mu,\tau}$
- KamLAND, Borexino: $\bar{\nu}_e \rightarrow \bar{\nu}_e$, $\nu_e \rightarrow \nu_e$

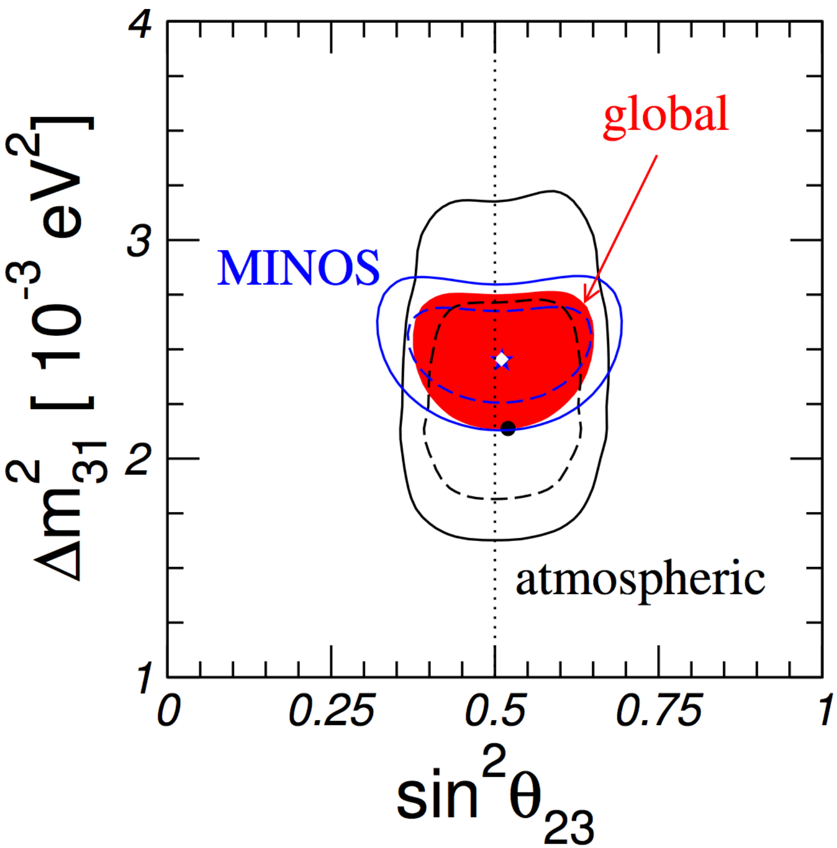
Leading Order Oscillation Picture

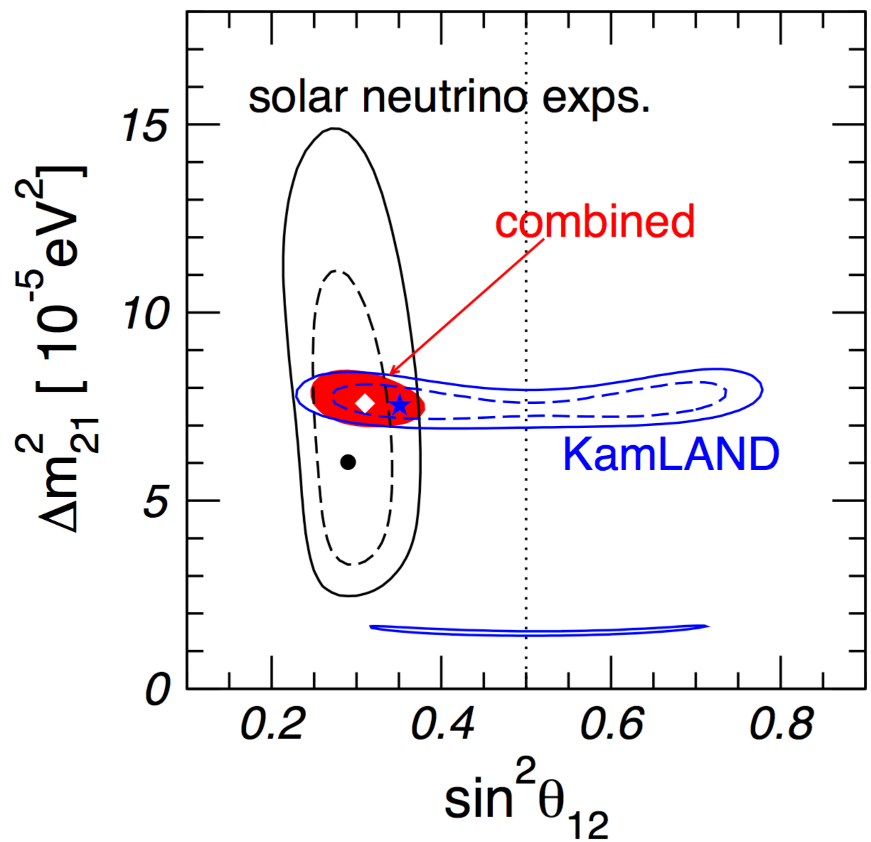
Atmospheric Oscillation

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

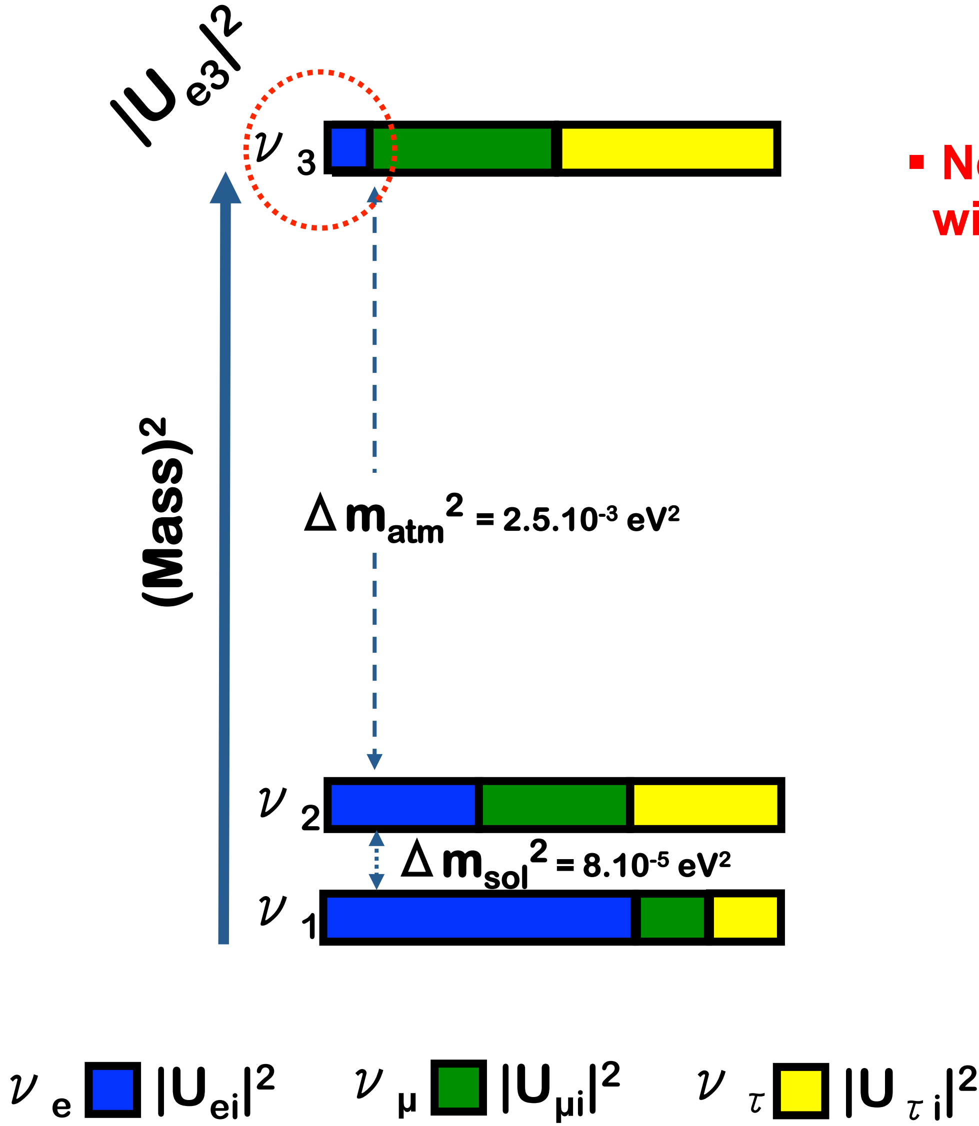
Solar Oscillation

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





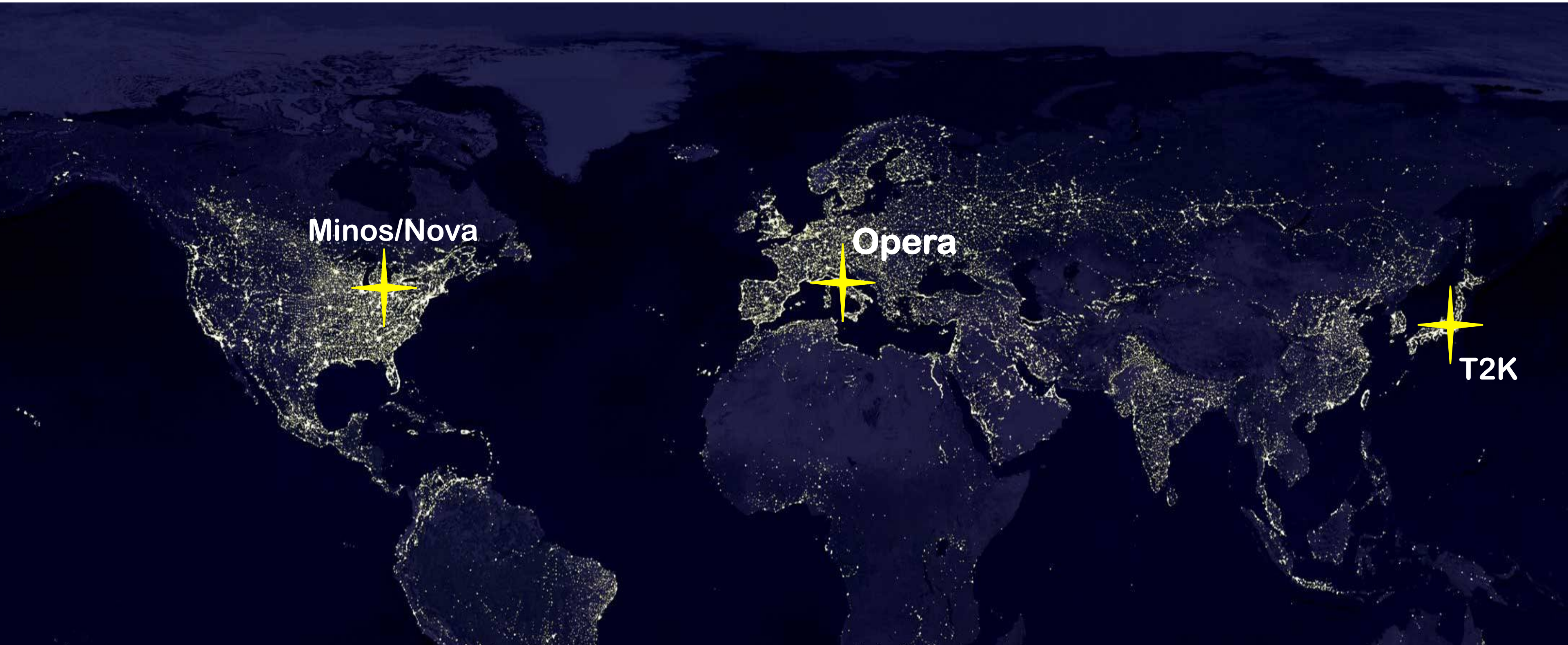
θ_{13}



- **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 → 'clean'
  - **L~1000 km, E~GeV**
    - accelerator experiments
    - appearance expt. @Beam
    - (θ_{13}, NH/IH, δ_{CP})
      → correlations & degeneracies

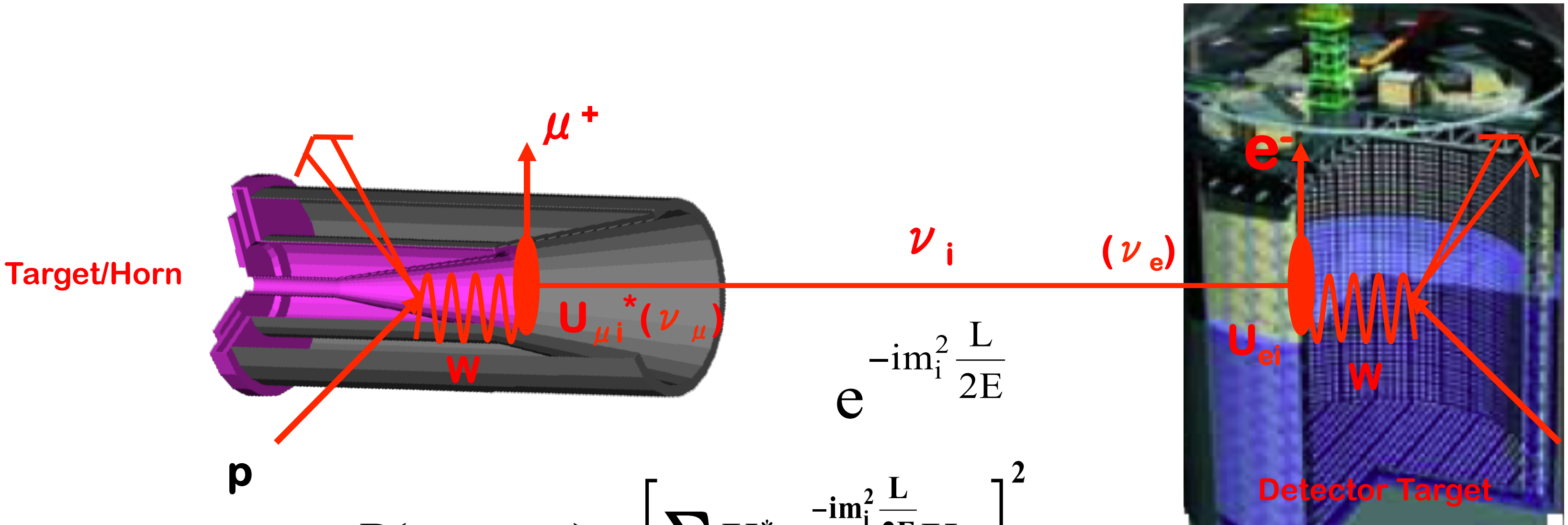
→ Complementary projects

Beam Neutrino Experiments



Experiment	Baseline	Size	Power	Channel
Minos	732 km	5 400 tons	0.3 MW	$\nu_\mu \to \nu_e$ & $\nu_\mu \to \nu_\mu$
Nova	812 km	15 000 m^3	0.7 MW	
T2K	295 km	22.5 000 m^3	0.75 MW	

ν-Beam: Oscillation Physics



$$P(\nu_\mu \to \nu_e) = \left[\sum_i U_{\mu i}^* e^{-im_i^2 \frac{L}{2E}} U_{ei} \right]^2$$

- Complex oscillation formula

➔ depends on $\sin^2(2\theta_{13})$, Δm_{31}^2, sign(Δm_{31}^2), δ

- >> MeV muon antineutrinos ➔ appearance experiments

➔ $\sin^2(2\theta_{13})$ measurement depends on δ-CP

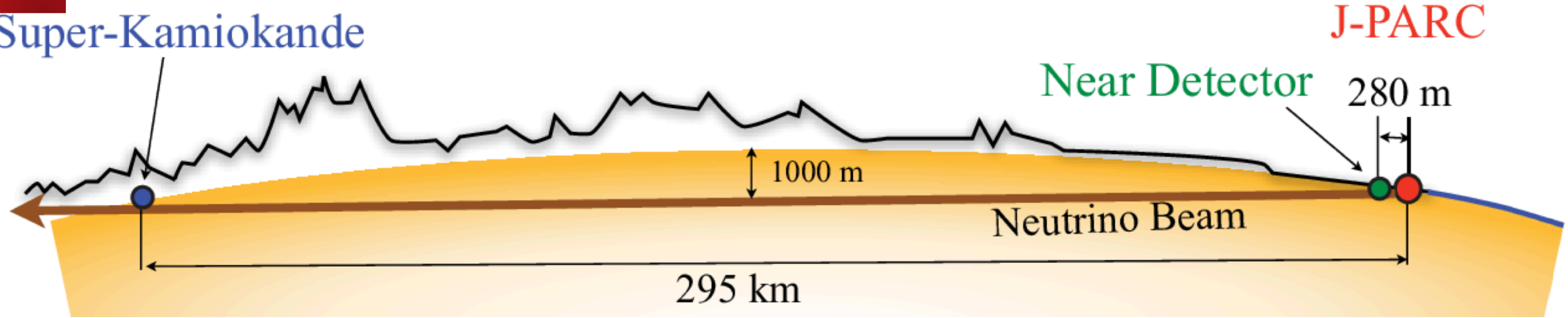
- >> MeV neutrinos + >>100 km baseline → matter effects

➔ $\sin^2(2\theta_{13})$ measurement independent of sign(Δm^2_{13})

Very sensitive to apparition

Correlation & degeneracies

T2K (Tokai to Kamioka) @JPARK

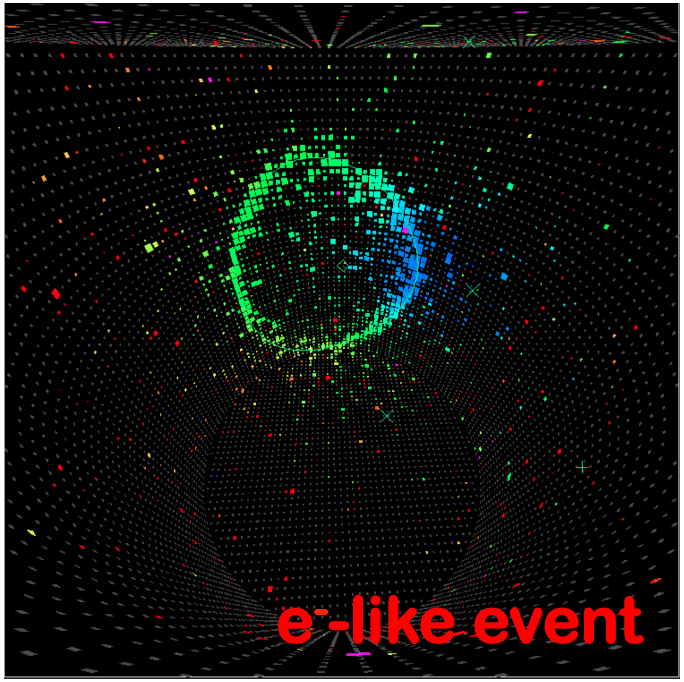


- **Channel:** $\nu_\mu \rightarrow \nu_e$ (1st goal: search for non-zero θ_{13}, beam contamination, NC-1π_0)
- **Channel:** $\nu_\mu \rightarrow \nu_\mu$ ($\sin^2 2\theta_{23}$ @ 1% & Δm^2_{23} @ 2%, single pion production)

- **Detection, CCQE:** $\nu_l + n \rightarrow p + l^-$ (l=e, μ)

- **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}

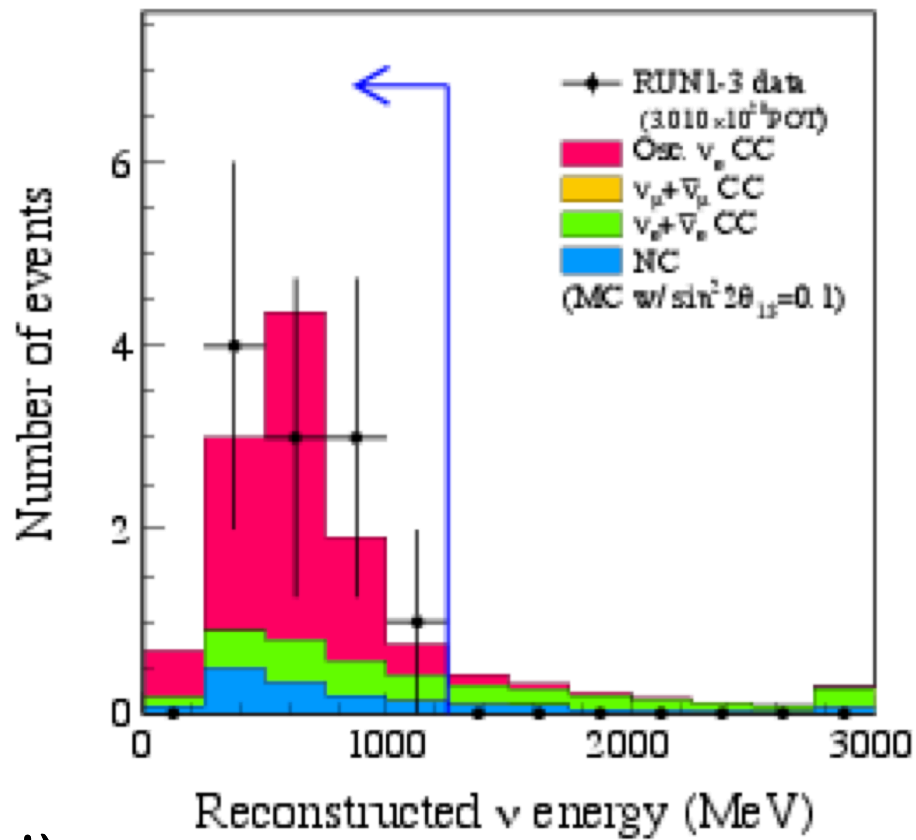
- New results on $\nu_\mu \rightarrow \nu_e$ based on **3 x 10^{20} pot** (4% exposure's goal)

- Expected **Background: 3.22±0.43**
  - intrinsic ν_e contamination
  - π^0 from NC interactions

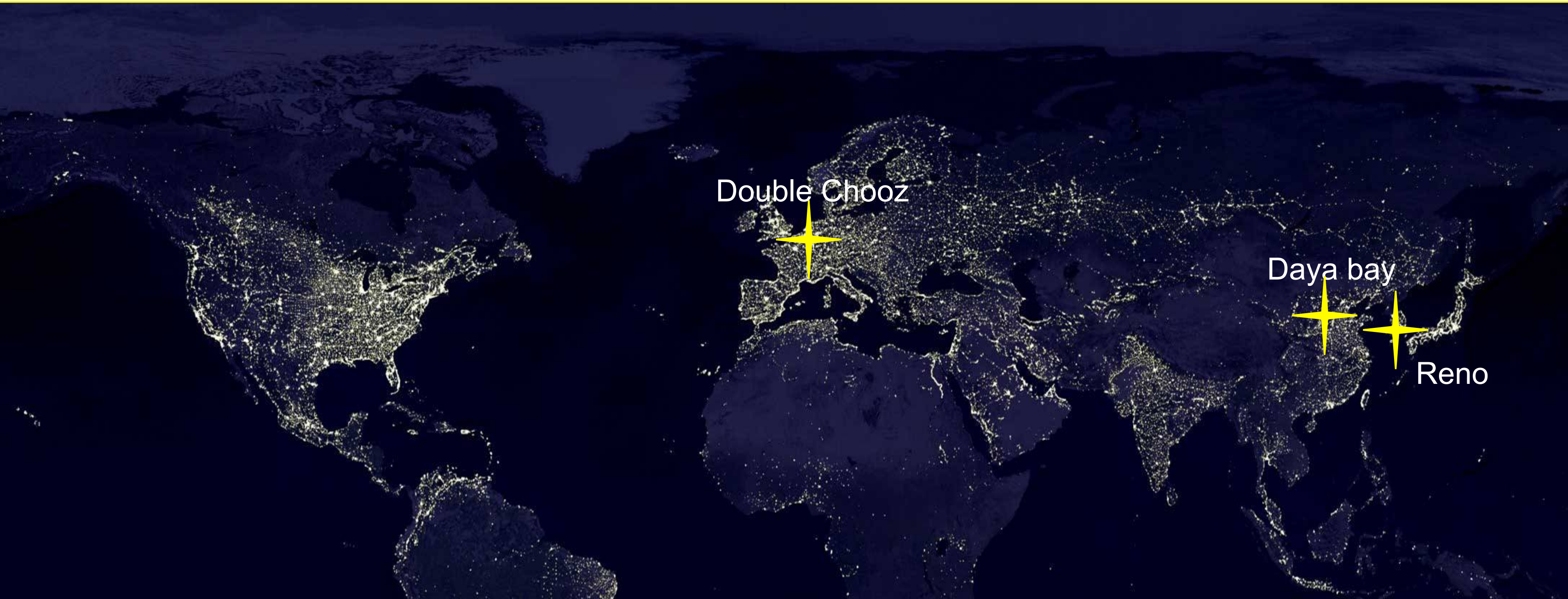
- **11 candidate events**
  Indication of ν_e appearance

- Under θ_{13}=0 hypothesis,
  P(obs>11 events) = 0.08% (3.2 σ)

- Next Goals:
  - Still limited by stat!
  - Achieve 5 σ in 2012 (8 x 10^{20} pot)
  - Upgrade JPARC (**7.5x 10^{21} pot in 2021**)

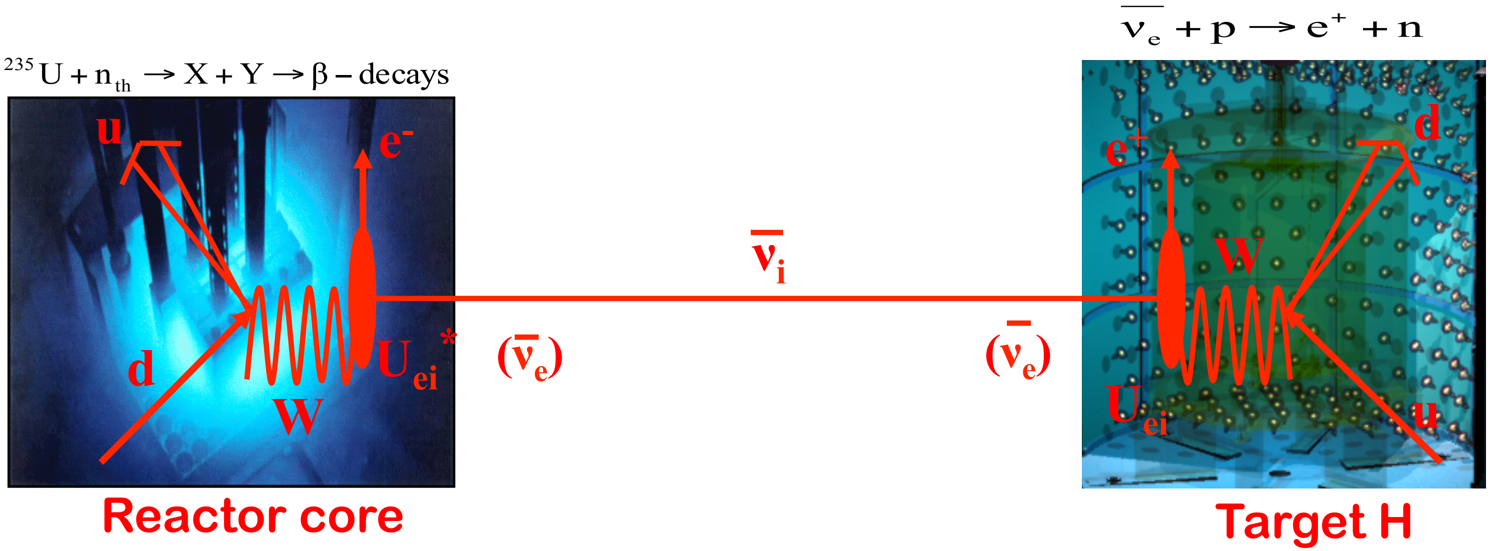


Reactor Neutrino Experiments



Experiment	Baseline	Target (far)	Power	Channel
Double Chooz	400 m / 1.1 km	10 m^3	8.6 GW (2)	$\bar{\nu}_e$ disappearance
Reno	350 / 1.4 km	20 m^3	16.4 GW (6)	$\bar{\nu}_e$ disappearance
Daya Bay	400 / 1.7 km	100 m^3	17.4 GW (6)	$\bar{\nu}_e$ disappearance

Reactor: Oscillation Physics



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

- 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 δ-CP

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

➔ $\sin^2(2\theta_{13})$ measurement independent of sign(Δm^2_{13})

} ‘clean’ information on θ_{13}

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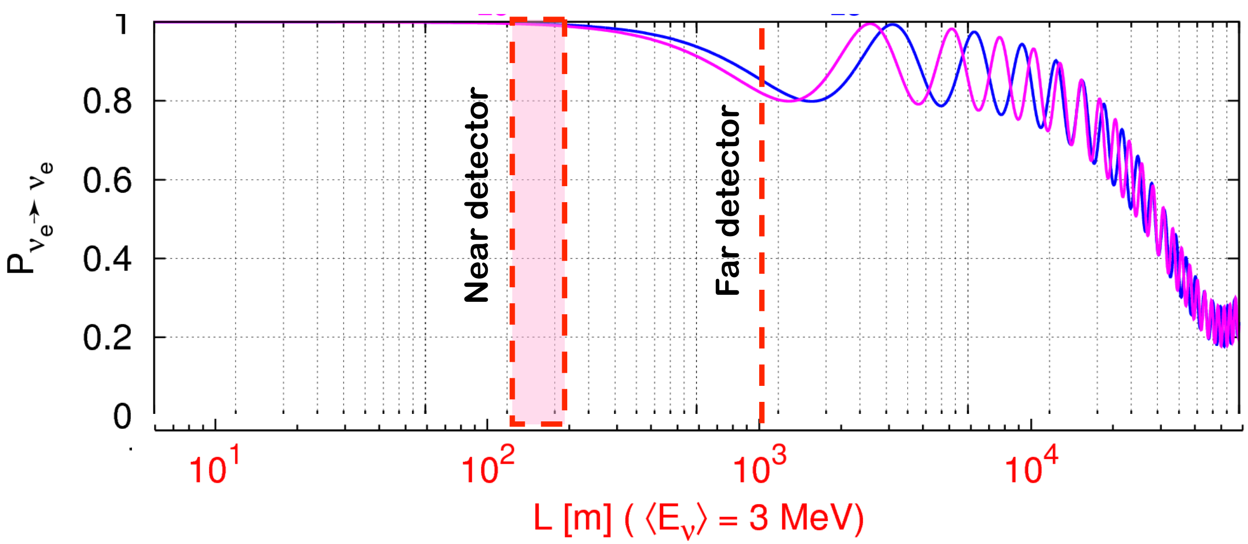
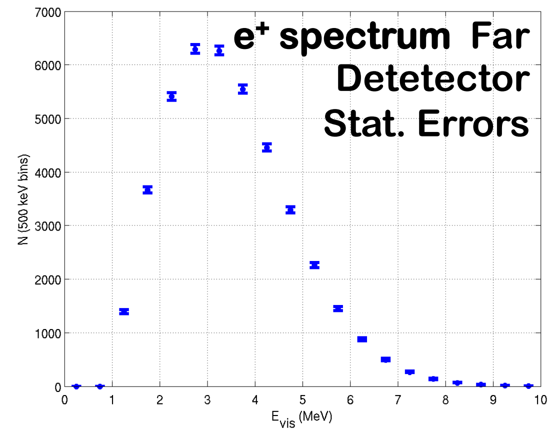
Reactor: Experimental Concept

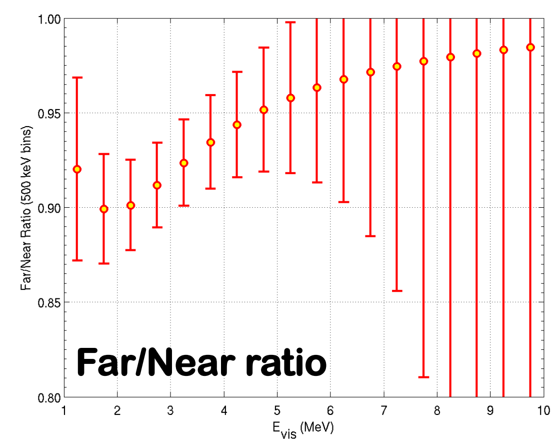
$P(\nu_e \rightarrow \nu_e) = 1 - \sin^2(2\theta_{13})\sin^2(\Delta m^2_{31} L/4E)$

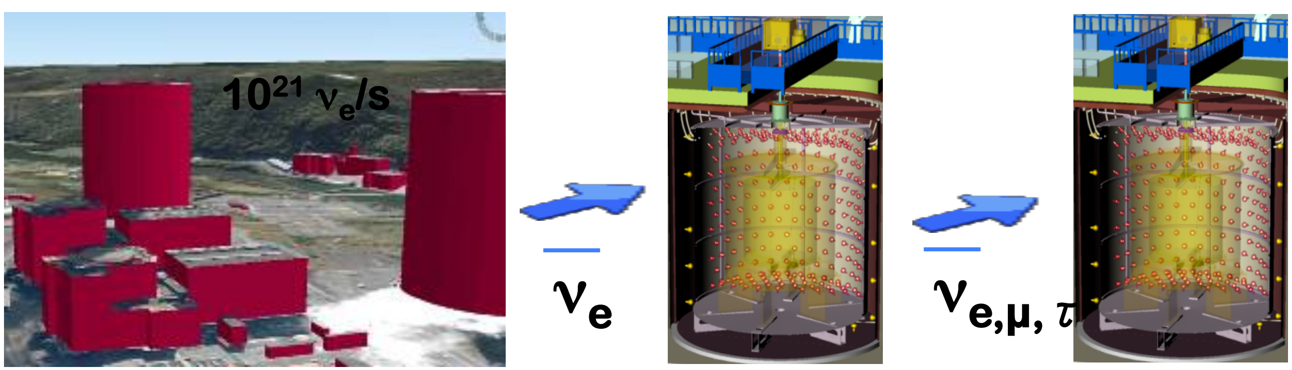




Δm^2_{atm}= 3.0 10^{-3} eV^2

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



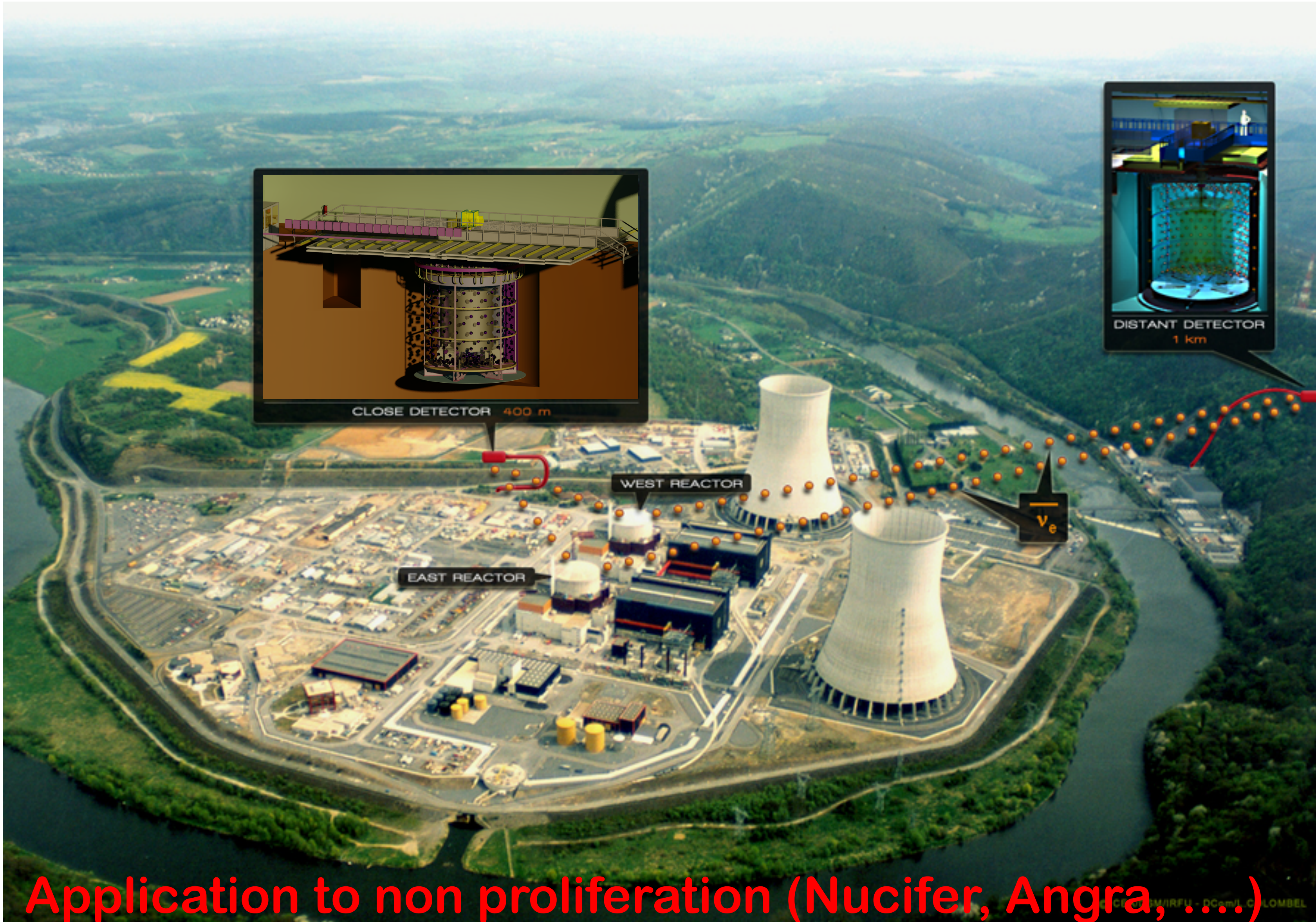


Chooz Nuclear Power Station
2 cores of 4.3 GW_{th} each

Near detector
400 m

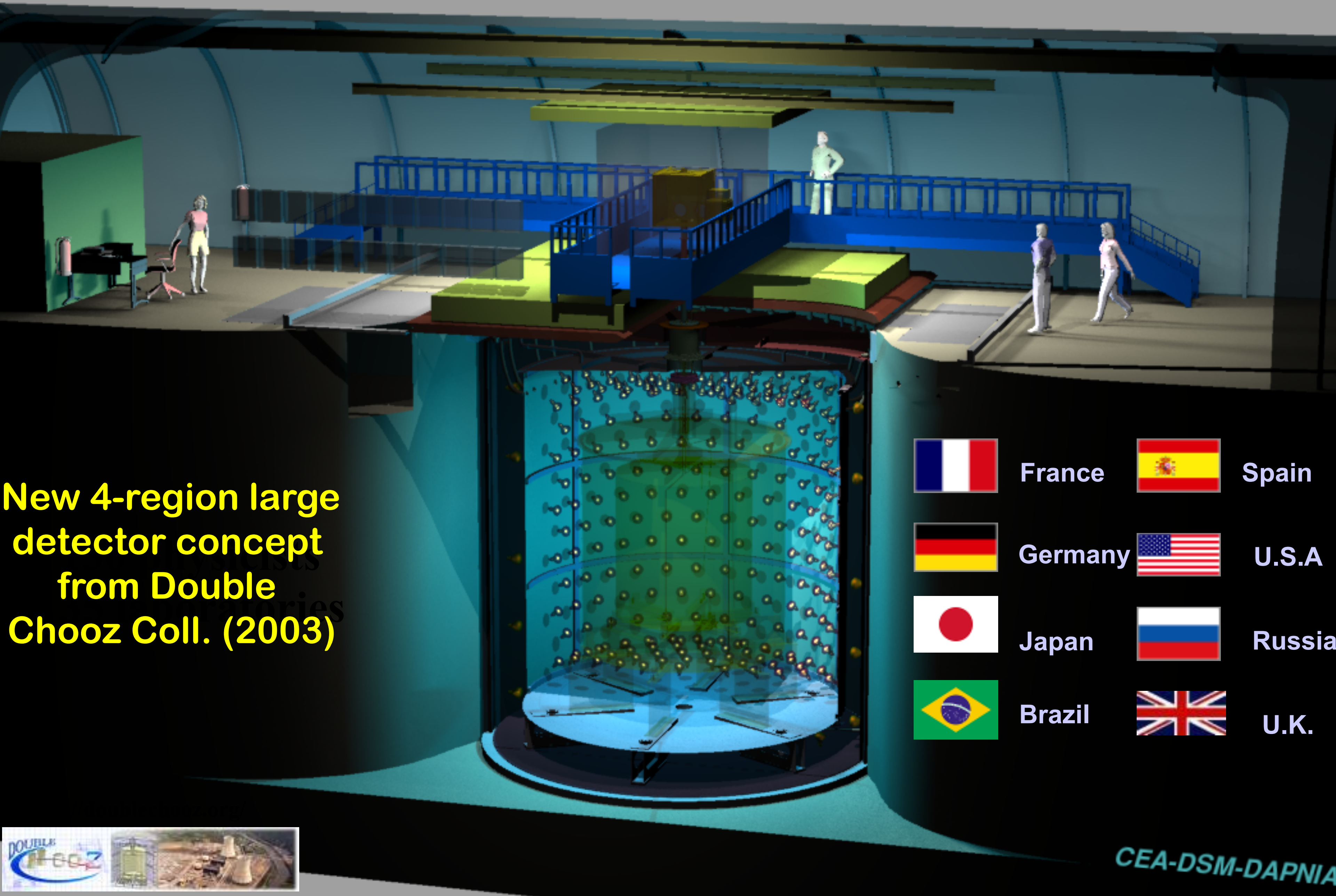
Far detector
1050 m

Double Chooz: Site

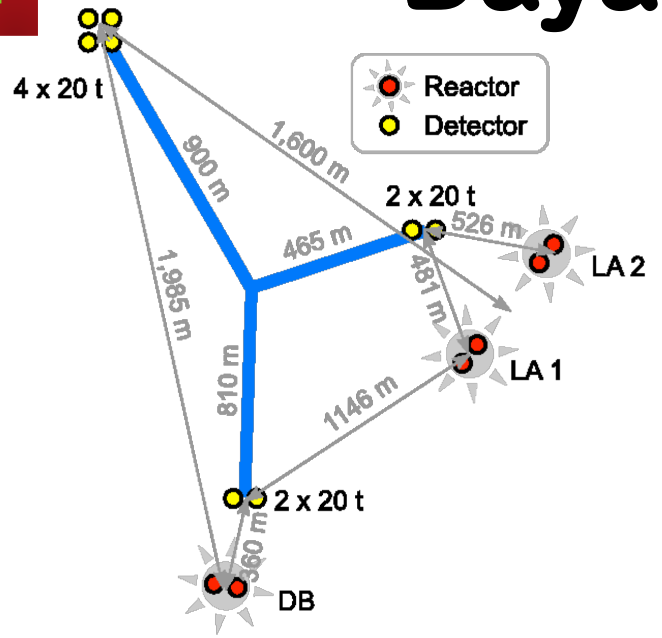


Application to non proliferation (Nucifer, Angra, ….)

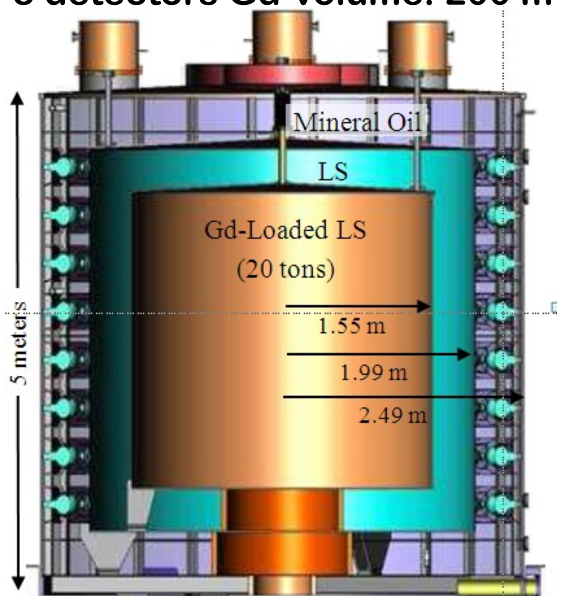
Double Chooz

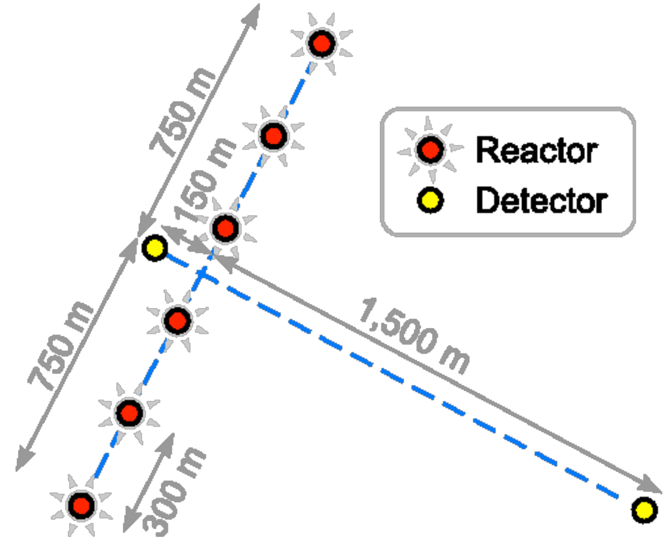


Daya Bay and Reno

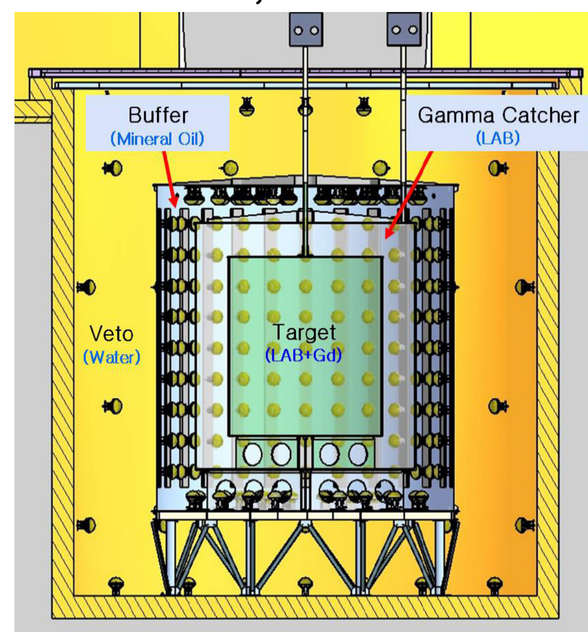


8 detectors Gd-volume: 200 m^3



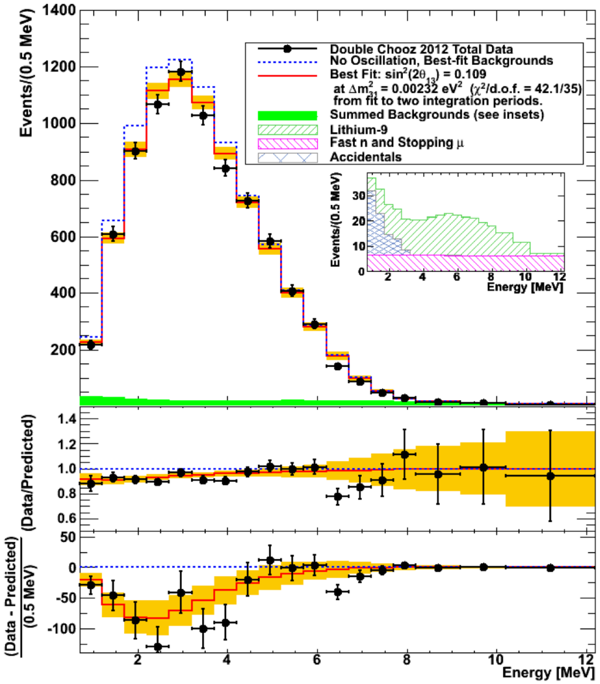


2 detectors, Gd-volume: 40 m^3



Reactor Results on $\sin^2(2\theta_{13})$

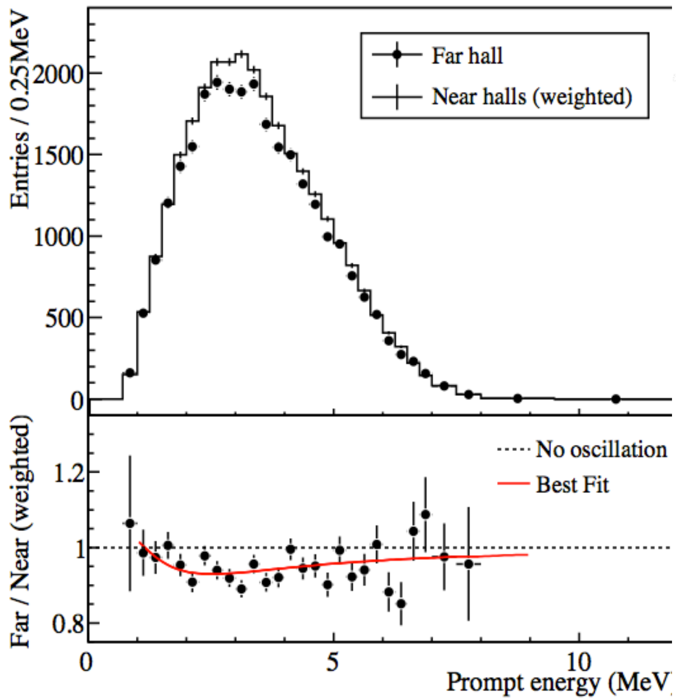
Double Chooz (Oct. 2011)



0.109±0.039(0.030stat±0.025sys)

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

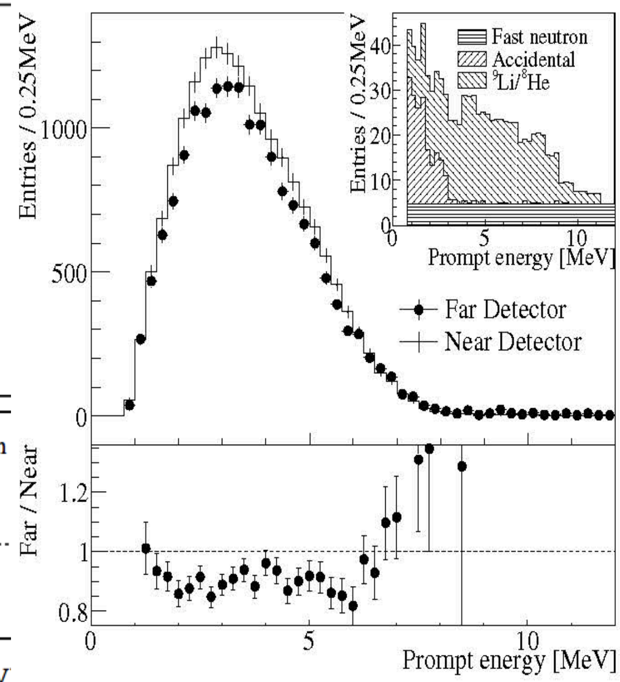
Daya Bay (March 2012)



0.089±0.011(0.010stat±0.005sys)

Leading precision
now 15% error
But still rate only analysis

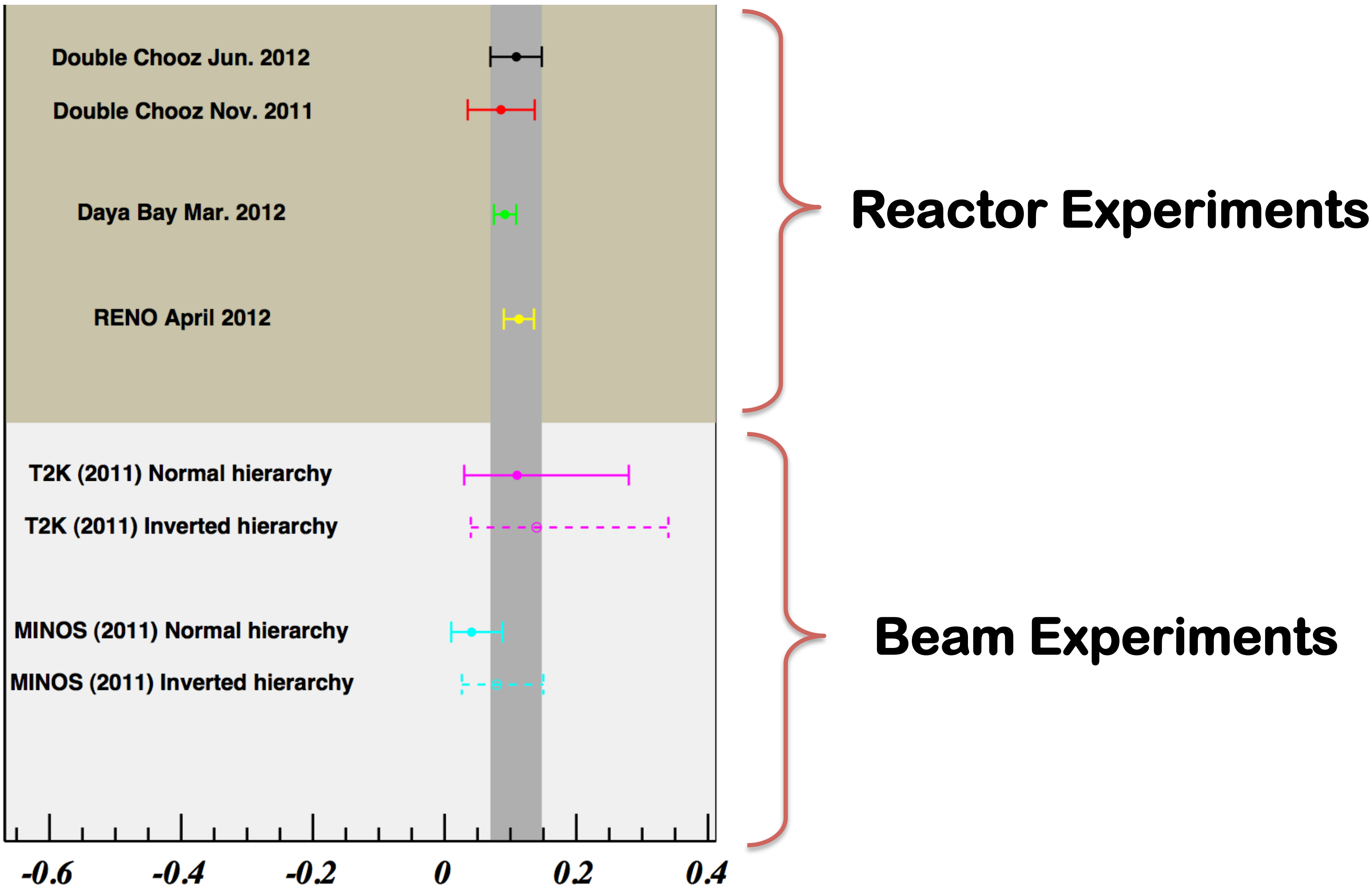
RENO (April 2012)



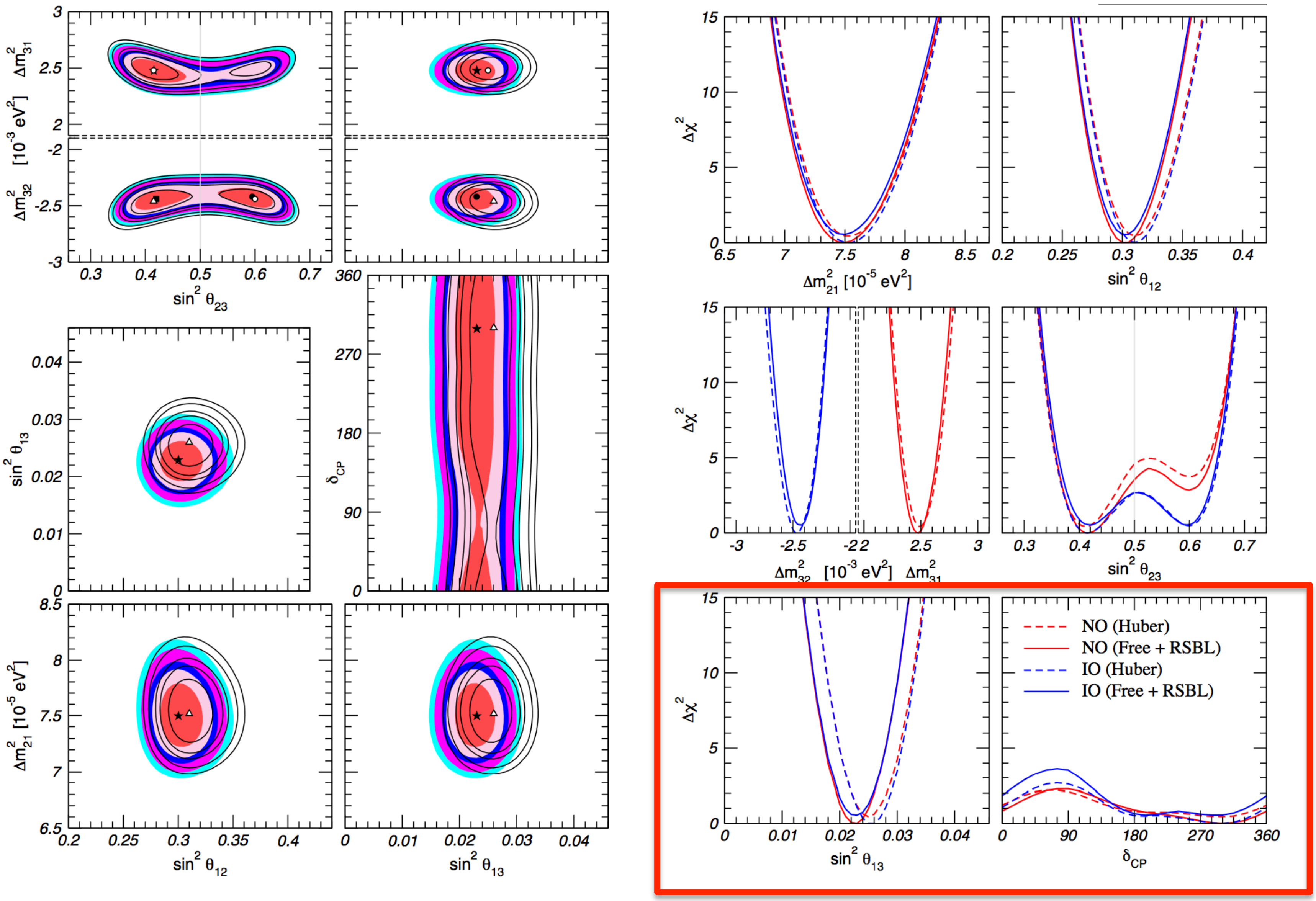
0.113±0.023(0.013stat±0.019sys)

Rate only measurement
Concerns on the analysis
[5-12] MeV region used
for osc. analysis…

Summary of the θ_{13} Results



Global Fit (NuFit 2012)

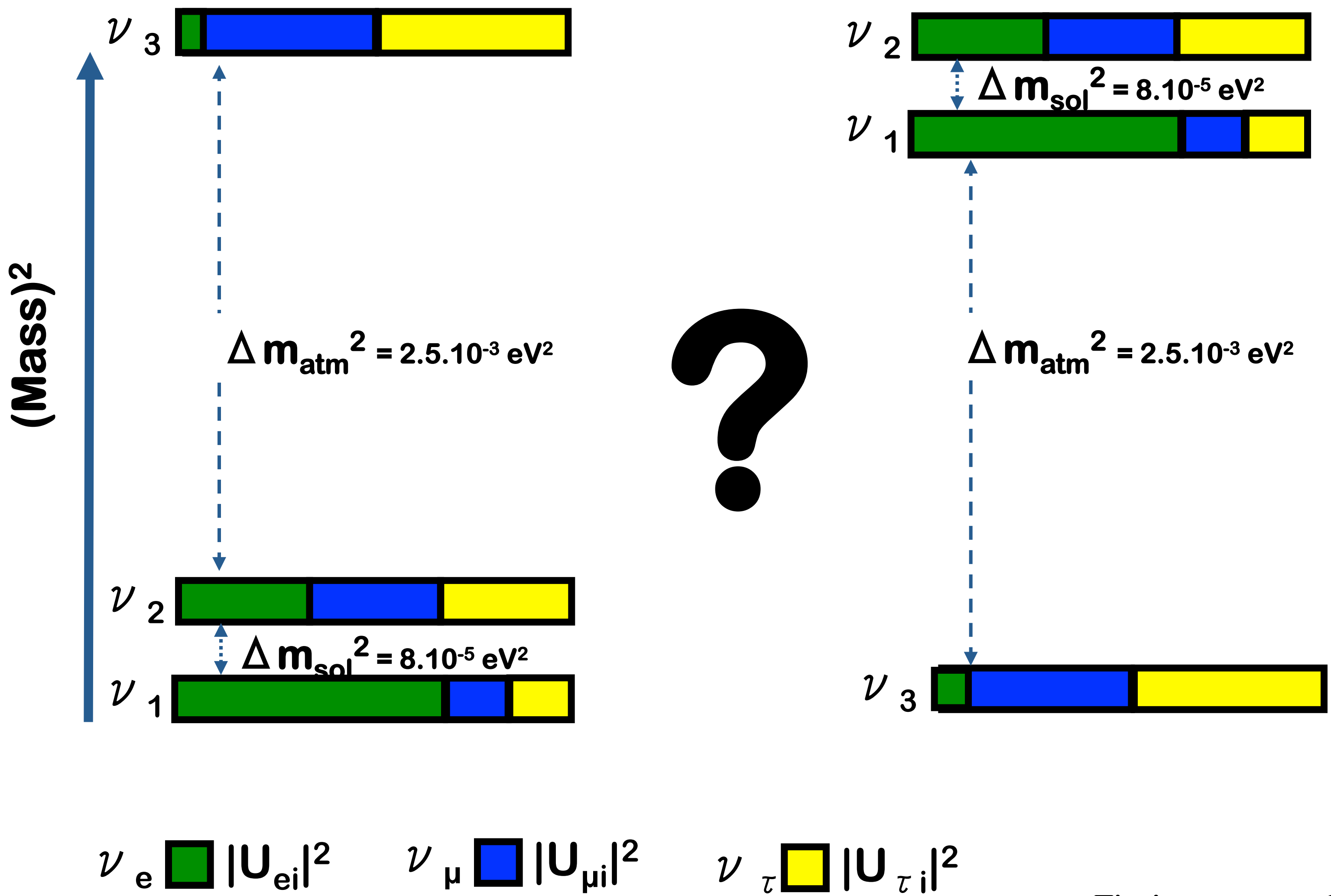


First 'constraint' on δ

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 ?

MH & Matter Effect

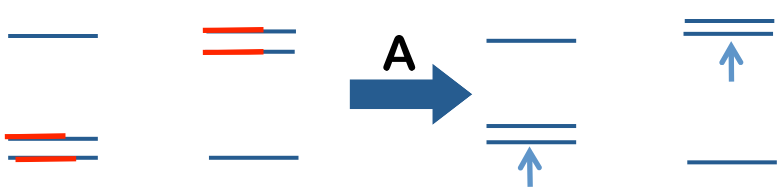
- Coherent neutrino forward scattering from ambient matter

- CC interaction of ν_e with the electrons creates a potential for ν_e

$$A \;\alpha\; \pm G_F N_e E_\nu$$

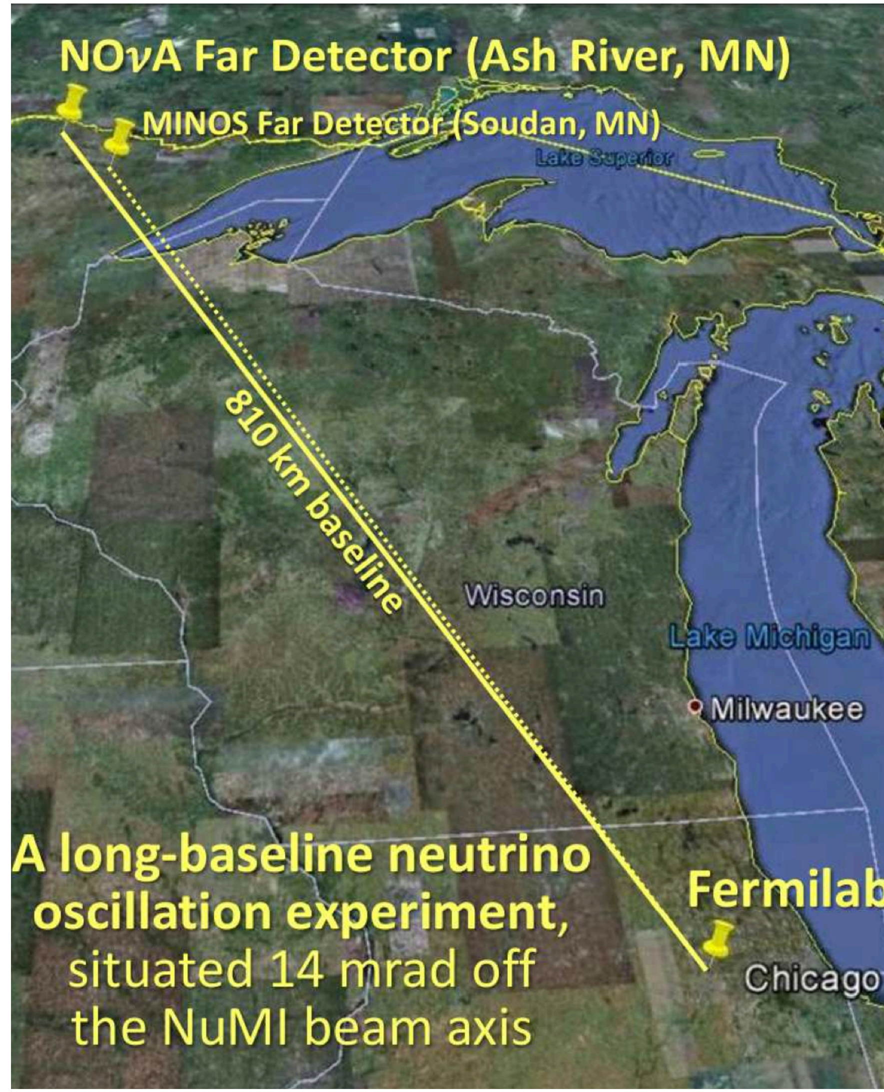
(+ for v, - for anti-v)

- 'A' modifies the mass eigenstates values and thus the oscillation prob.



- 'A' lead to $P(\nu_\alpha \rightarrow \nu_\beta) \neq P(\overline{\nu_\alpha} \rightarrow \overline{\nu_\beta})$

→ Mimicking CP-δ effect

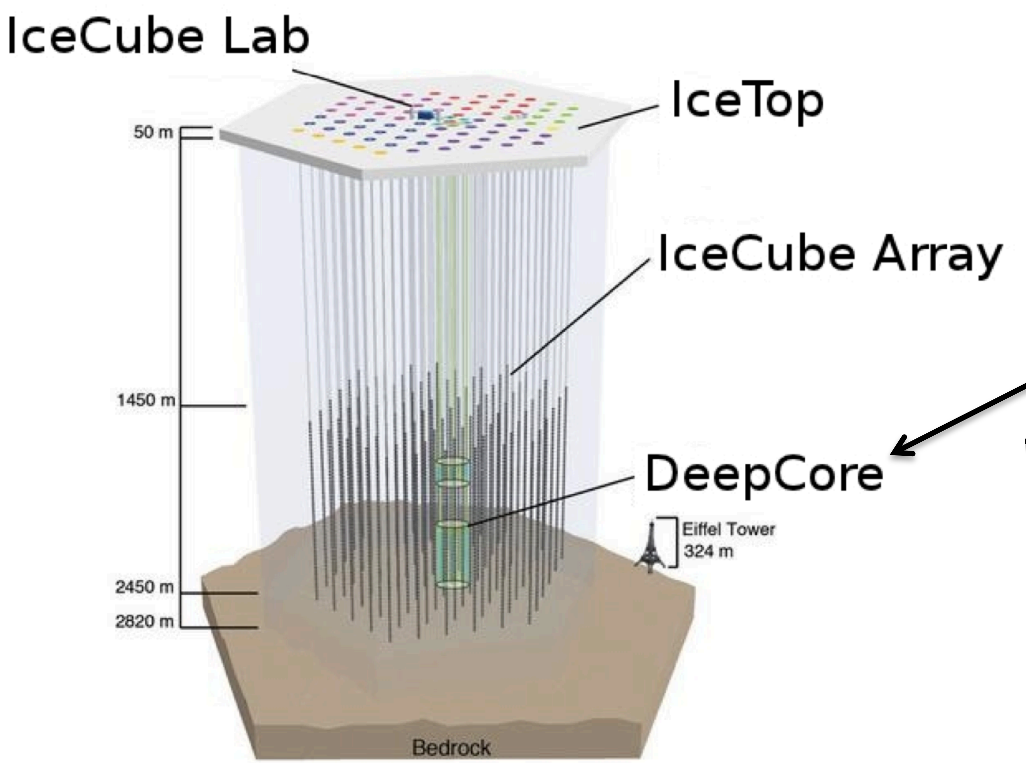


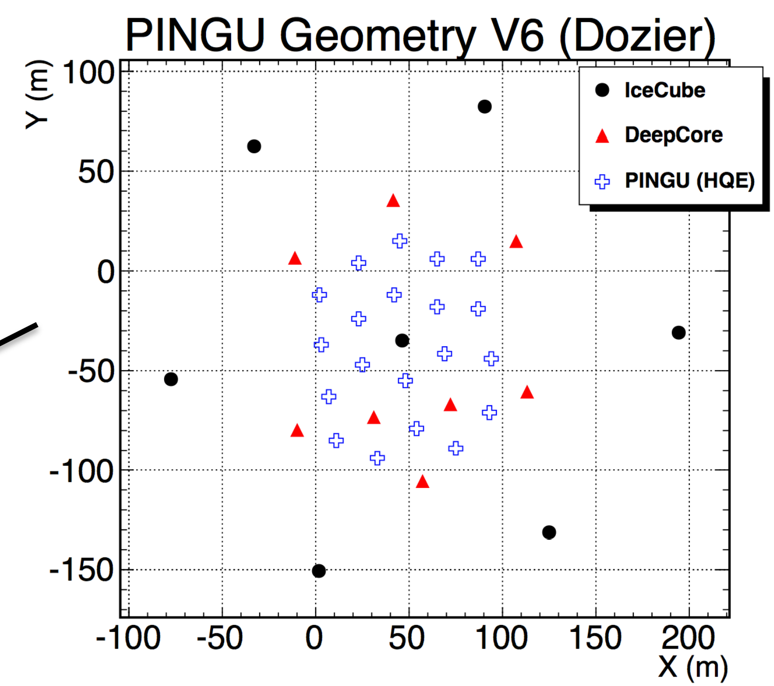
Nova: 40% chance tagging MH @2σ

IceCube Neutrino Telescope

Existing: 1 km^3 antarctic ice instrumented with 5160 PMTs
+ Deep Core 20 strings to reduce threshold

Next: PinGU → Add 20 strings within DeepCore



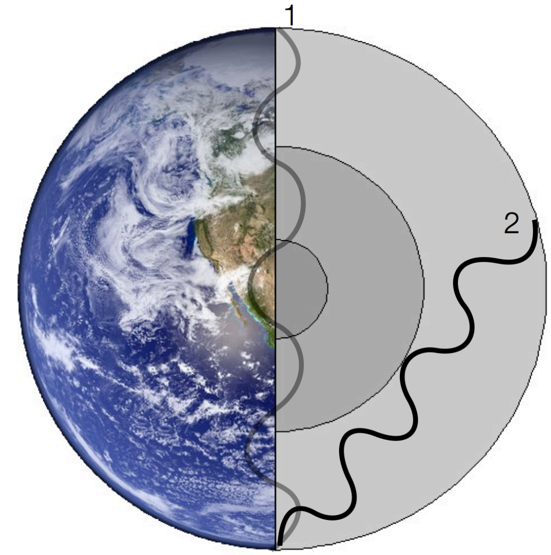


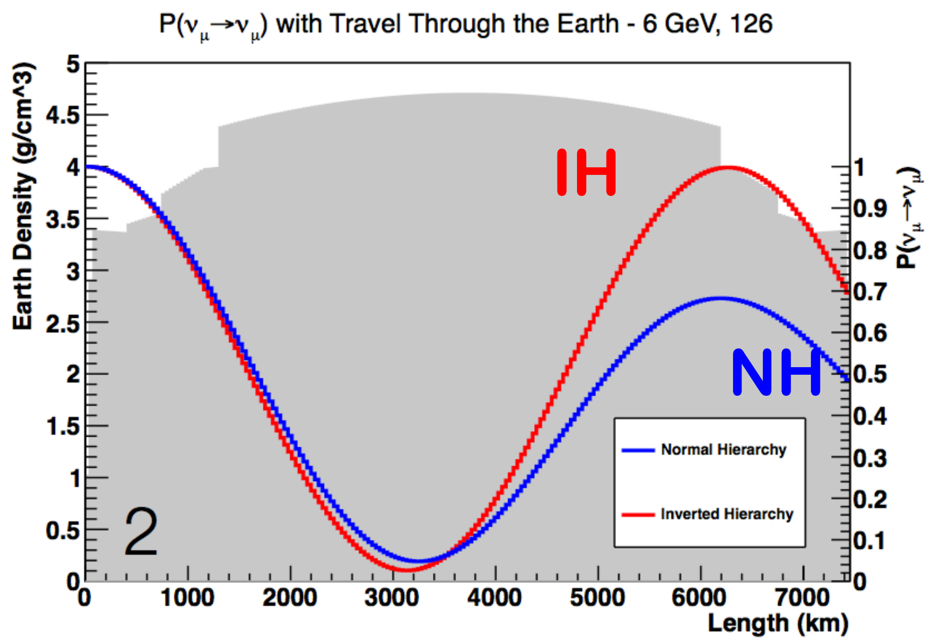
MH with PINGU (& ORCA)

- 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)



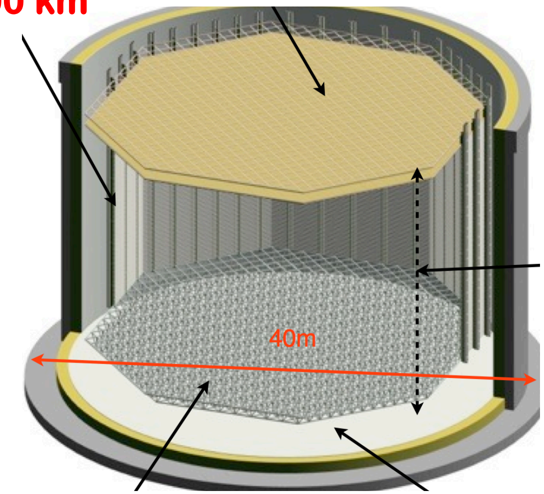


Question 3)

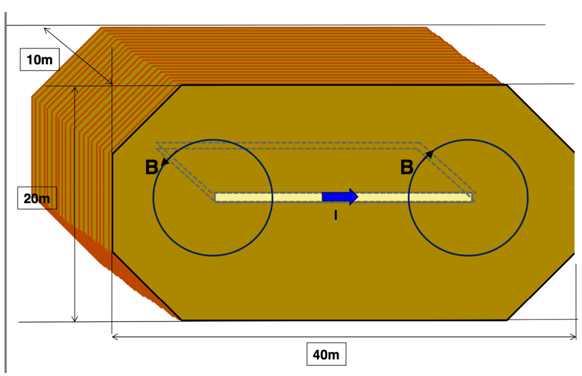
Do the behavior of ν violate CP?

MH & CPV: long term projects

L=2300 km



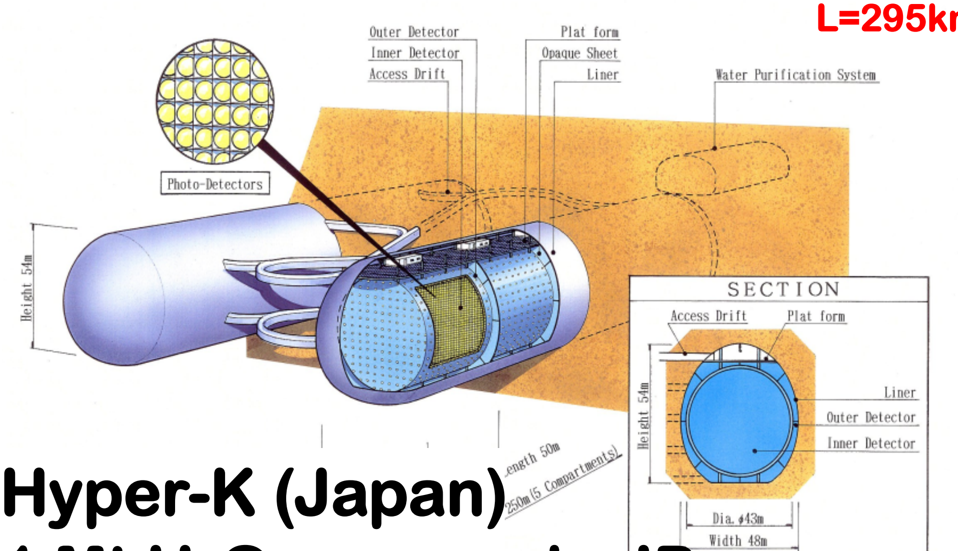
LBNO (Europe, underground)
20-100 kt LAr +
Magnetic Spectrometer



L=1300 km

LBNE (US)
10 kt LAr
(surface)

L=295km



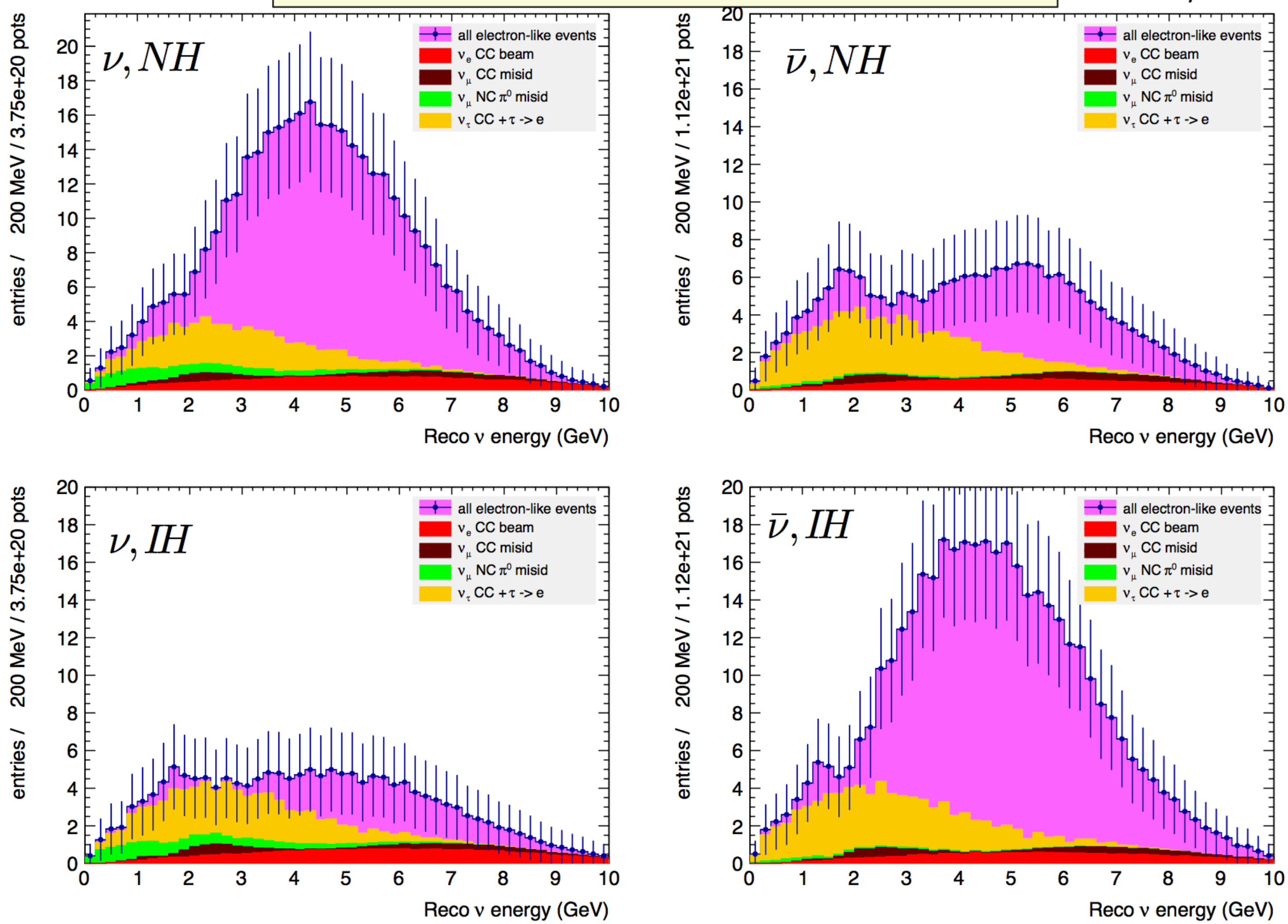
Hyper-K (Japan)
1 Mt H_2O + upgrade JParc

LBNO: Mass Hierarchy ($\overset{(-)}{\nu}_{\mu} \rightarrow \overset{(-)}{\nu}_{e}$)

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

Detector response and resolution included

Running m
ν/anti-ν:25



Towards CP-violation Search

$$P(\nu_e \rightarrow \nu_\mu) = |A|^2 + |S|^2 + 2\,A\,S\,\sin\delta$$

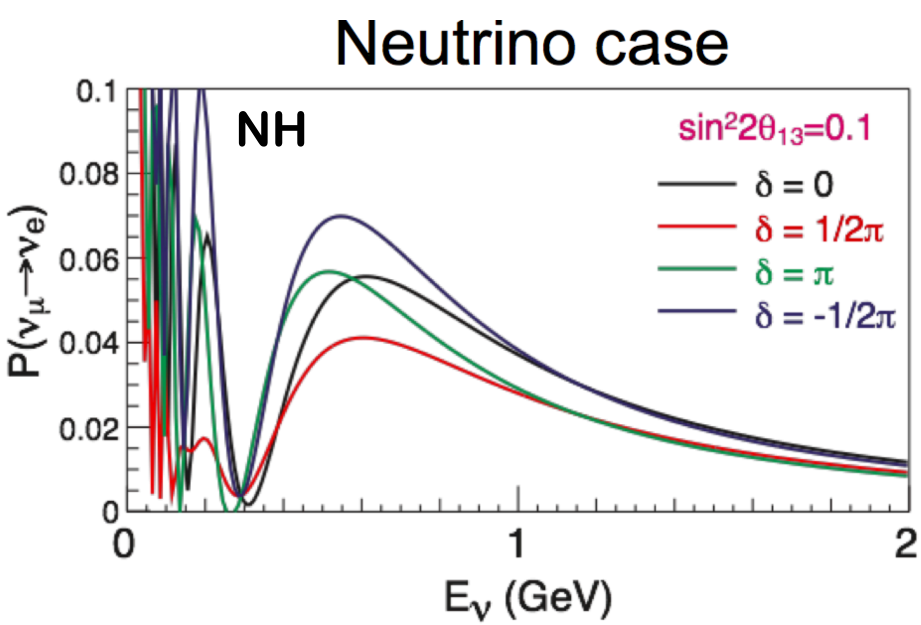
$$P(\bar{\nu}_e \rightarrow \bar{\nu}_\mu) = |A|^2 + |S|^2 - 2\,A\,S\,\sin\delta$$

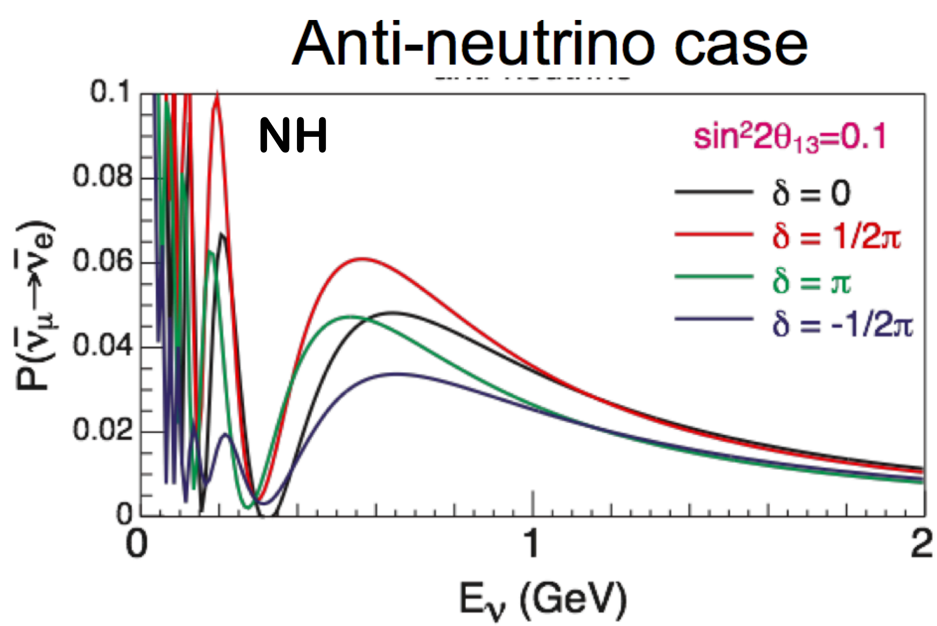
$$A_{CP} \propto \frac{P(\nu_e \rightarrow \nu_\mu) - P(\bar{\nu}_e \rightarrow \bar{\nu}_\mu)}{P(\nu_e \rightarrow \nu_\mu) + P(\bar{\nu}_e \rightarrow \bar{\nu}_\mu)}$$

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

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

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

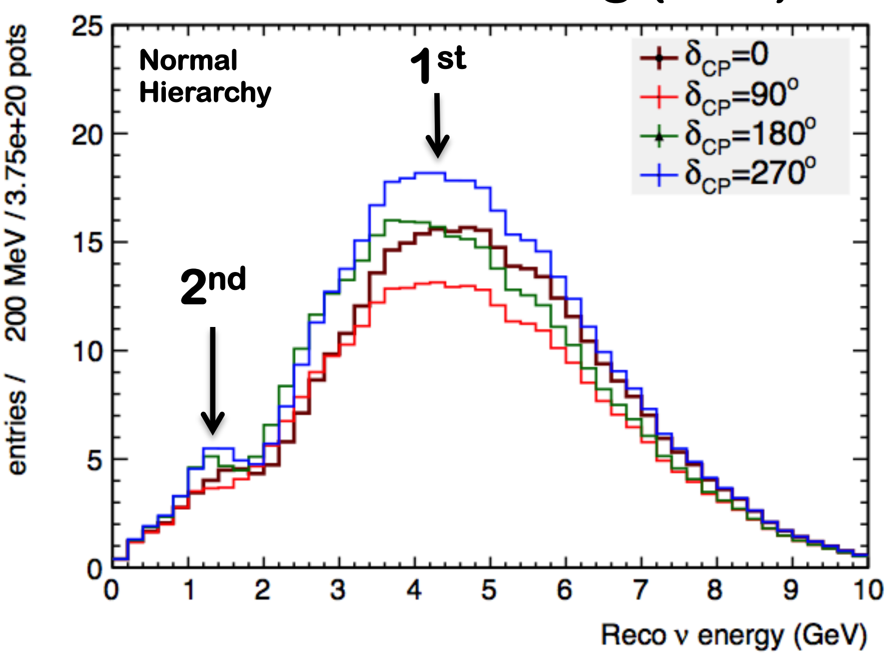




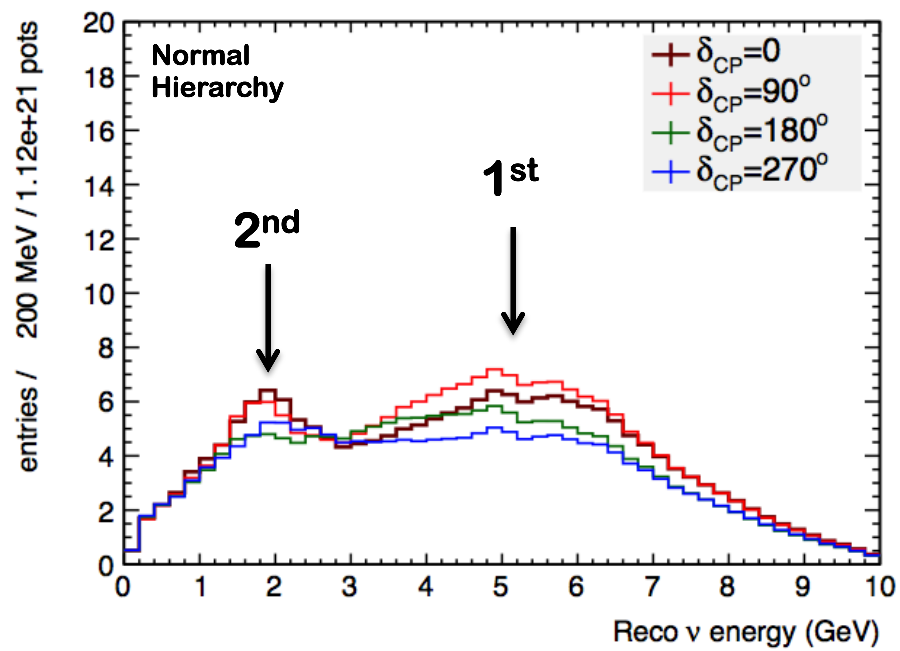
CPV Signal in LBNO (1.5e21 pot)

- Search for a $P(\nu_\mu \rightarrow \nu_e)$ / $P(\text{anti-}\nu_\mu \rightarrow \text{anti-}\nu_e)$ asymmetry
- LBNO: 20 kt, 12 years of data → limited by statistics!
  - Maximize #events at 1st max osc. peak
  - While enhancing 1st / 2nd oscillation peak ratio

Neutrino Running (25%)

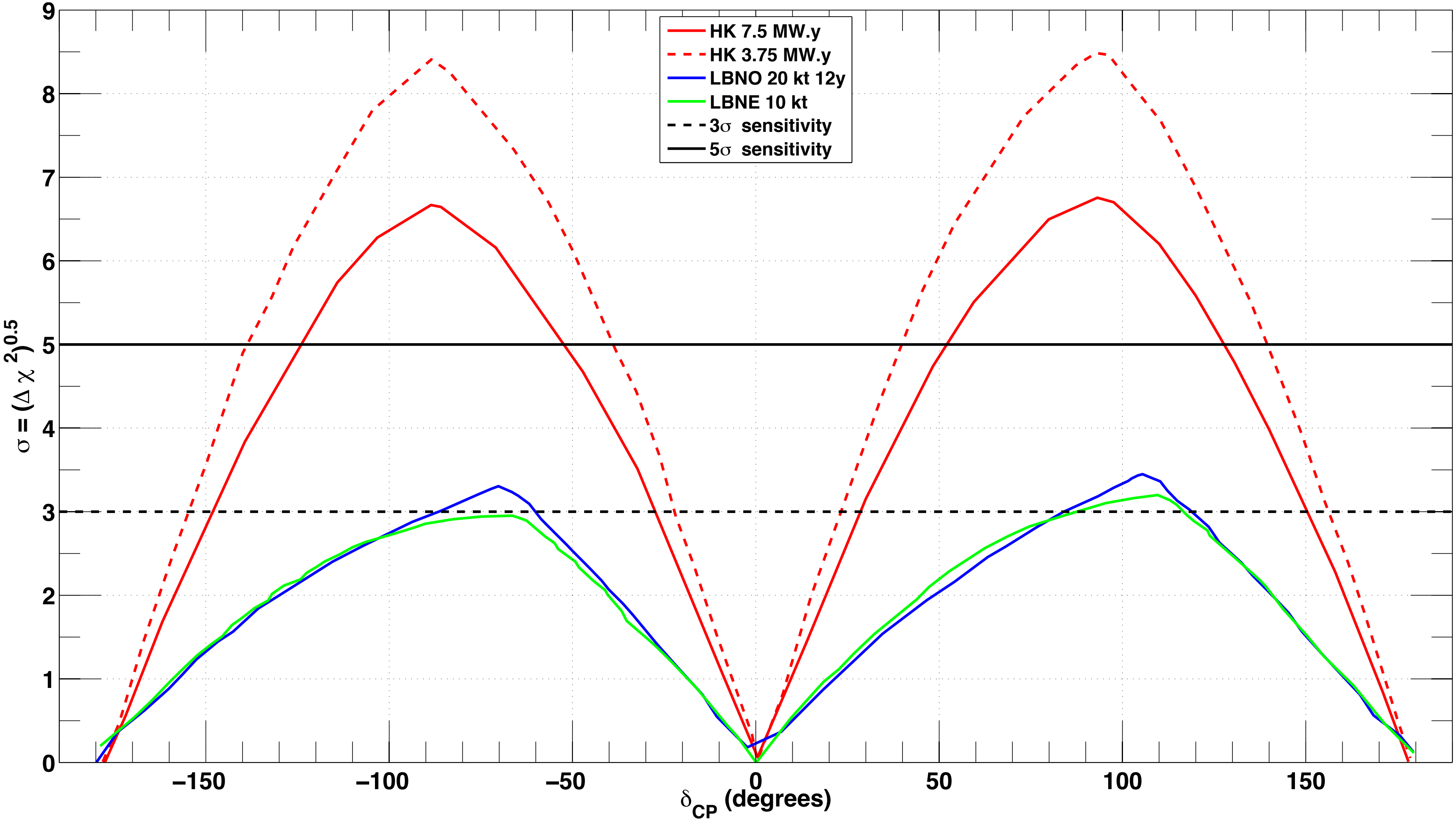


Anti-neutrino Running (75%)



LBNO(E), HK: CPV Sensitivity

Rejection of the null hypothesis for different CP values



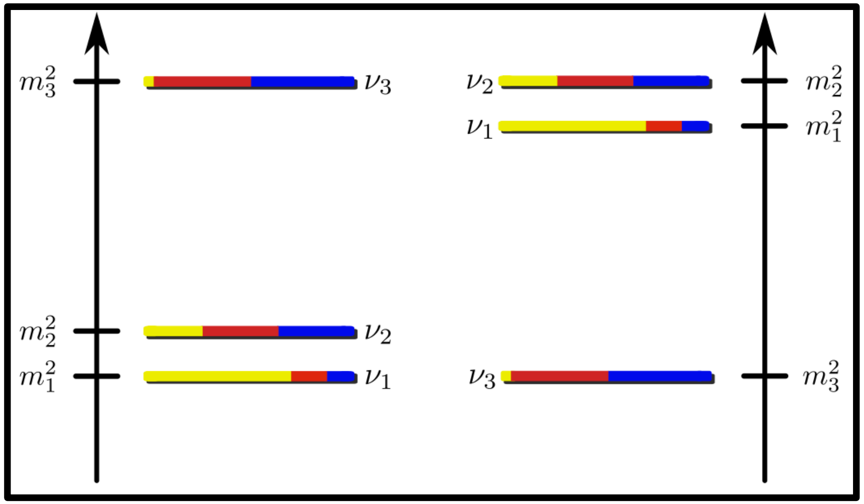
Th. Lasserre – SILAFAE 2012

Question 4)

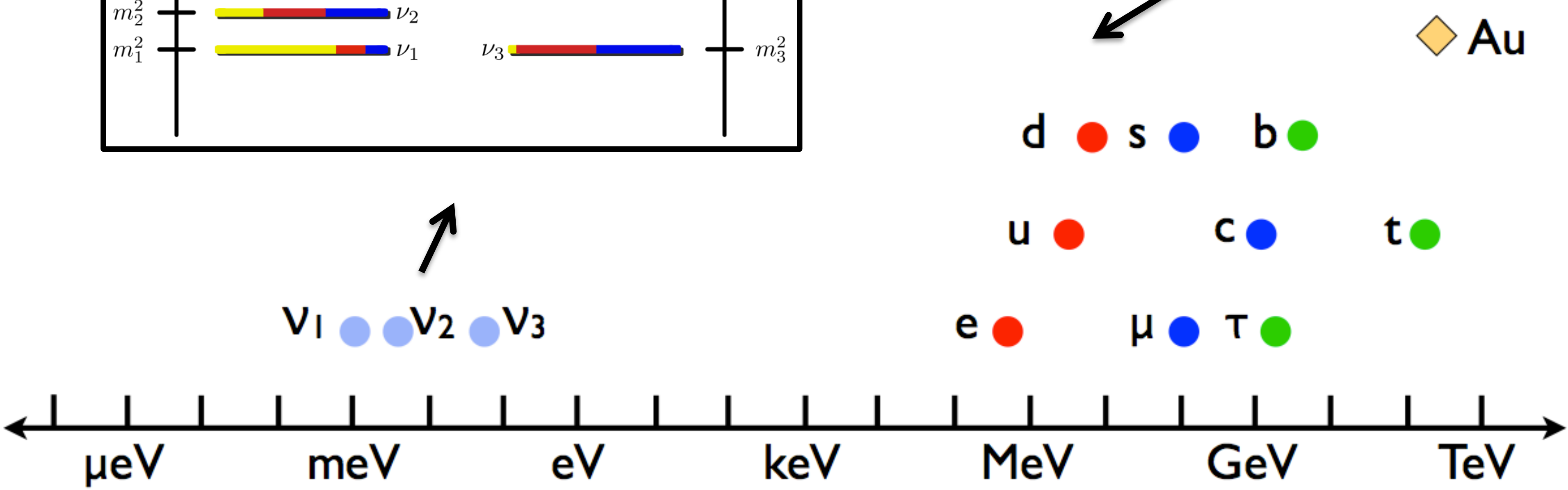
What are the masses of the mass eigenstates ?

Neutrino Mass Scale

What is the ν Mass Hierarchy?



What set the ν Mass Scale?



Finding the Neutrino Mass Scale

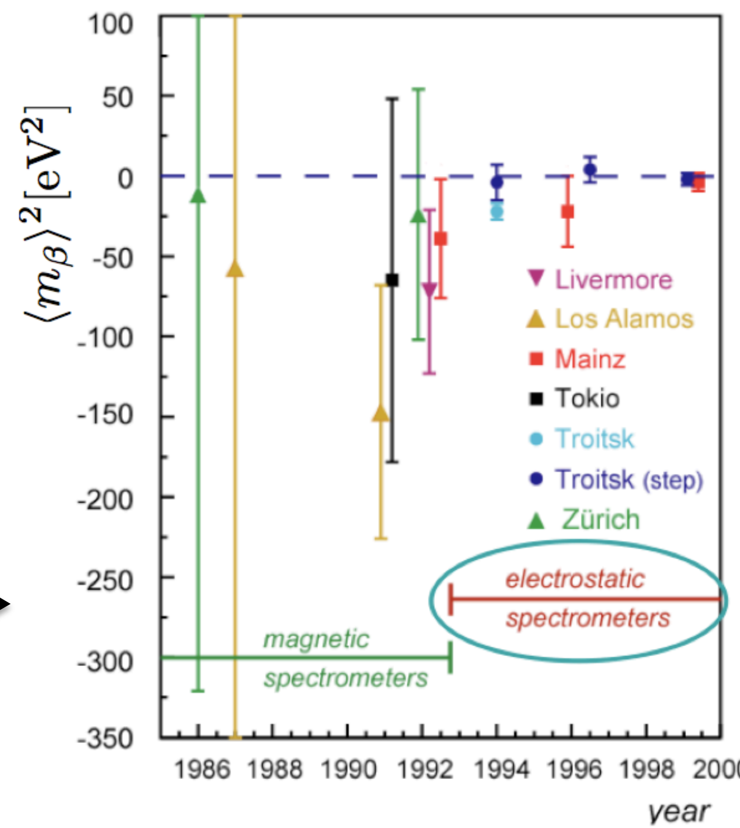
- Astrophysics
  - Supernovae, from 1987A m < 23eV
- Cosmology (look forward for Planck results in 2013)
  - CMB+ Large Scale Structures +… - $\sum m_i < 0.6 - 2$ eV
- Fermion Decays
  - μ , τ decays - relatively poor sensitivity
  - β decay
  - $\beta\ \beta$ decay
- Neutrino Oscillations
  - No absolute scale but only square of mass differences

Beta Decay

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

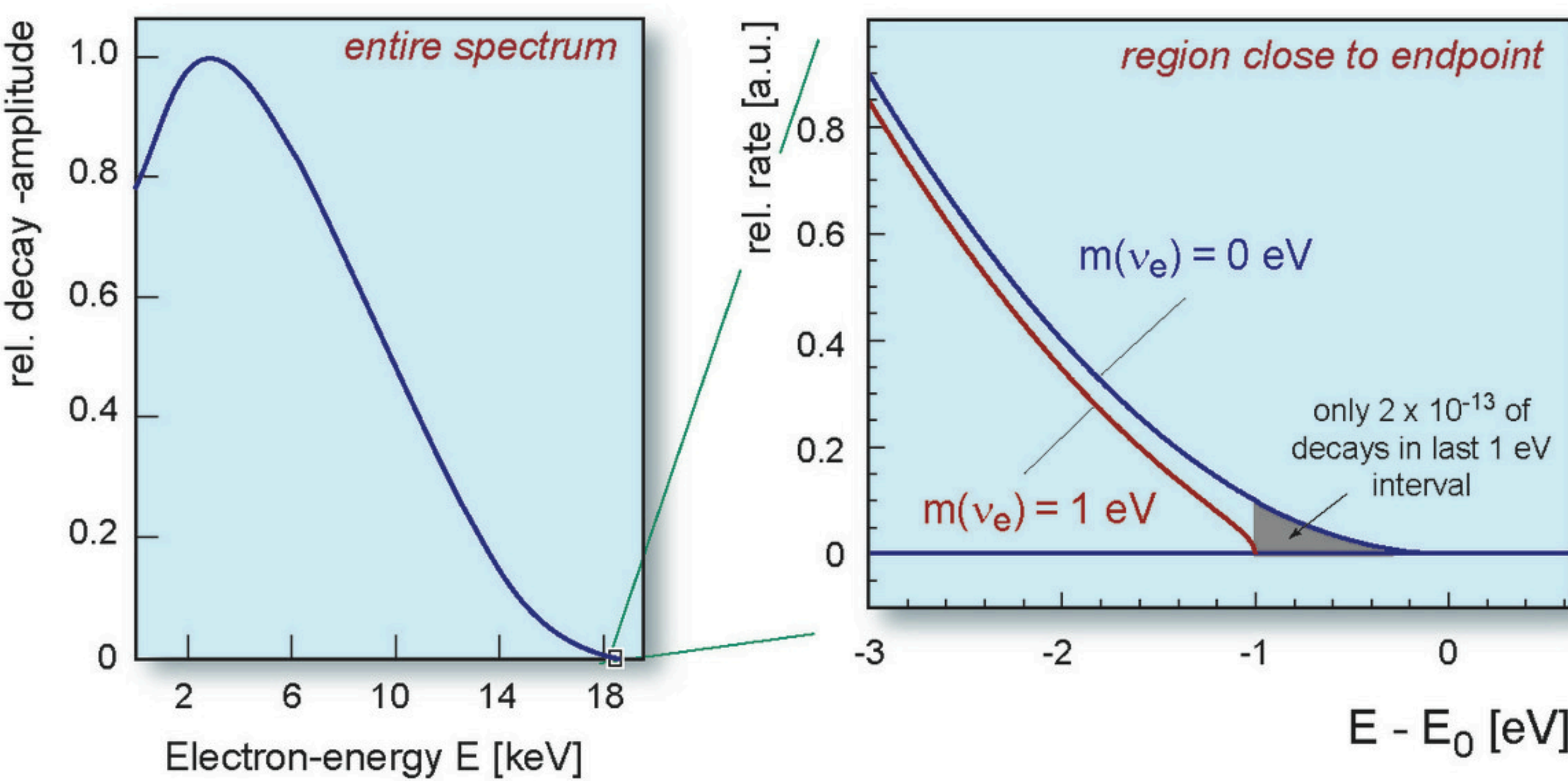
$$\langle m_\beta \rangle = \sqrt{\sum_{1,2,3,..} |U_{ei}|^2 m_i^2}$$

- **Best constraint by Mainz & Troitsk Experiments**
  - **$<m_\beta> < 2.2$ eV**



Absolute Mass From Beta decay

Tritium beta decay $^{3}_{1}H \rightarrow ^{3}_{2}He + e^{-} + \overline{\nu_e}$



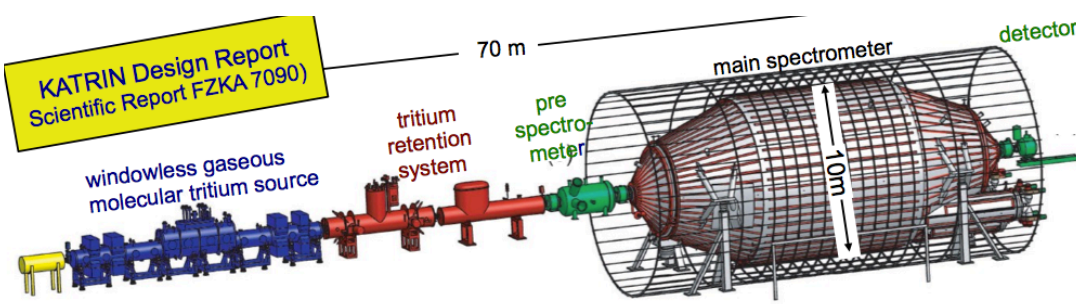
Beta Decay: KATRIN

- 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)

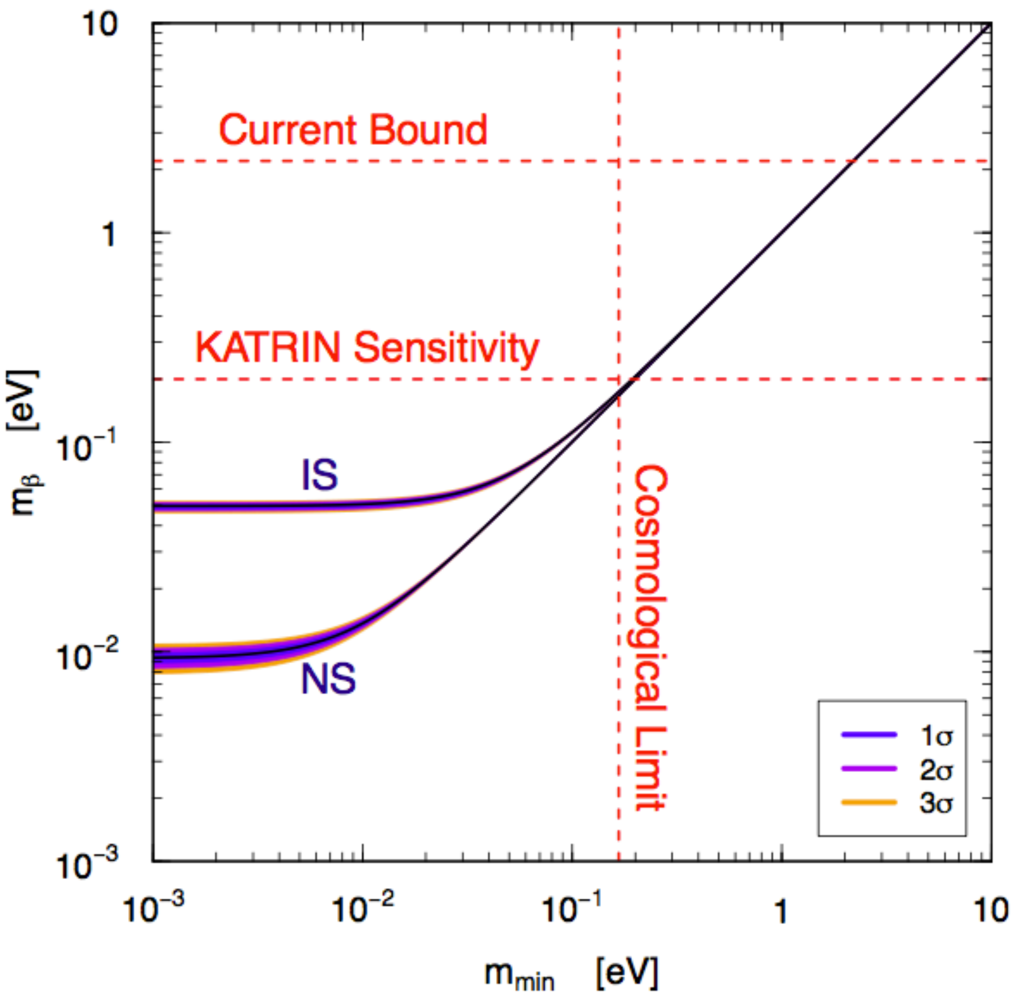
- Status: commissioning detector components. Data in 2015

- 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



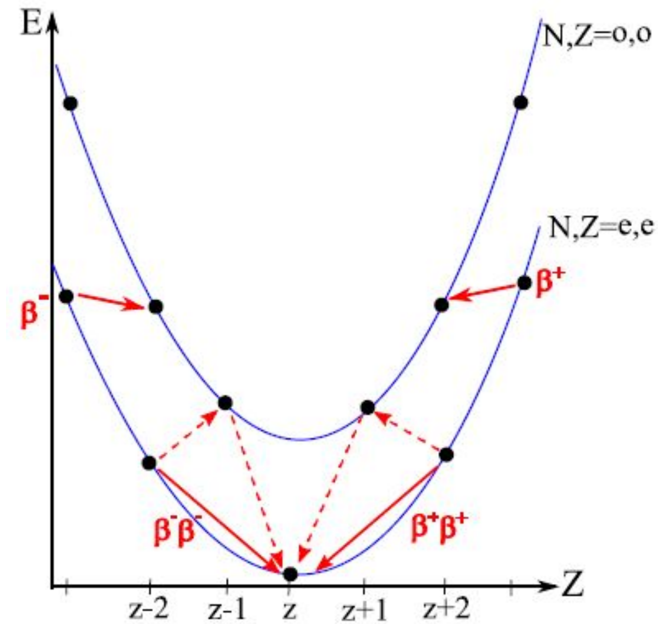
- $\langle m_\beta \rangle = \sqrt{\sum_{1,2,3,..} |U_{ei}|^2 m_i^2}$
- **Degenerate:** $\langle m_\beta \rangle = m_\nu$
- **IH:** $\langle m_\beta \rangle = \Delta m^2_{atm}$
- **NH:** $\langle m_\beta \rangle$ can be << Δm^2_{atm}

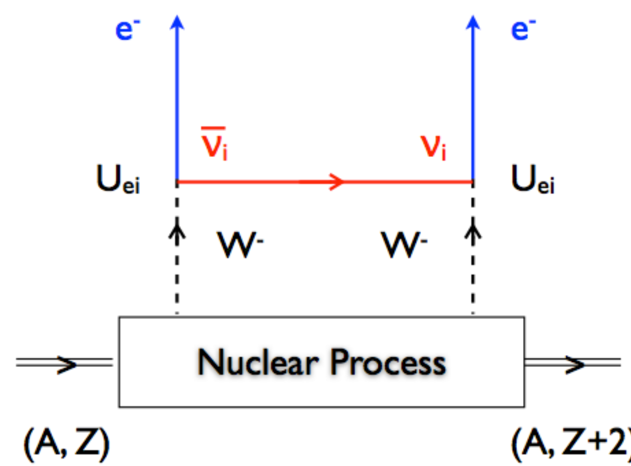
Question 4)

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

Double Beta Decay (ββ)

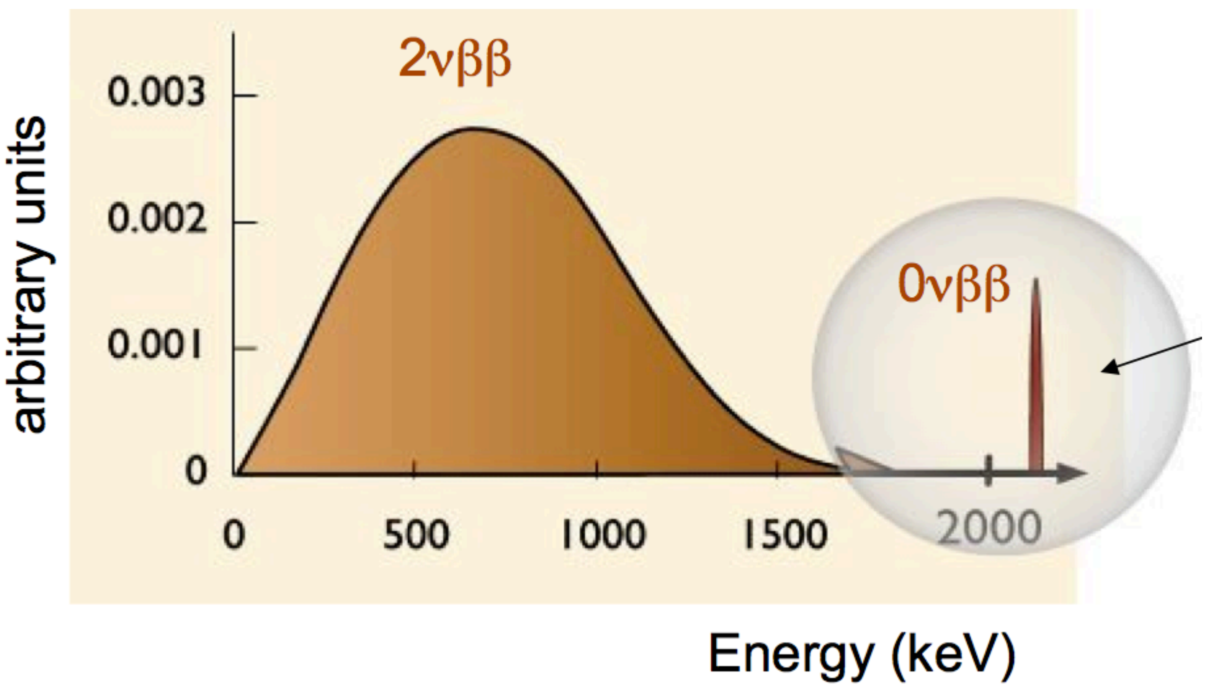
- Second-order process only detectable if first-order β decay is energetically forbidden
- **2ν:** ${}^{A}_{Z}X \rightarrow {}^{A}_{Z+2}X + 2e^{-} + 2\overline{\nu_e}$ **(detected)**
  - ΔL=0
  - $\left(T_{1/2}^{2\nu}\right)^{-1} = G_{2\nu}\left|M_{2\nu}\right|^2 \approx 10^{18-21}y$
- **0ν:** ${}^{A}_{Z}X \rightarrow {}^{A}_{Z+2}X + 2e^{-}$ **(not yet seen)**
  - ΔL=2 – Majorana Neutrino
  - $\left(T_{1/2}^{0\nu}\right)^{-1} = G_{0\nu}\left|M_{0\nu}\right|^2\left|m_{\beta\beta}\right|^2$
- **ββ mass:** $\langle m_{\beta\beta}\rangle = \left|\sum_{1,2,3,..} U_{ei}^2 m_i\right|$





2v0β: experimental signature

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



[Candidates with Q>2 MeV]

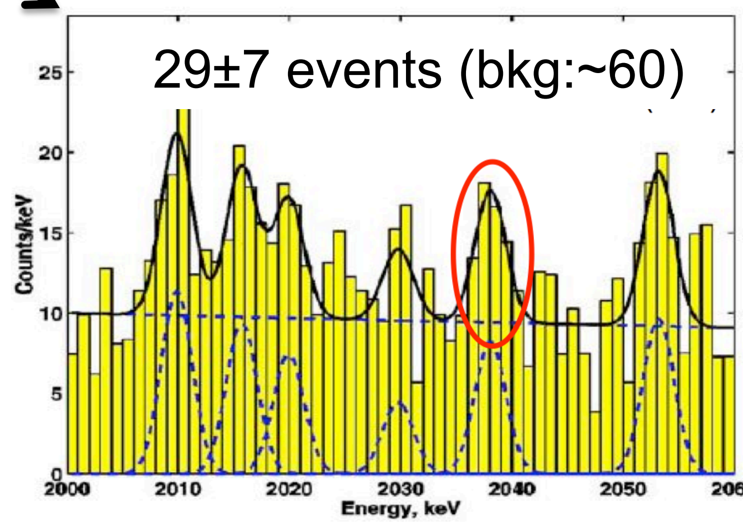
Candidate	Q[MeV]	%Abund
$^{48}Ca \rightarrow {}^{48}Ti$	4.271	0.187
$^{76}Ge \rightarrow {}^{76}Se$	2.040	7.8
$^{82}Se \rightarrow {}^{82}Kr$	2.995	9.2
$^{96}Zr \rightarrow {}^{96}Mo$	3.350	2.8
$^{100}Mo \rightarrow {}^{100}Ru$	3.034	9.6
$^{110}Pd \rightarrow {}^{110}Cd$	2.013	11.8
$^{116}Cd \rightarrow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

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

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

Claim of 0ν2β 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 4.2 σ
  - $T_{1/2}$ = [0.7-4.2] x 10^{25} y (3 σ)
  - $|m_{\beta\beta}|$ = [0.17-0.45] eV (90% CL)
  - <u>Analysis controversial</u>
- Benchmark for current projects
  - Need O(10^2 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}Se, ^{100}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}Se, ^{150}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

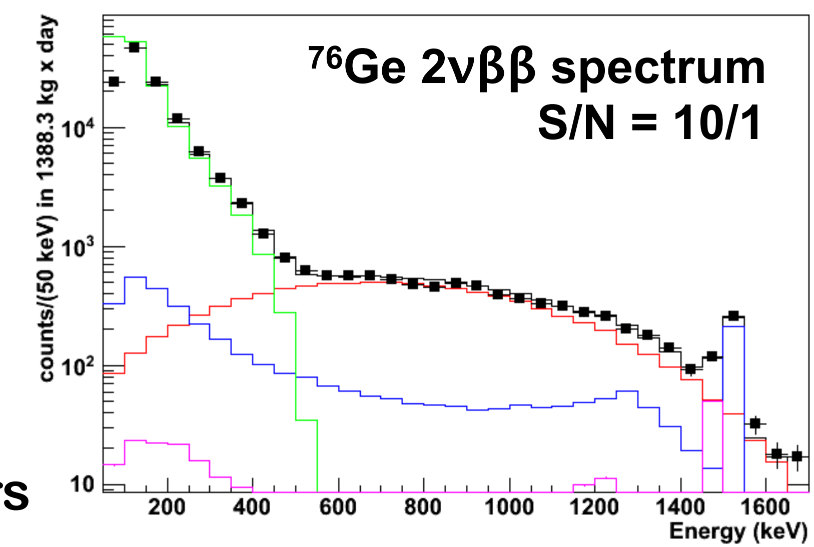
GERDA at LNGS

- Target: ^{76}Ge
  - Low $2\nu\beta\beta$ rate ($T_{1/2}=1.4\times10^{21}$ y)
  - High $Q_{\beta\beta}$ value (2039 keV)

- Detector: high purity ^{76}Ge-diodes (source & detector) immerged in Lar as shielding and coolant

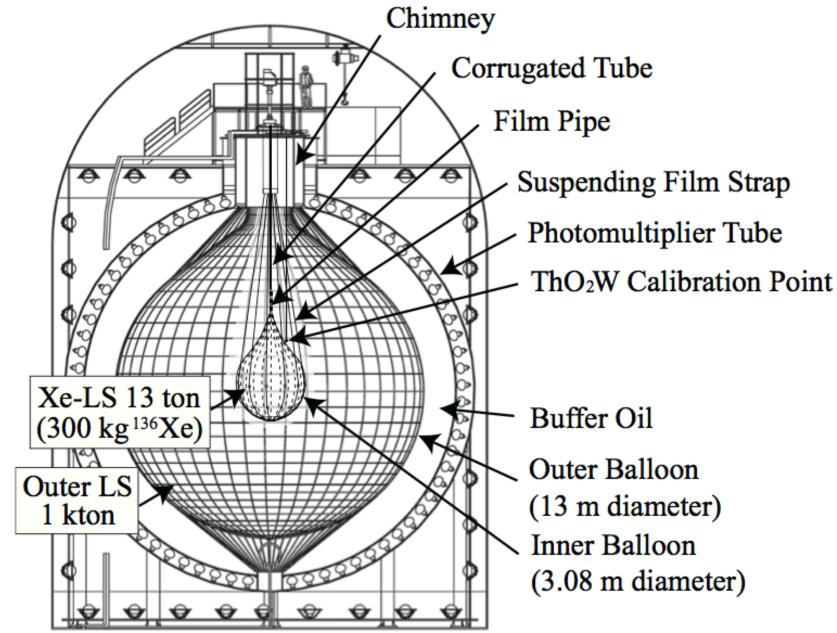
- Status (Phase 1):
  - Data taking since end 2011
  - Bkg: 0.017+0.009-0.005/(keV·kg·y)
  - → Factor 10 bkg reduction wrt HDM

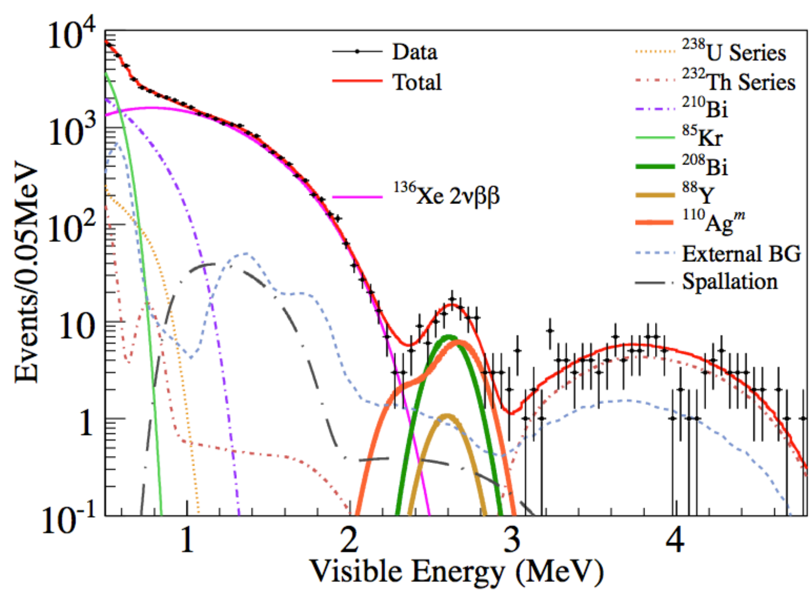
- Future (Phase 2):
  - Factor 10 bkg reduction by LAr scintillation and novel HP-Ge detectors



KamLAND-Zen at Kamioka

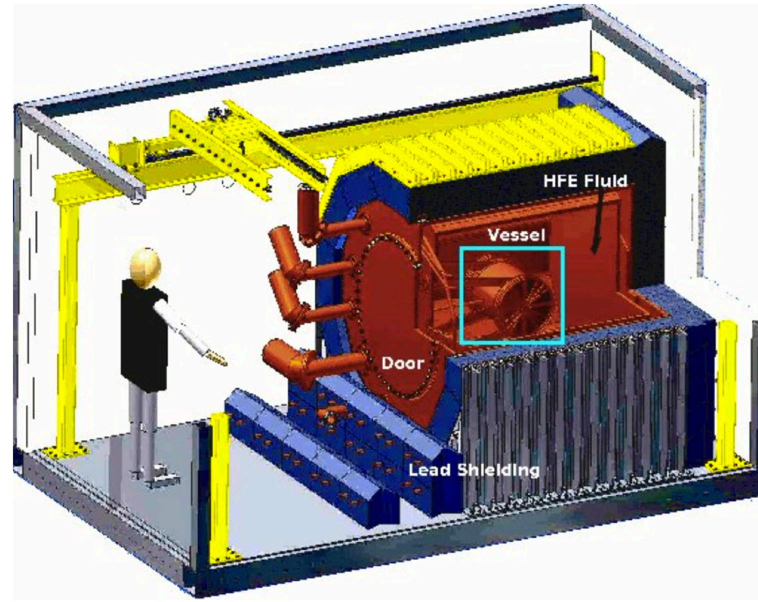
- KamLAND LS detector
- Liquid ^{136}Xe (92%) in balloon
- 77.6 day x 129 kg of ^{136}Xe
- 2ν2β
  - $T_{1/2} = (2.38 \pm 0.14) \times 10^{21}$ yr
  - Consistent with EXO
- 0ν2β
  - $T_{1/2} > 5.7 \times 10^{24}$ yr (90% CL)
  - But Fukushima Contamination
- Upgrade plan:
  - 1 ton ^{136}Xe
  - KamLAND upgrade



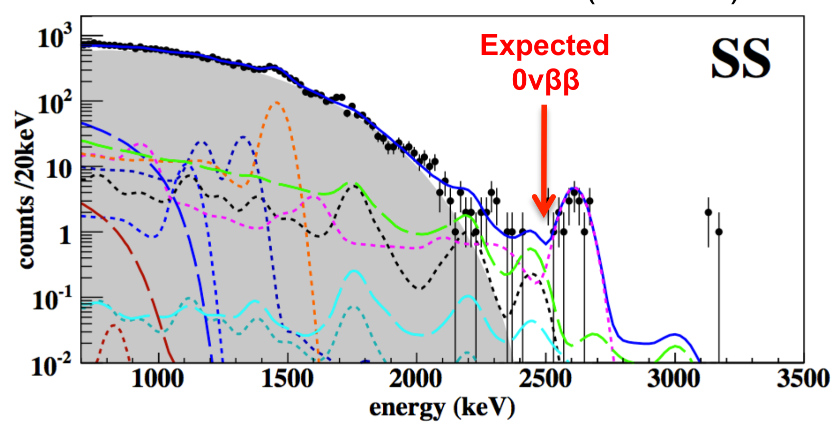


EXO-200 at WIPP

- 200 kg liquid enriched ^{136}Xe
- TPC (energy and position)
- Data taking since may 2011
  - 32.5 kg-yr
  - Bkg: 1.5×10^{-3} $kg^{-1} yr^{-1} keV^{1}$
- $2\nu2\beta$ (2011)
  - $T_{1/2} = (2.11 \pm 0.21) \times 10^{21}$ yr
- $0\nu2\beta$ (2012)
  - $T_{1/2} > 1.6 \times 10^{25}$ yr (90% CL)
  - $|m_{\beta\beta}| < 140–380$ meV
- Prospect: Barium tagging

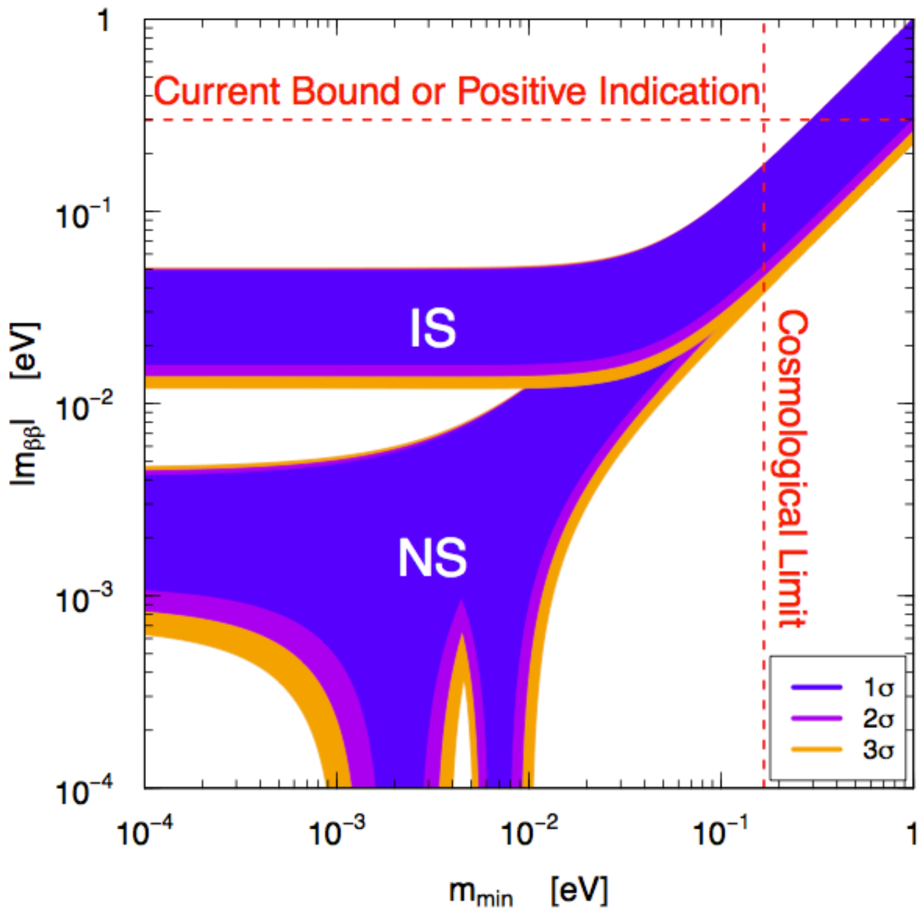


In contradiction with KK claim (90% CL)



Prospect of ββ0ν

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



- ββ0ν implications
  - ν = Majorana
  - L number violation
  - Credit to See-Saw mass generation mechanisms

Question 5)

Are there additional (sterile) ν states?

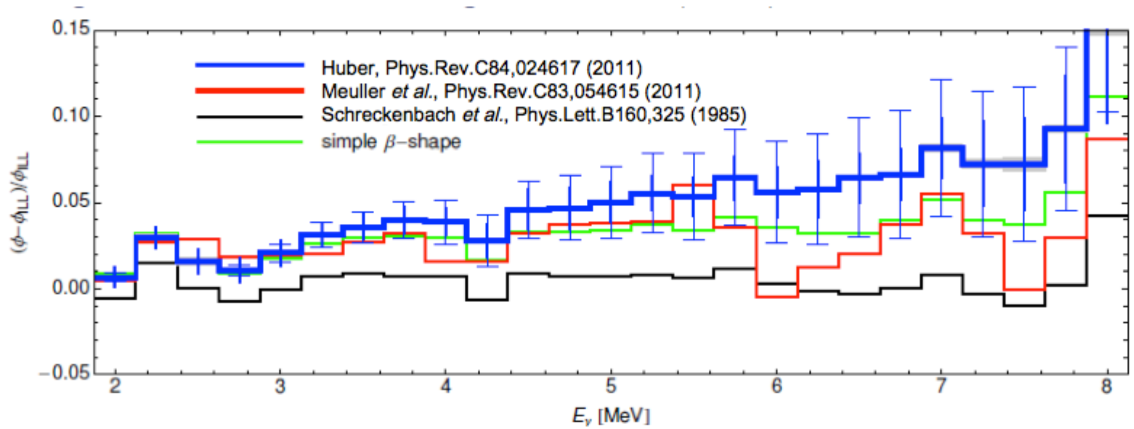
Anomalies & 4th Neutrino

Anomaly	Source	Type	Sensitivity to Oscillation	Channel	Significance
LSND	Decay-at-Rest	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	Total Rate, Energy	CC	3.8 σ
MiniBoone	Short baseline	$\nu_\mu \rightarrow \nu_e$	Total Rate, Energy	CC	3.8 σ
Gallium	Electron Capture	ν_e dis.	Total Rate	CC	3 σ
Reactor	Beta-decay	$\bar{\nu}_e$ dis.	Total Rate, Energy	CC	3 σ
Cosmology	Big-Bang	All	Number of ν, N_{eff}	CC	≈2 σ

→ could be interpreted by an existing eV² 4th neutrino state…

The Reactor Anomaly

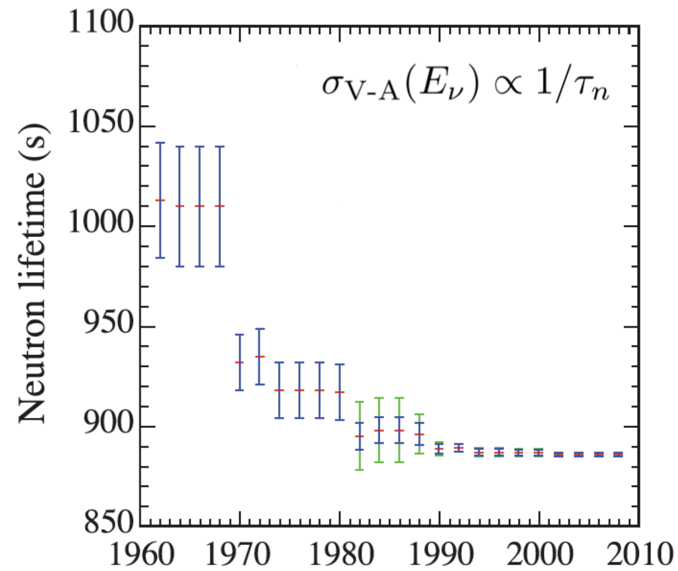
i) $\nu_{emission}$: Improved reactor neutrino spectra → +3.5%



PRC83, 054615 (2011)

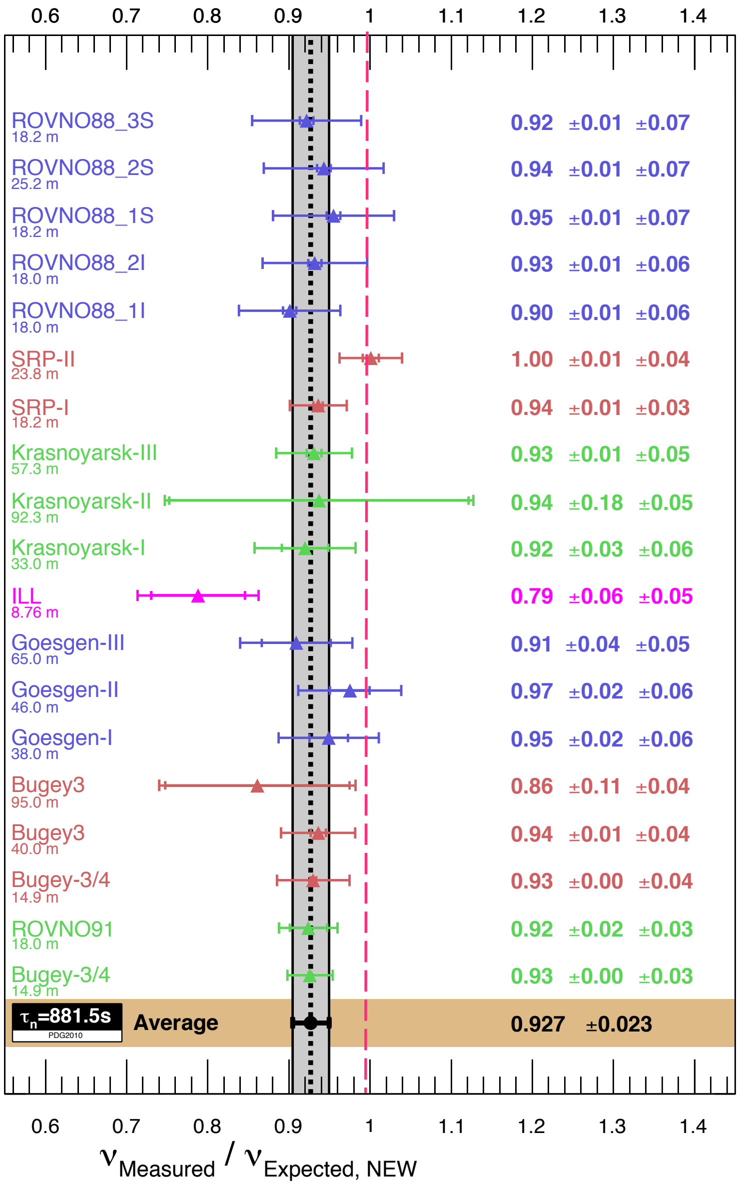
PRC84, 024617 (2011)

ii) $\nu_{detection}$: Reevaluation of σ_{IBD} → +1%
Evolution of the neutron life time



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

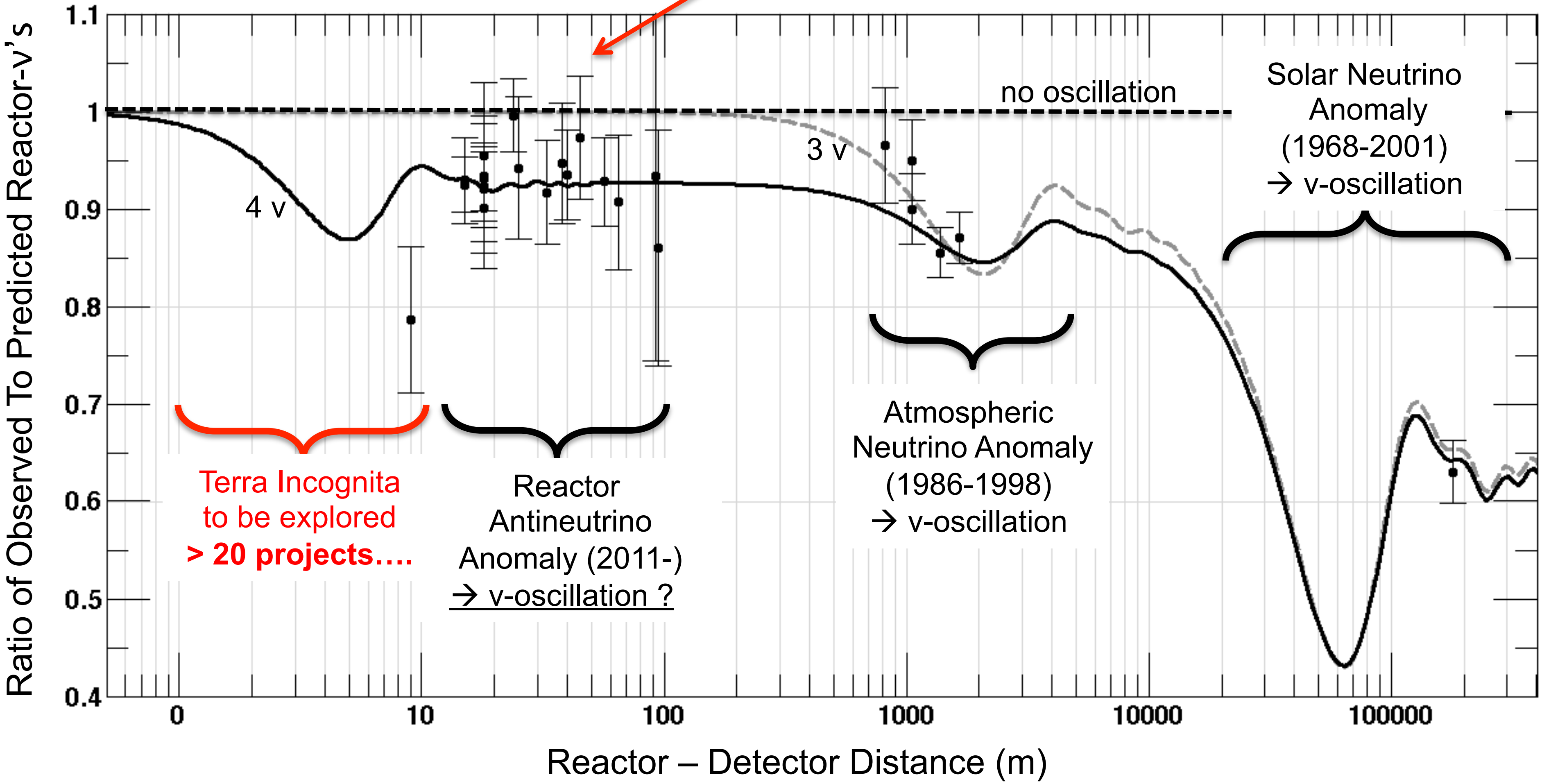
The reactor anomaly



- 19 experiments reanalyzed
- 7% deficit wrt the new prediction
    - ≈3%: reevaluation of emitted flux
    - ≈3%: reevaluation of
        - IDB cross section parameters
        - Neutron lifetime
        - Accounting for off eq. effect
- 99.7 % C.L. deviation from unity
- Artifact or new physics?

The Reactor Antineutrino Anomaly

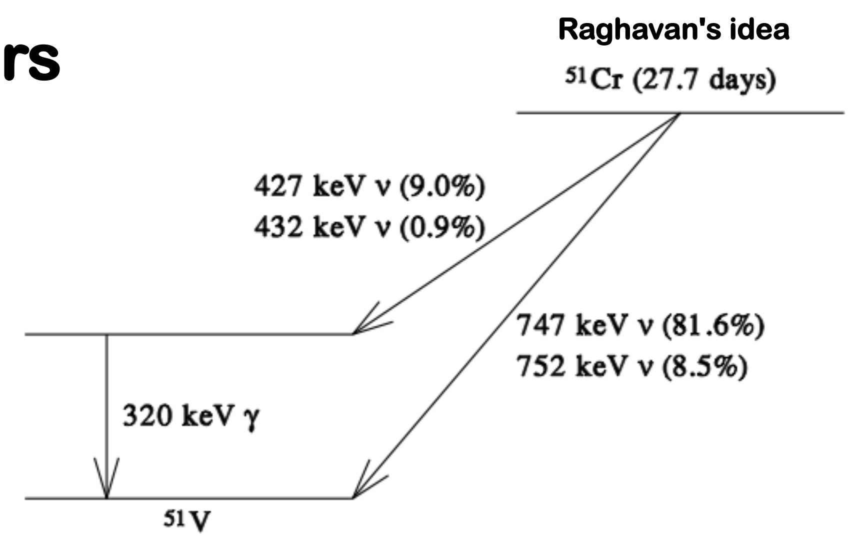
- **Observed/predicted averaged event ratio: R=0.927±0.023 (3.0 σ)**



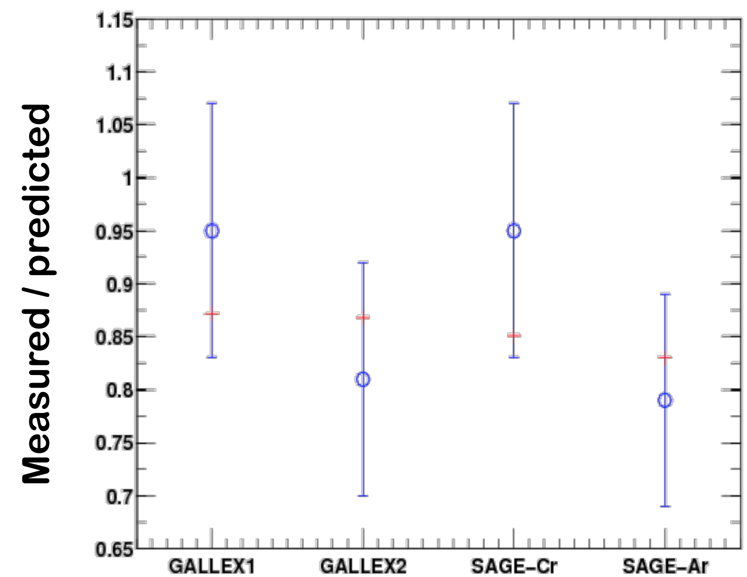
The Gallium Neutrino Anomaly

- **Test of solar neutrino detectors GALLEX and SAGE (ν_e's)**
  - **E ≈ MeV, Baseline range ≈ few m**

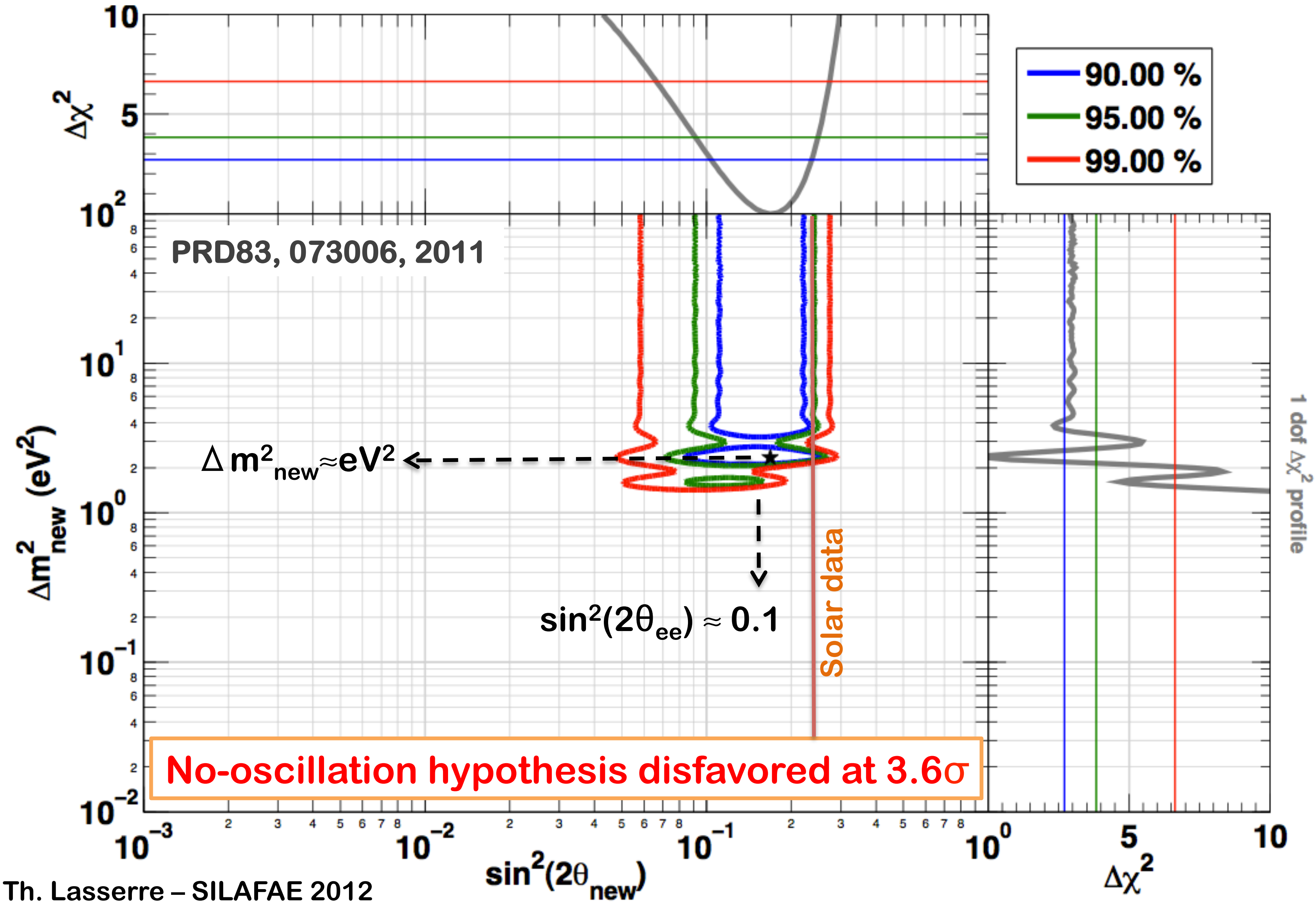
- **4 calibration runs ≈1 MCi EC ν_e emitters**
  - Gallex
    - ^{51}Cr source (750 keV)
  - Sage
    - ^{51}Cr & ^{37}Ar (810 keV)



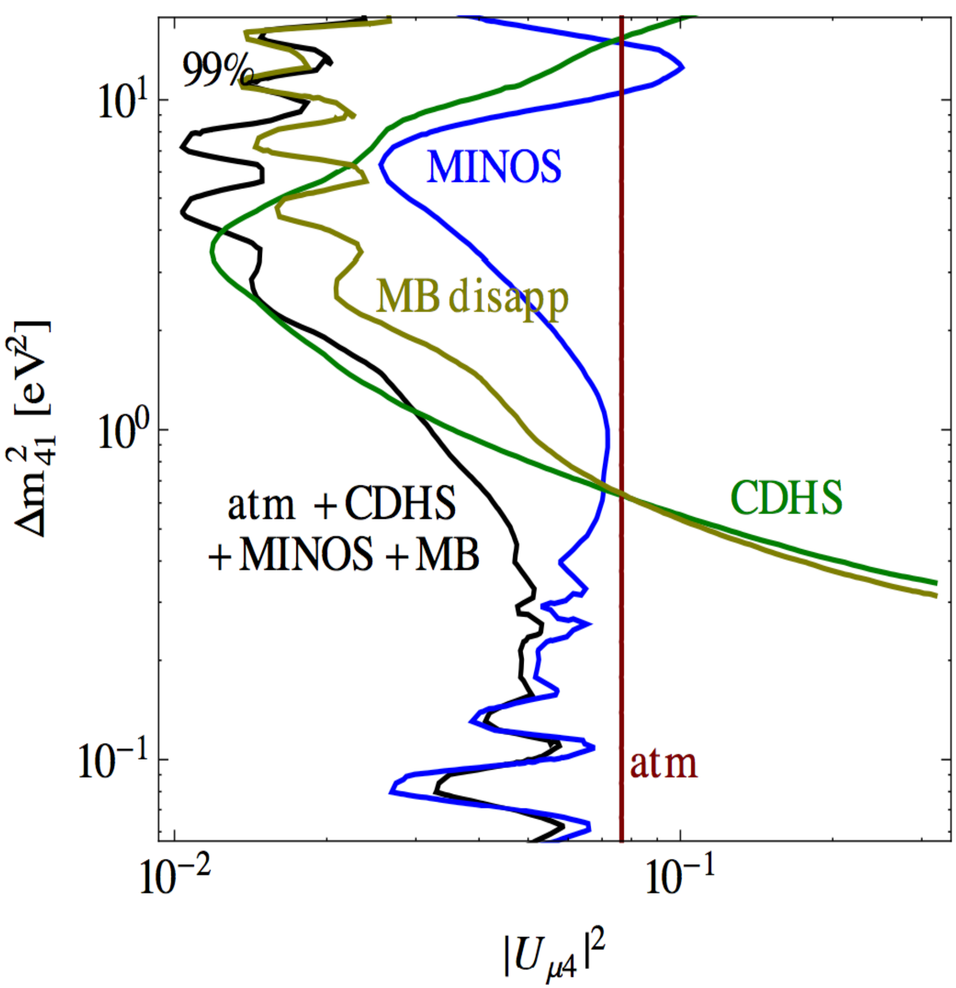
- **Deficit observed**
  - $R_{obs/pred}$=0.86±0.05 ($\sigma_{Bahcall}$)
  - $R_{obs/pred}$=0.76±0.085 (σ_{Haxton})



Gallium & Reactor: ν_e disappearance



ν_μ disappearance data



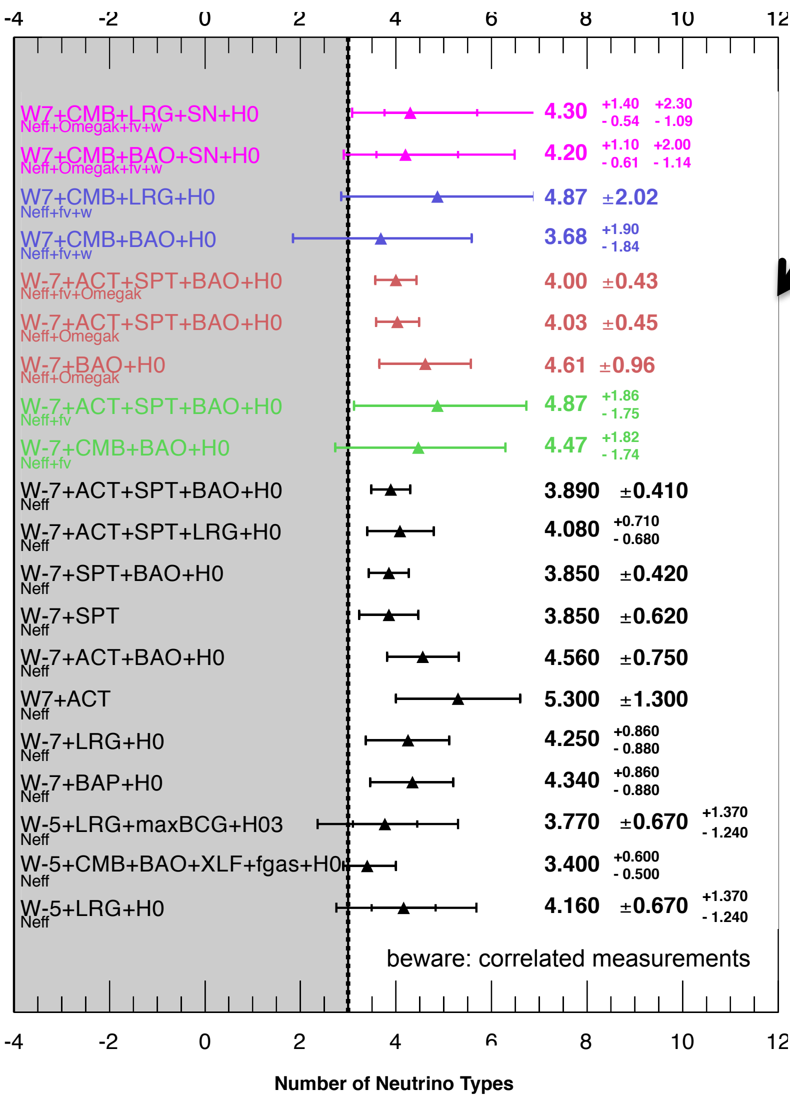
- **No anomaly for $\Delta m^2 \approx 1$ eV^2 but limited sensitivity**
- **No contradiction with ν_e disappearance data but ν_μ dis must be observed if $\approx$eV^2 sterile neutrino exists**
- **But strong constraint for $\nu_\mu \to \nu_e$ channel :**

  $\sin^2 2\theta_{\mu e} = 0.25 \sin^2 2\theta_{\mu\mu} \sin^2 2\theta_{ee}$

- **Impact on global fits: no satisfactory solution (tension with Miniboone)**

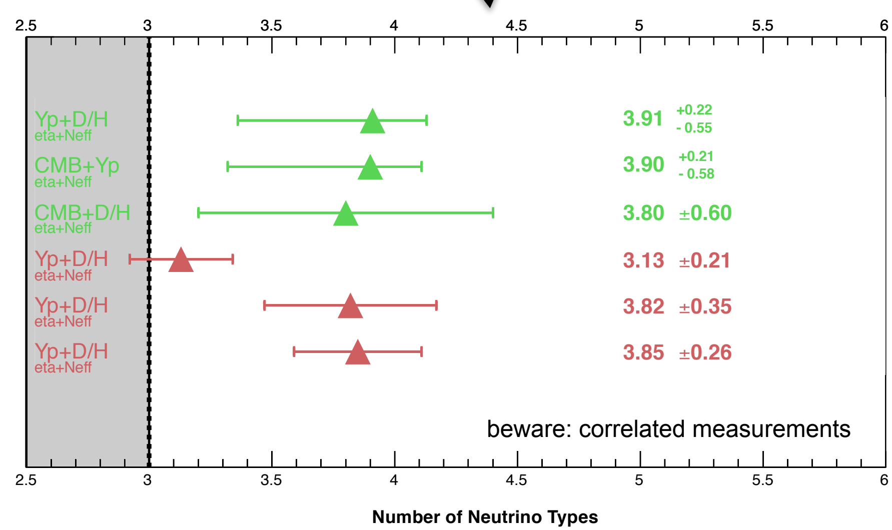
Number of ν's From Cosmology

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



Cosmic Microwave Background and Large Scale Structures

Big Bang Nucleosynthesis



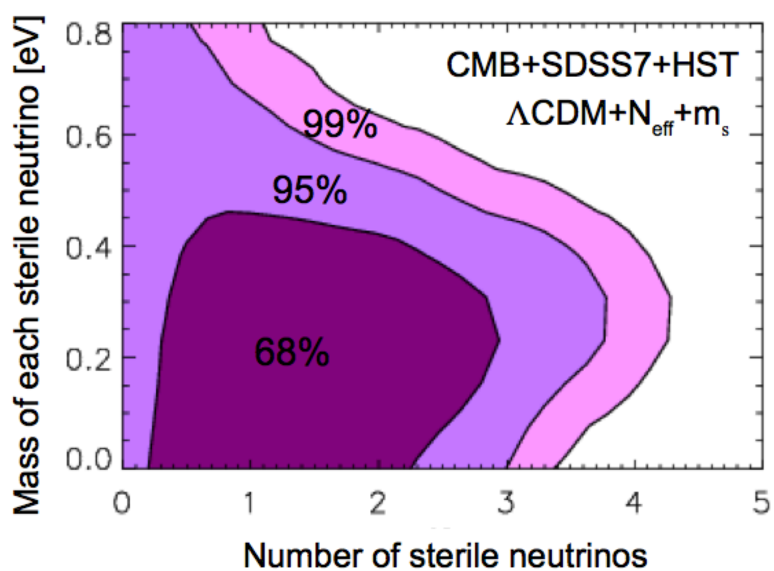
→ a 4th ν favored at 2σ

Neutrino Mass From Cosmology

- Standard candles (distance vs redshift)
  - Type I-a SN, BAO
- Cosmic microwave background anisotropies
  - COBE, WMAP, later Planck
- Large-scale structure (LSS) distribution
  - Galaxy clustering, Cluster abundance, Grav. lensing, Lyman

→ flat ΛCDM model

- Constraint on Neutrino mass and Number
  - $m_{heavier}$ < about 1 eV



Testing $\overset{(-)}{\nu}_e$ disappearance anomalies

- GA & RAA arise from comparisons between data and event prediction → Need a conclusive technique

- Input from Sterile Neutrino Fits
  - $\Delta m^2 \approx eV^2$ → $L_{osc}(m) = 2.5 \frac{E(MeV)}{\Delta m^2(eV^2)} \approx 2-10$ m
  - $\sin^2(2\theta_{new}) \approx 0.1$

- Experimental Specifications
  - Search for L, E, L/E pattern (shape only)
  - Complement with a rate analysis (direct test of RAA+GA)
  - $\Delta m^2 \approx eV^2$: compact source <<1m & good vertex resolution (<<1m)
  - $\sin^2(2\theta_{new})$: experiment with few % stat. syst. uncertainties

Many Other Projects: Overview

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

Light Sterile Neutrino White Paper arXiv:1204.5379

Oscillometry inside a ν-detector

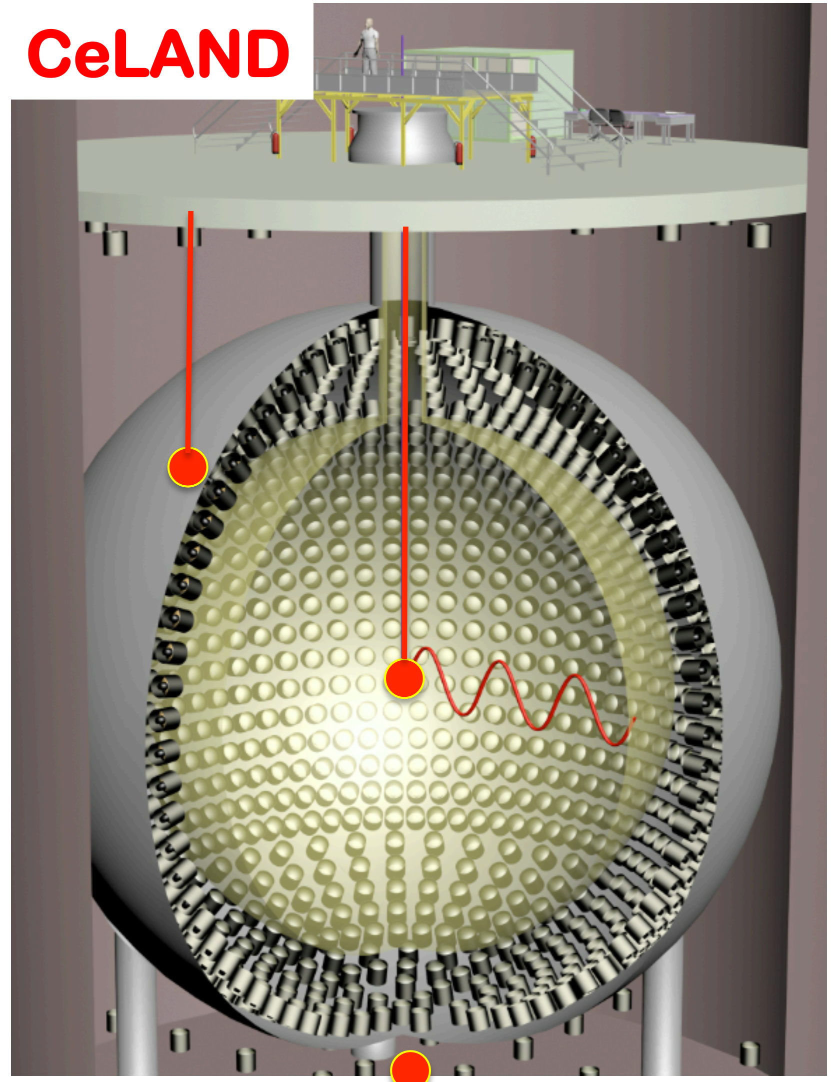
- **Place the ν-emitter inside or close to existing detectors**
  - **Very short Baseline (few m)**
  - **Low Background**

i) ν-source at center

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

ii) ν-source Outside LS

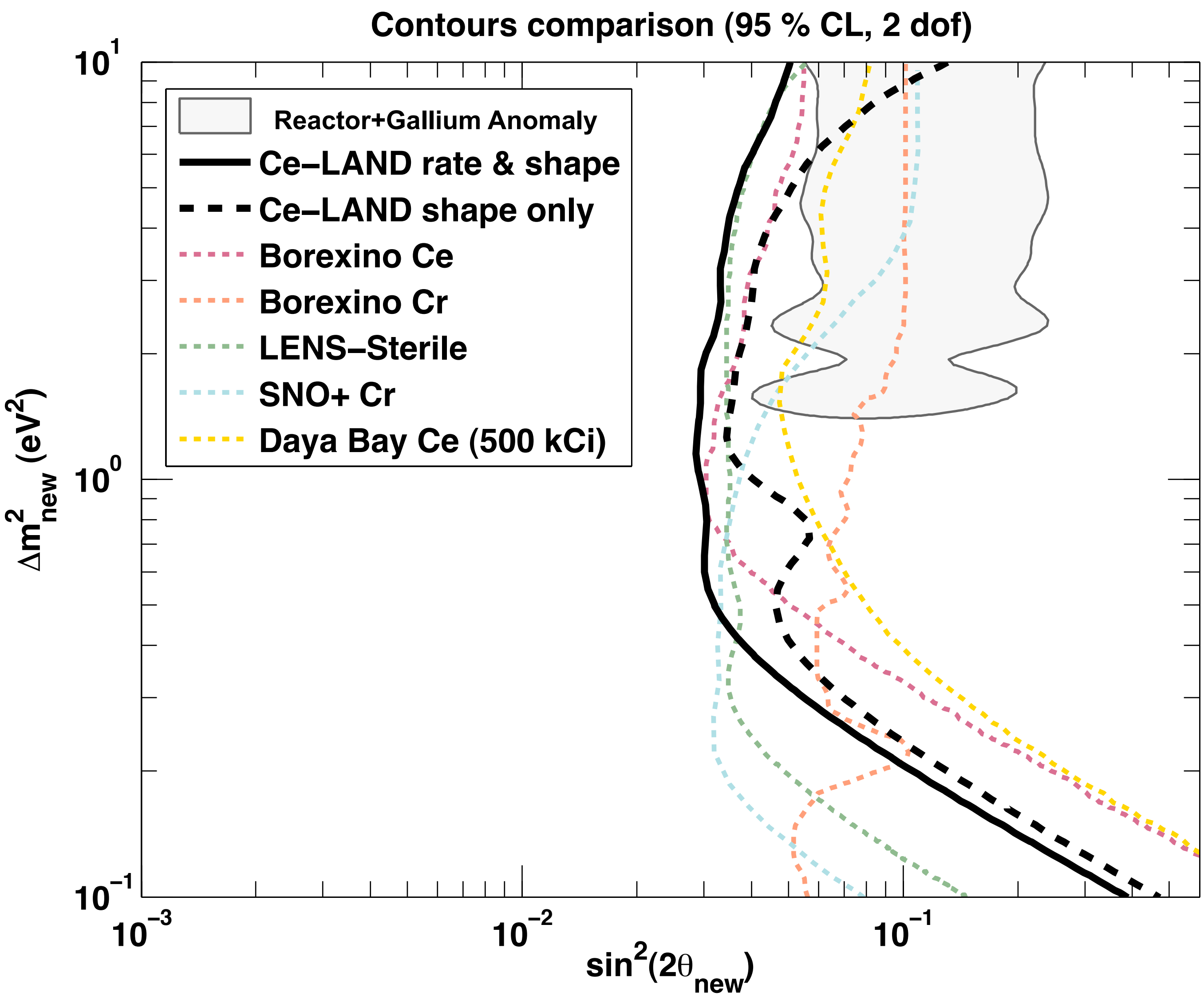
- **Specific oscillation pattern analytically computable**



ν-source proposals Overview

Type	channel	Background	Source	Production	Activity (Mci)		Proposal
ν_e	$\nu_e e \rightarrow \nu_e e$ Compton edge 5% E_{res} 15cm R_{res}	radioactivity (managable) Solar ν (irreducible) ν-Source (out ok but in ?)	^{51}Cr 0.75 MeV $t_{1/2}$=26d	n_{th} irradiation in Reactor	in	>3	Sage LENS
					out	5-10	SOX* SNO+
			^{37}Ar 0.8 MeV $t_{1/2}$=35d	n_{fast} irradiation in Reactor (breeder)	in	>1	-
					out	5	Ricochet (NC)
$\bar{\nu}_e$	$\bar{\nu}_e p \rightarrow e^+ n$ E_{th}=1.8 MeV (e^+,n) Coincidence 5% E_{res} 15cm R_{res}	reactor ν & ν-Source $\rightarrow$ Background free!	^{144}Ce E<3MeV $t_{1/2}$=285d	spent nuclear fuel reprocessing	in	0.005-0.05	CeLAND* SOX
					out	0.5	Daya-Bay
			^{90}Sr ^{106}Rh		-	-	-
			^{42}Ar	?	-	-	-

Source proposal sensitivities
Testing Gallium & Reactor Ano.



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Conclusion (1/2)

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

$$U_{CKM} = \begin{bmatrix} 1 & 0.2 & 0.001 \\ 0.2 & 1 & 0.01 \\ 0.001 & 0.01 & 1 \end{bmatrix} \qquad U_{PMNS} \approx \begin{bmatrix} 0.8 & 0.5 & 0.16 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{bmatrix}$$

- **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)

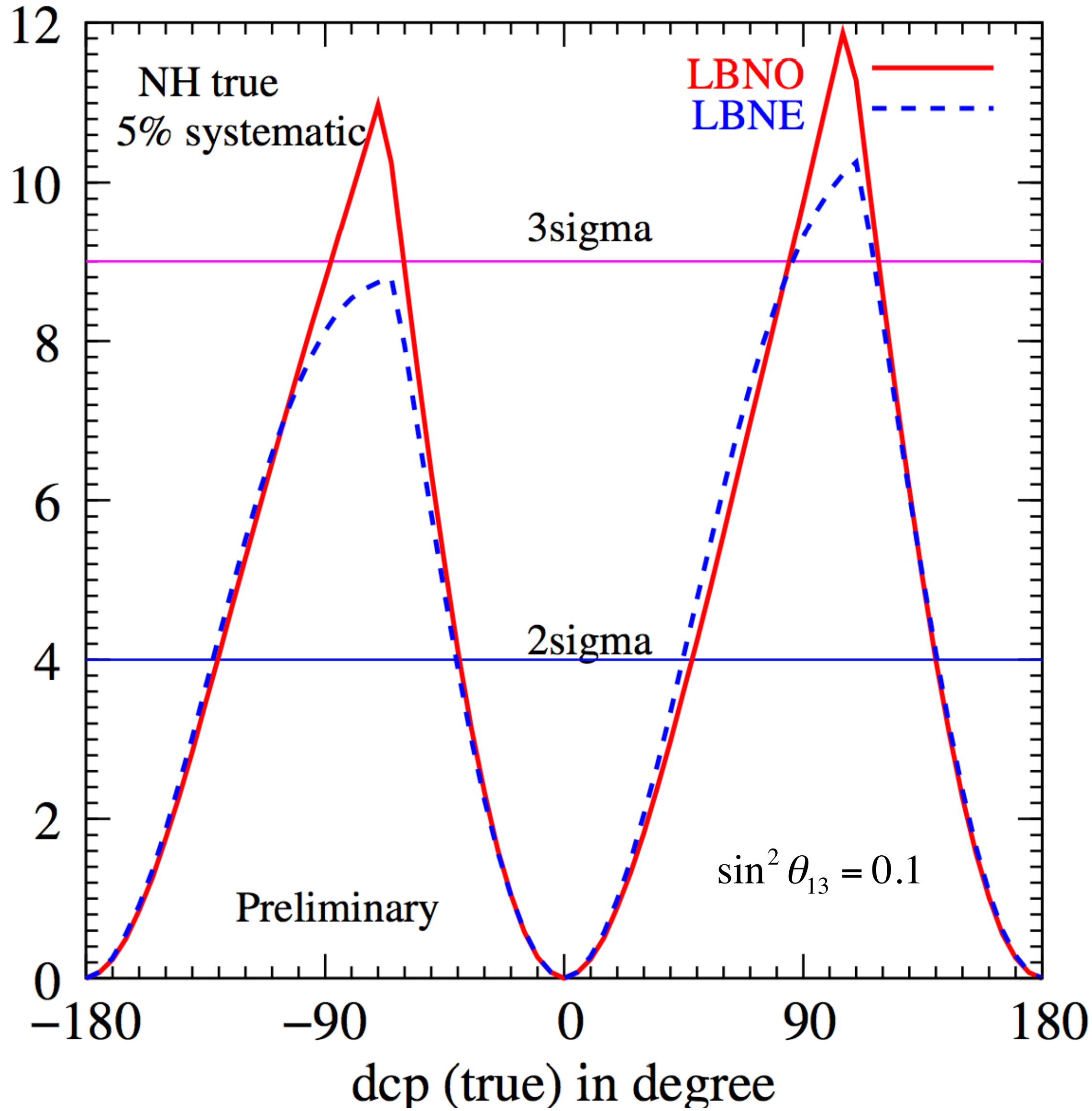
- A bunch of anomalies calling for clarification:
  - LSND (ν_S, $\Delta m^2 \approx eV^2$?) & Miniboone ?
  - Gallium Anomaly (ν_S, $\Delta m^2 \approx eV^2$?)
  - Reactor Anomaly (ν_S, $\Delta m^2 \approx eV^2$?)
- Hint in favor of sterile neutrinos is compatible with cosmological data (CMB, LSS, BBN), though $\approx$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 under study or review

Additional Slides

LBNO & LBNE CPV Sensitivity

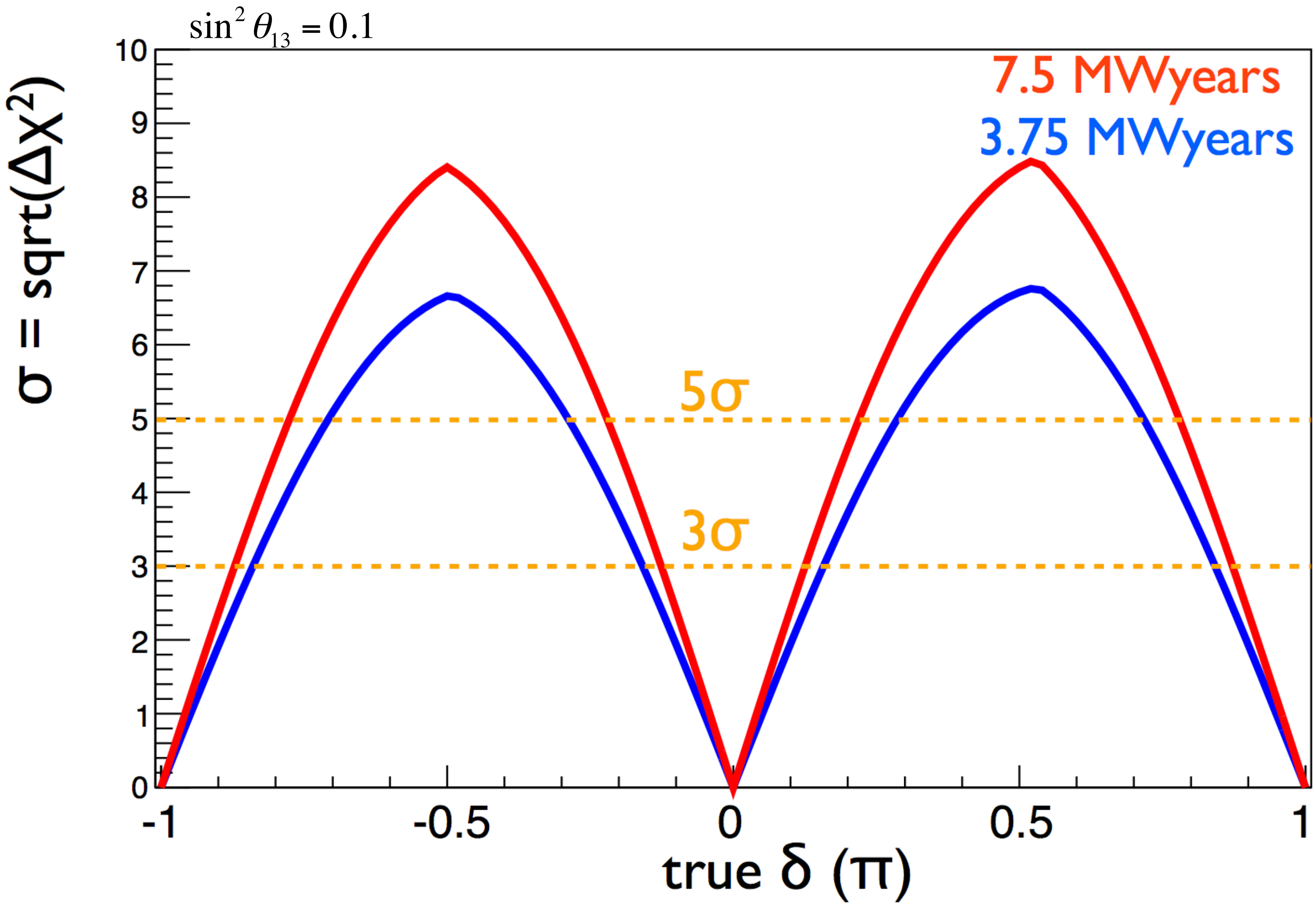
Fraction of δ in % for which expected CPV ($\sin\delta \neq 0$) significance is >3 σ

- Assume same systematic errors for both setups
- LBNE 10 kton @ 1300 km
- LBNO 20kton @ 2300 km



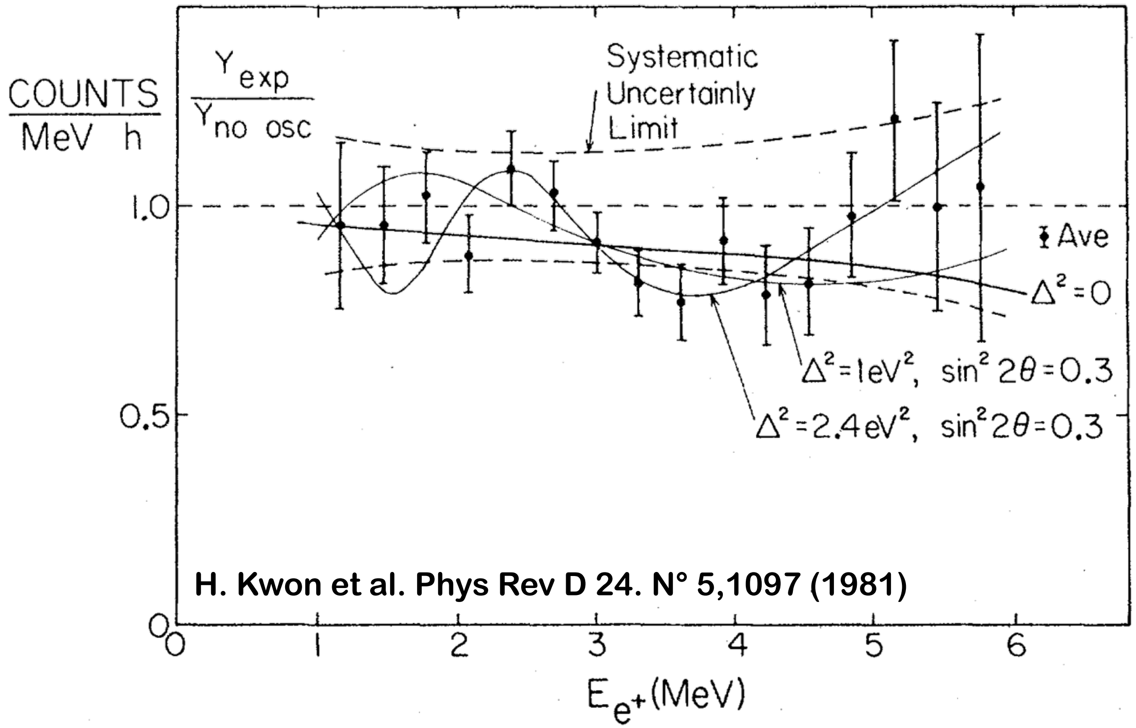
Hyper-K CPV Sensitivity

Fraction of δ in % for which expected CPV ($\sin\delta \neq 0$) significance is $>3\sigma$



Puzzling 1981 ILL ν-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!



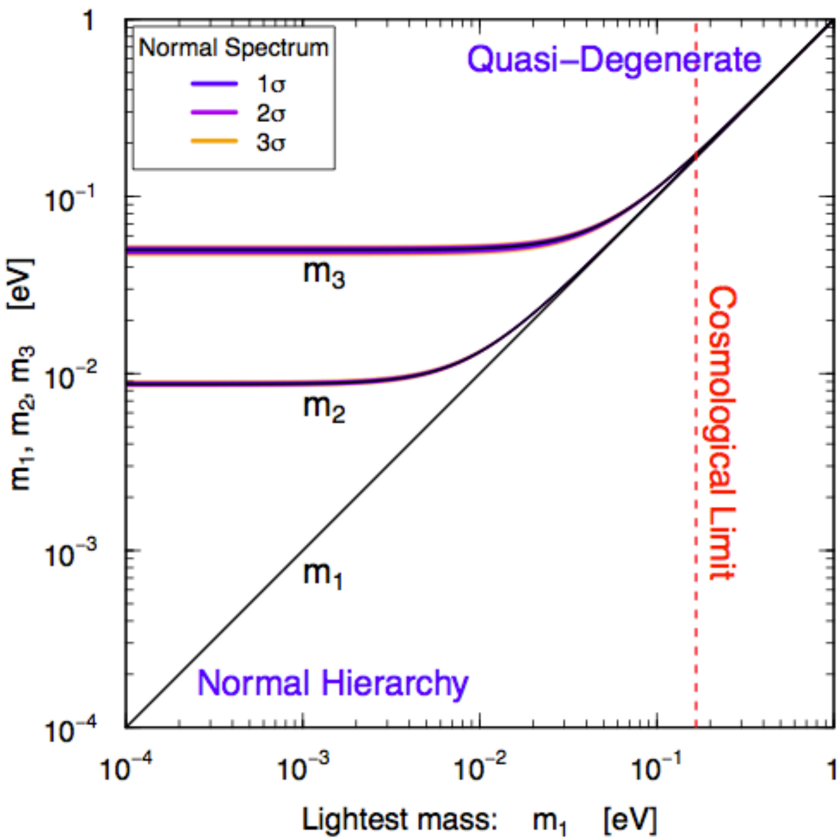
H. Kwon et al. Phys Rev D 24. N° 5,1097 (1981)

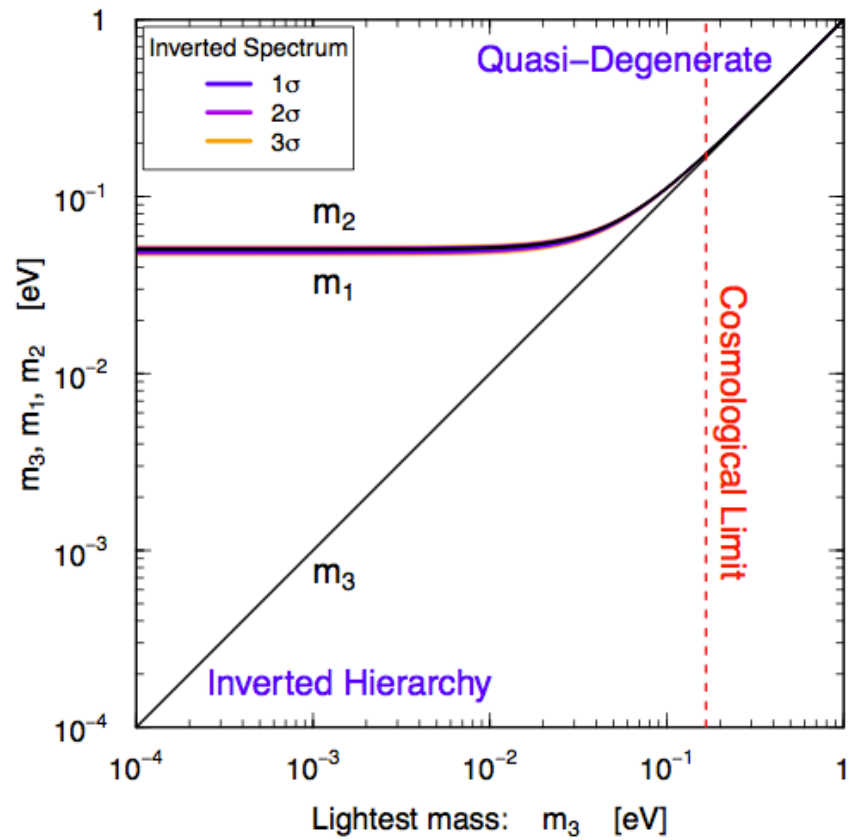
- Large errors, but a striking pattern is seen by eye ?

Two mass hierarchies allowed

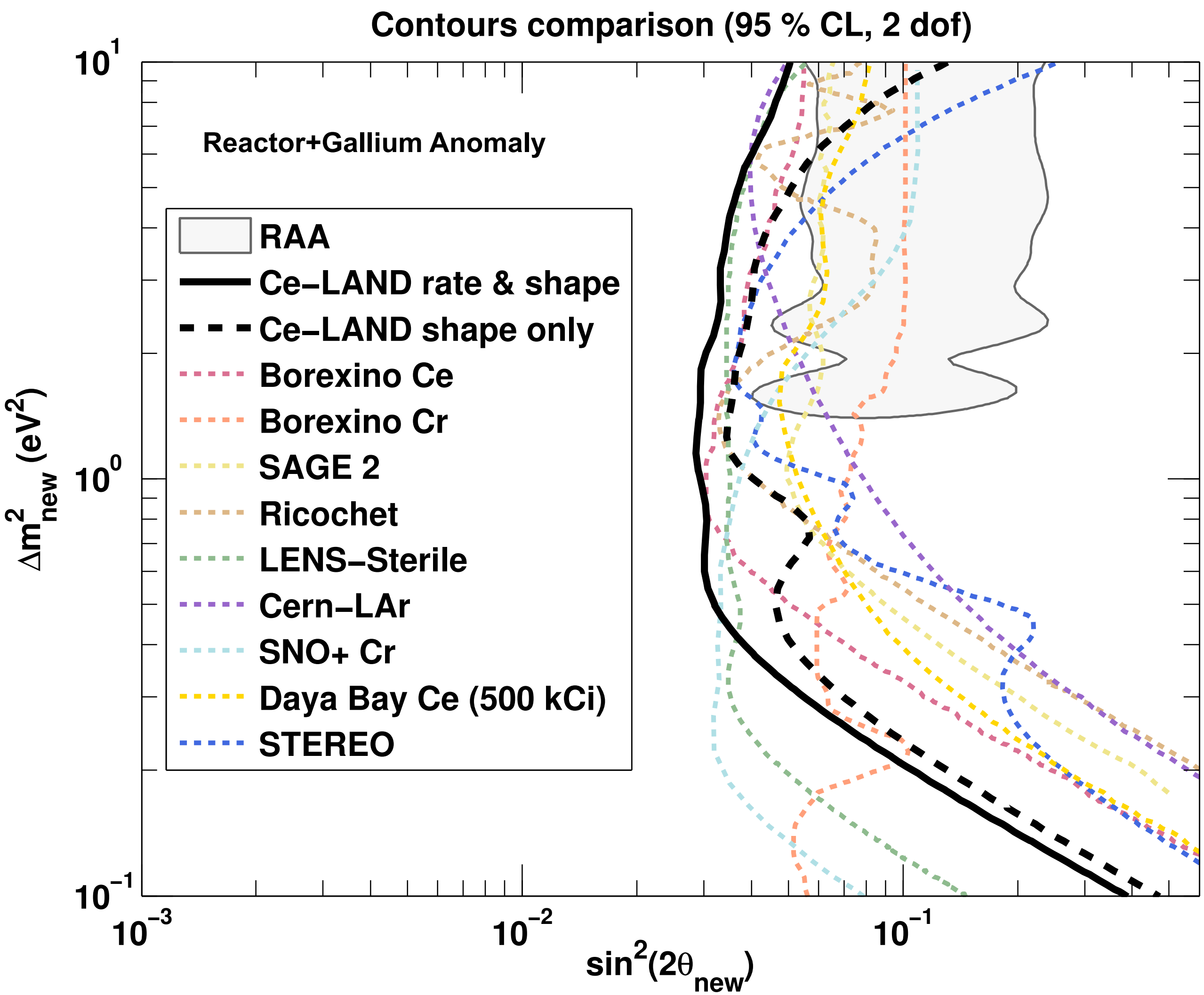
$$\text{NH}\begin{cases} m_3 = \sqrt{m_1^2 + m_{atm}^2} \\ m_2 = \sqrt{m_1^2 + m_{solar}^2} \\ m_1 \end{cases}$$

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





Other proposal sensitivities



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