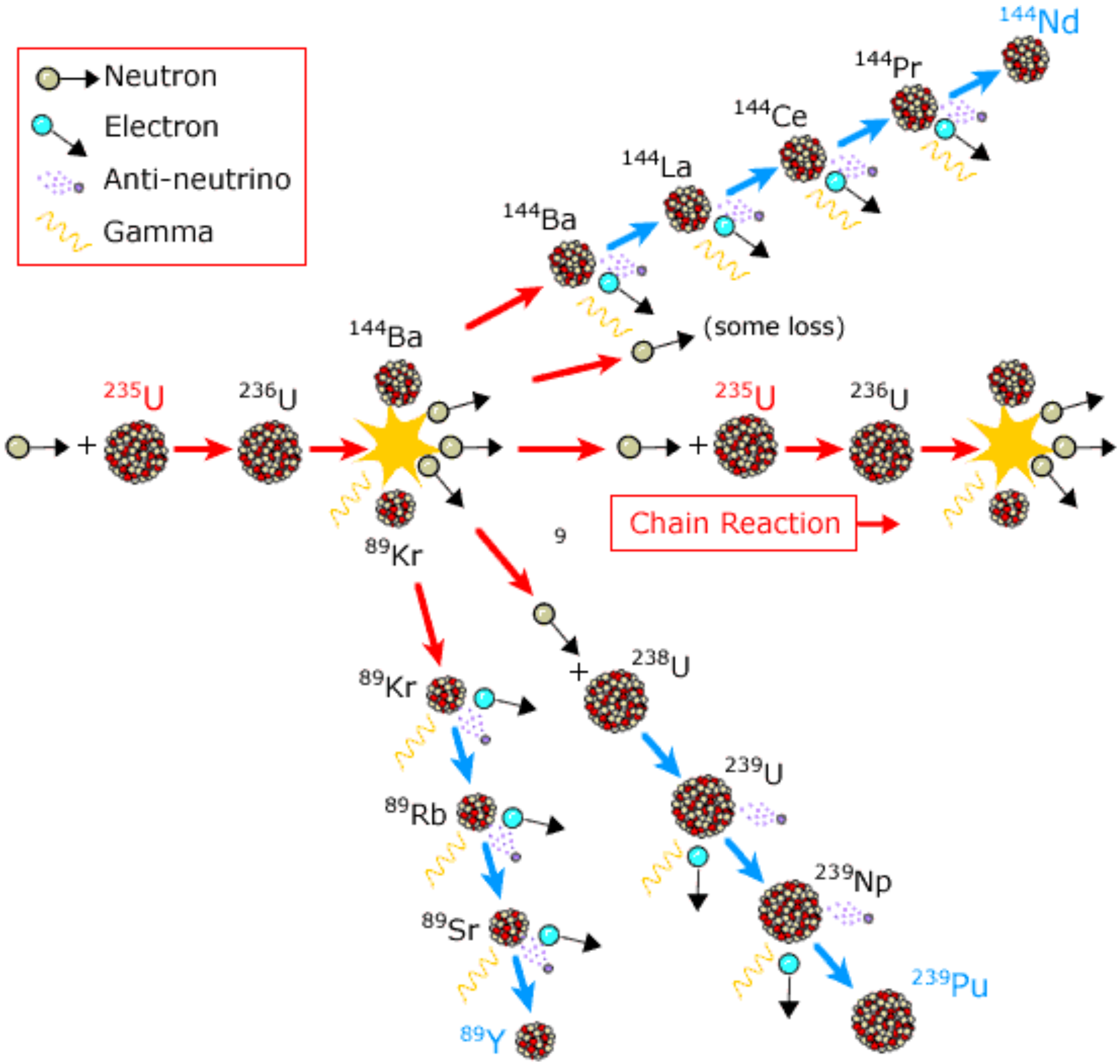
Lecture 5:
experiments at reactors

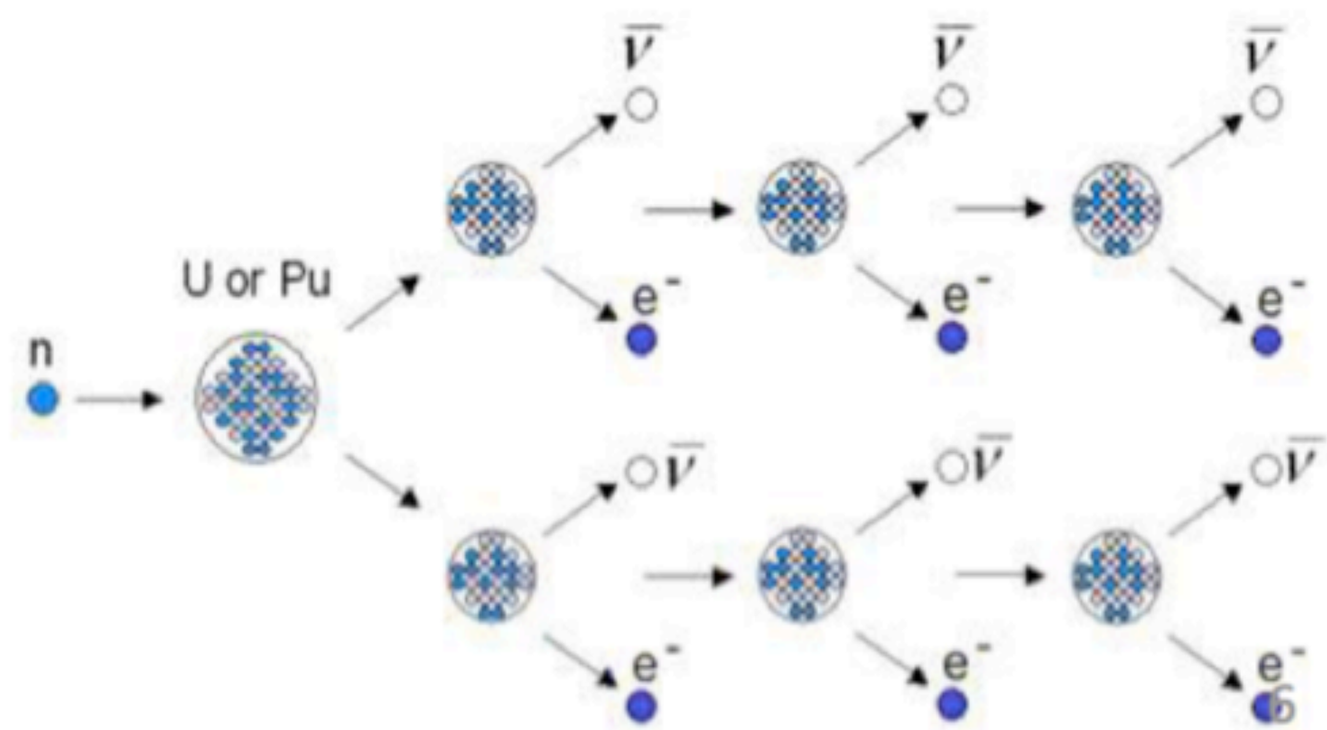
PhD Cycle XXXIV

Neutrini da reattore



Nuclear Reactors as Antineutrino Source

- **Reactors like Chooz A+B ➔ 8.5 GW_{th}**
- **Few percent of the released energy**
  ➔ escapes with anti-neutrinos
  ➔ $2*10^{21}\bar{\nu}$/s ←→ O(1 kW/m^2) @fence



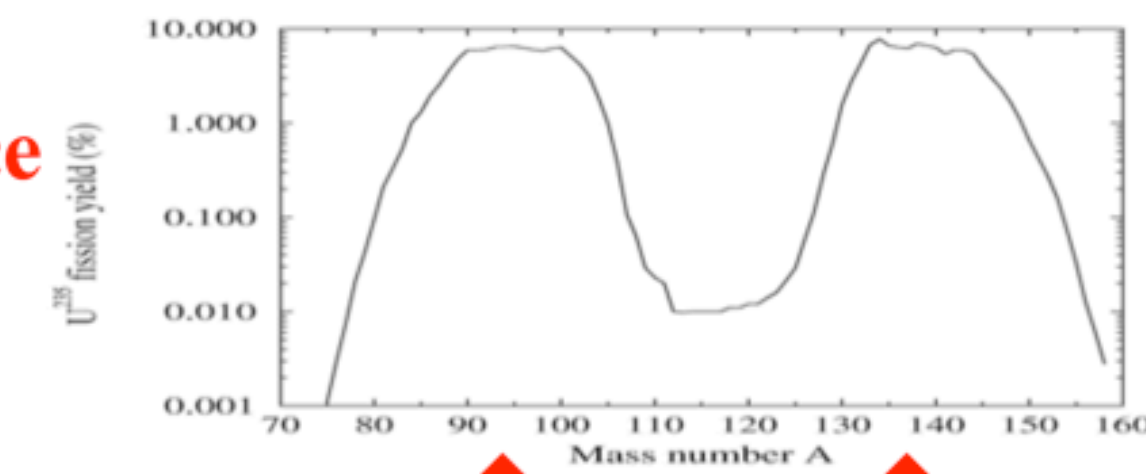
- **measured e^- spectrum of U^{235}, Pu^{239}, Pu^{241}**

➔ calculate $\bar{\nu}_e$ spectrum ➔ certain precision

➔ two "identical" detectors…

example: fission of U^{235}

$$^{235}_{92}U + n \rightarrow X_1 + X_2 + 2n$$

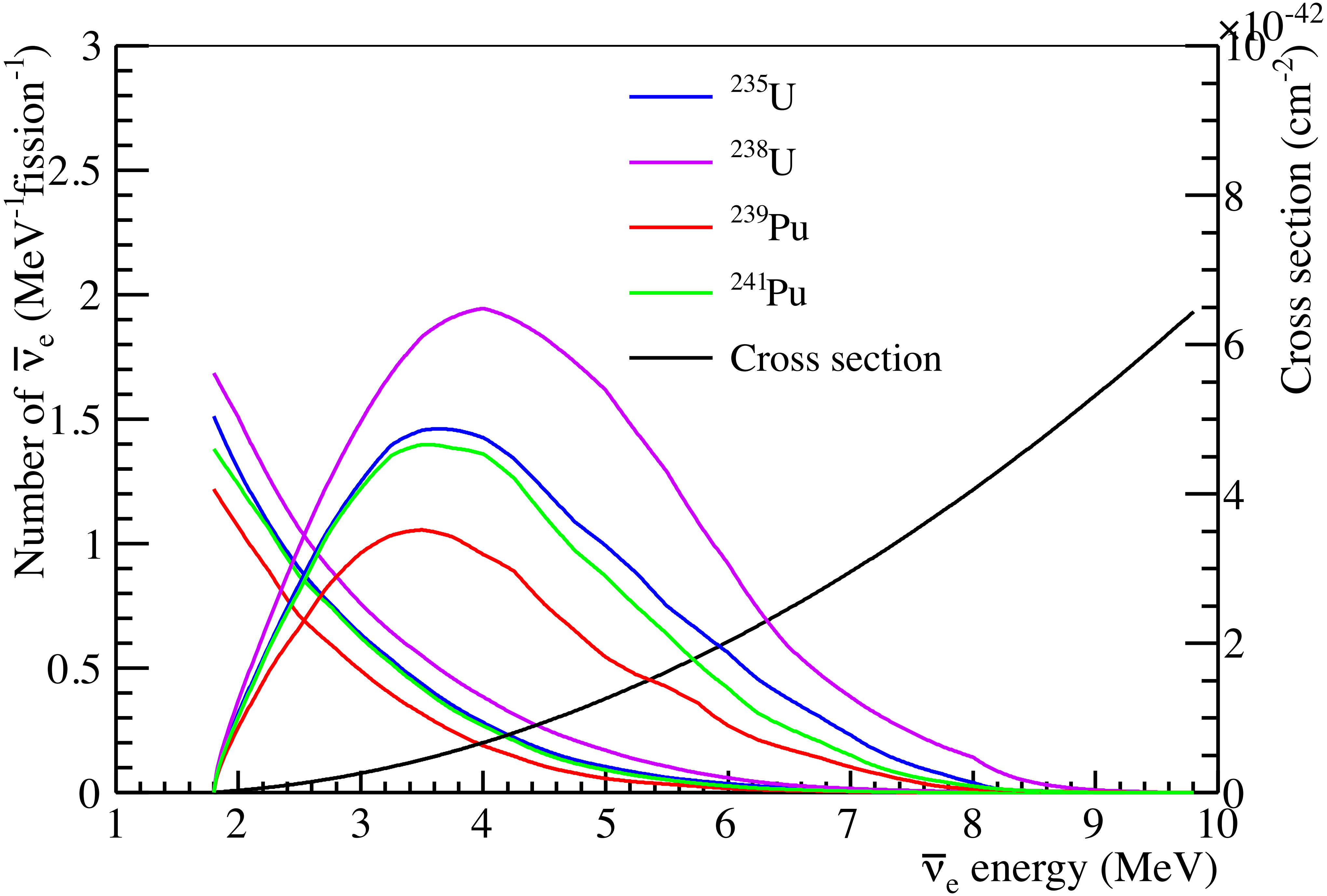


most likely A

➔ on average:

- 6 neutrons β-decay to 6 protons to reach stable matter
- 1.5 ν_e emitted with E > 1.8 MeV

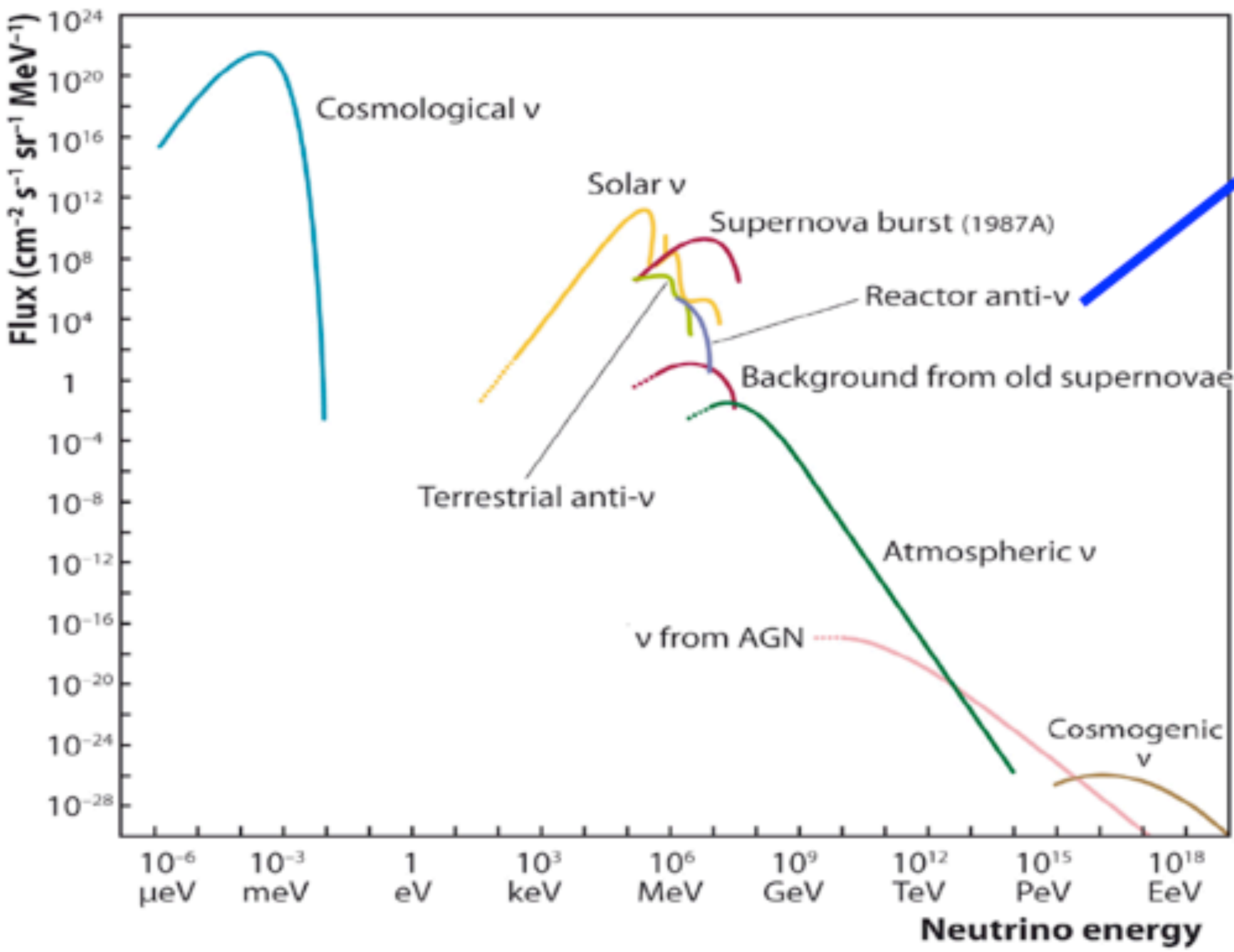
Flux



- **BUT: more than 800 nuclides from the fission of ^{235}U and others: ^{238}U, ^{239}Pu, ^{241}Pu, ...**
  → many instable fission products
  → reactor is during steady operation in a flow equilibrium

→ Uncertainties on the overall flux (see later that they play a big role in "anomalies")

The Neutrino Spectrum



10 GW at a distance of 150 km

reactor neutrinos:
ca. 4% of the thermal power P
3.9 GW → ca. 150 MW in ν's
dilution by distance R
flux $\Phi \sim P/R^2$
ca. 7kW/m² at 15m distance

But: Interaction is
- extremely weak
- grows with neutrino energy

source	flux	
reactor neutrinos (3 GW, at 10m distance)	5 x 10^13	/cm^2/s
solar neutrinos (on Earth)	6 x 10^10	/cm^2/s
supernova (50 kpc Abstand, for O(10) seconds)	~ 10^9	/cm^2/s
geo-neutrinos (on the Earth's continental surface)	6 x 10^6	/cm^2/s

Measuring $\sin^2 2\theta_{13}$ at reactors

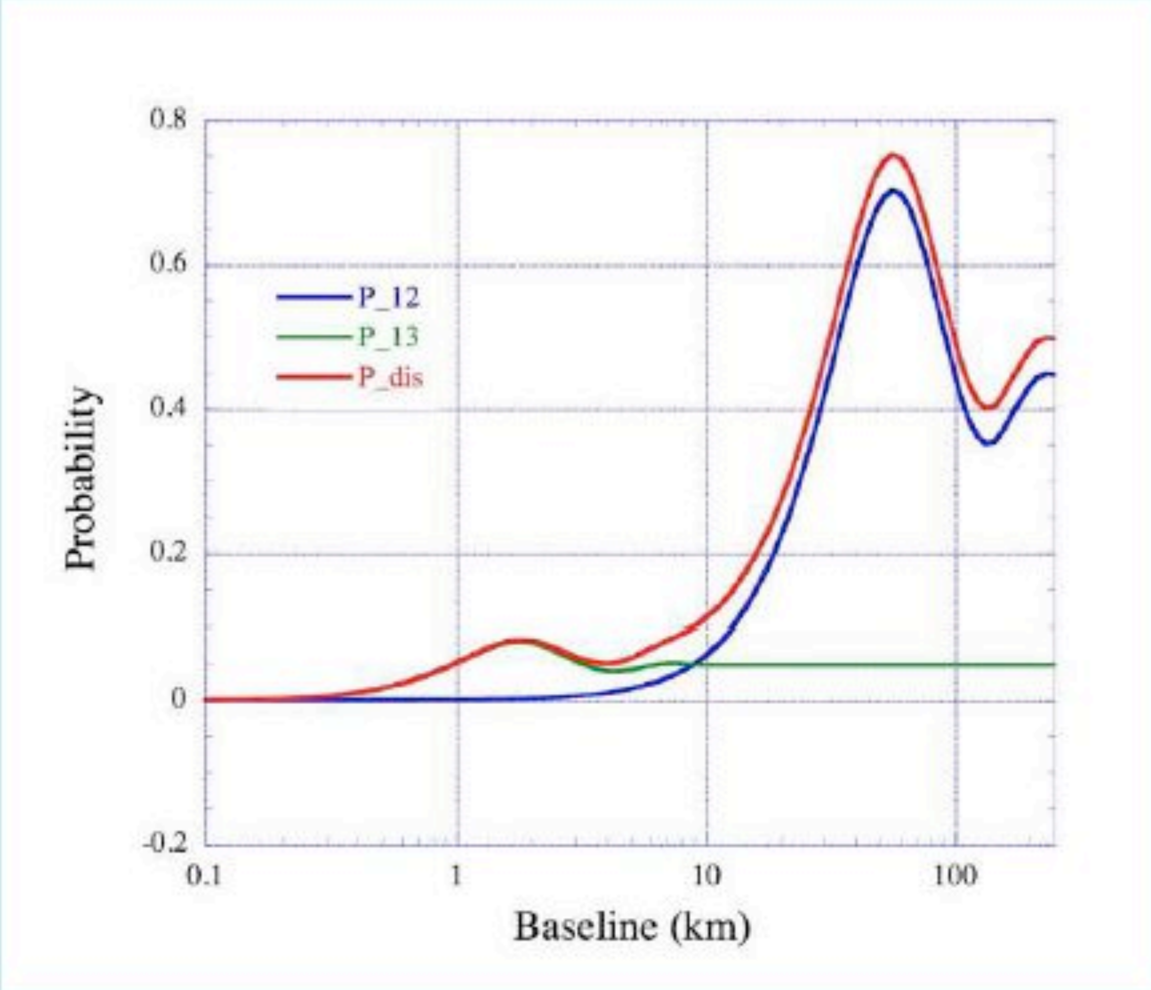
- Clean signal, no cross talk with δ and matter effects
- Relatively cheap compared to accelerator based experiments
- Provides the direction to the future of neutrino physics
- Rapidly deployment possible

at reactors:

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2(1.27\Delta m^2_{13} L/E) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2(1.27\Delta m^2_{12} L/E)$$

at LBL accelerators:

$$P_{\mu e} \approx \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2(1.27\Delta m^2_{23} L/E) + \cos^2\theta_{23} \sin^2 2\theta_{12} \sin^2(1.27\Delta m^2_{12} L/E) - A(\rho) \bullet \cos^2\theta_{13} \sin\theta_{13} \bullet \sin(\delta)$$



Reactor Neutrino Oscillations

$$P_{\bar{\nu_e}\to\bar{\nu_e}} = 1 - \sin^2 2\theta_{13} \sin^2\left(\Delta m^2_{ee}\frac{L}{4E}\right) - \sin^2 2\theta_{12} \cos^4 2\theta_{13} \sin^2\left(\Delta m^2_{21}\frac{L}{4E}\right)$$

Short Baseline

Long Baseline

$$\sin^2(\Delta m^2_{ee}\tfrac{L}{4E}) \equiv \cos^2\theta_{12}\sin^2(\Delta m^2_{31}\tfrac{L}{4E}) + \sin^2\theta_{12}\sin^2(\Delta m^2_{32}\tfrac{L}{4E})$$

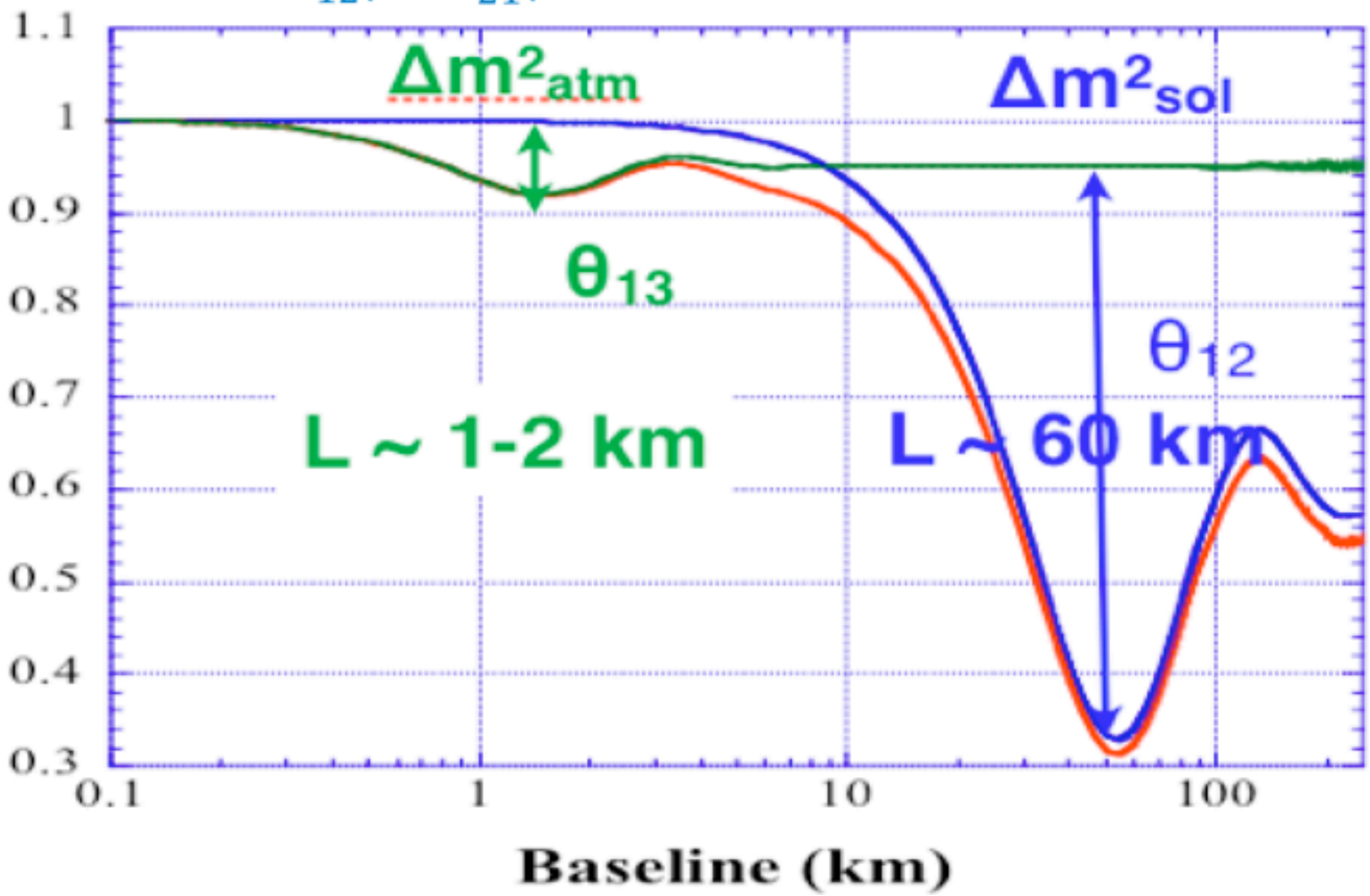
$$|\Delta m^2_{ee}| \simeq |\Delta m^2_{32}| \pm 5.21\times10^{-5}\text{eV}^2$$

$\cos^2\theta_{12}|\Delta m^2_{21}|$

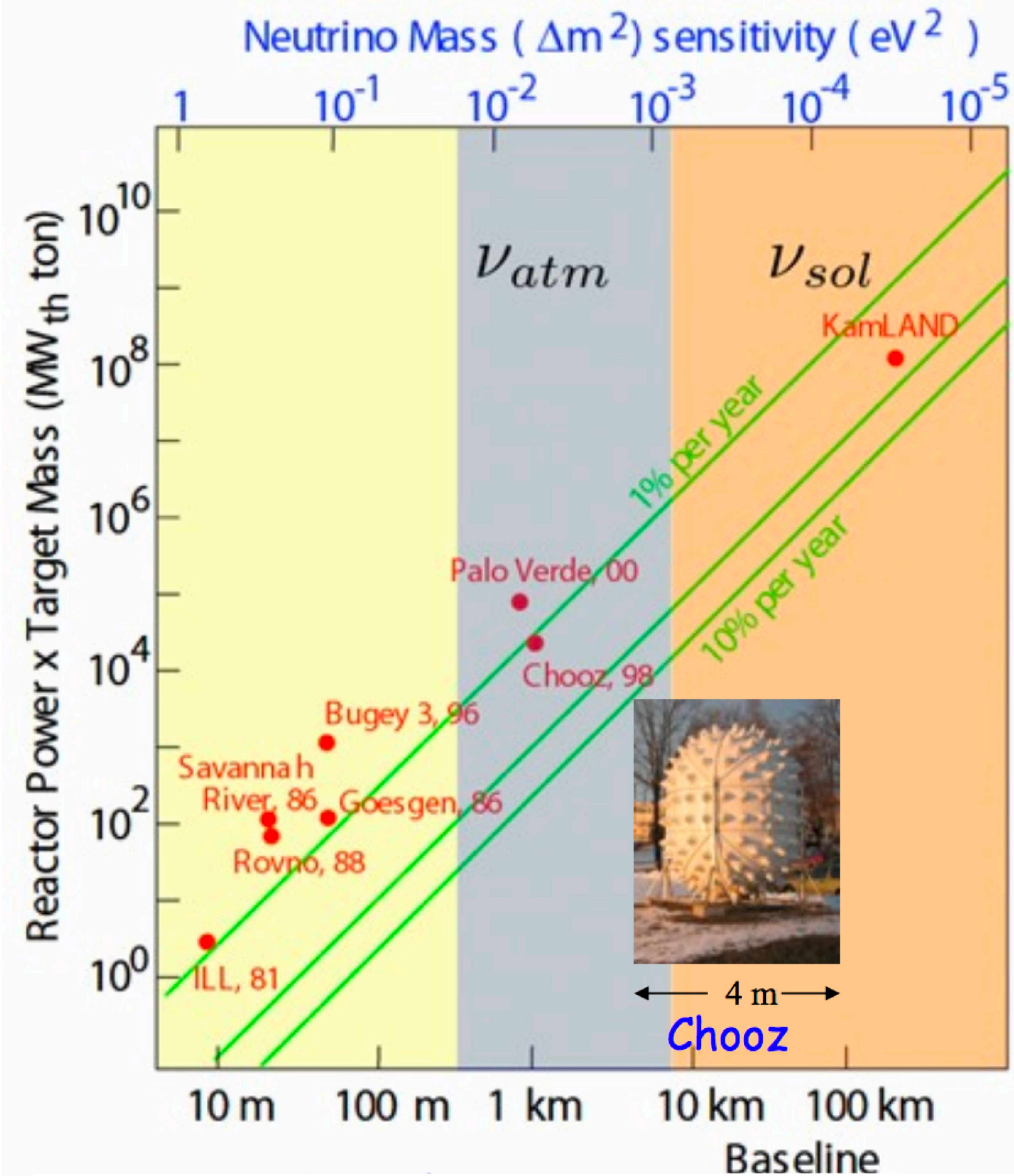
+: Normal Hierarchy

−: Inverted Hierarchy

[Nunokawa & Parke (2005)]



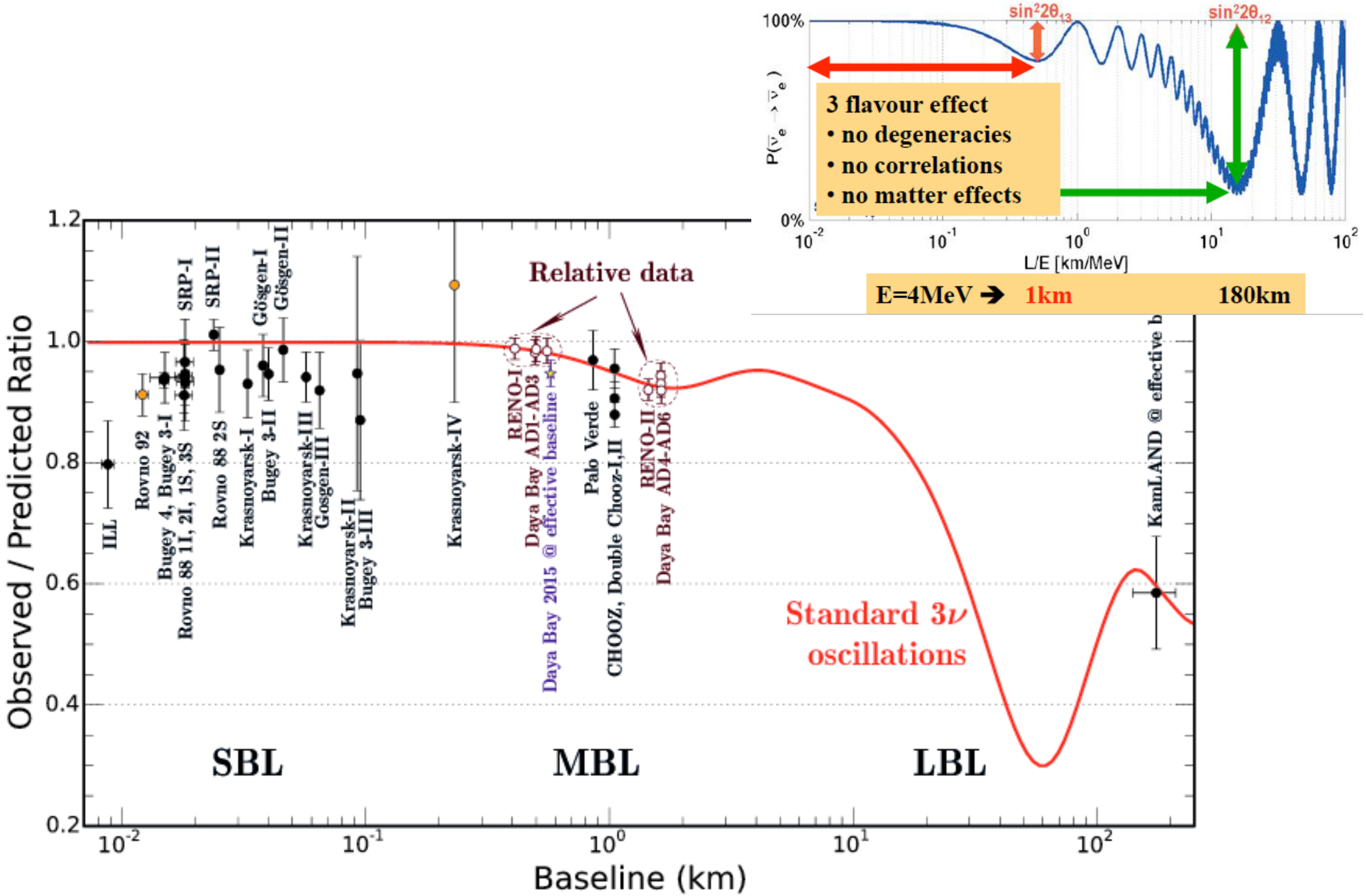
The past



Neutrino Mass (Δm 2) sensitivity (eV 2)
1
10-1
10-2
10-3
10-4
10-5
Reactor Power x Target Mass (MWth ton)
1010
108
106
104
102
100
νatm
νsol
KamLAND
1% per year
10% per year
Palo Verde, 00
Chooz, 98
Bugey 3, 96
Savannah River, 86
Goesgen, 86
Rovno, 88
ILL, 81
4 m
Chooz
10 m
100 m
1 km
10 km
100 km
Baseline

The present

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{31} L}{4E_\nu} - \left(\frac{\Delta m^2_{21} L}{4E_\nu}\right)^2 \cos^4\theta_{13} \sin^2 2\theta_{12}$$

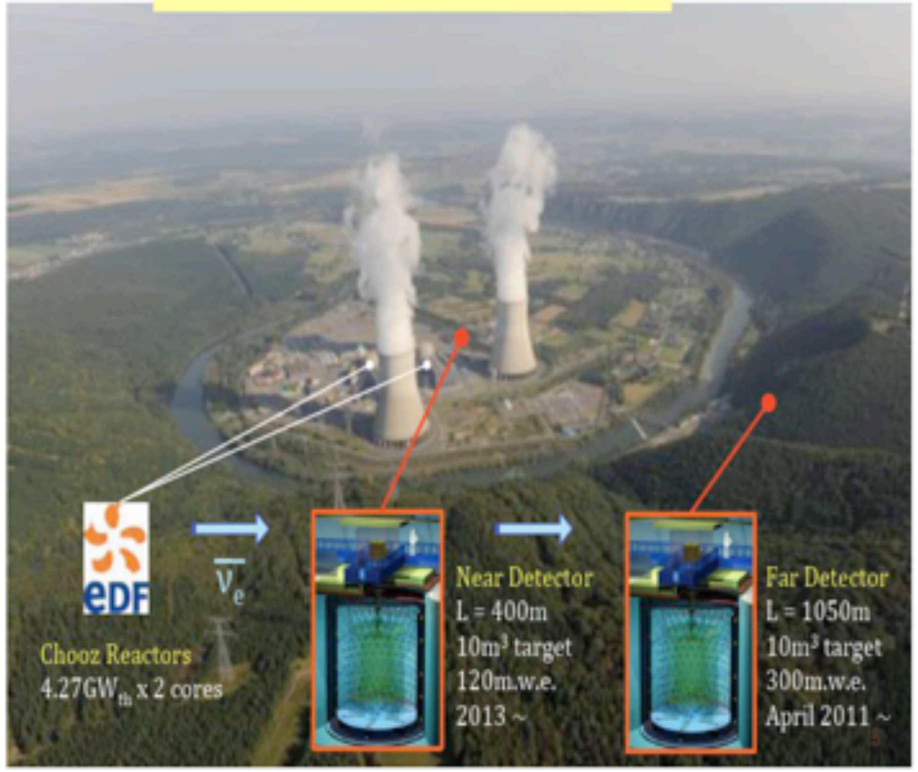


θ_{13}: Three on-going experiments

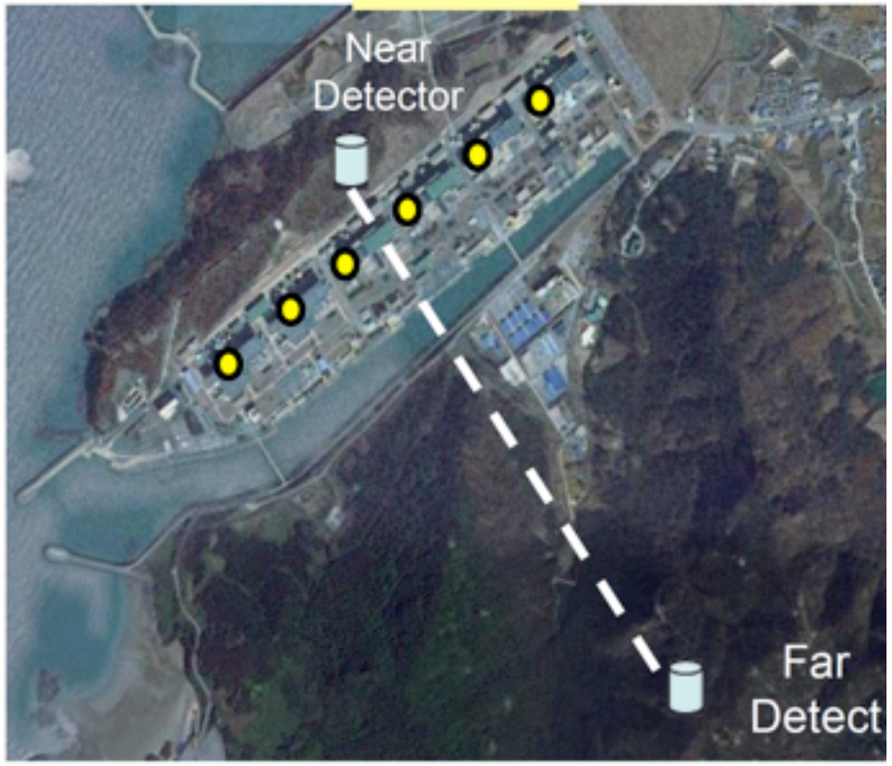
Experiment	Power (GW)	Baseline(m) Near/Far	Detector(t) Near/Far	Overburden (MWE) Near/Far	Designed Sensitivity (90%CL)
Daya Bay	17.4	470/576/1650	40//40/80	250/265/860	~ 0.008
Double Chooz	8.5	400/1050	8.2/8.2	120/300	~ 0.03
Reno	16.5	409/1444	16/16	120/450	~ 0.02

Daya Bay

Double Chooz

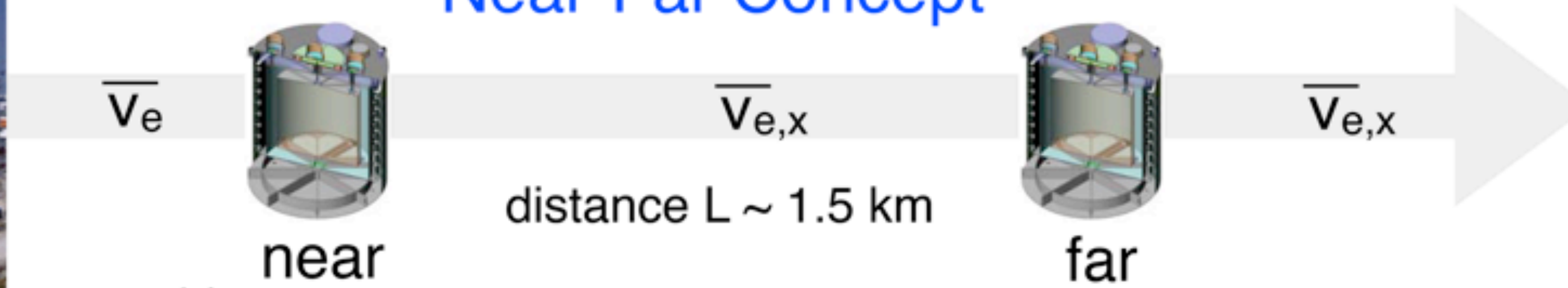


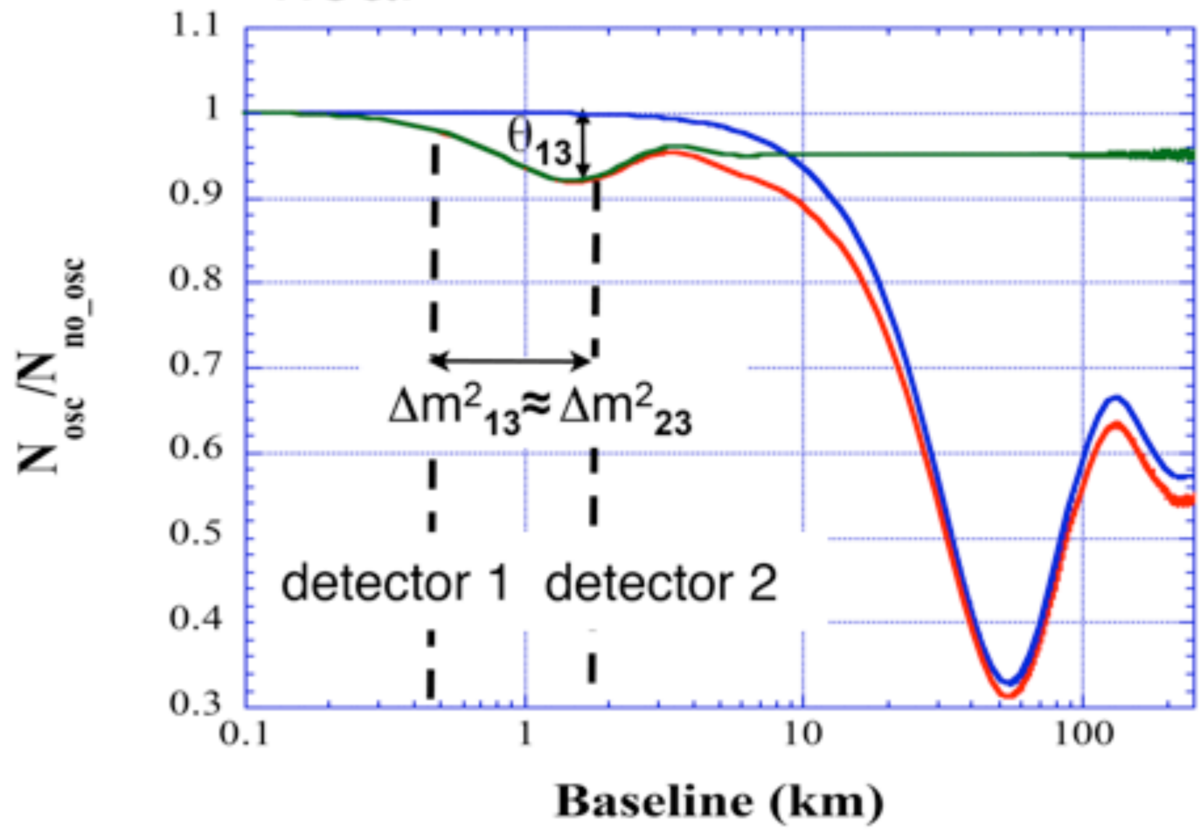
Reno



Measuring θ_{13} with Reactor Experiments

Near-Far Concept





Absolute Reactor Flux
Largest uncertainty in previous measurements

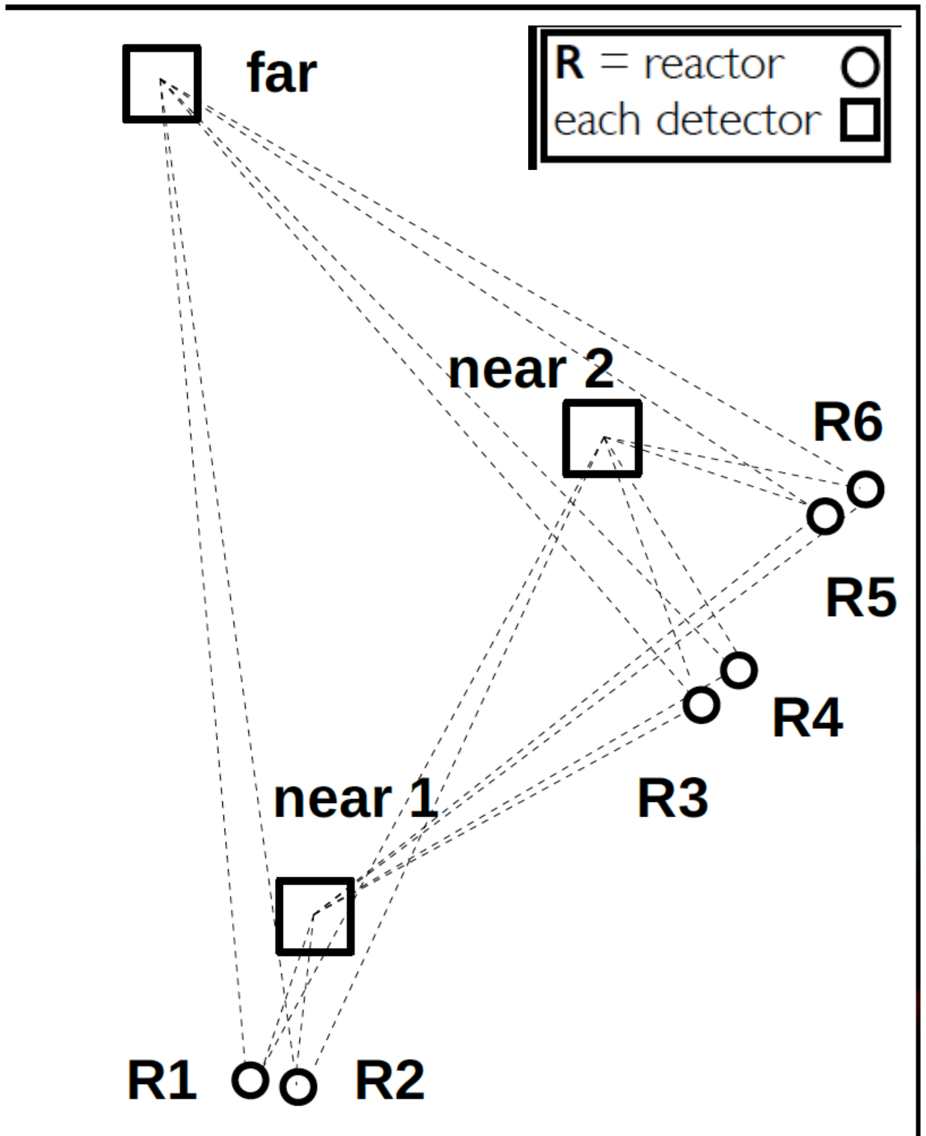
Relative Measurement
Removes absolute uncertainties!

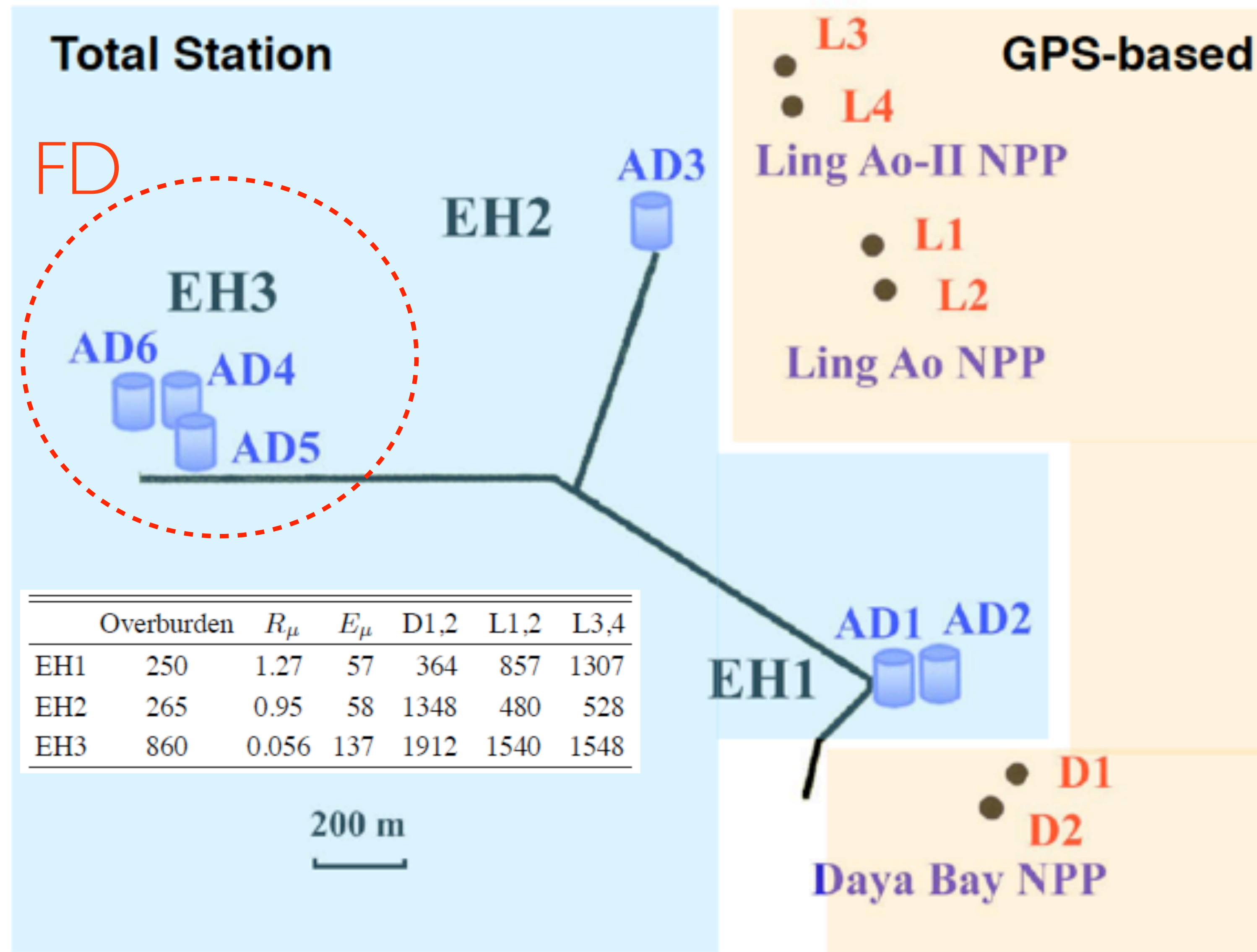
First proposed by L. A. Mikaelyan and V.V. Sinev, Phys. Atomic Nucl. 63 1002 (2000)

$$\frac{N_f}{N_n} = \left(\frac{N_{p,f}}{N_{p,n}}\right)\left(\frac{L_n}{L_f}\right)^2\left(\frac{\epsilon_f}{\epsilon_n}\right)\left[\frac{P_{sur}(E, L_f)}{P_{sur}(E, L_n)}\right]$$

far/near $\overline{\nu}_e$ ratio | target mass | distances | efficiency | oscillation deficit

Reactor-Detector Distance Survey





	Overburden	R_μ	E_μ	D1,2	L1,2	L3,4
EH1	250	1.27	57	364	857	1307
EH2	265	0.95	58	1348	480	528
EH3	860	0.056	137	1912	1540	1548

Negligible reactor flux uncertainty (<0.02%) from precise survey.

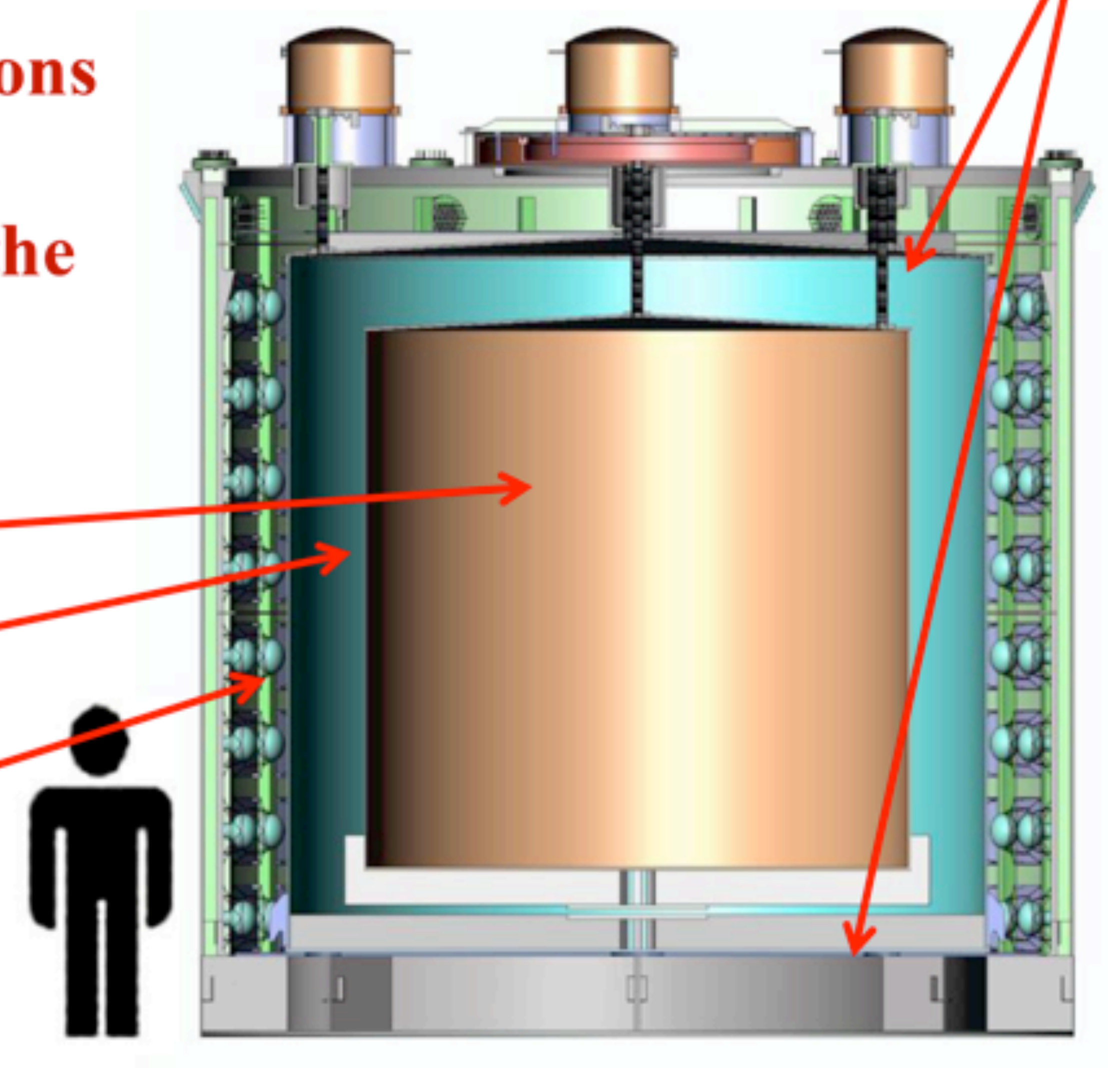
$$\frac{N_f}{N_n} = \left(\frac{N_{p,f}}{N_{p,n}}\right)\left(\frac{L_n}{L_f}\right)^2\left(\frac{\epsilon_f}{\epsilon_n}\right)\left[\frac{P_{sur}(E,L_f)}{P_{sur}(E,L_n)}\right]$$

distances

Detectors

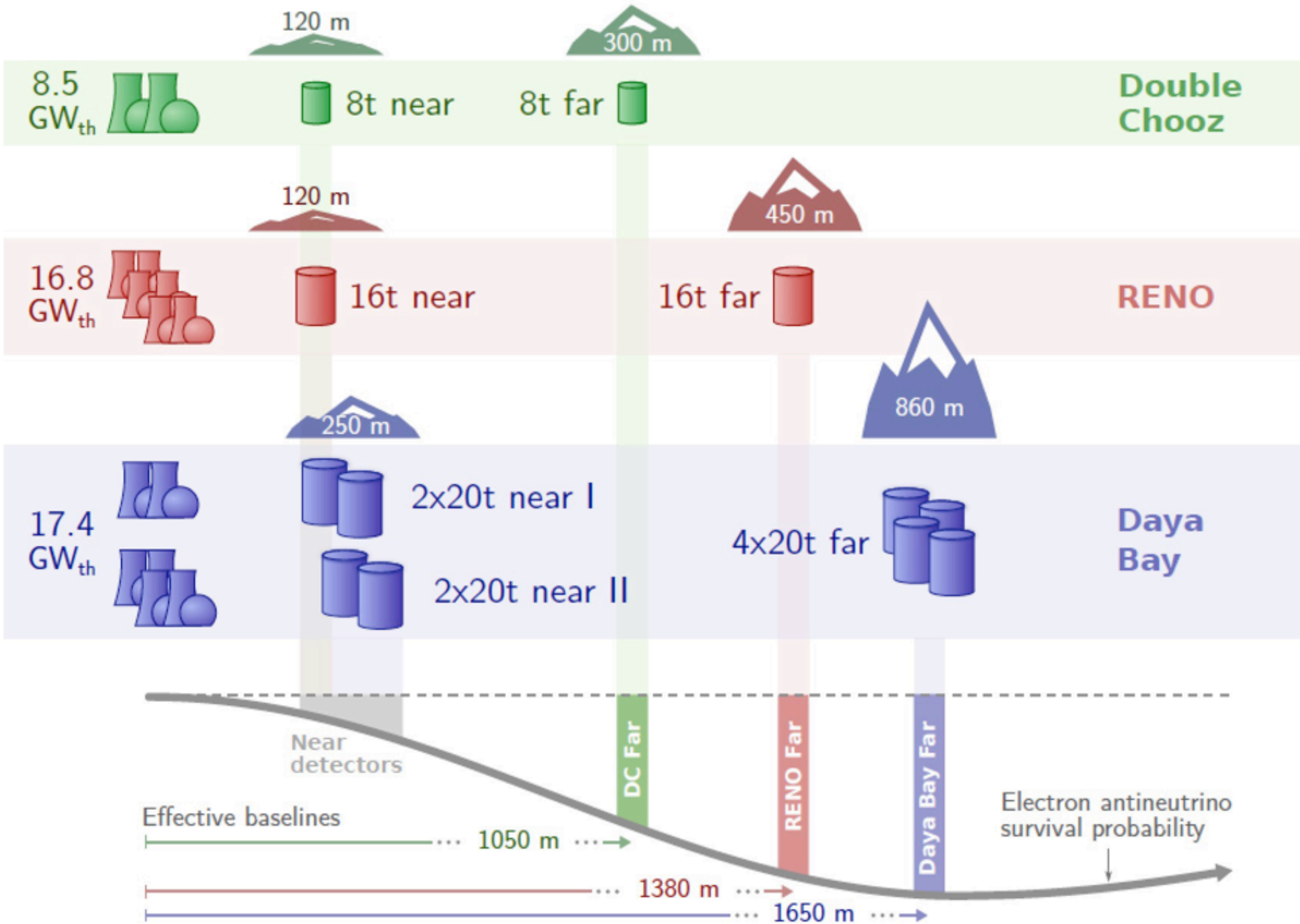
- **Neutrino detector(s) in a water pool**
  - ⇨ Water for shielding backgrounds
  - ⇨ Water for stabilizing running conditions
  - ⇨ Water Cherenkov for muon veto
  - ⇨ RPC/plastic scintillator at the top of the water pool for muon veto
- **Three-zone neutrino detector:**
  - ⇨ Target: Gd-loaded LS
    - ✓ ~ 10-20t for neutrino
  - ⇨ γ-catcher: normal LS
    - ✓ ~ 10-20t for energy containment
  - ⇨ Buffer shielding: oil
    - ✓ ~ 20-40t for shielding

optical reflectors



- **Light collection**

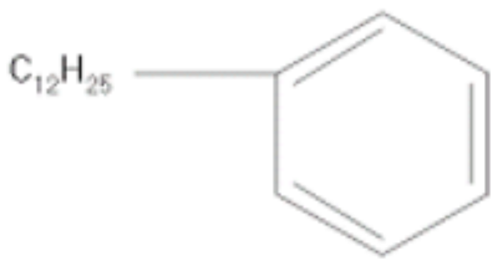
	PMT	Coverage	pe yield	pe yield/Coverage
Daya Bay	192 8"	~6%	163 pe/MeV	1.77
RENO	354 10"	~15%	230 pe/MeV	1
Double Chooz	390 10"	~16%	200 pe/MeV	0.81



⇒ ...and maximum overburden to reduce backgrounds from cosmic-ray muons

Detection of Reactor Antineutrinos

C_nH_{2n+1}-C_6H_5 (n=10~14)



Linear Alkyl Benzene (LAB)

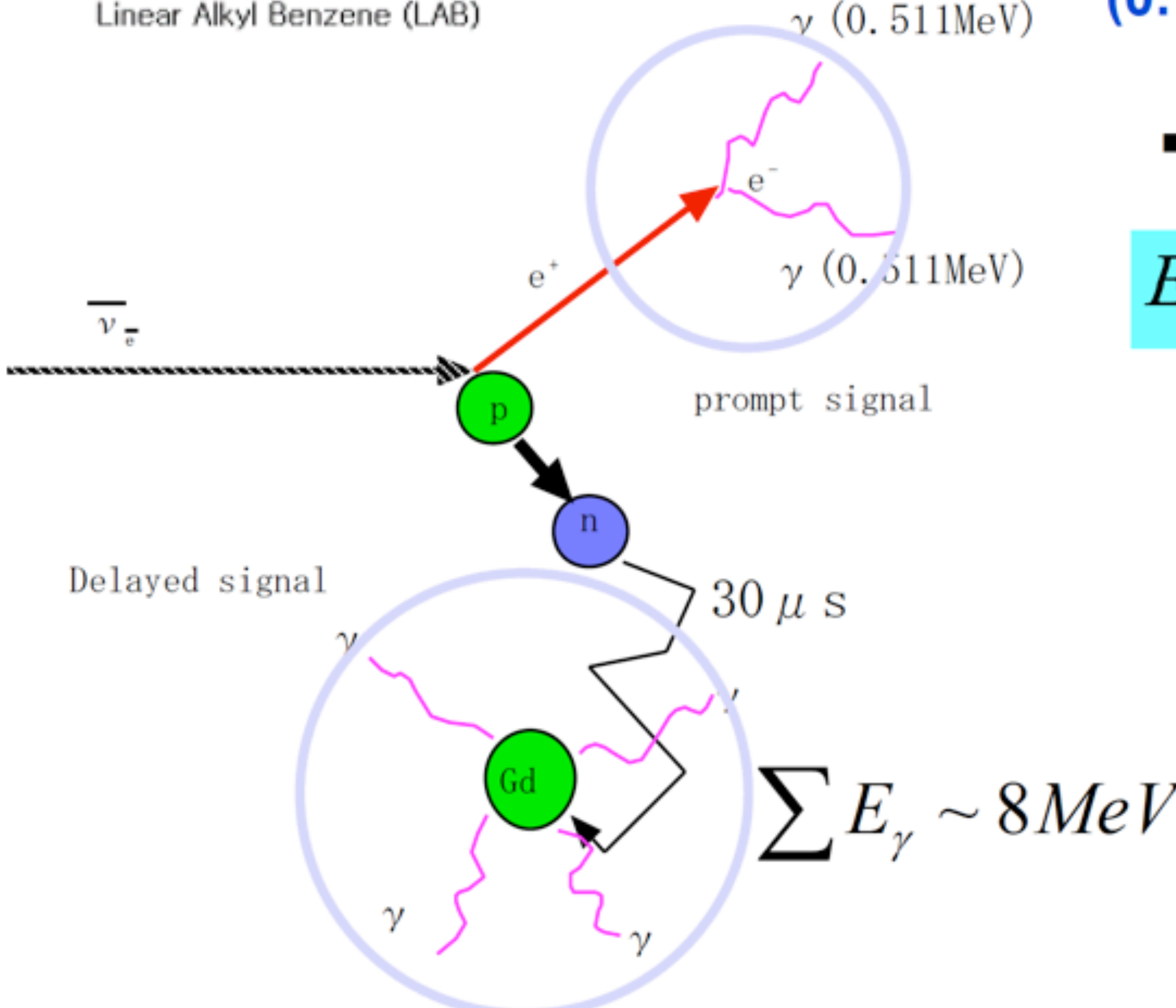
(prompt signal)

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

(delayed signal)

~180 μs: + p → D + γ (2.2 MeV)

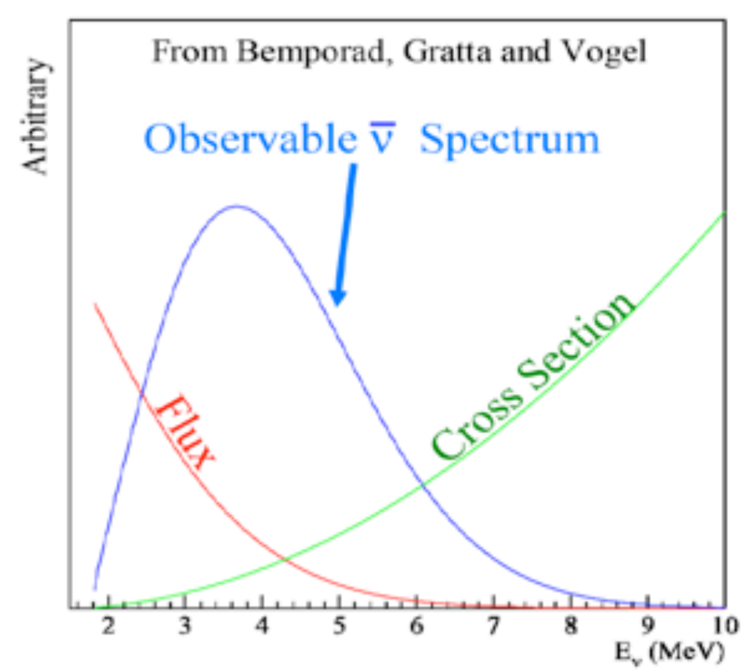
~28 μs (0.1% Gd): + Gd → Gd + γ's (8 MeV)



- **Neutrino energy measurement**

$$E_{\bar{\nu}} \cong T_{e^+} + T_n + (M_n - M_p) + m_{e^+}$$

10-40 keV ; 1.8 MeV



E(nu) = E_{prompt}+(M_n-M_p)-m_{e^-}

Cross section

positron energies are related by

$$E_\nu = E_e + T_n + m_n - m_p \simeq E_e + 1.293\,\mathrm{MeV}\,, \tag{12.14}$$

where T_n is the negligibly small recoil kinetic energy of the neutron. From eqn (5.37), the neutrino energy threshold is given by

$$E_\nu^{\rm th} = \frac{(m_n + m_e)^2 - m_p^2}{2\,m_p} \simeq 1.806\,\mathrm{MeV}\,, \tag{12.15}$$

which is slightly larger than the naive $m_n - m_p + m_e \simeq 1.804$ MeV. The cross-section is given by[69]

$$\sigma_{\rm CC}^{\bar\nu_e p} = \frac{G_{\rm F}^2\,|V_{ud}|^2}{\pi}\,(g_V^2 + 3\,g_A^2)\,E_e\,p_e\,, \tag{12.16}$$

$$\sigma_{\rm CC}^{\bar\nu_e p} = \frac{2\pi^2}{\tau_n\,m_e^5\,f}\,E_e\,p_e \simeq 9.56 \times 10^{-44}\left(\frac{E_e\,p_e}{\mathrm{MeV}^2}\right)\left(\frac{\tau_n}{886\,\mathrm{s}}\right)^{-1}\mathrm{cm}^2\,, \tag{12.17}$$

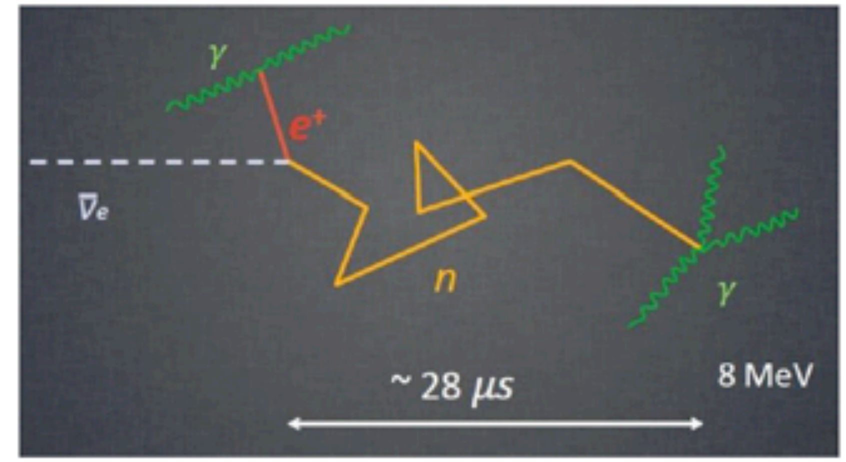
where f is the phase space integral in eqns (5.141) and (5.142). This form has the advantage of expressing the cross-section in terms of the well-measured quantities m_e and τ_n (see eqns (A.150) and (A.158)), eliminating the need to know the values of $|V_{ud}|$, g_V, and g_A.

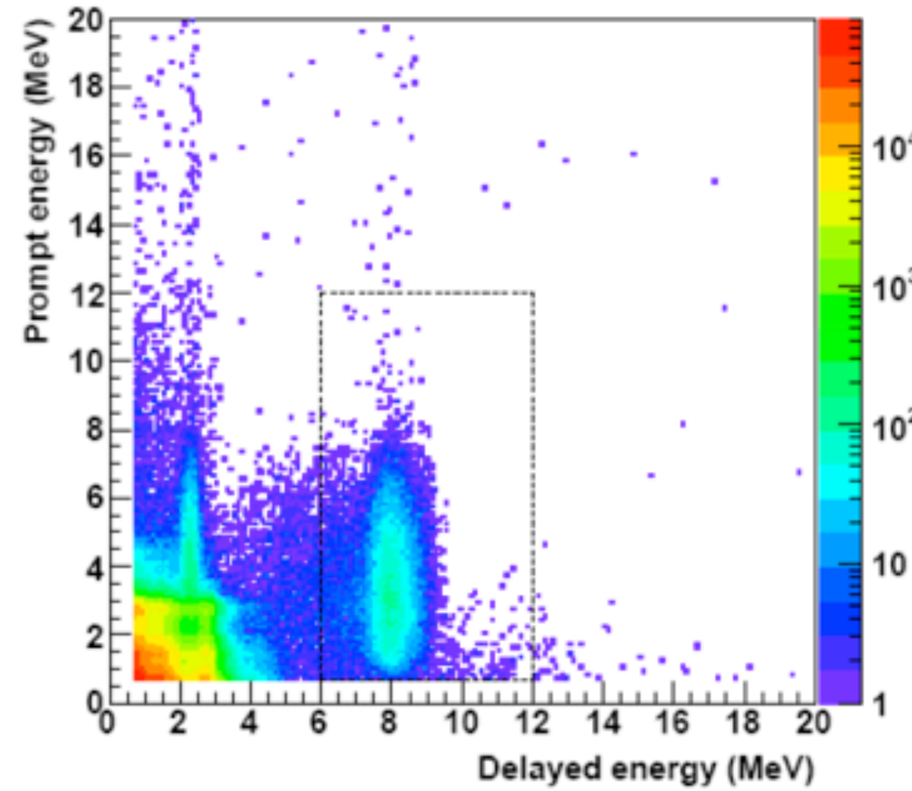
The threshold of about 1.8 MeV implies that only about 25% of the antineutrinos produced in a reactor can be detected, since the others are below threshold. The

x-sec grows linearly with E

Event Signature and Backgrounds

- **Signature:** $\bar{\nu}_e + p \rightarrow e^+ + n$
  - ⇨ **Prompt: e^+, 1-10 MeV,**
  - ⇨ **Delayed: n, 2.2 MeV@H, 8 MeV @ Gd**
  - ⇨ **Capture time: 28 μs in 0.1% Gd-LS**
- **Backgrounds**
  - ⇨ **Uncorrelated: random coincidence of γγ, γn or nn**
    - ✓ **γ from U/Th/K/Rn/Co… in LS, SS, PMT, Rock, …**
    - ✓ **n from α-n, μ-capture, μ-spallation in LS, water & rock**
  - ⇨ **Correlated:**
    - ✓ **Fast neutrons: n scattering - n capture**
    - ✓ **^{8}He/^{9}Li: β decay -n capture**
    - ✓ **Am-C source: γ rays - n capture**
    - ✓ **α-n: $^{13}C(\alpha,n)^{16}O$**





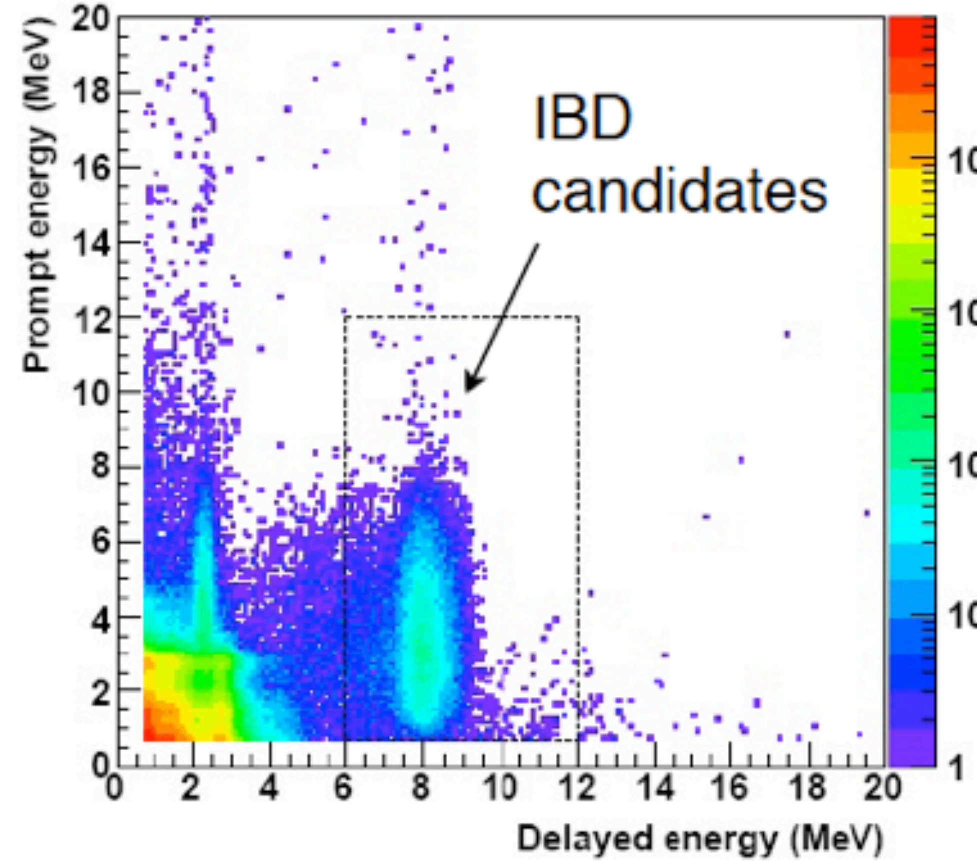
201 ... 7

Gd used because of delay @ 8 MeV (radiogenic BG dominates ≤ 3MeV) and high thermal neutron capture x-sec: 260 b *(see also slide 43)*

Antineutrino (IBD) Selection

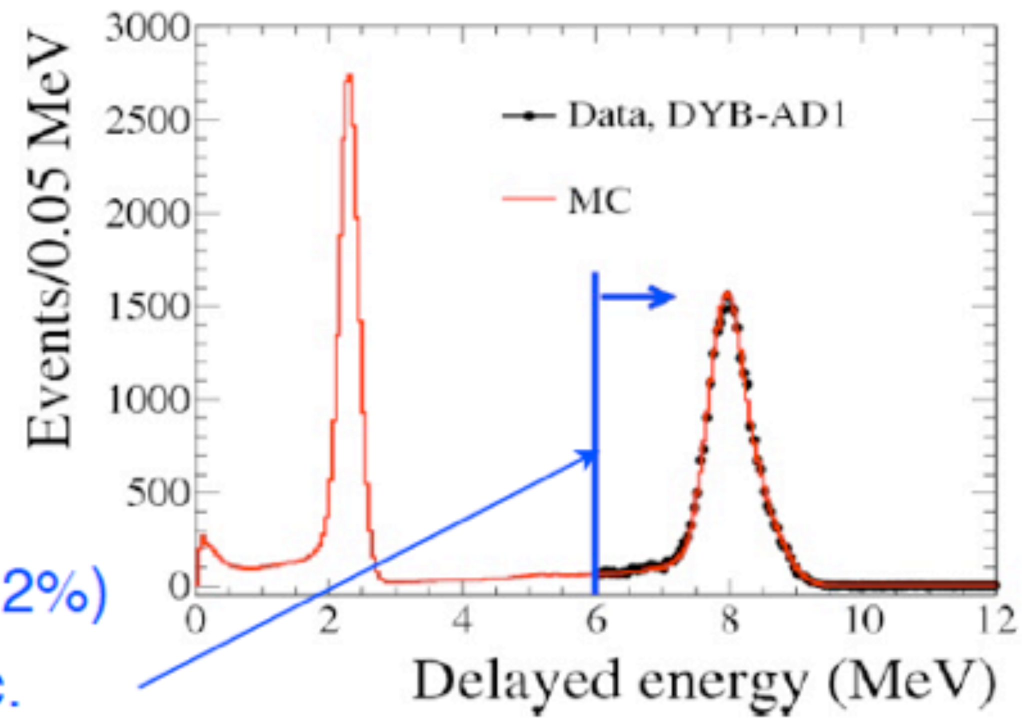
Selection of Prompt + Delayed

- Reject Flashers
- Prompt Positron: 0.7 MeV < E_p < 12 MeV
- Delayed Neutron: 6.0 MeV < E_d < 12 MeV
- Capture time: 1 μs < Δt < 200 μs
- Muon Veto:
  - Pool Muon: Reject 0.6ms
  - AD Muon (>20 MeV): Reject 1ms
  - AD Shower Muon (>2.5GeV): Reject 1s
- Multiplicity:
  - No other signal > 0.7 MeV in -200 μs to 200 μs of IBD.



Selection driven by uncertainty in relative detector efficiency

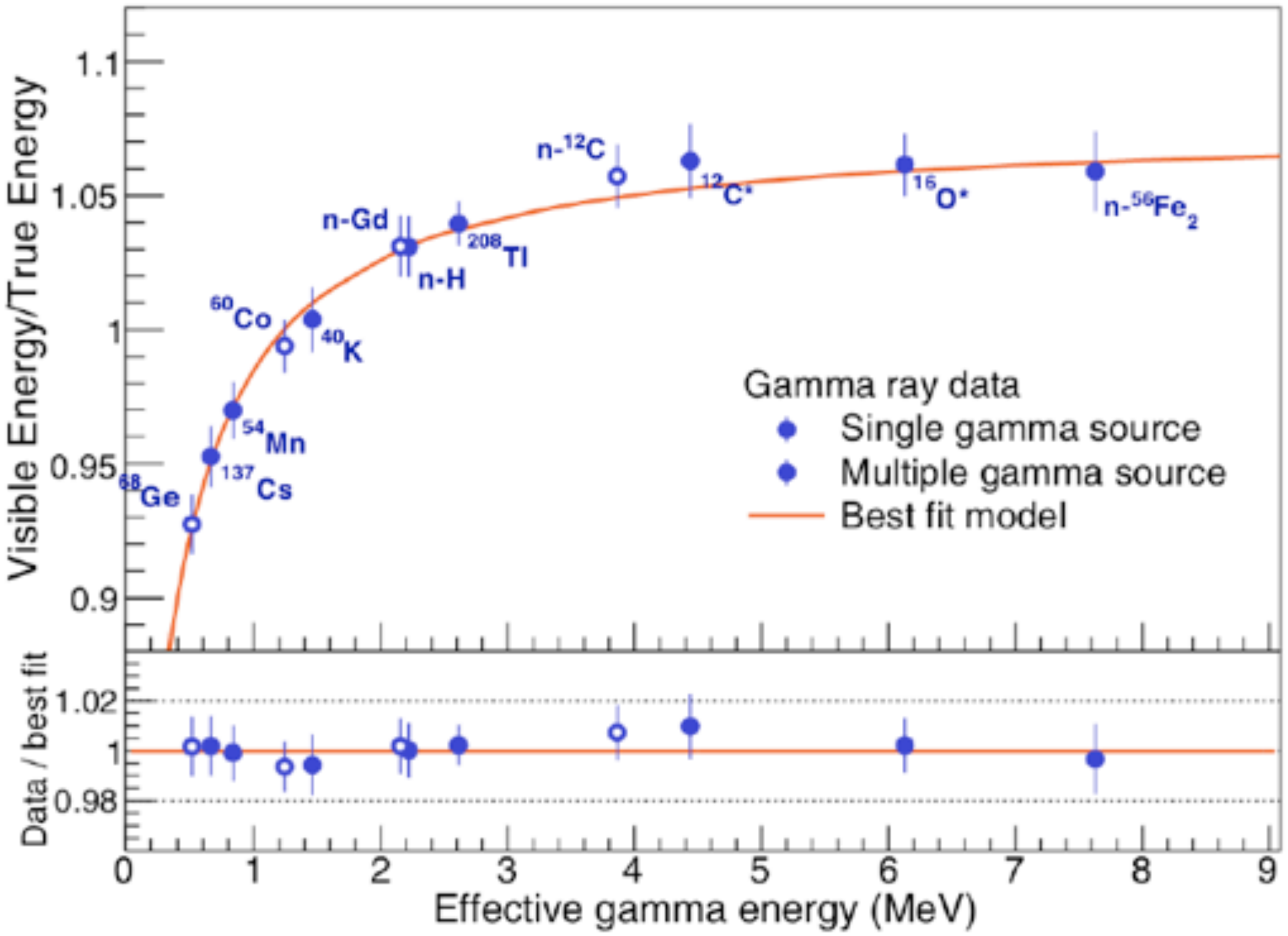
$$\frac{N_f}{N_n} = \left(\frac{N_{p,f}}{N_{p,n}}\right)\left(\frac{L_n}{L_f}\right)^2\left(\frac{\epsilon_f}{\epsilon_n}\right)\left[\frac{P_{sur}(E, L_f)}{P_{sur}(E, L_n)}\right]$$

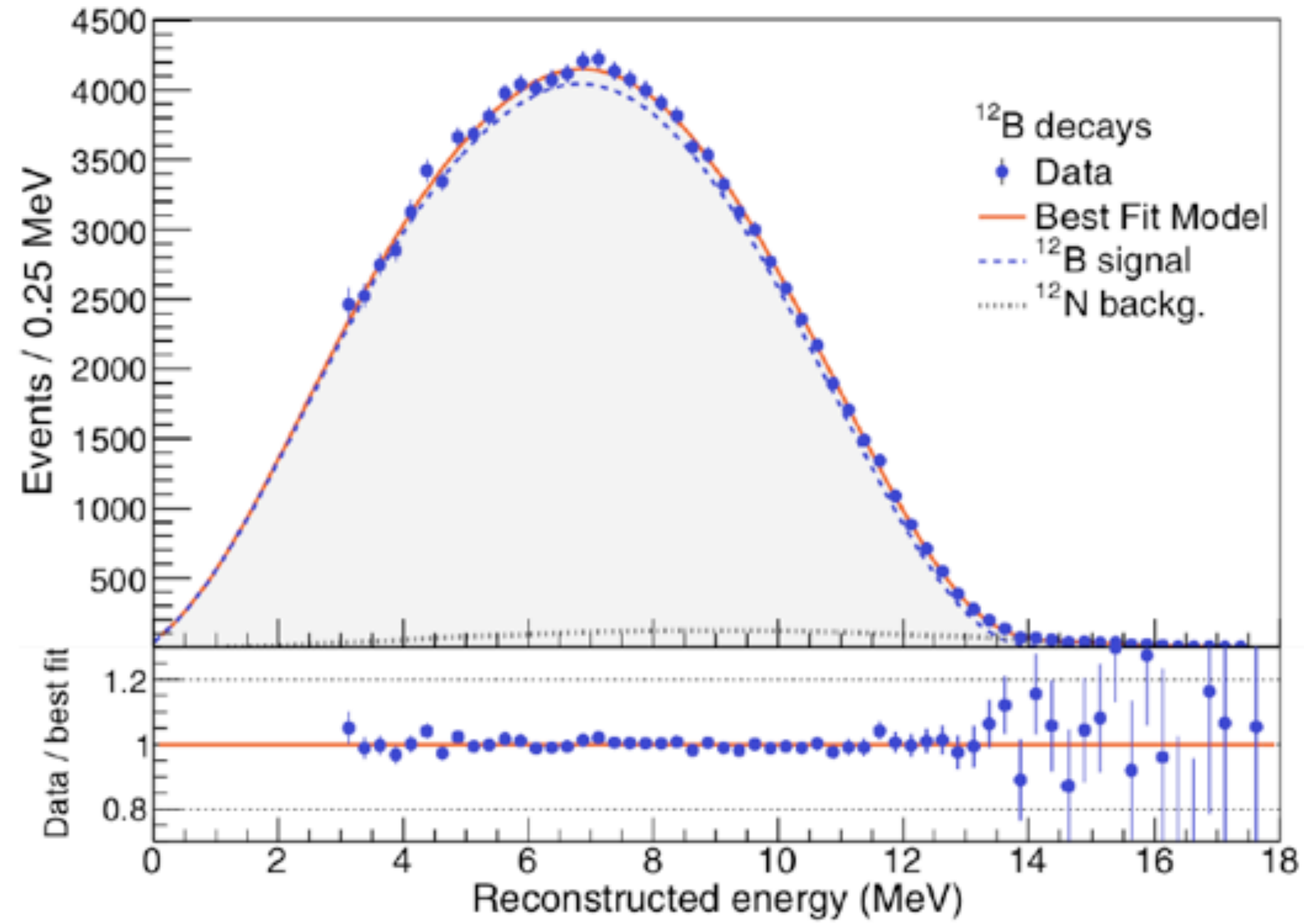


Uncertainty in relative E_d efficiency (0.12%) between detectors is largest systematic.

Energy model

Zeyuan Yu
Institute of High Energy Physics, China





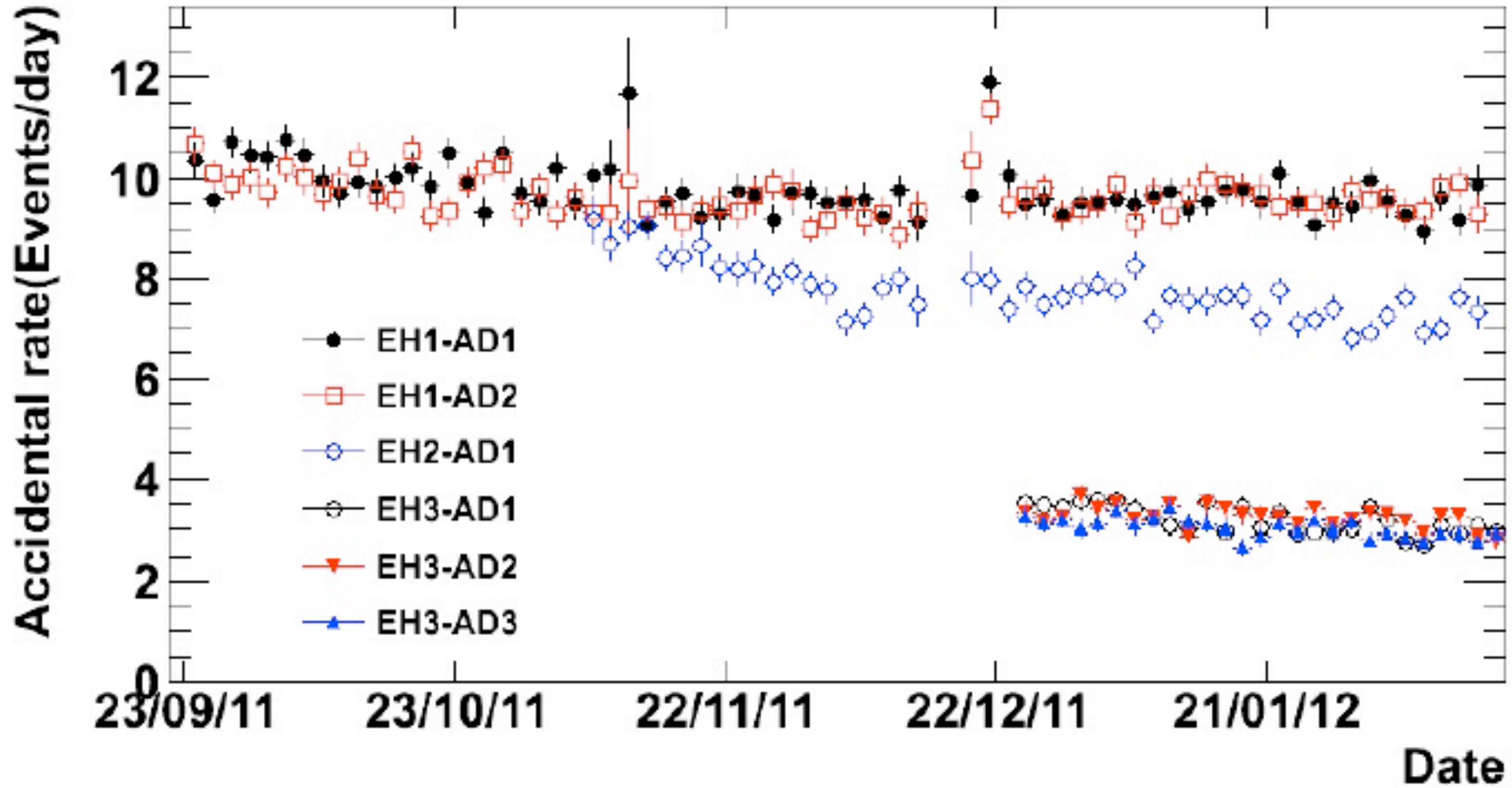
- **Energy model**
  - **Includes the non-linearity from LS and readout electronics**
  - **Built based on various γ peaks and continuous ^{12}B β spectrum**
- **Validated with**
  - **Michel electron; β+γ continuous spectra from $^{212/214}Bi$ and ^{208}Tl**
  - **Bench tests of Compton scattering electrons in LS**

Two single signals can accidentally mimic an antineutrino (IBD) signal

Rate and spectrum can be accurately predicted from singles data.

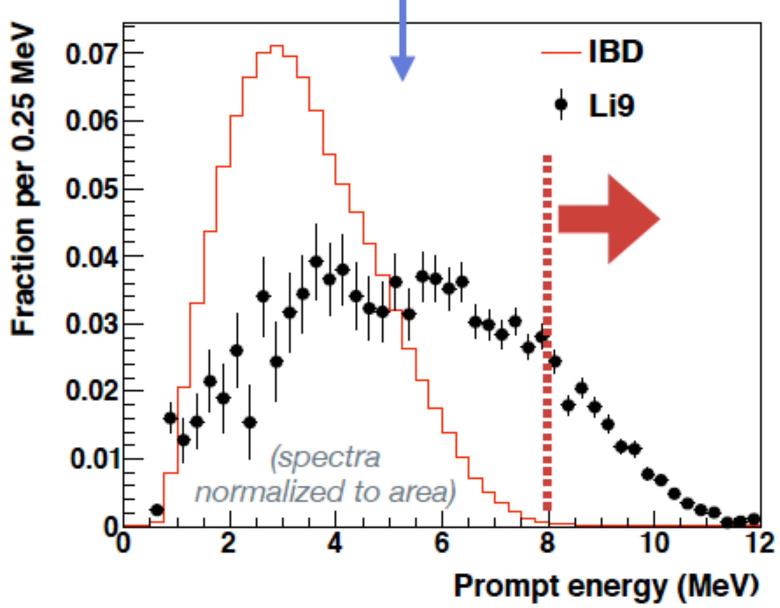
Multiple analyses/methods estimate consistent rates.

Accidentals/radioactivity

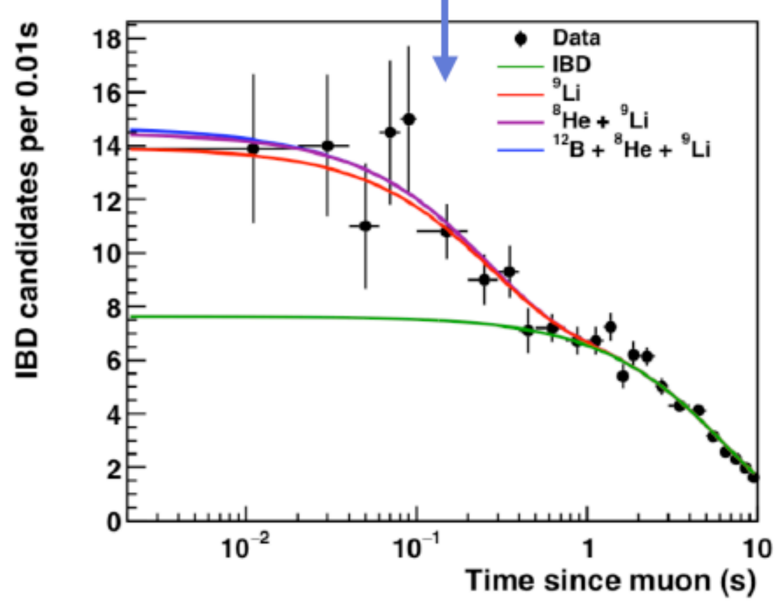


Cosmogenic

Apply a large E_{prompt} cut to enhance the ^{9}Li/^{8}He fraction:

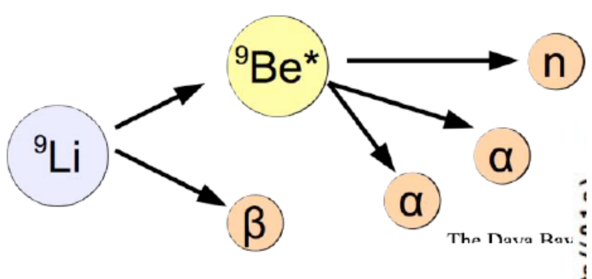


Fit the time-since-last-muon distribution



β-n decay:

- Prompt: β-decay
- Delayed: neutron capture



- Generated by cosmic rays
- Long-lived
- Mimic antineutrino signal

Mean lifetime: 257 ms (^{9}Li) and 172 ms (^{8}He) -- no full region veto

^{9}Li/^{8}He uncertainty in near ADs reduced from 50% to 30%

Summary of uncertainties and benefit of ND+FD

systematics	single detector (SD) (%)	multi-detector (MD) (%)
δ(detection)	~[2.0^{DYB},0.5^{DC}] (no fiducial volume)	→ ~0.2 (identical detectors)
δ(flux)	~3.0 [~5.0^{new}] (prediction) [~1.7 via **Bugey4**]	→ ≤0.5 (ND reactor monitor)
δ(background)	≤0.5 (radio-purity+overburden+vetoes)	↛ ≤0.5 (little or no suppression)

— systematics uncertainties ~1‰ each —

$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \sin^2 2\theta_{13} \sin^2\left(\Delta m^2_{ee} \frac{L}{4E}\right) - \sin^2 2\theta_{12} \cos^4 2\theta_{13} \sin^2\left(\Delta m^2_{21} \frac{L}{4E}\right)$$

Short Baseline — Long Baseline

$$\sin^2\left(\Delta m^2_{ee} \tfrac{L}{4E}\right) \equiv \cos^2\theta_{12} \sin^2\left(\Delta m^2_{31} \tfrac{L}{4E}\right) + \sin^2\theta_{12} \sin^2\left(\Delta m^2_{32} \tfrac{L}{4E}\right)$$

[Nunokawa & Parke (2005)]

$$|\Delta m^2_{ee}| \simeq |\Delta m^2_{32}| \pm 5.21 \times 10^{-5}\,\mathrm{eV}^2$$

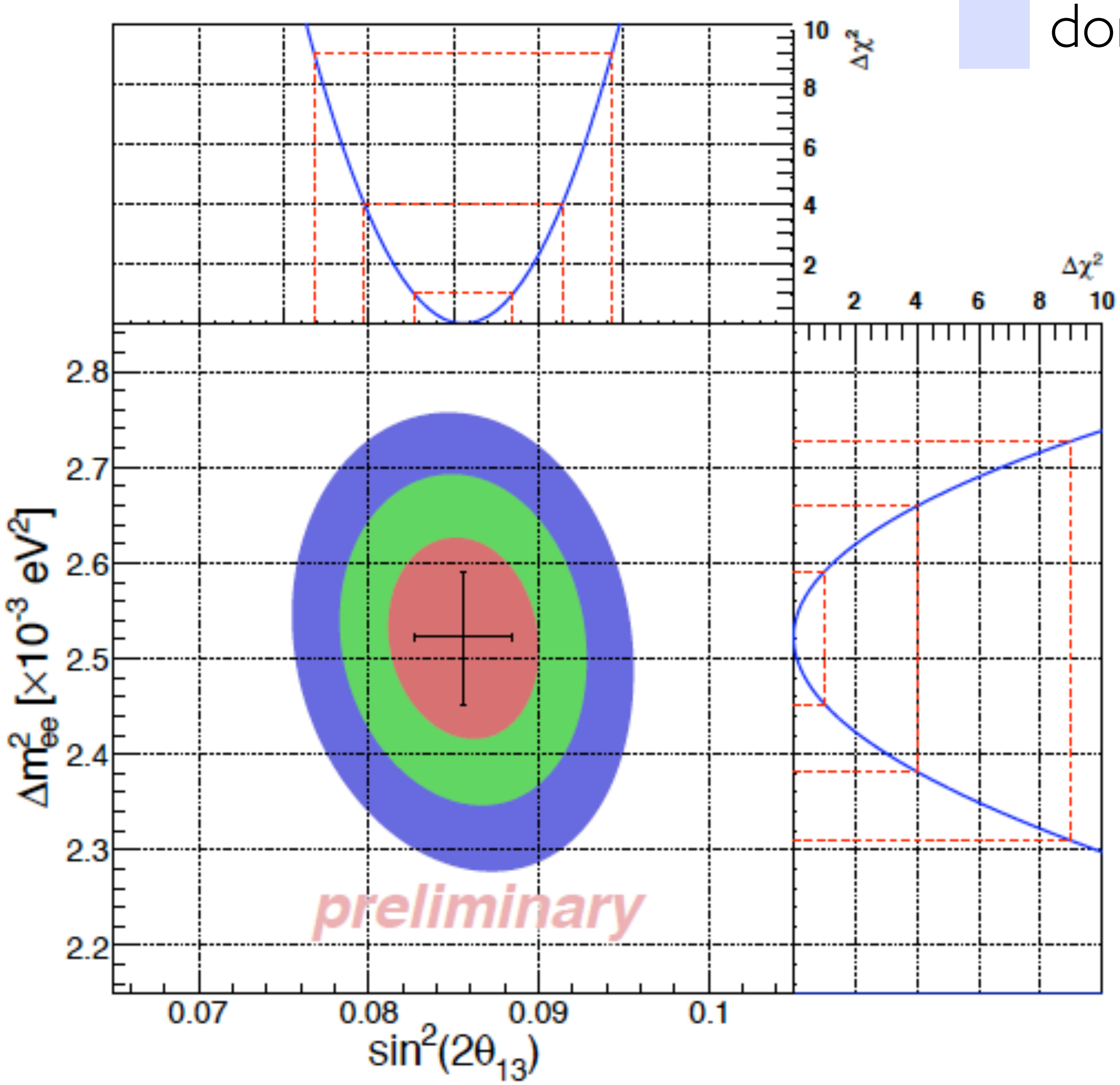
$\cos^2\theta_{12}|\Delta m^2_{21}|$

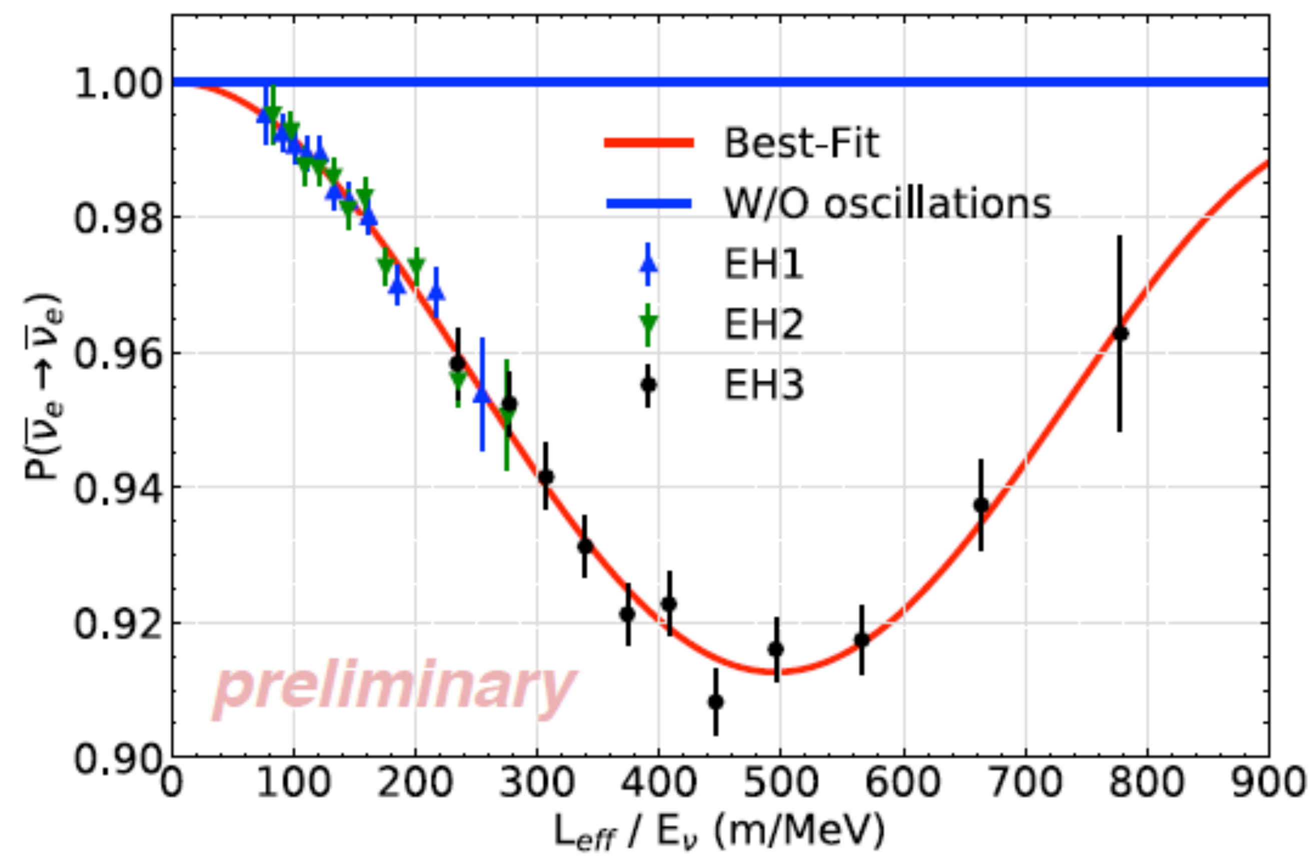
+: Normal Hierarchy
−: Inverted Hierarchy

Daya Bay

https://zenodo.org/record/1294112#.XFxP39F7mi4

dominates here





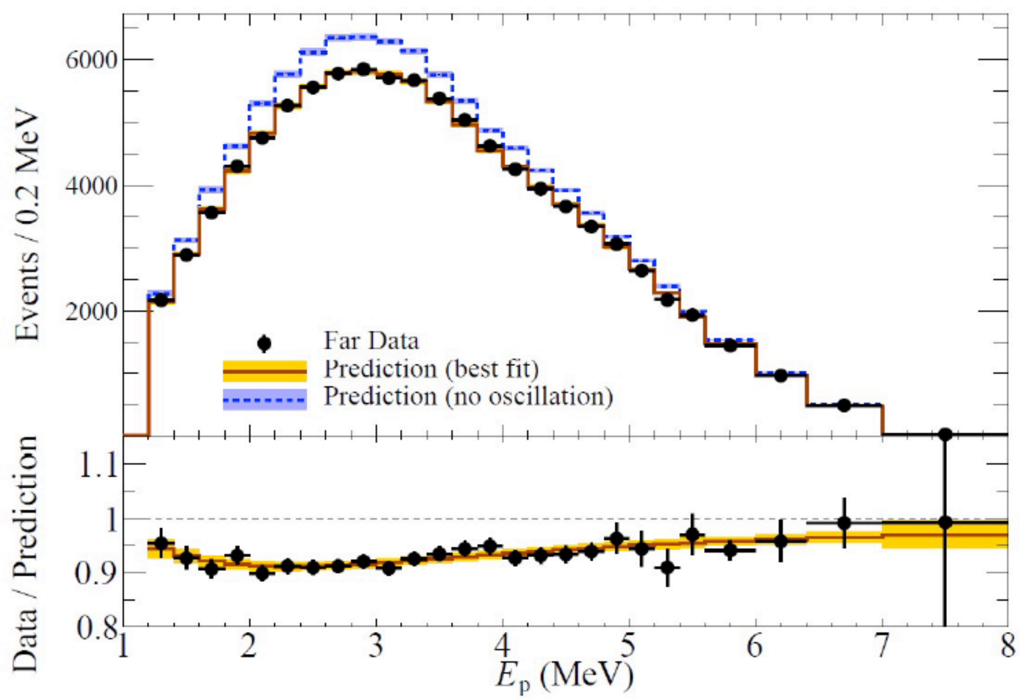
results with 1958 days →

$$\sin^2 2\theta_{13} = 0.0856 \pm 0.0029$$

$$|\Delta m^2_{ee}| = (2.52 \pm 0.07) \times 10^{-3}\ \mathrm{eV}^2$$

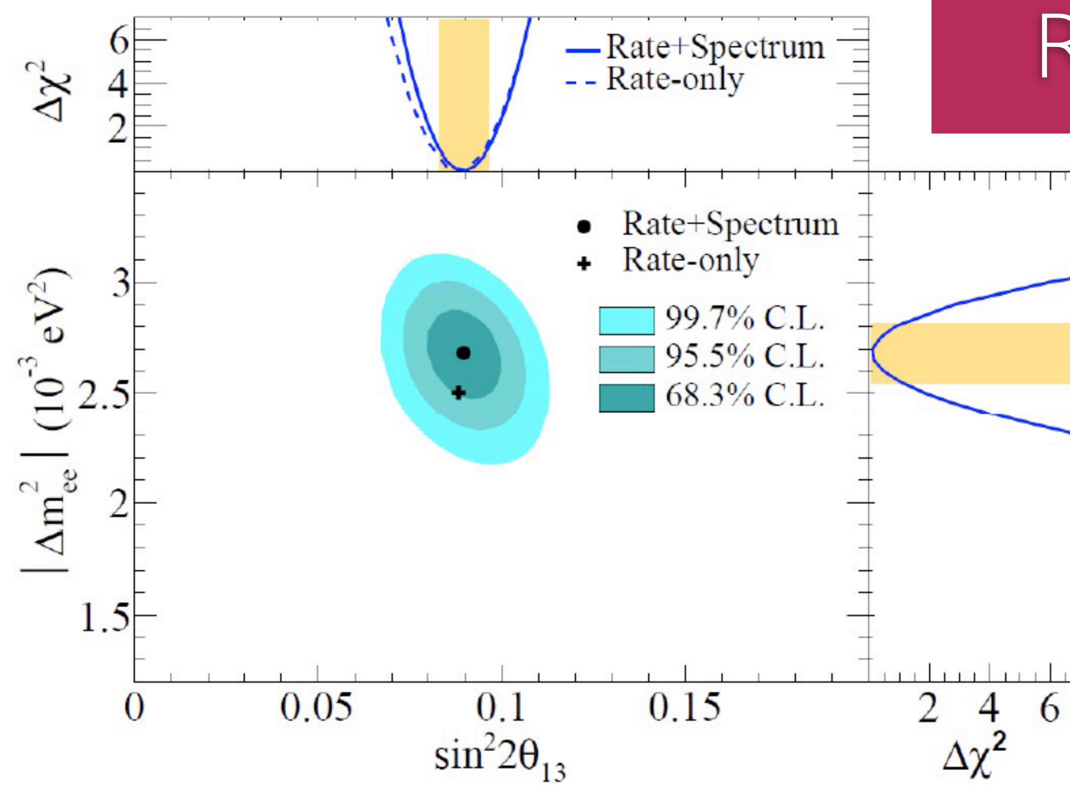
The statistical uncertainty contributes about 60% (50%) of the total θ_{13} (Δm^2_{ee}) uncertainty.

Reno

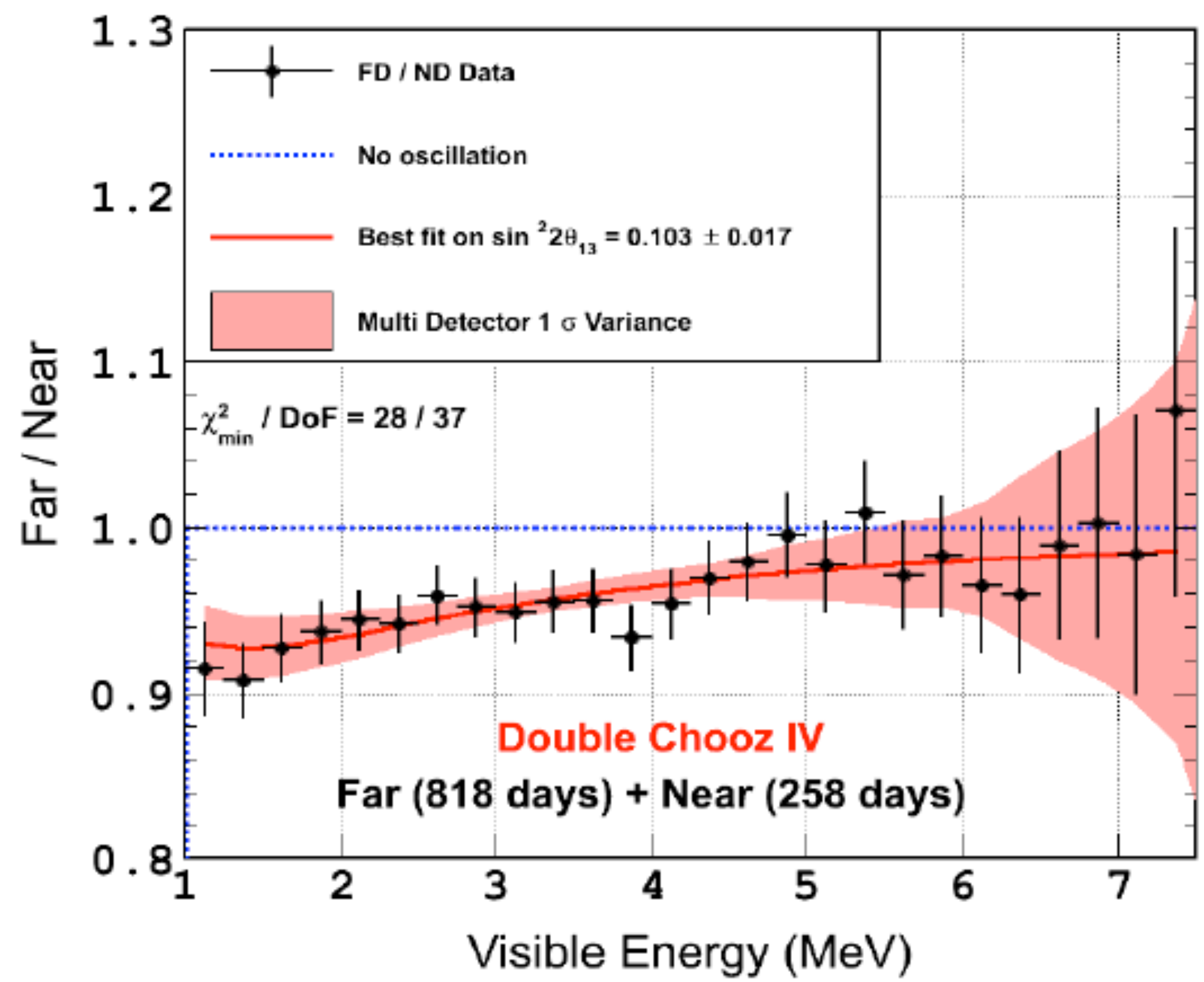


$\sin^2 2\theta_{13} = 0.0896 \pm 0.0048(\text{stat.}) \pm 0.0048(\text{syst.})$ (± 7.6%)

$|\Delta m_{ee}^2| = 2.68 \pm 0.12(\text{stat.}) \pm 0.07(\text{syst.})\ (\times 10^{-3}\ \text{eV}^2)$ (± 5.2 %) 9



arXiv:1806.00248

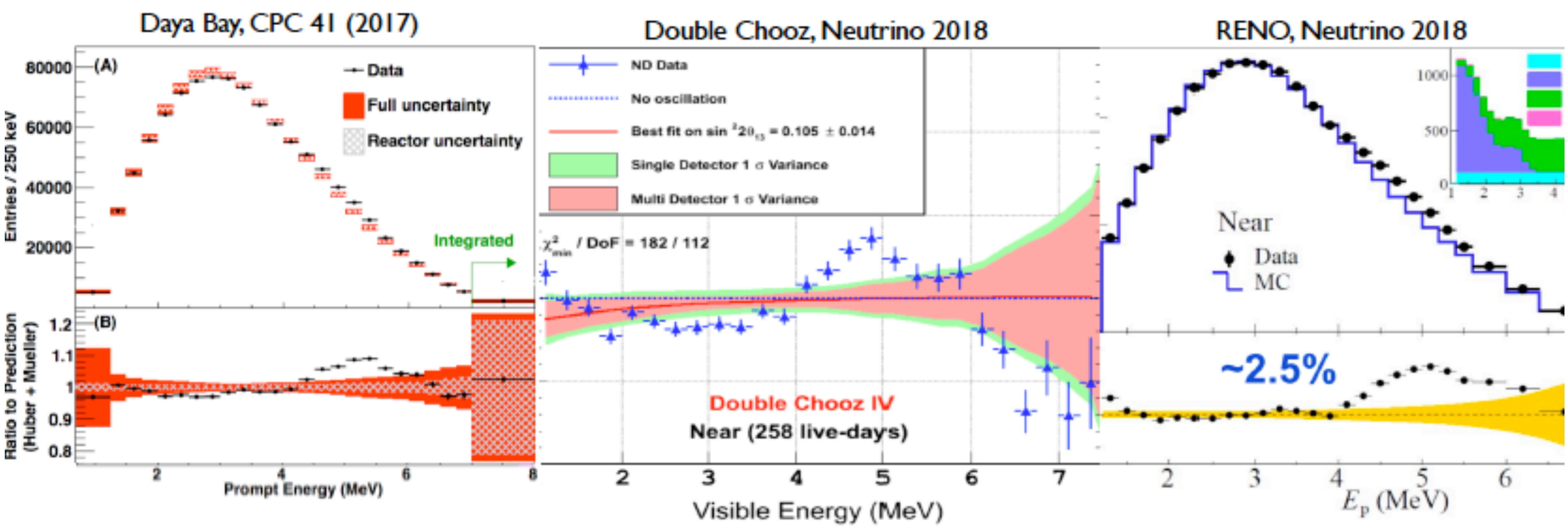


New from DC

https://zenodo.org/record/1286844#.XFxiRtF7mi4

Reactor Spectrum Anomaly

- Bad news: spectrum predictions also don't match the data.
  - Eye is first drawn to the 'bump' in the 4-6 MeV range.
  - Zooming out: kinda just looks bad generally across the entire spectrum…
- HOW is spectrum incorrectly predicted???



https://indico.ph.qmul.ac.uk/indico/getFile.py/access?contribId=15&resId=0&materialId=slides&confId=289

The future: mass ordering

Method from Petcov and Piai, Physics Letters B 553, 94-106 (2002)

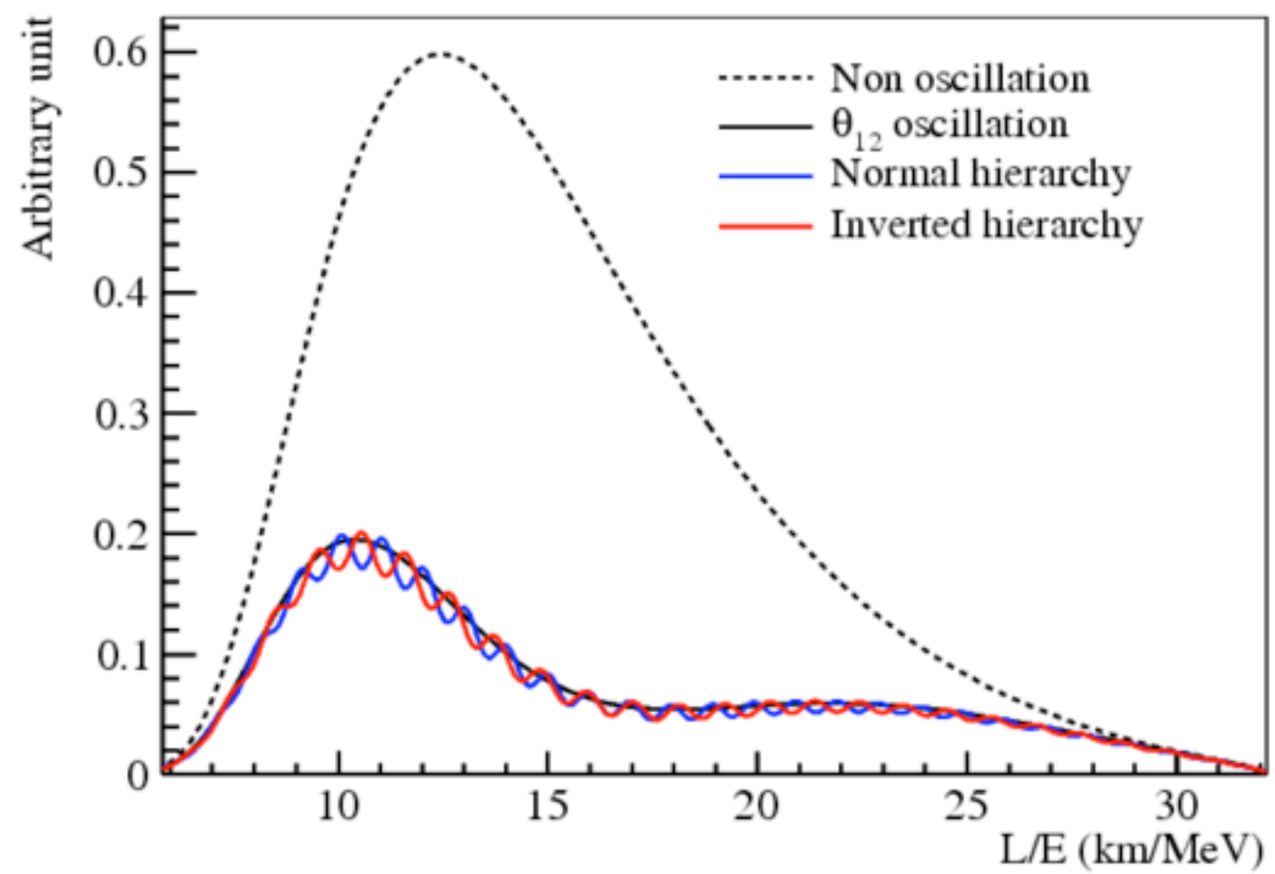
Survival probability

arXiv 1210.8141

$$P_{ee} = \left| \sum_{i=1}^{3} U_{ei} \exp\left(-i \frac{m_i^2}{2E_i}\right) U_{ei}^* \right|^2$$

$$\Delta_{ij} \equiv \frac{\Delta m_{ij}^2 L}{4E_\nu}, \quad (\Delta m_{ij}^2 \equiv m_i^2 - m_j^2)$$

$$\begin{aligned} &= 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2(\Delta_{21}) \\ &\quad - \cos^2\theta_{12}\sin^2 2\theta_{13}\sin^2(\Delta_{31}) \\ &\quad - \sin^2\theta_{12}\sin^2 2\theta_{13}\sin^2(\Delta_{32}) \end{aligned}$$



Or to make the effect of the mass hierarchy explicit, exploiting the approximation $\Delta m^2_{32} \approx \Delta m^2_{31}$:

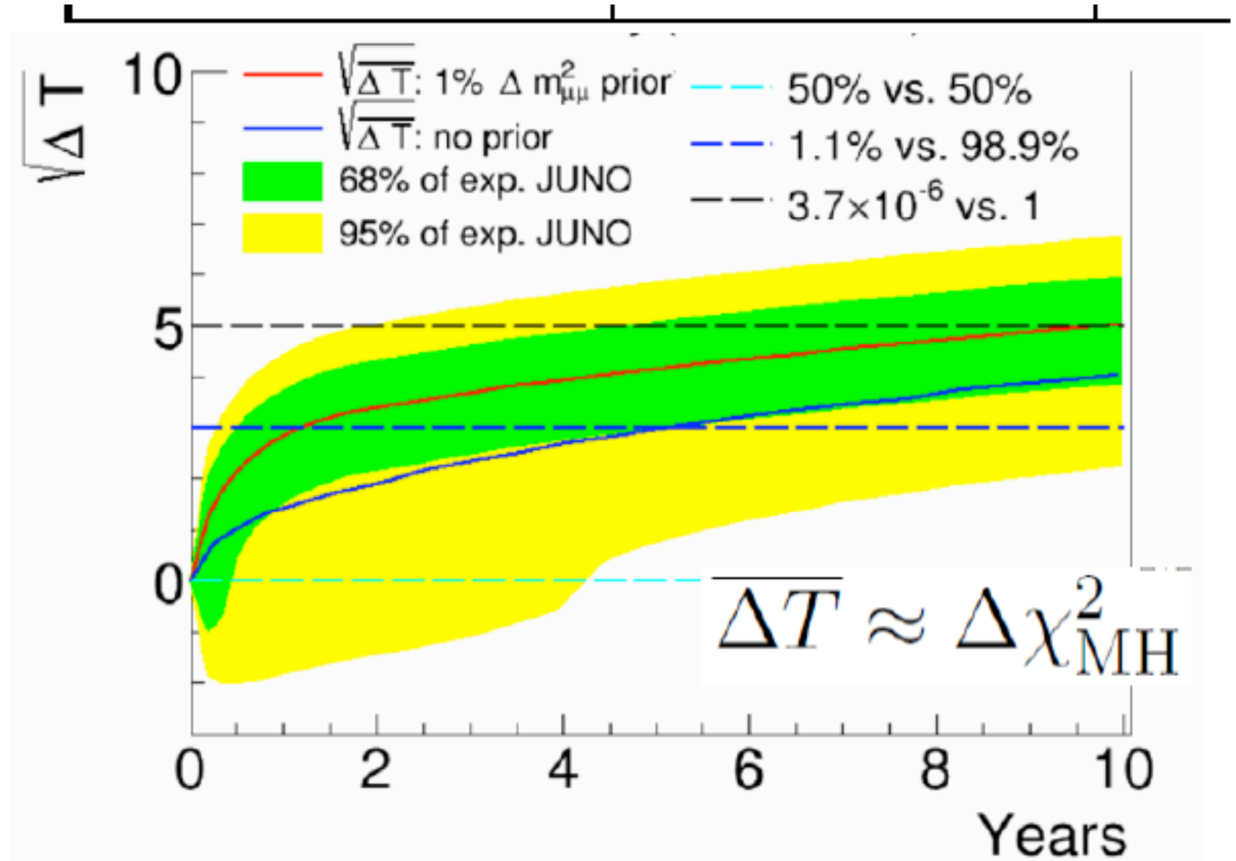
$$\begin{aligned} P_{ee} &= 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2(\Delta_{21}) \\ &\quad - \sin^2 2\theta_{13}\sin^2(|\Delta_{31}|) \\ &\quad - \sin^2\theta_{12}\sin^2 2\theta_{13}\sin^2(\Delta_{21})\cos(2|\Delta_{31}|) \\ &\quad \pm \frac{\sin^2\theta_{12}}{2}\sin^2 2\theta_{13}\sin(2\Delta_{21})\sin(2|\Delta_{31}|), \end{aligned}$$

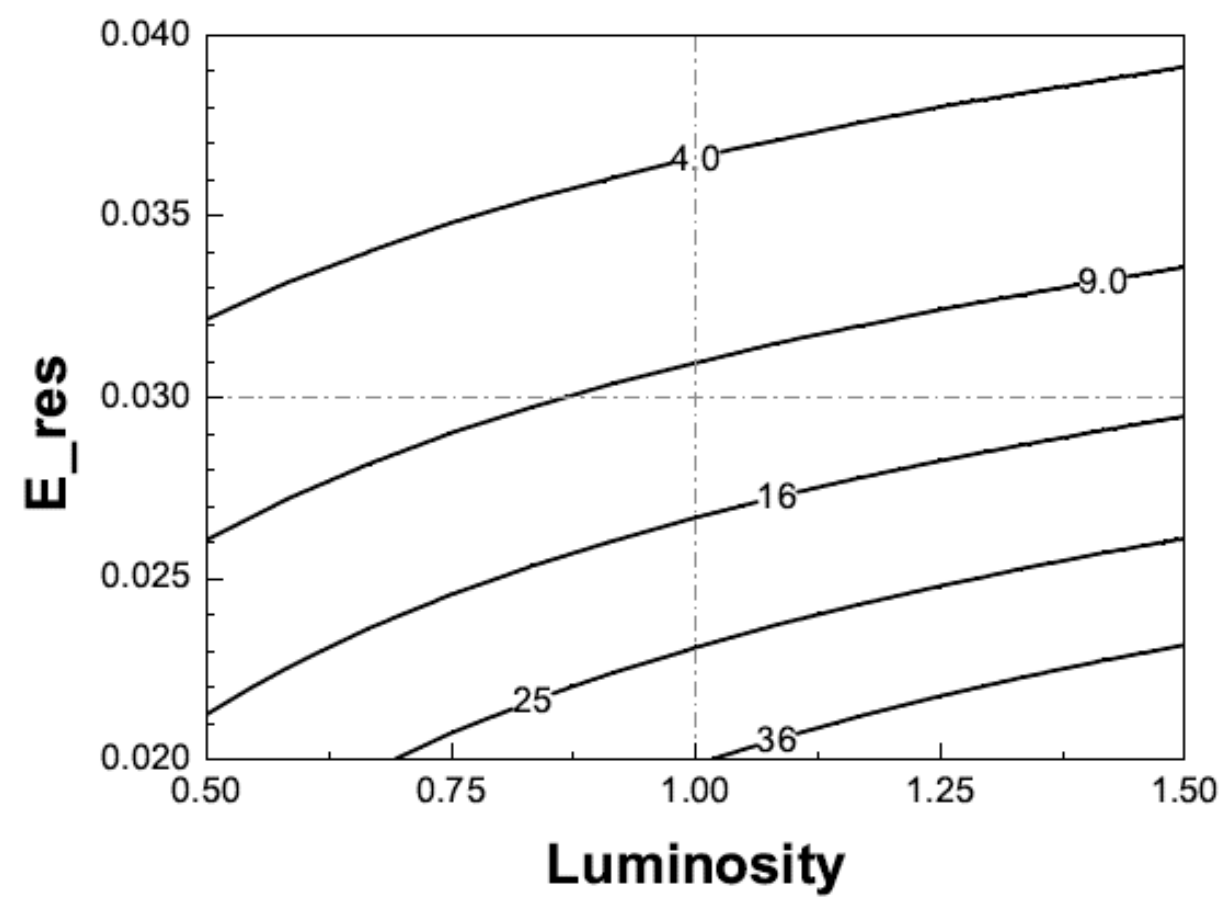
+ NH
- IH

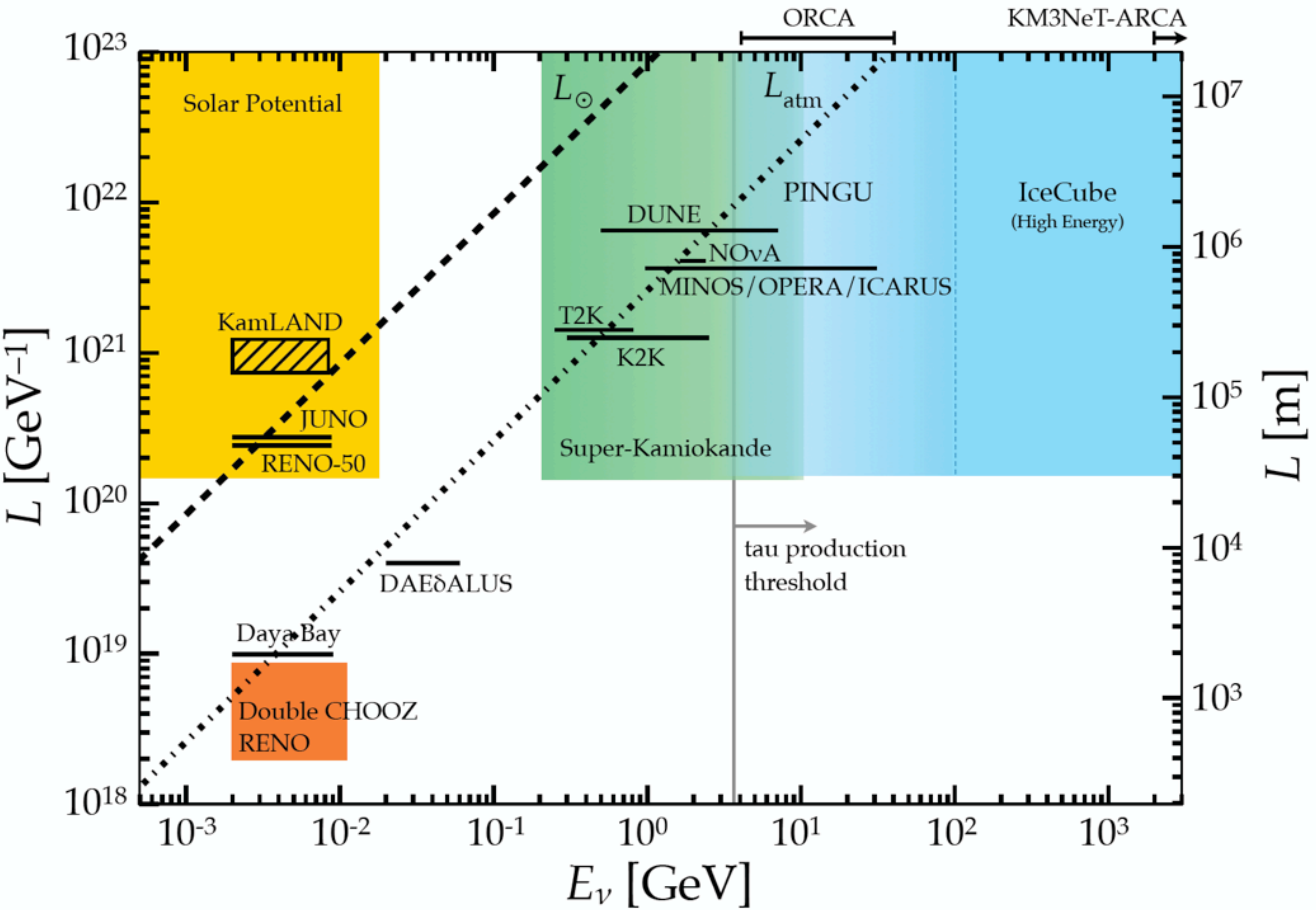
The big suppression is the "solar" oscillation → Δm^2_{21} , $\sin^2\theta_{12}$
The ripple is the "atmospheric" oscillation → $|\Delta m^2_{31}|$ from frequency
MH encoded in the phase
"high" value of θ_{13} crucial

Experiments at reactors

- JUNO in China
- Same concept as present detectors, but with a much better E_{res} to distinguish phase shifts
- Will also build ND
  - w/o a ND it could be a limit if reactor flux not nailed down to better than ~2%
- Can also do with accelerators and atmospheric, complementary







arXiv:1607.02671v1 [hep-ex] 9 Jul 2016

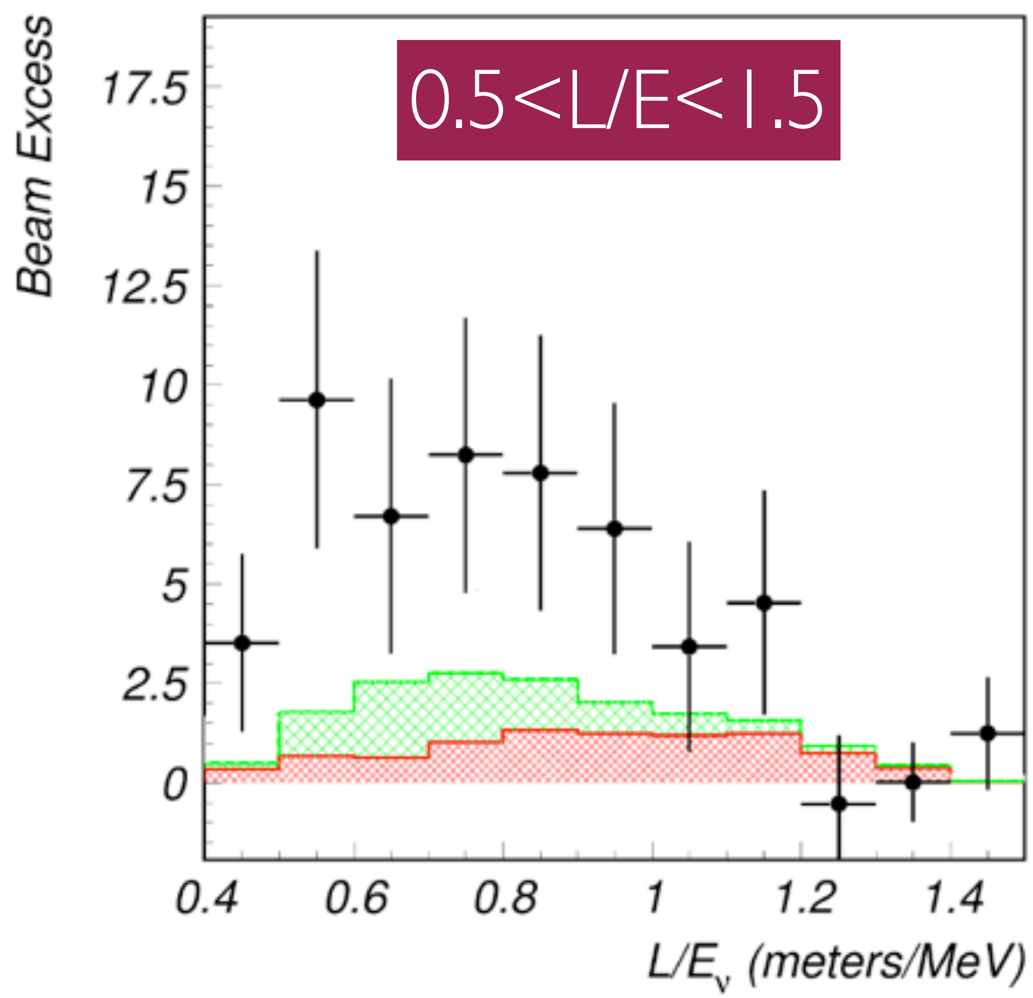
Anomalies

The past (and lingering...)

LSND

[PRL 75 (1995) 2650; PRC 54 (1996) 2685; PRL 77 (1996) 3082; PRD 64 (2001) 112007]

$\bar{\nu}_\mu \to \bar{\nu}_e \qquad 20\,\text{MeV} \le E \le 60\,\text{MeV}$



- Well-known source of $\bar{\nu}_\mu$

  μ^+ at rest $\to e^+ + \nu_e + \bar{\nu}_\mu$

  $L \simeq 30\,\text{m}$

  $\bar{\nu}_e + p \to n + e^+$

  Well-known detection process of $\bar{\nu}_e$

- $\approx 3.8\sigma$ excess

- But signal not seen by KARMEN at $L \simeq 18\,\text{m}$ with the same method

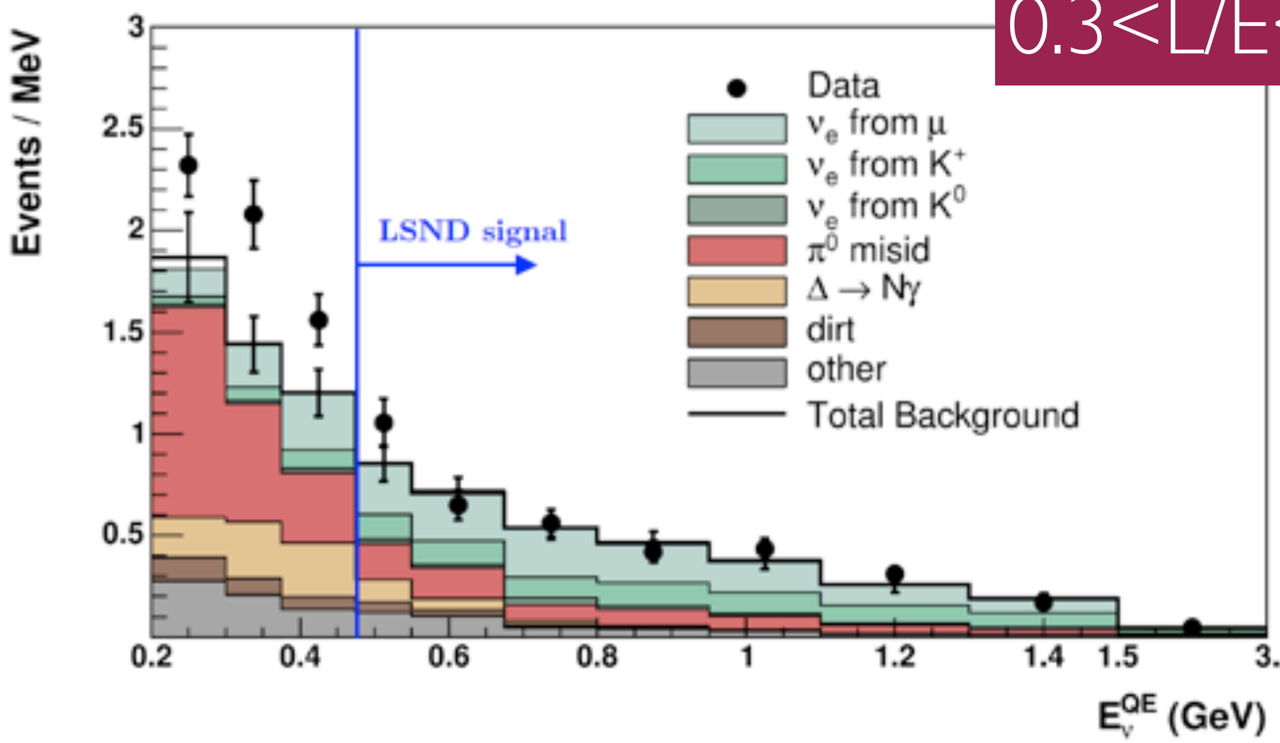
[PRD 65 (2002) 112001]

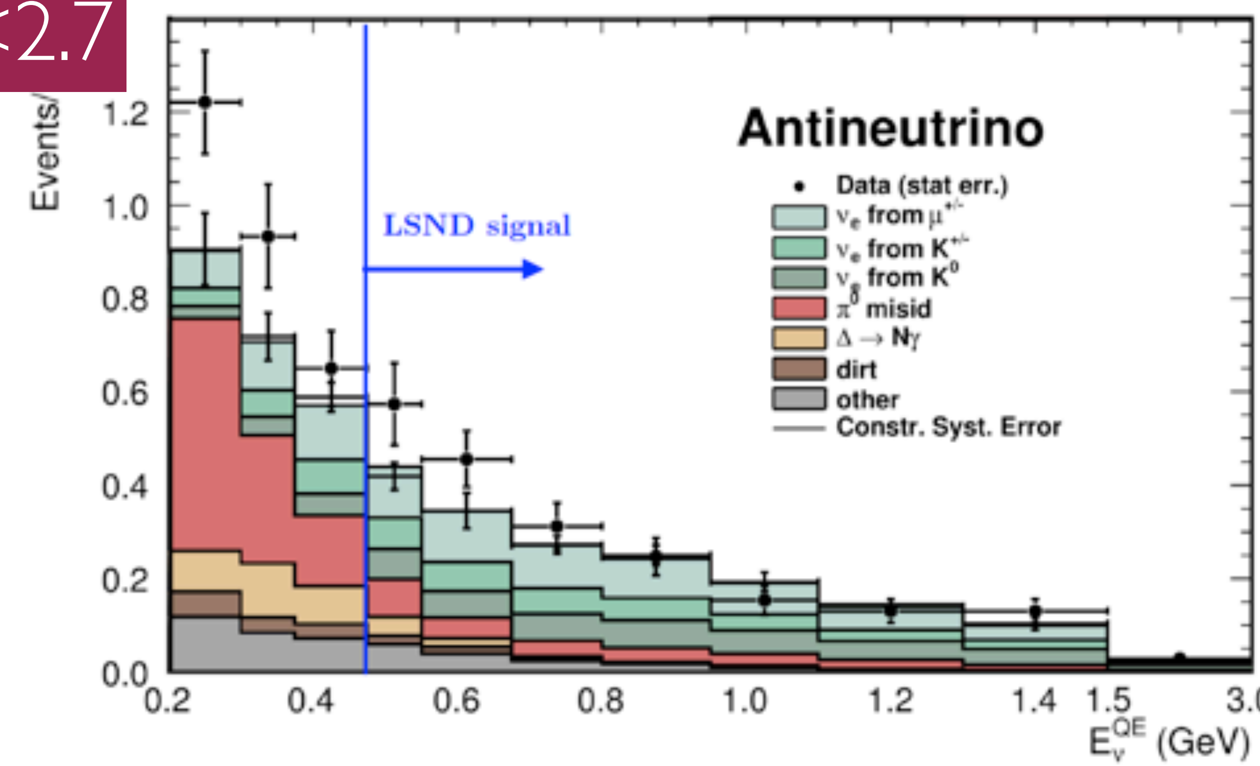
MiniBooNE

$L \simeq 541\,\text{m}$ $\qquad$ $200\,\text{MeV} \leq E \lesssim 3\,\text{GeV}$

$\nu_\mu \to \nu_e$ [PRL 102 (2009) 101802] $\qquad$ $\bar{\nu}_\mu \to \bar{\nu}_e$ [PRL 110 (2013) 161801]

0.3<L/E<2.7





- Purpose: check LSND signal.
- Different L and E.
- Similar L/E (oscillations).
- No money, no Near Detector.
- LSND signal: $E > 475\,\text{MeV}$.
- Agreement with LSND signal?
- CP violation?
- Low-energy anomaly!

MiniBooNE

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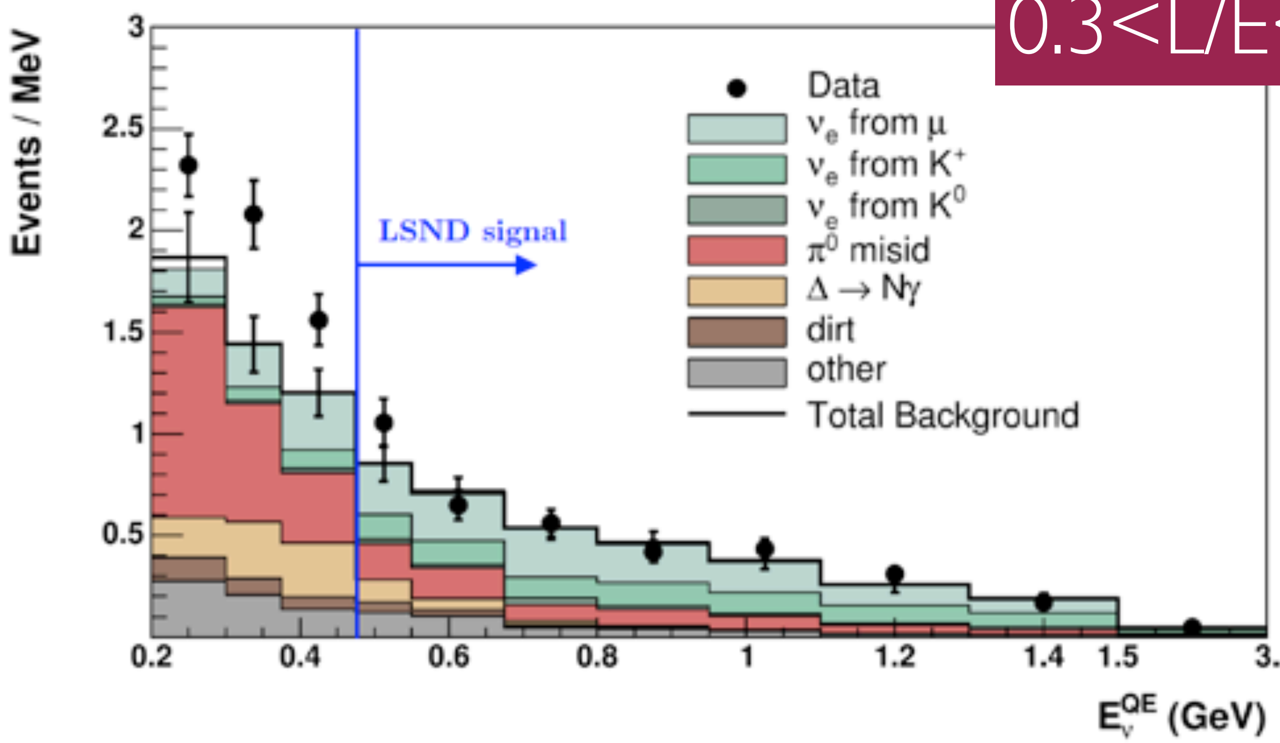

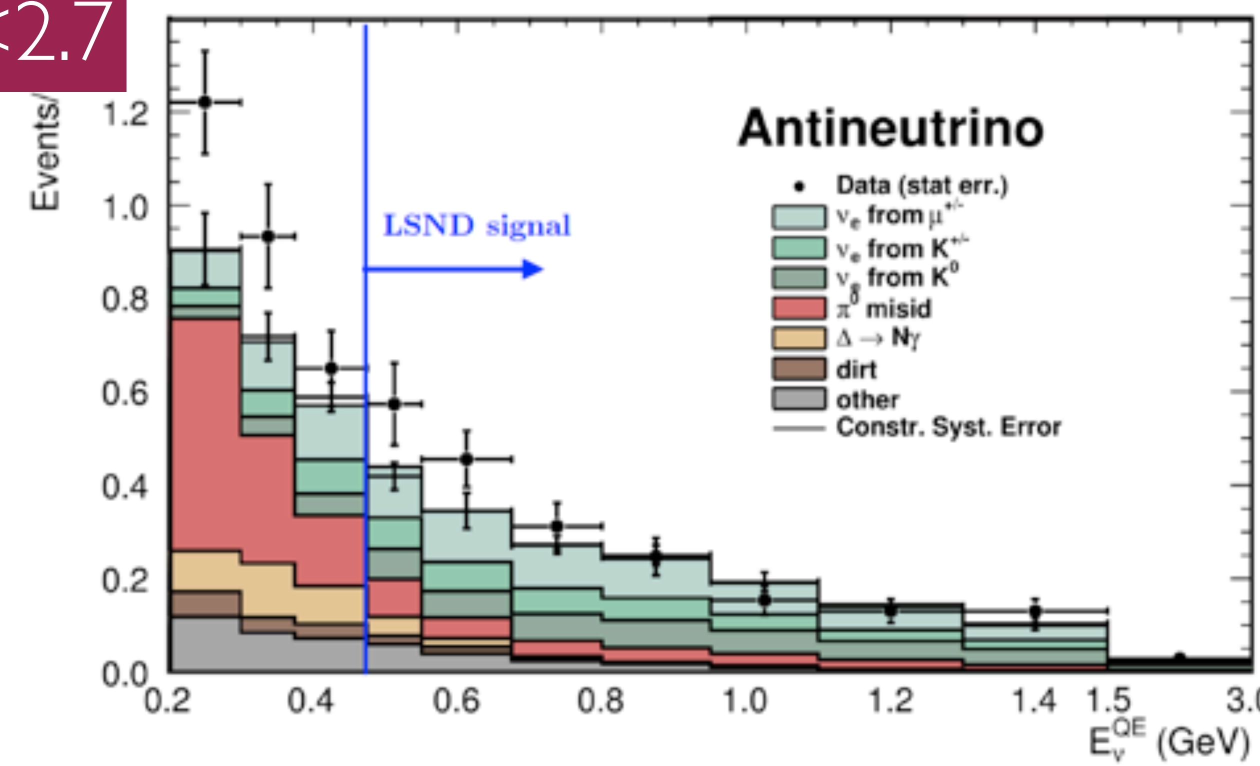

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- CP violation?
- Low-energy anomaly!

could it be bkgs?

Caveats from HARP (@CERN PS)

- The claim of a 3.8 σ significance of the LSND anomaly cannot be upheld
- LSND didn't take into account pion production by neutrons
- Improved simulation of the LSND beam stop shows that conventional background increases by a factor of 1.6
- Positrons from $^{12}N_{gs}$ beta decay were missed in LSND analysis
- We find significance of the "LSND anomaly" not large than 2.3 σ

	LSND published	This paper's analysis
'Beam excess'	117.9 ± 22.4	115.6 ± 27.9
Background I	19.5 ± 3.9	30.6 ± 8.8
Background II	10.5 ± 4.6	13.8 ± 8.2
'LSND anomaly'	87.9 ± 23.2	71.2 ± 30.4
Significance	$3.8\ \sigma$	$2.3\ \sigma$

See: https://hep.uchicago.edu/~elagin/HARP-CDP_vs_LSND/Elagin_UChicago_Lunch_on_LSND_excess.pdf

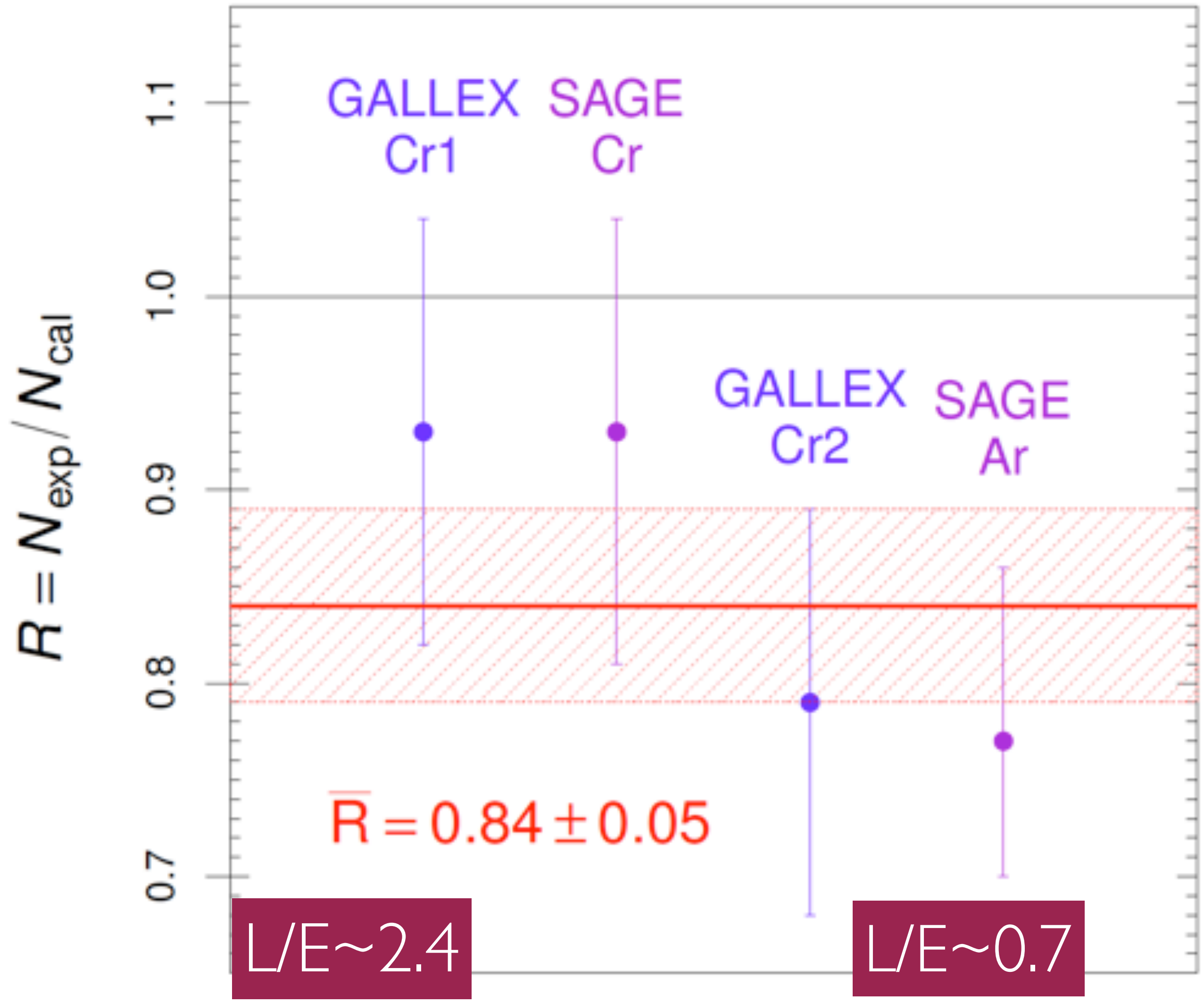
Gallium Anomaly

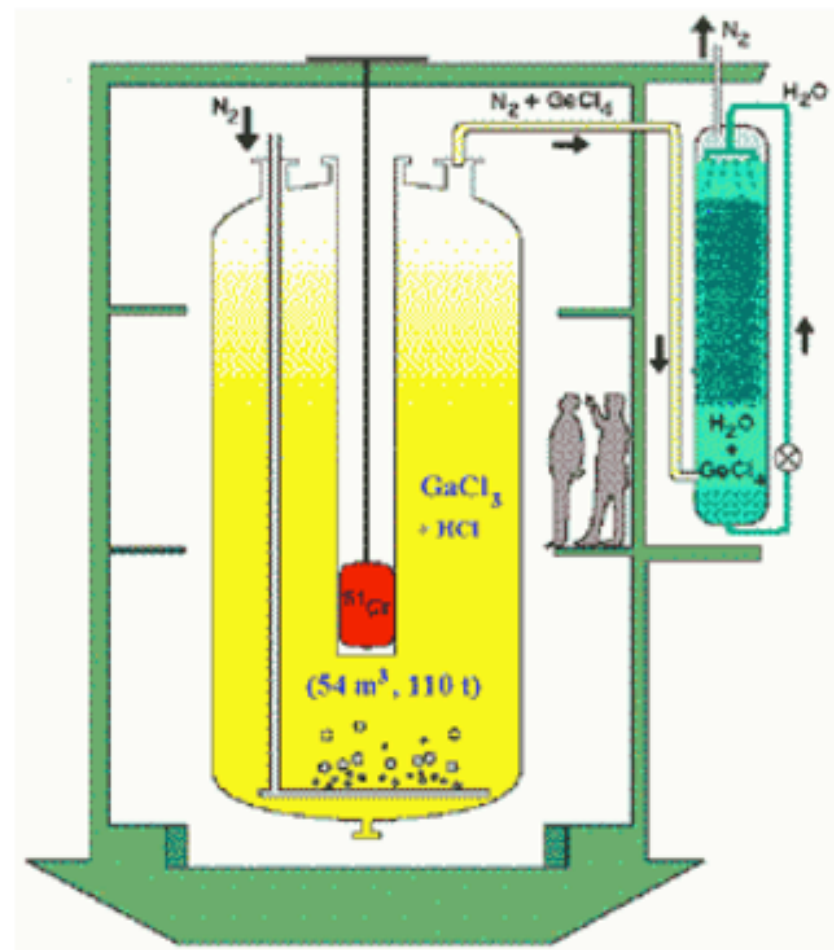
Gallium Radioactive Source Experiments: GALLEX and SAGE

ν_e Sources: $e^- + {}^{51}\text{Cr} \to {}^{51}\text{V} + \nu_e$ $\quad$ $e^- + {}^{37}\text{Ar} \to {}^{37}\text{Cl} + \nu_e$

$E \simeq 0.75\,\text{MeV}$ $\quad$ $E \simeq 0.81\,\text{MeV}$

Test of Solar ν_e Detection: $\nu_e + {}^{71}\text{Ga} \to {}^{71}\text{Ge} + e^-$





$\approx 2.9\sigma$ deficit

$\langle L \rangle_{\text{GALLEX}} = 1.9\,\text{m}$ $\quad$ $\langle L \rangle_{\text{SAGE}} = 0.6\,\text{m}$

[SAGE, PRC 73 (2006) 045805; PRC 80 (2009) 015807; Laveder et al, Nucl.Phys.Proc.Suppl. 168 (2007) 344, MPLA 22 (2007) 2499, PRD 78 (2008) 073009, PRC 83 (2011) 065504]

$\Delta m^2_{\text{SBL}} \gtrsim 1\,\text{eV}^2 \gg \Delta m^2_{\text{ATM}} \gg \Delta m^2_{\text{SOL}}$

Why $\Delta M^2 > 1$ eV?

LSND

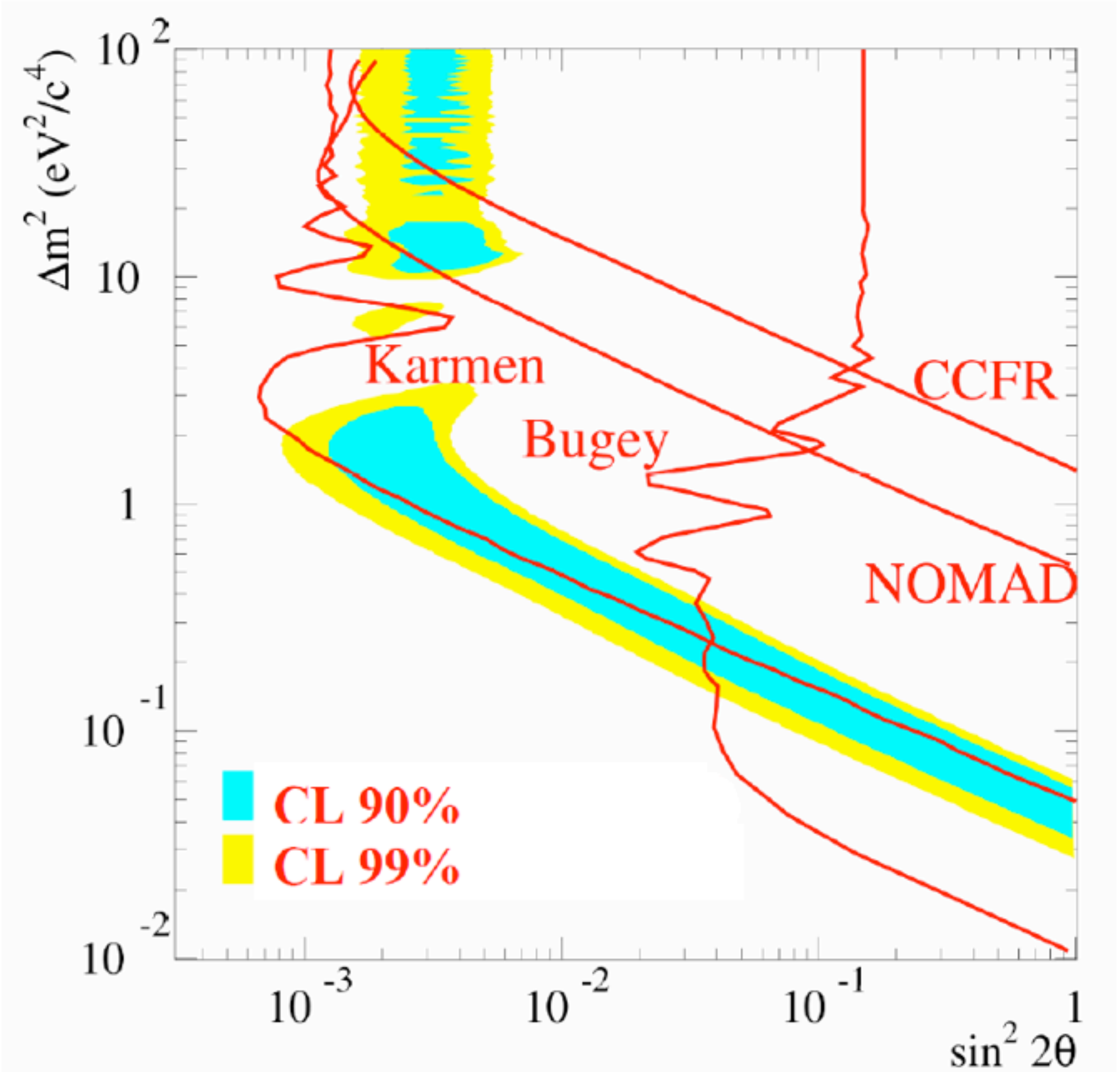
- **1993-1994 data: 16.4 (+9.7 - 8.9) ± 3.3**

  (alternative analysis by J.E. Hill do not find any excess PRL 75, 2654)
- **1993-1995 data: 51.0 (+20.2 – 19.5)**
- **Full dataset: 87.9± 22.4± 6.**

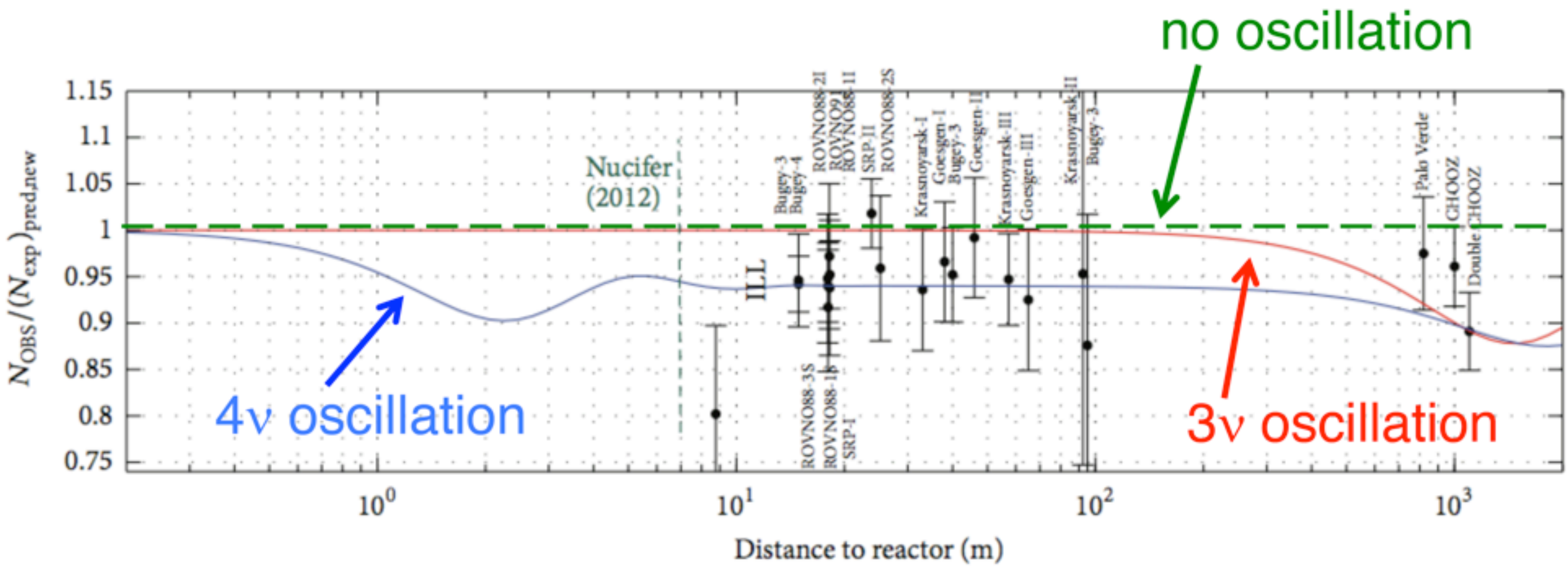
  $\Delta m^2 > 0.02$ eV^2.
- **BNL-E776, CCFR, NuTeV and NOMAD**

  exclude $\Delta m^2 > 10$ eV^2.
- **Bugey and CHOOZ ruled out**

  $\Delta m^2 < 0.2$ eV^2.
- **KARMEN2 $\Delta m^2 < 1$ eV^2 or $\Delta m^2 \sim 7$ eV^2.**



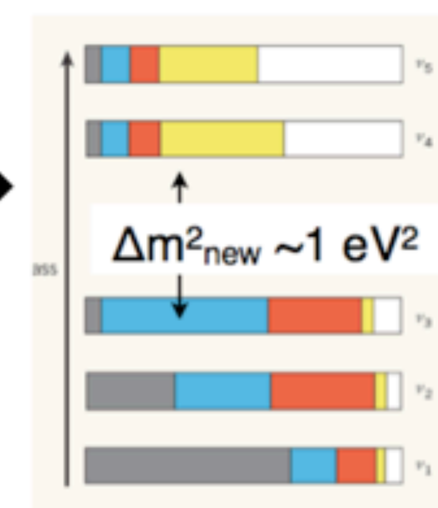
Surprise 1: The Reactor Anomaly



➔ an extra (sterile) neutrino with a small mixing angle and a mass O(eV) or heavier could have oscillated @ 10-100m

averaged out: reduction by ½ * $\sin^2(\theta_s) \simeq 0.06$

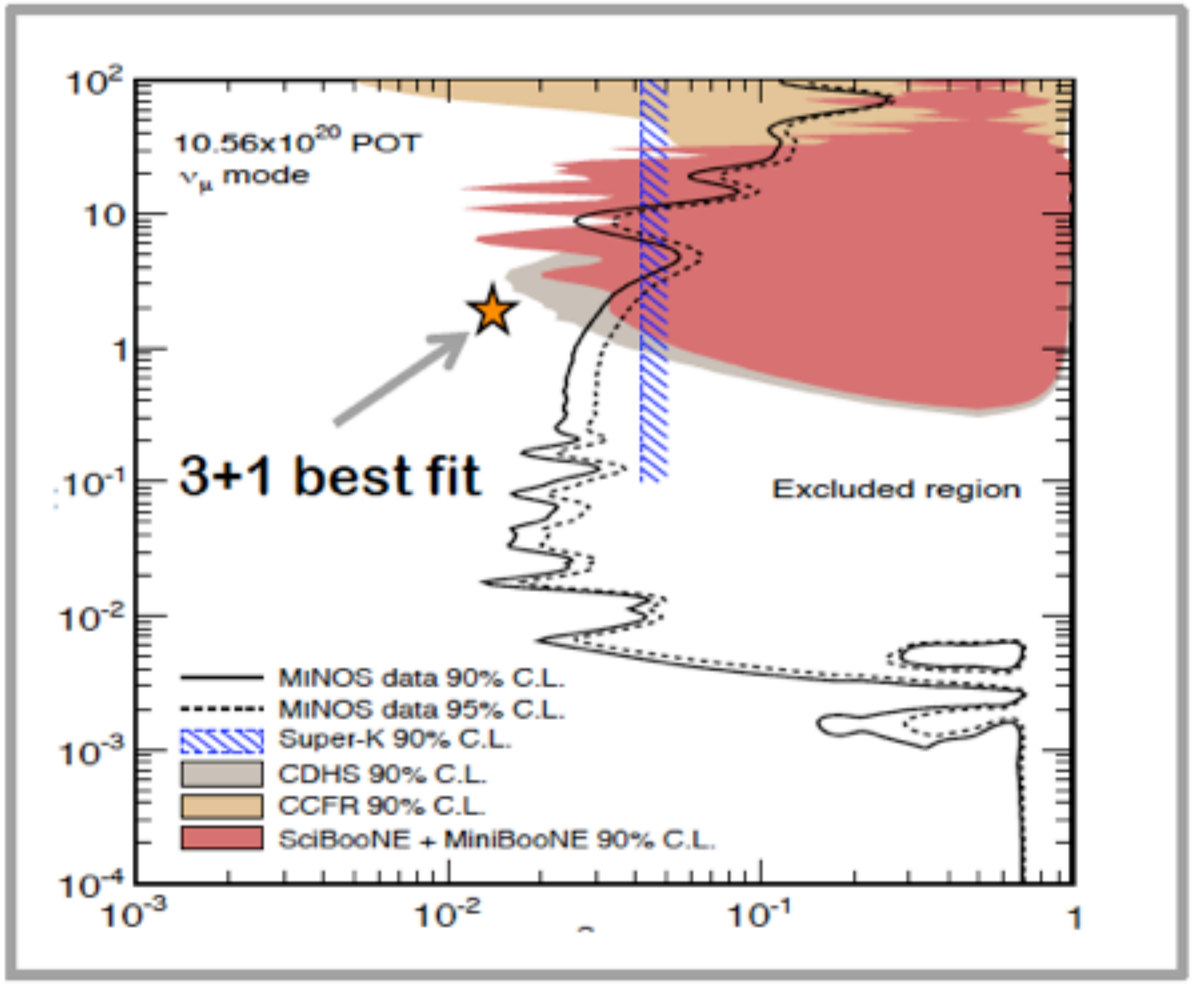
⟵➔ active ν-unitarity tested @ few % ➔ consistent ➔



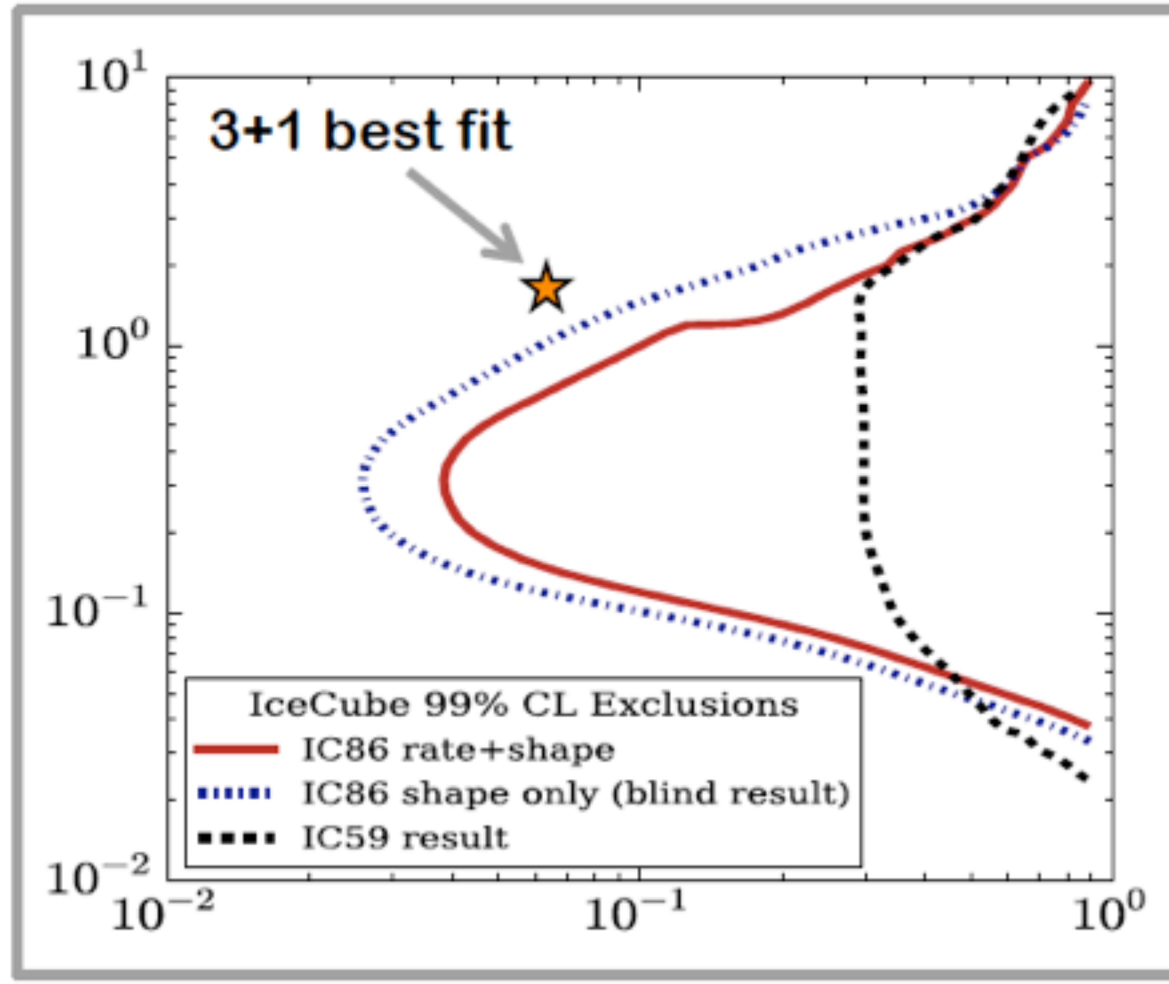
➔ check with a new experiment at shorter baseline

No anomaly in ν_μ disappearance

SBL & MINOS (NC)



IceCube

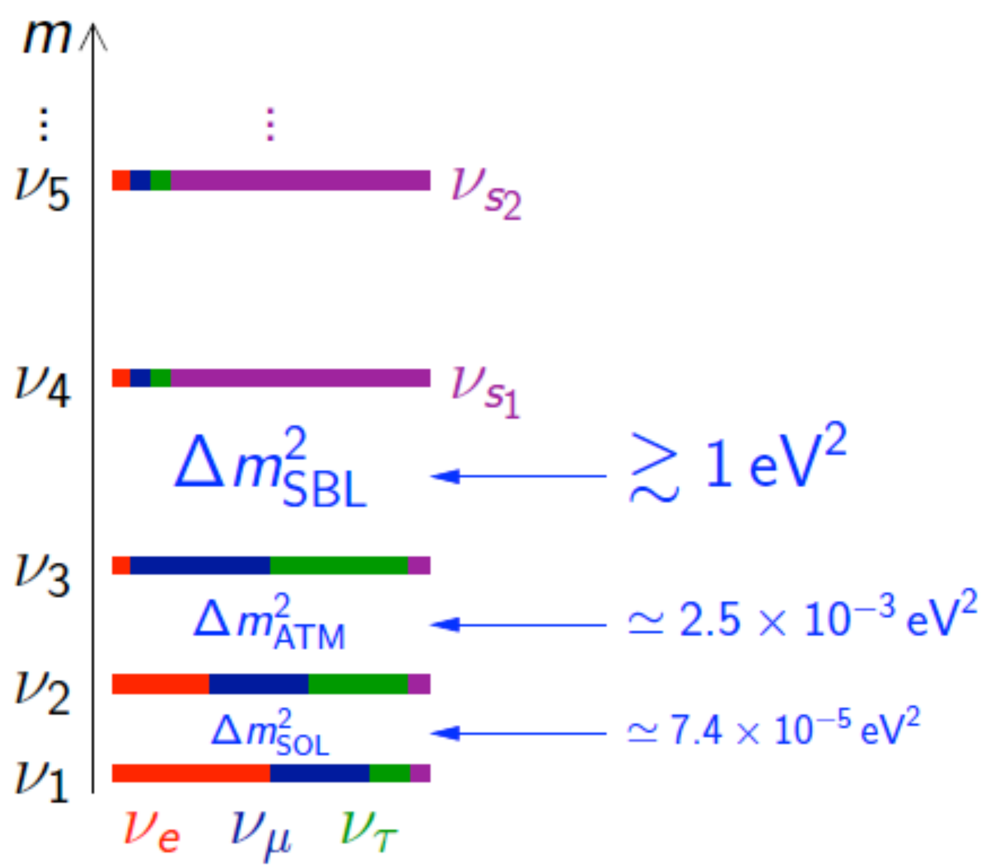


Δm^2

$\sin^2\theta_{\mu\mu}$ $\sin^2 2\theta_{\mu\mu}$

A thorn in the side of sterile neutrinos …

Beyond Three-Neutrino Mixing: Sterile Neutrinos



Anomalies caused by mixing in 4th family with a Δm^2 of the "good" range?

Terminology: a eV-scale sterile neutrino
means: a eV-scale massive neutrino which is mainly sterile

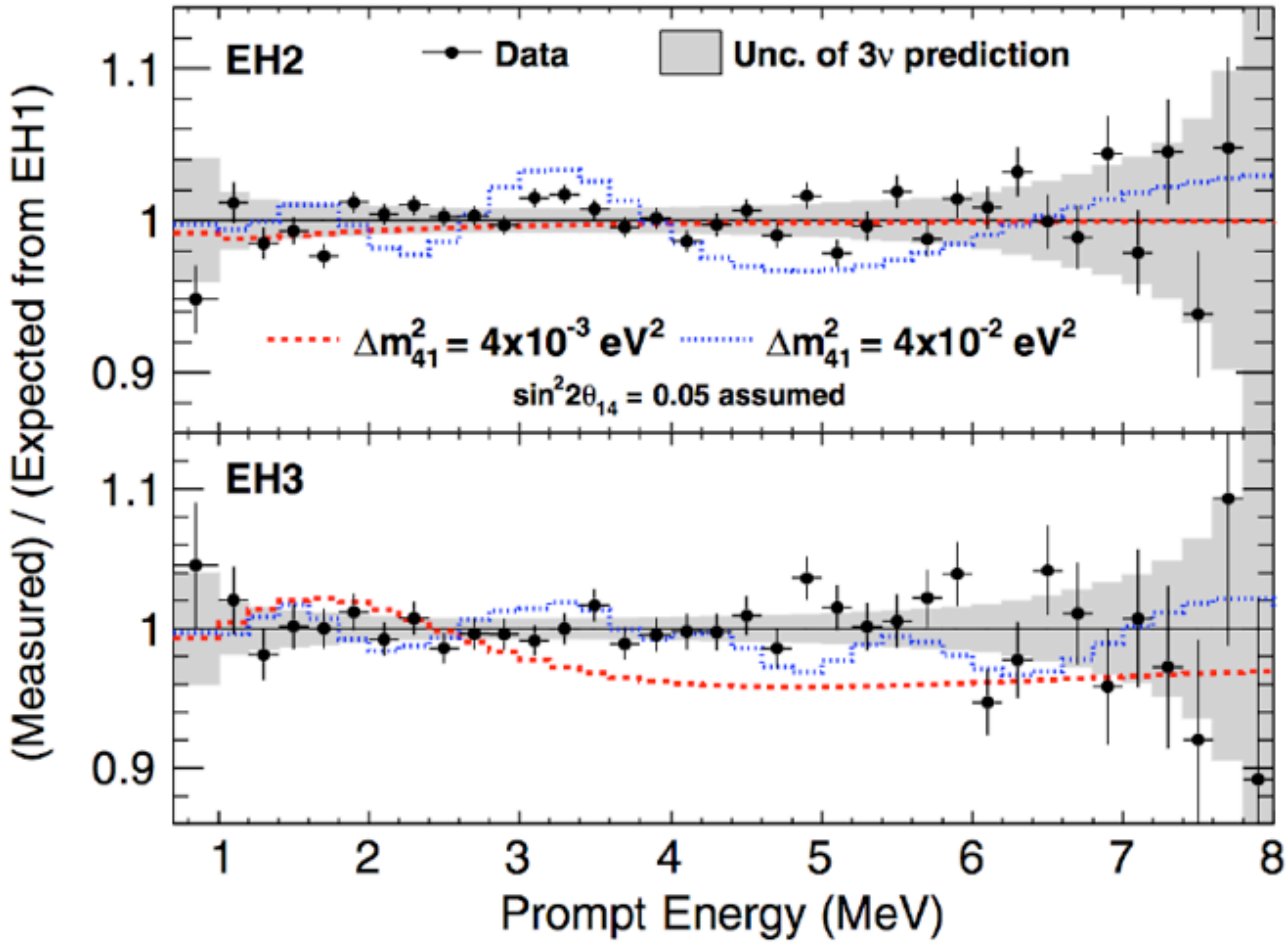
- Indications that would have to be a light sterile neutrino, if at all, to reconcile with app/disapp data
- See more here: https://agenda.infn.it/getFile.py/access?contribId=3&resId=0&materialId=slides&confId=12099

Sterile Neutrino Search at Daya Bay

- Daya Bay's high-statistics dataset can be used to search if there is room for a fourth neutrino:

To first order, signal would appear as an **additional spectral distortion** with a frequency different from standard 3-neutrino oscillations

Daya Bay's multiple baselines are a **big advantage** here: EH1 (~350m), EH2 (~500m), EH3 (~1600m)



– The issue however is that Daya Bay's results alone are **not directly comparable** to those of LSND & MiniBooNE:

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

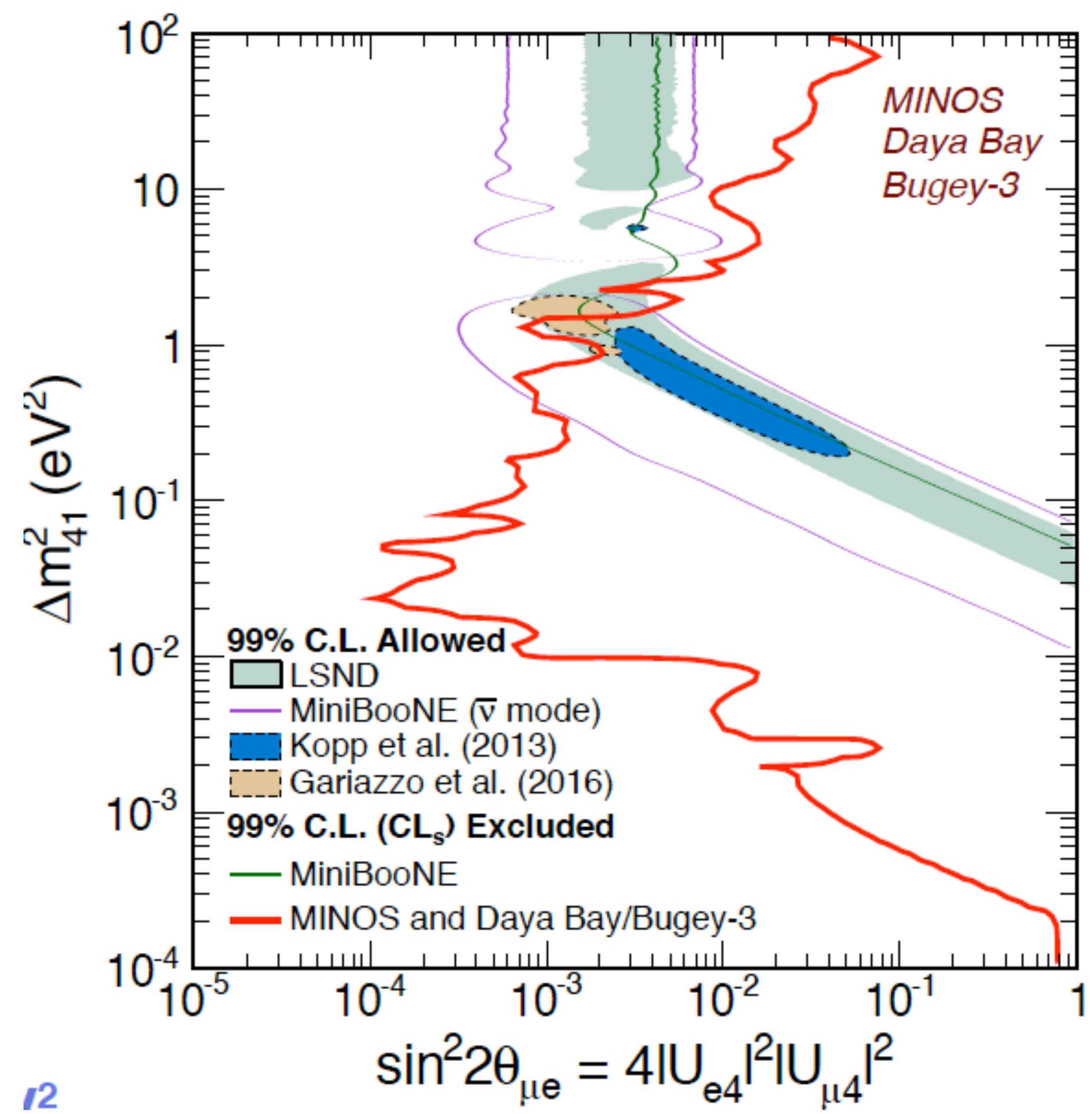
Daya Bay is sensitive to $|U_{e4}|^2 = \sin^2\theta_{14}$.

But LSND & MiniBooNE are sensitive to $|U_{e4}|^2 |U_{\mu 4}|^2$

$$P_{\nu_\mu \to \nu_e}(L/E) \approx 4|U_{e4}|^2|U_{\mu 4}|^2 \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

where $4|U_{e4}|^2 |U_{\mu 4}|^2 = \sin^2 2\theta_{14} \sin^2\theta_{24} = \sin^2 2\theta_{\mu e}$

38



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

2

Surprise 2: A Bump in the Spectrum

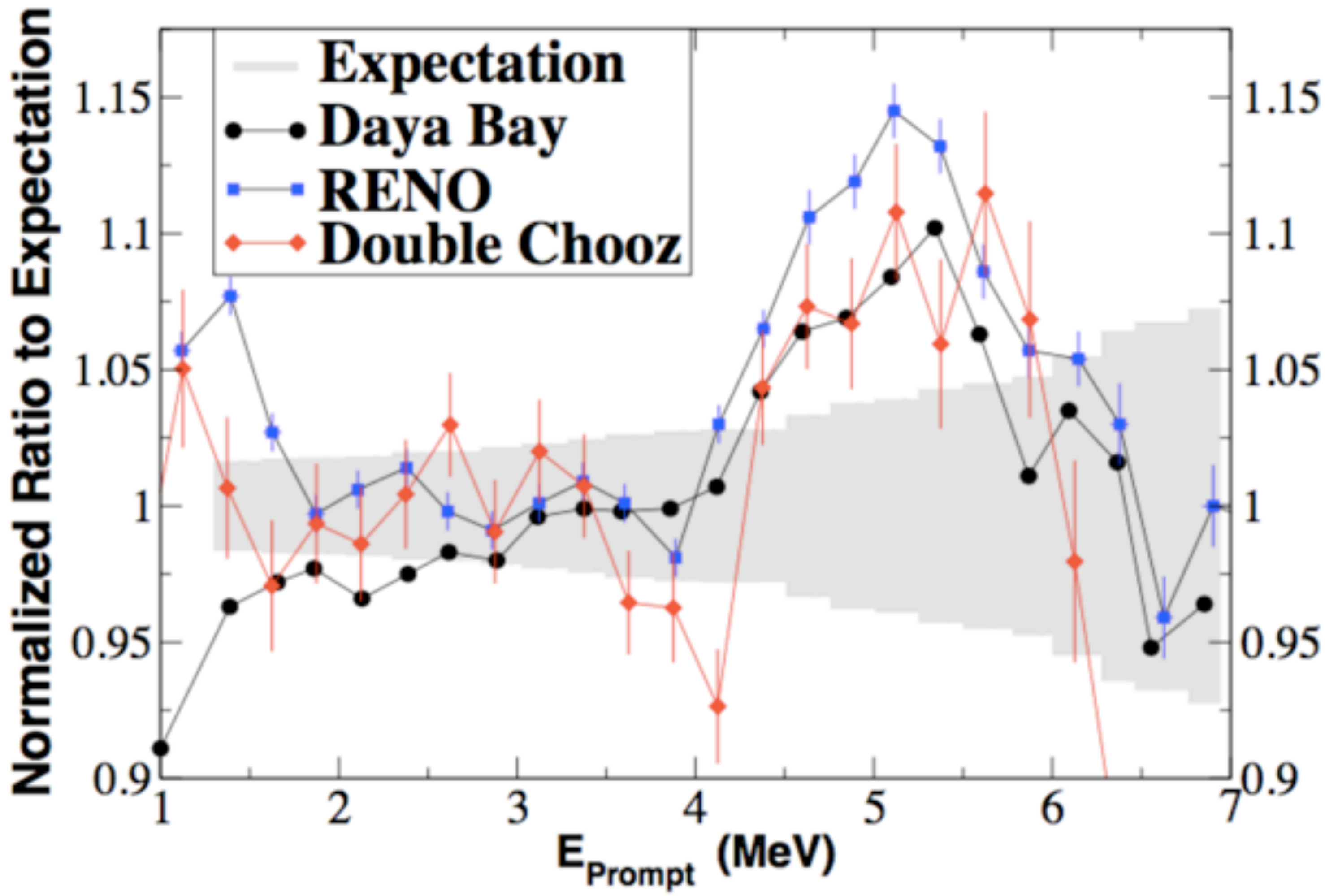
Double Chooz, RENO and Daya Bay:

→ all see unexpected bump in near and far spectrum

→ θ_{13} measurement robust

→ expectations are Huber (235U,239,241Pu) and Mueller (238U)

→ RENO has largest bump



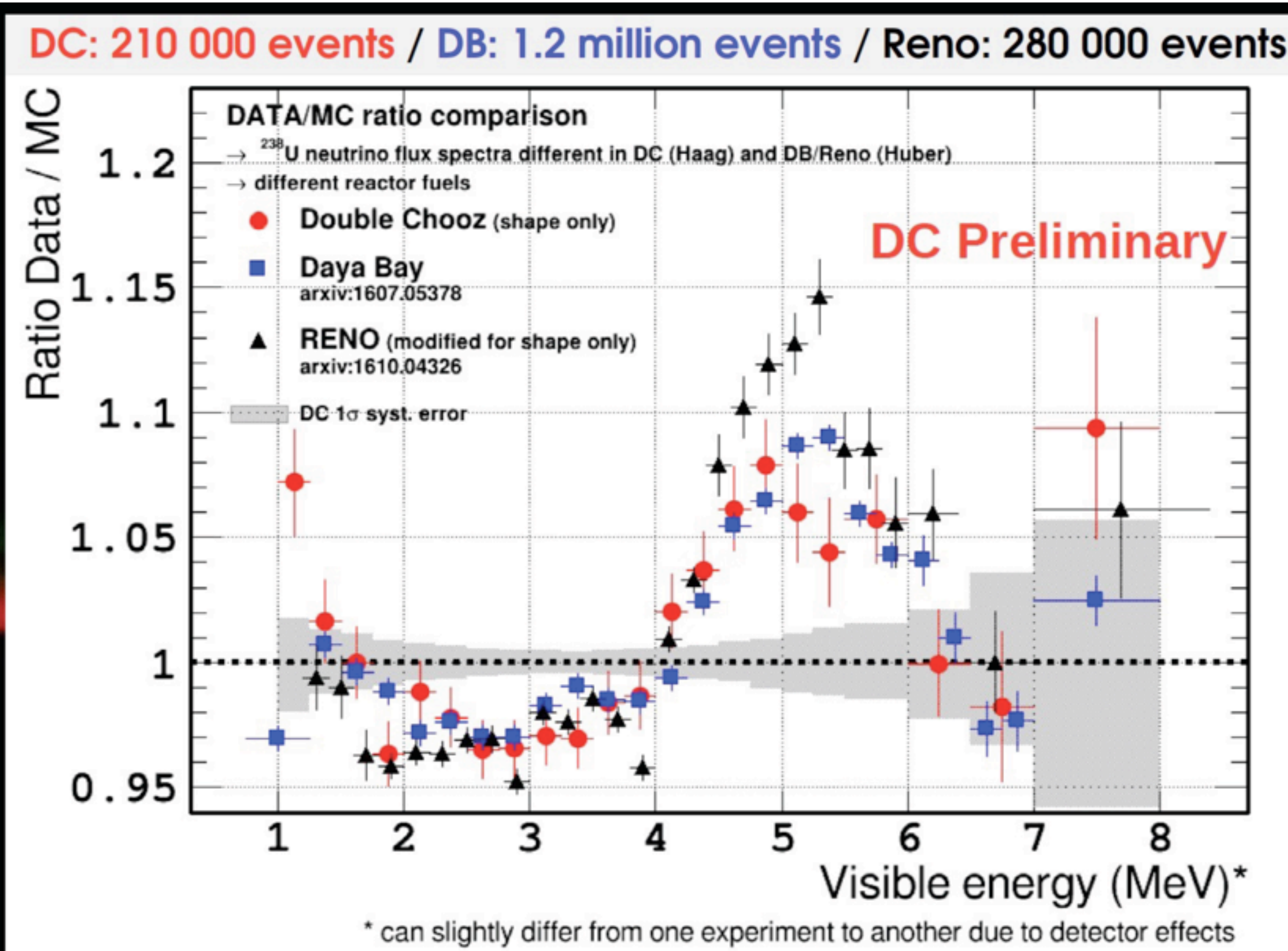
→ Double-Chooz used Huber and Haag (238U) for expected flux

High energy ν's ←→ short lived isotopes …little known

Nuclear theory:

theory errors …maybe explainable…

better ➔ experimental test

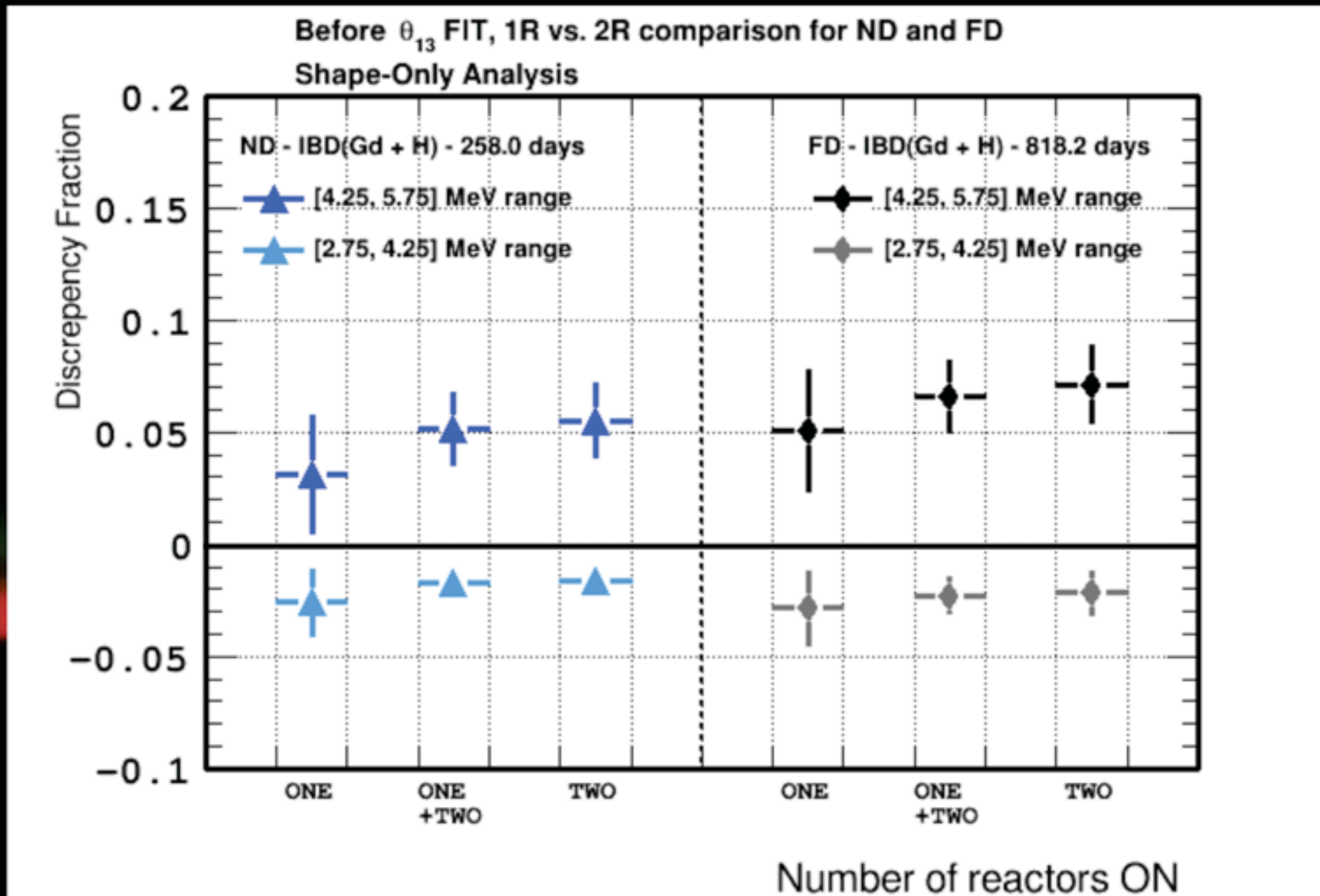


remarkable DYB≈DC (while different ^{238}U treatment)

non-trivial agreement: different BG, response, etc (all corrected)

Anatael Cabrera (CNRS-IN2P3 & APC)

clear features scaling with reactor..



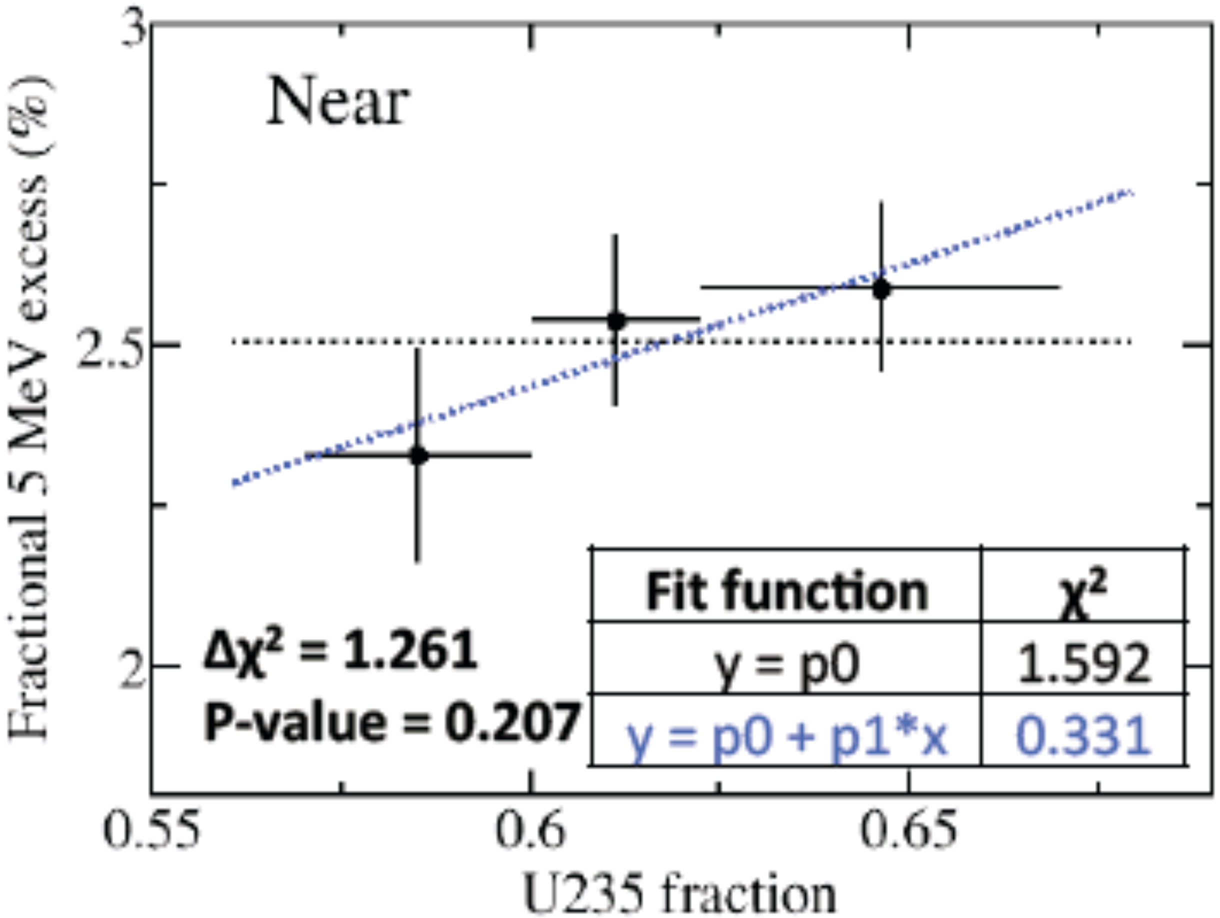
consistent with our observations in 2014
@JHEP 1410 (2014) 086 (only FD)

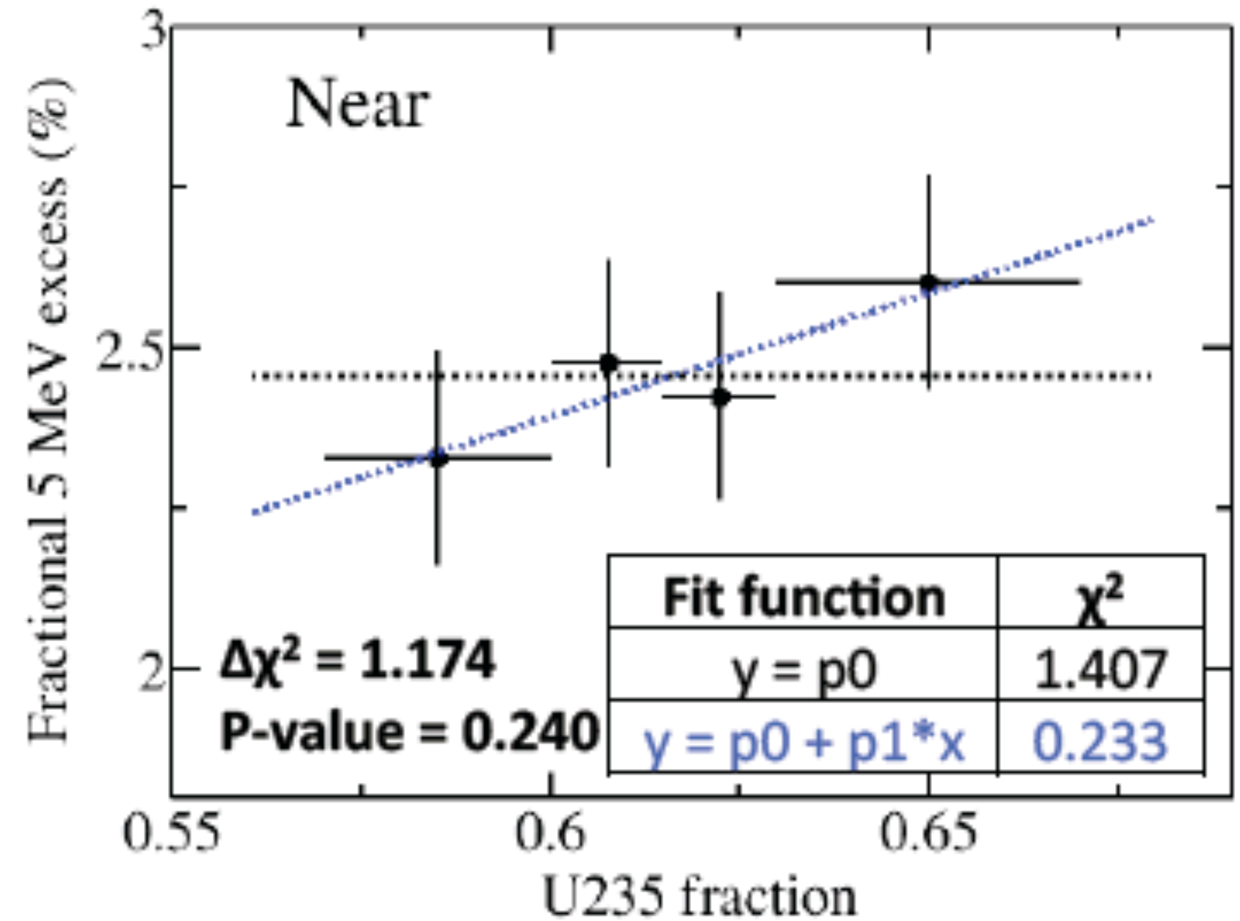
features scaling fractionally constant with reactor#
(i.e. reactor power)

- "deficit"? [2,4]MeV
- "excess"? [4,5]MeV

Reno

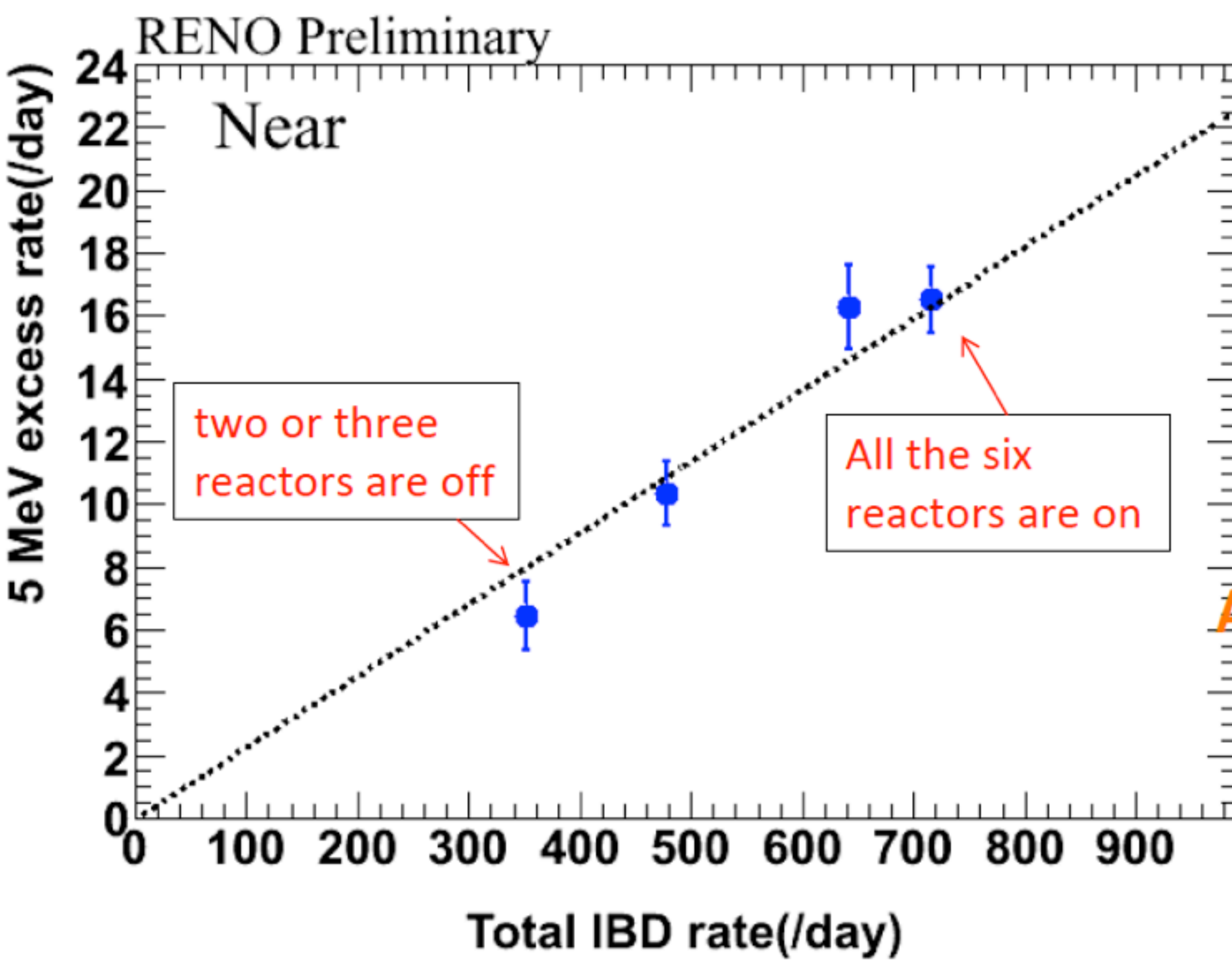
Correlation of 5 MeV excess with ^{235}U fraction





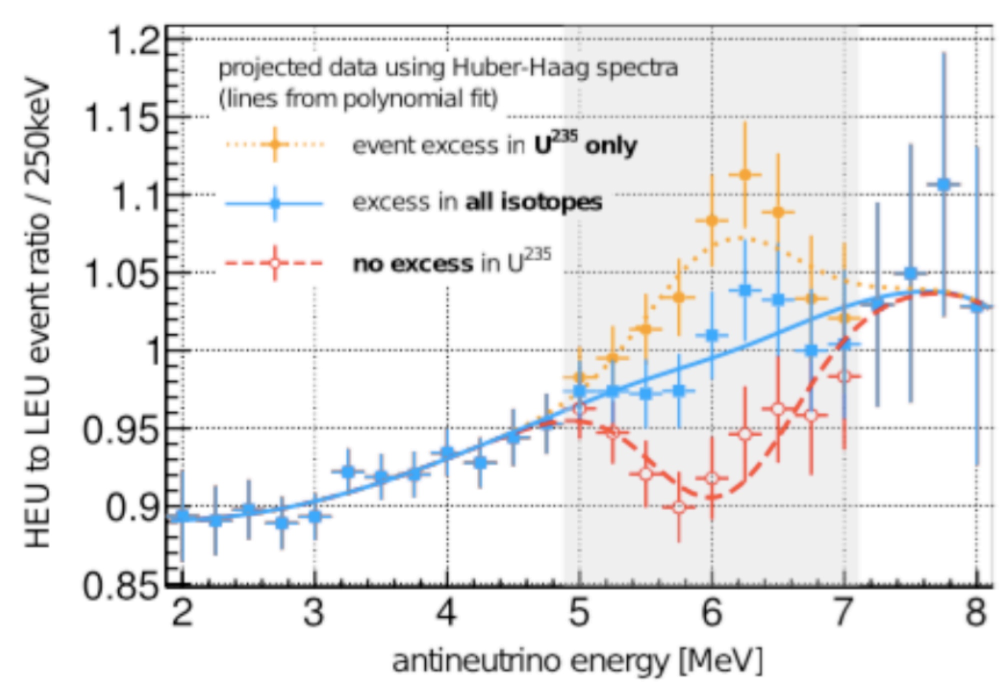
Excess seems correlated with reactor flux

Correlation of 5 MeV Excess with Reactor Power



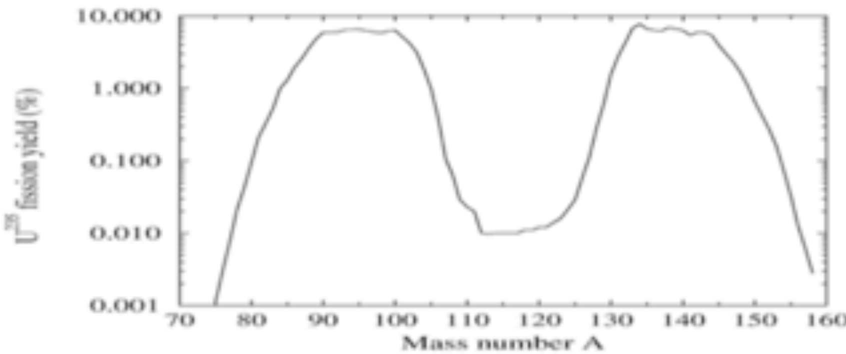
5 MeV excess has a clear correlation with reactor thermal power !

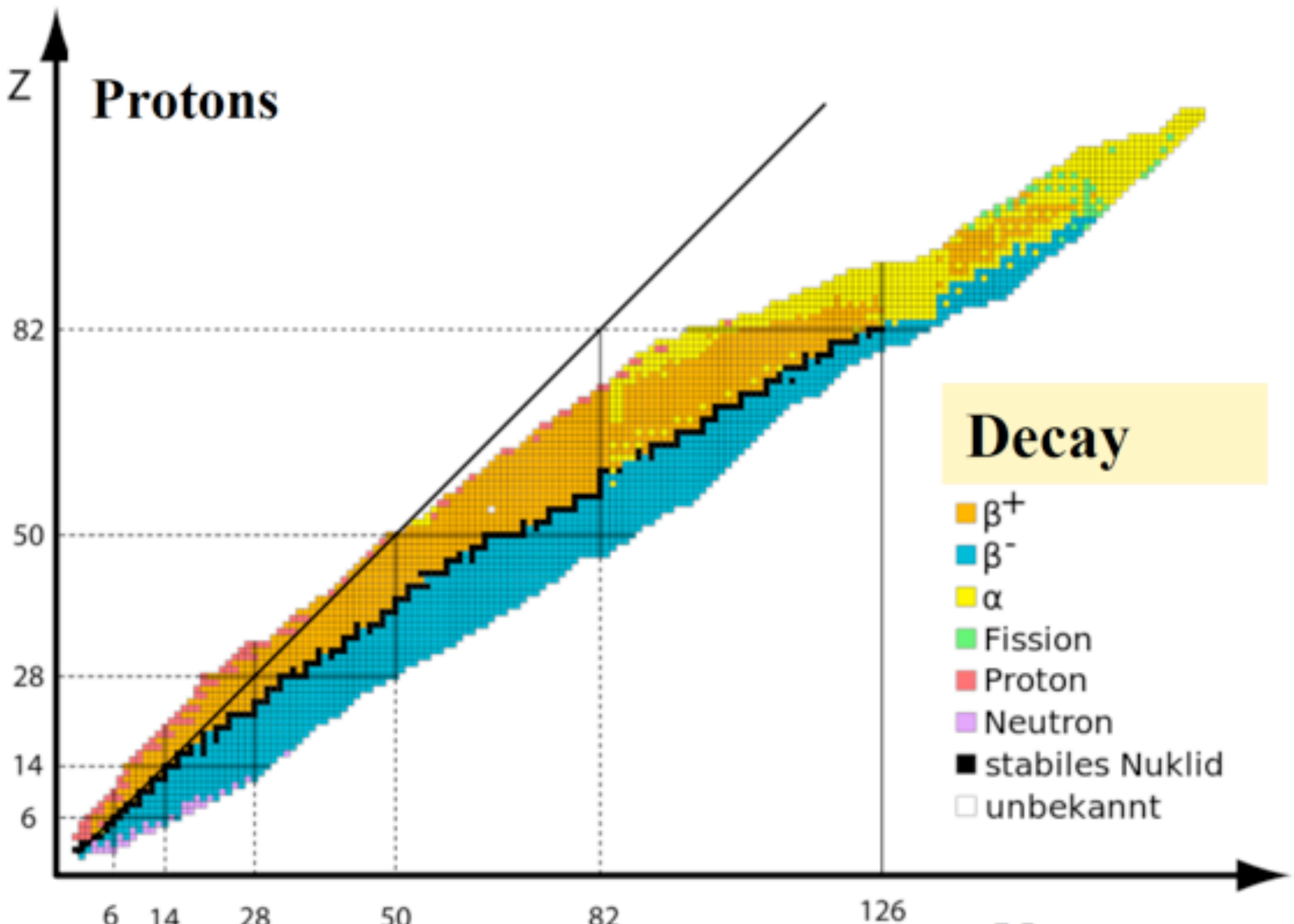
A new reactor neutrino component !!

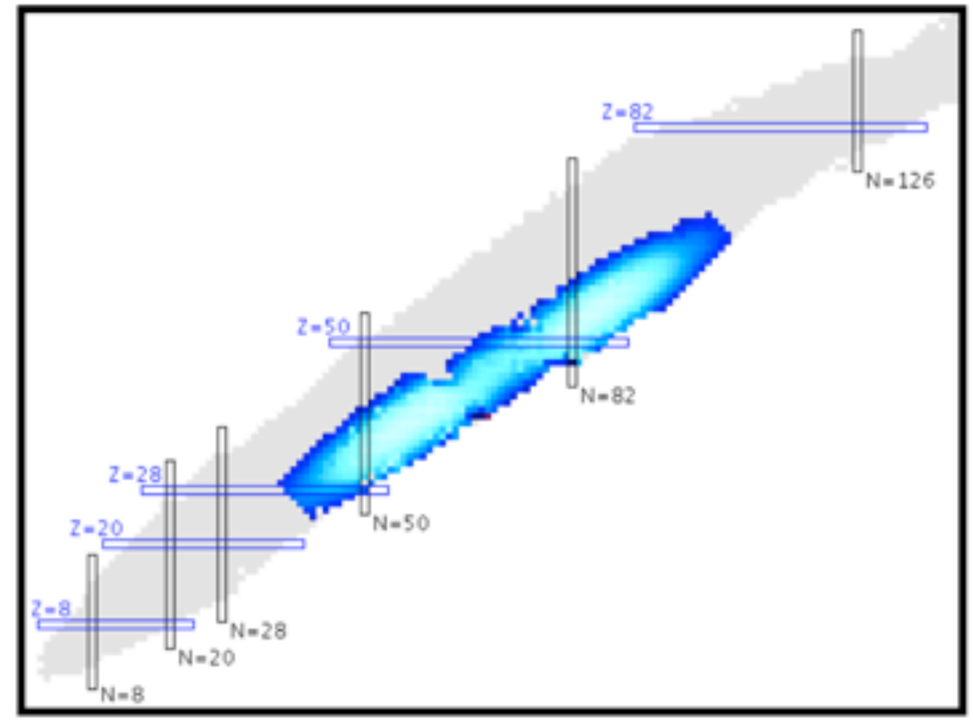


Calculating Reactor Neutrino Spectra

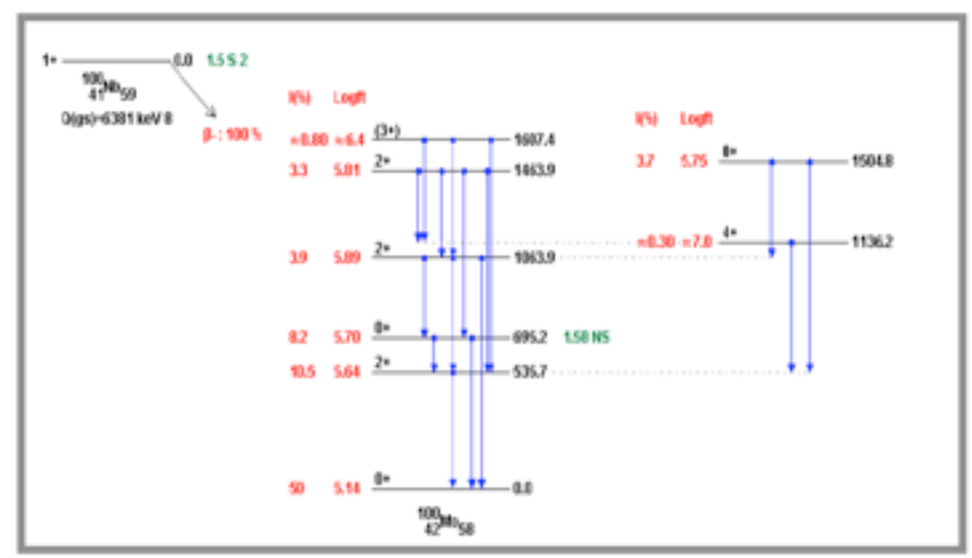
$$^{235}_{92}U + n \rightarrow X_1 + X_2 + 2n$$





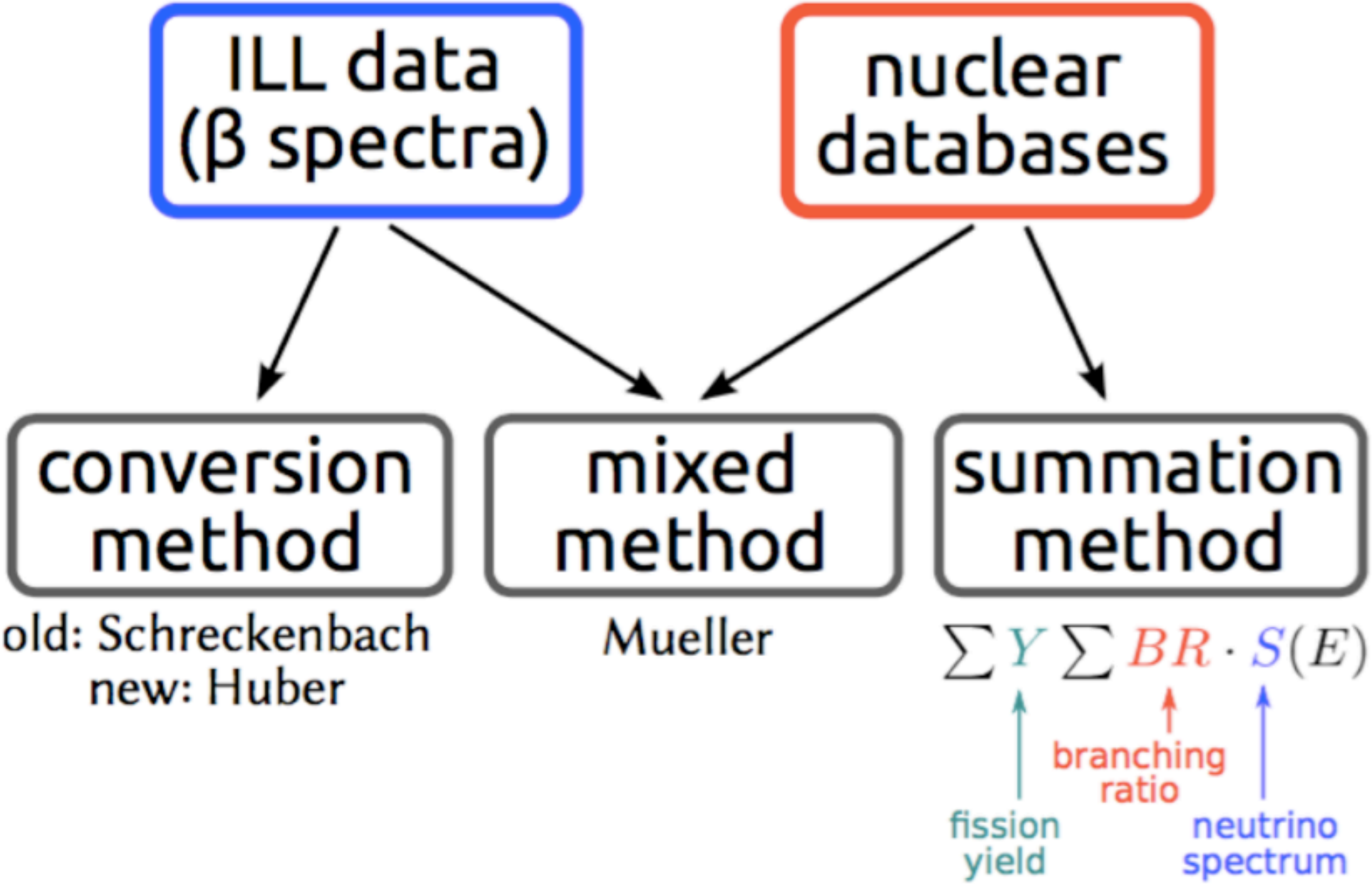


involves poorly known β-emitters



short lived ←→ high energy
→ spectral uncertainties?

Reactor Spectrum Predictions



➡ Several different inputs and (alternative) methods to model reactor neutrino spectrum

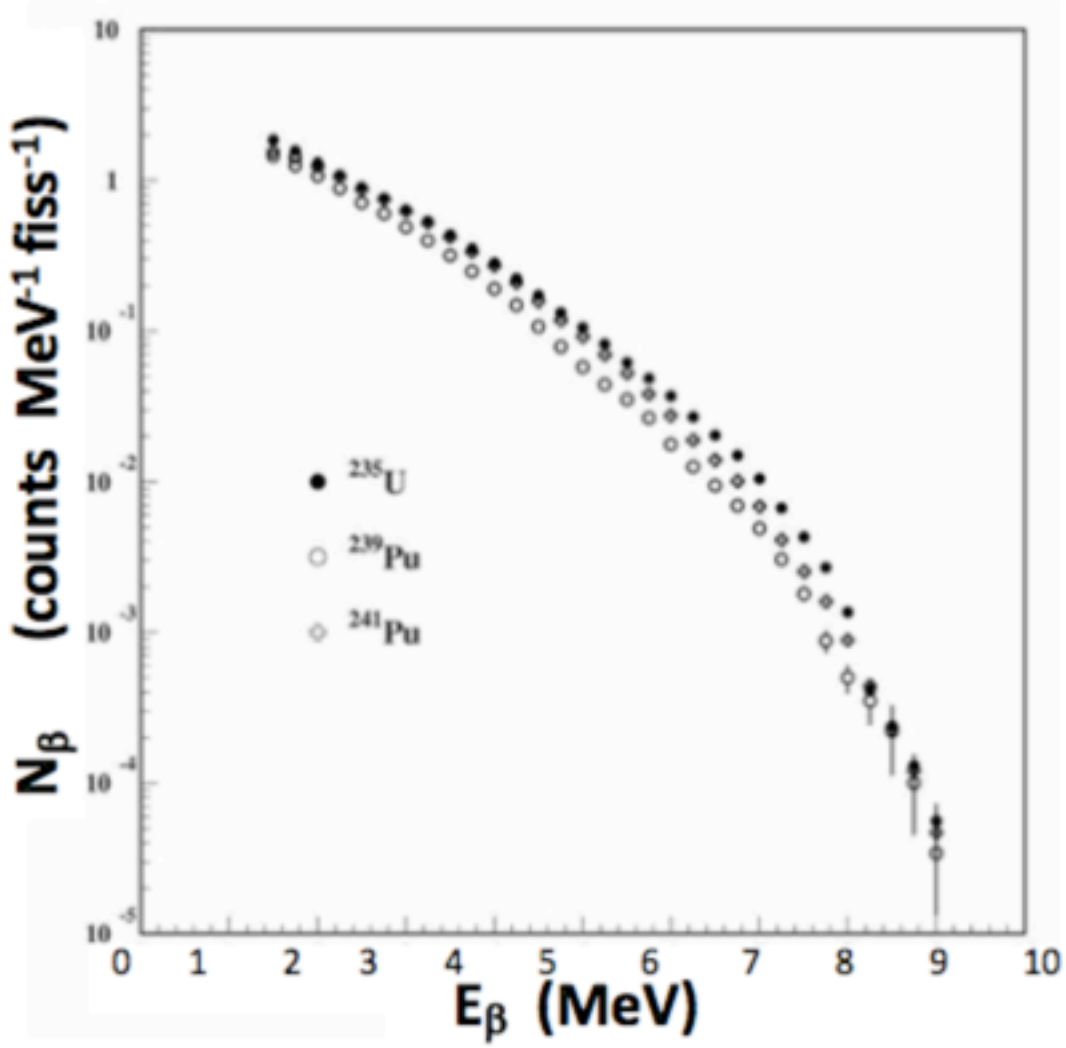
➡ Experiments have used different methods

The ILL β-Spectra

Expected ν-fluxes originally determined from measurements of electrons (β-spectra) at ILL
→ inversion: ν-spectra from β-decays

- ILL fission β-spectra for ^{235}U, ^{239}Pu, ^{241}Pu
- converted to antineutrino β-spectra by fitting to 30 end-point energies
- originally, used ENDF nuclear database

➔ beware of uncertainties…



K. Schreckenbach et al. PLB118, 162 (1985)

FIT

$$S_\beta(E) = \sum_{i=1,30} a_i \, S^i(E, E_o^i)$$

$$Z_{eff} \sim a + b\,E_0 + c\,E_0^2$$

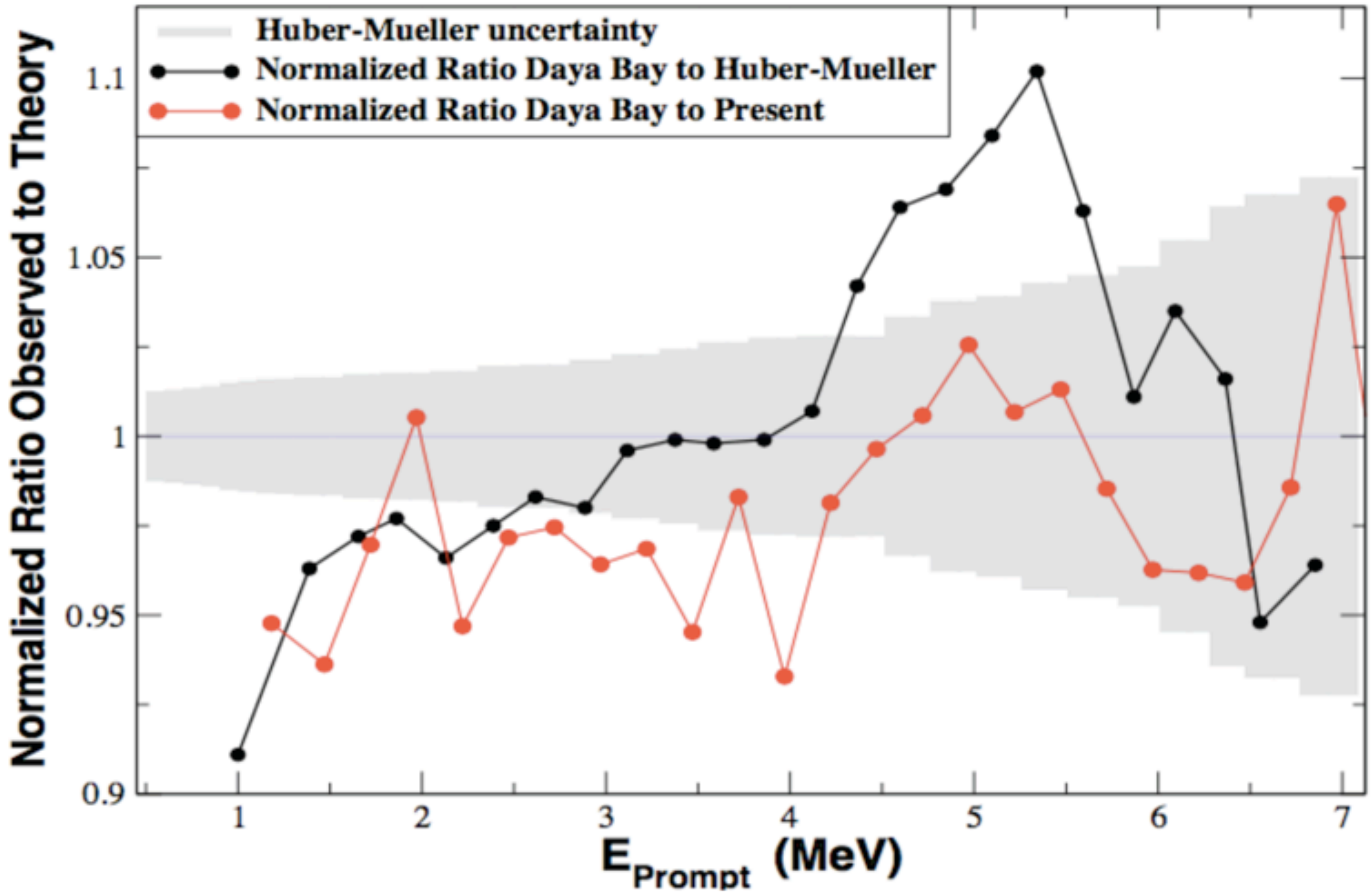
Z→ Z_{eff} and δ are parametrizations!

$$S^i(E, E_0^i) = E_\beta p_\beta (E_0^i - E_\beta)^2 F(E, Z)(1 + \delta_{corrections})$$

The Bump and improved Z_{eff}

what happens to the bump with the optimized Z_{eff} ?

➔ better!



➔ The bump depends on how the 'expected' spectrum was derived

➔ Shape differences partly reflect assumption in the conversion of β-spectra

➔ But: Beware of collecting effects that go in the right direction…

Sterile Hints & Plans for Tests

Project	neutrino	source	E (MeV)	L (m)	status
SAGE [166]	ν_e	^{51}Cr	0.75	$\lesssim 1$	in preparation
CeSOX [167, 168]	$\bar{\nu}_e$	^{144}Ce	1.8 – 3	5 – 12	in preparation
CrSOX [167]	ν_e	^{51}Cr	0.75	5 – 12	proposal
Daya Bay [169, 170]	$\bar{\nu}_e$	^{144}Ce	1.8 – 3	1.5 – 8	proposal
JUNO [171]	$\bar{\nu}_e$	^{144}Ce	1.8 – 3	$\lesssim 32$	proposal
LENS [172]	$\nu_e, \bar{\nu}_e$	^{51}Cr, ^{6}He	0.75, $\lesssim 3.5$	$\lesssim 3$	abandoned
CeLAND [173]	$\bar{\nu}_e$	^{144}Ce	1.8 – 3	$\lesssim 6$	abandoned
LENA [174]	ν_e	^{51}Cr, ^{37}Ar	0.75, 0.81	$\lesssim 90$	abandoned

Source experiments

tensions with cosmology…
➔ N_{eff} = 3.x < ~ 4
BBN…

Nevertheless:
➔ lab tests important

Also important:
➔ keV sterile ν =WDM..

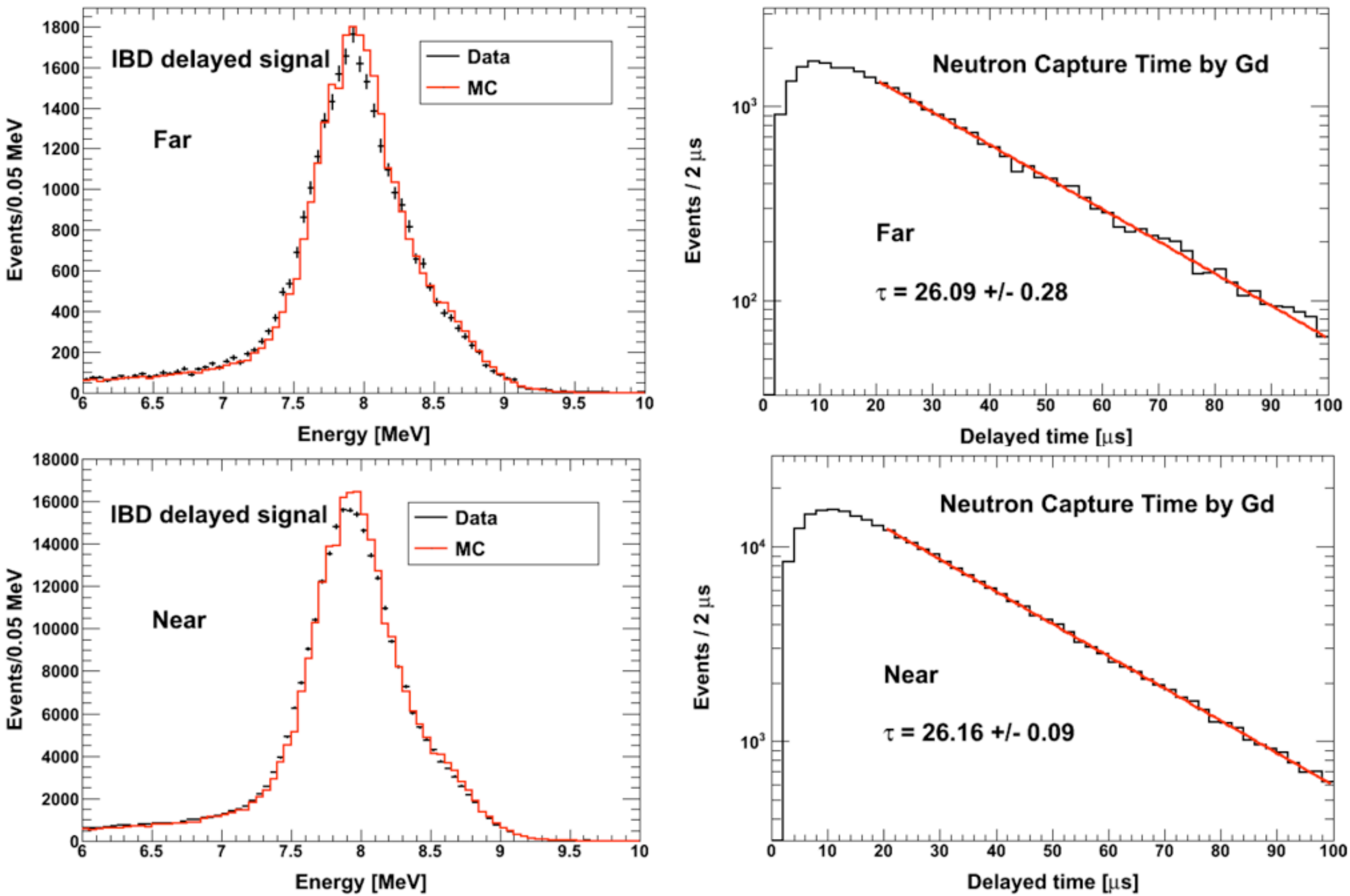
Project	P_{th} (MW)	M_{target} (tons)	L (m)	Depth (m.w.e.)	status
Nucifer (FRA) [175]	70	0.8	7	13	operating
Stereo (FRA) [176]	57	1.75	9 – 12	18	~~in preparation~~ ➔ **running**
DANSS (RUS) [177]	3000	0.9	10 – 12	50	~~in preparation~~ ➔ **running**
SoLid (BEL) [178]	45 – 80	3	6 – 8	10	in preparation
PROSPECT (USA) [179]	85	3, 10	7 – 12, 15 – 19	few	in preparation
NEOS (KOR) [180]	16400	1	25	10 – 23	~~in preparation~~ ➔ **result, withdrawn**
Neutrino-4 (RUS) [181]	100	1.5	6 – 11	10	proposal
Poseidon (RUS) [182]	100	3	5 – 8	15	proposal
Hanaro (KOR) [183]	30	0.5	6	few	proposal
CARR (CHN) [184]	60	~ 1	7, 11	few	proposal

Reactor experiments

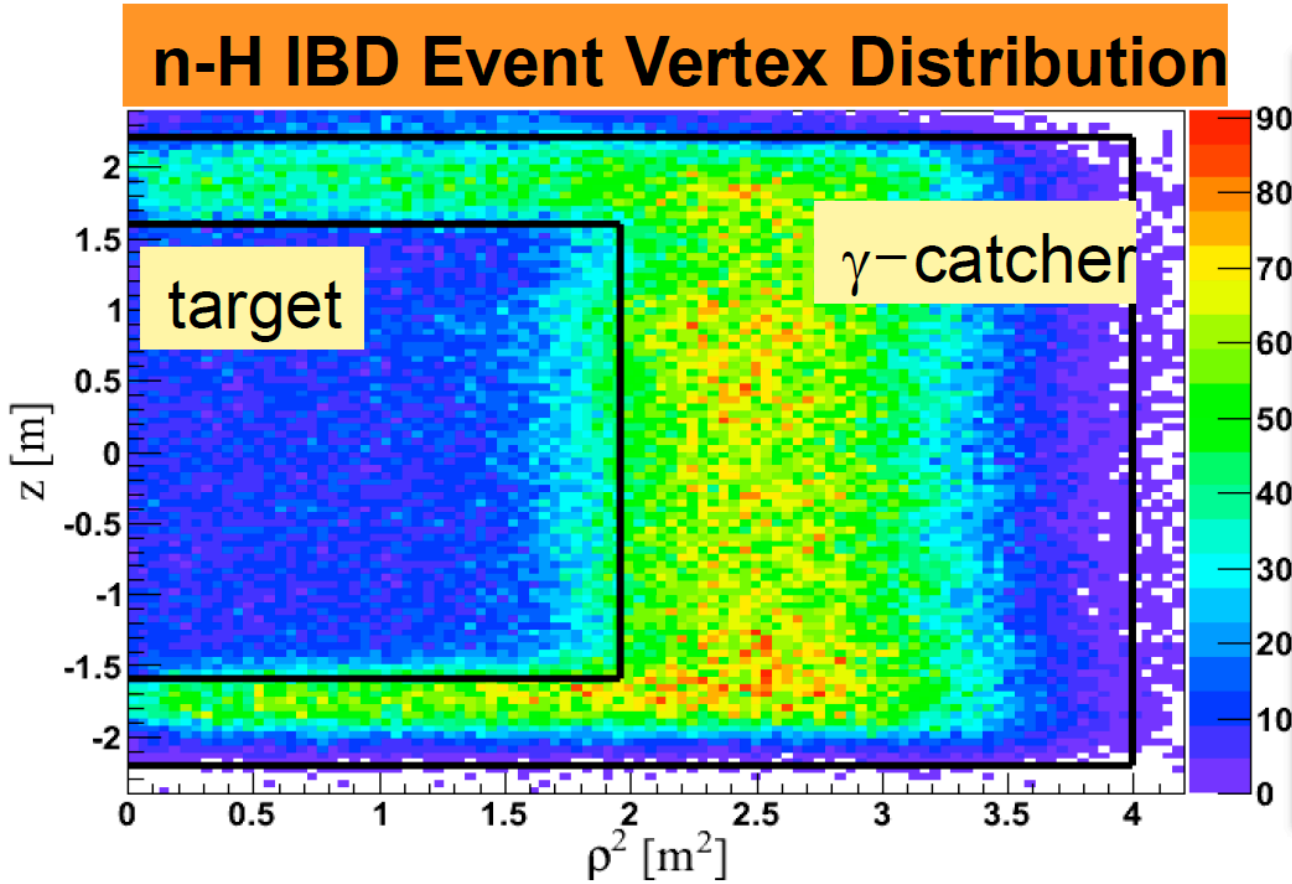
Giunti 1512.04758

Back up

Neutron Capture by Gd



Gd used because of delay @ 8 MeV (radiogenic BG dominates ≤ 3MeV)



	Near	Far
Live time(day)	379.663	384.473
IBD Candidate	249,799	54,277
IBD(/day)	619.916	67.823
Accidental (/day)	25.16±0.42	68.90±0.35
Fast Neutron(/day)	5.62±0.30	1.30±0.08
LiHe(/day)	9.87±1.48	3.19±0.37

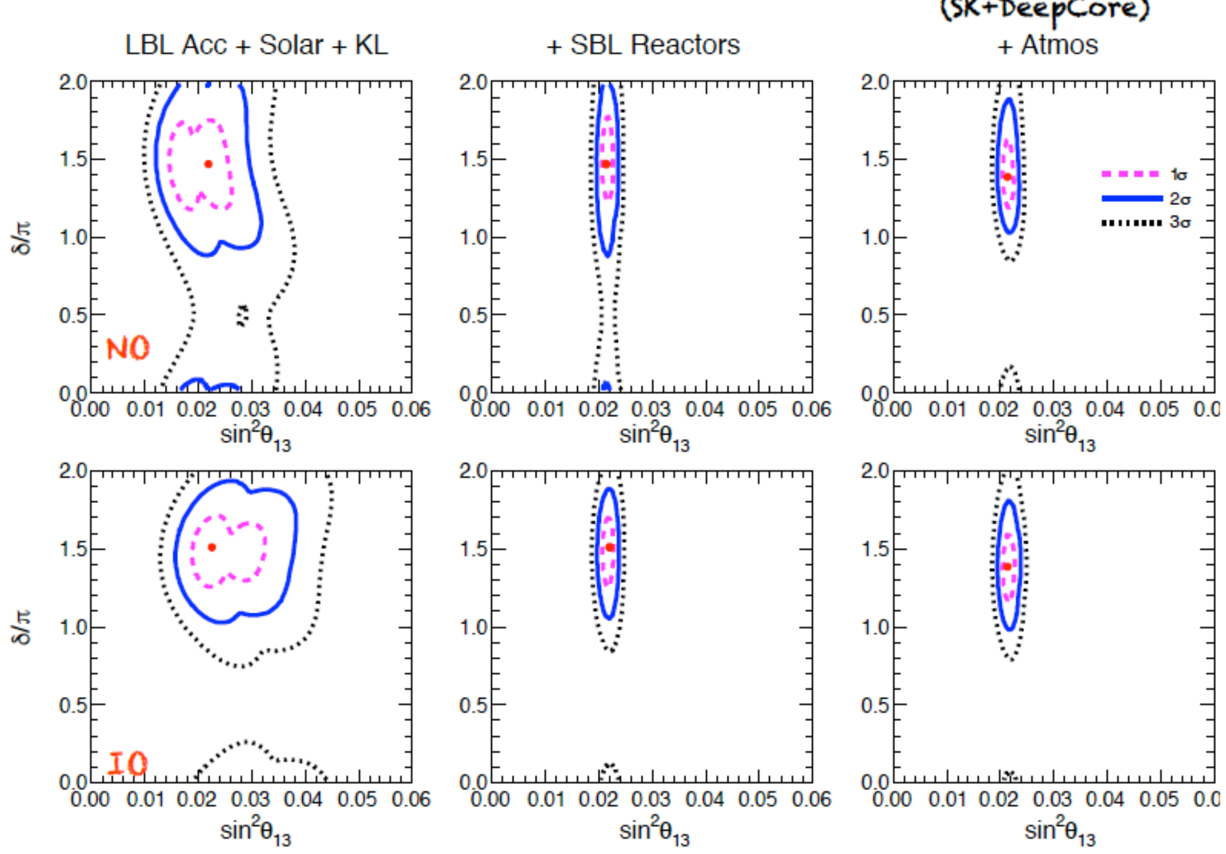
Analysis with n-H (lower average energy) and not n-Gd shows that origin of "IBD" is heavily polluted by external radioactivity instead

Backgrounds & uncertainties

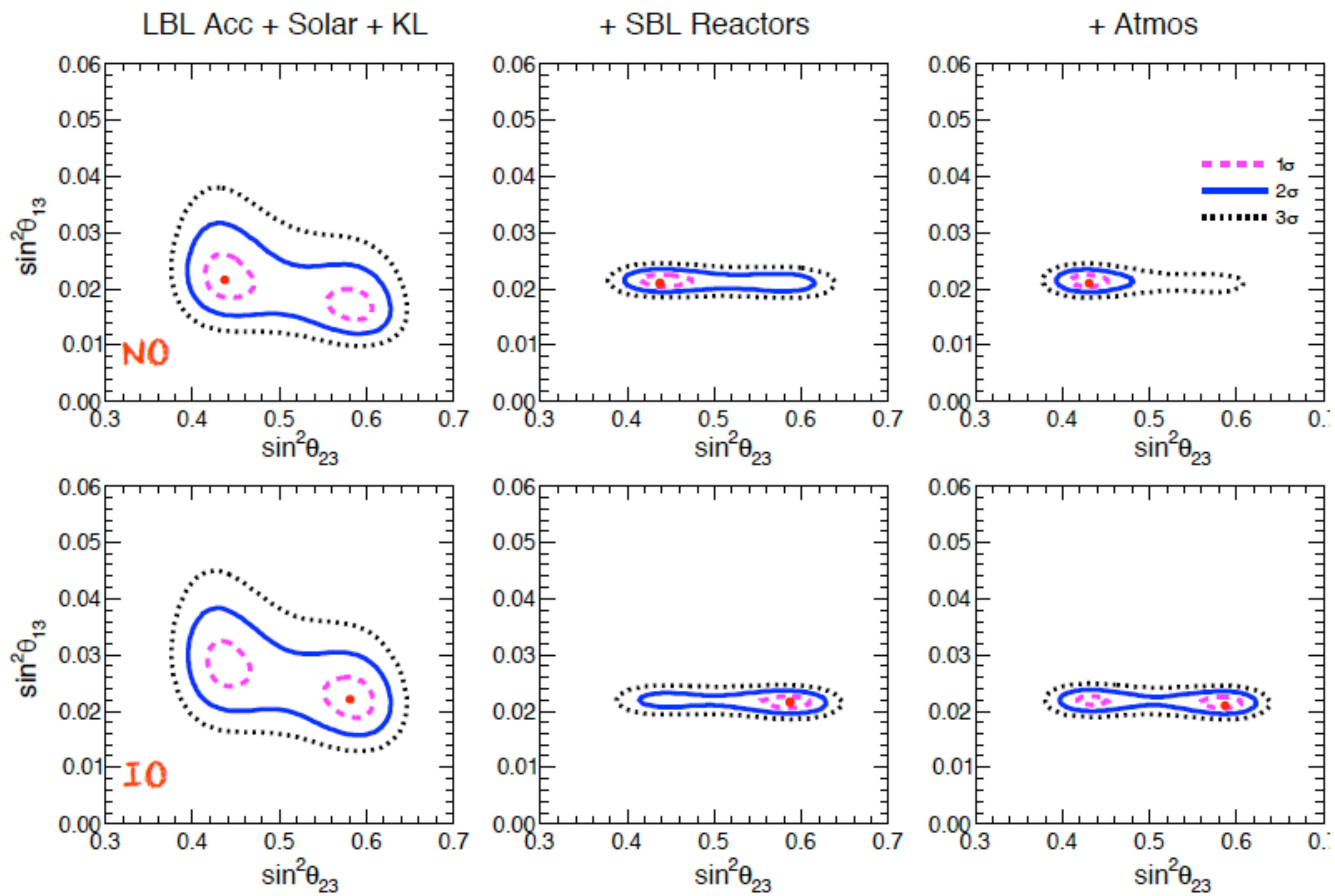
	Daya Bay		Reno		Double Chooz
	Near	Far	Near	Far	Far
Accidentals (B/S)	1.4%	4.0%	0.56%	0.93%	0.6%
Uncertainty(ΔB/B)	1.0%	1.4%	1.4%	4.4%	0.8%
Fast neutrons(B/S)	0.1%	0.06%	0.64%	1.3%	1.6%
Uncertainty(ΔB/B)	31%	40%	2.6%	6.2%	30%
^{8}He/^{9}Li (B/S)	0.4%	0.3%	1.6%	3.6%	2.8%
Uncertainty (ΔB/B)	52%	55%	48%	29%	50%
α-n(B/S)	0.01%	0.05%	-	-	-
Uncertainty(ΔB/B)	50%	50%	-	-	-
Am-C(B/S)	0.03%	0.3%	-	-	-
Uncertainty (ΔB/B)	100%	100%	-	-	-
Total backgrounds(B/S)	1.9%	4.7%	2.8%	5.8%	5.0%
Total Uncertainties (Δ(B/S))	0.2%	0.35%	0.8%	1.1%	1.5%

Reactor flux estimate

<table>
<tr><th></th><th colspan="2">Daya Bay</th><th colspan="2">Reno</th><th>Double Chooz</th></tr>
<tr><td></td><td>Corr.</td><td>Uncorr.</td><td>Corr.</td><td>Uncorr.</td><td>Corr./Uncorr.</td></tr>
<tr><td>Thermal power</td><td></td><td>0.5%</td><td></td><td>0.5%</td><td>0.5%</td></tr>
<tr><td>Fission fraction/Fuel composition</td><td></td><td>0.6%</td><td></td><td>0.7%</td><td>0.9%</td></tr>
<tr><td>Fission cross section /Bugey 4 measurement</td><td rowspan="3">3%</td><td></td><td>1.9%</td><td></td><td>1.4%</td></tr>
<tr><td>Reference spectra</td><td></td><td>0.5%</td><td></td><td>0.5%</td></tr>
<tr><td>IBD cross section</td><td></td><td>0.2%</td><td></td><td>0.2%</td></tr>
<tr><td>Energy per fission</td><td>0.2%</td><td></td><td>0.2%</td><td></td><td>0.2%</td></tr>
<tr><td>Baseline</td><td>0.02%</td><td></td><td>-</td><td></td><td>0.2%</td></tr>
<tr><td>Spent fuel</td><td></td><td>0.3%</td><td></td><td></td><td></td></tr>
<tr><td>Total</td><td>3%</td><td>0.8%</td><td>2.0%</td><td>0.9%</td><td>1.8%</td></tr>
</table>



Anti-correlation via appearance at accelerators, then constrained by reactors

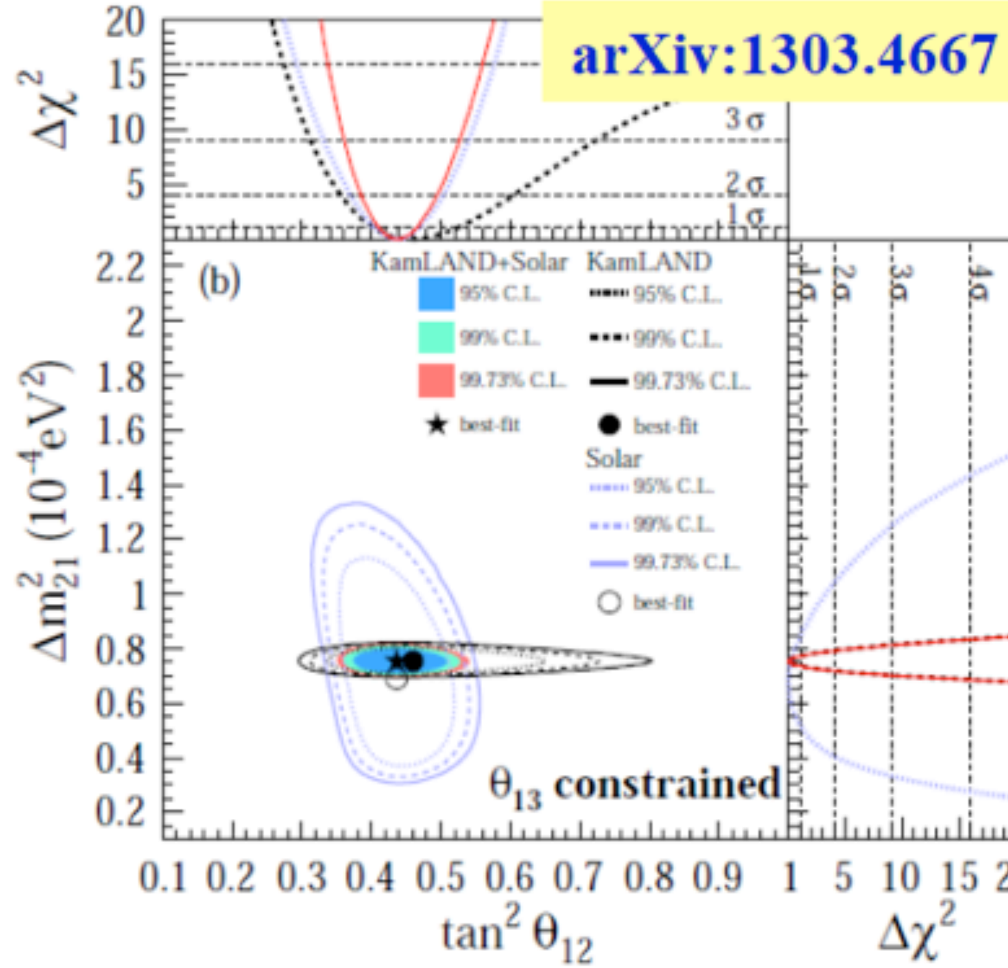


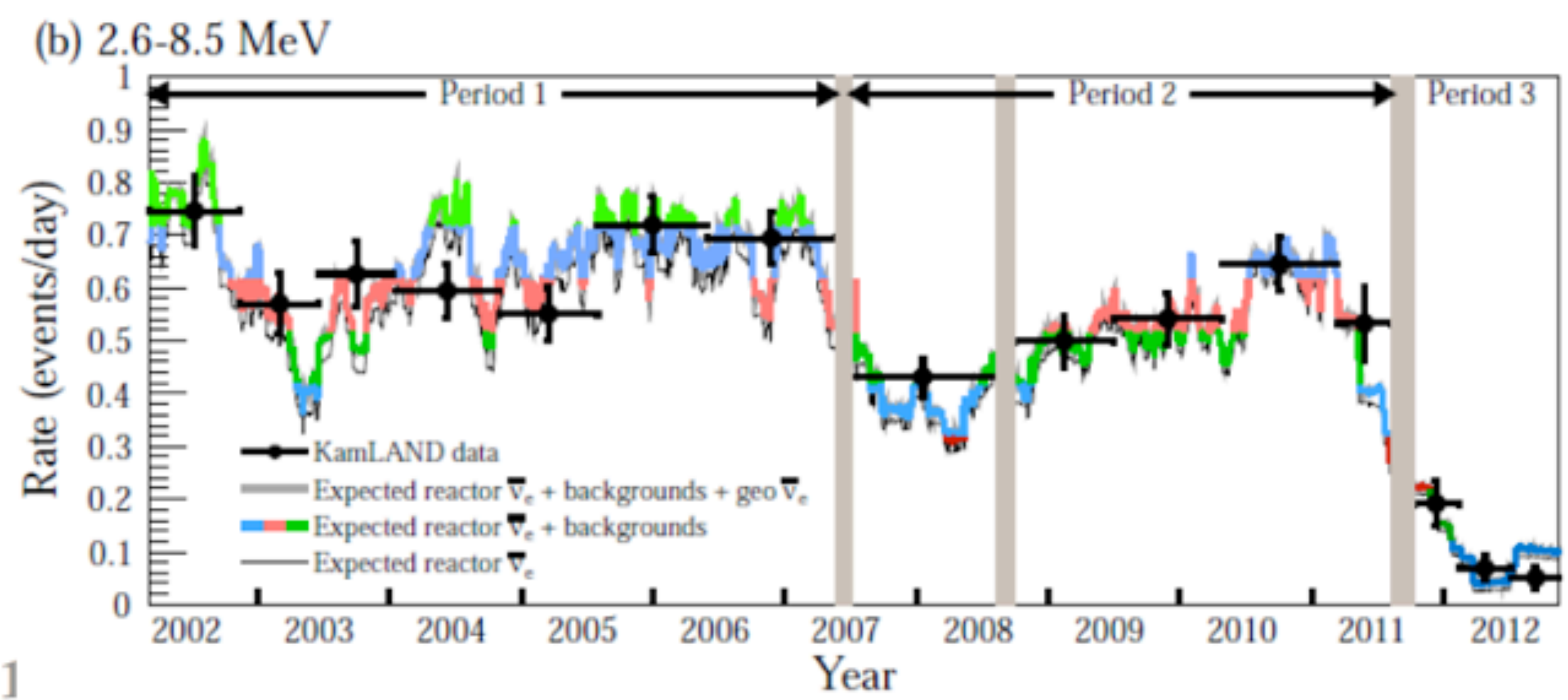
Latest KamLAND Results: θ_{12}

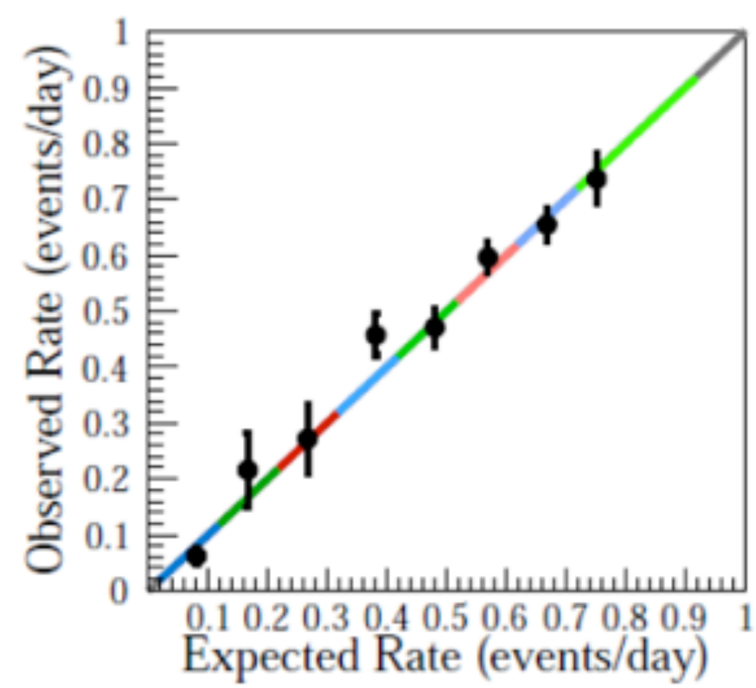
- **Reactors are all off in Japan since Mar. 2011:**
  - ⇨ A unique opportunity for precise measurement of backgrounds

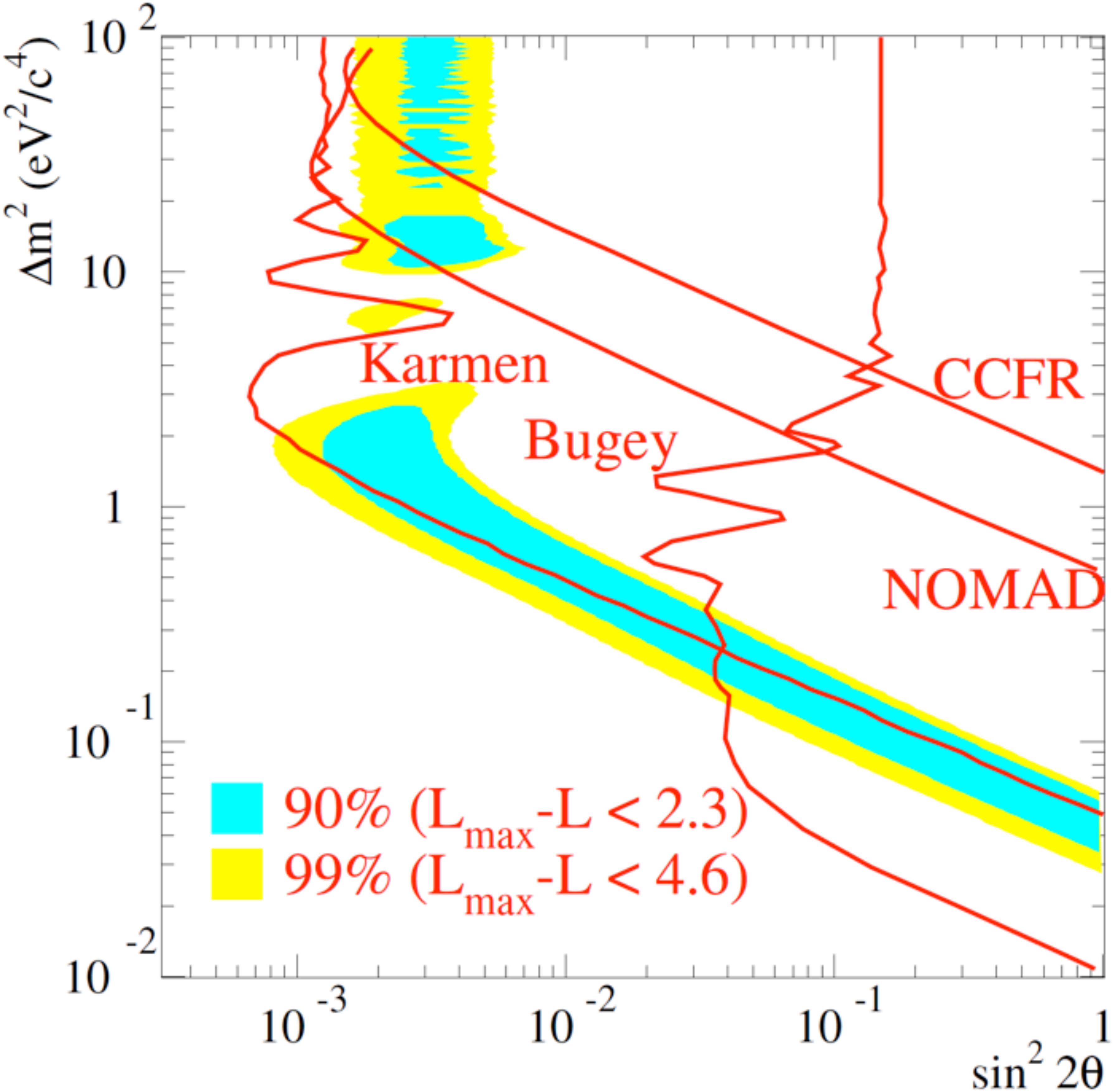
Data combination	Δm^2_{21}	$\tan^2\theta_{12}$	$\sin^2\theta_{13}$
KamLAND	$7.54^{+0.19}_{-0.18}$	$0.481^{+0.092}_{-0.080}$	$0.010^{+0.033}_{-0.034}$
KamLAND + solar	$7.53^{+0.19}_{-0.18}$	$0.437^{+0.029}_{-0.026}$	$0.023^{+0.015}_{-0.015}$
KamLAND + solar + θ_{13}	$7.53^{+0.18}_{-0.18}$	$0.436^{+0.029}_{-0.025}$	$0.023^{+0.002}_{-0.002}$

arXiv:1303.4667





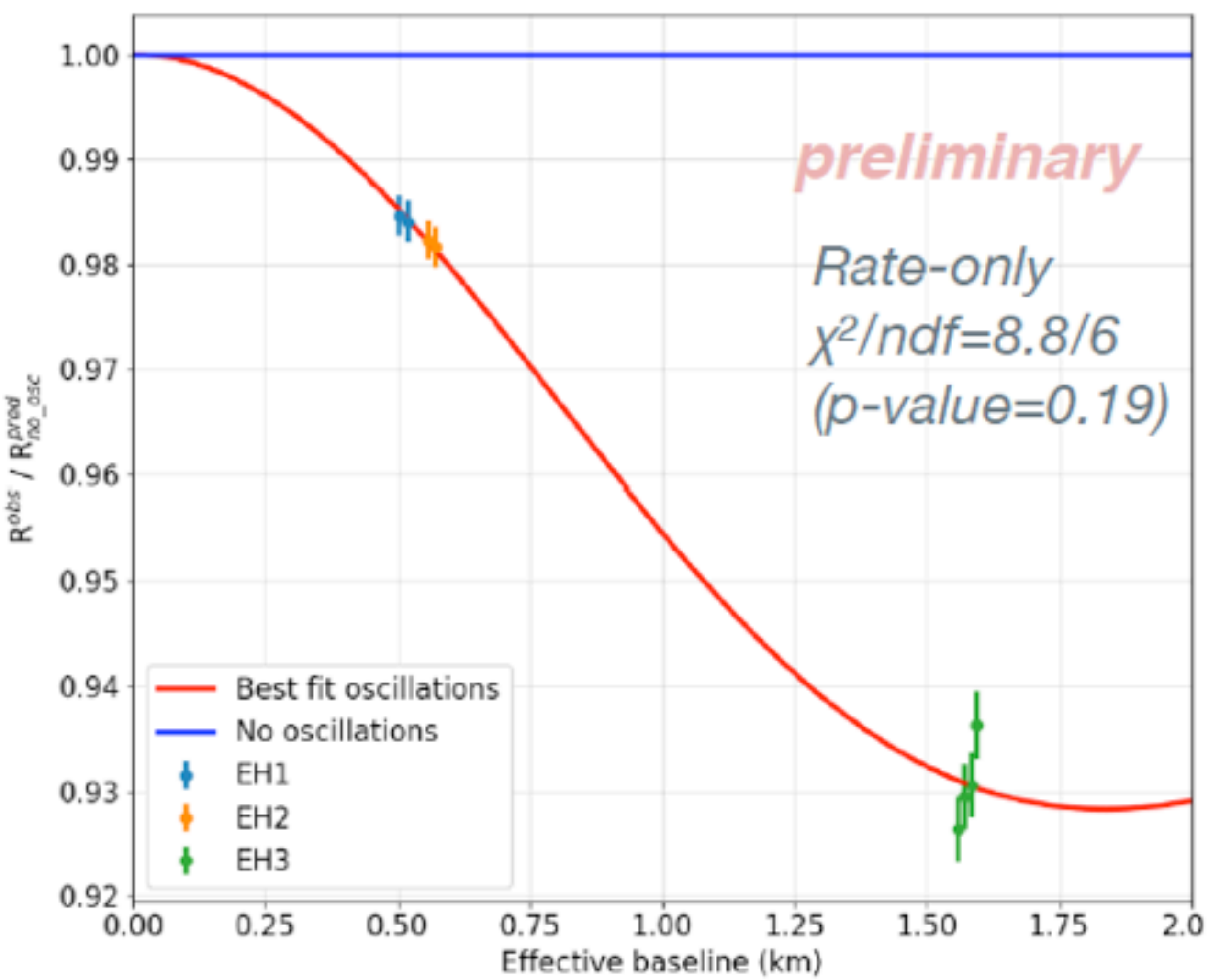


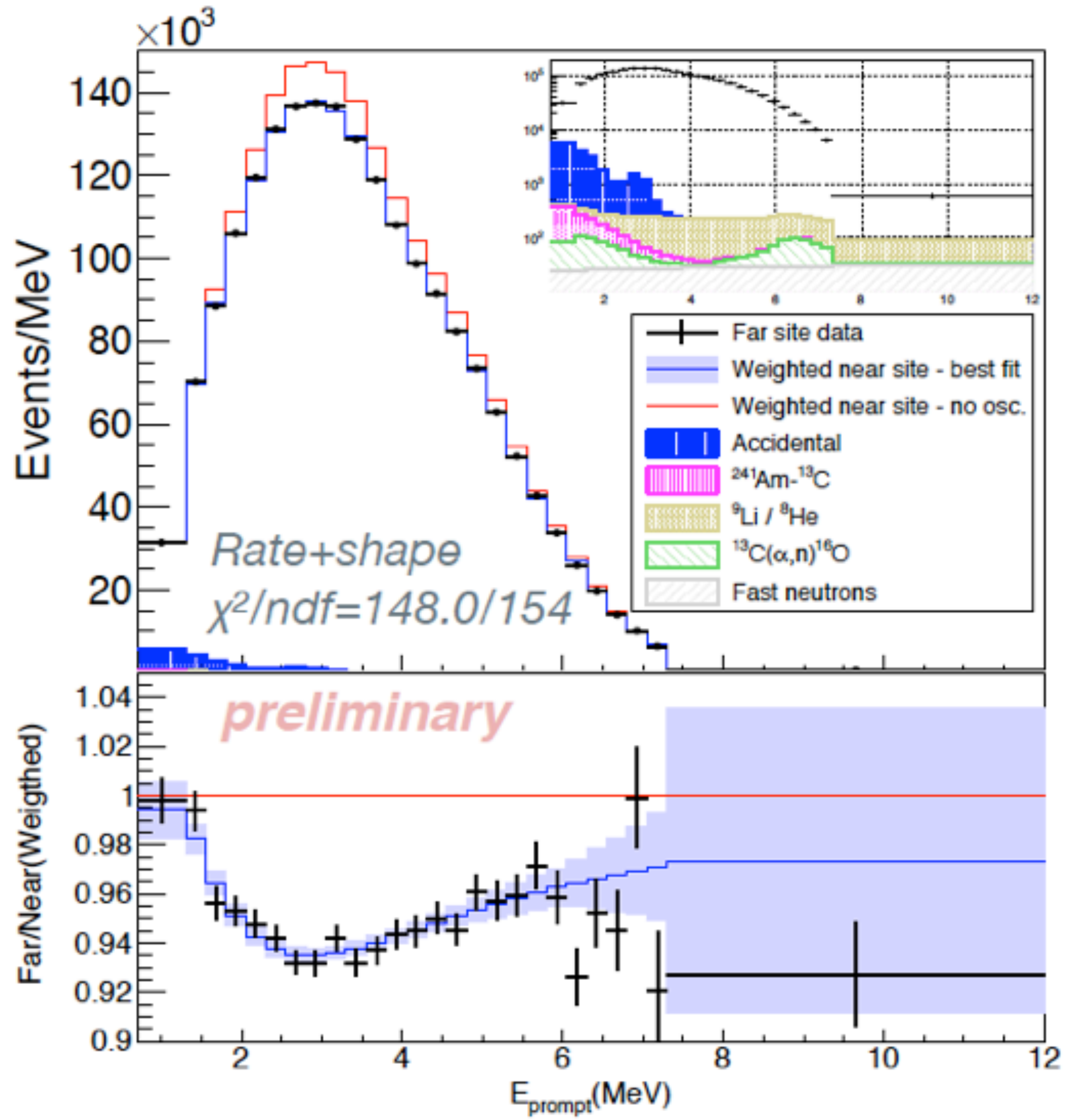


$$\Delta m^2_{SBL} \gtrsim 3 \times 10^{-2}\,eV^2 \gg \Delta m^2_{ATM} \simeq 2.5 \times 10^{-3}\,eV^2 \gg \Delta m^2_{SOL}$$

Oscillation Results with 1958 Days

- See a clear rate and shape distortion that fits well to the 3-neutrino hypothesis:





Nothing abnormal found with two far ADs whose rates deviate from best-fit

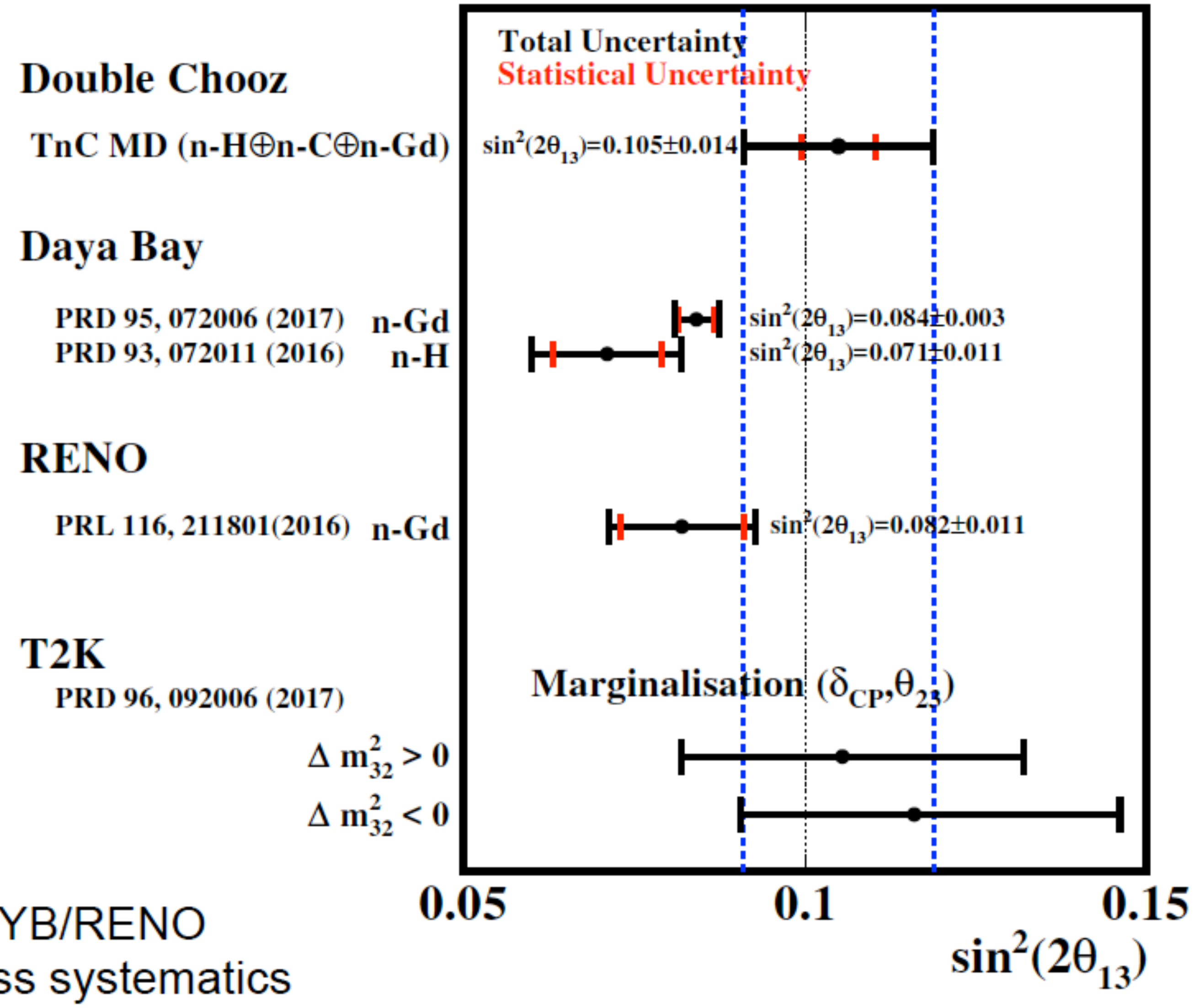
https://zenodo.org/record/1294112#.XFxP39F7mi4

https://arxiv.org/abs/1509.08168

TABLE I: Possible radioactive isotopes induced by cosmic-ray muon spallation at SK [13, 22, 23]. The fourth column lists the end point kinetic energy ($E_{\mathrm{kin.}}$). The fifth column lists the primary generation process of the radioactive isotopes.

Radioactive isotope	τ (s)	Decay mode	$E_{\mathrm{kin.}}$ (MeV)	Primary process
^{11}Be	19.9	β^-	11.51	$^{16}\mathrm{O}(n, \alpha + 2p)^{11}\mathrm{Be}$
		$\beta^-\gamma$	9.41+2.1(γ)	
^{16}N	10.3	β^-	10.44	$^{16}\mathrm{O}(n, p)^{16}\mathrm{N}$
		$\beta^-\gamma$	4.27+6.13(γ)	
^{15}C	3.53	β^-	9.77	$^{16}\mathrm{O}(n, 2p)^{15}\mathrm{C}$
		$\beta^-\gamma$	4.51+5.30(γ)	
^{8}Li	1.21	β^-	~13.0	$^{16}\mathrm{O}(\pi^-, \alpha + {}^2\mathrm{H} + p + n)^{8}\mathrm{Li}$
^{8}B	1.11	β^+	~13.9	$^{16}\mathrm{O}(\pi^+, \alpha + 2p + 2n)^{8}\mathrm{B}$
^{16}C	1.08	$\beta^- + n$	~4	$^{18}\mathrm{O}(\pi^-, n + p)^{16}\mathrm{C}$
^{9}Li	0.26	β^-	13.6	$^{16}\mathrm{O}(\pi^-, \alpha + 2p + n)^{9}\mathrm{Li}$
		$\beta^- + n$	~10	
^{9}C	0.18	$\beta^+ + p$	3~15	$^{16}\mathrm{O}(n, \alpha + 4n)^{9}\mathrm{C}$
^{8}He	0.17	$\beta^-\gamma$	9.67+0.98(γ)	$^{16}\mathrm{O}(\pi^-, {}^3\mathrm{H} + 4p + n)^{8}\mathrm{He}$
		$\beta^- + n$		
^{12}Be	0.034	β^-	11.71	$^{18}\mathrm{O}(\pi^-, \alpha + p + n)^{12}\mathrm{Be}$
^{12}B	0.029	β^-	13.37	$^{16}\mathrm{O}(n, \alpha + p)^{12}\mathrm{B}$
^{13}B	0.025	β^-	13.44	$^{16}\mathrm{O}(\pi^-, 2p + n)^{13}\mathrm{B}$
^{14}B	0.02	$\beta^-\gamma$	14.55+6.09(γ)	$^{16}\mathrm{O}(n, 3p)^{14}\mathrm{B}$
^{12}N	0.016	β^+	16.38	$^{16}\mathrm{O}(\pi^+, 2p + 2n)^{12}\mathrm{N}$
^{13}O	0.013	$\beta^+ + p$	8~14	$^{16}\mathrm{O}(\mu^-, \mu^- + p + 2n + \pi^-)^{13}\mathrm{O}$
^{11}Li	0.012	β^-	20.62	$^{16}\mathrm{O}(\pi^+, 5p + \pi^0 + \pi^+)^{11}\mathrm{Li}$
		$\beta^- + n$	~16	

1.5 σ difference (systematics!)



Combo is not easy as some systematics correlated (e.g. reactor/flux)

Two common DC/DYB/RENO workshops to discuss systematics

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