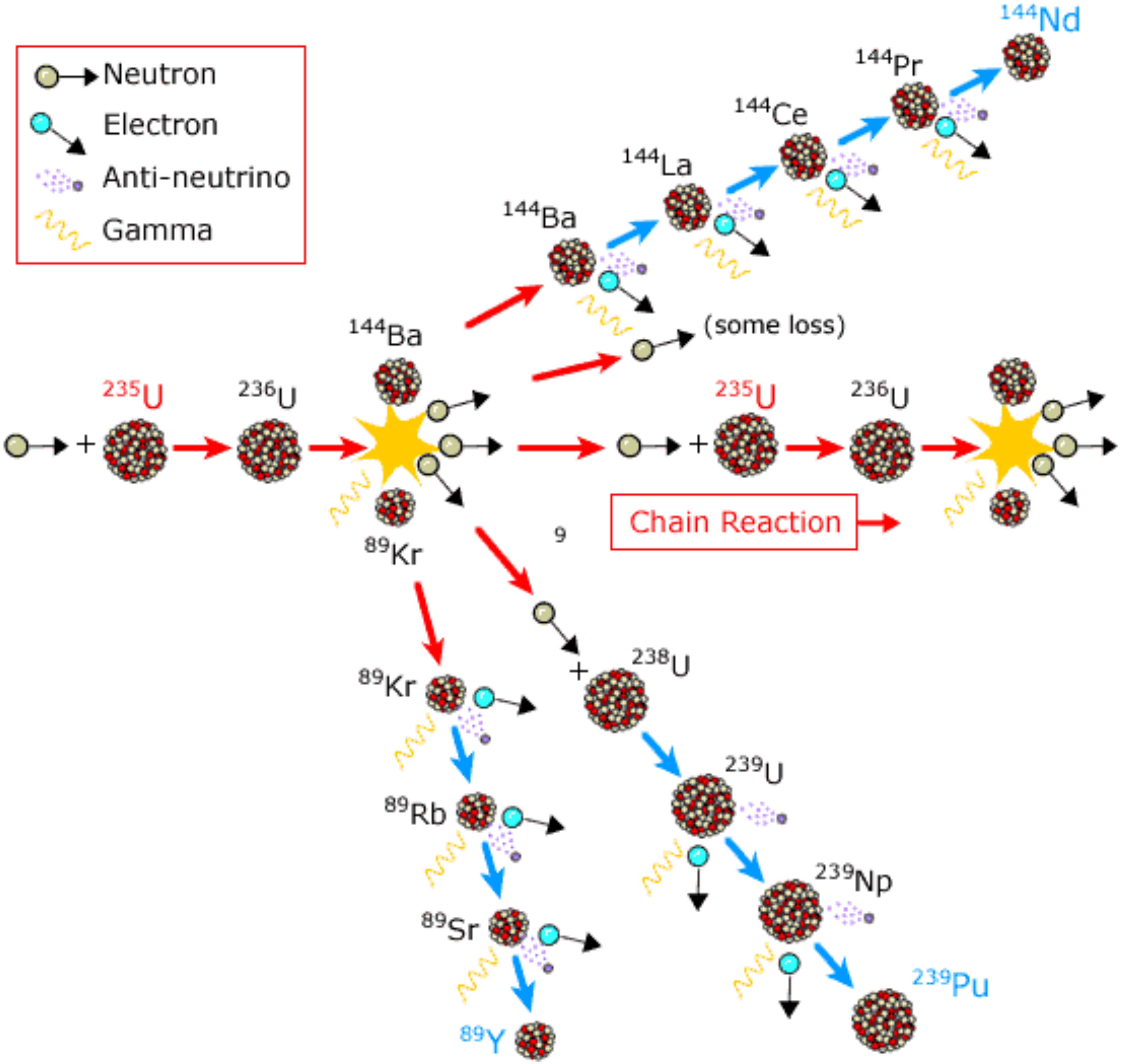
# Lecture 5:
# experiments at reactors

PhD Cycle XXXII

# Neutrini da reattore

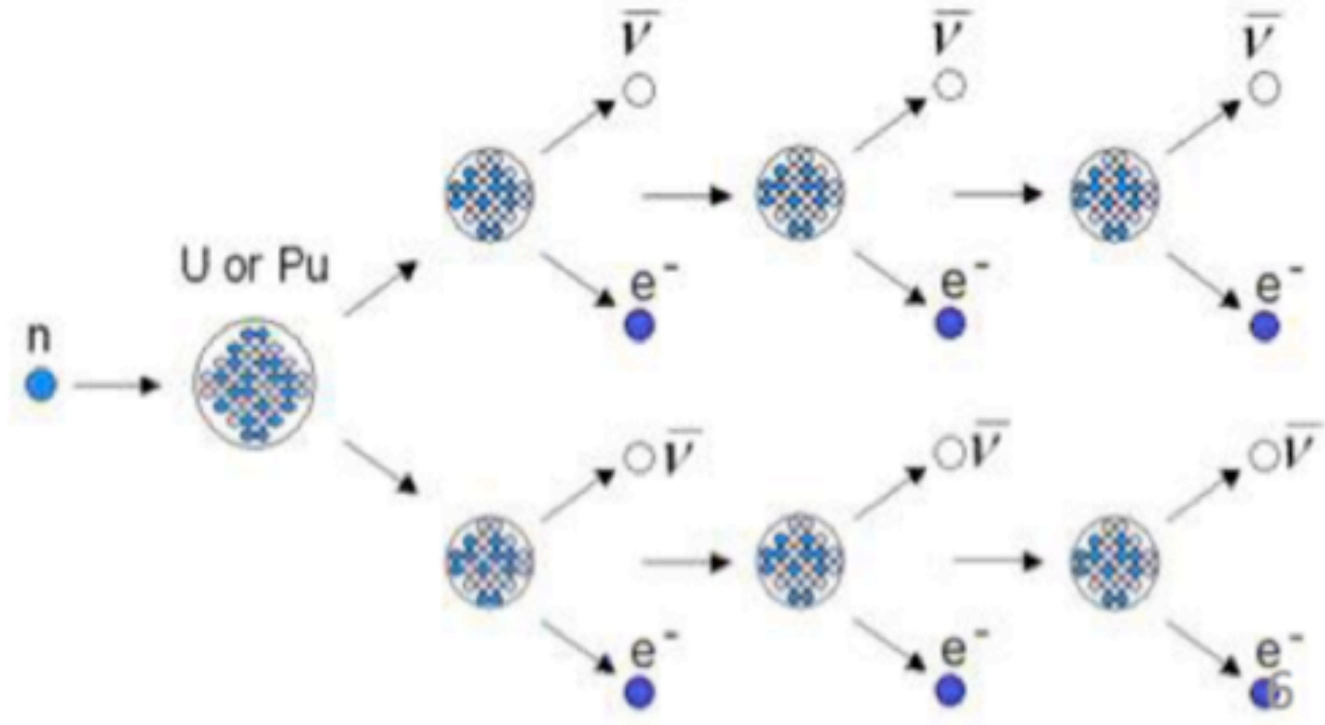


# Nuclear Reactors as Antineutrino Source

- **Reactors like Chooz A+B ➔ 8.5 $\text{GW}_{\text{th}}$**
- **Few percent of the released energy**

  **➔ escapes with anti-neutrinos**

  **➔ $2*10^{21}\bar{\nu}$/s ←→ O(1 kW/m$^2$) @fence**



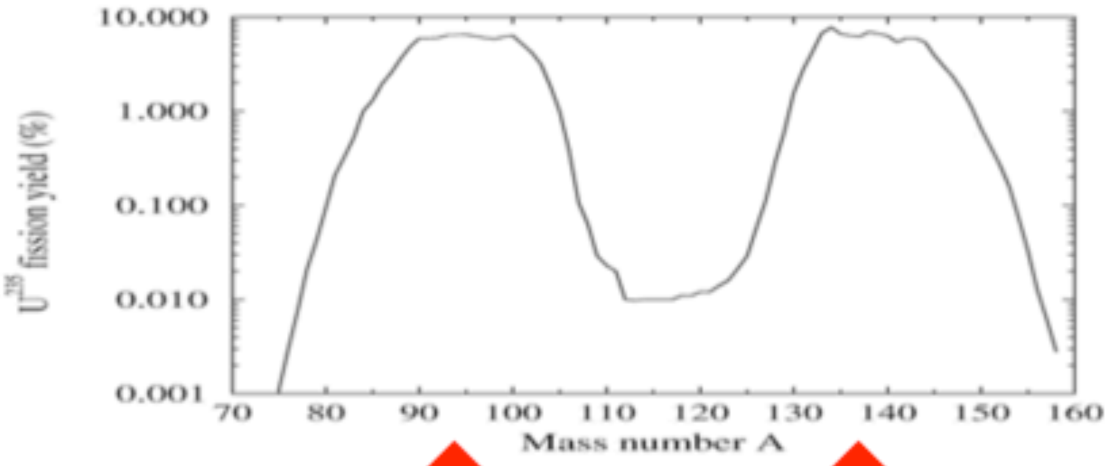
- **measured e$^-$ spectrum of U$^{235}$, Pu$^{239}$, Pu$^{241}$**

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

**➔ two “identical” detectors…**

**example: fission of U$^{235}$**

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

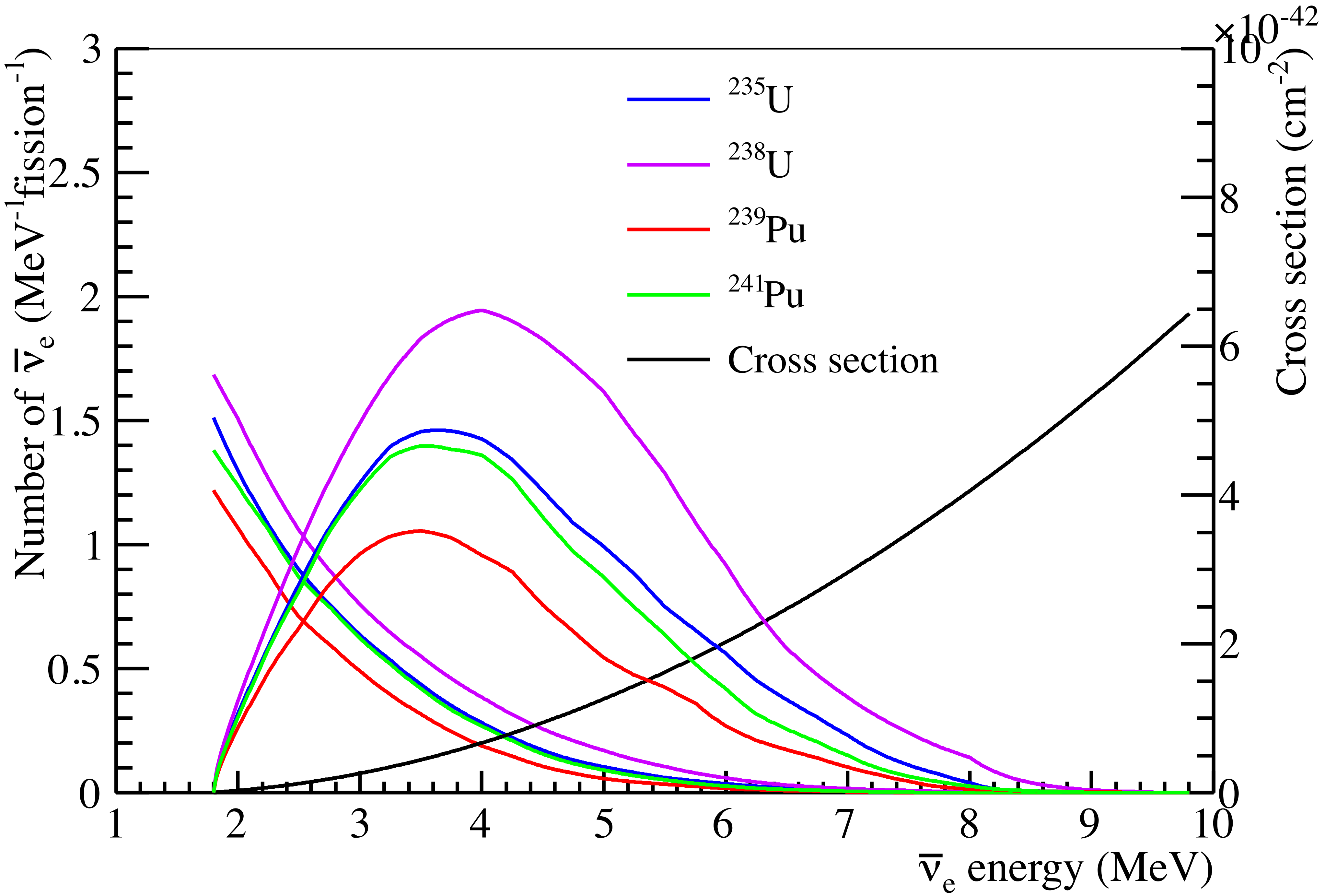


most likely A

➔ <u>on average:</u>

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

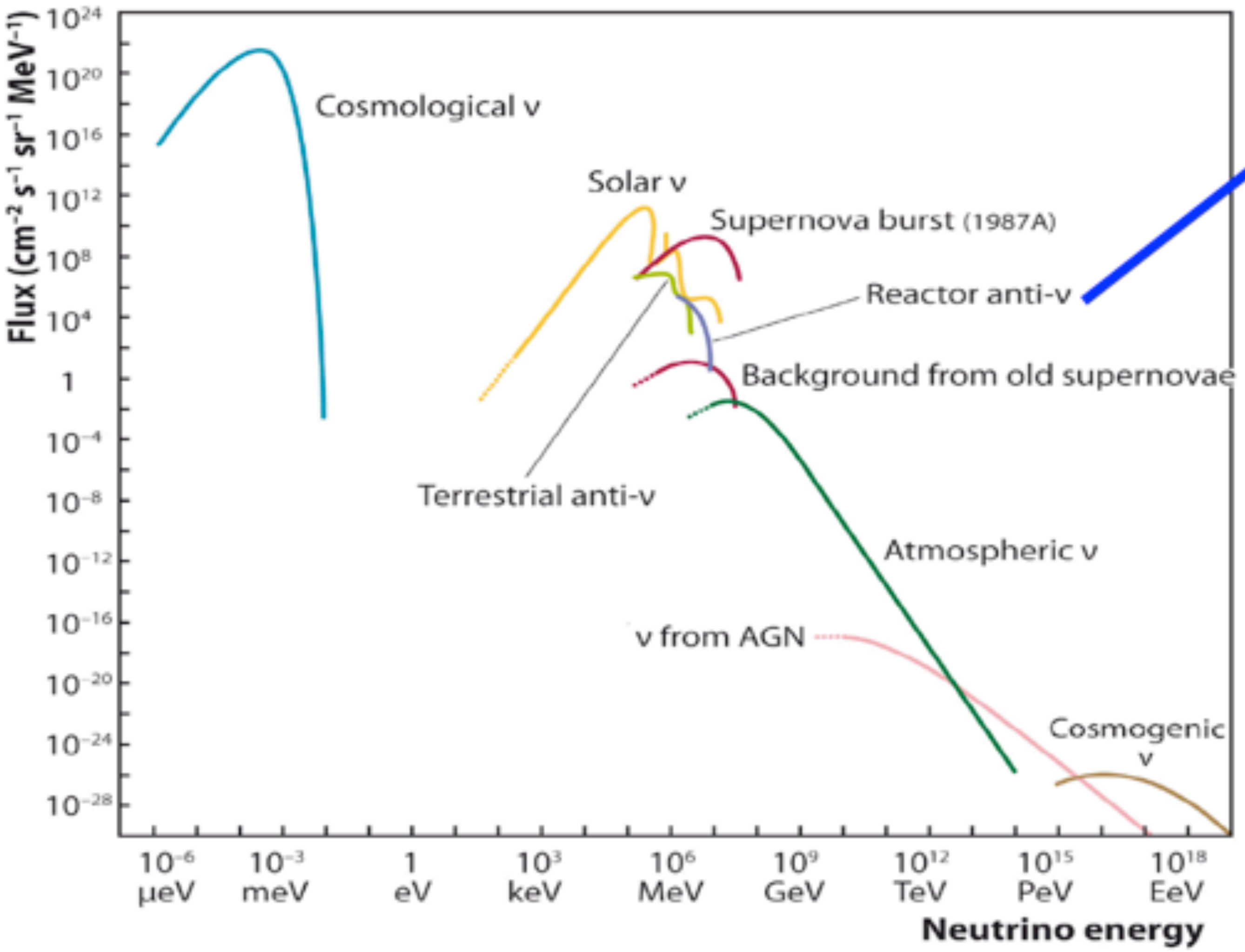
# Flux



- **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

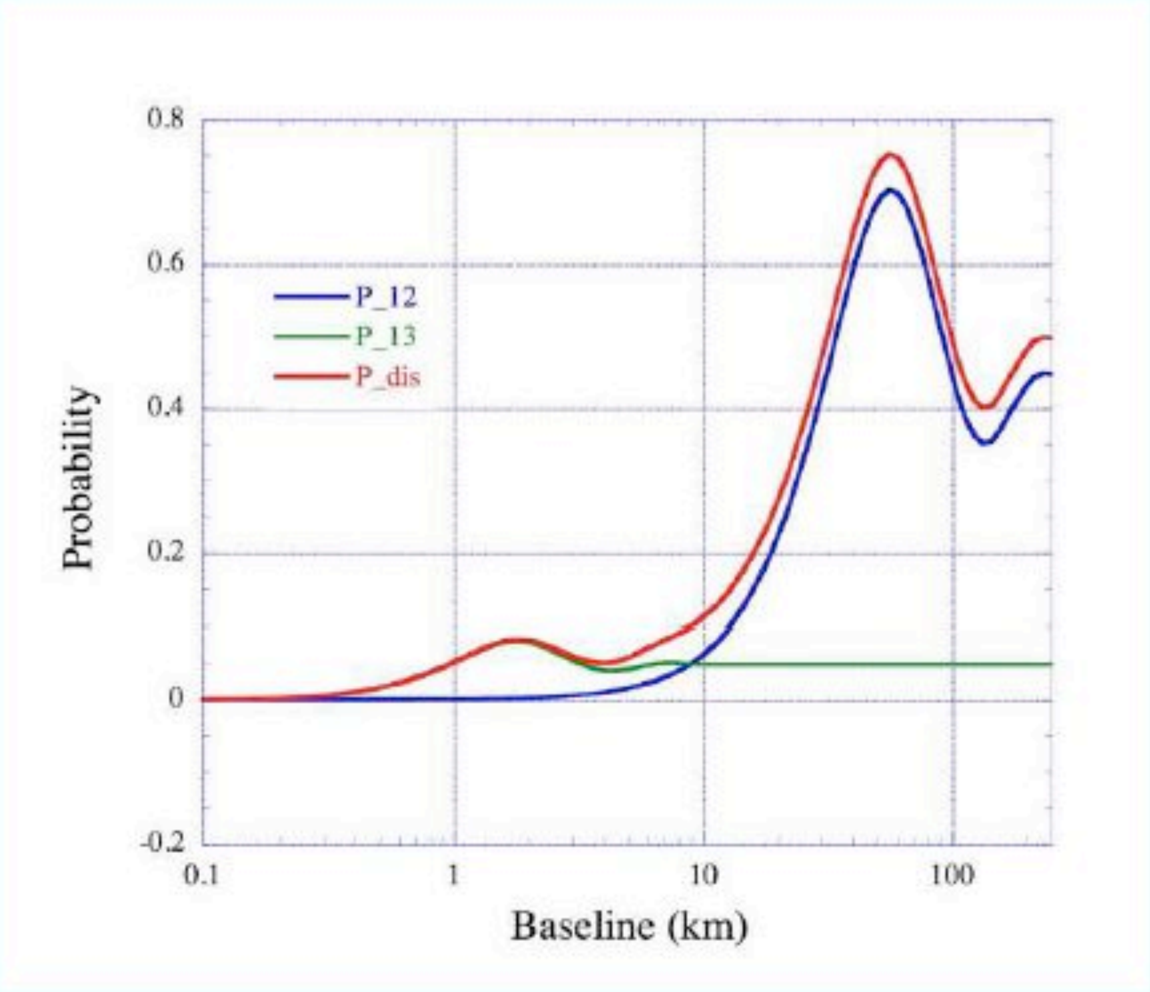
- Clean signal, no cross talk with $\delta$ and matter effects
- Relatively cheap compared to accelerator based experiments
- Provides the direction to the future of neutrino physics
- Rapidly deployment possible

**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

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

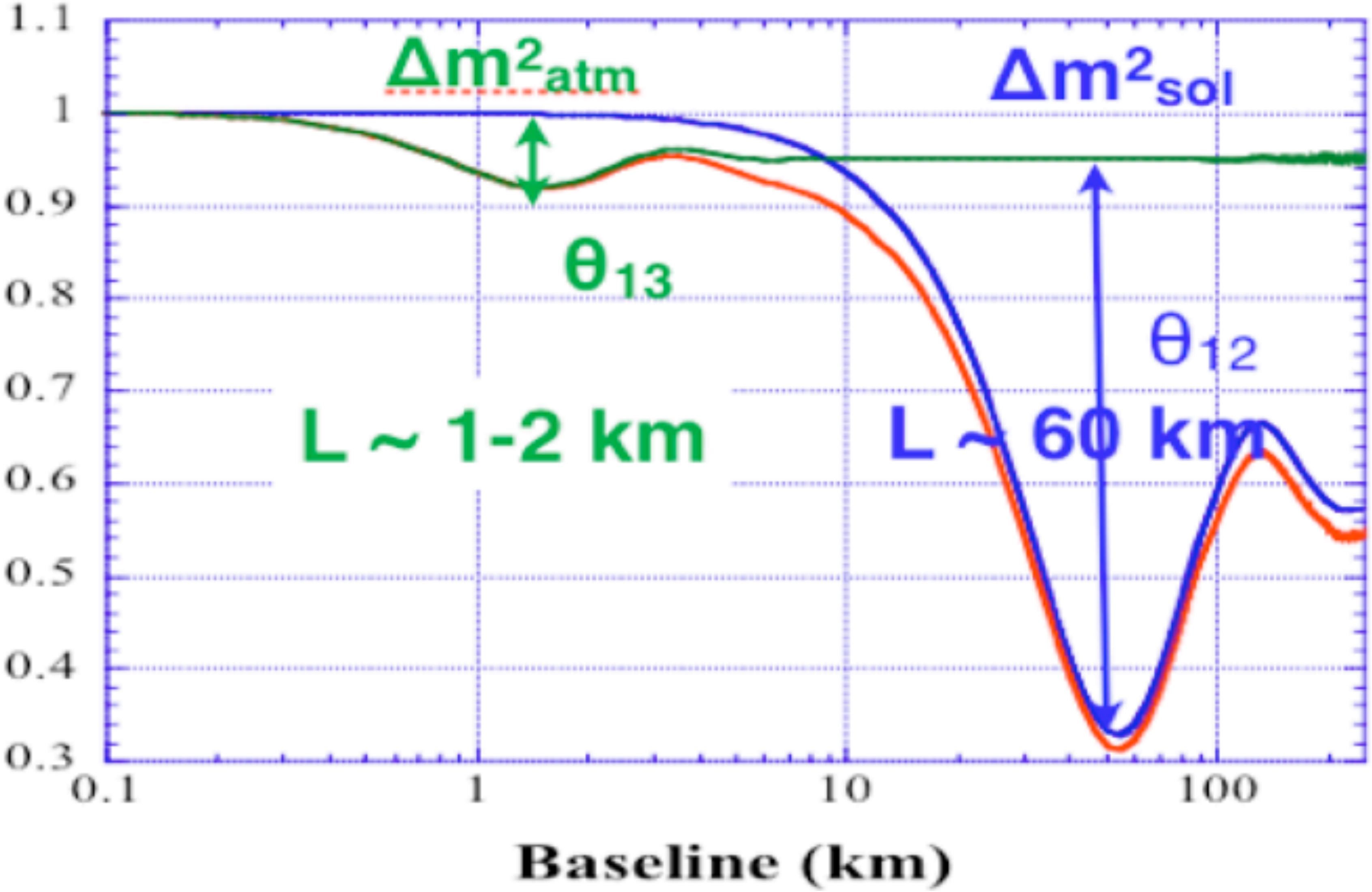
$$\sin^2(\Delta m^2_{ee} \tfrac{L}{4E}) \equiv \cos^2\theta_{12} \sin^2(\Delta m^2_{31} \tfrac{L}{4E}) + \sin^2\theta_{12} \sin^2(\Delta m^2_{32} \tfrac{L}{4E})$$

[Nunokawa & Parke (2005)]

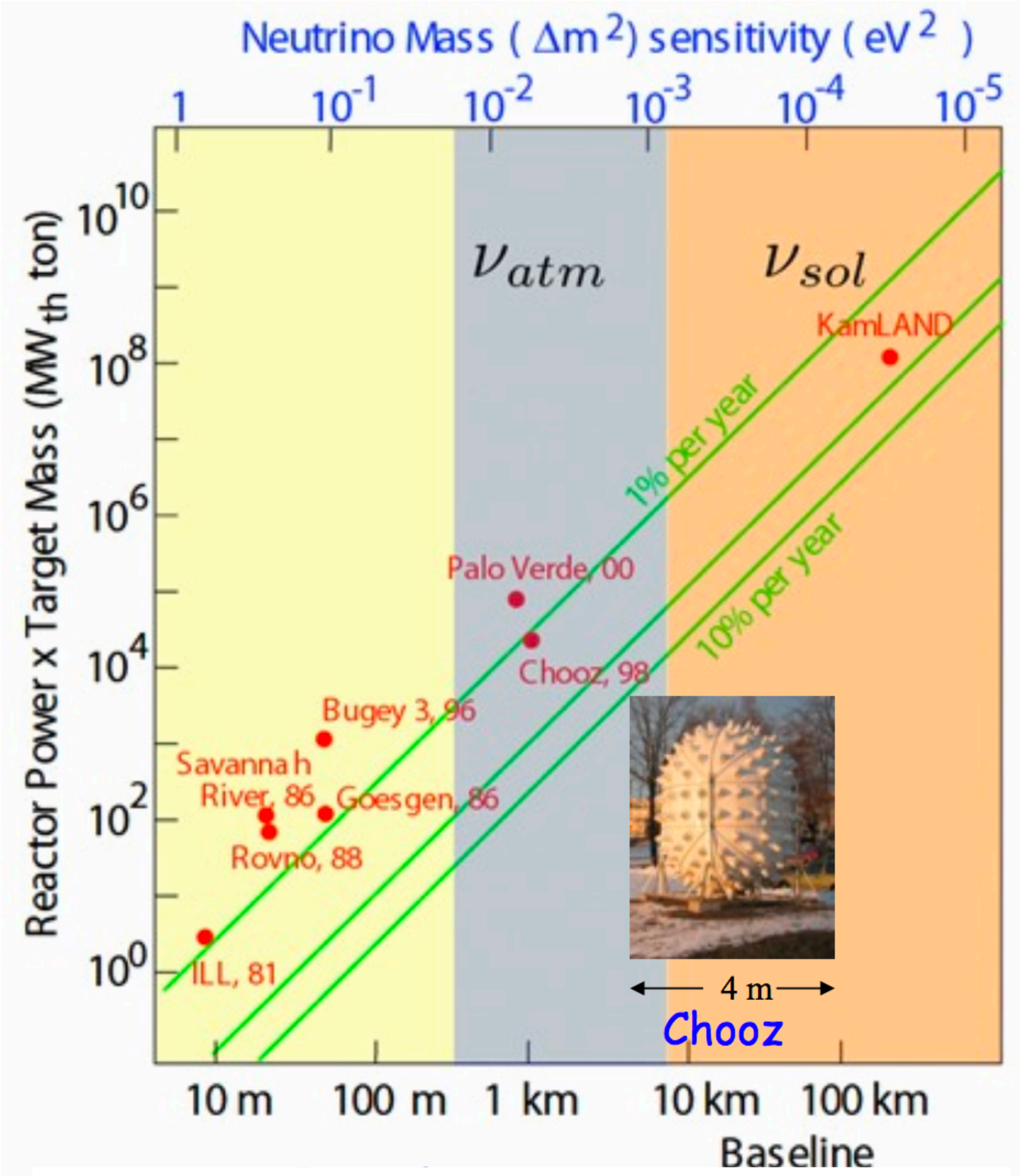
$$|\Delta m^2_{ee}| \simeq |\Delta m^2_{32}| \pm \underset{\cos^2\theta_{12}|\Delta m^2_{21}|}{5.21 \times 10^{-5}\mathrm{eV}^2}$$

+: Normal Hierarchy

−: Inverted Hierarchy

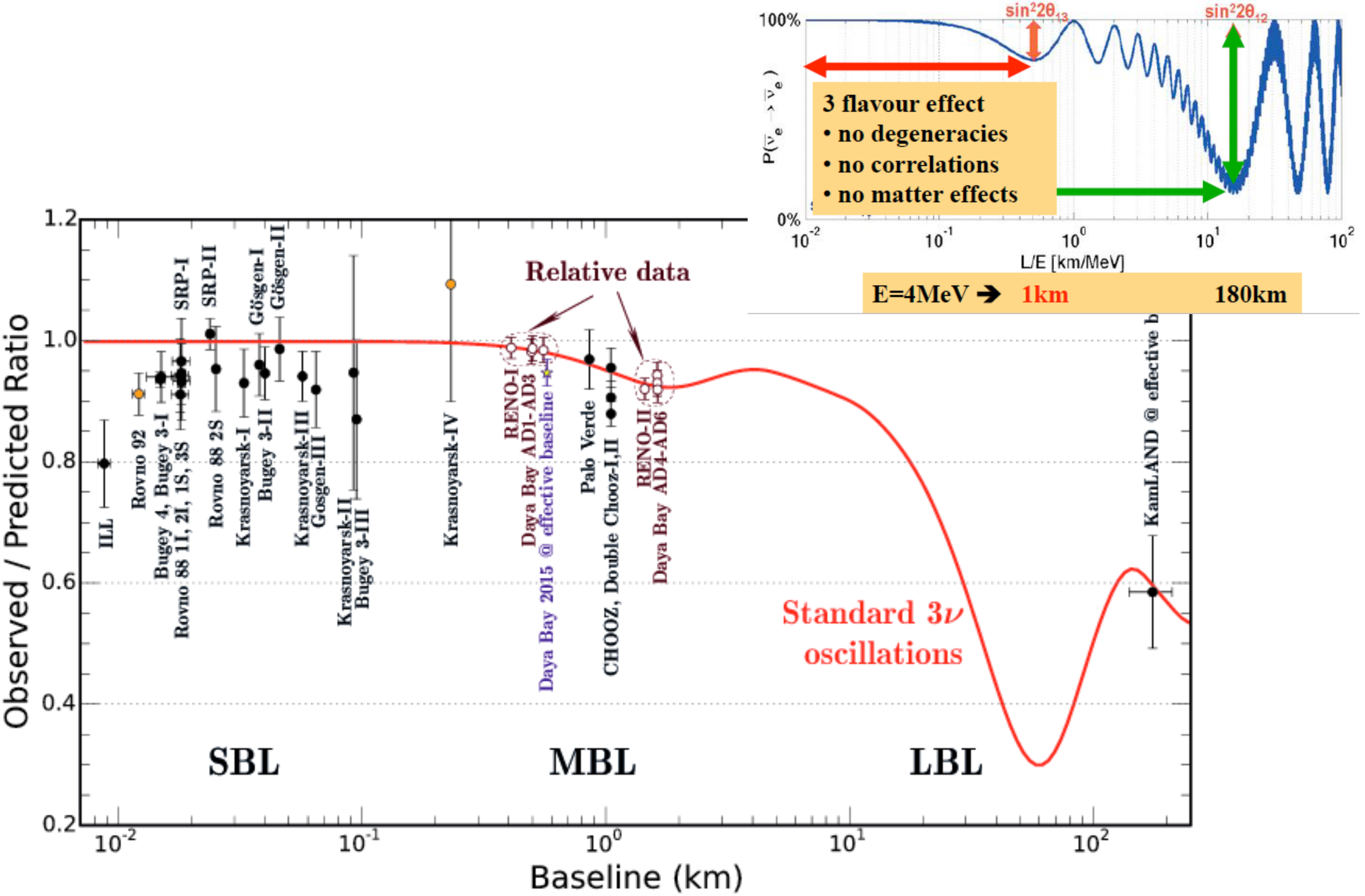


# The past


Neutrino Mass ( $\Delta m^2$) sensitivity ( $eV^2$ )
1
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-5}$
Reactor Power x Target Mass ($MW_{th}$ ton)
$10^{10}$
$10^8$
$10^6$
$10^4$
$10^2$
$10^0$
$\nu_{atm}$
$\nu_{sol}$
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

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



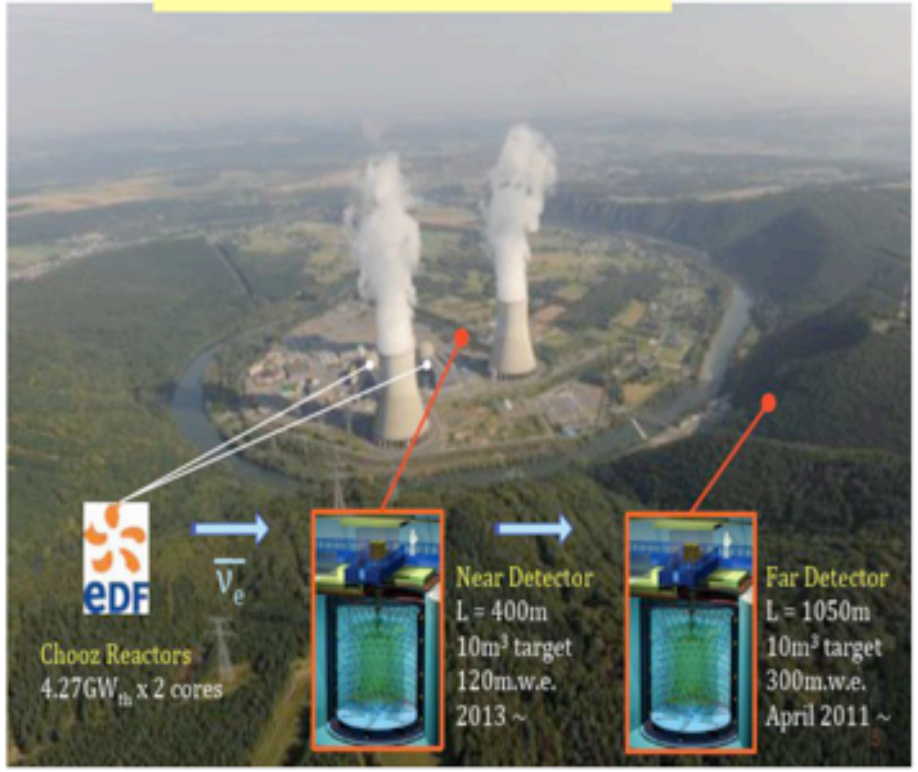
**3 flavour effect**
- **no degeneracies**
- **no correlations**
- **no matter effects**

# $\theta_{13}$: Three on-going experiments

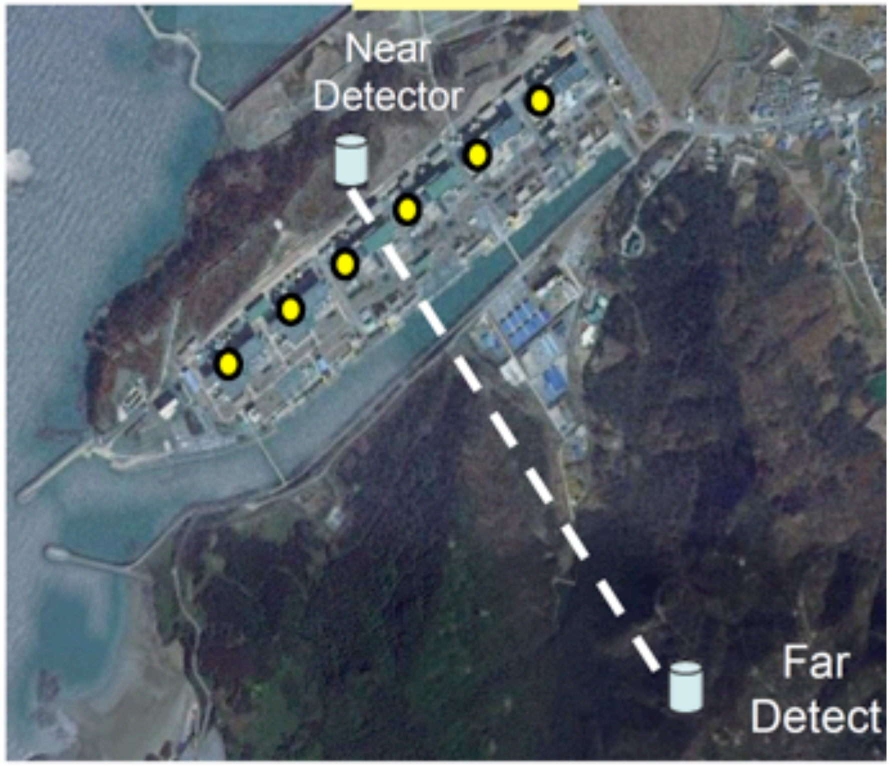
| Experiment | Power (GW) | Baseline(m) Near/Far | Detector(t) Near/Far | Overburden (MWE) Near/Far | Designed Sensitivity (90%CL) |
|---|---|---|---|---|---|
| Daya Bay | 17.4 | 470/576/1650 | 40//40/80 | 250/265/860 | ~ 0.008 |
| Double Chooz | 8.5 | 400/1050 | 8.2/8.2 | 120/300 | ~ 0.03 |
| Reno |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

**Daya Bay**

**Double Chooz**

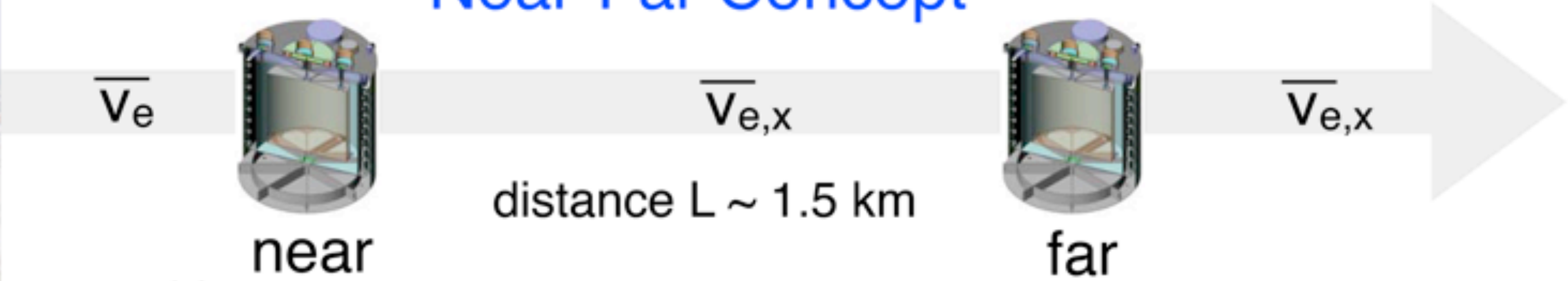


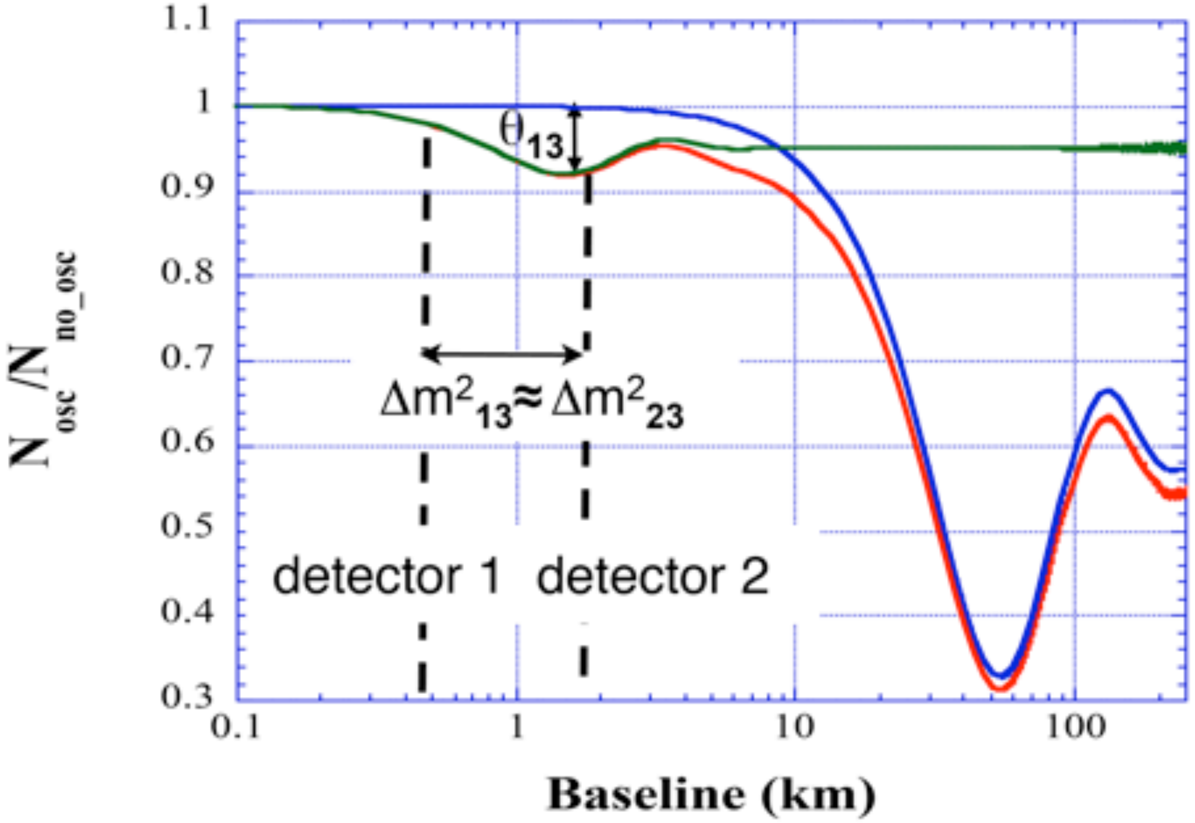
**Reno**



# Measuring $\theta_{13}$ with Reactor Experiments

## Near-Far Concept





**Absolute Reactor Flux**
Largest uncertainty in previous measurements

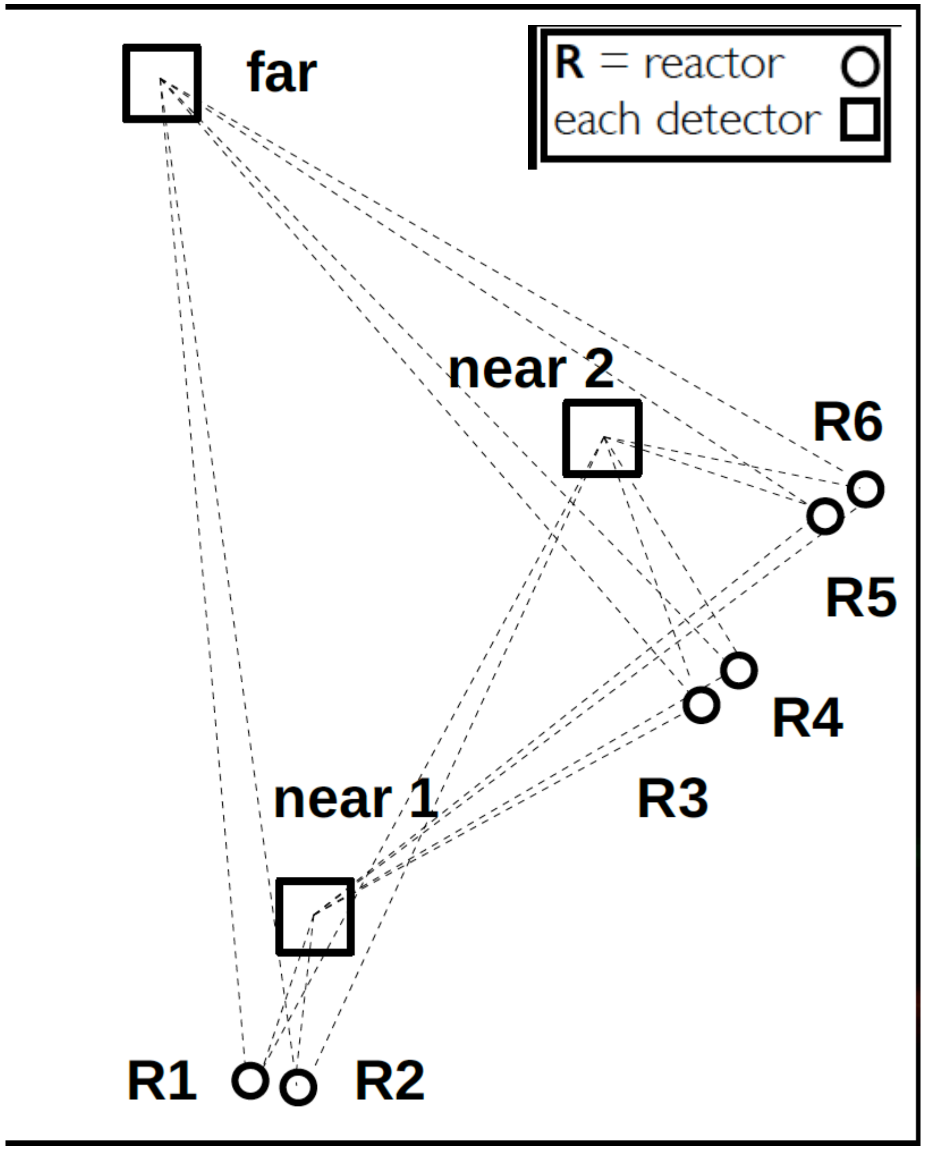
**Relative Measurement**
Removes absolute uncertainties!

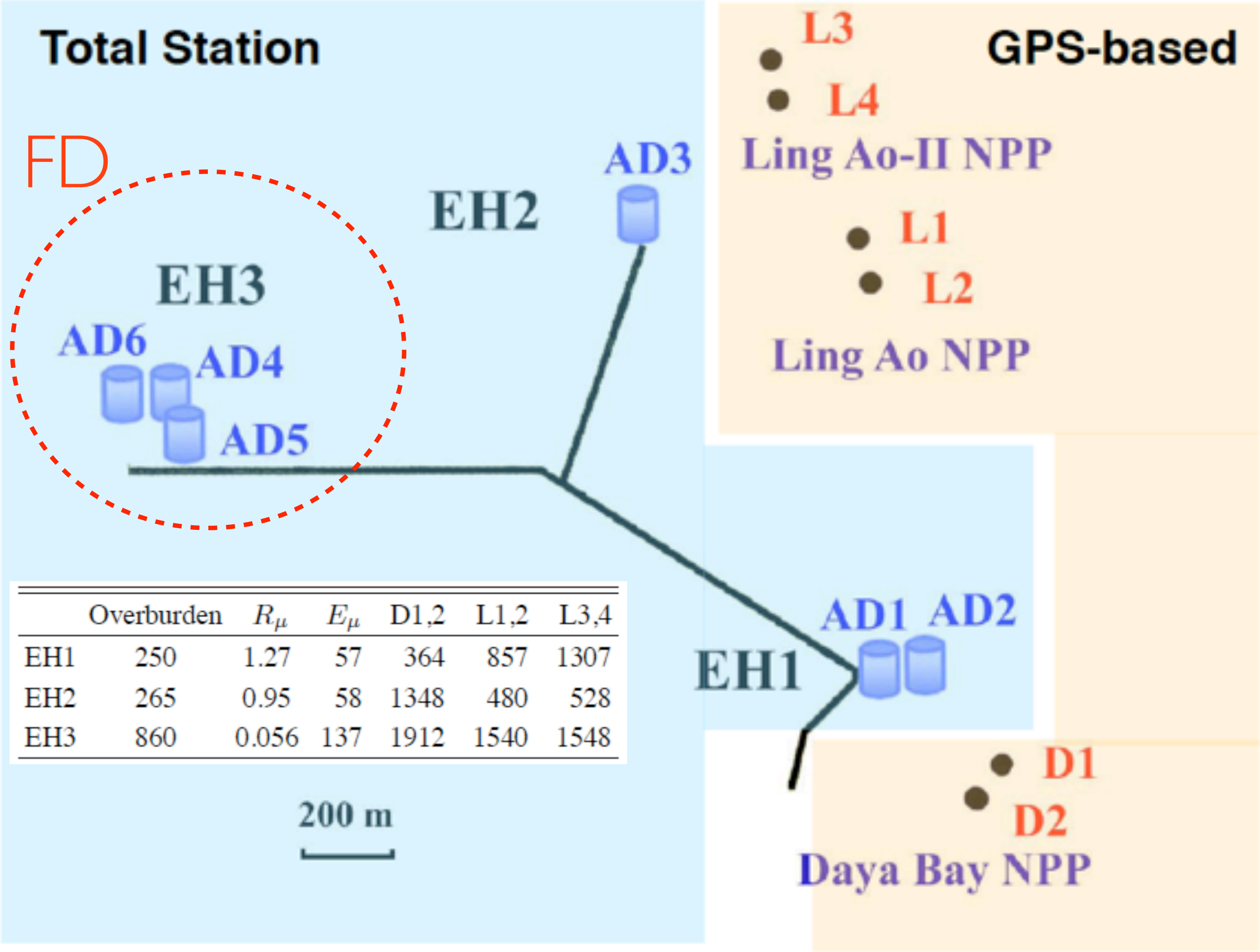
First proposed by L. A. Mikaelyan and V.V. Sinev, Phys. Atomic Nucl. 63 1002 (2000)

$$\frac{N_\mathrm{f}}{N_\mathrm{n}} = \left(\frac{N_\mathrm{p,f}}{N_\mathrm{p,n}}\right)\left(\frac{L_\mathrm{n}}{L_\mathrm{f}}\right)^2\left(\frac{\epsilon_\mathrm{f}}{\epsilon_\mathrm{n}}\right)\left[\frac{P_\mathrm{sur}(E,L_\mathrm{f})}{P_\mathrm{sur}(E,L_\mathrm{n})}\right]$$

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

# Reactor-Detector Distance Survey





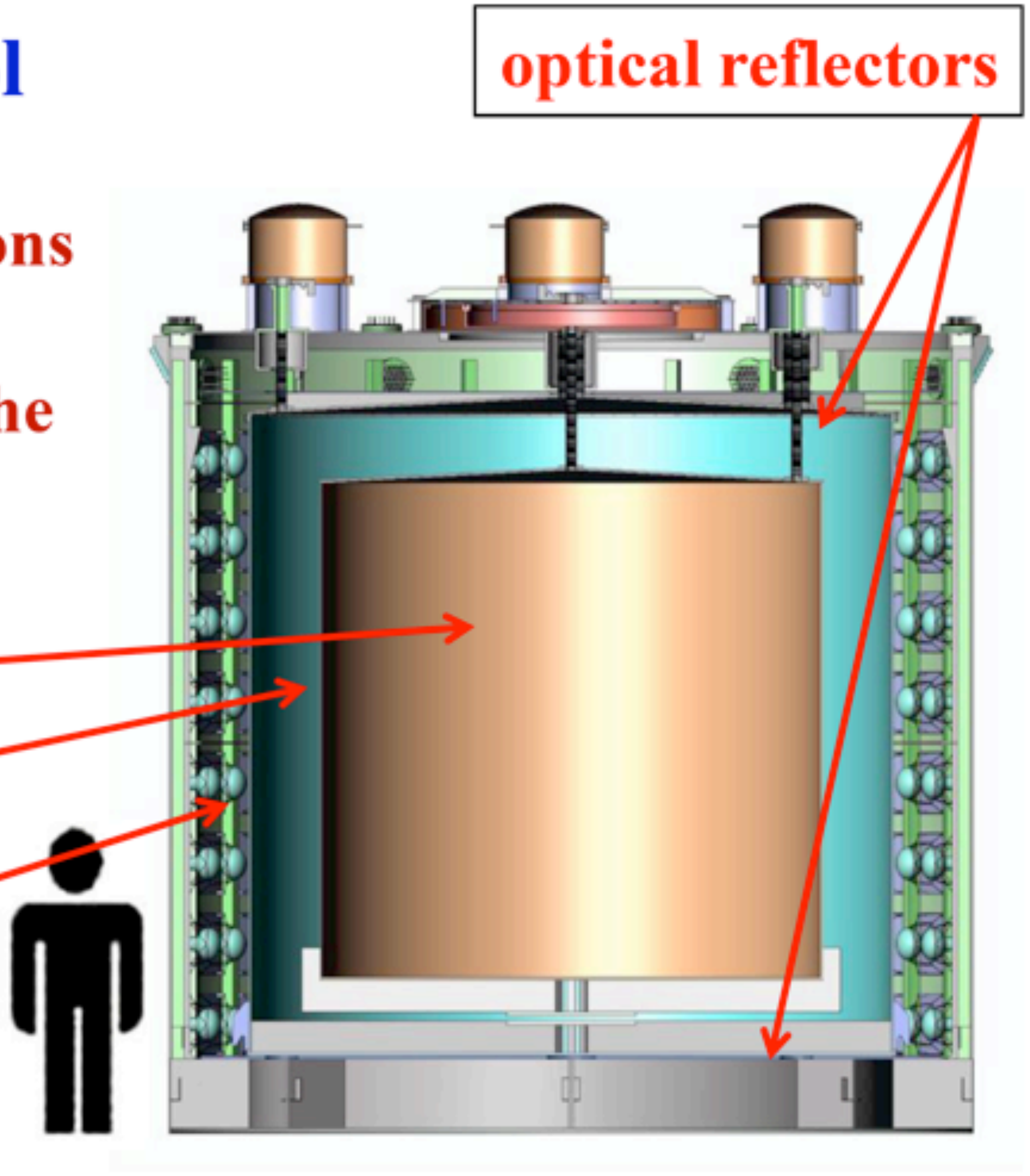
| | Overburden | $R_\mu$ | $E_\mu$ | D1,2 | L1,2 | L3,4 |
|---|---|---|---|---|---|---|
| EH1 | 250 | 1.27 | 57 | 364 | 857 | 1307 |
| EH2 | 265 | 0.95 | 58 | 1348 | 480 | 528 |
| EH3 | 860 | 0.056 | 137 | 1912 | 1540 | 1548 |

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

$$\frac{N_{\rm f}}{N_{\rm n}} = \left(\frac{N_{\rm p,f}}{N_{\rm p,n}}\right)\underbrace{\left(\frac{L_{\rm n}}{L_{\rm f}}\right)^2}_{\text{distances}}\left(\frac{\epsilon_{\rm f}}{\epsilon_{\rm n}}\right)\left[\frac{P_{\rm sur}(E,L_{\rm f})}{P_{\rm sur}(E,L_{\rm n})}\right]$$

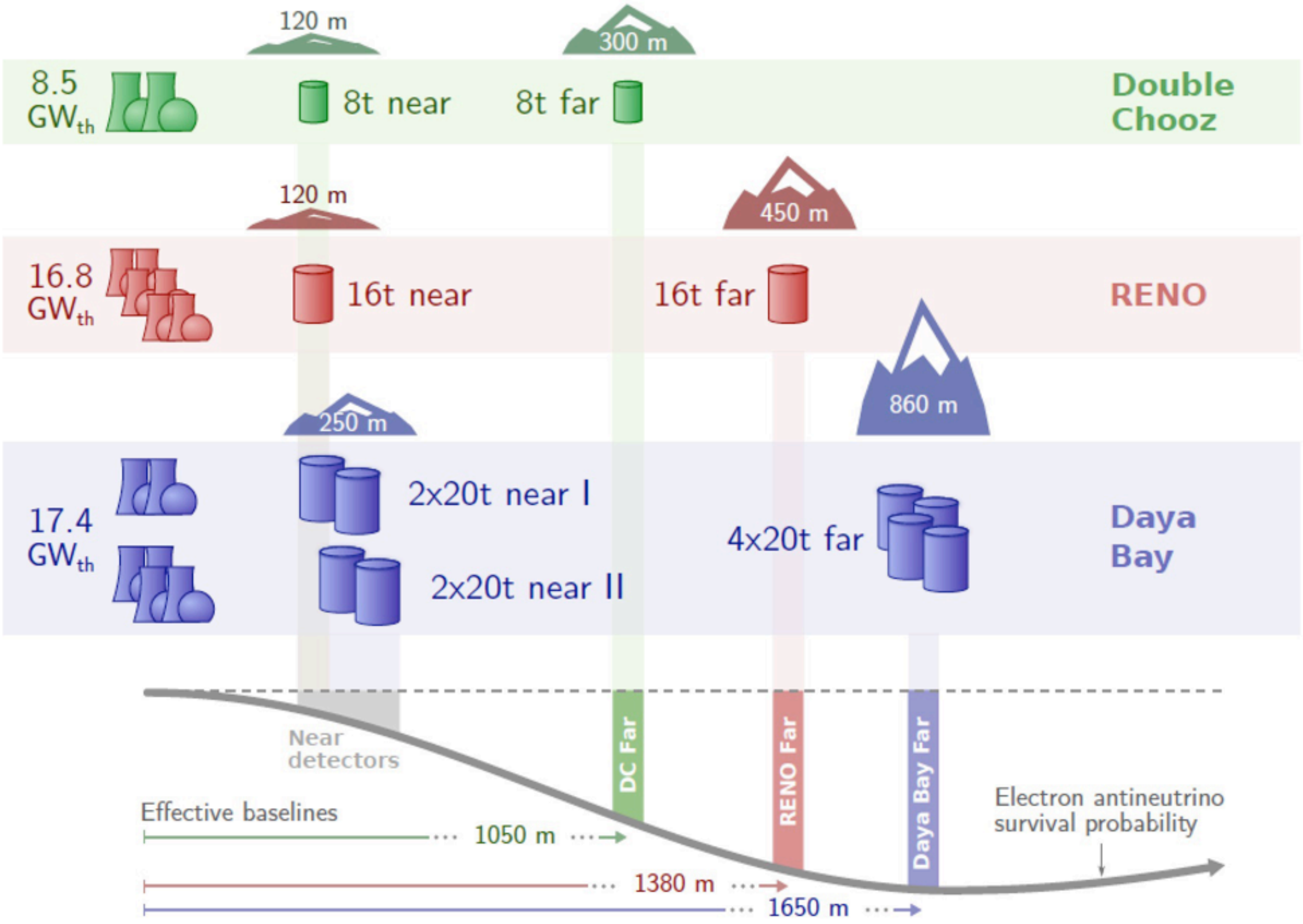
# Detectors

- 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



- Light collection

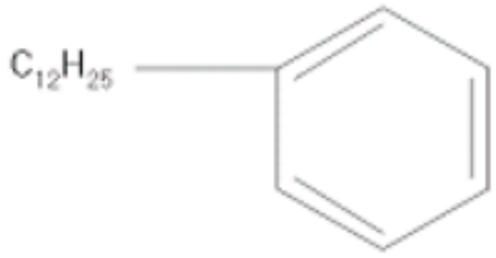
| | PMT | Coverage | pe yield | pe yield/Coverage |
|---|---|---|---|---|
| Daya Bay | 192 8" | ~6% | 163 pe/MeV | 1.77 |
| RENO | 354 10" | ~15% | 230 pe/MeV | 1 |
| Double Chooz | 390 10" | ~16% | 200 pe/MeV | 0.81 |



⇒ ...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)

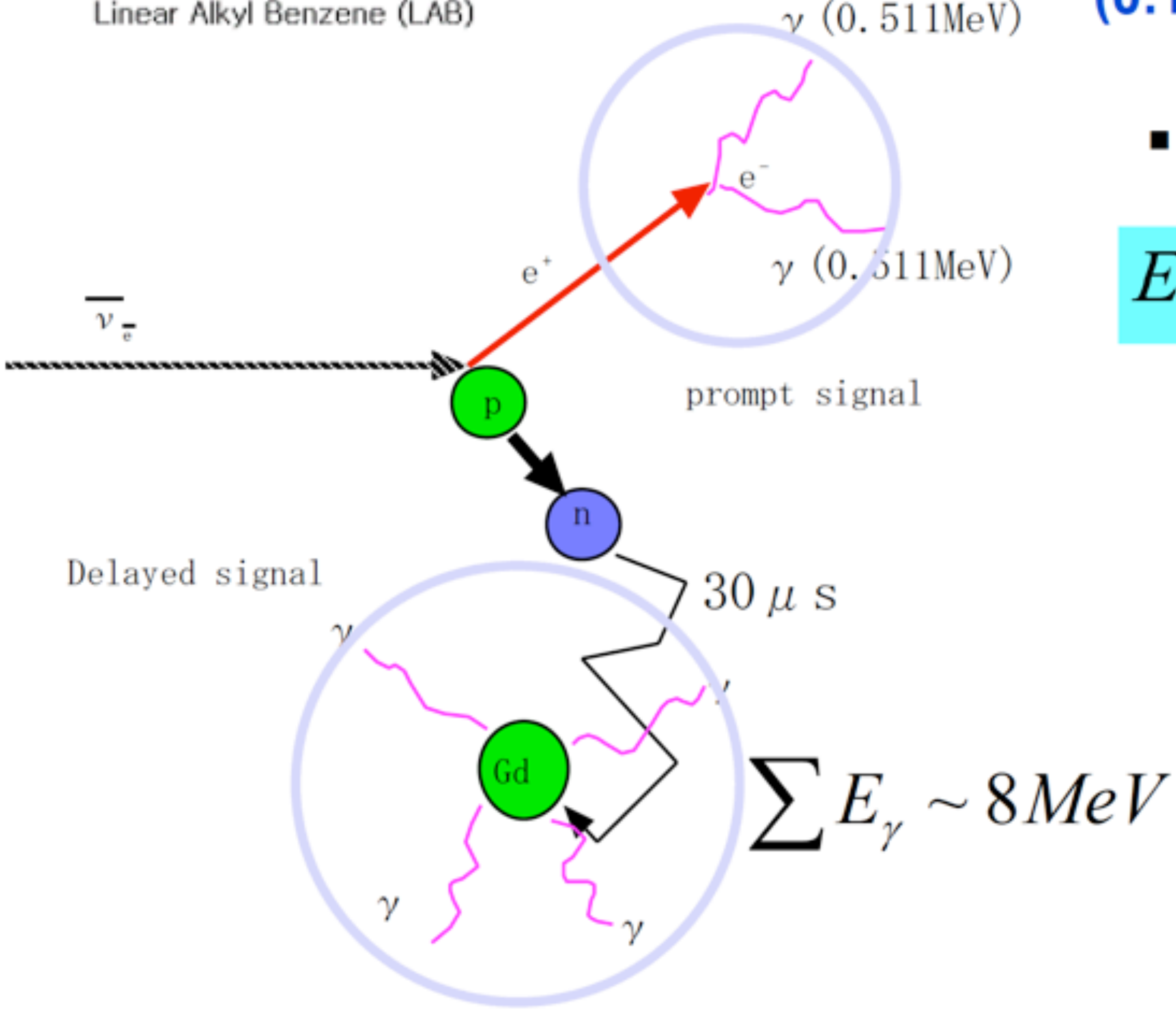
$$\bar{\nu}_e + p \rightarrow \boxed{e^+} + n$$

~180 μs (delayed signal)

+ p → D + γ (2.2 MeV)

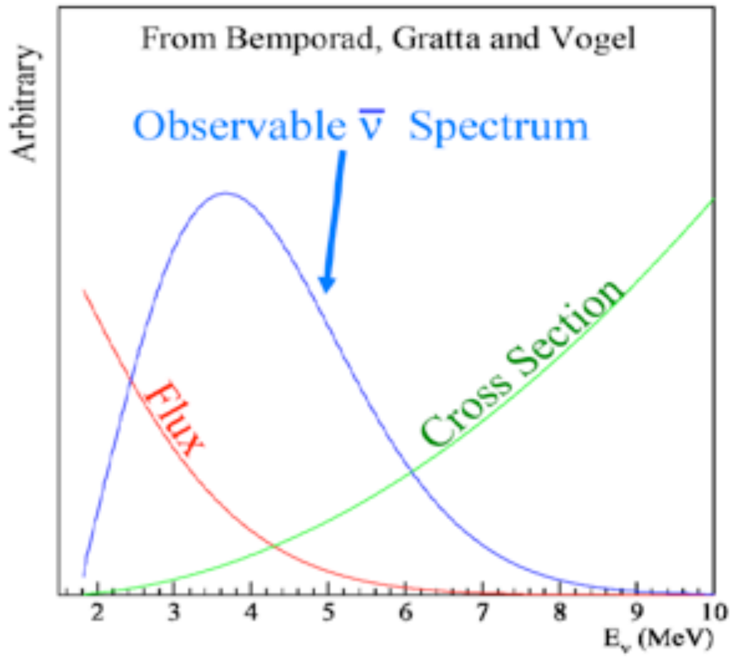
~28 μs (0.1% Gd)

+ Gd → Gd + γ's (8 MeV)



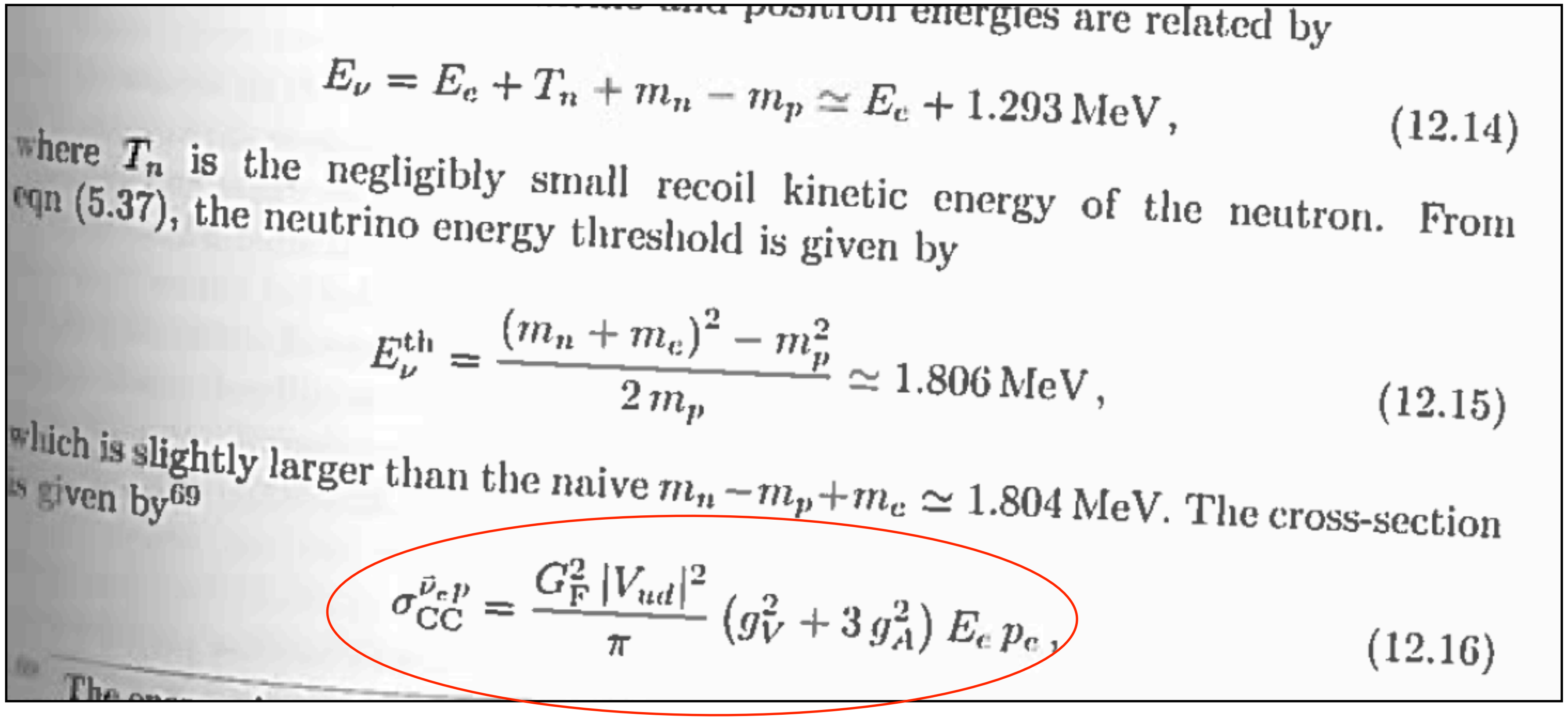
- **Neutrino energy measurement**

$$E_{\bar{\nu}} \cong T_{e^+} + \underbrace{T_n}_{10\text{-}40\ keV} + \underbrace{(M_n - M_p) + m_{e^+}}_{1.8\ MeV}$$



$E(nu) = E_{prompt}+(M_n-M_p)-m_e^-$

# Cross section



and positron energies are related by

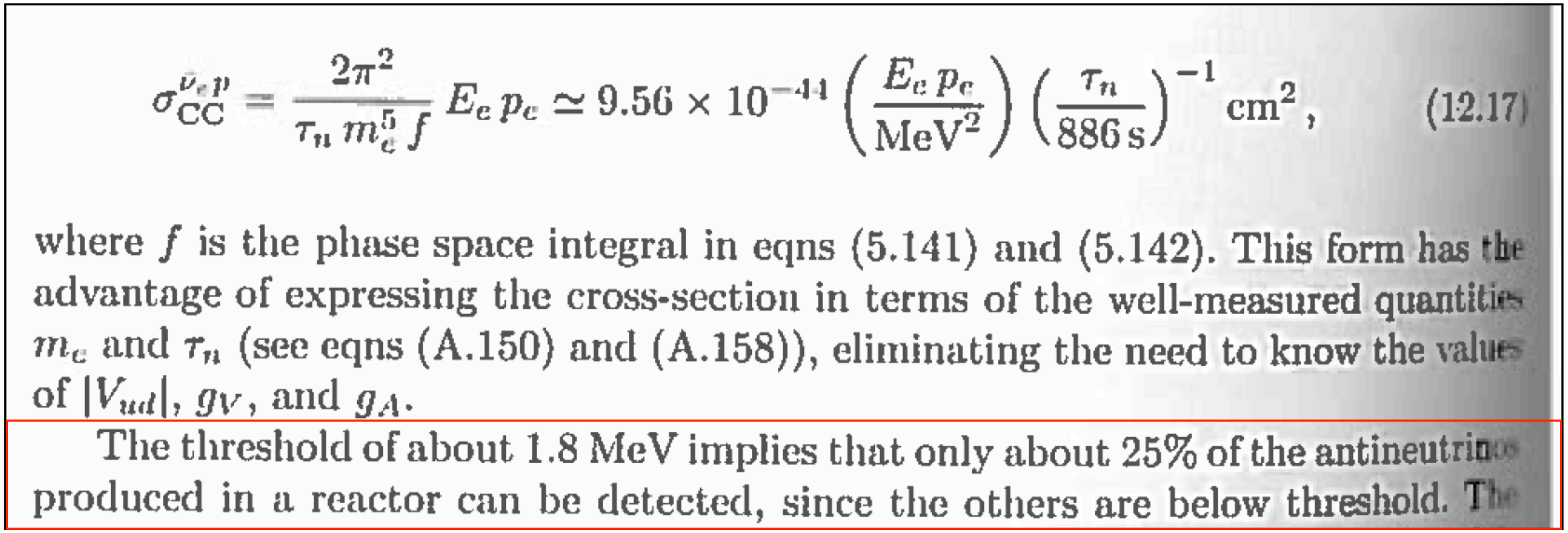
$$E_\nu = E_e + T_n + m_n - m_p \simeq E_e + 1.293\,\mathrm{MeV}, \qquad (12.14)$$

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

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

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

$$\sigma_{\mathrm{CC}}^{\bar{\nu}_e p} = \frac{G_F^2\,|V_{ud}|^2}{\pi}\,(g_V^2 + 3\,g_A^2)\,E_e\,p_e, \qquad (12.16)$$



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

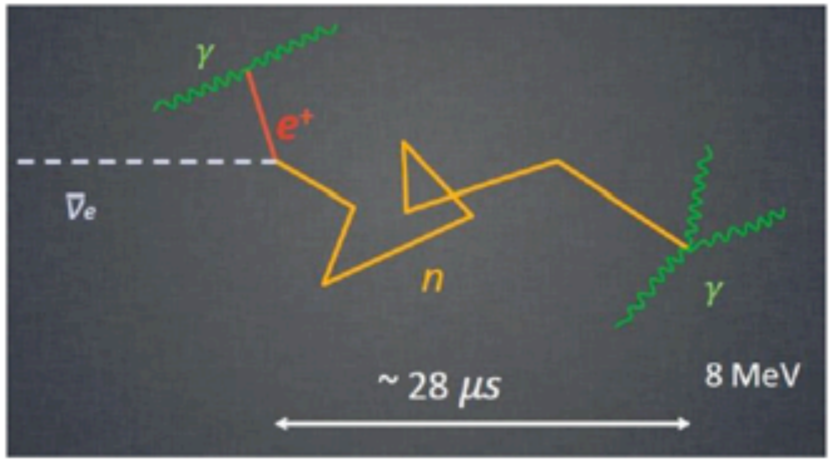
where $f$ is the phase space integral in eqns (5.141) and (5.142). This form has the advantage of expressing the cross-section in terms of the well-measured quantities $m_e$ and $\tau_n$ (see eqns (A.150) and (A.158)), eliminating the need to know the values of $|V_{ud}|$, $g_V$, and $g_A$.

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

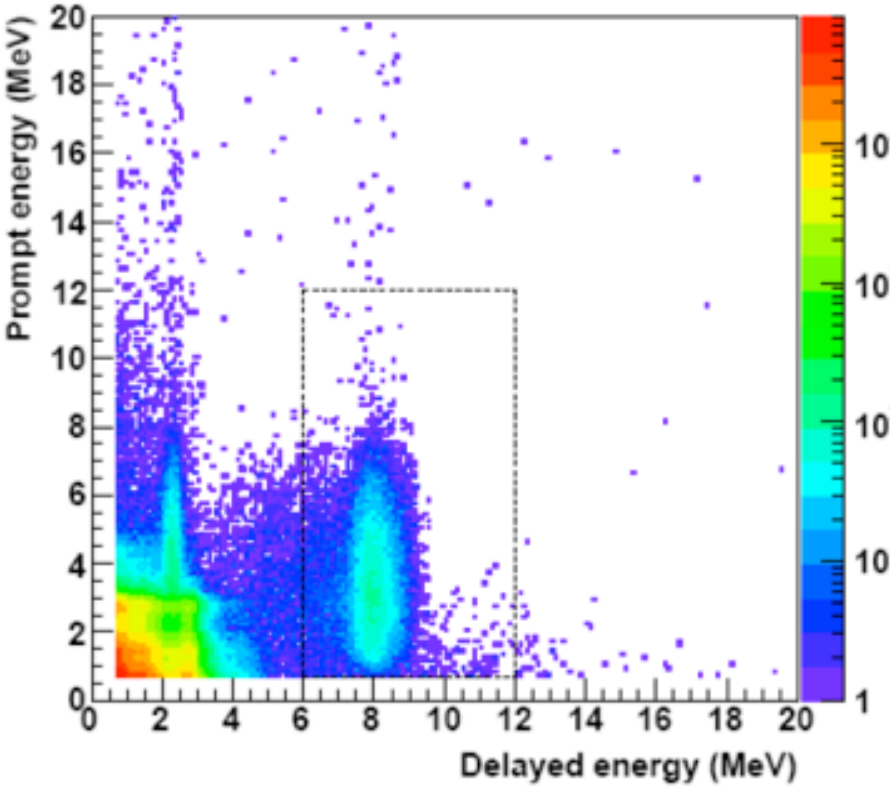
x-sec grows linearly with E

# 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: $^{13}C(\alpha,n)^{16}O$

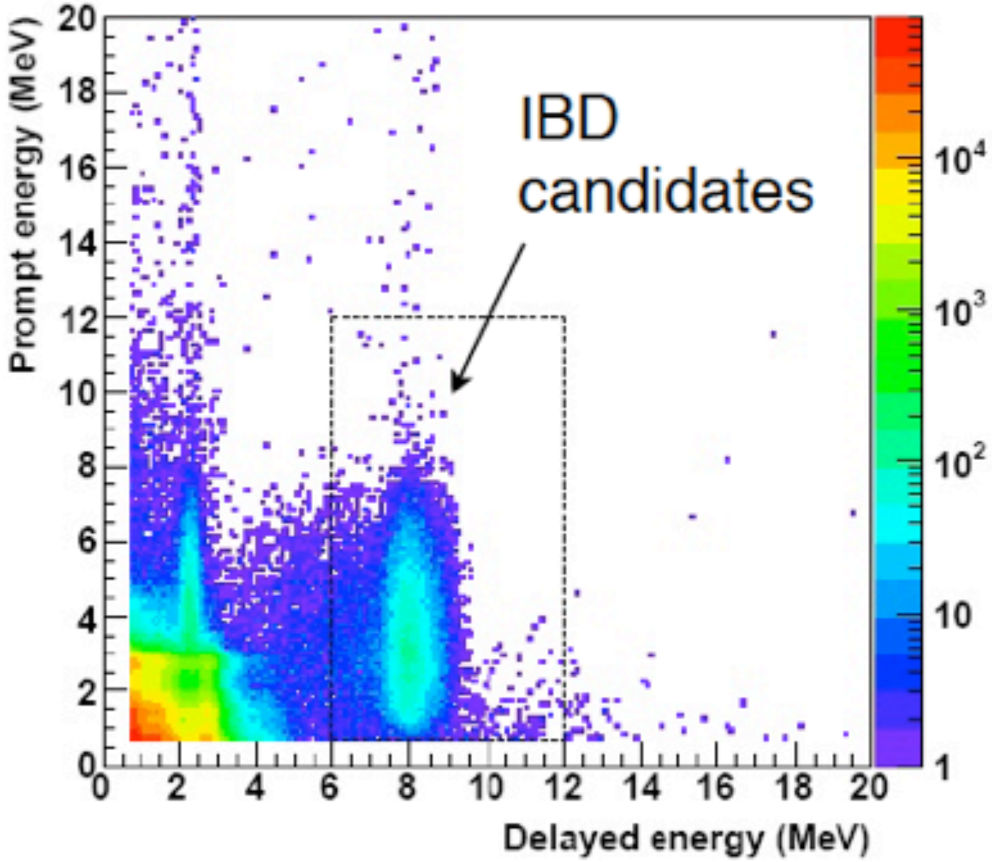


Gd used because of delay @ 8 MeV (radiogenic BG dominates ≤ 3MeV) and high thermal neutron capture x-sec: 260 b *(see also slide 43)*

# Antineutrino (IBD) Selection

## Selection of Prompt + Delayed

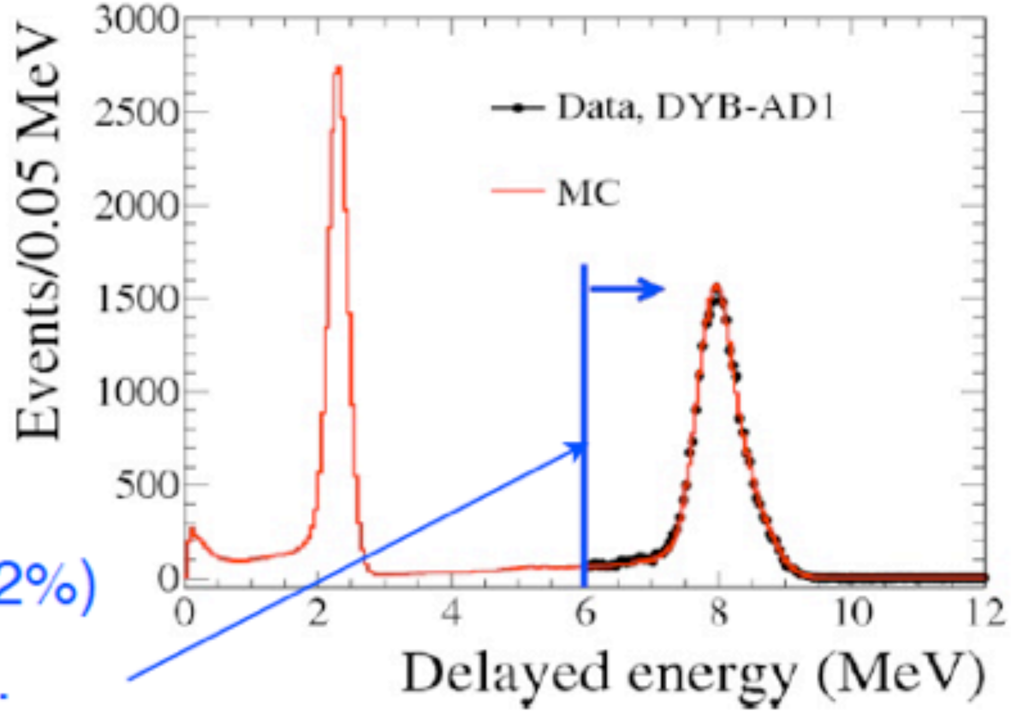
- Reject Flashers
- Prompt Positron: 0.7 MeV < $E_p$ < 12 MeV
- Delayed Neutron: 6.0 MeV < $E_d$ < 12 MeV
- Capture time: 1 μs < Δt < 200 μs
- Muon Veto:
  - Pool Muon: Reject 0.6ms
  - AD Muon (>20 MeV): Reject 1ms
  - AD Shower Muon (>2.5GeV): Reject 1s
- Multiplicity:
  - No other signal > 0.7 MeV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



Selection driven by uncertainty in relative detector efficiency

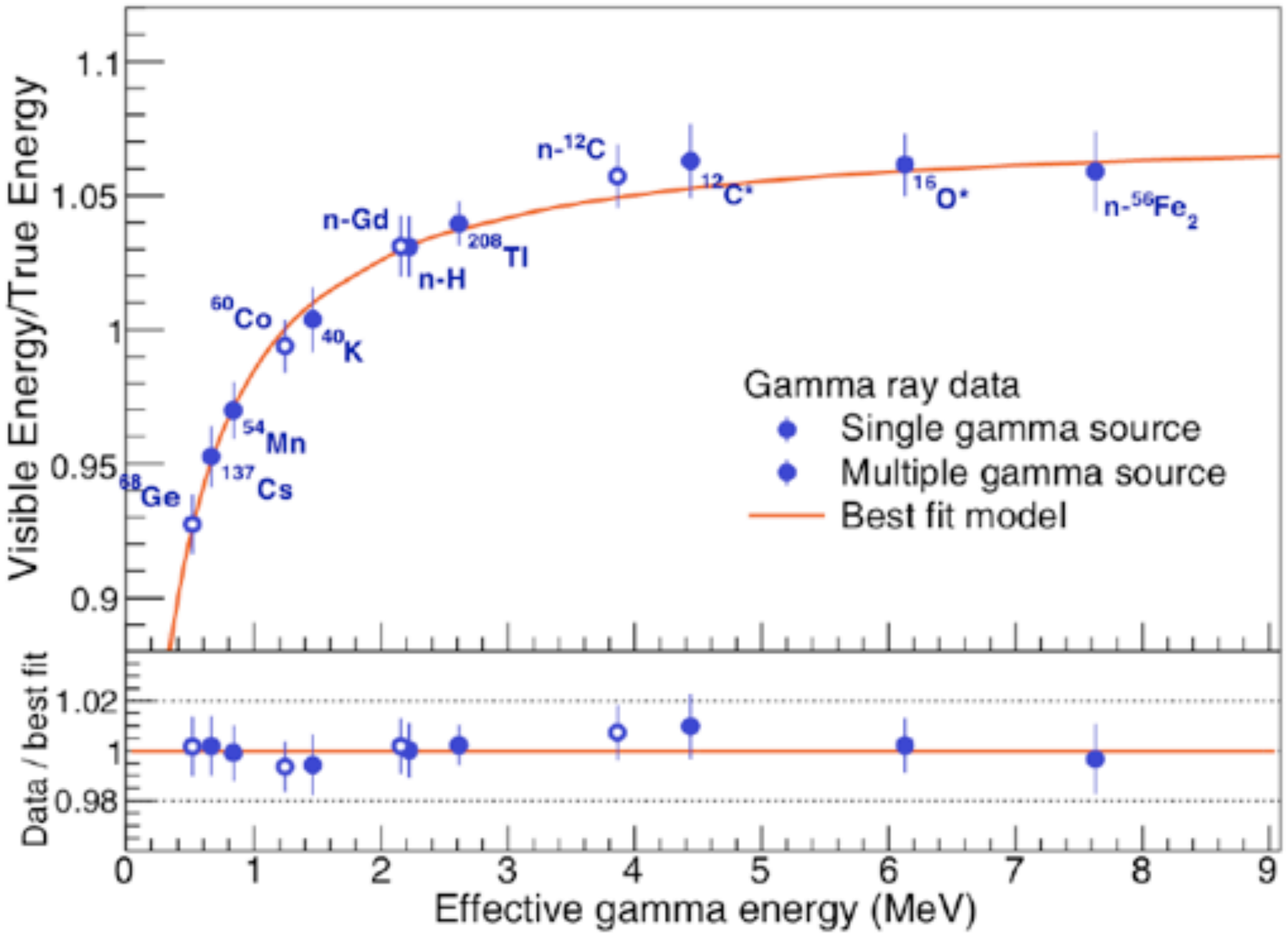
$$\frac{N_{\rm f}}{N_{\rm n}} = \left(\frac{N_{\rm p,f}}{N_{\rm p,n}}\right)\left(\frac{L_{\rm n}}{L_{\rm f}}\right)^2 \boxed{\left(\frac{\epsilon_{\rm f}}{\epsilon_{\rm n}}\right)} \left[\frac{P_{\rm sur}(E,L_{\rm f})}{P_{\rm sur}(E,L_{\rm n})}\right]$$

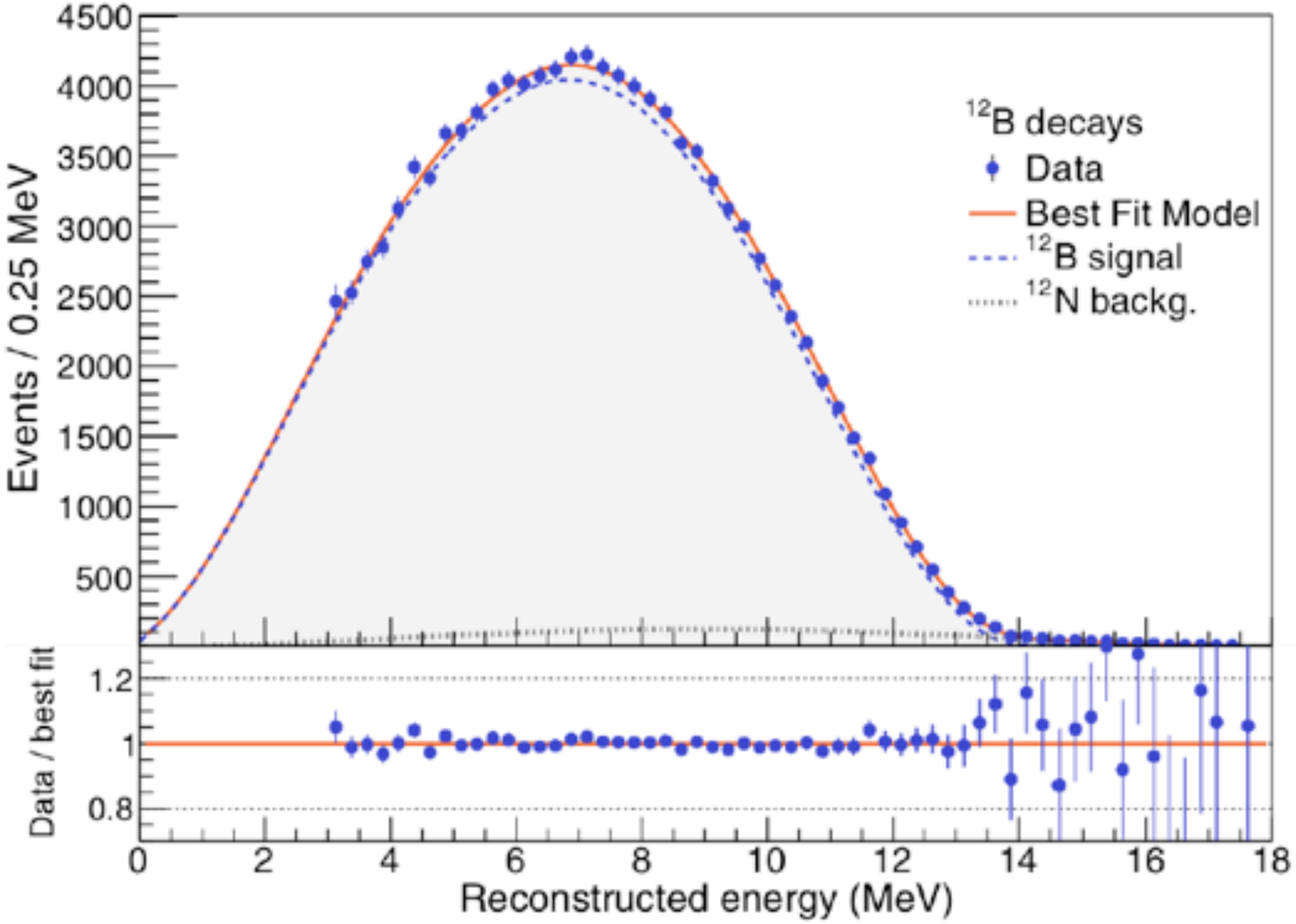
Uncertainty in relative $E_d$ efficiency (0.12%) between detectors is largest systematic.



# Energy model

**Zeyuan Yu**
**Institute of High Energy Physics, China**

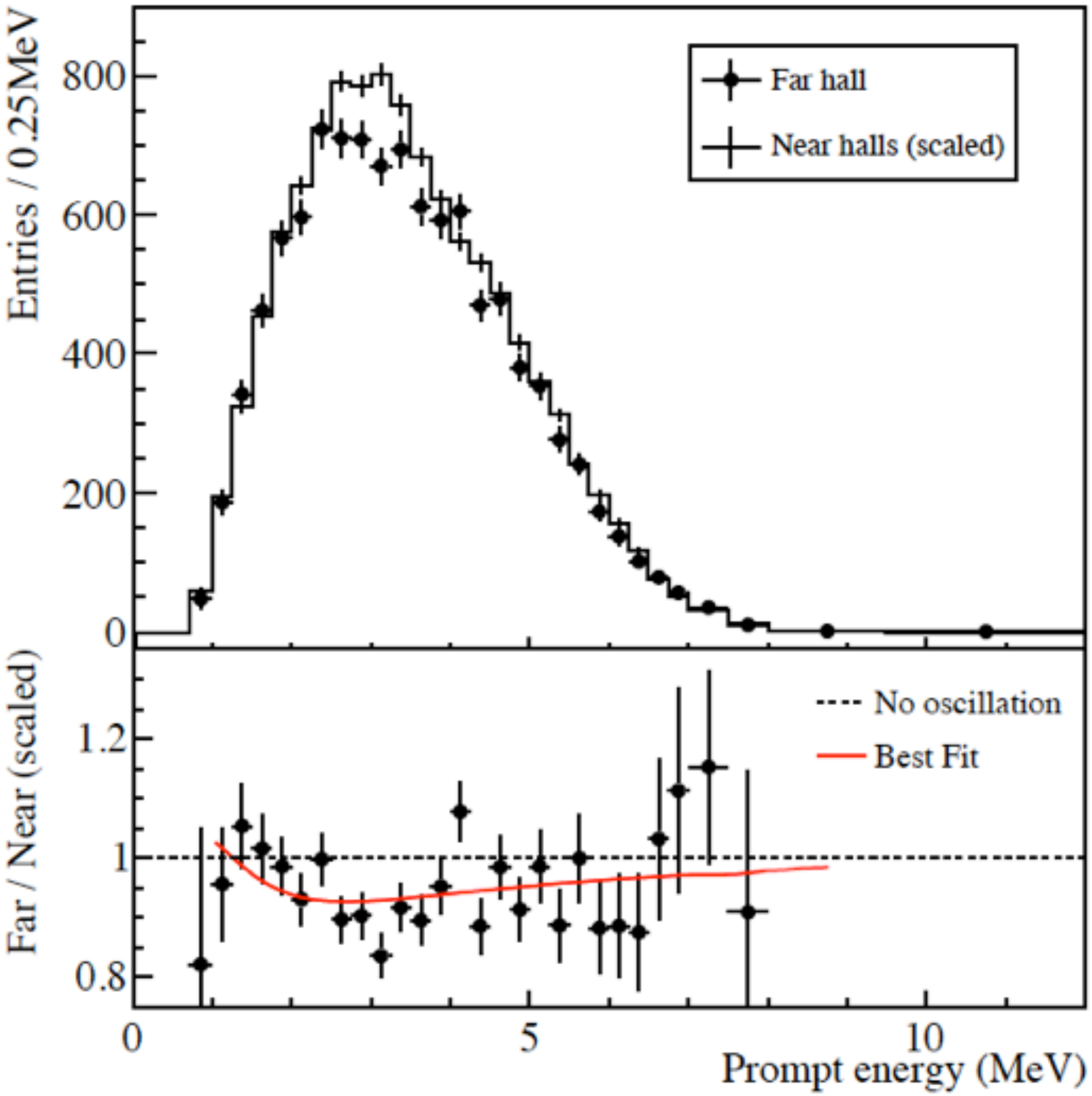




- **Energy model**
  - **Includes the non-linearity from LS and readout electronics**
  - **Built based on various $\gamma$ peaks and continuous $^{12}$B $\beta$ spectrum**
- **Validated with**
  - **Michel electron; $\beta$+$\gamma$ continuous spectra from $^{212/214}$Bi and $^{208}$Tl**
  - **Bench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

# Far vs. Near Comparison

## Compare measured rates and spectra



$$R = \frac{Far_{measured}}{Far_{expected}} = \frac{M_4 + M_5 + M_6}{\sum_{i=4}^{6}(\alpha_i(M_1 + M_2) + \beta_i M_3)}$$

$M_n$ are the measured rates in each detector. Weights $\alpha_i$,$\beta_i$ are determined from baselines and reactor fluxes.

R = 0.940 ± 0.011 (stat) ± 0.004 (syst)

Clear observation of far site deficit (~6%).

Spectral distortion consistent with oscillation.*

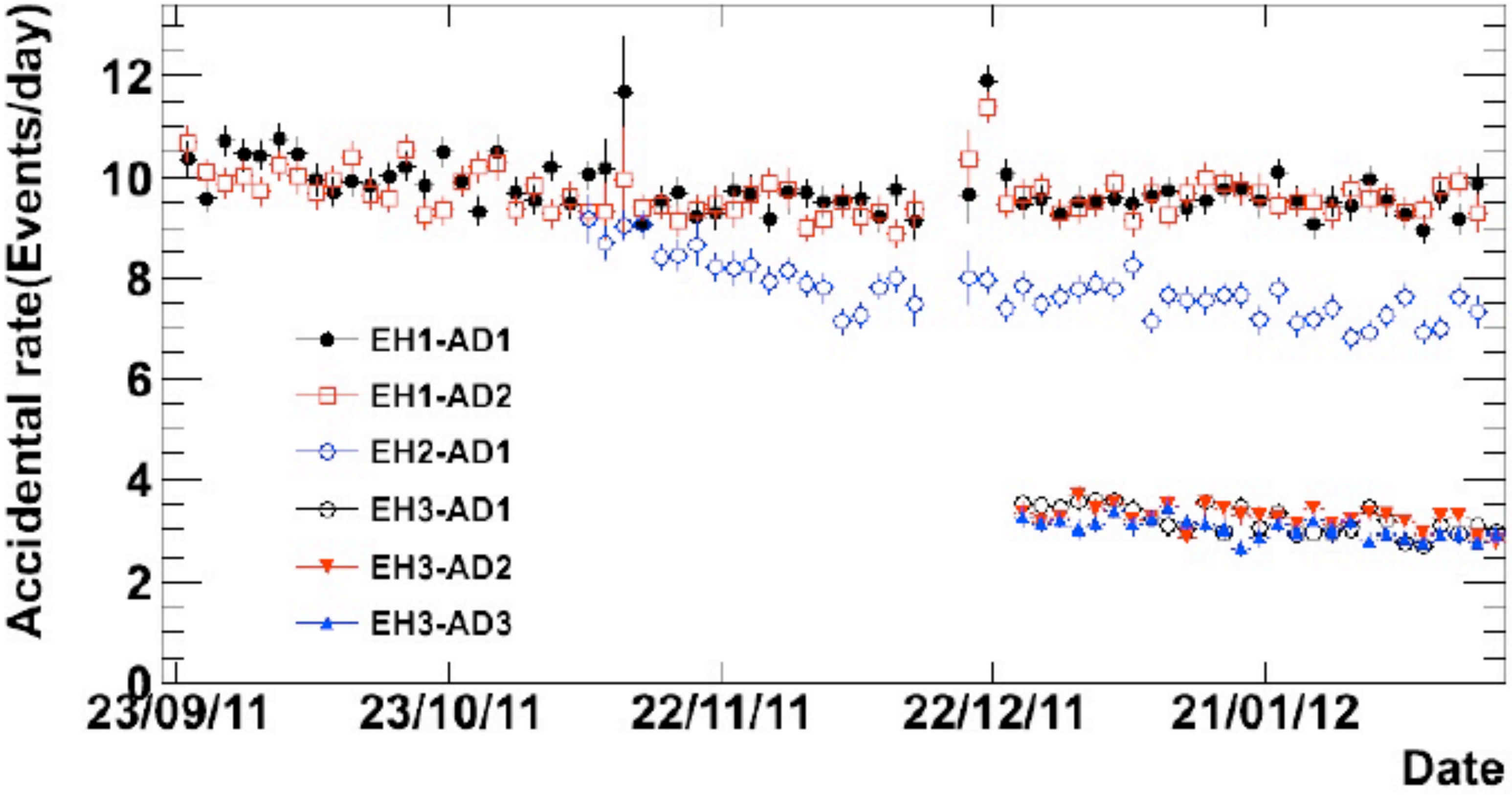
* Caveat: Spectral systematics not fully studied; $\theta_{13}$ value from shape analysis is not recommended.

# 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



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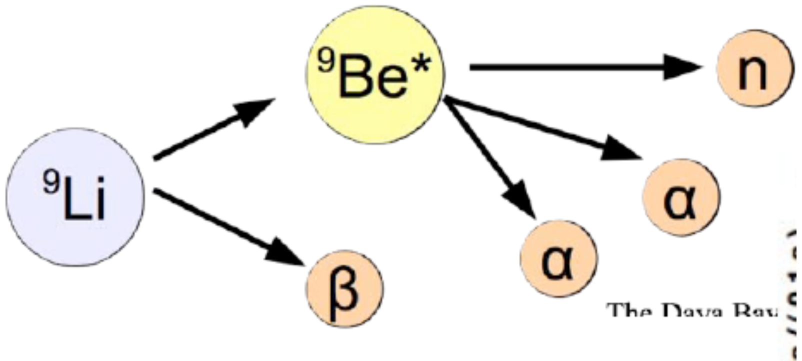
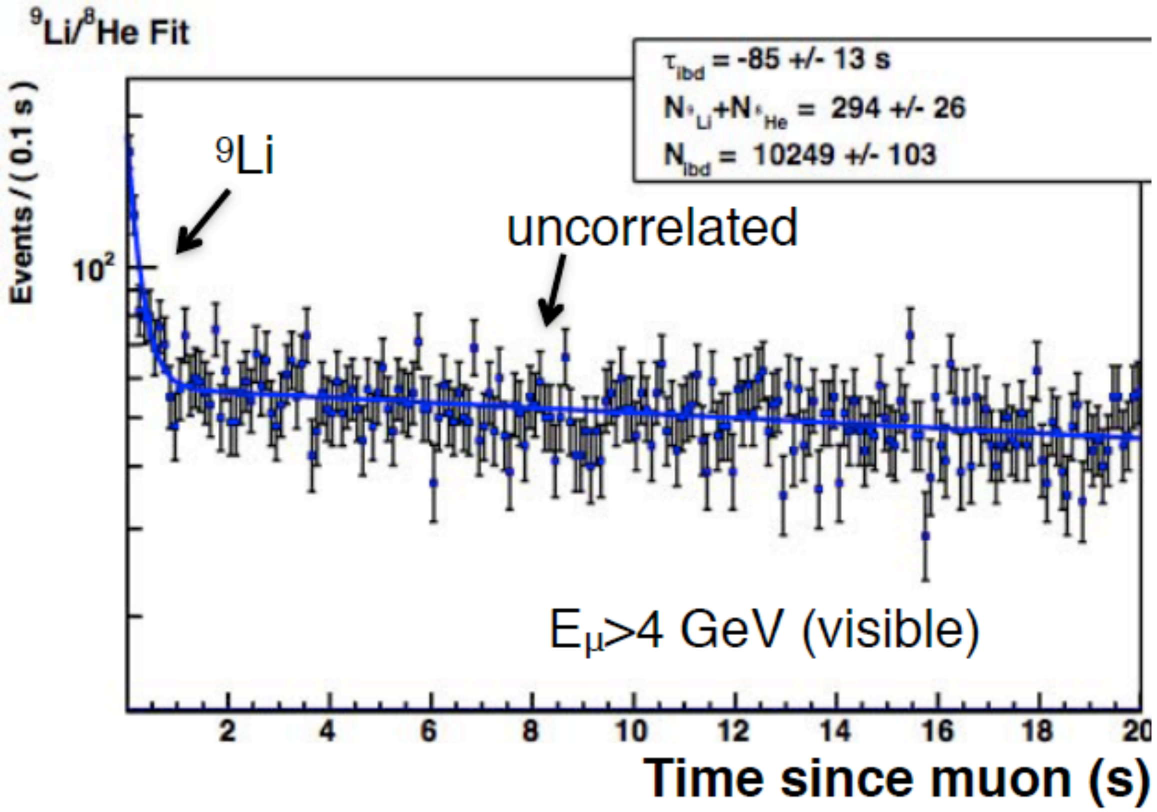
## Cosmogenic

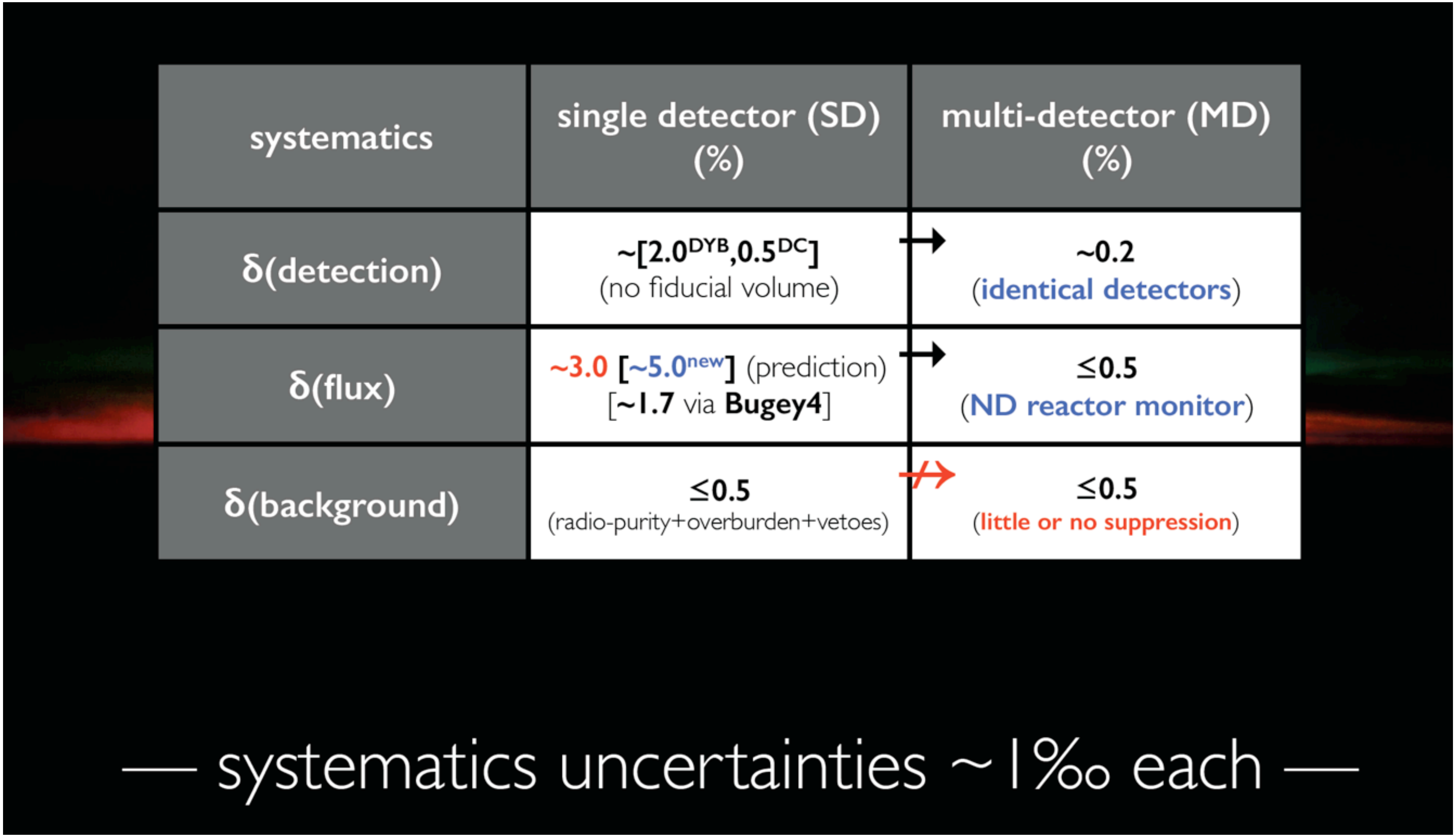
**β-n decay:**
- Prompt: β-decay
- Delayed: neutron capture



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



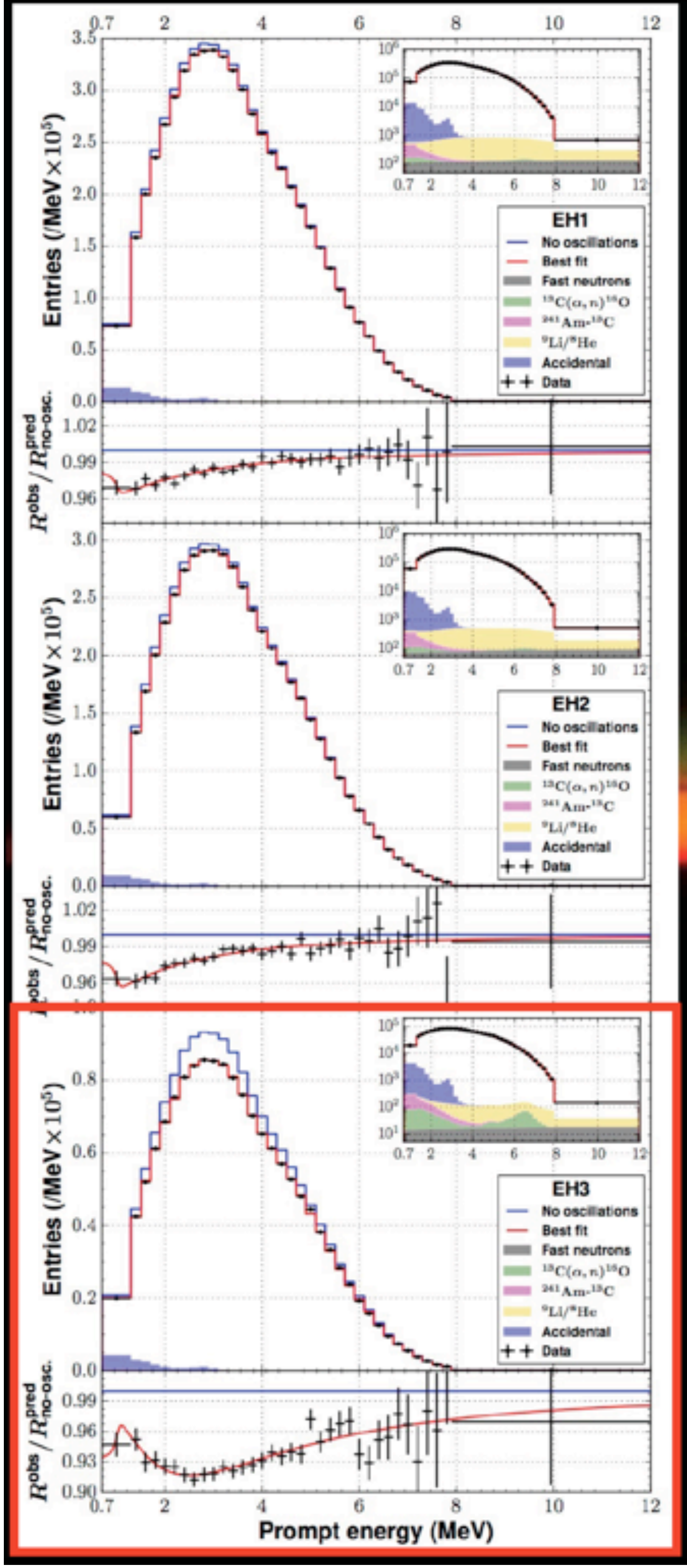
# Summary of uncertainties and benefit of ND+FD

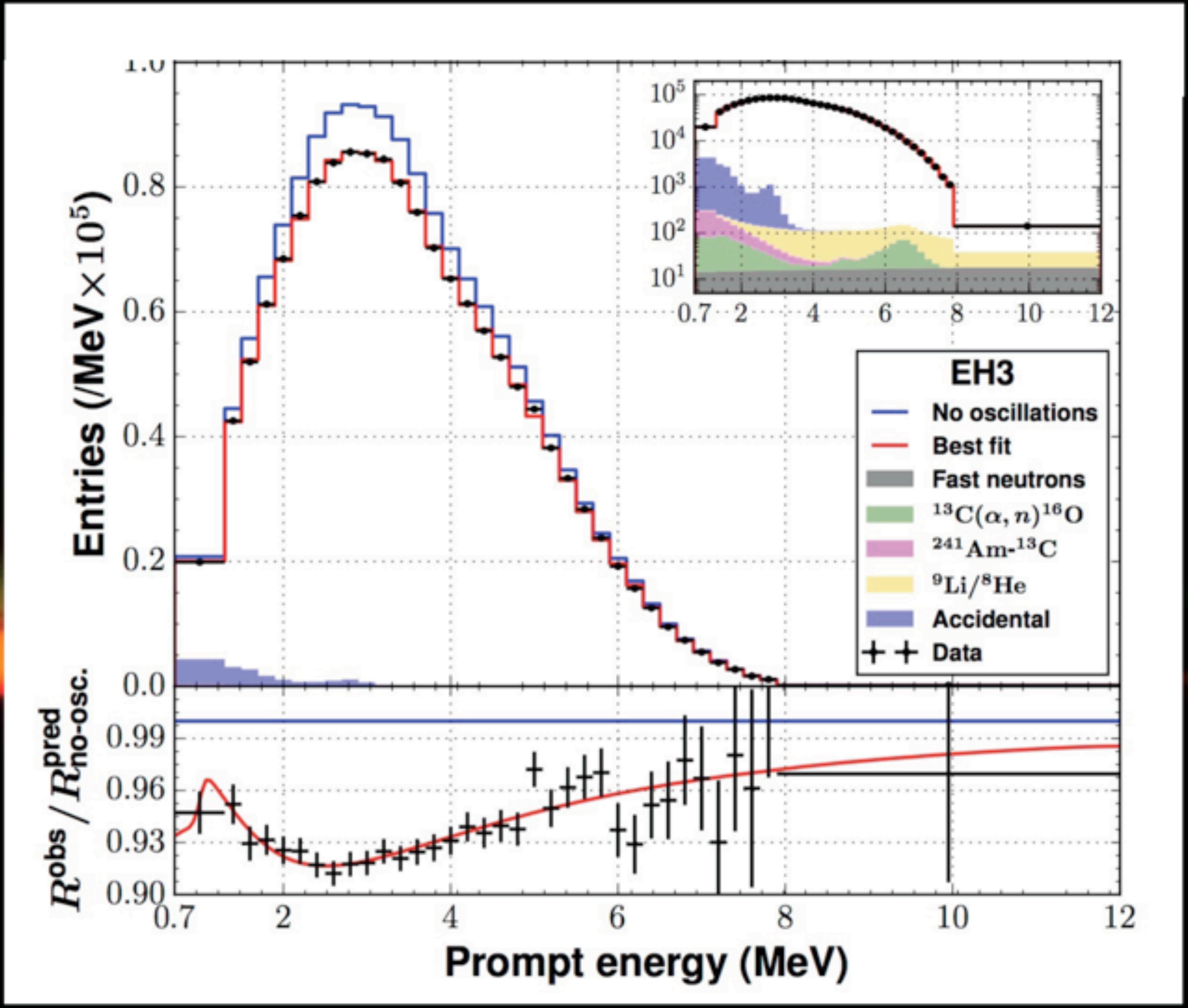


| systematics | single detector (SD) (%) | | multi-detector (MD) (%) |
|---|---|---|---|
| δ(detection) | **~[$2.0^{DYB}$,$0.5^{DC}$]**<br>(no fiducial volume) | → | **~0.2**<br>(**identical detectors**) |
| δ(flux) | **~3.0** **[~$5.0^{new}$]** (prediction)<br>[**~1.7** via **Bugey4**] | → | **≤0.5**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

— systematics uncertainties ~1‰ each —

# latest DYB result…





**excellent Rate+Shape measurements on $\sin^2(2\theta_{13})$ & $|\Delta m^2_{ee}|$**

**⇒ most precise measurements expected!**

*Anatael Cabrera (CNRS-IN2P3 & APC)*

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

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

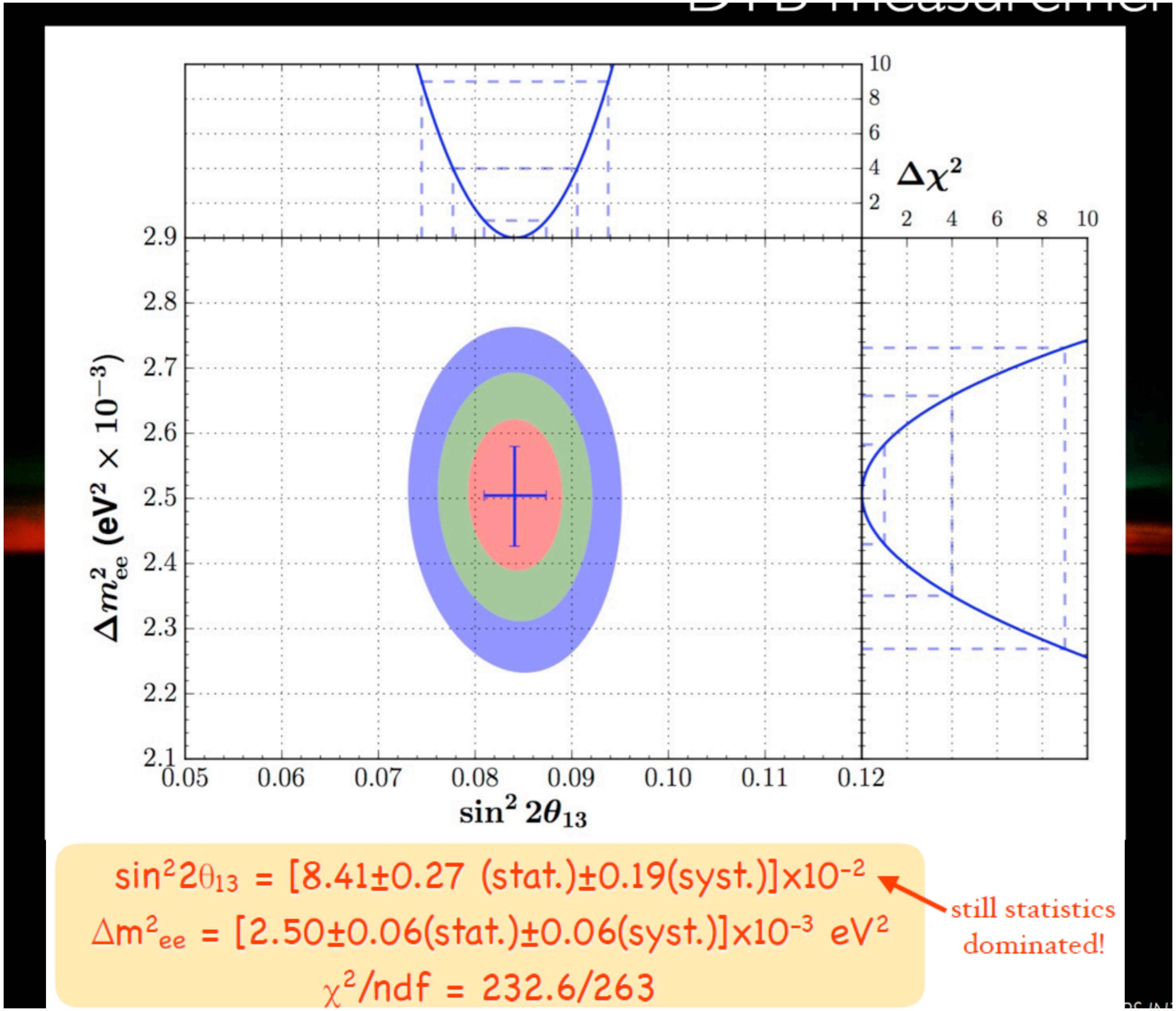
[Nunokawa & Parke (2005)]

$$|\Delta m^2_{ee}| \simeq |\Delta m^2_{32}| \pm \underbrace{5.21\times10^{-5}\text{eV}^2}_{\cos^2\theta_{12}|\Delta m^2_{21}|}$$

+: Normal Hierarchy
−: Inverted Hierarchy

**Daya Bay**

arXiv:1610.04802



$\sin^2 2\theta_{13}$ = [8.41±0.27 (stat.)±0.19(syst.)]x$10^{-2}$

$\Delta m^2_{ee}$ = [2.50±0.06(stat.)±0.06(syst.)]x$10^{-3}$ eV$^2$

$\chi^2$/ndf = 232.6/263

still statistics dominated!

see also (from 2 weeks ago): https://indico.cern.ch/event/595543/attachments/1413924/2165640/CERN2017_OchoaRicoux.pdf

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

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

[Nunokawa & Parke (2005)]

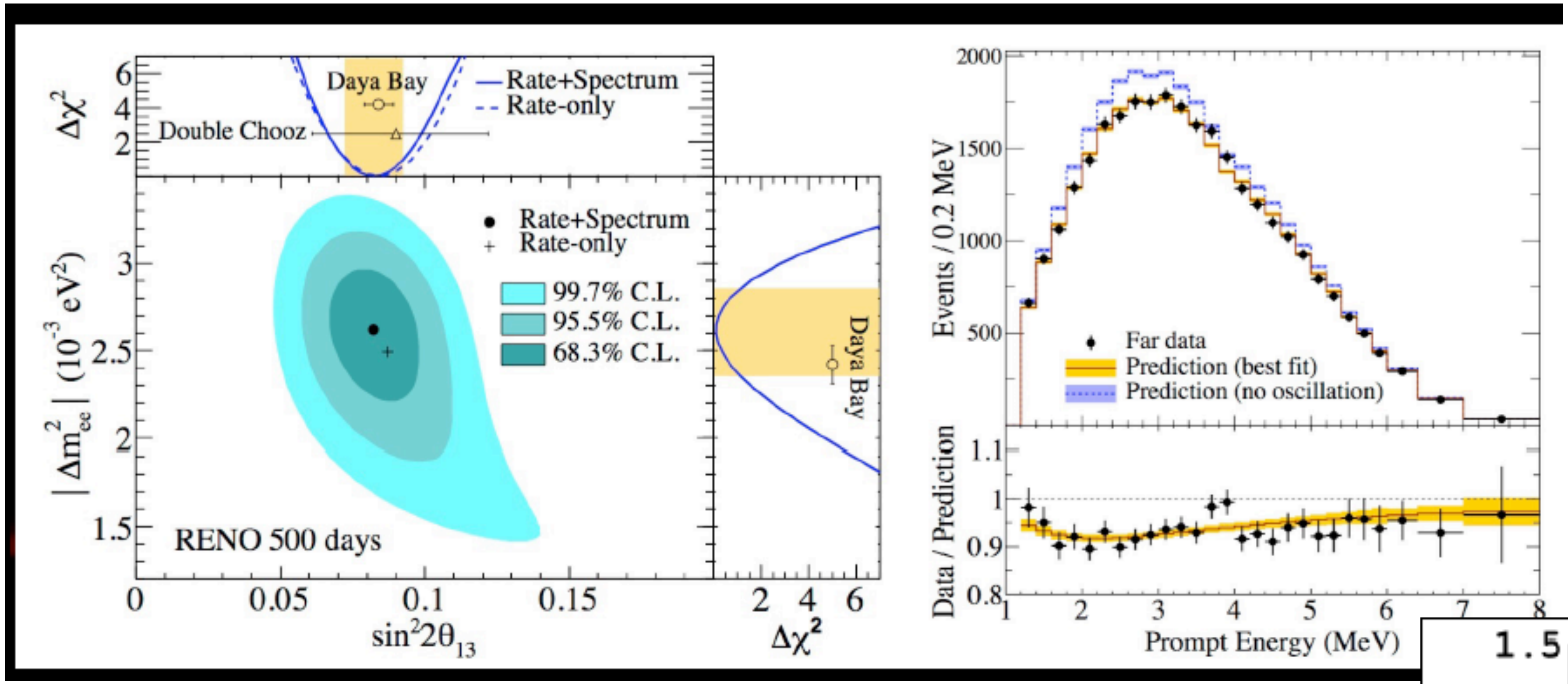
$$|\Delta m^2_{ee}| \simeq |\Delta m^2_{32}| \pm \underbrace{5.21 \times 10^{-5} \mathrm{eV}^2}_{\cos^2\theta_{12}|\Delta m^2_{21}|}$$

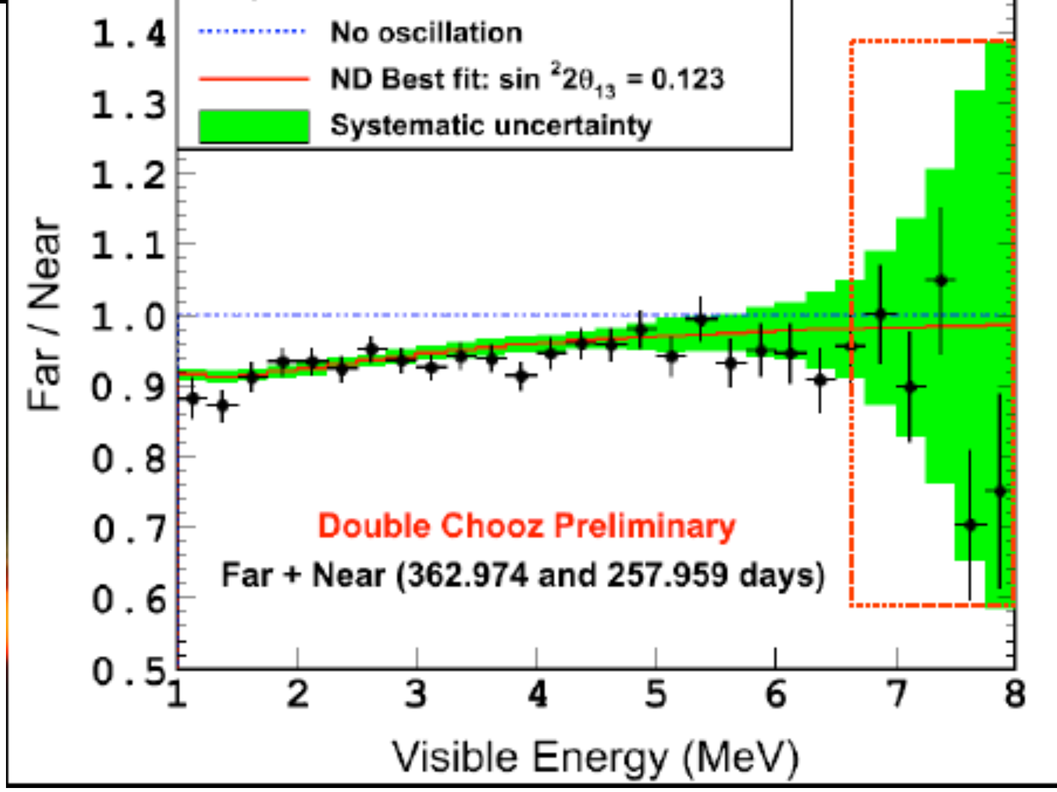
+: Normal Hierarchy

−: Inverted Hierarchy

**Reno**

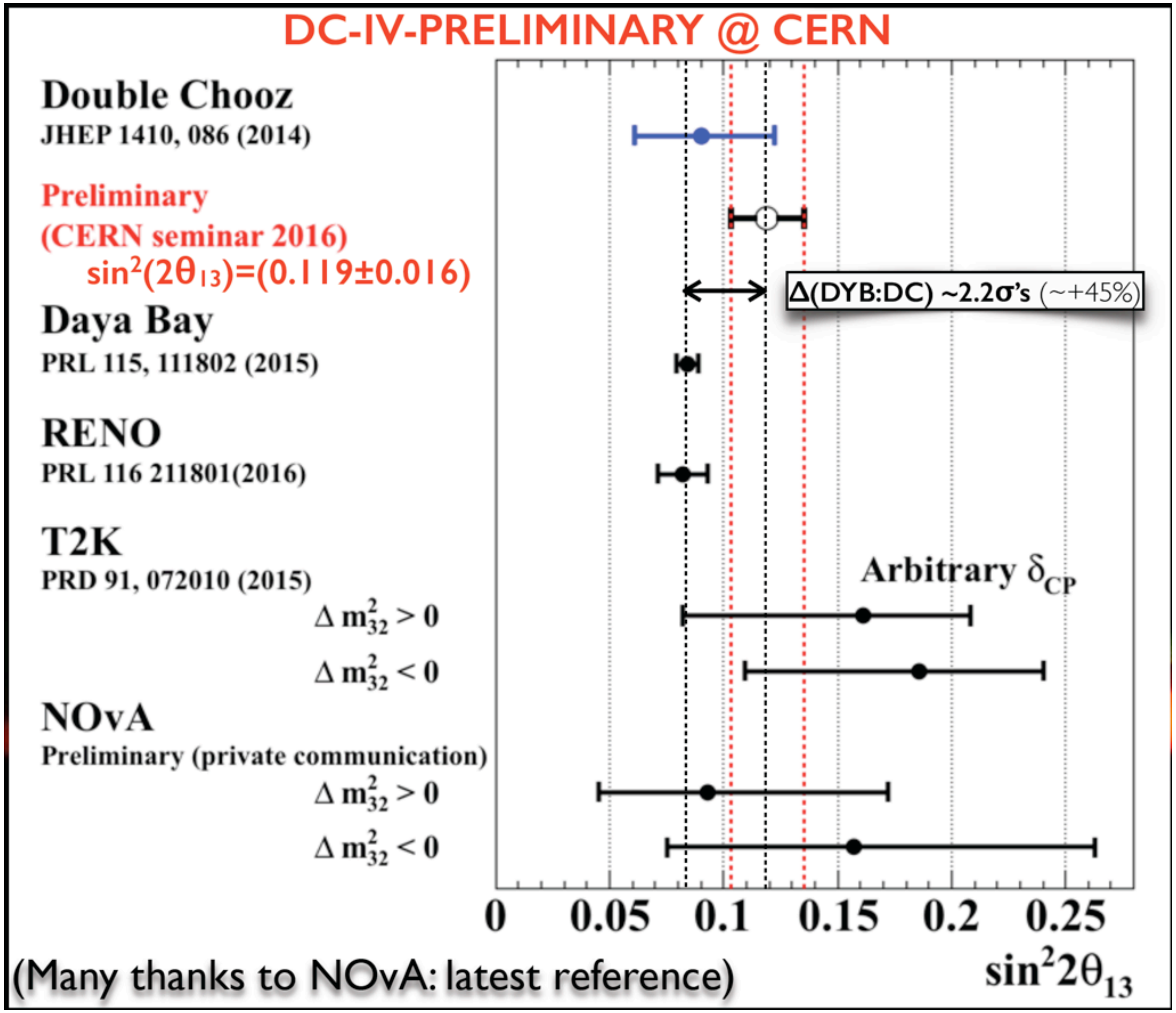
arXiv:1610.04326





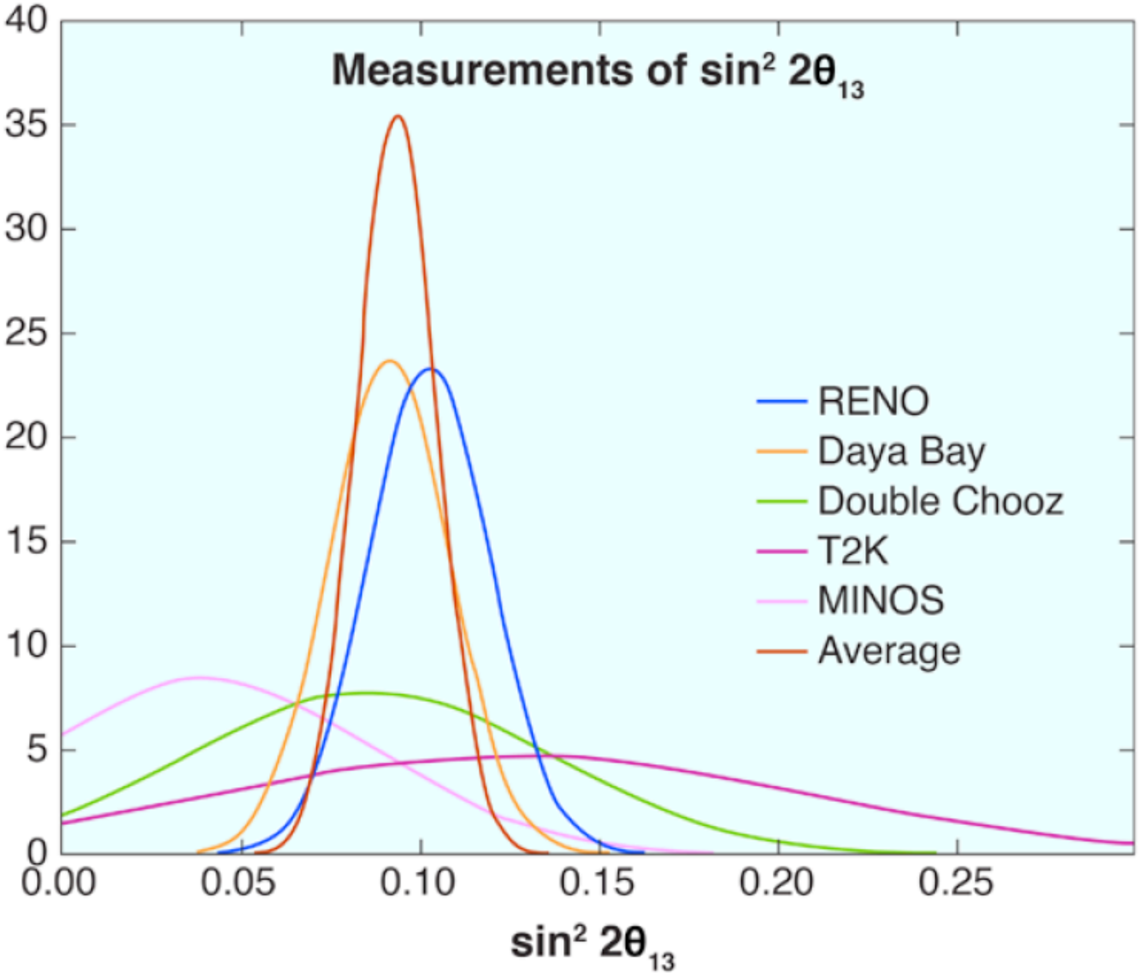
**New from DC**

https://indico.cern.ch/event/548805/



(Many thanks to NOvA: latest reference)

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



# The future: mass ordering

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

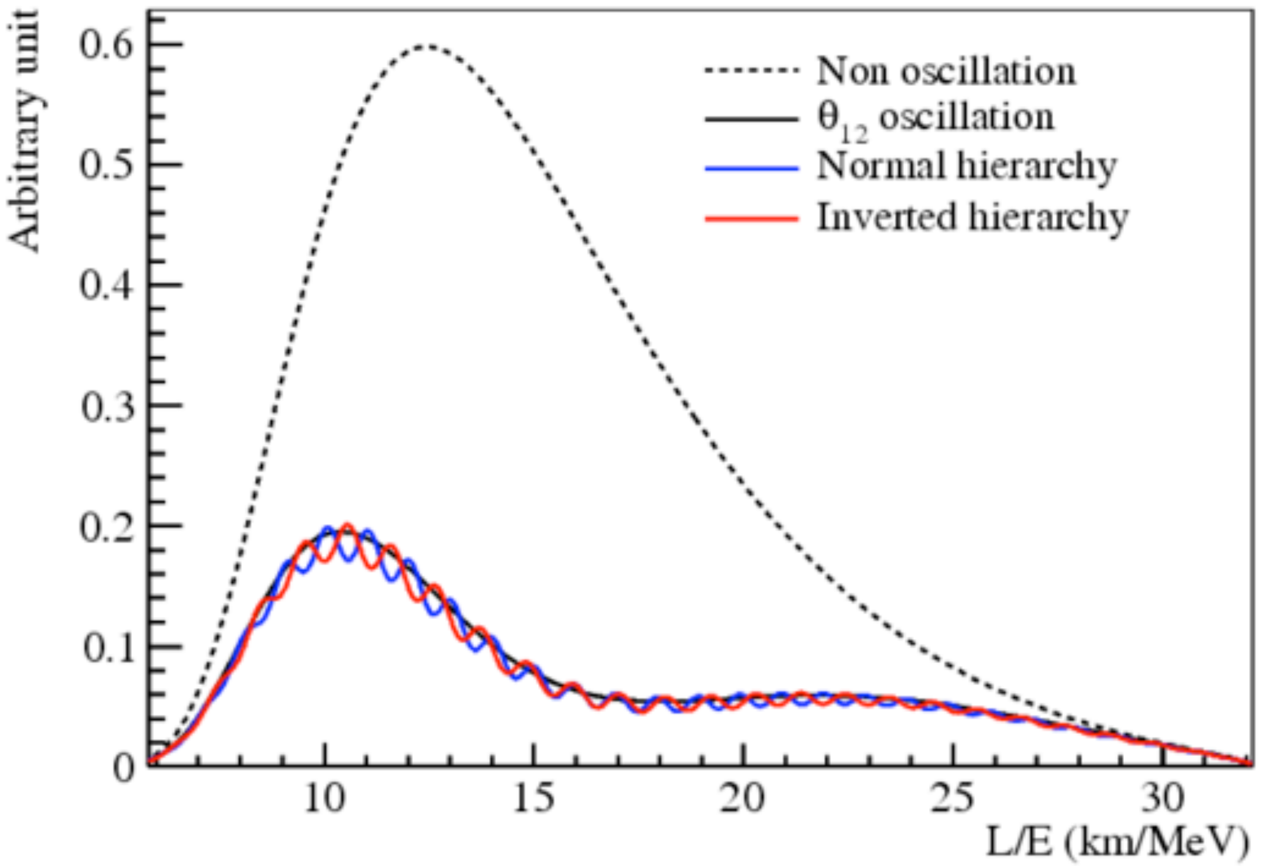
## Survival probability

arXiv 1210.8141

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

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

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



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

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

**+ NH**
**- IH**

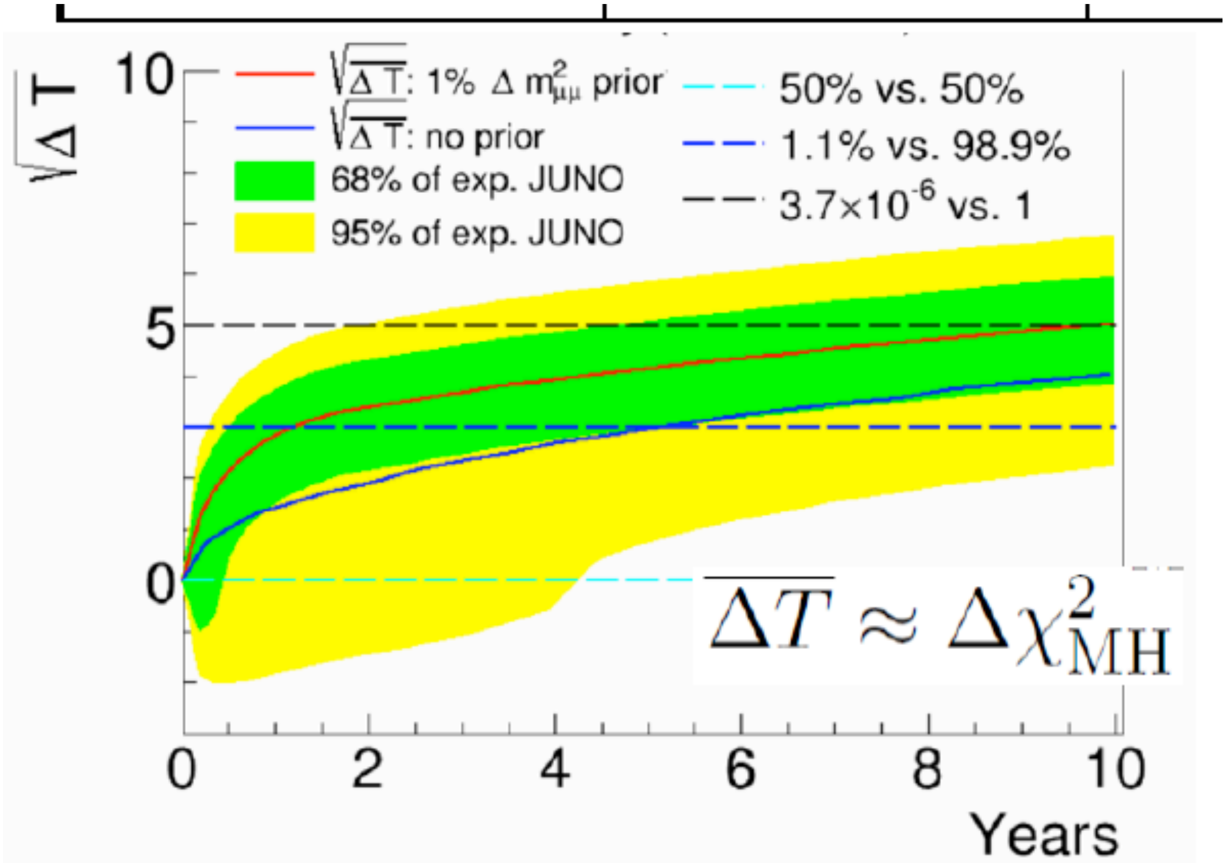
The big suppression is the "solar" oscillation → $\Delta m^2_{21}$ , $\sin^2\theta_{12}$
The ripple is the "atmospheric" oscillation → $|\Delta m^2_{31}|$ from frequency
MH encoded in the phase
**"high" value of $\theta_{13}$ crucial**

# Experiments at reactors

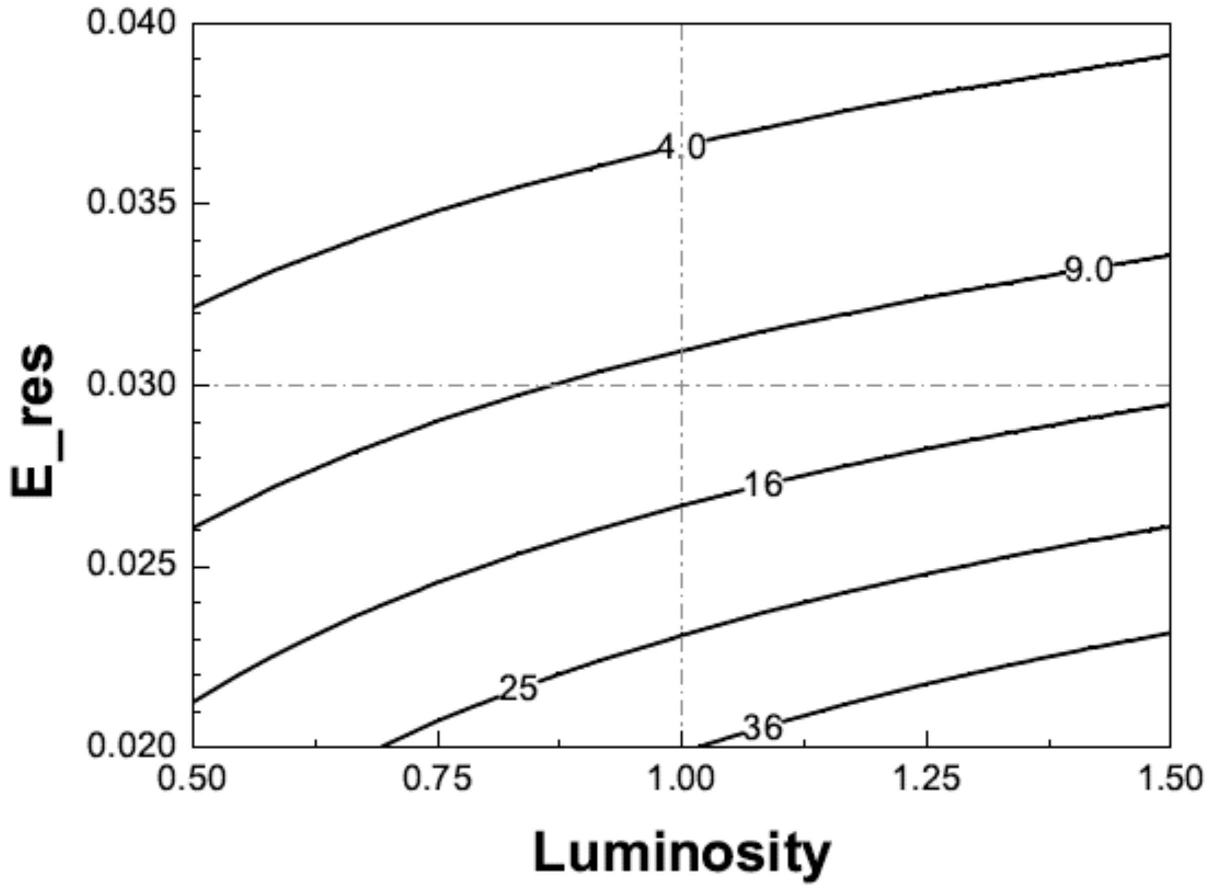
- JUNO in China
- Reno-50 in Korea

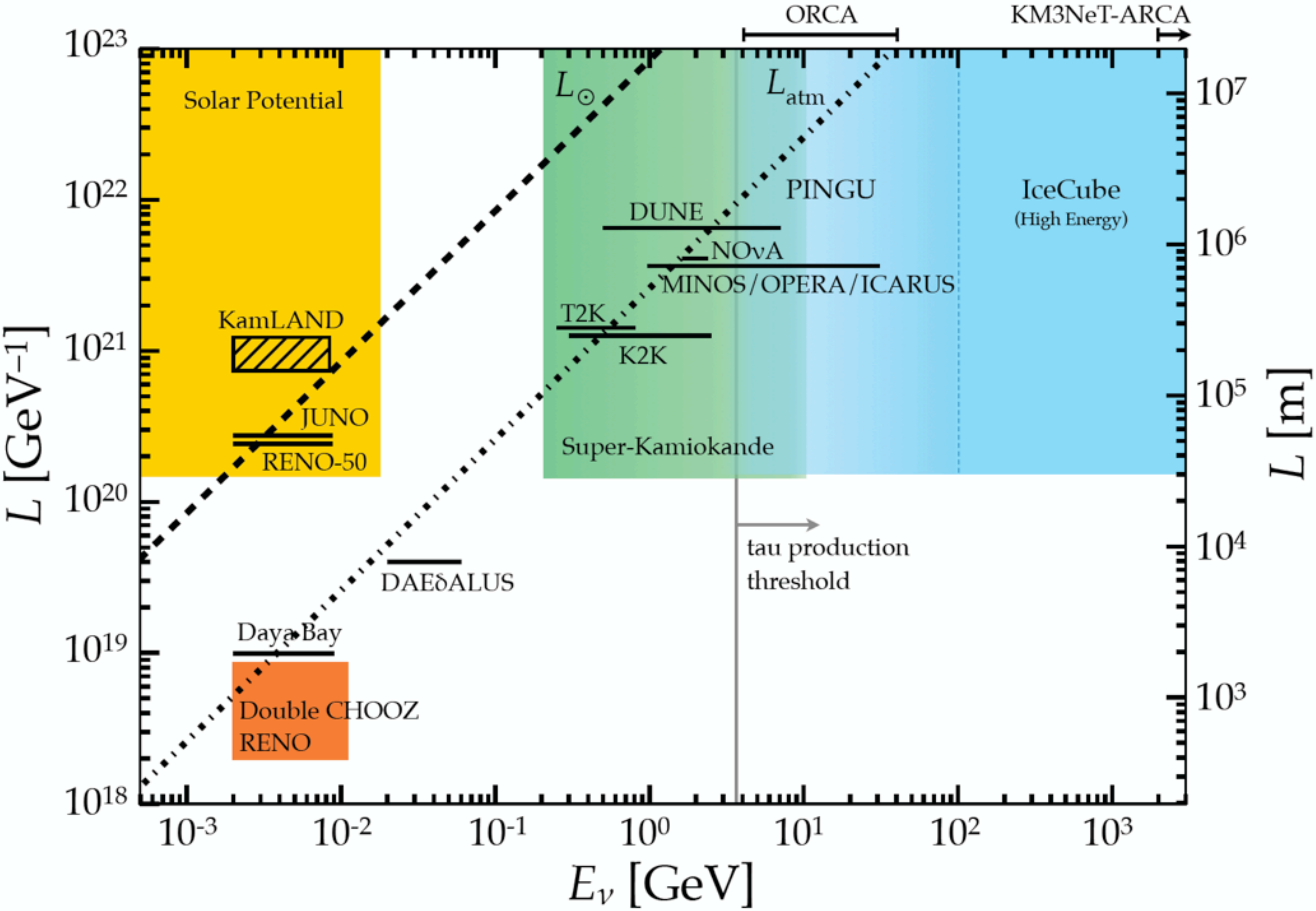
- Same concept as present detectors, but with a much better Eres to distinguish phase shifts
- No ND
  - but could be a limit if reactor flux not nailed down to better than ~2%

- Can also do with accelerators and atmospheric, complementary



$$\overline{\Delta T} \approx \Delta\chi^2_{\rm MH}$$





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

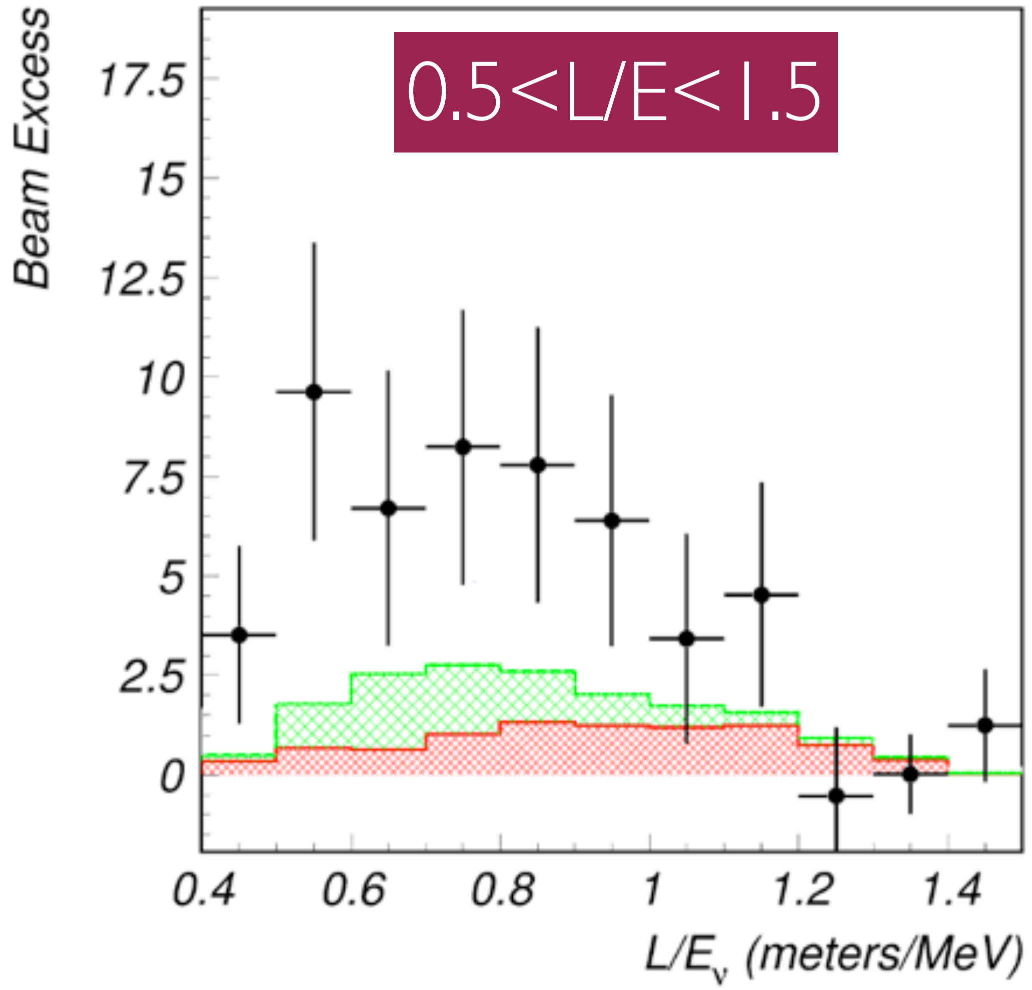
# Anomalies

# The past (and lingering...)

## LSND

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

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



0.5<L/E<1.5

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

  $\mu^+$ 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]

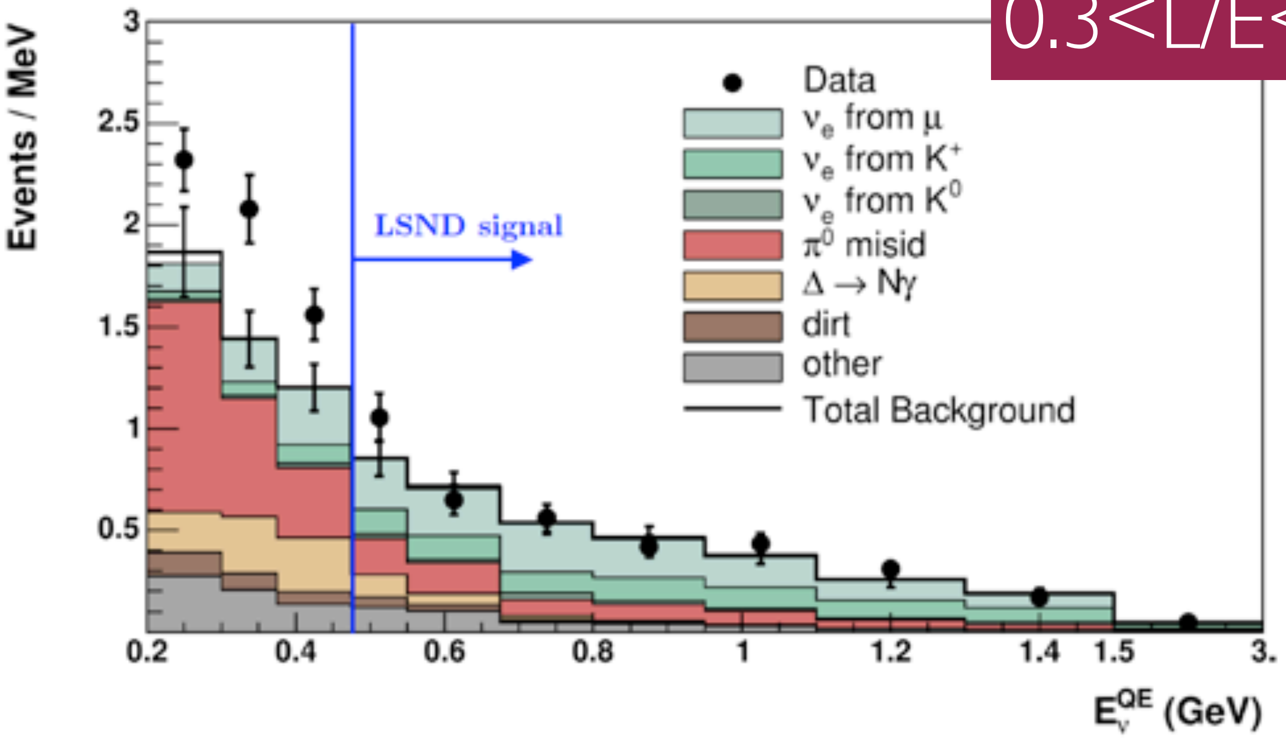
# MiniBooNE

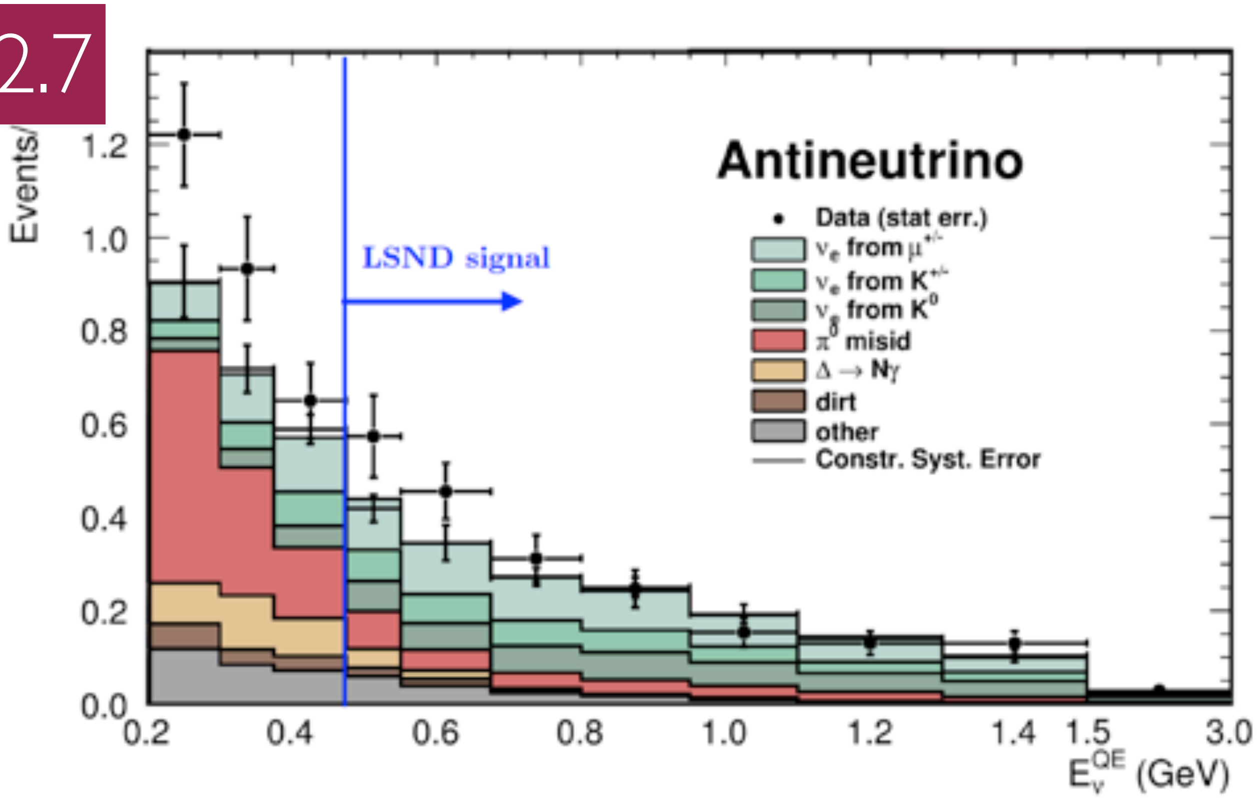
$L \simeq 541\,\text{m}$ $\qquad$ $200\,\text{MeV} \leq E \lesssim 3\,\text{GeV}$

$\nu_\mu \to \nu_e$ [PRL 102 (2009) 101802]

$\bar{\nu}_\mu \to \bar{\nu}_e$ [PRL 110 (2013) 161801]

0.3<L/E<2.7





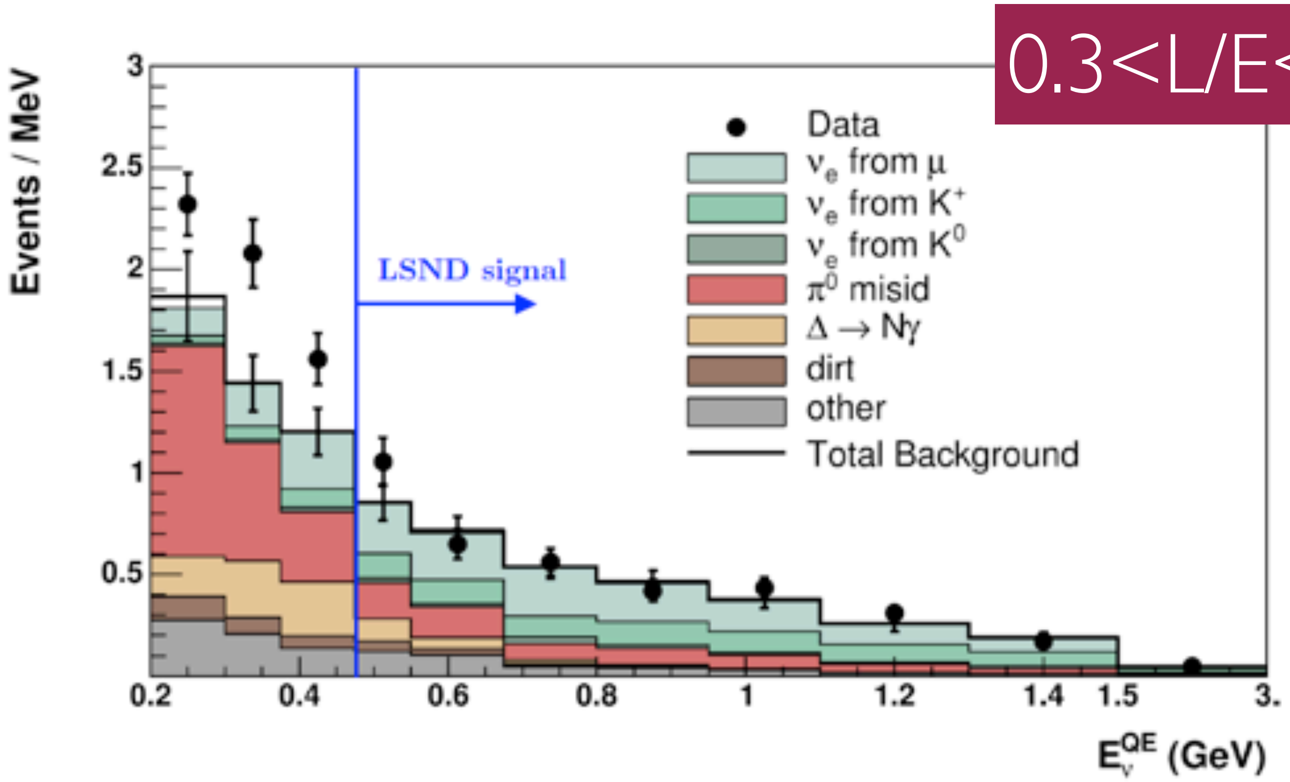
- Purpose: check LSND signal.
- Different $L$ and $E$.
- Similar $L/E$ (oscillations).
- No money, no Near Detector.
- LSND signal: $E > 475\,\text{MeV}$.
- Agreement with LSND signal?
- CP violation?
- Low-energy anomaly!

# MiniBooNE

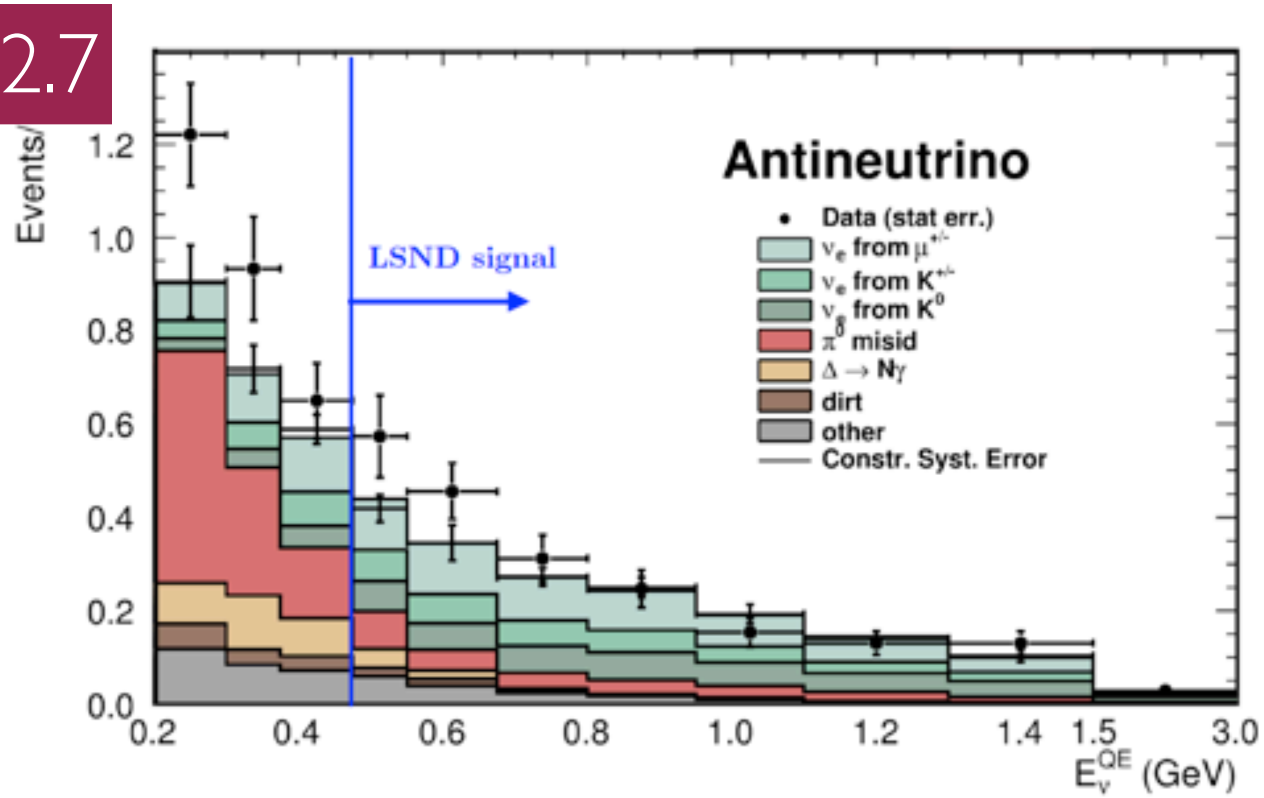
$L \simeq 541\,\mathrm{m}$ $200\,\mathrm{MeV} \leq E \lesssim 3\,\mathrm{GeV}$

$\nu_\mu \to \nu_e$ [PRL 102 (2009) 101802]

$\bar{\nu}_\mu \to \bar{\nu}_e$ [PRL 110 (2013) 161801]



0.3<L/E<2.7



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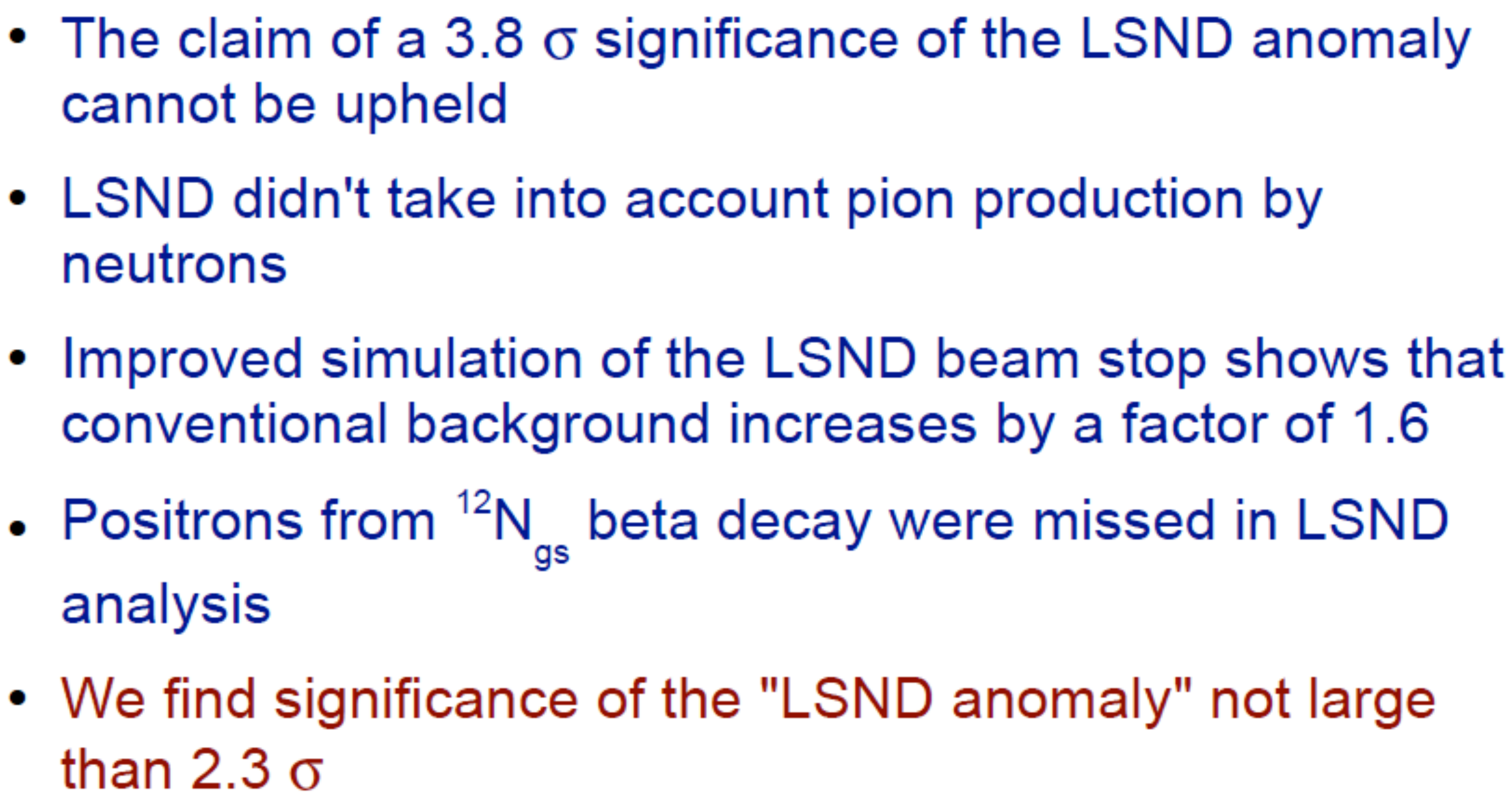
- Similar $L/E$ (oscillations).
- No money, no Near Detector.

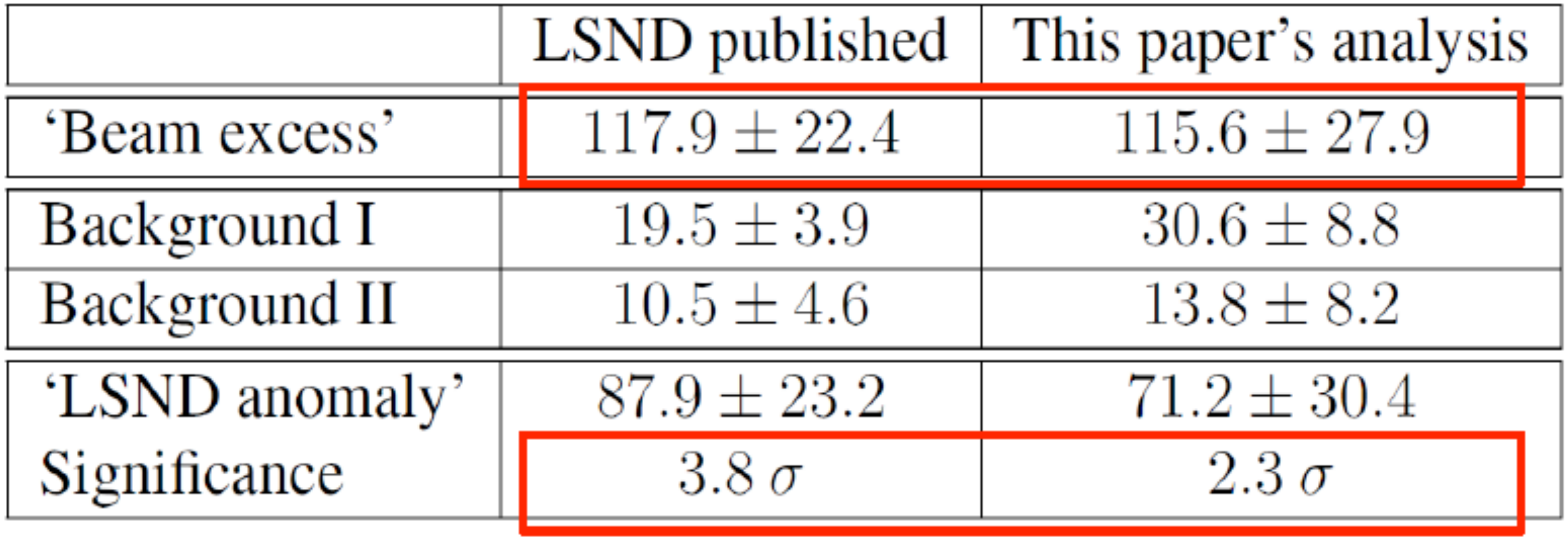
- LSND signal: $E > 475\,\mathrm{MeV}$.
- Agreement with LSND si
- CP violation?
- Low-energy anomaly!

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 σ | 2.3 σ |

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

# Gallium Anomaly

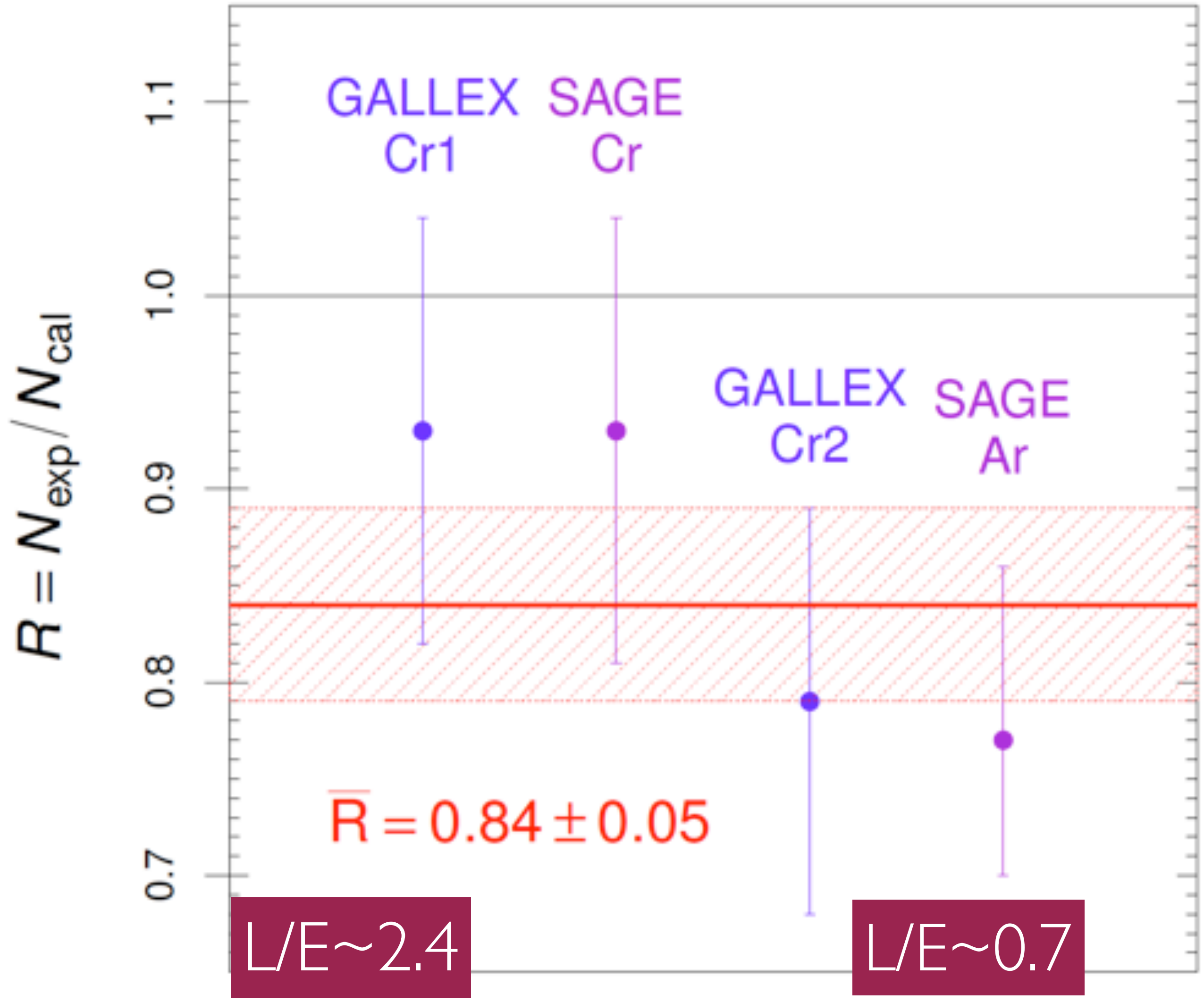
Gallium Radioactive Source Experiments: GALLEX and SAGE

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

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

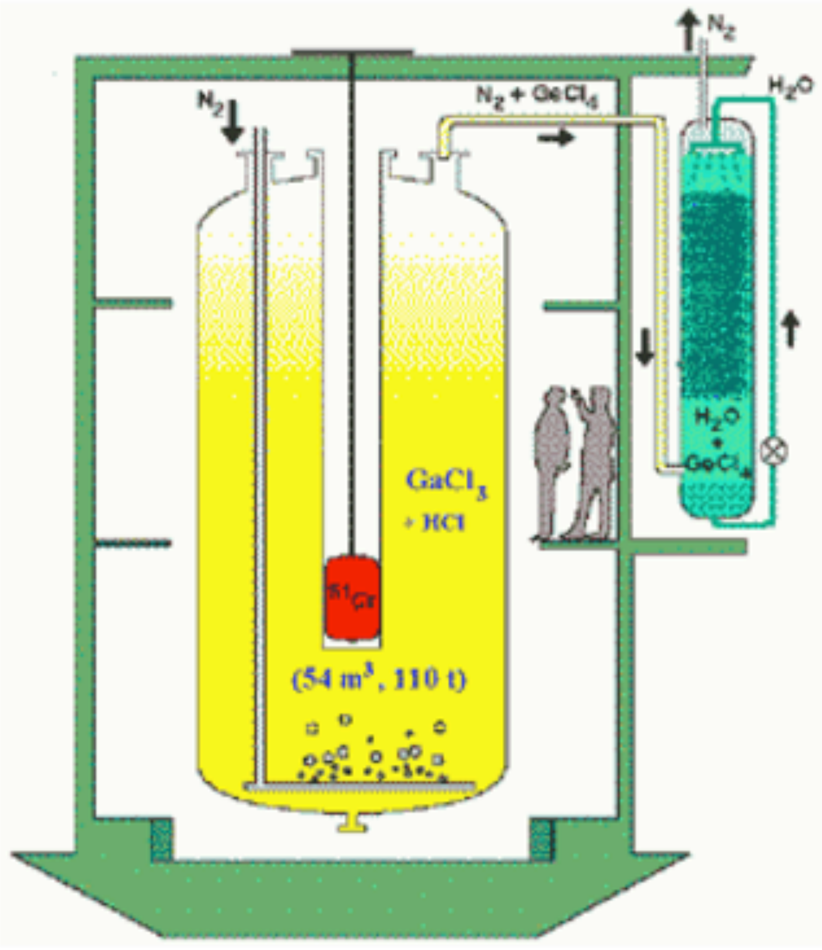
$\nu_e + {}^{71}\text{Ga} \to {}^{71}\text{Ge} + e^-$

Test of Solar $\nu_e$ Detection:



L/E~2.4 L/E~0.7

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



$\approx 2.9\sigma$ deficit

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

[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]

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

## LSND

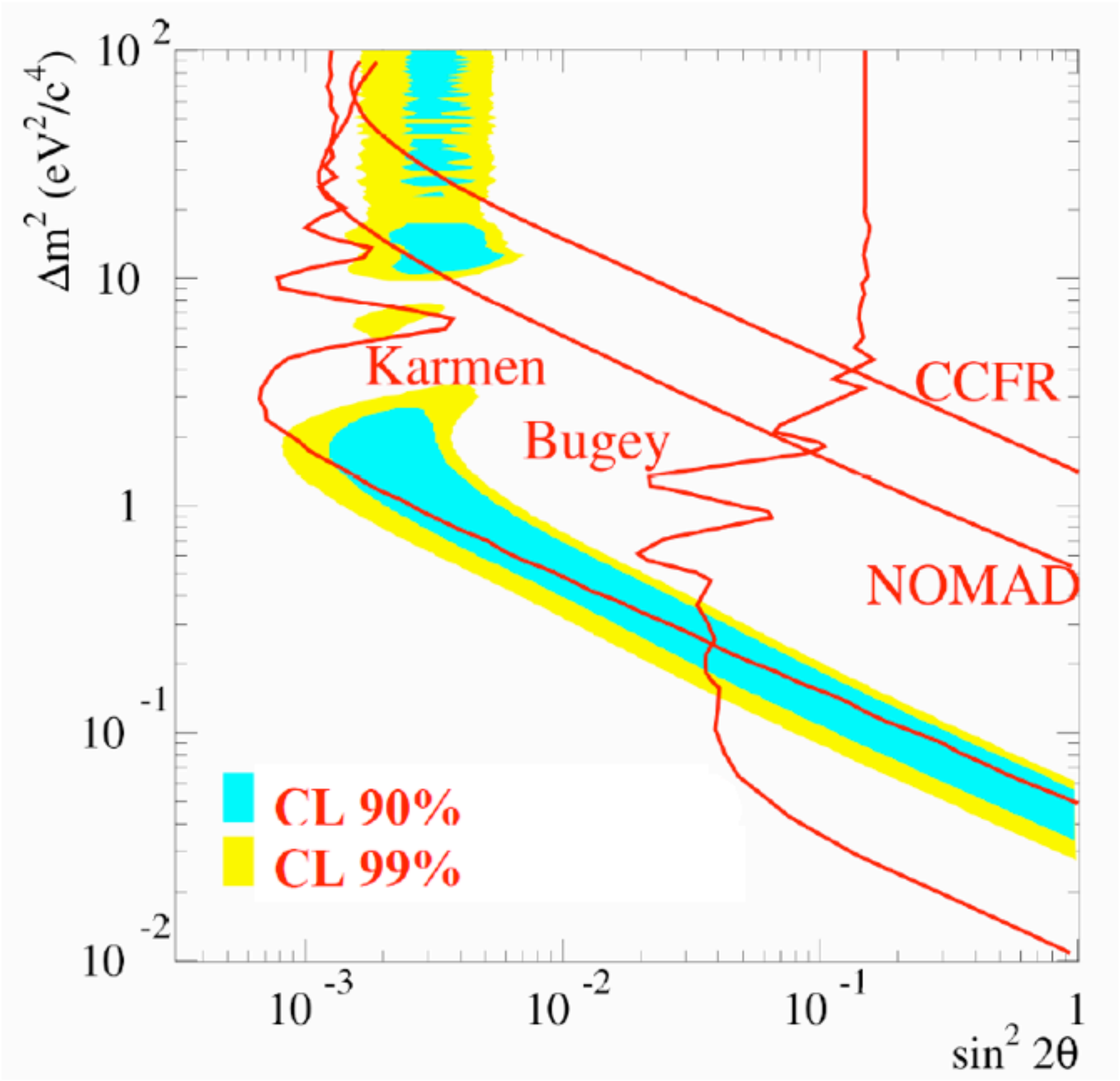
- 1993-1994 data: 16.4 (+9.7 - 8.9) ± 3.3

  (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.

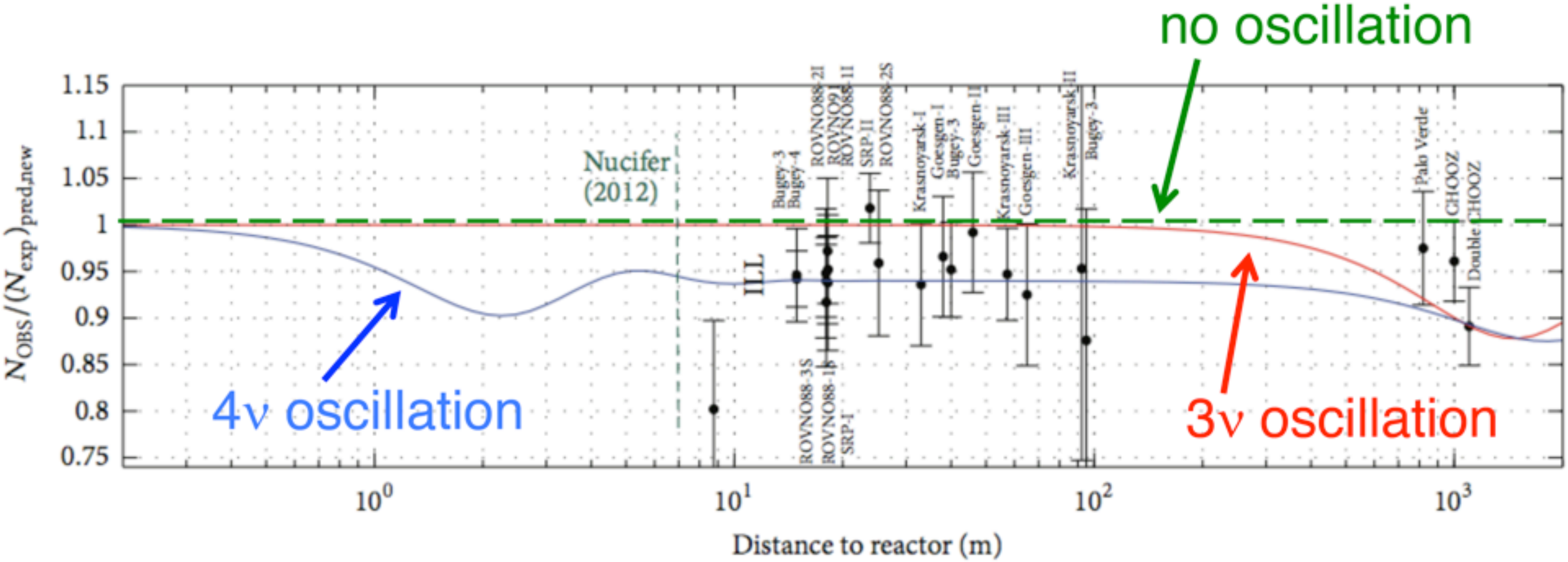
  $\Delta m^2 > 0.02$ eV$^2$.
- BNL-E776, CCFR, NuTeV and NOMAD

  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$^2$.



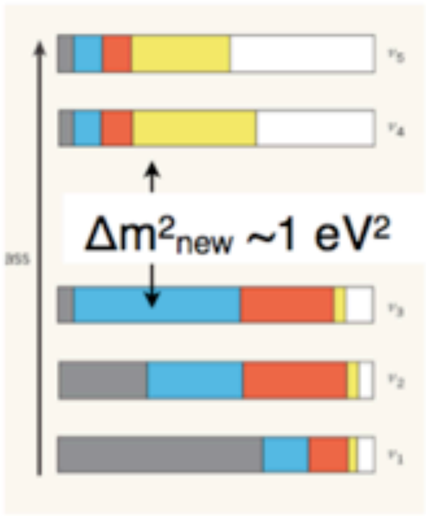
# Surprise 1: The Reactor Anomaly



- ➔ 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 * $\sin^2(\theta_s) \simeq 0.06$

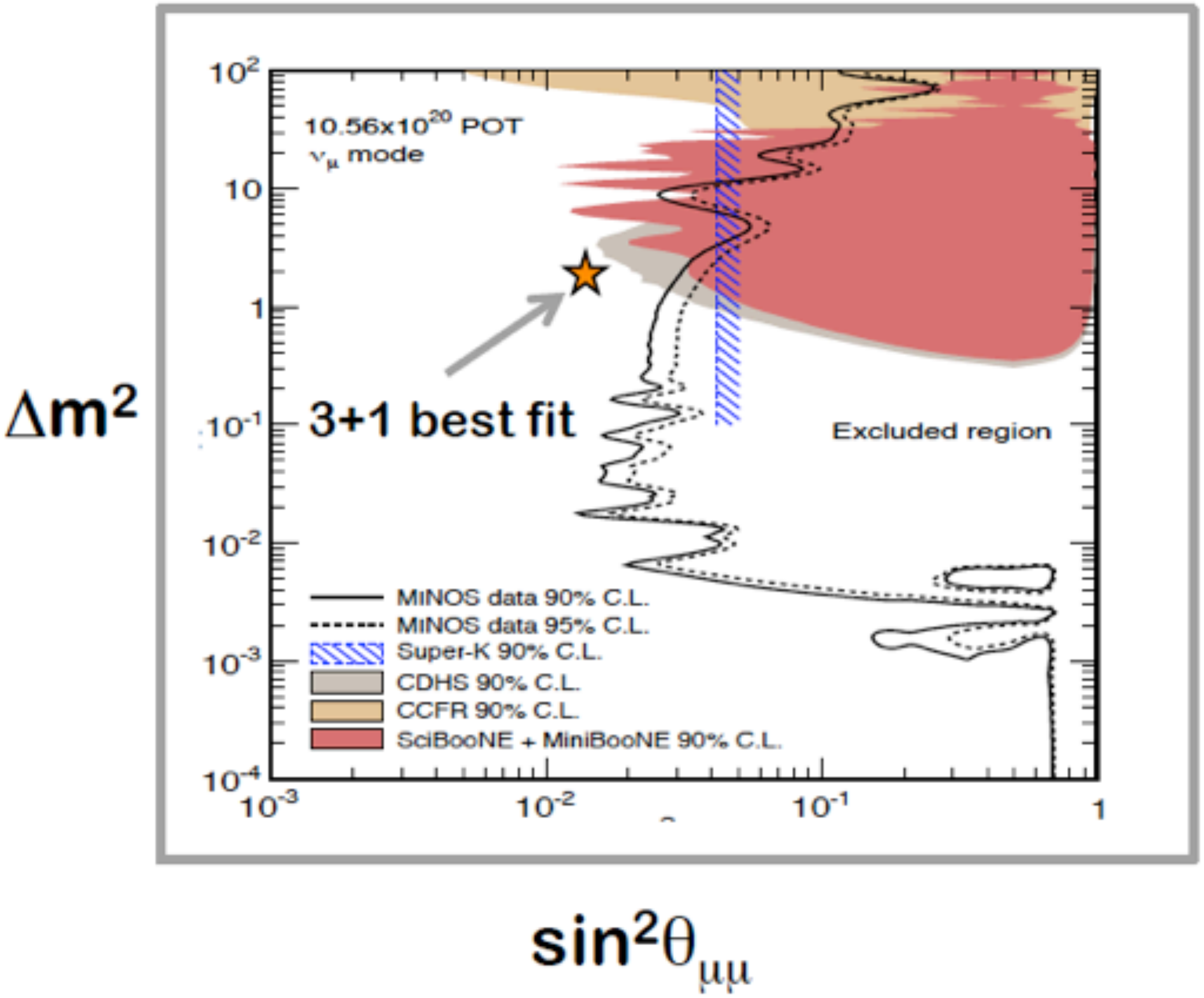
⇐⇒ active ν-unitarity tested @ few % ➔ consistent ➔



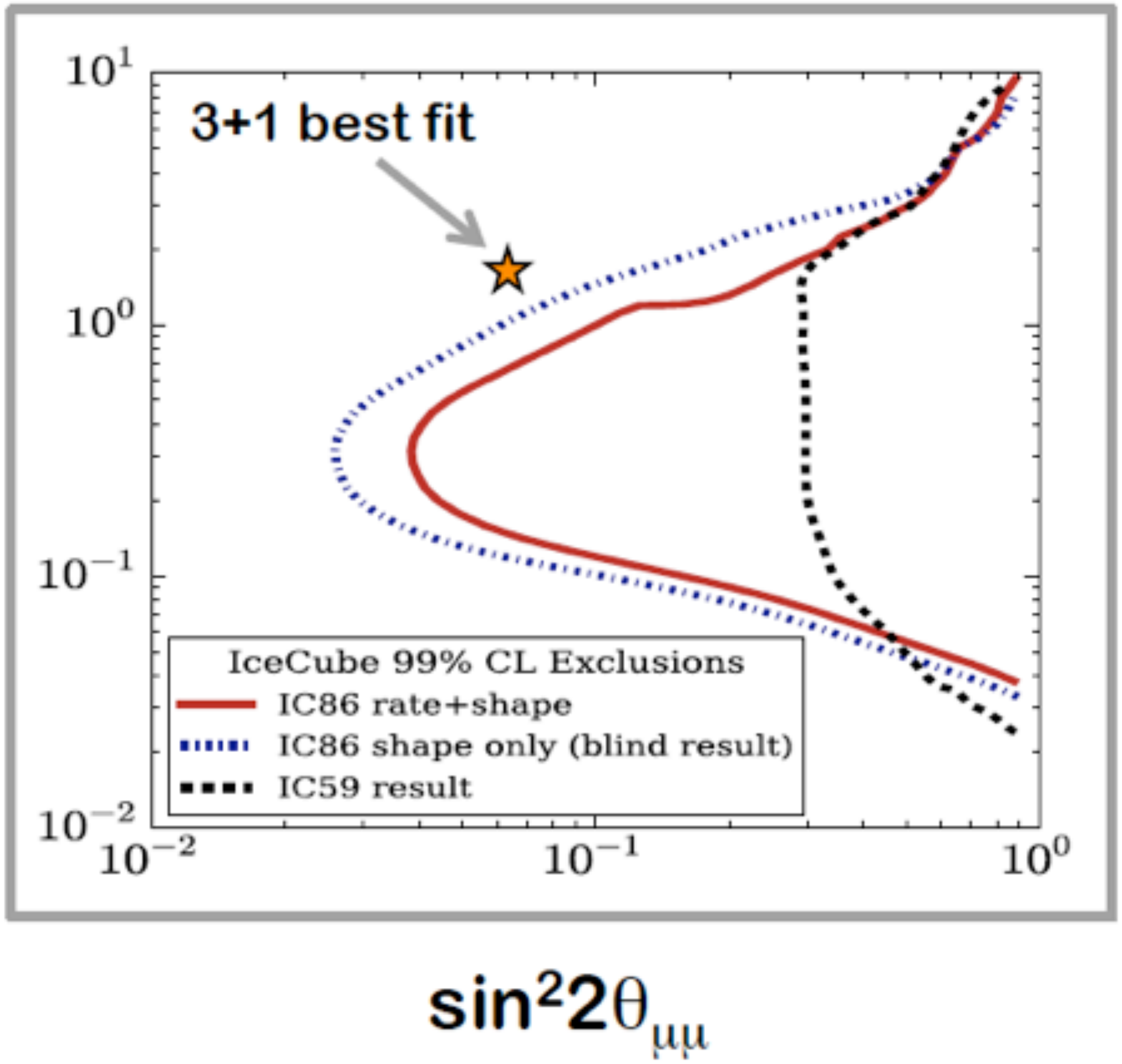
- ➔ check with a new experiment at shorter baseline

# No anomaly in $\nu_\mu$ disappearance

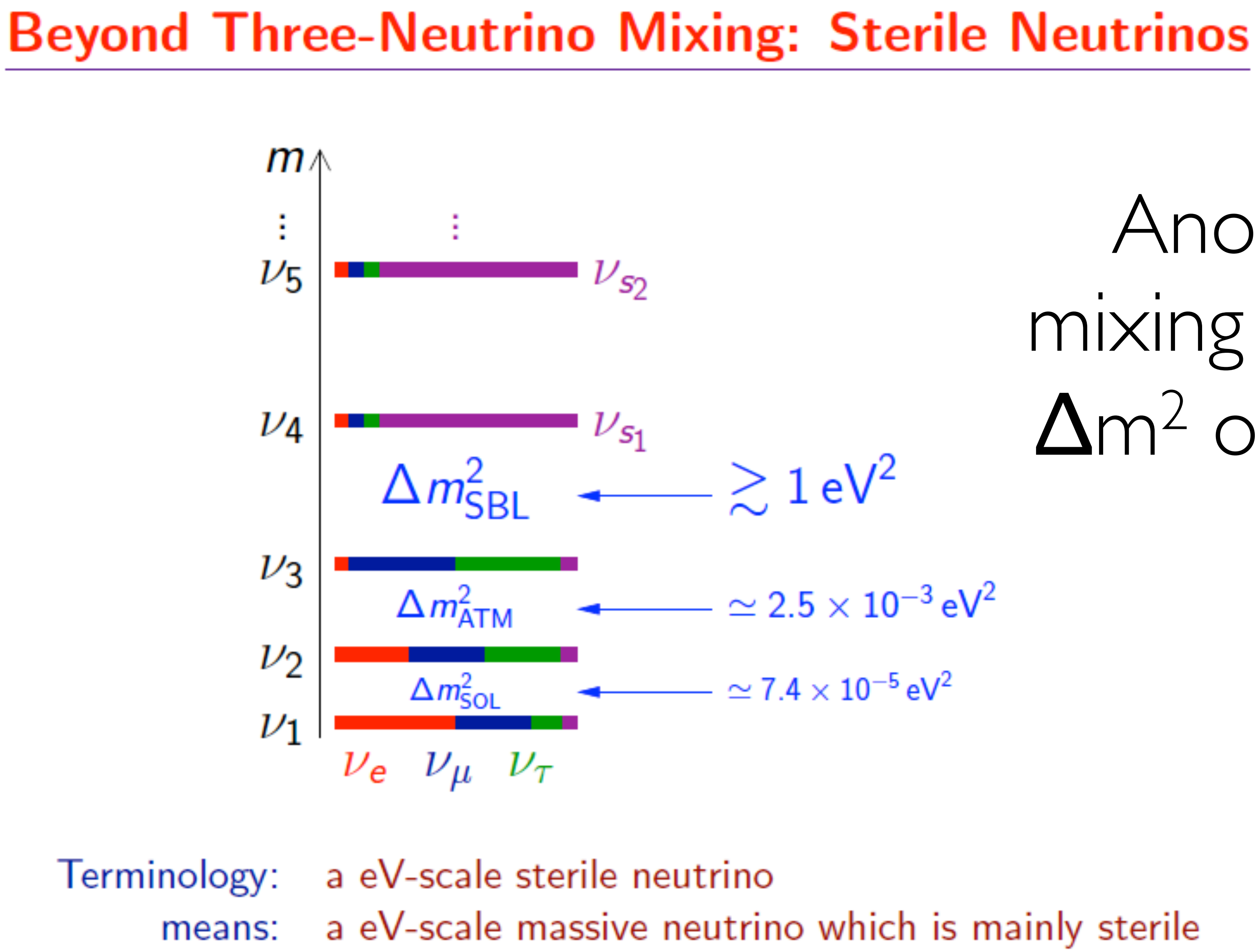
**SBL & MINOS (NC)**



**IceCube**



**A thorn in the side of sterile neutrinos ...**



## Beyond Three-Neutrino Mixing: Sterile Neutrinos

$m$

$\vdots$

$\nu_5$ — $\nu_{s_2}$

$\nu_4$ — $\nu_{s_1}$

$\Delta m^2_{\mathrm{SBL}} \longleftarrow \gtrsim 1\,\mathrm{eV}^2$

$\nu_3$

$\Delta m^2_{\mathrm{ATM}} \longleftarrow \simeq 2.5 \times 10^{-3}\,\mathrm{eV}^2$

$\nu_2$

$\Delta m^2_{\mathrm{SOL}} \longleftarrow \simeq 7.4 \times 10^{-5}\,\mathrm{eV}^2$

$\nu_1$

$\nu_e$ $\nu_\mu$ $\nu_\tau$

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

Anomalies caused by mixing in 4th family with a $\Delta m^2$ of the "good" range?

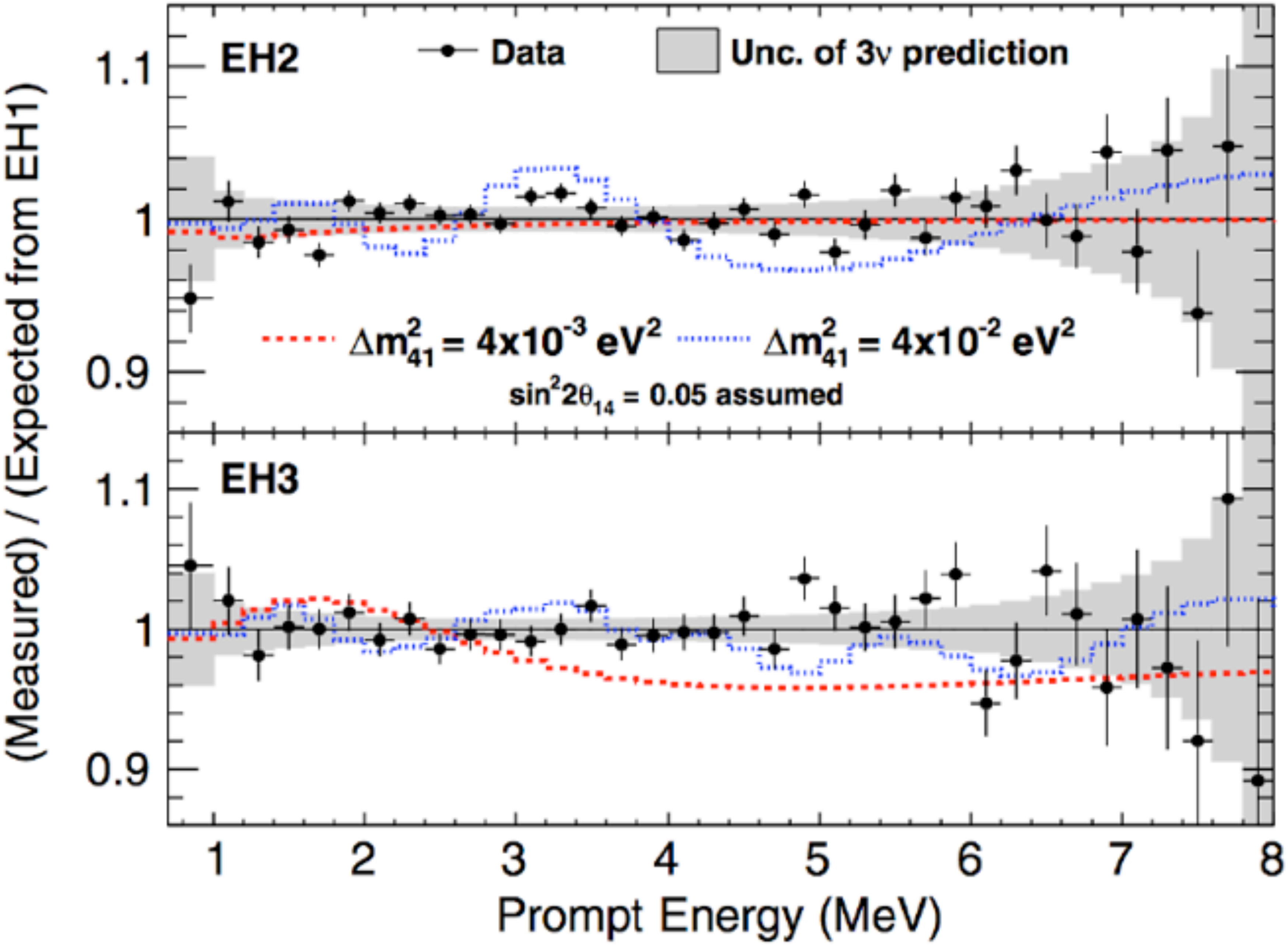
- Indications that would have to be a light sterile neutrino, if at all, to reconcile with app/disapp data
- See more here: https://agenda.infn.it/getFile.py/access?contribId=3&resId=0&materialId=slides&confId=12099

# 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:

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

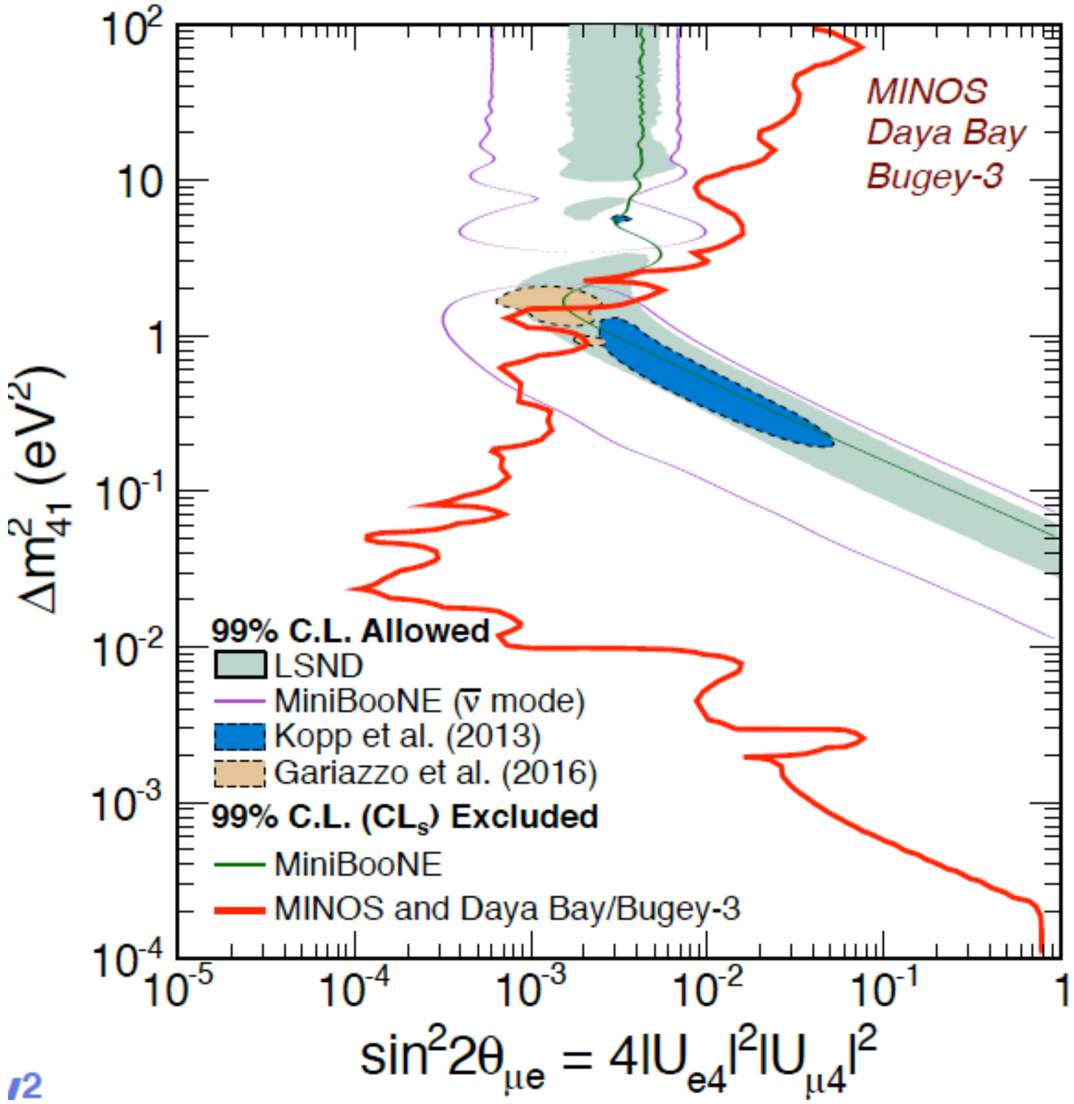
Daya Bay is sensitive to $|U_{e4}|^2 = \sin^2\theta_{14}$.

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

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



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

# Surprise 2: A Bump in the Spectrum

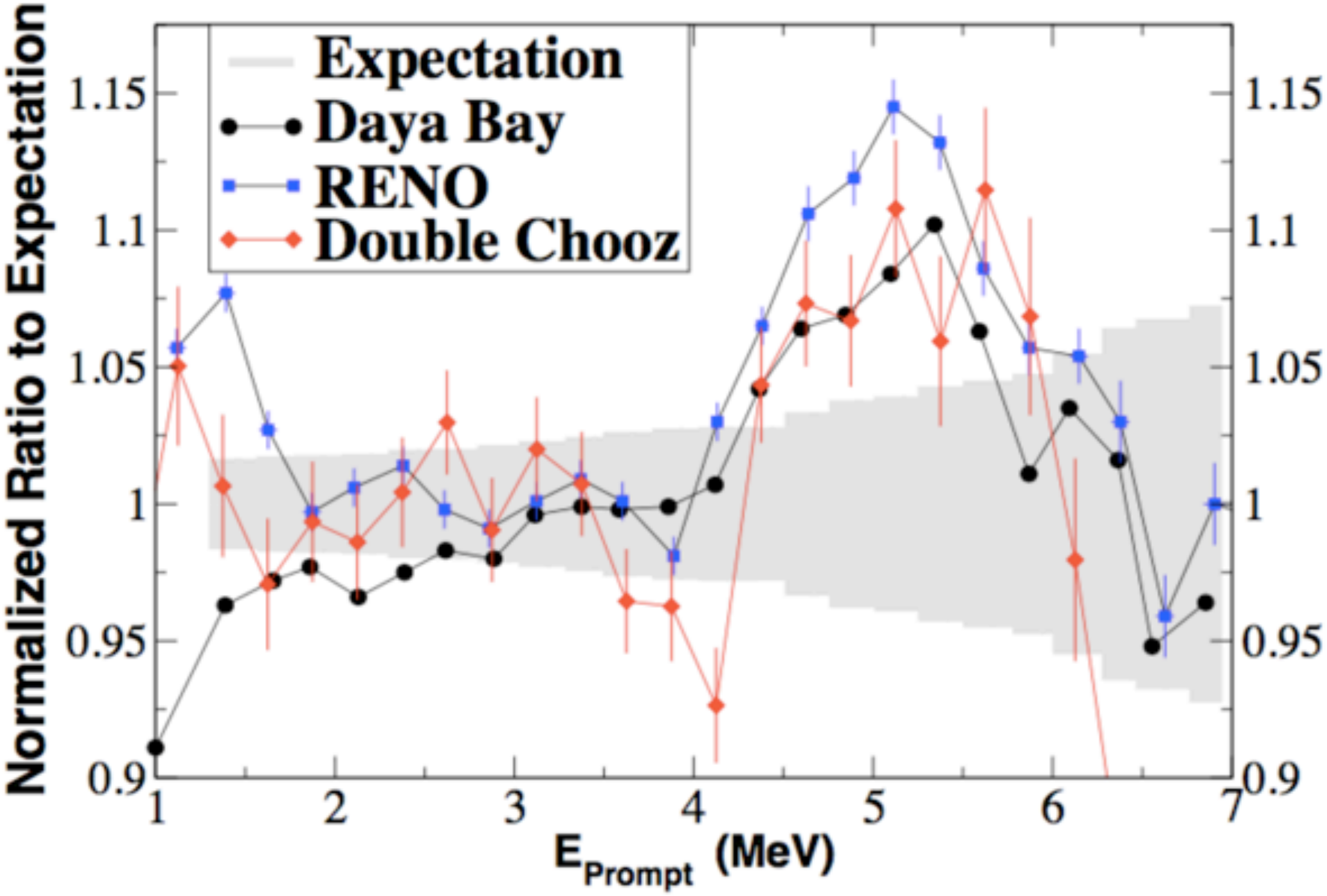
Double Chooz, RENO and Daya Bay:

→ all see unexpected bump in near and far spectrum

→ $\theta_{13}$ 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

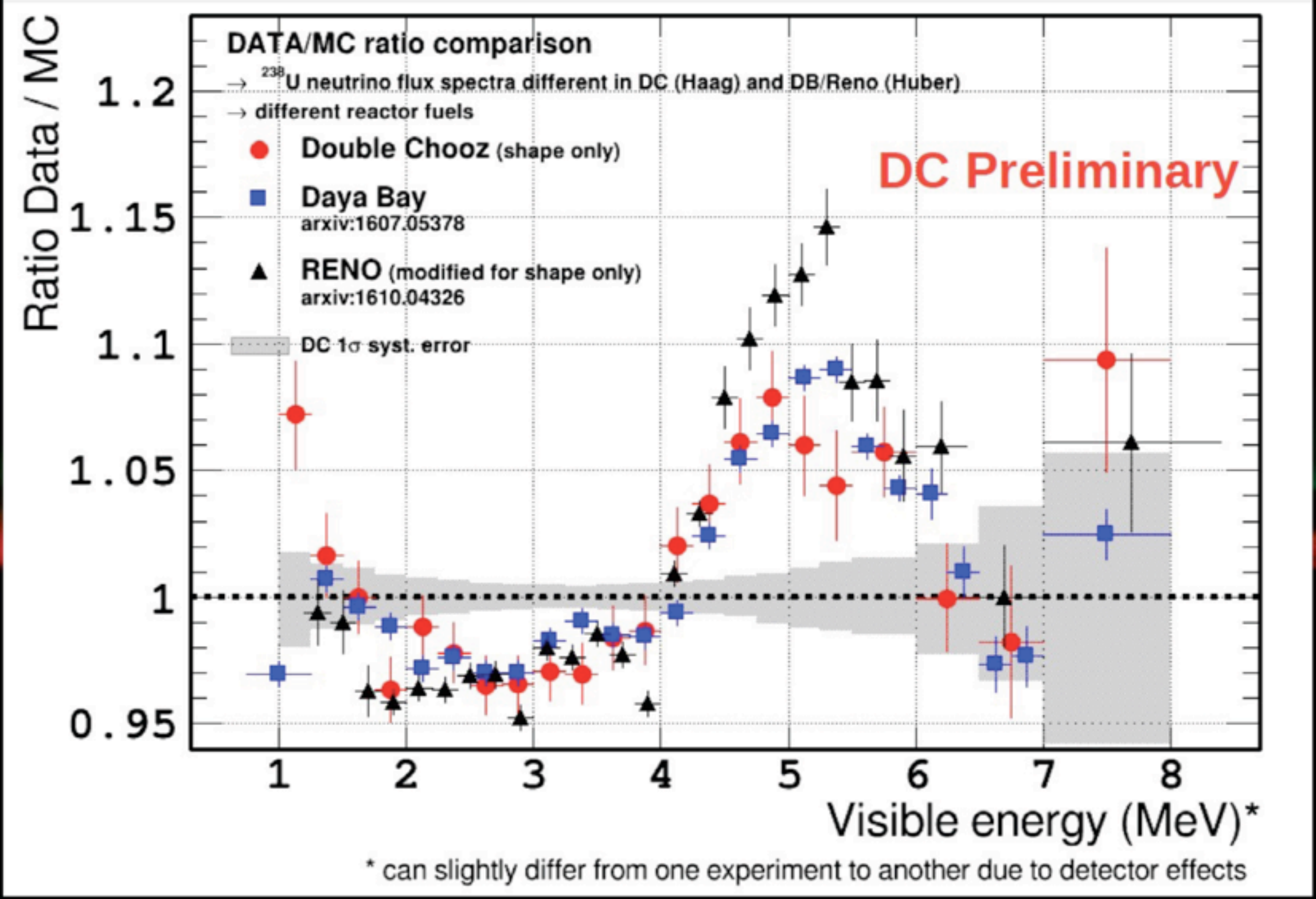
High energy ν's ←→ short lived isotopes …little known

Nuclear theory:

theory errors …maybe explainable…

better ➔ experimental test

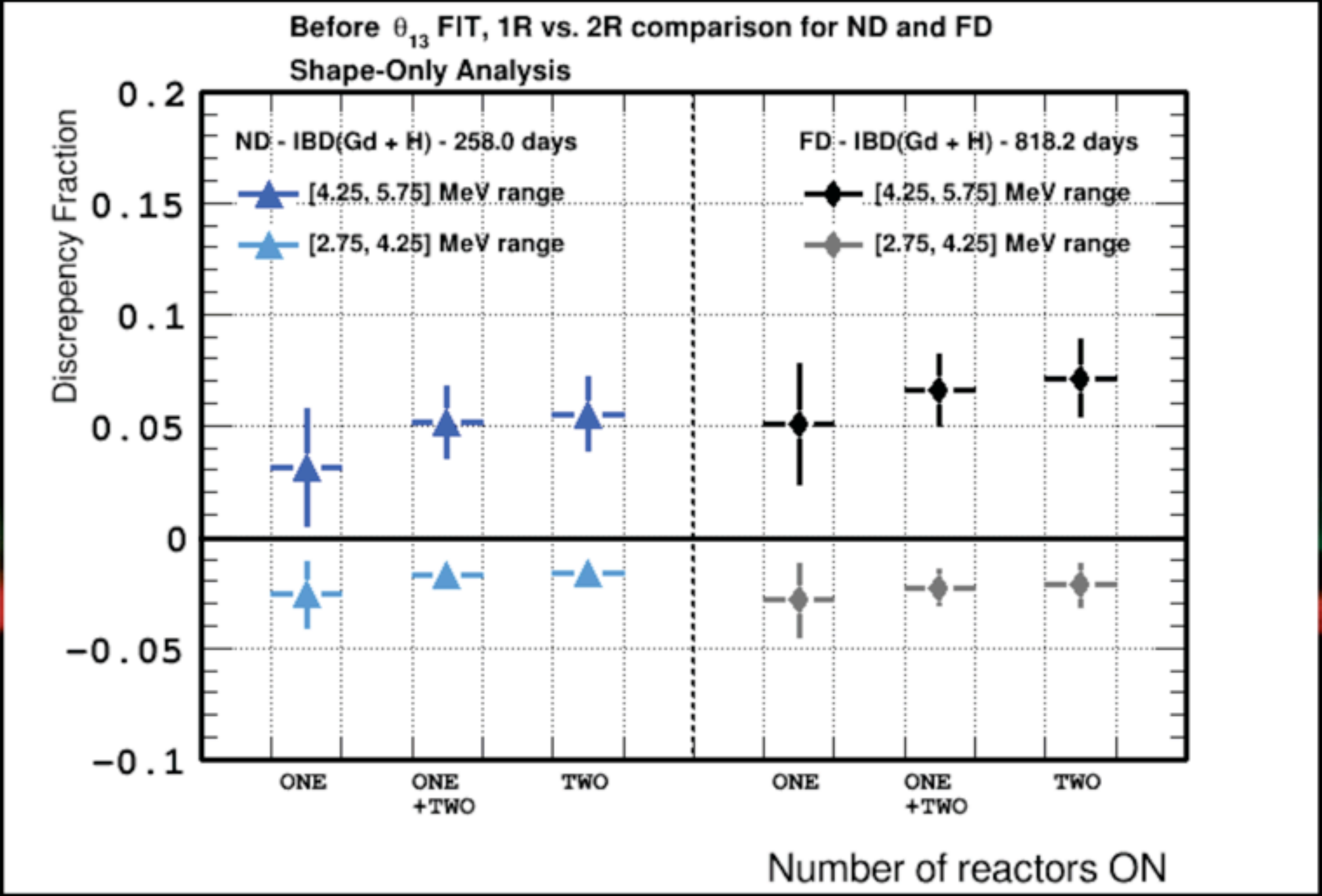
**DC: 210 000 events / DB: 1.2 million events / Reno: 280 000 events**



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

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

# clear features scaling with reactor..



consistent with our observations in 2014

**@JHEP 1410 (2014) 086** (only FD)

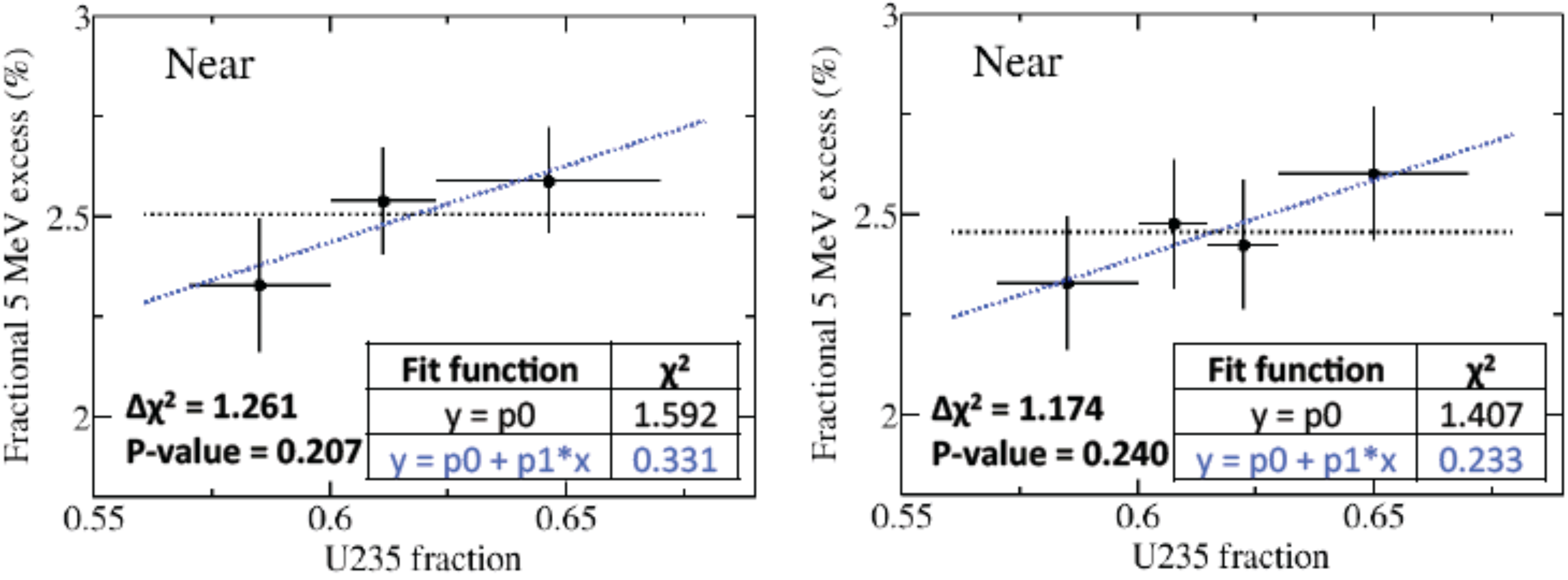
**features scaling fractionally constant with reactor#**

**(i.e. reactor power)**

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

Reno

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



$\Delta\chi^2 = 1.261$

P-value = 0.207

| Fit function | $\chi^2$ |
|---|---|
| y = p0 | 1.592 |
| y = p0 + p1*x | 0.331 |

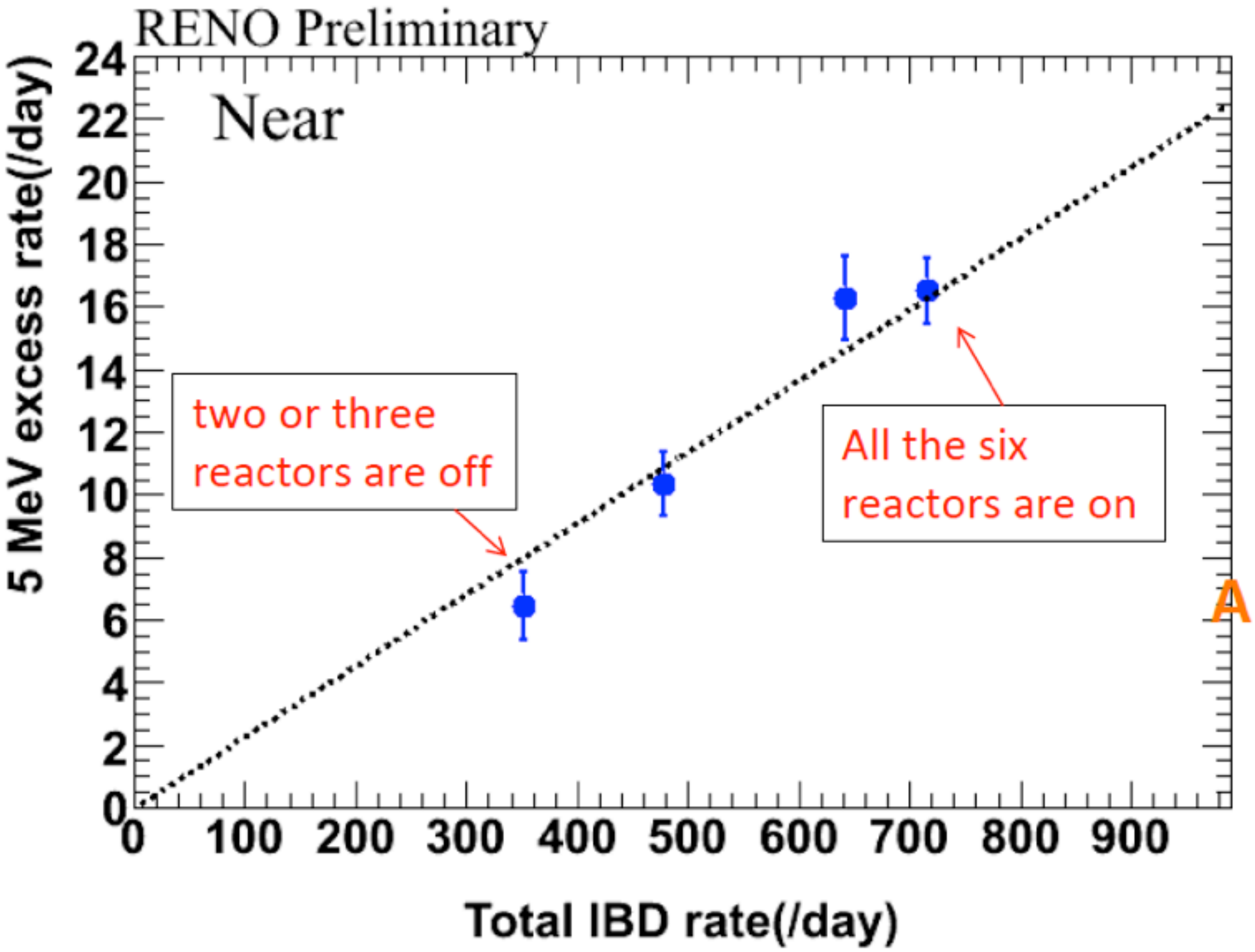
$\Delta\chi^2 = 1.174$

P-value = 0.240

| Fit function | $\chi^2$ |
|---|---|
| y = p0 | 1.407 |
| y = p0 + p1*x | 0.233 |

Excess seems correlated with reactor flux

# Correlation of 5 MeV Excess with Reactor Power

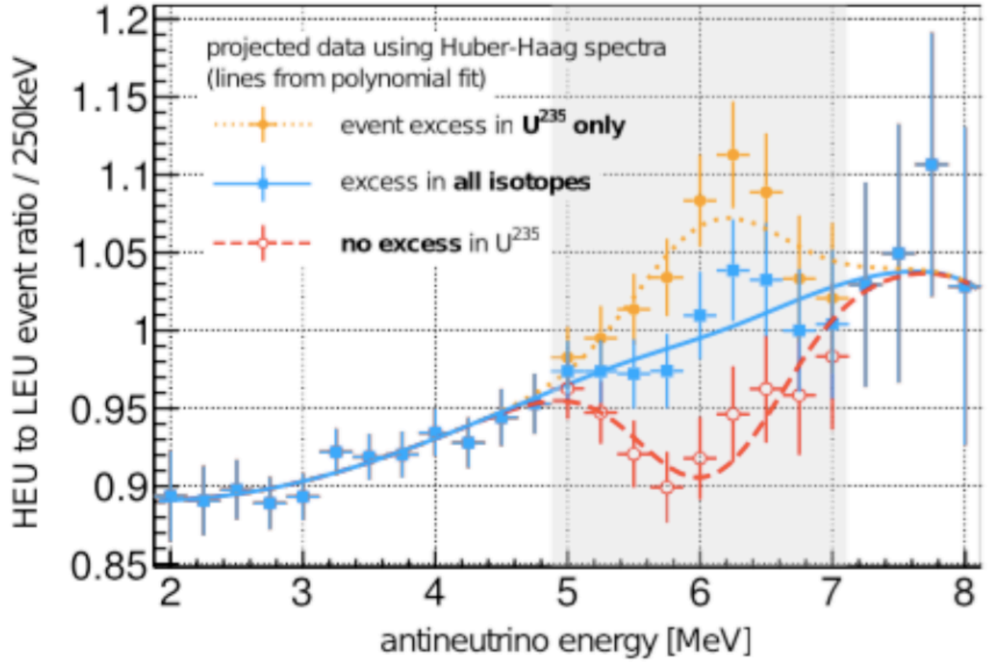


two or three reactors are off

All the six reactors are on

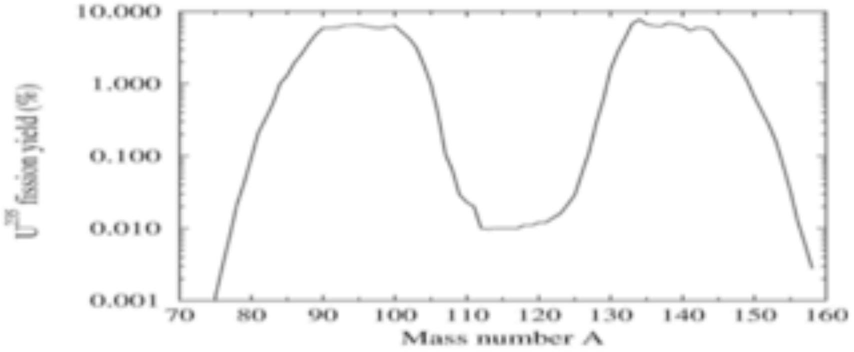
**5 MeV excess has a clear correlation with reactor thermal power !**

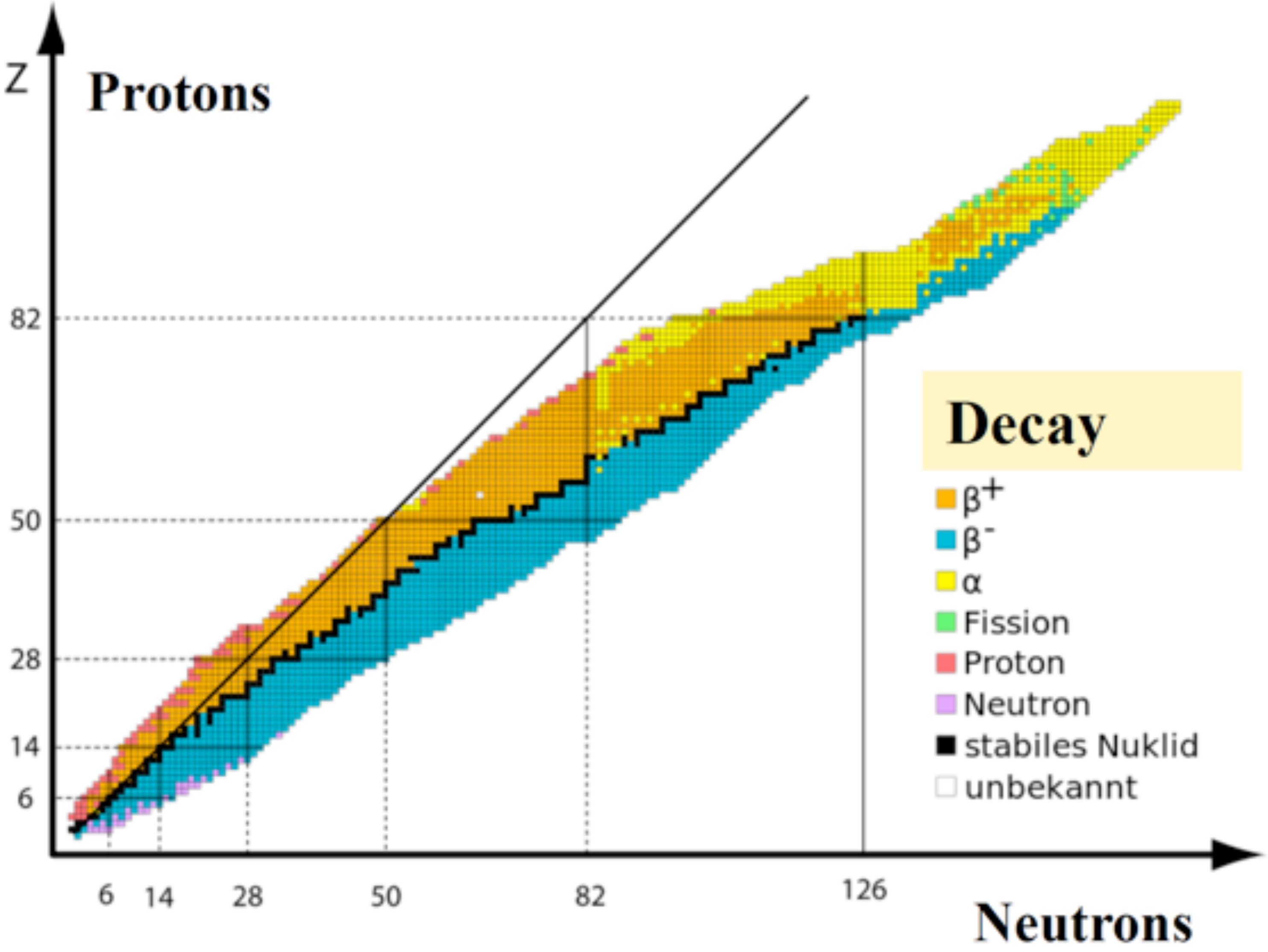
**A new reactor neutrino component !!**

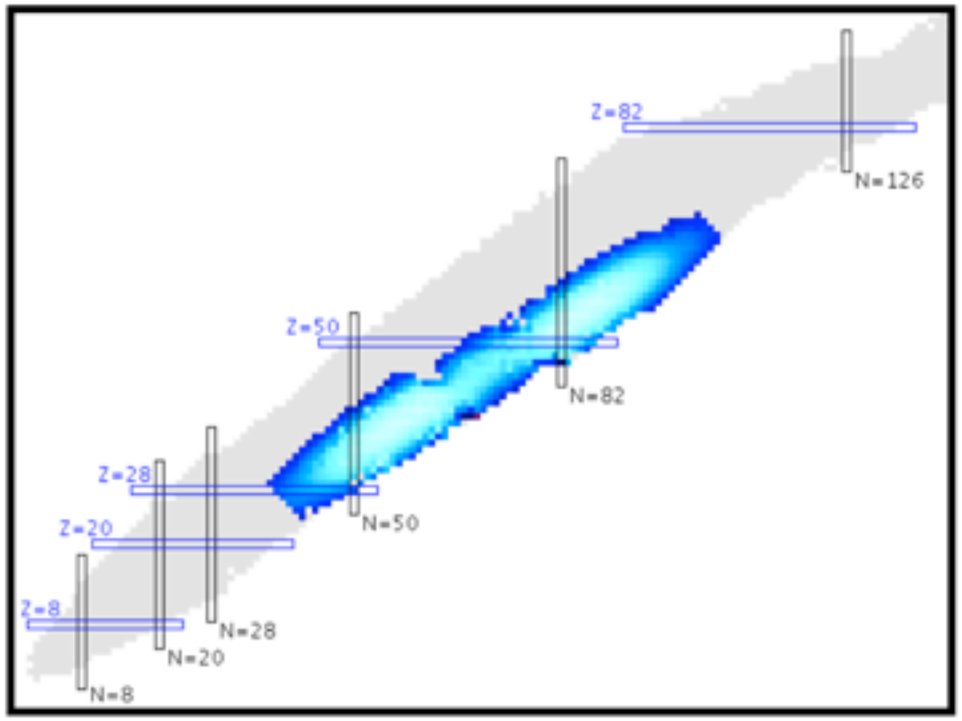


# Calculating Reactor Neutrino Spectra

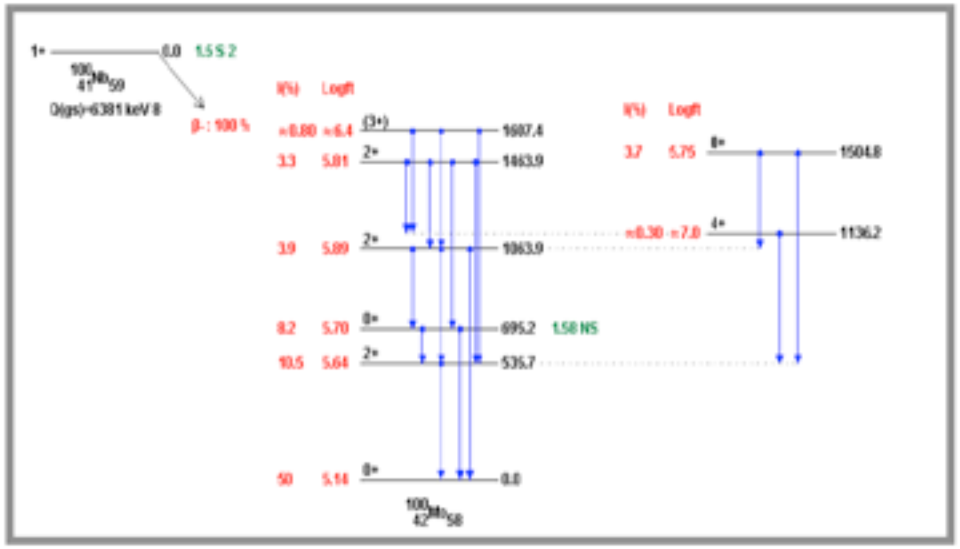
$${}^{235}_{92}U + n \rightarrow X_1 + X_2 + 2n$$





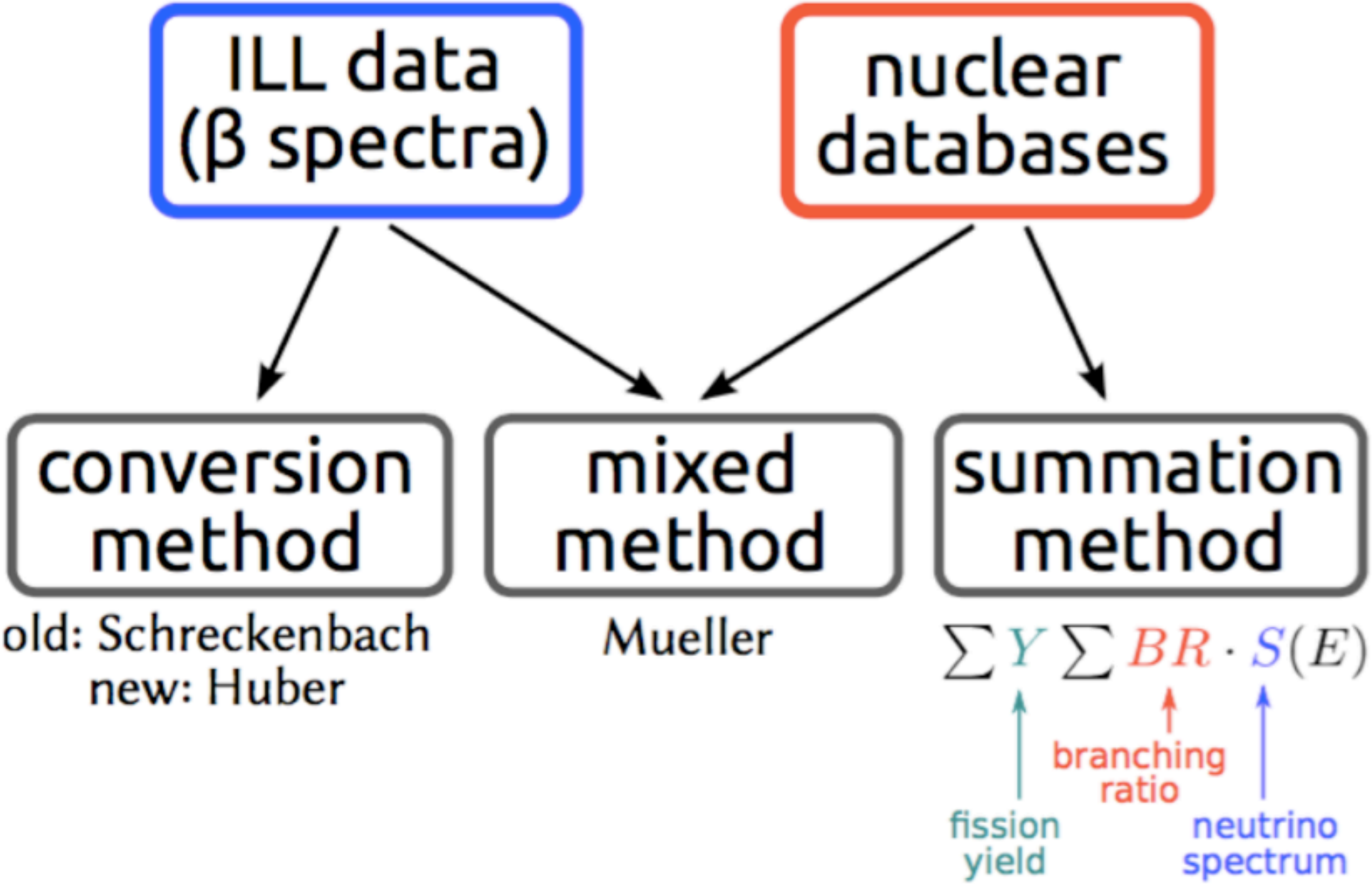


**involves poorly known β-emitters**



**short lived ←→ high energy**
**→ spectral uncertainties?**

# Reactor Spectrum Predictions



ILL data (β spectra)

nuclear databases

conversion method

mixed method

summation method

old: Schreckenbach
new: Huber

Mueller

$$\sum Y \sum BR \cdot S(E)$$

fission yield

branching ratio

neutrino spectrum

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

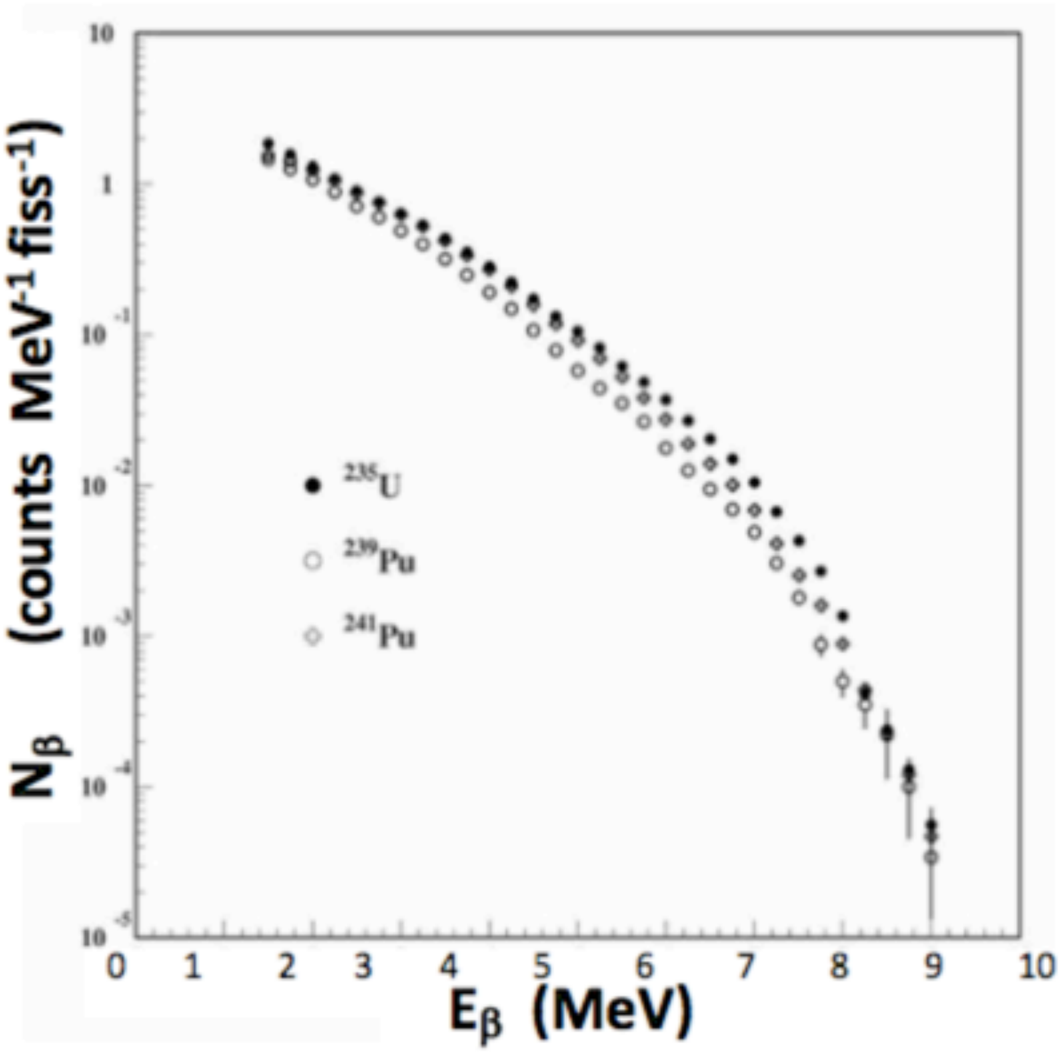
➡ Experiments have used different methods

# 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 235U, 239Pu, 241Pu
- 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

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

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

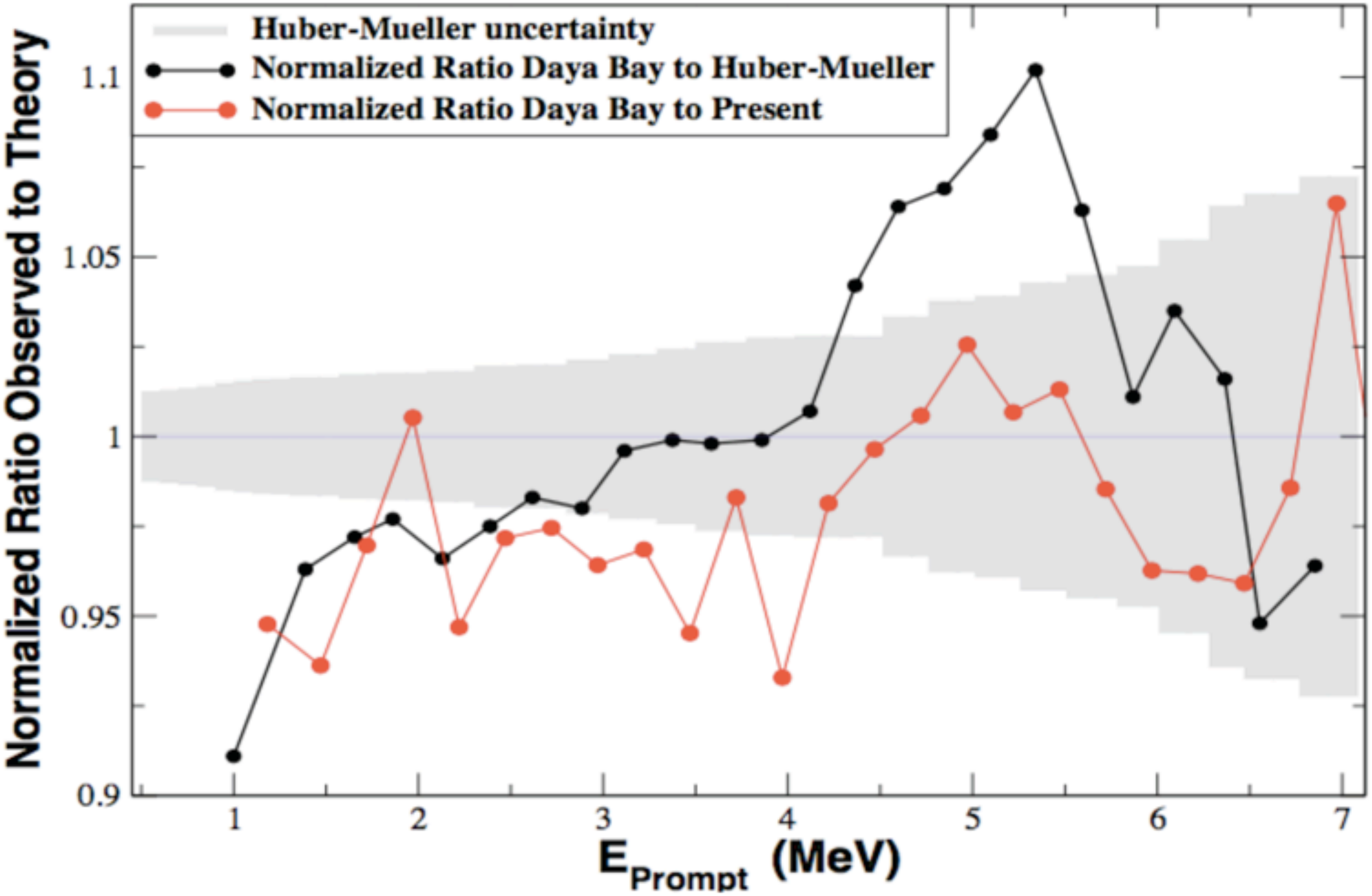
Z→ $Z_{\mathrm{eff}}$ and δ are parametrizations!

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

# 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] | $\nu_e$ | $^{51}$Cr | 0.75 | $\lesssim 1$ | in preparation |
| CeSOX [167, 168] | $\bar{\nu}_e$ | $^{144}$Ce | 1.8 – 3 | 5 – 12 | in preparation |
| CrSOX [167] | $\nu_e$ | $^{51}$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] | $\nu_e$ | $^{51}$Cr, $^{37}$Ar | 0.75, 0.81 | $\lesssim 90$ | abandoned |

**Source experiments**

tensions with cosmology…
➔ $N_{\mathrm{eff}} = 3.x < \sim 4$
BBN...

Nevertheless:
➔ lab tests important

Also important:
➔ keV sterile ν =WDM..

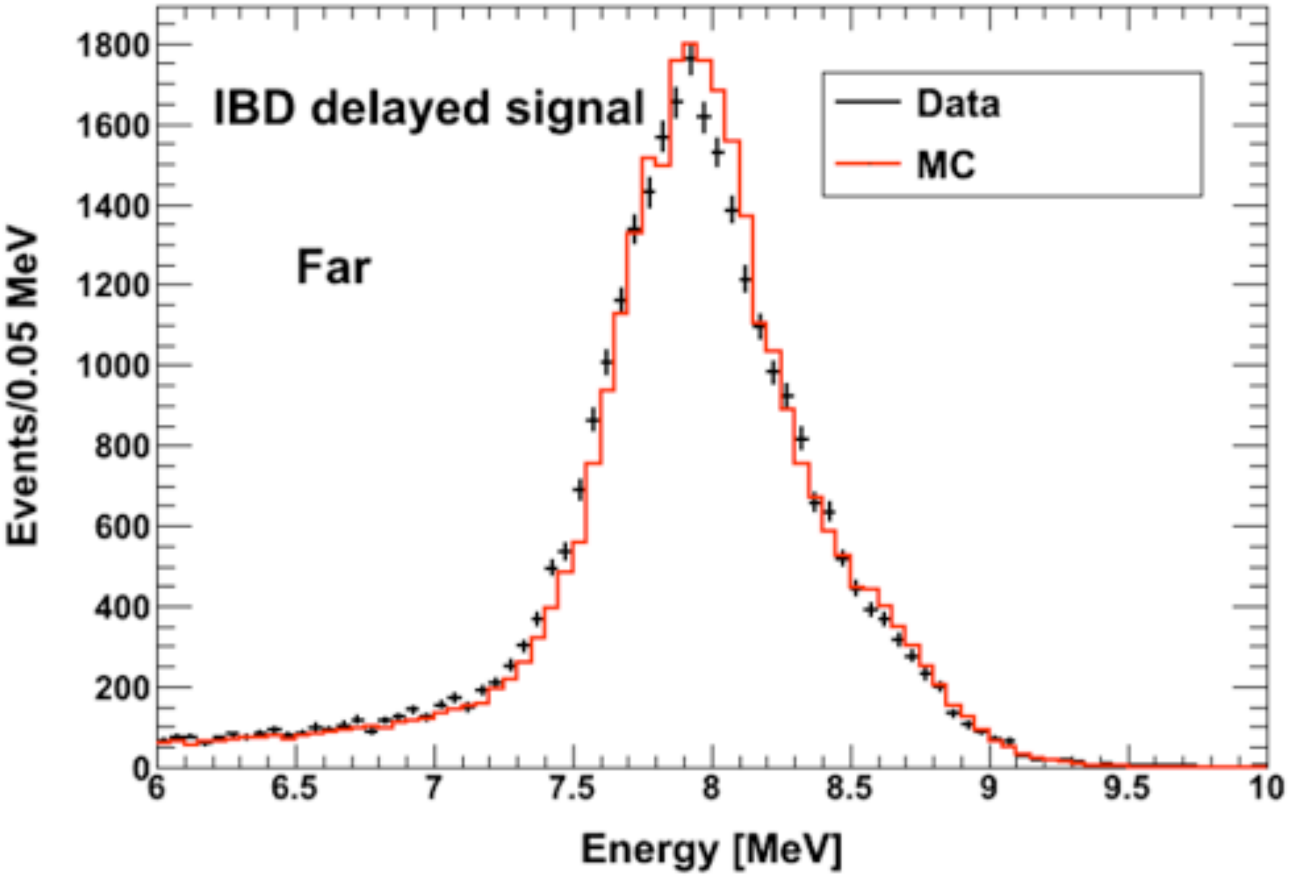
| Project | $P_{th}$ (MW) | $M_{target}$ (tons) | $L$ (m) | Depth (m.w.e.) | status |
|---|---|---|---|---|---|
| Nucifer (FRA) [175] | 70 | 0.8 | 7 | 13 | operating |
| Stereo (FRA) [176] | 57 | 1.75 | 9 – 12 | 18 | ~~in preparation~~ → running |
| DANSS (RUS) [177] | 3000 | 0.9 | 10 – 12 | 50 | ~~in 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 |

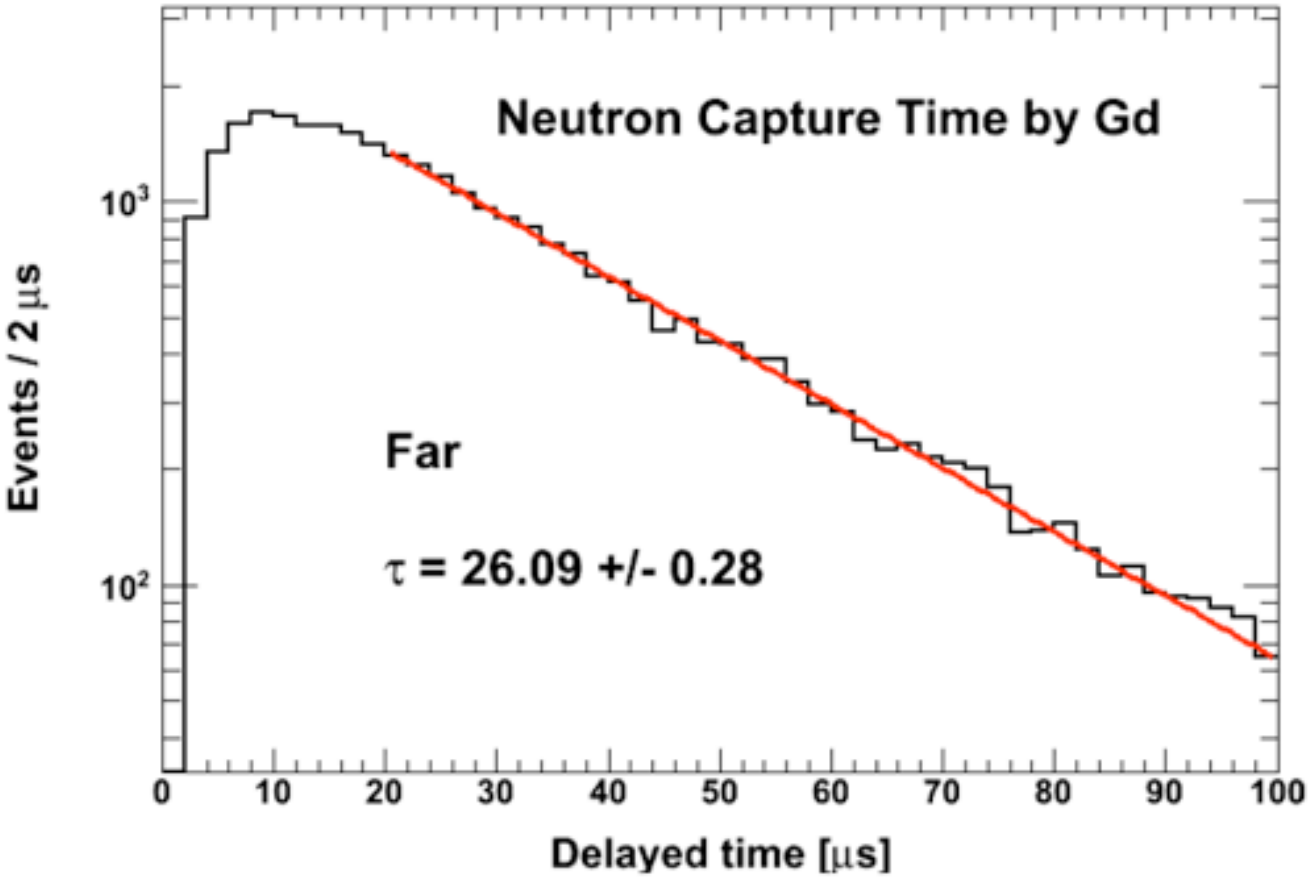
**Reactor experiments**

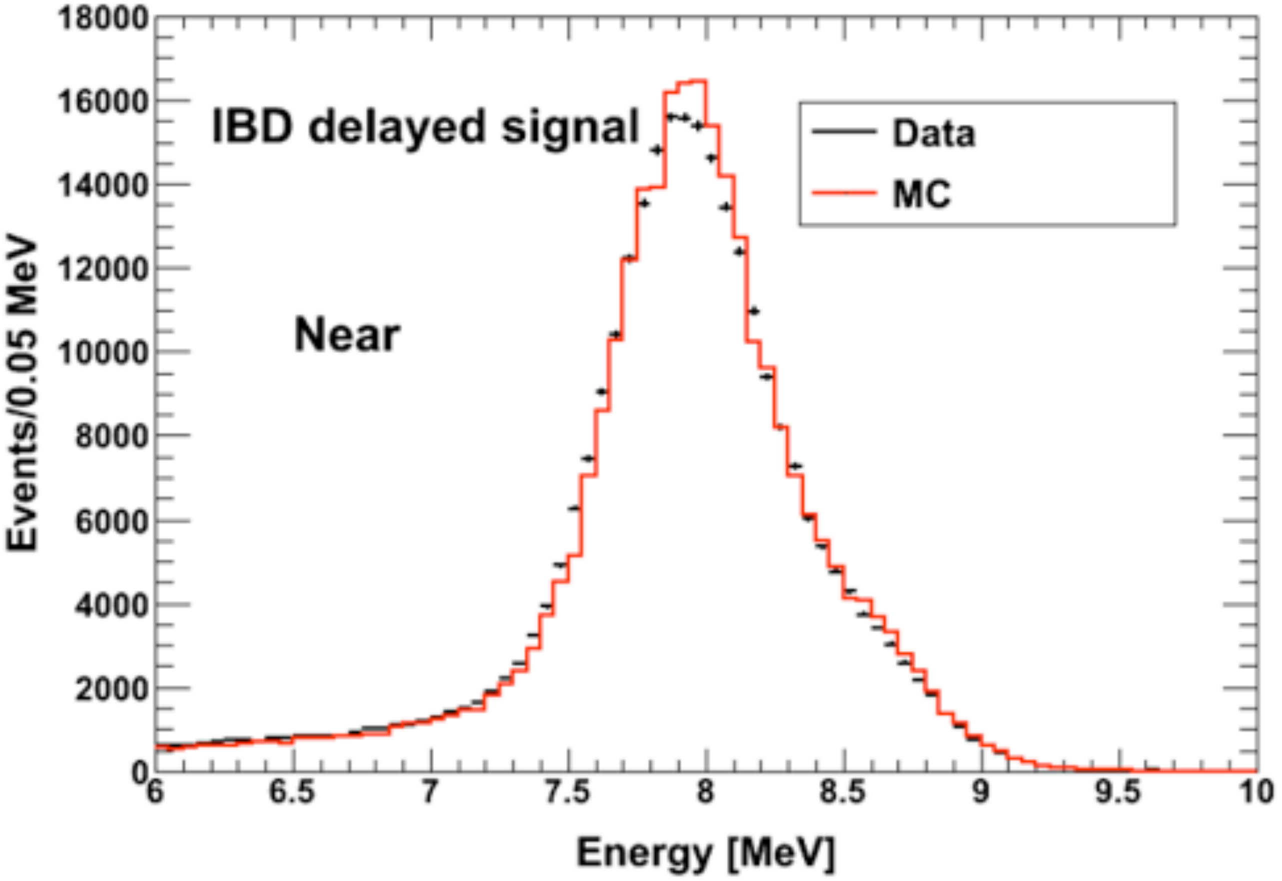
Giunti 1512.04758

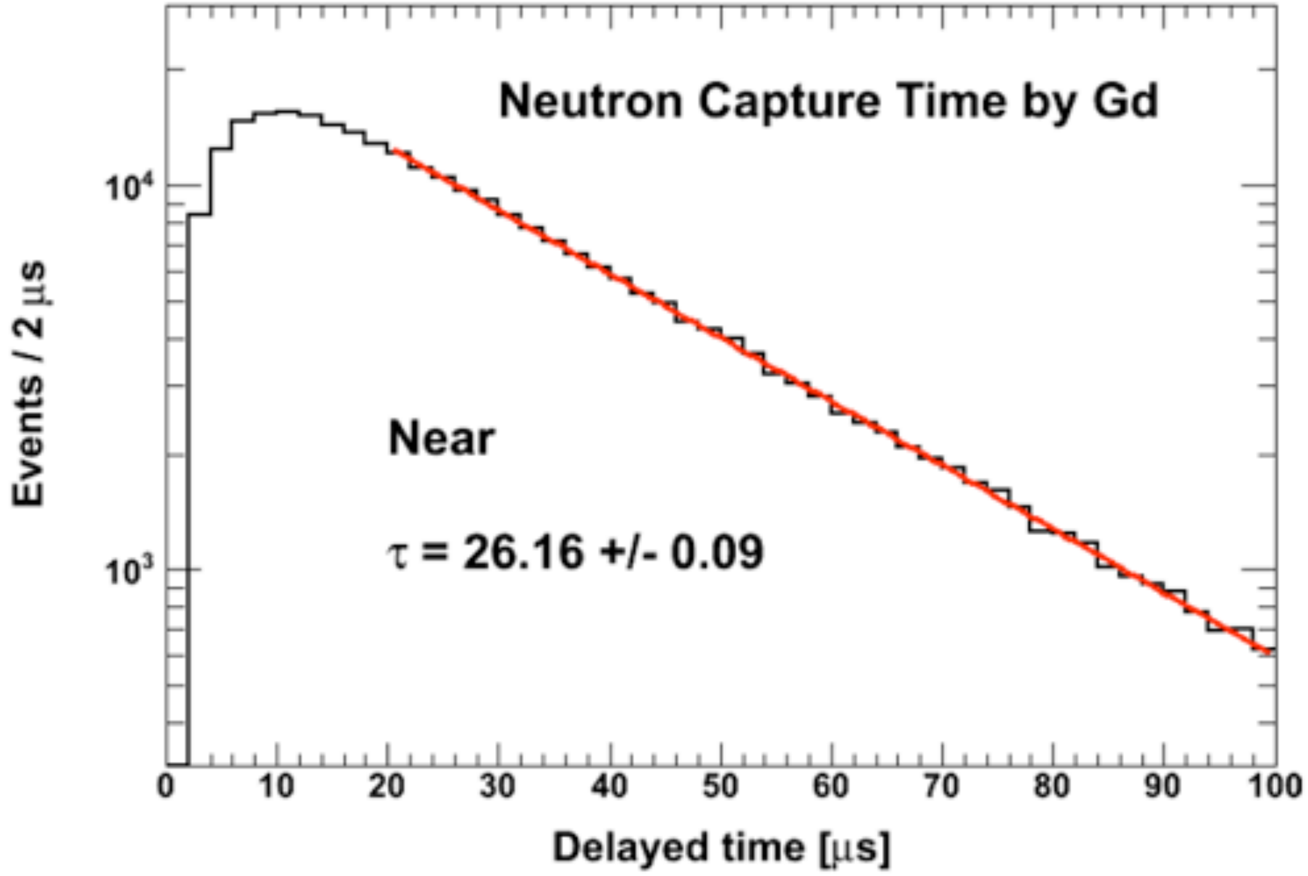
# Back up

# Neutron Capture by Gd

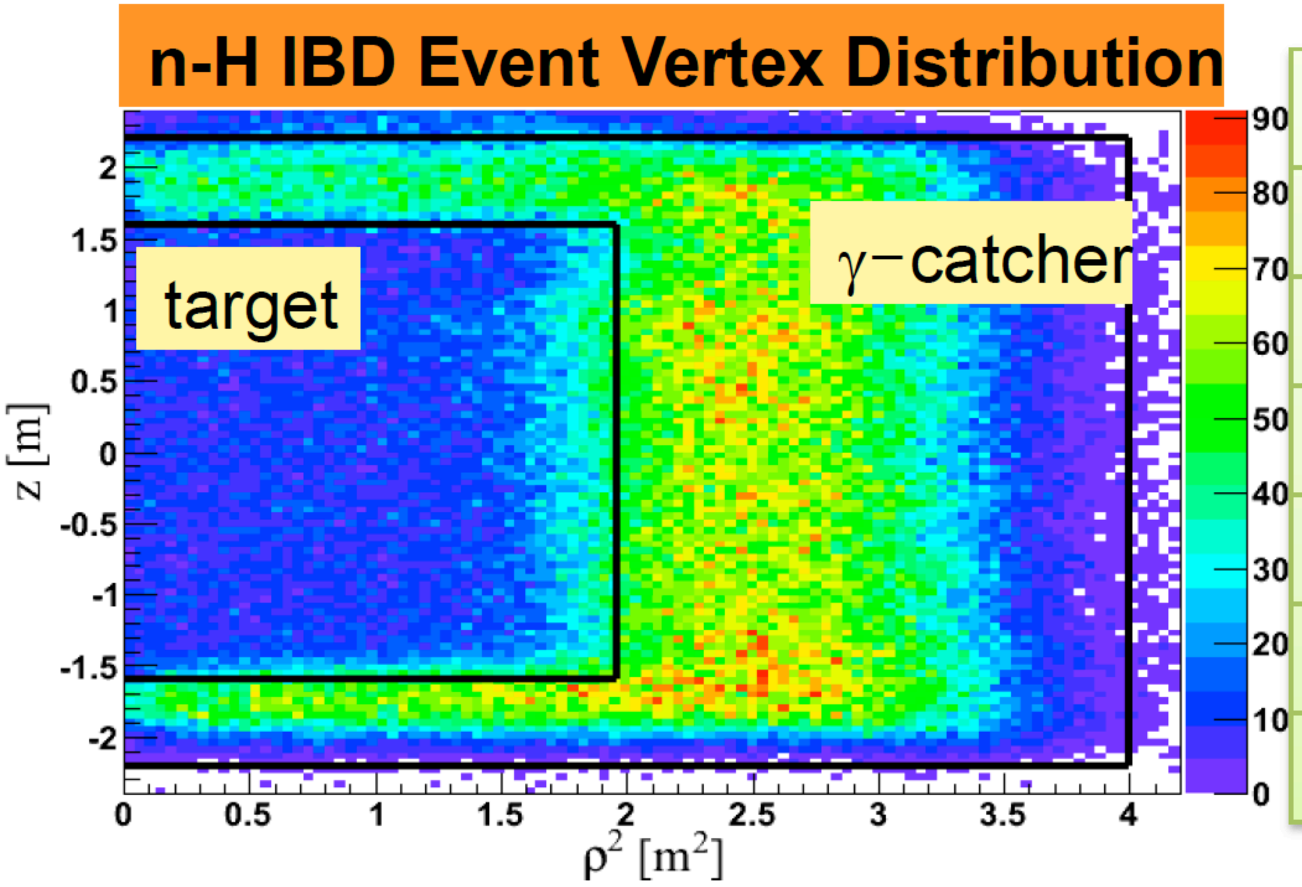








Gd used because of delay @ 8 MeV (radiogenic BG dominates ≤ 3MeV)


n-H IBD Event Vertex Distribution

| | 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 |

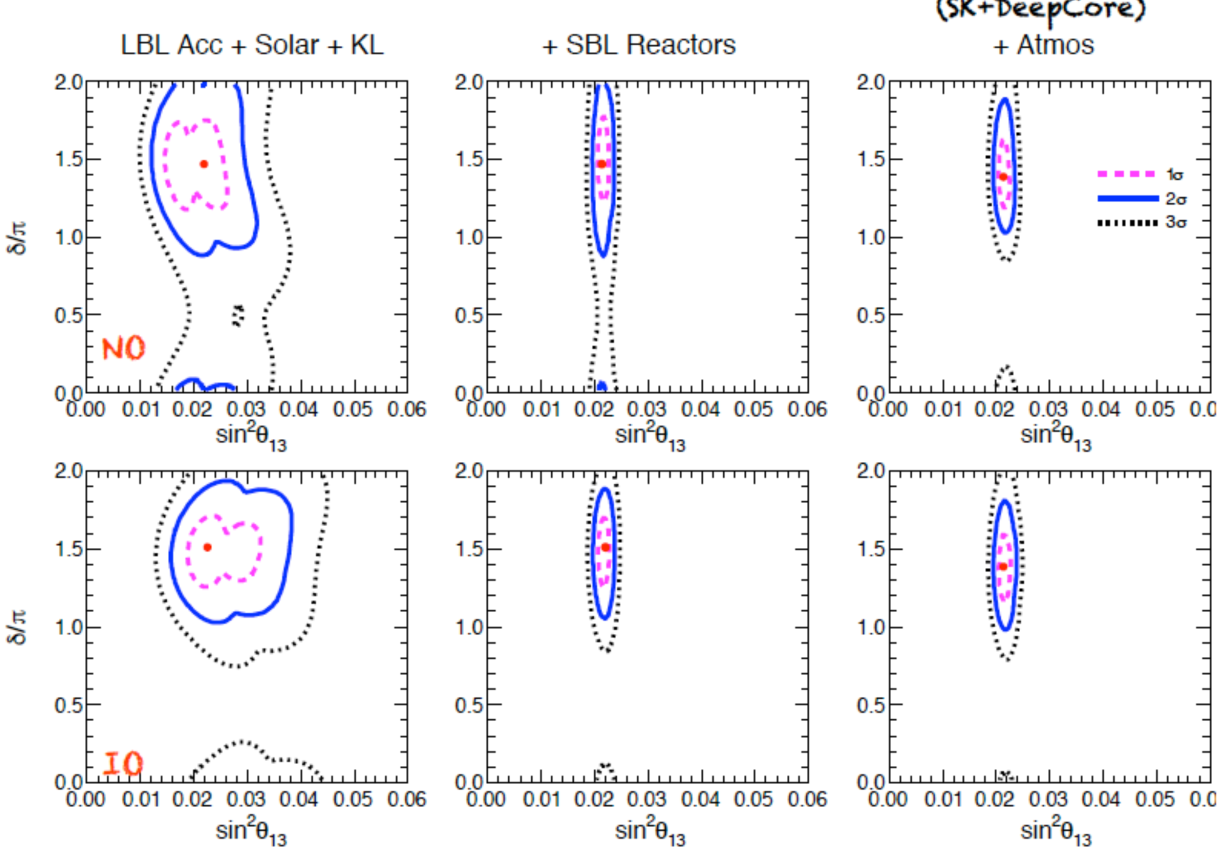
Analysis with n-H (lower average energy) and not n-Gd shows that origin of "IBD" is heavily polluted by external radioactivity instead

# Backgrounds & uncertainties

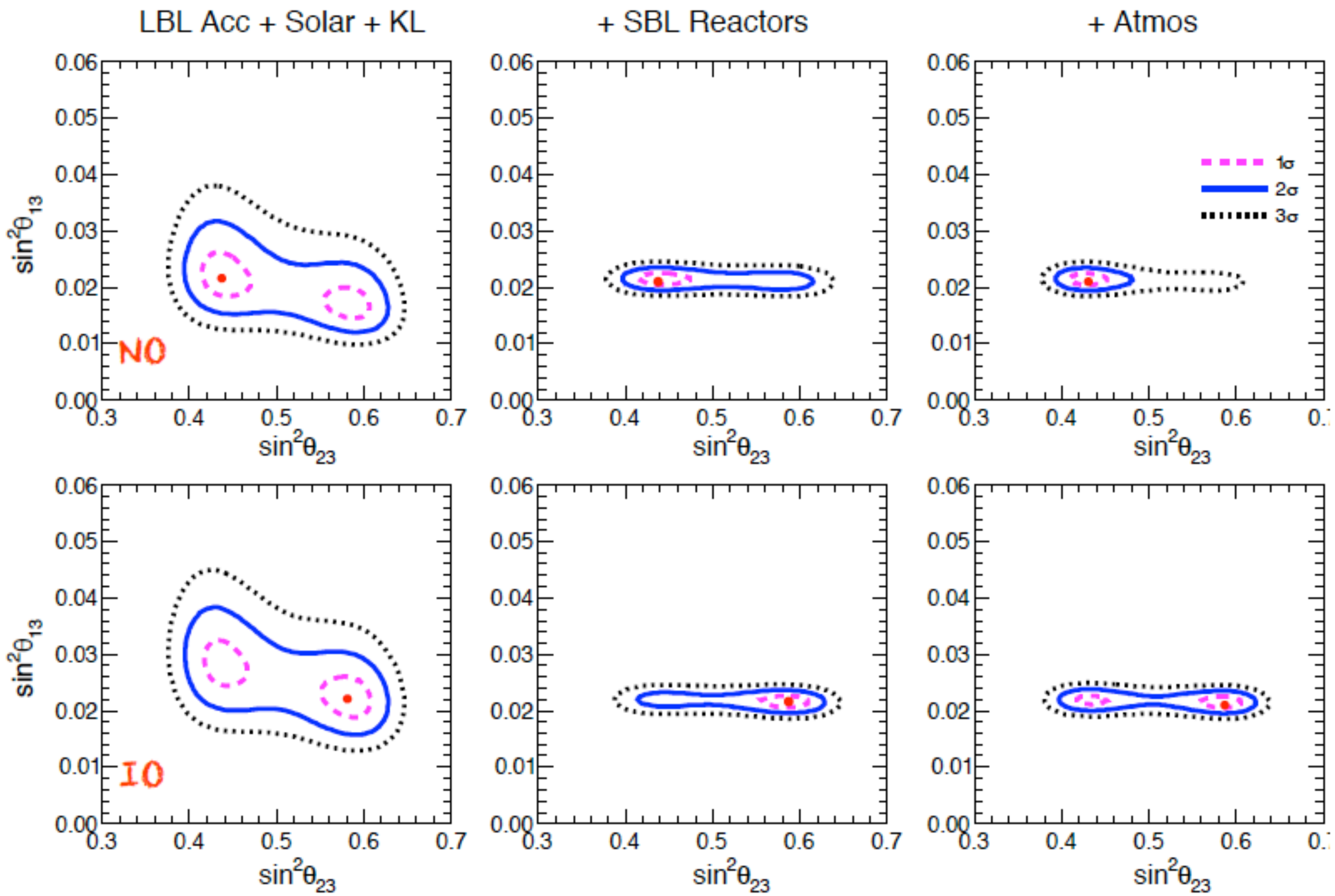
| | Daya Bay | | Reno | | Double Chooz |
|---|---|---|---|---|---|
| | Near | Far | Near | Far | Far |
| Accidentals (B/S) | 1.4% | 4.0% | 0.56% | 0.93% | 0.6% |
| Uncertainty(ΔB/B) | 1.0% | 1.4% | 1.4% | 4.4% | 0.8% |
| Fast neutrons(B/S) | 0.1% | 0.06% | 0.64% | 1.3% | 1.6% |
| Uncertainty(ΔB/B) | 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

| | Daya Bay | | Reno | | Double Chooz |
|---|---|---|---|---|---|
| | Corr. | Uncorr. | Corr. | Uncorr. | Corr./Uncorr. |
| Thermal power | | 0.5% | | 0.5% | 0.5% |
| Fission fraction/Fuel composition | | 0.6% | | 0.7% | 0.9% |
| Fission cross section /Bugey 4 measurement | 3% | | 1.9% | | 1.4% |
| Reference spectra | | | 0.5% | | 0.5% |
| IBD cross section | | | 0.2% | | 0.2% |
| Energy per fission | 0.2% | | 0.2% | | 0.2% |
| Baseline | 0.02% | | - | | 0.2% |
| Spent fuel | | 0.3% | | | |
| **Total** | **3%** | **0.8%** | **2.0%** | **0.9%** | **1.8%** |



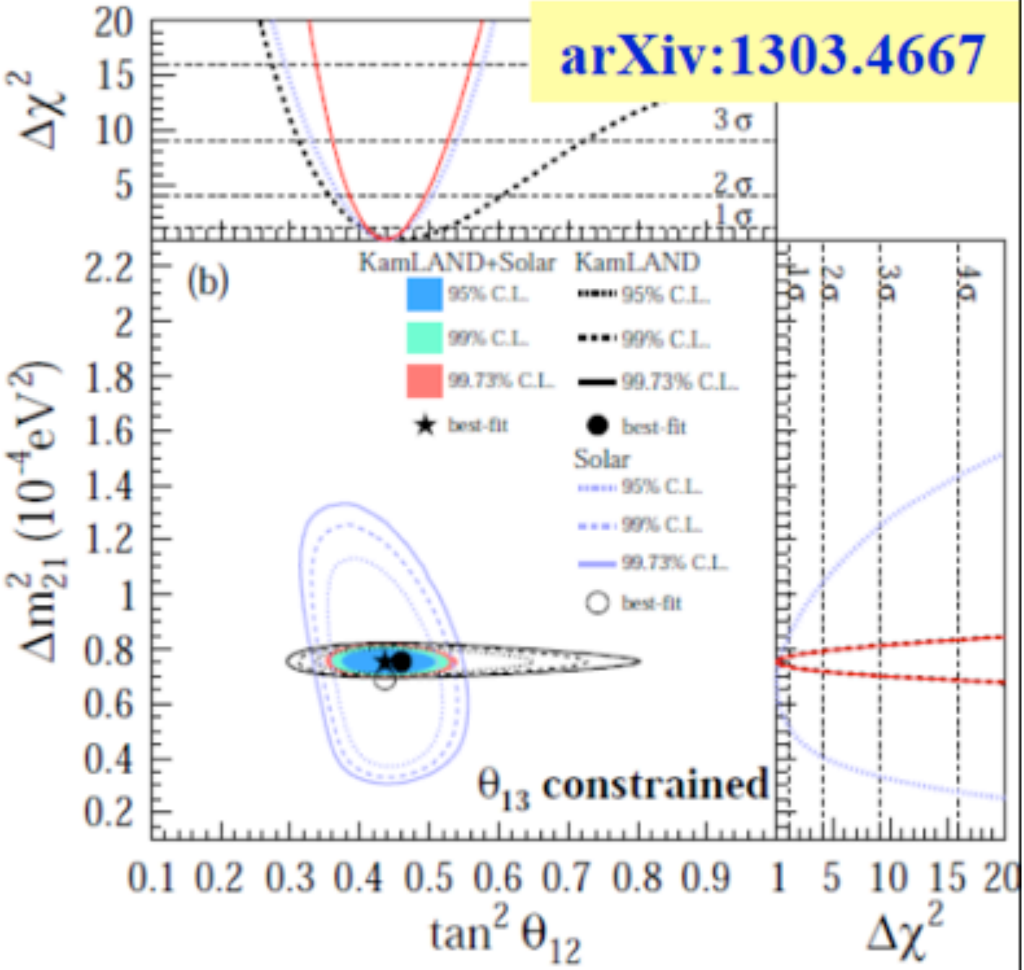
Anti-correlation via appearance at accelerators, then constrained by reactors



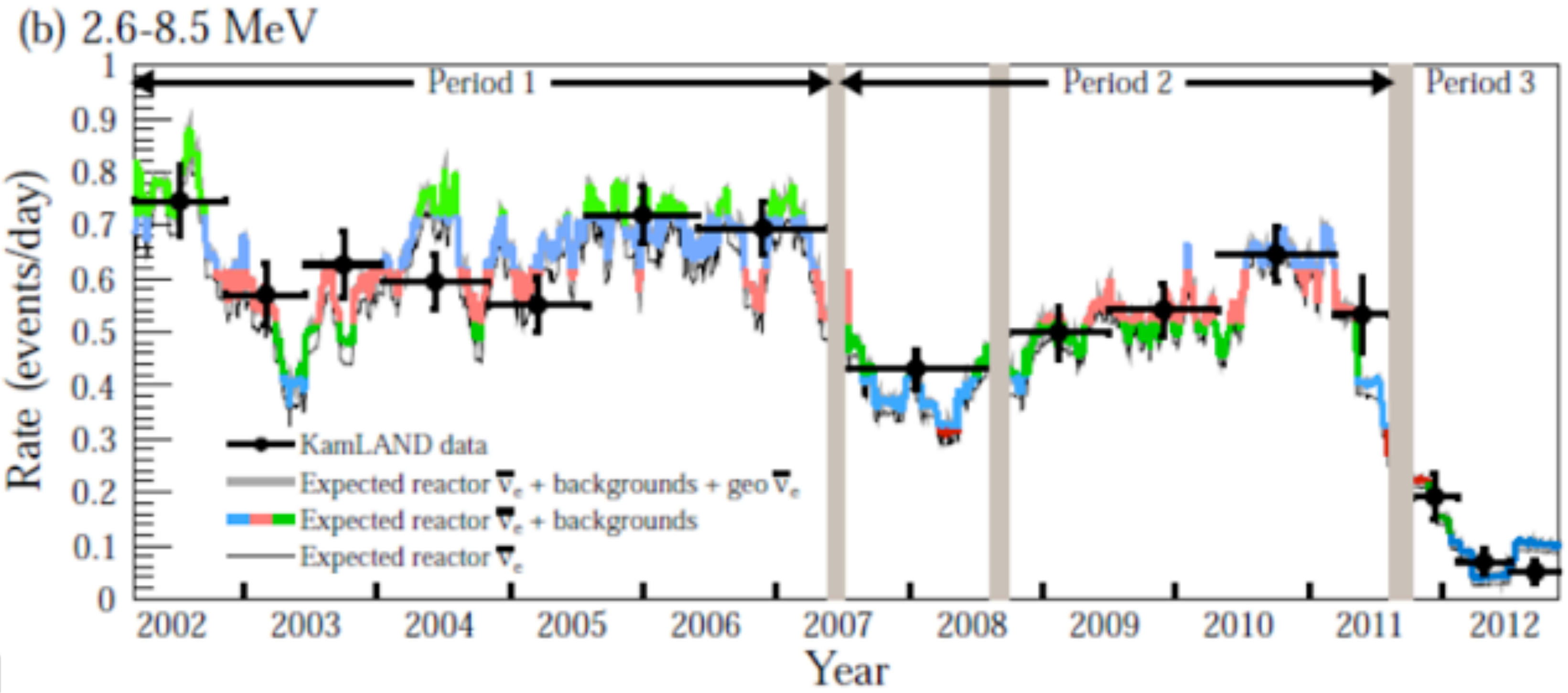
# Latest KamLAND Results: $\theta_{12}$

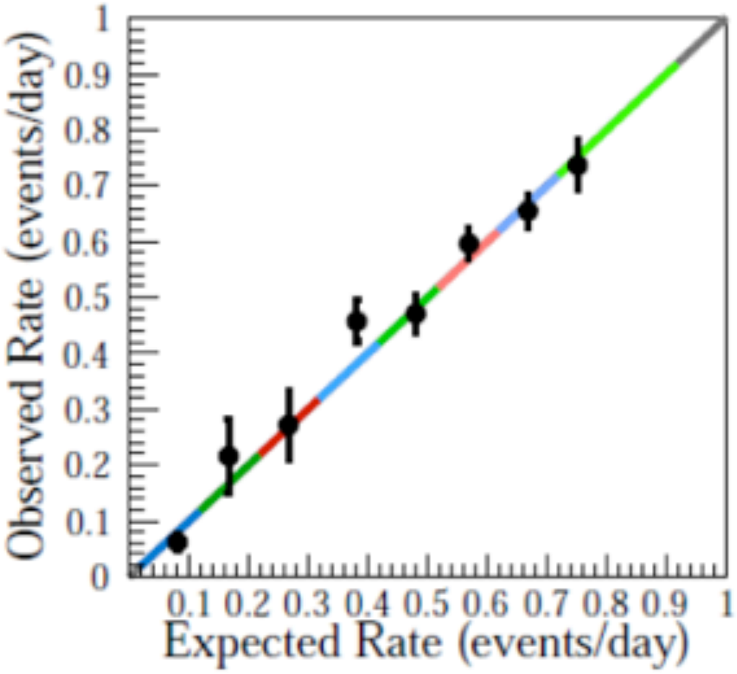
- **Reactors are all off in Japan since Mar. 2011:**
  - ⇨ A unique opportunity for precise measurement of backgrounds

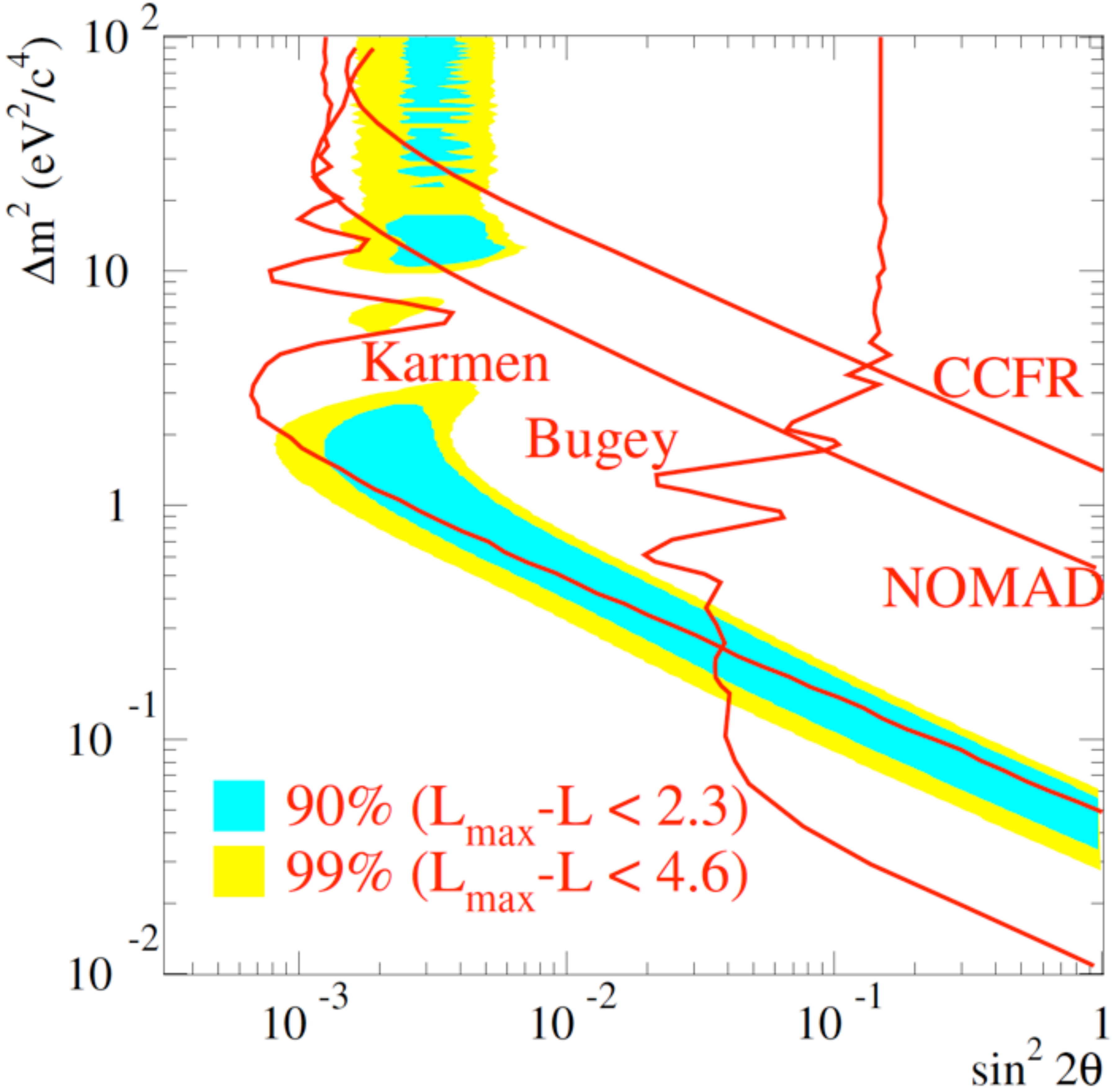
| Data combination | $\Delta m^2_{21}$ | $\tan^2\theta_{12}$ | $\sin^2\theta_{13}$ |
|---|---|---|---|
| KamLAND | $7.54^{+0.19}_{-0.18}$ | $0.481^{+0.092}_{-0.080}$ | $0.010^{+0.033}_{-0.034}$ |
| KamLAND + solar | $7.53^{+0.19}_{-0.18}$ | $0.437^{+0.029}_{-0.026}$ | $0.023^{+0.015}_{-0.015}$ |
| KamLAND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



**arXiv:1303.4667**







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