Latest Reactor Neutrino Oscillation Results from the Daya Bay Experiment

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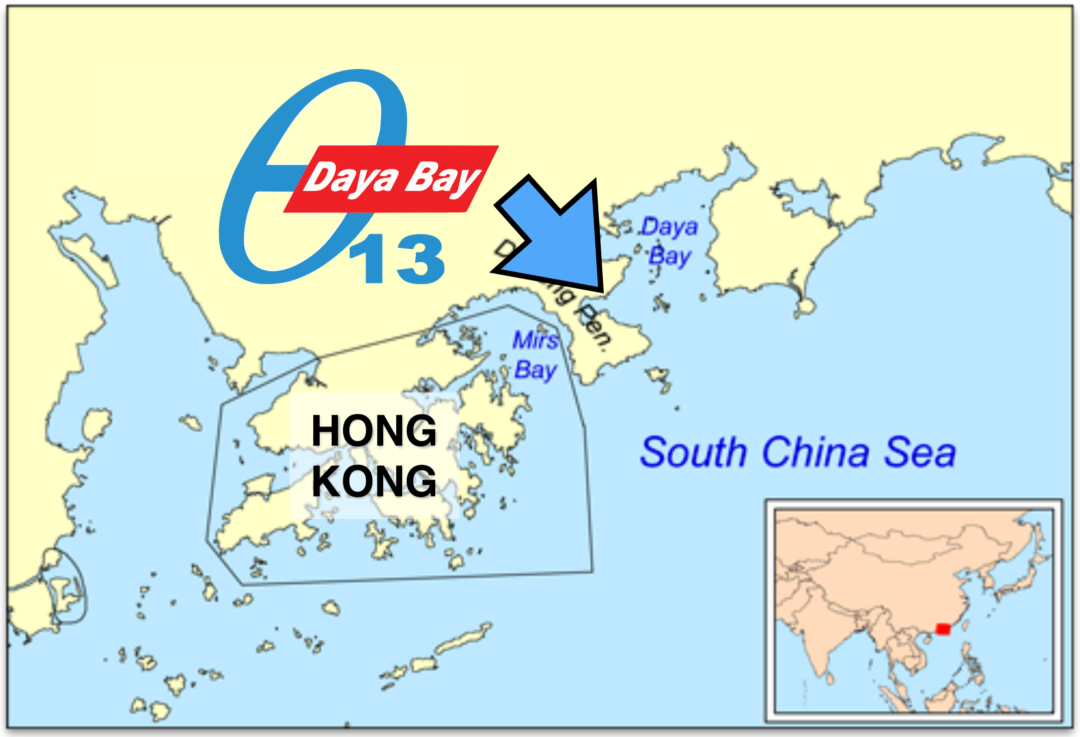
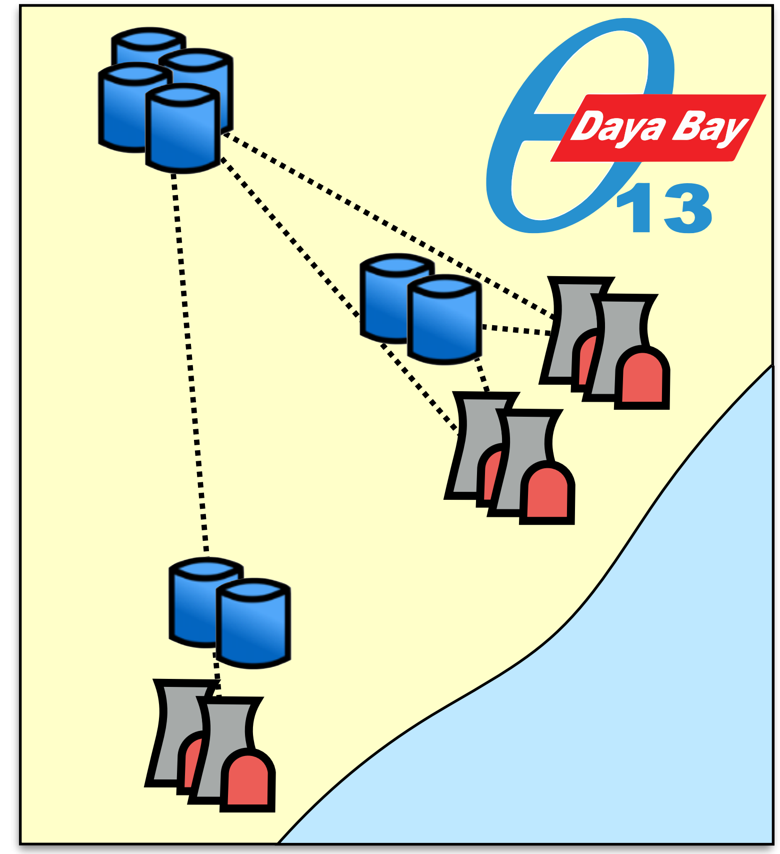
*on behalf of the Daya Bay Collaboration

ICHEP 2020 | PRAGUE

The Daya Bay Experiment Overview





- Primarily designed to precisely measure the θ_{13} mixing angle
- Using reactor antineutrino oscillation at the ~2 km baseline
- Discovered non-zero value of θ_{13} in 2012

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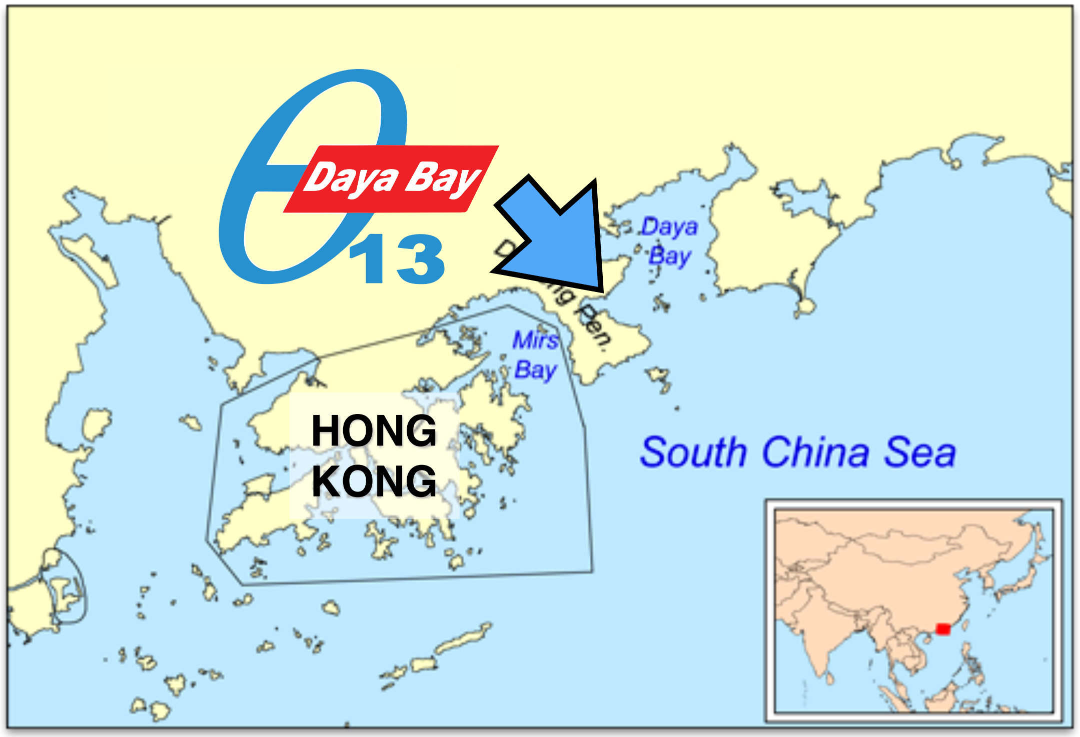
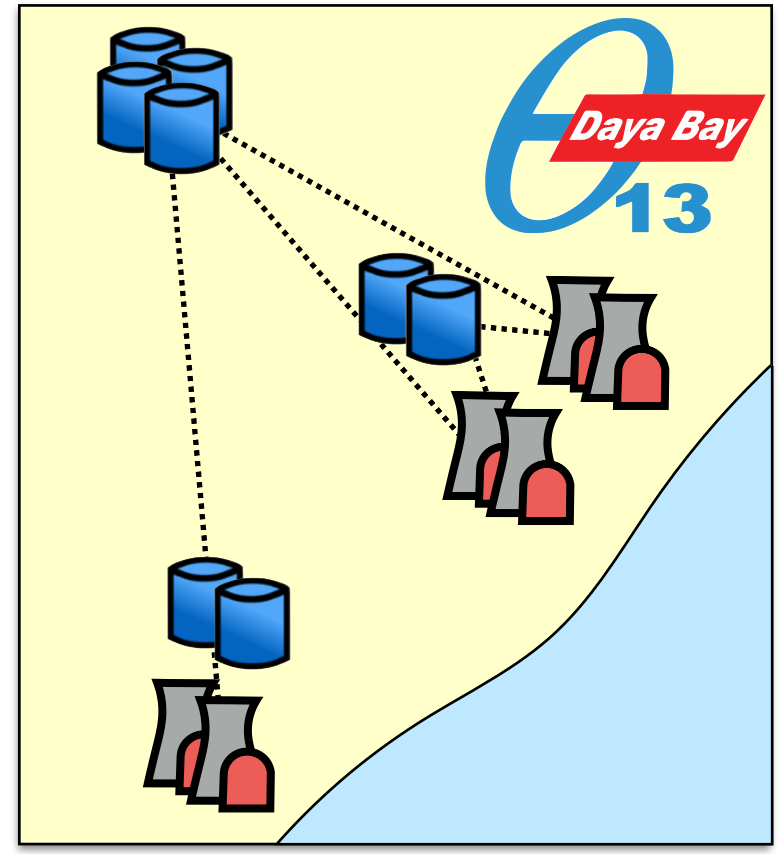
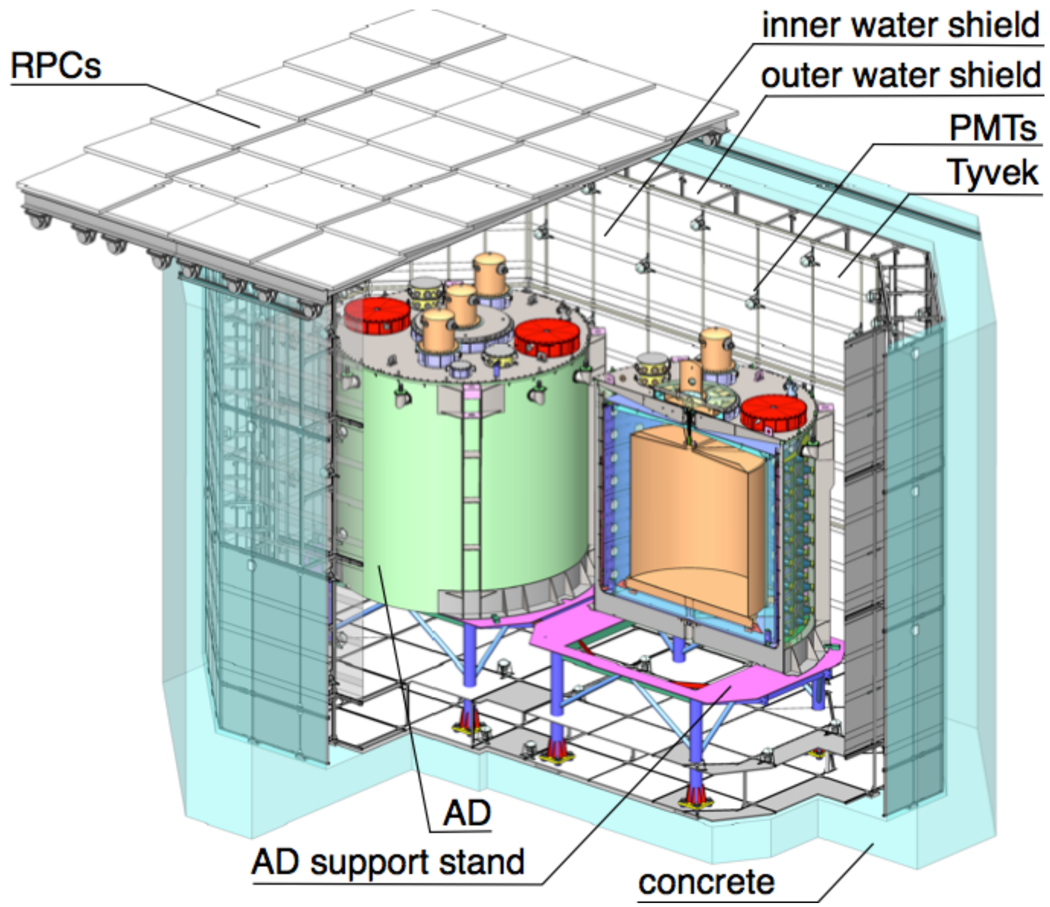
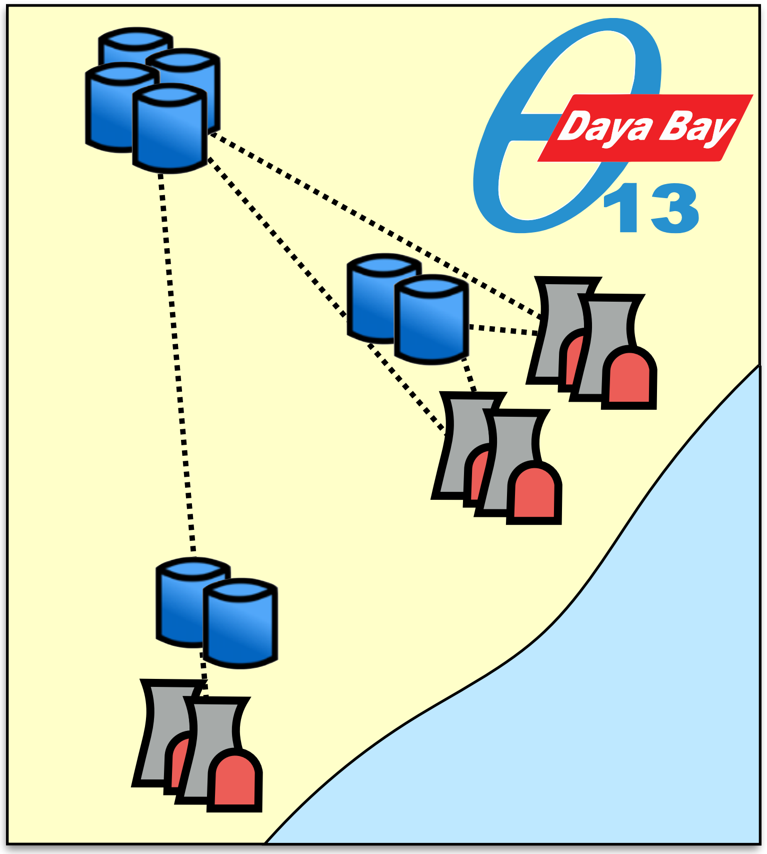




- 6 reactors with 2.9 GW_{th} each ➔ 17.4 GW_{th} total
- One of the most powerful reactor complexes in the world
- Nuclear reactors - strong source of pure electron antineutrinos
- Each Daya Bay reactor emits ~6×10^{20} $\bar{\nu}_e$/s isotropically

The Daya Bay Experiment Overview





- 8 functionally identical antineutrino detectors (ADs)
- Placed in 3 underground experimental halls at the optimal distance from the reactors
- Submerged in the instrumented ultra pure water pools

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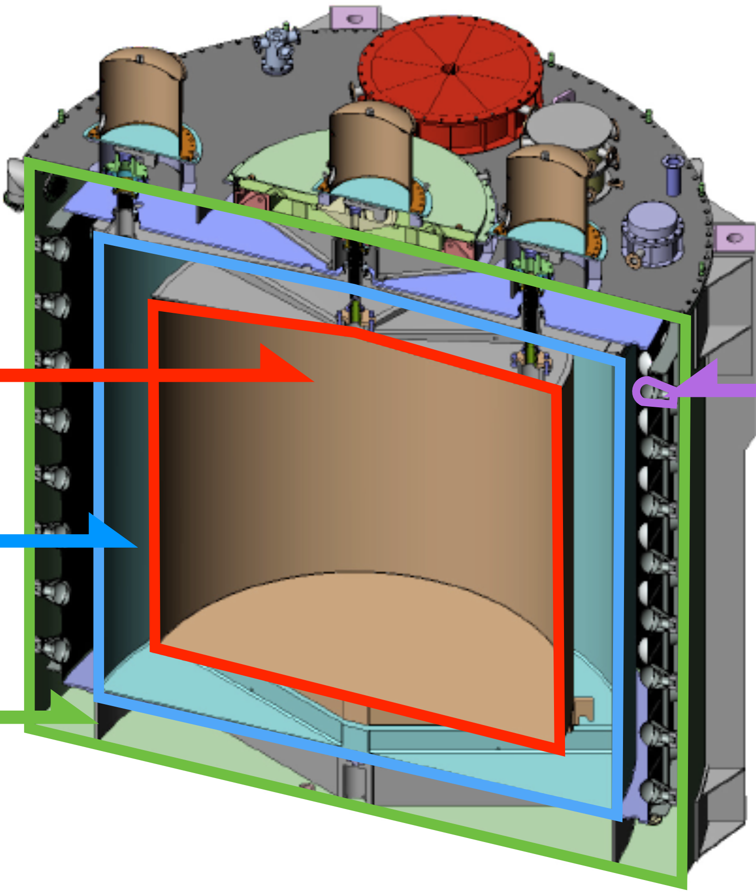
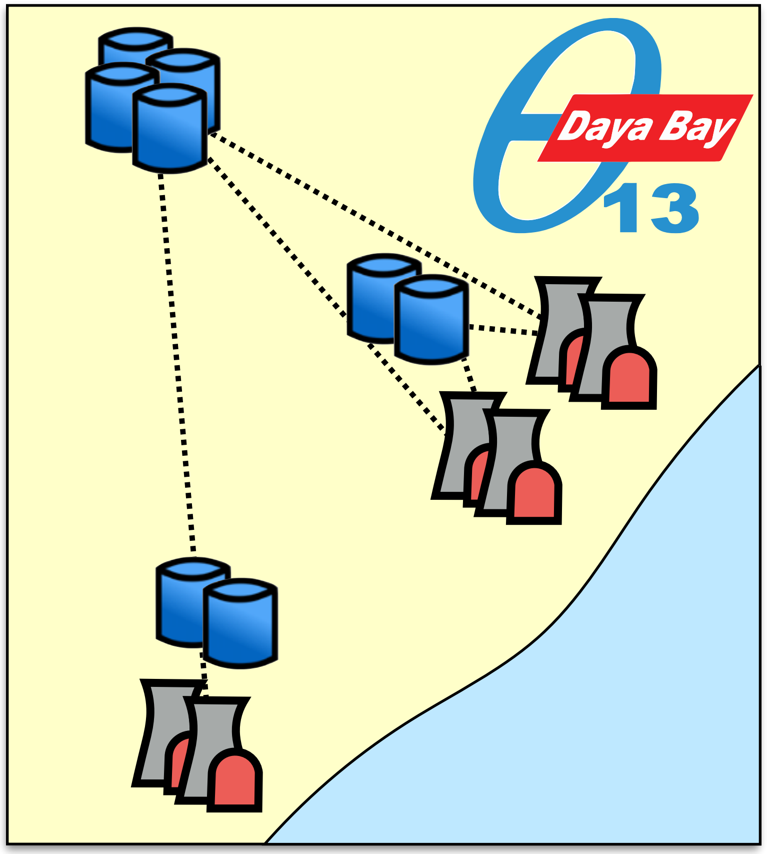
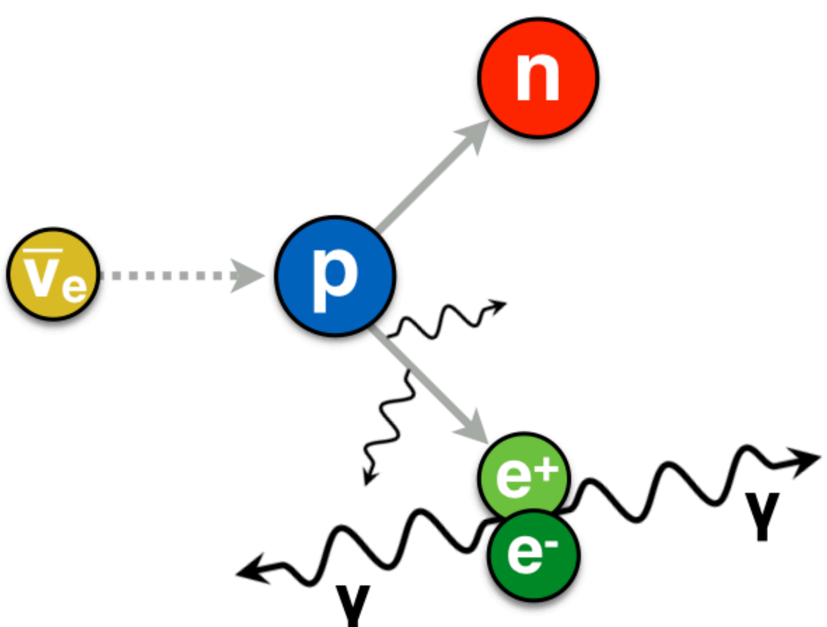




- 8 functionally identical antineutrino detectors (ADs)
- Placed in 3 underground experimental halls at the optimal distance from the reactors
- Submerged in the instrumented ultra pure water pools
- Each AD consists of 3 nested volumes: Gd-doped scintillator (main target), pure scintillator (γ-catcher), mineral oil (buffer)

Reactor Antineutrino Detection

- Primary interaction - inverse beta decay (IBD): $\bar{\nu}_e + p \rightarrow e^+ + n$
- Prompt signal energy related to incident antineutrino energy $E_{\bar{\nu}} \simeq E_p + 0.78$ MeV
- Spatial and time correlation of prompt and delayed signals greatly suppresses the background (background/signal <2% in Daya Bay)



Reactor Antineutrino Detection

Prompt signal

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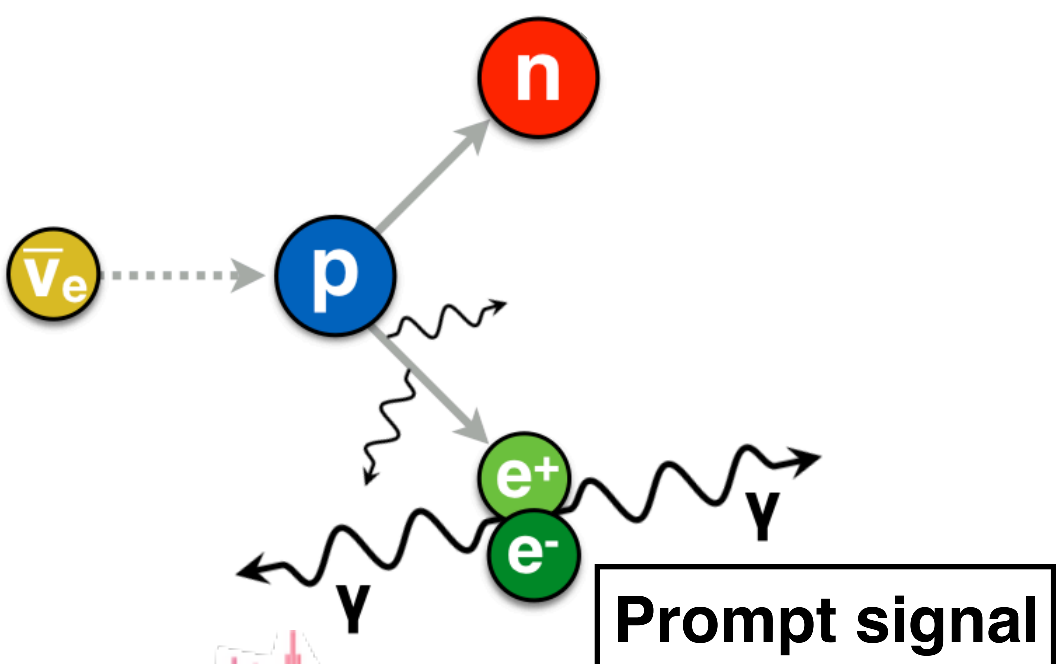

Prompt signal → Delayed signal

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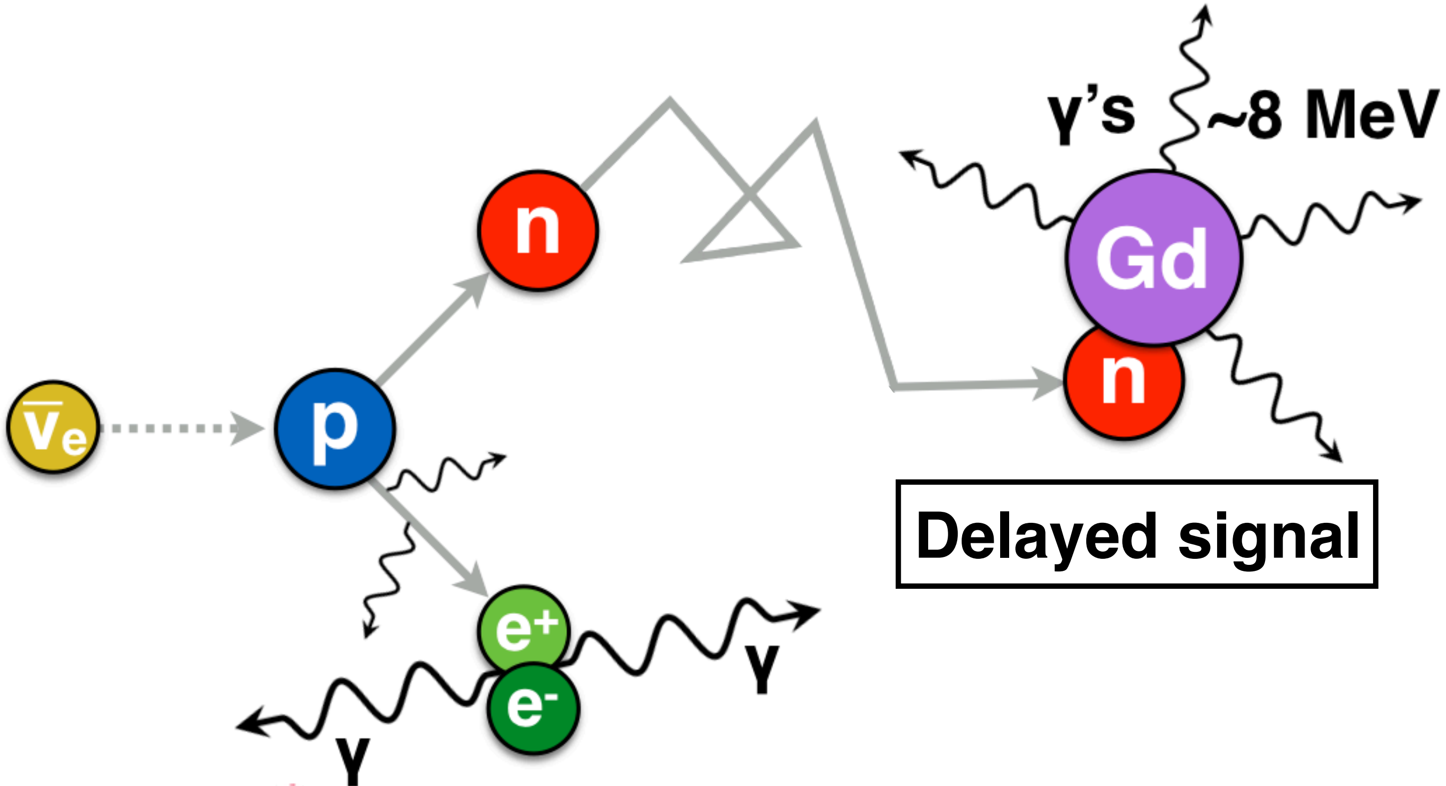

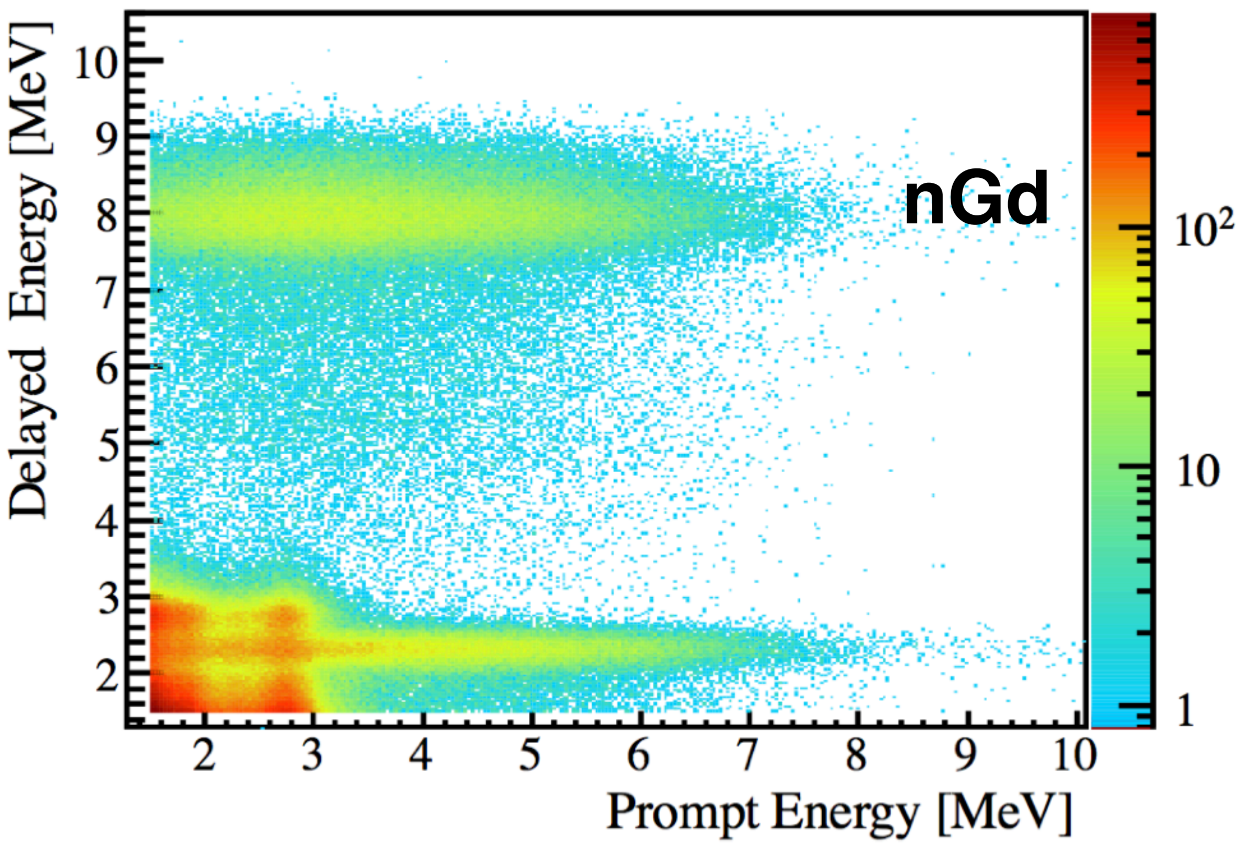

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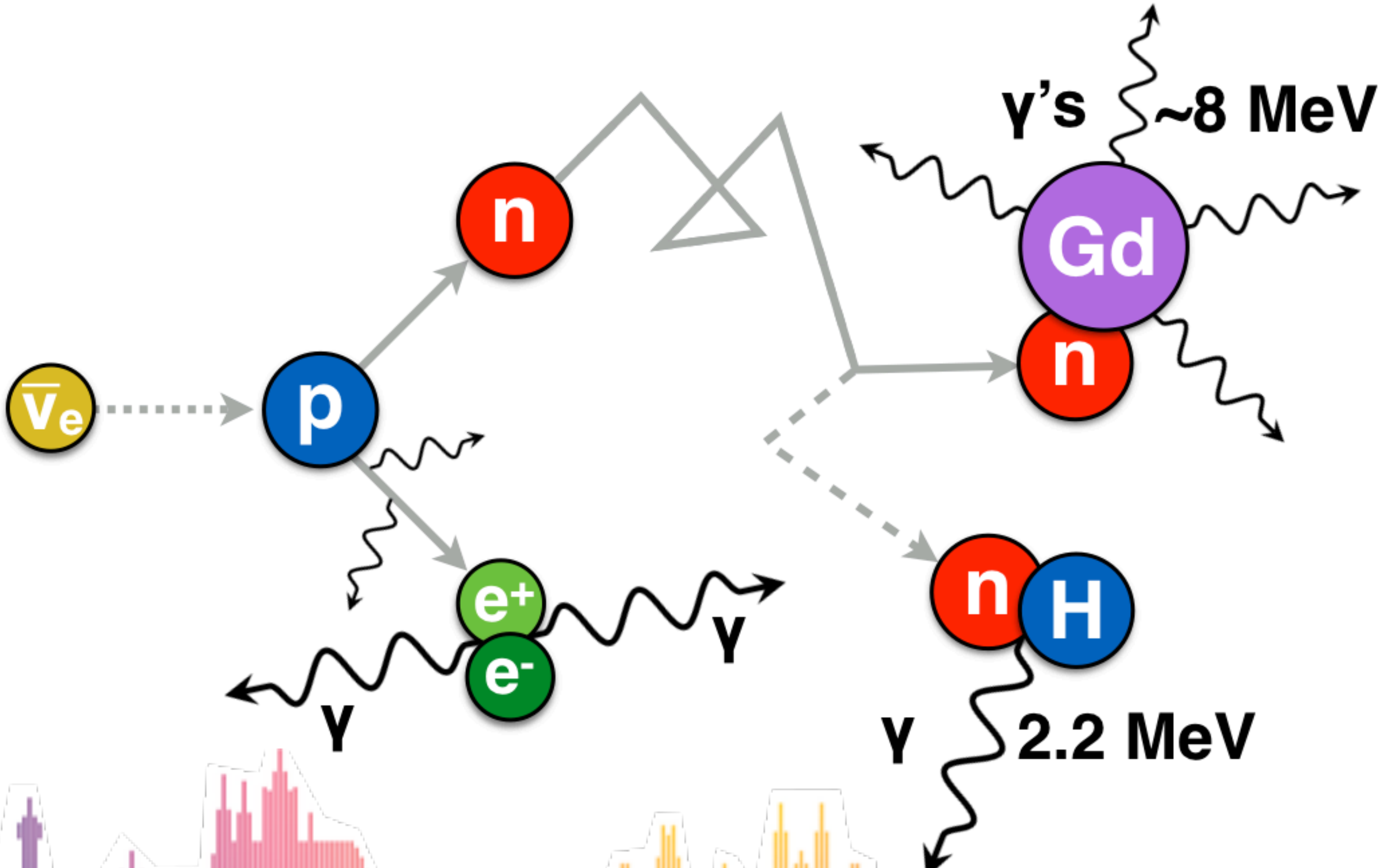

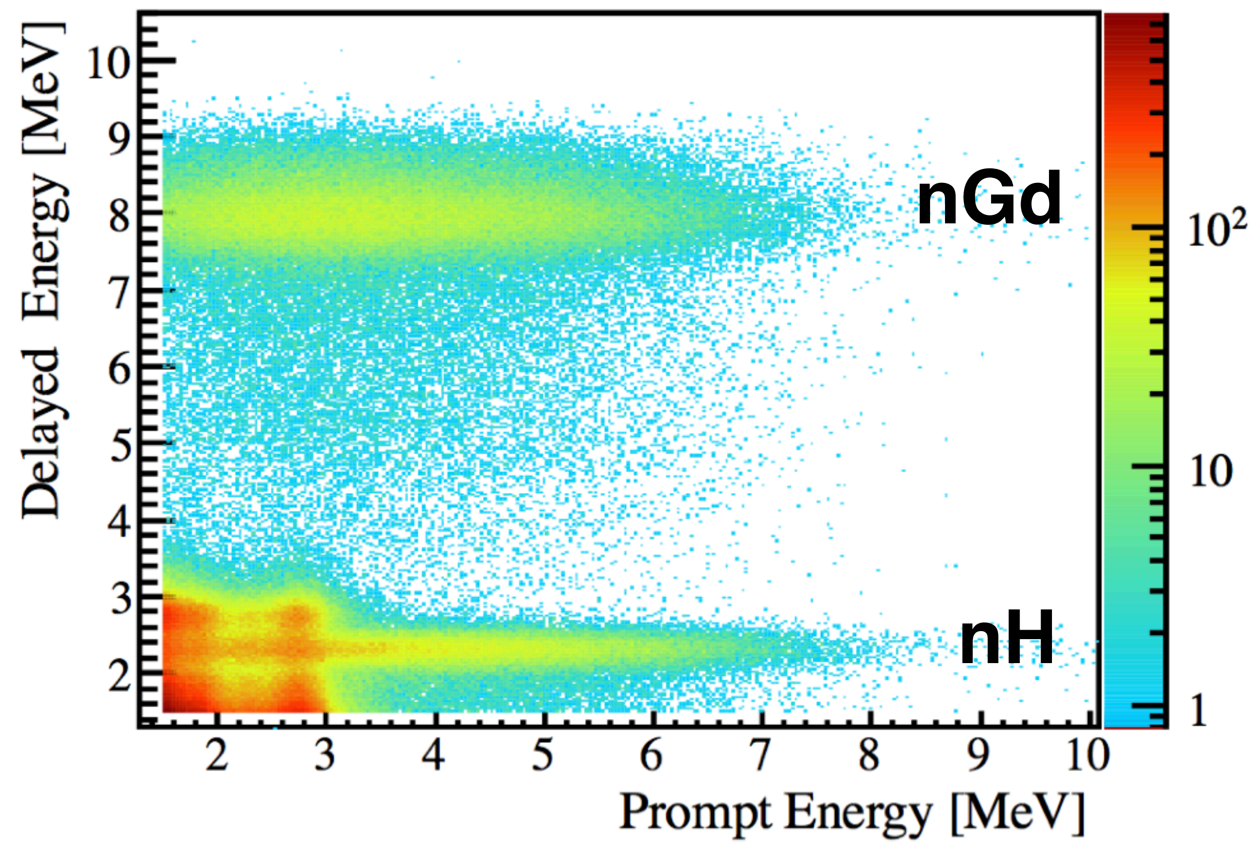

Reactor Antineutrino Detection

Prompt signal → e^+ ; Delayed signal → n

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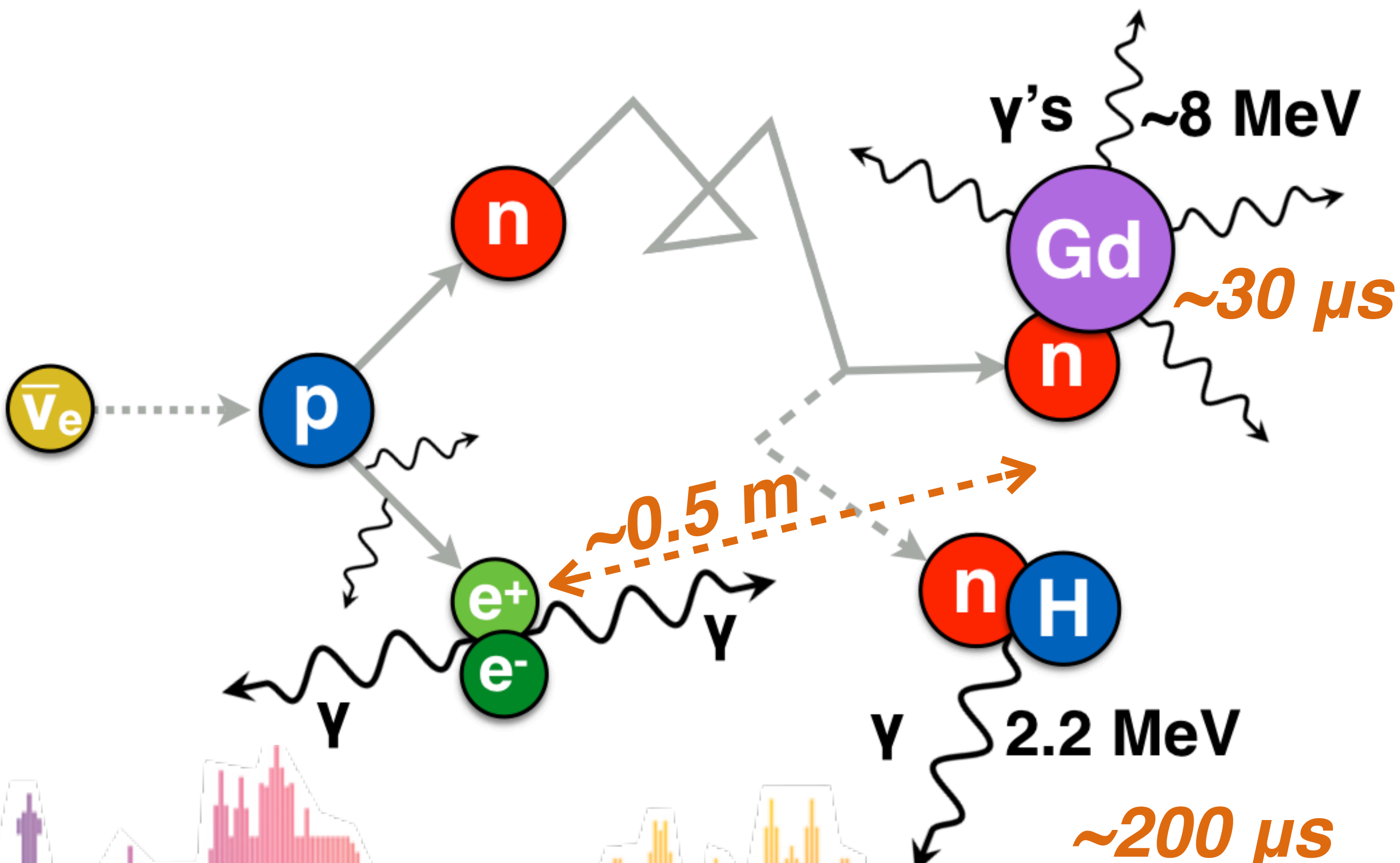
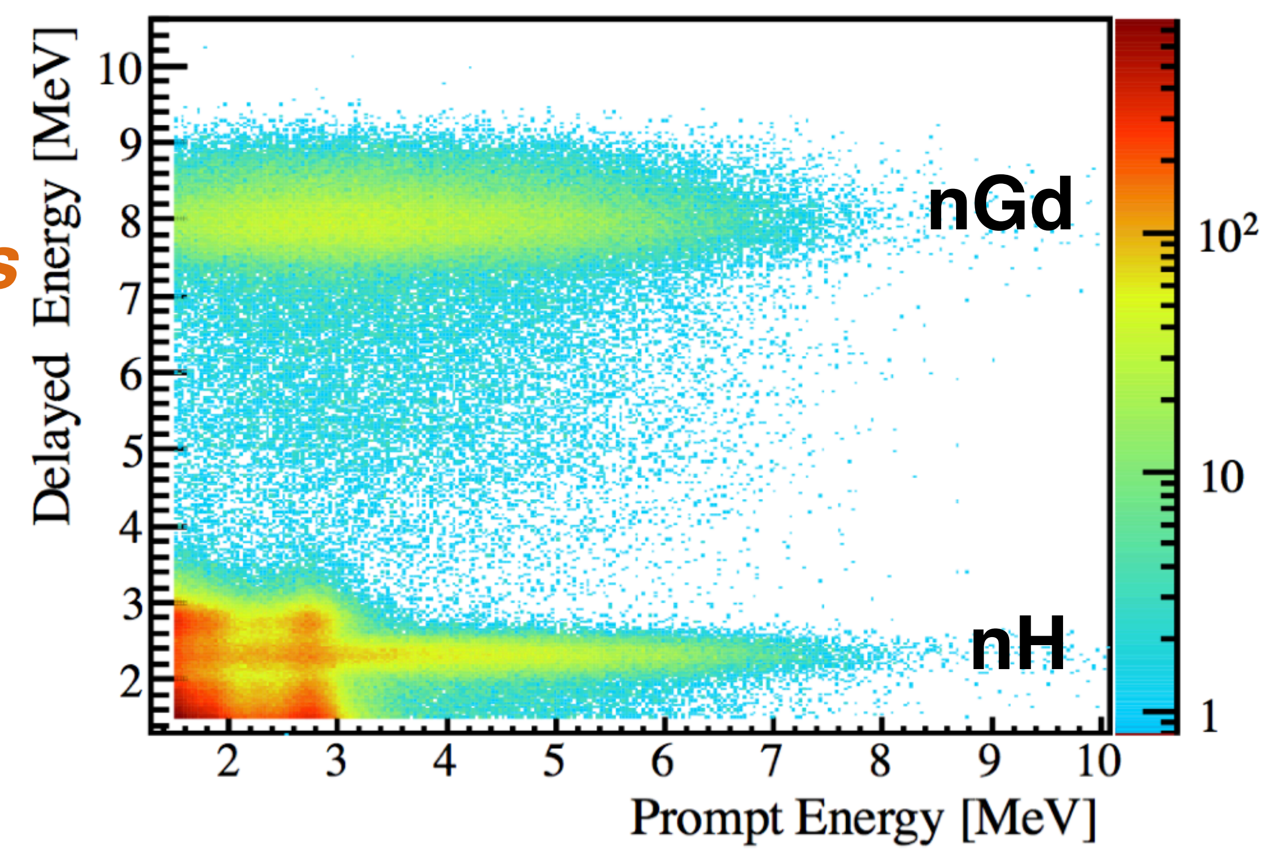




Neutrino Mixing and Oscillation

Three-neutrino mixing:

Atmospheric, accelerator ν — Solar, reactor L~60 km ν

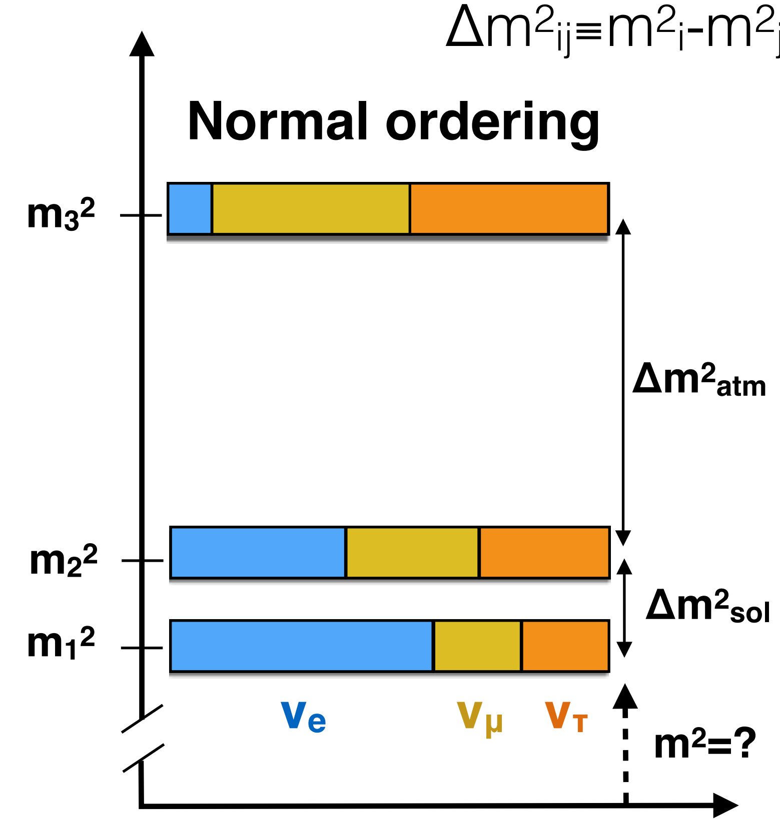
$$\text{Flavor states}\quad \begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}\quad \text{Mass states}$$

Reactor L~2 km, accelerator ν

$c_{ij}=\cos\theta_{ij}$
$s_{ij}=\sin\theta_{ij}$
$\Delta m^2_{ij}\equiv m^2_i-m^2_j$

Oscillation parameters:

Parameter	Value	Open questions
Δm^2_{21}	7.5×10^{-5} eV^2	—
$\lvert\Delta m^2_{31}\rvert\simeq\lvert\Delta m^2_{32}\rvert$	2.5×10^{-3} eV^2	Ordering?⇔$\Delta m^2_{31}\lesseqgtr0$
θ_{12}	33°	—
θ_{23}	45°?	Maximal?⇔$\theta_{23}\gtreqless45°$
θ_{13}*	9°	—
δ_{CP}	?°	Value?



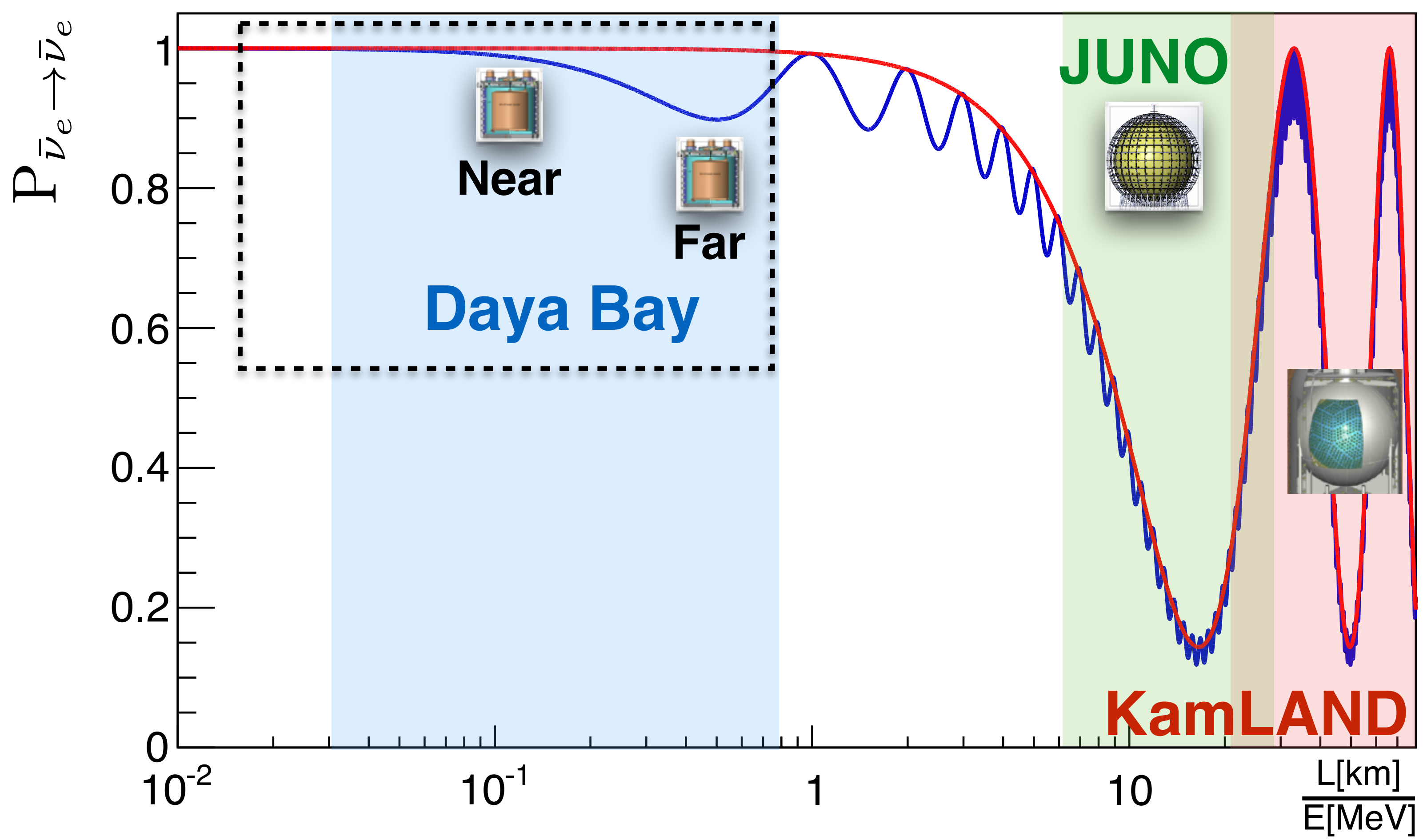
*Last to known angles - discovered by Daya Bay in 2012

Oscillation Measurement Principle

- Looking at the flux of $\bar{\nu}_e$ as a function of distance and energy
- Some $\bar{\nu}_e$'s disappear due to neutrino oscillation

Medium baseline — **Short baseline**

$$P_{\bar{\nu}_e\to\bar{\nu}_e}(L,E) = 1 - \sin^2 2\theta_{12}\cos^4\theta_{13}\sin^2\frac{\Delta m^2_{21}L}{4E} - \sin^2 2\theta_{13}\left(\cos^2\theta_{12}\sin^2\frac{\Delta m^2_{31}L}{4E} + \sin^2\theta_{12}\sin^2\frac{\Delta m^2_{32}L}{4E}\right)$$



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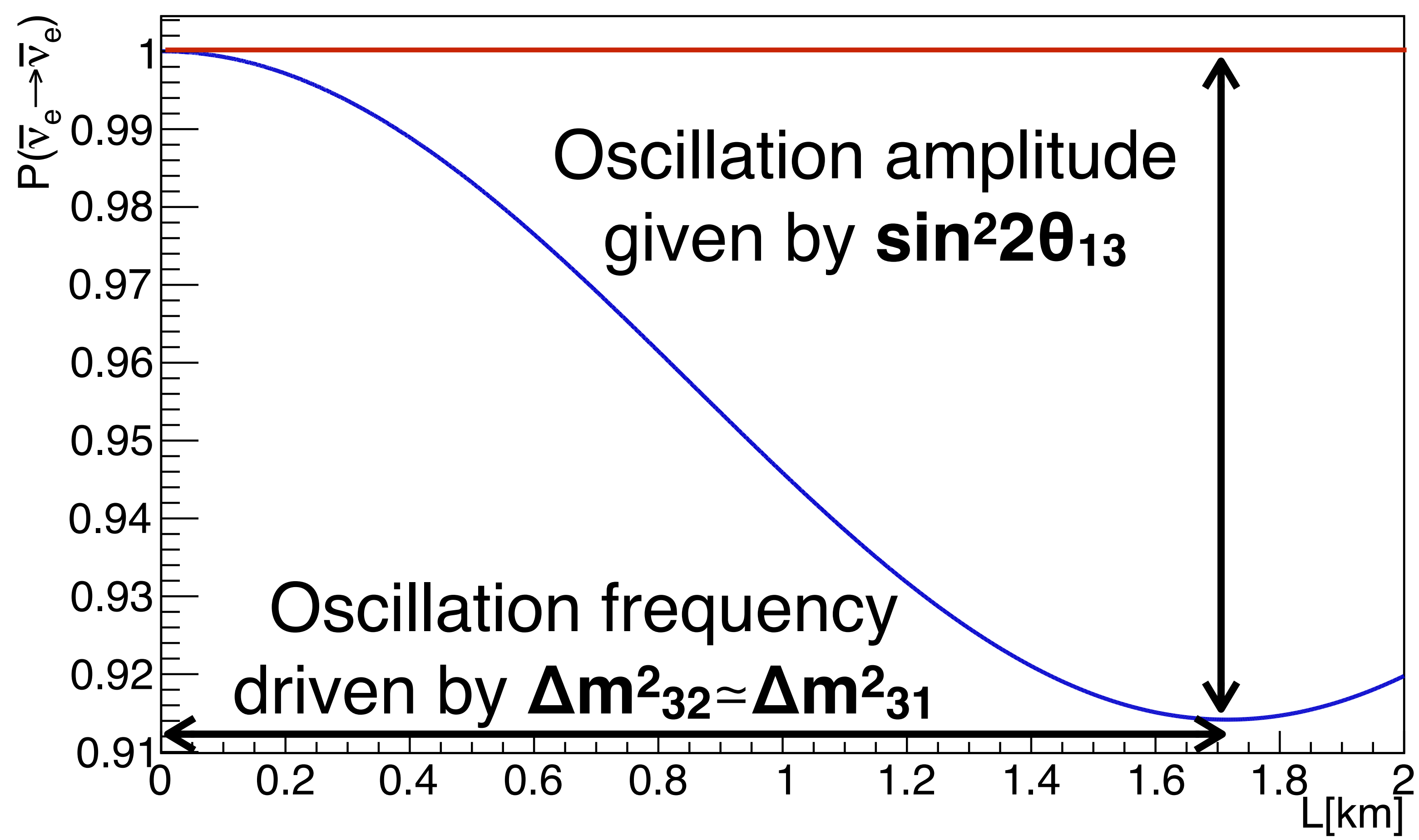

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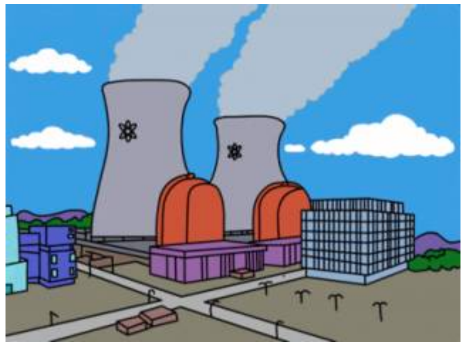
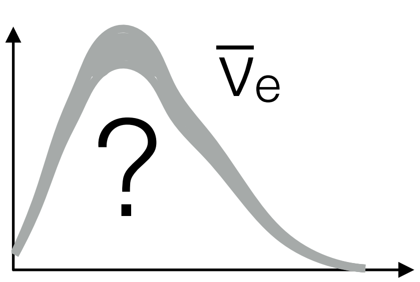
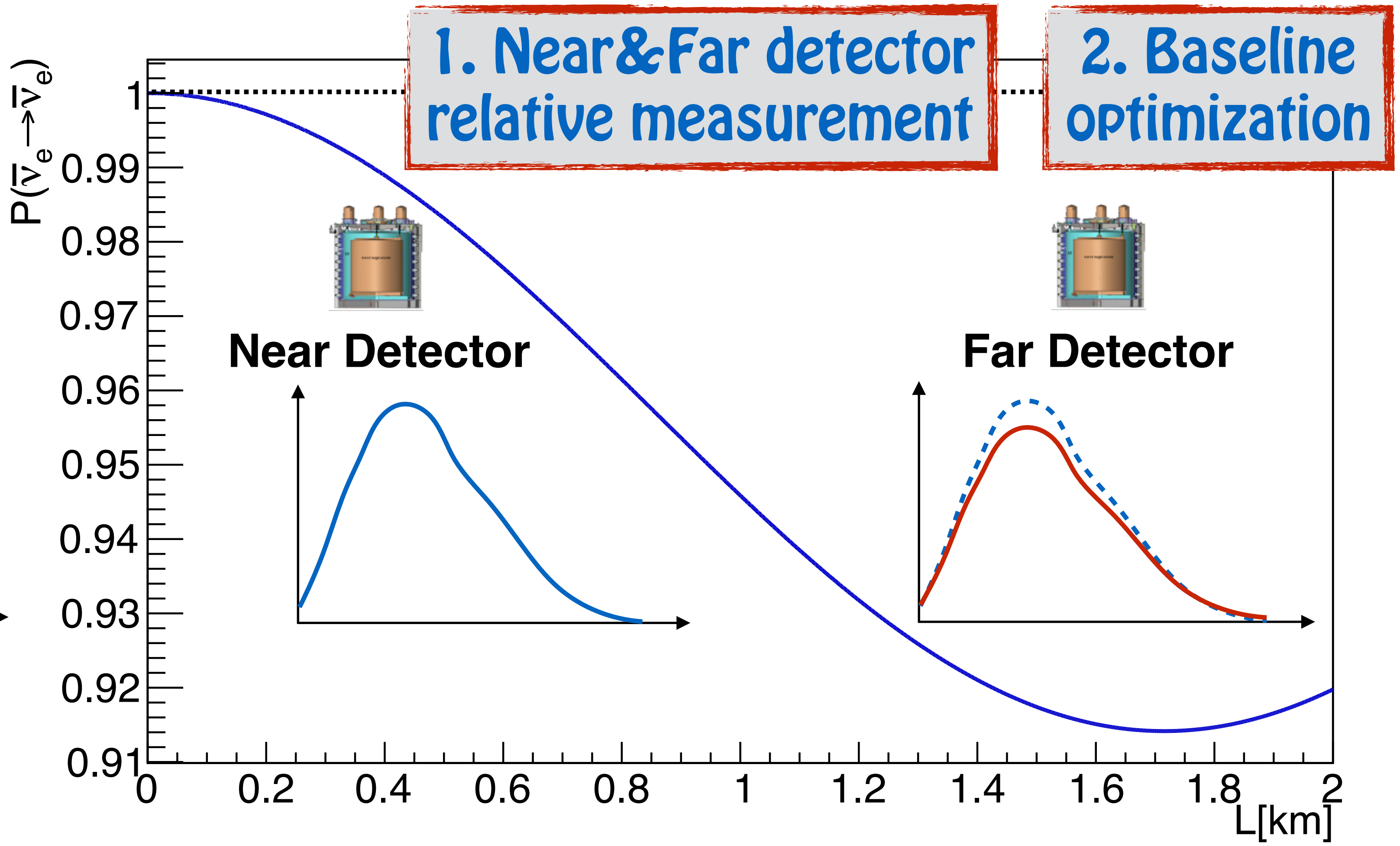


3. Powerful source, large detector(s)

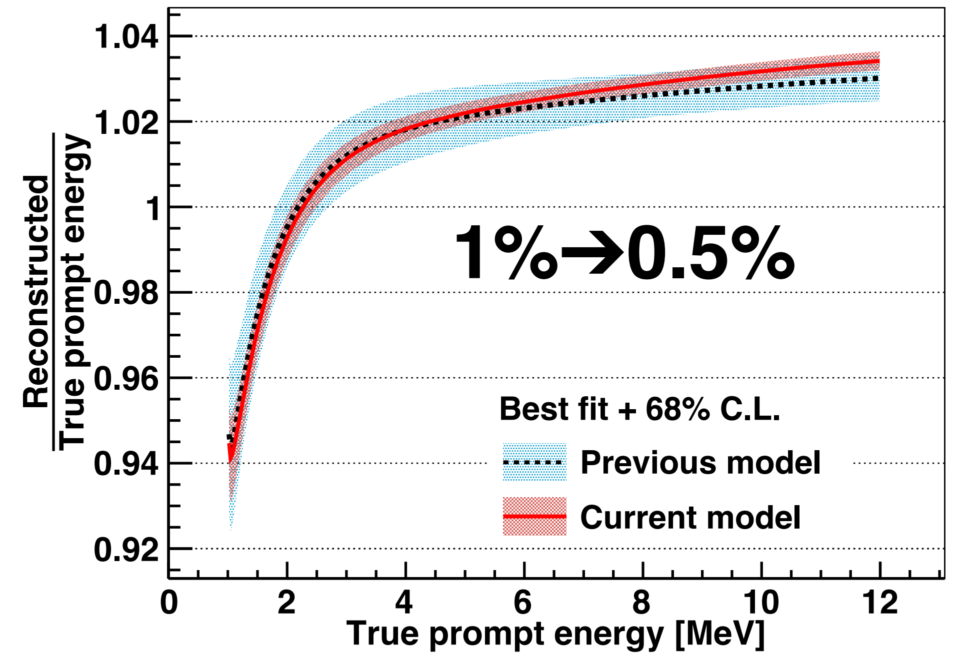


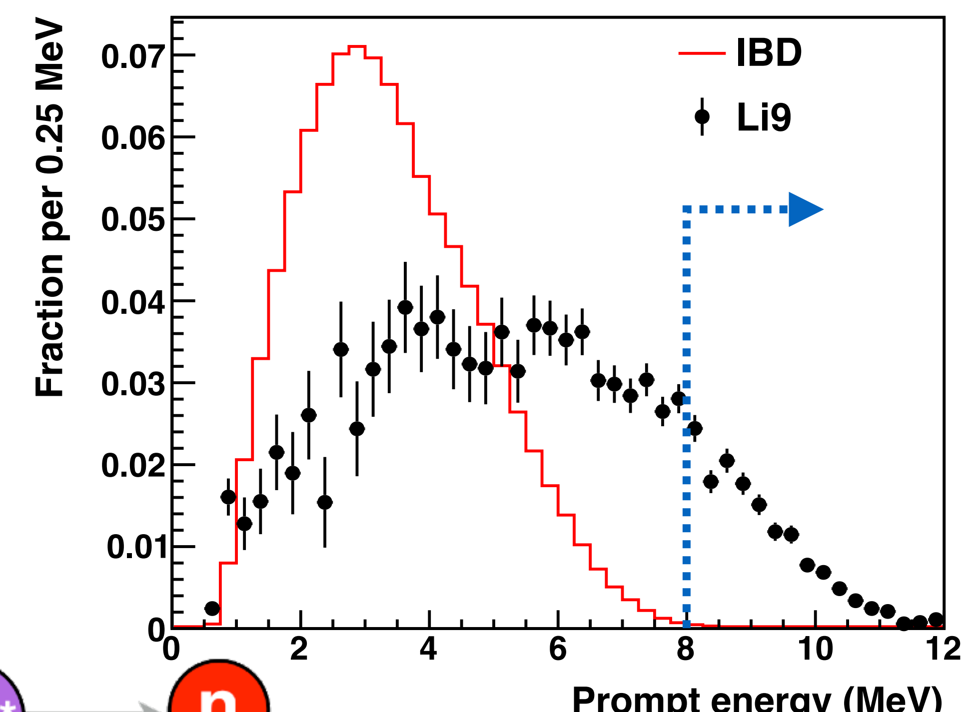
+4. Low background

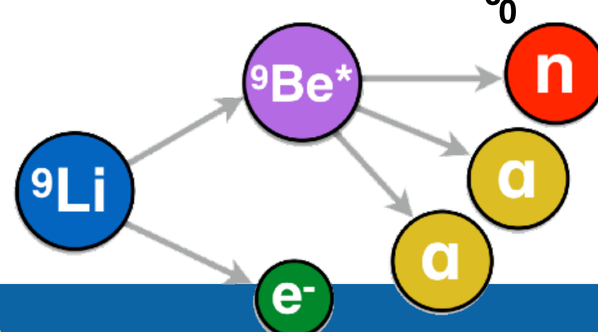


Systematics Improvements

- Absolute energy scale uncertainty <0.5%
  - Special calibration campaign with various radioactive source encapsulations
  - FADC readout in one AD to determine electronics non-linearity
- Reduction of the uncertainty of the $^{9}Li/^{8}He$ background
  - Dominant background uncertainty
  - Prompt energy cut to enhance the ^{9}Li/IBD - feasible due to large statistics
- Spent nuclear fuel uncertainty 100%→30%
  - Utilize precise spent nuclear fuel history provided by power plant



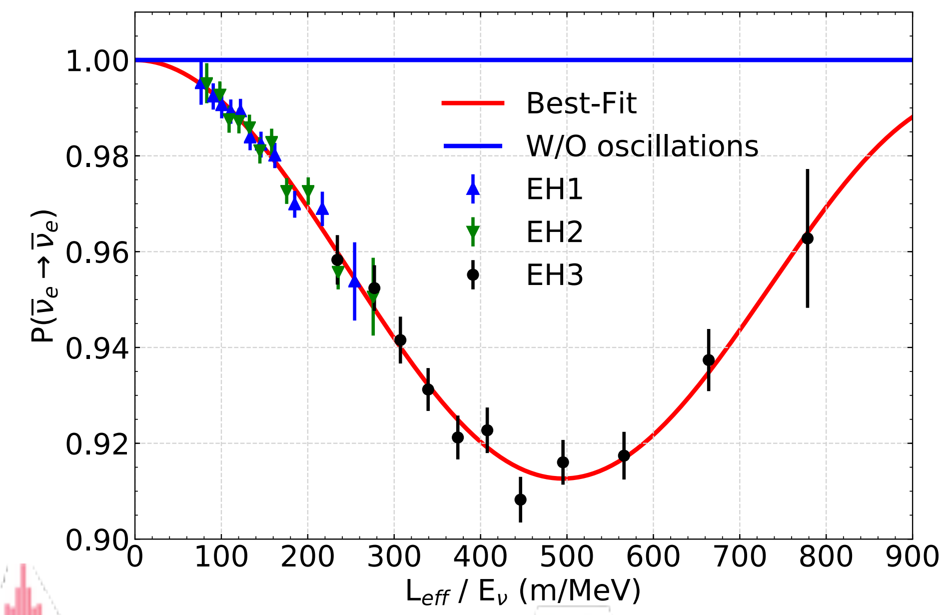


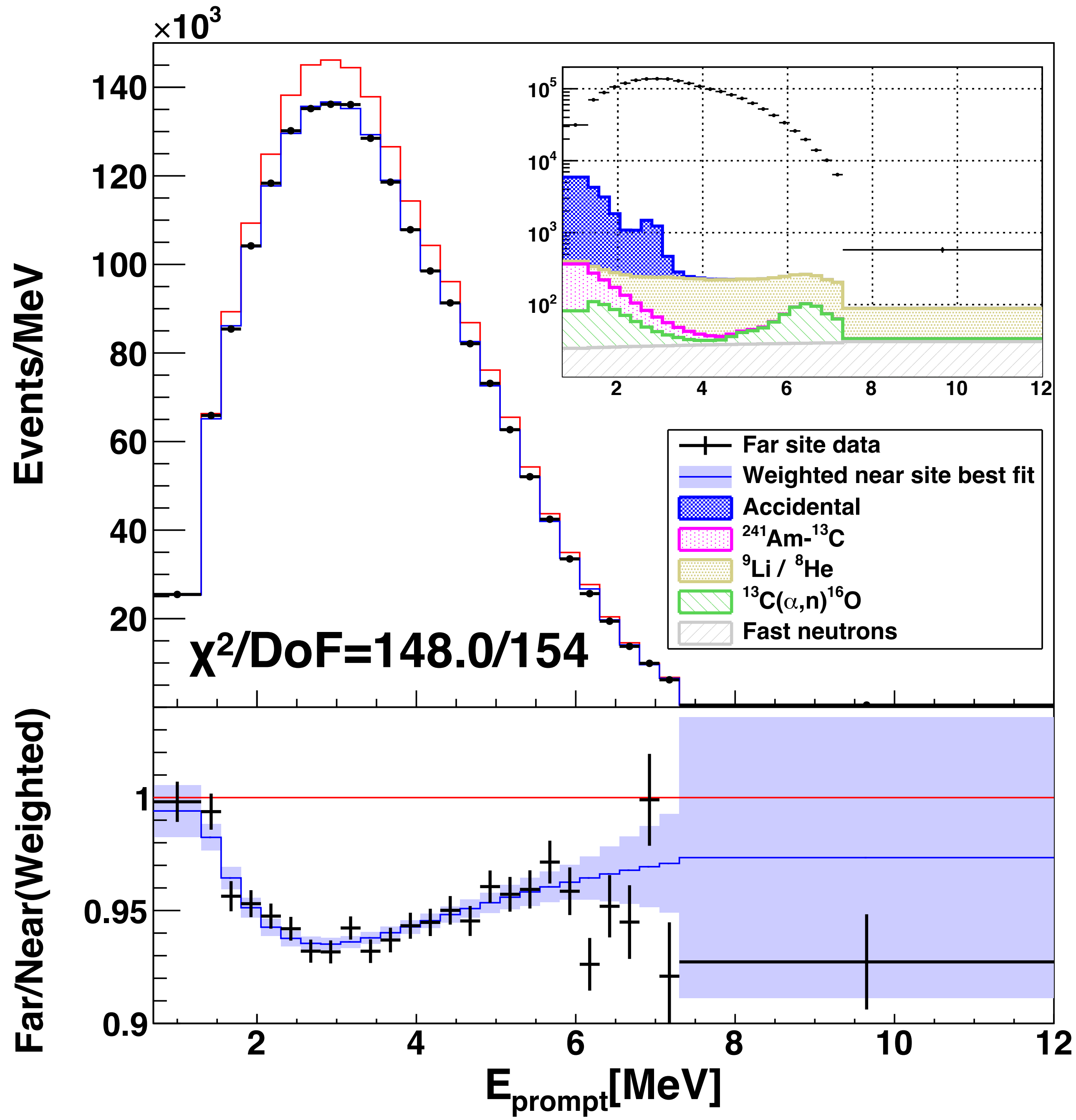


PRL 121, 241805 (2018)

Latest Measurement with nGd

- Based on 1958 days data set
- More than 3.9 million antineutrino interactions (with 0.5 million in far site)
  - The largest rector antineutrino data set in the world
- Consistent with 3-ν hypothesis





PRL 121, 241805 (2018)

Latest Oscillation Result with nGd

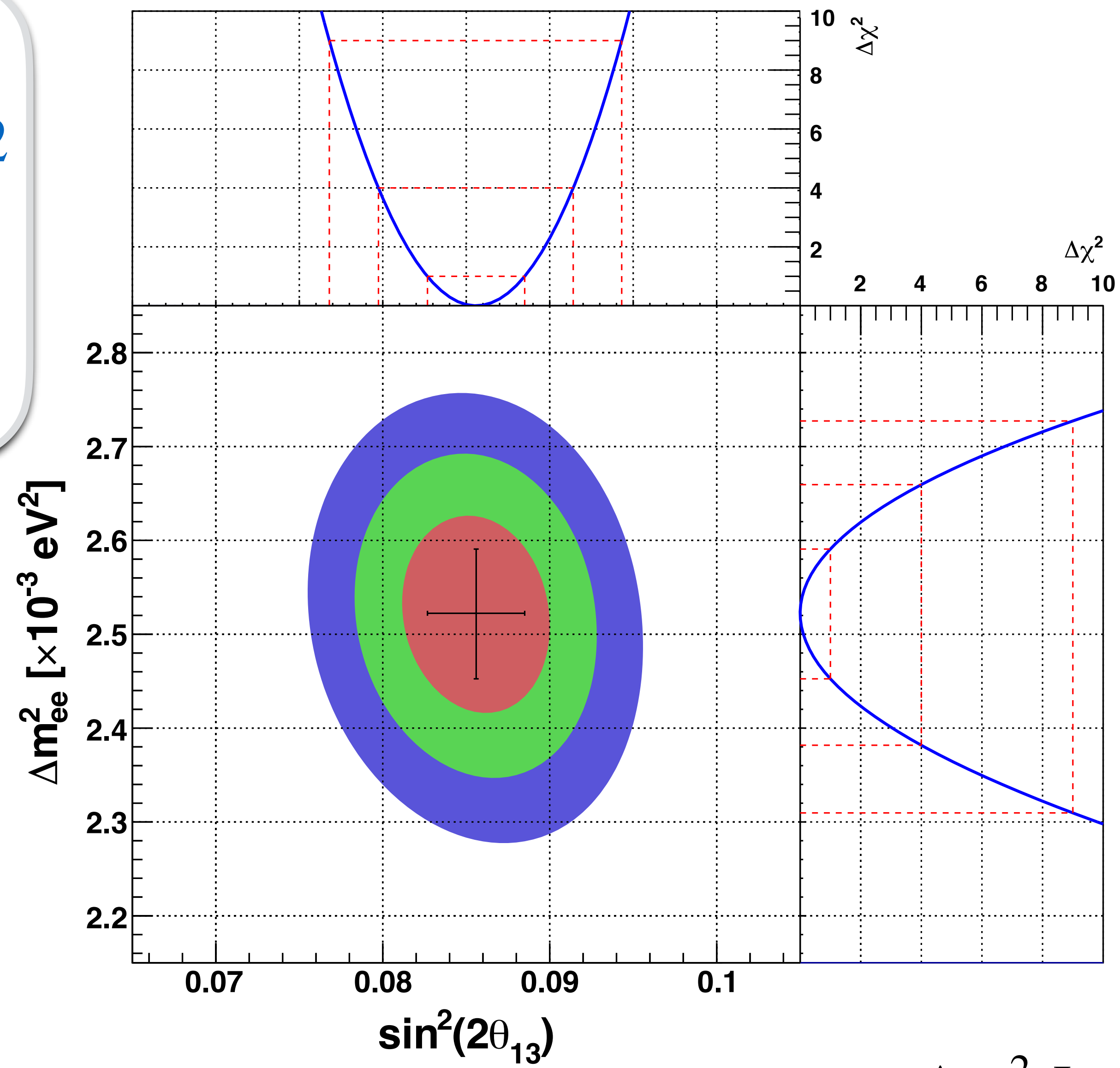
$$\sin^2 2\theta_{13} = 0.0856 \pm 0.0029$$

$$|\Delta m^2_{ee}| = \left(2.522^{+0.068}_{-0.070}\right) \times 10^{-3}\ \text{eV}^2$$

$$\Delta m^2_{32} = \left(2.472^{+0.068}_{-0.070}\right) \times 10^{-3}\ \text{eV}^2 \text{ (Normal ordering)}$$

$$\Delta m^2_{32} = -\left(2.575^{+0.068}_{-0.070}\right) \times 10^{-3}\ \text{eV}^2 \text{ (Inverted ordering)}$$

- Measurement of $\sin^2 2\theta_{13}$ with world-leading 3.4% precision
- Measurement of $|\Delta m^2_{ee}|$ with 2.8% precision, comparable to accelerator experiments
- Statistics still contributes by ~60% (~50%) to the $\sin^2 2\theta_{13}$ ($|\Delta m^2_{ee}|$) uncertainty

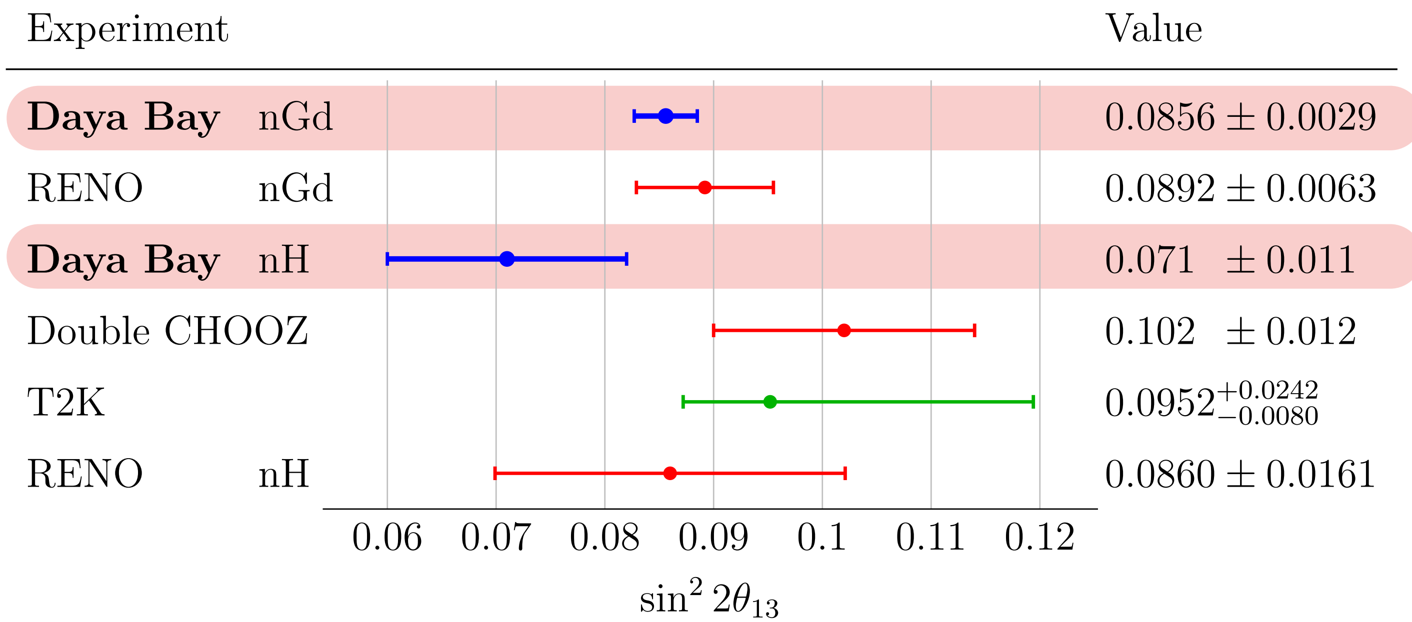


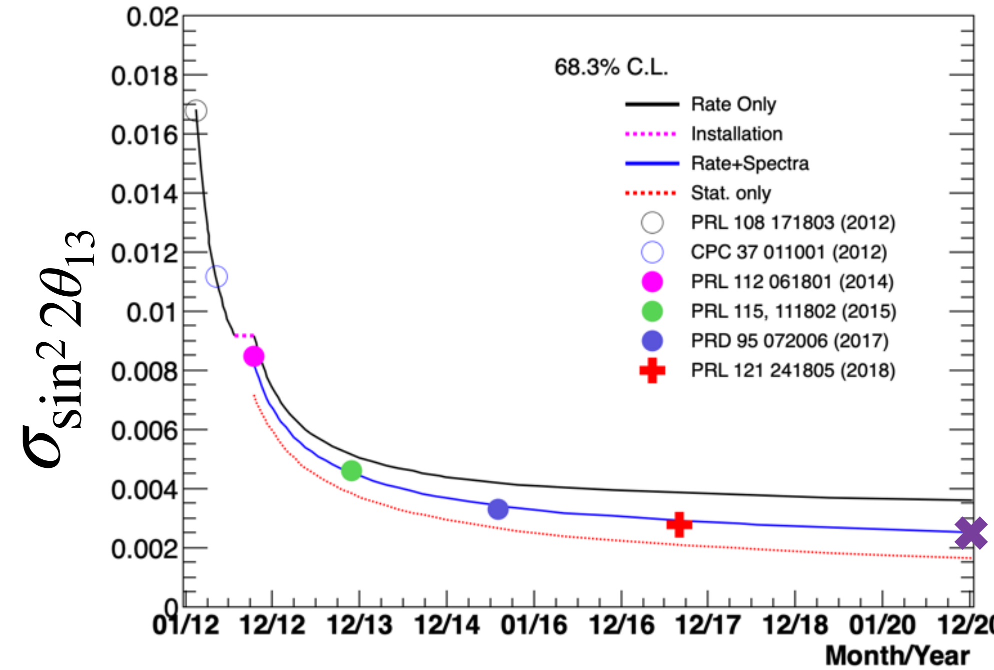
$$P_{\bar{\nu}_e \to \bar{\nu}_e}(L,E) \simeq 1 - \sin^2 2\theta_{12} \cos^4\theta_{13} \sin^2 \frac{\Delta m^2_{21} L}{4E} - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{ee} L}{4E}$$

Effective mass splitting

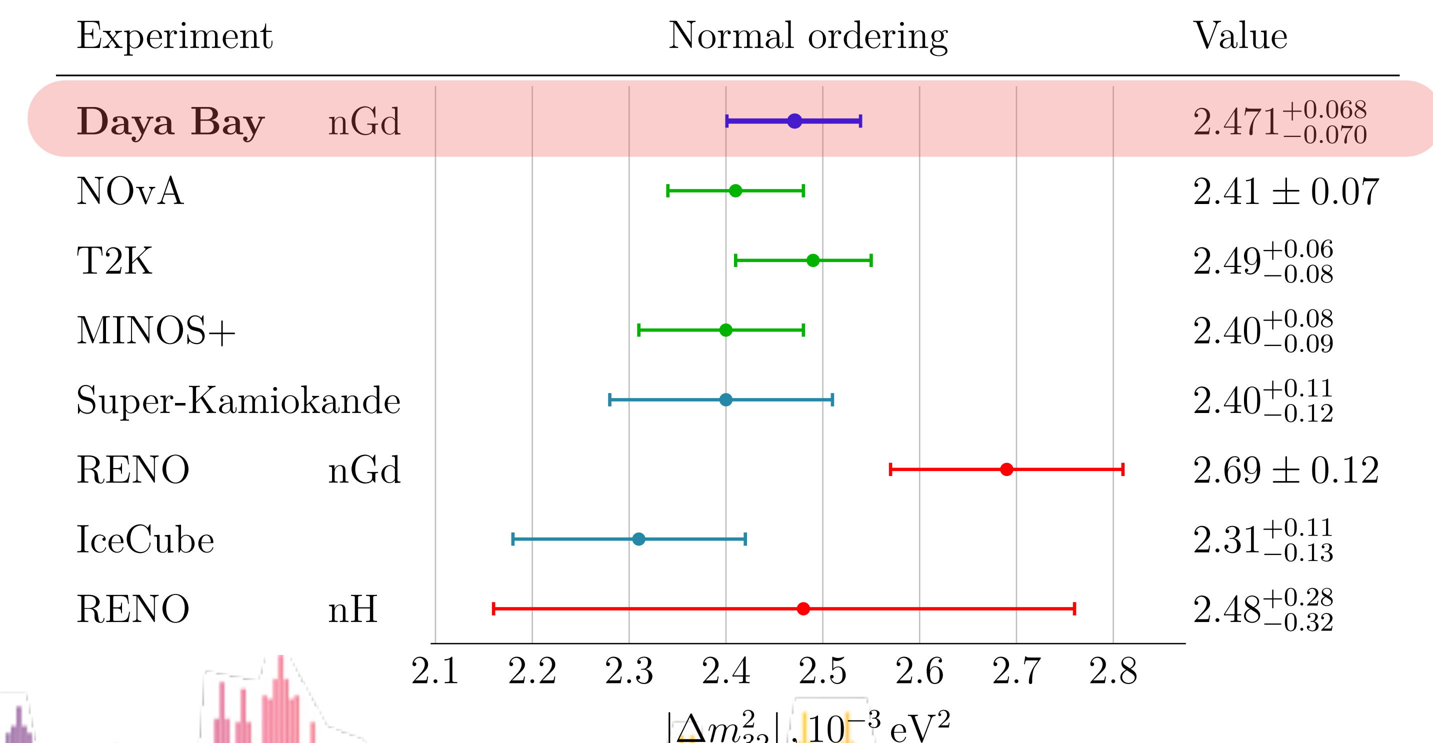
PRL 121, 241805 (2018)

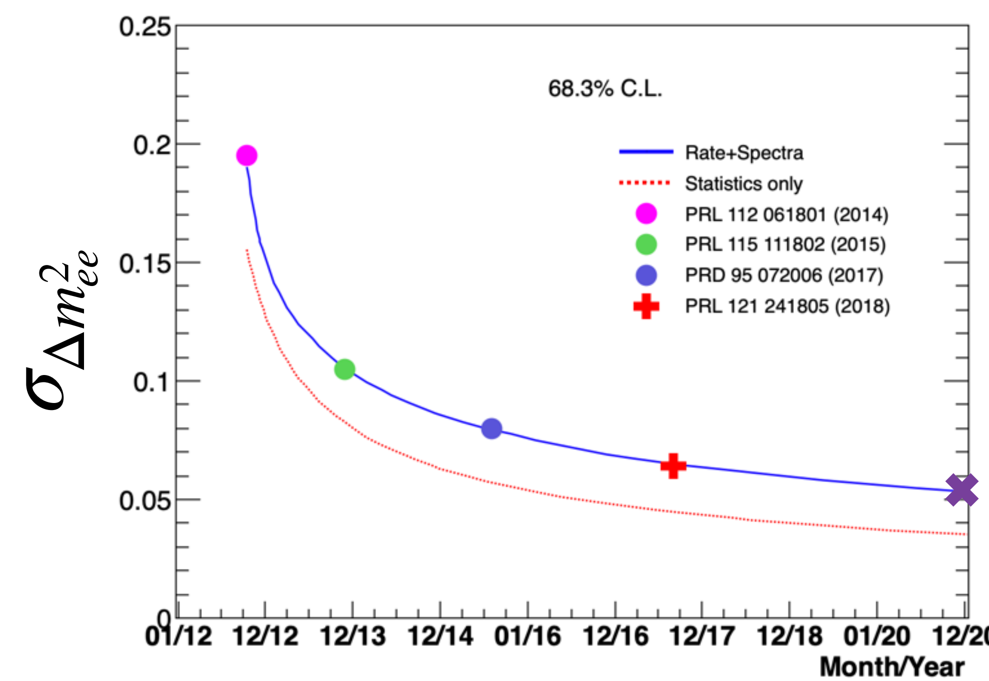
Global Comparison and Prospects





$\sin^2 2\theta_{13}$ uncertainty 3.4% ➔ 2.7%



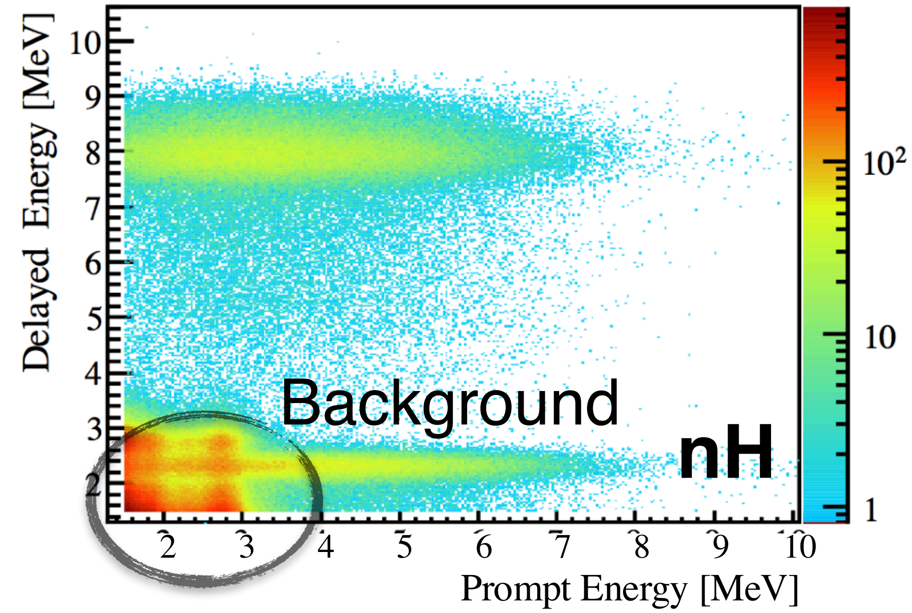


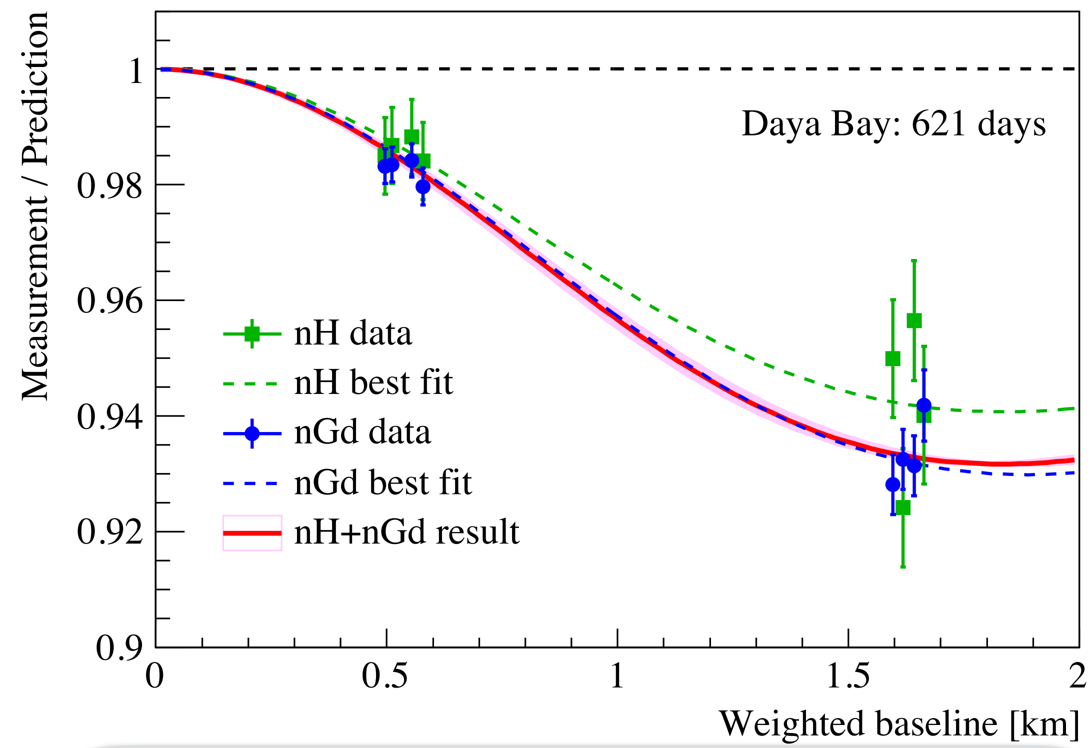
Δm^2_{ee} uncertainty 2.8% ➔ 2.1%

End of Daya Bay data taking

‘Latest’ Oscillation Result with nH

- nH - essentially independent analysis from nGd
  - Different statistical sample ✔
  - Mostly decoupled systematics ✔
- Challenges
  - Large background (bg/signal up to 1) ✘
  - Larger systematic uncertainties ✘
- ‘Latest’ rate-only analysis with only 621 days data set
- Update under intense preparation
  - Expected to be one of the most precise measurements of θ_{13} in the world





$$\sin^2 2\theta_{13} = 0.071 \pm 0.011$$

Assuming $\Delta m^2_{32} = (2.44 \pm 0.06) \times 10^{-3}$ eV^2 (NO)

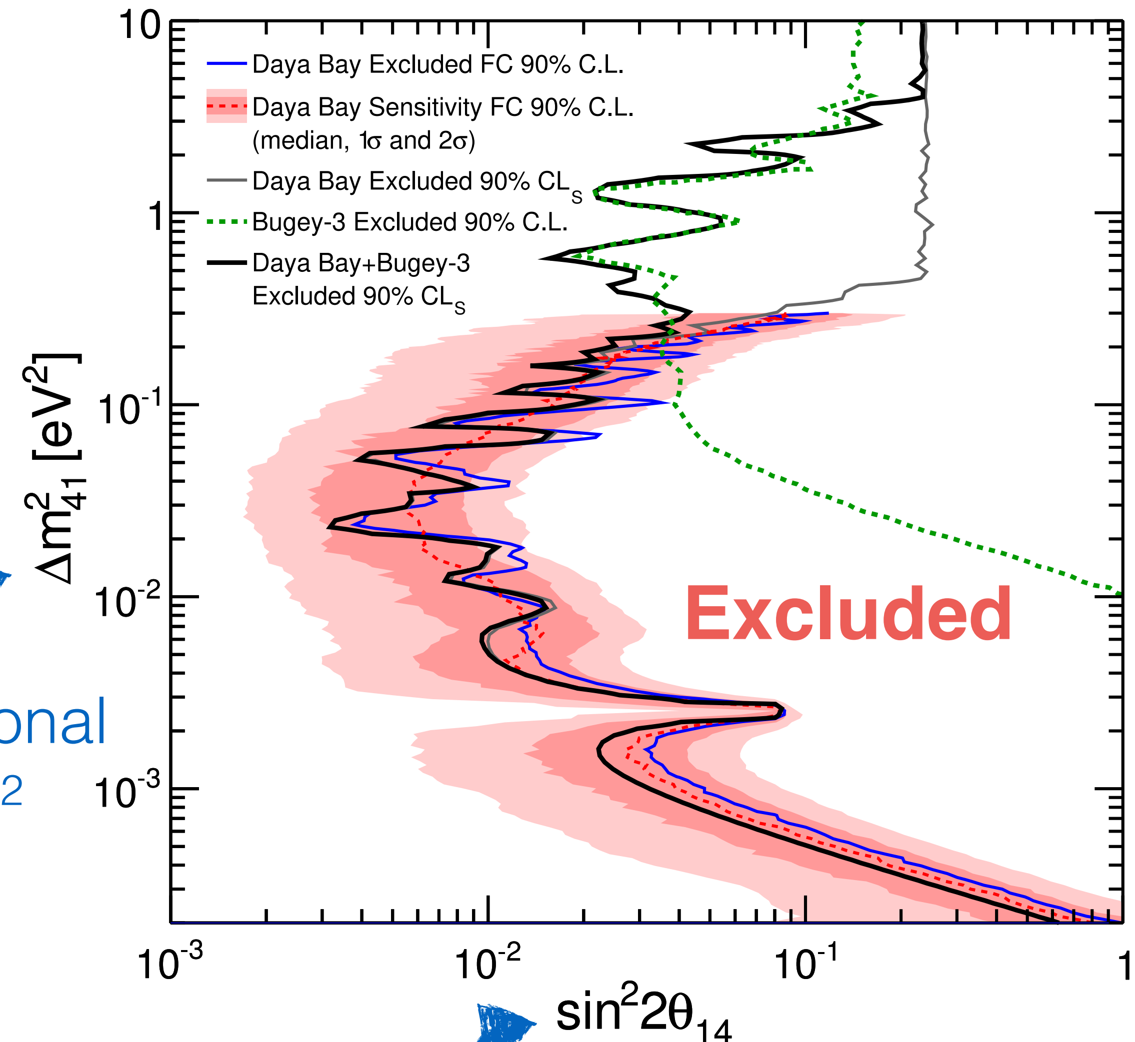
See poster by **Jinjing Li** 765

PRD 93, 072011 (2016)

Search for Light Sterile Neutrino

arXiv:2002.00301, accepted by PRL

- 'Sterile' neutrino signature in Daya Bay - an additional oscillation mode on top of the known one
- No significant signal observed using 1230-day data set
- Placed the most stringent limits on $\sin^2 2\theta_{14}$ for $\Delta m^2_{41}<0.2$ eV^2
- Further extended at larger Δm^2_{41} by combination with Bugey-3



Additional Δm^2

Additional mixing

See poster by **Zhuojun Hu** 432

$$P_{\bar{\nu}_e\to\bar{\nu}_e}(L,E) \approx 1-\sin^2 2\theta_{13}\sin^2\frac{\Delta m^2_{31}L}{4E}$$

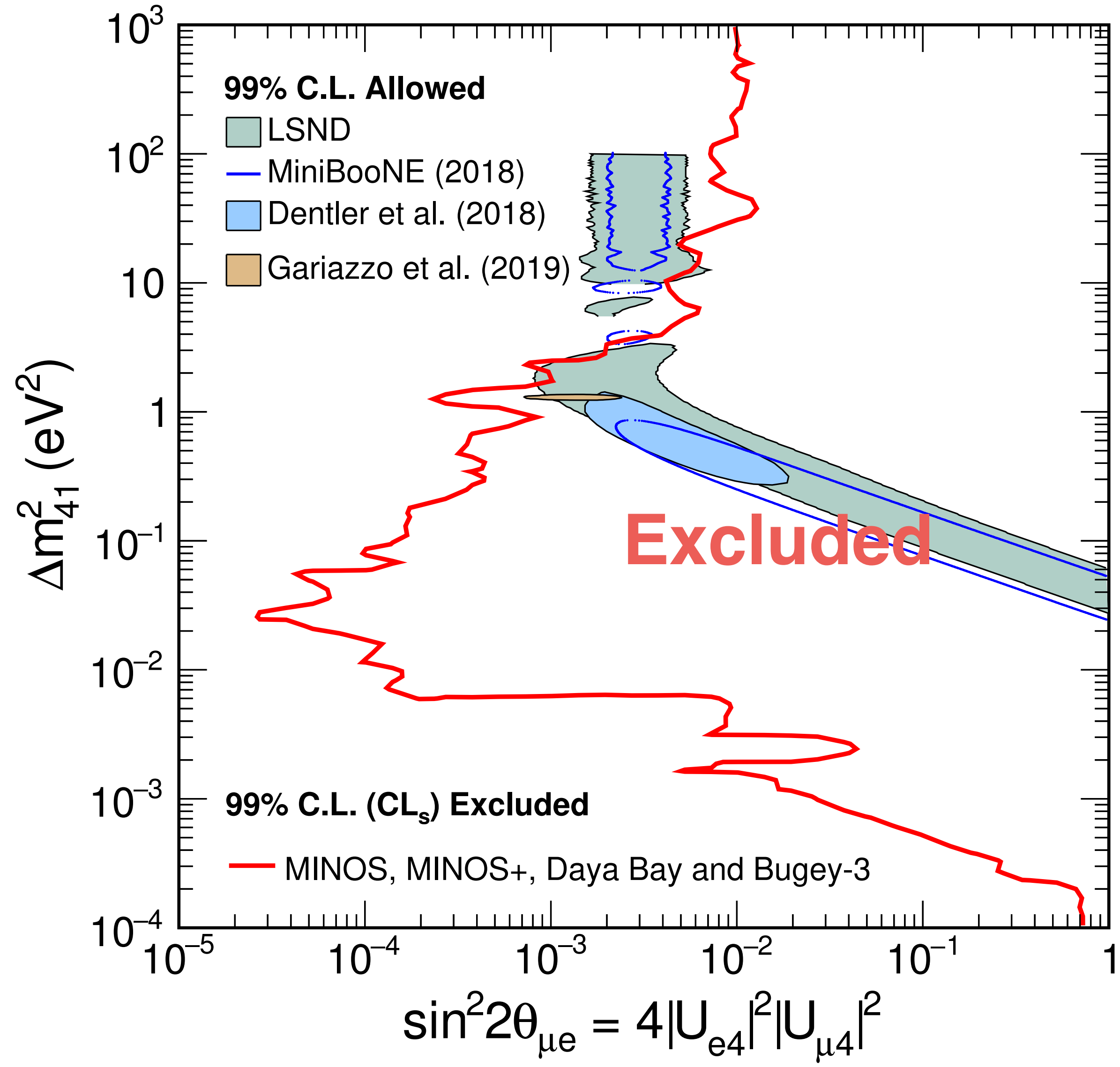
$$-\sin^2 2\theta_{14}\sin^2\frac{\Delta m^2_{41}L}{4E}$$

Additional oscillation mode

Search for Light Sterile Neutrino

arXiv:2002.00301, accepted by PRL

- Combined ν_s search with Bugey-3 and MINOS,MINOS+
- Excluded LSND and MiniBooNE 99% C.L. allowed regions at 99% CL_s for $\Delta m^2_{41}<1.6\ eV^2$
- Global ν_s (appearance) fits ruled out to >99% CL_s



See poster by **Zhuojun Hu** 432

$$P^{\text{short baseline}}_{\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e} \simeq \sin^2 2\theta_{\mu e} \sin^2 \frac{\Delta m^2_{41} L}{4E}$$

$$\sin^2 2\theta_{\mu e} \equiv \sin^2 2\theta_{14} \sin^2 \theta_{24}$$

Daya Bay, Bugey-3
$\bar{\nu}_e \to \bar{\nu}_e$

MINOS, MINOS+
$\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu$

Conclusions

- The latest Daya Bay reactor antineutrino oscillation measurement using nGd data sample with >5 years of data yielded:

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

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- Independent analysis using neutron capture on hydrogen with ~2 years of data provides consistent value of θ_{13}
  - New result under intense preparation
- Search for light sterile neutrino has not found any
  - Daya Bay, Bugey-3 and MINOS+ placed strong limits on ν_s mixing
- Data taking will finish in Dec 2020 - final Daya Bay result on θ_{13} will be the standard for the foreseeable future

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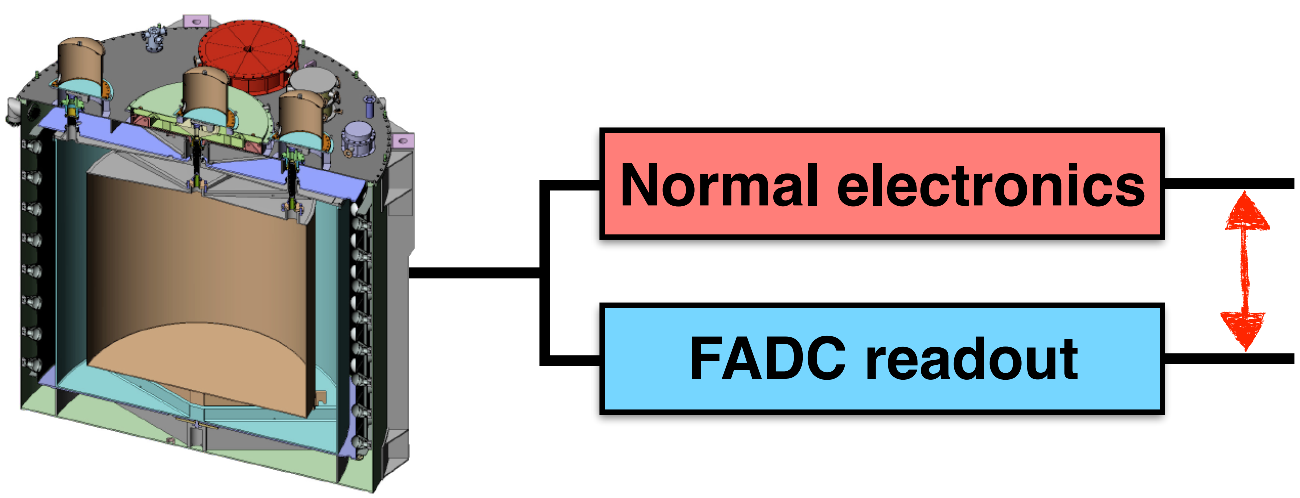
Stay tuned!

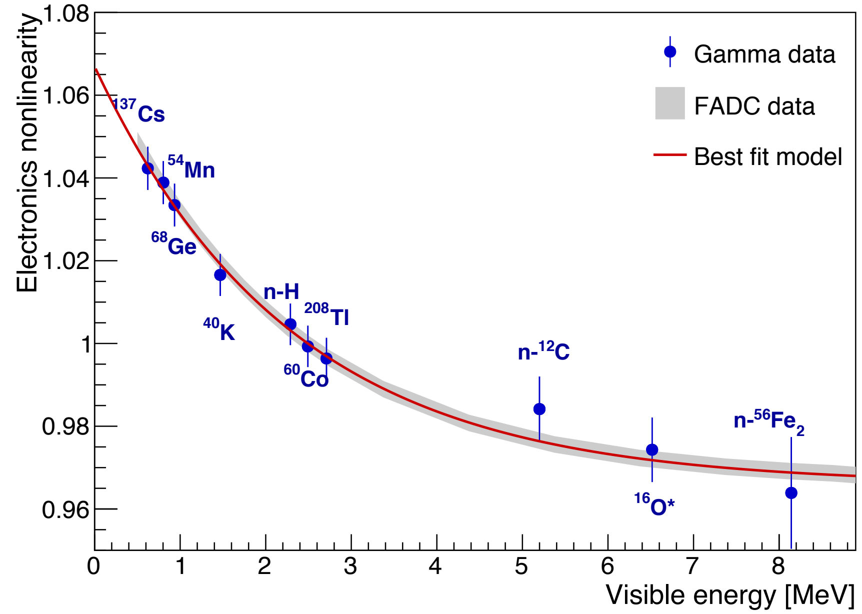
Extras

Absolute Energy Scale

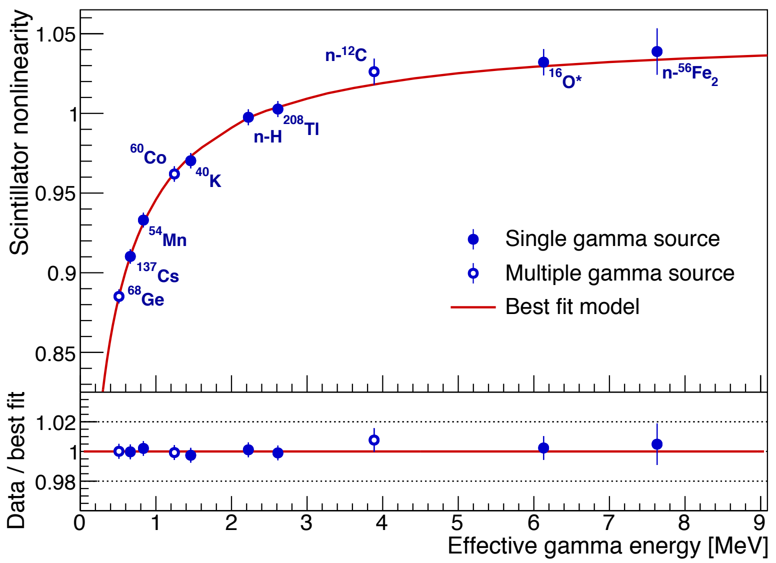
EH1-AD1

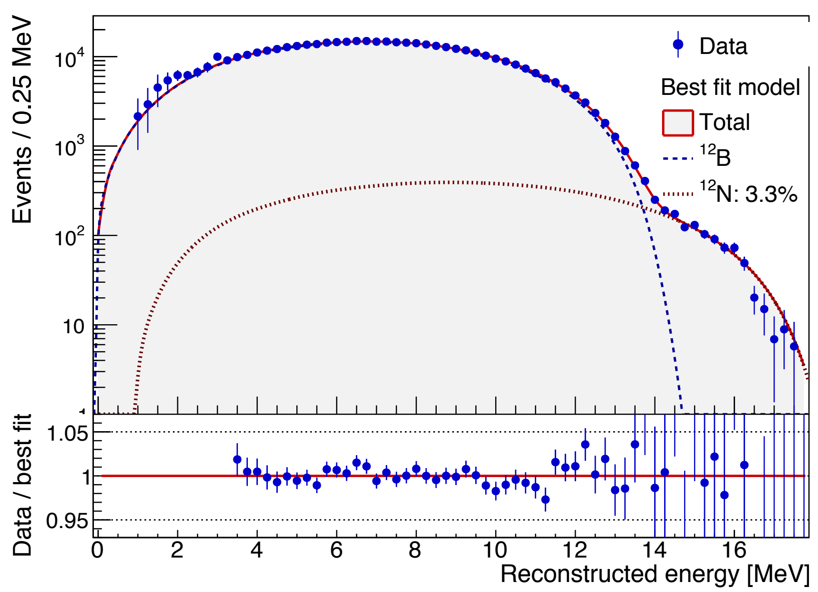


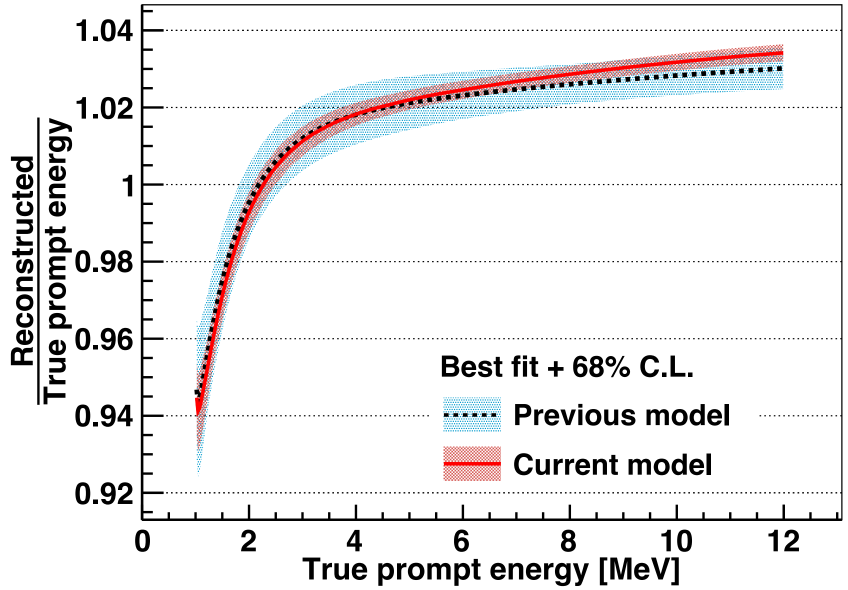
↔ **Comparison** → Direct measurement of the electronics non-linearity



γ lines measurement + ^{12}B electron spectrum = e⁺ energy response model







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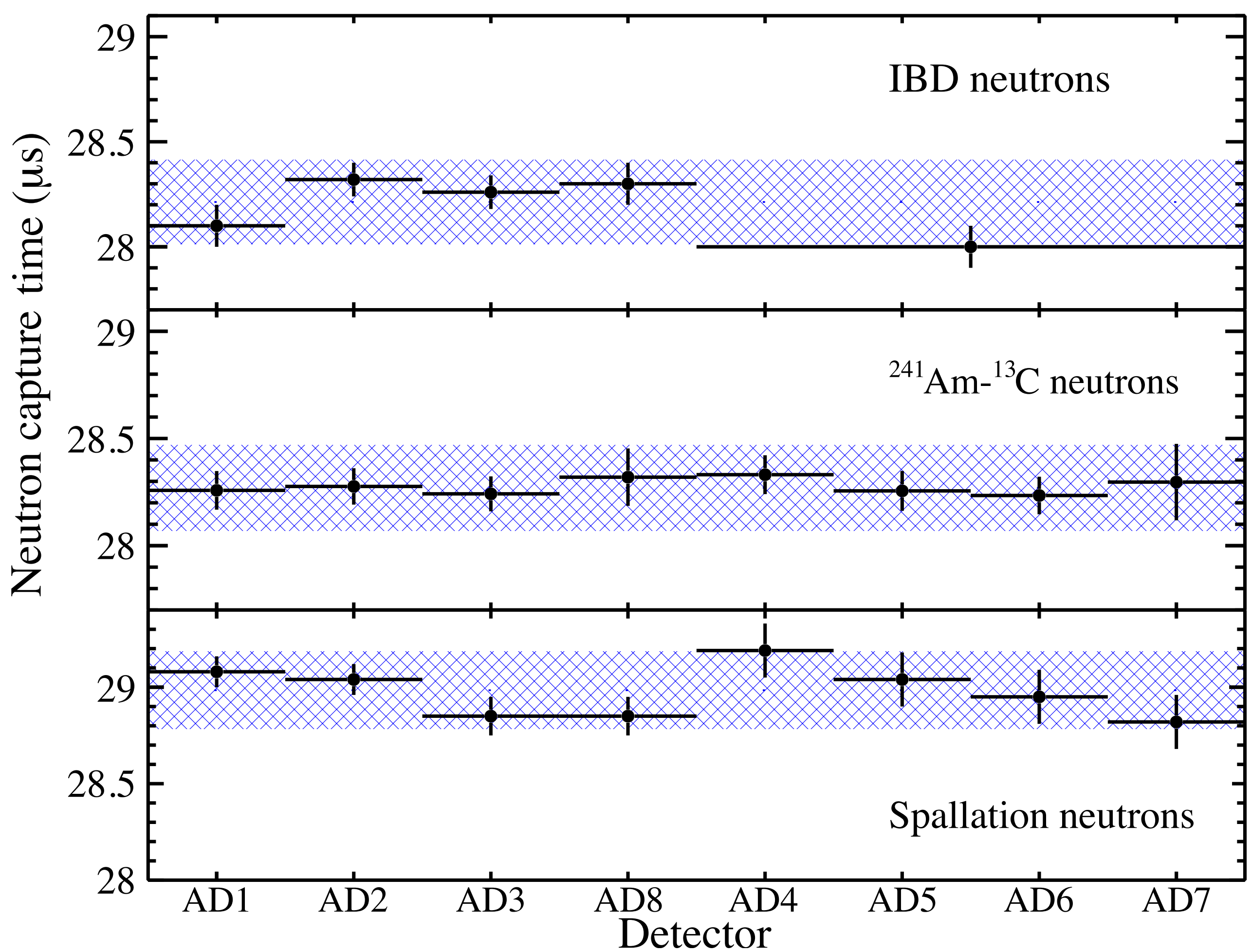
Dominant Relative Uncertainties

$\sin^2 2\theta_{13}$ uncertainty dominated by the 0.13% relative detection efficiency uncertainty

(which is dominated by Gd capture fraction of 0.1%)



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Δm^2_{ee} uncertainty dominated by the <0.2% relative energy scale uncertainty