Neutrino Physics with Reactors

Bedřich Roskovec*
Pontificia Universidad Católica de Chile

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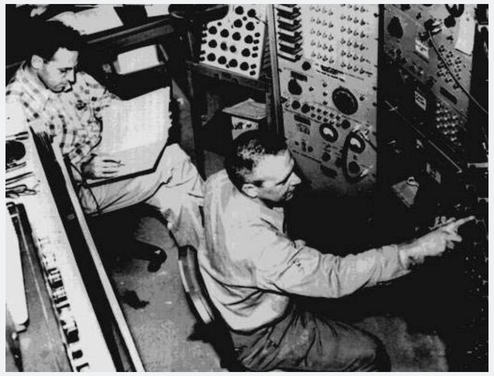
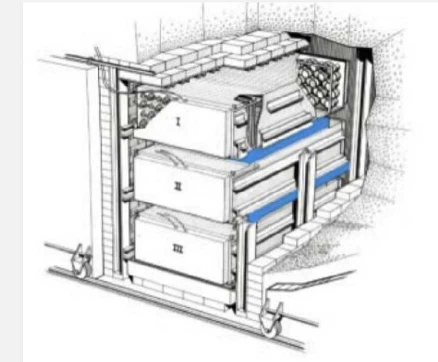
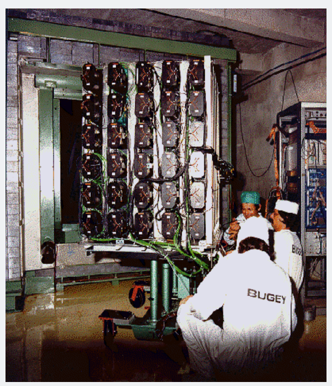
*member of Daya Bay and JUNO collaboration

Reactor Neutrinos - Decades of Measurements

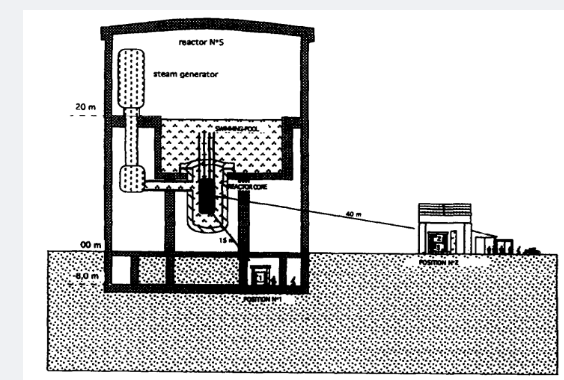


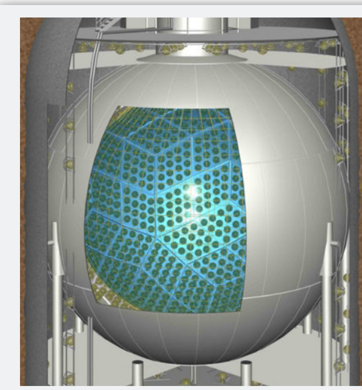
1950s: Savannah River
Discovery of (anti)neutrinos



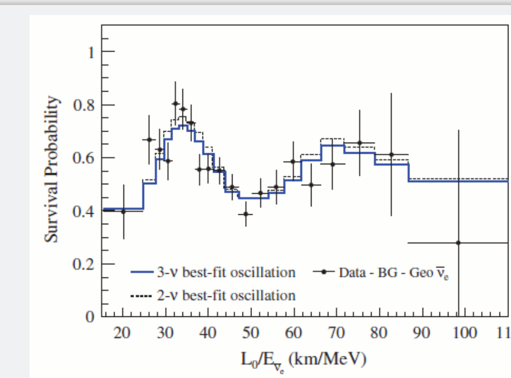


1980s+90s: ILL, Bugey,…
Reactor neutrino flux measurements

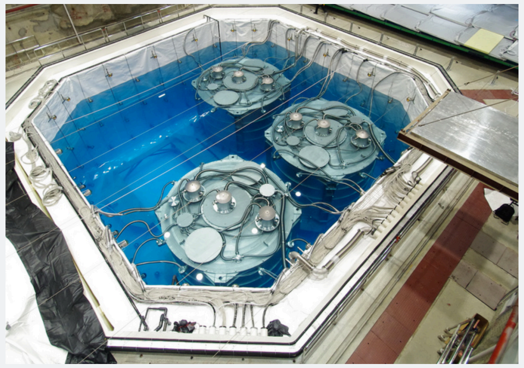




2000s: KamLAND
First evidence for Δm^2_{21}-driven oscillations

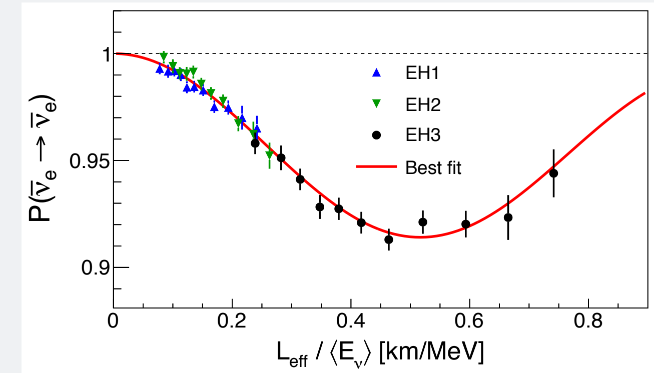


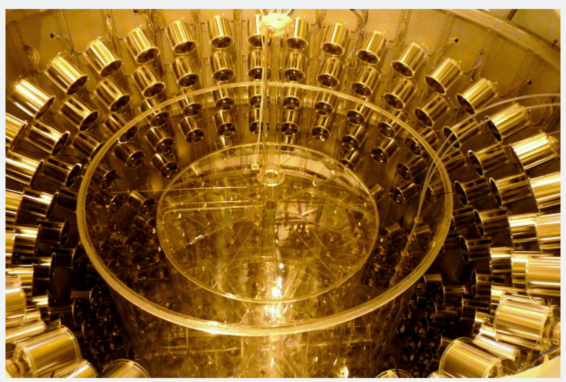
Era of the Precision Measurements



2012: **Daya Bay, RENO, Double CHOOZ**

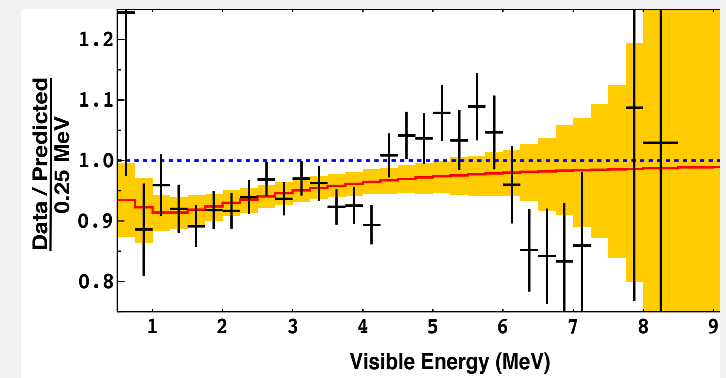
Non-zero θ_{13} mixing angle

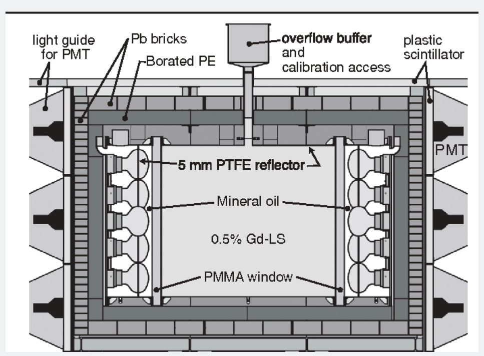




2014: **Double Chooz, Daya Bay, RENO,**

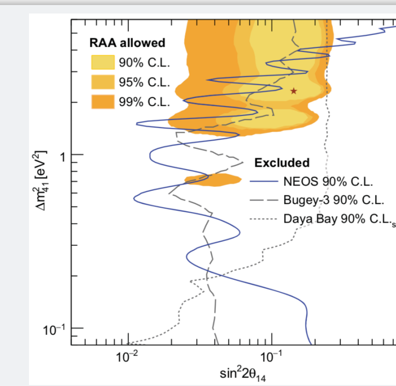
'Bump' in energy spectrum





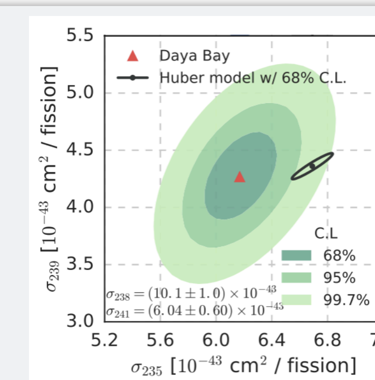
Since 2014: **Daya Bay, Double Chooz, RENO, NEOS, STEREO, PROSPECT,…**

Reactor anomaly & Sterile Neutrinos



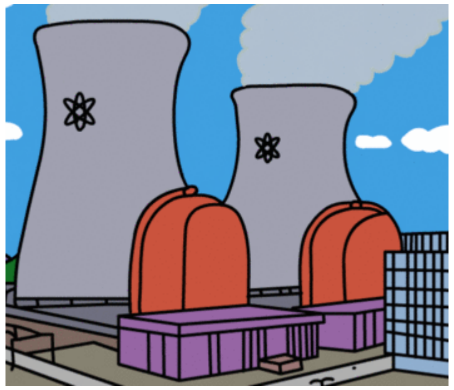
2017: **Daya Bay, RENO**

Fuel evolution



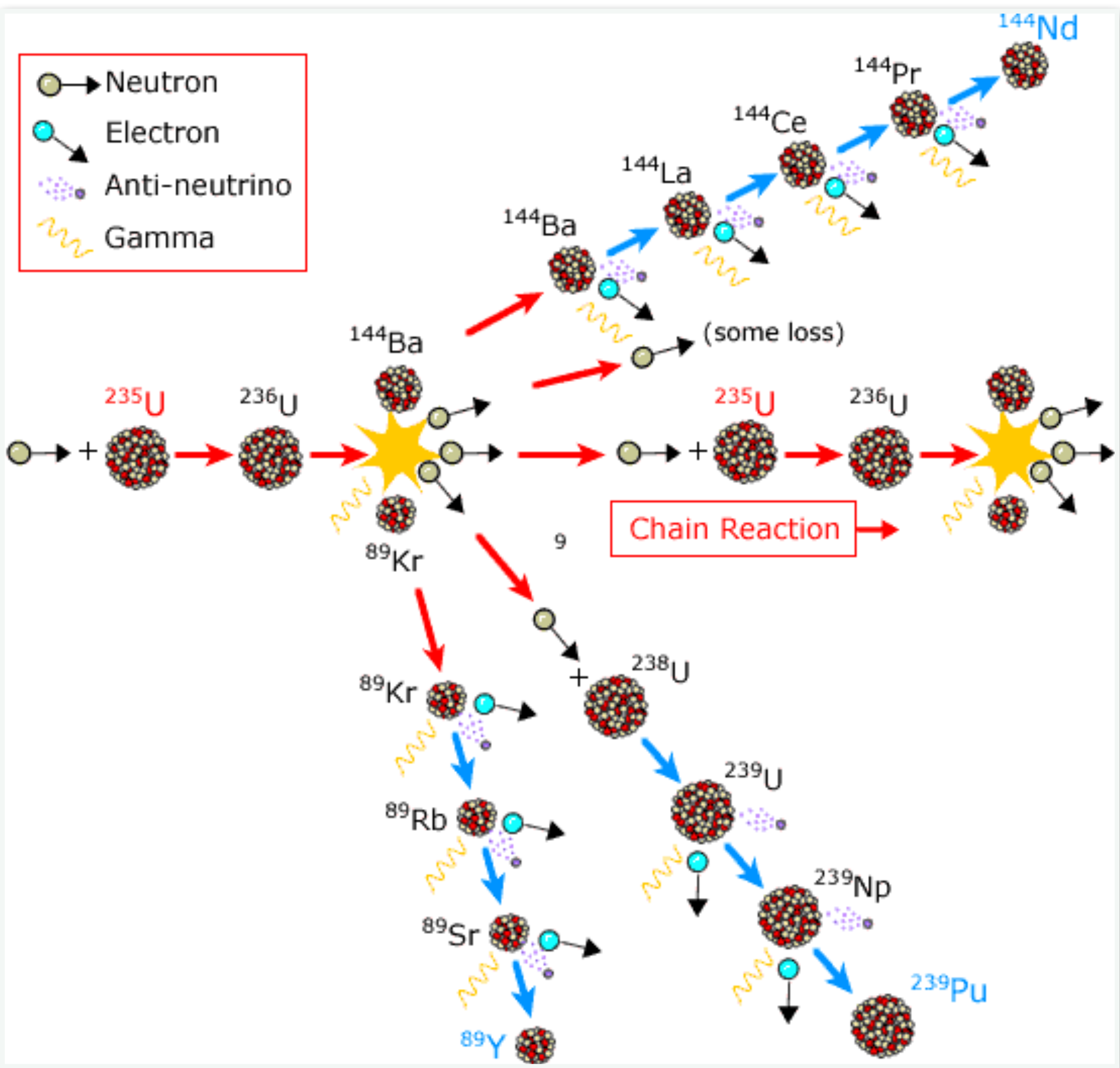
Outline

- **Reactor neutrinos**
  - Production process
  - Oscillations
- **Quest for θ_{13} mixing angle**
  - Experiments
  - Detection
  - Results
- **Reactor neutrino anomalies**
  - Reactor neutrino spectrum anomaly
  - Fuel evolution & reactor neutrino flux anomaly
- **A taste of upcoming experiments**

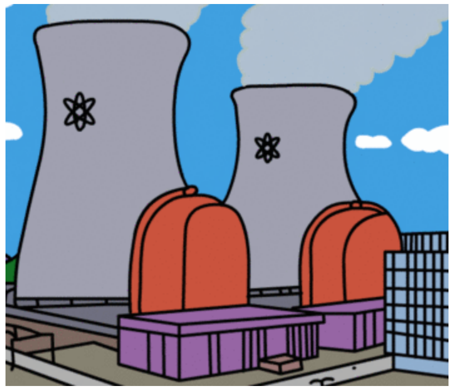


Nuclear reactor:
Four main isotopes participate in fissions:
^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu

Complex reactions in the reactor



Reactor Neutrinos



Nuclear reactor:
Four main isotopes participate in fissions:
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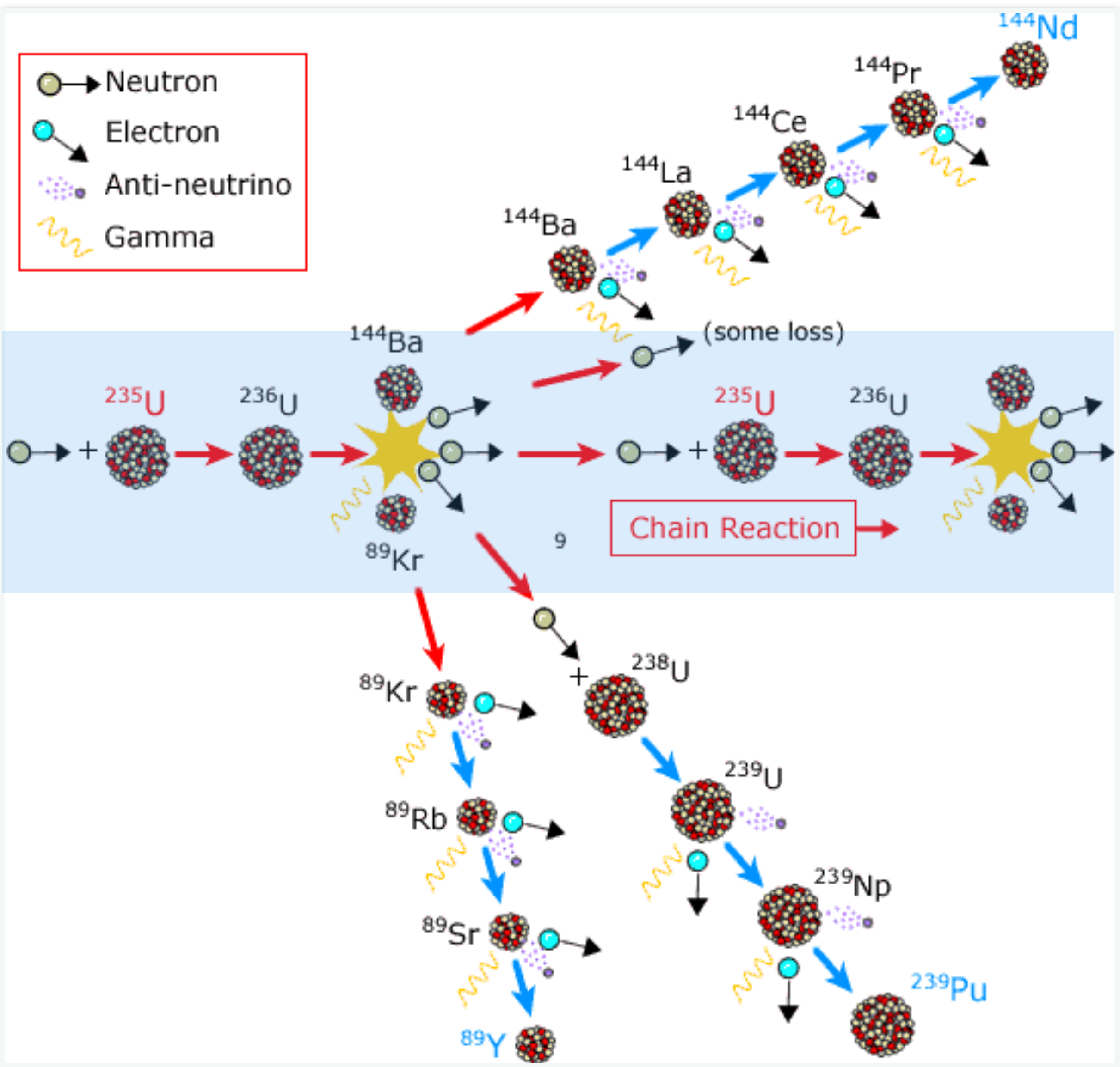
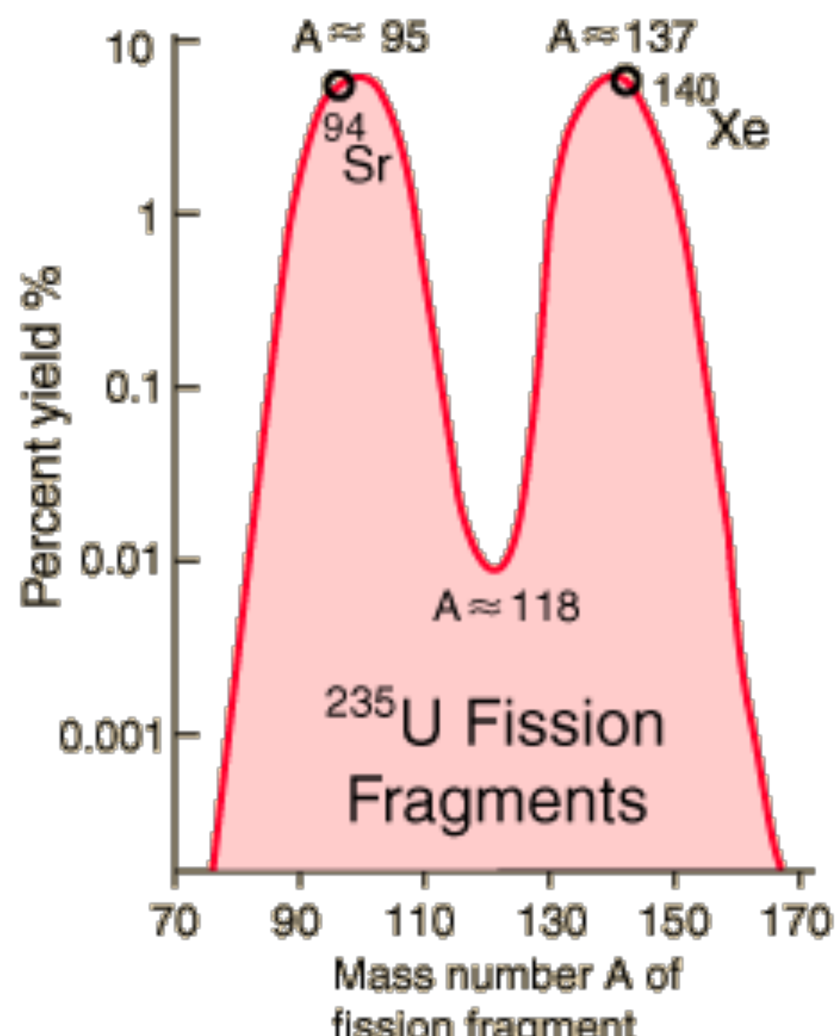
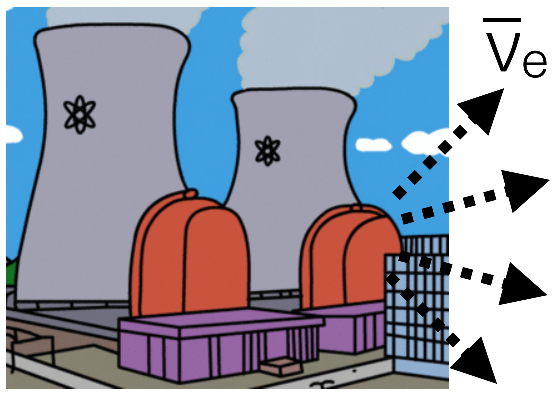
The basic chain reaction of ^{235}U



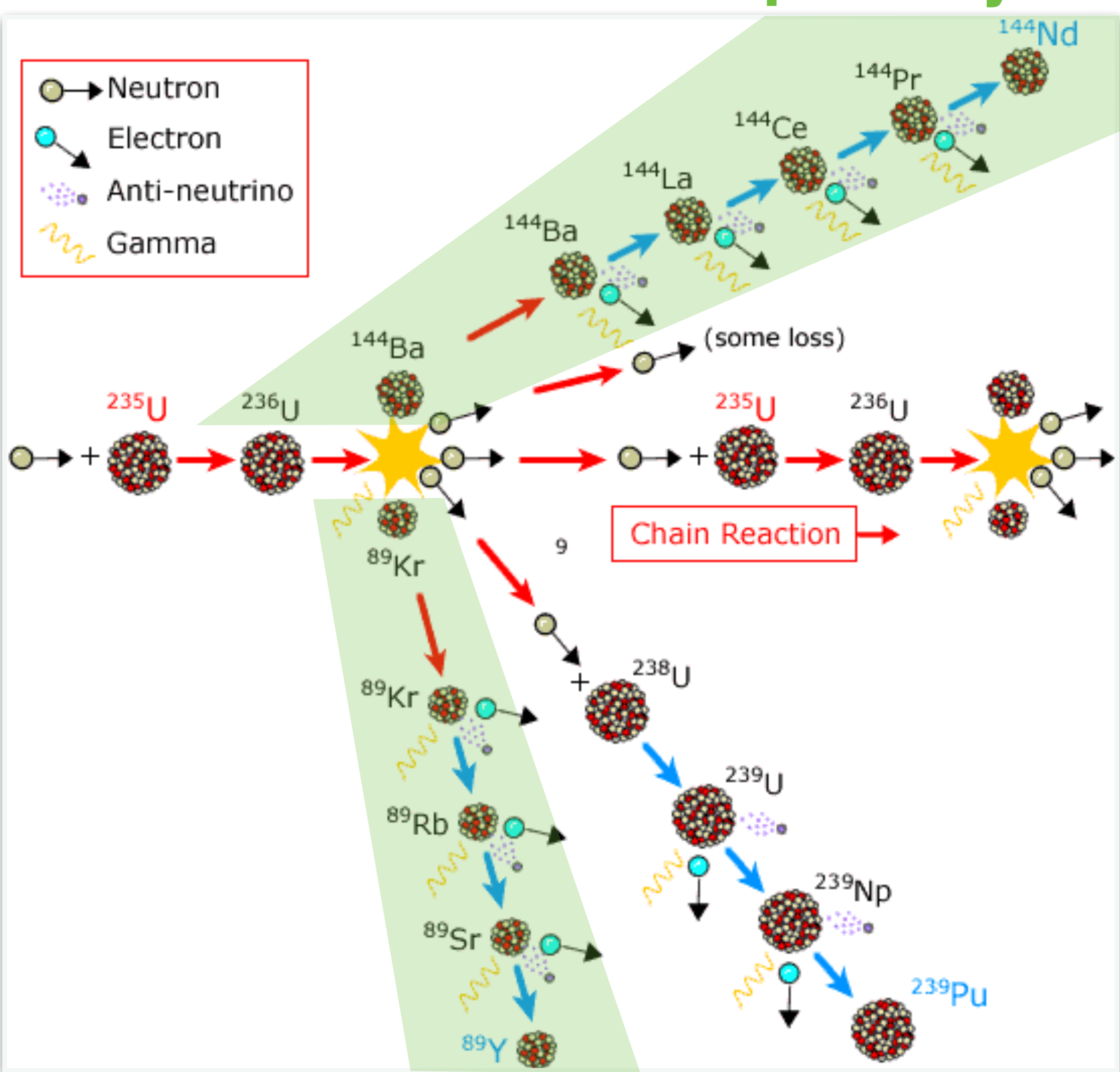


Reactor Neutrinos



Nuclear reactor:
Four main isotopes participate in fissions:
^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu

Neutron-rich elements - β decay cascade



Reactor: Source of pure $\bar{\nu}_e$

(Reactor neutrino = electron antineutrino)

$$^{A}_{Z}X \rightarrow {}^{\;\;A}_{Z+1}X' + e^- + \bar{\nu}_e$$

Reactor: Powerful source of $\bar{\nu}_e$

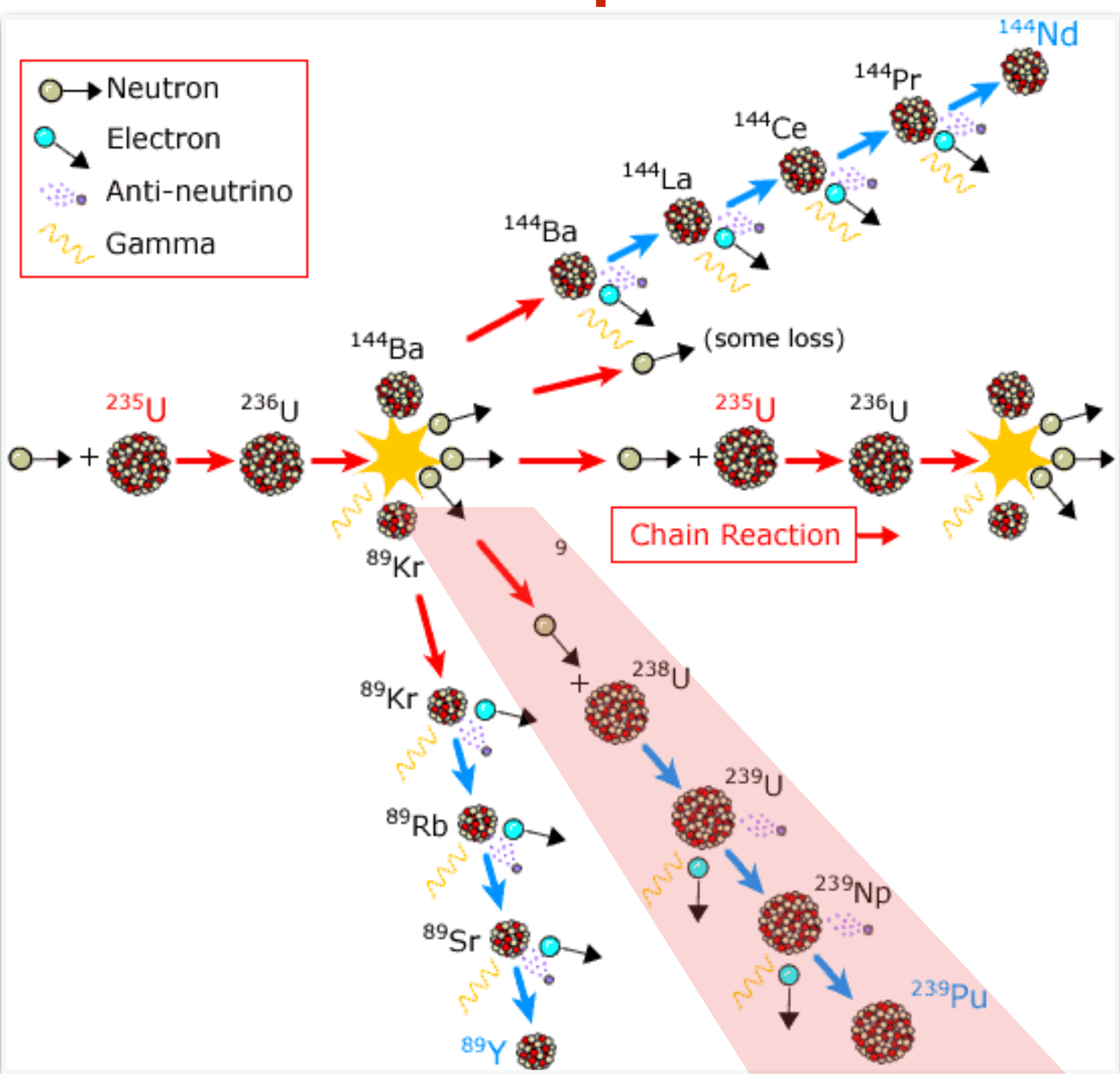
$$\sim 6\ \bar{\nu}_e \text{ per fission}$$

$$2 \times 10^{20}\ \bar{\nu}_e/\text{second}/\text{GW}_{th}$$

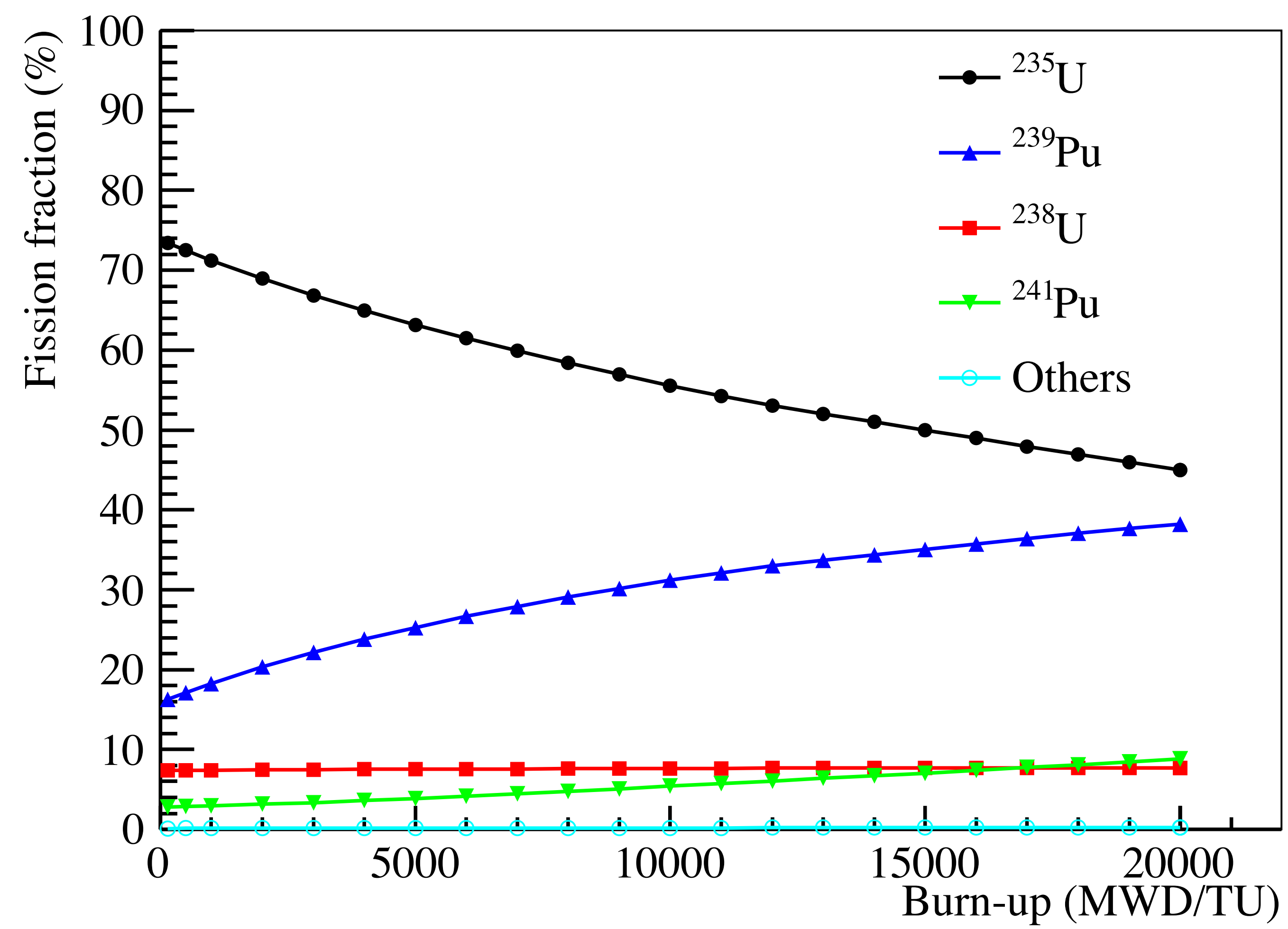
Reactor Neutrinos

Nuclear reactor:
Four main isotopes participate in fissions:
^{235}U, ^{238}U, **^{239}Pu,** ^{241}Pu

Production of plutonium



Evolution of the fuel with burn-up



Neutrino Mixing and Oscillations (2ν's)

flavor (weak) states   mixing matrix   mass states

Two-neutrino mixing:

$$\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = \begin{pmatrix}\cos\theta & \sin\theta\\ -\sin\theta & \cos\theta\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\end{pmatrix}$$

$\nu_1 \leftrightarrow m_1$

$\nu_2 \leftrightarrow m_2$

$\Delta m^2 \equiv m_2^2 - m_1^2$

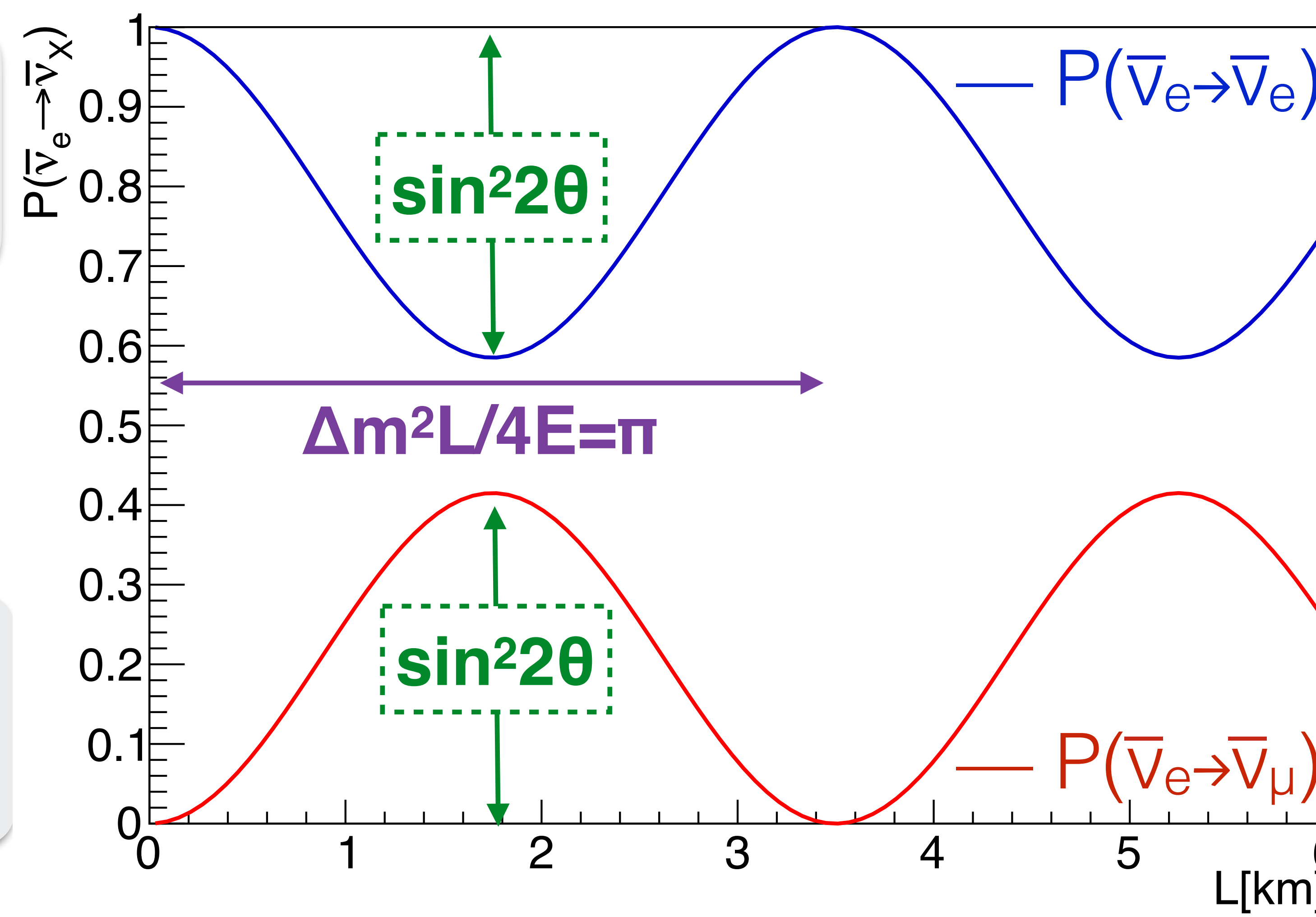
Disappearance

$$P_{\nu_e\to\nu_e}(L,E) = 1 - \sin^2 2\theta \sin^2\frac{\Delta m^2 L}{4E}$$

$$P_{\nu_e\to\nu_e} + P_{\nu_e\to\nu_\mu} = 1$$

Appearance

$$P_{\nu_e\to\nu_\mu}(L,E) = \sin^2 2\theta \sin^2\frac{\Delta m^2 L}{4E}$$



Neutrino Mixing and Oscillations (3ν's)

Three-neutrino mixing:

Atmospheric, accelerator ν

Solar, reactor L~60 km ν

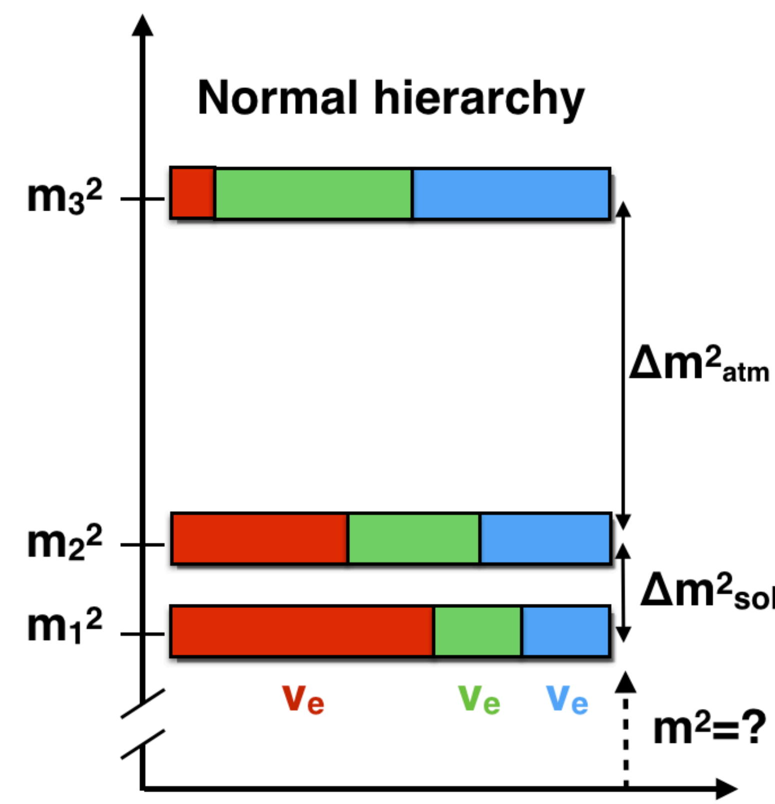
$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix} \begin{pmatrix}c_{13} & 0 & s_{13}e^{i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{-i\delta} & 0 & c_{13}\end{pmatrix} \begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12}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

Reactor L~2 km, accelerator ν

$c_{ij}=\cos\theta_{ij}$
$s_{ij}=\sin\theta_{ij}$

Oscillation parameters:

Parameter	Value	Open questions
Δm^2_{21}*	7.5×10^{-5} eV^2	—
$\lvert\Delta m^2_{31}\rvert\approx\lvert\Delta m^2_{32}\rvert$*	2.5×10^{-3} eV^2	Hierarchy?⇔$\Delta m^2_{31}\lessgtr 0$
θ_{12}*	33°	—
θ_{23}	45°?	Maximal?⇔$\theta_{23}\gtrless 45°$
θ_{13}*	9°	—
δ_{CP}	?°	Value?



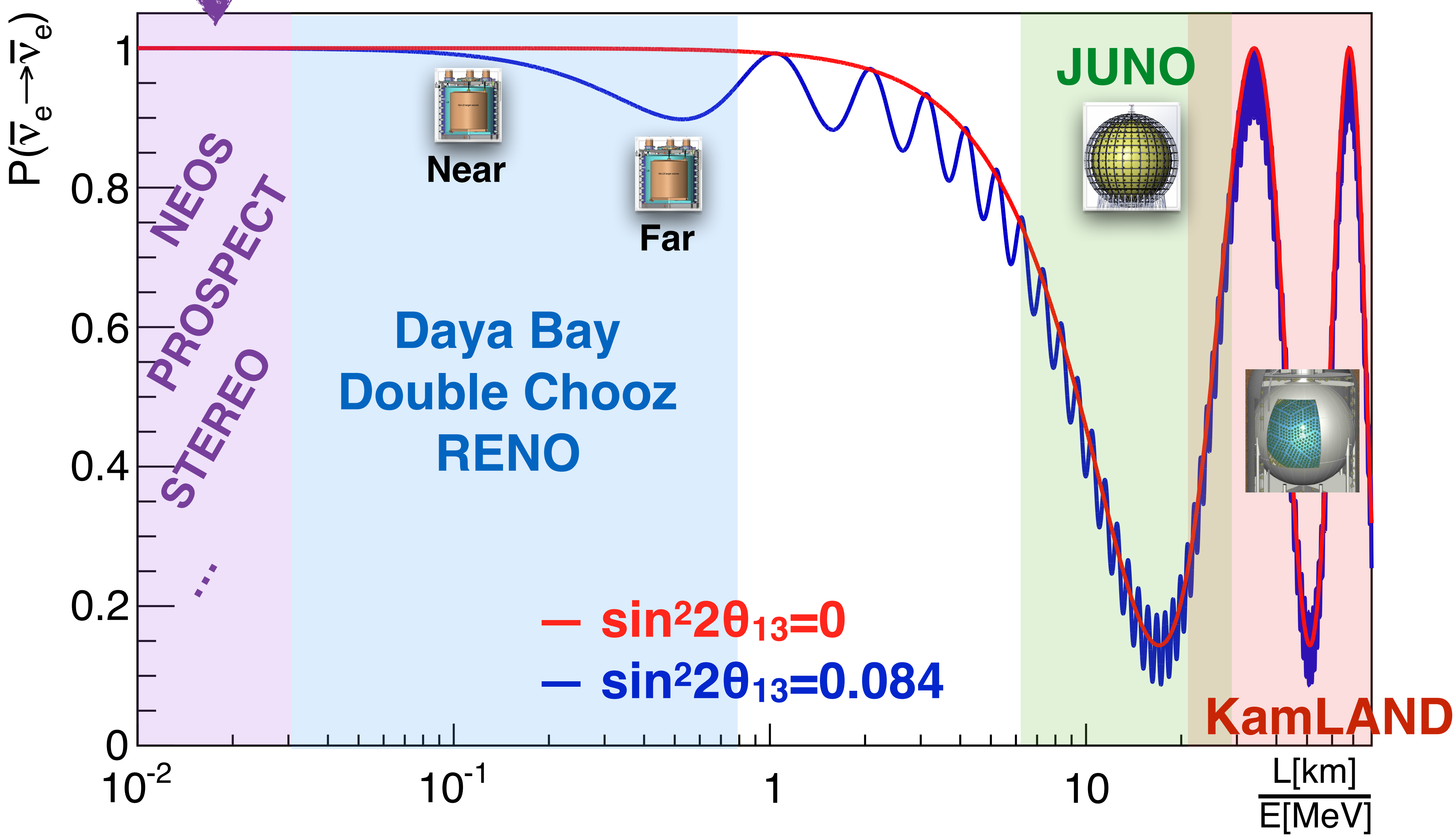
*Are measured by reactor neutrinos

Reactor Neutrino Oscillations

Two modes of oscillations: $P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{12} \cos^4 \theta_{13} \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right)$ **Medium baseline**

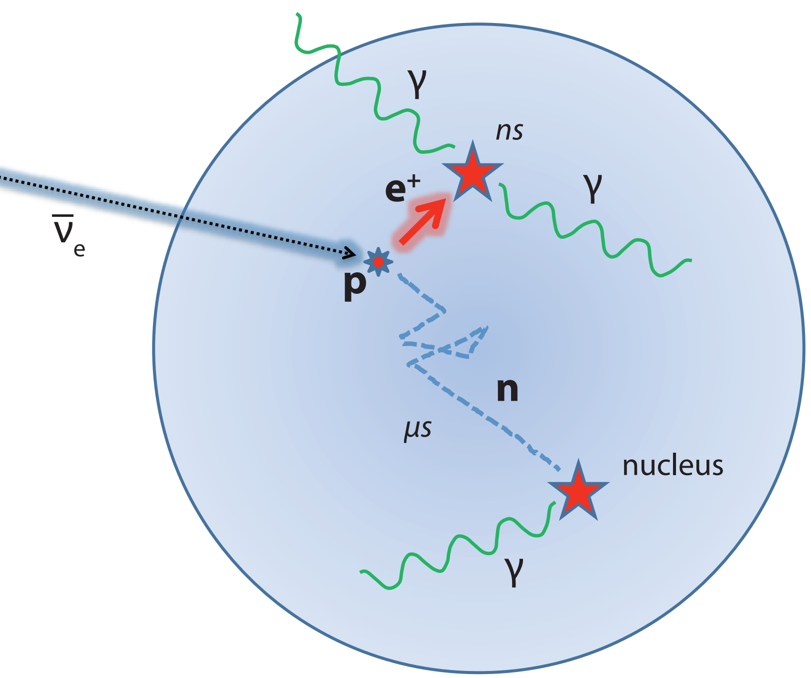
$- \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{ee} L}{4E}\right)$ **Short baseline**

Is there 3rd mode?!?



Reactor Neutrino Detection

- **Primary method** - Inverse beta decay (IBD) in liquid scintillator



Coincidence in time

prompt signal — delayed signal

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

$$\text{KamLAND, DB, DC, RENO} \rightsquigarrow n + H \rightarrow D + \gamma \text{ (2.22 MeV)}$$

$$\text{DB, DC, RENO} \rightsquigarrow n + Gd \rightarrow Gd^* \rightarrow Gd + \gamma\text{'s (8 MeV)}$$

$$\text{Savannah River} \rightsquigarrow n + Cd \rightarrow Cd^* \rightarrow Cd + \gamma\text{'s (9 MeV)}$$

$$\text{BUGEY3, PROSPECT} \rightsquigarrow n + Li \rightarrow Li \rightarrow \alpha + T \text{ (4.78/}{\sim}\text{0.5 MeV)}$$

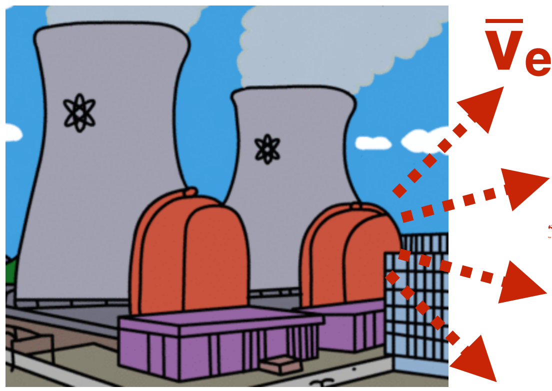
- **Why IBD?**
  - Relatively large cross-section
  - Distinctive coincidence signature
  - Targets (H) already part of liquid scintillator

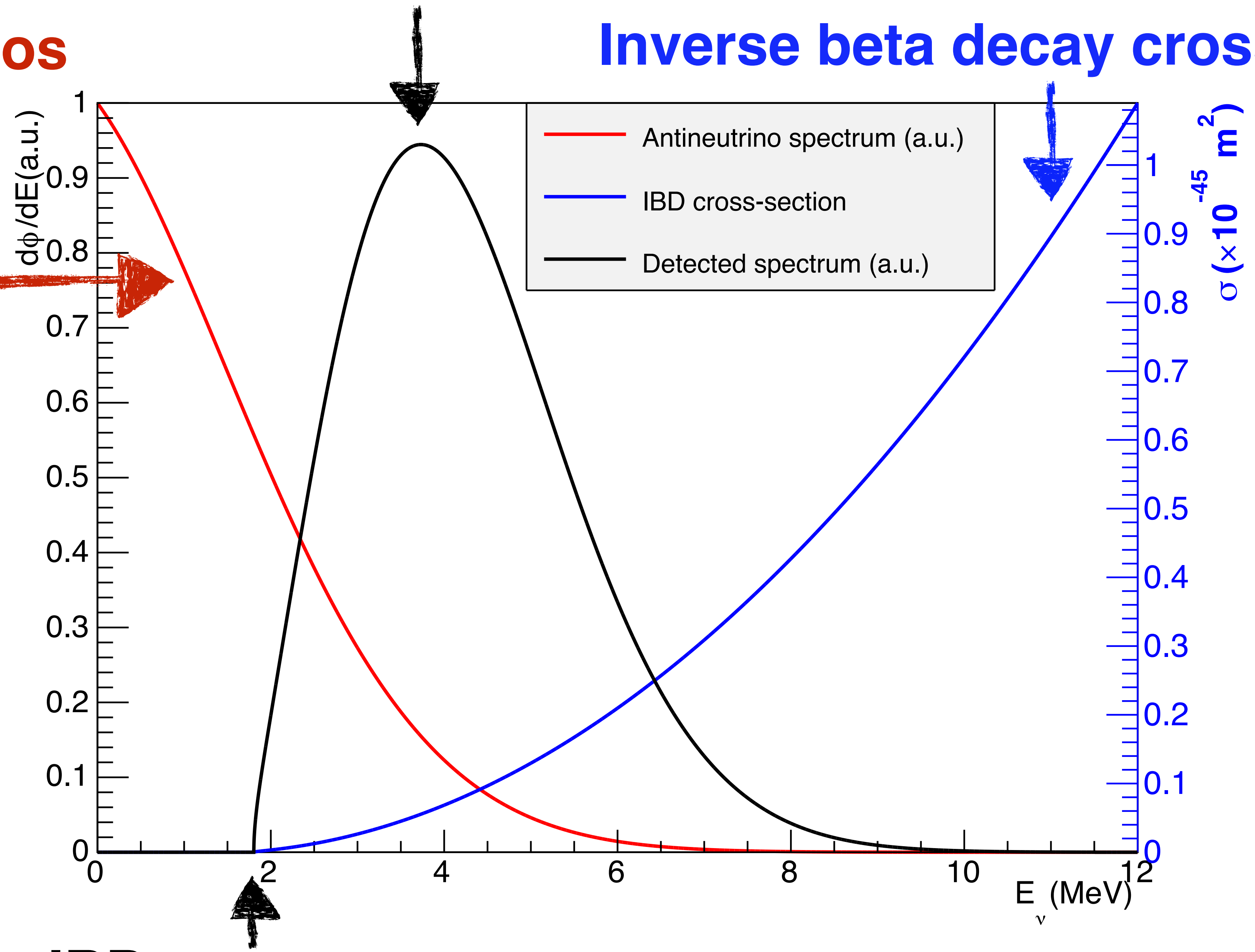
Detected Spectrum via Inverse Beta Decay

Typical detected spectrum

Flux of antineutrinos

Inverse beta decay cross-section



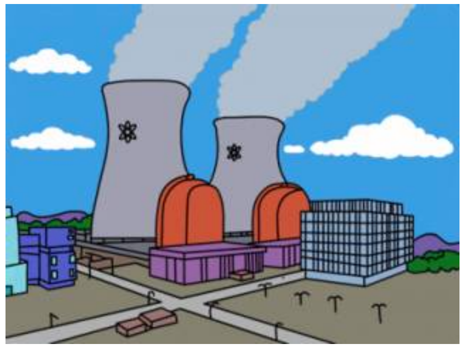


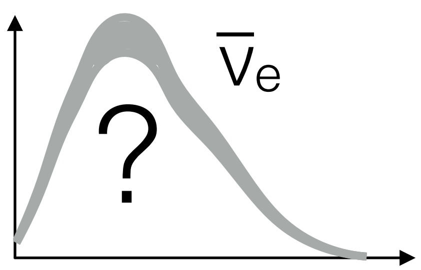
IBD: $\bar{\nu}+p \rightarrow e^{+}+n$

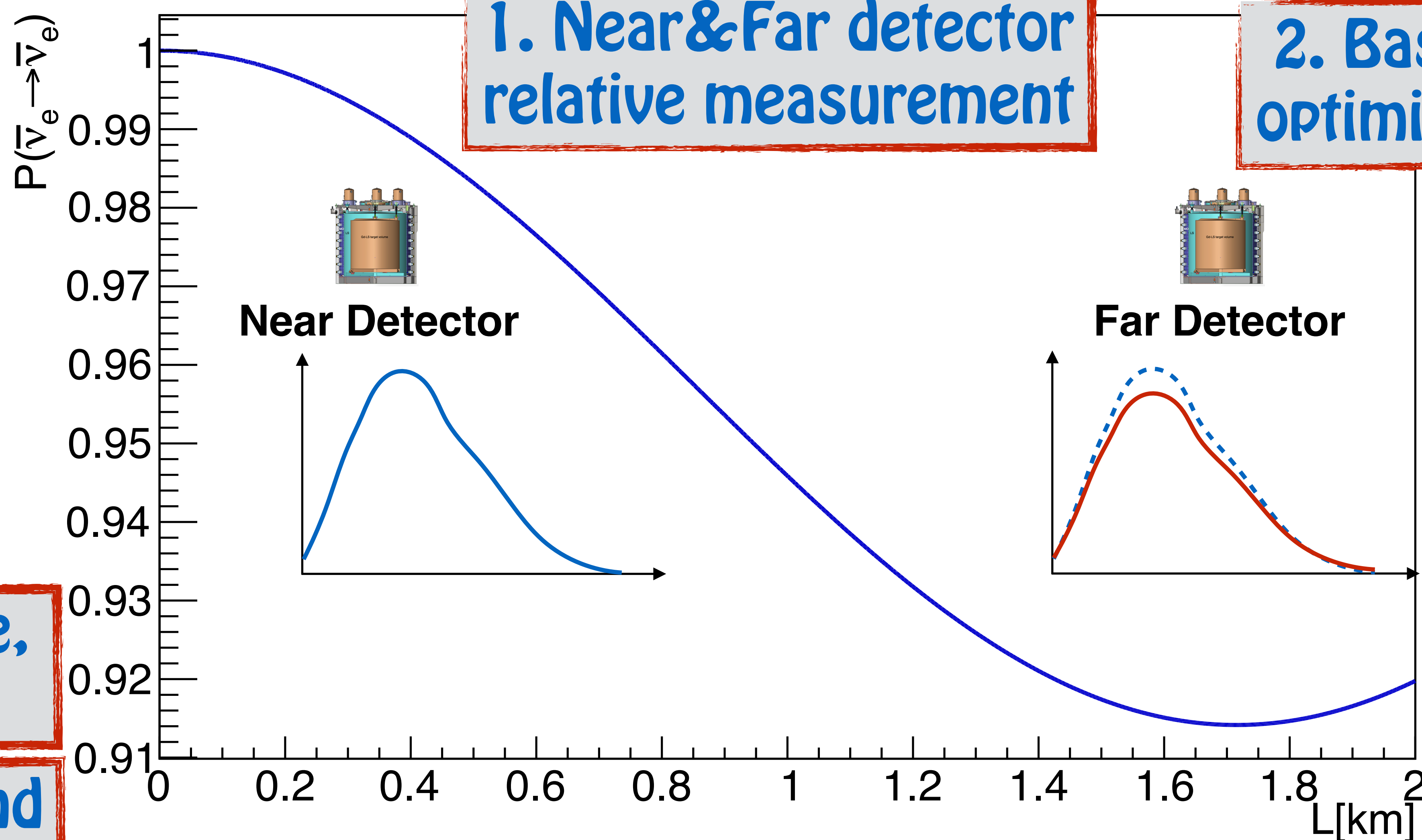
Threshold 1.8 MeV

Road to Measurement of θ_{13}

- Upper limit by CHOOZ experiment $\sin^2 2\theta_{13} < 0.15$ @ $\Delta m^2 = 2.4\times10^{-3}\ \mathrm{eV}^2$
- Main limitation - uncertainty in **expected flux** and **detection efficiency**
- Key features for success of current experiments:







1. Near&Far detector relative measurement

2. Baseline optimization

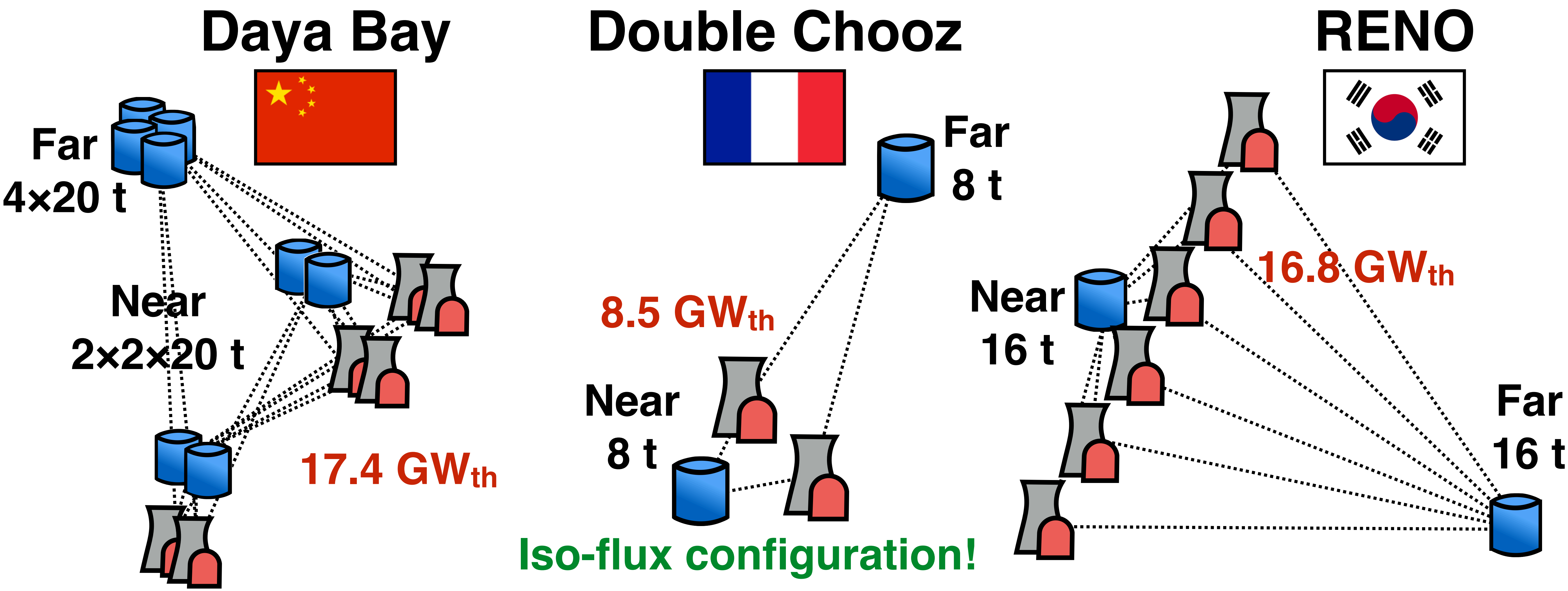
3. Powerful source, large detector(s)

+4. Low background

Mykaelyan & Sinev: Far/Near ratio reduces systematics:

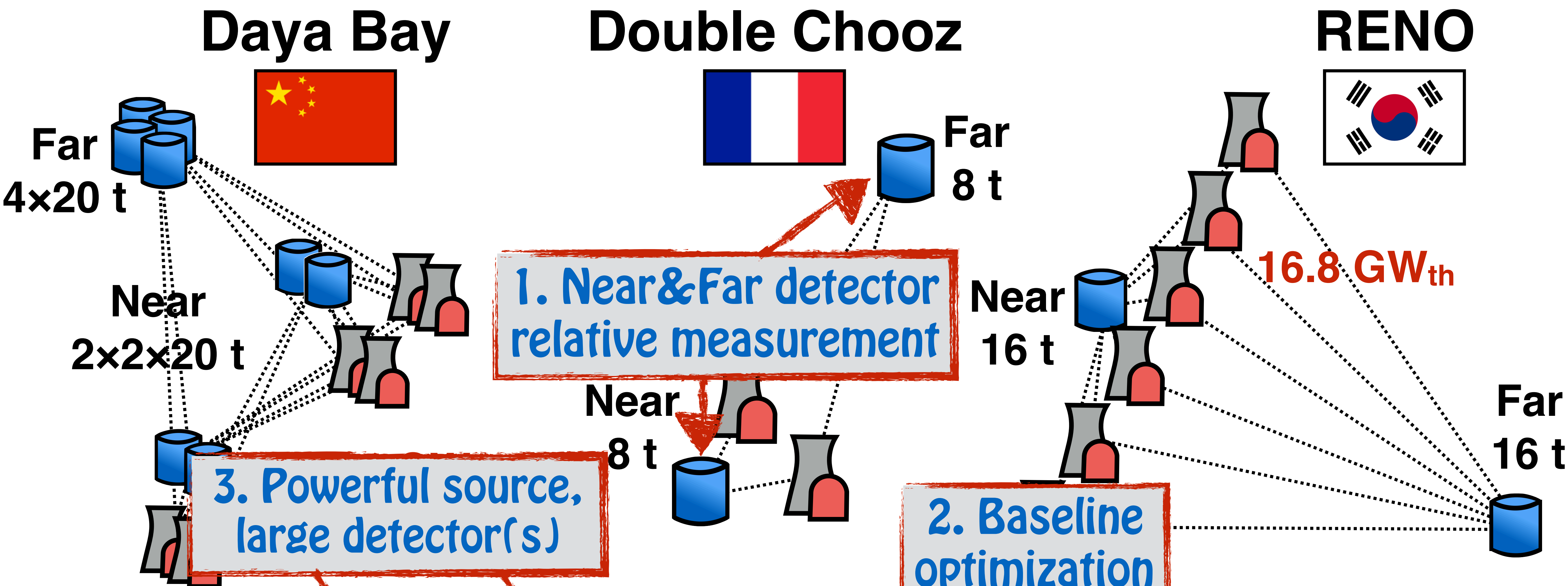
$$\frac{R_{Far}}{R_{Near}} = \left(\frac{L_{Near}}{L_{Far}}\right)^2 \left(\frac{N_{Far}}{N_{Near}}\right) \left(\frac{\varepsilon_{Far}}{\varepsilon_{Near}}\right) \left(\frac{P_{Far}(L_{Far})}{P_{Near}(L_{Near})}\right)$$

Experiments



	Power [GW_{th}]	GdLS mass Near/Far [t]	Distance Near/Far [m]	Overburden [mwe]	Running until
Daya Bay	17.4	2×2×20 4×20	365, 490 1650	250 860	2020
Double Chooz	16.8	8 8	400 1050	120 300	Dec 2017 (Finished)
RENO	8.5	16 16	290 1380	120 450	2020-2021

Experiments



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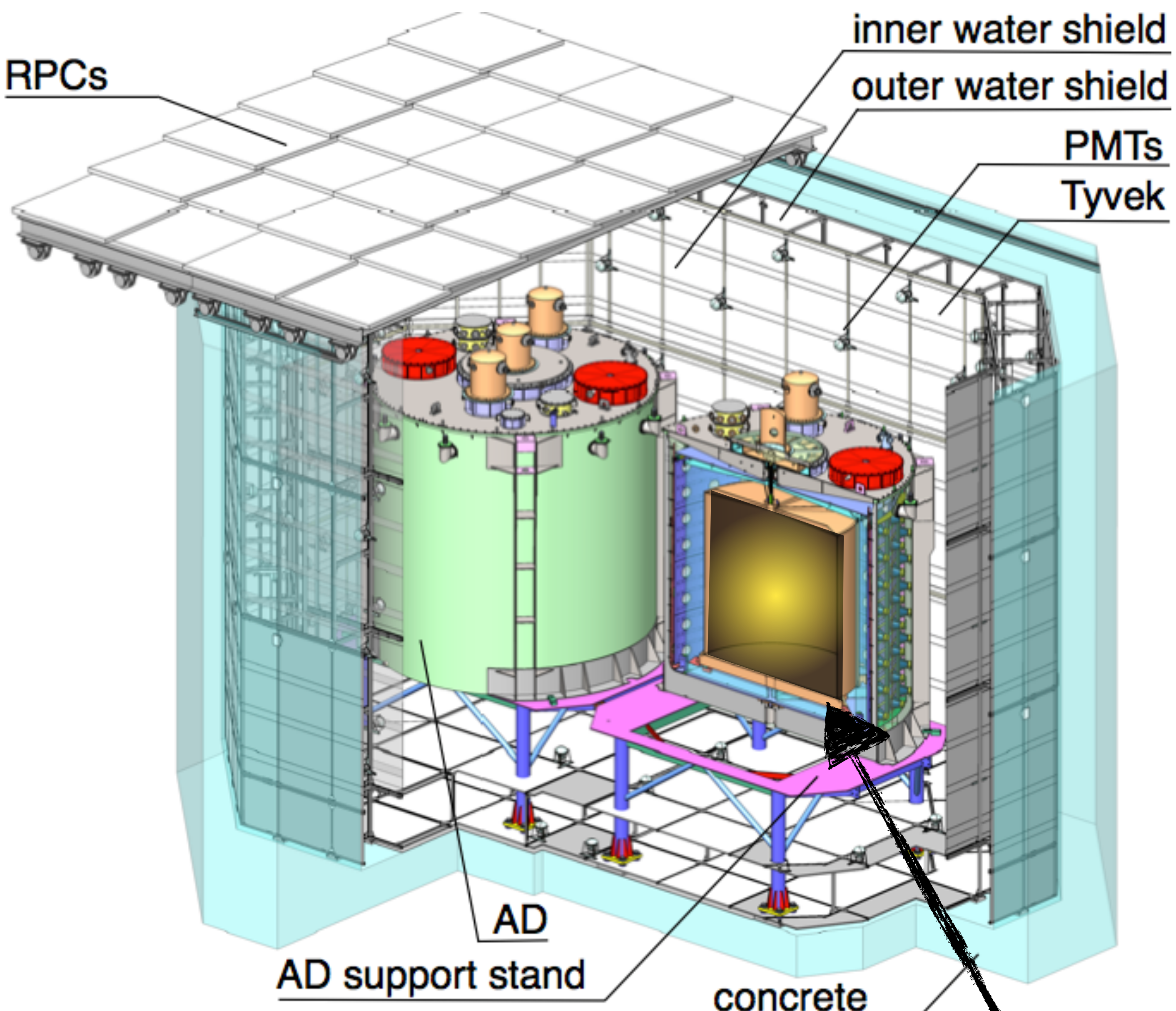
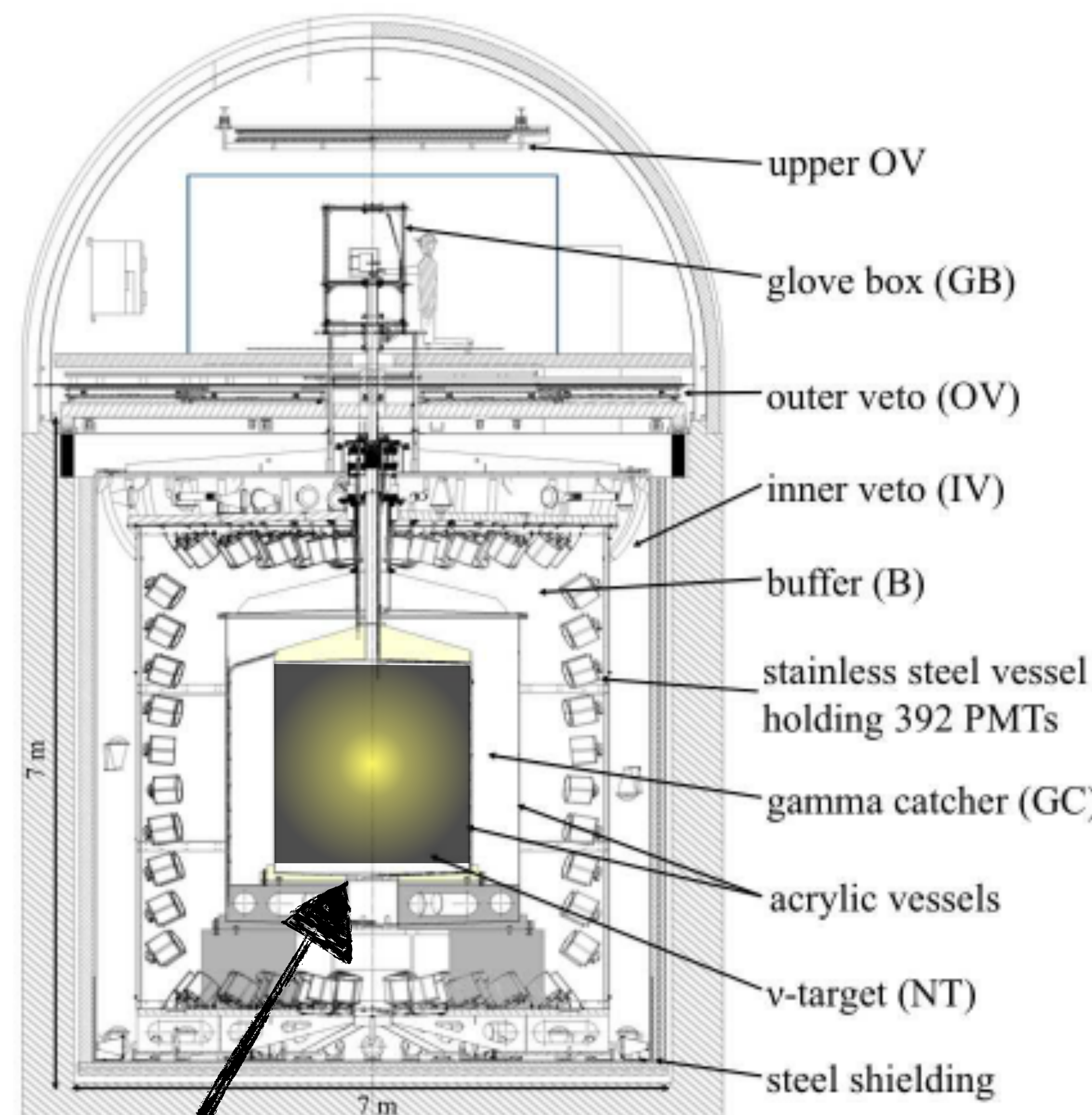
Detector Design

Daya Bay & RENO



Double Chooz

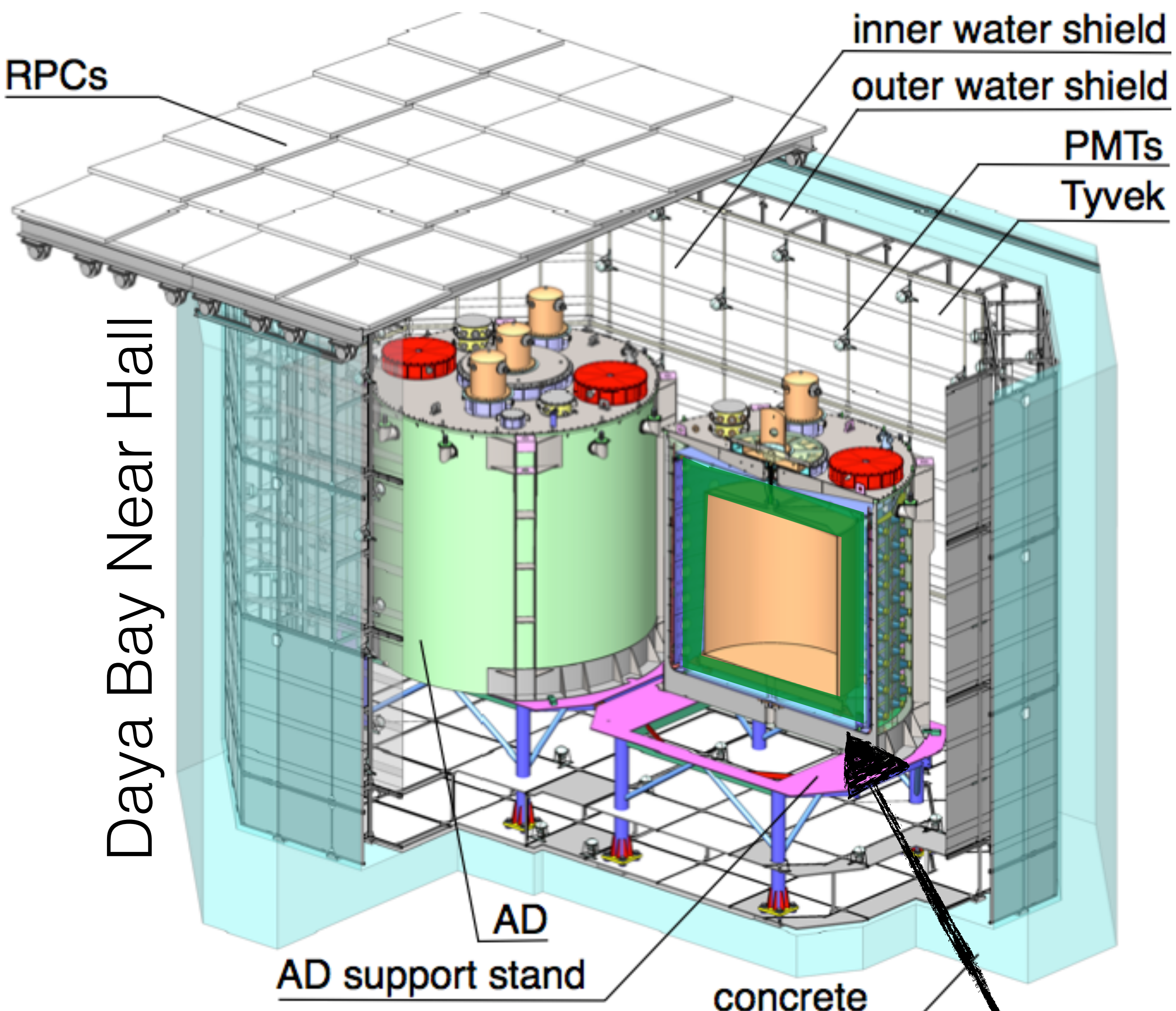


Gadolinium-doped liquid scintillator

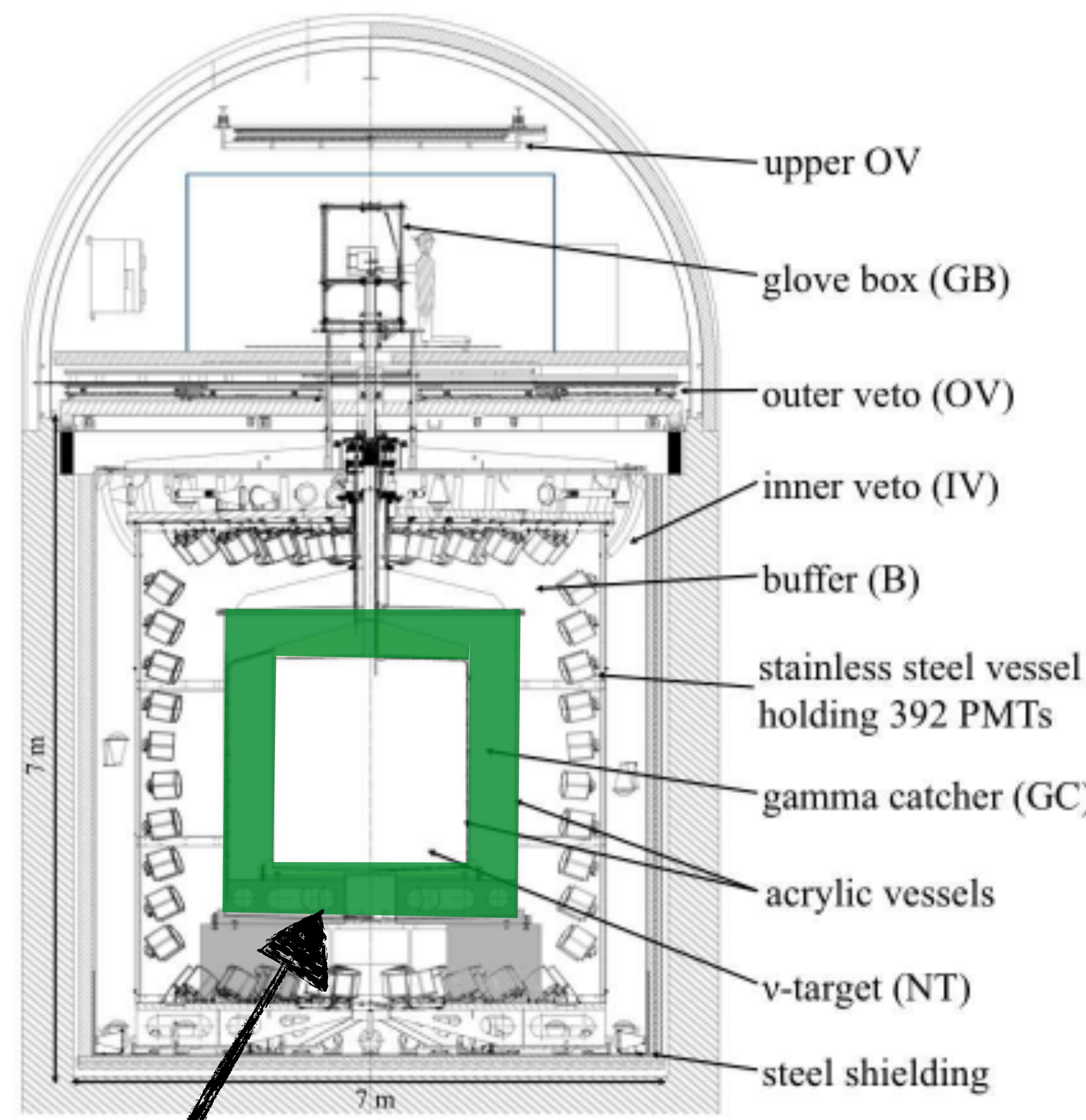
Detector Design

Daya Bay & RENO

Daya Bay Near Hall



Double Chooz

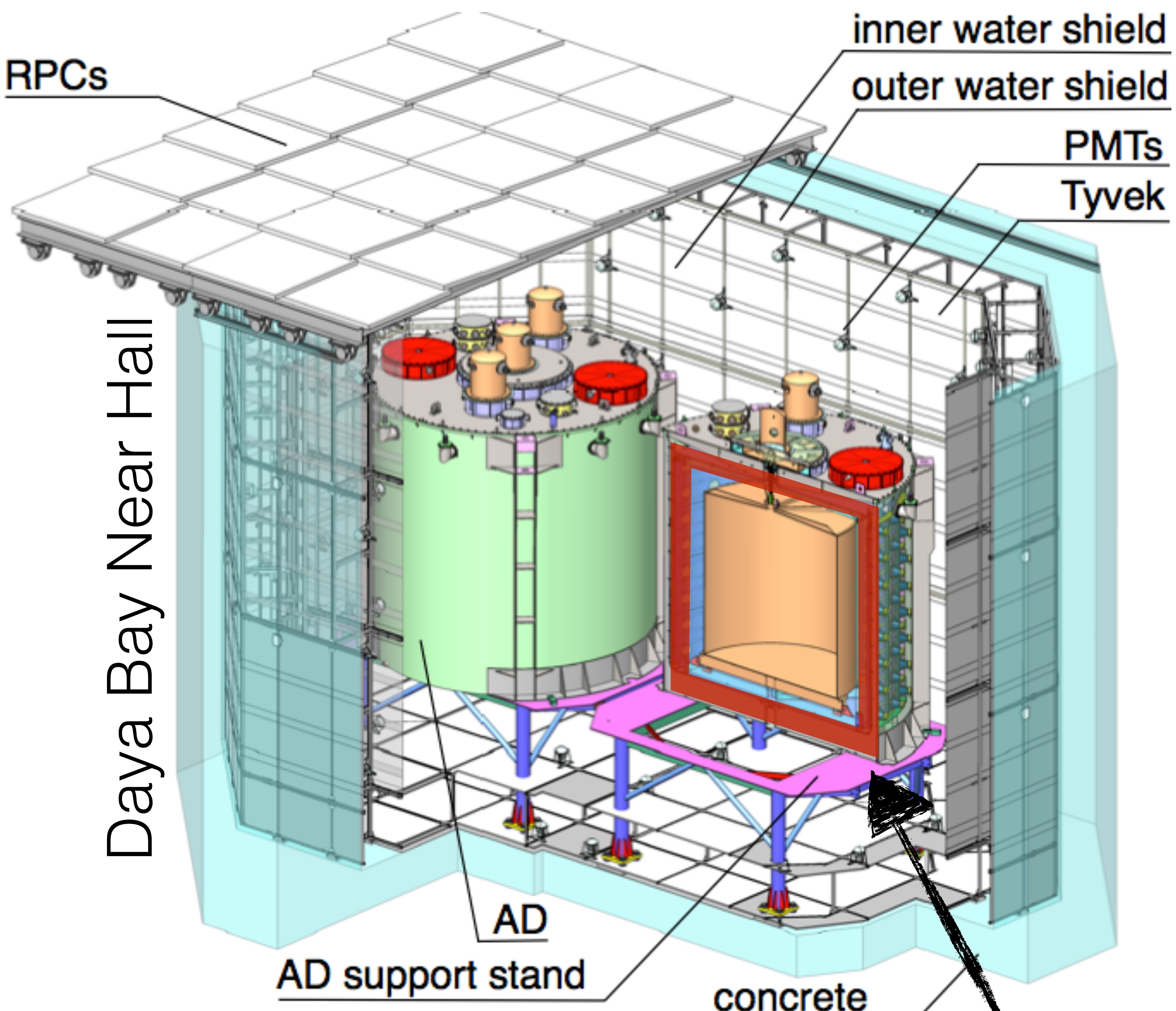


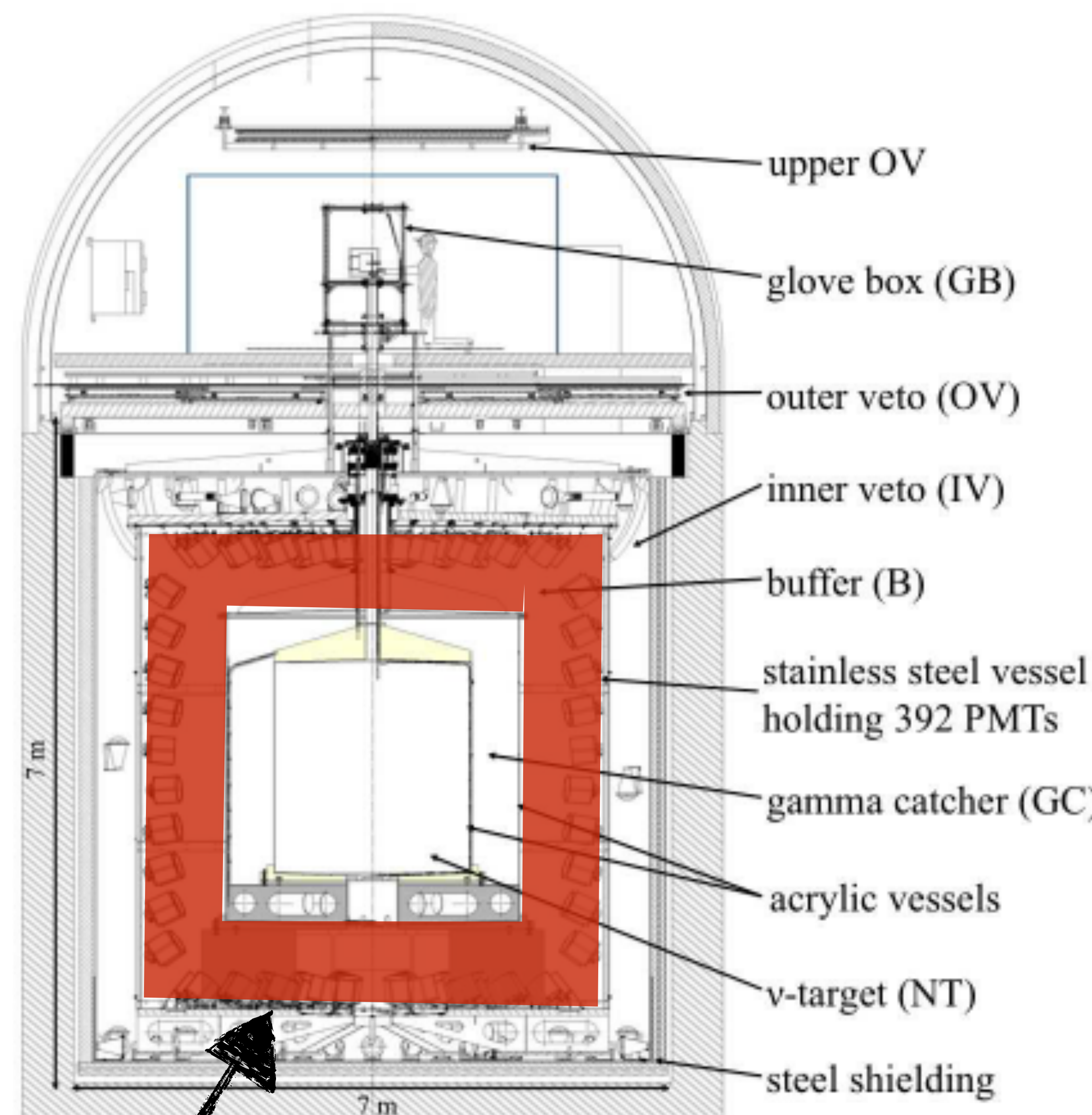
Liquid scintillator γ-catcher

Detector Design

Daya Bay & RENO

Double Chooz

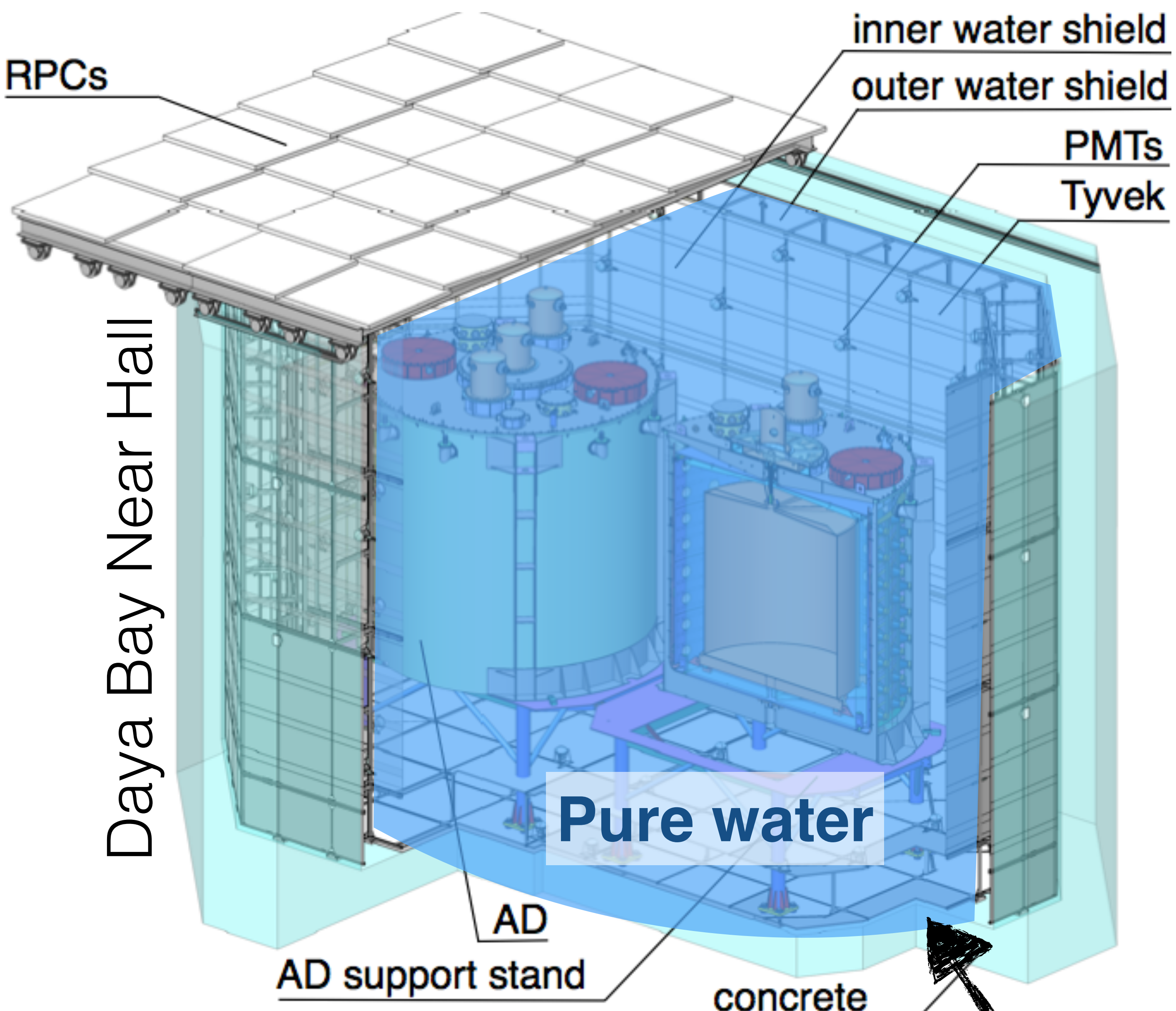




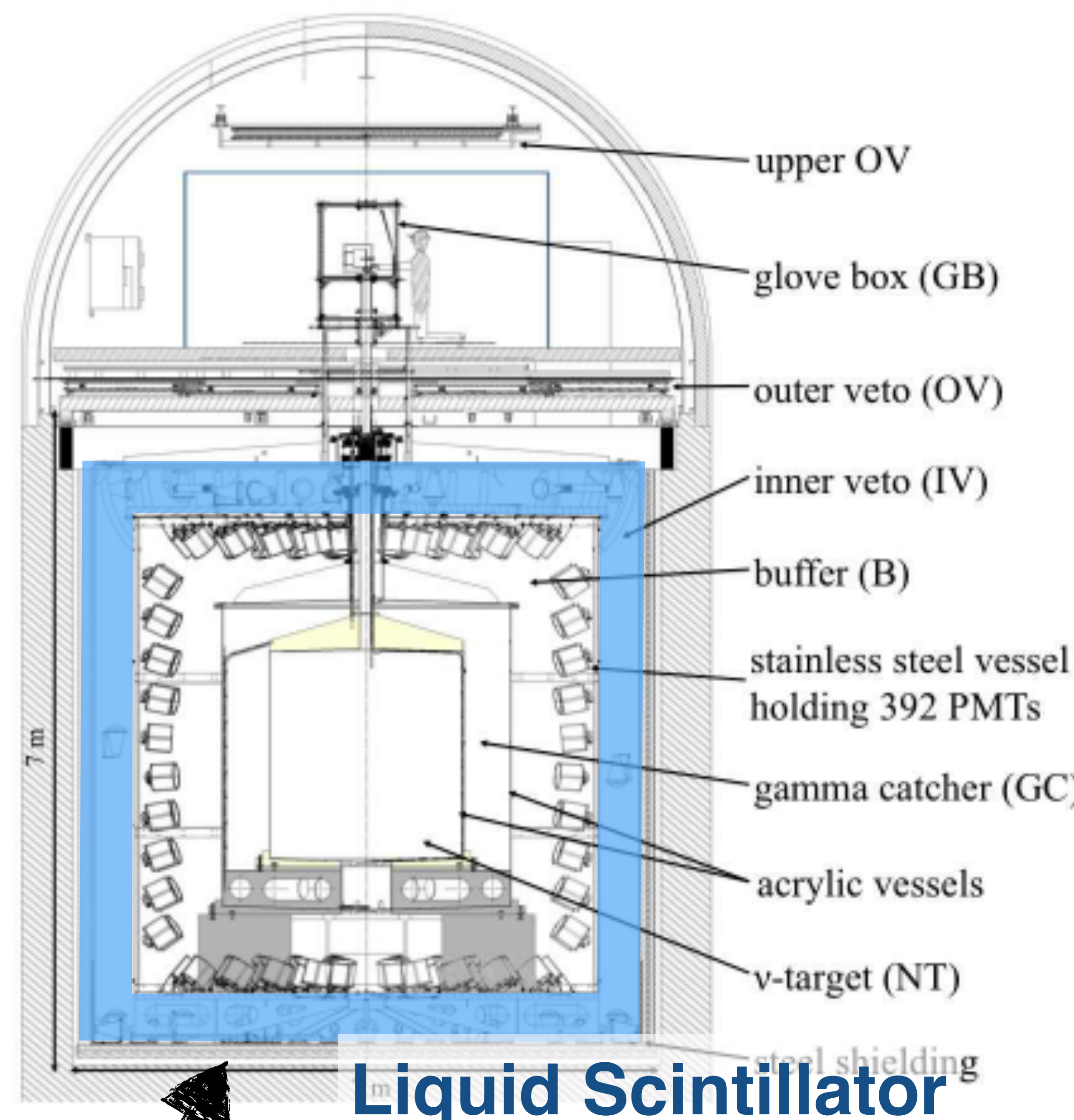
Non-scintillating transparent mineral oil with PMTs

Detector Design

Daya Bay & RENO



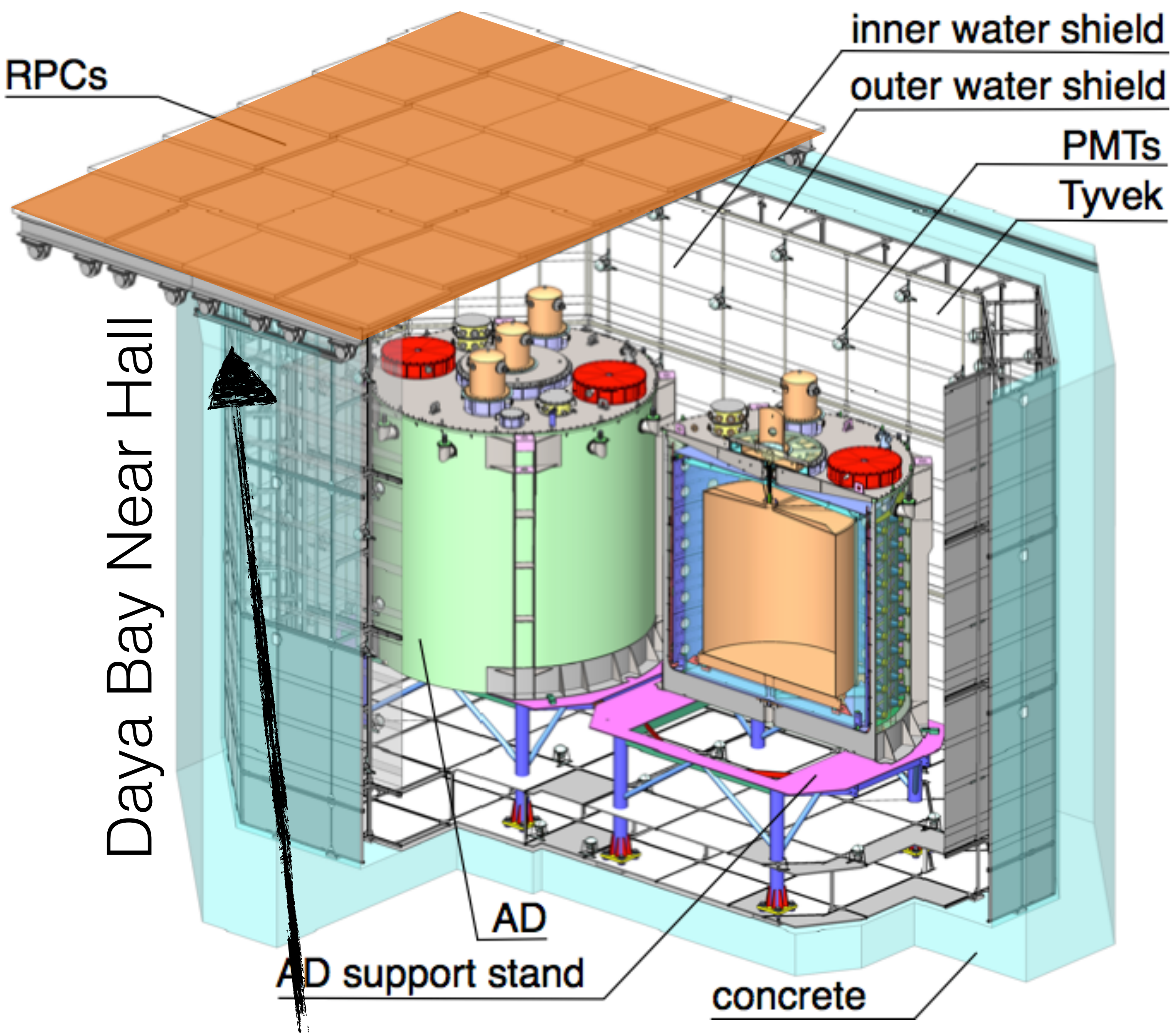
Double Chooz



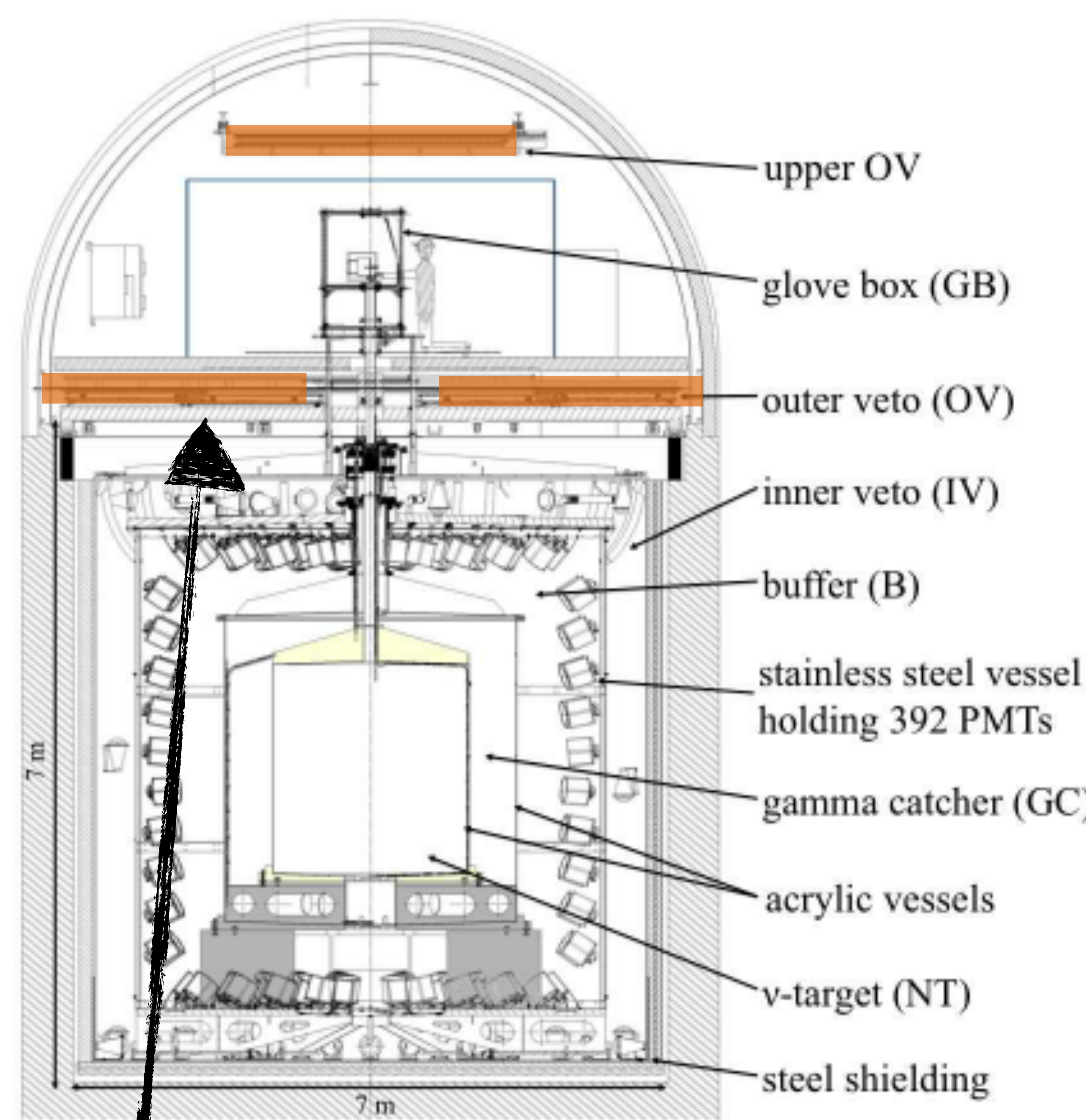
Cherenkov detector for shielding and cosmic muon detection

Daya Bay

Double Chooz



Daya Bay Near Hall



4-layer RPC (Daya Bay)

Plastic scintillator for muons

IBD Selection

- Apply muon veto to suppress backgrounds
- Search for time coincidence of prompt and delayed signal

Double Chooz

nH+nC+nGd together

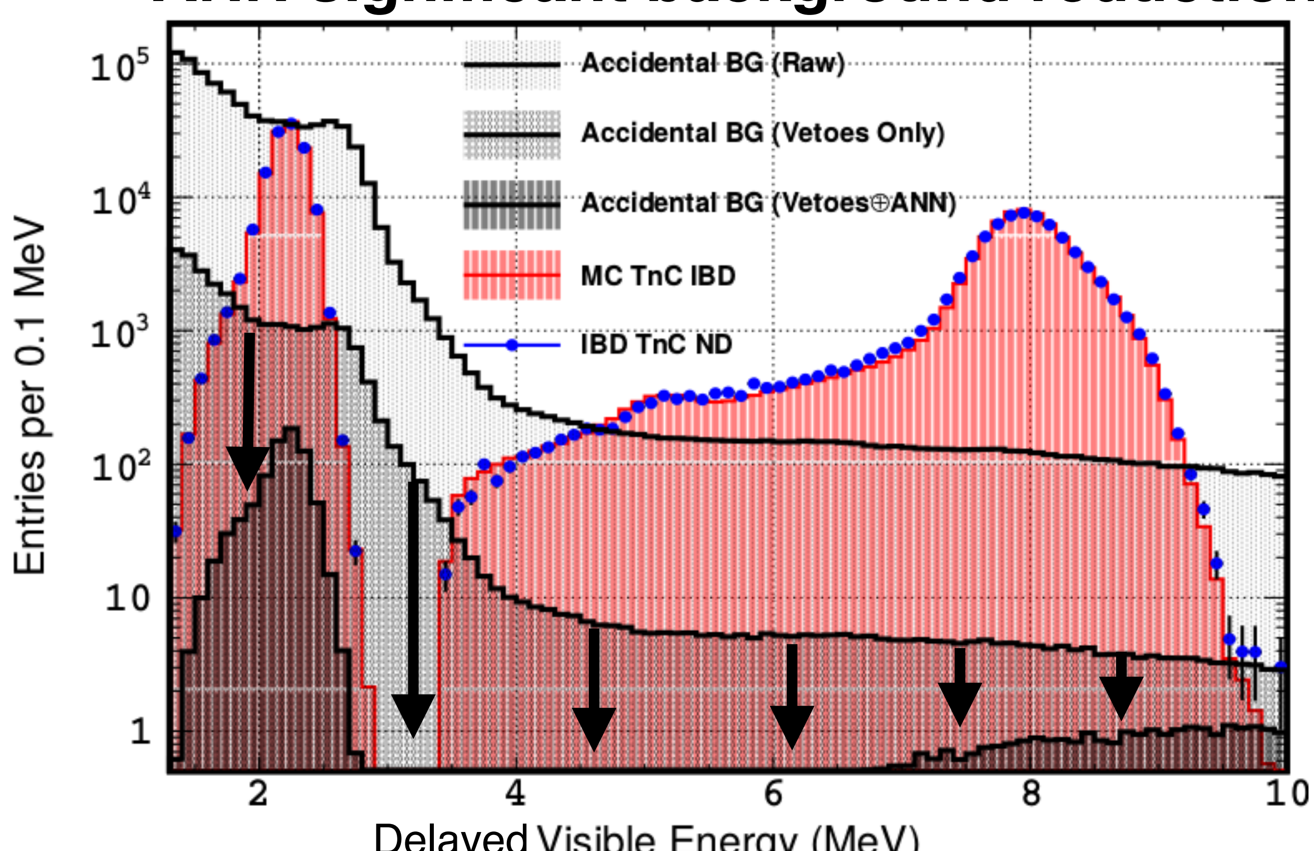
- Artificial neural network (ANN) used for candidate selection

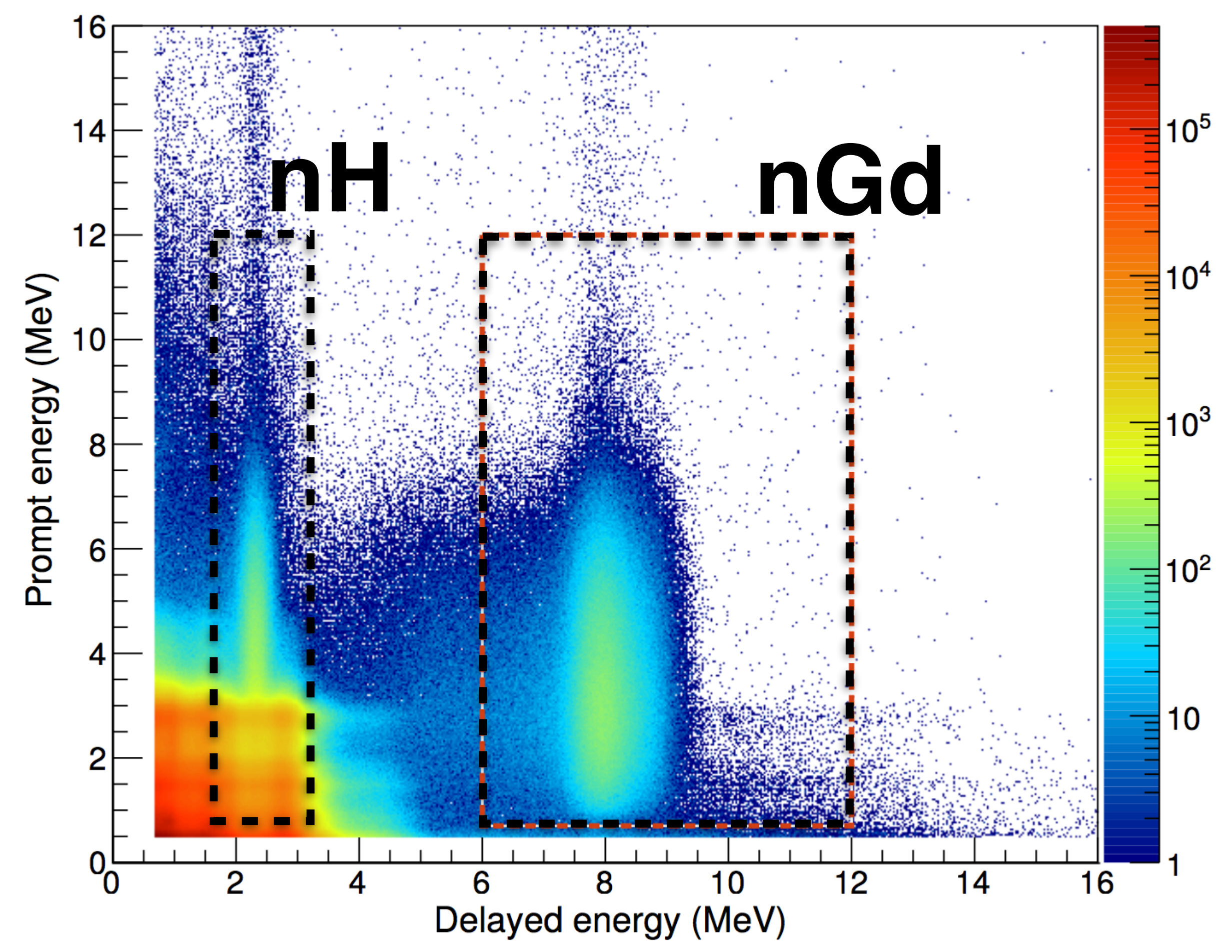
Daya Bay & RENO

nH and nGd treated separately

- Prompt and delayed energy cut
- Time coincidence cut
- Distance cut for nH

ANN significant background reduction





IBD Backgrounds

+4. Low background

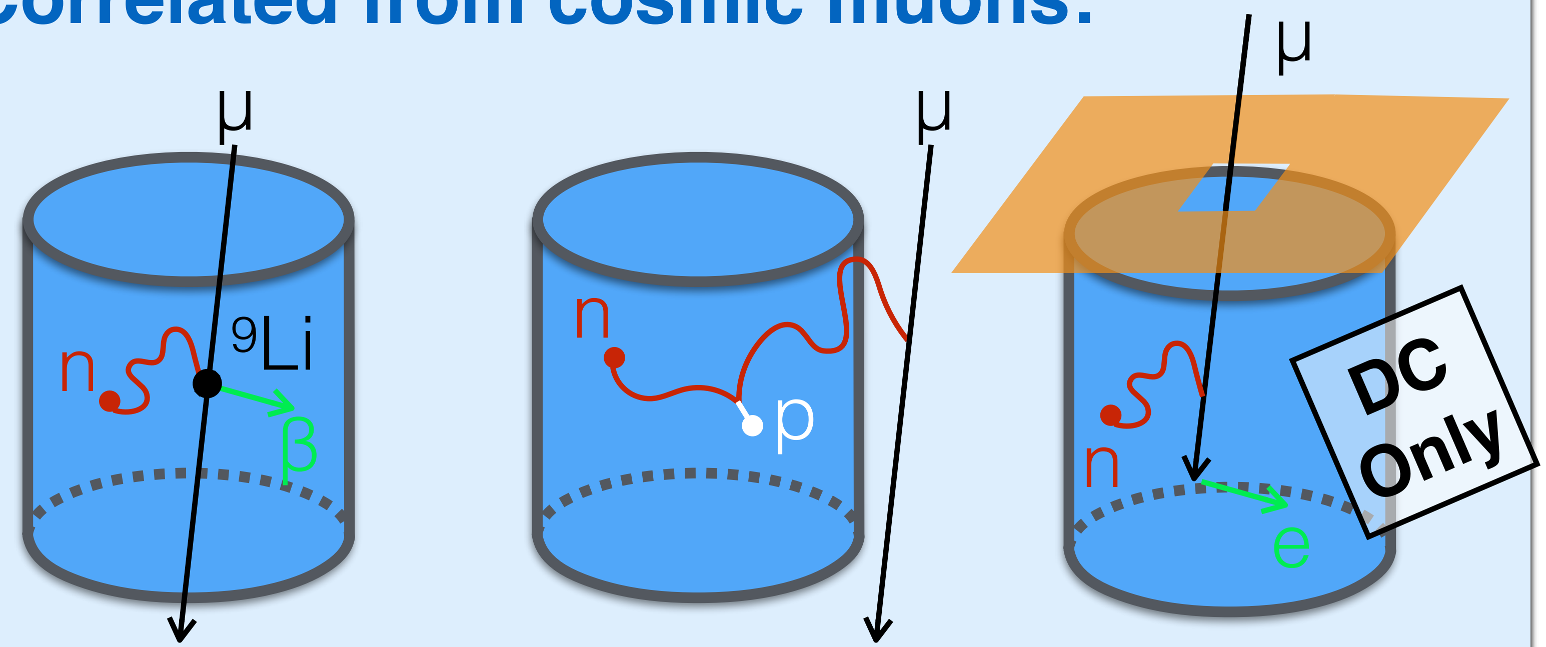
- IBD-like signature: Prompt&delayed energy, time proximity
- Low background: B/S **2%** (DYB) and **5%** (DC&RENO) in far detector(s)

Uncorrelated:

Accidental coincidence

Radioactivity γ
+
High-energy β decay

Correlated from cosmic muons:



^{9}Li/^{8}He Isotopes

β decay
+
n capture

Fast neutrons

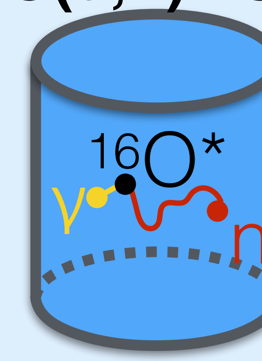
Recoil on p
+
n capture

Unvetoed muons

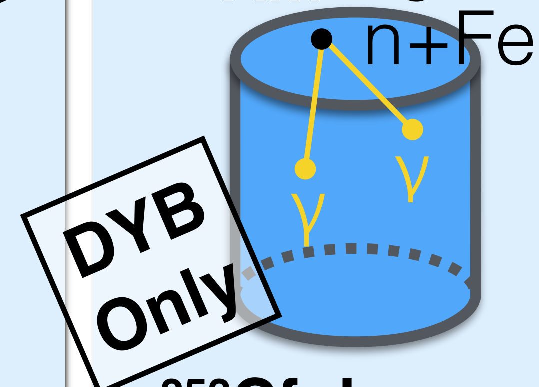
Muon ionization
+
n capture/ muon decay

Others:

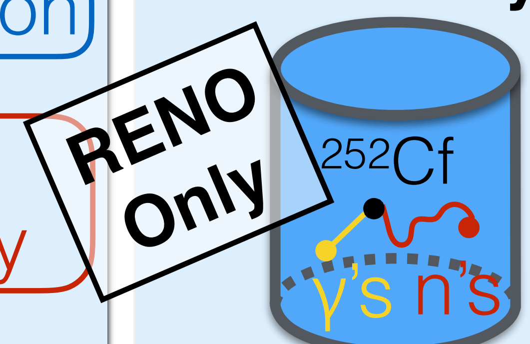
^{13}C(α,n)^{16}O



^{241}Am-^{13}C



^{252}Cf decay



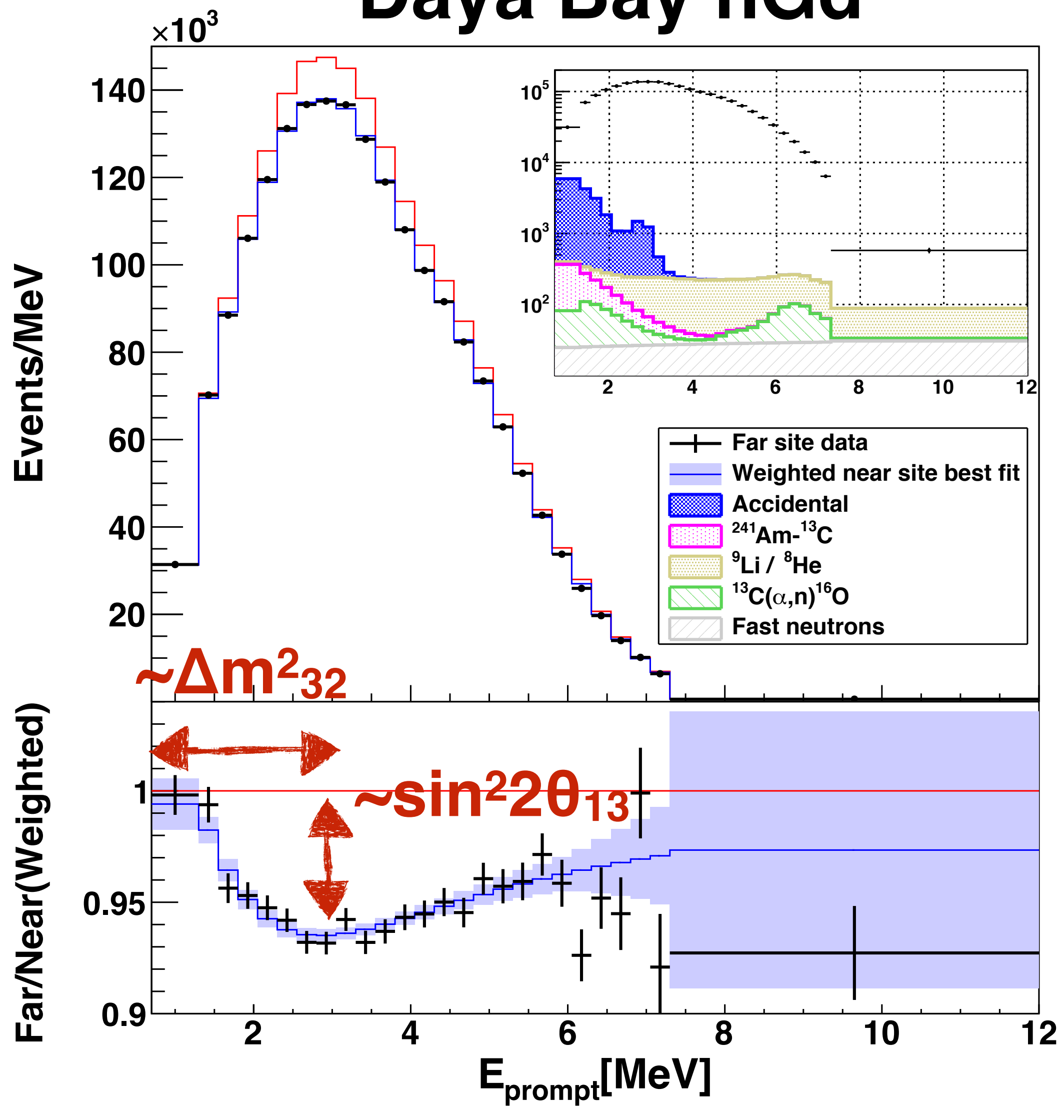
Importance of Relative Measurement

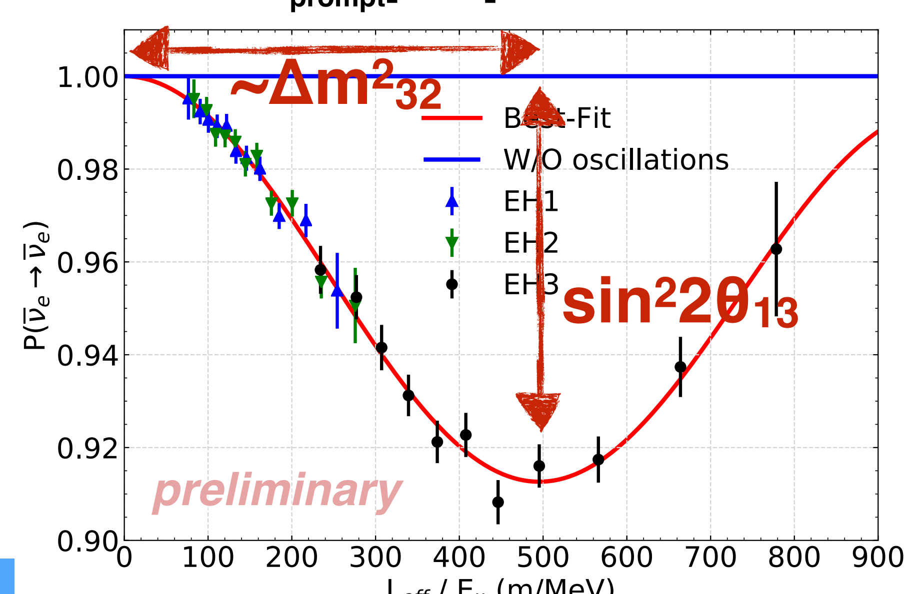
	Reactor flux		IBD detection	
	Correlated	Uncorrelated	Correlated	Uncorrelated
Daya Bay	1.5%	**0.2%**	1.2%	**0.13%**
Double Chooz	1.7%	**0.1%**	0.5%	**0.2%**
RENO	2.0%	**0.9%**	0.97%	**0.13%**

- Essentially only **uncorrelated uncertainties matter** for the relative far/near measurement
- Correlated uncertainties play role in absolute measurement of reactor neutrino flux and spectrum (see later)

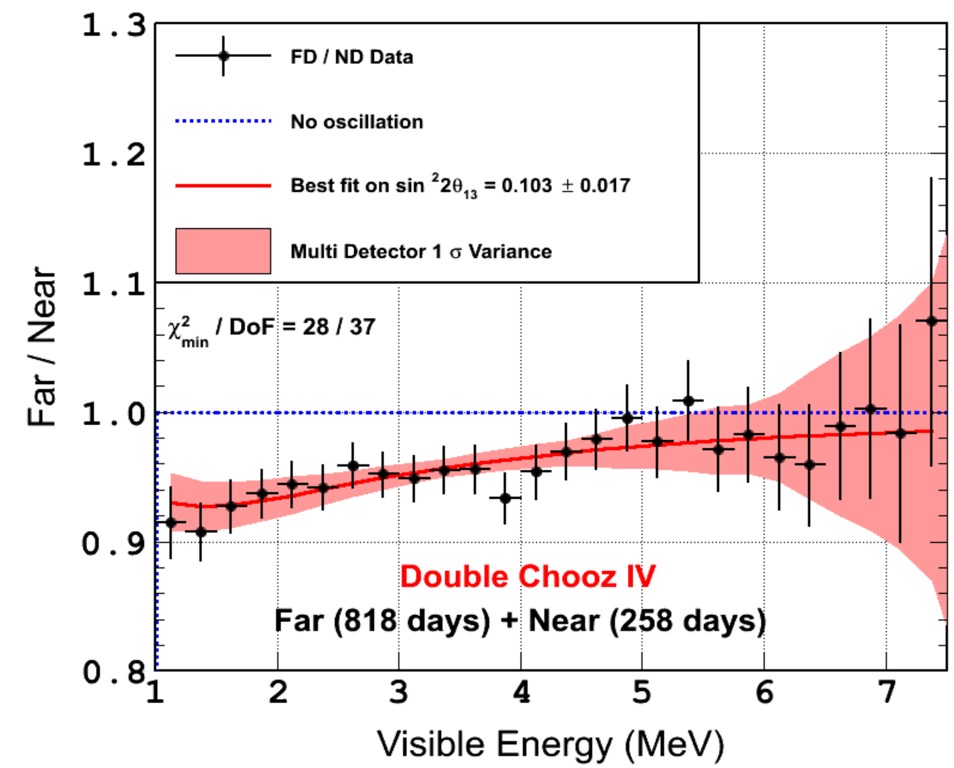
Spectrum Modulation

Daya Bay nGd

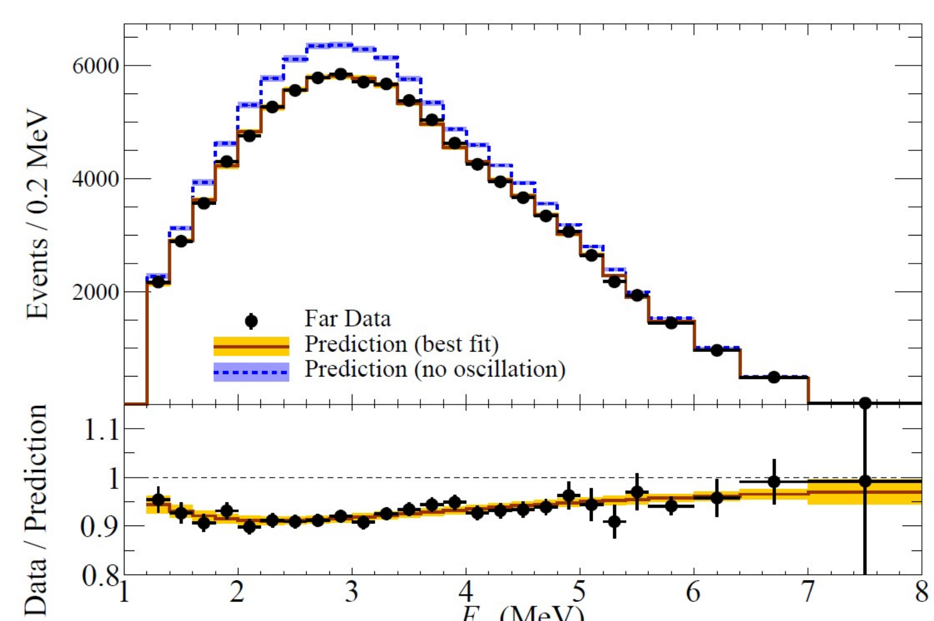




Double Chooz nH+nC+nGd



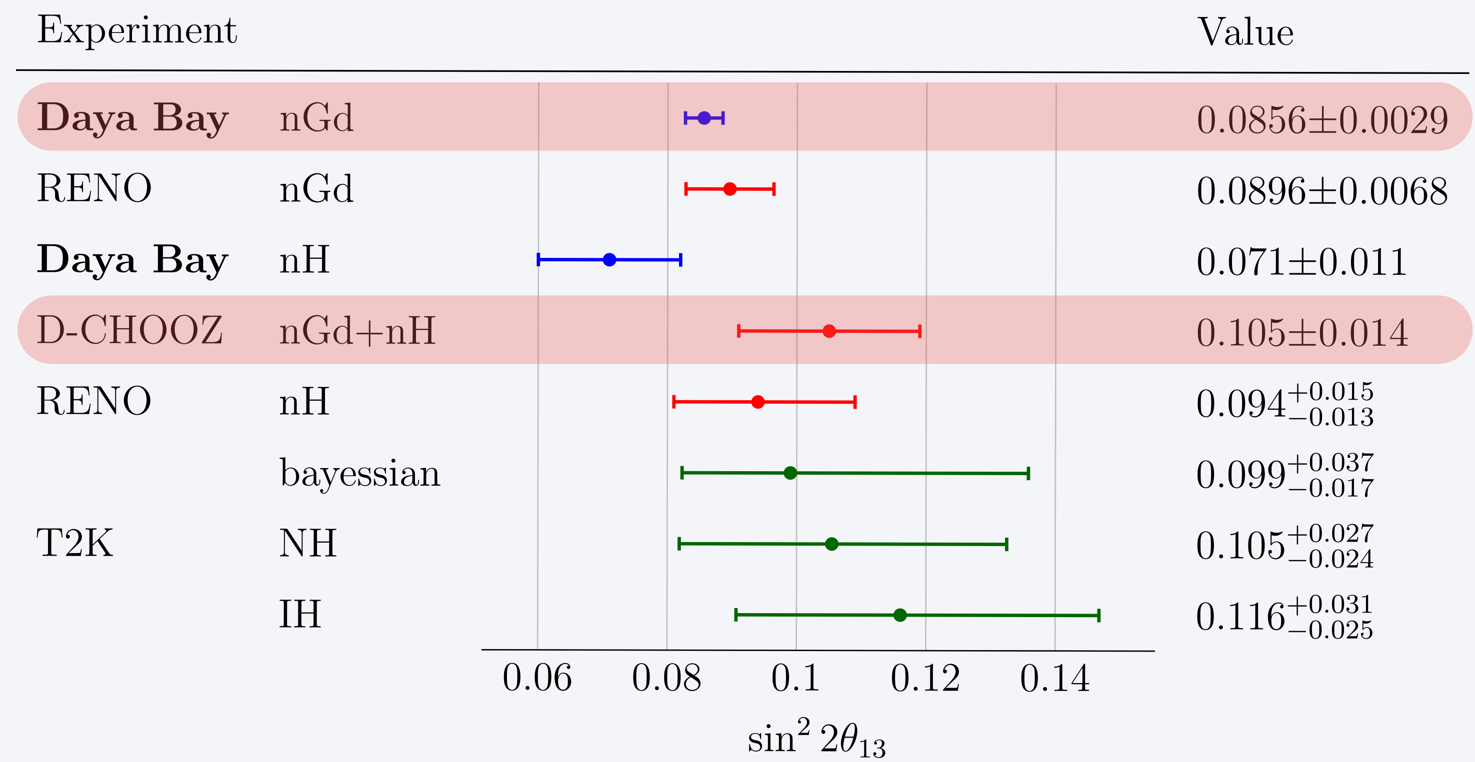
RENO nGd



Oscillation Results

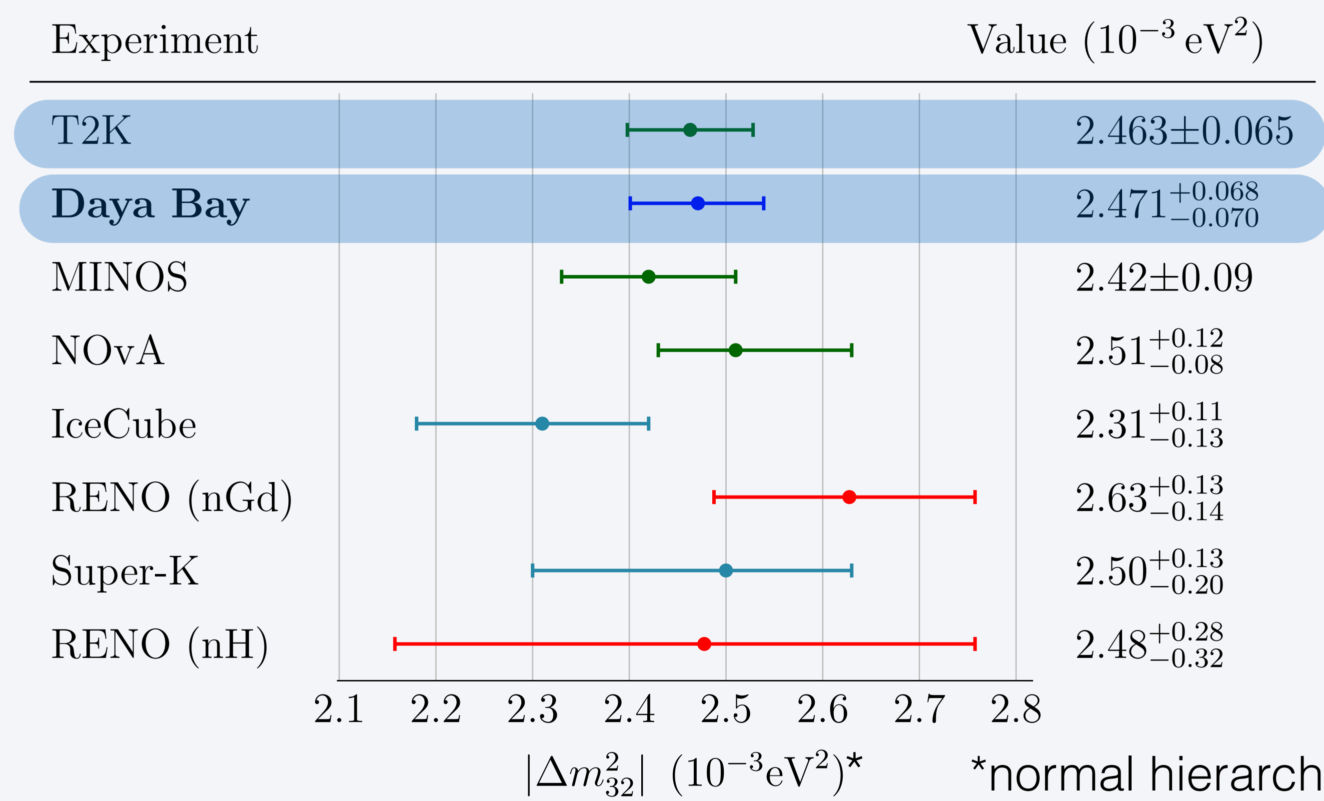
$\sin^2 2\theta_{13}$

- Daya Bay precision 3.4% - best known mixing angle
- 1σ tension between Daya Bay and Double Chooz



Δm^2_{32}

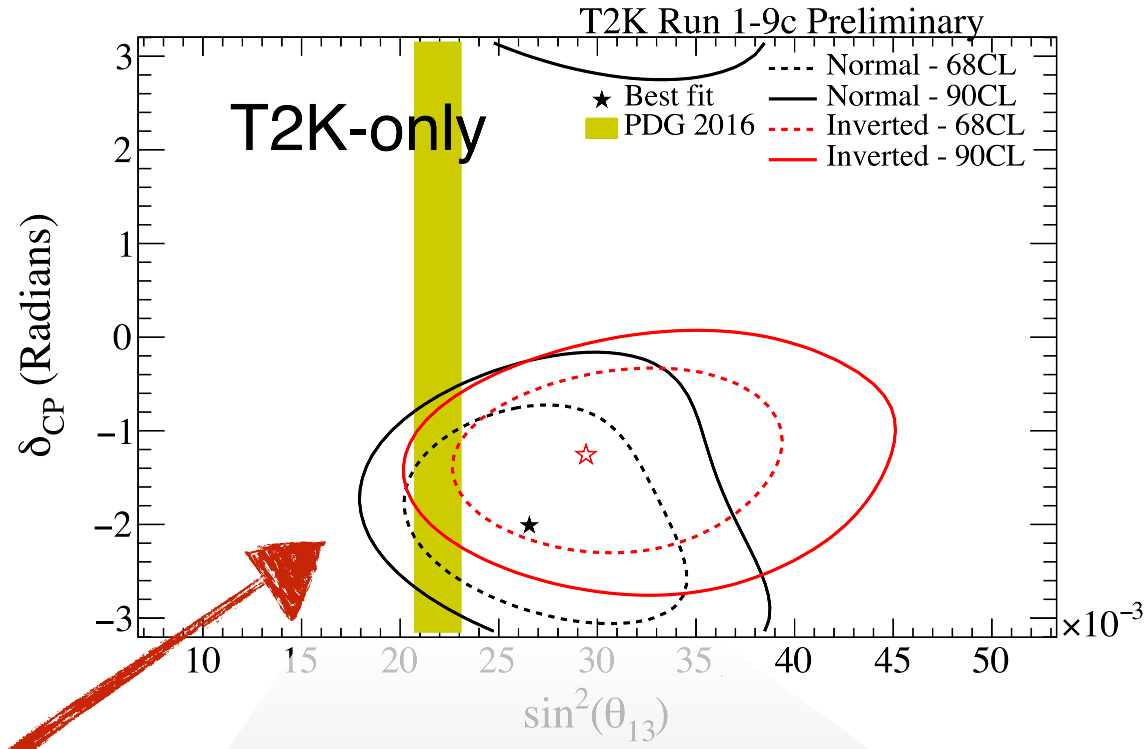
- Daya Bay's result is consistent and of comparable precision to that of accelerator experiments
- Further improvement by JUNO (see later)

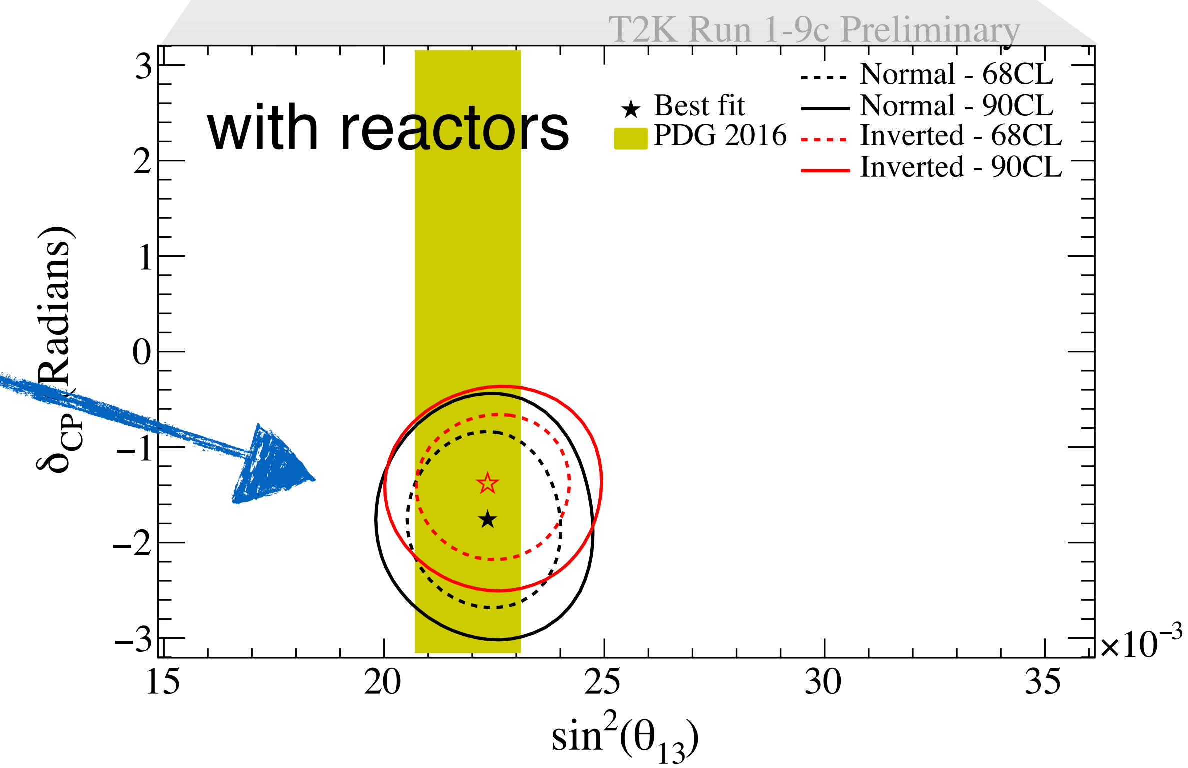


Why θ_{13} Matters?

- Non-zero θ_{13} mixing angle allows CP-violation in lepton sector
- CP-violation can be tested in appearance experiments such as **T2K** and **NOvA** which look at $\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e$ oscillations
- δ_{CP} is linked to θ_{13} - uncertainty on the angle is propagated to the uncertainty on phase
- Precise measurement done by reactor experiments very important for δ_{CP} measurement

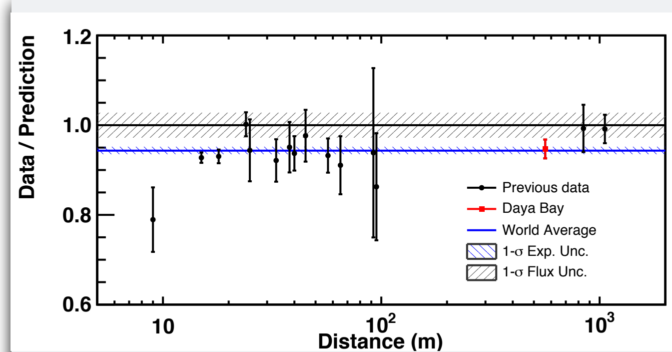
T2K result for demonstration:





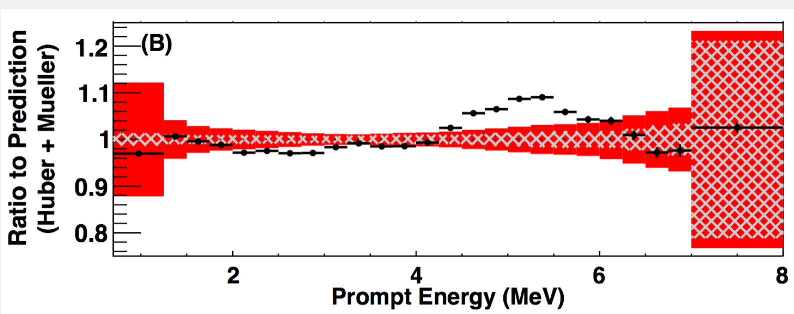
Absolute Measurements

- Reactor Neutrinos Anomalies -> discrepancy between measurement and prediction



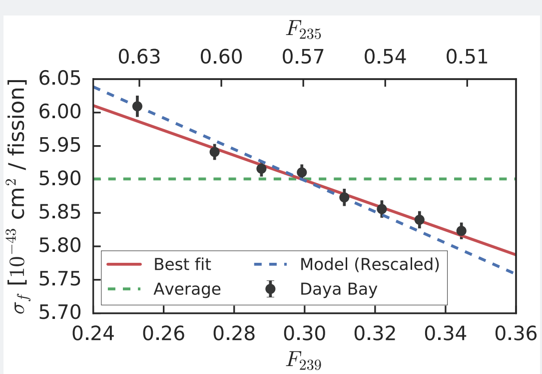
Reactor (neutrino flux) anomaly

Reanalysis of reactor flux prediction in 2011



Reactor neutrino spectrum anomaly

'Bump' in the spectrum observed by Double Chooz, Daya Bay, RENO in 2014



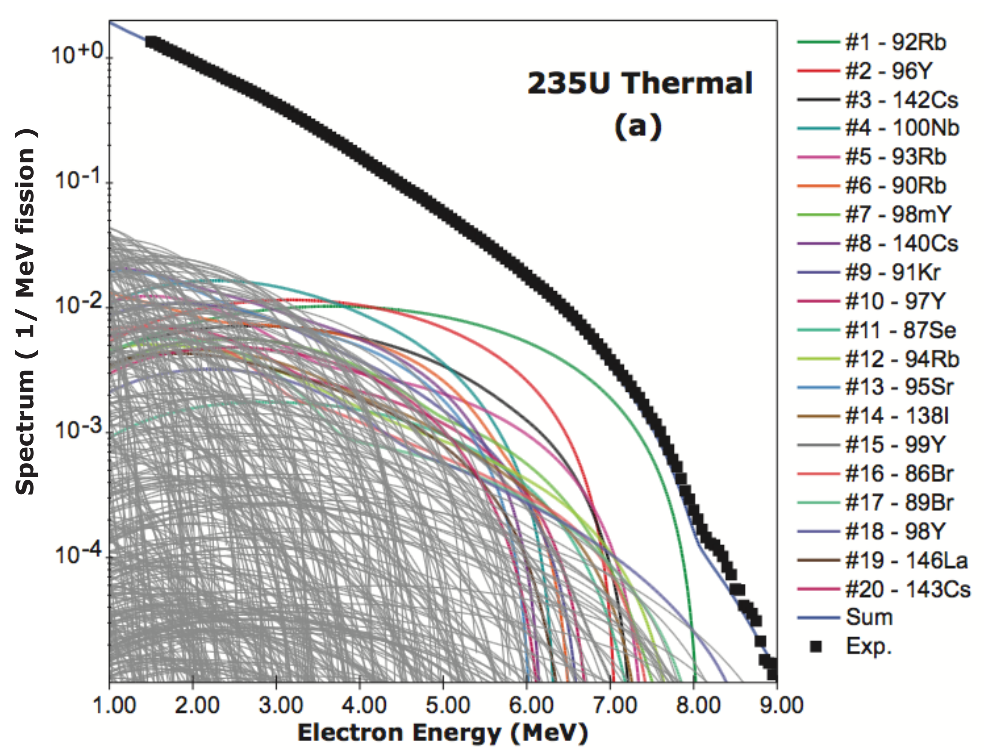
Deeper look at reactor flux anomaly with reactor fuel evolution

Reported by Daya Bay and RENO in 2017

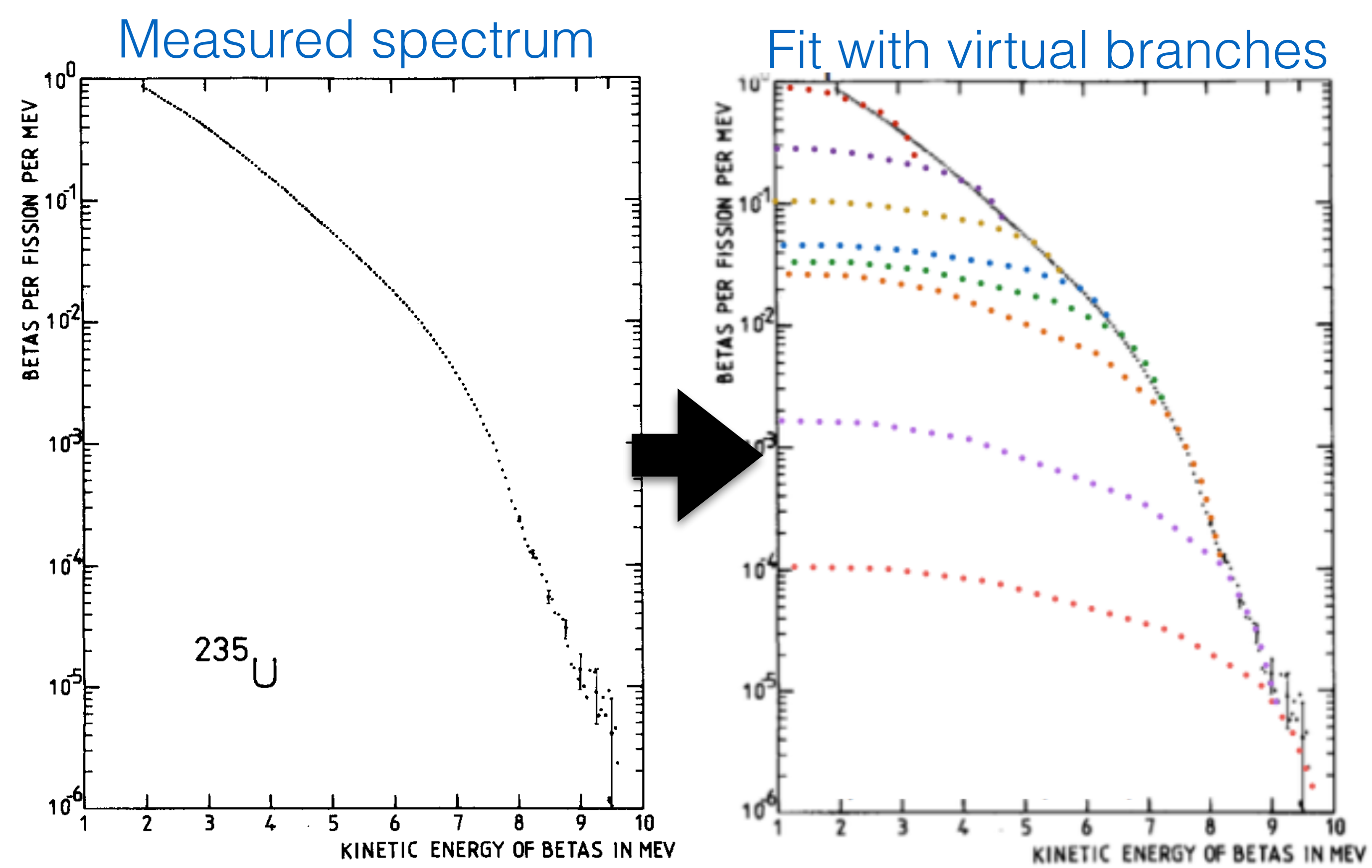
Prediction of Reactor Spectrum and Flux

- **Summation (ab initio) method**
  - Sum spectra of each decay branch of all fission fragments based on nuclear database
  - More than 6000 branches
  - Not all branches sufficiently covered in database
  - Claimed ~10% uncertainty

- **Conversion method**
  - Electron spectrum from fission fragments converted to $\overline{\nu}_e$ spectrum
  - Performed at ILL in 80s & 90s
  - Uncertainty ~2.7%
  - Leading method nowadays



Sonzogni et al PRC 91,011301



Schreckenbach et al. PLB 160 (1985)

Huber+Mueller Model

Huber's ILL spectrum conversion for ^{235}U, ^{239}Pu, ^{241}Pu

Huber P. Phys. Rev. C 84:024617 (2011); erratum ibid. 85:029901 (2012)

+

Mueller's ab-inicio calculation for ^{238}U

Mueller T. A. et al. Phys. Rev. C 83:054615 (2011)

Spectrum for individual branch

Shape correction $C\neq1$ for forbidden decays

$$S(E_{\bar{\nu}}, E_0^i, Z) = K p_e E_e (E_0 - E_e)^2 F(Z, E_e) C(Z, E_e)(1 + \delta(Z, A, E_e))$$

Fermi function

Correction $\delta=\delta_{WM}+\delta_{FS}+\delta_{RC}$

δ_{WM} - Weak magnetism corr.

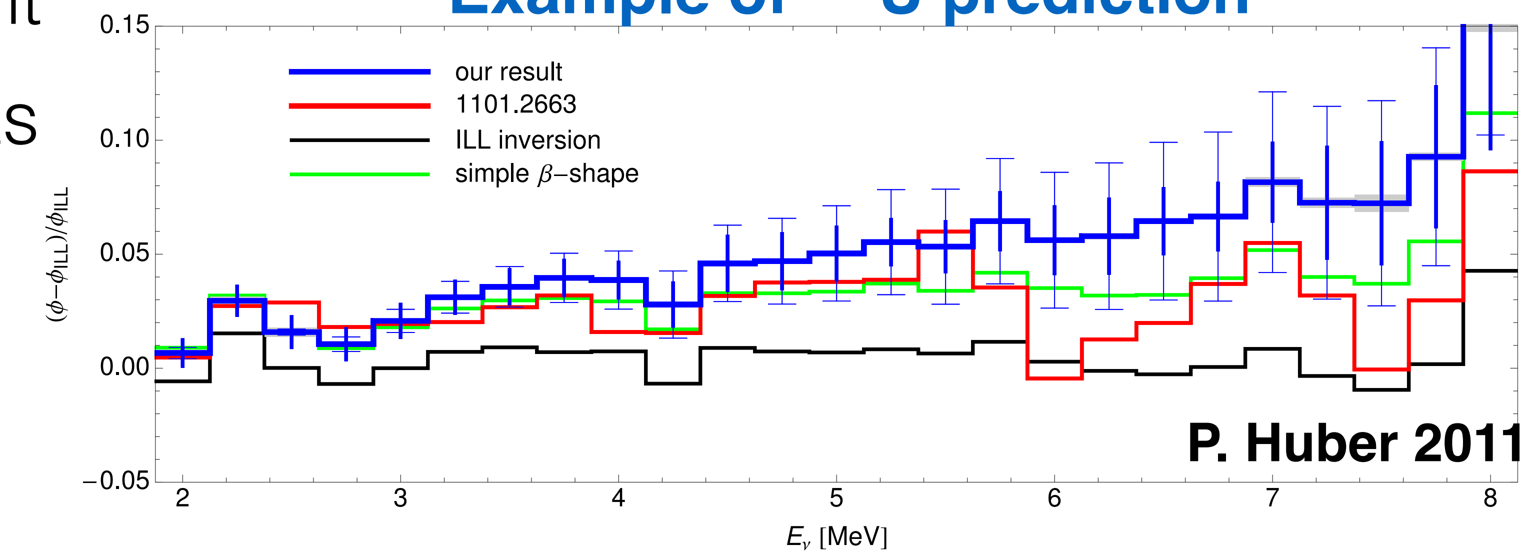
δ_{FS} - Finite structure corr.

δ_{R} - Radiative corr.

Main reasons for higher prediction in H+M:

- Finite structure and Weak Magnetism correction more careful treatment
- Newer ⟨Z⟩(E) of fission fragments
- Updated neutron lifetime

Example of ^{235}U prediction



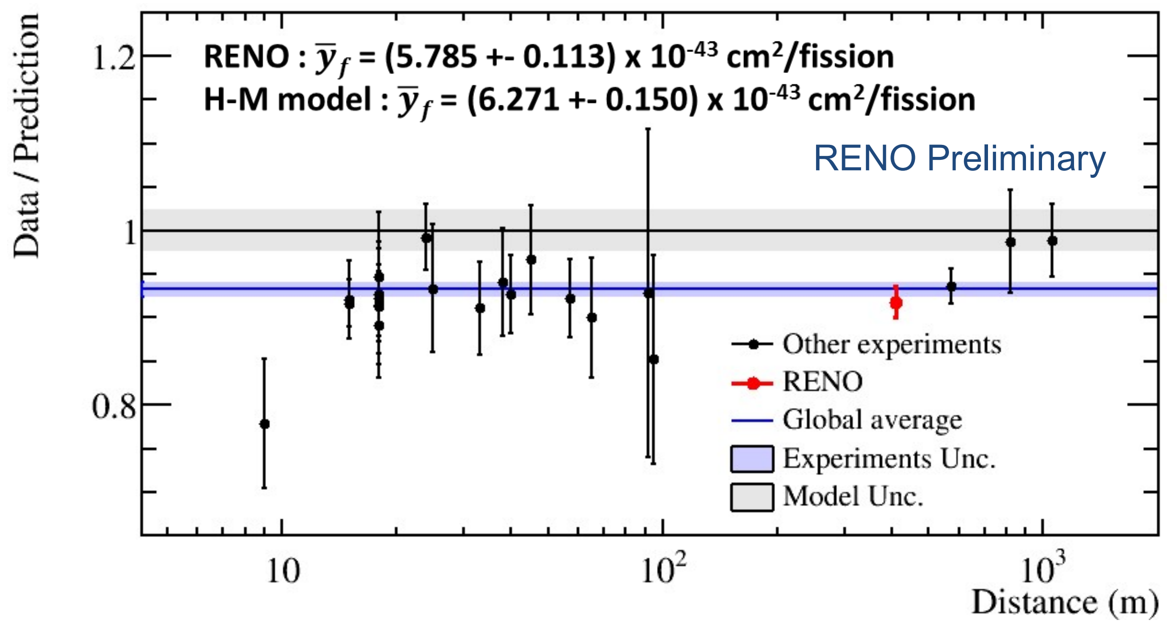
Reactor (Neutrino Flux) Anomaly

- **Flux deficit observed w.r.t. Huber+Muller model**
  - **Daya Bay** R=0.952±0.014
  - **Double Chooz** R=0.945±0.008
  - **RENO** R=0.918±0.018

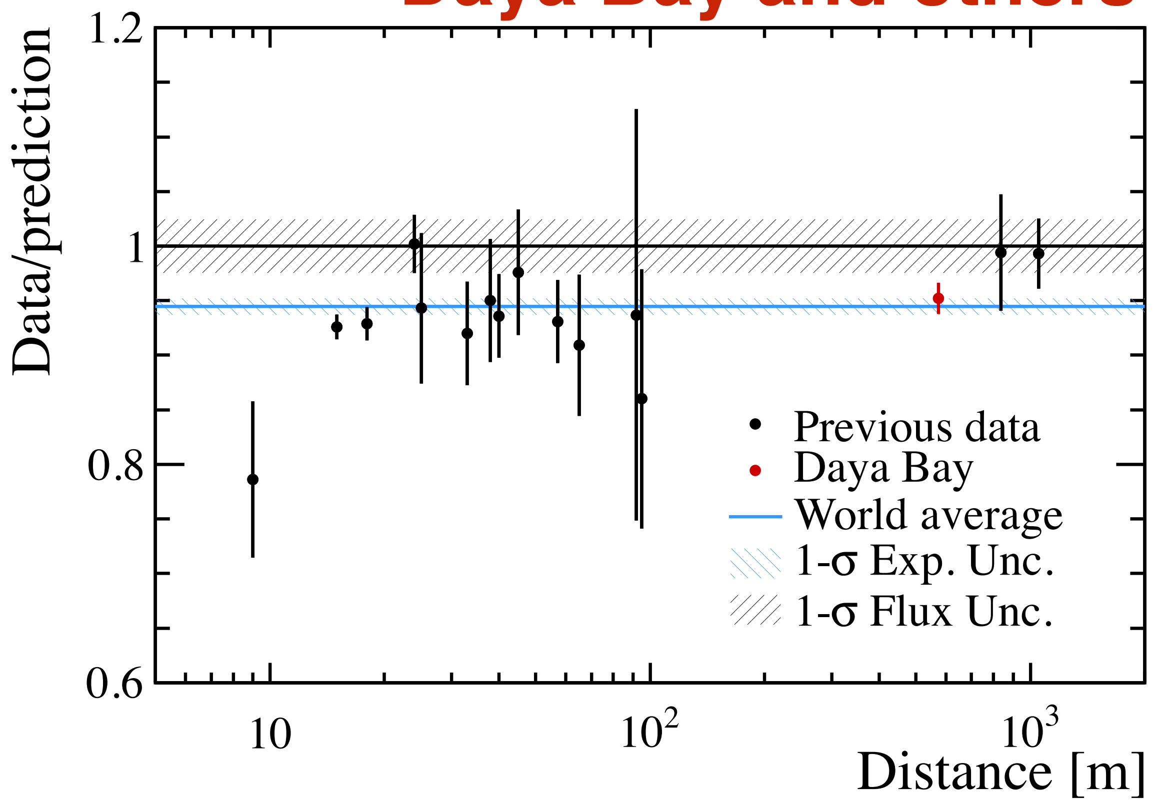
$$R = \frac{\text{Measured}}{\text{Model (Huber+Muller)}}$$

- **Similar effect observed**
  - by several experiments
  - at different reactors
  - at different baselines
- **Possible explanations**
  - Not a detector/reactor effect
  - Prediction issues - particular isotope responsible? (see later)
  - New phenomena - Sterile ν's

RENO and others



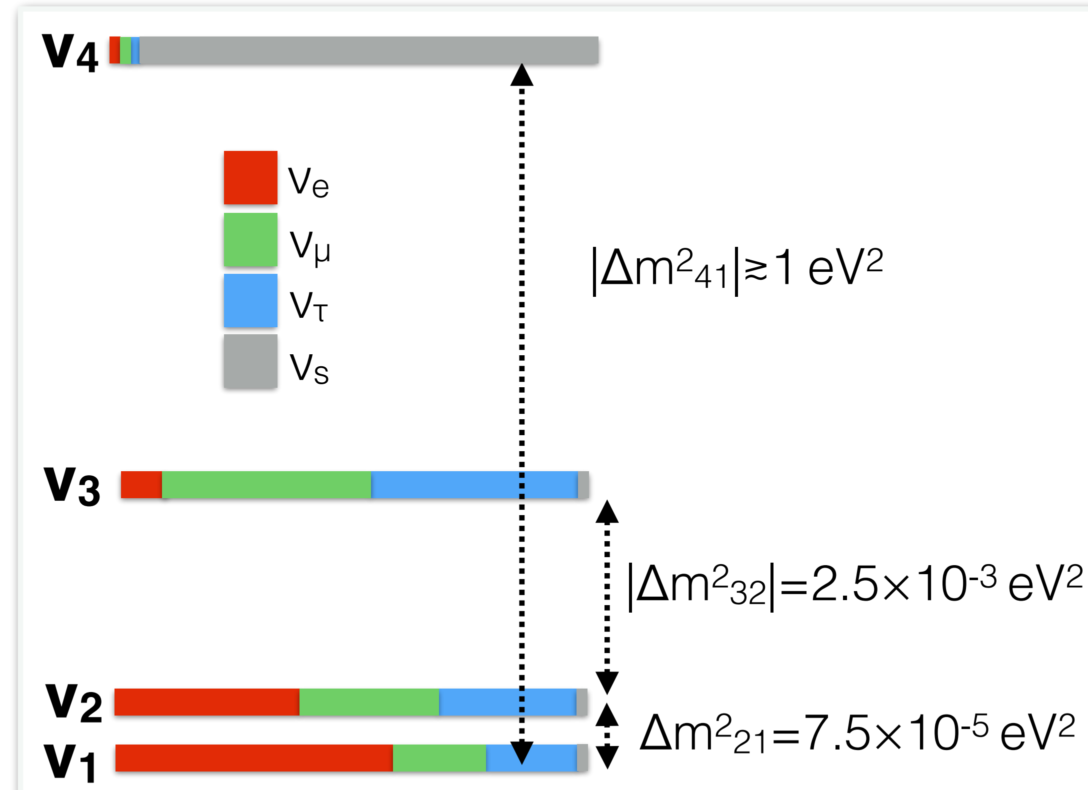
Daya Bay and others

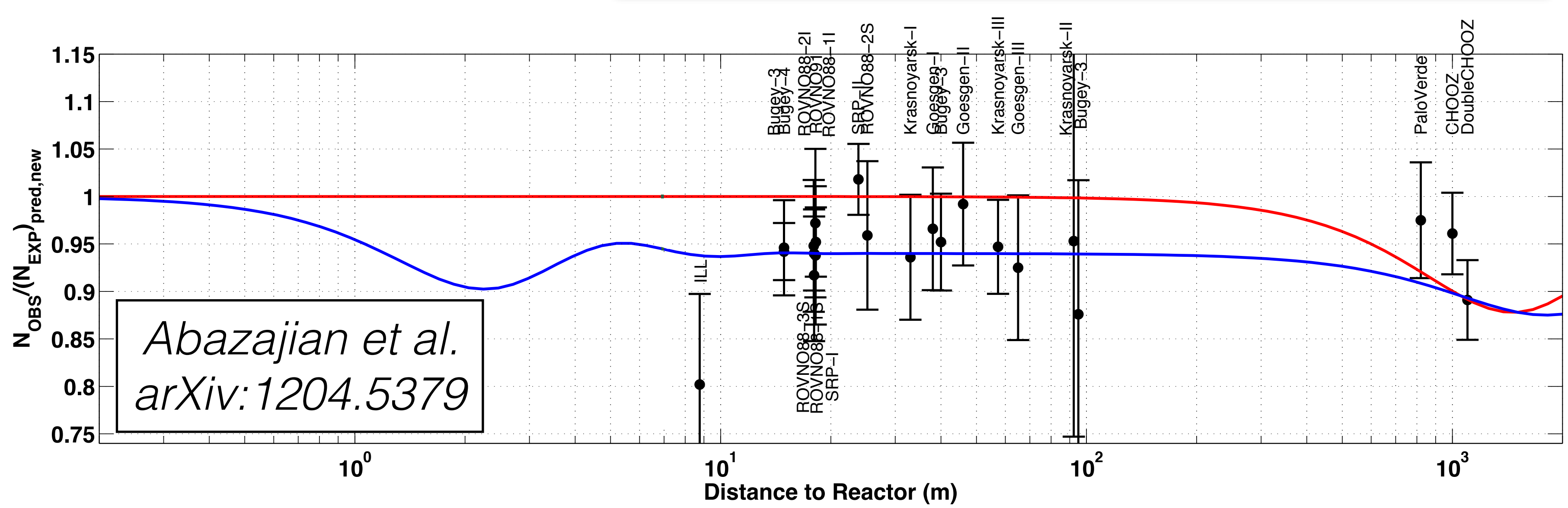


Sterile Neutrinos

Covered in talk by Jaison Lee

- **Existence of sterile neutrinos can explain the anomaly**
  - $\Delta m^2_{new} \gtrsim 1\ \mathrm{eV}^2 \Leftrightarrow L_{osc} <$ few m
  - Fast oscillations averaged
- **Hints of steriles elsewhere**
  - Radioactive calibration sources at GALLEX, SAGE
  - Accelerator experiments LSND and MiniBooNE

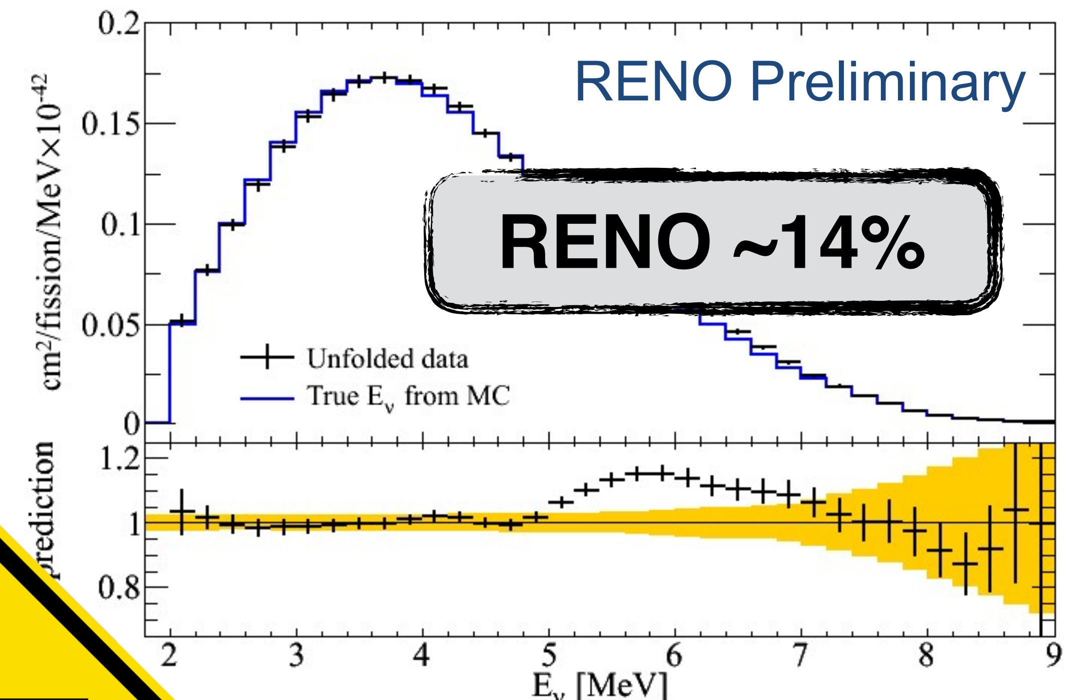


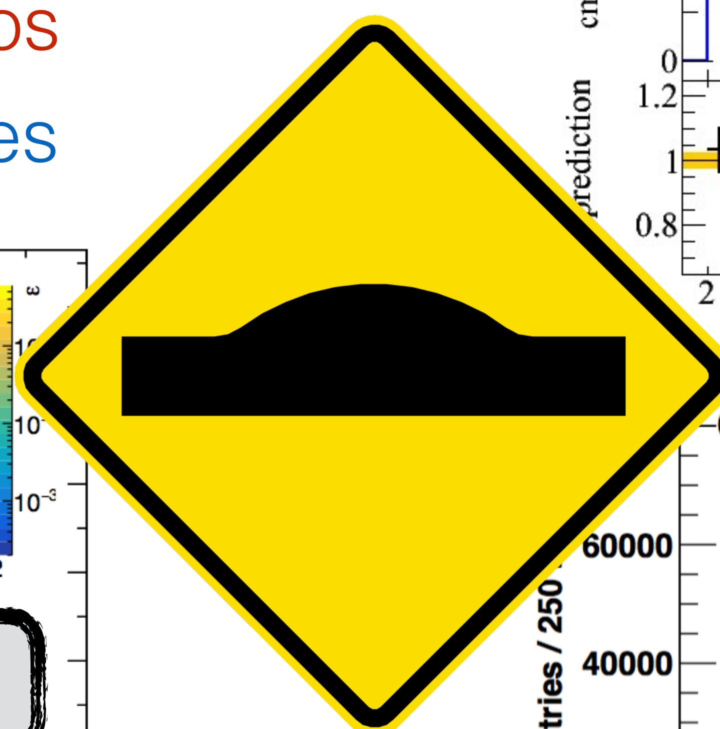


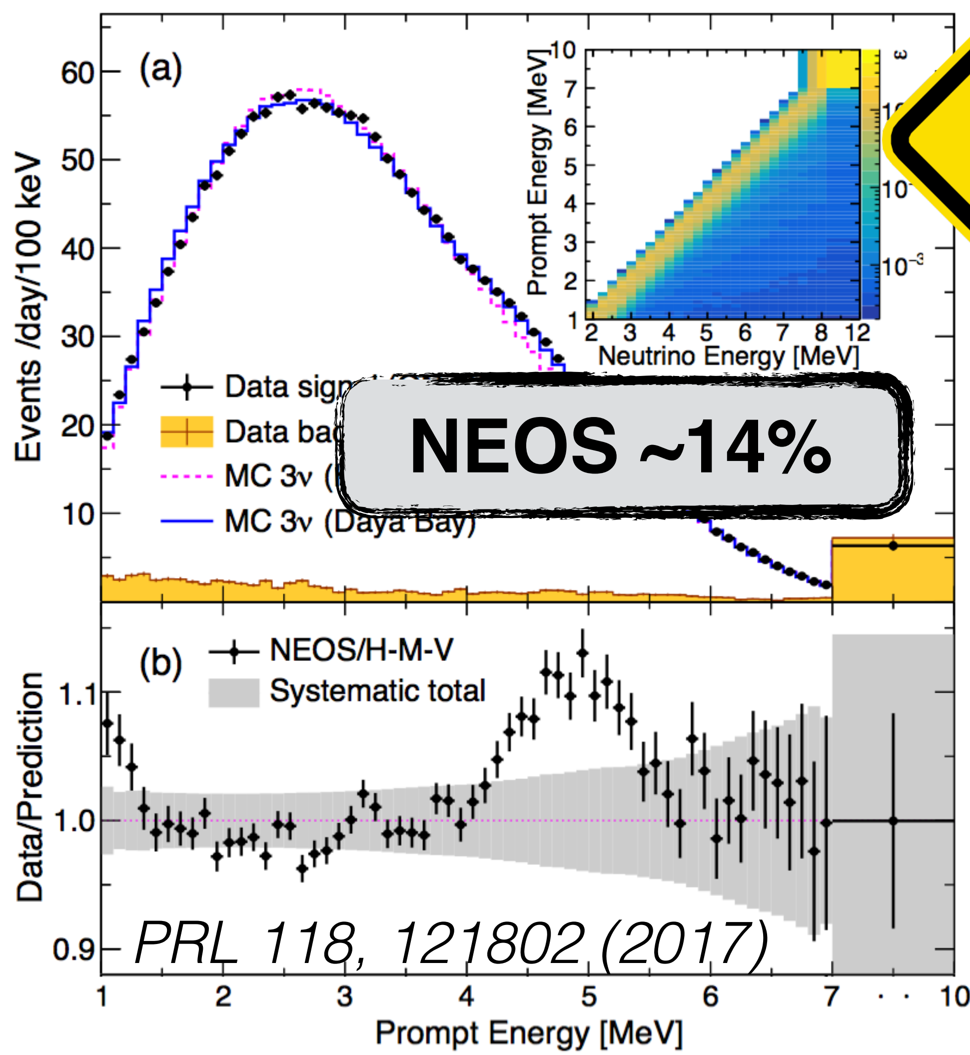
Abazajian et al. arXiv:1204.5379

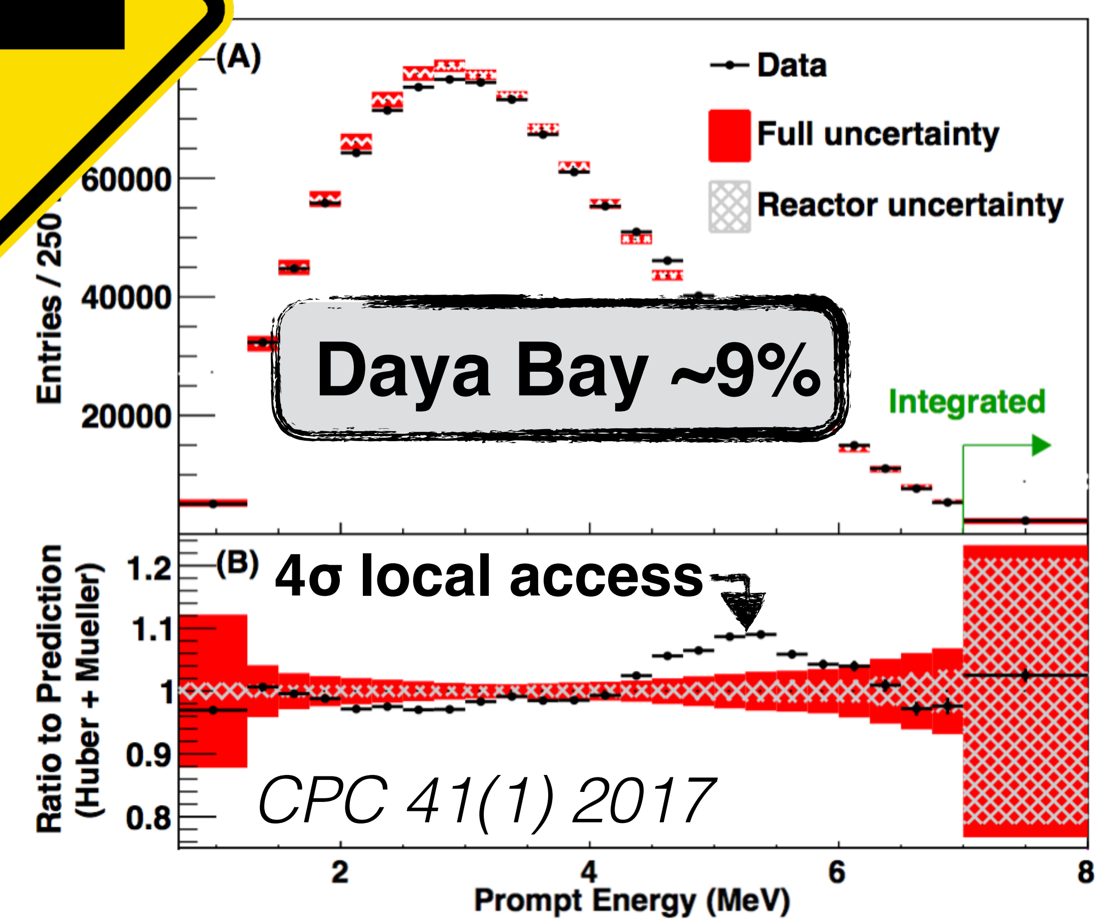
Reactor Neutrino Spectrum Shape Anomaly

- **Obvious ‘Bump’ (excess over prediction) at 4-6 MeV in prompt spectrum**
  - Not a detector effect
  - Not due to sterile neutrinos
  - Could be prediction issues







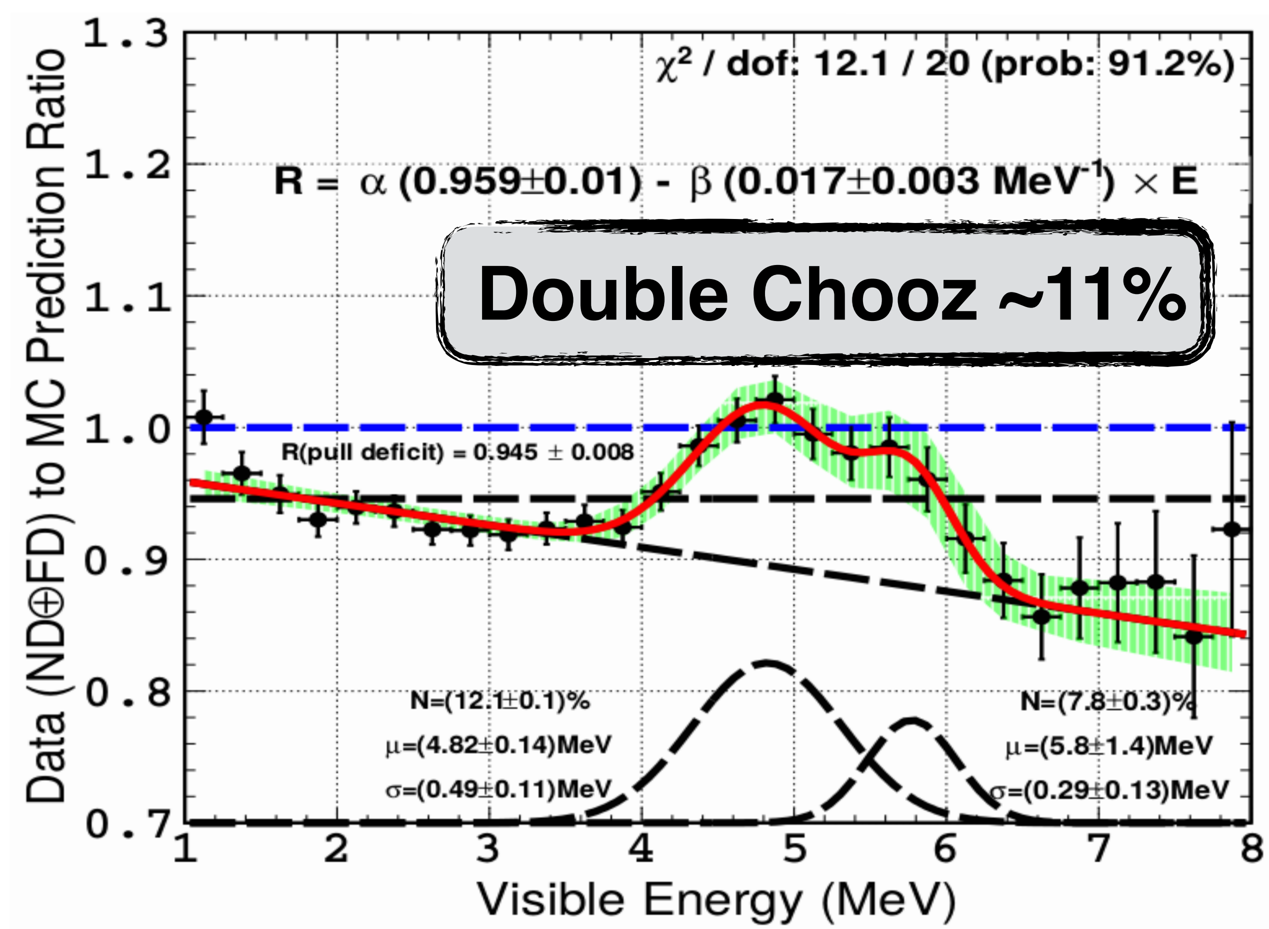


Origin of the Bump

- Origin of the 'bump' is unknown - several hypotheses:
  - Forbidden decay corrections - not as assumed
  - Harder n spectrum in the reactor than in ILL measurement
  - **Eventual problem in ILL measurement**
  - **^{238}U spectrum loosely constrained - different ^{238}U contribution among experiments ⇔ different size of the bump**

Can be tested by ^{235}U reactors

- Further (empirical) structure of the bump suggested by Double Chooz

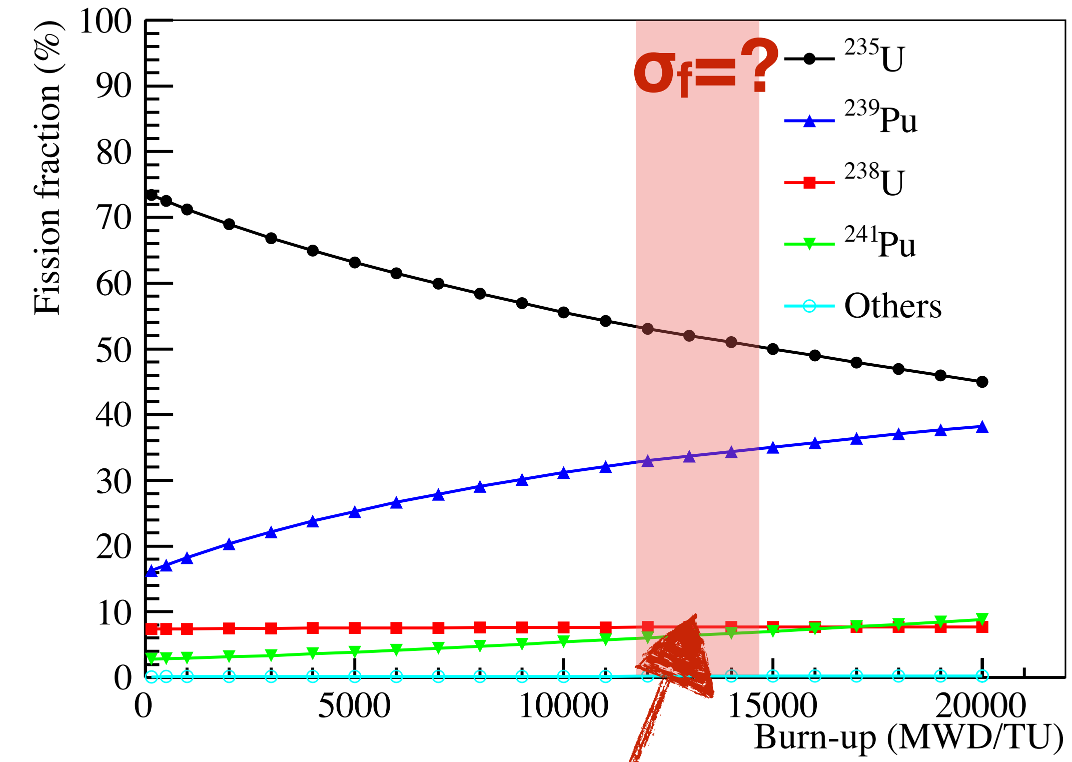


Reactor Fuel Evolution (at Daya Bay)

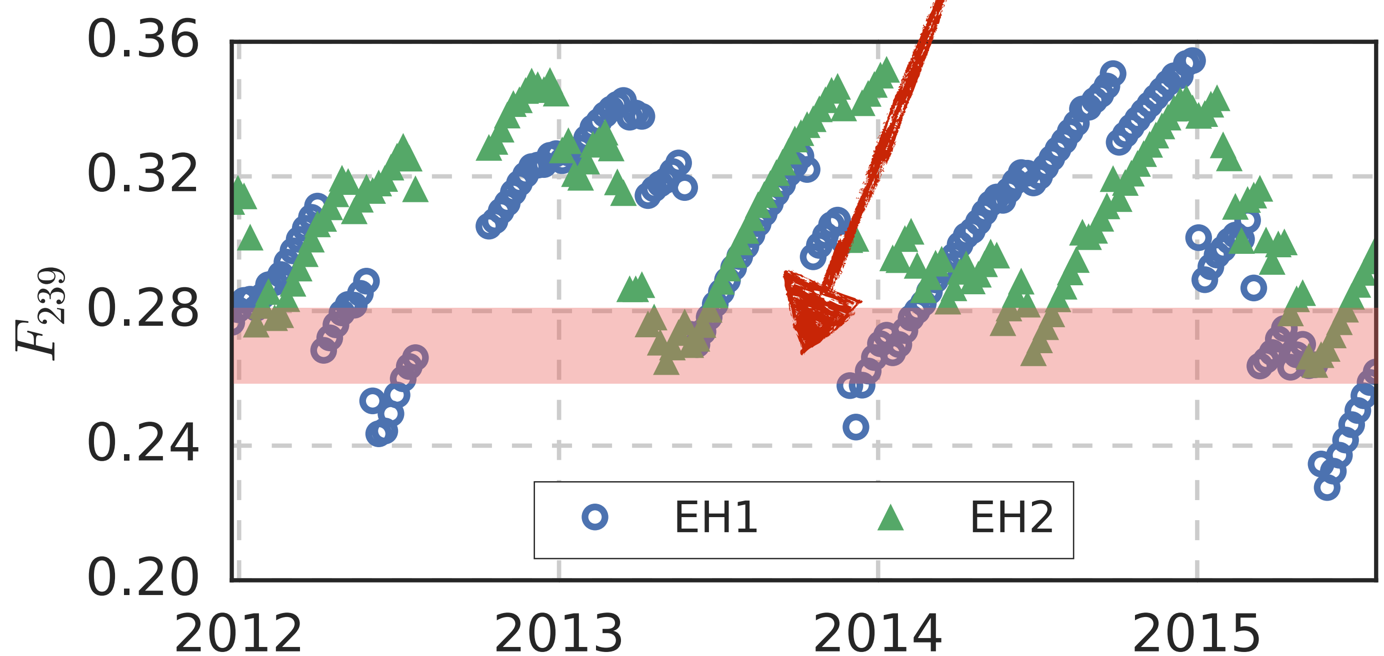
- **Fuel evolution expected - measured by Rovno (90s), SONGS (00's)**

$$\sigma_f = \sum_i f_i \times \sigma_f^i$$

Total IBD yield — Isotope fission fraction — Isotope IBD yield



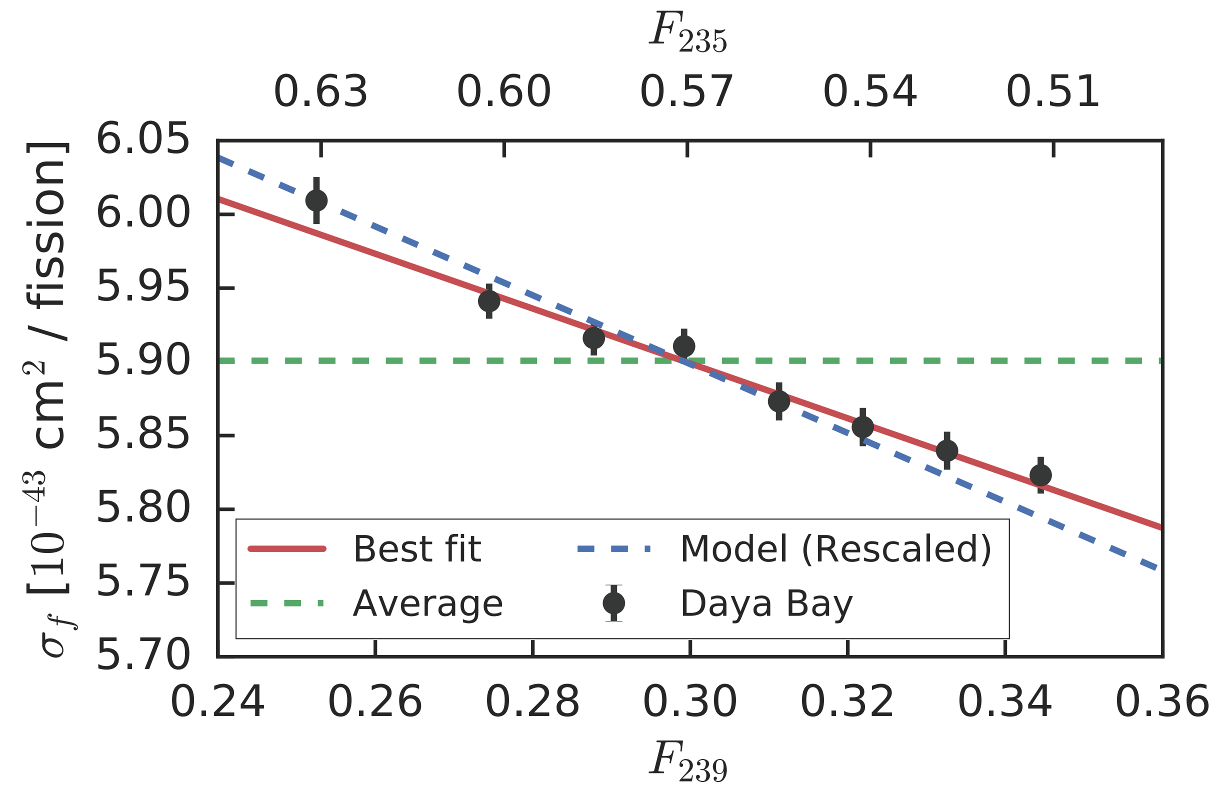
- Since $\sigma_f^{235U} \neq \sigma_f^{238U} \neq \sigma_f^{239Pu} \neq \sigma_f^{241Pu}$ we expect change in total IBD yield
- Change in total IBD yield + Fission fraction evolution ➔ Disentangle isotopic contribution
- Daya Bay data binned by effective fission fraction of ^{239}Pu
- Allowed by spectacular statistics of 2.2 millions events in near halls

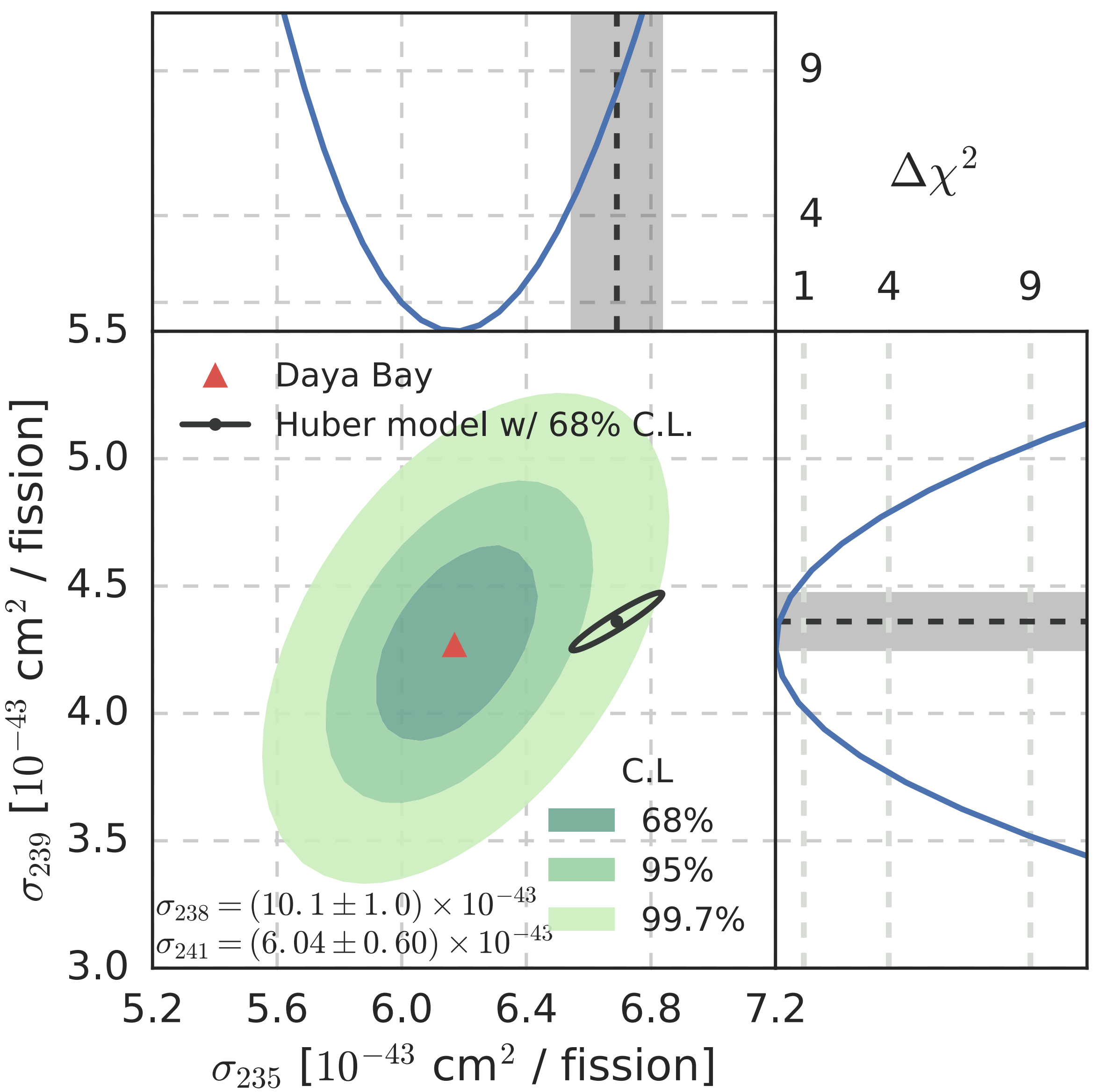


PRL 118, 251801 (2017)

Reactor Anomaly and Fuel Evolution

- **Fuel evolution measured by Daya Bay with unprecedented precision in 2017**
  - Obvious linear change of $\sigma_f(F_{239})$
  - **Does not agree with prediction**





- Allowed to disentangle ^{235}U and ^{239}Pu yields (with conservative constraints on ^{238}U and ^{241}Pu)
- ^{235}U lower than H-M model by 7.8% while ^{239}Pu consistent
- **Suggests prediction issues**

PRL 118, 251801 (2017)

Conclusions from Fuel Evolution

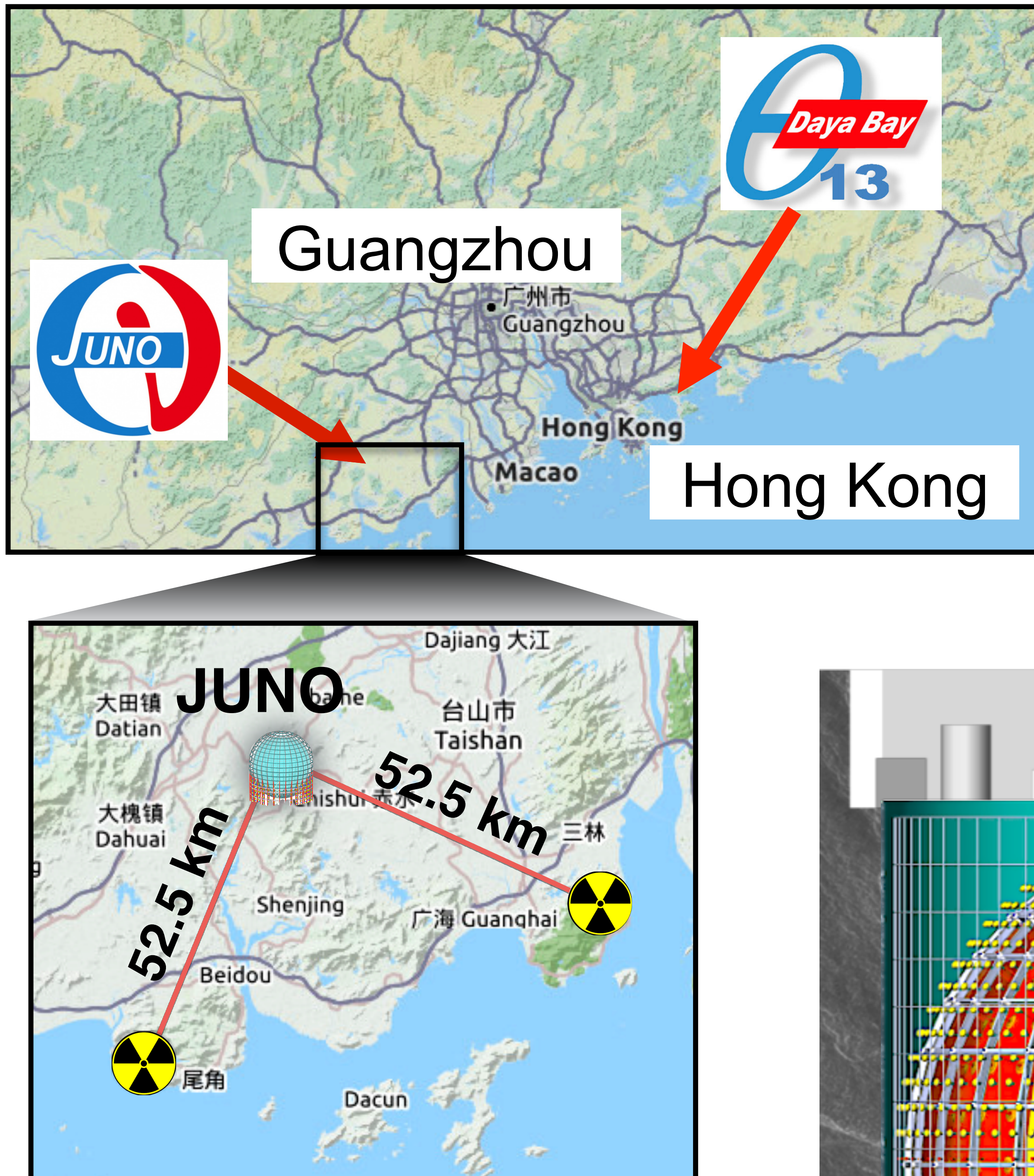
- **Fuel evolution discrepancy closely linked to flux anomaly**
  - Daya Bay measurement suggest that ^{235}U incorrect prediction is behind most of the reactor flux anomaly
  - Explanation of flux anomaly purely by **sterile neutrinos** $\Leftrightarrow$ **equal deficit** disfavoured at **2.8σ**

Reactor Flux Anomaly Cause	Suggests	$\Delta\chi^2/NDF$	Confidence level
^{235}U only	Prediction issues	0.17/1	Very probable
^{239}Pu only	Prediction issues	10.0/1	Disfavored at 3.2σ
All isotopes w/ equal deficit	Sterile neutrinos	7.9/1	Disfavored at 2.8σ

Nevertheless, Daya Bay did not rule out sterile neutrinos completely!

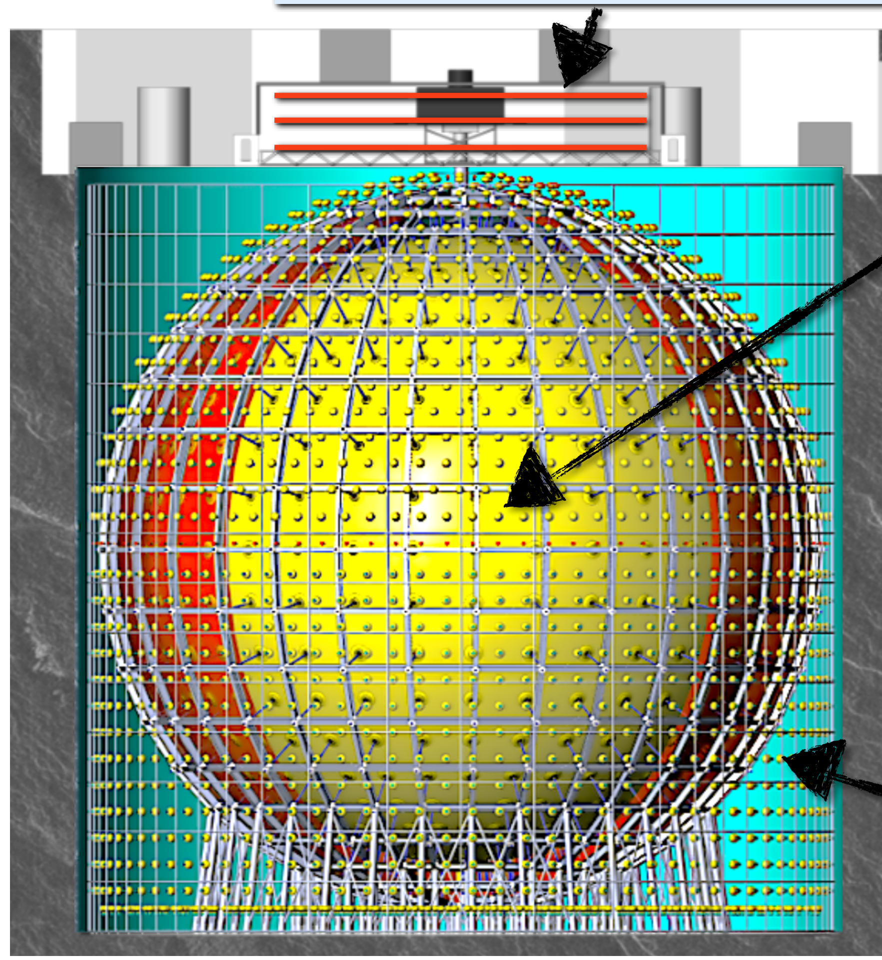
Composite model still possible

JUNO Overview



- **Powerful source:** 10 nuclear reactors (26.6 TW$_{th}$ in 2021, later 35.8 GW$_{th}$)
- **Ideal baseline:** 52.5 km
- **Shielding:** 700 m underground

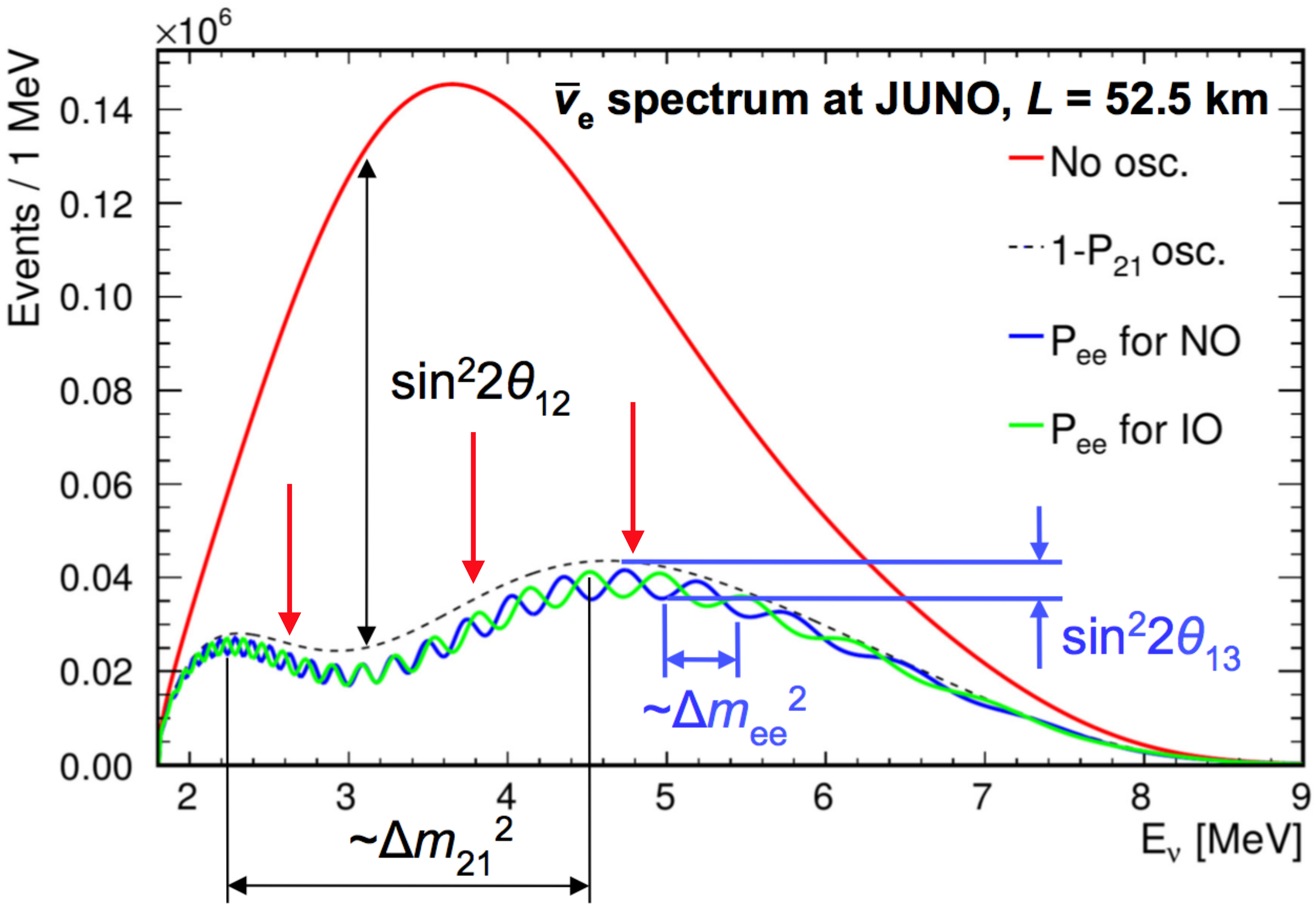
Top tracker
3 layers of plastic scintillator

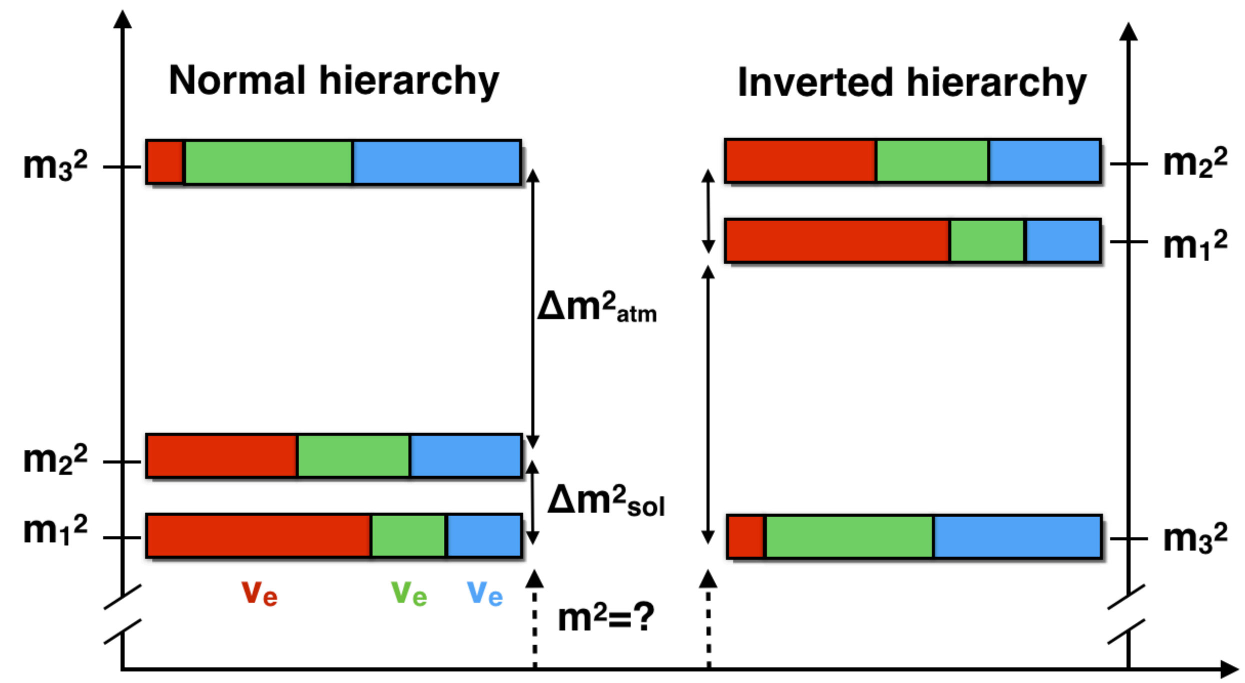


Central detector
- **20 kt liquid scintillator** (largest LS in the world)
- **18k 20-inch PMTs** resolution 3%@1 MeV 75% photo coverage
- **25k 3-inch PMTs** for systematics control

Water pool
Ultra-pure water Cherenkov detector with 2k 20-inch PMTs

Neutrino Mass Hierarchy @ JUNO





Normal $m_3>m_2\ (m_1)$ → **Inverted** $m_3<m_1\ (m_2)$

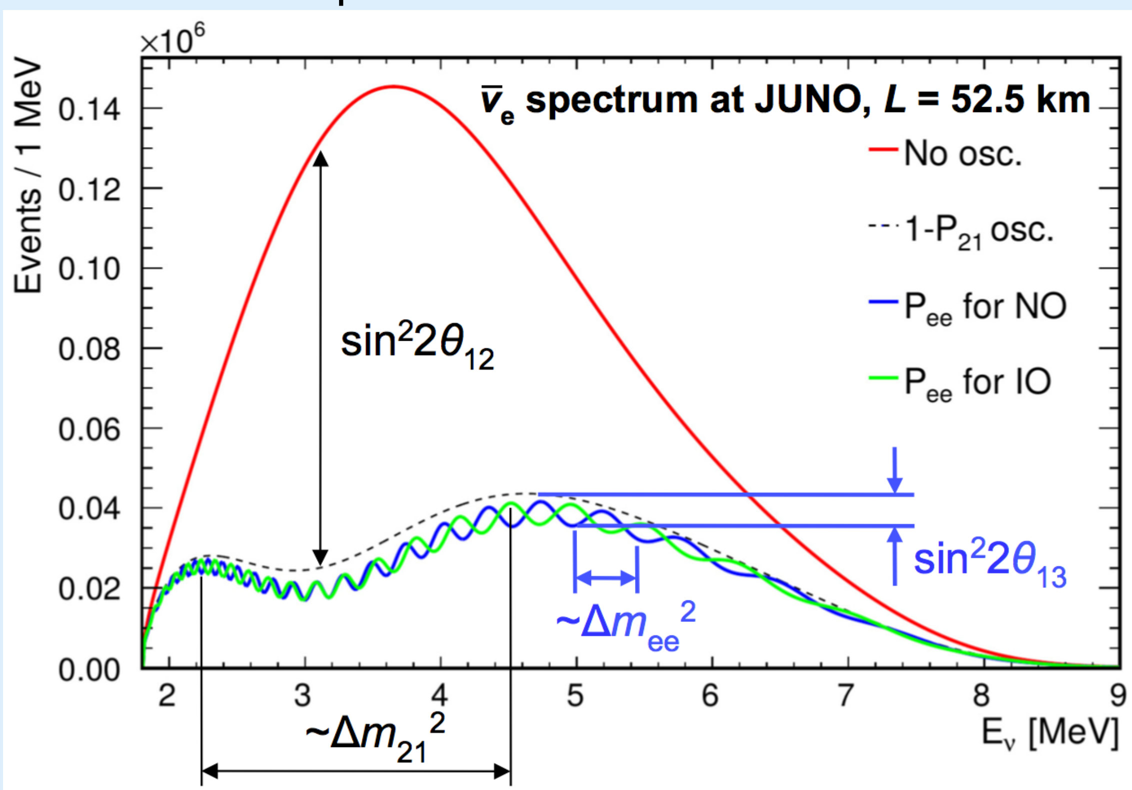
$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{12}\cos^4\theta_{13}\sin^2\left(\frac{\Delta m^2_{21}L}{4E}\right) - \cos^2\theta_{12}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right) - \sin^2\theta_{12}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{32}L}{4E}\right)$$

- JUNO first experiment to observe **solar and atmospheric neutrino oscillation modes simultaneously**
- Neutrino mass hierarchy (ordering) identified based on different phase throughout the whole spectrum

JUNO Physics Program

Reactor neutrino oscillations:

- Mass hierarchy determination
- Precise measurement of particular oscillation parameters

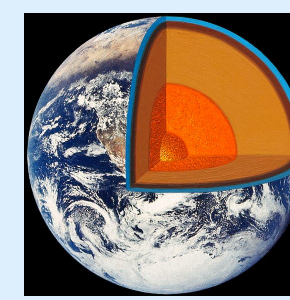


Parameter	Current precision (1σ)	Improvement by JUNO
$\sin^2 2\theta_{12}$	5%	<0.7%
Δm_{21}^2	2.3%	<0.6%
Δm_{31}^2	2.5% sign unknown	<0.5% sign determination

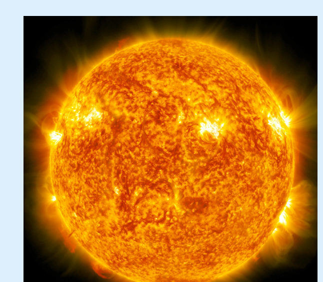
Other physics:

- **Supernova (SN) neutrinos**
  - 10^4 events from SN @ 10 kpc
  - Testing SN models
  - Possibility of independent determination of MH

- **Diffused SN neutrinos**
  - 1-4 events per year
  - Discovery if measured



- **Geoneutrinos**
  - From U/Th decays
- **Solar neutrinos**
  - ^{7}Be neutrinos detected via elastic scattering



- **Proton decay**
  - $p \to K^+ + \nu$
- **…and more**

Very Short Baseline Experiments

More detail in talk by Jaison Lee

Not extensive list of VSBL experiments

Experiment	Reactor power [MW_{th}]	Distance [m]	Target Mass [t]	Target type
NEOS	2700	25	1	GdLS
DANSS	3000	10-12	0.9	GdPS
STEREO	58	9-11	1.8	GdLS
PROSPECT	85	7-12	1	^{6}LiLS
SOLID	100	6-9	1.6	^{6}LiPS

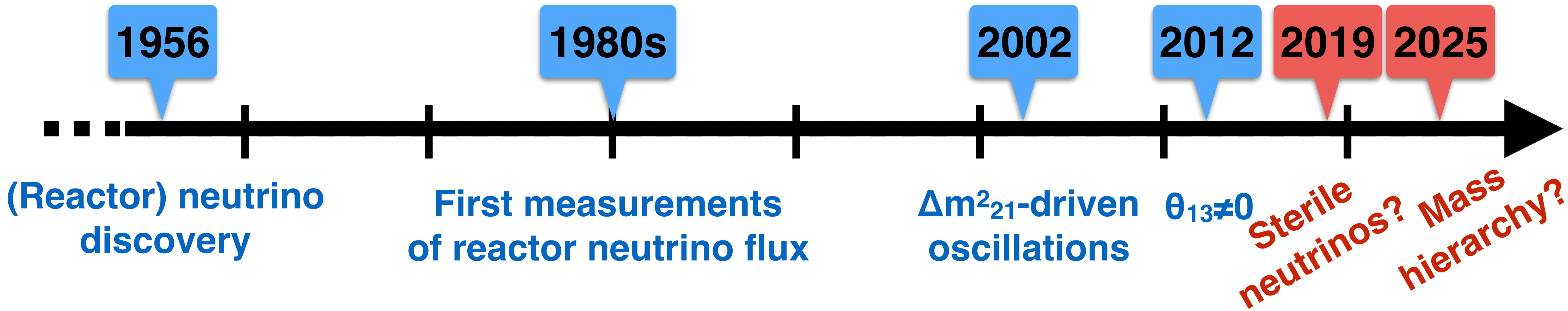
LS=Liquid Scintillator PS=Plastic Scintillator

- **Hunt for sterile neutrinos** at ~1 eV scale ⇔ explanation of flux anomaly
- Precise **measurement of reactor neutrino flux and energy spectrum** for different fuel composition
  - Commercial reactors with mixture of ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu
  - Research reactors with mainly ^{235}U
- Challenge prediction models - measurement of ^{235}U yield&spectrum

Conclusions

- Non-zero θ_{13} paved the way for CP-violation search in lepton sector and measurement of mass hierarchy with oscillations
- Precise measurement of the θ_{12}, Δm^2_{21}, Δm^2_{32} and neutrino mass hierarchy ahead with JUNO reactor neutrino experiment
- Recently, anomalies in reactor neutrinos observed:
    - Reactor Flux Anomaly
    - 'Bump' in the spectrum
- Dedicated very short-baseline measurements needed to resolve those
- **Nuclear reactors continue to provide us with one of the most fruitful environments for studying the elusive neutrino**

Outlook



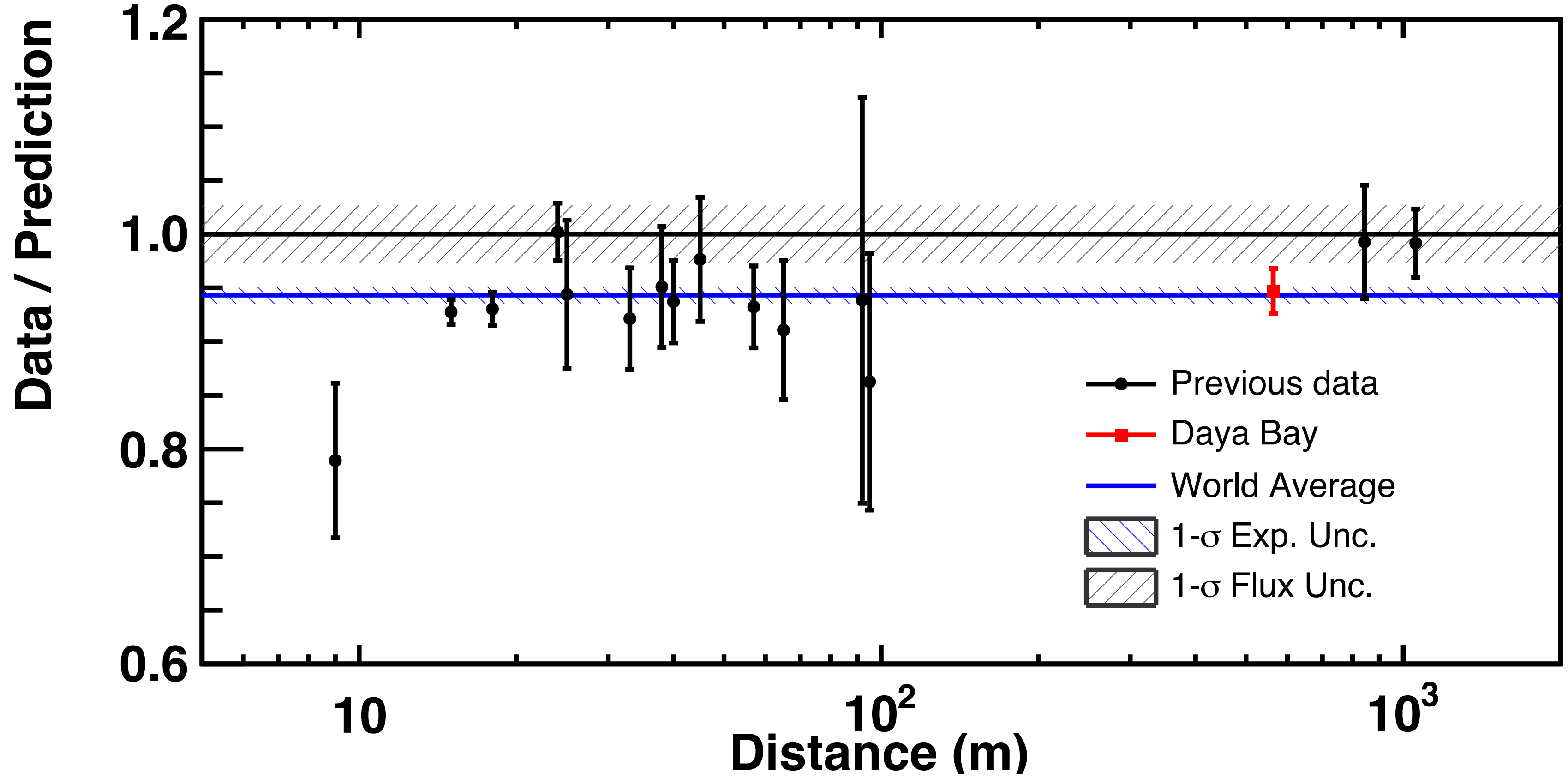
Stay tuned… Reactor neutrinos picking up the pace!?!

Thank you!

Extras

Past Flux Measurements

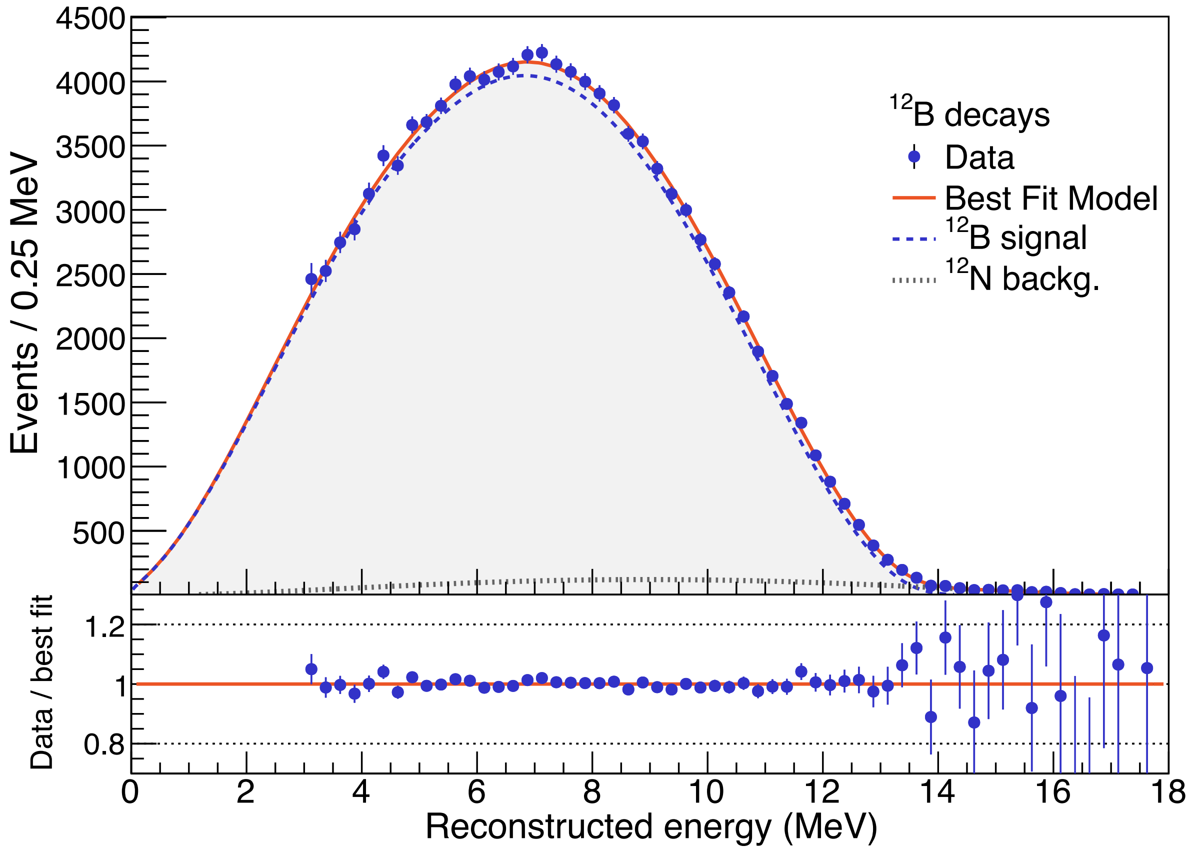
#	Exp.
1	Bugey-4
2	ROVNO91
3	Bugey-3-I
4	Bugey-3-II
5	Bugey-3-III
6	Goesgen-I
7	Goesgen-II
8	Goesgen-III
9	ILL
10	Krasn. I
11	Krasn. II
12	Krasn. III
13	SRP-I
14	SRP-II
15	ROVNO88-1I
16	ROVNO88-2I
17	ROVNO88-1S
18	ROVNO88-2S
19	ROVNO88-3S
20	Palo Verde
21	CHOOZ



‘Bump’ Not a Detector Effect

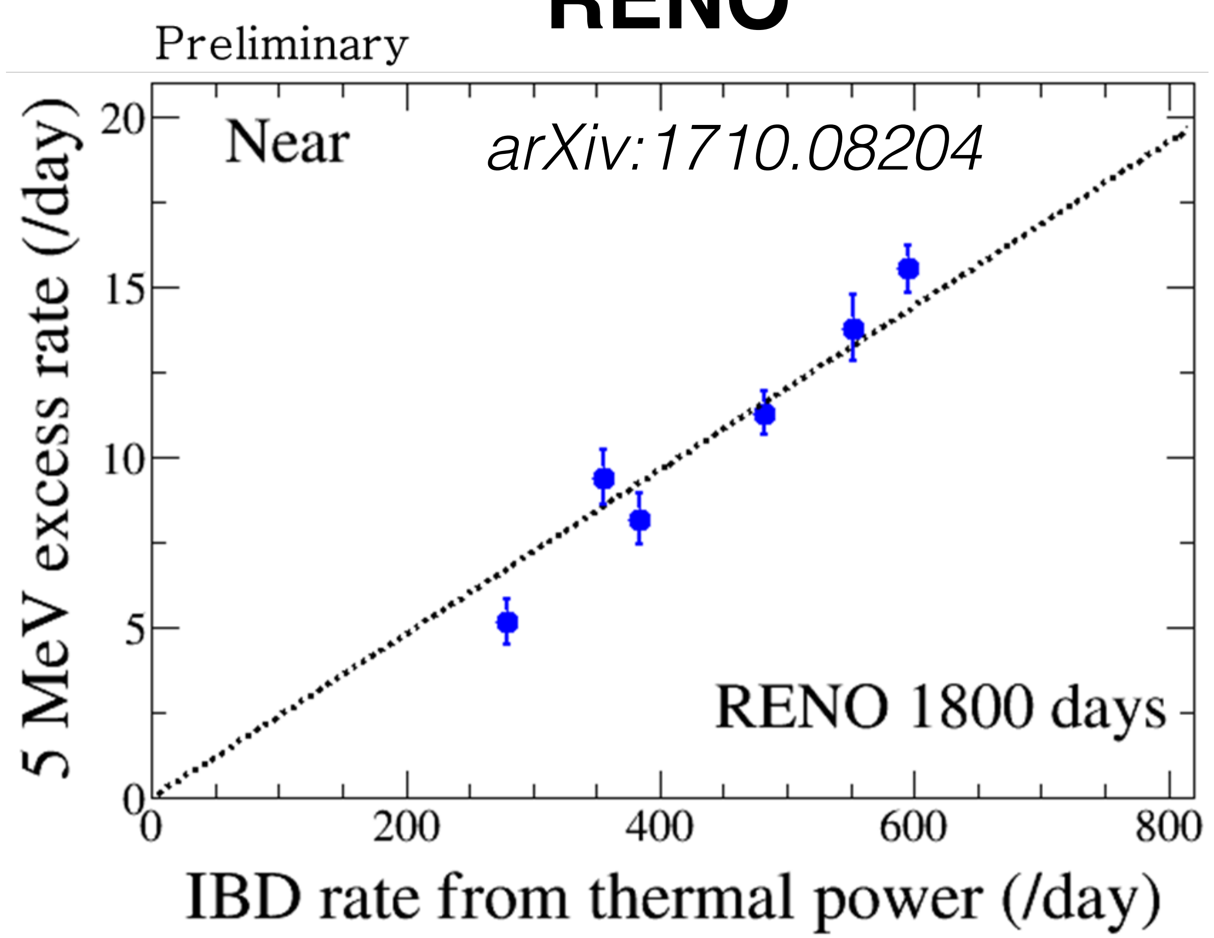
- **Not a background**
  - Reactor power correlated
- **Not a detector nonlinearity**
  - Not observed in other than IBD data, e.g. ^{12}B
  - Any physical process known with such a ‘bump’ effect

Daya Bay



PRD 95, 072006 (2017)

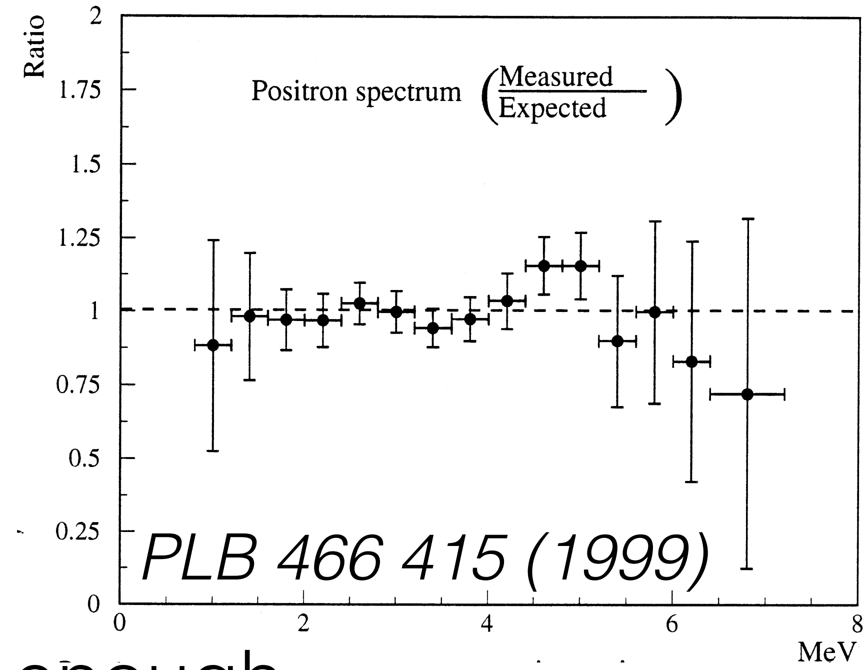
RENO



‘Bump’ in Past

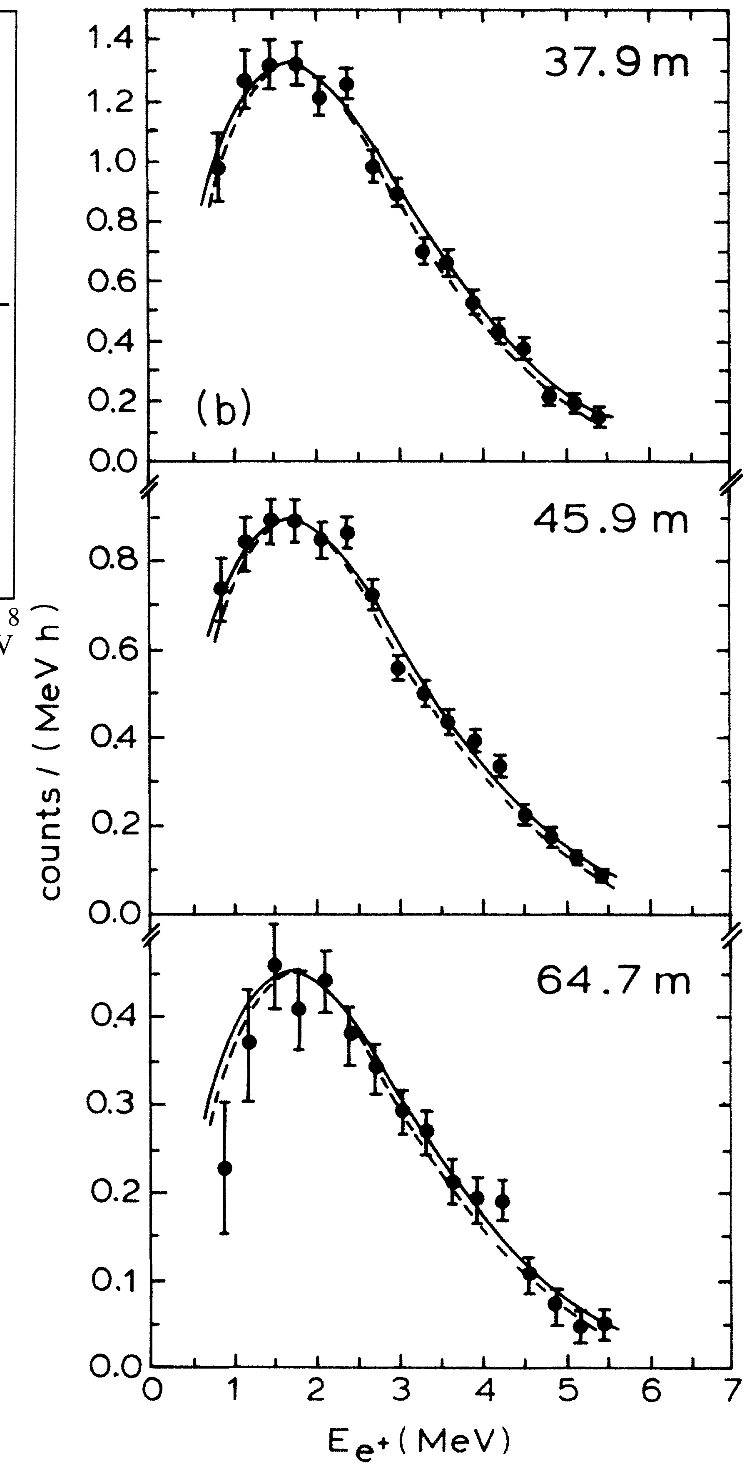
- **‘Bump’ observed in past**
  - Observed by several experiments in 80s/90s
  - However, most precise measurement from Bugey-3 agrees <5%
  - Bump was not seen with enough significance then

CHOOZ



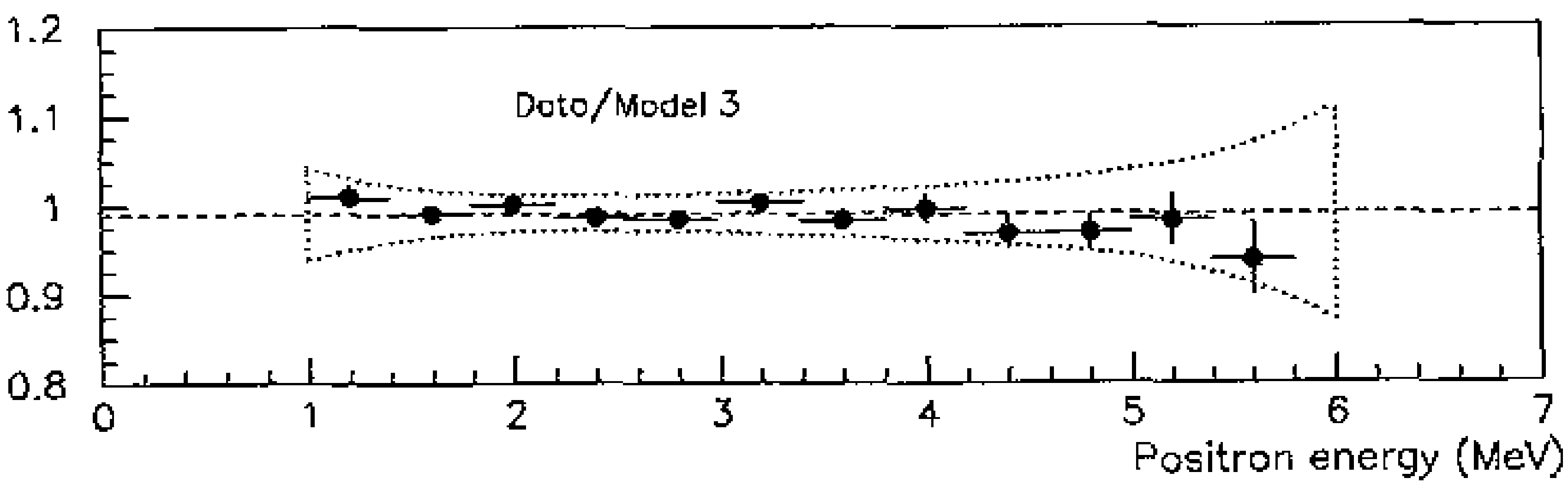
PLB 466 415 (1999)

Gösgen



PRD 34 2621 (1986)

Bugey-3



Phys.Lett. B374 (1996)