Reactor Neutrino Experiments

a tale about accuracy & precision

Marco Grassi
APC - Paris

MARIE CURIE ACTIONS

Today's Menu: a θ_{13}-oriented Review

Hors d'oeuvre

Neutrinos Do Oscillate!

What is mixing angle θ_{13} and why it is important

Main Dish

θ_{13} Experiments

How to perform a permille-level measurement in the neutrino sector

Side Dish

Characterization of antineutrino from reactors

Reactor Flux & Spectrum

Dessert

Other Reactor Experiments

Very short baseline: searching for hypothetical **non-interacting neutrinos**

Medium baseline: to determine the neutrino **mass ordering** (and much more)

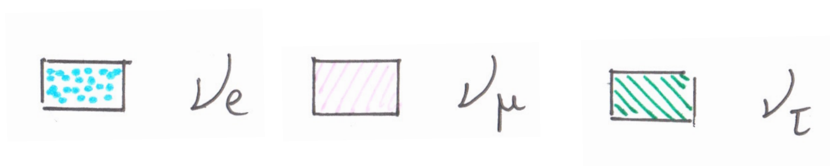
Neutrino Oscillation - Our Current Understanding

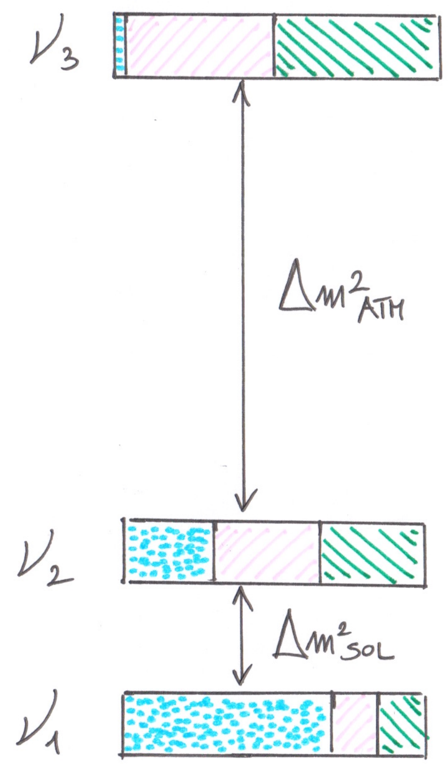
Three Flavor Eigenstates

Three Mass Eigenstates

$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U_{\alpha,i}\,|\nu_i\rangle$$

$$\alpha = e, \mu, \tau$$





Oscillation Probability

$$P_{\alpha\beta} \sim \sin^2 2\vartheta \; \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

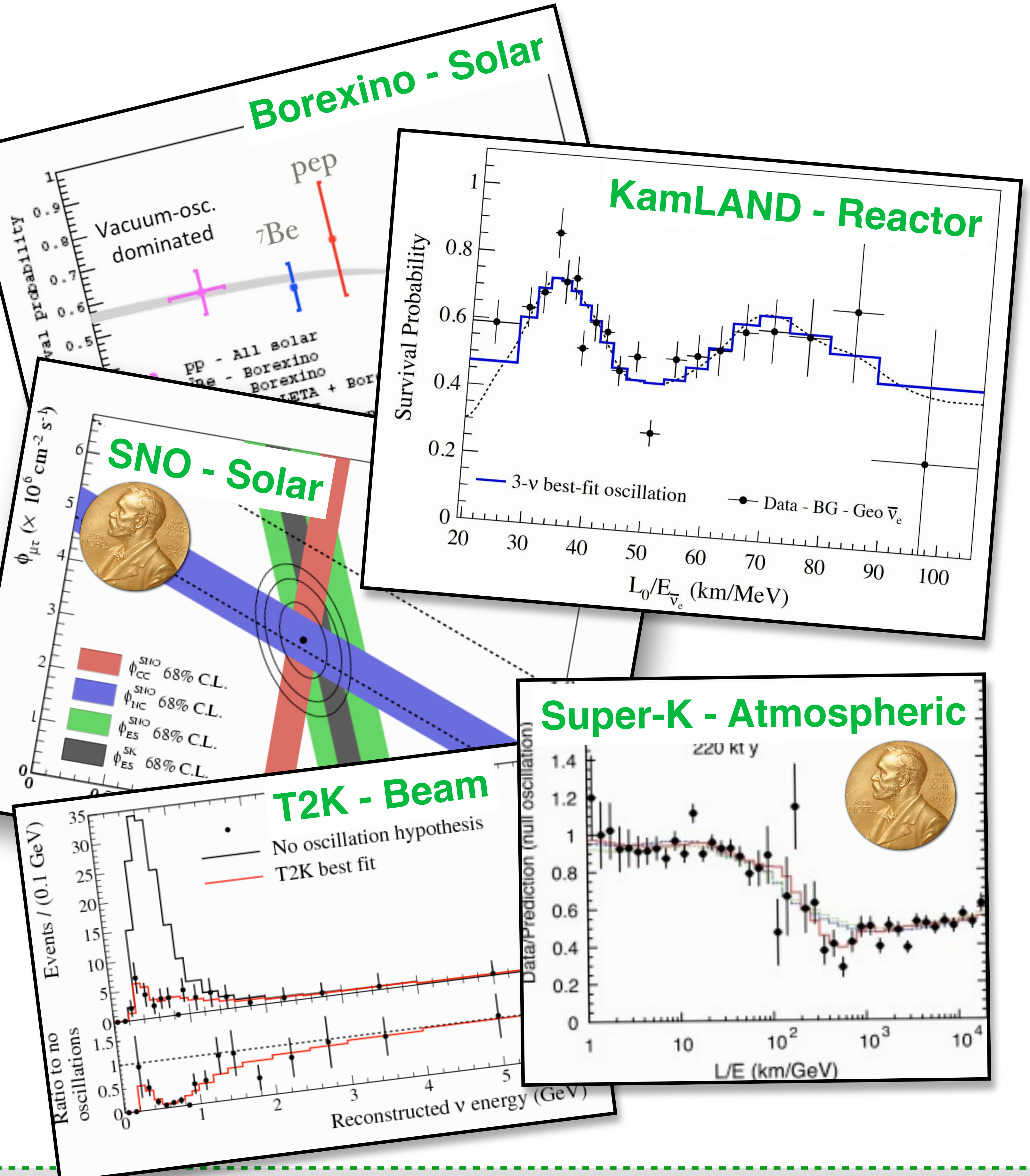
Mass Splitting

$\Delta m^2 = (m_1)^2 - (m_2)^2$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\vartheta_{23} & \sin\vartheta_{23} \\ 0 & -\sin\vartheta_{23} & \cos\vartheta_{23} \end{pmatrix} \begin{pmatrix} \cos\vartheta_{13} & 0 & \sin\vartheta_{13}\, e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\vartheta_{13}\, e^{i\delta} & 0 & \cos\vartheta_{13} \end{pmatrix} \begin{pmatrix} \cos\vartheta_{12} & \sin\vartheta_{12} & 0 \\ -\sin\vartheta_{12} & \cos\vartheta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric **Reactor (L~1km)** **Solar**

Neutrino Oscillation - Experimental Summary



Neutrino oscillation firmly **established**

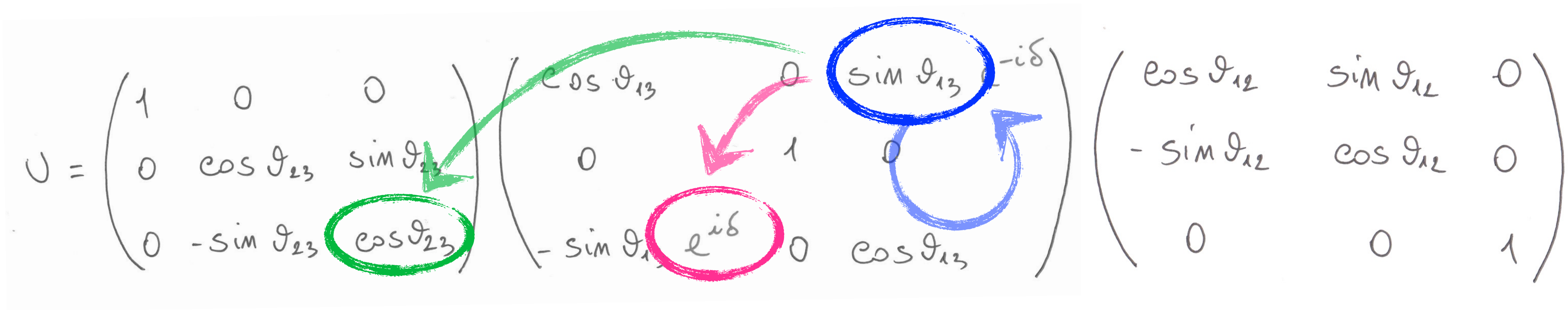
Great **variety** of sources, energies, baselines and experimental techniques

Current precision

Δm^2_{SOL}	2.3%
Δm^2_{ATM}	1.6%
$\sin^2(\theta_{12})$	5.8%
$\sin^2(\theta_{13})$	4% ←
$\sin^2(\theta_{23})$	~9%

PRD 95 (2017) 096014

Why is θ_{13} important



Atmospheric | Reactor (L~1km) | Solar

Last mixing angle waiting to be measured (till 2012)

(first efforts by Chooz and Palo Verde in late 90s resulted in upper limits)

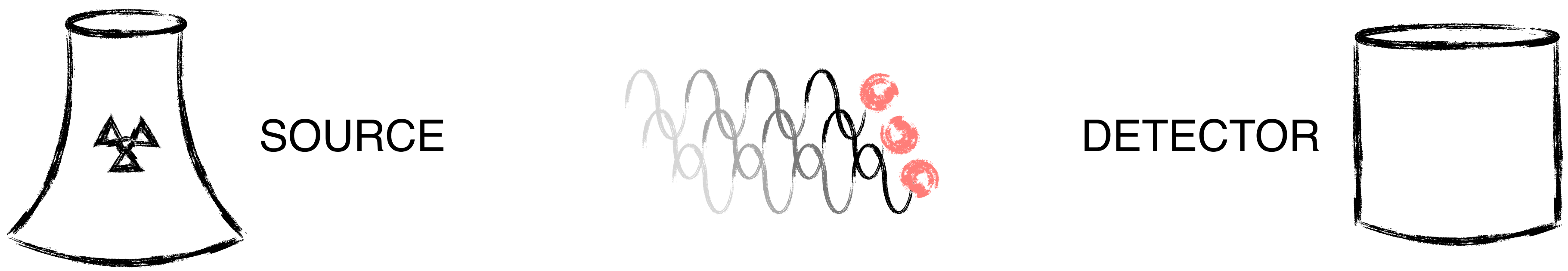
θ_{13} sets our capability to determine neutrino **mass ordering**

Precise θ_{13} allows to constrain open issues in neutrino physics

θ_{23} octant

CP phase

Why at Nuclear Reactors



Nuclear Power Plants

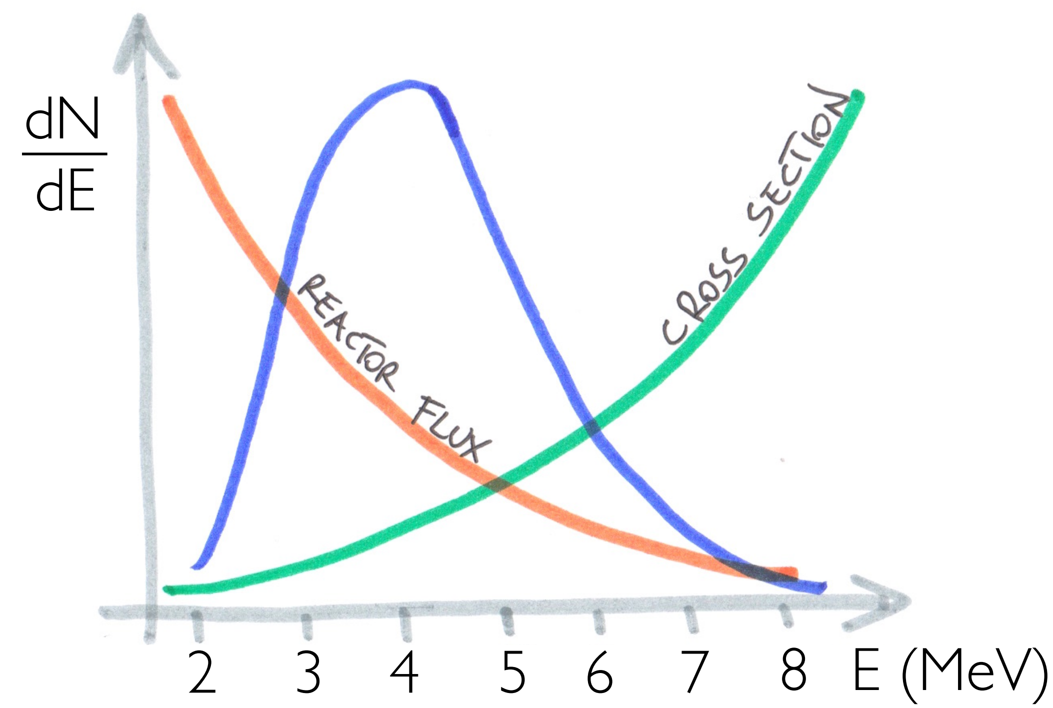
Energy by breaking heavy nuclei

Fission fragments are unstable

Decaying through cascade of β decays

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

3 GW_{th} reactor : $\sim 10^{20}$ $\bar{\nu}_e$ / s



Cleanest θ_{13} measurement

Not dependent on any other oscillation parameter

Detection cross section very well known

Short-Baseline Reactor Neutrino Experiments

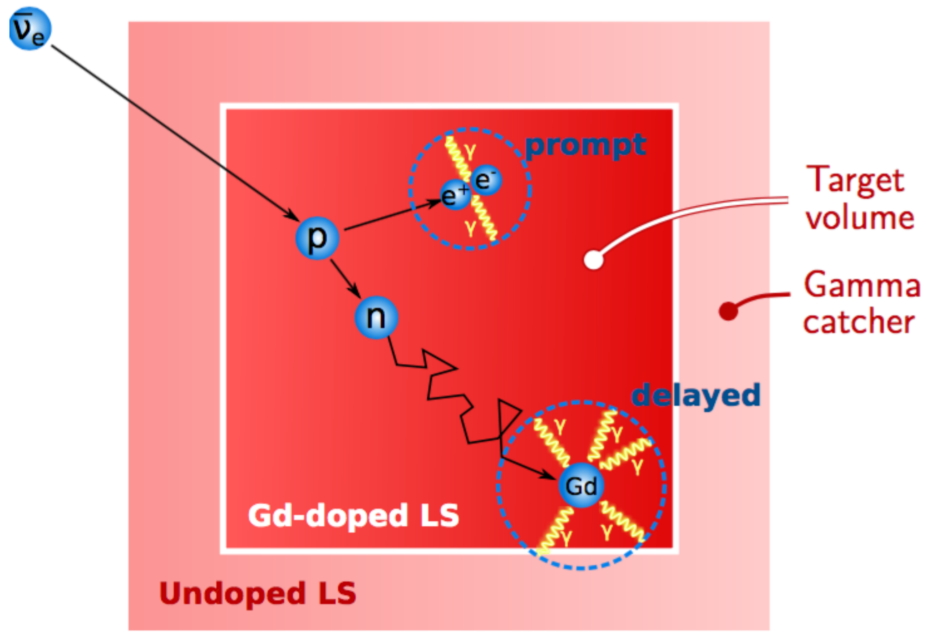
Double Chooz

RENO

$$\begin{pmatrix} \cos\vartheta_{13} & 0 & \sin\vartheta_{13}\, e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\vartheta_{13}\, e^{i\delta} & 0 & \cos\vartheta_{13} \end{pmatrix}$$

Daya Bay

Antineutrino Detection



Liquid Scintillator Detectors

- **High Light Yield** (Resolution & Energy Threshold)
- **Large Proton Abundance** (antineutrino target)
- **Doping capability** (improve background rejection)
- **Large Volumes** (compensate low cross section)

Inverse Beta Deta

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

PROMPT

$$+ p \xrightarrow{\tau \approx 200\ \mu s} D + \gamma \quad (2.2\,\mathrm{MeV})$$

$$+ Gd \xrightarrow{\tau \approx 28\ \mu s} Gd^* \rightarrow Gd + n\gamma \quad (8\,\mathrm{MeV})$$

DELAYED

prompt + delayed energy depositions (powerful background rejection)

Gadolinium capture: higher **energy** and lower capture **time** with respect to H

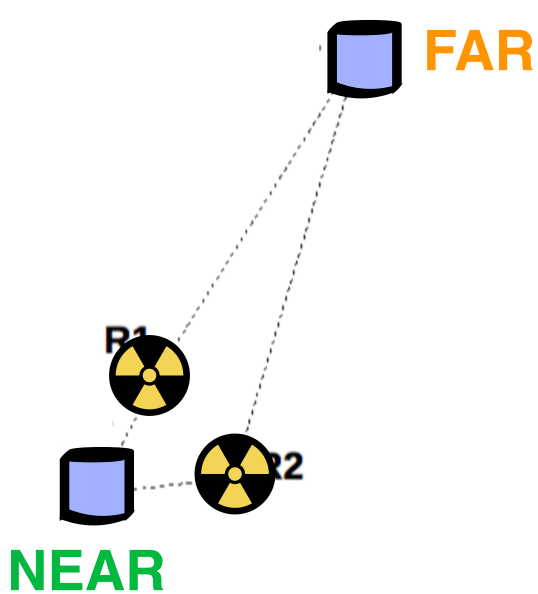
Analysis Strategy

Overcome **uncertainties** in expected and measured **reactor** antineutrino flux (main limitation of Chooz and Palo Verde)

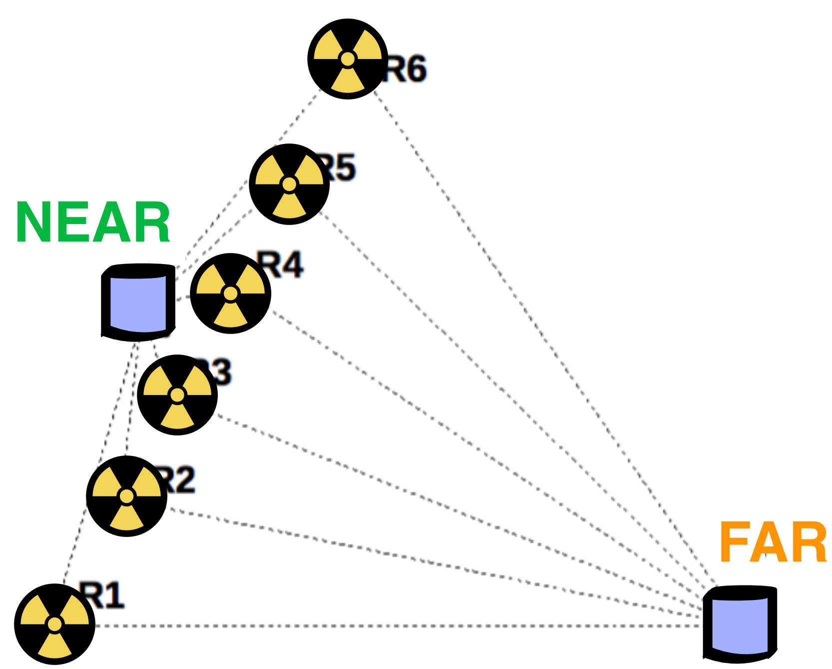
Mykaelyan & Sinev: **ratio** between far and near detector to reduce uncertainties

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

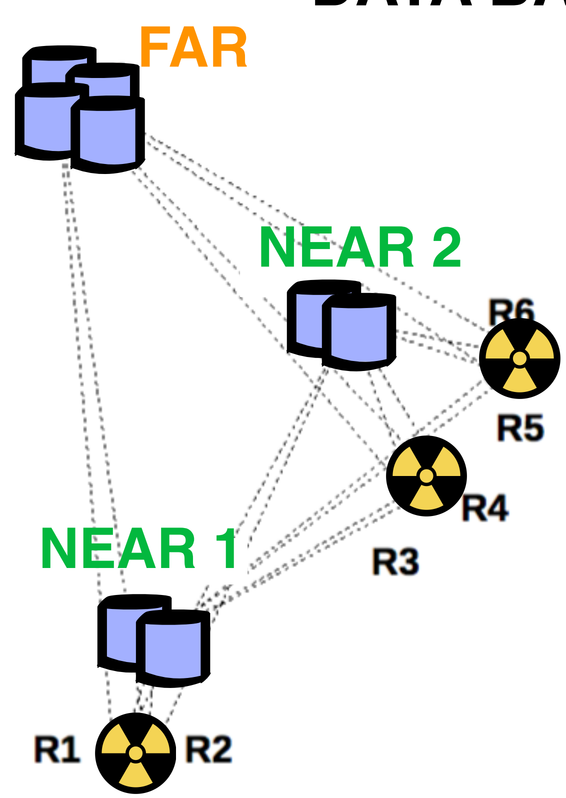
DOUBLE CHOOZ



RENO

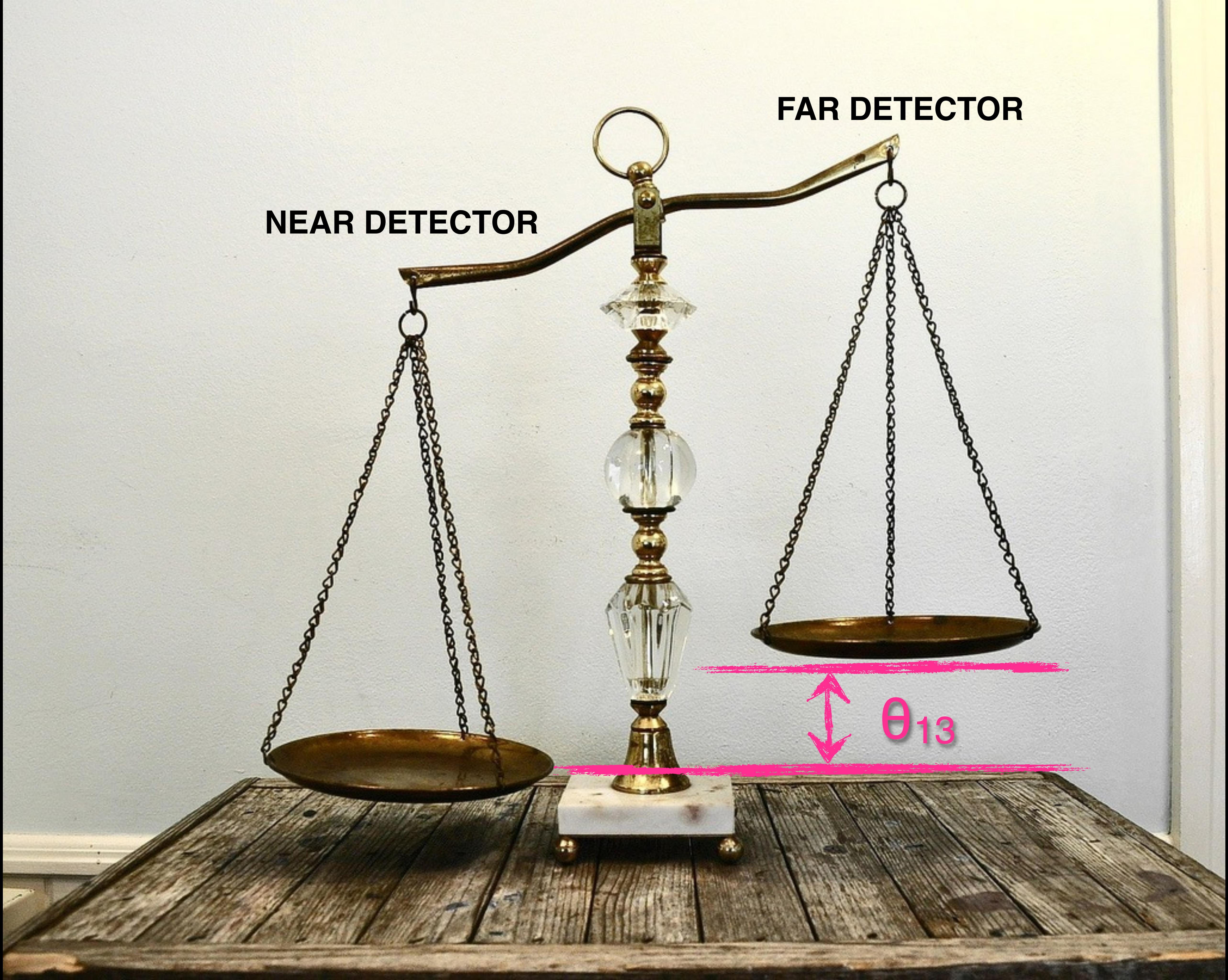


DAYA BAY



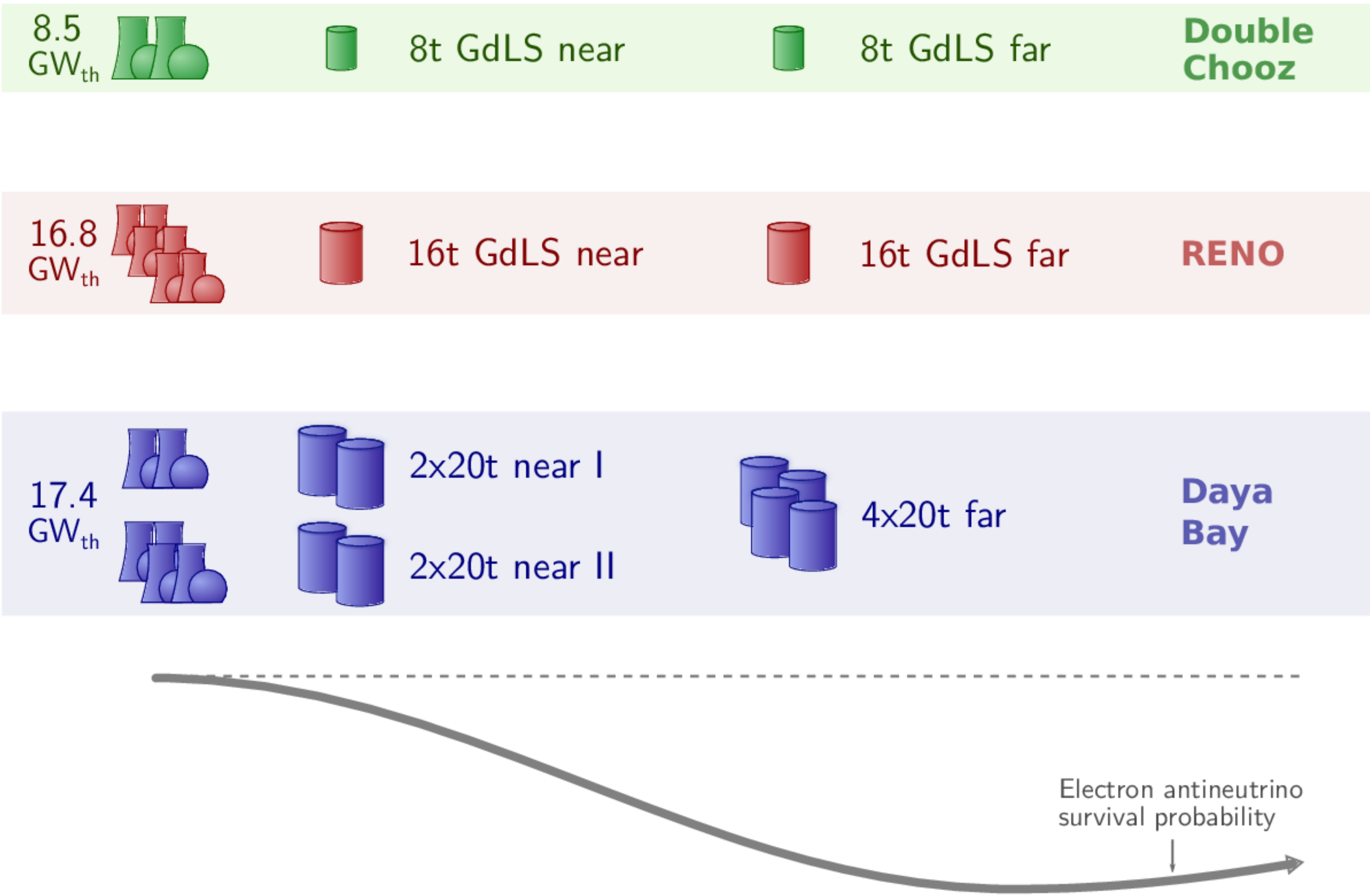
Signal selection criteria designed to **minimize relative uncertainties**

Mikaelyan et al. Phys.Atom.Nucl. 63 (2000) 1002 - Cucoanes et al. 1501.00356


FAR DETECTOR
NEAR DETECTOR
θ_{13}

Comparison of Experimental Setups

Large **identical** detectors close to powerful nuclear reactors

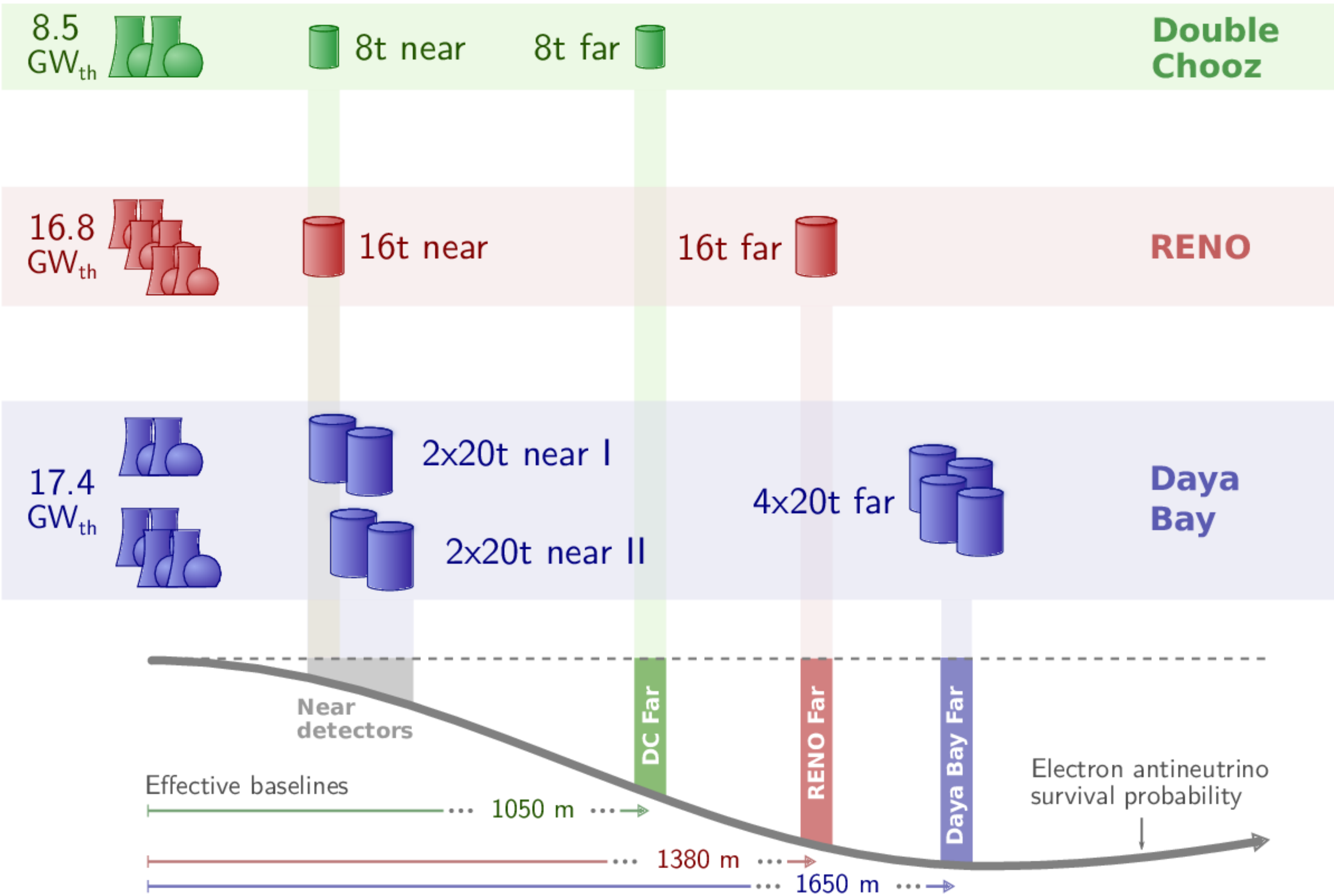


Daya Bay: identical pairs of detectors side-by-side

Jetter @ COSPA (2014)

Comparison of Experimental Setups

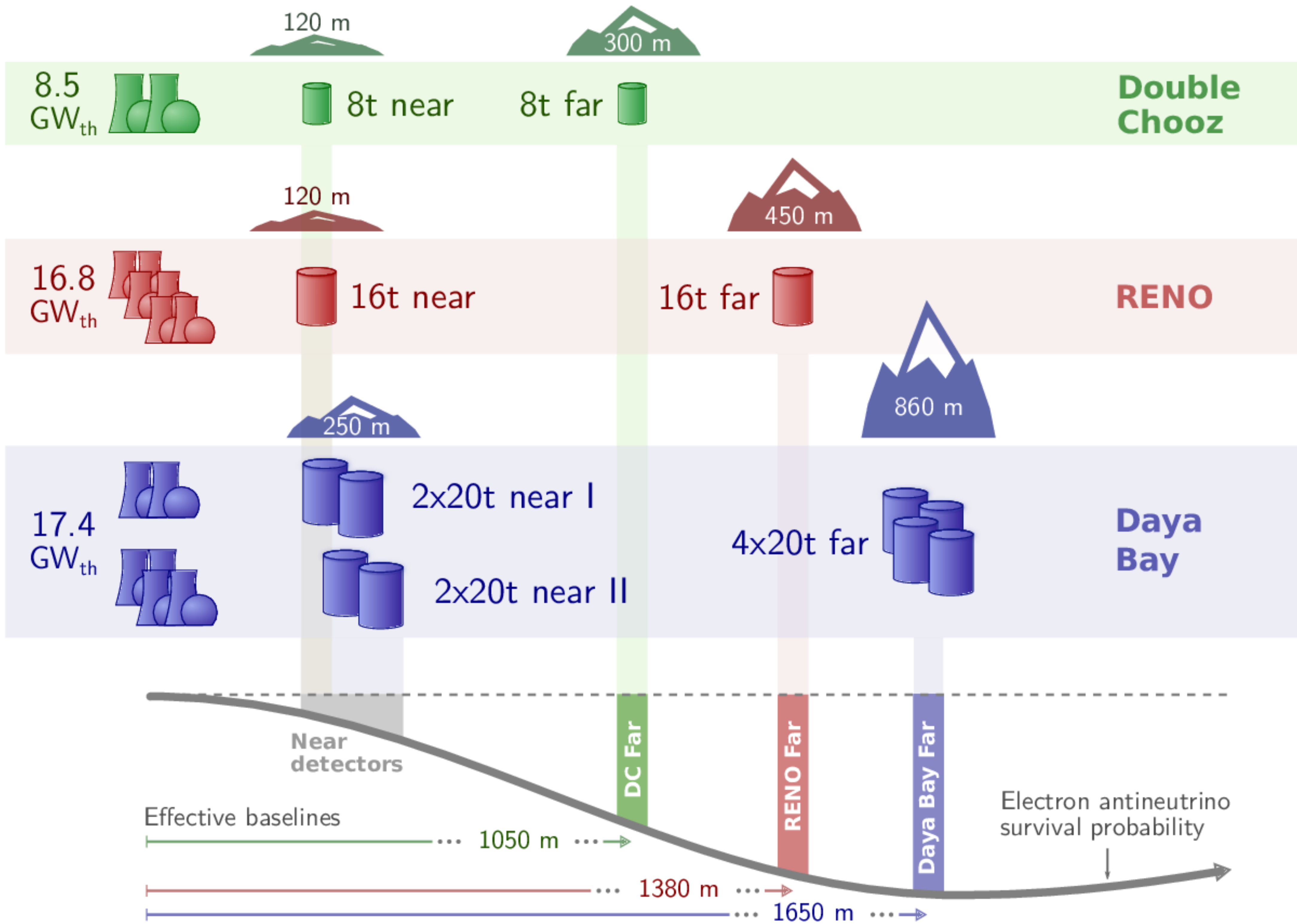
Optimize baseline to get maximum oscillation at far site



Optimization possible thanks to **previous** accelerator + atmospheric Δm^2 **measurements**

Jetter @ COSPA (2014)

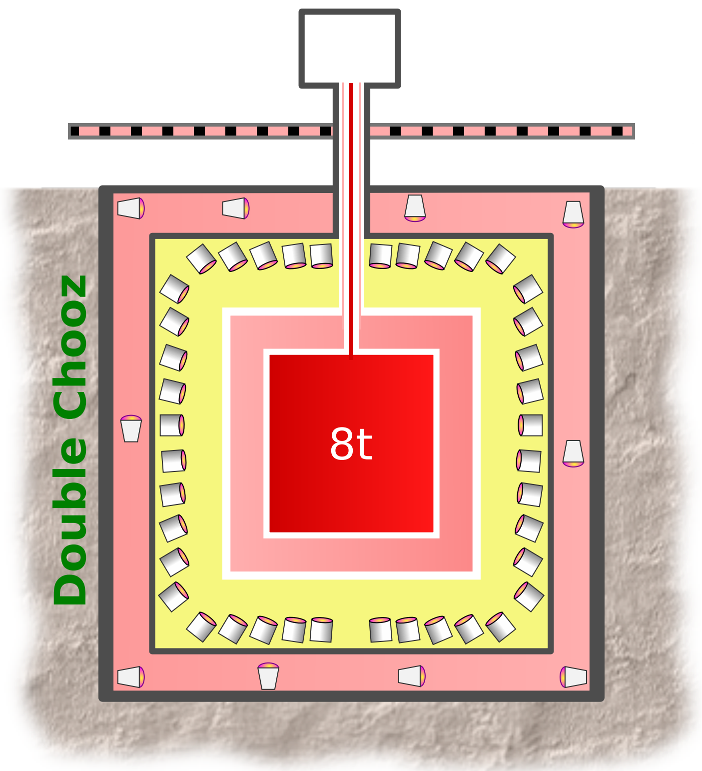
Comparison of Experimental Setups



Maximize overburden to reduce background induced by **cosmic rays**

Jetter @ COSPA (2014)

Comparison of Detector Designs

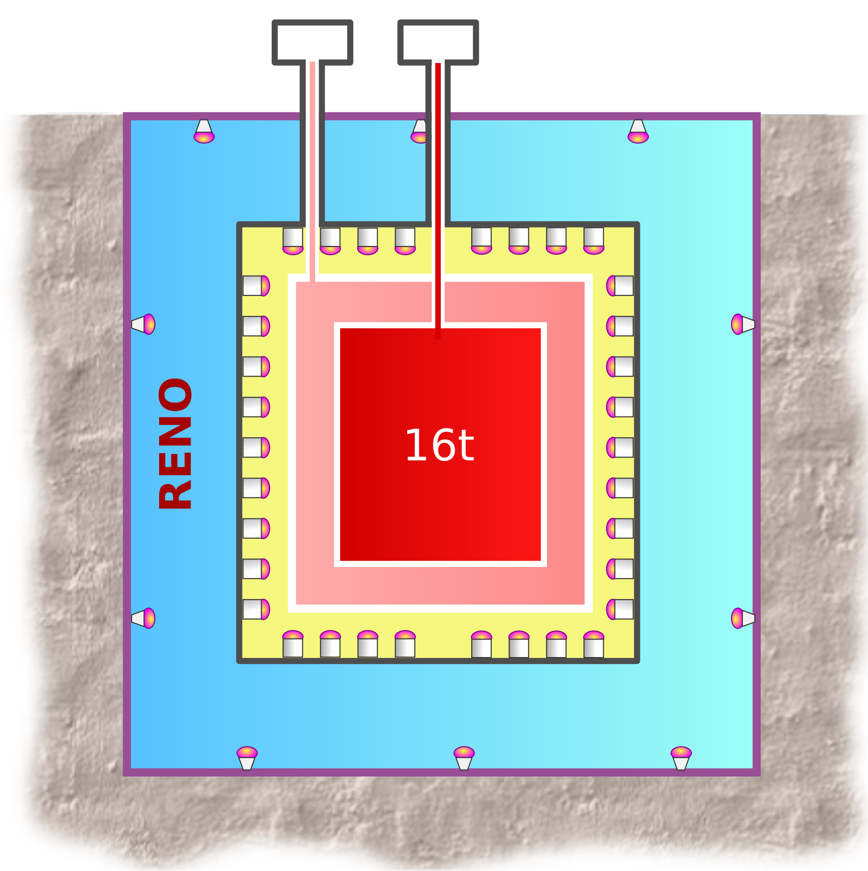


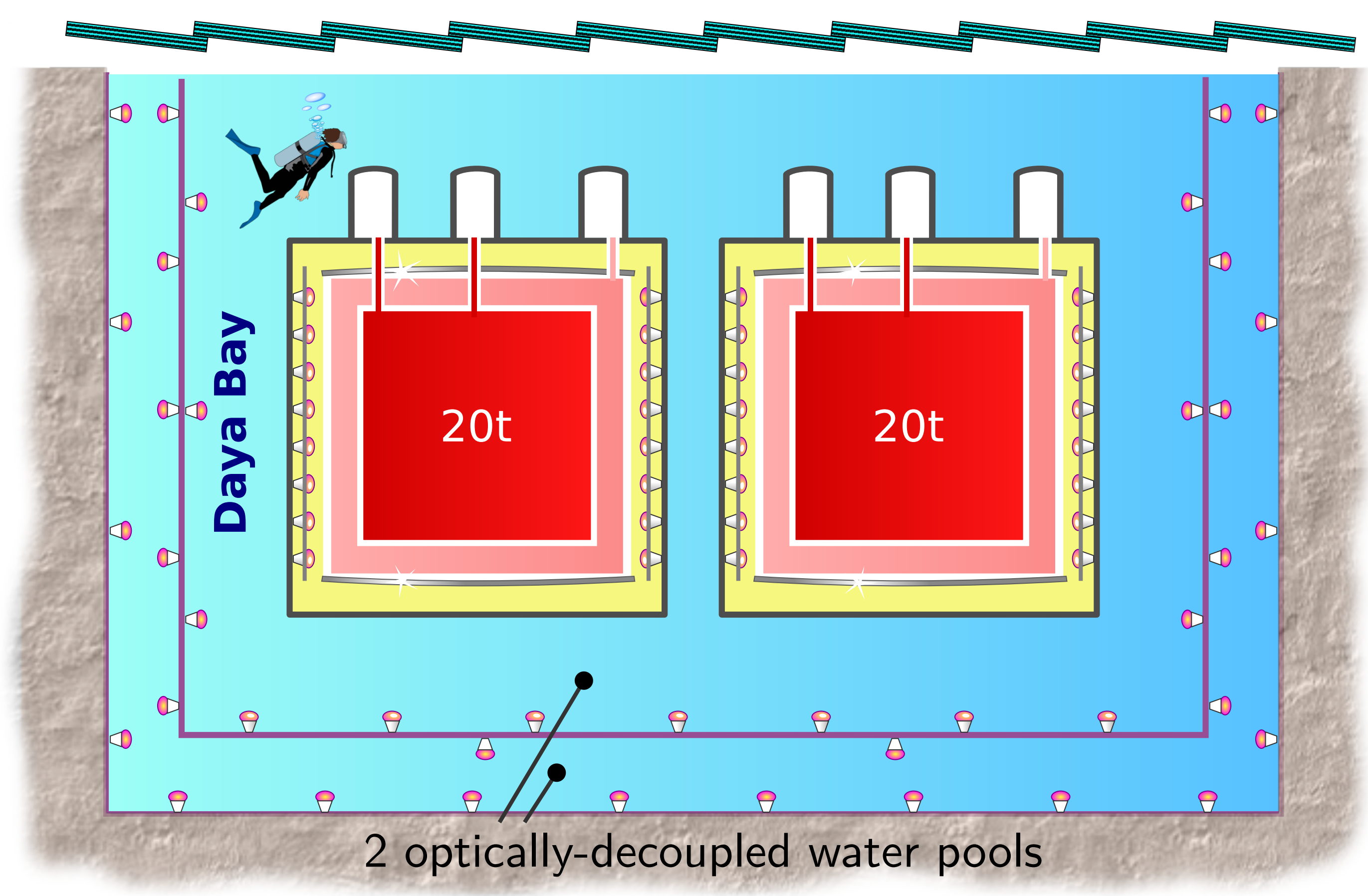
Antineutrino detectors

- Target: Gd-doped LS
- γ catcher: undoped LS
- Buffer: mineral oil
- Acrylic vessels
- Steel vessels

Muon veto system

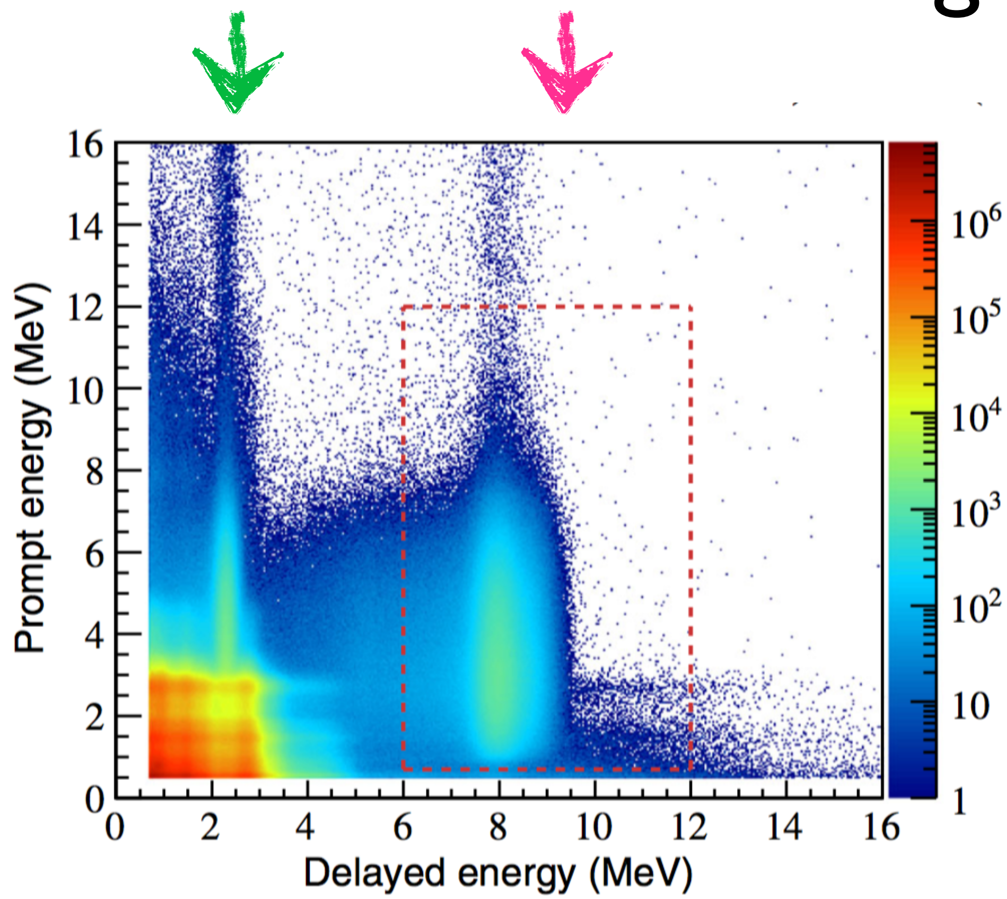
- LS inner veto (Double Chooz)
- Water Čerenkov (RENO+DB)
- Rock/concrete
- Plastic scintillator top (DC)
- RPC top (Daya Bay)
- Tyvek structures





Jetter @ COSPA (2014)

Signal Selection



DYB & RENO

Main result on **n captures on Gd**

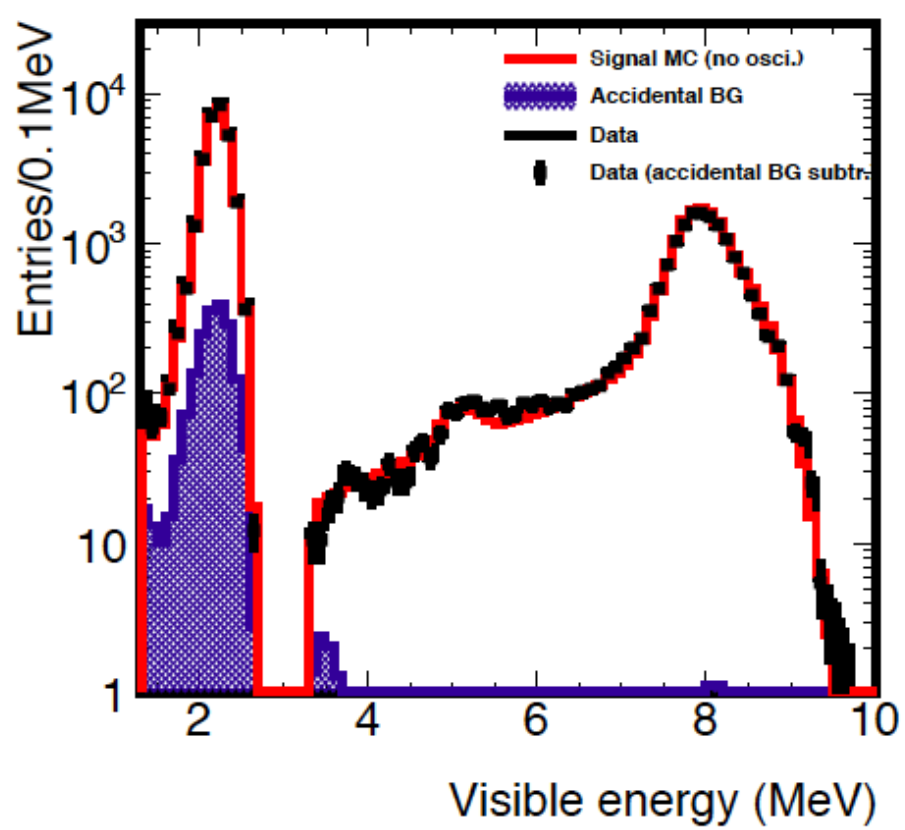
(**n captures on H** give compatible result)

Cut-Based Analysis

Prompt & Delayed Energy

Prompt-delayed spatial and temporal correlation

Muon Veto



DC puts together all n captures (H, Gd, C)

Selection based on Artificial Neural Network
(after muon veto)

Input quantities are same of other exps

As a result: **30t effective target volume**
(thanks to powerful bkg suppresion)

DYB: PRD 95 (2017) 072006 & PRD 93 (2016) 072011 - DC: Cabrera@CERN

Backgrounds

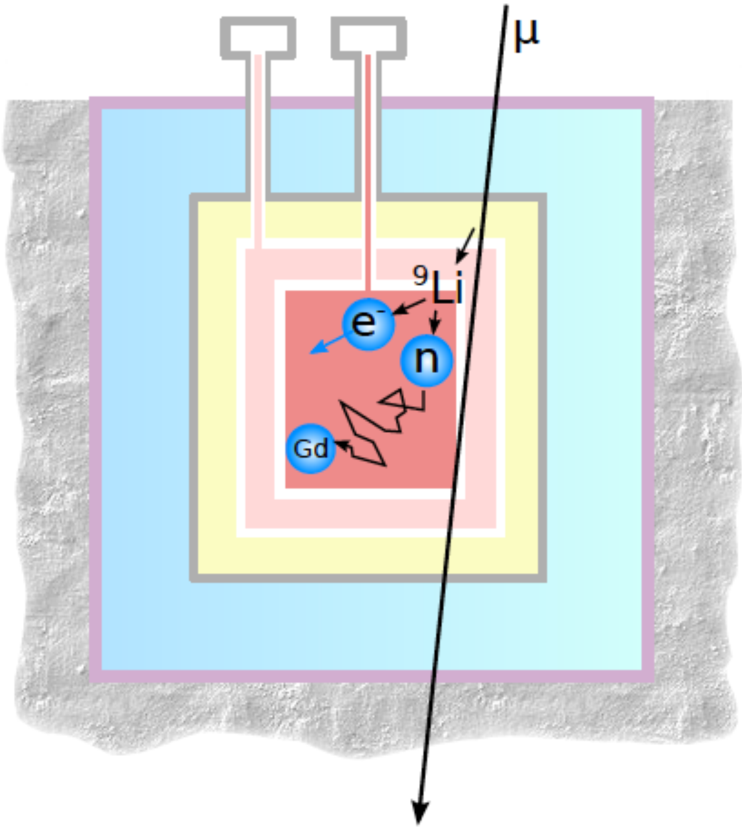
Background event must have prompt-delayed structure to pass selection

Accidental (random) coincidences:
γ ray from rock + high energy β decays from muon-nuclear interactions

Muon-related events with **correlated** energy depositions (deeper is better):

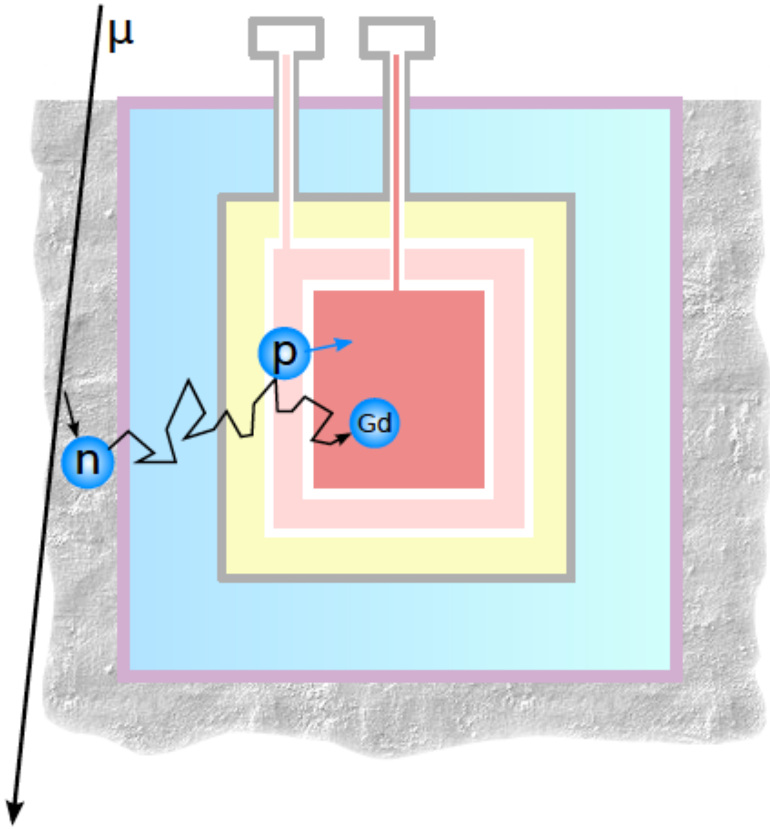
Isotope Decays

β-n decays of ^{9}Li & ^{8}He



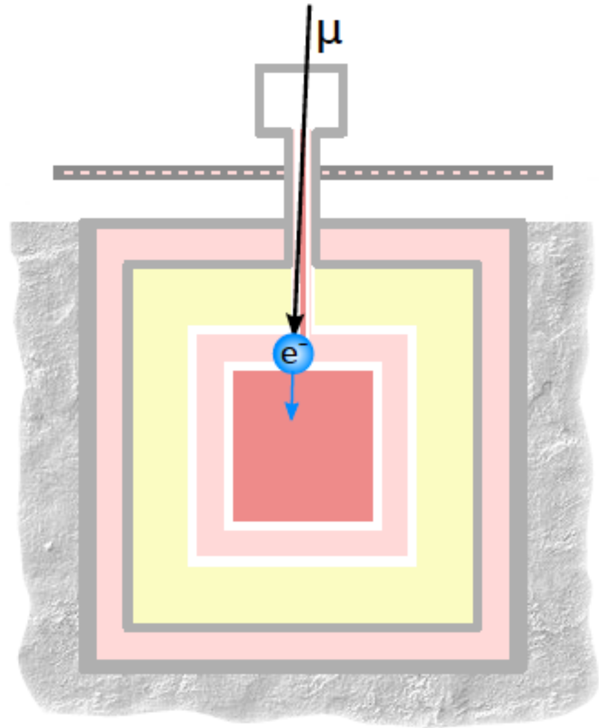
Fast Neutron

p recoil + **n capture**



Untagged Muon Decay

μ ionization + **e ionization**



Double Chooz Only

Systematic Uncertainties

Single ▸ **Multi** Detector: uncertainty suppression works!

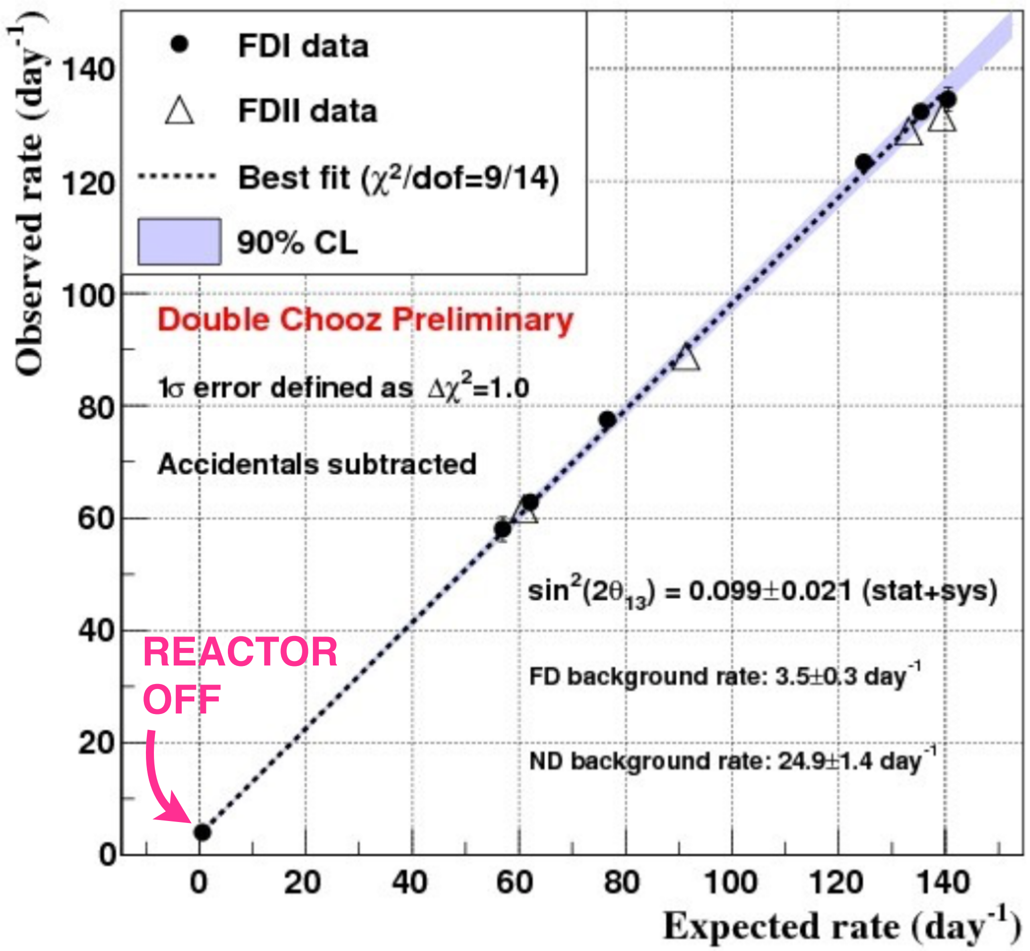
Permille systematics in neutrino physics (“precision era”)

Make θ_{13} the best known mixing angle

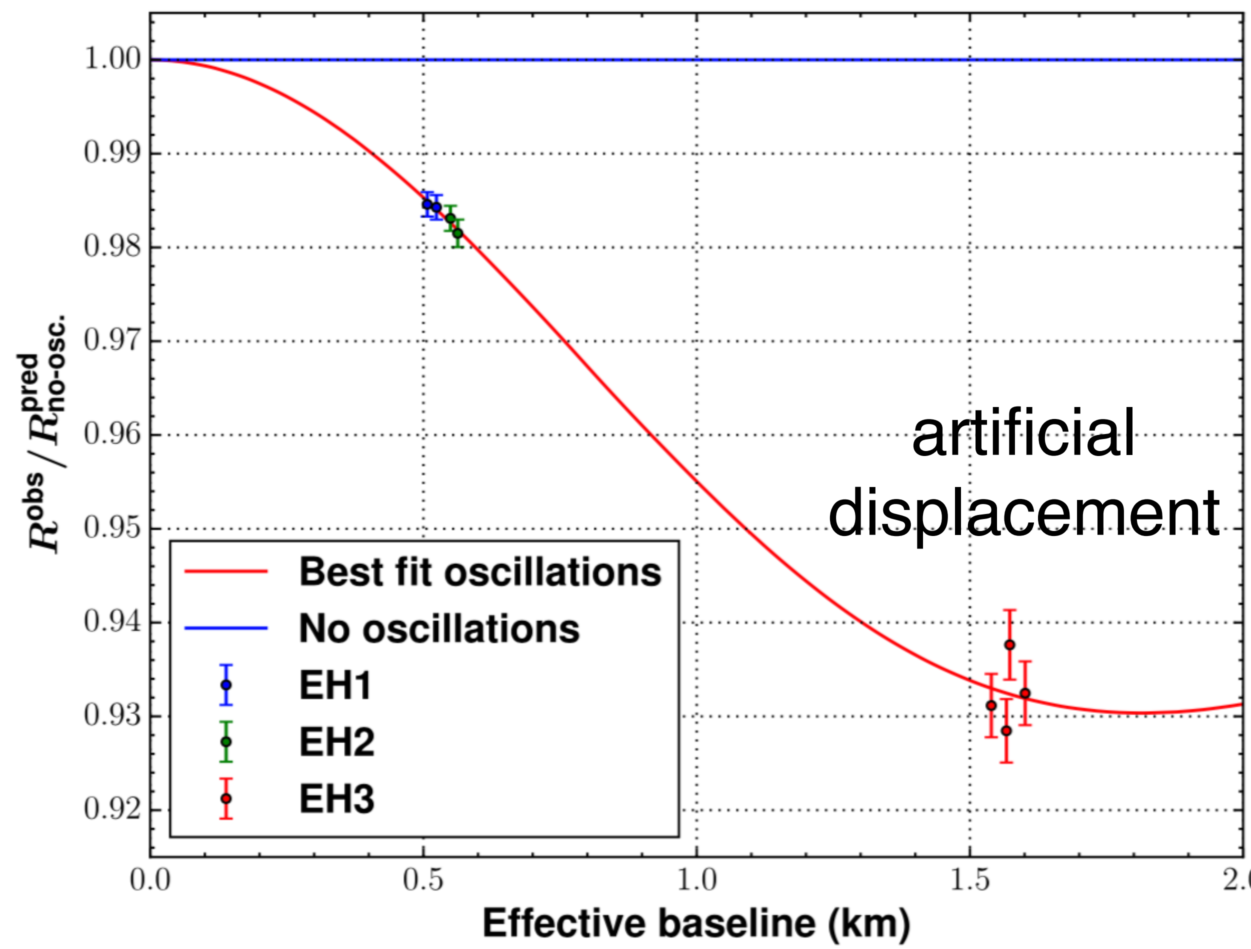
Uncertainty	**Double Chooz**		**Daya Bay**		**Reno**	
	Single Detector	Multi Detector	Single Detector	Multi Detector	Single Detector	Multi Detector
Detection	0.7%	0.6%	1.9%	0.1%	1%	0.2%
Flux	1.7%	0.1%	2%	0.2%	2%	0.9%
Background	0.6%	0.2%	0.2%	0.2%	7%	7%

Rate Only Result

DC: Reactor Rate Modulation



Daya Bay



$\sin^2(2\theta_{13}) = 0.099 \pm 0.021$

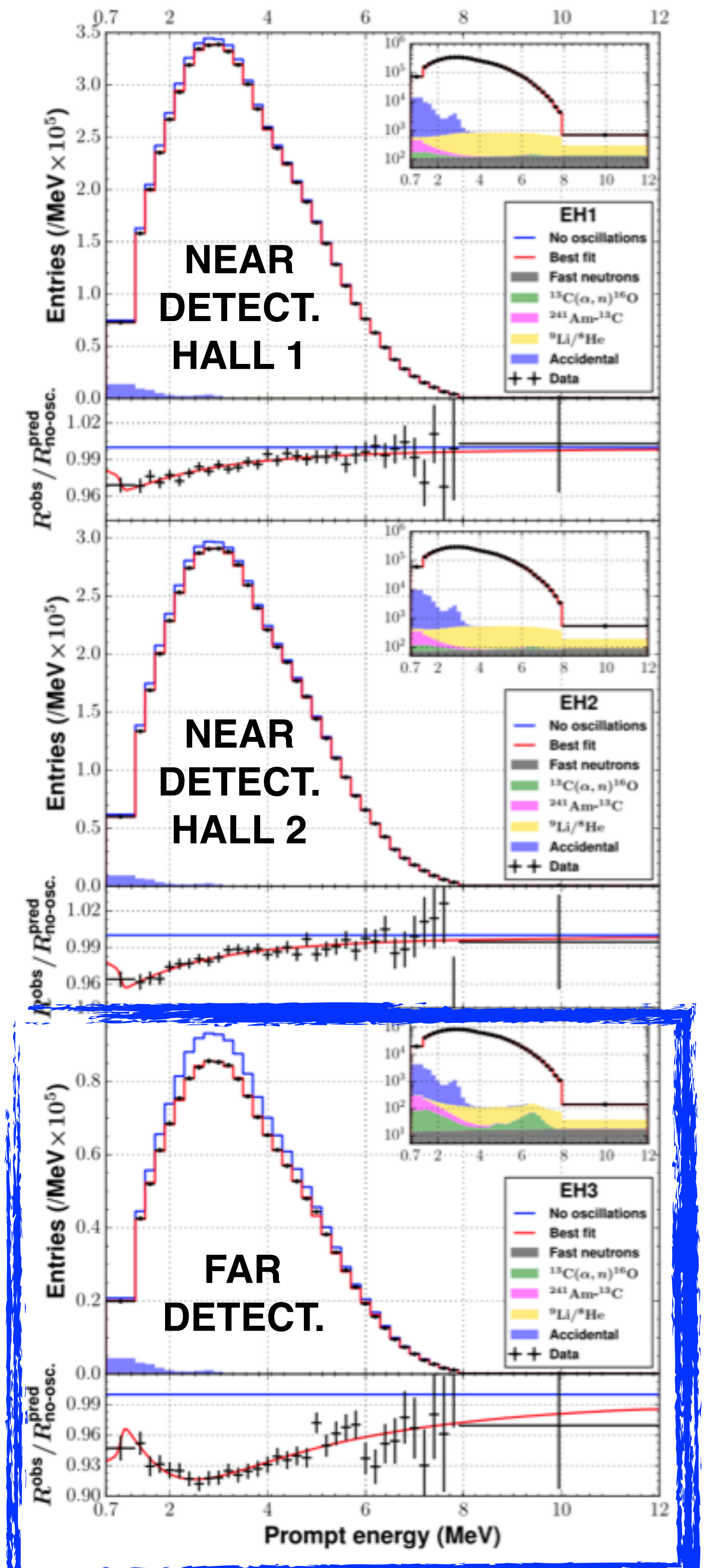
$\sin^2(2\theta_{13}) = 0.0850 \pm 0.0030 \pm 0.0028$

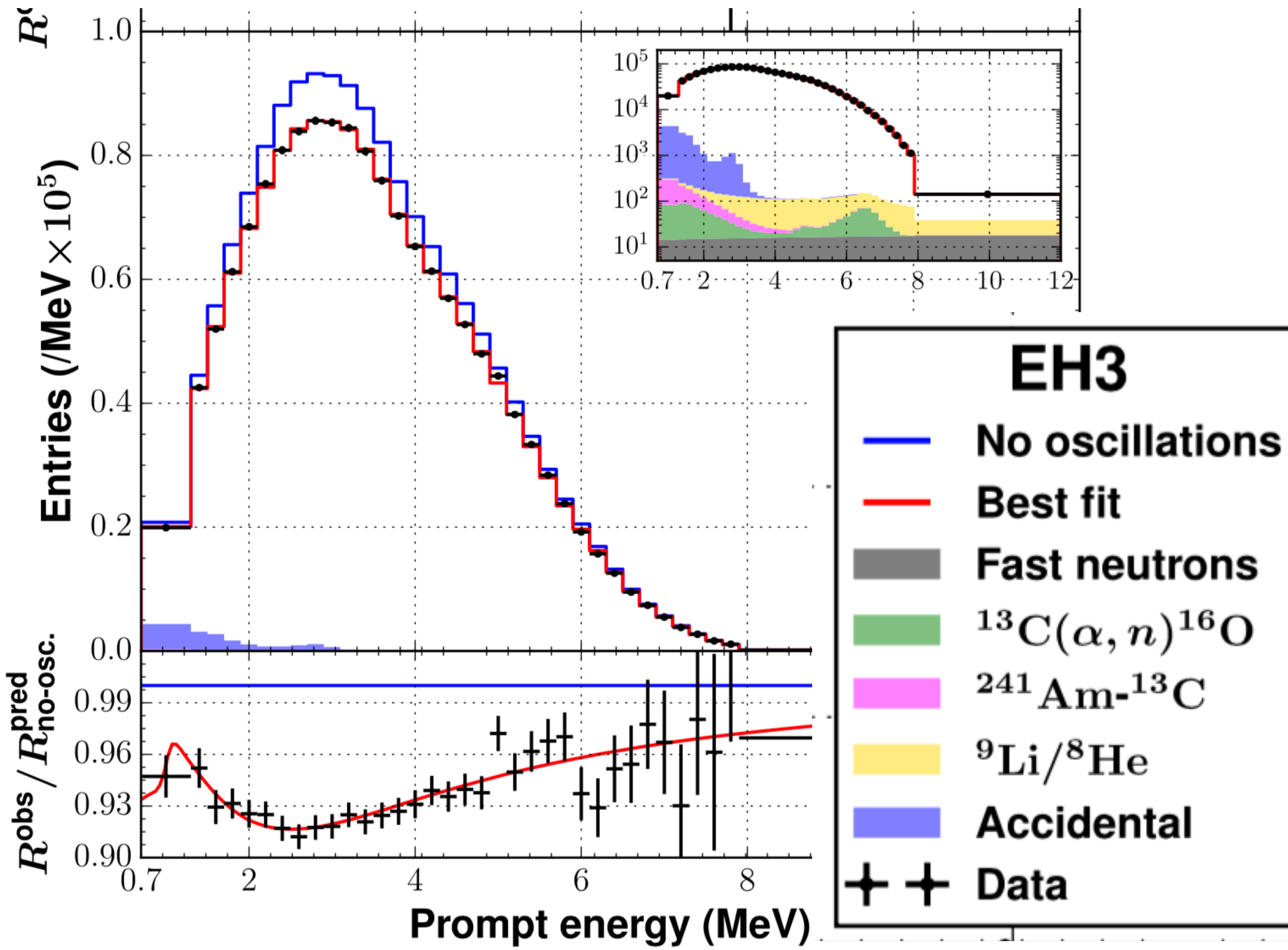
Reno: $\sin^2(2\theta_{13}) = 0.087 \pm 0.009$ (stat) ± 0.007(sys)

External mass splitting information from muon neutrino disappearance

DC: Buck @ LNGS (2017) - DYB: PRD 95 (2017) 072006 - RENO: 1610.04326

Daya Bay Spectral θ_{13} Result

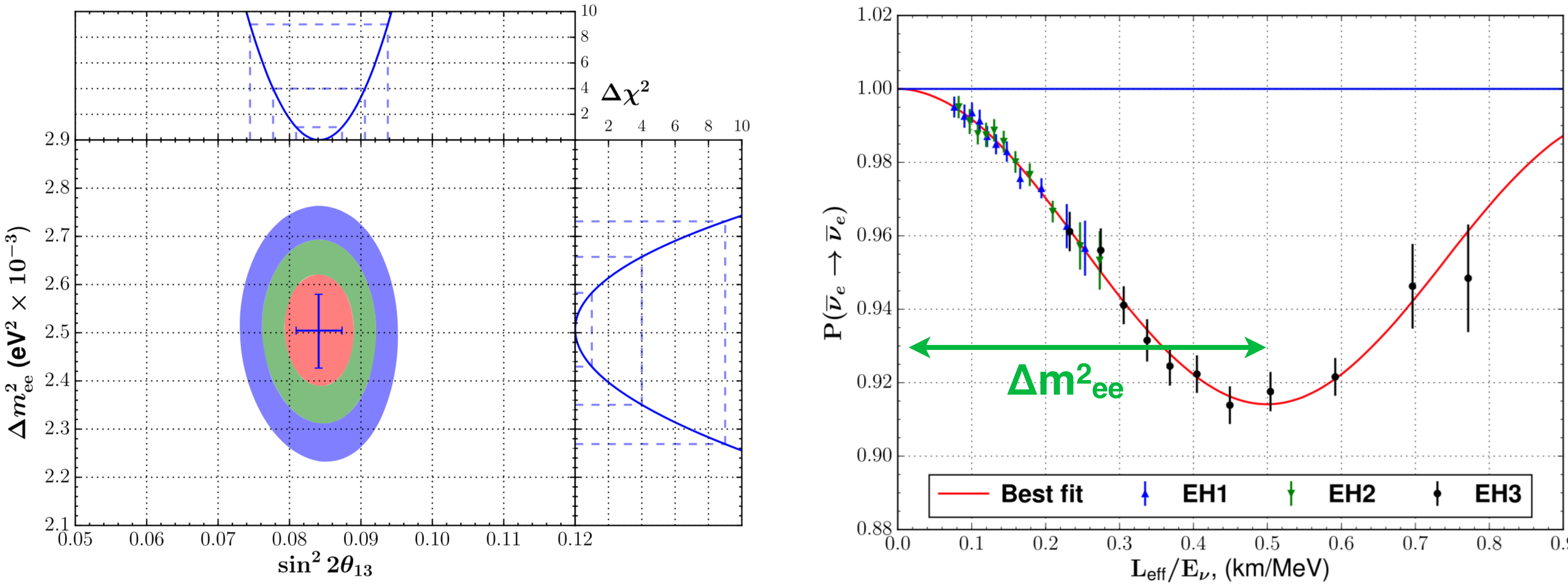




$\sin^2(2\theta_{13}) = 0.0841 \pm 0.0027$ (stat) ± 0.0019 (sys)

PRD 95 (2017) 072006

Daya Bay Mass Splitting Result



THIS MEASUREMENT　　　　KamLAND

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

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

Δm^2_{31} & Δm^2_{32} indistinguishable @ ~1km baseline

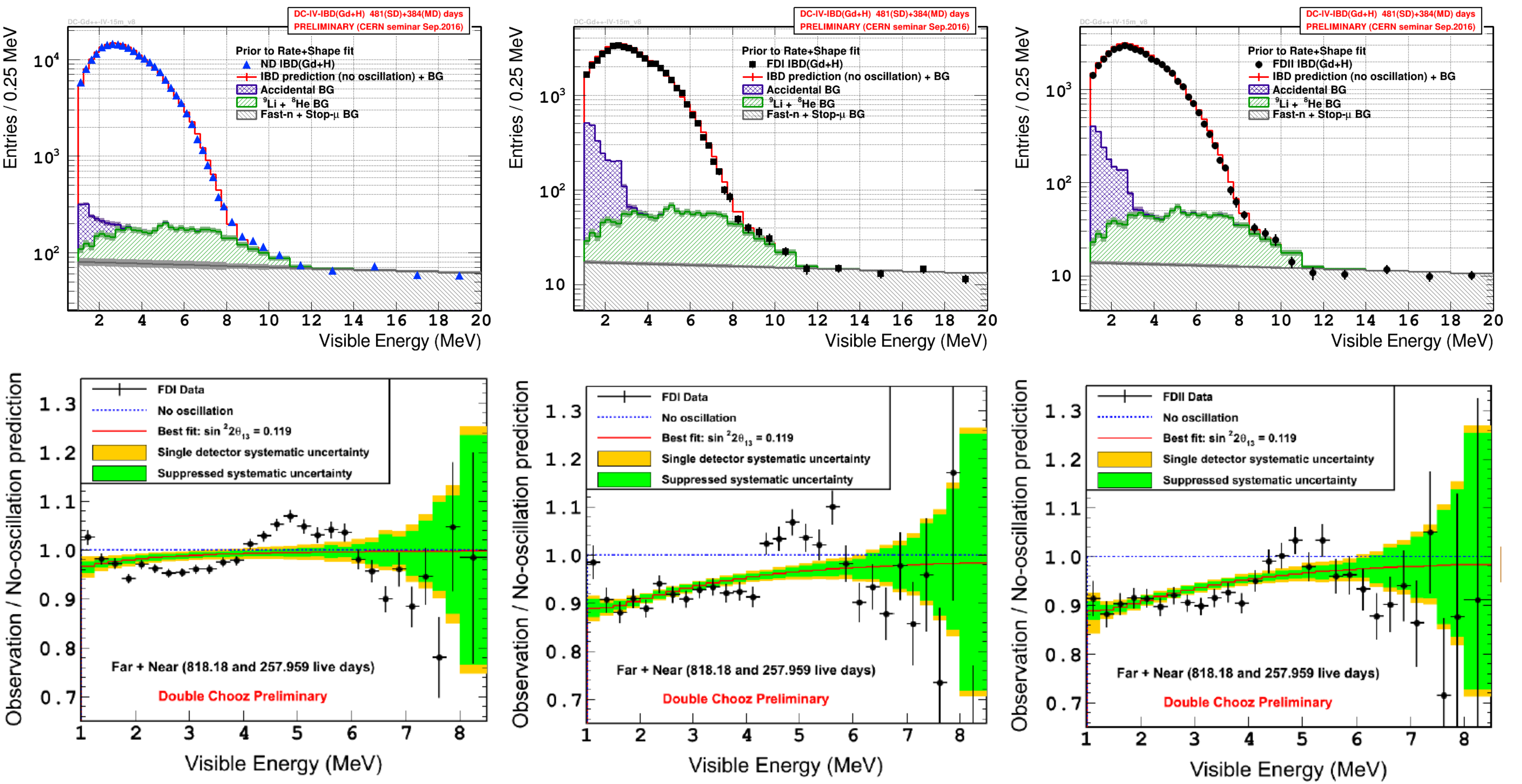
$|\Delta m^2_{ee}| = [2.50 \pm 0.06 \text{ (stat)} \pm 0.06 \text{(sys)}] \times 10^{-3}$ eV²

Complementary to **accelerator** measurements (different systematics)

PRD 95 (2017) 072006

Double Chooz Result

Near Detector | Far Detector (phase I) | Far Detector (phase II)

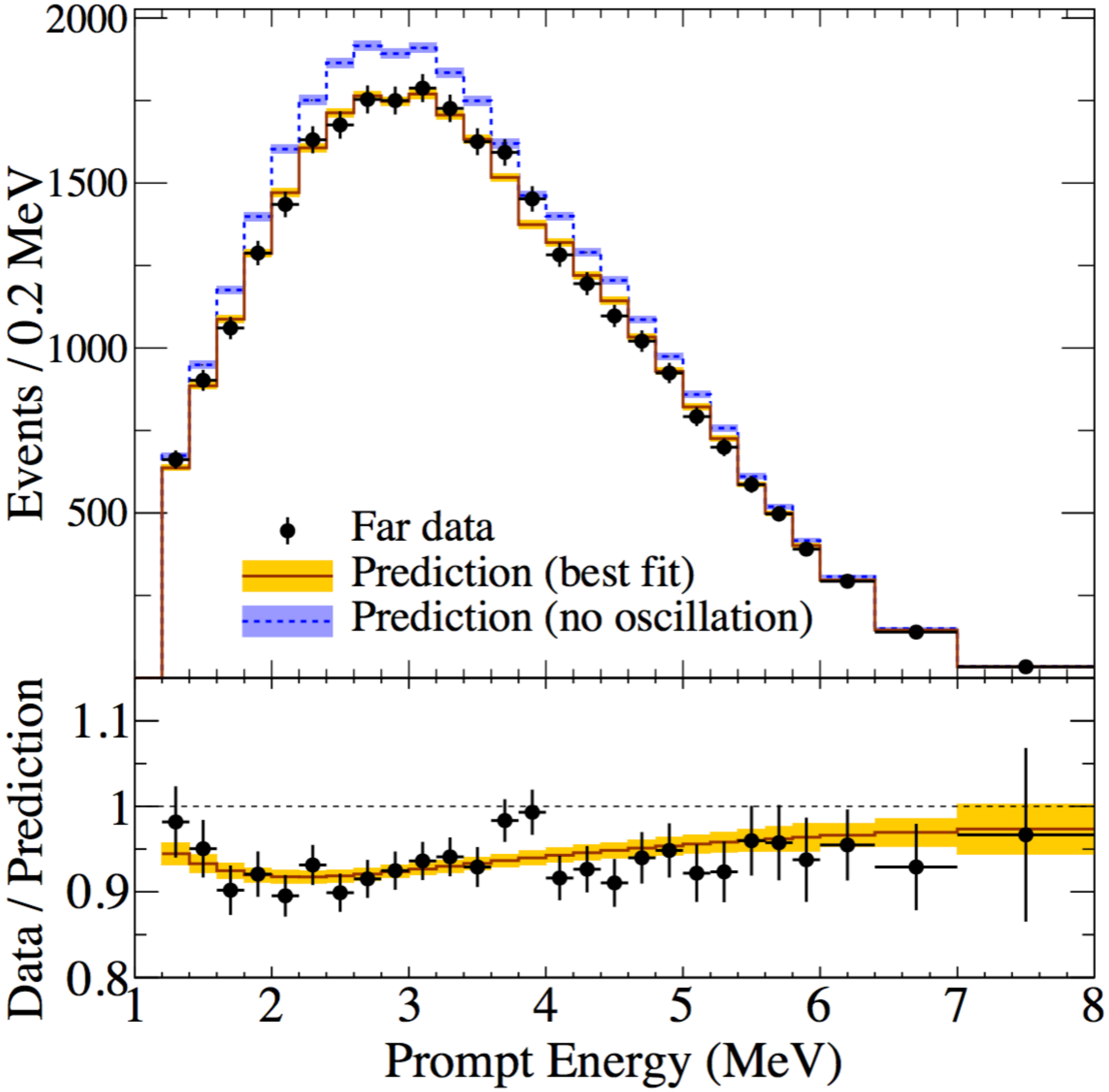


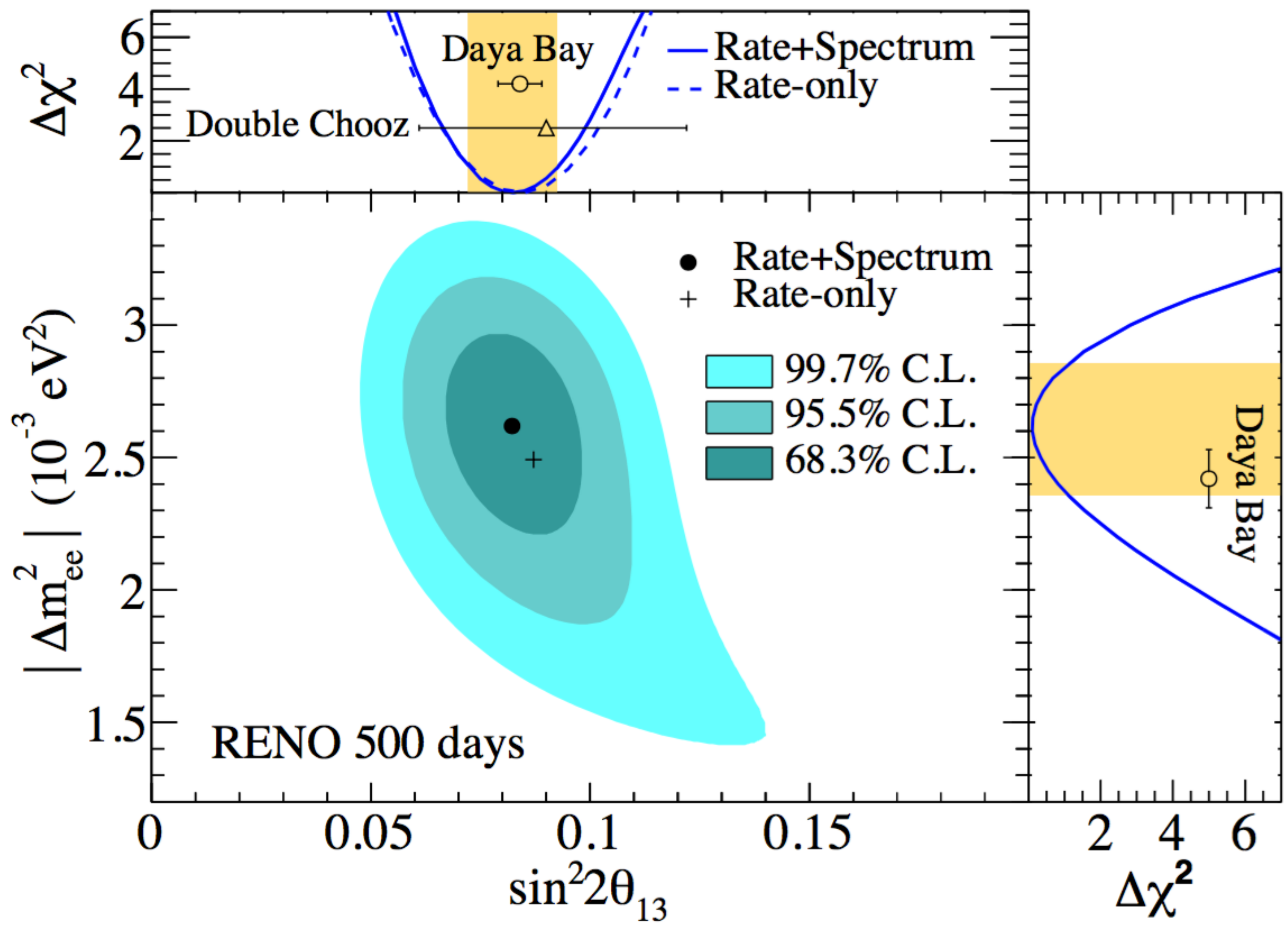
Detectors compared to MC before being compared among each in other in the fit

$\sin^2(2\theta_{13}) = 0.119 \pm 0.016$

Cabrera @ CERN (2016)

Reno Spectral Result





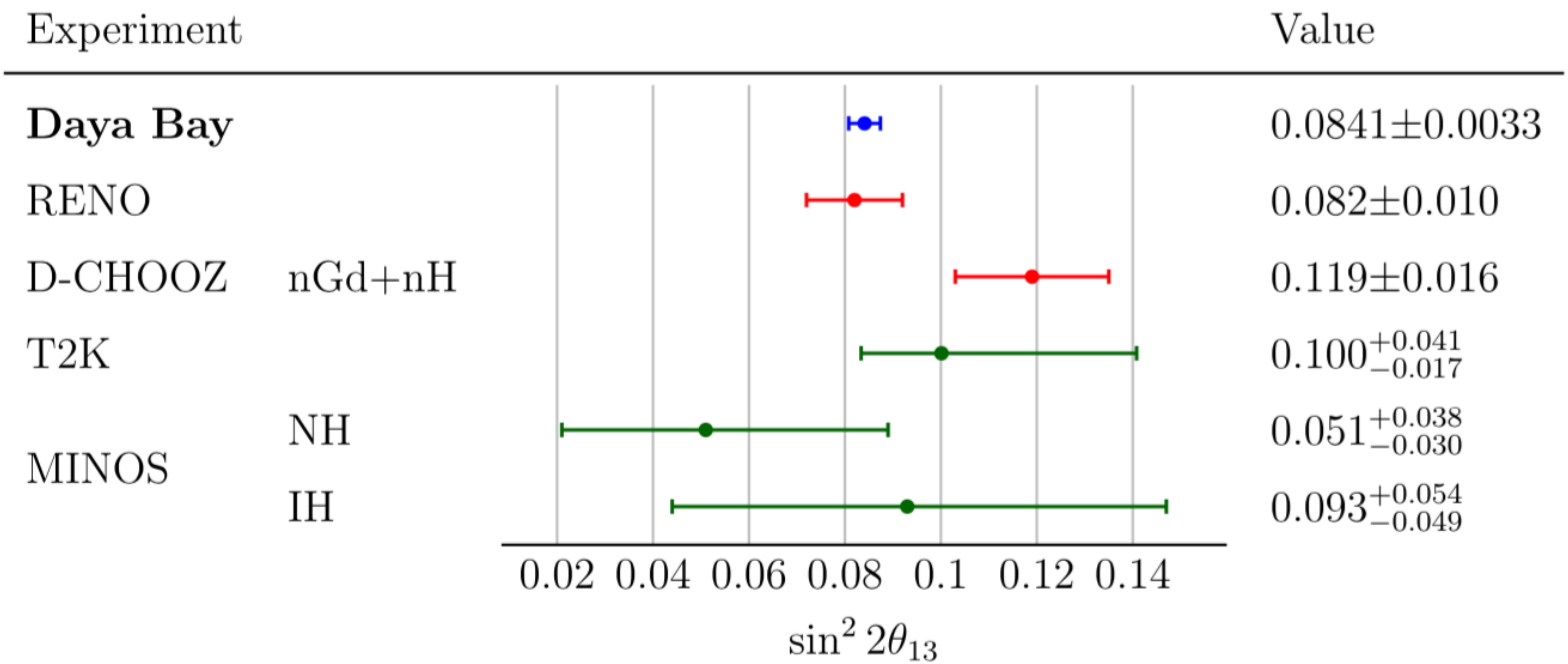
$|\Delta m^2_{ee}|$ defined as in the case of Daya Bay

$\sin^2(2\theta_{13})$ = 0.082 ± 0.009 (stat) ± 0.006 (sys)

$|\Delta m^2_{ee}|$ = [2.62 ± 0.23 (stat) ± 0.13(sys)] × 10^{-3} eV^2

arXiv 1610.04326

Results Summary



~2σ discrepancy between Daya Bay and Double Chooz

Little statistical component - Need to work on assessing (even better) **systematic unc.**

3 experiments **redundant by construction** - should get same value modulo statistics

All three experiments working together to sort it out (2 workshops already held)

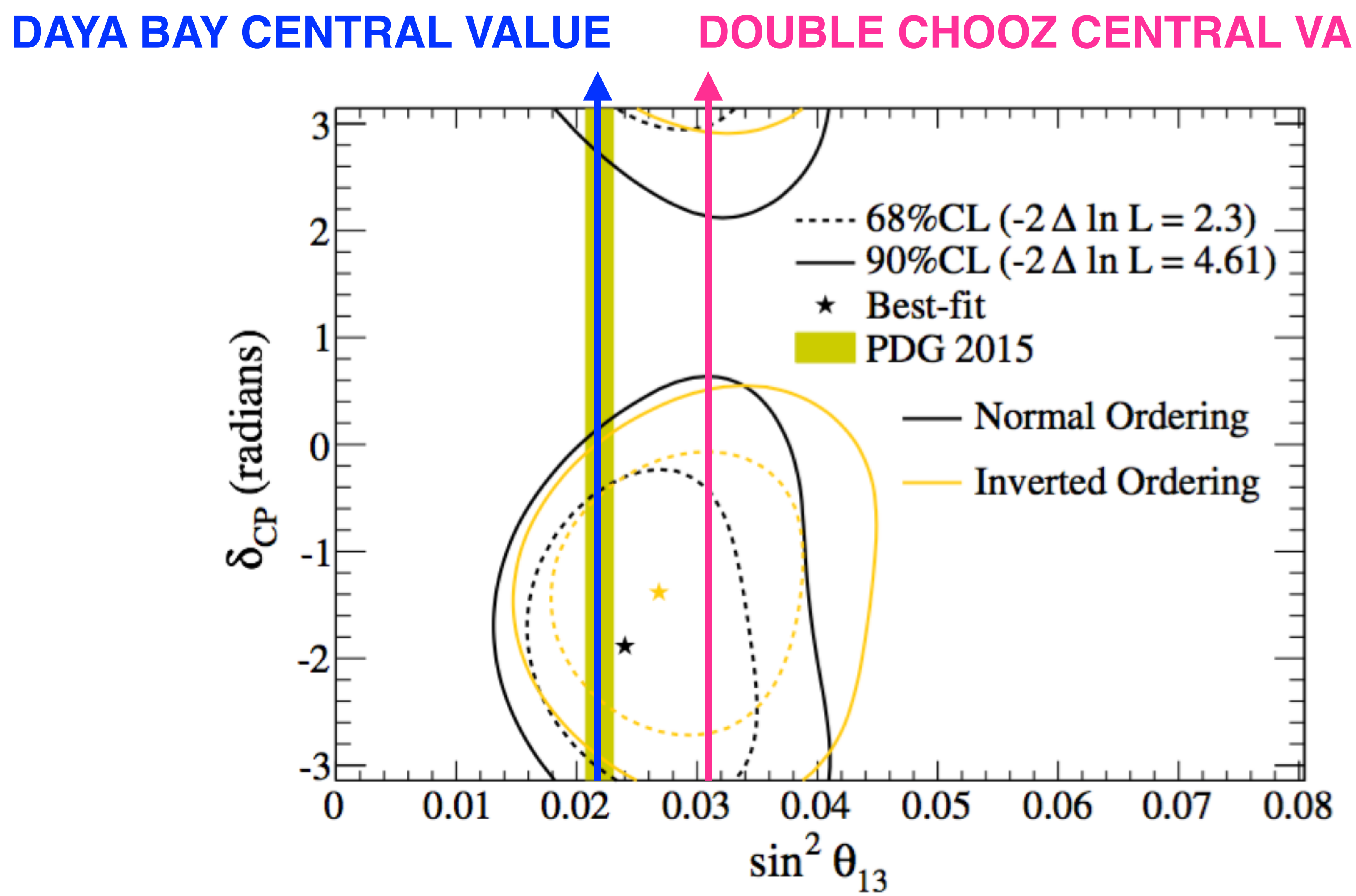
PRD 95 (2017) 072006

Impact of θ_{13} Discrepancy: Accuracy Matters!

θ_{13} experiments always pushed for **high precision** (θ_{13} was thought to be ~0)

θ_{13} **central value** (accuracy) plays an important role when combined to other exps

T2K **excludes CP conservation** at 90% CL using θ_{13} global fit (DYB dominated)



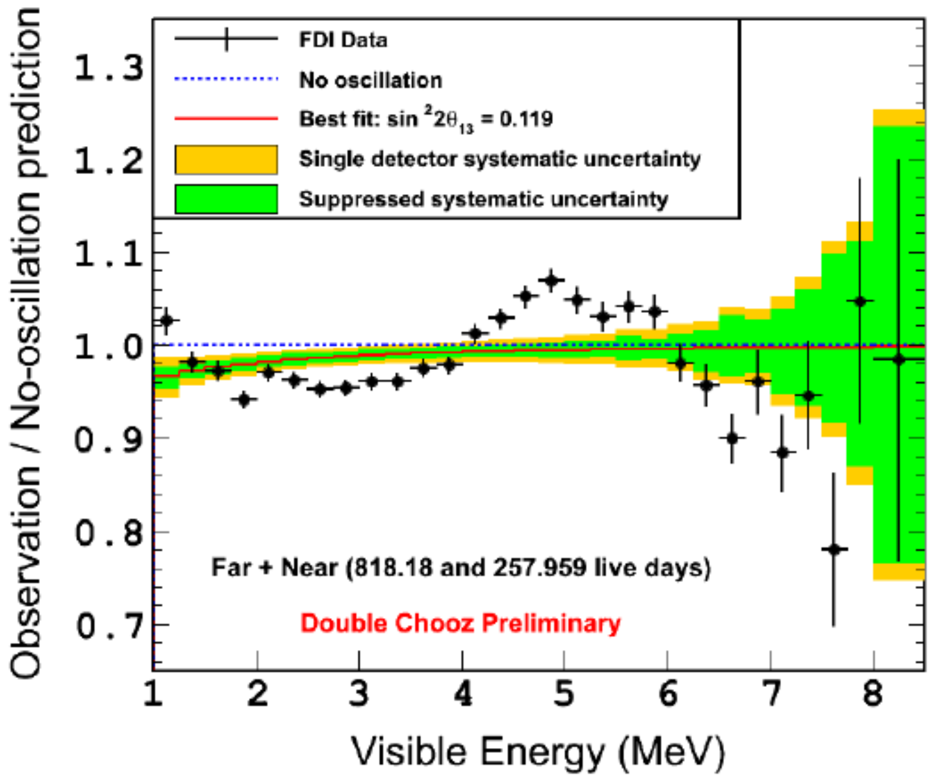
Solving discrepancy is pivotal for the field!

T2K: PRL 118 (2017) 151801

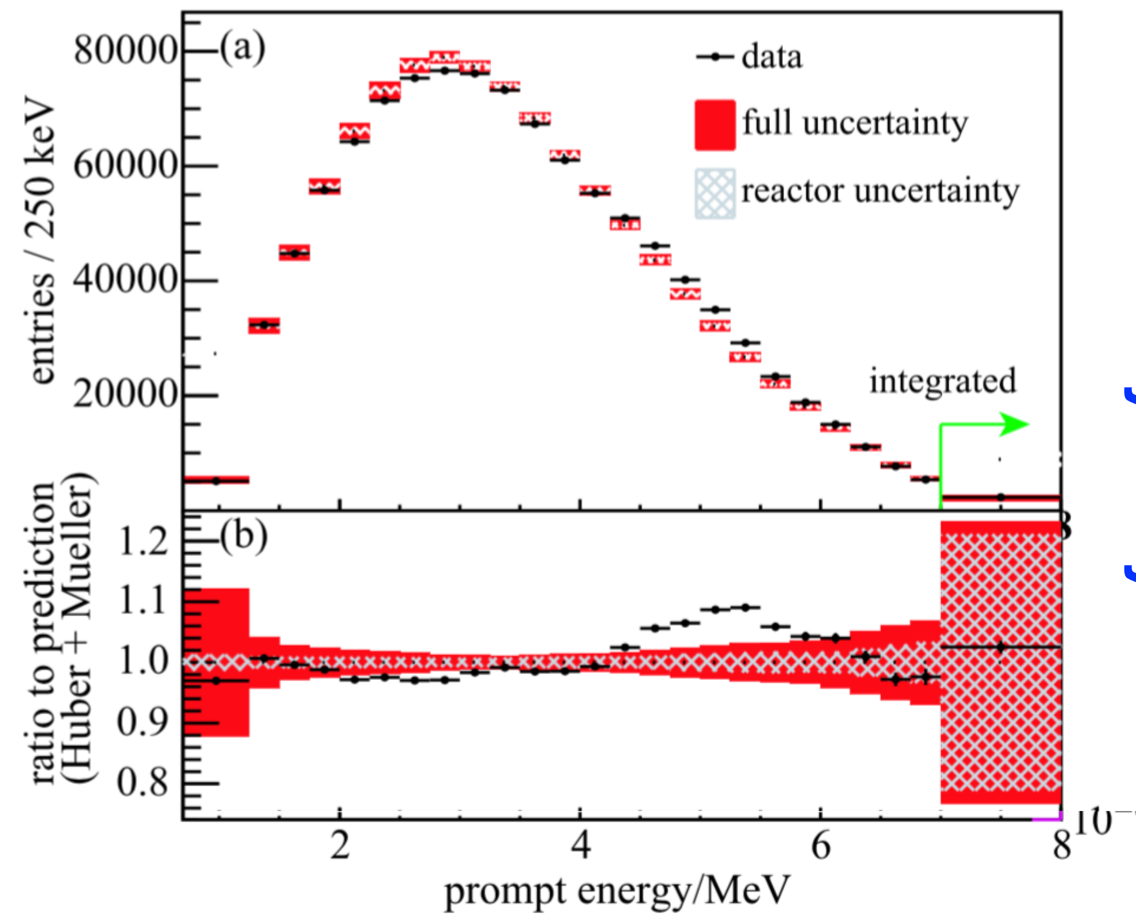
From Relative to Absolute Measurements

Observed Distortion in the Neutrino Spectrum

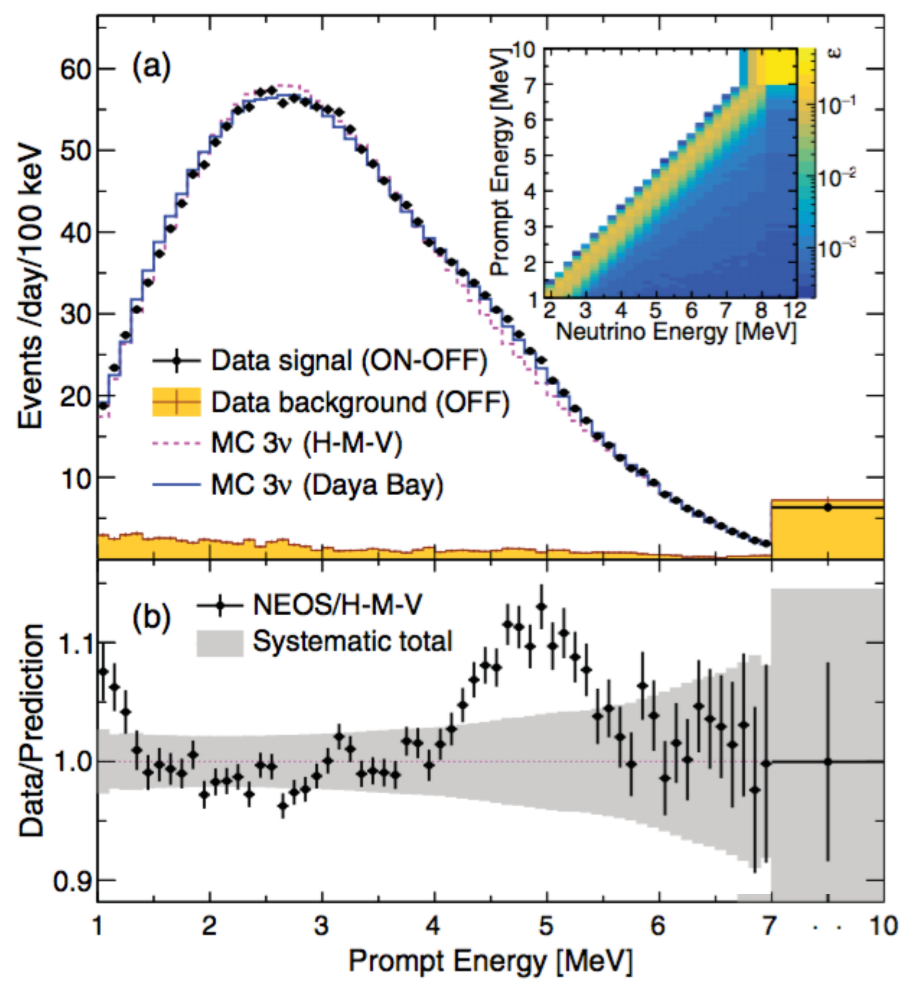
Double Chooz



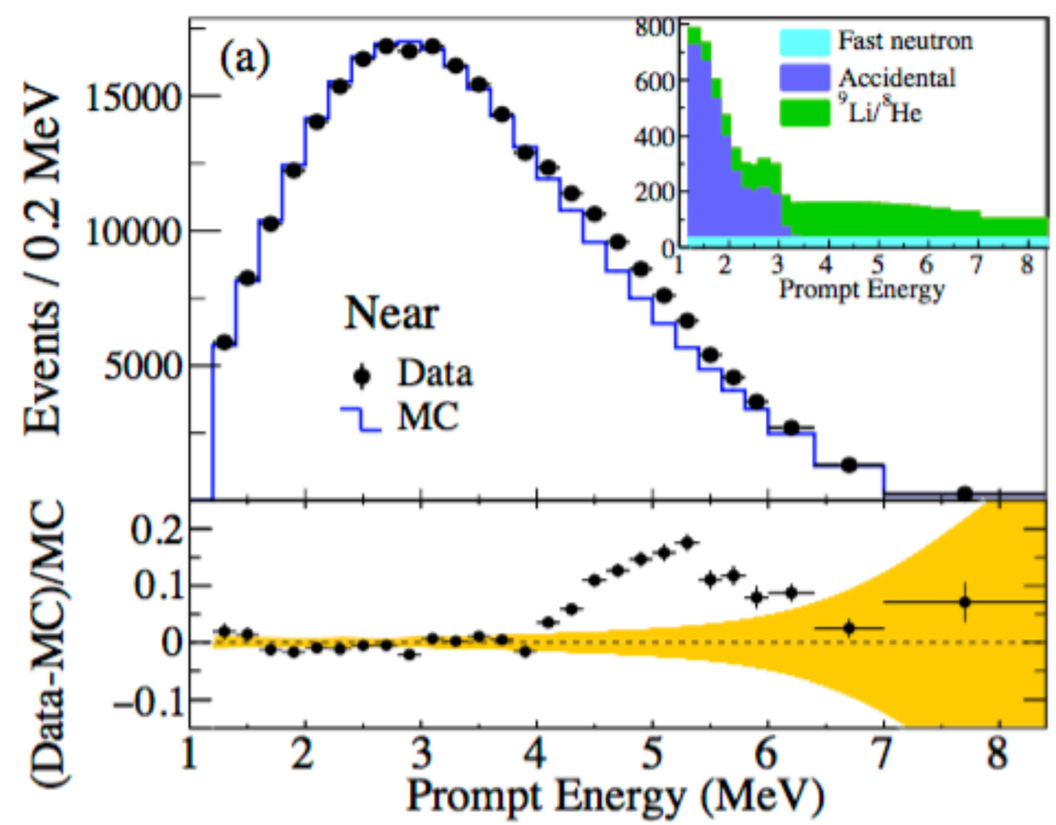
Daya Bay



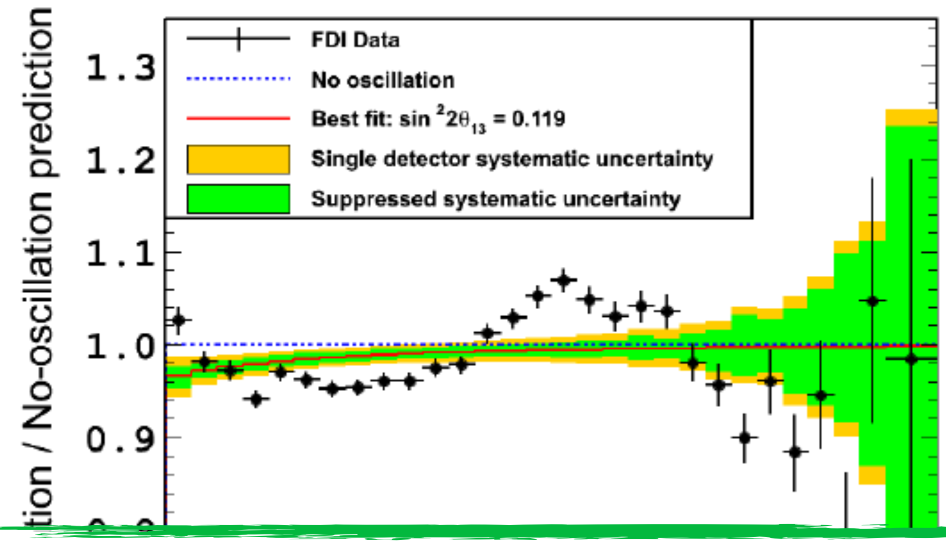
NEOS

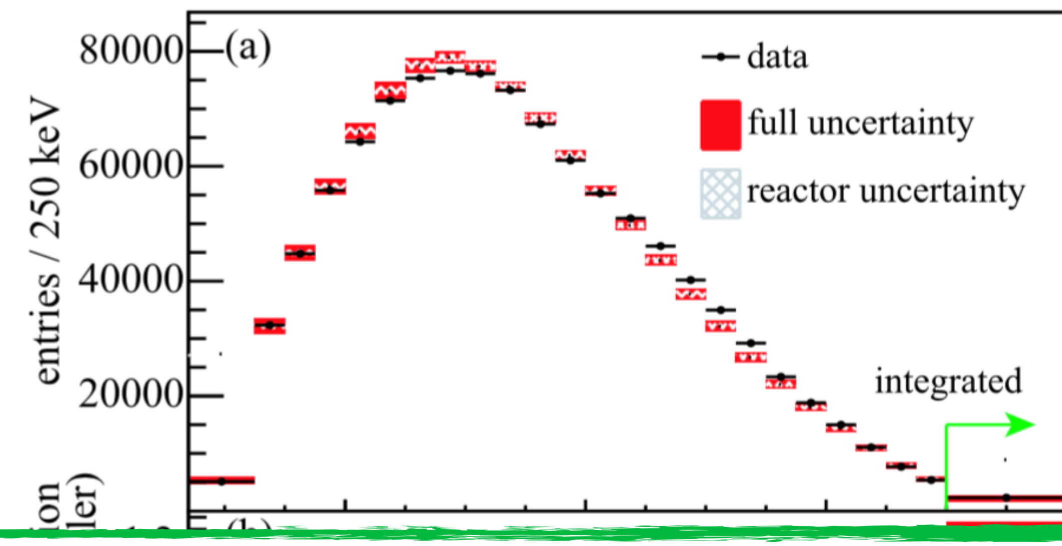


RENO



Observed Distortion in the Neutrino Spectrum





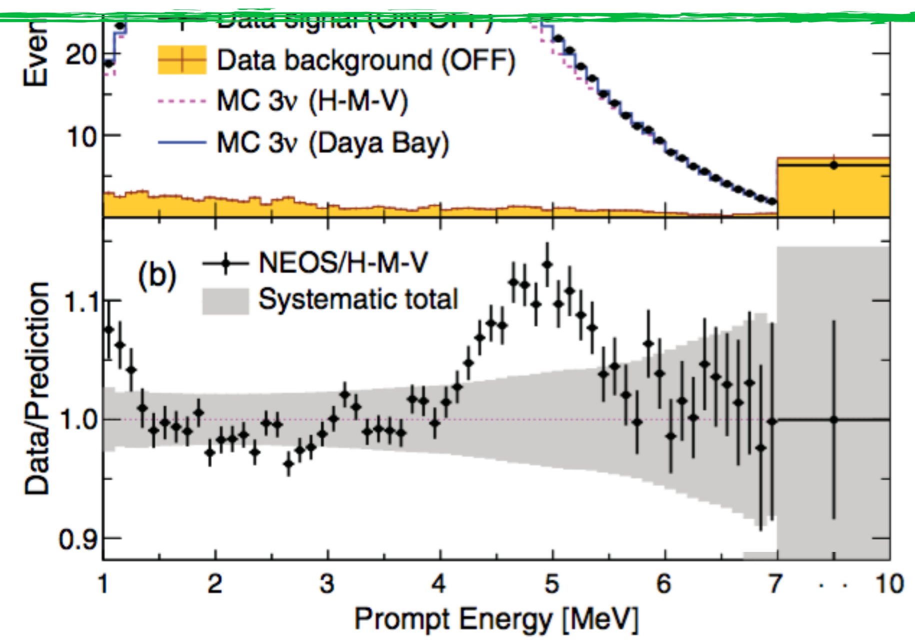
FACTS

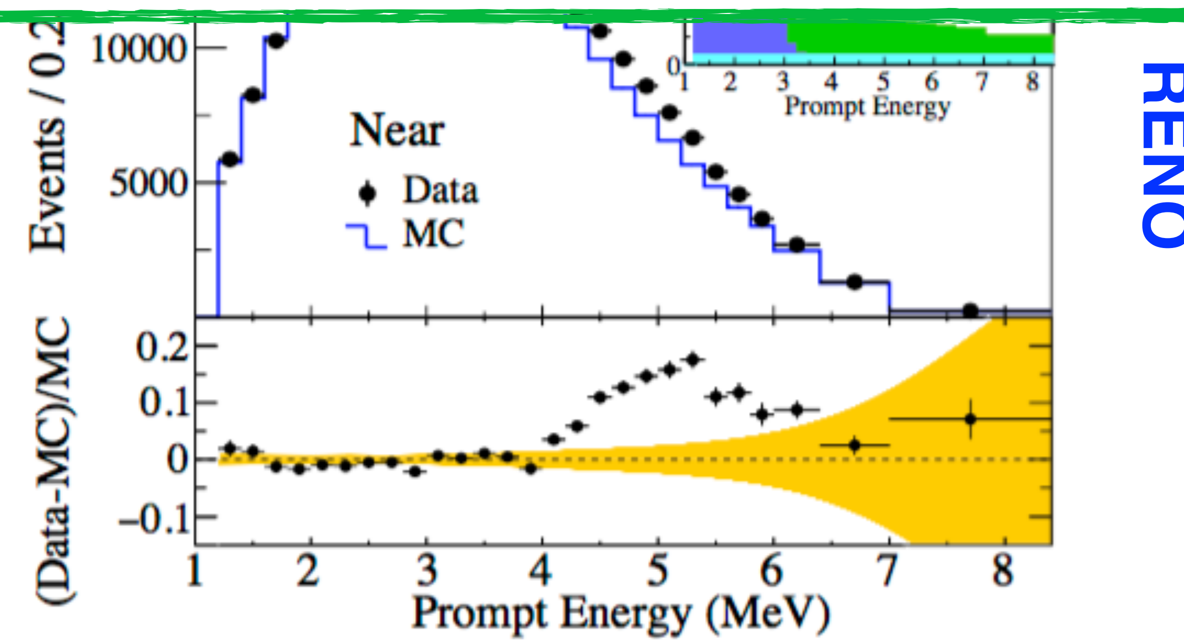
Distortion in the antineutrino spectrum at ~5MeV

Present in both near and far detectors

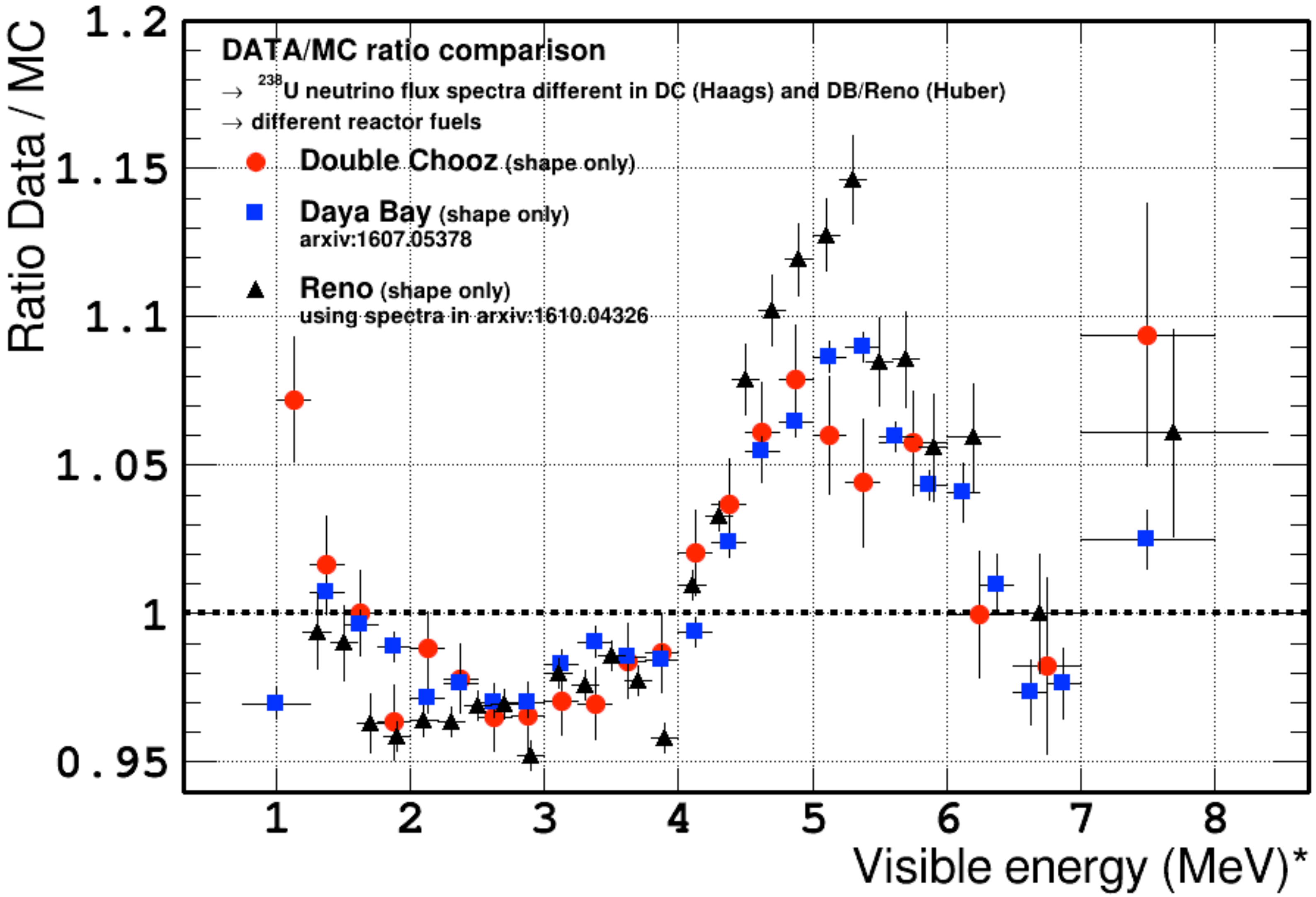
It cancels out in near-far comparison - **it does NOT affect θ_{13} measurement**

Significance scales with reactor power





Unofficial Comparison Among Experiments



* can slightly differ from one experiment to another due to detector effects

Prediction

DYB & RENO
Huber (^{235}U ^{239,241}Pu)
Muller (^{238}U)

DC
Huber (^{235}U ^{239,241}Pu)
Haag (^{238}U)

DYB & DC
same reactor manufacturer

Comparison of three θ_{13} experiments - **Data and prediction normalized to unity**

Goal: **check consistency among shapes**

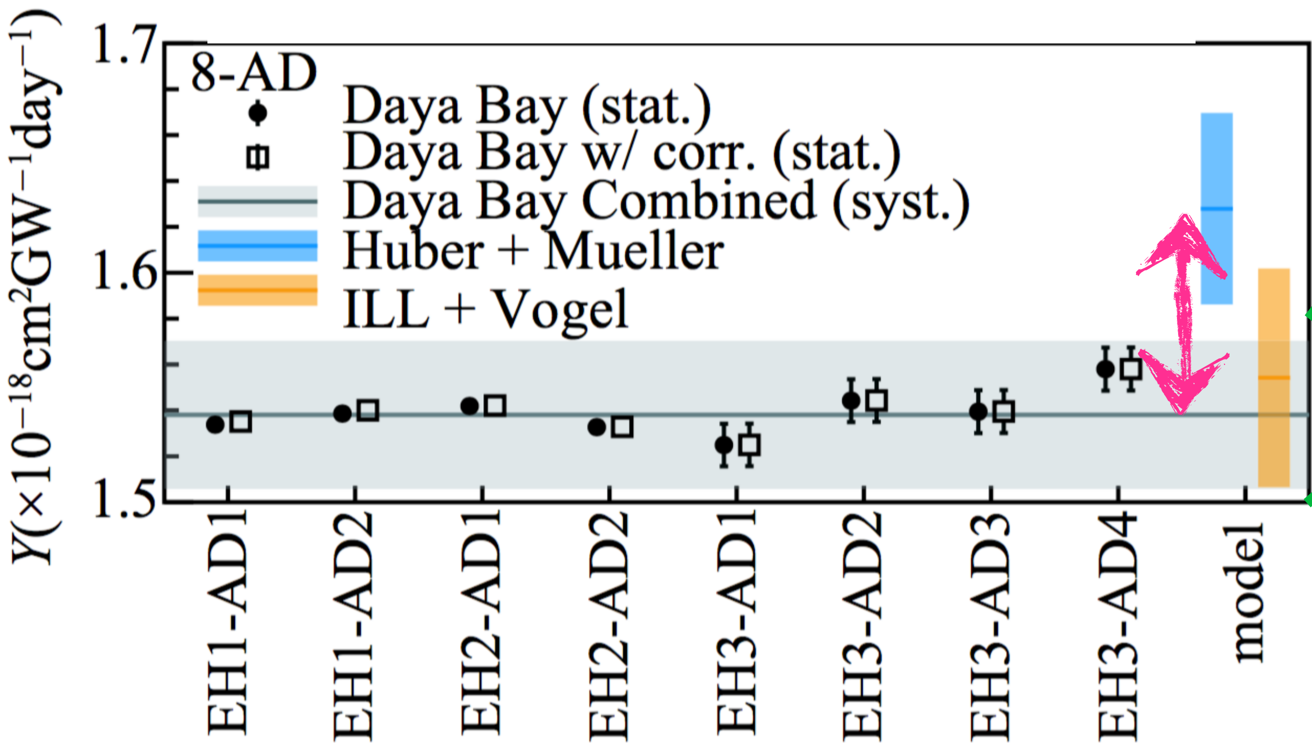
Peak consistently around E(PROMPT) ~ 5 MeV ▸ E(ν) ~ 6MeV

Not granted since - both reactor fuels and predictions are different

Cabrera @ CERN (2016)

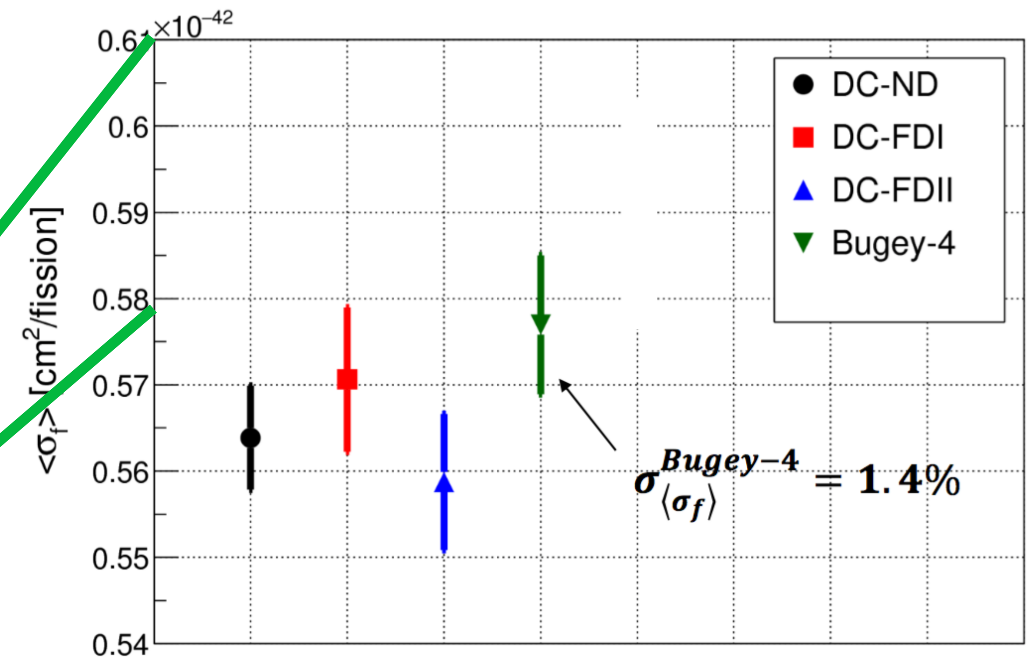
Absolute Neutrino Yield from Reactors

Daya Bay



(5.90 ± 0.13) × 10^{-43} cm²/fission

Double Chooz



(5.64 ± 0.06) × 10^{-43} cm²/fission

Average IBD cross section per fission in the nuclear reactor (or **yield/GW/day**)

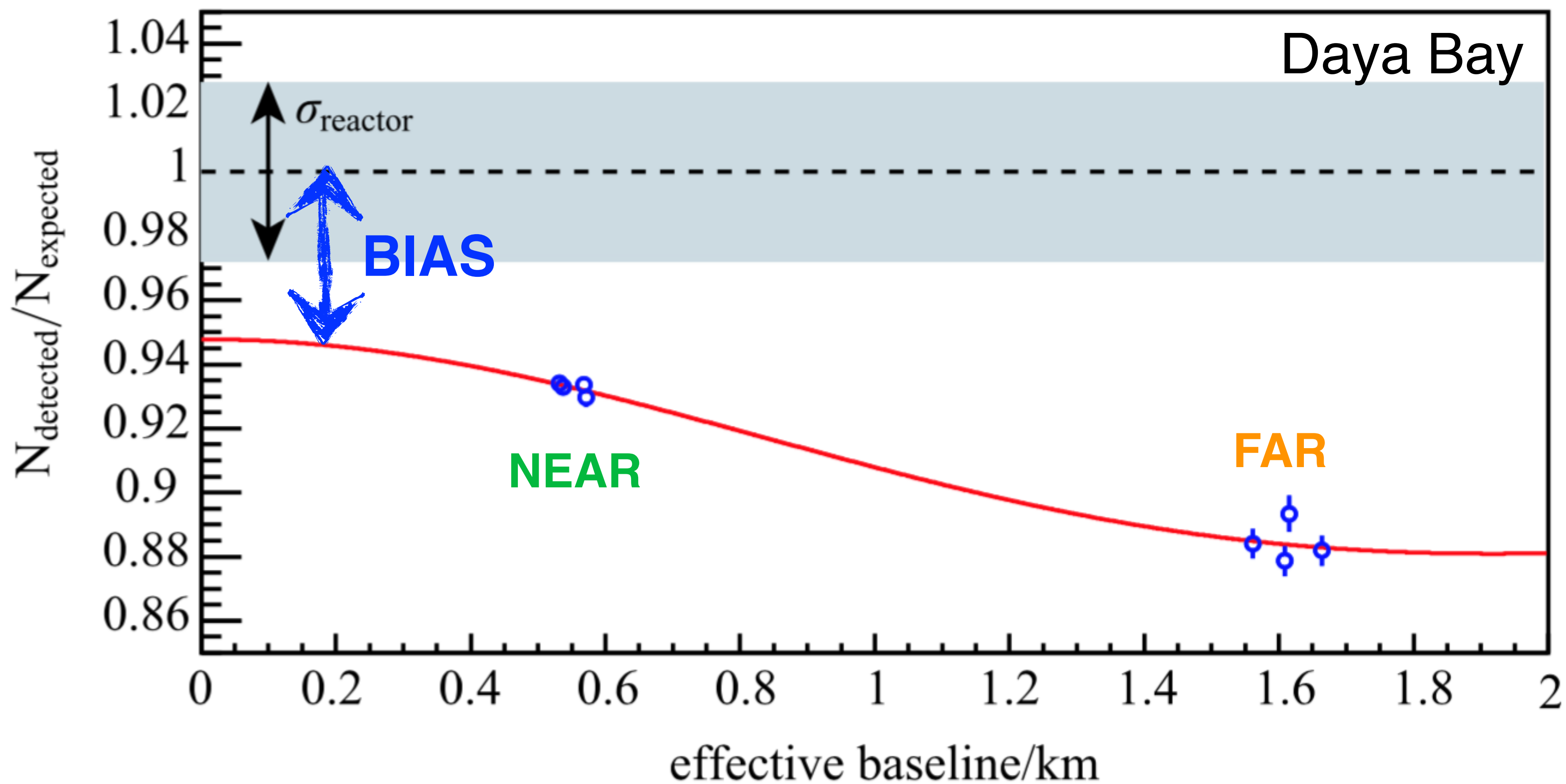
Direct comparison not trivial because of different fuel composition

Single detector systematic uncertainties now matter (DYB 1.9% - DC: 0.7%)

Discrepancy with respect to latest prediction

PRL 118 (2017) 251801 - CPC 41 (2017) 013002

Antineutrino Flux Deficit With Respect to Prediction



Antineutrino Flux depends on oscillation probability

Once extrapolated at reactor such match **prediction**

Prediction is based on **β spectra** measurements (ILL data)

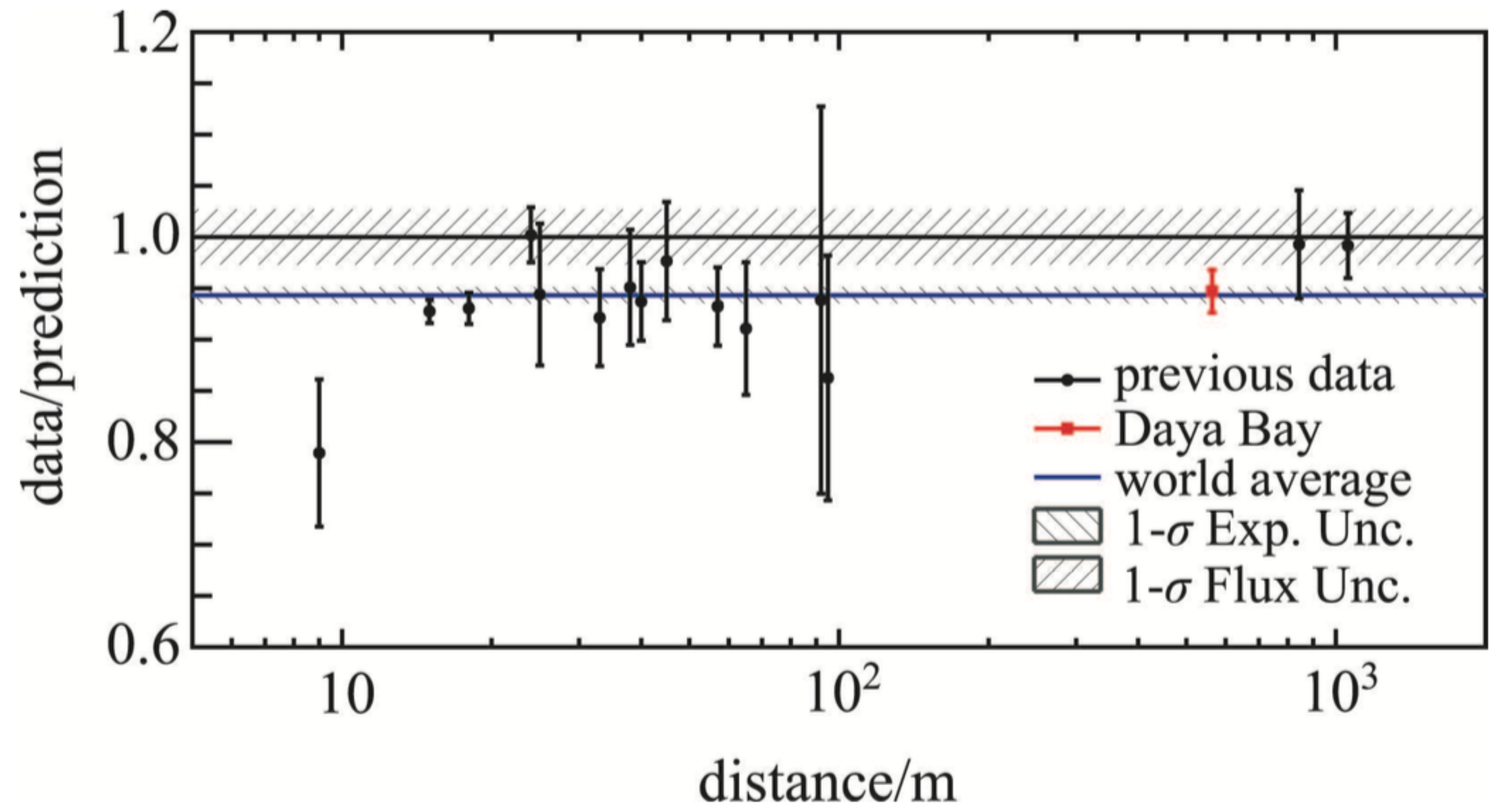
Discrepancy **exceeds uncertainty** in reactor prediction

CPC 41 (2017) 013002 - PLB 160 (1985) 325 - PLB 118 (1982) 162 - PLB 218 (1989) 365

Consistent Flux Deficit Across Experiments

#	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

Comparison of **21 measurements** to Huber+Muller prediction



$$R = \frac{\text{MEASUREMENT}}{\text{PREDICTION}} = \mathbf{0.943} \pm 0.008\ \text{(exp.)} \pm 0.023\ \text{(model)}$$

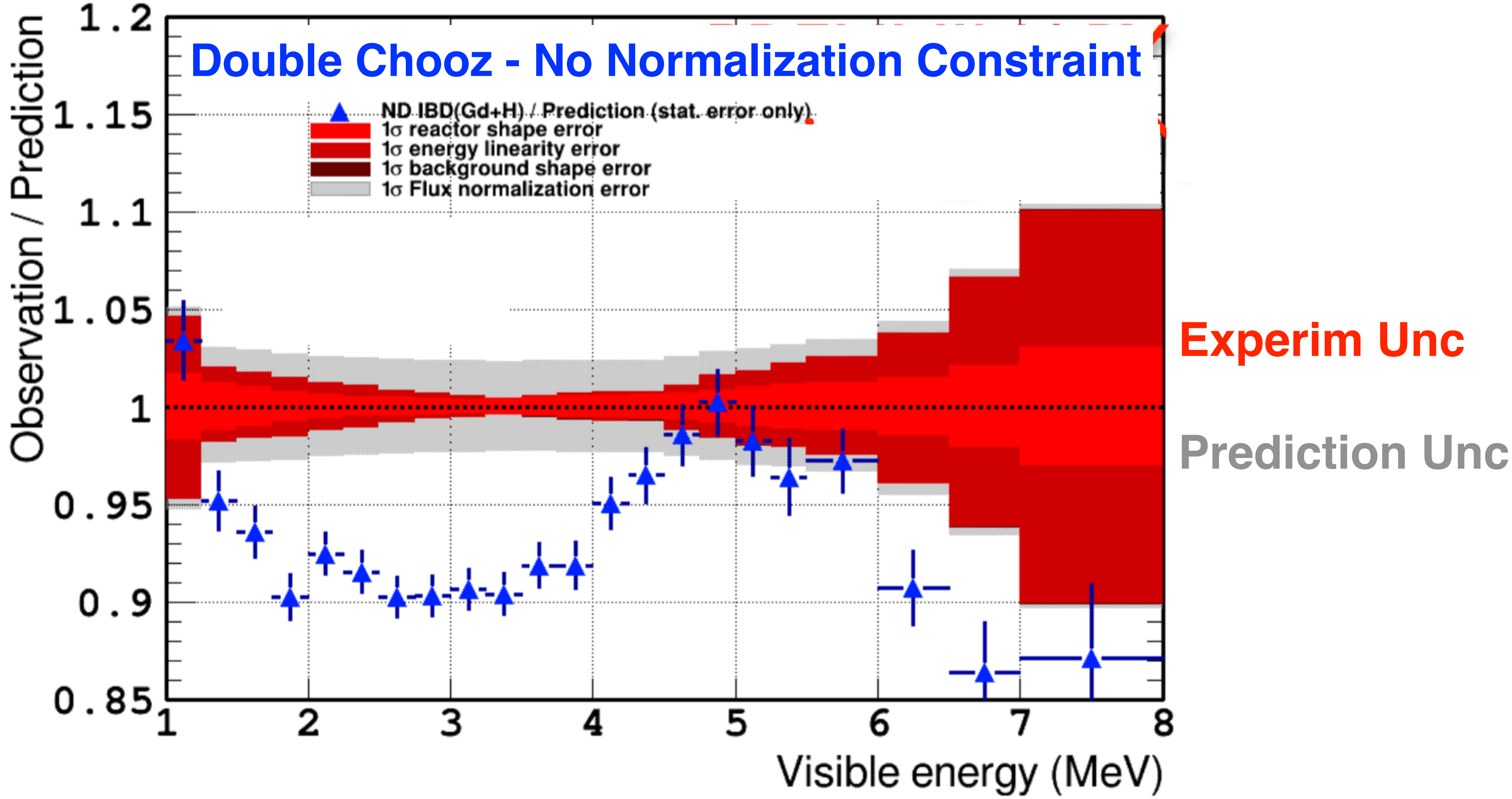
So-called "**Reactor Neutrino Anomaly**"

Accuracy Problem (once again)

central value different from prediction

CPC 41 (2017) 013002, PRC 83 (2011) 054615, PRC 84 (2011) 024617, PRD 83 (2011) 073006

A Bump or a Hole?



Spectrum distortion now taking into account flux deficit

The only region in **agreement** with prediction is now the so-called “bump”

Understating the **reactor anomaly** cannot be decoupled from understating the **reactor spectrum**

Cabrera @ CERN (2016)

What's Going on With Reactor Antineutrinos?

A non-comprehensive list of **reasons** why flux prediction might be **biased**

Disclaimer: I won't discuss how likely is each hypothesis

This slide is just to show that this is a **very difficult** issue

Additional source of ν in the reactor not arising from fission product

Unaccounted decays of the fission products (believed to be forbidden)

Neutron spectrum in reactors is **harder** than expected

A **single fission isotope** behaving different from expected

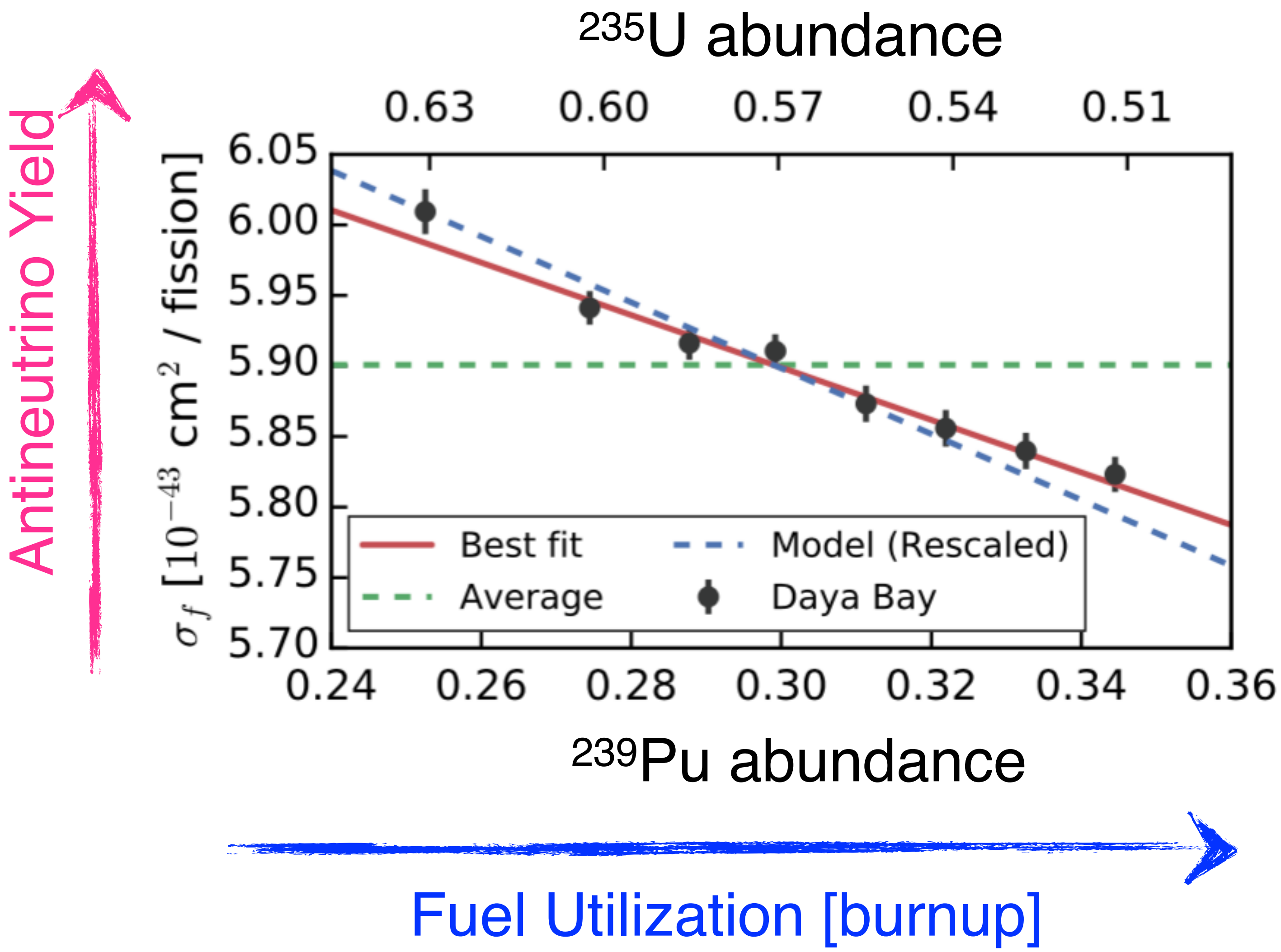
A possible mistake in old **experimental data** (ILL) used to build nowadays predictions

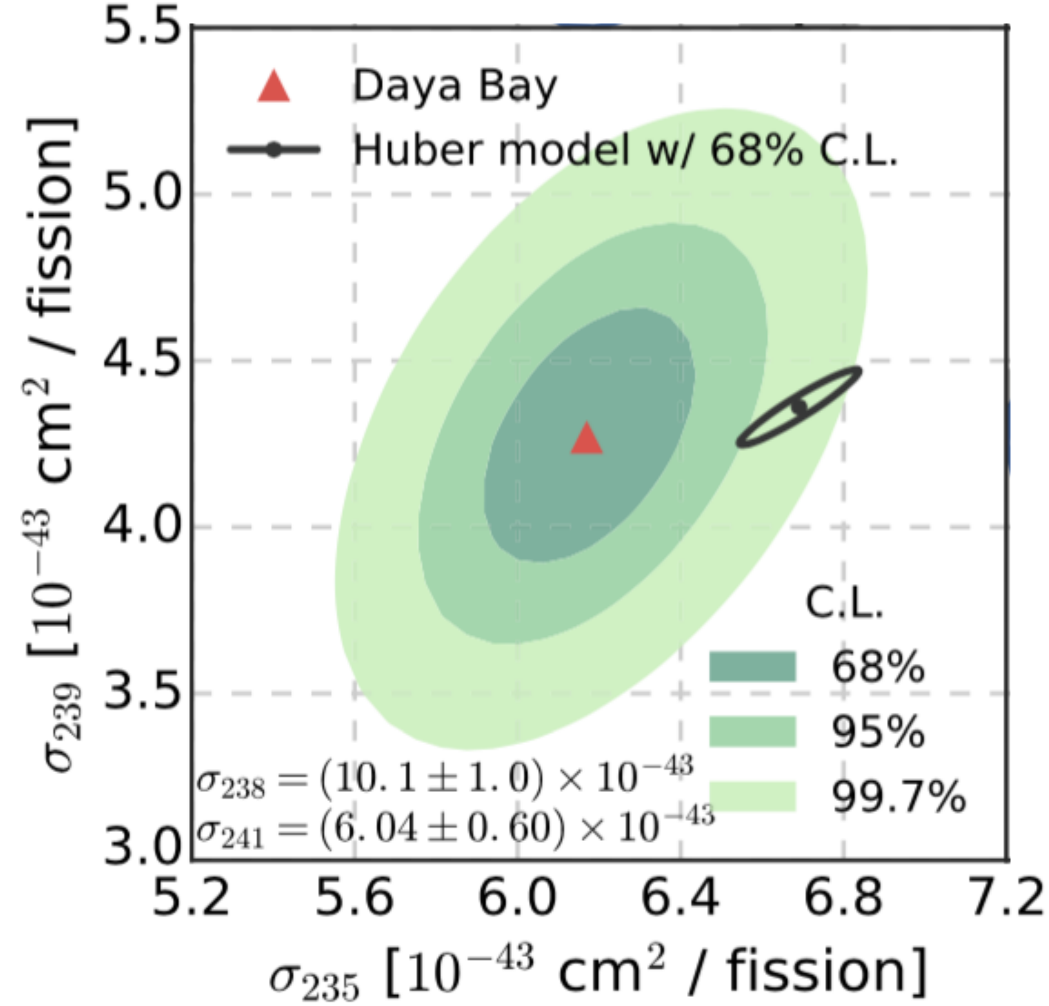
A possible issue in **nuclear databases** used to perform "ab-initio" calculations

Existence of a 4th non-interacting (**sterile**) neutrino family

Hayes @ NuPhys (2016)

Daya Bay Analysis of Antineutrino Flux





Antineutrino yield **evolves** differently with respect to expectation

Very recent result. Community is still scrutinizing it (cf. Giunti @ WIN 2016)

However strong indication that there is **something not understood in ^{235}U** flux

PRL 118 (2017) 251801

What to Conclude from Reactor Data so Far

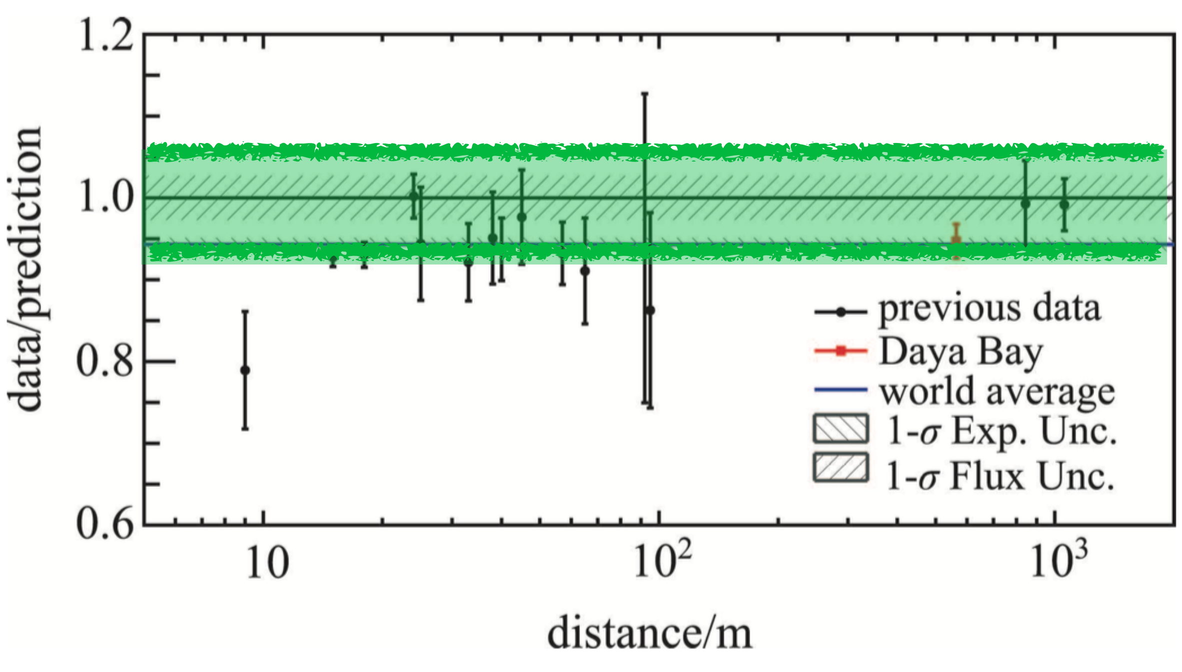
Many mechanisms might contribute to normalization issue

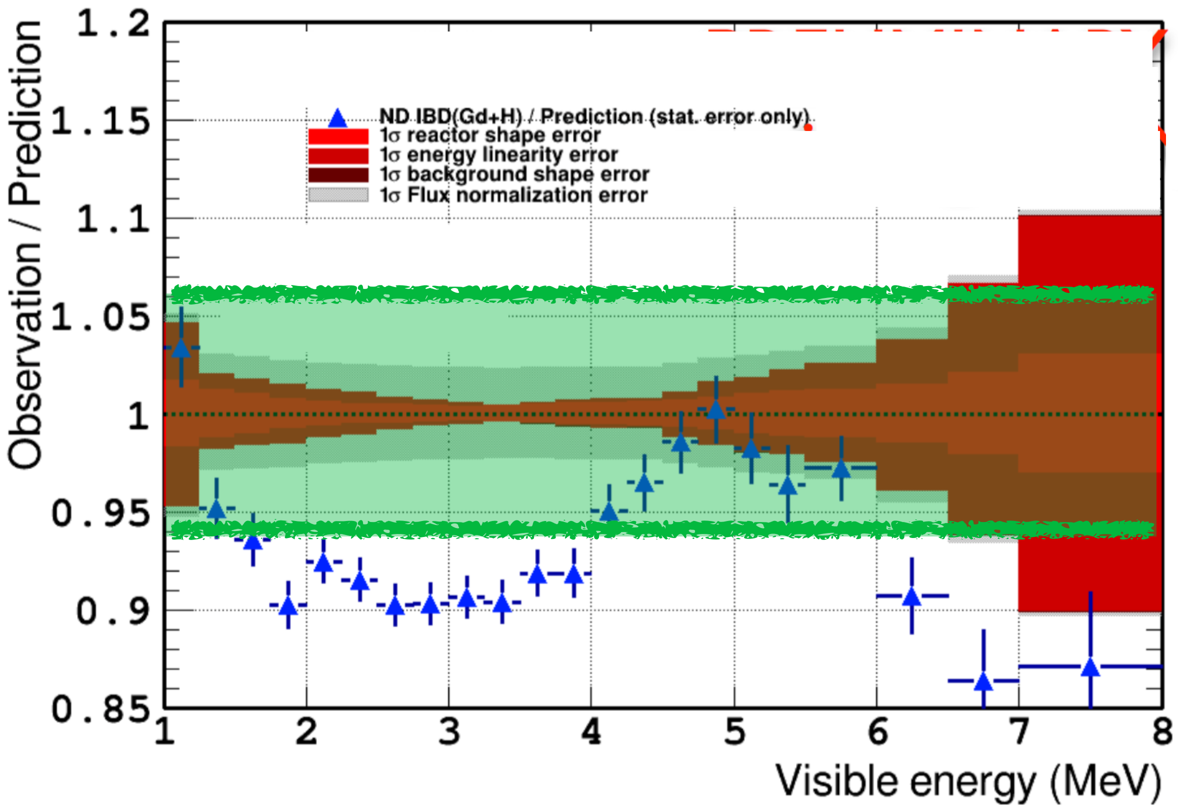
Hard to sort out single source of **accuracy problem** (possibly many)

Better to say 2.4% **precision** in predicted flux is **overestimated**

Temporary/pragmatical approach: **inflate uncertainty** band

Reactor Anomaly might **no longer be an anomaly**





Very Short Baseline Experiments

Sterile Hypothesis Intriguing because of other exp. hints

LSND (dis. DAR), **MiniBoone** (app. beam), **Gallex** (dis. radiochem.), GNO, SAGE

Important: hints are in **tension** among each other

Many **ongoing/proposed exp.** to test this hypothesis at short distance from reactors

Name	Pth (MW)	L(m)	Depth (mwe)	Target (tons)	Technology	Segmented
Neos	2700	25	20	1	Gd-LS	N
DANSS	3000	10-12	50	0.9	Gd-PS	Y
Neutrino-4	100	6-11	5-10	1.5	Gd-LS	Y
Stereo	57	9-11	10	1.7	Gd-LS	Y
Nucifer	70	7.25	surf	1	Gd-LS	N
Poseidon	100	5-15	?	1.5	Gd-LS	N
Hanaro	30	6	?	0.06	Gd-LS	N
Solid	100	6-11	10	1.6	^{6}Li-PS	Y
Prospect	85	7-12	few	3	^{6}Li-PS	Y
NuLat	20	5	?	1	^{6}Li-PS	Y
Chandler	1790	?	surf	0.08	^{6}Li-PS	Y

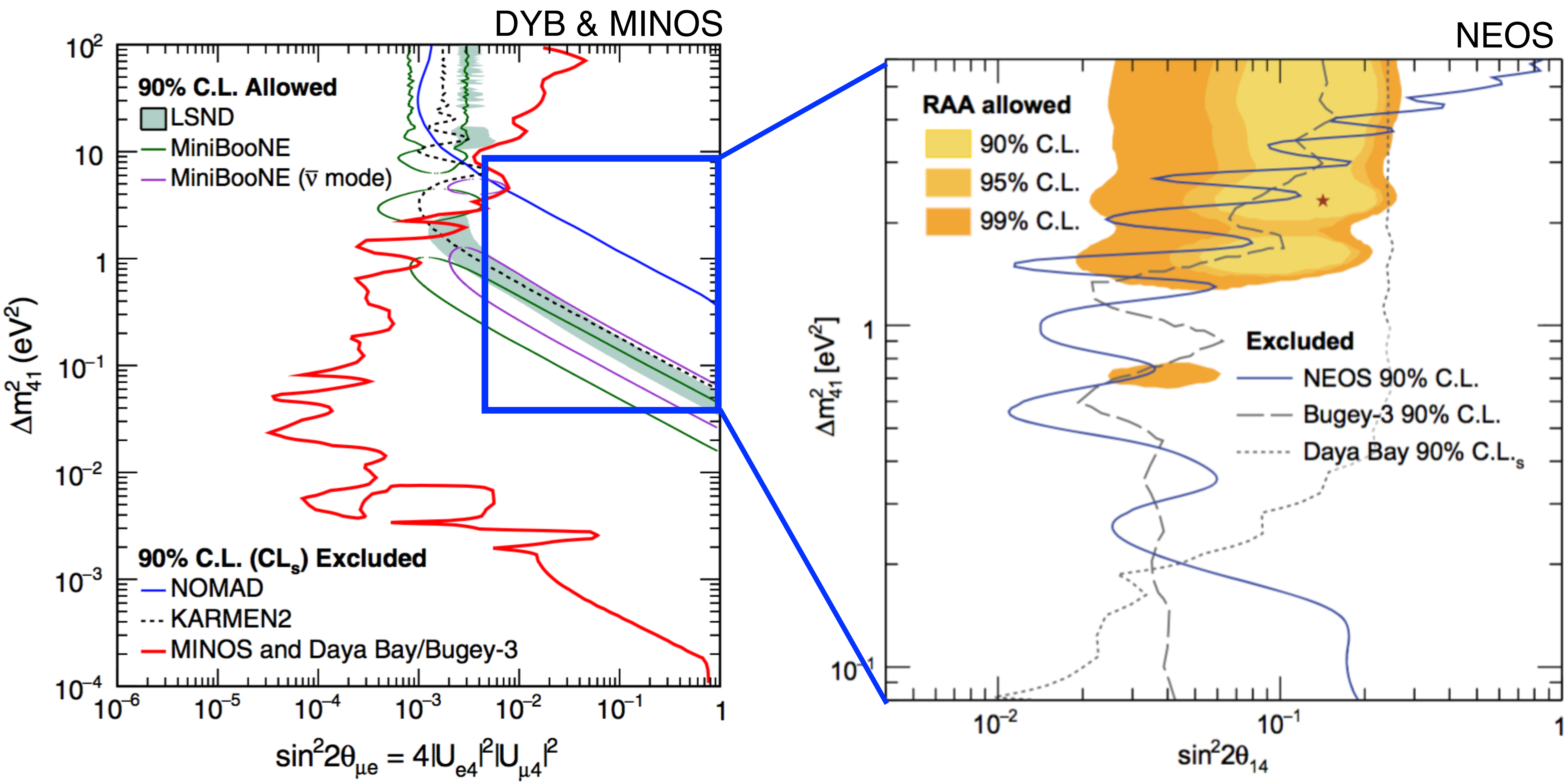
Buck @ LGNS (2017) - Heeger @ FROST (2016)

Broader Sterile Limits from DYB+Minos & NEOS

Daya Bay and **MINOS** sensitive to complementary ranges of oscillation params

Combination able to **exclude most of previous claims** (LSND,MiniBooNE) at 95%CL

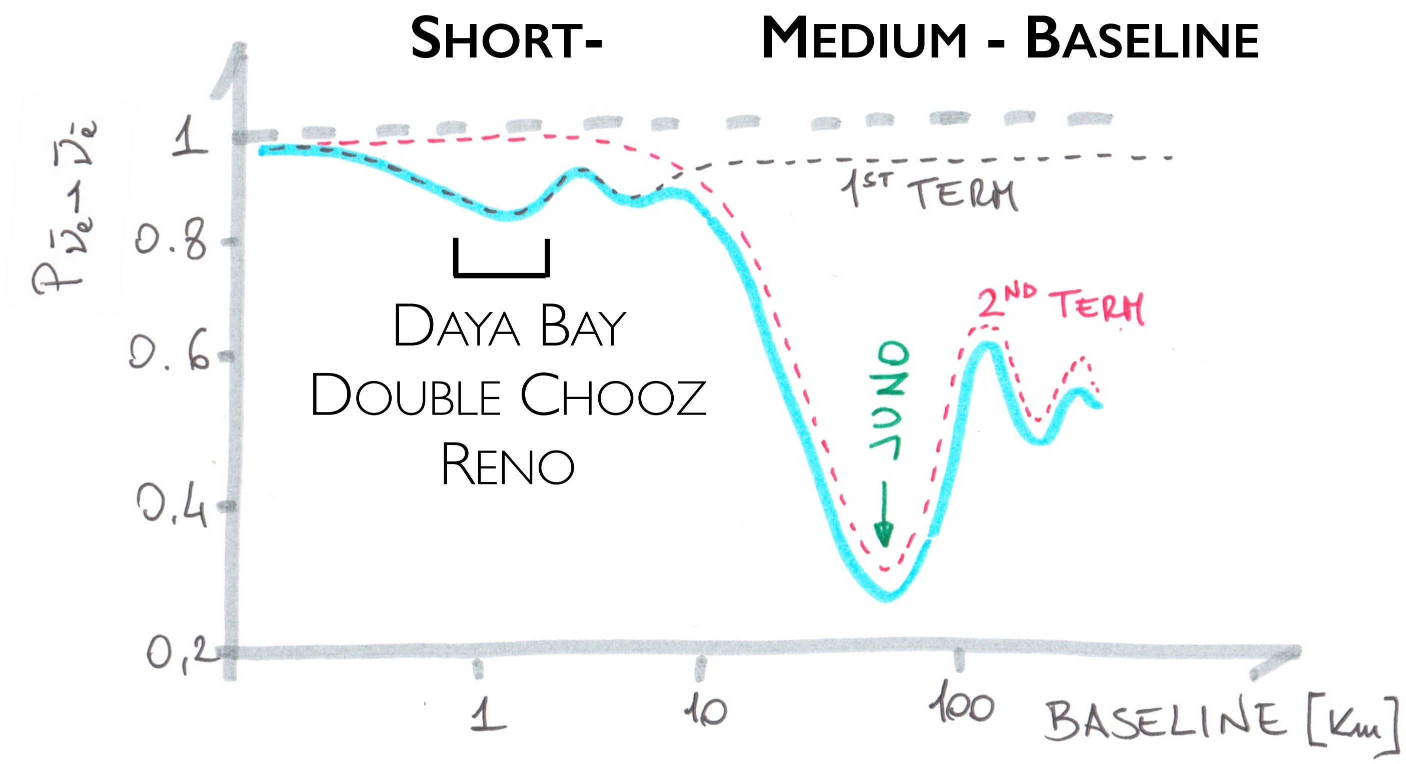
NEOS just joined the quest (caveat: result based on normalization to DYB)

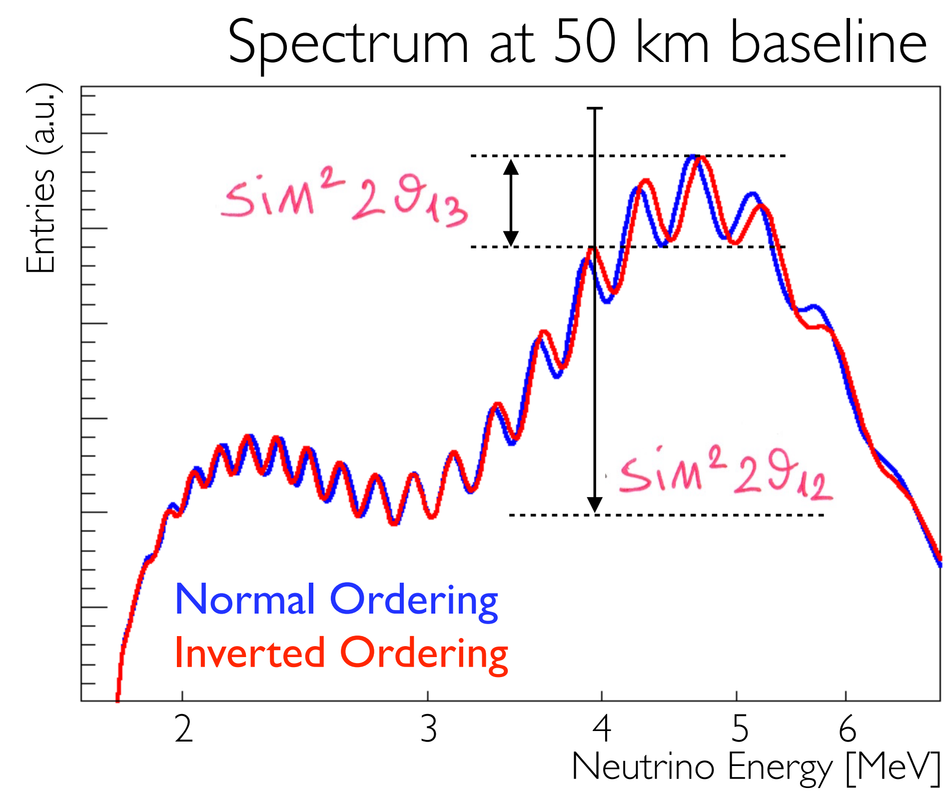


DYB & MINOS: PRL 117 (2016) 150801 - NEOS: PRL 118 (2017) 121802


What's Next…

JUNO: a Medium-Baseline Reactor Experiment





Primary Goal: determine neutrino mass ordering

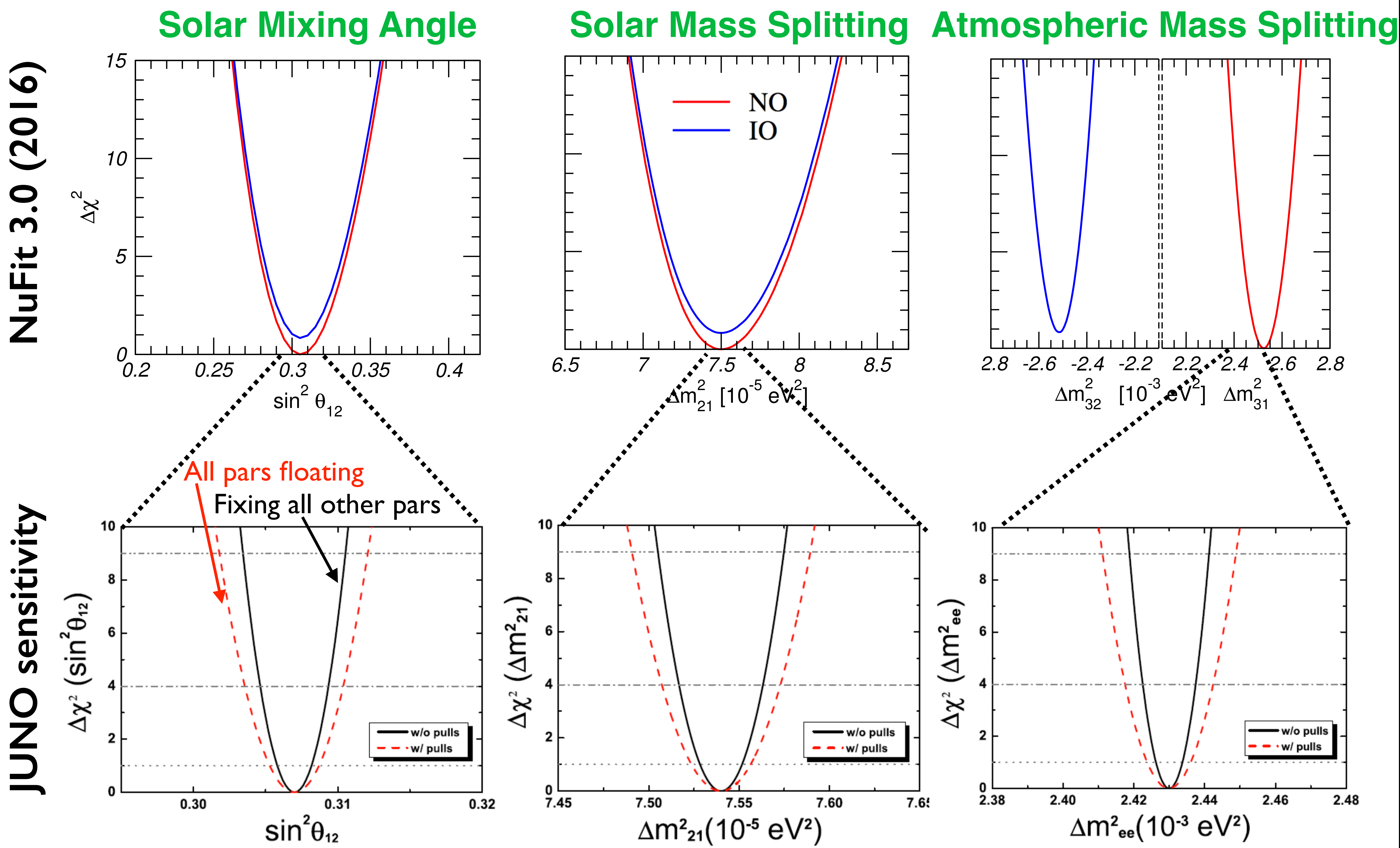
$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \sin^2 2\vartheta_{13} \cdot \sin^2\left(\cos^2\vartheta_{12} \sin^2\Delta_{31} + \sin^2\vartheta_{12} \sin^2\Delta_{32}\right) \quad \text{FAST}$$

$$- \sin^2 2\vartheta_{12} \cos^4\vartheta_{13} \sin^2\Delta_{21} \quad \text{SLOW}$$

Exploit interference between Δm^2_{ATM} & Δm^2_{SOL}

$$\Delta_{ij} = \Delta m^2_{ij} \frac{L}{4E}$$

Sensitivity to Oscillation Parameters (Direct Constraints)



$\sin^2(\theta_{12})$: 0.54%

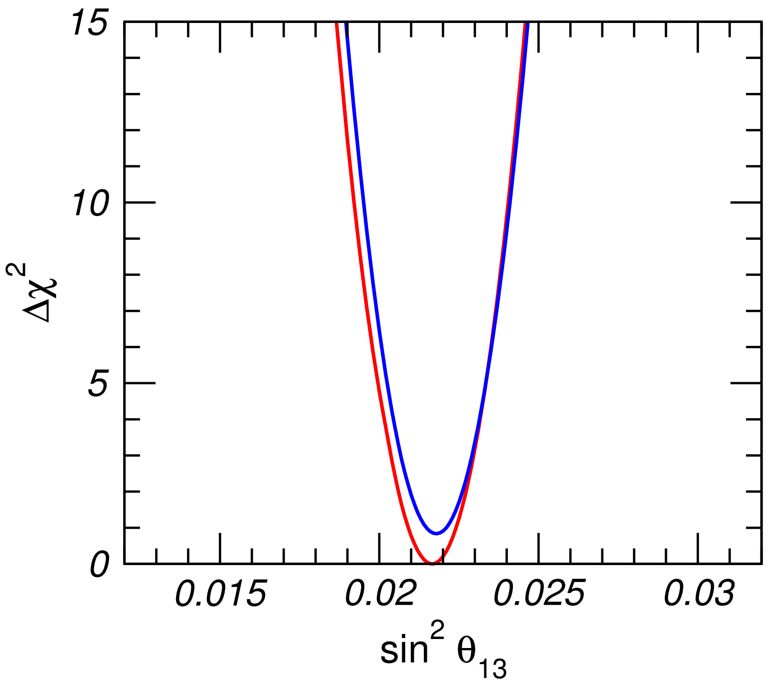
Δm^2_{21}: 0.24%

Δm^2_{ee}: 0.27%

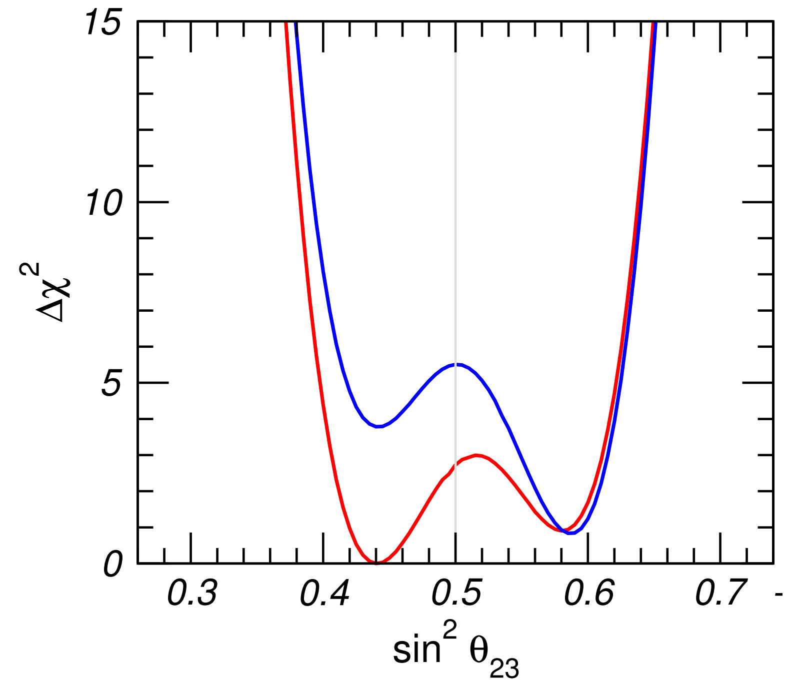
Sensitivity to Oscillation Parameters (Indirect Constraints)

NuFit 3.0 (2016)

Reactor θ_{13}



θ_{23} octant



JUNO precision comparable to Double Chooz nowadays (~15 %)

Might be the only experiment to crosscheck θ_{13} accuracy

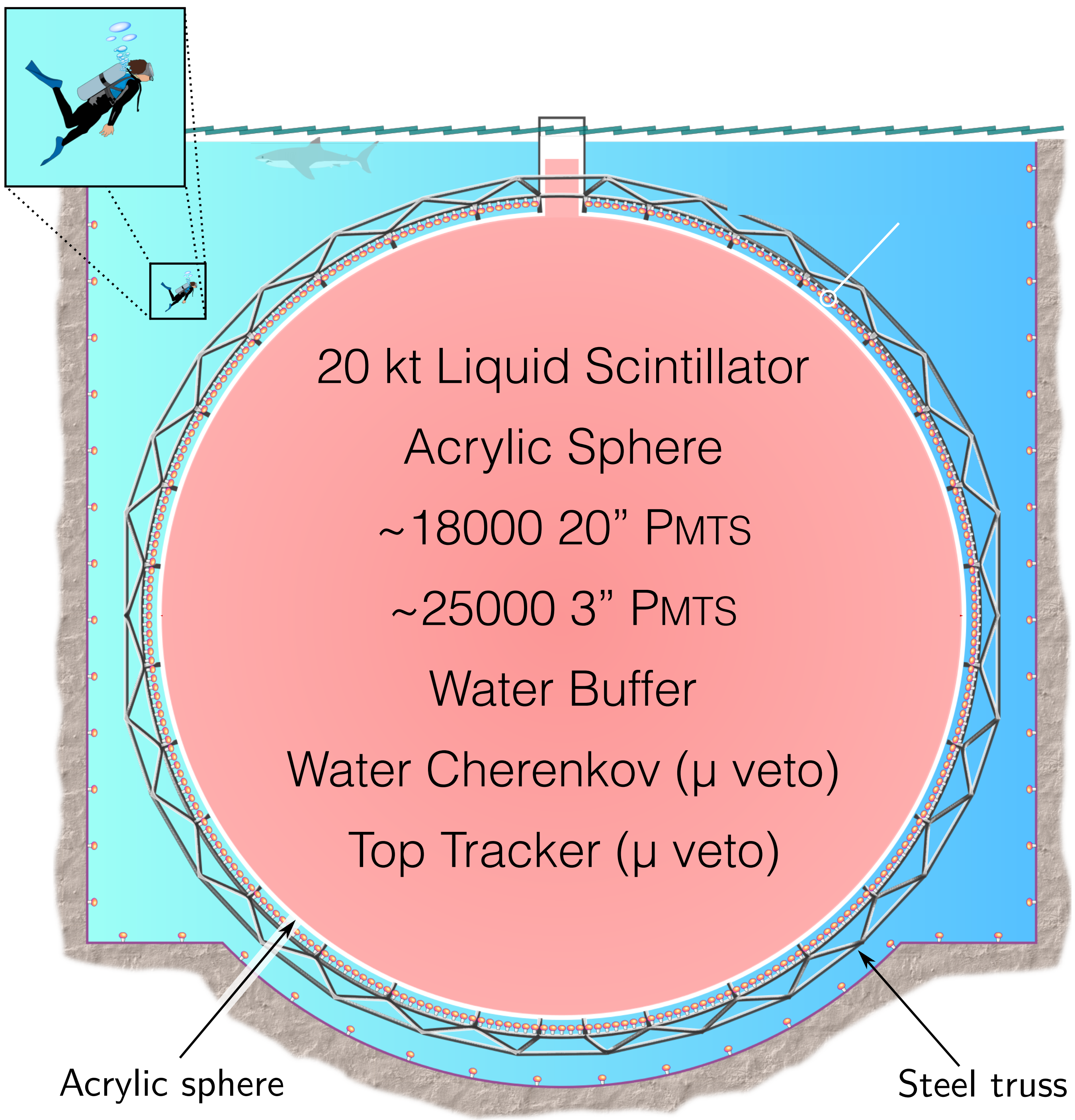
Normal Ordering

Inverted Ordering

Through mass ordering determination

Detector Overview

Liquid Scintillator (Anti)neutrino Detector



2 Key parameters:

LARGE & PRECISE

	DETECTOR TARGET MASS	RESOLUTION
KamLAND	1000 t	$6\%/\sqrt{E}$
Double Chooz	8 t	$8\%/\sqrt{E}$
RENO	16 t	$8\%/\sqrt{E}$
Daya Bay	20 t	$8\%/\sqrt{E}$
Borexino	300 t	$5\%/\sqrt{E}$
JUNO	20000 t	$3\%/\sqrt{E}$

Conclusions

θ_{13}: from being the last unknown mixing angle to be the **most precise (4%)**

Precision is not enough: settling **accuracy** is the next goal

Through antineutrinos we unveiled possible **issues in reactor models** (unspotted in nuclear physics for decades)

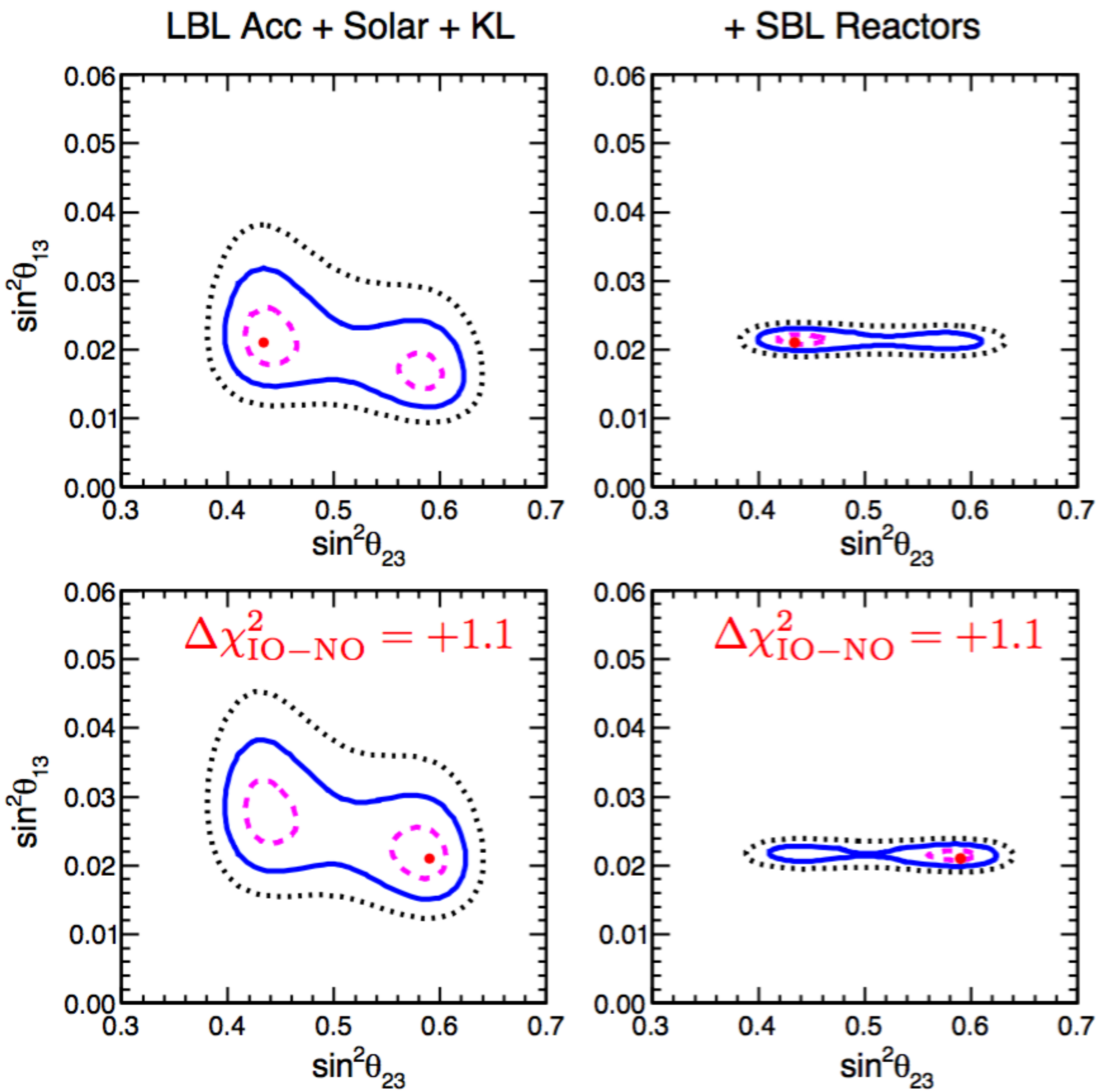
Confirmed **deficit** in total flux and showed **distortion** in energy spectrum (Is reactor anomaly still an anomaly?)

Stringent **limit on sterile** neutrino phase space

Reactor Antineutrino Experiments have **still a lot to say** (neutrino mass ordering, permille estimation of mixing parameters)

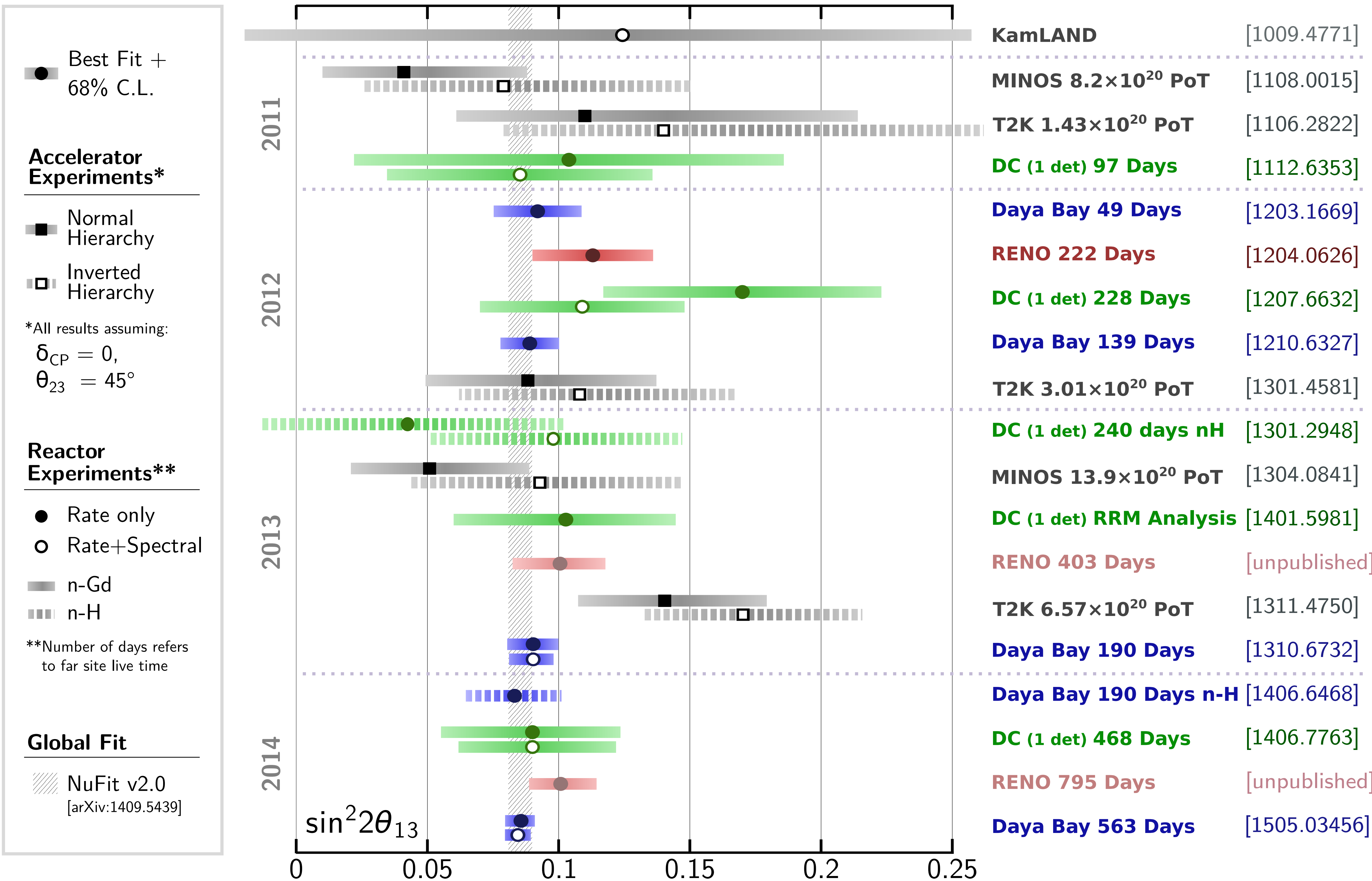
EMPTY

Impact of θ13 on θ23



Marrone @ WIN (2017)

Early History of $\sin^2(2\theta_{13})$



Reactor Models

Two fissile antineutrino spectrum models

1) ILL + Vogel

ILL model of ^{235}U, ^{239}Pu, ^{241}Pu — Phys. Lett. B 118, 162 (1982); Phys. Lett. B 160, 325 (1985); Phys. Lett. B 218, 365 (1989)

Vogel's theoretical model of ^{238}U — Phys. Rev. C 24, 1543 (1981)

2) Huber + Muller

- Huber's model of ^{235}U, ^{239}Pu and ^{241}Pu — Phys. Rev. C 84, 024617 (2011)
- Muller's model of ^{238}U — Phys. Rev. C 83, 054615 (2011)

→ Chosen as reference because of improved treatment of beta-to-antineutrino conversions

DYB Event Rate

	EH1		EH2		EH3			
	AD1	AD2	AD3	AD8	AD4	AD5	AD6	AD7
ΔN_p [%]	0.00 ± 0.03	0.13 ± 0.03	-0.25 ± 0.03	0.02 ± 0.03	-0.12 ± 0.03	0.24 ± 0.03	-0.25 ± 0.03	-0.05 ± 0.03
				Selection A				
$\bar{\nu}_e$ candidates	597616	606349	567196	466013	80479	80742	80067	66862
DAQ live time [days]	1117.178	1117.178	1114.337	924.933	1106.915	1106.915	1106.915	917.417
ϵ_μ	0.8255	0.8221	0.8573	0.8571	0.9824	0.9823	0.9821	0.9826
$\bar{\epsilon}_m$	0.9744	0.9747	0.9757	0.9757	0.9759	0.9758	0.9756	0.9758
Accidentals [day^{-1}]	8.46 ± 0.09	8.46 ± 0.09	6.29 ± 0.06	6.18 ± 0.06	1.27 ± 0.01	1.19 ± 0.01	1.20 ± 0.01	0.98 ± 0.01
Fast neutron [AD^{-1} day^{-1}]	0.79 ± 0.10		0.57 ± 0.07		0.05 ± 0.01			
^9Li, ^8He [AD^{-1} day^{-1}]	2.46 ± 1.06		1.72 ± 0.77		0.15 ± 0.06			
^{241}Am-^{13}C, 6-AD [day^{-1}]	0.27 ± 0.12	0.25 ± 0.11	0.28 ± 0.13		0.22 ± 0.10	0.21 ± 0.10	0.21 ± 0.10	
^{241}Am-^{13}C, 8-AD [day^{-1}]	0.15 ± 0.07	0.16 ± 0.07	0.13 ± 0.06	0.15 ± 0.07	0.04 ± 0.02	0.03 ± 0.02	0.03 ± 0.02	0.05 ± 0.02
$^{13}C(\alpha, n)^{16}O$ [day^{-1}]	0.08 ± 0.04	0.07 ± 0.04	0.05 ± 0.03	0.07 ± 0.04	0.05 ± 0.03	0.05 ± 0.03	0.05 ± 0.03	0.05 ± 0.03
$\bar{\nu}_e$ rate, $R_{\bar{\nu}}$ [day^{-1}]	653.03 ± 1.37	665.42 ± 1.38	599.71 ± 1.12	593.82 ± 1.18	74.25 ± 0.28	74.60 ± 0.28	73.98 ± 0.28	74.73 ± 0.30