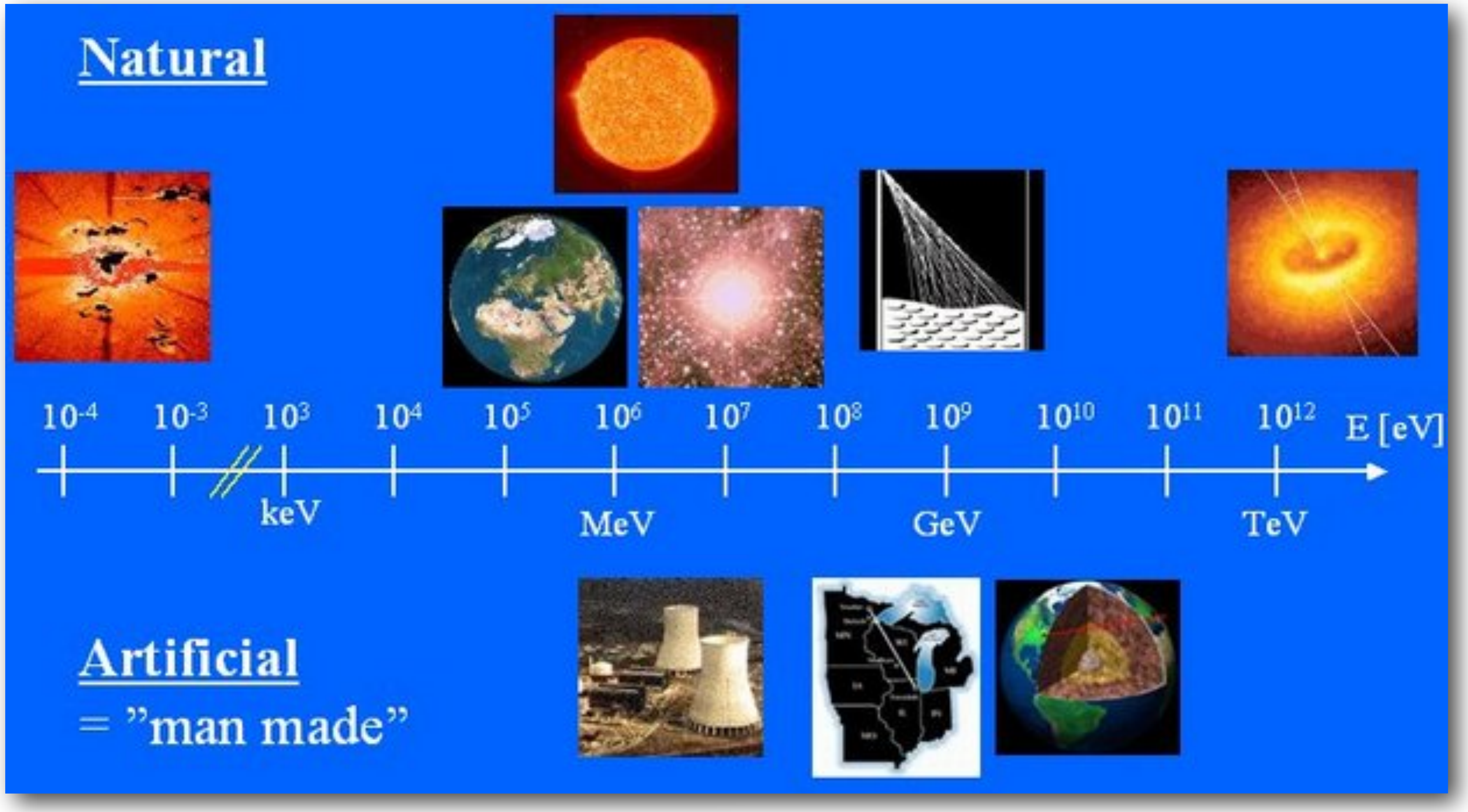
Running and Future Experiments with Reactor Neutrinos

Andi S. Cucoanes @ Subatech Nantes

A Shortlist of Topics

- Introduction: neutrino mixing
- Reactor Θ_{13} experiments: Double Chooz, Daya Bay and Reno
- Reactor antineutrino spectrum and the 5 MeV distortion
- Reactor Θ_{13} systematics.
- Reactor antineutrino anomaly and the sterile neutrino seaches: SoLid and Stereo
- Applied neutrino physics for non-proliferation: Nucifer
- (Even more) exotic physics at reactors: MH with Juno

A World of Neutrinos



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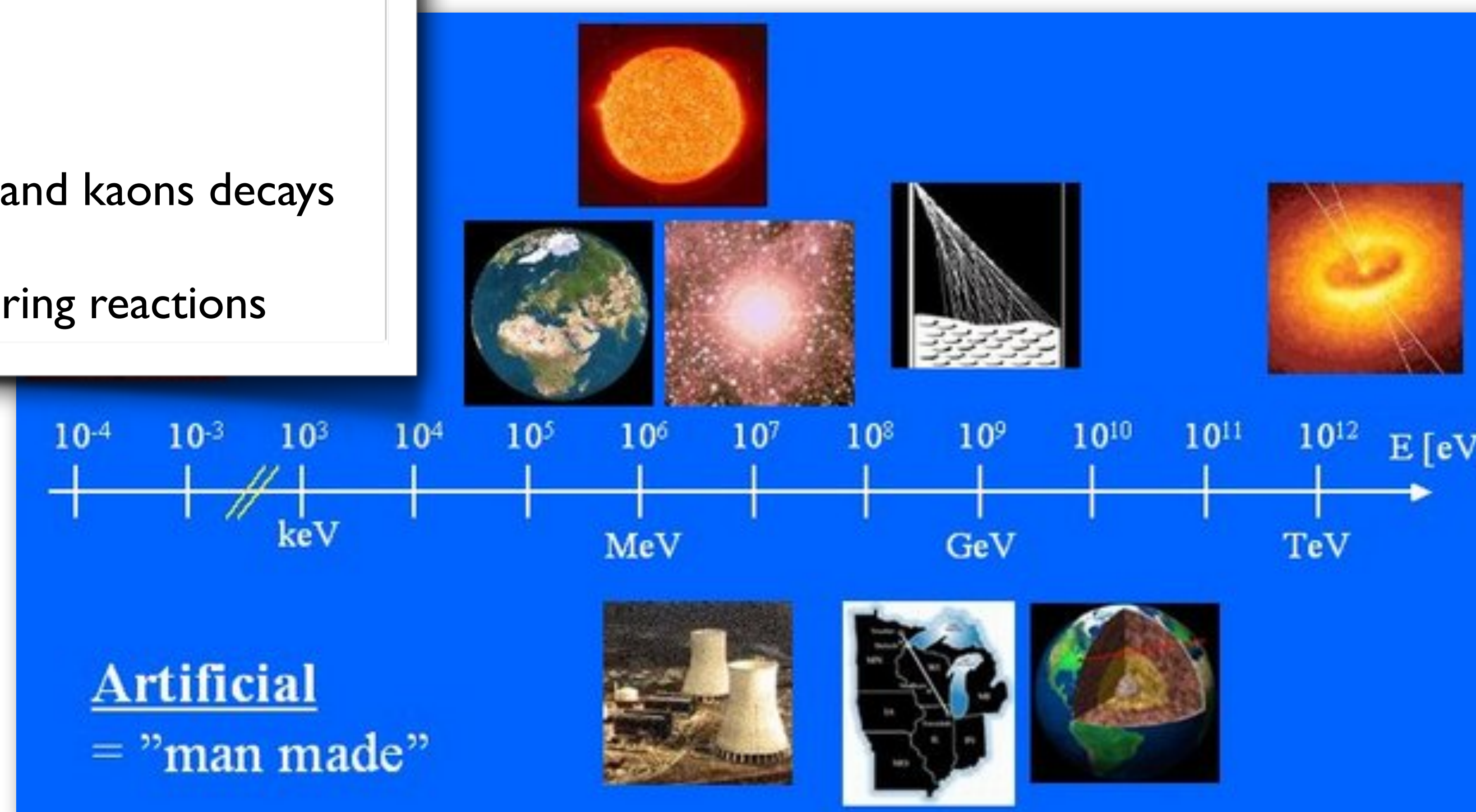
«Natural» neutrinos

- Sun by nuclear fusion reactions
- Earth's atmosphere by cosmic rays
- Earth's crust by natural radioactivity of U and Th
- Big-Bang explosion
- Cosmic accelerators by pions and kaons decays
- Supernovae by different scattering reactions



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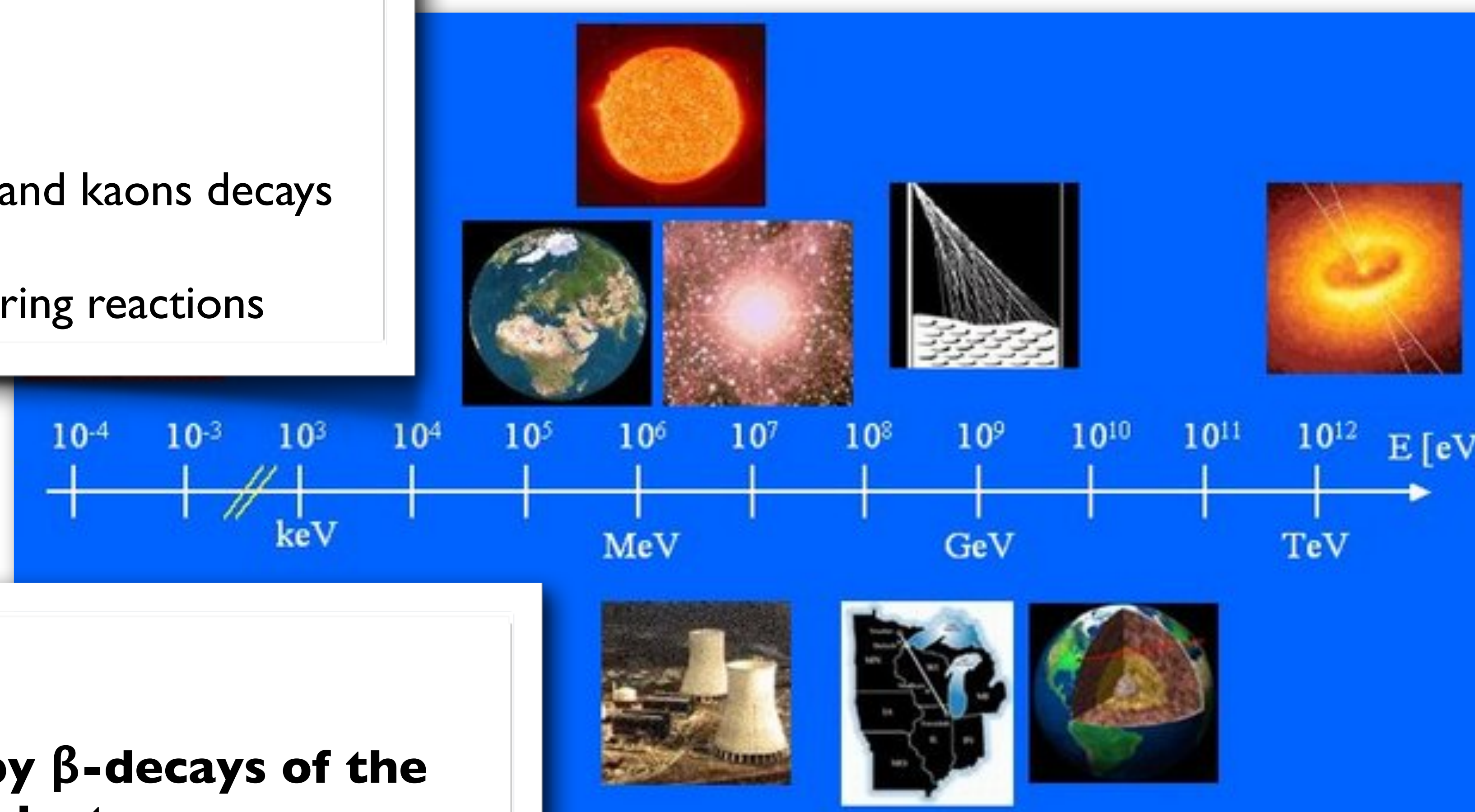

«Artificial» neutrinos

Nuclear reactors by β-decays of the nuclear fission products

Particle accelerators by pions and kaons decays

Neutrino Oscillations: Formalism

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electroweak eigenstates *(interaction)* $\neq$ mass eigenstates *(propagation)*

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«Atmospheric»

Amplitude: Θ_{23} (**14%**)
Frequency: Δm_{23}^2 (**3%**)

«Coupling»

Θ_{13} (**10%**) δ_{CP} (?)

«Solar»

Amplitude: Θ_{12} (**5.4%**)
Frequency: Δm_{12}^2 (**2.6%**)

$$\begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix}$$

$P(\nu_\mu \rightarrow \nu_\mu)$

Atmospheric exp. + accelerator LBL

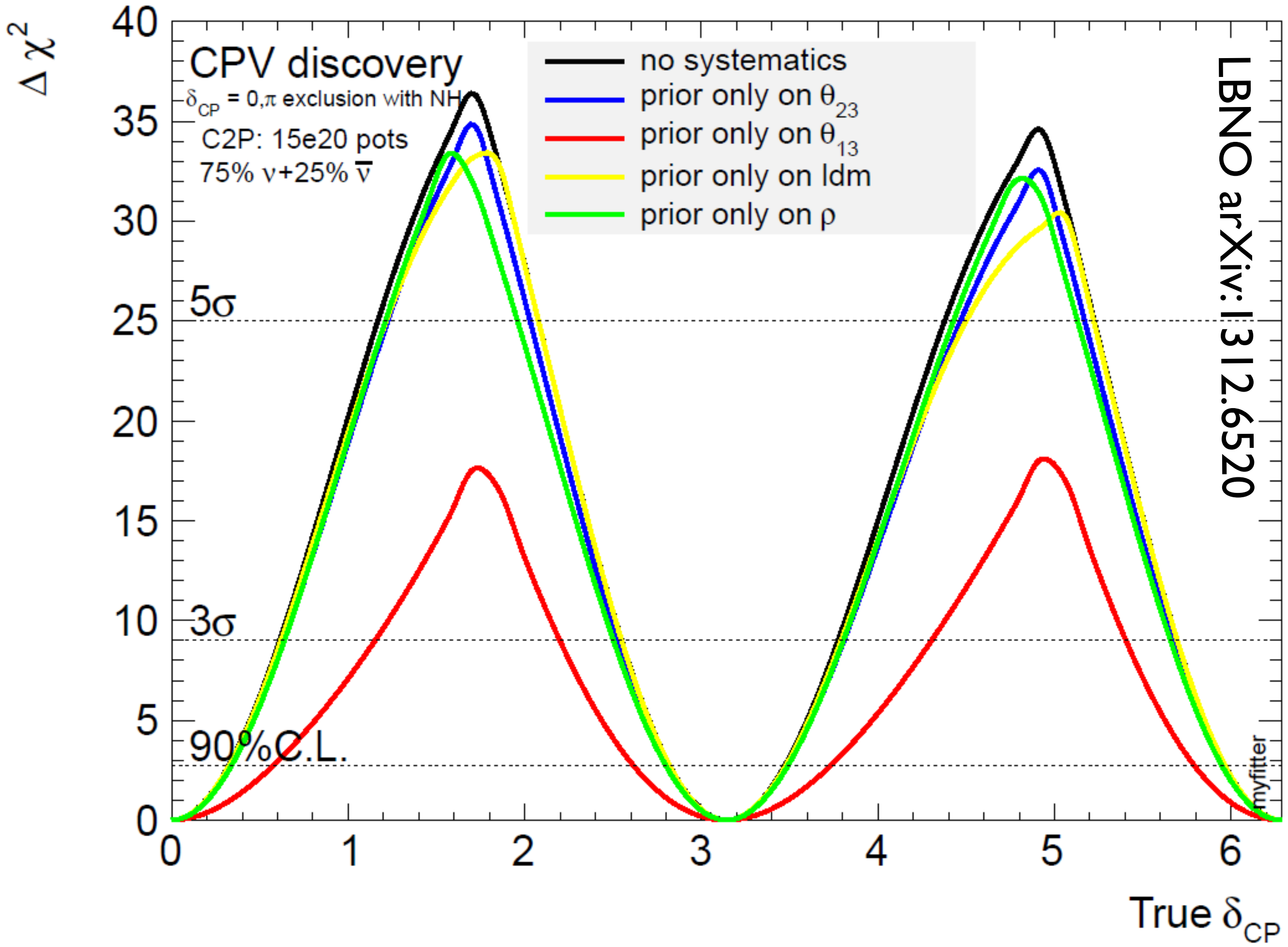
$P(\nu_e \rightarrow \nu_e) + P(\nu_\mu \rightarrow \nu_e)$

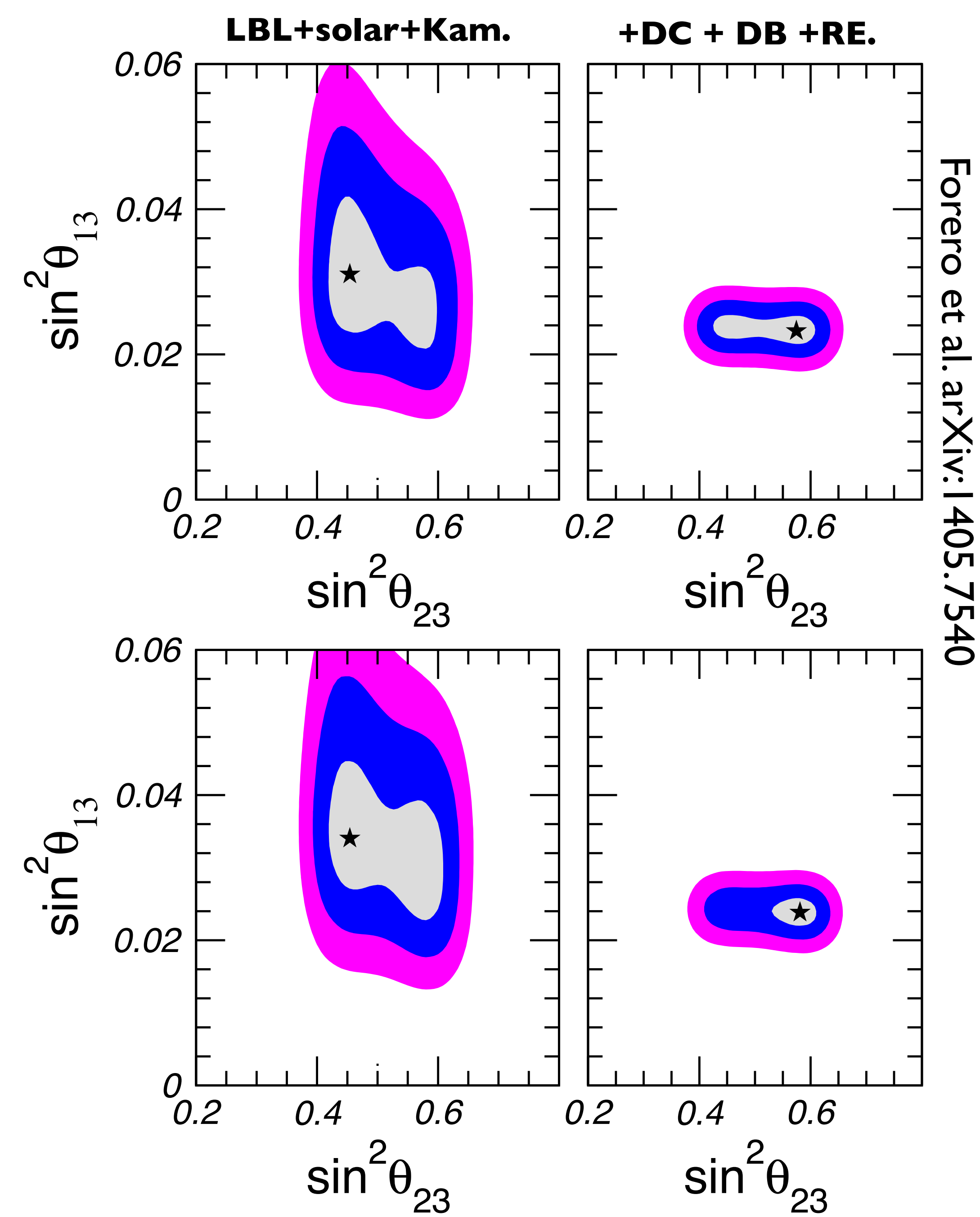
Reactor MBL + accelerator LBL

$P(\nu_e \rightarrow \nu_x)$

Solar exp. + reactor LBL

Why High Θ_{13} Precision is Important ?





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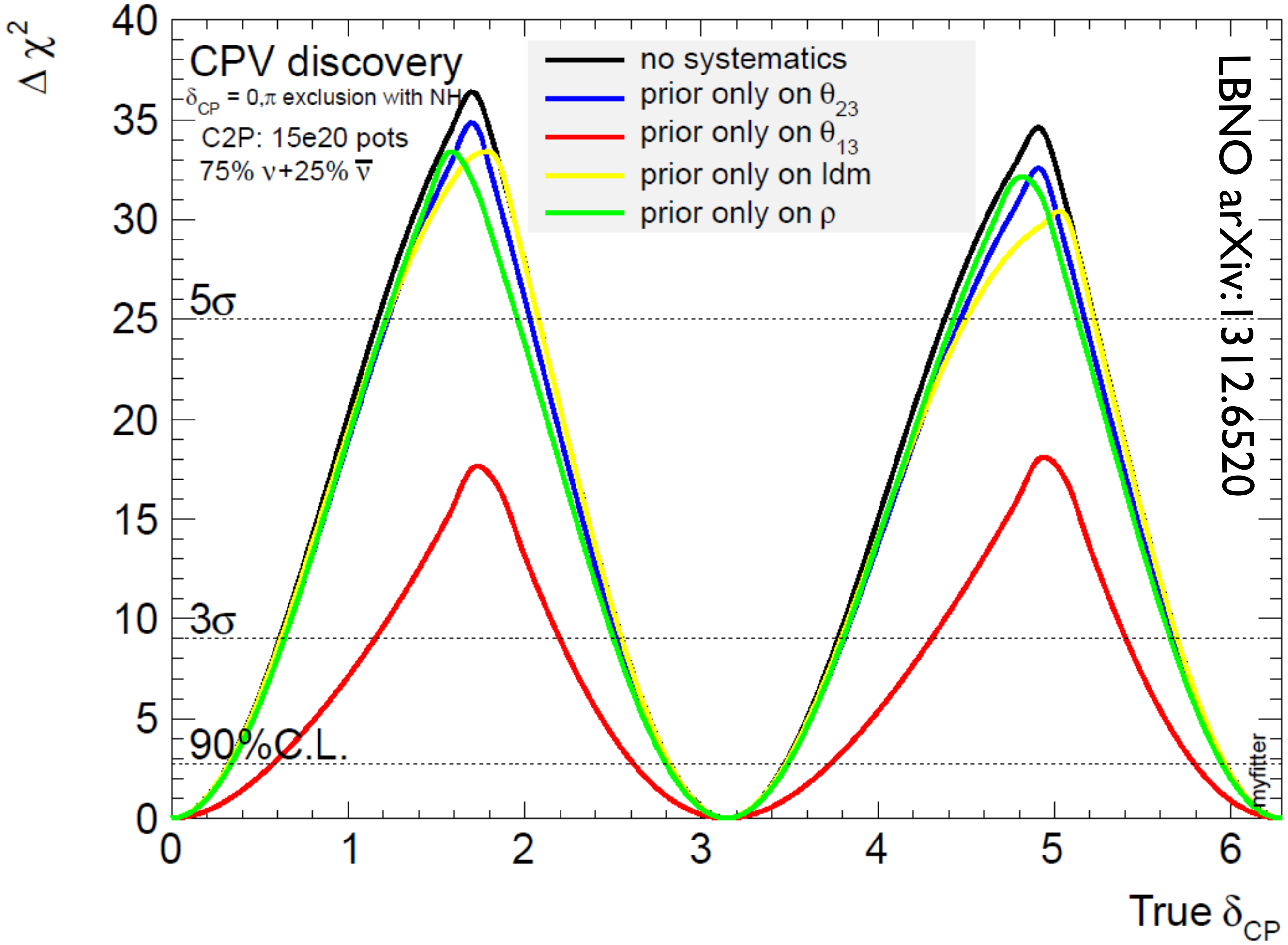

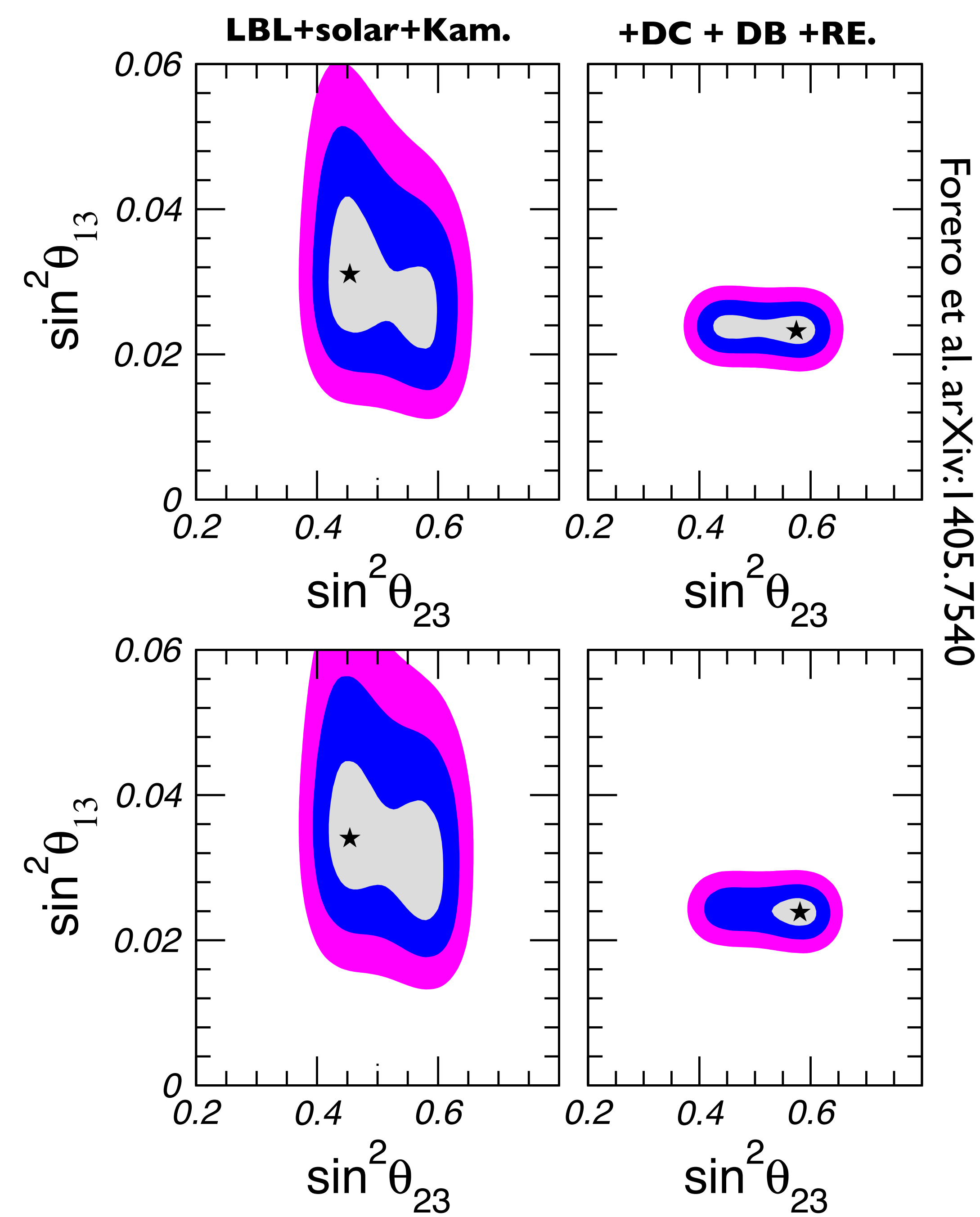

θ_{13} precision ...

... is a crucial ingredient for the sensitivity of the future δ_{CP} experiments.

... is correlated to other oscillation parameters via global fits

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Long history since the first detection of neutrino by Reines and Cowan using a reactor in '50s.

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Highly intense (~ $2*10^{20}$ ν_e/GW_{th}/s) **and completely isotropic source** → Compensate for the tiny interaction probability.

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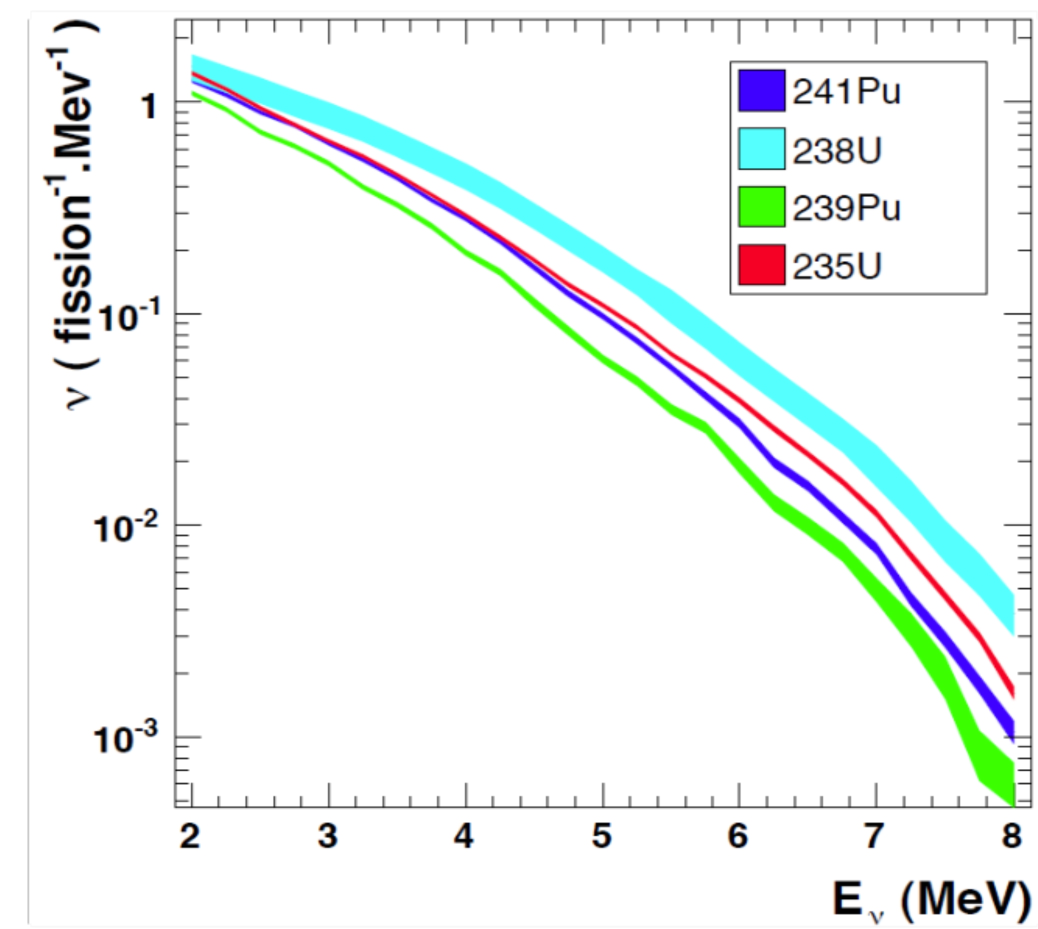

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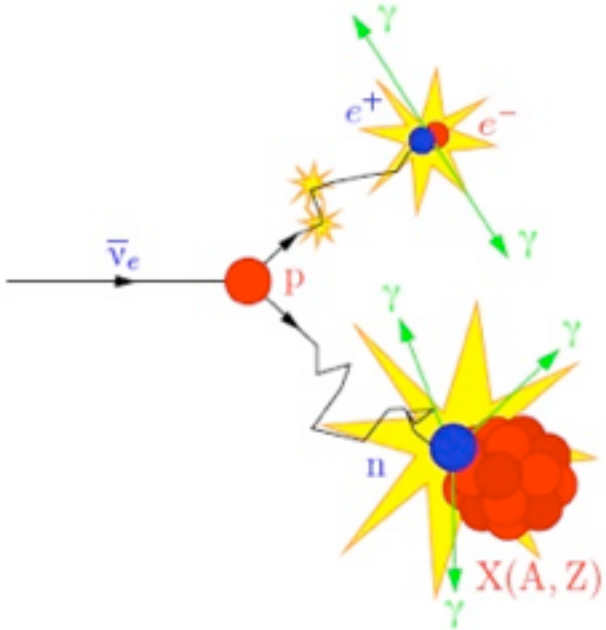
Antineutrinos from β^- decays of the fission products of ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu → **complicated but well-understood source.**

A «golden» detection channel: IBD

Low energy antineutrinos (≲10 MeV): detection via inverse β-decay:

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



Prompt event: dE/dx of e^+ and e^+e^- annihilation: $E_p \simeq 1\text{-}9$ MeV

Delayed event: nuclear capture: E_d = 8MeV (Gd) or 2.2MeV (H)

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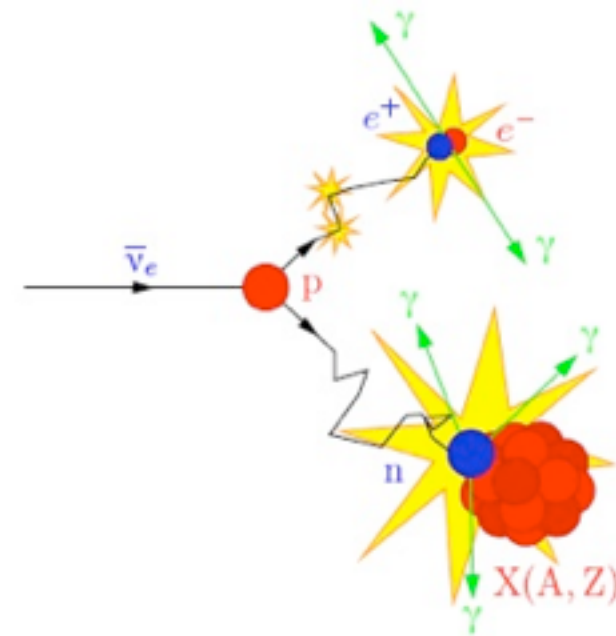

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- **Antineutrino energy can be directly measured:** $E_p = E_\nu - 0.8$ MeV
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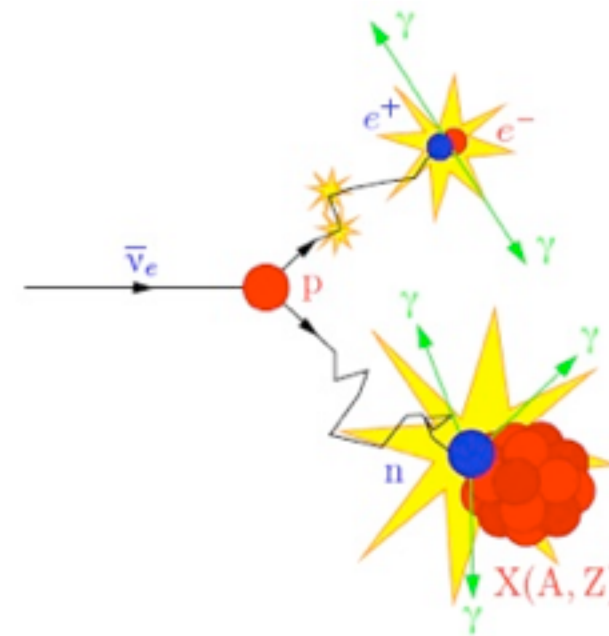

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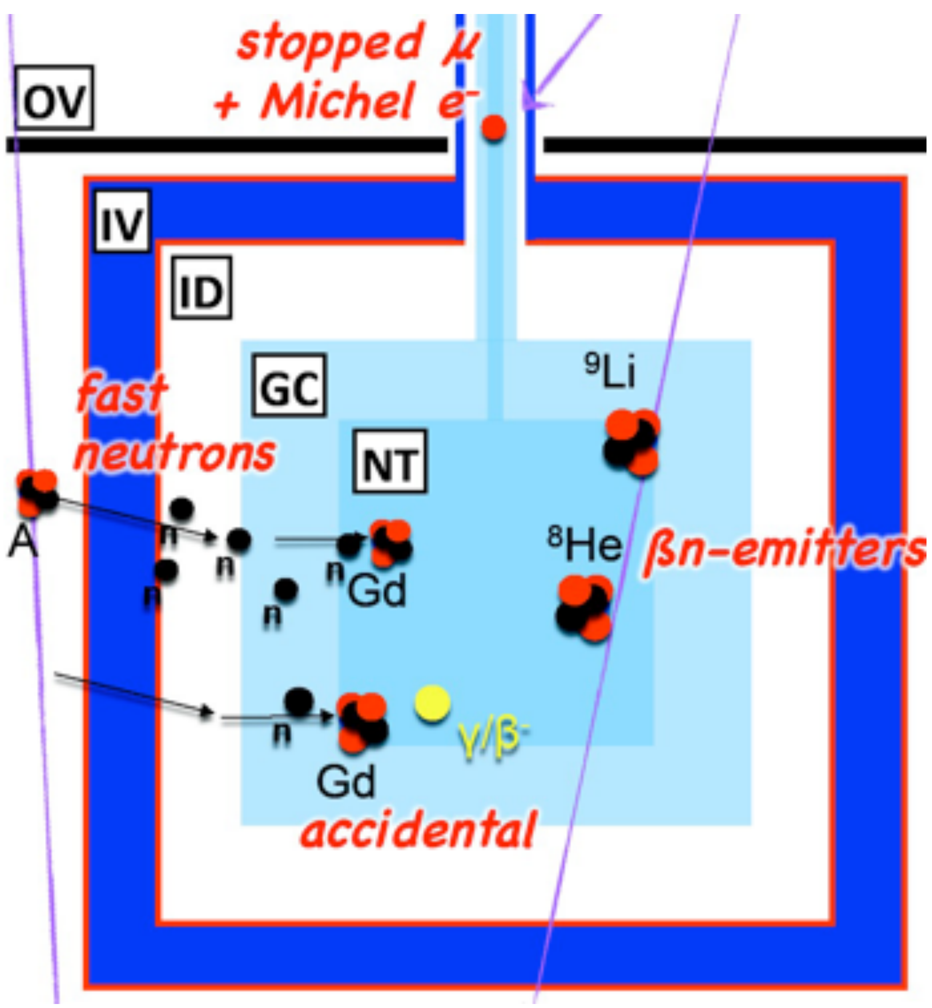
Select prompt-delayed events with right energy (nGd and nH), time window (~200 μs) and distance (<1m).

Background

	Accidental coincidences	Muon induced fast neutrons	β-n emitters: $^{9}Li/^{8}He$
Prompt	radioactivity γ	recoiled proton	electron endep
Delayed	capture of muon induced neutrons	neutron cature (same particle as induced prompt event)	neutron capture
Measurement	Off-time window	IV-tagged events	Δt from the high energetic (≳600MeV) muons and prompt events



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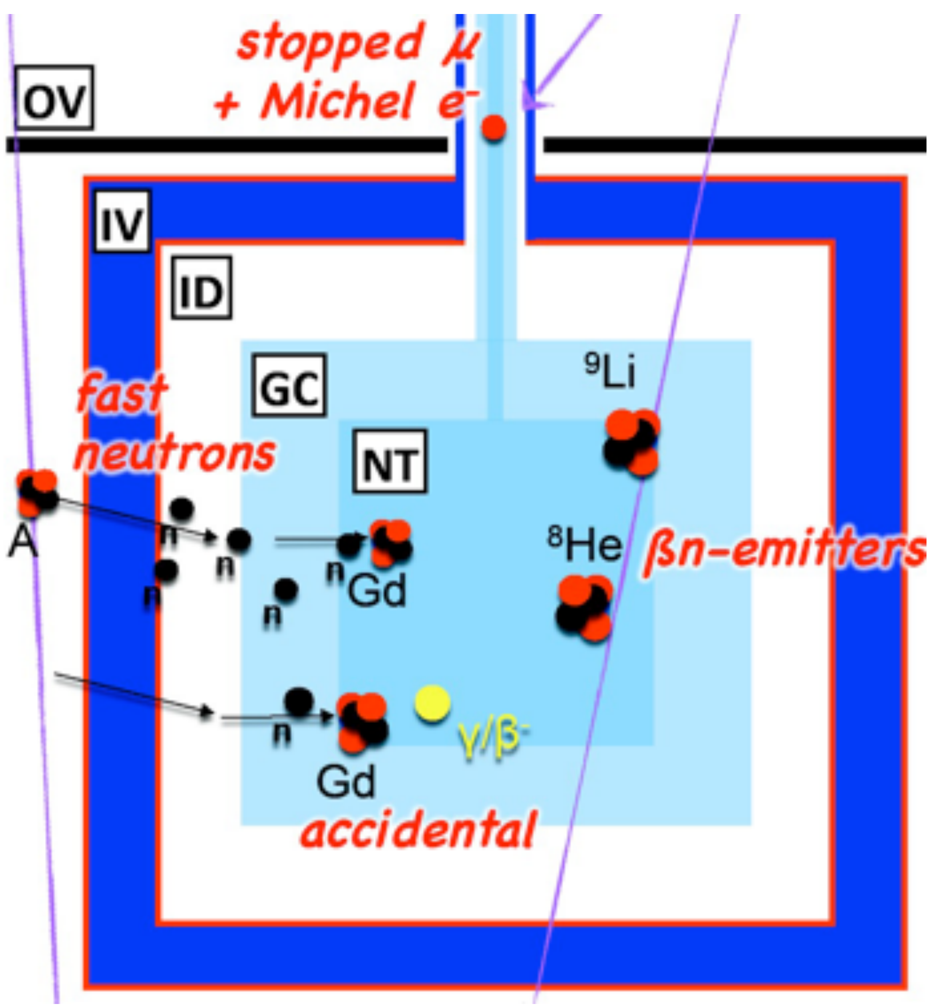
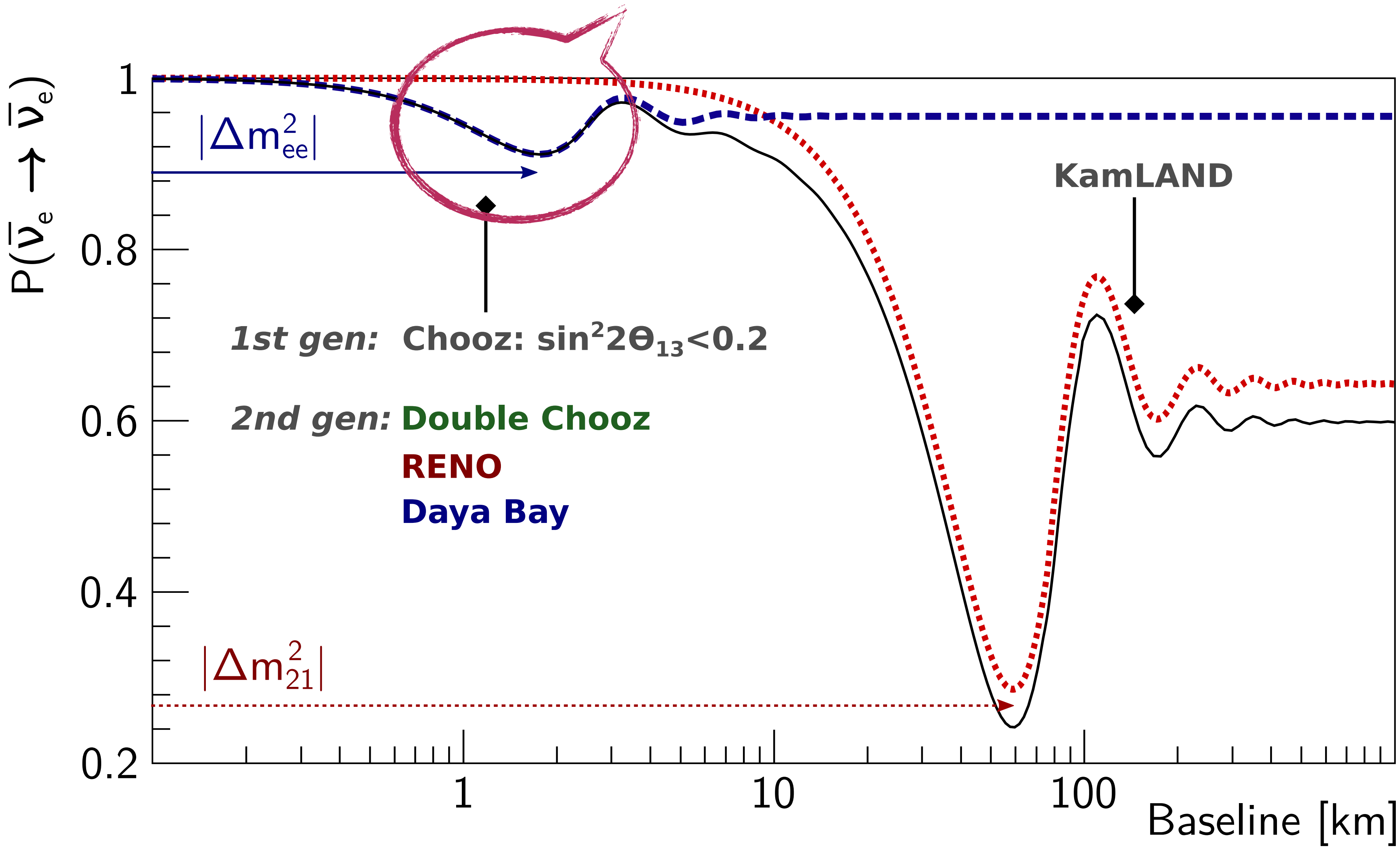


Reject muon-related events: select a quiet time window between muons (> 1ms) Wait substantial time if muon goes through the target, specially for high energetic muons.

A Clean Θ_{13} Measurement

$$P(\overline{\nu}_e \rightarrow \overline{\nu}_e) = 1 - \sin^2(2\theta_{13}) \cdot \sin^2\left(\frac{1.27 \cdot \Delta m^2_{31}[eV^2] \cdot L[m]}{E[MeV]}\right)$$



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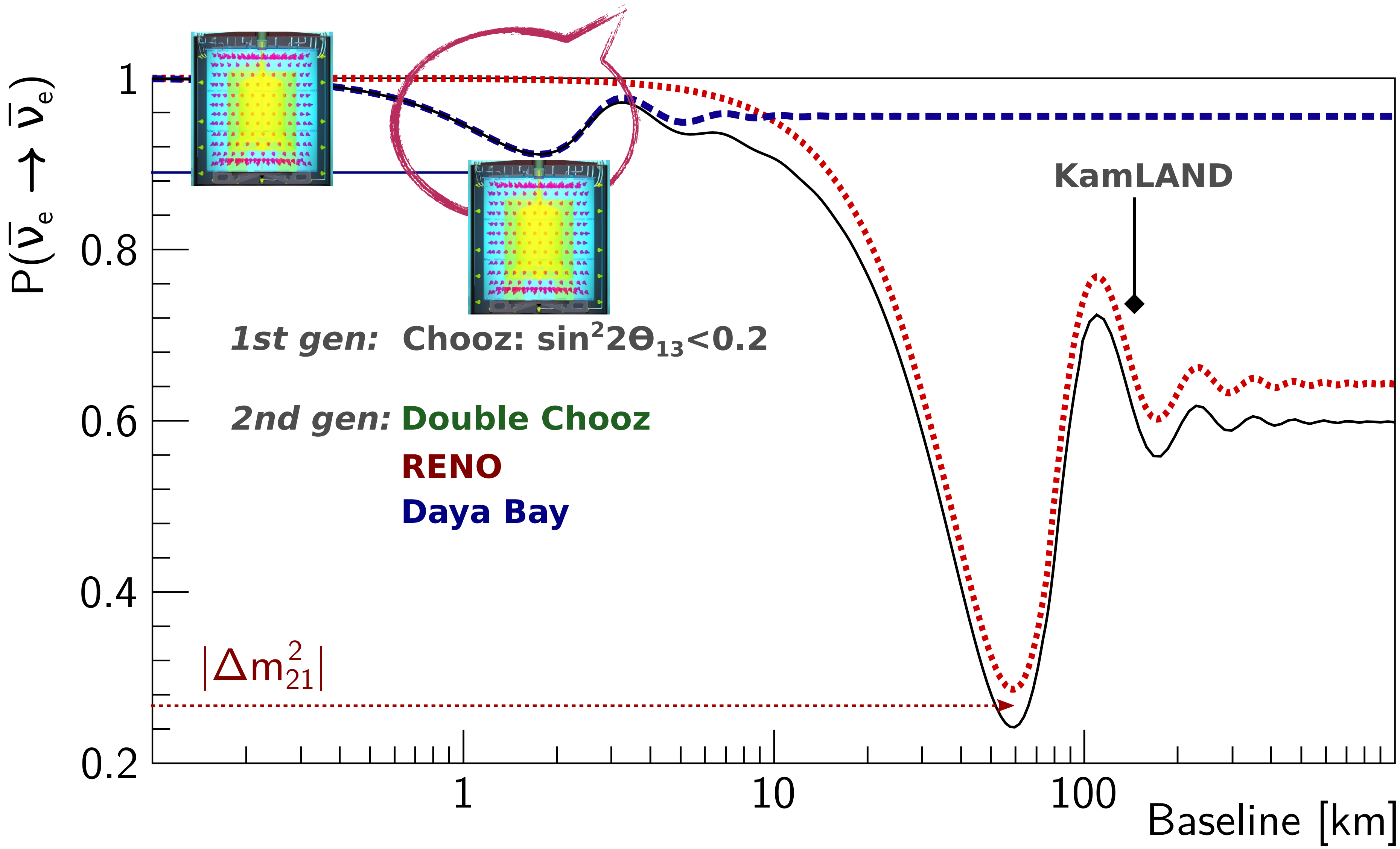

Flux and spectrum are compared with the no-oscillation hypothesis.
Identical Near/Far detectors → reduces the correlated inter-detector uncertainties.

Θ_{13} with Reactor Neutrinos: a Direct Competition in Particle Physics

Running θ_{13} Reactor Experiments

	Total reactor power [GW_{th}] / No. of reactors	Fiducial Far / Near [t]	Overburden Far / Near [m.w.e.]
Double Chooz	8.5 / 2	8 / 8	300 / 120
Reno	16.8 / 6	16 / 16	450 / 120
Daya Bay	17.4 / 6	80 / 80	860 / 260

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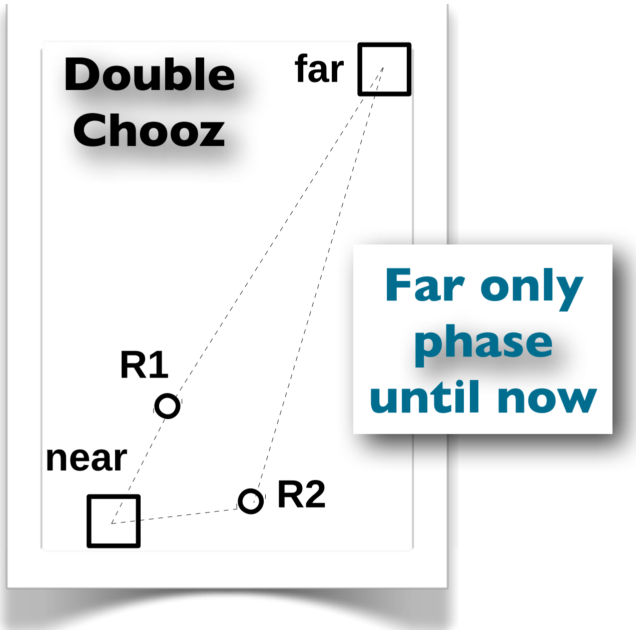

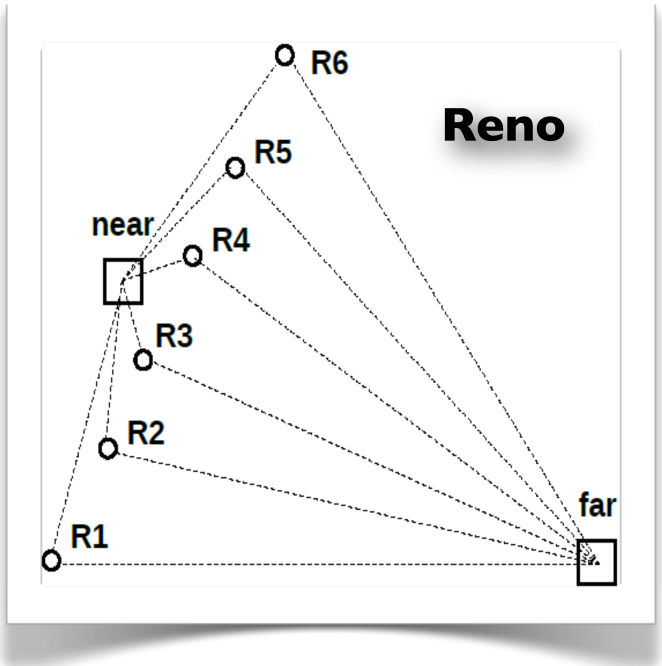

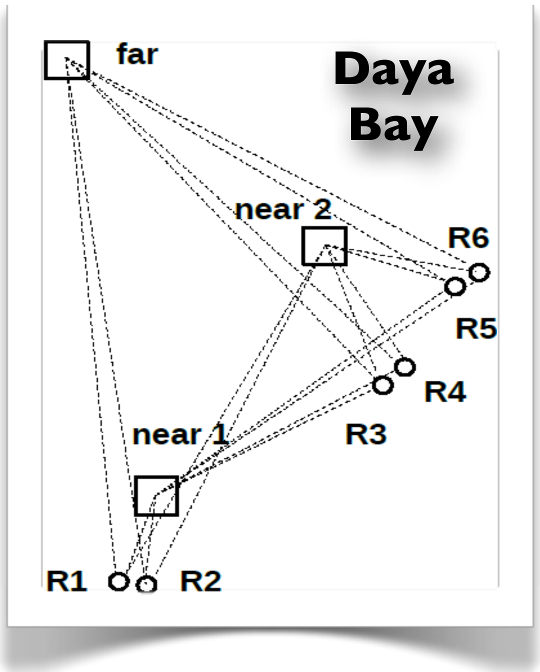

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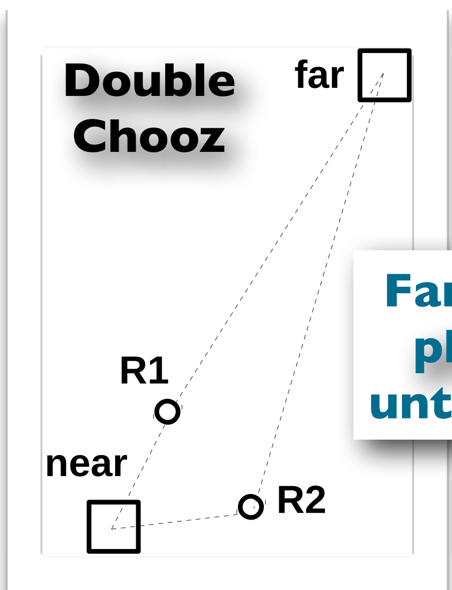
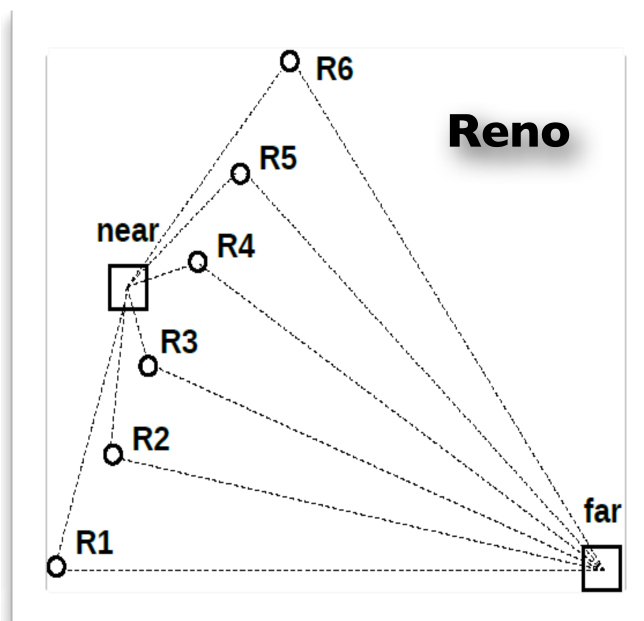
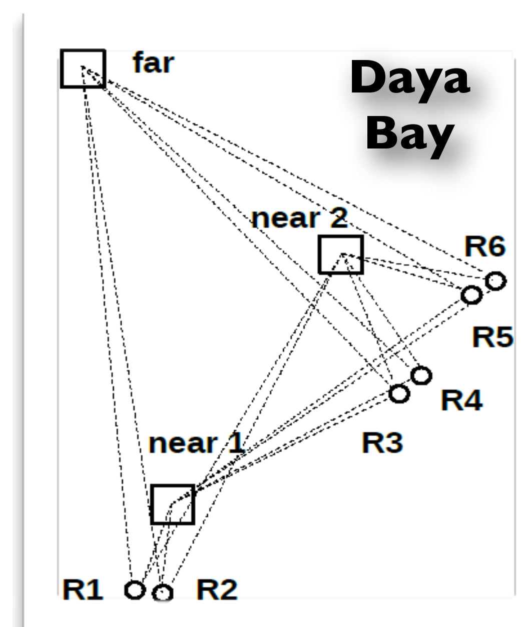
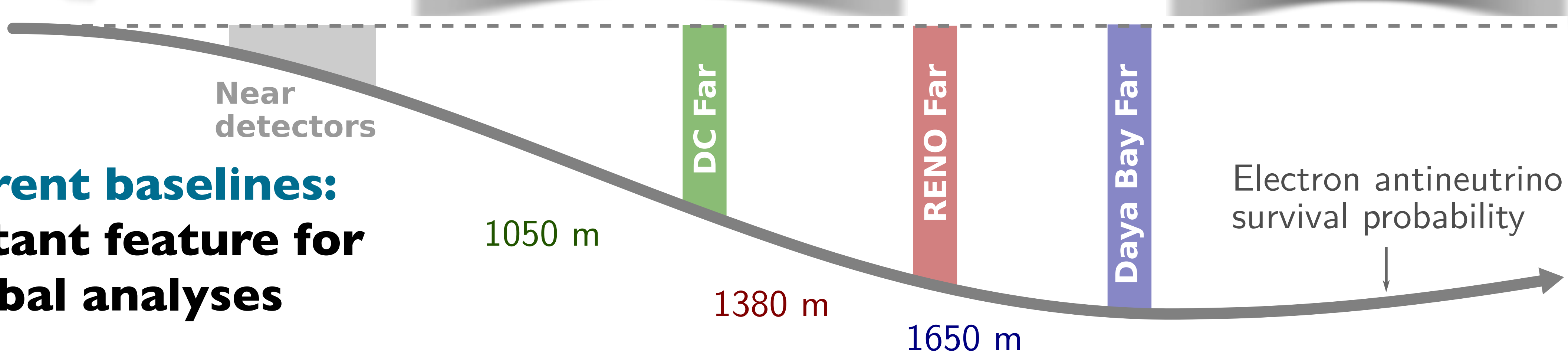


Far only phase until now



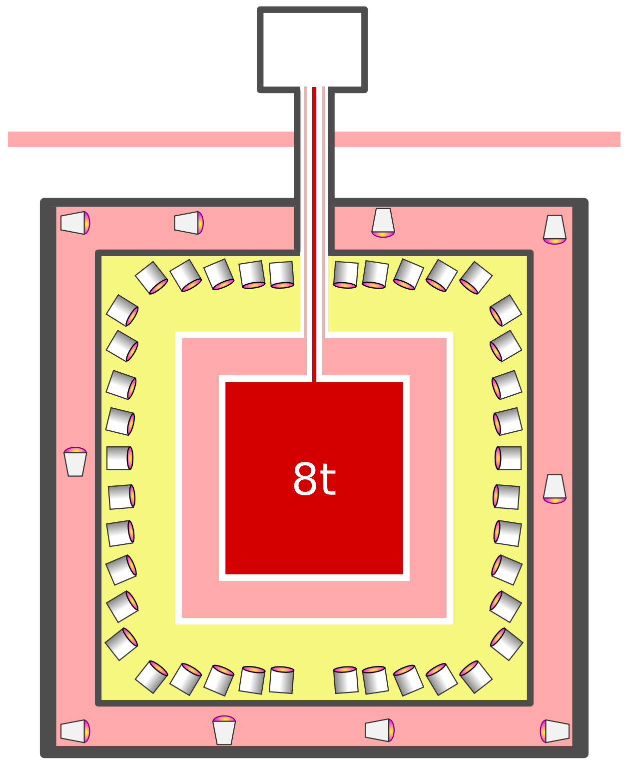




Different baselines: important feature for global analyses

Detectors Design: A Comparison

Double Chooz



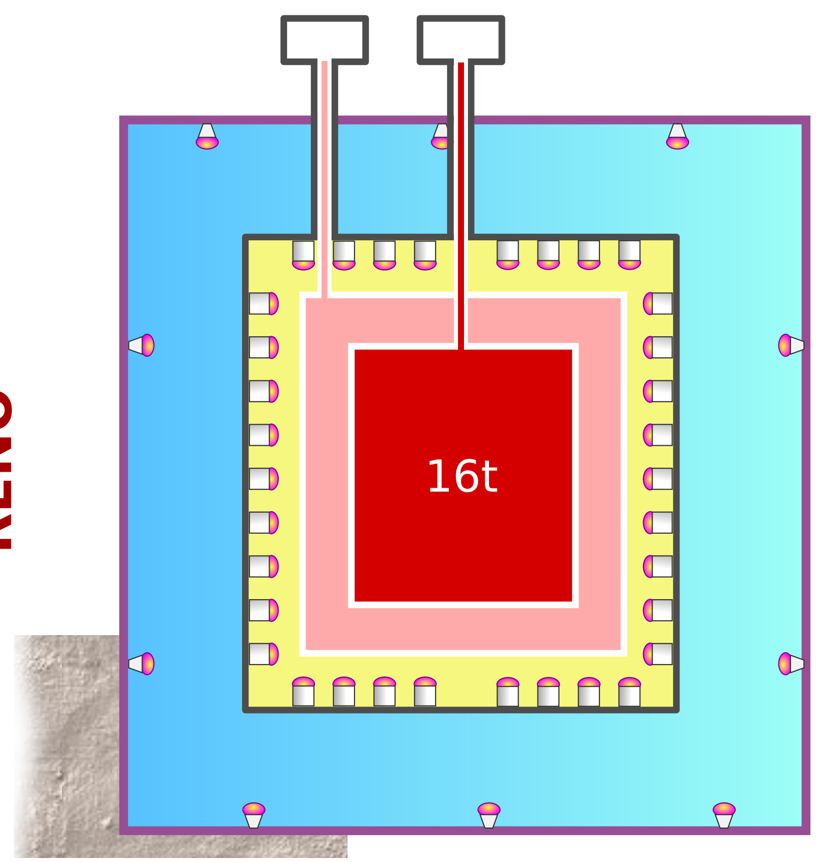
Antineutrino detectors

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

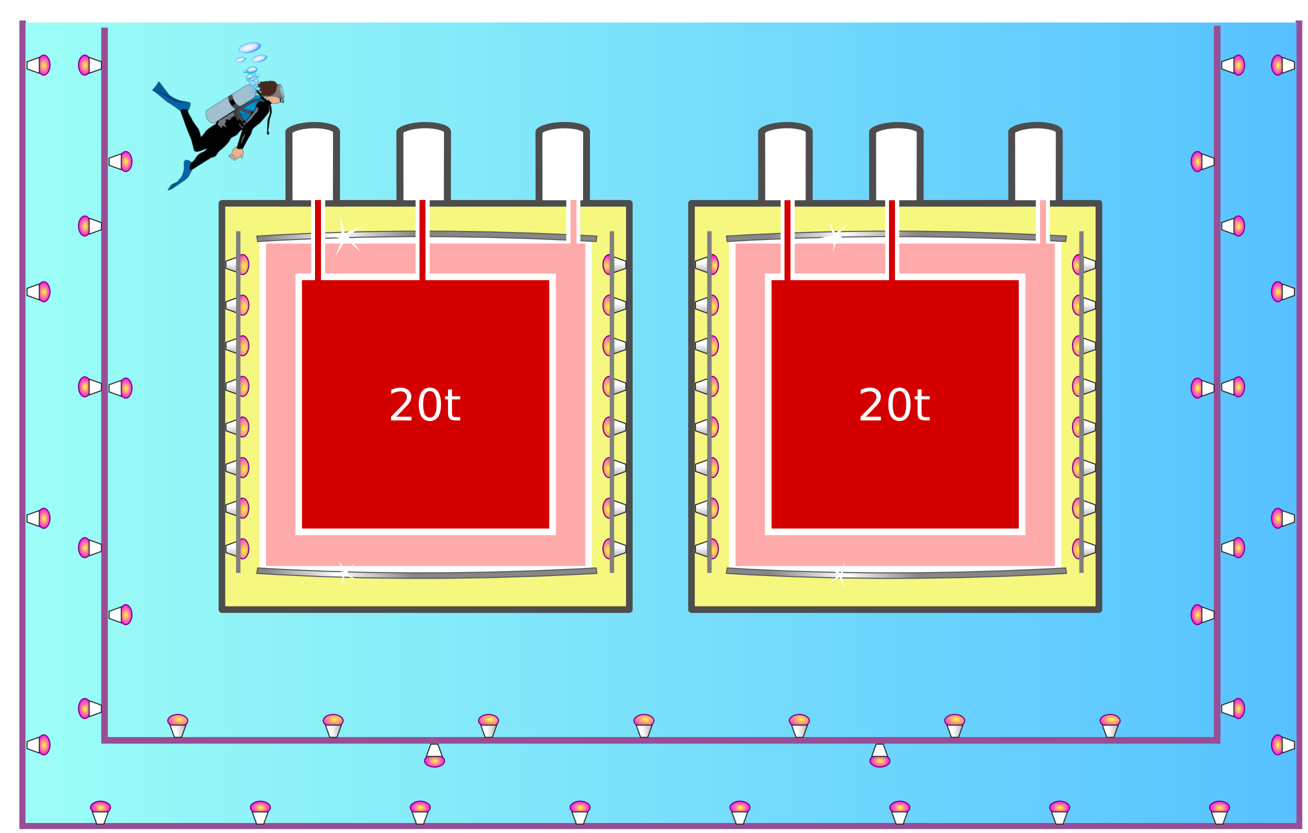
Muon veto system

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

RENO



Daya Bay



Rate Only Oscillation Analyses

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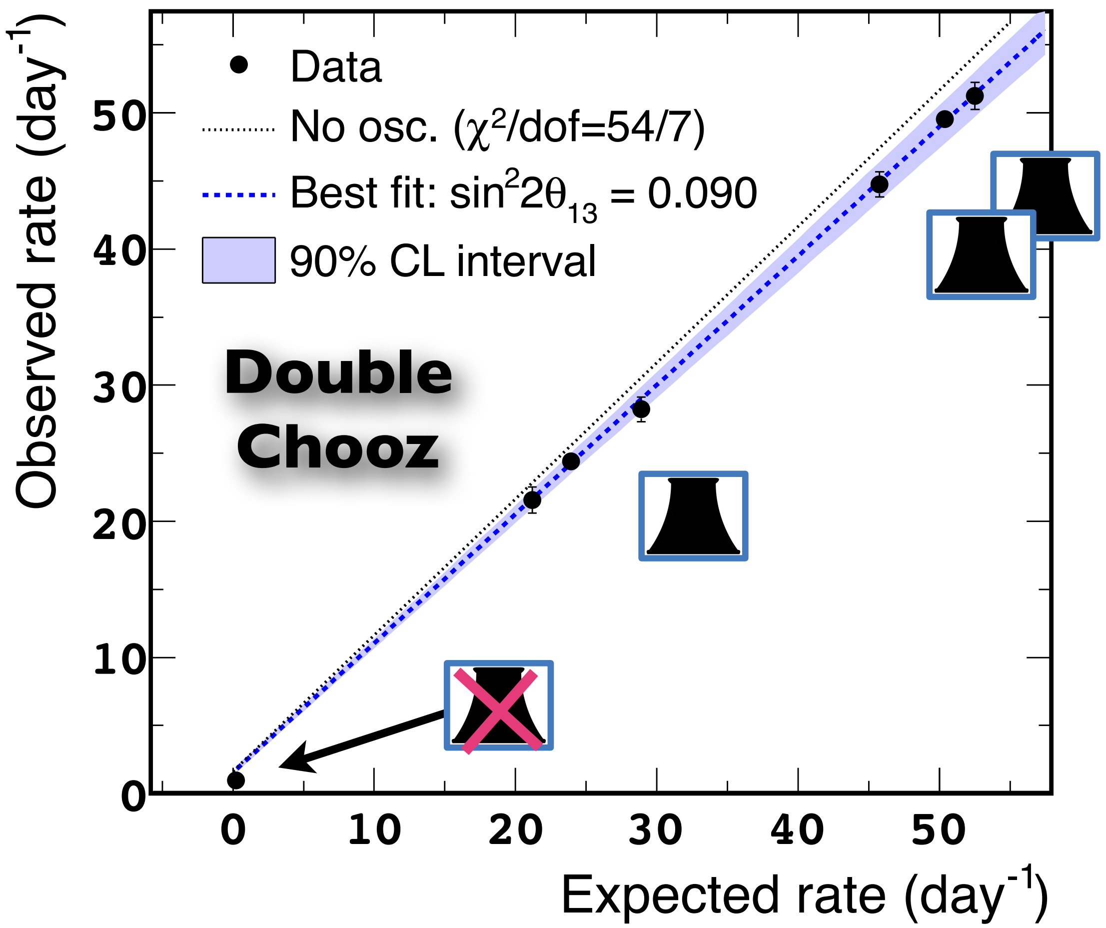

Double Chooz RRM analysis: θ_{13} & background fitted simultaneously using reactor power variations.

Intercept = background
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Improve fit precision by reactor OFF data, background model.

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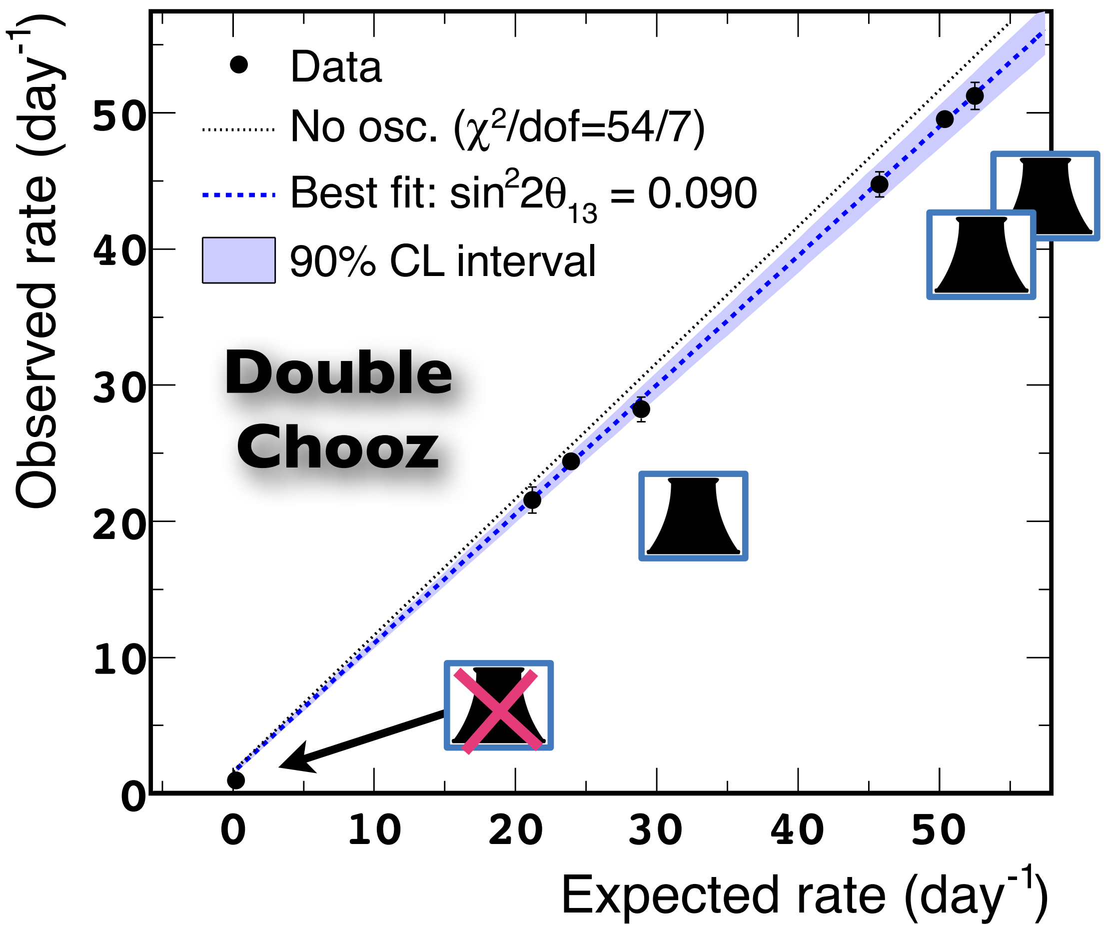

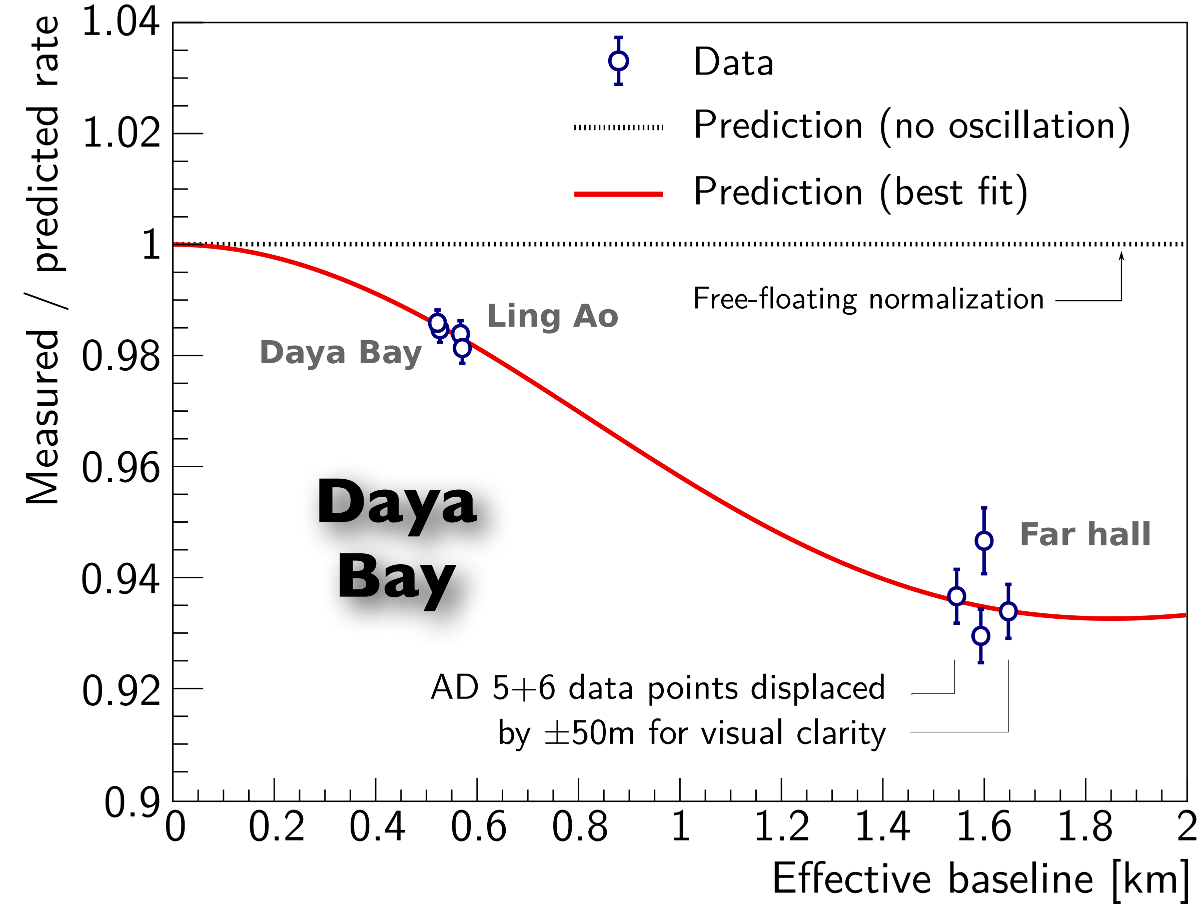

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Daya Bay Rate-Only analysis:
Absolute rate is not constrained

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

M_n are the measured rates in each detector.
Weights α_i,β_i are determined from baselines and reactor fluxes.

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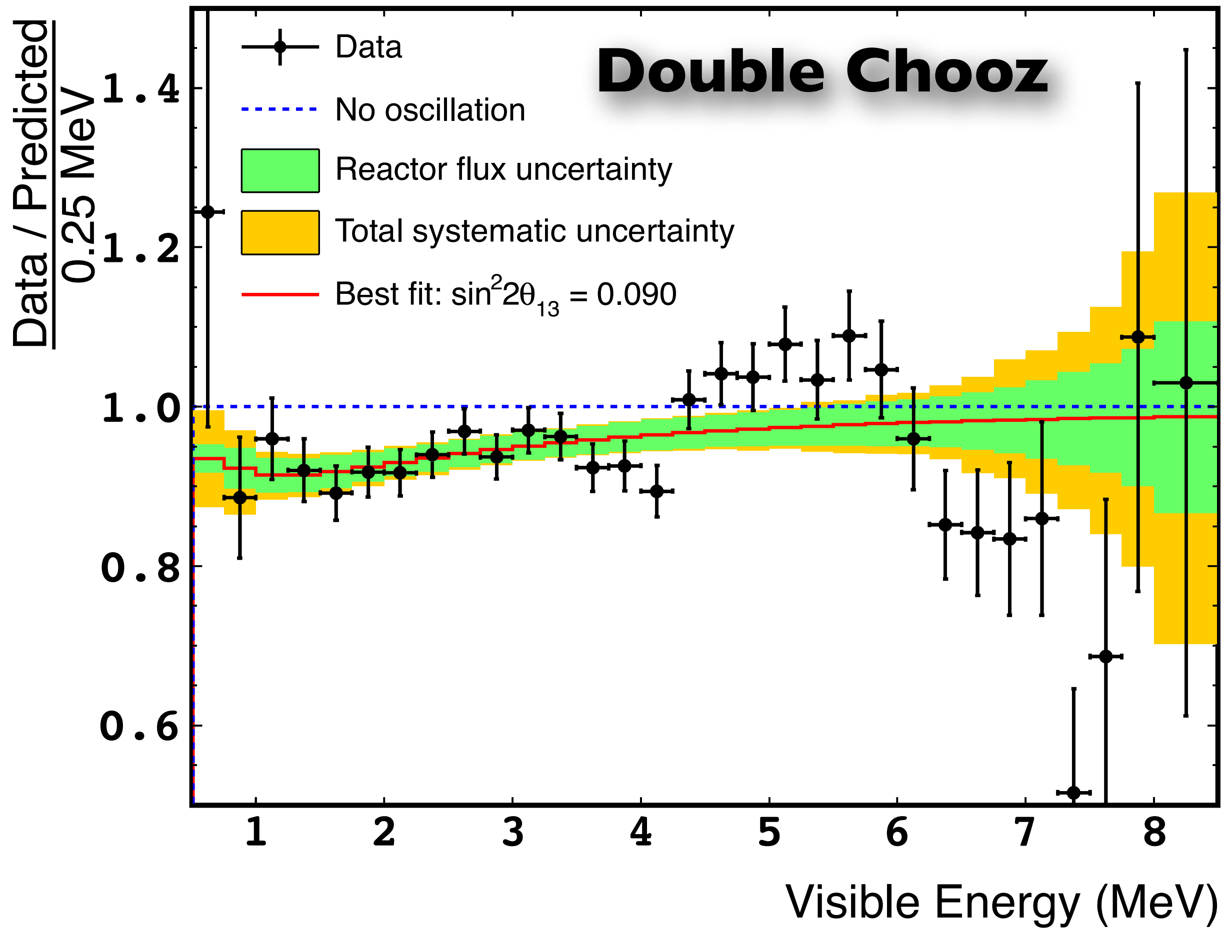

Double Chooz: Chi² minimization with simultaneous fit on Θ_{13} and background

input: DATA
background rate&shape measurements
energy scale parameters
Δm^2
residual neutrino rate (OFF measurement)
cov matrix for rest of systematics

output: Θ_{13} + remeasurement of background

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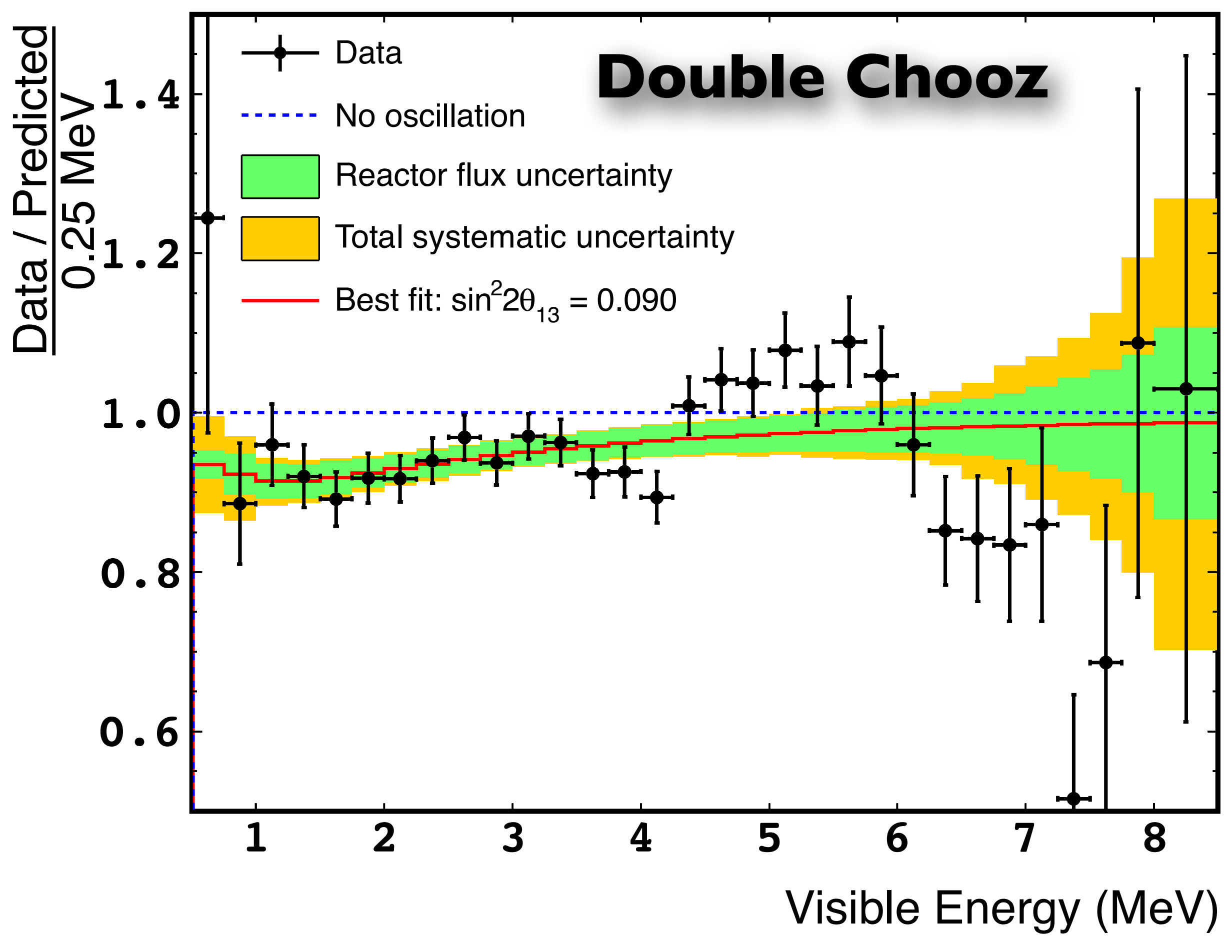

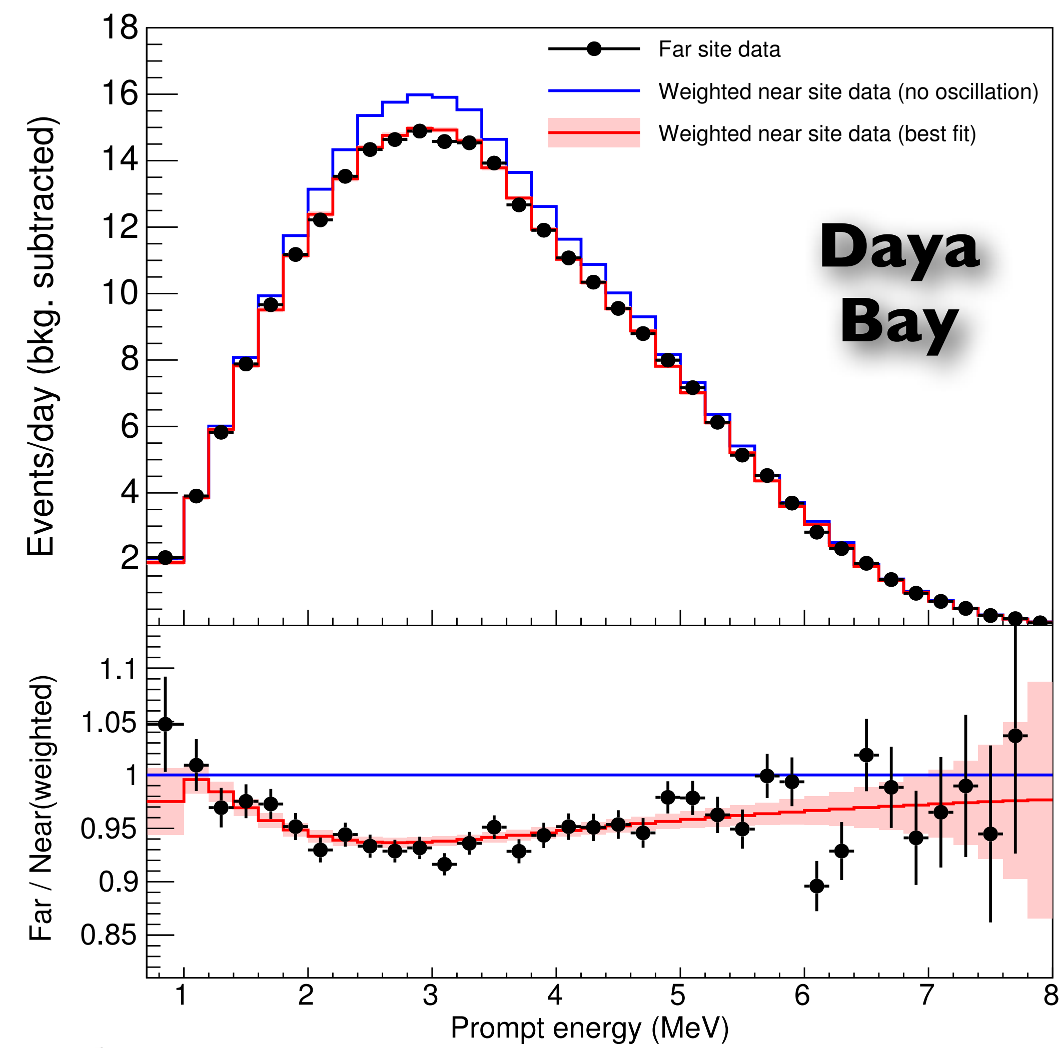

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Data from Near/Far detectors and background measurements as inputs

The most precise Θ_{13} measurement up to date

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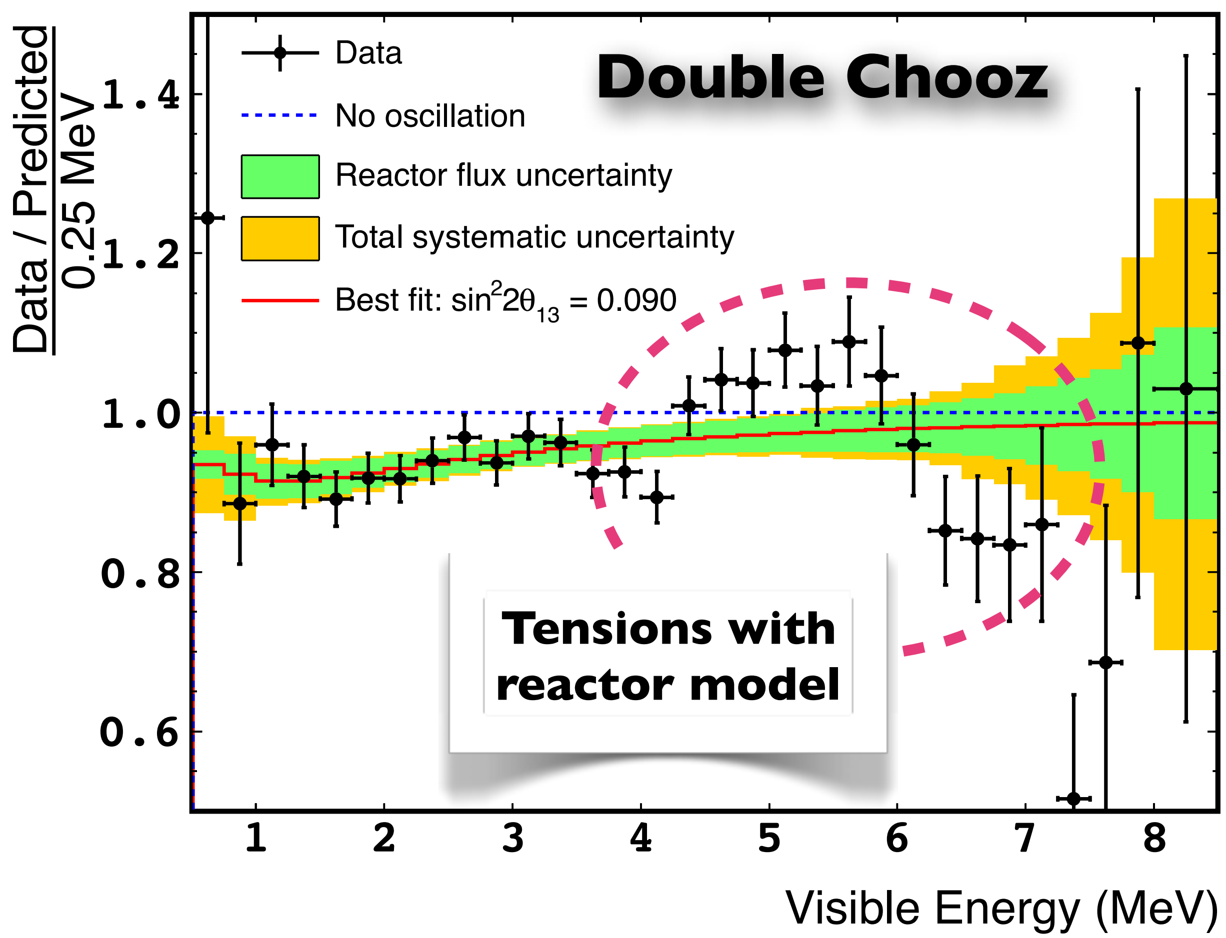

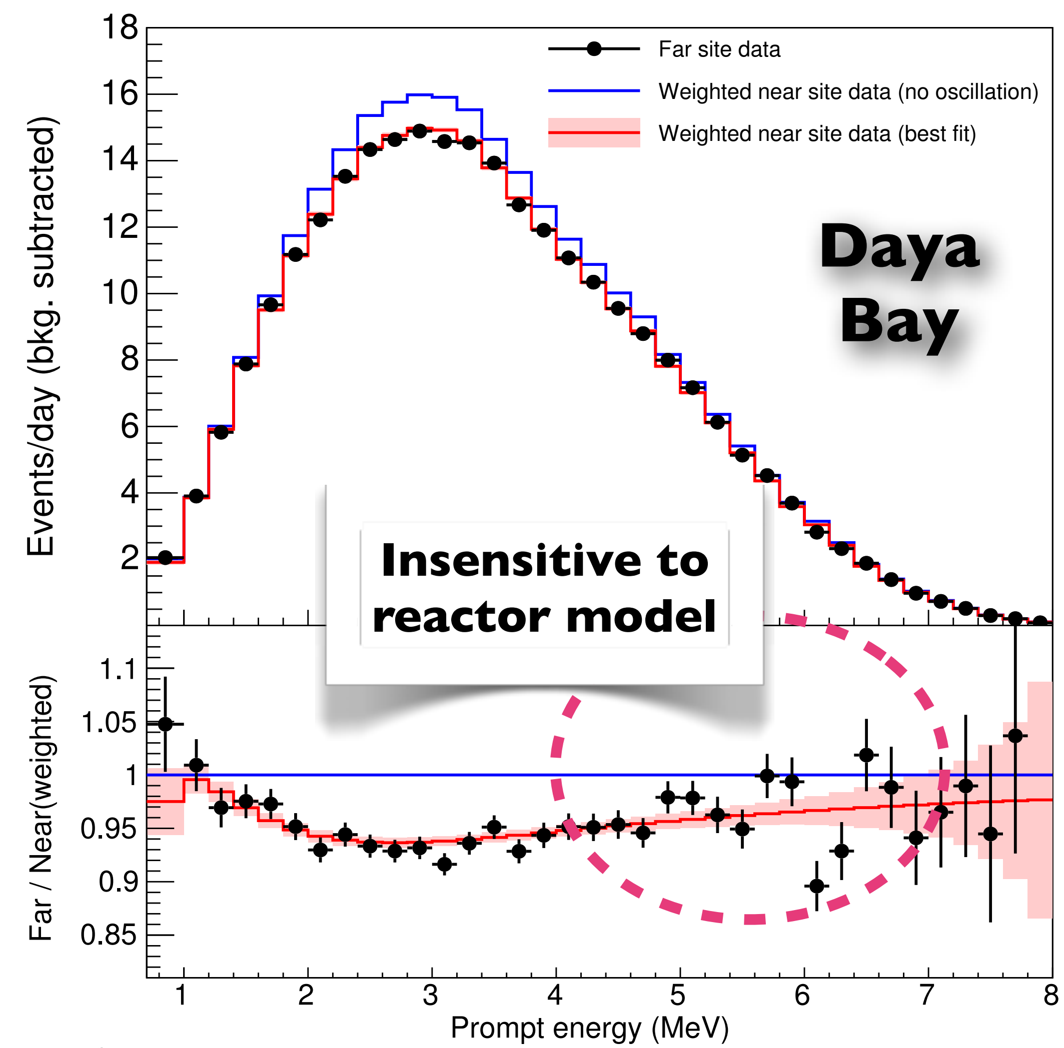

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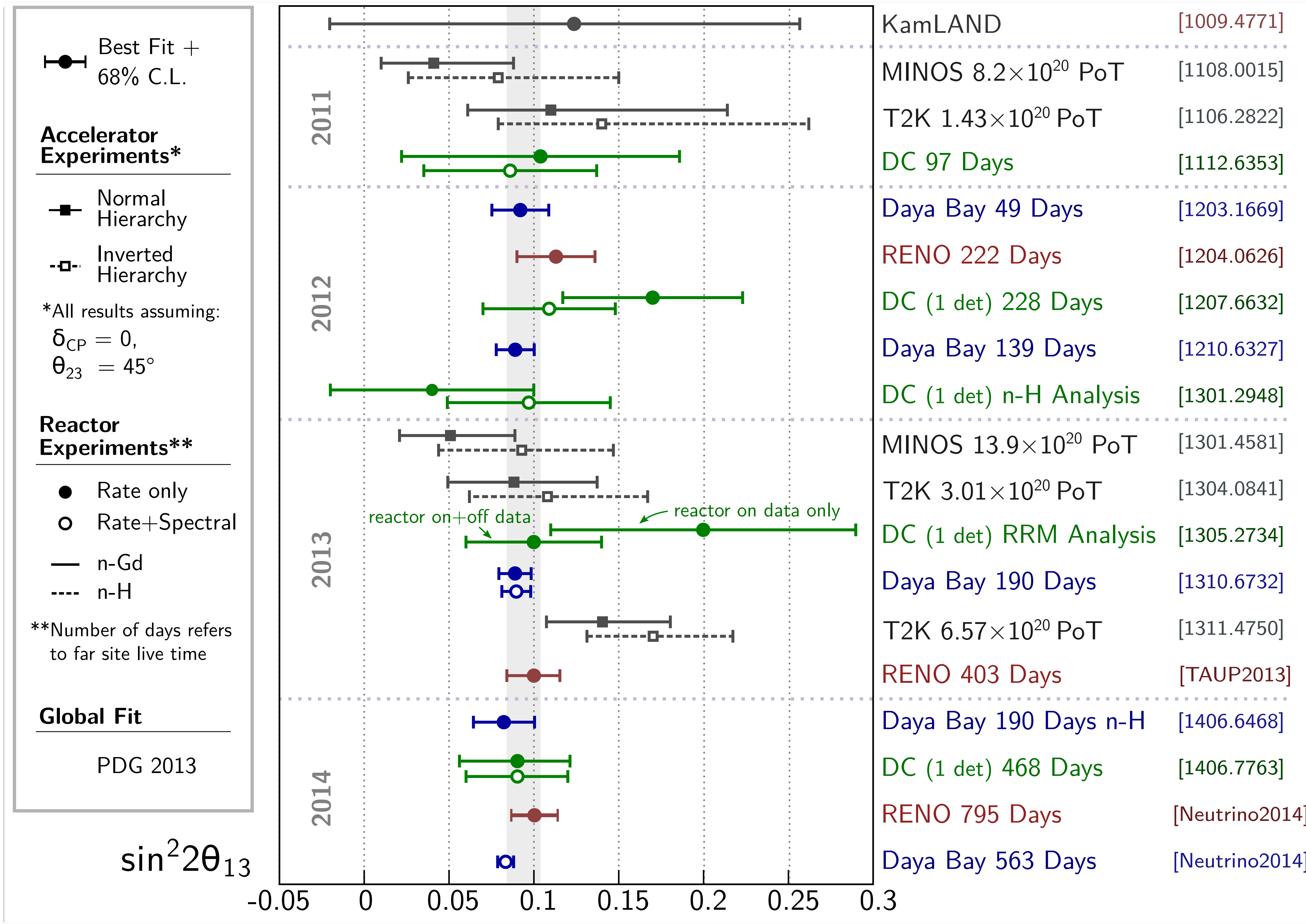
An Overview on Θ_{13} Precision



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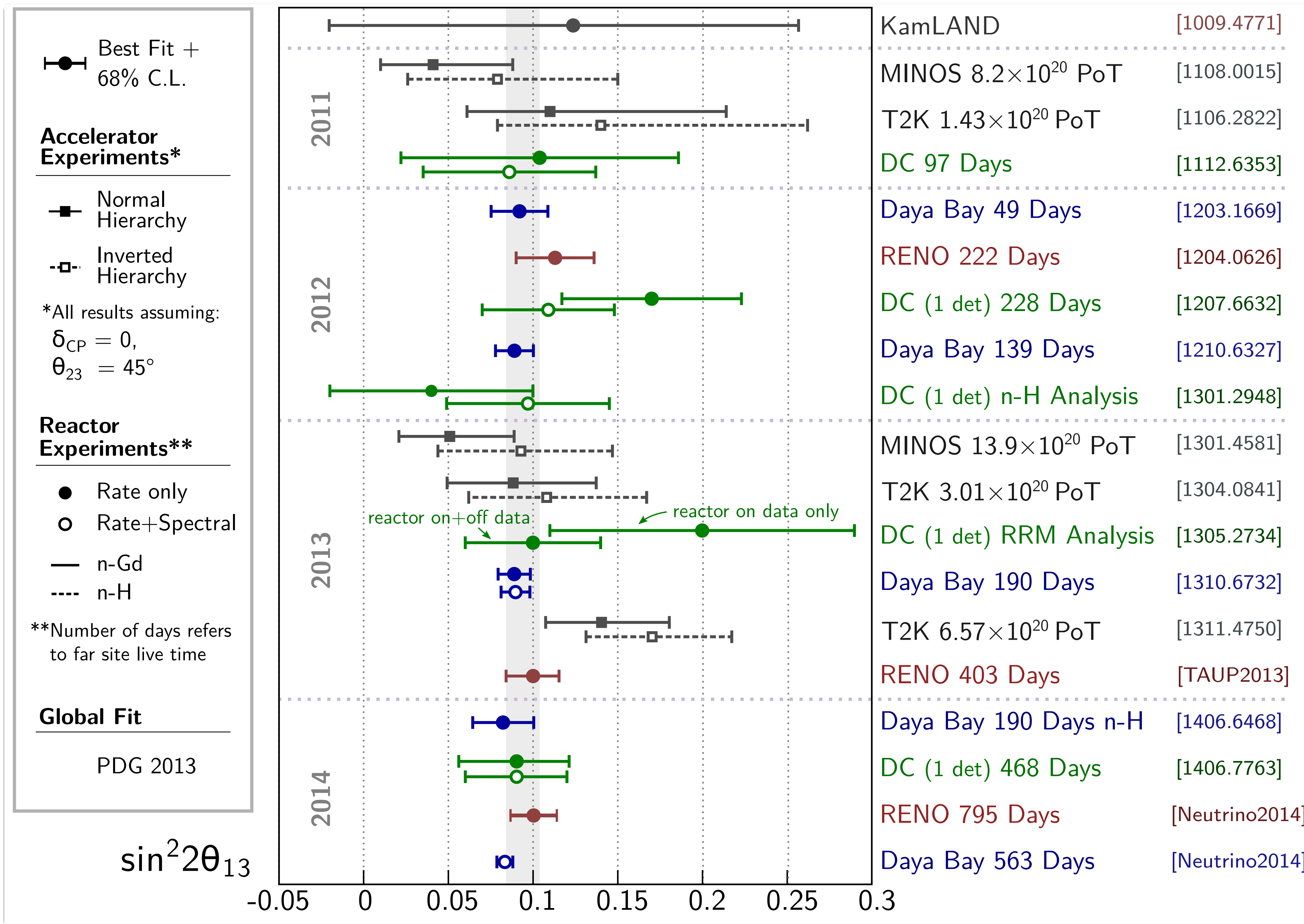
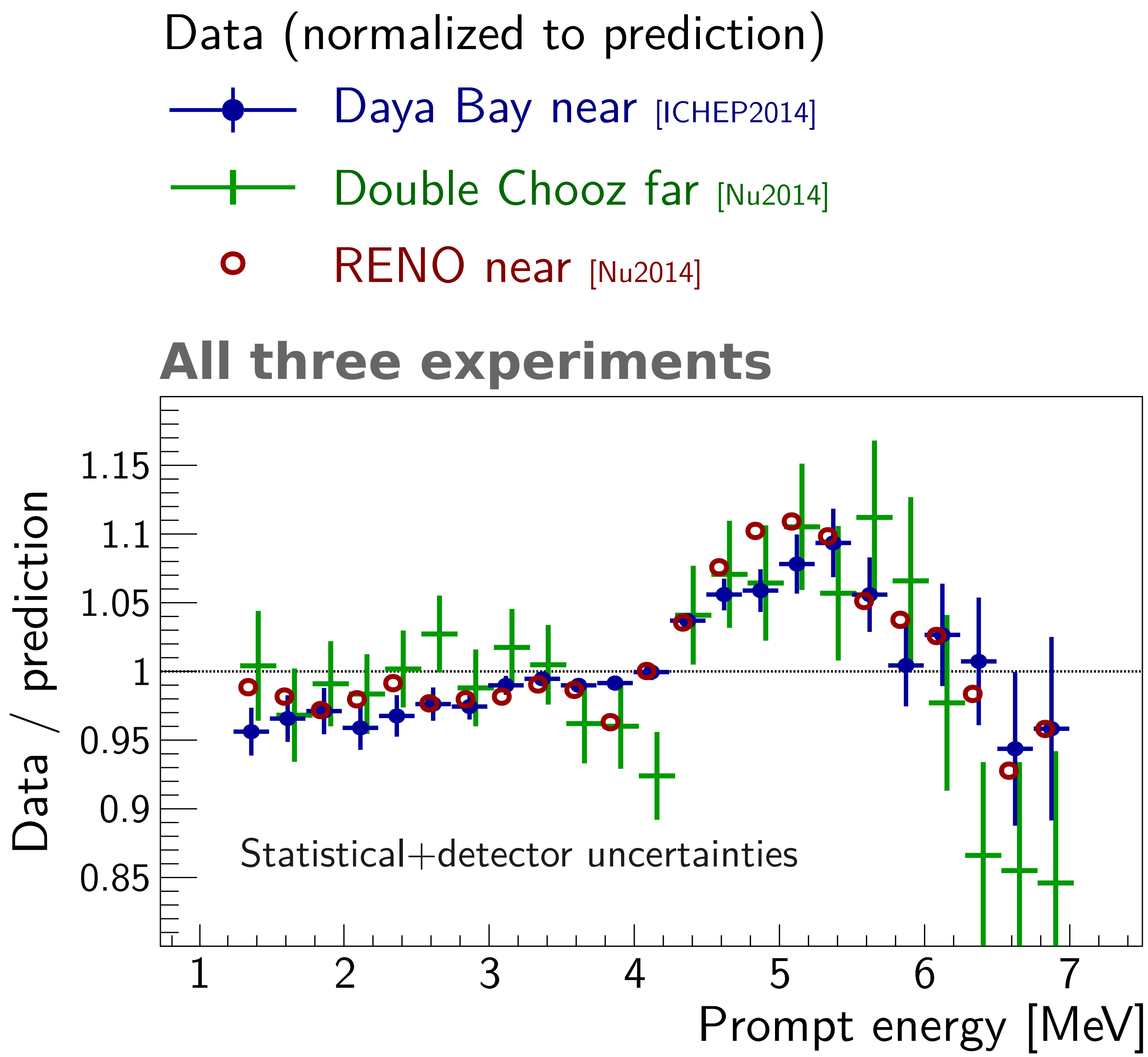
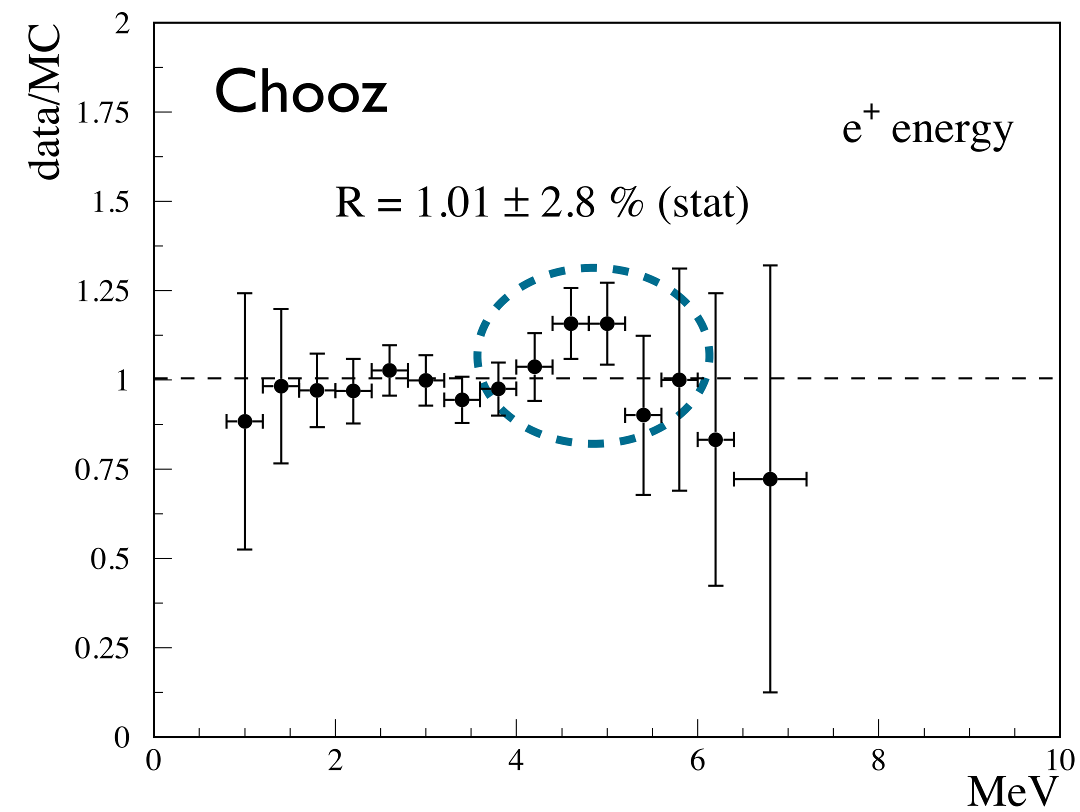


High precision of the measurement, validation with multiple analyses.
Consistent results btw. reactor experiments and btw. reactor and beam experim.

The «bump» issue

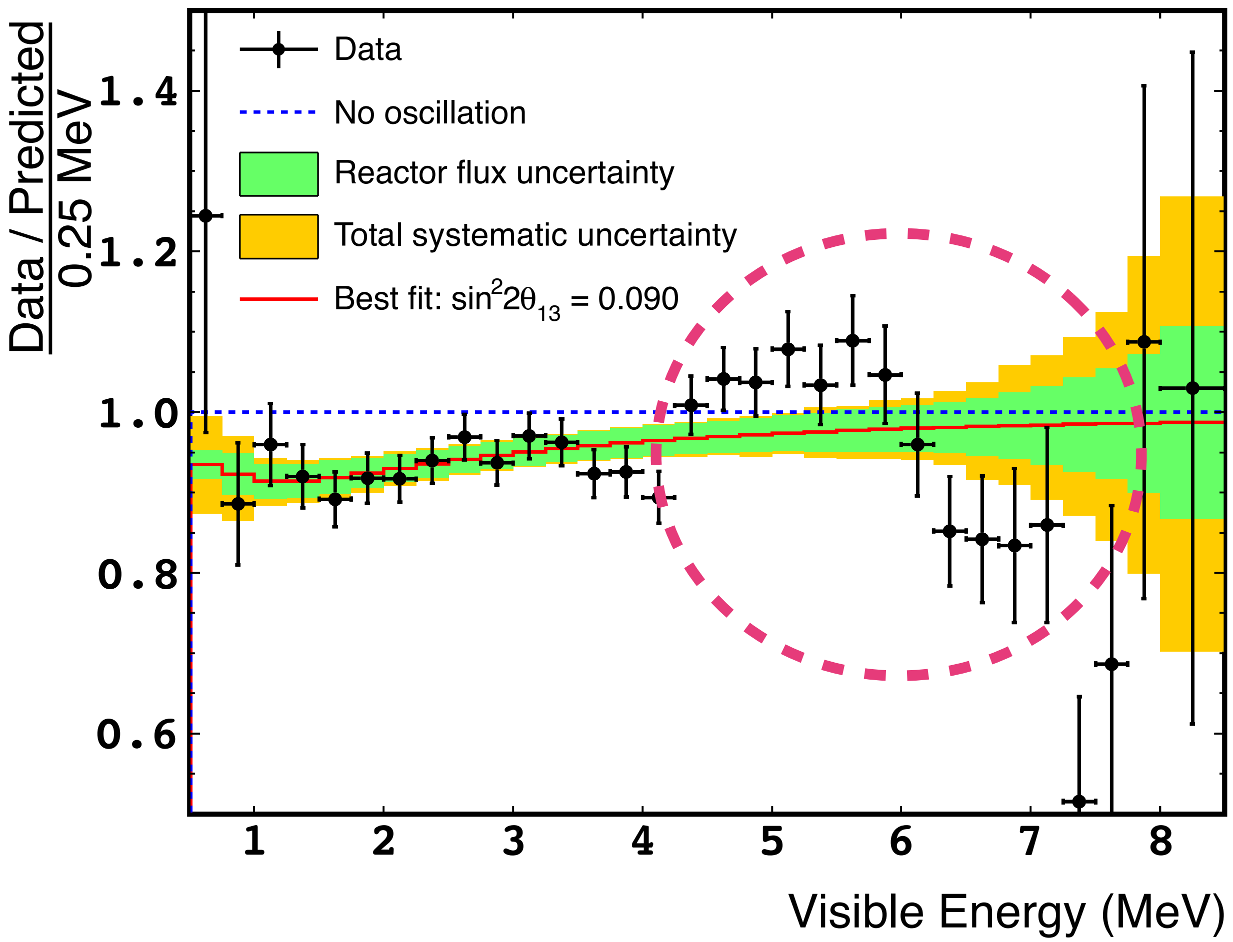
Spectral Distortion

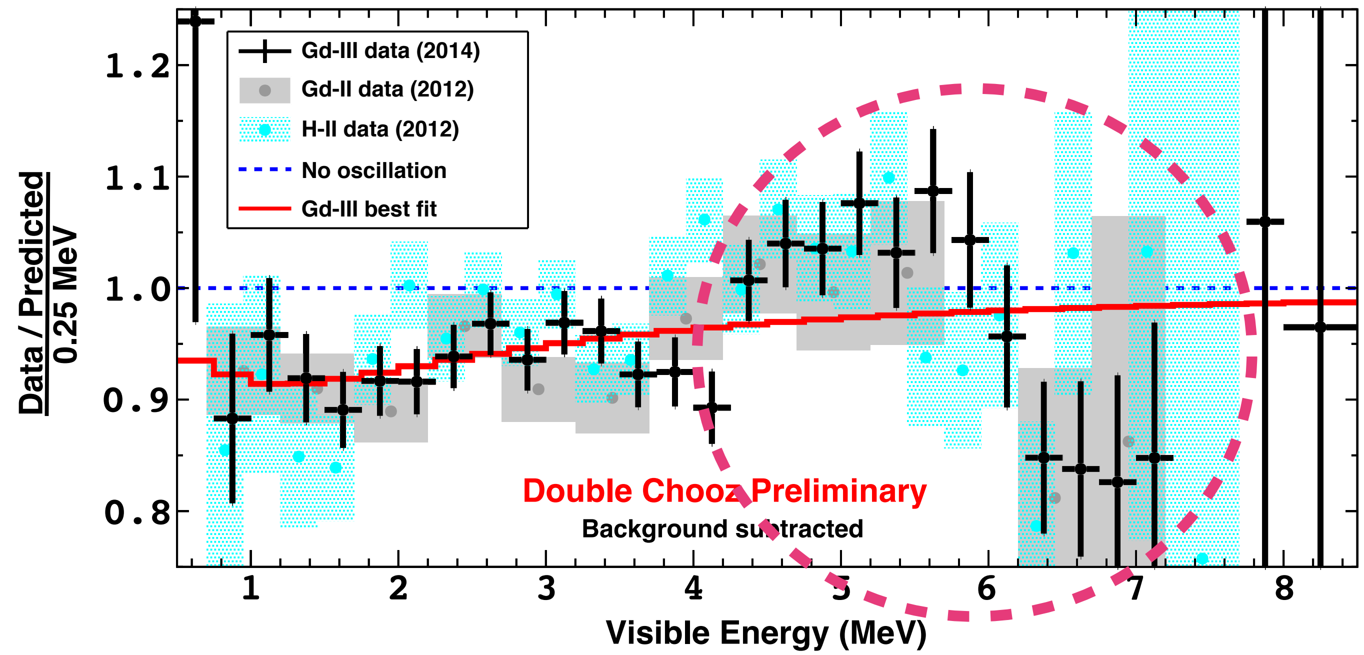




Spectral distortion [4,7] MeV seen in Double Chooz, Reno and Daya Bay.
Previous hints given by CHOOZ and Rovno, not seen in Bugey.
Experiments with different background, electronics, scintillator, etc.

Spectral Distortion in Double Chooz





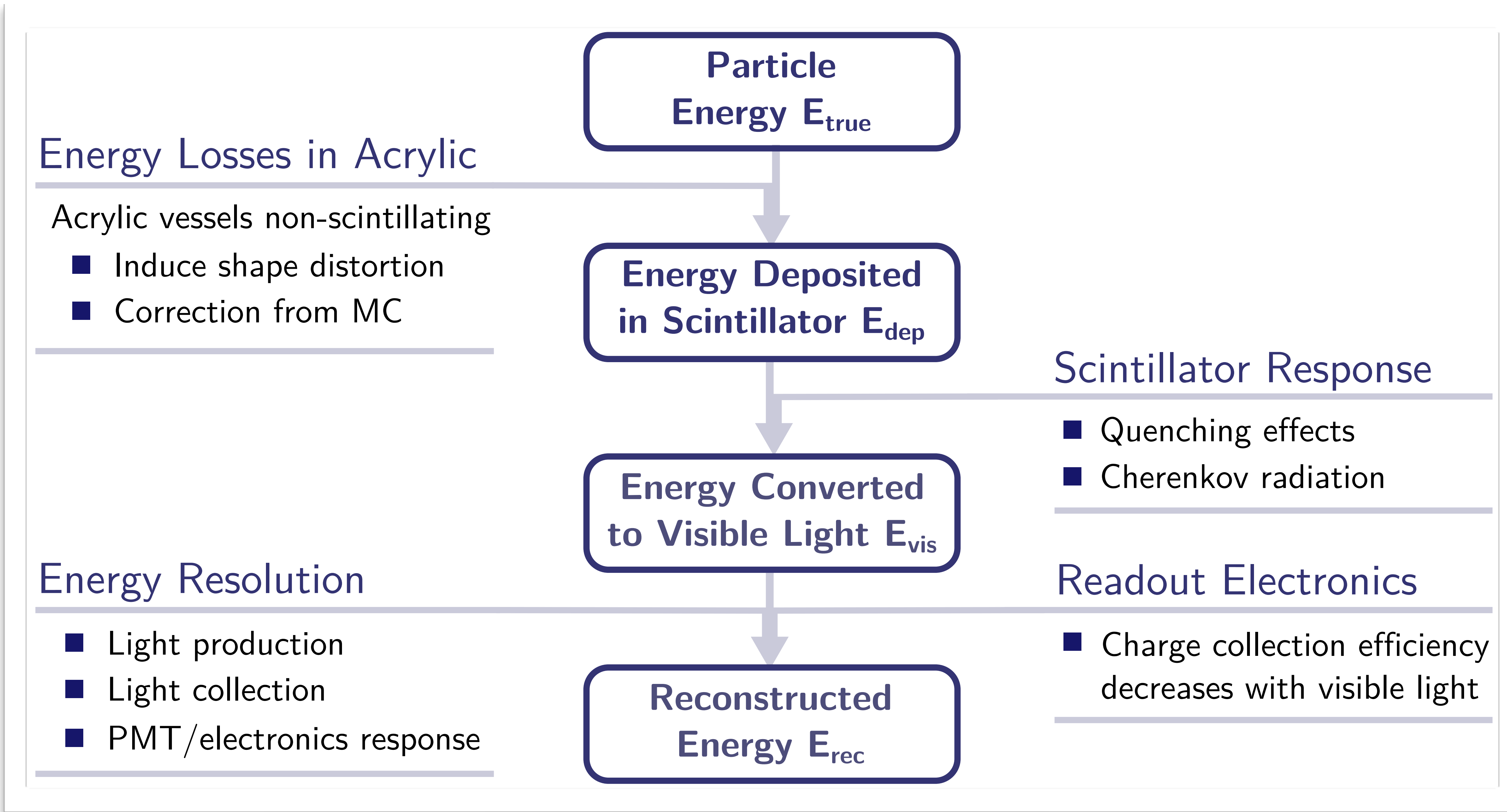
~3σ excess [4,6] MeV and 1.6σ deficit [6,8] MeV → more room in the future (stat. and reactor syst. dominated)

Observation in the same time with the other Θ_{13} experiments, despite poorest DC statistics.

More statistics increases the clarity, however, seen also in past analysis (porer: statistics, bkg reduction, energy scale) and for n-Gd and n-H analyses (different: volume, bkg, cuts).

No impact on Θ_{13}: agreement btw. different analyses, agreement Data/MC ≲3.5MeV

1-st Suspect: Energy Scale



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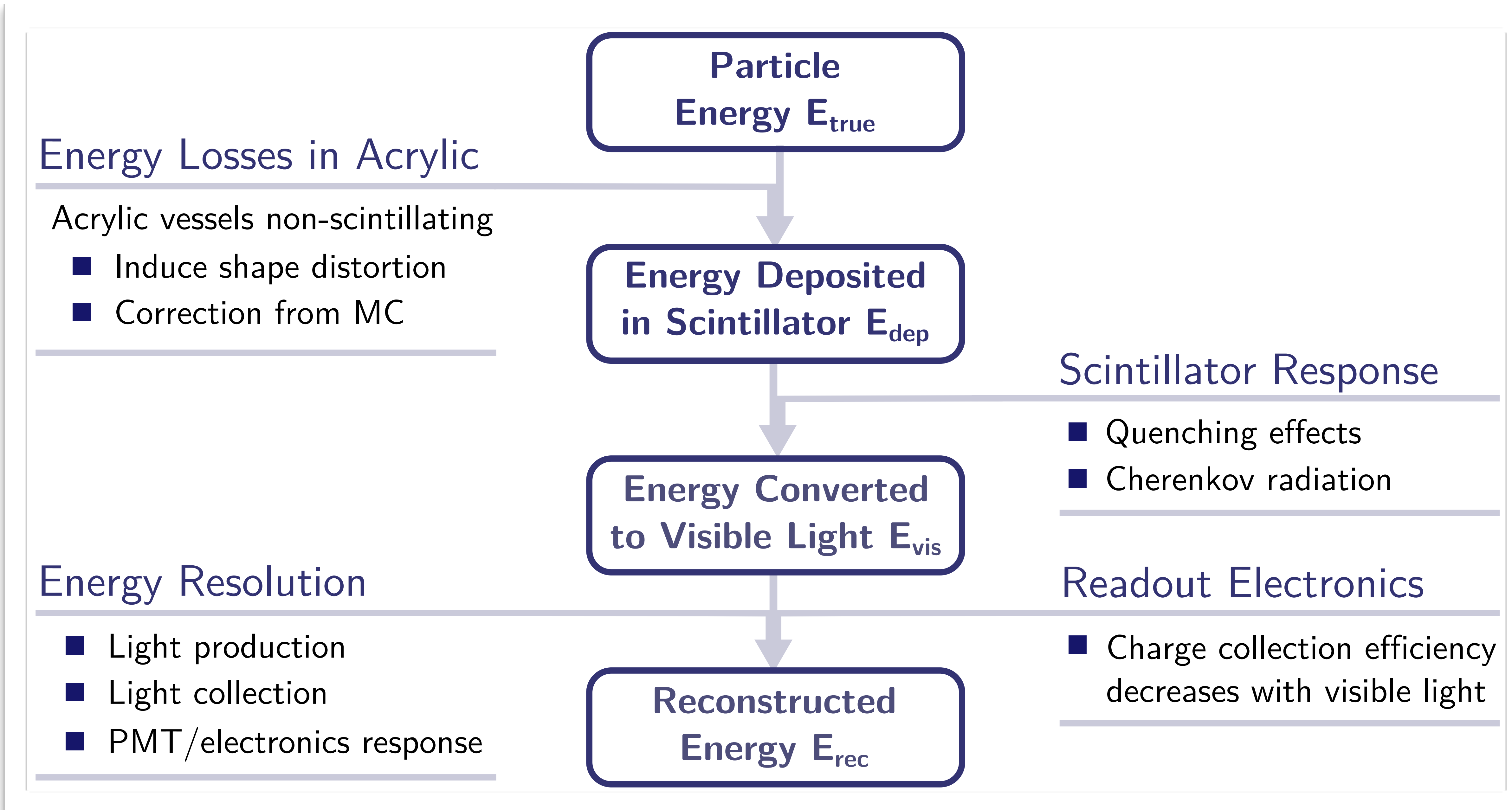
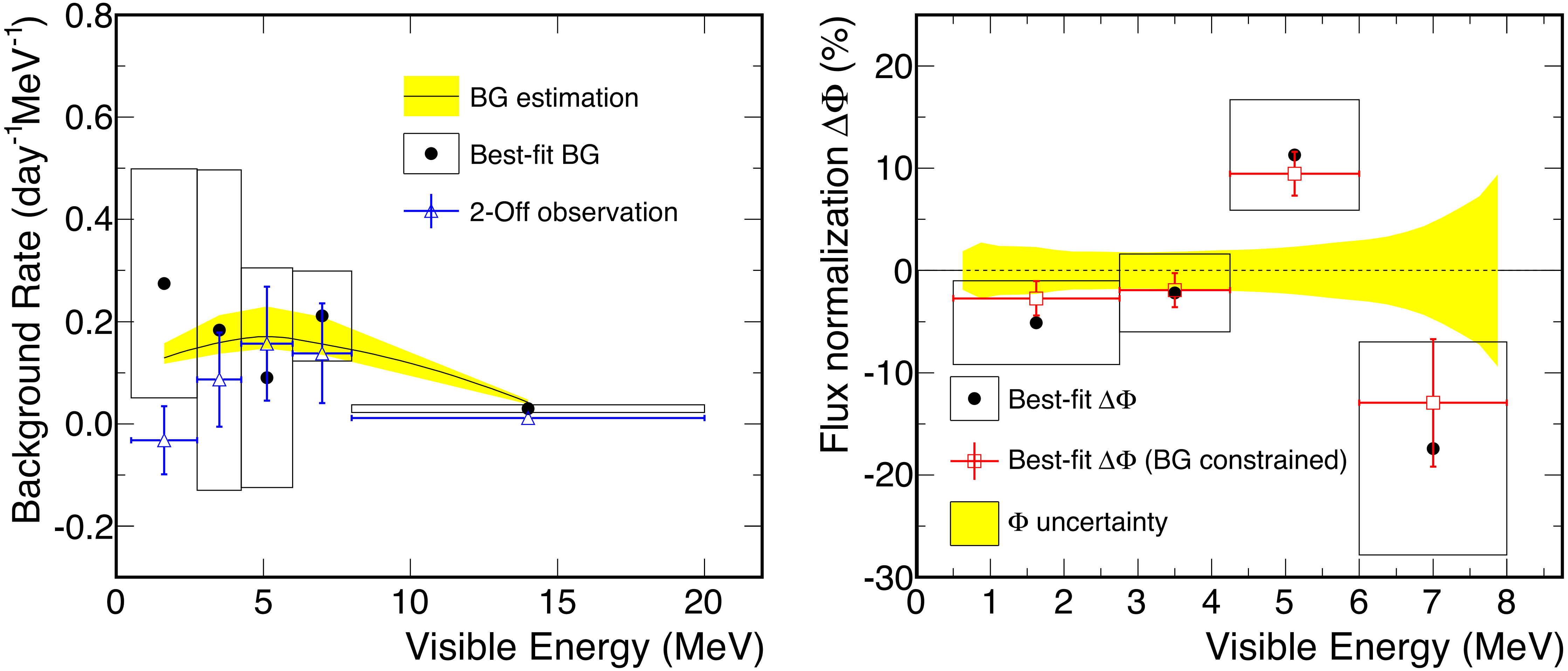


Total non-linearity = scintillator non-linearity ⊗ electronics non-linearity

Complex model, need to be validated by calibration data

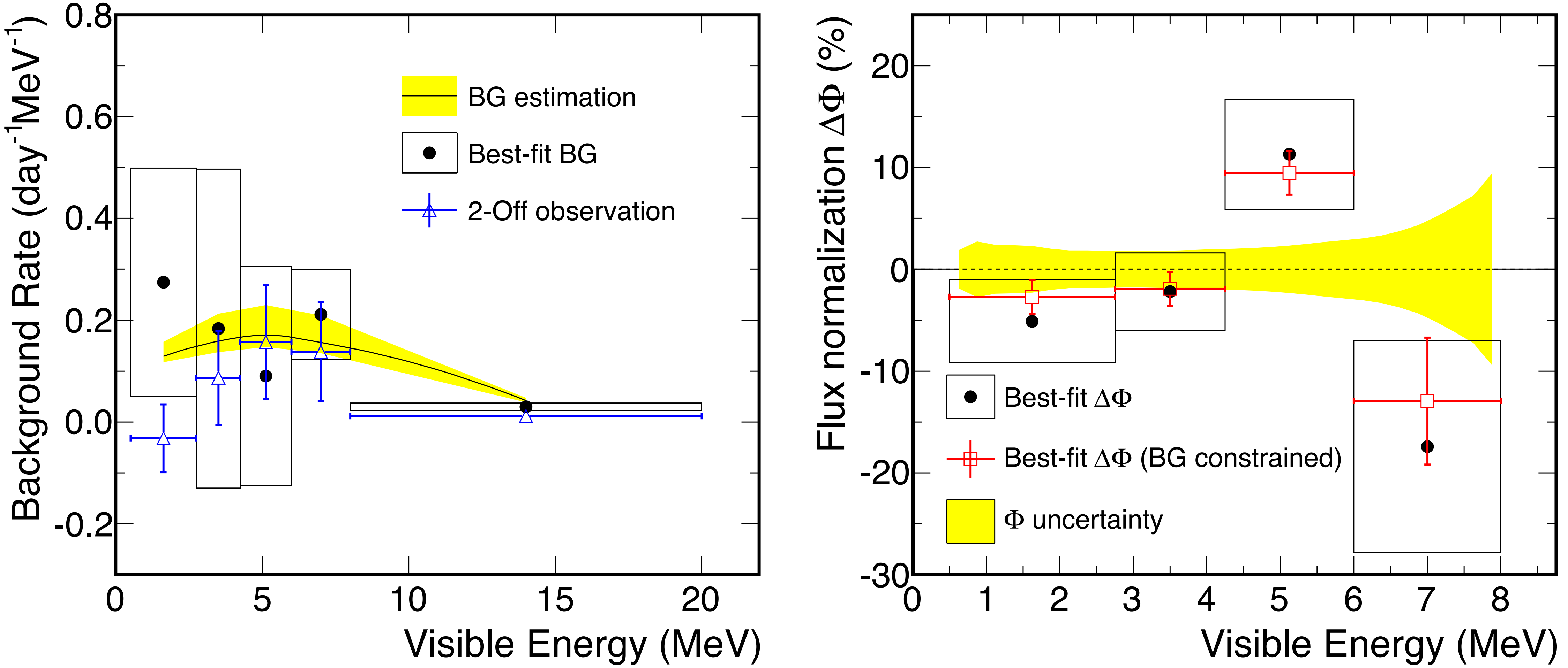
Other Suspects: Background and Reactor Flux

Dedicated energy binned RRM analysis capable in distinguishing the background and reactor flux hypotheses as the cause of the excess. (Θ_{13} value of Daya Bay plugged in).



Other Suspects: Background and Reactor Flux

Dedicated energy binned RRM analysis capable in distinguishing the background and reactor flux hypotheses as the cause of the excess. (Θ_{13} value of Daya Bay plugged in).



The observed spectrum distortion originates from the reactor flux prediction, while the unknown background hypothesis is not favored.

Reactor Flux Prediction

$$N_\nu^{expected}(E_\nu) = Norm(N_p, L, P_{th}(t), \sum \alpha_k W_k) \cdot \sum \alpha_k \mathbf{S_k(E_\nu)}$$

Estimating $S_k(E_\nu)$, spectra per fission

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Problem: Some β-branches with incomplete info, big uncertainties, etc.

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Problem: 'Virtual' spectra not well-defined: what forbiddenness, charge, etc. should they have?

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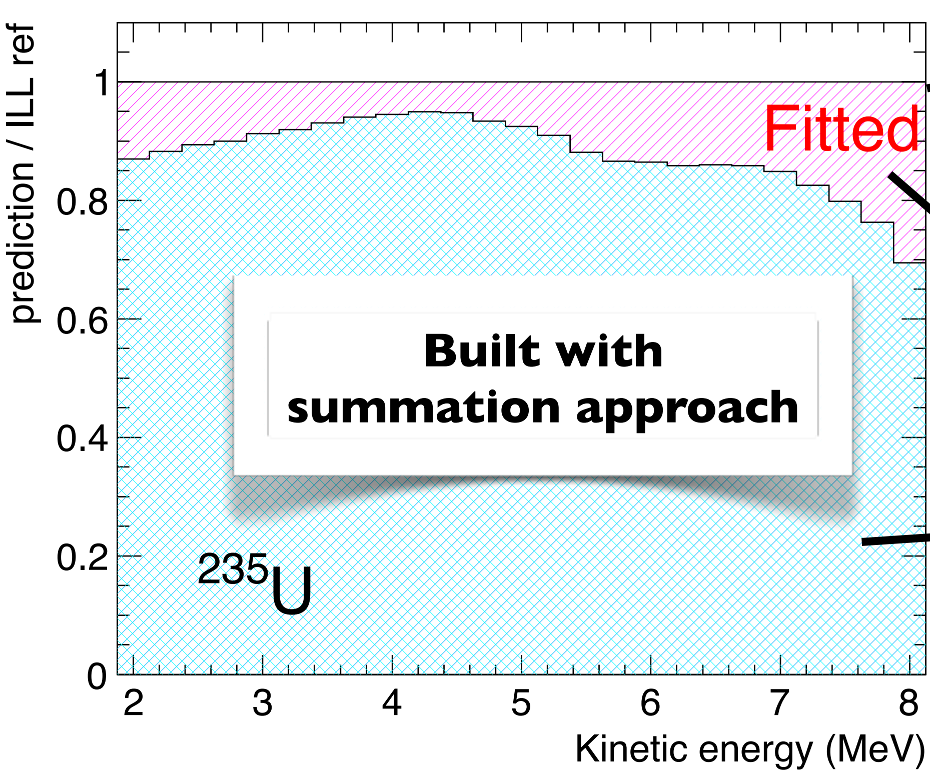
Mixed approach using nuclear databases + virtual branches to reproduce the ILL spectra. Mueller et al, PRC 83 (2011), Huber PRC 84 (2011).



Accurate reference of total fission β spectra
Schreckenbach et.al. (ILL) and Haag et.al.

Fit of residual: five effective branches are fitted to the remaining 10% → suppresses error of full summation approach

"true" distribution of all known β-branches (Summation approach), describes >90% of ILL e- data → reduces sensitivity to virtual branches approximations.

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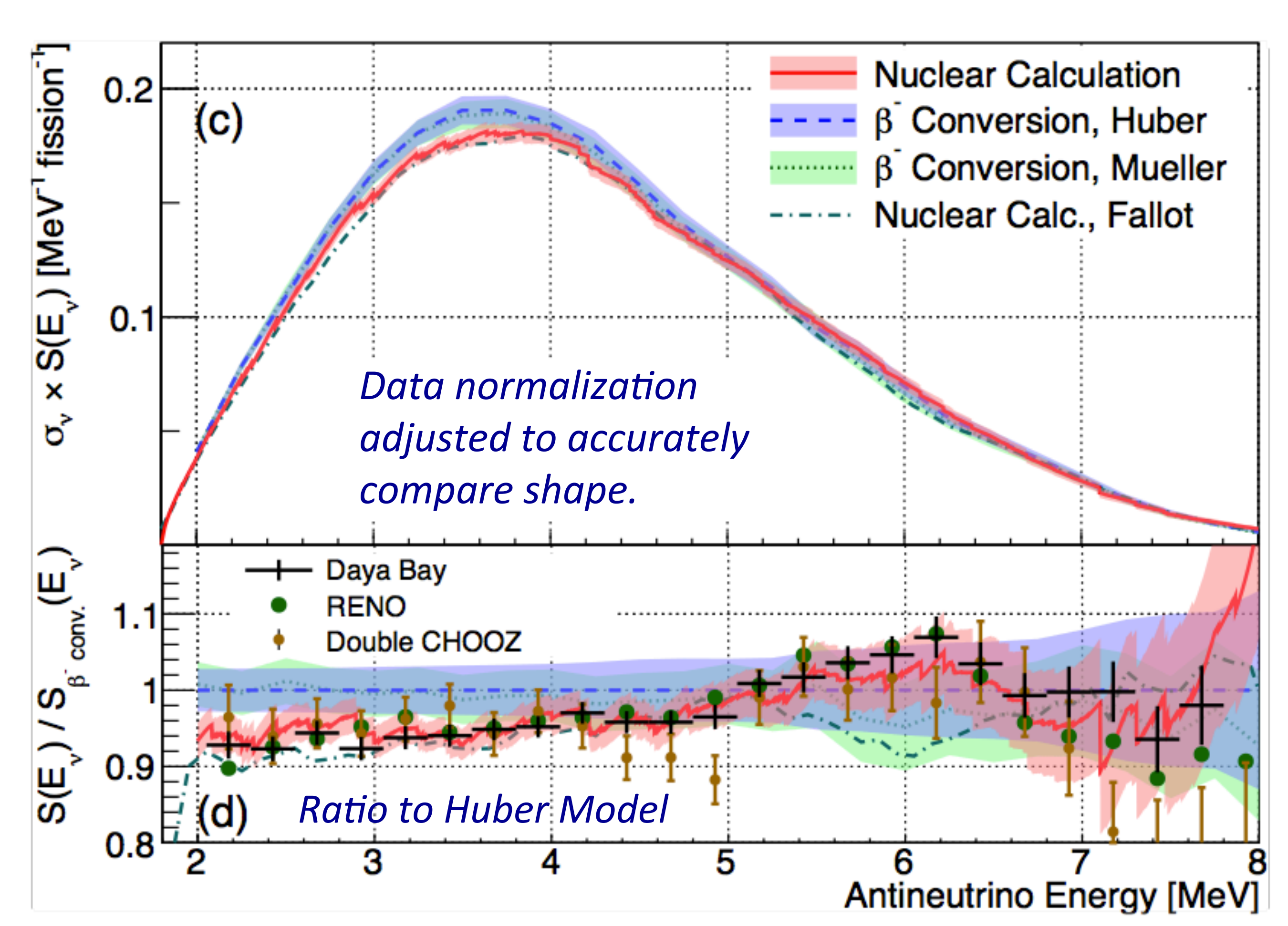

Preliminary estimations based on summation method (D.Dwyer, T.Langford, PRL 114 012502) agrees with the measurements.

Reactor Θ_{13} : Challenges

Challenges of Reactor Θ_{13}

high precision physics ☞ it's all about systematics ...

$\delta^{detection}$: detection uncertainty

Main components: IBD selection cuts, Np, Gd/H fraction, Trigger/DAQ

Trigger/DAQ: *My PhD: Design Studies for the Double Chooz Trigger (2009).*
F. Beissel, A. Cabrera, A.S. Cucoanes et al. JINST 8 T01003 (2013)

$\delta^{detection}$(Trigger/DAQ) < 0.1% for Double Chooz

- **Trigger efficiency** studied with multiple independent methods (sources, RND triggers, etc.)
- **Low readout threshold** (300KeV) far from physics events (~1MeV)

Gd/H fraction: *Double Chooz Collab. (Y. Abe et al.) PRL 108, 131801 (2012)*

$\delta^{detection}$(Gd/H fraction) = 0.4% for Double Chooz

- Analysis of the **fraction of neutron events captured on Gd and H** studied with analytical models and calibration data (^{252}Cf scans).

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Near/Far setups eliminates an important contribution, however it requires an excellent detector understanding
Issue: uncorrelated inter-detector systematics

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$\delta^{background}$: background (BG) uncertainty

Main components: cosmogenic induced BG, accidental BG, light noise BG

Cosmogenic induced BG: *My PhD: Design Studies for the Double Chooz Trigger (2009).*
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- Identification and analysis of the **muon events,** the most important source of cosmogenic induced BG with online reconstruction algorithms.

Accidental BG: Identification of the **accidental BG events in Gamma Catcher volume** with on a new method of identification of the interaction volume based on the statistical analysis of the difference between the responses of the scintillators.

Light noise BG: *(Double Chooz Collab. (Y. Abe et al.) PRL 108, 131801 (2012)*

Analysis of the **rejection cut for the light noise** for the first Θ_{13} analysis of Double Chooz.

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Analysis of the **rejection cut for the light noise** for the first Θ_{13} analysis of Double Chooz.

Each site has a different background contribution, Near detectors have more signal but also more background
Issue: normalization and shape of each background

Challenges of Reactor Θ_{13}

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δ^{flux}: antineutrino flux uncertainty

«A priori» (proposals of Double Chooz, Daya Bay and Reno), δ^{flux} has to be negligible based on the relative Near/Far measurement, but ...

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	δ^{flux}	$\delta^{detection}$	$\delta^{background}$
Reno	**0.9%**	0.2%	0.6%
Daya Bay	**0.8%**	0.2%	0.2%
Double Chooz	**1.7%**	0.6%	0.7%

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Up to now: not a coherent approach to deal with this systematic uncertainty in Θ_{13} reactor experiments.

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→ cancel in Near/Far setups.

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Uncertainties of $P_{th}(t)$ and α_k are **partially** correlated *between reactors.*
→ could be supressed in Near/Far setups (this talk)

$P_{th}(t)$ is driven by an instumental measurement done by the power plant and $\alpha_k(t)$ is driven by reactor simullations.
→ uncertainties difficult to be improved directly.

Reactor Induced Systematics

A.S.C. et al. arXiv:1501.00356 (submitted to JHEP): Analytical approach for δ^{flux} calculation, cross-checked by simulations. Calculation of SF for Double Chooz, Daya Bay and Reno. Direct application to Juno, Reno 50.

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$$\delta^{flux} = \mathbf{SF} * \delta^{R}$$

$(\delta^{R})^2 = (\delta^{R}_{c})^2 + (\delta^{R}_{u})^2$

correlation between reactors

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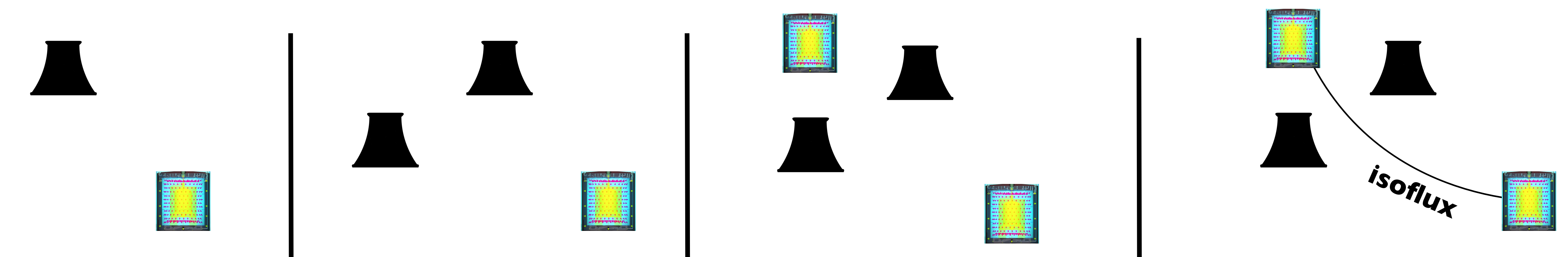


$SF = 1$
(no suppression)

$SF = f(N^R, \delta^R_{c,u})$
(suppression)

If $\delta^R = \delta^R_c$, $SF = 1$
(no suppression)

$SF = f(N^R, \delta^R_{c,u}$, geo)
(more suppression)

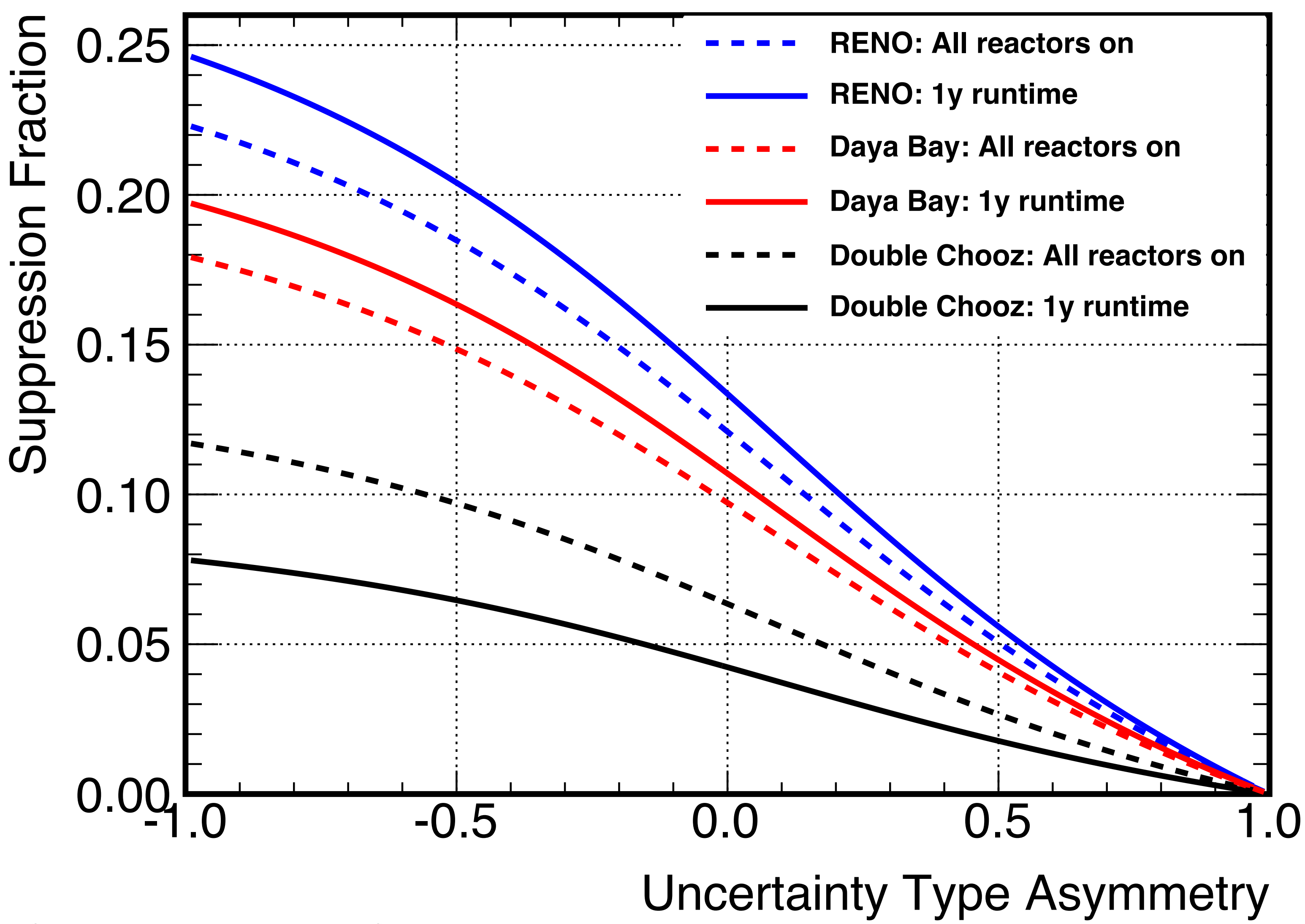
If $\delta^R = \delta^R_c$, $SF = 0$
(maxim. suppression)

$SF = 0$
(maximal suppression)

ISOFLUX: Near and Far see the same relative contribution from reactors

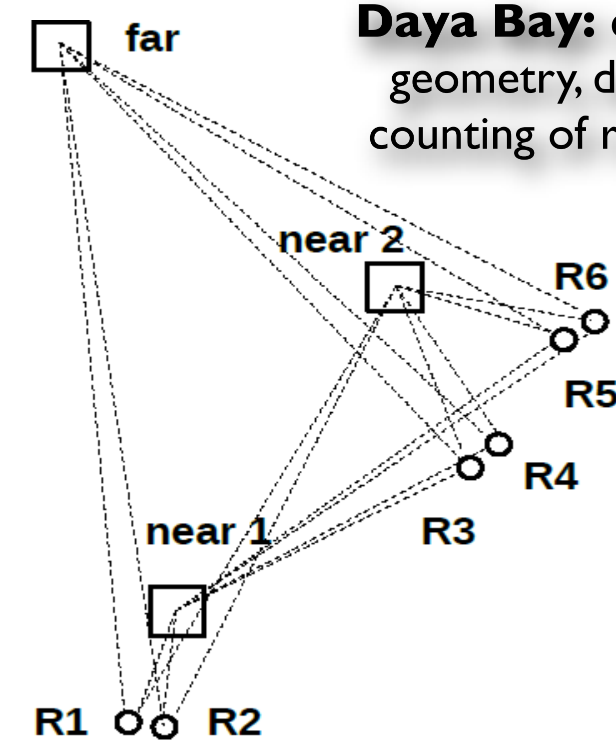
Suppression of δ^R: all experiments

Continuous curves: **2 months 1 reactor off/year**
Dotted curves: **all reactors running**

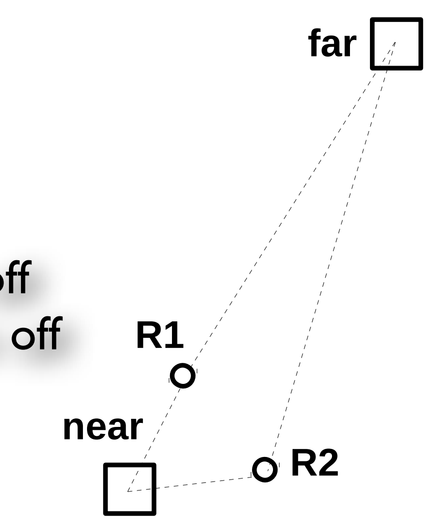


uncorrelated

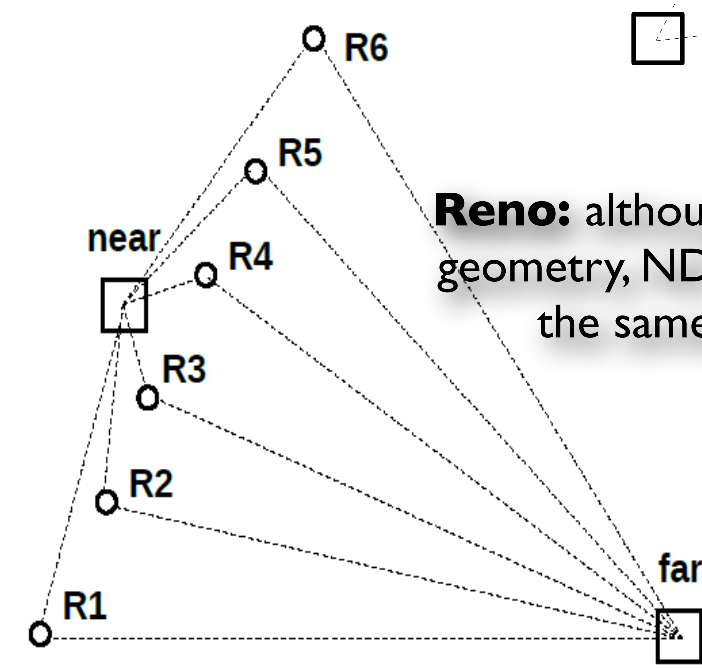
correlated



Daya Bay: complex geometry, double-counting of reactors



Double Chooz: slighty off axis but SF = 0 for 1 reactor off



Reno: although appealing geometry, ND do not see the same as FD

Suppression of δ^R : a short summary

	P_{th} [%]	α_k [%]	Spent Fuel [%]	Total now	This work	$\delta^{det}/\delta^{bkg}$ [%]
Double Chooz	0.5	0.9	included	**1.1**	**0.08**	0.2 (??) / 0.3 (??)
Daya Bay	0.5	0.6	0.3	**0.8**	**0.16**	0.2 / 0.2
Reno	0.5	0.7	unknown	**0.9**	**0.22**	0.2 / 0.5

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Reno	0.5	0.7	unknown	**0.9**	**0.22**	0.2 / 0.5

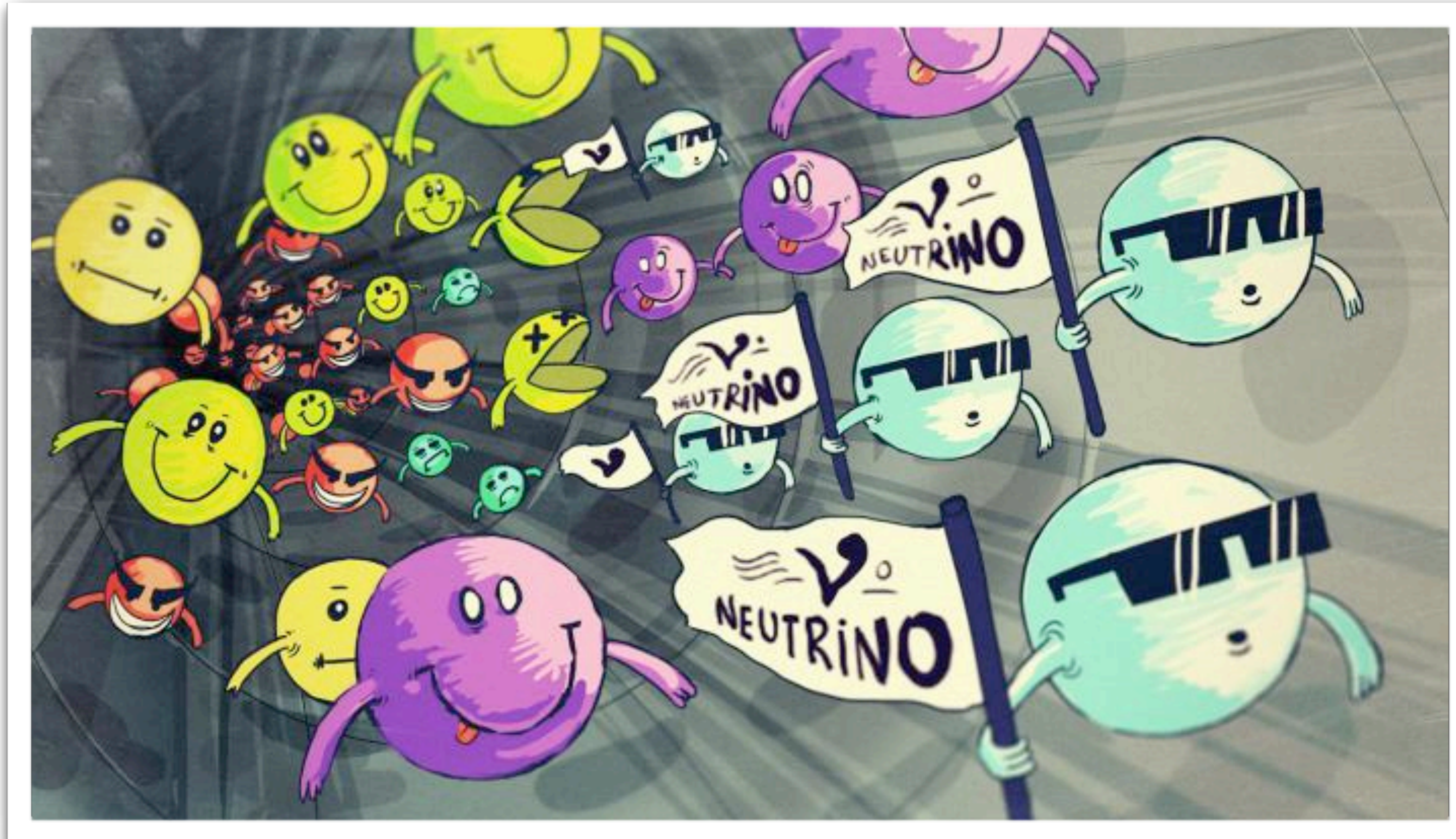
All Θ_{13} reactor exp. conceived to maximize the «isofluxness» (Far a «perfect» monitor of Near), but none suceeded → **Multi-detector exp. do not cancel δ^{flux} automatically**.

Up to now, the experiments used conservative approaches, totally correlated for single-detector exp. (Double Chooz phase 1) and totally uncorrelated for multi-detector exp. (Daya Bay, Reno).

Strong site geometry, error type, and number of reactors dependence.
Strongest suppression for simplest site: Double Chooz but Daya Bay and Reno favored by the big number of reactors.

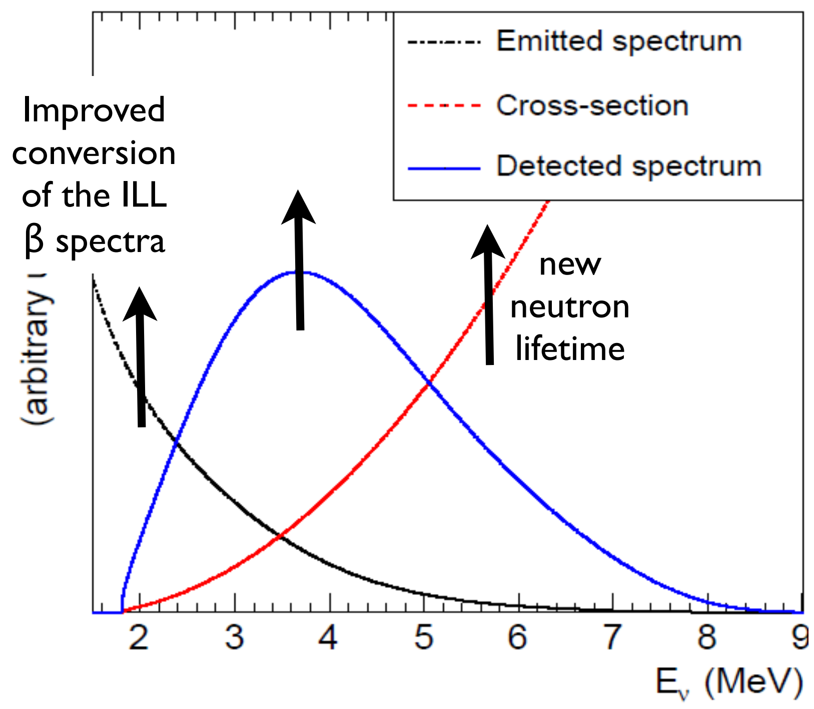
Inter-reactor correlation needs further studies. No consensus up to now.

δ^{flux} will be not the main systematics in Double Chooz Near/Far phase, unlike the Far only phase.



Seeking the sterile ones …

Reactor Antineutrino Anomaly (RAA)



Triggered by the need of accurate antineutrino spectrum predictions for Double Chooz: **reevaluation of the antineutrino spectra emitted by reactors -> new normalization with ~3.5% shift**

Mueller et al., PRC83 (2011), Huber, PRC84 (2011)

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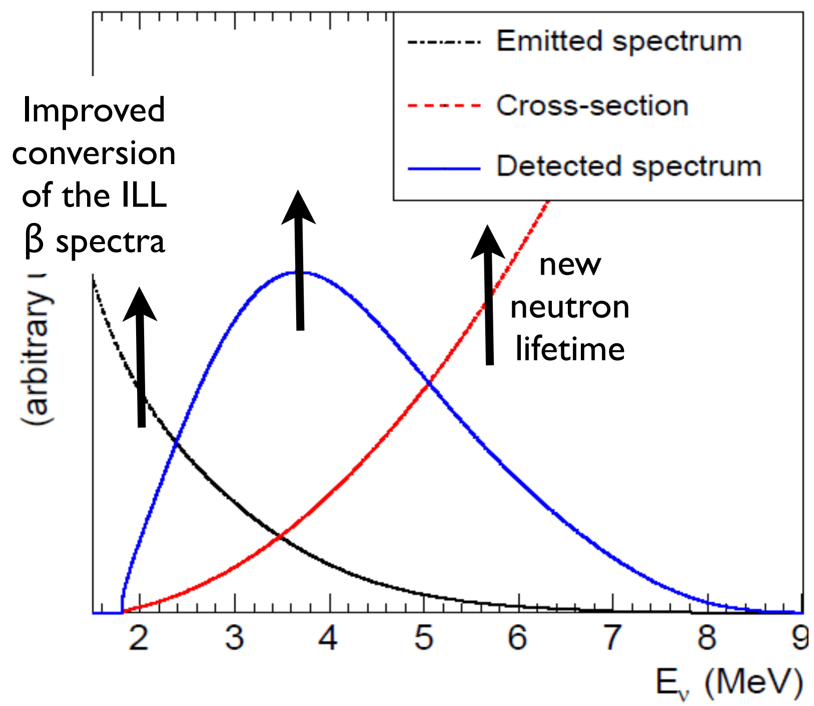

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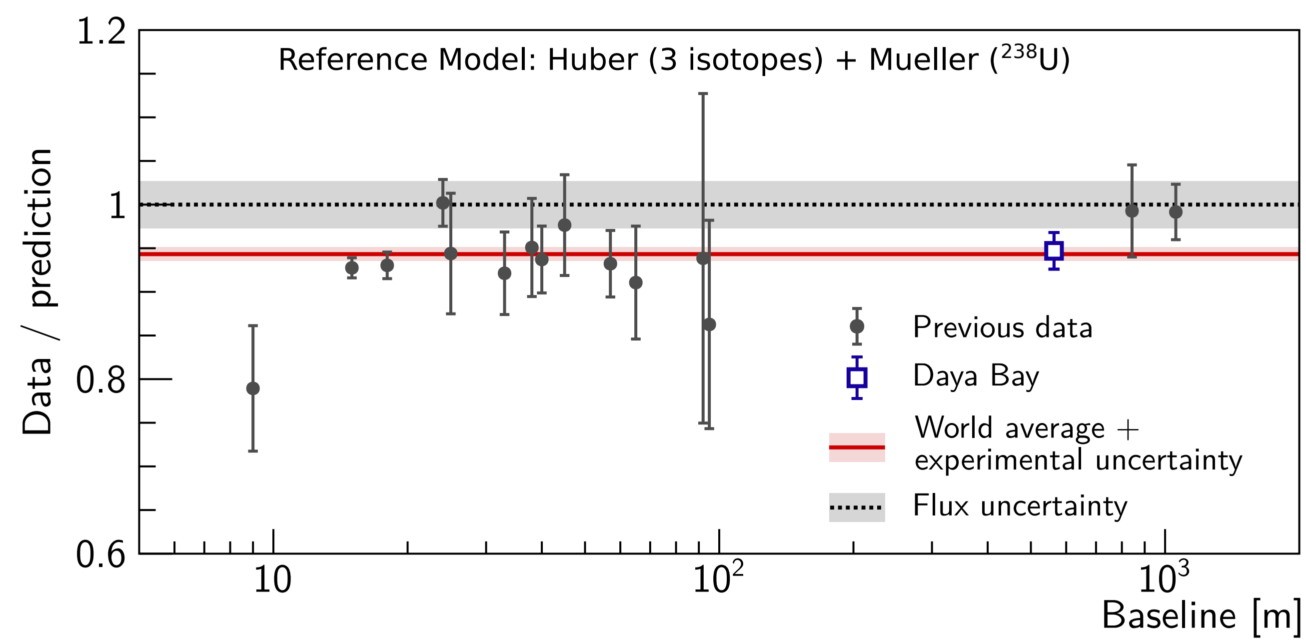
Re-analysis of 19 SBL reactor experiments *G.Mention et al. PRD83 (2011):* **Observed to predicted event rate < 1**



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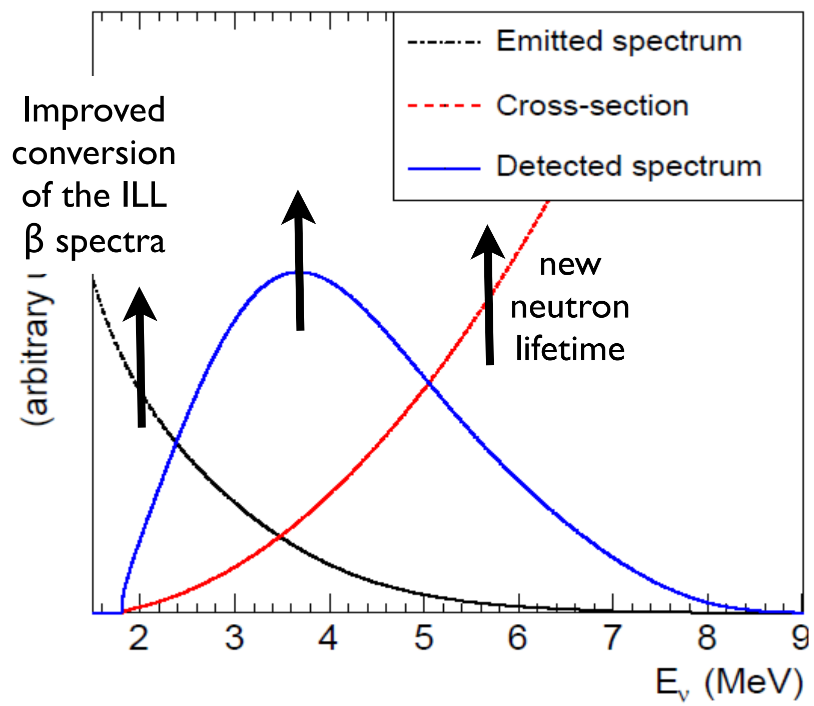

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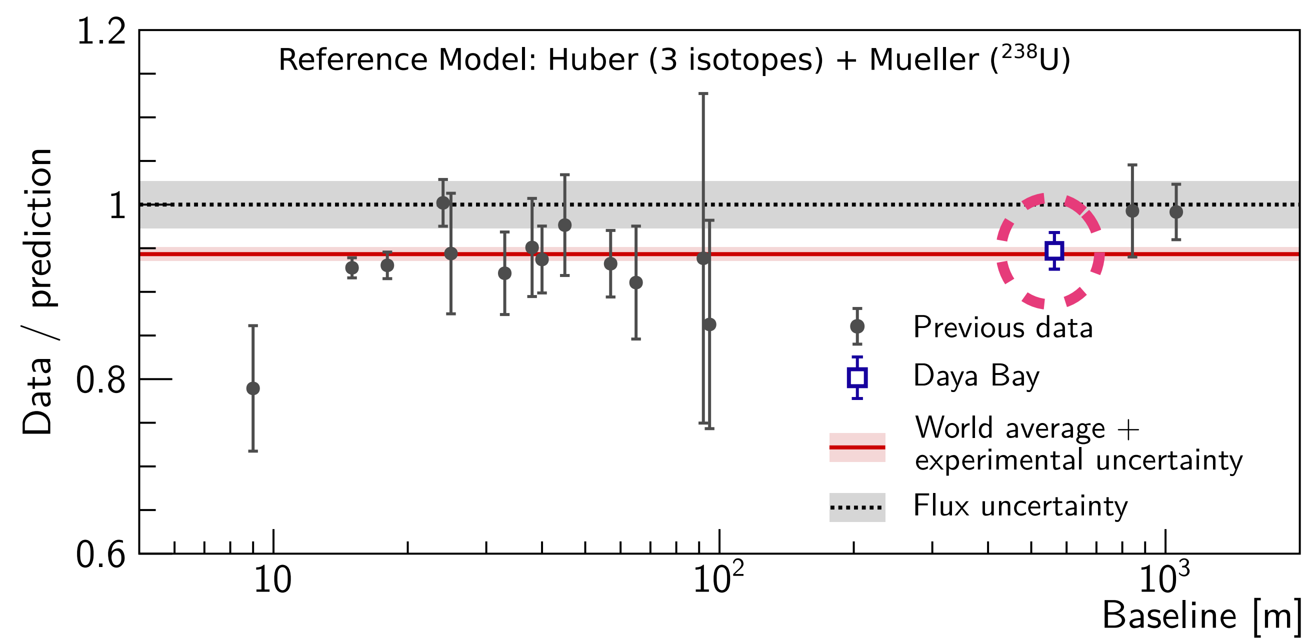
$$R^{RAA} = 0.943 \pm 0.008$$
$$R^{Daya\ Bay} = 0.947 \pm 0.022$$



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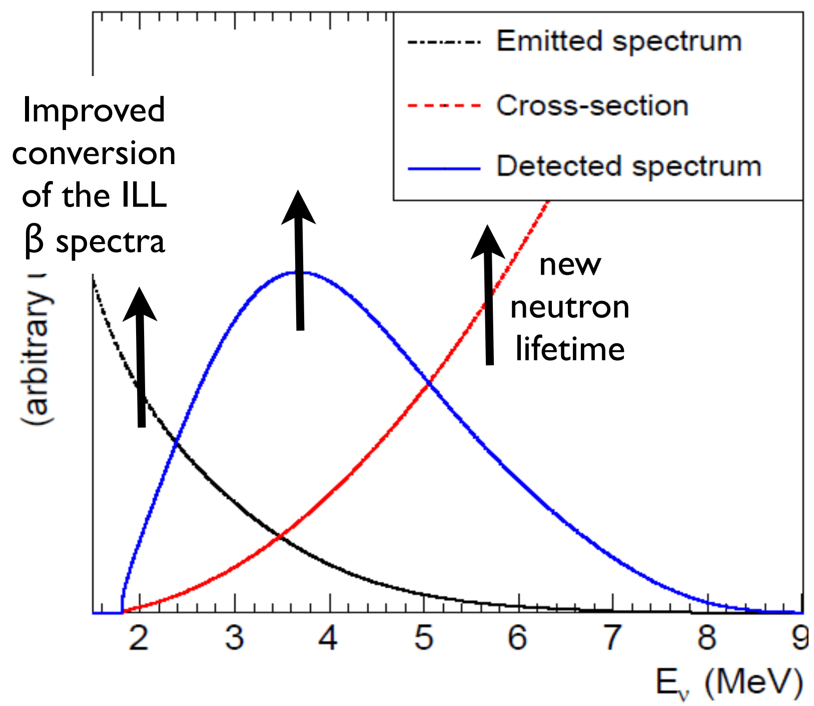

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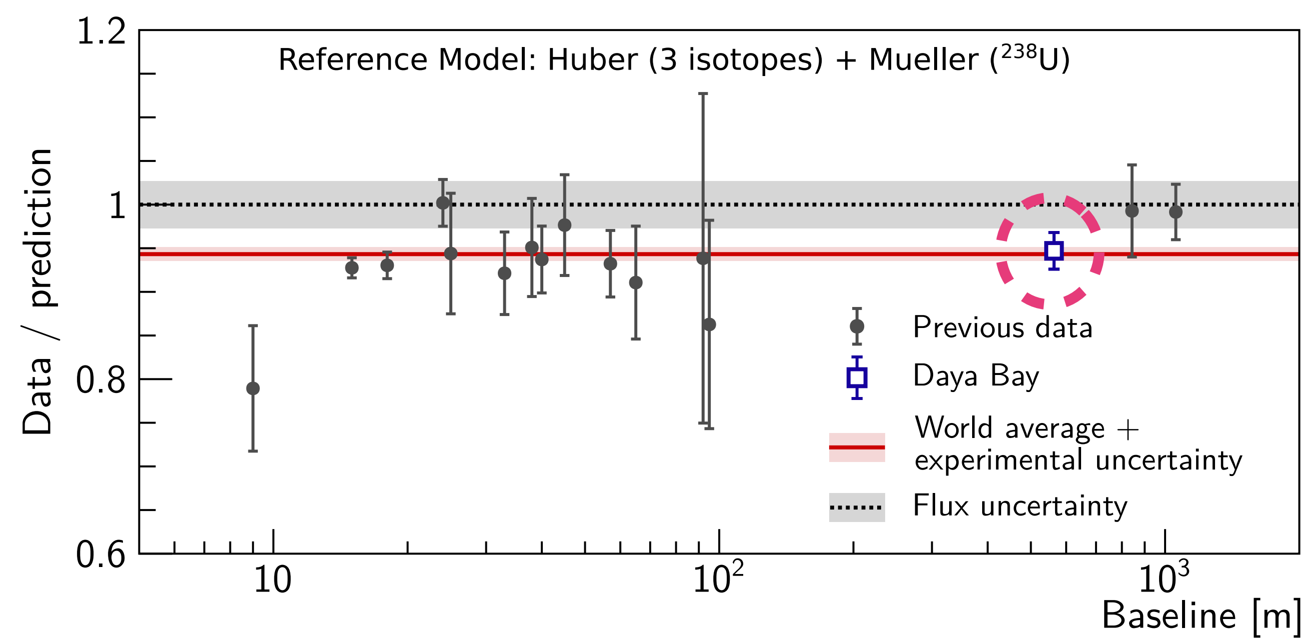

This deficit could be explained by a SBL neutrino oscillation ($\nu_e \rightarrow \nu_s$) or by a missunderstanding of the neutrino flux.

Short Baseline Reactor Experiments

Multiple motivations:

- Directly address sterile neutrino explanation of RAA measuring the $\bar{\nu}_e$ deficit
- Precision measurement of ^{235}U reactor antineutrino spectrum: additional constraint on models seeking to explain newly observed spectral feature
- Develop detection technology for reactor safeguards

Multiple challenges:

- High efficiency and energy resolution
- High correlated background due to low overburden
- Excellent detector stability, safe to the power plant
- Detailed reactor simulations

Multiple proposals: SoLid, Stereo, Danss, Prospect, etc.

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Experiments with multiple physics goals
Common specifications and challenges → place for synergies

SoLid@BR2 (Mol, Belgium)

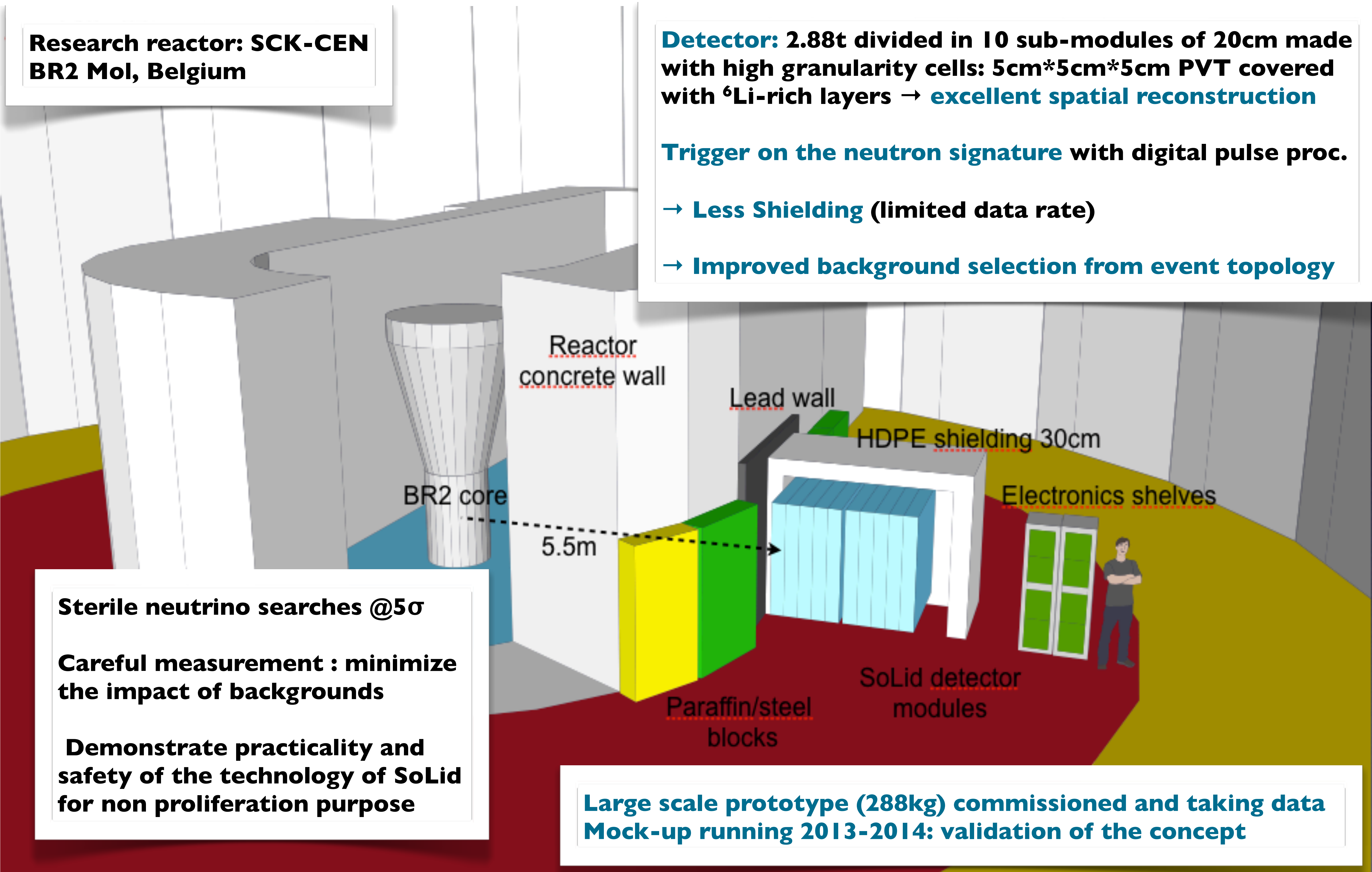
Research reactor: SCK-CEN BR2 Mol, Belgium

Detector: 2.88t divided in 10 sub-modules of 20cm made with high granularity cells: 5cm*5cm*5cm PVT covered with ^{6}Li-rich layers → **excellent spatial reconstruction**

Trigger on the neutron signature with digital pulse proc.

→ **Less Shielding** (limited data rate)

→ **Improved background selection from event topology**



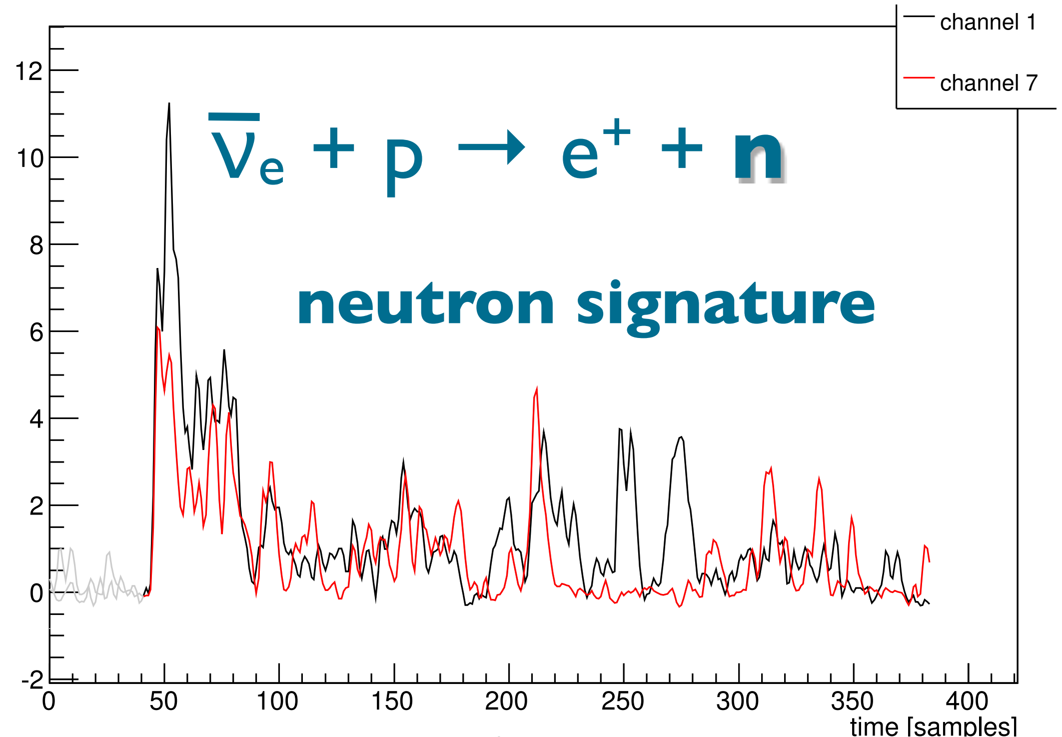
Sterile neutrino searches @5σ

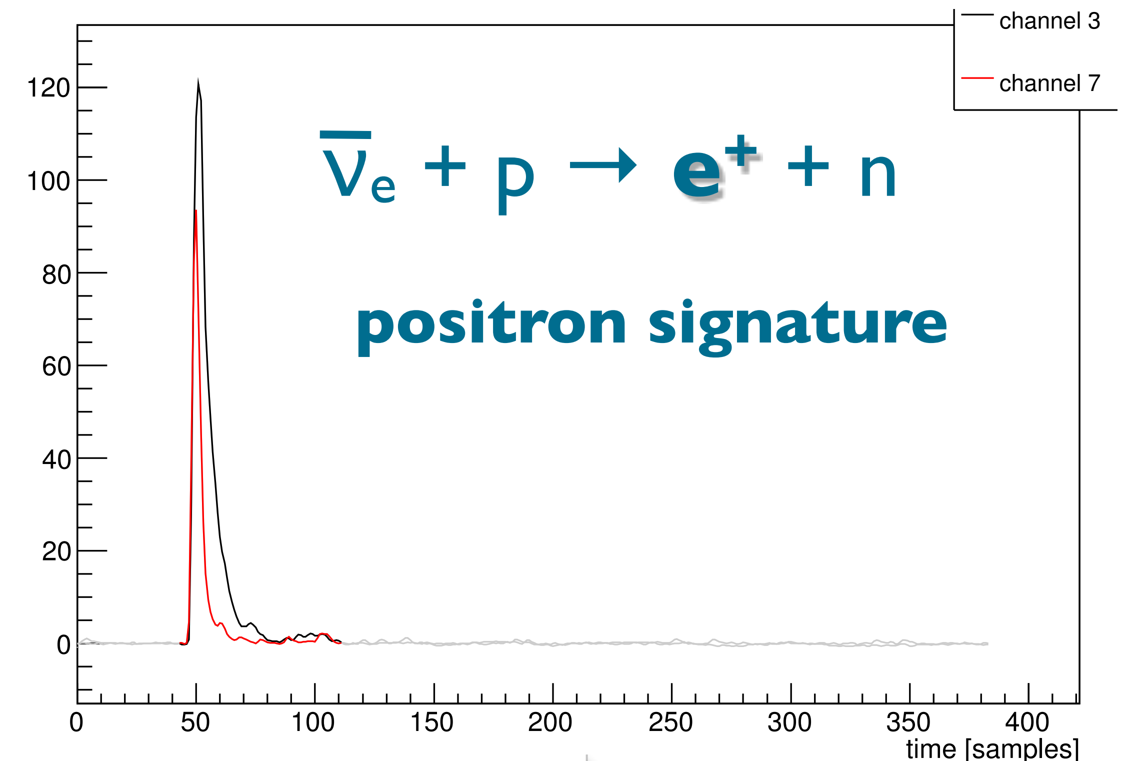
Careful measurement : minimize the impact of backgrounds

Demonstrate practicality and safety of the technology of SoLid for non proliferation purpose

Large scale prototype (288kg) commissioned and taking data
Mock-up running 2013-2014: validation of the concept

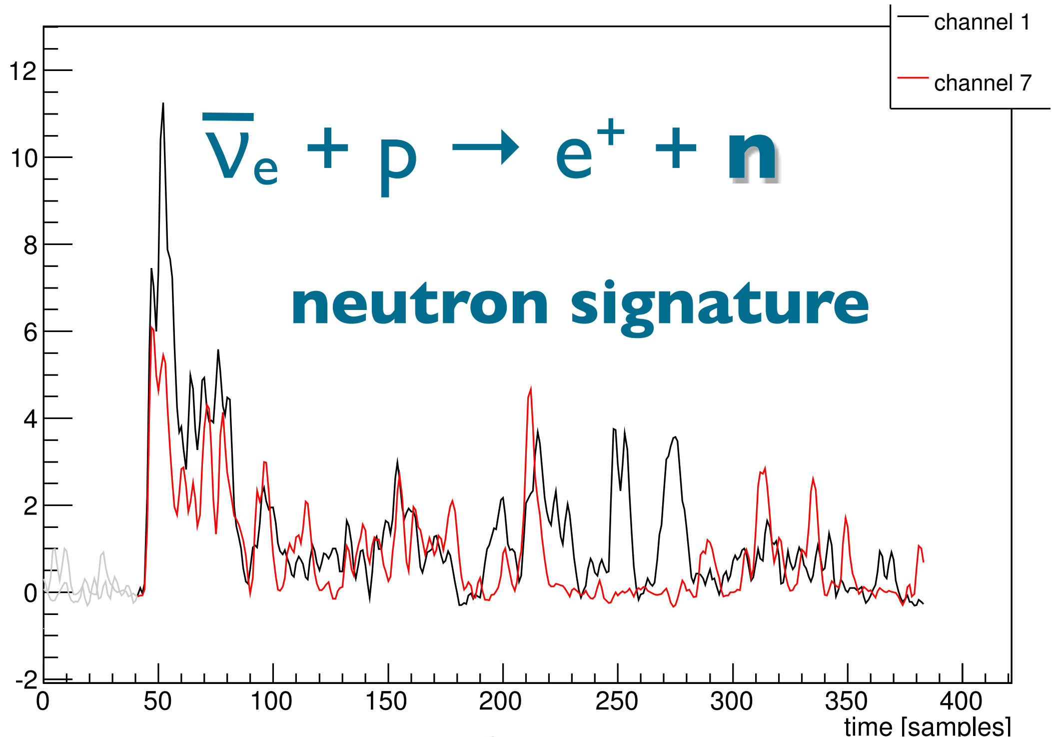
SoLid: Detection

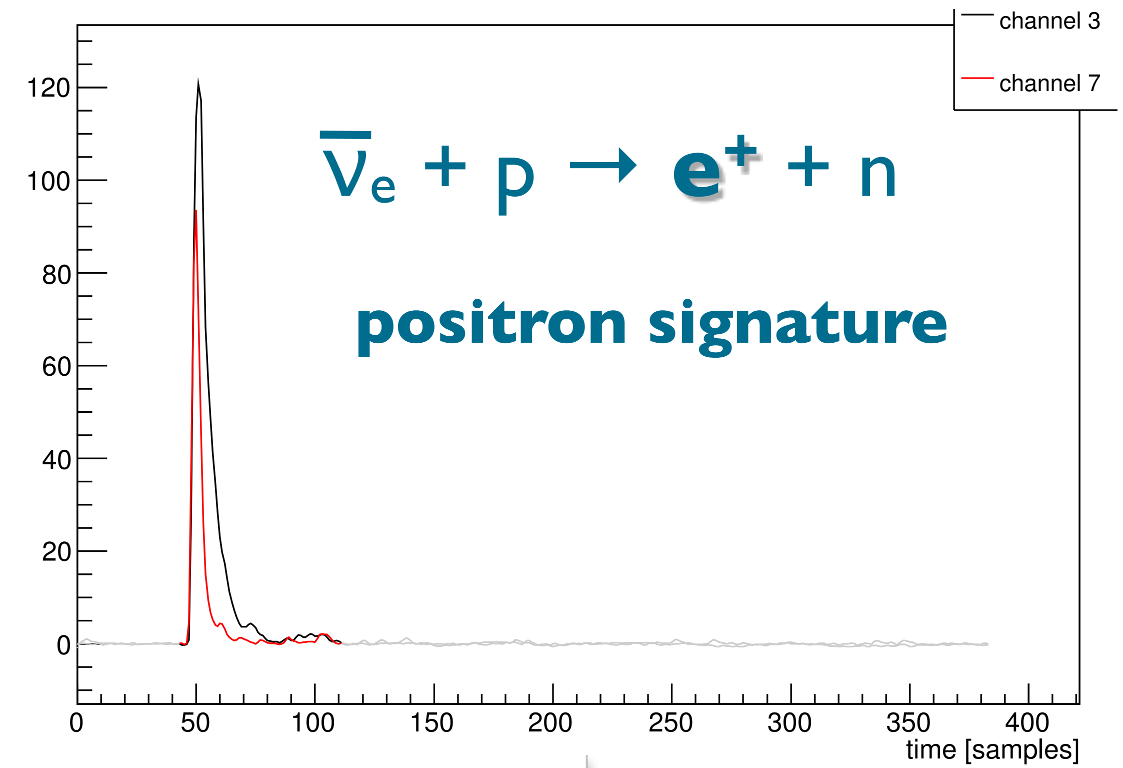




Clear identification of IBD candidates

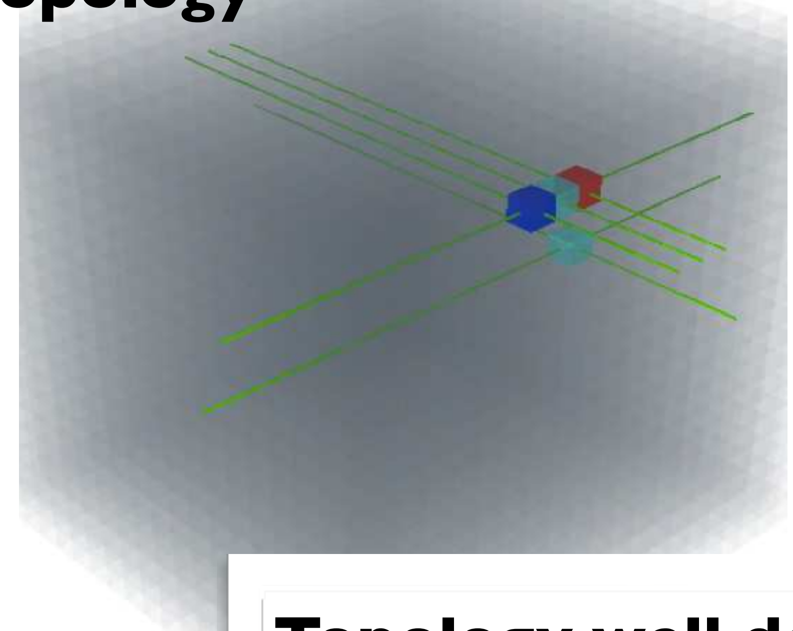
SoLid: Detection



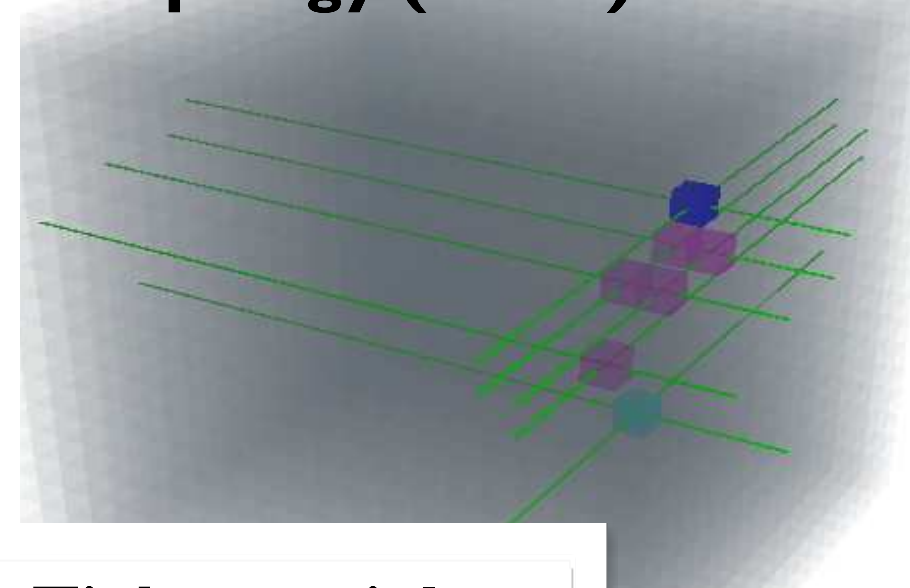


Clear identification of IBD candidates

IBD topology



BKG topology (fast n)



Topology well defined in space → Tight spatial cut

Stereo@ILL (Grenoble)

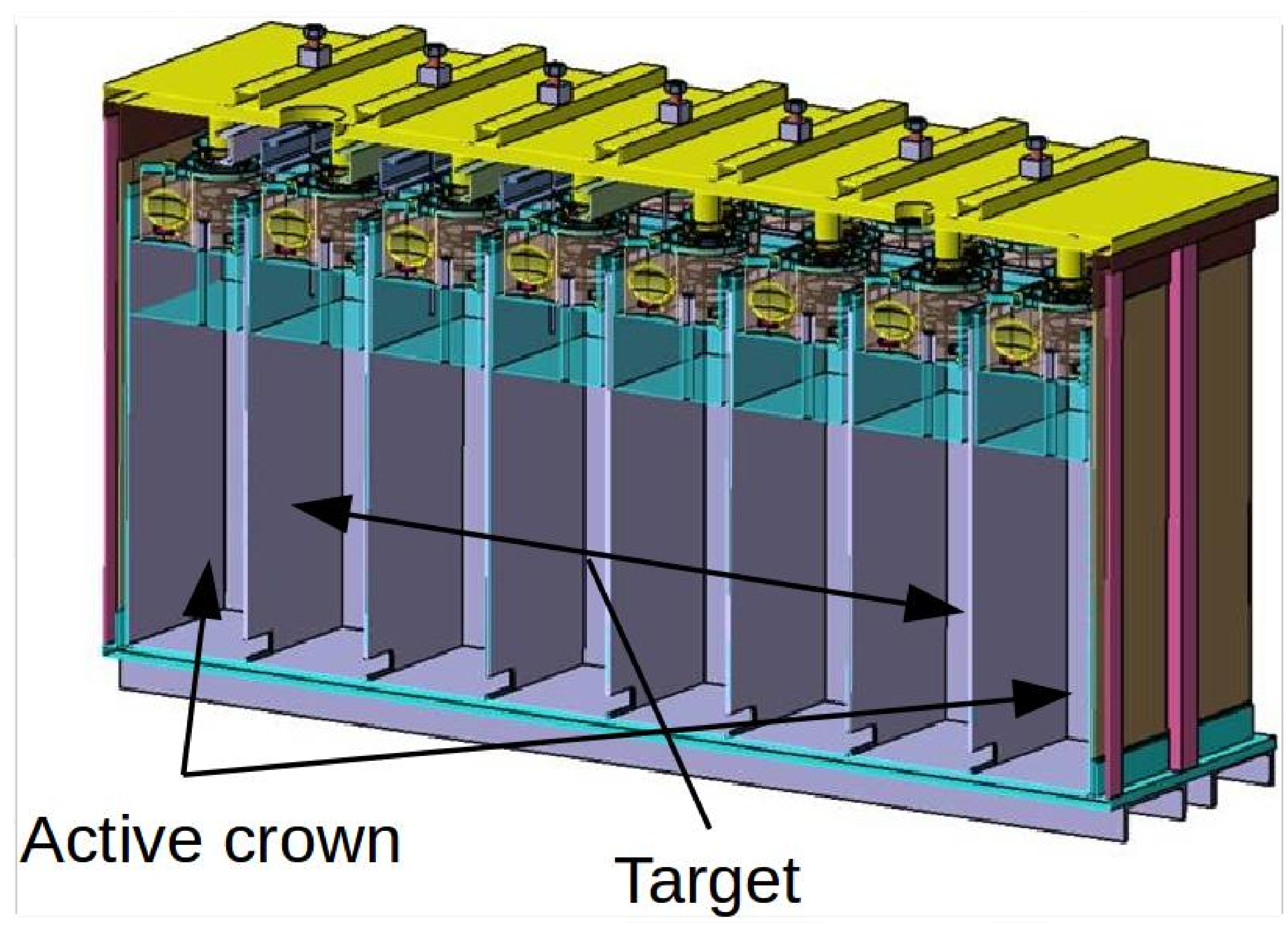
Relative measurement in 5 cells (independent from reactor normalization and history).

58 MW research reactor. High ^{235}U enrichment and compact core.

Synergy with Nucifer and Double Chooz (mature technology).

Begining of data taking at end of 2015, several prototypes for validation of the detector response.

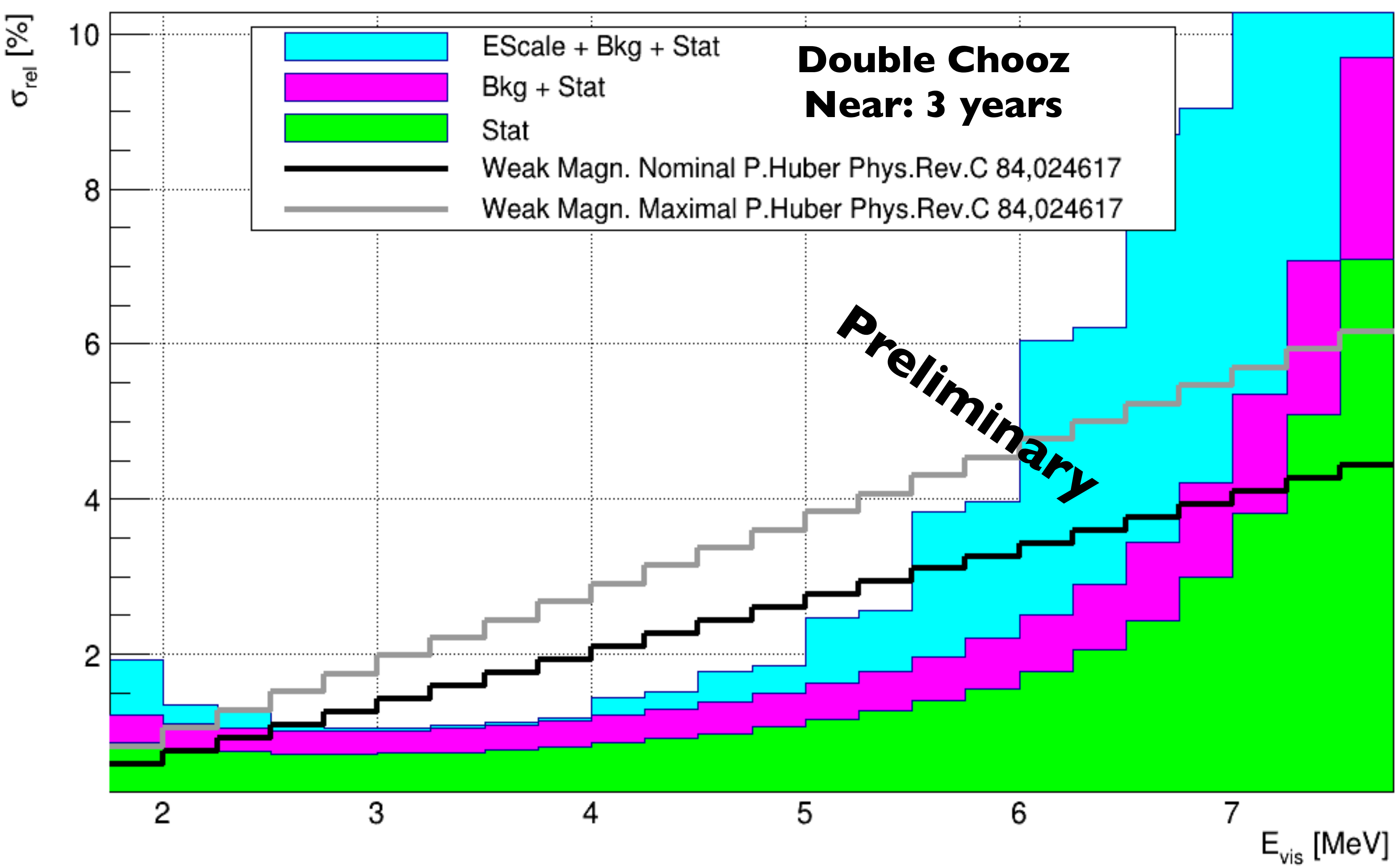
Segmented target: 5*40cm cells → 2m^3
Gd-doped liquid scintillator, 4 PMT/cell
Active Veto + Gamma Catcher: 2m^3
Acrylic buffer for uniform response,
(**Important) shielding**



Testing RAA: Reactor Spectrum Uncertainty

The uncertainties of several electro-weak corrections for the calculation of β/antineutrino spectra dominate the normalization of the reactor antineutrino spectrum (*Mueller et al, Huber)*.

The size of weak magnetism correction (due to decaying quark in β-decay which is not free but bound in the nucleon) **is the major source of reactor spectra uncertainty.**



Testing RAA: Reactor Spectrum Uncertainty

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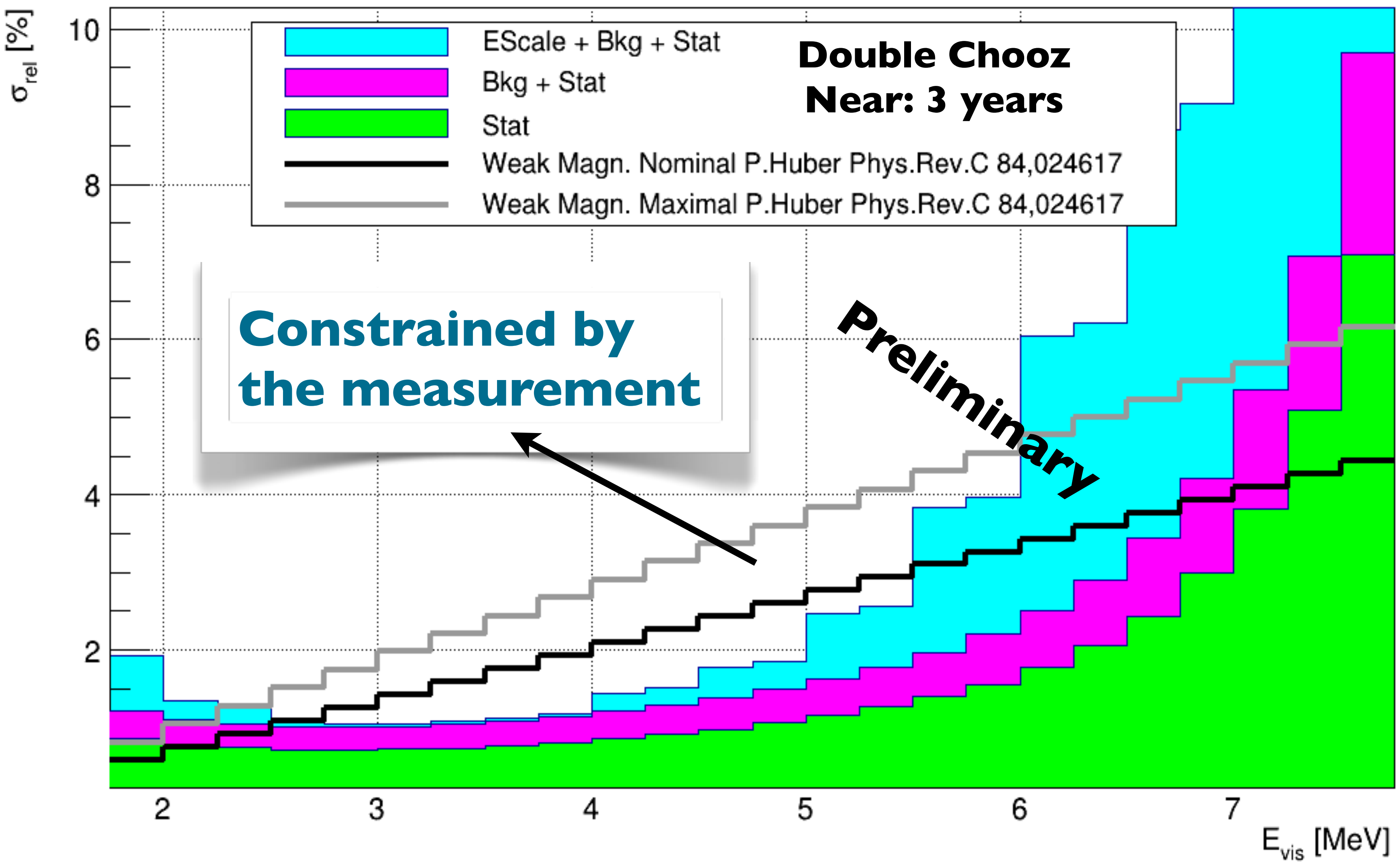

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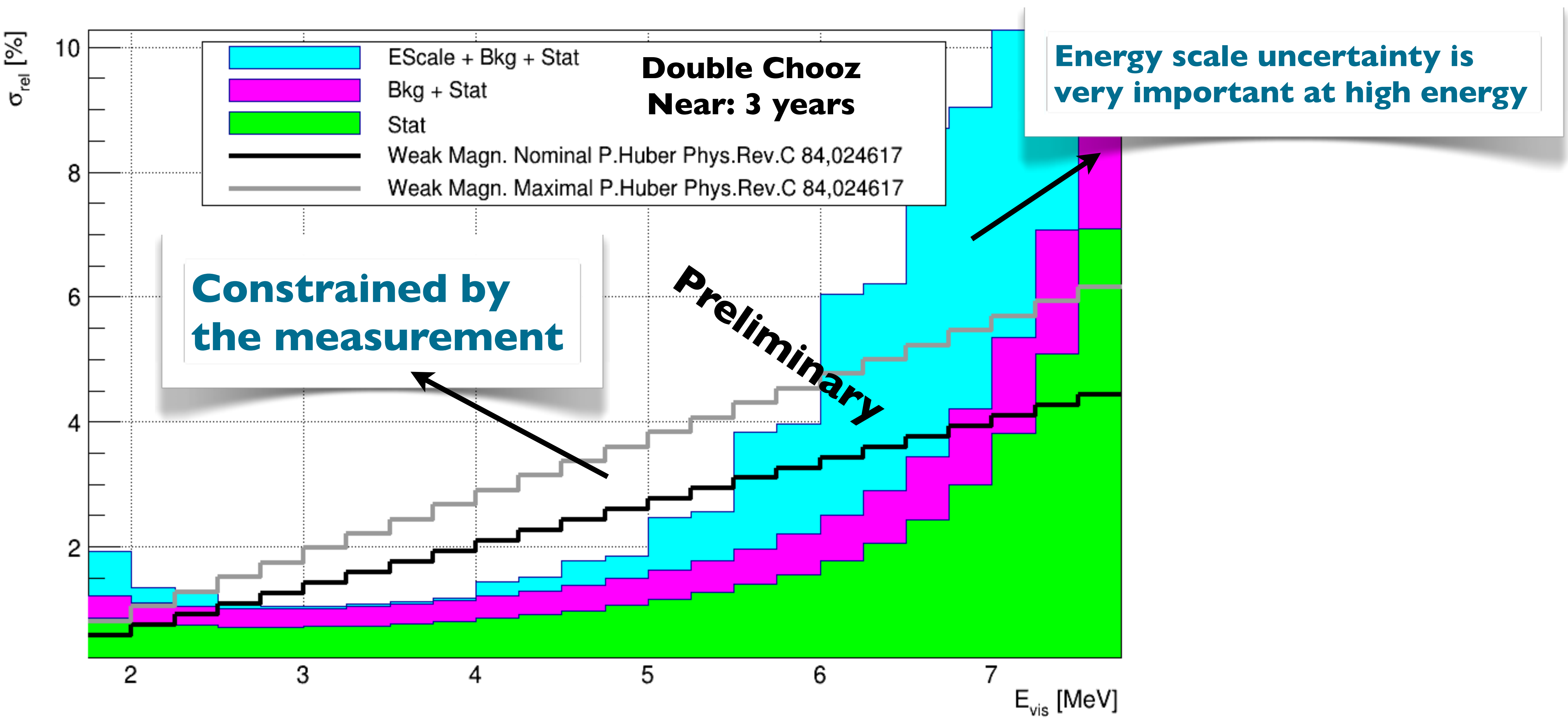

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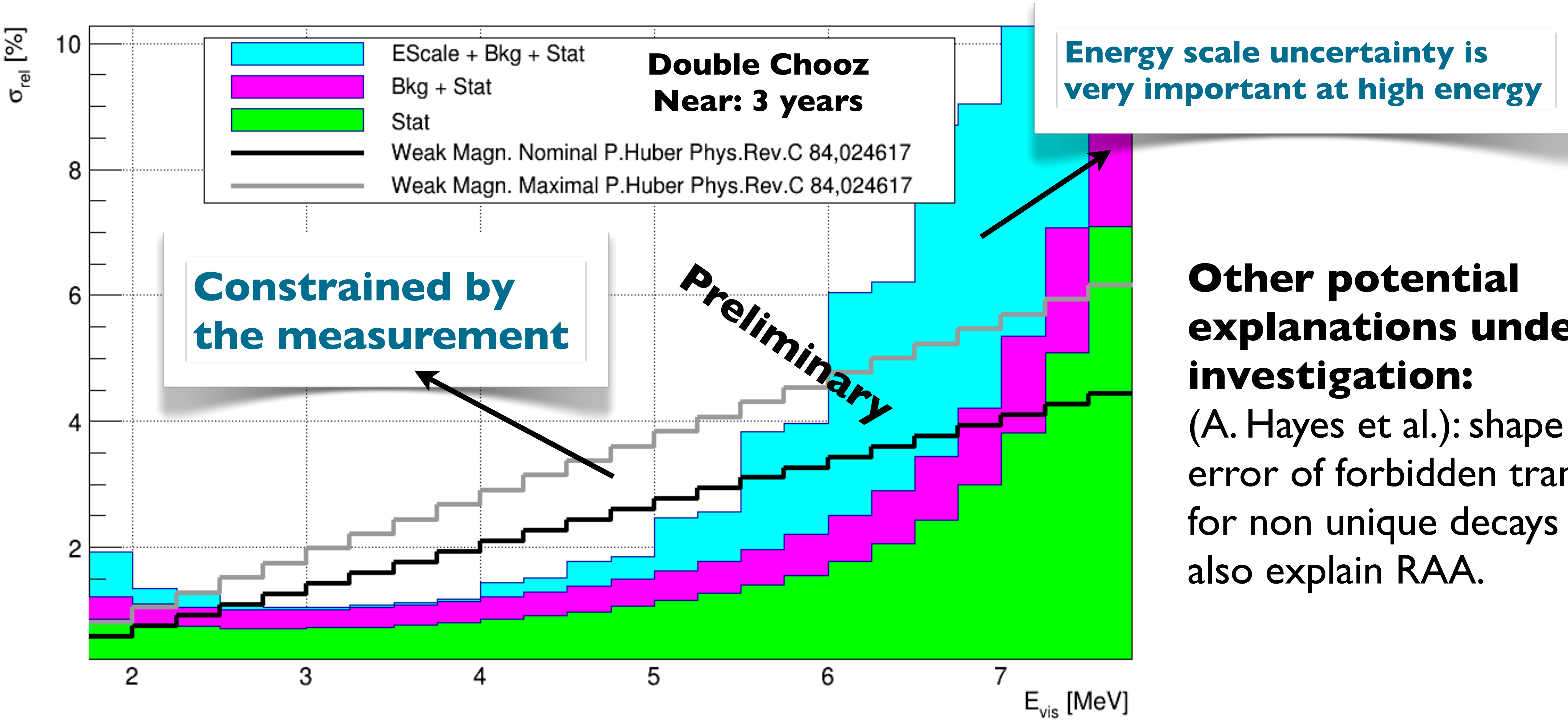

Other potential explanations under investigation:
(A. Hayes et al.): shape error of forbidden transitions for non unique decays could also explain RAA.

Neutrinos for peace

Antineutrinos for Non-Proliferation

Antineutrino flux emitted by reactors …
… is produced in β decays of the n-rich fission products.
Distribution of the fission products is specific for each of the core isotopes.

direct info. of the nuclear fuel composition
→ can be used for non-proliferation against nuclear weapons

	^{235}U	^{239}Pu
E_{fis} [MeV]	201.7	210
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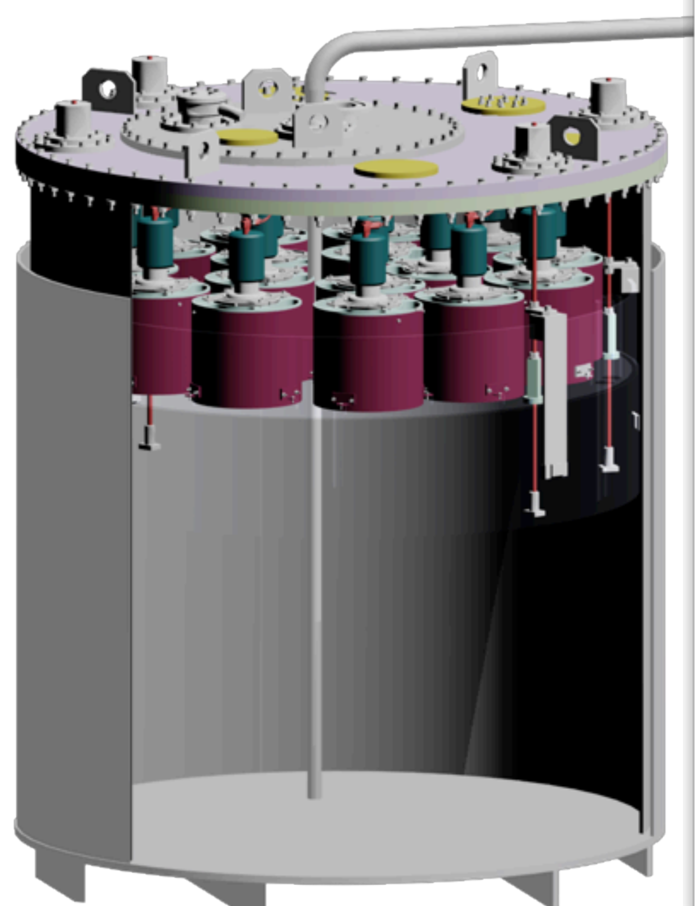
Nucifer@Osiris

Target: 850l Gd loaded liquid scintillator,
16 PMT isolated with acrylic buffer.
Active muon veto and passive shielding.



Nucifer: ON/OFF Analysis

	Accidentals /day	Correlated /day (after subtraction)
Reactor OFF	**75 ± 1**	**1063 ± 10**
Reactor ON	**3793 ± 1**	**1384 ± 15**

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Clear neutrino detection but still very high accidental rate. It could be much smaller for a deployment at a comercial reactor.

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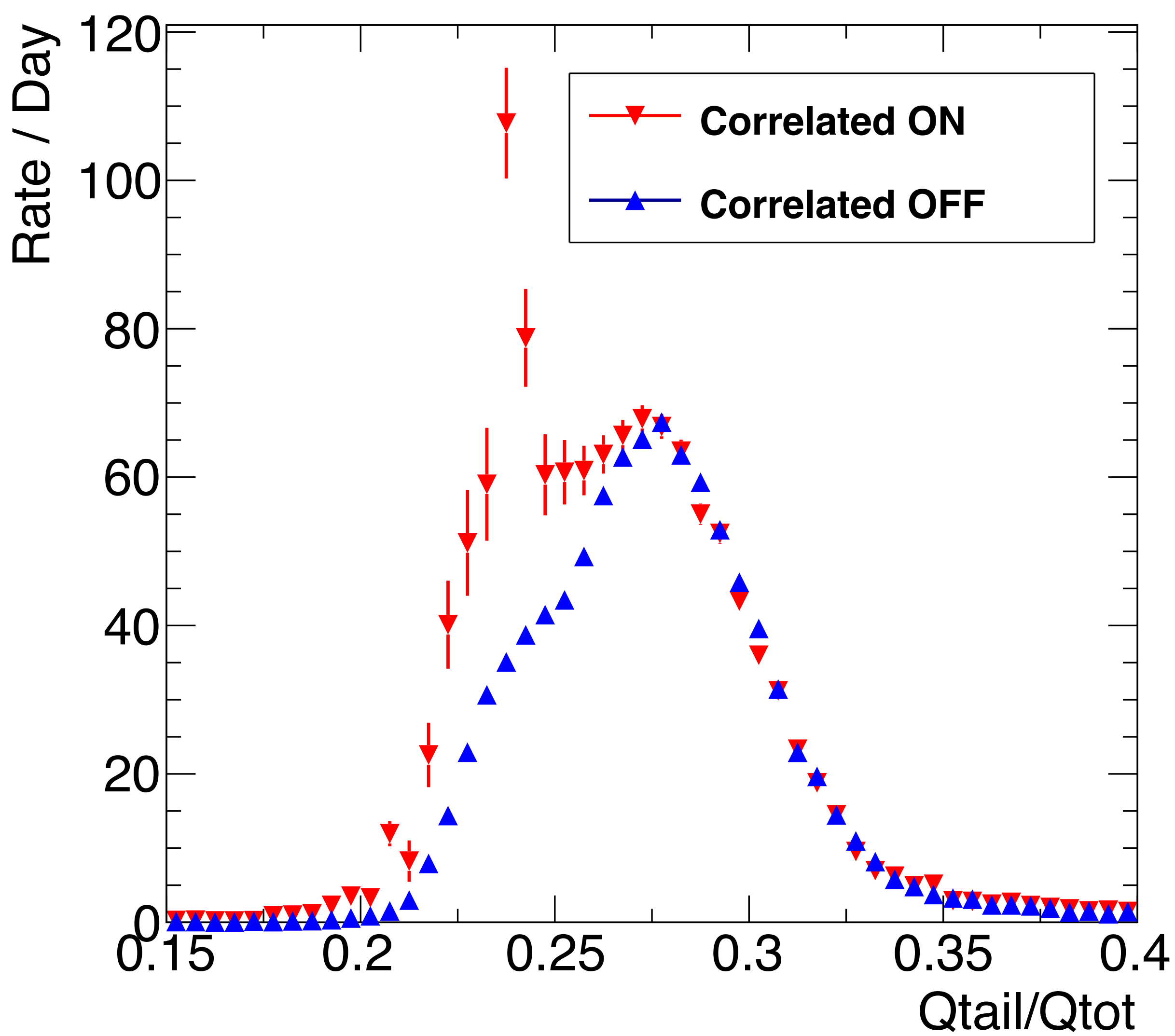

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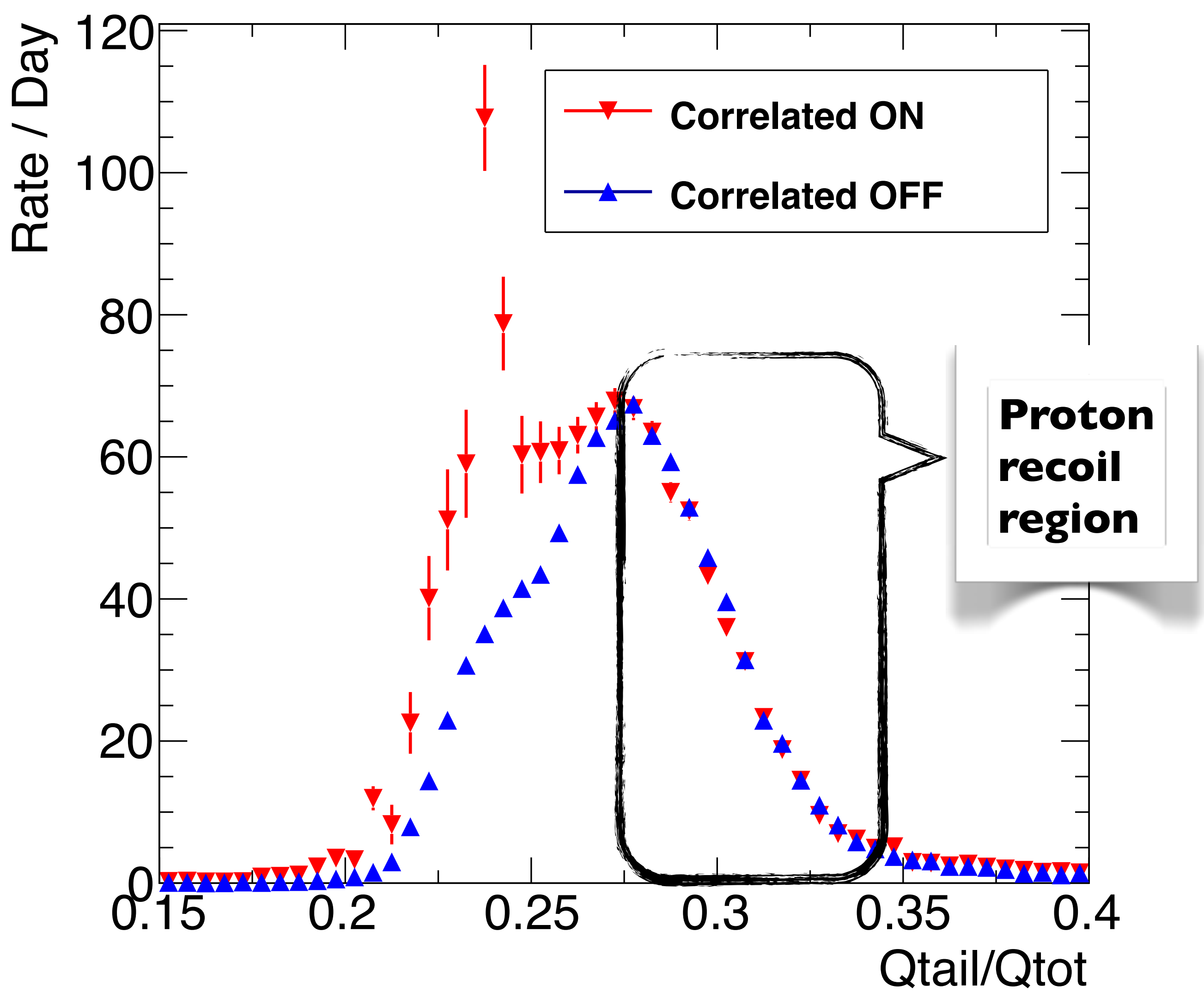

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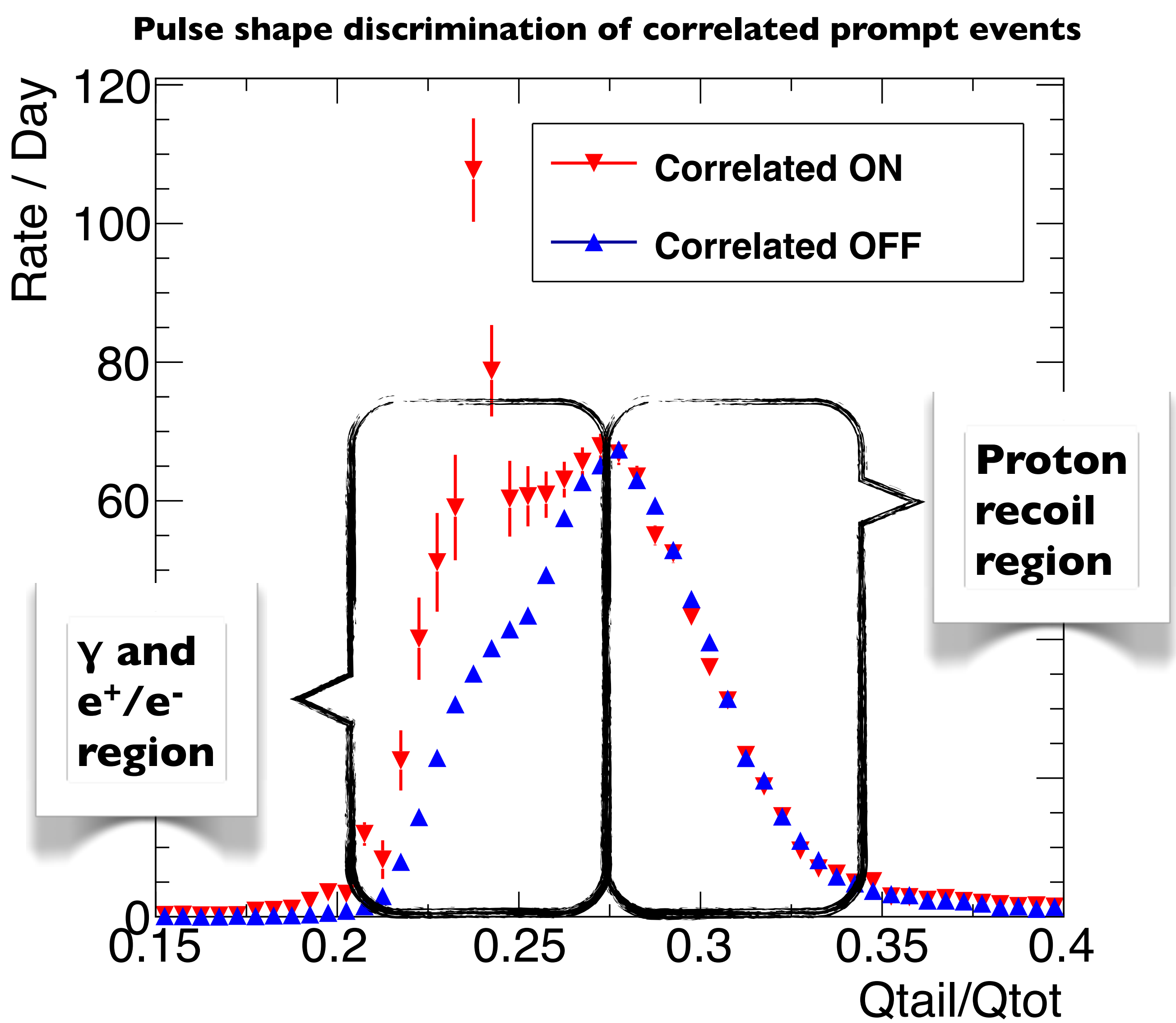

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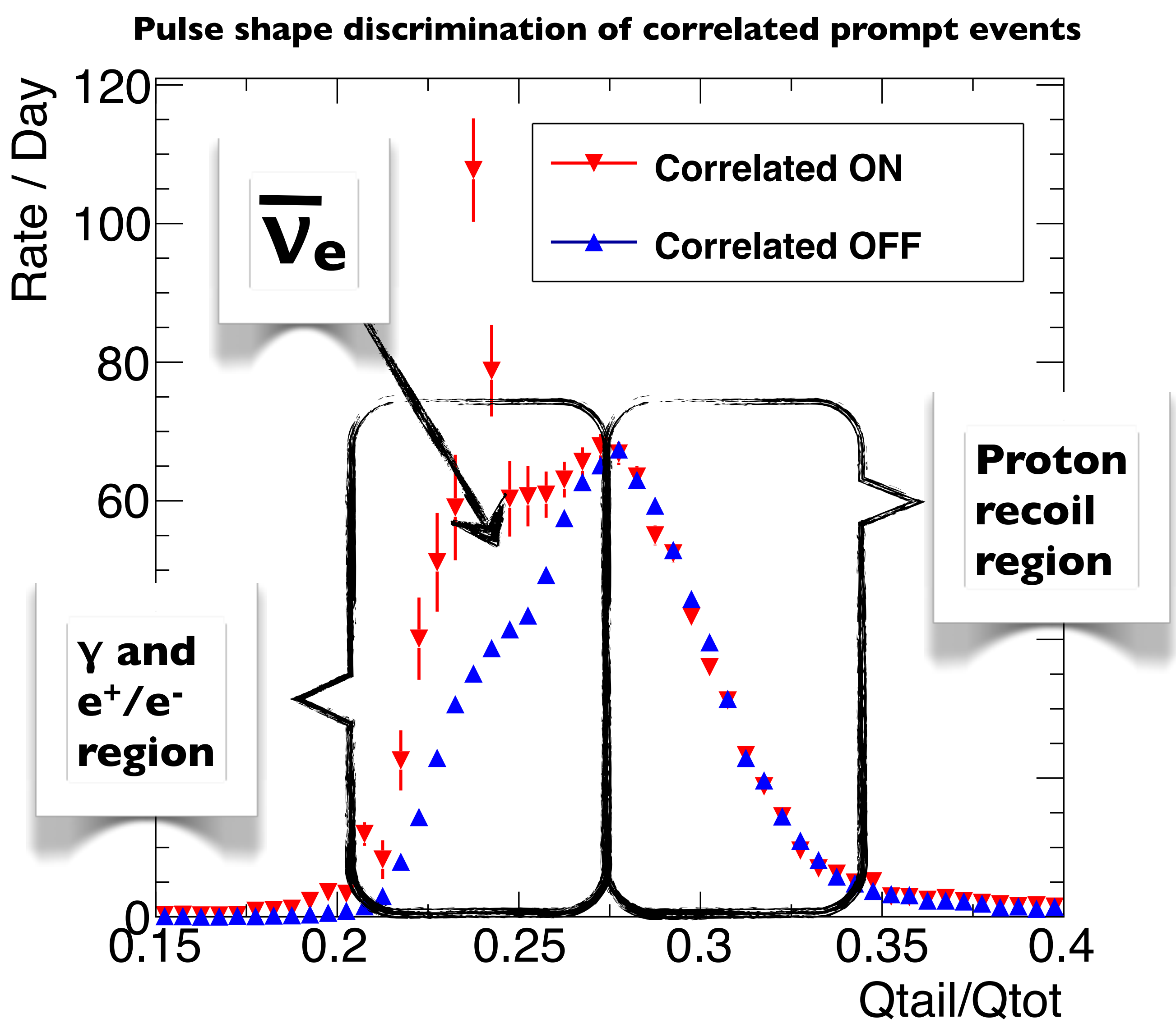

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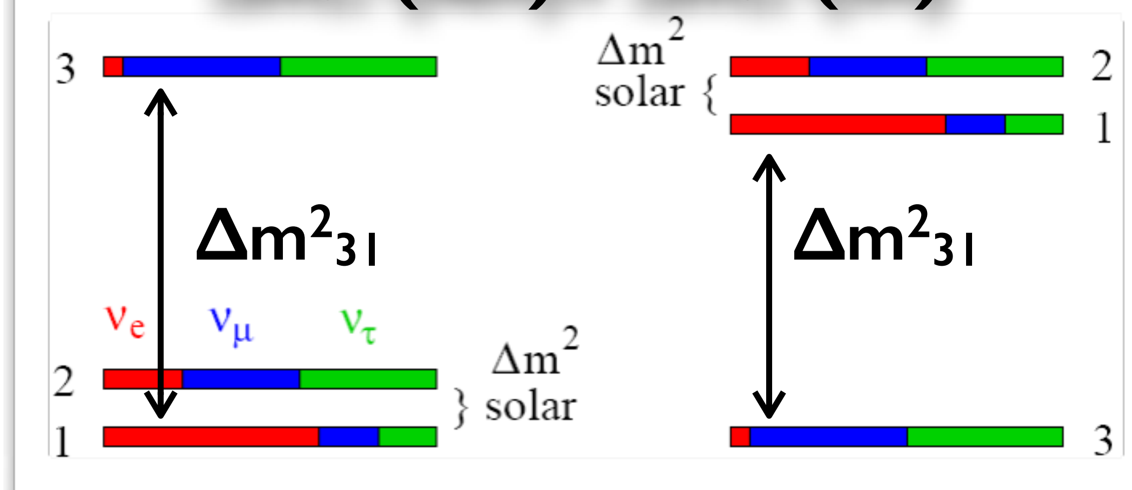
Future
NEXT EXIT

MH Reactor Experiments: Juno, Reno50

Proposed experiments:
JUNO (China), RENO-50 (Korea)

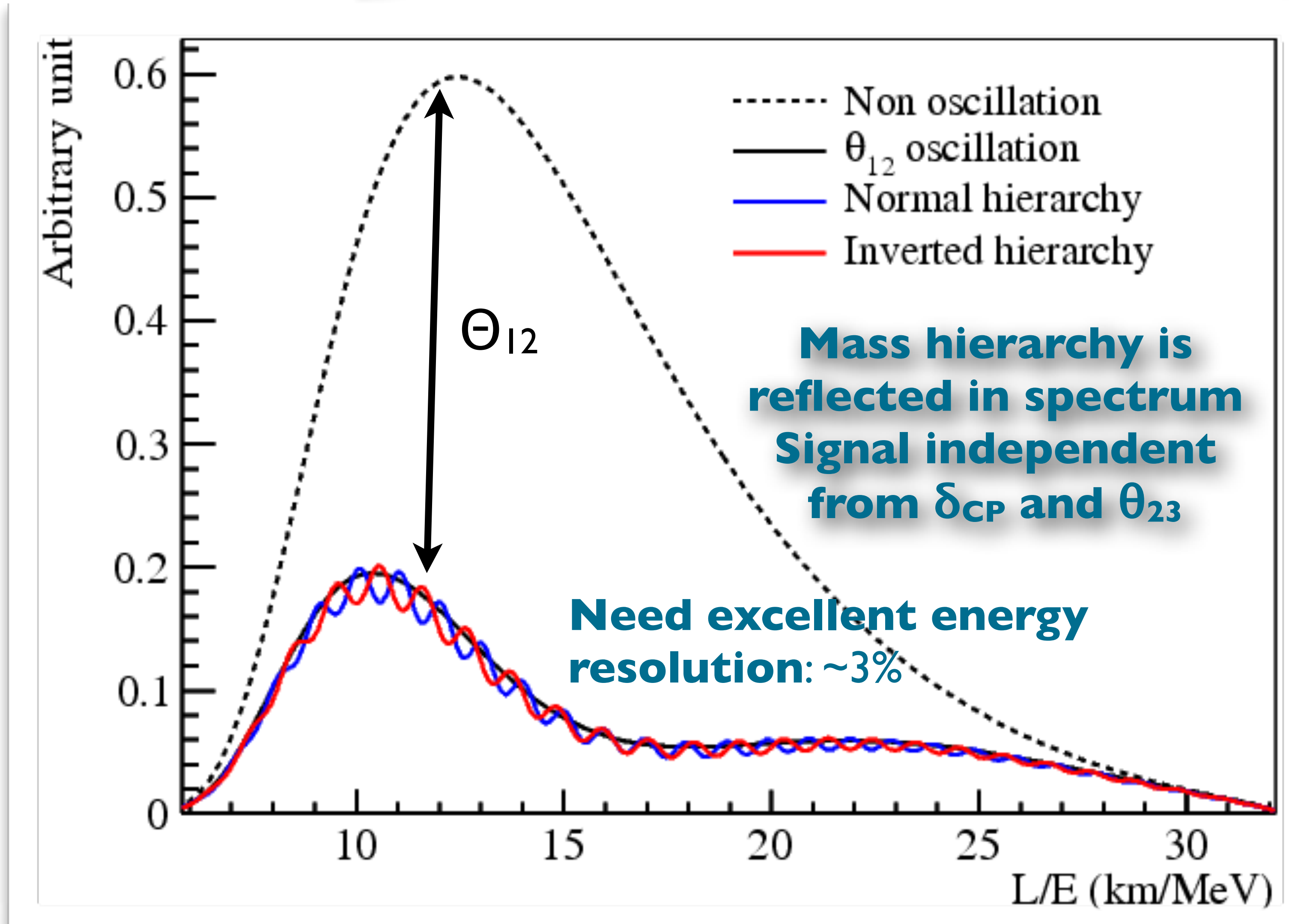
Big ...
... **targets**: ~20kton JUNO, 18kton RENO-50
... **reactor power**: ~36 GWth JUNO, ~16.5 GWth RENO-50
... **overburden**: 500 m rock for JUNO
... **costs**
Multiple baselines (<500km)

$\Delta m_{31}^2(NH) \neq \Delta m_{31}^2(IH)$



Motivation:

- **Mass hierarchy**
- Precise measurement of mixing par.
- Supernova-, Geo-, Solar- neutrinos
- Sterile neutrino searches (sources)
- Accelerator neutrinos (T2RENO-50)
- Exotic searches (proton decay)



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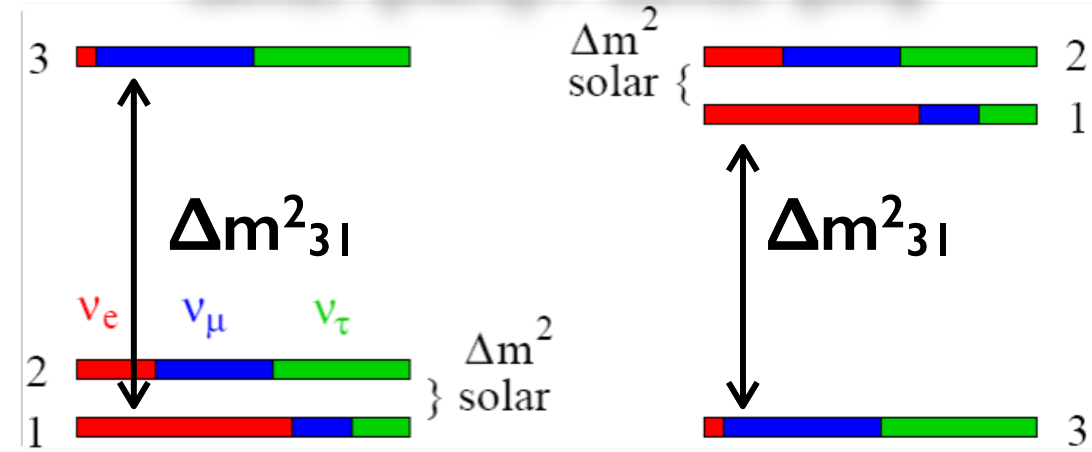

The suppression of the reactor induced systematics from A.S.C. et al. arXiv:1501.00356 could be applied to MH experiments, too. Ongoing study.

How the spectral distortion of the reactor spectrum is affecting the mass hierarchy measurement ?

- A priori the magnitude of the spectral distortion is comparable to that of the mass hierarchy.
- However the MH gives a distinct energy dependent signature.

To Remember

- Neutrino physics has entered the precision era.
- Current reactor experiments at L~1-2 km continuously increase the precision of θ_{13}. Possible improvements of the reactor induced systematics are studied.
- State-of-the-art reactor spectrum predictions are not matched by recent direct spectrum measurements.
- Next generation of reactor neutrino experiments will focus on mass hierarchy determination an the precise measurements of the neutrino mixing matrix.
- Improved calculations of the reactor antineutrino spectrum triggered the reactor antineutrino anomaly. A solution is given by the sterile neutrino hypothesis. Other solutions are under investigation, too.
- Short-baseline (L~10 m) measurements offer opportunities for definitive short-baseline oscillation search and non-proliferation studies.