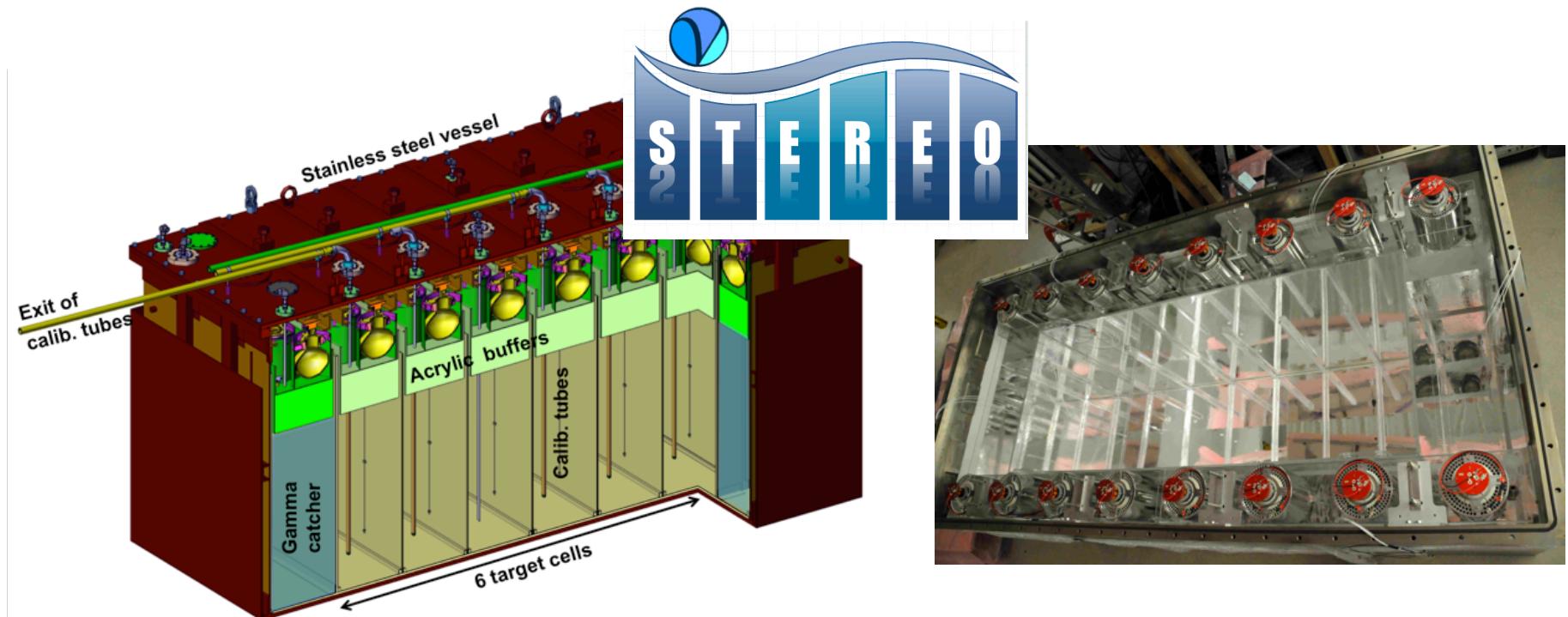




Recent results from



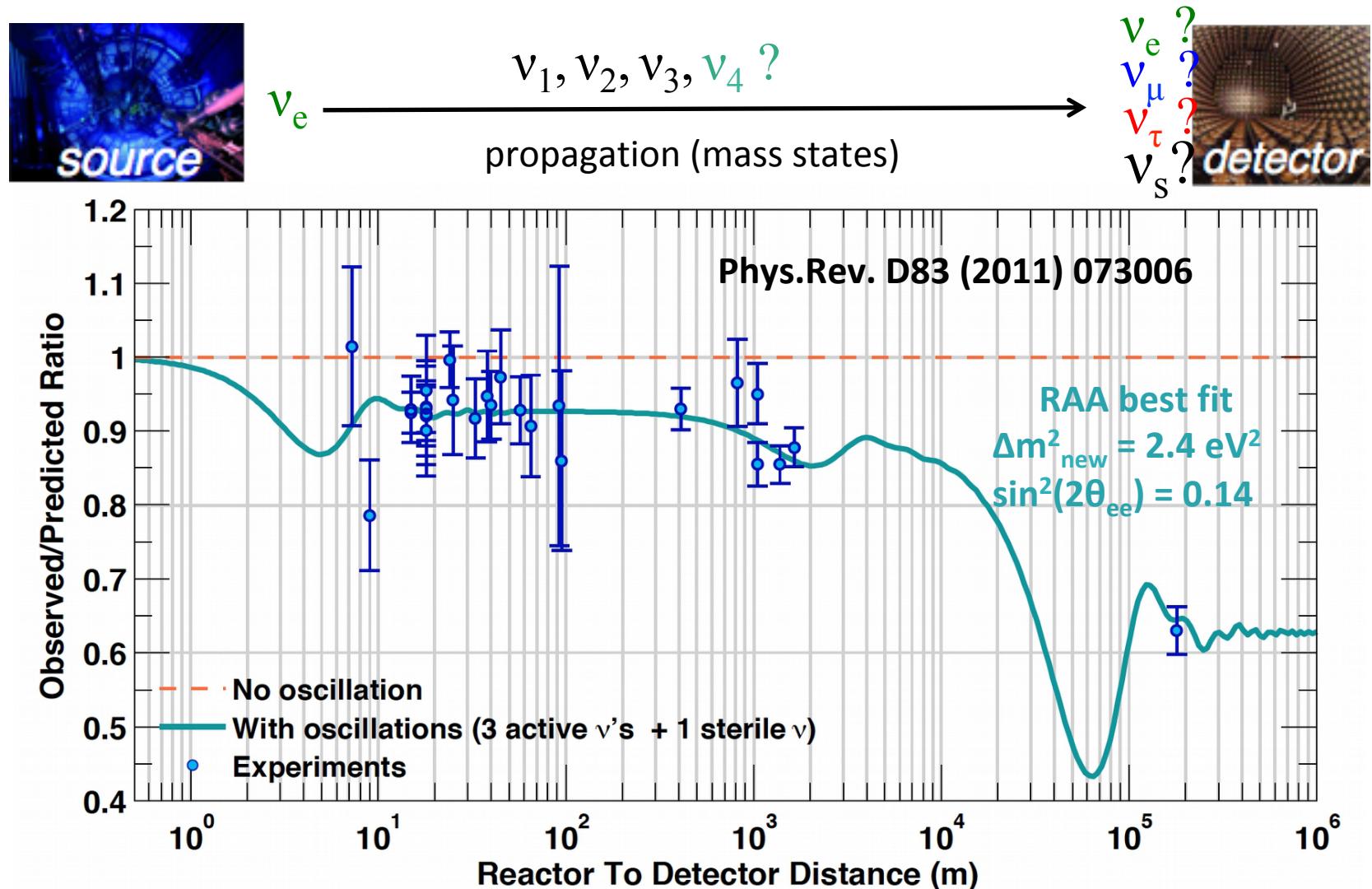
Pablo del Amo Sánchez

EPS HEP 2019

13/07/19



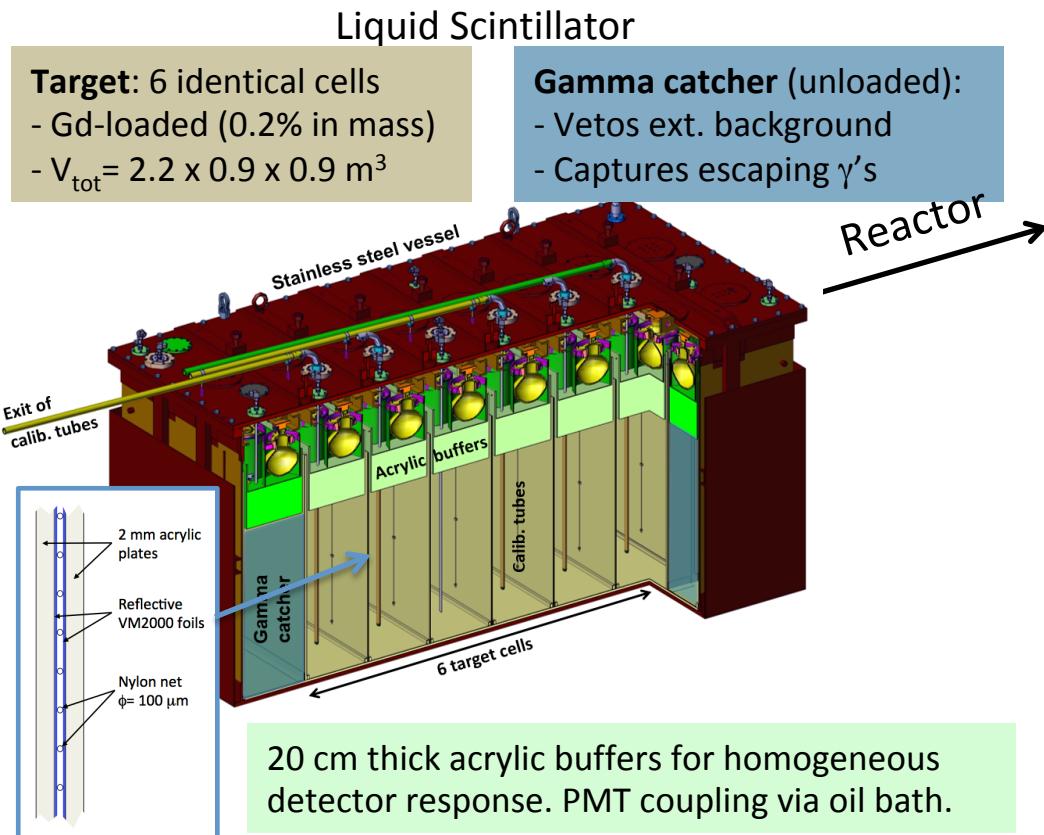
Reactor Anti- ν Anomaly



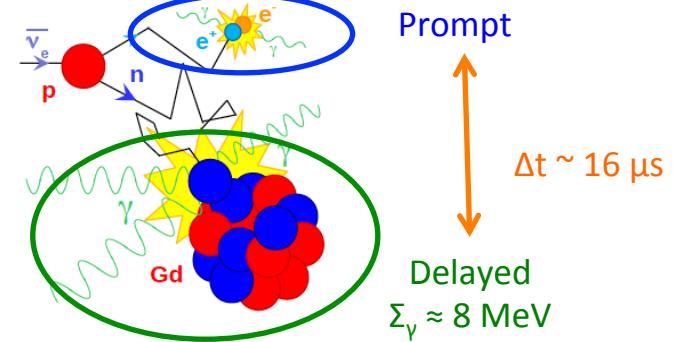
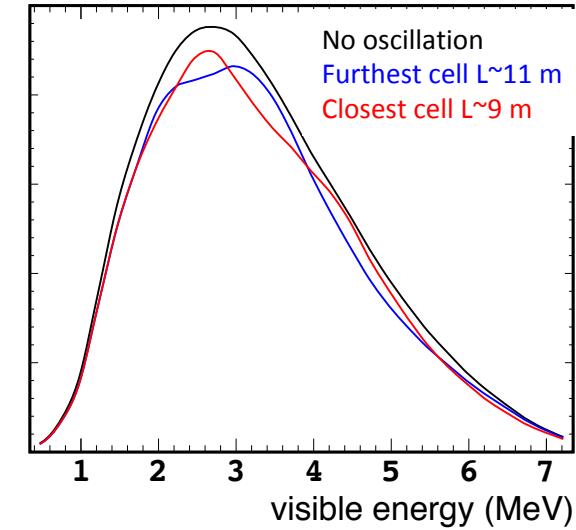
STEREO detector

JINST 13, 07 (2018): P07009

- Compare 6 target cells to measure oscillation-driven distortions in the $E_{\bar{\nu}_e}$ spectrum.
- Mitigate sensitivity to predicted spectrum.



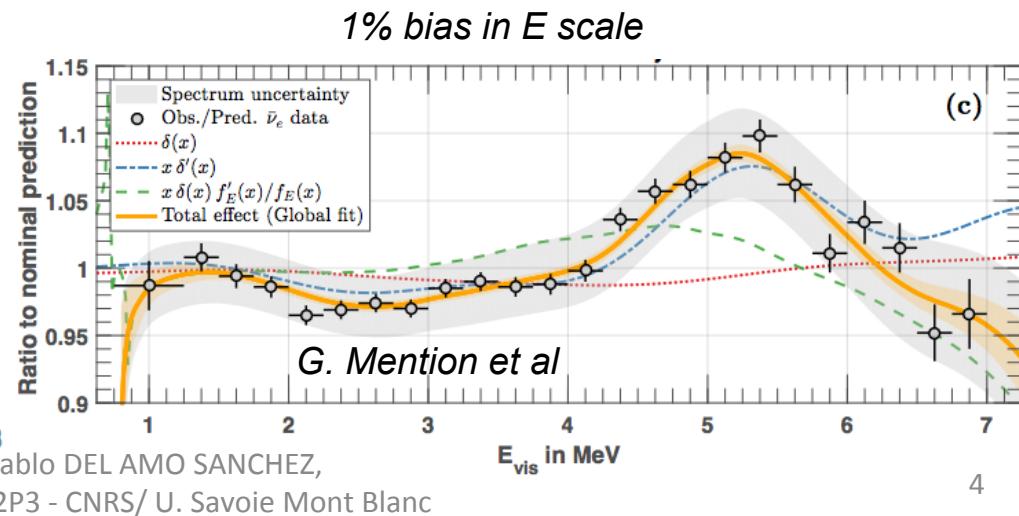
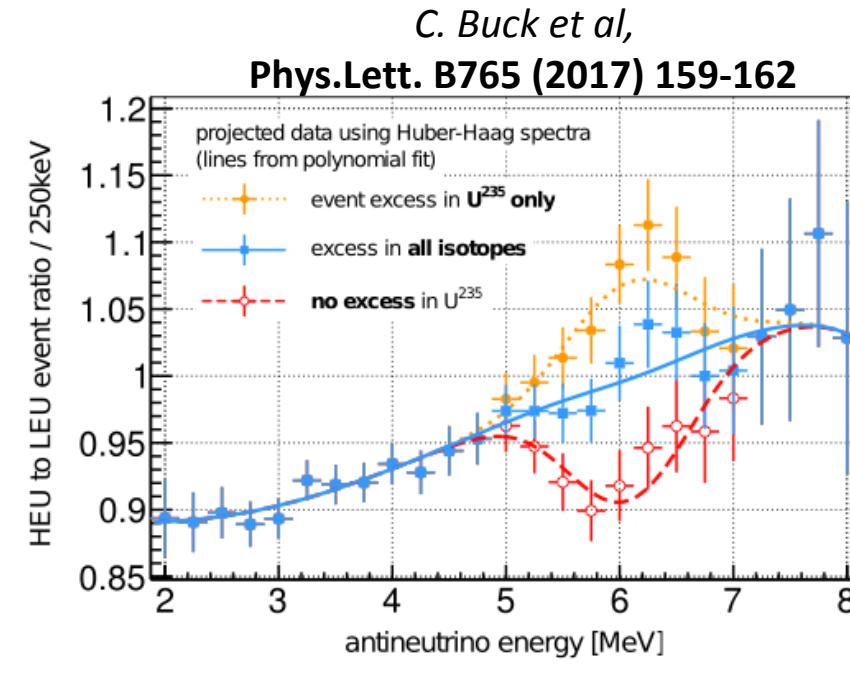
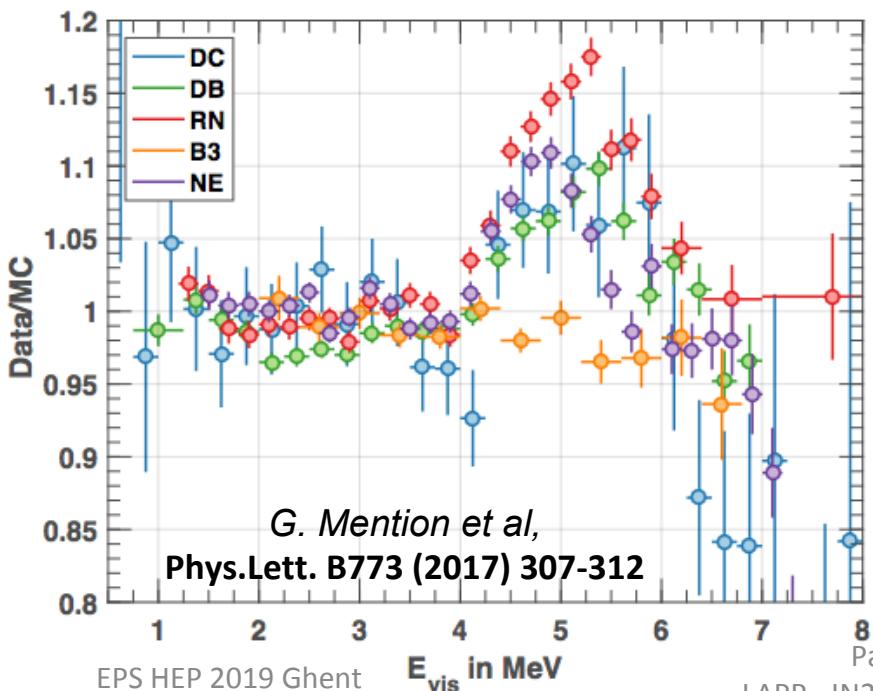
$$\sin^2(2\theta)=0.14, \Delta m^2=2.4 \text{ eV}^2$$



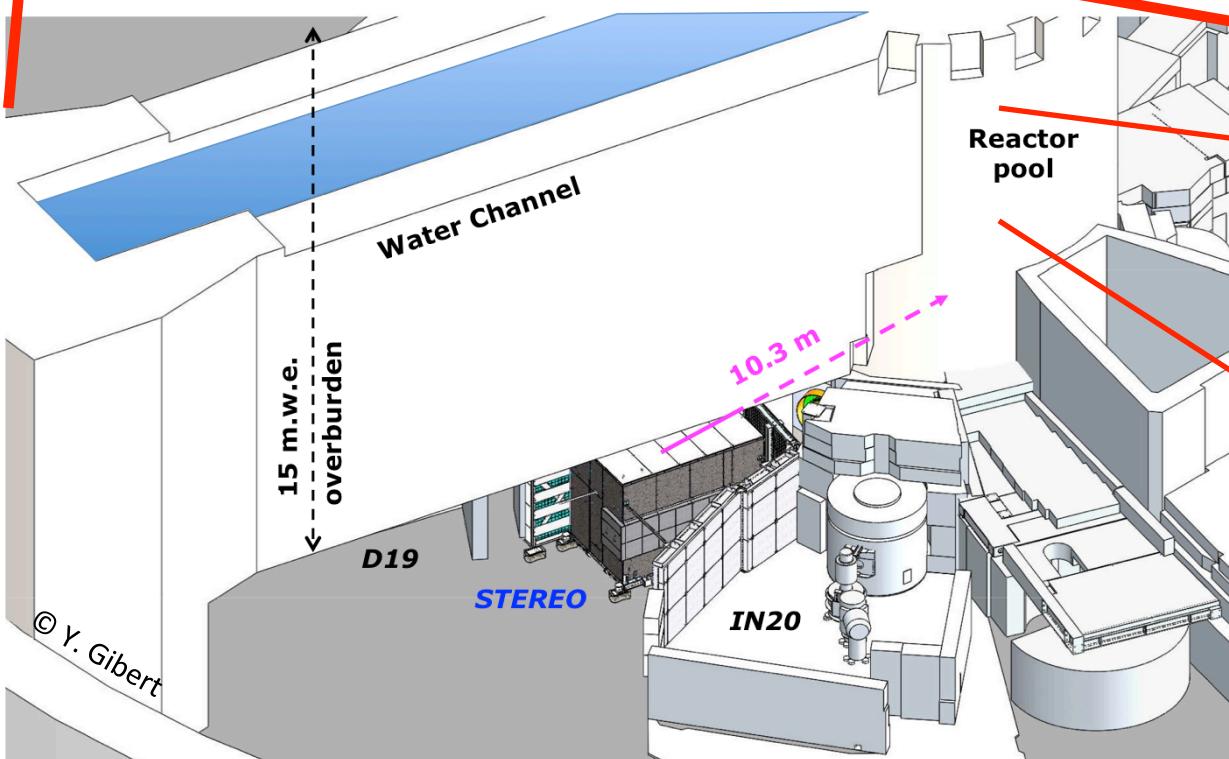
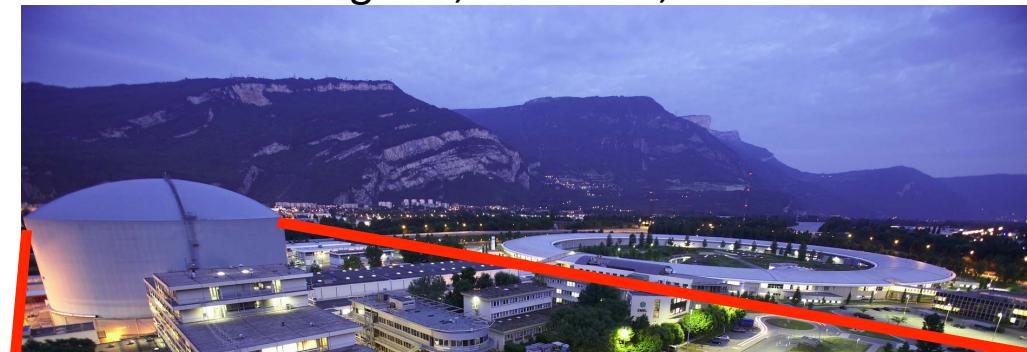
$\bar{\nu}$ detection through Inverse Beta Decay
(prompt + delayed coincidence)

Reactor ν spectrum

- Bump at around 5 MeV
 - Problem in reactor ν prediction? Bias?
Underestimated systematics?
 - Experiment calibration problem? 1% bias in E scale suffices...
- ⇒ Measurement of ~pure ^{235}U useful



ILL Site



- 57 MW_thermal
- $\varnothing 40 \text{ cm} \times 80 \text{ cm}$
- Highly enriched: 93% ^{235}U (fissions > 99% ^{235}U)
- 3-4 cycles/yr x 50 days/cycle
- 10^{19} s^{-1} pure $\bar{\nu}_e$ flux

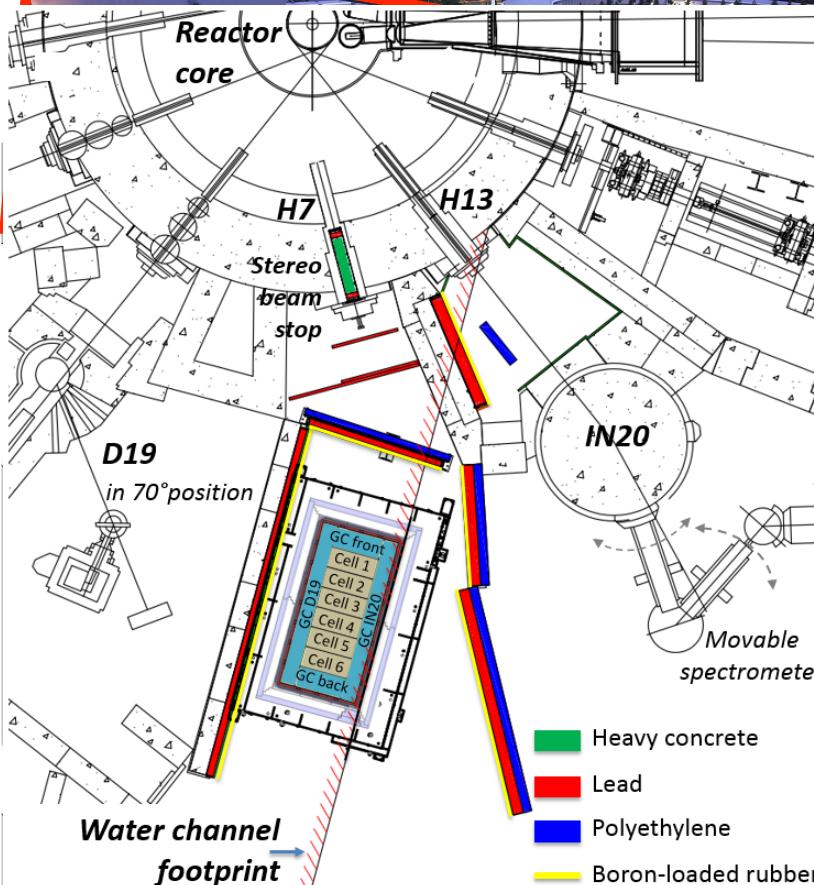
Compact core



Challenging mitigation of the background generated by:

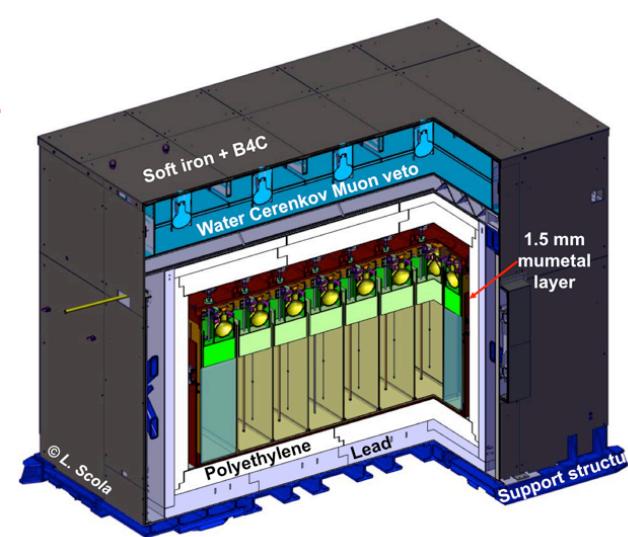
- Cosmic-rays
- Neighboring experiments

ILL Site



Heavy passive shielding added around detector and on front and side walls:

- > 100 tons Pb
- > 9 tons Borated PE
- B_4C rubber
- (soft iron)



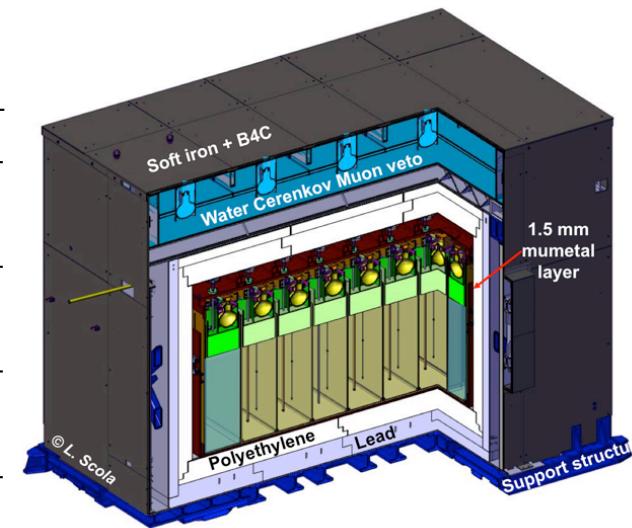
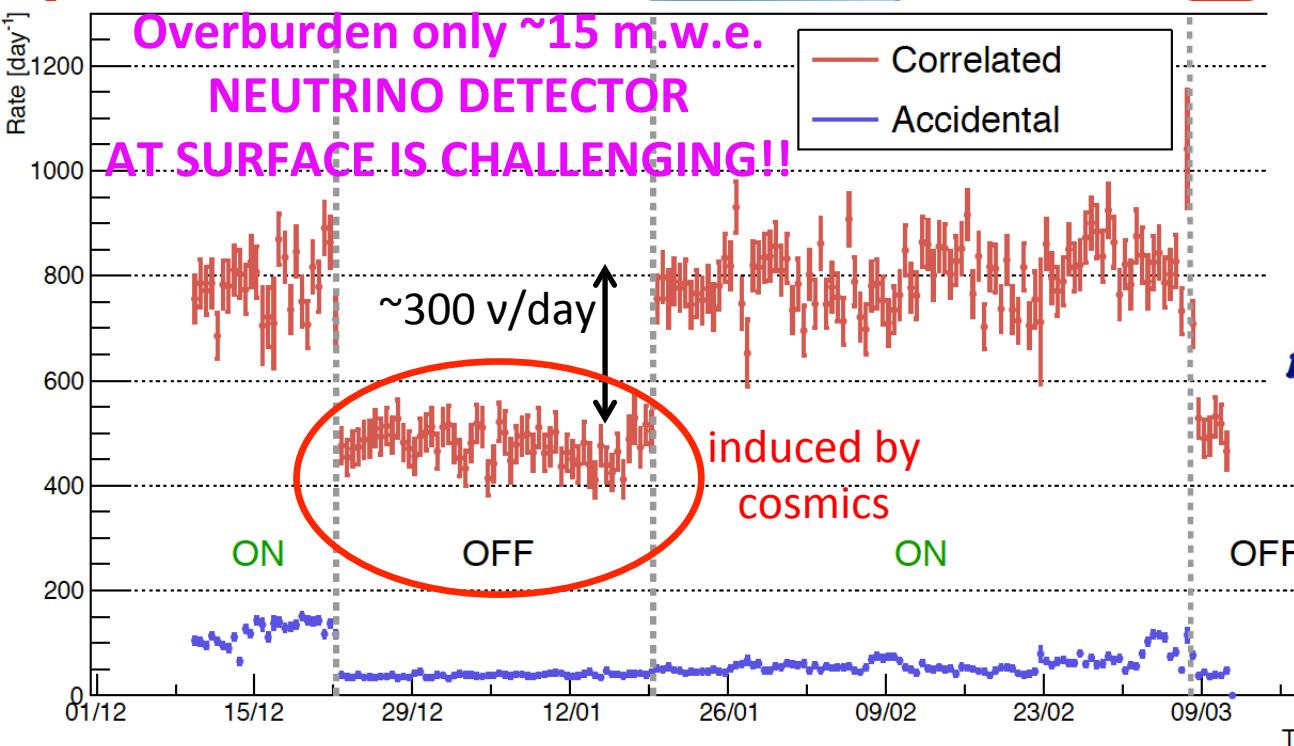
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ILL Site



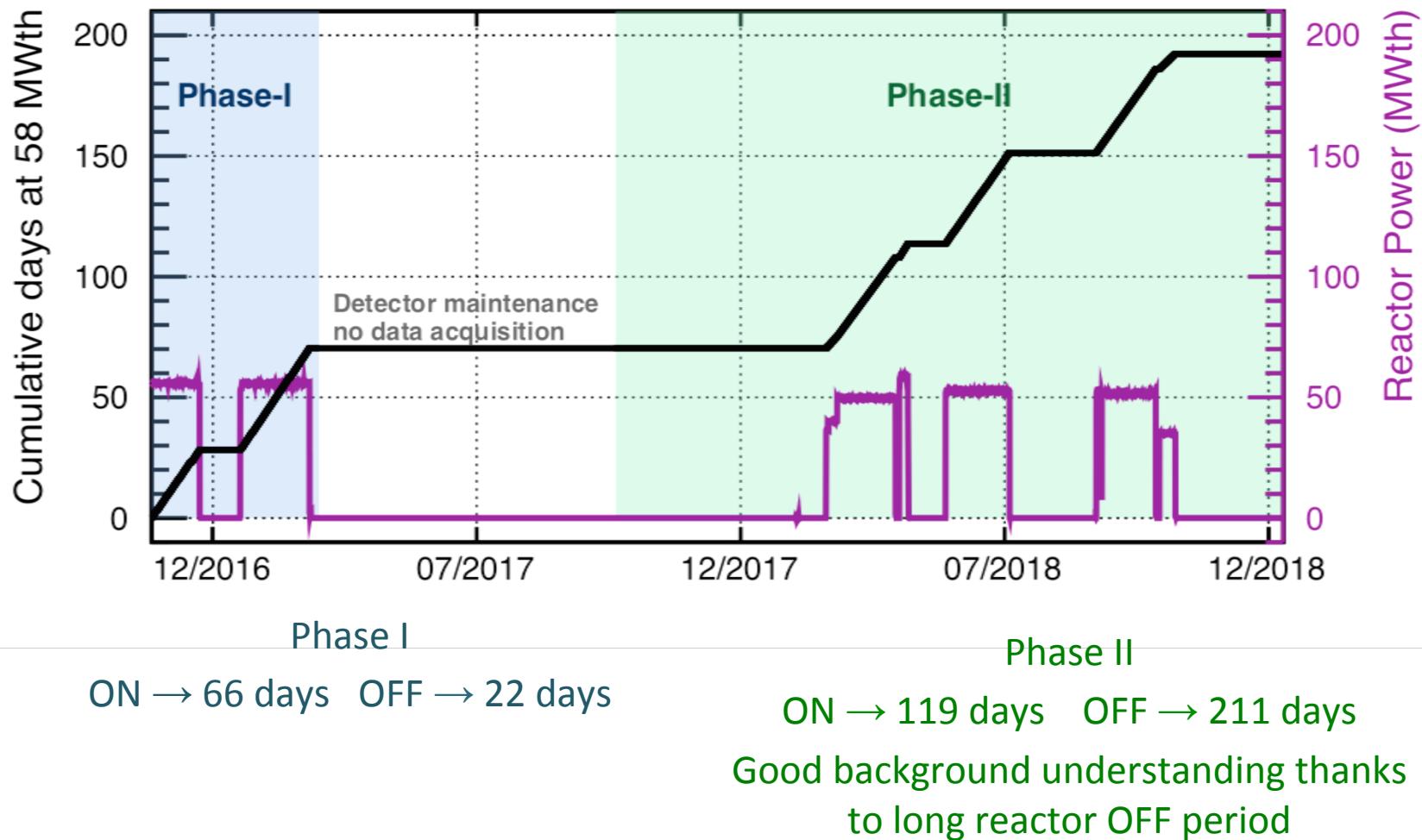
- 57 MW_thermal
- Ø40 cm × 80 cm
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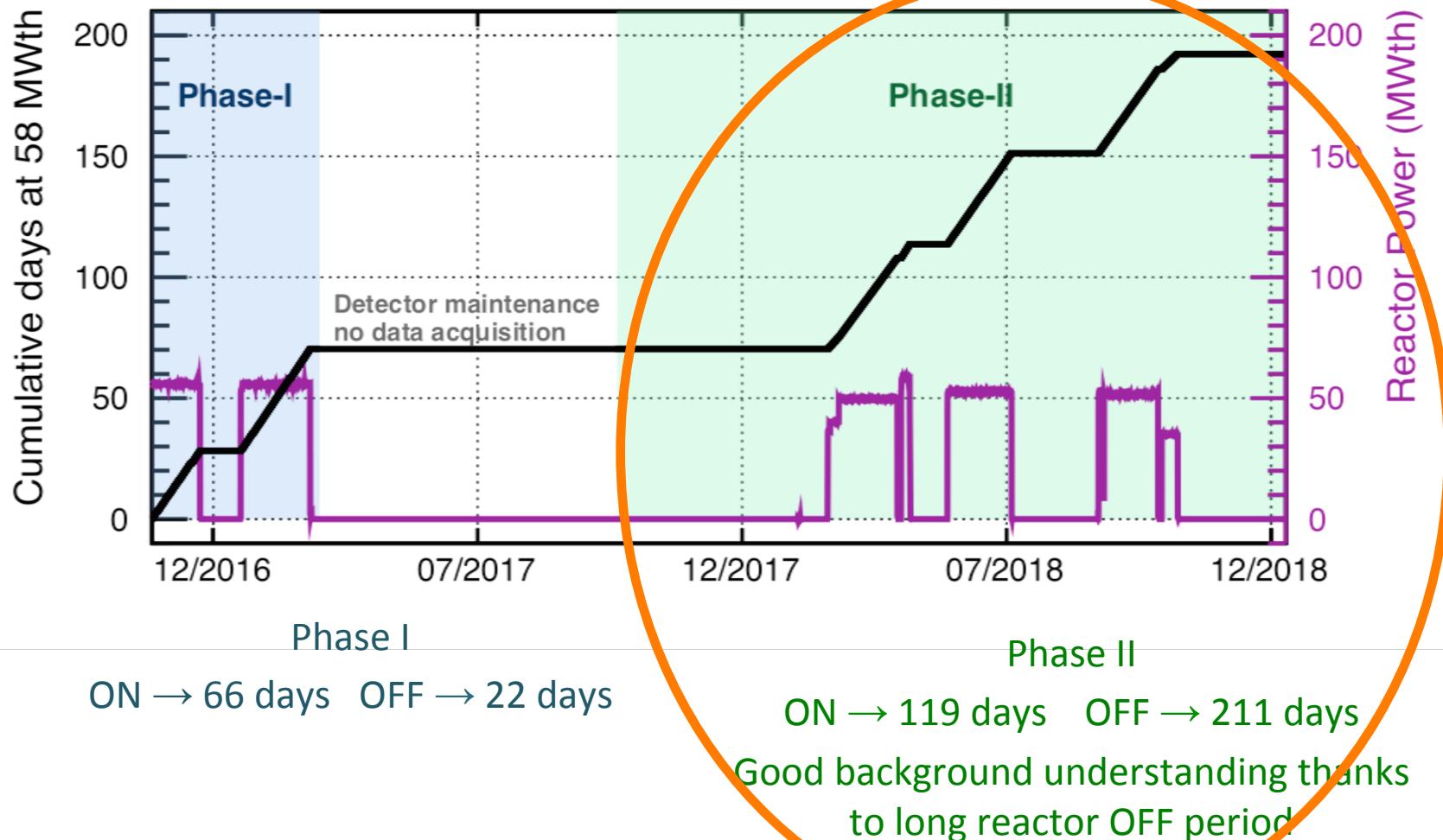
- Cosmic-rays
- Neighboring experiments

Dataset



+ calibration runs (hourly LEDs, weekly ^{54}Mn , monthly AmBe, bi-annual ^{68}Ge , ^{137}Cs , ^{60}Co , ^{24}Na)

Dataset



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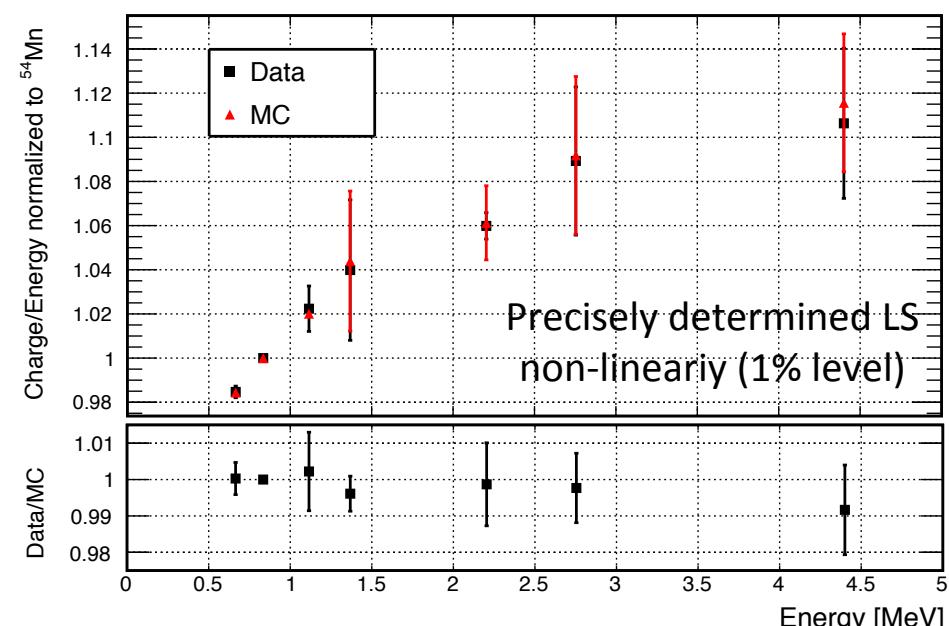
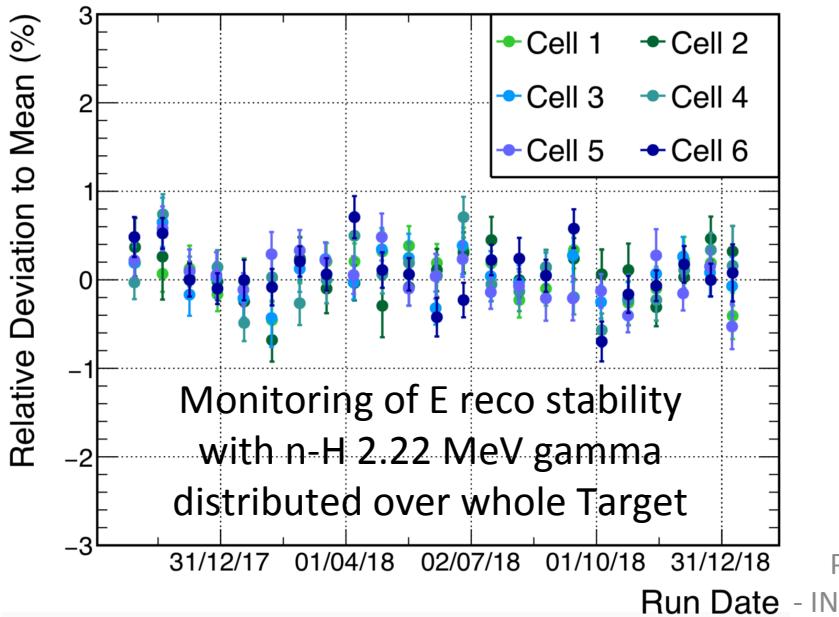
E reconstruction & calibration

- Correct for optical cross-talk among cells in energy reco algorithm:

$$Q_j = R_{ji} \times E_i^{\text{dep}} \quad \text{where} \quad R_{ji} = C_i \times L_{ji} \quad \Rightarrow \quad \vec{E}^{\text{reco}} = \vec{R}^{-1} \times \vec{Q}$$

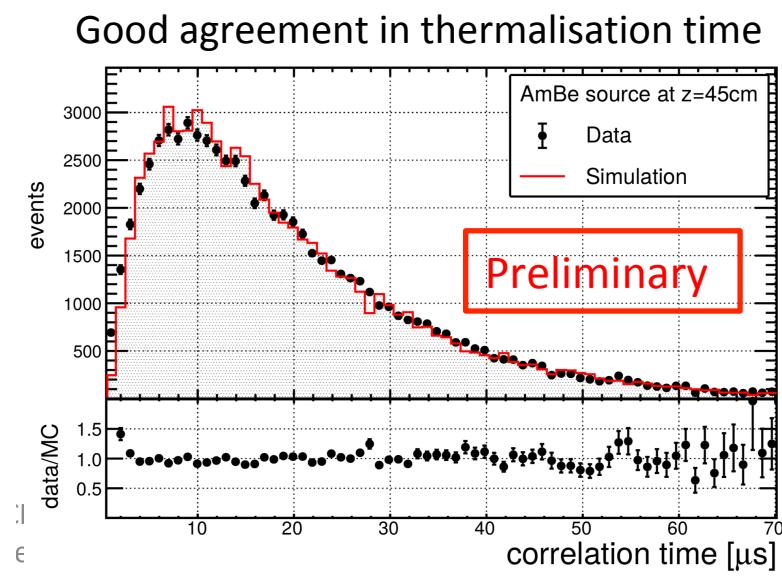
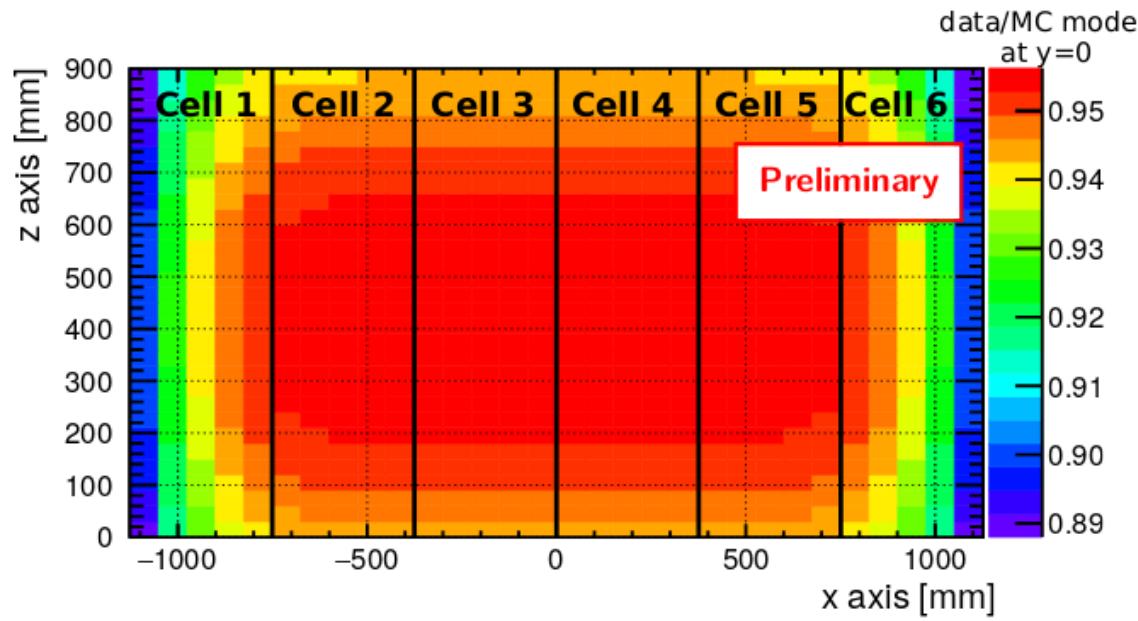
with

- R_{ji} response matrix
- C_i calib coeffs (collected photons in cell i from ^{54}Mn calib runs $\sim 220 \text{ pe/MeV}$)
- L_{ji} optical crosstalk from cell i to cell j $\sim 6 - 8\%$



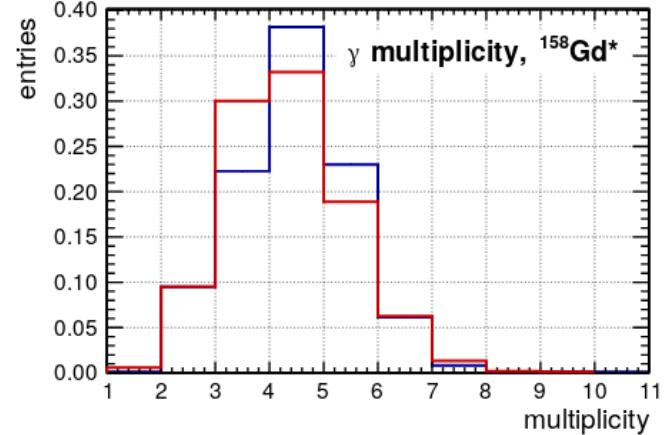
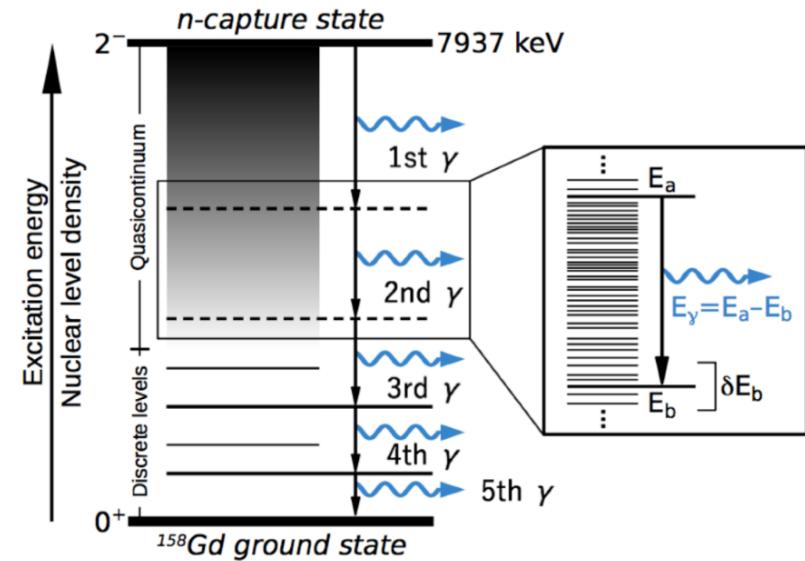
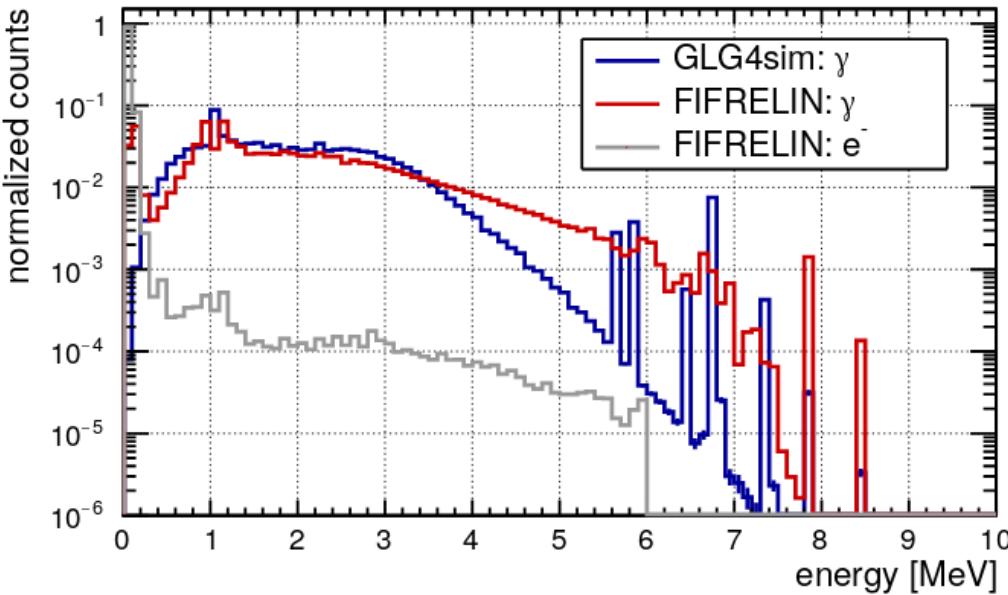
Neutron efficiency

- Neutron efficiency, dominant uncertainty in neutrino selection efficiency
- Use AmBe gamma-neutron source that mimics IBD coincidence
- Build 3D model of Data/MC discrepancy



n -Gd γ cascade

- Especially important for small detectors where higher energy γ more likely to escape
- New n -Gd γ cascade from FIFRELIN nuclear code (O. Litaize et al., Eur. Phys. J. A (2015) 51: 177)
 - More higher energy γ than in GLG4sim (and slightly lower γ multiplicity)



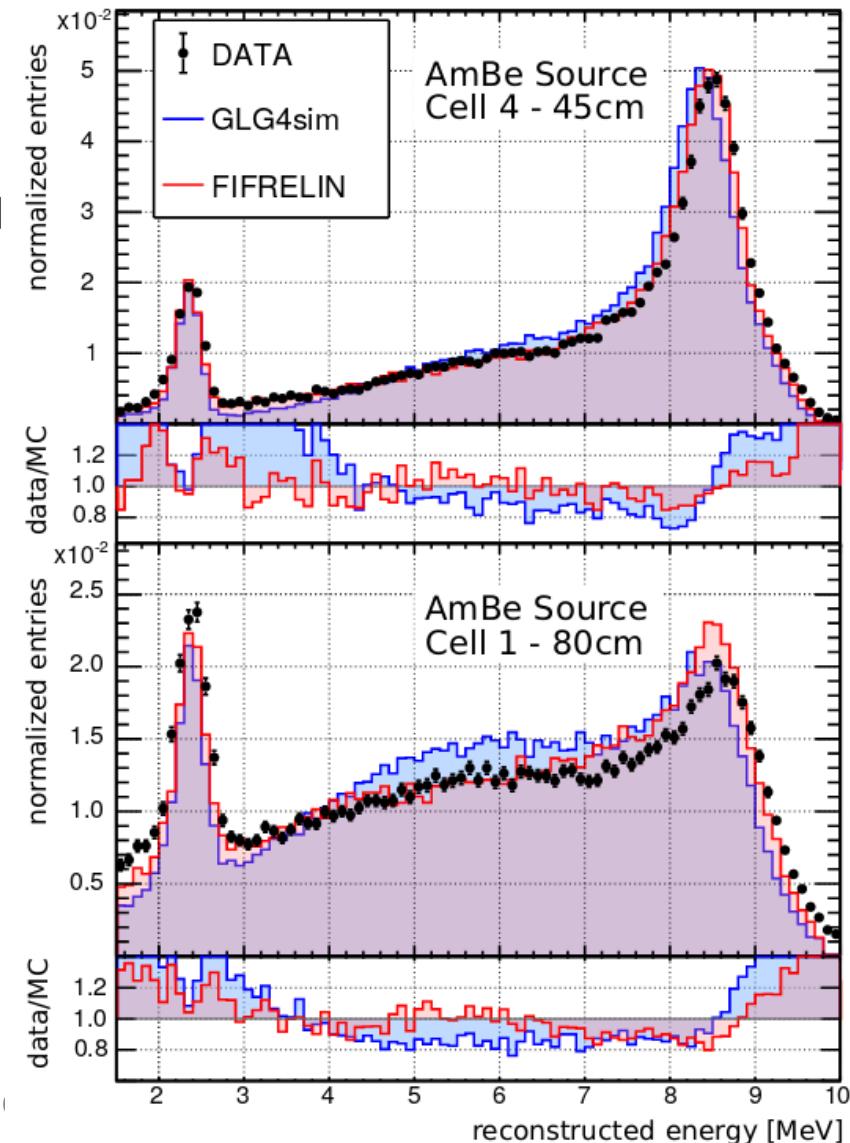
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 - More higher energy γ than in GLG4sim (and slightly lower γ multiplicity)

	Cell 4 (central) Central position	Cell 1 (border) Top position
$\varepsilon_{\text{Gd}}^{\text{Data}} / \varepsilon_{\text{Gd}}^{\text{MC}}$	GLG4sim	0.9744 ± 0.0003
	FIFRELIN	0.9918 ± 0.0003
$\varepsilon_{\text{IBD}}^{\text{Data}} / \varepsilon_{\text{IBD}}^{\text{MC}}$	GLG4sim	0.9814 ± 0.0004
	FIFRELIN	1.0035 ± 0.0005
$\varepsilon_{\text{tot}}^{\text{Data}} / \varepsilon_{\text{tot}}^{\text{MC}}$	GLG4sim	0.9562 ± 0.0005
	FIFRELIN	0.9953 ± 0.0006

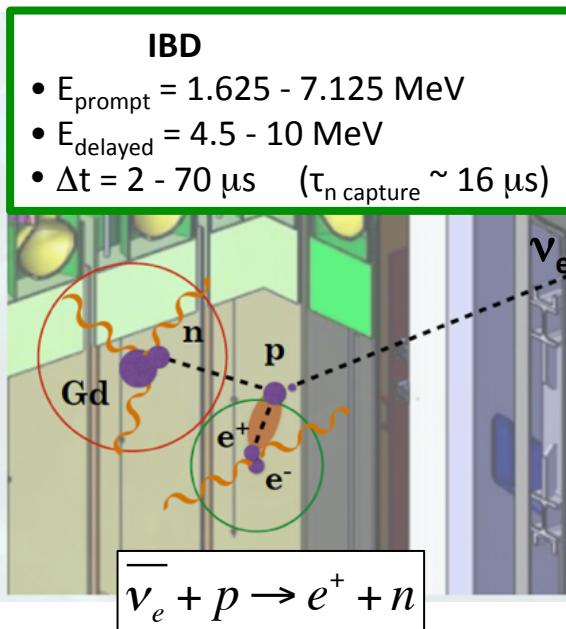
See [arXiv:1905.11967](https://arxiv.org/abs/1905.11967) & [zenodo/2653787](https://zenodo.3654503/n-Gd_gamma_cascade_v1.0.tar.gz)

- Good agreement in cell centre, disagreement in corners due to n mobility, corrected by map

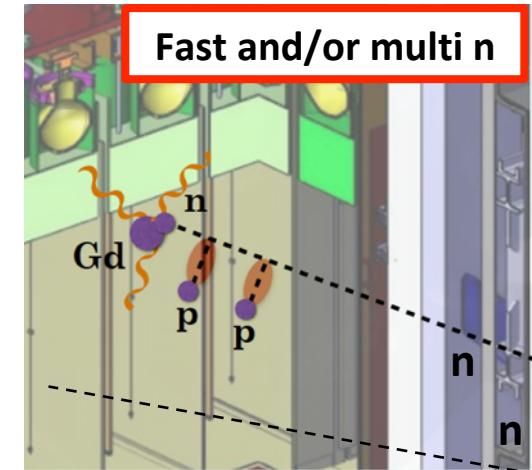
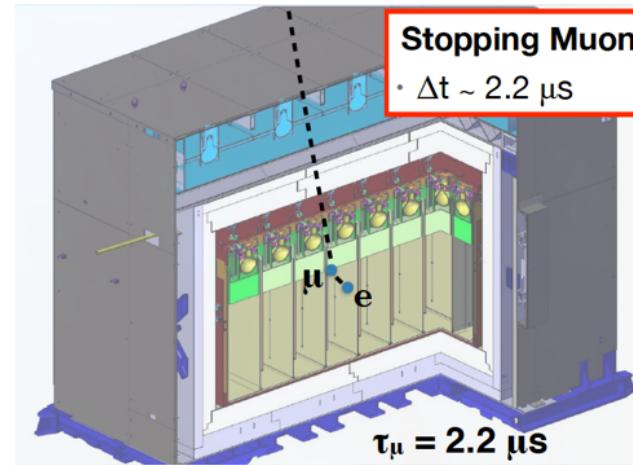


Selection cuts

Neutrino selection



Background rejection (cosmic rays)

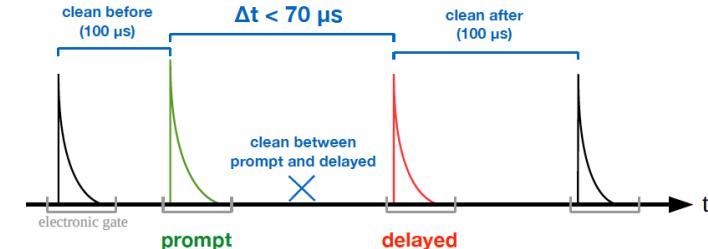


- Charge asymmetry per cell: $Q_{\max}/Q_{\text{tot}} < 0.50$
- $\Delta t_{\text{last Veto } \mu} > 100 \mu\text{s}$
- Isolated prompt-delayed pair

Topology cuts:

- E_{prompt} in neighbour cell $< 1.0 \text{ MeV}$
- E_{prompt} in other cells $< 0.4 \text{ MeV}$
- E_{delayed} in target $> 1 \text{ MeV}$
- $D_{\text{prompt-delayed}} < 60 \text{ cm}$

**Mean signal
cut eff:
 $61.4 \pm 0.9 \%$**

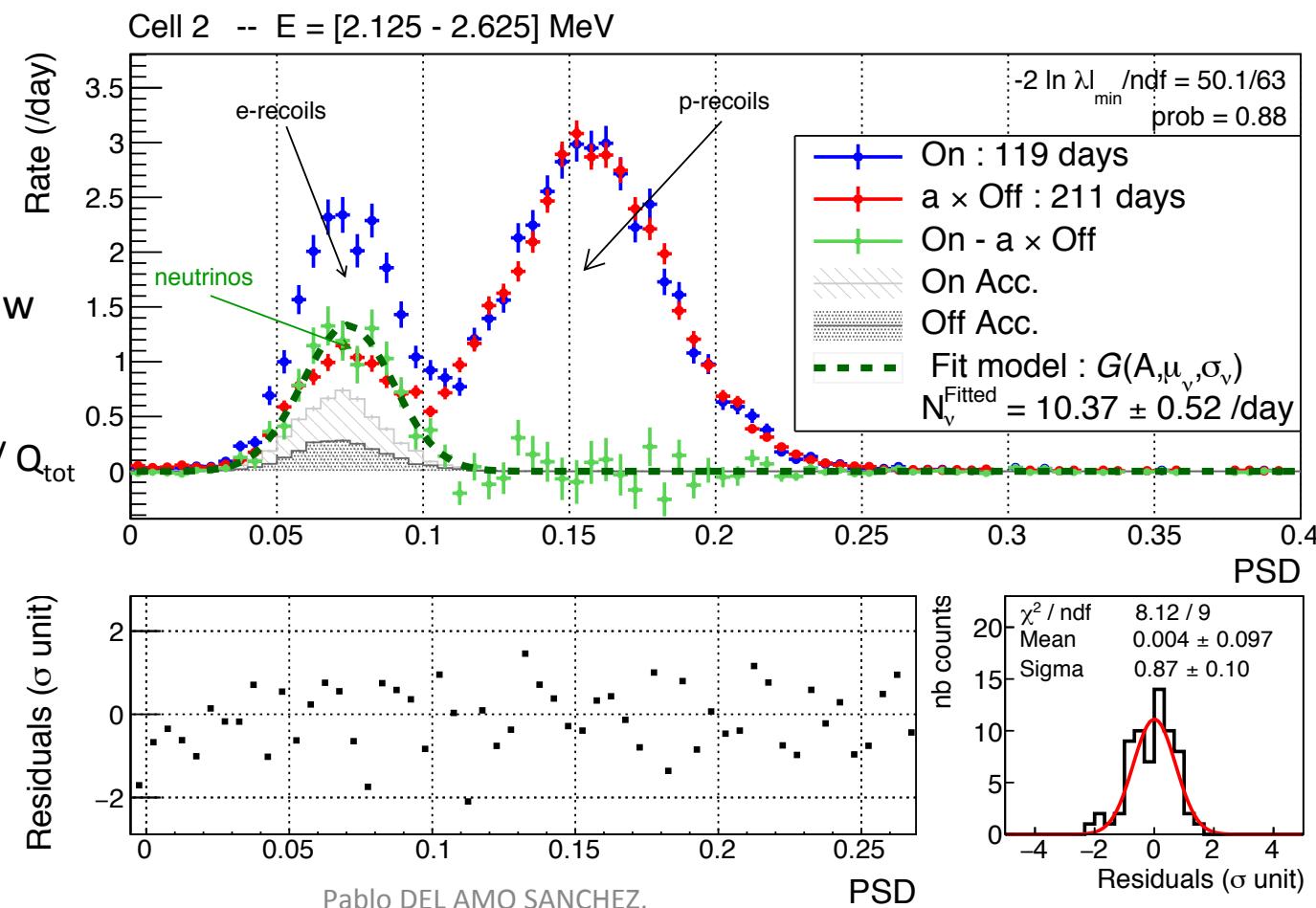
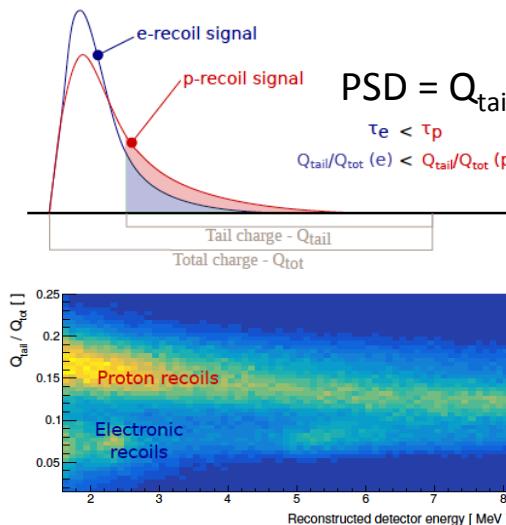


Background subtraction

Fit Pulse Shape Discrimination (PSD) to extract neutrino signal from correlated backgrounds (e.g. fast neutron from spallation by cosmics) in each cell and energy bin

Background shape
from OFF data

Accidentals from
displaced-time window



Oscillation fit

- Compare measured spectra of all cells via a MC prediction of the detector response:

$$\chi^2 = \sum_I^{N_{\text{Cells}}} \sum_i^{N_{\text{Ebins}}} \left(\frac{D_{I,i} - \phi_i M_{I,i}(\mu, \sigma, \vec{\alpha})}{\sigma_{I,i}} \right)^2 + \sum_I^{N_{\text{Cells}}} \left(\frac{\alpha_I^{\text{NormU}}}{\sigma_I^{\text{NormU}}} \right)^2 + \left(\frac{\alpha^{\text{EscaleC}}}{\sigma^{\text{EscaleC}}} \right)^2 + \sum_I^{N_{\text{Cells}}} \left(\frac{\alpha_I^{\text{EscaleU}}}{\sigma_I^{\text{EscaleU}}} \right)^2$$

$$M_{I,i}(\mu, \sigma, \vec{\alpha}) = M_{I,i}(\mu, \sigma) \times (1 + \alpha_I^{\text{NormU}} + (\alpha^{\text{EscaleC}} + \alpha^{\text{EscaleU}}) \times S_{I,i}^{\text{Escale}}(\mu))$$

α , nuisance parameters (norm, E scale)

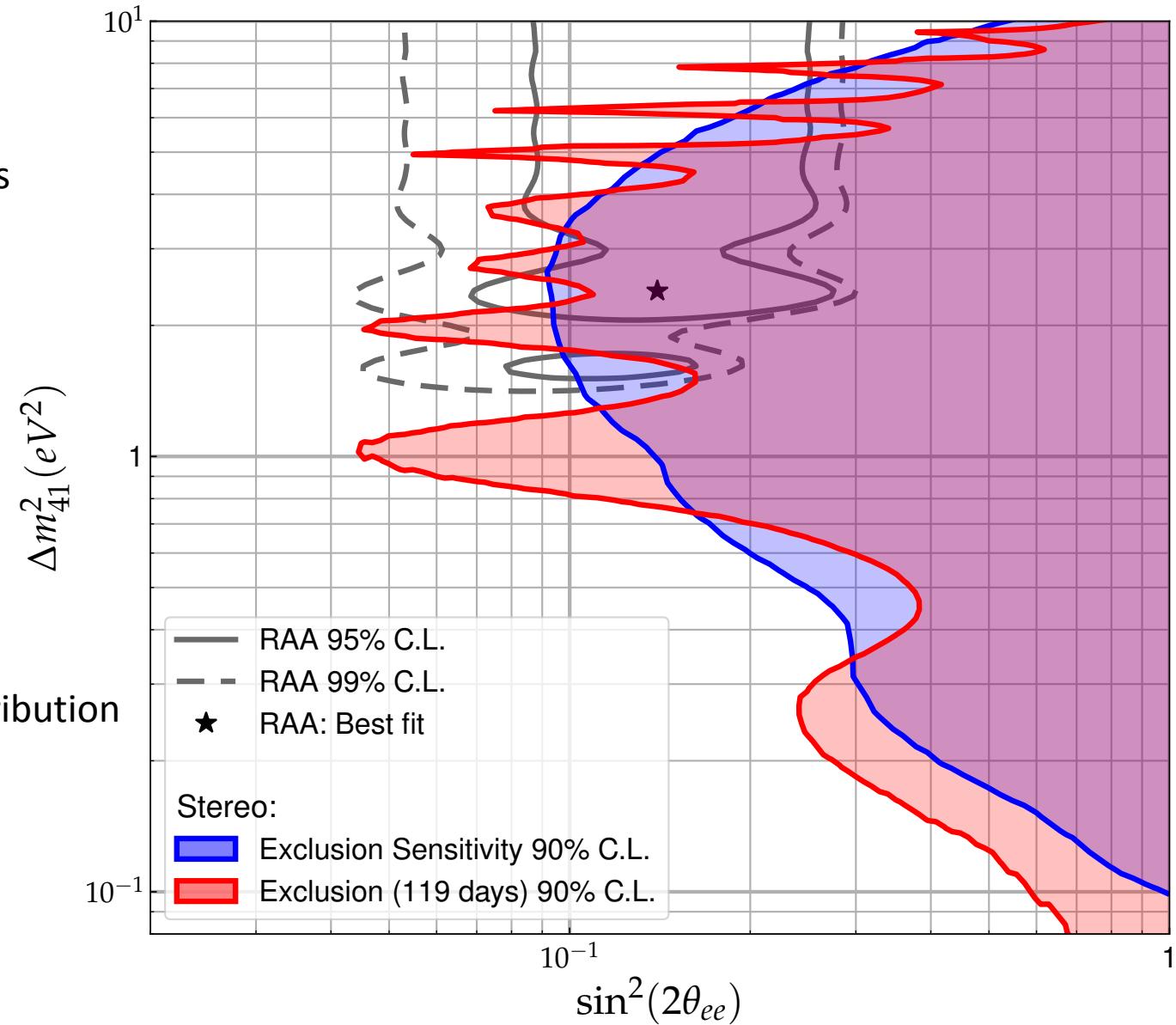
For cell I and energy bin i:

- $D_{I,i}$ observed spectrum in data
- $M_{I,i}$ MC prediction
- ϕ_i factor common to all cells correcting the MC prediction to suit the observed spectrum in data

Independent of spectrum prediction

Phase II Oscillation results

- Do not reject the no oscillation hypothesis (p-value = 0.40)
- Raster scan in Δm^2
- RAA best fit point excluded at $\sim 99\%$ C.L.
- Non-normal $\Delta\chi^2$ distribution estimated from MC pseudo experiments

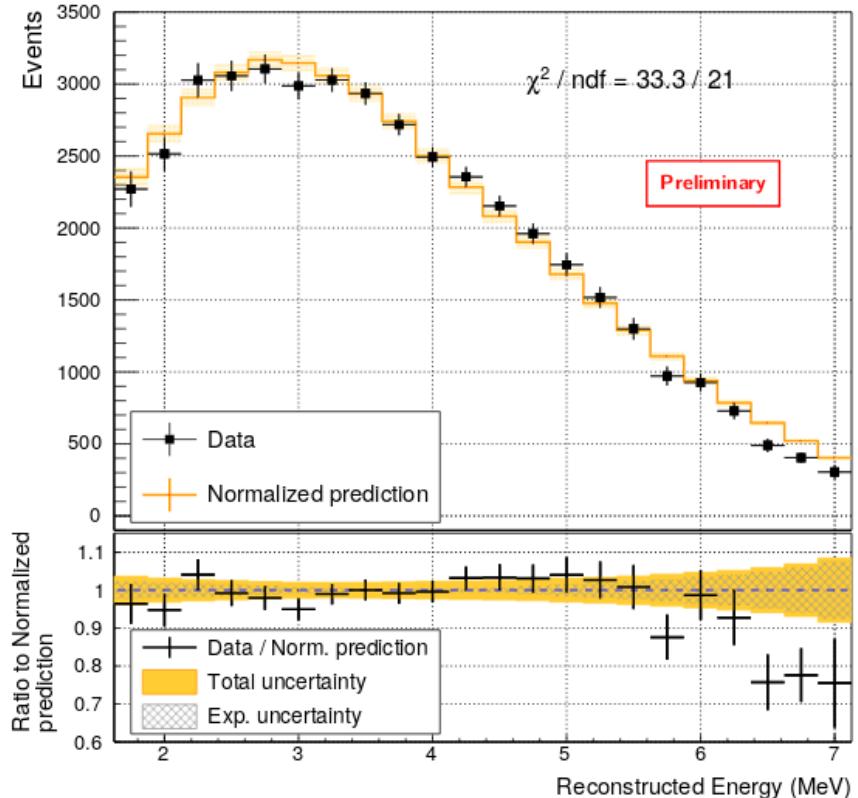
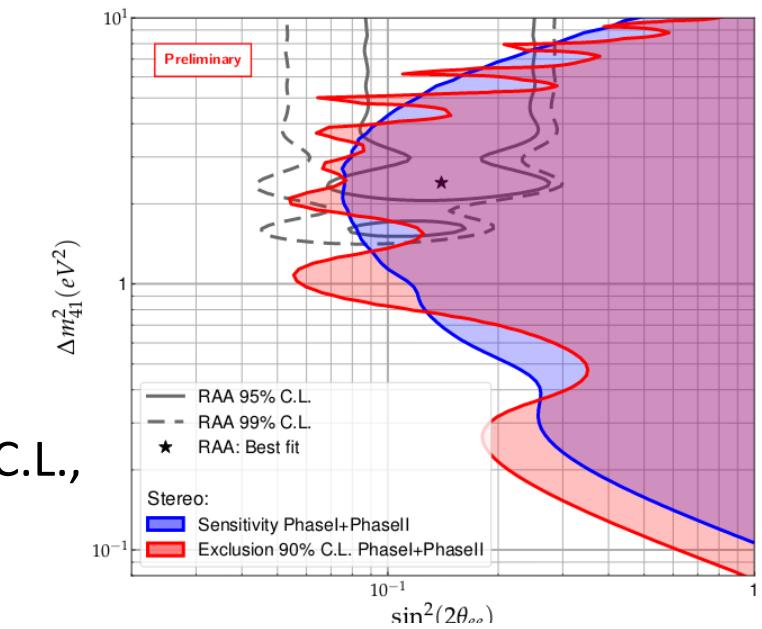


Conclusions

- 43.4 k nu detected in Phase II, 65.6 k in total
- STEREO rejects the RAA best fit point at > 99% C.L., excludes large part of the sterile neutrino oscillation parameter space
- Statistics to be doubled by mid-2020
- Systematics approaching < 1% level

- New work improving n-Gd γ cascade (arXiv:1905.11967 & zenodo/2653787)

- Stay tuned for STEREO's upcoming papers on reactor spectrum and flux, and Phases I + II oscillation combination



Questions?

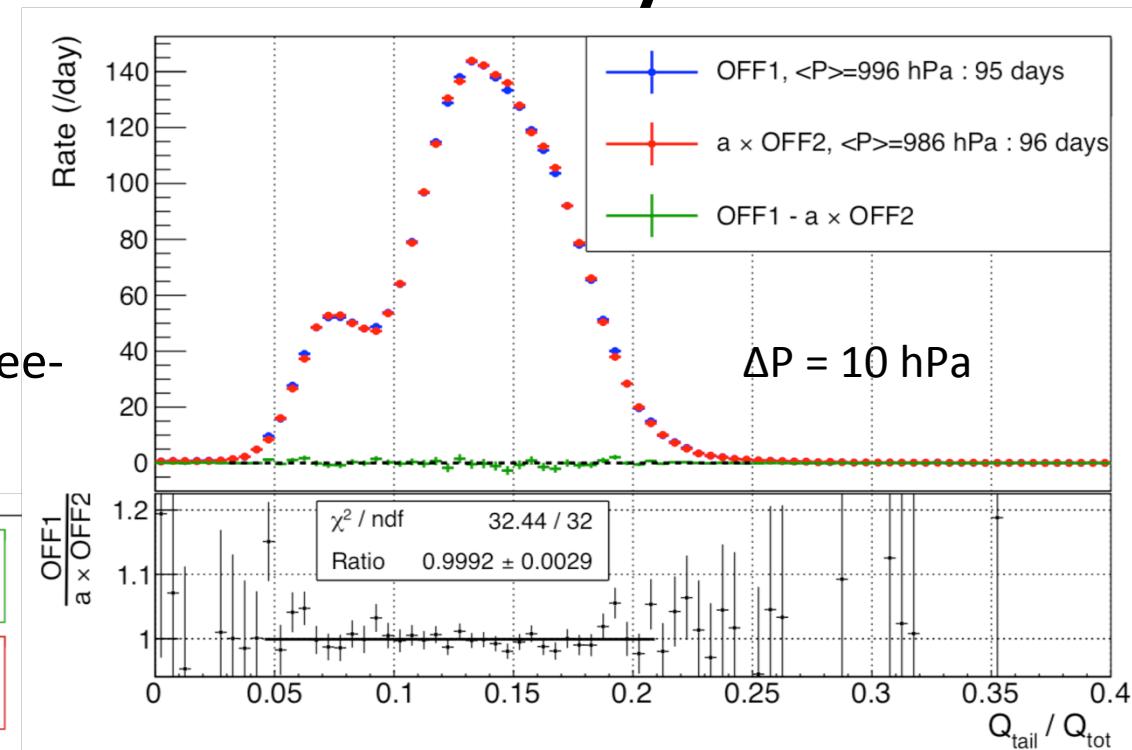
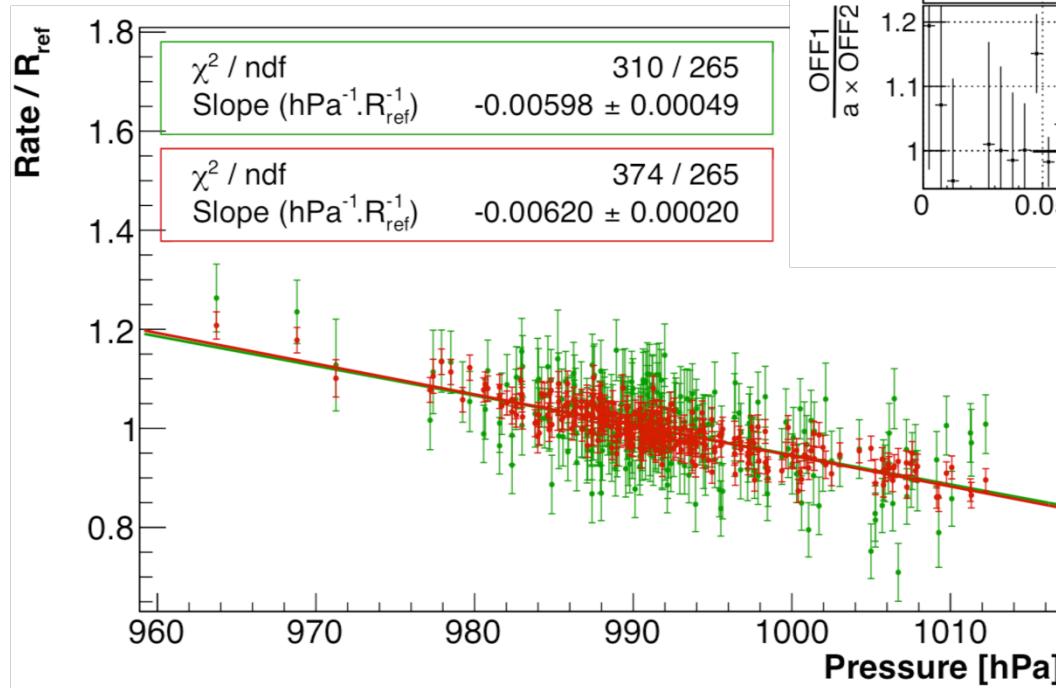
The STEREO Collaboration



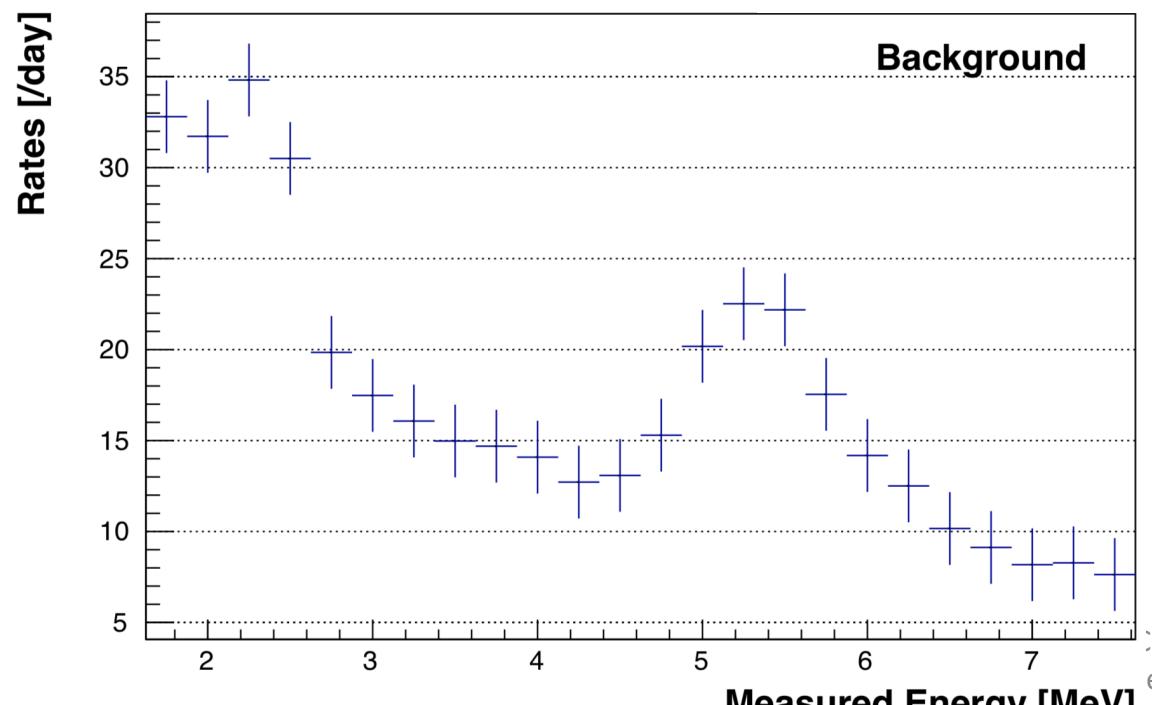
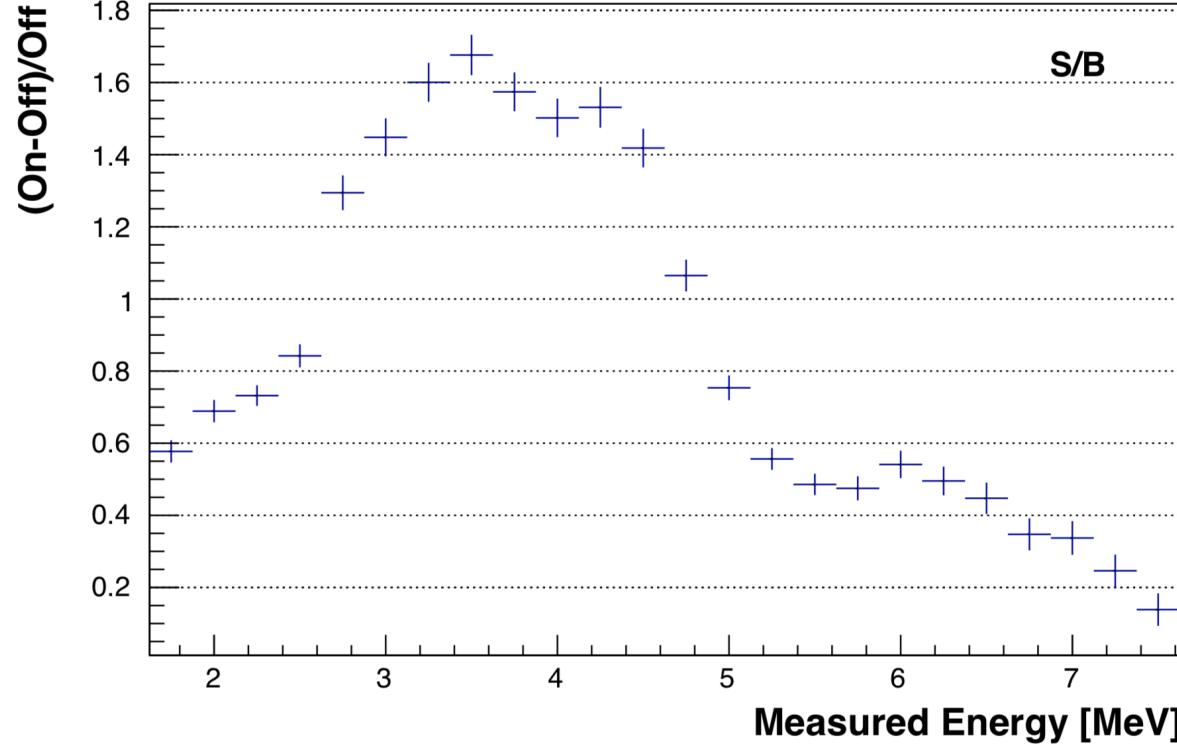
Website:
<http://stereo-experiment.org>

Background stability

- PSD background distribution the same for different atmos pressures, once norm corrected
- Norm correction in good agreement with expectations

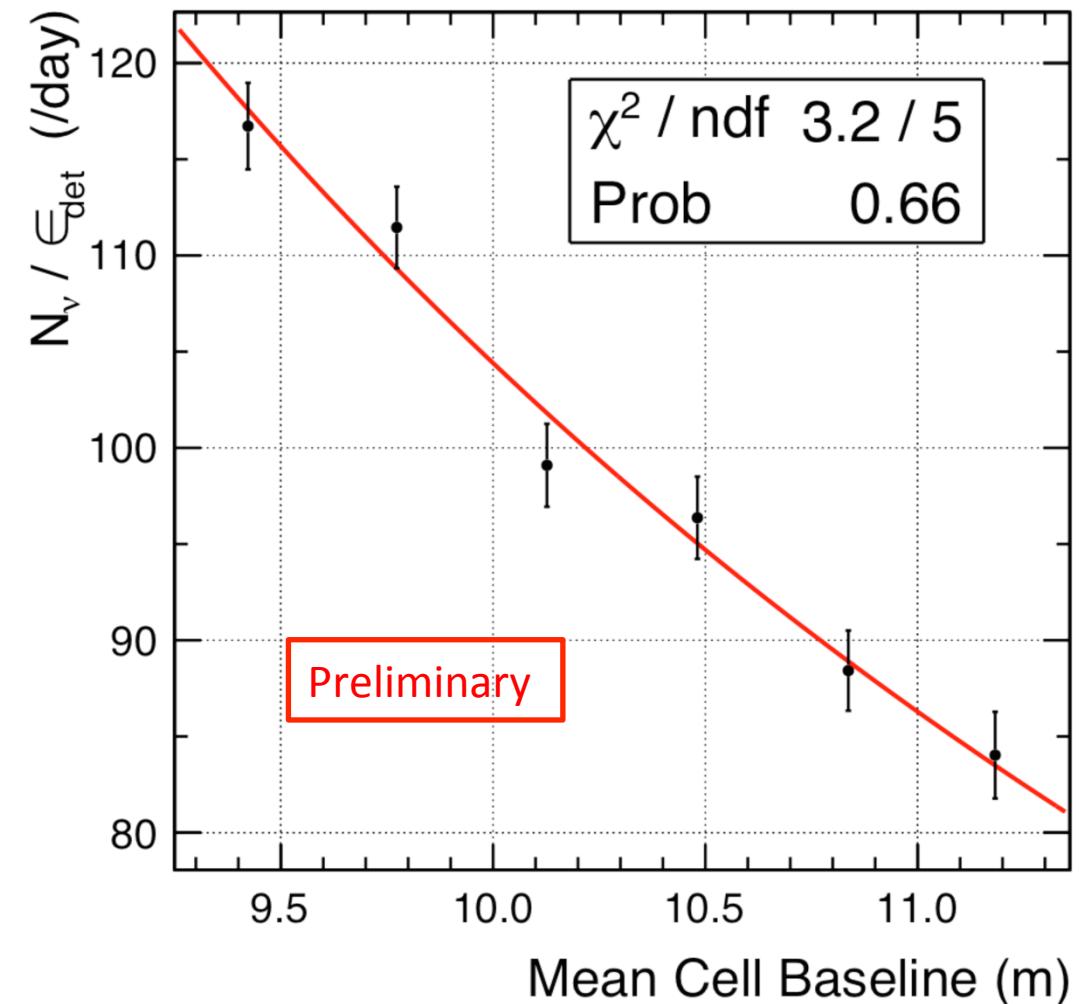


Background

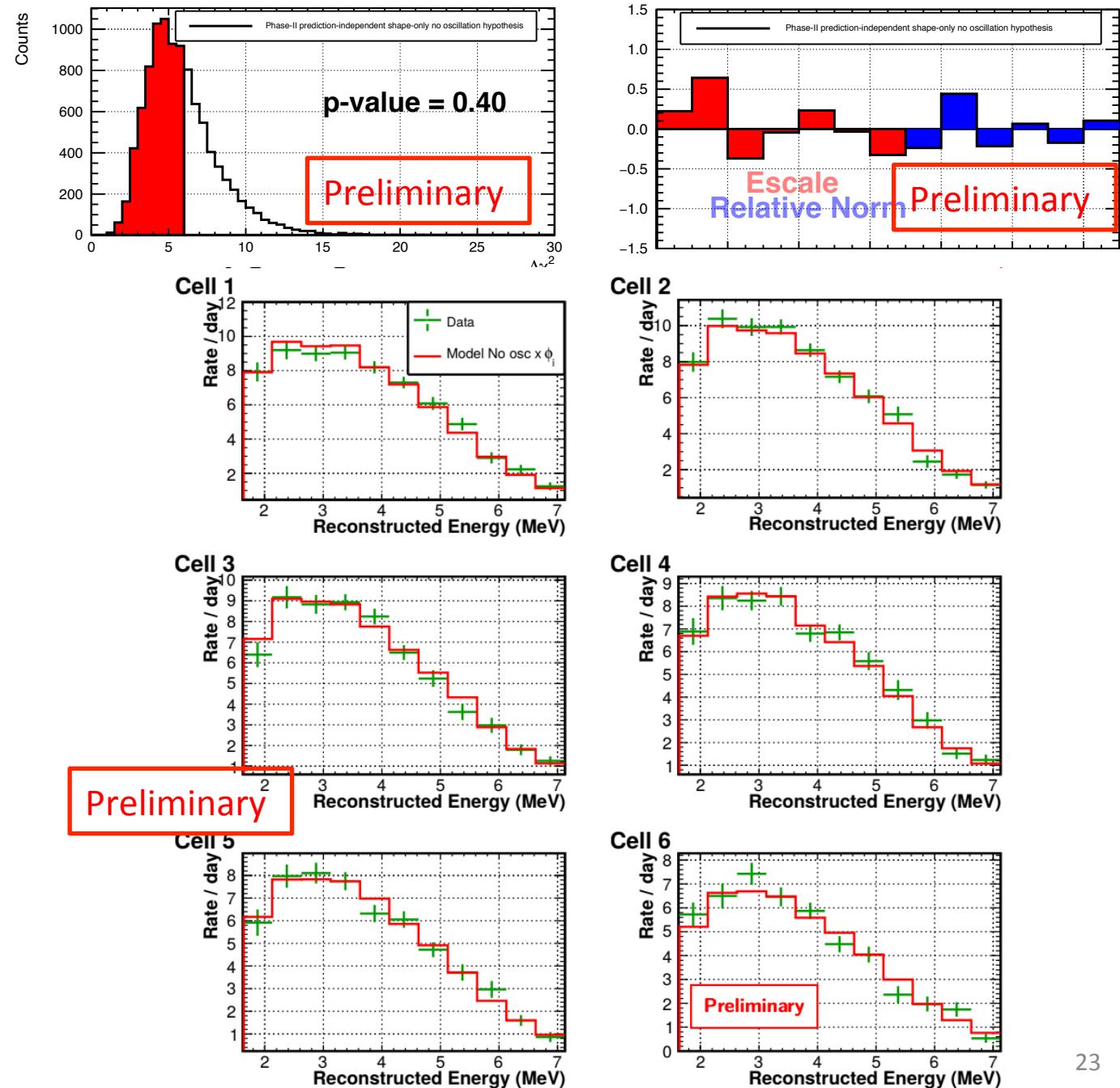


1/L² law

- Detected neutrino rates corrected by detection eff in excellent agreement with 1/L² law

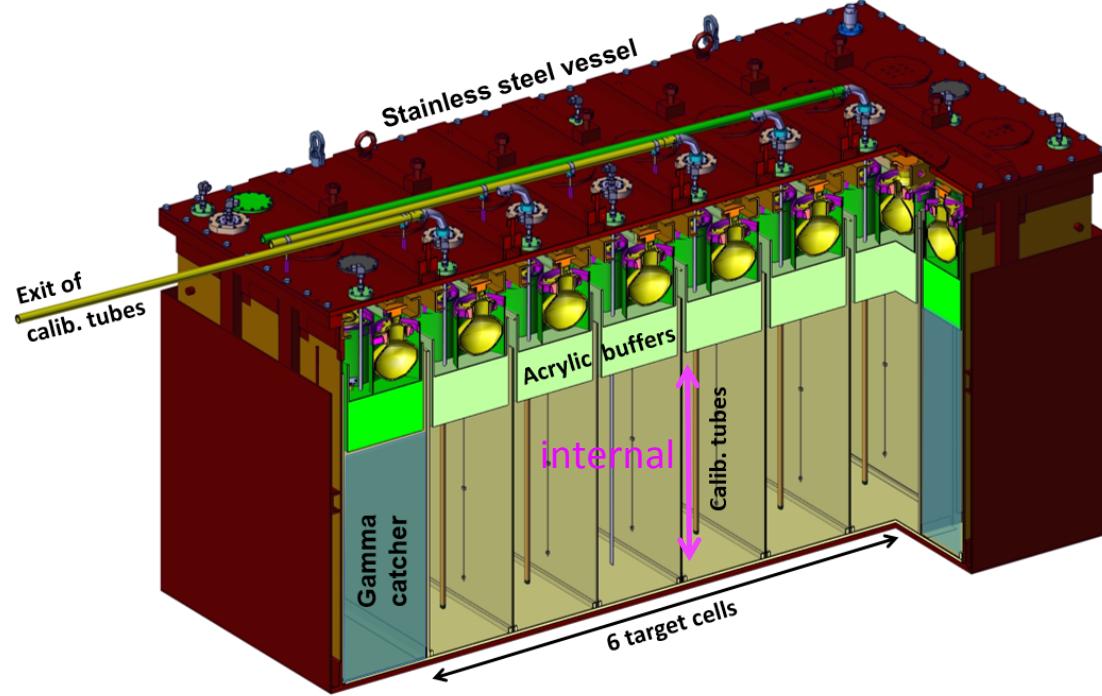


- STEREO does not reject the no-oscillation hypothesis ($p = 0.40$)
- Fitted pull terms all $< 1 \sigma$
- Good agreement between Data and Non-oscillated Model



STEREO calib systems

Need to calibrate every (small) active volume independently



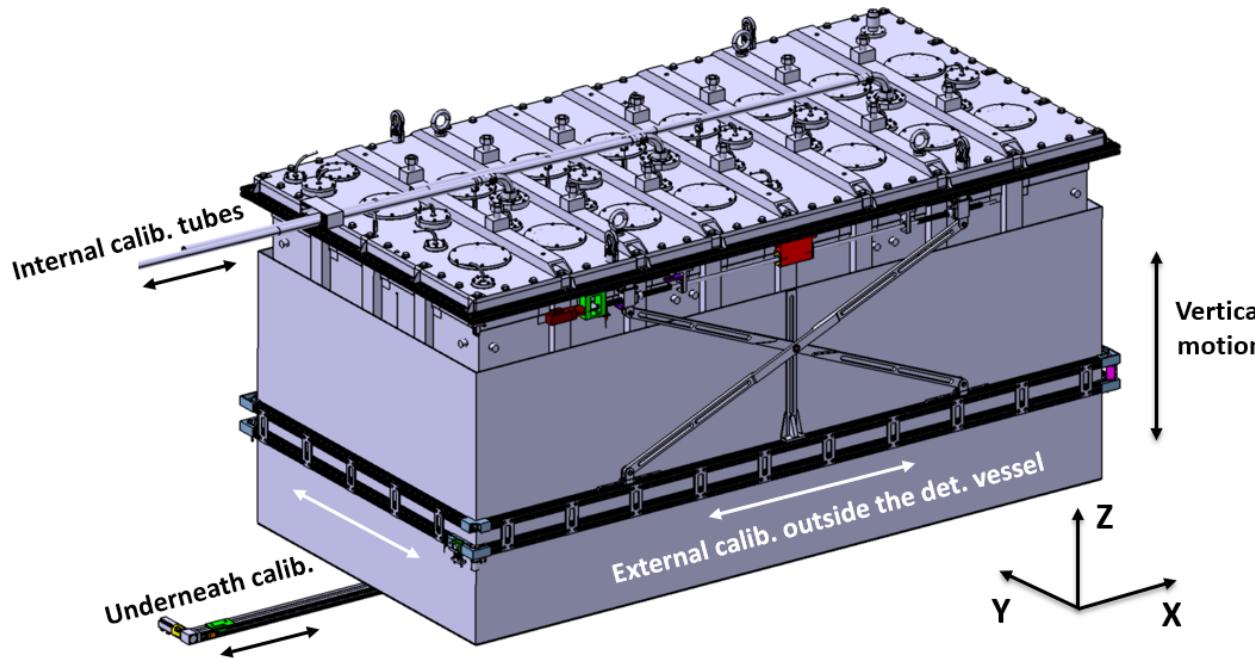
3 different ways to expose active volumes to radioactive sources:

- internal calib tubes
(Target only, 5 cells)
- outside steel vessel,
around GC
- outside steel vessel,
below central axis

Source	^{68}Ge	^{124}Sb	^{137}Cs	^{54}Mn	^{65}Zn	^{60}Co	^{24}Na	AmBe
γ -ray energies (MeV)	0.511	0.603	0.662	0.835	1.11	1.17	1.37	2.22 ($\text{H}(\text{n},\gamma)$)
Initial Activity (kBq)	90	2.4	37	90	3.3	50	5.9	4.43 $250 \cdot 10^3$ (^{241}Am)

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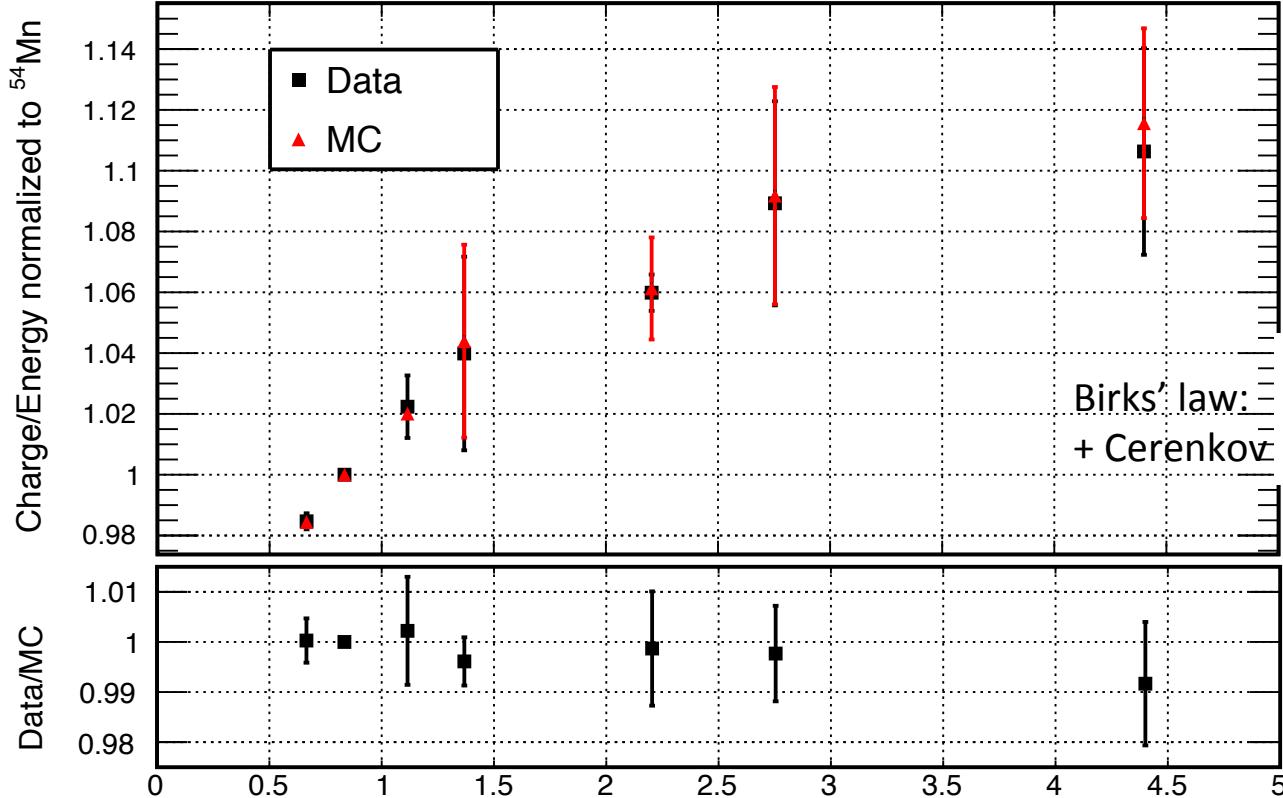


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Quenching



Precisely determined LS
non-linearity (1% level)

$$\frac{dL}{dx} = S \frac{\frac{dE}{dx}}{1 + K_{\text{Birks}} \frac{dE}{dx}}$$

Very good Data/MC
agreement after k_B tuning

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