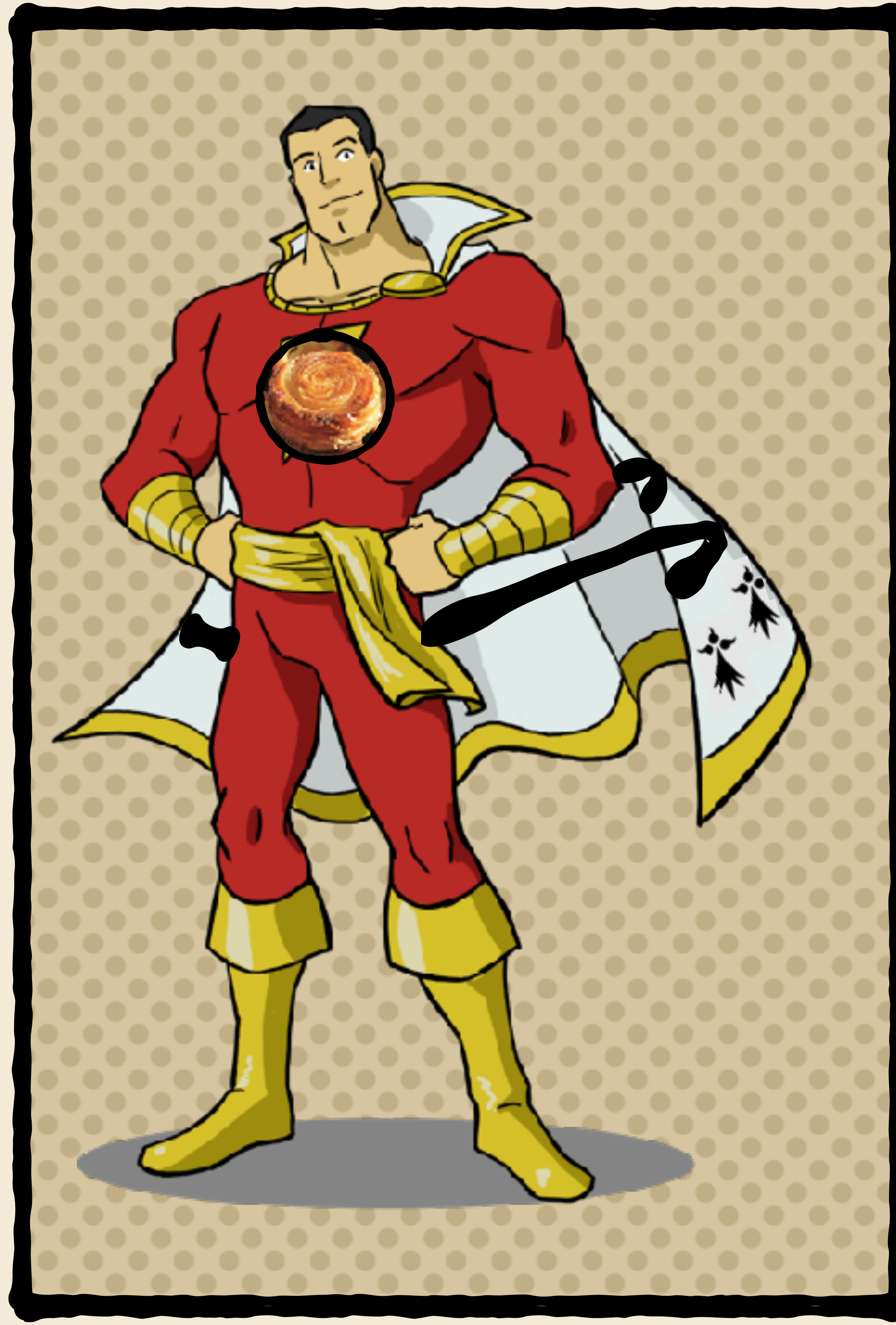
Sterile neutrino search with the STEREO experiment

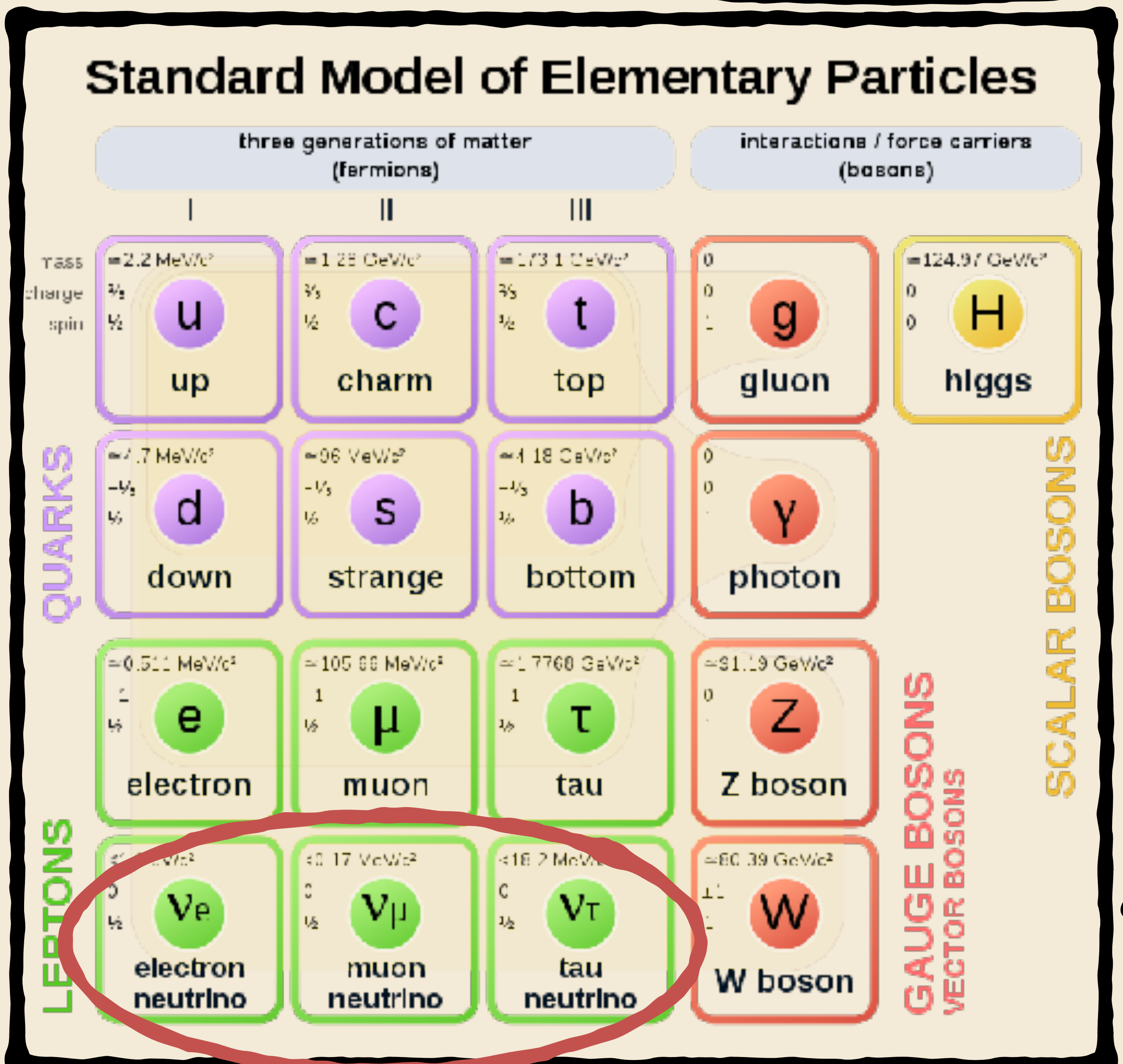
Loïc Labit - LAPP

JRJC 24-30/11/19

The adventures of Kouigna-man at the festnoze



The neutrino secret identity

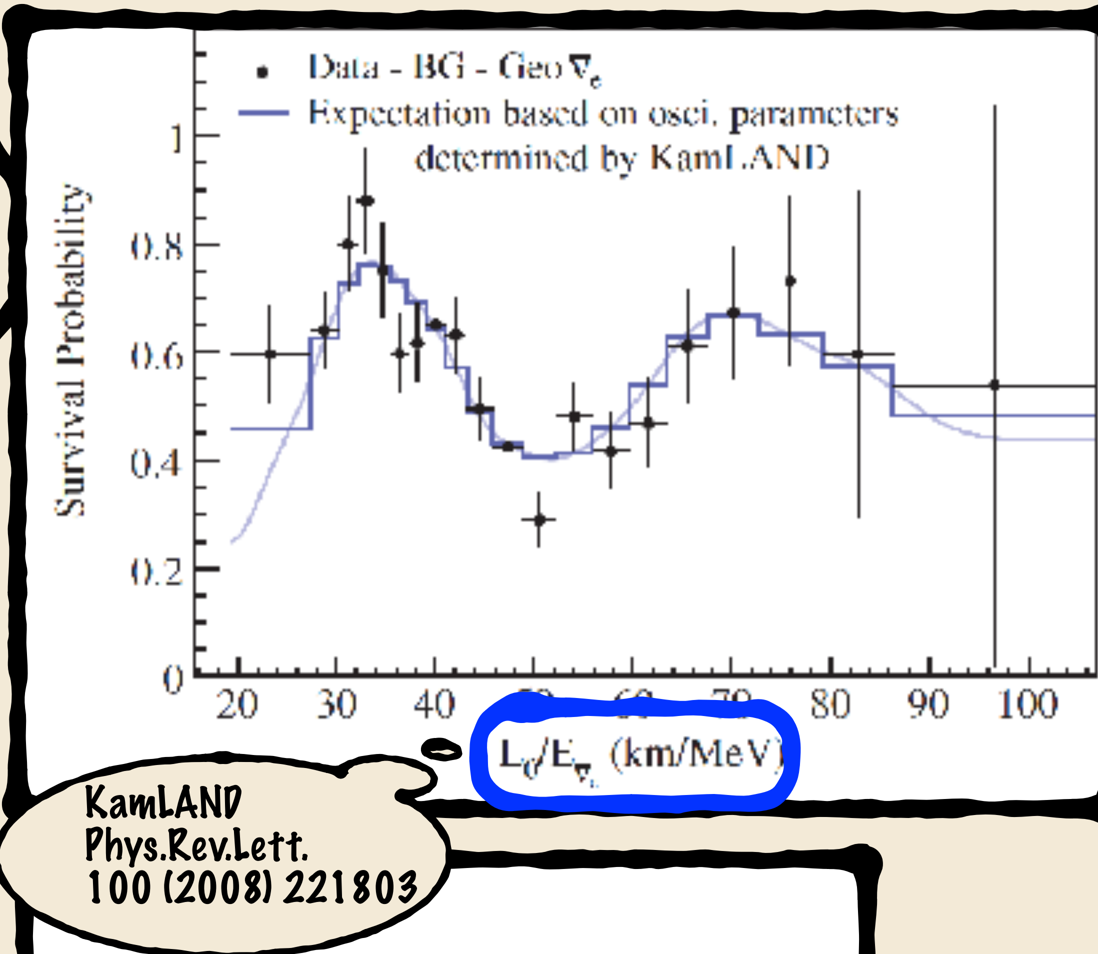


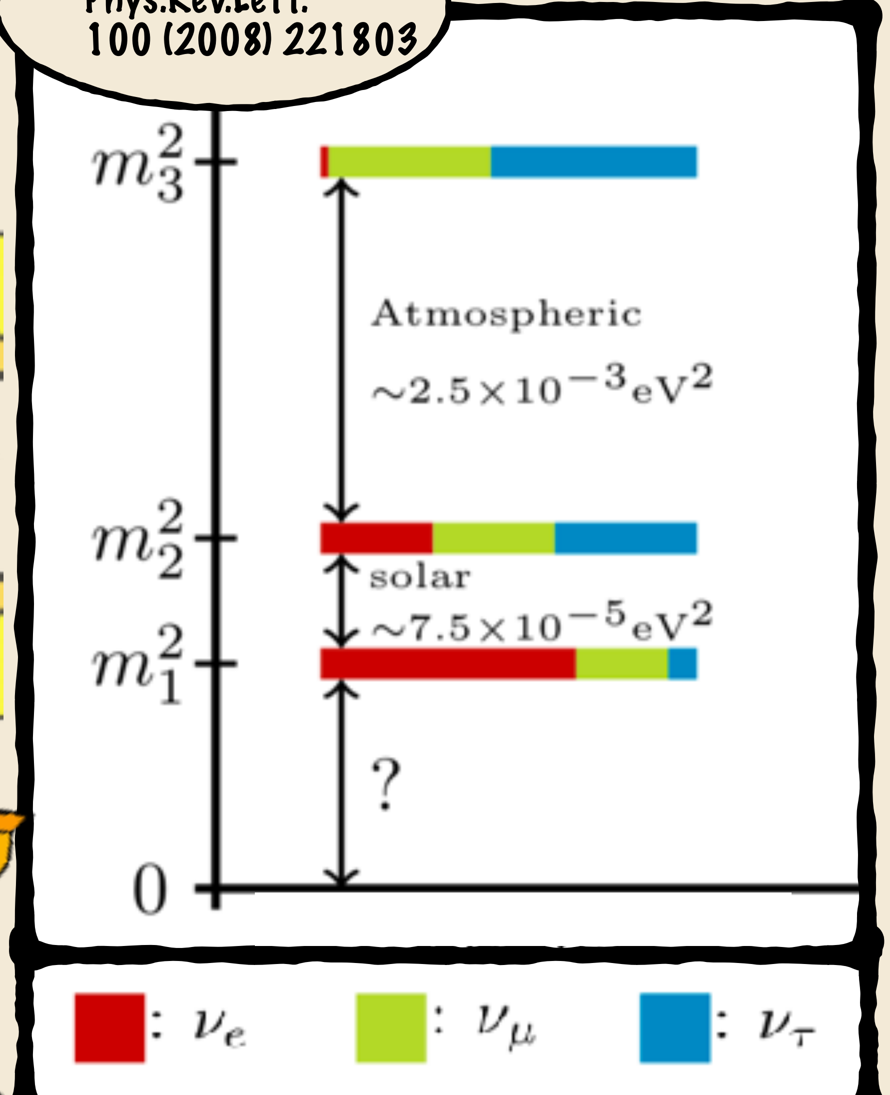
- Neutral lepton
- Weak interaction only : $\sigma_{IBD} \sim 10^{-43}\ cm^2$
- Mass < 1 eV but non zero
- Most mass models require a sterile neutrino
- Sterile neutrino: no weak interaction but oscillation with other flavours possible

The neutrino superpower: Oscillation

* Oscillation depends on the mass difference squared between mass eigenstates and mixing angles
* Explain neutrino solar and atmospheric anomaly

$$P(\nu_e \to \nu_x) = \sin^2(2\theta)\sin^2(1.27\frac{\Delta m^2 L}{E})$$





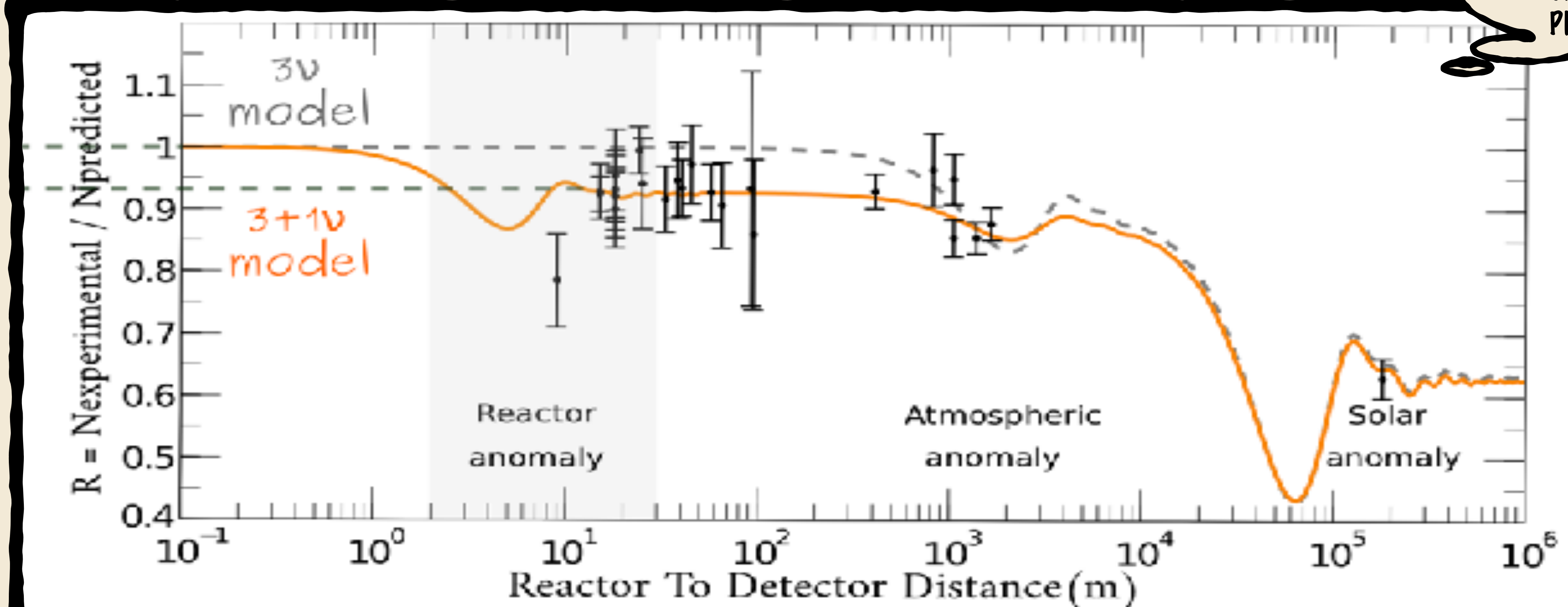
The supervillain: Reactor Antineutrino Anomaly

Huber et al, Phys.Rev. C84 (2011) 024617

Mueller et al, Phys.Rev. C83 (2011) 054615

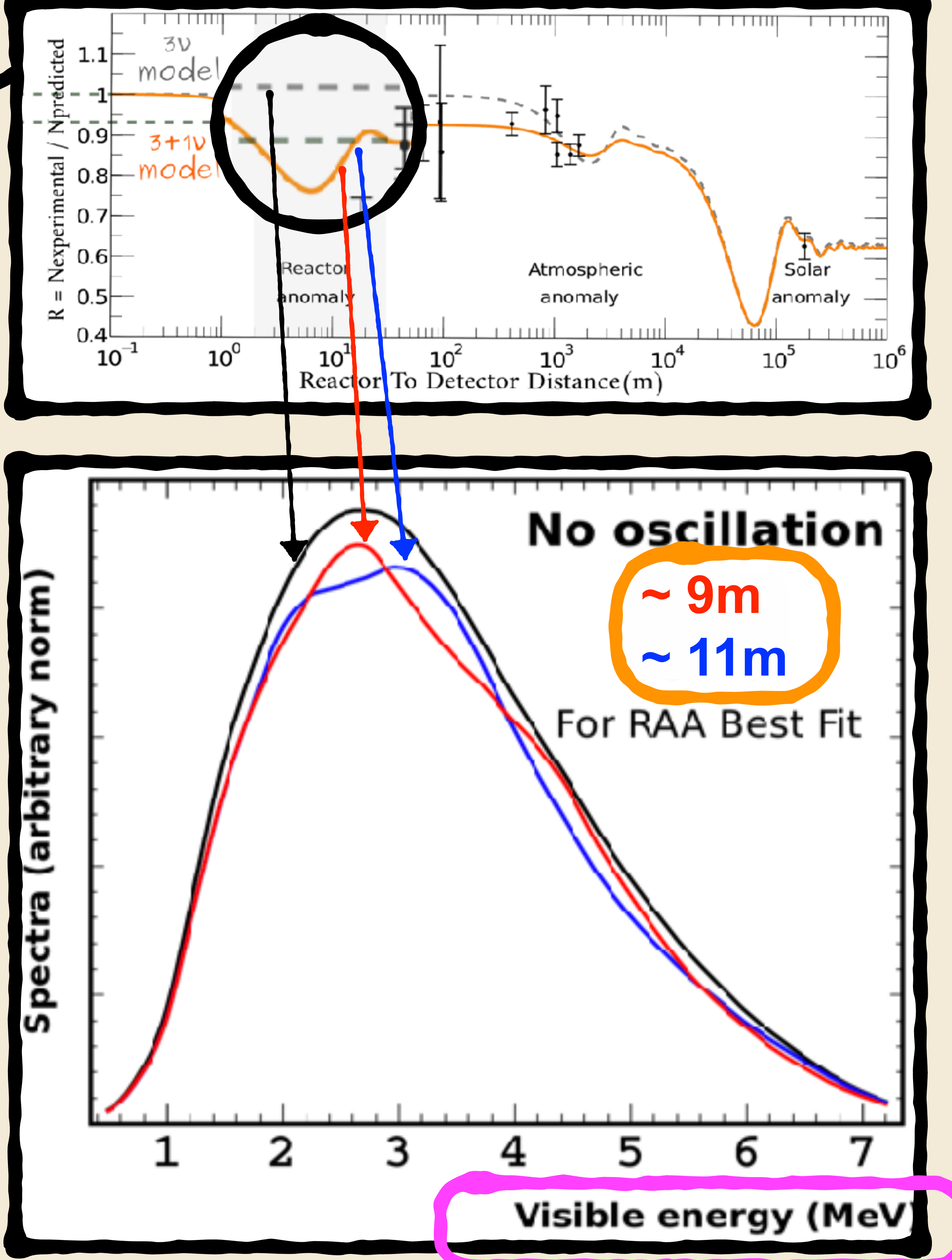
* Following flux reevaluation in 2011 :
  - 7% deficit between observed and expected flux
  - 3σ significance
  - maximum effect at short baseline <10m
  - oscillation parameters best fit : $\Delta m^2 = 2.4$ eV^2 and $\sin^2(2\theta_{new}) = 0.14$

G. Mention et al, The Reactor Antineutrino Anomaly . Phys. Rev., D83 :073006, 2011.



The bad guy's weakness: Oscillation detection

* Unambiguous signature
* Energy spectrum modulation depending on the baseline
* $$P(\nu_e \rightarrow \nu_x) = \sin^2(2\theta)\sin^2(1.27\frac{\Delta m^2 L}{E})$$
* Small effect $\lessapprox$ 10% so good energy response knowledge is required

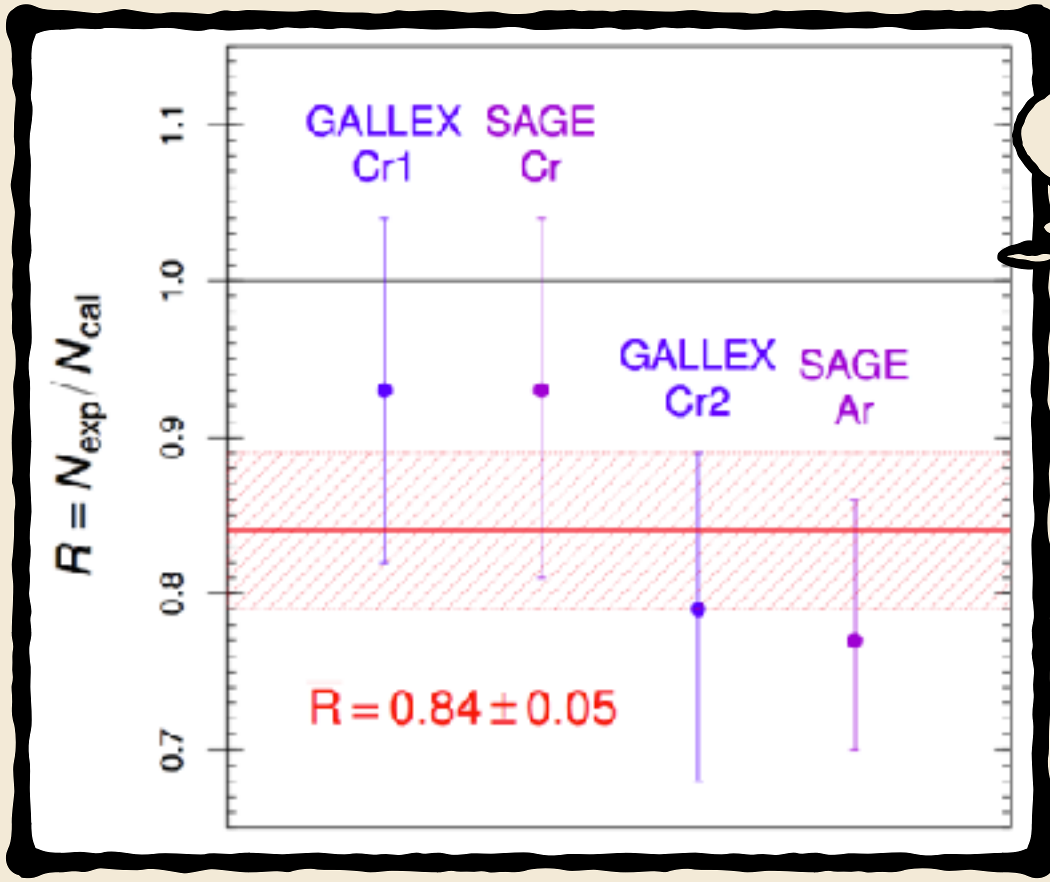


Another bad guy: Gallium anomaly

- GALLEX and SAGE experiments designed to measure solar neutrino flux
- Calibration with Cr and Ar sources :
  - Detected/expected ν = 0.84±0.05
- Can be explained by same sterile neutrino as RAA

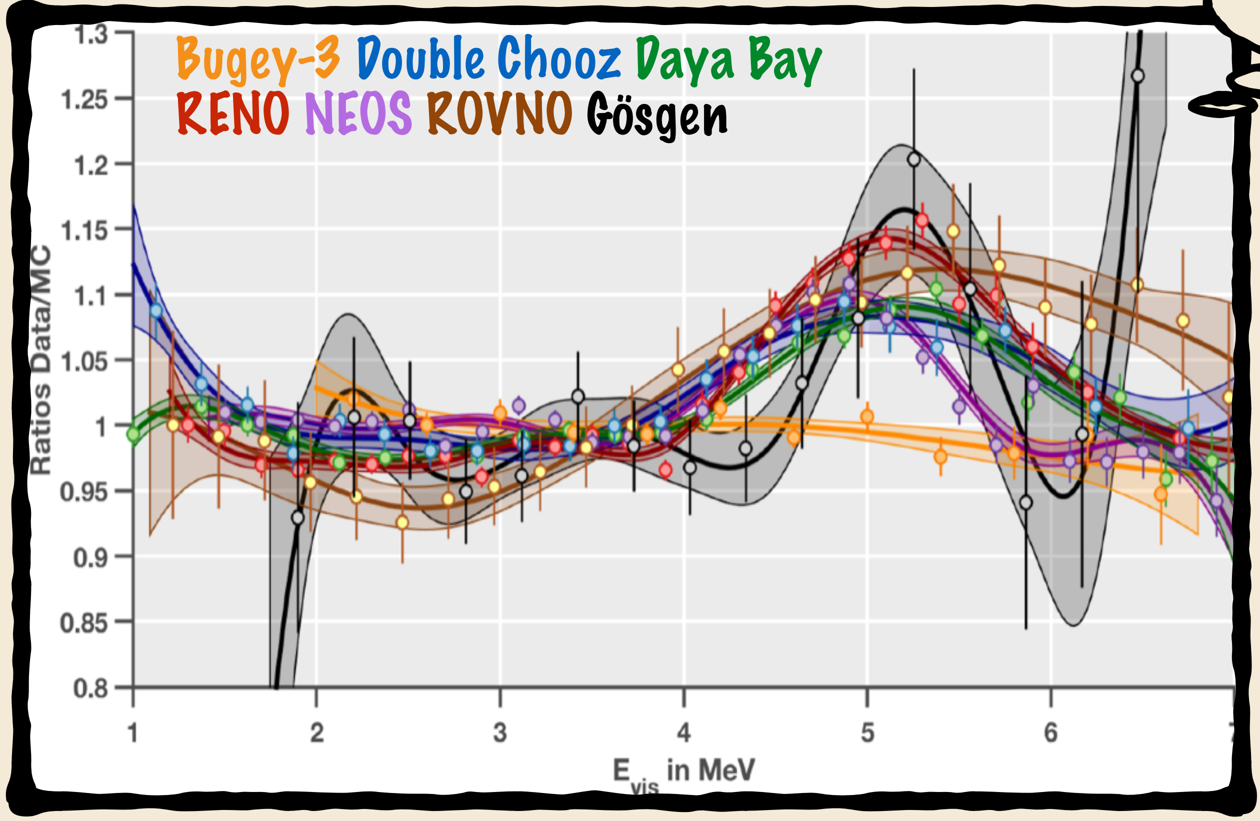
Abdurashitov et al. (SAGE) 2006 PRC73 045805

Anselmann et al. (GALLEX) 1995 PLB342 440
Hampel et al. (GALLEX) 1998 PLB420 114



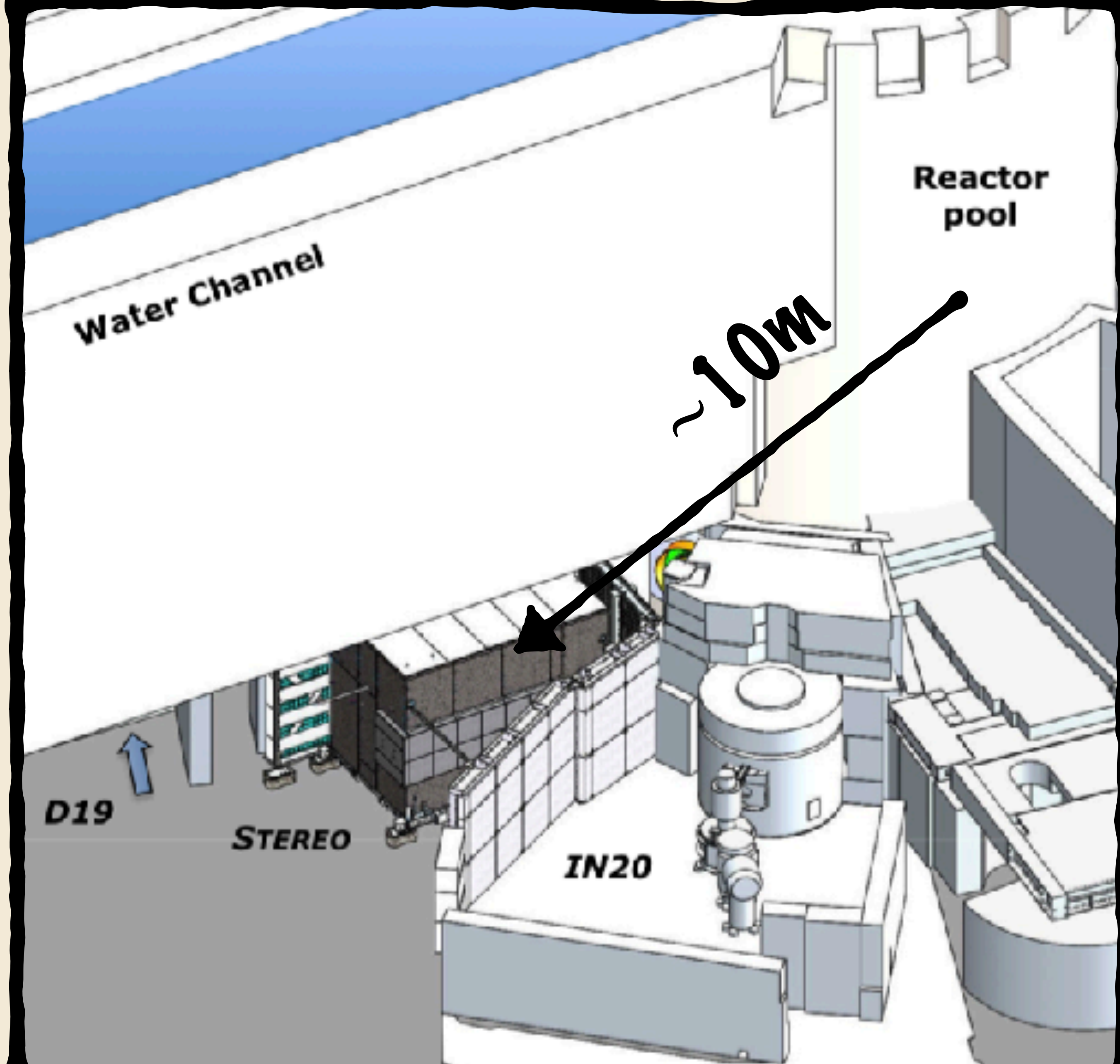
The secret mission: Spectral distortion

* Several experiments observed unpredicted bump ~ 5 MeV in reactor neutrino spectrum
* Could be linked to underestimation of some isotopes
* Pure U-235 measurement useful



G. Mention et al, Phys.Lett. B773 (2017) 307-312

The secret base: ILL in Grenoble

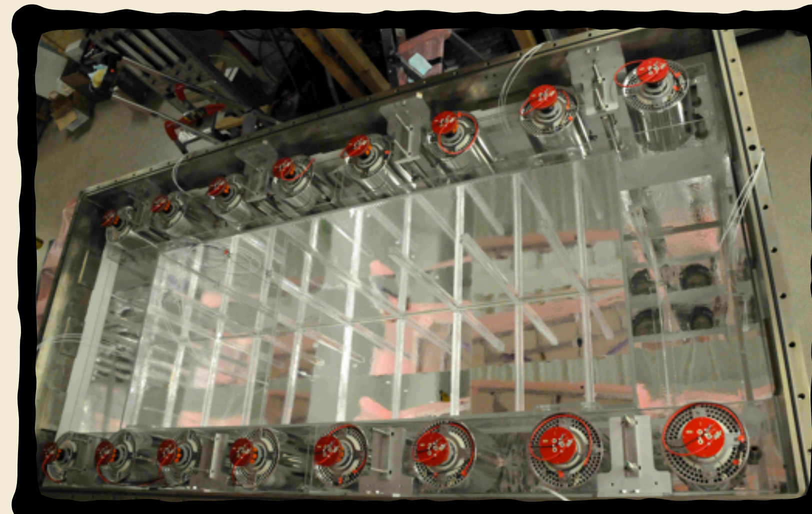


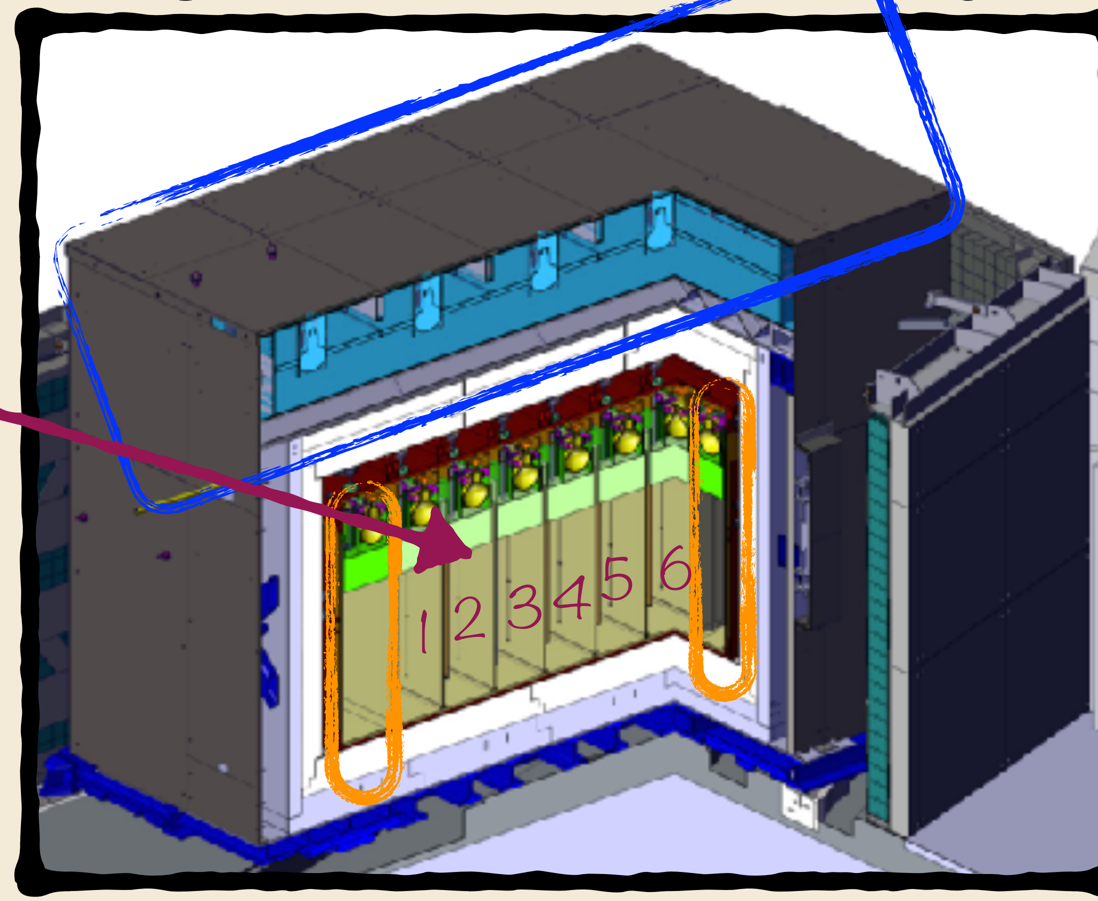
* Compact research reactor core:
  - 40cm ø X80 cm
  - 57 MW
  - 45 days/cycle & 3 cycle/year
  - highly enriched 93% 235 U fuel
* Baseline between 9.4 and 11.2m

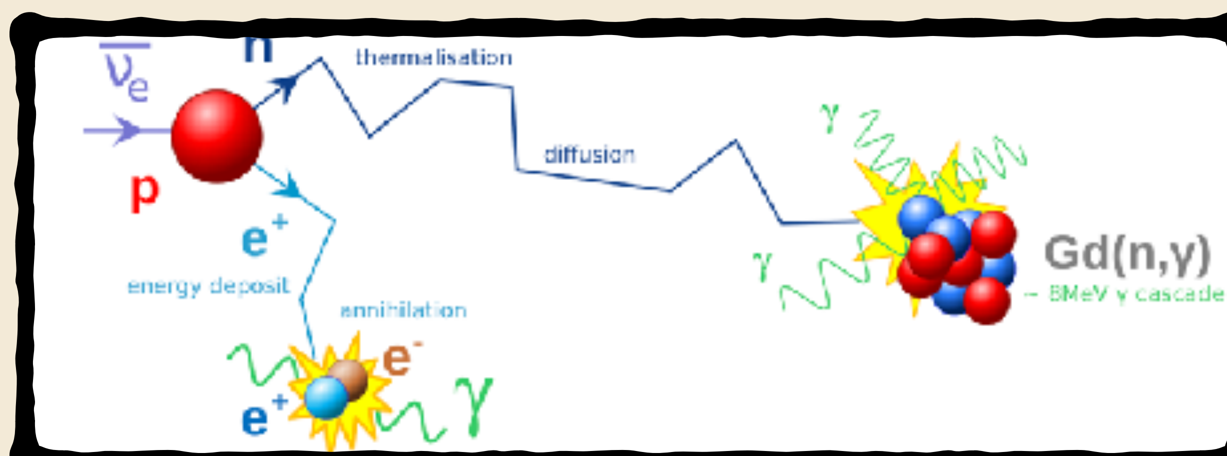
The magic weapon: STEREO Detector

- Gd doped liquid scintillator target:
  - segmented in 6 identical cells
- Gamma catcher: non-doped liquid scintillator
- Water Cerenkov muon veto
- Inverse beta decay detection:
  - $\bar{\nu} + p \rightarrow e^{+} + n$

  Time coincidence :
  - prompt signal : ionisation and positron annihilation
  - delayed signal ~ 15µs later neutron capture on Gd

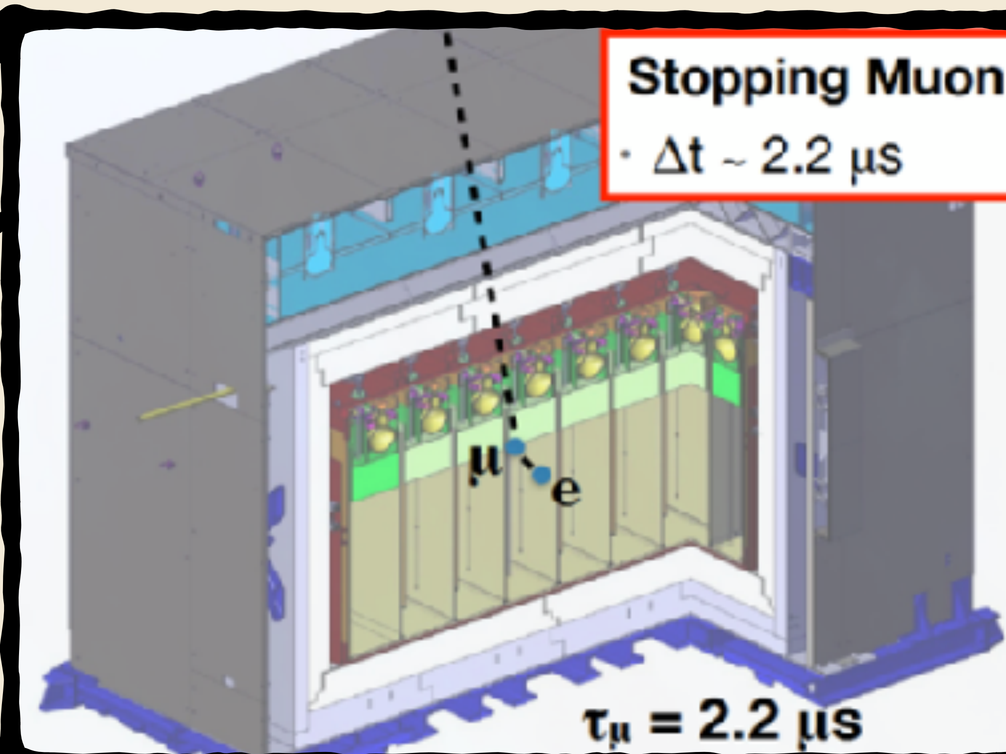


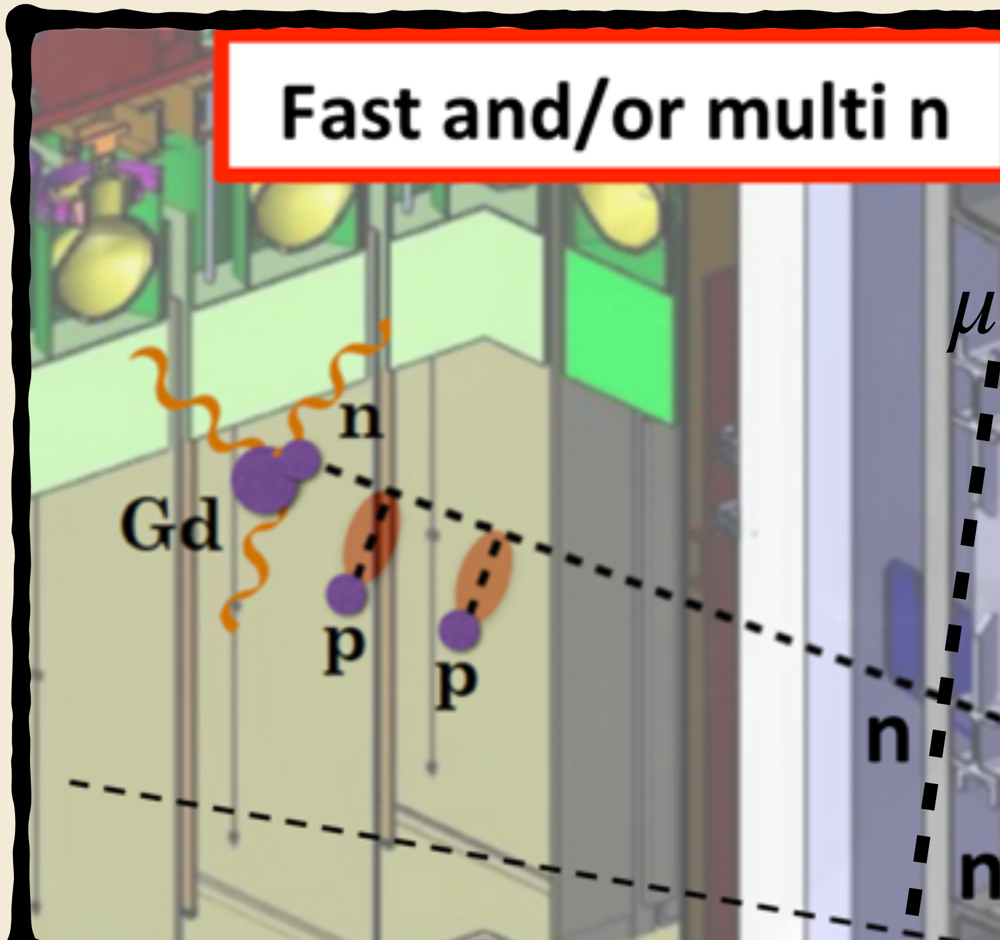




The supervillain acolyte: Cosmic induced background

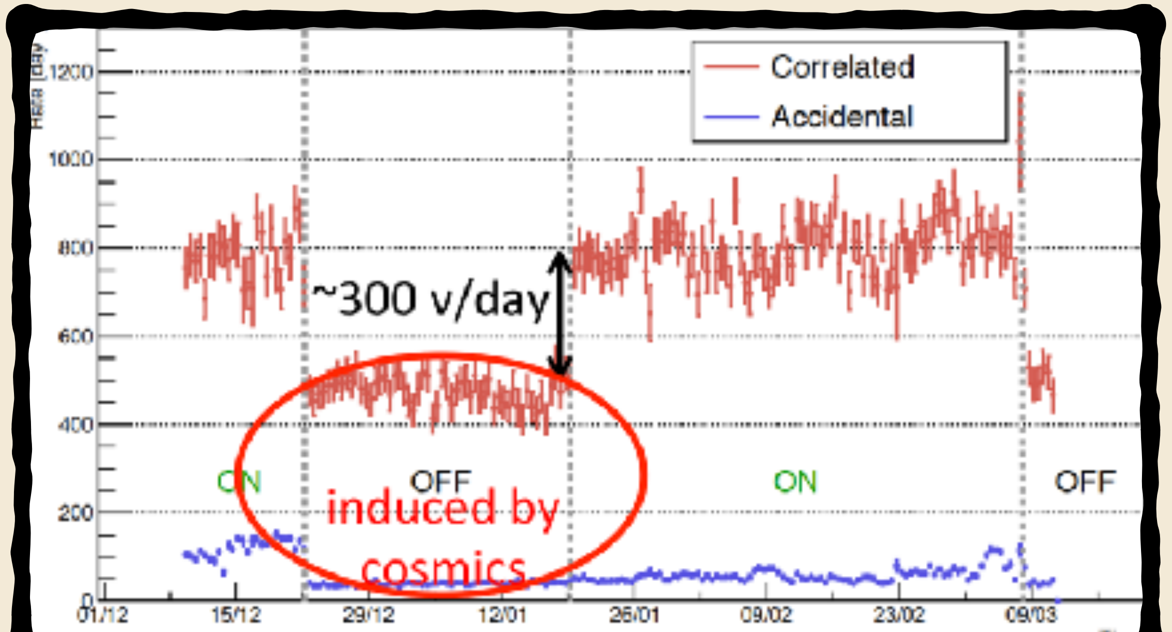
* Dominant bkg induced by cosmic:
  - stopping muon
  - Fast neutron
* Muon bkg mitigated by water channel and muon veto
* Neutron bkg mitigated by passive shielding 100 tons (lead, PE, B4C)

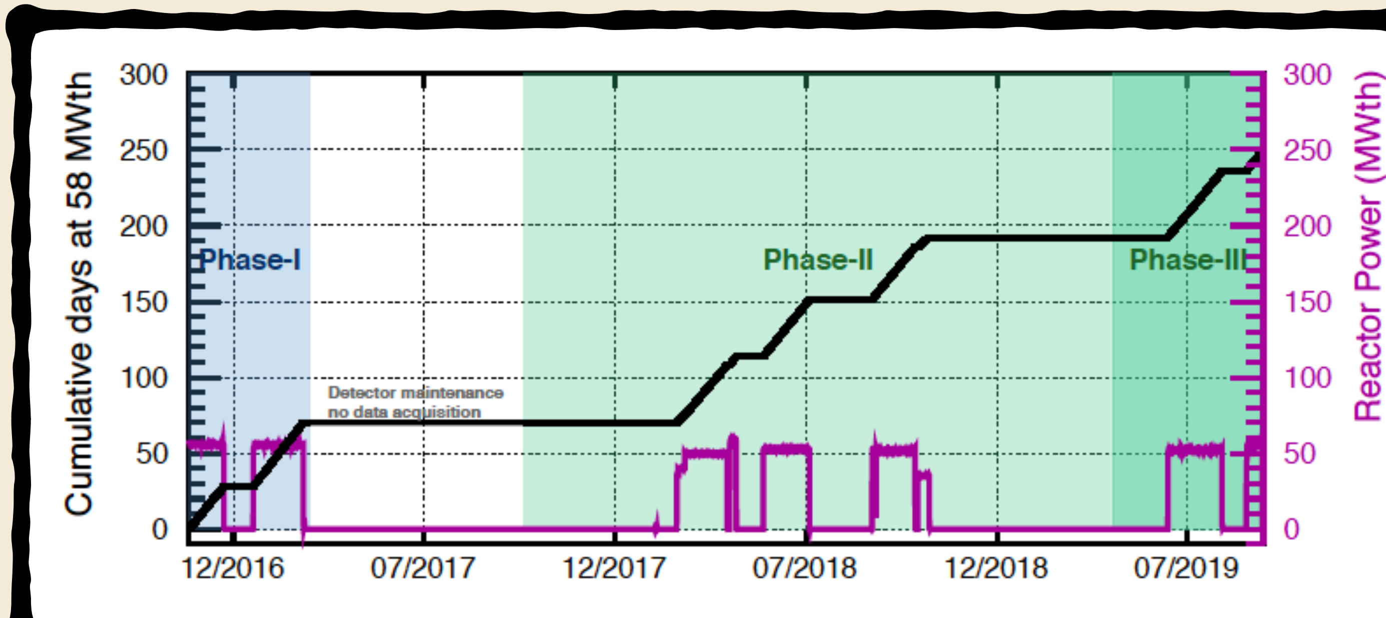




The action plan : Data taking

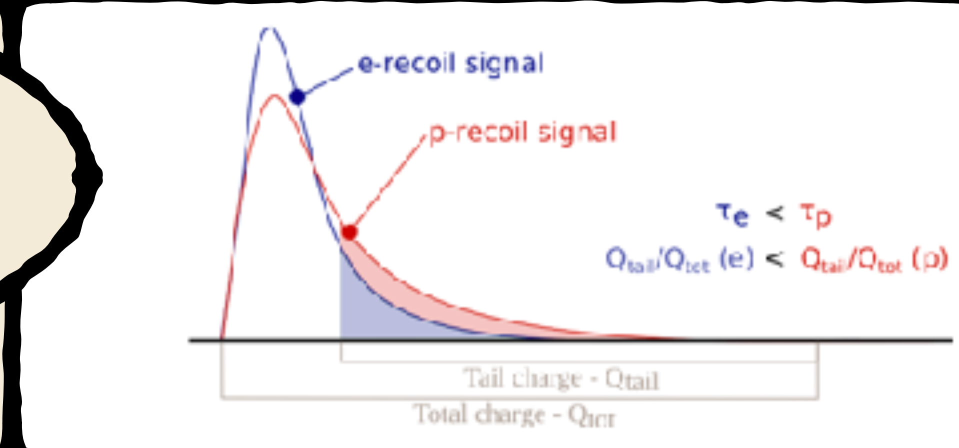
* Data taking started in November 2016
  - 185 days reactor ON
  - 233 days reactor OFF
* Number of ON days ≈ OFF days : important for bkg subtraction
* Data taking planned until end of 2020

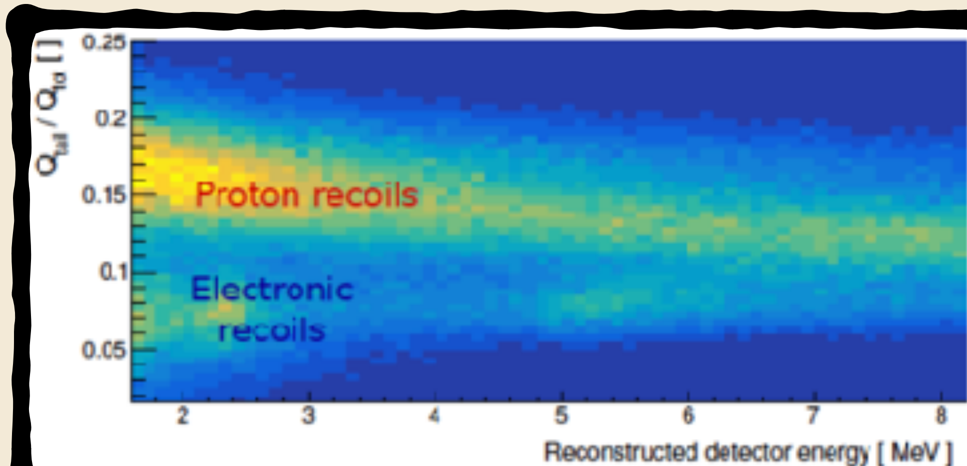


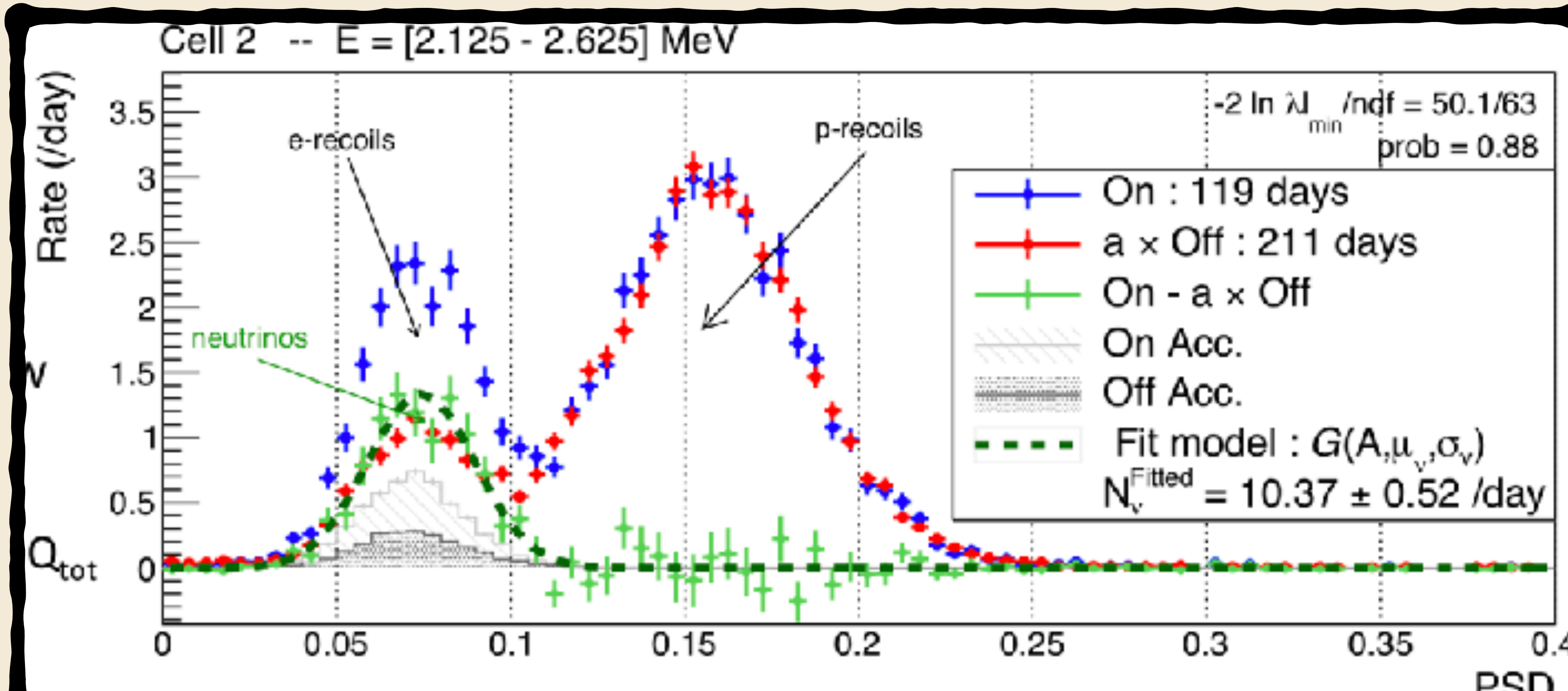


The ally: Pulse Shape Discrimination

* PSD = Qtail/Qtot
* Fit PSD to extract ν from correlated bkg
* Bkg shape from OFF data
* Accidentals from shifted time window



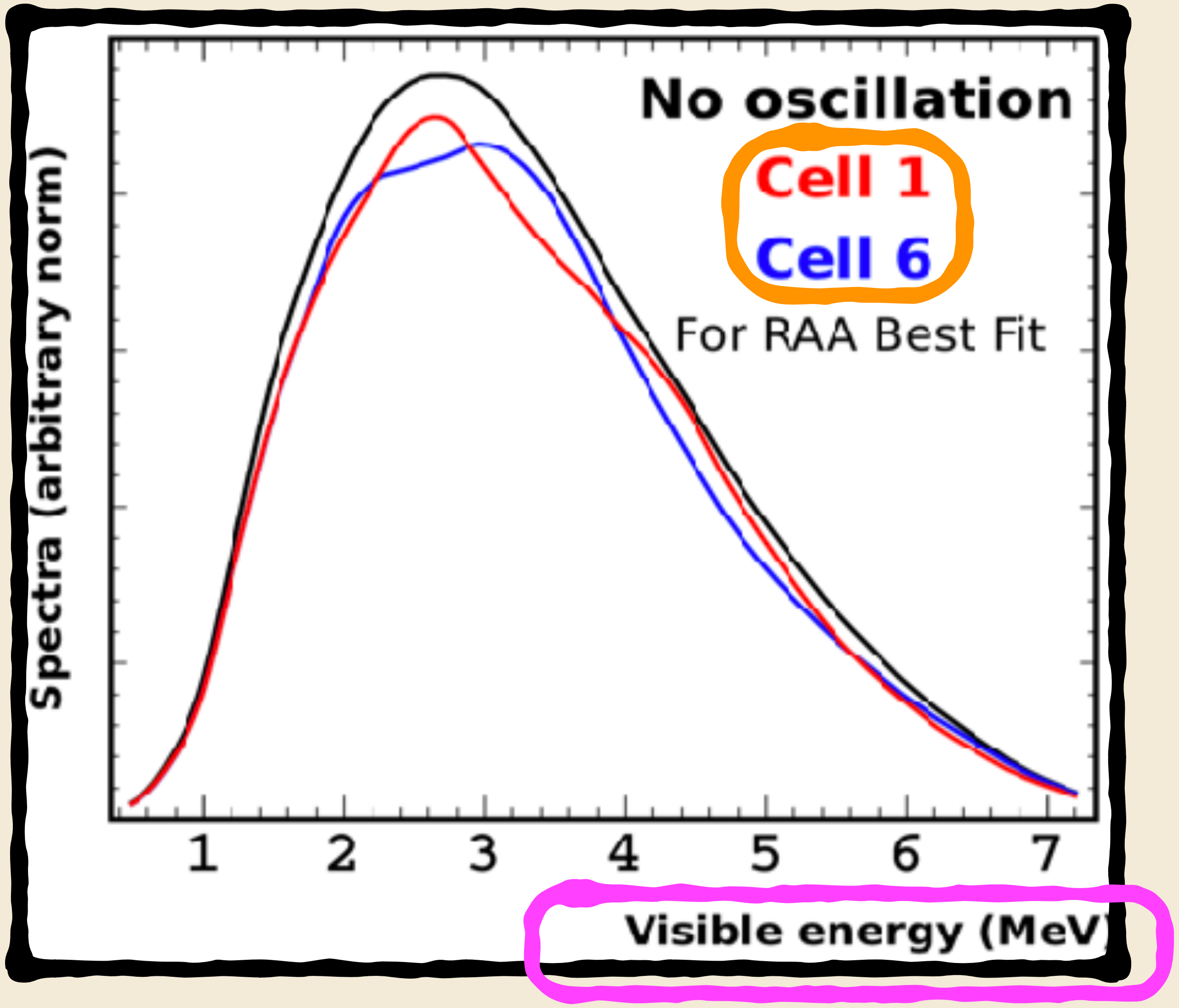




The bad guy's weakness: Oscillation detection

Once more

* Energy spectrum modulation depending on the baseline
* $P(\nu_e \rightarrow \nu_x) = \sin^2(2\theta)\sin^2(1.27\frac{\Delta m^2 L}{E})$
* Small effect $\lessapprox$ 10% so good energy response knowledge is required



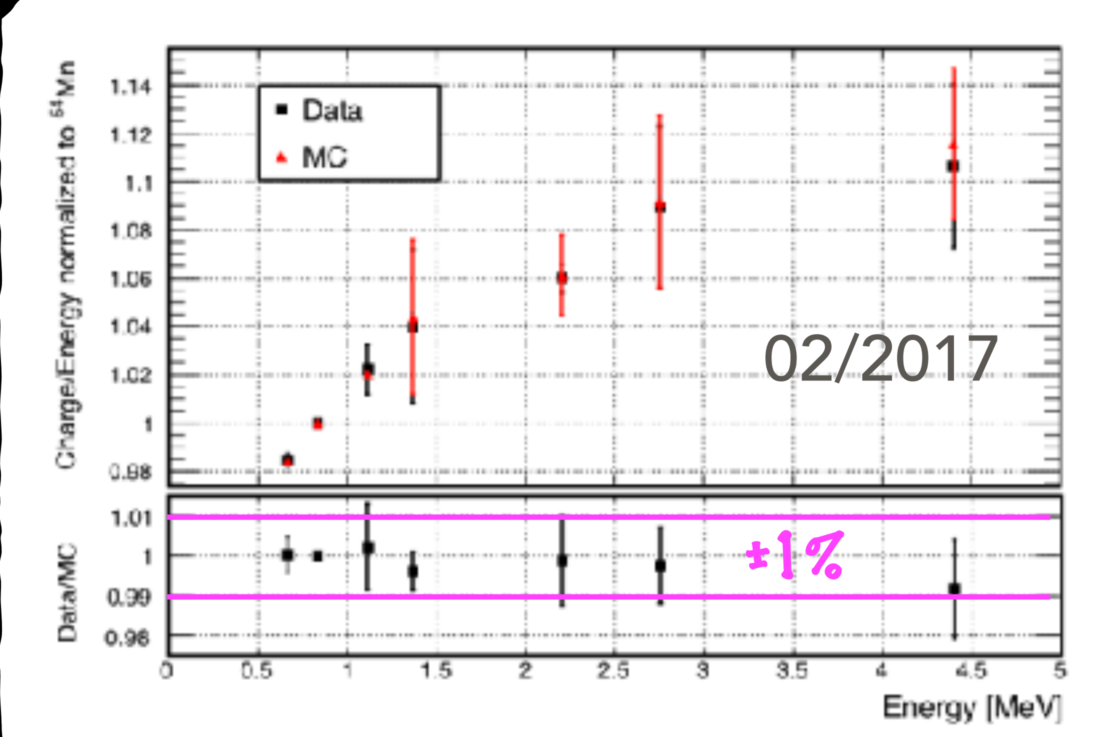
The training : Liquid non-linearity response study

* Liquid scintillator emits scintillation photons
* Number of photons (light yield) is modelled by Birks' law:

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

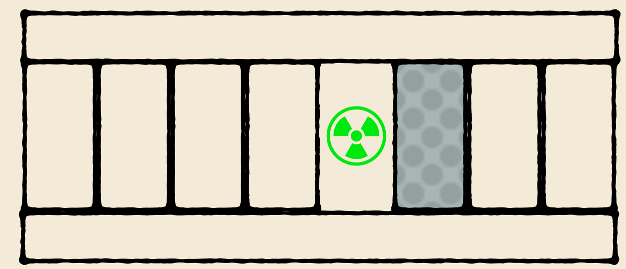
* Low energy particles are more quenched (have a lower light yield by unit of deposited energy)
* Cerenkov light for higher energies
* Goal of new study:
  - better precision
  - time stability

STEREO collab, Phys.Rev.Lett. 121 (2018) no.16, 161801

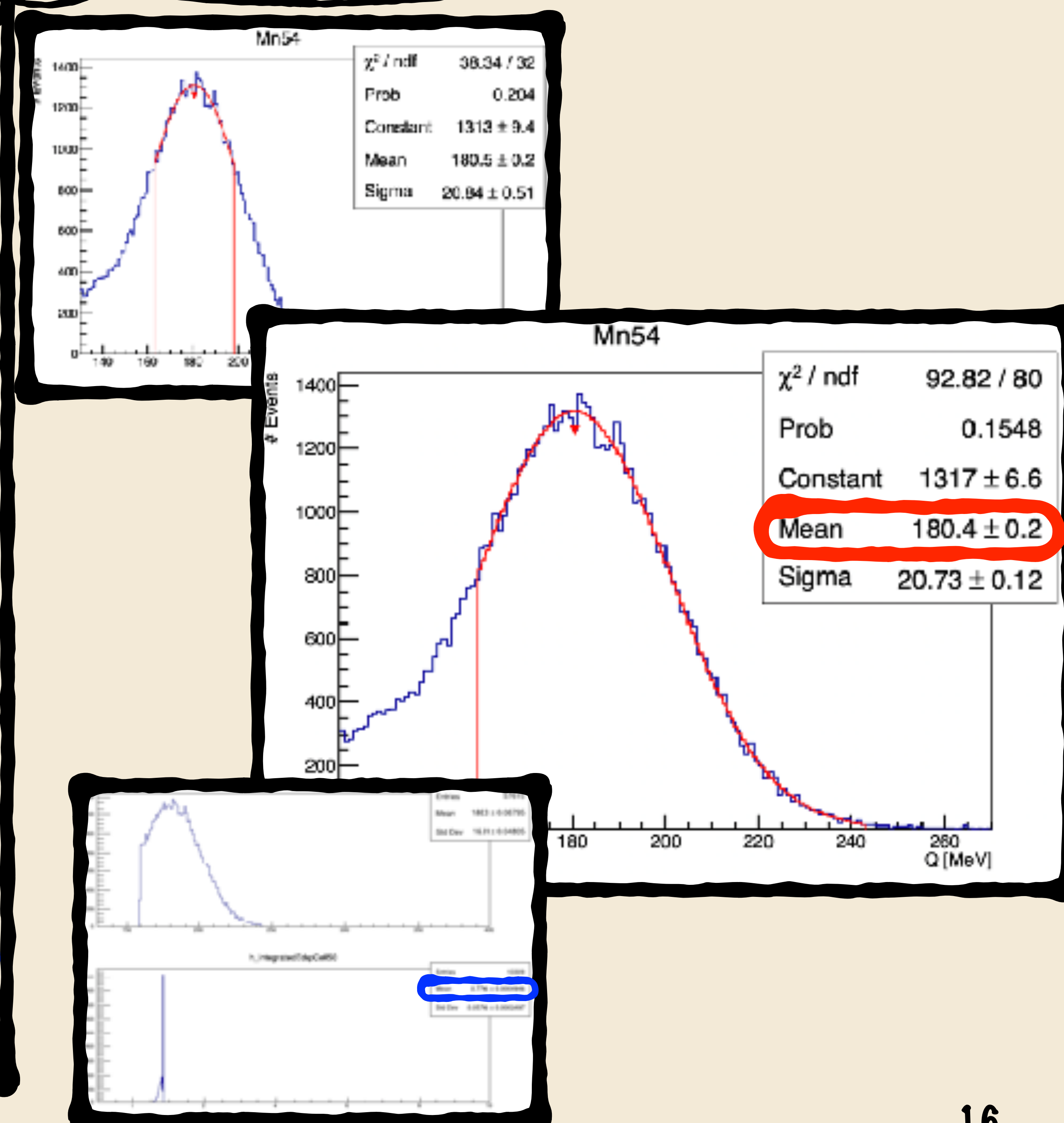


Source	Cs 137	Mn 54	Zn 65	K 42	Na 24	AmBe
gamma Energy [MeV]	0.66	0.83	1.12	1.52	1.37 & 2.75	(2.22) 4.44 + neutron

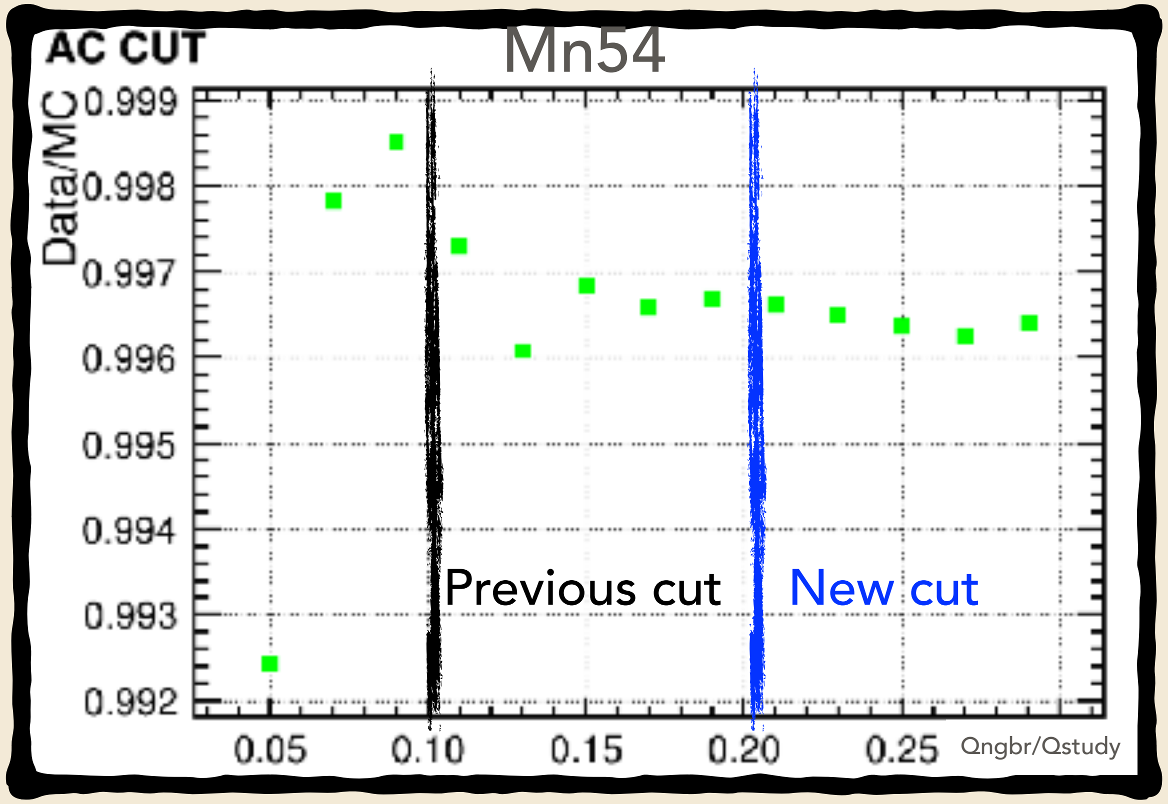
The new skill: Method



- Study cell response with source in the neighbour cell:
  - better gamma separation for multi-gamma source
  - proton recoil mitigation for AmBe source
- Isolation cut : charge in neighbour cells <20% charge in study cell
- 2 fits method:
  - 1st gaussian fit on limited range around max [Qmax±1.3x√Qmax] to avoid bias in the mean due to non-gaussian left tail
  - 2nd gaussian fit on asymmetric range [Qmean-1.5σ ; Qmean+3σ]
- Calibration coefficient CC = Qmean/<Edep>



Mastering the new skill: Method optimisation



* Optimisation of isolation cuts
* Improved fit stability
* Asymmetric fit range optimised to reduce mean charge uncertainty

The radioactive stuff : AmBe source

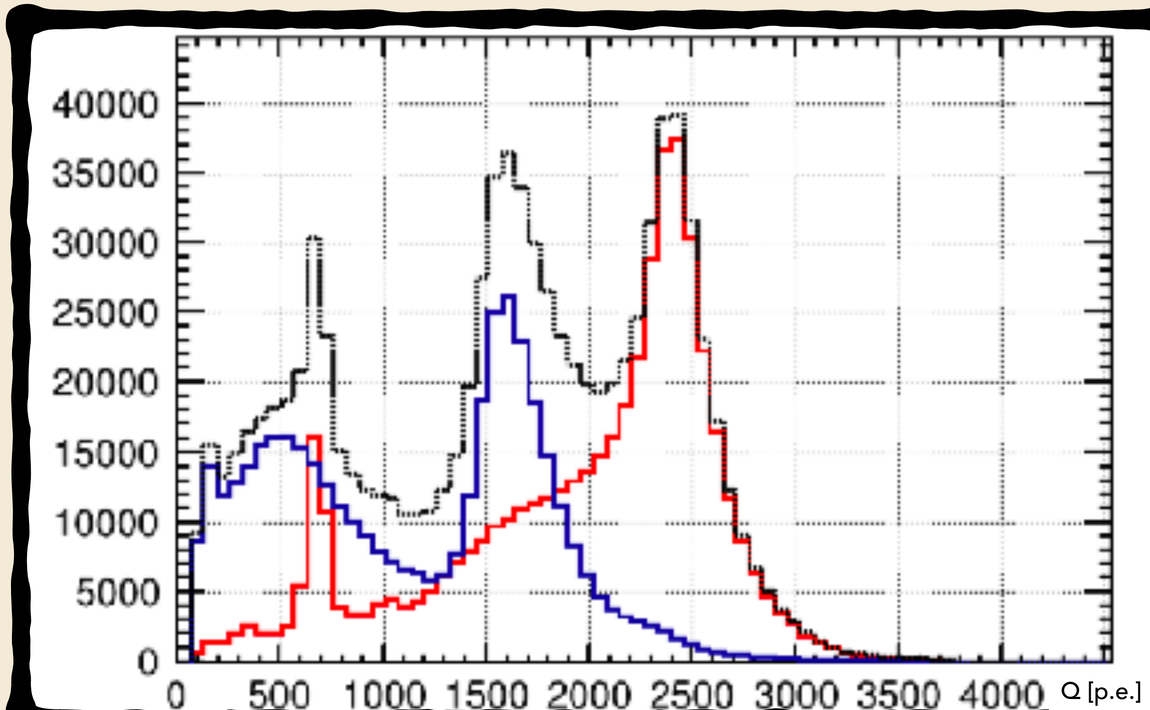
- Only high energy source
- 4.44 MeV gamma and 2-8MeV neutron emitted simultaneously
- Bkg in the 4.44 MeV gamma due to proton recoils of neutron and Gd cascade
- Simple charge selection around 4.44 MeV peak gives >40% of fake events
- Is it possible to reduce the bkg for this source ?

$$^{241}Am \rightarrow ^{237}Np + \alpha$$

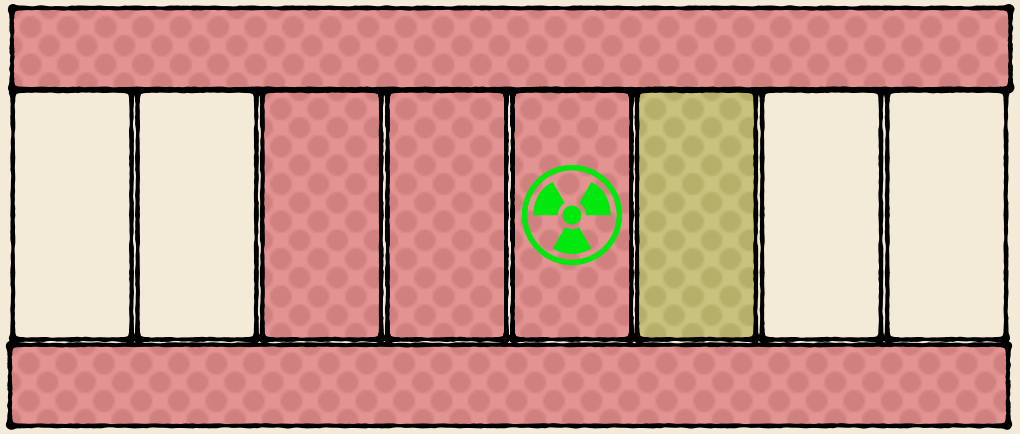
$$\alpha + ^{9}Be \rightarrow ^{13}C^{*}$$

$$^{13}C^{*} \rightarrow ^{12}C^{**} + n$$

$$^{12}C^{**} \rightarrow ^{12}C + \gamma[4.438 MeV]$$



AmBe cleaning strategy

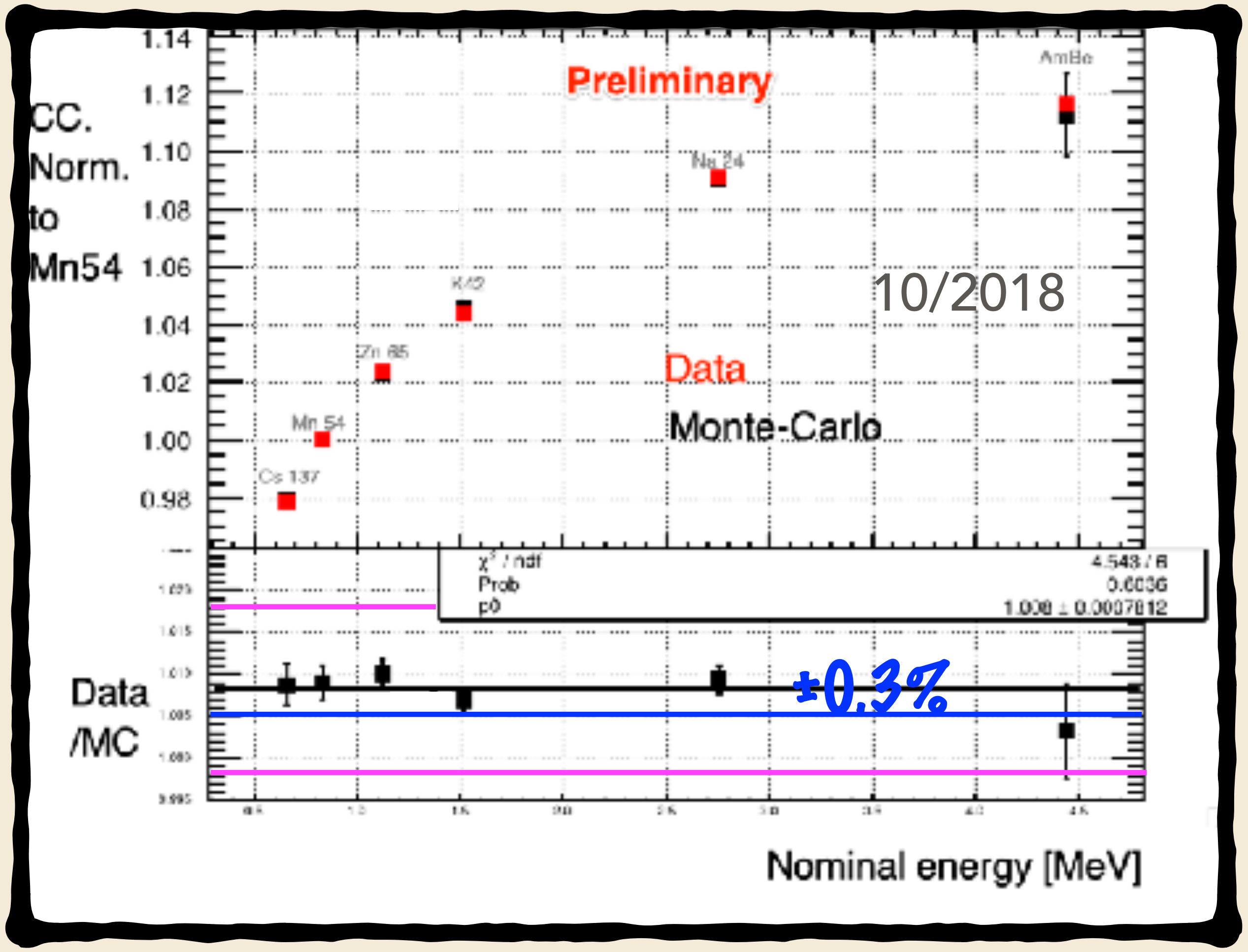


* Time coincidence between gamma in study cell and neutron capture on Gd
* Ask that neutron capture happens as far as possible from study cell
* Fake events proportion reduced from
> 40% to < 2%

	n-Gd events	Proton recoils
Without coincidence	~23%	~15%
With coincidence	~1%	~1%

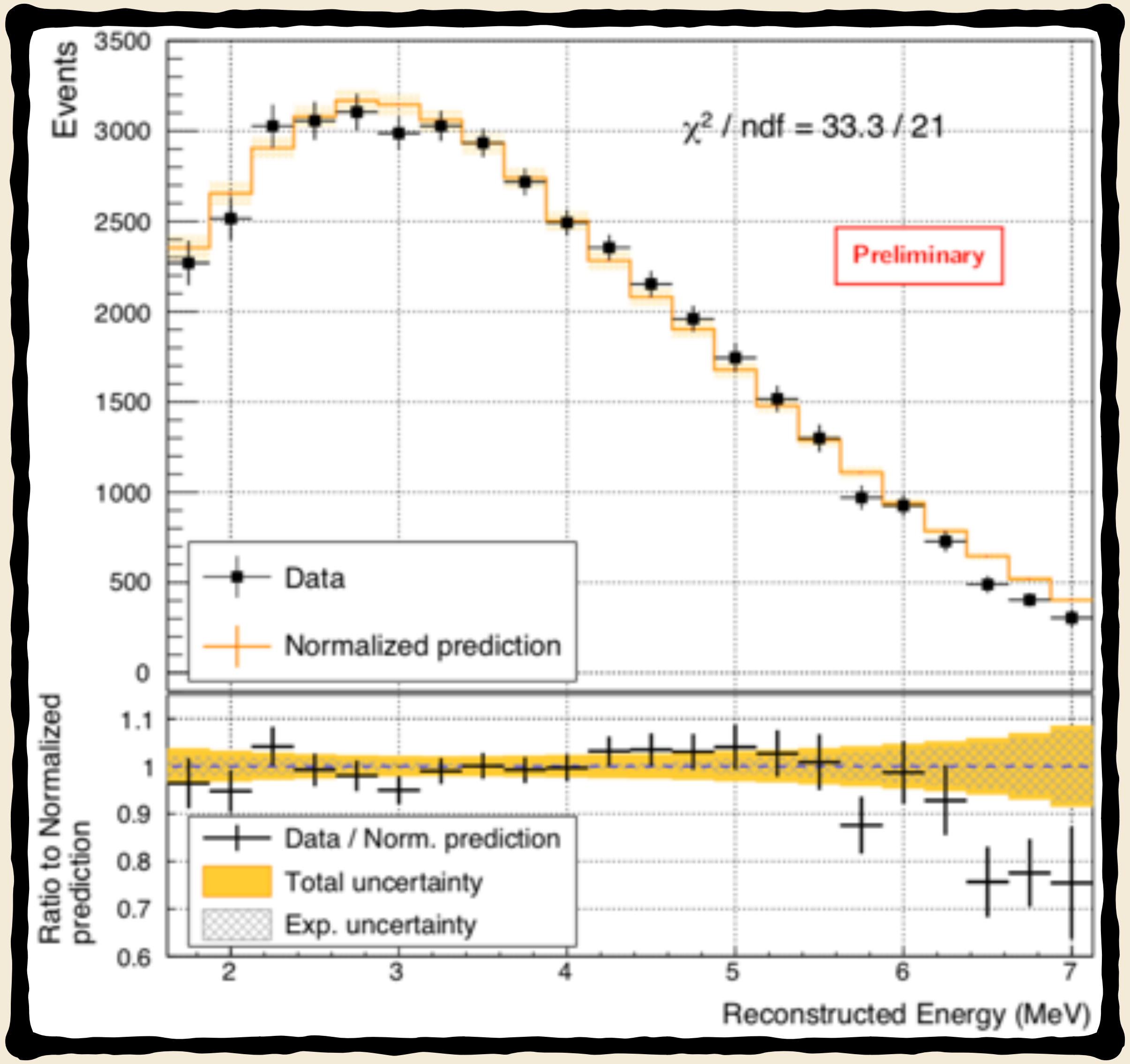
The first victory: Quenching result

* Good Data/MC agreement
* Data from 2018 compatible with data from 2017
* Data/MC dispersion improved to 0.3%



The return from the secret mission: Spectrum shape results

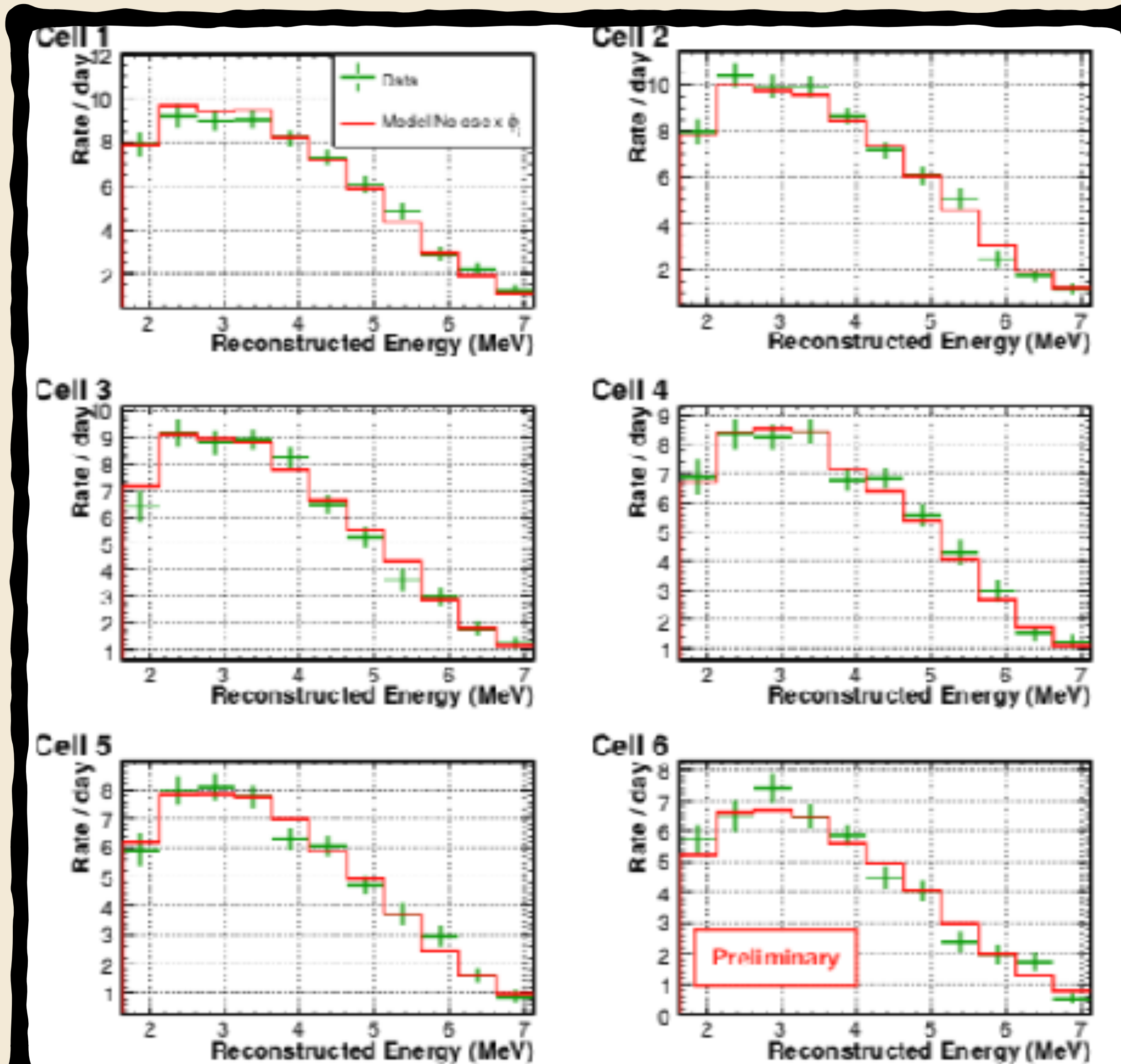
* Measured vs predicted spectrum U-235
* More statistics required to draw conclusion on bump



The final fight: Oscillation analysis formalism

- Only spectrum shape analysis
- Comparison between cells and energy bins independent from prediction
- Each energy bin is scaled by a free parameter common to all cells ϕ_i
- Systematic effects parameterised by nuisance parameters $\vec{\alpha}$
- D = measured spectrum
  M = simulated spectrum

$$\chi^2 = \sum_l^{N_{Cells}} \sum_i^{N_{Ebins}} \left(\frac{D_{l,i} - \phi_i M_{l,i}(\mu, \sigma, \vec{\alpha})}{\sigma_{l,i}} \right)^2 + \sum_l^{N_{Cells}} \left(\frac{\alpha_l^{NormU}}{\sigma_l^{NormU}} \right)^2 + \left(\frac{\alpha_l^{EScaleC}}{\sigma_l^{EScaleC}} \right)^2 + \left(\frac{\alpha_l^{EScaleU}}{\sigma_l^{EScaleU}} \right)^2$$



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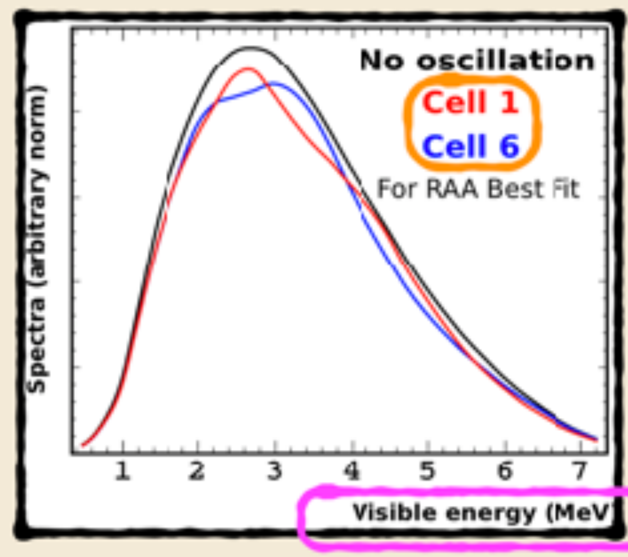
$$\ldots + \left(\frac{\alpha_l^{EScaleU}}{\sigma_l^{EScaleU}} \right)^2$$

* Only ...
* Co...
* pa... parameter...
* D = measured spectrum
  M = simulated spectrum

Once more

The bad guy's weakness: Oscillation detection

* Energy spectrum modulation depending on the baseline
* $P(\nu_e \to \nu_x) = \sin^2(2\theta)\sin^2(1.27\frac{\Delta m^2 L}{E})$
* Small effect $\lesssim$ 10% so good energy response knowledge is required



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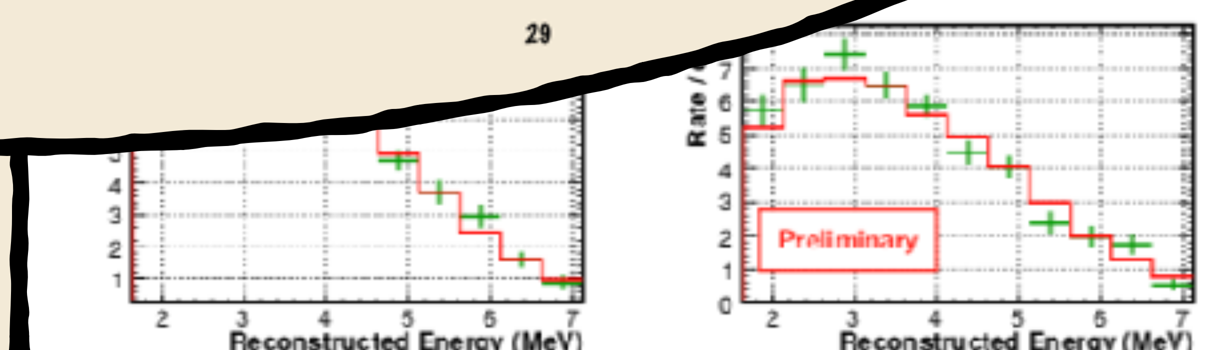

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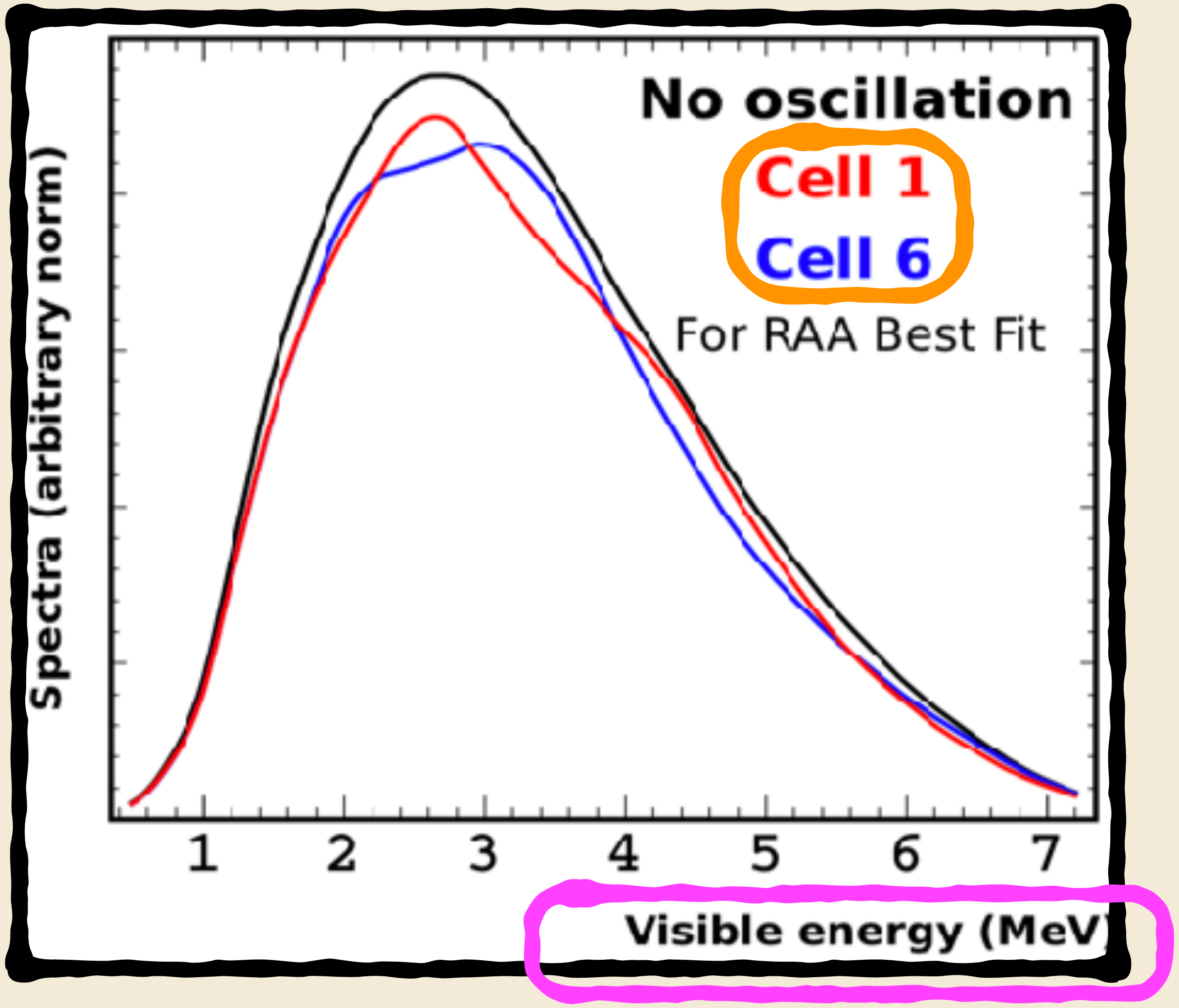

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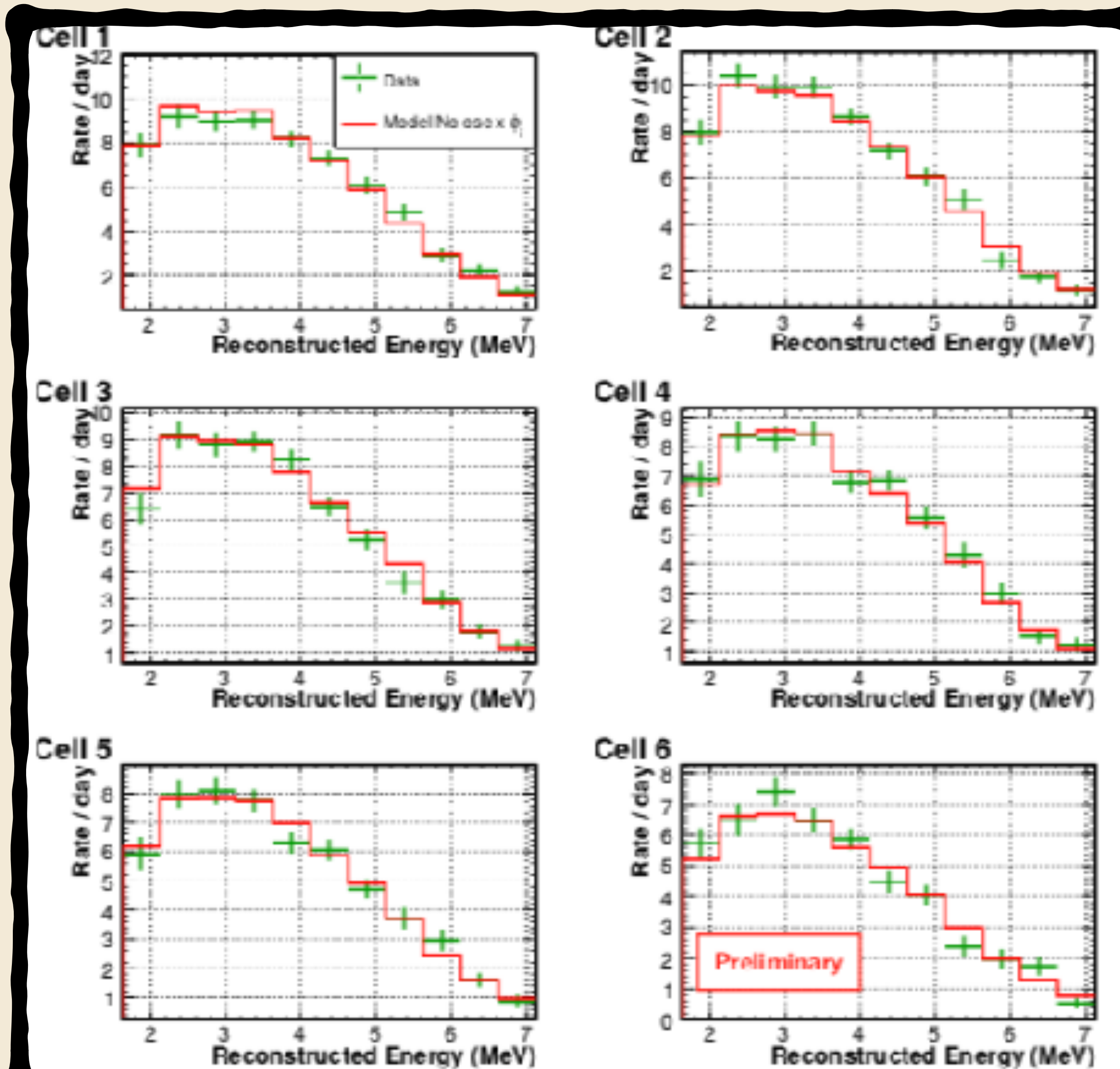
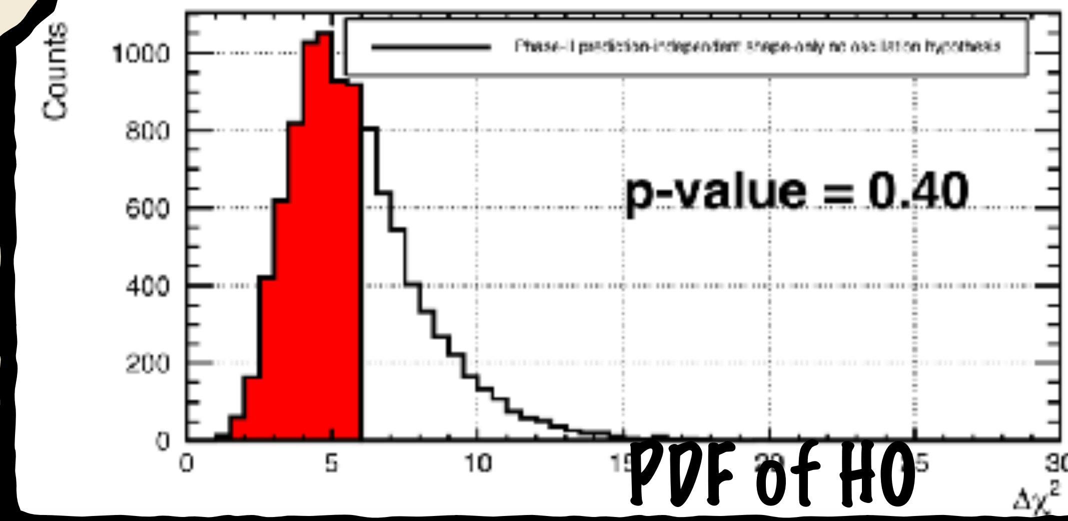
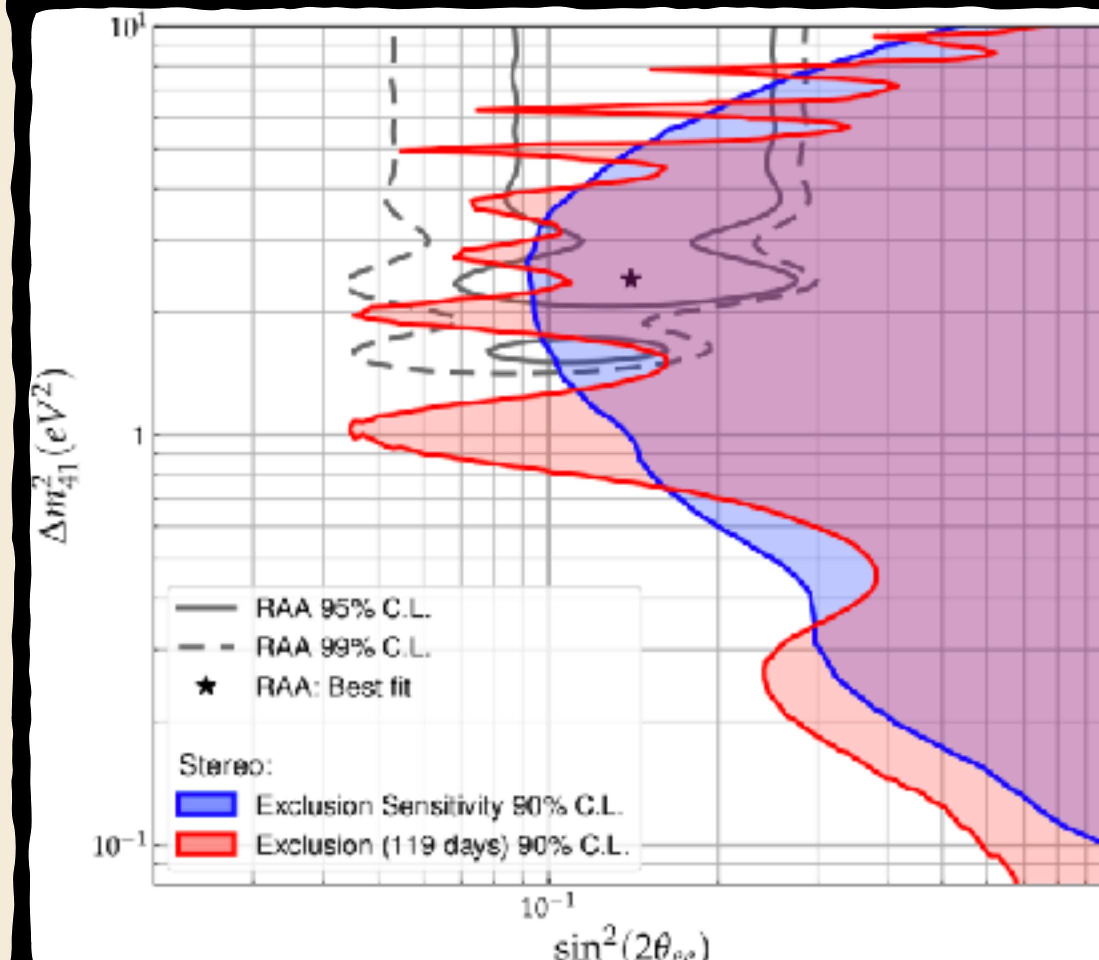


Oscillation analysis results

* $\Delta\chi^2 = \chi^2(\theta_{H0}, \Delta m^2_{H0}, \hat{\vec{\alpha}}) - \chi^2(\hat{\theta}, \Delta\hat{m}^2, \hat{\vec{\alpha}})$
* PDF of H0 generated over many pseudo-experiments
* Discovery test:
  null hypothesis H0 (non oscillation) not rejected
* So limit on signal:
  Exclusion contour
* Best-fit value of the RAA rejected at >99% confidence level





* Good chunk of RAA parameter space excluded... but bad guy not completely defeated yet
* At the end of 2020 STEREO should have enough stats to exclude the remaining favoured island in the oscillation parameter space
* And more stats to draw a conclusion about 5 MeV bump

To be continued ...

Thank you
for your attention

The crazy doctors

Back up

2 flavours case

- Take mass eigenstates as plane waves:

$$|\nu_1(t)> = |\nu_1> e^{i(\overrightarrow{p_1}\cdot\overrightarrow{x} - E_1 \cdot t)} = |\nu_1> e^{-i\mathbf{p_1 x}}$$

$$|\nu_2(t)> = |\nu_2> e^{-i\mathbf{p_2 x}}$$

- We can link mass eigenstates and interaction eigenstates by a 2x2 unitary matrix

$$\begin{pmatrix}\nu_e \\ \nu_x\end{pmatrix} = \begin{bmatrix}\cos(\theta) & \sin(\theta) \\ -sin(\theta) & \cos(\theta)\end{bmatrix}\begin{pmatrix}\nu_1 \\ \nu_2\end{pmatrix}$$

* At t=0 electronic neutrino produced:

$$|\nu(t=0)> = |\nu_e> = \cos(\theta)|\nu_1> + \sin(\theta)|\nu_2>$$

$$|\nu(t)> = \cos(\theta)|\nu_1> e^{-i\mathbf{p_1 x}} + \sin(\theta)|\nu_2> e^{-i\mathbf{p_2 x}}$$

* At a time-space point $\mathbf{x} = \begin{pmatrix} T \\ \overrightarrow{L} \end{pmatrix}$ so

$$\mathbf{px} = ET - \overrightarrow{p}\overrightarrow{L} = \phi$$

* And inverting previous relation:

$$\begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} = \begin{bmatrix} \cos(\theta) & -\sin(\theta) \\ sin(\theta) & \cos(\theta) \end{bmatrix} \begin{pmatrix} \nu_e \\ \nu_x \end{pmatrix}$$

$$|\nu(t)>=\cos(\theta)(\cos(\theta)|\nu_e>-\sin(\theta)|\nu_x>)e^{-i\phi_1}+\sin(\theta)(\sin(\theta)|\nu_e>+\cos(\theta)|\nu_x>)e^{-i\phi_2}$$

$$|\nu(t)>=e^{-i\phi_1}\left[(\cos^2(\theta)+e^{-i\Delta\phi}\sin^2(\theta))|\nu_e>-(1-e^{-i\Delta\phi})\cos(\theta)\sin(\theta)|\nu_x>\right]$$

$$|\nu(t)>=c_e|\nu_e>+c_x|\nu_x>$$

- **Finally :** $P(\nu_e\rightarrow\nu_x)=c_xc_x^*=(1-e^{i\Delta\phi})(1-e^{-i\Delta\phi})\cos^2(\theta)\sin^2(\theta)$

$$P(\nu_e\rightarrow\nu_x)=sin^2(2\theta)sin^2(\frac{\Delta\phi}{2})$$

- **Assuming momentum of the 2 mass eigenstates is equal:** $\vec{p_1}=\vec{p_2}=\vec{p}$

$$\Delta\phi=(E_1-E_2)T=p\left[(1+\frac{m_1^2}{p^2})^{\frac{1}{2}}-(1+\frac{m_2^2}{p^2})^{\frac{1}{2}}\right]$$

- **Since m<<E** $\Delta\phi\approx\frac{m_1^2-m_2^2}{2E}L$

$$P(\nu_e\rightarrow\nu_x)=\sin^2(2\theta)sin^2(1.27\frac{\Delta m^2[eV^2]L[m]}{E[MeV]})$$