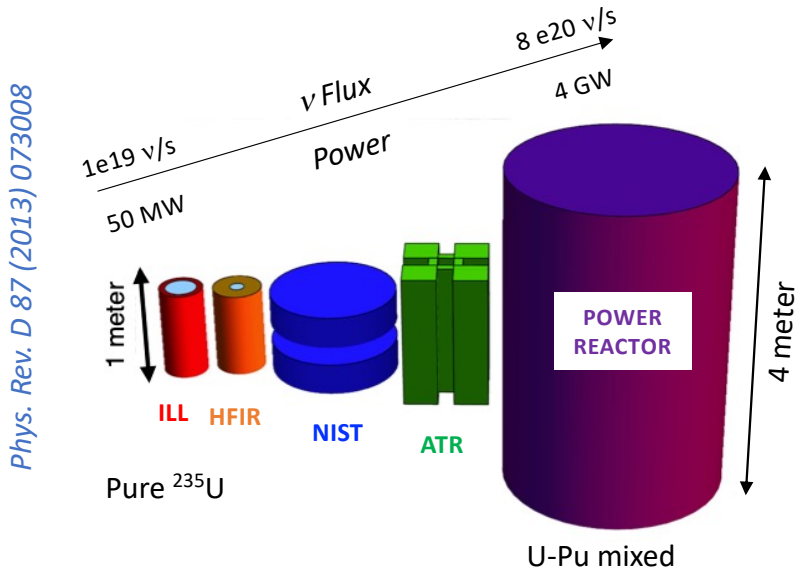
Which of the ν_e or the 1 eV sterile ν hypothesis disappears? A status of short-baseline measurements of compact $\overset{(-)}{\nu}_e$ sources and their tentative interpretation

IRN Neutrino meeting
Paris, Nov-Dec 2021

David Lhuillier
CEA - Saclay

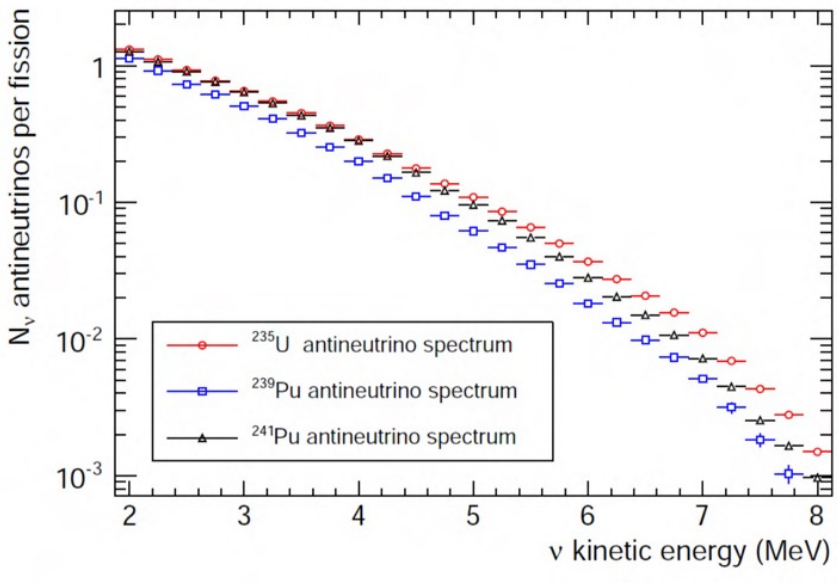
Compact Sources - Reactors

n-rich fission products (FP) undergo β^- decays
→ **pure $\overline{\nu}_e$ source**



Most intense man-controlled ν source
→ High stat for precision measurements

Phys. Rev. C, 83:054615, 2011



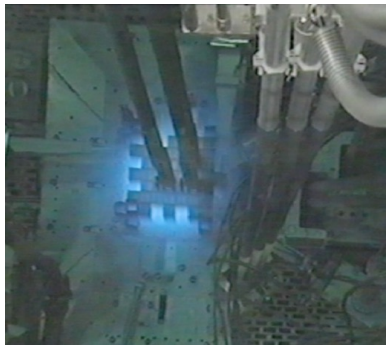
Complex predictions of ν fission spectra:

- 100's of contributing FPs with time evolving β^- activity.
- Complementary "conversion" and "summation" methods.

→ Sub-10% accuracy is challenging

Compact Sources – ^{51}Cr (and ^{37}Ar)

Irradiation of ^{50}Cr-enriched samples in reactor n flux



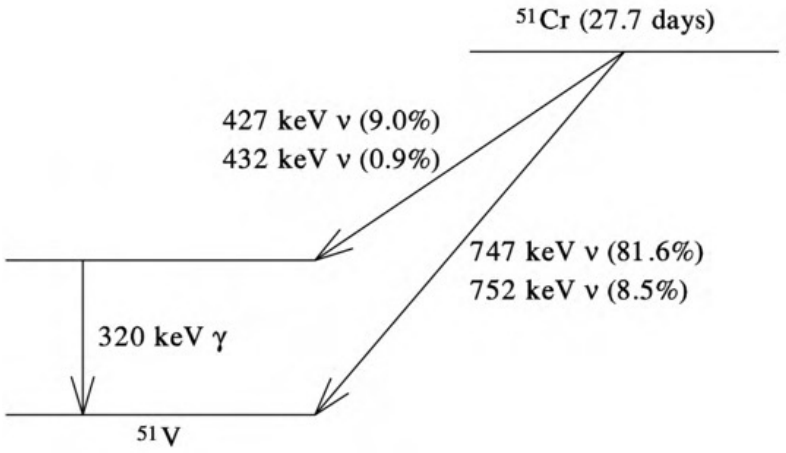
Courtesy of M. Cribier

62 PBq compact source!

Pure ν_e source from electron conversion

$^{51}Cr + e^- \rightarrow {}^{51}V + \nu_e$

$T_{1/2} = 27.7$ d



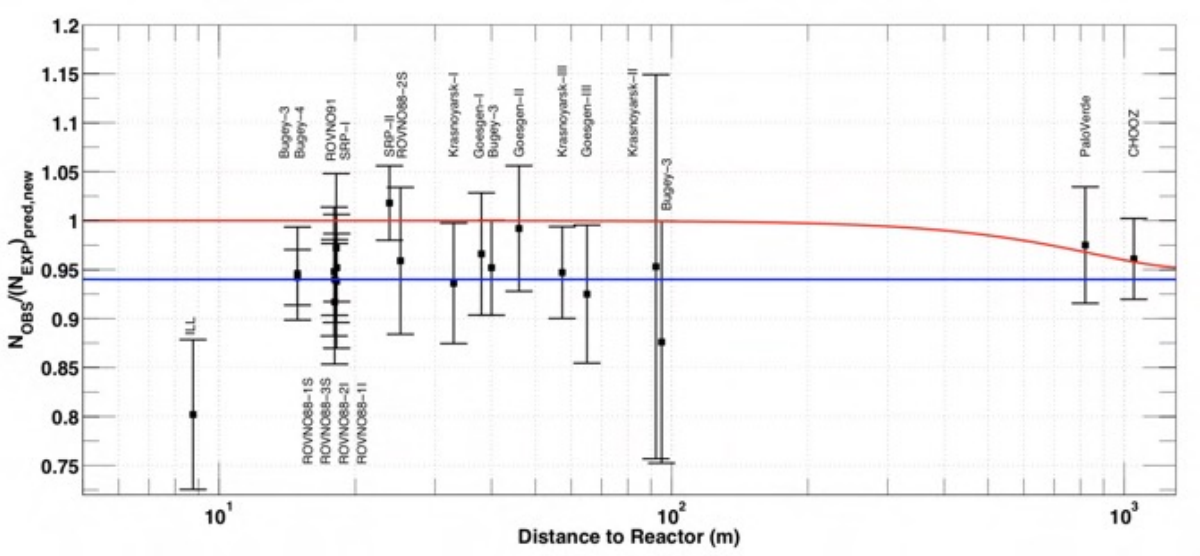
Lower rate than reactors but well controlled neutrino spectrum, meant to calibrate GALLEX and SAGE experiments:

- Conversion lines
- Accurate measurements of the activity

Steady improvement of the precision of neutrino measurements leads to anomalies when comparing with predictions…

Anomalies – Rate deficit

Phys. Rev. D 83 (2011) 073006

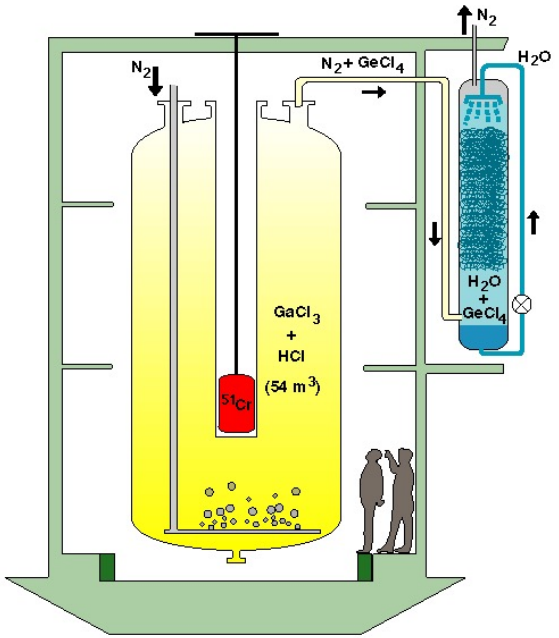


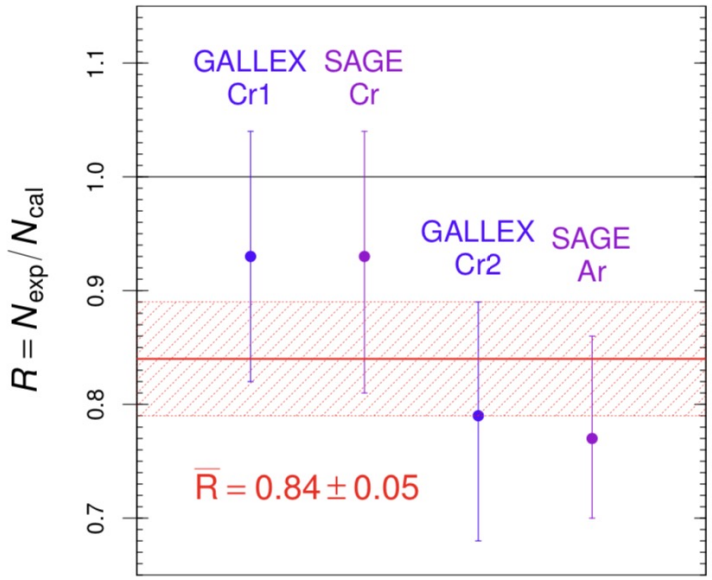
- Correction of approximations in the conversion of fission β-spectra measured at ILL.
  +
- Accumulation of long-lived isotopes (off-equilibrium effect)
  +
- Update of neutron life time

→ **~6% deficit w.r.t. prediction**

Anomalies – Rate deficit

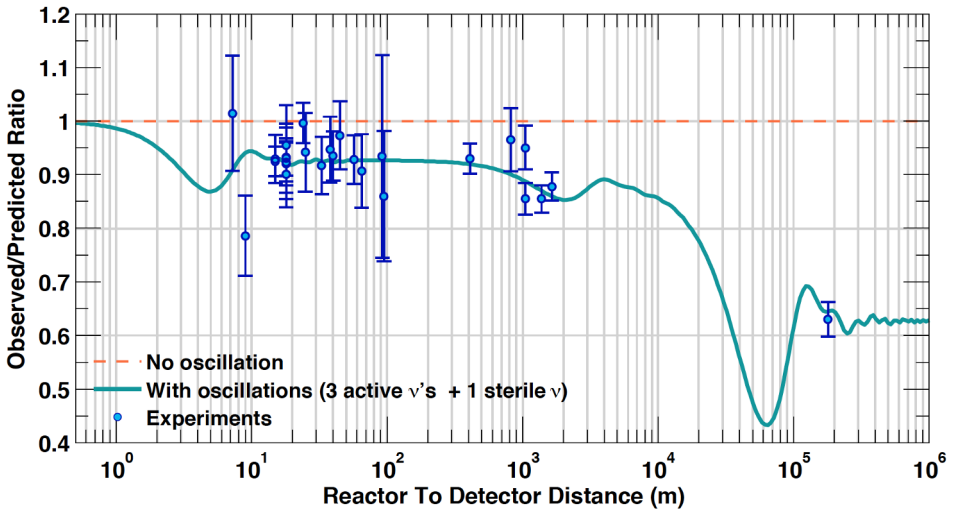
- Gallex and Sage experiments: low threshold measurements of the ν_e solar flux via $\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$
- MCi ν_e sources used to calibrate the response of the detector led to a deficit of measured events w.r.t. prediction…





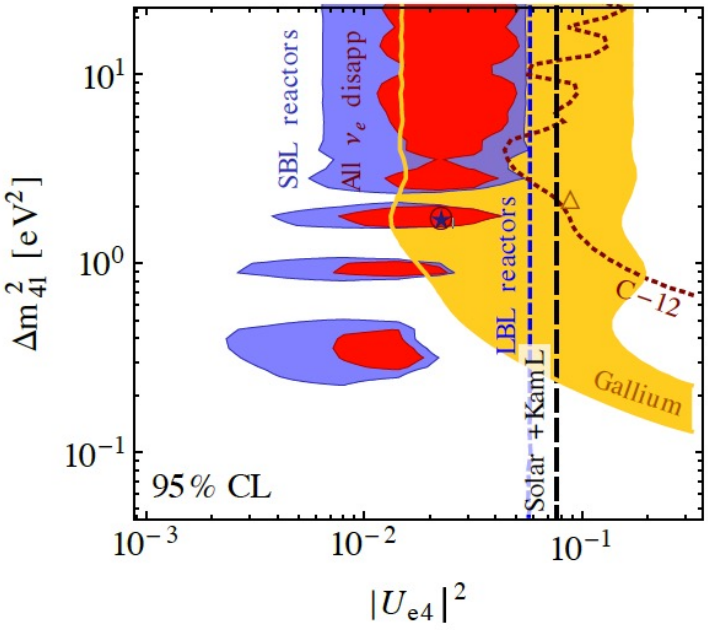
Sterile ν hypothesis

- Disappearance channel: $P_{\overline{\nu}_e \to \overline{\nu}_e} = 1 - \sin^2(2\theta_{ee}) \sin^2(\Delta m^2 L / 4E)$
- Rate only anomalies → high Δm^2 (≥1 eV^2)
  → meter scale oscillation length for MeV neutrinos



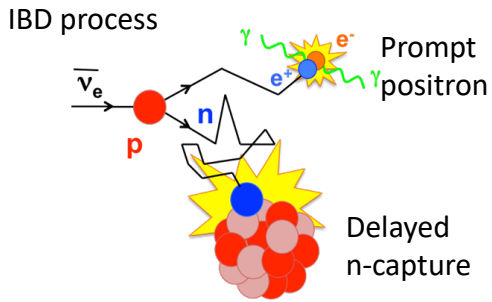
- Compatibility of the gallium and reactor anomalies in the ν_e disappearance sector.

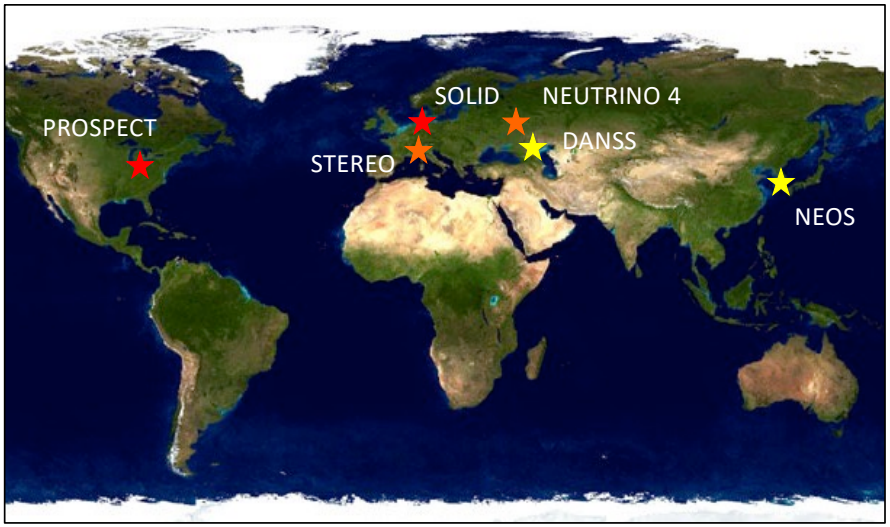
JHEP 1305 (2013) 050



Worldwide program @ reactors

Look for oscillation patterns at very short baselines in a model independent way using relative variation in E and L bins.





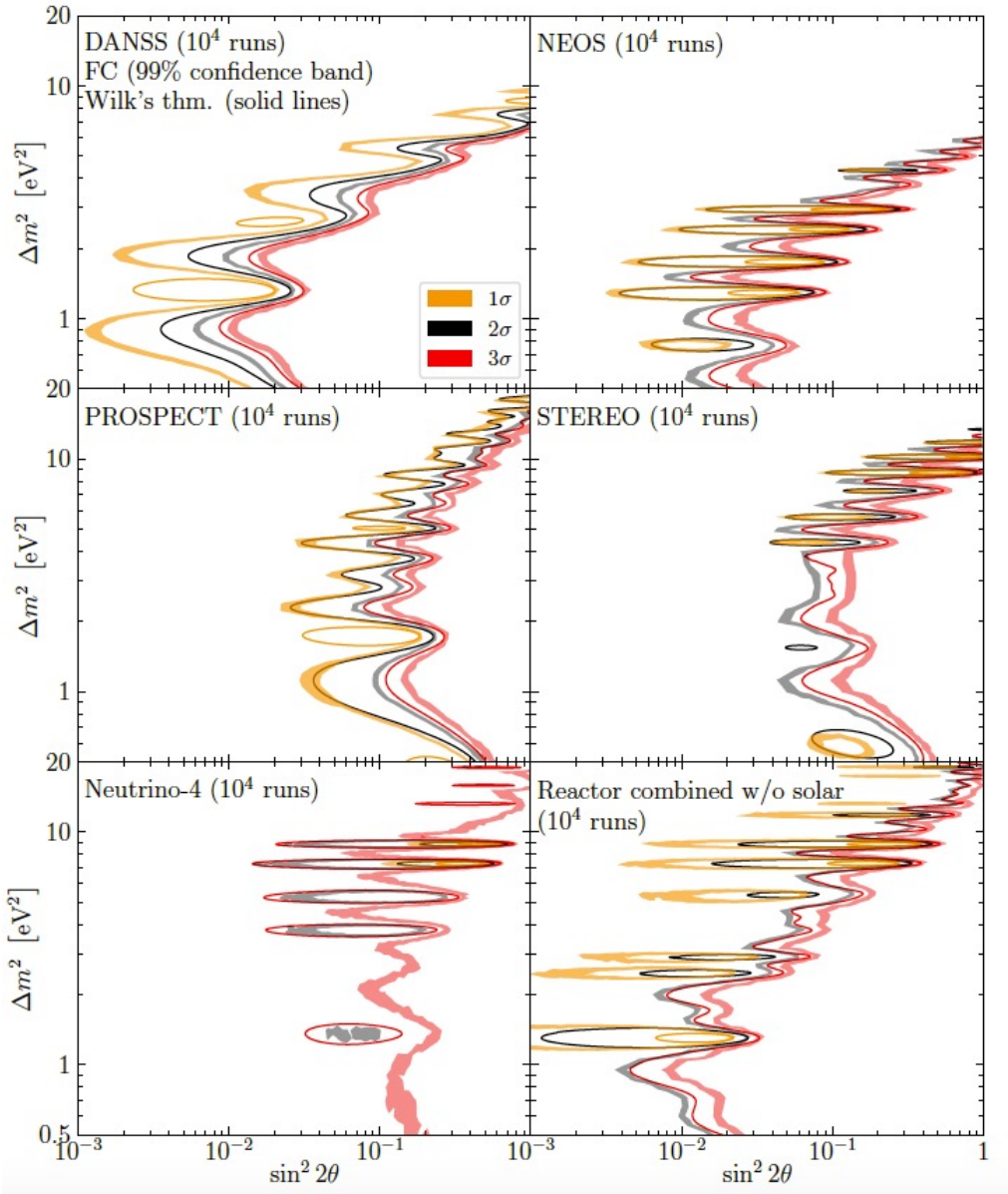
Experiment	Relative Measurement	Prompt Discrimination	Delayed Discrimination	Reactor	S/B
DANSS	Movable	-	Gd in plastic	Power	20
PROSPECT	Segmented	PSD in LS	Li in LS	Research	1
STEREO (see Loic's talk)	Segmented	PSD in LS	Gd in LS	Research	0.9
NEOS	DB/RENO ref. spectrum	-	Gd in LS	Power	20
Neutrino4	Movable + segmented	-	Gd in LS	Research	0.5
SoLid (see Noë's talk)	Segmented	Annihilation γ-tracks	Li in plastic	Research	0.3

- Power reactor : high stat, high S/B, but reduced sensitivity to large Δm^2 due to core size, U-Pu mix.
- Research reactor : compact core, pure ^{235}U spectrum but large cosmic background.

Oscillations Contours

arXiv:2111.12530 [hep-ph]

- Global analysis of all short baseline reactor data.
- All data made available by the experiments allow a full Feldman-Cousins approach (color bands).
- Significant impact as it reduces the significance by about 1 σ with respect to a naïve application of the Wilks' theorem (color lines).
- No single experiment favors a sterile oscillation at more than 2.4 σ (NEOS, Neutrino4).
- **Combined reactor data are compatible with no sterile neutrino oscillation at 1.1 σ.**

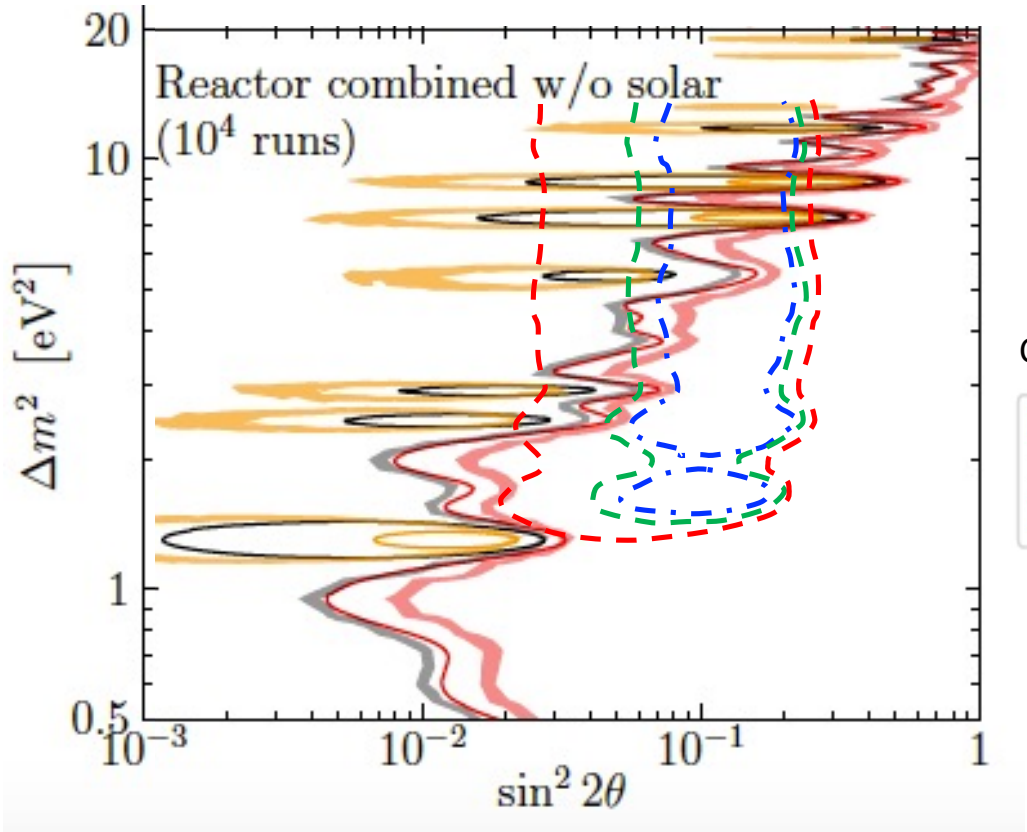


Oscillations Contours

- The sterile neutrino hypothesis is rejected with high C.L. for $\Delta m^2 \leq 4\ eV^2$
- High mass sector severely constrained by cosmology in the framework of the ΛCDM model
- Upcoming KATRIN data will put direct constraint complementary to the reactor sensitivity.

1 eV sterile ν's stock price is down…

arXiv:2111.12530 [hep-ph]



Initial RAA contours

- 90 % C.L.
- 95 % C.L.
- 99 % C.L.

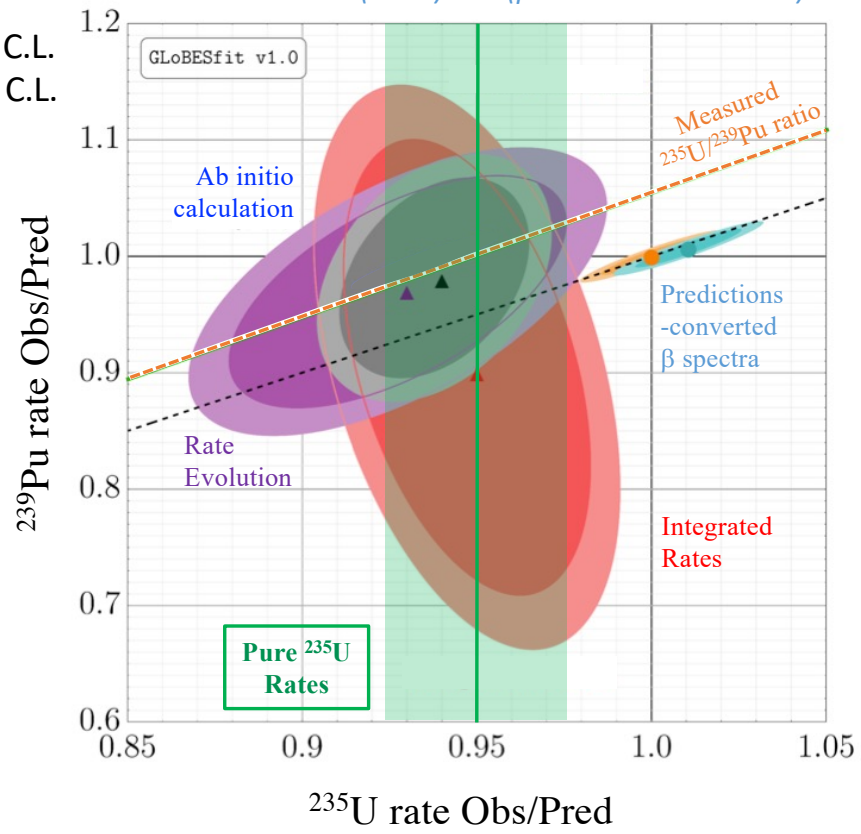
Combined reactor

- 1σ
- 2σ
- 3σ

Alternative hypothesis: norm bias in the predicted ν fission spectra

JHEP 01 (2021) 167 (pure ^{235}U band added)

Dark: 95% C.L.
Light: 99% C.L.



All integrated rates with various mean fuel compositions

DB and RENO separation of U and Pu contributions

All combined

Subset of pure ^{235}U integrated rates

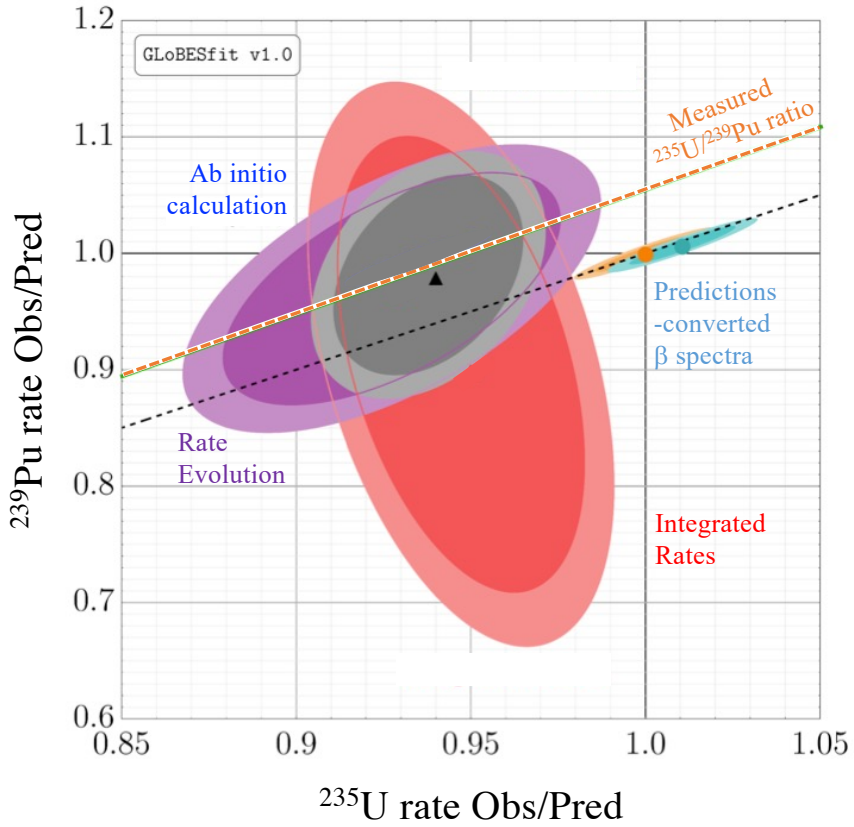
Ratio of rates 235U/239Pu measured 5% lower than HM (with % level uncertainty?) *Phys. Rev. D 104 (2021) 7, L071301*

HM predictions and Equal relative variations of U&Pu rates from there.

Alternative hypothesis: norm bias in the predicted ν fission spectra

JHEP 01 (2021) 167

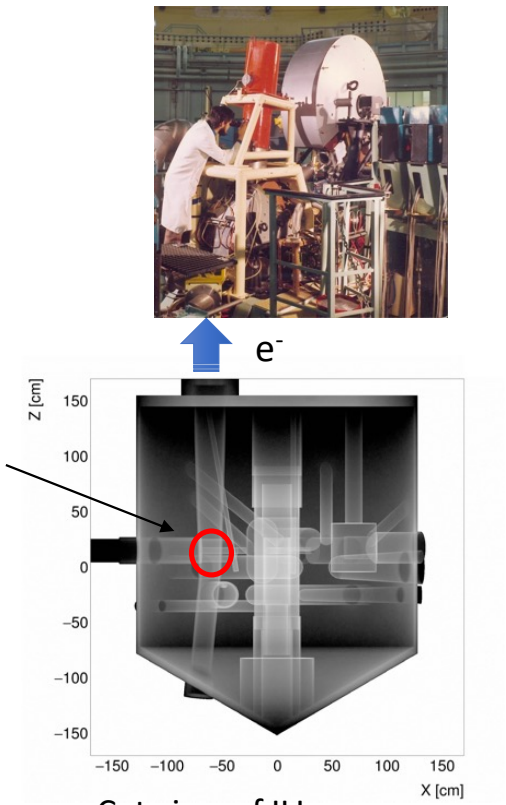
Dark: 95% C.L.
Light: 99% C.L.



- Impressive convergence of results: the RAA is driven by a ~6% deficit of ^{235}U and no deficit of ^{239}Pu
- Reject further the sterile mixing hypothesis
- Possible norm bias in the reference ILL spectra?

Converted ν Spectra

Target foil of fissile element ^{235}U , ^{239}Pu , ^{241}Pu exposed to the flux of thermal neutrons

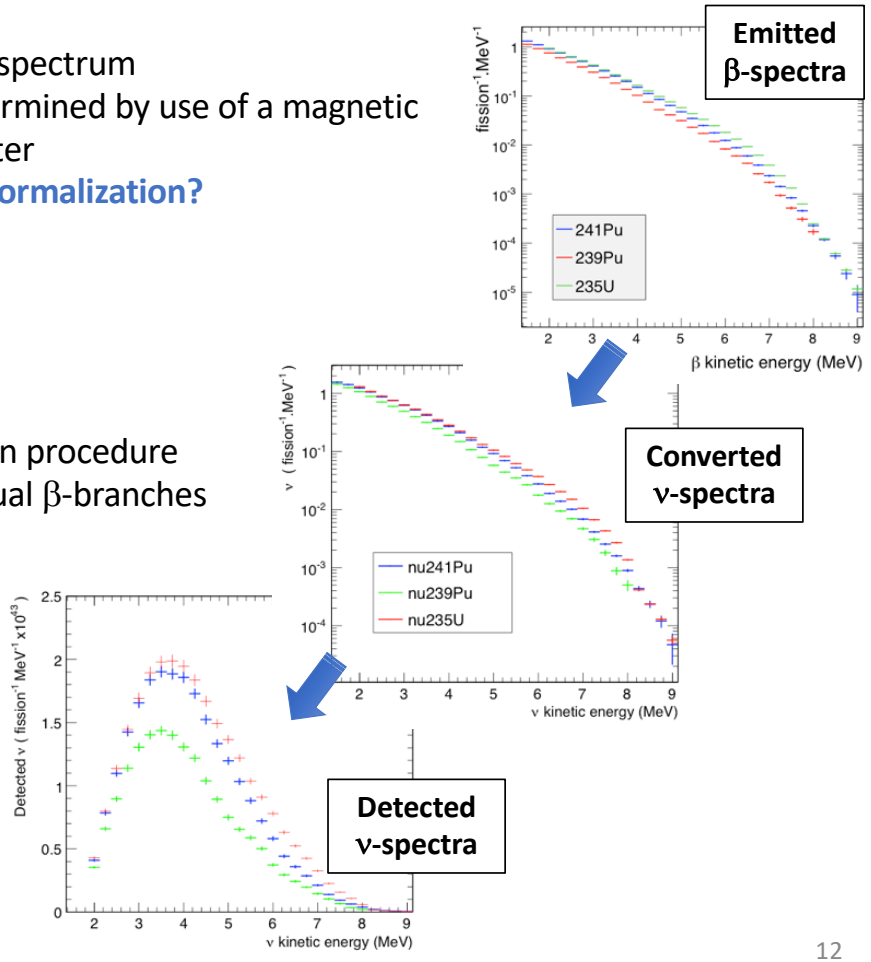


Cut view of ILL core
(courtesy of A. Onillon)

Total fission β-spectrum

- Shape determined by use of a magnetic spectrometer
- **Absolute normalization?**

Conversion procedure using virtual β-branches



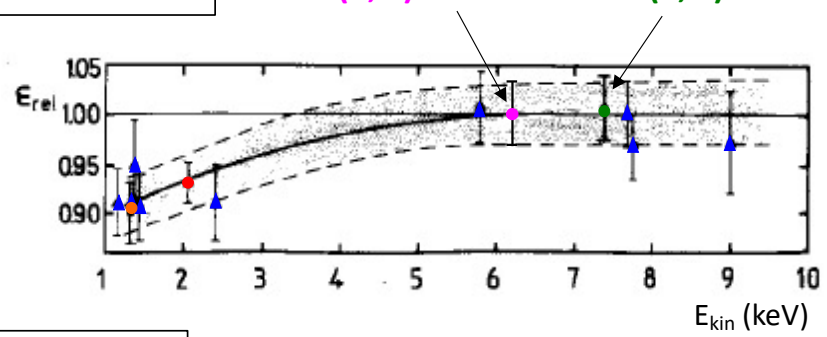
Normalization of the ILL Data

Required knowledge of thermal neutron flux on target is replaced by the measurement of the electron rate from a reference e-conversion line:

$$N_{\beta/fission} = \frac{Rate_{fission}}{\sigma_{fission} \times n_{fission}^{target}} \times \frac{1}{\Phi_n} = \frac{Rate_{fission}}{\sigma_{fission} \times n_{fission}^{target}} \times \frac{\sigma_{calib} \times n_{calib}^{target}}{Rate_{calib}}$$

Absolute calibrations:

^{197}Au(n,e$^-$)^{198}Au ^{207}Pb(n,e$^-$)^{208}Pb



Relative calibrations: ^{115}In and ^{113}Cd targets

- **^{235}U was calibrated with Pb, ^{239}Pu with Au line**

→ **Norm uncertainties of ^{235}U and ^{239}Pu are independent!**

- Ongoing review of all related nuclear data, reduced significance of the RAA expected.
  A. Onillon et al., https://arxiv.org/pdf/1911.06834.pdf

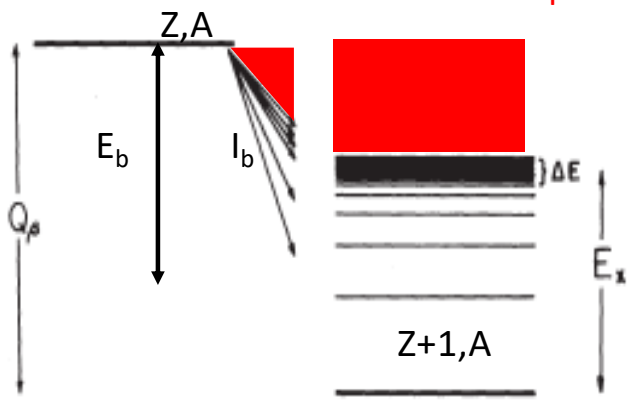
- Direct neutrino measurements are becoming more accurate than nuclear data…

Summation Models

Pandemonium effect: underestimated contribution of low end point transitions

Compute the weighted sum of all β-branches from all fission products:

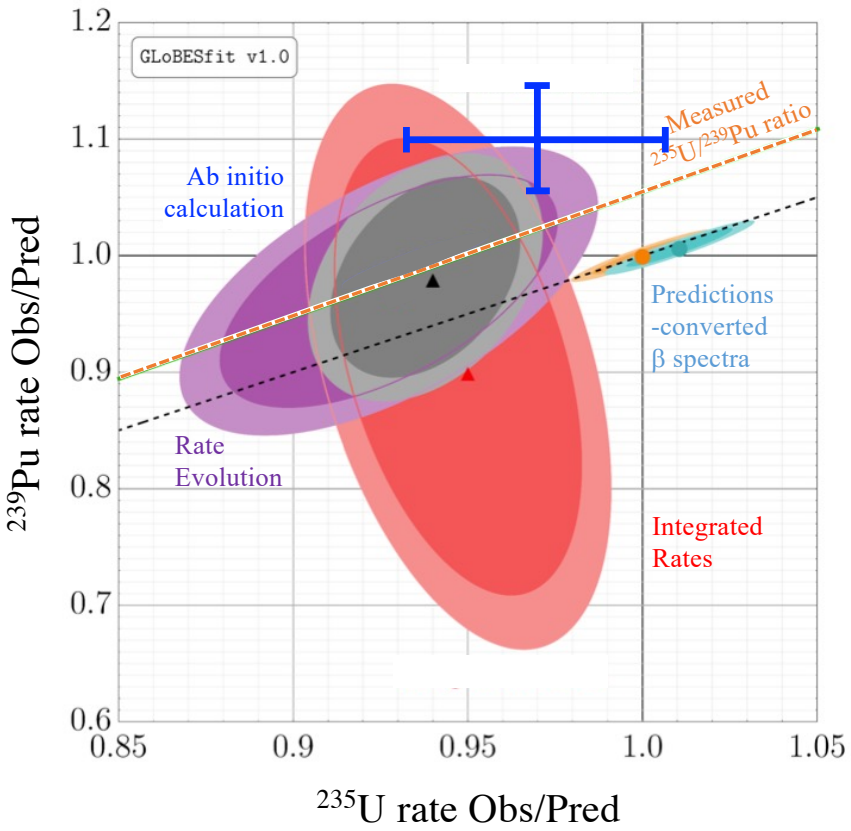
$$S_f(E,t) = \sum_f A_f(t) \sum_b I_b \times S_f^b(E)$$



- $A_f(t)$ from reactor simulations or cumulative fission yield for long irradiation time
- $S_f^b(E)$ from nuclear databases + models for poorly known nuclei (high E part of the spectrum)
- I_b is biased by the "pandemonium effect" in most nuclear databases. Program of TAGS (Total Absorption Gamma Spectrometer) measurements to correct this.
- Steady improvement of nuclear data make this approach more and more accurate. Estimation of uncertainties remain challenging.

Summation Models

L. Perisse PhD. Thesis, Univ. Paris-Saclay, 2021

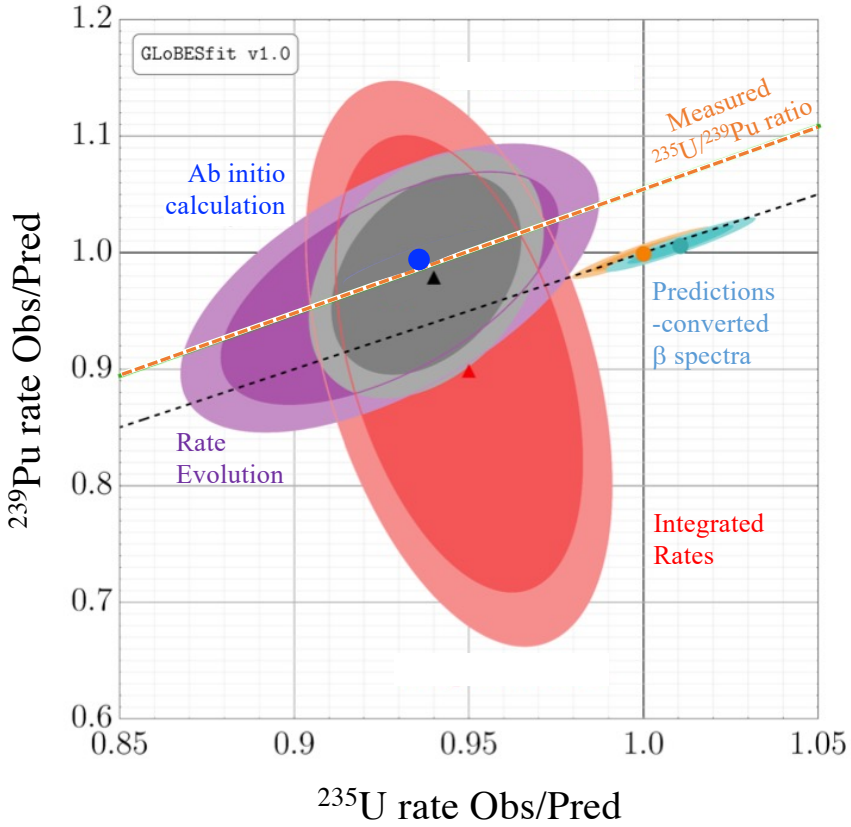


First attempt to propagate uncertainties using:

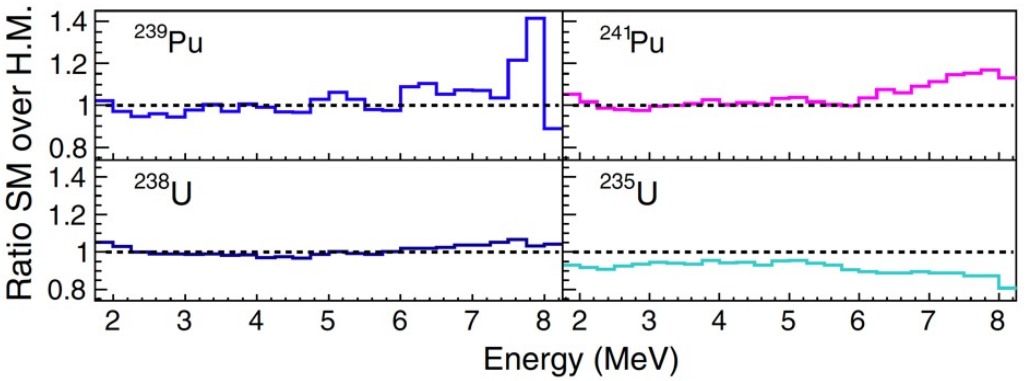
- Upgraded BESTIOLE code
- Available TAGS data
- Effective model for the unknown nuclei
- Cumulative fission yields.

See Lorenzo Perisse's talk.

Summation Models



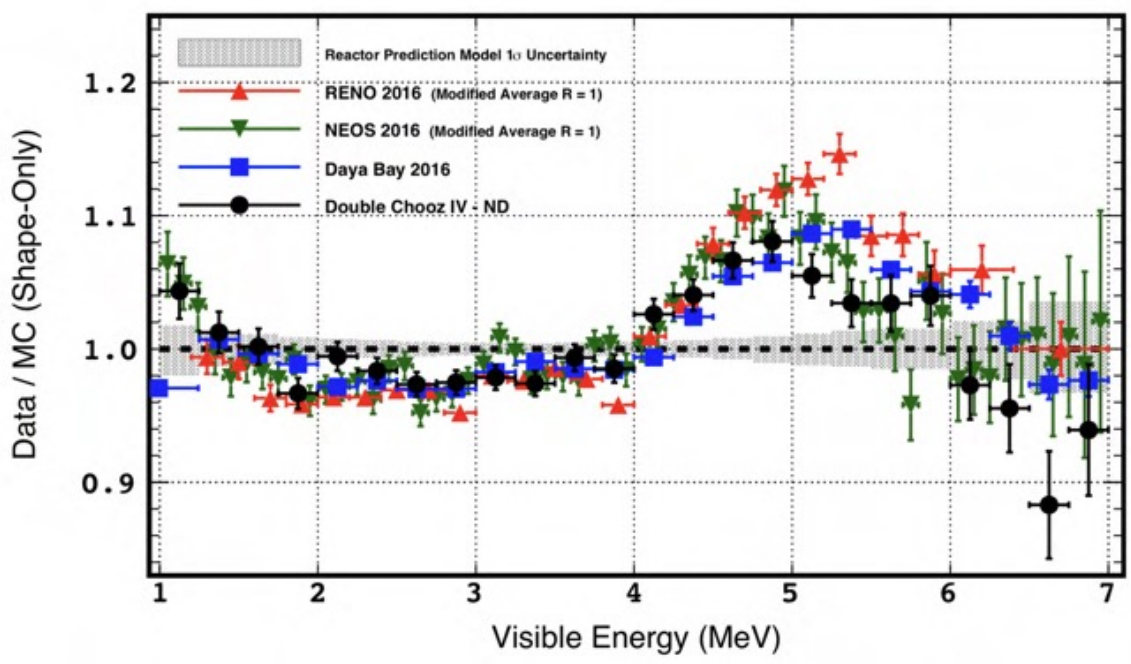
Phys. Rev. Lett. 123, 022502 (2019)



- Includes
  - Most recent TAGS measurements
  - Activities of all FP's from MURE evolution code
  - Gross-theory for unknown transitions

Predicted rates very close to the combined data!

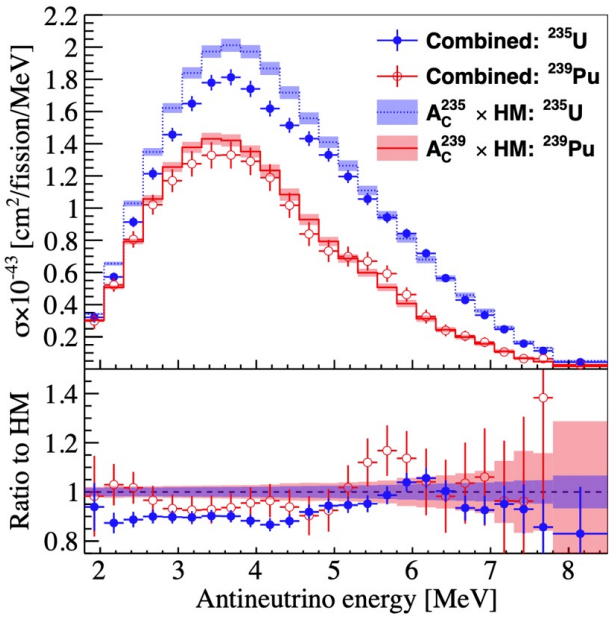
Anomalies – Reactor Spectrum Shape



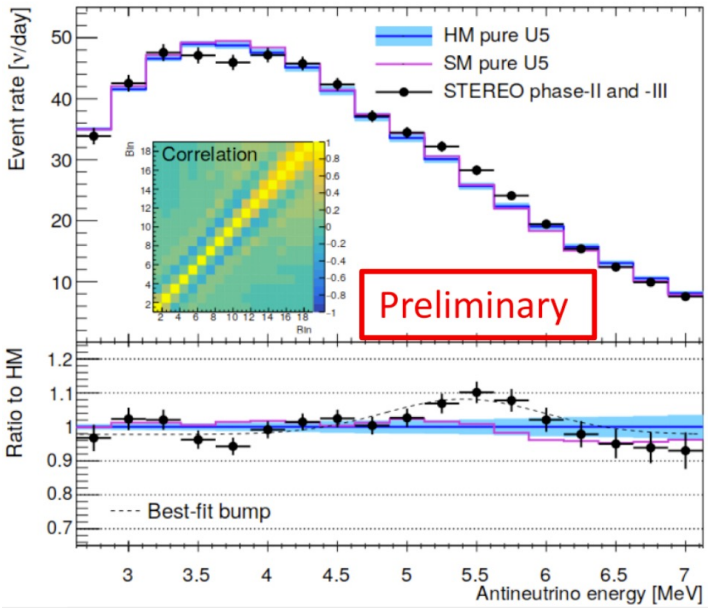
- High precision "θ_{13}" experiments first revealed a local distortion in shape with respect to the prediction, around 5 MeV.
- Mainly decoupled from the rate deficit (≤1% impact)

Accurate reference spectra from direct neutrino measurements !

Daya Bay - Prospect



STEREO all data, shape only – See Loïc's talk



- Accurate and complementary spectra from DB, RENO, DC, NEOS, PROSPECT, STEREO…
- Unfolding to provide reference spectra in "true" antineutrino energy.
- DB-Prospect (*arXiv:2106.12251 [nucl-ex]*) & STEREO-Prospect (*arXiv:2107.0337 [nucl-ex]*) joint analyses.
- Upcoming JUNO-TAO, Prospect-II data.

- **Consistent "bump" distortion seen in mixed U-Pu and pure U spectra**

A new summation model with corrected unknown transitions

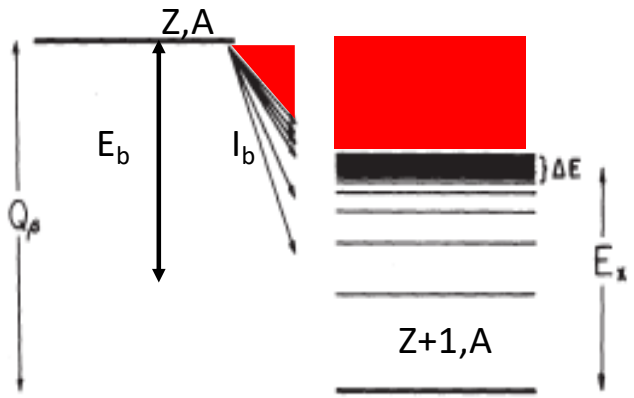
Courtesy of A. Letourneau & V. Savu

β-branch intensity extracted from a new phenomenological β-strength. I_b distribution is taken from TAGS data to build a generic correction for missing transitions.

$$S_f(E,t) = \sum_f A_f(t) \sum_b I_b \times S_f^b(E)$$

Fission fragment activities after 12h of irradiation , calculated with FISPACT-II

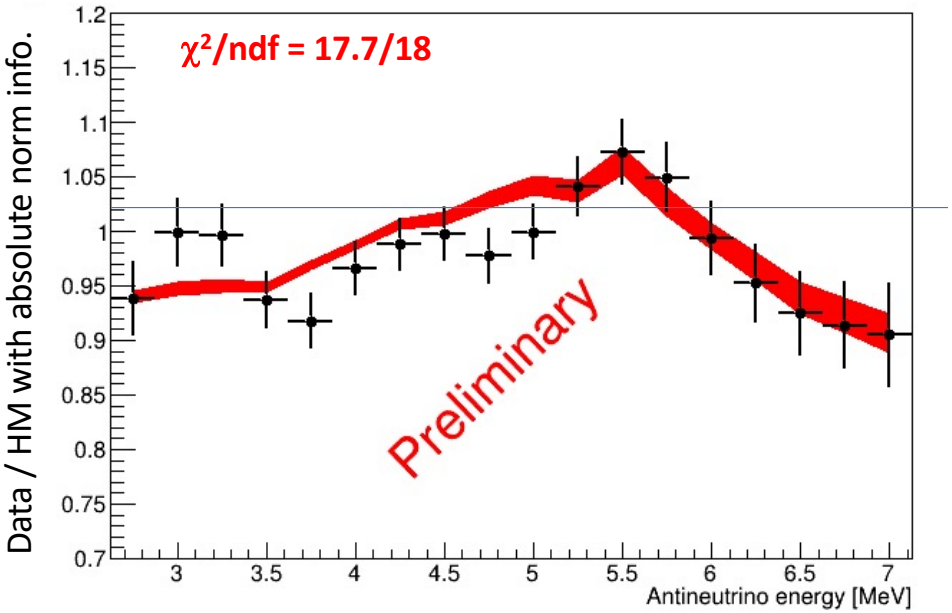
Beta or antineutrino energy spectra at the branch level, calculated with BESTIOLE

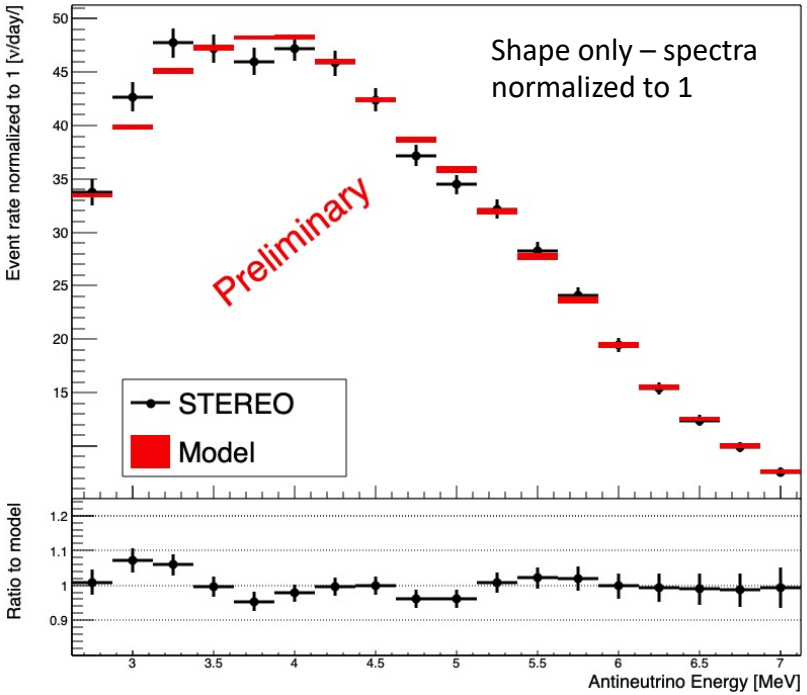


→ **Pandemonium correction extrapolated to all nuclei**

Stereo results

V. Savu, PhD thesis, Univ. Paris-Saclay, 2021





- **Able to achieve good agreement with STEREO data both in norm and shape!**
- Ongoing work to check predictions of Pu spectrum and ratio of the two isotopes with this model.

Tentative Conclusion

- Combination of all reactor measurements **reject the sterile neutrino hypothesis**, most of the RAA 95% CL contour is covered at 95% CL.

- The **norm and shape** of the fission neutrino spectra are now accurately known **from direct neutrino measurements!**

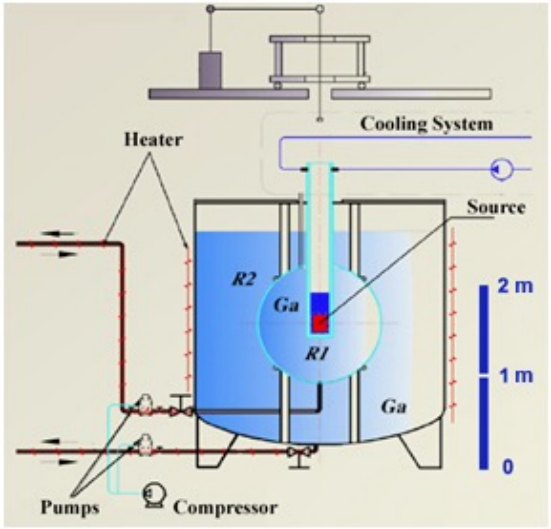
- **All reactor anomalies are likely to find explanation in biases of nuclear data** :
  - Data and updated predictions favor 5% norm bias in the ^{235}U spectrum. Compatible with independent normalisation of the ILL β-spectra for ^{235}U and ^{239}Pu isotopes. Makes the significance of the RAA vanish.
  - Combined effects of the correction of pandemonium and description of forbidden transitions seems to provide enough leverage to explain the bump. Why it was not seen on the β-spectra measured at ILL remains an open question.

→ **It looks like we are in the best situation with the reactor experiments having done the job in their study of the reactor anomalies, rejecting the sterile ν , providing reference ν fission-spectra and pointing to the relevant systematics of the predictions. But "BEST" should be written in capital letters…**

BEST Situation

3.4 MCi source of ^{51}Cr delivered at the Baksan Neutrino Observatory in July 2019

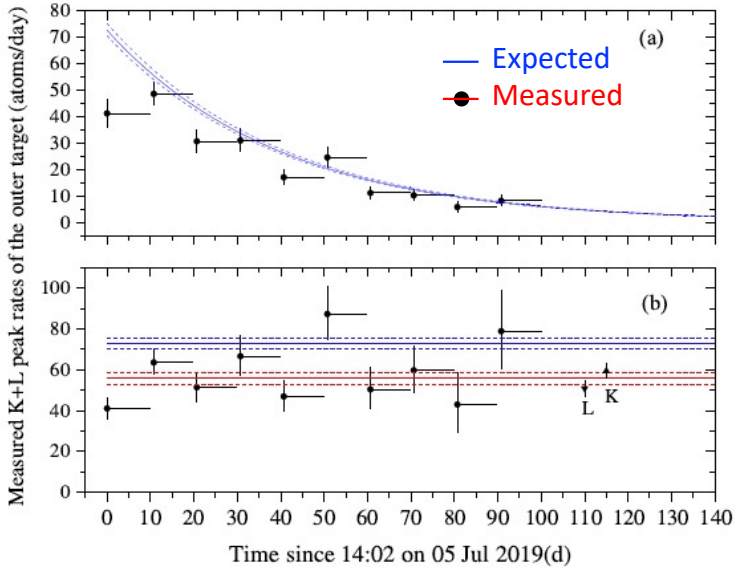
Detector design with inner and outer volumes of liquid Ga to test the deficit at ~50 cm and ~1 m baselines



Ratio of observed/measured events:

R_{in} = 0.791 ± 0.05

R_{out} = 0.766 ± 0.05

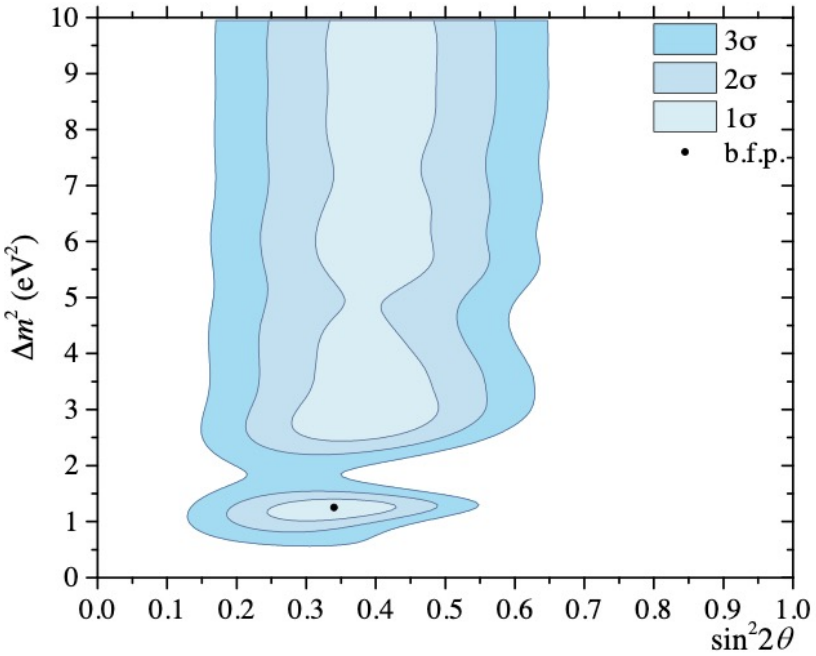


- ~20% deficit with no significant dependence on distance
- Significance ≥ 5 σ !

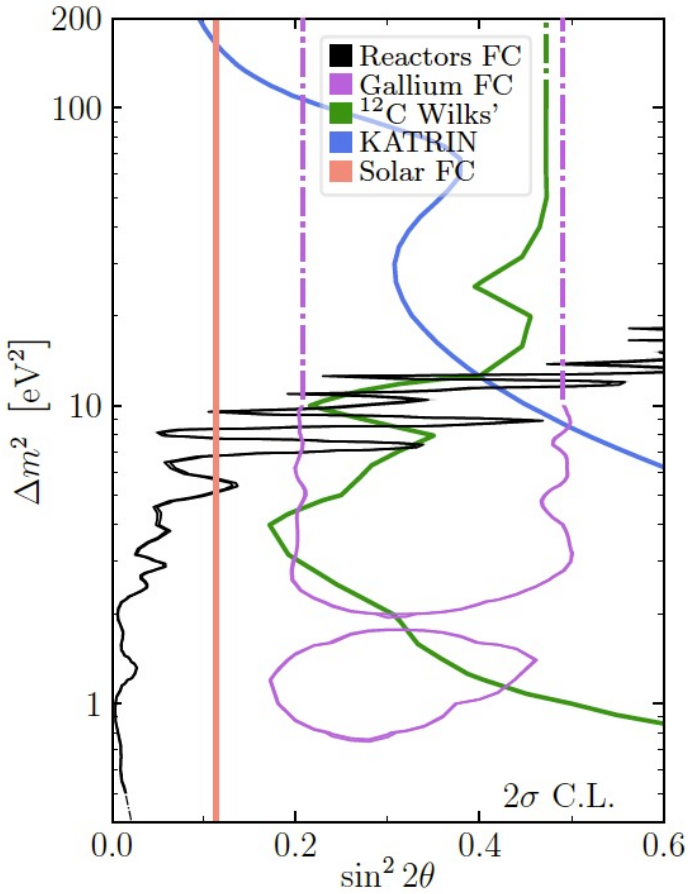
Gallium anomaly

All Gallium data combined.

arXiv:2109.11482v1 [nucl-ex]



Pure norm signal leads to a contour in the form of a vertical band with a very large mean mixing angle ~40%



Severe tensions with other data:

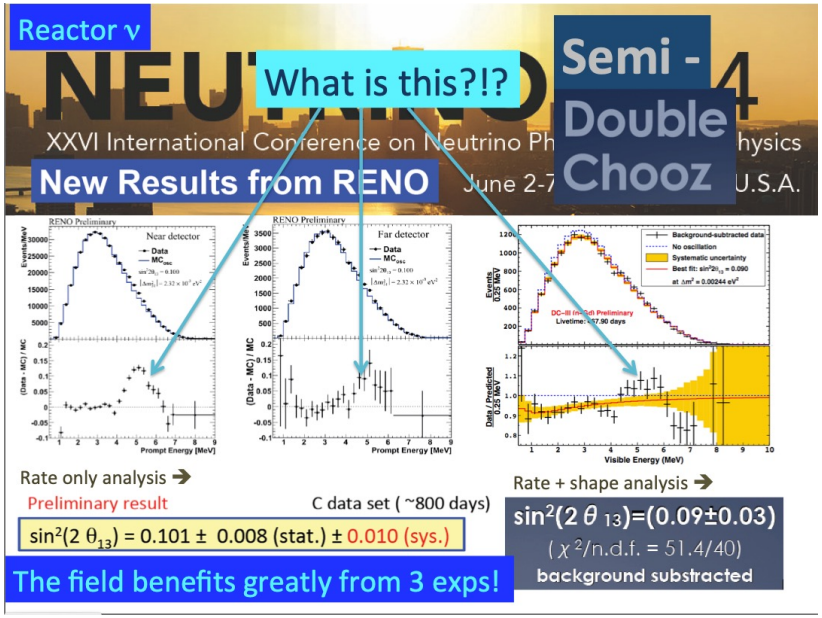
- Solar neutrinos
- Reactor data for $\Delta m^2 \leq 10$ eV^2
- Large scale structures in cosmos don't like heavy ν's with large mixing.
- Upcoming KATRIN data will bring complementary constraints at high Δm^2.

Way out

- Oscillations length below 50 cm with MeV neutrinos → we might be left with pure rate deficits for a while
- Norm bias… is a tantalizing explanation given the situation with reactor data:
  - $\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$ cross section: transition to g.s. is well known from the life time of the symmetric process of e^- capture in ^{71}Ge. More uncertain contributions from excited states can increase a bit the uncertainty but only increase the deficit.
  - Activity measurements: several complementary methods tested, each with few % accuracy. This scenario would require coherent biases of several independent nuclear data. No recent review done however…
  - Extraction of Ge atoms from the detector? A priori validated by different experiments.
- Exotic new physics ??

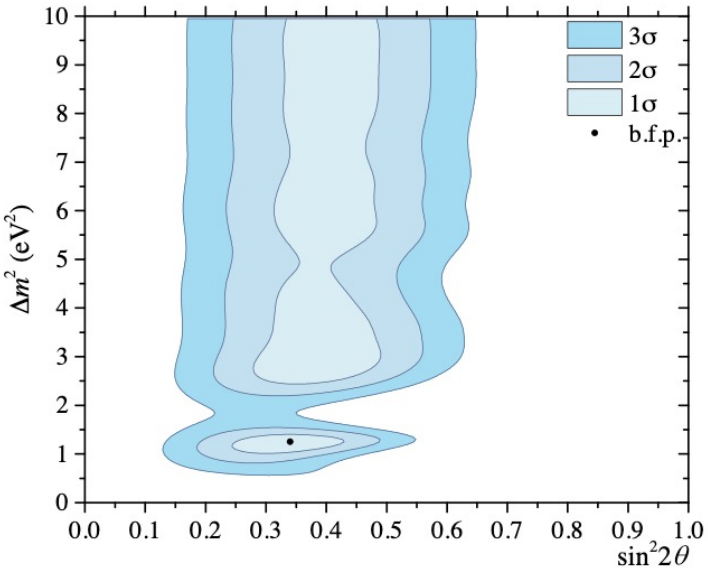
Concl(f)usion

Dave Wark summary talk @ Neutrino 2014



- High precision reactor ν data collected since then.
- Reject the sterile ν hypothesis, provide reference ν fission spectra and supersede some relevant nuclear data.

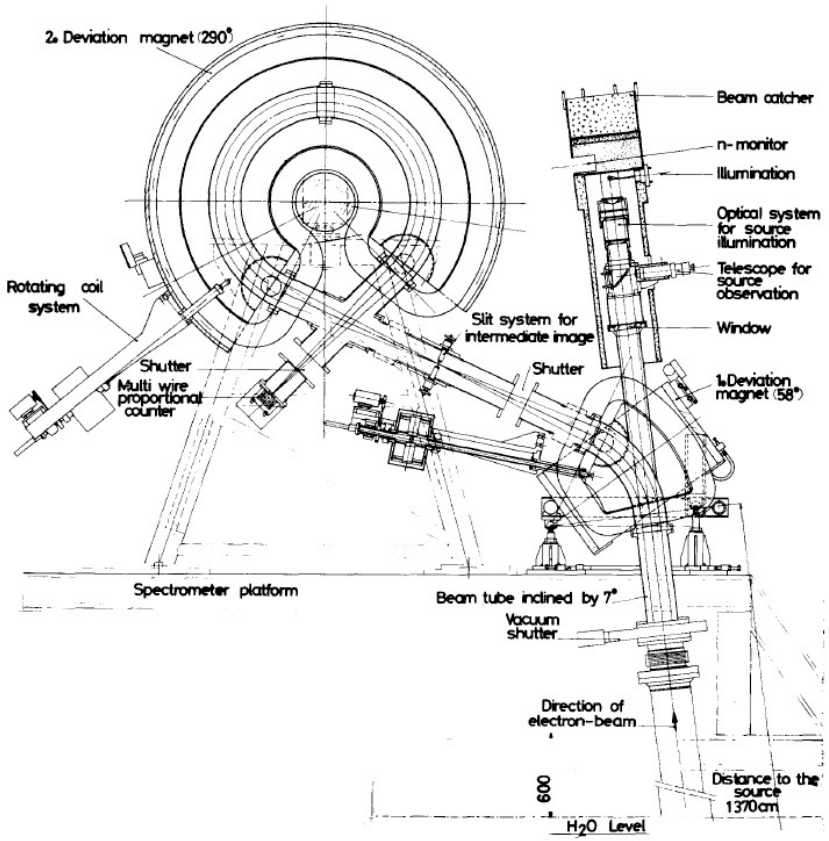
2021 What is this ?



- Anomalies go with improved precision… and paves to way of progress in particle physics. We have to understand “this” with complementary tests.

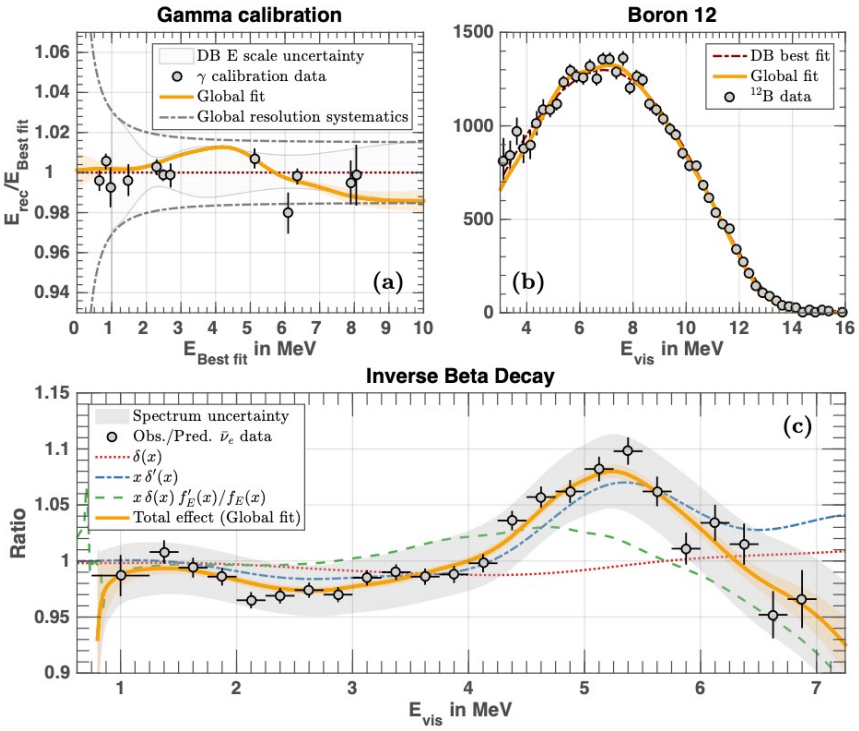
BILL Spectrometer

NIM 154 (1978) 127-149



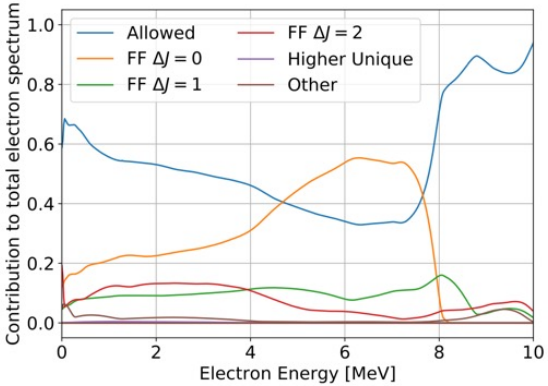
Bias in the E scale when scanning the intensity of the magnetic field?

Phys. Lett. B 773 (2017) 307-312



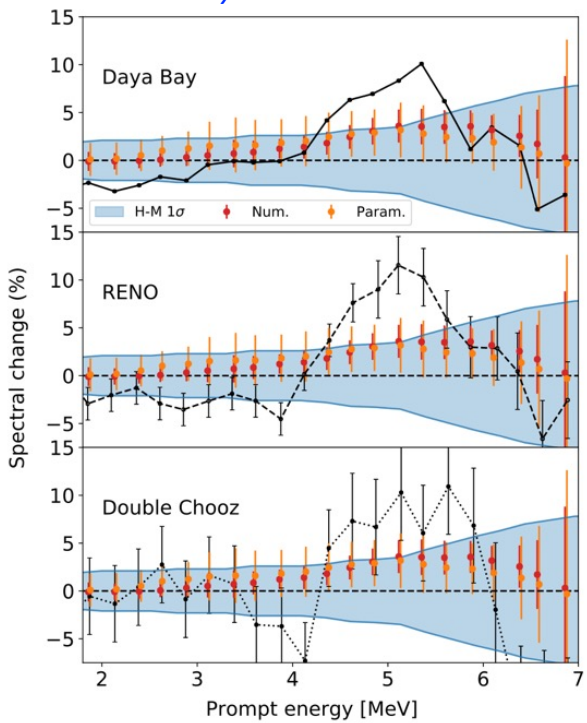
Forbidden transitions

Dominant contribution of forbidden β-decays above ~4 MeV



- Shell-model calculation of the shape of forbidden β-decays, included in the conversion method.
- Combination of this correction with the correction of the pandemonium effect could reach a good agreement with the experimental neutrino spectrum shapes.

L. Hayen et al. arXiv:1908.08302



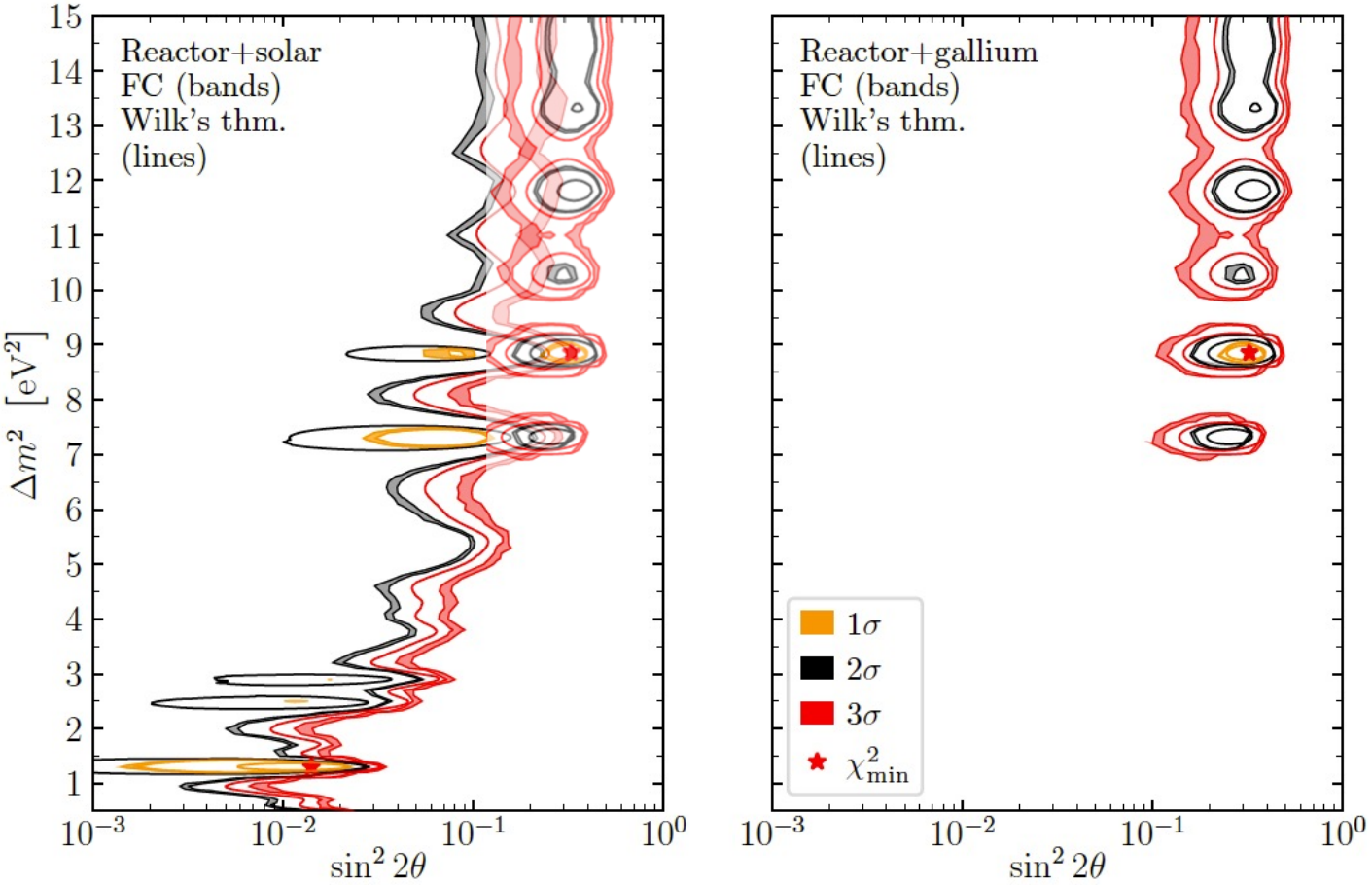
BEST results

TABLE I. A summary of the likelihood fits for the production rate from each extraction, the combined fit of all extractions, and the predicted production rate. The quoted measurement uncertainties are statistical.

	Inner Volume				Outer Volume			
Exposure Dates (DoY)	K+L Candidates	Number fit to ^{71}Ge	^{51}Cr Production	Production Rate (Atoms/d)	K+L Candidates	Number fit to ^{71}Ge	^{51}Cr Production	Production Rate (Atoms/d)
186.585-196.376	180	176.3	175.5	$49.4^{+4.2}_{-4.0}$	181	133.4	129.6	$41.1^{+5.3}_{-5.2}$
197.362-206.372	129	111.5	107.7	$44.9^{+5.9}_{-5.6}$	174	163.8	158.6	$63.6^{+5.7}_{-5.5}$
207.282-216.374	132	117.6	115.4	$62.9^{+7.4}_{-7.1}$	116	92.5	88.2	$51.4^{+7.3}_{-6.9}$
217.286-226.371	93	87.3	85.6	$73.3^{+8.6}_{-8.0}$	98	82.3	78.9	$66.6^{+9.8}_{-9.2}$
227.258-236.458	134	60.2	58.4	$49.8^{+8.2}_{-7.7}$	120	64.0	59.5	$46.9^{+7.9}_{-7.2}$
237.342-246.369	81	48.8	47.7	$69.5^{+12.0}_{-11.0}$	97	62.3	59.3	$87.3^{+13.2}_{-12.3}$
247.243-256.368	91	45.0	43.9	$64.6^{+12.6}_{-11.6}$	69	38.0	34.4	$50.4^{+10.6}_{-9.6}$
257.241-266.369	59	33.6	32.4	$53.8^{+12.2}_{-11.0}$	68	43.4	39.2	$59.7^{+11.7}_{-10.8}$
267.240-276.369	106	23.7	22.7	$49.9^{+16.5}_{-14.9}$	66	20.2	17.0	$43.0^{+15.3}_{-13.5}$
277.201-286.367	88	25.2	24.3	$69.1^{+19.4}_{-17.3}$	81	31.8	28.0	$78.8^{+20.0}_{-18.1}$
Combined	1093	724.0	708.2	$54.9^{+2.5}_{-2.4}$	1069	738.8	699.8	$55.6^{+2.7}_{-2.6}$
Predicted				$69.41^{+2.5}_{-2.0}$				$72.59^{+2.6}_{-2.1}$

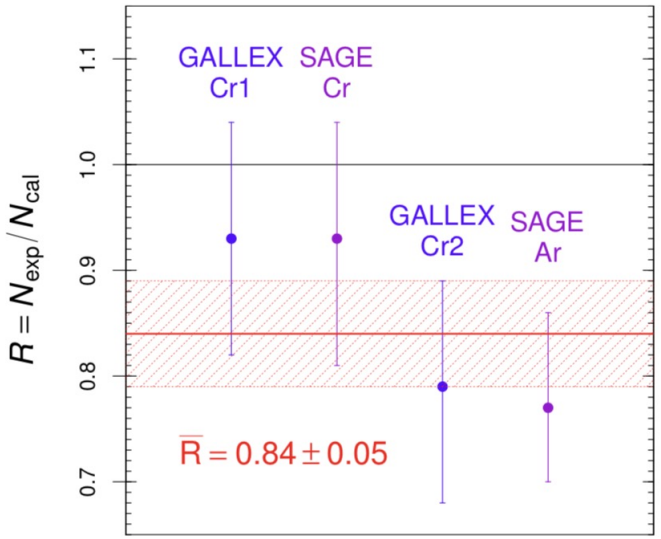
ν_e anomalies

arXiv:2111.12530 [hep-ph]



Anomalies – Rate deficit

$\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$



Bias in the cross-section?

- Transition to ^{71}Ge ground state determined by the lifetime of inverse reaction
- Contributions from excited states are more uncertain but can only increase the cross-section.

Phys. Lett. B 795 (2019) 542-547

State	$g_A = 0.955(6)$
$1/2^-_{g.s.}$	$5.53 \pm 0.07 \times 10^{-45}$
$5/2^-_1$	$1.21 \pm 0.61 \times 10^{-46}$
$9/2^+_1$	$\leq 10^{-56}$
$3/2^-_1$	$1.94 \pm 0.97 \times 10^{-47}$
total	$5.67 \pm 0.10 \times 10^{-45}$