(Light) Sterile Neutrino searches

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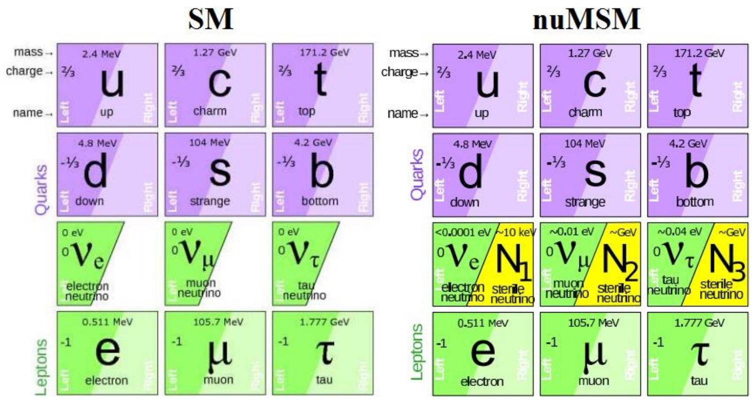
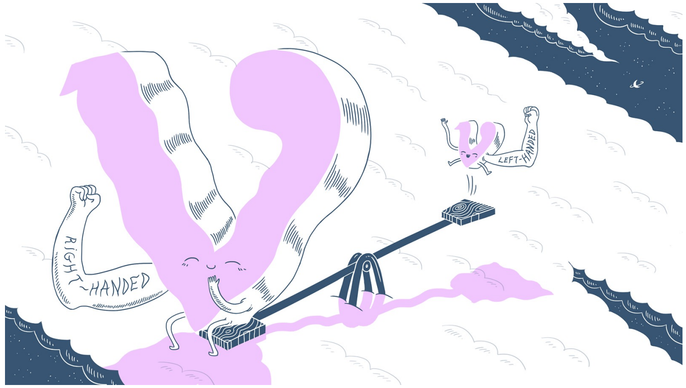
Kyoto, 27th March 2023

International Conference on the Physics of the Two Infinities

Sterile neutrinos: what? why? what for?





What?

- SM $SU(2)_L$ singlets
- Don’t couple with W, Z bosons
- …but mix with regular (*active*) neutrinos!

Why?

- Arise in most mass models for neutrinos

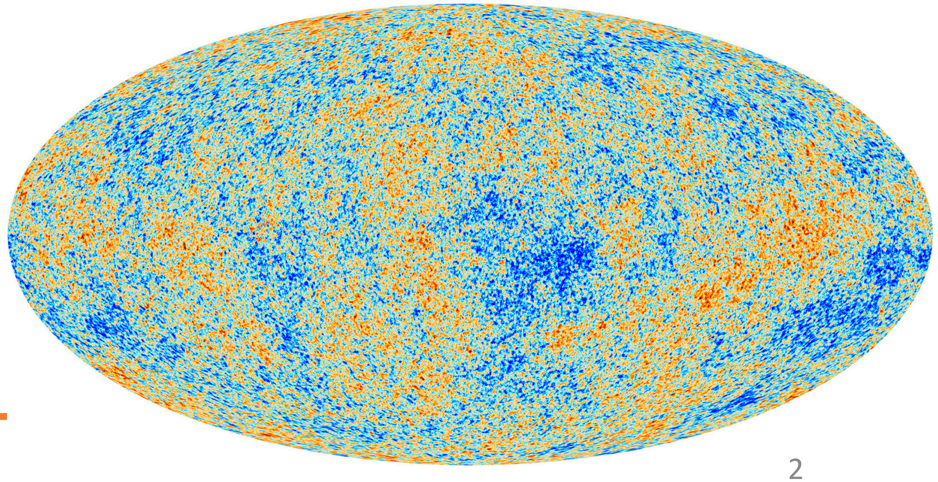
e.g. Seesaw models

What for?

- (warm) Dark Matter candidate if m ~ few keV
- Baryon Asymmetry via leptogenesis

e.g. νMSM (Asaka, Blanchet, Shaposhnikov 2005 …)

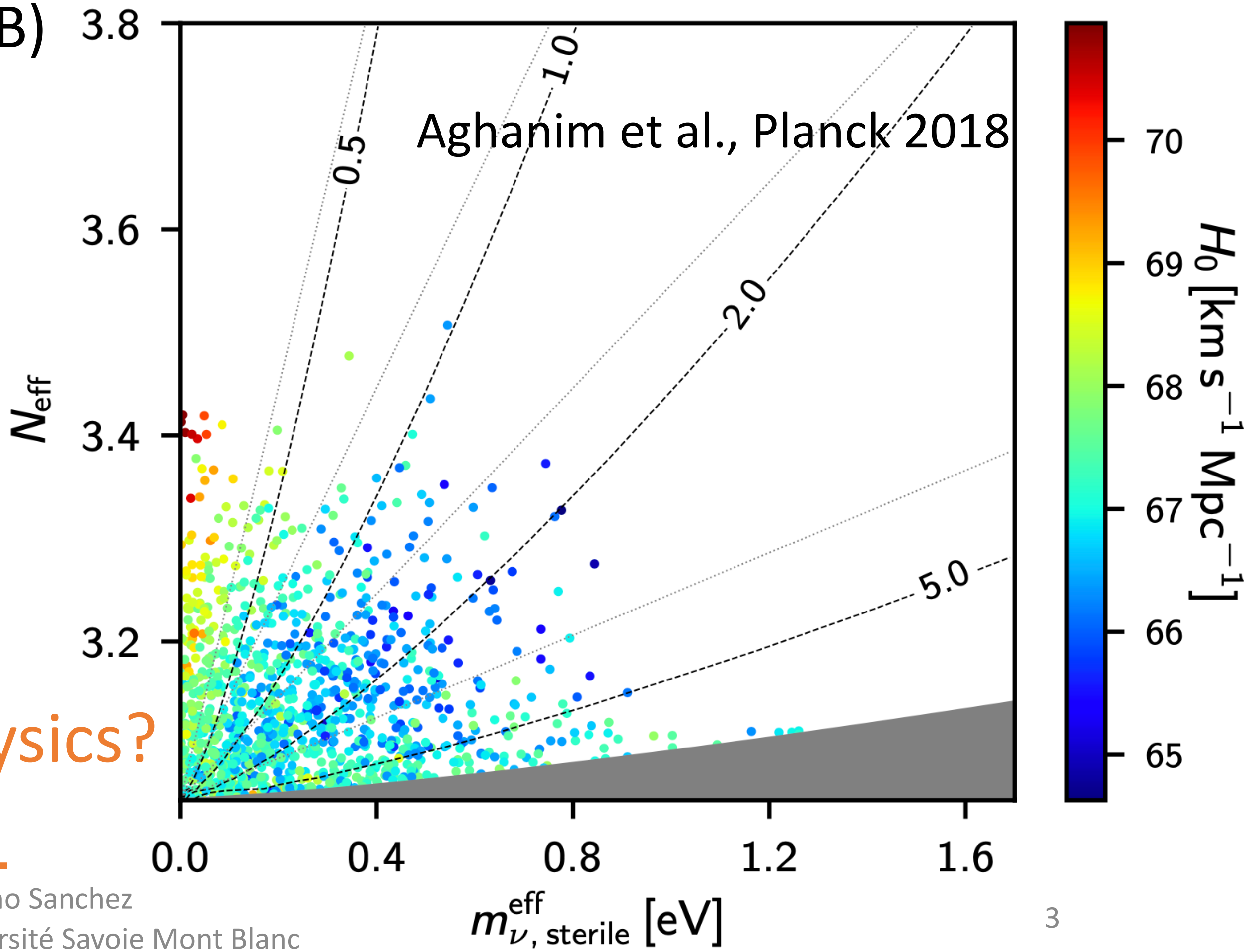
- **Can explain anomalies in (short baseline) oscillation exps…**



Sterile neutrinos and cosmology: CMB

- Bounds on N_{eff} et $m^{eff}_{\nu,sterile}$ from cosmology (Big Bang Nucleosynthesis, CMB, Large Scale structure):

$$N_{eff} < 3.31, \quad m^{eff}_{\nu,sterile} < 0.67 \text{ eV (95\%CL CMB)}$$

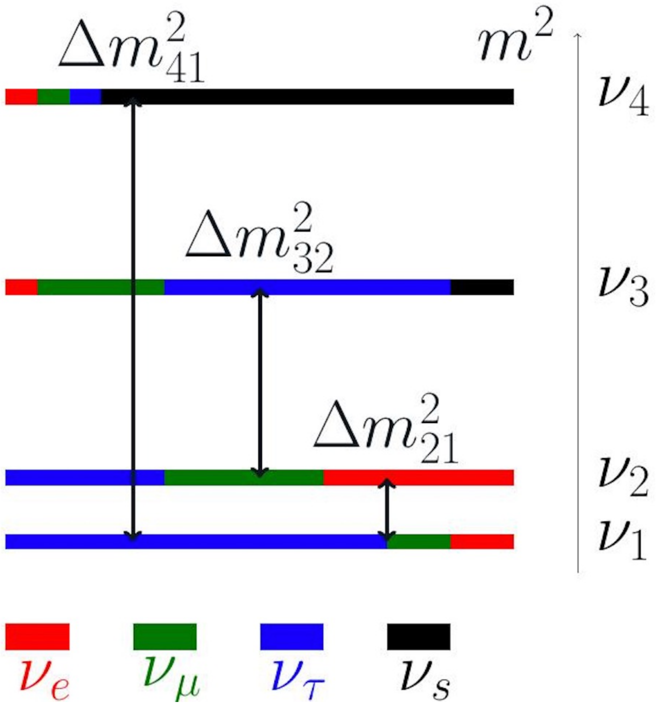


- Several ways to avoid these constraints:
  - Incomplete ν thermalisation
  - Large primordial lepton asymmetry
  - ν_4 coupling to dark sector
  - …

(see e.g. review Prog.Part.Nucl.Phys. **111**, 103736 (2020))

Which bounds/results from particle physics?

Oscillations with sterile neutrinos



$\Delta m^2_{41} \sim 1\ eV^2$

Coupling to sterile neutrinos leads to *faster* oscillations driven by Δm^2_{41} :

$$P(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta)\sin^2\left(1.27\frac{\Delta m^2_{41}[eV^2]L\ [m]}{E\ [MeV]}\right)$$

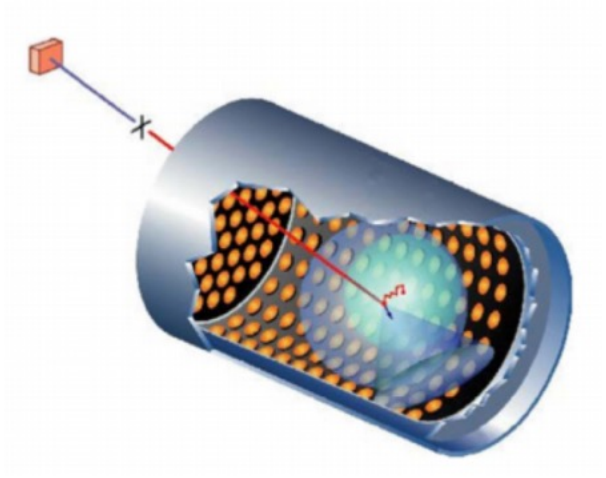
$$U_{PMNS} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \longrightarrow U_{3+1} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

The LSND Anomaly

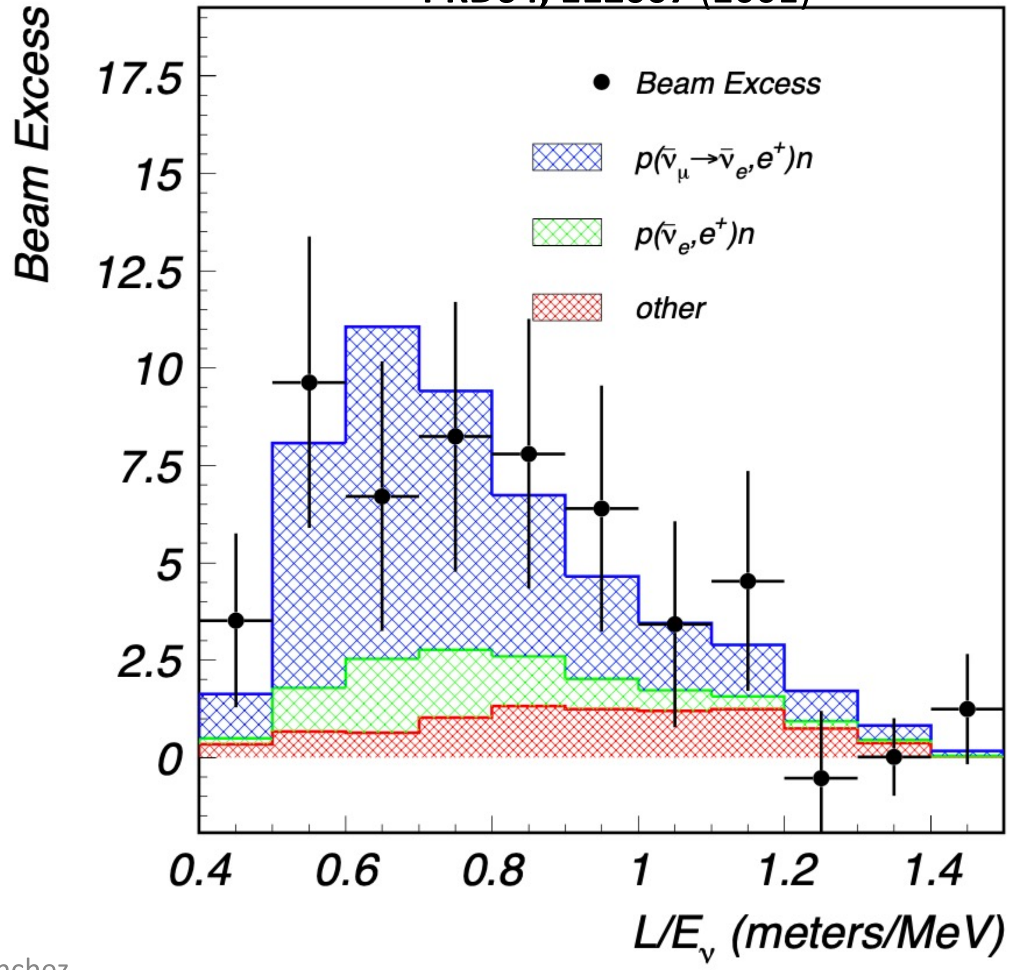
Excess of $\overline{\nu_e}$ events observed by LSND experiment in a $\overline{\nu_\mu}$ beam:

$\overline{\nu_\mu} \rightarrow \overline{\nu_e}$ oscillation?

Δm^2_{LSND} ~1eV^2 >> (known) Δm^2_{atm} , Δm^2_{solar}



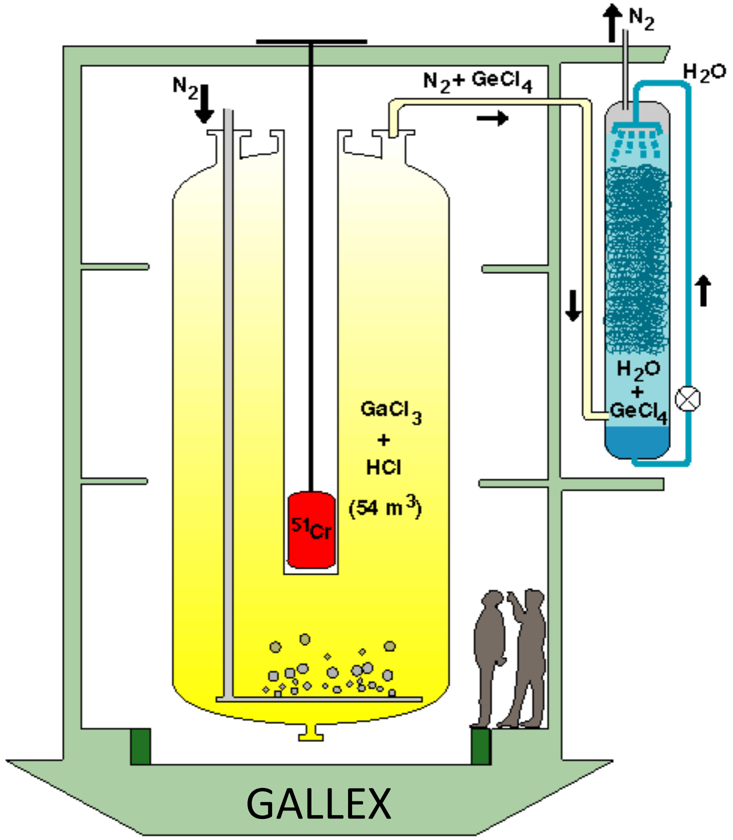
PRD64, 112007 (2001)



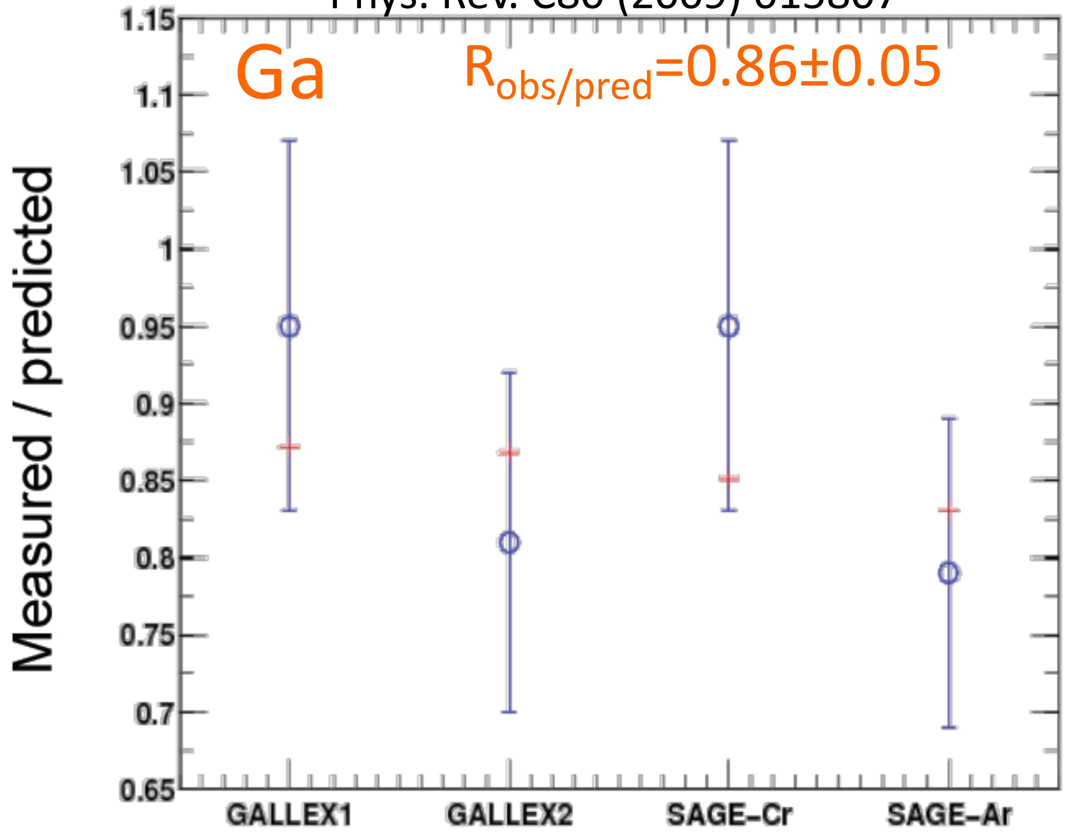
The Gallium anomaly

1990's radiochemical exps SAGE and Gallex for solar ν: $\nu + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$

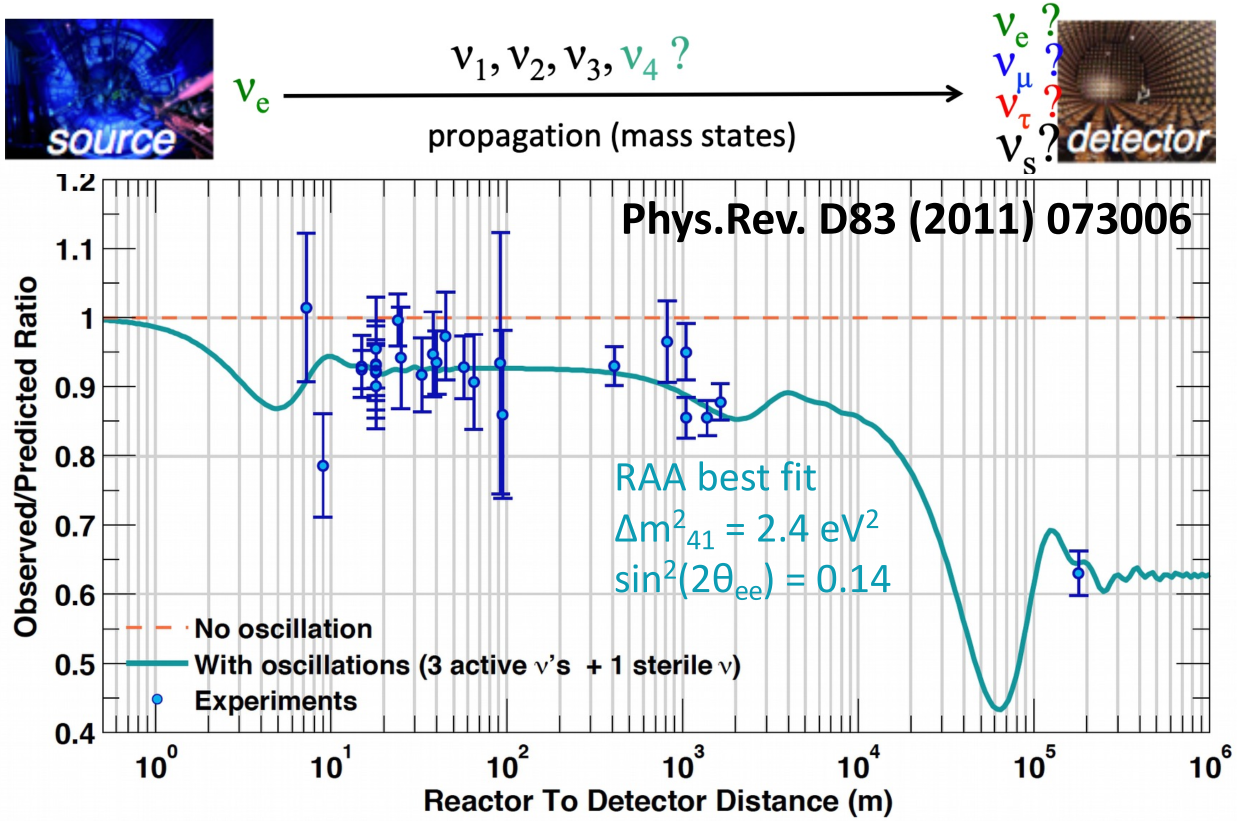
~3σ deficit wrt expectations in calibration runs



Phys. Lett. B685 (2010) 47-54
Phys. Rev. C80 (2009) 015807



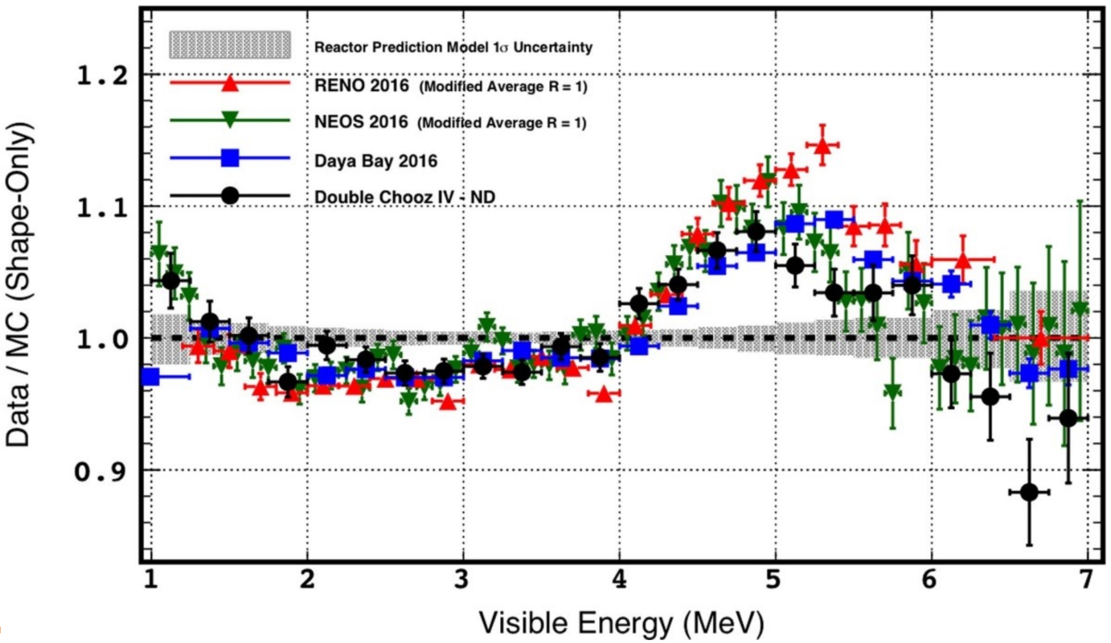
Reactor Antineutrino Anomaly(ies)



Reactor Antineutrino Anomaly (2011): ~6% deficit observed in measured reactor antineutrino fluxes when compared with latest predictions. **PRD83, 073006** (2011) **PRC83, 054615** (2011) **PRC84, 024617** (2011)

Sterile neutrino with $\sin^2(2\theta_{ee})$~0.17 , Δm^2_{41}~2.3 eV^2 would explain RAA and Gallium anomalies

Daya Bay, RENO, Double Chooz (2014): intriguing excess around 5 MeV wrt spectrum predictions ("5 MeV bump")

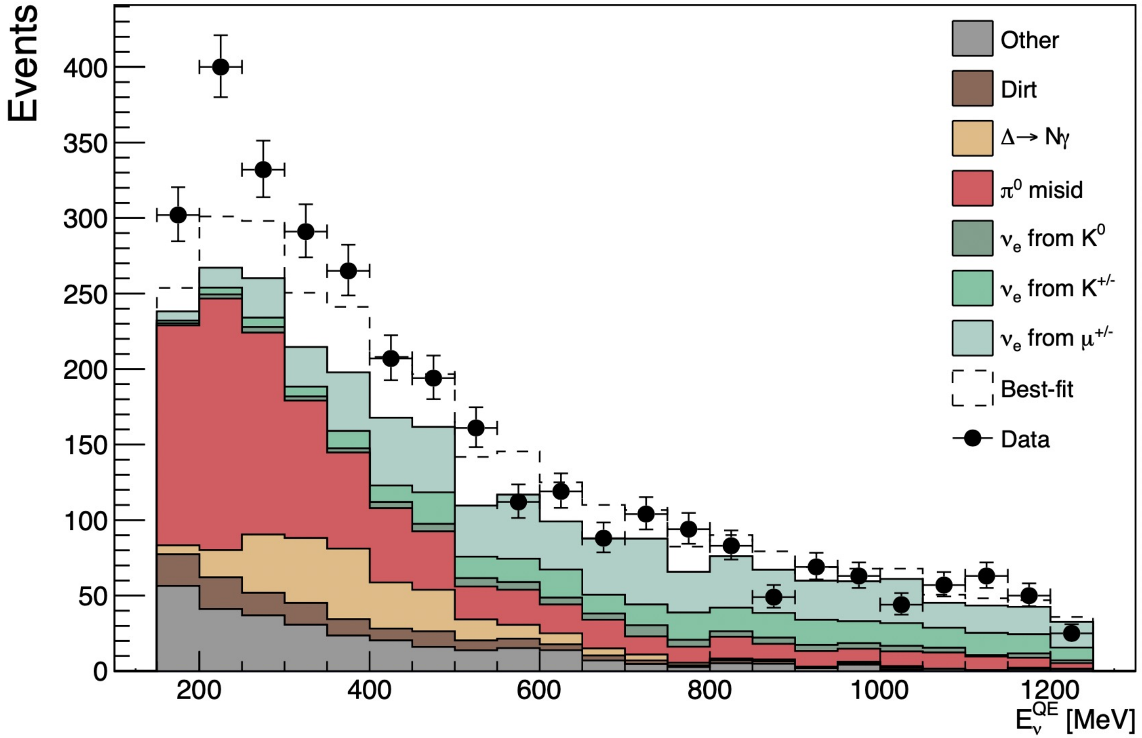


MiniBooNE

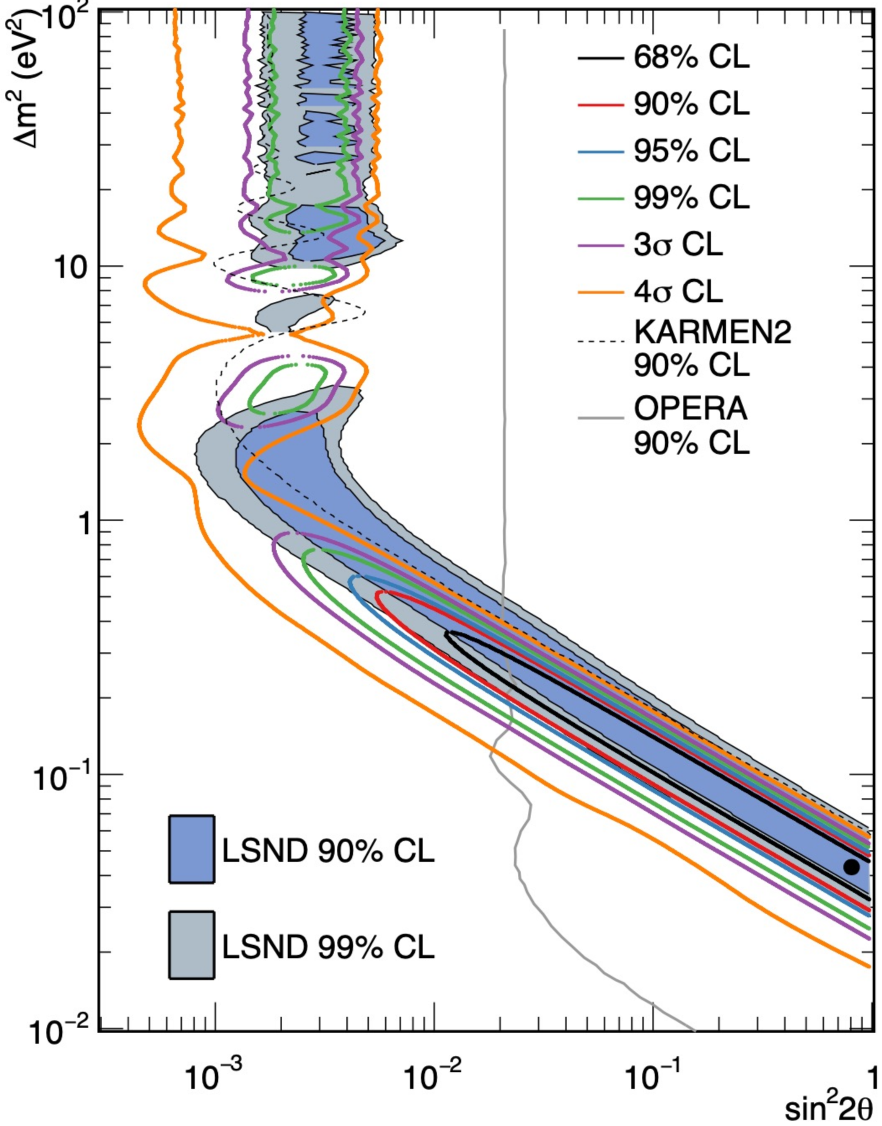
- MiniBooNE to test LSND anomaly:

ν_μ beam, different L, E but same L/E ratio

- Observed low energy excess too (4.7 σ)!
- Electron-like background or LSND-like oscillation?

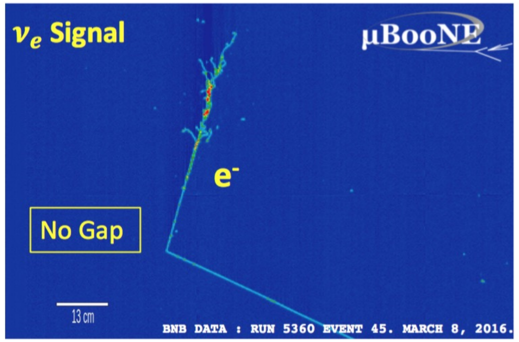


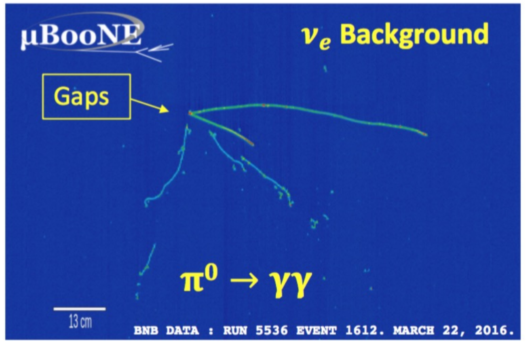
MiniBooNE PRD **103**, 052002 (2021)



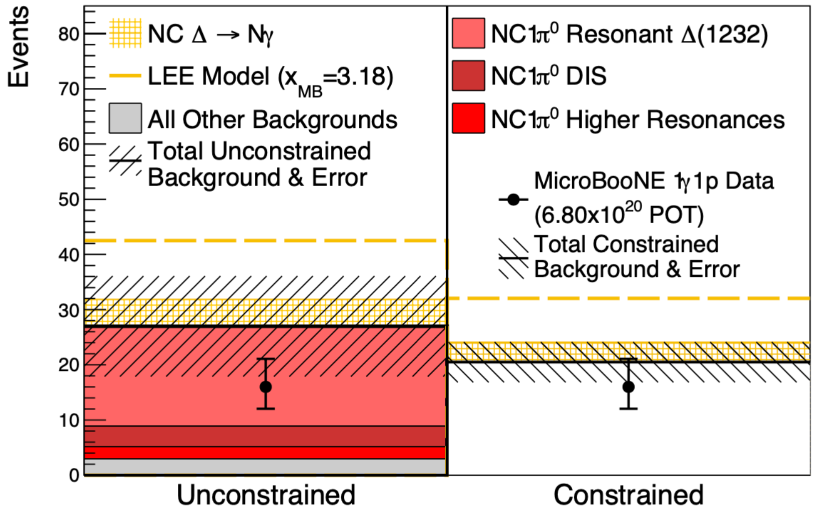
MicroBooNE

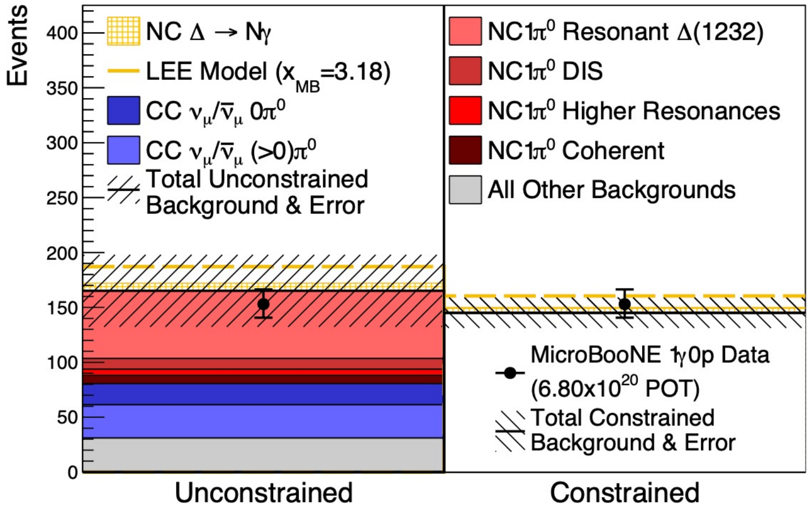
- LAr TPC technology to discriminate e^- from γ
- Tested both hypotheses for MiniBooNE excess:
  - γ origin (background). γ backgrounds consistent with expectations
  - e^- origin (oscillation). No oscillation found.



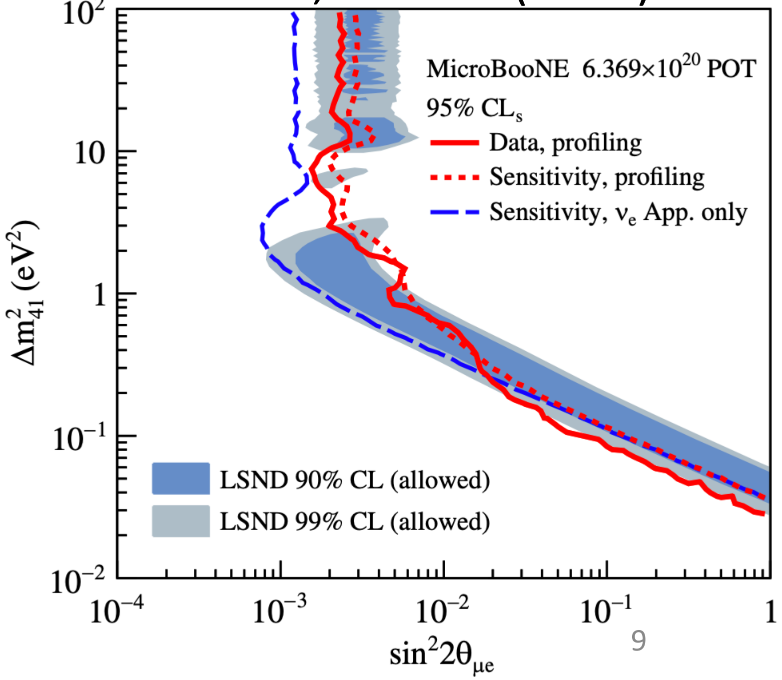


PRL **128**, 11801 (2022)





PRL **130**, 011801 (2023)



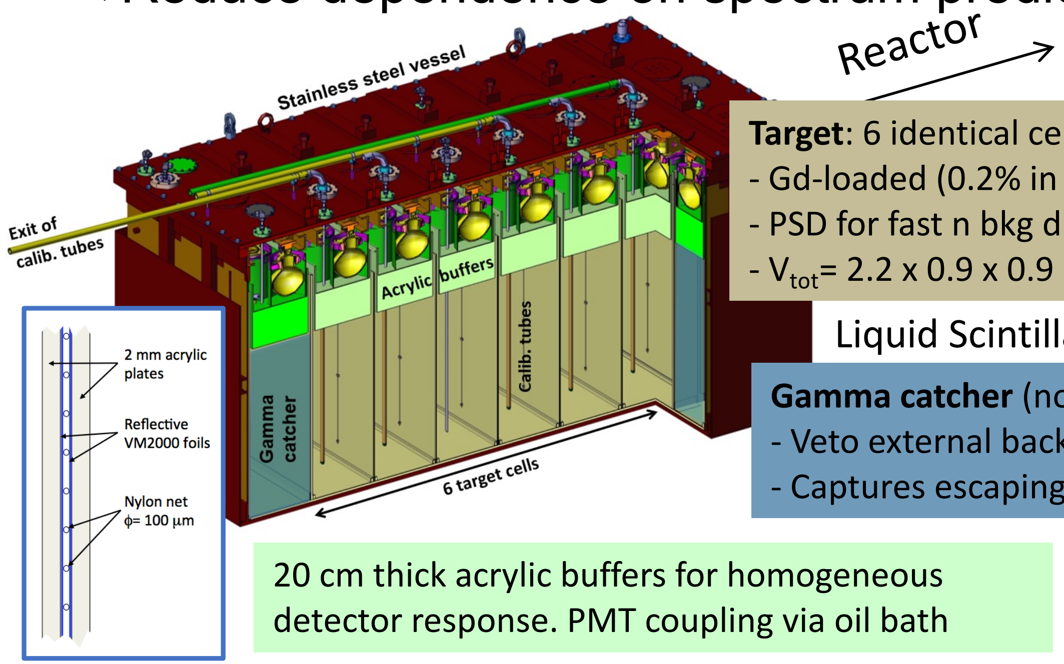
The STEREO detector

JINST 13, 07 (2018): P07009

How to give an unambiguous answer to the Reactor Anomaly?

Compare of 6 target cells looking for oscillation-like distortions in E_ν spectra

⇒Reduce dependence on spectrum prediction

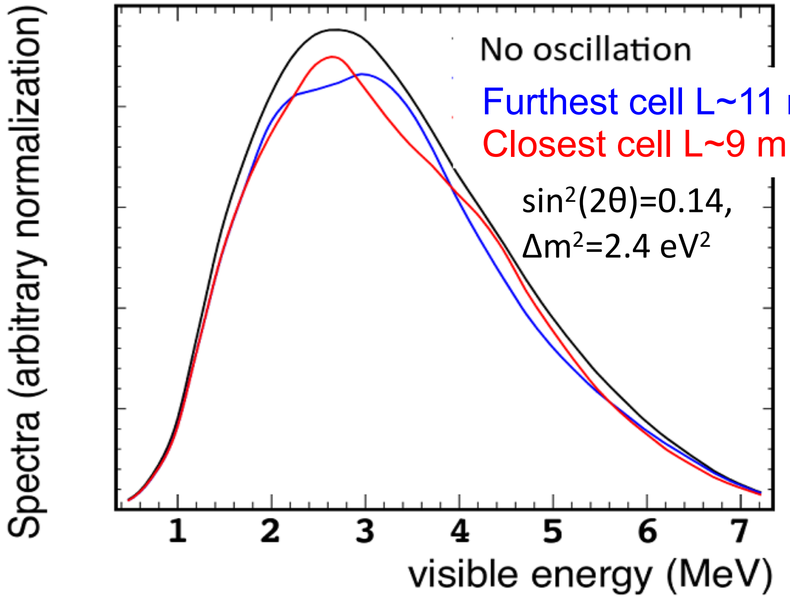


Target: 6 identical cells
- Gd-loaded (0.2% in mass)
- PSD for fast n bkg discrimination
- V_{tot}= 2.2 x 0.9 x 0.9 m^3

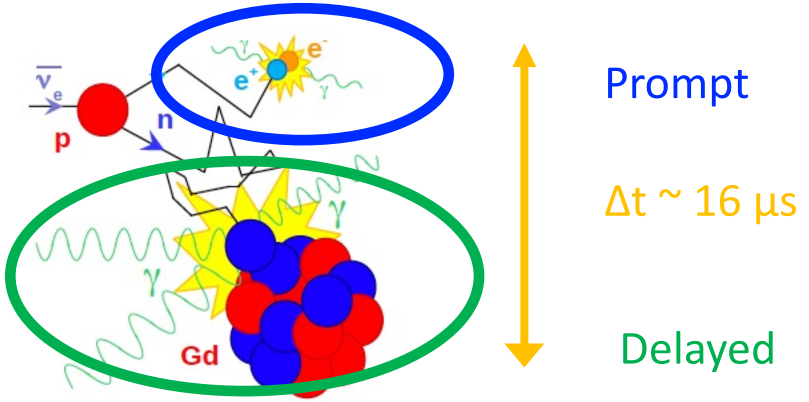
Liquid Scintillator

Gamma catcher (no Gd):
- Veto external background
- Captures escaping γ's

20 cm thick acrylic buffers for homogeneous detector response. PMT coupling via oil bath



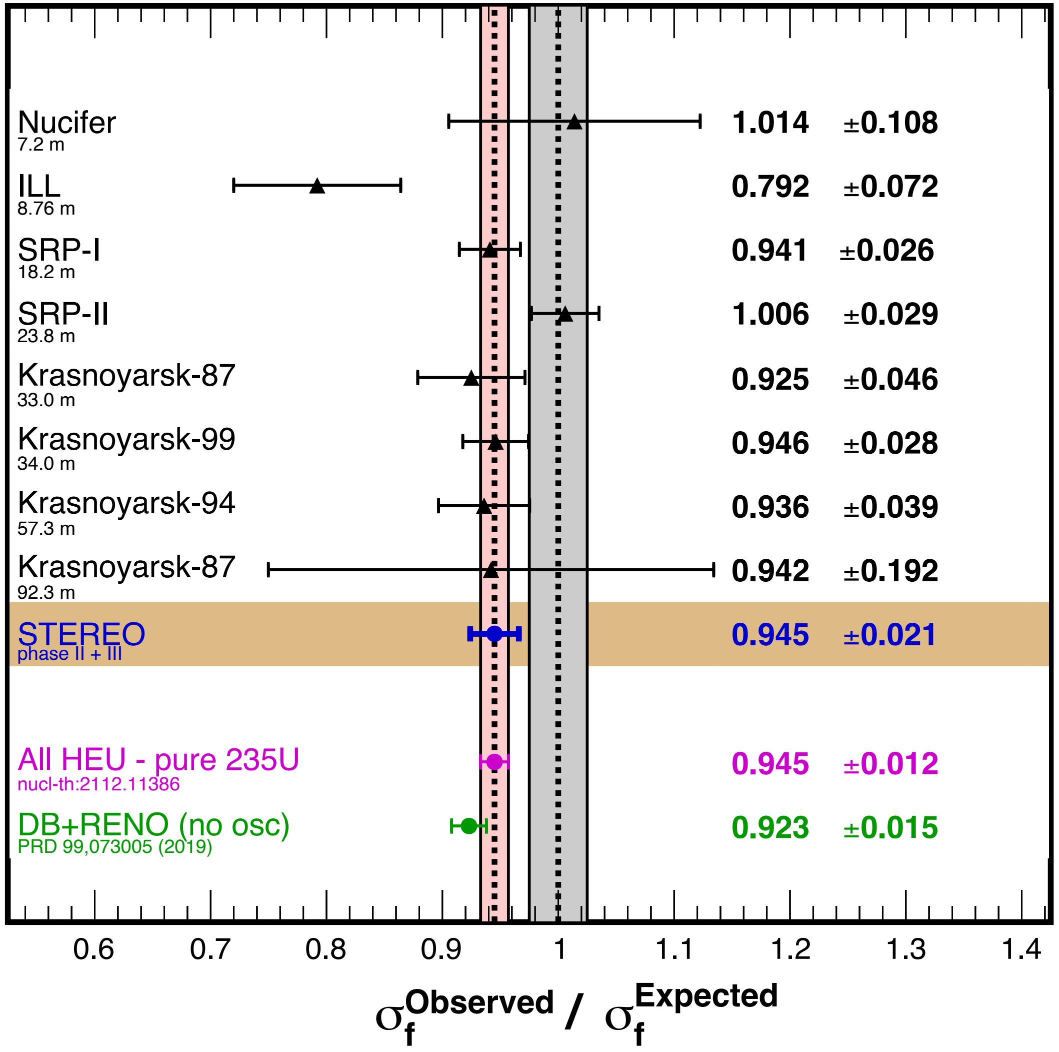
ν detection through Inverse Beta Decay (prompt + delayed coincidence)



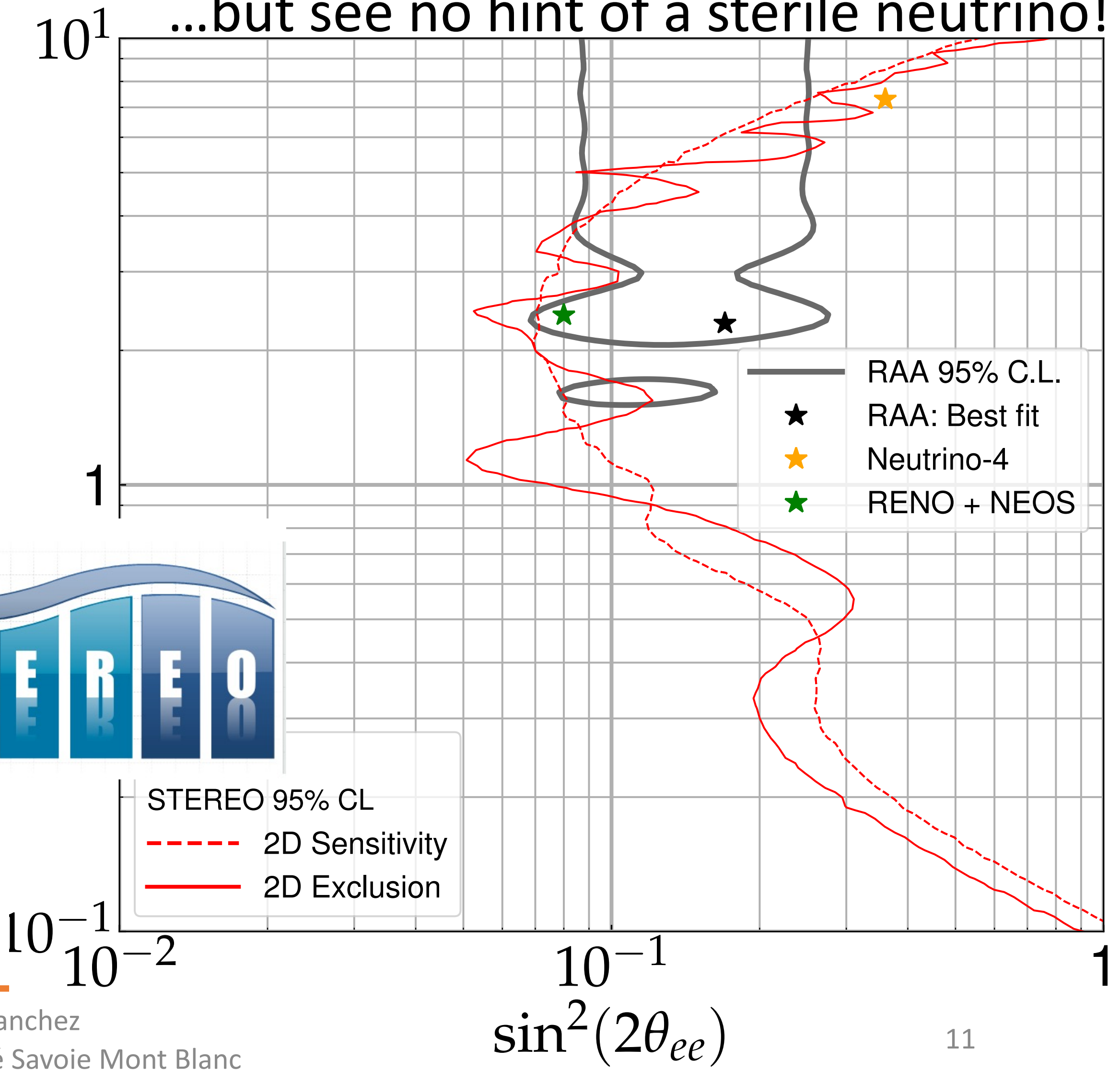
Reactor Antineutrino Anomaly: STEREO

Nature **613**, 257-261 (2023)

STEREO also measures a ~5% flux deficit…

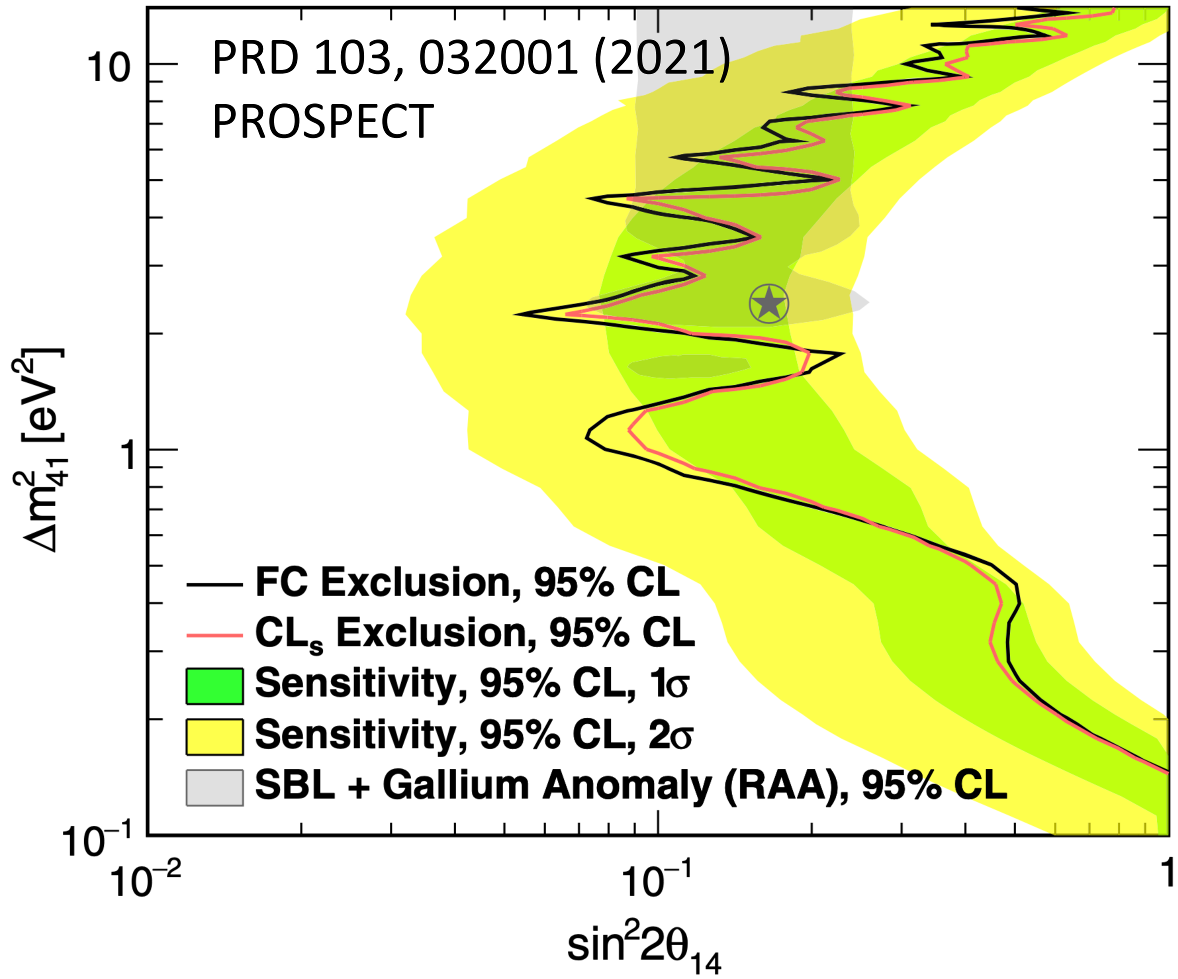


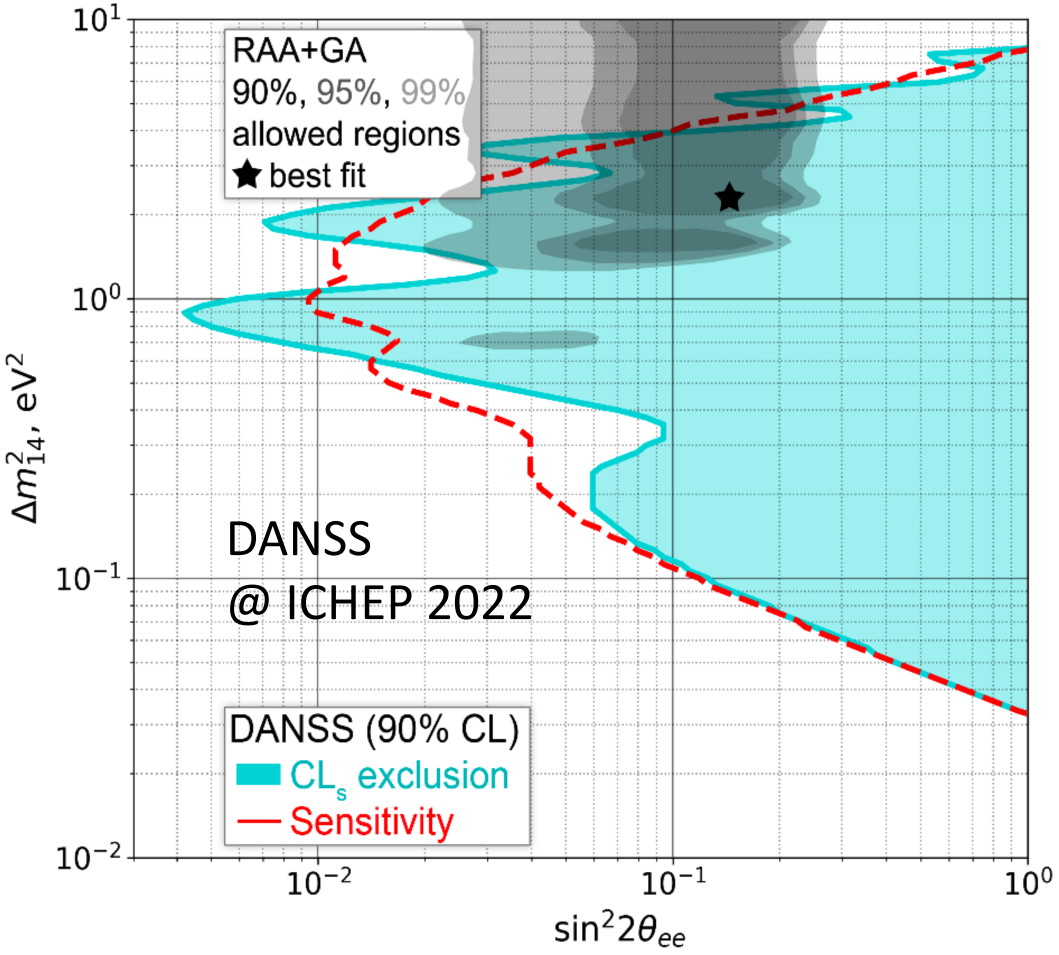
…but see no hint of a sterile neutrino!



Reactor Antineutrino Anomaly: other exps

- A lot of experiments tested the RAA! DANSS, PROSPECT, SoLid, NEOS, Neutrino-4...

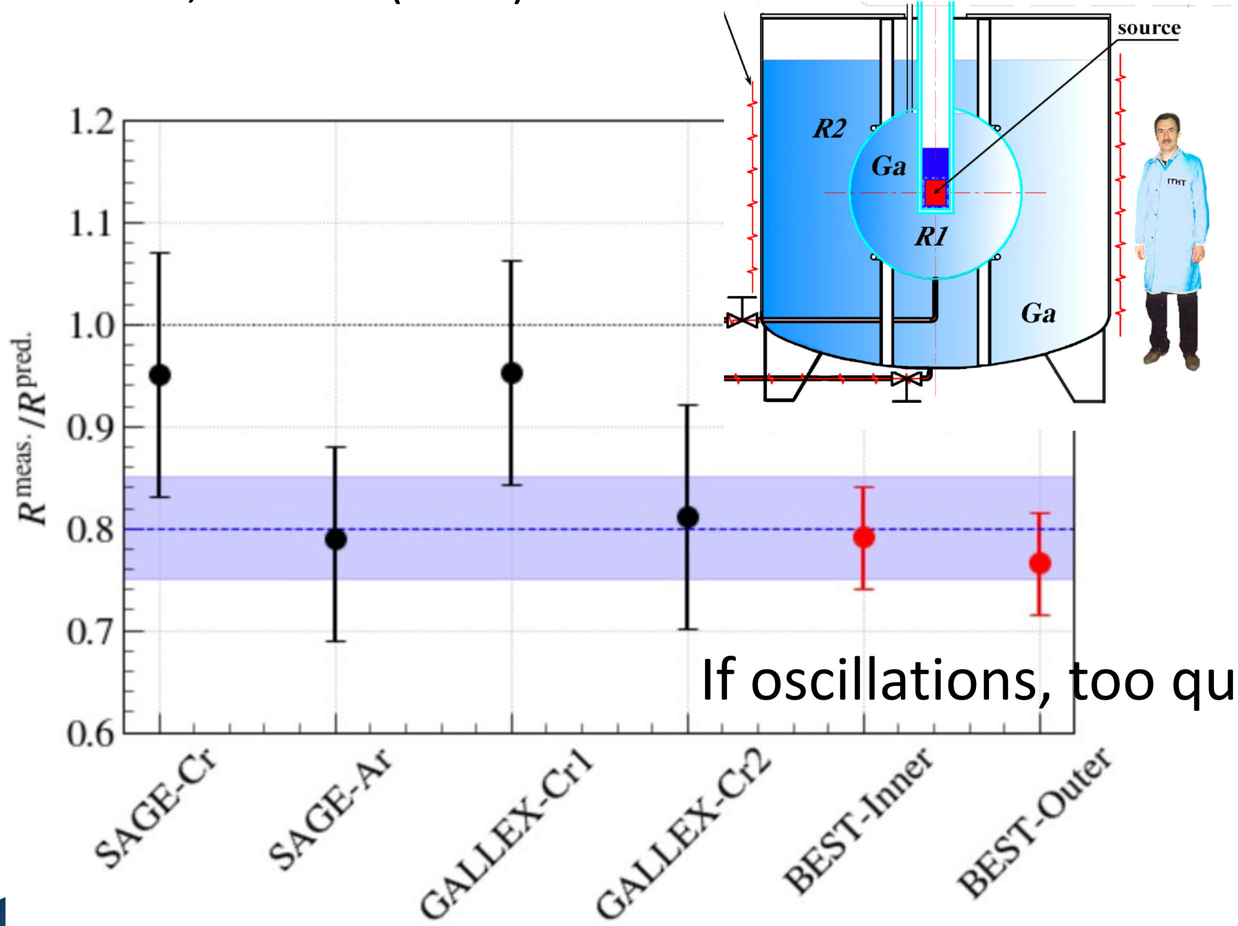




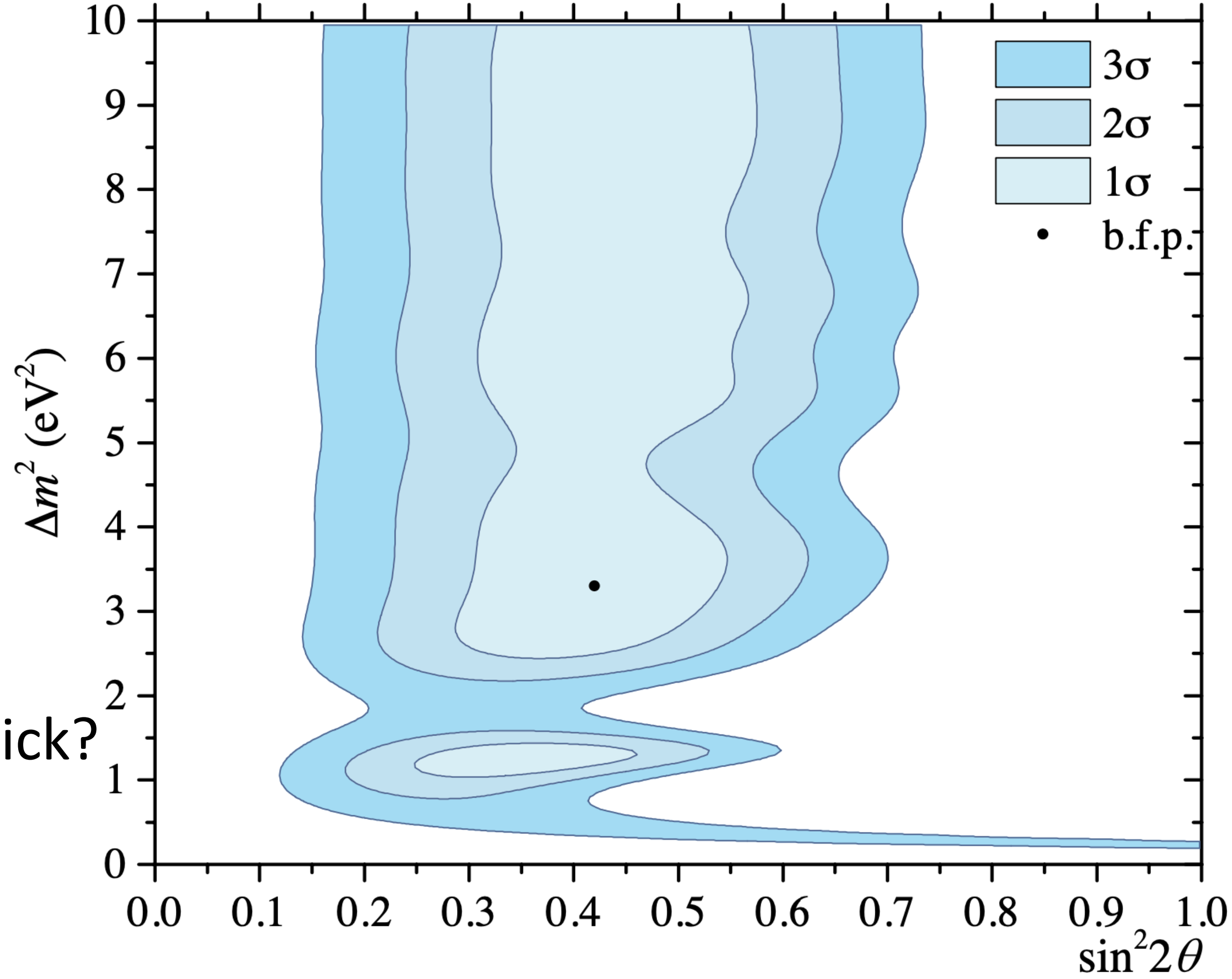
Ga anomaly, The Return™: the BEST exp

Baksan Experiment on Sterile Transitions (BEST)

PRL 128, 232501 (2022)

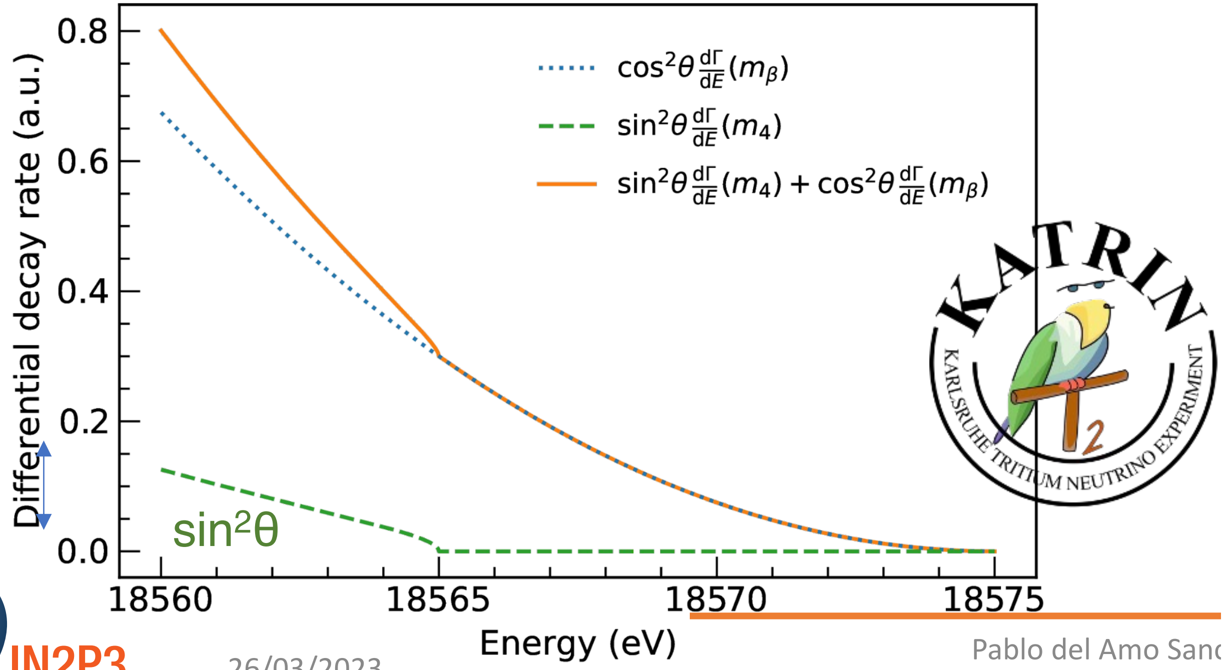


If oscillations, too quick?

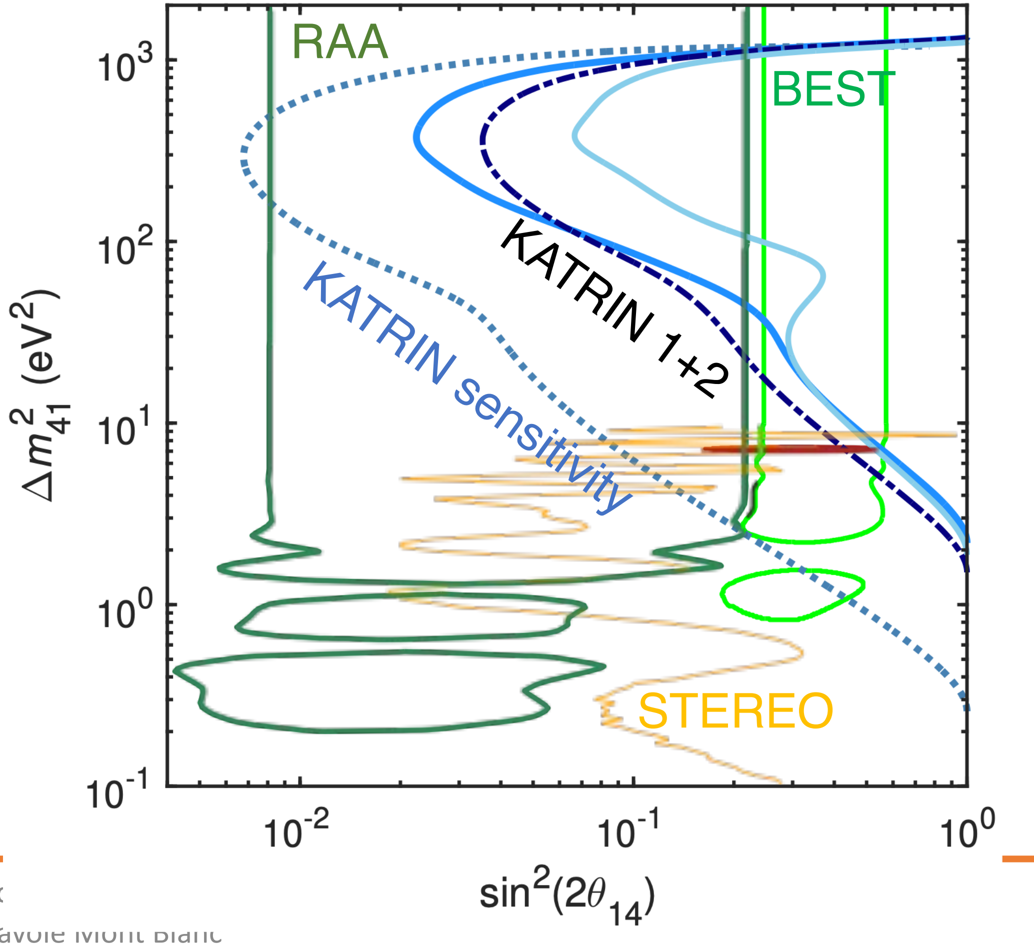


KATRIN

- KATRIN measures β spectrum of $^3H \longrightarrow {}^3He + e^- + \overline{\nu_e}$
- Sterile ν would induce a shoulder in tail
- Reject mostly $\Delta m^2 \gtrsim 10$ eV^2! ⟶ BEST?
- Sensitive to up to $m_{\nu s}$ ~keV!



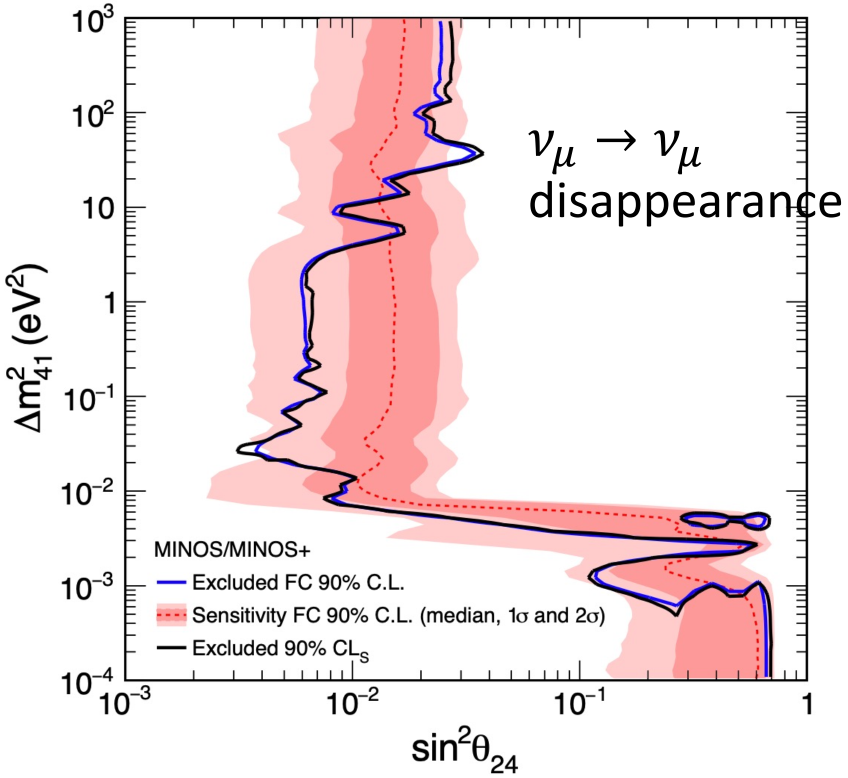
KATRIN Collab.,PRD 105, 072004 (2022)

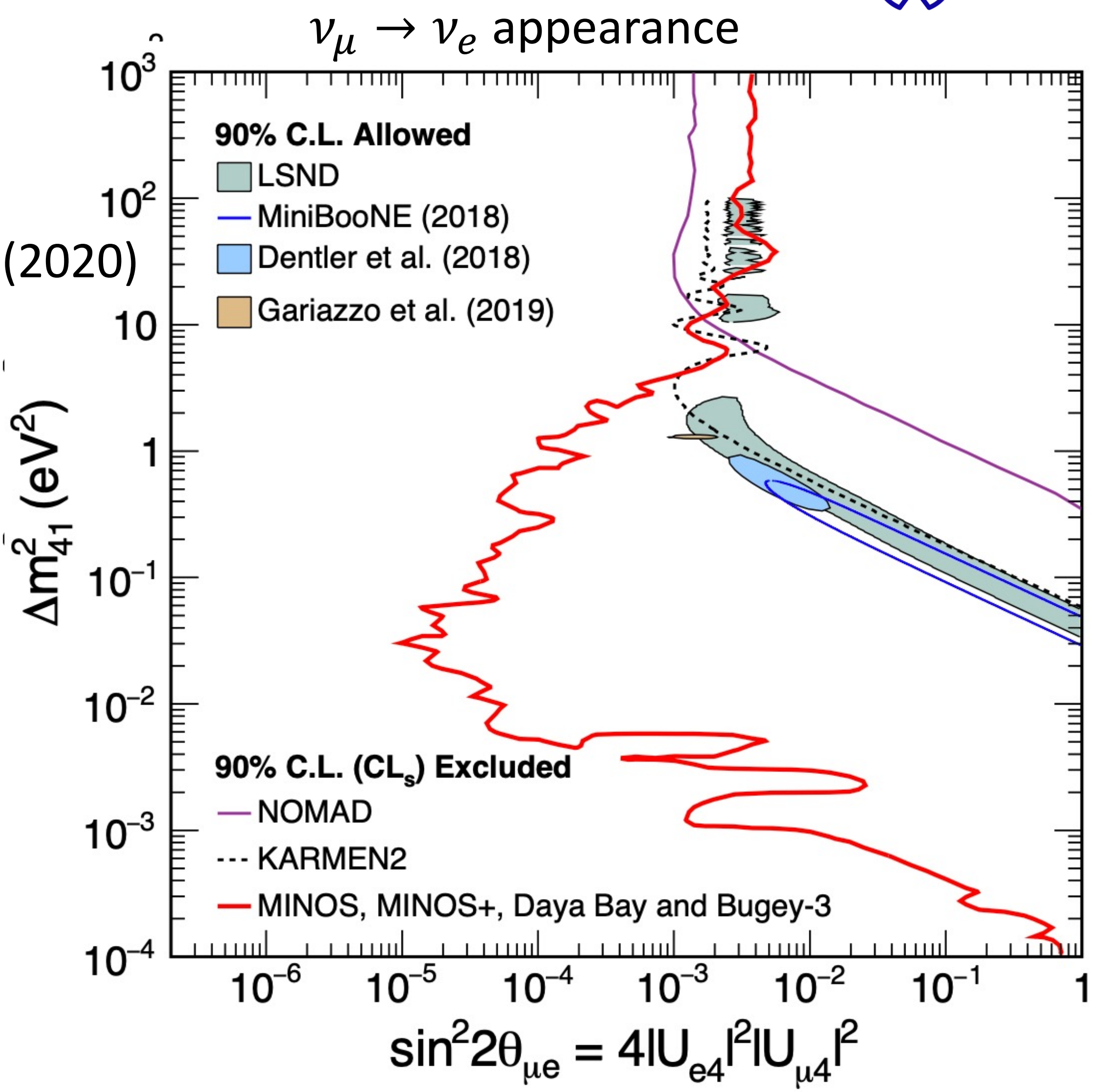


Global fits: 3 active +1 sterile

- In the 3+1 model (3 active+1 sterile), ν_μ disappearance and ν_e disappearance constrain $\nu_\mu \to \nu_e$ appearance (LSND!)
- Extremely disvafoured!!!

PRL **125**, 071801 (2020)

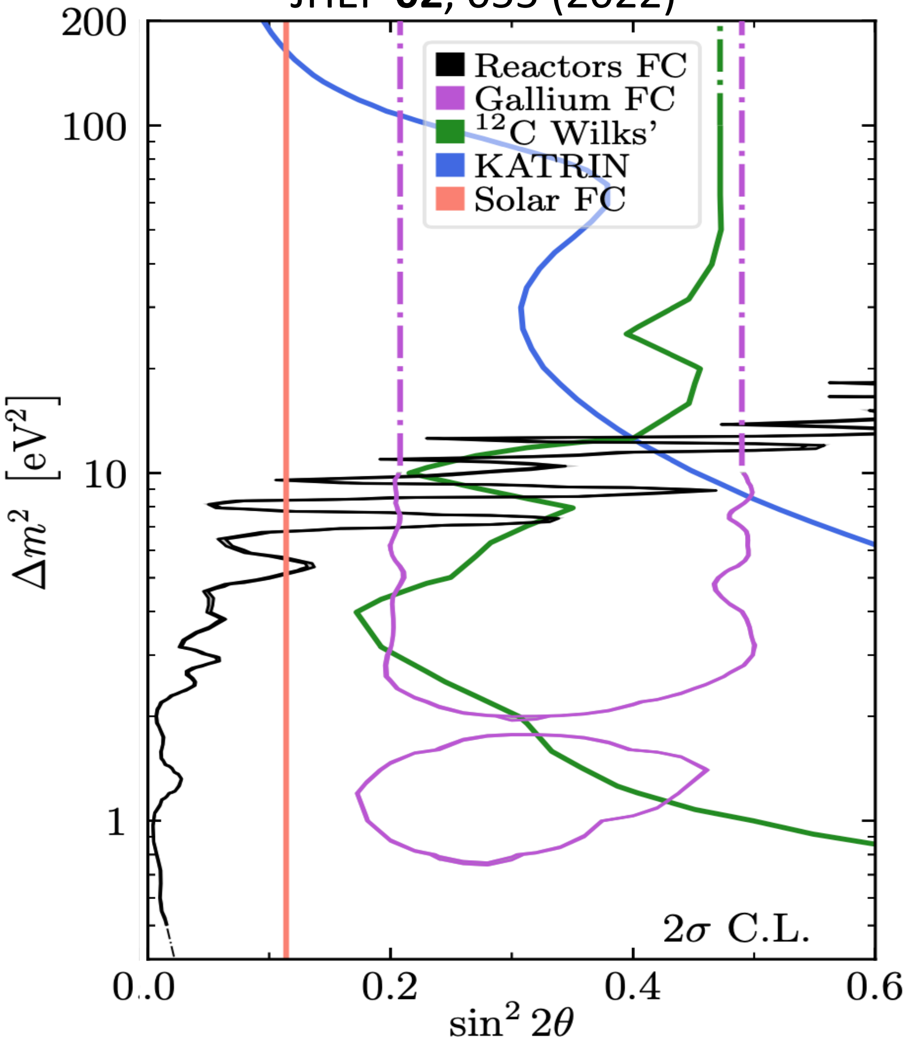




Global fits

- Combination of all reactor experiment + bound from solar neutrinos rejects Ga exp favoured region (Schwetz et al., JHEP **02**, 055 (2022), see also Giunti et al, JHEP 10, 164 (2022))

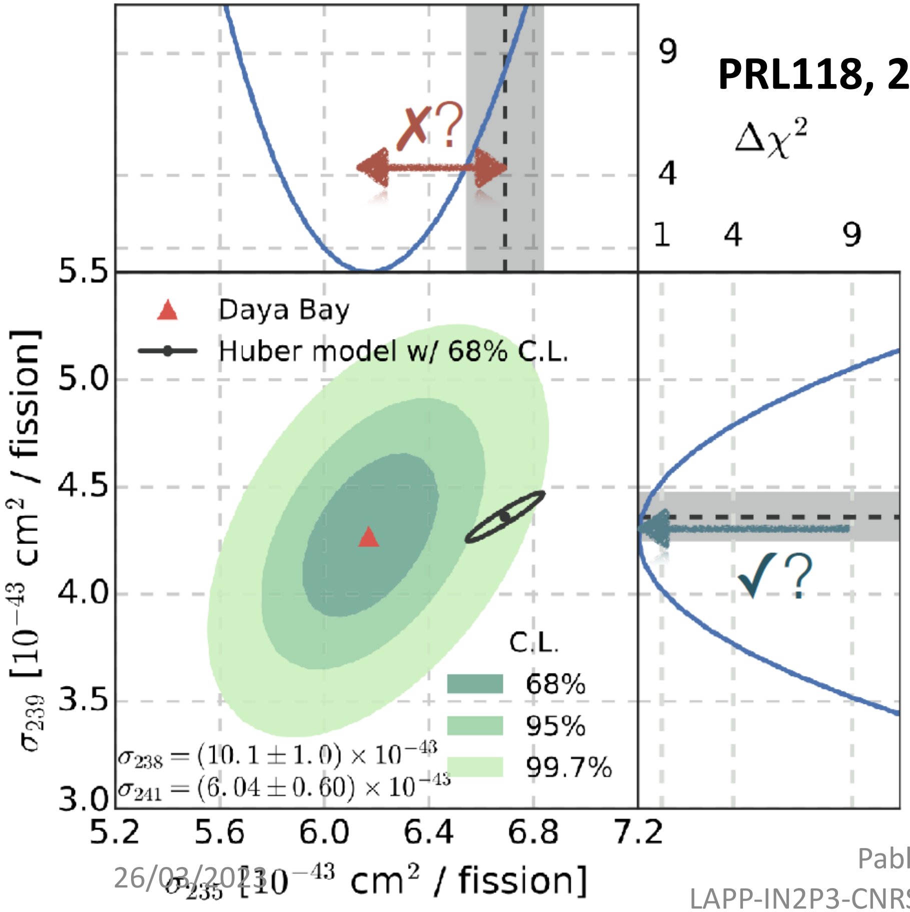
JHEP **02**, 055 (2022)



Reactor Anomaly: a nuclear data problem?

- Daya Bay (2017):

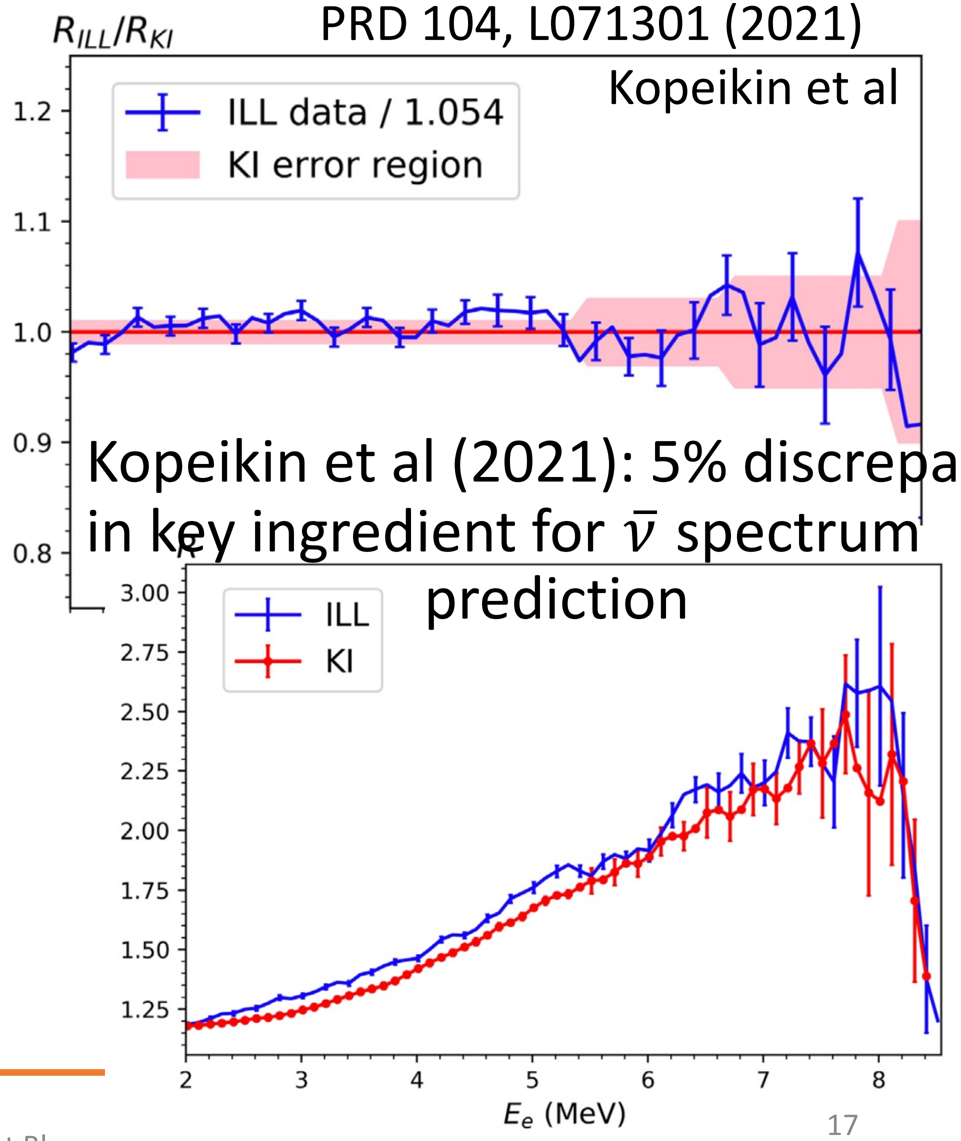
~8% discrepancy in observed ^{235}U xs σ_ν



PRL118, 251801

PRD 104, L071301 (2021)

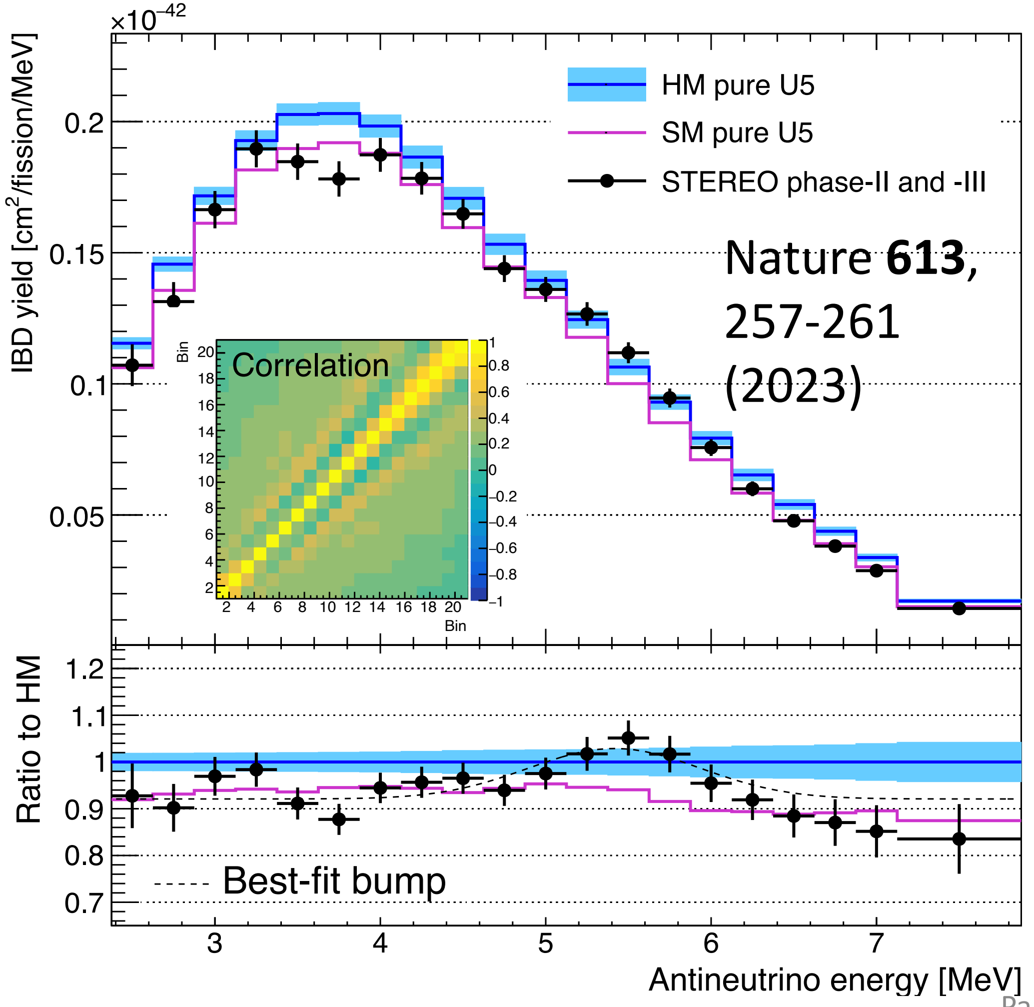
Kopeikin et al



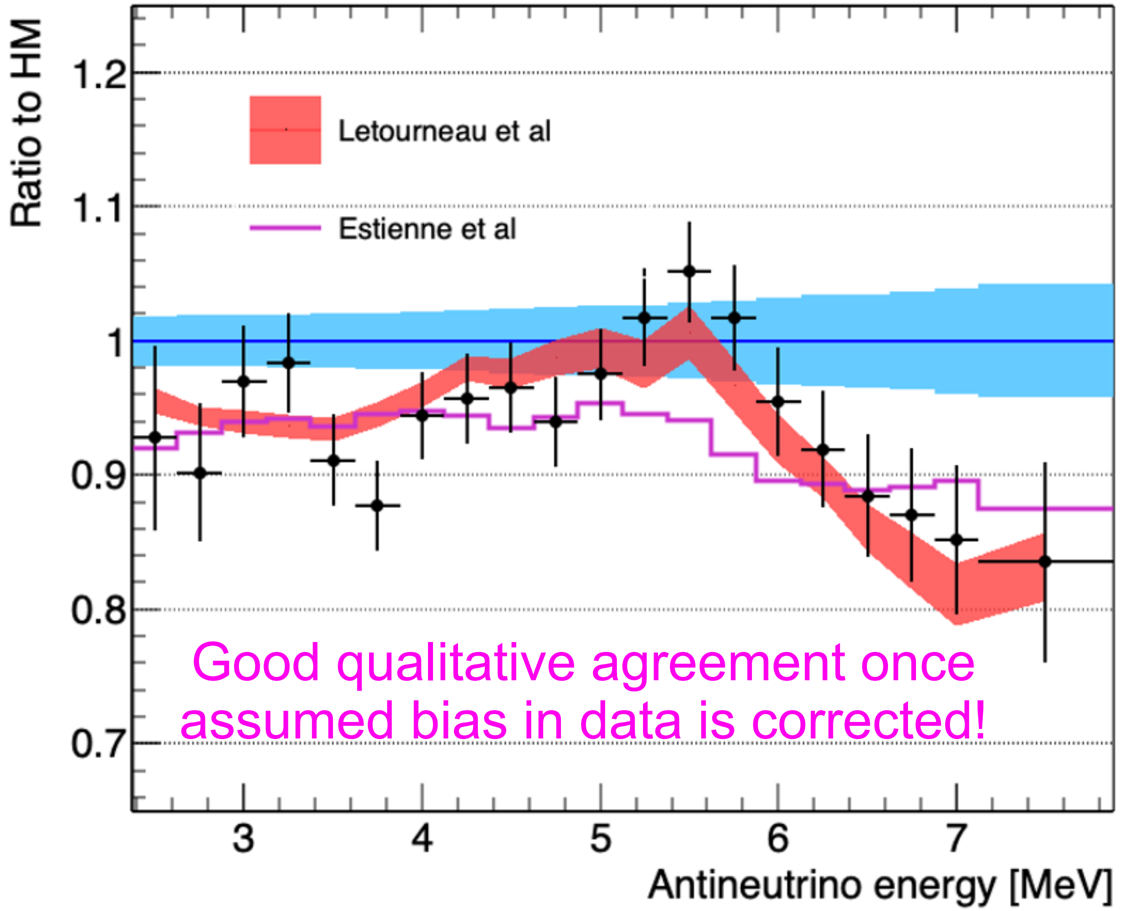
Kopeikin et al (2021): 5% discrepancy in key ingredient for $\bar{\nu}$ spectrum prediction

RAA: a nuclear data problem? STEREO's take

Most precise pure $^{235}U\ \bar{\nu}$ spectrum:

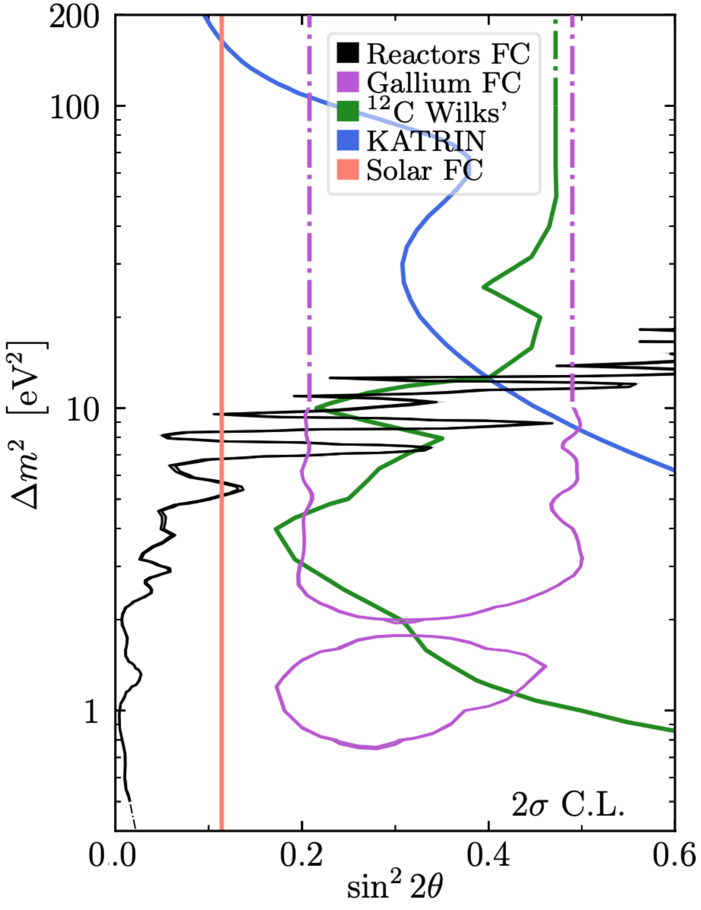


- Test nuclear data with reactor neutrinos!
- A. Letourneau *et al* (PRL 130 (2023) 2, 021801):



Ga anomaly: a nuclear data explanation?

Recent proposals from Giunti et al (arXiv:2212.09722) and Kopp et al (arXiv:2303.05528)

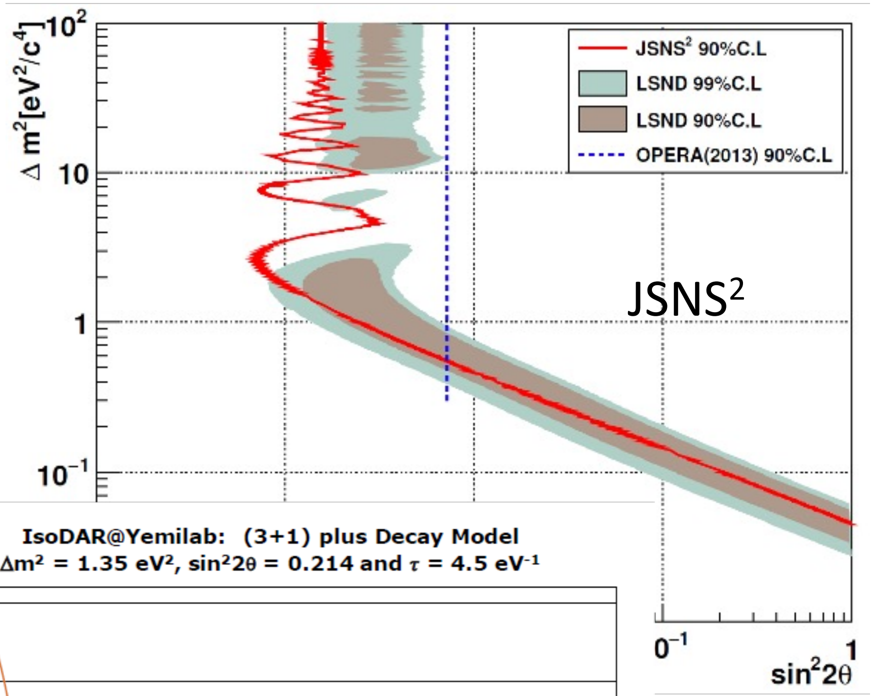


JHEP **02**, 055 (2022)

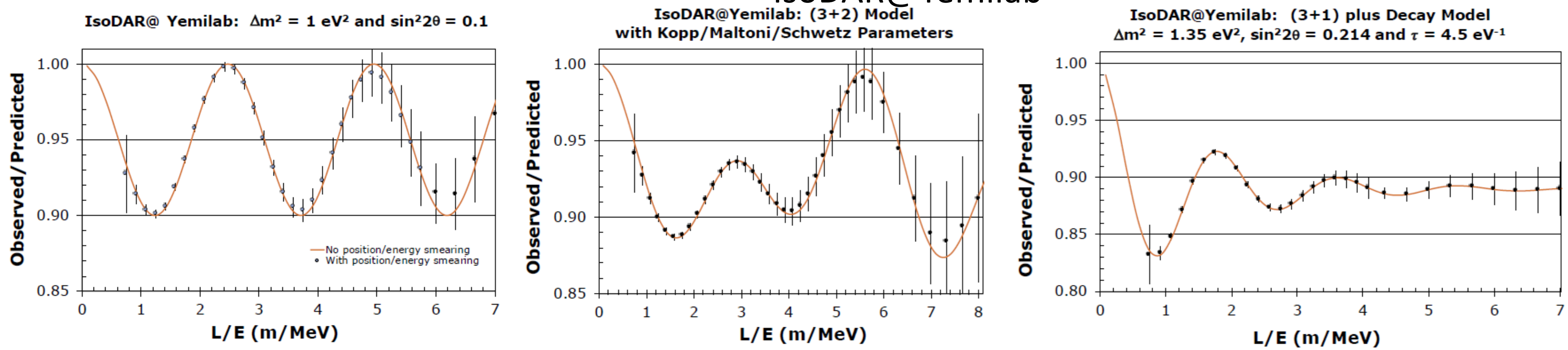
- increase in $T_{1/2}$(^{71}Ge) (significant dispersion in existing measurements)
- excited states (^{71}Ga or ^{71}Ge) could change the xs σ_ν
- 2% errors in ^{51}Cr BR (calorimetric determination of activity)
- ...or BSM physics...

Current and future experiments: JSNS^2, IsoDAR

- JSNS^2: test LSND anomaly, ν_μ from decay-at-rest μ, same IBD technology
- IsoDAR@Yemilab: $^8Li \rightarrow {}^8Be + e^- + \bar{\nu}_e$ Liquid Scintillator detector
- JUNO-TAO, PROSPECT-II…

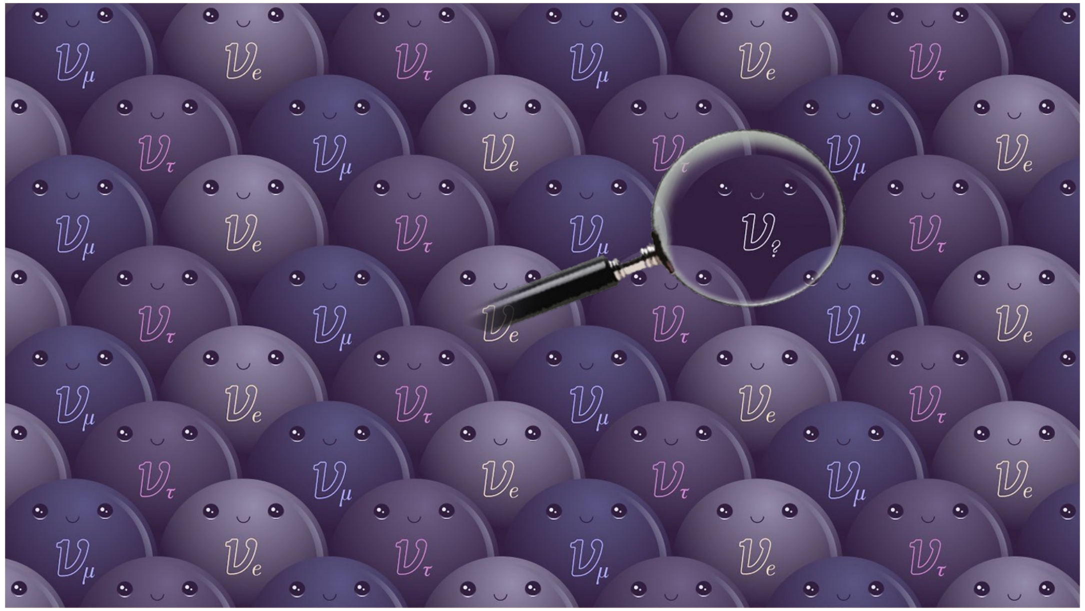


IsoDAR@Yemilab

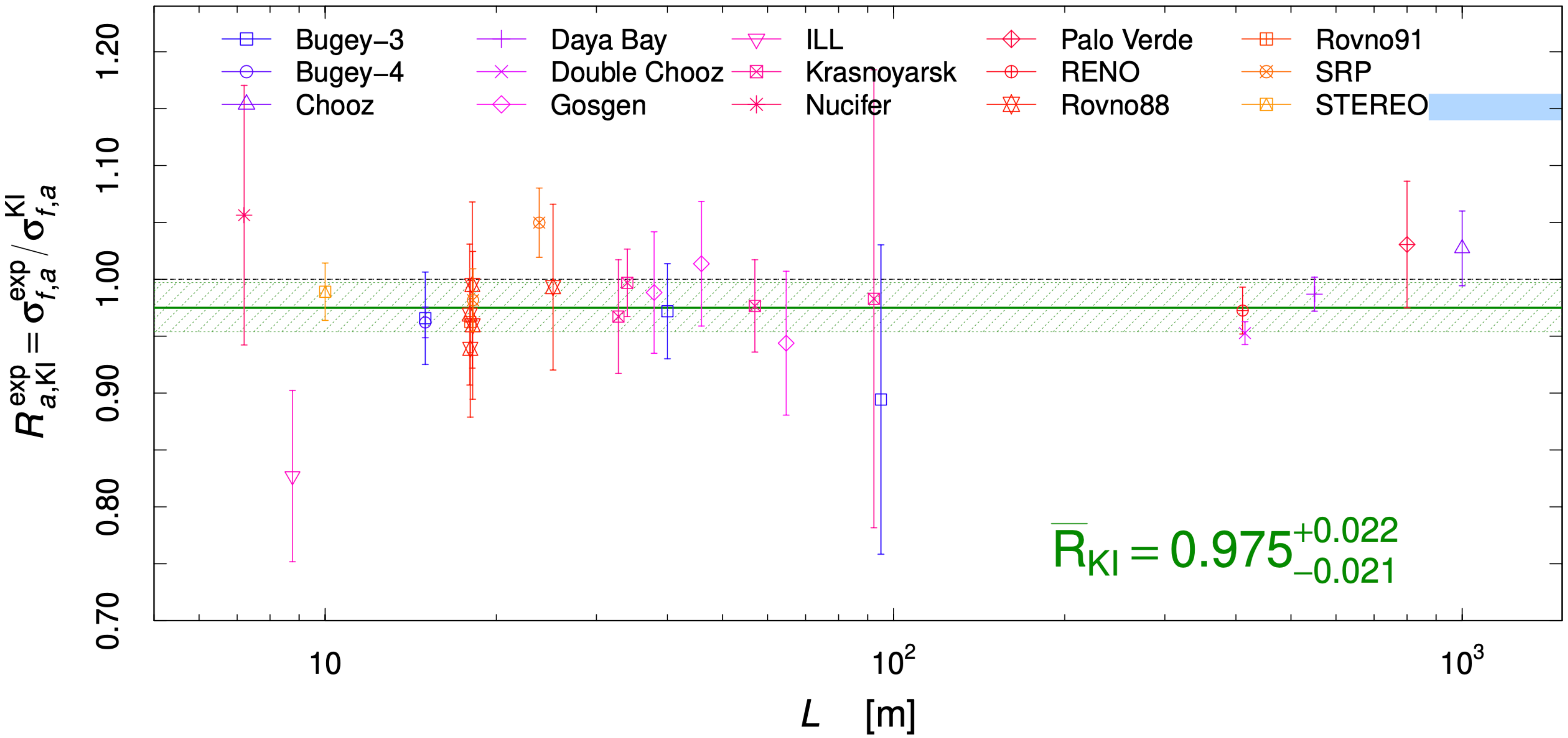


Conclusions

- Sterile neutrinos, missing piece in our understanding of neutrinos
- No evidence of light (~eV^2) sterile neutrinos
- Reactor Antineutrino Anomaly solved, Ga Anomaly on the way?
- Still no final answer for the LSND/MiniBooNE saga → $JSNS^2$?
- Honed many tools for the future along the way!
- Exciting future experiments/results!

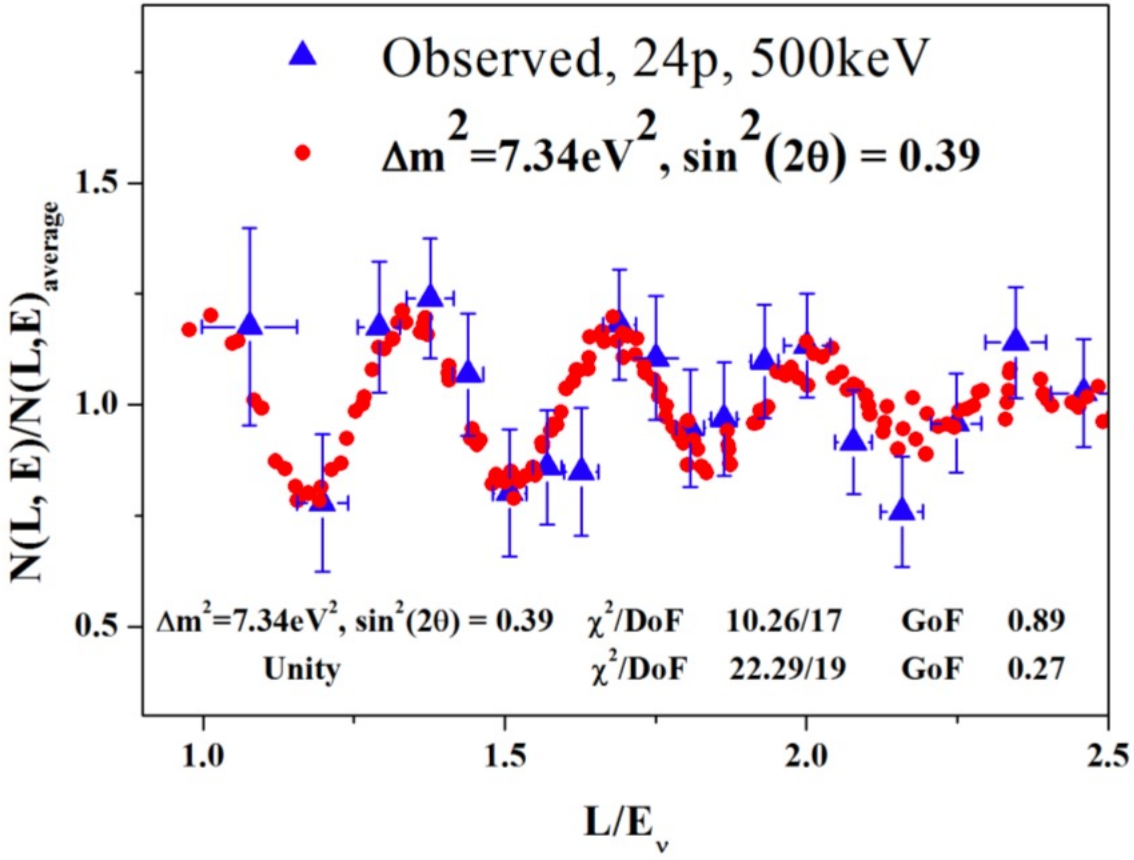


Reactor Antineutrino Anomaly today

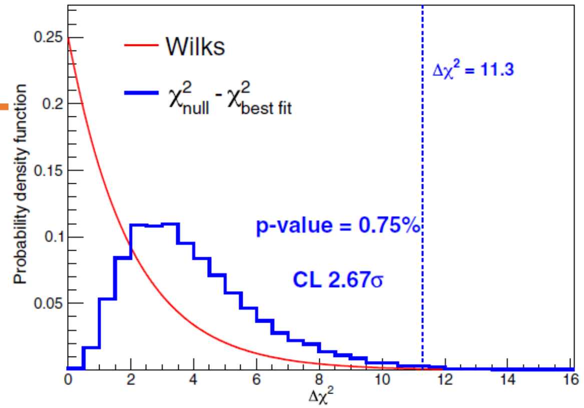


Giunti et al.
Phys.Lett.B829,137054
No RAA (1.1 σ)

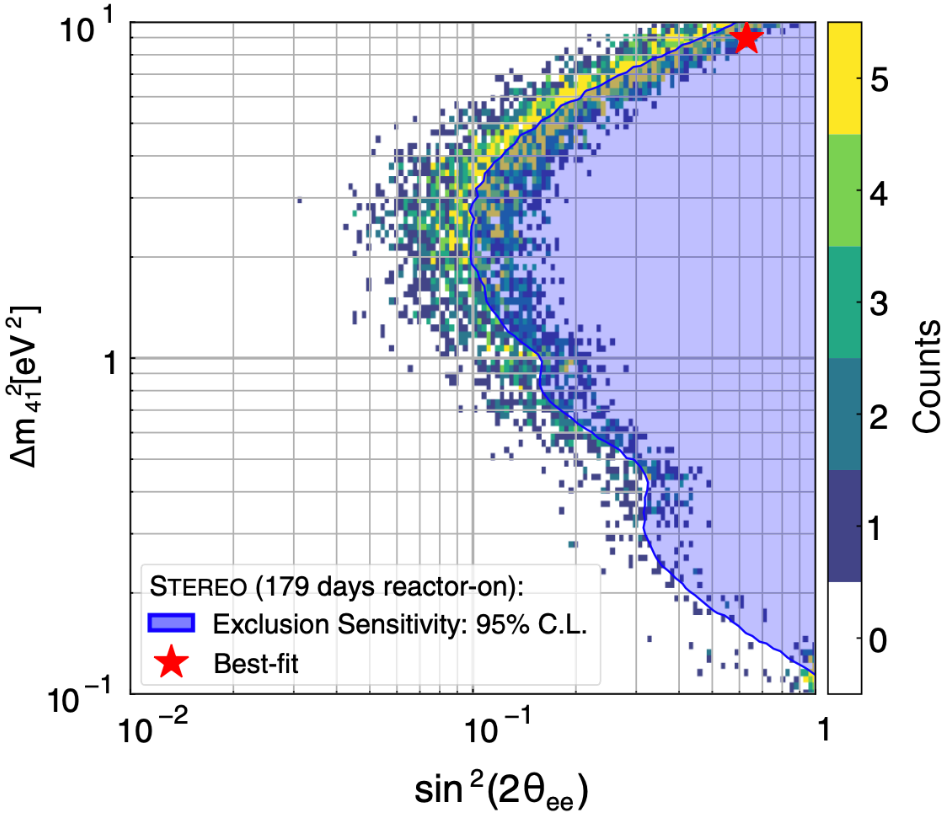
Neutrino-4



Observed, 24p, 500keV
Δm²=7.34eV², sin²(2θ) = 0.39
N(L, E)/N(L,E)average
Δm²=7.34eV², sin²(2θ) = 0.39 χ²/DoF 10.26/17 GoF 0.89
Unity χ²/DoF 22.29/19 GoF 0.27
L/Eν



Wilks
χ²null - χ²best fit
Δχ² = 11.3
p-value = 0.75%
CL 2.67σ
Probability density function
Δχ²



STEREO (179 days reactor-on):
Exclusion Sensitivity: 95% C.L.
Best-fit
Δm²41[eV²]
sin²(2θee)
Counts

Aside: ν spectrum prediction

- Complex spectrum:
  - Thousands of branches
  - Forbidden transitions
  - Poorly known unstable nuclei
  - Dependence on core configuration and history (burnup)

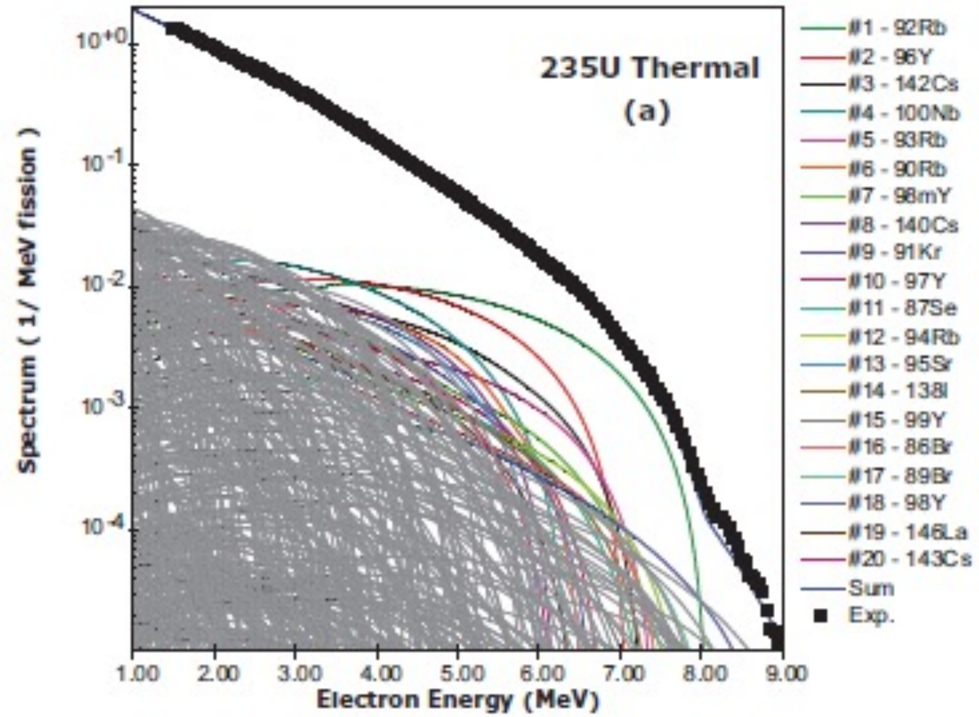
- The summation method

P. Vogel et al, Phys. Rev. C 24, 1543 (1981)

Weighted sum of contributions of each decay using nuclear databases (JEFF, ENDF)

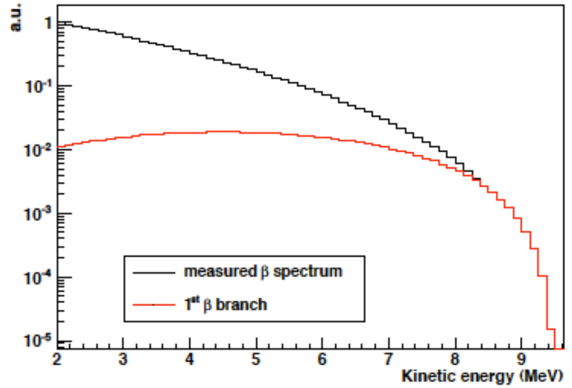
- The conversion method

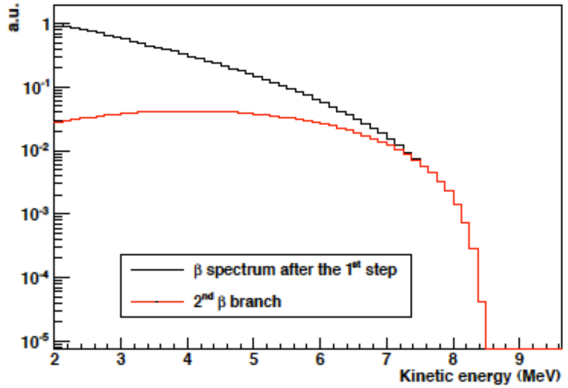
A.A. Sonzogni et al., PRC91, 011301 (2015)

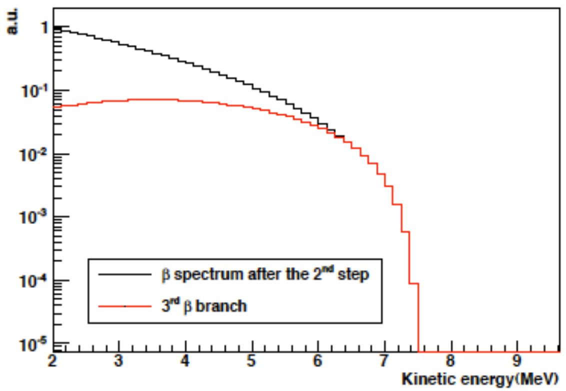


Aside: ν spectrum prediction

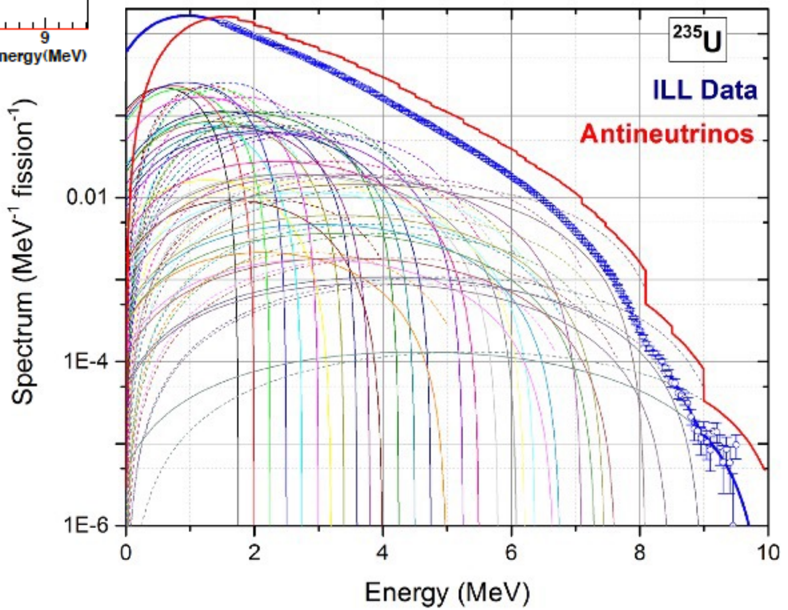
- The conversion method: *K. Schreckenbach et al., Phys. Lett. 99B, 251 (1981).*
  - Irradiate ^{235}U, ^{239}Pu or ^{241}Pu target foils with thermal n; measure resulting β spectrum
  - Convert e- in ν spectra by removing "effective β branches" *Phys. Lett. 160B, 325 (1985)*

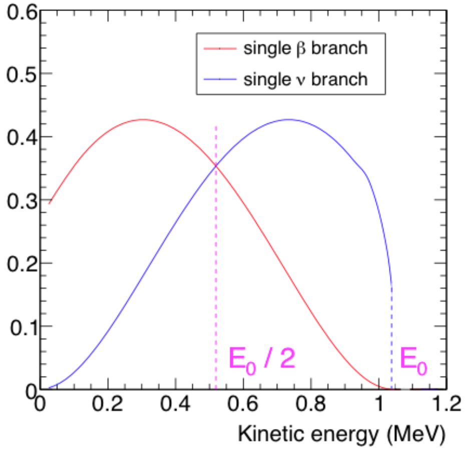


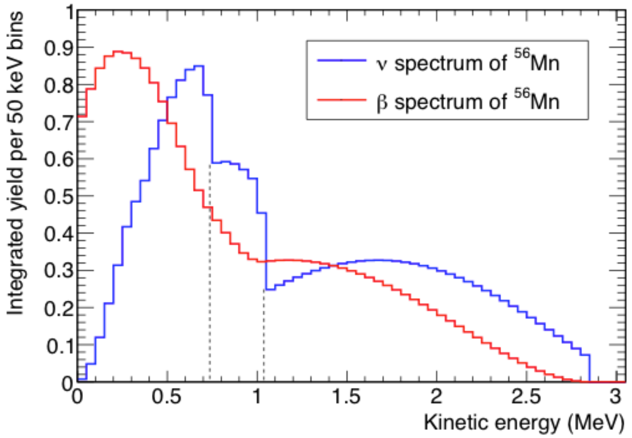




30 virtual branches







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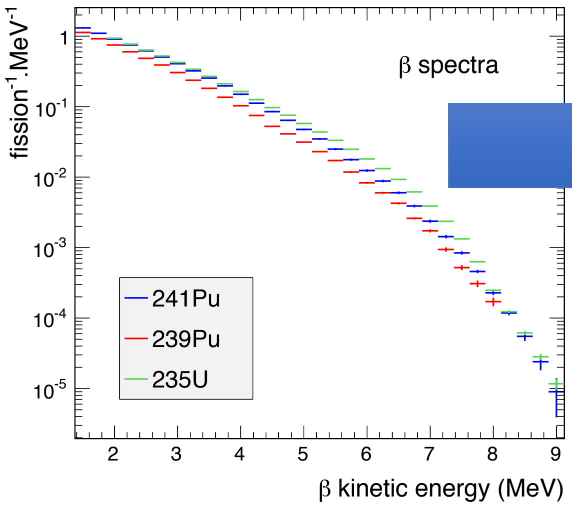
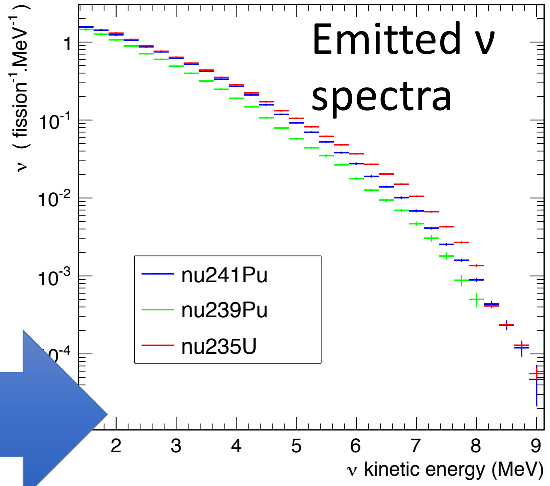
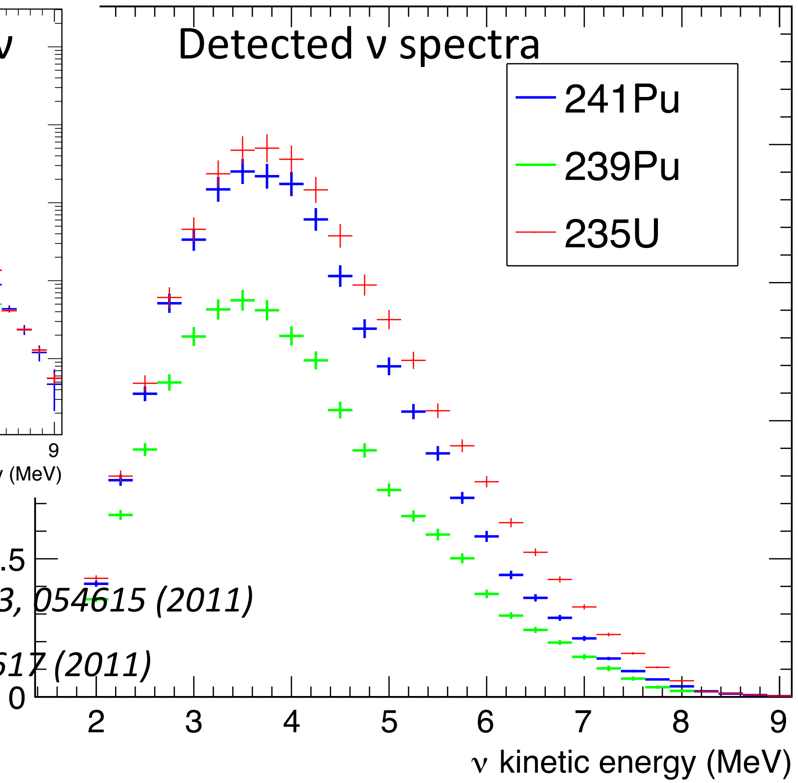
  - Irradiate ^{235}U, ^{239}Pu or ^{241}Pu target foils with thermal n; measure resulting β spectrum
  - Convert e- in ν spectra by removing “effective β branches” *Phys. Lett. 160B, 325 (1985)*







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

P. Huber, Phys. Rev. C84, 024617 (2011)