# Short-baseline neutrino anomalies

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ALPs'23 Workshop, Obergurgl (March 30th , 2023)

Instituto de Física Teórica UAM-CSIC

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MINISTERIO DE CIENCIA E INNOVACIÓN
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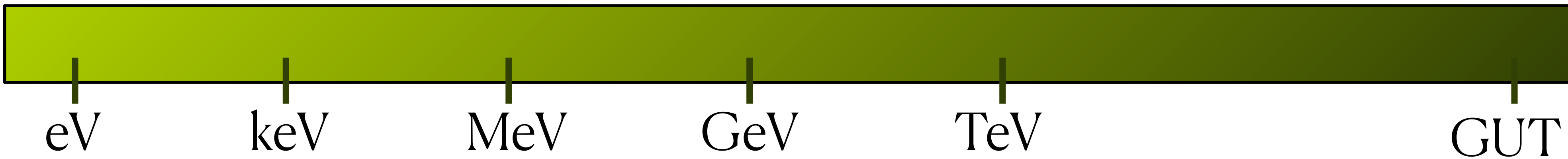
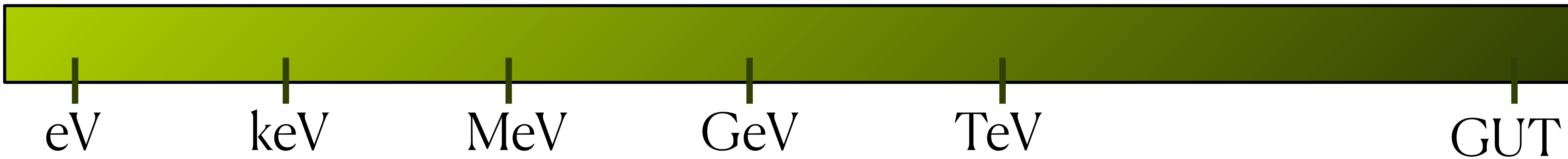
EXCELENCIA SEVERO OCHOA

# Sterile neutrino searches

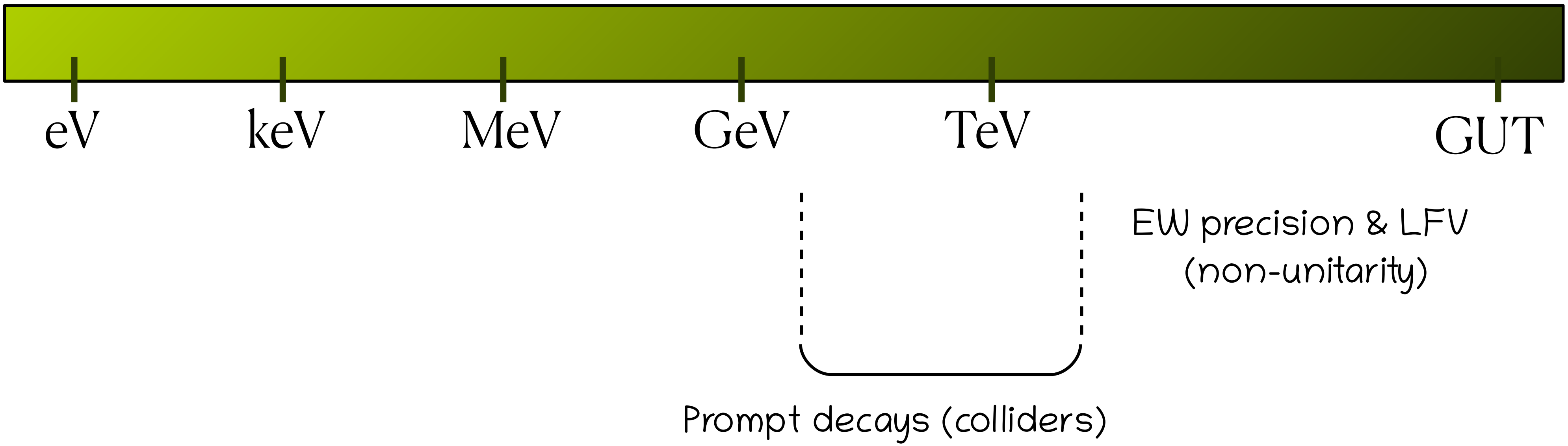


# Sterile neutrino searches

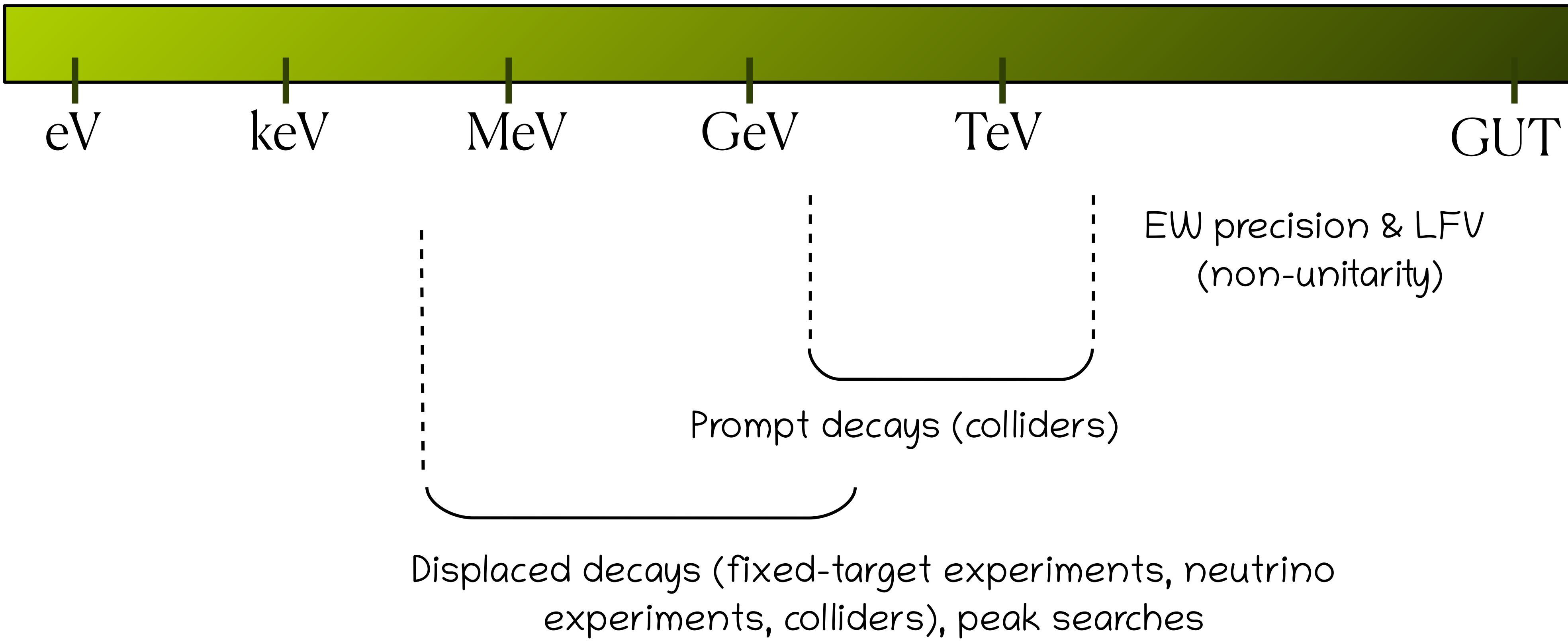



EW precision & LFV
(non-unitarity)

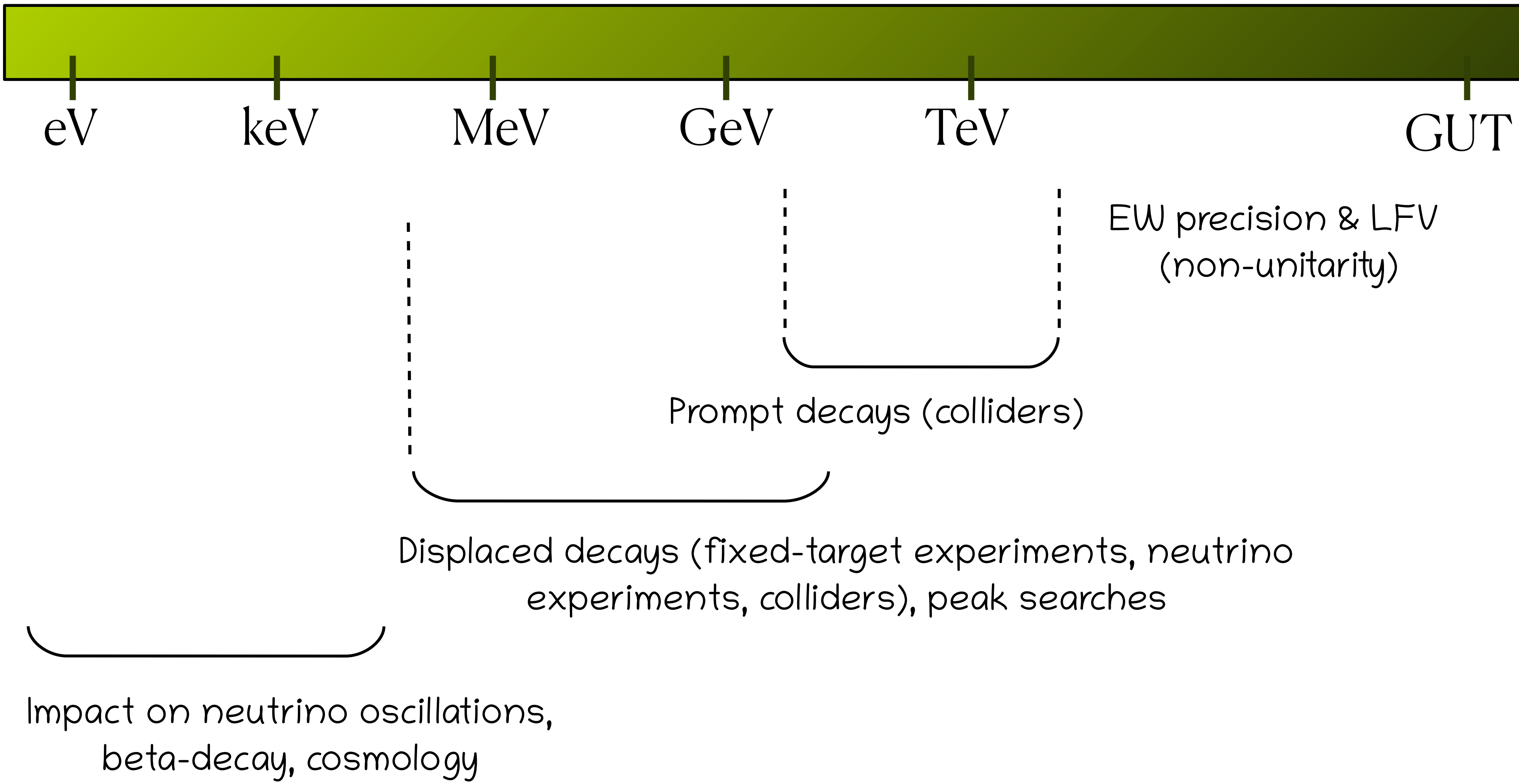
# Sterile neutrino searches



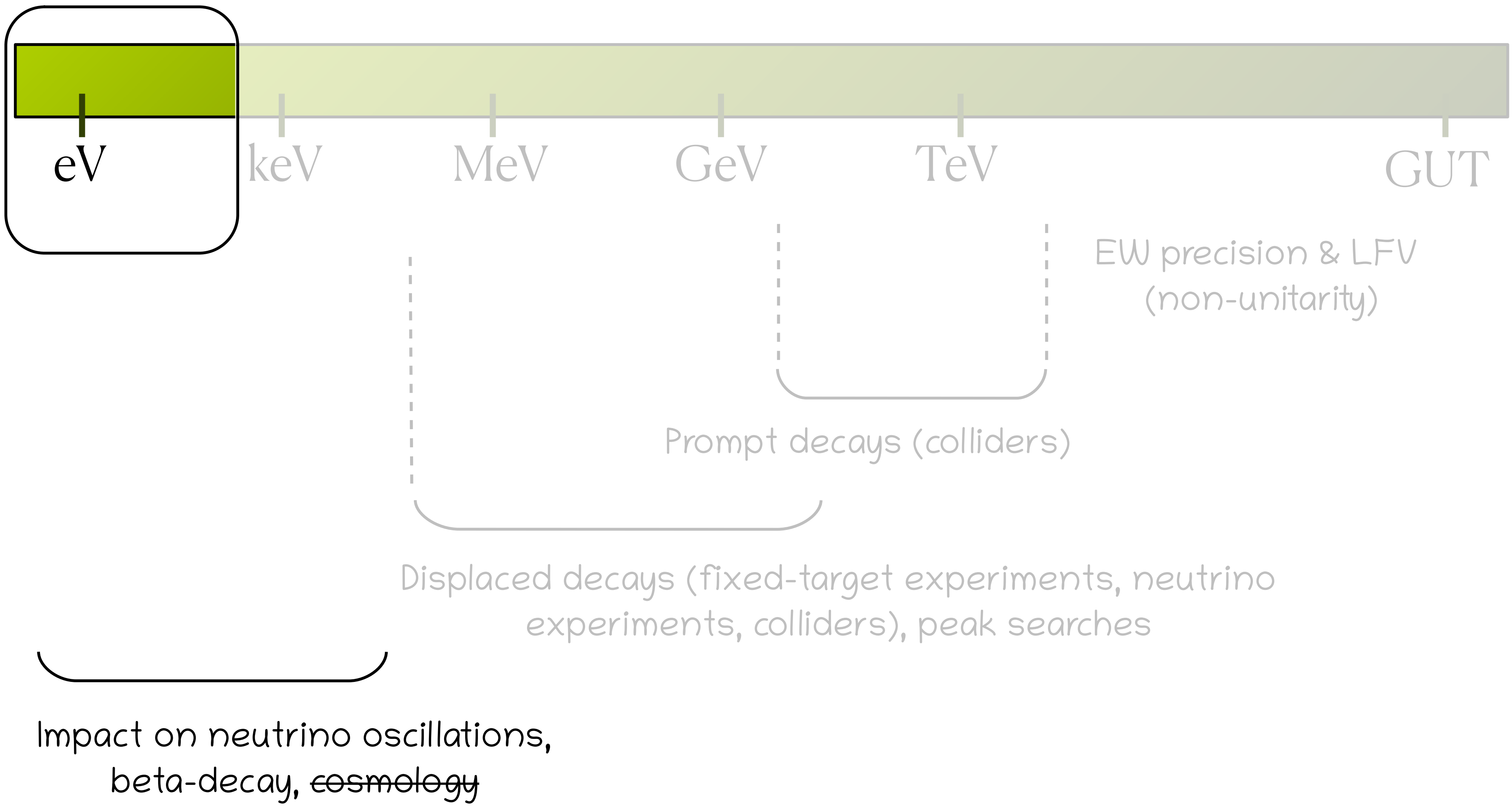
# Sterile neutrino searches



# Sterile neutrino searches



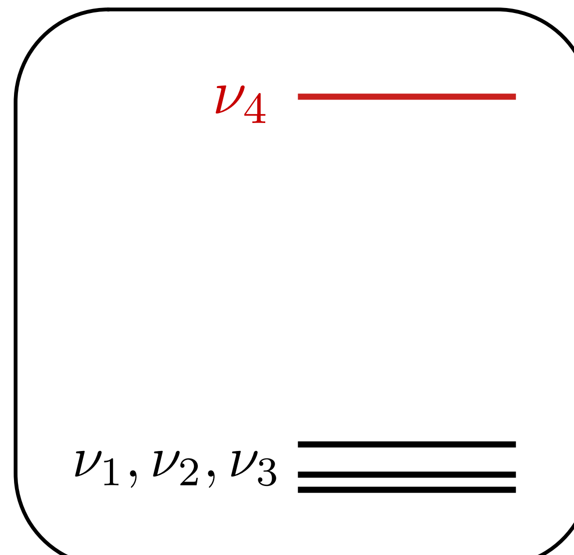
# Sterile neutrino searches



# eV-scale sterile neutrinos


$$i\frac{d}{dt}\Psi_\nu = (UH_0U^\dagger + V)\Psi_\nu$$

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




Oscillations depend on

$$\frac{\Delta m^2 L}{4E} \simeq 1.27\frac{\Delta m^2(\mathrm{eV})L(\mathrm{m})}{E(\mathrm{MeV})}$$

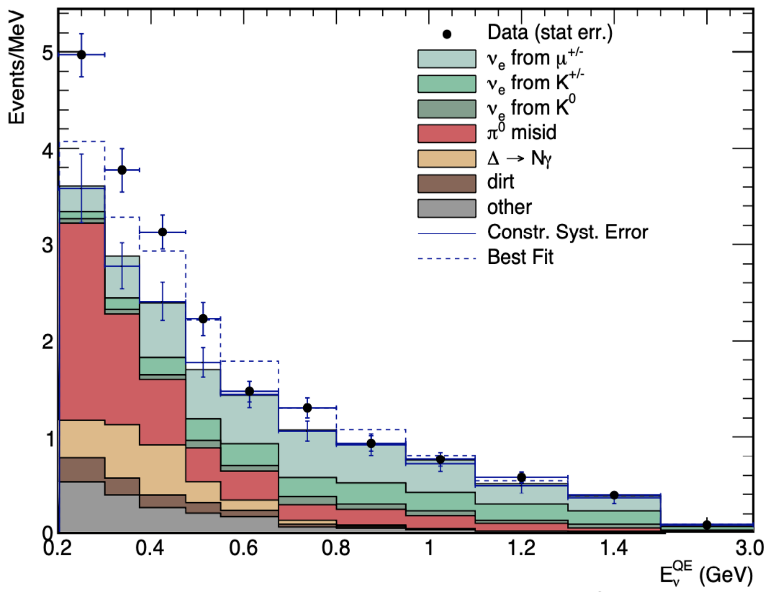
# $\nu_e$ and $\bar{\nu}_e$ appearance ($P_{\mu e}$)

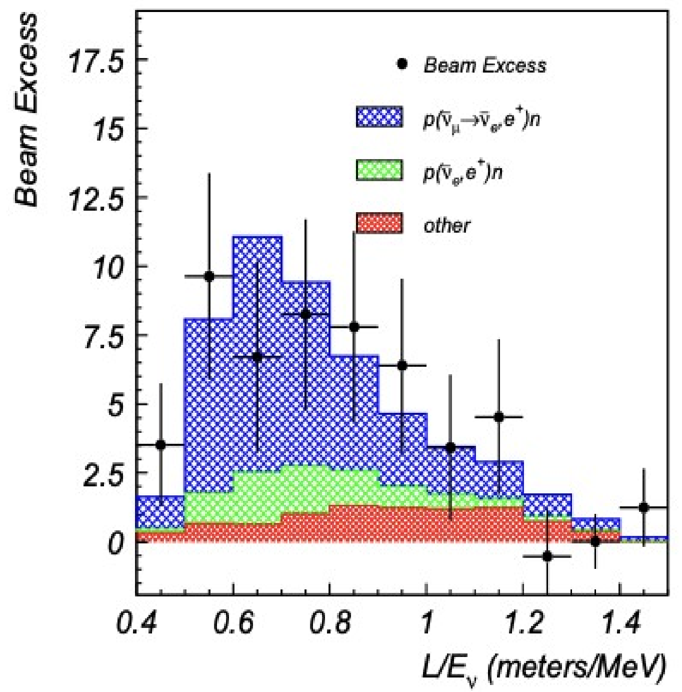
$$P_{\mu e} = \sin^2 2\theta_{\mu e} \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

$$4|U_{e4}|^2|U_{\mu 4}|^2$$

LSND
MiniBooNE
MicroBooNE

# eV-scale sterile neutrinos

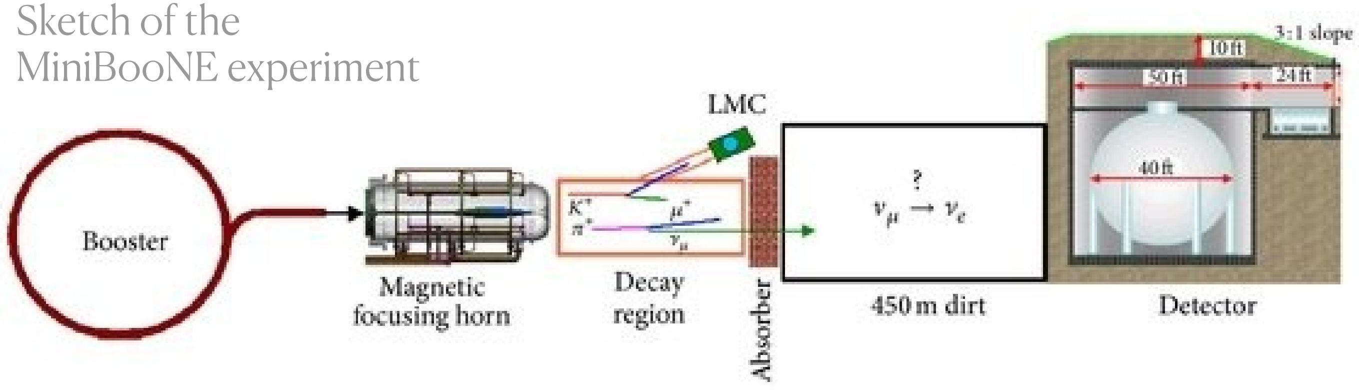


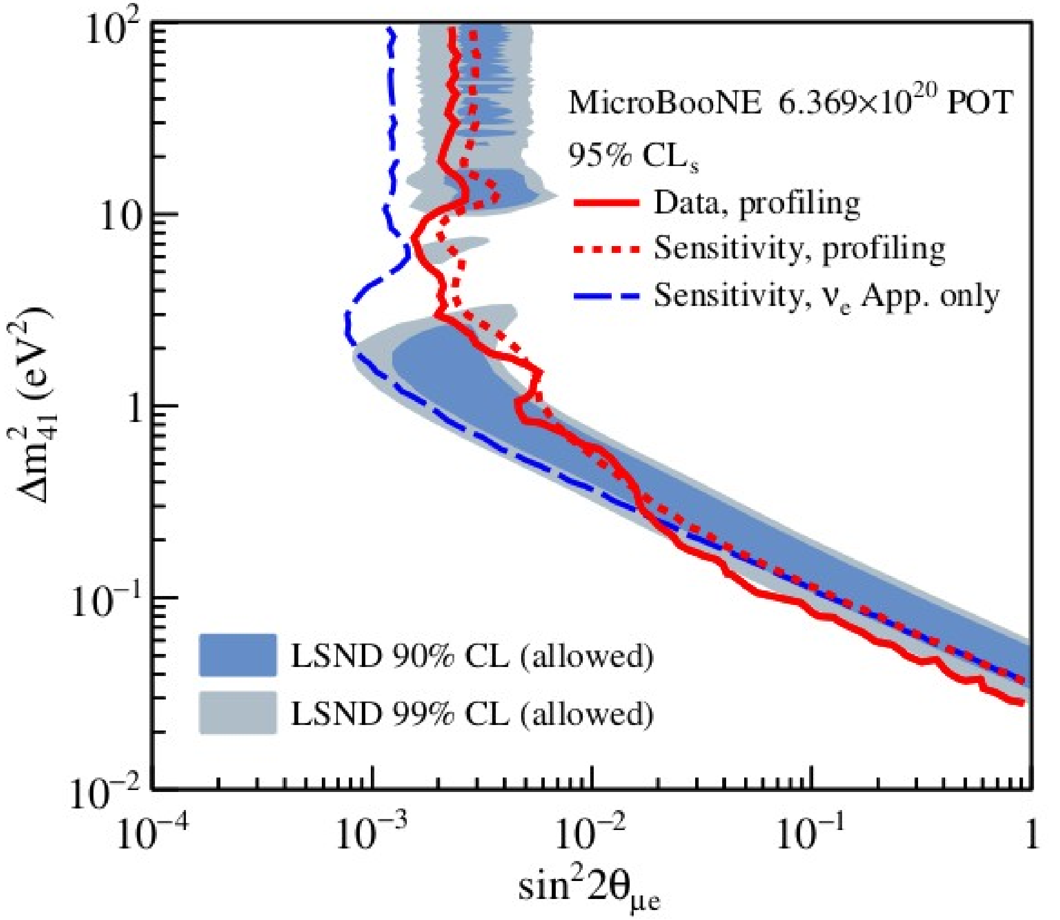

MiniBooNE: ~4.8σ
LSND: ~3.8σ

LSND coll., hep-ex/0104049
MiniBooNE coll.,1805.12028

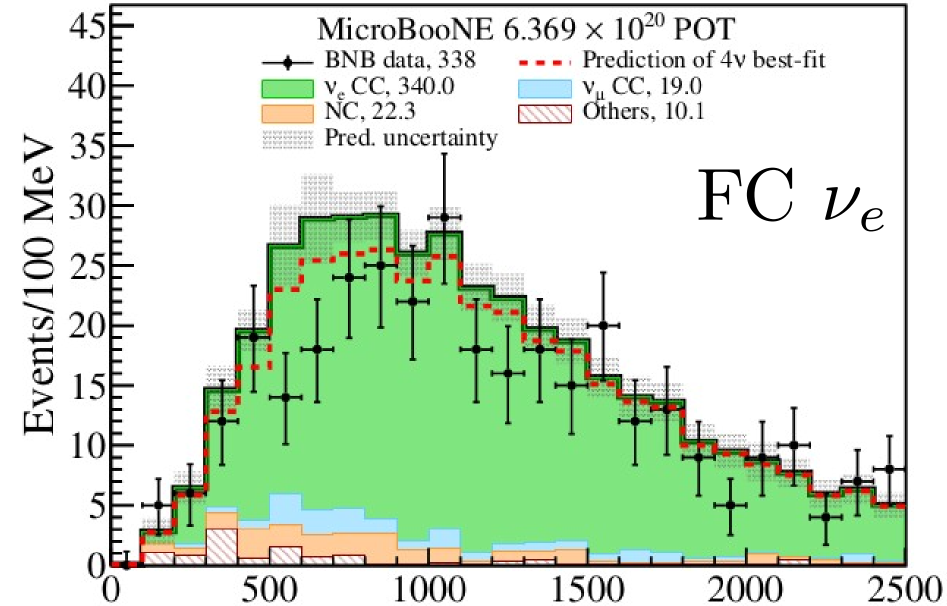
Sketch of the MiniBooNE experiment

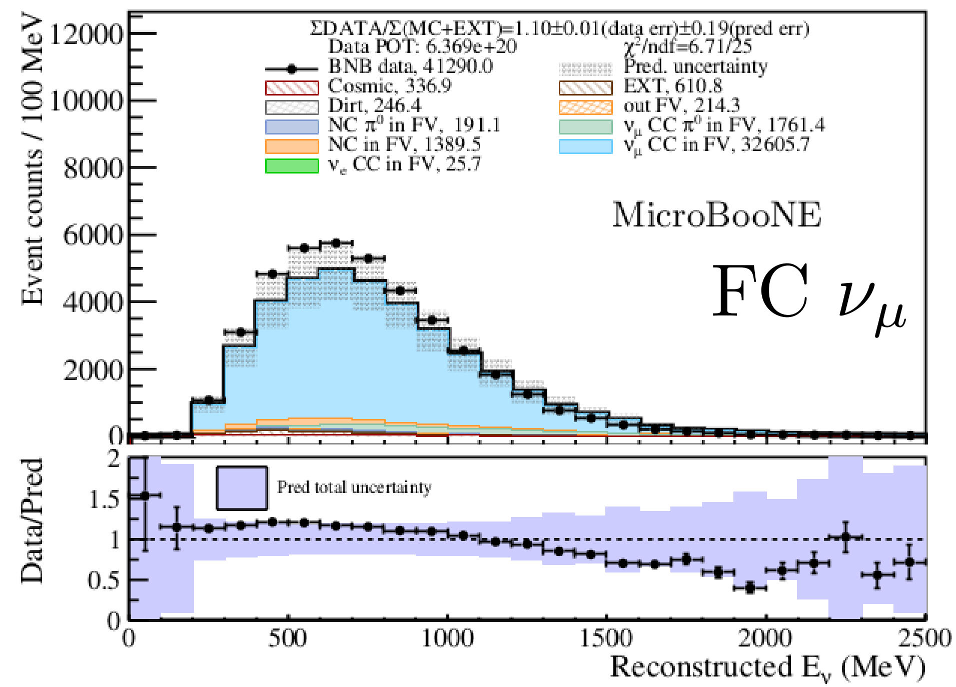


# MicroBooNE




MicroBooNE coll., 2210.10216



# $\nu_e$ and $\bar{\nu}_e$ disappearance ($P_{ee}$)

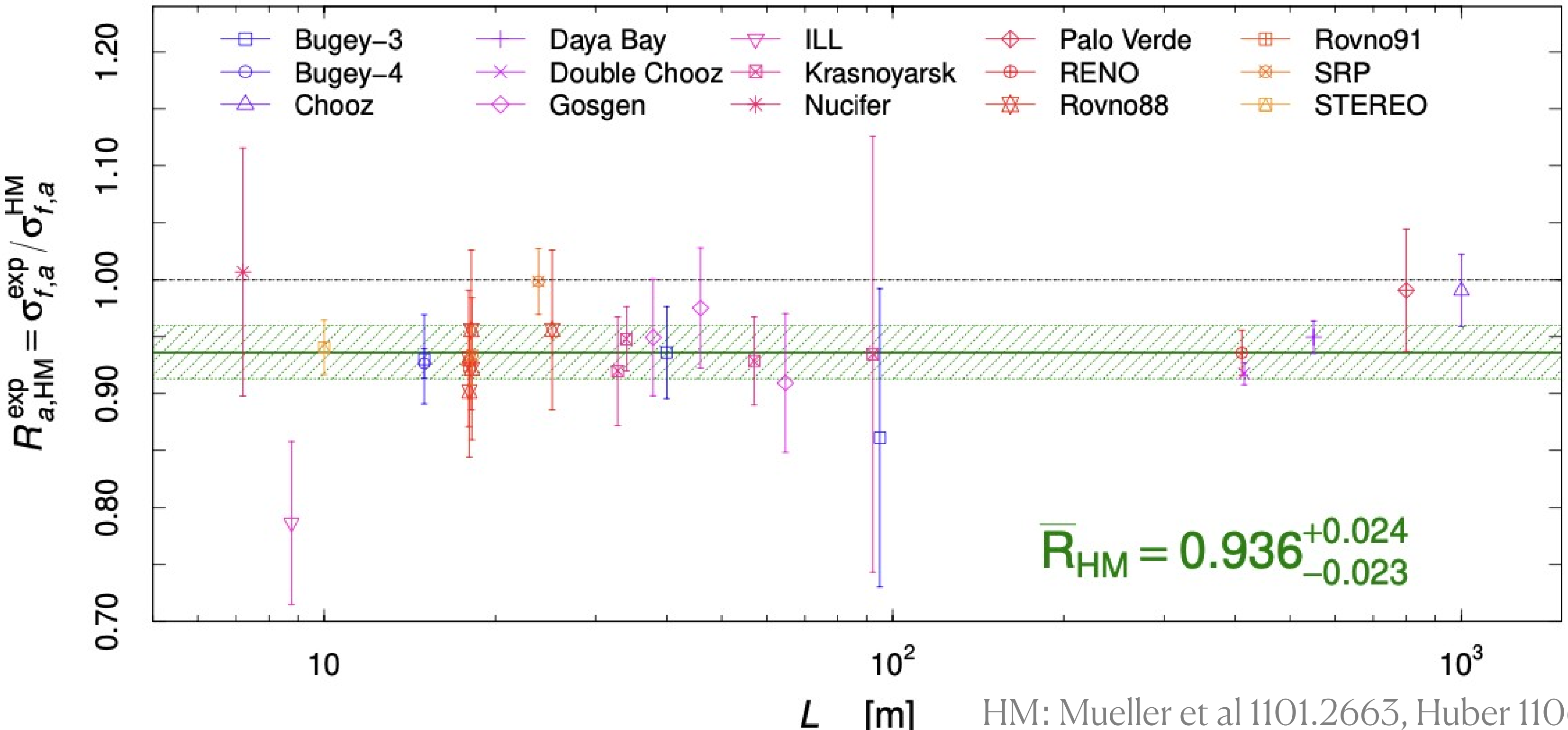
$$P_{ee} \equiv P(\nu_e \to \nu_e) = 1 - \sin^2 2\theta_{ee} \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

$$4|U_{e4}|^2(1 - |U_{e4}|^2)$$

Reactors
Gallium experiments
Solar neutrinos

# Reactor antineutrino anomaly

Situation in 2011:

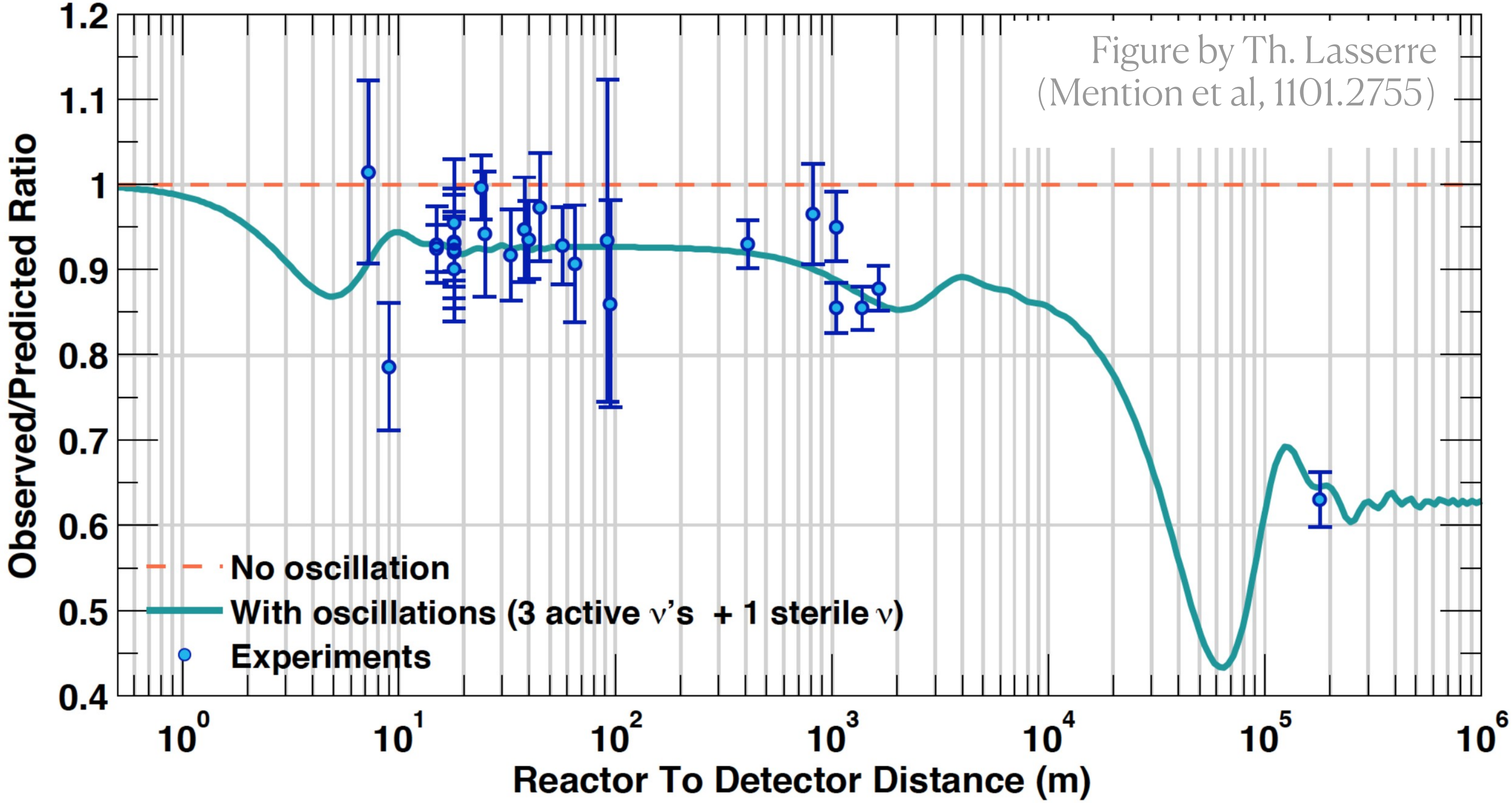



HM: Mueller et al 1101.2663, Huber 1106.0687; Mention et al, 1101.2755

Figure from Giunti, Li, Ternes, Xin, 2110.06820

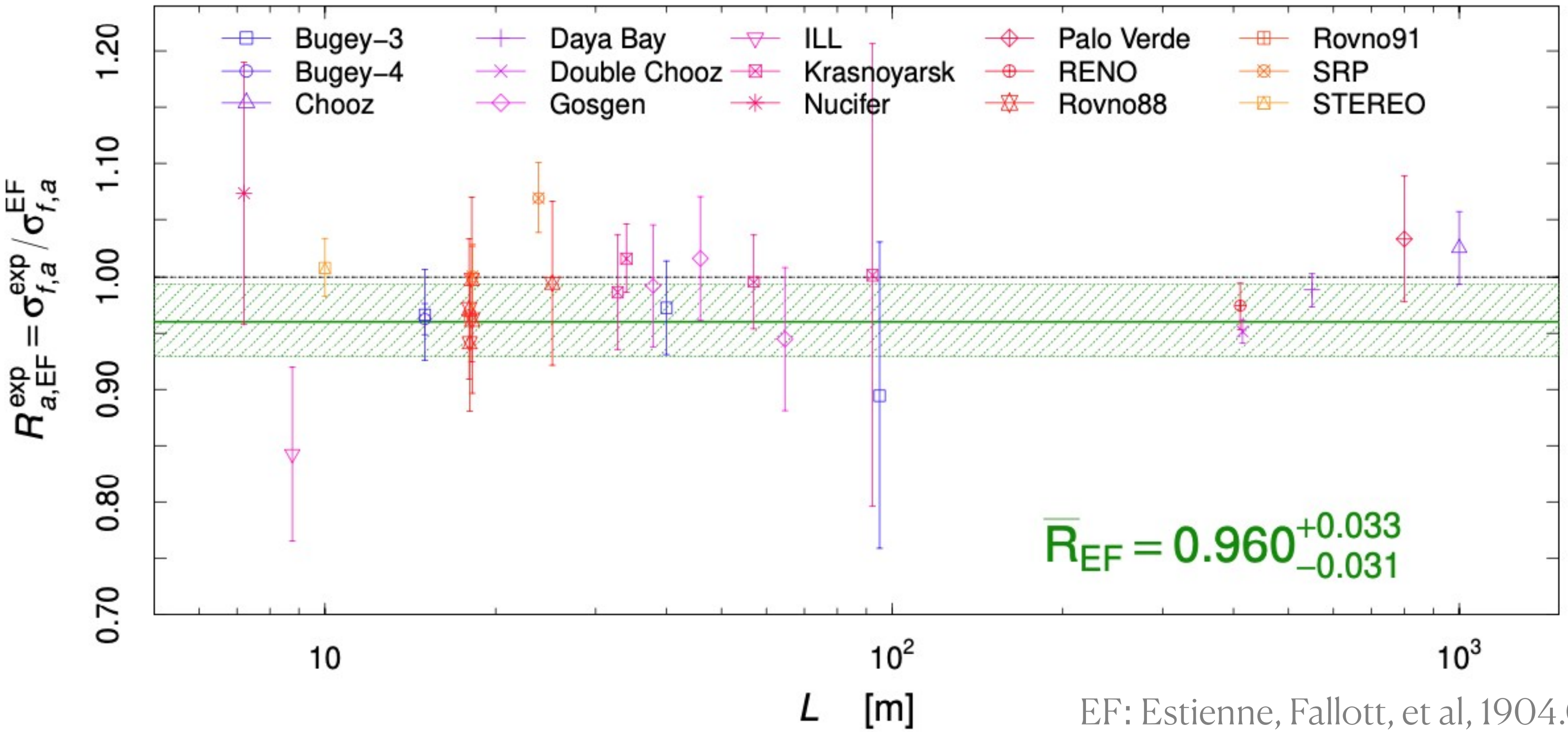
# Reactor antineutrino anomaly

$$P_{ee} = 1 - \sin^2 2\theta_{ee} \sin^2 \left( 1.27 \frac{\Delta m^2 \, [\mathrm{eV}^2] \, L \, [\mathrm{m}]}{E_\nu \, [\mathrm{MeV}]} \right)$$



# Reactor antineutrino anomaly?

Situation in 2022:

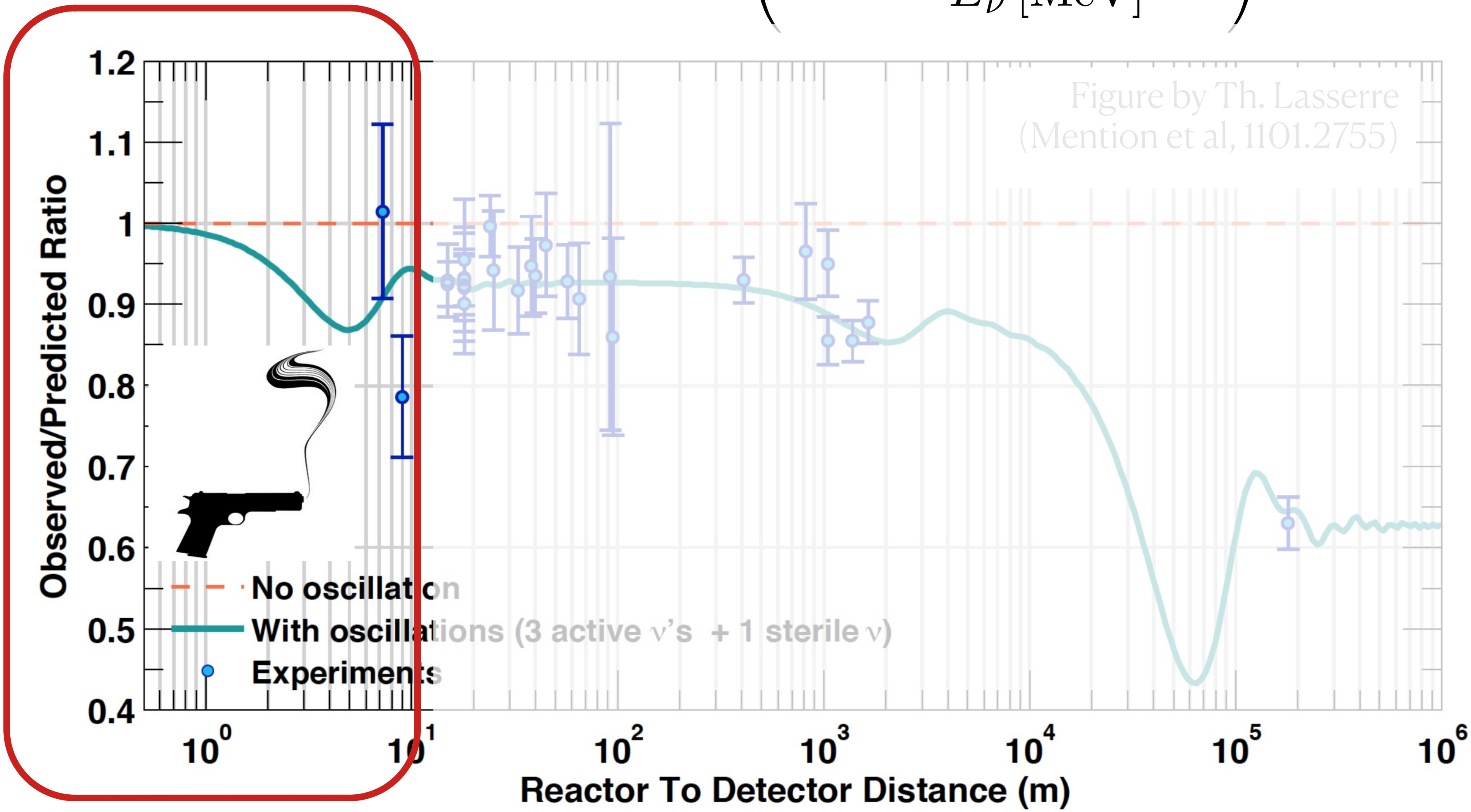



EF: Estienne, Fallott, et al, 1904.09358;

Berryman and Huber, 1909.09267 & 2005.01756
Figure from Giunti, Li, Ternes, Xin, 2110.06820

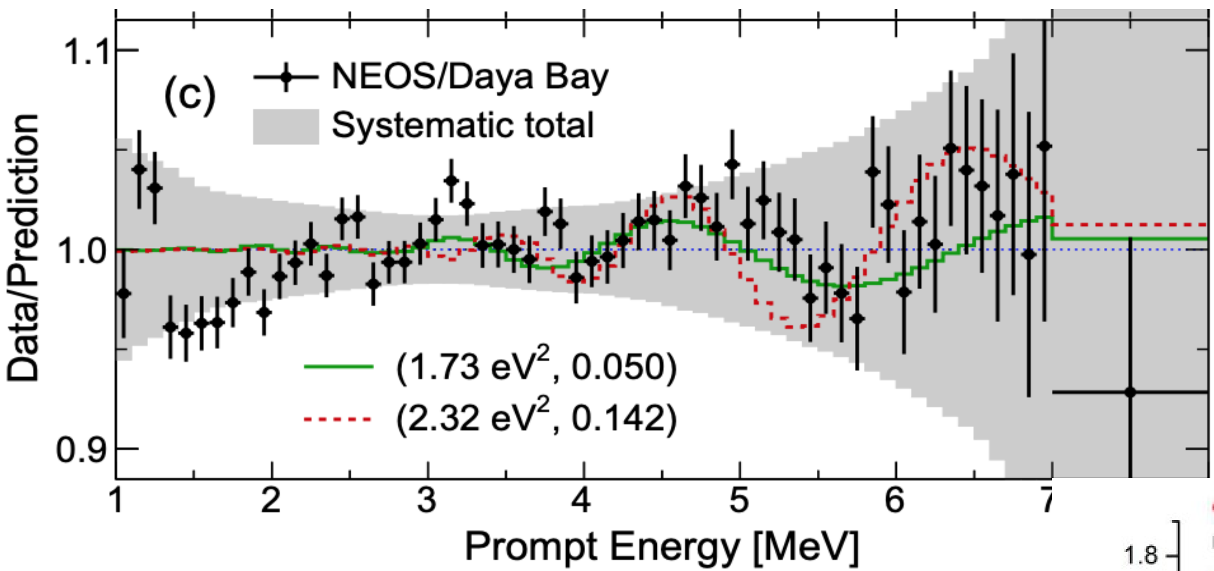
# Short-baseline Reactors

$$P_{ee} = 1 - \sin^2 2\theta_{ee} \sin^2 \left( 1.27 \frac{\Delta m^2 \, [\mathrm{eV}^2] \, L \, [\mathrm{m}]}{E_\nu \, [\mathrm{MeV}]} \right)$$

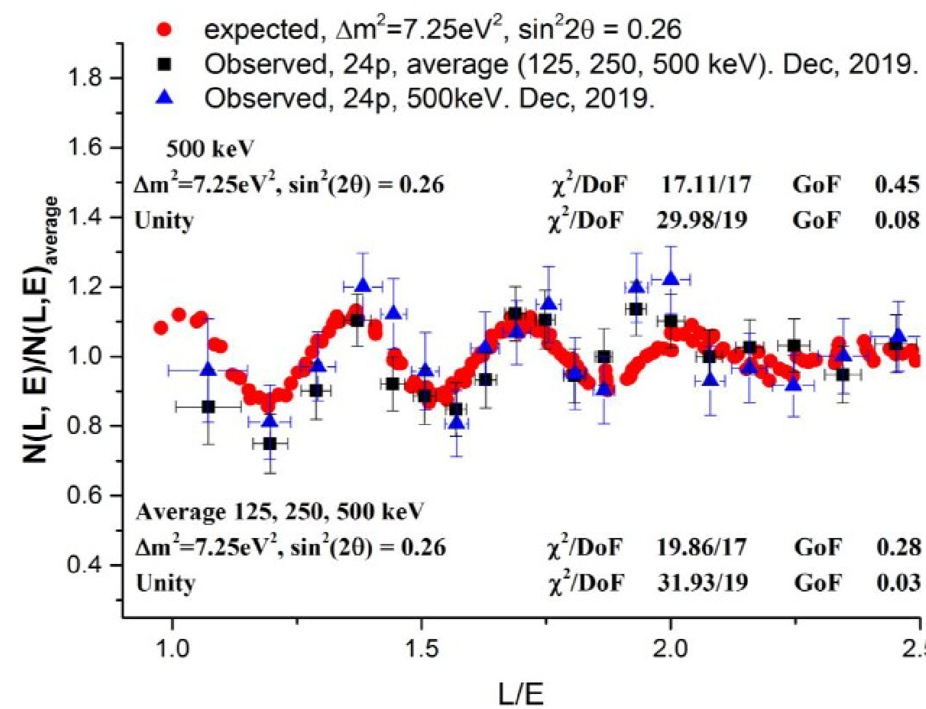


# Very short-baseline reactors

NEOS coll., 1610.05134




Neutrino-4 coll., 2005.05301

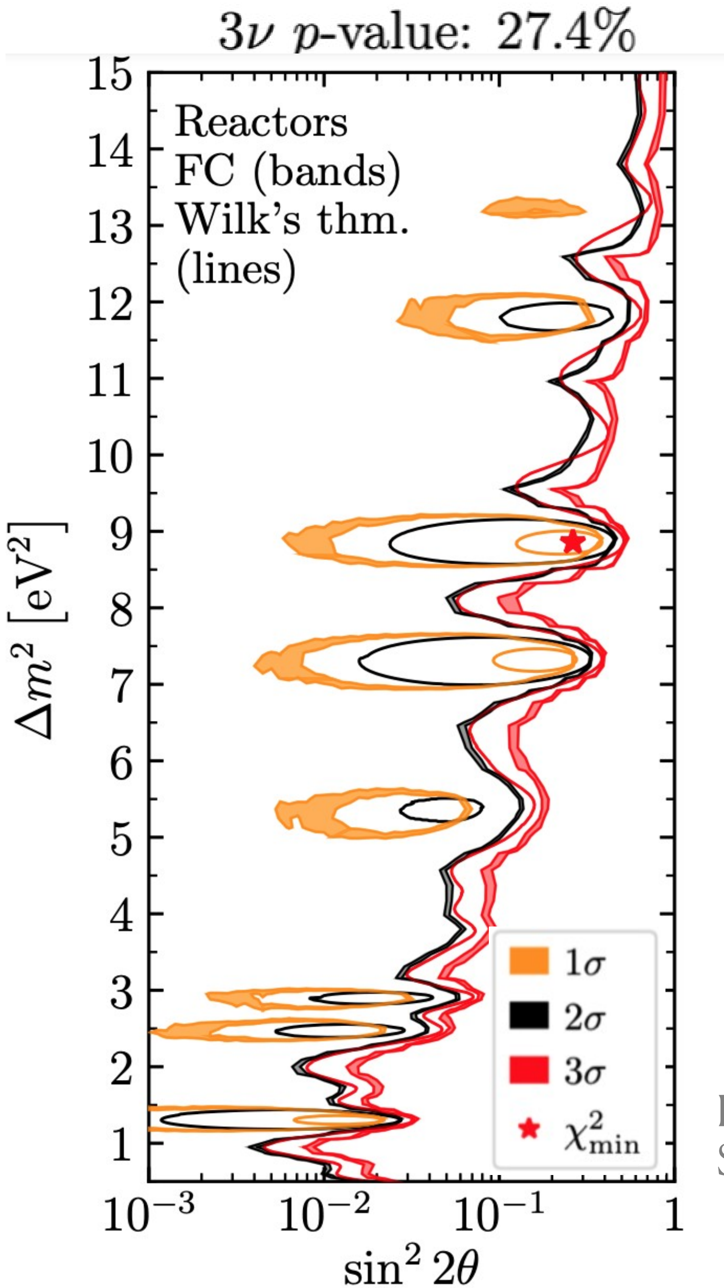



Quick highlights:

None of the vSBL reactor experiments observed a clear signal at high significance

(**exception:** Neutrino-4 did report a signal at approx. 3σ)

# Reactors

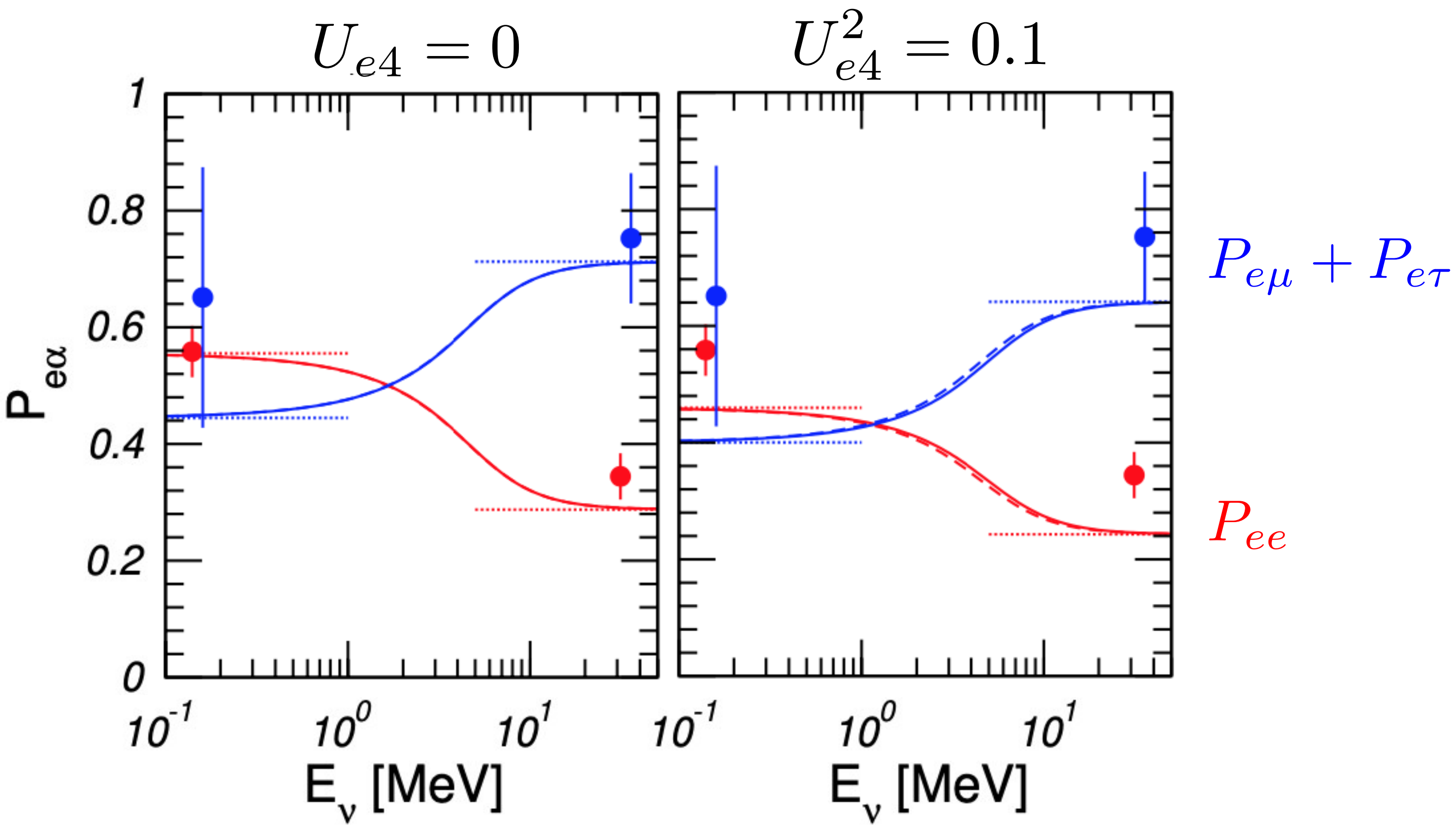



Berryman, Coloma, Huber, Schwetz, Zhou, 2111.12530

Global fit using data from:

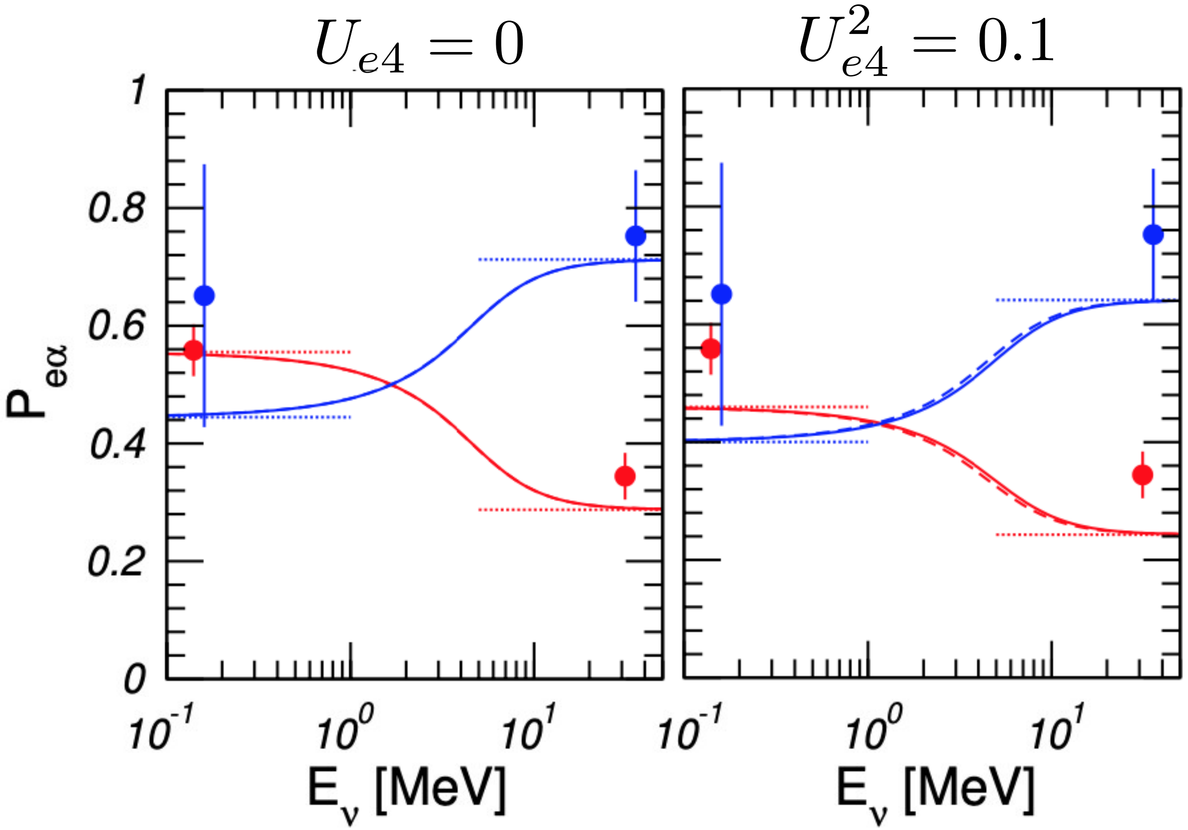
DANSS (talk at EPS-HEP 2021)
STEREO, 1912.06582
PROSPECT, 2006.11210
Neutrino-4, 2005.05301 (v2)
NEOS, 1610.05134

# Solar neutrinos




Goldhagen, Maltoni, Reichard, Schwetz, 2109.14898
(solar analysis as in Esteban et al, 2007.14792)

# Solar neutrinos

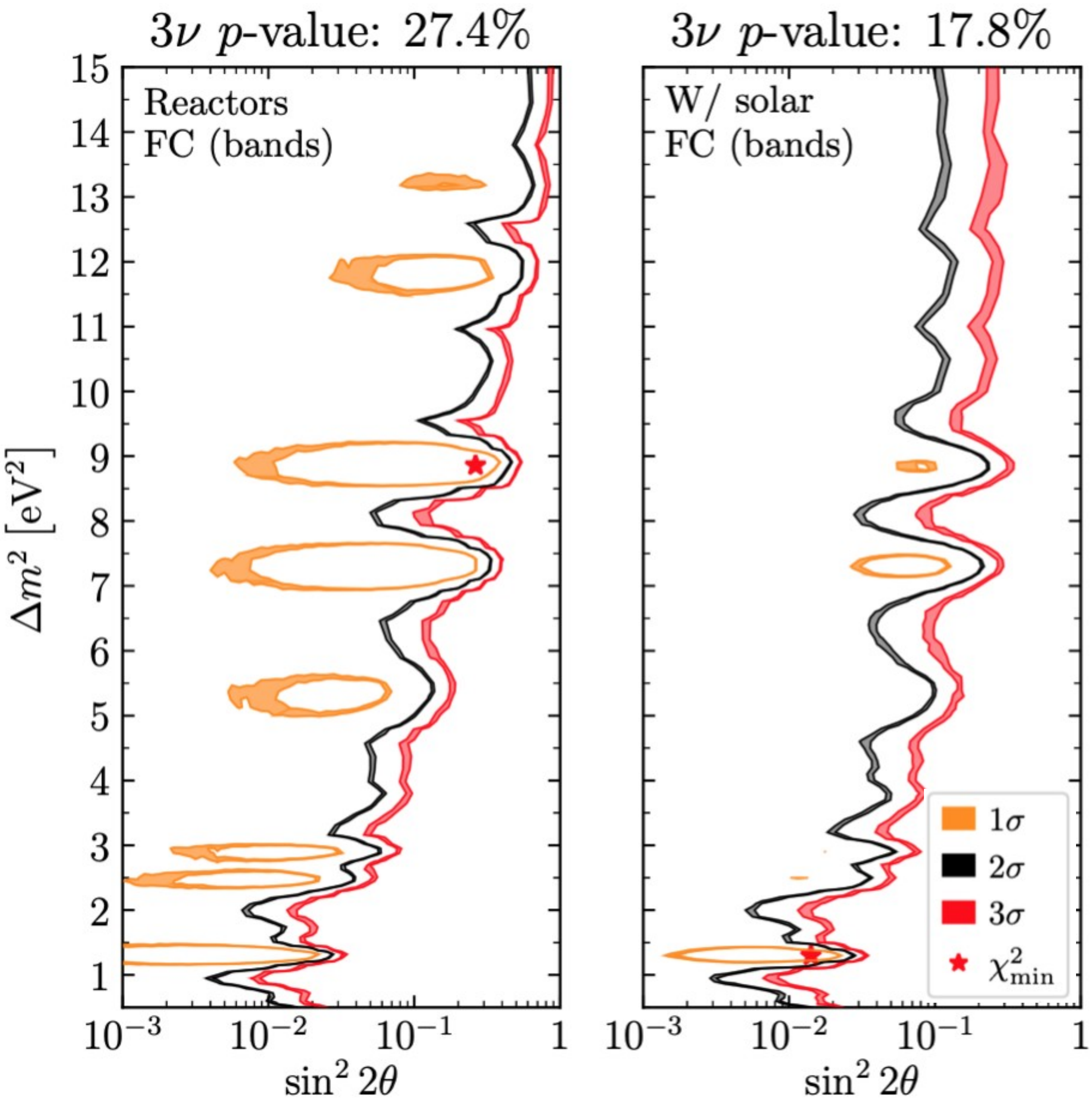



$$|U_{e4}|^2 < 0.168$$

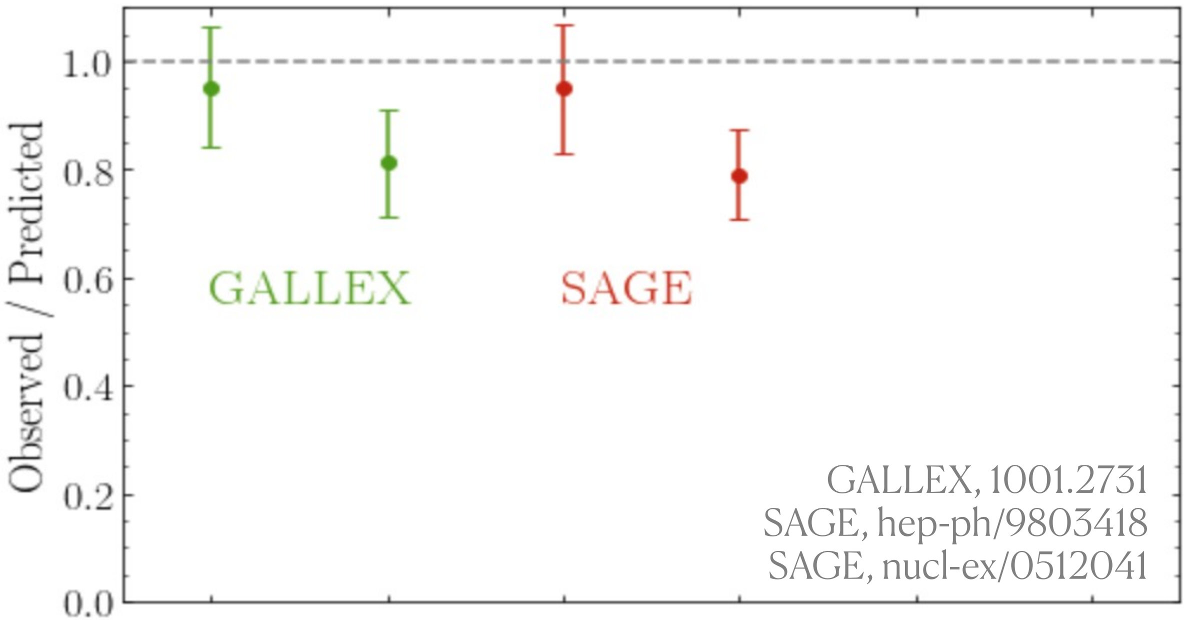
(90% C.L.)

Goldhagen, Maltoni, Reichard, Schwetz, 2109.14898
(solar analysis as in Esteban et al, 2007.14792)

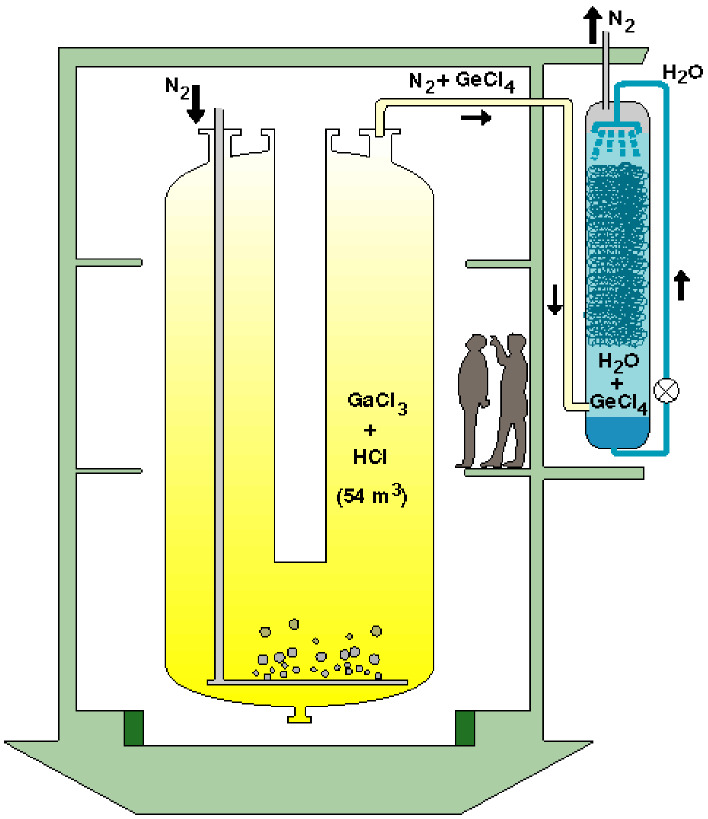
Reactors    Reactors + Solar



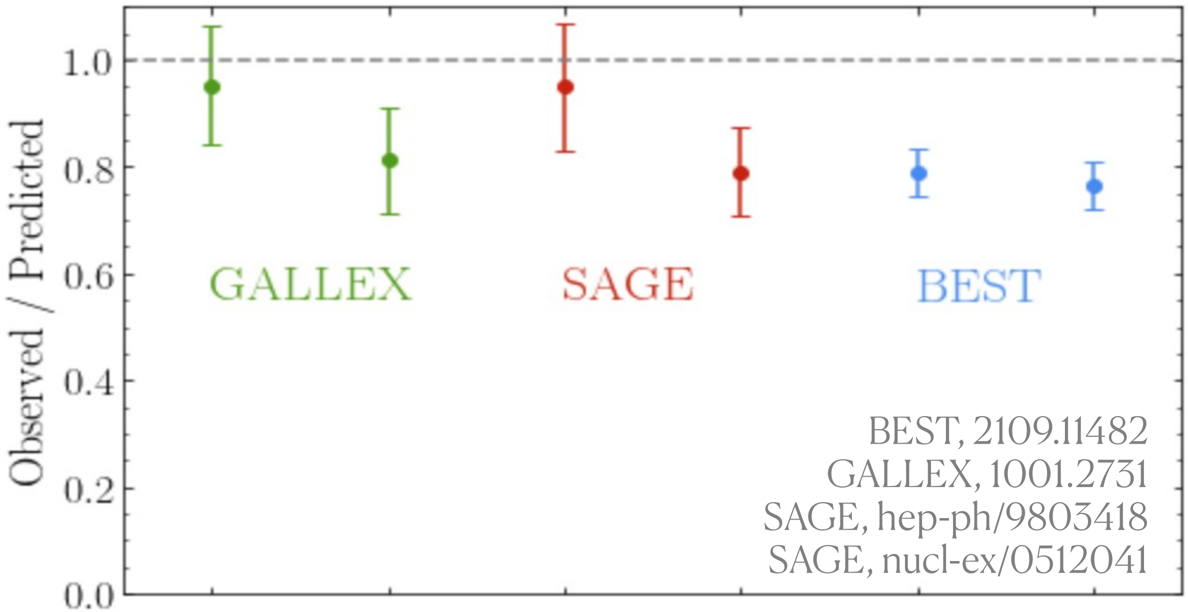
# Gallium experiments




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



# Gallium experiments




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

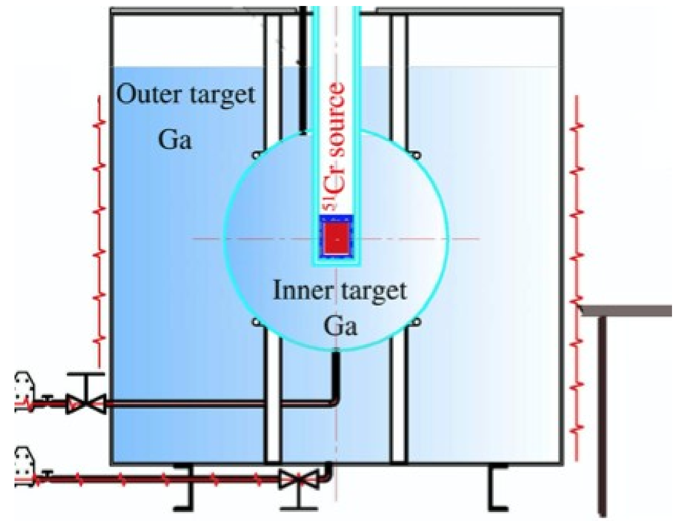
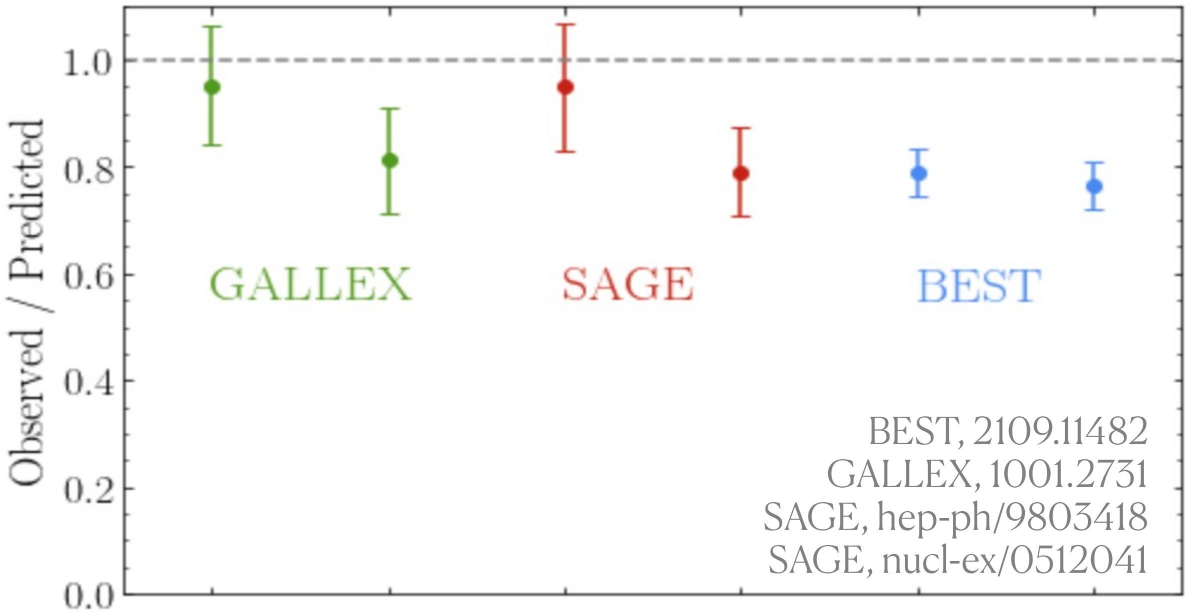
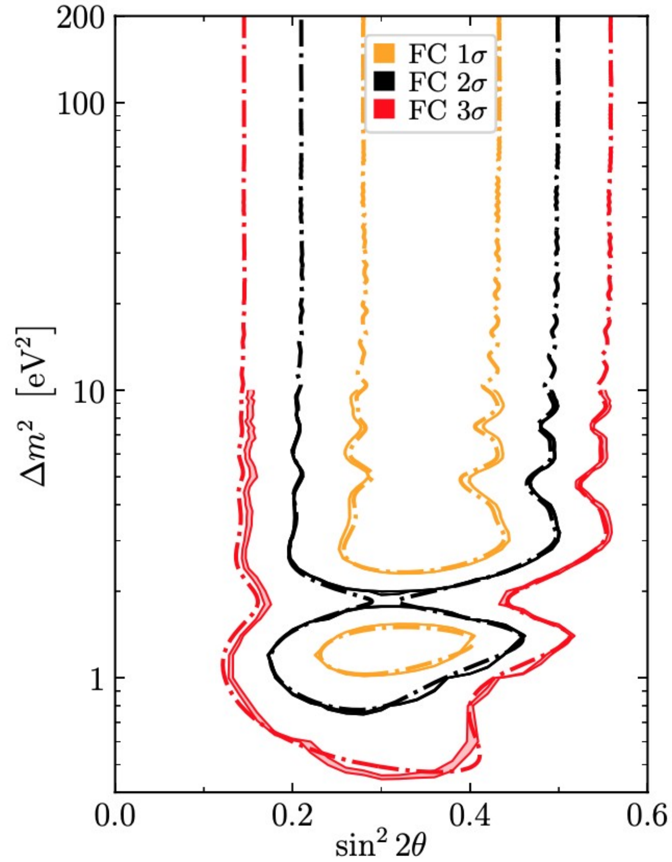



Figure from 2109.11482

# Gallium experiments



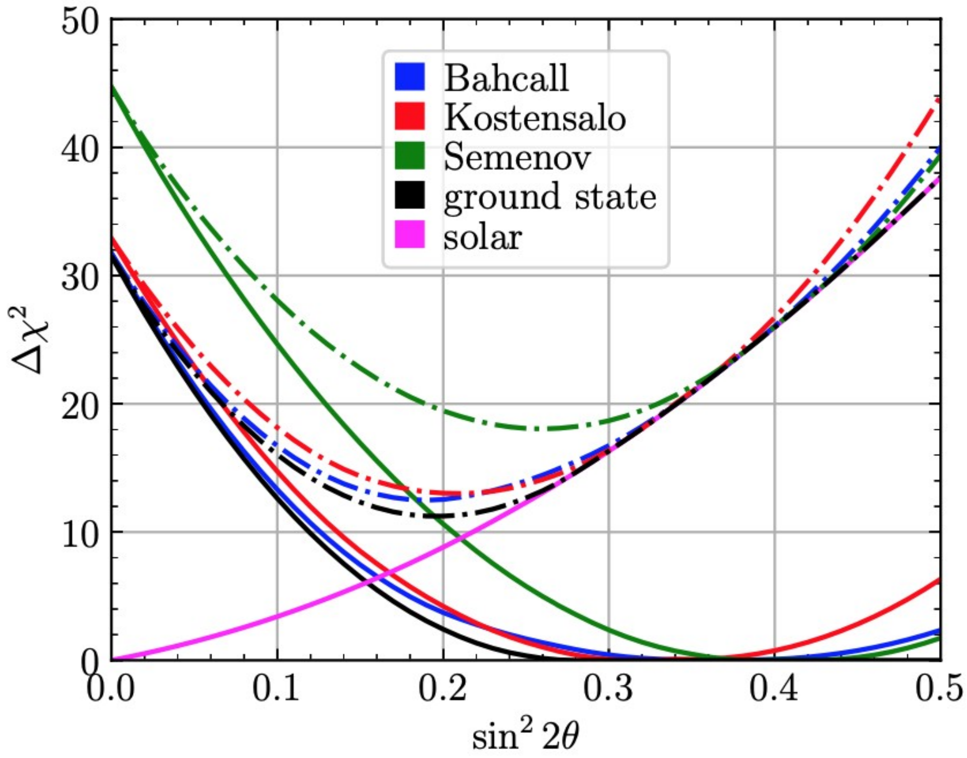




→ From MC simulation:

$p_0 < 2.7 \times 10^{-8}$ (5.6σ)

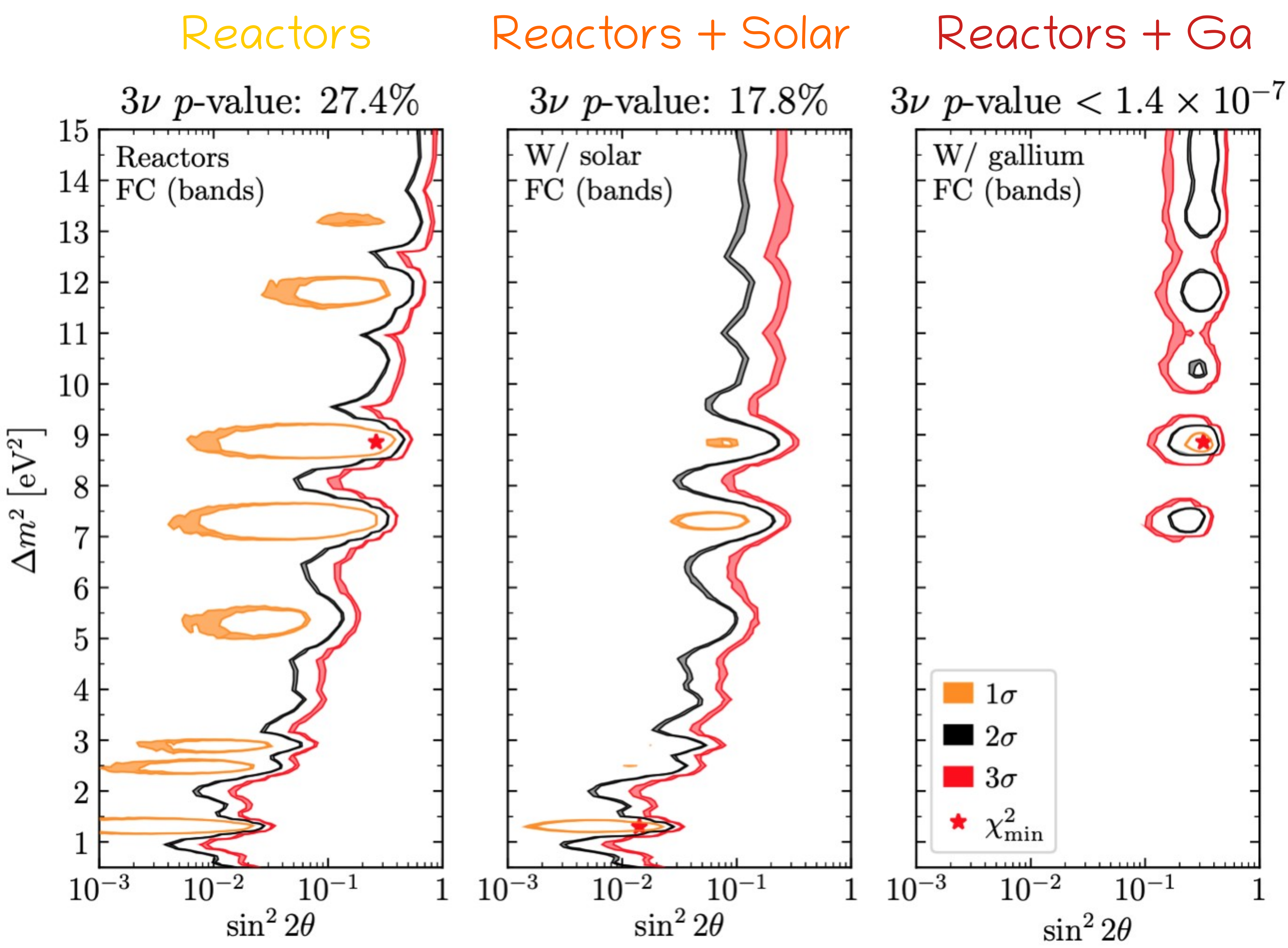
Berryman, Coloma, Huber, Schwetz, Zhou, 2111.12530
(see also Barinov, Gorbunov, 2109.14654)

# Consistency tests: Solar vs Ga




→ Tension above 3σ!

| Data set | $\chi^2_{\rm PG}$/dof | $p^{(W)}$ | $\#\sigma^{(W)}$ | $p_{\rm b.f.}$ | $\#\sigma_{\rm b.f.}$ |
|---|---|---|---|---|---|
| Reactor vs Solar | 0.65/1 | 0.42 | 0.8 | 0.39 | 0.9 |
| Reactor vs Gallium | 1.4/2 | 0.50 | 0.67 | 0.62 | 0.5 |
| Solar vs Gallium | 13.0/1 | $3.1 \times 10^{-4}$ | 3.6 | $1.6 \times 10^{-3}$ | 3.2 |
| Reactor vs Solar vs Gallium | 15.6/3 | $1.4 \times 10^{-3}$ | 3.2 | $5.1 \times 10^{-3}$ | 2.8 |



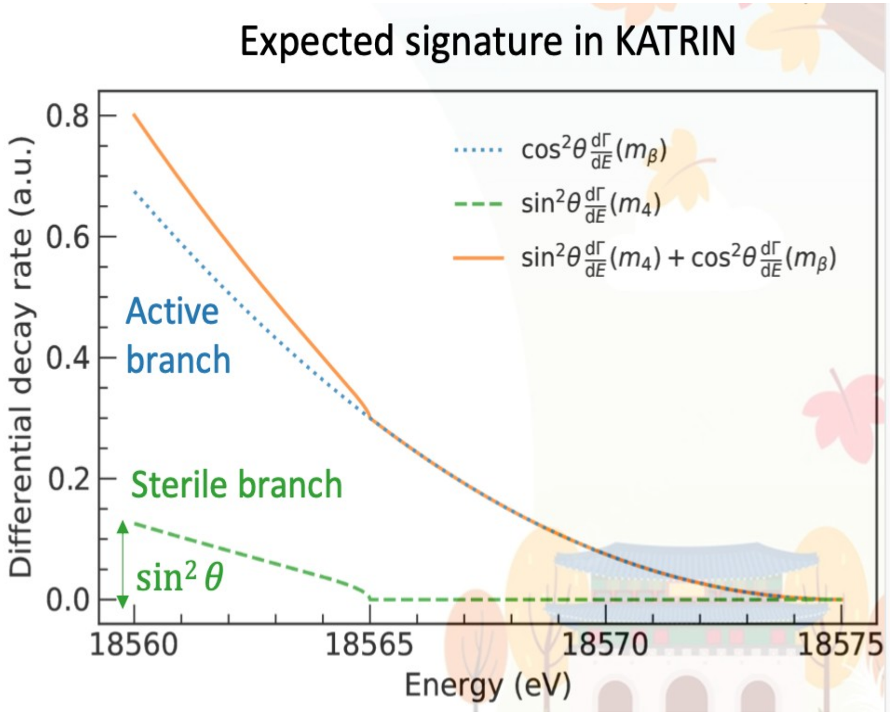
Reactors
Reactors + Solar
Reactors + Ga
3ν p-value: 27.4%
3ν p-value: 17.8%
3ν p-value < 1.4 × 10^−7
Reactors
FC (bands)
W/ solar
FC (bands)
W/ gallium
FC (bands)
Δm² [eV²]
sin² 2θ
1σ
2σ
3σ
χ²min

# Other probes:
# end-point of beta-decay

$$m_\nu^2 = \sum_{i=1}^{4} |U_{ei}|^2 m_i^2$$

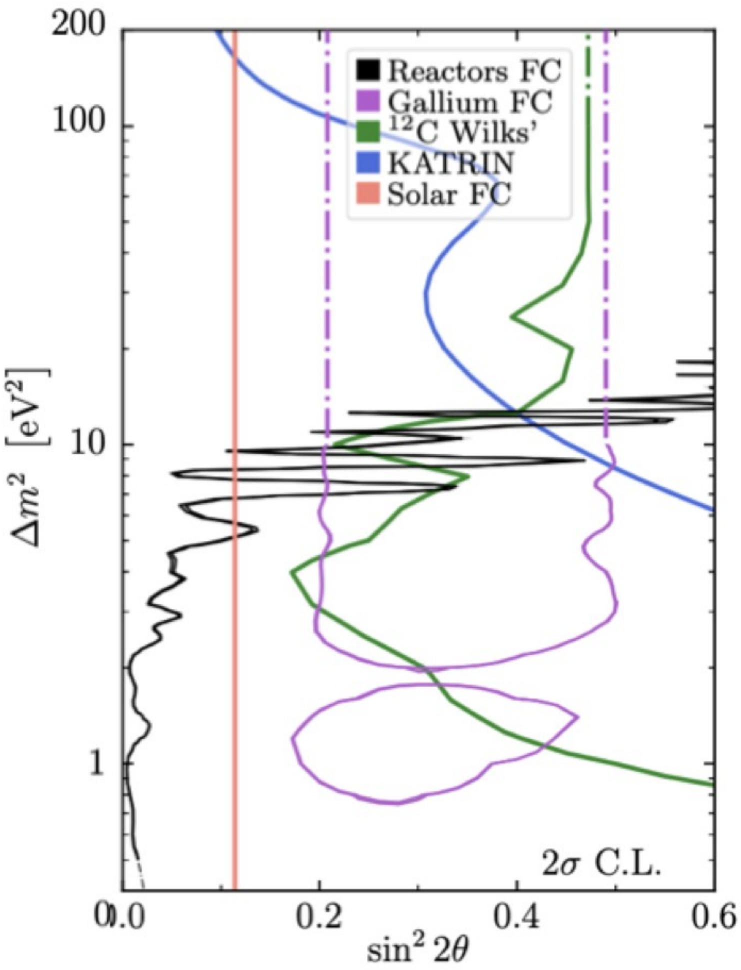
KATRIN

# KATRIN



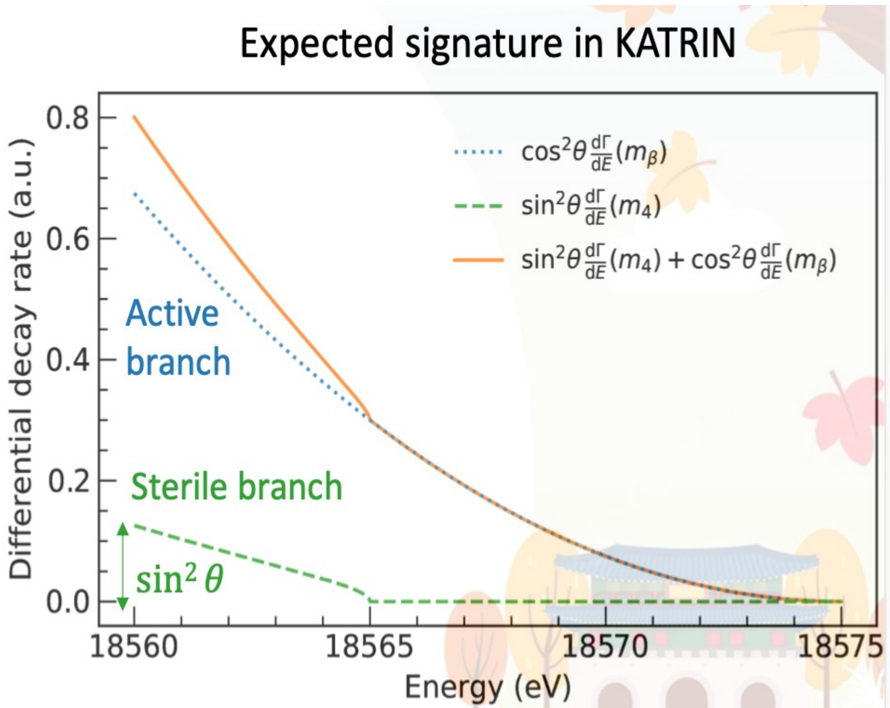

Riis and Hannestad, 1008.1495;
Formaggio and Barrett, 1105.1326

# KATRIN




Berryman, Coloma, Huber, Schwetz, Zhou, 2111.12530

KATRIN, 2011.05087




Riis and Hannestad, 1008.1495; Formaggio and Barrett, 1105.1326

# Summary

- LSND and MiniBooNE remain unexplained
  - MicroBooNE has shown first results for 3+1 (still limited)
- Reactor flux anomaly: mostly resolved (?)
- Reactor spectra: significance of hints reduced to $\sim 1\sigma$
- Gallium anomaly (dominated by BEST) is above $5\sigma$
  - FC does not change this; nor does the cross section
- Global picture
  - Solar + reactor spectra: compatible, consistent with 3-nu ($1.3\sigma$)
  - Ga + reactor spectra: compatible, favors steriles ($>5\sigma$)
  - Ga + solar: in tension at $3\sigma$
  - Ga + reactor flux: in tension too…
- In the near future, KATRIN will probe the region at high mass

Thanks!

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PID2019-108892RB-I00, CEX2020-001007-S

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# Backup

# Dependence on capture cross sec.

| Reference | $\sigma(\text{Cr})$ | $\sigma_{\text{g.s.}}(\text{Cr})$ | $\sigma(\text{Ar})$ | $\sigma_{\text{g.s.}}(\text{Ar})$ |
|---|---|---|---|---|
| Bahcall [56] | $58.1 \pm 2.1$ | 55.2 | $70.0 \pm 4.9$ | 66.2 |
| Kostensalo *et al.* [54] | $56.7 \pm 1.0$ | $55.3 \pm 0.7$ | $68.0 \pm 1.2$ | $66.2 \pm 0.9$ |
| Semenov [57] | $59.38 \pm 1.16$ | $55.39 \pm 0.19$ | $71.69 \pm 1.47$ | $66.25 \pm 0.23$ |

[56] Bahcall, hep-ph/9710491
[54] Kostensalo, Suhonen, Giunti, Srivastava, 1906.10980
[57] Semenov, Phys. Atom. Nucl. 83 (2020) 1549.

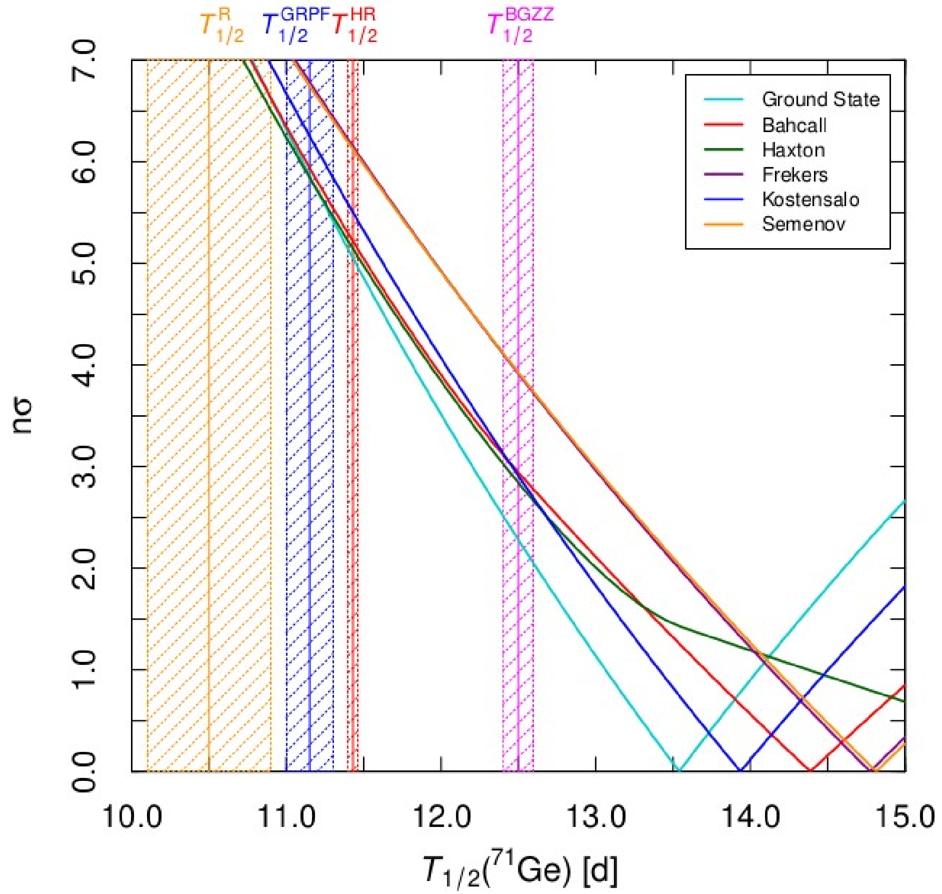
| | GALLEX & SAGE | | BEST | | All gallium combined | | | |
|---|---|---|---|---|---|---|---|---|
| Cross section | $\Delta\chi^2_{3\nu}$ | $\#\sigma^{(W)}$ | $\Delta\chi^2_{3\nu}$ | $\#\sigma^{(W)}$ | $\sin^2 2\theta_{\text{min}}$ | $\Delta m^2_{\text{min}}$ | $\Delta\chi^2_{3\nu}$ | $\#\sigma^{(W)}$ |
| Bahcall | 3.7 | 1.4 | 31.3 | 5.2 | 0.35 | $1.3\,\text{eV}^2$ | 31.7 | 5.3 |
| Kostensalo | 4.9 | 1.7 | 31.5 | 5.2 | 0.32 | $1.3\,\text{eV}^2$ | 32.9 | 5.4 |
| Semenov | 9.4 | 2.6 | 42.4 | 6.2 | 0.39 | $1.3\,\text{eV}^2$ | 44.7 | 6.4 |
| Ground state | 3.4 | 1.3 | 29.7 | 5.1 | 0.29 | $1.3\,\text{eV}^2$ | 31.5 | 5.3 |

Our default choice → Kostensalo

Berryman, Coloma, Huber, Schwetz, Zhou, 2111.12530
(see also Barinov, Gorbunov, 2109.14654)

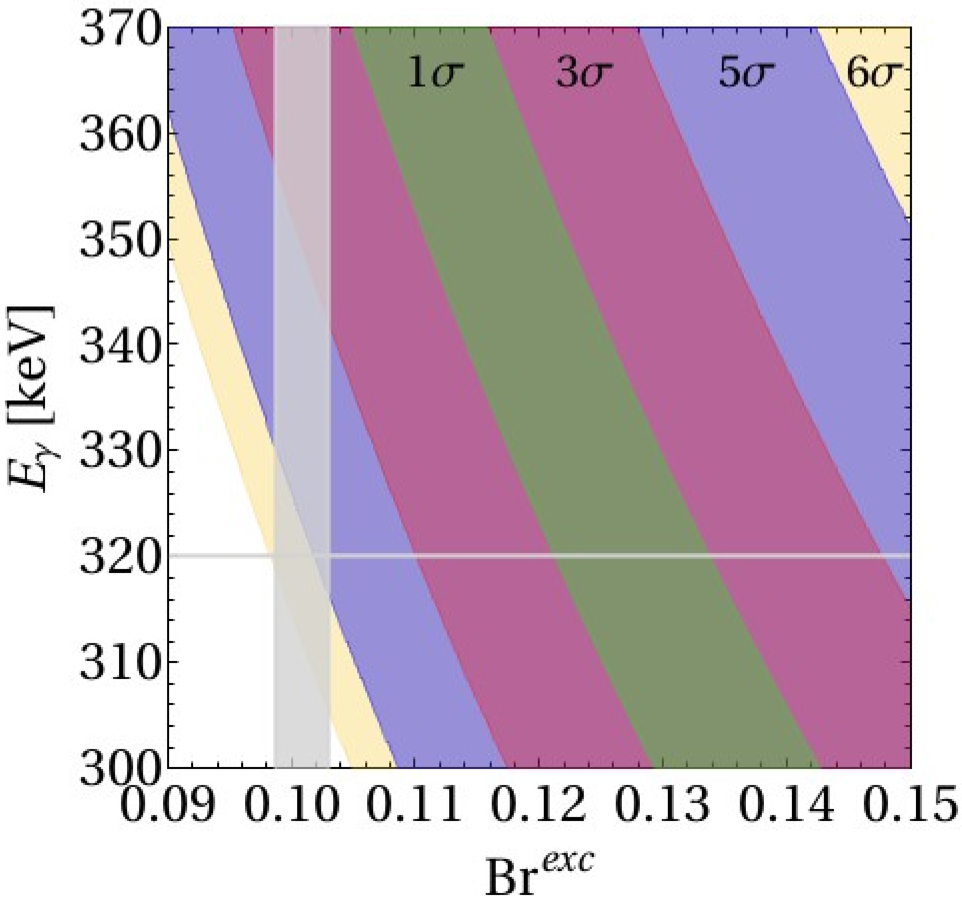
# Dependence on capture cross sec.

$$\sigma_{\rm gs} = \frac{G_{\rm F}^2 \cos^2\vartheta_{\rm C}}{\pi} g_A^2 {\rm BGT_{gs}} \langle p_e E_e F(Z_{\rm Ge}, E_e)\rangle = \frac{\pi^2 \ln 2}{m_e^5 f t_{1/2}(^{71}{\rm Ge})} \langle p_e E_e F(Z_{\rm Ge}, E_e)\rangle$$

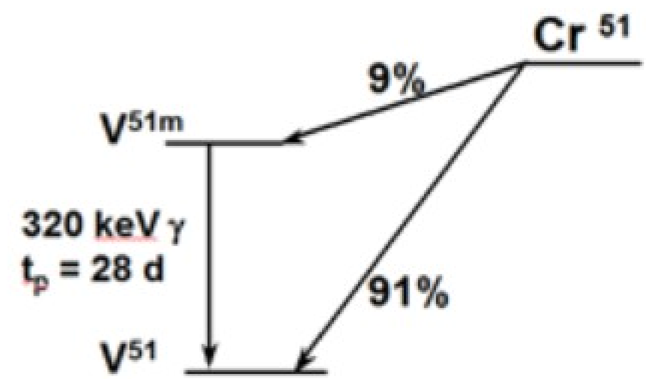



Giunti and Ternes, 2212.09722

# Further scrutiny



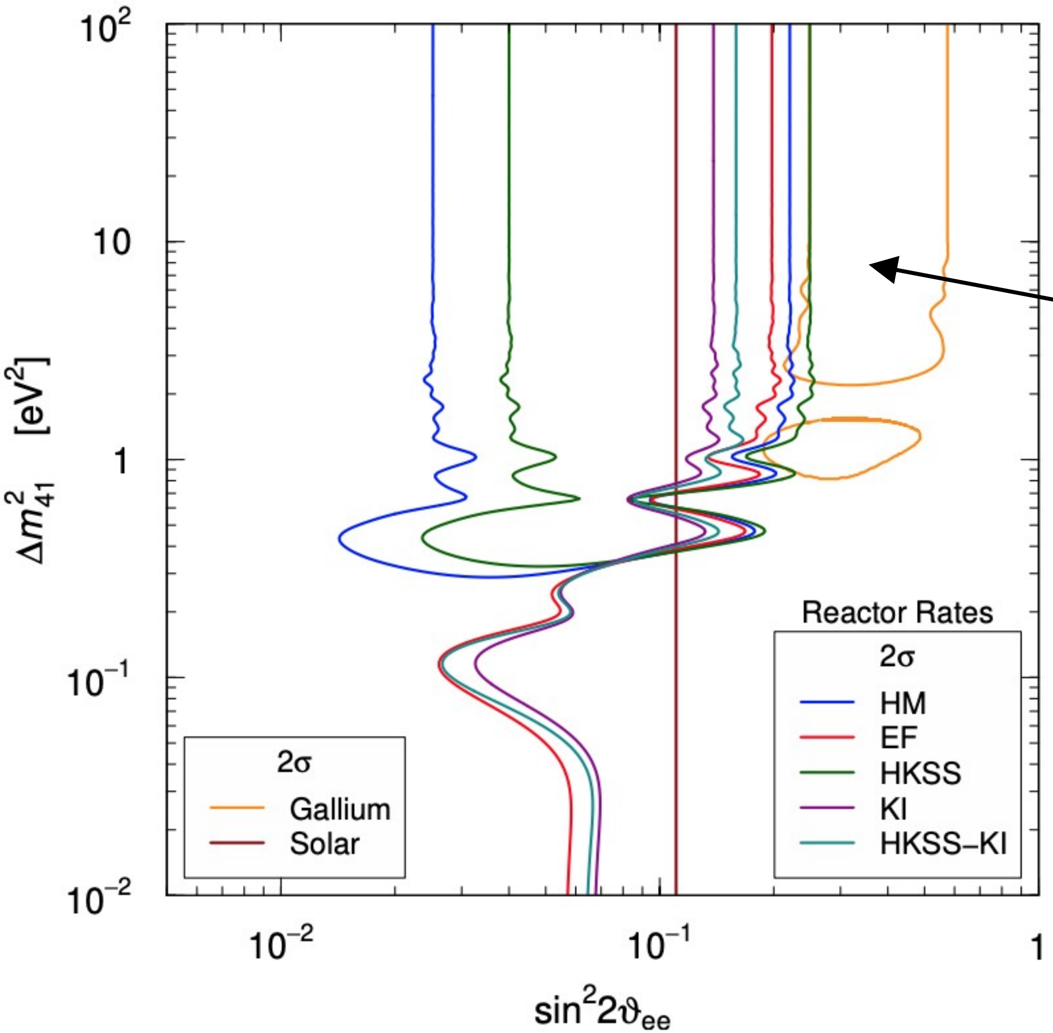

The source calibration is done calorimetrically; however, the BR to the excited state is only 10%...

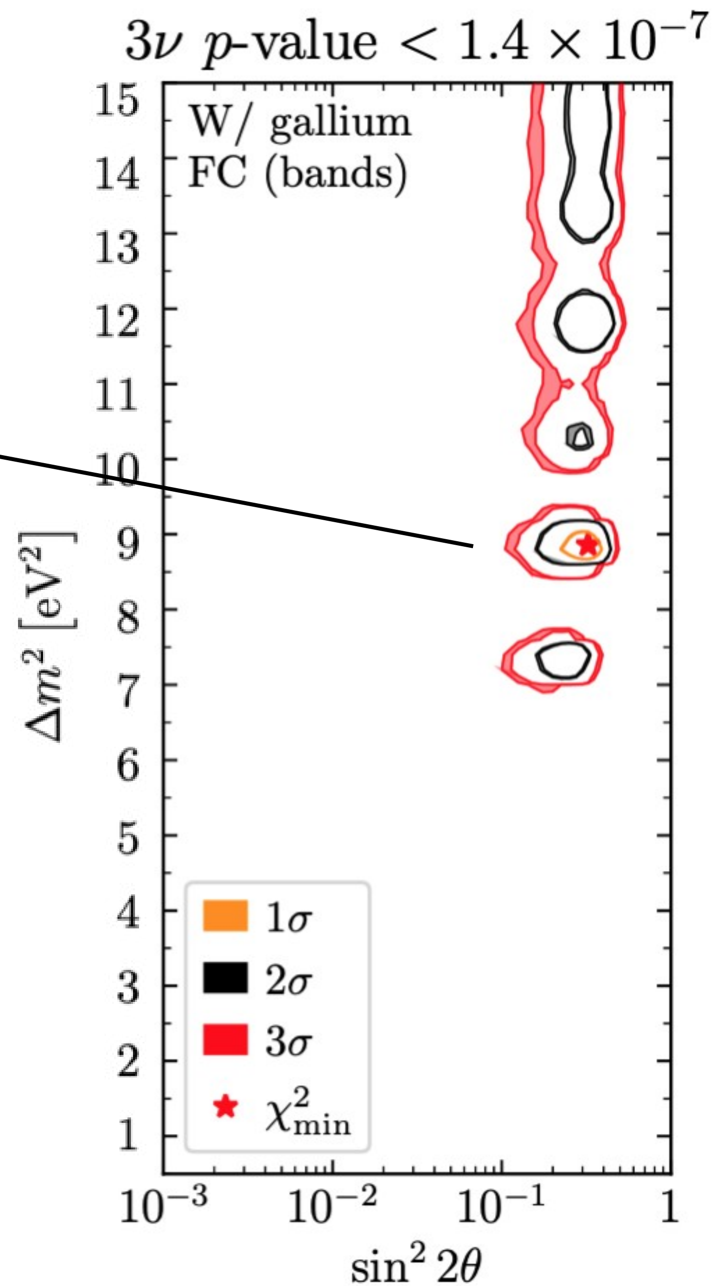



Brdar, Gehrlein, Kopp, 2303.05528

Reactors + Ga

→ Gallium in significant tension with new reactor flux predictions too…

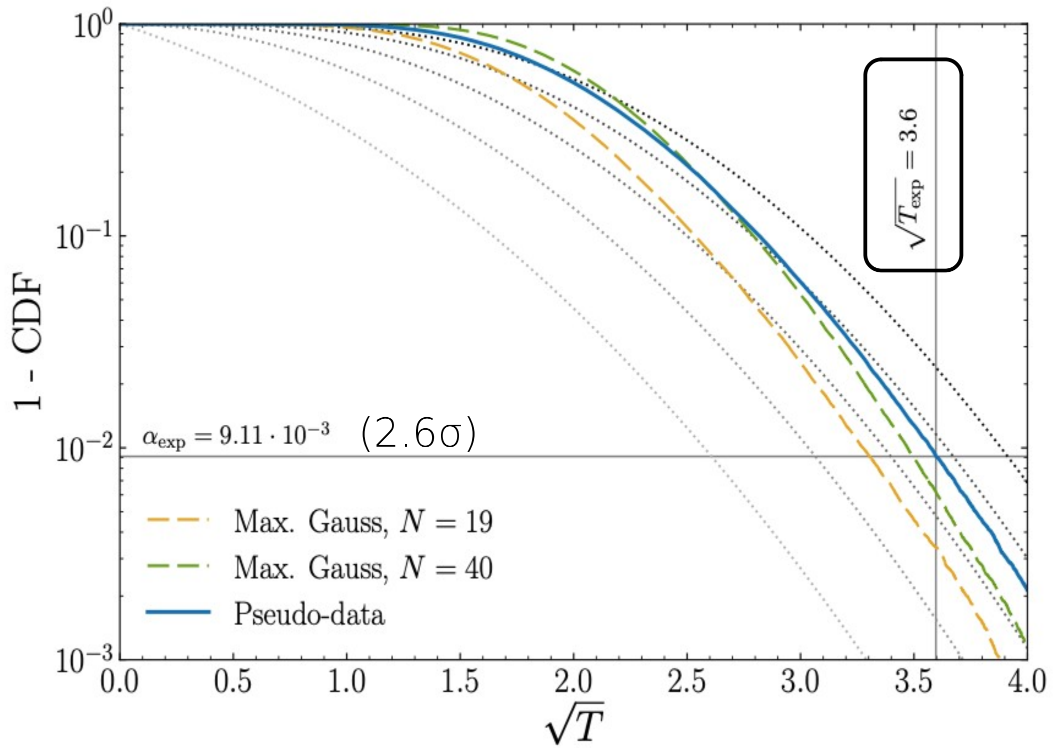


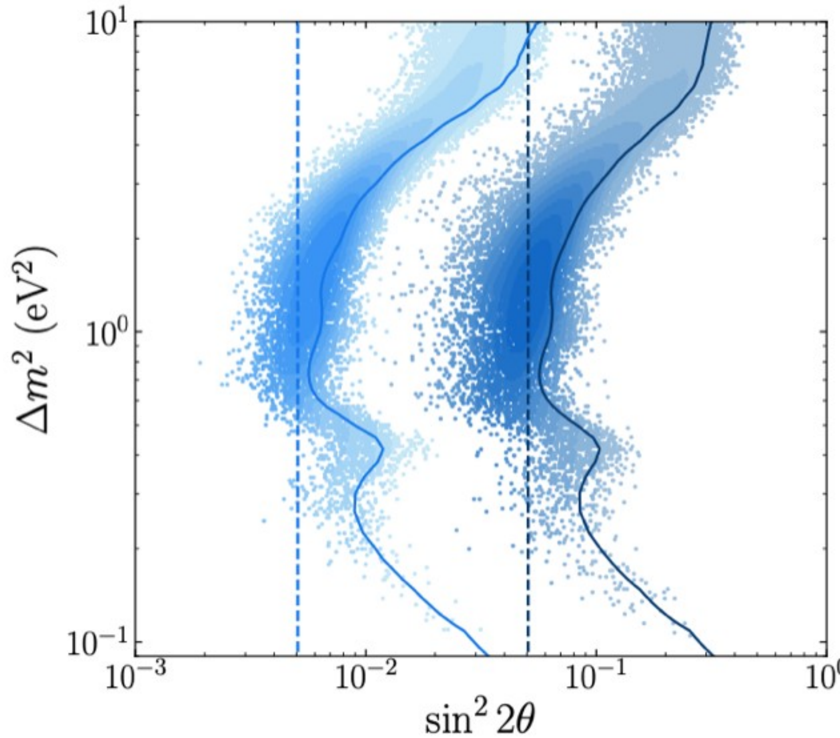

Berryman and Huber, 1909.09267 & 2005.01756
Figure from Giunti, Li, Ternes, Xin, 2110.06820

# Oscillations or fluctuations?

Neutrino-4 (actual data)




Toy experiment



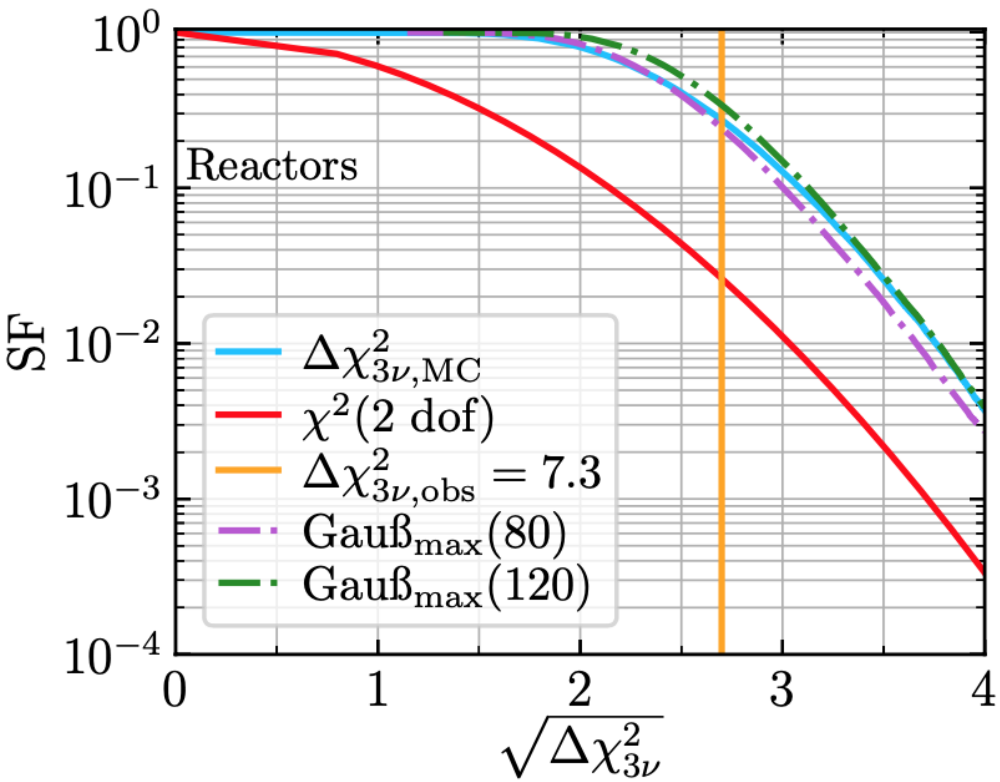

$$T = \chi^2_{3\nu} - \chi^2_{\rm min}$$

Coloma, Huber, Schwetz, 2008.06083
(see also Giunti, 2004.07577; Agostini, Neumair, 1906.11854;
PROSPECT and STEREO collaborations, 2006.13147)

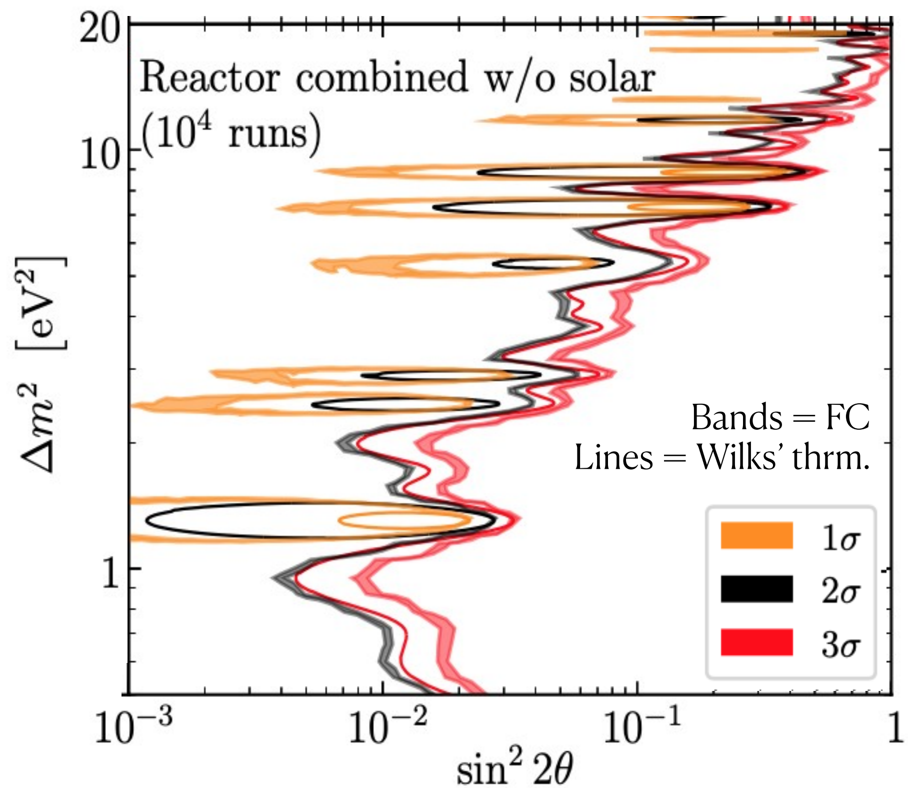
# Combined reactors: FC analysis

$$\Delta\chi^2_{3\nu} = \chi^2_{3\nu} - \chi^2_{\min}$$

3-nu hypothesis, p-value: $p_0 = 27.4\%$




$$\Delta\chi^2(\{\Theta\}) = \chi^2(\{\Theta\}) - \chi^2_{\min}$$




Berryman, Coloma, Huber, Schwetz, Zhou, 2111.12530