Open Questions in Neutrino Physics

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Oscillations

What we know about neutrinos

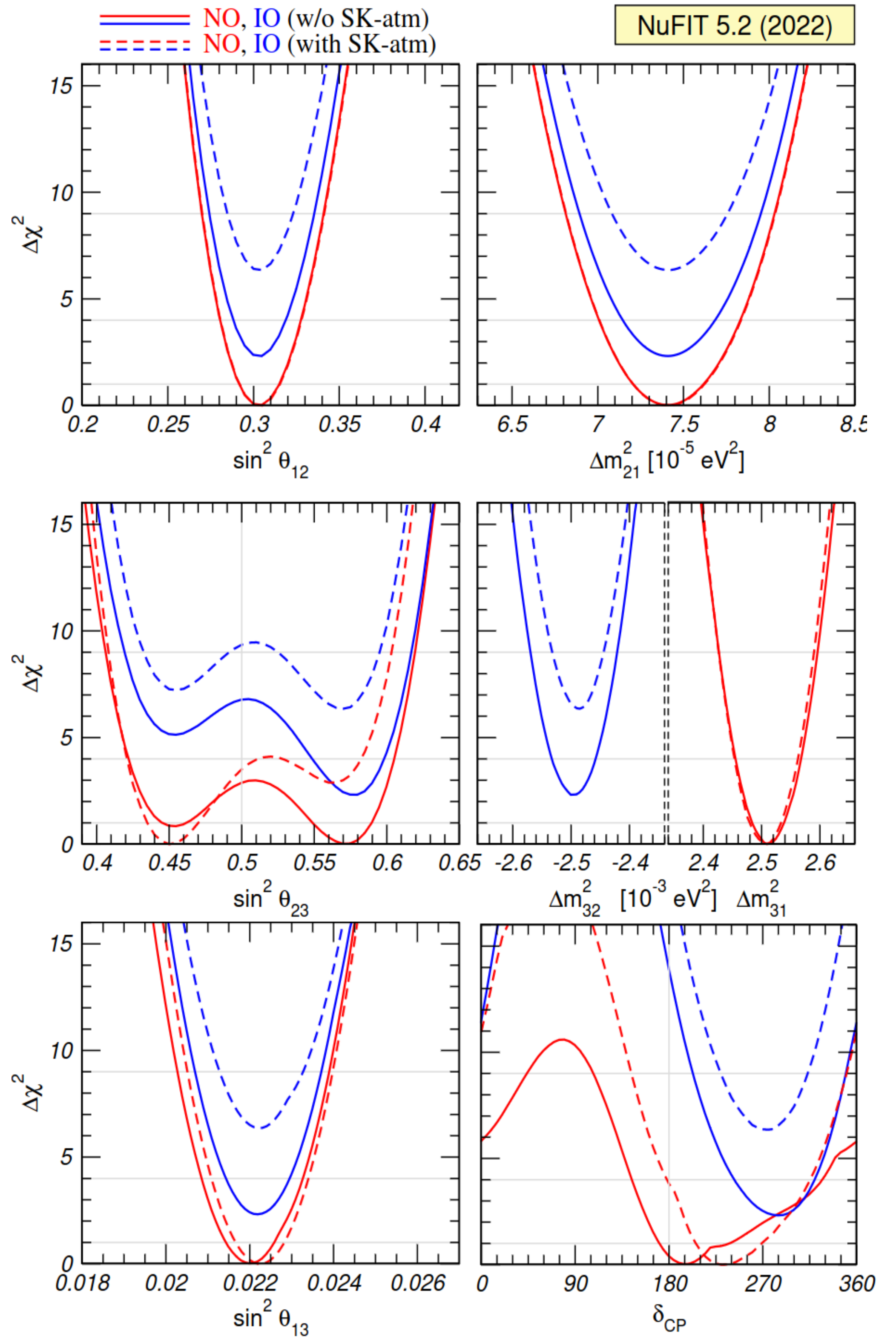
http://www.nu-fit.org, 2007.14792

Similar results from
Bari group (Capozzi et al., 2107.00532)
and Valencia group (deSalas et al., 2006.11237)

Known:

$$\left.\begin{array}{c}\theta_{12}\\ \theta_{13}\\ |\Delta m^2_{31}|\\ \Delta m^2_{21}\end{array}\right\}$$ Precision between 2% - 6% (at 1 σ)

See talk by Justyna Lagoda



What we don't know about neutrinos

http://www.nu-fit.org, 2007.14792

Similar results from
Bari group (Capozzi et al., 2107.00532)
and Valencia group (deSalas et al., 2006.11237)

Known:

θ_{12}

θ_{13}

$|\Delta m^2_{31}|$

Δm^2_{21}

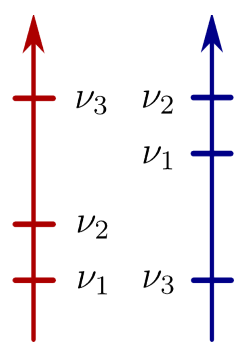
Unknown:

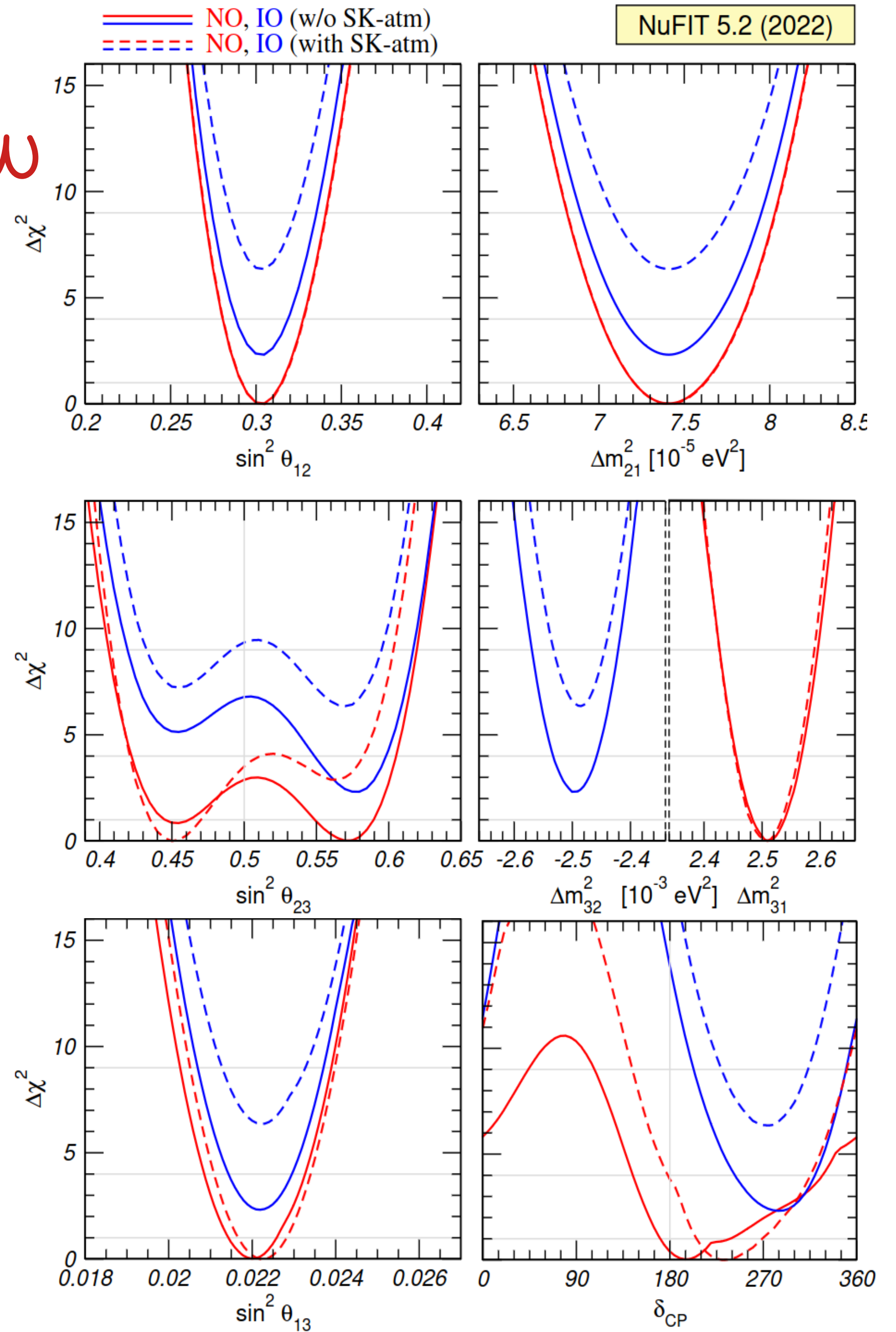
$\delta_{\rm CP}$?

$\text{sgn}(\Delta m^2_{31})$?

$\theta_{23}\left\{\begin{array}{l}\text{octant?}\\ \text{maximal?}\end{array}\right.$

See talk by Justyna Lagoda





Pilar Coloma - IFT

Unknowns in oscillations

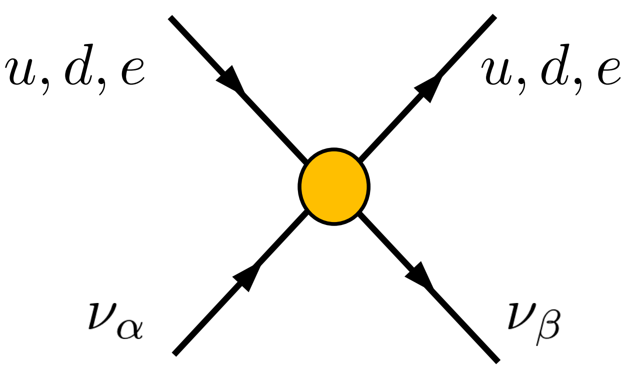
- Are these measurements robust in presence of new physics?

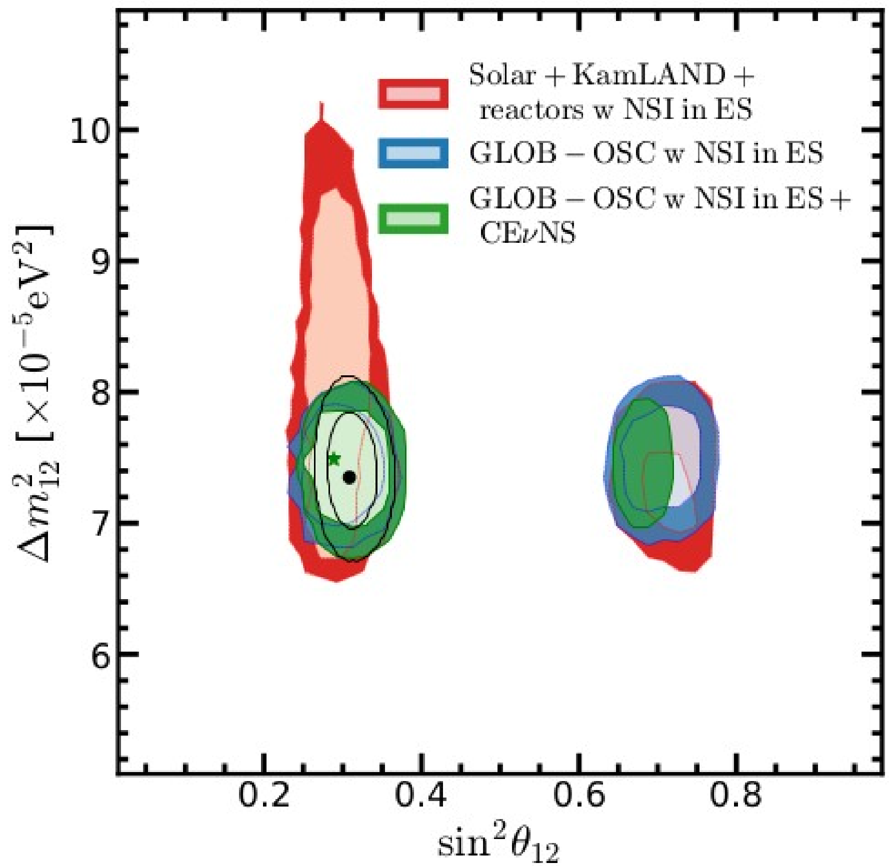
Generally speaking, yes...

Gonzalez-Garcia, Maltoni, Salvado, 1103.4365;
Gonzalez-Garcia & Maltoni, 1307.3092

...except for the solar mixing angle ("LMA-Dark" degeneracy)

Miranda, Tortola, Valle, hep-ph/0406280

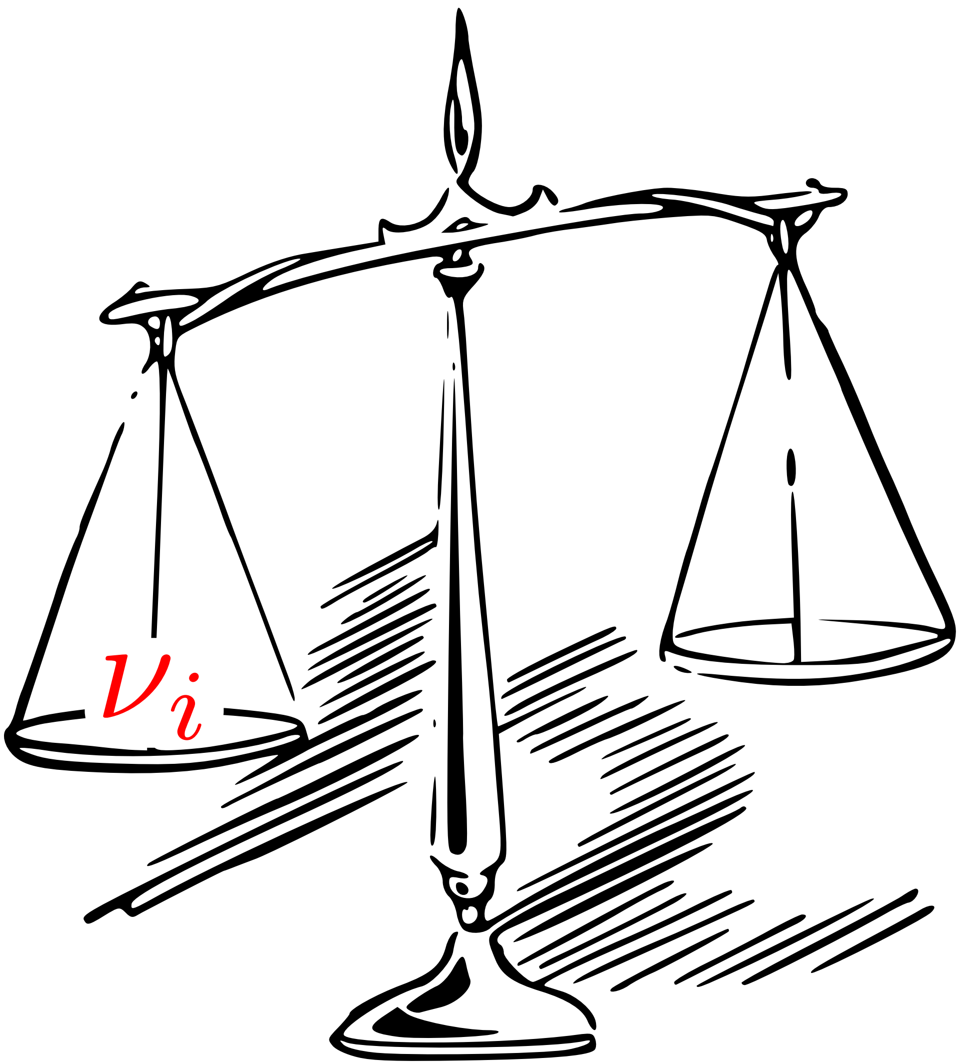




Coloma, Gonzalez-Garcia, Maltoni, Pinheiro, Urrea, 2305.07698

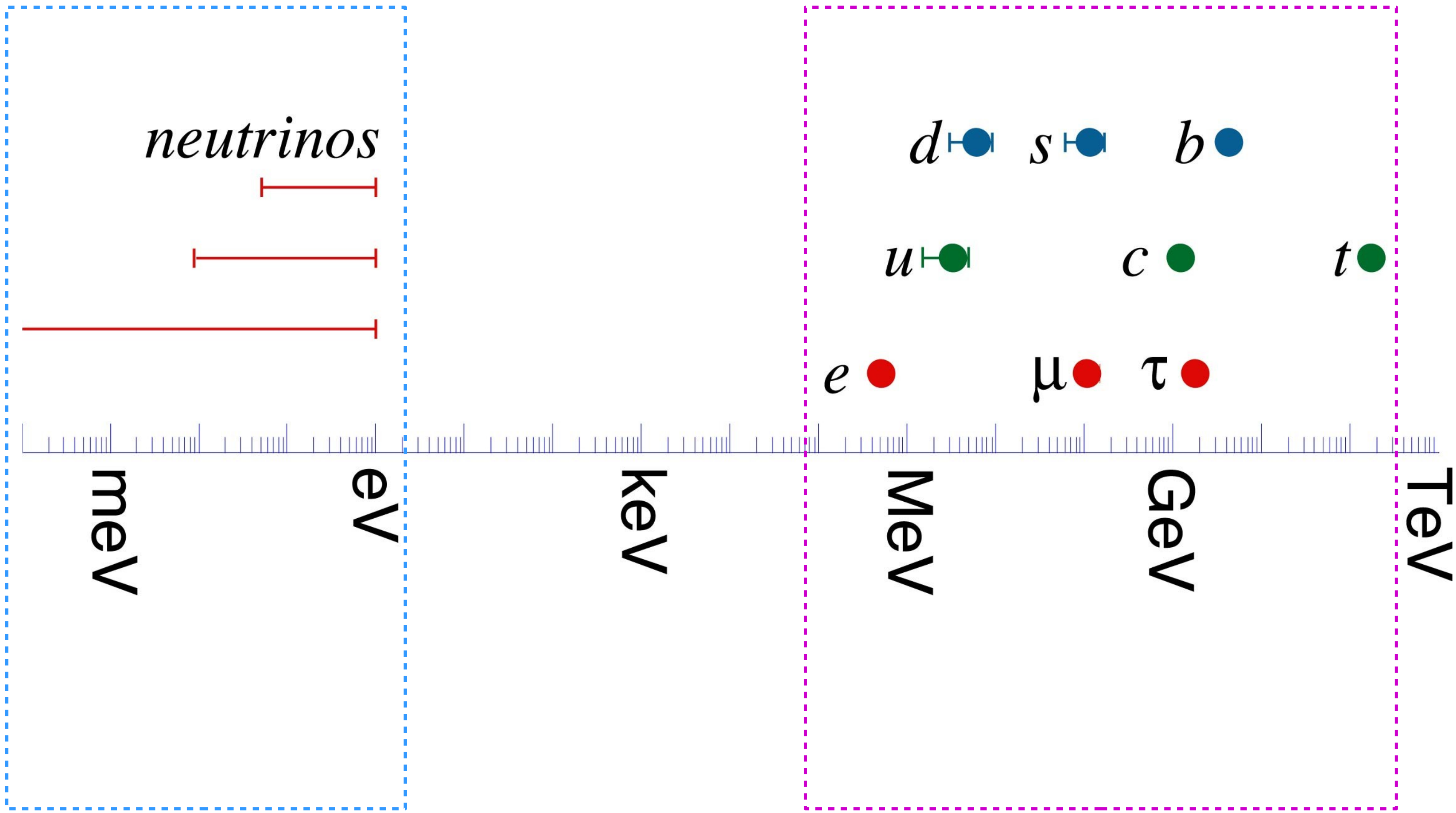
Neutrino masses

Neutrinos have MASS



mmm...ok,
but how
much?

Neutrinos have MASS



See Elisa Resconi's talk


Majorana
Dirac

$$Y_\nu \widetilde{\phi} \bar{L}_L \nu_R$$

$$Y_\nu \widetilde{\phi} \bar{L}_L \nu_R$$

why so light?

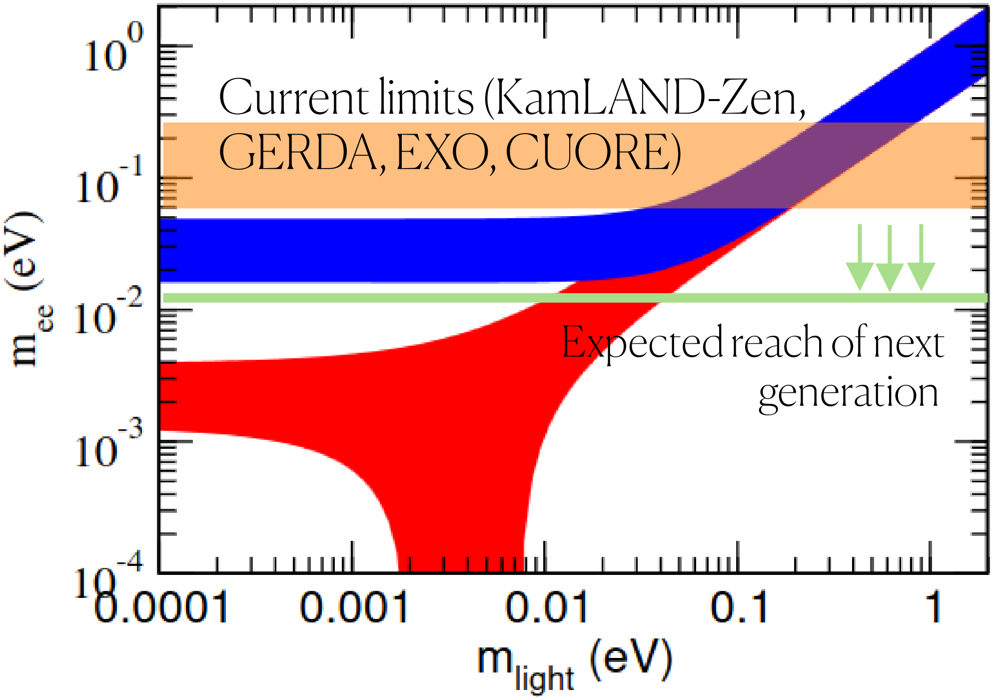
also, why is L conserved?

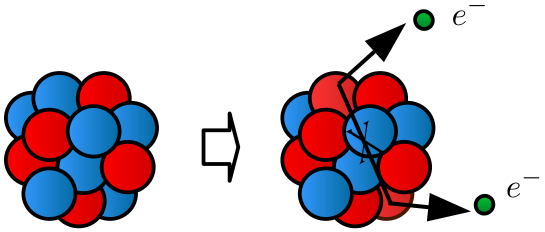
is it a fundamental symmetry?

$$\frac{c}{\Lambda}(\bar{L}^c\tilde{\phi}^*)(\tilde{\phi}^\dagger L)$$

Weinberg, '79

See Elisa Resconi's talk

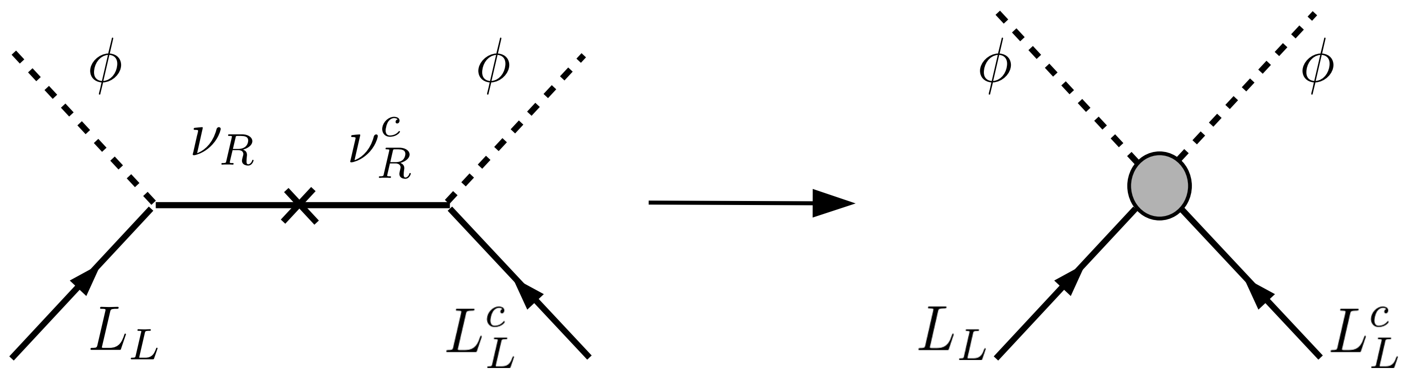




which mechanism generates neutrino masses?

what is the scale associated to the new particle?

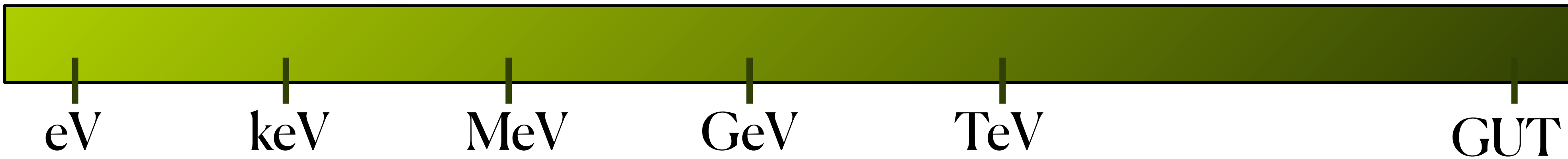
N_R, where are you?



$$Y_\nu \bar{L}_L \widetilde{\phi} \nu_R + \frac{1}{2} M \overline{\nu}_R^c \nu_R$$

$$m_\nu = \frac{Y_\nu^\dagger Y_\nu v^2}{M}$$

N_R, where are you?

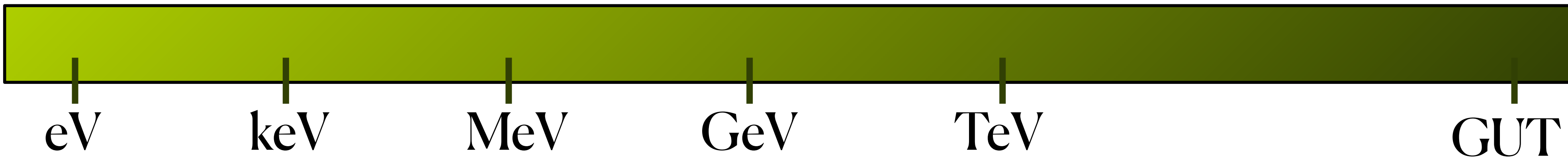


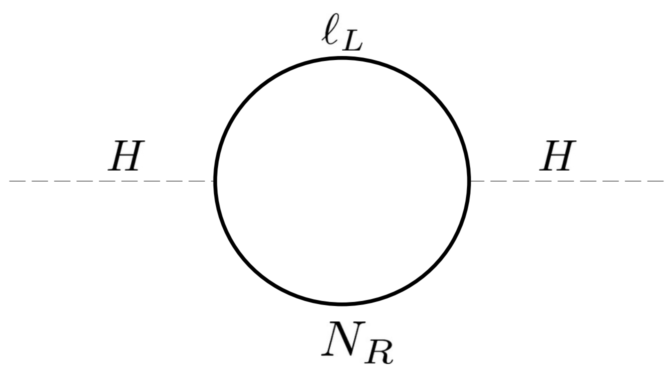
Traditional type-I Seesaw
$y \sim O(1)$

Viable Leptogenesis

Type I Seesaw:
Minkowski '77, Gell-Mann, Ramond, Slansky '79, Yanagida '79, Mohapatra, Senjanovic '80

N_R, where are you?





$$\delta\mu^2 \approx \frac{Y_\nu^2}{4\pi^2} M_R^2 \log\left(\frac{q}{M_R}\right)$$

Vissani, hep-ph/9709409
Casas, Espinosa, Hidalgo, hep-ph/0410298

Traditional type-I Seesaw
y ~ O(1)

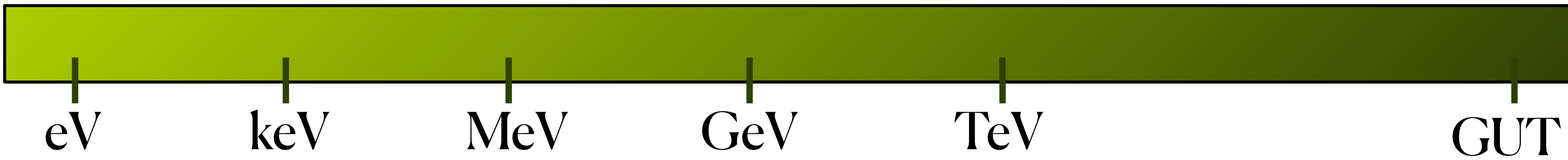
Viable Leptogenesis

Large contributions to hierarchy problem

Only indirect tests:
EW precision & LFV
(non-unitarity)

See Xabier Marcano's talk

N_R, where are you?

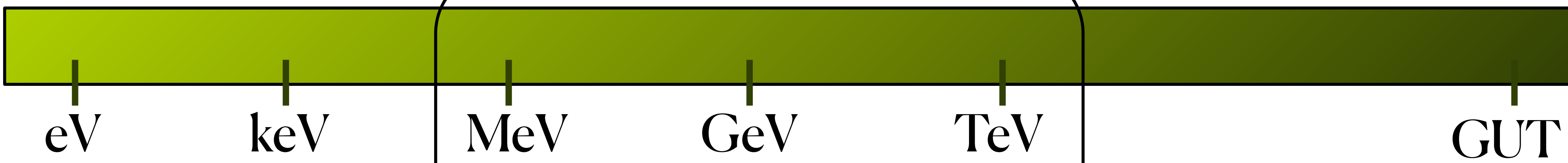


Testable in cosmology, beta-decay, astrophysical X-ray searches, oscillations

Cosmological bounds are strong!

See e.g., Boyarsky, Ovchynnikov, Ruchayskiy, Syvolap, 2008.00749

N_R, where are you?



L could be an approximate symmetry (pseudo-Dirac neutrinos)

Leptogenesis also possible

Does not worsen hierarchy problem

Directly testable

Akhmedov, Rubakov, Smirnov, hep-ph/9803255

See also: Asaka, Shaposhnikov, hep-ph/0505013; Hernandez, Kekic, Lopez-Pavon, Racker, Salvado, 1606.06719; Drewes, Garbrecht, Gueter, Klaric, 1609.09069

New efforts

New searches

MicroBooNE searches, 1911.10545 & 2207.03840
T2K search, 1902.07598
ArgoNeuT search, 2106.13684
Belle search, 2212.10095
BaBar search, 2207.09575
NA62 searches, 2005.09575
...

New efforts

New searches

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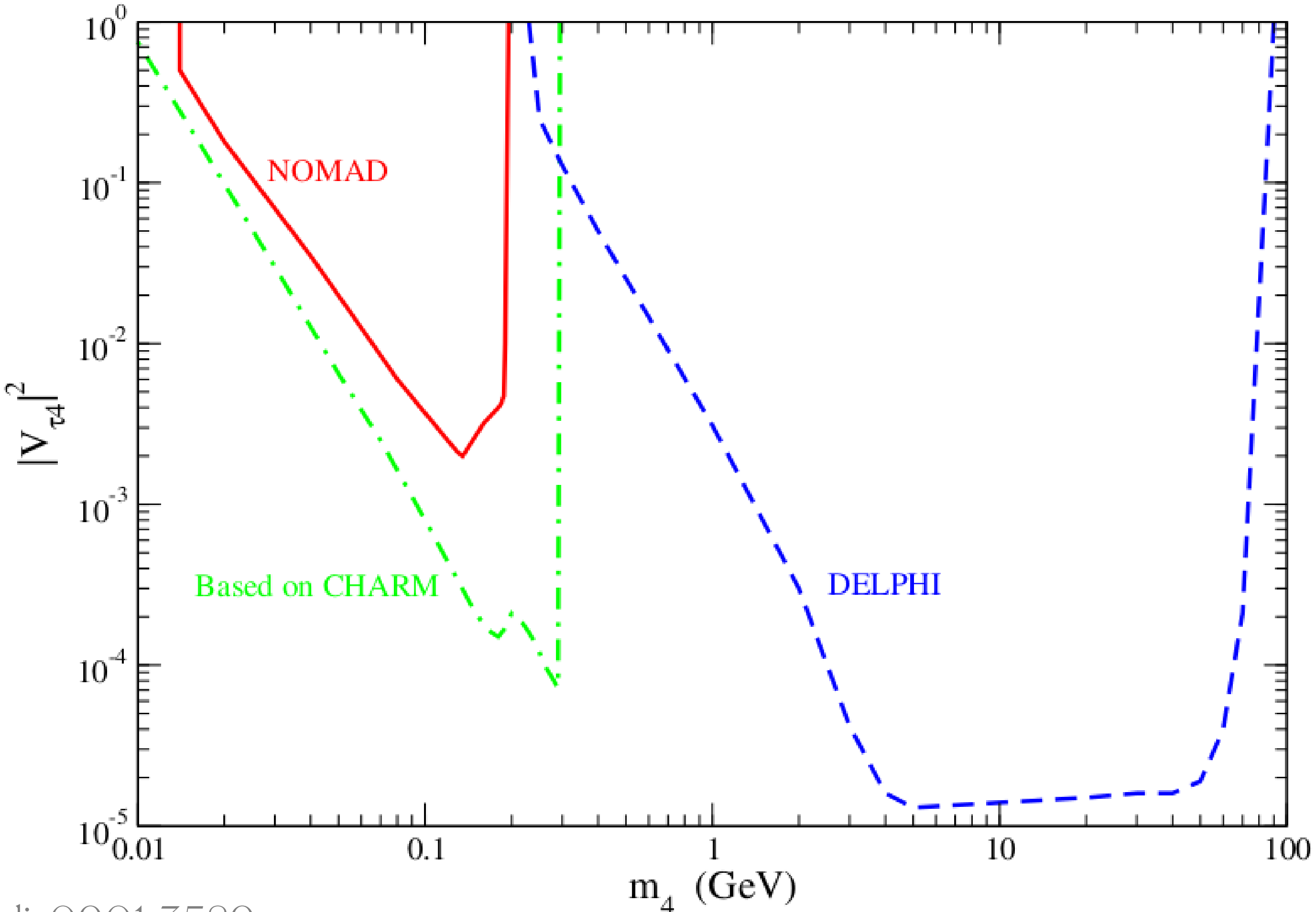
BaBar search, 2207.09575
NA62 searches, 2005.09575
...

New analyses/Recasts

Recasts of MicroBooNE data: Kelly & Machado, 2106.06548
Atmospheric HNL searches using SK & Icecube data: Arguelles, Coloma, Hernandez, Munoz, 1910.12839; Coloma, Hernandez, Munoz, Shoemaker, 1911.09129
HNL searches using Borexino & SK data: Plestid, 2010.09523 & 2010.04193
HNL searches using SK: Gustafson, Plestid, Shoemaker, 2205.02234
Reanalysis of BEBC data: Barouki, Marocco, Sarkar, 2208.00416
Recasts of CHARM data: Boiarska, Boyarsky, Mikulenko, Ovchynnikov, 2107.14685
Recast of LSND data: Ema, Liu, Lyu, Pospelov, 2306.07315
...

New efforts

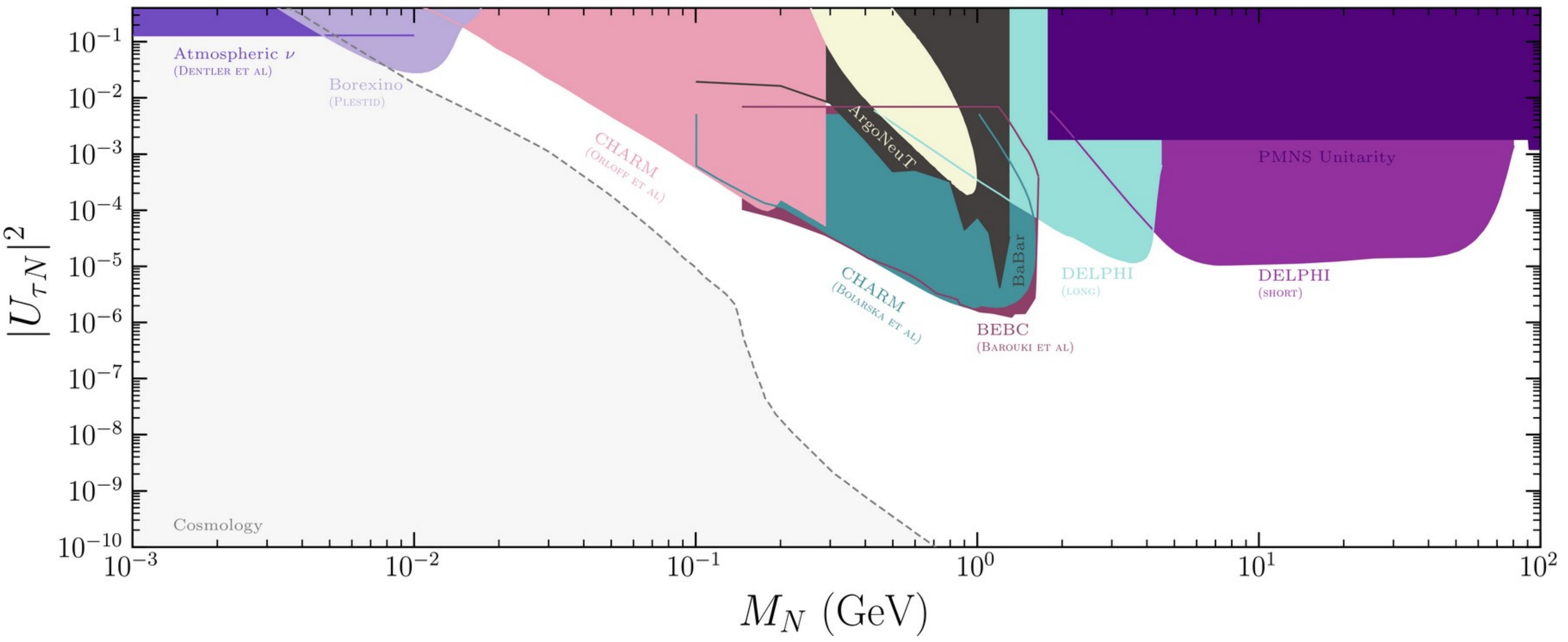
Bounds on the tau sector until ~2018:



Atre, Han, Pascoli, 0901.3589

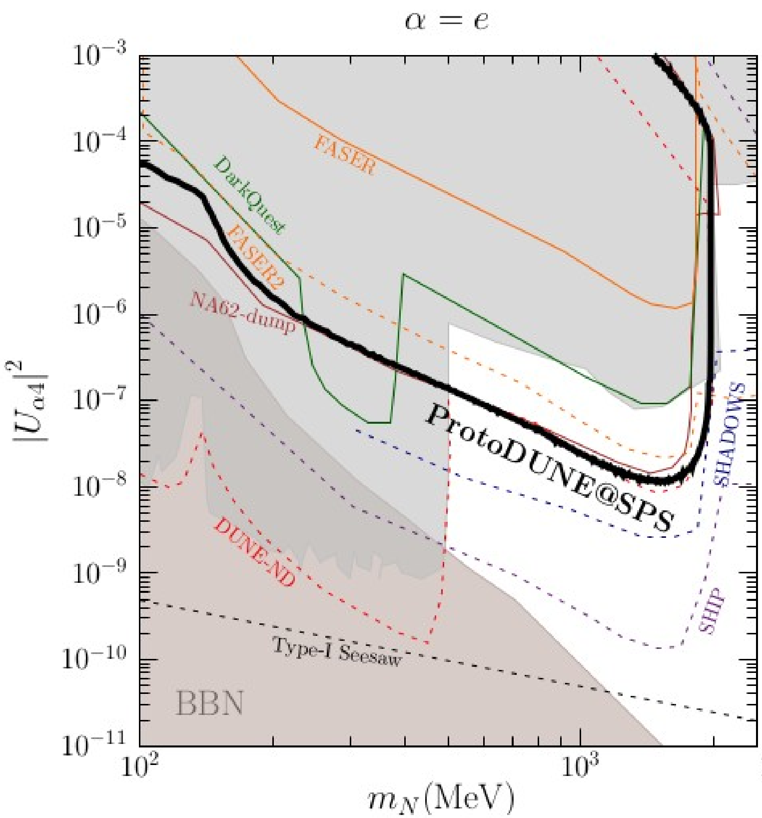
New efforts

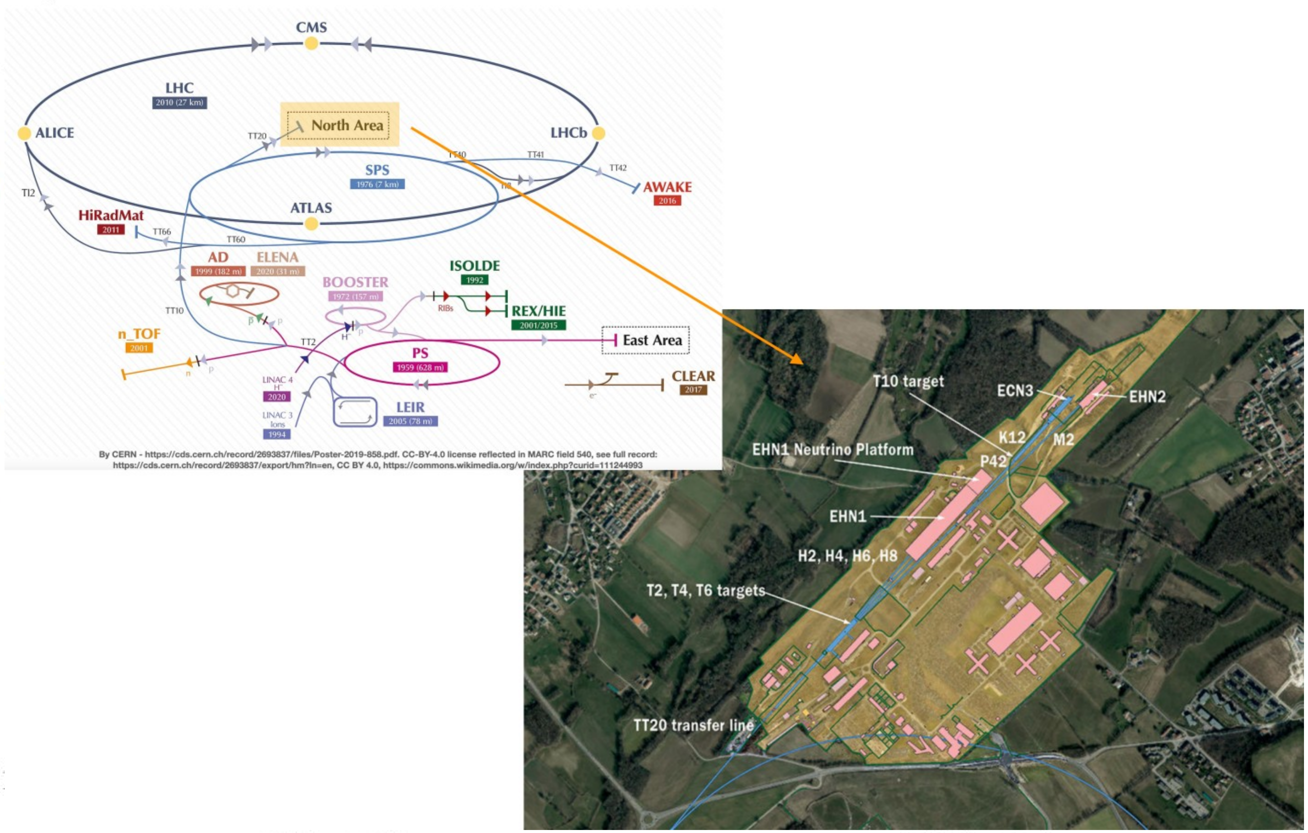
Bounds on the tau sector today:



Fernandez-Martínez, González-López, Hernández-García, Hostert, López-Pavón, 2304.06772

New proposals



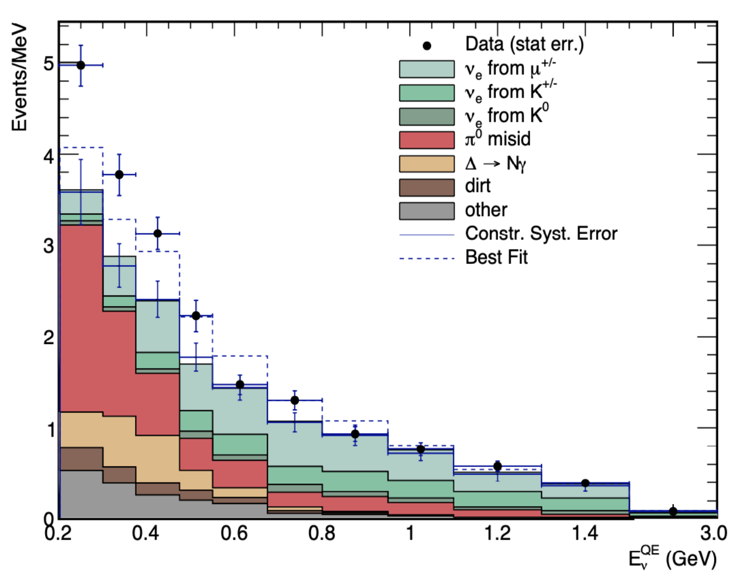


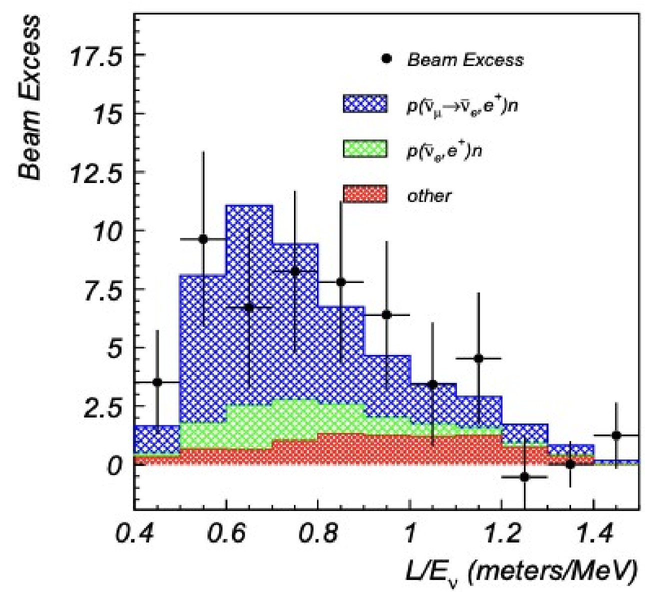
Decays considered: $N \to \nu ee, \nu\mu\mu, \nu e\mu, e\pi, \mu\pi, \nu\pi^0$

Coloma, Lopez-Pavon, Molina-Bueno, Urrea, 2304.06765

Anomalies

LSND/MiniBooNE





MiniBooNE: ~4.7σ
LSND: ~3.8σ

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

MicroBooNE results disfavors the sterile neutrino as an explanation for the MiniBooNE excess at > 97 % CL

MicroBooNE, 2110.14054

See Benjamin Bogart's talk

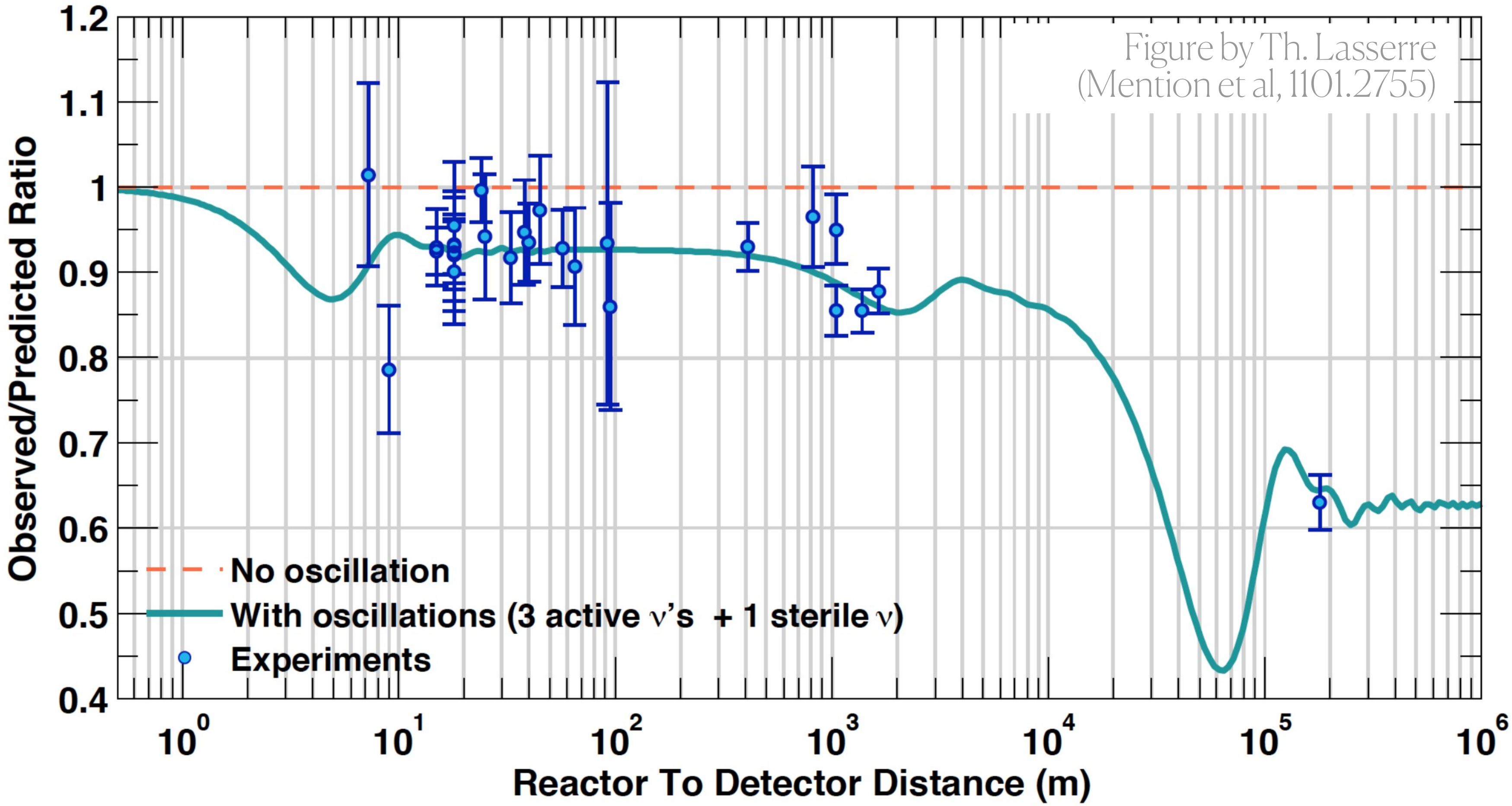
→ A signal in appearance requires disappearance as well:

$$\sin^2 2\theta_{\mu e} \simeq \frac{1}{4} \sin^2 2\theta_{ee} \sin^2 2\theta_{\mu\mu}$$

(see e.g. Dentler, Hernandez-Cabezudo, Kopp, et al, 1803.10661)

Reactor antineutrino anomaly?

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



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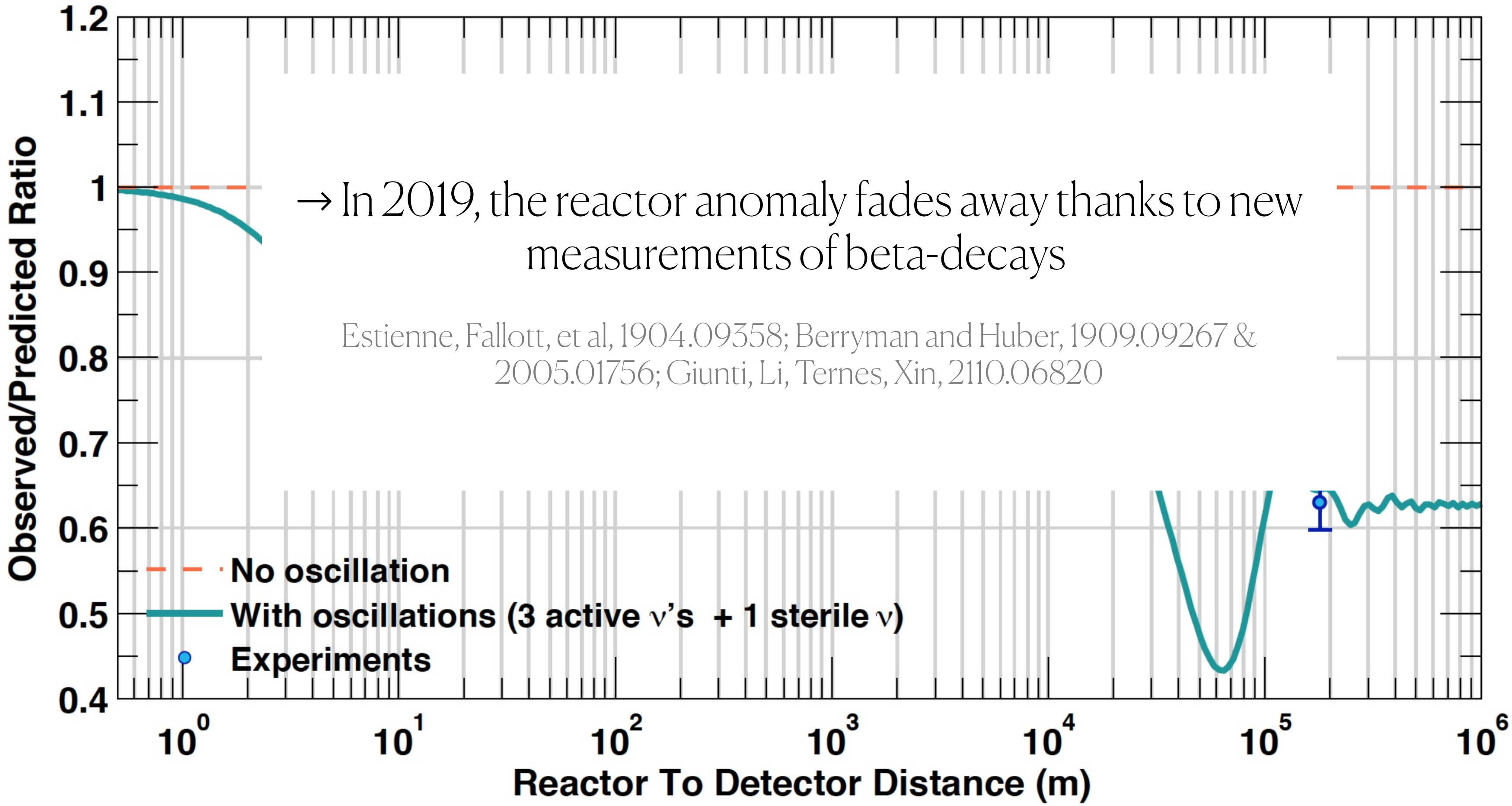
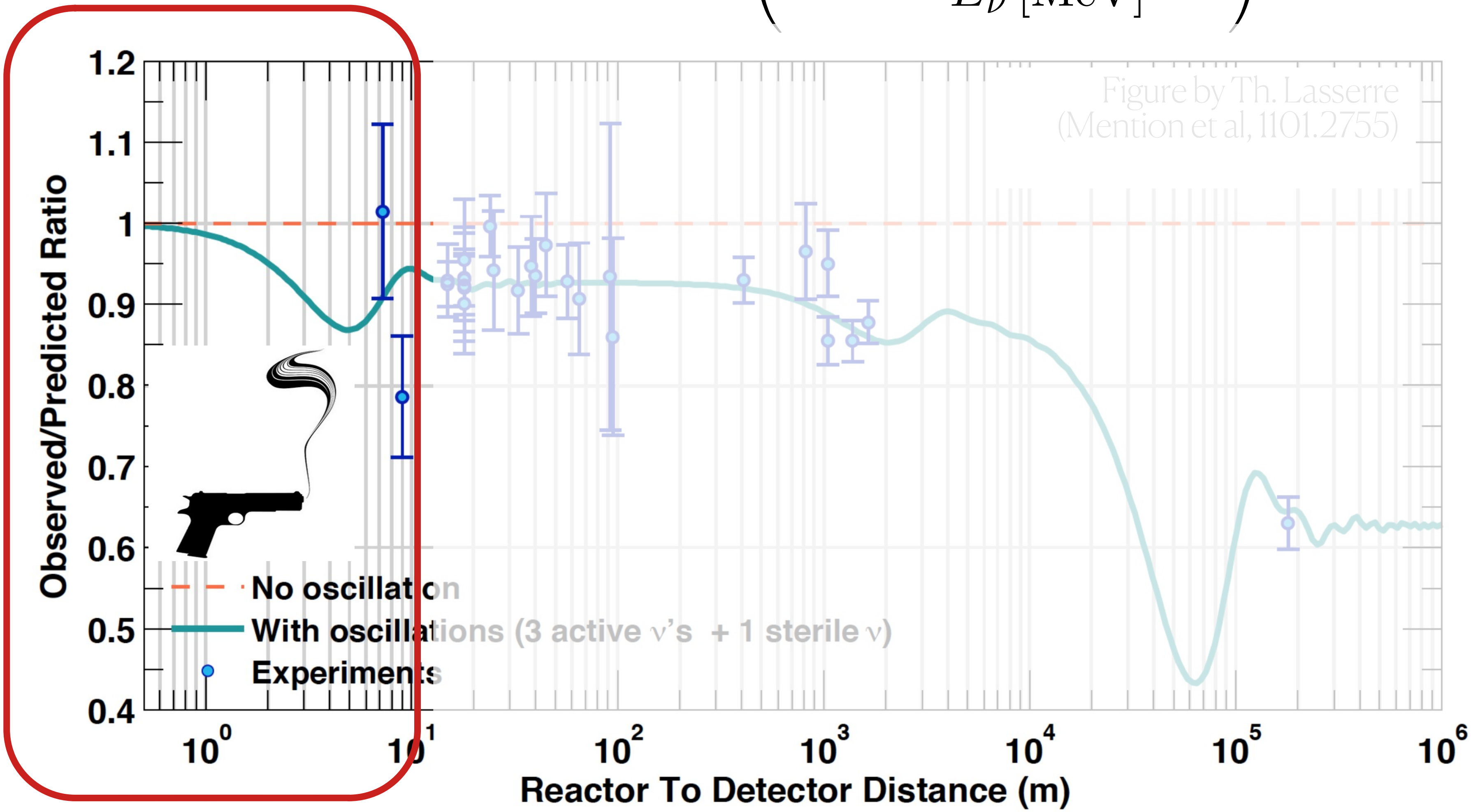


→ In 2019, the reactor anomaly fades away thanks to new measurements of beta-decays

Estienne, Fallott, et al, 1904.09358; Berryman and Huber, 1909.09267 & 2005.01756; Giunti, Li, Ternes, Xin, 2110.06820

Very Short-Baseline Reactors

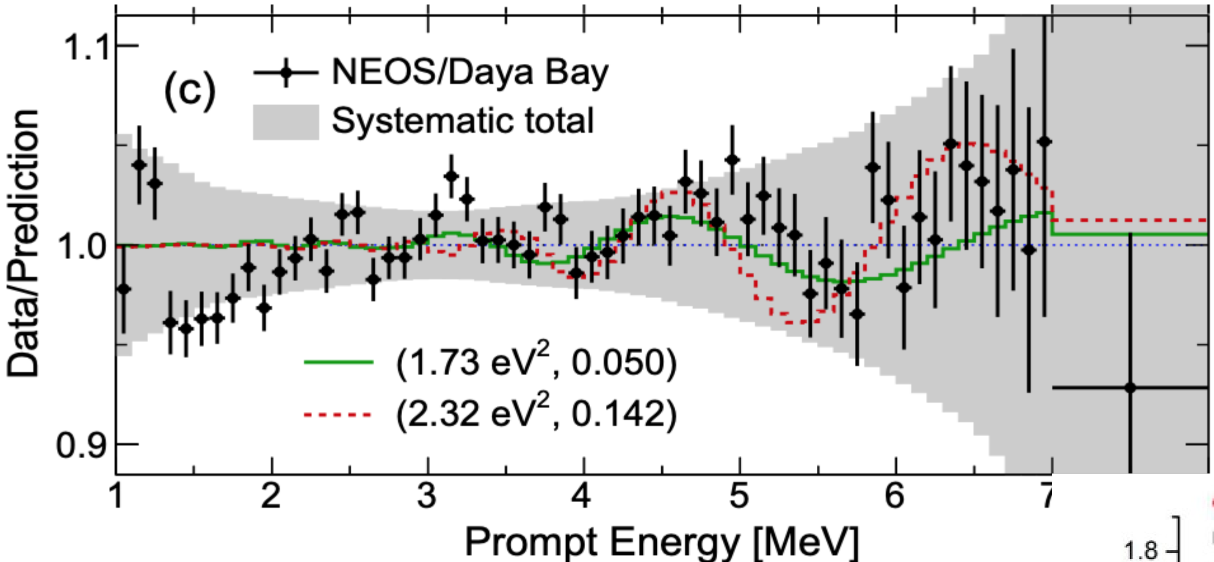
$$P_{ee} \simeq 1 - \sin^2 2\theta_{ee} \sin^2\left(1.27 \frac{\Delta m^2\,[\mathrm{eV}^2]\; L\,[\mathrm{m}]}{E_\nu\,[\mathrm{MeV}]}\right)$$



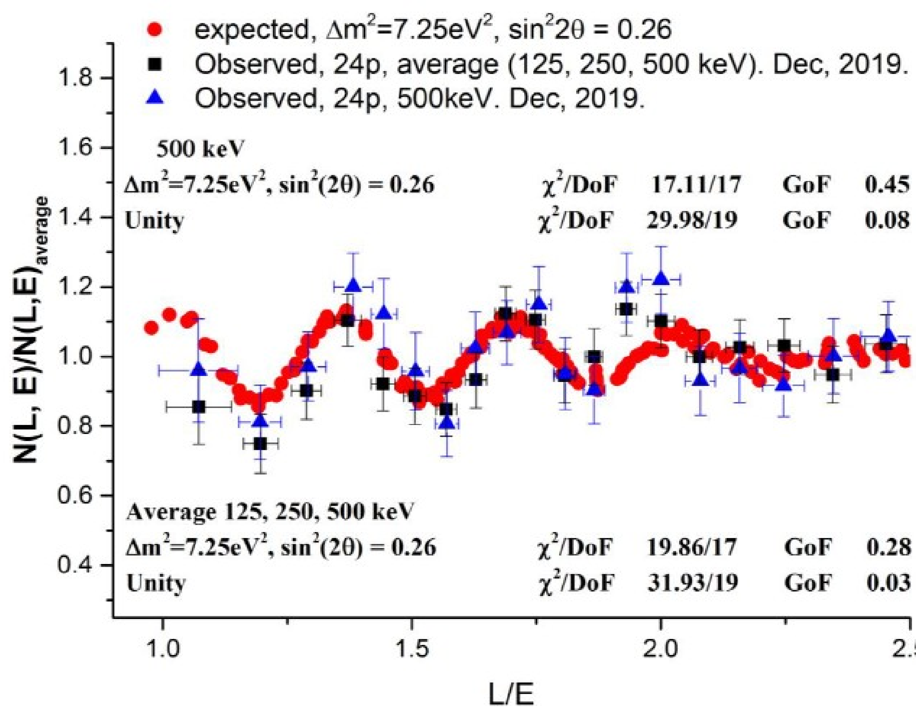
Very Short-Baseline reactors

(PROSPECT, STEREO, NEOS, DANSS, Neutrino-4)

NEOS coll., 1610.05134



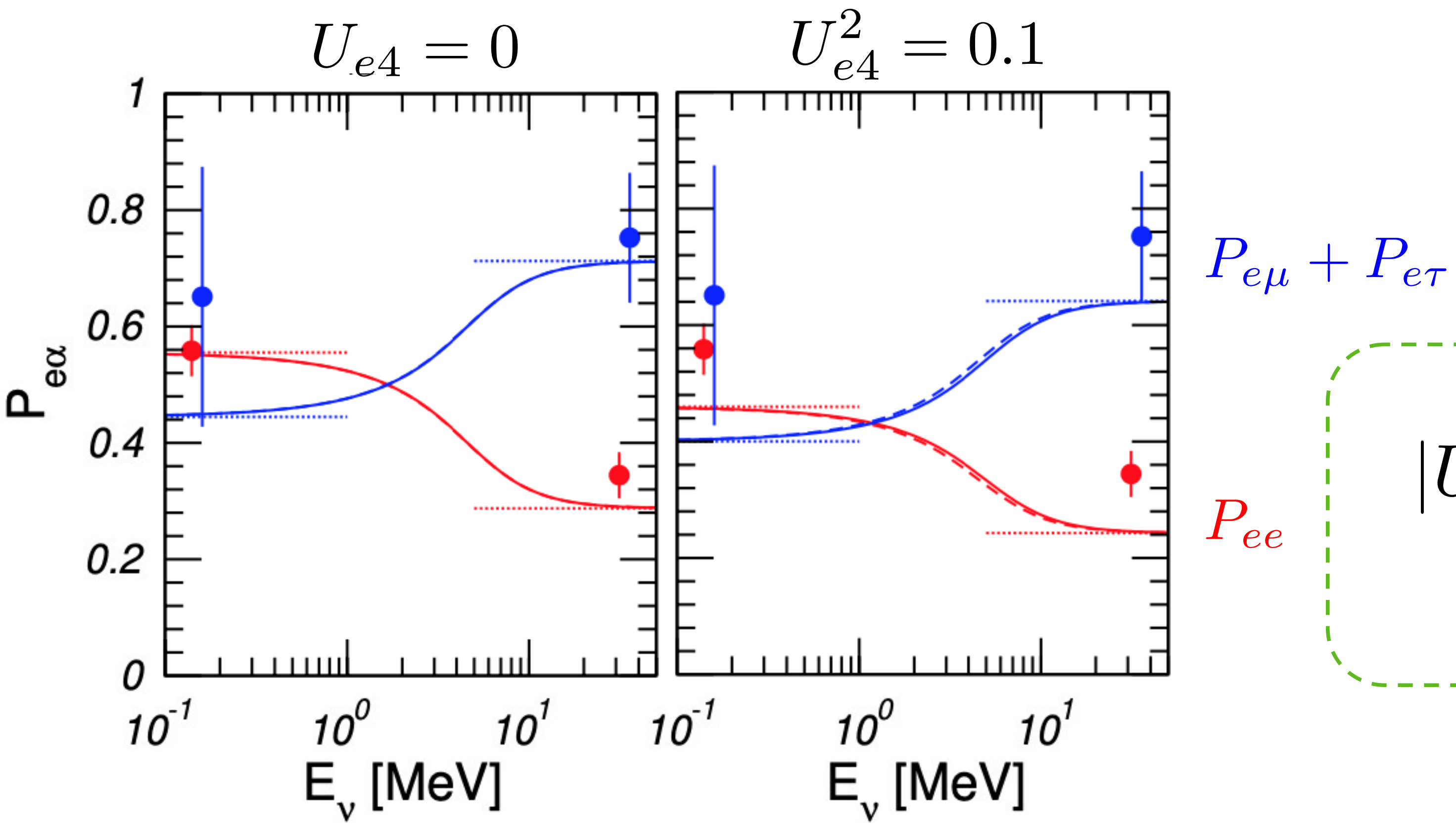
Neutrino-4 coll., 2005.05301



→ Was there a signal beyond statistical fluctuations?

Agostini, Neumair, 1906.11854
Giunti, 2004.07577
PROSPECT & STEREO, 2006.13147
Coloma, Huber, Schwetz, 2008.06083

Solar neutrinos

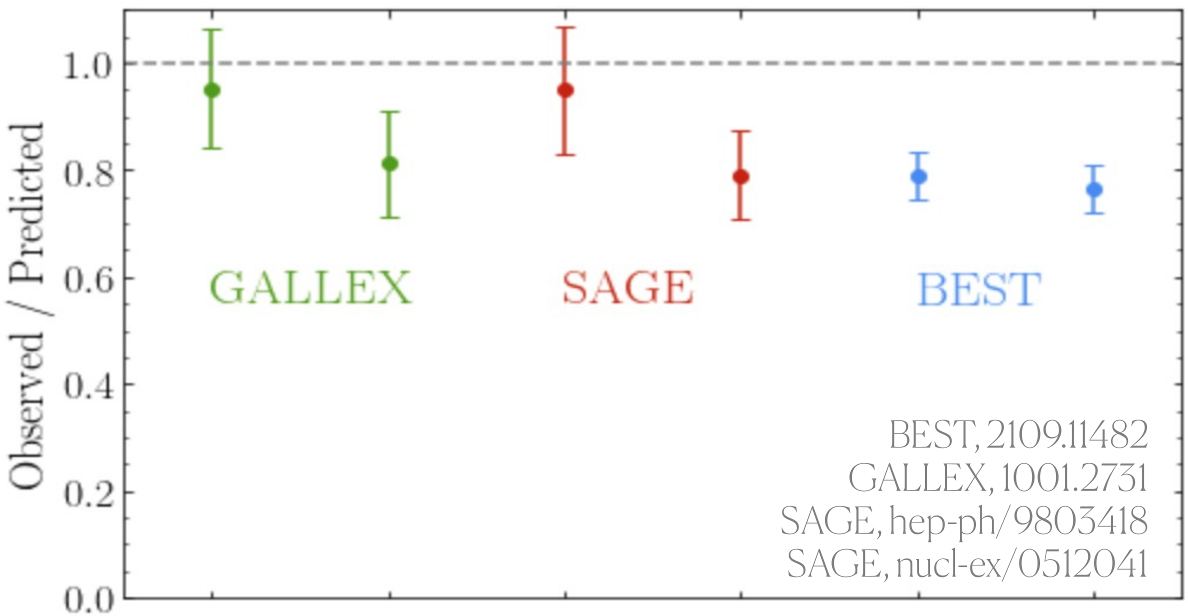


$$|U_{e4}|^2 < 0.168$$

(90% C.L.)

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

Gallium experiments



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

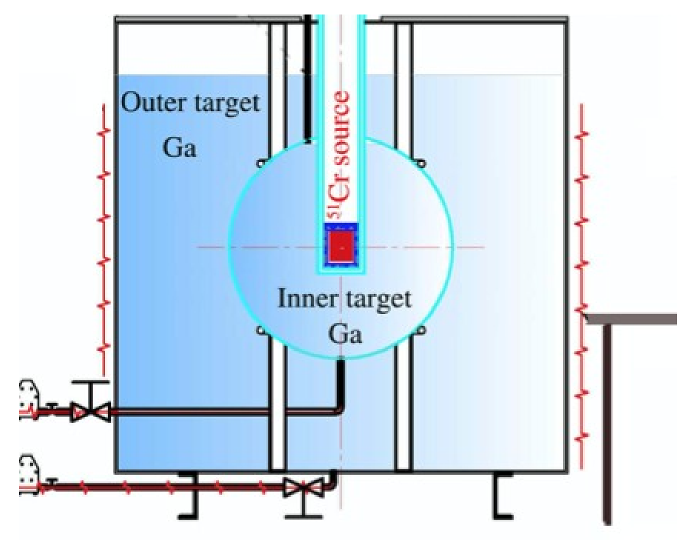
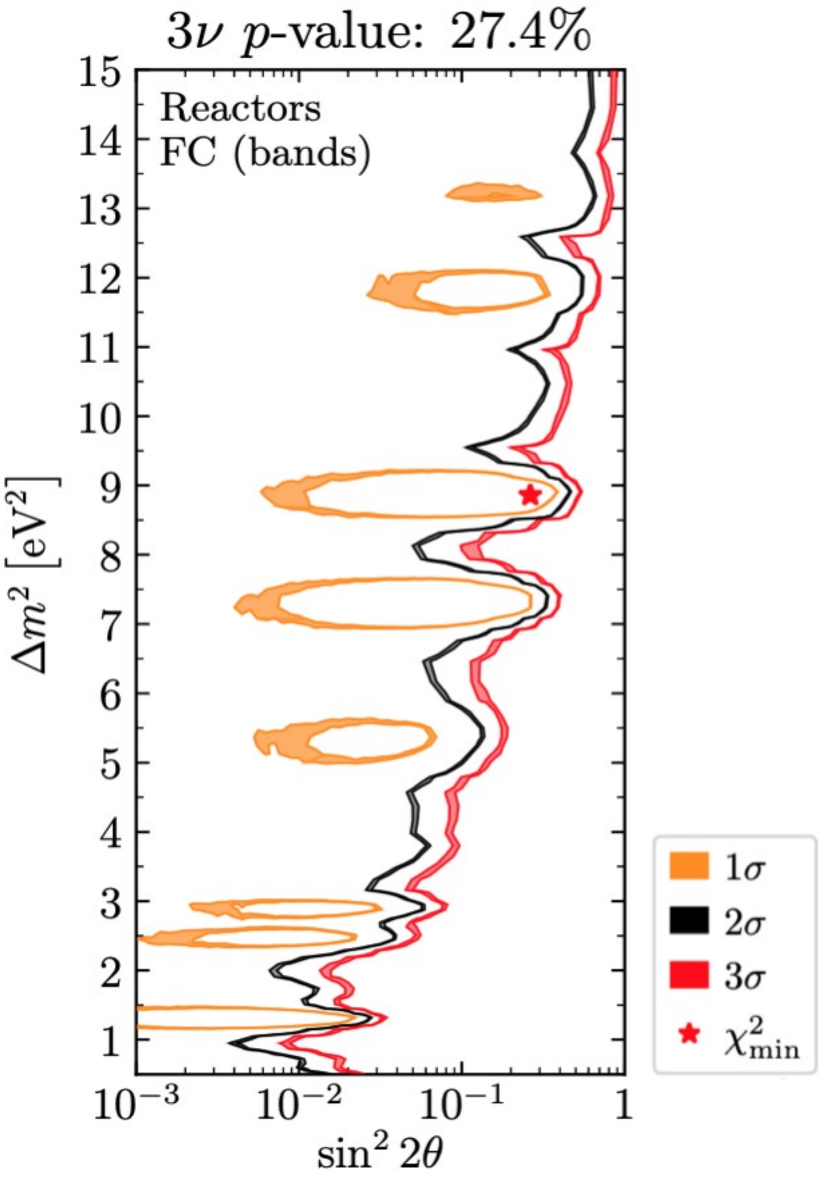


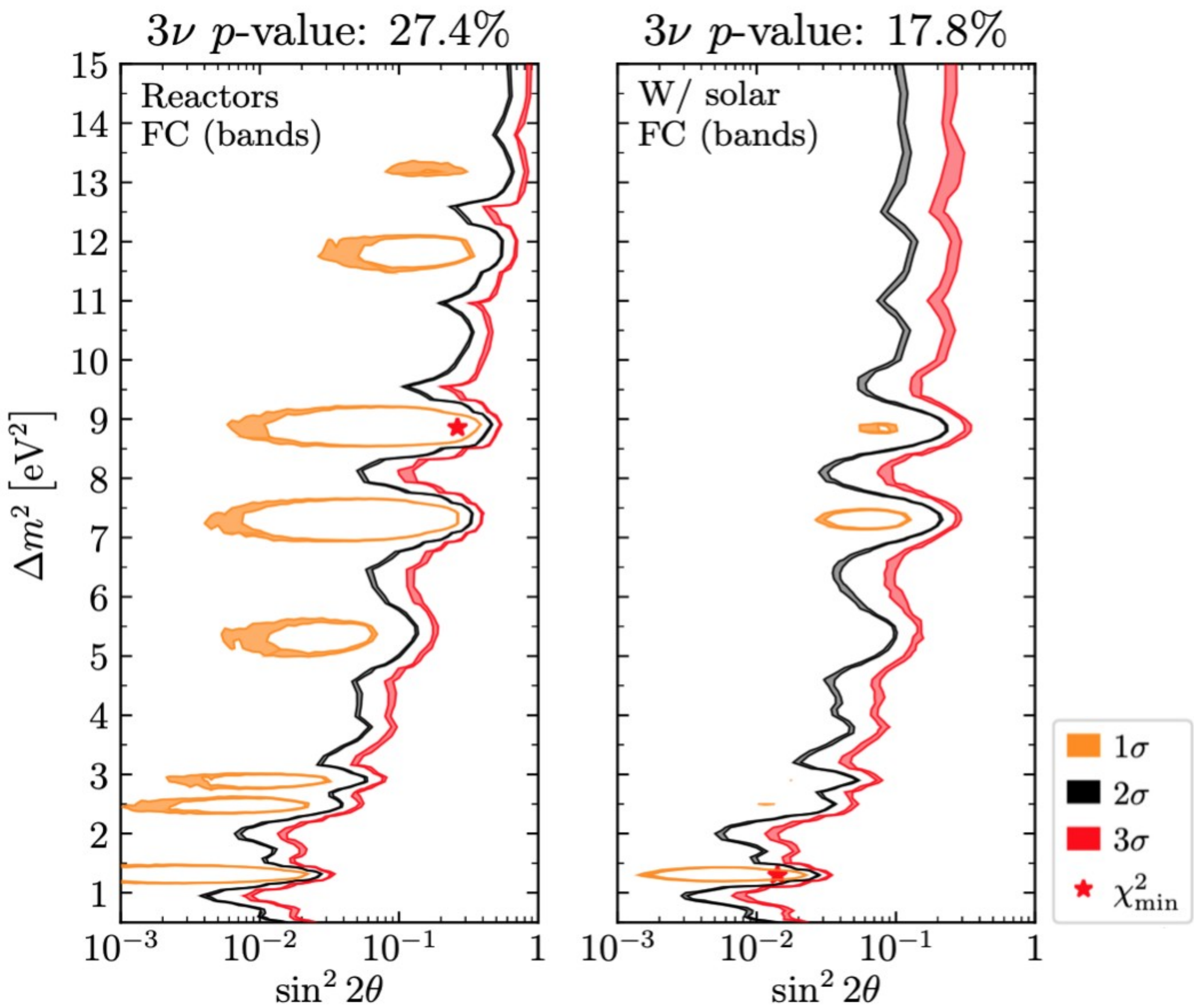
Figure from 2109.11482

Reactors



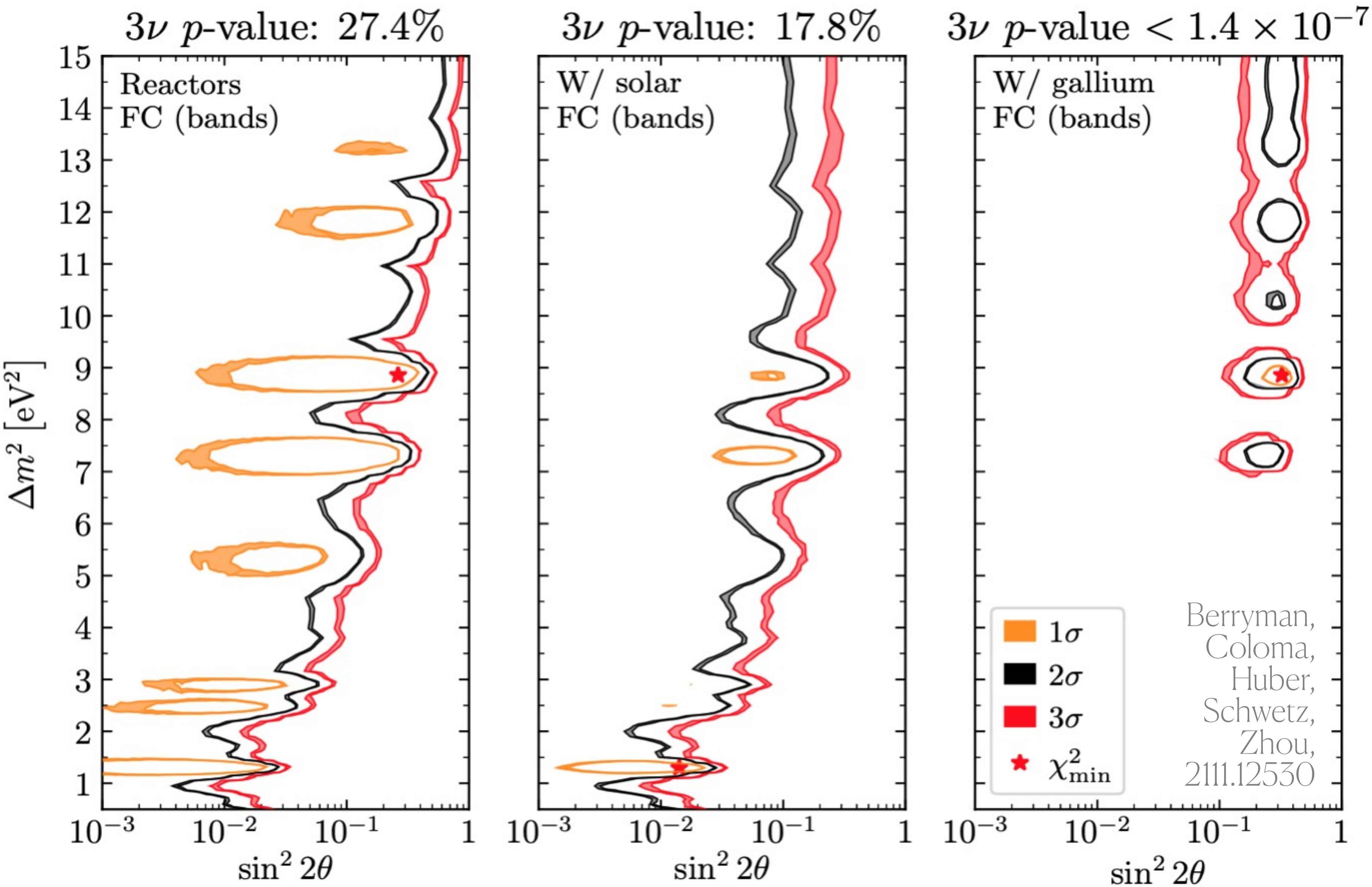
Berryman, Coloma, Huber, Schwetz, Zhou, 2111.12530

Reactors　　Reactors + Solar



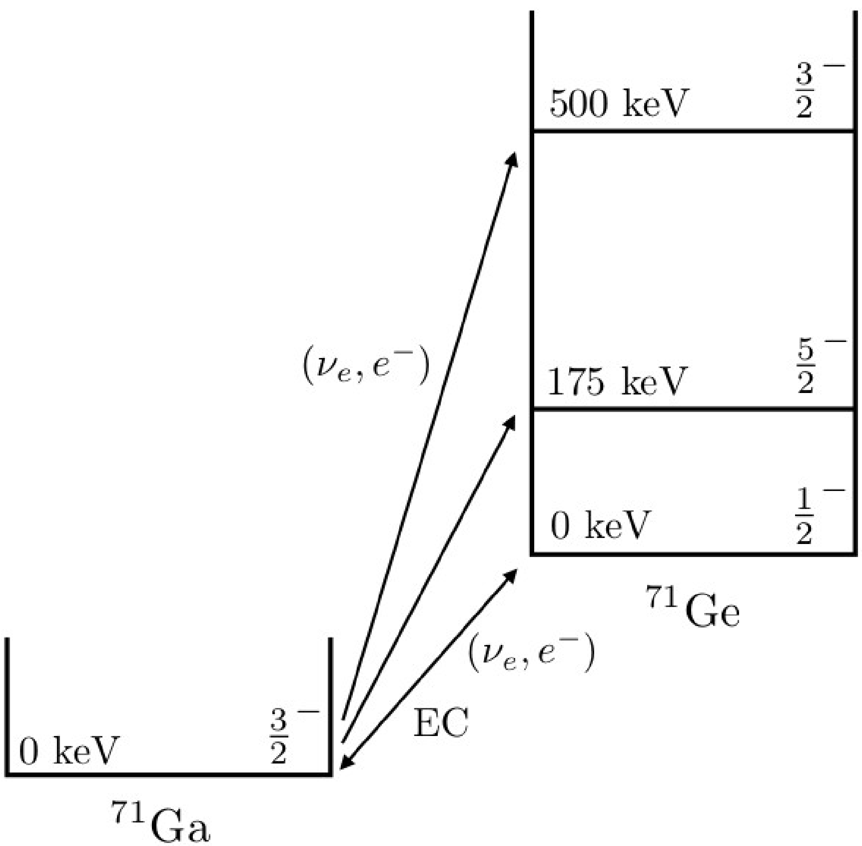
Berryman, Coloma, Huber, Schwetz, Zhou, 2111.12530

Reactors | Reactors + Solar | Reactors + Ga



Then…what about Gallium?

- SM explanations not satisfactory. Usual suspects include:
    - cross section



Several calculations available:

Bahcall, hep-ph/9710491
Semenov, Phys. Atom. Nucl. 83 (2020) 1549
Kostensalo et al, 1906.10980
Haxton, Rule, Elliott, Gavrin, Ibragimova, 2303.13623

→ Significance always remains above 5σ

Then…what about Gallium?

- SM explanations not satisfactory. Usual suspects include:
  - ~~cross section~~
  - determination of Ge half-life

$$T_{1/2}^{\rm BGZZ}(^{71}{\rm Ge}) = 12.5 \pm 0.1\,{\rm d} \quad \text{(Bisi, Germagnoli, Zappa, and Zimmer, 1955) [39]},$$
$$T_{1/2}^{\rm R}(^{71}{\rm Ge}) = 10.5 \pm 0.4\,{\rm d} \quad \text{(Rudstam, 1956) [40]},$$
$$T_{1/2}^{\rm GRPF}(^{71}{\rm Ge}) = 11.15 \pm 0.15\,{\rm d} \quad \text{(Genz, Renier, Pengra, and Fink, 1971) [41]},$$
$$T_{1/2}^{\rm HR}(^{71}{\rm Ge}) = 11.43 \pm 0.03\,{\rm d} \quad \text{(Hampel and Remsberg, 1985) [42]}.$$

Giunti, Li, Ternes, Xin, 2212.09722

Then…what about Gallium?

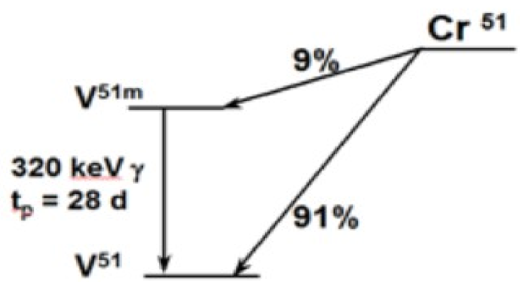
- SM explanations not satisfactory. Usual suspects include:
  - ~~cross section~~
  - determination of Ge half-life

$$T_{1/2} = 11.46 \pm 0.04 \text{ d}$$

Collar & Yoon, 2307.05353

Then…what about Gallium?

- SM explanations not satisfactory. Usual suspects include:
  - ~~cross section~~
  - ~~determination of Ge half-life~~
  - calibration of the source, Ge extraction efficiency



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

Brdar, Gehrlein, Kopp, 2303.05528

Then…what about Gallium?

- SM explanations not satisfactory. Usual suspects include:
    - ~~cross section~~
    - ~~determination of Ge half-life~~
    - calibration of the source, Ge extraction efficiency (?)

- Other BSM explanations possible, although with significant fine-tuning, e.g.
    - sterile neutrino coupled to ultra-light DM — Brdar, Gehrlein, Kopp, 2303.05528
    - non-standard neutrino decoherence — Farzan & Schwetz, 2306.09422

The anomaly can be probed with future data from MicroBooNE, KATRIN and DANSS, or maybe even by the BEST collaboration

…and what about MiniBooNE?

→ SM explanations are insufficient. Backgrounds are the usual suspects in this case.

The MiniBooNE excess has been **heavily scrutinized** by the collaboration as well as by the theory/pheno community

The significance may be somewhat reduced with a different background treatment or Monte Carlo tune, but remains between 3σ-4σ

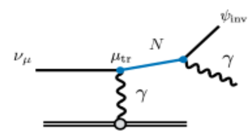
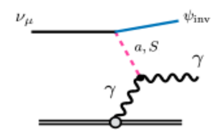
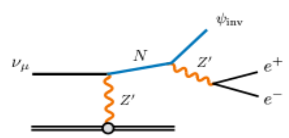
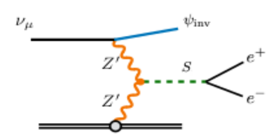
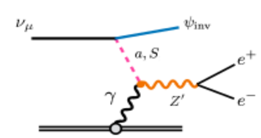
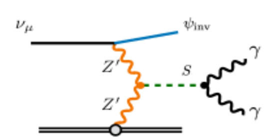
See e.g., MiniBooNE coll.,1805.12028;
Alvarez-Ruso, Nieves, Wang, 1501.05995;
Brdar & Kopp, 2109.08157;
Kelly & Kopp, 2210.08021

MicroBooNE has set severe constraints on the explanation from single photons from radiative decay of Δ resonance

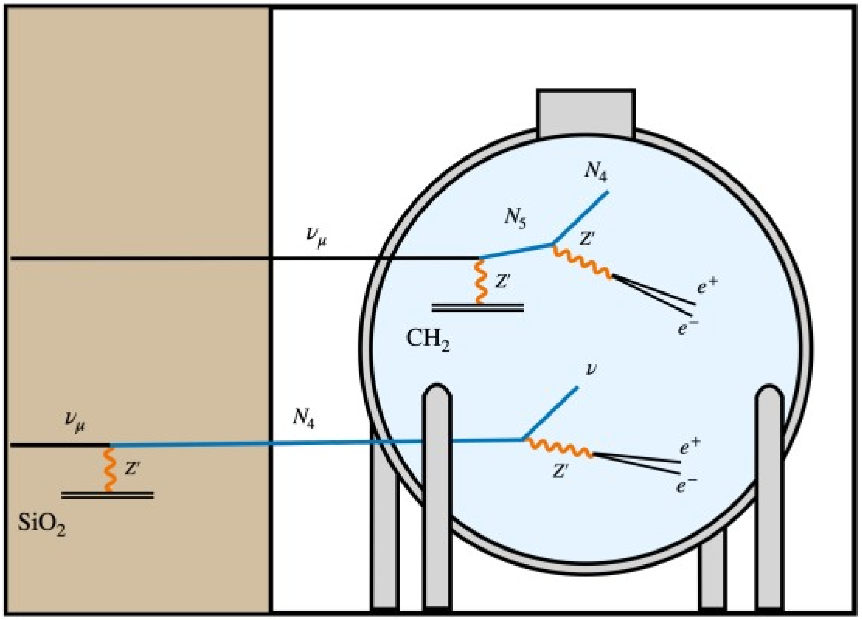
MicroBooNE coll., 2110.00409

...and what about MiniBooNE?

→ What about BSM explanations then?

Topology	Model	Diagram
single γ	neutrino upscattering	
	neutrino-induced inverse-Primakoff scattering	
e^+e^-	neutrino upscattering	
	neutrino-induced bremsstrahlung	
	neutrino-induced Primakoff scattering	
	neutrino-induced inverse-Primakoff scattering	
$\gamma\gamma$	neutrino-induced Primakoff scattering	

Viable BSM explanations recently reviewed in:
Abdullahi, Hoefken Zink, Hostert, Massaro, Pascoli,
2308.02543



Summary and outlook

- Many open questions still remain in neutrinos
    - in oscillations
    - in relation to neutrino masses
    - surrounding the experimental anomalies
    - ...and many others!

- Fortunately, we count with an intense experimental program which allows us to explore several fronts
- Stay tuned!

Thanks!

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MINISTERIO DE CIENCIA E INNOVACIÓN

European Union
European Social Fund

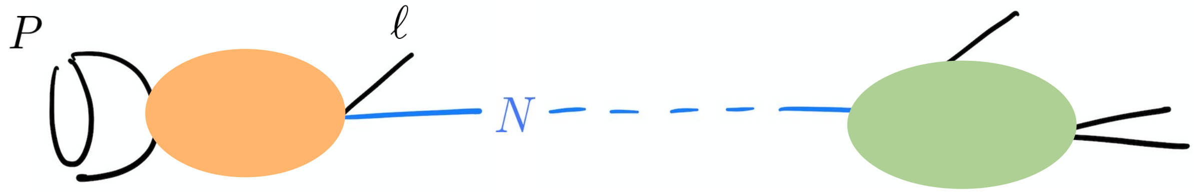
AGENCIA ESTATAL DE INVESTIGACIÓN

EXCELENCIA SEVERO OCHOA

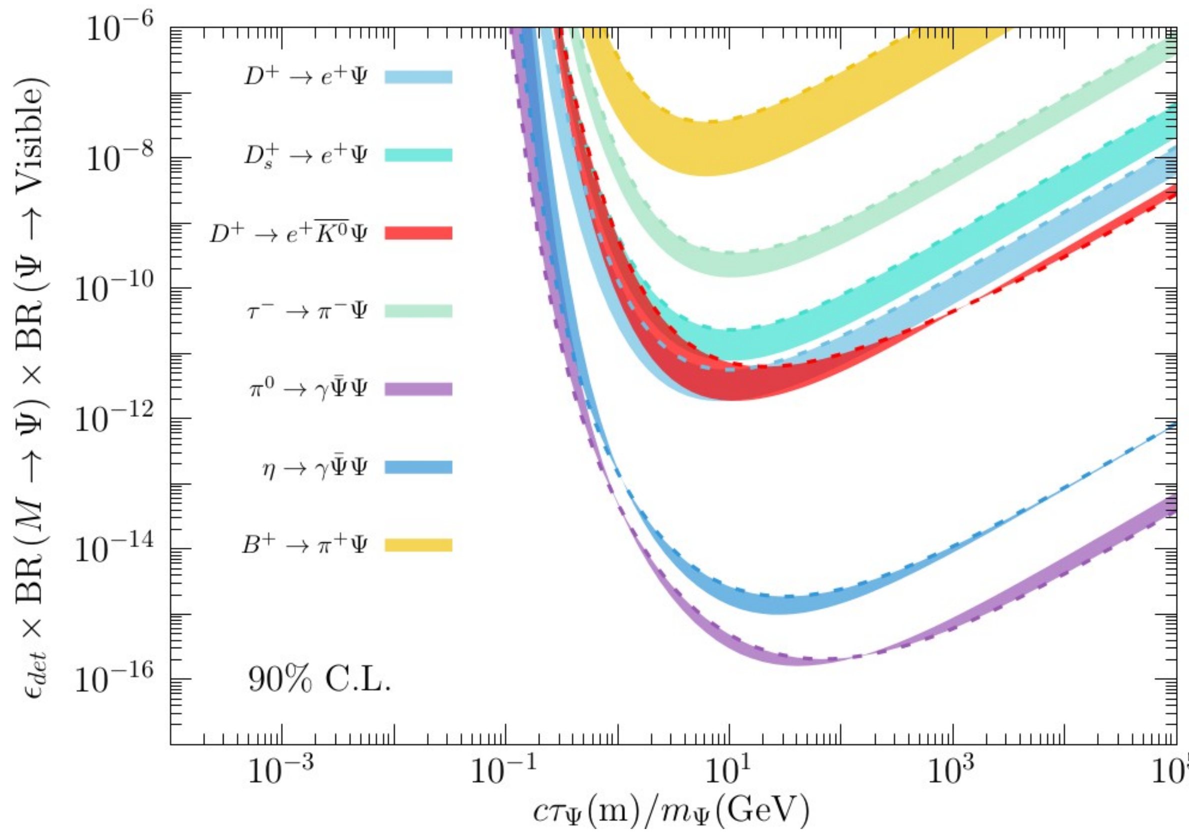
HIDDeN

Backup / Spares

Non-minimal possibilities



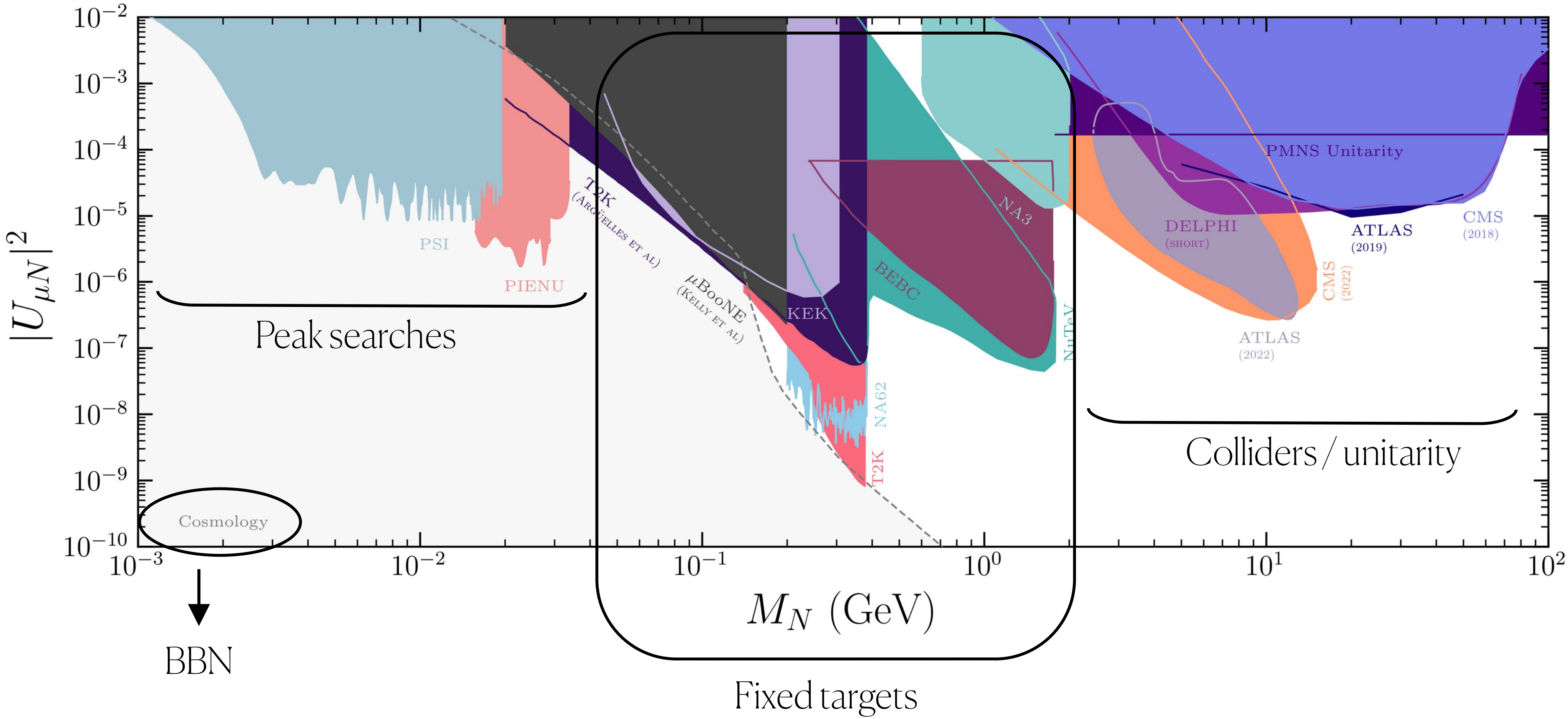
May lead to:
- shorter lifetimes!
- different particles in the final state!



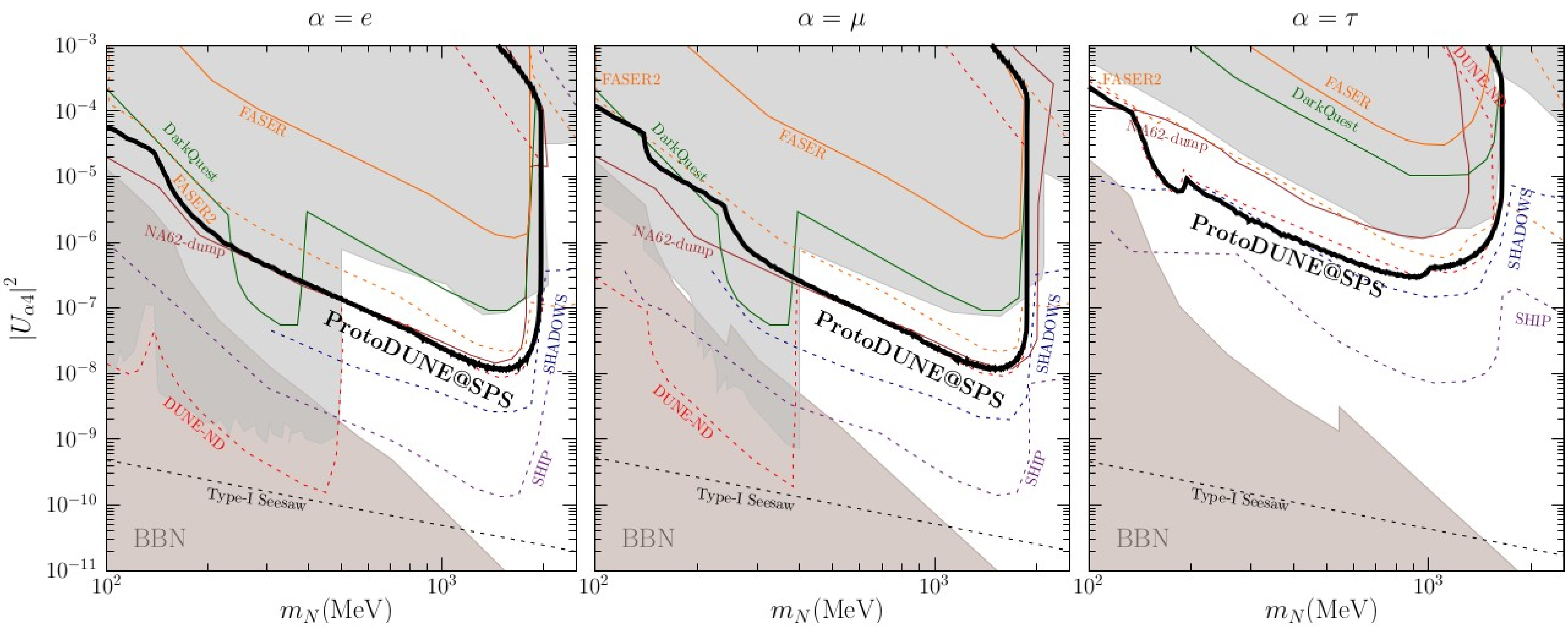
Coloma, Lopez-Pavon, Molina-Bueno, Urrea, 2304.06765

New efforts

Fernandez-Martínez, González-López, Hernández-García, Hostert, López-Pavón, 2304.06772



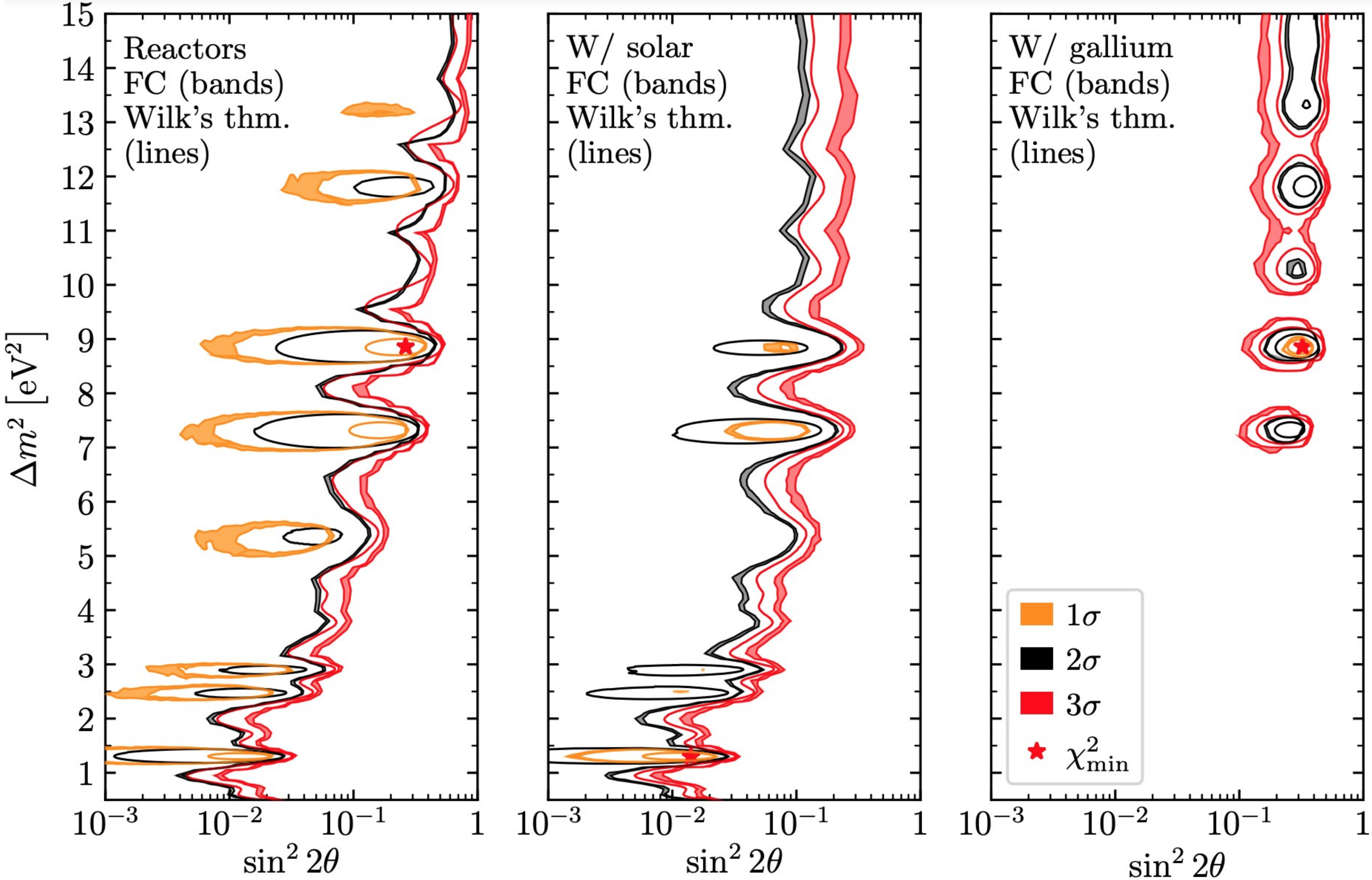
New proposals



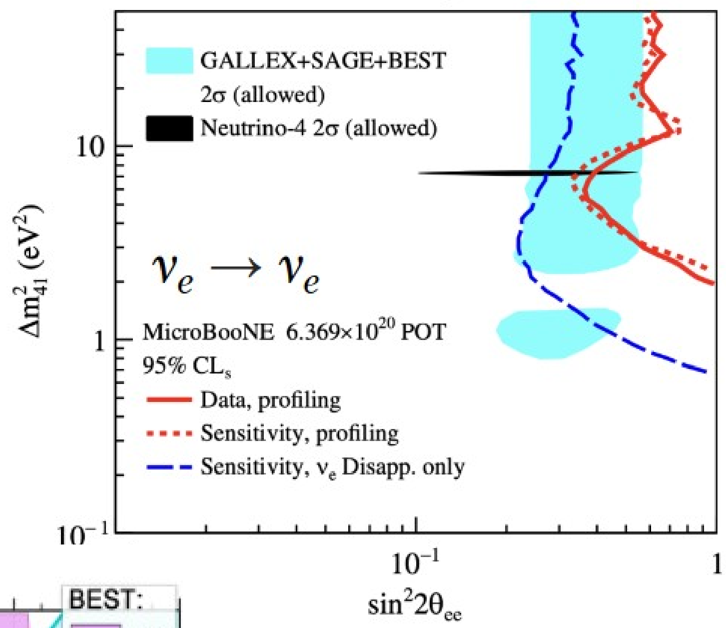
Decays considered: $N \to \nu ee, \nu\mu\mu, \nu e\mu, e\pi, \mu\pi, \nu\pi^0$

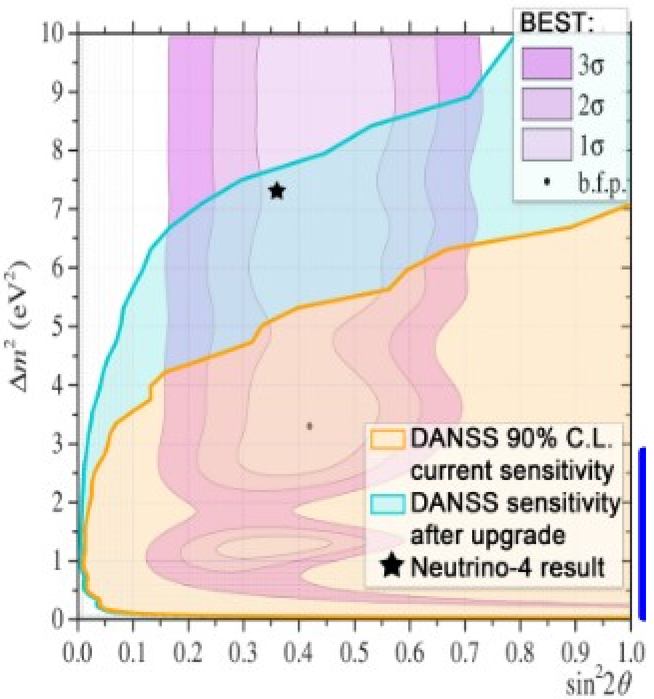
Coloma, Lopez-Pavon, Molina-Bueno, Urrea, 2304.06765

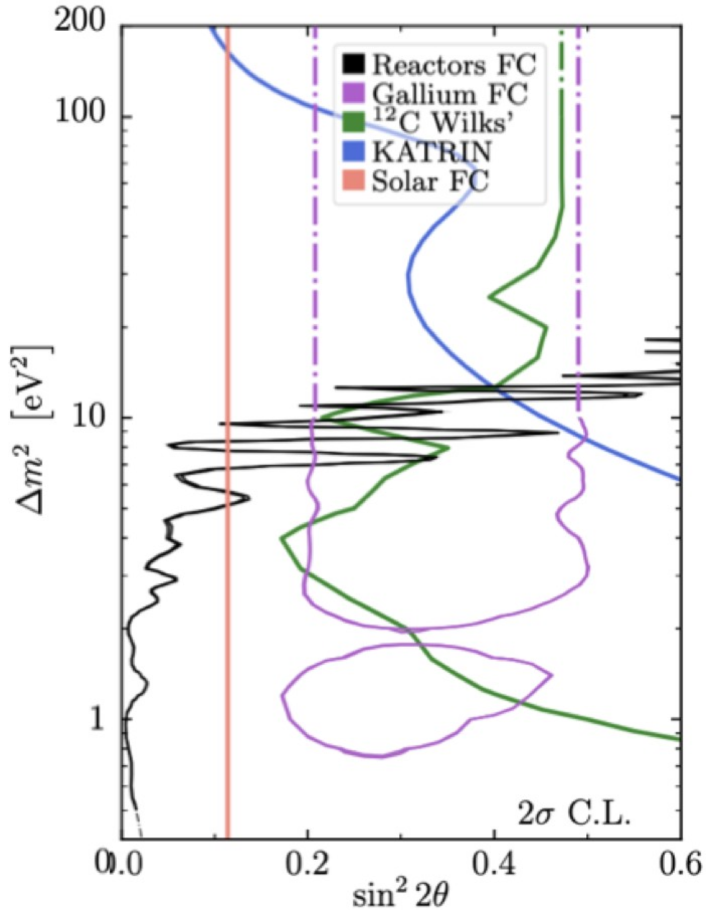
Berryman, Coloma, Huber, Schwetz, Zhou, 2111.12530



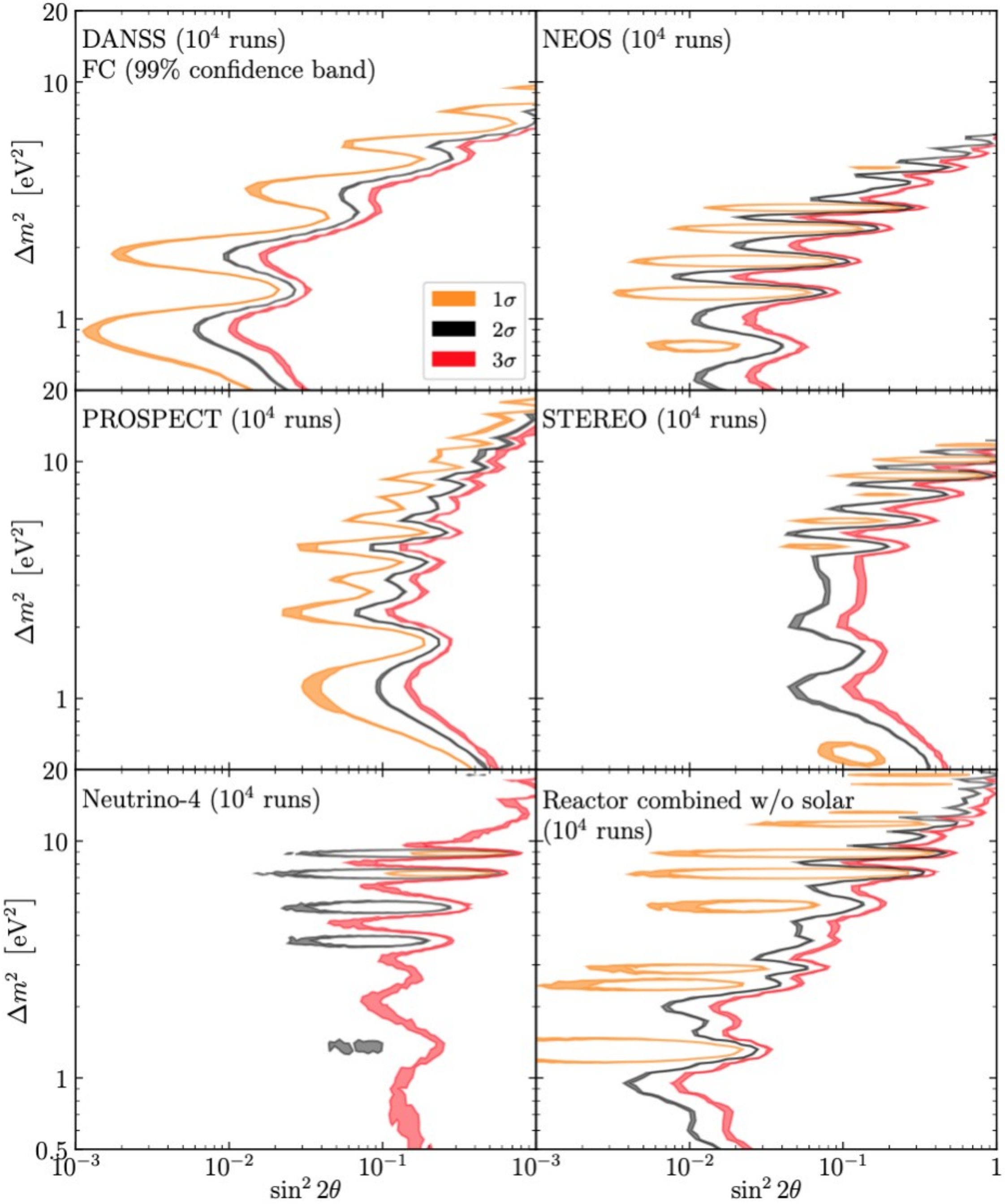
Future probes







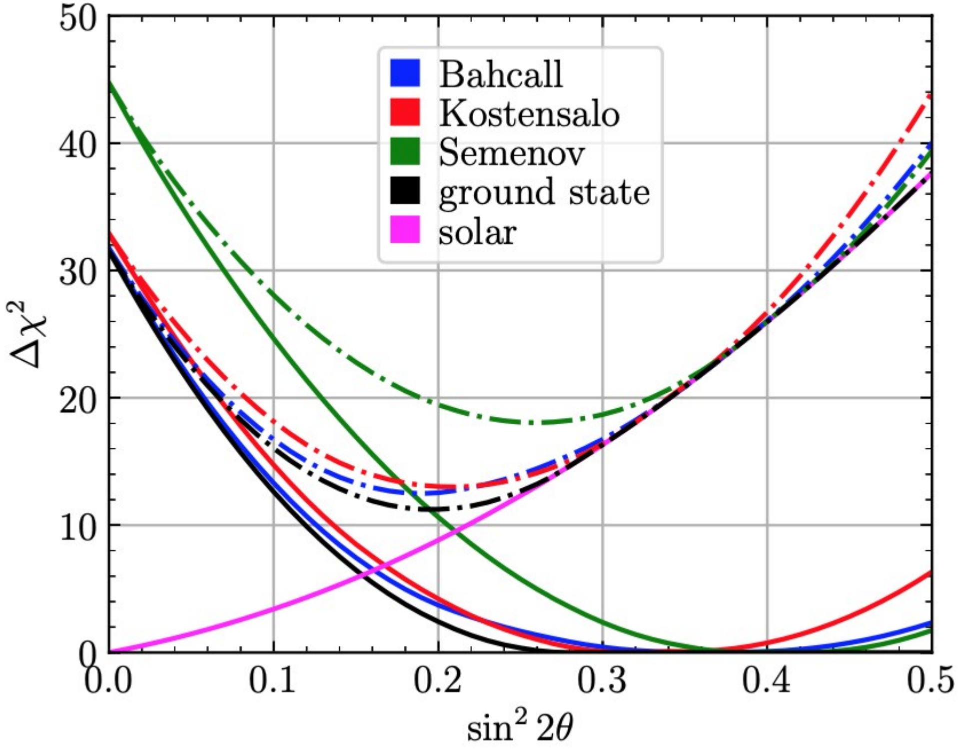
Berryman, Coloma, Huber, Schwetz, Zhou, 2111.12530



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

Consistency tests: Solar vs Ga



Parameter goodness-of-fit (PG):

$$\chi^2_{\rm PG} = \chi^2_{\rm min,comb} - \sum_k \chi^2_{{\rm min},k}$$

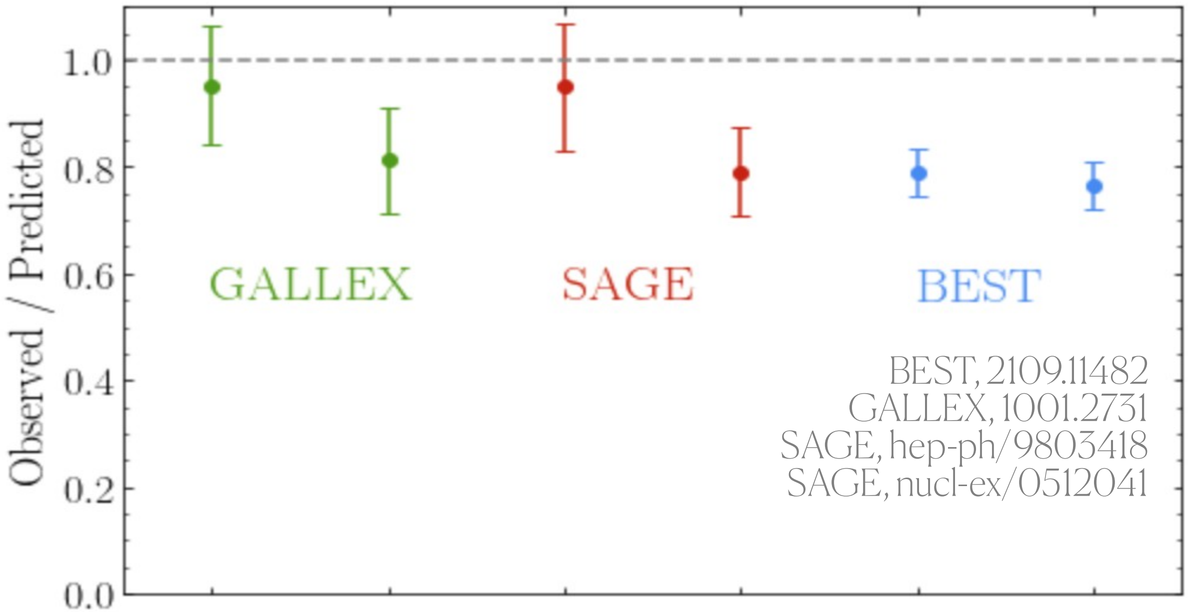
expected to be chi-squared distributed with

$$\sum_k P_k - P \text{ dof},$$

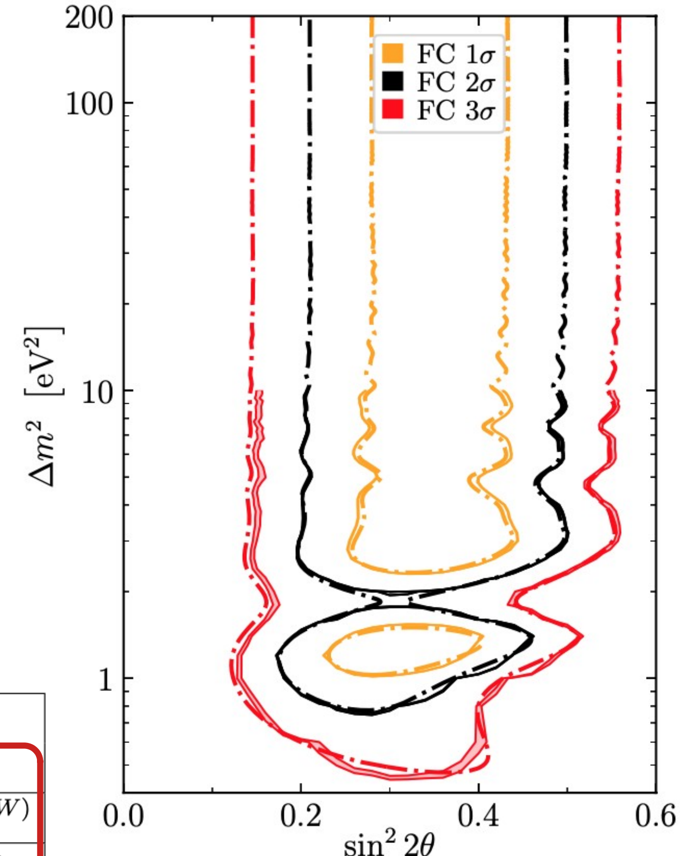
Maltoni, Schwetz, Tortola, Valle, hep-ph/0207157;
Maltoni, Schwetz, hep-ph/0304176

Data set	$\chi^2_{\rm PG}/{\rm dof}$	$p^{(W)}$	$\#\sigma^{(W)}$	$p_{\rm b.f.}$	$\#\sigma_{\rm b.f.}$
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	3.1×10^{-4}	3.6	1.6×10^{-3}	3.2
Reactor vs Solar vs Gallium	15.6/3	1.4×10^{-3}	3.2	5.1×10^{-3}	2.8

Gallium experiments



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



→ From MC simulation:

$p_0 < 2.7 \times 10^{-8}$ (5.6σ)

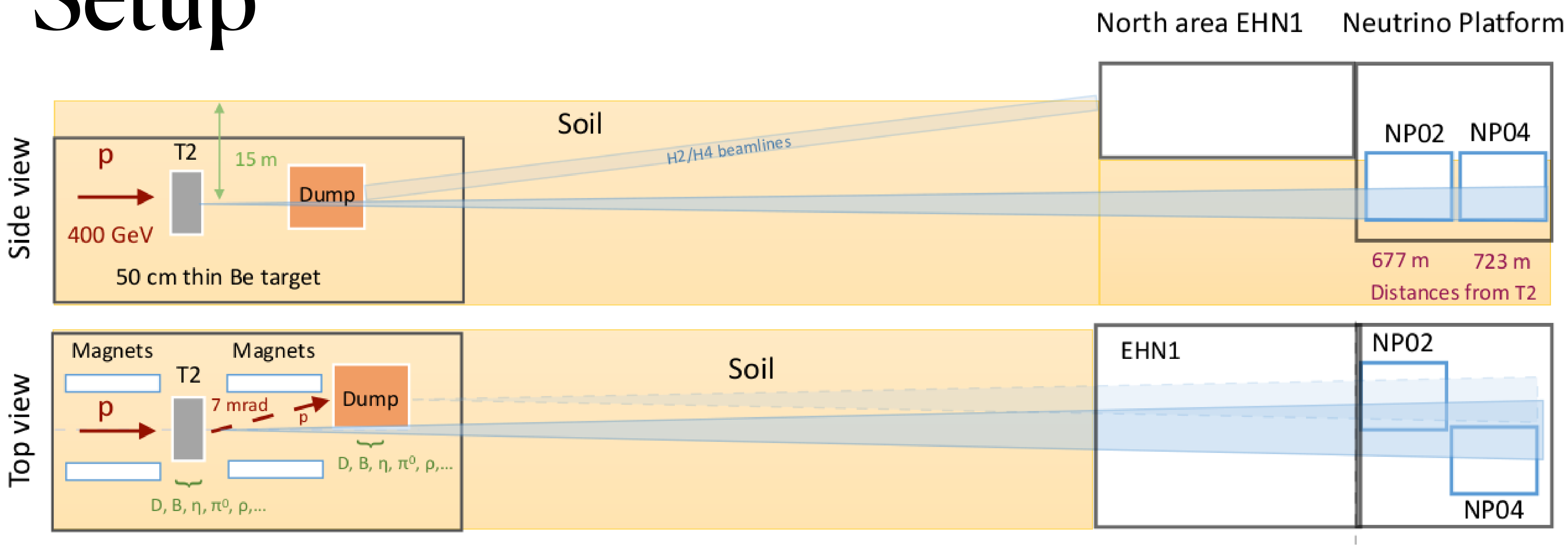
Berryman, Coloma, Huber, Schwetz, Zhou, 2111.12530
(see also Barinov, Gorbunov, 2109.14654)

Ga capture cross sections

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

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

Setup



Main features:

- no decay volume
- very high proton energy!

Meson yields (per PoT):

π^0	η	η'	D	D_s	τ
4.03	0.46	0.05	$4.8 \cdot 10^{-4}$	$1.4 \cdot 10^{-4}$	$7.4 \cdot 10^{-6}$

ρ	ω	ϕ	J/ψ	B	Υ
0.54	0.53	0.019	$4.4 \cdot 10^{-5}$	$1.2 \cdot 10^{-7}$	$2.3 \cdot 10^{-8}$