Reevaluating Reactor Antineutrino Anomalies with Updated Flux Predictions

Jeff Berryman, U. Kentucky/U.C. Berkeley

Based on: arXiv:1909.09267 (w/ P. Huber)

With further shameless references to:

Phys. Rev. D99 (2019) no.5, 055045, arXiv:1803.08506 (w/ V. Brdar, P. Huber);

Phys. Rev. D100 (2019) no.2, 023540 , arXiv:1905.03254;

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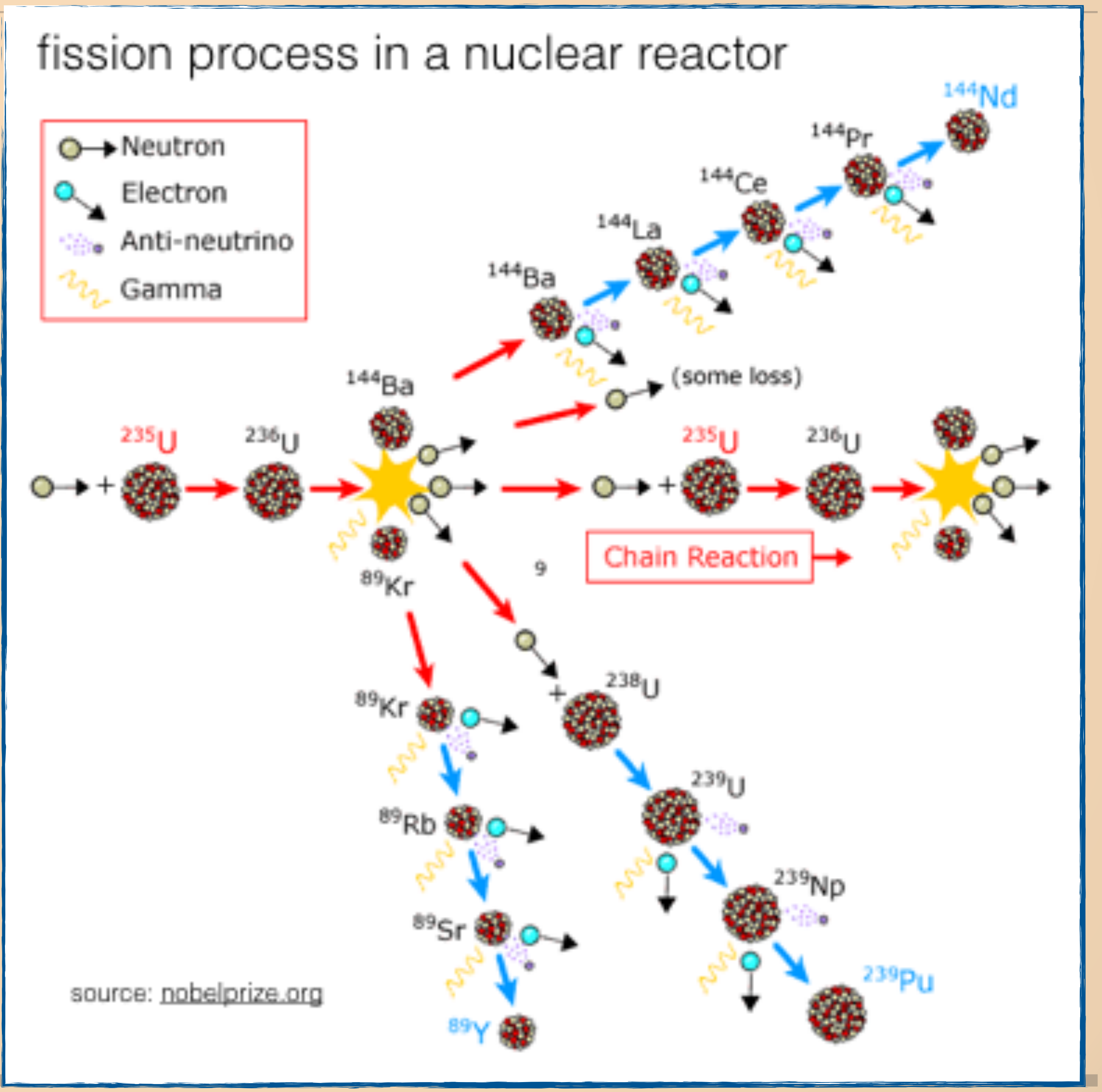
Outline

- *Part 1:* The Basics of Reactor Antineutrinos & Anomalies
  - *Part 1.1:* Evidence for Sterile Neutrinos?
  - *Part 1.2*: The 5 MeV Bump
- *Part 2:* Yet Another Global Fit…
  - *Part 2.1*: The Global Dataset
  - *Part 2.2*: New Flux Predictions
  - *Part 2.3:* What Does the Future Hold?
- *Part 3*: What Is This All About?
  - *Part 3.1*: Why Sterile Neutrinos are a Problem in Cosmology

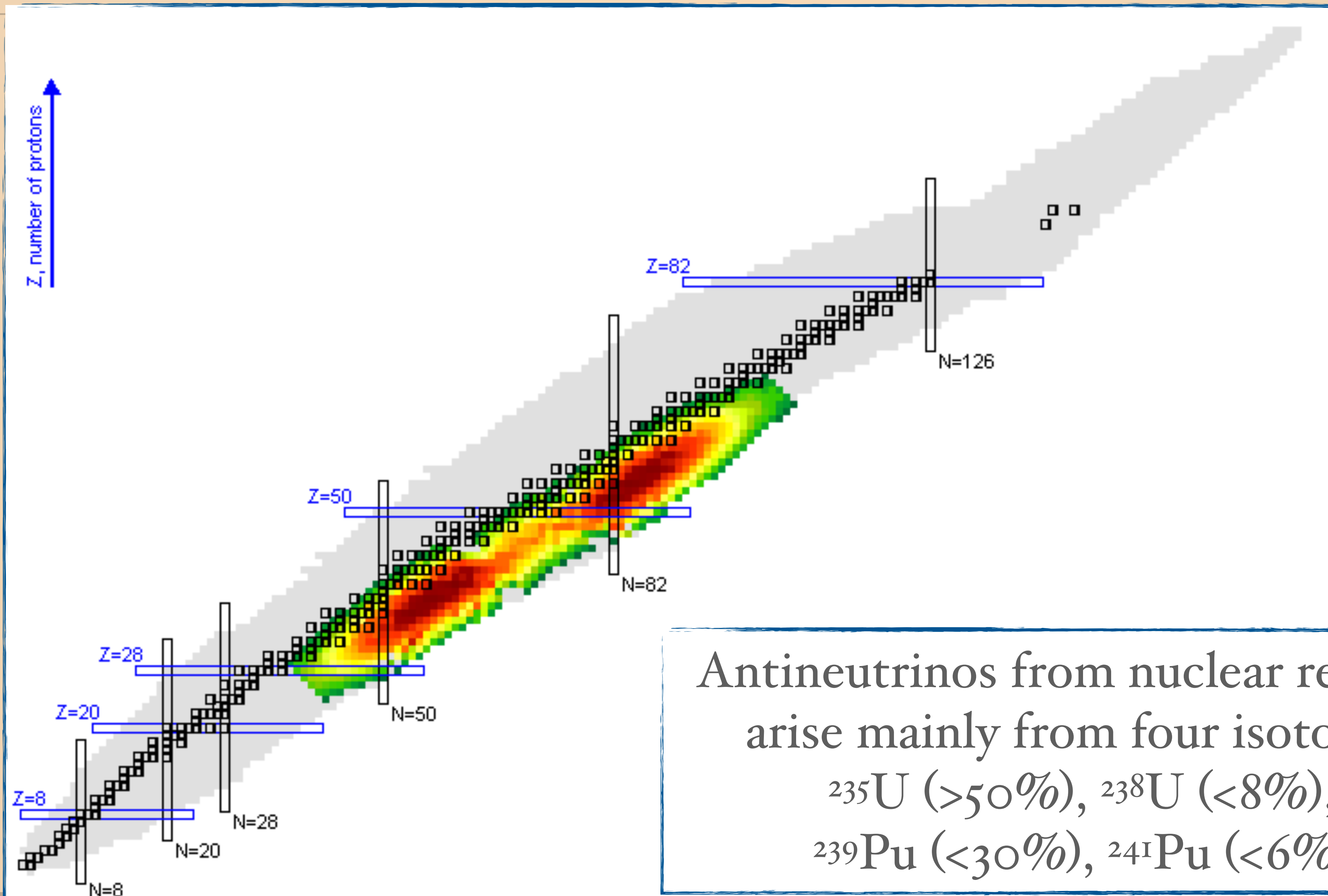
Part 1:
Prolegomena

Antineutrinos from Reactors

Nuclear fission produces neutron-rich fission fragments; beta decays ensue!



Antineutrinos from Reactors



Antineutrinos from nuclear reactors arise mainly from four isotopes: ^{235}U (>50%), ^{238}U (<8%), ^{239}Pu (<30%), ^{241}Pu (<6%)

Fission yields from ^{235}U; www.nndc.bnl.gov/nudat2

Antineutrinos from Reactors

Producing a *prediction* for the spectrum of antineutrinos is *really, really difficult*!

Two basic approaches:

1. *Ab Initio Method*: Go to nuclear databases, add up all the beta decays of all the fission fragments.
2. *Conversion Method*: Measure the spectrum of *electrons* from fission fragments → use what we know about beta decay to infer the antineutrino spectrum

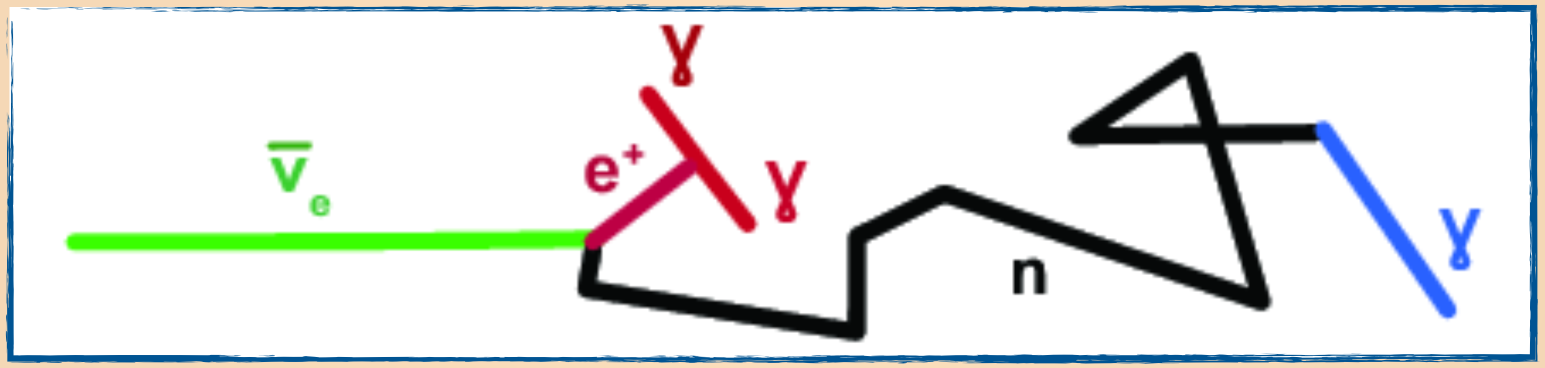
The latter performed by Mueller, et al., and Huber*

**Th. A. Mueller, et al., Phys. Rev. C83 (2011) 054615; P. Huber, Phys. Rev. C84 (2011) 024617 (Erratum: Phys. Rev. C85 (2012) 029901)*

Detecting Reactor Antineutrinos

- The classic detection process is *inverse beta decay (IBD)*

$$\overline{\nu}_e + p^+ \rightarrow e^+ + n$$



- *Magnetic moment* searches use antineutrino-electron scattering
  - Few experiments have actually made this measurement; not better than 25%! (*TEXONO, MUNU*)

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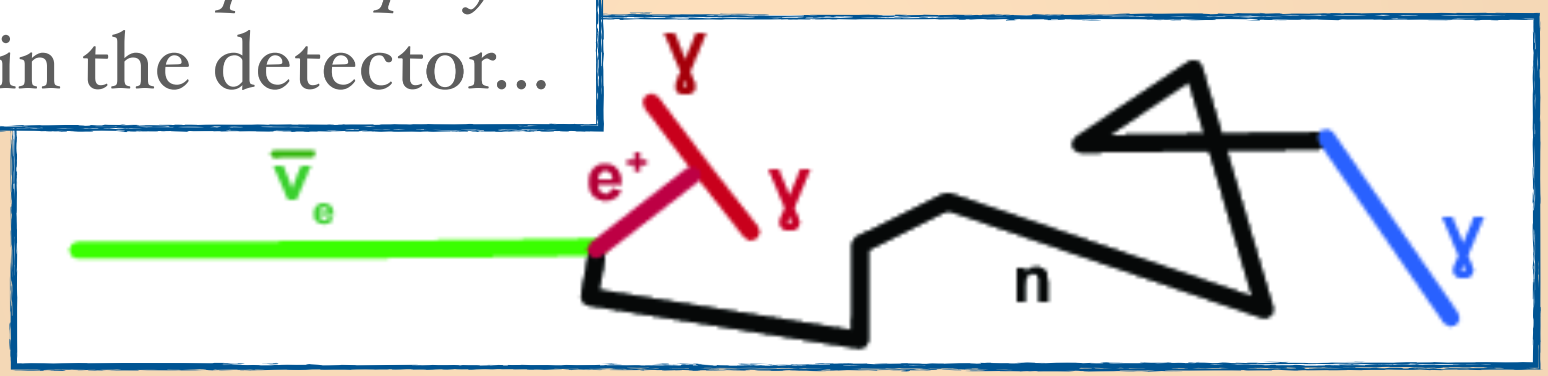

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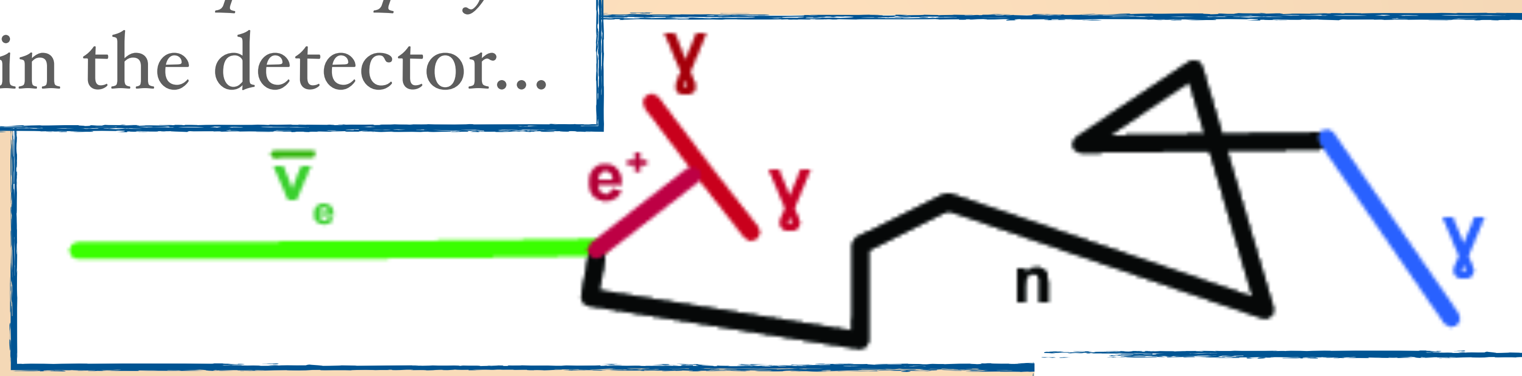

...and the neutron is captured for a *delayed* energy deposition!

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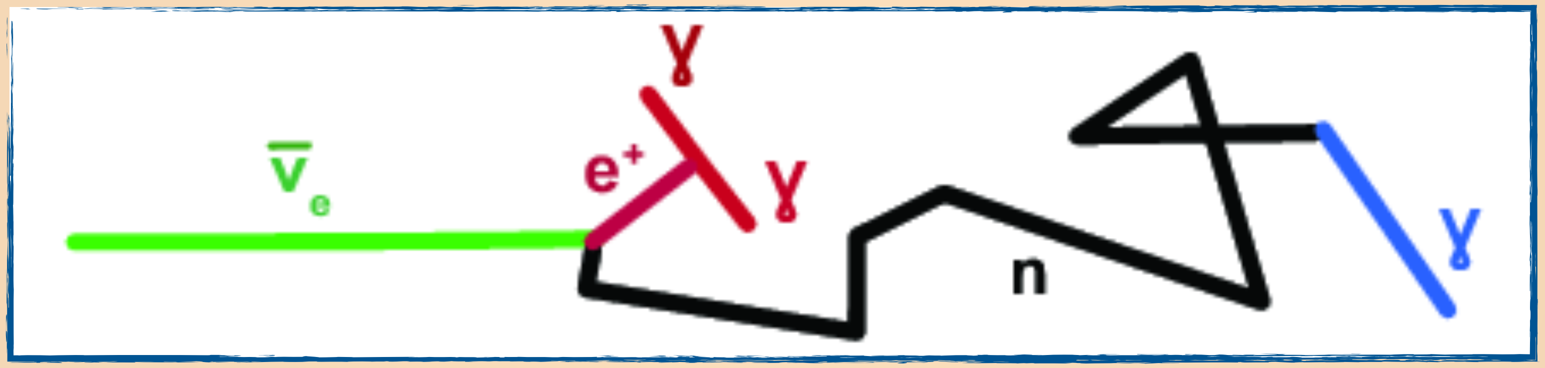

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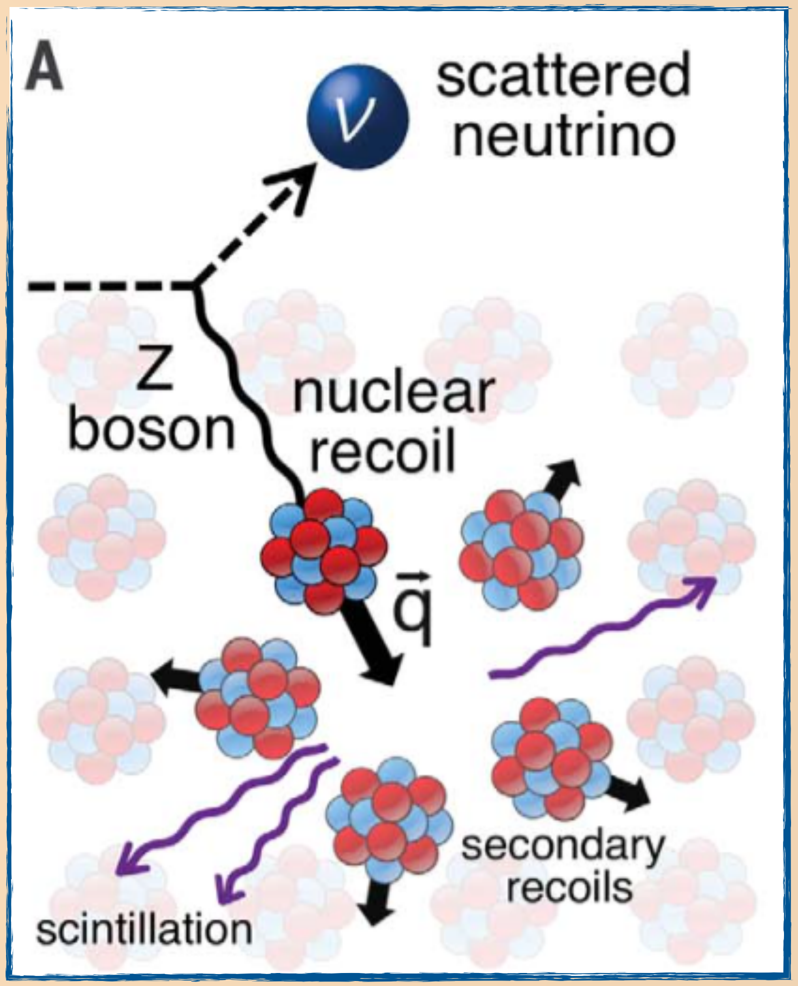
Detecting Reactor Antineutrinos

- New kid on the block: *Coherent Elastic Neutrino-Nucleus Scattering*, a.k.a., CEνNS:
  - Neutrino scatters off of *entire nucleus* instead of individual nucleons
  - Proposed to exist in 1974; discovered only in 2017



$$\frac{d\sigma_\alpha}{dE_\nu} = \frac{G_F^2}{2\pi} Q_\alpha^2 F^2(q^2) M_{(N,Z)} \left(2 - \frac{M_{(N,Z)} E_r}{E_\nu^2}\right)$$

D. Akimov, et al., Science 357, 1123–1126 (2017)

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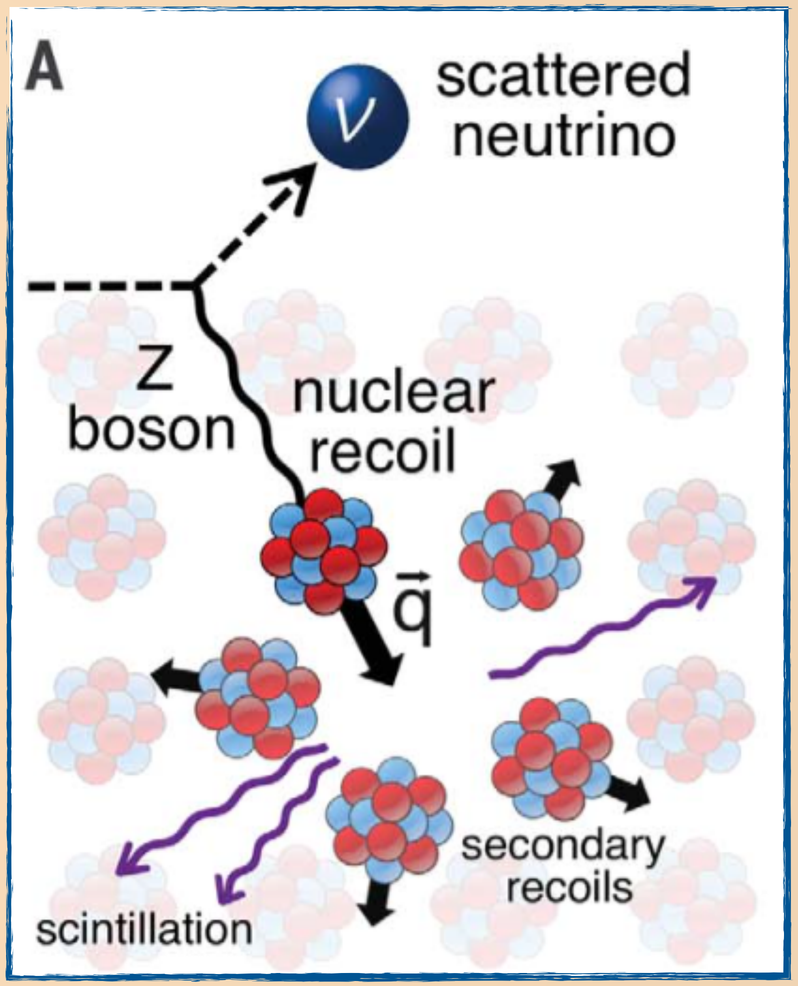

Sensitive to nuclear structure – important source of uncertainty!

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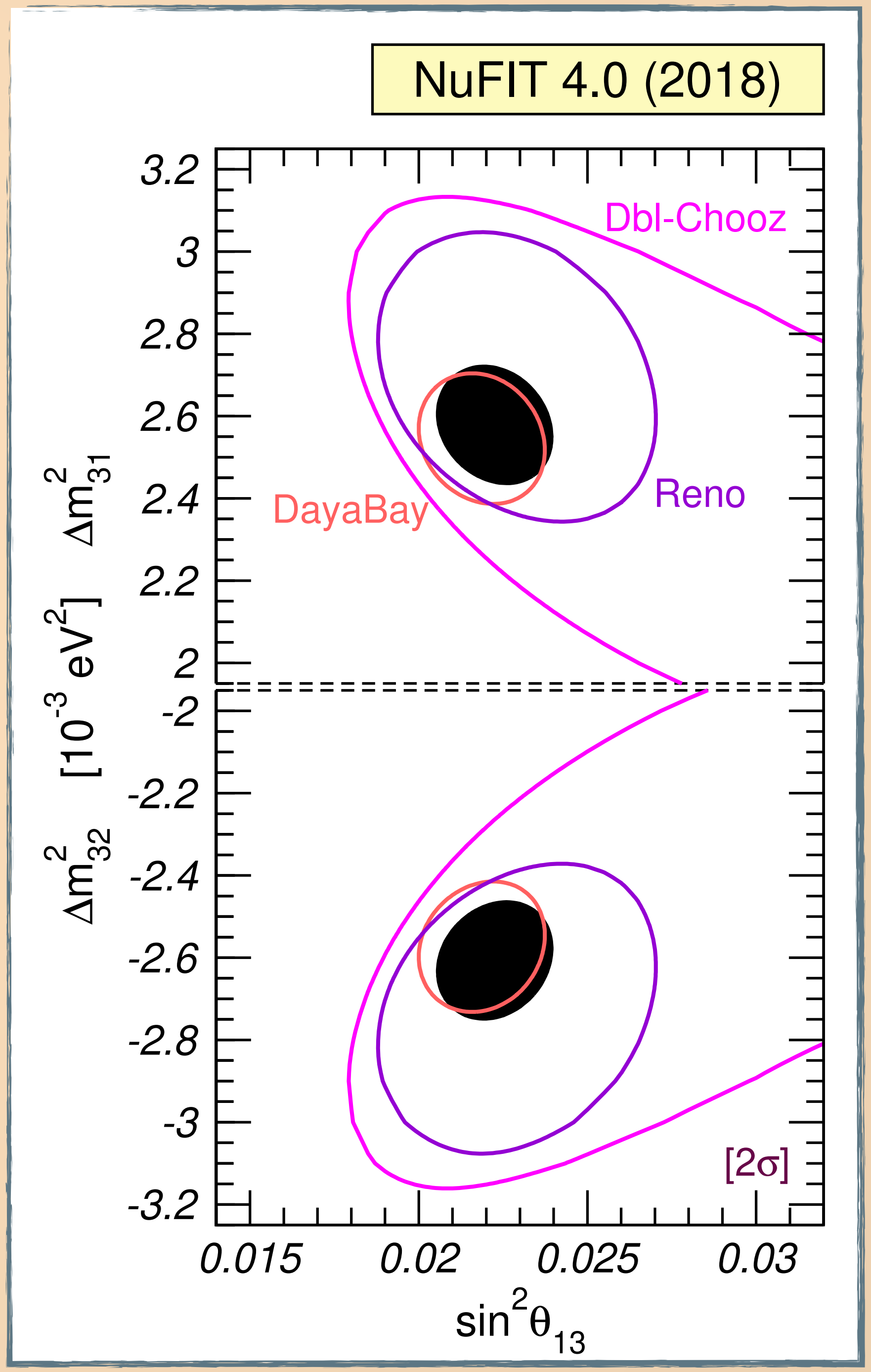
Establishing Three-Neutrino Oscillations

- Medium-baseline experiments (Daya Bay, RENO, Double Chooz) have measured θ_{13} to be *small* but *nonzero*
- KamLAND has measured the *solar* mixing parameters (θ_{12} & Δm^2_{21}) independently of solar experiments (*note the mild tension!*)



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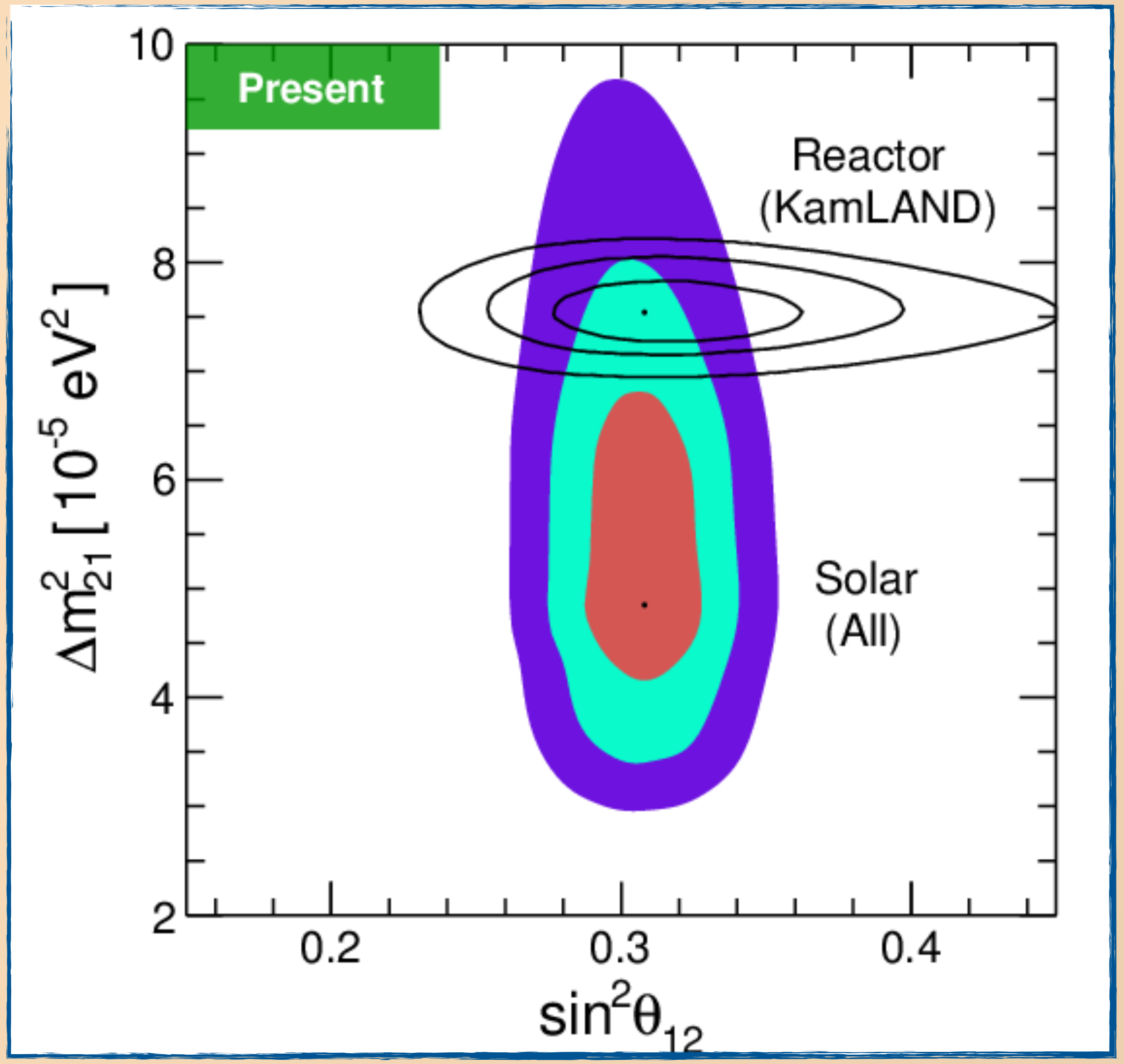

F. Capozzi, et al., 1808.08232

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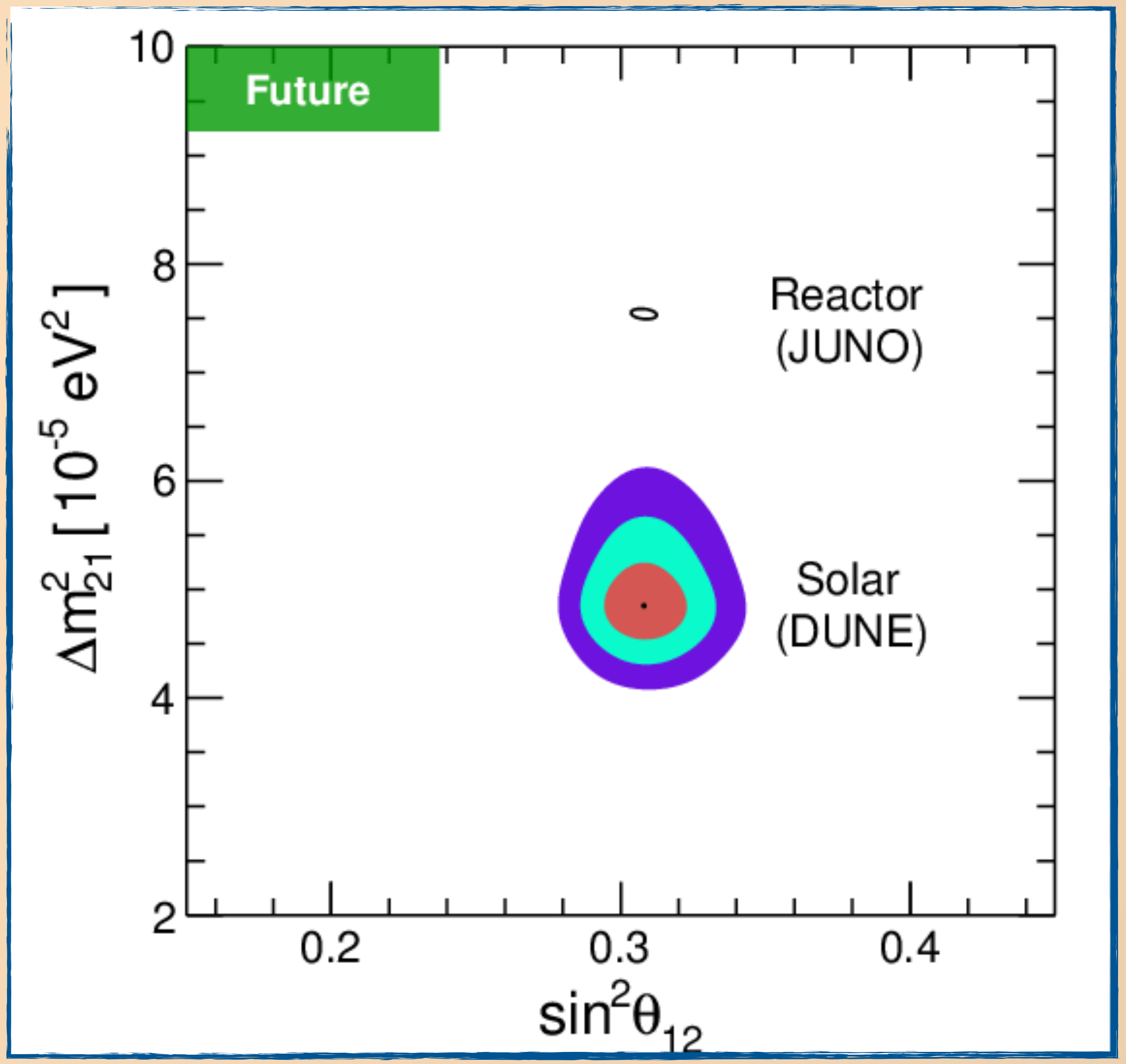

F. Capozzi, et al., 1808.08232

Hints for More Neutrinos?

a	Experiment	f_{235}^a	f_{238}^a	f_{239}^a	f_{241}^a	R_a^{exp}	σ_a^{exp} [%]	σ_a^{cor} [%]	σ_a^{the} [%]	L_a [m]
1	Bugey-4	0.538	0.078	0.328	0.056	0.932	1.4	1.4	2.5	15
2	Rovno91	0.606	0.074	0.277	0.043	0.930	2.8		2.4	18
3	Rovno88-1I	0.607	0.074	0.277	0.042	0.907	6.4	3.1	2.4	18
4	Rovno88-2I	0.603	0.076	0.276	0.045	0.938	6.4		2.4	18
5	Rovno88-1S	0.606	0.074	0.277	0.043	0.962	7.3	2.2	2.4	18
6	Rovno88-2S	0.557	0.076	0.313	0.054	0.949	7.3	3.1	2.5	25
7	Rovno88-2S	0.606	0.074	0.274	0.046	0.928	6.8		2.4	18
8	Bugey-3-15	0.538	0.078	0.328	0.056	0.936	4.2		2.5	15
9	Bugey-3-40	0.538	0.078	0.328	0.056	0.942	4.3	4.0	2.5	40
10	Bugey-3-95	0.538	0.078	0.328	0.056	0.867	15.2		2.5	95
11	Gosgen-38	0.619	0.067	0.272	0.042	0.955	5.4		2.4	37.9
12	Gosgen-46	0.584	0.068	0.298	0.050	0.981	5.4	2.0 3.8	2.4	45.9
13	Gosgen-65	0.543	0.070	0.329	0.058	0.915	6.7		2.4	64.7
14	ILL	1	0	0	0	0.792	9.1		2.4	8.76
15	Krasnoyarsk87-33	1	0	0	0	0.925	5.0	4.1	2.4	32.8
16	Krasnoyarsk87-92	1	0	0	0	0.942	20.4		2.4	92.3
17	Krasnoyarsk94-57	1	0	0	0	0.936	4.2	0	2.4	57
18	Krasnoyarsk99-34	1	0	0	0	0.946	3.0	0	2.4	34
19	SRP-18	1	0	0	0	0.941	2.8	0	2.4	18.2
20	SRP-24	1	0	0	0	1.006	2.9	0	2.4	23.8
21	Nucifer	0.926	0.061	0.008	0.005	1.014	10.7	0	2.3	7.2
22	Chooz	0.496	0.087	0.351	0.066	0.996	3.2	0	2.5	≈ 1000
23	Palo Verde	0.600	0.070	0.270	0.060	0.997	5.4	0	2.4	≈ 800
24	Daya Bay	0.561	0.076	0.307	0.056	0.946	2.0	0	2.5	≈ 550
25	RENO	0.569	0.073	0.301	0.056	0.944	2.2	0	2.4	≈ 411
26	Double Chooz	0.511	0.087	0.340	0.062	0.935	1.4	0	2.5	≈ 415

S. Gariazzo, et al., JHEP 1706 (2017) 135

Hints for More Neutrinos?

a	Experiment	f^a_{235}	f^a_{238}	f^a_{239}	f^a_{241}	R^{exp}_a	σ^{exp}_a [%]	σ^{cor}_a [%]	σ^{the}_a [%]	L_a [m]
1	Bugey-4	0.538	0.078	0.328	0.056	0.932	1.4	1.4 (rows 1–2)	2.5	15
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3	Rovno88-1I	0.607	0.074	0.277	0.042	0.907	6.4	3.1 (rows 3–4); 2.2 (rows 3–7)	2.4	18
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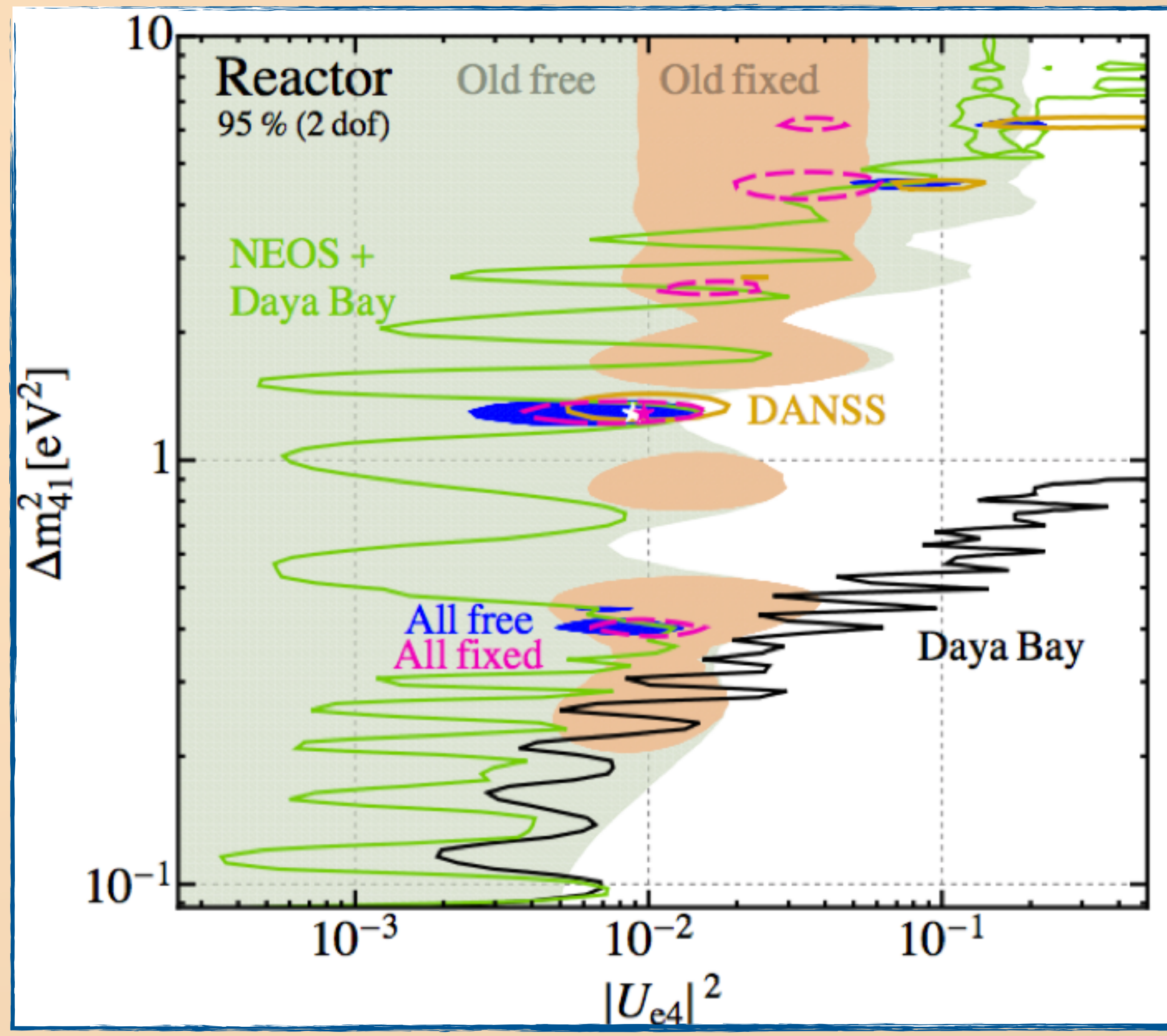
We almost always see fewer antineutrinos than we expect!

S. Gariazzo, et al., JHEP 1706 (2017) 135

Hints for More Neutrinos?

Experiment	References	Comments	(Data points)
Reactor experiments			(233)
ILL	[59]		
Gösgen	[60]		
Krasnoyarsk	[61–63]		
Rovno	[64, 65]		
Bugey-3	[66]	spectra at 3 distances with free bin-by-bin normalization	
Bugey-4	[67]		
SRP	[68]		
NEOS	[23, 29]	ratio of NEOS and Daya Bay spectra	
DANSS	[26]	ratios of spectra at two baselines (updated w.r.t. [21])	
Double Chooz	[33]	near detector rate	
RENO	[69, 70]	near detector rate	
Daya Bay spectrum	[71]	spectral ratios EH3/EH1 and EH2/EH1	
Daya Bay flux	[37]	individual fluxes for each isotope (EH1, EH2)	
KamLAND	[72]	very long-baseline reactor experiment ($L \gg 1\,\mathrm{km}$)	



M. Dentler, et al., JHEP 08, 010 (2018)

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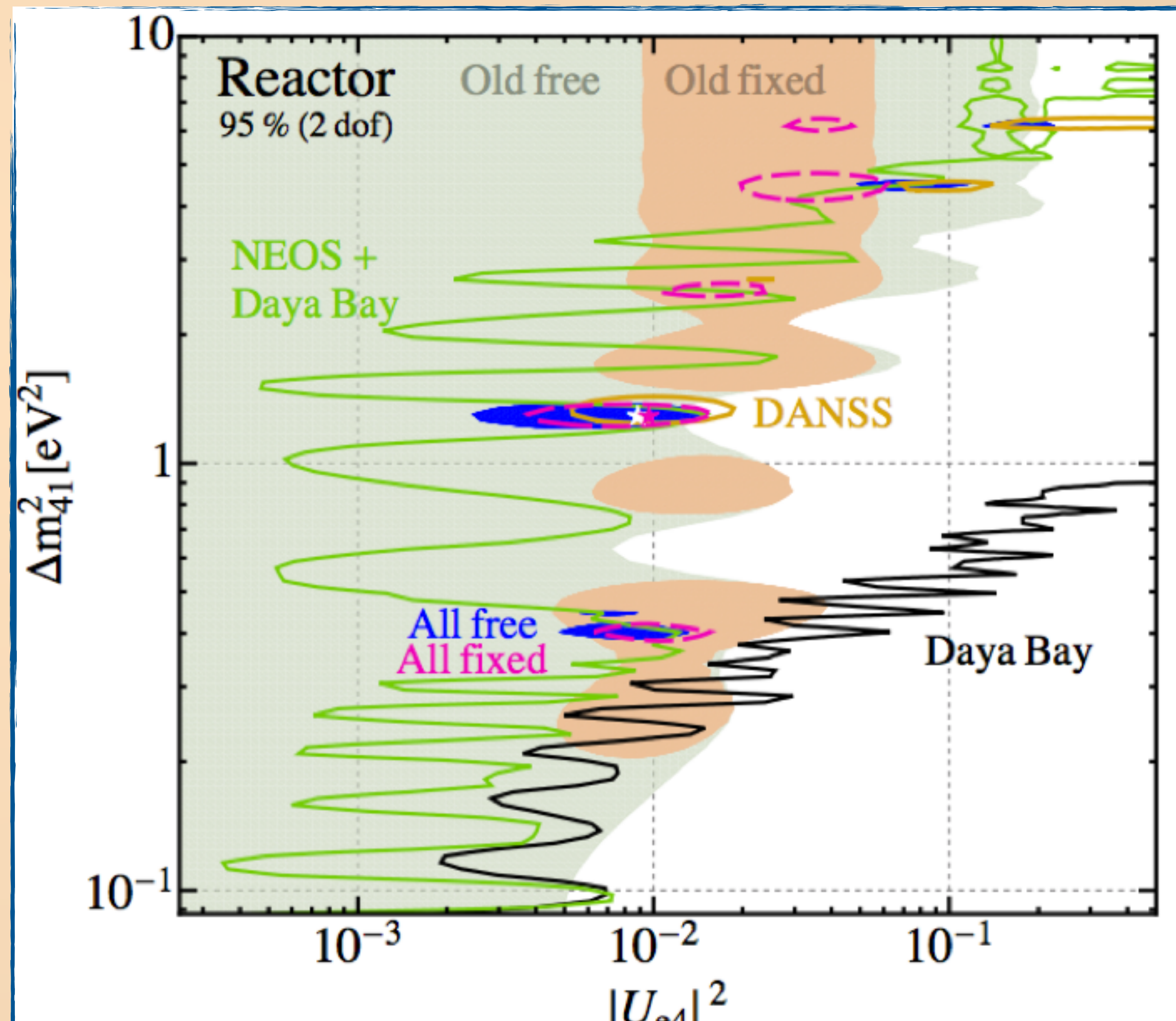
Ratios of spectra, too!



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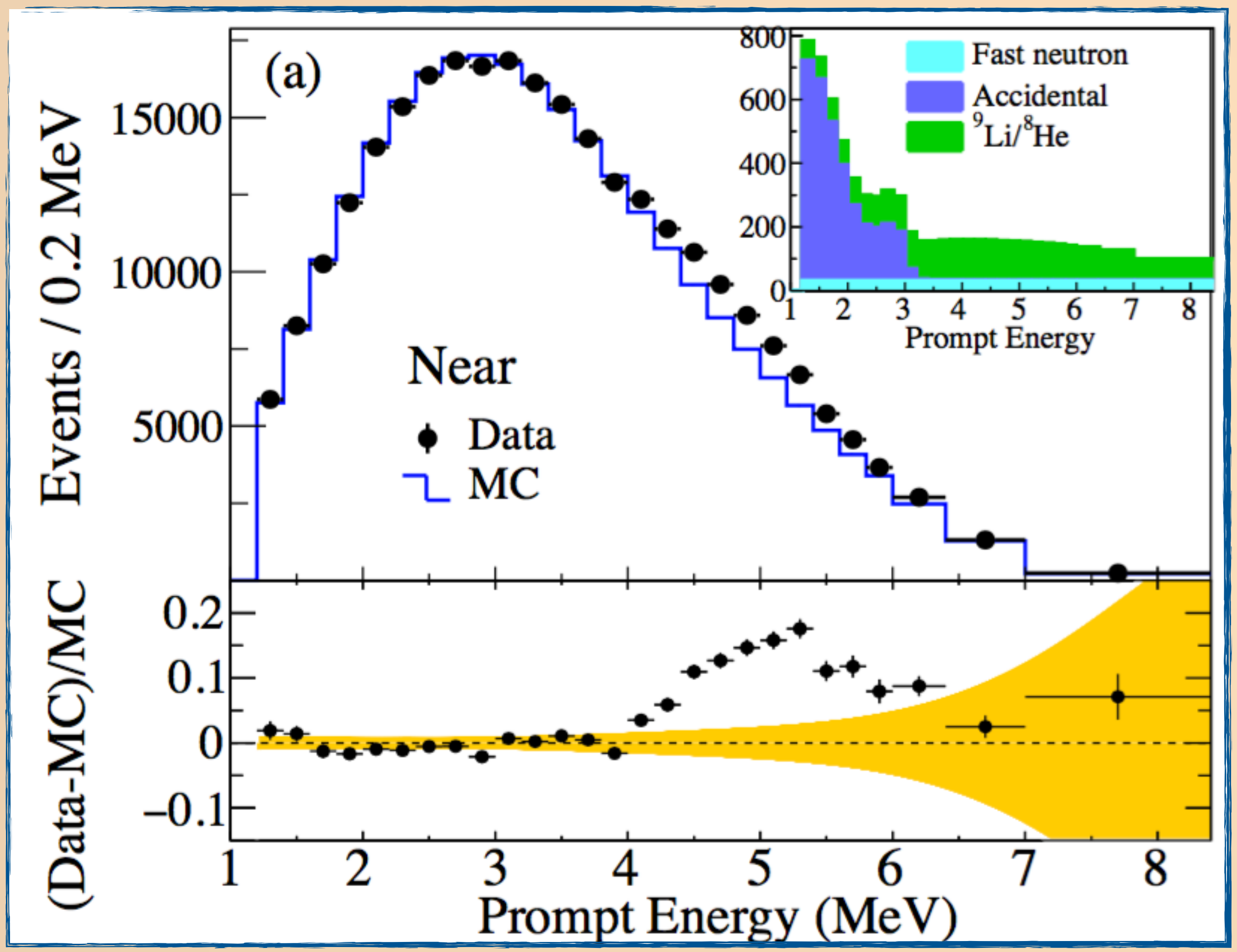
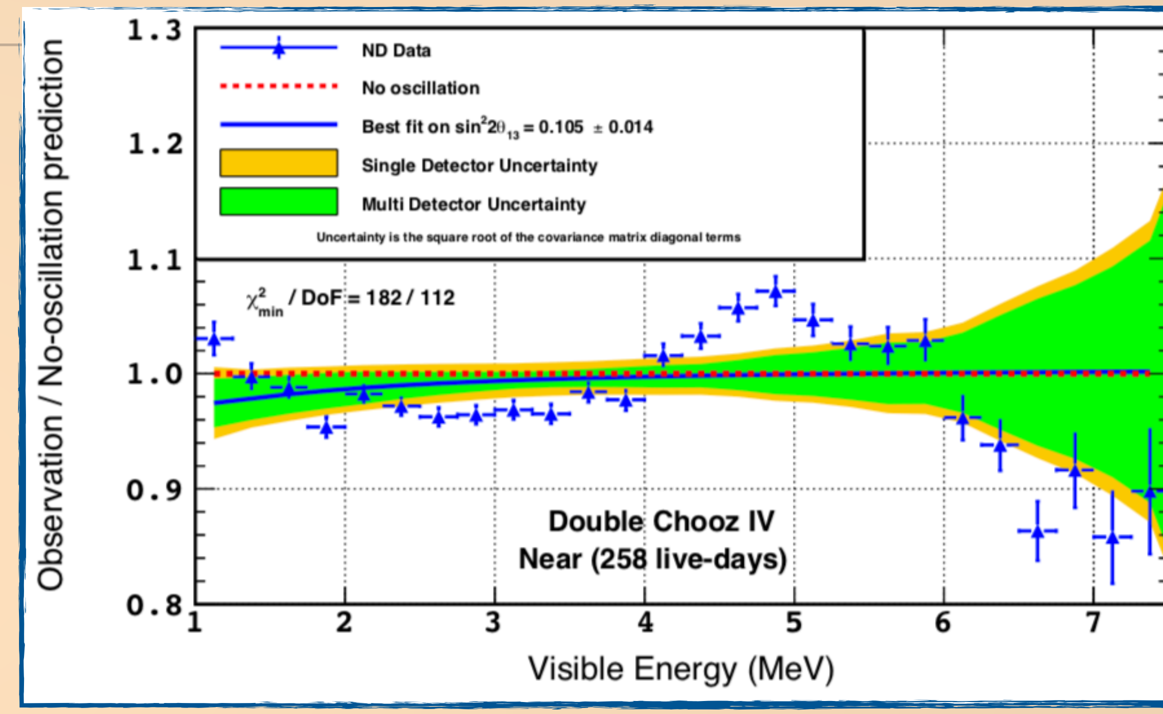
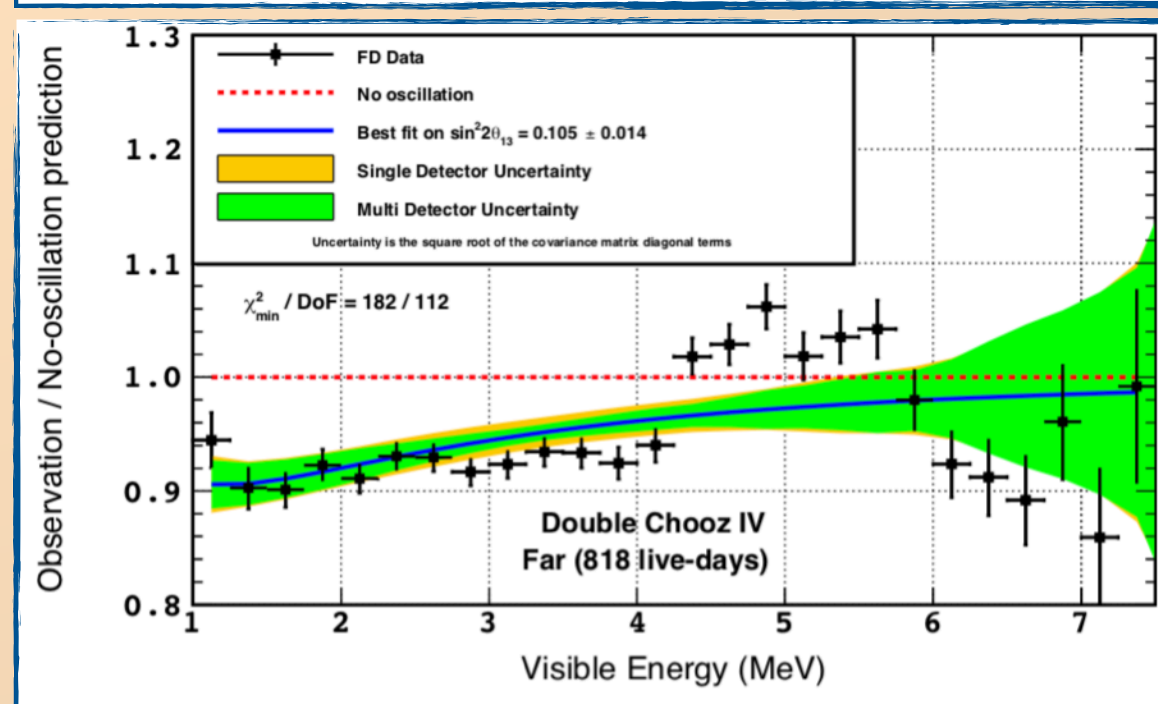
The 5 MeV Bump







RENO Collaboration, Phys. Rev. D98 (2018) no.1, 012002; Double Chooz Collaboration, 1901.09445; Daya Bay Collaboration, 1904.07812; NEOS Collaboration, Phys. Rev. Lett. 118 (2017) no.12, 121802

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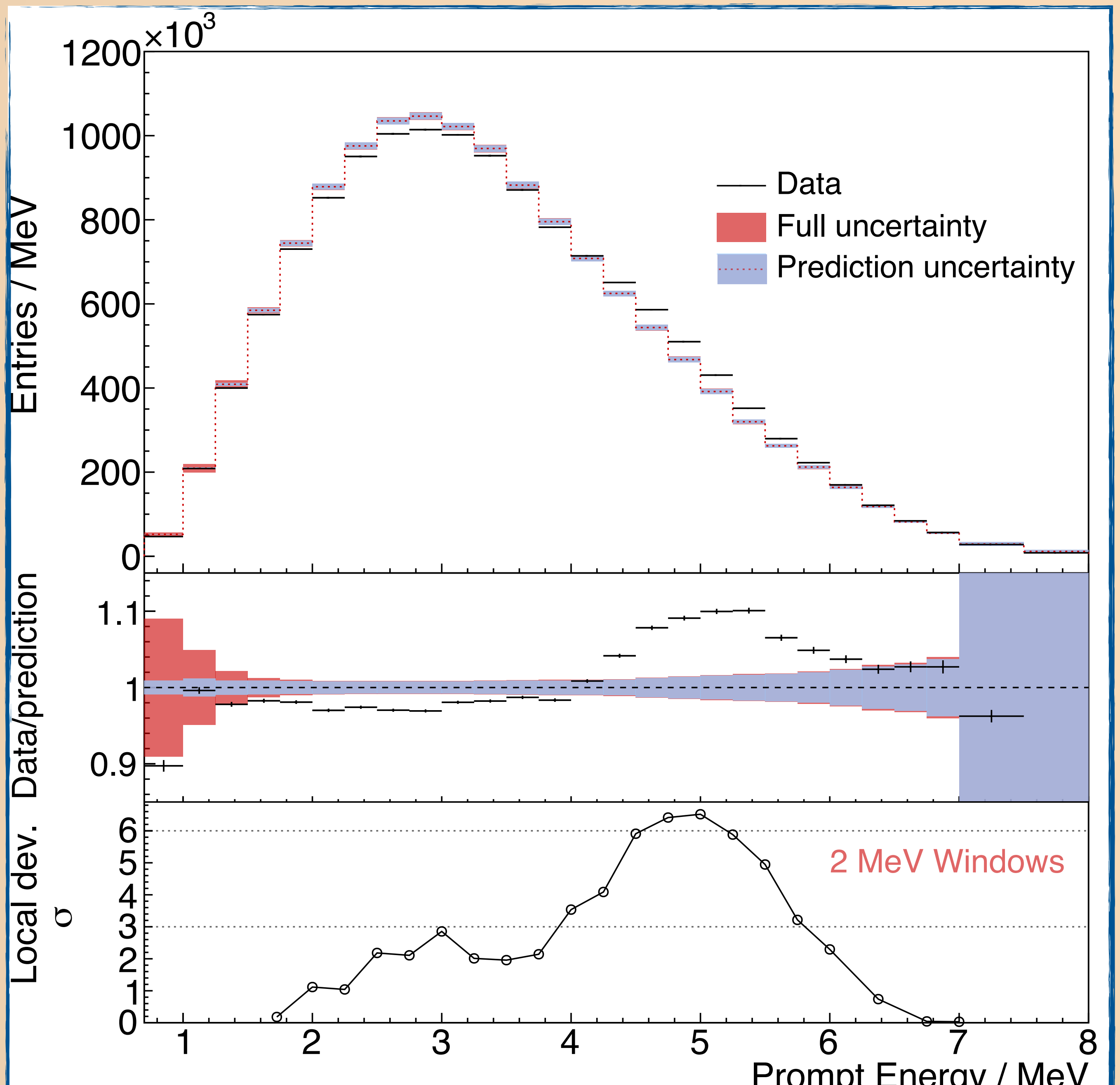

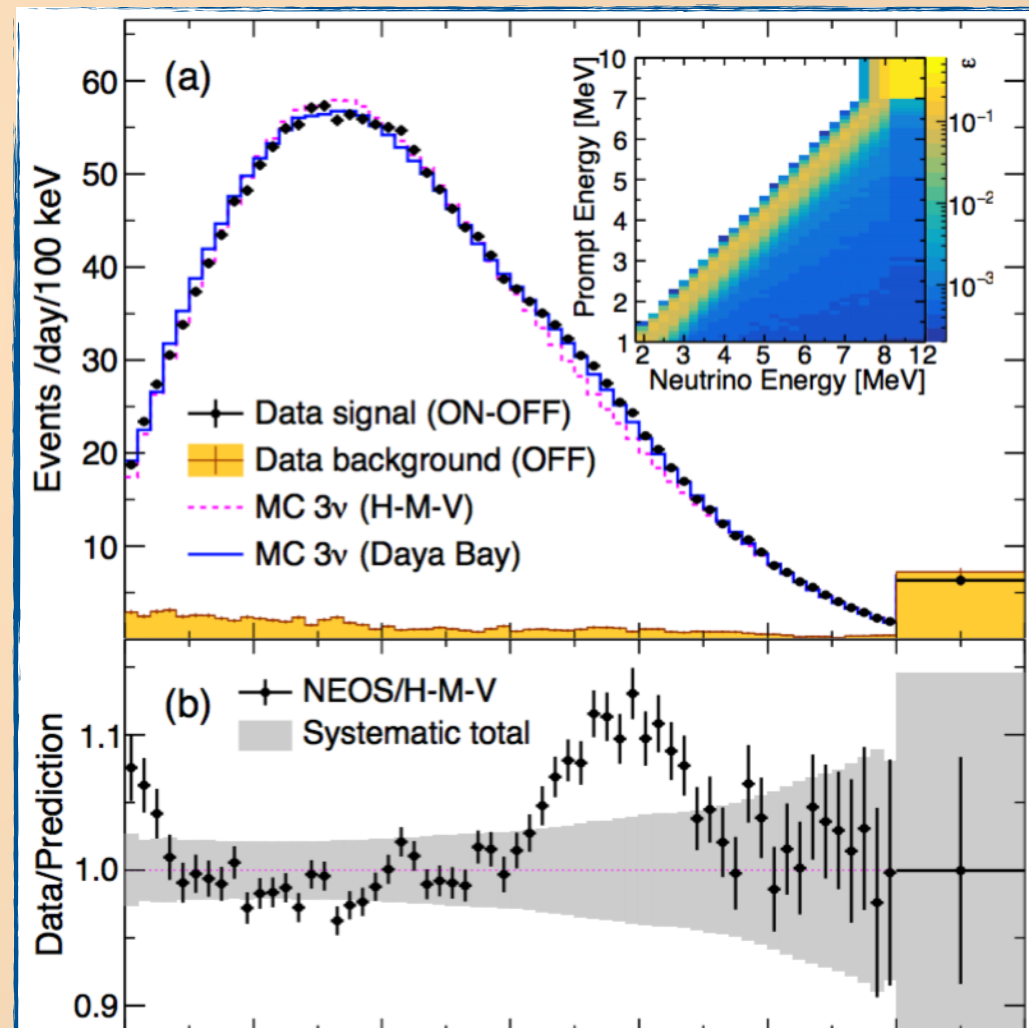

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Causes of the Anomalies?

- Possible explanations:
  - Oscillations with four (or more!) neutrinos
  - Reactor fluxes need to be reevaluated
    - Normalizations?
    - Shapes?
  - Different new physics
    - We looked into this – not likely to be the case!

Data	Analysis	Best fit ($\sin^2 2\theta_{14}$, Δm^2_{41})	χ^2_{min}/dof	$\Delta\chi^2$(no osc.)	p-value/#σ (no osc.)
React-old	flux-fixed	(0.12, 1.72)	52.1/68	9.4	0.0091/2.6σ
React-old	flux-free	(0.06, 0.46)	51.6/66	2.8	0.25/1.2σ
React-all	flux-fixed	(0.12, 2.99)	196.0/236	11.3	0.0036/2.9σ
React-all	flux-free	(0.04, 1.72)	187.5/234	5.6	0.061/1.9σ
Global	flux-fixed	(0.06, 1.72)	554.3/594	11.9	0.0026/3.0σ
Global	flux-free	(0.04, 1.72)	545.2/592	7.0	0.031/2.2σ

M. Dentler, et al., JHEP 11, 099 (2017)

Analysis	Δm^2_{41} [eV^2]	$\lvert U^2_{e4}\rvert$	χ^2_{min}/dof	$\Delta\chi^2$(no-osc)	significance
DANSS+NEOS	1.3	0.00964	74.4/(84 – 2)	13.6	3.3σ
all reactor (flux-free)	1.3	0.00887	185.8/(233 – 5)	11.5	2.9σ
all reactor (flux-fixed)	1.3	0.00964	196.0/(233 – 3)	15.5	3.5σ
$\overset{(-)}{\nu}_e$ disap. (flux-free)	1.3	0.00901	542.9/(594 – 8)	13.4	3.2σ
$\overset{(-)}{\nu}_e$ disap. (flux-fixed)	1.3	0.0102	552.8/(594 – 6)	17.5	3.8σ

M. Dentler, et al., JHEP 08, 010 (2018)

JMB, V. Brdar, P. Huber, Phys. Rev. D99 (2019) no.5, 055045

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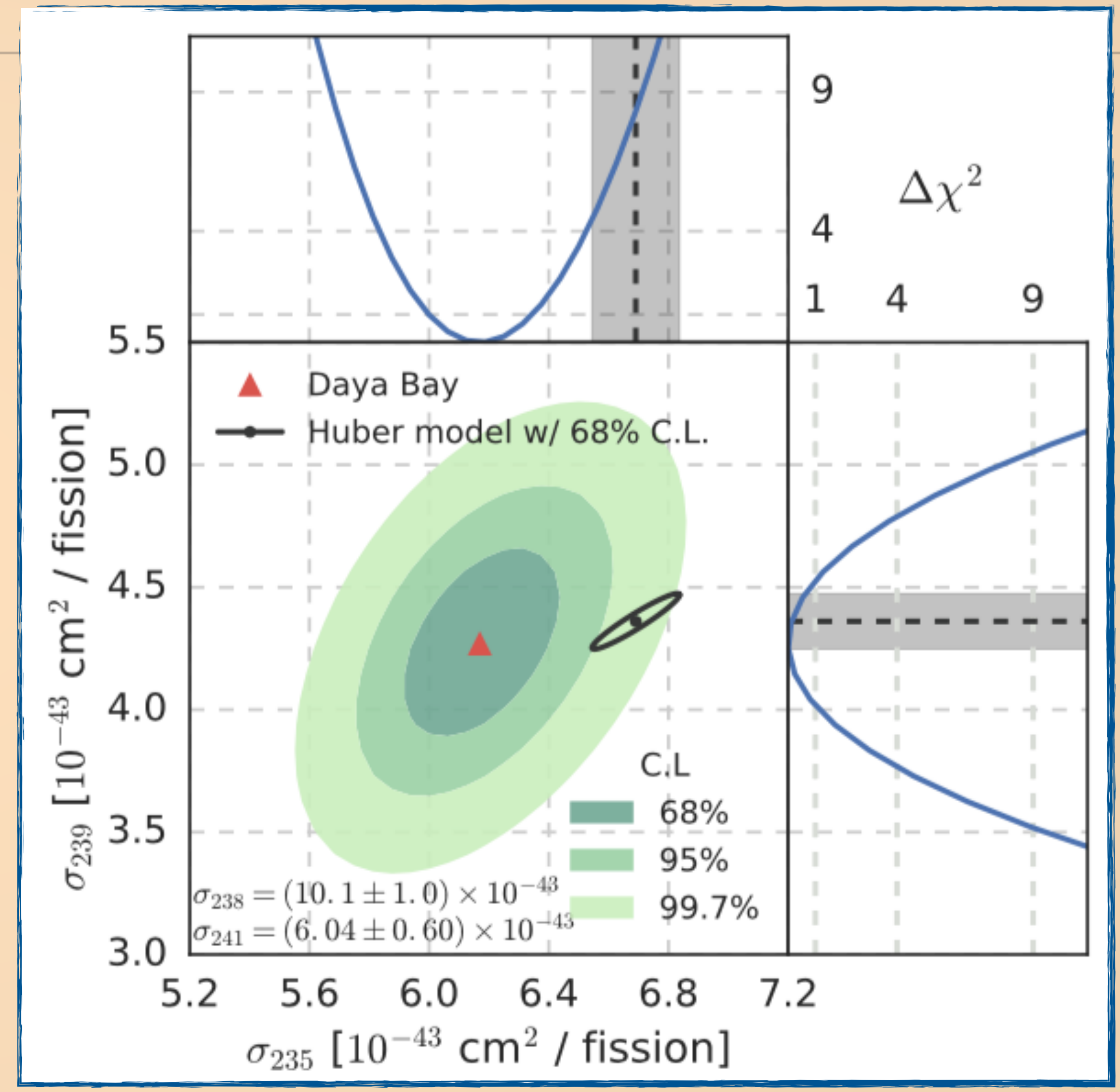


Daya Bay Collaboration, Phys. Rev. Lett. 118 (2017) no.25, 251801

Analysis	$\chi^2_{\min}$/dof	gof	$\sin^2 2\theta_{14}^{\rm bfp}$	$\Delta\chi^2$(no osc)
fixed fluxes + ν_s	9.8/(8 − 1)	18%	0.11	3.9
free fluxes (no ν_s)	3.6/(8 − 2)	73%		

M. Dentler, et al., JHEP 11, 099 (2017)

JMB, V. Brdar, P. Huber, Phys. Rev. D99 (2019) no.5, 055045

Part 2:
Fitting the Global Dataset

Developing a Global Fit

- The idea is fairly simple: combine all experimental results together, accounting for, e.g., correlations. This is nothing new!
- However, develop it in **`GLoBES`** & allow for it to be widely distributed:

1. Let people make *informed criticisms* of the analyses.
2. Allow for *modifications*: test your own NP scenario, use a new flux model, updated cross sections, etc.

(NB: We're waiting to publish before making it available to the public. Check back soon!)

Experimental Data Set(s)

Two types of measurements:

- *Rate measurements*:
  - *Integrated Rate*: Bugey(-3 & -4); Chooz; Double Chooz; Gösgen; ILL; Krasnoyarsk ('87, '94, '99); Nucifer; Palo Verde; Rovno ('88 & '91); Savannah River
  - *Rate Evolution*: Daya Bay, RENO
  - Total: 40 Data Points
- *Spectrum measurements*: Bugey-3; DANSS; Daya Bay; Double Chooz; NEOS; RENO
  - Total: 212 Data Points

Analyzing Rates

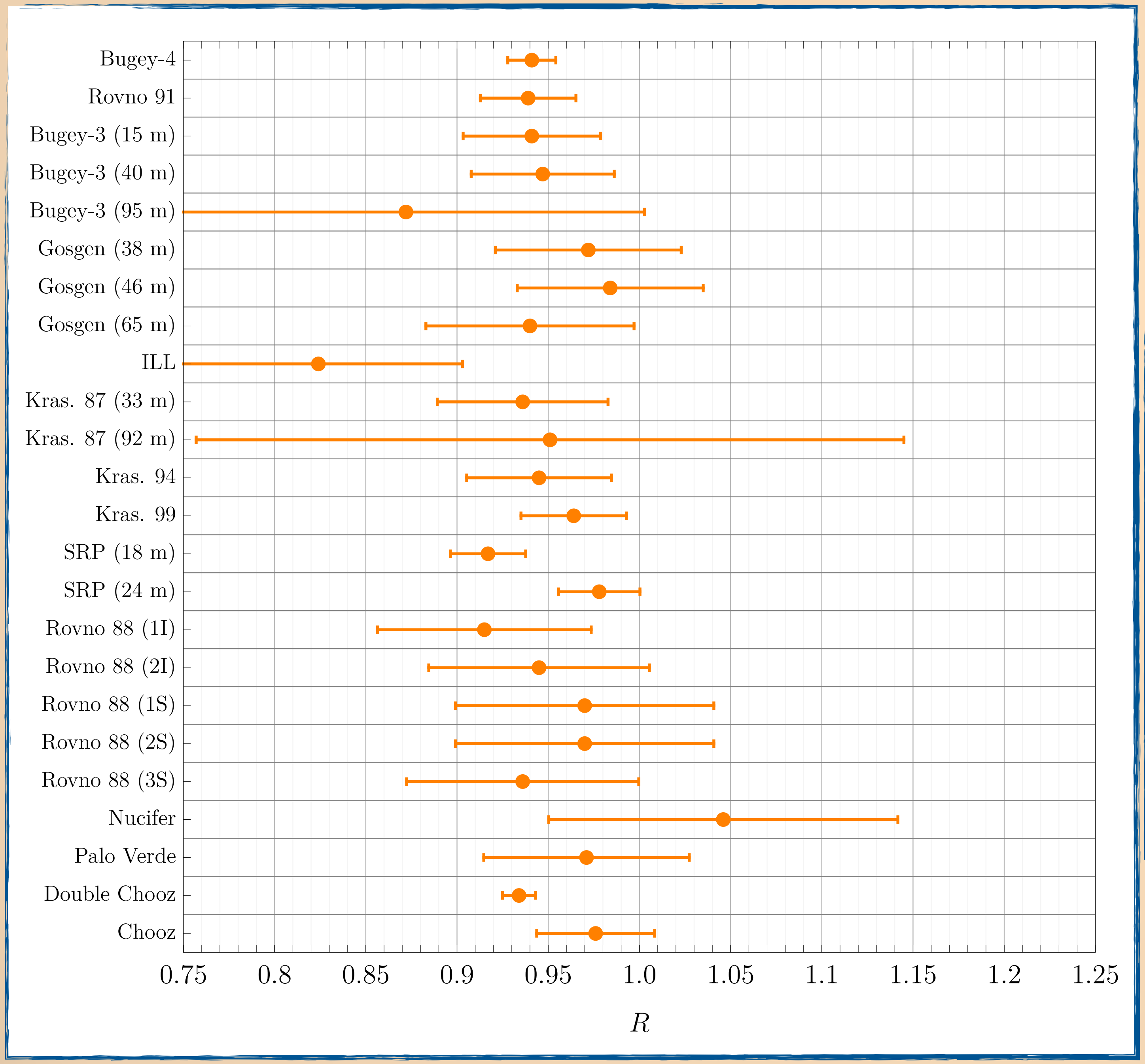
The gist of the analysis:

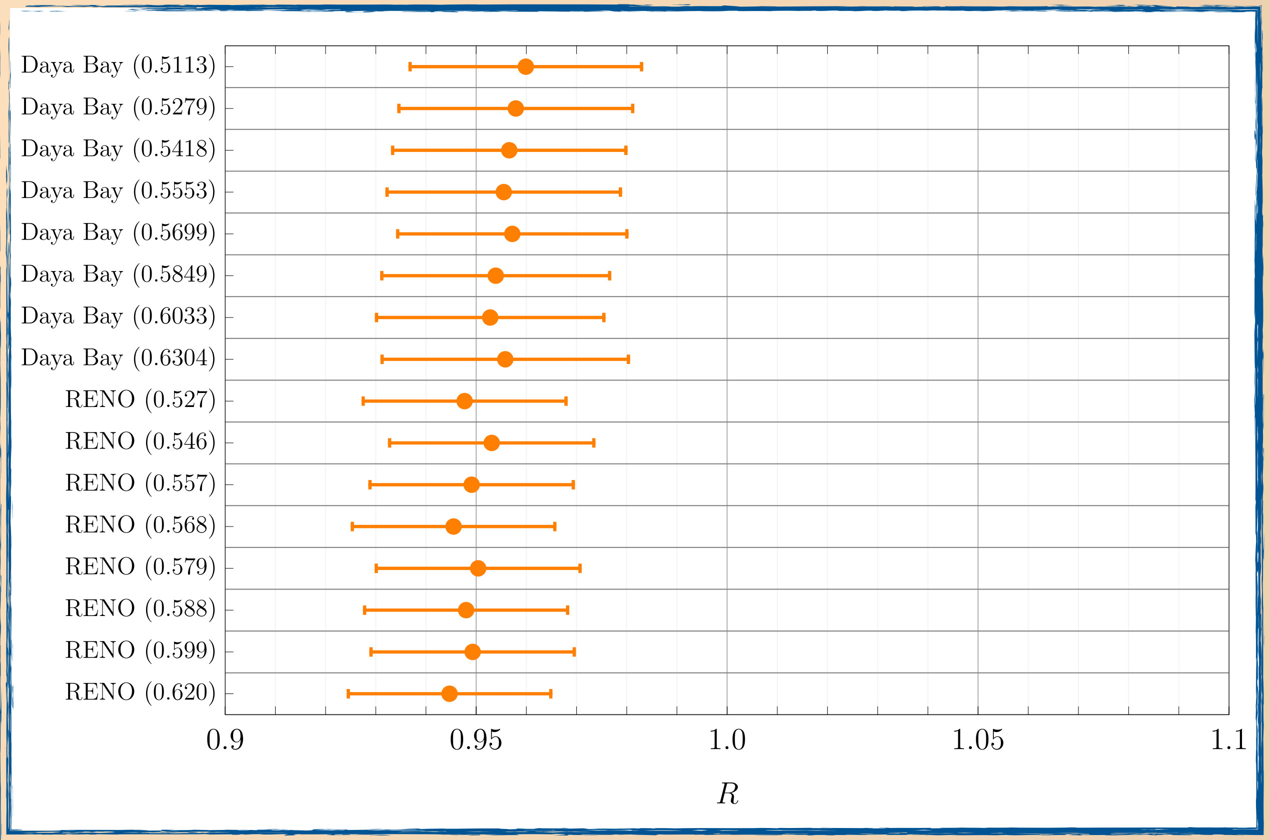
1. Calculate $4\nu/3\nu$ ratio $\vec{R}_{\text{pred}}$ over parameter space:
   a. Energy resolution, fuel fractions, etc., all accounted for.
   b. Experiments get their own *oscillation engines*.
2. Recalculate the experimentally measured ratios $\vec{R}_{\text{exp}}$:
   a. These are calculated from the *original papers*.
3. Accounting for *correlations*, calculate:

$$\chi^2 = (\vec{R}_{\text{exp}} - \vec{R}_{\text{pred}})^T \cdot V_{\text{exp}}^{-1} \cdot (\vec{R}_{\text{exp}} - \vec{R}_{\text{pred}}) + \vec{\xi}^T \cdot V_{\text{th}}^{-1} \cdot \vec{\xi},$$

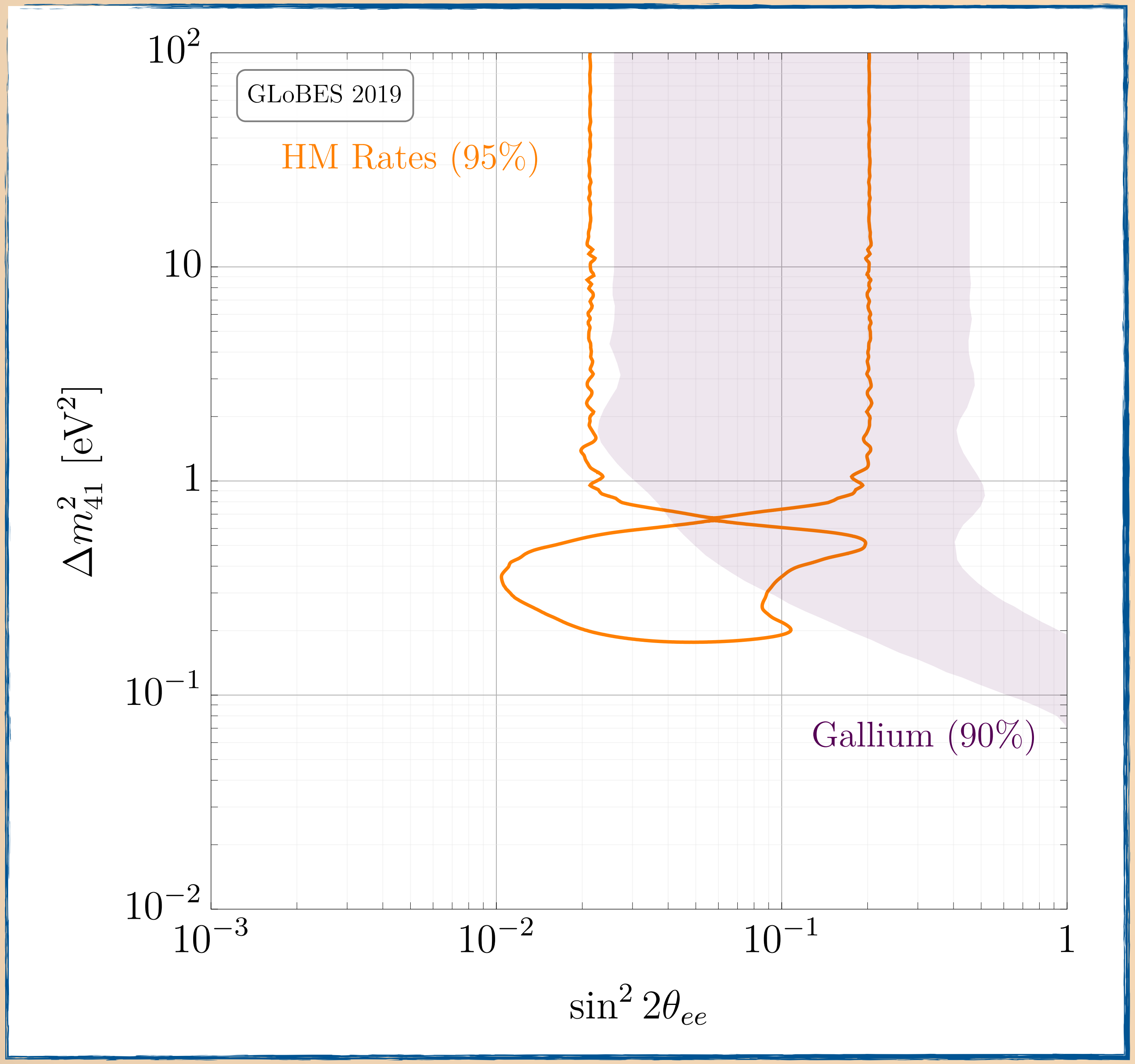
JMB, P. Huber, arXiv:1909.09267; further work in preparation

Analyzing Rates





HM Rate Analysis



- This is consistent with previous analyses:
  - *M. Dentler, et al., JHEP 08, 010 (2018)*
  - *C. Giunti, et al., Phys. Rev. D99 (2019) no.7, 073005*
- For context, also showing recent reevaluation of the gallium anomaly
- Total significance: 2.3σ

J. Kostensalo, et al., Phys. Lett. B795 (2019) 542-547

New Flux Predictions

This year, two new reactor antineutrino flux predictions have appeared, each using different techniques!

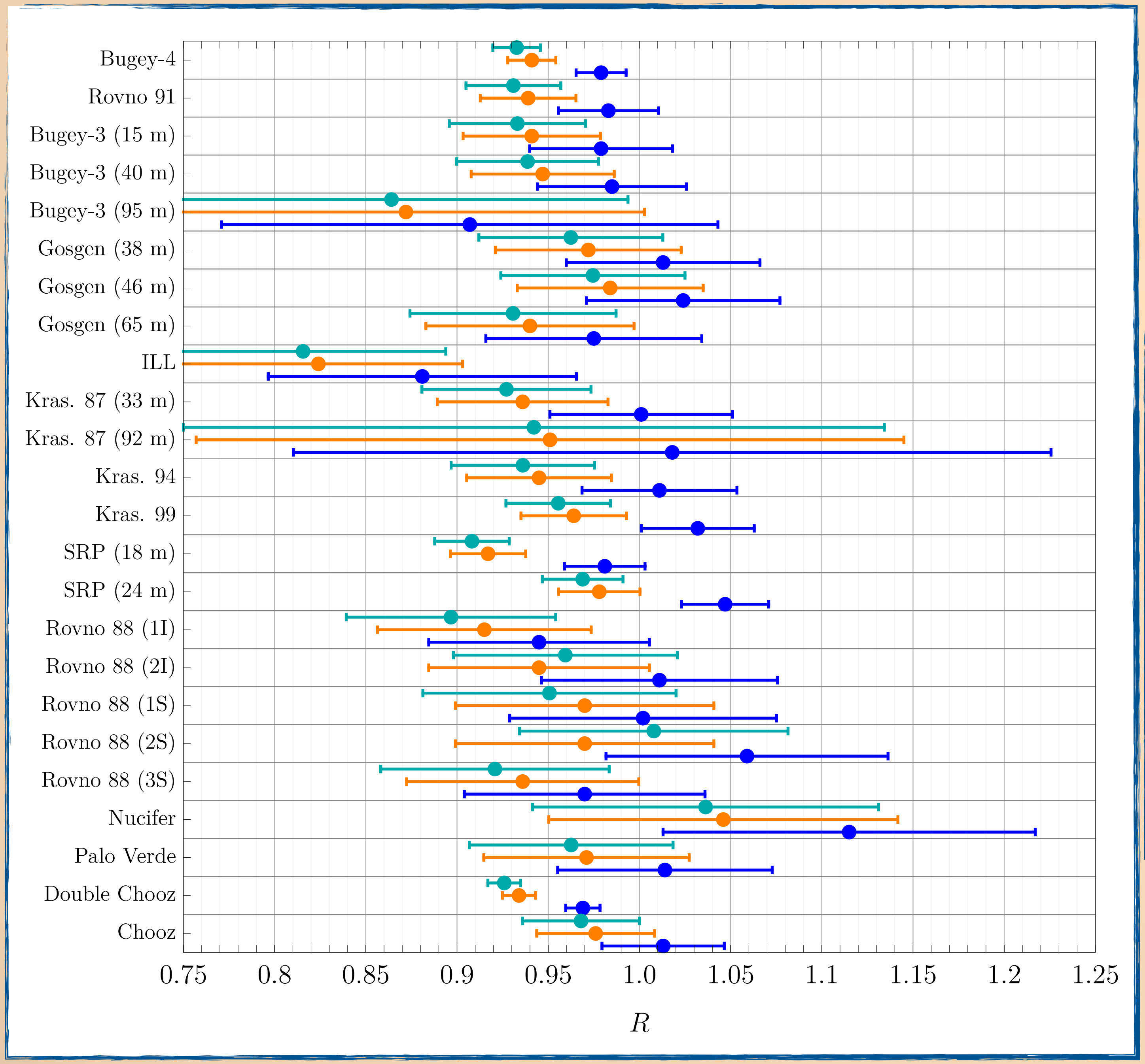
Estienne, et al.: *Ab initio* calculation (but no uncertainty estimates)

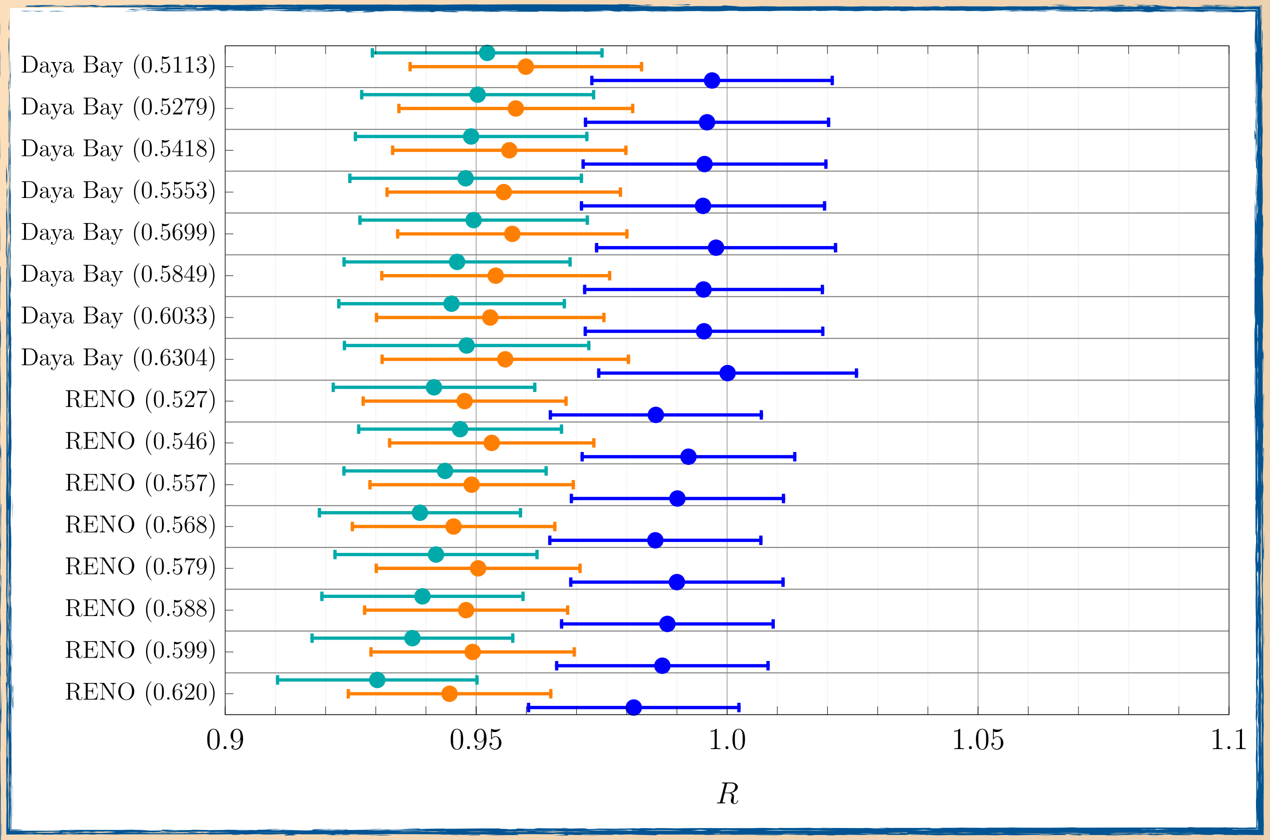
Hayen, et al.: Conversion method with improved estimates of *forbidden* contributions – with uncertainties!

How do these change the situation?

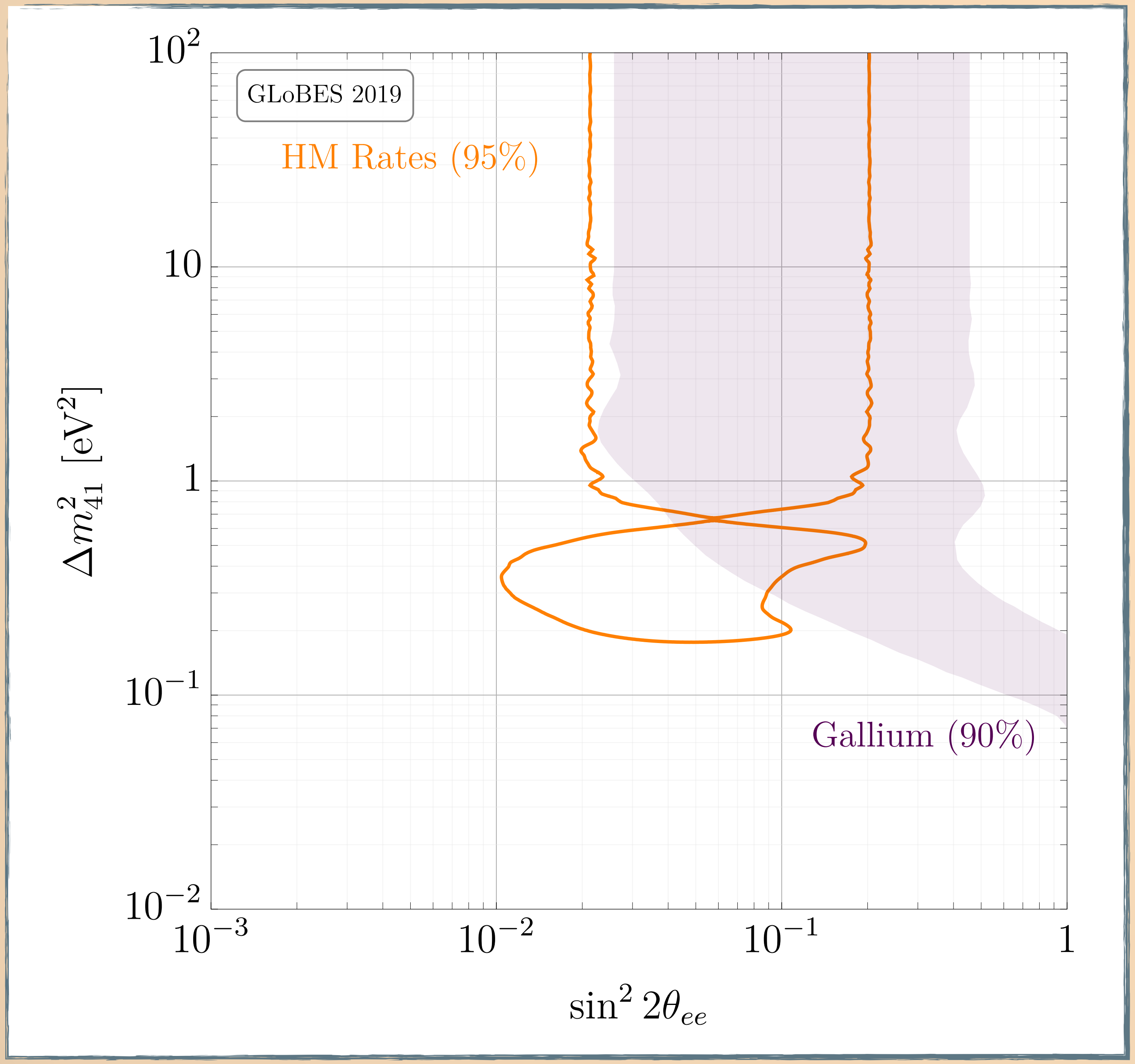
M. Estienne, et al., Phys. Rev. Lett. 123 (2019) no.2, 022502; L. Hayen, et al., arXiv:1908.08302

New Flux Predictions





All Rate Analyses



J. Kostensalo, et al., Phys. Lett. B795 (2019) 542-547

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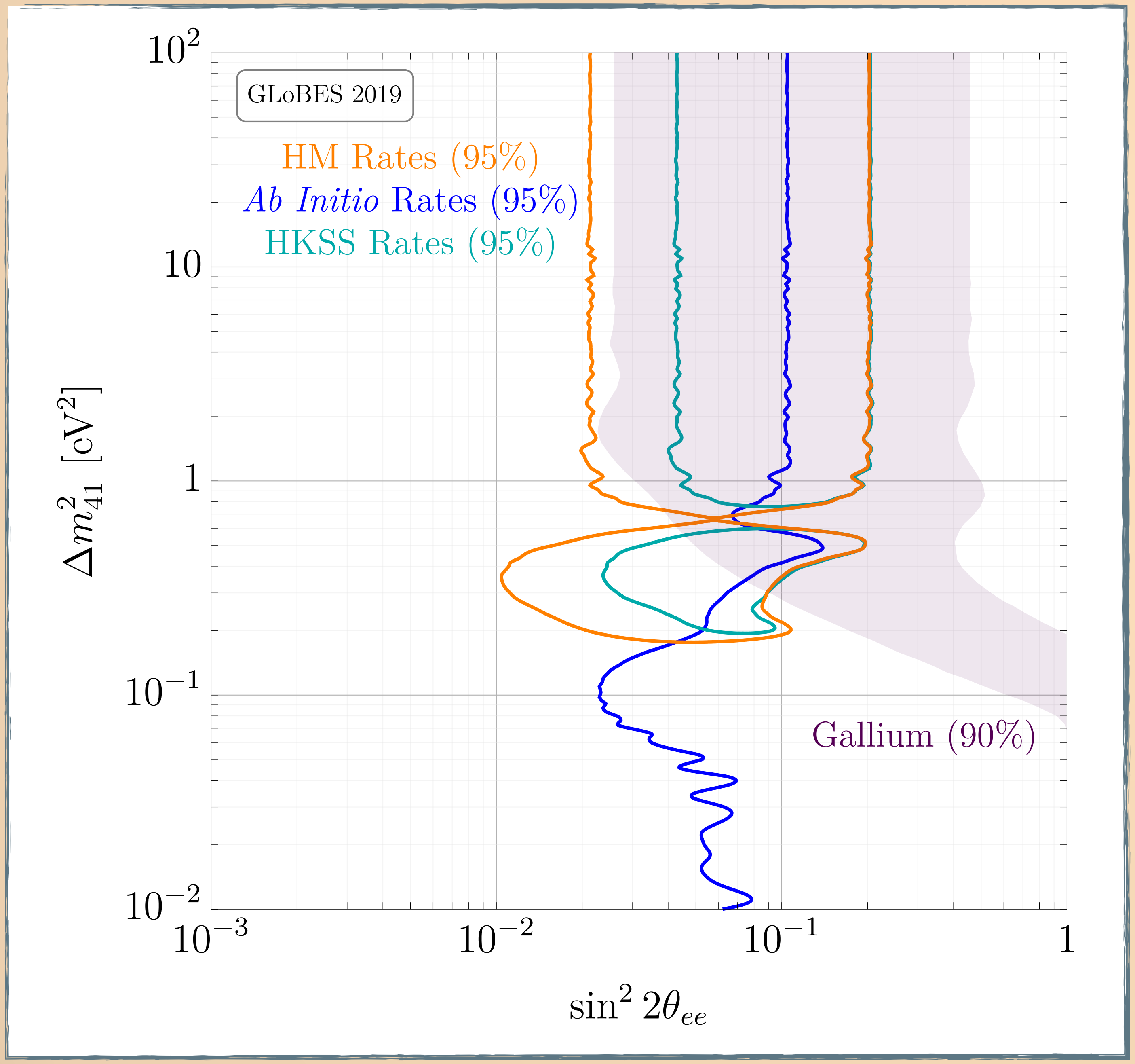


- These two new results *diverge* in their preference for a sterile neutrino!
  - HM Rates: 2.3σ
  - *Ab initio* Rates: 0.95σ
  - HKSS Rates: 2.8σ

Which one of these (if any) is the correct choice?

J. Kostensalo, et al., Phys. Lett. B795 (2019) 542-547

Analyzing Spectra

The experimental inputs we use are:

1. Bugey-3: Ratio of spectra at 15 m and 40 m; no 95 m (*25*)
2. DANSS: Ratio of spectra at 10.7 m and 12.7 m; no 11.7 m (*24*)
3. Daya Bay: Ratios of spectra – EH2/EH1 and EH3/EH1 (*52*)
4. Double Chooz: Ratio of spectra at near and far detectors (*26*)
5. NEOS*: Ratio of NEOS data relative to antineutrino spectrum *measured at Daya Bay* (*60*)
6. RENO: Ratio of spectra at near and far detectors (*25*)

These ratios are (largely) independent of the particular flux model that we use in our analysis!

JMB, P. Huber, arXiv:1909.09267; further work in preparation

Analyzing Spectra

- We compute a χ^2 function of the form

$$\chi^2 = \sum_A (\vec{S}^A_{\text{exp}} - \vec{S}^A_{\text{pred}})^T \cdot (V_A)^{-1} \cdot (\vec{S}^A_{\text{exp}} - \vec{S}^A_{\text{pred}})$$

- For everyone *except NEOS*,

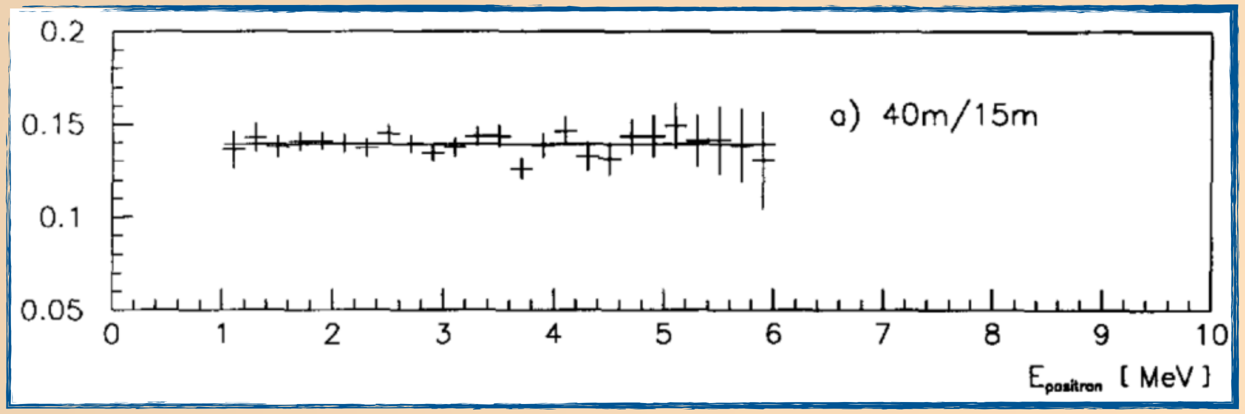
$$\vec{S}^A_{\text{pred}} \sim \frac{N^A_{4\nu,\text{near}}}{N^A_{4\nu,\text{far}}}$$

- For NEOS,

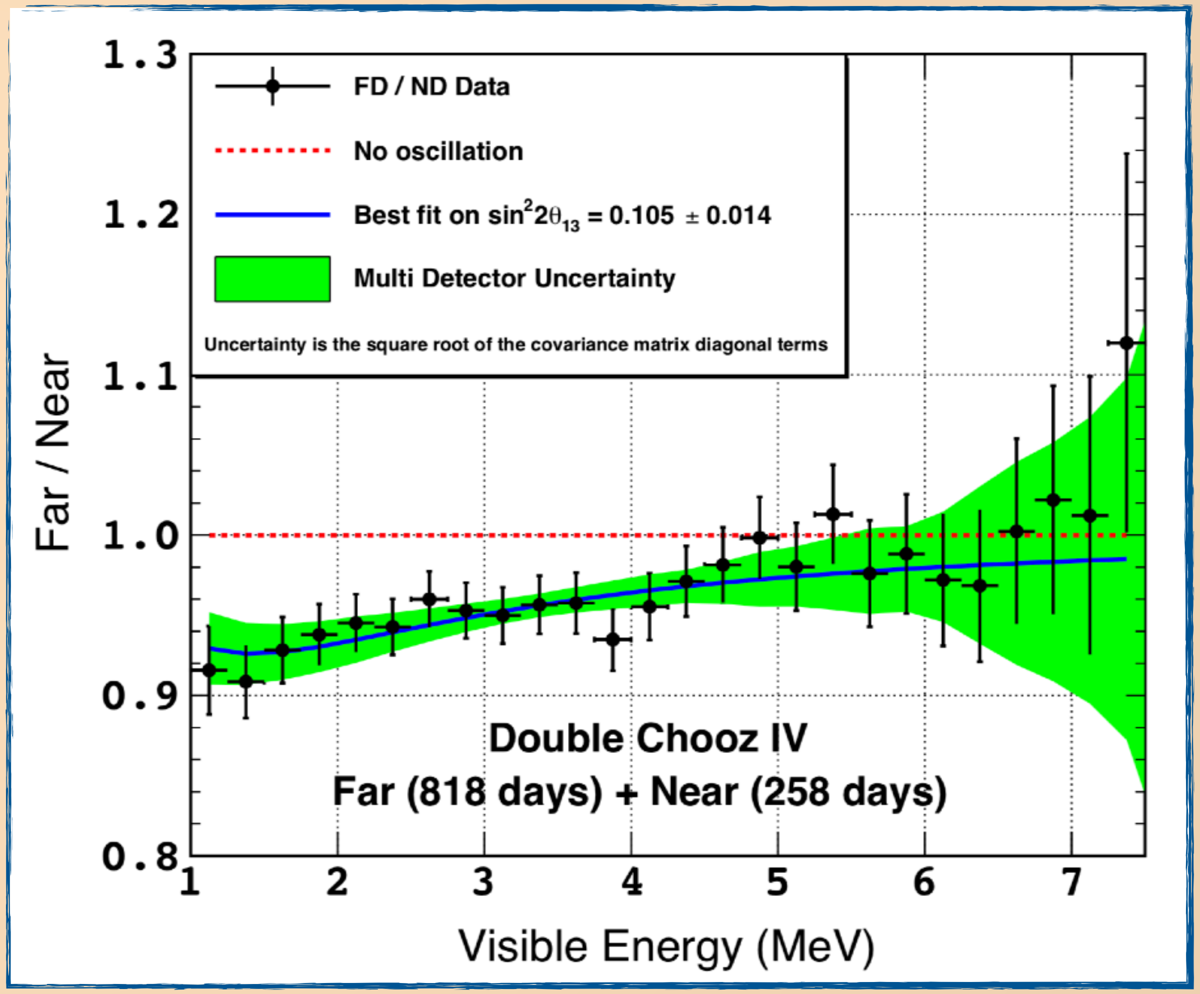
$$\vec{S}^{\text{NEOS}}_{\text{pred}} \sim \frac{N^{\text{NEOS}}_{4\nu} / N^{\text{DB,EH1}}_{4\nu}}{N^{\text{NEOS}}_{3\nu} / N^{\text{DB,EH1}}_{3\nu}}$$

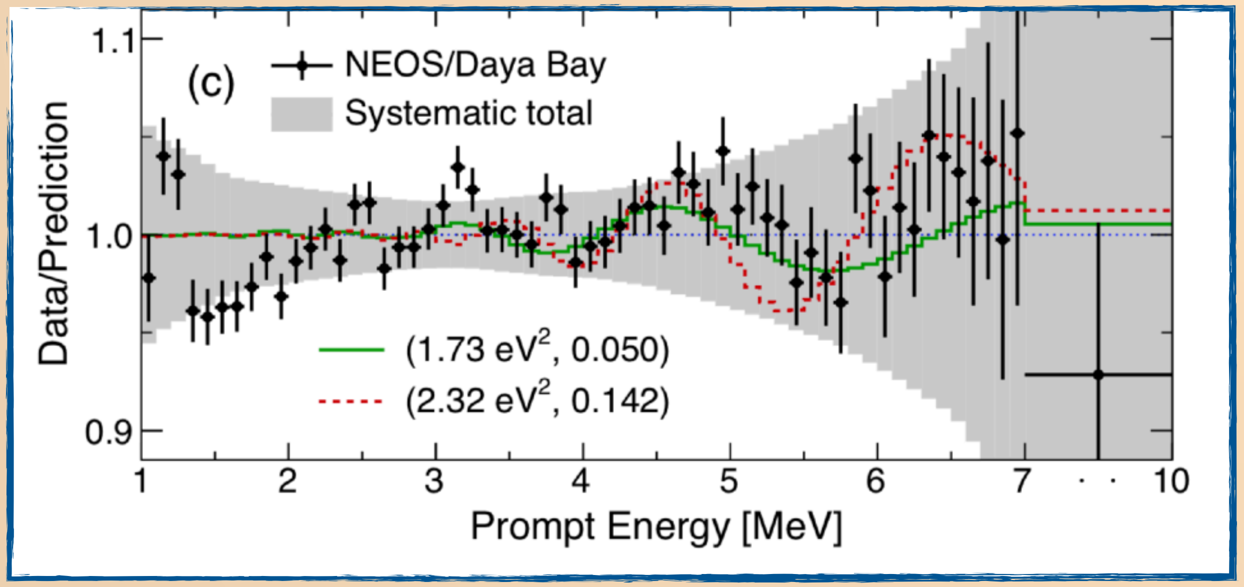
Analyzing Spectra

Bugey-3 (1995)



Double Chooz (2019)

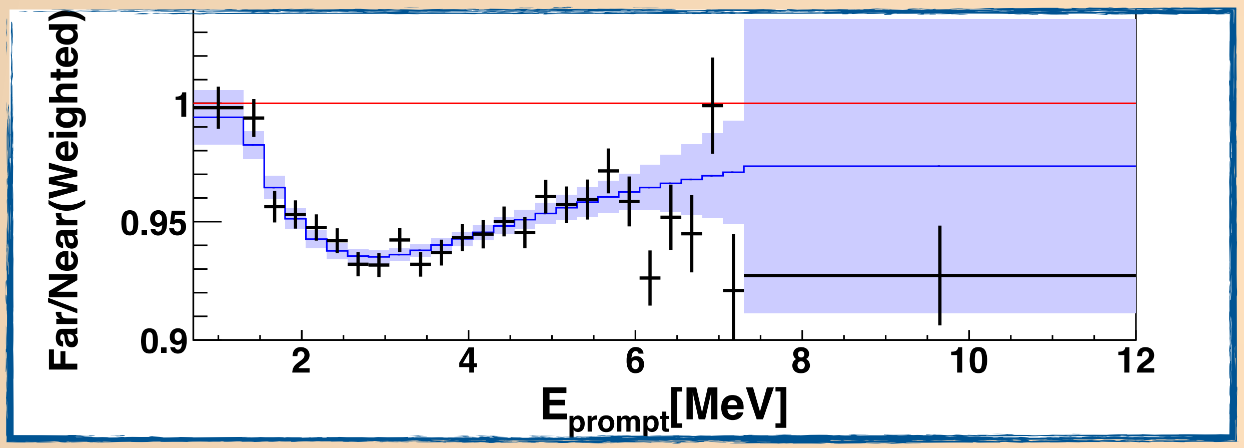


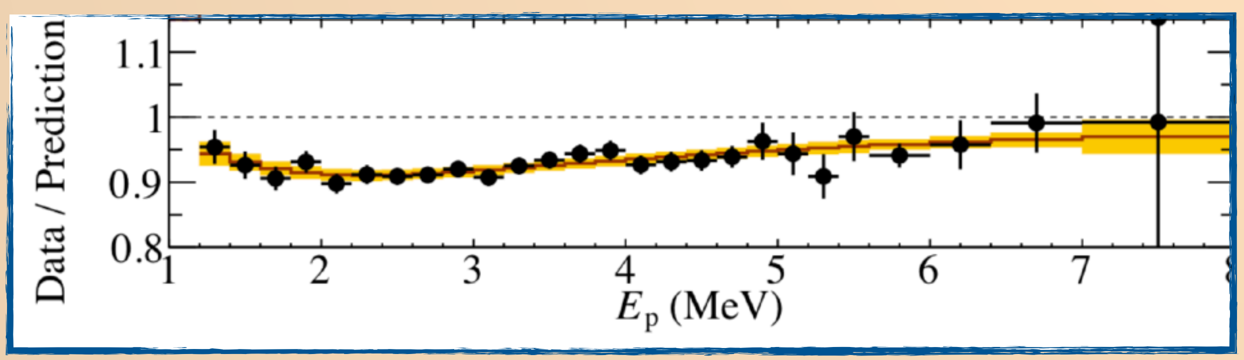


NEOS/Daya Bay (2017)

Analyzing Spectra

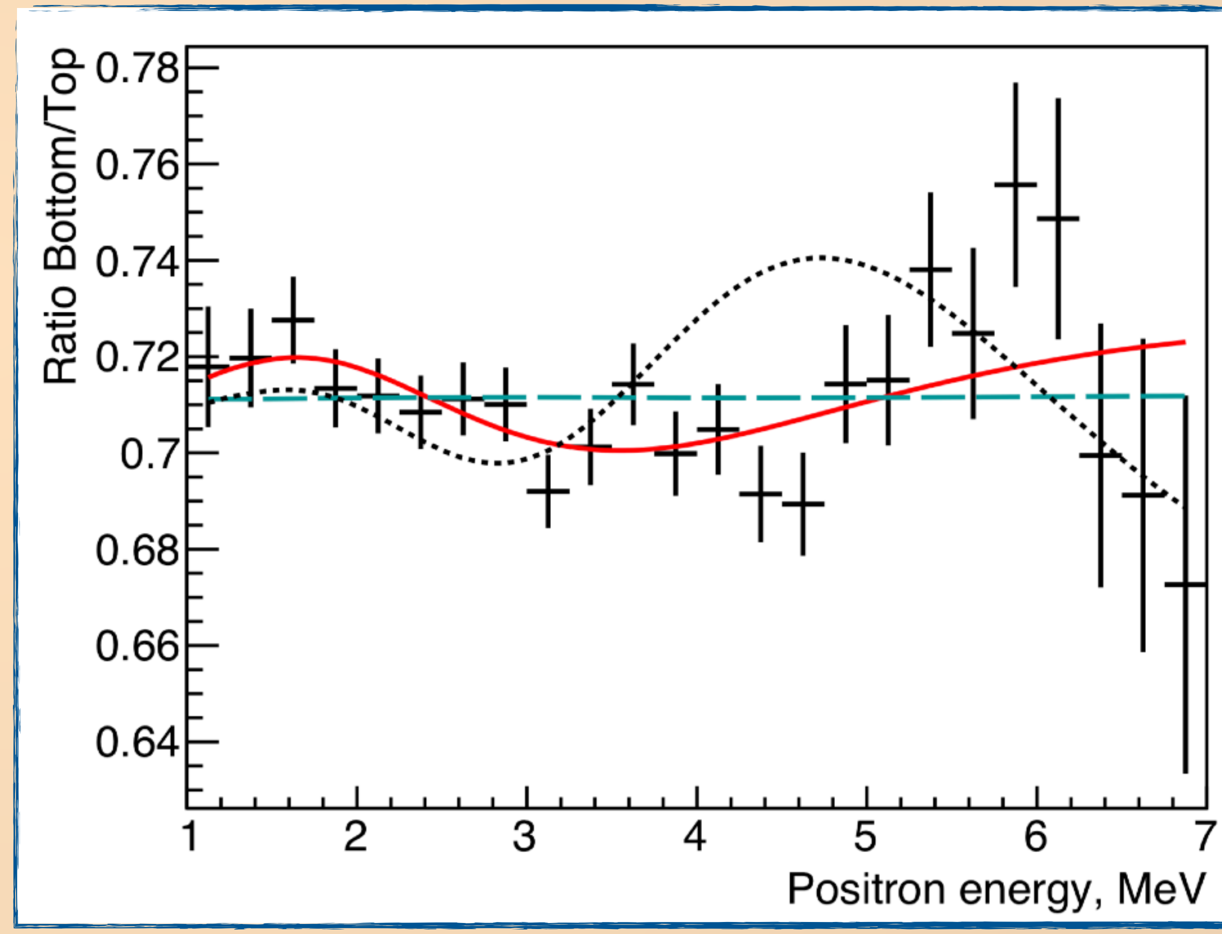
Daya Bay, EH3 (2018)



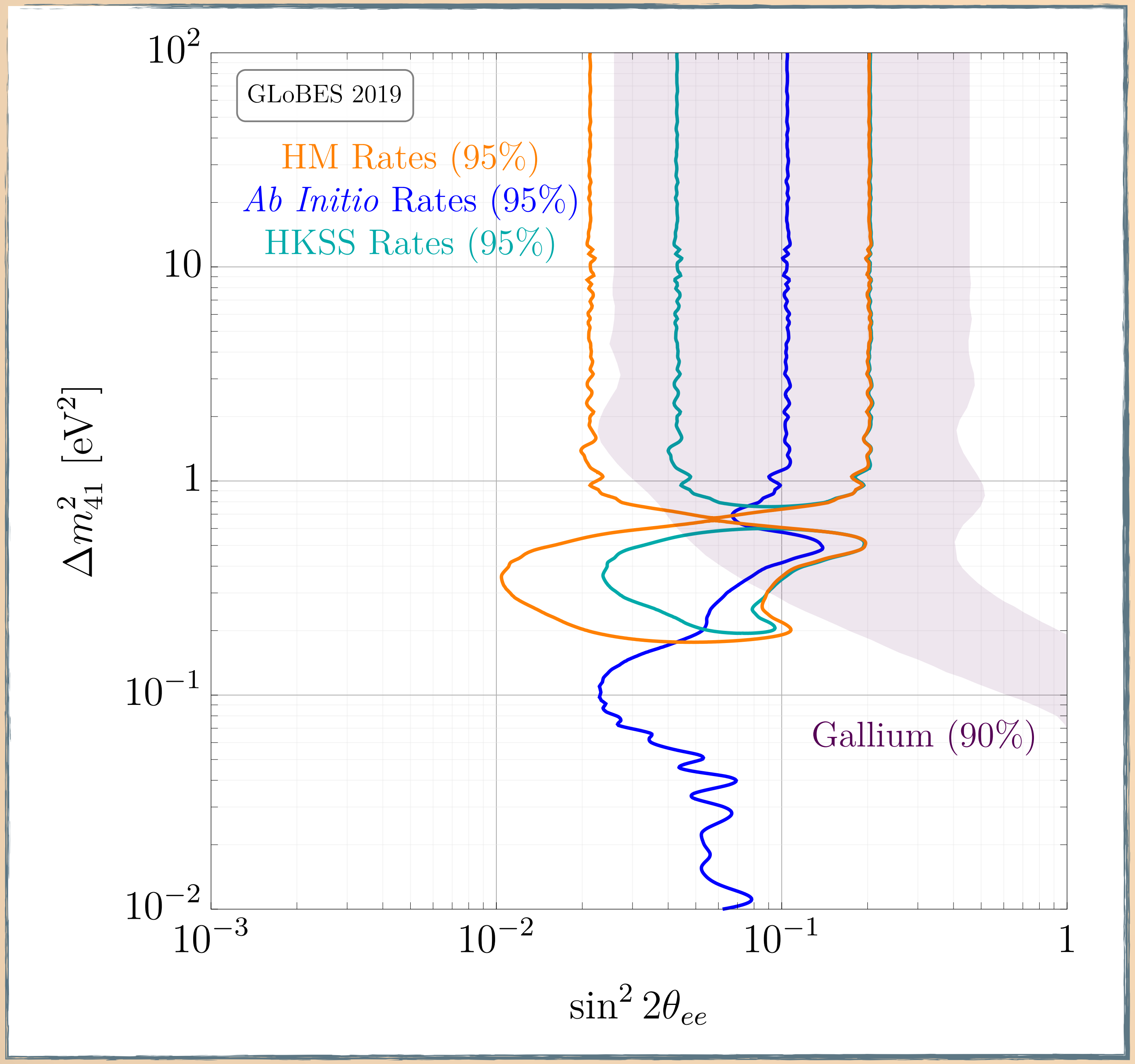


RENO (2018)

DANSS (2018)



Spectral Analysis



J. Kostensalo, et al., Phys. Lett. B795 (2019) 542-547

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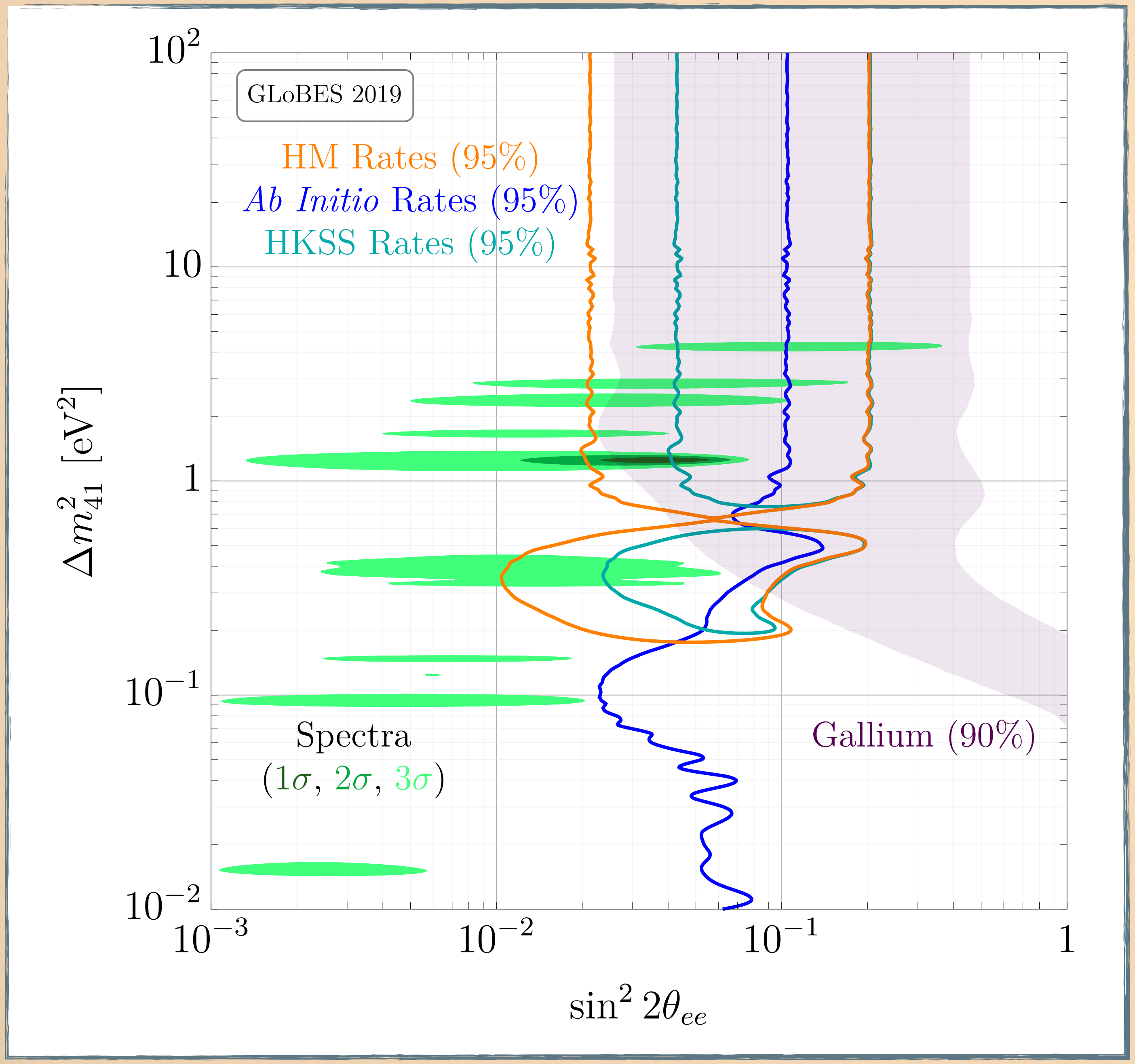


- The evidence is modestly strong – 3.1σ!
  - *DANSS+NEOS*: 3.3σ!
- We don't combine rate and spectra – BUT:
  - Clearly consistent with *ab initio*
  - Mostly OK with HM
  - Mild tension with HKSS!

J. Kostensalo, et al., Phys. Lett. B795 (2019) 542-547

Sidebar: How Could Things Go Wrong?

What are the ways in which this analysis is deficient?

1. Experimental analyses are *complicated*; exact replication is essentially impossible!
   (Lack of published data; experimental geometry; operating conditions; detector response models, etc.)
2. *Statistical methods* are *way* oversimplified!
   (Often not χ^2-distributed; e.g., $\Delta\chi^2$=6.18 may *actually* correspond to $<2\sigma$!)

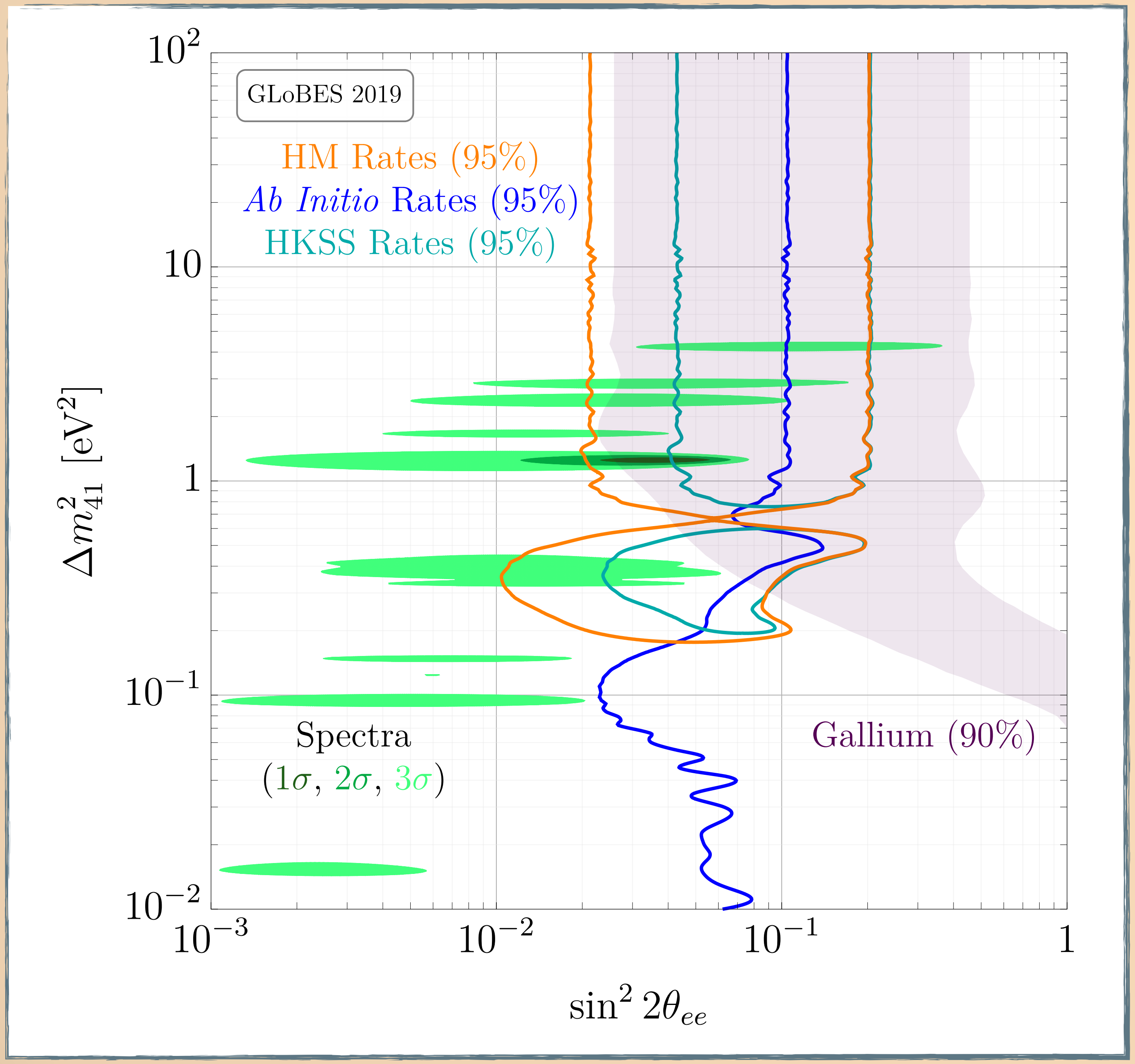
(*See A. Diaz, et al., arXiv:1906.00045 for more discussion of these points*)

What Comes Next?

- *Ongoing reactor experiments*: PROSPECT, STEREO, SoLid, Neutrino-4; CONUS
- *Future reactor experiments*: JUNO; RED100, MINER, CONNIE, etc.
- *Source experiments*: COHERENT; IsoDAR, BEST, ~~SOX~~

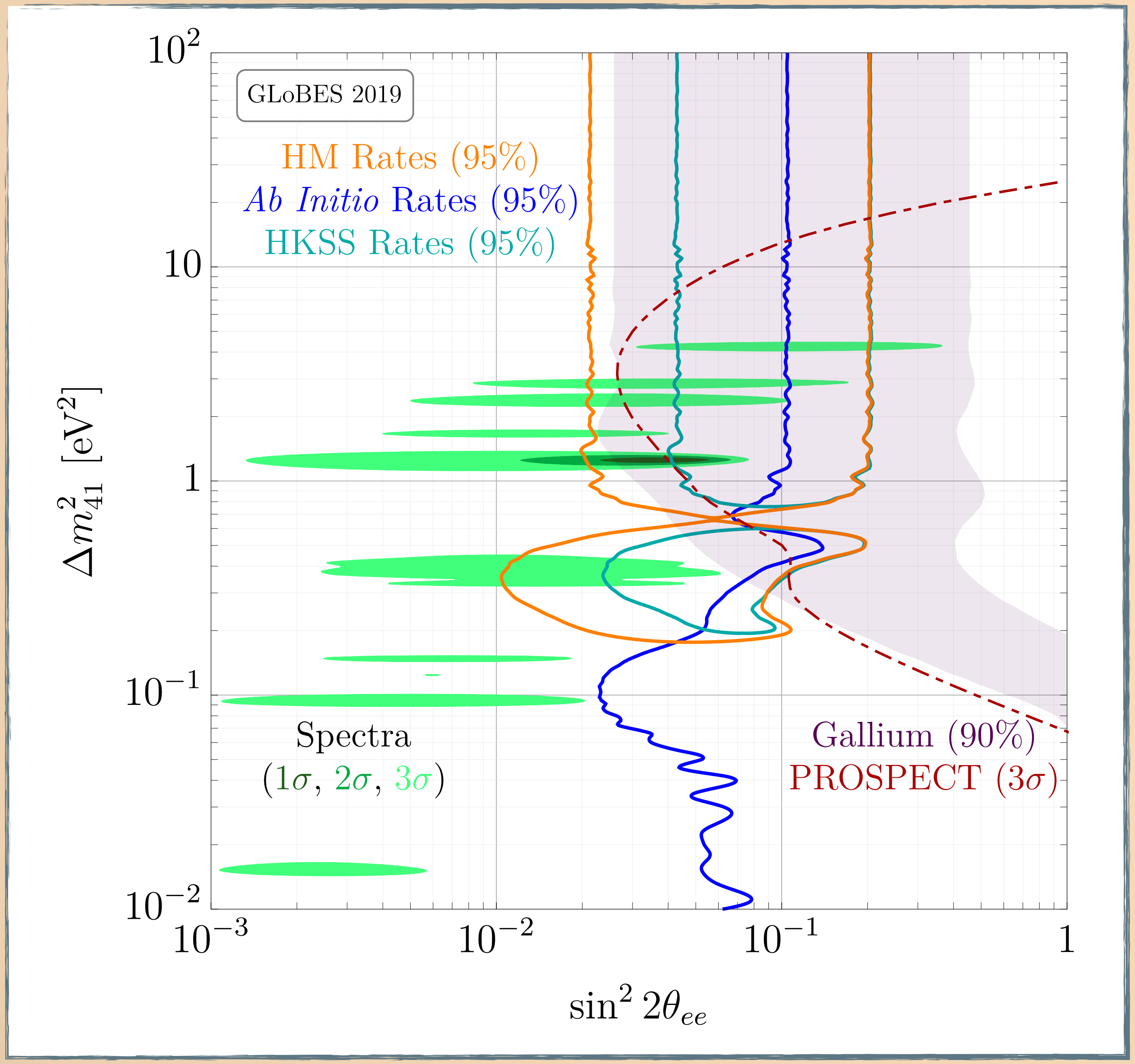
What can we expect in this parameter space in the future?

The Future: PROSPECT



J. Kostensalo, et al., Phys. Lett. B795 (2019) 542-547;
J. Ashenfelter, et al., J. Phys. G43, 113001 (2016)

The Future: PROSPECT

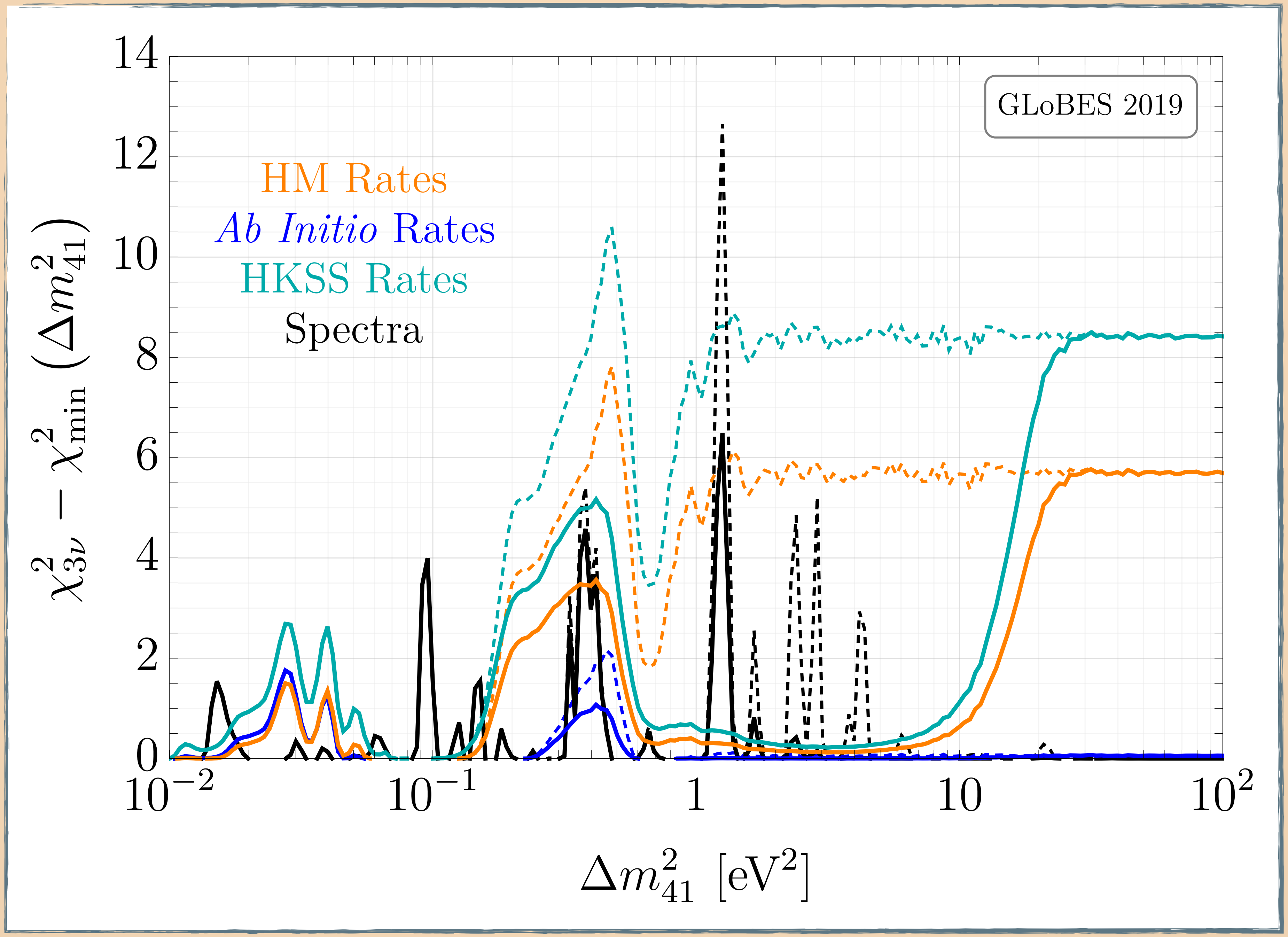


- PROSPECT looks to have reasonable sensitivity in the range 1-10 eV^2
- Best way to quantify?
  - Assume PROSPECT gets null result
  - Capture *global* structure of each analysis

$$\chi^2_{3\nu} - \chi^2_{\min}\left(\Delta m^2_{41}\right)$$

J. Kostensalo, et al., Phys. Lett. B795 (2019) 542-547;
J. Ashenfelter, et al., J. Phys. G43, 113001 (2016)

The Future: PROSPECT



Part 3:
Why Should You Care?

What’s the Big Idea?

Reactors are complicated (anti)neutrino sources!

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Reactors are complicated (anti)neutrino sources!

There are plenty of opportunities for us to fool ourselves:

1. *The rate anomaly* and *the bump* are almost certainly commentaries on our knowledge of the fluxes.
2. *The spectral anomaly* could possibly be due to some unknown systematic – DANSS? (Neutrino-4?)
3. *Statistics of fitting frequencies* is not quite so clear-cut; issues related to *statistical coverage* (*M. Agostini & B. Neumair, arXiv:1906.11854*)

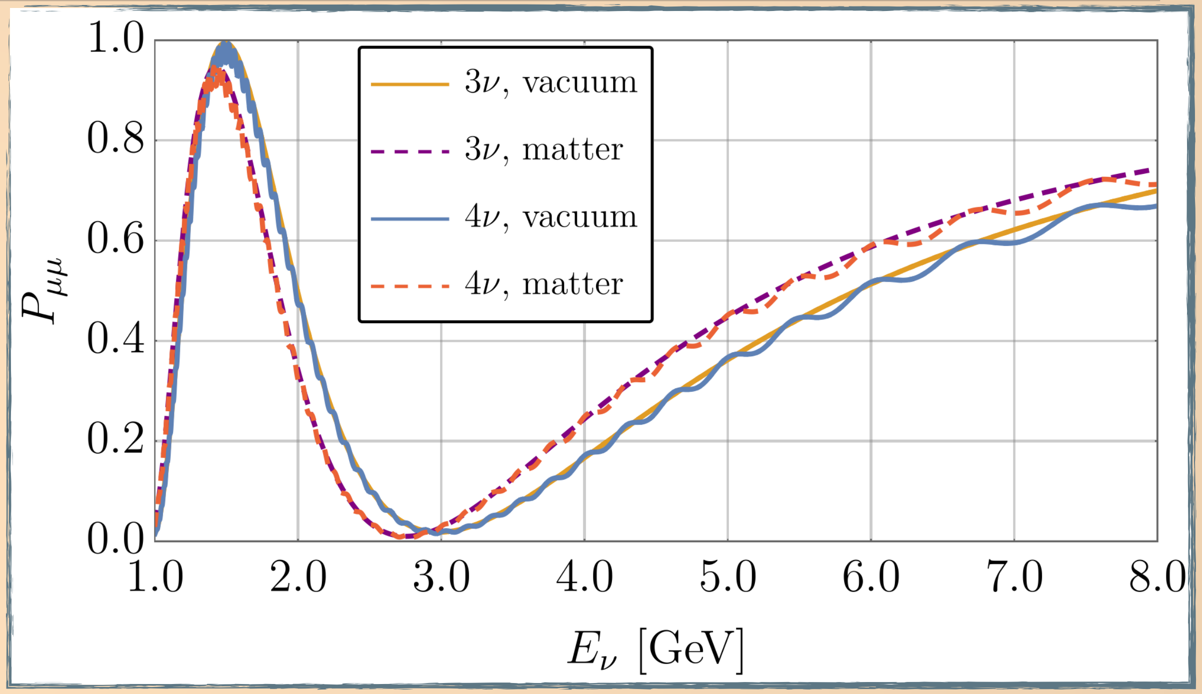
There are real *physical* and *economic* consequences to making sure these questions are answered correctly!

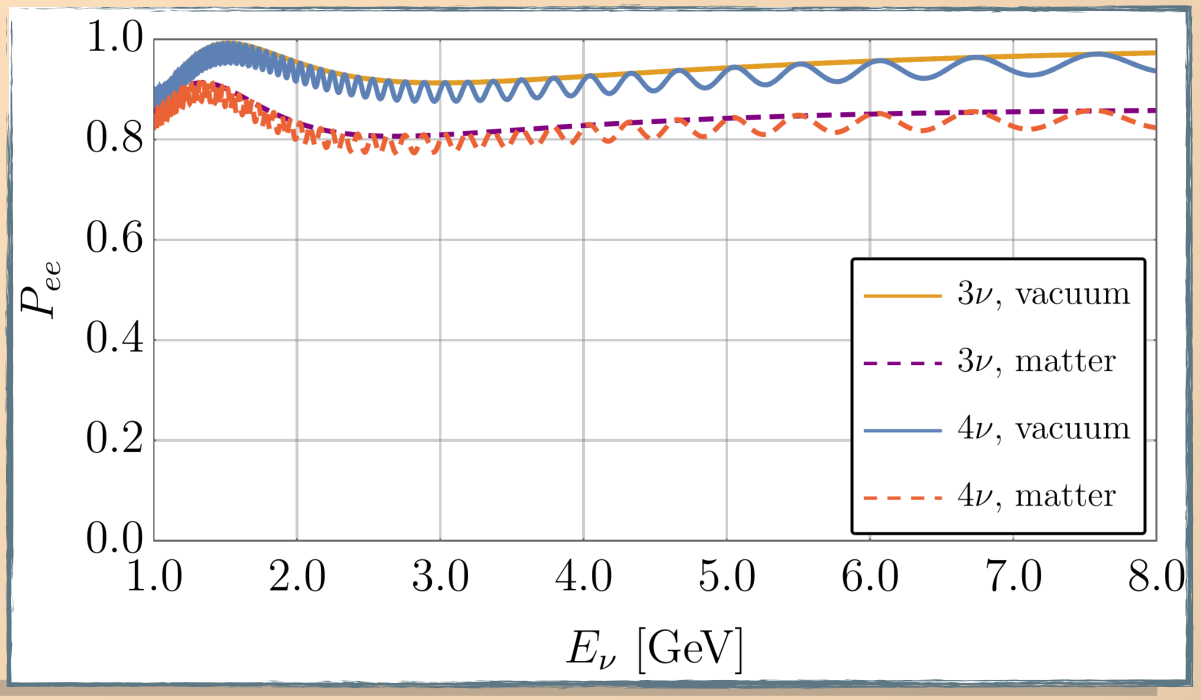
One Such Consequence:
Sterile Neutrinos in the Early Universe

JMB, Phys. Rev. D100 (2019) no.2, 023540

Sterile Neutrinos: Oscillations vs. Cosmology

- *Oscillations*: Extra wiggles on top of 3ν oscillation pattern
- *Cosmology*: Shifts in, *e.g.*, CMB relative to ΛCDM predictions
- Described by different – but related – physical parameters:
  Oscillations: $\{\Delta m^2_{41},\ \sin^2 2\theta_{\alpha\beta}\}$
  Cosmology: $\{\Delta N_{\text{eff}},\ m^{\text{eff}}_{\text{sterile}}\}$





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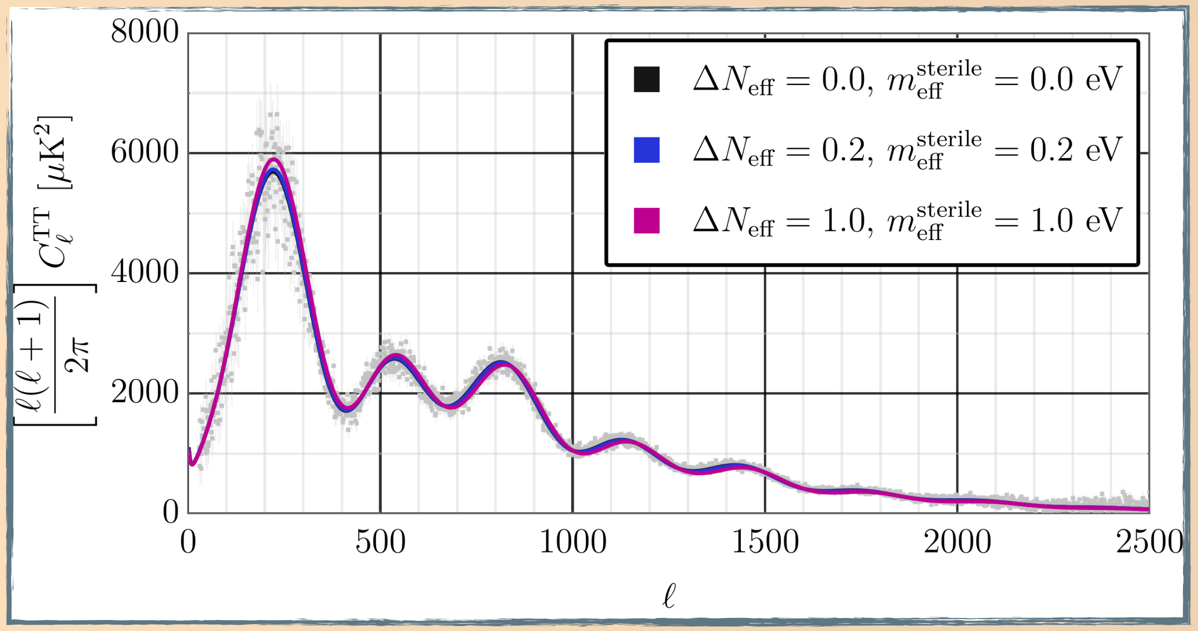

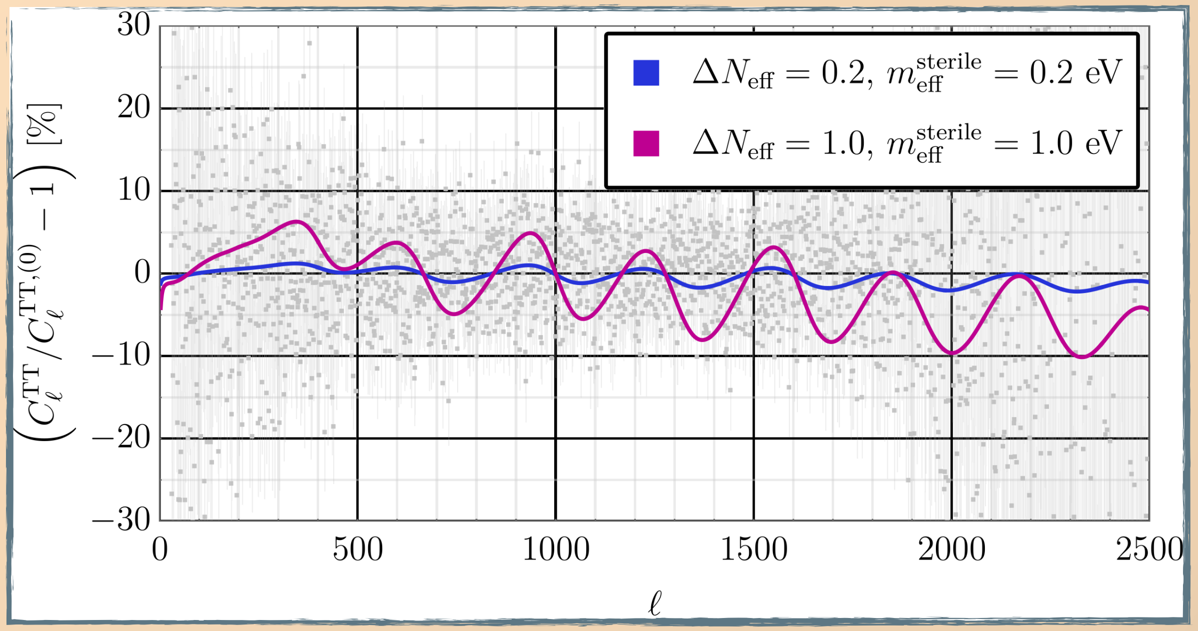

Neutrinos in the Early Universe

- Simplifying assumption: *two-neutrino fluid*

$$\begin{pmatrix} \nu_a \\ \nu_s \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} \longrightarrow \rho = \frac{1}{2} f_0 \left(P_0 + \vec{\sigma} \cdot \vec{P} \right)$$

$$\frac{dP_0}{dt} = R^{(a)}$$

$$\frac{d\vec{P}}{dt} = \left(\vec{B} + \vec{V}^{(a)} \right) \times \vec{P} - D^{(a)} \left(P_x \, \hat{x} + P_y \, \hat{y} \right) + R^{(a)} \, \hat{z}$$

S. Hannestad, et al., JCAP 1207, 025 (2012)

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Vacuum + Matter Potential — Damping — Repopulation

S. Hannestad, et al., JCAP 1207, 025 (2012)

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Vacuum + Matter Potential | Damping | Repopulation

$$P_i^{\pm} = P_i \pm \overline{P}_i$$

$$P_a^{\pm} = P_0^{\pm} + P_z^{\pm}$$

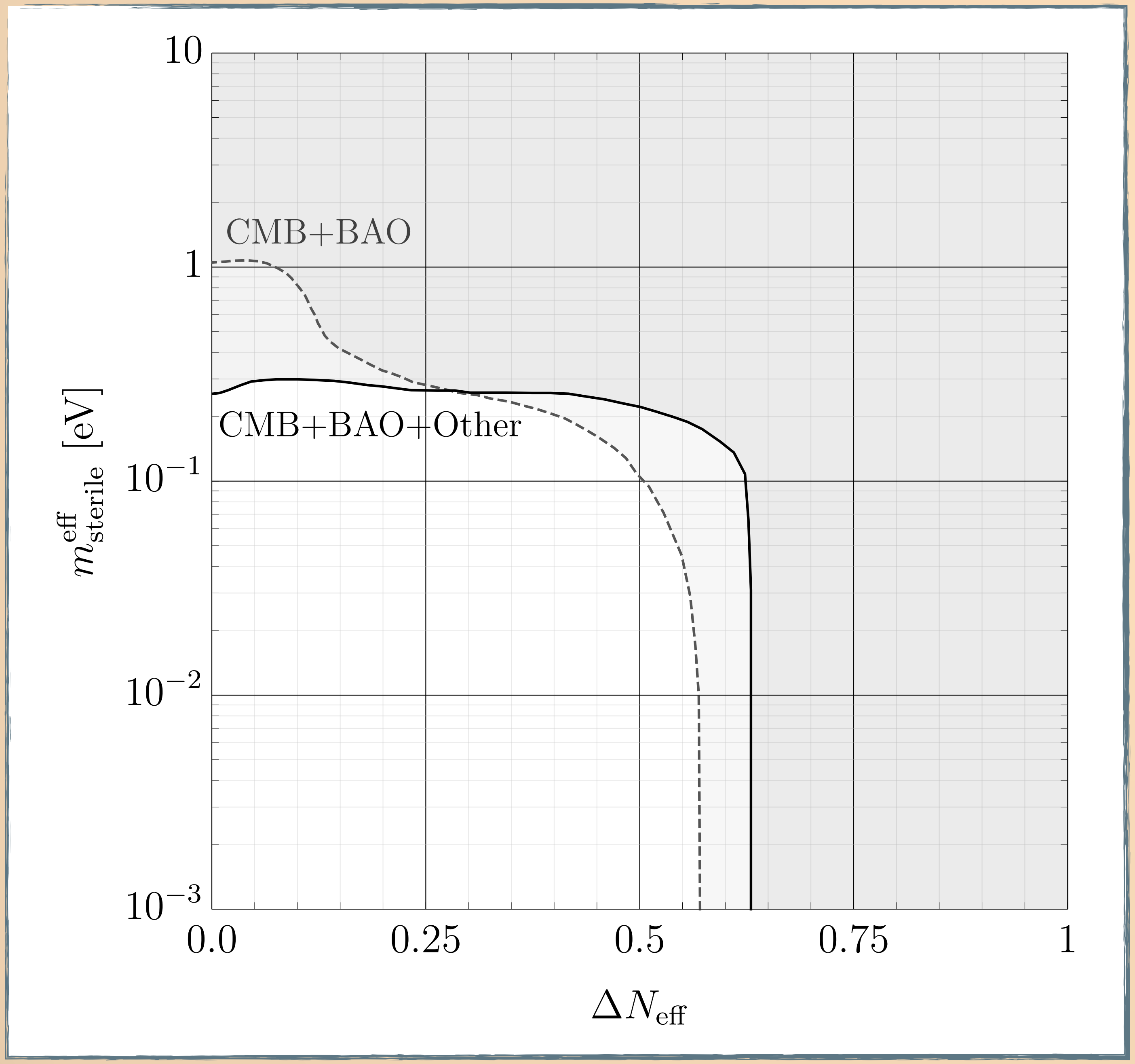
$$P_s^{\pm} = P_0^{\pm} - P_z^{\pm}$$

$$\Delta N_{\text{eff}} = \frac{\int dx\, x^3 f_{\text{eq}}(x, \mu{=}0)\, P_s^{+}(x)}{4 \int dx\, x^3 f_{\text{eq}}(x, \mu{=}0)}$$

$$m_{\text{sterile}}^{\text{eff}} = \left(\Delta N_{\text{eff}} \right)^{3/4} \sqrt{\Delta m_{41}^2}$$

S. Hannestad, et al., JCAP 1207, 025 (2012)

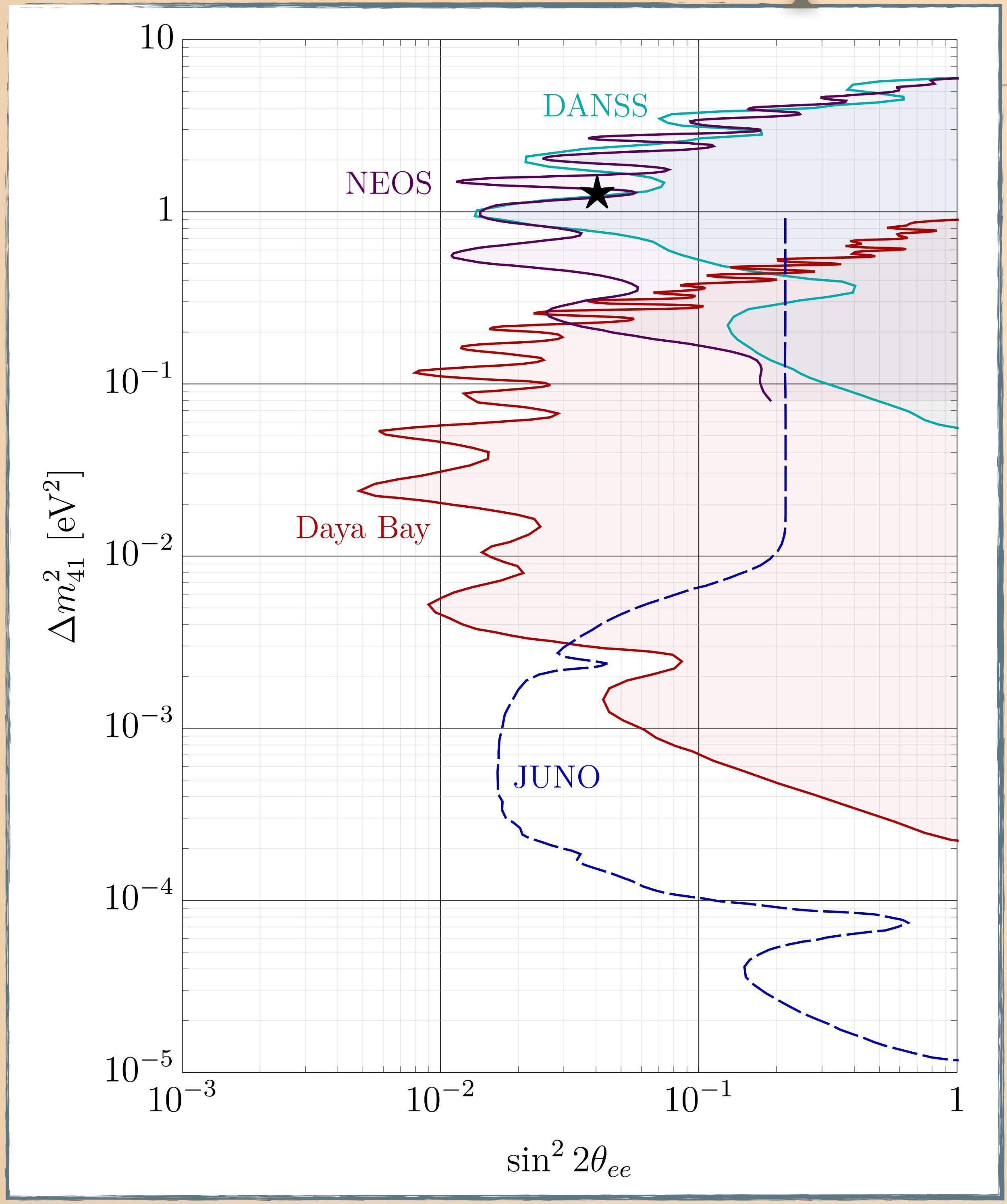
Sterile Neutrino Cosmology



- <u>*"CMB+BAO"*</u>:
  - Planck 2015 TT,TE,EE+lowP
  - BAO data (BOSS; 6dFGS; SDSS MGS)
- <u>*"CMB+BAO+Other"*</u>:
  - Hubble constant
  - Planck cluster & lensing data
  - CFHTLenS weak lensing

L. Feng, et al., Eur. Phys. J. C77, 418 (2017)

Reactor Experiments



M. Dentler, et al., JHEP 08, 010 (2018)

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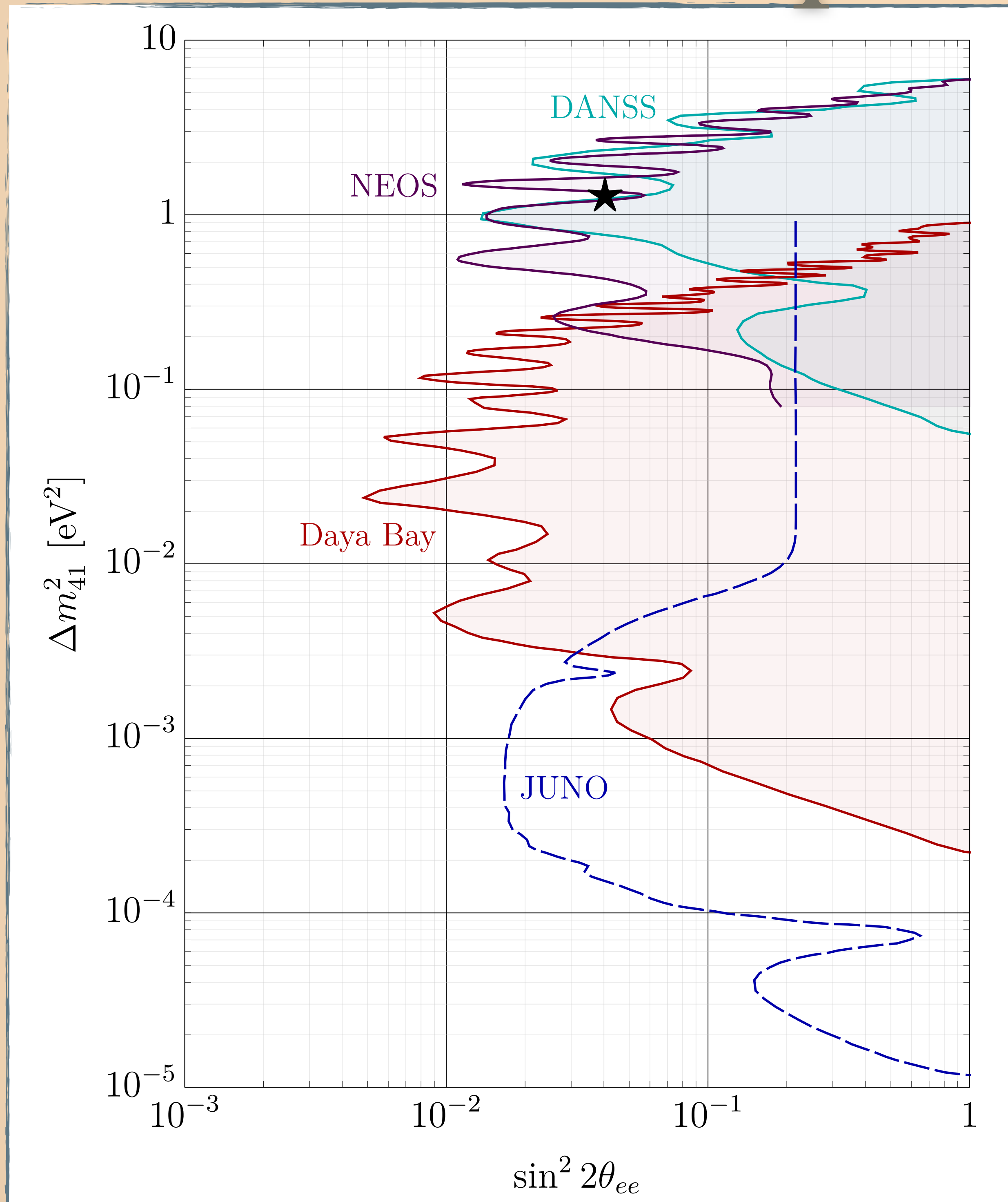

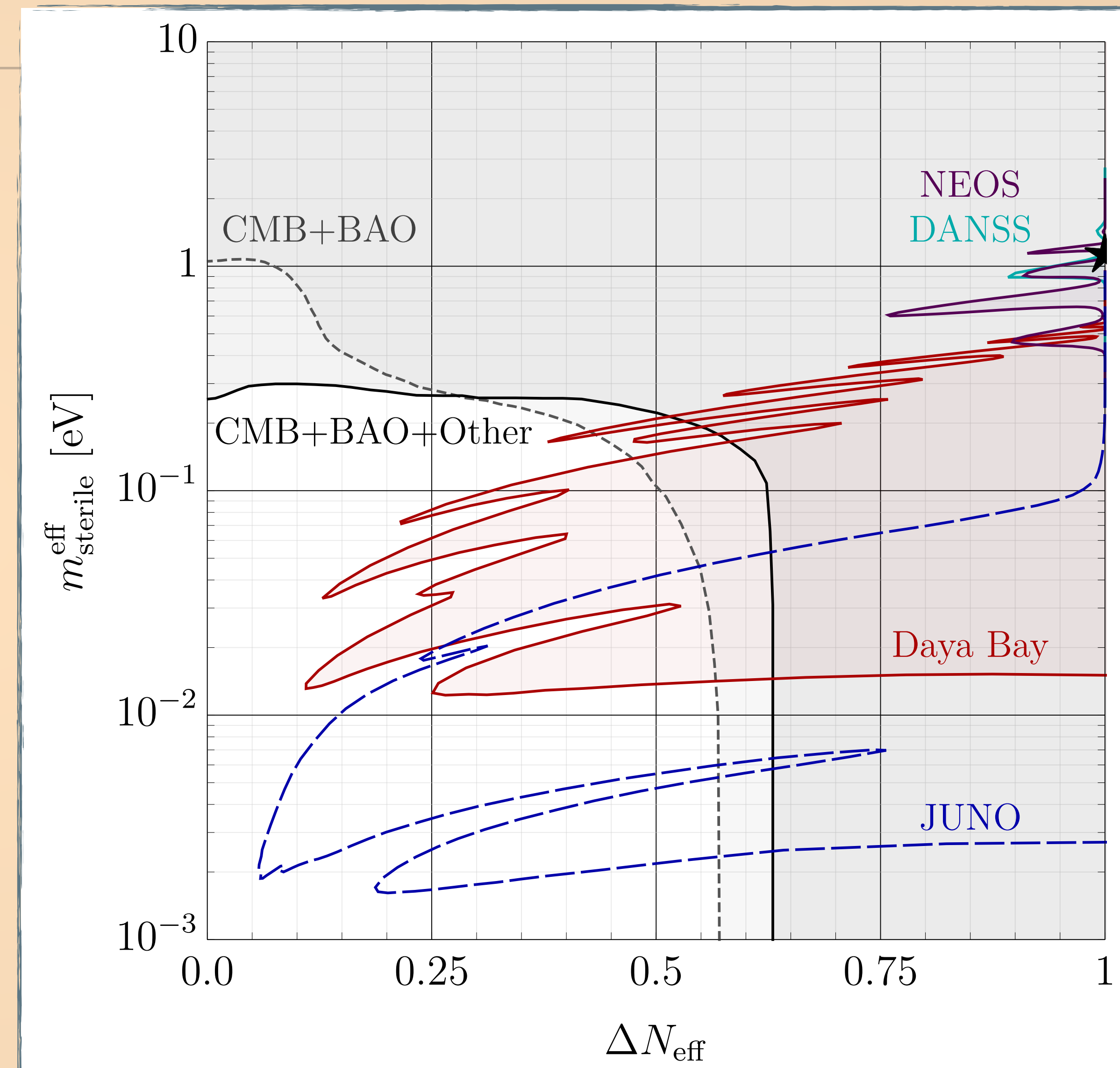

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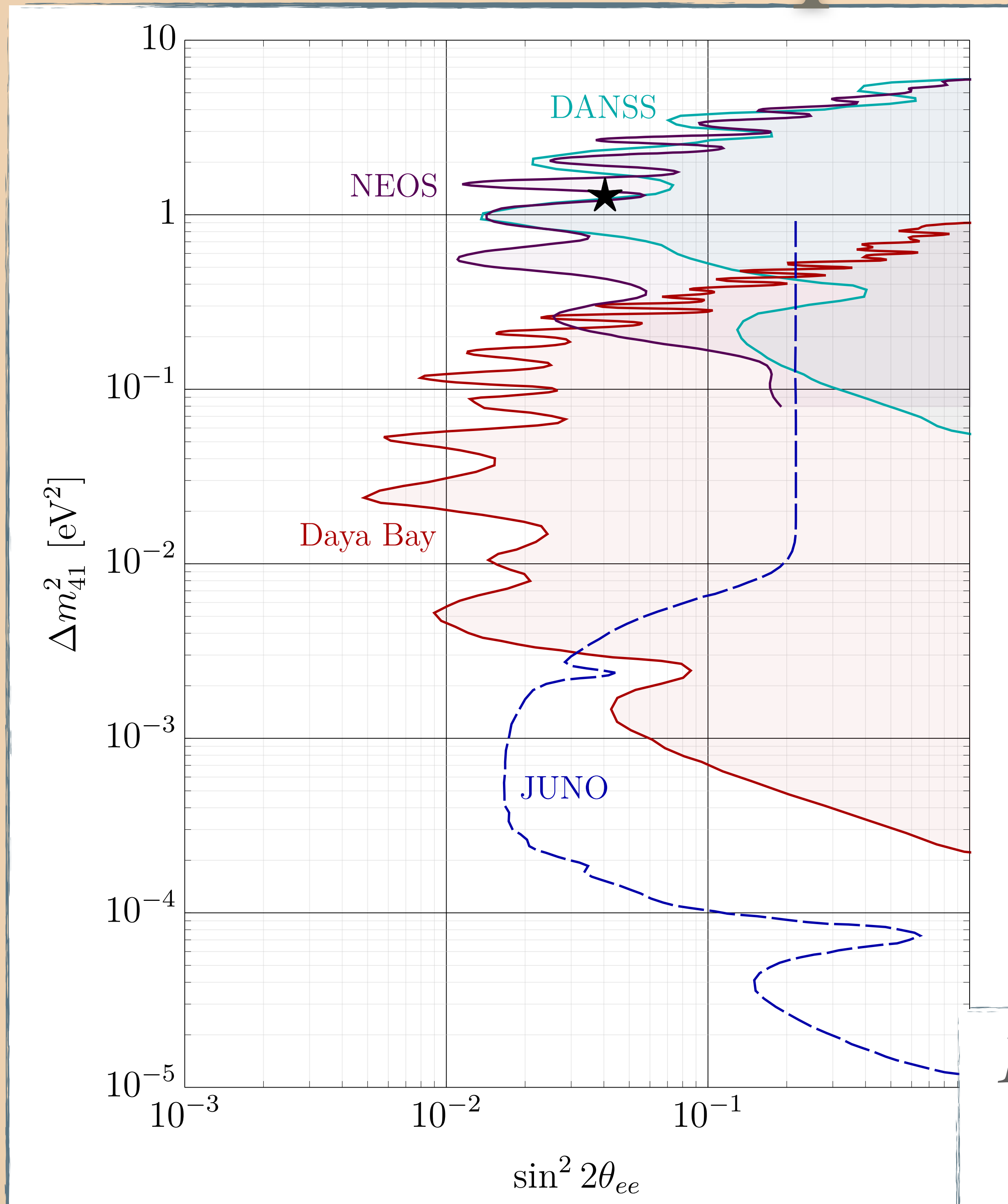
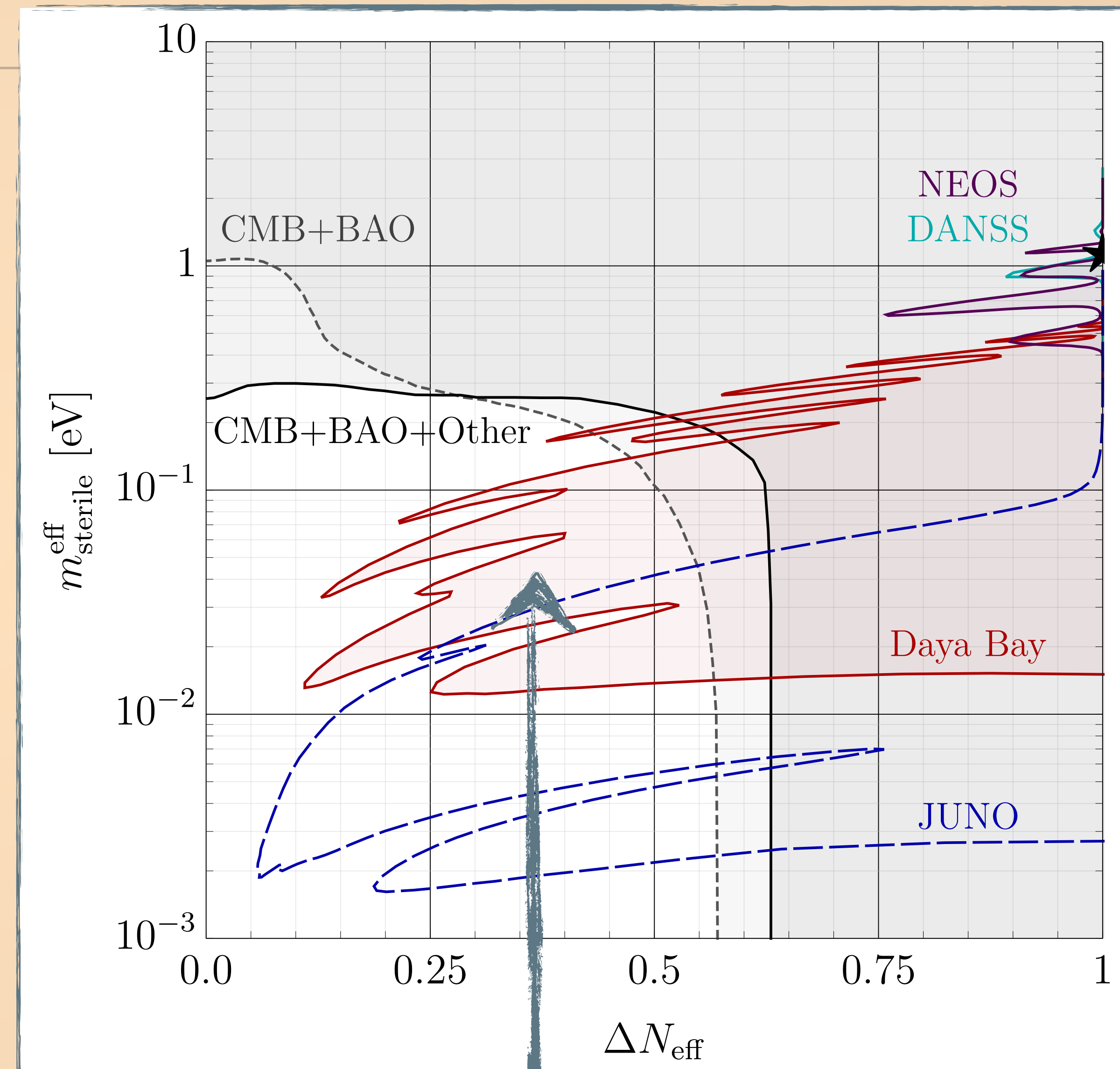
Reactor Experiments





Daya Bay can already probe parameter space to which astrophysical/cosmological experiments are insensitive!

M. Dentler, et al., JHEP 08, 010 (2018)

Reconciling the Reactor Anomaly with Cosmology

Cosmological measurements very strongly disfavor the sterile-neutrino interpretation of the reactor anomaly. How to reconcile?

1. The reactor anomaly is an aberration
2. The two-neutrino framework misses essential physics
3. The initial lepton asymmetry of the Universe is large (~10^{-3}–10^{-2})
4. Neutrinos have additional interactions → new matter potential
5. We've misunderstood something about cosmology

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Note added: A new result has appeared where this system is studied in full 3+1 glory – they find *the same thing*!

S. Gariazzo, et al., 1905.11290

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S. Gariazzo, et al., 1905.11290

Conclusions

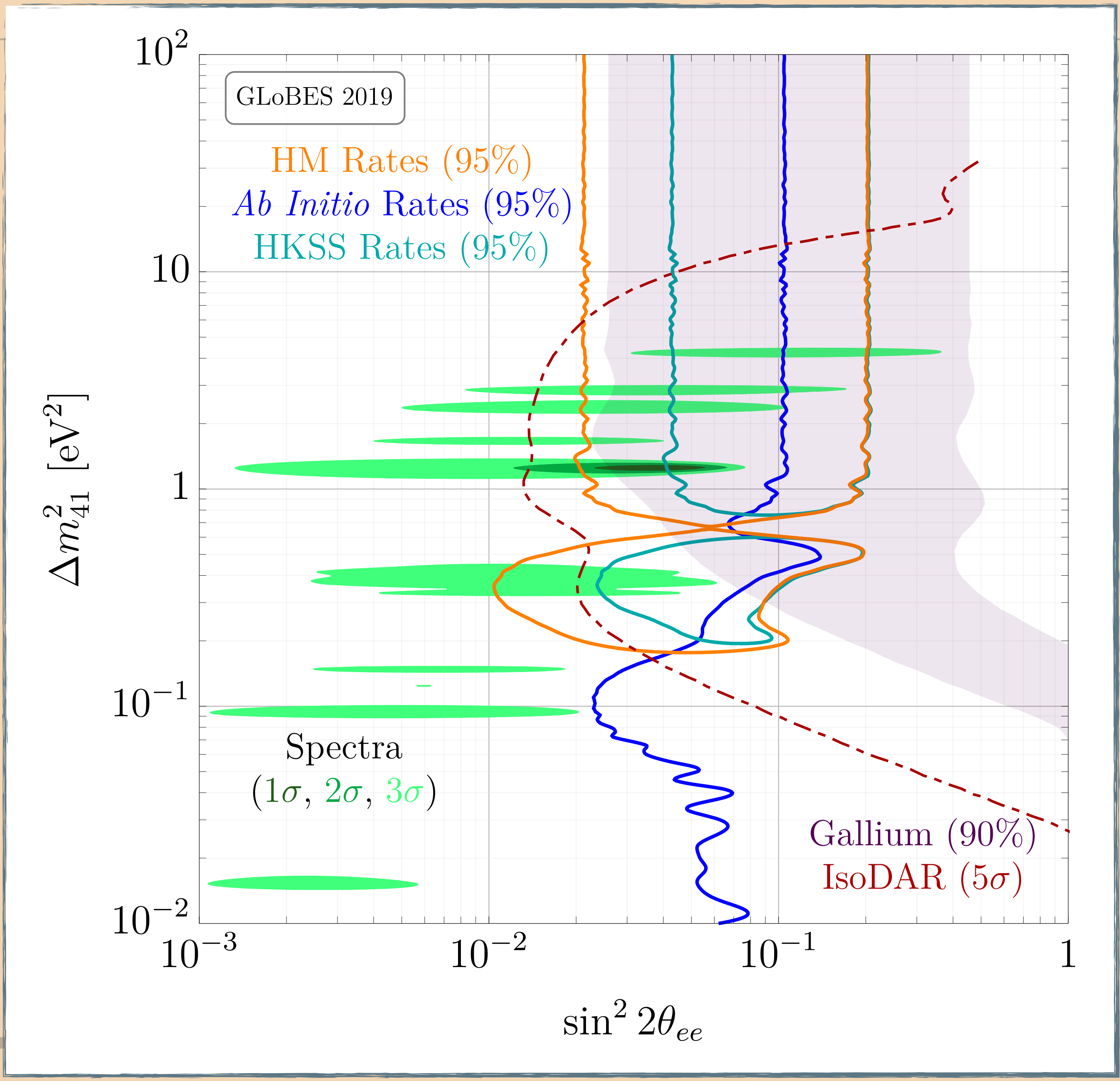
- The evidence for a sterile neutrino is *super ambiguous!*
- We're going to build more experiments, *but we need to be smart about which ones we build!*
- The ramifications of getting this right/ wrong – for physics and for the scientific enterprise – *could be long-reaching!*

Let’s see what happens over the next decade!

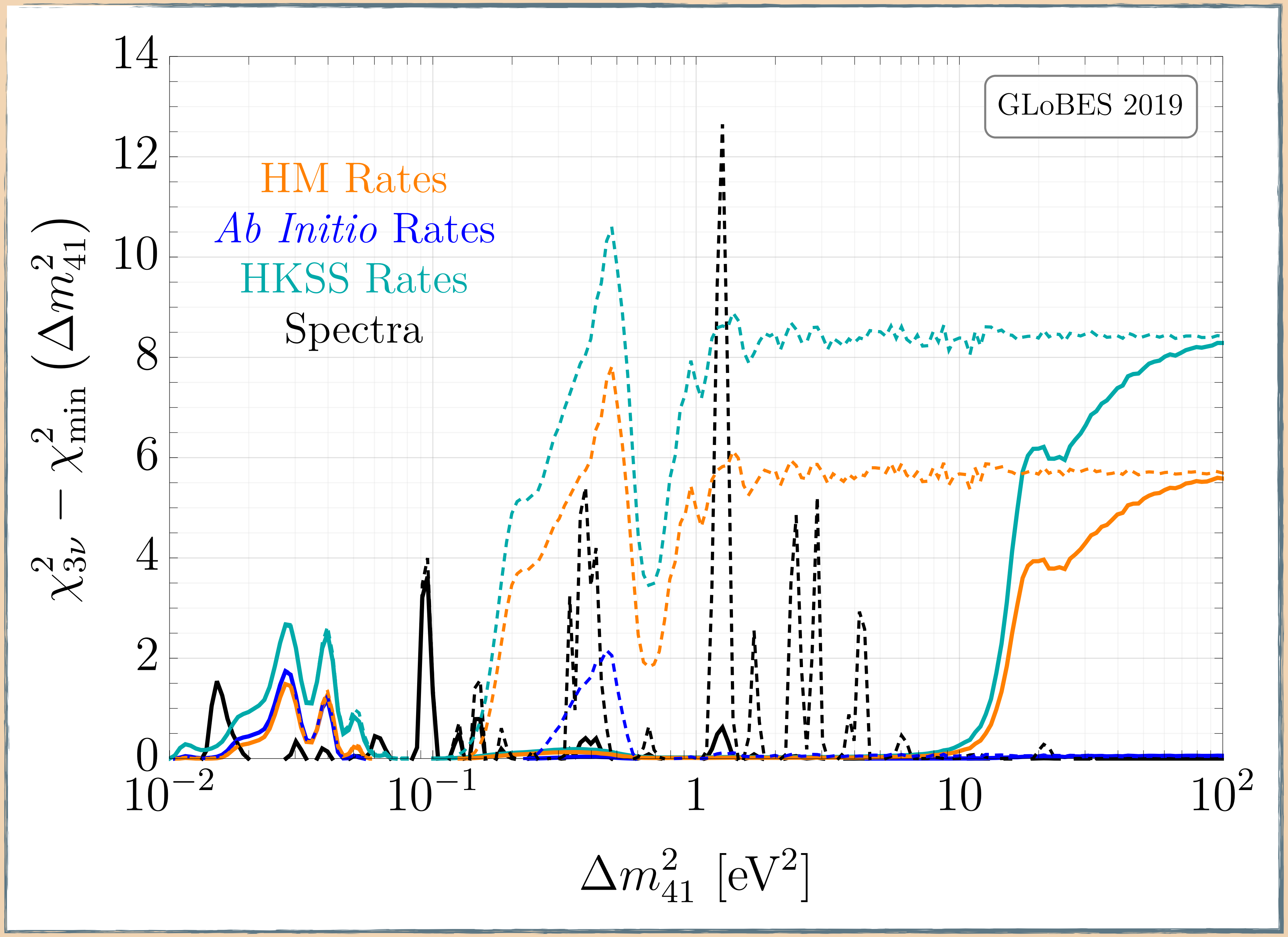
Thank you for your attention!

Back-Up

The Future: IsoDAR



The Future: IsoDAR



More Details on Evolution of Neutrino Fluid

$$i\frac{d\rho_{\vec{p}}}{dt} = \left[\Omega^0_{\vec{p}}, \rho_{\vec{p}}\right] + \left[\Omega^{\rm int}_{\vec{p}}, \rho_{\vec{p}}\right] + \mathbf{C}\left[\rho_{\vec{p}}, \overline{\rho_{\vec{p}}}\right]$$

$$\frac{dP_0}{dt} = R^{(a)}$$

$$\frac{d\vec{P}}{dt} = \left(\vec{B} + \vec{V}^{(a)}\right) \times \vec{P} - D^{(a)}\left(P_x\,\hat{x} + P_y\,\hat{y}\right) + R^{(a)}\,\hat{z}$$

$$\vec{B} = \left(\frac{\Delta m^2}{2p}\right)(\sin 2\theta,\ 0,\ -\cos 2\theta)$$

$$\vec{V}^{(a)} = \left(V_1^{(a)} + V_L^{(a)}\right)\hat{z}$$

$$V_1^{(a)} = -\frac{7\pi^2 G_F}{45\sqrt{2}M_Z^2}\,p\,T^4\left(n_{\nu_a} + n_{\overline{\nu}_a}\right)g_a$$

$$V_L^{(a)} = \frac{2\sqrt{2}\zeta(3)}{\pi^2}G_F T^3 L^{(a)}$$

$$g_{\mu,\tau} = 1 \qquad g_e = 1 + 4\sec^2\theta_W/\left(n_{\nu_e} + n_{\overline{\nu}_e}\right)$$

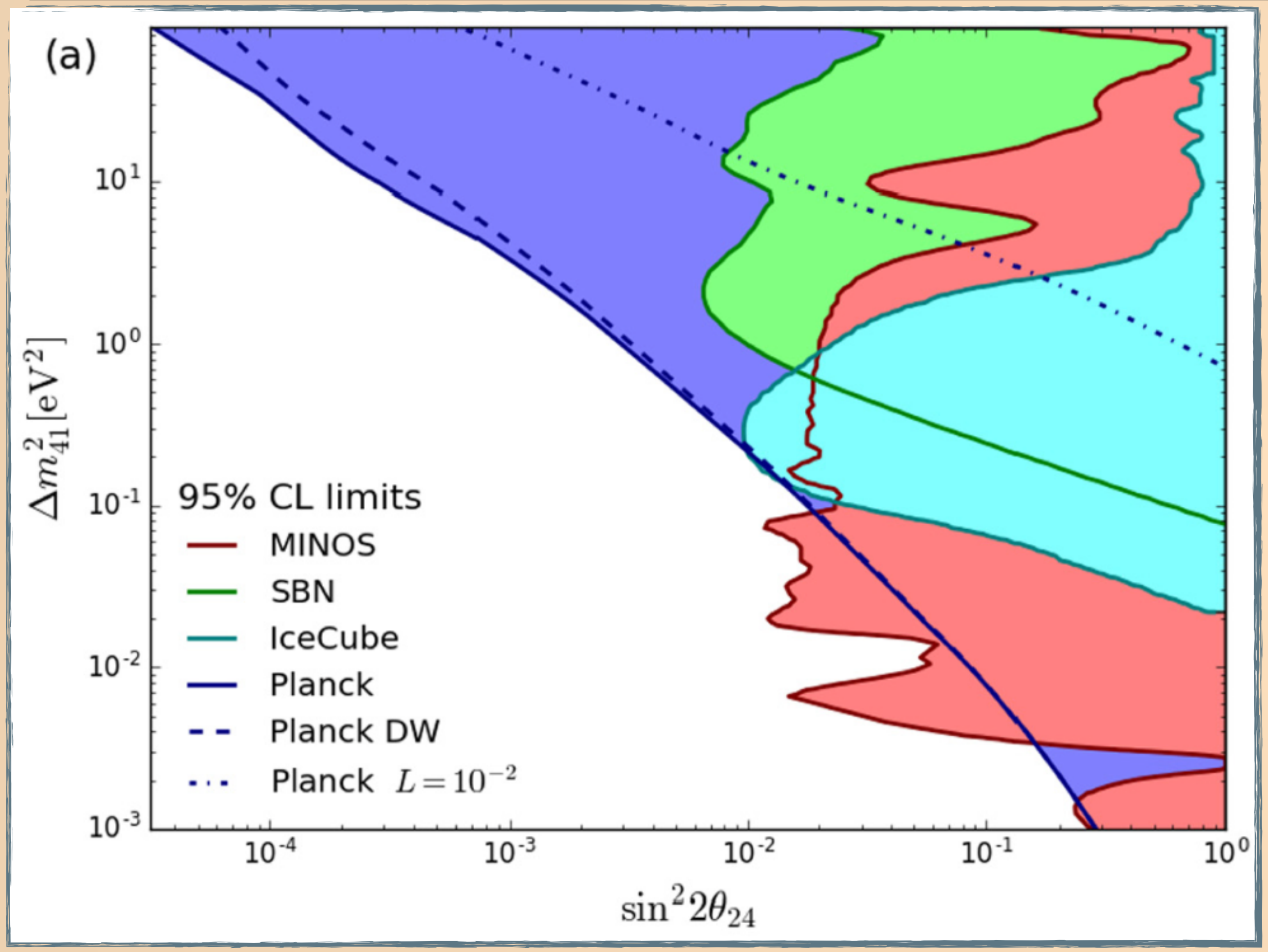
$$\begin{aligned} L^{(e)} &= \left(\frac{1}{2} + 2\sin^2\theta_W\right)L_e \\ &\quad + \left(\frac{1}{2} - 2\sin^2\theta_W\right)L_p - \frac{1}{2}L_n \\ &\quad + 2L_{\nu_e} + L_{\nu_\mu} + L_{\nu_\tau} \\ L^{(\mu,\tau)} &= L^{(e)} - L_e - L_{\nu_e} + L_{\nu_\mu,\nu_\tau} \end{aligned}$$

$$D^{(a)} \approx \tfrac{1}{2}\Gamma^{(a)} \qquad \Gamma^{(a)} = C^{(a)}G_F^2 p T^4$$

$$C^{(e)} \approx 1.27 \qquad C^{(\mu,\tau)} \approx 0.92$$

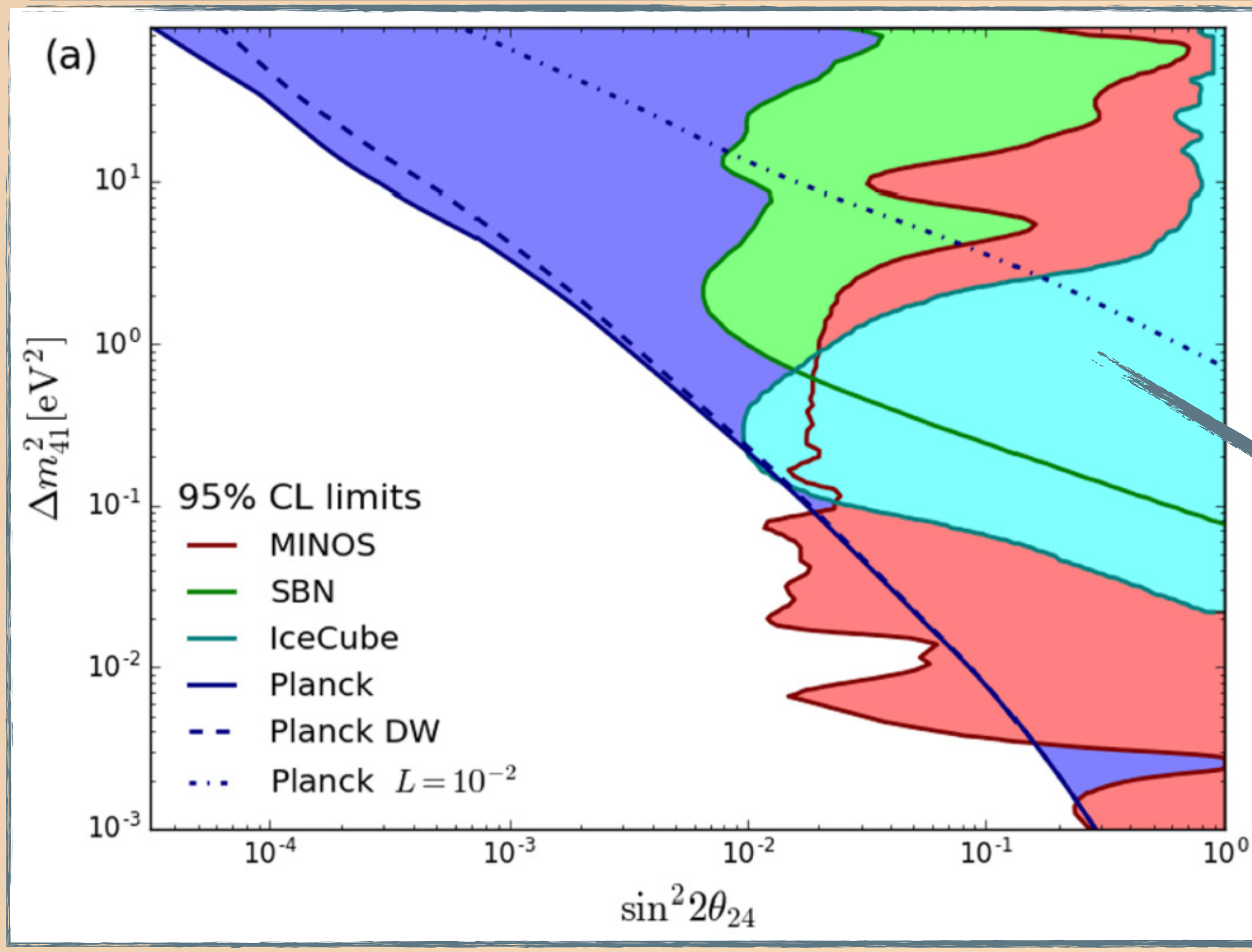
$$R^{(a)} \approx \Gamma^{(a)}\left[\frac{f_{\rm eq}(p,\mu_{\nu_a})}{f_0} - \frac{1}{2}\left(P_0 + P_z\right)\right]$$

Previous Work

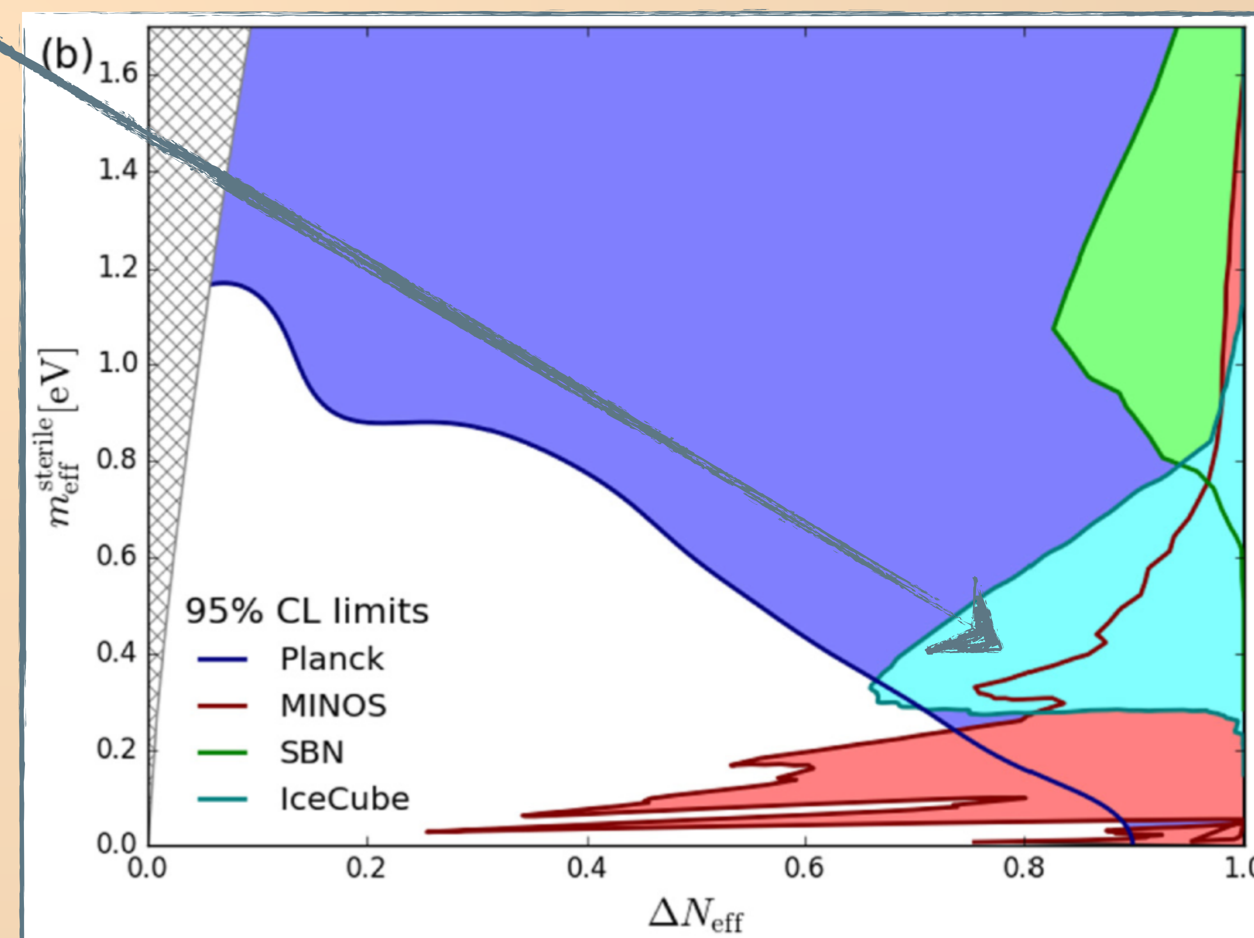


S. Bridle, et al., Phys. Lett. B764, 322 (2017);
S. Hannestad, et al., JCAP 1304, 032 (2013)

Previous Work



Use LASAGNA module to translate points in *oscillation* parameter space into *cosmology* parameter space



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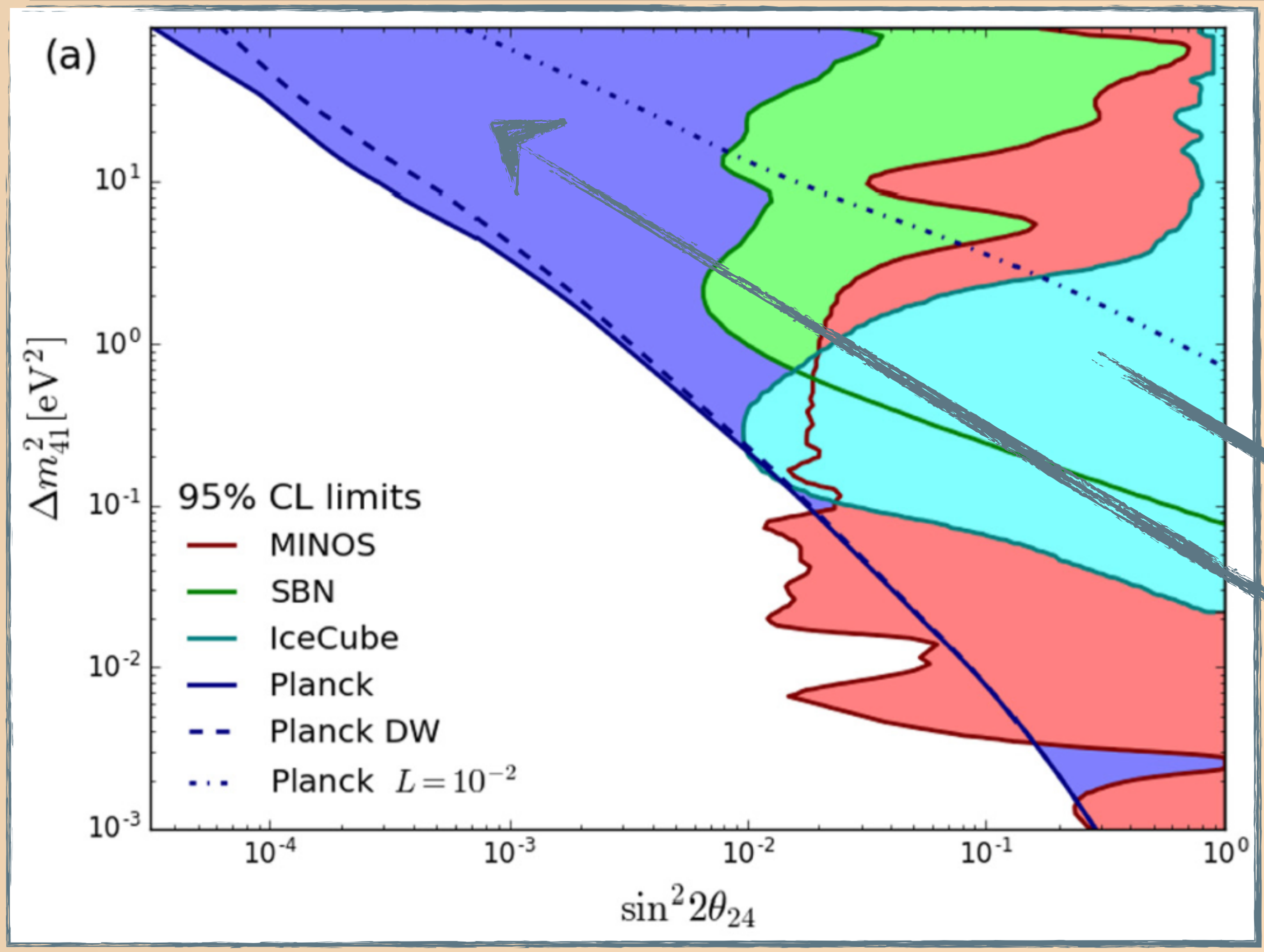
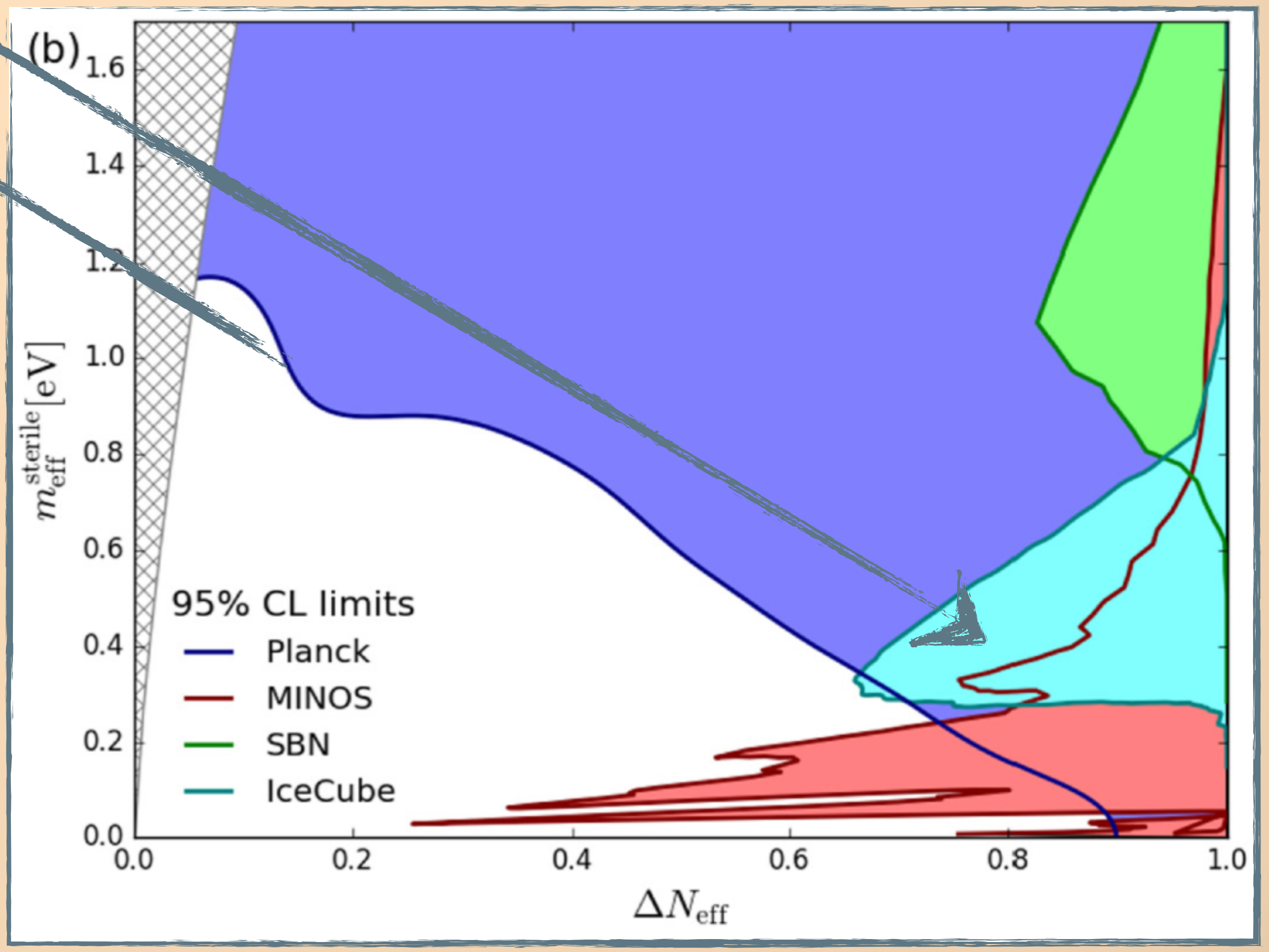
S. Hannestad, et al., JCAP 1304, 032 (2013)

Previous Work



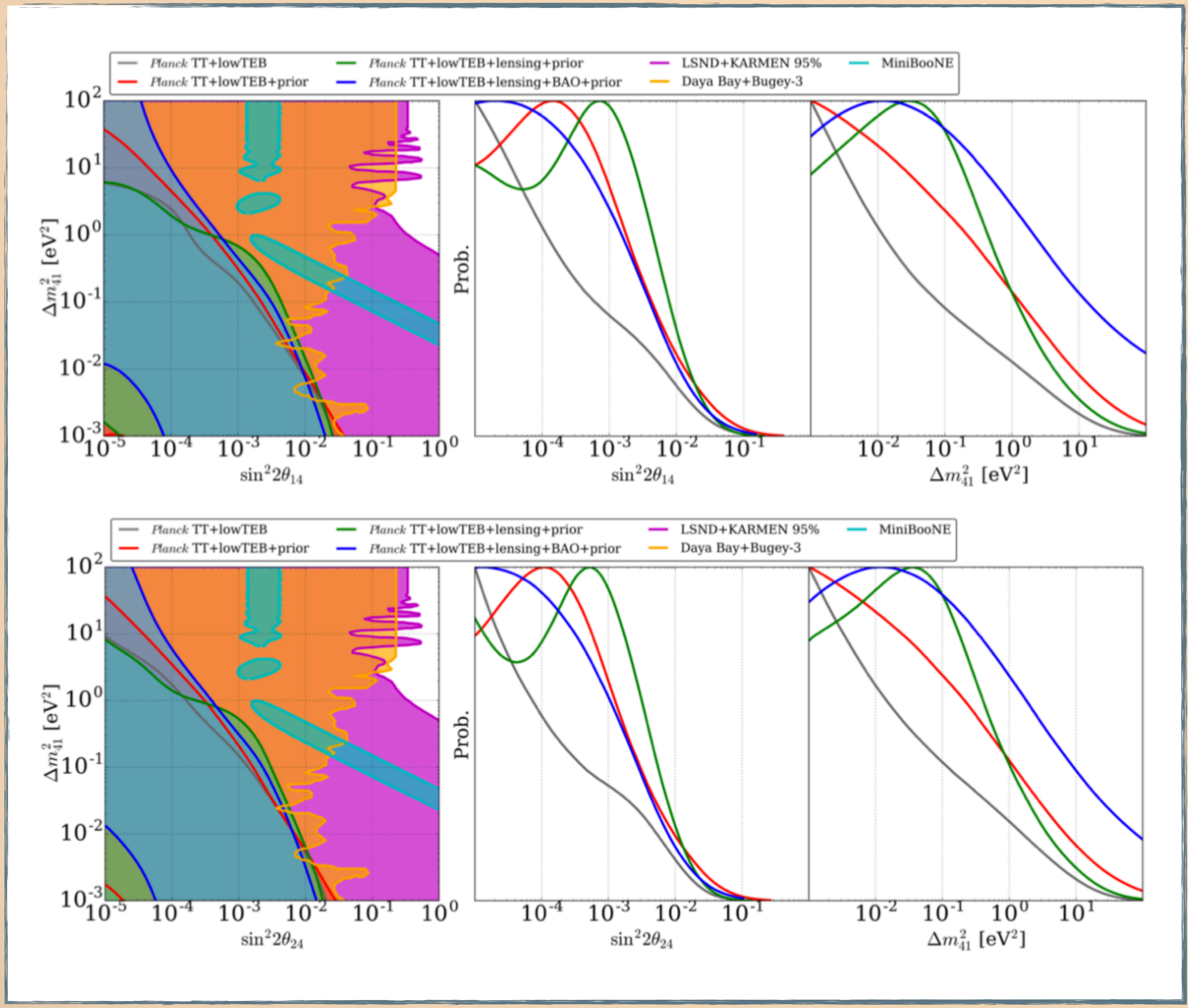
Use LASAGNA module to translate points in *oscillation* parameter space into *cosmology* parameter space



This relation depends on the *initial lepton number asymmetry!*

S. Bridle, et al., Phys. Lett. B764, 322 (2017);
S. Hannestad, et al., JCAP 1304, 032 (2013)

Previous Work



Essentially what we want to do, but in reverse!

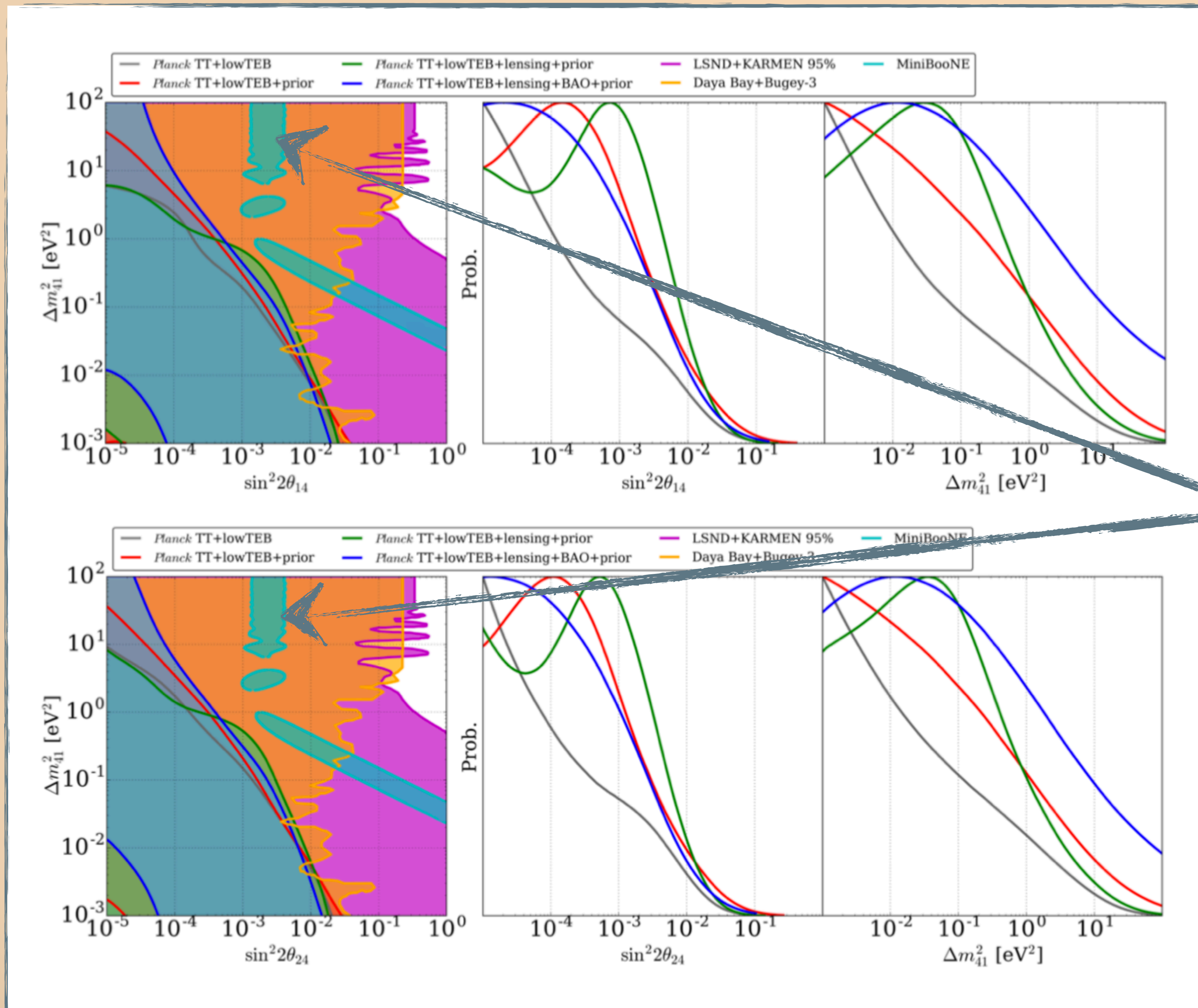
<u>Two critiques:</u>

1. MiniBooNE probes neither of these spaces

2. These bounds only constrain θ_{14}

A. Knee, et al., 1812.02102

Previous Work



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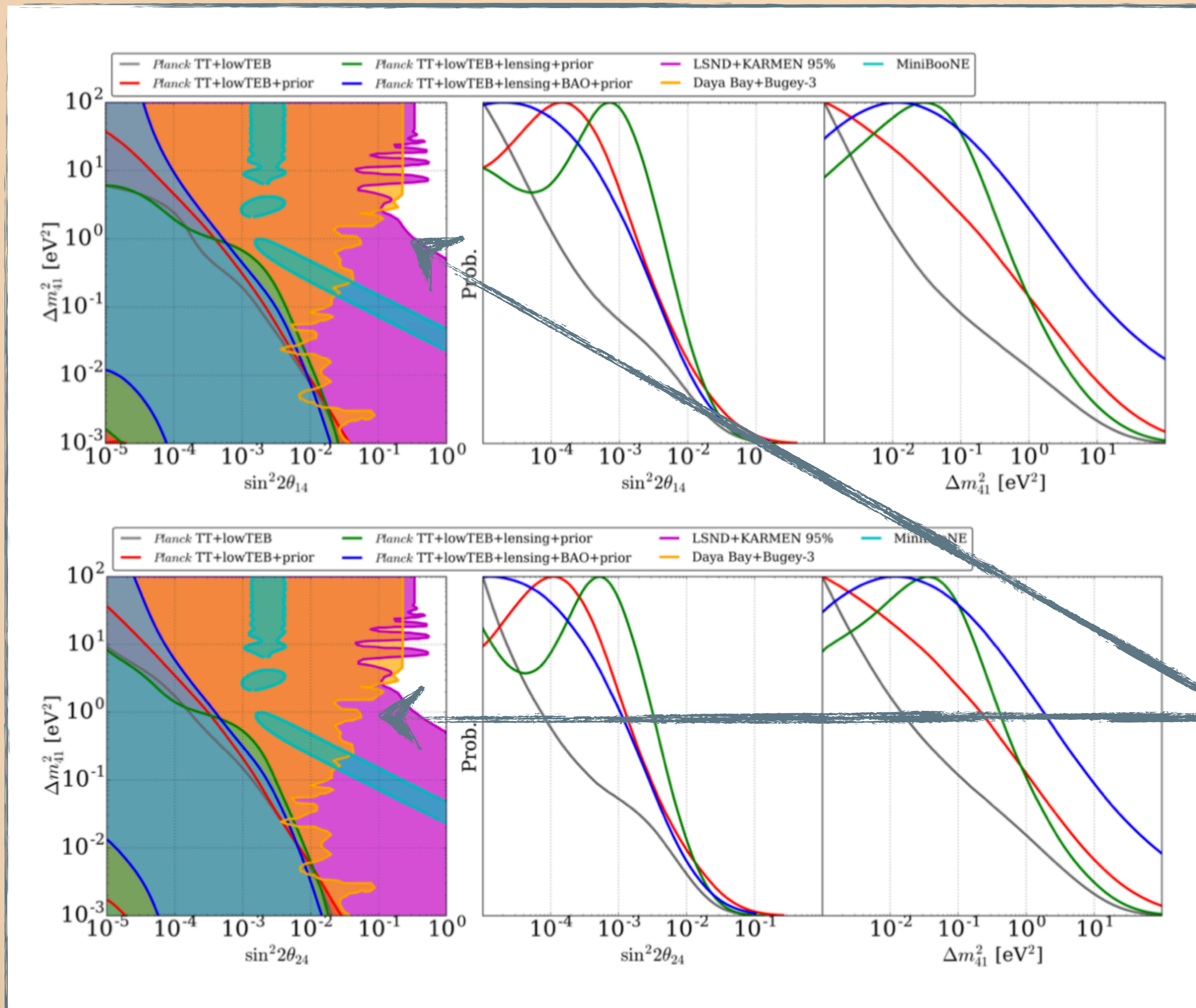

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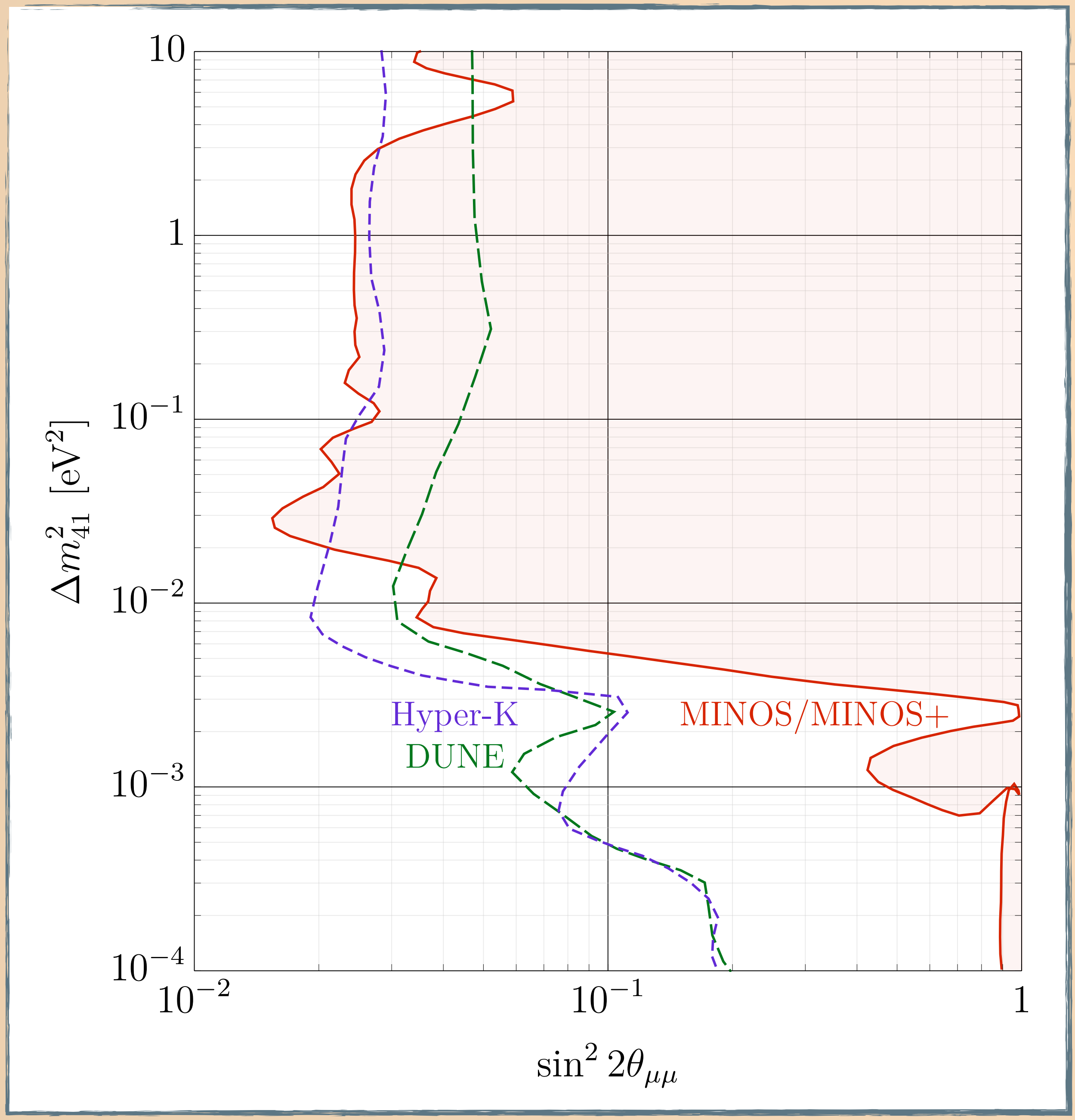
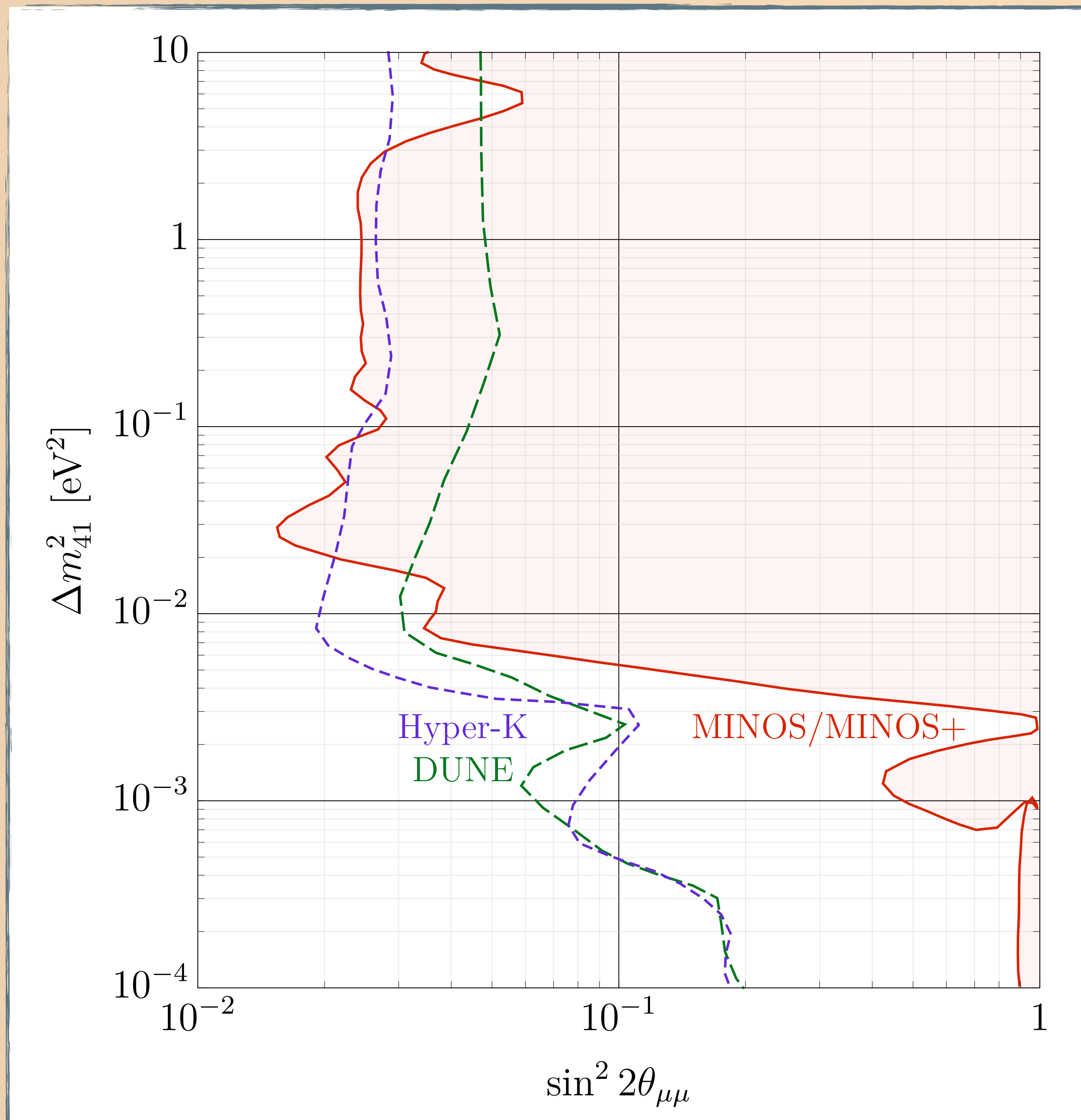
A. Knee, et al., 1812.02102

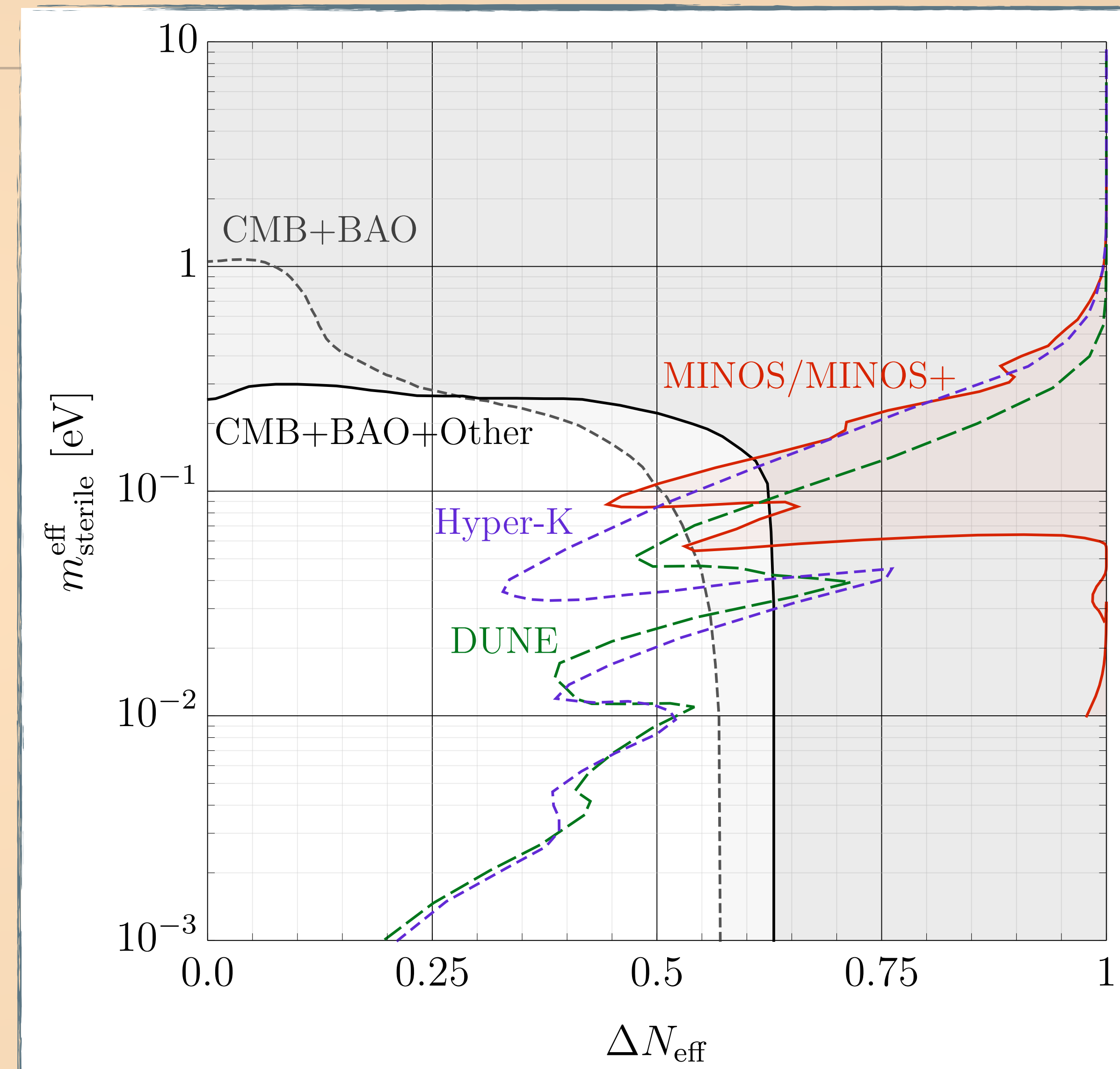
Accelerator Experiments



JMB, et al., Phys. Rev. D92, 073012 (2015)
K. J. Kelly, Phys. Rev. D95, 115009 (2017)

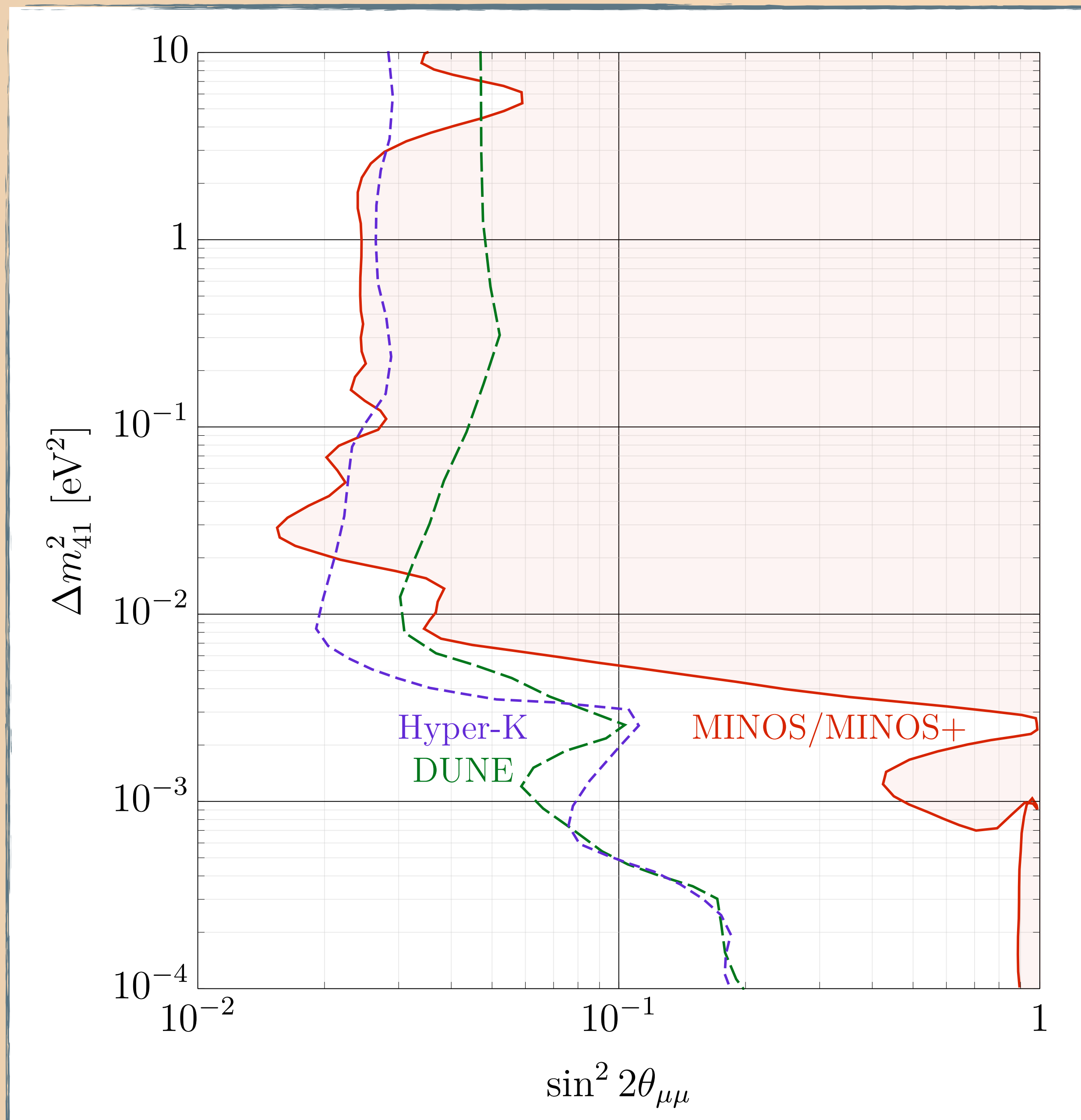
Accelerator Experiments

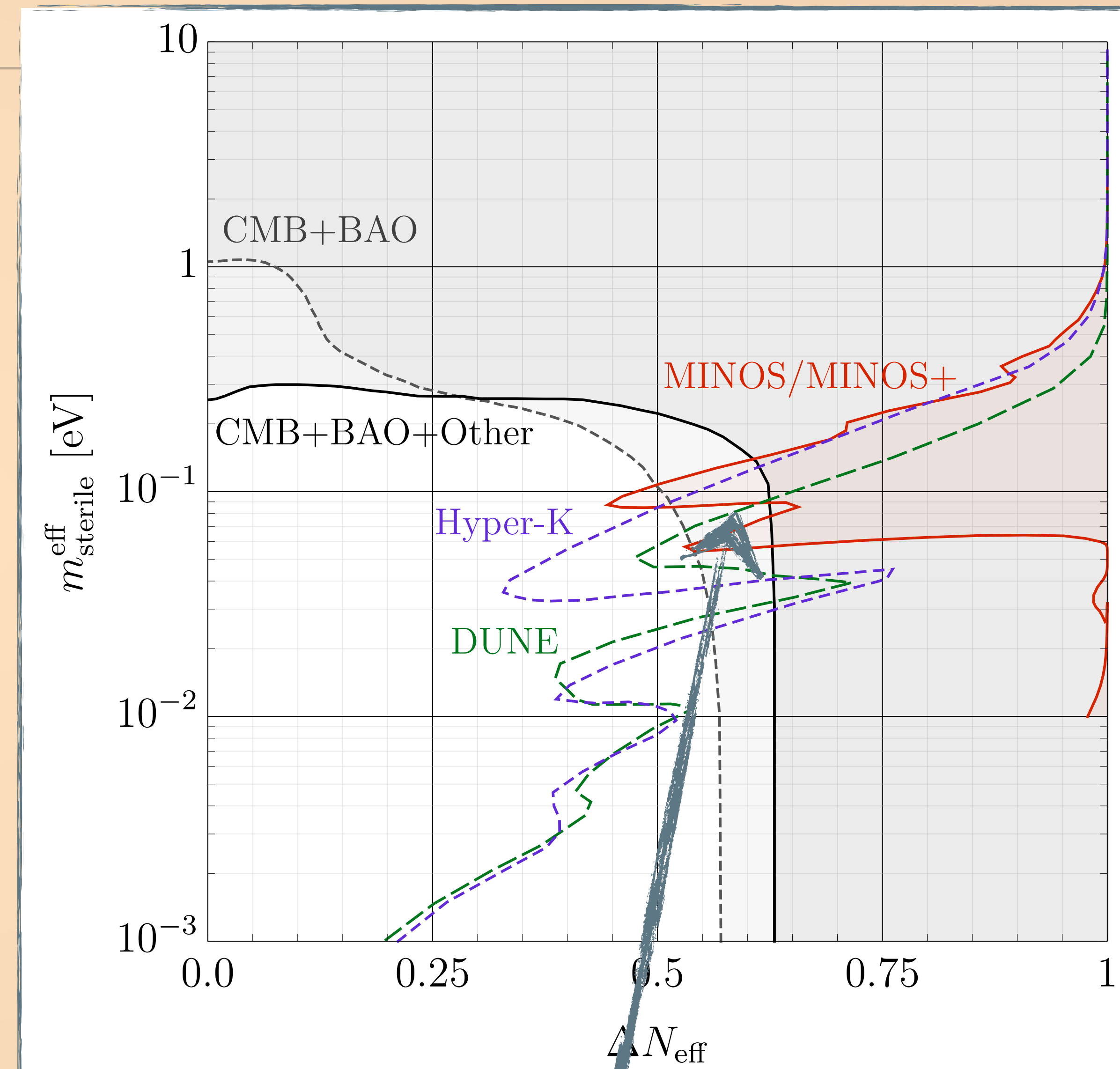




JMB, et al., Phys. Rev. D92, 073012 (2015)
K. J. Kelly, Phys. Rev. D95, 115009 (2017)

Accelerator Experiments





MINOS/MINOS+ doesn't make as sizable an impact as previously claimed

JMB, et al., Phys. Rev. D92, 073012 (2015)
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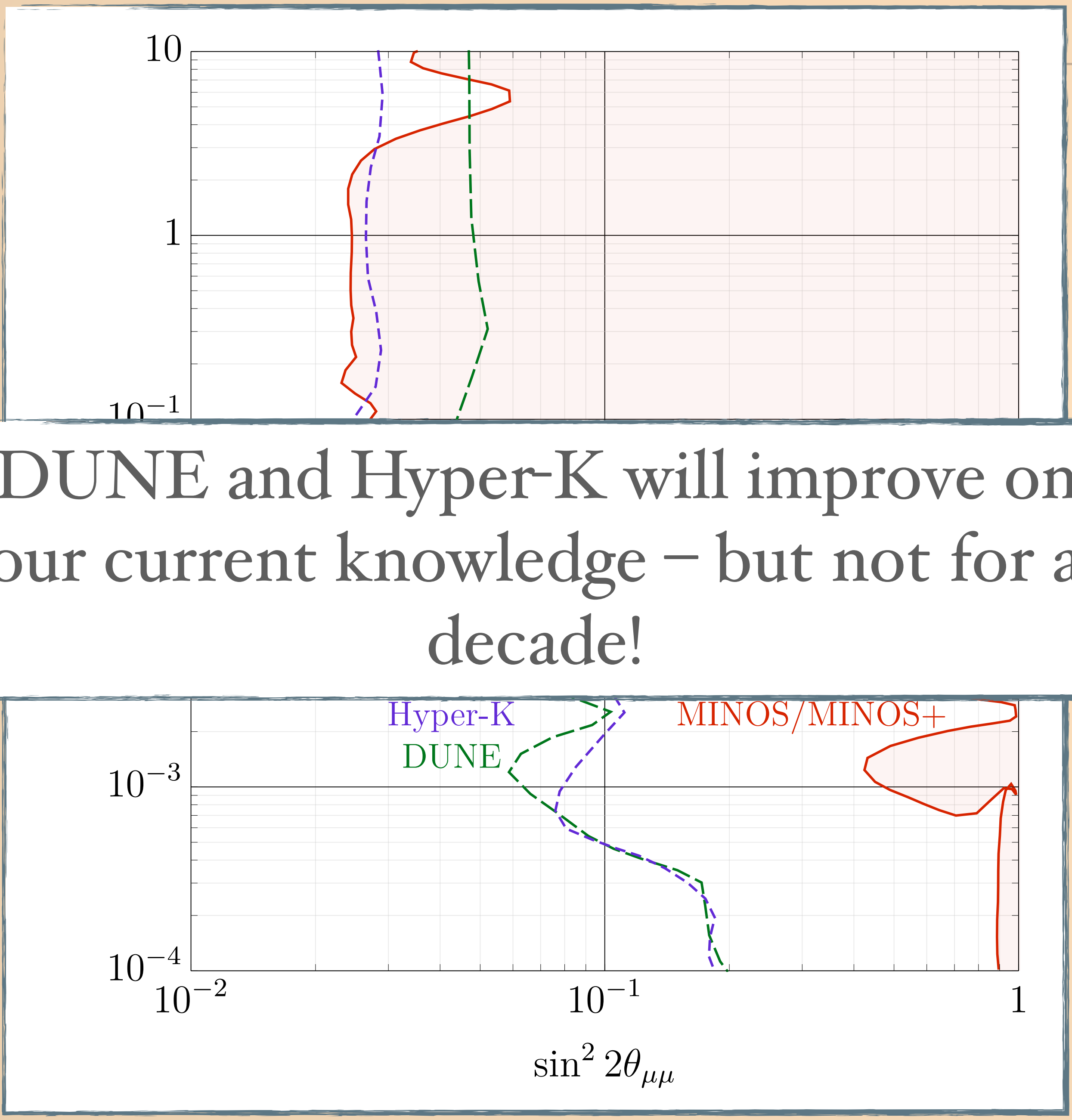
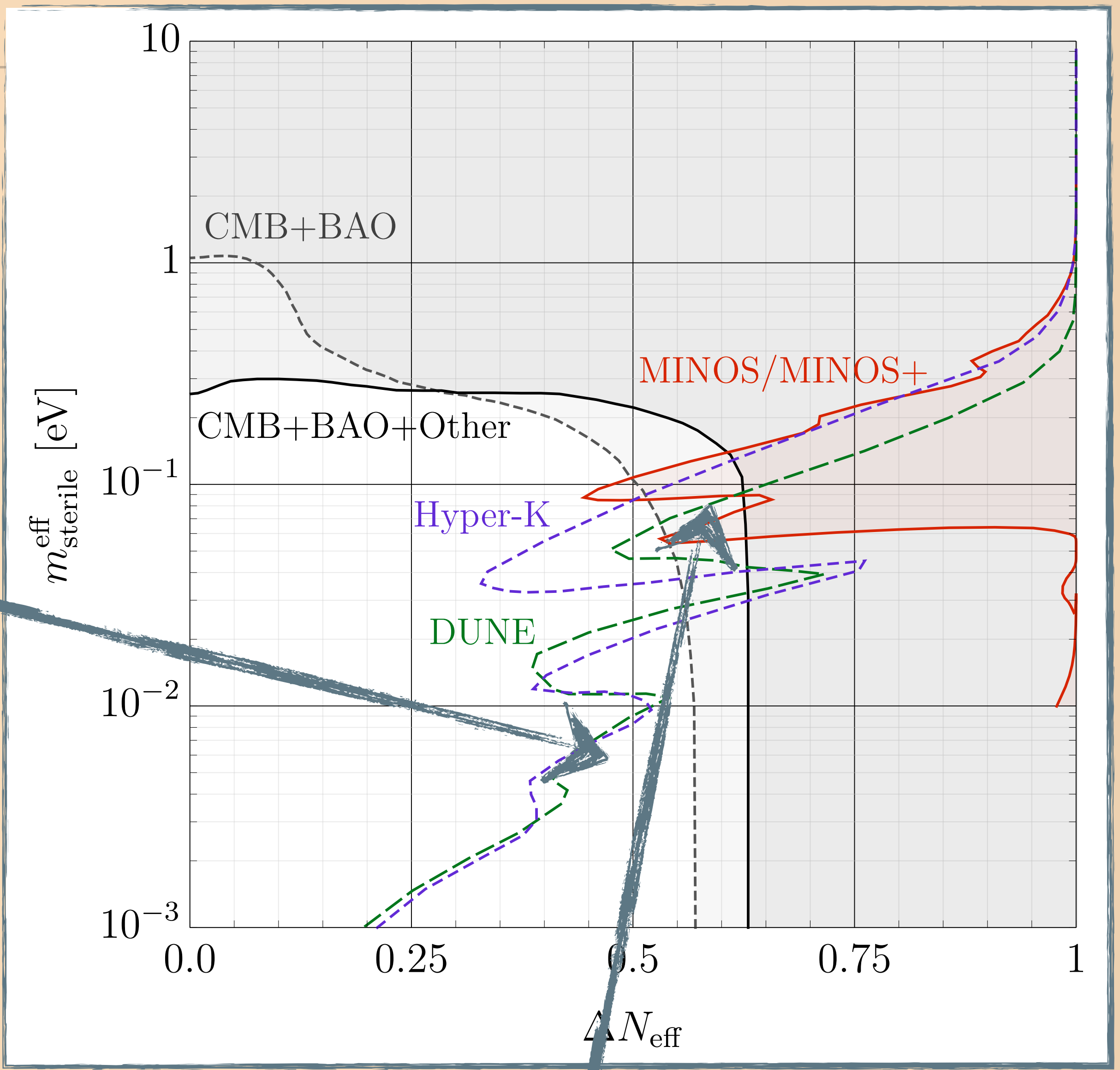


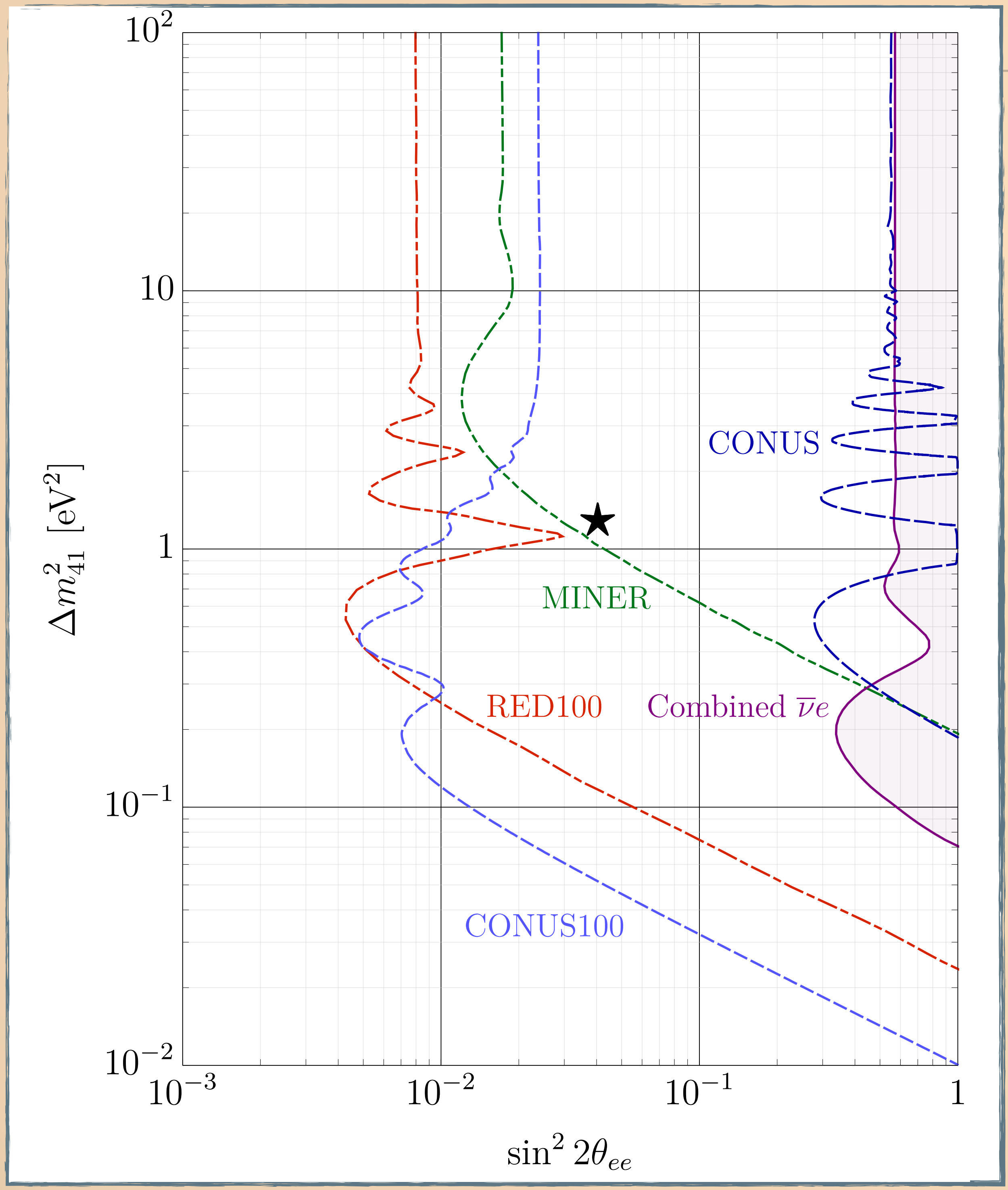


DUNE and Hyper-K will improve on our current knowledge – but not for a decade!

MINOS/MINOS+ doesn't make as sizable an impact as previously claimed

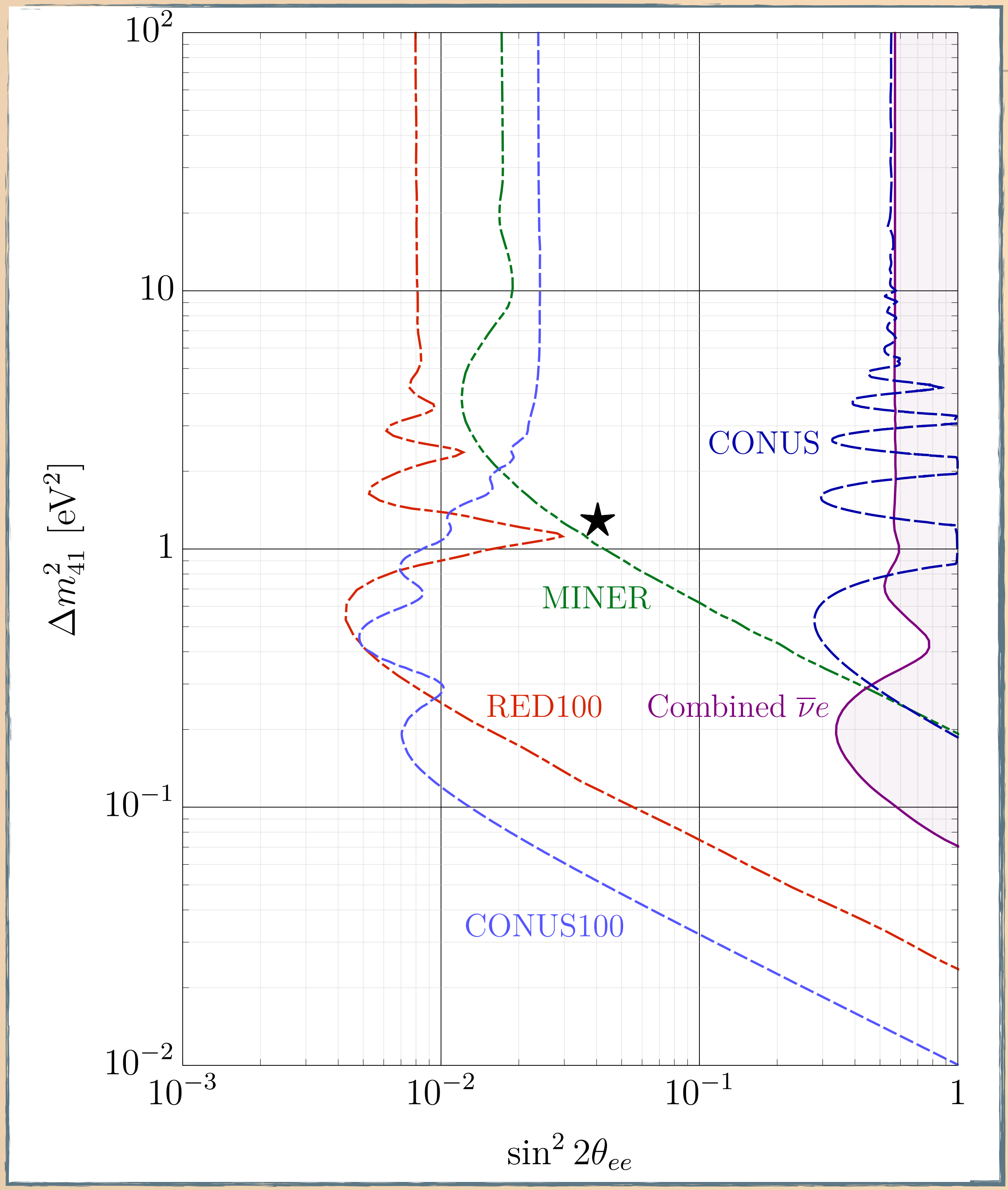
JMB, et al., Phys. Rev. D92, 073012 (2015)
K. J. Kelly, Phys. Rev. D95, 115009 (2017)

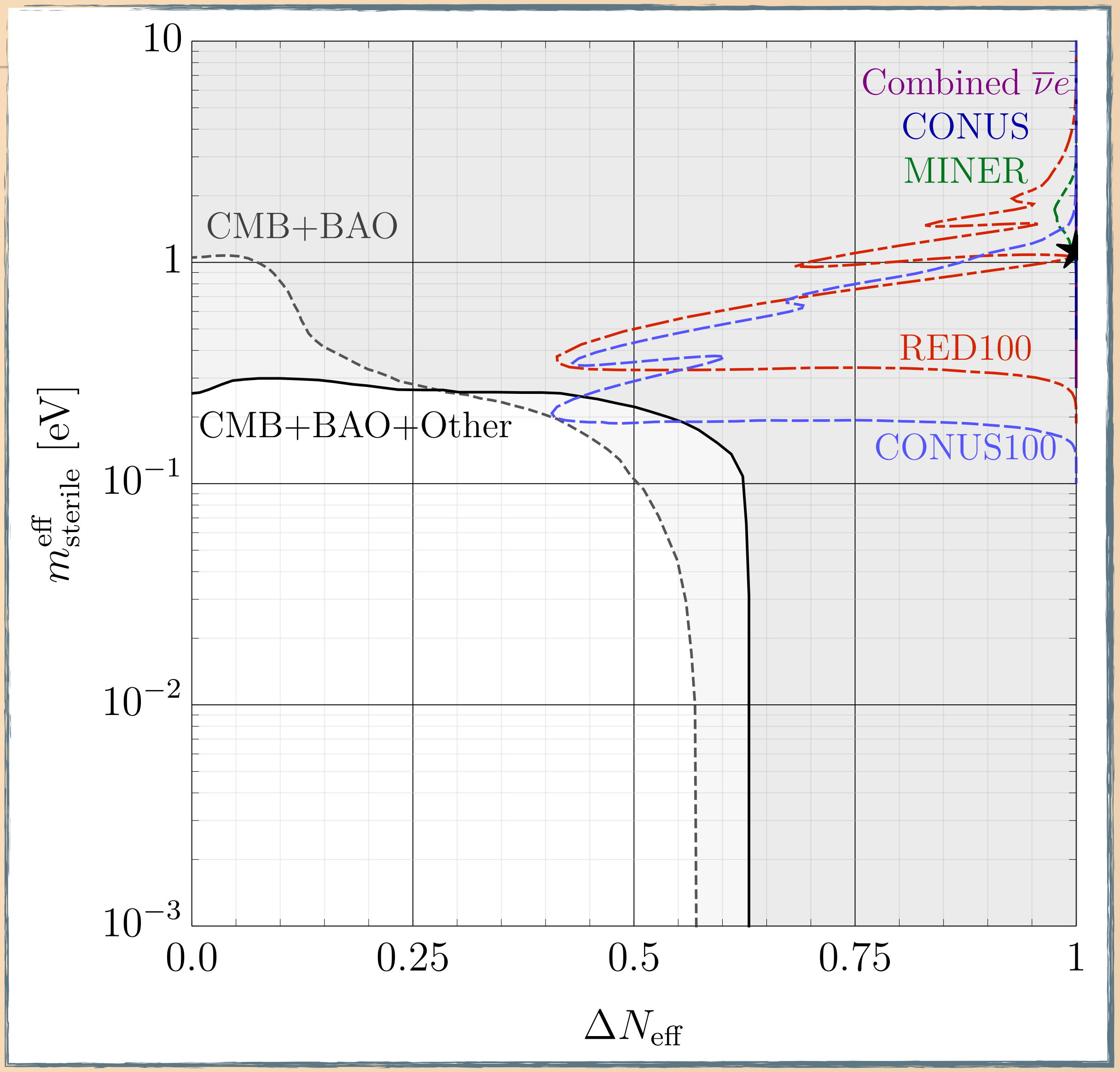
Low-Threshold Experiments



B.C. Cañas, et al., Phys. Lett. B776, 451 (2018)

Low-Threshold Experiments





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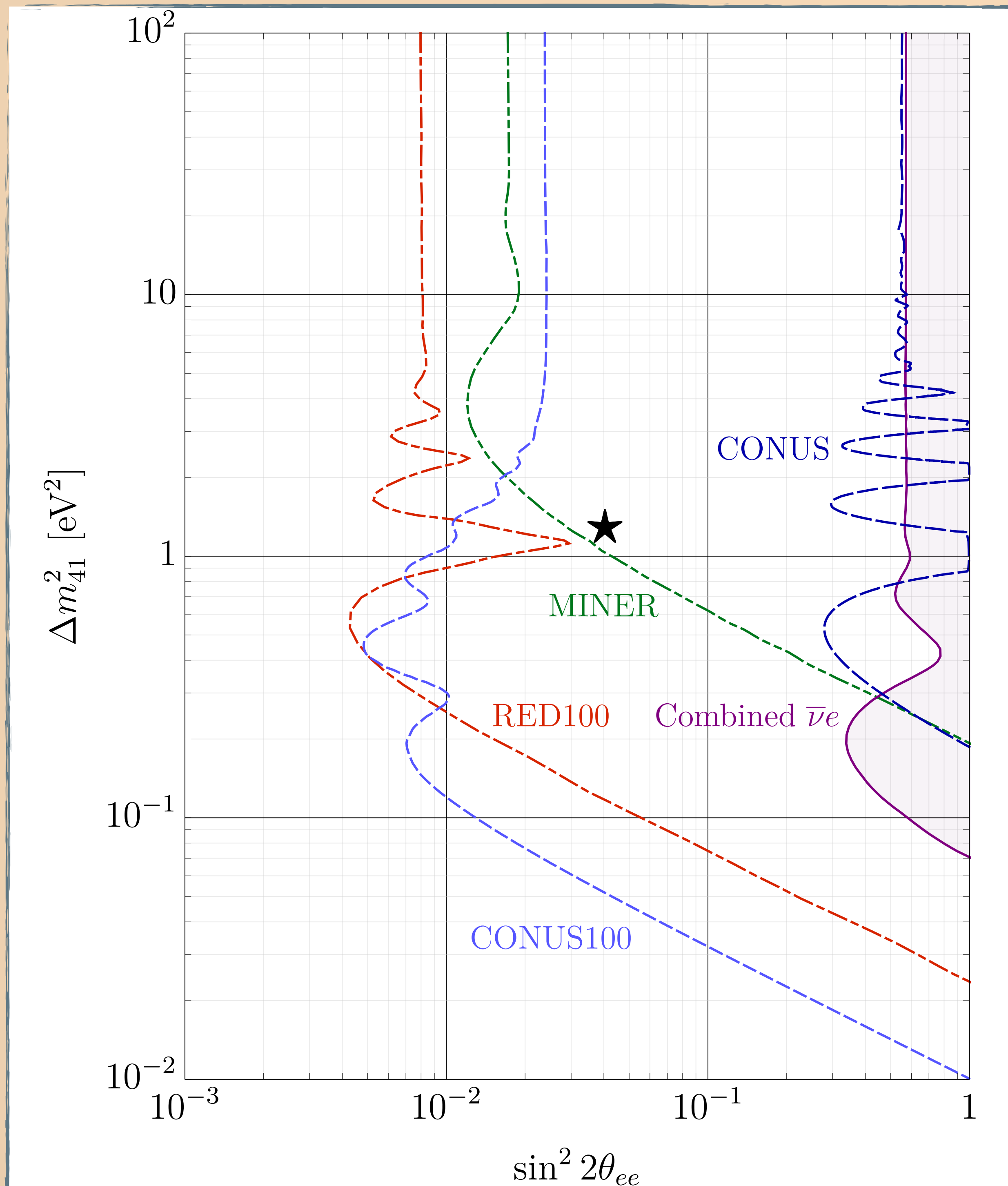
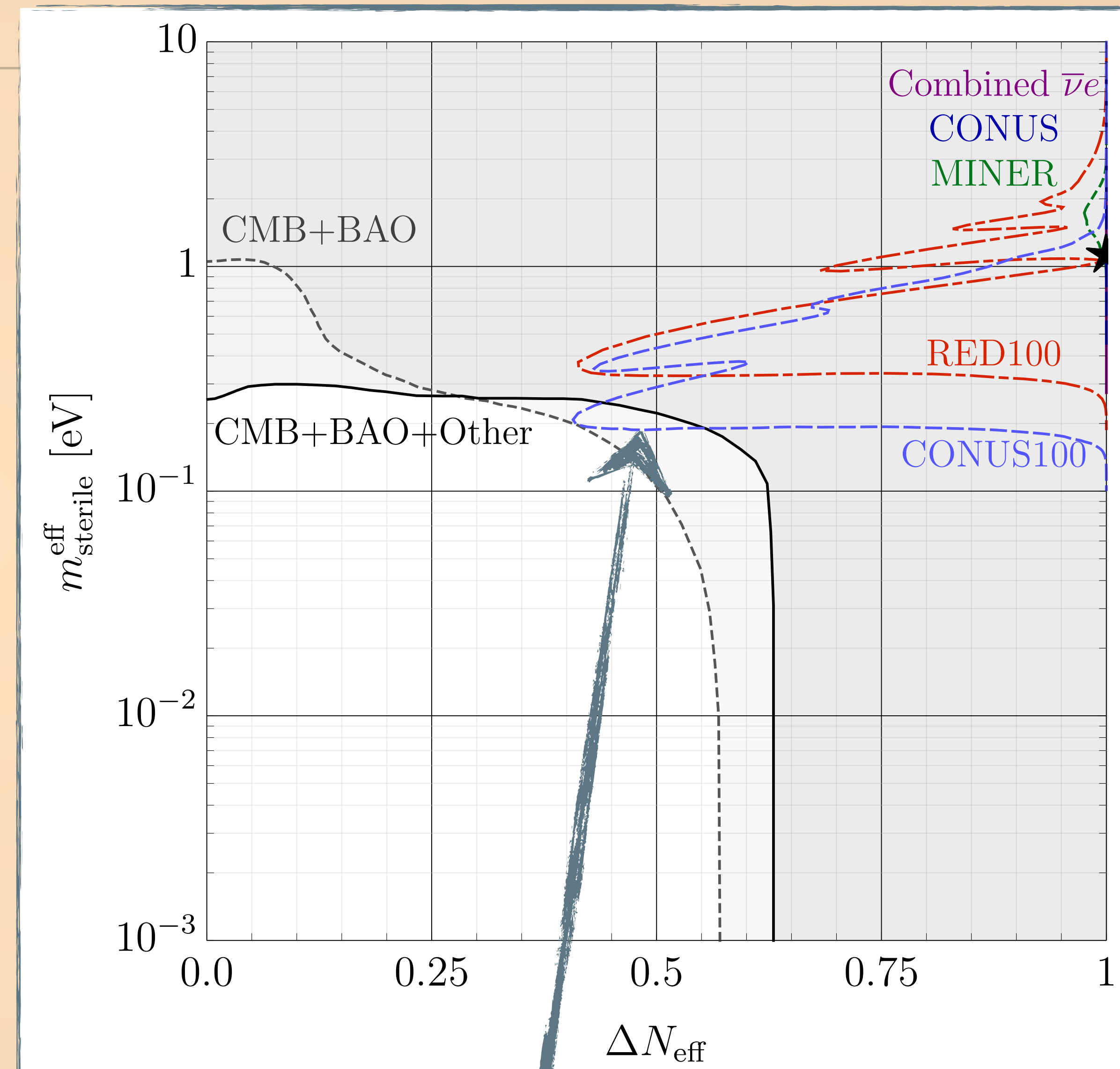
Low-Threshold Experiments

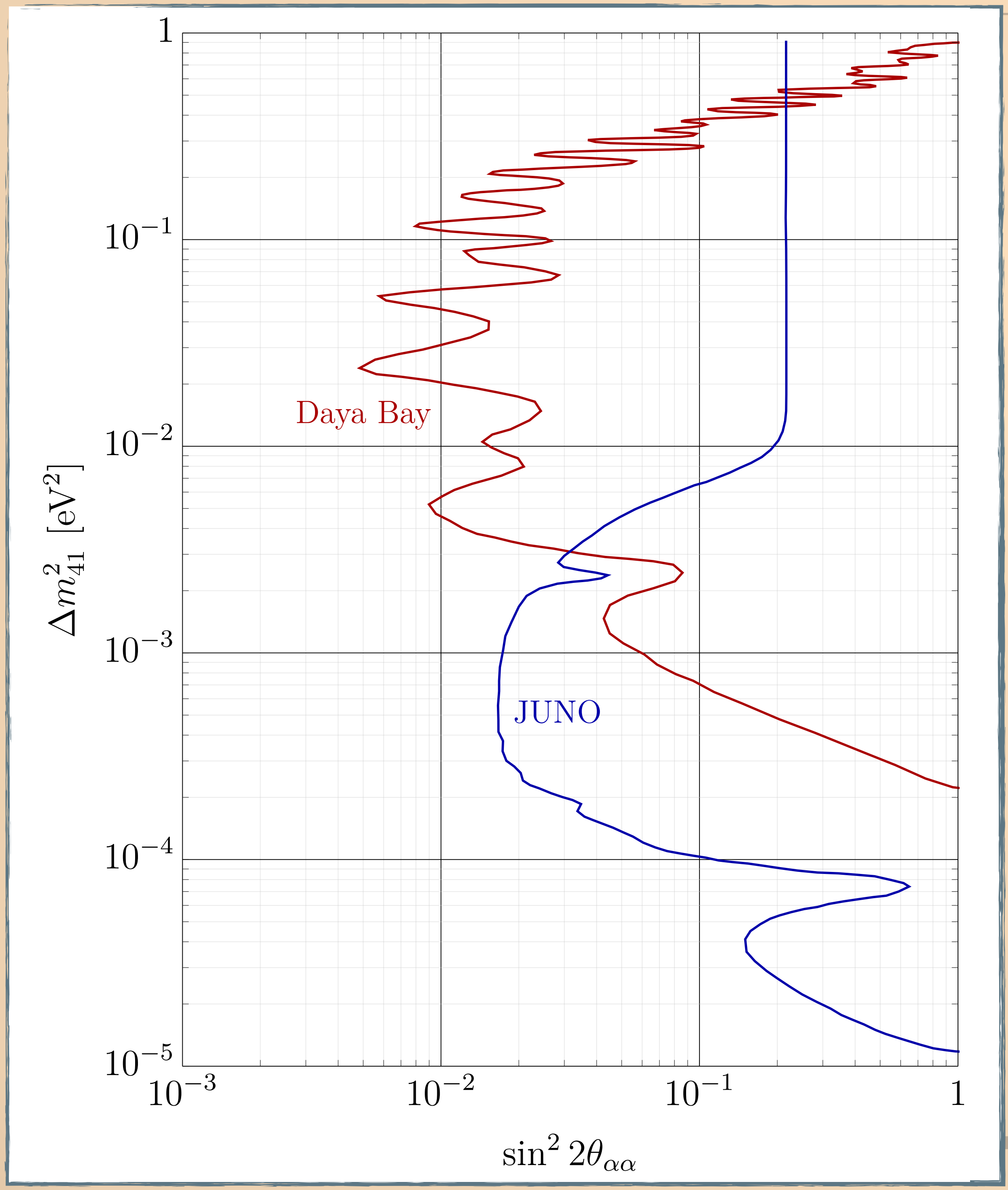


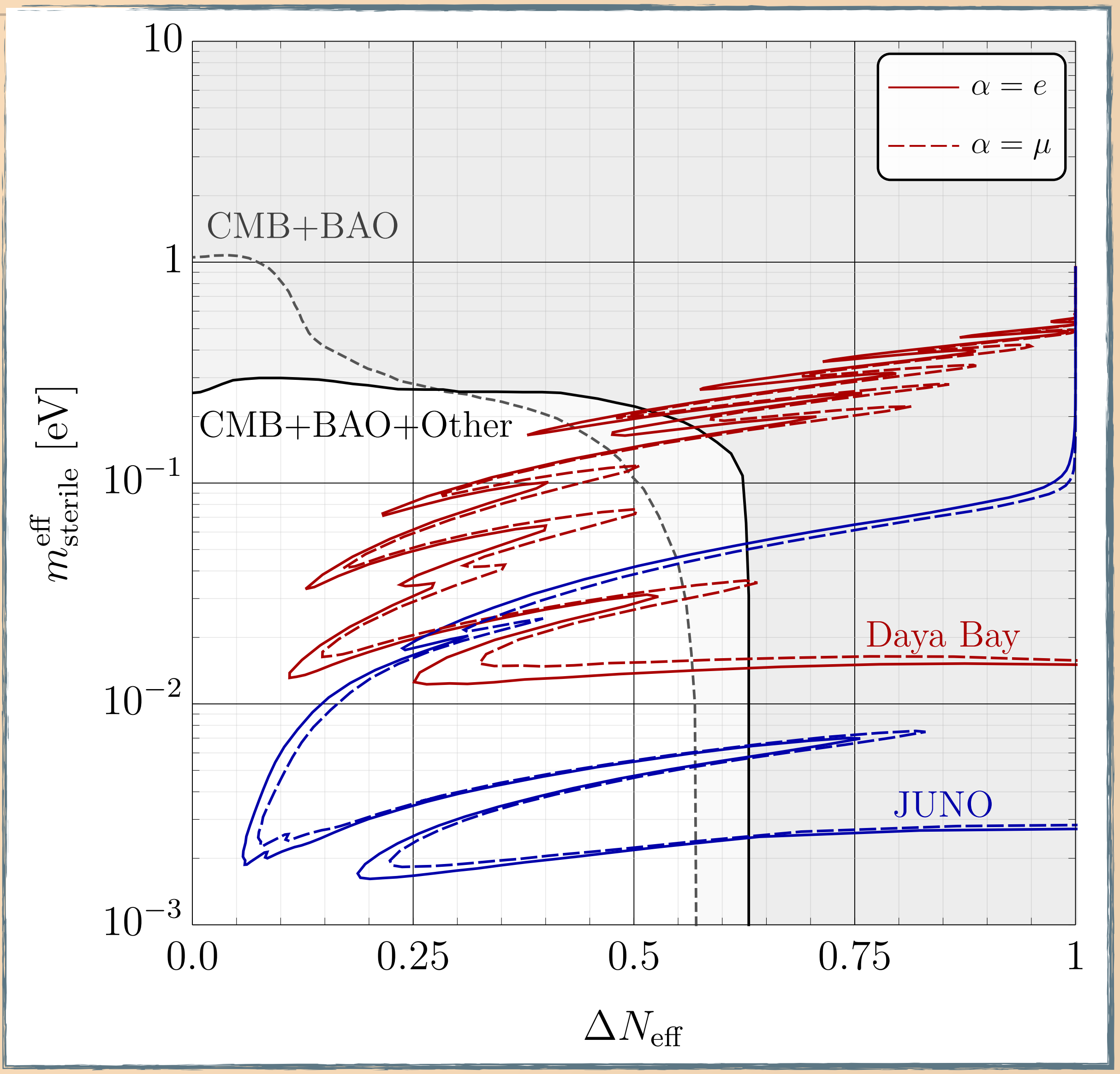


Even with aggressive assumptions, these experiments don't contribute to our knowledge of cosmology!

B.C. Cañas, et al., Phys. Lett. B776, 451 (2018)

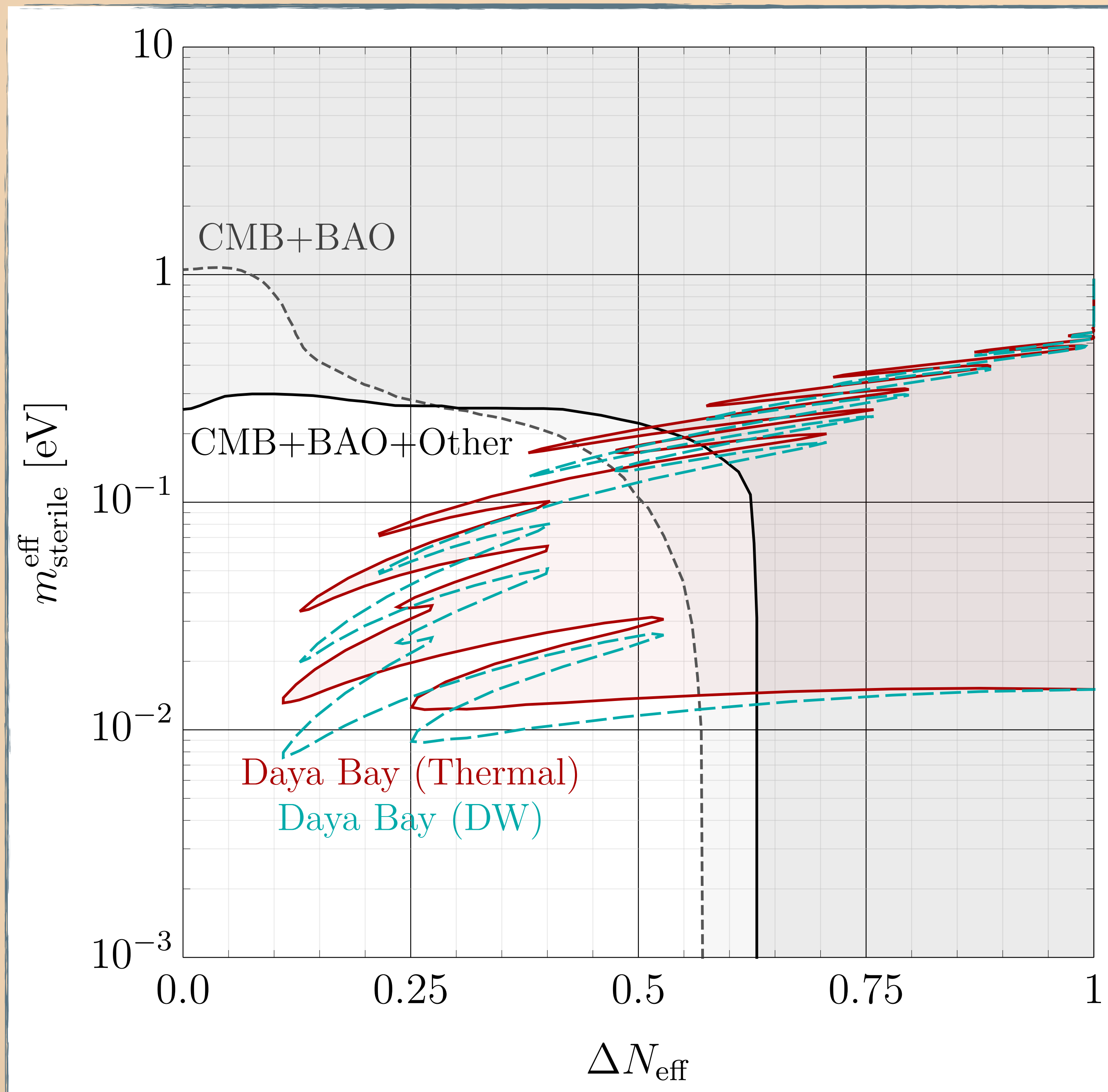
Electron- vs. Muon-Type Oscillations





The difference between electron- and muon-type oscillations is conceptually important – but numerically small

Thermal Distribution vs. Dodelson-Widrow



Thermally distributed sterile:

$$m^{\text{eff}}_{\text{sterile}} = (\Delta N_{\text{eff}})^{3/4} \sqrt{\Delta m^2_{41}}$$

Dodelson-Widrow (DW) sterile:

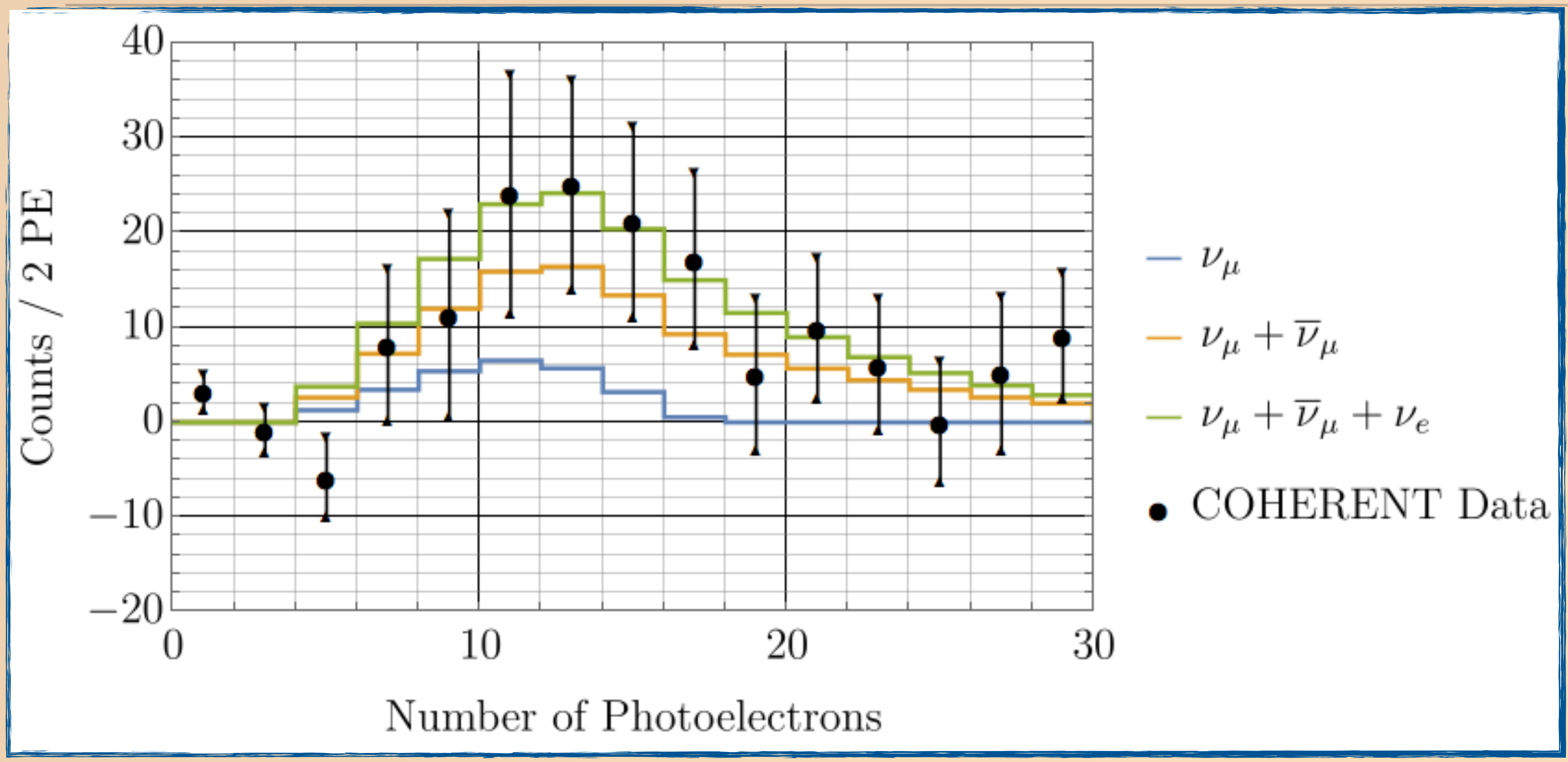
$$m^{\text{eff}}_{\text{sterile}} = \Delta N_{\text{eff}} \sqrt{\Delta m^2_{41}}$$

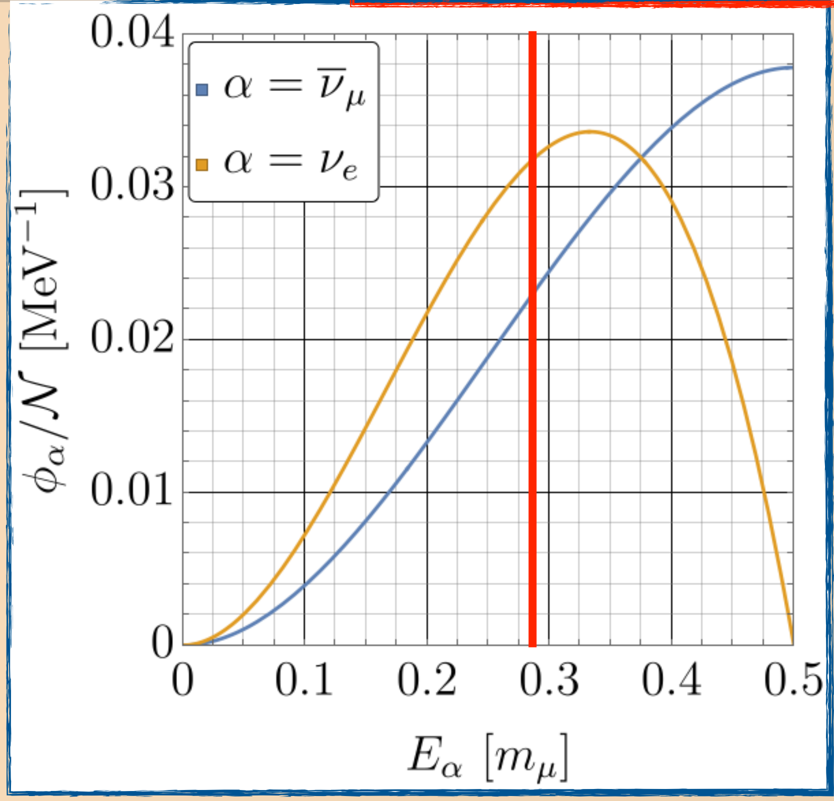
The difference between thermally-distributed and Dodelson-Widrow is not quantitatively important

S. Dodelson & L. M. Widrow, PRL 72, 17 (1994)

COHERENT Analysis: Details

Monochromatic ν_μ





$$n_{\rm PE} = 1.17 \left(\frac{E_r}{\rm keV}\right)$$

$$\frac{dN_\alpha}{dE_r} = n_{(N,Z)} \int dE_\nu \, \phi_\alpha(E_\nu) \times \frac{d\sigma_\alpha}{dE_\nu}$$

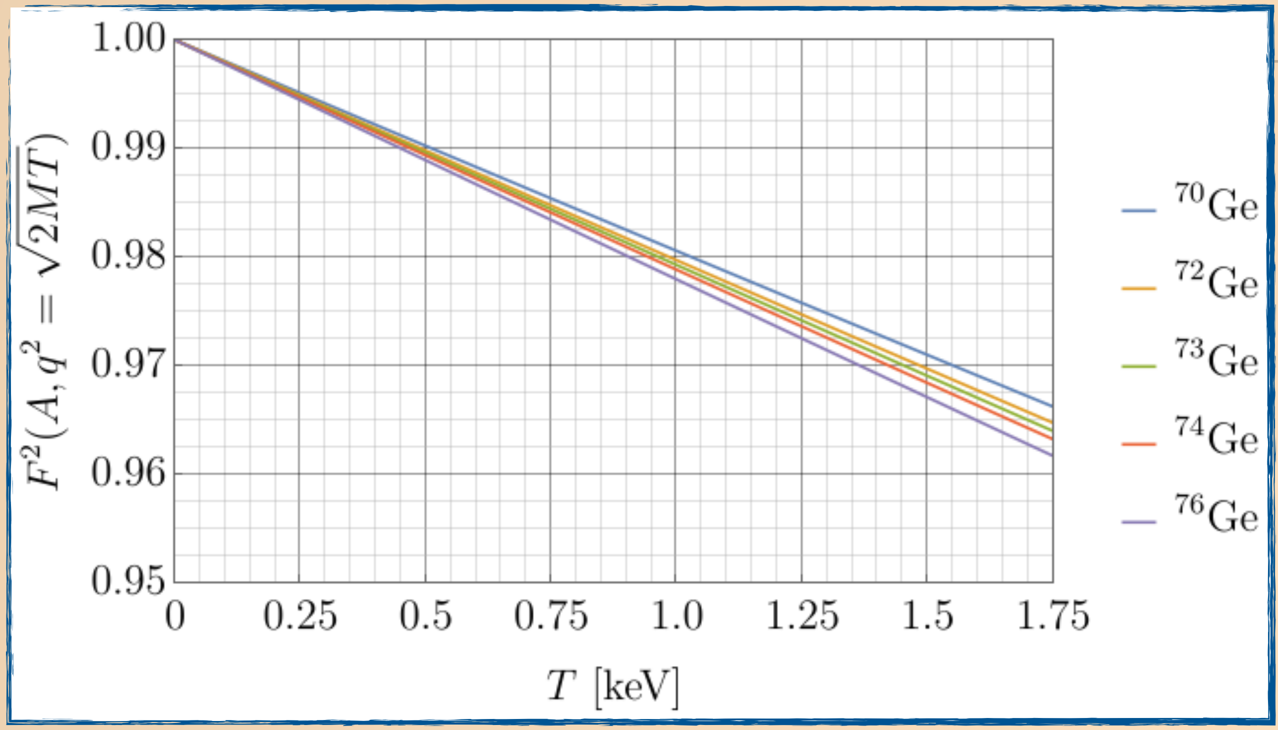
$$\mathcal{N} \equiv \frac{r N_{\rm POT}}{4\pi L^2}$$

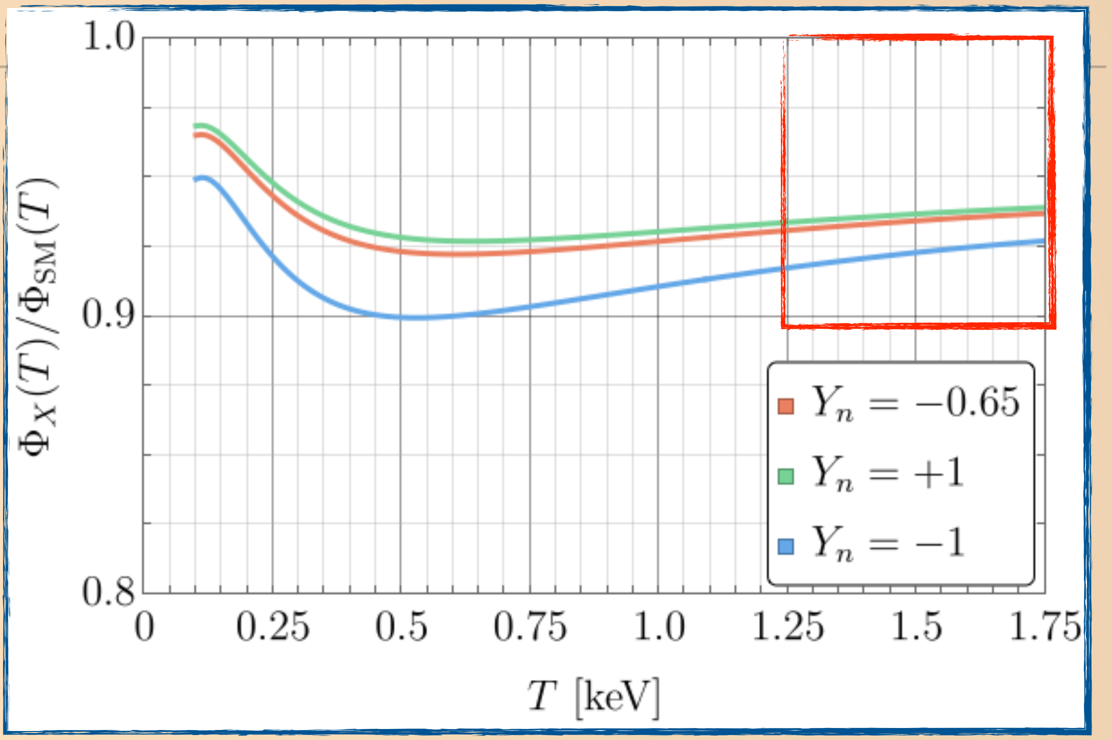
$$\chi^2 = \sum_i \left(\frac{N_i^{\rm exp} - (1+\alpha) N_i^{\rm NP}(g_X, M_X)}{\sigma_i^{\rm exp}}\right)^2 + \left(\frac{\alpha}{\sigma_\alpha}\right)^2$$

~28%

J. Liao & D. Marfatia, Phys. Lett. B775 (2017) 54-57

CONUS Analysis: Details





$$N_i = \sum_{\{(N,Z)\}} \Delta t\, N_{(N,Z)} \int_{E_r^i}^{E_r^i+\Delta E_r} dE_r \int_{0\ \mathrm{MeV}}^{8\ \mathrm{MeV}} dE_\nu\, \Phi(E_\nu) \frac{d\sigma}{dE_\nu} \times \Theta\left(2E_\nu^2/M_{(N,Z)} - E_r\right)$$

$$\chi^2 = \sum_i \frac{\left(N_i^{\mathrm{SM}} - (1+\alpha) N_i^{\mathrm{NP}}(g_X, M_X)\right)^2}{\sigma_{\mathrm{stat},\,i}^2 + \sigma_{\mathrm{sys},\,i}^2} + \left(\frac{\alpha}{\sigma_\alpha}\right)^2$$

~2%

$$\sigma_{\mathrm{stat},\,i} = \sqrt{N_i^{\mathrm{SM}} + N_i^{\mathrm{bkg}}} \qquad \sigma_{\mathrm{stat},\,i} = \sigma_f \left(N_i^{\mathrm{SM}} + N_i^{\mathrm{bkg}}\right)$$

Y. Farzan, et al., arXiv:1802.05171

CONUS vs. CONUS100

$$\frac{d\sigma}{dT} = \frac{G_F^2 M}{\pi} P_{ee} Q_{\rm eff}^2 F_{\rm Helm}^2(q^2)\left(1 - \frac{MT}{2E_\nu^2}\right)$$

$$N_i = \Delta t \sum_f n_f \int_{T_i}^{T_i+\Delta T} dT \int_0^\infty dE_\nu \Phi(E_\nu)\,\frac{d\sigma_f}{dT}\,\Theta(2E_\nu^2 - MT)$$

$$\chi^2 = \sum_i \frac{\left(N_i^0 - (1+\alpha)N_i(\sin^2 2\theta_{ee}, \Delta m_{41}^2)\right)^2}{N_i + N_{\rm bkg} + \sigma_f^2\,(N_i + N_{\rm bkg})^2} + \frac{\alpha^2}{\sigma_\alpha^2}$$

- CONUS: 4.0 kg natural Ge; $T \in [1.2, 1.75]\,\mathrm{keV}$; $\sigma_\alpha = 0.02$; $\sigma_f = 0.01$; one year of running
- CONUS100: 100.0 kg enriched Ge; $T \in [0.1, 1.75]\,\mathrm{keV}$; $\sigma_\alpha = 0.005$; $\sigma_f = 0.001$; five years of running
- Background rate: 1 count/(day*keV*kg)

Y. Farzan, et al., JHEP 05, 066 (2018)
V. I. Kopeikin, Phys. Atom. Nucl. 75, 143 (2012)