

Neutrinos

Salvador Rosauro-Alcaraz

LPCA & U. Clermont-Auvergne



Introduction

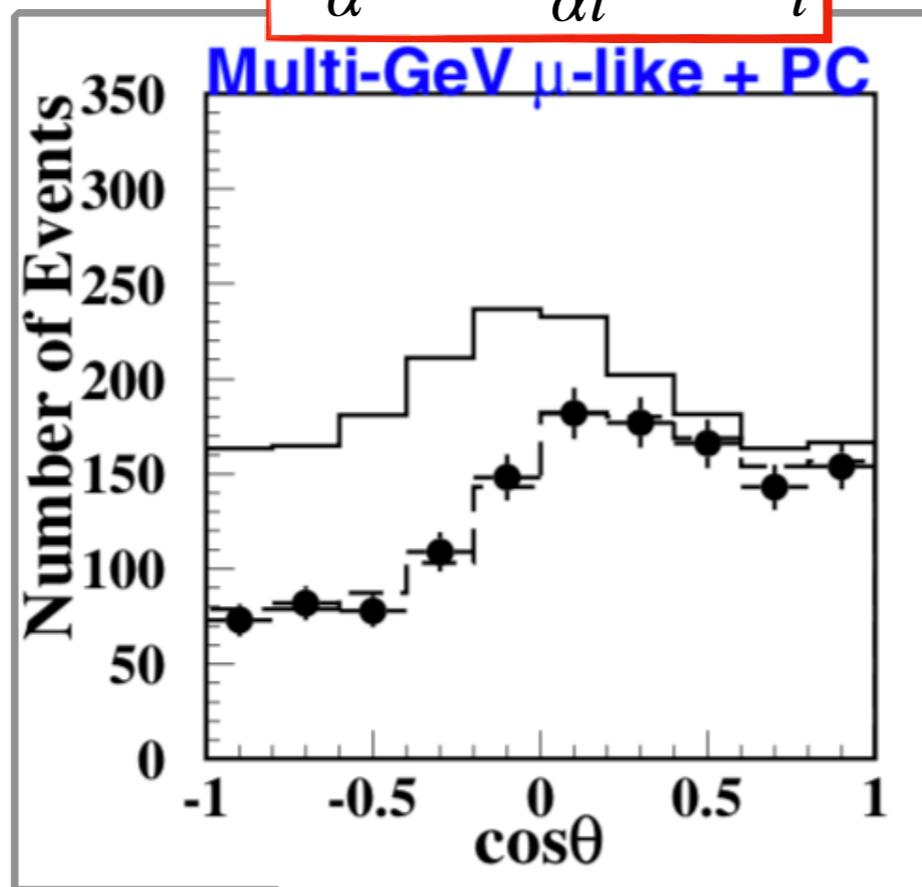
Neutrino oscillations



Torn between identities - tau-, electron - or muon-neutrino?

$$m_\nu \neq 0$$

$$\nu_\alpha = U_{\alpha i}^{\text{PMNS}} \nu_i$$



Super-Kamiokande Collaboration,
arXiv: hep-ex/0105023

$$P_{\mu\mu} \simeq 1 - \sin^2 2\theta_{23} \sin^2 \left(\frac{\Delta m_{\text{atm}}^2 L}{4E} \right)$$

Introduction

Neutrino
oscillations

$$m_\nu \neq 0$$



Only experimental evidence
for BSM from the laboratory

Physics BSM

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Physics BSM

Plan for the talk

- Current status & known unknowns
- Origin of neutrino masses & pheno
- Connections to other SM open problems

Neutrino sector

Current status

$$U^{\text{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times P(\alpha_1, \alpha_2)$$

NuFit 6.1, I. Esteban *et al.*, arXiv:2410.05380

SNO, Borexino,
KamLAND + **JUNO**

Solar sector

$$\Delta m_{21}^2 = 7.537^{+0.10}_{-0.094} \cdot 10^{-5} \text{eV}^2$$

$$\sin^2 \theta_{12} = 0.3088^{+0.0067}_{-0.0066}$$

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SK, T2K, NOvA,
MINOS, IC

Atmospheric
sector

$$|\Delta m_{31}^2| \simeq 2.5^{+0.019}_{-0.021} \cdot 10^{-3} \text{eV}^2$$
$$\sin^2 \theta_{23} = 0.47^{+0.017}_{-0.017}$$

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Daya Bay, RENO,
T2K, NOvA

Reactor sector

$$\sin^2 \theta_{13} = 0.02215^{+0.0006}_{-0.0006}$$

Neutrino sector

Current status

Several parameters to be determined

Mass ordering

Absolute mass scale

CP violation

Octant of θ_{23}

Majorana nature

Neutrino sector

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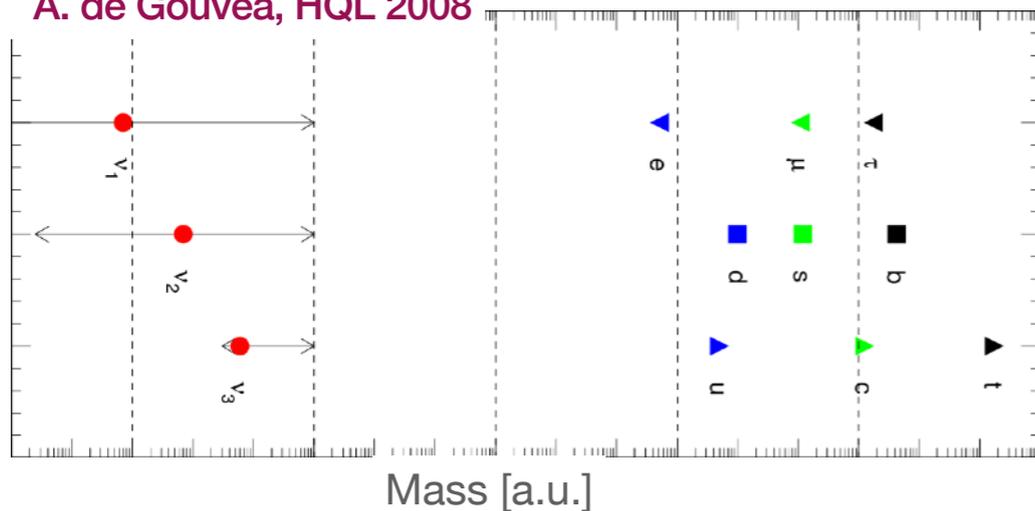
Octant of θ_{23}

Majorana nature

See talk by F. Mahmoudi

Half of the flavor puzzle!

A. de Gouvea, HQL 2008



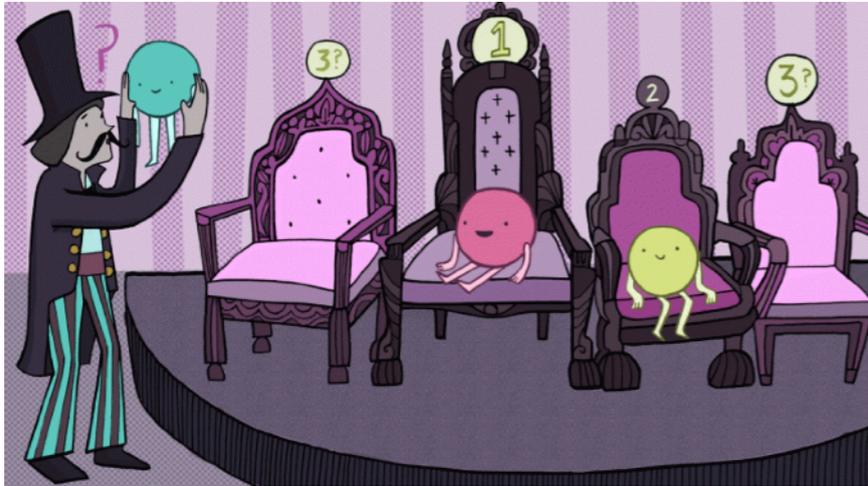
S. King, DISCRETE 2014

	CKM			PMNS		
	d	s	b	ν_1	ν_2	ν_3
u	Yellow	Blue	.	Yellow	Blue	.
c	Green	Yellow	.	Green	Blue	Yellow
t	.	.	Yellow	Green	Blue	Yellow
ν_e				Yellow	Blue	.
ν_μ				Green	Blue	Yellow
ν_τ				Green	Blue	Yellow

Neutrino sector

Known unknowns

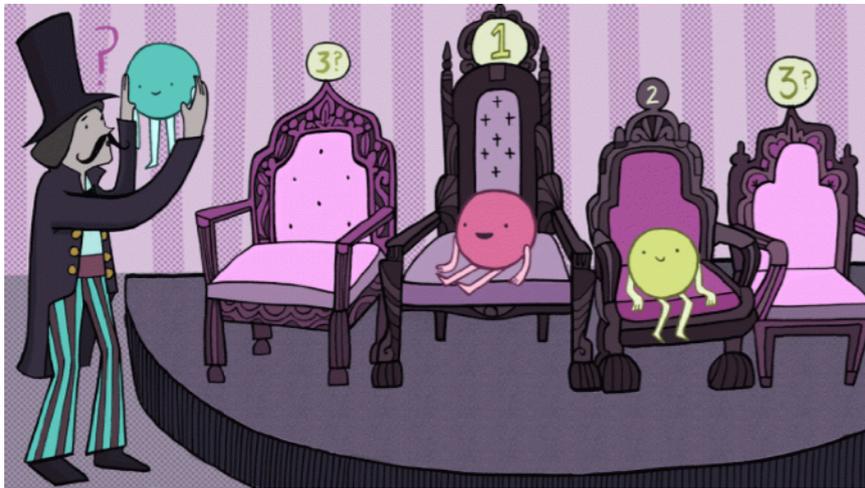
Mass ordering



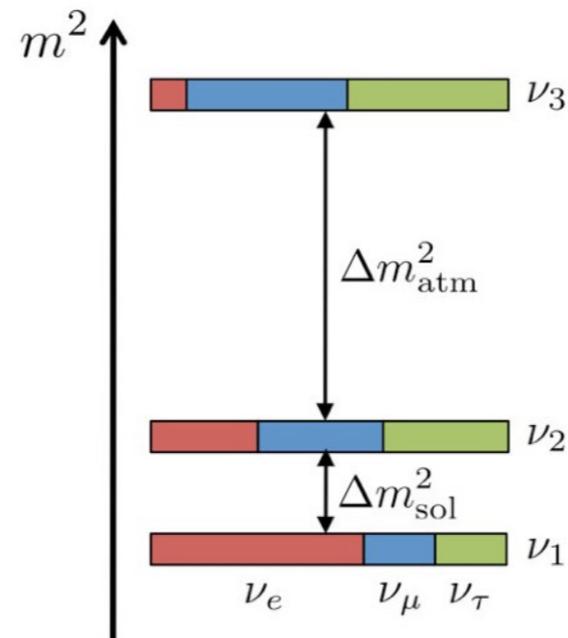
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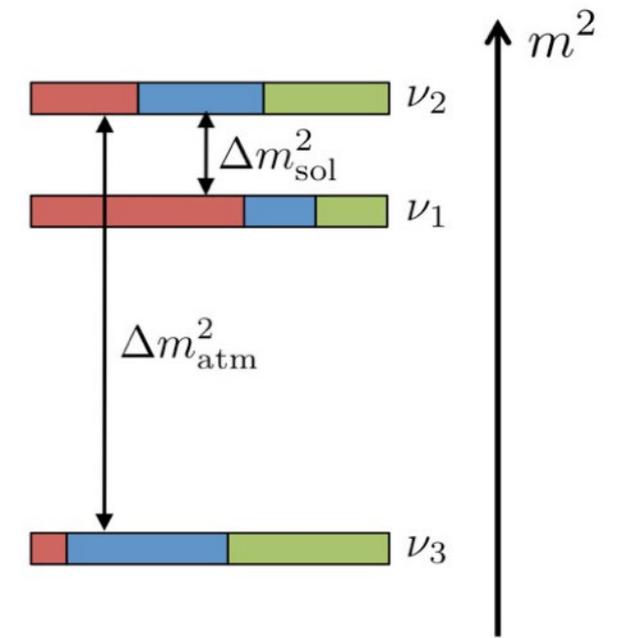
Mass ordering



normal hierarchy (NH)



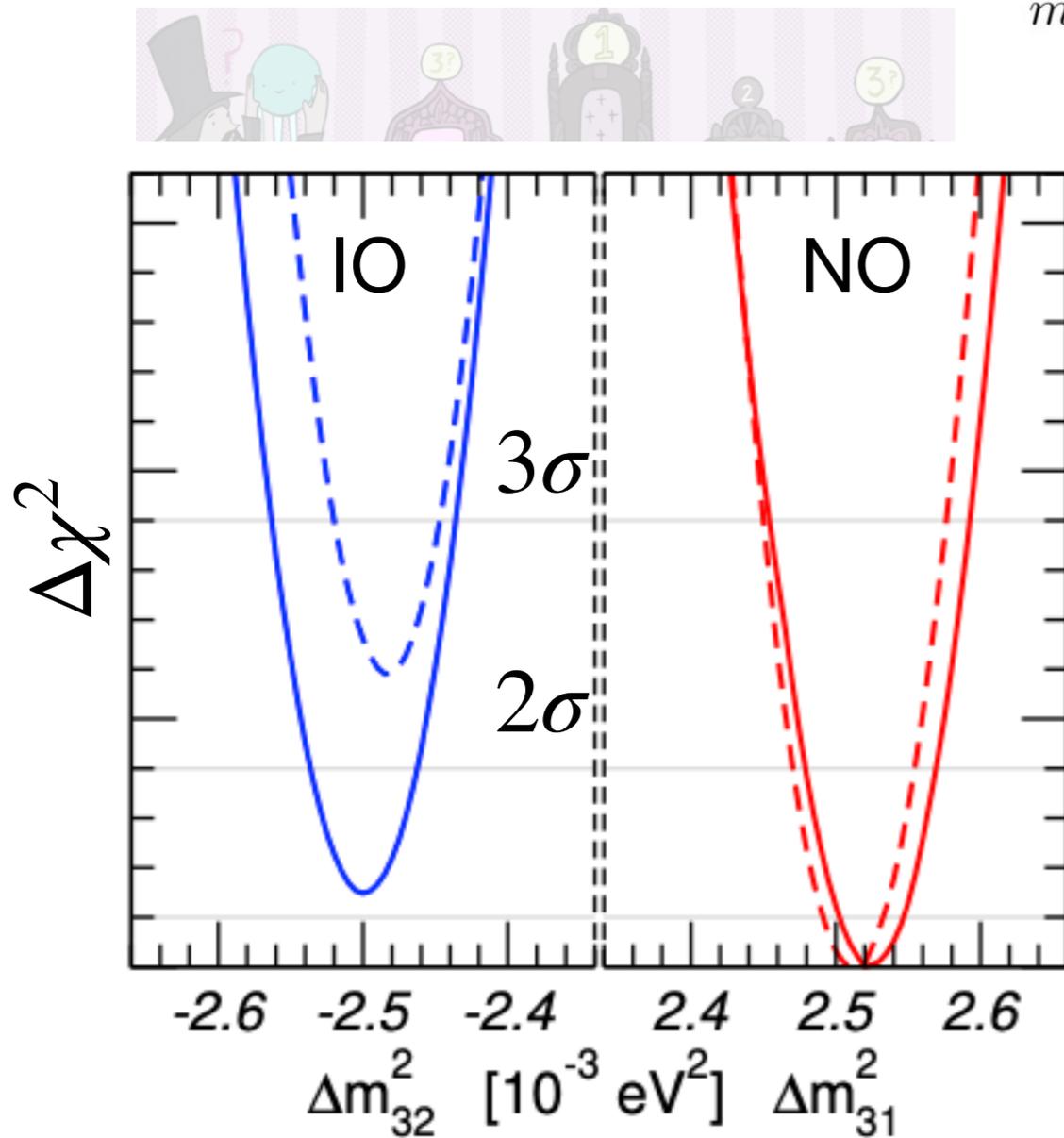
inverted hierarchy (IH)



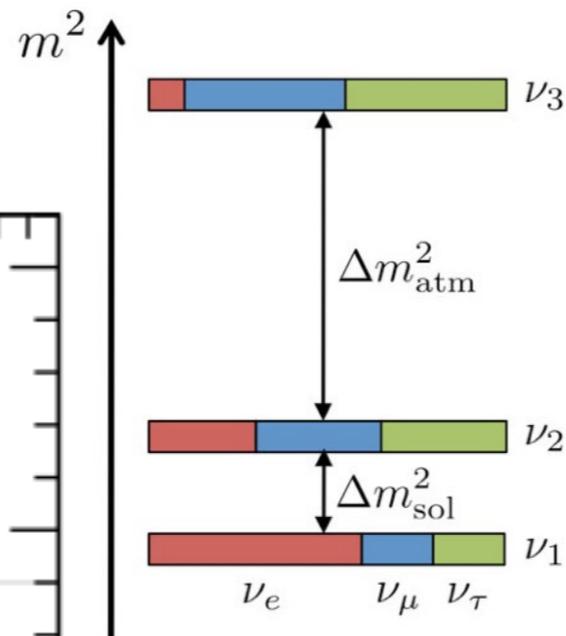
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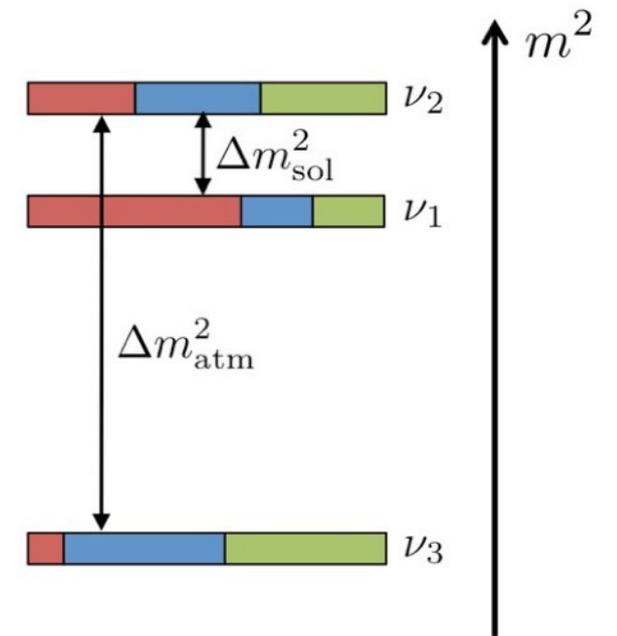
Mass ordering



normal hierarchy (NH)



inverted hierarchy (IH)



From the global fits

NuFit 6.1, I. Esteban et al., arXiv:2410.05380

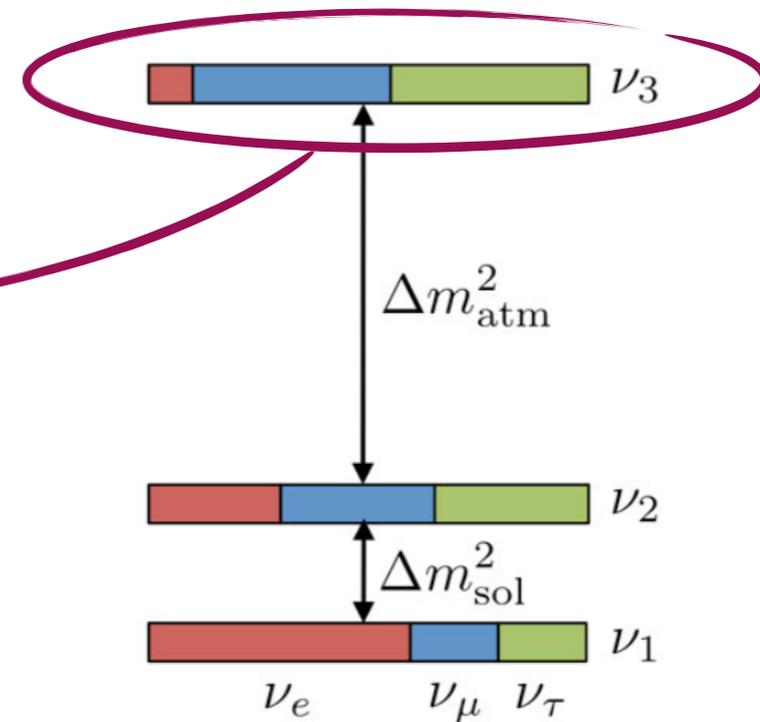
(Mild) preference for NO

Neutrino sector

Known unknowns

Octant of θ_{23}

Does ν_3 have more ν_μ or ν_τ content? 



Neutrino sector

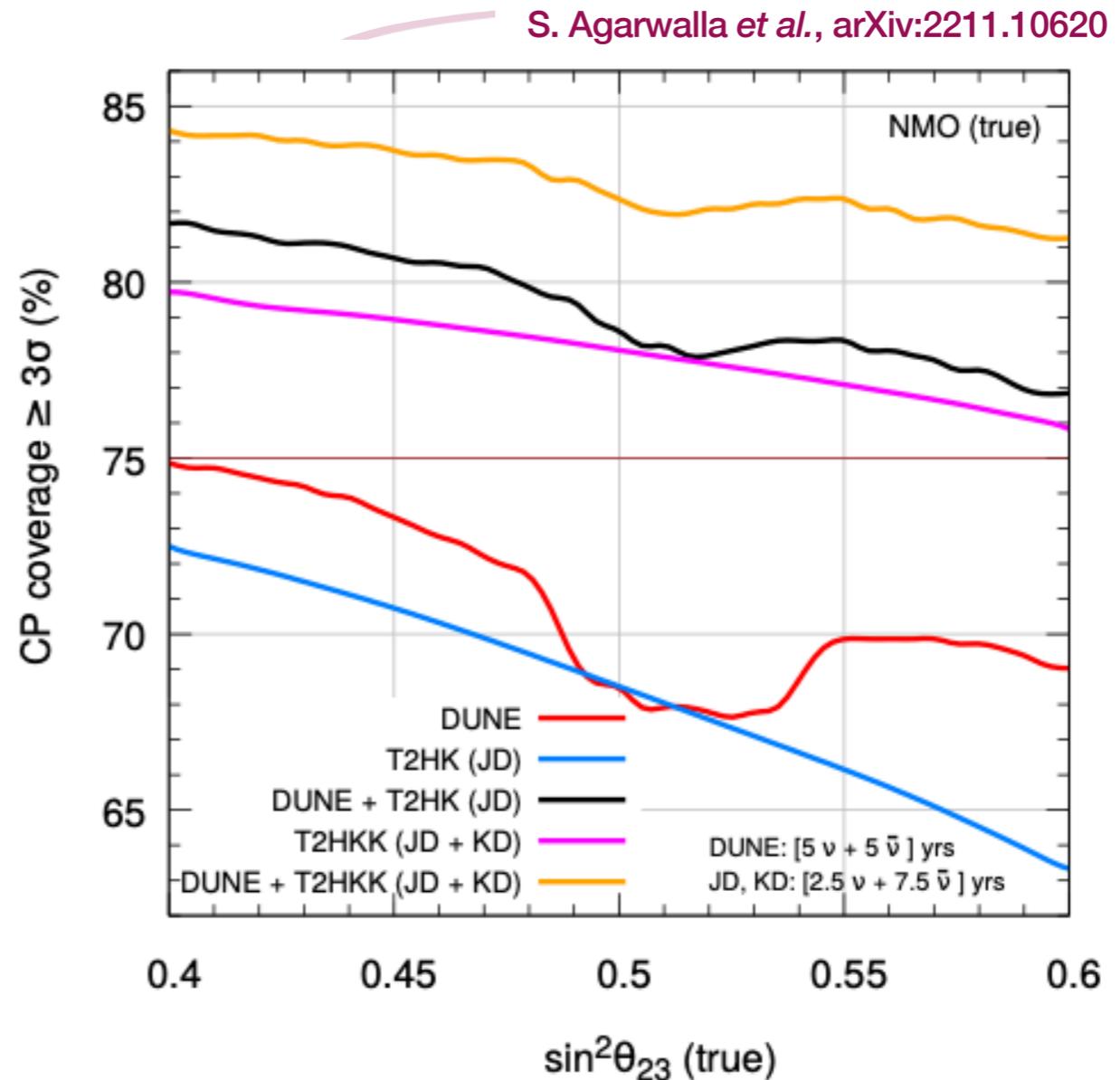
Known unknowns

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Does ν_3 have more ν_μ or ν_τ content? ◀

Precise determination allows to

Improve prospects for CP violation



Neutrino sector

Known unknowns

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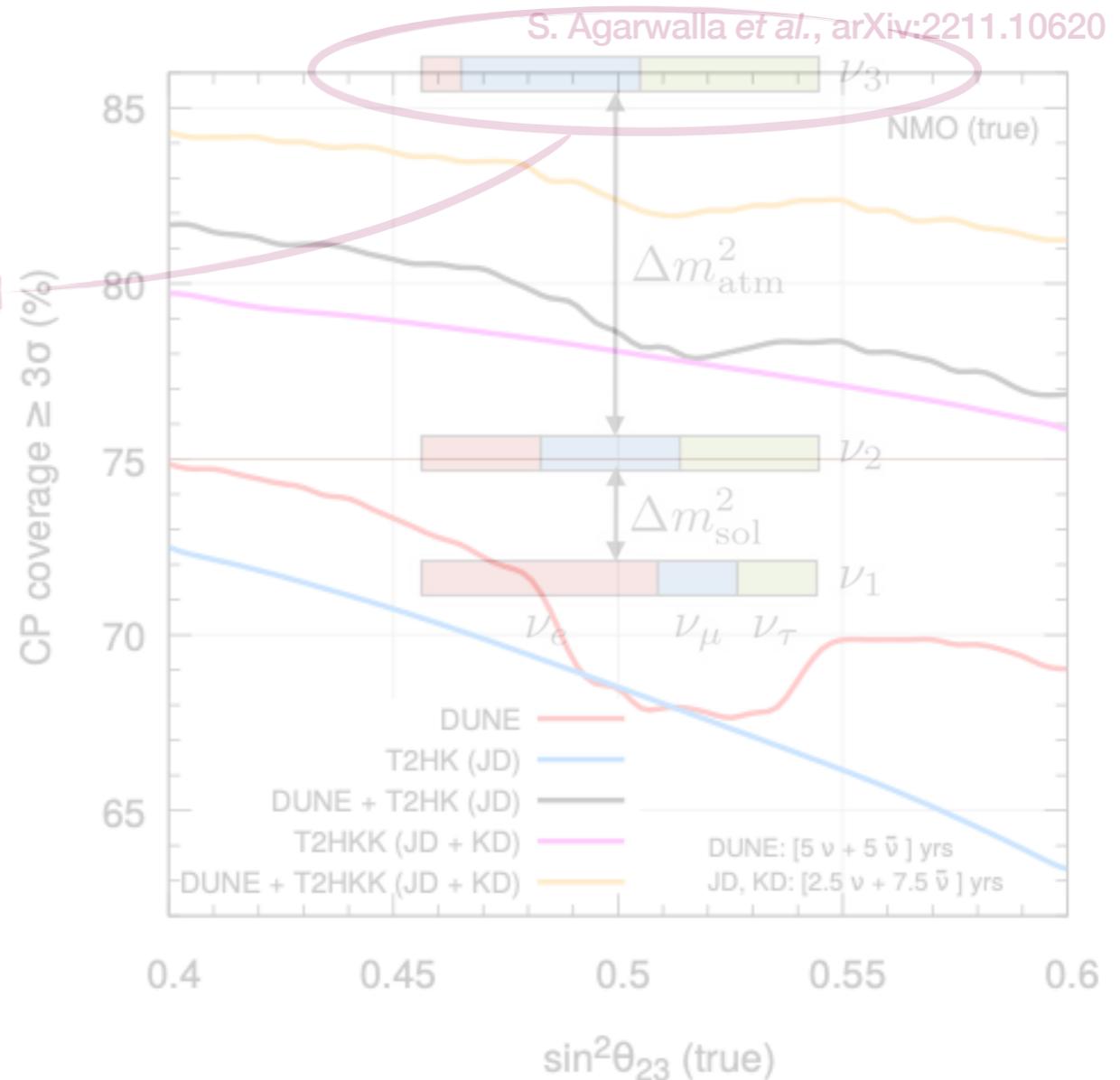
Does ν_3 have more ν_μ or ν_τ content?

Precise determination allows to

Improve prospects for CP violation

Constrain models tackling the flavor problem

M. Blennow *et al.*,
arXiv:2005.12277

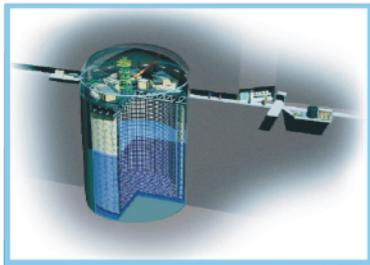


Neutrino sector

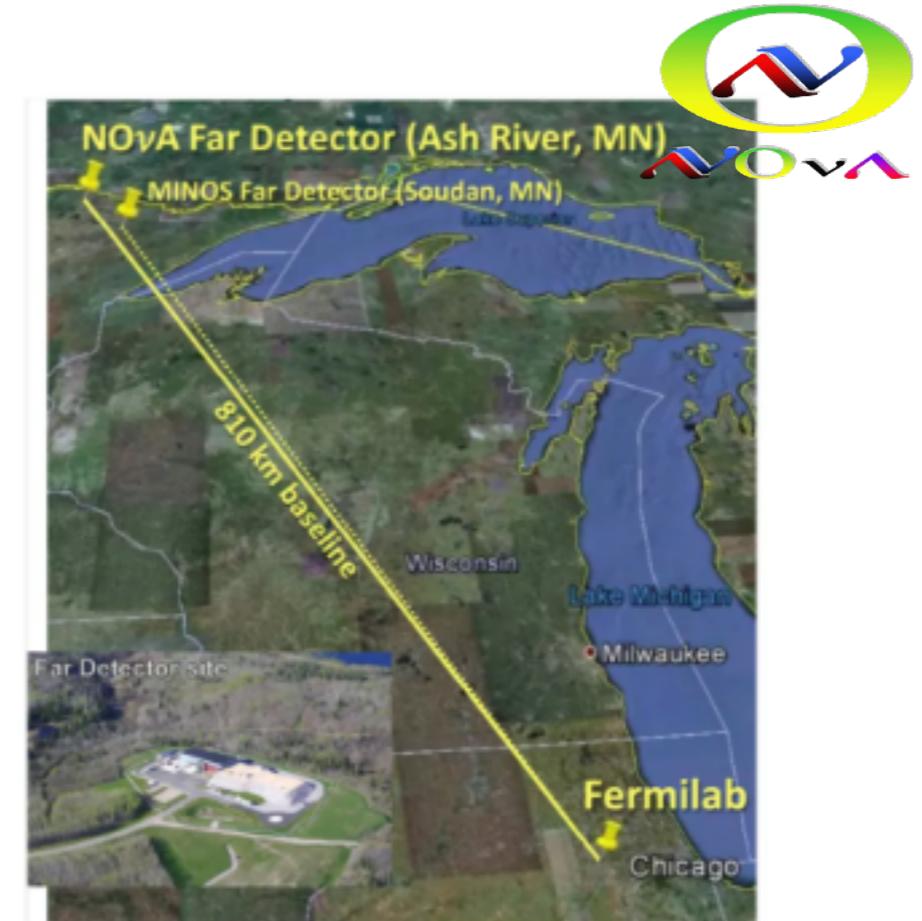
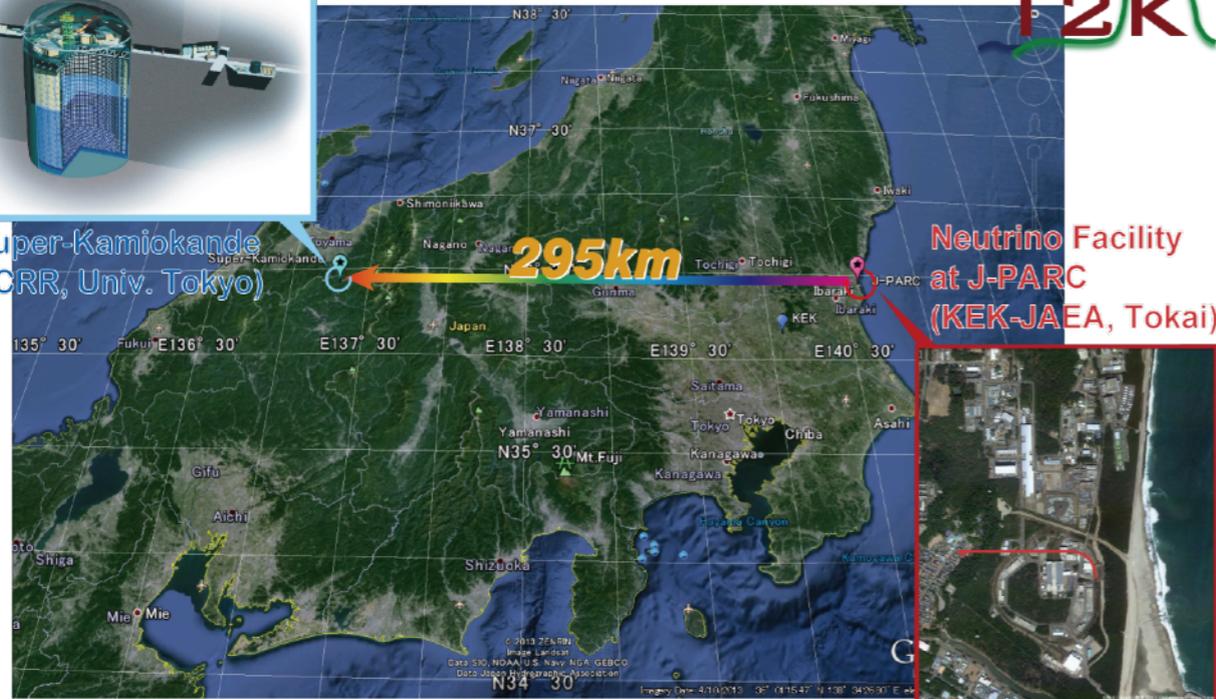
Known unknowns

CP violation

T2K: shorter baseline,
cleaner CPV effect



Super-Kamiokande
(ICRR, Univ. Tokyo)



NOvA: longer baseline,
large matter effects,
more sensitive to MO

Neutrino sector

Known unknowns

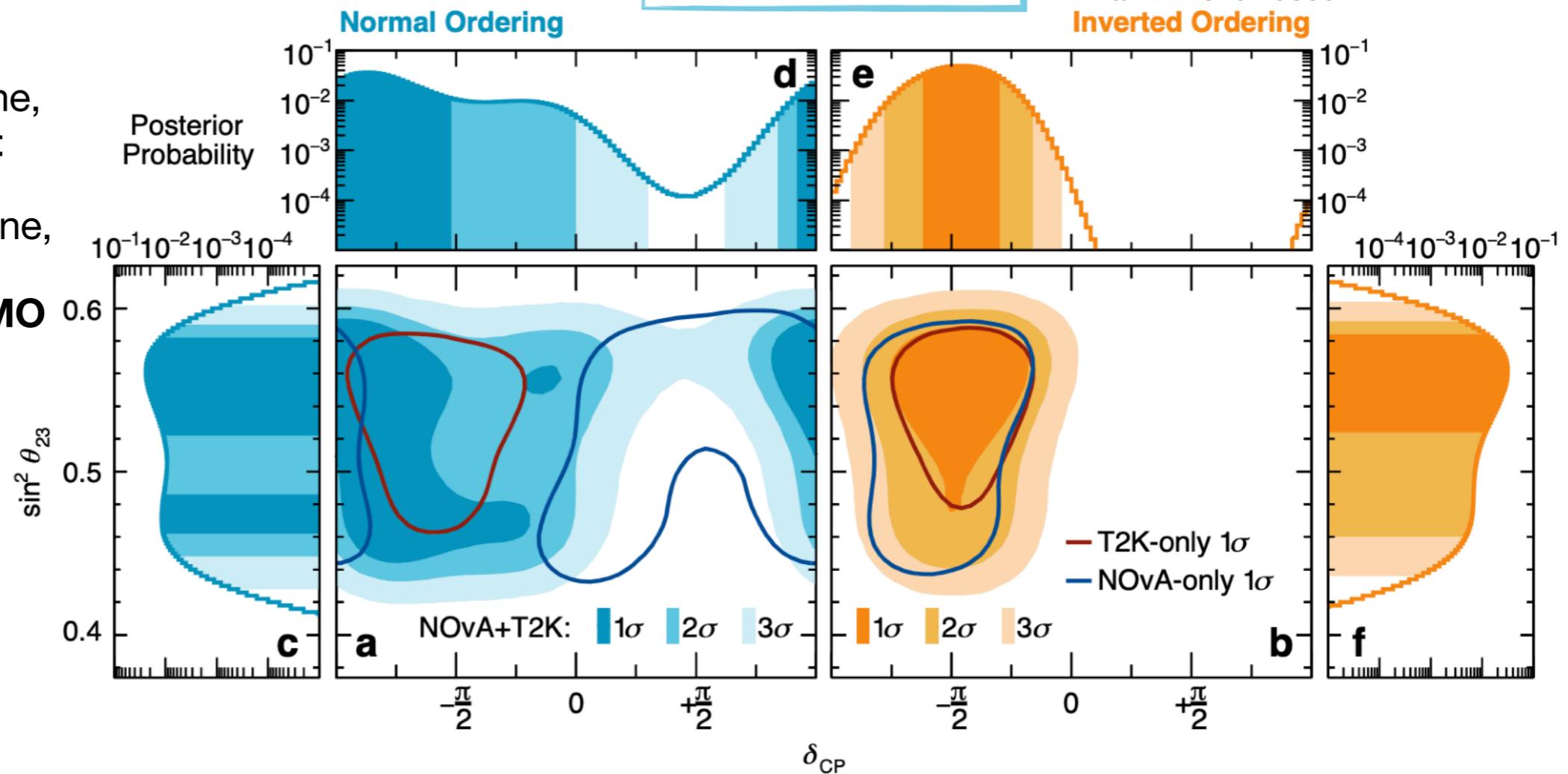
CP violation

Combined analysis

T2K & NOvA Collaborations,
arXiv:2510.19888
Inverted Ordering

T2K: shorter baseline,
cleaner CPV effect

NOvA: longer baseline,
large matter effects,
more sensitive to MO



Neutrino sector

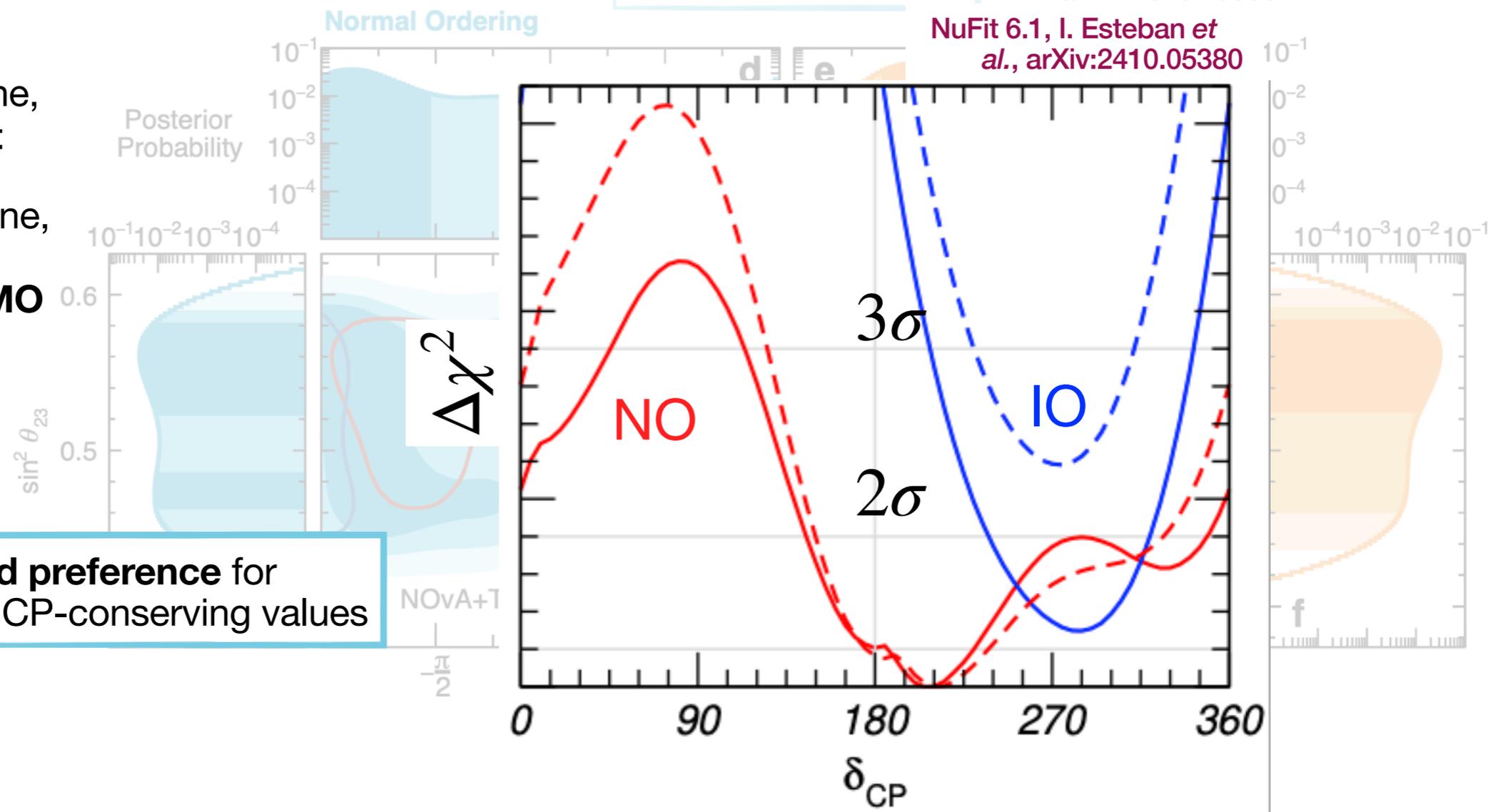
Known unknowns

CP violation

T2K: shorter baseline, cleaner CPV effect

NOvA: longer baseline, large matter effects, more sensitive to MO

Very mild preference for close to CP-conserving values



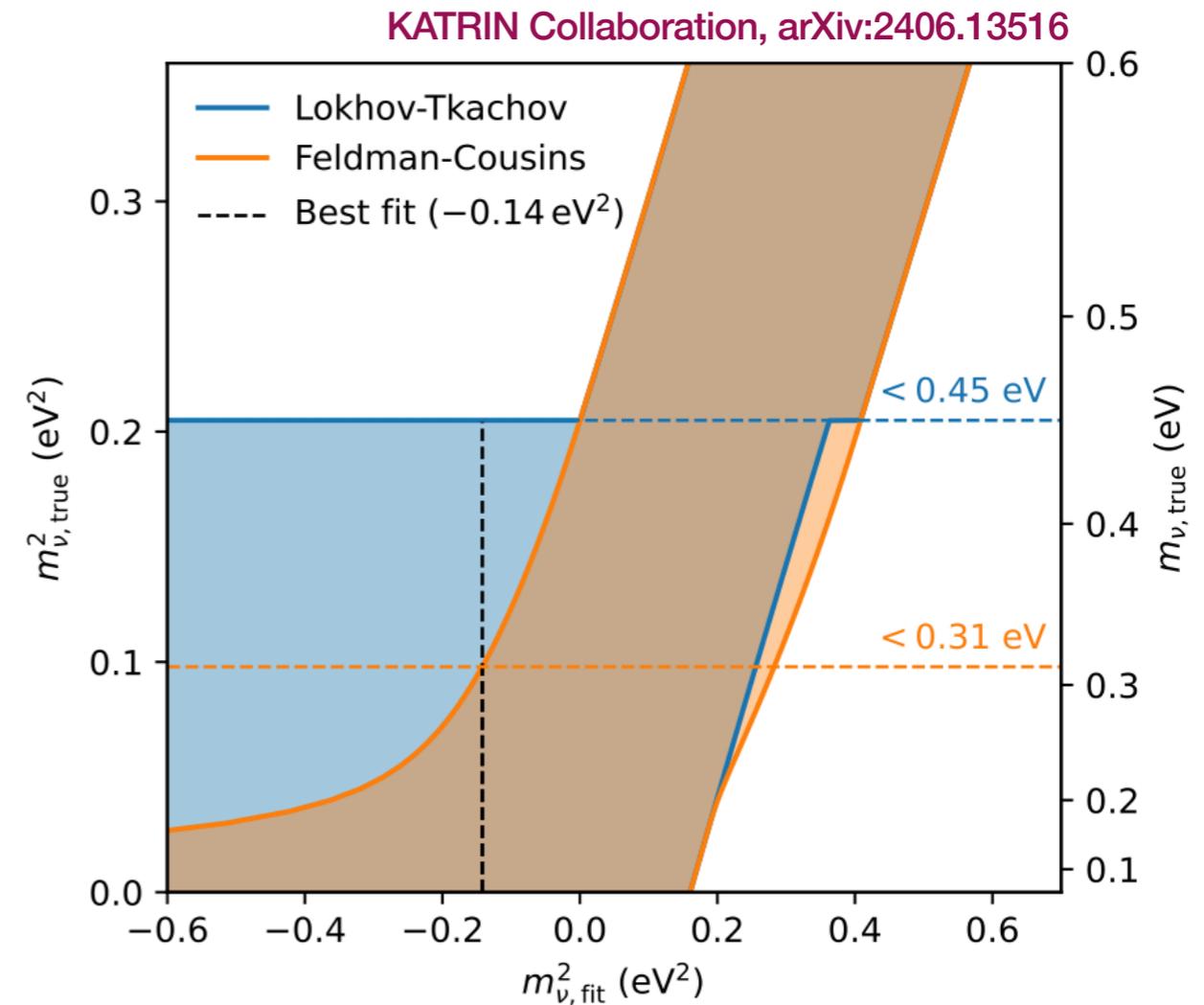
Neutrino sector

Known unknowns

Absolute mass scale

Direct searches: Tritium β decay endpoint

$$m_\nu < 0.45 \text{ eV @ 90\% CL}$$



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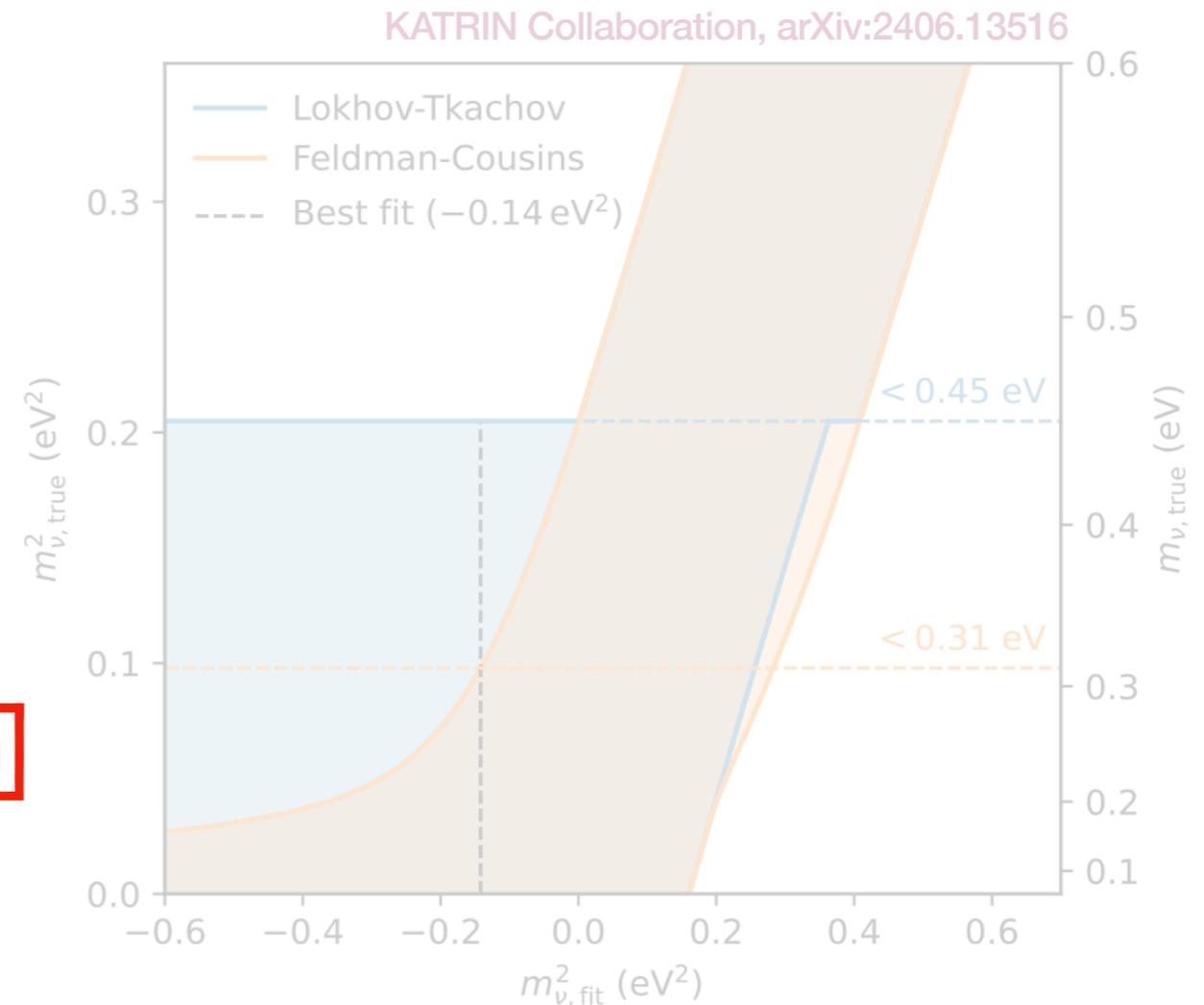
Cosmology: energy density in ν , $\sum m_{\nu_i} n_\nu$

DESI Collaboration, arXiv:2503.14744

$$\sum m_{\nu_i} < 0.064 \text{ eV @ 95\% CL}$$

CMB + DESI DR2 BAO

For Λ CDM



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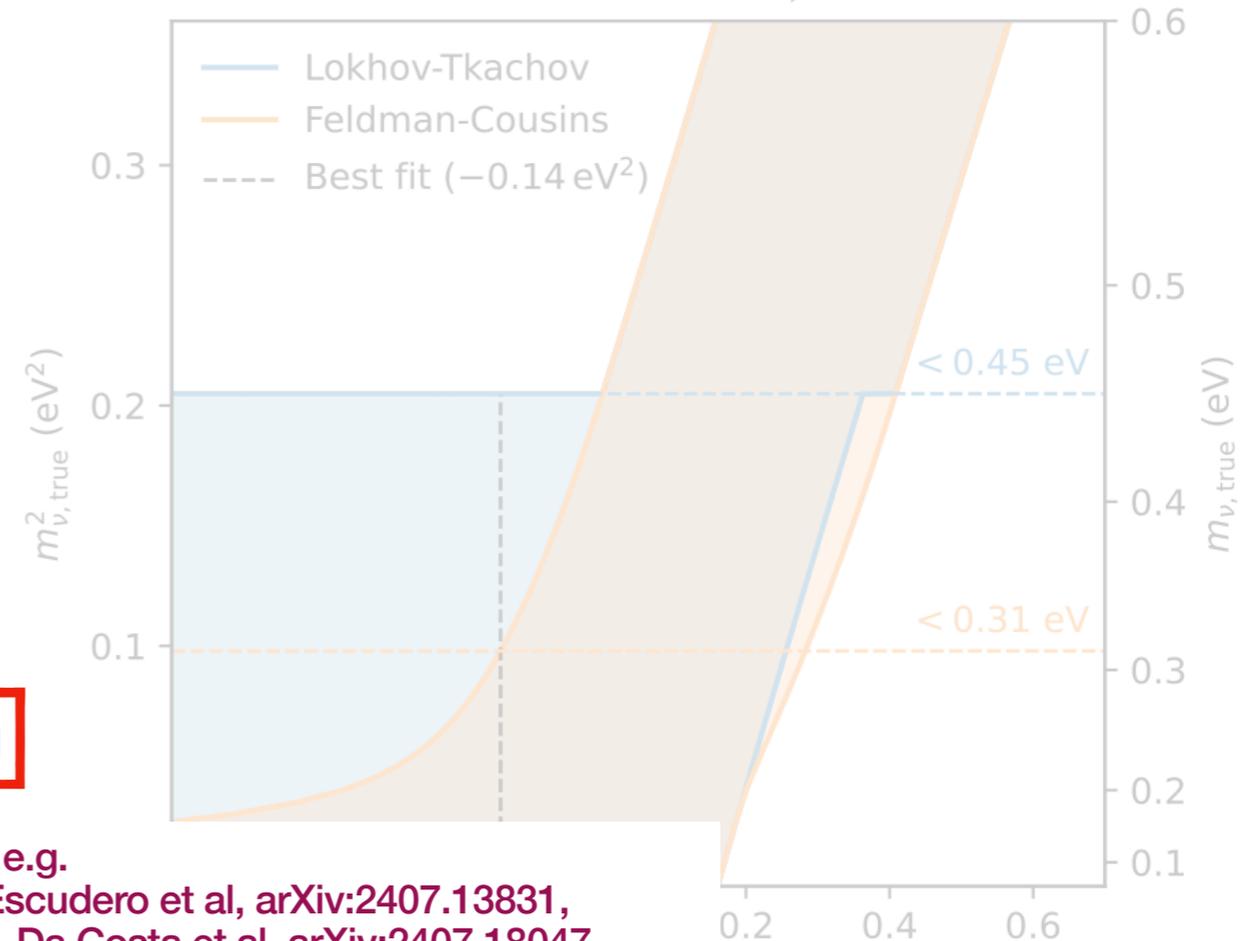
For Λ CDM

From oscillations

$$\sum m_{\nu_i} \geq 0.059 \text{ eV for NO}$$

$$\sum m_{\nu_i} \geq 0.099 \text{ eV for IO}$$

KATRIN Collaboration, arXiv:2406.13516



See e.g.
M. Escudero et al, arXiv:2407.13831,
S. S. Da Costa et al, arXiv:2407.18047,
T. Bertolez-Martinez et al, arXiv:2411.14524,
J. Aguilar et al, 2507.12401

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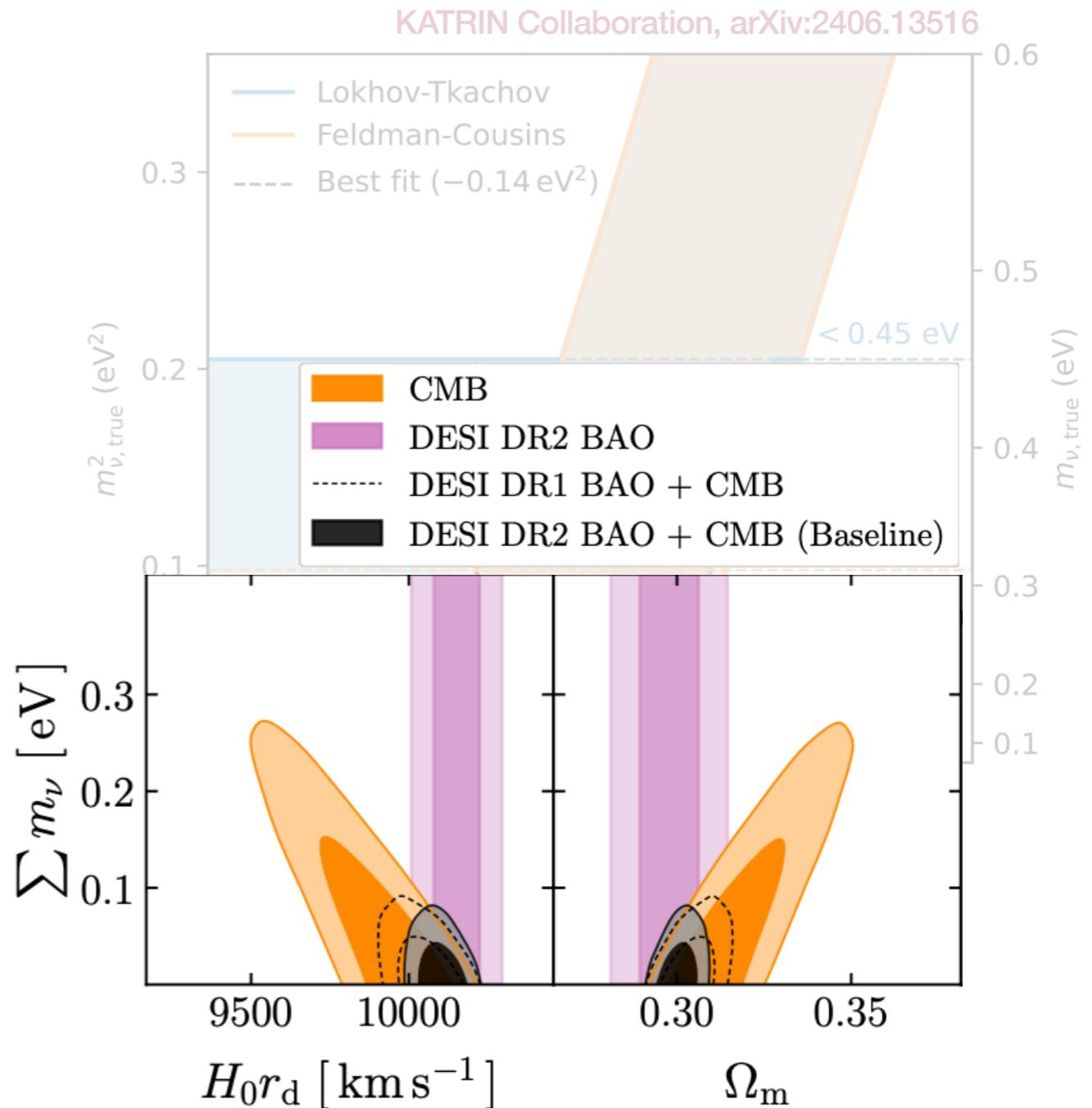
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If dynamical dark energy is introduced

DESI Collaboration, arXiv:2503.14744

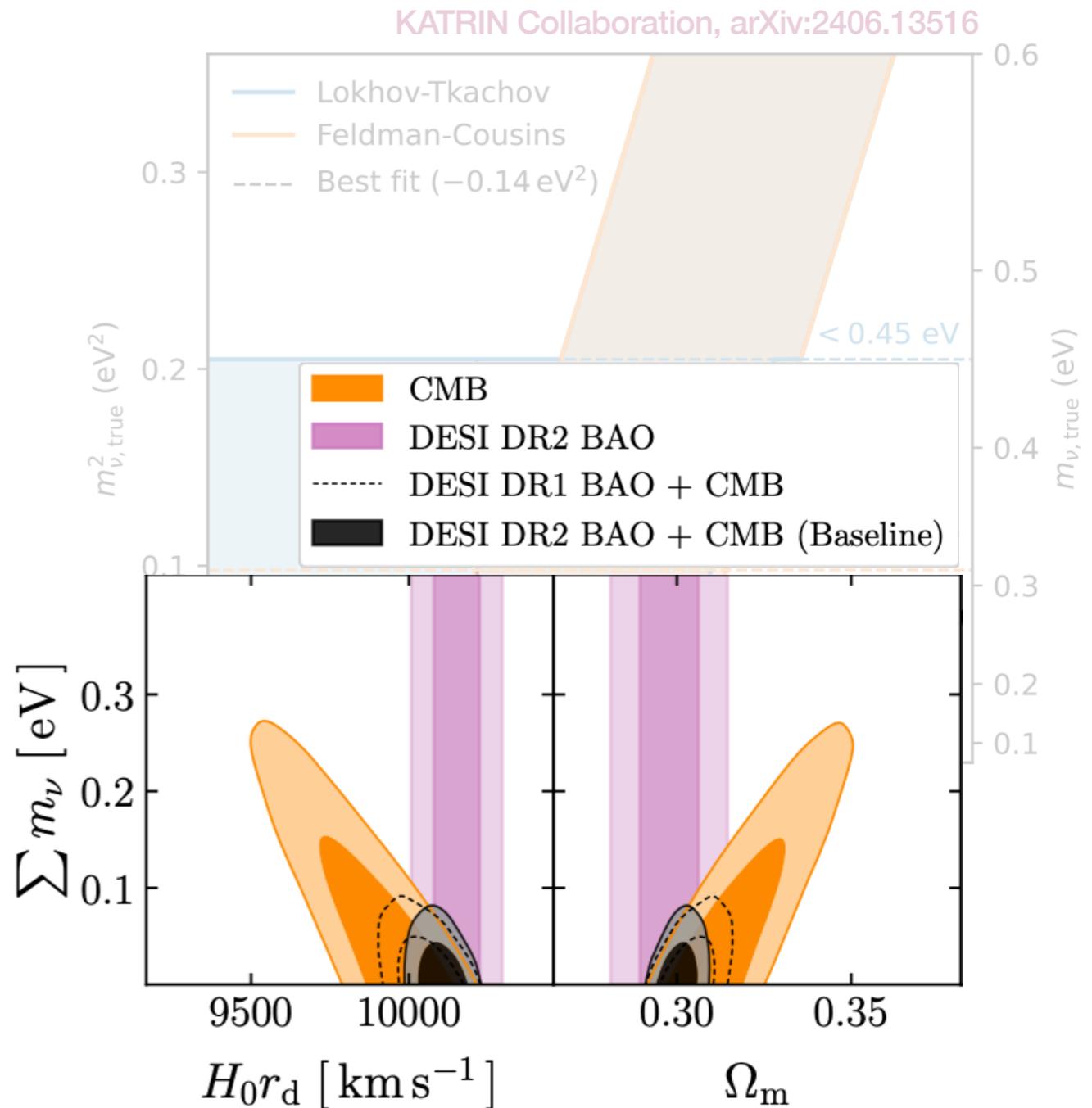
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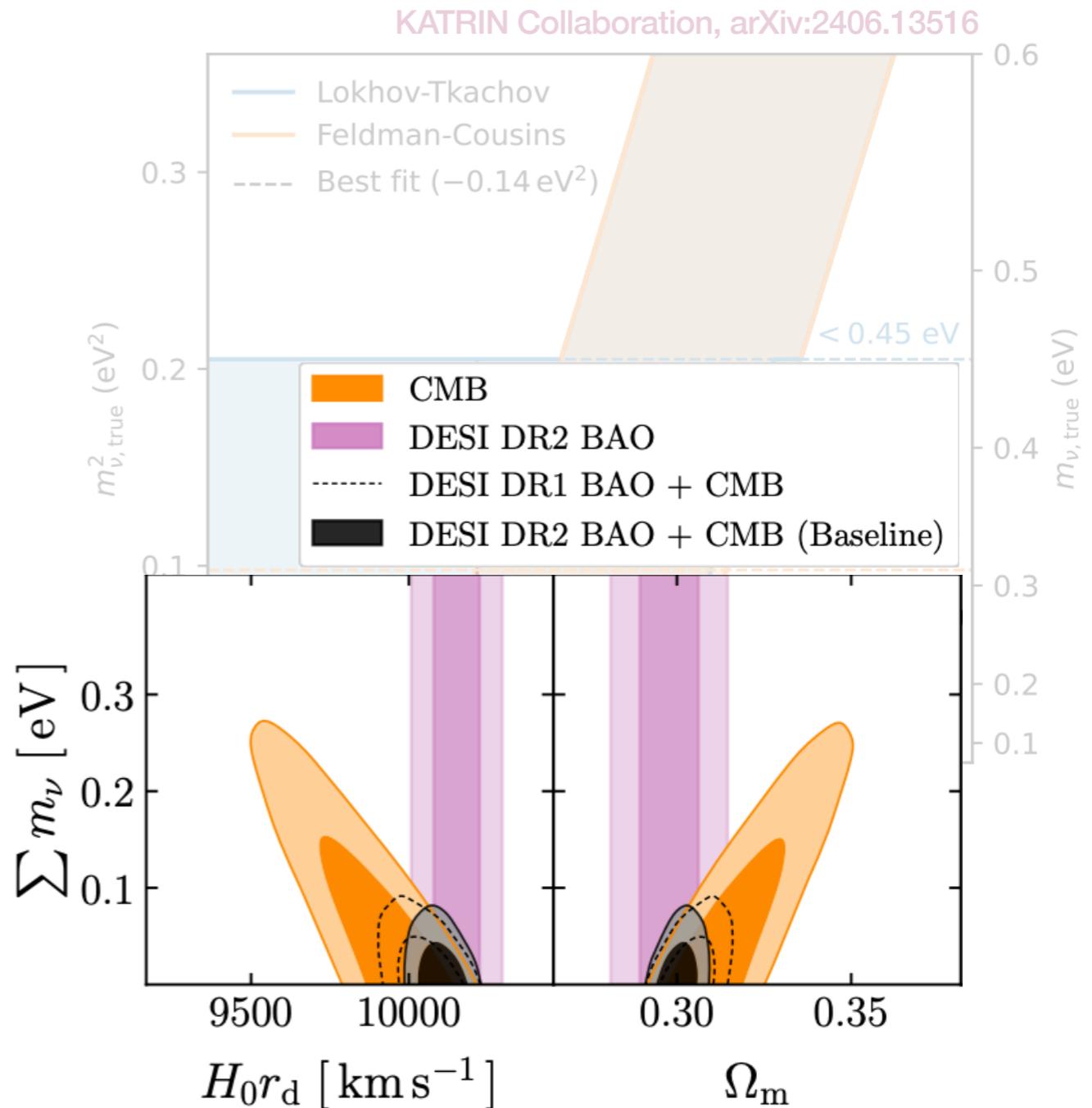
$$\sum m_{\nu_i} < 0.163 \text{ eV @ 95\% CL}$$

CMB + DESI DR2 BAO

From oscillations

$$\sum m_{\nu_i} \geq 0.059 \text{ eV for NO}$$

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Neutrino sector

Known unknowns

Absolute mass scale

Direct searches: Tritium β decay endpoint

$$m_\nu < 0.45 \text{ eV @ 90\% CL}$$

Cosmological dark energy is introduced

DESI

Keep posted on DESI & EUCLID data

$$\sum m_{\nu_i} < 0.163 \text{ eV @ 95\% CL}$$

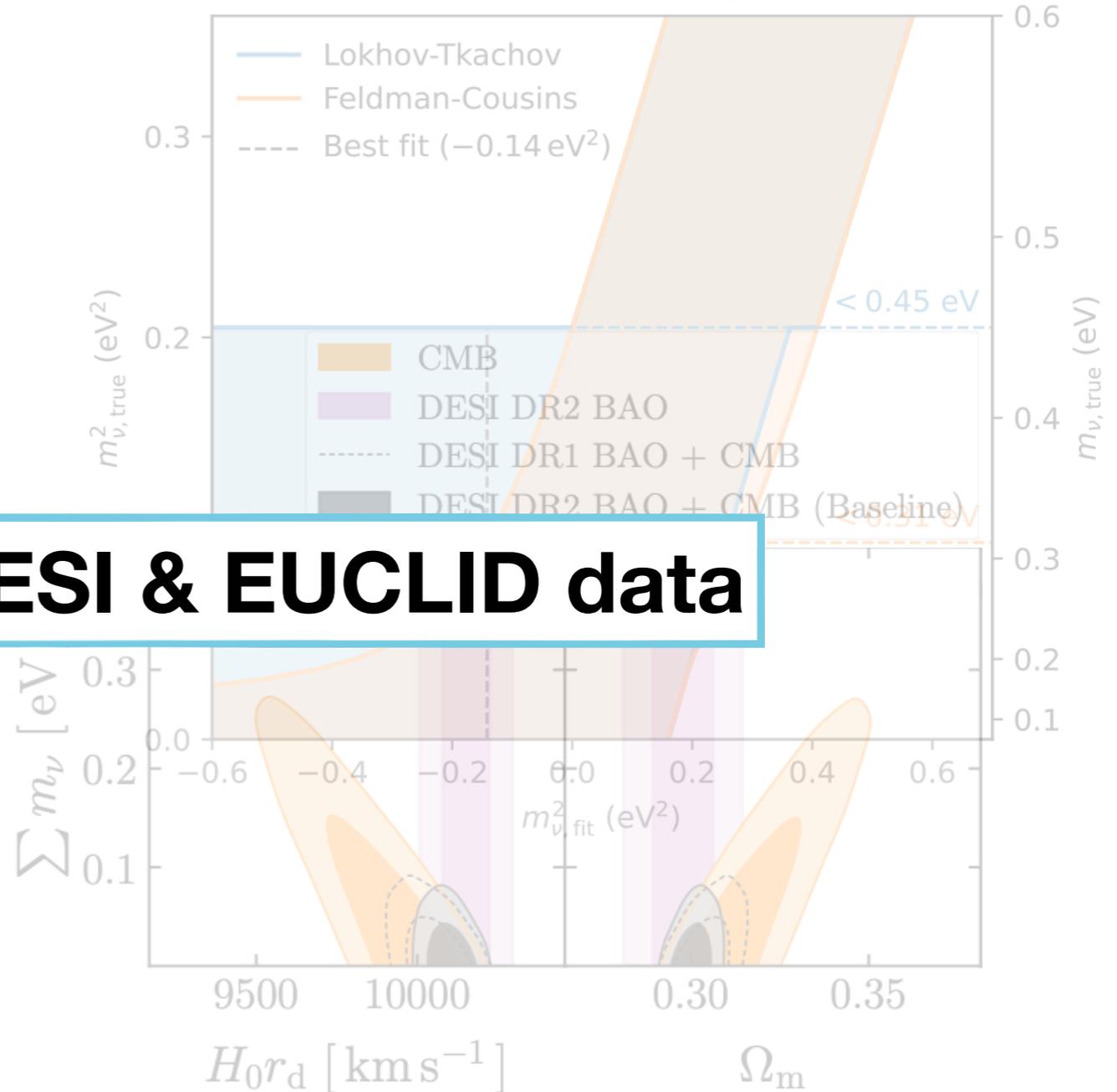
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KATRIN Collaboration, arXiv:2406.13516

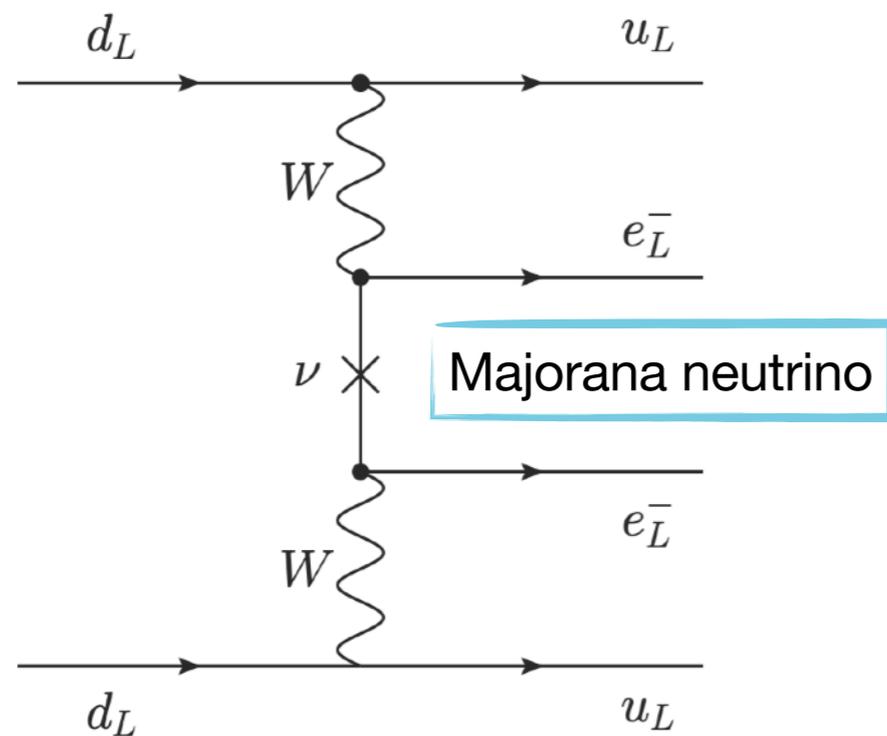


Neutrino sector

Known unknowns

Majorana or Dirac?

Search for $0\nu 2\beta$ decay



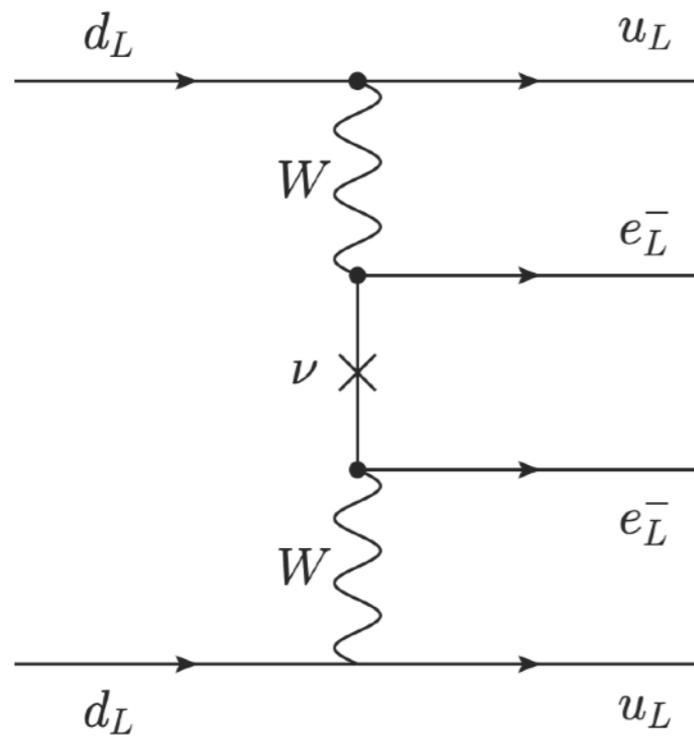
J. J. Gómez-Cadenas *et al.*, '23

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$$1/T_{1/2}^{0\nu} = G^{0\nu} |M^{0\nu}|^2 m_{\beta\beta}^2$$



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$0\nu 2\beta$ half-lifetime

J. J. Gómez-Cadenas *et al.*, '23

Isotope	$T_{1/2}^{0\nu}$ (years)	Experiment
^{48}Ca	$> 5.8 \times 10^{22}$	ELEGANT VI [197]
^{76}Ge	$> 1.8 \times 10^{26}$	GERDA [2]
^{82}Se	$> 4.6 \times 10^{24}$	CUPID-0 [8]
^{96}Zr	$> 9.2 \times 10^{21}$	NEMO-3 [54]
^{100}Mo	$> 1.8 \times 10^{24}$	CUPID-Mo [7]
^{116}Cd	$> 2.2 \times 10^{23}$	Aurora [61]
^{128}Te	$> 3.6 \times 10^{24}$	CUORE [198]
^{130}Te	$> 2.2 \times 10^{25}$	CUORE [4]
^{136}Xe	$> 2.3 \times 10^{26}$	KamLAND-Zen [6]
^{150}Nd	$> 2.0 \times 10^{22}$	NEMO-3 [71]

Neutrino sector

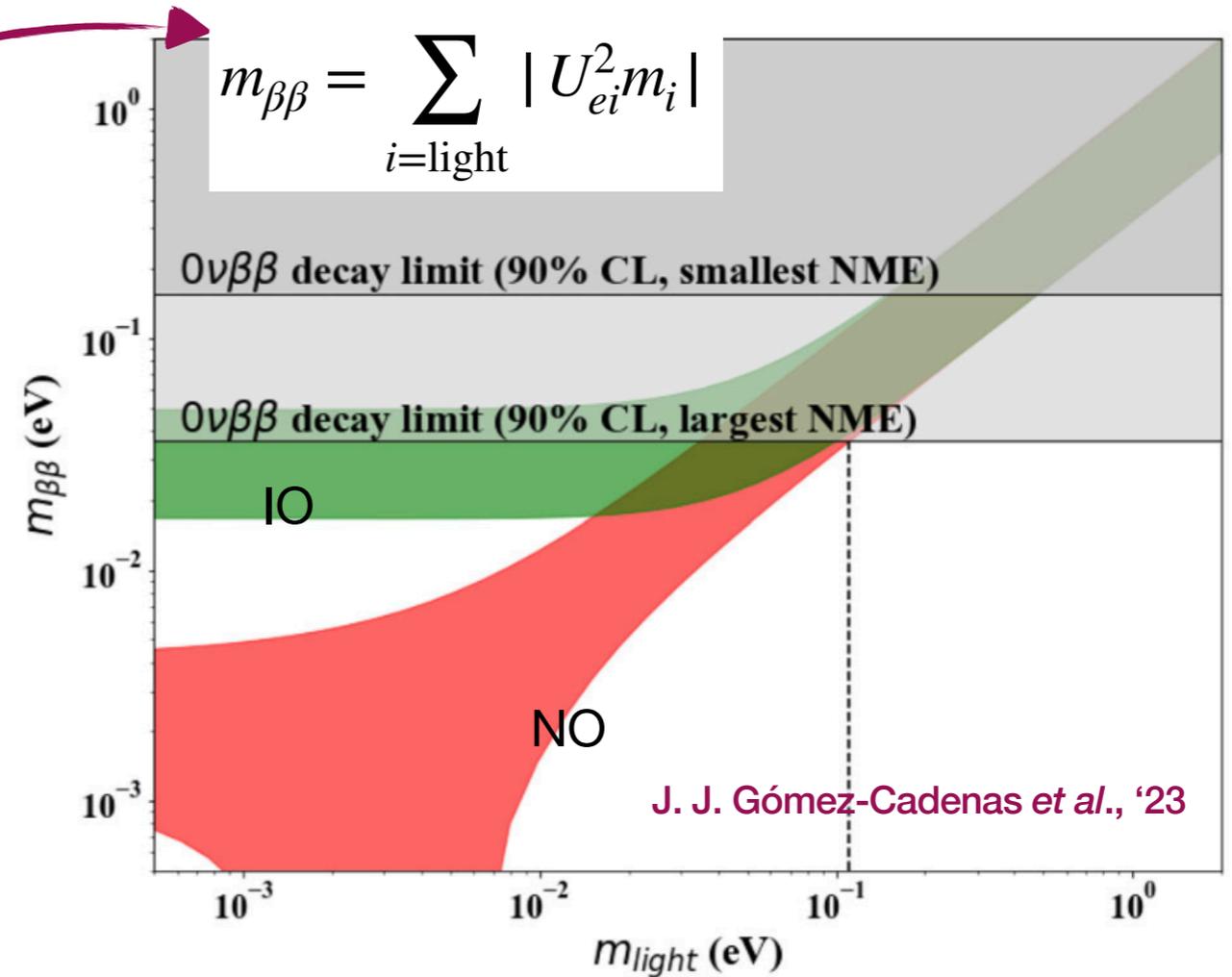
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$0\nu 2\beta$ half-lifetime

Nuclear matrix element



Neutrino sector

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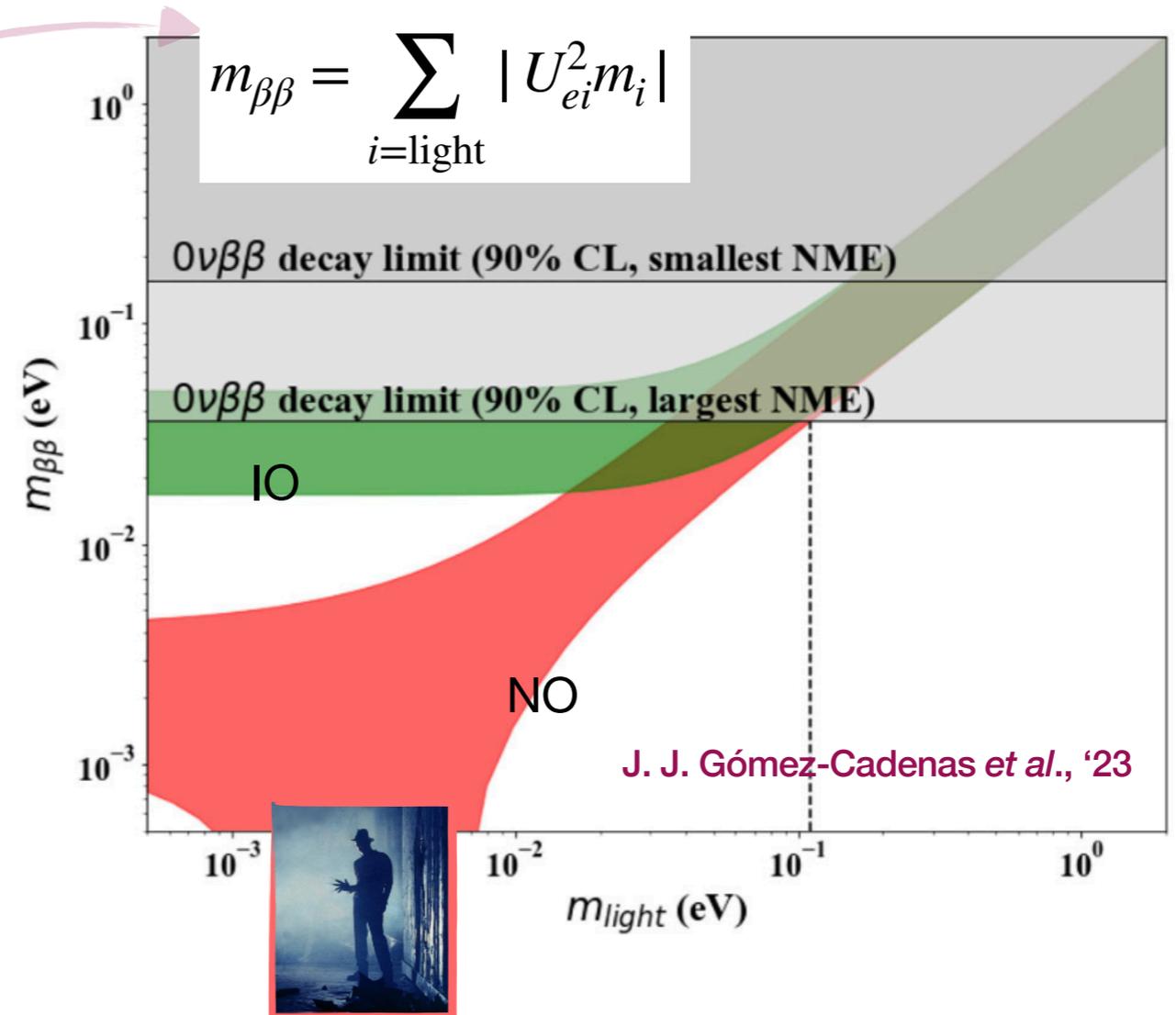
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Prospects are different depending on **MO** and **absolute mass scale**



Neutrino sector

Entering the precision era

Mass ordering

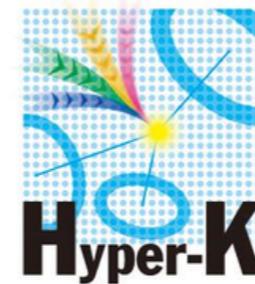
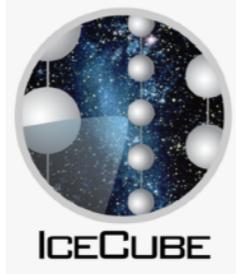
Absolute mass scale

CP violation

Octant of θ_{23}

Majorana nature

Current and future experiments will try to answer these questions



We are entering an era of **precision in neutrino physics**

Neutrino sector

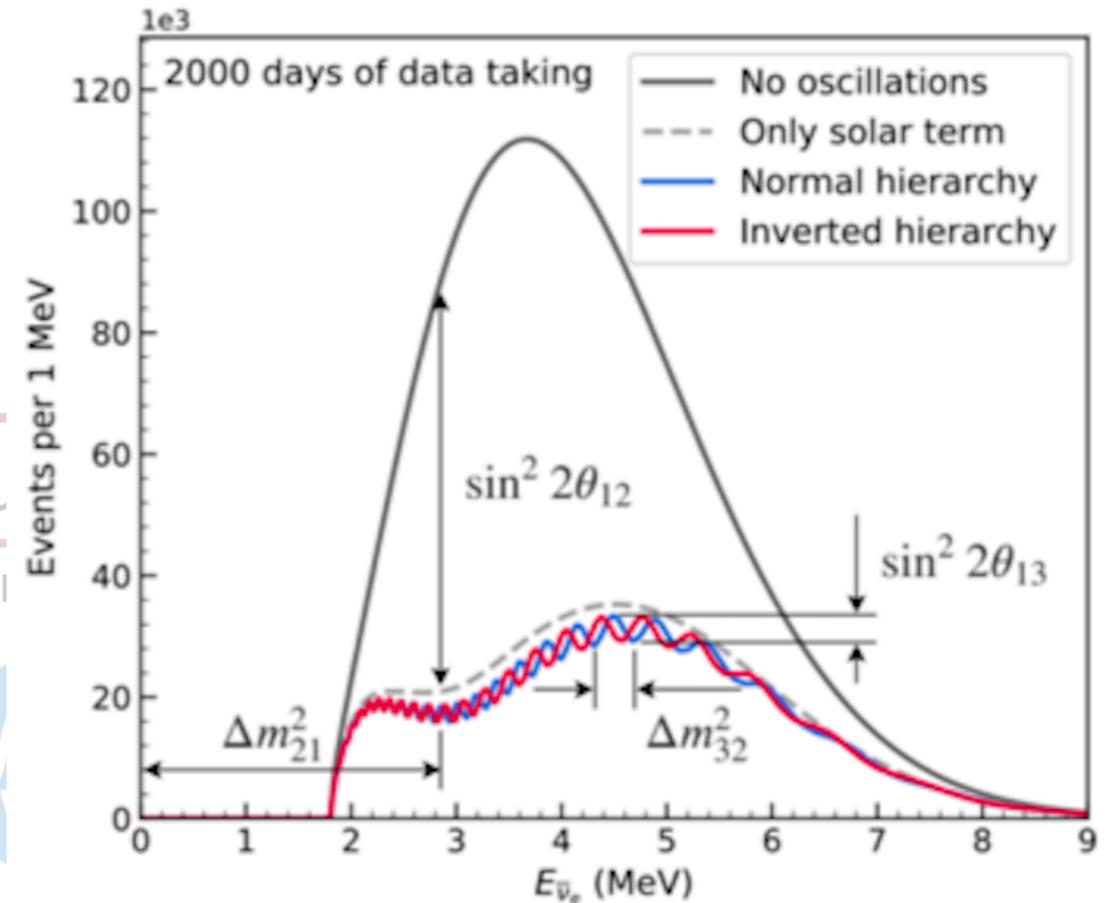
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World leading precision

59 days of data!

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JUNO Collaboration,
arXiv:2511.14593

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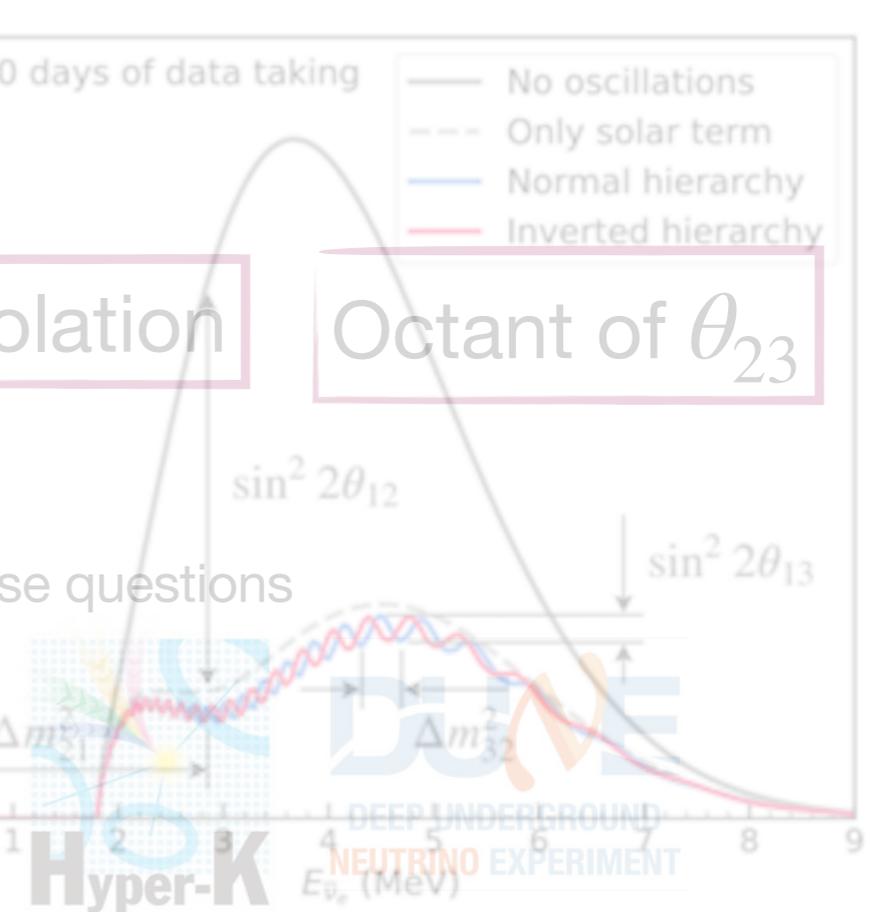
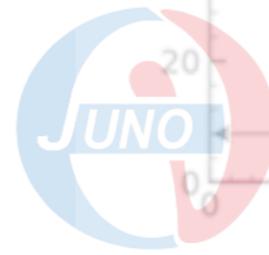
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Is this all?

SNO, Borexino,
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JUNO Collaboration,
arXiv:2511.14593

Neutrino masses

Open window on Physics BSM

Neutrino oscillations

$$m_\nu \neq 0$$



Only experimental evidence for BSM from the laboratory

Physics BSM

Unknown unknowns

What is the origin of ν masses?

Why is leptonic mixing so different from the quark one?

Are neutrinos Dirac or Majorana particles?

Do neutrinos have interactions beyond their SM ones?

What is the scale of NP?

Connections to other SM open problems (DM, BAU, ...)?

Index

Neutrino
oscillations

$$m_\nu \neq 0$$



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Physics BSM

Unknown unknowns

- Current status & known unknowns
- Origin of neutrino masses & pheno
- Connections to other SM open problems

Origin of neutrino masses

Effective Field Theory perspective

Single $d = 5$ operator in the SMEFT

$$\mathcal{O}_{d=5} = \frac{1}{\Lambda} (\bar{L}_L^c \tilde{H}^*) c_\nu (\tilde{H}^\dagger L_L)$$

S. Weinberg, Phys. Rev. Lett (1979)

Scale of New Physics

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Neutrinos are Majorana

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S. Weinberg, Phys. Rev. Lett (1979)

Neutrinos are Majorana

$$m_\nu = \frac{c_\nu v_H^2}{2\Lambda} \lesssim 0.1 \text{ eV}$$

For $c_\nu \sim 1$, Λ is at the GUT scale

No further experimental evidence beyond oscillations and $0\nu 2\beta$ decay

Origin of neutrino masses

Renormalizable operators

Introduce **RH counterpart**,
as for any other SM fermion

$$\mathcal{L} \supset - \bar{L}_L Y_\nu \tilde{H} N_R + h.c.$$

$$m_\nu = \frac{v Y_\nu}{\sqrt{2}}$$

No signal beyond oscillations
and direct mass measurements



Origin of neutrino masses

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SM singlet!



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Origin of neutrino masses

Type-I Seesaw

Introduce **RH counterpart**,
as for any other SM fermion

See e.g. Y. Cai *et al.*, arXiv:1711.02180
One of the three ways to generate
the Weinberg operator at tree-level

P. Minkowski, Phys. Lett. B (1977)
R. N. Mohapatra & G. Senjanovic, Phys. Rev. Lett (1980)
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SM singlet!



Origin of neutrino masses

Type-I Seesaw

Introduce **RH counterpart**,
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See e.g. Y. Cai *et al.*, arXiv:1711.02180
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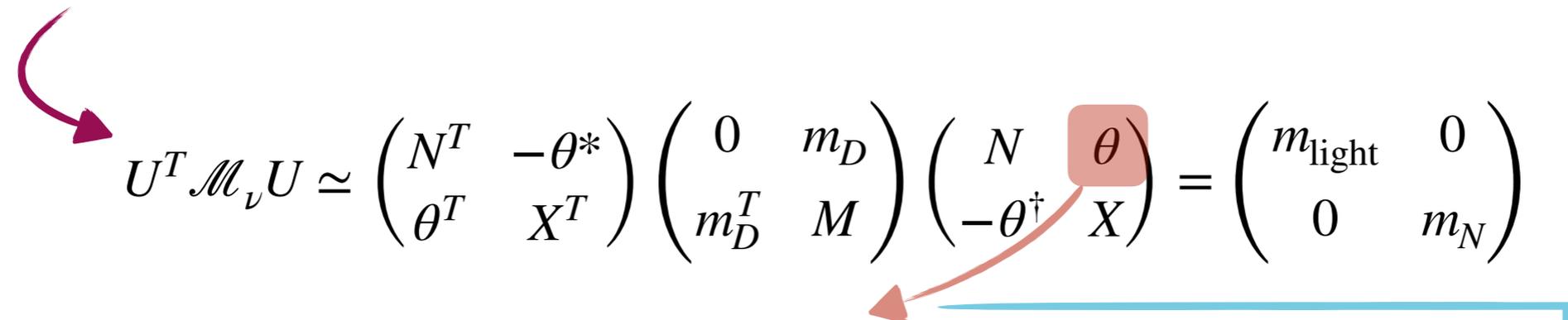
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Active-heavy mixing $\theta \sim m_D M^{-1} = v_H Y_\nu M^{-1} / \sqrt{2}$

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Mixing matrix measured
in oscillations: **not unitary**

$$\text{Only } N^\dagger N + \theta\theta^\dagger = \mathbb{1}$$

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Mixing matrix measured in oscillations: **not unitary**

$$N \simeq \begin{pmatrix} 1 - \alpha_{ee} & 0 & 0 \\ \alpha_{\mu e} & 1 - \alpha_{\mu\mu} & 0 \\ \alpha_{\tau e} & \alpha_{\tau\mu} & 1 - \alpha_{\tau\tau} \end{pmatrix} U_{\text{PMNS}} \quad \text{with } \alpha_{\beta\rho} = \frac{1}{1 + \delta_{\beta\rho}} (\theta\theta^\dagger)_{\beta\rho}$$

Origin of neutrino masses

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Modification of weak interactions

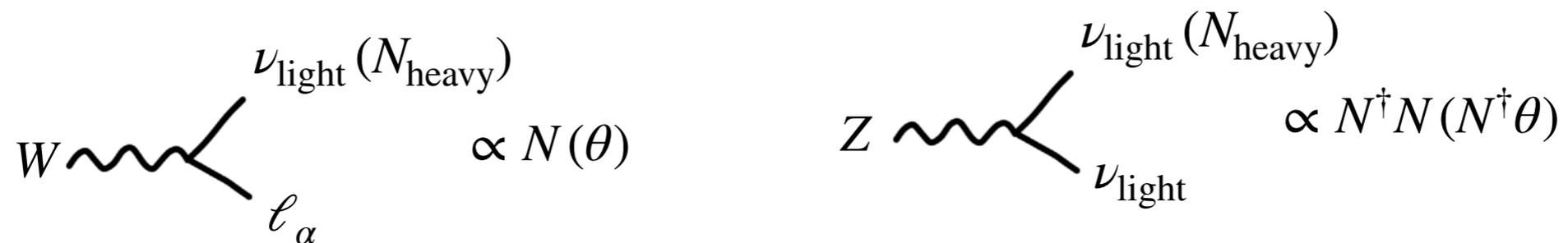
$$W \begin{matrix} \nearrow \nu_{\text{light}} (N_{\text{heavy}}) \\ \searrow \ell_\alpha \end{matrix} \propto N(\theta)$$

$$Z \begin{matrix} \nearrow \nu_{\text{light}} (N_{\text{heavy}}) \\ \searrow \nu_{\text{light}} \end{matrix} \propto N^\dagger N (N^\dagger \theta)$$

Origin of neutrino masses

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Modification of weak interactions

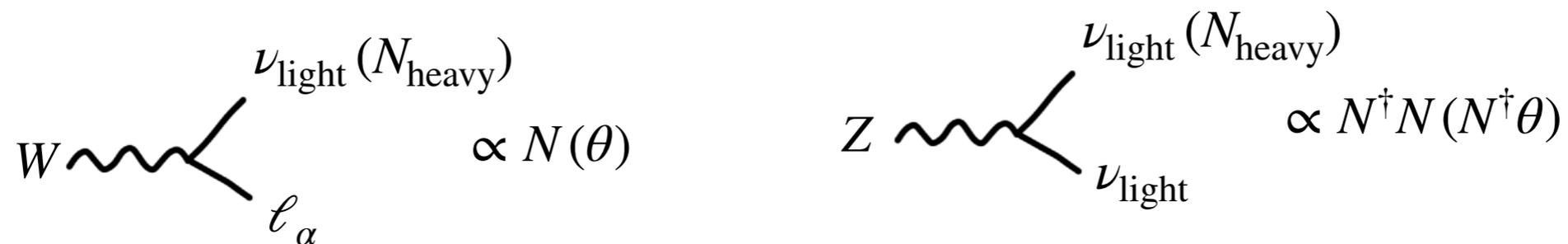


Signal to be searched for!

Origin of neutrino masses

Type-I Seesaw

Modification of weak interactions



Signal to be searched for!

What is the scale of NP?

$$\mathcal{L} \supset -\bar{L}_L Y_{\nu} \tilde{H} N_R - \frac{1}{2} \bar{N}_R^c M N_R + h.c.$$

Origin of neutrino masses

NP scale: theory perspective

Low-scale seesaw

Lightness of neutrino masses from approximate lepton number symmetry

Example: **Inverse Seesaw**

R. Mohapatra & J. Valle, '86

$$\mathcal{L} \supset - \bar{L}_L Y_\nu \tilde{H} N_R - \bar{N}_L M_D N_R - \frac{1}{2} \bar{N}_L^c \mu N_L + h.c.$$

Particular texture of the Majorana mass

Origin of neutrino masses

NP scale: theory perspective

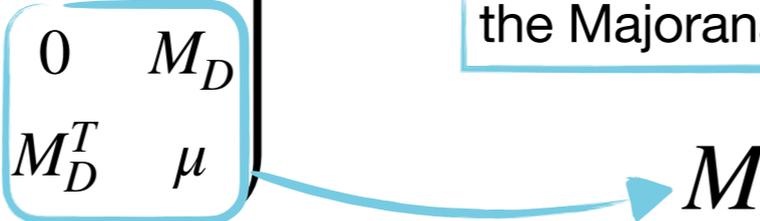
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$$\mathcal{M}_\nu = \begin{pmatrix} 0 & m_D & 0 \\ m_D^T & 0 & M_D \\ 0 & M_D^T & \mu \end{pmatrix}$$


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Only source of LNV

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$$\mathcal{M}_\nu = \begin{pmatrix} 0 & m_D & 0 \\ m_D^T & 0 & M_D \\ 0 & M_D^T & \mu \end{pmatrix}$$

$$\mu \ll m_D, M_D$$

$$m_{\text{light}} \sim \theta^2 \mu, \quad \theta \sim m_D M_D^{-1}$$

Even when $\mu \rightarrow 0$ we can have sizable θ

Rich experimental prospects!

What is the NP scale?

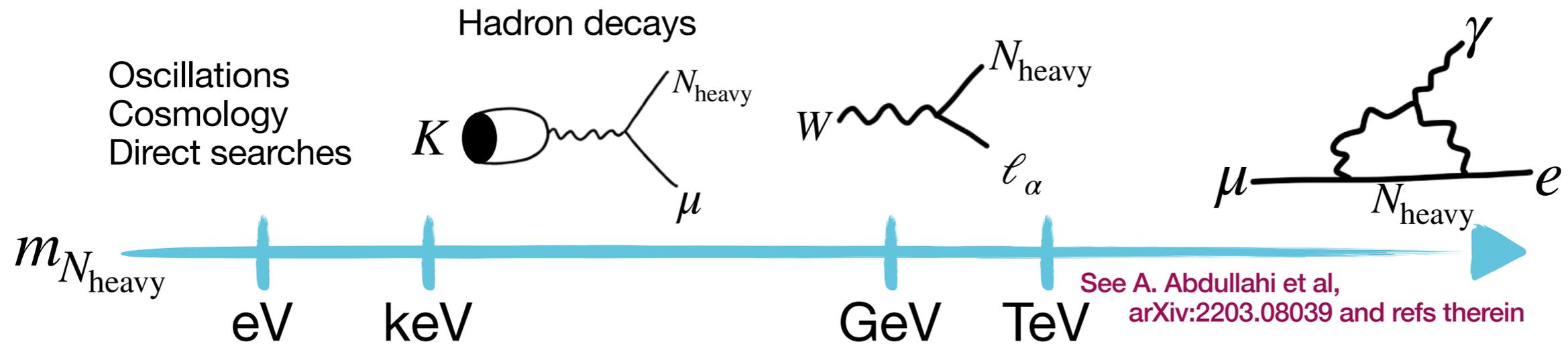
Experimental searches

$$\mathcal{L} \supset -\bar{L}_L Y_\nu \tilde{H} N_R - \frac{1}{2} \bar{N}_R^c M N_R + h.c.$$

$$\mathcal{L}_{CC} \supset -\frac{g}{\sqrt{2}} W_\mu \theta \bar{\ell}_\alpha \gamma^\mu P_L N_{\text{heavy}} + h.c.$$

$$\theta \sim v_H Y_\nu / M$$

Portal between **SM** and heavy neutrinos, controlled by mixing θ



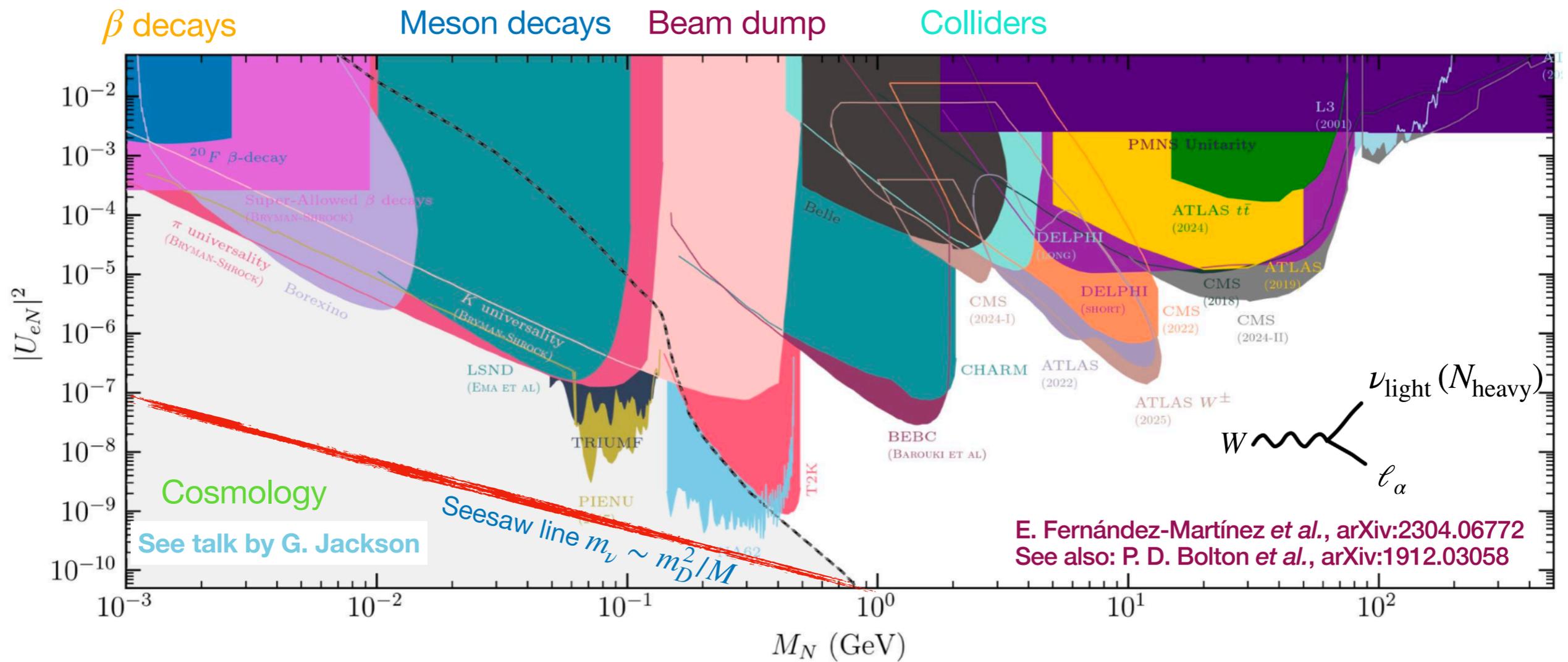
What is the NP scale?

Production at fixed-target and colliders



What is the NP scale?

Production at fixed-target and colliders



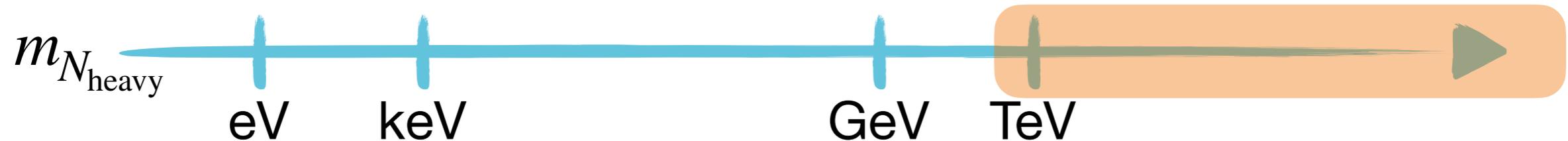
What is the NP scale?

Indirect constraints



What is the NP scale?

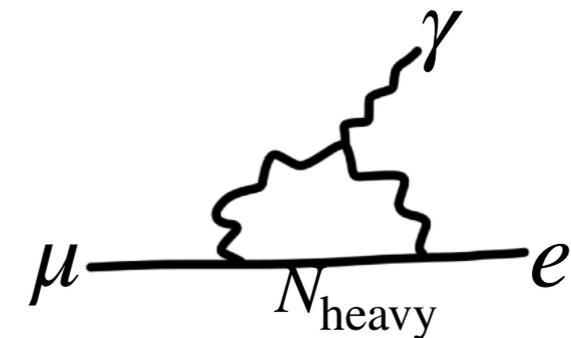
Indirect constraints



Z-boson invisible width

$$N^\dagger N = \mathbb{1} - \theta\theta^\dagger$$

Charged lepton flavor violation



$$\Gamma_{inv}^Z \sim \Gamma_{SM}^Z \left[1 - \frac{1}{3} (|\theta_{ei}|^2 + |\theta_{\mu i}|^2 + 4|\theta_{\tau i}|^2) \right]$$

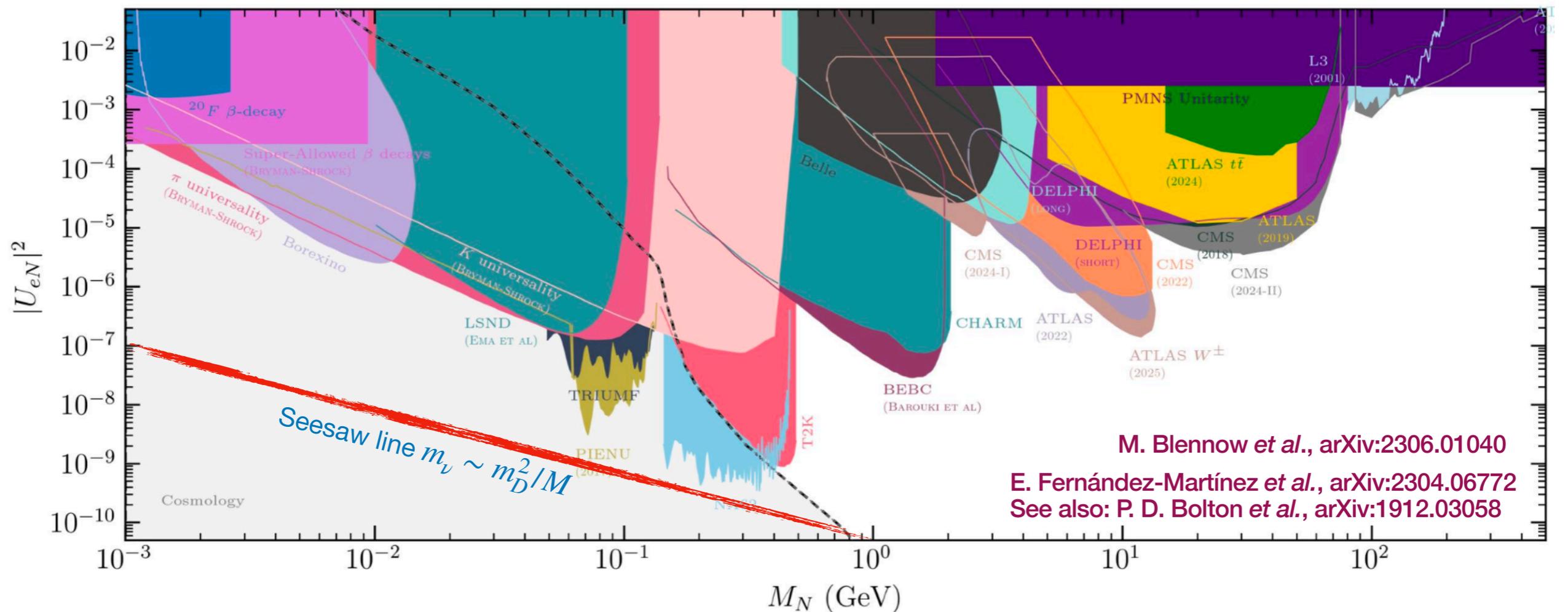
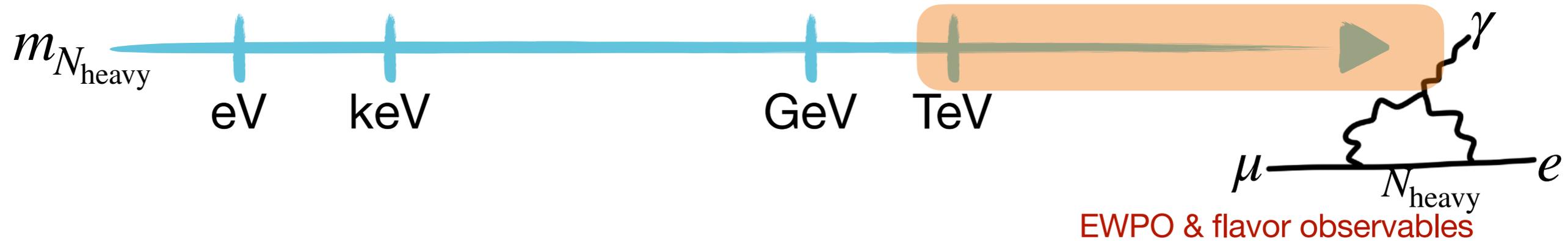
$$\mathcal{B}(\mu \rightarrow e\gamma) \propto |\theta_{ei}\theta_{\mu i}^*|^2$$

Global analysis of EWPO & searches for cLFV

M. Blennow *et al.*, arXiv:2306.01040

What is the NP scale?

Indirect constraints



Index

Neutrino
oscillations

$$m_\nu \neq 0$$



Only experimental evidence
for BSM from the laboratory

Physics BSM

Unknown unknowns

- Current status & known unknowns
- Origin of neutrino masses & pheno
- Connections to other SM open problems

Connection with other SM open problems

Baryogenesis

A. Ibarra & G. Ross,
arXiv:hep-ph/0312138

Need at least $2 N_R$ to
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ARS leptogenesis

Generation of the **BAU** through **oscillations and scatterings: at least one HNL out-of-equilibrium**

E. K. Akhmedov, V. Rubakov and A. Y. Smirnov, '98
P. Hernandez *et al.*, arXiv:1508.03676
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See M. Drewes *et al.*, arXiv:171102862 for a review

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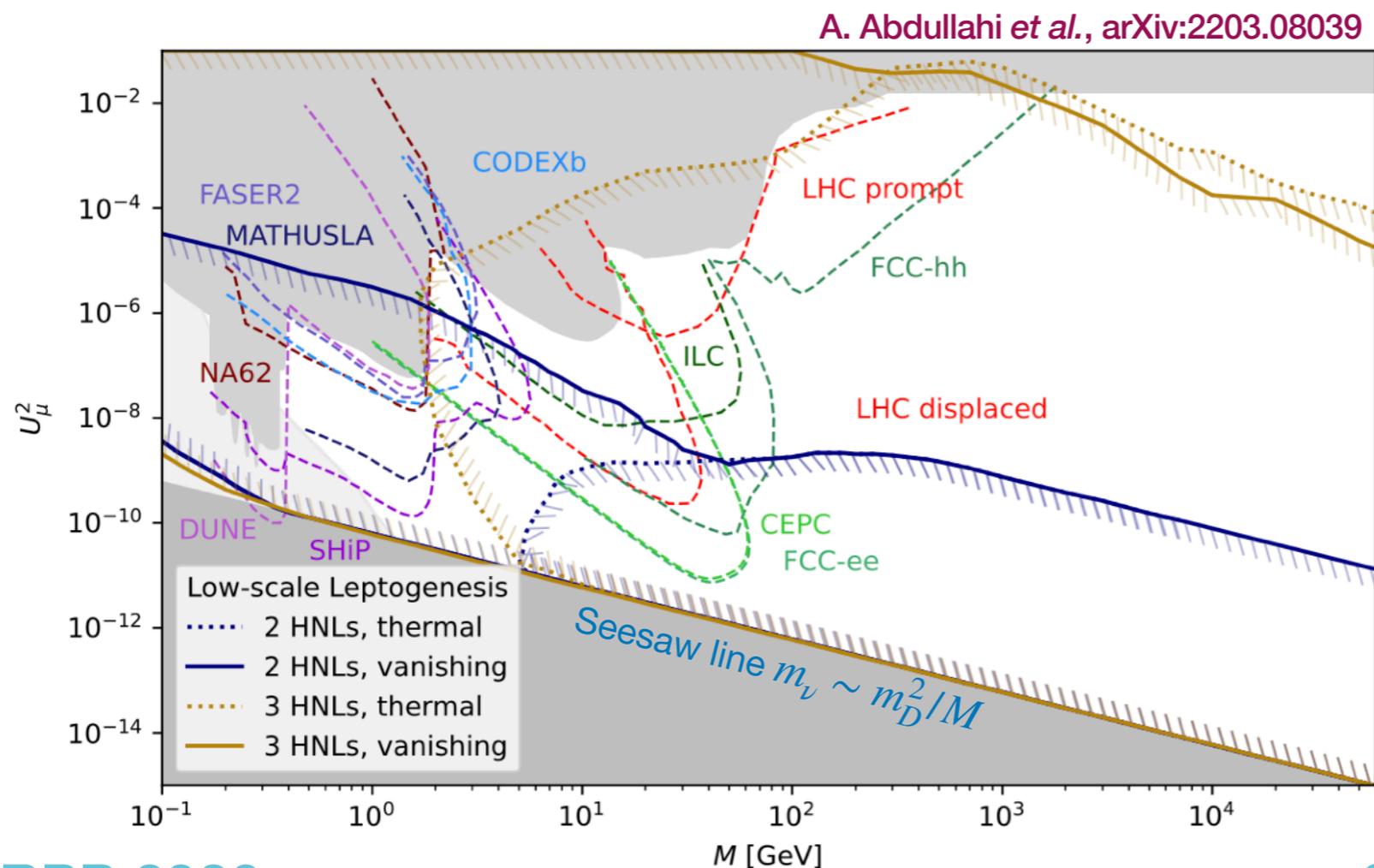
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Adding an **additional** N_R , its **mass** lies at $\mathcal{O}(\text{keV})$ **scale and its mixing is suppressed**

Good DM candidate! S. Dodelson & L. Widrow, arXiv: hep-ph/9303287

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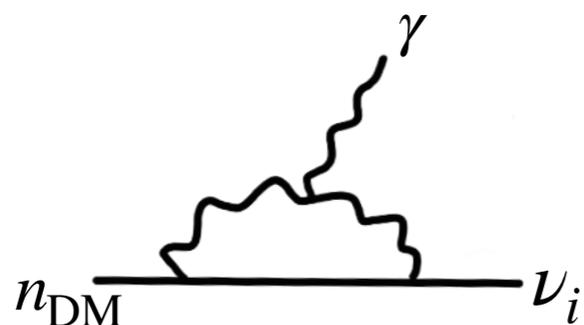
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Signal completely **unrelated** to that
searched for in **direct DM experiments**



$$\propto G_F^2 \left| \theta_{\alpha\text{DM}} \right|^2 m_{\text{DM}}^5$$

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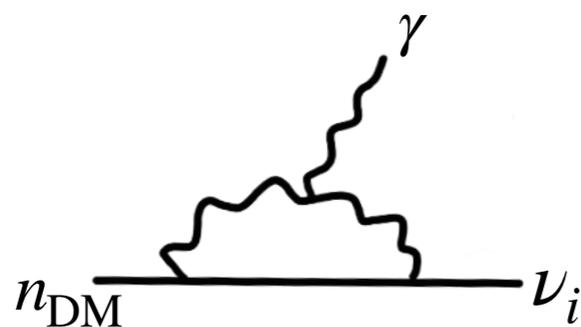
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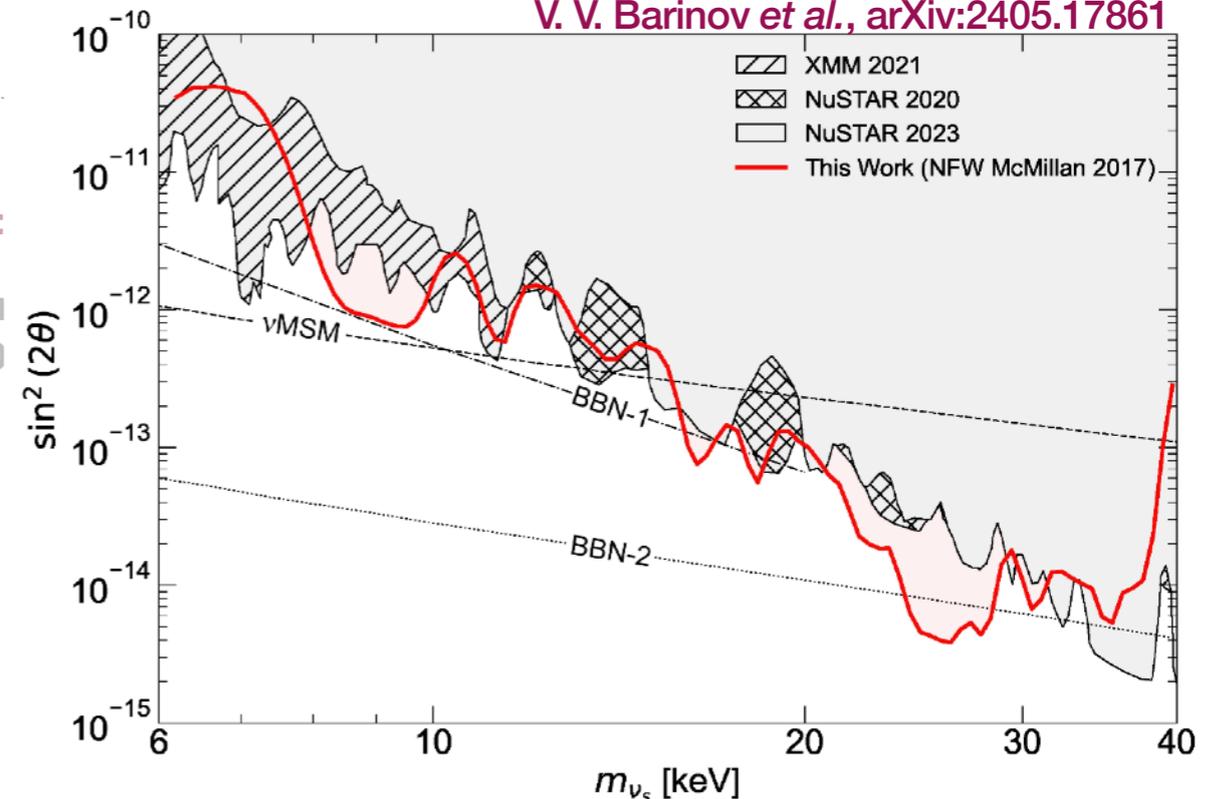
S. Dodelson & L. Widrow, arXiv:

Signal completely unsearched for in direct D

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X. Shi & G. M. Fuller, arXiv:astro-ph/9810076

M. Shaposhnikov, arXiv:0804.4542

J. Ghiglieri & M. Laine, arXiv:2004.10766

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Allowed parameter space with L-asymmetry

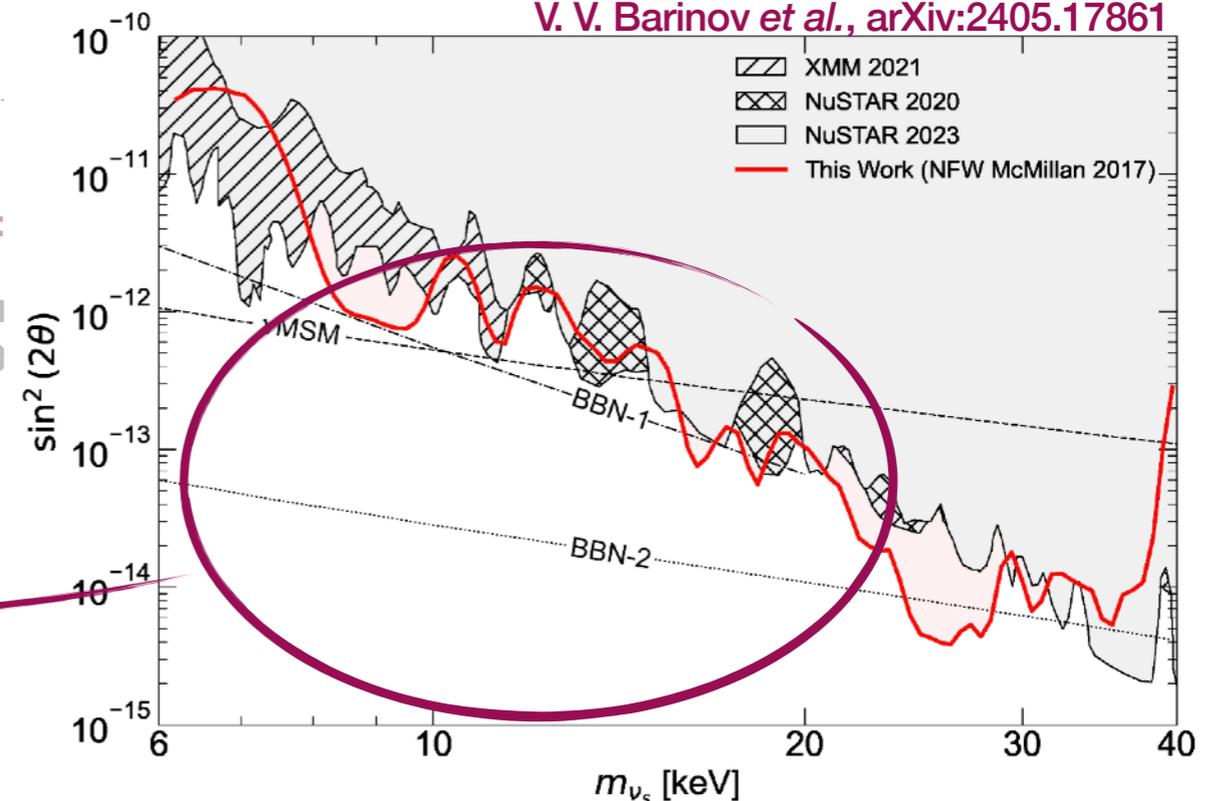
See talk by J. Froustey

n_{DM}

$$\propto G_F^2 |\theta_{\alpha\text{DM}}|^2 m_{\text{DM}}^5$$

ν_i

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At $T \sim 100$ GeV

Freeze-in via 2-body decays

$$N_{\text{heavy}} \rightarrow h + n_{\text{DM}}$$

Mixing suppressed!

(Even more so at $T \neq 0$)

A. Abada et al., arXiv:1406.6556
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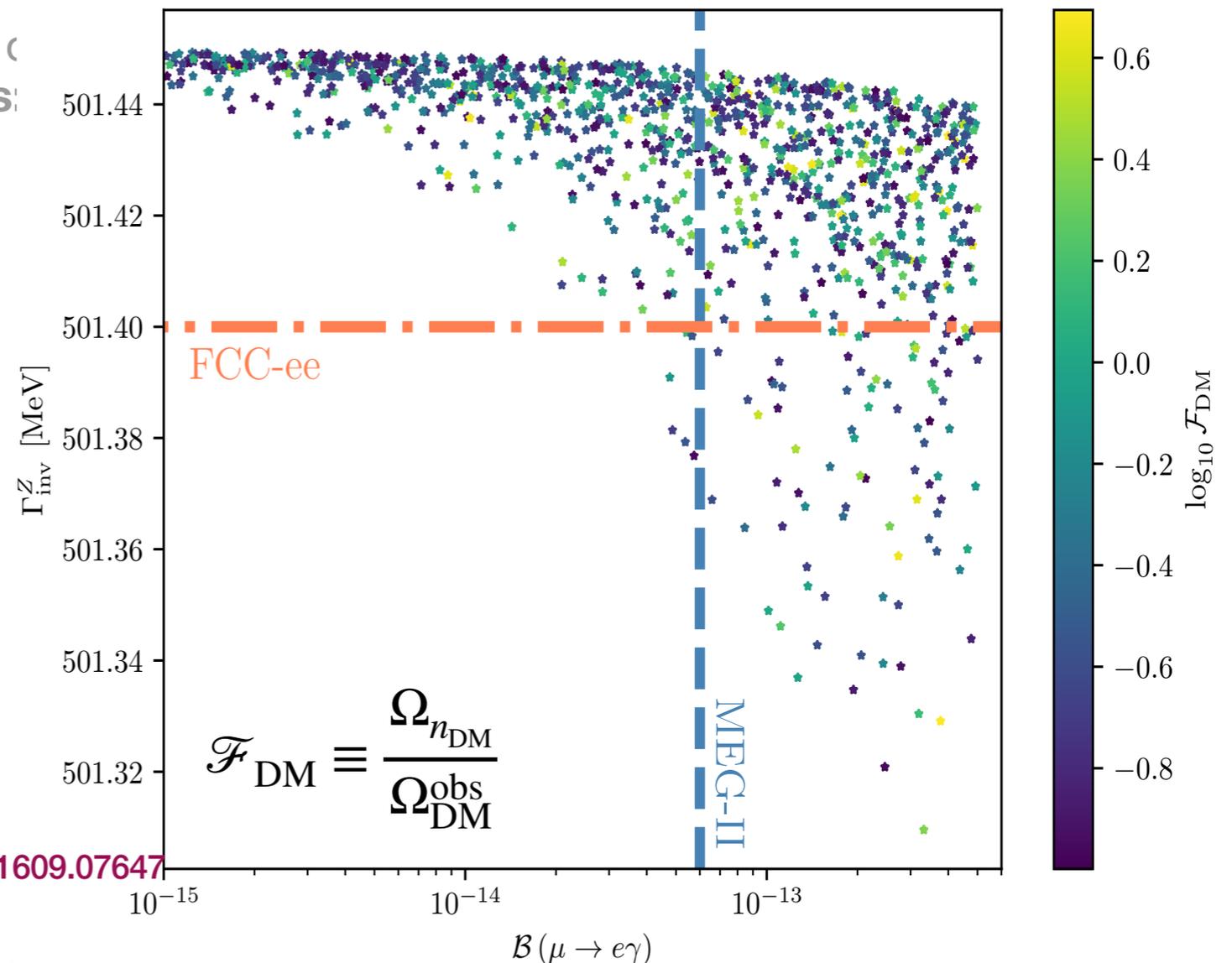
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A. Abada, G. Arcadi, M. Lucente & SRA, arXiv:2503.20017



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Generation α scatterings:

MEG-II already improved bounds

Sterile ν dark matter

$\mu - e$ conversion in nuclei will also be improved in the future

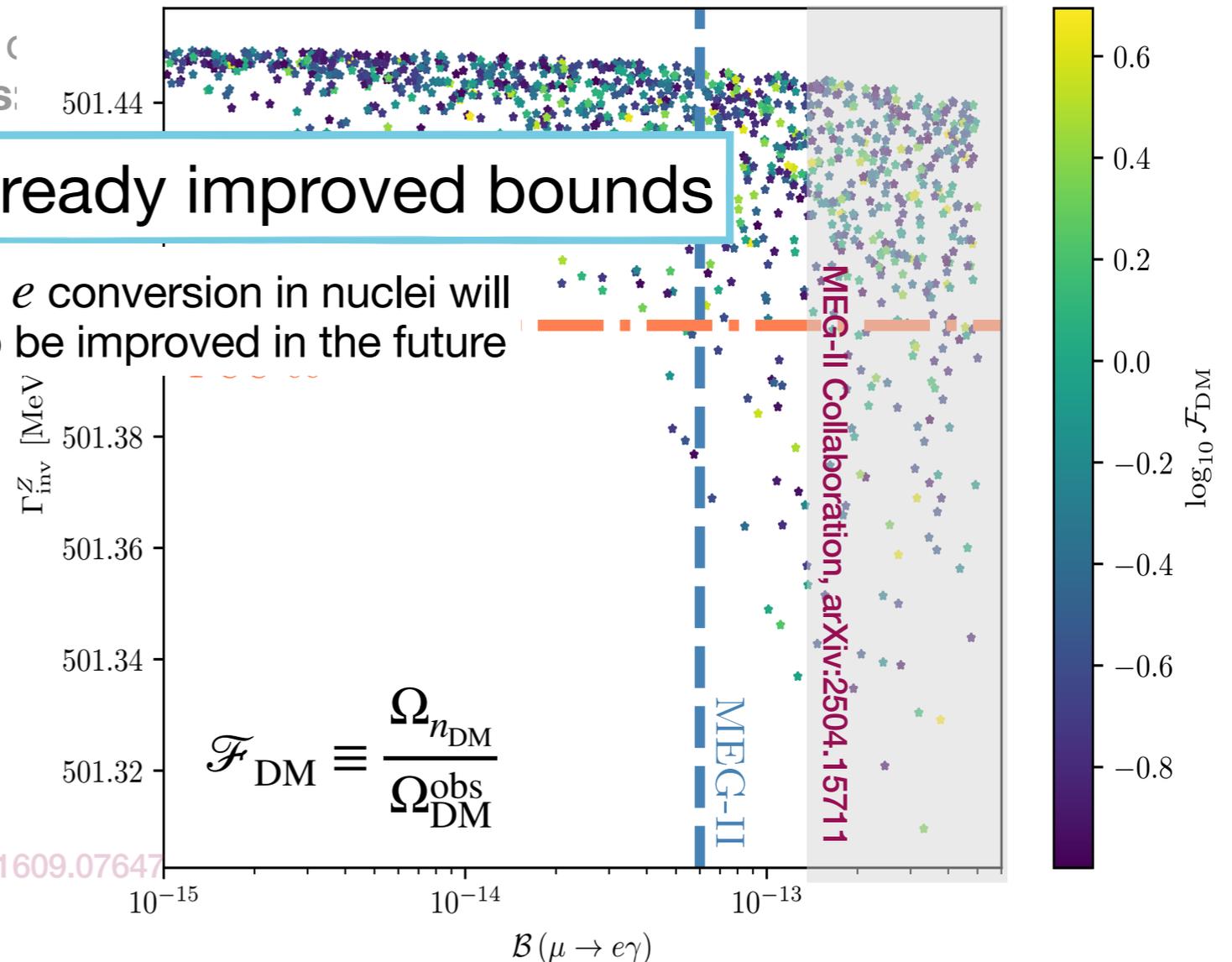
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Connection with other SM open problems

Neutrino portal

$$\mathcal{L} \supset -\bar{L}_L Y_\nu \tilde{H} N_R - \frac{1}{2} \bar{N}_R^c M N_R + h.c.$$

SM singlet!

What if N_R is part of a more complex BSM sector?

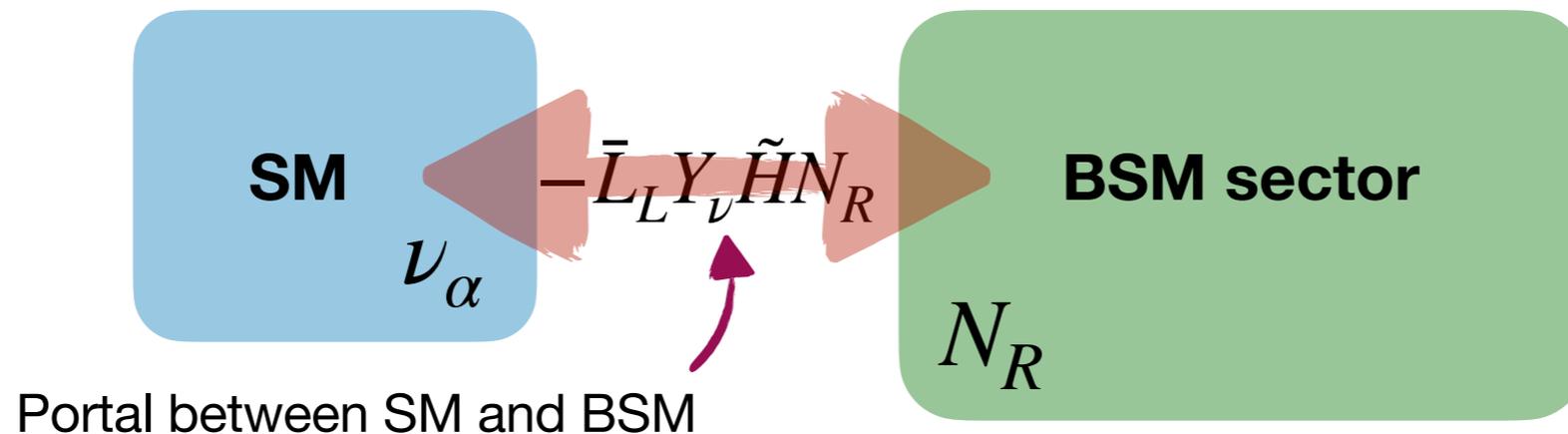
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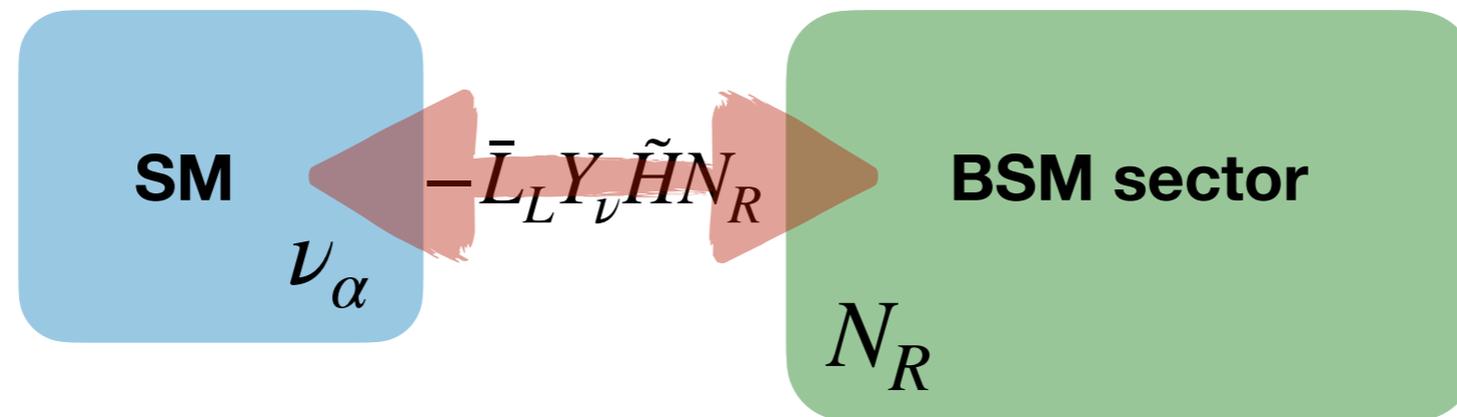
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Only renormalizable SM coupling to singlet fermions

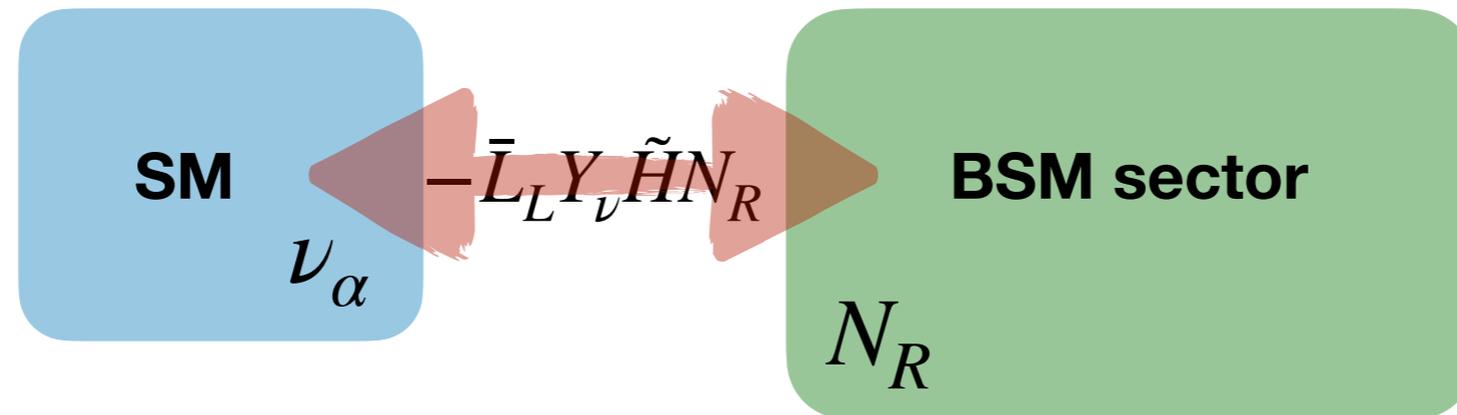
Other portals are:

Scalar portal ϕ , $\mathcal{L} \sim \lambda_{H\phi} |\phi|^2 (H^\dagger H)$

Vector portal Z'_μ , $\mathcal{L} \sim -\epsilon Z'_{\mu\nu} B^{\mu\nu}$

Connection with other SM open problems

Neutrino portal



Dark sector coupled to (heavier) N_R

Could have DM- ν interactions through active-heavy mixing

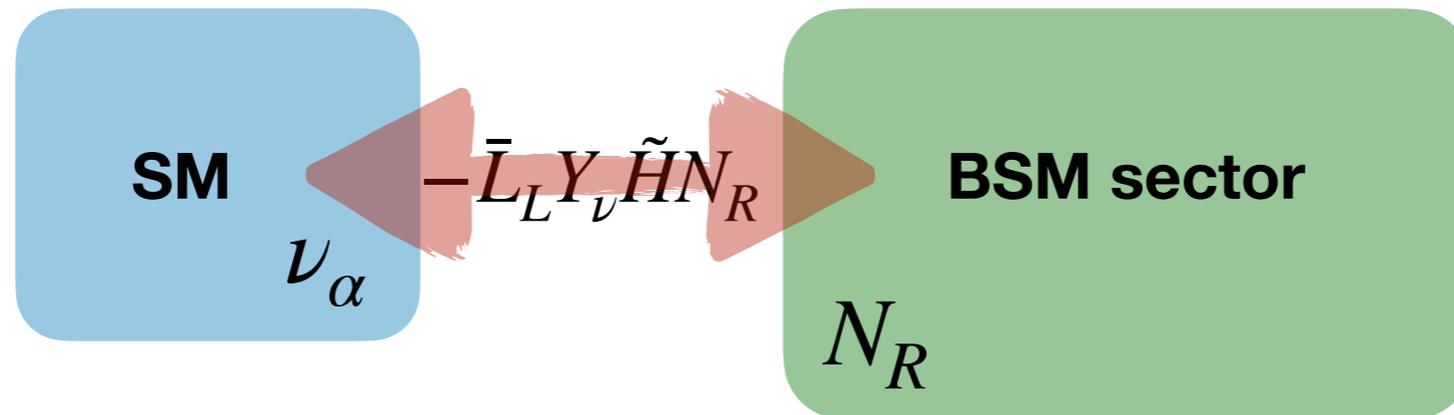
M. Blennow et al (SRA), arXiv:1903.00006;
B. Batell et al, arXiv:170907001;
Escudero et al, arXiv:1606.01258

In general have N_R , DM and a mediator

Avoid (in)direct detection experiments

Connection with other SM open problems

Neutrino portal



Dark sec

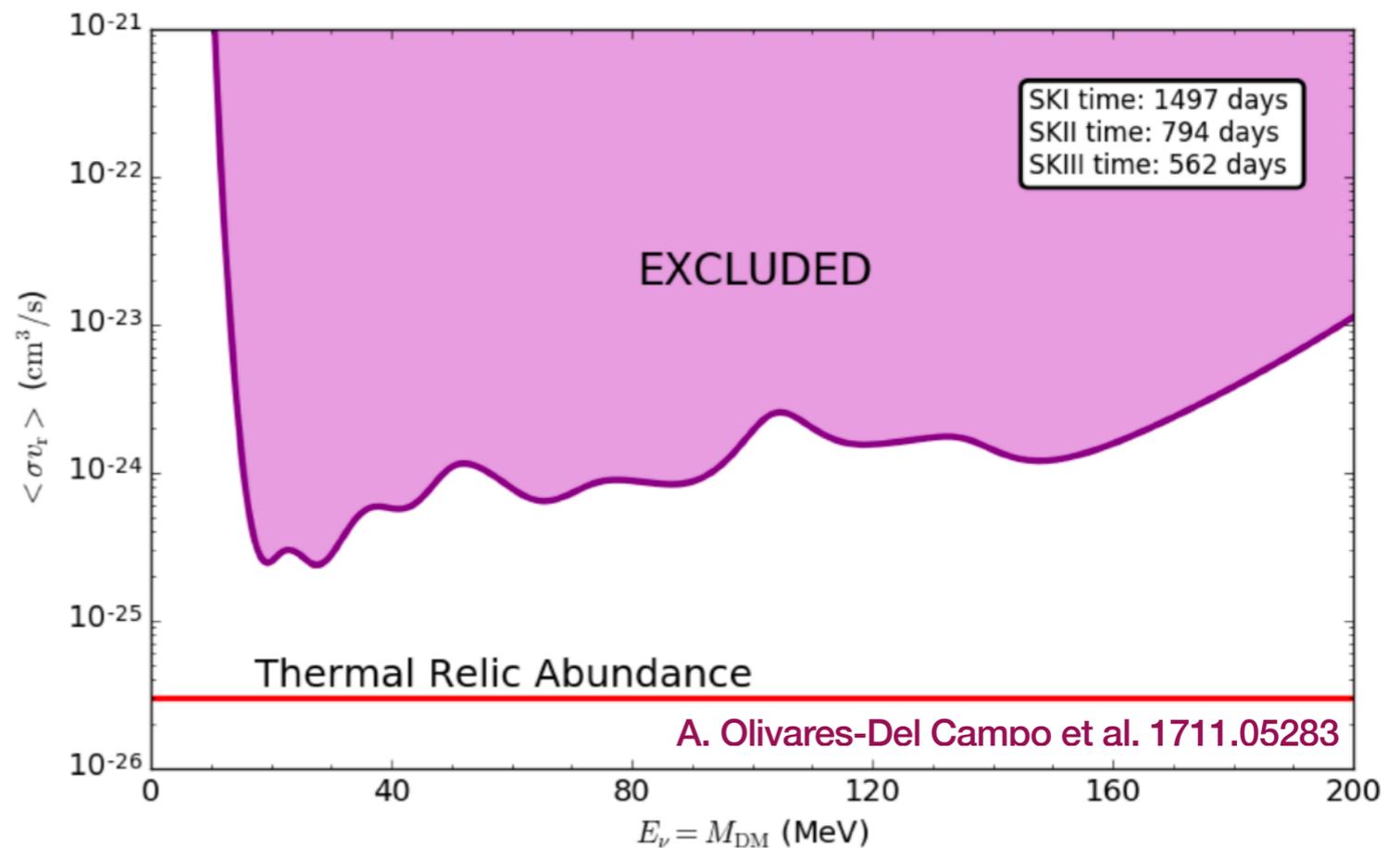
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In general I

How do we look for DM?

Neutrino detectors



Conclusions

- **Neutrino oscillations** mean non-zero **neutrino masses**

Compelling hint of **new physics**

- **Great experimental effort** to complete the 3ν oscillation picture

Need for a **corresponding theoretical effort** to improve predictions and **reduce systematics**

Era of precision in neutrino physics!

Great effort to **extend future experiments beyond 3ν oscillations**

- Including N_R to explain m_ν offers **rich phenomenology**

Collider searches, $0\nu 2\beta$ decay, **cosmology**, **non-unitarity**, **flavor violation...**

- **Connection** to other **SM open problems**

Baryogenesis, **dark matter**, **flavor puzzle...**

- N_R **as link** between **SM** and other **BSM sectors**

Thank you!

Back up slides

Neutrino sector

Known unknowns

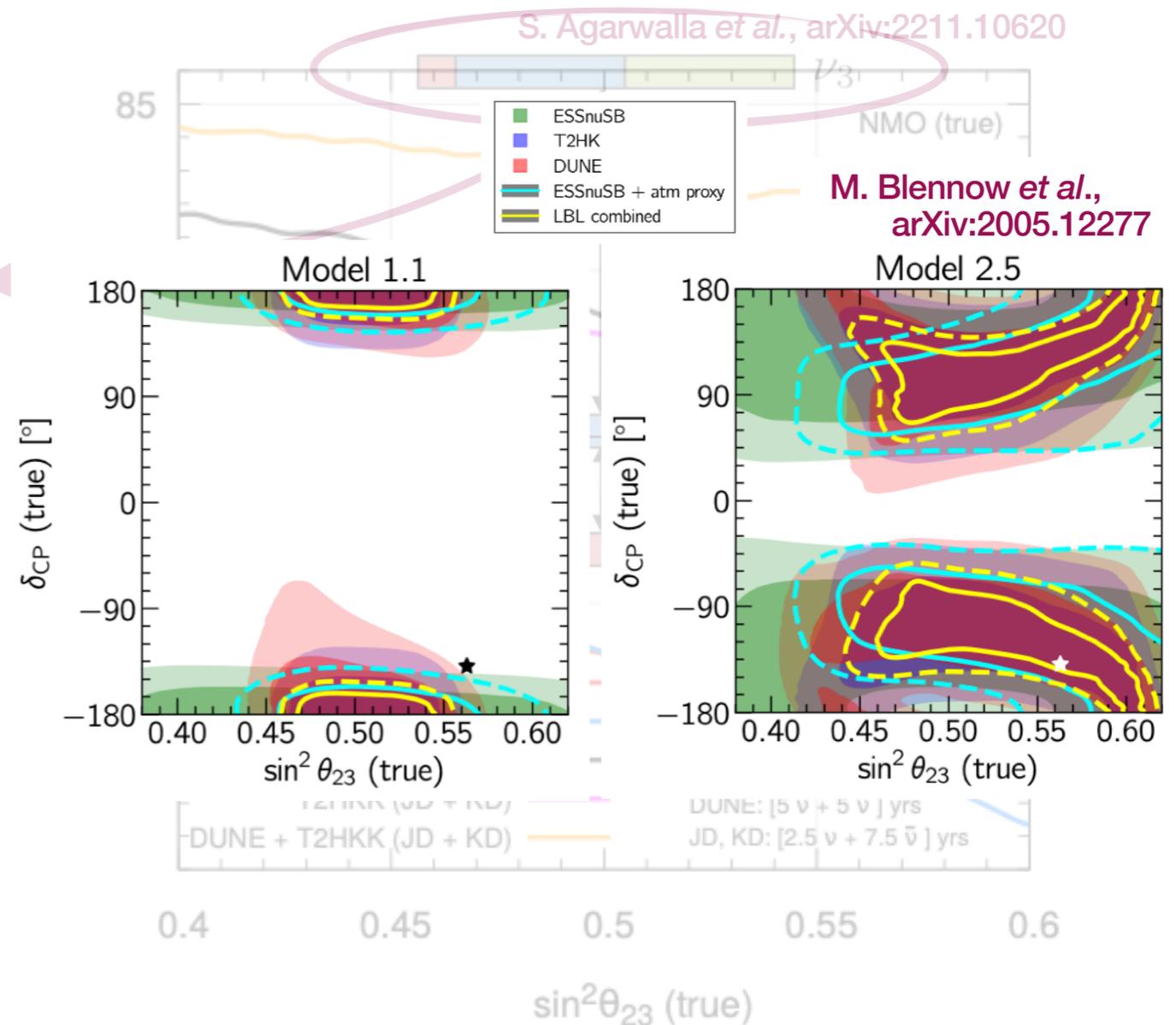
Octant of θ_{23}

Does ν_3 have more ν_μ or ν_τ content? ◀

Precise determination allows to

Improve prospects for CP violation

Constrain models tackling the flavor problem



Neutrino sector

Known unknowns

Majorana or Dirac?

$$1/T_{1/2}^{0\nu} = G^{0\nu} [M^{0\nu}]^2 m_{\beta\beta}^2$$

$0\nu 2\beta$ half-lifetime

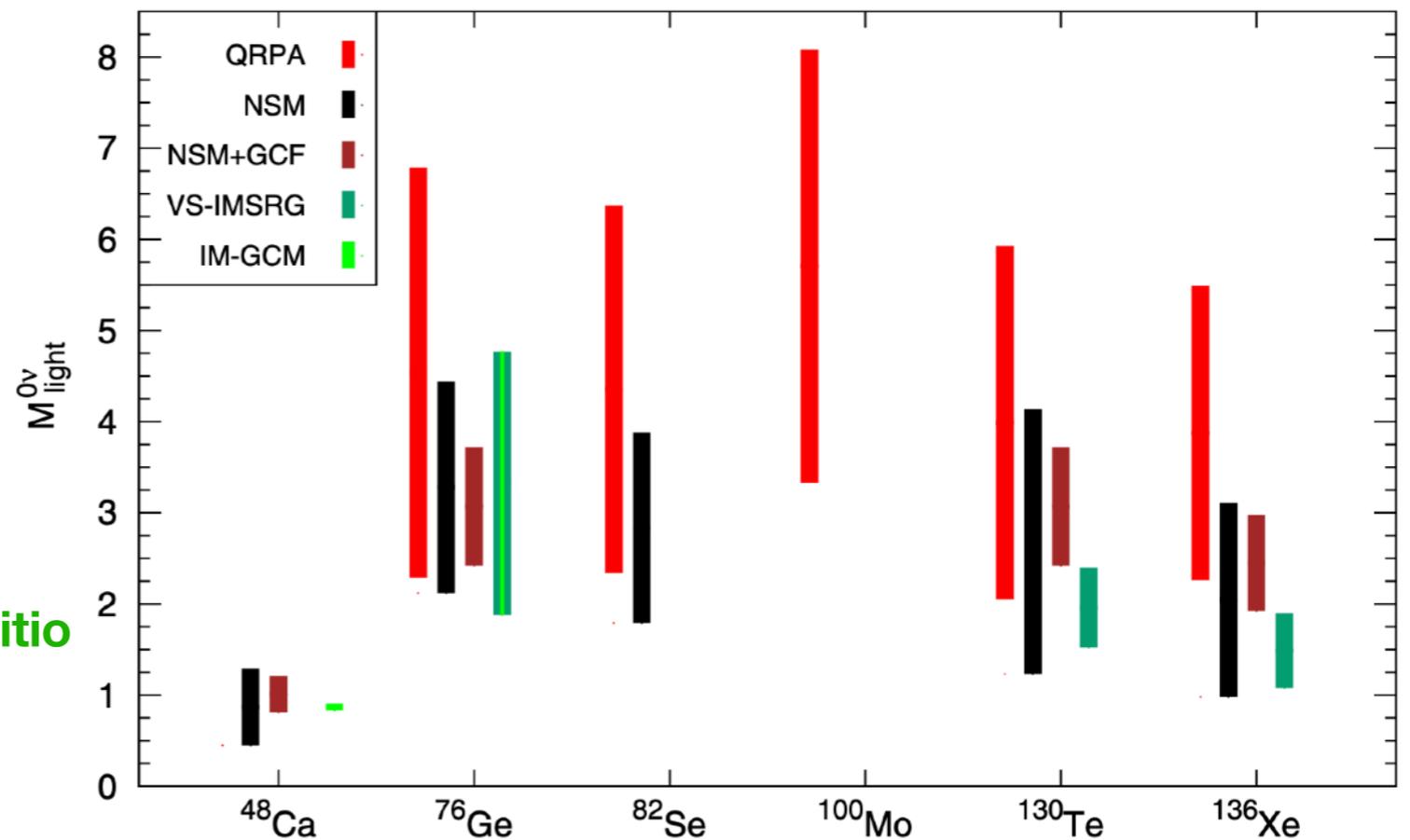
Nuclear matrix element

V. Cirigliano *et al.*, arXiv:1802.10097

M. Agostini *et al.*, arXiv:2202.01787

Great progress to reduce uncertainties: **ab-initio computations**, inclusion of **short-range contribution**

J. J. Gómez-Cadenas *et al.*, '23



Origin of neutrino masses

NP scale: theory perspective

New scale not related to EW symmetry breaking!

$$\mathcal{L} \supset -\bar{L}_L Y_\nu \tilde{H} N_R - \frac{1}{2} \bar{N}_R^c M N_R + h.c.$$

$$\theta \sim m_D M^{-1} = v_H Y_\nu M^{-1} / \sqrt{2}$$

High-scale seesaw

Lightness of neutrino masses from hierarchy between v_H and M

J. Dror et al, '19; S.F. King et al, '20; W. Buchmuller et al, '19; F. Vissani, '97; J. A. Casas et al, '04, I. Brivio & M. Trott, '17

See A. M. Abdullahi et al, arXiv:2203.8039 for longer list of references

$$Y_\nu \sim 1, \quad M \sim \mathcal{O}(10^{14}) \text{ GeV}$$

$$m_\nu \sim -m_D M^{-1} m_D^T$$



Leptogenesis
Embedding in GUTs

M. Fukugita & T. Yanagida, '86; J. A. Harvey & M. S. Turner, '90; M. Plumacher et al., '96; L. Covi et al., '96



Hierarchy problem
Experimentally untestable!

$$\theta \sim 10^{-12}$$

Origin of neutrino masses

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$$\theta \sim m_D M^{-1} = v_H Y_\nu M^{-1} / \sqrt{2}$$

Low-scale seesaw

Smallness of neutrino masses from approximate lepton number symmetry

$$Y_\nu \sim 0.1, \quad M \sim \mathcal{O}(10^{2-3}) \text{ GeV}$$

See e.g. R. Mohapatra & J. Valle, '86; J. Bernabeu et al, '87; M. Malinsky et al., '05; B. Gavela et al., '09; E. K. Akhmedov et al, '95

E. K. Akhmedov et al, '98; T. Asaka & M. Shaposhnikov, '05; P. Hernández et al, '15; A. Pilaftsis & T. E. J. Underwood, '03

M. Shaposhnikov, '08;
J. Ghiglieri & M. Laine, '20

See P. Agrawal et al, '21 and A. Abdullahi et al, '22

Resonant/ARS leptogenesis ✓

Connection to DM ✓

In reach for experiments!

$$\theta \sim 10^{-2}$$

Origin of neutrino masses

Low-scale seesaw

Lightness of neutrino masses from approximate lepton number symmetry

Example: **Inverse Seesaw**

R. Mohapatra & J. Valle, '86

$$\mathcal{L} \supset -\bar{L}_L Y_\nu \tilde{H} N_R - \bar{N}_L M_D N_R - \frac{1}{2} \bar{N}_L^c \mu N_L + h.c.$$

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & m_D & 0 \\ m_D^T & 0 & M_D \\ 0 & M_D^T & \mu \end{pmatrix}$$

$$\mu \ll m_D, M_D$$

$$m_{\text{light}} \sim \theta^2 \mu, \quad \theta \sim m_D M_D^{-1}$$

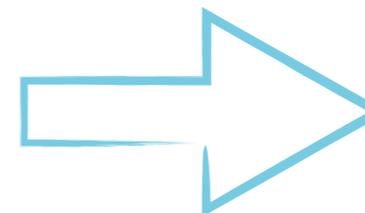
Even when $\mu \rightarrow 0$ we can have sizable θ

Introduce n_{N_L} of N_L and n_{N_R} of N_R

Rich experimental prospects!

n_{N_R} pseudo-Dirac pairs with $m_{N_{\text{heavy}}} \sim M_D$

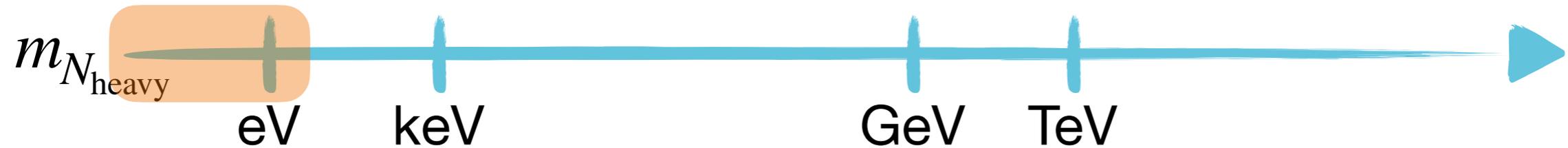
$n_{N_L} - n_{N_R}$ Majorana singlets with $m_{N_{\text{heavy}}} \sim \mu$



Hierarchy of masses

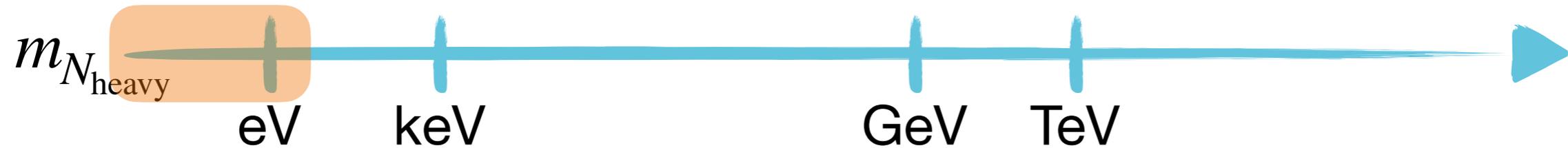
What is the NP scale?

Looking for NP at oscillation experiments



What is the NP scale?

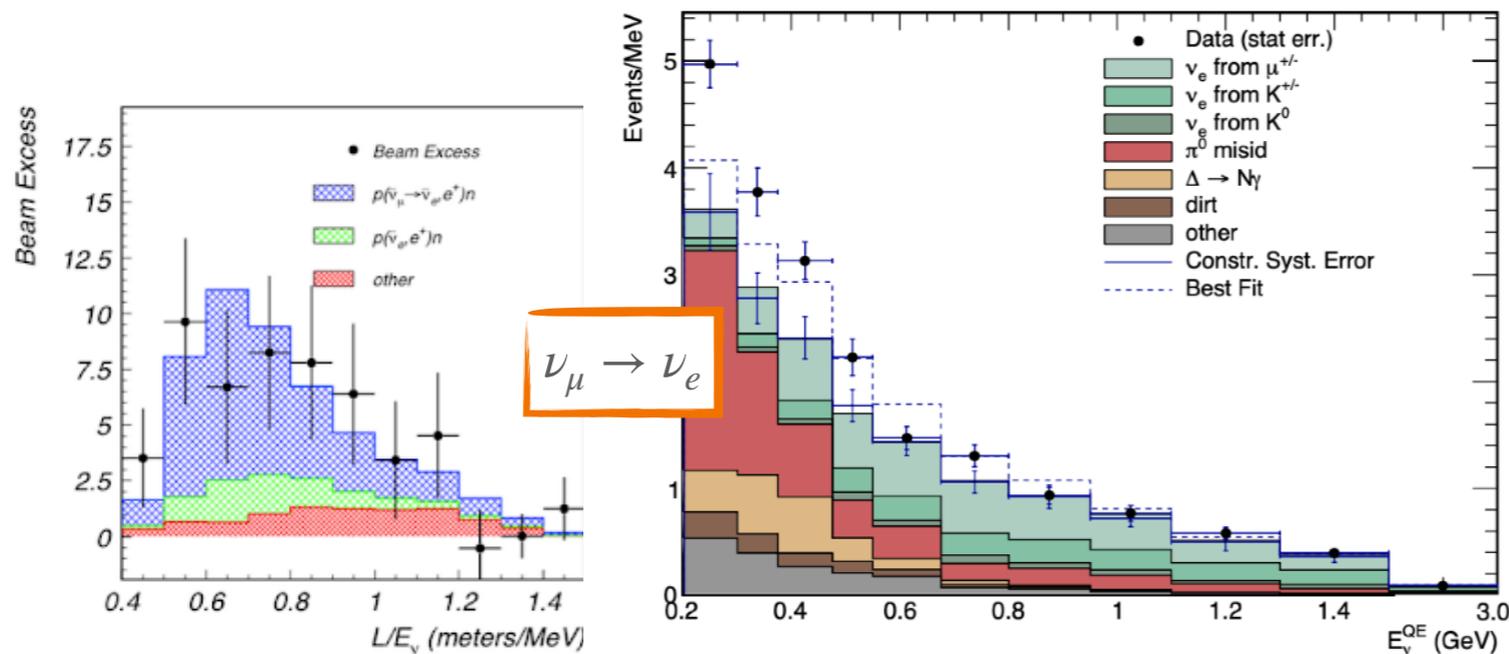
Looking for NP at oscillation experiments



Anomalies over the years in ν

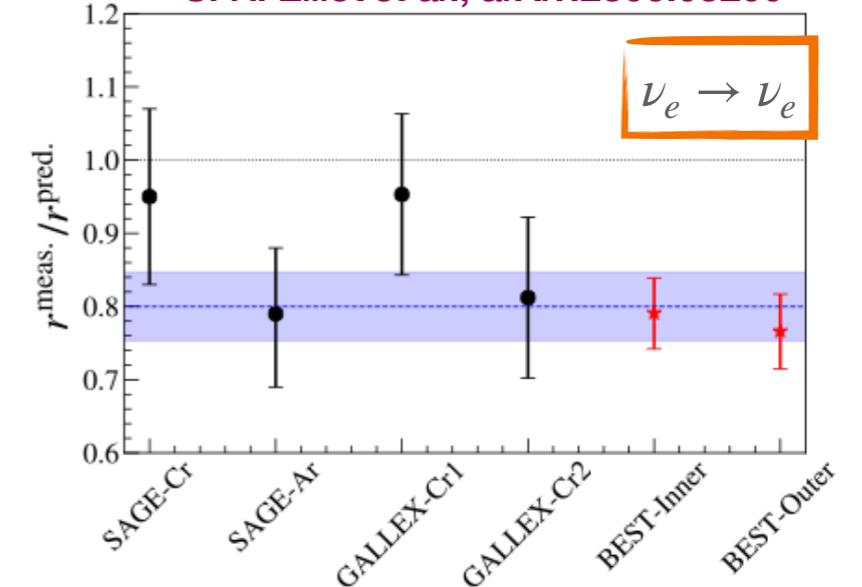
$$P_{\alpha\beta} = \sin^2 2\theta_{\alpha\beta} \sin^2 \left(\frac{\Delta m_{41}^2 L}{4E} \right)$$

MiniBooNE Collaboration, arXiv:1805.12028



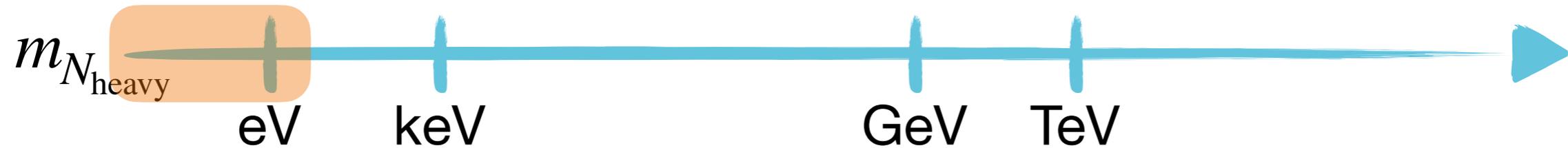
LSND Collaboration, arXiv: hep-ex/0104049

S. R. Elliot et al., arXiv:2306.03299



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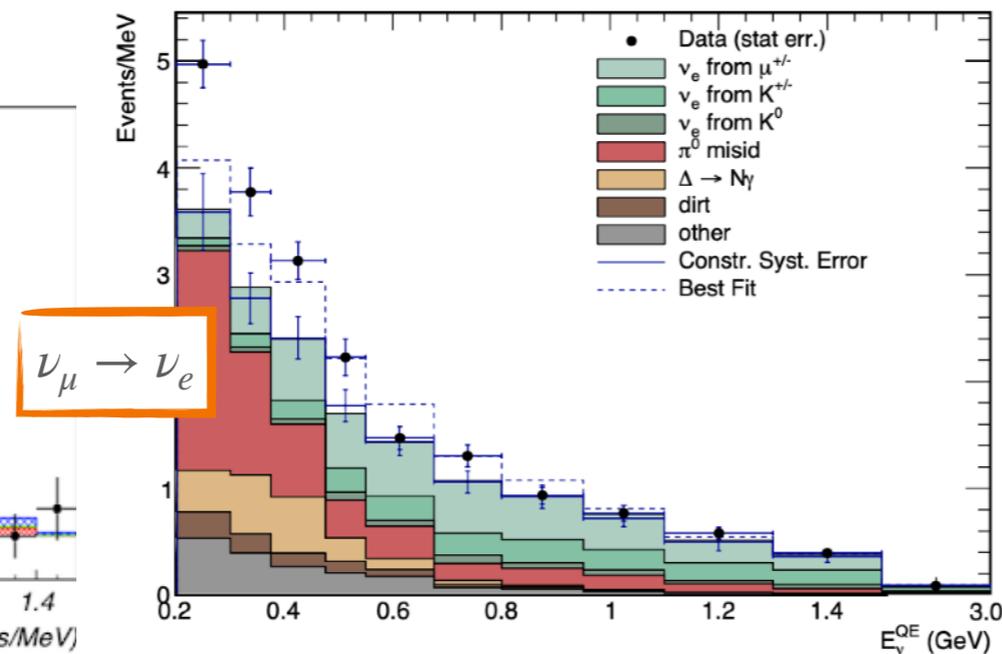
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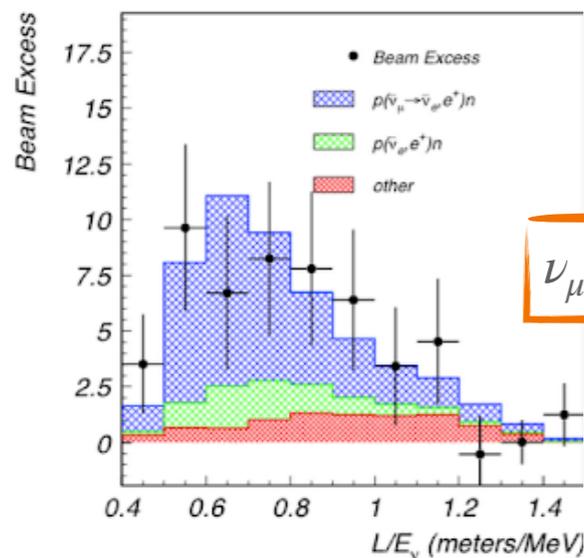
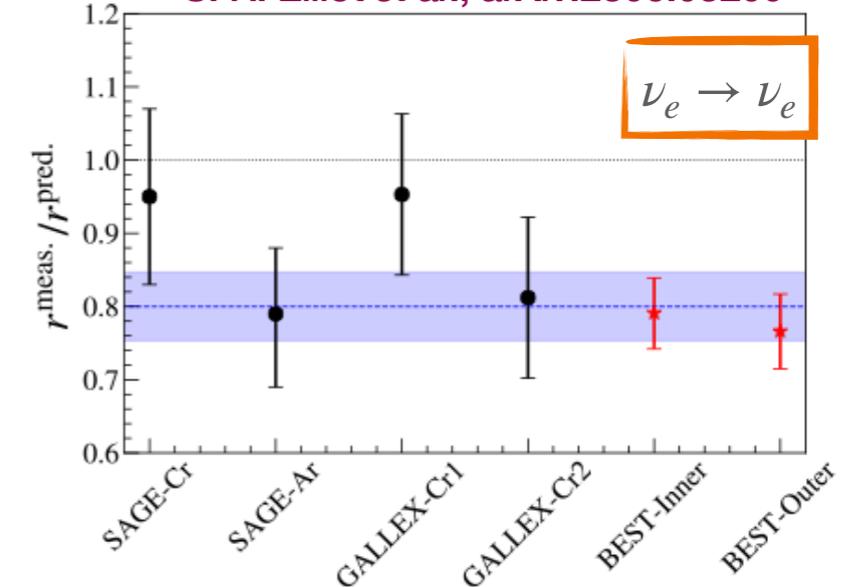
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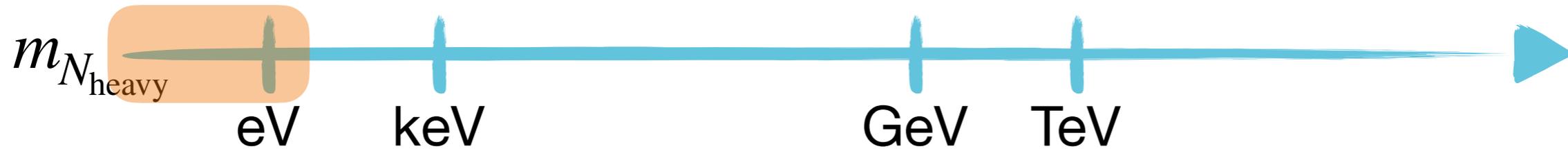
LSND Collaboration, arXiv: hep-ex/0104049

We are entering an era of **precision in neutrino physics**

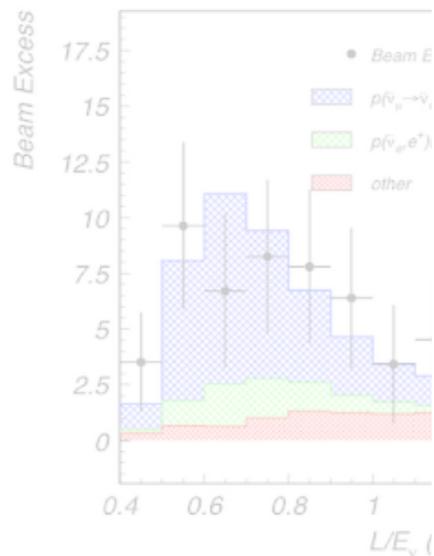
Use next-generation experiments beyond standard oscillations

What is the NP scale?

Looking for NP at oscillation experiments



Anomalies over the years in ν

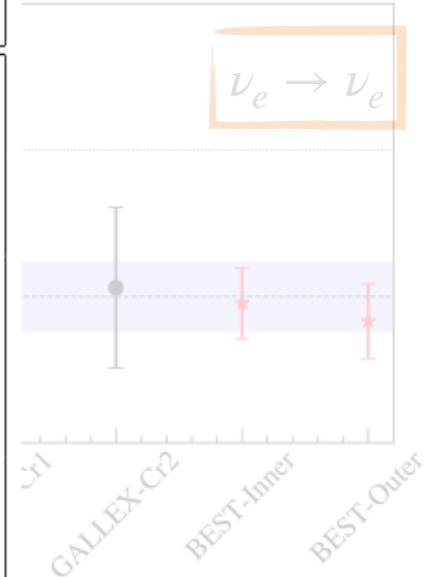


LSND Collaboration, arXiv:

	High-scale Non-Unitarity ($m > \text{EW}$)	Low-scale Non-Unitarity $\Delta m^2 \gtrsim 100 \text{ eV}^2$ $\Delta m^2 \sim 0.1 - 1 \text{ eV}^2$	
α_{ee}	$1.3 \cdot 10^{-3}$ [60]	$2.4 \cdot 10^{-2}$ [61]	$1.0 \cdot 10^{-2}$ [61]
$\alpha_{\mu\mu}$	$2.2 \cdot 10^{-4}$ [60]	$2.2 \cdot 10^{-2}$ [62]	$1.4 \cdot 10^{-2}$ [63]
$\alpha_{\tau\tau}$	$2.8 \cdot 10^{-3}$ [60]	$1.0 \cdot 10^{-1}$ [62]	$1.0 \cdot 10^{-1}$ [62]
$ \alpha_{\mu e} $	$6.8 \cdot 10^{-4}$ ($2.4 \cdot 10^{-5}$) [60]	$2.5 \cdot 10^{-2}$ [64]	$1.7 \cdot 10^{-2}$
$ \alpha_{\tau e} $	$2.7 \cdot 10^{-3}$ [60]	$6.9 \cdot 10^{-2}$	$4.5 \cdot 10^{-2}$
$ \alpha_{\tau\mu} $	$1.2 \cdot 10^{-3}$ [60]	$1.2 \cdot 10^{-2}$ [65]	$5.3 \cdot 10^{-2}$

$$\left(\frac{\Delta m_{41}^2 L}{E} \right)$$

arXiv:2306.03299



Limits on non-unitarity parameters

What is the NP scale?

Looking for NP at oscillation experiments

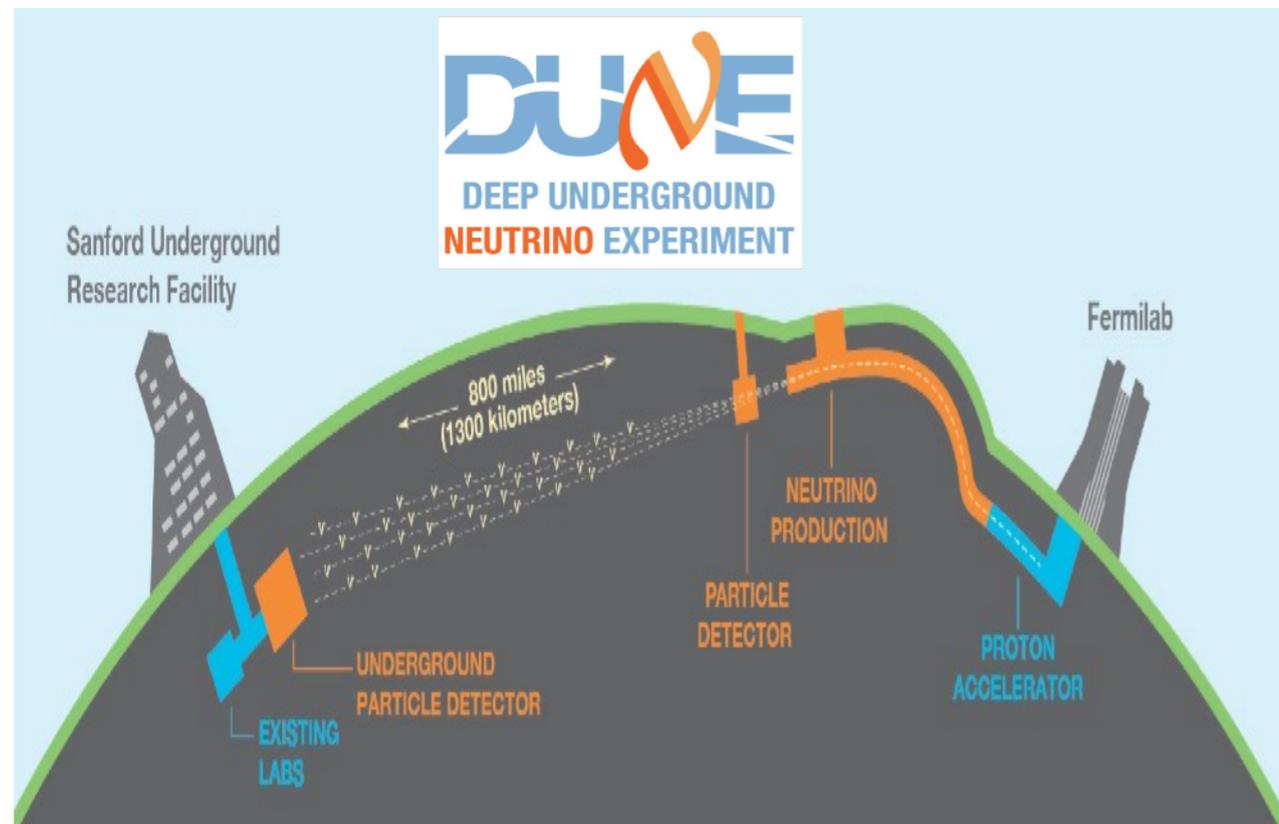
We are entering an era of **precision in neutrino physics**

Use next-generation experiments beyond standard oscillations

Near detectors will have infinite statistics



Systematic uncertainties will be the bottleneck!



For physics @ FD, we use ND to mitigate systematics

For the ND, we do not have a nearer detector to do the same

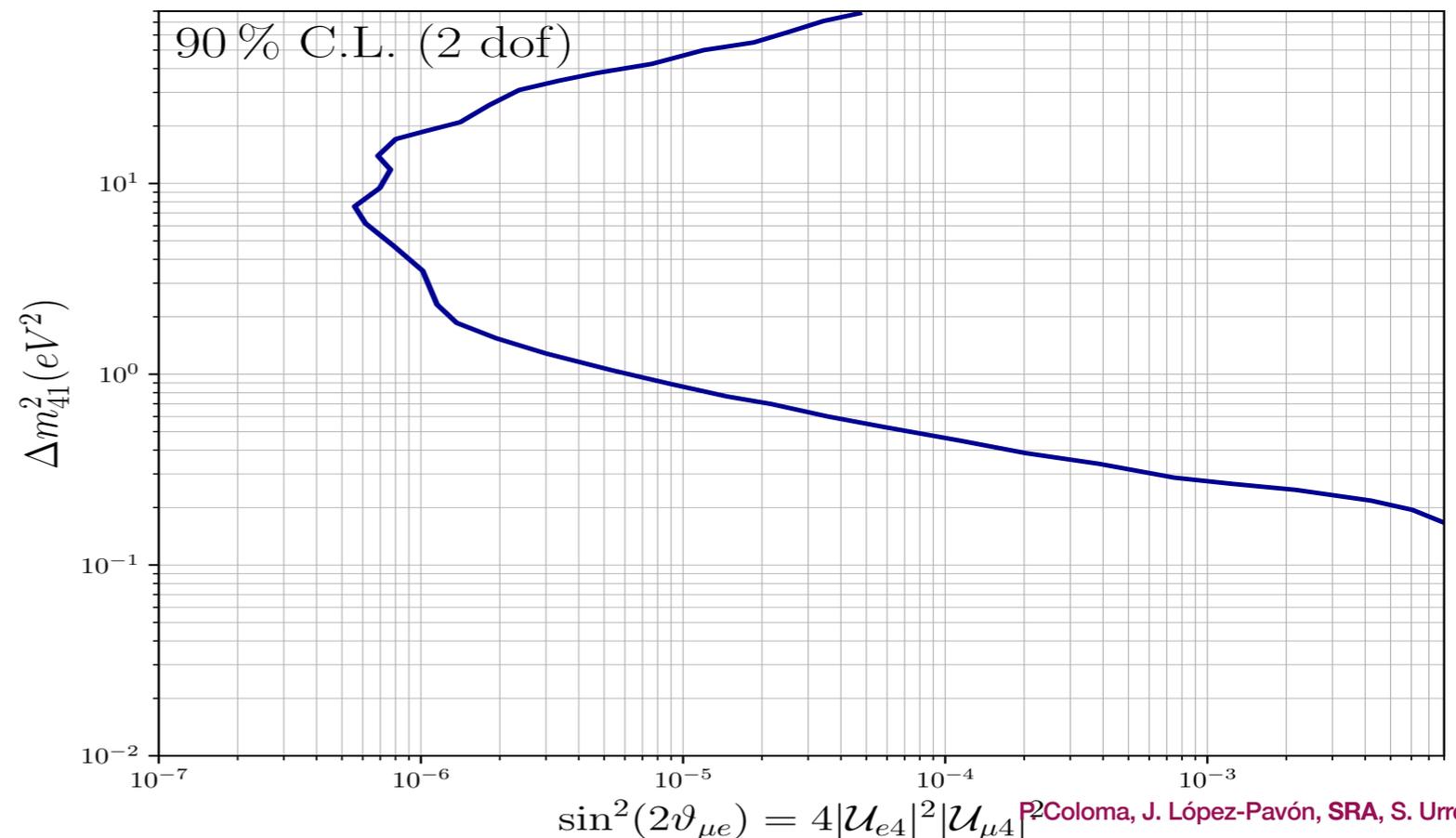
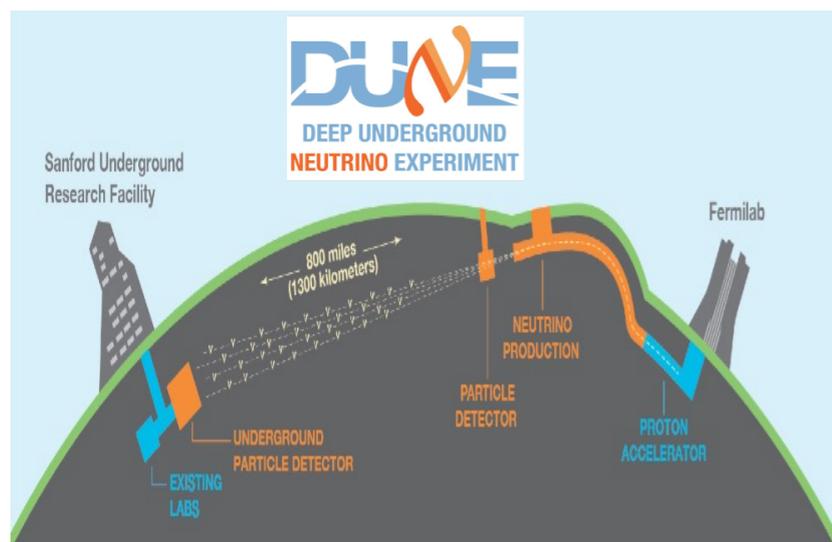
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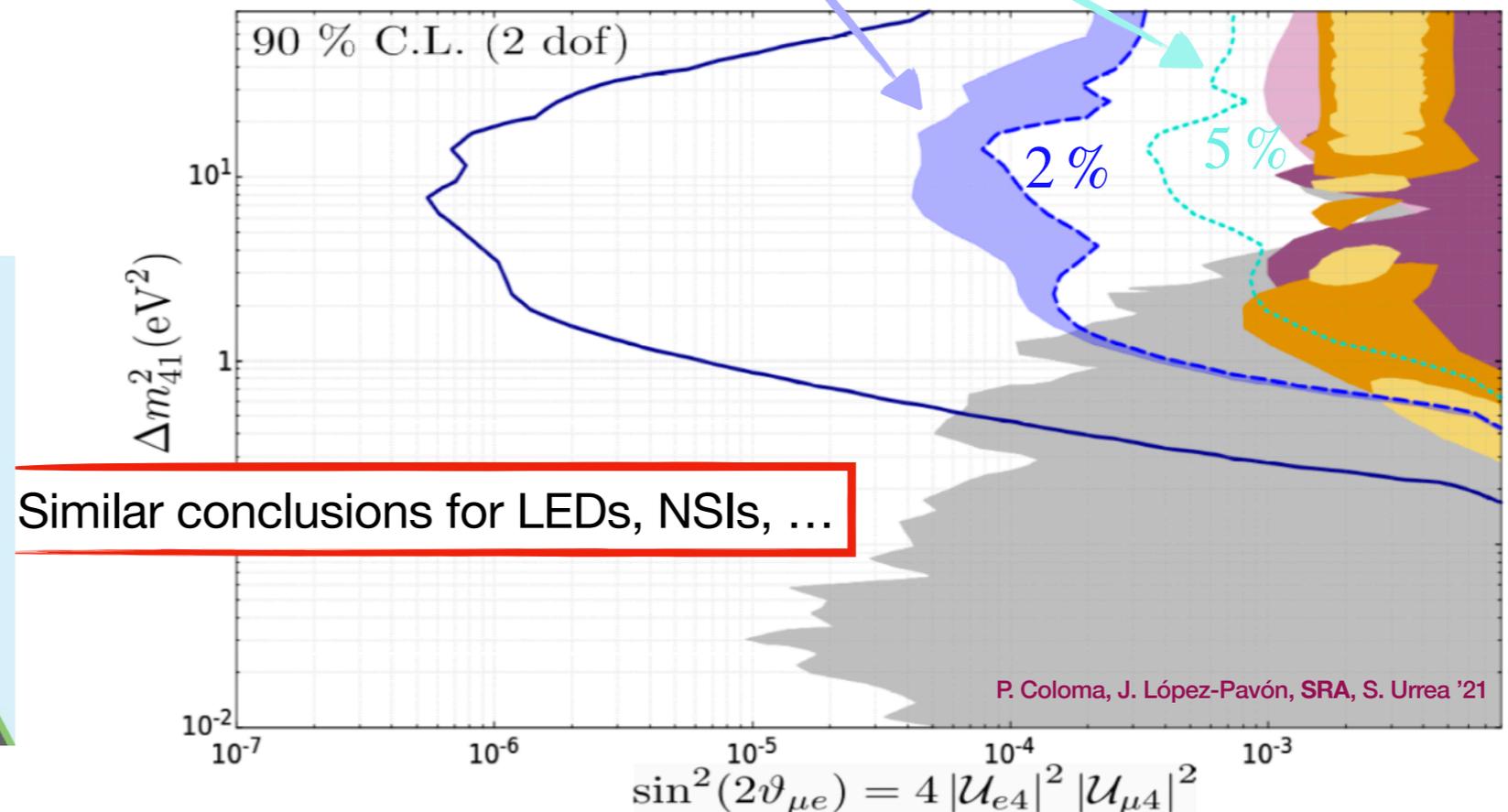
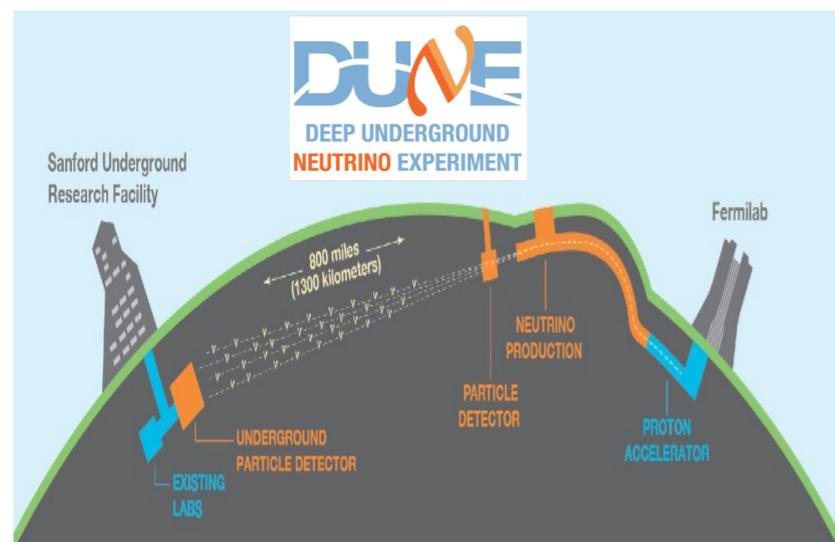
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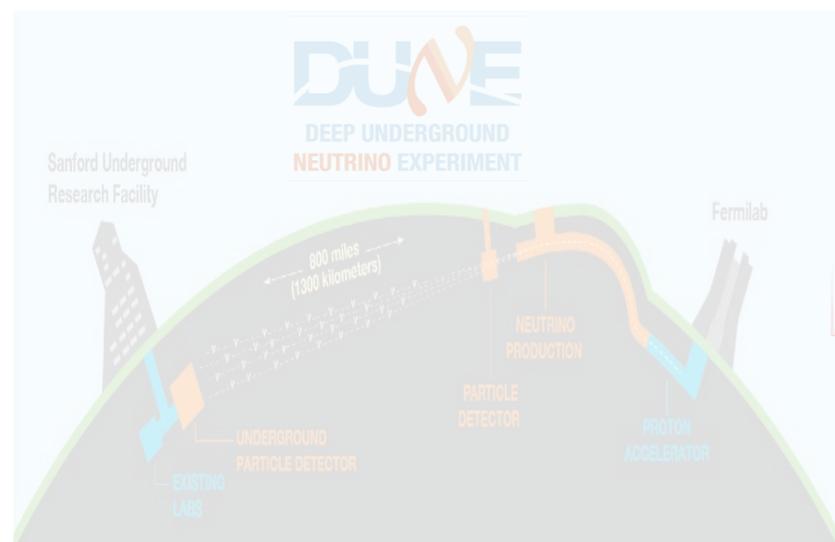
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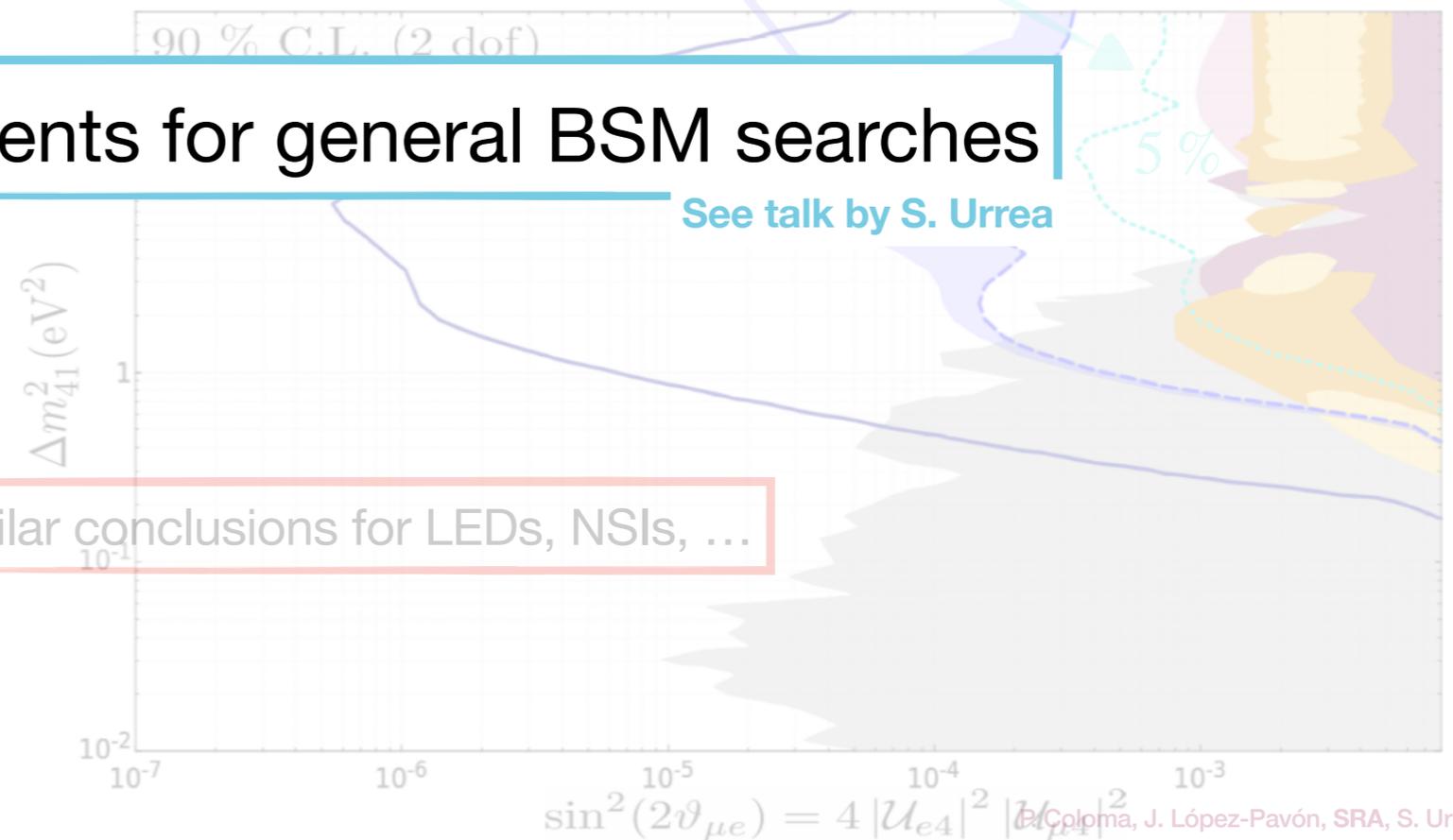
Systematic uncertainties will be the bottleneck!

Use ν experiments for general BSM searches

See talk by S. Urrea



Similar conclusions for LEDs, NSIs, ...



Serile neutrino DM

Production mechanisms

Temperatures $T \lesssim 1 \text{ GeV}$

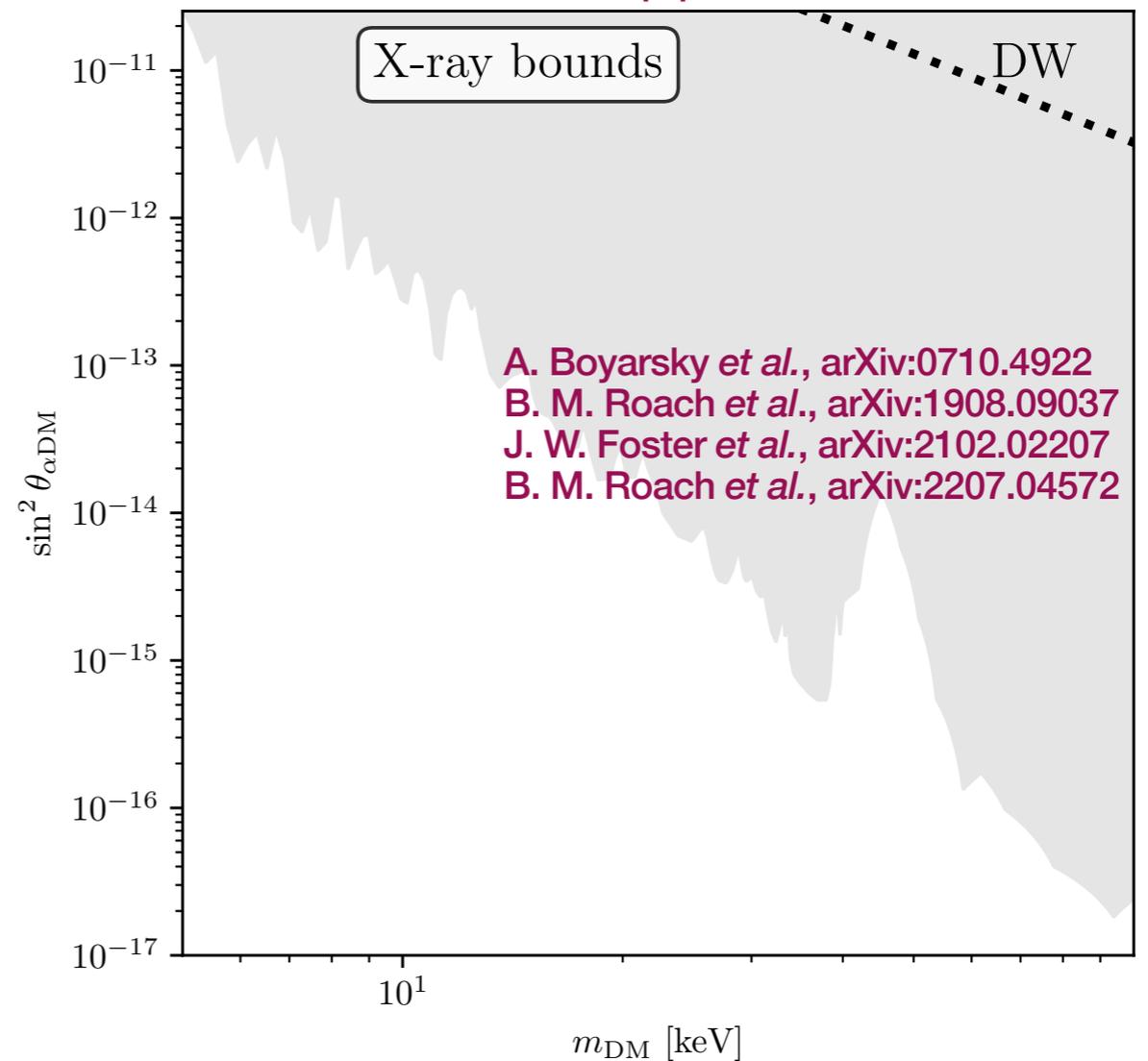
Dodelson-Widrow mechanism

S. Dodelson & L. Widrow,
arXiv: hep-ph/9303287

Production through oscillations
and collisions in the plasma

$$\Omega_{\text{DM}} h^2 \propto \left| \theta_{\alpha\text{DM}} \right|^2 m_{\text{DM}}$$

T. Asaka, M. Laine & M. Shaposhnikov,
arXiv:hep-ph/0612182



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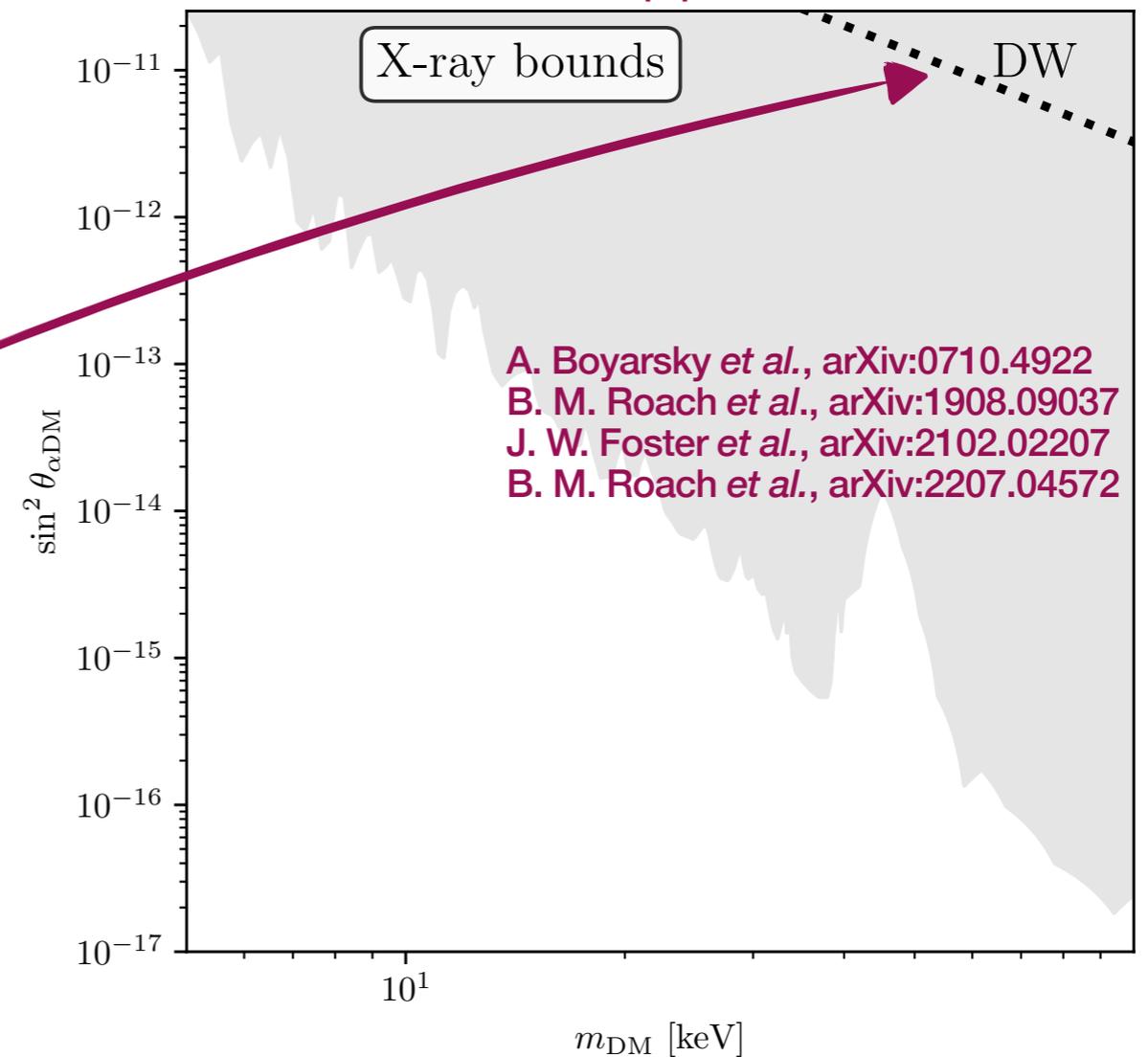
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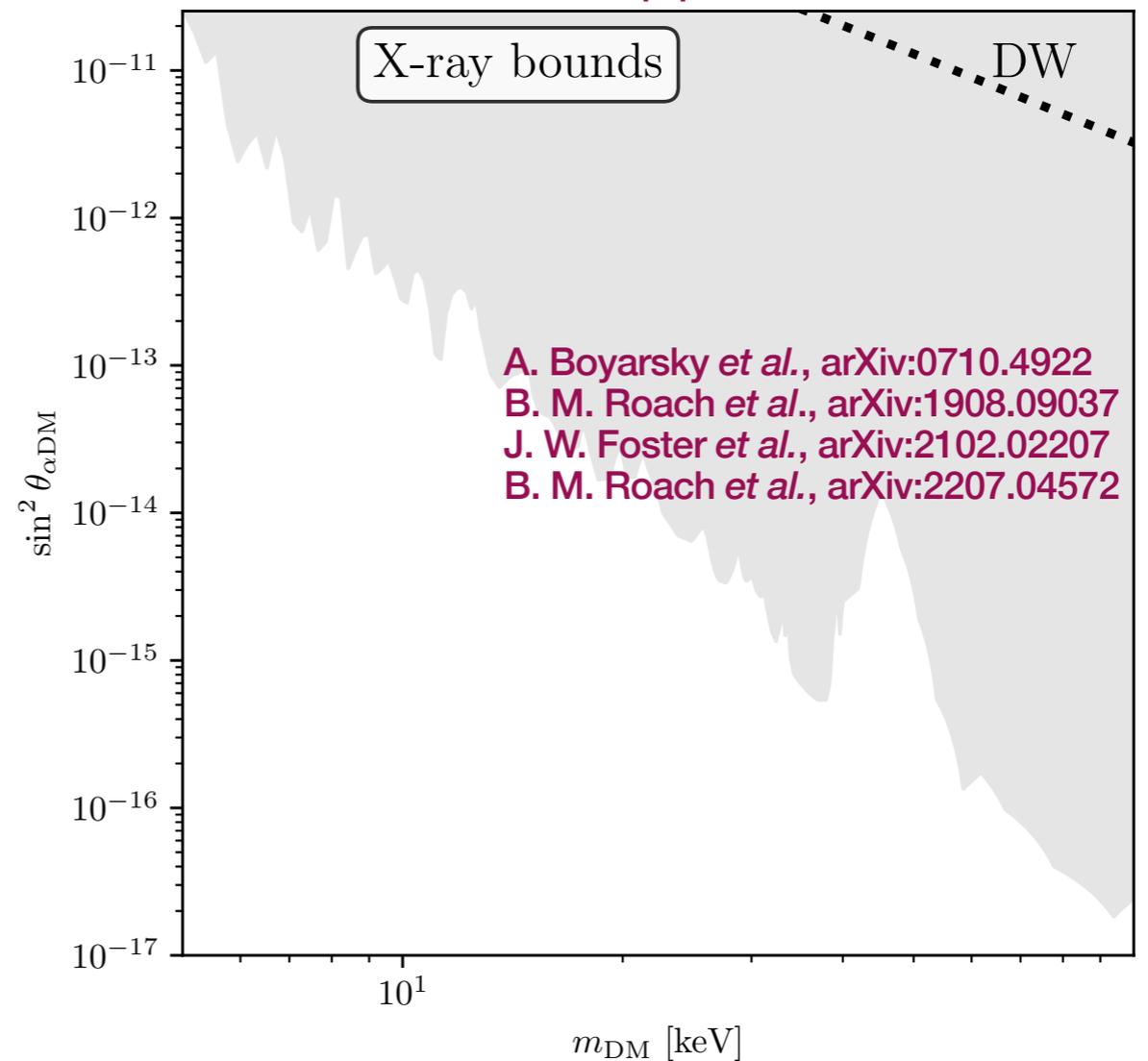
Ruled out

Shi-Fuller mechanism

X. Shi & G. M. Fuller, arXiv:astro-ph/9810076

Resonant production in the presence of a
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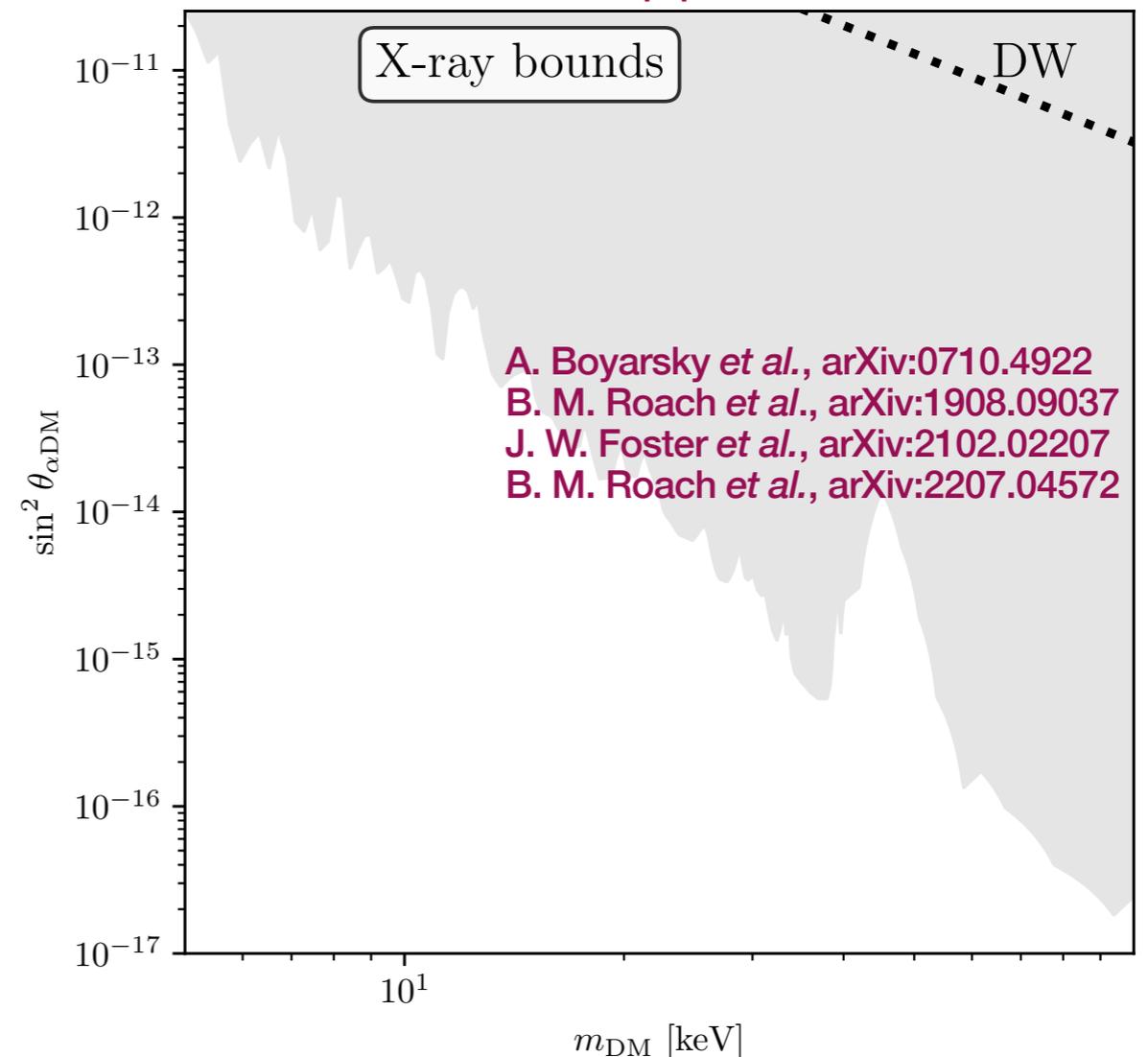
Simultaneous generation of
baryon asymmetry and DM

T. Asaka & M. Shaposhnikov,
arXiv:hep-ph/0505013
M. Shaposhnikov, arXiv:0804.4542

Fine tuning necessary

J. Ghiglieri & M. Laine, arXiv:2004.10766

T. Asaka, M. Laine & M. Shaposhnikov,
arXiv:hep-ph/0612182



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Freeze-in via 2-body decays

$$\left. \begin{aligned} Z(h) &\leftrightarrow \nu_i + n_{\text{DM}} \\ W &\leftrightarrow \ell_\alpha + n_{\text{DM}} \\ n_N &\leftrightarrow h(Z) + n_{\text{DM}} \end{aligned} \right\} \Gamma_s \propto |\theta|^2 \ll H$$

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$$\frac{df_{\text{DM}}}{dt} = \Gamma_s(p, t) \left[f_{\text{DM}}^{\text{eq}}(p, t) - \cancel{f_{\text{DM}}(p, t)} \right]$$

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A. Abada et al., arXiv:1406.6556

D. Boyanovsky & L. Lello, arXiv:1609.07647

M. Lucente, arXiv:2103.03253

A. Datta et al., arXiv:2104.02030

A. Abada et al., arXiv:2308.01341

A. Abada et al., arXiv:2503.20017

Crucial to account for thermal effects

Serile neutrino DM

Production mechanisms

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Freeze-in via 2-body decays

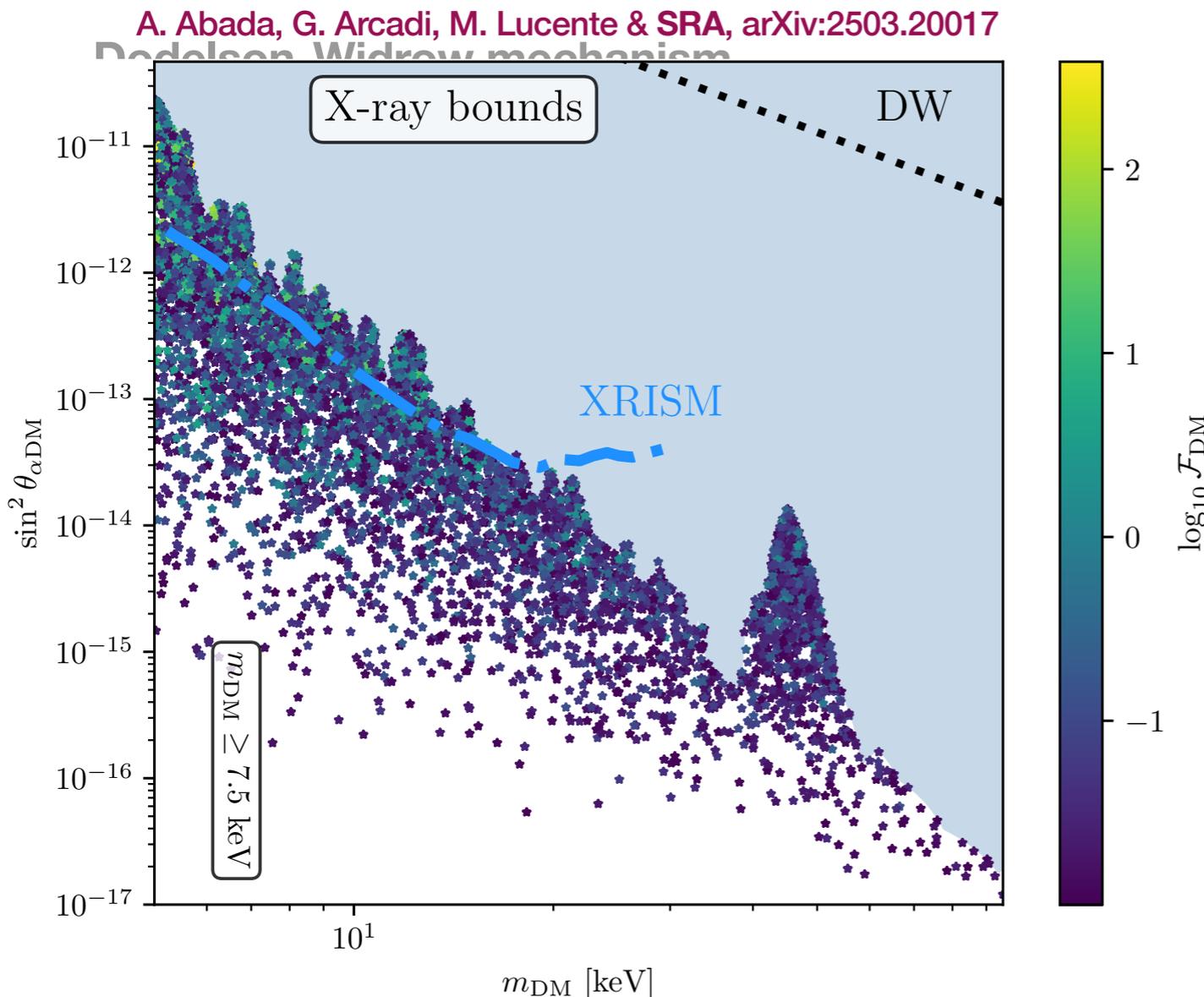
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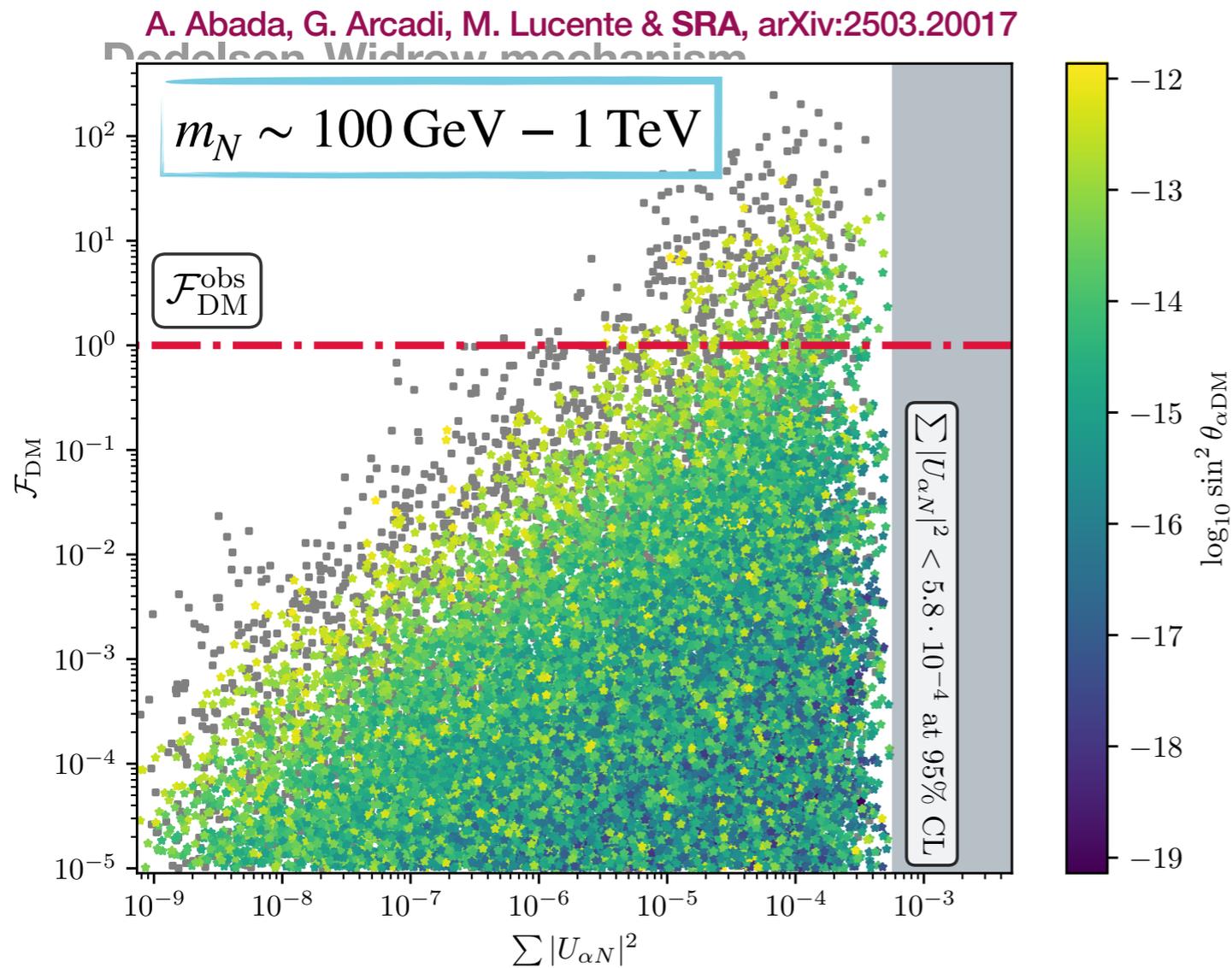
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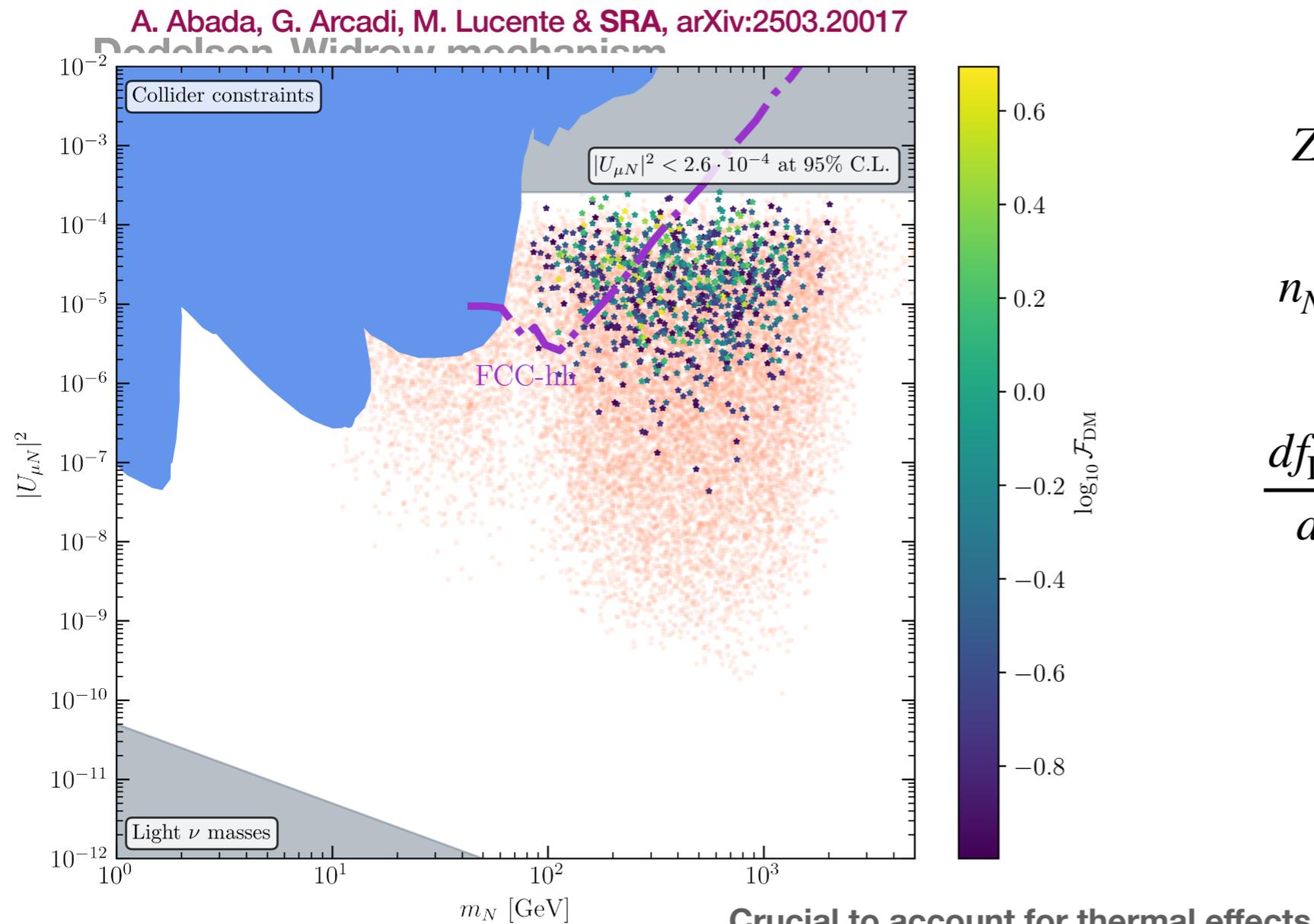
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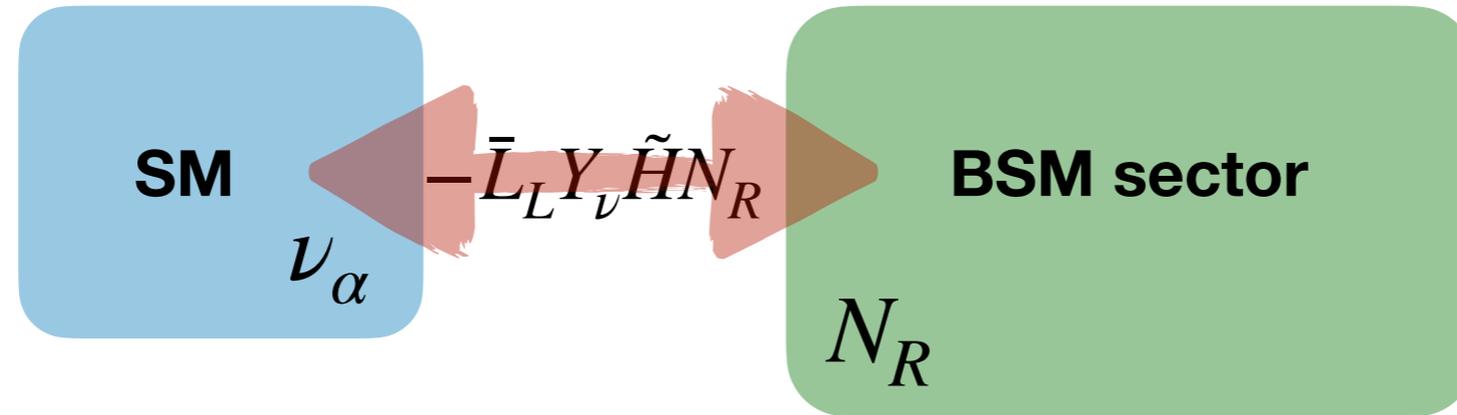
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Connection with other SM open problems

Neutrino portal



If N_R is the only light species in BSM sector

Exploit EFT with N_R : ν SMEFT

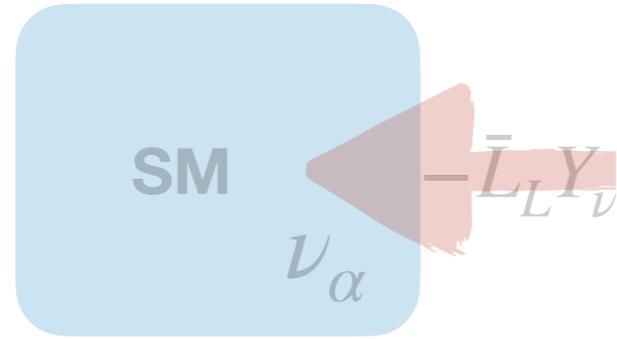
Any process with missing energy could have N_R in the final state

$B \rightarrow K\nu\nu$ in Belle-II

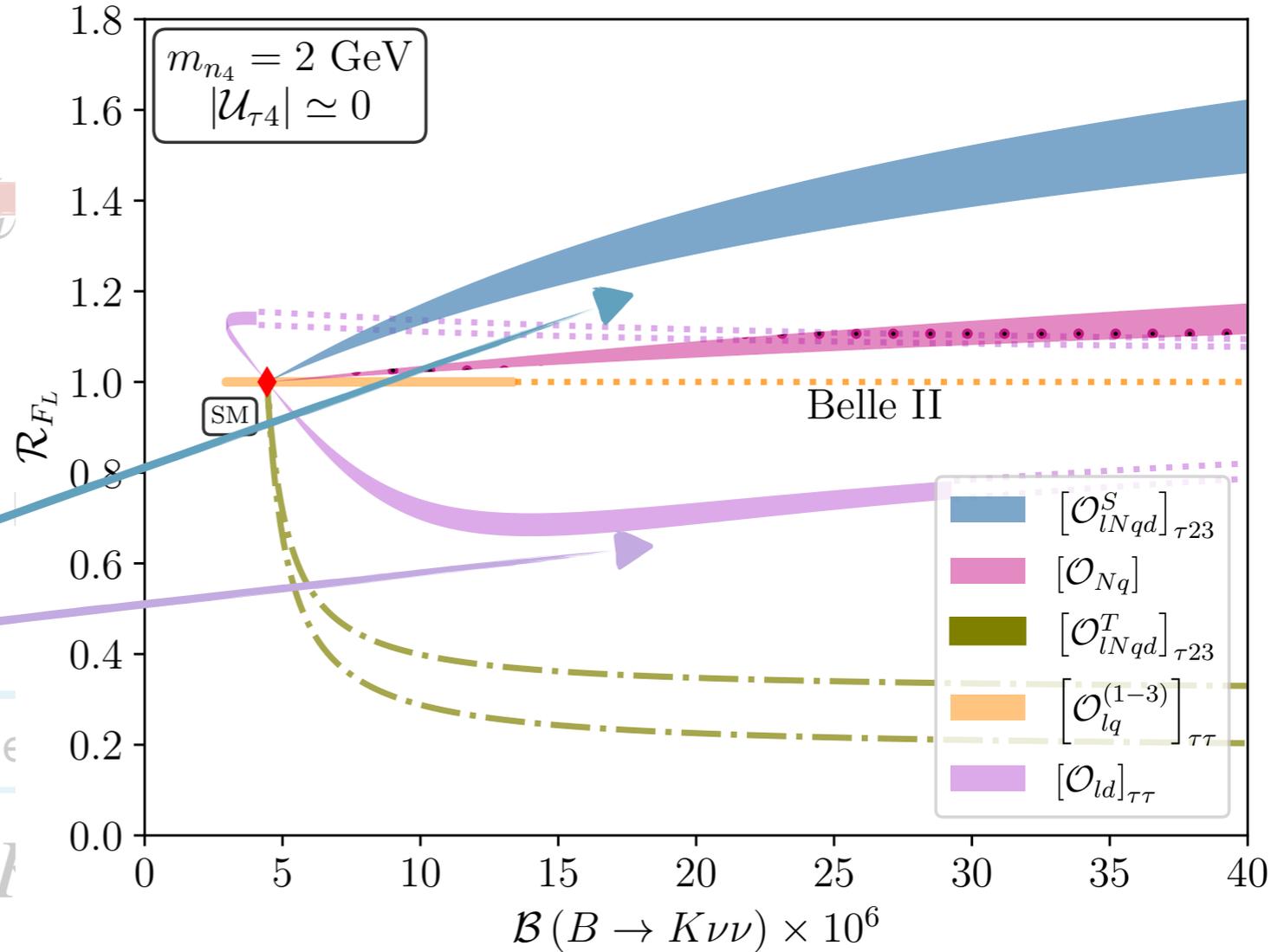
$$\mathcal{L}_{\nu\text{SMEFT}}^{(6)} \supset \frac{1}{\Lambda^2} \left\{ \begin{aligned} & \mathcal{C}_{Nd} (\bar{s}_R \gamma_\mu b_R) (\bar{N}_R \gamma^\mu N_R) + \mathcal{C}_{NQ} (\bar{s}_L \gamma_\mu b_L) (\bar{N}_R \gamma^\mu N_R) \\ & + [\mathcal{C}_{LNQd}]_i (\bar{s}_L b_R) (\bar{\nu}_{Li} N_R) - V_{cs} [\mathcal{C}_{LNQd}]_i (\bar{c}_L b_R) (\bar{\ell}_{Li} N_R) \\ & + [\mathcal{C}_{LNQdT}]_i (\bar{s}_L \sigma^{\mu\nu} b_R) (\bar{\nu}_{Li} \sigma_{\mu\nu} N_R) - V_{cs} [\mathcal{C}_{LNQdT}]_i (\bar{c}_L \sigma^{\mu\nu} b_R) (\bar{\ell}_{Li} \sigma_{\mu\nu} N_R) + h.c \end{aligned} \right\}$$

Connection with other SM open problems

Neutrino portal



[L. P. Leal, SRA, '24]



Different behavior for operators
with N_R and those with **SM ν**

Any process with missing e

$B \rightarrow l$

$$\mathcal{L}_{\nu SMEFT}^{(6)} \supset \frac{1}{\Lambda^2} \left\{ \begin{aligned} & \mathcal{C}_{Nd} (\bar{s}_R \gamma_\mu b_R) (\bar{N}_R \gamma^\mu N_R) + \mathcal{C}_{Nq} (\bar{s}_L \gamma_\mu b_L) (\bar{N}_R \gamma^\mu N_R) \\ & + [\mathcal{C}_{LNQd}]_i (\bar{s}_L b_R) (\bar{\nu}_{Li} N_R) - V_{cs} [\mathcal{C}_{LNQd}]_i (\bar{c}_L b_R) (\bar{\ell}_{Li} N_R) \\ & + [\mathcal{C}_{LNQdT}]_i (\bar{s}_L \sigma^{\mu\nu} b_R) (\bar{\nu}_{Li} \sigma_{\mu\nu} N_R) - V_{cs} [\mathcal{C}_{LNQdT}]_i (\bar{c}_L \sigma^{\mu\nu} b_R) (\bar{\ell}_{Li} \sigma_{\mu\nu} N_R) + h.c \end{aligned} \right\}$$