Outlook on neutrino theory and phenomenology

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INFN, Sezione di Bologna

Second International Conference on the Physics of the Two Infinities, University of Tokyo

Neutrino masses

Status from oscillations

Neutrino oscillations

$$\boxed{m_\nu \neq 0}$$

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

Neutrino masses

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$\boxed{m_\nu \neq 0}$

Only experimental evidence for BSM from the laboratory

Physics BSM

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Physics BSM

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What do we know?

NuFit 6.0, I. Esteban *et al.*, arXiv:2410.05380

SNO, Borexino, KamLAND	**Solar sector**	$\Delta m^2_{21} = 7.49^{+0.19}_{-0.19} \cdot 10^{-5}\mathrm{eV}^2$ $\sin^2\theta_{12} = 0.308^{+0.012}_{-0.011}$
SK, T2K, NOvA, MINOS, IC	**Atmospheric sector**	$\Delta m^2_{31} = 2.5^{+0.019}_{-0.021} \cdot 10^{-3}\mathrm{eV}^2$ $\sin^2\theta_{23} = 0.47^{+0.017}_{-0.017}$
Daya Bay, RENO, T2K, NOvA	**Reactor sector**	$\sin^2\theta_{13} = 0.02215^{+0.0006}_{-0.0006}$

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Physics BSM

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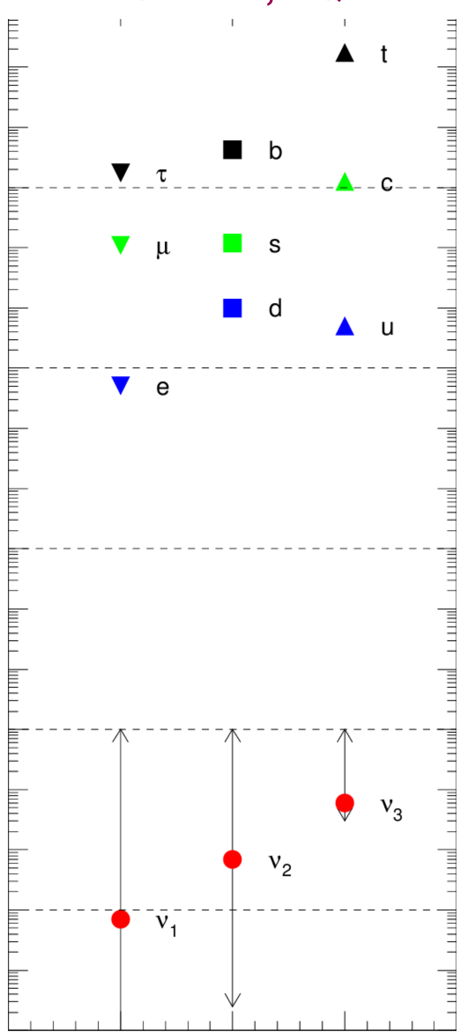
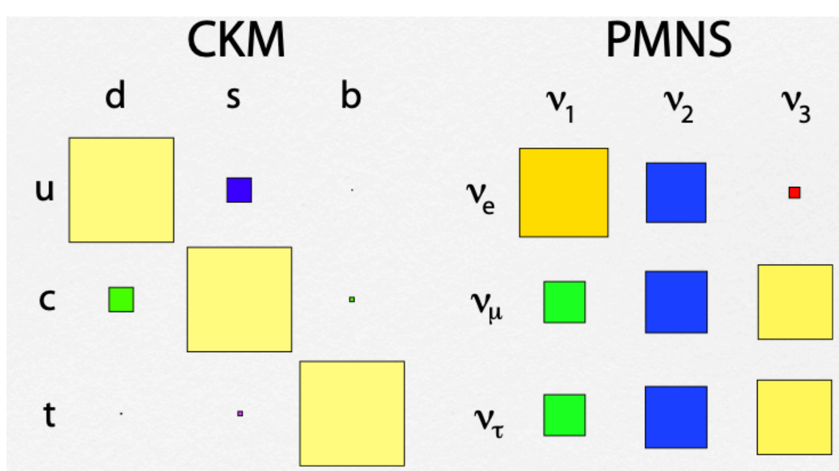
A. de Gôuvea, HQL 2008



Half of the SM flavor puzzle!



S. King, DISCRETE 2014

NuFit 6.0, I. Esteban *et al.*, arXiv:2410.05380

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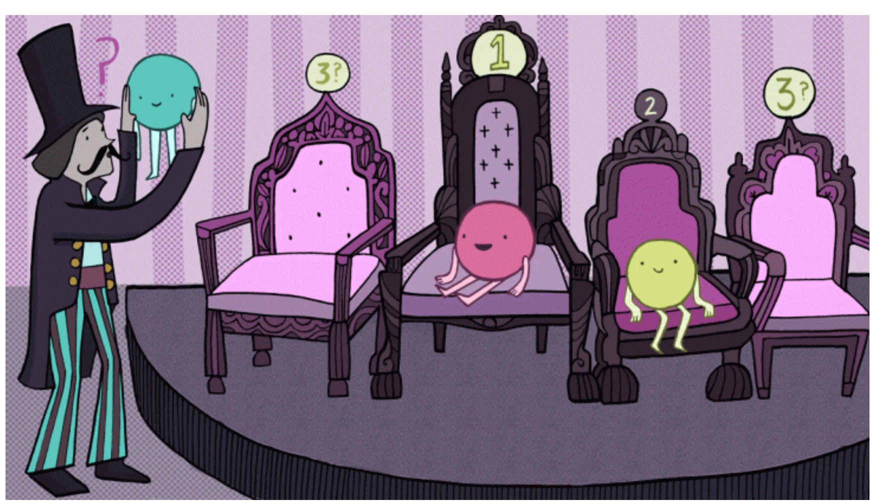
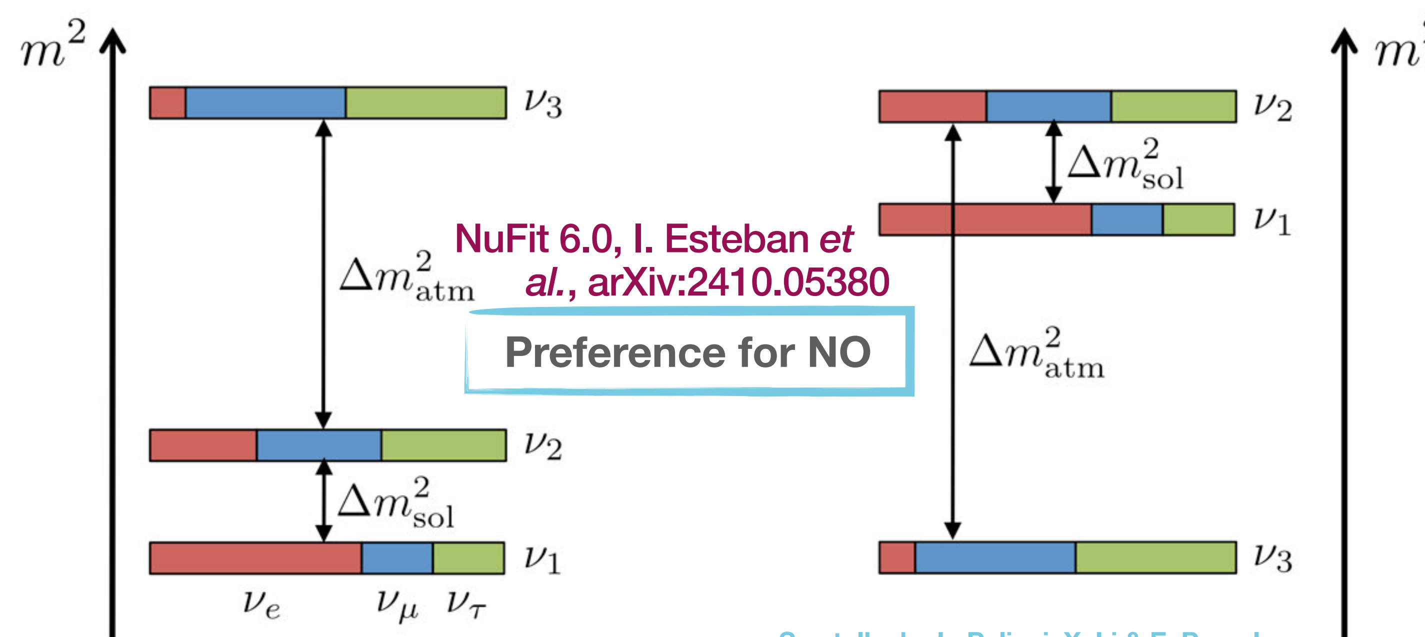
Known unknowns

Mass ordering





NuFit 6.0, I. Esteban *et al.*, arXiv:2410.05380

Preference for NO

See talks by L. Pelicci, X. Li & E. Percale

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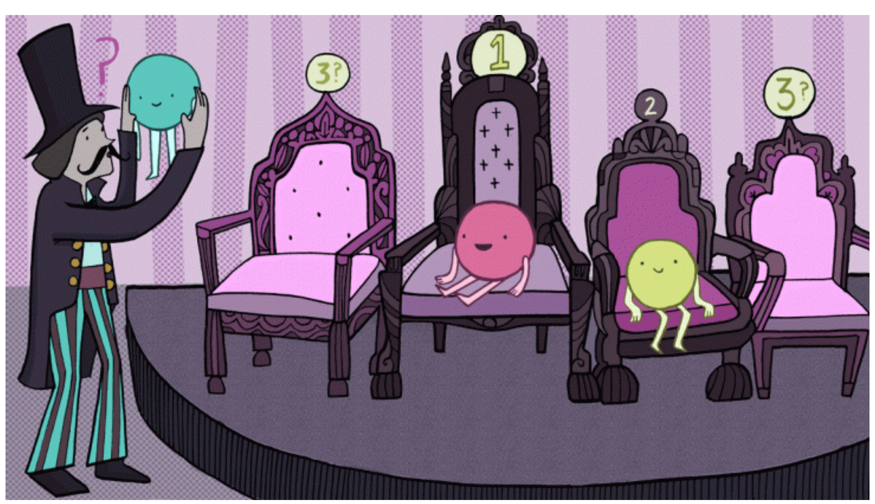
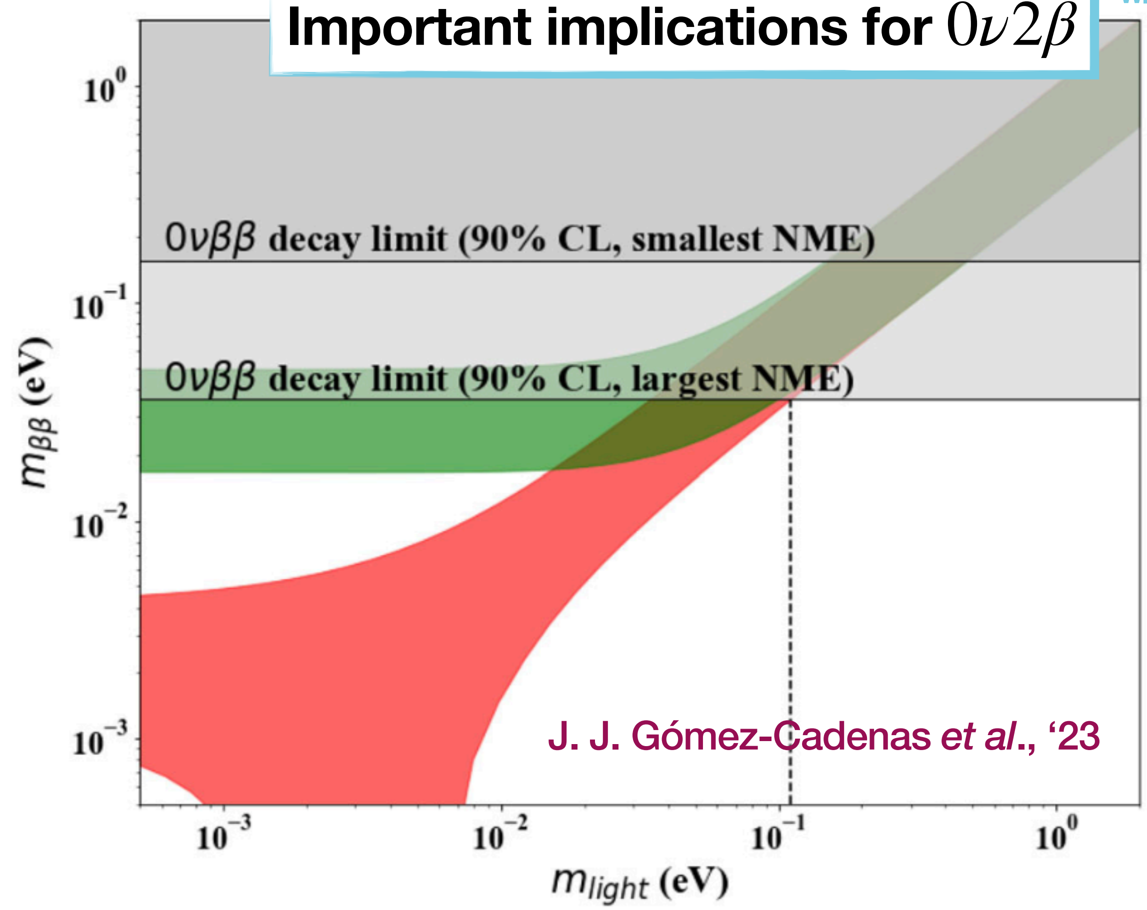


Important implications for $0\nu2\beta$

See talk by R. Cesarano, W. Parker & K. Heeger



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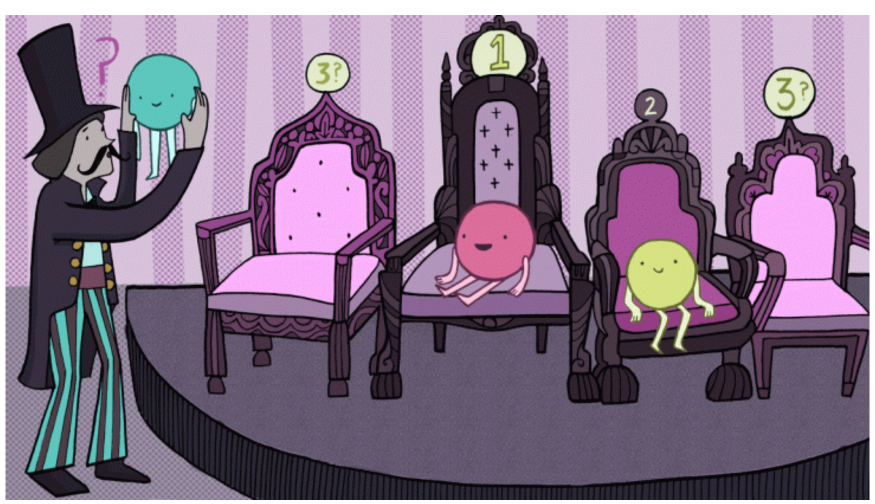

See talks by J. Liu, J. Yu & G. Rossi

**Complementarity
with cosmology**

Sensitive to $\sum m_{\nu_i}$

DESI Collaboration, arXiv:2503.14744

$$\boxed{\sum m_{\nu_i} < 0.064\,\mathrm{eV}}$$

CMB + DESI DR2 BAO
@ 95% CL

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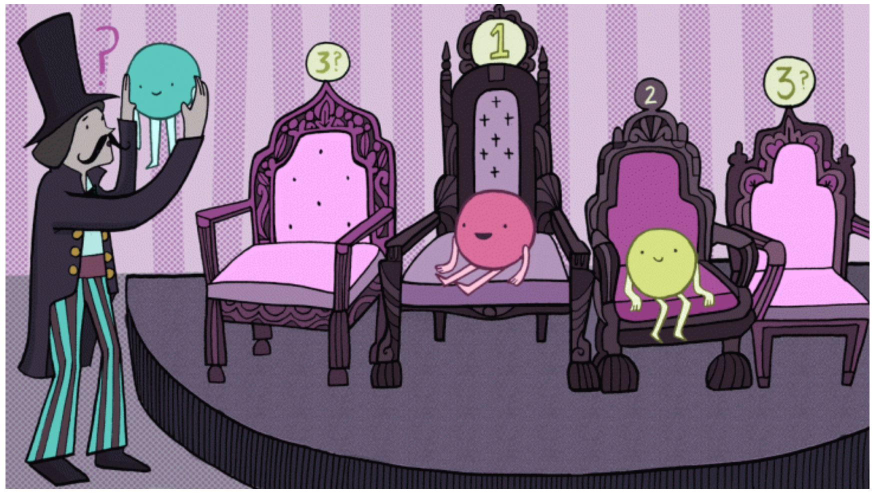

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From oscillations

$$\sum m_{\nu_i} \geq 0.059\,\mathrm{eV}\ \mathrm{for\ NO}$$
$$\sum m_{\nu_i} \geq 0.099\,\mathrm{eV}\ \mathrm{for\ IO}$$

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Known unknowns

CP violation

T2K: shorter baseline,
cleaner CPV effect

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

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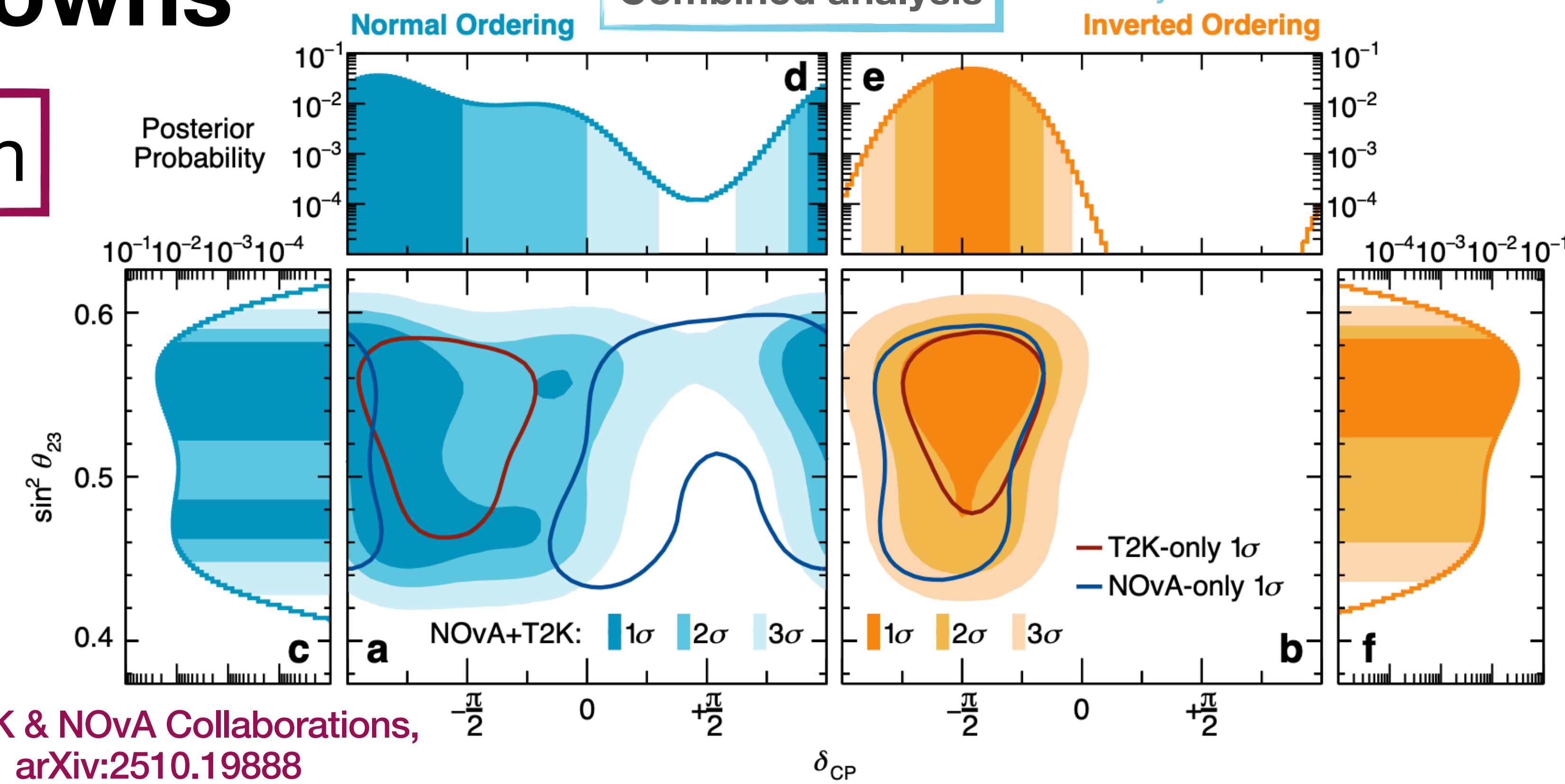
Combined analysis

See talk by M. Sanchez



T2K & NOvA Collaborations, arXiv:2510.19888

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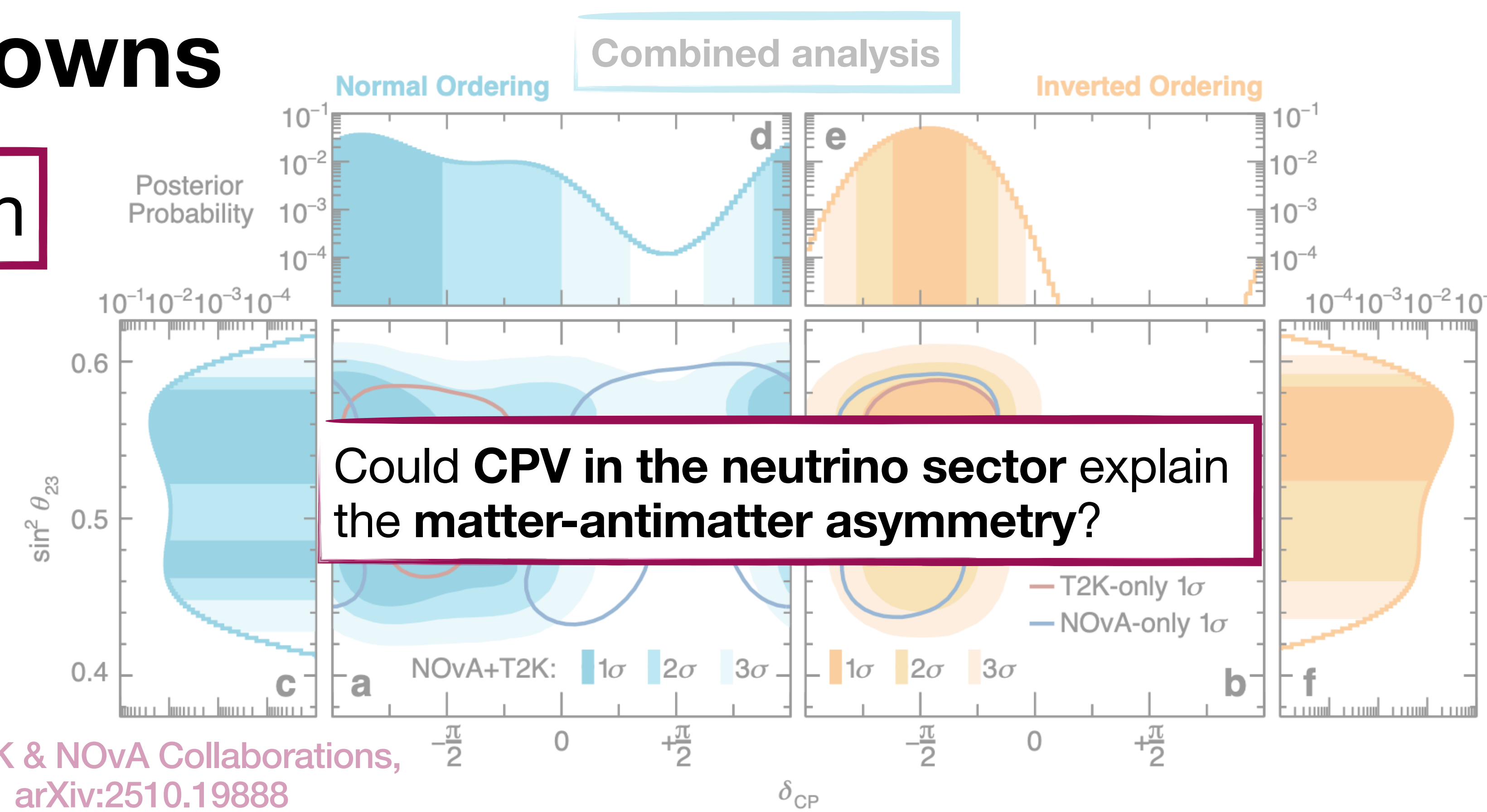

Could **CPV in the neutrino sector** explain the **matter-antimatter asymmetry**?

T2K & NOvA Collaborations, arXiv:2510.19888

Neutrino masses

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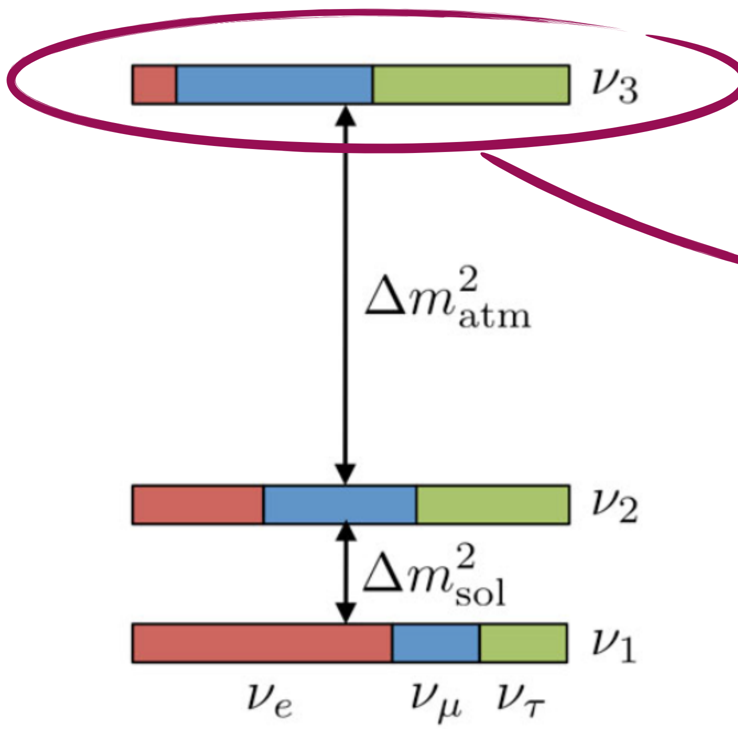

Octant of θ_{23}

Does ν_3 have more ν_μ or ν_τ content?

Neutrino masses

Status from oscillations

Neutrino oscillations

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Physics BSM

Known unknowns

See talks by L. Périssé, S. Biagi, A. Blanchet, L. Mellet, T. Leplumey, A. Santos, C. Bronner & N. K. Neilson

Mass ordering

CP violation

Octant of θ_{23}

Current and future experiments will try to answer these questions

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

Neutrino masses

Open window on Physics BSM

Neutrino oscillations

$\boxed{m_\nu \neq 0}$

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?

Origin of neutrino masses

Renormalizable operators

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

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

SM singlet!

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)
T. Yanagida, Conf. Proc C7902131 (1979)
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New scale not related to EW symmetry breaking!

Lepton number violation

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

Need at least 2 N_R to explain oscillation data

$$U^T \mathscr{M}_\nu U \simeq \begin{pmatrix} N^T & -\theta^* \\ \theta^T & X^T \end{pmatrix} \begin{pmatrix} 0 & m_D \\ m_D^T & M \end{pmatrix} \begin{pmatrix} N & \theta \\ -\theta^\dagger & X \end{pmatrix} = \begin{pmatrix} m_{\text{light}} & 0 \\ 0 & m_N \end{pmatrix}$$

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

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Active-heavy mixing

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Not unitary

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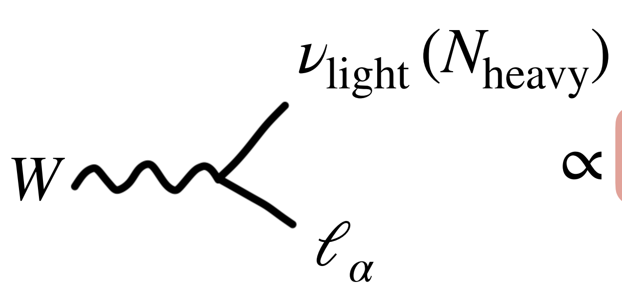
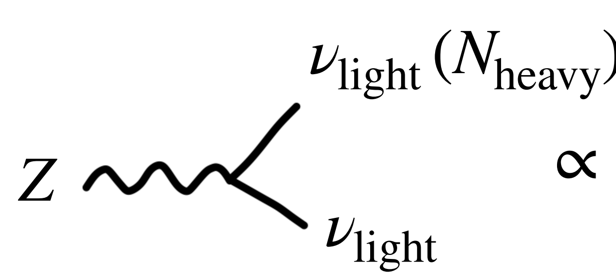
Modification of weak interactions



$\propto N(\theta)$



$\propto N^\dagger N (N^\dagger \theta)$

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What is the scale of NP?

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High-scale seesaw

Lightness of neutrino masses from hierarchy between v_H and M

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$$Y_\nu \sim 1, \quad M \sim \mathcal{O}(10^{15})\,\text{GeV}$$

Lightness of neutrino masses from hierarchy between v_H and M

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

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M. Fukugita & T. Yanagida, '86

Leptogenesis, but **no** further **experimental signature**

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Low-scale seesaw

Lightness of neutrino masses from approximate lepton number symmetry

See e.g. R. Mohapatra & J. Valle, '86; M. Malinsky *et al.*, '05; B. Gavela *et al.*, '09; G. Senjanovic & F. Vissani, '11

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Low-scale seesaw

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

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See e.g. R. Mohapatra & J. Valle, '86; M. Malinsky *et al.*, '05; B. Gavela *et al.*, '09; G. Senjanovic & F. Vissani, '11

Phenomenologically very attractive

Origin of neutrino masses

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Example: **Inverse Seesaw**

R. Mohapatra & J. Valle, ‘86

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

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Only source of L-breaking

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

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

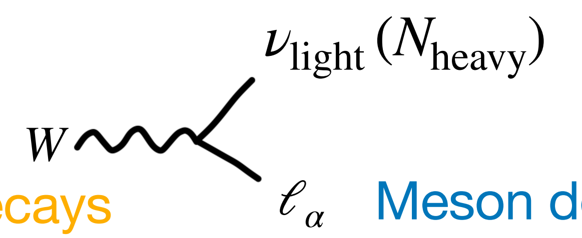
$$m_{\text{light}} \sim \theta^2 \mu, \quad \theta \sim m_D M^{-1}$$

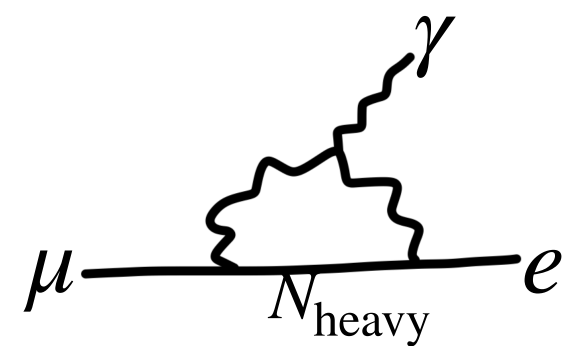
Even when $\mu \to 0$ we can have sizable θ

What is the NP scale?

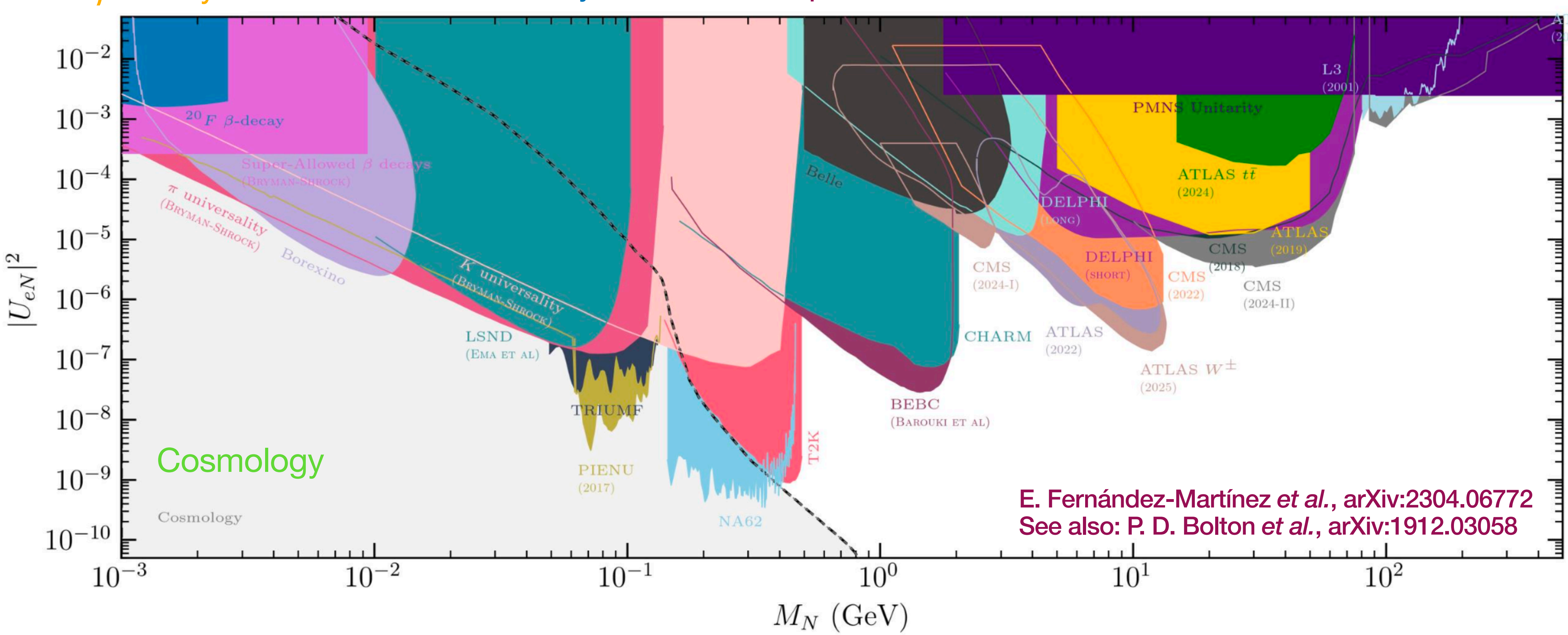
Rich phenomenology

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





β decays   Meson decays   Beam dump   Colliders   EWPO & flavor observables



E. Fernández-Martínez *et al.*, arXiv:2304.06772
See also: P. D. Bolton *et al.*, arXiv:1912.03058

What is the NP scale?

Connections with other SM open problems

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

Need at least 2 N_R to explain oscillation data

Baryogenesis

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
P. Hernandez *et al.*, arXiv:1606.06719
See M. Drewes *et al.*, arXiv:171102862 for a review

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Dark matter

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

Good DM candidate!

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

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

Need at least 2 N_R to explain oscillation data

Baryogenesis

ARS Leptogenesis

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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

Dark matter

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

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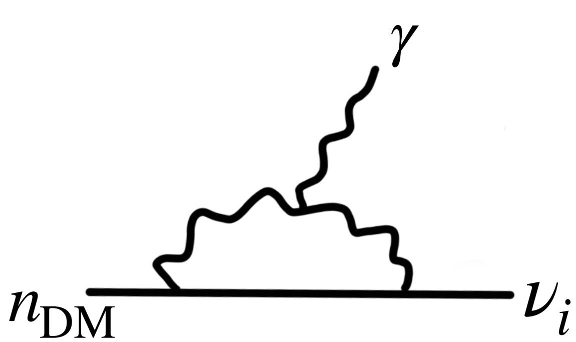
Signal completely **unrelated to** that searched for in **direct DM experiments**



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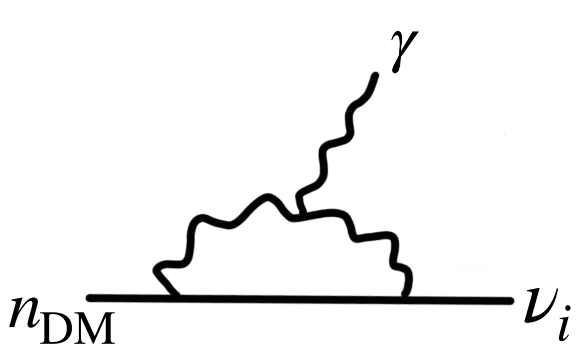

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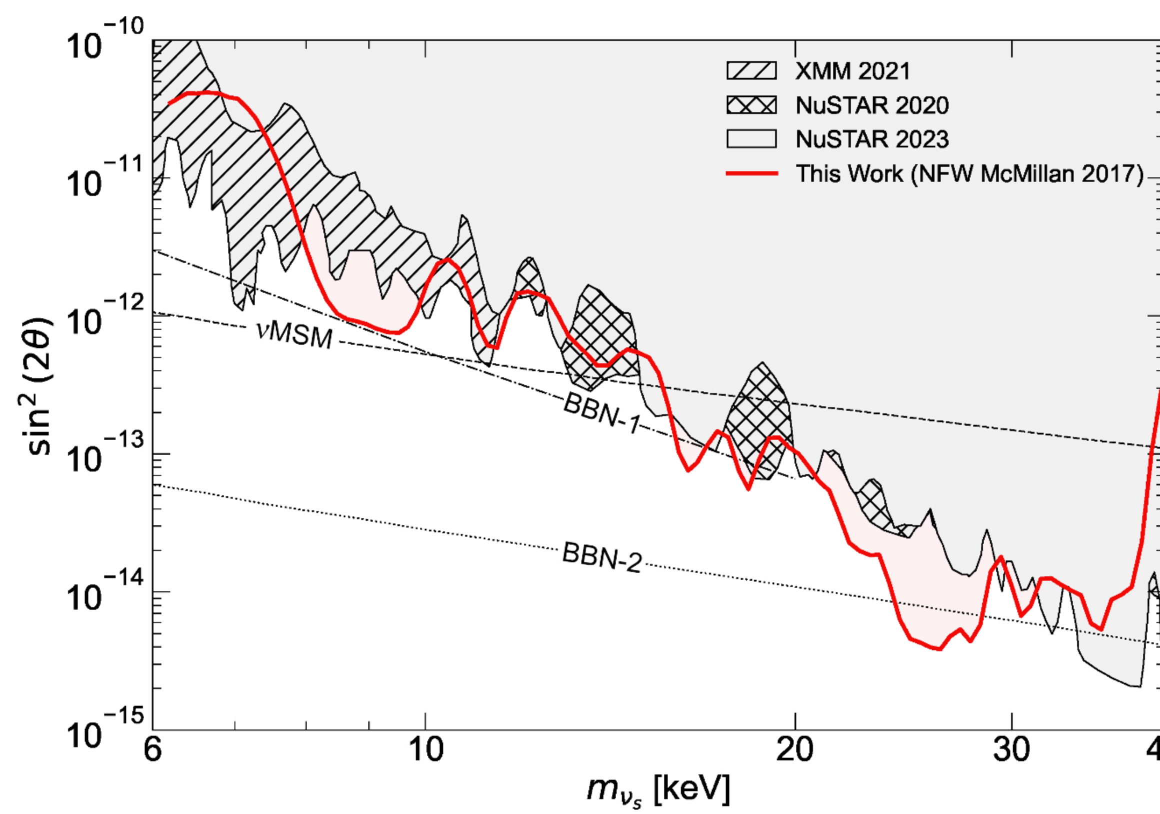

Serile neutrino DM

Production mechanisms

Temperatures $T \lesssim 1\,\mathrm{GeV}$

Dodelson-Widrow mechanism

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Production through oscillations and collisions in the plasma

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

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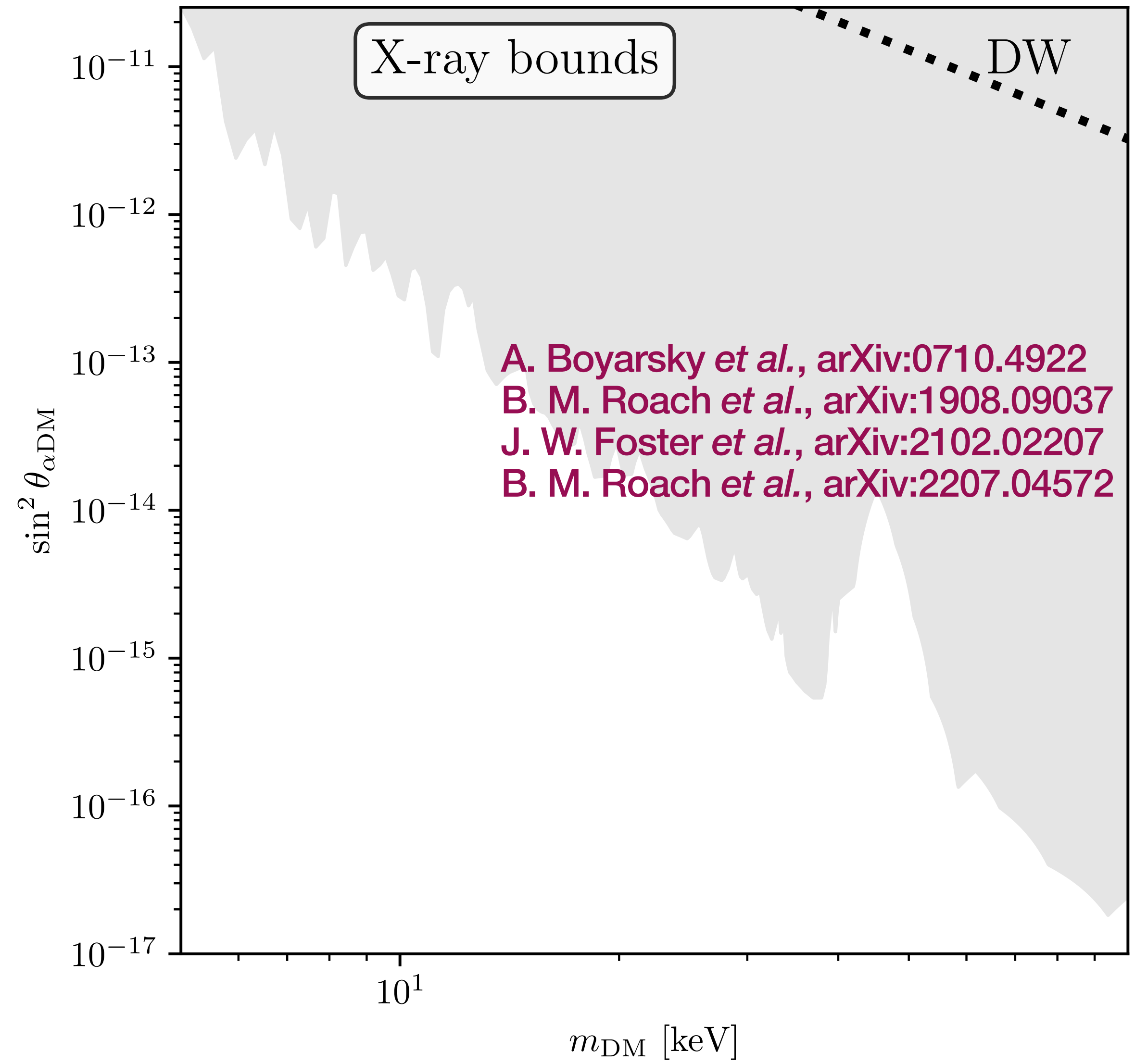

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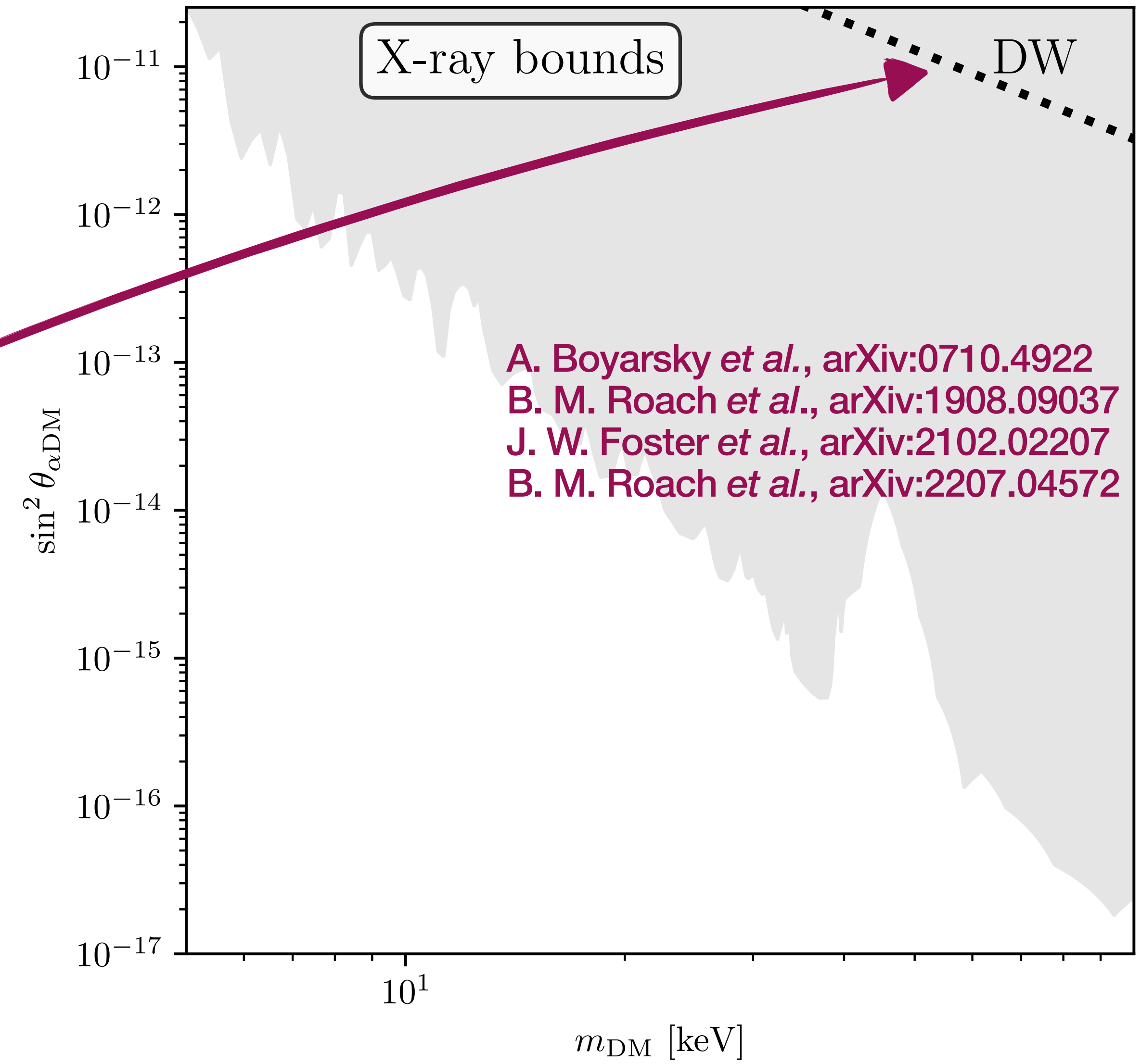

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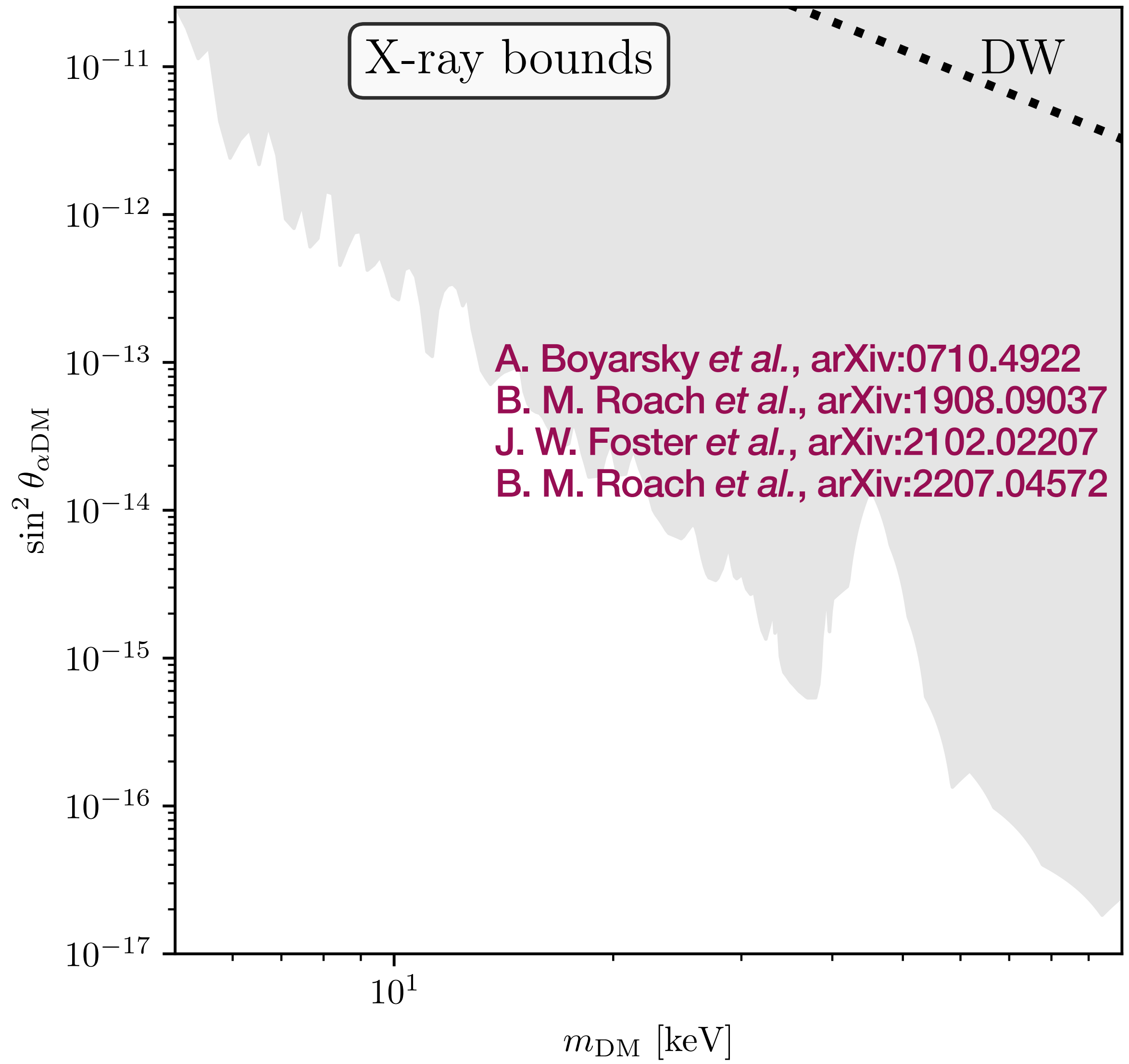

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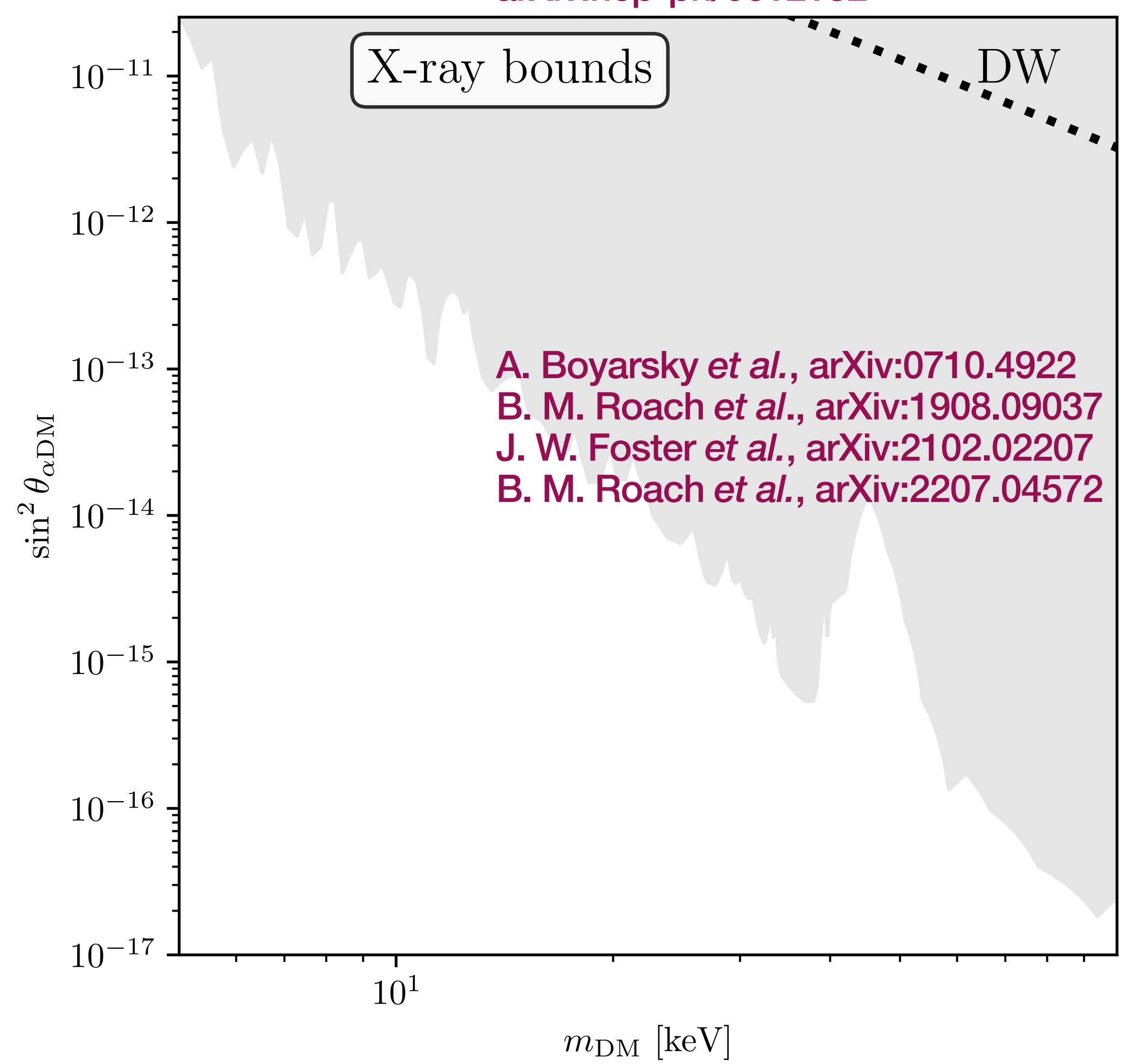

A. Boyarsky *et al.*, arXiv:0710.4922
B. M. Roach *et al.*, arXiv:1908.09037
J. W. Foster *et al.*, arXiv:2102.02207
B. M. Roach *et al.*, arXiv:2207.04572

Fine tuning necessary
J. Ghiglieri & M. Laine, arXiv:2004.10766

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

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Crucial to account for thermal effects

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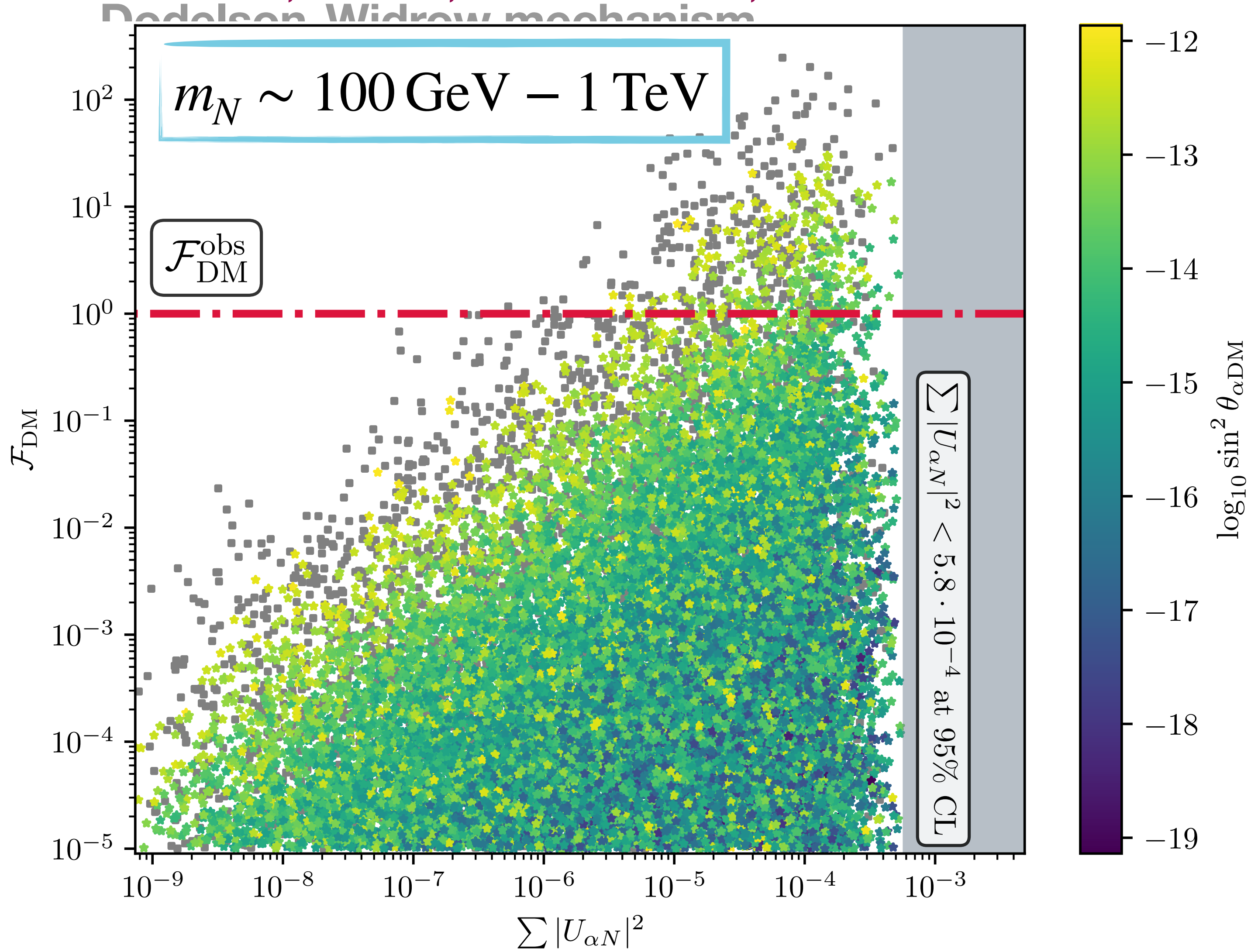

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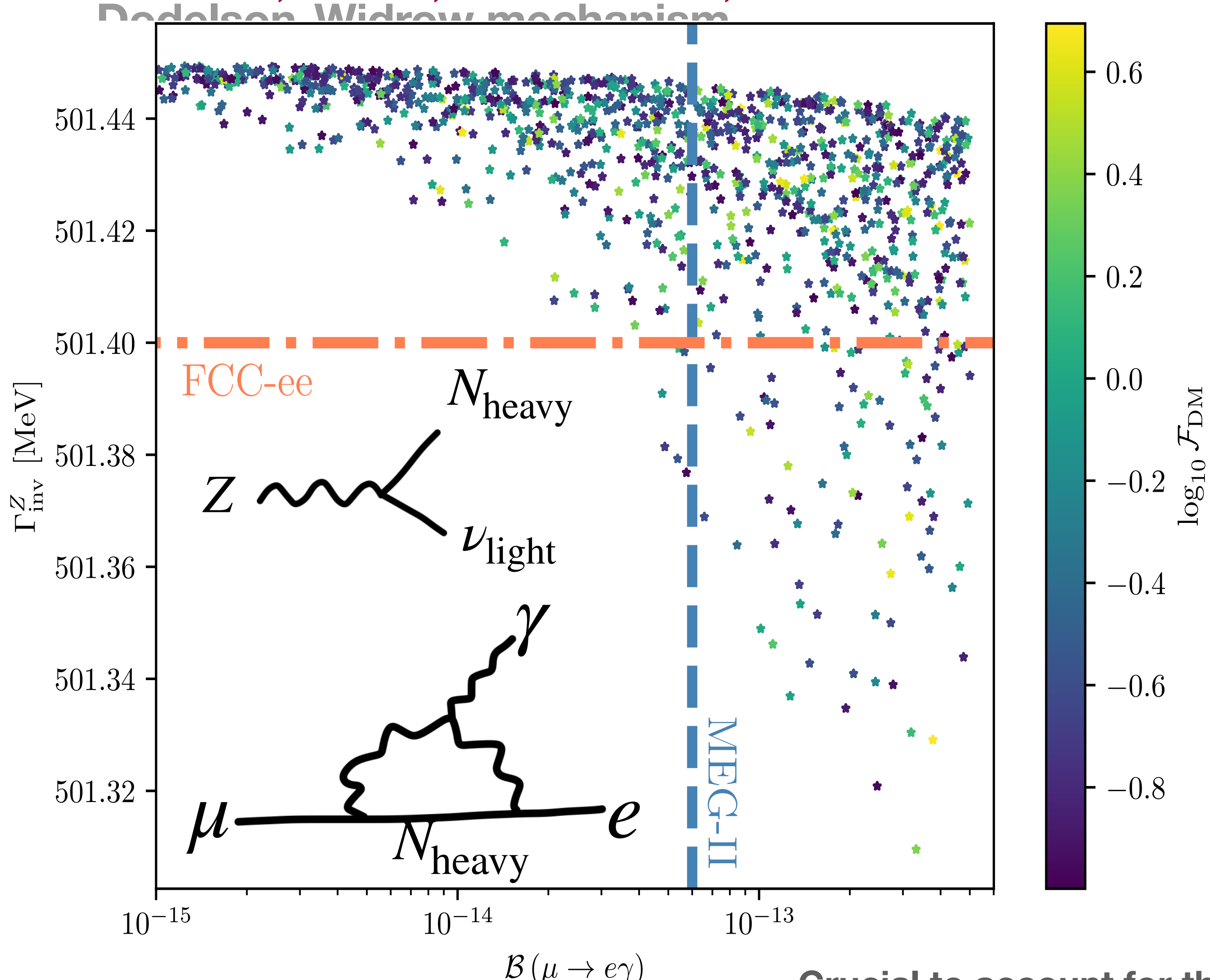

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What is the NP scale?

Connections with other SM open problems

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

SM singlet!

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

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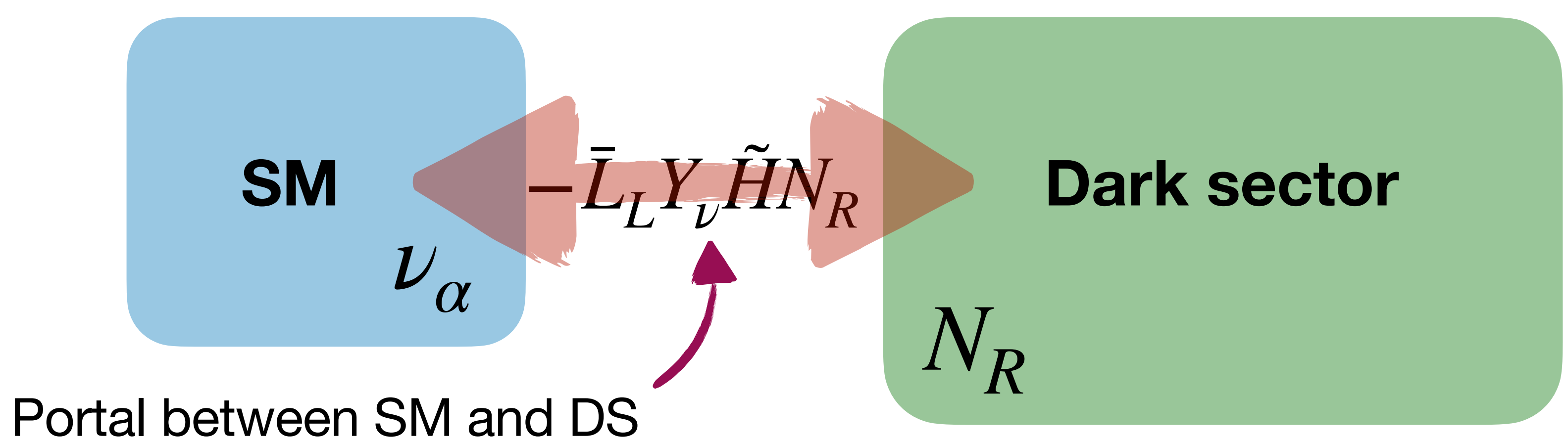

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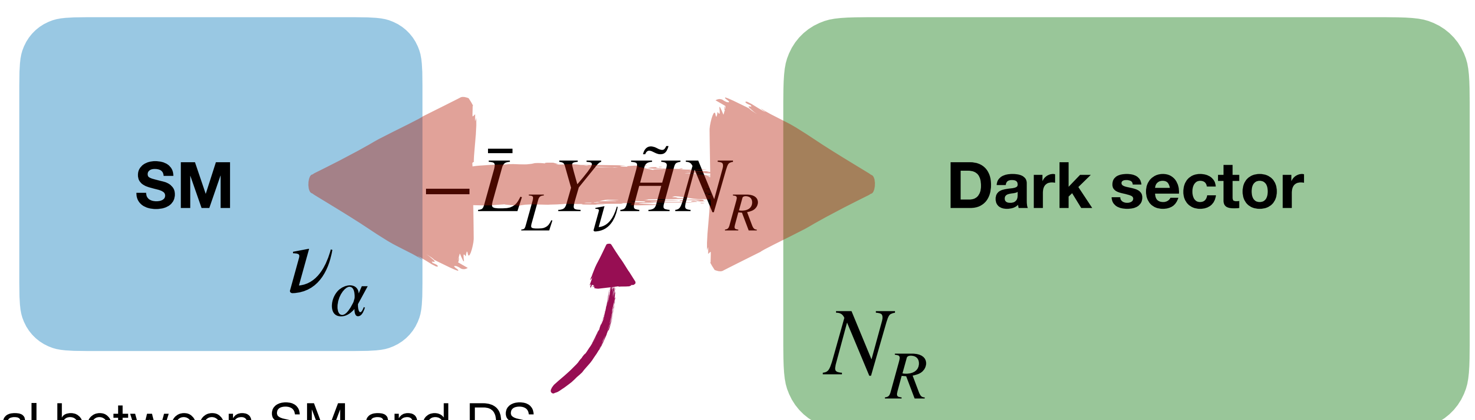

Portal between SM and DS

Only renormalizable SM coupling to singlet fermions

Other portals are:

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

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

What is the NP scale?

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What if the HNL mass is generated by a new scalar vev?

$$\mathscr{L} \simeq -\bar{L}_L Y_\nu \tilde{H} N_R - \bar{N}_L \phi Y_N N_R + h.c. \boxed{-V(\phi, H)}$$

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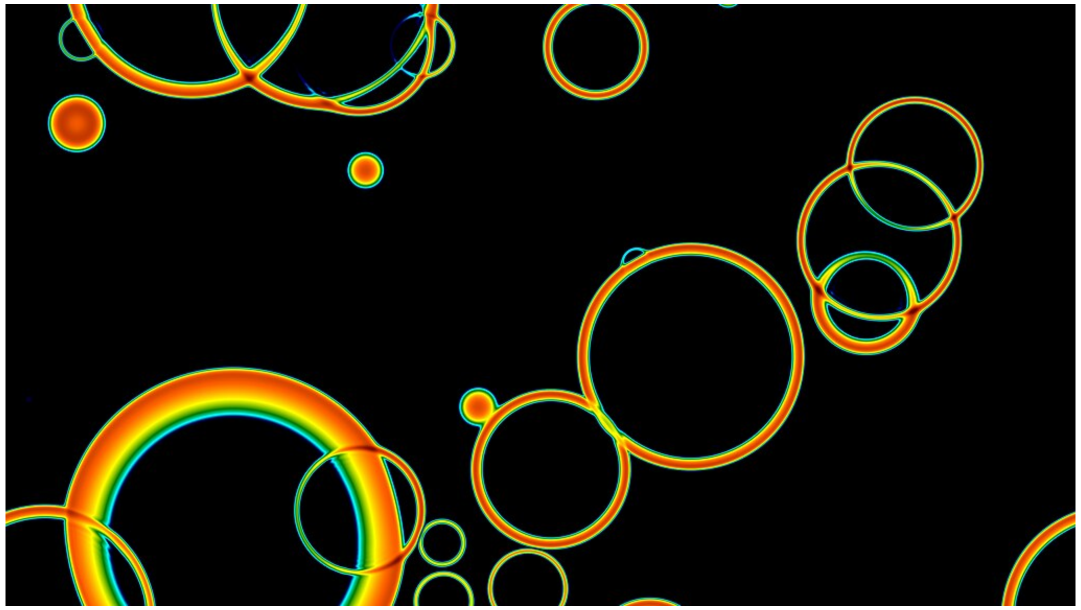

Potential for having a **FOPT from the scalar sector**!

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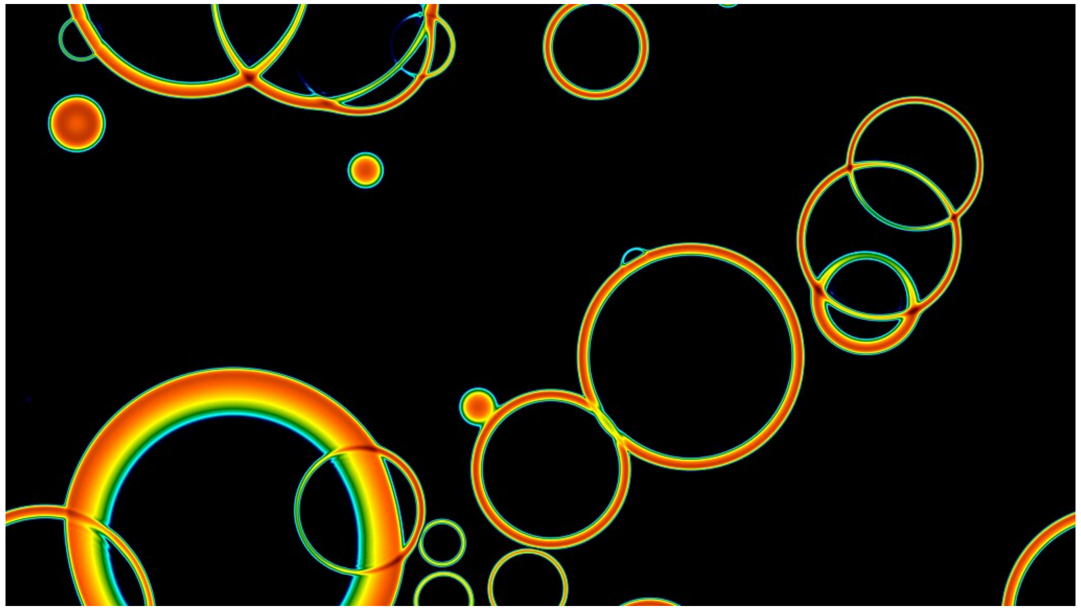

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Sakharov's conditions
- Out of equilibrium → FOPT
- CP violation → CP violation from neutrino sector
- Baryon number violation → Sphalerons violate $B + L$

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νEWBG

P. Hernández & N. Rius, arXiv:hep-ph/9611227
E. Fernández-Martínez *et al.*, arXiv:2007.11008
E. Fernández-Martínez *et al.*, arXiv:2210.16279

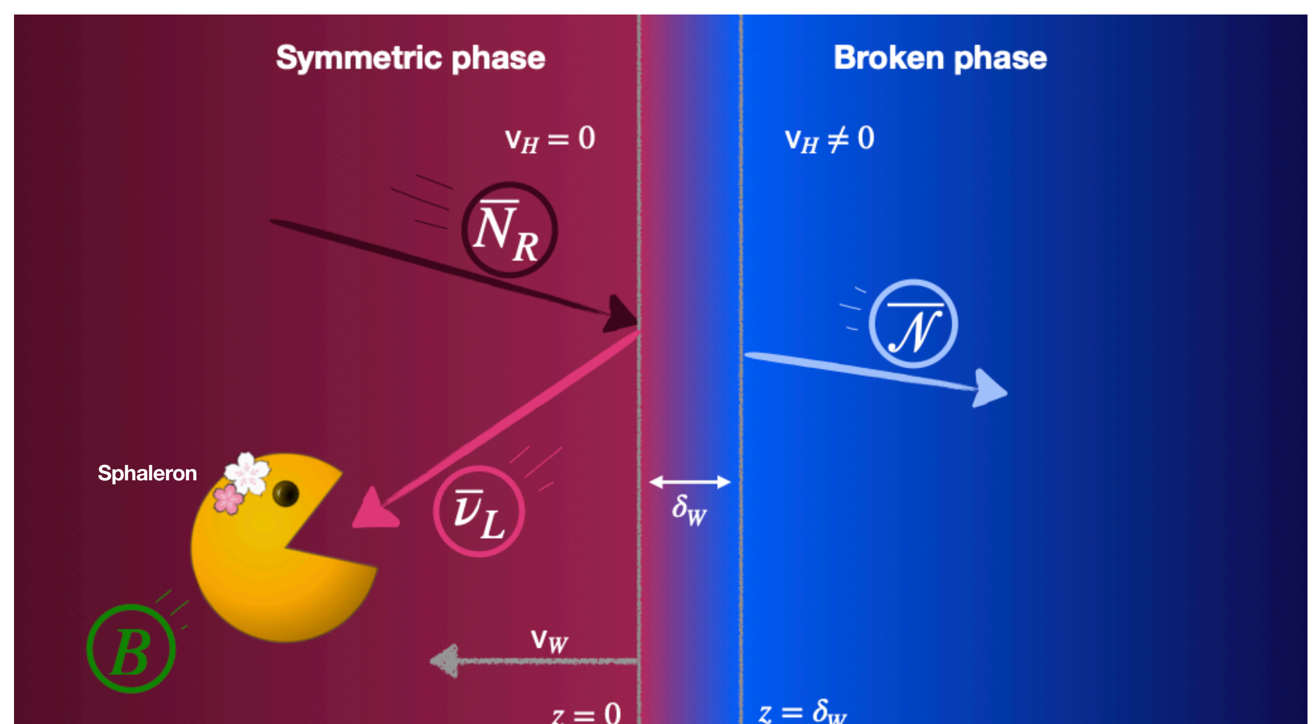
Lepton asymmetry in the neutrino sector during EW FOPT

Sphaleron processes

Baryon asymmetry in symmetric phase

Bubble wall expansion

Bubble wall traps it and BAU freezes-out



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HNLs mass below TeV

Large Yukawa couplings

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Large Yukawa couplings

Rich interplay between new scalar and HNL

Production beyond Drell-Yann through scalar mixing?

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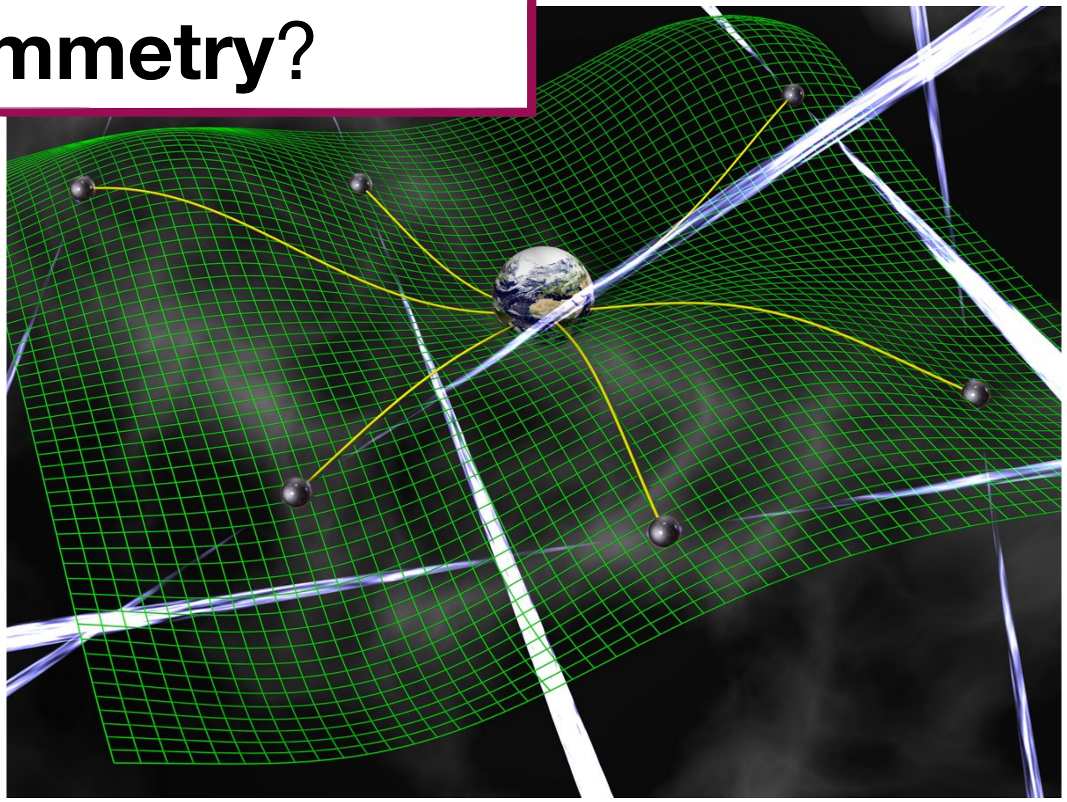

See talk by S. Babak

Could account for PTAs observations

NANOGrav Collaboration, arXiv:2009.04496
NANOGrav Collaboration, arXiv:2306.16219
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F. Costa *et al.*, arXiv:250115649

See also e.g. Goncalves *et al.*, arXiv::2502.19478;
S. Balan *et al.*, arXiv:2502.19478

$$\mathscr{L} = (D_\mu \phi)^\dagger (D^\mu \phi) - \frac{1}{4} Z'_{\mu\nu} Z'^{\mu\nu} + \mu_\phi^2 \phi^* \phi - \frac{\lambda_\phi}{4} (\phi^* \phi)^2$$

Large GW spectrum, supercooling is necessary

Classically conformal scalar potential

$$\boxed{g_D \simeq \left\{ \frac{16\pi^2 \lambda_\phi}{3} \left[1 - \frac{\lambda_\phi}{8\pi^2} (5 + 2\log 2) \right] \right\}^{1/4}}$$

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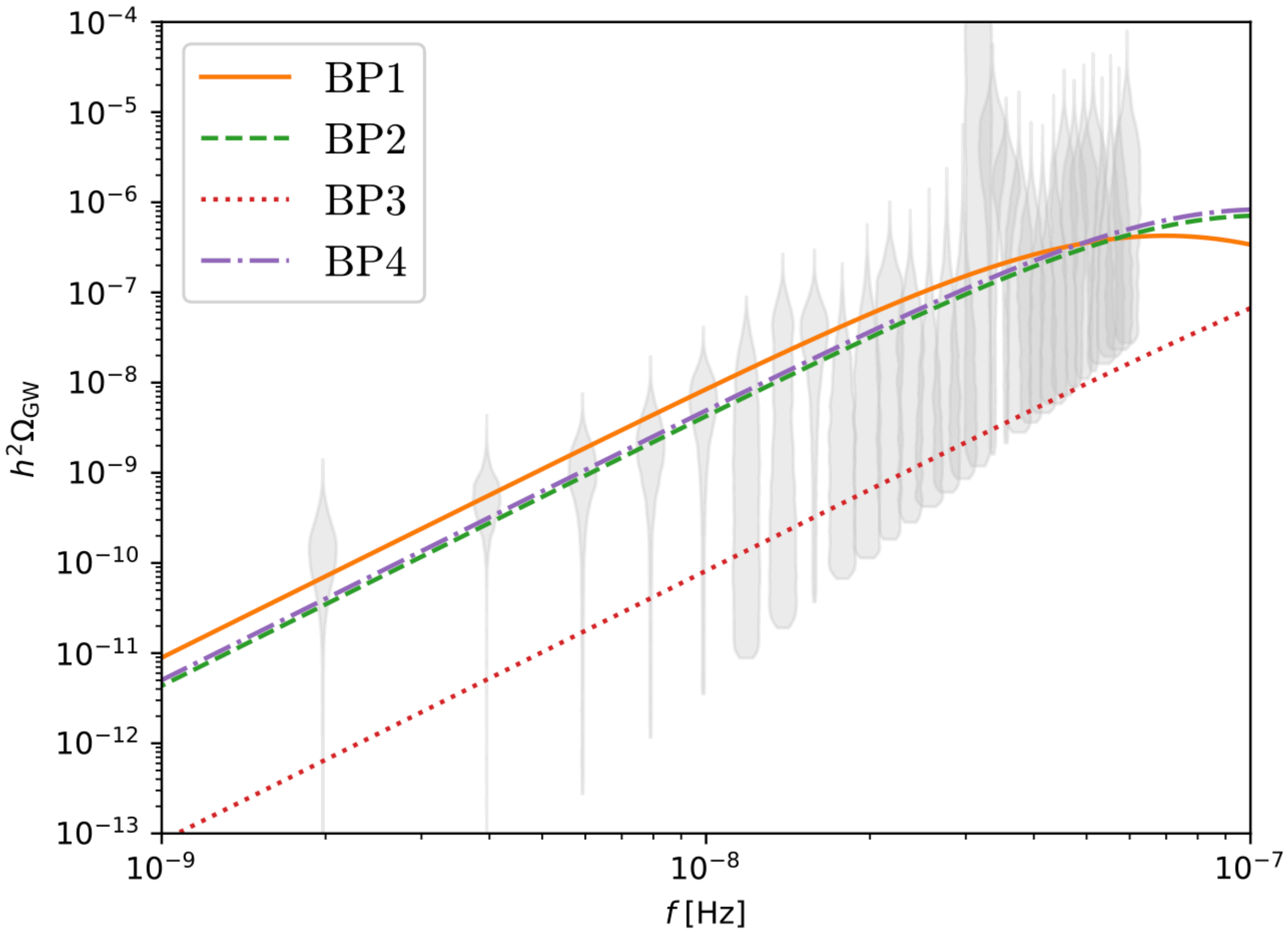
F. Costa, J. Hoefen-Kink, M. Lucente,



$$^{\mu\nu} + \mu_\phi^2 \phi^*\phi - \frac{\lambda_\phi}{4}(\phi^*\phi)^2$$

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Distinct hierarchy between gauge and scalar sector to be searched for experimentally

See e.g. A. Abdullahi, M. Hostert, D. Massaro, S. Pascoli, 2302.05410

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!

- 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 rich **dark sector**

Bright future, driven by an ambitious experimental program

Thank you!

Back up slides

Neutrino masses

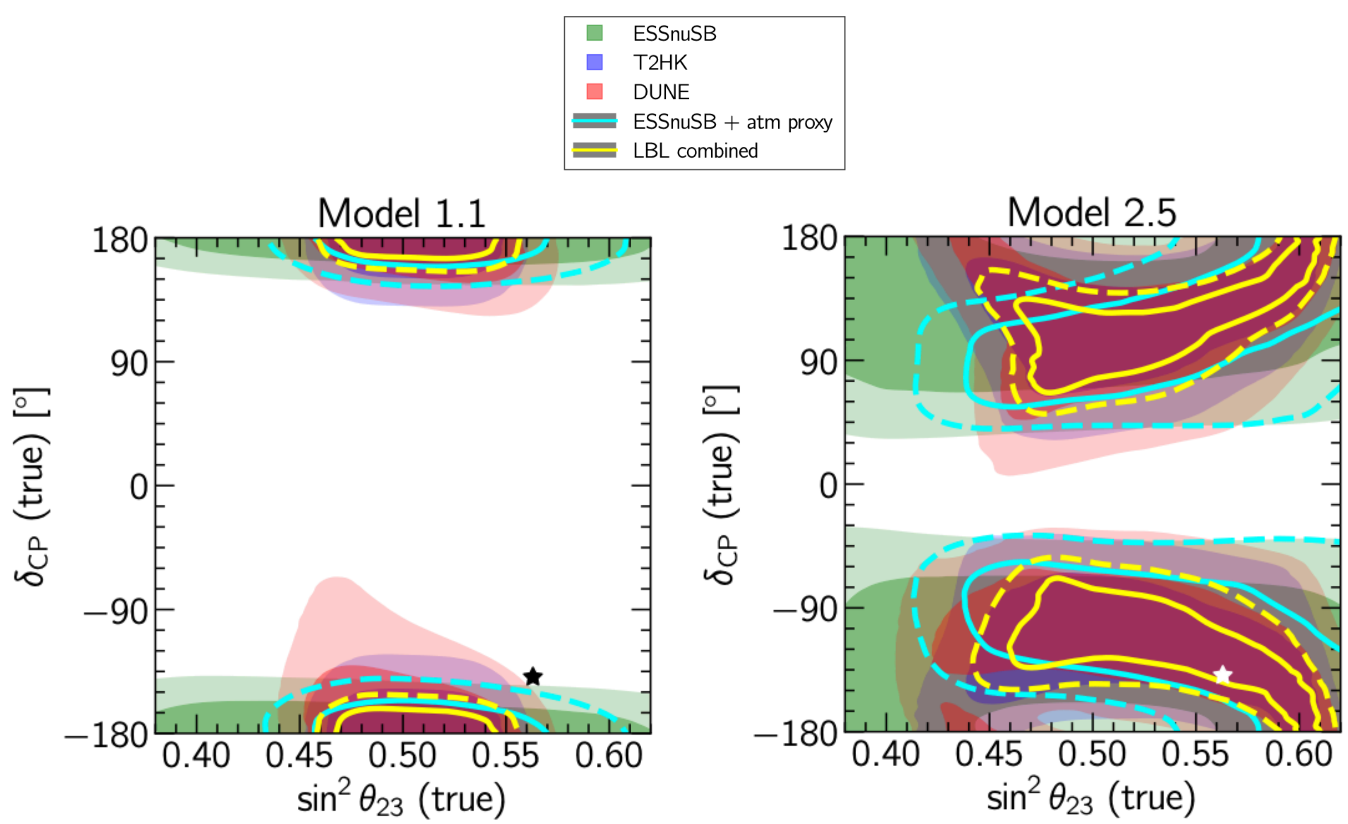
Status from oscillations

Neutrino oscillations

Physics BSM

Only experimental evidence
for BSM from the laboratory

Known unknowns



$\boxed{\text{Octant of } \theta_{23}}$

Does ν_3 have more ν_μ or ν_τ content?

Implications for models
tackling the flavor problem

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

Origin of neutrino masses

Effective Field Theory perspective

Single $d = 5$ operator in the SMEFT

S. Weinberg, '79

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

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Scale of New Physics

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

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

No further experimental evidence beyond oscillations and $0\nu2\beta$ decay

What is the NP scale?

Connections with other SM open problems

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

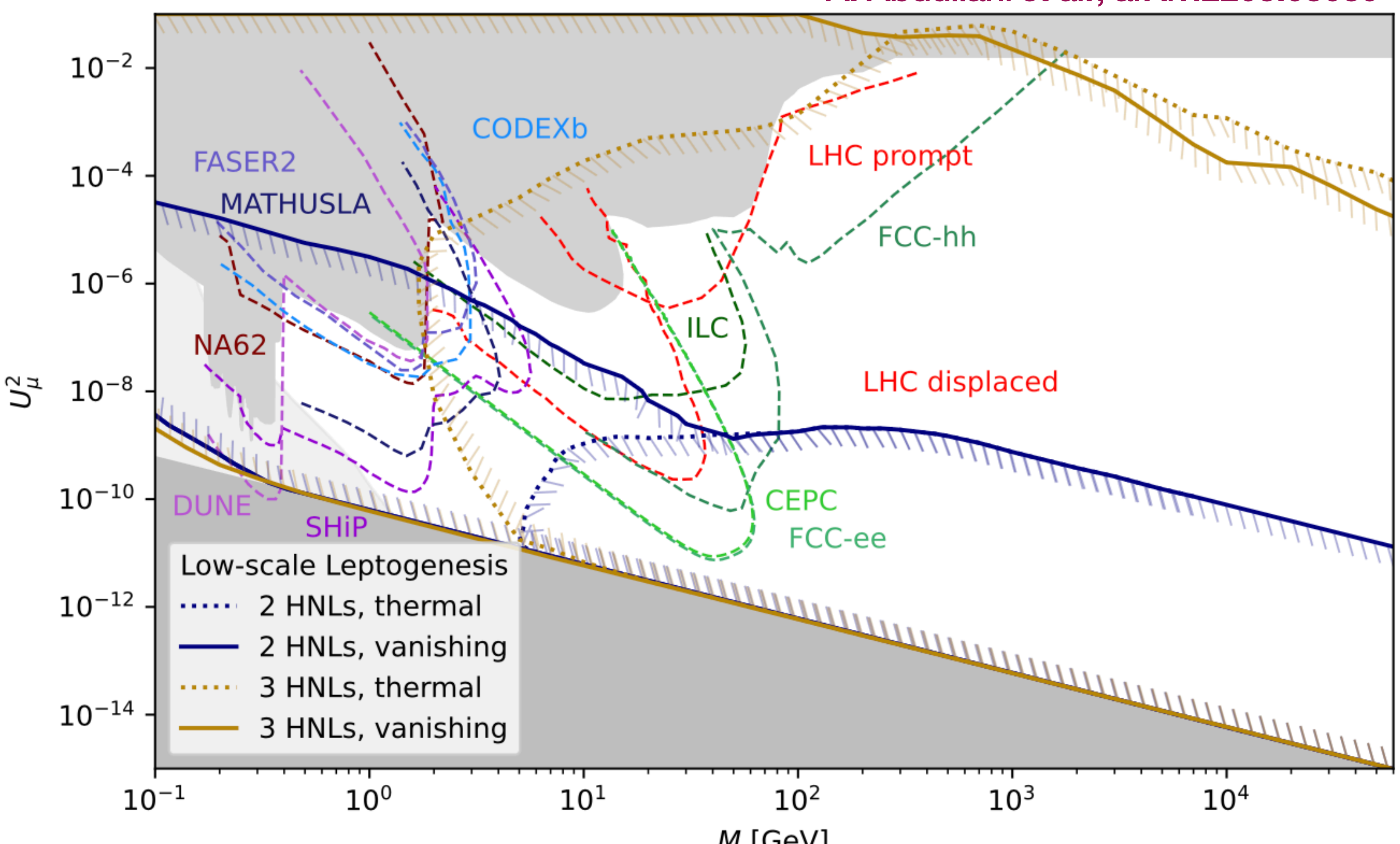
Need at least 2 N_R to explain oscillation data

Baryogenesis

ARS Leptogenesis

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

A. Abdullahi *et al.*, arXiv:2203.08039



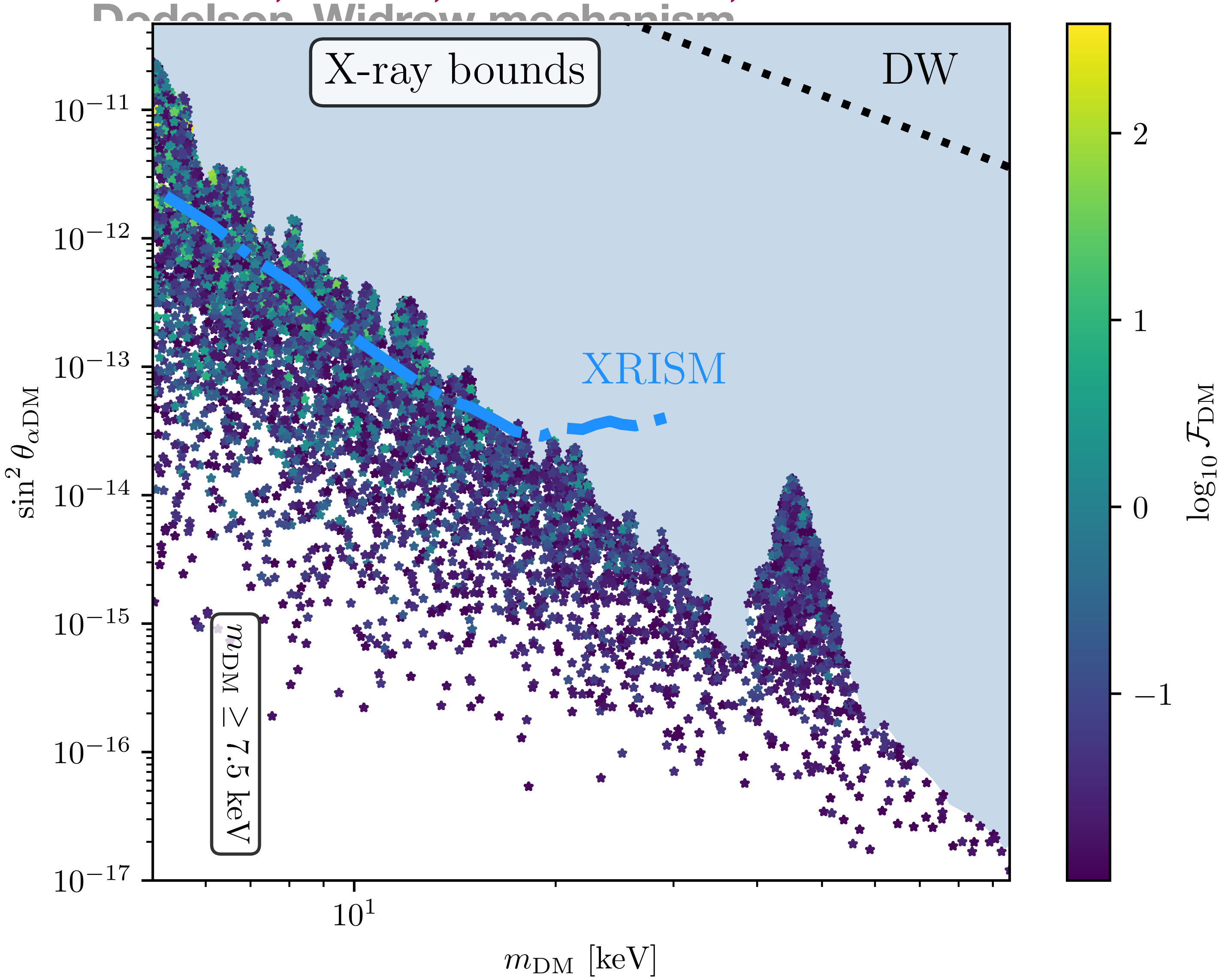
E. K. Akhmedov, V. Rubakov and A. Y. Smirnov, '98
P. Hernandez *et al.*, arXiv:1508.03676
P. Hernandez *et al.*, arXiv:1606.06719
See M. Drewes *et al.*, arXiv:171102862 for a review

Serile neutrino DM

Production mechanisms

A. Abada, G. Arcadi, M. Lucente & **SRA**, arXiv:2503.20017

Dodelson-Widrow mechanism



$\boxed{\text{Temperatures } T \sim 100\,\text{GeV}}$

Freeze-in via 2-body decays

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

DM never reaches equilibrium

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

$\boxed{\text{How much DM is produced?}}$

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

Crucial to account for thermal effects

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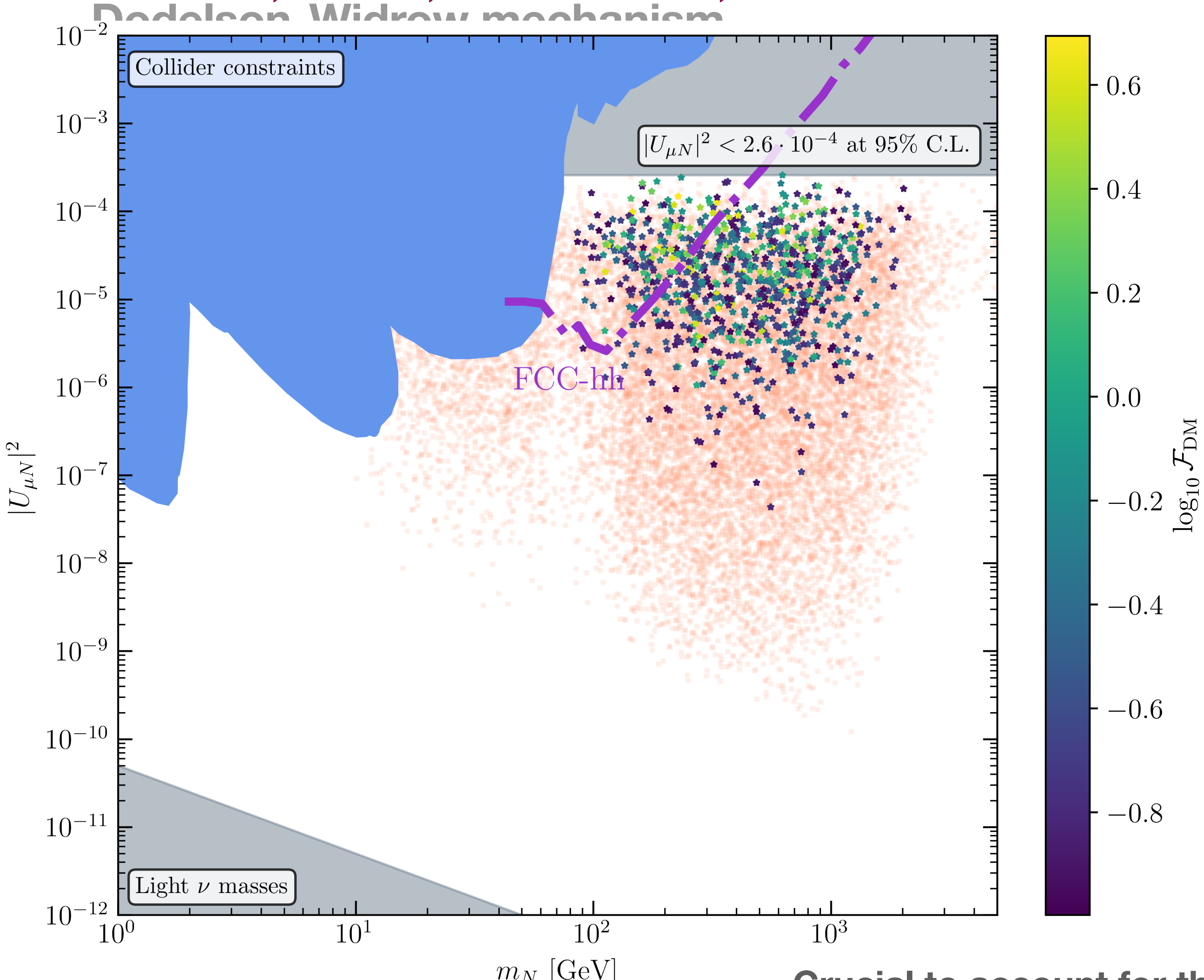

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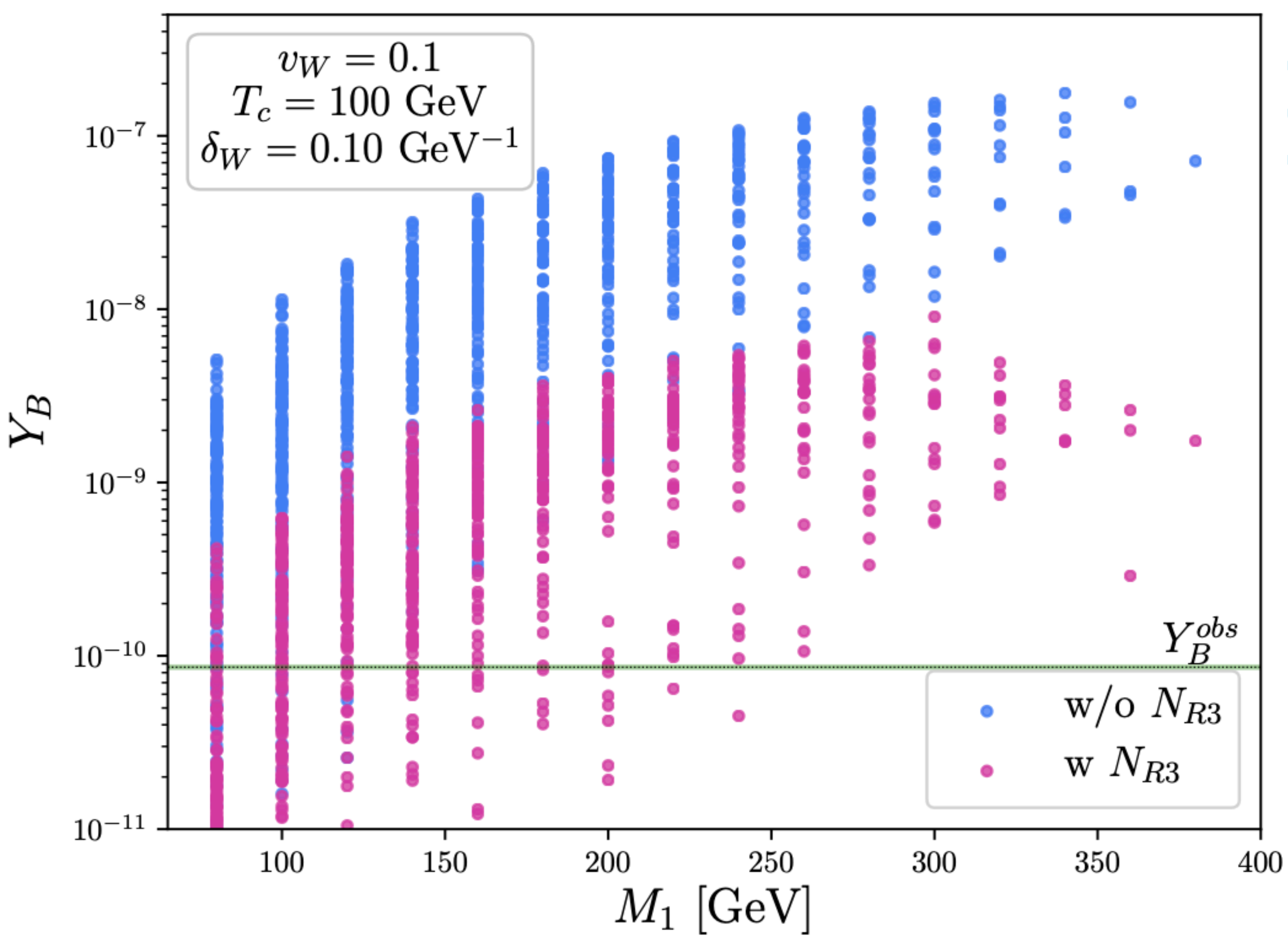
What is the NP scale?

Connections with other SM open problems

What if the HNL mass is generated by a new scalar vev?

$$\mathscr{L} \simeq -\bar{L}_L Y_\nu \tilde{H} N_R - \bar{N}_L \phi Y_N N_R + h.c. \boxed{-V(\phi, H)}$$

Potential for having a **FOPT from the scalar sector**!



FOPT

CP violation from neutrino sector

Sphalerons violate $B + L$

E. Fernández-Martínez, J. López-Pavón, T. Ota & **SRA**, arXiv:2007.11008

E. Fernández-Martínez, J. López-Pavón, J. M. No, T. Ota & **SRA**, arXiv:2210.16279

HNLs mass below TeV

Large Yukawa couplings

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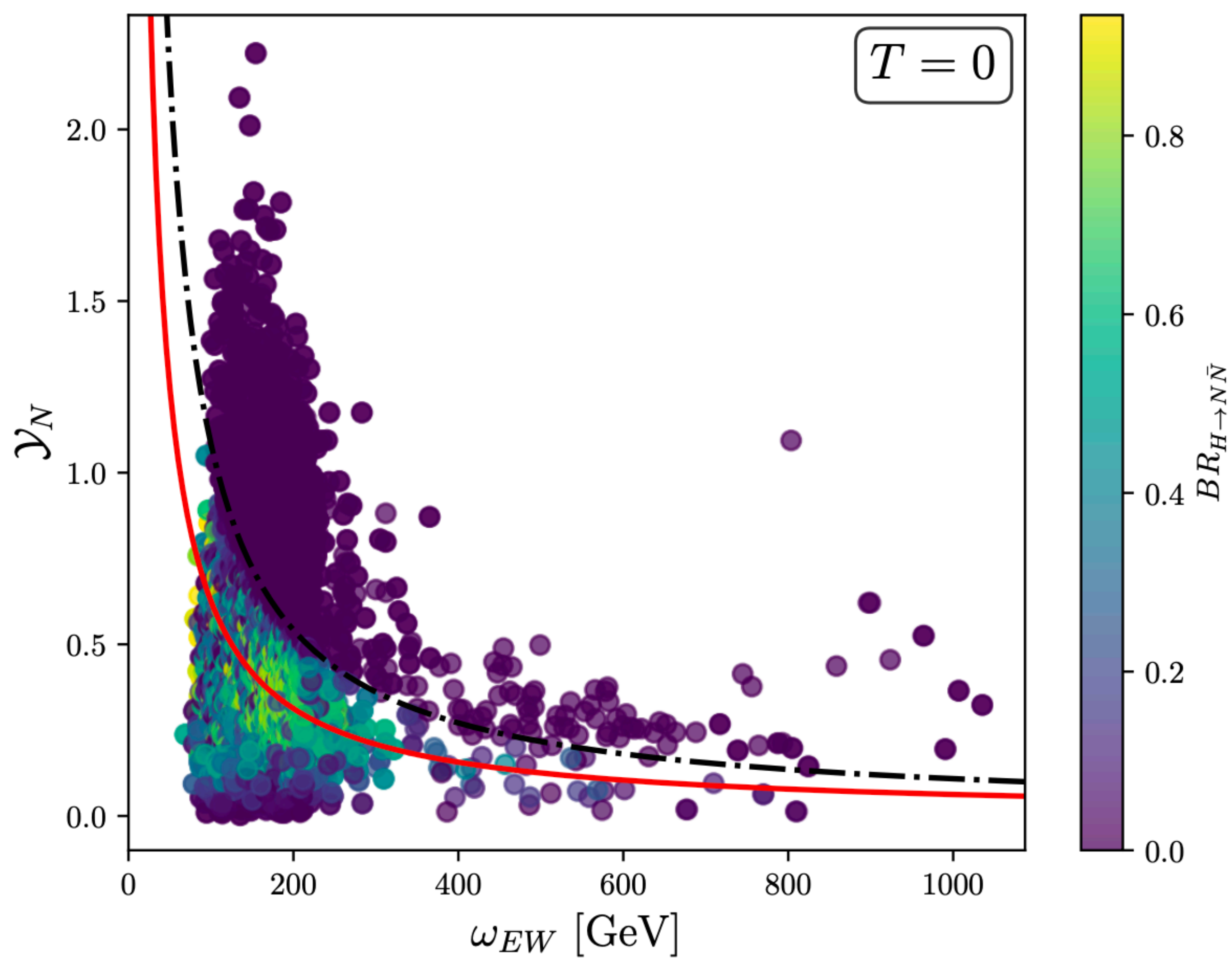

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HNLs mass below TeV

Large Yukawa couplings

Rich interplay between new scalar and HNL

Production beyond Drell-Yann through scalar mixing?