Neutrino Theory Overview

Enrique Fernández-Martínez

Evidence for ν mass from oscillations

Evidence for ν masses and mixings from LFV in oscillation phenomenon in many experiments with great agreement between them:

The known

SNO, Borexino
KamLAND

"Solar sector"

$$\begin{cases} \Delta m^2_{21} = 7.4^{+0.2}_{-0.2} \cdot 10^{-5}\text{eV}^2 \\ \sin^2\theta_{12} = 0.308^{+0.012}_{-0.011} \end{cases}$$

SK, T2K, IC
MINOS, NOνA

"Atm. sector"

$$\begin{cases} |\Delta m^2_{31}| = 2.51^{+0.02}_{-0.02} \cdot 10^{-3}\text{eV}^2 \\ \sin^2\theta_{23} = 0.47^{+0.02}_{-0.02} \end{cases}$$

Daya Bay
RENO, T2K, NOνA

$$\sin^2\theta_{13} = 0.0221 \pm 0.0006$$

See talk by Kate Scholberg

I. Esteban, M. C. Gonzalez-Garcia, M. Maltoni, I. Martinez-Soler, J. P. Pinheiro and T. Schwetz 2410.05380

Evidence for new physics from oscillations

The existence of BSM Physics in the ν sector to account for their masses and mixings is well-established

But still several open questions to reveal the underlying theory…

Known unknowns

The known unknowns

Mass ordering?
$sign(\Delta m^2_{31})$?

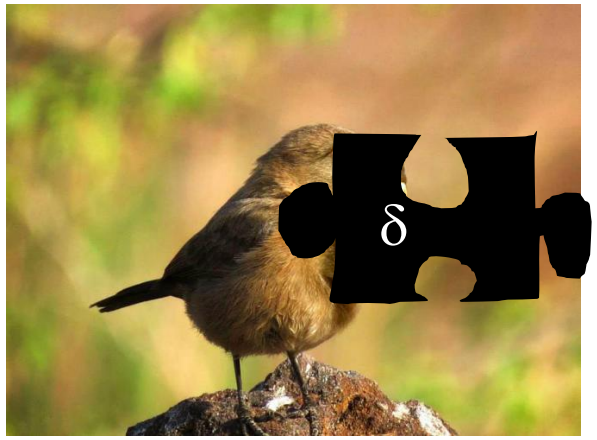
CP violation phase?
δ?

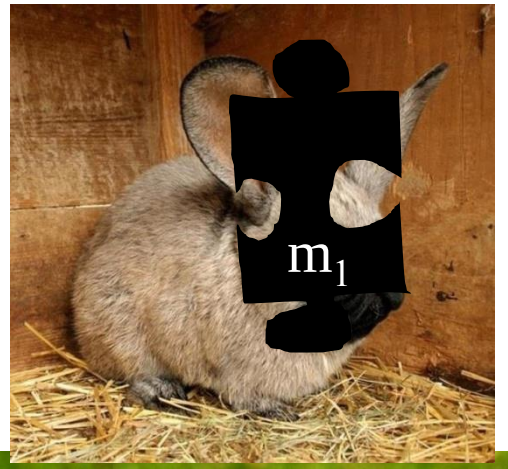
Absolute mass scale?

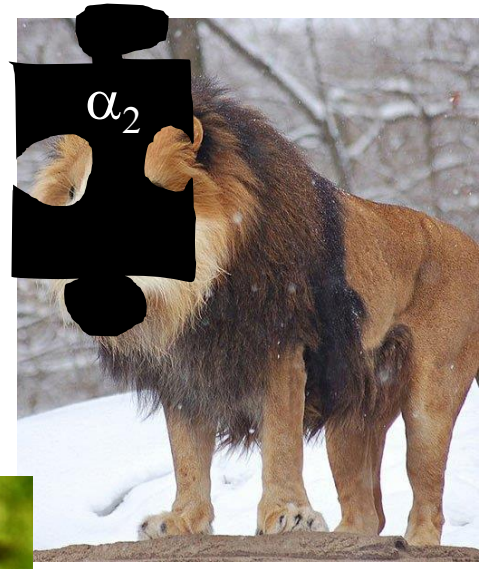
Majorana Nature and phases?

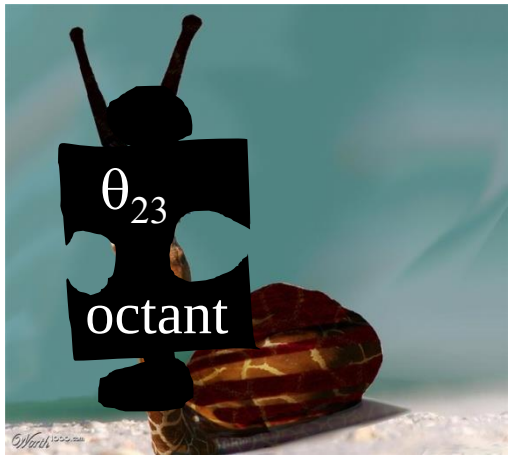
This is half of the flavour puzzle

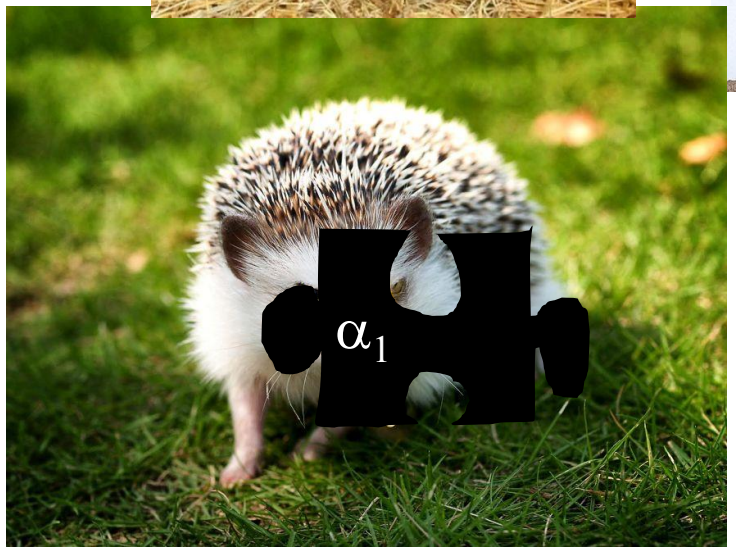
See talk by Sophie Renner

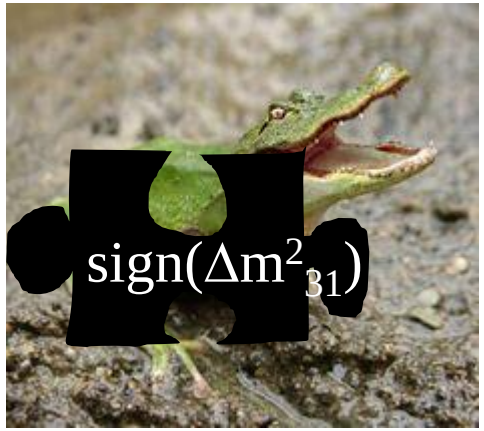












This is half of the flavour puzzle

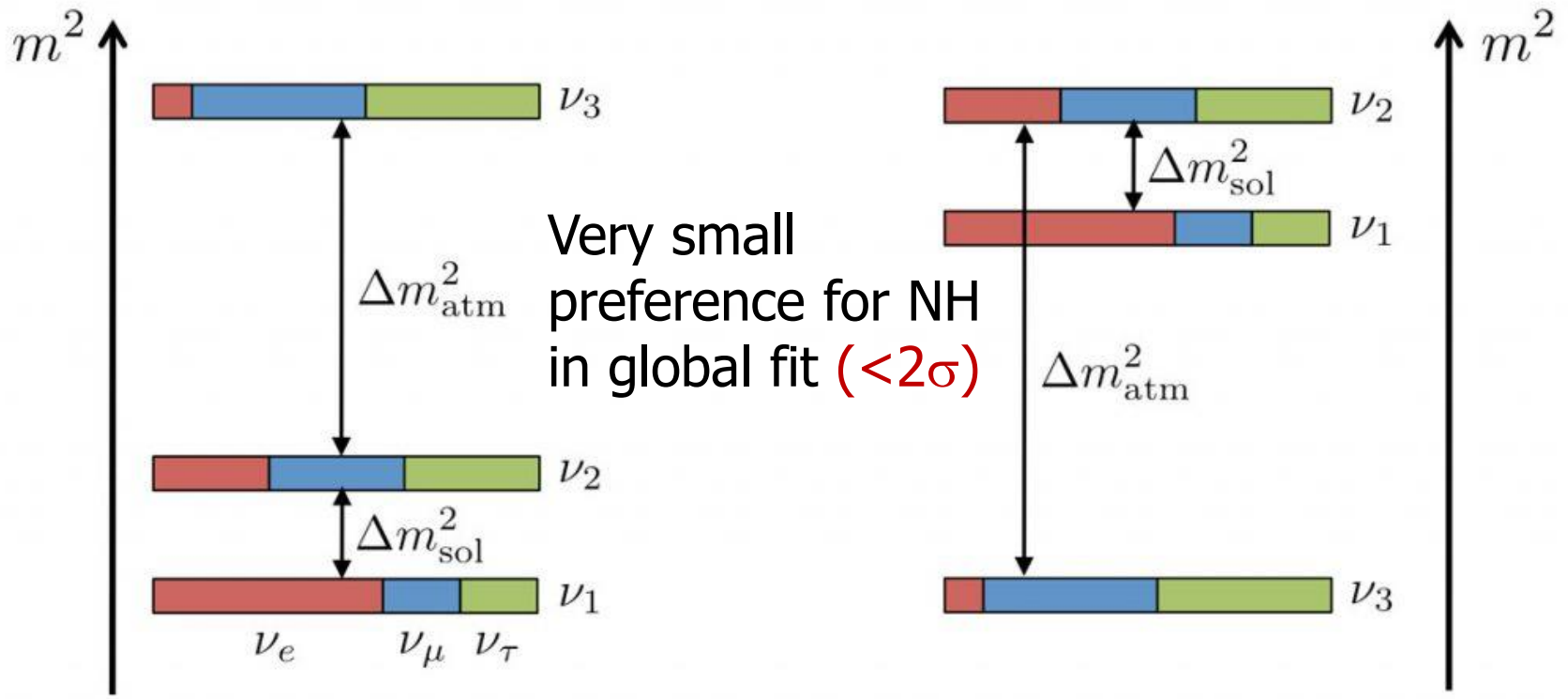
No animals were harmed in the making

Mass Ordering

The known unknowns

Mass ordering?
$sign(\Delta m^2_{31})$?

Normal hierarchy (NH) or (NO) Inverted hierarchy (IH) or (IO)



Very small preference for NH in global fit (<2σ)

See Kate Scholberg's, Laura Pérez Molina's, Mariangela Settimo's, Justyna Łagoda's, Víctor Carretero's and Runze Zhao's talks for the present status and future prospects

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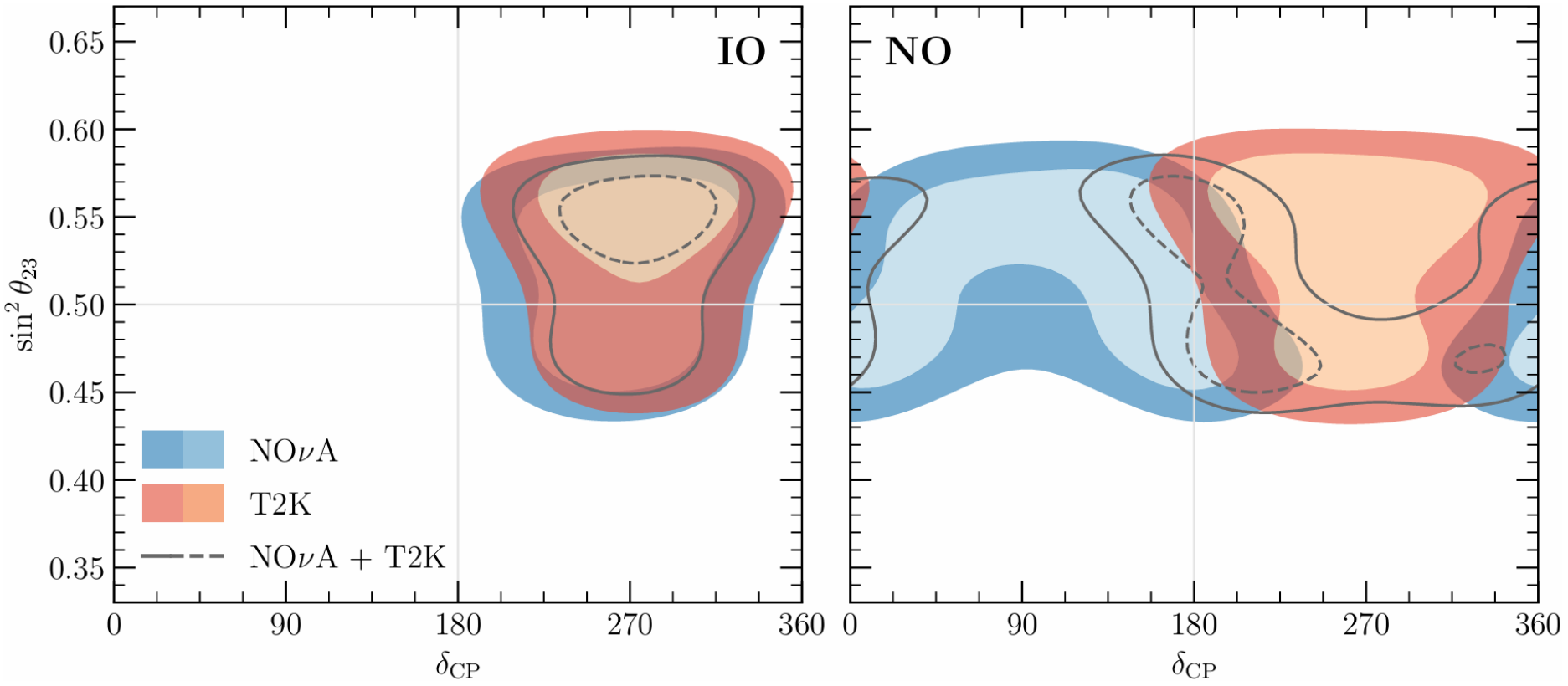
CP violation

~2σ tension between the two present measurements of δ



T2K and NOνA already have interesting hints but the situation is still very unclear

See Kate Scholberg's, Claire Dalmazzone's, Laura Pérez Molina's, Ritam Kundu's, Georgios Fanourakis and Katarzyna Kowalik's talks

I. Esteban, M. C. Gonzalez-Garcia, M. Maltoni, I. Martinez-Soler, J. P. Pinheiro and T. Schwetz 2410.05380

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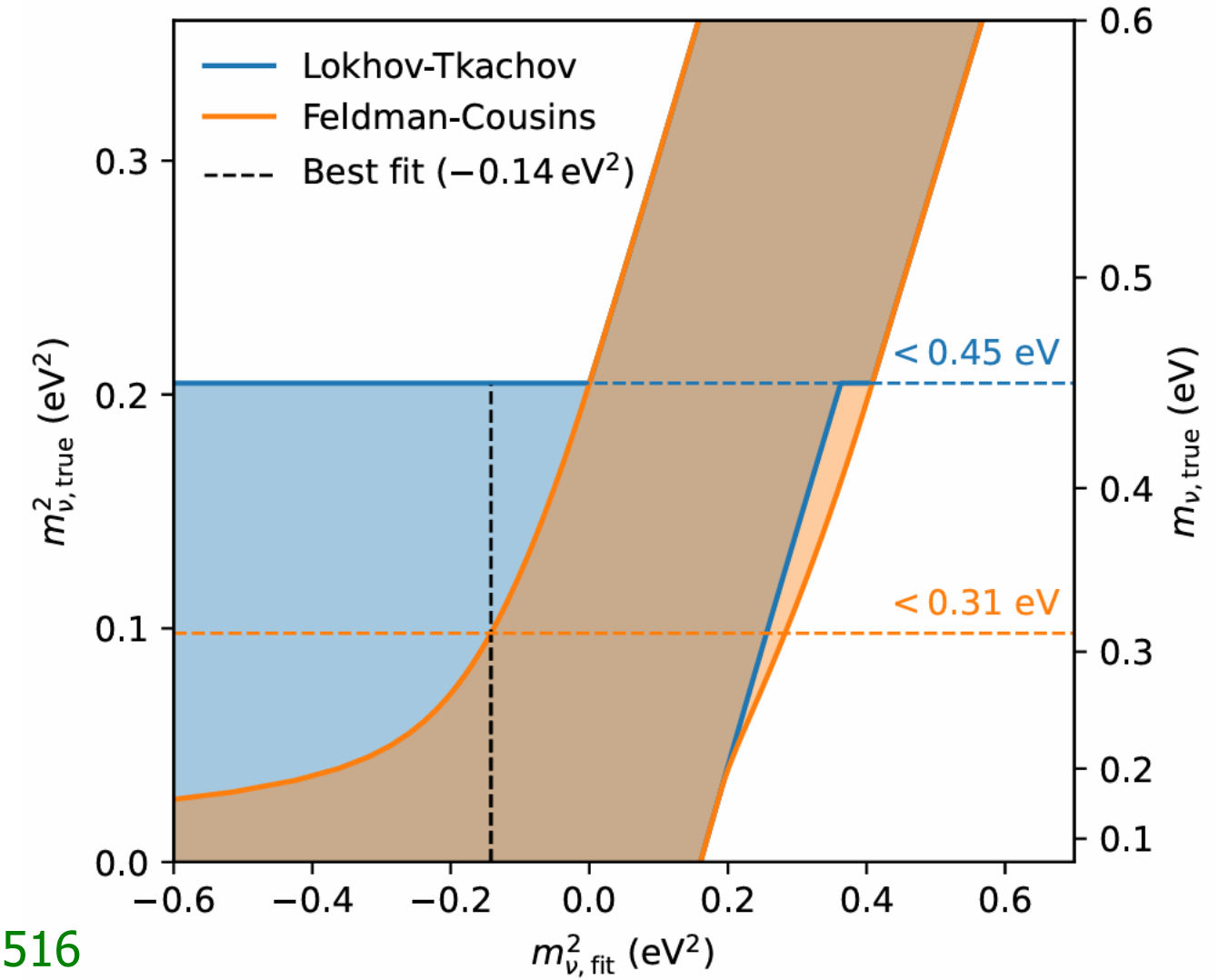

KATRIN 2406.13516

Recent new bound on the effective ν_e mass from KATRIN

See Kate Scholberg's, Jaroslav Storek's and Matteo De Gerone's talks

Searches for ν mass from cosmology

Cosmology is instead sensitive to sum of ν masses

$$\sum_i m_i$$

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Very stringent bounds when adding new DESI results at 95% CL:

$$\sum_i m_i \leq 0.072\ eV \quad \text{(CMB+DESI DR1) 2404.03002}$$

$$\sum_i m_i \leq 0.064\ eV \quad \text{(CMB+DESI DR2) 2503.14744}$$

See talk by Julian Bautista

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But minimum value from oscillation data (more than 3σ):

$$\sum_i m_i \geq 0.059\ eV$$ for NO if $m_1 = 0$

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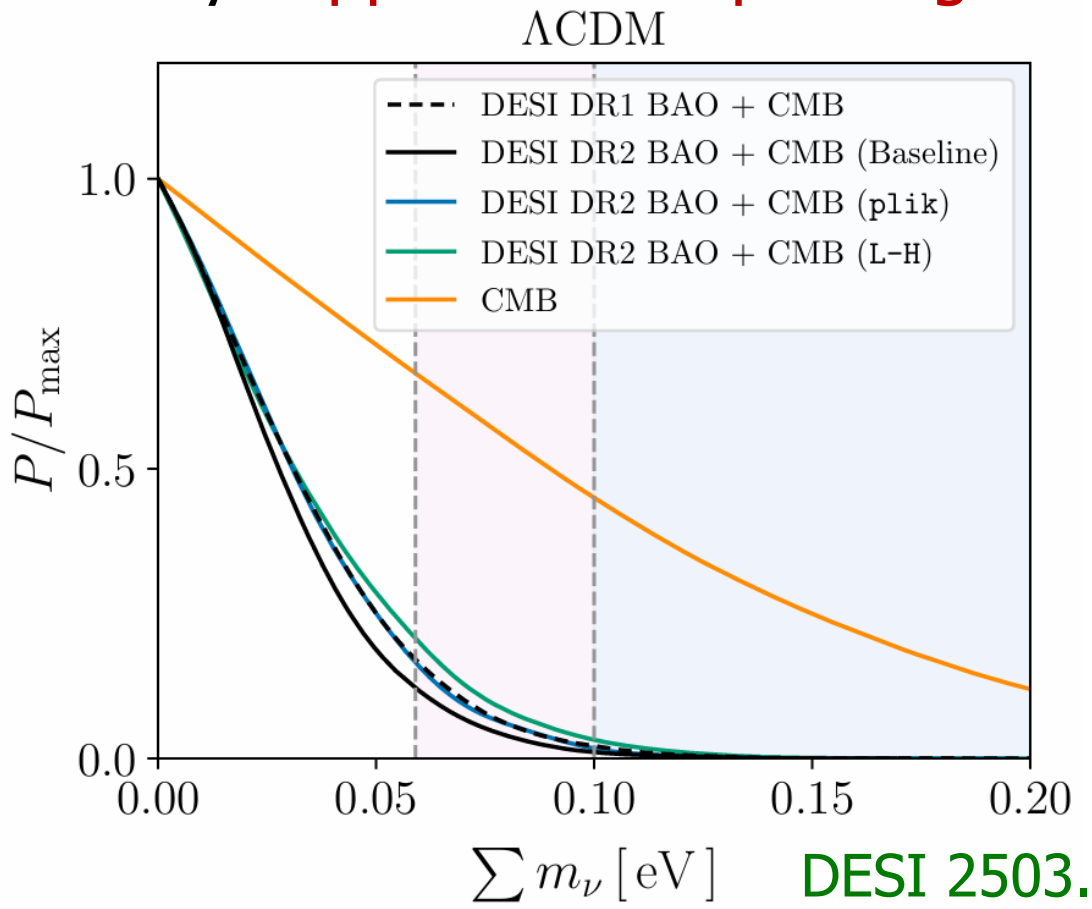

DESI 2503.14744

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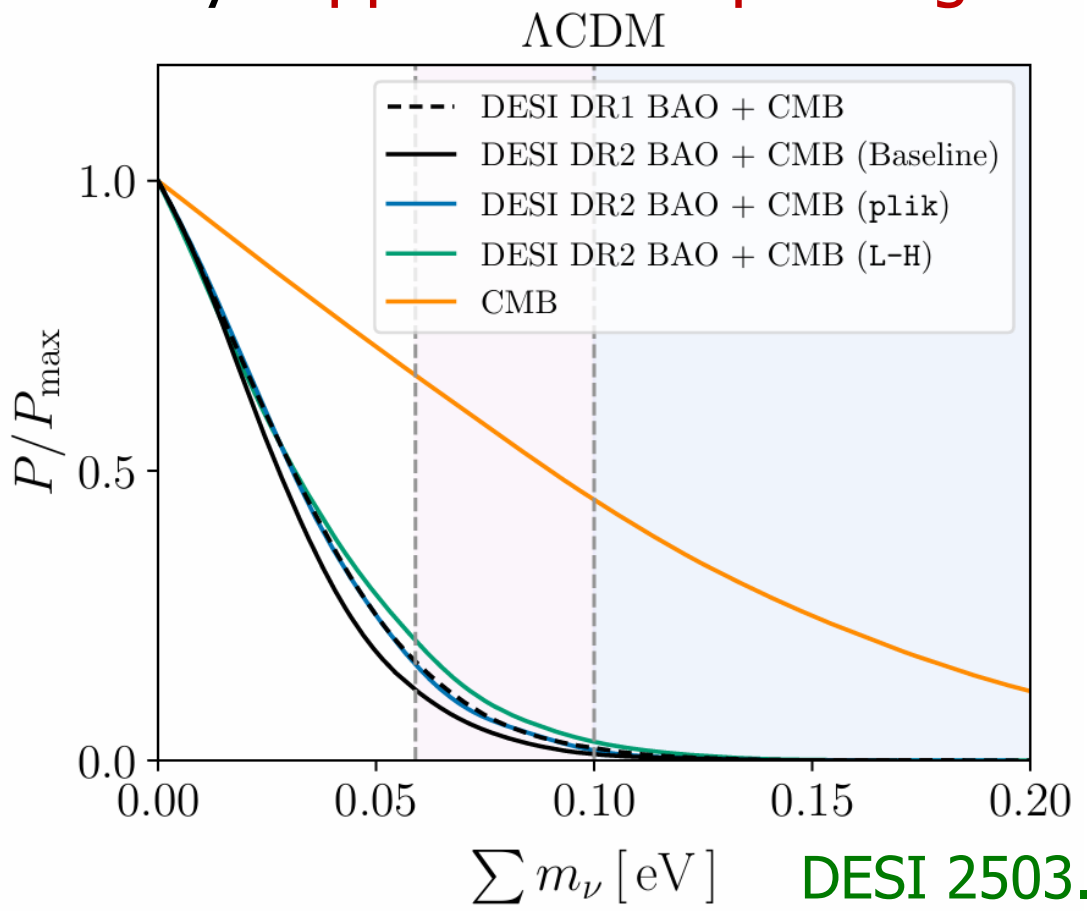


DESI 2503.14744

Why??

Where does the sensitivity come from?

Two main effects:

see also M. Loverde and Z. J. Weiner 2410.00090 and
T. Bertólez-Martínez et al 2411.14524

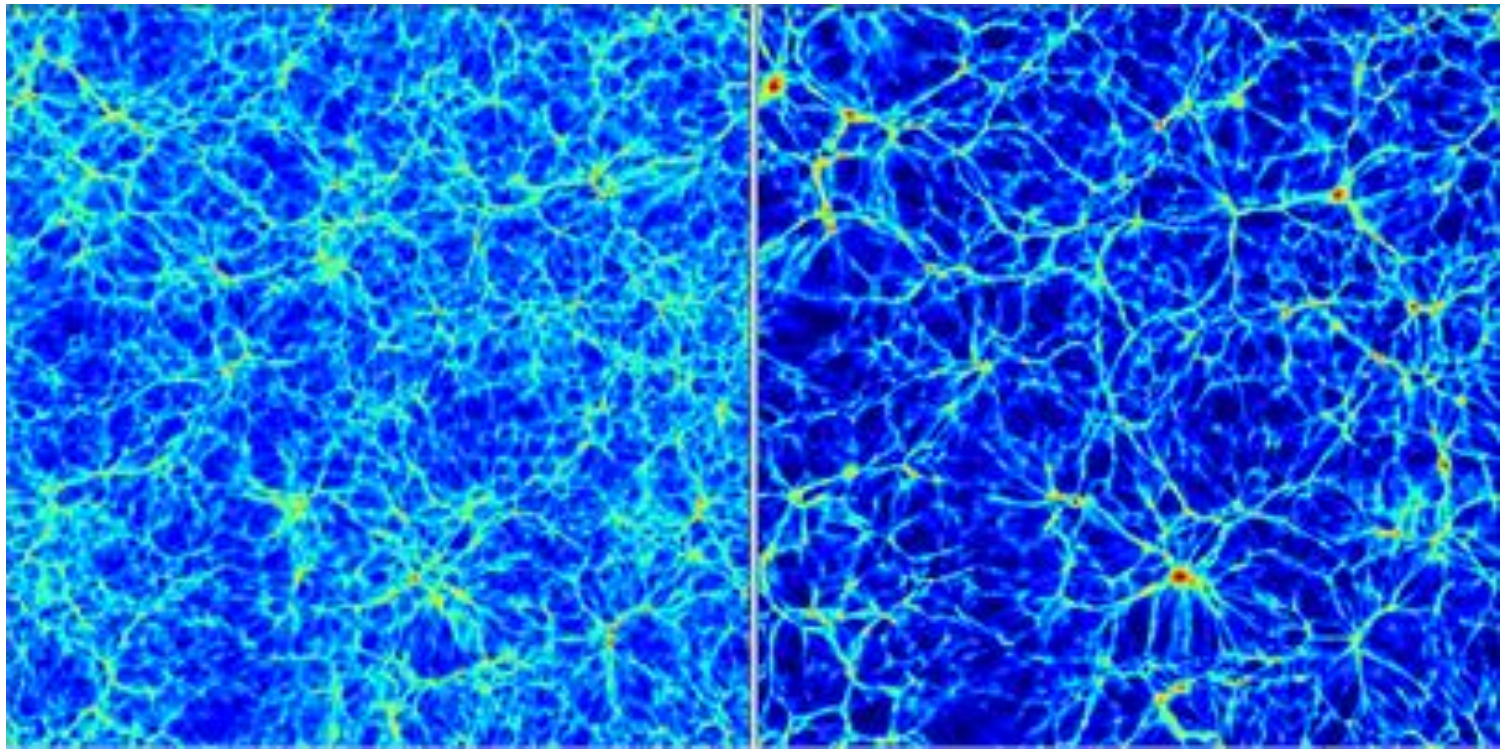
Where does the sensitivity come from?

Two main effects:

1) "Perturbations"

ν free stream and suppress formation of small structures as they do not fall into the smallest potential wells (scales below ~20Mpc)

$\sum_i m_i = 0$ $\sum_i m_i = 1.9\ eV$



Plot from S. Agarwal and H. Feldman 1006.0689

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See Elizabeth Johana Gonzalez's, William D'Assignies Doumerg's and Julian Bautista's talks

Plot from S. Agarwal and H. Feldman 1006.0689

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Two main effects:

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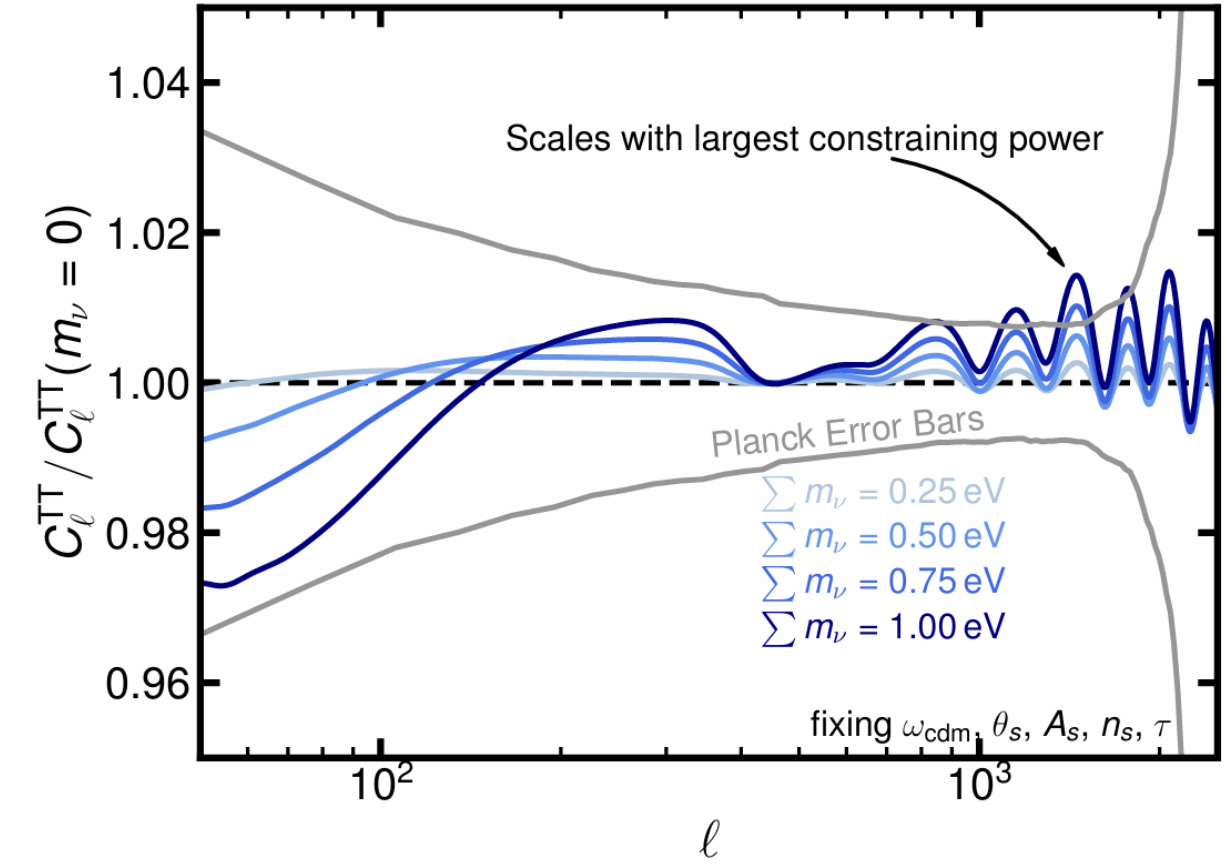
Relativistic ν will also reduce the lensing of CMB photons from LSS.

At Planck this is reflected by sharper peaks, particularly at small angular scales



D. Naredo-Tuero, M. Escudero, EFM, X. Marcano and V. Poulin 2407.13831

Why never a hint from cosmology?

Most (if not all) cosmological datasets are combined with Planck data

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Planck 2018 1807.06209

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A preference for $A_{\rm lens} > 1$ is also present in WMAP data
E. Calabrese, A. Slosar, A. Melchiorri, G. F. Smoot and O. Zahn 0803.2309

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Thus, analyses containing WMAP or Planck data will prefer

$$\sum_i m_i = 0$$

or even larger lensing, if allowed

Why never a hint from cosmology?

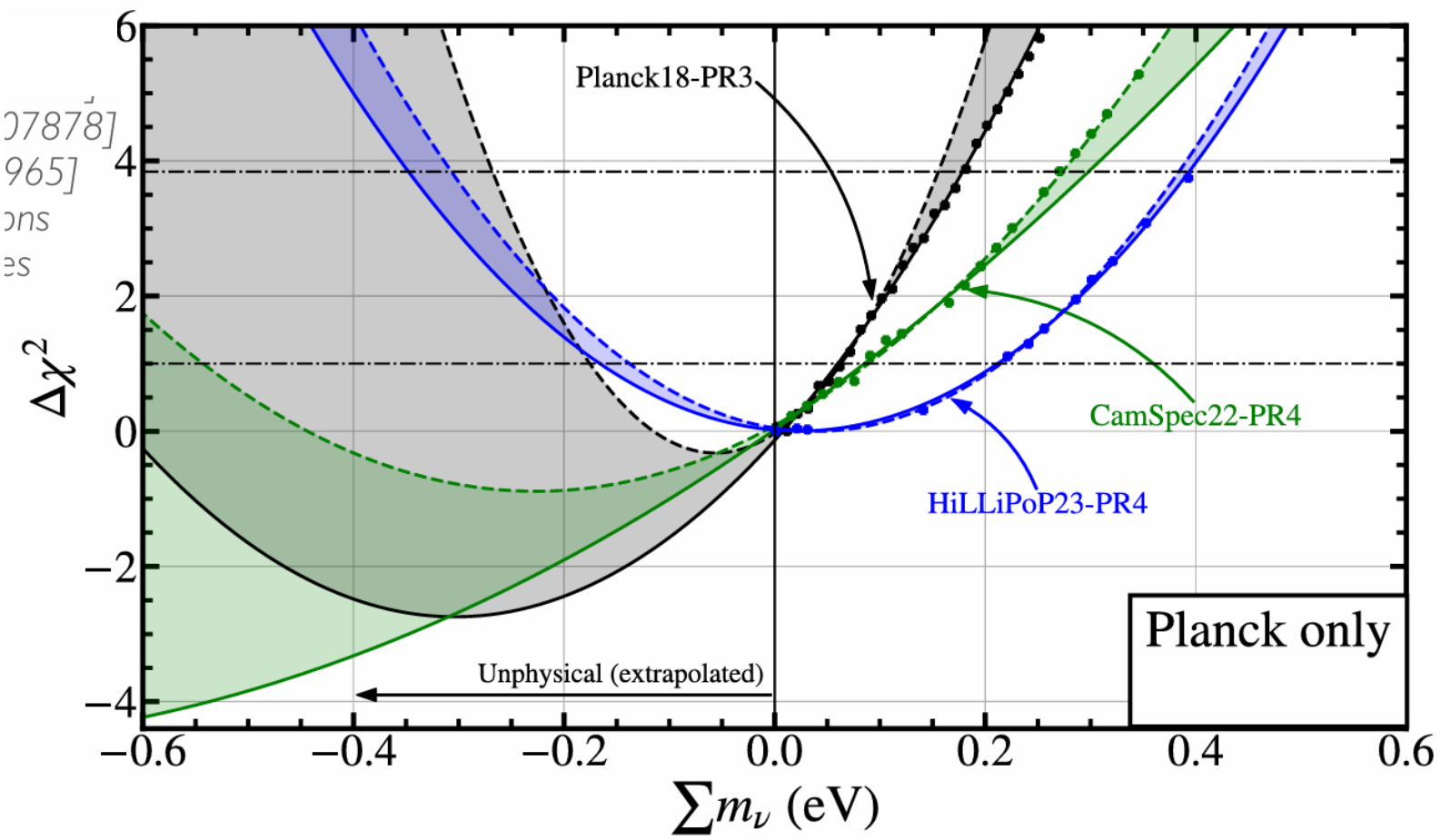
Planck 2018 legacy analysis reported a "lensing anomaly". Namely, if allowed to scale freely, the likelihood prefers stronger lensing than even for massless ν at 2.8σ ($A_{\rm lens} > 1$) Planck 2018 1807.06209

Interestingly, subsequent reanalyses by members of Planck improving on several aspects reduce the lensing anomaly:

- "CamSpec22" $A_{\rm lens} > 1$ at 1.7σ
  E. Rosenberg, S. Gratton, G. Efstathiou 2205.10869

- "HiLLiPoP23" $A_{\rm lens} > 1$ at 0.75σ
  M. Tristram et al 2309.10034

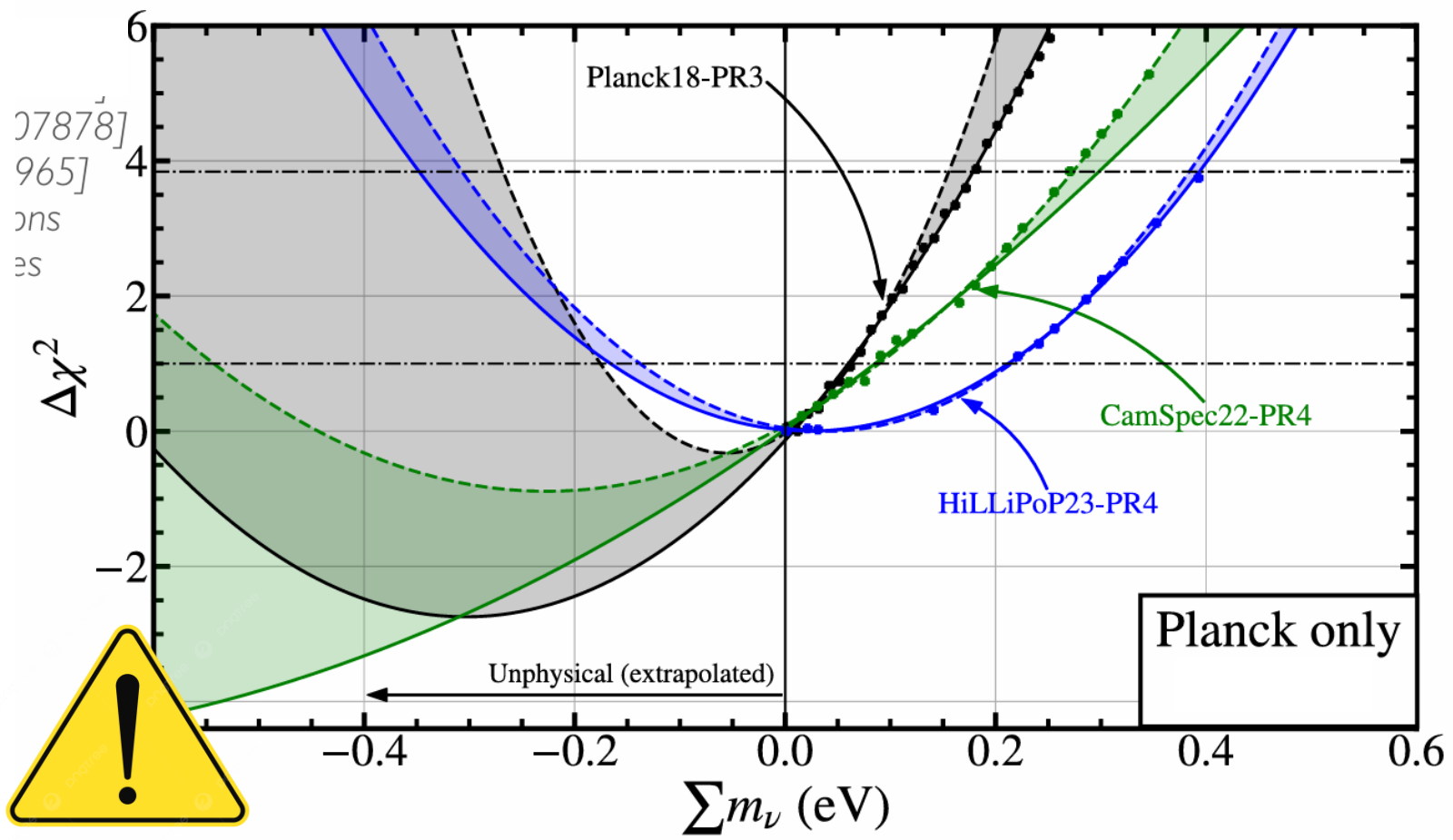
Bound relaxed with new Planck likelihoods



Bound from Planck significantly relaxed with new likelihoods with reduced lensing anomaly

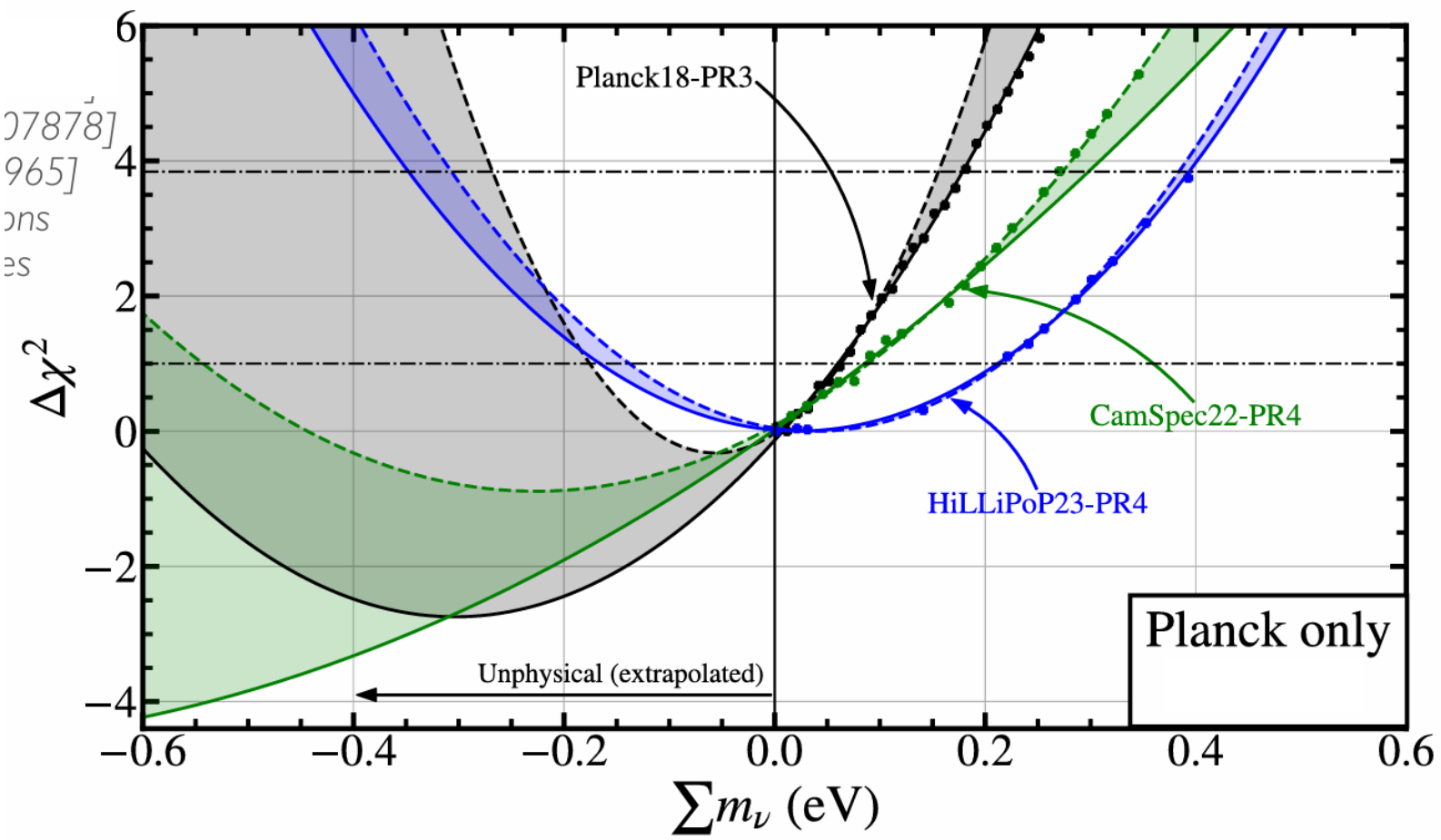
D. Naredo-Tuero, M. Escudero, EFM, X. Marcano and V. Poulin 2407.13831

Bound relaxed with new Planck likelihoods



DISCLAIMER!!: The extrapolation to negative region is only a means to derive and compare frequentist and Bayesian bounds and NOT intended to be interpreted physically. The preference for $\Sigma m_i<0$ is just another reflection of the lensing anomaly and hence absent for HiLLiPoP23

Bound relaxed with new Planck likelihoods



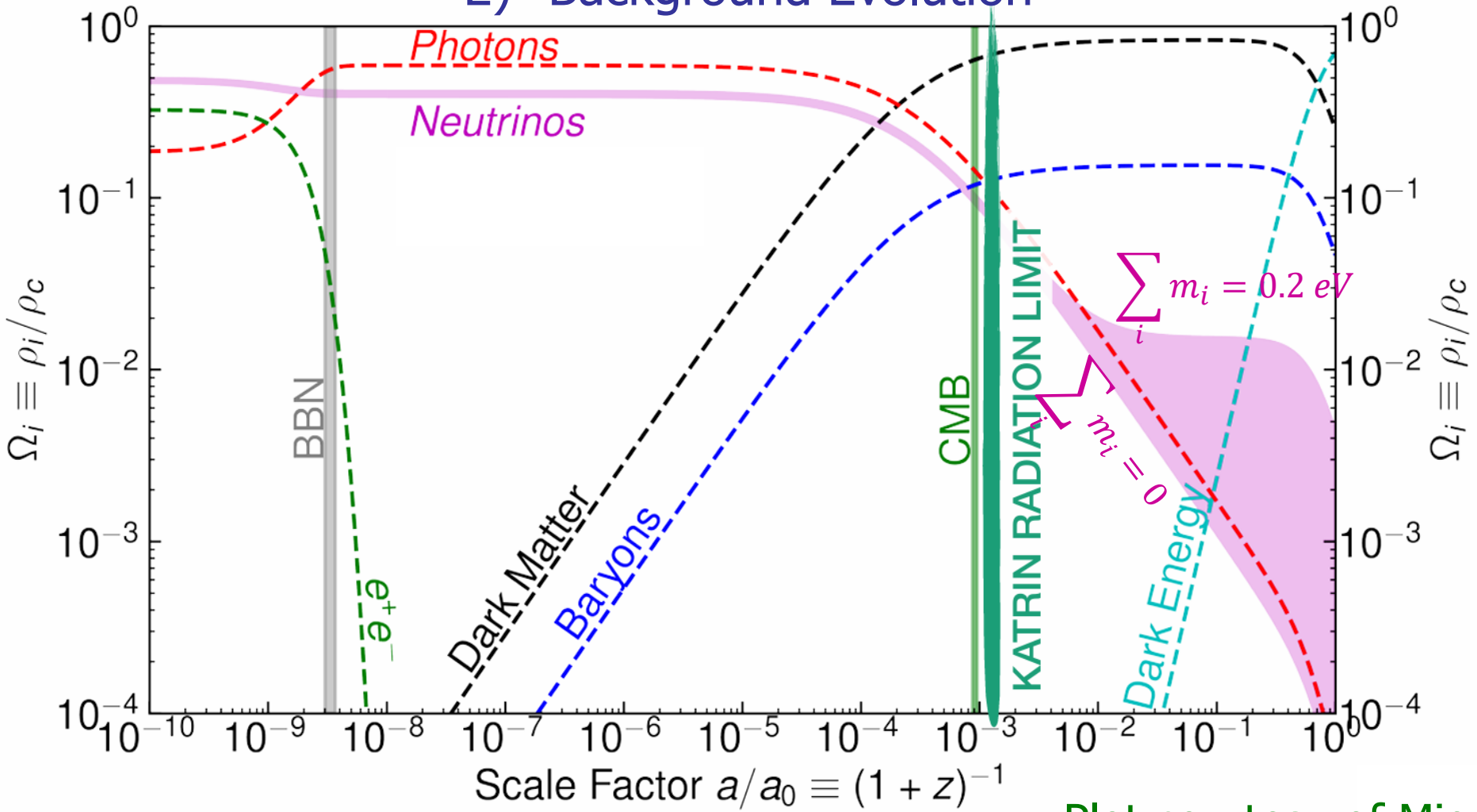
For further discussion for this preference see:

I. J. Allali and A. Notari 2406.14554; D. Green and J. Meyers 2407.07878;
W. Elbers, C. S. Frenk, A. Jenkins, B. Li and S. Pascoli 2407.10965

Where does the sensitivity come from?

Two main effects:

2) "Background Evolution"



Plot courtesy of Miguel Escudero

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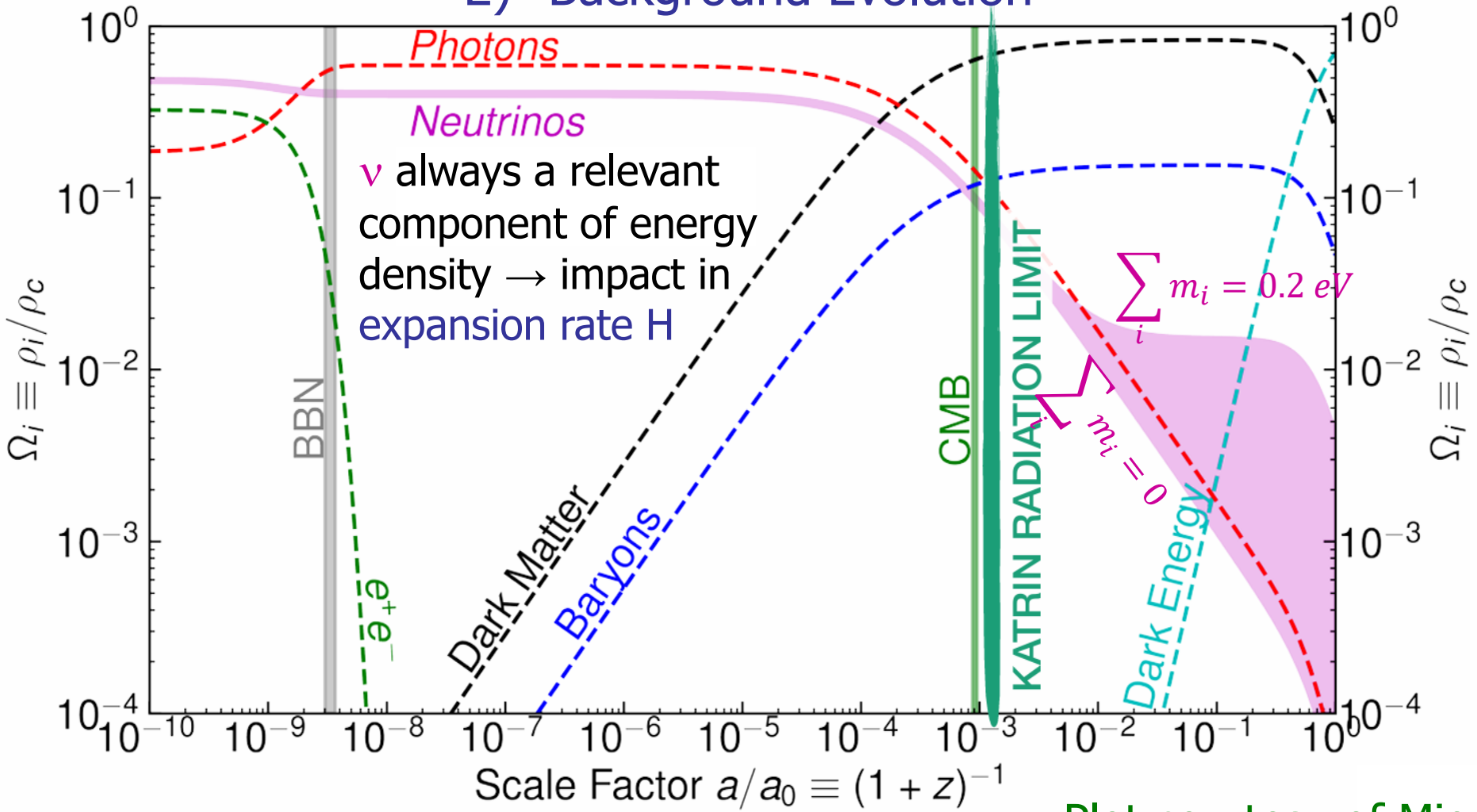

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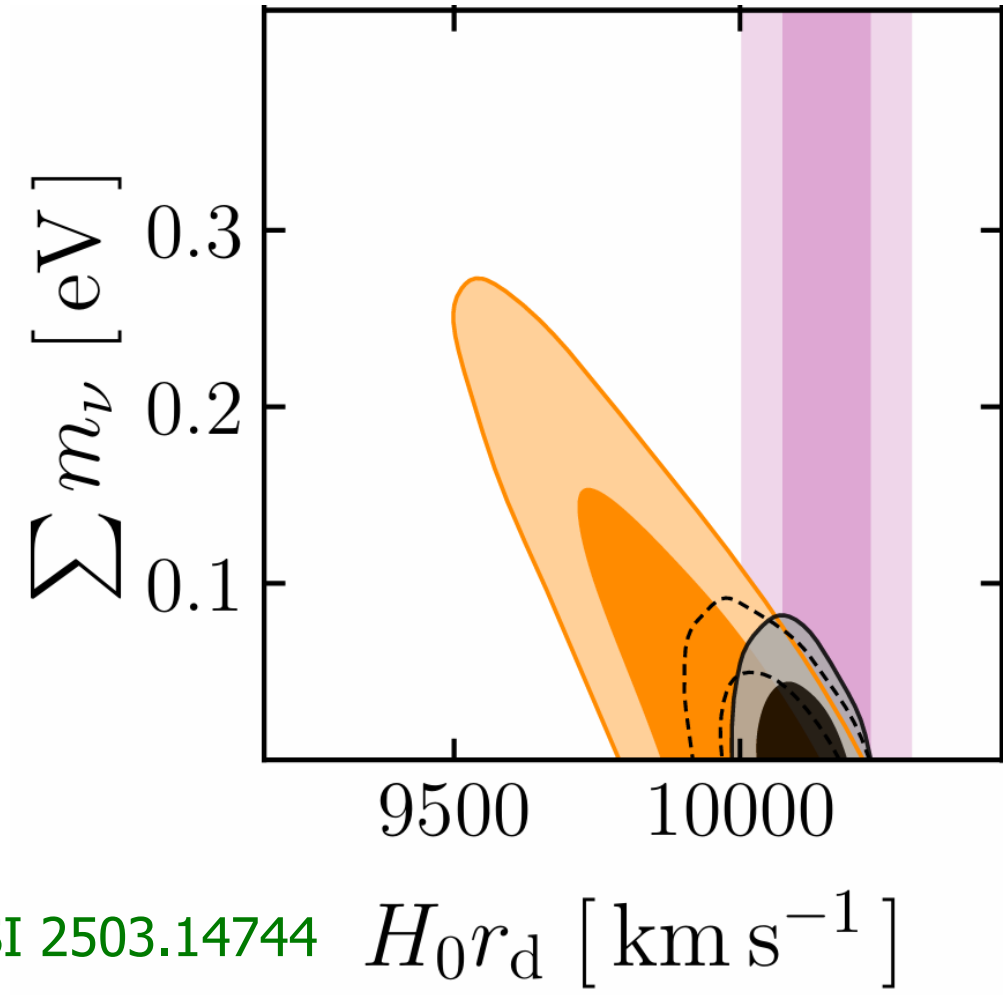

DESI 2503.14744

Mild tension between DESI and Planck preferred regions.

DESI pushes to large H_0 which makes Planck's bound on m_ν stronger.

Where does the sensitivity come from?

Two main effects:

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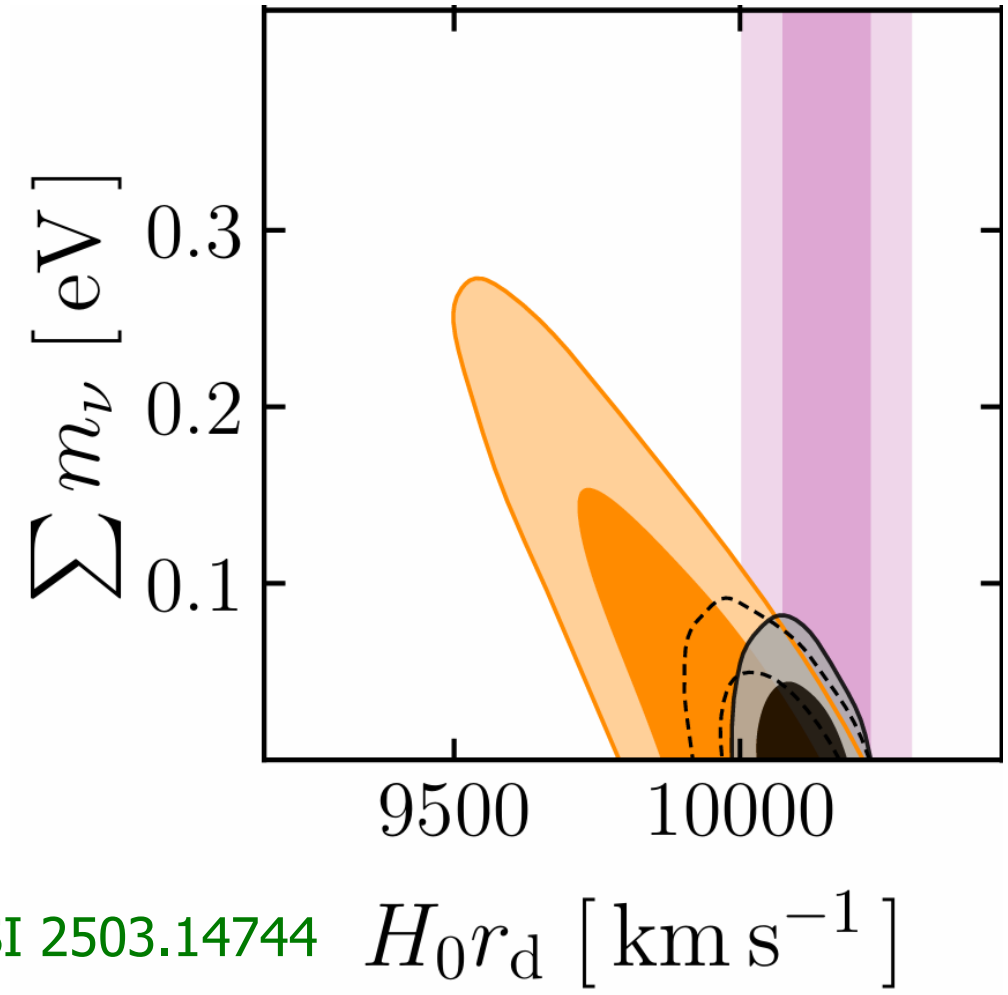
See Camille Bonvin's talk



DESI 2503.14744

This tension is also behind the preference for dynamical DE. If the DE e.o.s. is allowed to vary $w_0 + w_a(1-a)$ the bound relaxes to:

$$\sum_i m_i \leq 0.163\ eV$$

Will be very interesting to see how this situation evolves with more data. Particularly with DESI and EUCLID full shape analyses.

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Neutrinoless double beta decay

See talks by Kate Scholberg, Ana Sofia Inácio, Miroslav Macko, Mathieu Pageot, Jing-yu Zhu, Malgorzata Haranczyk and Giovanna Saleh

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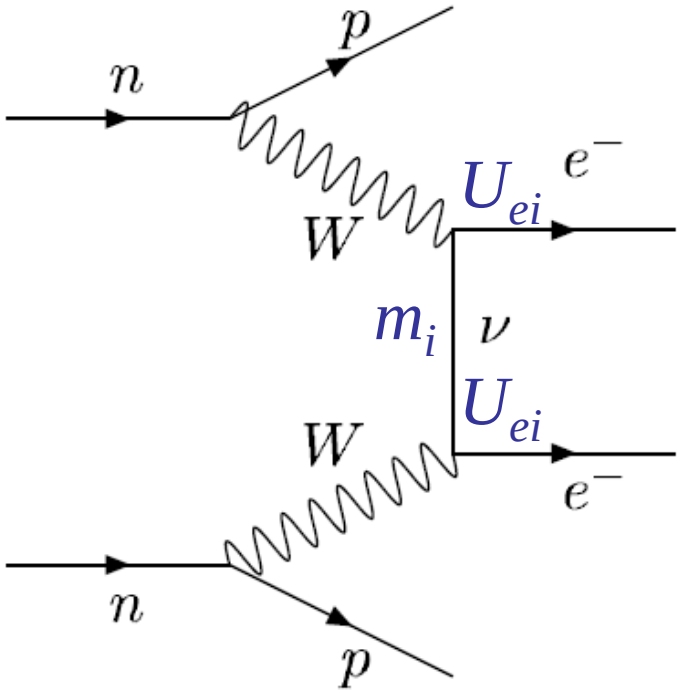

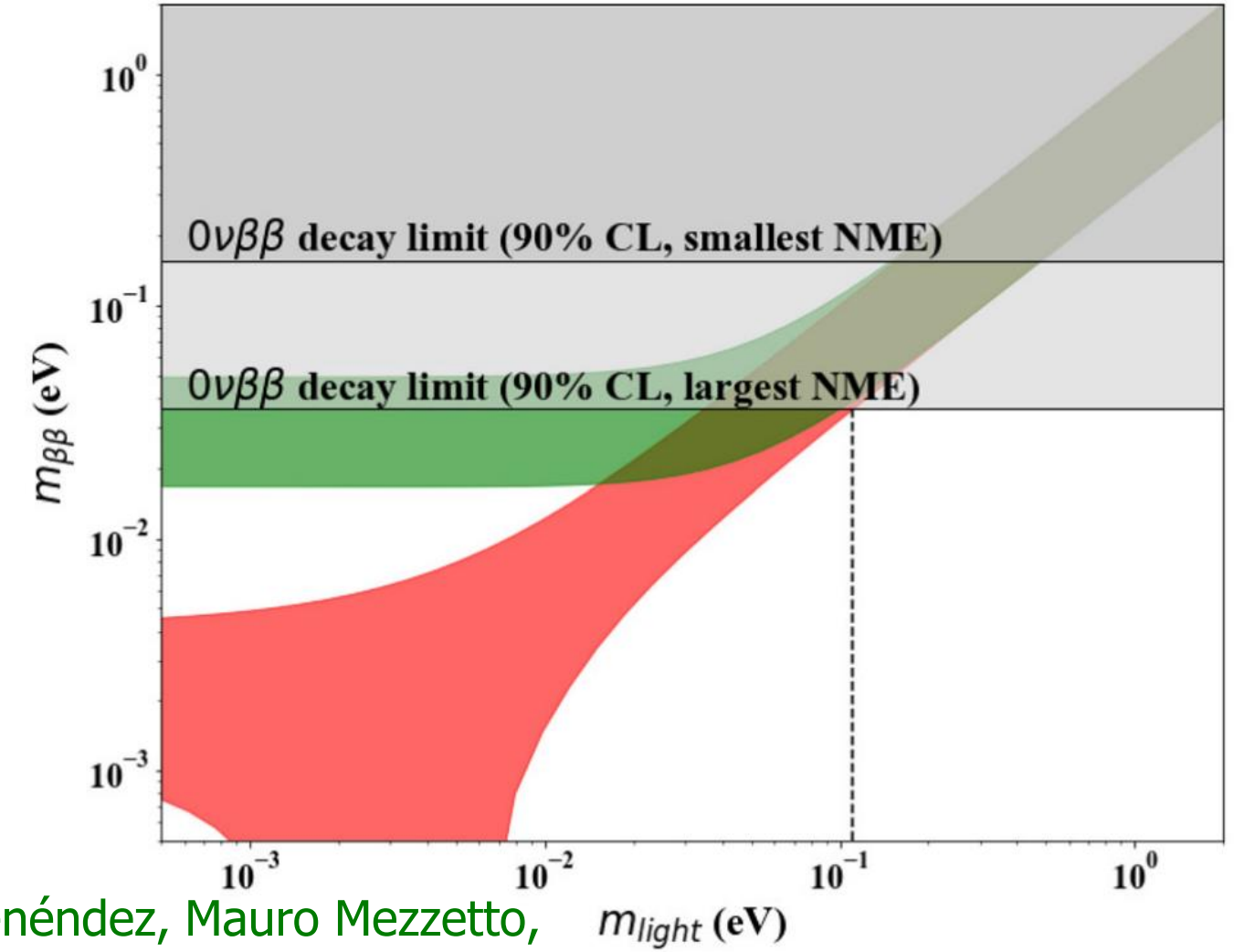

J.J. Gómez-Cadenas, J. Martín-Albo, Javier Menéndez, Mauro Mezzetto, F. Monrabal, M. Sorel Riv.Nuovo Cim. 46 (2023) 10, 619-692

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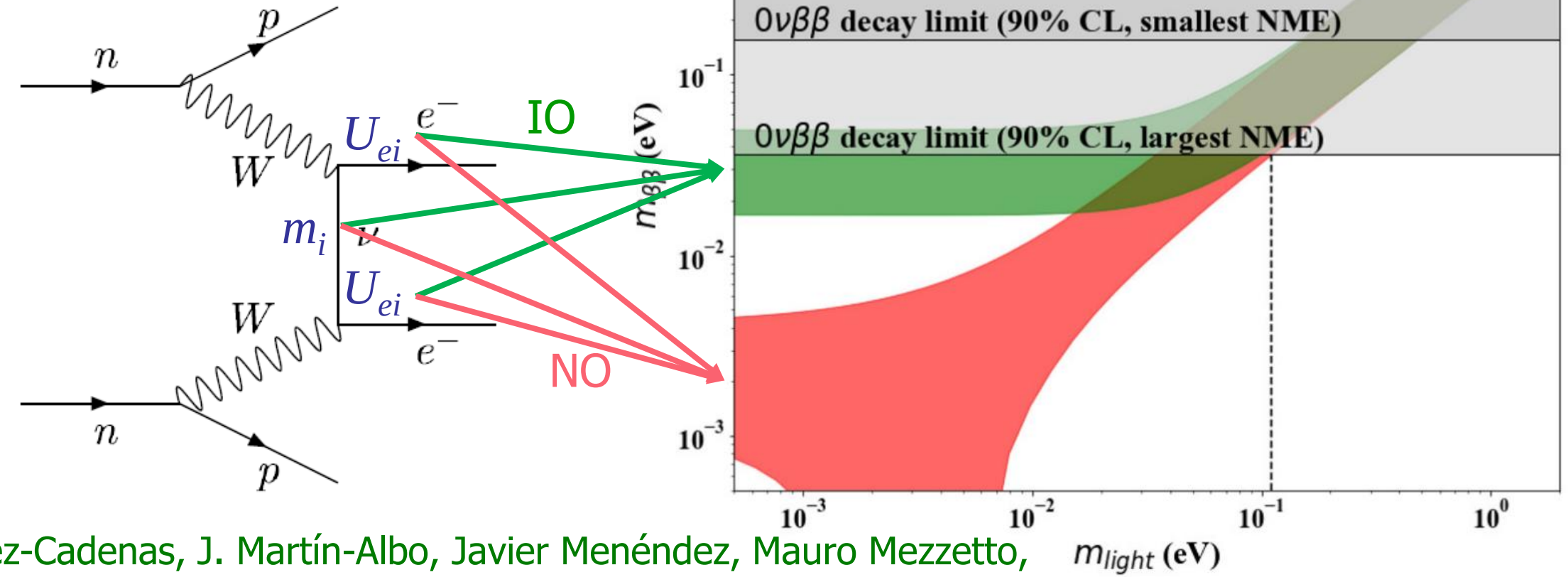

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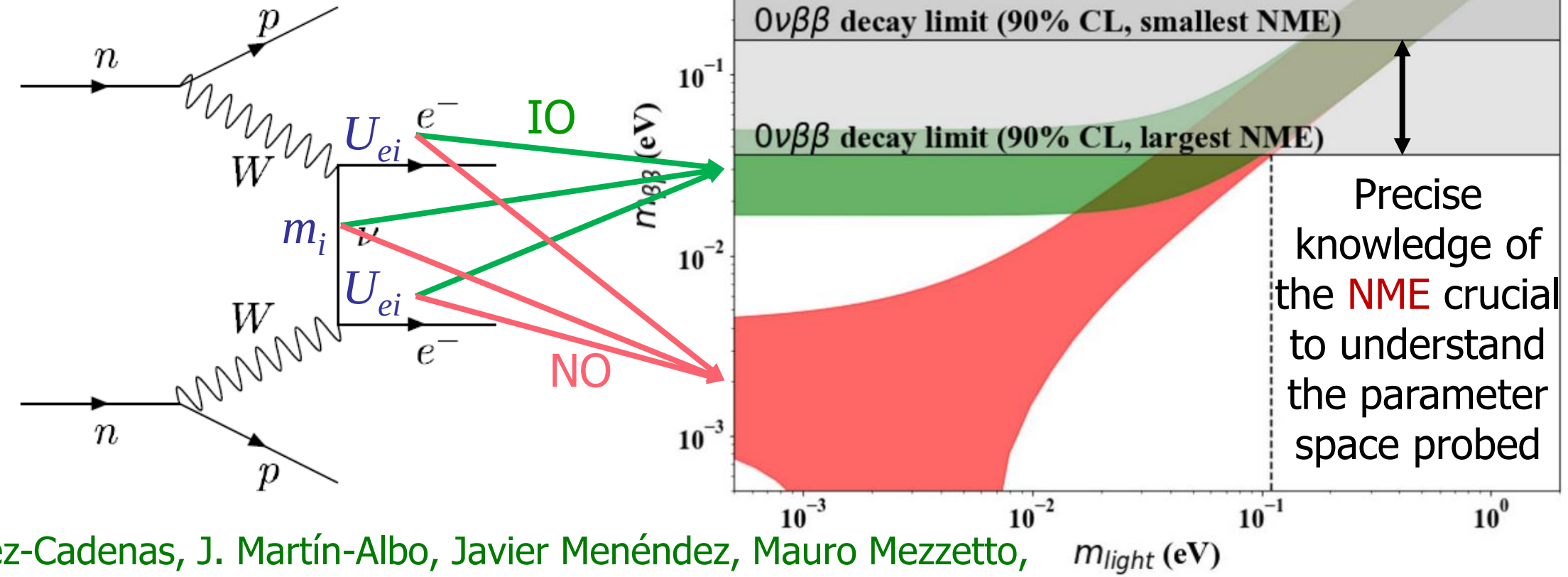

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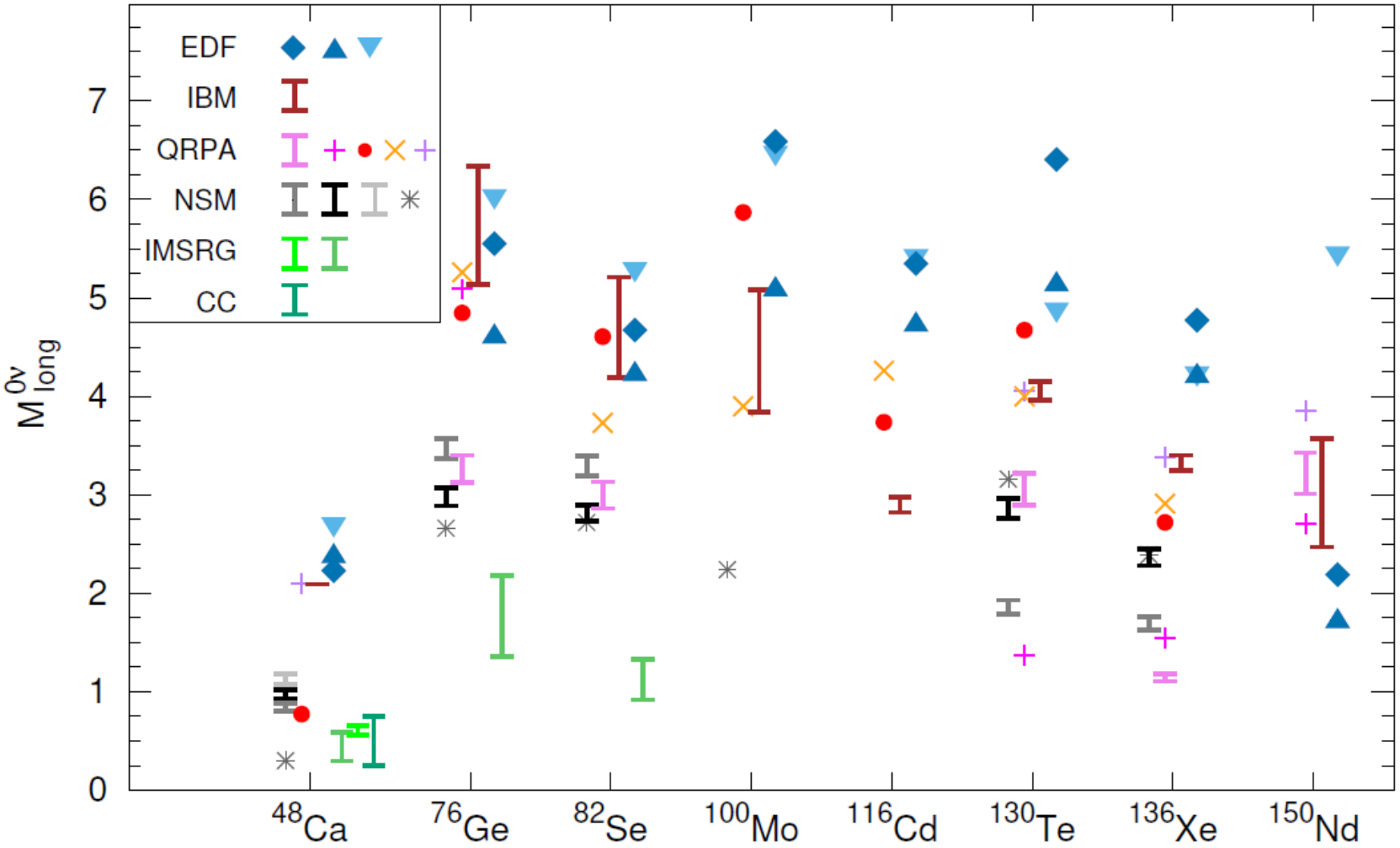
Neutrinoless double beta decay

Status of Nuclear Matrix Elements in 2022



M. Agostini, G. Benato, J. Detwiler, J Menendez, F. Vissani 2202.01787

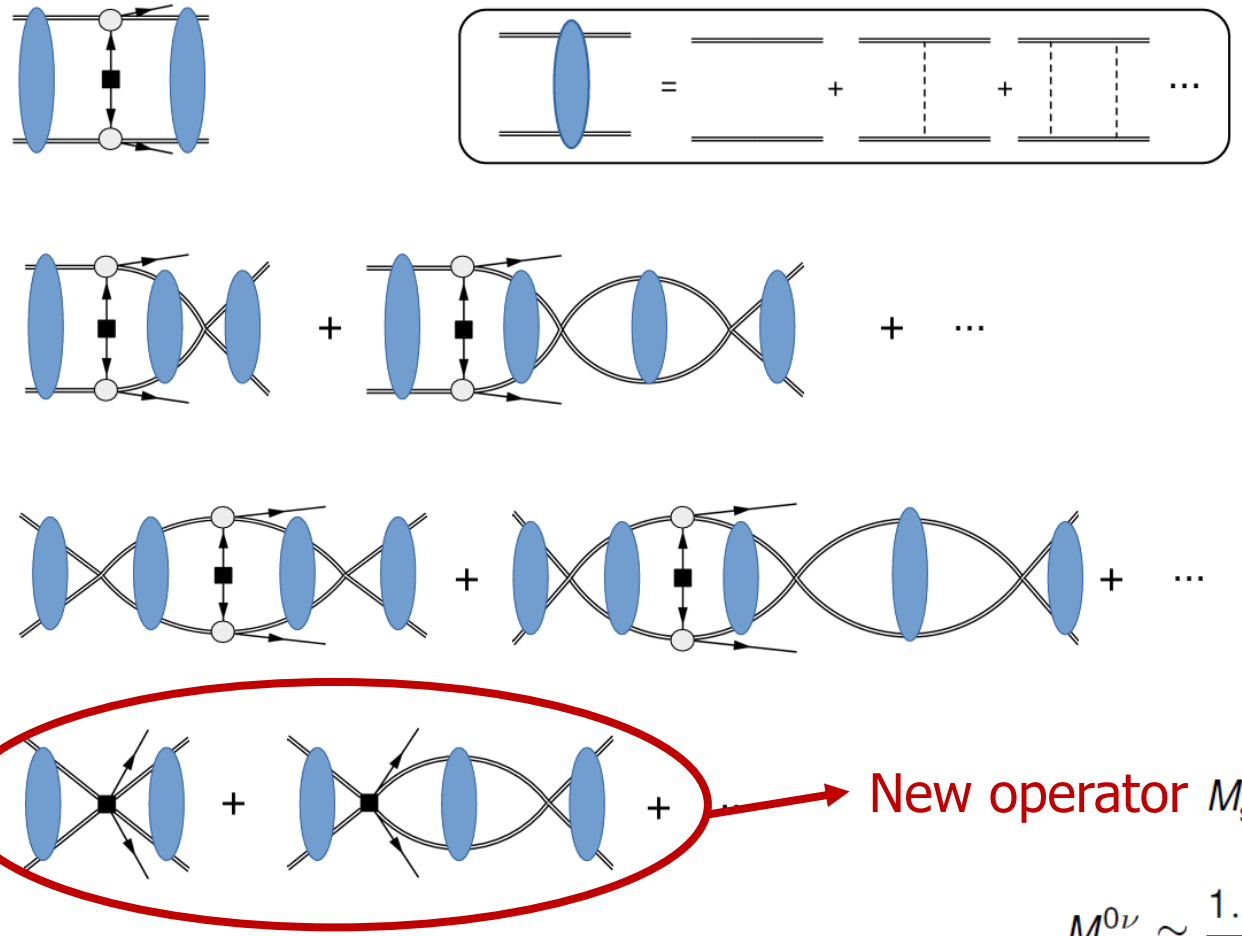
Precise knowledge of the NME crucial to understand the parameter space probed

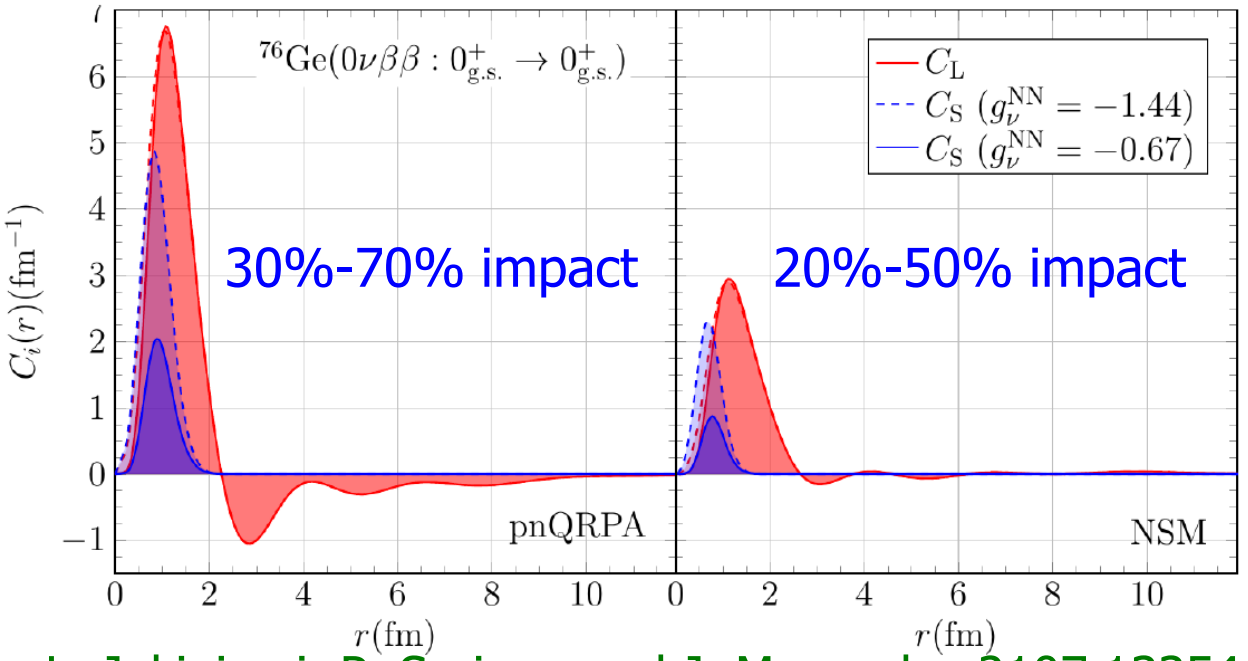
But very large spread of predictions using different methods to treat the many-body problem:

energy-density functional (EDF)
interacting boson model (IBM)
quasiparticle random-phase approximation (QRPA)
nuclear shell model (NSM)
(IMSRG) and (CC) new ab-initio computations!

Neutrinoless double beta decay

Short-range leading operator previously overlooked needs to be included:





L. Jokiniemi, P. Soriano and J. Menendez 2107.13354

New operator $M^{0\nu}_{\mathrm{short}} \equiv \frac{1.2A^{1/3}\,\mathrm{fm}}{g_A^2}\langle 0^+_f|\sum_{n.m}\tau_m^-\tau_n^-\,1\,[\frac{2}{\pi}\int j_0(qr)\,2g_\nu^{NN}\,g(p/\Lambda)\,p^2dp]|0^+_i\rangle$

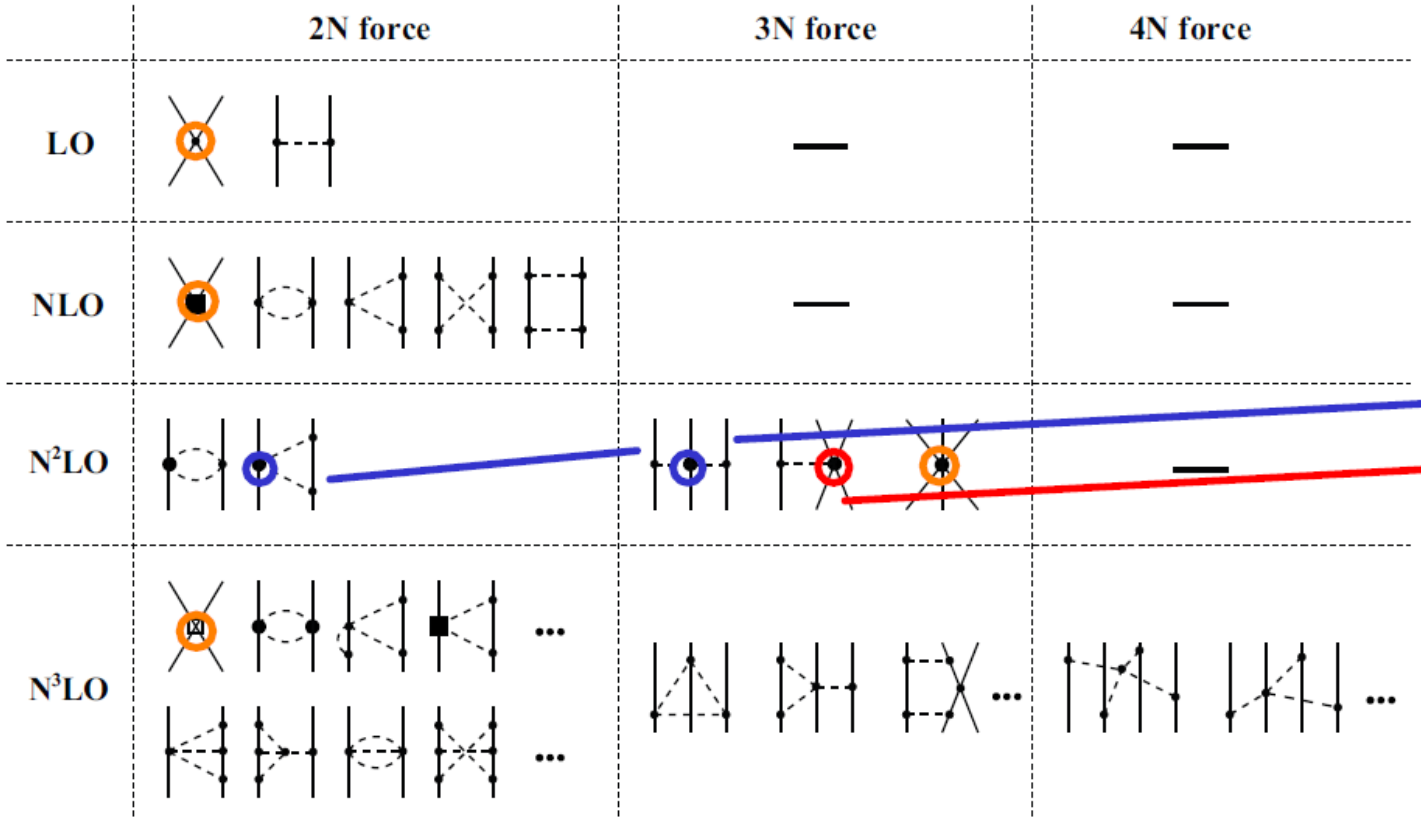
$M^{0\nu}_{\mathrm{GT}} \simeq \frac{1.2A^{1/3}\,\mathrm{fm}}{g_A^2}\langle 0^+_f|\sum_{n.m}\tau_m^-\tau_n^-\,\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2\,[\frac{2}{\pi}\int j_0(qr)\,\frac{1}{p^2}\,g_A^2\,f^2(p/\Lambda_A)\,p^2dp]|0^+_i\rangle$

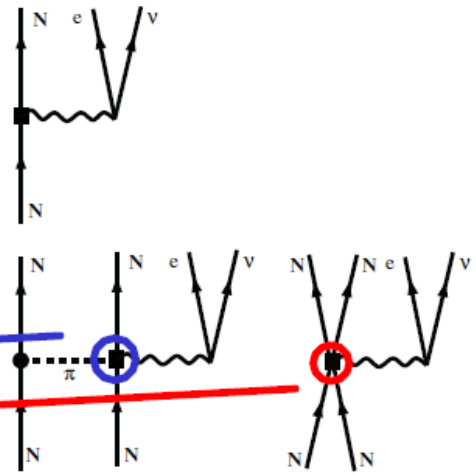
V. Cirigliano, W. Dekens, J. de Vries, M. L. Graesser,
E. Mereghetti, S. Pastore and U. van Kolck 1802.10097

Neutrinoless double beta decay

Precise knowledge of the NME crucial to understand the parameter space probed

New ab-initio computations based on chiral EFT are now feasible and results start to be available for some nuclei. The systematic uncertainties are under better control.

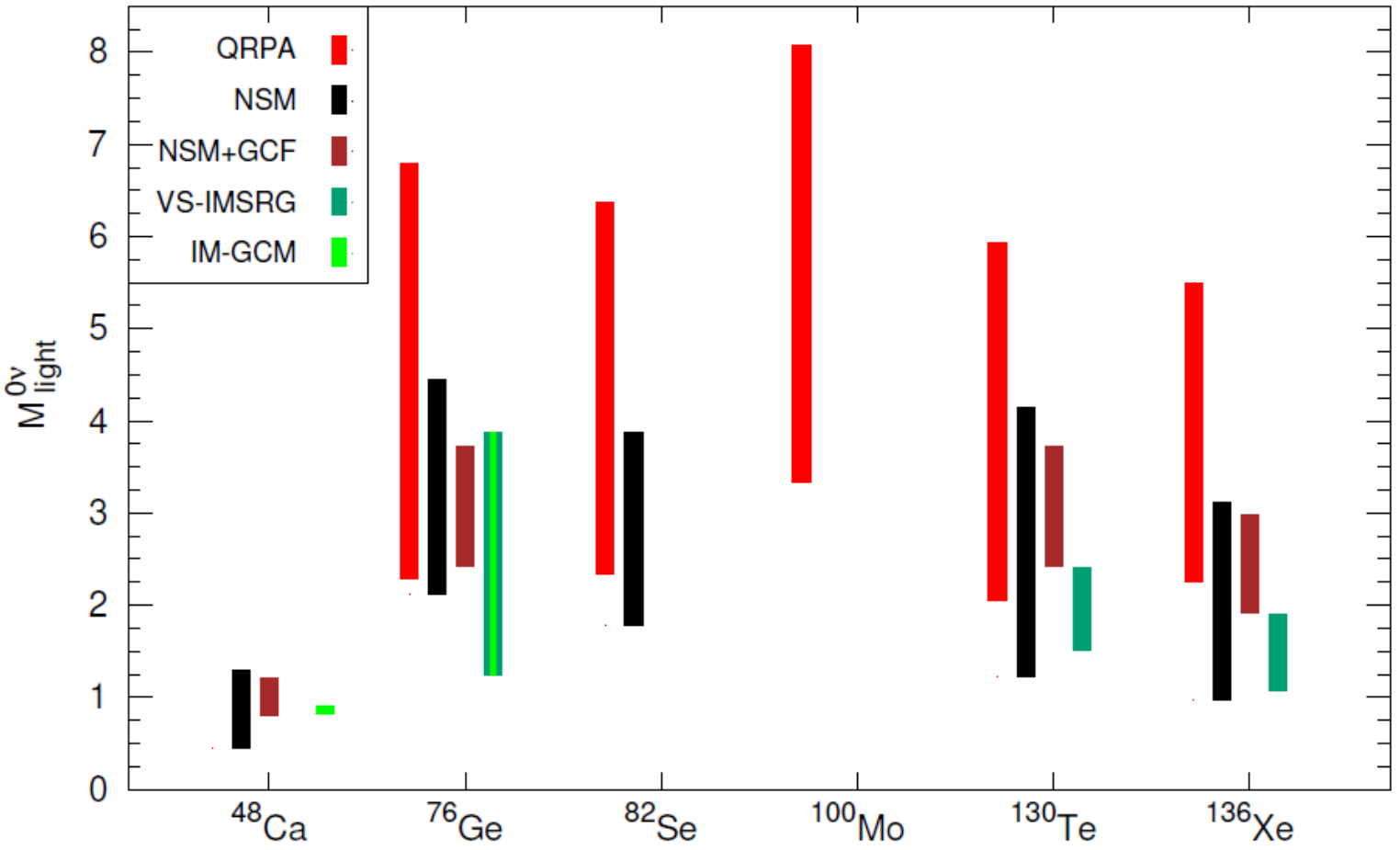




H. Hergert 2008.05061
A. Ekström, C. Forssén, G. Hagen, G.R. Jansen, W. Jiang, T. Papenbrock 2212.11064

Neutrinoless double beta decay

Present status of Nuclear Matrix Elements



Short-range contribution now included in all computations

Systematic uncertainty estimated for all approaches and under better control for the ab-initio computations

Reasonable agreement within uncertainties

J.J. Gómez-Cadenas, J. Martín-Albo, Javier Menéndez, Mauro Mezzetto, F. Monrabal, M. Sorel Riv.Nuovo Cim. 46 (2023) 10, 619-692

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CP violation phase?
δ?

Absolute mass scale?

Majorana Nature and phases?

ν and BSM

The unknown unknowns

Adapted from: P. Coloma, L. Koerner, I. Shoemaker and J. Yu Snowmass report
see arXiv:2209.10362 for summary and links to dedicated analyses

ν and BSM

ν masses require BSM physics

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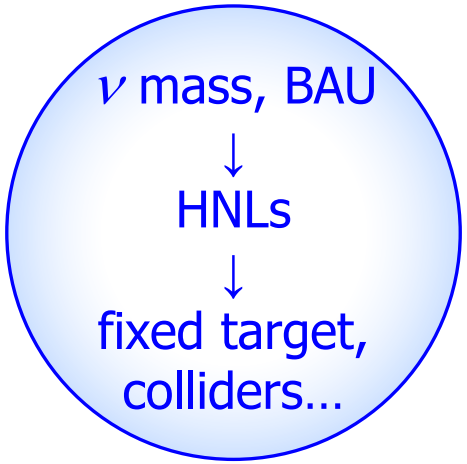
ν and BSM

ν masses require BSM physics

Simplest option to add ν_R to the SM content



See talks by Francesco Paolo Di Meglio, Javier Lizana and Jonathan Kriewald

May solve other open problems of the SM: Baryogenesis via Leptogenesis, ν as DM or as portals to the dark sector, intrinsic part of the flavour puzzle…

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ν and BSM

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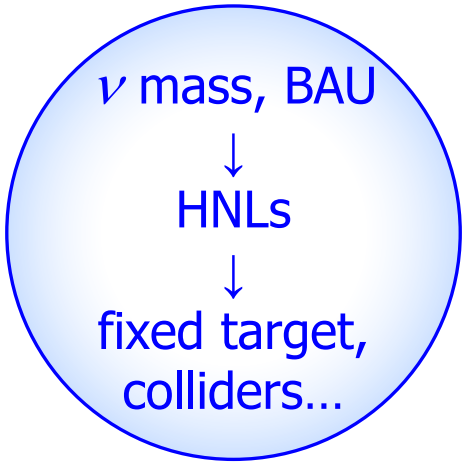

Probed in fixed target including ND of oscillation experiments: NuTeV, T2K, NA62, ProtoDUNE, SHiP, DUNE, ICARUS, SBND, μBooNE…
Or from atmospheric: SK, IceCube, HK ESSνSB, INO-ICAL, KM3NeT-ORCA,…
Also in nuclear decay kinematics: KATRIN/Tristan, HUNTER…
Collider searches: ATLAS, CMS, Faser, Belle II…

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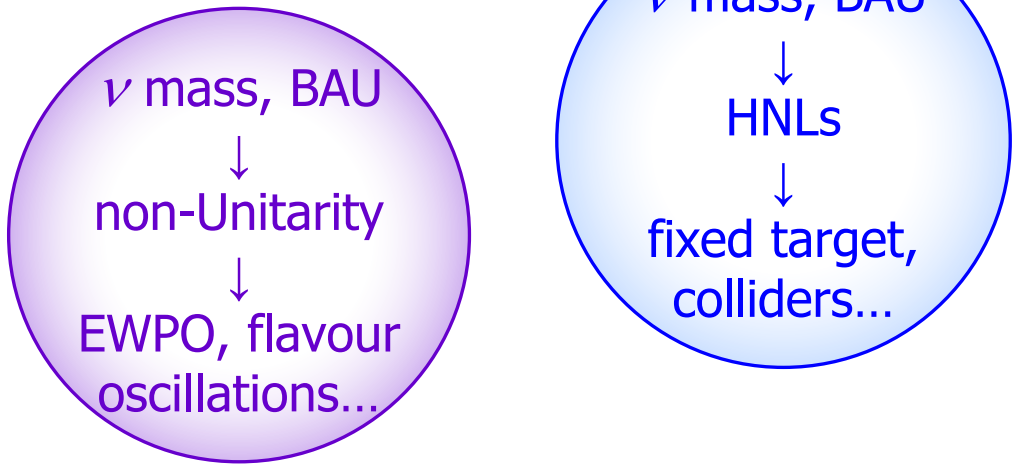
ν and BSM

ν masses require BSM physics

Simplest option to add ν_R to the SM content

See talks by Chiara Lastoria and Zhi-zhong Xing



If they are too heavy to be produced: indirect searches from PMNS non-unitarity: electroweak precision and flavour observables

May solve other open problems of the SM: Baryogenesis via Leptogenesis, ν as DM or as portals to the dark sector, intrinsic part of the flavour puzzle…

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ν and BSM

ν masses require BSM physics

Simplest option to add ν_R to the SM content

See talks by Rudolph Rogly, Filippo Varanini, Anyssa Navrer-Agasson, Ken Long, Thiago Junqueira De Castro Bezerra and Nicola McConkey

If they are very light they participate in oscillations

Adapted from: P. Coloma, L. Koerner, I. Shoemaker and J. Yu Snowmass report
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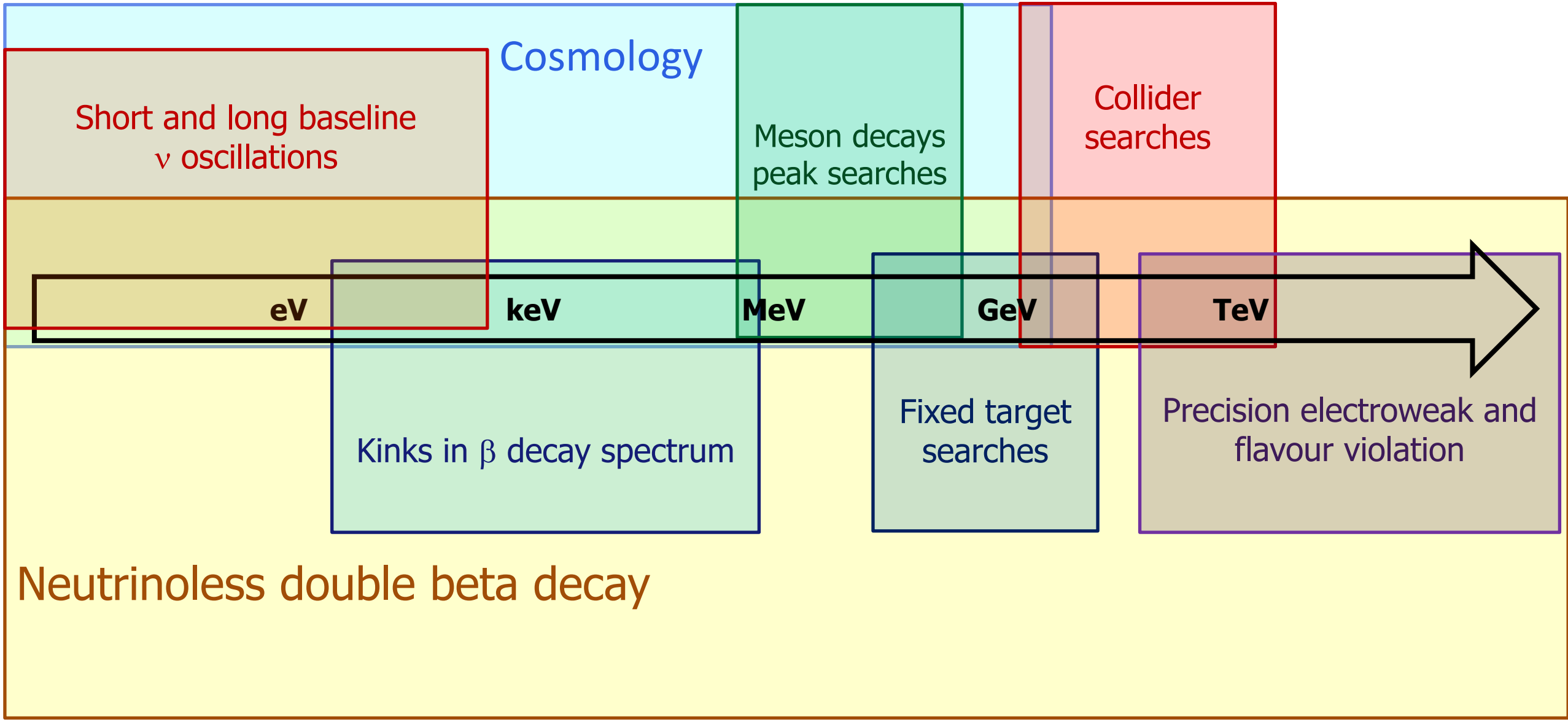
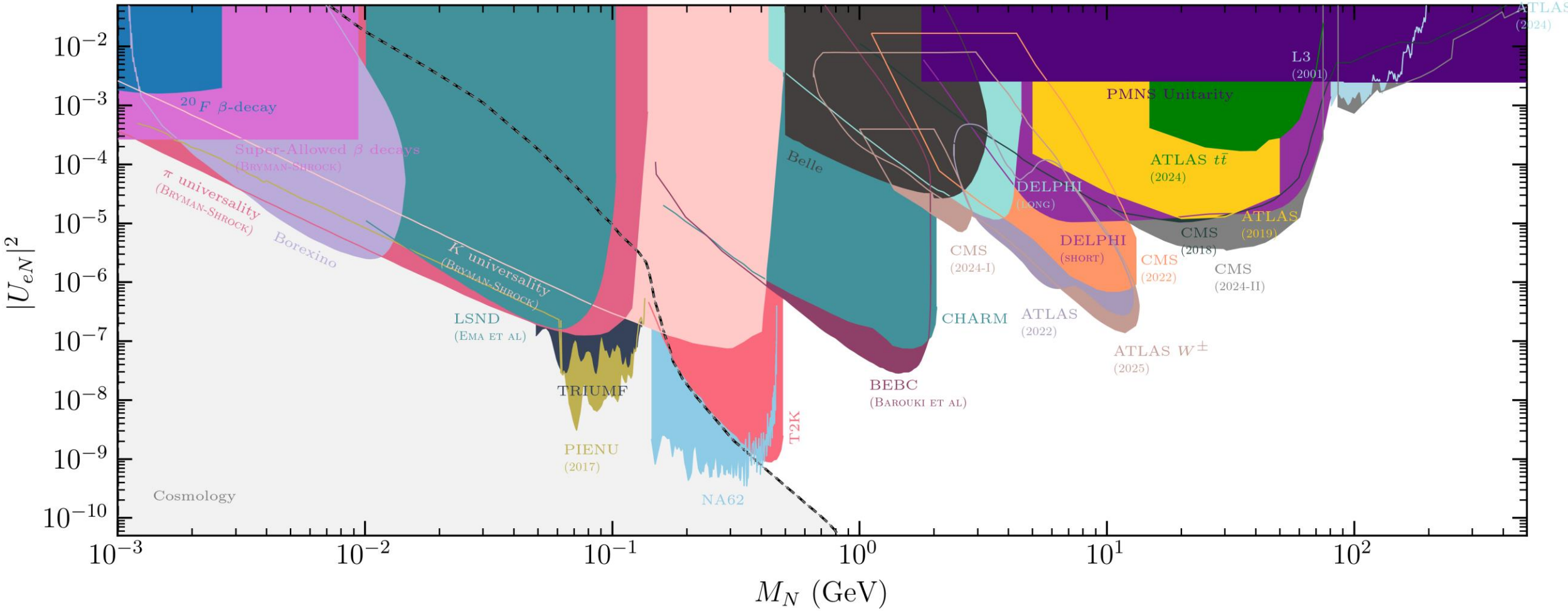
A new physics scale

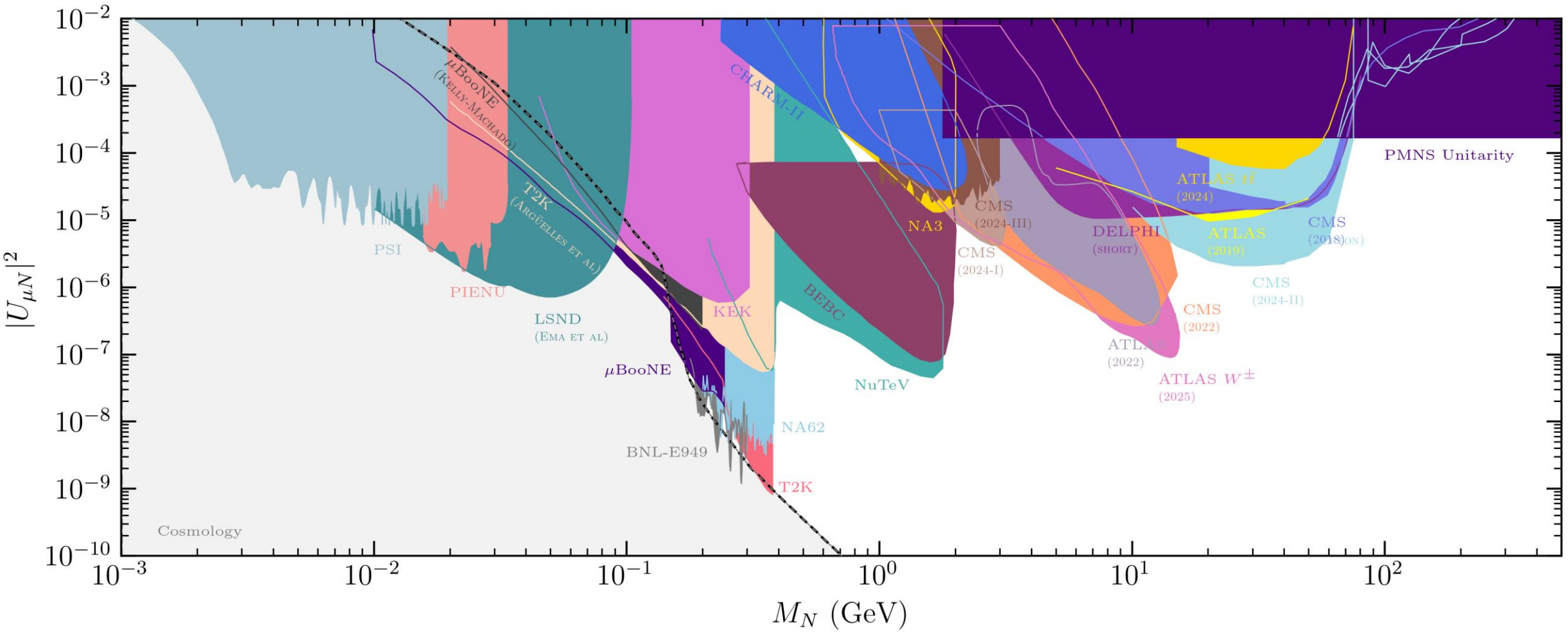


Looking for ν_R



EFM, M. González-López, J. Hernández-García, M. Hostert, J. López-Pavón arXiv:2304.06772
https://github.com/mhostert/Heavy-Neutrino-Limits
See also: P. D. Bolton, F. F. Deppisch and P. S. B. Dev arXiv:1912.03058

Looking for ν_R



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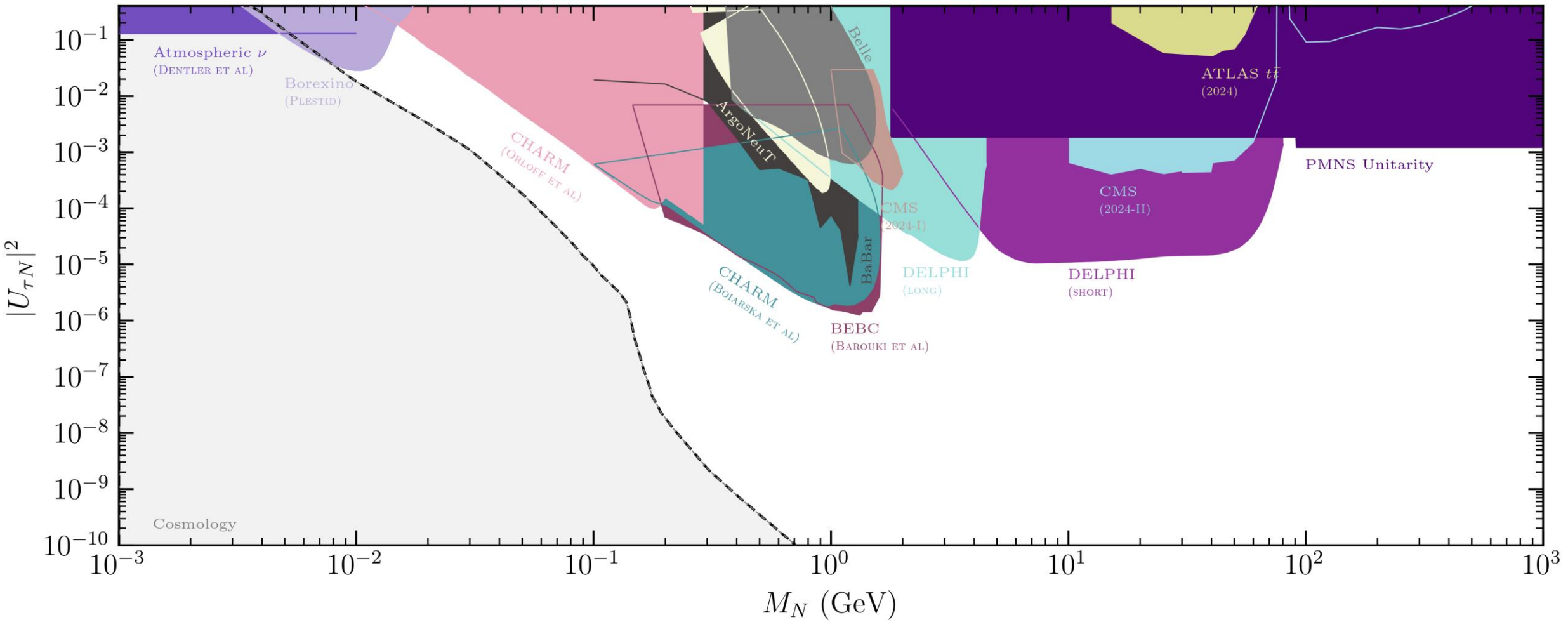

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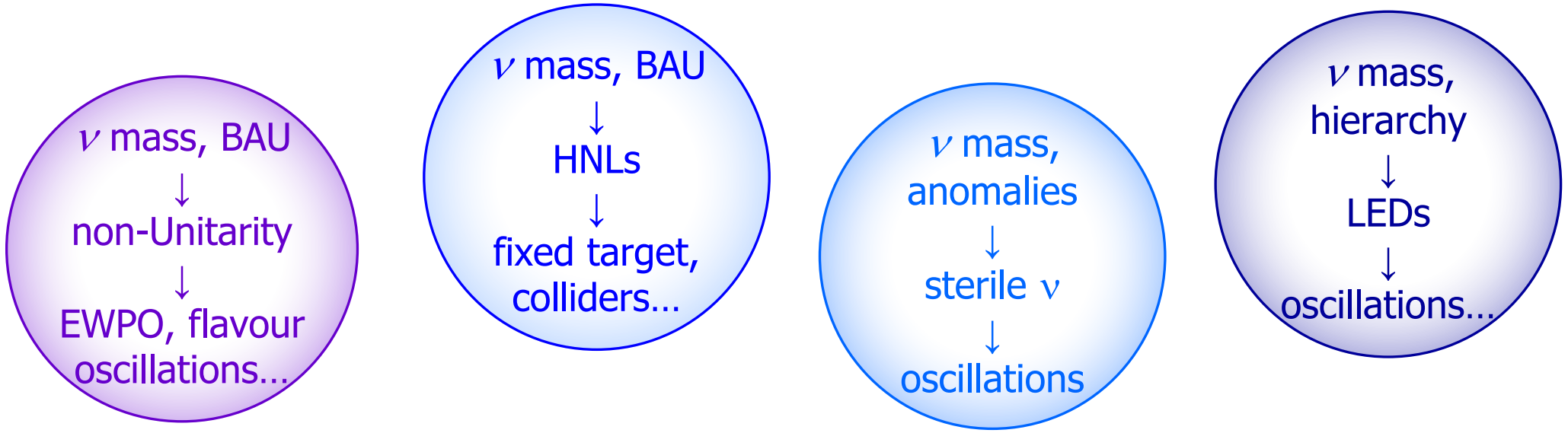
ν and BSM

Possible connections to other open problems: Large Extra Dimentions may address the hierarchy problem and ν masses

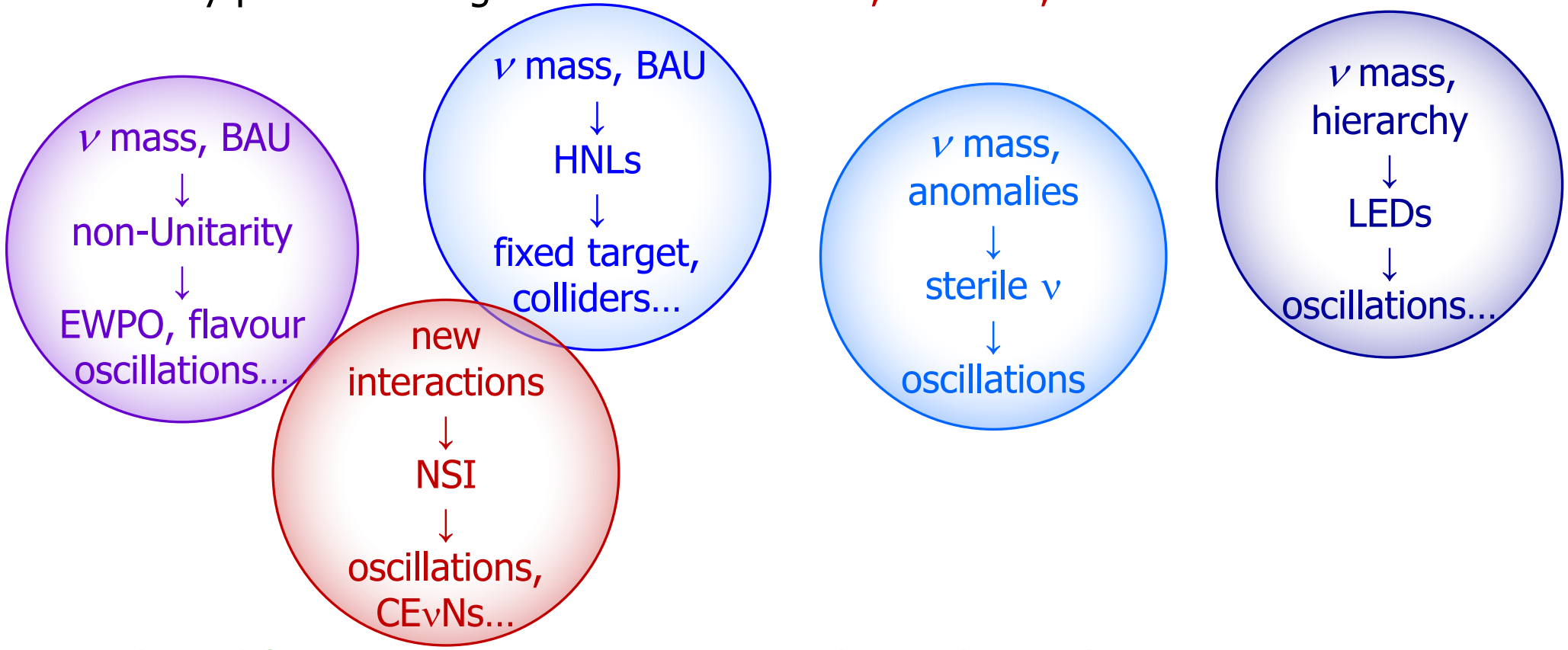


Similar pheno to steriles but with characteristic masses and mixings: solar, reactors, MINOS/MINOS+, NOνA, T2K, IceCube, HK, ESSνSB, INO-ICAL, KM3NeT-ORCA, DUNE, JUNO/TAO, SUPERCHOOZ/CLOUD…

Adapted from: P. Coloma, L. Koerner, I. Shoemaker and J. Yu Snowmass report
see arXiv:2209.10362 for summary and links to dedicated analyses

ν and BSM

Also searches for non-standard ν properties:
NSI: affect oscillations solars, MINOS/MINOS+, NOνA, T2K, IceCube, HK, ESSνSB, INO-ICAL, KM3NeT-ORCA, DUNE IsoDAR…
and directly probed through CEνNs: COHERENT, CONNIE, CONUS...



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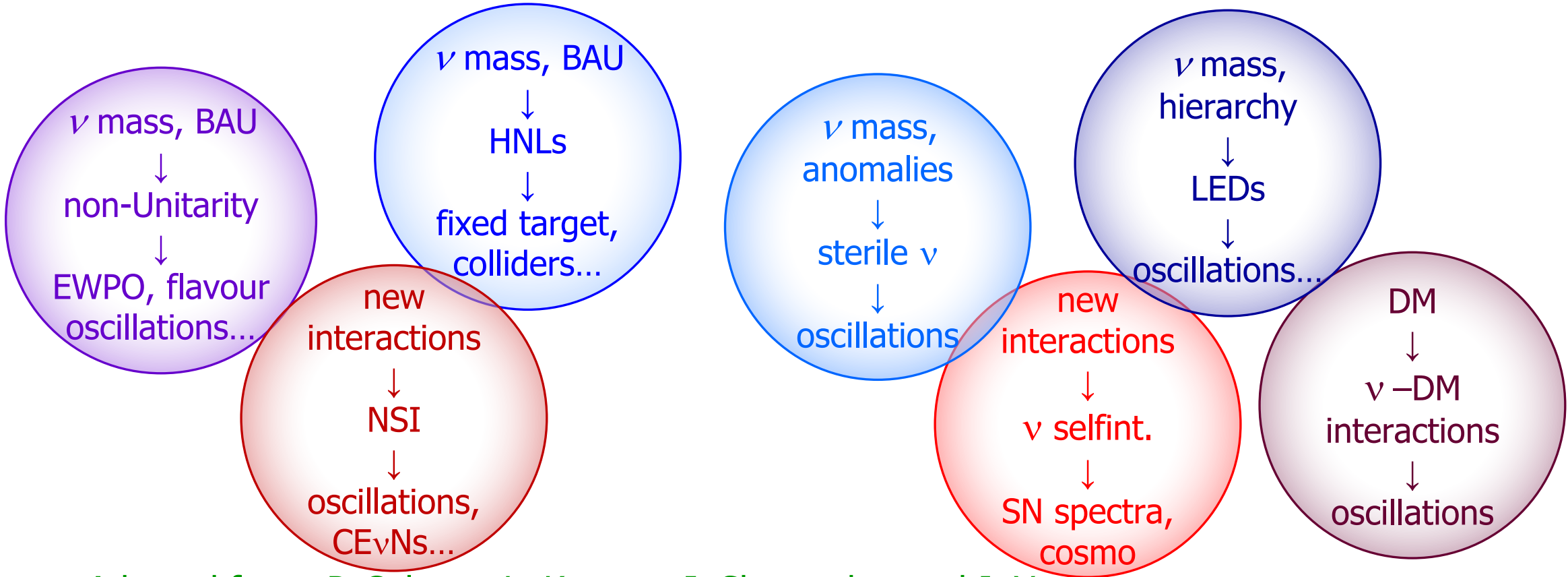
ν and BSM

Also searches for non-standard ν properties:
Longer range forces or interactions with DM → modified matter potentials
Self-interactions → impact cosmological abundance and distort SN fluxes



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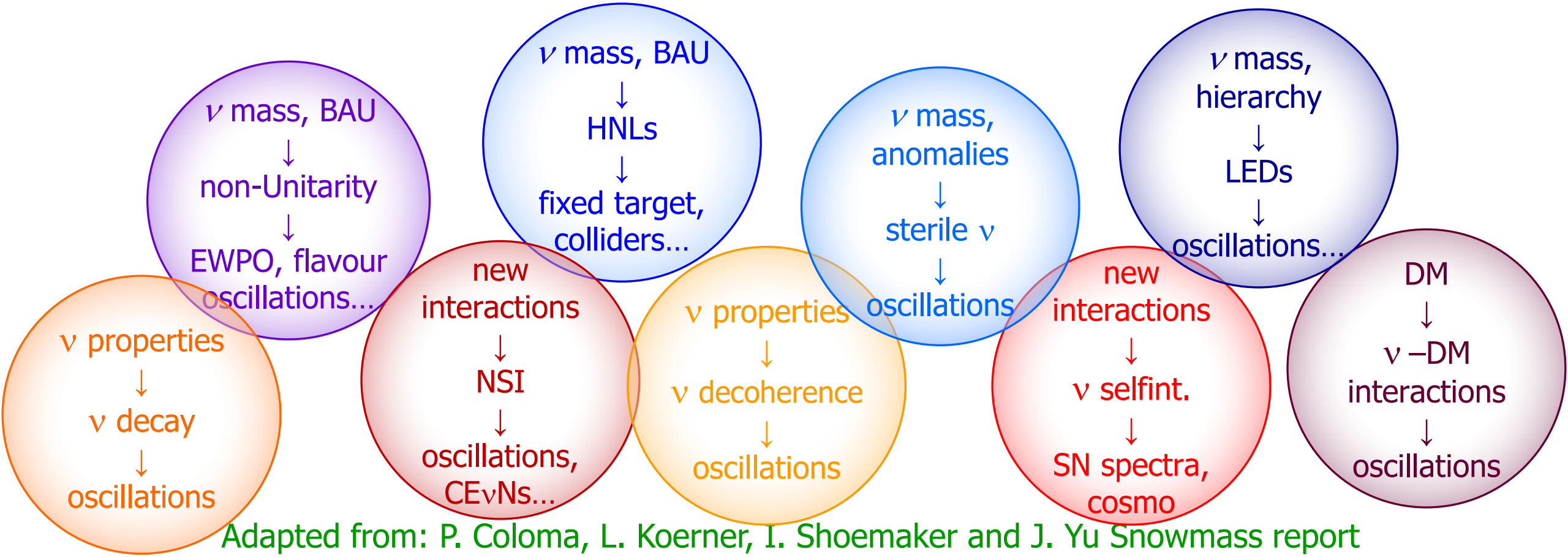
ν and BSM

Also searches for non-standard ν properties:
Neutrino decay or decoherence would also impact oscillations: solar, MINOS/MINOS+, NOνA, T2K, IceCube, HK, ESSνSB, INO-ICAL, KM3NeT-ORCA, DUNE, JUNO,…



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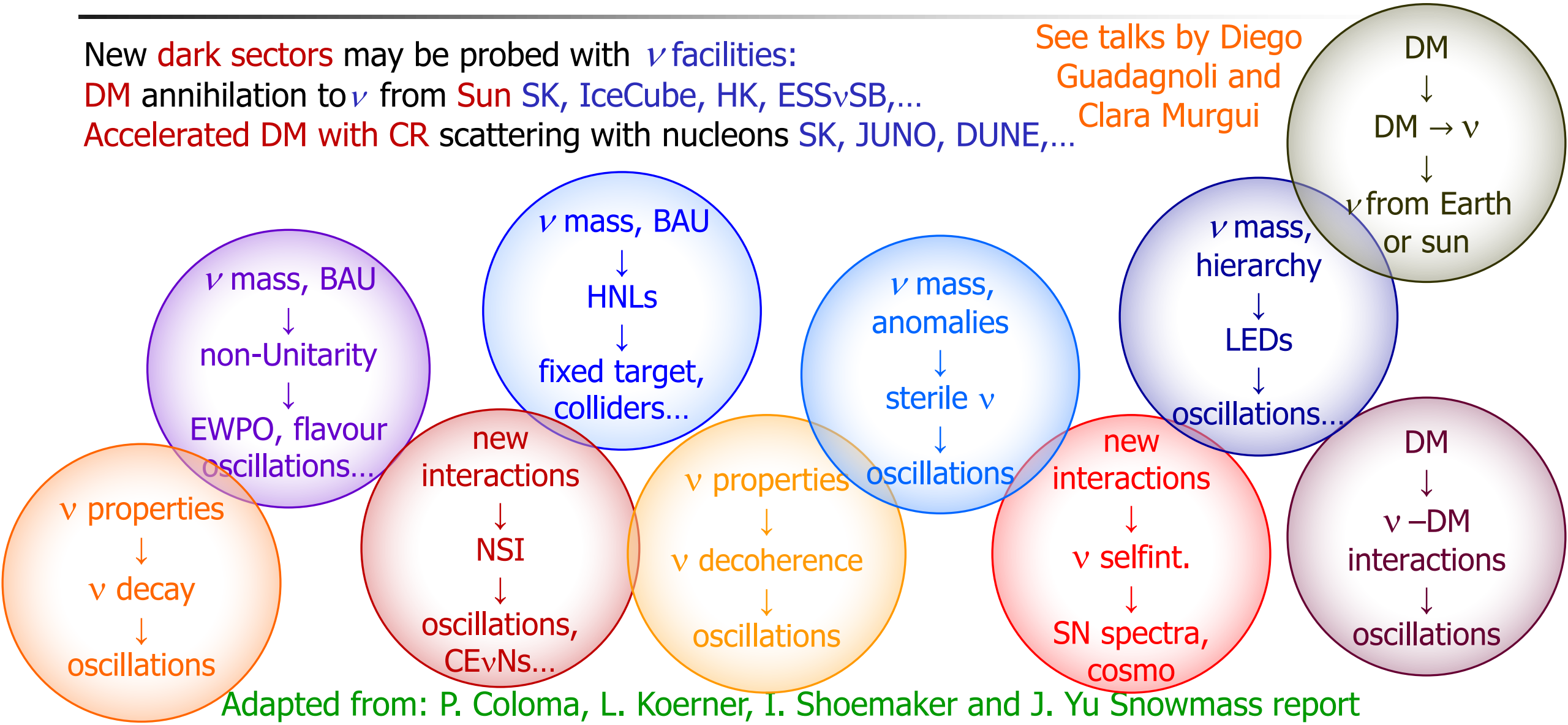
ν and BSM

New dark sectors may be probed with ν facilities:
DM annihilation to ν from Sun SK, IceCube, HK, ESSνSB,…
Accelerated DM with CR scattering with nucleons SK, JUNO, DUNE,…

See talks by Diego Guadagnoli and Clara Murgui



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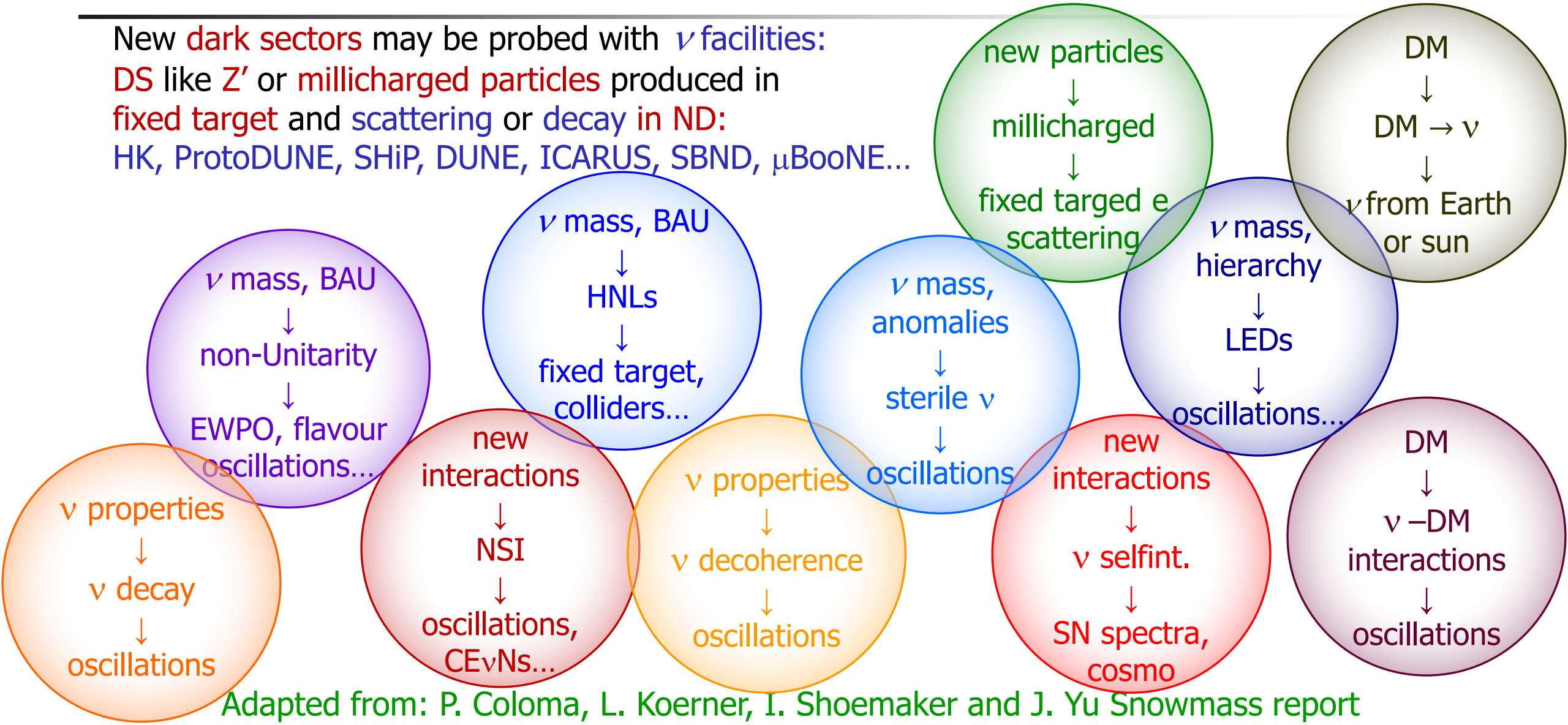
ν and BSM

New dark sectors may be probed with ν facilities:
DS like Z' or millicharged particles produced in
fixed target and scattering or decay in ND:
HK, ProtoDUNE, SHiP, DUNE, ICARUS, SBND, μBooNE…



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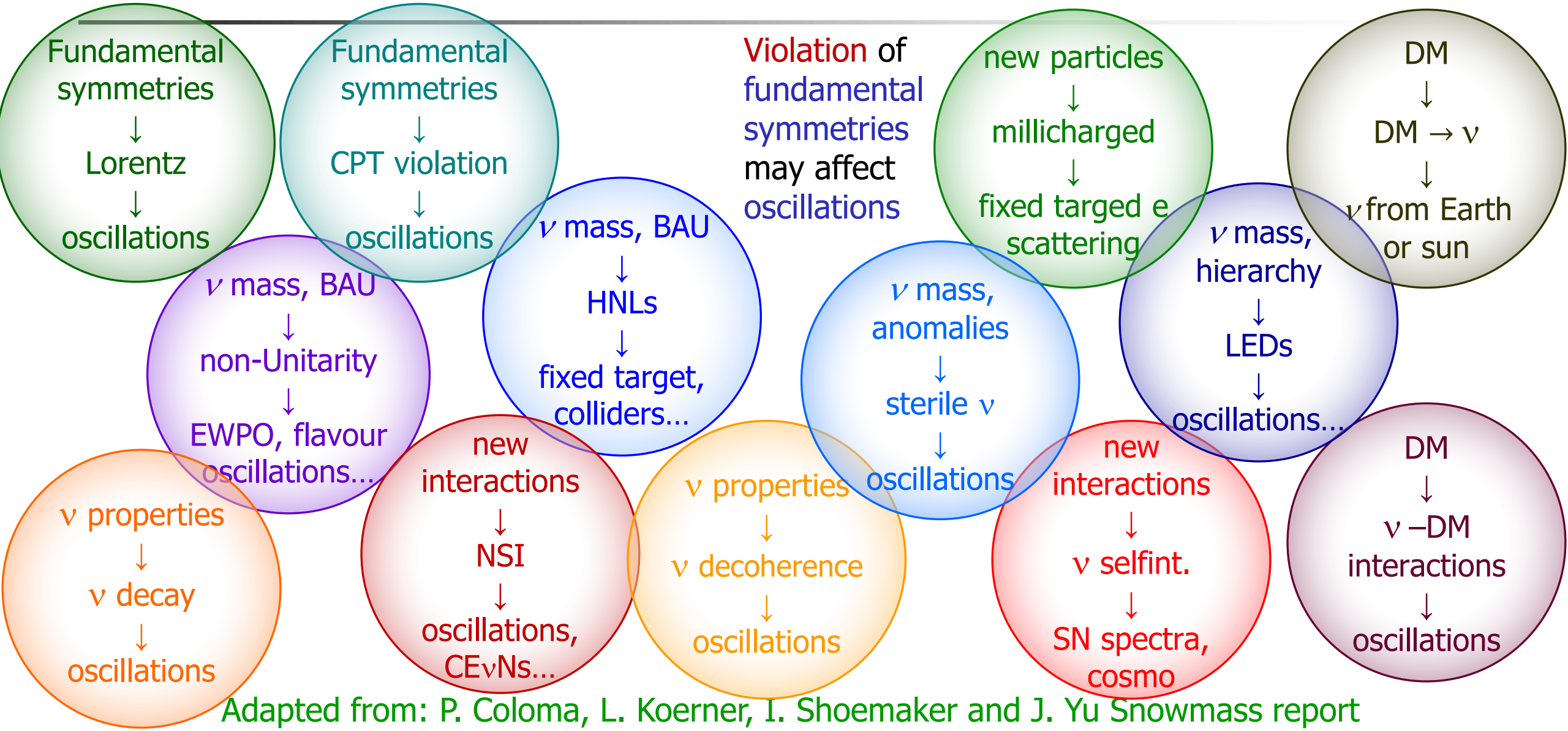

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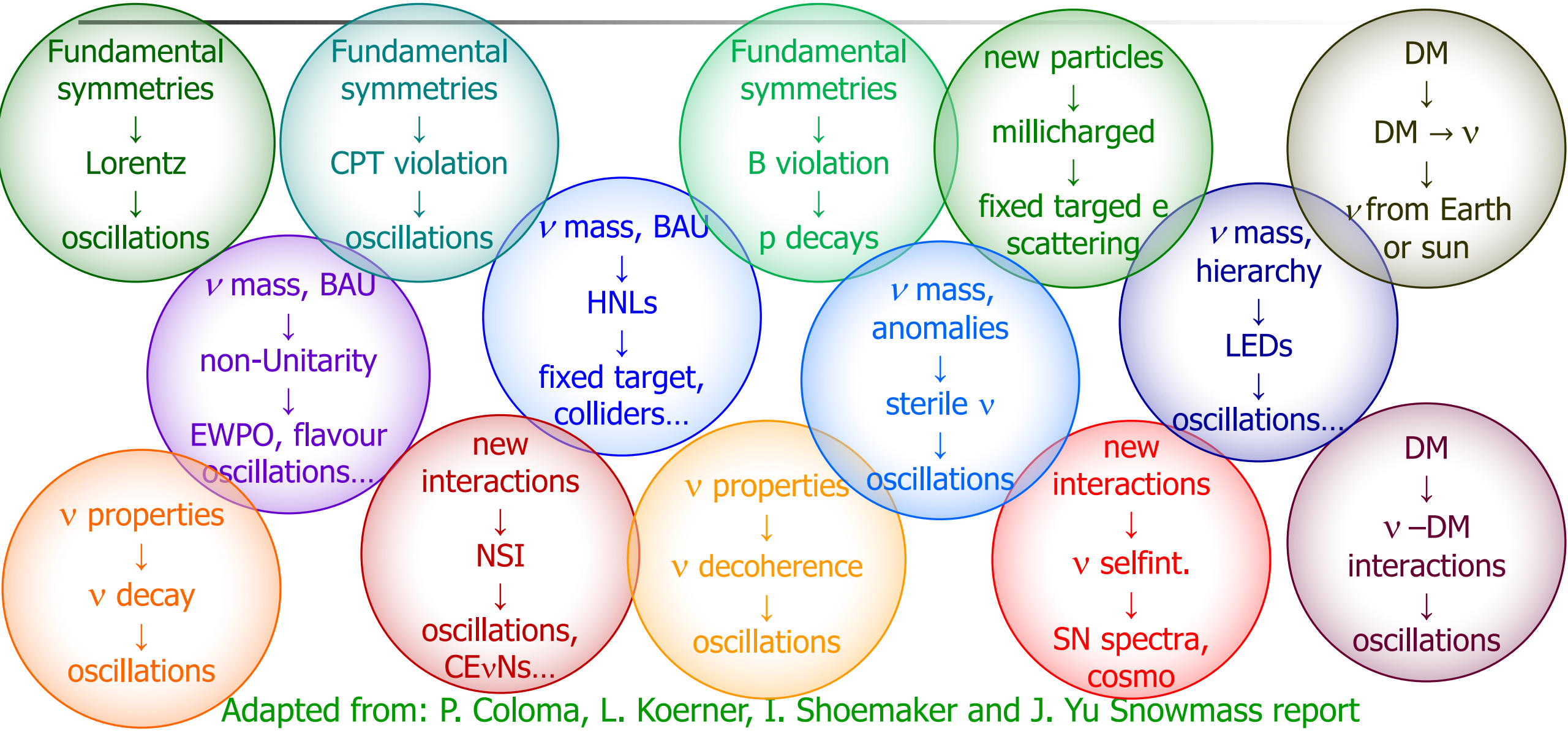

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Conclusions

- Neutrino masses and mixings imply BSM physics
- Still many open questions and interesting progress in many fronts:
  - Strikingly strong bound on ν mass from cosmology. Stay tuned for future EUCLID and DESI results!
  - Solid progress on NME for $0\nu\beta\beta$ crucial to test Majorana nature.
- The simplest SM extension for ν masses, right-handed neutrinos, already imply a lot of new phenomenology to search for:
  - Non-unitarity, searches at colliders, fixed target, cosmology, $0\nu\beta\beta$,...
- Also offers connections to other open problems of the SM
  - Baryogenesis, Dark Matter, Flavour puzzle...
- Neutrino detectors can also probe for other BSM physics
- Neutrino physics is an excellent window BSM!

The two effects together

95% CL $\sum_i m_i$ (eV)	Bayesian	Frequentist
Dataset		
Planck2018+DESI DR2	0.069	0.064
HiLLiPoP2023+DESI DR2	0.077	

DESI 2503.14744

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