Thomas Schwetz
Karlsruhe Institute of Technology
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Why (light) new νs?

New-ν Physics: From Colliders to Cosmology, Durham, UK, 9-11 April 202514 Feb. 2025

HIDDeν
Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

Karlsruher Institut für Technologie

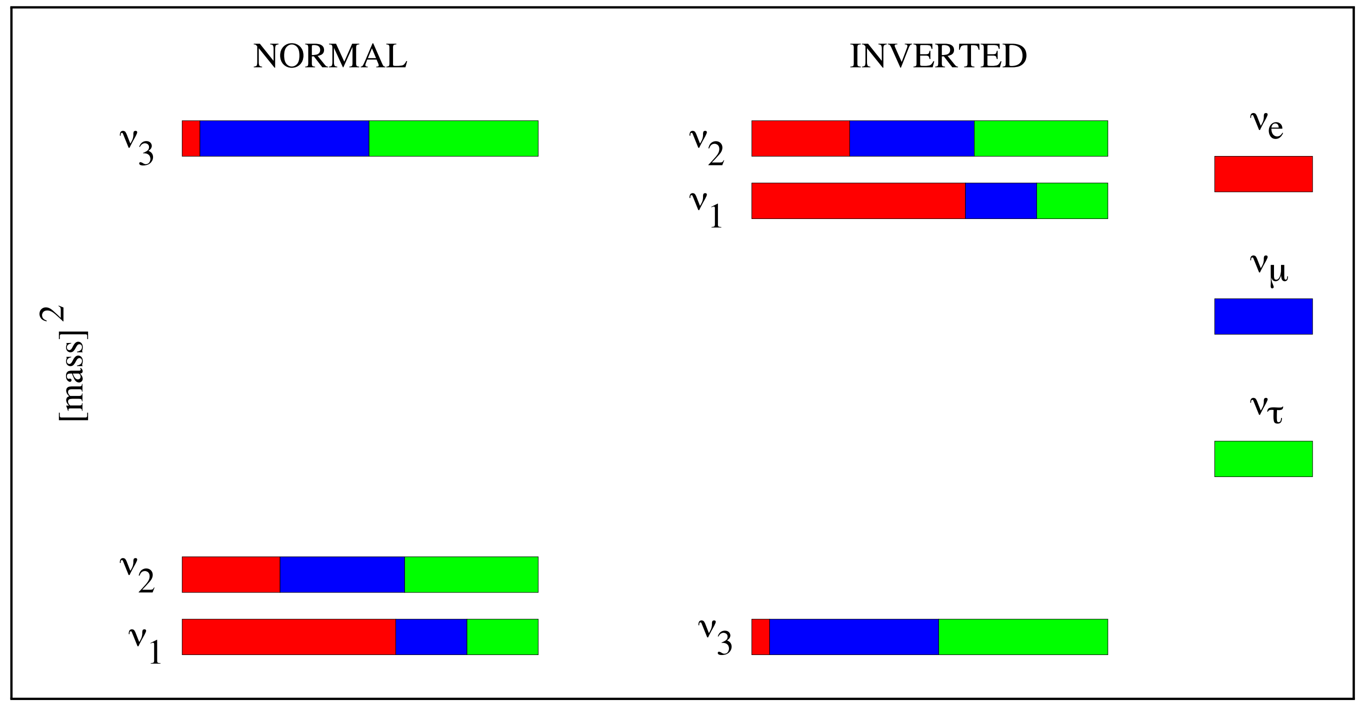
Outline

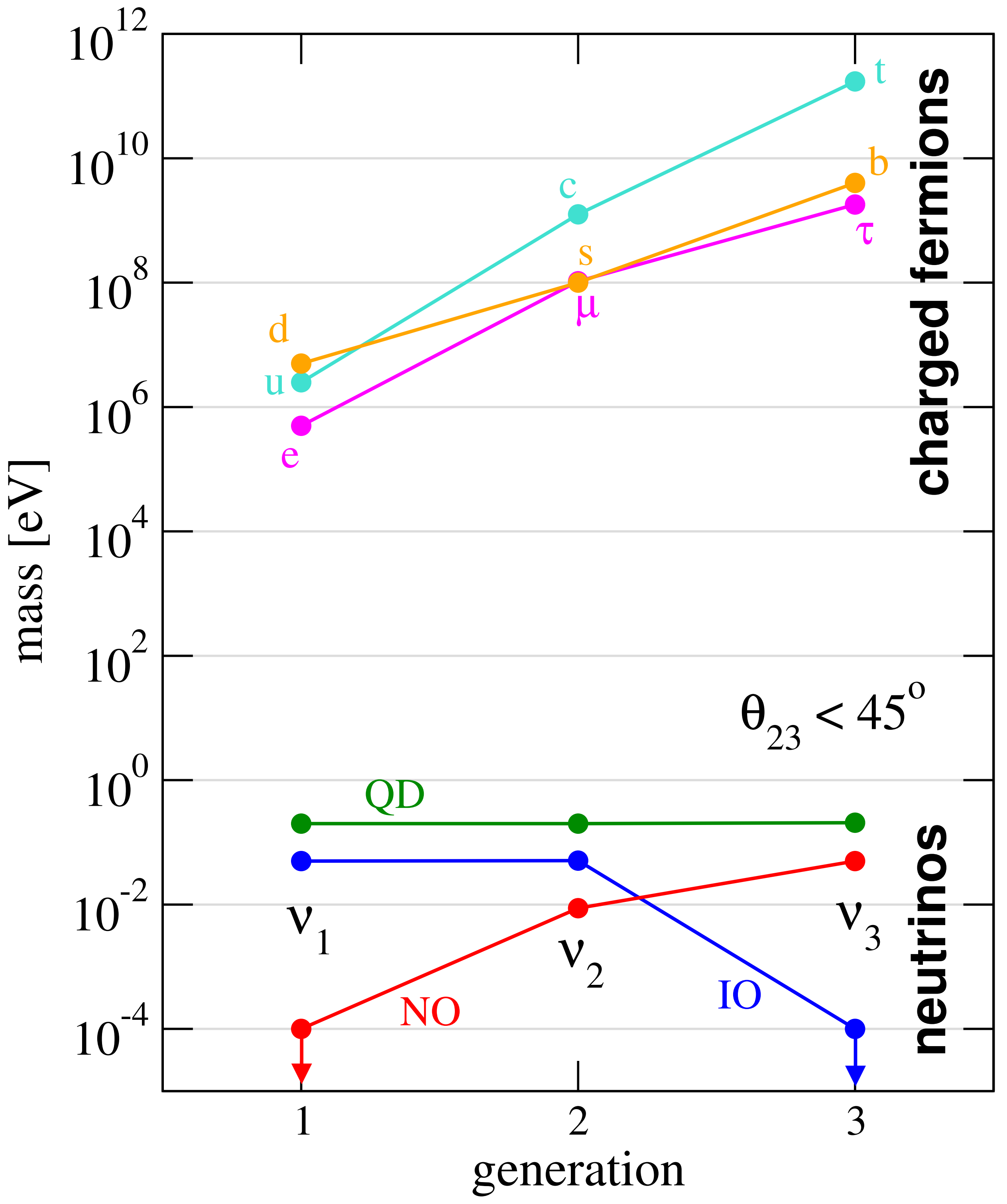
- Introduction — why new νs ?

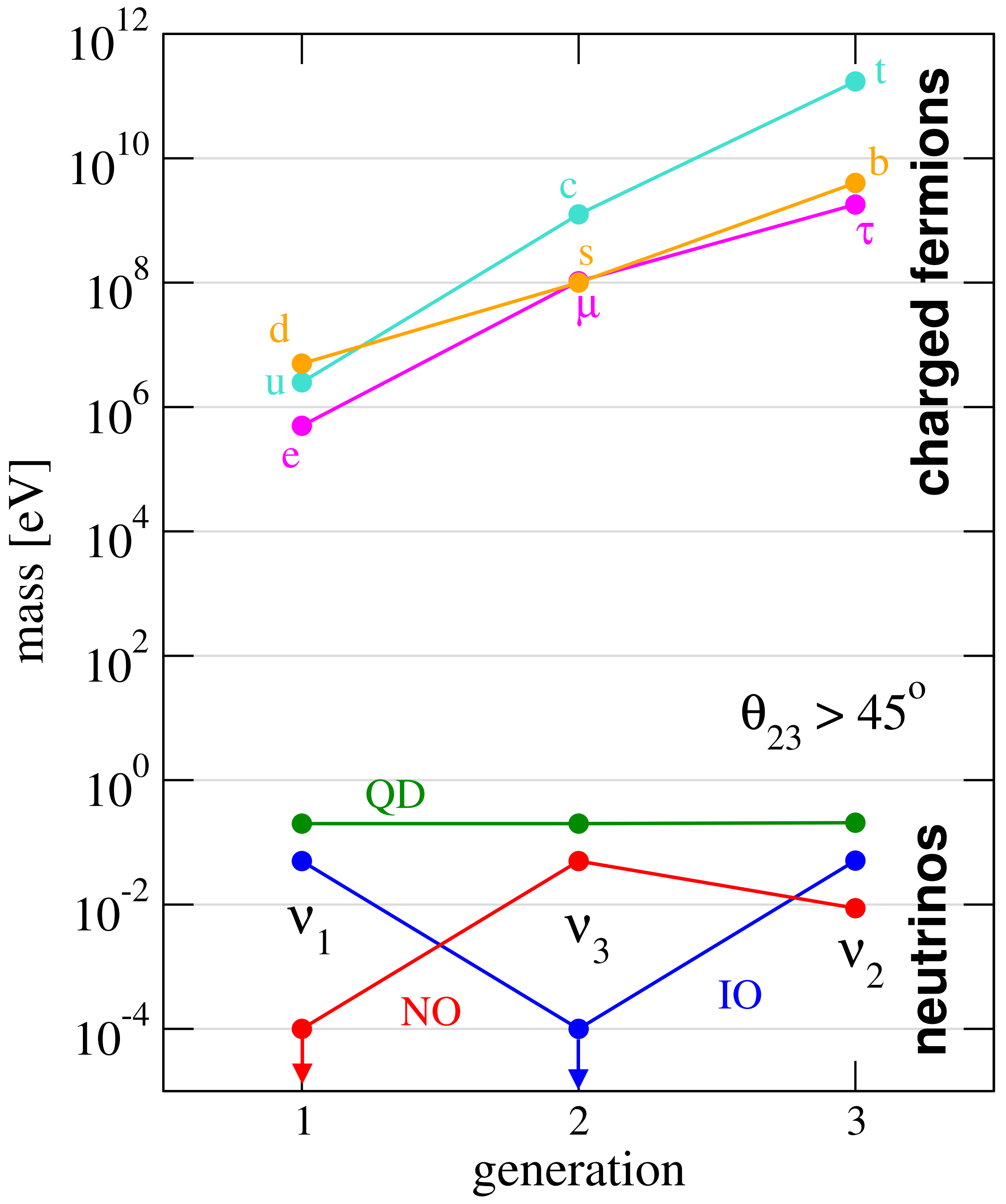
- Phenomenological motivations for new νs:
  - new νs dark matter?
  - new νs for short-baseline anomalies?
  - new νs and missing neutrino mass in cosmology?

The neutrino challenge

- neutrino masses are tiny
- mixing of leptons is very different than for quarks







Leptons

$$\theta_{12} \approx 33^\circ \quad \theta_{23} \approx 45^\circ \quad \theta_{13} \approx 9^\circ$$

Quarks

$$\theta_{12} \approx 13^\circ \quad \theta_{23} \approx 2^\circ \quad \theta_{13} \approx 0.2^\circ$$

$$U_{PMNS} = \frac{1}{\sqrt{3}} \begin{pmatrix} \mathcal{O}(1) & \mathcal{O}(1) & \epsilon \\ \mathcal{O}(1) & \mathcal{O}(1) & \mathcal{O}(1) \\ \mathcal{O}(1) & \mathcal{O}(1) & \mathcal{O}(1) \end{pmatrix}$$

$$U_{CKM} = \begin{pmatrix} 1 & \epsilon & \epsilon \\ \epsilon & 1 & \epsilon \\ \epsilon & \epsilon & 1 \end{pmatrix}$$

In the Standard model neutrinos are massless

- absence of right-handed neutrinos
  no Dirac mass for neutrinos

- lepton-number is an accidental symmetry at the renormalizable level
  given SM fields and gauge symmetry, lepton number cannot be violated at dim. 4 $\rightarrow$ no Majorana mass can be generated

$\rightarrow$ neutrino mass requires physics beyond the SM

Standard Model EFT

- **Weinberg 1979:** unique dim-5 operator consistent with gauge-symmetry of SM

$$\frac{Y^2_{ab}}{\Lambda}\,\overline{L^c_a}\tilde{\phi}^*\,\phi^\dagger L_b \quad \rightarrow \quad \frac{1}{2}\,\overline{\nu^c_{aL}}m_{ab}\nu_{bL} \qquad\qquad m_{ab} \sim Y^2_{ab}\frac{\langle\phi\rangle^2}{\Lambda}$$

scale of new physics

EWSB: Majorana neutrino mass

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- **Weinberg 1979:** unique dim-5 operator consistent with gauge-symmetry of SM

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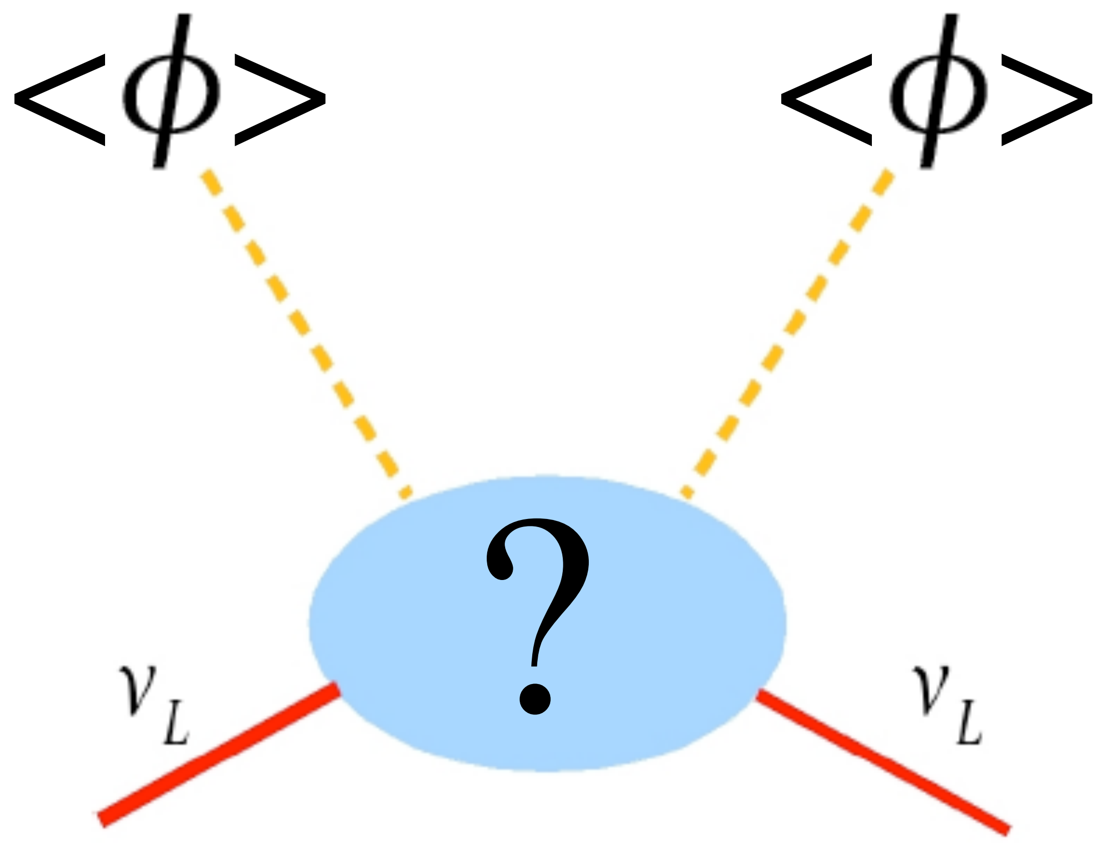
scale of new physics

EWSB: Majorana neutrino mass

- No indication of scale of new physics!

$$m_\nu \approx 0.06\,\mathrm{eV}\left(\frac{Y}{1}\right)^2\left(\frac{10^{15}\,\mathrm{GeV}}{\Lambda}\right) \approx 0.06\,\mathrm{eV}\left(\frac{Y}{10^{-6}}\right)^2\left(\frac{1\,\mathrm{TeV}}{\Lambda}\right)$$

Beyond the Weinberg operator

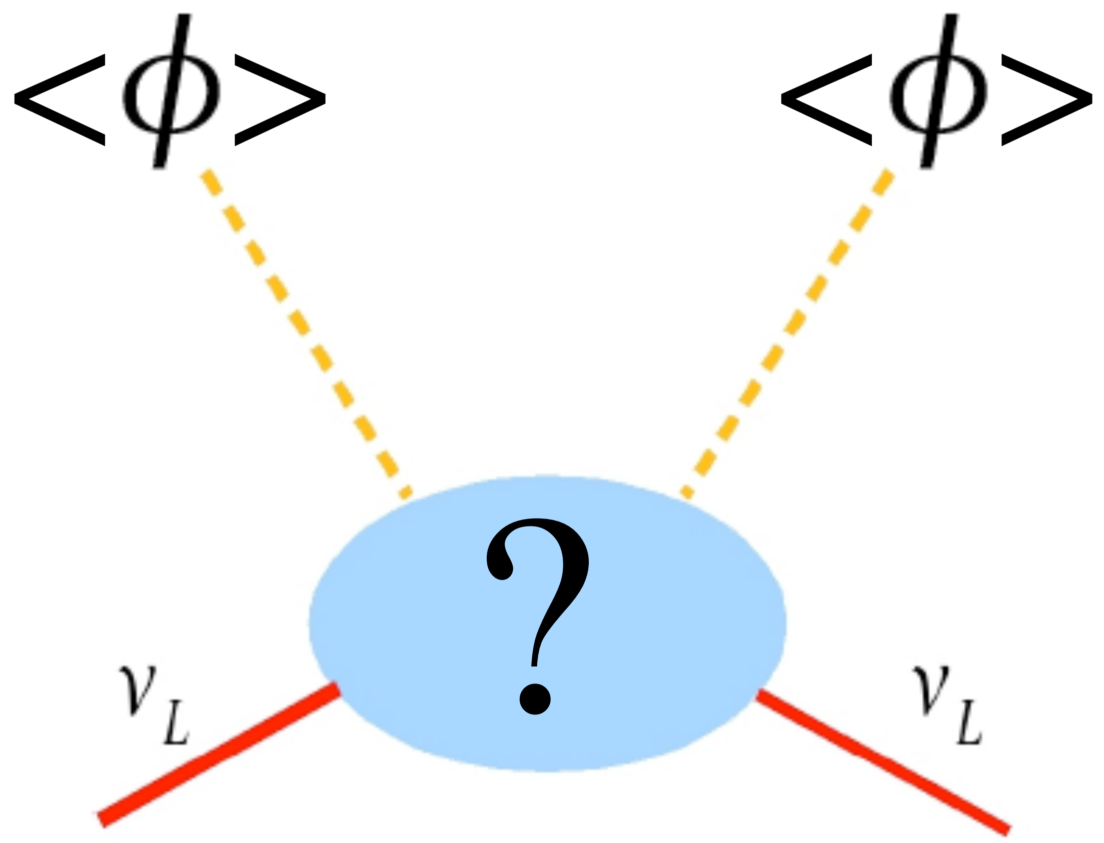


What is the new physics responsible for neutrino mass?

- What is its energy scale?

- UV completion of the Weinberg operator?
  - tree-level: seesaw type I (singlet fermion), II (triplet scalar), III (triplet fermion)
  - many realisations at loop level (radiative neutrino mass models)

Beyond the Weinberg operator



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  - many realisations at loop level (radiative neutrino mass models)

- Most (but not all!) UV completions involve **fermionic SM gauge singlets**:

sterile neutrinos, right-handed neutrinos, heavy neutral leptons

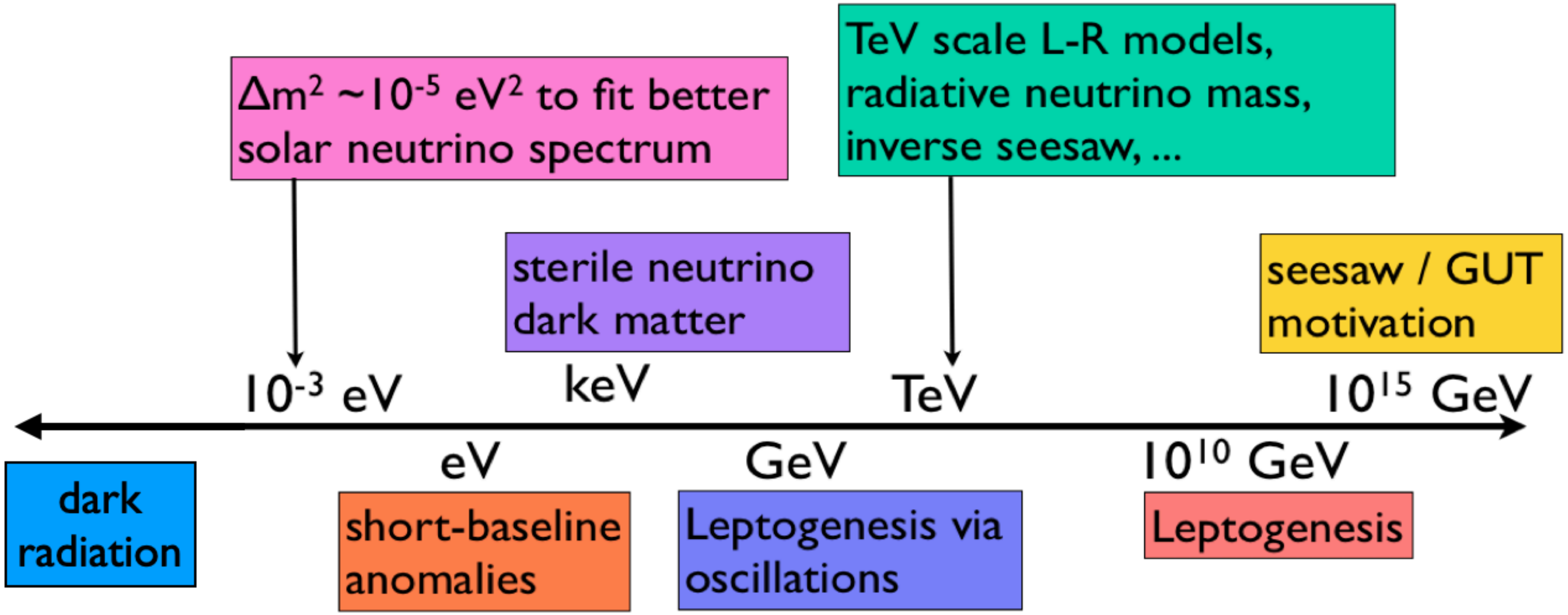
for this talk: **new-νs** („nu-nus“)

We have no proof for the existence of new-νs

well-known examples of neutrino mass generation
without new fermionic degrees-of-freedom,
e.g. Higgs-triplet (type-II seesaw),
radiative models (Zee, Zee-Babu)

… but for the existence of new-ν physics!

Where to look for new-νs?



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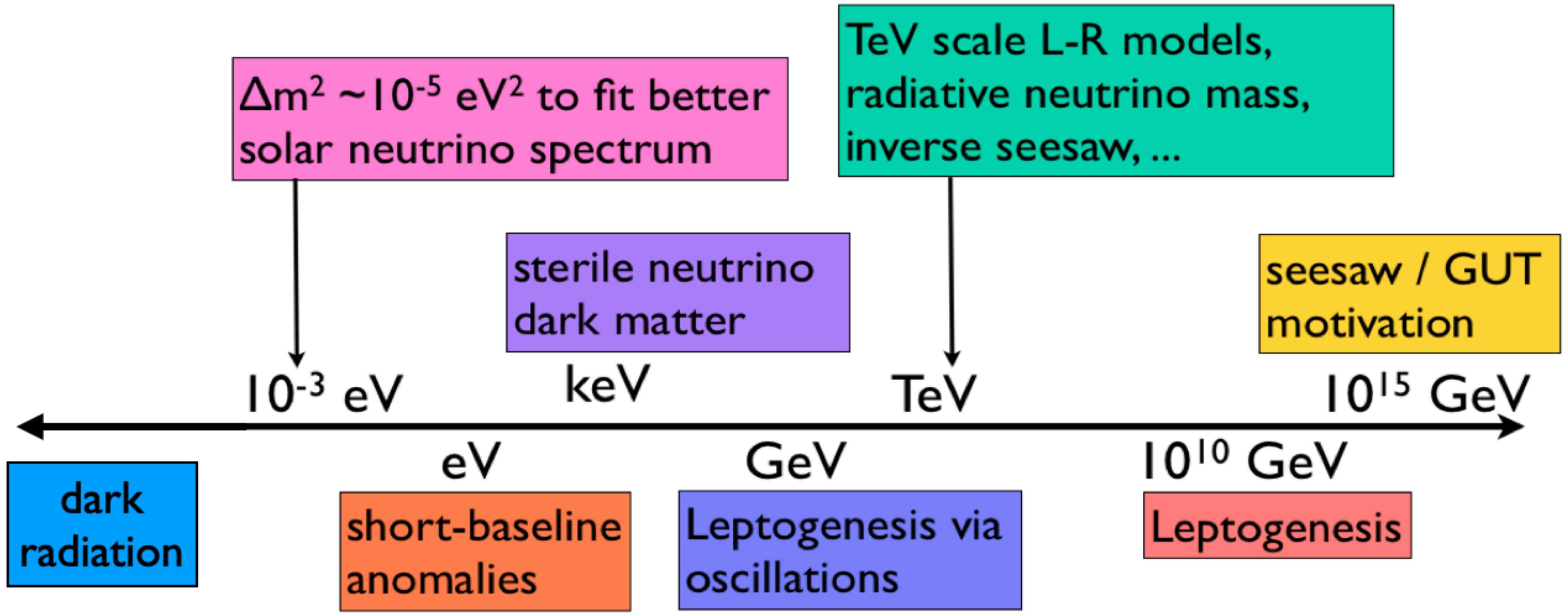
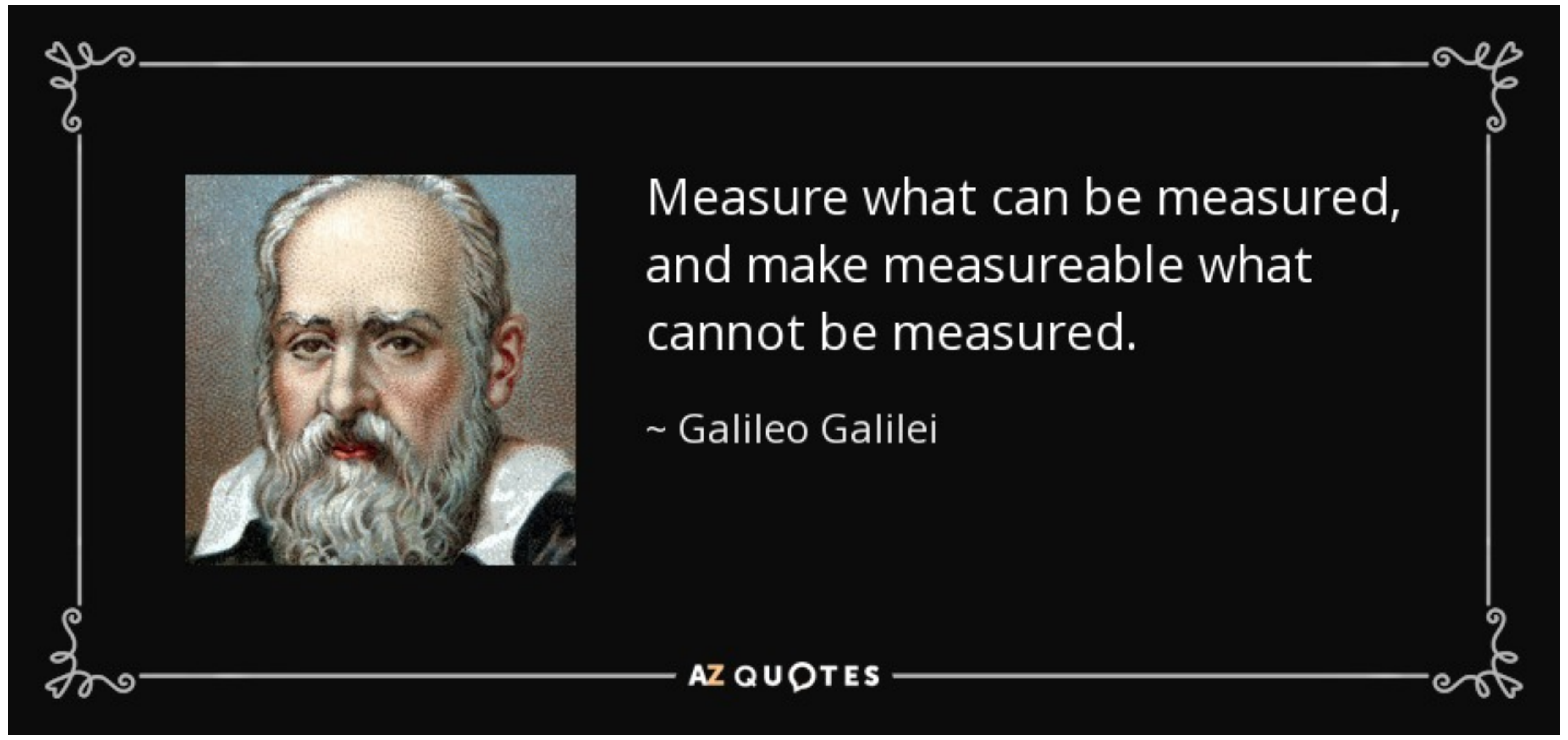


- unfortunately little guidance from theory
- follow „Galileo's principle“?

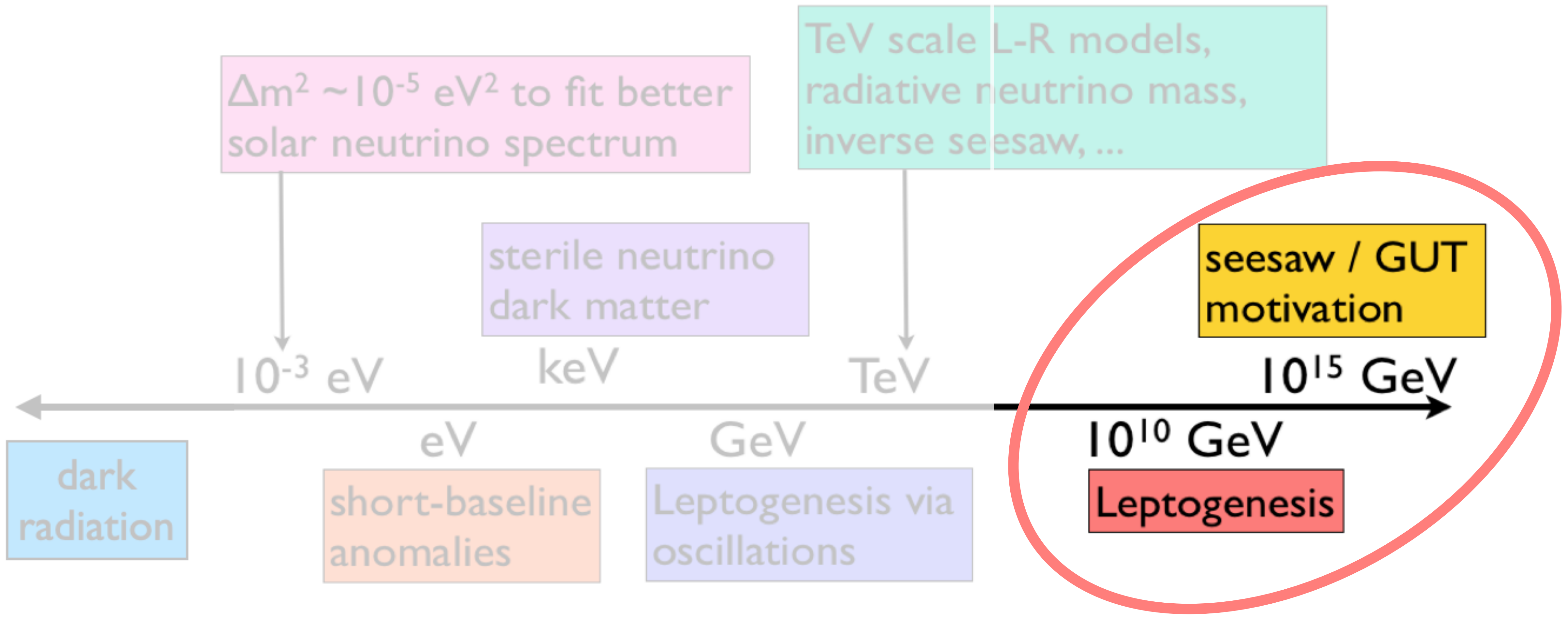


https://www.azquotes.com/quote/905195

Heavy new-νs: ~10^6–10^{16} GeV

motivation:

- high-scale seesaw
- high-scale leptogenesis
- GUTs



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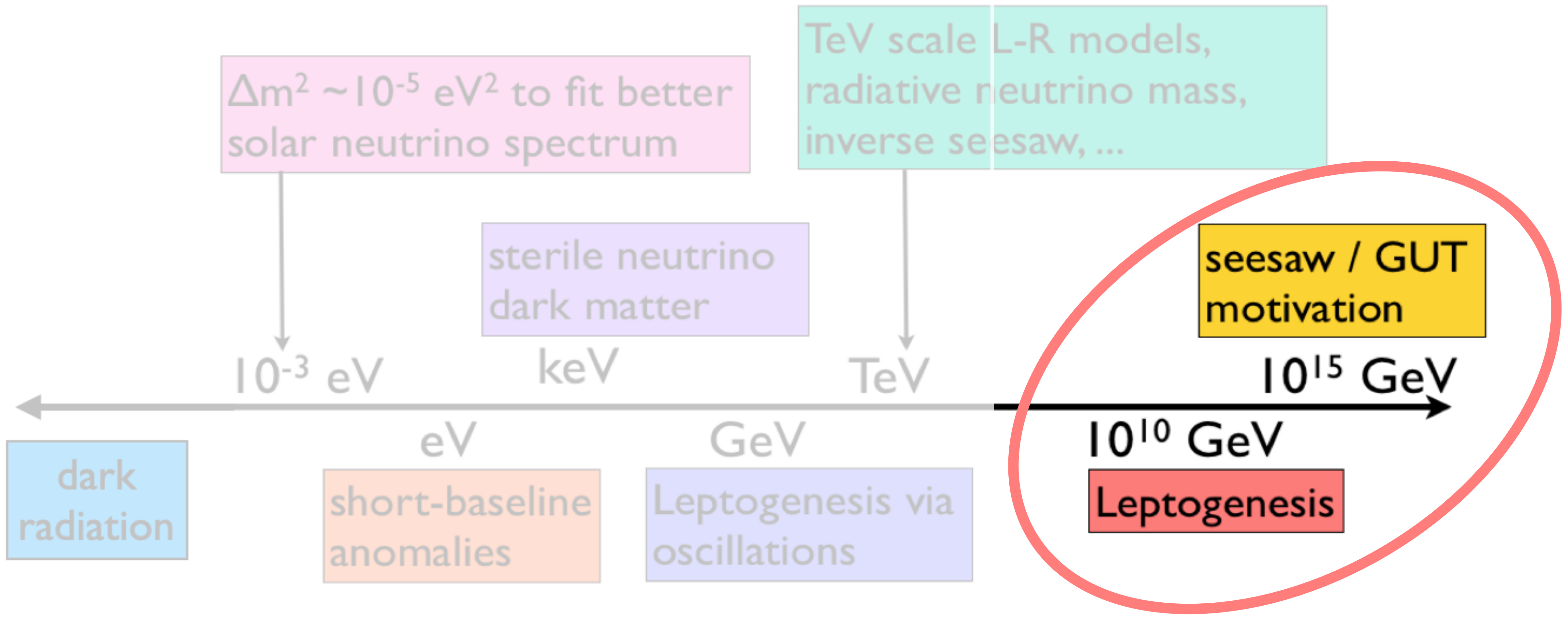

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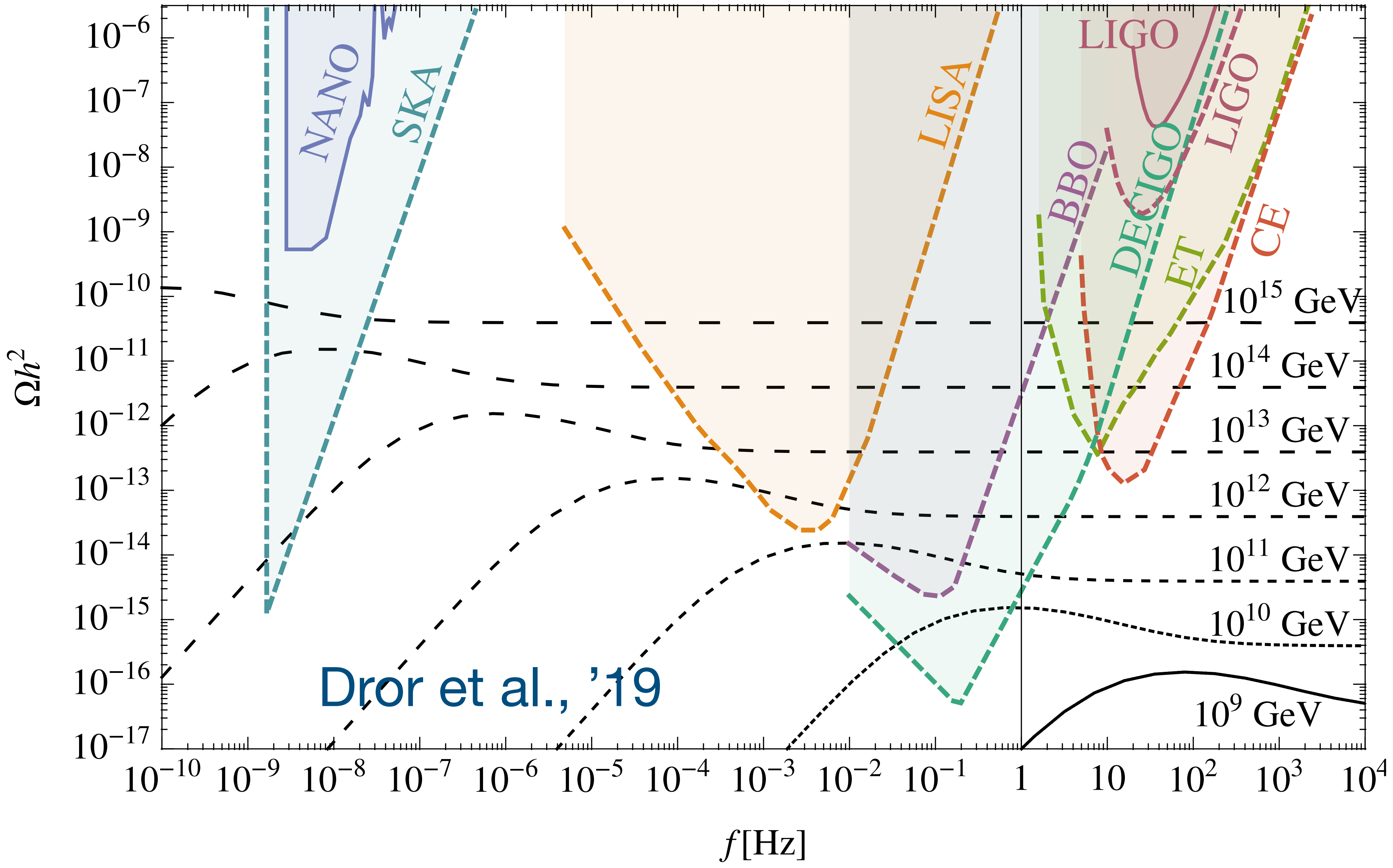
possible signatures:

- proton decay (DUNE, HyperK)
- stochastic gravitational waves from cosmic strings due to breaking of symmetry possibly related to Majorana mass (e.g., B-L, GUT)

Buchmüller, Domcke, Kamada, Schmitz ’13; Dror, Hiramatsu, Kohri, Murayama, White ’19; King, Pascoli, Turner, Zhou ’20;…



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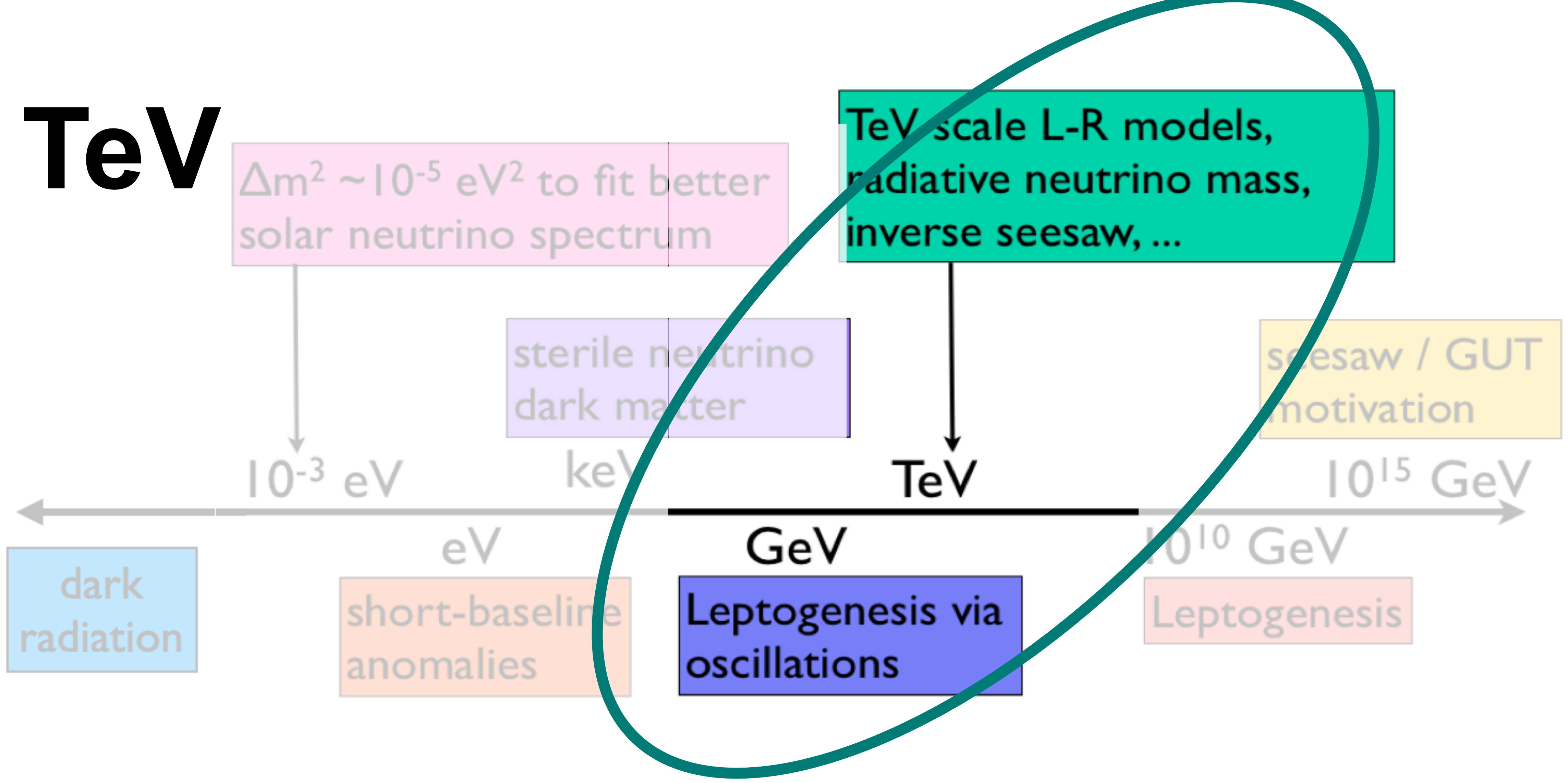
„weak scale“ new-νs: 0.1 GeV–10 TeV



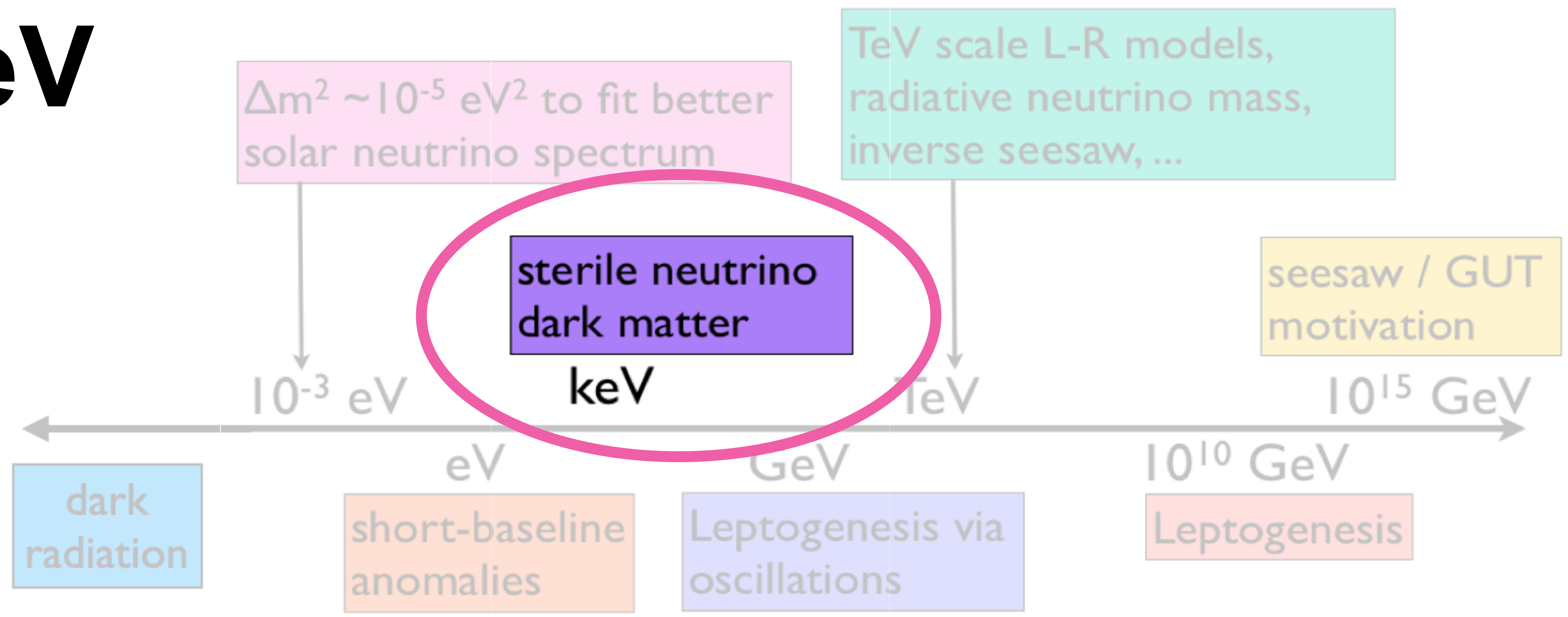
motivation:

- low-scale seesaw (type-II, inverse seesaw, νMSM, …)
- TeV-scale left-right symmetric models
- loop-induced neutrino masses
- links to dark matter candidates
- ARS leptogenesis via HNL oscillations

rich „particle physics signatures“:

- HNLs, W_R, extended Higgs sector,… (collider, beam-dumps),
- charged lepton-flavour violation

new-ν dark matter: 1 keV – 100 keV



motivation:

- 2-parameter model for DM: θ_s, m_s
- very predictive in its minimal version

review: Boyarsky et al., arXiv:1807.07938

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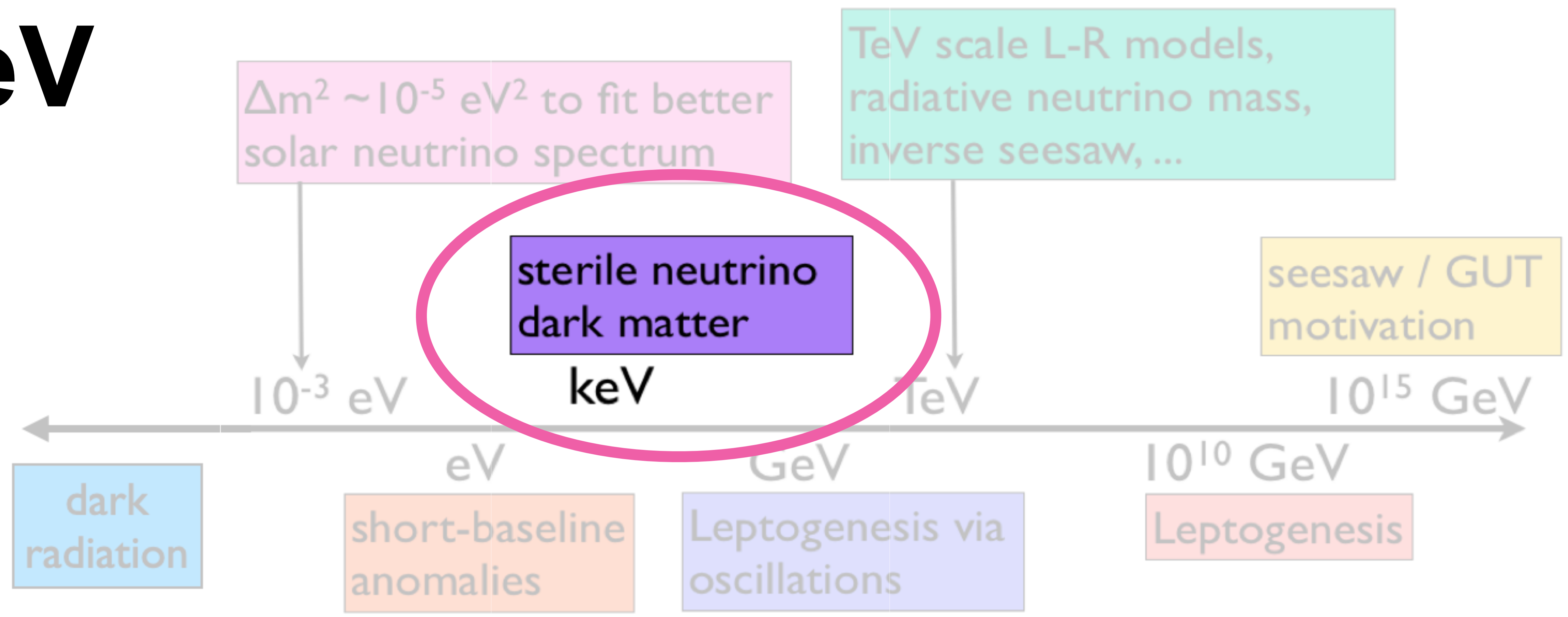

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DM production rate: $\Gamma \sim G_F^2 T^5 \sin^2 2\theta_m$

$$\sin^2(2\theta_m) = \frac{\Delta^2(p)\sin^2(2\theta)}{\Delta^2(p)\sin^2(2\theta) + [\Delta(p)\cos(2\theta) - V_D - V_T]^2}.$$

$$\Delta = \Delta m^2/(2p_\nu)\,,\; V_T \simeq G_F^2 T^4 p_\nu\,,\; V_D \simeq G_F T^3 L_\nu$$

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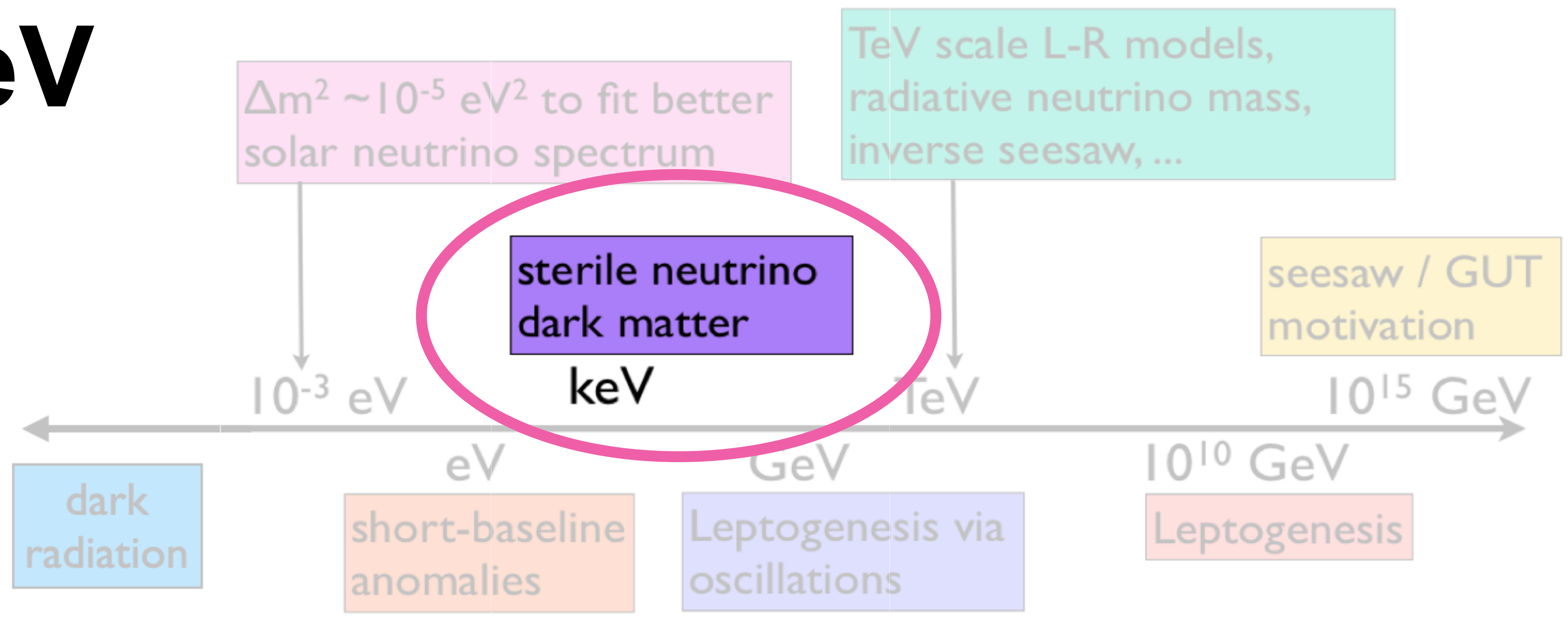

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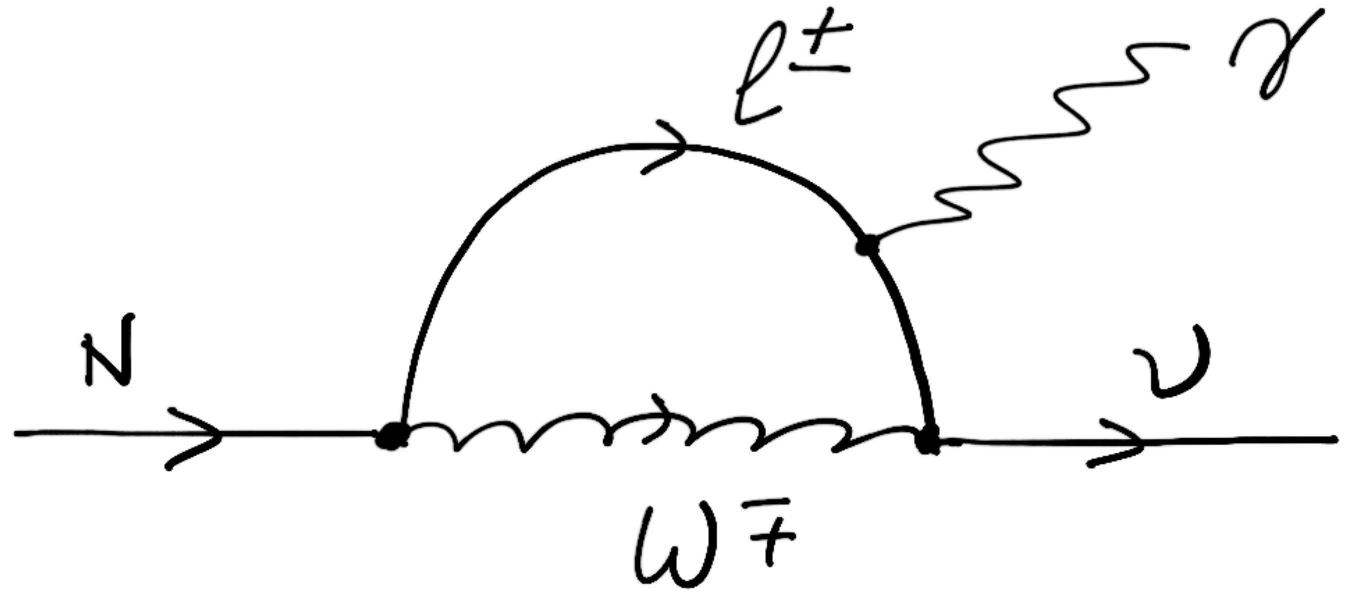
loop-induced decay (X-ray signature):

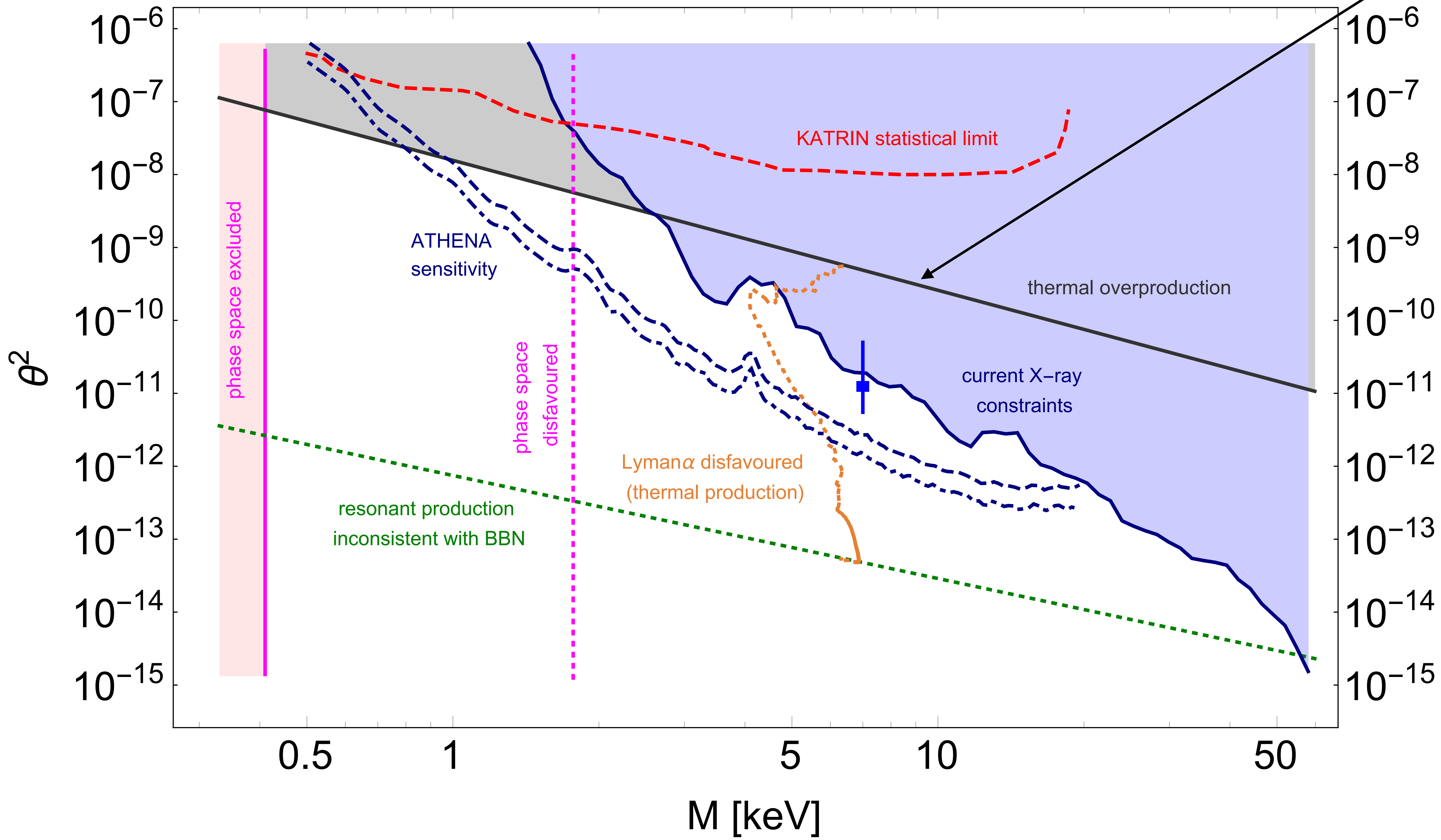
$\Gamma \sim G_F^2 \theta^2 m_s^5$



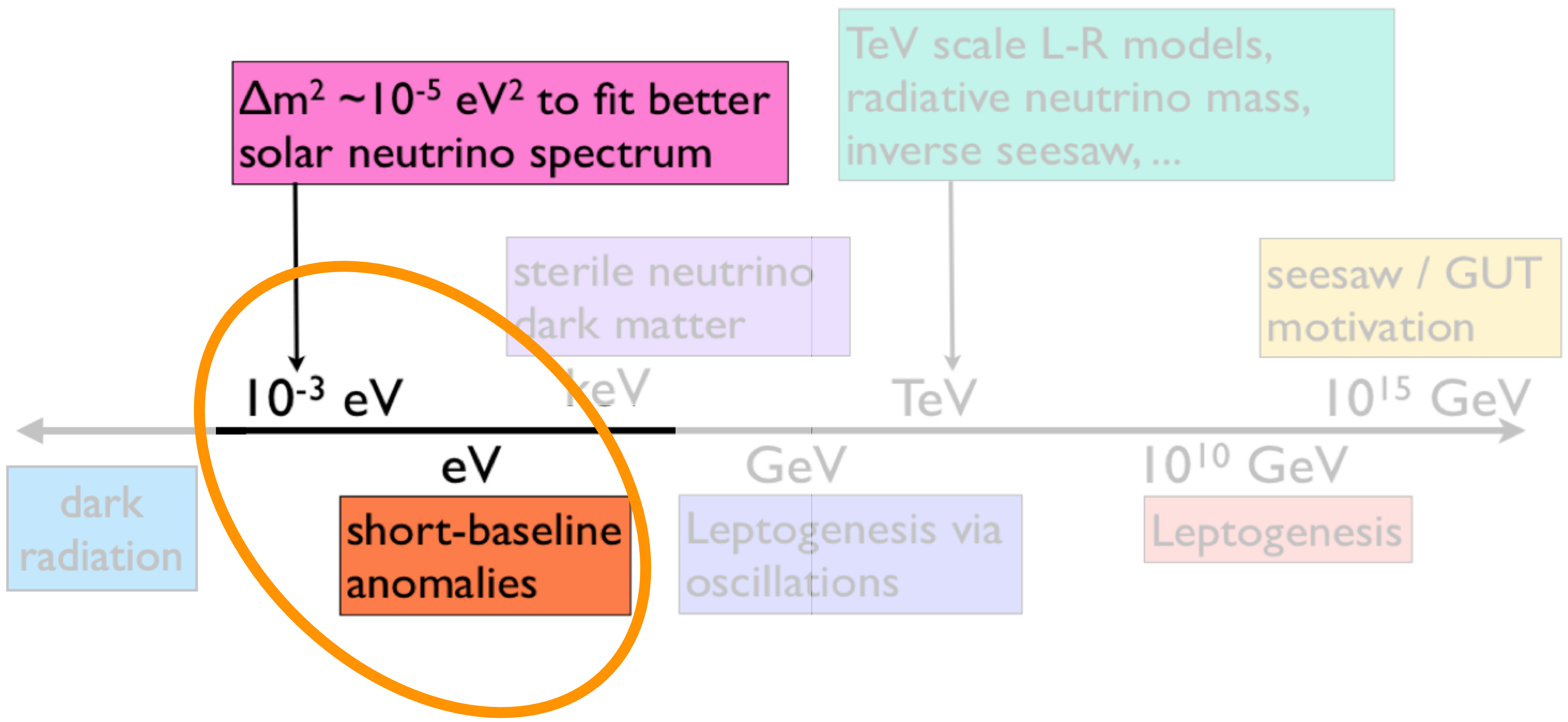
new-ν dark matter: 1 keV – 100 keV

minimal scenario ruled out

Boyarsky et al., [arXiv:1807.07938]



„oscillation scale“: < 10 eV



motivation:

- phenomenological (effects in oscillations, short-baselines)
- not well motivated from „top-down“ perspective
- (very) low-scale seesaw models exist

Short-baseline anomalies

Anomaly	Channel	Status	Explanation?
Reactor rate and shape	$\nu_e \to \nu_e$	fading away ($< 2\sigma$) systematics dominated	
Gallium / BEST	$\nu_e \to \nu_e$	very significant (~5σ)	
LSND	$\nu_\mu \to \nu_e$	significant (3.8σ) ~25 yr anomaly	
MiniBooNE	$\nu_\mu \to \nu_e$	very significant (4.8σ) relies on background estimate	

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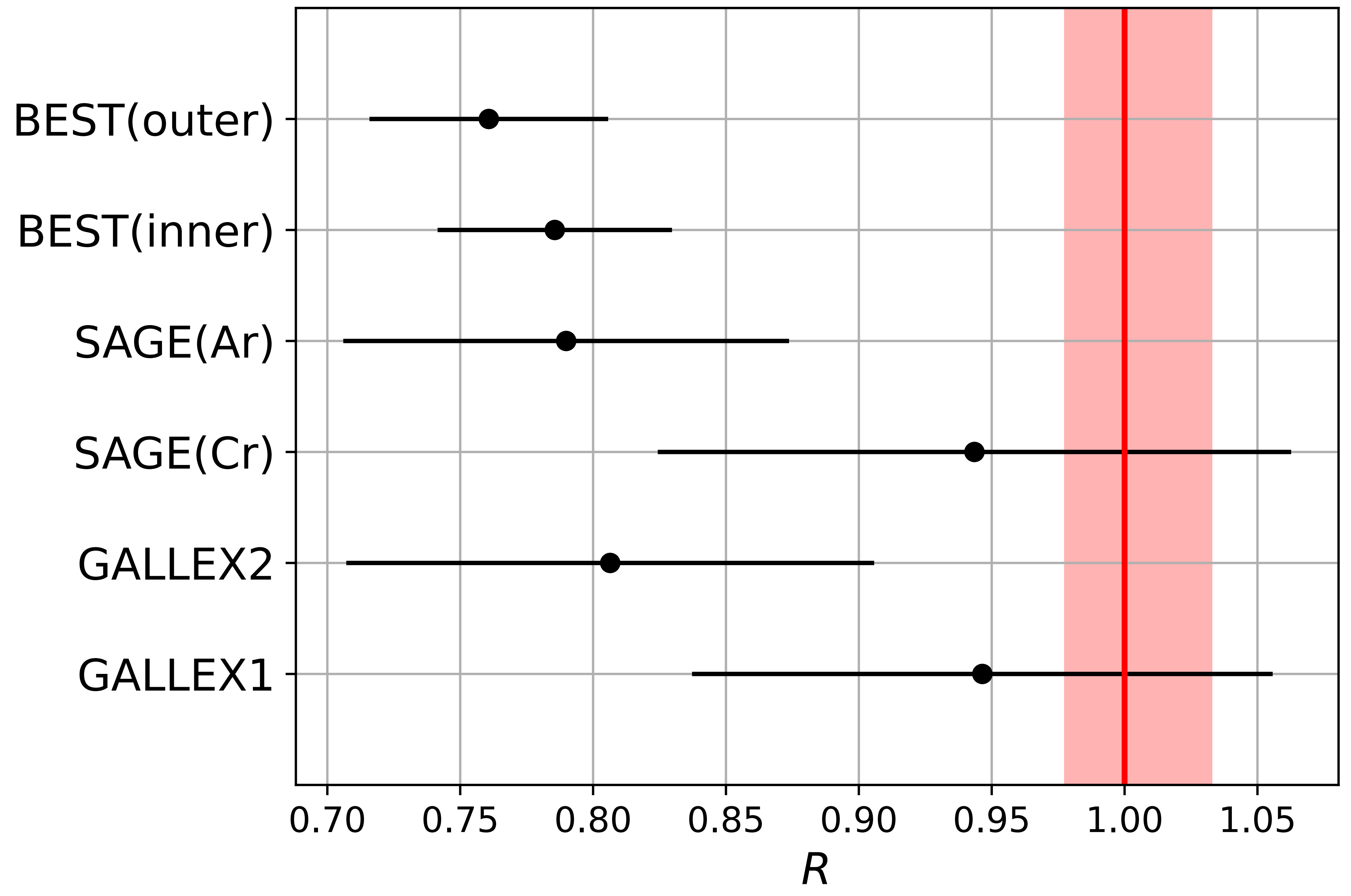
The gallium anomaly and BEST results

- Measurements of gallium solar neutrino experiments GALLEX and SAGE with radioactive ^{51}Cr or ^{37}Ar sources lead to rates lower than expected

	$\chi^2_{\text{null}}/\text{dof}$	p-value
CS1, BEST	32.1/2	1.1×10^{-7} (5.3σ)
CS1, all	36.3/6	2.4×10^{-6} (4.7σ)
CS2, BEST	34.7/2	2.9×10^{-8} (5.5σ)
CS2, all	38.4/6	9.4×10^{-7} (4.9σ)

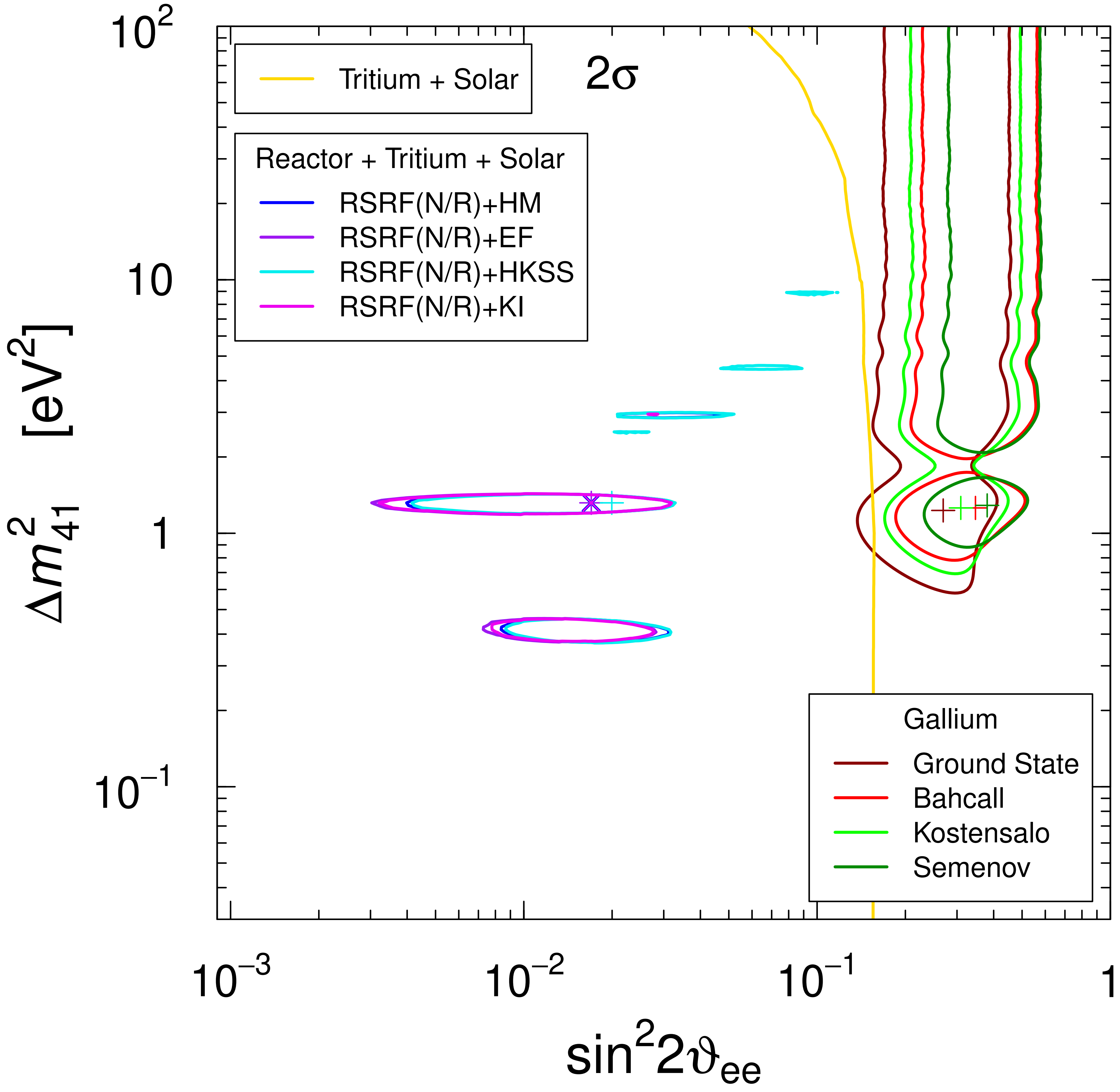
Farzan, TS, 2306.09422
cross sections CS1, CS2 from
Haxton et al., 2303.13623

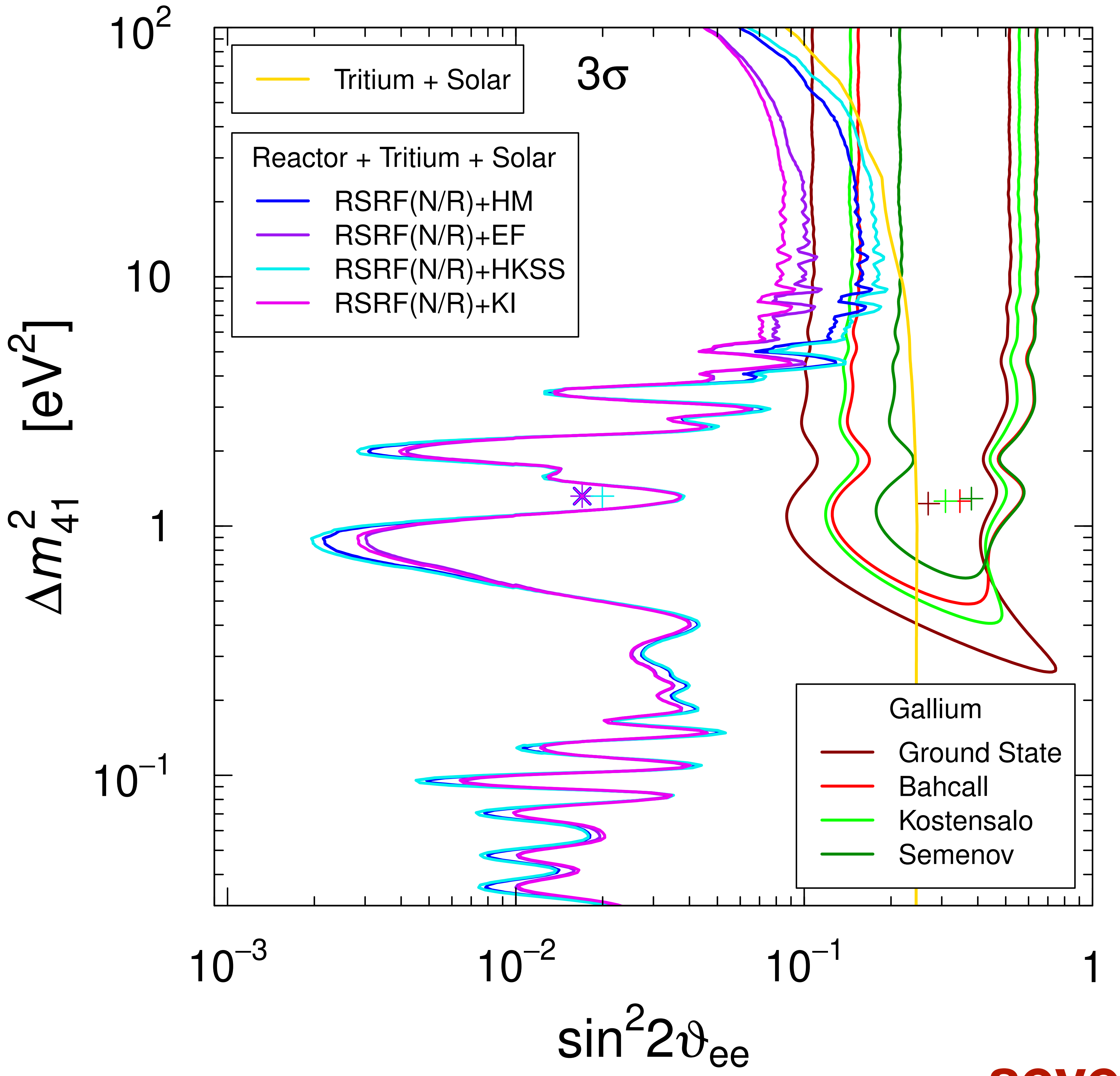
BEST coll., Barinov et al., Phys. Rev. Lett. 128 (2022), no. 23 232501; Phys. Rev. C 105 (2022), no. 6 065502



Can it be explained by eV sterile neutrino oscillations?

- in tension with solar neutrinos, reactor experiments and cosmology!





Giunti, Li, Ternes, Tyagi, Xin, 2209.00916

see also Berryman, Coloma, Huber, TS, Zhou, 2111.12530; Goldhagen, Maltoni, Reichard, TS, 2109.14898;

severe tension of $4-5\sigma$

Short-baseline anomalies

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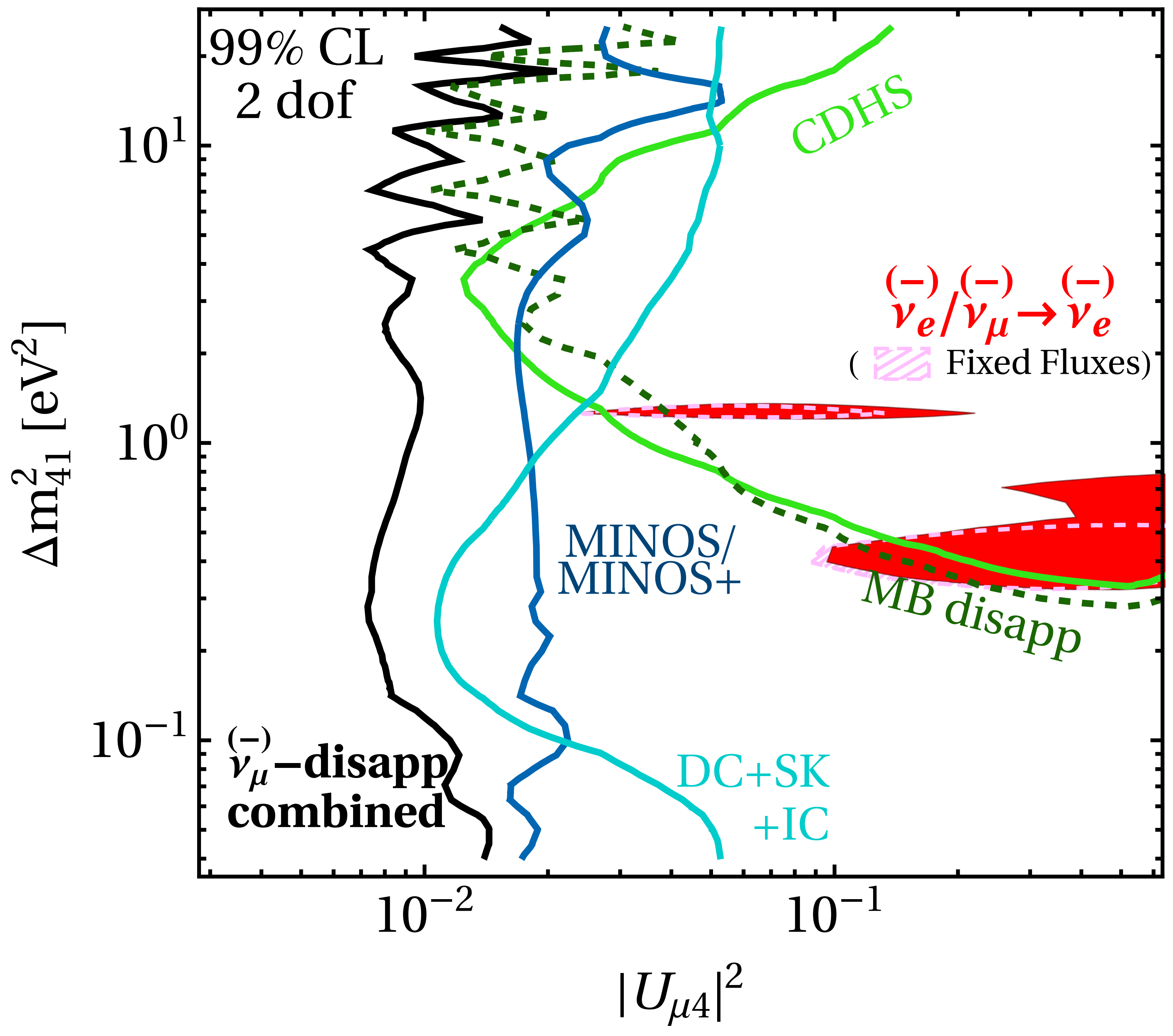
Reactor rate and shape	$\nu_e \to \nu_e$	fading away ($< 2\sigma$) systematics dominated	systematics/nuclear physics
Gallium / BEST	$\nu_e \to \nu_e$	very significant (~5σ)	sterile oscillations in strong tension w reactor, solar, cosmology difficult to explain exotic decoherence? [Farzan, TS, '23]
LSND	$\nu_\mu \to \nu_e$	significant (3.8σ) ~25 yr anomaly	
MiniBooNE	$\nu_\mu \to \nu_e$	very significant (4.8σ) relies on background estimate	

Strong tension btw appearance and disappearance

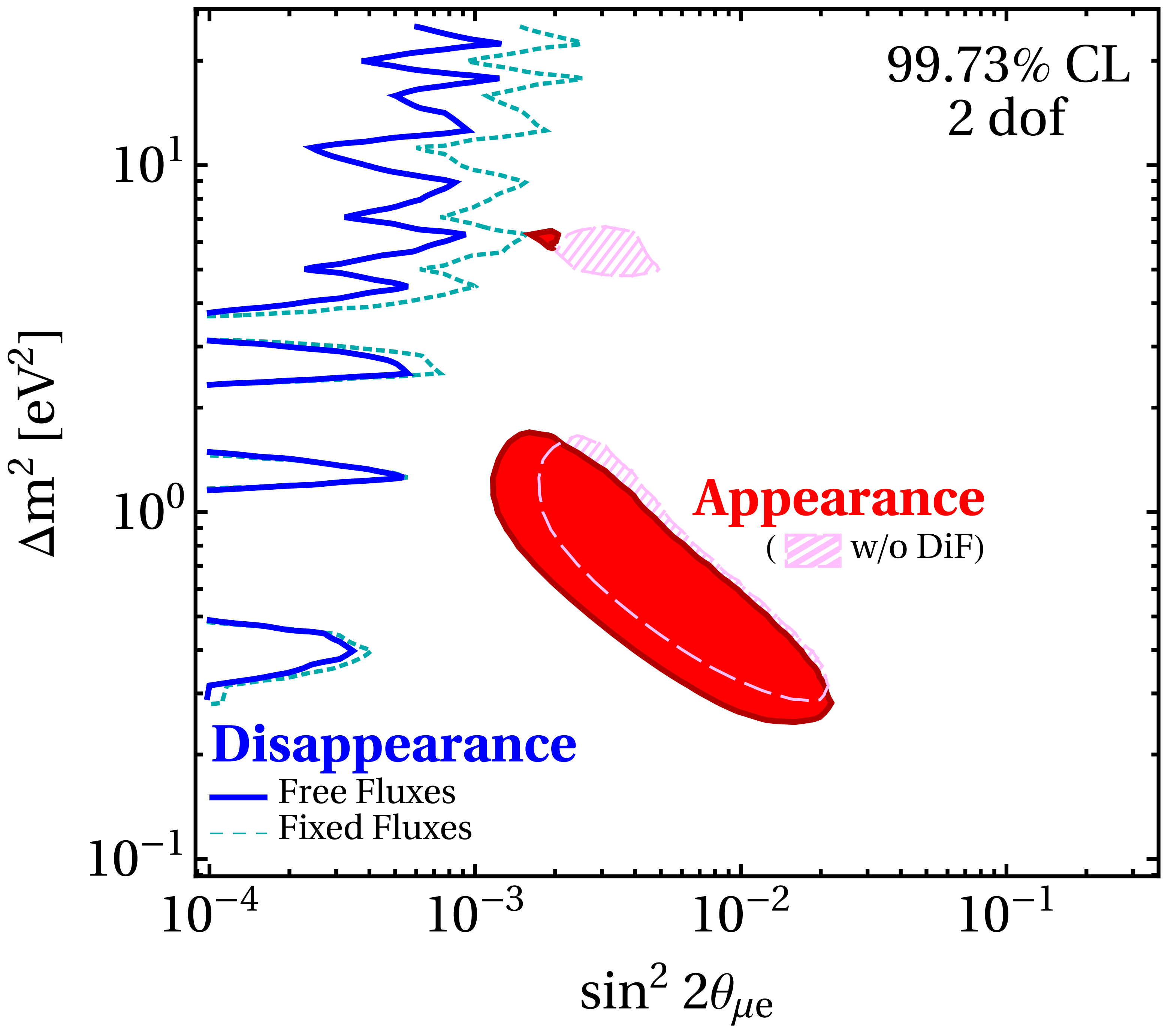
$$\sin^2 2\theta_{\mu e} \approx \frac{1}{4} \sin^2 2\theta_{ee} \sin^2 2\theta_{\mu\mu}$$

sterile oscillation explanation of LSND/MiniB robustly disfavoured



non-observation of oscillations in ν_μ disappearance (CDHS, MiniB, MINOS+, SK, IceCube)

Dentler et al, 1803.10661



consistency of appearance and disapp. data with a p-value $< 10^{-6}$

MiniBooNE and a decaying sterile neutrino

Palomares, Pascoli, TS, hep-ph/0505216; Gninenko, 0902.3802, 1009.5536; Bertuzzo, Jana, Machado, Zukanovich, 1807.09877; Ballett, Pascoli, Ross-Lonergan, 1808.2915; Arguelles, Hostert, Tsai, 1812.08768; Fischer, Hernandez, TS, 1909.09561; Dentler, Esteban, Kopp, Machado, 1911.01427; deGouvea, Peres, Prakash, Stenico, 1911.01447; Brdar, Fischer, Smirnov, 2007.14411; Abdallah, Gandhi, Roy, 2010.06159; Abdullahi, Hostert, Pascoli, 2007.11813; Abdullahi et al., 2308.02543; Hoster, Kelly, Zhou, 2406.04401; …

- sterile neutrino N with m_N ~ keV to ~500 MeV
- produce N either by mixing or by up-scattering
- decay:
  - $N \to \phi\, \nu_e$ with standard neutrino interaction in detector
  - electromagn. decay inside MB detector $N \to \nu\gamma \,/\, \nu e^{\pm} \,/\, \nu\pi^0 \,/ \ldots$ (no LSND)
- exciting new physics / rich phenomenology / predict signatures in existing (near detectors) and/or upcoming experiments (e.g., Fermilab SBN, DUNE, HK, IceC)

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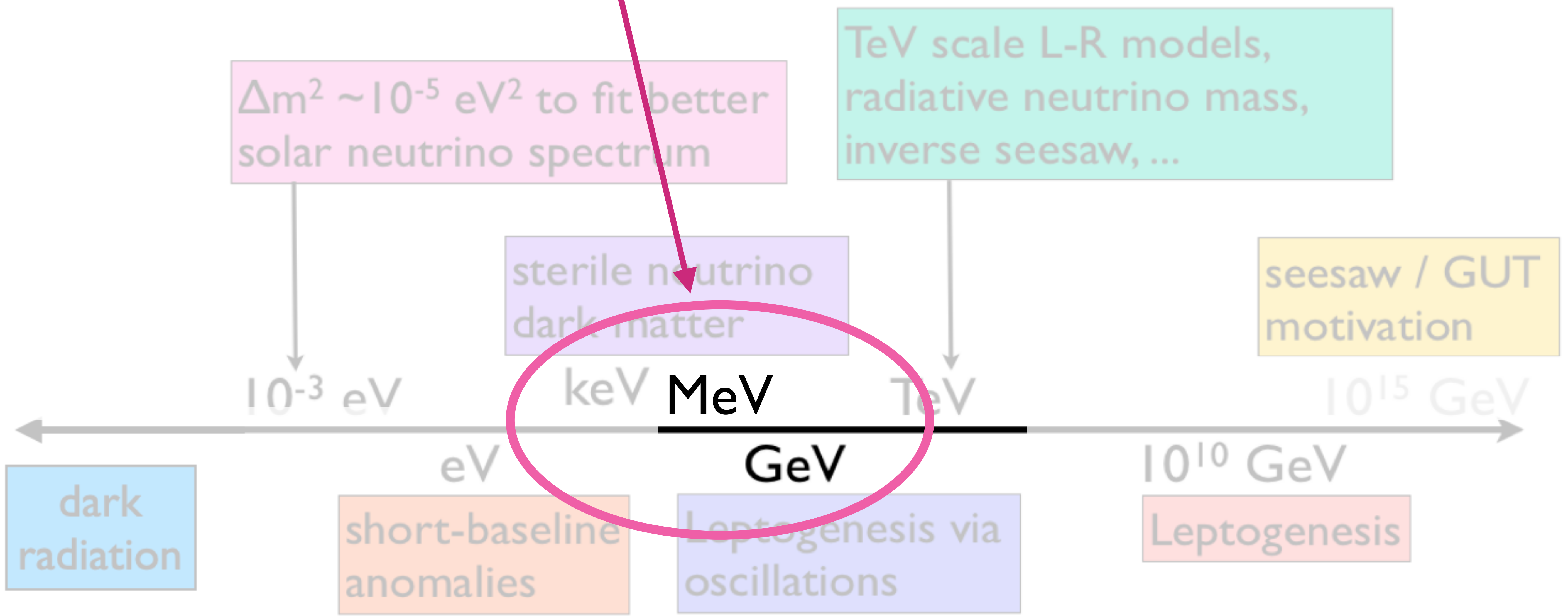
- sterile neutrino
- produce N eithe
- decay:
  - $N \to \phi \nu_e$ with
  - electromagn. (no LSND)
- exciting new ph existing (near detectors) and/or upcoming experiments (e.g., Fermilab SBN, DUNE, HK, IceC)



Short-baseline anomalies — summary

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The cosmo anomaly:

Why is neutrino mass not seen in cosmology?

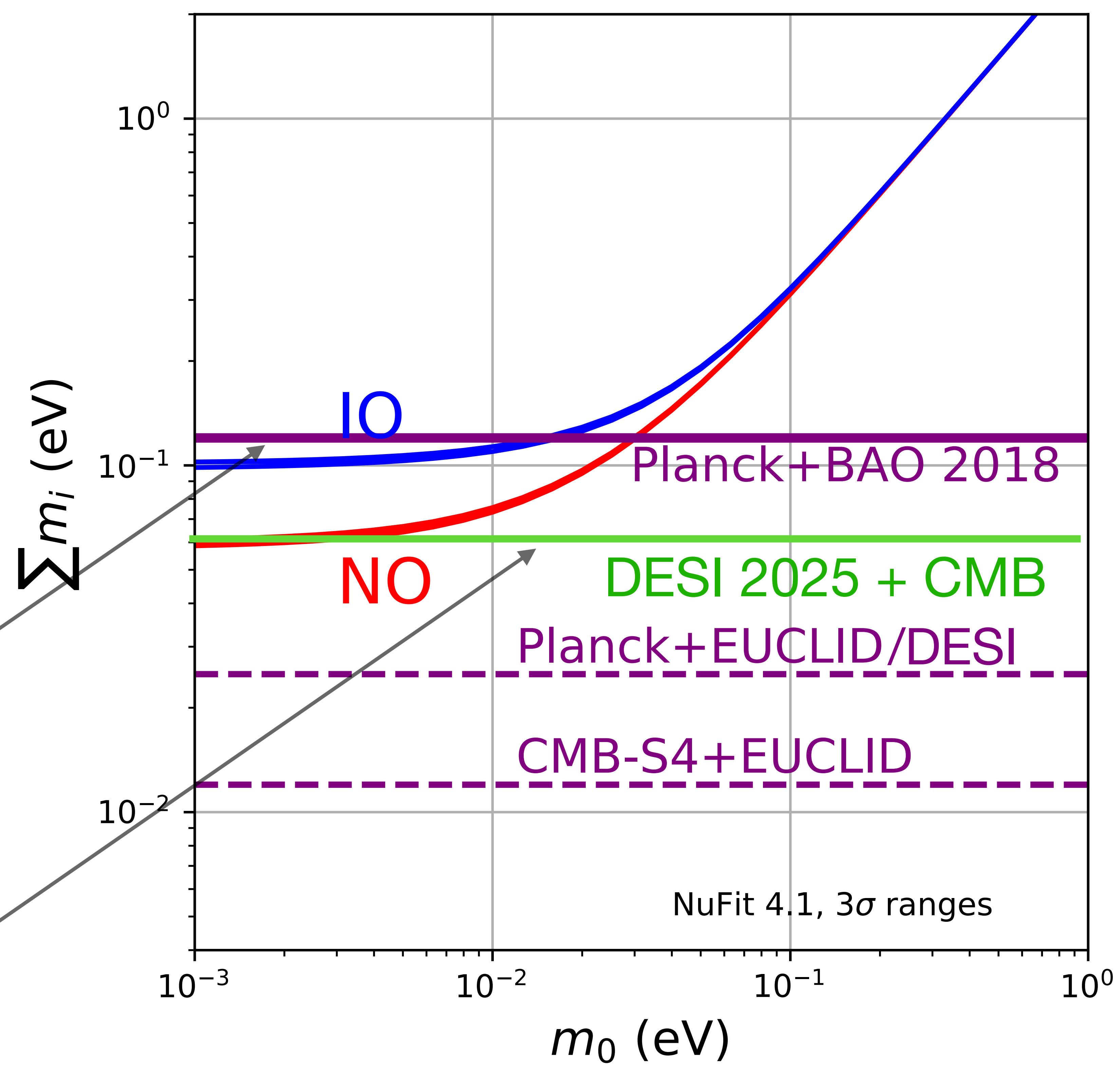
Neutrino mass from cosmology

$$\Sigma \equiv \sum_{i=1}^{3} m_i = \begin{cases} m_0 + \sqrt{\Delta m^2_{21} + m_0^2} + \sqrt{\Delta m^2_{31} + m_0^2} & \text{(NO)} \\ m_0 + \sqrt{|\Delta m^2_{32}| + m_0^2} + \sqrt{|\Delta m^2_{32}| - \Delta m^2_{21} + m_0^2} & \text{(IO)} \end{cases}$$

- minimal values predicted from oscillation data for $m_0 = 0$:

$$\Sigma_{\min} = \begin{cases} 98.6 \pm 0.85\,\mathrm{meV} & \text{(IO)} \\ 58.5 \pm 0.48\,\mathrm{meV} & \text{(NO)} \end{cases}$$

- **Upper bounds from current data:**
  - $\Sigma m_\nu < 0.12\,\mathrm{eV}\ (95\,\%\ \mathrm{CL})$ Planck CMB+BAO 2018
  - $\Sigma m_\nu < 0.064\,\mathrm{eV}\ (95\,\%\ \mathrm{CL})$ DESI 2025 + CMB



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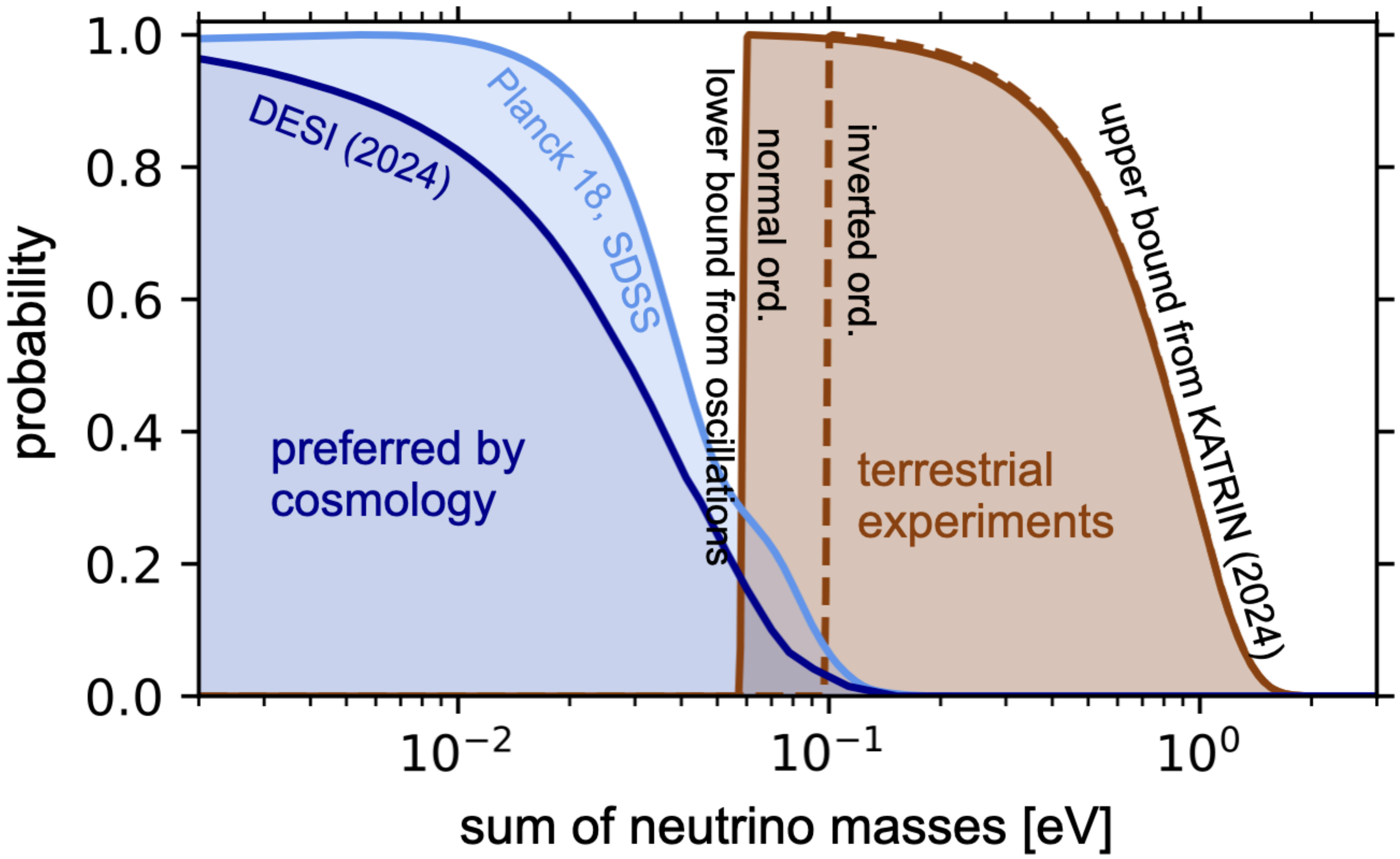
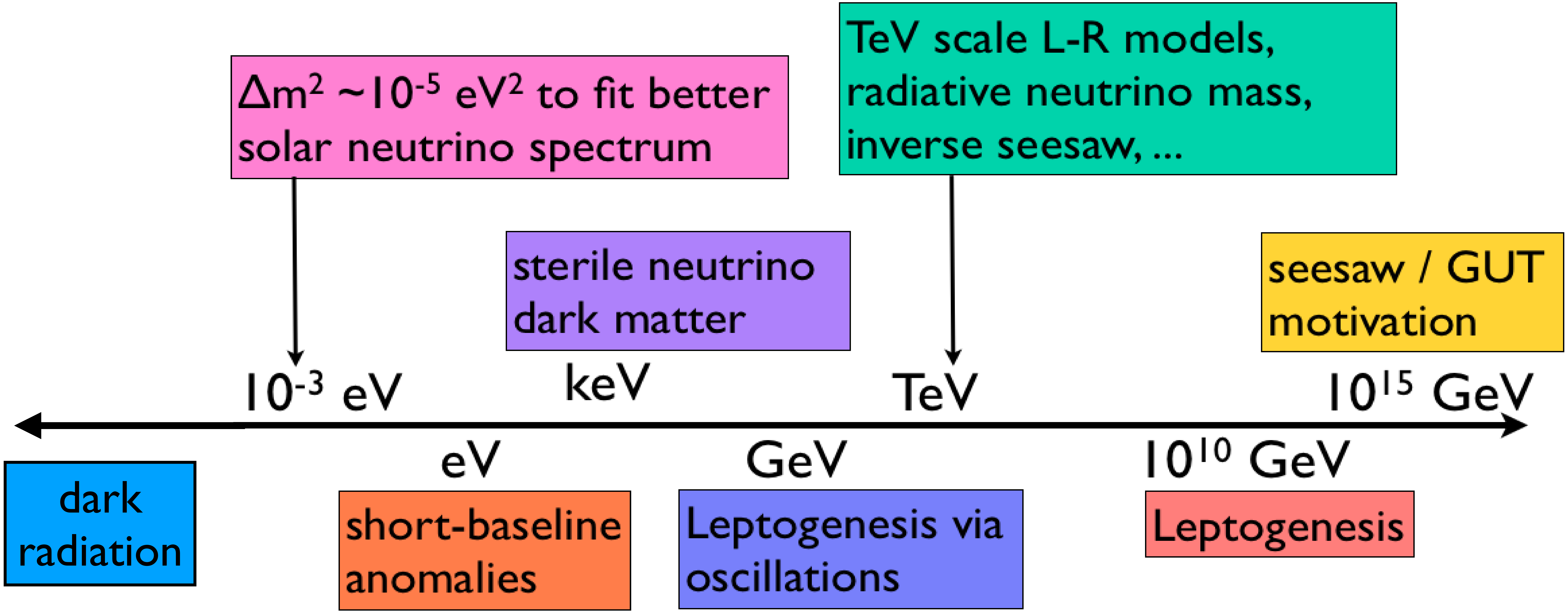
Tension between cosmology and oscillation results?

updated from Gariazzo, Mena, TS, 2302.14159



Hint for the existence of new-νs?



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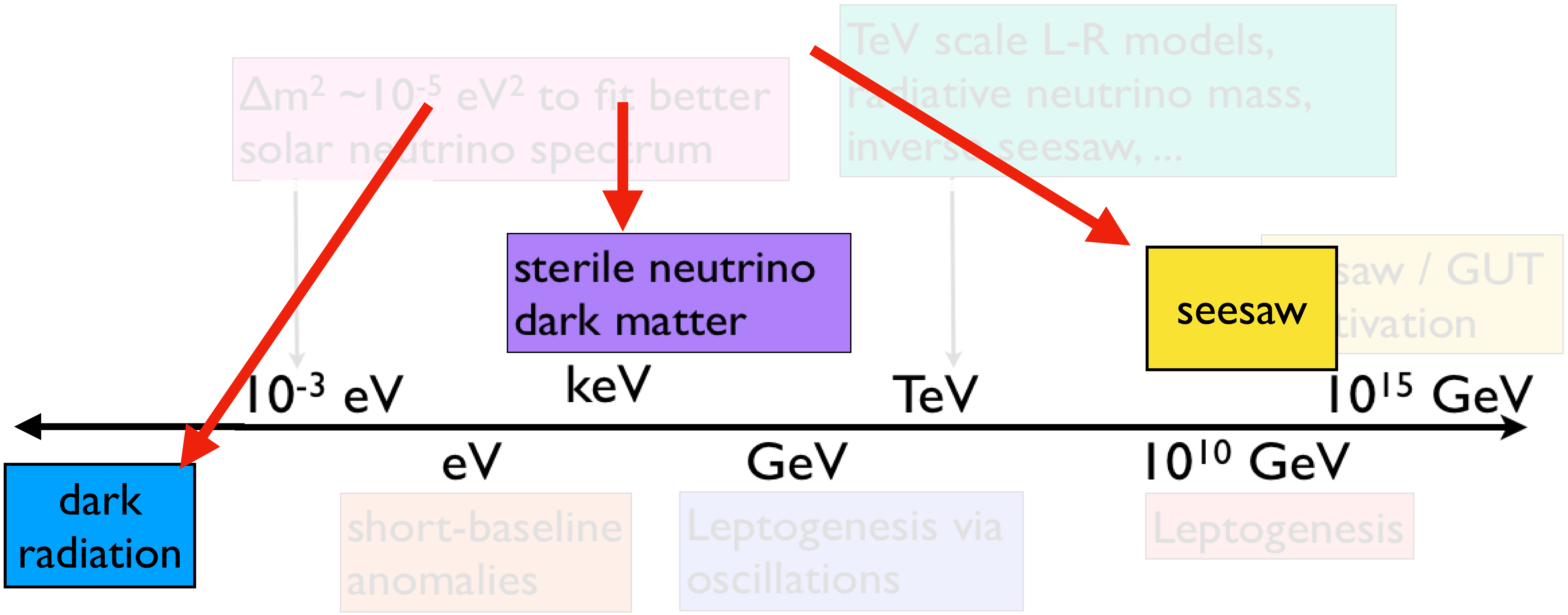
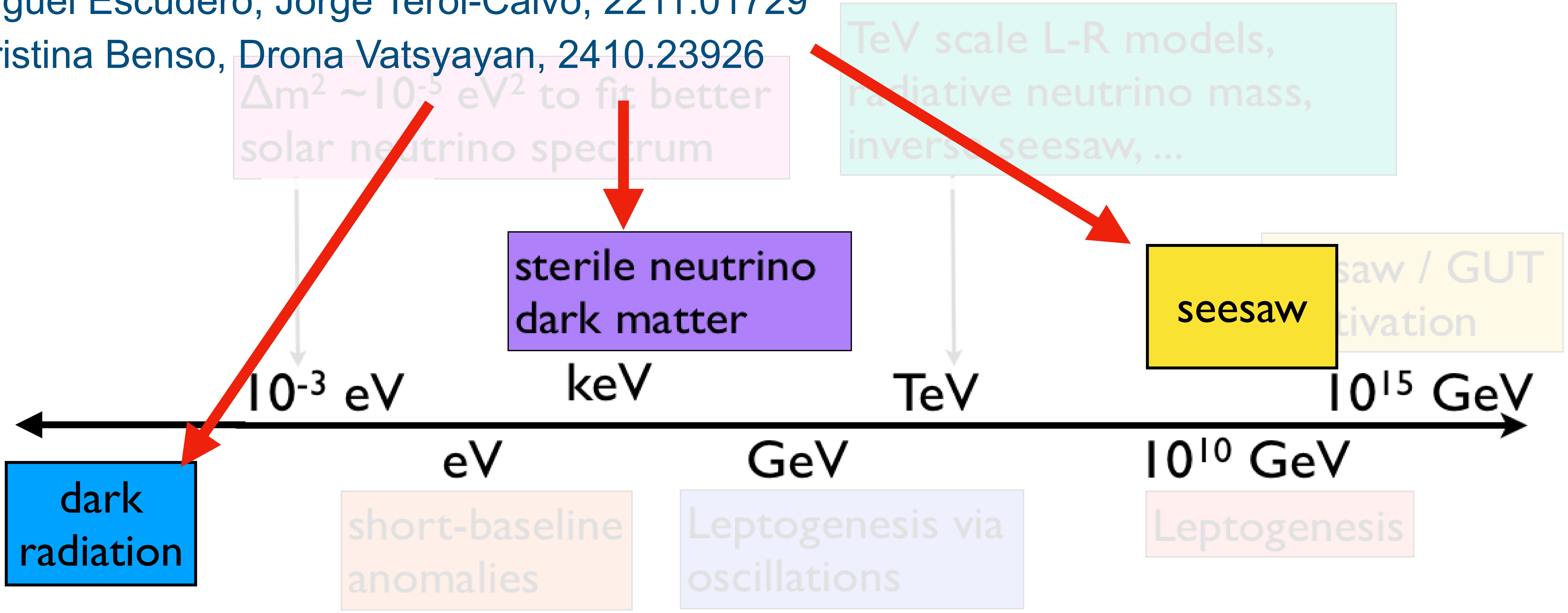


Hint for the existence of new-νs?

work with

Miguel Escudero, Jorge Terol-Calvo, 2211.01729

Cristina Benso, Drona Vatsyayan, 2410.23926



Cosmology bounds can be relaxed in non-standard scenarios

incomplete!

- dynamical dark energy

  Green, Meyers, 2407.07878;…; DESI DR2 2503.14743: $\sum m_\nu \lesssim 0.16\,\mathrm{eV}$

- neutrino decay into dark radiation

  Chacko et al. 1909.05275; 2002.08401; Escudero et al., 2007.04994;
  Barenboim et al.,2011.01502; Chacko et al. 2112.13862: $\sum m_\nu < 0.42\,\mathrm{eV}$

- time dependent neutrino mass

  Lorenz et al. 1811.01991; 2102.13618; Esteban, Salvado, 2101.05804; Sen, Smirnov, 2407.02462, 2306.15718;

- modified momentum distribution

  Cuoco et al., astro-ph/0502465; Barenboim et al., 1901.04352; Alvey, Sabti, Escudero, 2111.14870

- reduced neutrino density + dark radiation

  Beacom, Bell, Dodelson, 04; Farzan, Hannestad, 1510.02201; Renk, Stöcker et al., 2009.03286;
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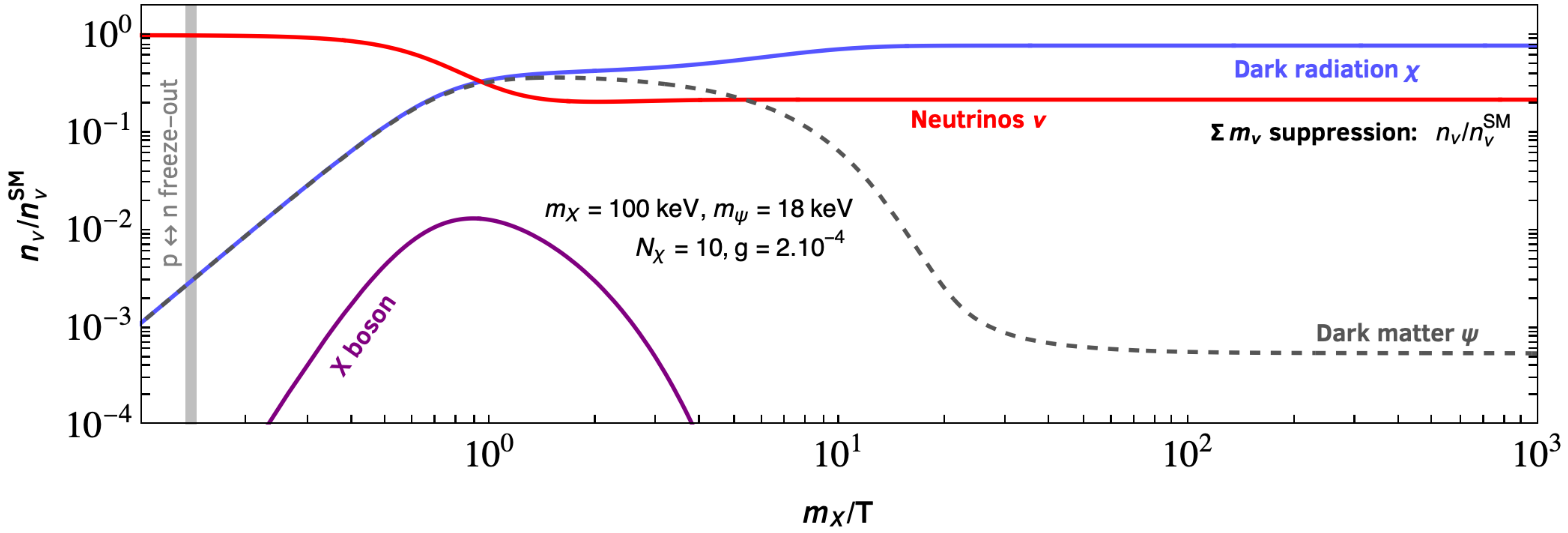
  Escudero, TS, Terol-Calvo, 2211.01729

- introduce a set of N_χ massless new-νs
- a mediator X coupled to neutrinos
- convert active neutrinos into massless new-νs after BBN but before CMB decoupling
- ~10 keV new-ν dark matter freeze-out in the dark sector



Farzan, Hannestad, 1510.02201; Escudero, TS, Terol-Calvo, 2211.01729; Benso, TS, Vatsyayan, 2410.23926

A seesaw model for large neutrino mass and dark radiation

Escudero, TS, Terol-Calvo, 2211.01729

- 3 heavy new-νs (seesaw)
- new abelian gauge symmetry $U(1)_X$
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Yukawa sector

$$-\mathcal{L} = \overline{N_R}\, Y_\nu\, \ell_L\, \widetilde{H}^\dagger + \frac{1}{2}\,\overline{N_R}\, M_R\, N_R^c + \overline{N_R} Y_\Phi\, \chi_L\, \Phi + \text{h.c.}$$

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Scalar potential

$$V = \mu_H^2 H^\dagger H + \lambda_H \left(H^\dagger H\right)^2 + \mu_\Phi^2 |\Phi|^2 + \lambda_\Phi |\Phi|^4 + \lambda_{H\Phi} |\Phi|^2 H^\dagger H$$

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Gauge interaction

$$\mathscr{L}_{\text{int}} = g_X\, Z'_\mu\, \bar{\chi}\gamma^\mu \chi$$

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$$m_D = \frac{v_{\rm EW}}{\sqrt{2}} Y_\nu \,, \quad \Lambda = \frac{v_\Phi}{\sqrt{2}} Y_\Phi$$

$$-\mathcal{L} = \overline{N_R}\, Y_\nu\, \ell_L\, \widetilde{H}^\dagger + \frac{1}{2}\, \overline{N_R}\, M_R\, N_R^c + \overline{N_R} Y_\Phi\, \chi_L\, \Phi + \text{h.c.}$$

$$\Lambda \ll m_D \ll M_R$$

$$\mathcal{M}_n = \begin{pmatrix} 0 & m_D & 0 \\ m_D^T & M_R & \Lambda \\ 0 & \Lambda^T & 0 \end{pmatrix}$$

$$m_{\rm heavy} \approx M_R$$

$$m_{\rm active} \approx m_D^2/M_R$$

$$m_\chi = 0\,, \quad \theta_{\nu\chi} \approx \Lambda/m_D$$

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$$\mathscr{L}_{\text{int}} = g_X\, Z'_\mu\, \bar{\chi}\gamma^\mu\chi \qquad g_X = \frac{m_{Z'}}{v_\Phi}$$

$$\lambda_{Z'}^{\chi\chi} = g_X$$

$$\lambda_{Z'}^{\chi\nu} = g_X\theta_{\nu\chi}$$

$$\lambda_{Z'}^{\nu\nu} = g_X\theta_{\nu\chi}^2$$

couplings to neutrinos induced by mixing: $Z' \leftrightarrow \nu\nu/\nu\chi/\chi\chi$

A seesaw model for large neutrino mass and dark radiation

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$$\mathscr{L}_{\text{int}} = g_X\, Z'_\mu\, \bar{\chi}\gamma^\mu \chi$$

$$g_X = \frac{m_{Z'}}{v_\Phi}$$

indep. params for pheno:

$$m_\nu, M_R, \theta_{\nu\chi}$$

$$v_\Phi, m_{Z'}$$

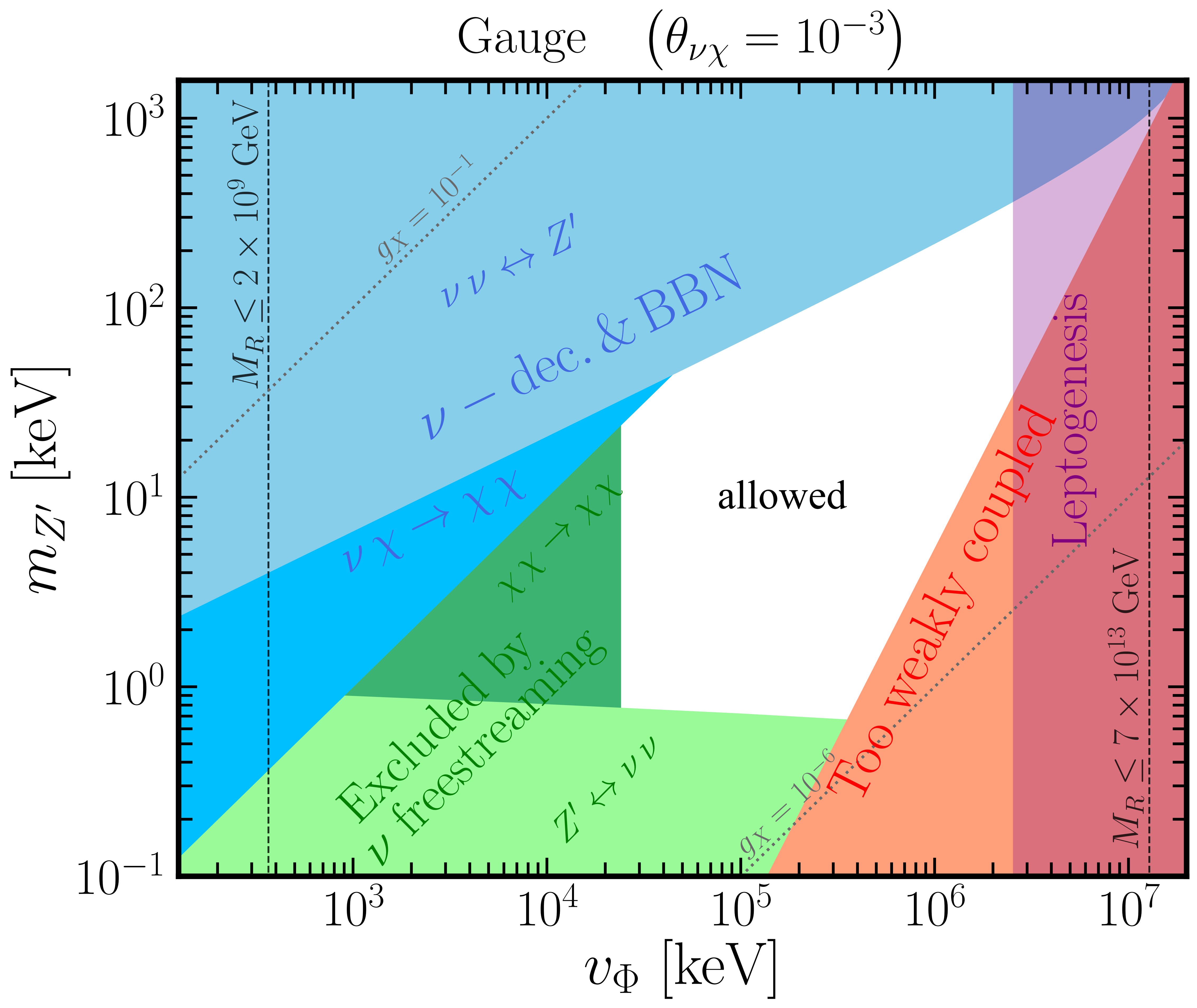
Available parameter space

$$\theta_{\nu\chi} \simeq 10^{-3}$$

$$m_{Z'} \sim 10\,\mathrm{keV}$$

$$v_\Phi \sim 100\,\mathrm{MeV}$$

$$g_X = \frac{m_{Z'}}{v_\Phi} \sim 10^{-4}$$



Karlsruher Institut für Technologie

Extending the model to include keV sterile neutrino dark matter

- 3 heavy new-νs (seesaw)
- new abelian gauge symmetry $U(1)_X$
- a scalar Φ charged under $U(1)_X$
- a set of N_χ massless new-νs charged under $U(1)_X$

- add one more heavy new-ν neutrino *N'*

  $\Rightarrow$one of the χ will also pick up a seesaw induced mass $\rightarrow \psi$

Benso, TS, Vatsyayan, 2410.23926

Extending the model to include keV sterile neutrino dark matter

neutral fermion mass matrix
in the basis $(\chi_L^c, \nu_L^c, \psi_L^c, N', N)$

$$\mathcal{M}_n = \begin{pmatrix} 0 & 0 & 0 & \Lambda' & \Lambda \\ 0 & 0 & 0 & m_D{}' & m_D \\ 0 & 0 & 0 & \kappa' & \kappa \\ \Lambda'^T & m_D^T{}' & \kappa'^T & M' & 0 \\ \Lambda^T & m_D^T & \kappa^T & 0 & M \end{pmatrix}$$

assume hierarchies:

$$M \gg M' \gg m_D \gg \kappa' \gg \Lambda \gg m'_D, \kappa, \Lambda' .$$

$$M' m_D^2 \ll M \kappa'^2$$

$$m_\chi = 0$$
$$m_\nu \approx m_D M^{-1} m_D^T$$
$$m_\psi \approx \kappa' M'^{-1} \kappa'^T .$$
$$m_{N'} \approx M'$$
$$m_N \approx M .$$

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assume hierarchies:

$$M \gg M' \gg m_D \gg \kappa' \gg \Lambda \gg m_D', \kappa, \Lambda' \,.$$

$$M' m_D^2 \ll M \kappa'^2$$

$$\begin{aligned} m_\chi &= 0 \\ m_\nu &\approx m_D M^{-1} m_D^T \\ m_\psi &\approx \kappa' M'^{-1} \kappa'^T \,. \\ m_{N'} &\approx M' \\ m_N &\approx M \,. \end{aligned}$$

keV DM candidate

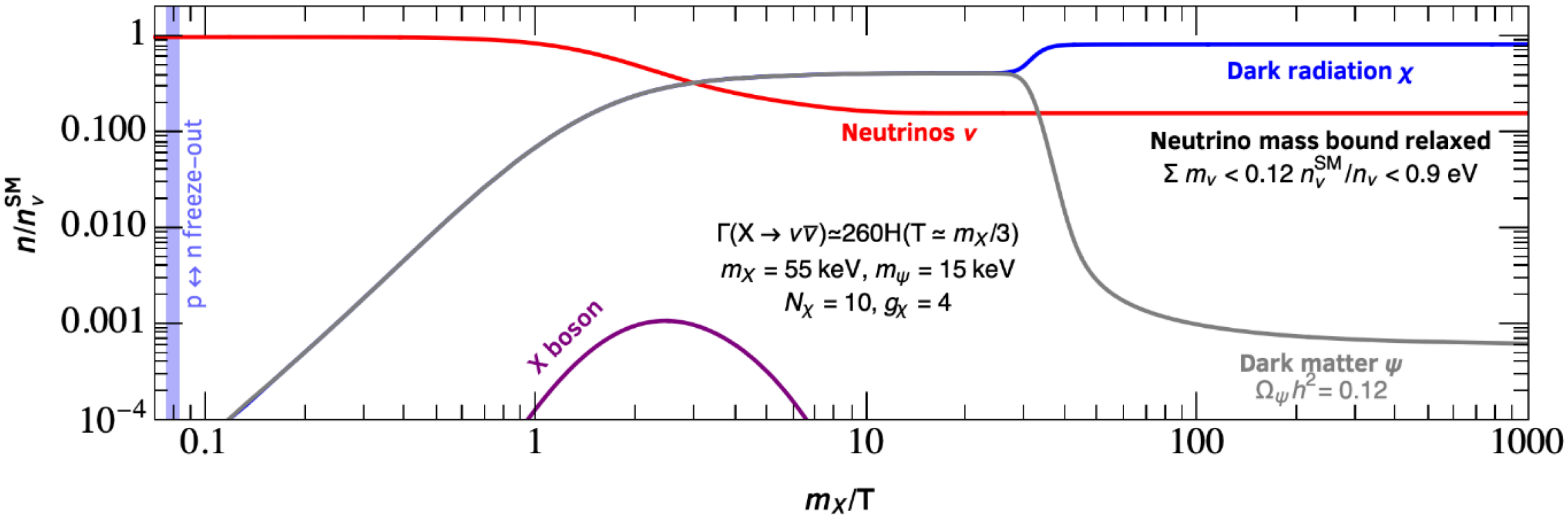
mixing and interactions:

$$\theta_{\nu\psi} = \frac{m_D'}{\kappa'}\,, \quad \theta_{\chi\psi} = 0$$

$$\mathscr{L}_{\text{int}} = g_X Z'_\mu \overline{\psi} \gamma^\mu \psi$$

DM production via dark freeze-out

similar to Berlin, Blinov, 1706.07046, 1807.04282



- assume $m_\psi < m_{Z'}$
- ψ thermalizes with the dark fluid via $\psi\psi \leftrightarrow Z'$
- DM freeze-out for $T_{DS} \lesssim m_\psi$

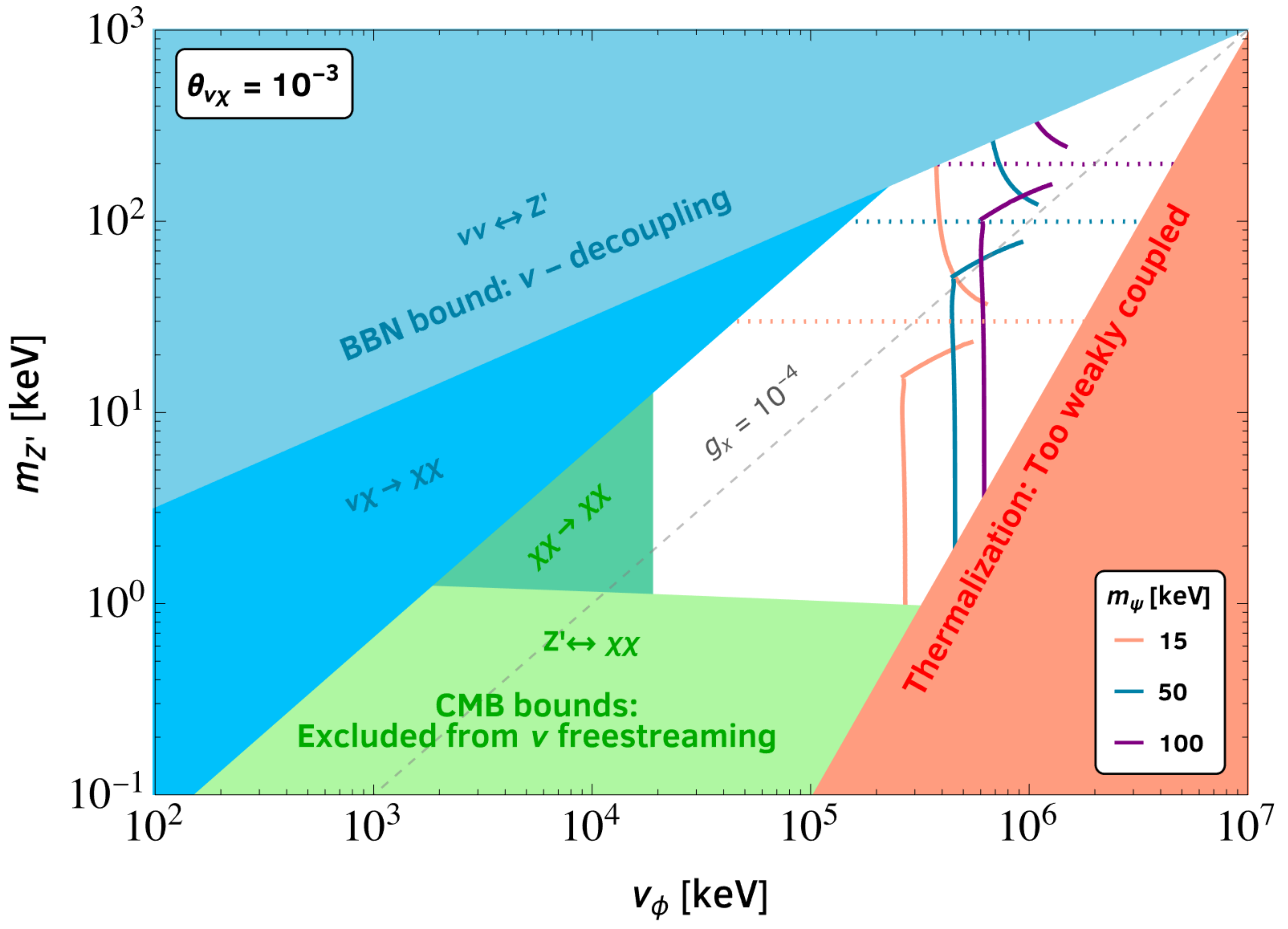
$$\Omega_\psi h^2 \simeq x_f \frac{10^{-10}\,\mathrm{GeV}^{-2}}{\langle\sigma v\rangle_{\psi\psi\to\chi\chi}}$$

$$\langle\sigma v\rangle_{\psi\psi\to\chi\chi} = N_\chi \frac{g^4}{4\pi} \frac{m_\psi^2}{(m_{Z'}^2 - 4m_\psi^2)^2}$$

Right DM abundance in the relevant parameter region

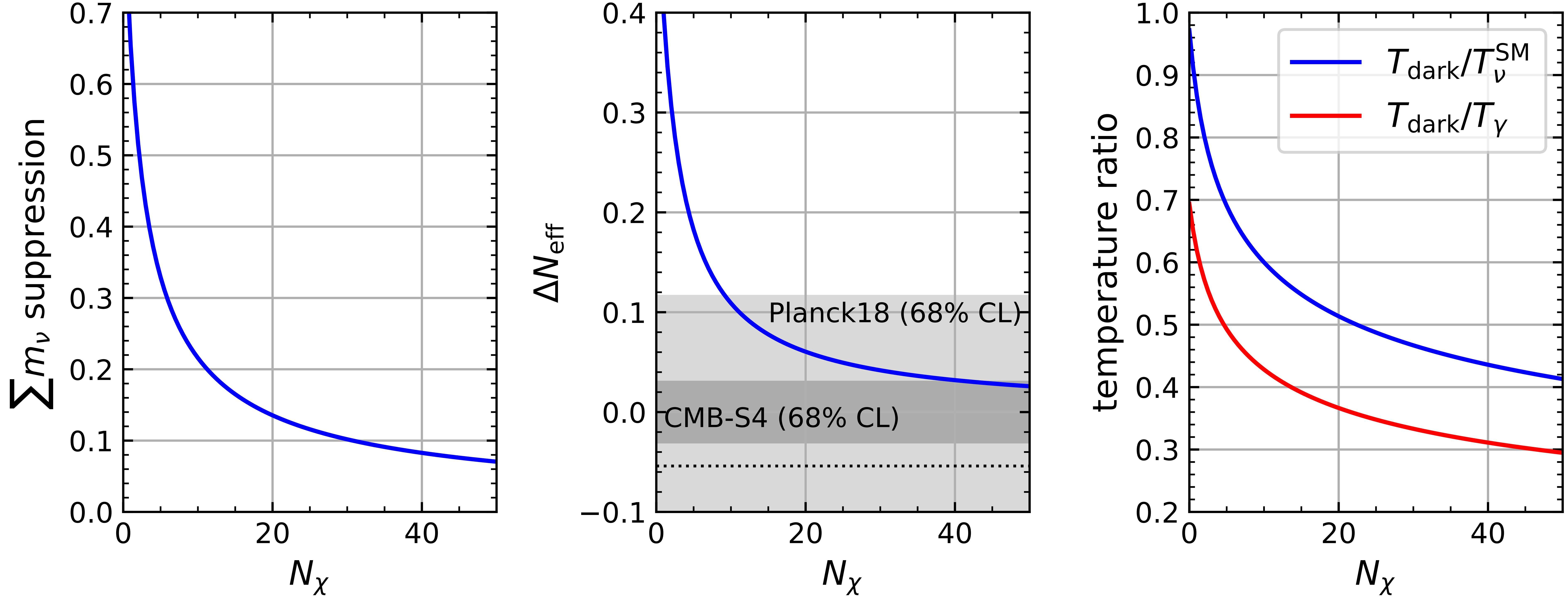
- DM mass
  $15\,\mathrm{keV} \lesssim m_\psi \lesssim 100\,\mathrm{keV}$

- DM stability and X-ray constraints:
  $\psi \to \nu\chi\chi, \psi \to \nu\gamma$
  suppressed by $\theta^2_{\nu\psi}$
  require $\theta_{\nu\psi} \lesssim 10^{-8}$



Signatures of the model

Benso, TS, Vatsyayan, 2410.23926



massless dofs: $4N_\chi + 2$

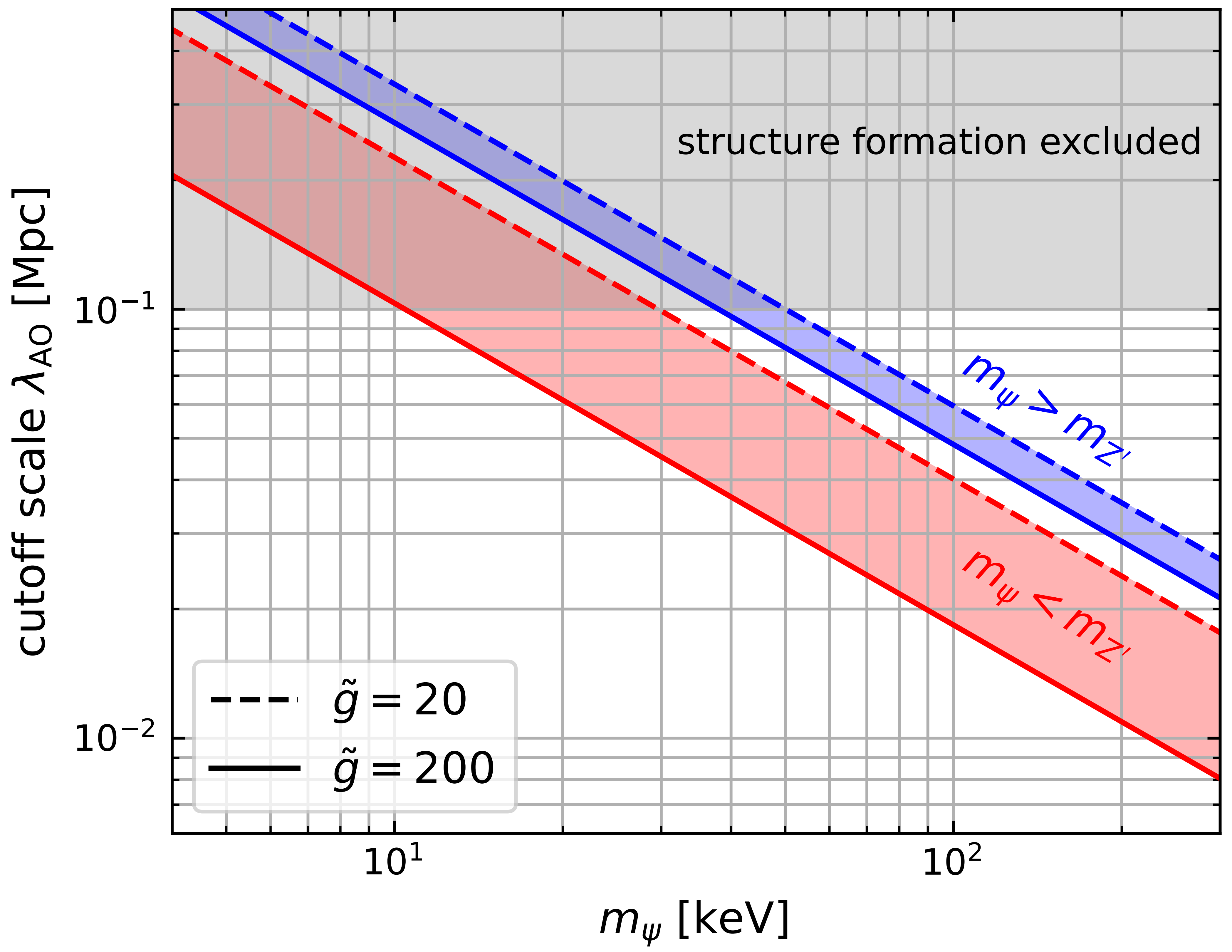
Signatures of the model

Benso, TS, Vatsyayan, 2410.23926

warm DM candidate:
potentially observable cut-off in matter power spectrum

determined by kinetic decoupling of DM from dark radiation

Berlin, Blinov, 1807.04282;
Bringmann, Ihle, Kersten, Walia, 1603.04884



Summary — why new νs?

- theory suggests (but does not proof) the existence of new-νs,
- but theory gives us very little guidance on where they are
- look for them everywhere we can

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- theory suggests (but does not proof) the existence of new-νs,
- but theory gives us very little guidance on where they are
- look for them everywhere we can

„Science is a bit like the joke about the drunk who is looking under a lamppost for a key that he has lost at the other side of the street, because that's where the light is. It has no other choice.“
Noam Chomsky

backup

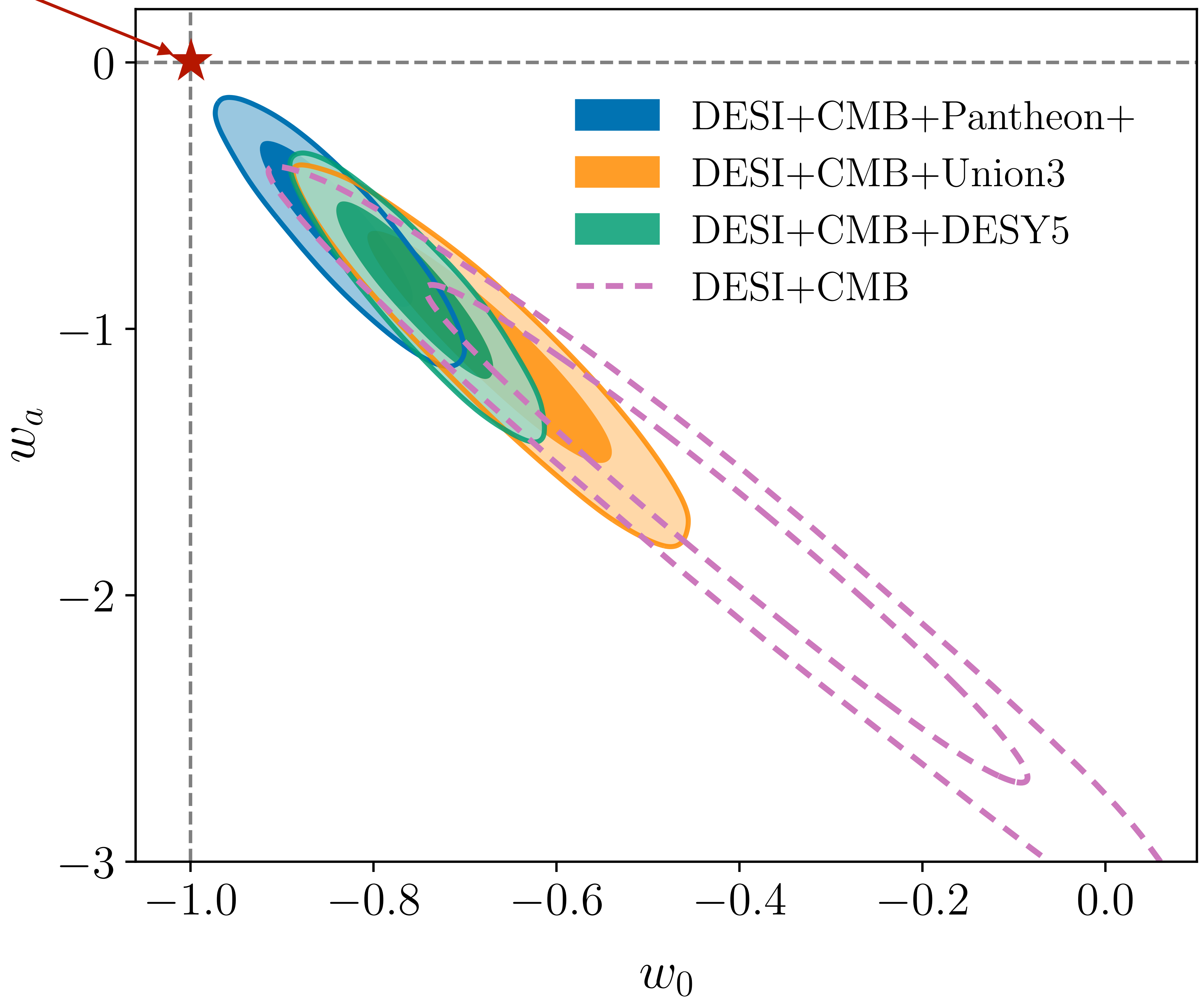
Hint for dynamical dark energy?

$\mathrm{cosm.const.}: w_0 = -1, w_a = 0$

DESI DR2 2025 [2503.14738]

DE equation of state: $p = w\rho$

$$w(z) = w_0 + w_a \frac{z}{1+z}$$



$2.8\sigma - 4.2\sigma$ indication for deviation from cosmolog. const.

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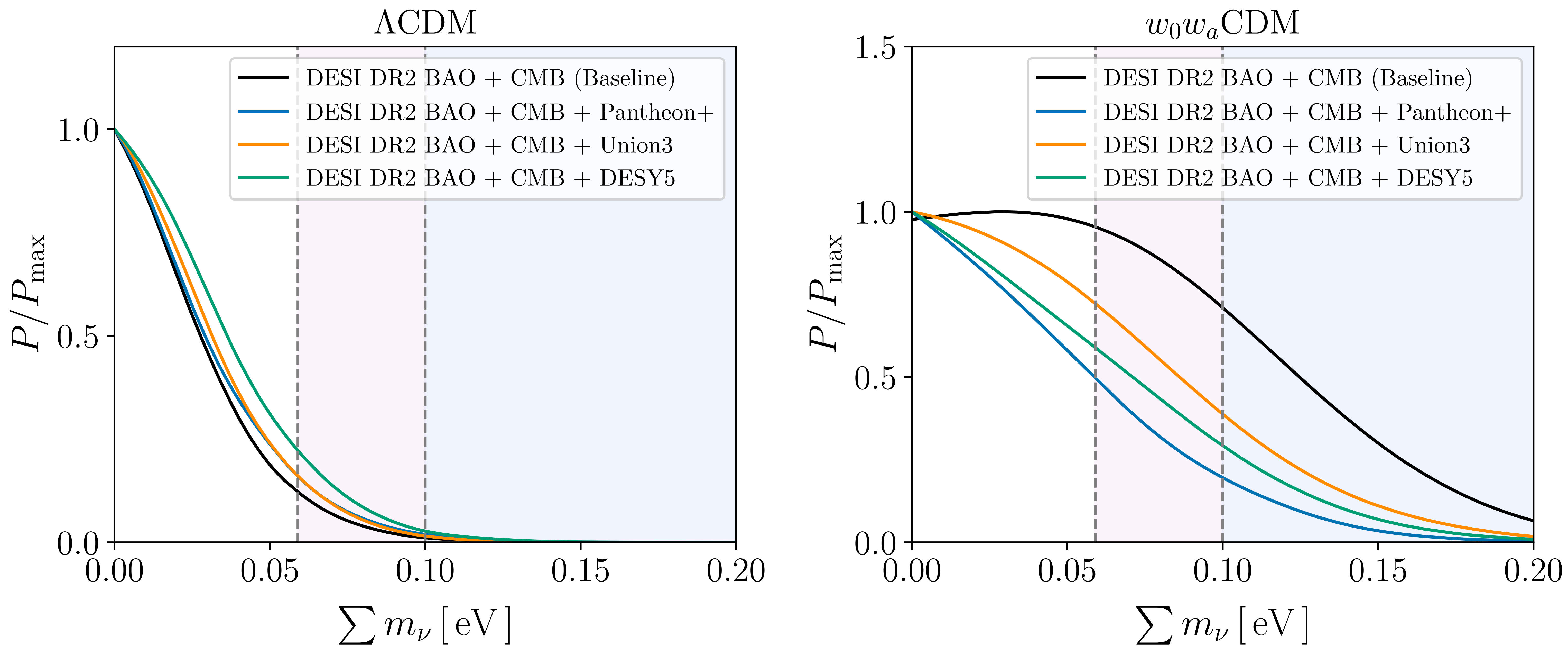
Dynamical dark energy and neutrino mass limit

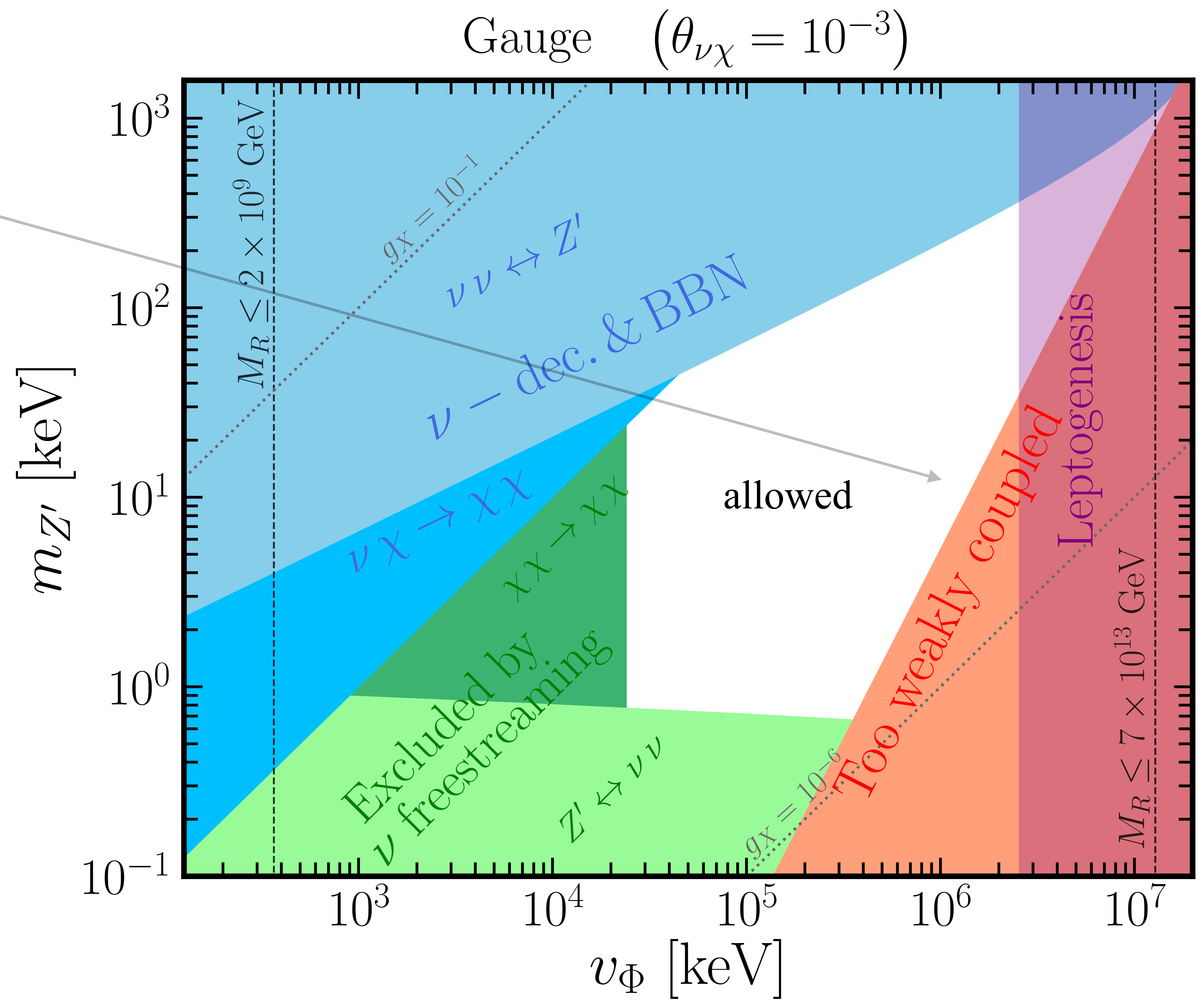
	$\sum m_\nu$ [eV]
$\boldsymbol{\Lambda}$**CDM**$+\sum \boldsymbol{m_\nu}$	
DESI BAO+CMB [Camspec]	< 0.0642
DESI BAO+CMB [L-H]	< 0.0774
DESI BAO+CMB [Plik]	< 0.0691

	$\sum m_\nu$ [eV]
$\boldsymbol{w_0 w_a}$**CDM**$+\sum \boldsymbol{m_\nu}$	
DESI BAO+CMB	< 0.163
DESI BAO+CMB+Pantheon+	< 0.117
DESI BAO+CMB+Union3	< 0.139
DESI BAO+CMB+DESY5	< 0.129



DESI DR2
[2503.14743]

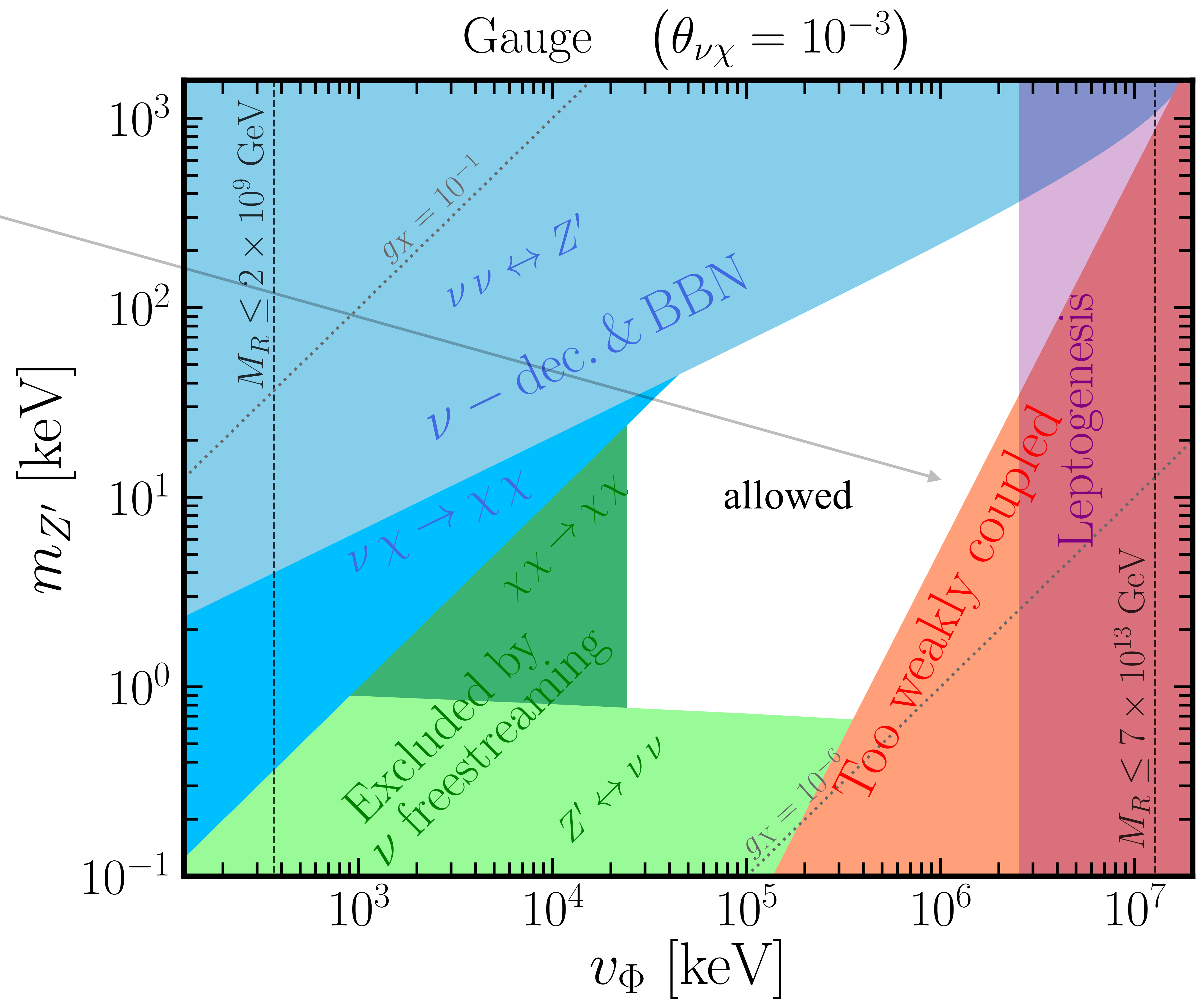
Available parameter space



Available parameter space

- thermalization of the dark sector:

$$\Rightarrow \quad \langle \Gamma(\nu\nu \to Z') \rangle \gtrsim H(T = m_{Z'}/3)$$



Available parameter space

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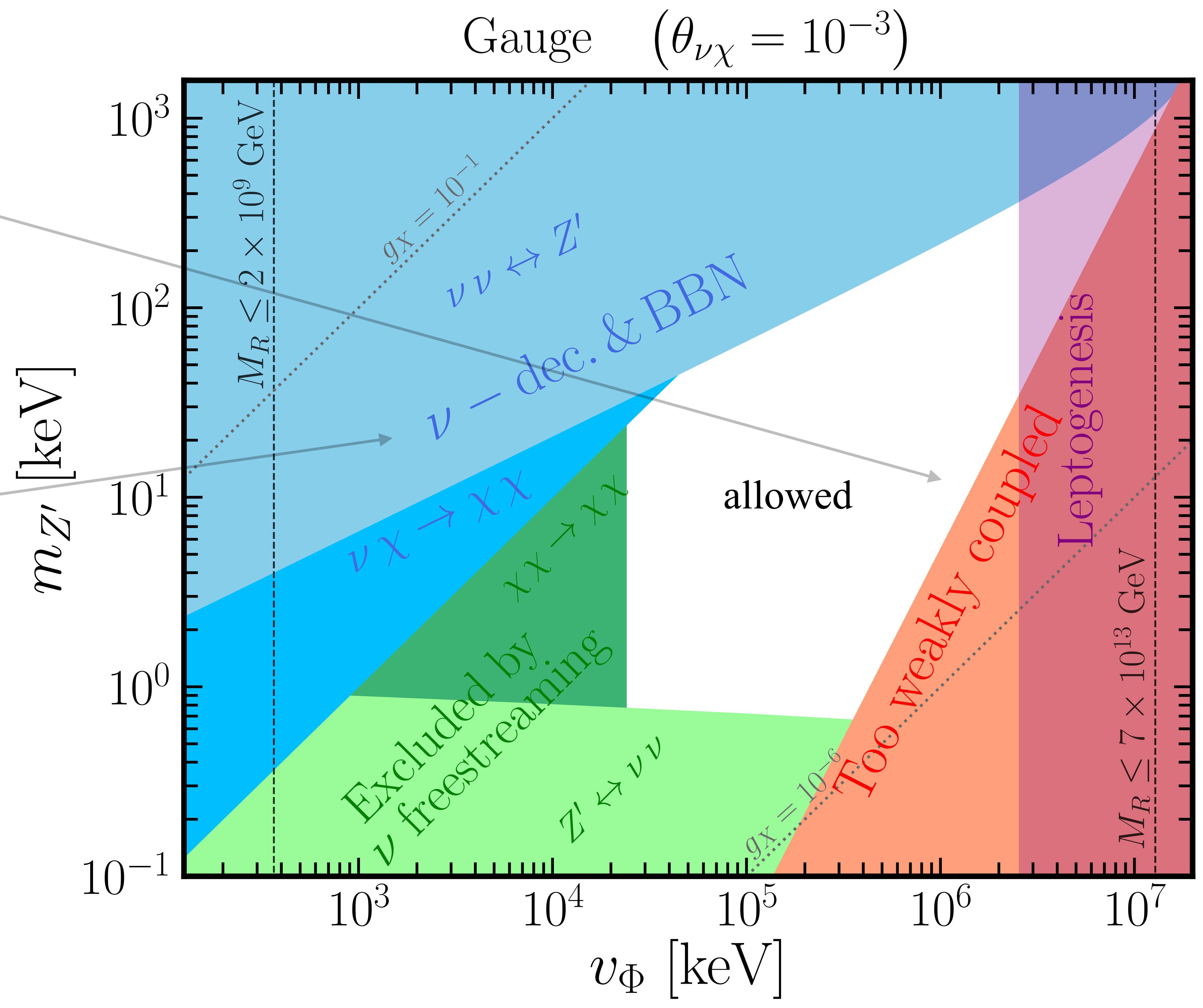
  $$\Rightarrow \quad \langle \Gamma(\nu\nu \to Z') \rangle \gtrsim H(T = m_{Z'}/3)$$

- avoid thermalization of the dark sector before BBN:

  $$\langle \Gamma(\nu\nu \to Z') \rangle < H(T = 0.7\,\mathrm{MeV})$$



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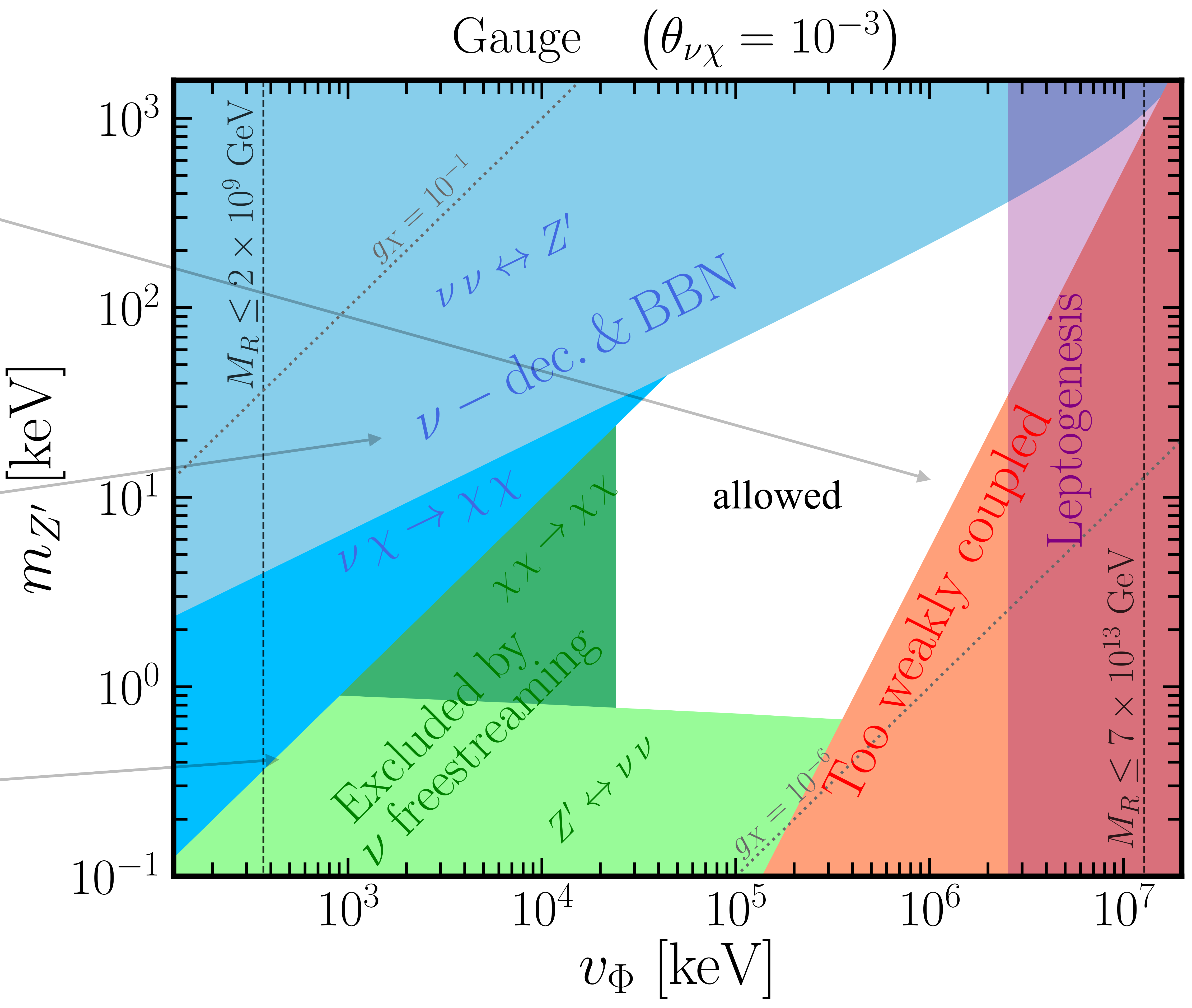
- free-streaming of neutrinos & dark radiation before/around recombination

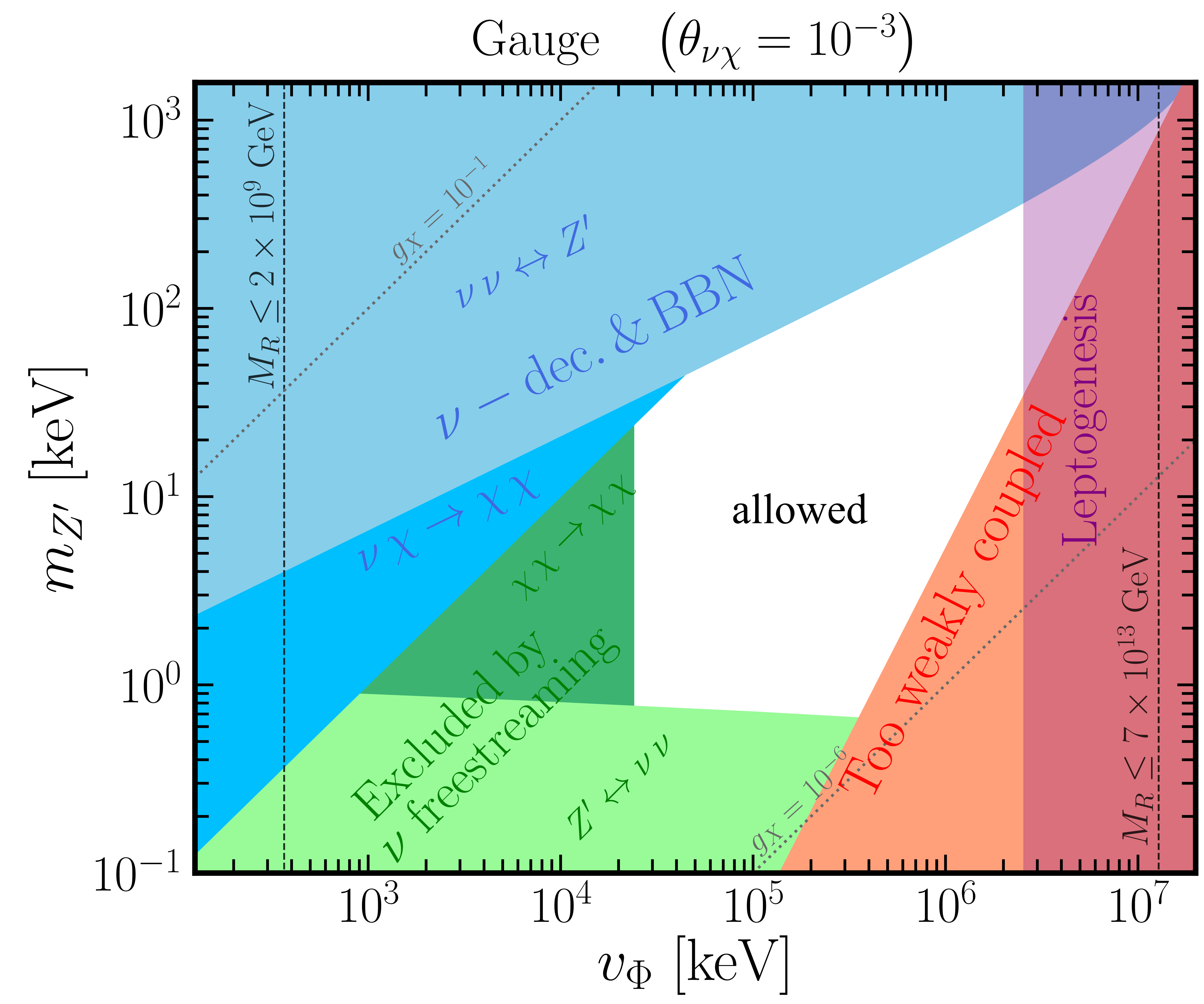
  $\langle \Gamma \rangle < H$ for $z < 10^5$

  Taule, Escudero, Garny, 2207.04062



Neutrino mixing with massless states $\theta_{\nu\chi}$

- avoid thermalization of χ prior neutrino decoupling due to oscillations
- take into account effective potential due to self-interactions



Neutrino mixing with massless states $\theta_{\nu\chi}$

$$10^{-4} \lesssim \theta_{\nu\chi} \lesssim 10^{-1}$$

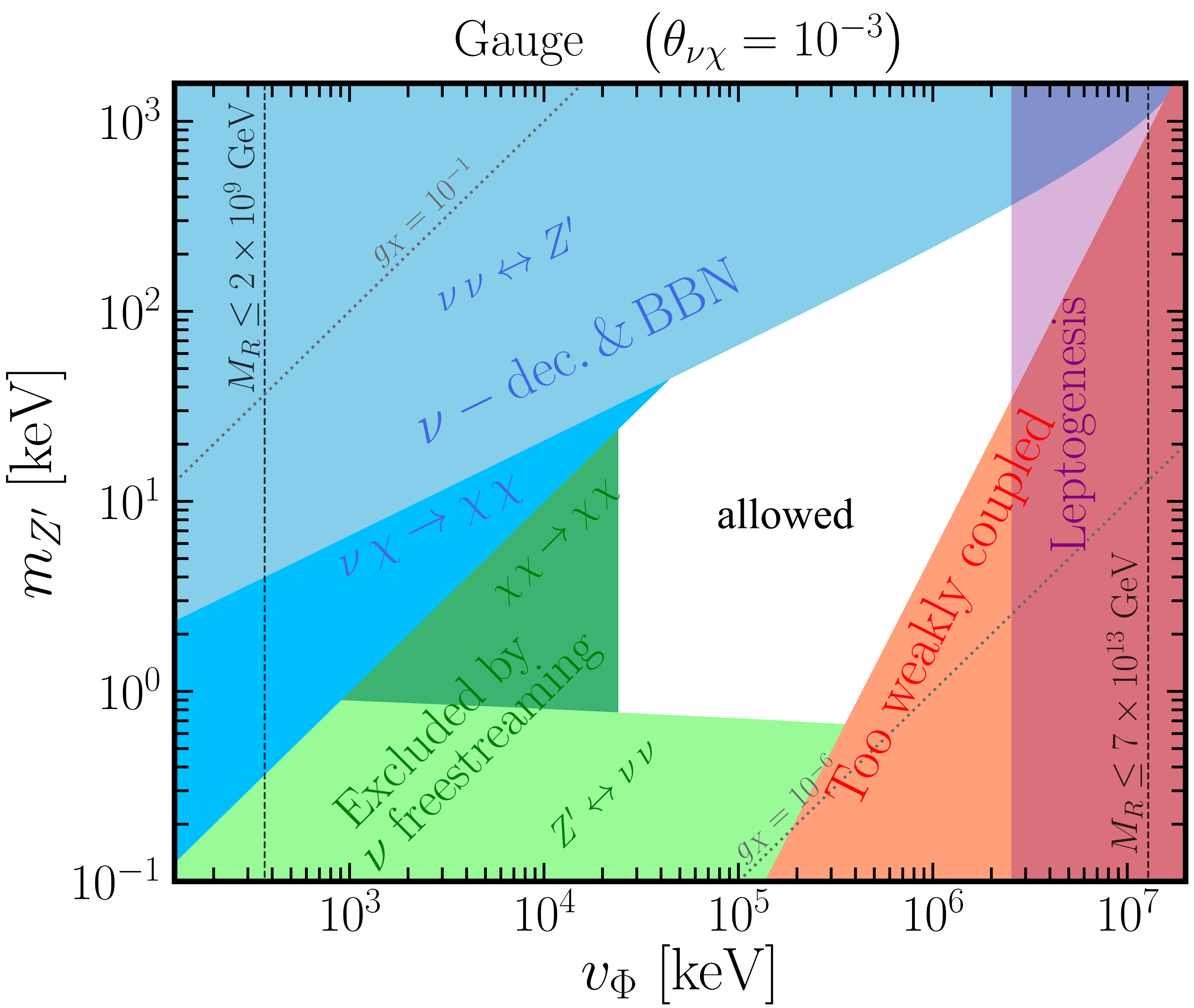
upper range potentially testable in oscillation experiments

T. Ota, 2411.16356

Constraints on heavy RH neutrinos

$$M_R \lesssim 10^{10} - 10^{14}\,\mathrm{GeV}$$

- perturbativity of Yukawa $Y_\Phi \overline{N}_R \chi_L \Phi$
- loop-induced Higgs portal $\lambda_{\Phi H} |\Phi|^2 H^\dagger H$ remains small to avoid thermalization of Φ prior BBN



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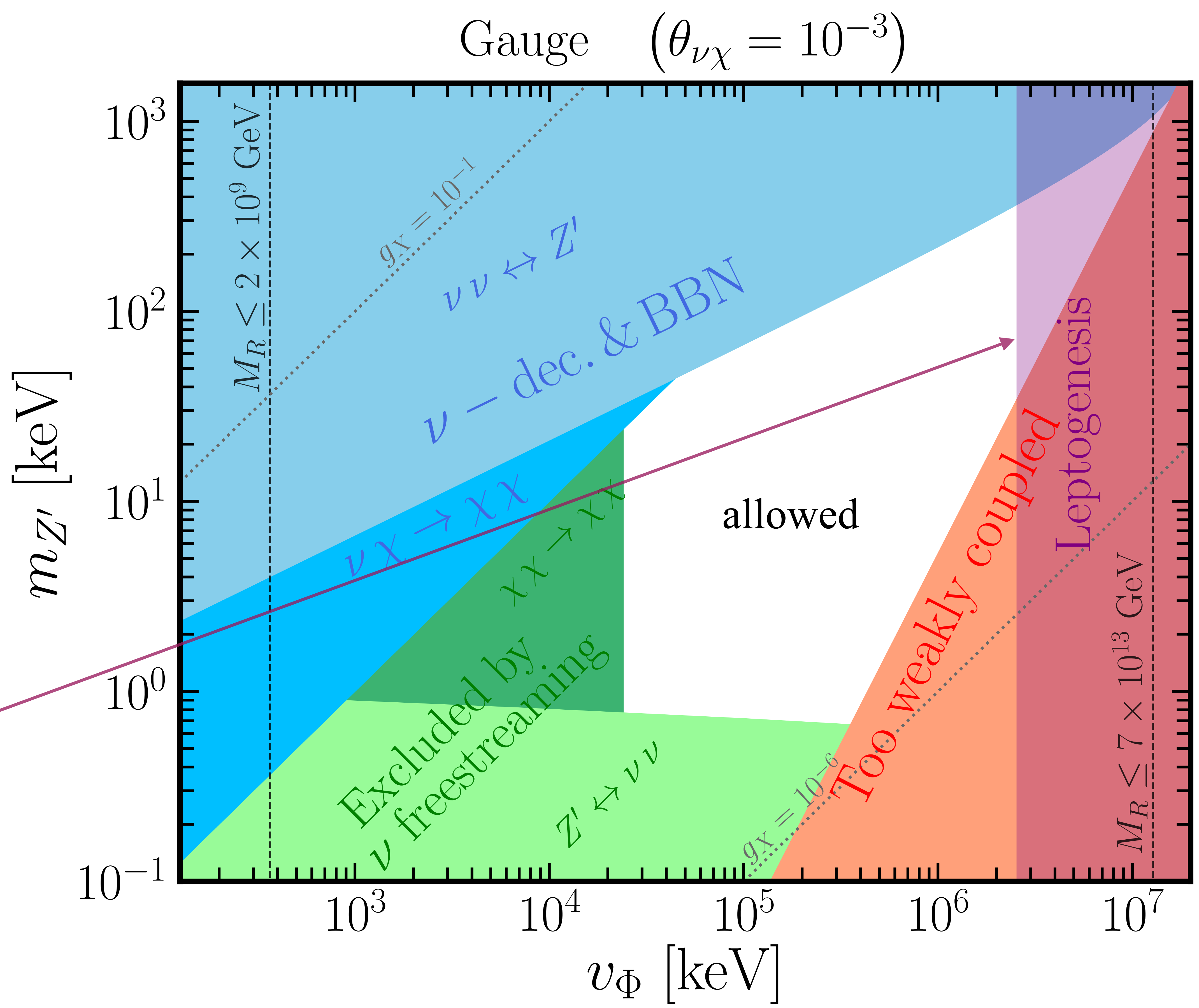

Comment on leptogenesis:

- standard thermal LG works if $N \to HL$ dominates over $N \to \phi\chi$
- otherwise χ would thermalize and conflict with N_{eff} $\Rightarrow$ require $T_{RH} < M_R$ (allows still for $T_{RH} \gg T_{EW}$)

Signatures in a super nova

- SN cooling arguments for SN1987A exclude

$$3 \times 10^{-7} \frac{\mathrm{keV}}{m_{Z'}} \lesssim \lambda_{Z'}^{\nu\nu} \lesssim 10^{-4} \frac{\mathrm{keV}}{m_{Z'}}$$

Fiorillo, Raffelt, Vitagliano, 2209.11773

weaker than BBN constraint $\lambda_{Z'}^{\nu\nu} \lesssim 10^{-7}(\mathrm{keV}/m_{Z'})$

- Future galactic SN at 10 kpc: neutrino signal in HyperK from $Z' \to \nu\nu$: sensitivity down to

$$\lambda_{Z'}^{\nu\nu} \sim 10^{-9}(\mathrm{keV}/m_{Z'})$$

Akita, Im, Masud, 2206.06852