Dark matter searches and neutrino masses

3rd November 2024

Torino Welcome Day

Jorge Terol Calvo

INFN Torino

Istituto Nazionale di Fisica Nucleare

- Bachelor and Master's at Universitat de València and IFIC
- PhD at IAC and Universidad de La Laguna (Just finished in Sept.)
- Dark matter searches with astrophysics data.
- Pheno related with neutrino mass models

Searching for dark matter waves with pulsars

- Search with PPTA (Australia) and QUIJOTE (Canary Islands)

  A. Castillo, J. Martin-Camalich, **J. Terol-Calvo**, et al., *JCAP 06 (2022) no.06, 014*

- Search with EPTA (Europe)

  N. Porayko, P. Usynina, **J. Terol-Calvo**, et al., *2411.XXXXX*

Axion Dark Matter

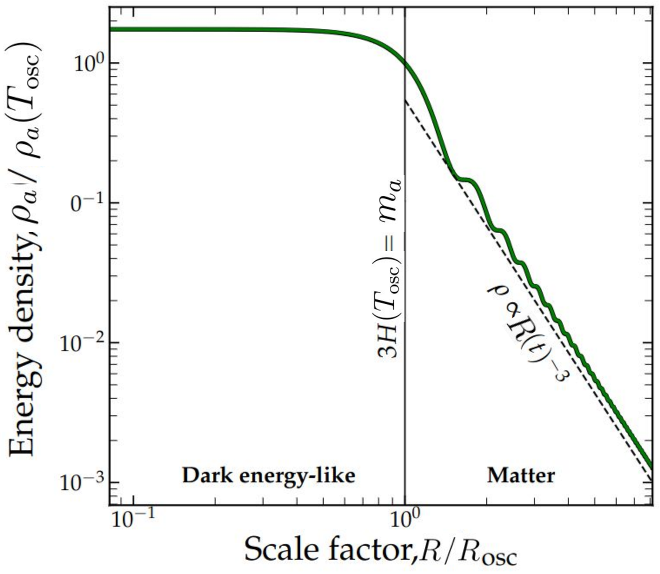
- Misalignment mechanism

$$\ddot{a} + 3H\dot{a} + m_a^2 a = 0$$

$$\rho_a(T_{\rm osc}) = \frac{1}{2} m_a^2 f_a^2 \theta_i^2$$

$$\rho_a(T_0) = \rho_a(T_{\rm osc}) \left(\frac{R(T_{\rm osc})}{R(T_0)}\right)^3 = \frac{1}{2} m_a^2 f_a^2 \theta_i^2 \left(\frac{g_{*,S}(T_0) T_0^3}{g_{*,S}(T_{\rm osc}) T_{\rm osc}^3}\right)$$

$$\Omega_a h^2 \simeq 0.12 \left(\frac{f_a \theta_i}{10^{13}\ \rm GeV}\right)^2 \left(\frac{m_a}{2\ \mu\rm eV}\right)^{1/2}$$



J. Preskill, M. B. Wise, and F. Wilczek.
L. F. Abbott and P. Sikivie.
M. Dine and W. Fischler. Phys. Lett. 120B (1983)

ALP-photon interaction

- Modified Maxwell equations

Harari & Sikivie, Phys. Lett. B 289 (1992) 67–72

$$\frac{g_{a\gamma}}{4} a F_{\mu\nu}\tilde{F}^{\mu\nu} \to \frac{g_{a\gamma}}{4} a\mathbf{E}\cdot\mathbf{B}$$

$$\partial_\mu F^{\mu\nu} + g_{a\gamma}\partial_\mu\left(\tilde{F}^{\mu\nu}a\right) = 0$$
$$\partial_\mu \tilde{F}^{\mu\nu} = 0$$

- Dispersion relation is affected

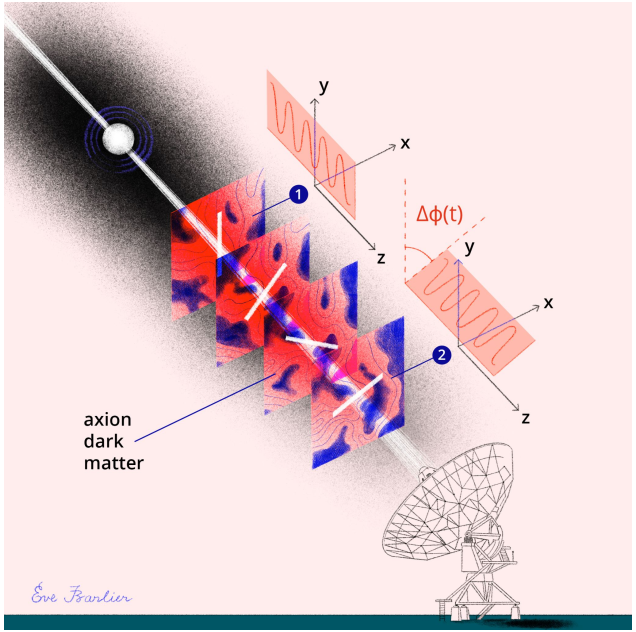
$$\omega_\pm \simeq k \pm \frac{1}{2} g_{a\gamma}\left(\partial_t a + \nabla a \cdot \widehat{\mathbf{k}}\right)$$

- Change of the polarisation plane

$$\Delta\phi = \frac{g_{a\gamma}}{2}\int_{t_s}^{t_o} \frac{da}{dt} dt = \frac{g_{a\gamma}}{2}\Delta a$$

ALP as wave dark matter

- ALP wave behavior makes the polarisation change periodic



$$\Delta\phi = \frac{g_{a\gamma}}{2}\int_{t_s}^{t_o}\frac{da}{dt}dt = \frac{g_{a\gamma}}{2}\Delta a$$

$$a(t) = a_0 \cos\left(m_a t + \delta\right)$$

$$a_{0,i} = \sqrt{2\rho_i} m_a^{-1} \alpha_i$$

Stochastic nature of wave dark matter

- ALP wave behavior makes the polarisation change periodic

$$\Delta\phi(t) = \phi_a \cos(m_a t + \varphi_a)$$

$$\phi_a = 2.24^\circ \left(\frac{g_{a\gamma}}{10^{-12}\ \mathrm{GeV}^{-1}}\right)\left(\frac{m_a}{10^{-22}\ \mathrm{eV}}\right)^{-1}\left(\frac{\rho_{DM}}{1\ \mathrm{GeV\ cm}^{-3}}\right)^{1/2}$$

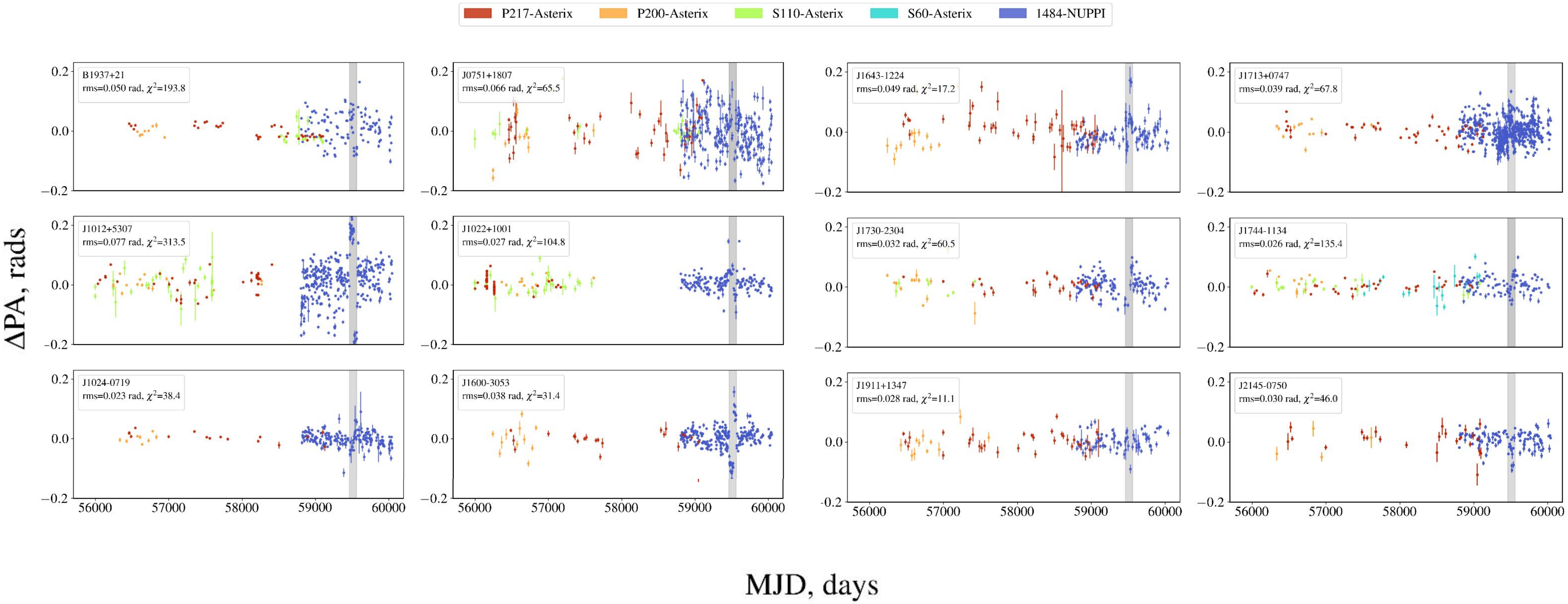
Search for polarisation oscillations

- Sources considered PPTA

Pulsar	$D_{\rm Earth}$ [pc]	$D_{\rm GC}$ [kpc]	$\rho_{\rm DM}$ [GeV/cm^3]	OT [yr]
J0437-4715	156	8.16	0.35	4.40
Crab-QUIJOTE	2000	10.11	0.23	4.56
J0613-0200	990	8.98	0.29	4.71
J0711-6830	110	8.11	0.35	4.78
J1022+1001	640	8.39	0.33	4.60
J1024-0719	1200	8.49	0.32	4.66
J1045-4509	590	8.03	0.36	4.78
J1600-3053	1870	6.44	0.53	4.78
J1603-7202	3400	6.22	0.56	4.66
J1643-1224	1200	7.02	0.45	4.60
J1713+0747	1310	7.13	0.44	4.78
J1730-2304	470	7.67	0.39	4.55
J1732-5049	1875	6.45	0.52	3.61
J1744-1134	410	7.73	0.38	4.78
J1824-2452	5500	2.85	1.90	4.45
J1857+0943	1180	7.08	0.45	4.66
J1909-3744	1157	7.04	0.45	4.70
J1939+2134	4800	6.86	0.47	4.12
J2124-3358	440	7.83	0.37	4.78
J2129-5721	7000	6.21	0.56	4.56
J2145-0750	710	7.79	0.38	4.56

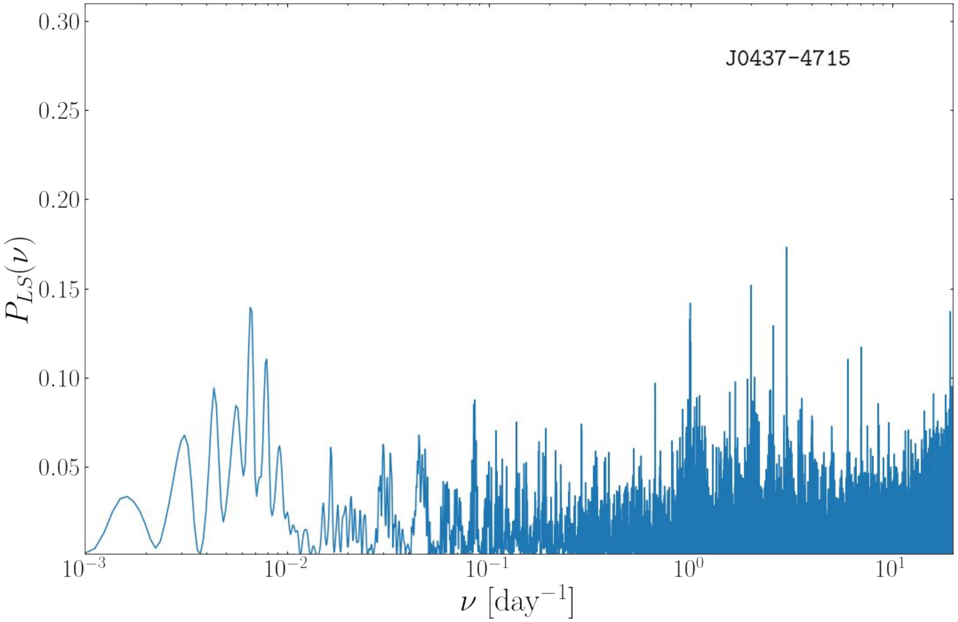
Search for polarisation oscillations

- Sources considered EPTA



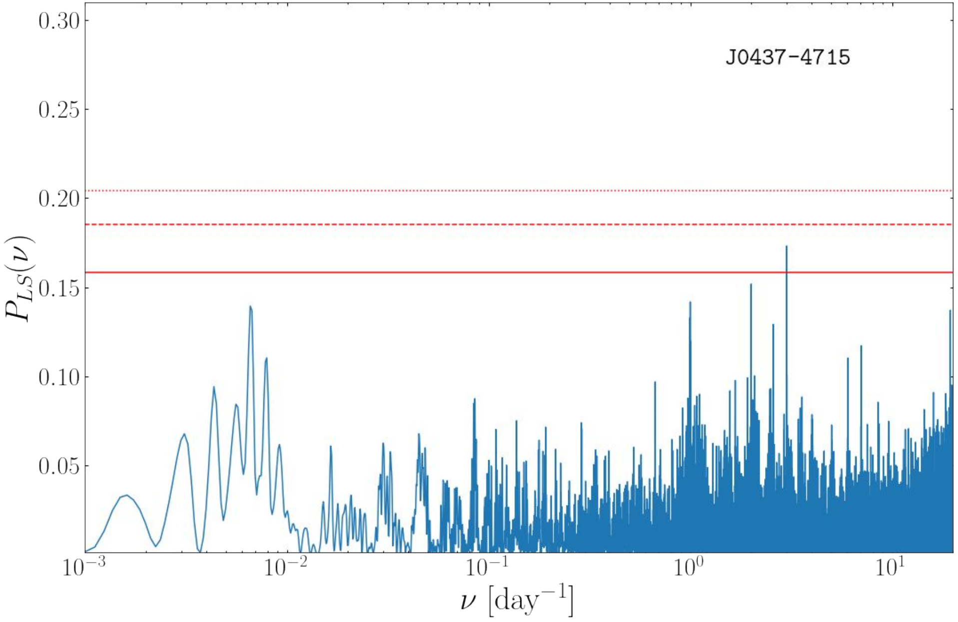
Search for polarisation oscillations

- Analysis with Generalised Lomb-Scargle Periodograms



Search for polarisation oscillations

- Signal search with FAP

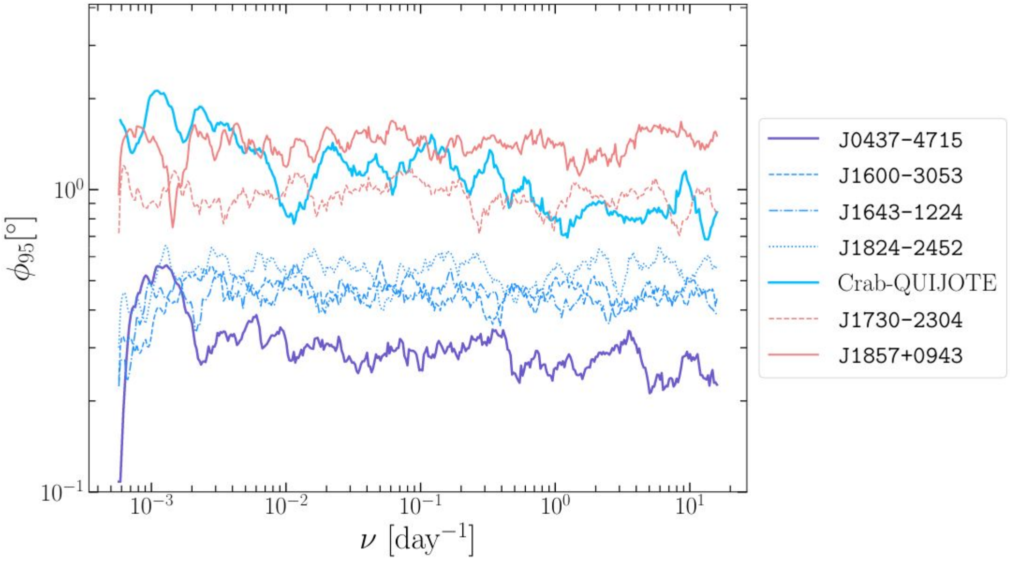


1%
5%
32%

Bounds on polarisation oscillations

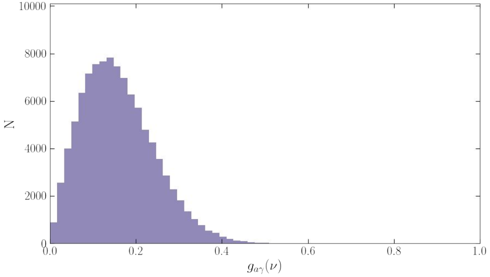
- Individual bounds on a generic signal

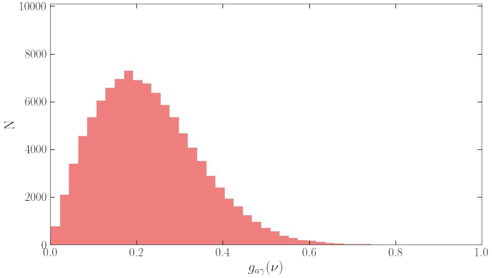
$$\Delta\phi_{\text{sim}} = \phi \cos(2\pi\nu t + \varphi)$$

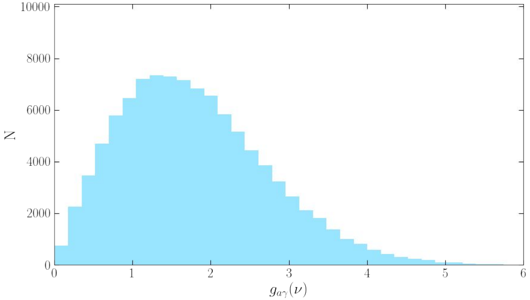


Bounds on ALP induced polarisation oscillations

- Need to do a combined analysis







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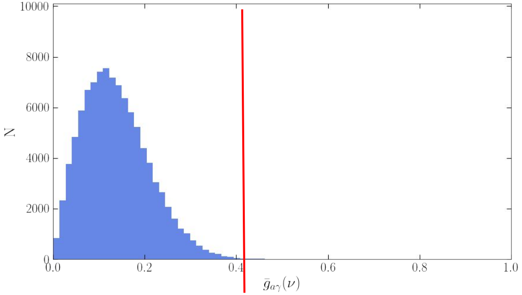
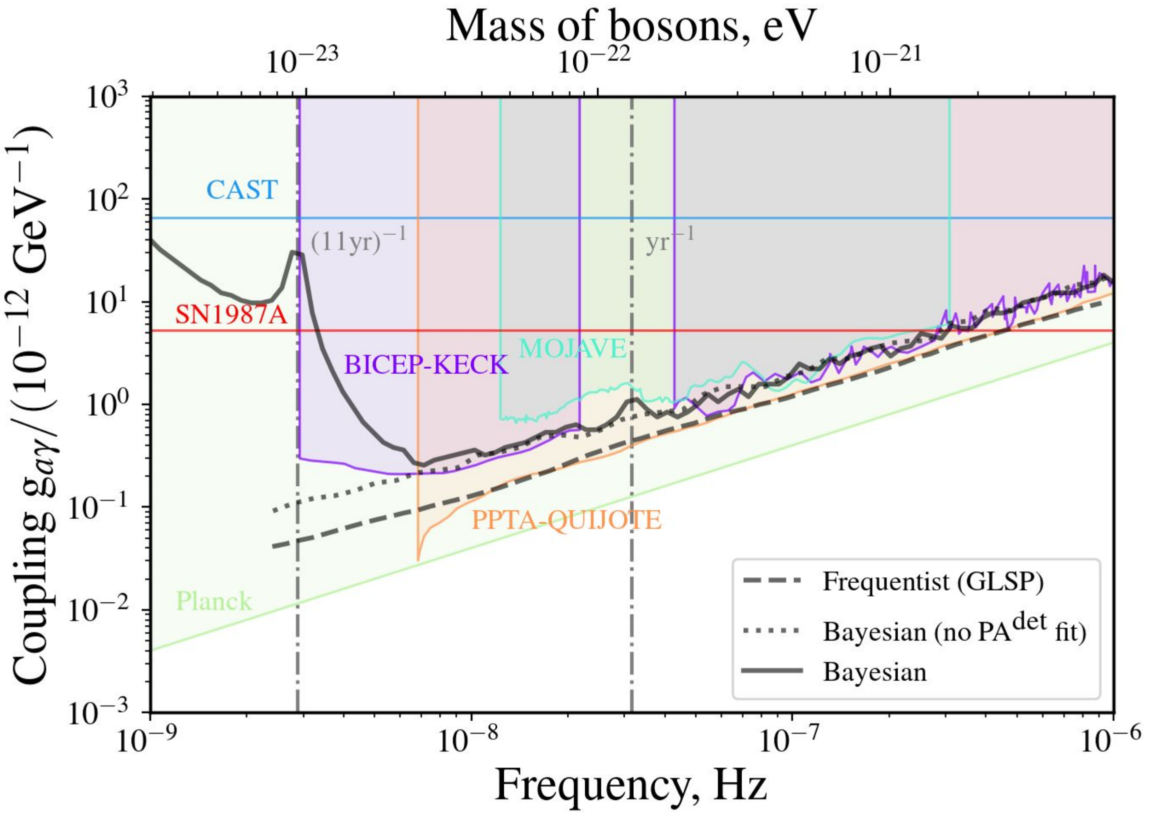
- Weighted mean distribution, 95% C.L.



Bounds on ALP induced polarisation oscillations



Neutrino masses evading cosmology bounds

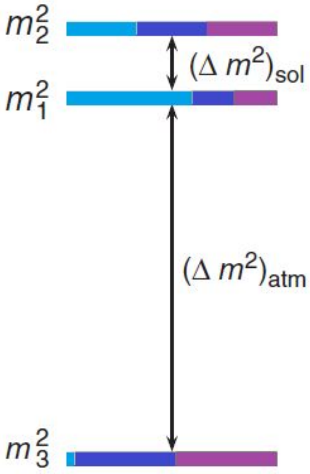
- A seesaw model for large neutrino masses in concordance with cosmology

  M. Escudero, T. Schwetz and **J. Terol-Calvo**, JHEP 02 (2023) 142
  M. Escudero, T. Schwetz and **J. Terol-Calvo**, JHEP 06 (2024) 119

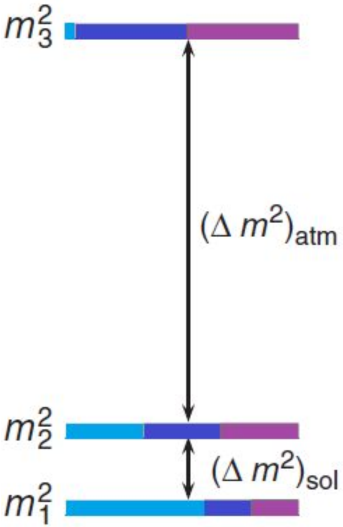
Experimental status of ν masses

- Oscillations can set lower limit, but ordering is still unknown

IO:



NO:



$$\sum m_\nu \gtrsim 0.1\,\mathrm{eV}$$

$$\sum m_\nu \gtrsim 0.06\,\mathrm{eV}$$

Experimental status of ν masses

- Kinematic upper limit: β decay

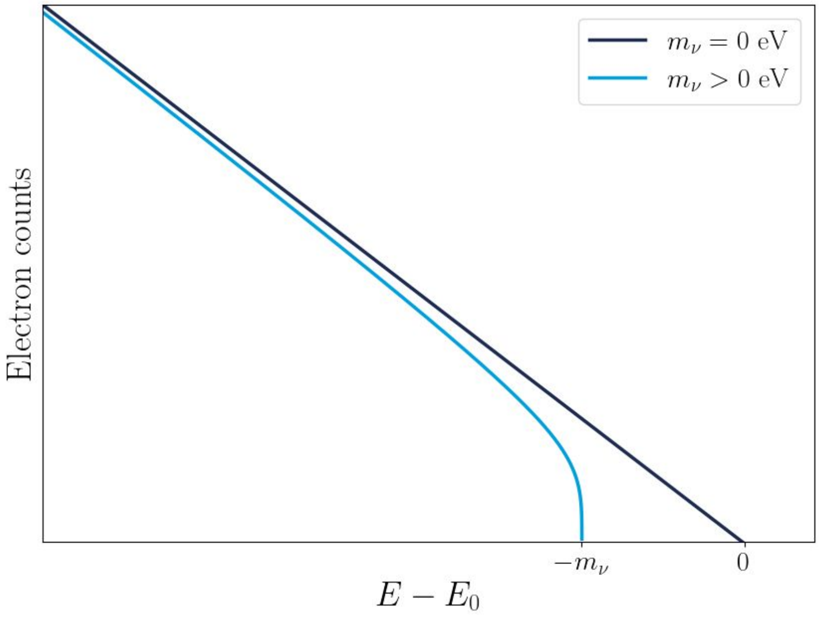
- KATRIN leads the search

$$m_\beta \equiv \left(\sum_{i=1}^{3} |U_{ei}|^2 m_i^2 \right)^{1/2} < 0.45\,\text{eV}\ [90\%\ \text{CL}]$$

KATRIN Collab., 2406.13516

- Future sensitivity: 0.2 eV

KATRIN Collab., Eur. Phys. J. C 80 no. 3, (2020) 264



Neutrino masses evading cosmology bounds

Cosmology status of ν masses

- Effect on
  - CMB : ISW, Lensing
  - LSS: Small scale suppression, BAO

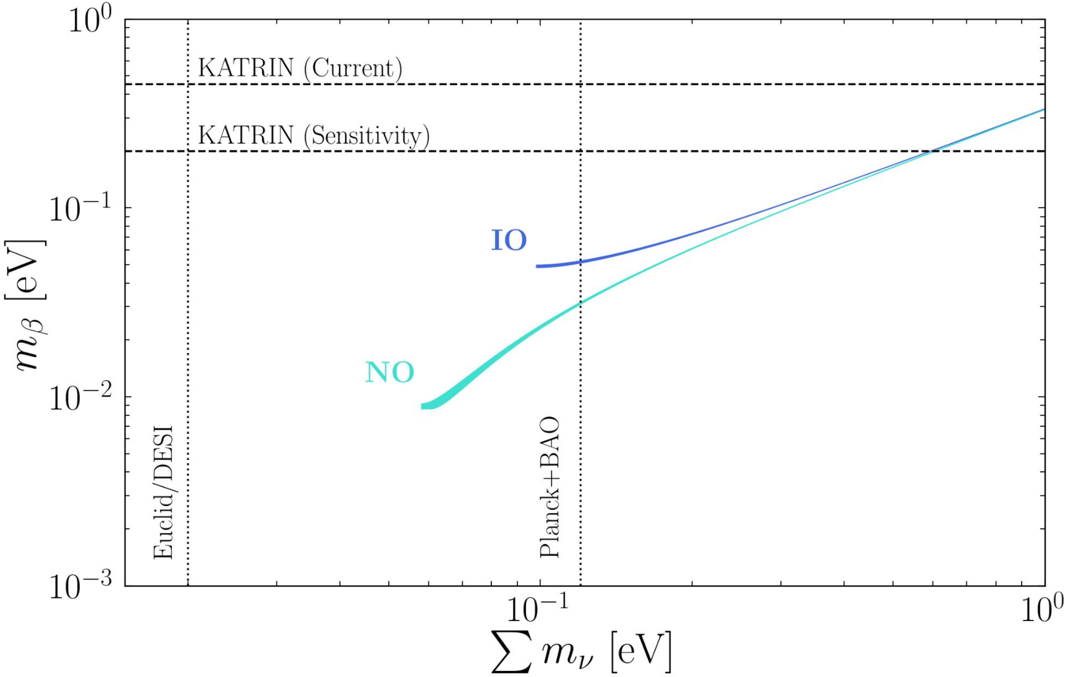
Lesgourgues & Pastor, Phys. Rept. 429 (2006) 307–379

- Planck + BAO:

$$\sum m_\nu < 0.12\,\mathrm{eV}\,[95\%\,\mathrm{CL}]$$

Planck Collab., Astron. Astrophys. 641 (2020) A6

Global picture for ν masses



Neutrino masses evading cosmology bounds

Can we reconcile cosmology and experiments?

- Cosmology is actually sensitive to ρ
  - Planck + BAO:

$$\sum m_\nu \times \left[\frac{n_\nu^0}{56\,\mathrm{cm}^{-3}}\right] < 0.12\,\mathrm{eV} \quad [95\%\ \mathrm{CL}]$$

- Reduce n_ν^0 adding new species, χ

Farzan & Hannestad, JCAP 02 (2016) 058

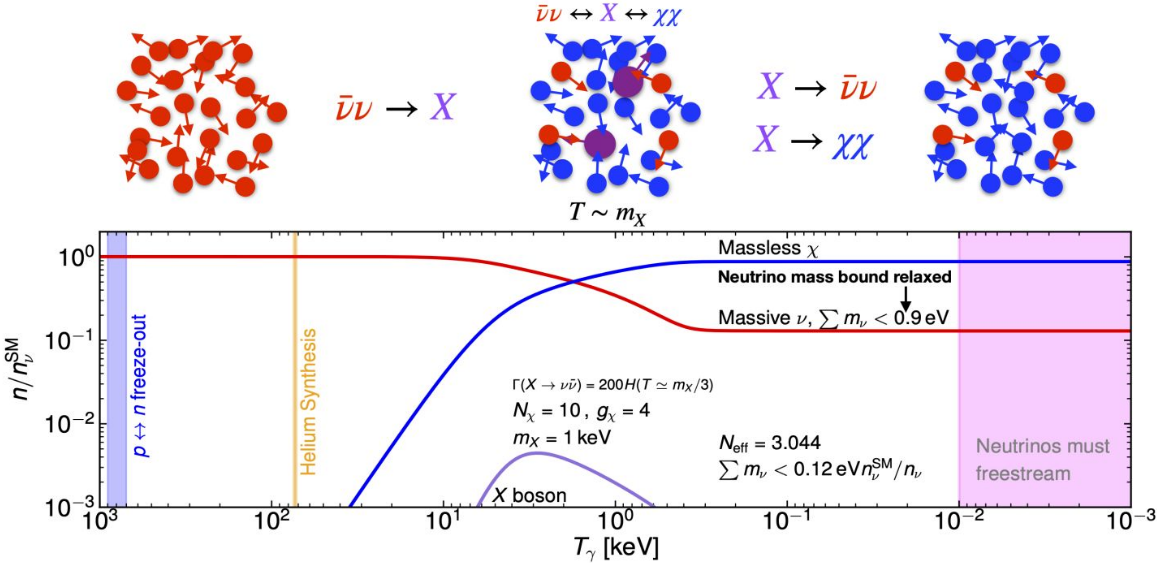
  - Cannot do it before BBN, T~MeV
  - Cannot do it after recombination, T~eV

Neutrino masses evading cosmology bounds

Can we reconcile cosmology and experiments?

- New boson needed, X

$$\langle\Gamma(\bar{\nu}\nu \to X)\rangle > H \qquad \langle\Gamma(X \to \chi_i + \text{anything})\rangle > H$$



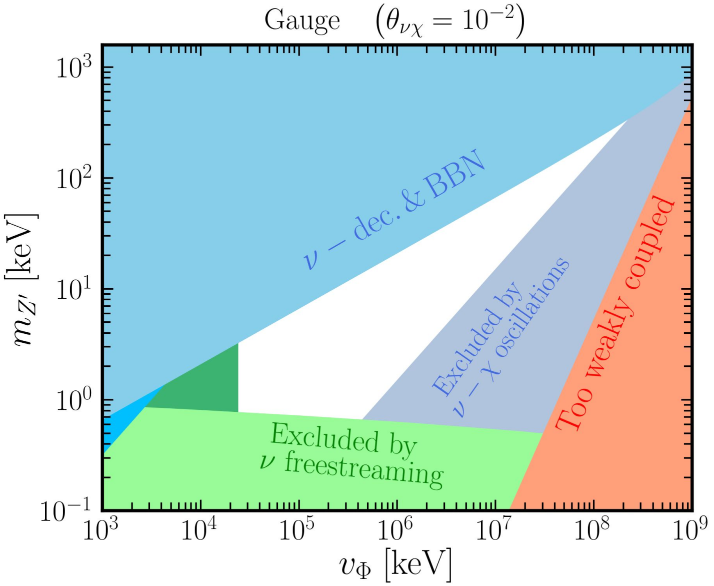
The particle physics model, extension to the SM

- 3 fermion singlets, N_R, seesaw type I.
- New abelian symmetry, U(1).
- Scalar, Φ, charged with +1 under the new symmetry.
- N_χ fermions, χ, charged with -1 under the new symmetry.

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

Parameter space where the model can work

- Gauge model

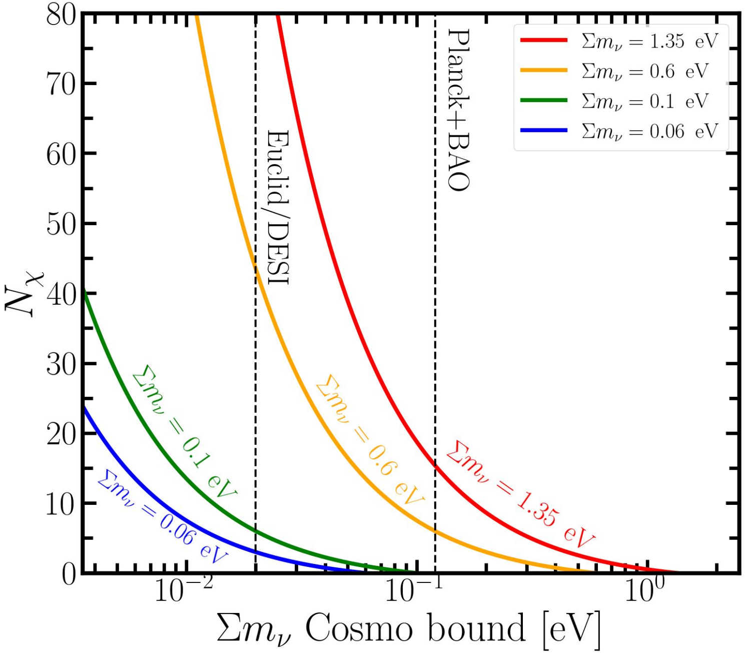


- Thermalisation of Z'
- Alter BBN producing Z' or χ
- Oscillations ν-χ pre-BBN
- ν and χ must freestream at recombination

THANK YOU!

Can we reconcile cosmology and experiments?

- Mass bound changes with N_χ



$$\sum m_\nu < 0.12\,\mathrm{eV}\,(1 + g_\chi N_\chi/6) \quad [95\%\,\mathrm{CL}]$$

Neutrino masses evading cosmology bounds

Can we reconcile cosmology and experiments?

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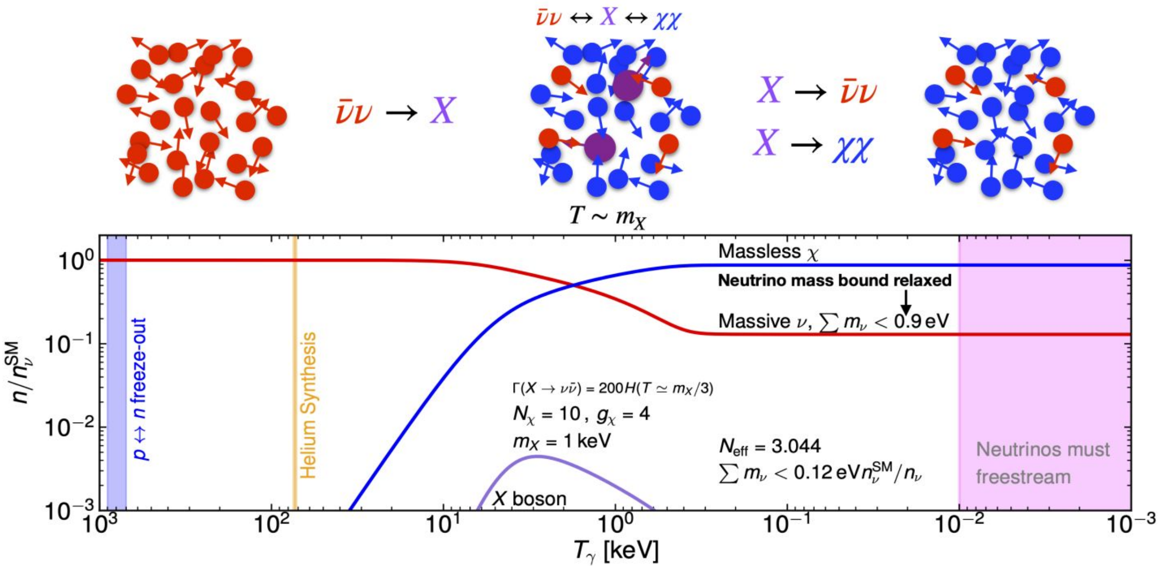
$$\langle \Gamma(\bar{\nu}\nu \to X) \rangle > H \qquad \langle \Gamma(X \to \chi_i + \text{anything}) \rangle > H$$



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The particle physics model, extension to the SM

- Neutrino mass matrix

$$\begin{pmatrix} 0 & m_D & 0 \\ m_D^T & M_R & \Lambda \\ 0 & \Lambda^T & 0 \end{pmatrix} \longrightarrow \begin{pmatrix} m_{\text{active}} & 0 & 0 \\ 0 & m_{\text{heavy}} & 0 \\ 0 & 0 & m_{\text{sterile}} \end{pmatrix}$$

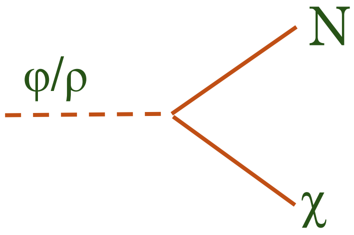
$$\Lambda \ll m_D \ll M_R$$

$$\begin{aligned} m_{\text{active}} &\approx m_D\, M_R^{-1}\, m_D^T + \Lambda\, \Lambda^T\, M_R^{-1} \approx m_D\, M_R^{-1}\, m_D^T, \\ m_{\text{heavy}} &\approx M_R + m_D\, M_R^{-1}\, m_D^T + \Lambda\, \Lambda^T\, M_R^{-1} \approx M_R, \\ m_{\text{sterile}} &= 0, \end{aligned}$$

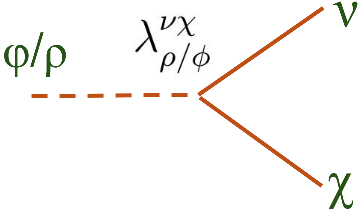
The particle physics model, extension to the SM

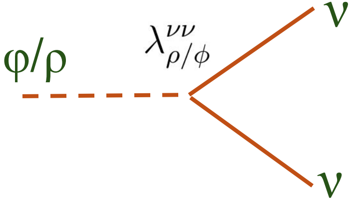
- Scalar interaction, scalar or pseudoscalar acts as X

$$\overline{N_R} Y_\Phi \, \chi_L \, \Phi + \text{h.c.} \quad :$$



- Mixing brings desired interactions





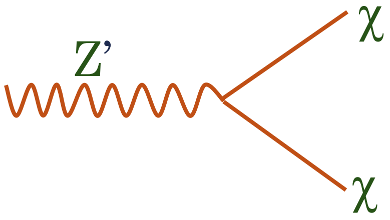
$$\lambda^{\nu\chi}_{\rho/\phi} = \frac{m_\nu}{v_\Phi}\,\theta_{\nu\chi}$$

$$\lambda^{\nu\nu}_{\rho/\phi} = \frac{m_\nu}{v_\Phi}\,\theta^2_{\nu\chi}$$

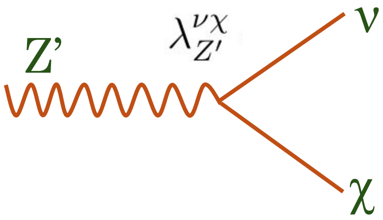
The particle physics model, extension to the SM

- Gauge interaction, Z' plays the role of X

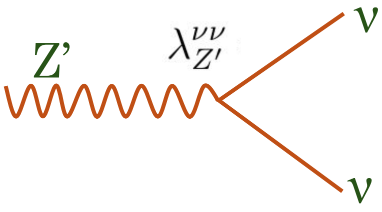
$$Q_f\, g_X\, Z'_\mu\, \bar{f}\, \gamma^\mu\, f$$:



- Mixing brings desired interactions



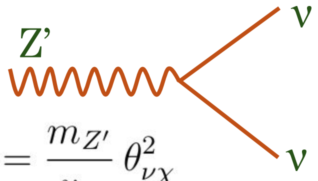
$$\lambda_{Z'}^{\nu\chi} = \frac{m_{Z'}}{v_\Phi}\,\theta_{\nu\chi}$$



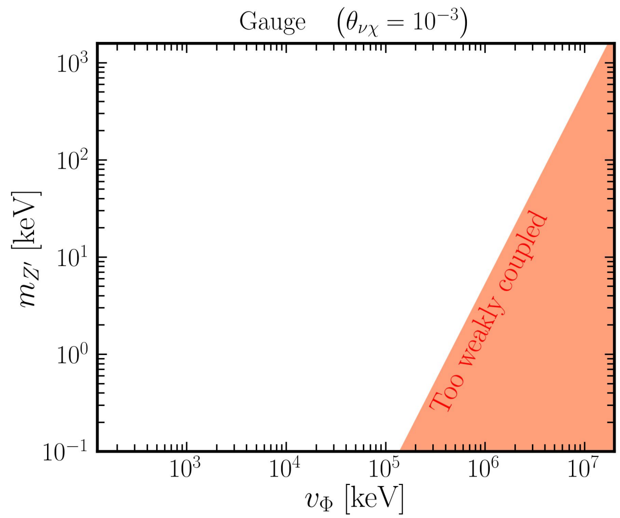
$$\lambda_{Z'}^{\nu\nu} = \frac{m_{Z'}}{v_\Phi}\,\theta_{\nu\chi}^2$$

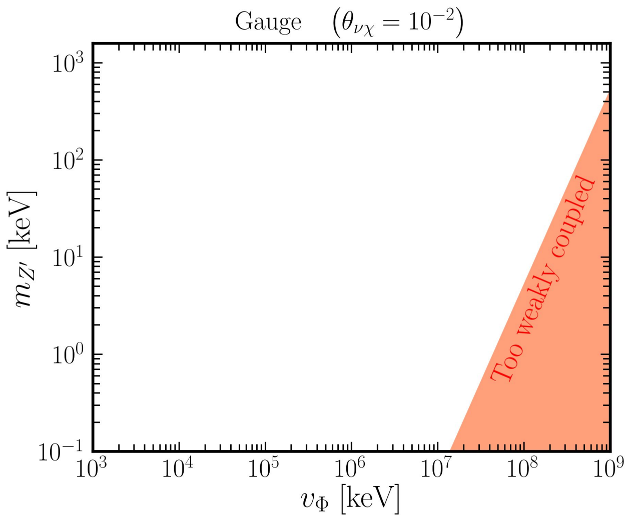
Parameter space where the model can work

- Gauge model as benchmark
- Thermalisation of Z



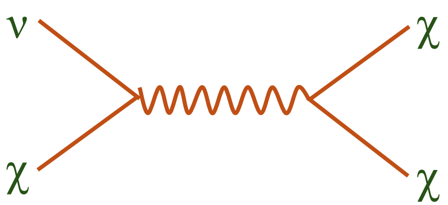
$$\lambda^{\nu\nu}_{Z'} = \frac{m_{Z'}}{v_\Phi}\,\theta^2_{\nu\chi}$$

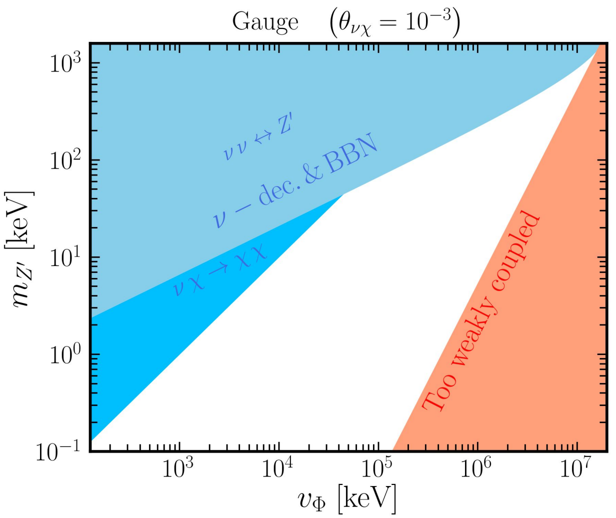


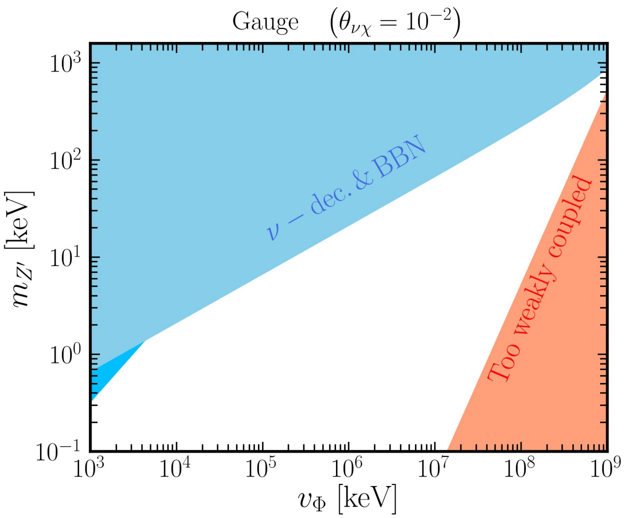


Parameter space where the model can work

- Gauge model
- Alter BBN producing Z' or χ

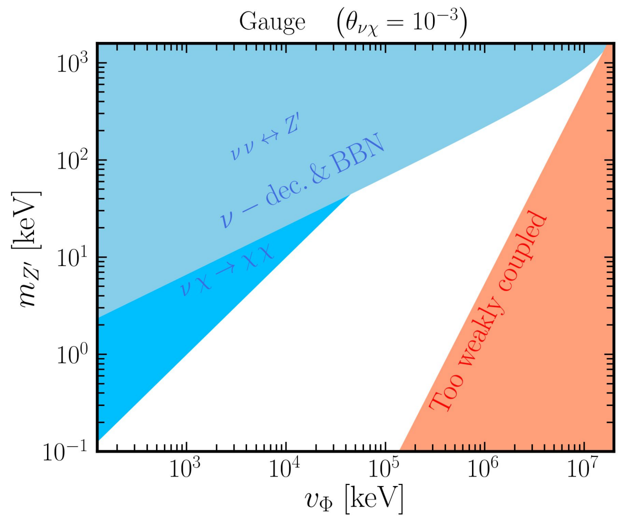


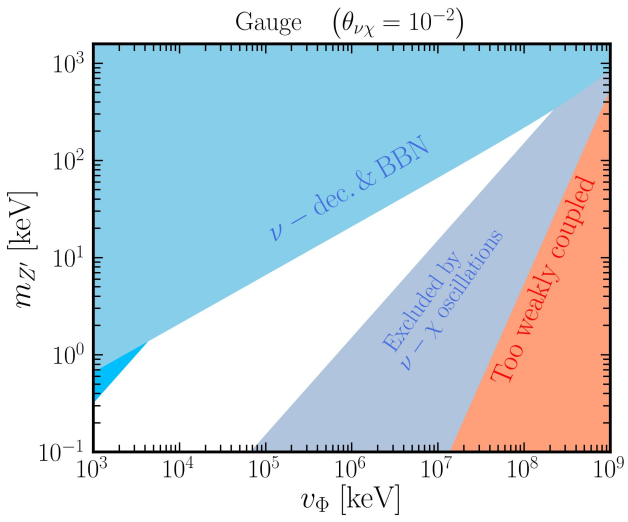




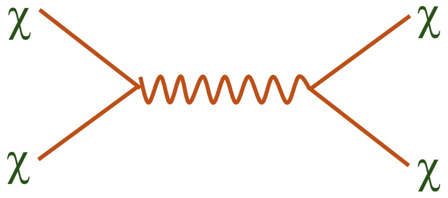
Parameter space where the model can work

- Gauge model
- Oscillations ν-χ pre-BBN

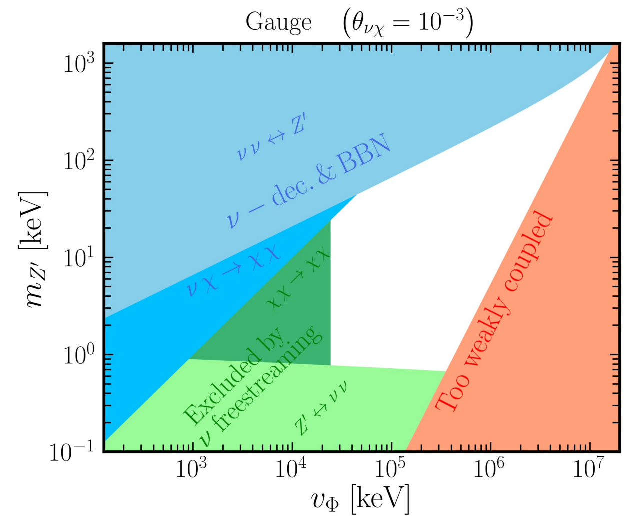


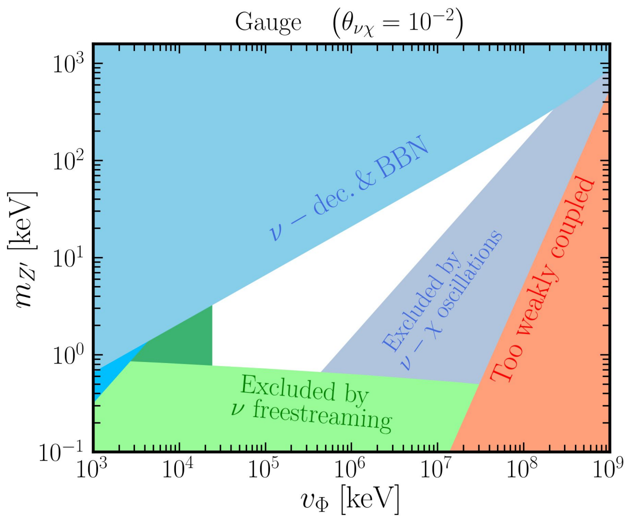


Parameter space where the model can work



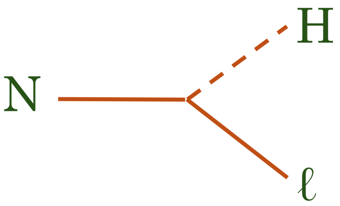
- Gauge model
- ν and χ must freestream at recombination

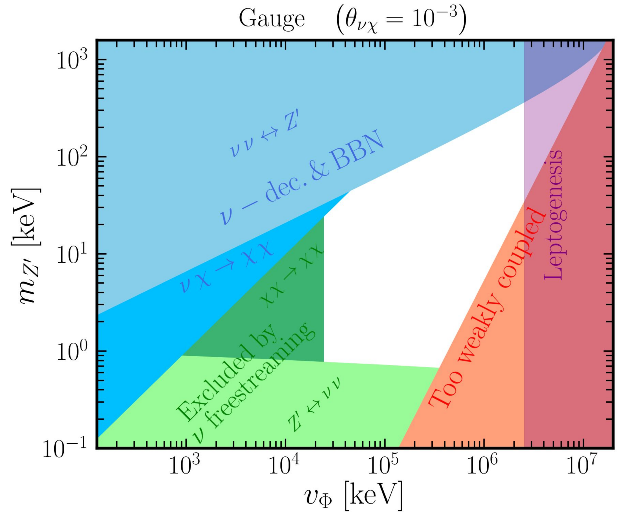


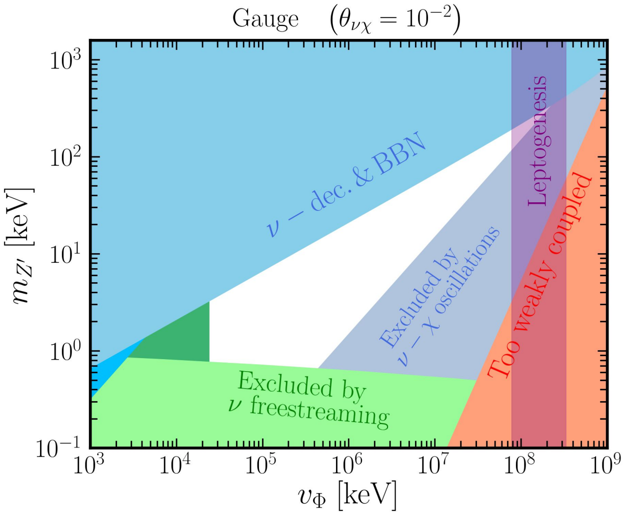


Parameter space where the model can work

- Gauge model
- Leptogenesis is viable

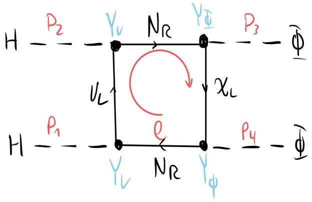




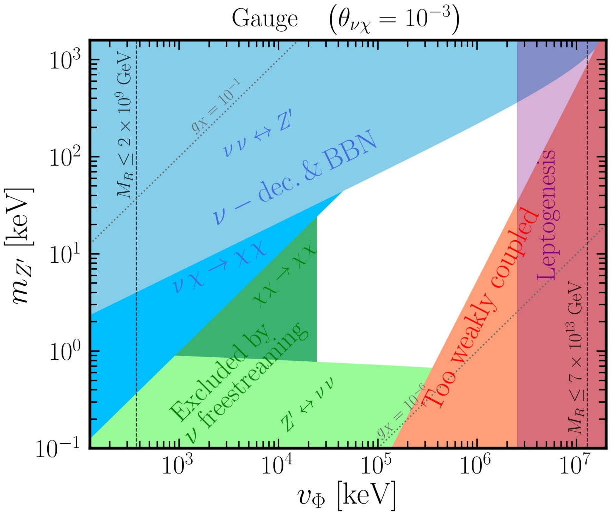


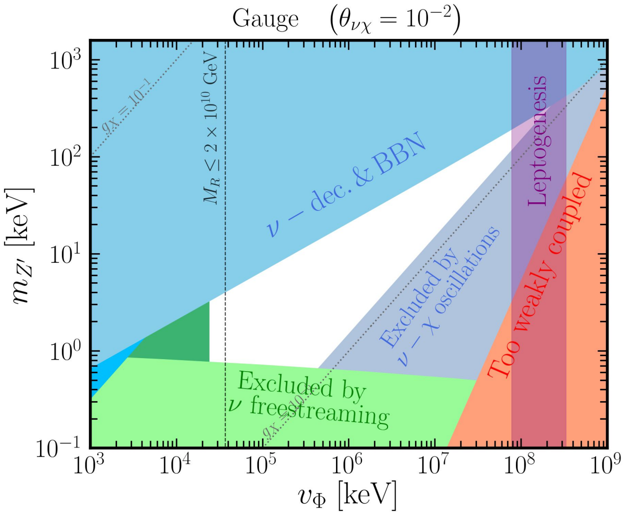
Parameter space where the model can work

- Gauge model
- Additional upper limits on MR



$$Y_\Phi = \frac{\sqrt{m_\nu M_R}}{v_\Phi}\theta_{\nu\chi} \leq \sqrt{4\pi}$$





Parameter space where the model can work

- Global model, disfavoured