Neutrino Portals to Dark Matter

Arsenii Titov

Institute for Particle Physics Phenomenology,
Department of Physics, Durham University, UK

In collaboration with **M. Blennow**, **E. Fernandez-Martinez**,
A. Olivares-Del Campo, **S. Pascoli** and **S. Rosauro-Alcaraz**

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Outline

- Introduction
- Constraints on DM interactions with SM particles
- Coupling to the full lepton doublet
- Neutrino portal
  - with a scalar mediator
  - with a vector mediator
- Conclusions

Introduction

Most significant experimental evidences for BSM physics:

- neutrino masses and mixing
- existence of dark matter (DM)

Elusive components of the Universe:

- neutrinos participate in weak interactions and gravity
- DM feels gravity and ?

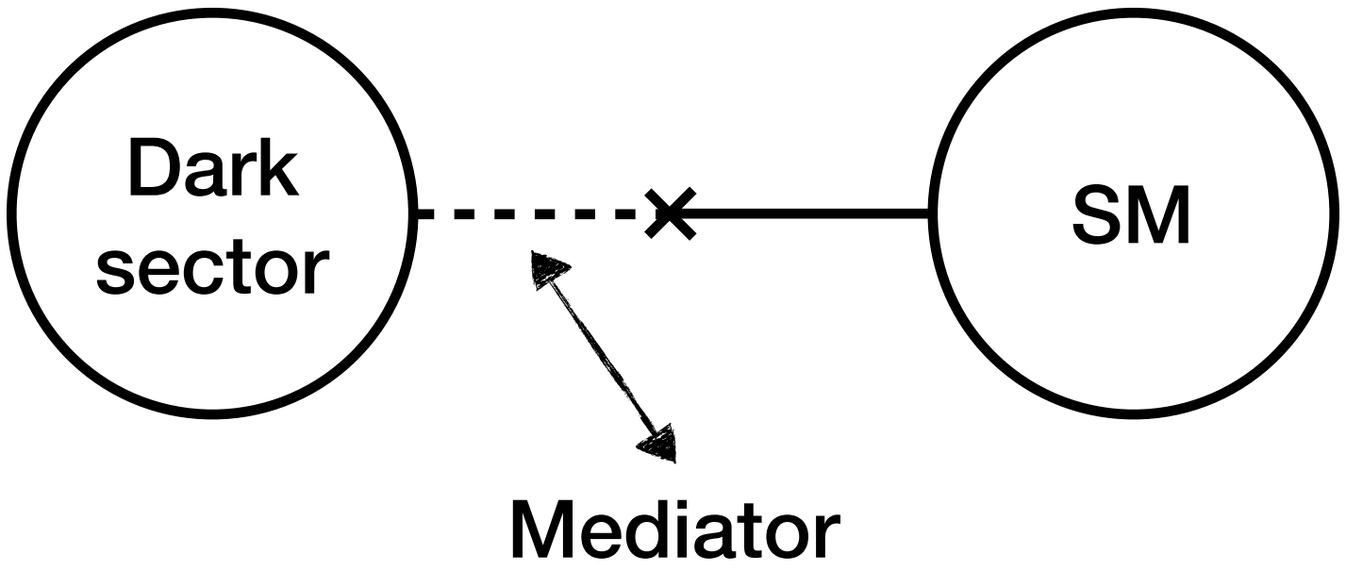
Is there a connection between these two sectors?

Introduction

Aim: *gauge-invariant* scenarios in which DM-neutrino interactions dominate the DM phenomenology

Naively, gauge invariance ⇒
DM-neutrino interactions = DM-charged lepton interactions

Portal paradigm:



Constraints on DM-SM interactions

- Indirect detection searches for DM annihilation to neutrinos (Borexino, SK and HK, DUNE, DARWIN)

- Indirect detection searches for DM annihilation to charged leptons (Planck, Fermi-LAT)

- Direct detection searches (XENON1T and prospects for DM scattering off electrons with Si, Ge, Xe)

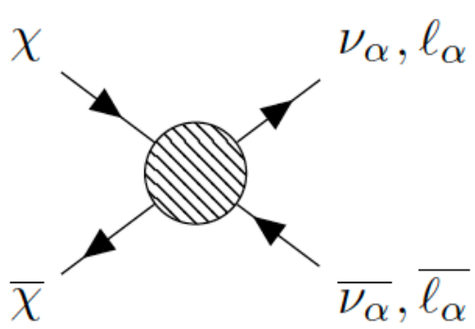
- Constraints from cosmology (CMB and BBN)

  $\Rightarrow \quad m_\chi \gtrsim 10 \text{ MeV}$

Coupling to the full lepton doublet

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \bar{\chi}\left(i\gamma^\mu\partial_\mu - m_\chi\right)\chi + \frac{c_\alpha}{\Lambda^2}\,\bar{\chi}\gamma_\mu\chi\,\overline{L_\alpha}\gamma^\mu L_\alpha$$

χ is a Dirac fermion DM candidate, $\quad L_\alpha = \begin{pmatrix}\nu_{\alpha L}\\ \ell_{\alpha L}\end{pmatrix}, \;\; \alpha = e,\mu,\tau$

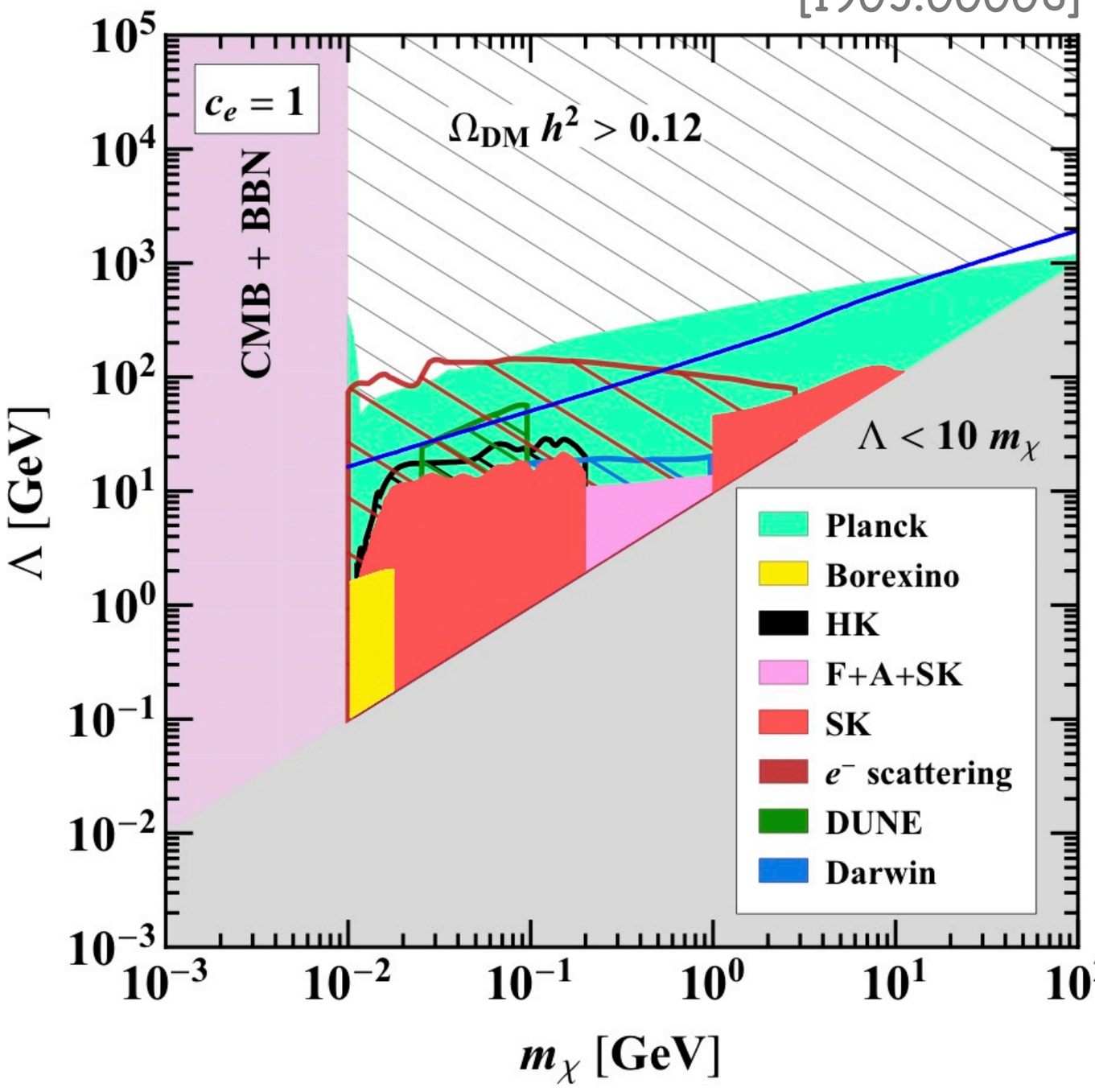


$$\langle\sigma v_r\rangle \approx \frac{c_\alpha^2 m_\chi^2}{2\pi\Lambda^4}\left(1-\frac{m_\alpha^2}{4m_\chi^2}\right)\sqrt{1-\frac{m_\alpha^2}{m_\chi^2}}$$

$\bar{\chi}\gamma_\mu\gamma_5\chi$ would lead to velocity-suppressed $\langle\sigma v_r\rangle_{\chi\bar{\chi}\to\nu\bar{\nu}}$

Coupling to the full lepton doublet

[1903.00006]

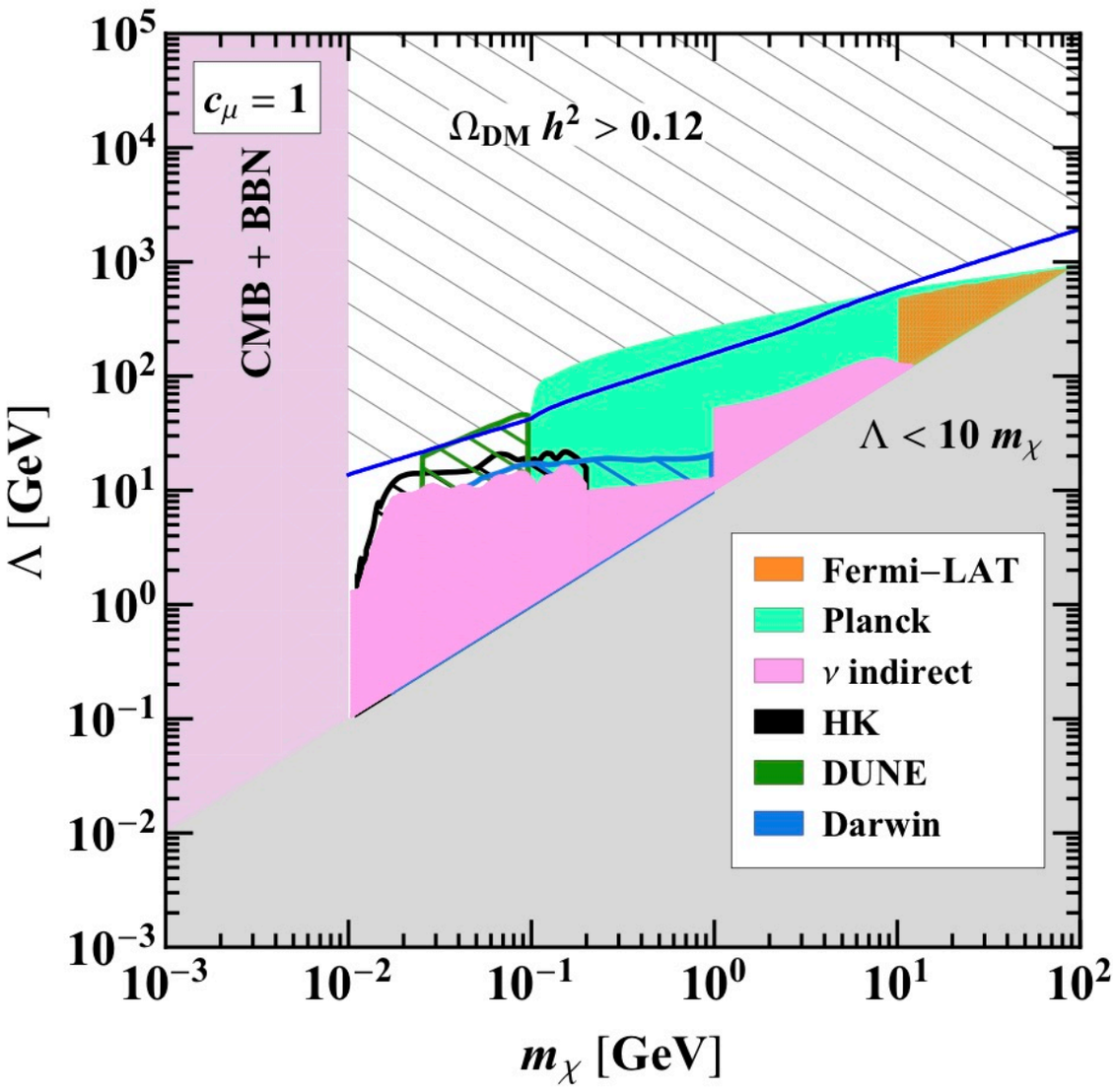


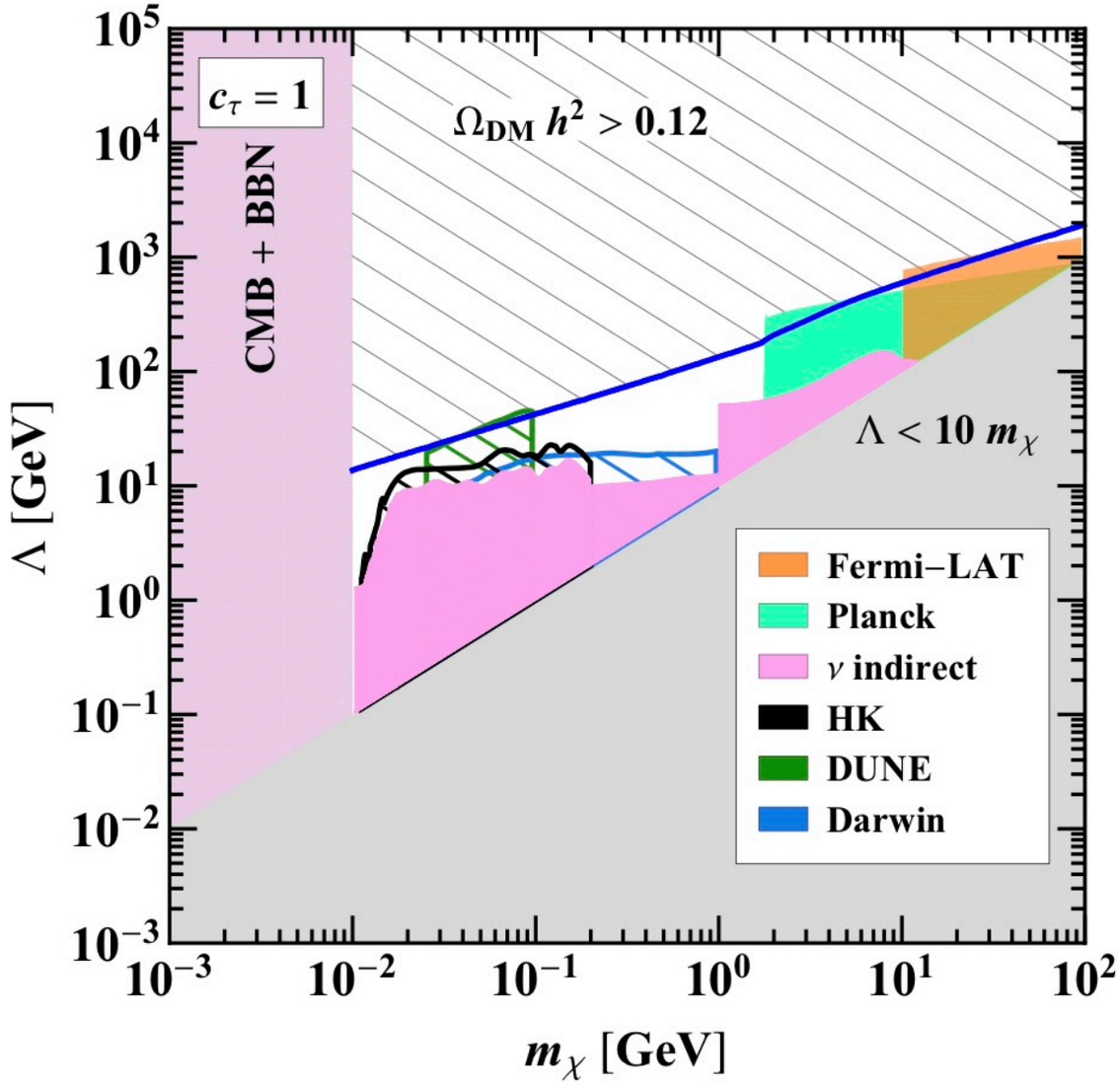
Constraints:

[Planck'18]
[Borexino'06, Olivares-Del Campo et al.'17]
[Olivares-Del Campo et al.'18]
[Beacom et al.'06]
[Olivares-Del Campo et al.'17, SK'15]
[Essig et al.'18]
[Klop/Ando'18]
[McKeen/Raj'18]

`micrOMEGAs` [Belanger et al.'01]

Coupling to the full lepton doublet





Neutrino portal

[Pospelov et al.'07, Falkowski et al.'09'11, Lindner et al.'10, Cherry et al.'14]

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \overline{N}\left(i\gamma^\mu\partial_\mu - m_N\right)N - \left[\lambda_\alpha \overline{L_\alpha}\tilde{H}N_R + \text{h.c.}\right]$$

N is a (pseudo-)Dirac sterile neutrino, $\tilde{H} = i\sigma_2 H^*$

$$M_\nu = \begin{pmatrix} \lambda_\alpha v \\ m_N \end{pmatrix}, \quad v = \langle H^0 \rangle = 174 \text{ GeV}$$

$$m_4 = \sqrt{m_N^2 + \sum_\alpha |\lambda_\alpha|^2 v^2}$$

$$m_i = 0, \quad i = 1,2,3 \quad \text{(lepton number symmetry)}$$

Lepton number breaking terms to generate light ν masses:

$\mu\,\overline{N_L}N_L^c$ "inverse" seesaw [Malinsky et al.'05]

$\lambda'_\alpha \overline{L_\alpha}\tilde{H}N_L^c$ "linear" seesaw [Mohapatra/Valle'86, Bernabeu et al.'87]

Neutrino portal

PMNS matrix

active-heavy mixing

$$\begin{pmatrix} \nu_{\alpha L} \\ N_L \end{pmatrix} = \begin{pmatrix} U_{\alpha i} & U_{\alpha 4} \\ U_{si} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_{iL} \\ \nu_{4L} \end{pmatrix}, \quad \alpha = e, \mu, \tau, \quad i = 1,2,3$$

sterile-light mixing

sterile-heavy mixing

$$U_{\alpha 4} = \frac{\theta_\alpha}{\sqrt{1 + \sum_\alpha |\theta_\alpha|^2}}, \quad U_{s4} = \frac{1}{\sqrt{1 + \sum_\alpha |\theta_\alpha|^2}}, \quad \theta_\alpha = \frac{\lambda_\alpha v}{m_N}$$

For $m_4 >$ the EW scale, the global constraints allow for relatively large active-heavy mixing [Fernandez-Martinez et al.'16]:

$$|\theta_e| = 0.031, \quad |\theta_\mu| = 0.011, \quad |\theta_\tau| = 0.044$$

(central values at 1σ)

Neutrino portal with a scalar mediator

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \overline{\chi}\left(i\gamma^\mu\partial_\mu - m_\chi\right)\chi + \overline{N}\left(i\gamma^\mu\partial_\mu - m_N\right)N + \partial_\mu S^*\partial^\mu S$$
$$- \left[\lambda_\alpha\overline{L_\alpha}\tilde{H}N_R + \overline{\chi}\left(y_L N_L + y_R N_R\right)S + \text{h.c.}\right]$$
$$- \mu_S^2|S|^2 - \lambda_S|S|^4 - \lambda_{SH}|S|^2 H^\dagger H$$

[Bertoni et al.'14, Batell et al.'17]

- Global $U(1)_L$ lepton number symmetry:

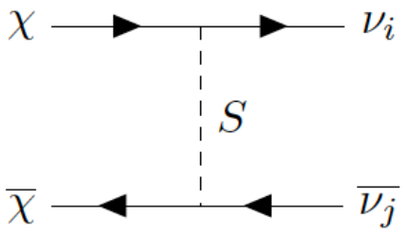
$$L(L_\alpha) = L(N) = L(S^*)$$

- Global $U(1)_D$ dark symmetry:

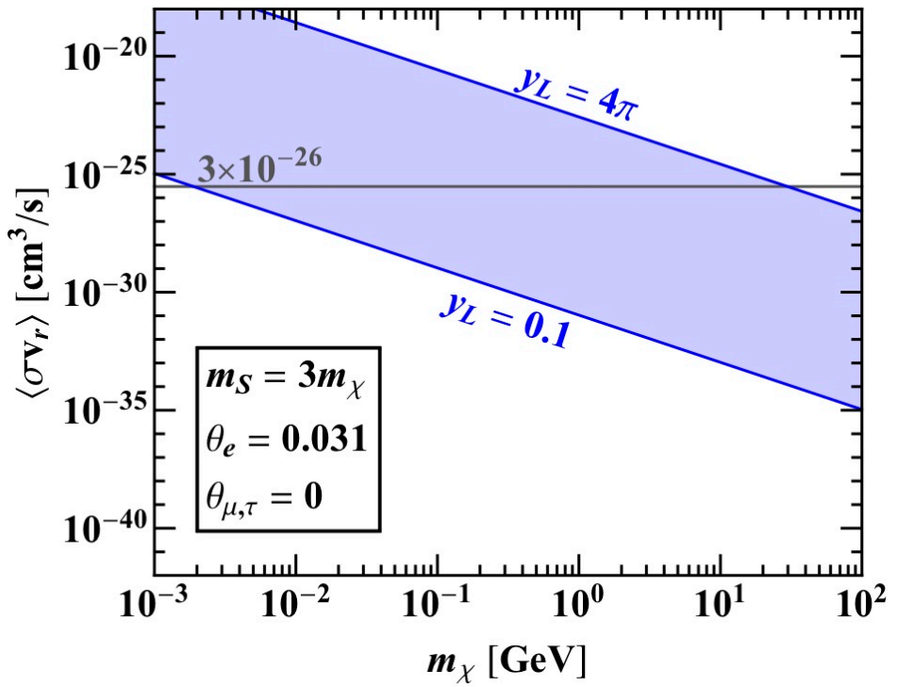
$$Q_D(\chi) = Q_D(S)$$

Neutrino portal with a scalar mediator

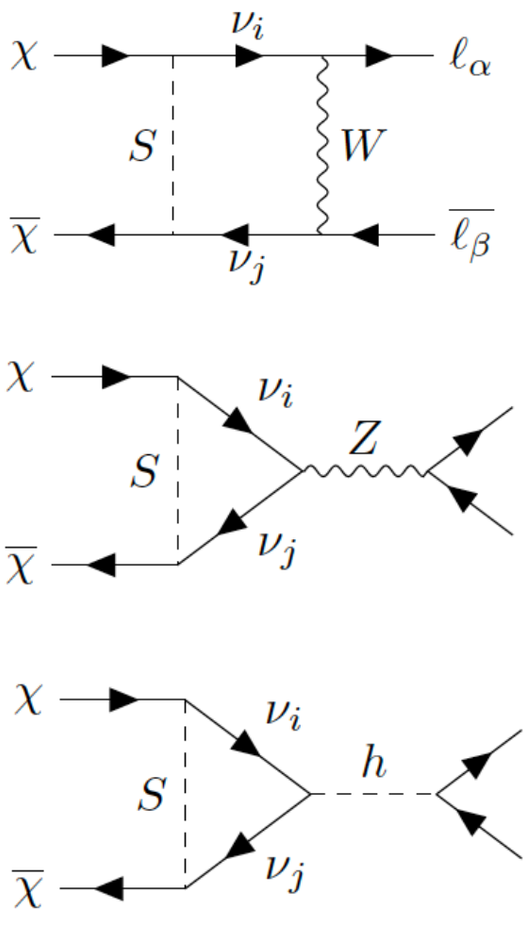
Annihilation to neutrinos

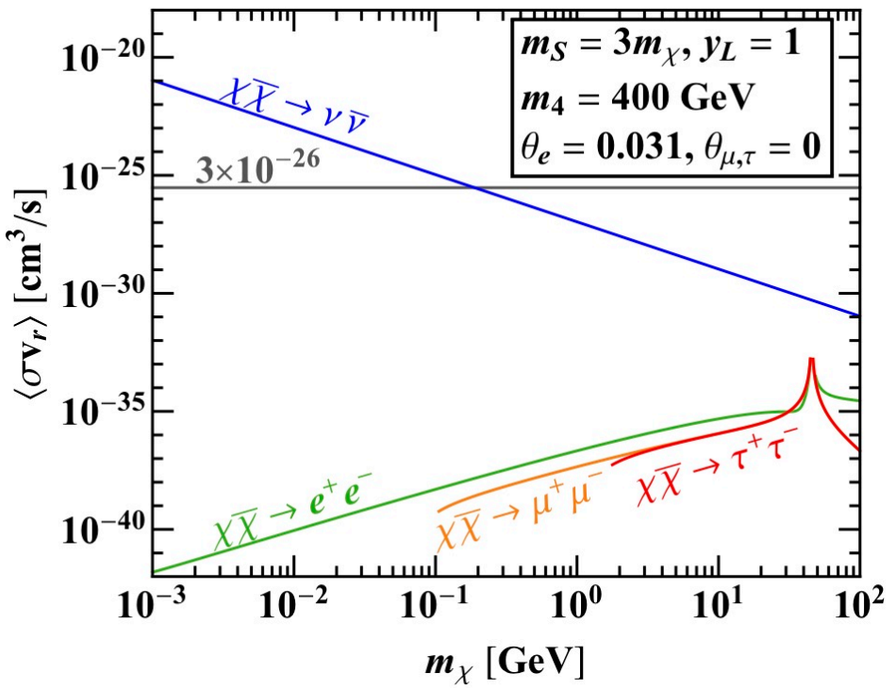


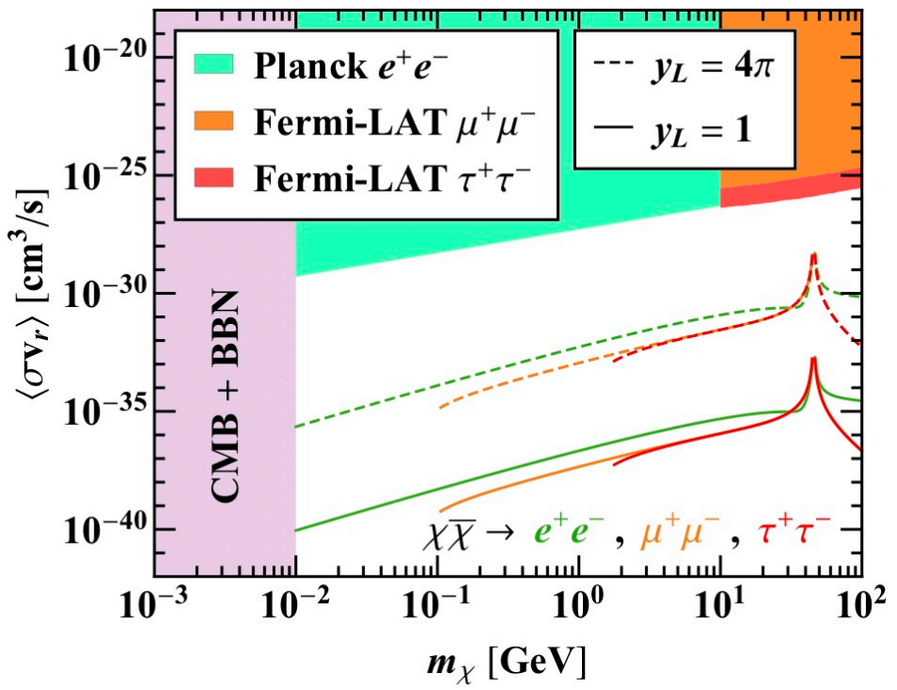
$$\langle \sigma v_r \rangle \approx \frac{y_L^4}{32\pi} \left(\sum_{\alpha=e,\mu,\tau} \left|\theta_\alpha\right|^2 \right)^2 \frac{m_\chi^2}{\left(m_\chi^2 + m_S^2\right)^2}$$



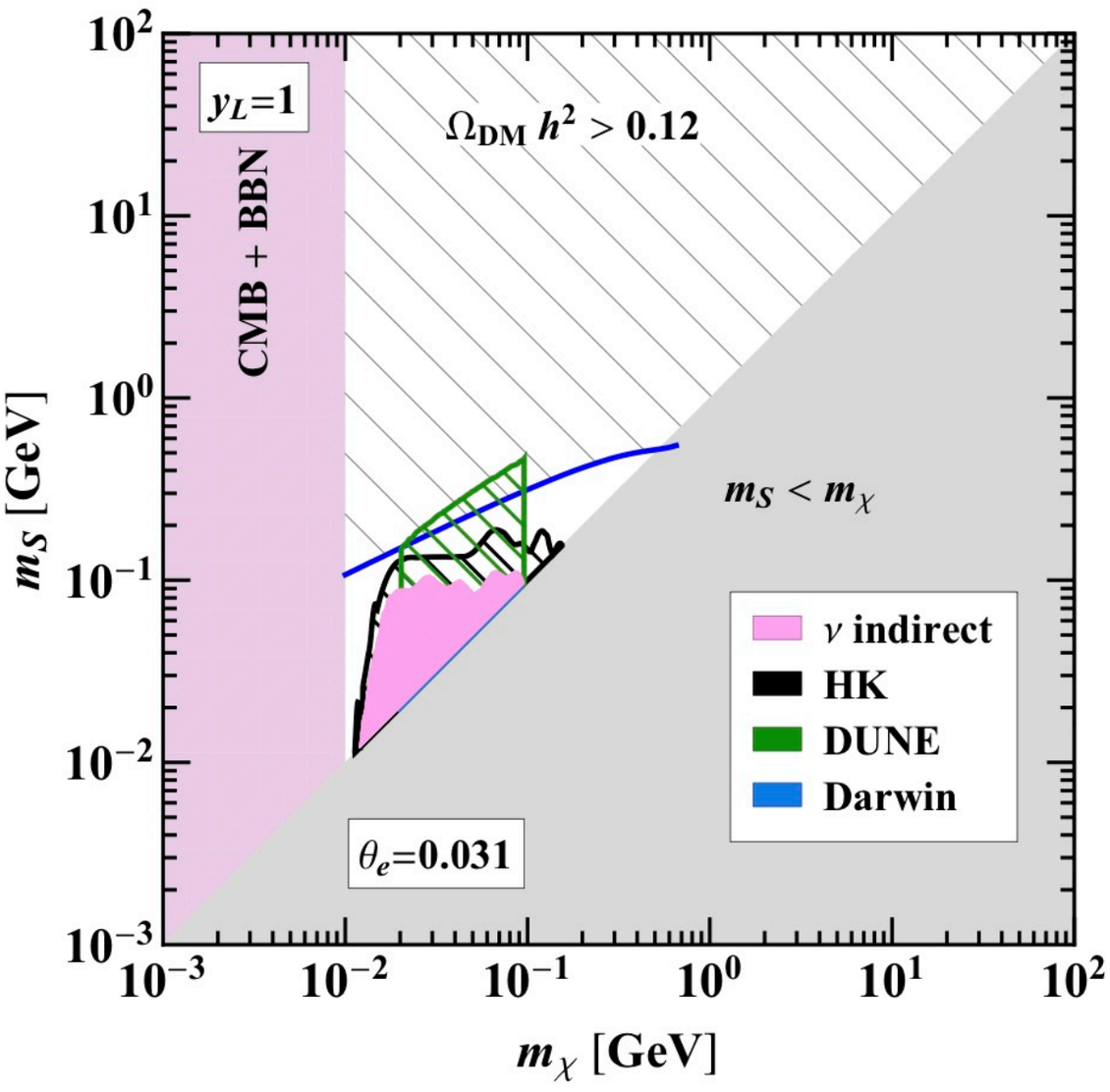
Annihilation to charged leptons

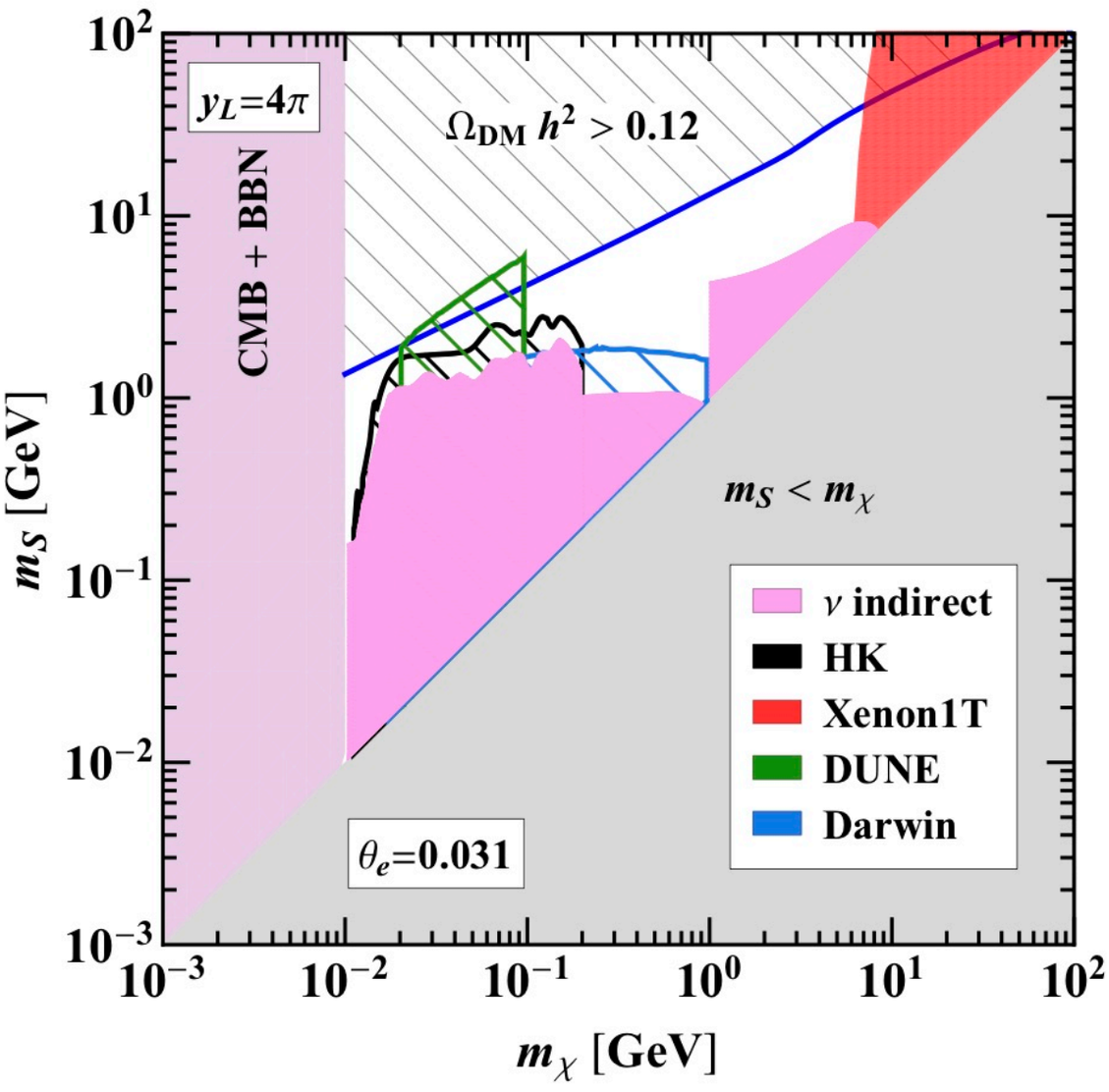






Neutrino portal with a scalar mediator





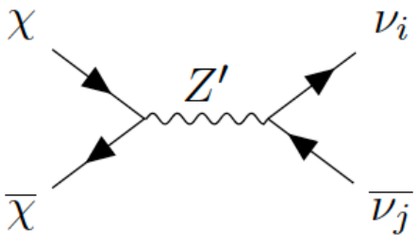
Neutrino portal with a vector mediator

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \bar{\chi}\left(i\gamma^\mu\partial_\mu - m_\chi\right)\chi + \bar{N}\left(i\gamma^\mu\partial_\mu - m_N\right)N$$
$$+ g'\overline{\chi_R}\gamma^\mu\chi_R Z'_\mu + g'\overline{N_L}\gamma^\mu N_L Z'_\mu - \left[\lambda_\alpha\overline{L_\alpha}\tilde{H}N_R + \text{h.c.}\right]$$
$$- \frac{1}{4}Z'_{\mu\nu}Z'^{\mu\nu} + \frac{1}{2}m^2_{Z'}Z'_\mu Z'^\mu$$

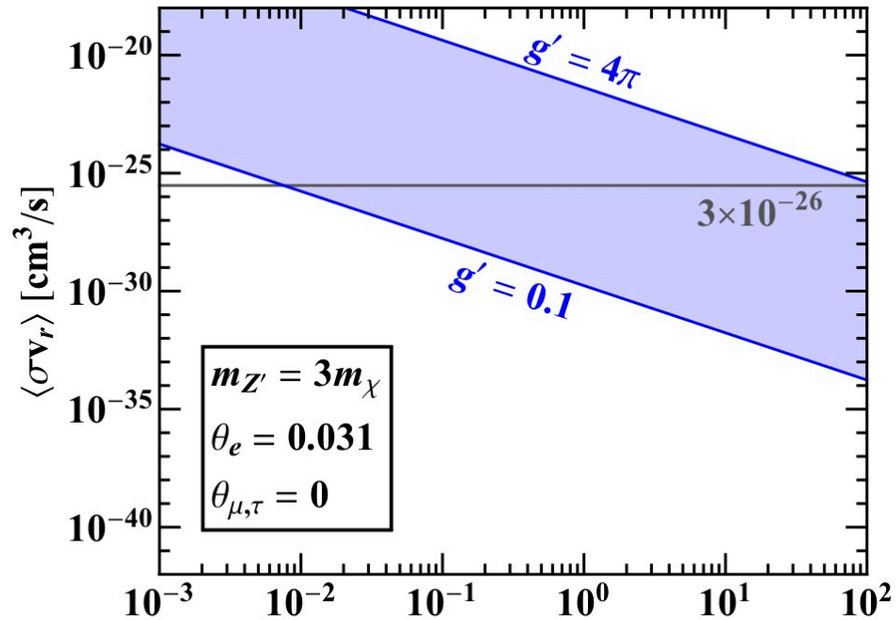
- Spontaneously broken $U(1)'$ gauge symmetry
- $\mathbb{Z}_2$ symmetry to prevent sterile neutrino-DM mixing
- Anomaly free (same g')

Neutrino portal with a vector mediator

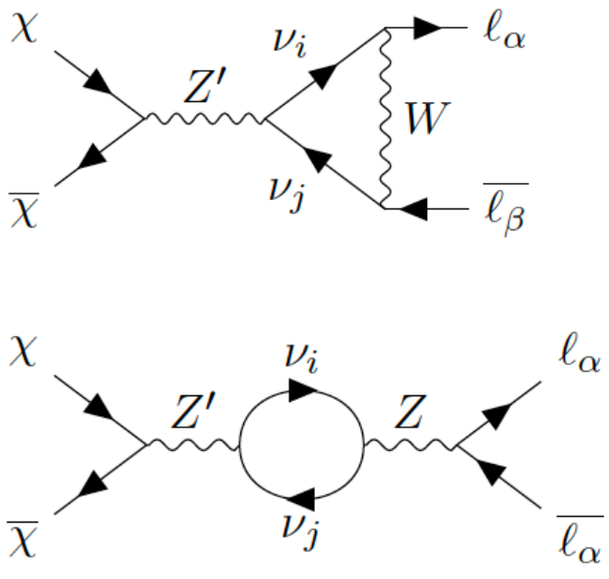
Annihilation to neutrinos

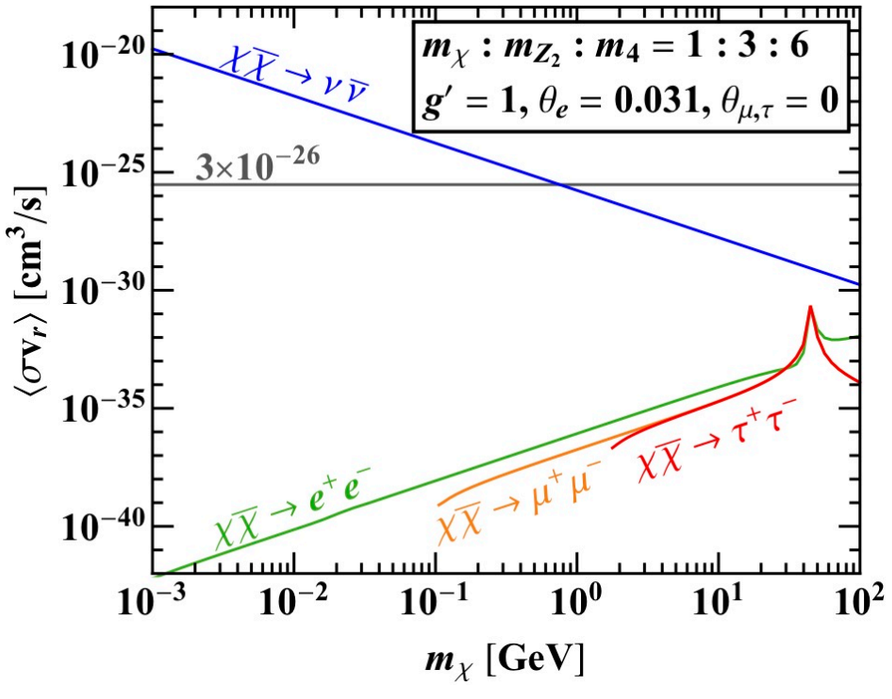


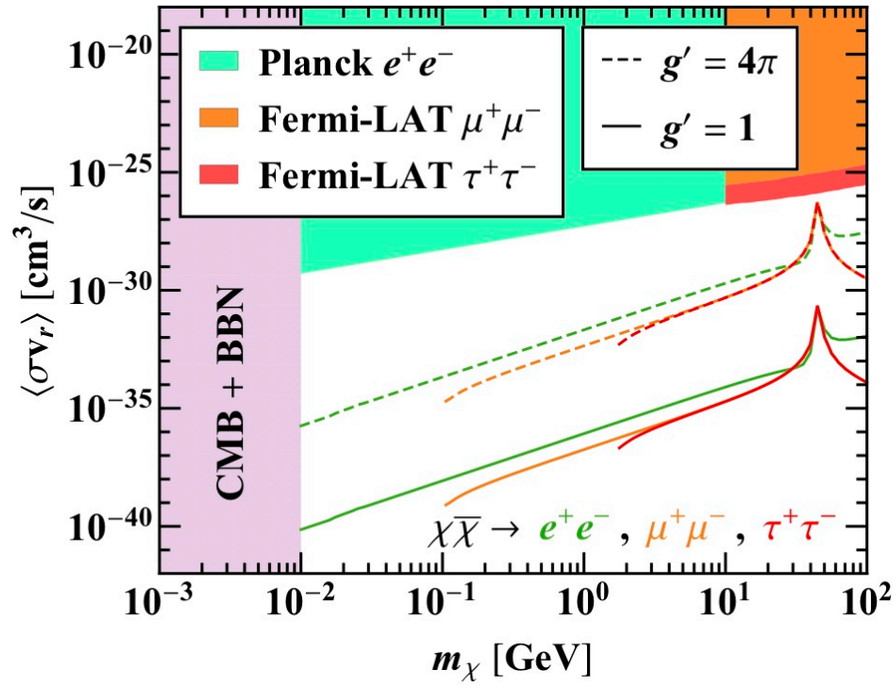
$$\langle \sigma v_r \rangle \approx \frac{g'^4}{8\pi} \left(\sum_{\alpha=e,\mu,\tau} \left| \theta_\alpha \right|^2 \right)^2 \frac{m_\chi^2}{(4m_\chi^2 - m_{Z'}^2)^2}$$



Annihilation to charged leptons

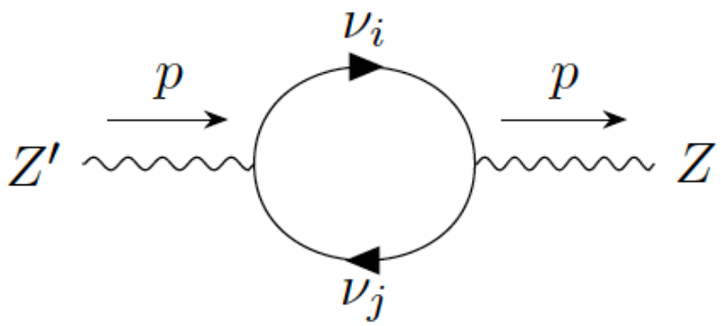






Neutrino portal with a vector mediator

$Z - Z'$ mixing



$$\mathscr{L}_{Z'Z} = -\frac{\sin\epsilon}{2} Z'_{\mu\nu} Z^{\mu\nu} + \delta m^2 Z'_\mu Z^\mu$$

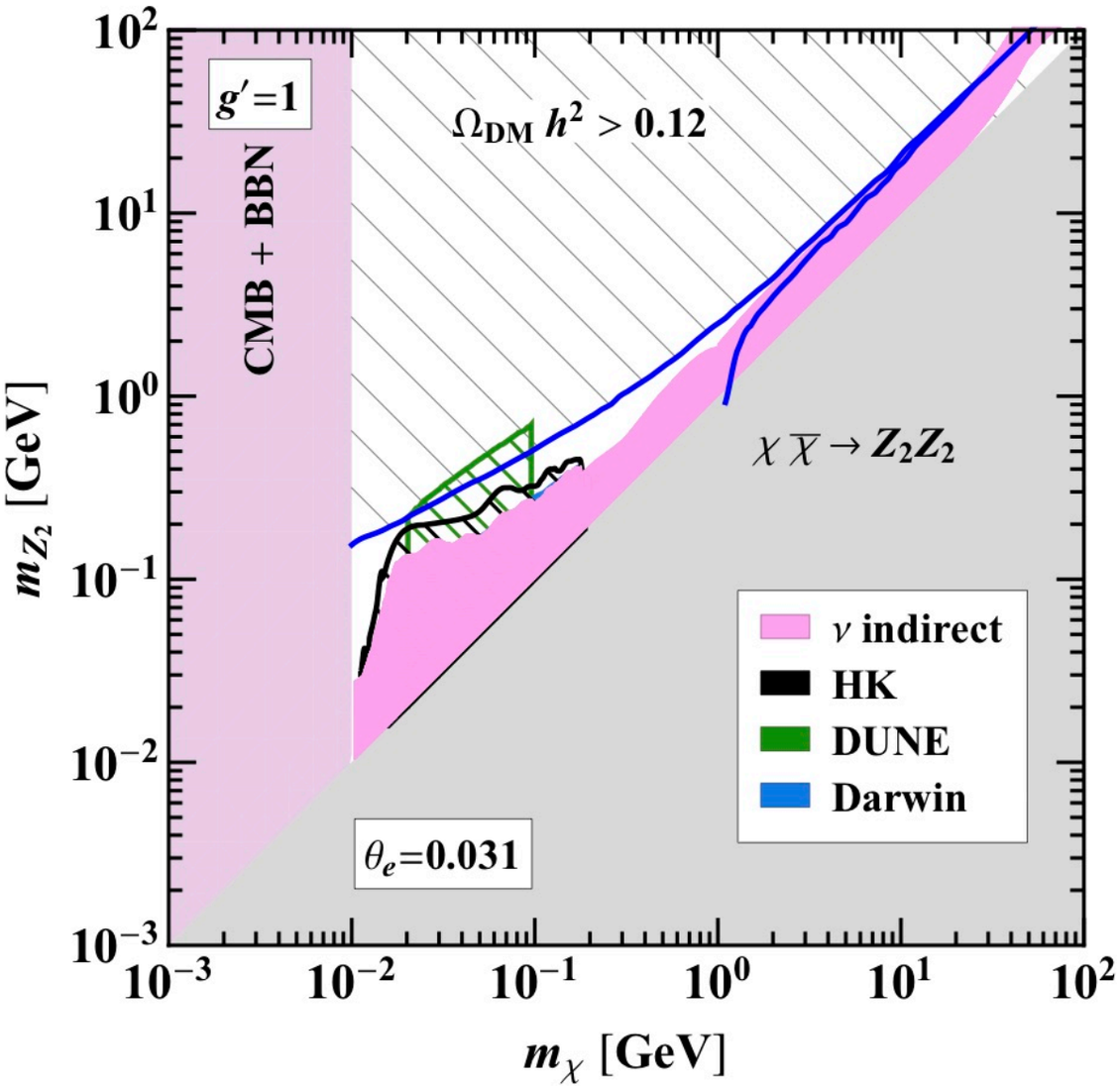
$$\delta m^2 = \frac{2}{(4\pi)^2} g' \frac{g}{\cos\theta_W} |U_{s4}|^2 \left(1 - |U_{s4}|^2\right) m_4^2 f_1\left(\frac{m_4^2}{p^2}\right)$$

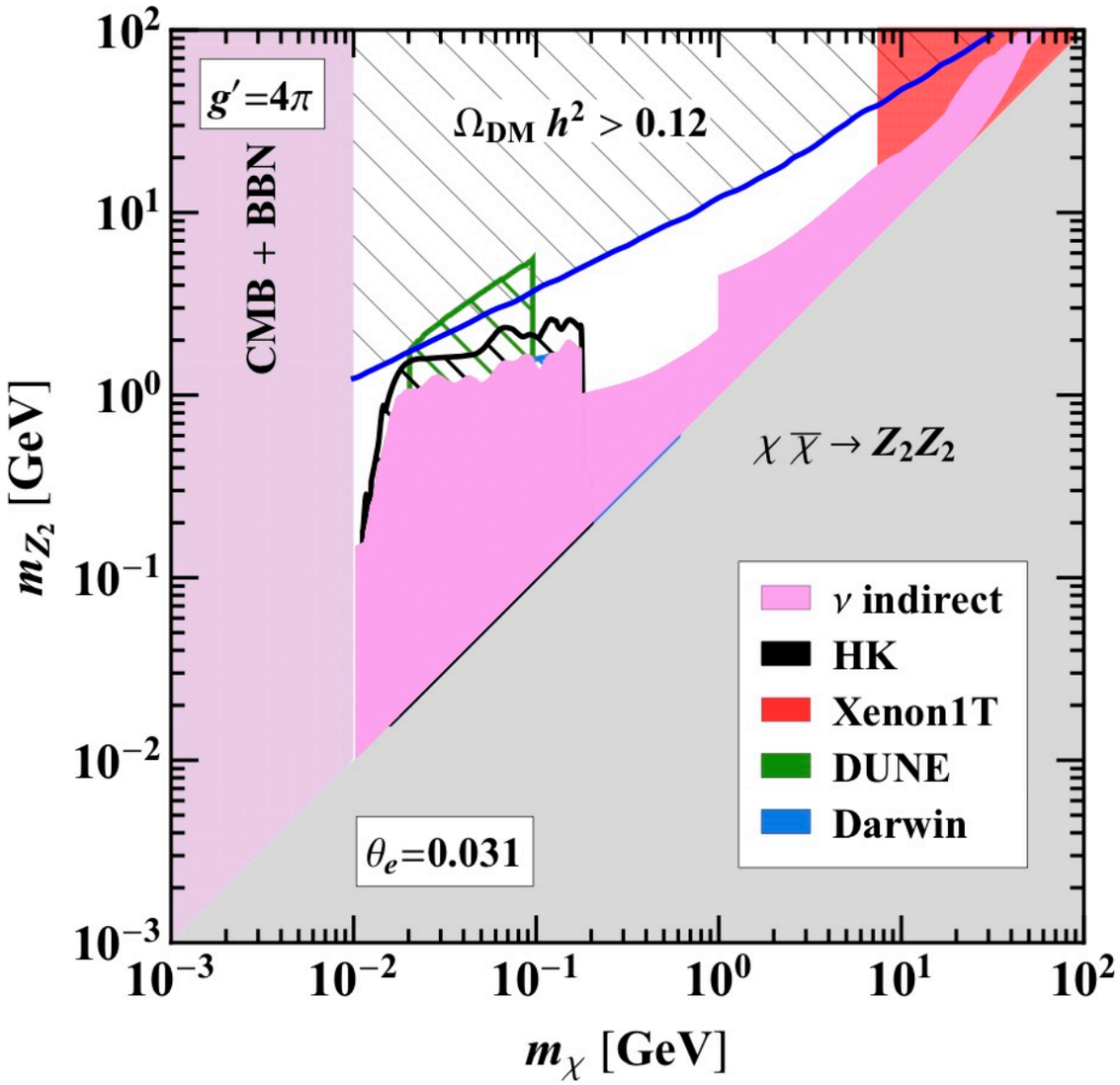
$$\sin\epsilon = \frac{2}{(4\pi)^2} g' \frac{g}{\cos\theta_W} |U_{s4}|^2 \left(1 - |U_{s4}|^2\right) f_2\left(\frac{m_4^2}{p^2}\right)$$

$$f_1(x) = \frac{1}{12}\left[4x^2\left(1-x^{-1}\right)^3 \coth^{-1}(1-2x) + 2x - x^{-1}\log(x) - 2\sqrt{x\left(4-x^{-1}\right)^3}\arctan\left((4x-1)^{-1/2}\right)\right]$$

$$f_2(x) = -\frac{x^2}{6}\left[4\left(2x-3+x^{-2}\right)\coth^{-1}(1-2x) + 4 + x^{-2}\log(x) - 2\sqrt{x^{-1}(4-x^{-1})}\left(2+x^{-1}\right)\arctan\left((4x-1)^{-1/2}\right)\right]$$

Neutrino portal with a vector mediator





Conclusions

- Possible connection between neutrinos and DM realised in a *gauge-invariant* way
- Coupling to the full lepton doublet
  - Unless DM is lighter than the charged lepton it couples to, the bounds from DM annihilation to charged leptons rule out almost all the parameter space
- Neutrino portal with i) scalar and ii) vector couplings
  - DM-neutrino interactions are realised at tree level, while DM-charged lepton and DM-quark interactions are loop-suppressed
  - Present neutrino detectors (SK, Borexino) set the most stringent constraints through searches for DM annihilation to neutrinos
  - Future projects (DUNE, HK, DARWIN) will be able to probe the cross section down to the value required to explain the DM abundance solely by annihilation to SM neutrinos

Acknowledgements

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Backup slides

Portals to dark sector

Three well-known portals to dark sector:

- vector portal $B^{\mu\nu}Z'_{\mu\nu}$ [Okun'82, Galison/Manohar'84, Holdom'86]
- Higgs portal $H^\dagger HS$ [Silveira/Zee'85, Patt/Wilczek'06]
- neutrino portal $\bar{L}\tilde{H}N_R$ [Minkowski'77, Yanagida'79, Gell-Mann et al.'79, Glashow'79, Mohapatra/Senjanovich'80]

$Z'_{\mu\nu} = \partial_\mu Z'_\nu - \partial_\nu Z'_\mu$ is the field strength of a new vector boson Z'_μ

S is a SM singlet scalar

N_R is a SM singlet RH fermion, and $\tilde{H} = i\sigma_2 H^*$

The neutrino portal is particularly appealing in view of the evidence for neutrino masses and mixing

Indirect detection: neutrinos

- DM annihilating in high density regions, e.g., Milky Way,
  $\Rightarrow$ monochromatic flux of neutrinos with $E_\nu = m_\chi$

$$\frac{\mathrm{d}\Phi}{\mathrm{d}E_\nu} \propto \langle \sigma v_r \rangle \mathcal{J}_{\mathrm{avg}}\, \delta(E_\nu - m_\chi) \propto \langle \sigma v_r \rangle \int\int \rho^2(r)\, \mathrm{d}l\, \mathrm{d}(cos\psi)\, \delta(E_\nu - m_\chi)$$

[Yüksel et al.'07, Palomares-Ruiz/Pascoli'07]

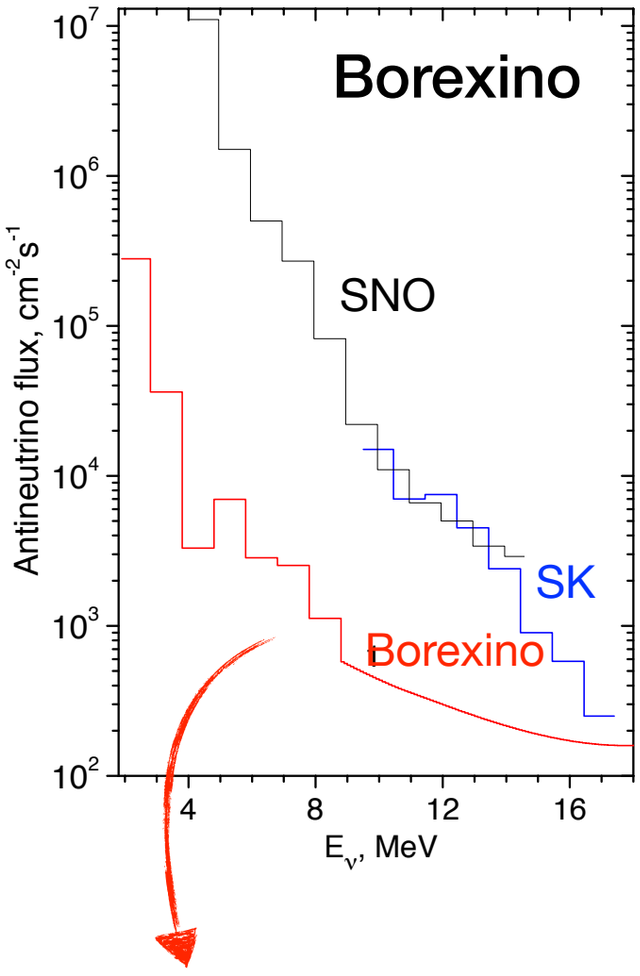
- Cosmic diffuse neutrino flux from DM annihilations in all halos in the Universe $\Rightarrow$ general upper bound on $\langle \sigma v_r \rangle$

[Beacom et al.'06]

Indirect detection: neutrinos

Present

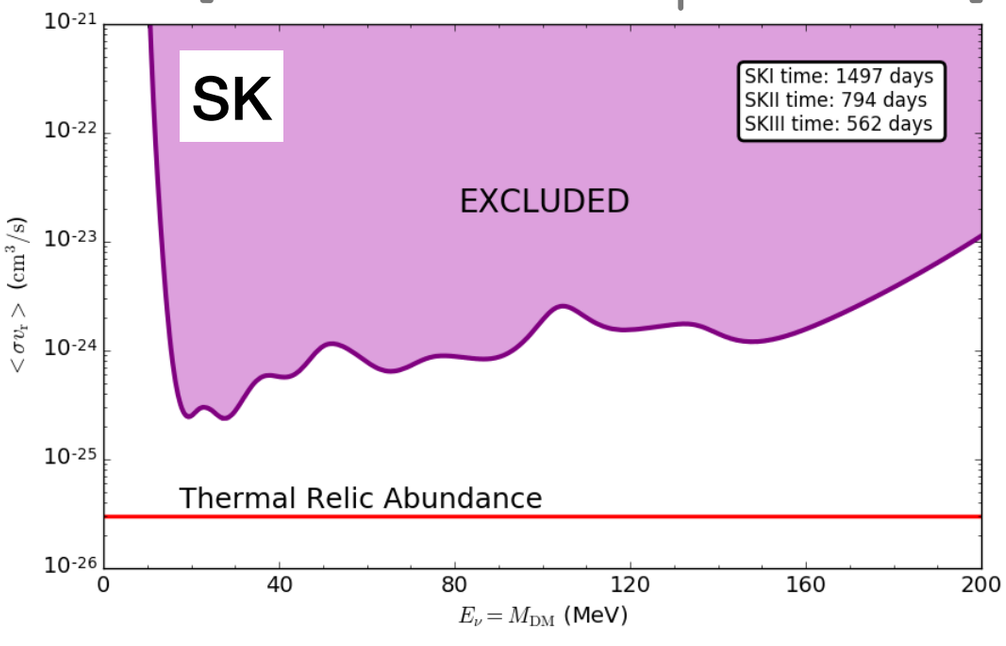
[Borexino'06]

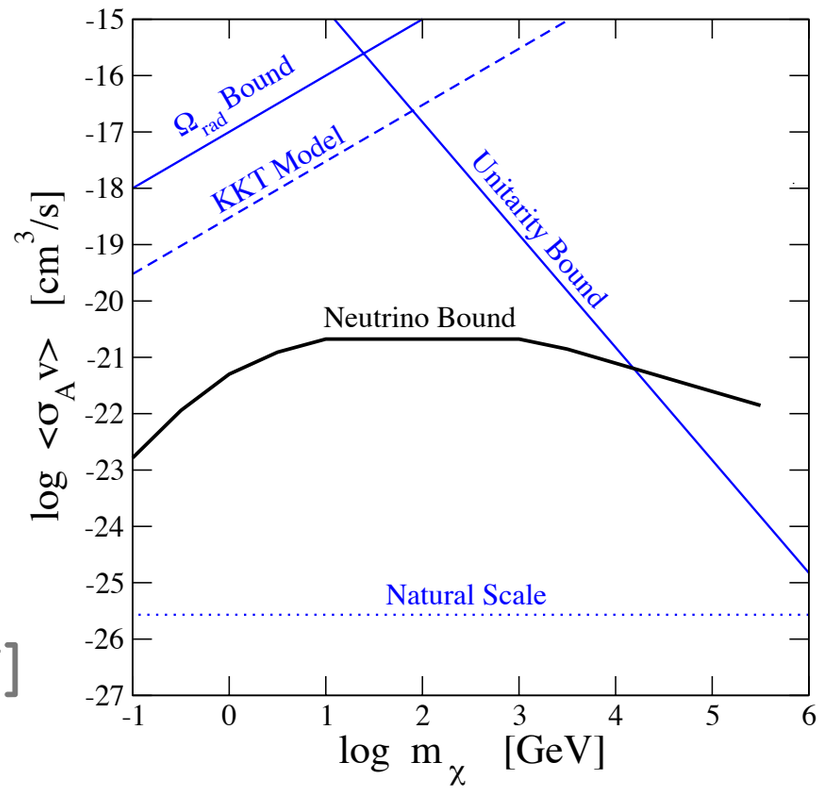


$\langle \sigma v_r \rangle \lesssim 10^{-22} - 10^{-20}$ cm^3/s

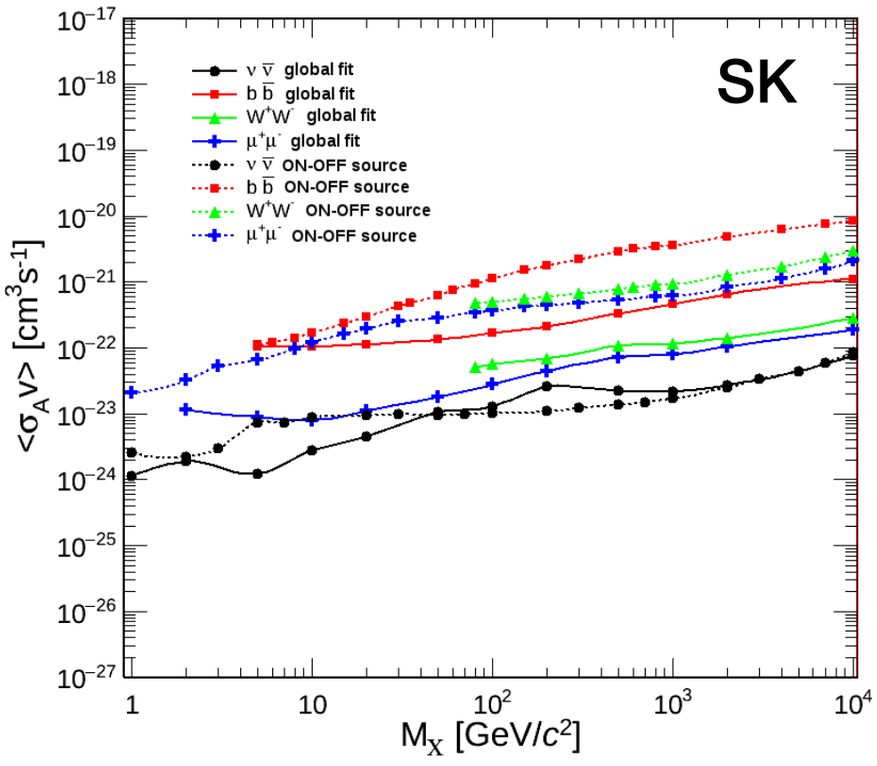
[Olivares-Del Campo et al.'17]

[Olivares-Del Campo et al.'17]





[Frankiewicz for SK'15]



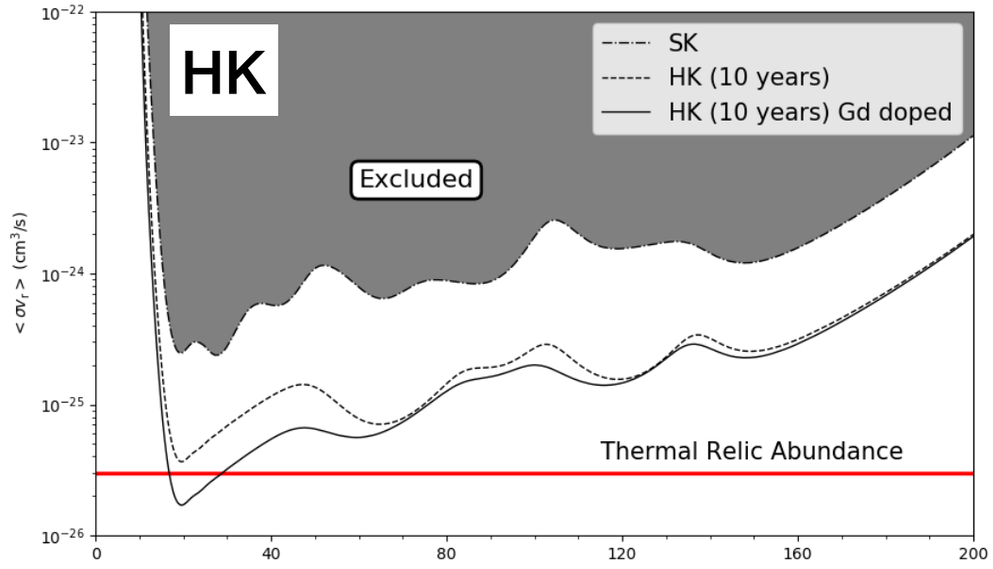
Fréjus + AMANDA + SK

[Beacom et al.'06]

Indirect detection: neutrinos

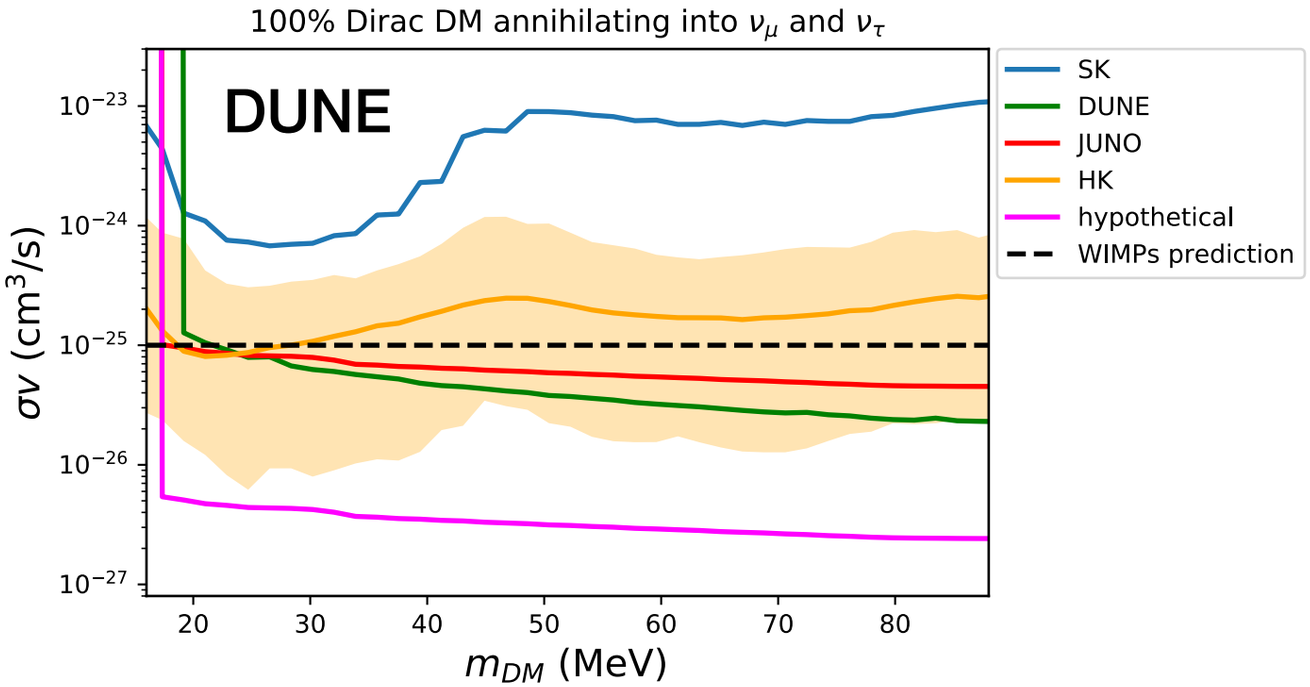
Future

[Olivares-Del Campo et al.'18]

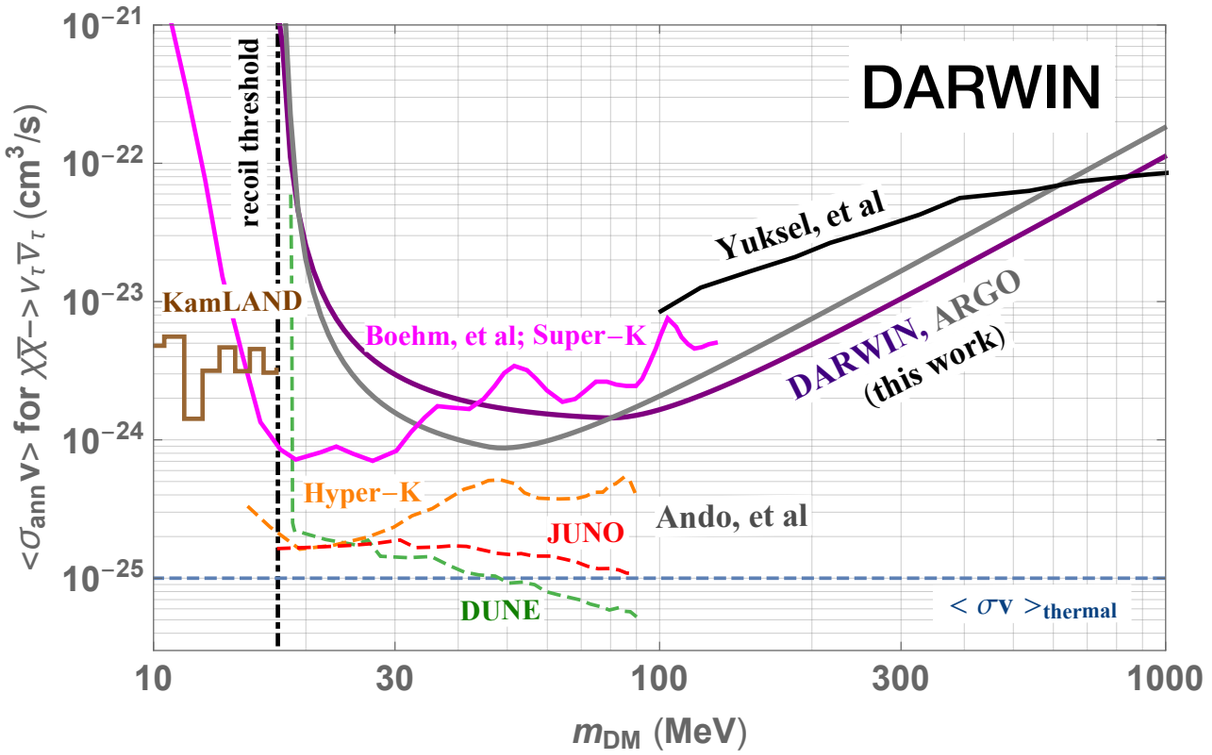


MEMPHYS (if it happens)

[Klop/Ando'18]

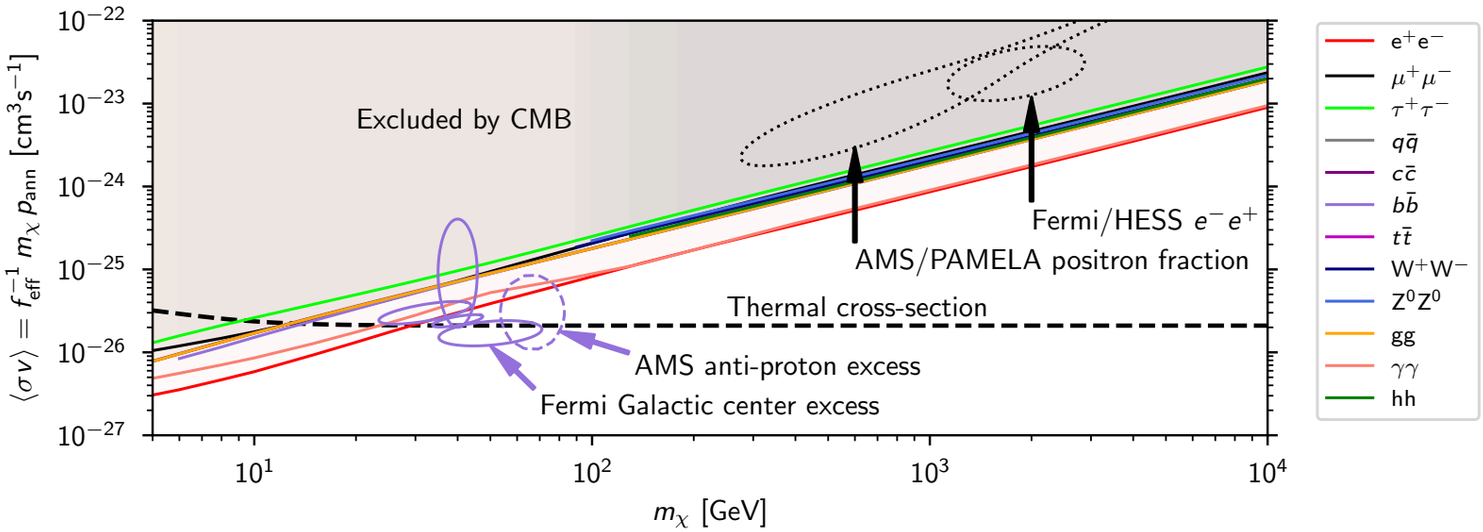


[McKeen/Raj'18]

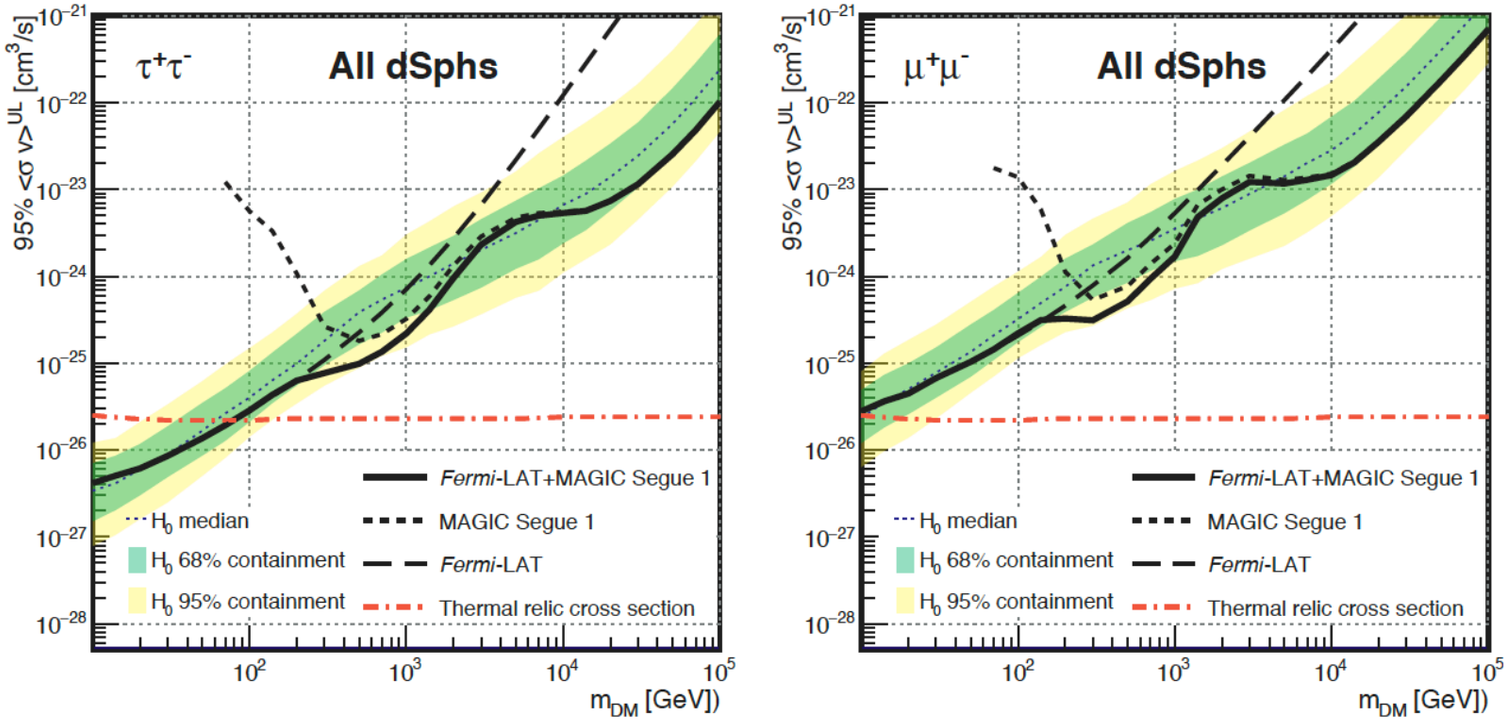


Indirect detection: charged leptons

Planck [Planck'18]



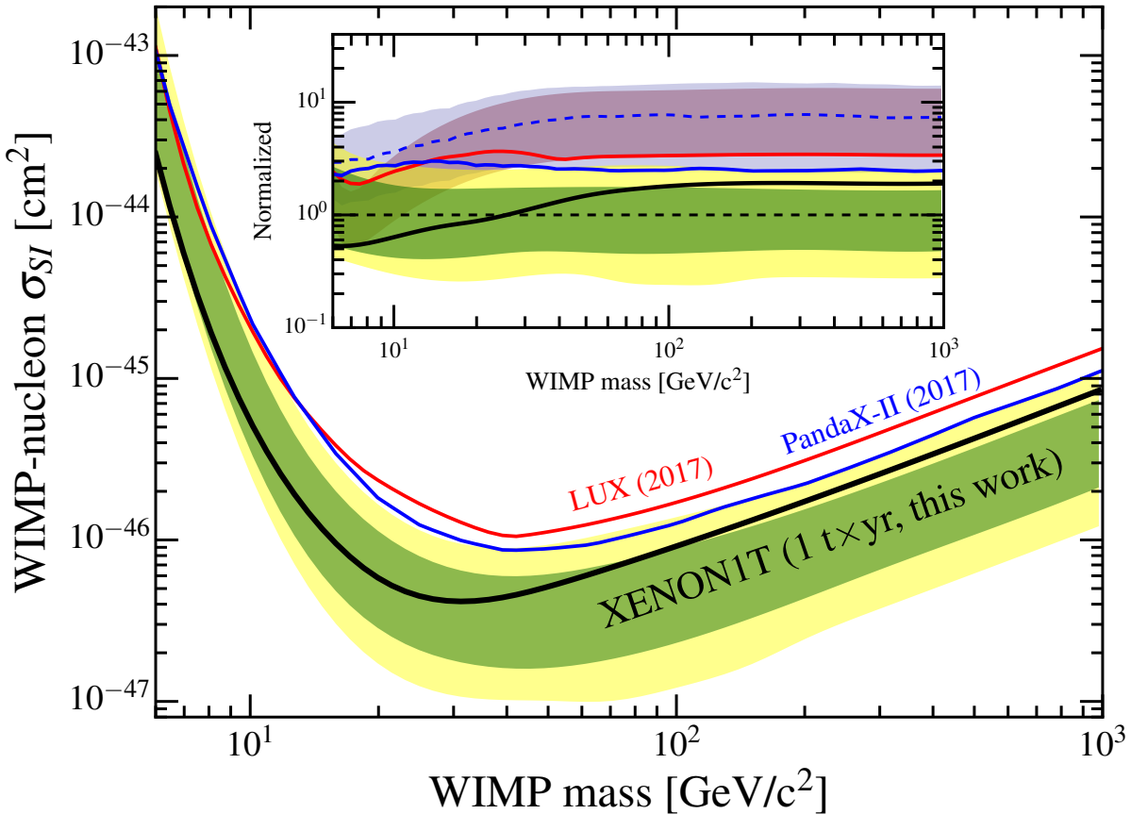
Fermi-LAT + MAGIC [MAGIC/Fermi-LAT'16]



Direct detection

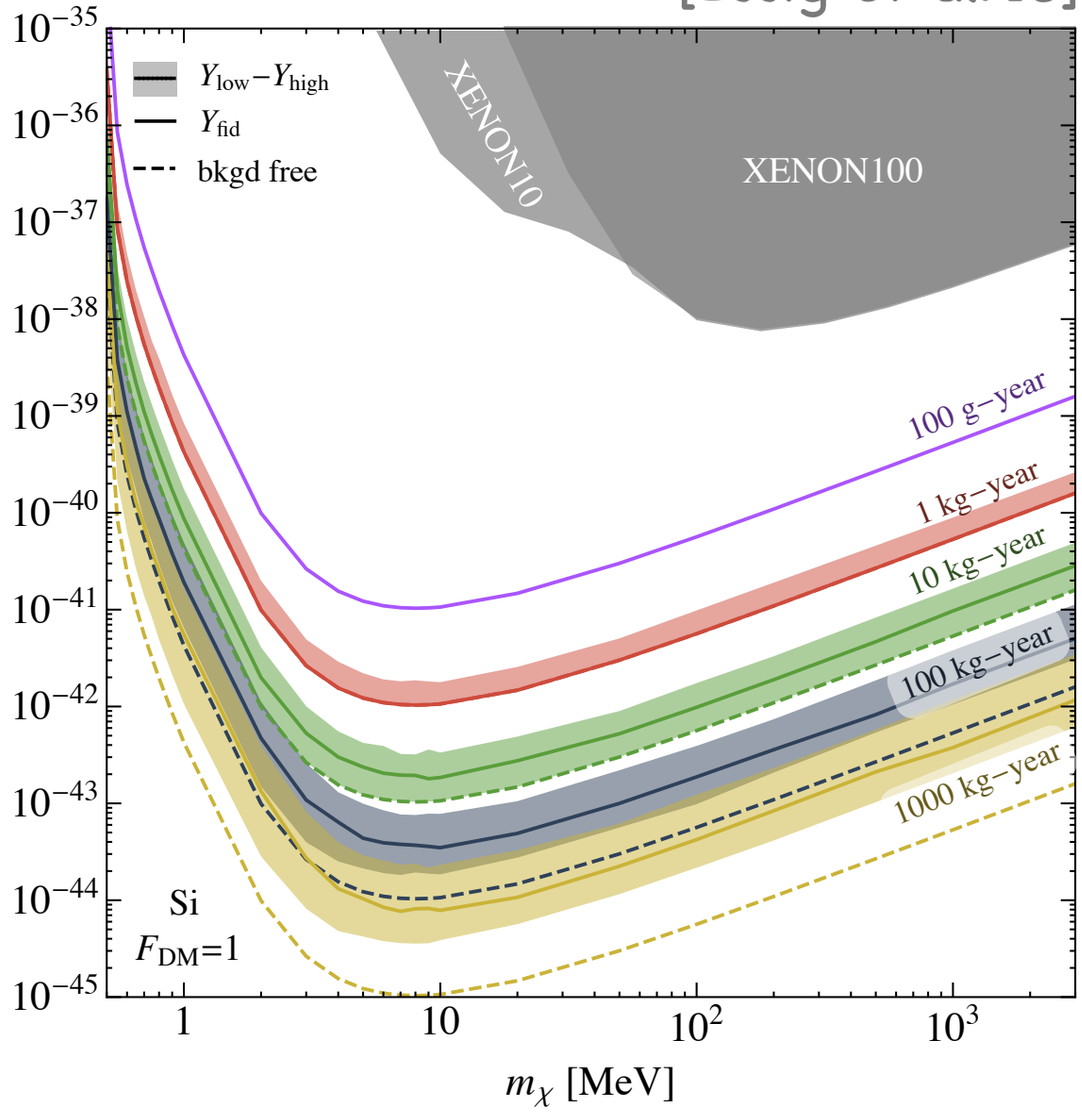
Scattering off nuclei

XENON1T [XENON'18]



Scattering off electrons

[Essig et al.'18]



Constraints from cosmology

- Big Bang nucleosynthesis [Serpico/Raffelt'04, Iocco et al.'08]
- Cosmic microwave background [Boehm et al.'13, Nollett/Steigman'14, Escudero'18]

$$\Rightarrow \quad m_\chi \gtrsim 10 \text{ MeV}$$

Neutrino portal with a scalar mediator

[Pospelov et al.'07]

Direct annihilation regime

$$m_\chi < m_4$$

$$\chi\overline{\chi} \to \nu_i\overline{\nu_i}$$

Neutrino Yukawa has to be large to avoid DM overproduction

Large DM-neutrino interaction

[Bertoni et al.'14, Batell et al.'17]

Heavy DM phenomenology

[Gonzalez-Macias/Wudka'15, Gonzalez-Macias et al.'16]

Secluded annihilation regime

$$m_\chi > m_4$$

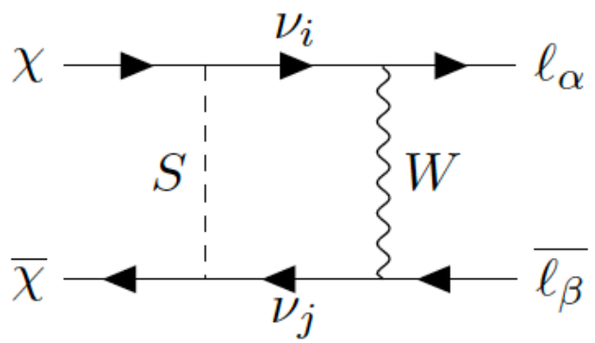
$$\chi\overline{\chi} \to \nu_4\overline{\nu_4}\,, \quad \nu_4 \to \dots$$

Neutrino Yukawa can be small

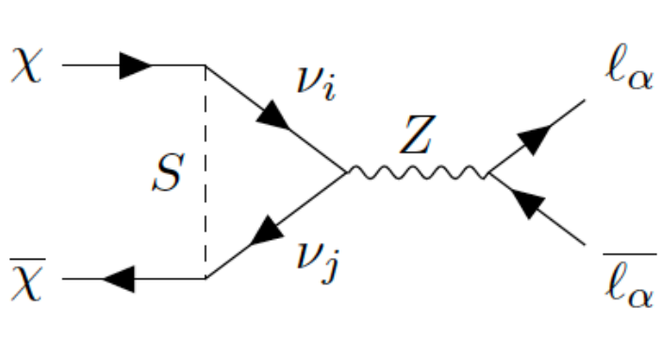
Indirect signatures from the heavy neutrino decays

[Escudero et al.'16, Batell et al.'17, Folgado et al.'18, Bandyopadhyay et al.'18]

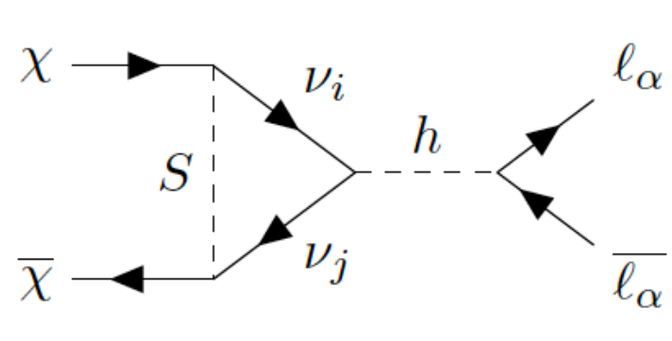
Neutrino portal with a scalar mediator



$$a_{SW}\frac{g^2}{m_W^2}\overline{\chi}\gamma^\mu P_R\chi\,\overline{\ell}_\alpha\gamma_\mu P_L\ell_\beta$$



$$a_Z\frac{g}{\cos\theta_W}\overline{\chi}\gamma^\mu P_R\chi Z_\mu$$



suppressed by
charged lepton Yukawa

In the limit of zero external momenta (ZEM)

$$a_{SW} = |U_{s4}|^2 U_{\alpha 4}U^*_{\beta 4}\frac{y_L^2}{(4\pi)^2}G\left(\frac{m_S^2}{m_4^2}\right) \qquad a_Z = |U_{s4}|^2\left(1-|U_{s4}|^2\right)\frac{y_L^2}{(4\pi)^2}G\left(\frac{m_S^2}{m_4^2}\right)$$

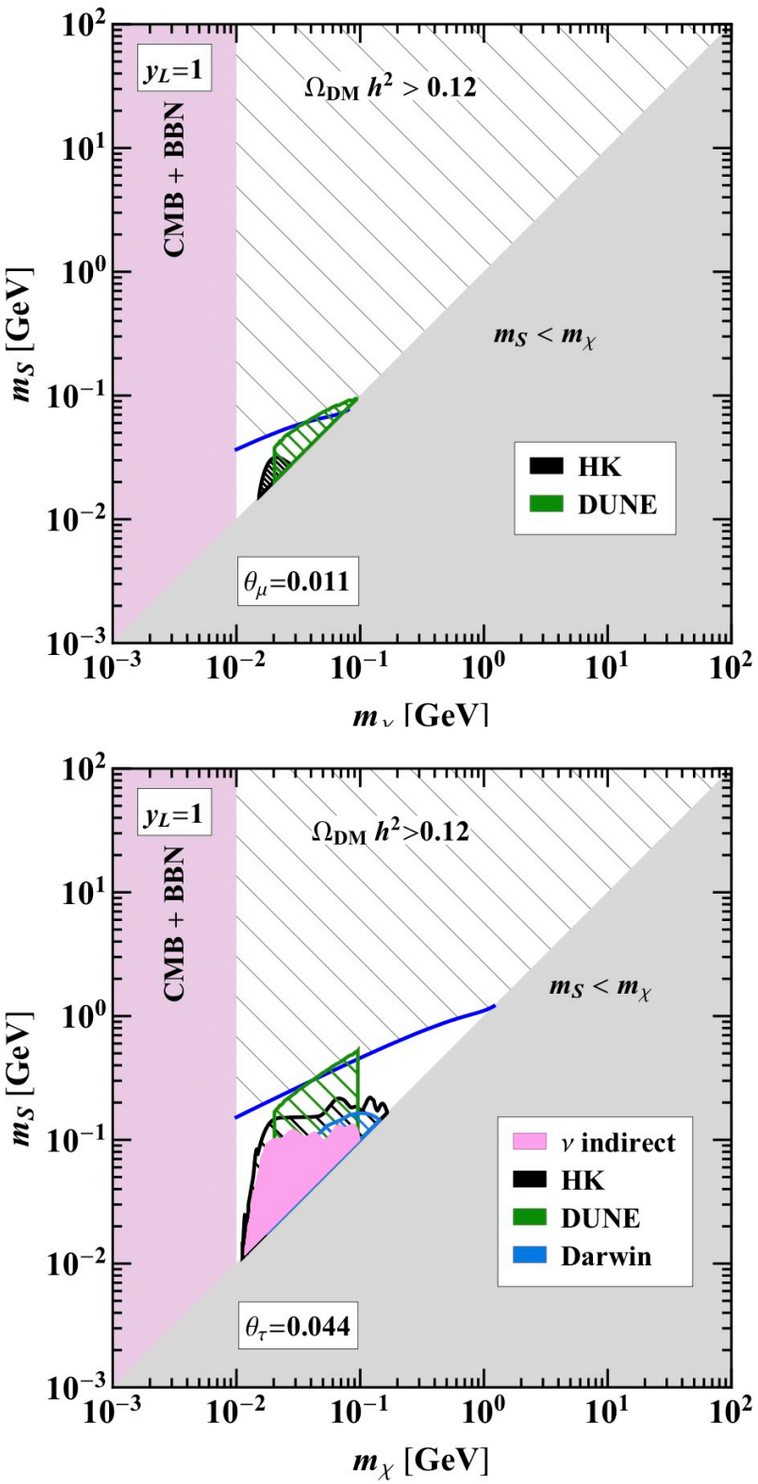
$$G(x) = \frac{x-1-\log x}{4\,(1-x)^2}$$

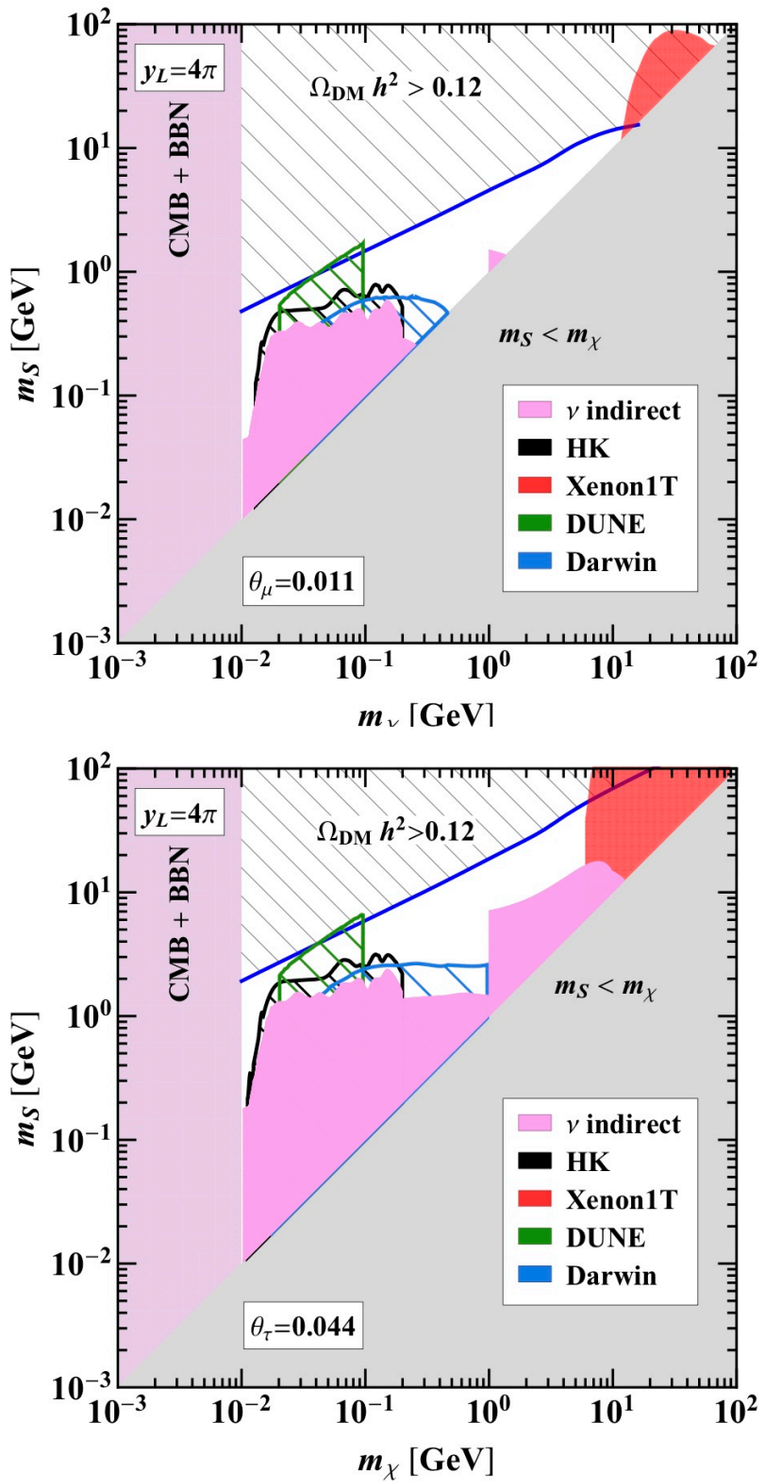
`FeynRules` [Christensen/Duhr'08, Alloul et al.'13]

`FeynArts` [Hahn'00] + `FormCalc` [Hahn/Perez-Victoria'98]

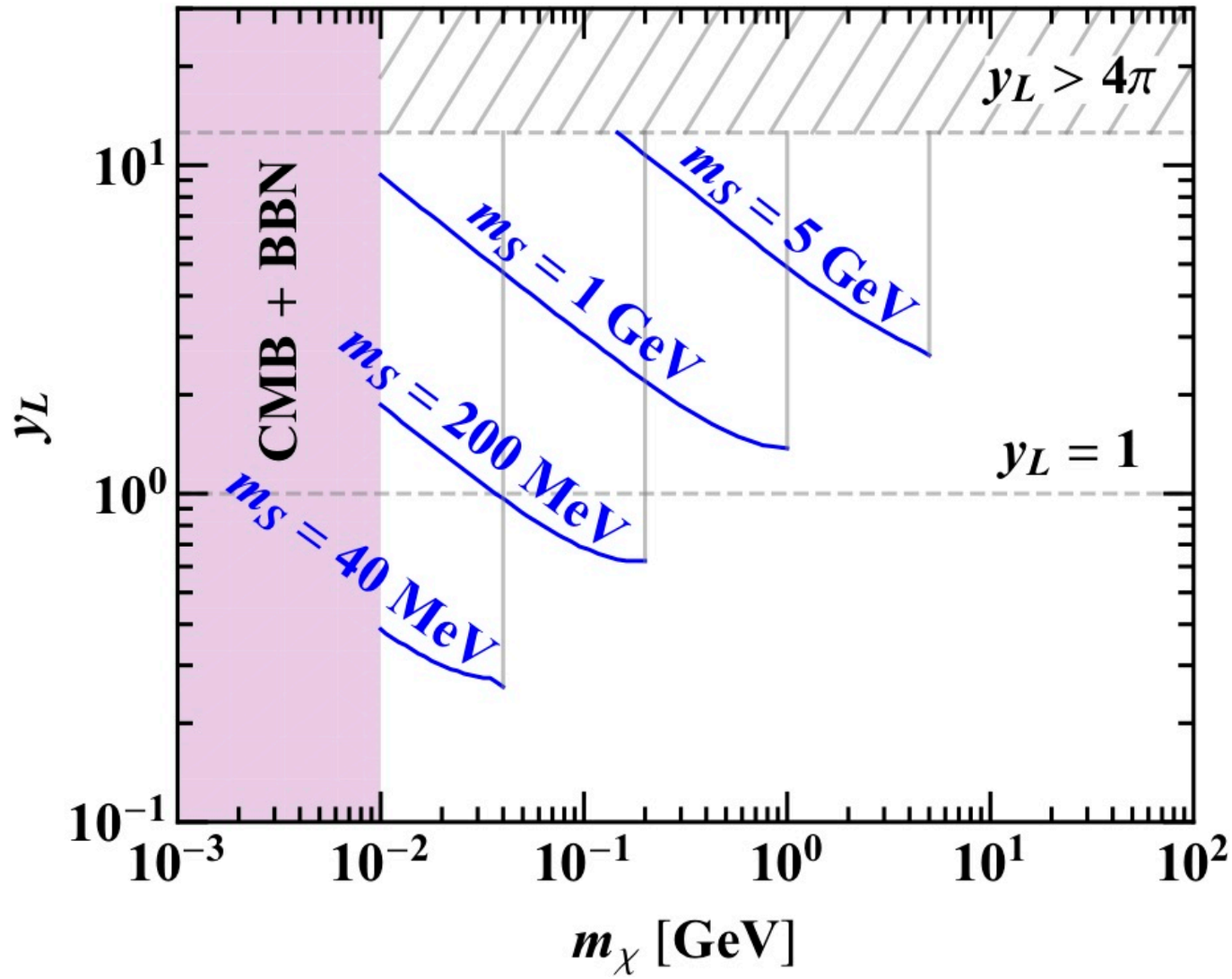
`LoopTools` [Hahn/Perez-Victoria'98] (numerical) and `ANT` [Angel et al.'13] (analytical @ ZEM)

Neutrino portal with a scalar mediator



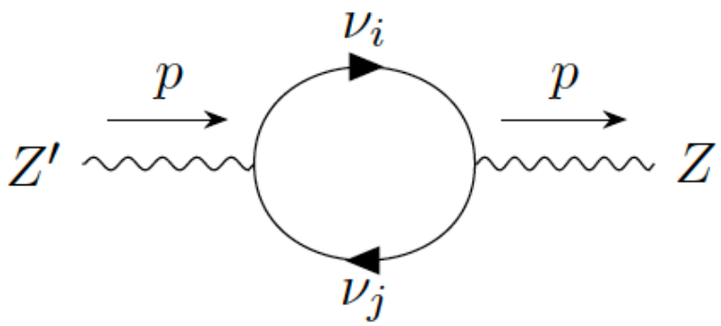


Neutrino portal with a scalar mediator



Neutrino portal with a vector mediator

$Z - Z'$ mixing



The mass eigenstates Z_1 and Z_2 :

$$m^2_{Z_{1,2}} = \frac{\sec^2\epsilon}{2}\left(m^2_Z + m^2_{Z'} - 2\delta m^2 \sin\epsilon \mp \Delta\right)$$

$$\Delta = \mathrm{sgn}\left(m^2_{Z'} - m^2_Z\left(1 - 2\sin^2\epsilon\right) - 2\delta m^2 \sin\epsilon\right)\sqrt{m^4_Z + m^4_{Z'} + 4\delta m^4 - 4\left(m^2_Z + m^2_{Z'}\right)\delta m^2 \sin\epsilon - 2m^2_Z m^2_{Z'}\left(1 - 2\sin^2\epsilon\right)}$$

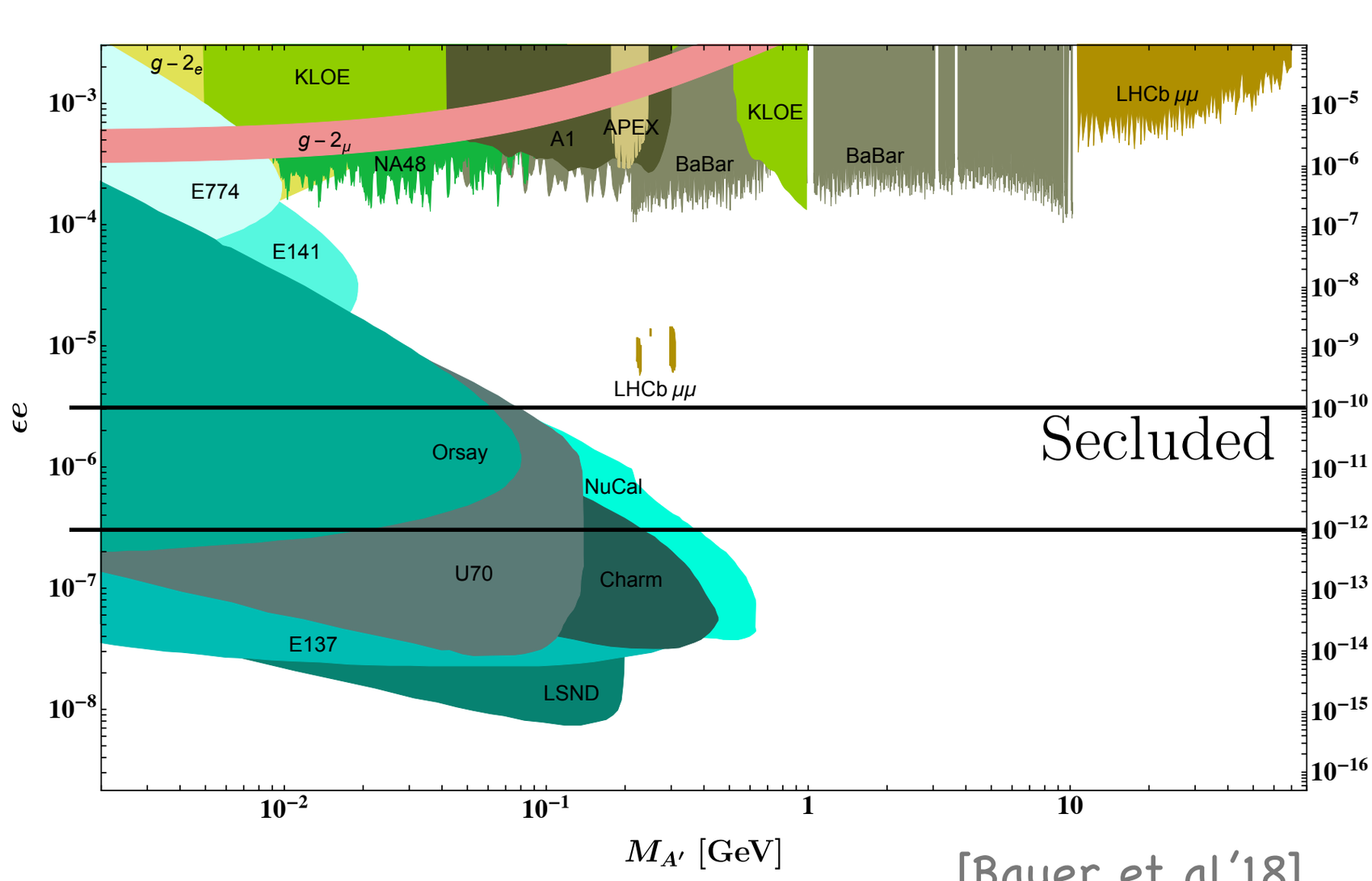
$$Z_\mu = \left(\cos\xi - \tan\epsilon\sin\xi\right) Z_{1\mu} - \left(\sin\xi + \tan\epsilon\cos\xi\right) Z_{2\mu}$$

$$Z'_\mu = \sec\epsilon\left(\sin\xi\, Z_{1\mu} + \cos\xi\, Z_{2\mu}\right)$$

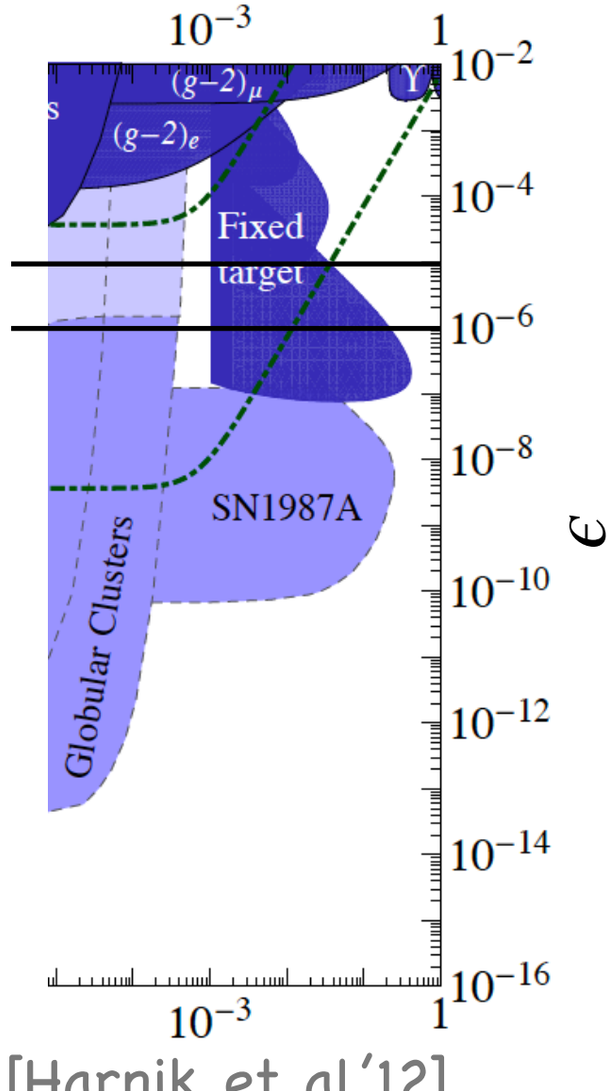
$$\tan\left(2\xi\right) = \frac{2\cos\epsilon\left(m^2_Z\sin\epsilon - \delta m^2\right)}{m^2_{Z'} - m^2_Z\left(1 - 2\sin^2\epsilon\right) - 2\delta m^2\sin\epsilon}$$

Neutrino portal with a vector mediator

$Z - Z'$ mixing $\quad \epsilon \sim 10^{-6} - 10^{-5} \quad$ for $\quad g' = 1$

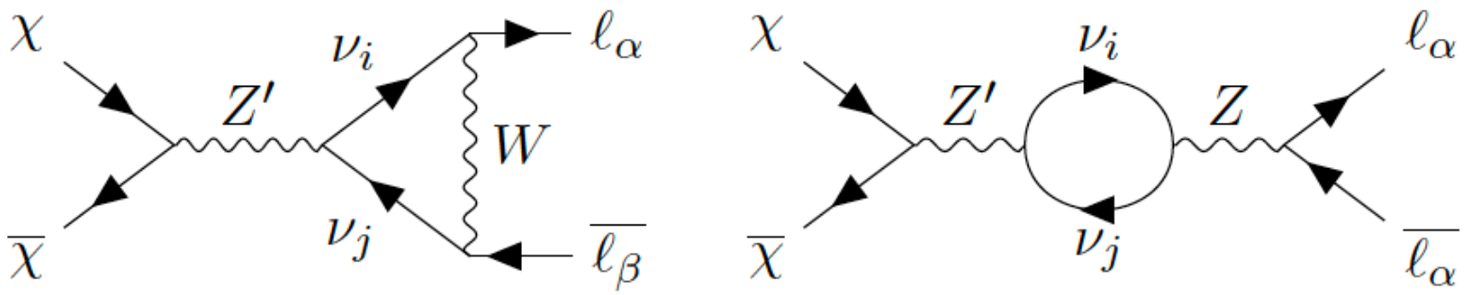


[Bauer et al.'18]



[Harnik et al.'12]

Neutrino portal with a vector mediator



$$a_W g' \overline{\ell}_\alpha \gamma^\mu P_L \ell_\beta Z'_\mu$$

In the limit of zero external momenta

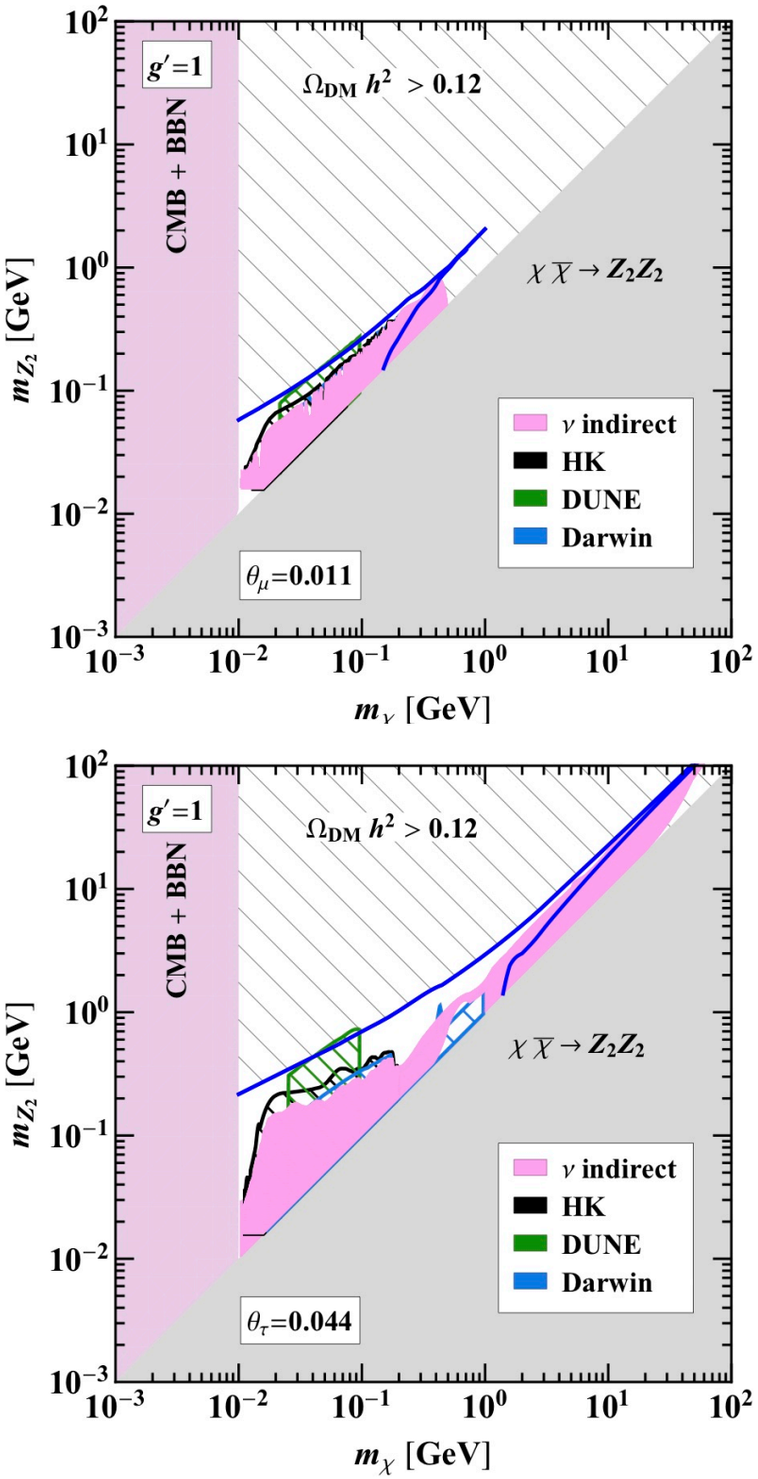
$$a_W = |U_{s4}|^2 U_{\alpha 4} U^*_{\beta 4} \frac{g^2}{(4\pi)^2} \frac{m_4^2}{2m_W^2}$$

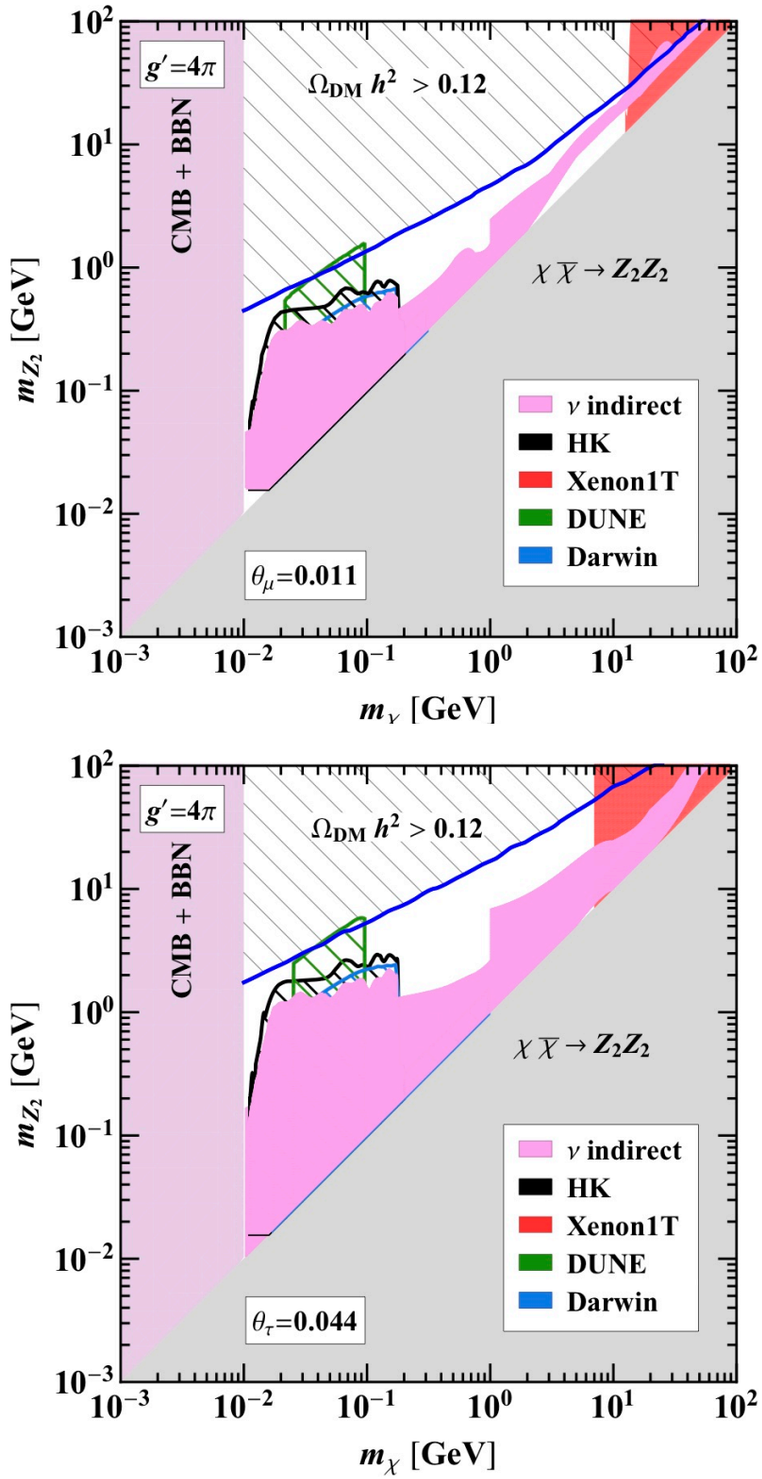
`FeynRules` [Christensen/Duhr'08, Alloul et al.'13]

`FeynArts` [Hahn'00] + `FormCalc` [Hahn/Perez-Victoria'98]

`LoopTools` [Hahn/Perez-Victoria'98]

Neutrino portal with a vector mediator





Neutrino portal with a vector mediator