Neutrino Portal to Dark Matter

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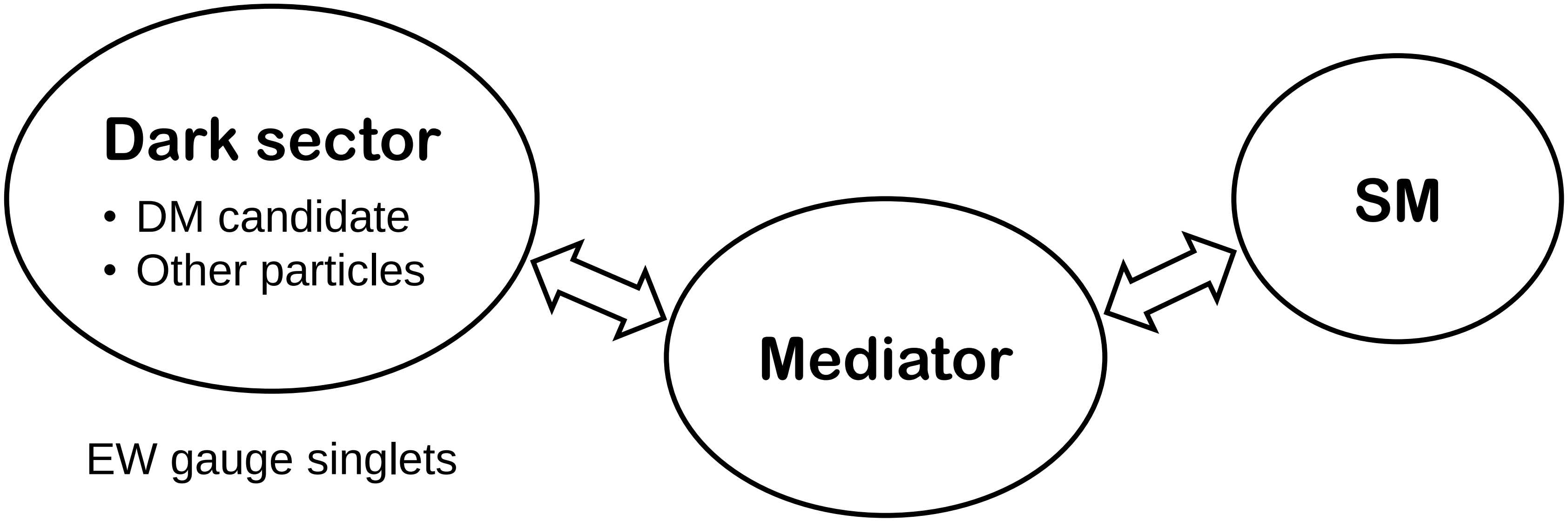
Outline

- Introduction: portal paradigm
- Model
  - DM annihilation to neutrinos
  - DM annihilation to charged leptons
- Experimental constraints
  - Indirect detection
  - Direct detection
- Parameter space of the model
- Conclusions

Introduction: portal paradigm



- Vector portal: $B_{\mu\nu} X^{\mu\nu}$ [Okun'82, Galison/Manohar'84, Holdom'86]
- Higgs portal: $H^\dagger H\, S$ [Silveira/Zee'85, Patt/Wilczek'06]
- Neutrino portal: $\overline{L}\, \tilde{H}\, N_R$ [Minkowski'77, Yanagida'79, Glashow'79, Gell-Mann et al.'79, Mohapatra/Senjanovich'80, Pospelov et al.'07]

Introduction: portal paradigm

Secluded annihilation

$m_{\mathrm{DM}} > m_{\mathrm{med}}$

DM DM → Mediator Mediator

Mediator-SM coupling
can be small

DM DM → N N, N → …

Indirect signatures

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

[See poster by Folgado]

Direct annihilation

$m_{\mathrm{DM}} < m_{\mathrm{med}}$

DM DM → SM SM

[Pospelov et al.'07]

Large mediator-SM coupling
to avoid DM overproduction

DM DM → $\boldsymbol{\nu\,\nu}$

Large DM-neutrino interaction

[Bertoni et al.'14]

Heavy DM phenomenology

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

On the mediator-SM coupling

- Type I seesaw mechanism:

$$\mathcal{L} \supset -\lambda\,\overline{L}\,\tilde{H}\,N_R - \frac{1}{2}\,M\,\overline{N_R^c}\,N_R$$

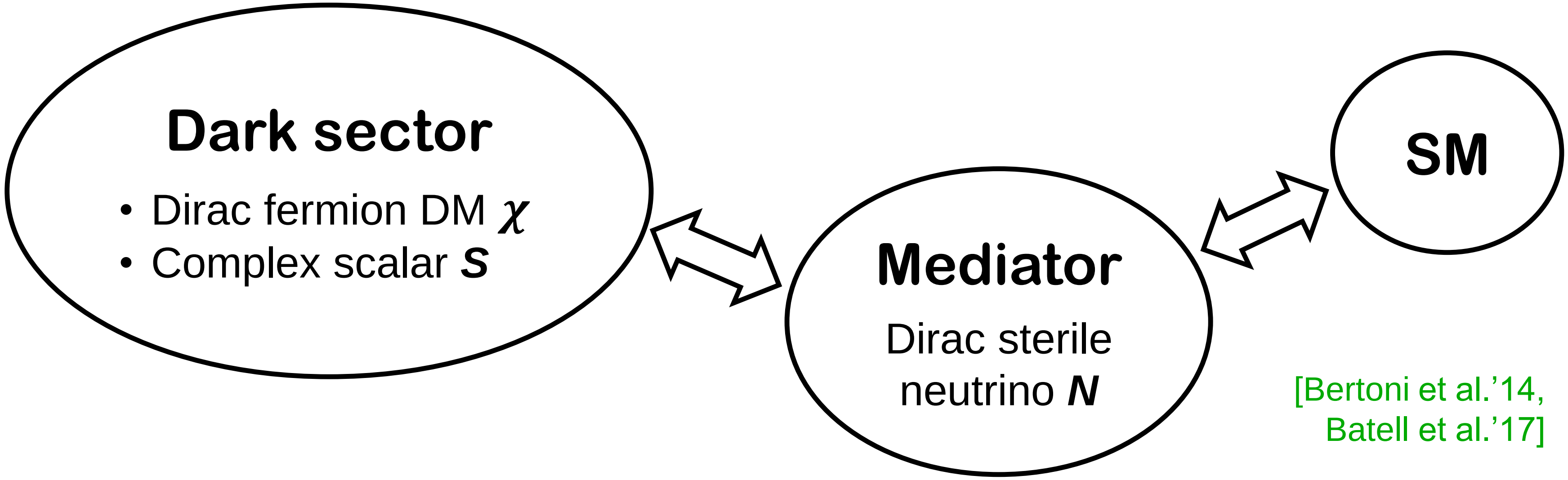
Mixing $\theta \sim \lambda\, v/M$ is proportional to light neutrino masses, and thus, suppressed

- (Approximate) global $U(1)_L$ lepton number symmetry:

$$\mathcal{L} \supset -\lambda\,\overline{L}\,\tilde{H}\,N_R - m_N\,\overline{N_L}\,N_R$$

Mixing is not proportional to light neutrino masses, and thus, can be (relatively) large

Model



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

$$-\mathcal{L} \supset m_\chi \overline{\chi}\chi + m_N \overline{N} N + \left[\lambda_\alpha \, \overline{L_\alpha} \tilde{H} N_R + \overline{\chi}\left(y_L N_L + y_R N_R\right) S + \text{h.c.}\right]$$
$$+ \mu_S^2 \left|S\right|^2 + \lambda_S \left|S\right|^4 + \lambda_{SH} \left|S\right|^2 H^\dagger H$$

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

$$\mathrm{L}(L) = \mathrm{L}(N) = \mathrm{L}(S^*)$$

- Global $U(1)_D$ dark symmetry

$$\mathrm{Q}_D(\chi) = \mathrm{Q}_D(S)$$

Model

Neutrino sector

$$m_4 = \sqrt{m_N^2 + \sum_\alpha \lambda_\alpha^2 \, v^2} \qquad\qquad m_{1,2,3} = 0$$

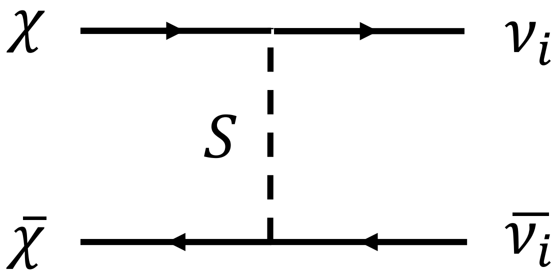
$$\begin{pmatrix} \nu_{\alpha L} \\ N_L \end{pmatrix} = \begin{pmatrix} U_{\alpha i} & U_{\alpha 4} \\ U_{si} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_{iL} \\ \nu_{4L} \end{pmatrix} \qquad \alpha = e, \mu, \tau \quad i = 1, 2, 3$$

$$U_{\alpha 4} = \frac{\lambda_\alpha \, v}{m_4} = \frac{\theta_\alpha}{r} \qquad U_{s4} = \frac{m_N}{m_4} = \frac{1}{r} \qquad r = \sqrt{1 + \sum_\alpha |\theta_\alpha|^2}$$

The mixing angles are not proportional to the light neutrino masses and can be (relatively) large

DM annihilation to neutrinos

$m_\chi < m_S < m_4$ (direct annihilation regime)



$$\langle \sigma v \rangle \approx \frac{y_L^4 \, |U_{si}|^4}{32\,\pi} \frac{m_\chi^2}{\left(m_\chi^2 + m_S^2\right)^2}$$

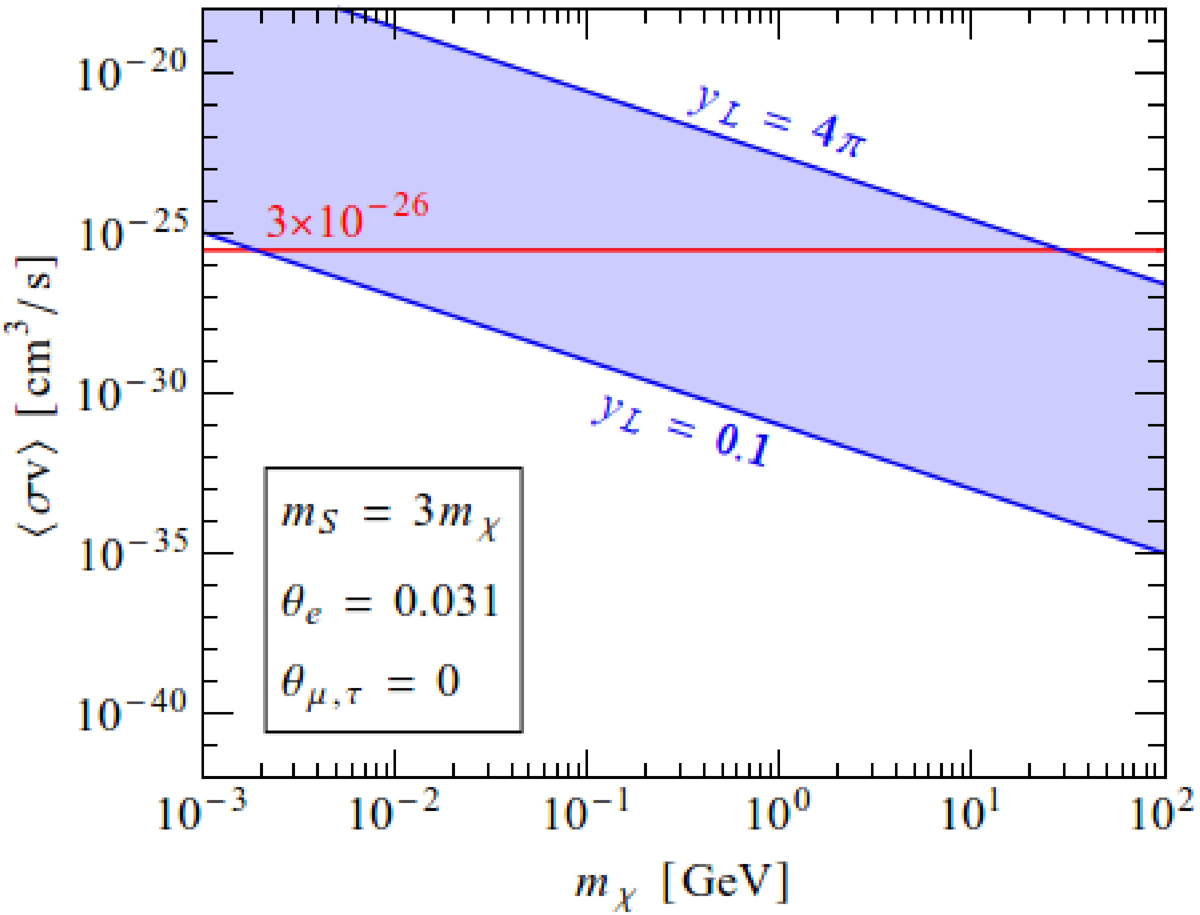
Thermal freeze-out:

$$\Omega_{\rm DM} h^2 \approx \frac{3 \times 10^{-27} \ {\rm cm}^3/{\rm s}}{\langle \sigma \, v \rangle}$$

[Jungman et al.'95]

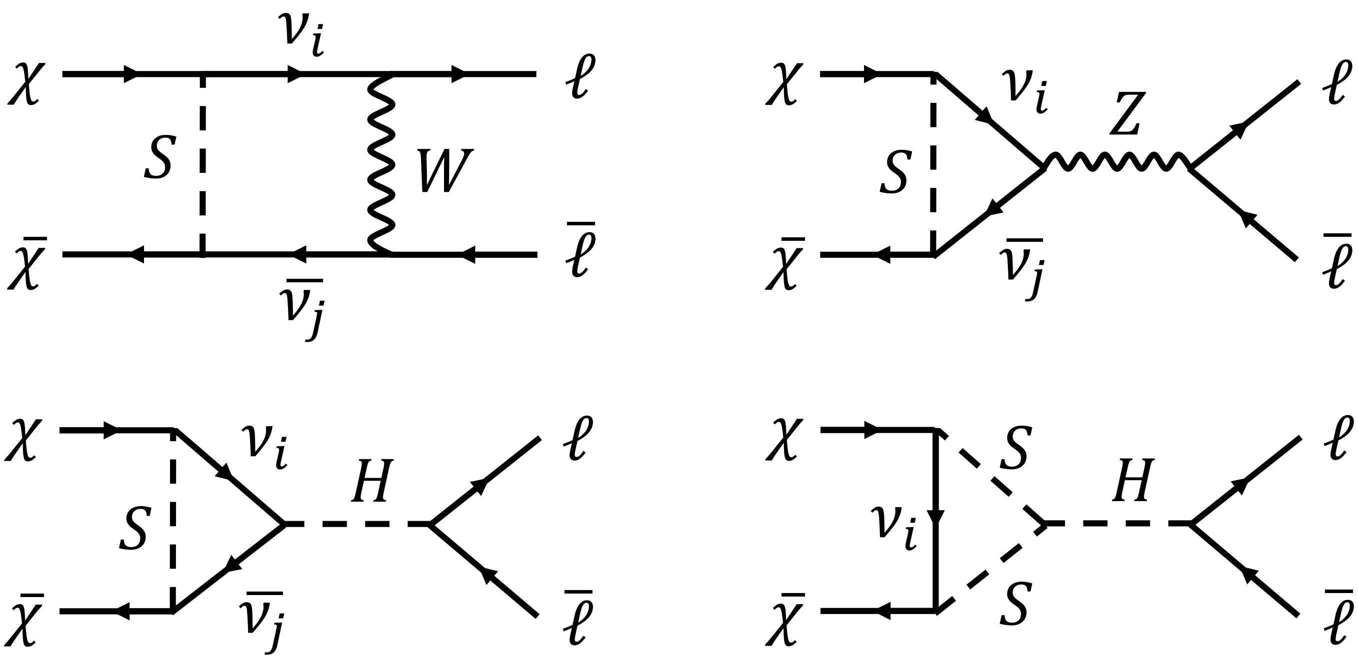
$\langle \sigma \, v \rangle \approx 3 \times 10^{-26} \ {\rm cm}^3/s$ to reproduce (roughly) the DM abundance

DM annihilation to neutrinos



The value of θ_e is taken from [Fernandez-Martinez et al.'16]

DM annihilation to charged leptons



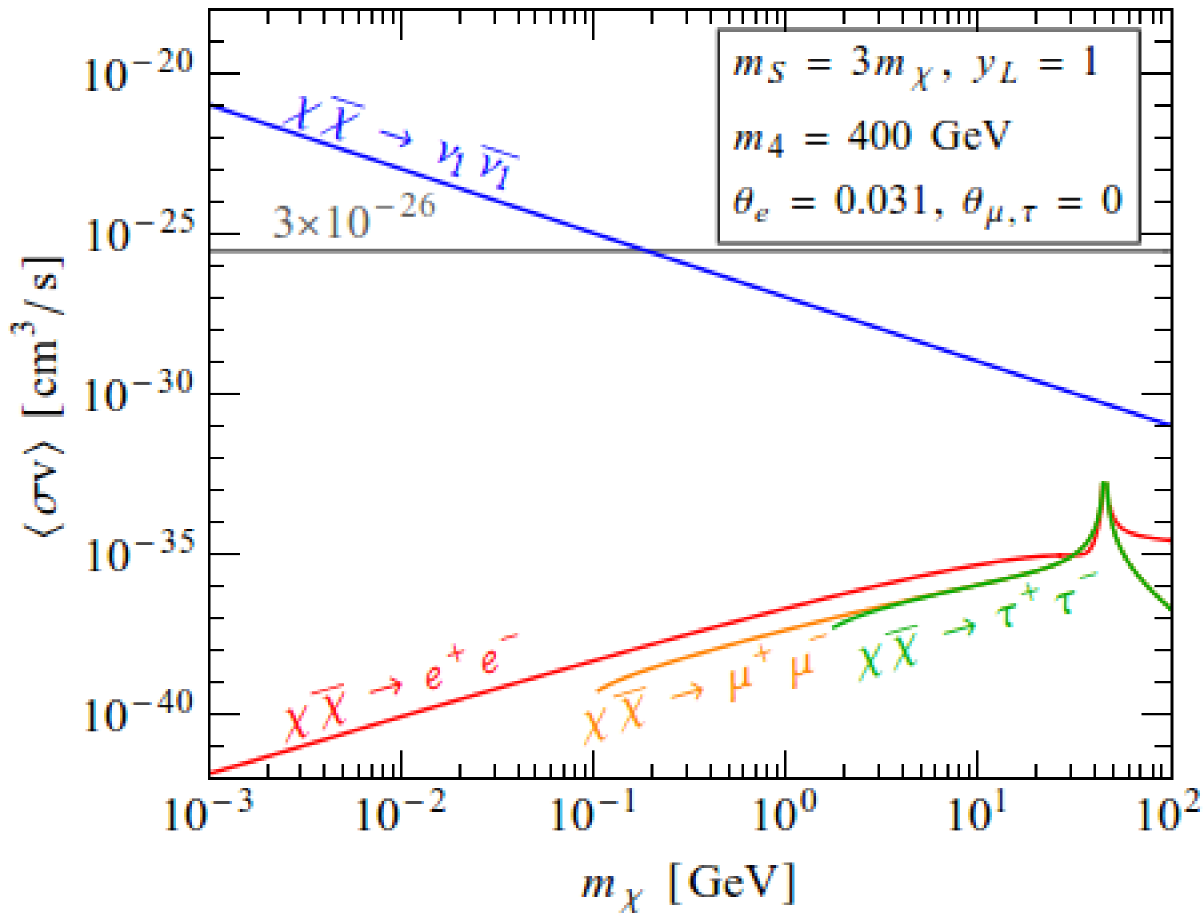
FeynRules [Christensen/Duhr'08, Alloul et al.'13]

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

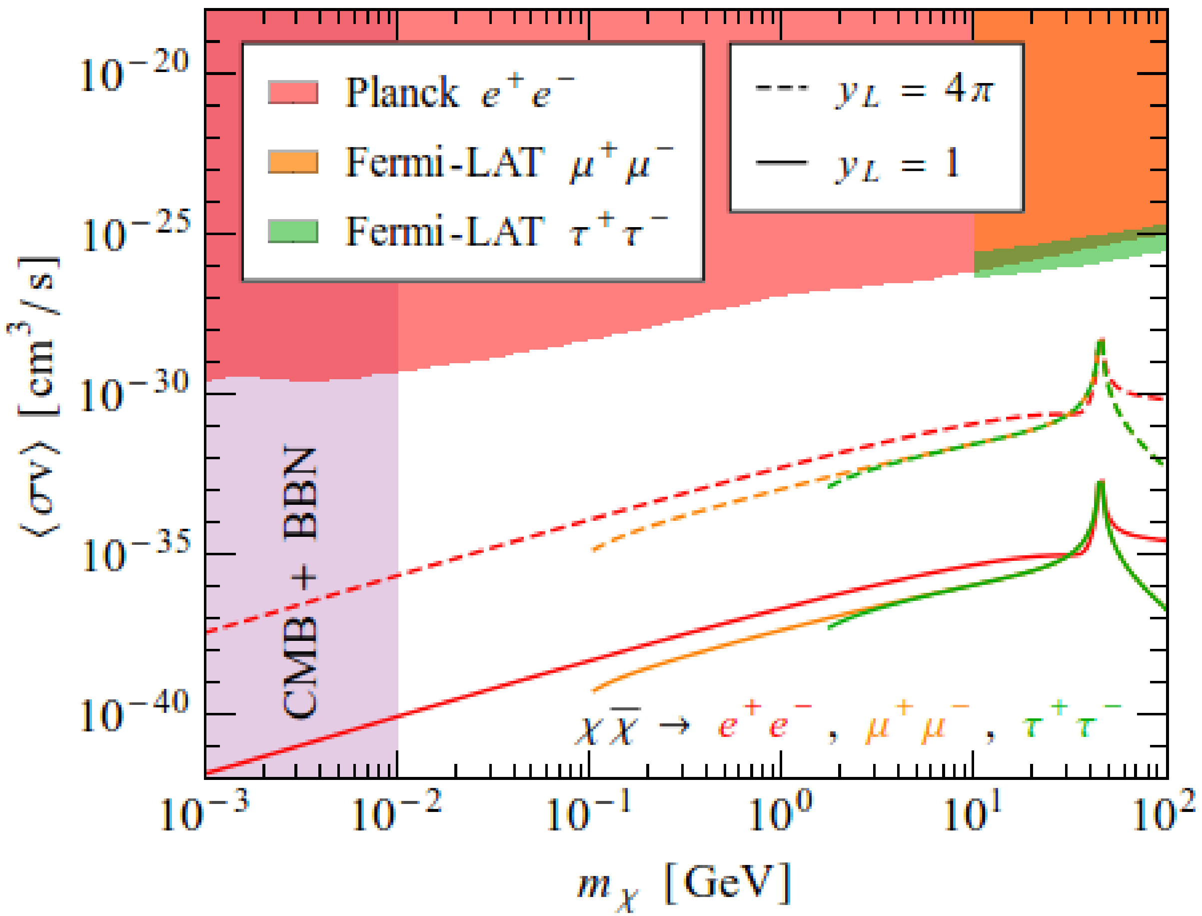
- LoopTools [Hahn/Perez-Victoria'98]: exact (numerical)
- ANT [Angel et al.'13]: zero external momenta approximation (analytical)

The approximation works very well

DM annihilation to charged leptons



Charged leptons: ID constraints



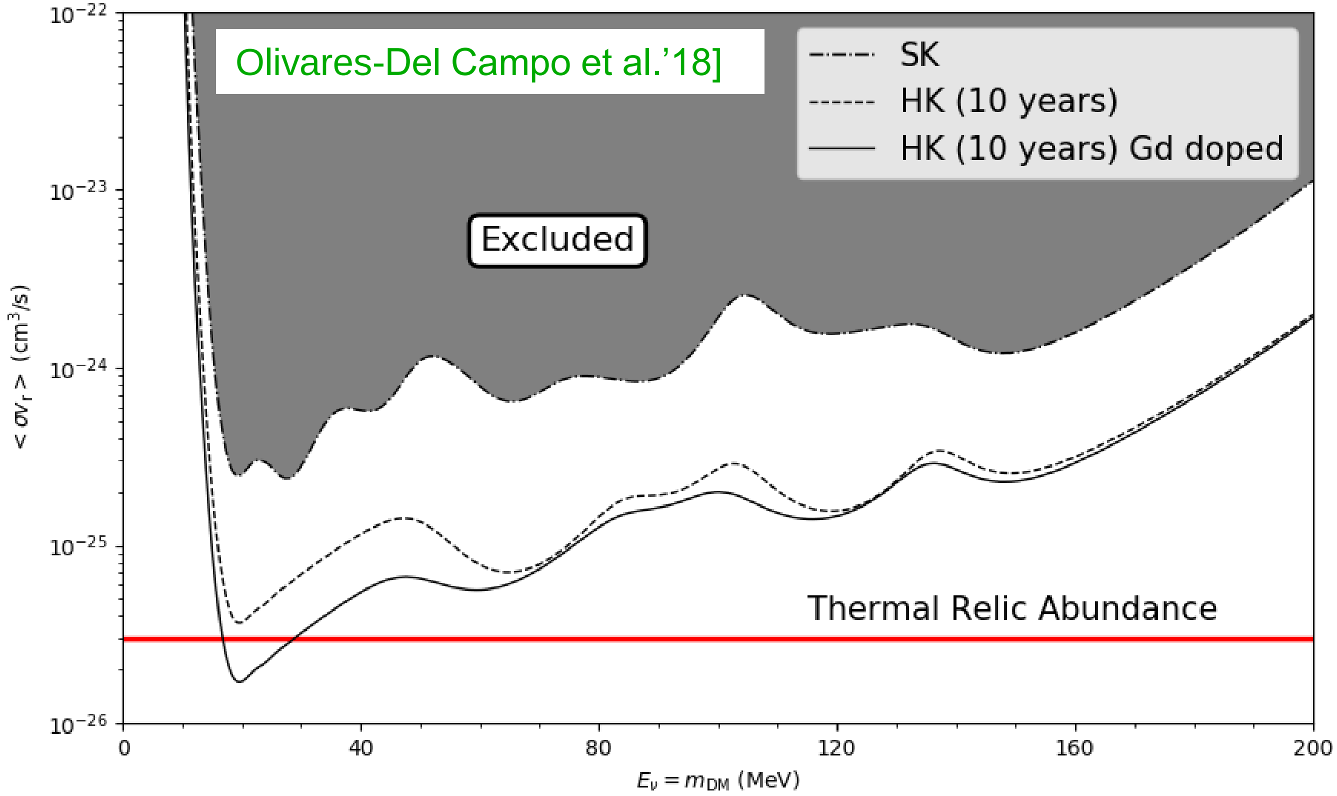
Planck [Slatyer'15] Fermi-LAT [MAGIC/Fermi-LAT'16]

Neutrino experiments

DM DM $\rightarrow \boldsymbol{\nu}\,\boldsymbol{\nu}$: monochromatic flux of ν's with $E_\nu = m_\chi$ [Palomares-Ruiz/Pascoli'07]

DM annihilation in the Milky Way halo
10–200 MeV: Super-K and Hyper-K

[Palomares-Ruiz/Pascoli'07, Palomares-Ruiz'07, Olivares-Del Campo et al.'17'18]

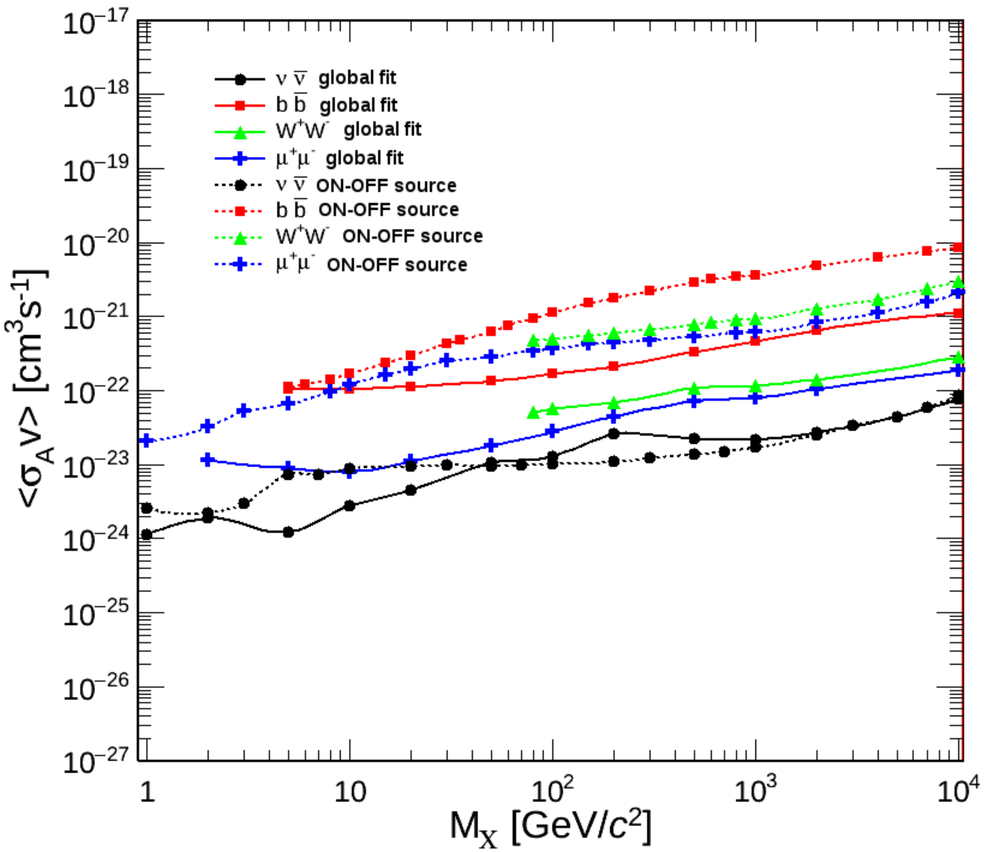


Neutrino experiments

DM annihilation in the galactic centre

$1\text{–}10^4$ GeV: Super-K analysis

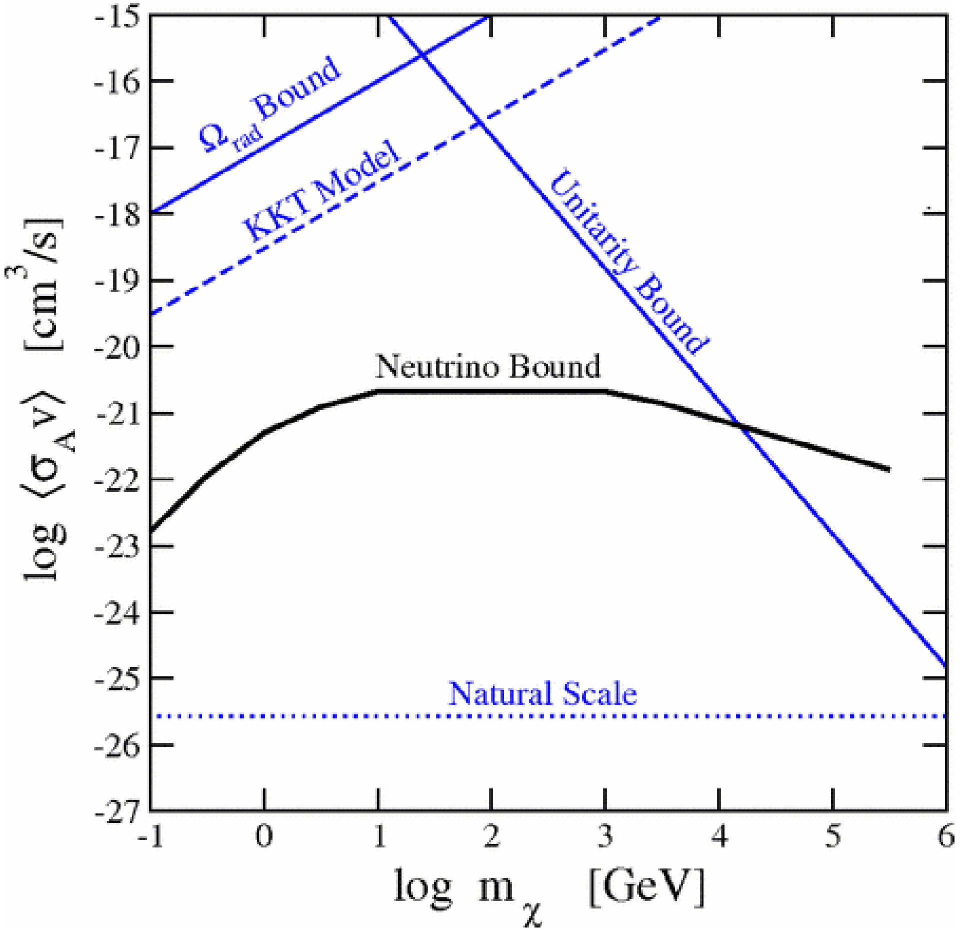
[Frankiewicz for Super-K'15]



Neutrino experiments

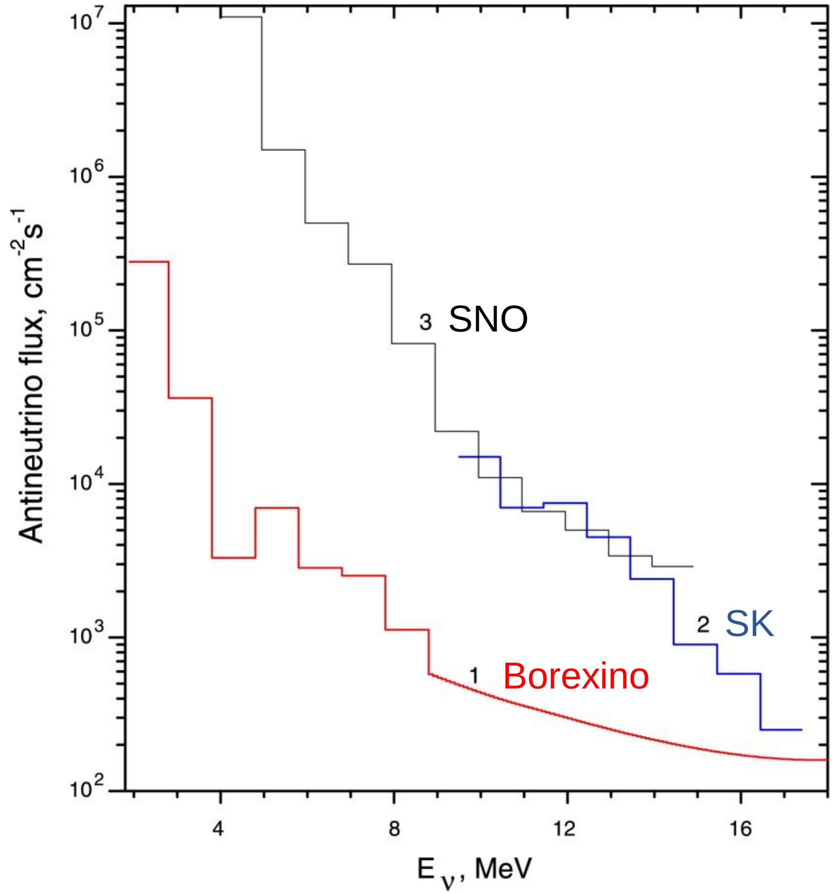
Cosmic diffuse neutrino flux from DM annihilations in all halos in the Universe

0.1–10^5 GeV: Super-K, Fréjus, AMANDA [Beacom et al.'06]

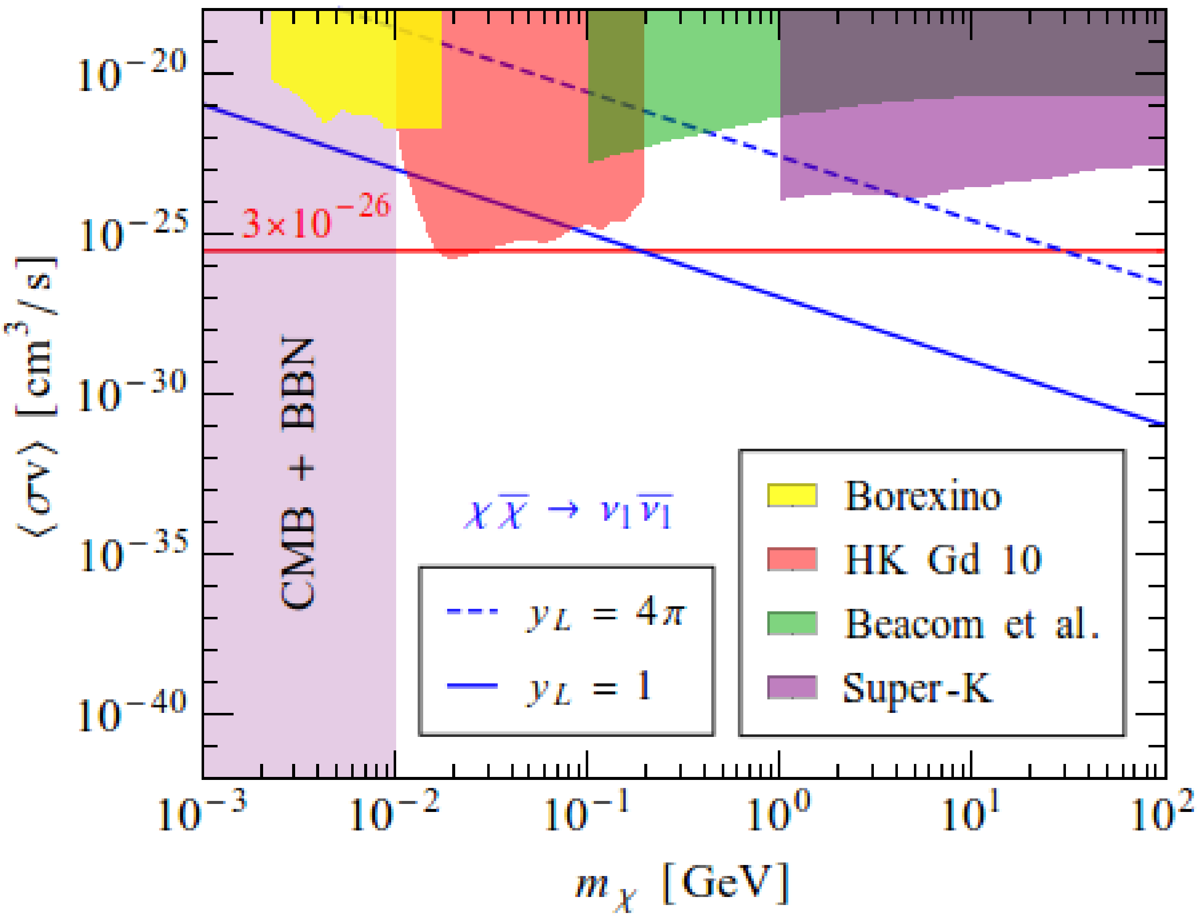


Neutrino experiments

Monochromatic antineutrino flux measured by Borexino [Borexino'10]
⇒ conservative upper bound on $\langle \sigma v \rangle$
2–17 MeV: Borexino [Olivares-Del Campo et al.'17]



Neutrinos: ID constraints



Direct detection

$$\mathcal{L} \supset a_Z \frac{g}{c_W} \overline{\chi} \gamma^\mu P_R \chi Z_\mu$$

[Batell et al.'17]

$$a_Z = |U_{s4}|^2 \left(1 - |U_{s4}|^2\right) \frac{y_L^2}{16\,\pi^2} G\left(\frac{m_S^2}{m_4^2}\right)$$

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

in the limit of zero external momenta

Effective DM-nucleon SI scattering cross section:

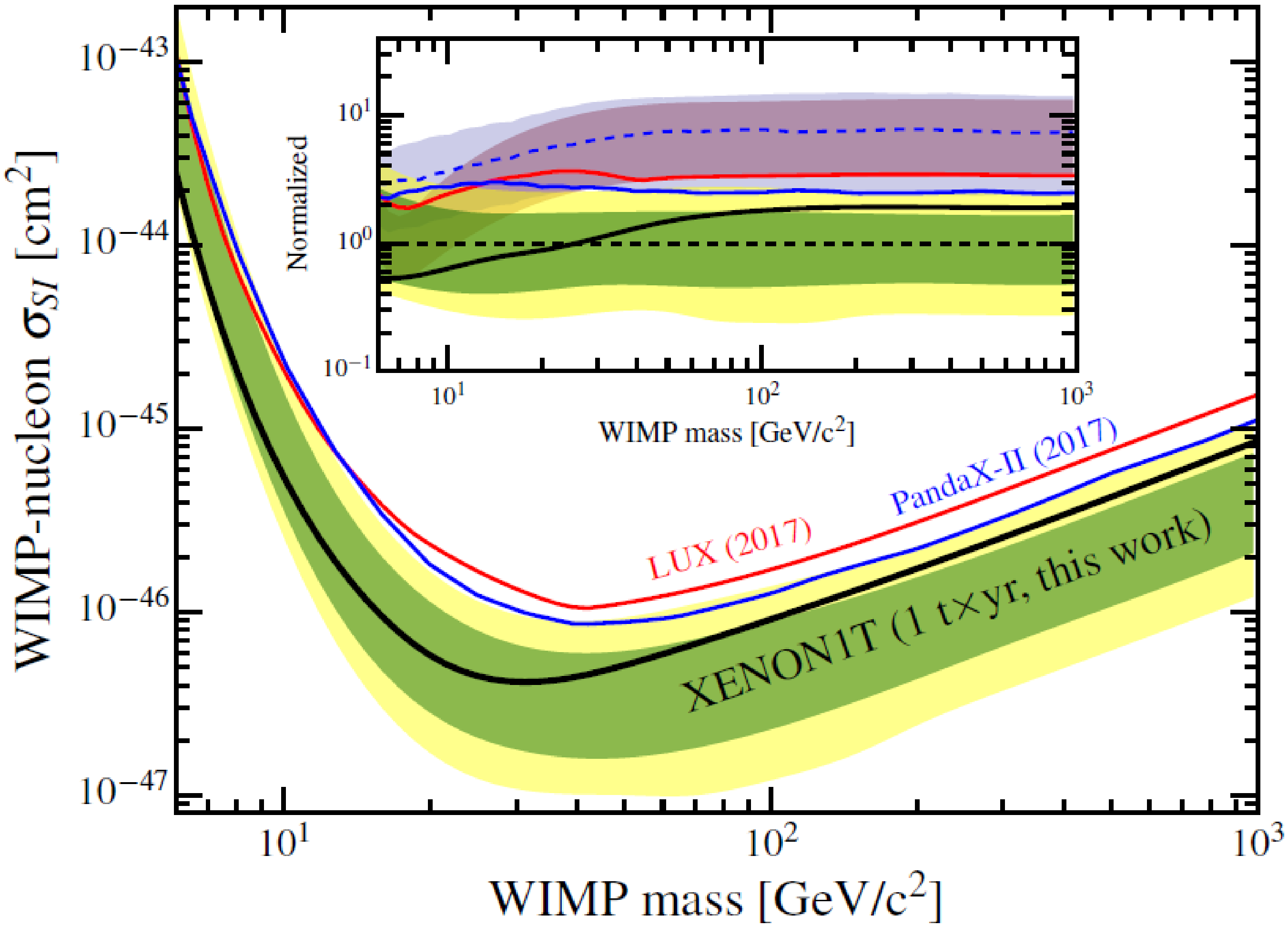
$$\sigma_n = \frac{\mu_n^2}{\pi} \frac{(Z\, f_p + (A-Z)\, f_n)^2}{A^2}$$

$$\mu_n = \frac{m_\chi\, m_n}{m_\chi + m_n} \qquad f_p = -\frac{1}{\sqrt{2}} (1 - 4 s_W^2)\, G_F\, a_Z \qquad f_n = \frac{G_F\, a_Z}{\sqrt{2}}$$

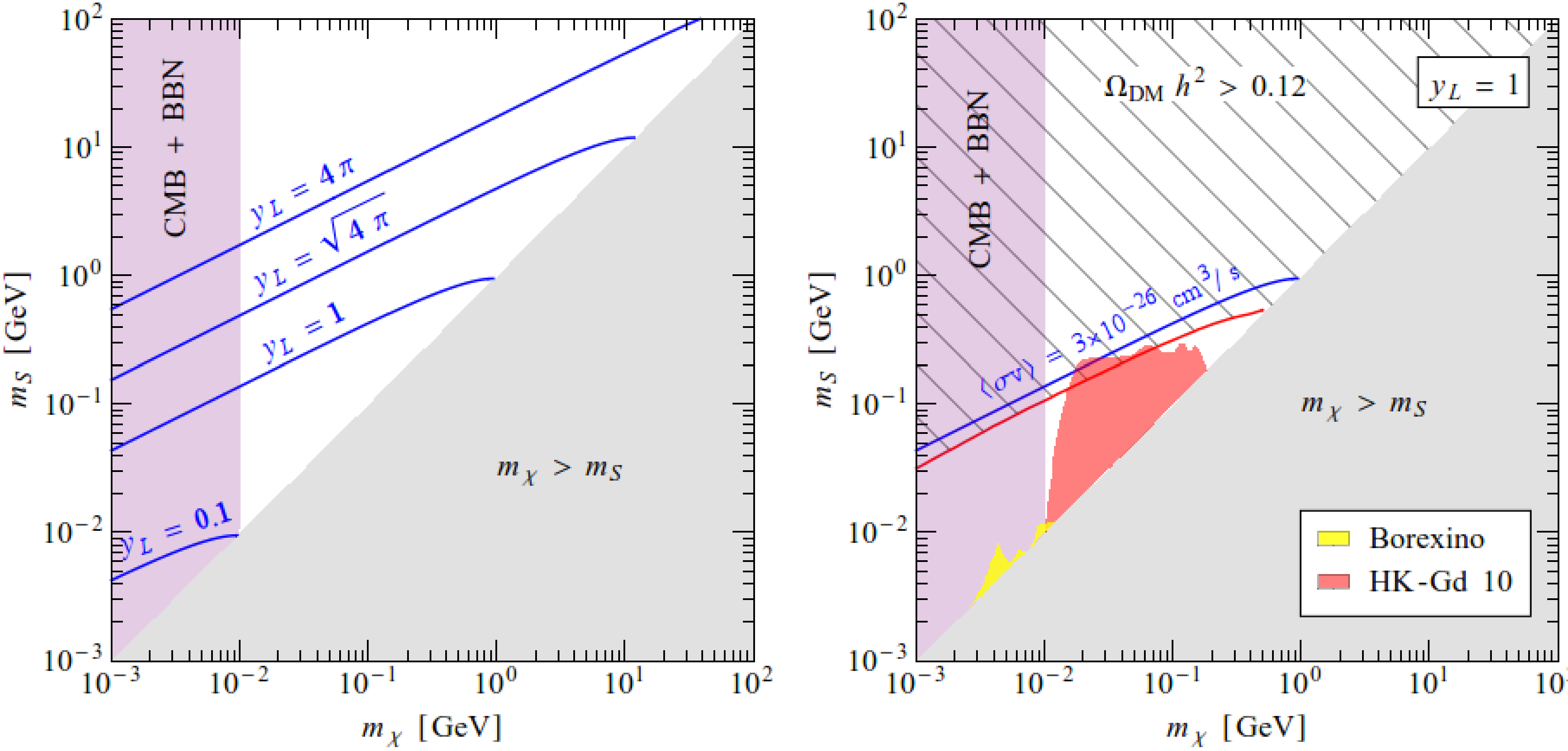
Direct detection

6–10^3 GeV: XENON1T

[XENON'18]

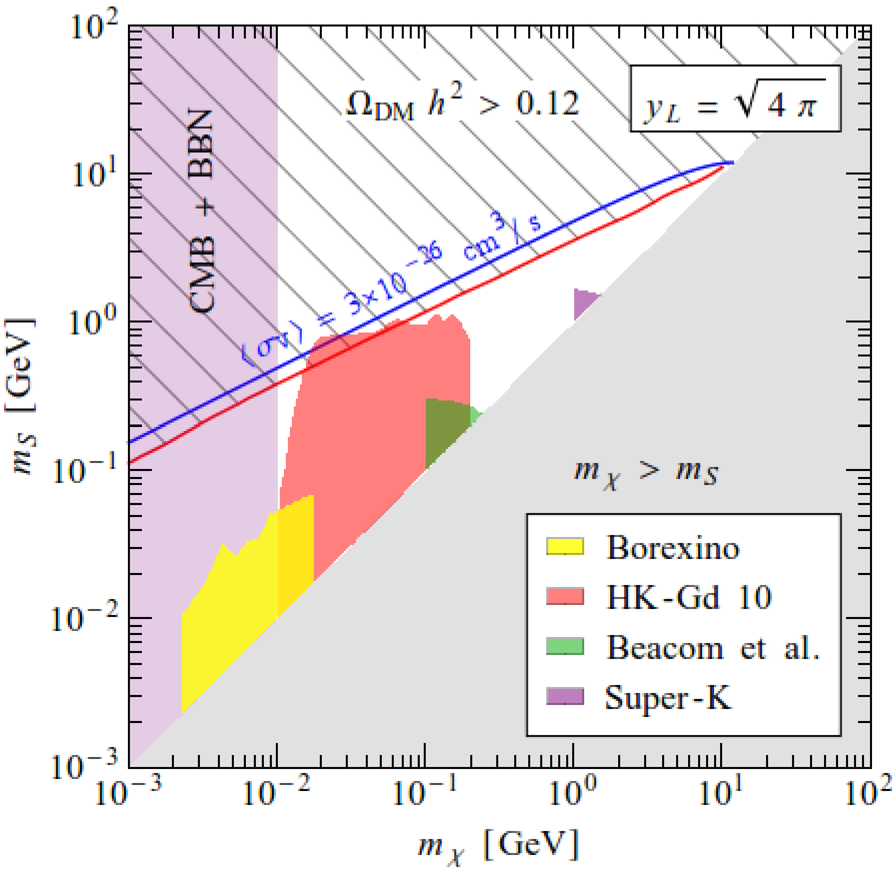


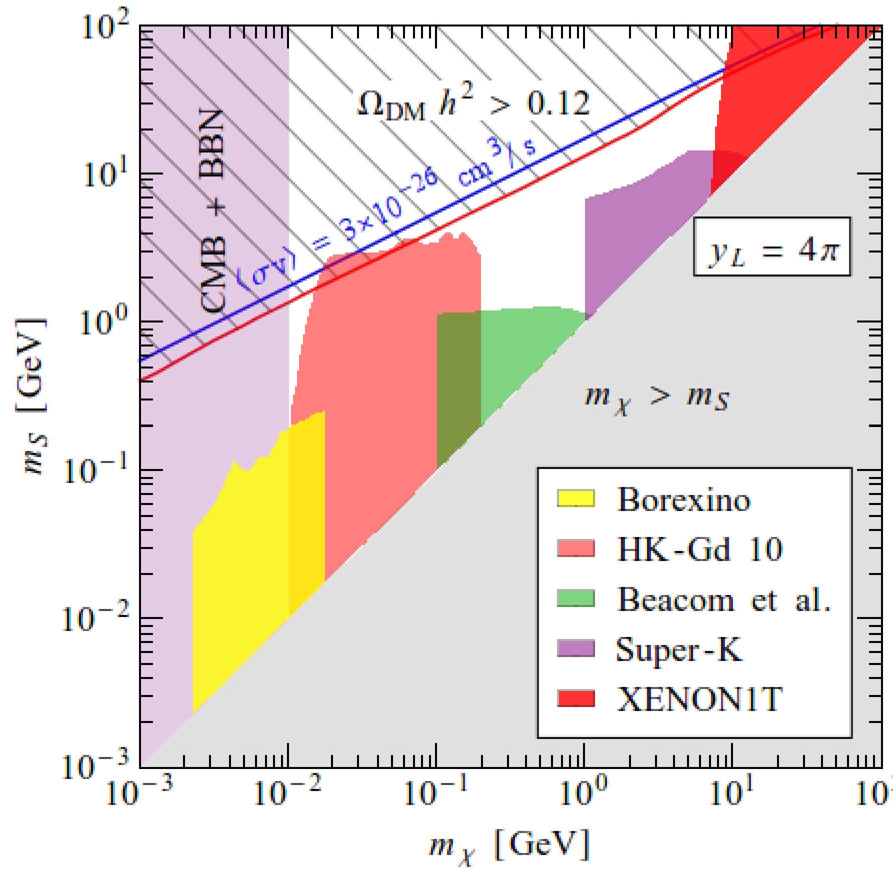
Parameter space: m_{DM}–m_S plane



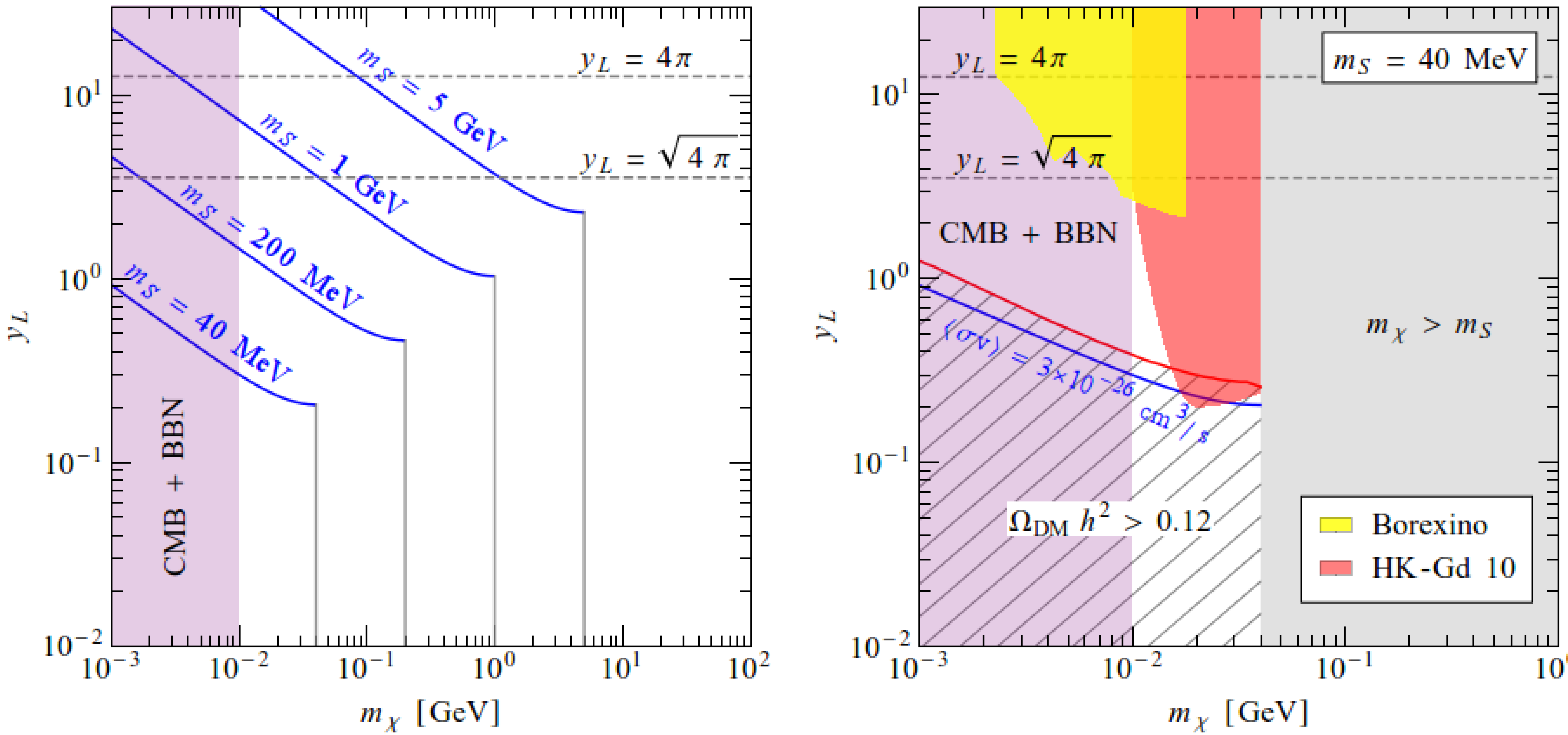
The red line along which $\Omega_{\rm DM} h^2 = 0.12$
is obtained with micrOMEGAs [Bélanger et al.'01]

Parameter space: m_{DM}–m_S plane

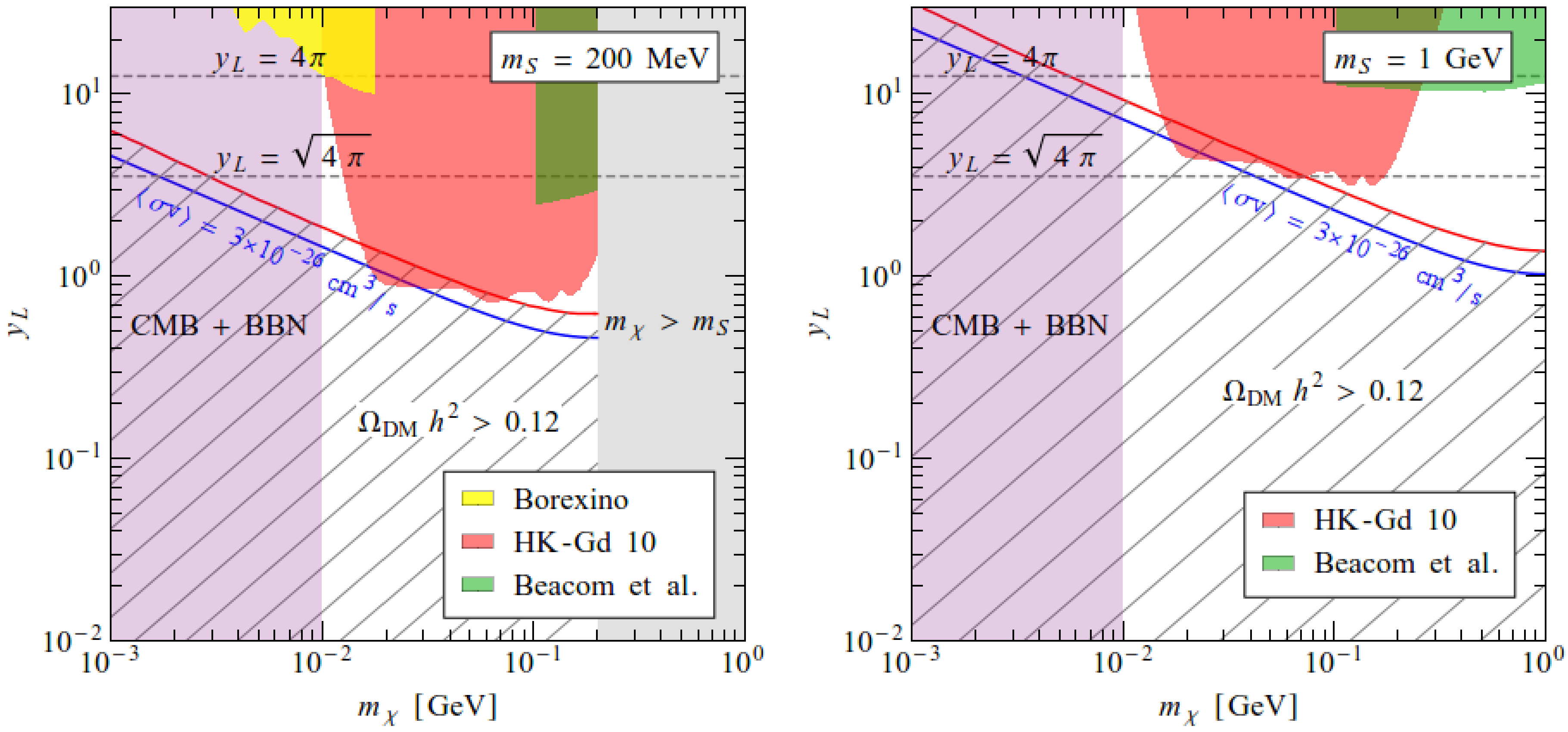




Parameter space: m_{DM}–y_L plane



Parameter space: m_{DM}–y_L plane



Conclusions

- Example of a gauge-invariant model realising sizeable DM–neutrino interactions
- Neutrino experiments dominate sensitivity to DM
- DM–charged lepton and DM–quark interactions are loop suppressed
- The model evades ID constraints from search for DM annihilation to charged leptons

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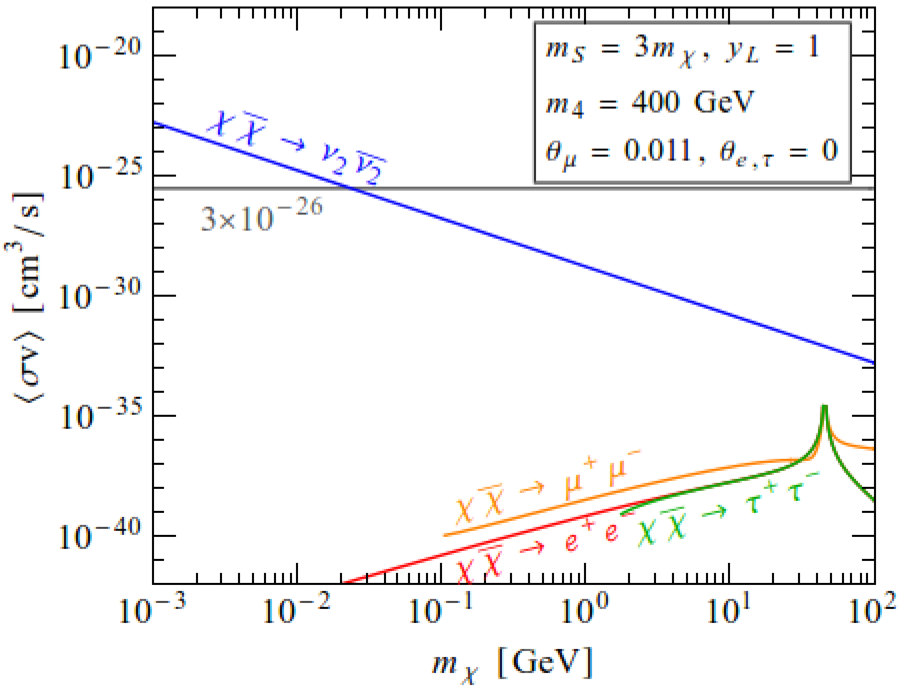
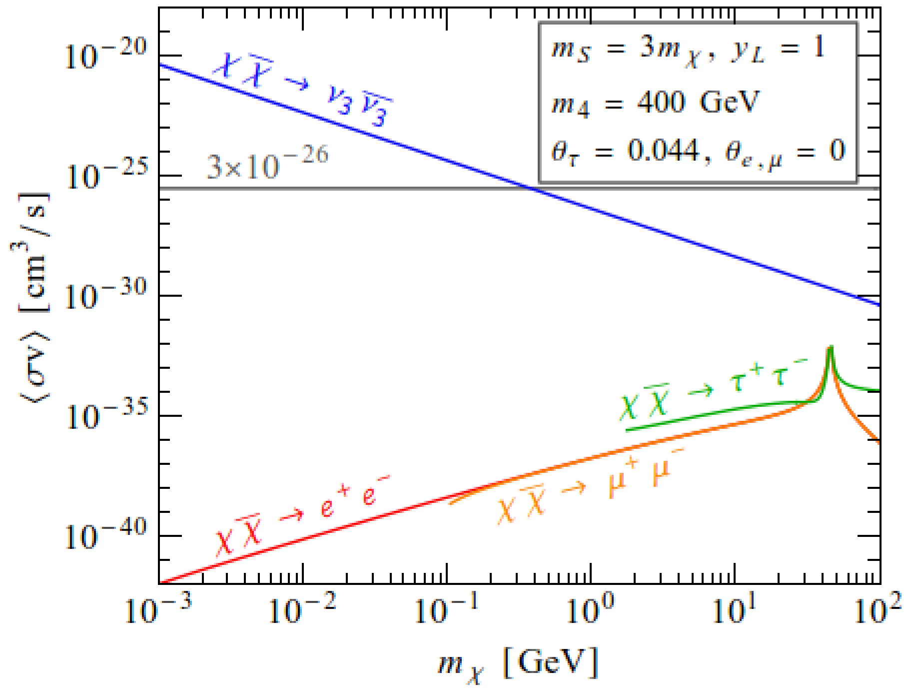
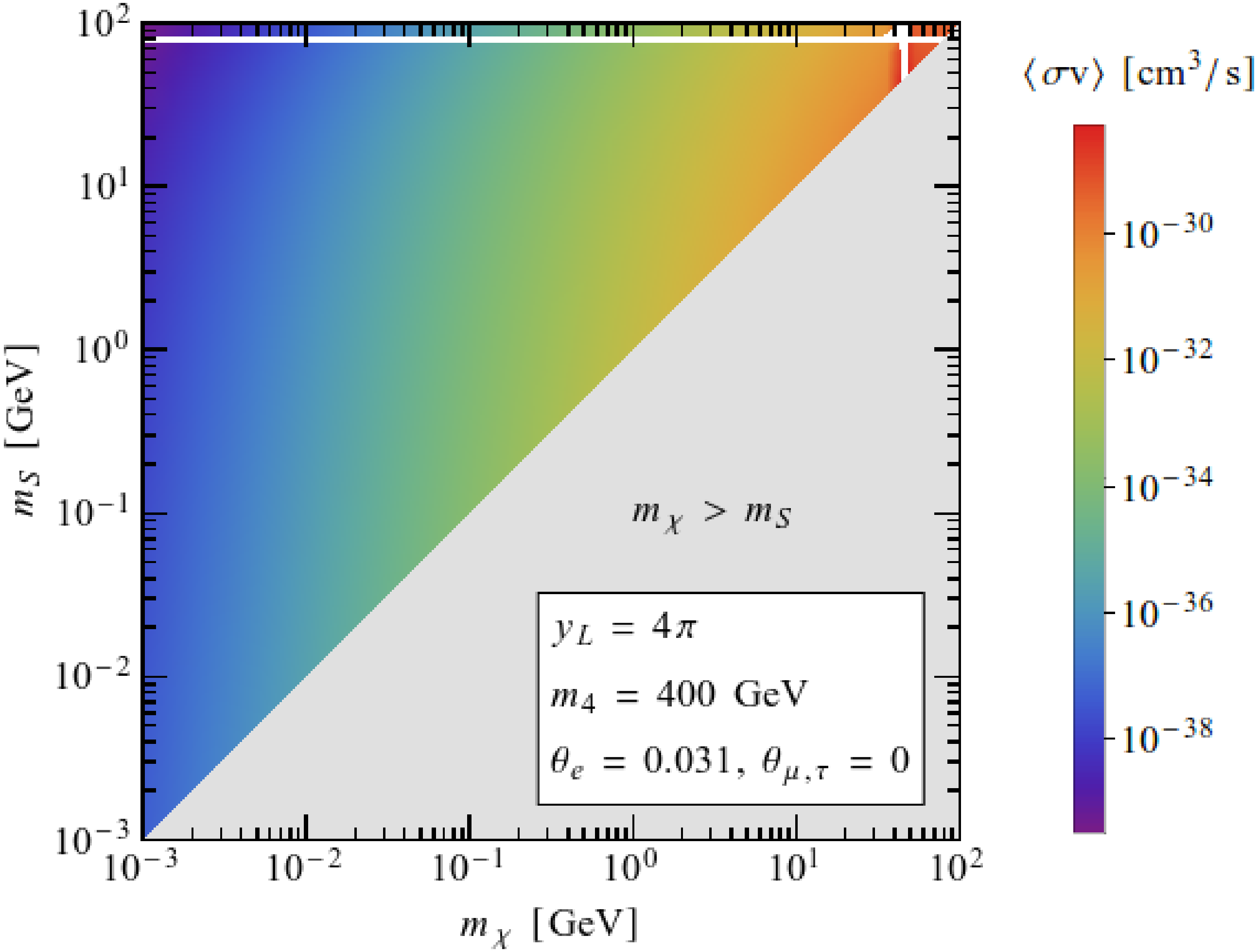
Backup

DM annihilation to charged leptons





Annihilation to e^+e^-



Neutrino flux from DM annihilation

Differential neutrino and antineutrino flux per flavor produced by DM annihilations in the Milky Way halo [Palomares-Ruiz/Pascoli'07]:

$$\frac{\mathrm{d}\Phi}{\mathrm{d}E_\nu} = \frac{1}{3} \langle \sigma\, v \rangle\, \mathcal{J}_{\mathrm{avg}}\, \frac{R_0\, \rho_0^2}{m_\chi^2}\, \delta(E_\nu - m_\chi)$$

$$R_0 = 8.5\ \mathrm{kpc} \qquad \rho_0 = 0.3\ \mathrm{GeV/cm^3}$$

$$\mathcal{J}_{\mathrm{avg}} = \frac{1}{2\, R_0\, \rho_0^2} \int_{-1}^{1} \int_{0}^{l_{\mathrm{max}}} \rho^2(r)\, \mathrm{d}l\, \mathrm{d}(\cos\psi) \approx 5$$

[Yüksel et al.'07]

$$r = \sqrt{R_0^2 - 2\, l\, R_0\, \cos\psi + l^2} \qquad l_{\mathrm{max}} = \sqrt{R_{\mathrm{halo}}^2 - \sin^2\psi\, R_0^2}$$