Strong Dark Matter Constraints from Higher-Order Annihilations in the Sun

Talk at the 29$^{\text{th}}$ IMPRS EPP Workshop

Based on JCAP12(2013)043 (P1) and JCAP04(2014)012 (P2)

in collaboration with Alejandro Ibarra and Sebastian Wild

Maximilian Totzauer

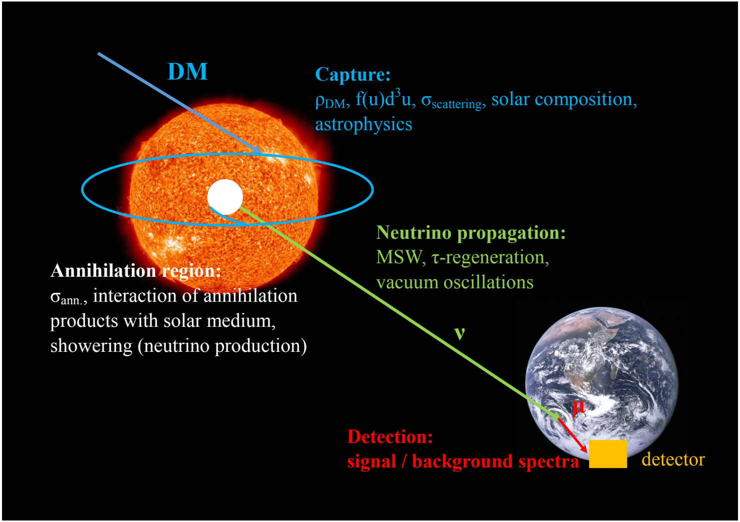
July 7, 2014

Objective

New constraints on the WIMP-nucleon scattering cross section.

Outline

What's the idea?



Constraining $\sigma_{\text{scattering}}$ with indirect detection?

Differential equation governing the dark matter density

- $\frac{\mathrm{d}N_{\mathrm{DM}}^{\mathrm{Sun}}}{\mathrm{d}t} = \Gamma_{\mathrm{C}} - \underbrace{C_{\mathrm{A}} \left(N_{\mathrm{DM}}^{\mathrm{Sun}}\right)^2}_{=2\Gamma_{\mathrm{A}}} - C_{\mathrm{E}} N_{\mathrm{DM}}^{\mathrm{Sun}}$

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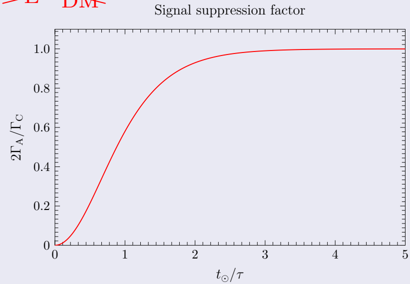

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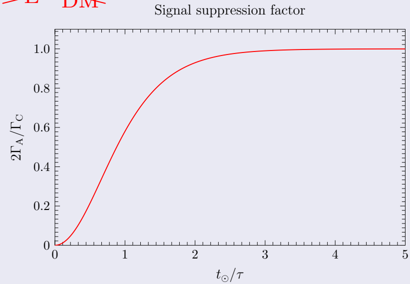

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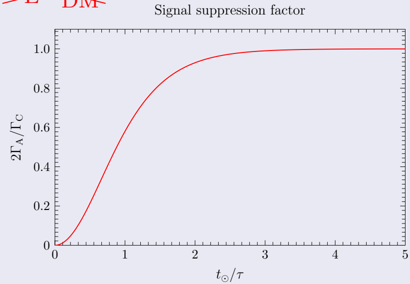

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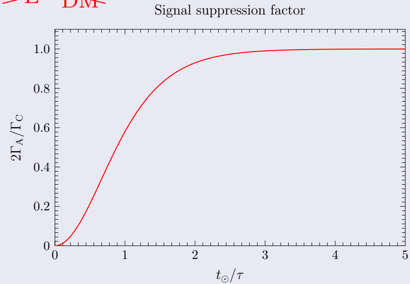

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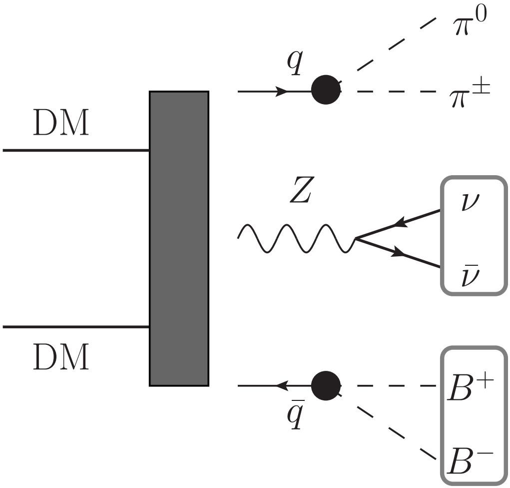
- Equilibration is model-dependent (see P1)

Which annihilation can be studied?



Limits so far calculated for e.g. W^+W^-, $b\bar{b}$ (PRL.110.131302)

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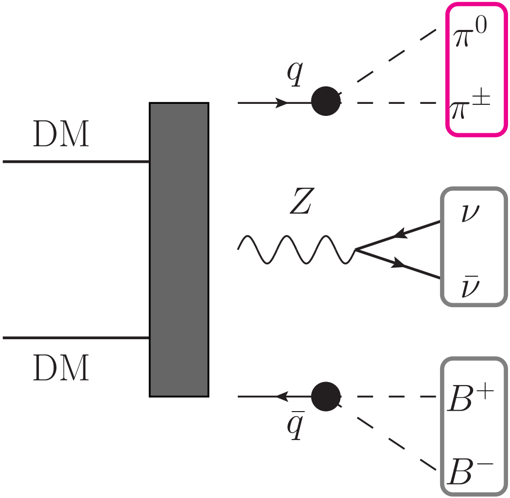

not yet constrained:
light quarks,
e^+e^-, $\mu^+\mu^-$ ($\ell\bar{\ell}$)

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Yes, they can! Account for higher-order effects:

- Electroweak final state radiation (FSR), e.g. $\mathrm{DM\,DM} \to e^+e^- \to e^+W^-\nu_e$
- Highly-energetic gluons, $W^\pm$ or Z-bosons at loop level, e.g. $\mathrm{DM\,DM} \to e^+e^- \to ZZ \to$ neutrinos
- Dark matter models with Internal Bremsstrahlung features, e.g. $\mathrm{DM\,DM} \to u_R\bar{u}_R Z$, $Z \to$ neutrinos

The model

- Toy model extension of the SM:
  - additional Majorana fermion (DM particle) χ
    $(1, 1, 0)$ w.r.t. $SU(3)_C \times SU(2)_L \times U(1)_Y$
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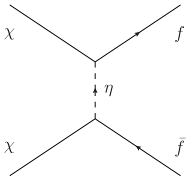
- Toy model can be recovered in the MSSM.

Annihilation in the toy model



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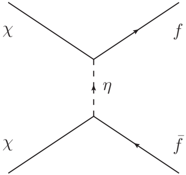

helicity/velocity suppressed:

$$(\sigma_{\mathrm{A}} v)_{\chi\chi\to \mathrm{f\bar{f}}} \simeq (\ldots) \underbrace{\left(\frac{m_f}{m_\chi}\right)^2}_{10^{-10}} + (\ldots) \underbrace{v_\chi^2}_{10^{-9}(\mathrm{Sun})}$$

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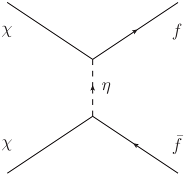

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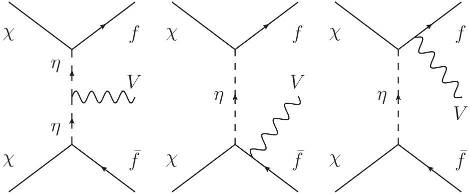

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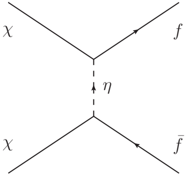

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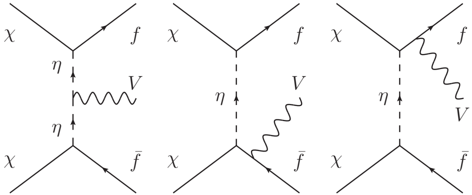

$$(\sigma_{\mathrm{A}} v)_{\chi\chi\to \mathrm{f}\bar{\mathrm{f}}\mathrm{V}} \simeq (\ldots)\,\frac{\alpha_\chi}{\pi}$$

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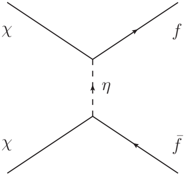

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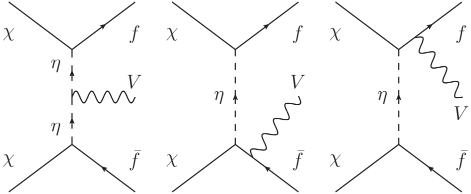

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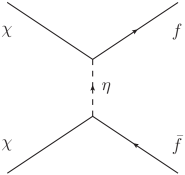

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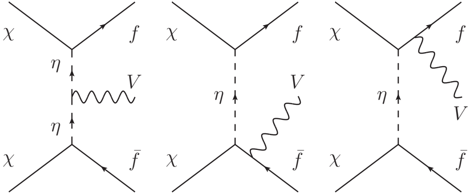

$$(\sigma_A v)_{\chi\chi\to f\bar{f}V} \simeq (\dots)\,\frac{\alpha_X}{\pi}$$

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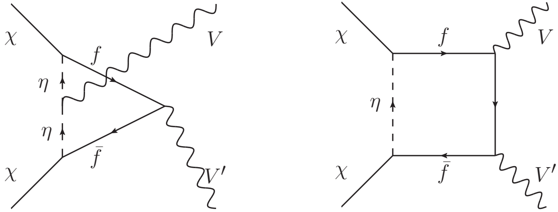
~~WIMPSim~~

$\rightarrow$ own routines needed

Annihilation in the toy model



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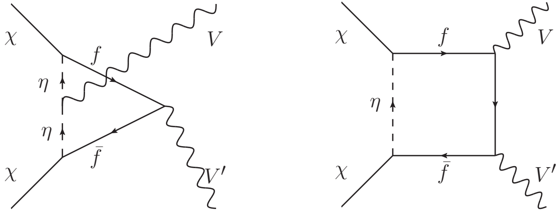
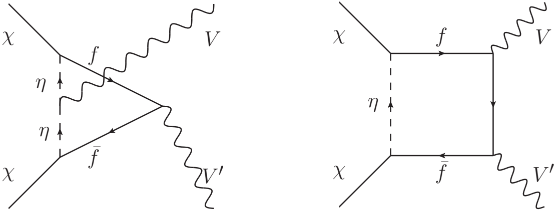


Dominant annihilation channel for $m_\eta/m_\chi \geq 2-3$

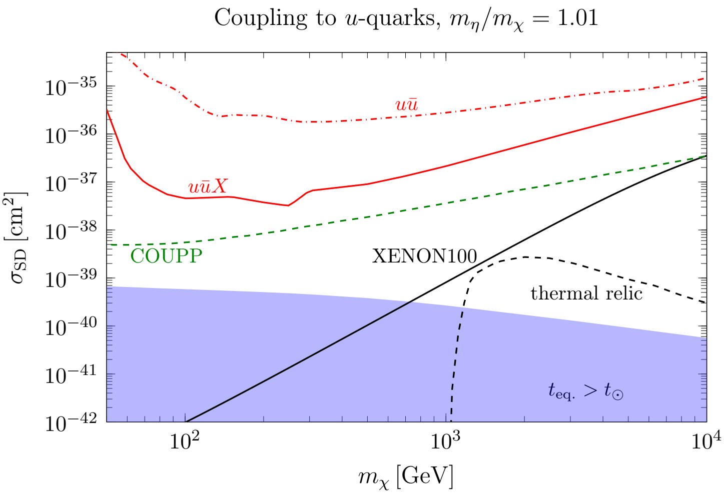
Annihilation in the toy model



Dominant annihilation channel for $m_\eta/m_\chi \geq 2-3$

Amplitudes for gg, $\gamma\gamma$, γZ known from MSSM-studies, amplitudes for ZZ calculated for the first time.

Limits on the SD cross section in our model



Scenario with generic contact interaction

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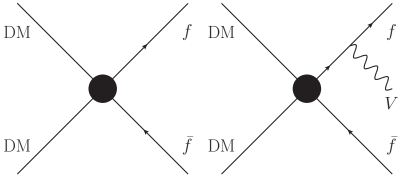

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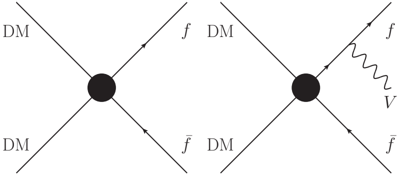
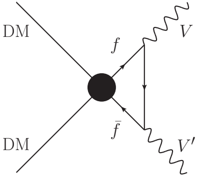


- Case 2:



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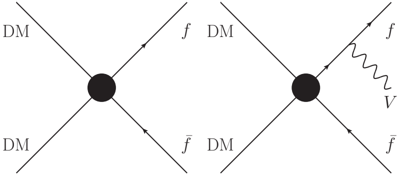

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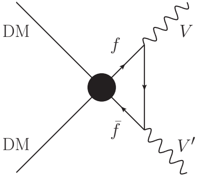
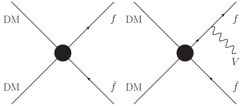
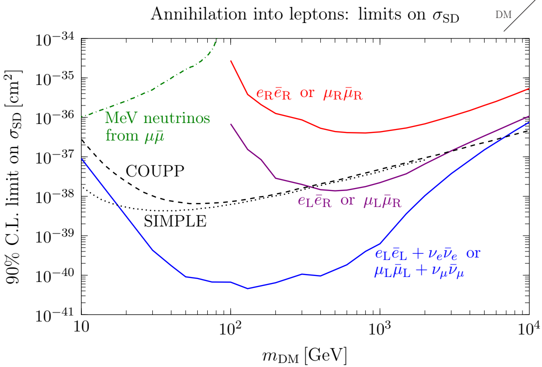


- Benchmark cases of either pure $\sigma_{\rm SD}$ or pure $\sigma_{\rm SI}$ analyzed

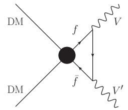
CASE 1: Limits from IceCube on σ_{SD} – leptons

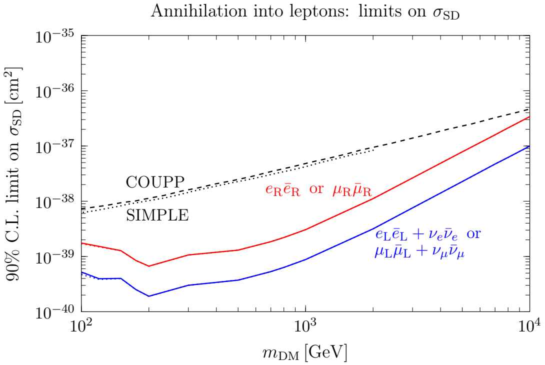




Limits from MeV neutrinos from Bernal et al. (JCAP08(2013)011)

CASE 2: Limits from IceCube on $\sigma_{\rm SD}$ – leptons





Conclusion & Outlook

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Outlook

- The assumption of equilibration is vital for feasibility of the method in the future → discussed in P1
- Limits on anapole/dipole moment in leptophilic models are calculable (Ibarra & Wild, in preparation)

Thank you for your attention!

Capture processes for coupling to u_R

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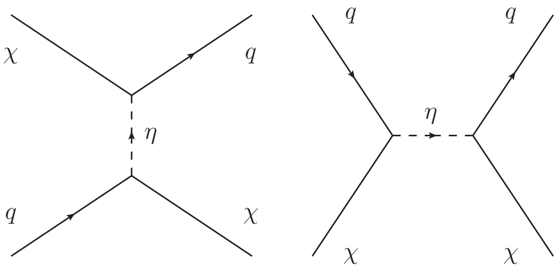

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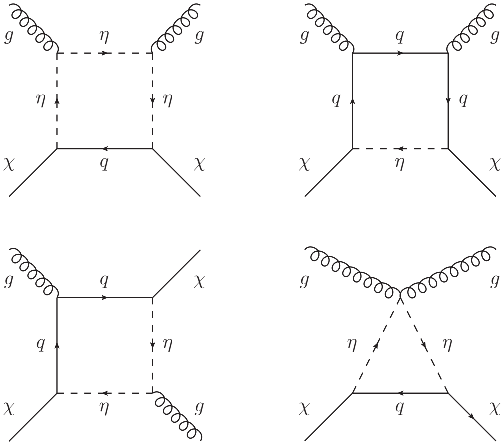
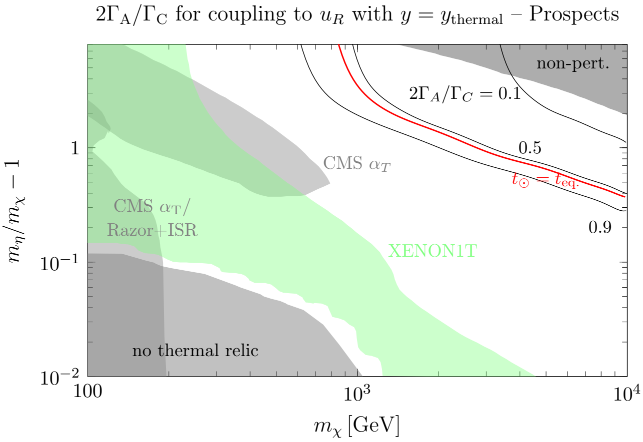


Where a thermal relic coupling to u_R is in equilibrium



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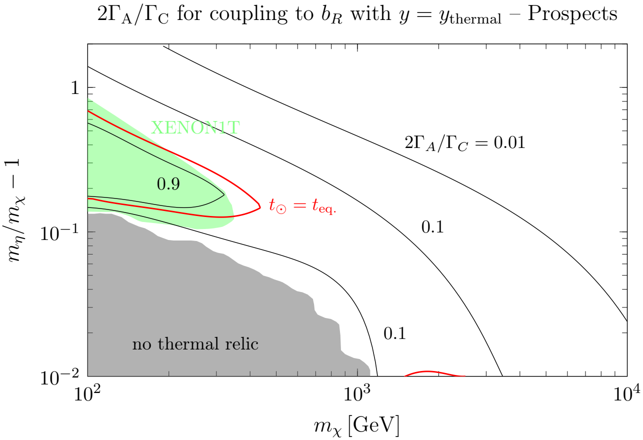
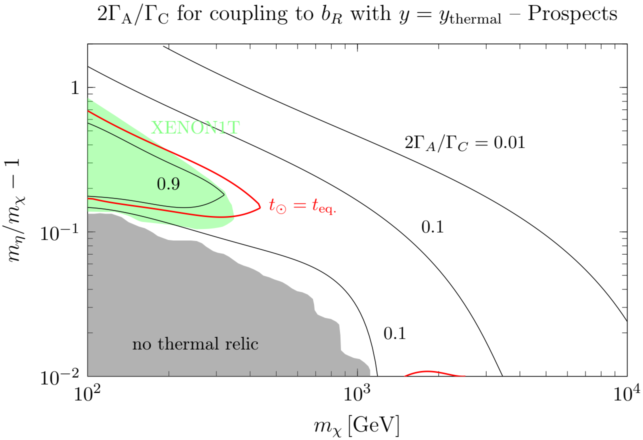


Where a thermal relic coupling to b_R is in equilibrium



⇒ Only small regions in parameter space correspond to equilibrium.

The case of asymmetric capture of particle-antiparticle

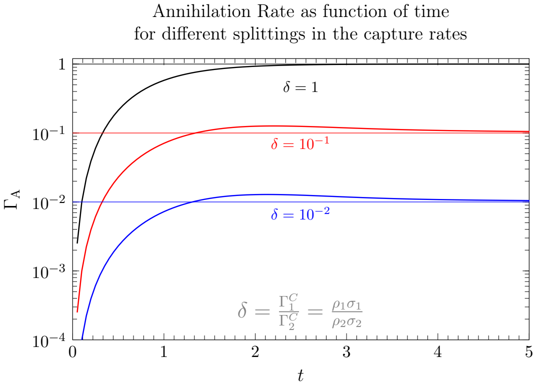


Figure : Annihilation rate as a function of time for different capture rates in case the relic dark matter density consists of particles and antiparticles.

Capture rates in the Sun or the Earth – Comparison

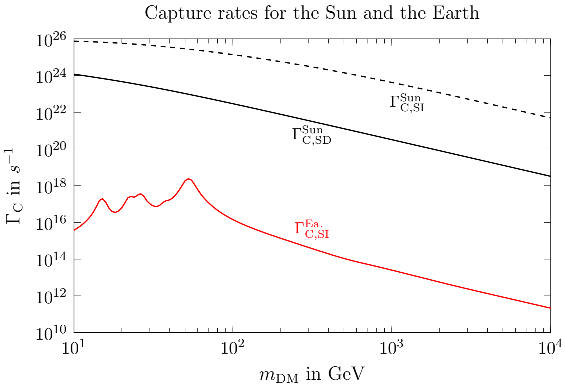


Figure : Capture rates in the Sun and the Earth for a generic scattering cross section value of $10^{-40}\,\mathrm{cm}^2$, local dark matter density of $0.4\,\mathrm{GeV cm}^{-3}$ and a Maxwell-Boltzmann distribution with 3D velocity dispersion of $270\,\mathrm{kms}^{-1}$ and a galactic escape speed of $600\,\mathrm{kms}^{-1}$ that truncates the velocity distribution.

The dependence of the annihilation constant with mass

The annihilation constant in the Sun is found to scale as $m_{\mathrm{DM}}^{3/2} \left\langle \sigma_{\mathrm{ann}} v \right\rangle$. This arises from the fact that

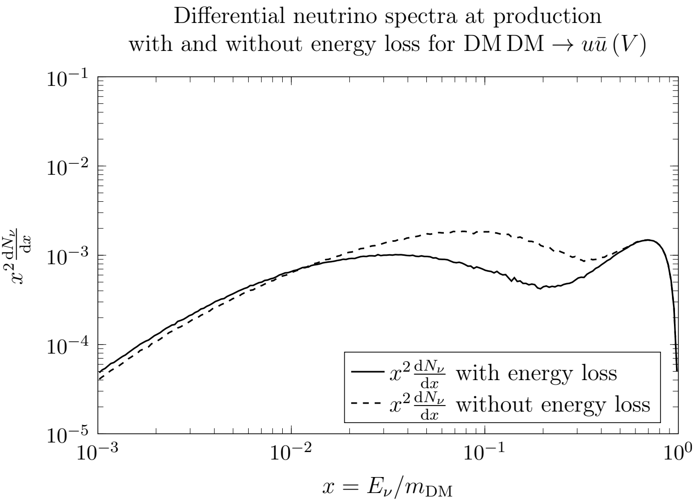
$$C_{\mathrm{A}} = \left\langle \sigma_{\mathrm{ann}} v \right\rangle \frac{\int_0^{R_\odot} 4\pi r^2 n^2 (r) \, \mathrm{d}r}{\left[\int_0^{R_\odot} 4\pi r^2 n (r) \, \mathrm{d}r \right]^2}$$

$$n(r) = n_0 \exp\left(-m\Phi(r) / T\right)$$

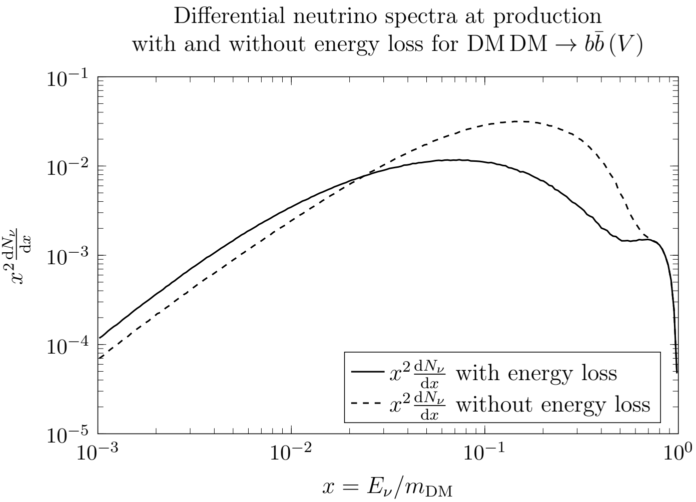
$$\Phi(r) \approx C \rho r^2$$

In the last line, it was used that the density of dark matter is centered closely around the core even for small dark matter masses of about 50 GeV. With this result, one gets the mentioned proportionality to $m_{\mathrm{DM}}^{3/2}$ to a *very* good approximation.

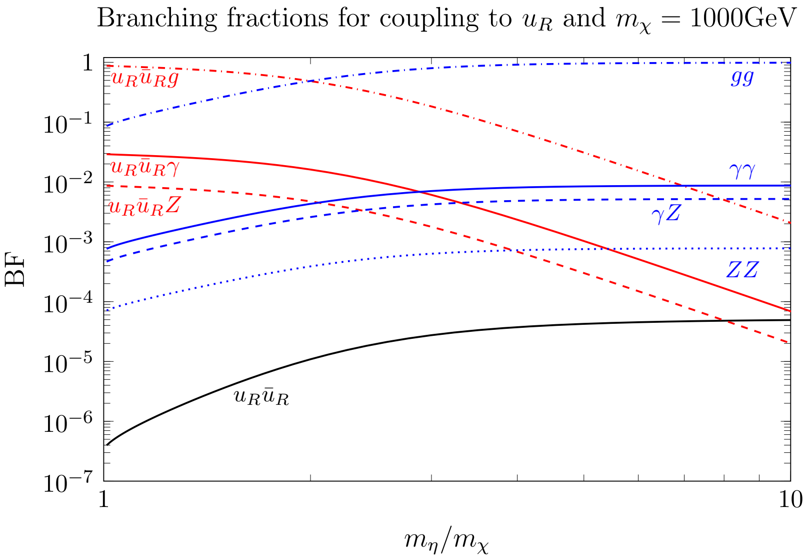
Example: Neutrino spectra at Earth – energy loss



Example: Neutrino spectra at Earth – energy loss



Annihilation processes – branching fractions



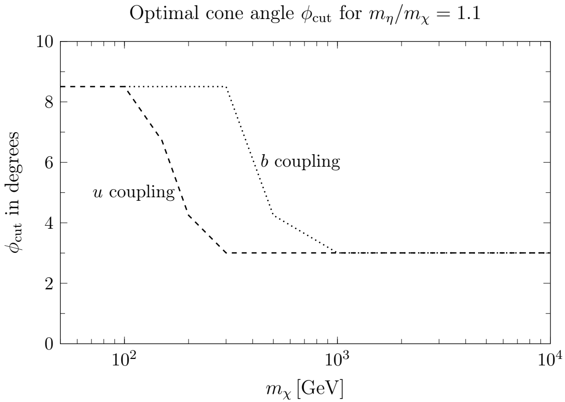
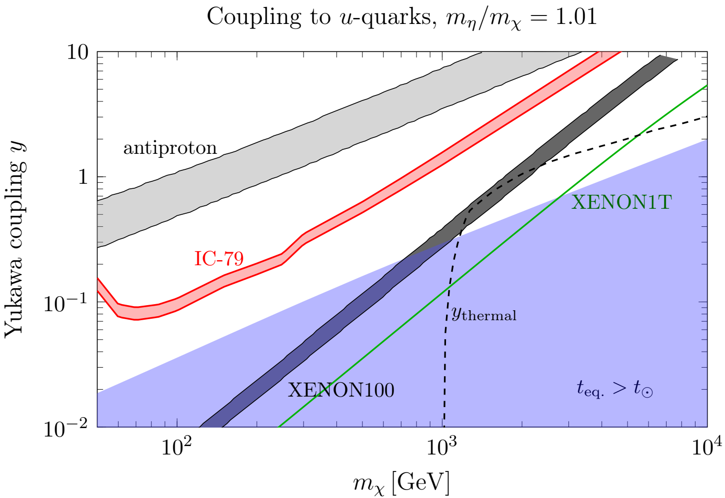
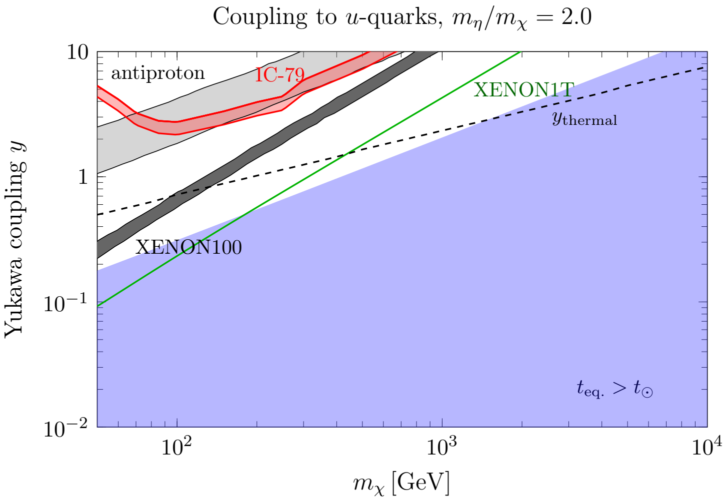


Figure : Optimal cut angles $\phi_{\rm cut}$ for a given mass splitting of $m_\eta/m_\chi = 1.1$. Higher dark matter masses lead to neutrinos with higher average energy. Their tracks can be reconstructed with higher accuracy and hence the optimal cone angle decreases.

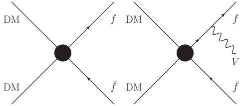
Constraints on the Yukawa coupling - case of u_R, small mass splitting

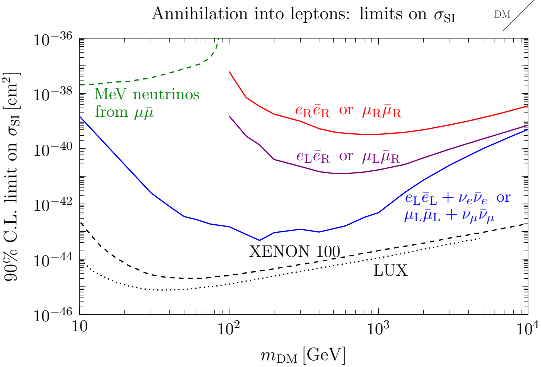


Constraints on the Yukawa coupling - case of u_R, larger mass splitting



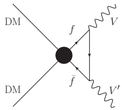
CASE 1: Limits from IceCube on σ_{SI} – leptons

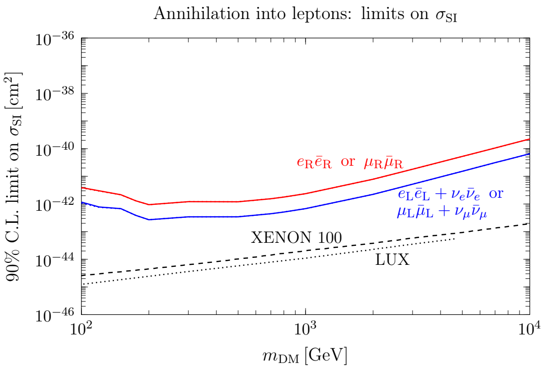




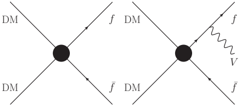
Limits from MeV neutrinos from Bernal et al. (JCAP08(2013)011)

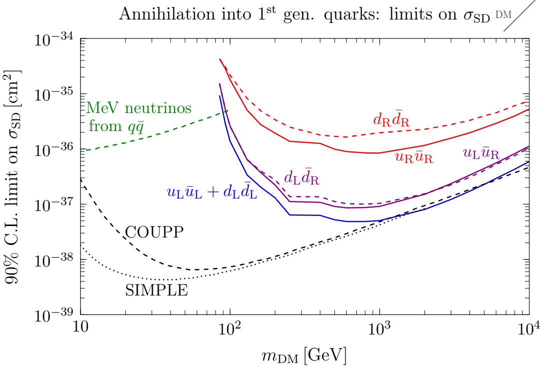
CASE 2: Limits from IceCube on $\sigma_{\rm SI}$ – leptons





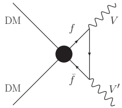
CASE 1: Limits from IceCube on σ_{SD} – quarks

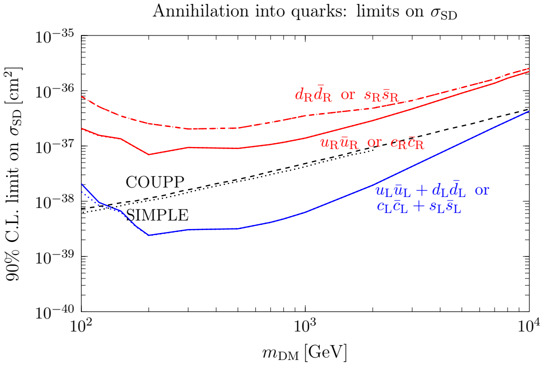




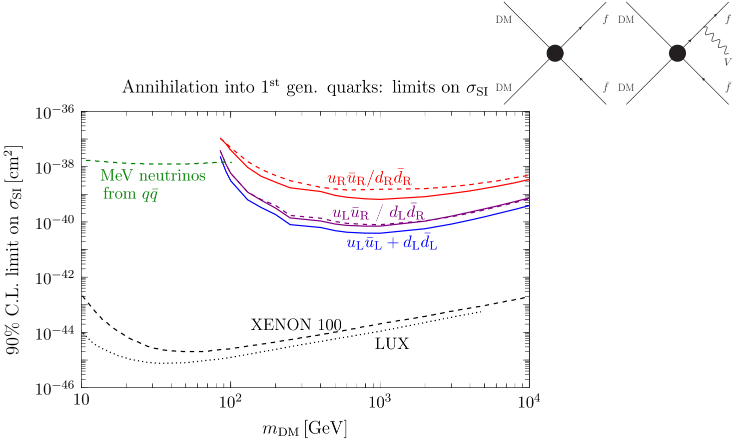
Limits from MeV neutrinos from Bernal et al. (JCAP08(2013)011)

CASE 2: Limits from IceCube on σ_{SD} – quarks



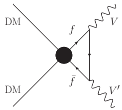


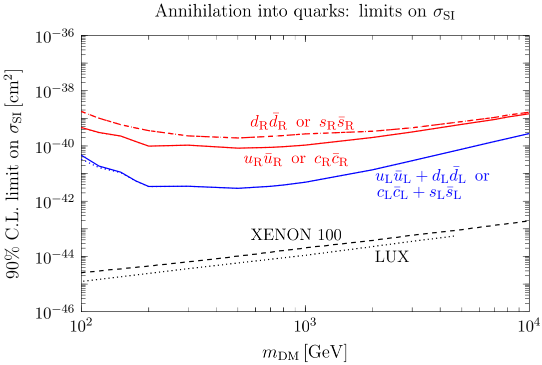
CASE 1: Limits from IceCube on $\sigma_{\rm SI}$ – quarks



Limits from MeV neutrinos from Bernal et al. (JCAP08(2013)011)

CASE 2: Limits from IceCube on σ_{SI} – quarks





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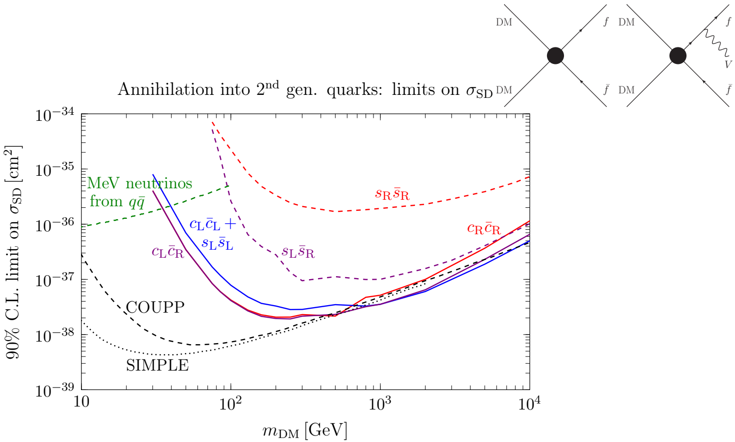

Limits from MeV neutrinos from Bernal et al. (JCAP08(2013)011)

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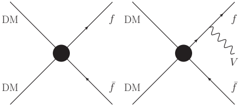

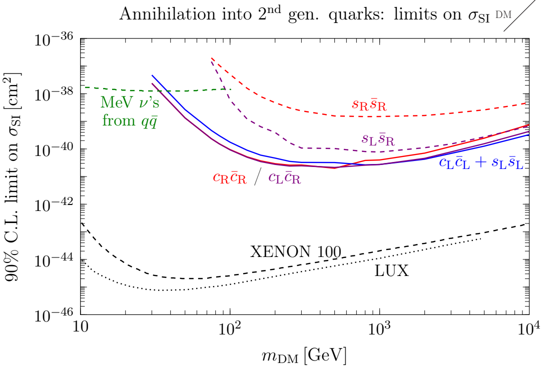

Limits from MeV neutrinos from Bernal et al. (JCAP08(2013)011)