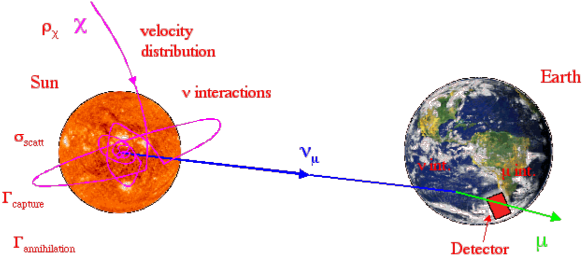
Sensitivity of neutrino telescopes to solar dark matter annihilations into light quarks, electrons and muons

Sebastian Wild

Technische Universität München

MIAPP mini-workshop on dark matter and neutrinos, February 20, 2015

Neutrinos from dark matter annihilations in the Sun



[Figure from J. Edsjo]

- If dark matter is a WIMP with non-zero $\sigma_{\chi N}$, it can be **captured** in the Sun
- After accumulating in the center of the Sun, dark matter starts to **annihilate**
  $\hookrightarrow$ among all stable SM particles in the final state, only neutrinos can escape the Sun
- Experimental signature: excess of ν's correlated with the direction of the Sun
  $\hookrightarrow$ Smoking-gun signature for particle dark matter!
- If capture and annihilation is in equilibrium, then the neutrino flux is $\propto \sigma_{\chi N}$
  $\hookrightarrow$ results can be compared to direct detection experiments

Stopping of particles in the Sun

Center of the Sun: $\rho_{\mathsf{matter}} \simeq 160$ g/cm^3
$\Rightarrow$ the SM annihilation products can be **strongly affected** by interactions with the solar medium!

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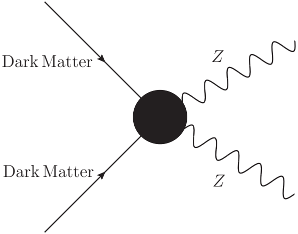

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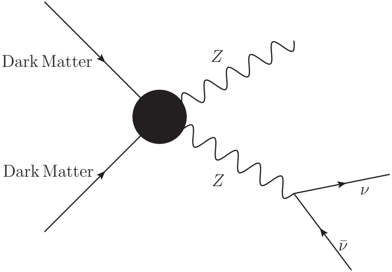

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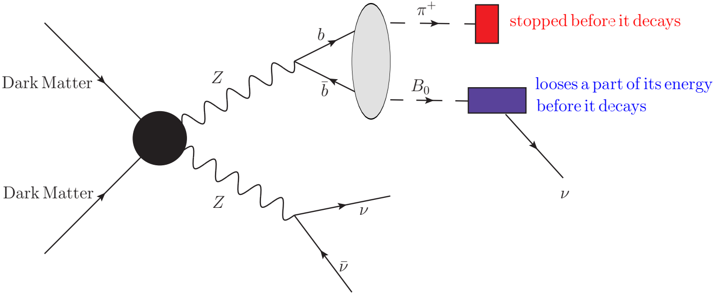

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- $\tau_{B\text{-mesons}} \simeq \tau_{\text{interaction}}$ $\Rightarrow$ B mesons lose part of energy before decaying
- $\tau_{\pi^\pm} \gg \tau_{\text{interaction}}$ $\Rightarrow$ π^+ decay at rest, π^- are captured by nuclei

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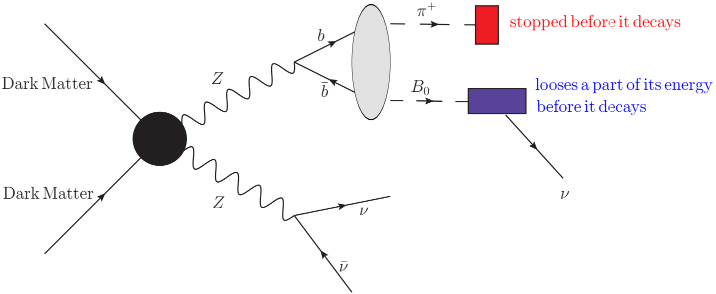

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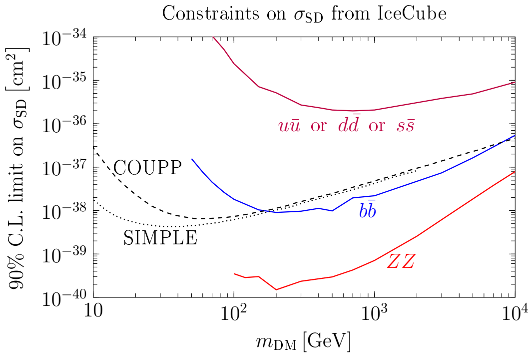
- $\tau_{\mu^\pm} \gg \tau_{\text{interaction}}$ $\Rightarrow$ $\mu^\pm$ decay at rest

Constraints on σ_{SD}: standard annihilation channels



"Naive", first-order classification of annihilation channels:

- $\nu\bar{\nu}$, ZZ, W^+W^-, $\tau^+\tau^-$: strong neutrino signal ⇒ strong constraints
- $b\bar{b}$: softer neutrino spectrum, but still competitive constraints on σ^p_{SD}
- $u\bar{u}$, $d\bar{d}$, $s\bar{s}$: mainly produce pions ⇒ considerably weaker constraints
- e^+e^-, $\mu^+\mu^-$: no high-energy neutrinos at all ⇒ no signal (?)

Constraining annihilations into $q\bar{q}, e^+e^-, \mu^+\mu^-$

Two (rather) recent ideas to constrain annihilations into $q\bar{q}, e^+e^-, \mu^+\mu^-$:

(1) Higher-order effects can lead to the production of weak gauge bosons

$\hookrightarrow$ high energy ν's from Z, $W^\pm$ decays

Ibarra, Totzauer, SW [1311.1418, 1402.4375]
see also Baratella et. al. [1312.6408]

(2) Search for the MeV neutrinos produced from decays of stopped π^+ and $\mu^\pm$

Bernal, Martin-Albo, Palomares-Ruiz [1208.0834]
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$\hookrightarrow$ covered in the talk by Sergio Palomares-Ruiz!

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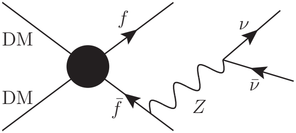
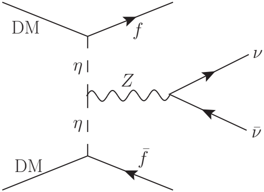
Higher-order annihilations in the Sun

- Higher-order effects **generically** lead to the emission of Z, $W^{\pm}$ bosons in these annihilation channels! Examples are:

weak final state radiation



virtual internal bremsstrahlung



$$\Downarrow$$

Generation of a ν flux in previously unconstrained annihilation channels

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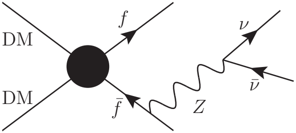

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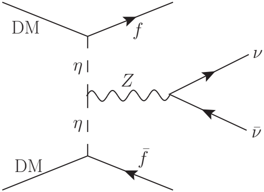


$\Downarrow$

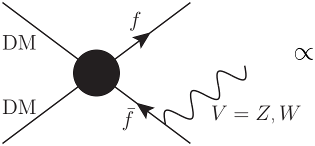
Generation of a ν flux in previously unconstrained annihilation channels

- A generic DM model falls into one of **two classes**:
  - a) dominant annihilation channel is DM DM $\rightarrow f\bar{f}$
  - b) DM DM $\rightarrow f\bar{f}$ is helicity/velocity suppressed
- We derive separate limits on σ_{SD} for both scenarios

Case a): weak final state radiation in DM DM $\to f\bar{f}$

a) Models with dominant annihilation DM DM $\to f\bar{f}$
  $\hookrightarrow$ relevant if no helicity suppression is present
  $\hookrightarrow$ relevant e.g. for Dirac DM or for Majorana DM annihilating into $f_L\bar{f}_R$

- Most important source of neutrinos for $m_{\text{DM}} \gtrsim 100$ GeV: production of Z and W bosons via **weak final state radiation** (FSR)
  $\hookrightarrow$ calculation is completely model-independent!
  (We use PYTHIA 8.176 for that)

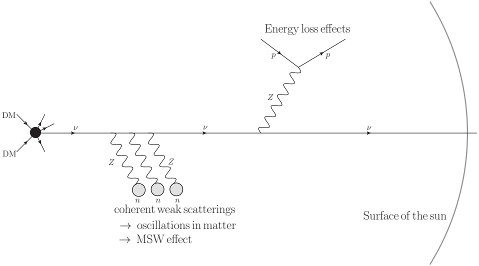


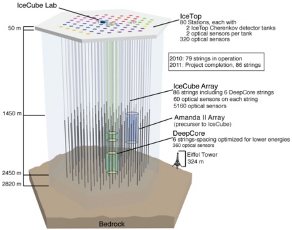
$\propto \langle \sigma v \rangle_{f\bar{f}}$ · splitting function

- Particularly interesting example: FSR splitting $l_L^- \to W^-\nu_l$
  $\hookrightarrow$ high-energetic ν from the final state leg: $E_{\nu_l} \simeq m_\chi$

Propagation and detection of high-energy neutrinos

Once produced by DM annihilations, the neutrinos propagate out of the Sun:





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  [Blennow, Edsjö, Ohlsson 0709.3898]

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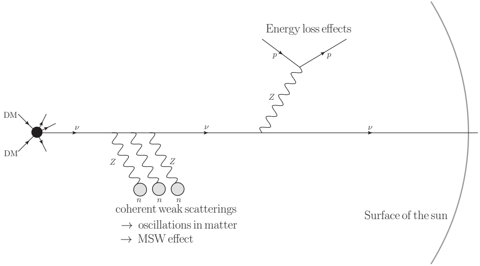
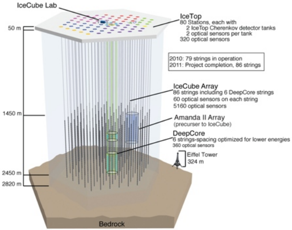
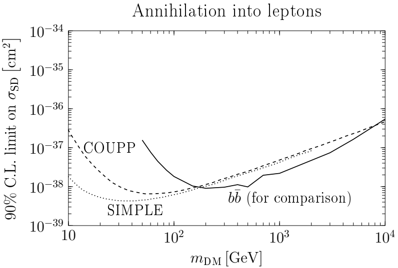




- We take into account matter oscillation and absorption effects by using the event-by-event Monte Carlo *WimpSim* [Blennow, Edsjö, Ohlsson 0709.3898]
- We derive constraints from the **IceCube 79-string data**, using a likelihood ratio test based on the number of events within $\theta_{\mathsf{Sun}} < \theta_{\mathsf{max}}$
  $\hookrightarrow$ we (indirectly) include the spectral information of the ν signal by optimizing θ_{max} separately for every dark matter mass and annihilation channel

Case a): weak final state radiation in DM DM $\rightarrow f\bar{f}$



Ibarra, Totzauer, SW [1402.4375]

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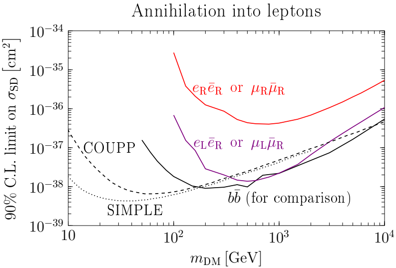

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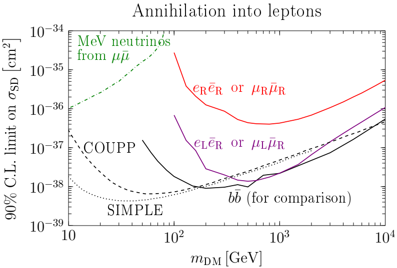
- The constraints on σ_{SD} depend on the helicity of the final state fermion f
  $\hookrightarrow$ tighter constraints for annihilation into left-handed fermions

Case a): weak final state radiation in DM DM → $f\bar{f}$



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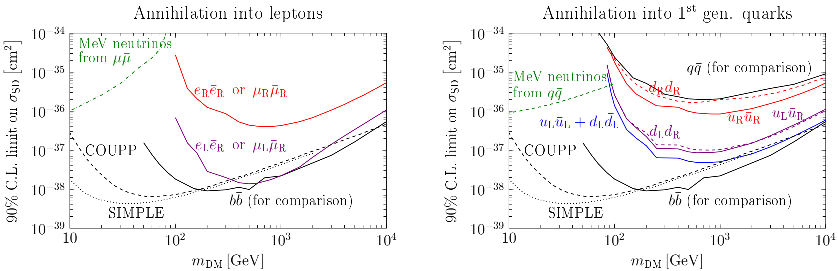

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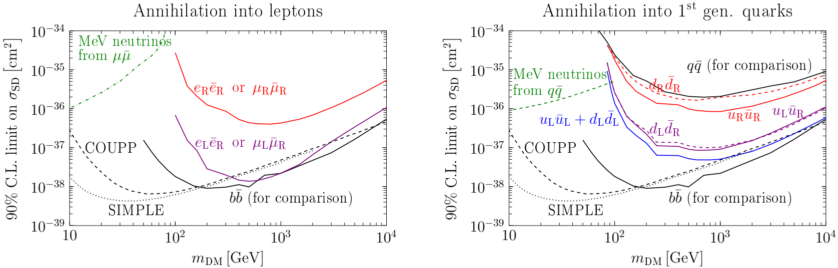

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In several cases, the resulting constraints are

a) **significantly stronger** when taking into account weak FSR
b) comparable to the limits from annihilation into e.g. $b\bar{b}$
c) stronger than the best direct detection limits on σ_{SD}

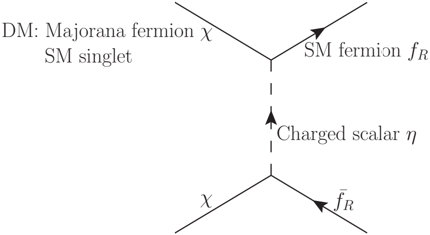
Case b): DM DM $\to f\bar{f}$ is helicity suppressed

b) Models where DM DM $\to f\bar{f}$ is helicity/velocity suppressed

$\hookrightarrow$ relevant e.g. for Majorana DM annihilating into $f_L\bar{f}_L$ or $f_R\bar{f}_R$

$\hookrightarrow$ in this case, the ν-flux is not model-independent anymore

- **Simplified model** for Dark Matter with helicity suppression:



$$\langle \sigma v \rangle_{f\bar{f}} \propto (\dots)\cdot (m_f/m_\chi)^2 + (\dots)\cdot v_{\text{rel}}^2$$

- Dark Matter particle: Majorana fermion χ, SM singlet
- Next-to-lightest new particle: Charged scalar η
- $\mathcal{L}_{\text{int}} = y\,\bar{\chi} f_R^\dagger \eta + \text{h.c.}$

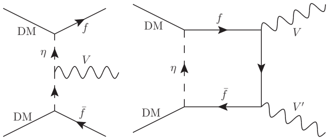
Case b): DM DM $\to f\bar{f}$ is helicity suppressed

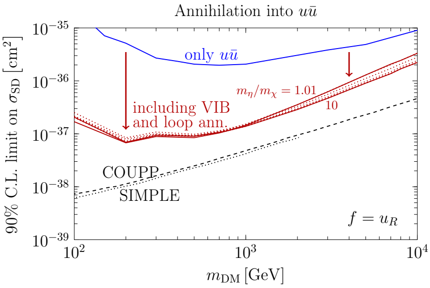
One example: dark matter coupling to u_R

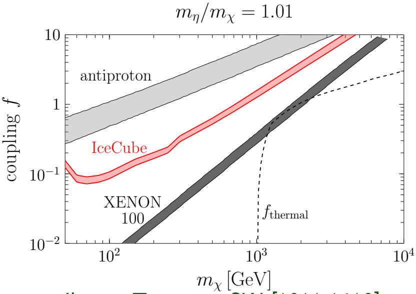
$\hookrightarrow$ dominant annihilation channels:

virtual internal bremsstrahlung $\chi\chi \to u\bar{u}V$

one loop annihilations $\chi\chi \to VV$



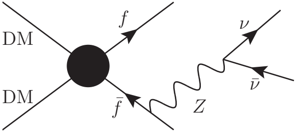


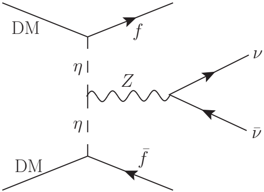


Ibarra, Totzauer, SW [1311.1418]

Taking into account VIB and loop annihilations, the limits improve by $\simeq 1$ order of magnitude with respect to pure $u\bar{u}$ annihilation

Conclusions





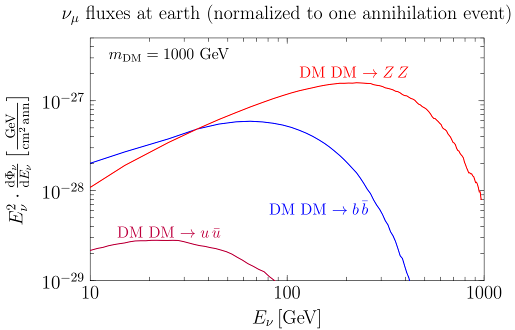
If dark matter annihilates dominantly into light quarks, e^- or μ^-, no high-energetic neutrinos are produced at tree-level

- ↪ **Higher-order effects** generically lead to production of high-energetic ν's: weak final state radiation, virtual internal bremsstrahlung, one-loop annihilation into gauge bosons
- ↪ The resulting **limits on σ_{SD} from IceCube** are quite strong for some cases, and sometimes even better than the best direct detection limits on σ_{SD}

↪ this hold for both helicity suppressed and non-suppressed scenarios

Backup slides

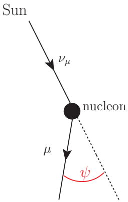
Neutrino fluxes at earth: some examples

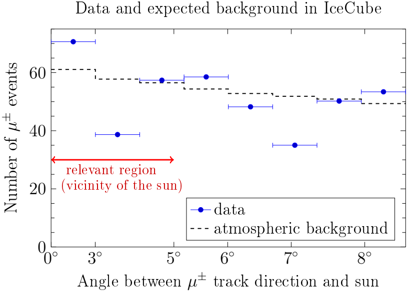


- DM DM $\to Z\,Z$: hard spectrum due to prompt ν's from $Z \to \nu\bar{\nu}$
  $\hookrightarrow$ favorable for detection as $A_{\rm eff} \propto E_\nu^2$
- DM DM $\to b\,\bar{b}$: softer spectrum, as B hadrons and mesons lose part of their energy before decaying
- DM DM $\to u\,\bar{u}$: almost no high-energy ν's, as all pions and kaons are stopped in the Sun before decaying

Constraints from IceCube 79-string data

[IceCube collaboration 2013]

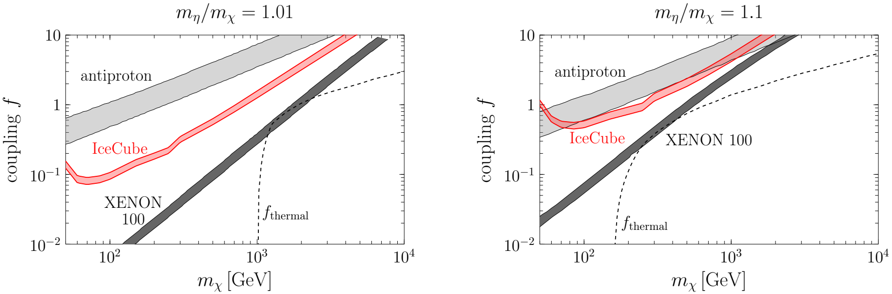




Assuming equilibrium, we use the IceCube 79-string data to derive limits on σ_{SD}^{p}:

- We use a likelihood ratio test to constrain the number of signal events within a given cone angle around the Sun
- We (indirectly) include the spectral information of the ν signal by **optimizing the cone angle** around the Sun separately for every dark matter mass and annihilation channel

Limits on the Yukawa coupling f - comparing approaches



Ibarra, Totzauer, SW '13

- For a compressed spectrum, IceCube constraints on the Yukawa coupling f are **competitive**, in particular with PAMELA $\bar{p}/p$
  $\hookrightarrow$ for this, taking into account the $2 \to 3$ channels is crucial!
- XENON 100 constraints are still the most stringent one in this scenario
- More details in the paper: Ibarra, Totzauer, SW [1311.1418]
  - Scenario of coupling to b_R
  - Thorough **analysis of the equilibration condition**, including its interplay with XENON 100 and collider limits