Dirac dark matter with a charged mediator: a comprehensive one-loop analysis of the direct detection phenomenology

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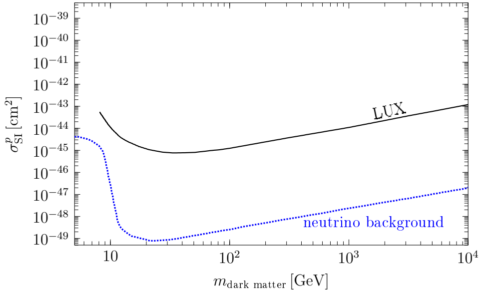
Technische Universität München, Munich

"Exploring the dark sector"
KIAS, Seoul, March 18, 2015

Based on 1503.03382 (Alejandro Ibarra, SW)

Loop effects in direct detection: some simple estimates



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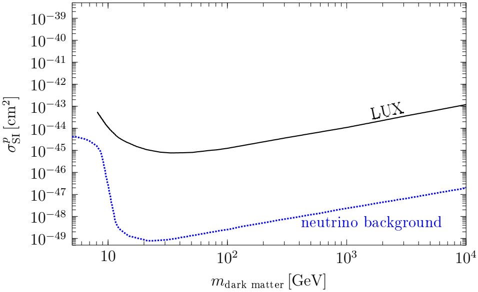

- Consider a **Dirac dark matter** particle χ
- If χ can scatter of nucleons N at **tree-level** via the exchange of a Z...:
  $\hookrightarrow \mathcal{L}_{\rm eff} = f_N\,\bar{\chi}\gamma^\mu\chi\bar{N}\gamma_\mu N$ with $f_N \sim \frac{G_F}{4\sqrt{2}}$

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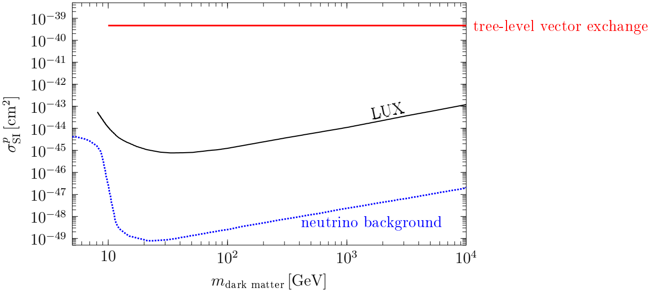

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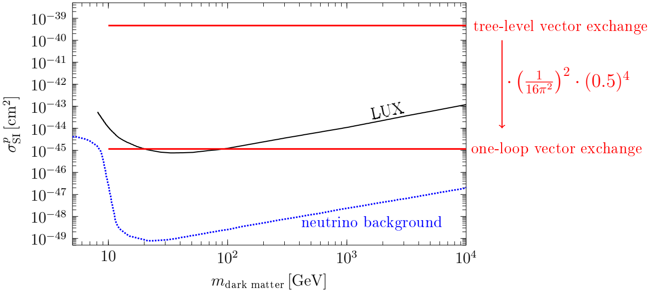

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  $\hookrightarrow \sigma_{\chi p} \simeq 5\cdot 10^{-40}\,\text{cm}^2 \cdot \left(\frac{1}{16\pi^2}\right)^2 \cdot (0.5)^4 \simeq 10^{-45}\,\text{cm}^2 \simeq \sigma_{\chi p}^{(\text{LUX})}$

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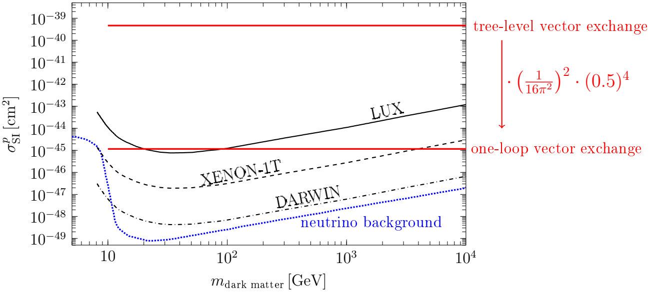

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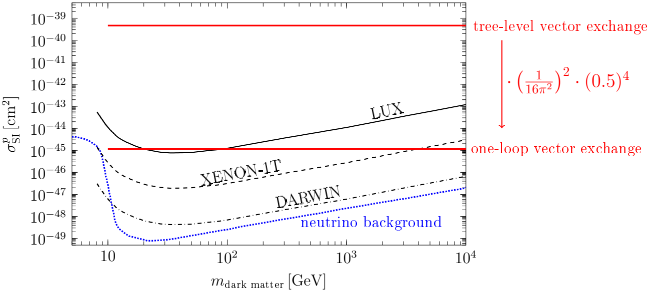

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$\Downarrow$

Direct detection experiments are getting sensitive to loop-induced scattering!

A simplified model of Dirac dark matter

- **Dark matter particle** χ: Dirac fermion, SM singlet $(\mathbf{1},\mathbf{1})_0$
  $\hookrightarrow$ no tree-level coupling to Z, $W^\pm$ or h
- **Scalar mediator** η
  $\hookrightarrow$ couples χ to <u>one</u> SM fermion f_R via $\mathcal{L} = -y\,\eta^\dagger \bar{\chi} f_R$
  $\hookrightarrow$ $m_\eta > m_\chi$

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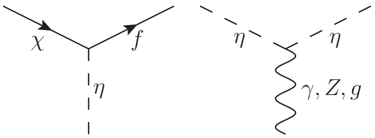
Coupling to...	Quantum numbers of η
e_R, μ_R or τ_R	$(\mathbf{1},\mathbf{1})_{-1}$
u_R, c_R or t_R	$(\mathbf{3},\mathbf{1})_{2/3}$
d_R, s_R or b_R	$(\mathbf{3},\mathbf{1})_{-1/3}$



- Scenarios with coupling to a left-handed SM fermion doublet are very similar
  $\hookrightarrow$ see the paper for detailed discussion of all the possible cases

Thermal parameter space

- Only three parameters:
  DM mass m_χ, mass splitting m_η/m_χ, Yukawa coupling y
- The requirement of $\Omega_\chi h^2 \simeq 0.12$ fixes $y \equiv y_{\text{thermal}}(m_\chi, m_\eta/m_\chi)$
  $\hookrightarrow$ main annihilation channel for the freeze-out: $\chi\chi \to f\bar{f}$
  $\hookrightarrow$ For $m_\eta/m_\chi \lesssim 1.2$, also coannihilations are important, e.g. $\eta\eta^\dagger \to \gamma\gamma$

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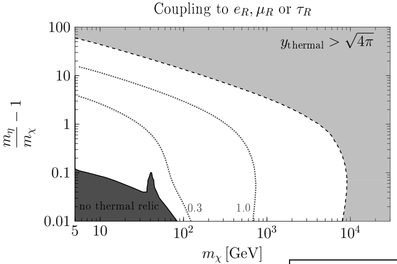
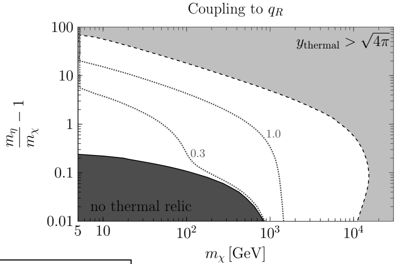
For every coupling scenario $(e_R, u_R, \ldots)$, the **thermal parameter space** is only two-dimensional, spanned by m_χ and m_η/m_χ





$\Downarrow$

Highly testable models!

Intermediate outline

- In the paper, we analyze the direct detection phenomenology for all 15 possible coupling scenarios:
  $e_R,\ (\nu_e, e_L),\ u_R,\ d_R,\ (u_L, d_L)\ \times$ three generations

- In this talk, I will present the results for coupling to

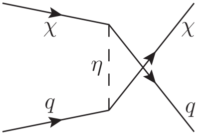
  1) u_R
  2) τ_R
  3) b_R
  4) t_R

  $\hookrightarrow$ this selection encapsulates most of the interesting features appearing in all possible coupling scenarios

- Some of these cases have (partially) already been discussed:
  Agrawal& [1109.3516,1402.7369,1404.1373], Bai, Berger [1308.0612,1402.6696], Chang& [1307.8120,1402.7358], Kopp& [1401.6457]

Case (1): Coupling to u_R

- If χ couples to the u or d quark, scattering off nuclei is possible at tree-level:



$$\Rightarrow \quad \mathcal{L}_{\text{eff}}^{(\text{SI})} \propto \frac{y^2}{m_\eta^2 - m_\chi^2} \bar{\chi}\gamma^\mu \chi N \gamma_\mu N$$

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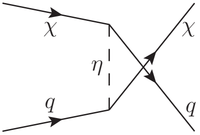

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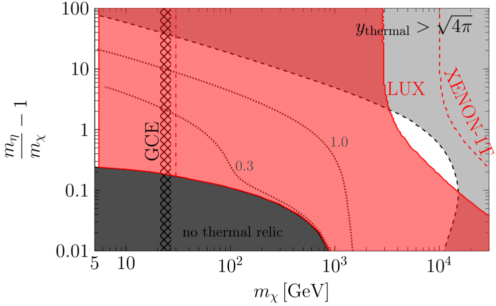

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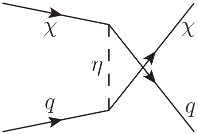

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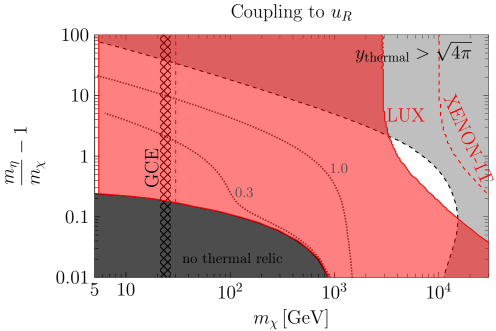


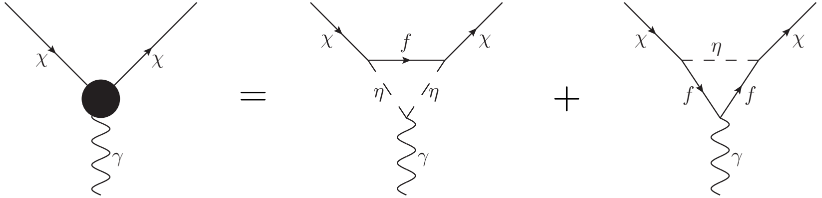
For coupling to u_R to d_R, LUX already excludes almost the whole thermal parameter space

- However: $\mathcal{L}_{\text{eff}}^{\text{(SI)}} \equiv 0$ for coupling to $f_R \notin \{u_R, d_R\}$
  $\hookrightarrow$ in these scenarios, there is **no SI interaction at tree-level**!

Case (2): Coupling to τ_R - Leptophilic dark matter

Dark matter coupling to τ_R (or any other RH or LH lepton):

- One-loop diagrams induce an **effective DM-photon coupling**:



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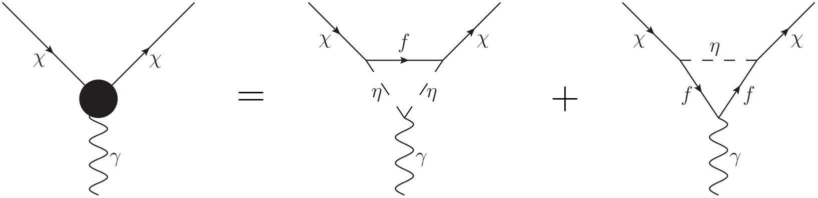

$$\mathcal{L}_{\text{eff}}^{(\gamma)} = \underbrace{\frac{\mu_\chi}{2}\,\overline{\chi}\sigma^{\mu\nu}\chi F_{\mu\nu}}_{\text{magn. dipole moment}} + \underbrace{b_\chi\,\overline{\chi}\gamma^\mu\chi\partial^\nu F_{\mu\nu}}_{\text{charge radius}}$$

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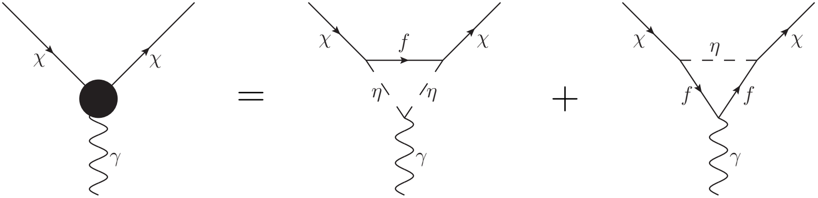

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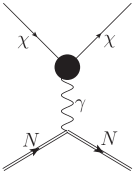
- μ_χ and b_χ are calculable (finite) functions of m_χ, m_η and y
- Similar diagrams induce an effective coupling $\bar{\chi}\chi Z$
  $\hookrightarrow$ suppressed by $(m_f/m_\chi)^2 \Rightarrow$ irrelevant for leptophilic dark matter

Case (2): Coupling to τ_R - Leptophilic dark matter



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- Scattering off a nucleus with mass m_A and spin J_A:

$$\frac{\mathrm{d}\sigma_{\chi A}}{\mathrm{d}E_R} = \alpha_{\text{em}}\mu_\chi^2 Z^2\left(\frac{1}{E_R} - \frac{m_A}{2\mu_{\text{red}}^2 v^2}\right)\left[F_{\text{SI}}(E_R)\right]^2 \longrightarrow \text{long-range dipole-charge interaction}$$

$$+ \frac{\mu_A^2\mu_\chi^2 m_A}{\pi v^2}\cdot\frac{J_A+1}{3J_A}\left[F_{\text{dipole}}(E_R)\right]^2 \longrightarrow \text{dipole-dipole interaction } \propto \mu_A^2$$

$$+ \frac{2m_A Z^2\alpha_{\text{em}}}{v^2}\left(b_\chi + \frac{\mu_\chi}{2m_\chi}\right)^2\left[F_{\text{SI}}(E_R)\right]^2 \longrightarrow \text{spin-independent contact interaction}$$

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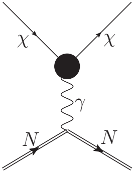

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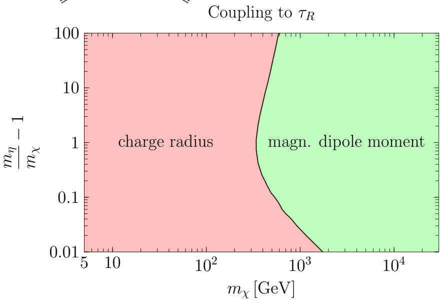
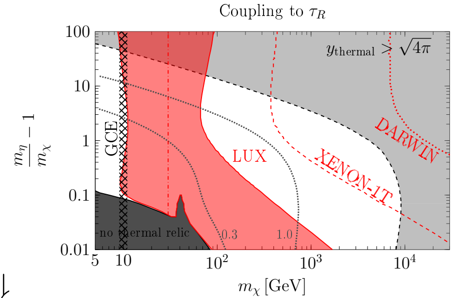




$\Downarrow$

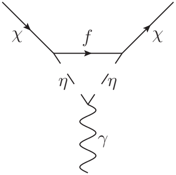
- LUX already excludes a thermal relic for $m_\chi \lesssim 100$ GeV
- Future DD experiments can completely close in on that scenario

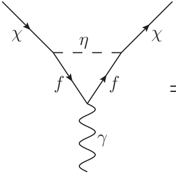
$\hookrightarrow$ ... even for $m_\chi \gtrsim 1$ TeV

$\hookrightarrow$ ... despite the fact that the scattering is only loop-induced!

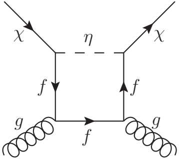
Case (3): Coupling to b_R

- Again, there is no tree-level scattering off nuclei
- Relevant one-loop diagrams:





$\Rightarrow$ charge radius & magnetic dipole moment of χ



$\Rightarrow$ effective dark matter-gluon coupling $\bar{\chi}\chi G^{\mu\nu}G_{\mu\nu}$

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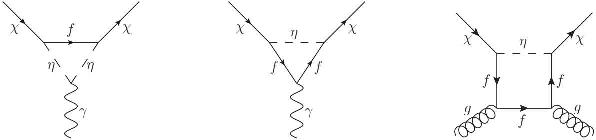
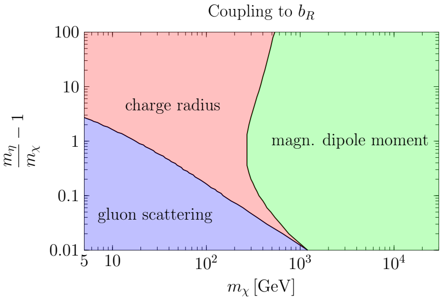
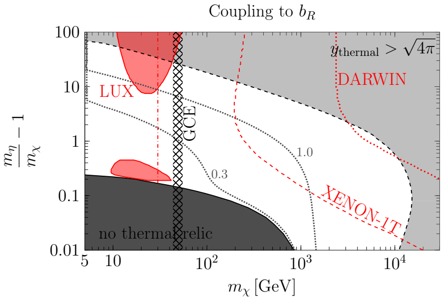




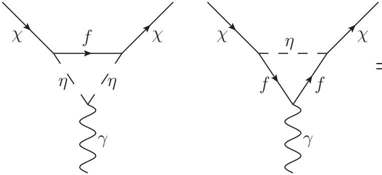


- Excellent prospects for future direct detection experiments
- In this model, the dominant annihilation mode is $\chi\bar{\chi} \to b\bar{b}$

$\hookrightarrow$ for $m_{\rm DM} \simeq 50$ GeV, this model could explain the **Galactic Center Excess** observed by Fermi

$\hookrightarrow$ well within the reach of XENON-1T!

Case (4): Coupling to t_R



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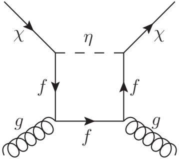

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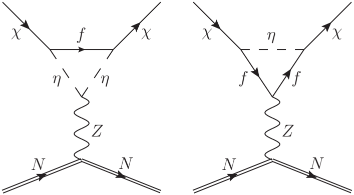
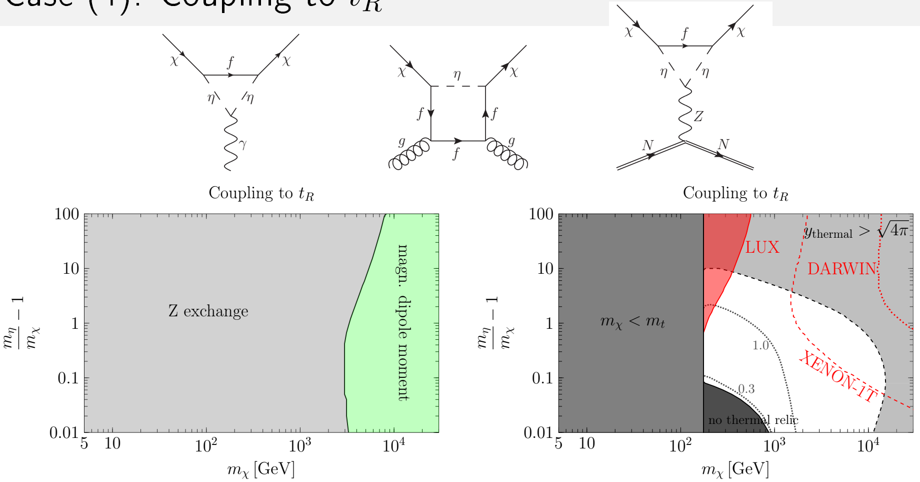


$\Rightarrow$ effective $\bar{\chi}\chi Z$ vertex
$\hookrightarrow \mathcal{L}_{\text{eff}} = f_{\text{V,Z}}\,\bar{\chi}\gamma^{\mu}\chi\,\bar{N}\gamma_{\mu}N$ with
$f_{\text{V,Z}} \propto (m_f/m_\chi)^2$

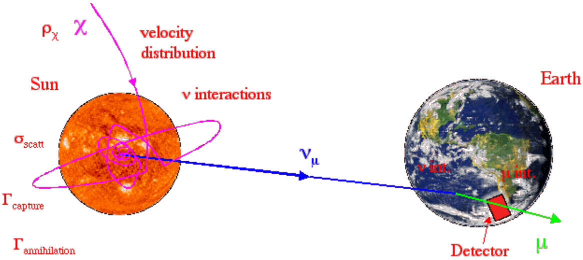
Case (4): Coupling to t_R



- For DM coupling to the top-quark, the one-loop Z exchange is dominant for $m_\chi \lesssim 5$ TeV
- LUX only constrains a rather small part of the thermal parameter space
- However: XENON-1T will be sensitive to dark matter masses $\gtrsim 1$ TeV

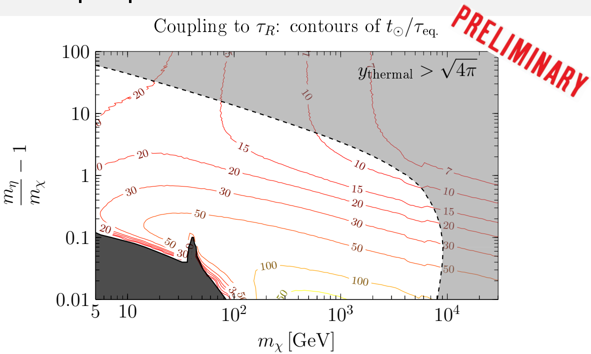
Outlook: leptophilic dark matter in the Sun?

Can dark matter be captured and annihilate in the Sun,
if it is **purely leptophilic**?



- The IceCube/Super-K limits can be very strong for leptophilic annihilations, e.g. DM DM $\to \tau^+\tau^-$ or DM DM $\to \nu\bar{\nu}$
- The magnetic dipole moment of χ leads to a dipole-dipole interaction with protons
  $\hookrightarrow$ similar to spin-dependent scattering off protons

Equilibration of leptophilic Dark Matter in the Sun



- Again, we fix the coupling y to its thermal value $\left(\Omega_{\mathsf{DM}} h^2 = 0.12\right)$
- $A_\odot = \frac{1}{2} C_\odot \tanh^2\left(t_\odot/\tau_{\mathsf{eq}}\right)$ with $\tau_{\mathsf{eq}} \propto \dfrac{1}{\sqrt{\sigma_{\mathsf{capture}} \cdot \langle\sigma v\rangle}}$

  $\hookrightarrow$ **Equilibrium condition**: $t_\odot/\tau_{\mathsf{eq}} \gg 1$

  $\hookrightarrow$ contour lines show constant values of $t_\odot/\tau_{\mathsf{eq}}$

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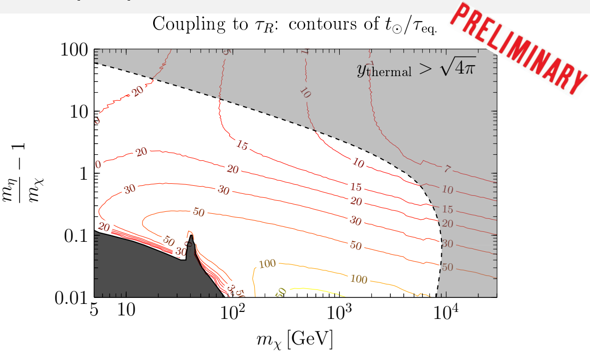

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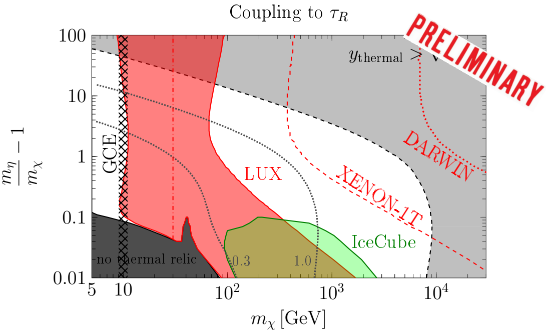
  ↪ contour lines show constant values of $t_\odot/\tau_{eq}$

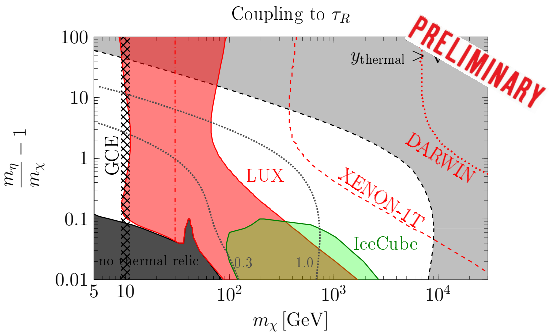
$\Downarrow$

In our simplified model of leptophilic Dirac Dark Matter,
we indeed have equilibration in the whole thermal parameter space

IceCube and LUX limits on leptophilic Dirac dark matter



IceCube and LUX limits on leptophilic Dirac dark matter



Complementarity between LUX and IceCube:

↪ For large DM masses and small mass splitting of χ and η, IceCube is stronger than LUX

↪ LUX and IceCube are affected differently by systematics, e.g. the dark matter velocity distribution

Conclusions

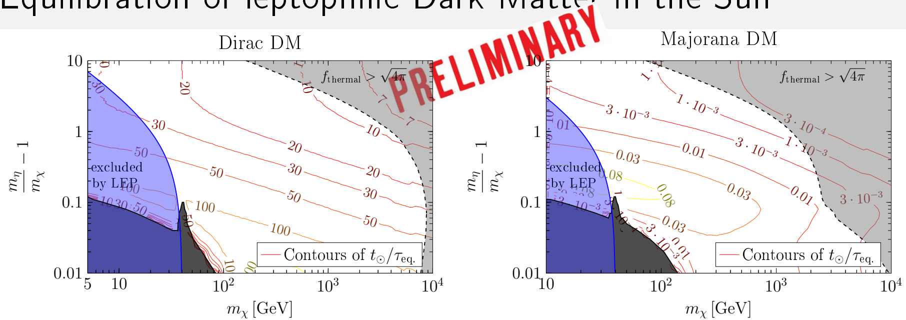
- Direct detection experiments have already reached the necessary sensitivity to probe dark matter-nucleon interactions mediated **only at one-loop order**

- We demonstrated this in the context of a simplified model with a singlet Dirac fermion as the dark matter particle
  $\hookrightarrow$ for **any** possible coupling scenario of dark matter, LUX already excludes part of the thermal parameter space
  $\hookrightarrow$ future direct detection experiments have excellent prospects to probe **large parts** of the parameter space, even multi-TeV dark matter
  $\hookrightarrow$ this approach is complementary and competitive to other searches:
    - LHC: monojet, direct production of η, ...
    - indirect detection with γ's from dwarf galaxies
    - for leptophilic DM: indirect detection with e^+/e^- (AMS-02)

- Furthermore, via the one-loop scattering diagrams, leptophilic dark matter can be captured in the Sun
  $\hookrightarrow$ limits from IceCube can be competitive with LUX in some parts of the parameter space

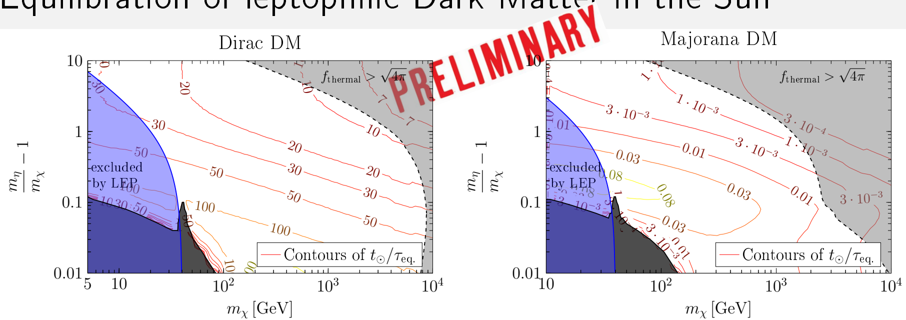
Backup slides

Equilibration of leptophilic Dark Matter in the Sun



- For this plot, we fix the coupling f to its **thermal value** $\left(\Omega_{\rm DM} h^2 = 0.12\right)$

Equilibration of leptophilic Dark Matter in the Sun



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- $A_\odot = \frac{1}{2} C_\odot \tanh^2\left(t_\odot/\tau_{\mathsf{eq}}\right)$ with $\tau_{\mathsf{eq}} \propto \dfrac{1}{\sqrt{\sigma_{\mathsf{capture}} \cdot \langle \sigma v \rangle}}$

  $\hookrightarrow$ **Equilibrium condition**: $t_\odot/\tau_{\mathsf{eq}} \gg 1$

  $\hookrightarrow$ contour lines show constant values of $t_\odot/\tau_{\mathsf{eq}}$

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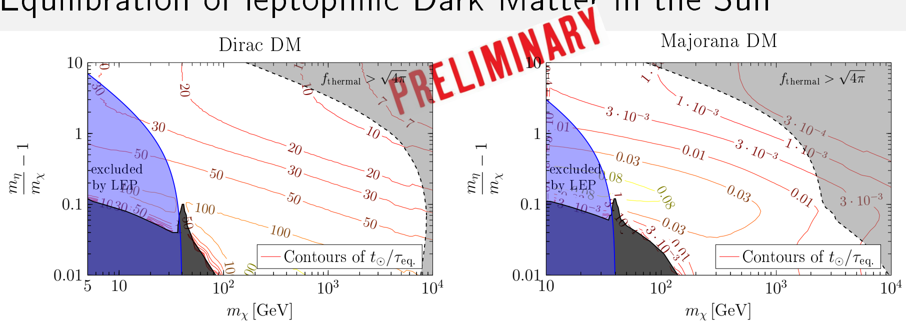

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$\Downarrow$

In our simplified model of leptophilic Dark Matter...
- DM **is** in equilibrium in the Sun if it is a Dirac fermion
- DM **is not** in equilibrium in the Sun if it is a Majorana fermion

IceCube and LUX limits on leptophilic Dirac Dark Matter

- Dirac Dark Matter annihilates into $f\bar{f}$ (no helicity suppression)
  $\hookrightarrow$ **strong neutrino signal** for DM coupling to τ_R,
  or to any left-handed lepton doublet
  $\hookrightarrow$ for coupling to e_R or μ_R neutrinos (only) from weak FSR

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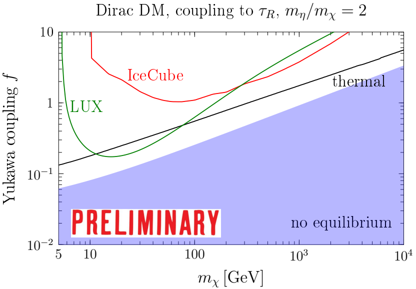

$\Rightarrow$

Leptophilic Dirac DM coupling to τ_R
or to any left-handed lepton doublet:
For $m_\chi \gtrsim 100$ GeV, IceCube limits can be **stronger than LUX**

- Black line: Yukawa coupling f leading to $\Omega h^2 = 0.12$
- Remark: Leptophilic Majorana Dark Matter is not in equilibrium in the Sun
  $\hookrightarrow$ no meaningful limits from IceCube