Forbidden dark matter annihilation into leptons with full collision terms

Based on [JCAP 08 (2023) 075] in collaboration with Amin Aboubrahim and Michael Klasen

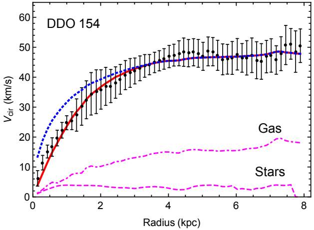
Luca Wiggering

LDW 2023, KIT, 21^{st} September 2023

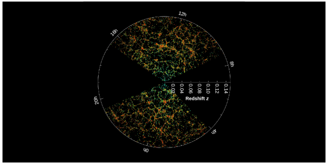
How do we know that there is dark matter?

Overwhelming qualitative and quantitative evidence for dark matter on all scales!

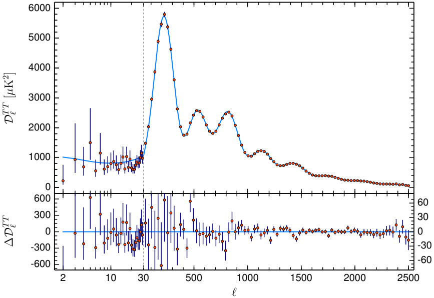
Rotation curves of spiral galaxies [1705.02358]



Galaxy surveys [Credit: SDSS]



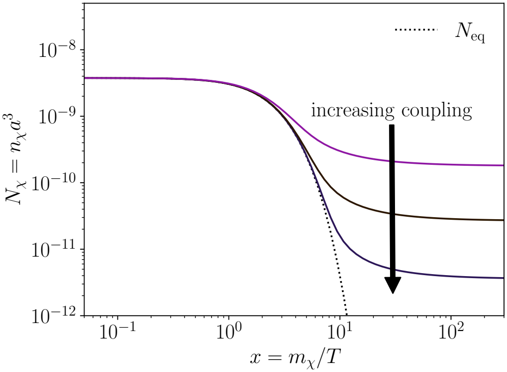
Cosmic microwave background [1807.06209]



$\Omega_\chi h^2 = 0.120(1)$ **PLANCK 2018**

Weakly Interacting Massive Particles

- well-motivated from particle physics [Supersymmetry, Extra Dimensions, ...]
- are produced thermally in the early Universe via freeze-out



$$\frac{\mathrm{d}n_\chi}{\mathrm{d}t} + 3Hn_\chi = \langle \sigma_{\mathrm{ann}} v \rangle \left((n_\chi^{\mathrm{eq}})^2 - n_\chi^2 \right)$$

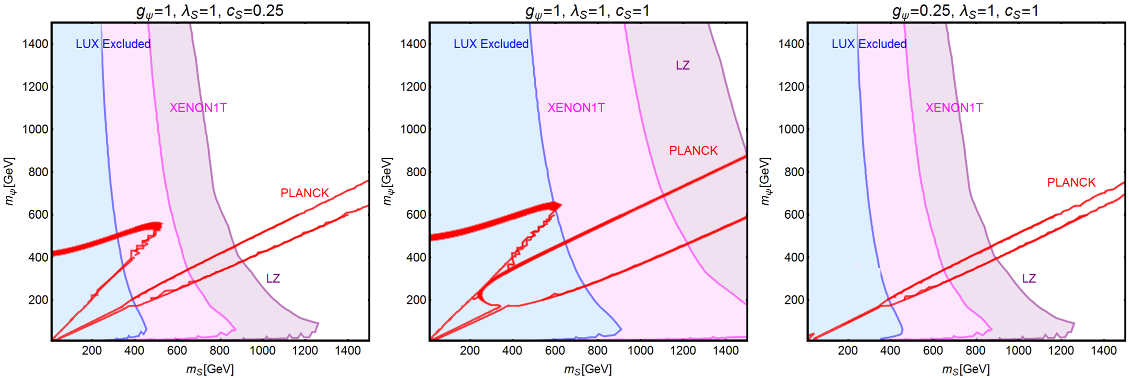
$$\Omega_\chi h^2 = 0.120 \sim \frac{1}{\langle \sigma_{\mathrm{ann}} v \rangle_{\mathrm{fo}}}$$

$$\langle \sigma_{\mathrm{ann}} v \rangle_{\mathrm{fo}} \approx \begin{cases} 2.2 \times 10^{-26}\,\mathrm{cm}^3/\mathrm{s} & , m_\chi > 10\,\mathrm{GeV} \\ 5.2 \times 10^{-26}\,\mathrm{cm}^3/\mathrm{s} & , m_\chi \sim 0.3\,\mathrm{GeV} \end{cases}$$

[1204.3622]

Waning of the WIMP?

[1703.07364]

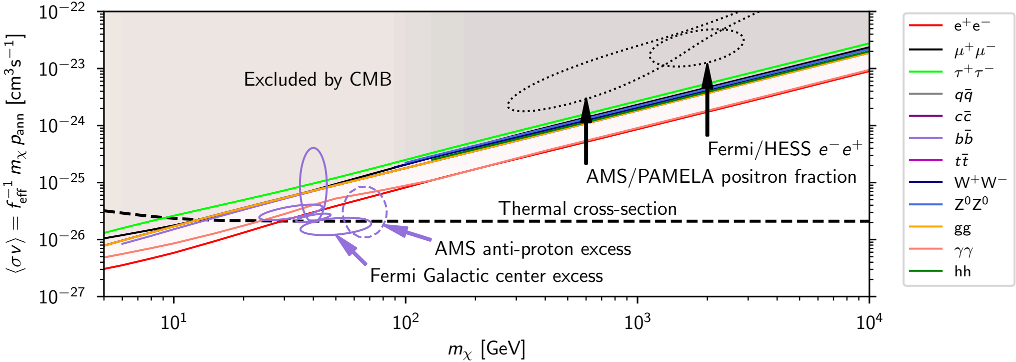


$$\mathcal{L} = g_\psi \bar{\psi}\psi S - \frac{c_S}{\sqrt{2}}\frac{m_f}{v_h}\bar{f}fS - \frac{1}{3}m_S\lambda_S S^3$$

The simplest models (SM dark portals) are substantially ruled out but not (yet) dead!

What about light thermal dark matter?

CMB constraints on the dark matter annihilation cross section [1807.06209]



Is light thermal dark matter with direct couplings to SM particles experimentally viable?

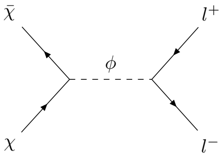
Forbidden dark matter

- Example effective model [2012.11766]:

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}\phi(\Box - m_\phi^2)\phi + \bar{\chi}(i\partial\!\!\!/ - m_\chi)\chi - g_{ij}^S \phi \bar{l}_i l_j - i g_{ij}^P \phi \bar{l}_i \gamma_5 l_j - g_\chi^S \phi \bar{\chi}\chi - i g_\chi^P \phi \bar{\chi}\gamma_5 \chi$$

  UV-completion possible in the S2HDM [2203.05579]

- Annihilation process:



$$\sim \quad \frac{1}{(s-m_\phi^2)+m_\phi^2\Gamma_\phi^2}$$

- Forbidden regime given by $m_\chi < m_l$ so that $\langle \sigma_{\chi\chi\to ll} v\rangle \to 0$ for $T \to 0$ [Griest, Seckel 1990] [1505.07107]

Going beyond the kinetic equilibrium description

Number density equation fails for resonant or forbidden dark matter.

[1706.07433][2103.01944]

$$\frac{\mathrm{d}n_\chi}{\mathrm{d}t} + 3Hn_\chi = \langle\sigma_{\mathrm{ann}}v\rangle((n_\chi^{\mathrm{eq}})^2 - n_\chi^2)$$

Critical assumption: $f_\chi = \frac{n_\chi}{n_\chi^{\mathrm{eq}}} f_\chi^{\mathrm{eq}}$ with $f_\chi^{\mathrm{eq}} = e^{-E/T}$ (kinetic Eq between DS and VS)

Approaches beyond kinetic equilibrium:

- cBE: ansatz $f_\chi(E) \sim e^{-E/T_\chi}$ with $T \neq T_\chi$ (assuming maximally efficient self-scattering)

$$(1) \quad \frac{\mathrm{d}n_\chi}{\mathrm{d}t} = \ldots \qquad\qquad (2) \quad \frac{\mathrm{d}T_\chi}{\mathrm{d}t} = \langle C_{\mathrm{el}}\rangle_2 \cdots + \ldots$$

- fBE: solve the full momentum-dependent Boltzmann equation for f_χ

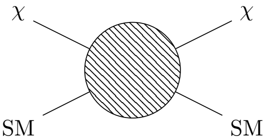
$$\partial_t f_\chi - Hp\partial_p f_\chi = C_{\mathrm{ann}}[f_\chi] + C_{\mathrm{el}}[f_\chi] + C_{\mathrm{self}}[f_\chi]$$

State-of-the-art DM abundance calculation

Public code DRAKE [2103.01944] allows calculation of $\Omega_\chi h^2$ with cBE and and the fBE

However:

- default $C_{\rm el}$ relies on Fokker-Planck type operator [1602.07624] (assumes NR DM + small momentum transfer)



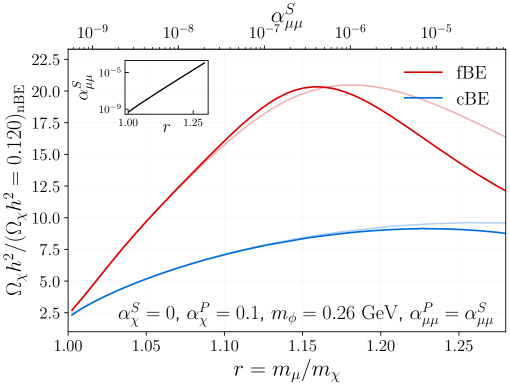
$$C_{\rm el} \simeq C_{\rm FP} = \frac{\gamma(T)}{2}\left[TE\partial_p^2 + \left(p + 2T\frac{E}{p} + T\frac{p}{E}\right)\partial_p + 3\right] f_\chi(p)$$

- **FP approximation breaks down for forbidden DM** $\longrightarrow$ resort to full $C_{\rm el}$
- DM self-scattering processes not available

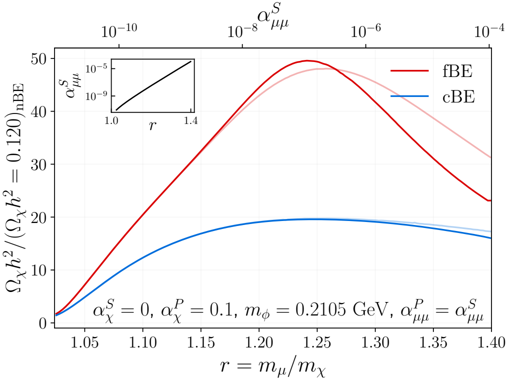
So we set up our own Boltzmann solver in C++ for performance reasons.

Comparison - annihilation into muons

Away from the resonance $(m_\phi \gg 2m_\mu)$



Close to the resonance $(m_\phi \approx 2m_\mu)$



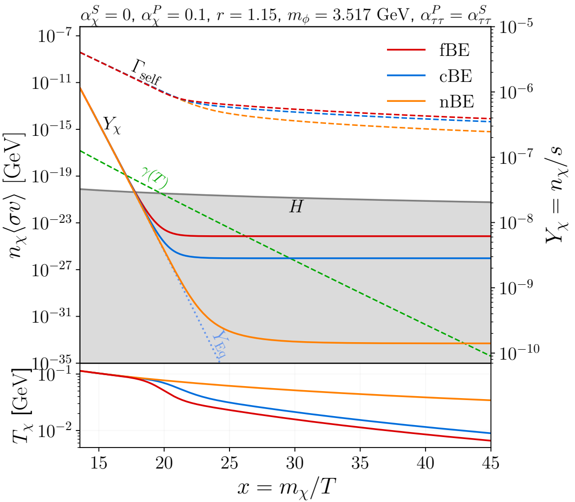
full $C_{\rm el}$ = non-transparent

$C_{\rm FP}$ = lighter shading

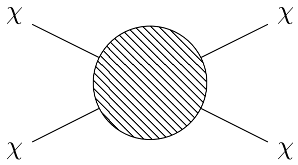
$\longrightarrow$ increase of the relic density by up to a factor of 50

Similar findings for annihilation into τ-leptons

What about the impact of DM self-scattering?



Up to now DM self-scattering is missing:

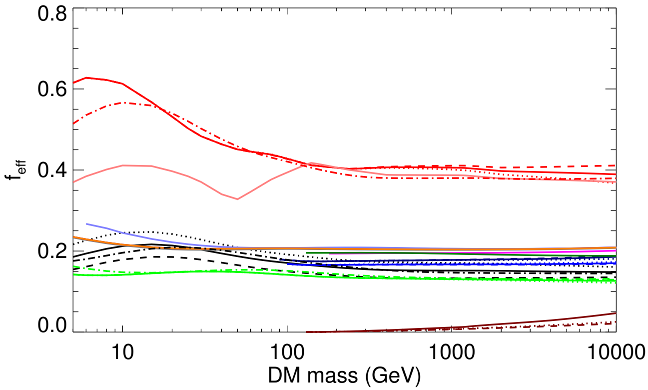


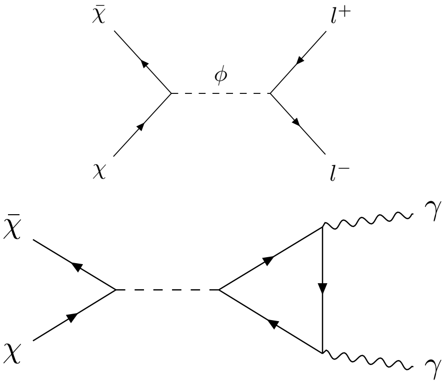
- C_{self} implemented but numerically unstable since $\Gamma_{\text{self}} = 2 n_\chi \langle \sigma_{\text{self}} v \rangle \gg H$
  $\longrightarrow$ maximally efficient self-scattering rate
  $\longrightarrow$ cBE approach is sufficient
- for first full treatment of DM self-scattering see [2204.07078]

Pheno

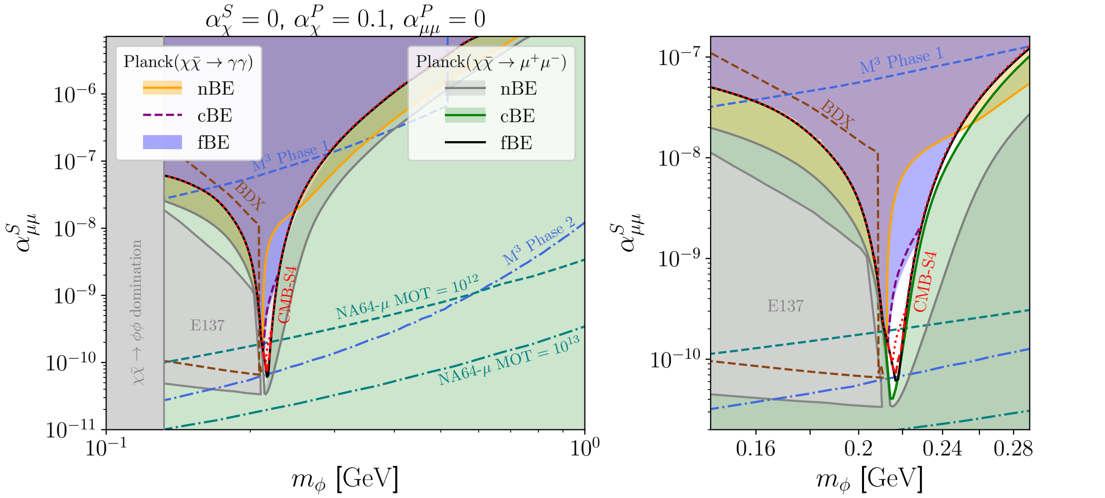
Radiative annihilation probes forbidden DM

- Planck limit: $f_{\rm eff}\langle\sigma v\rangle/m_\chi \leq 3.5\times10^{-28}$ cm^3/s/GeV [1807.06209], $f_{\rm eff}$ from [1506.03811]
- CMB-S4 is expected to improve this limit by a factor 2 - 3 [1610.02743]



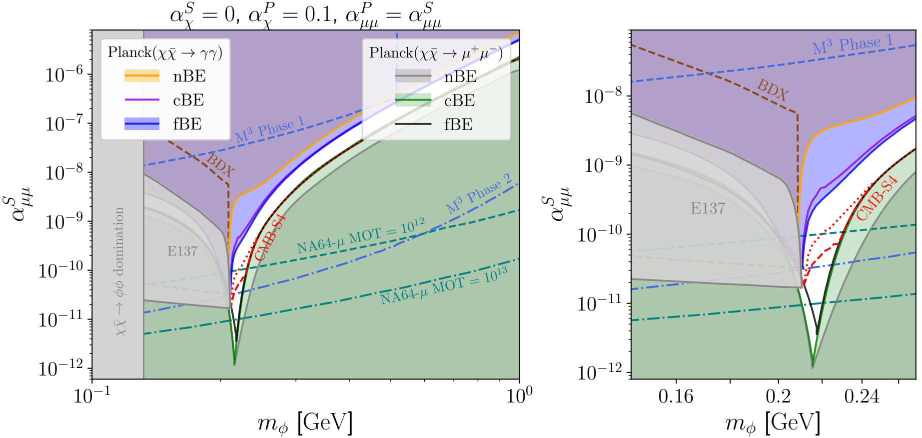


Exclusion limits - annihilation into muons for $\alpha^P_{\mu\mu} = 0$



Full calculation excludes previously open parameter regions by more than an order of magnitude.

Exclusion limits - annihilation into muons for $\alpha^P_{\mu\mu} = \alpha^S_{\mu\mu}$

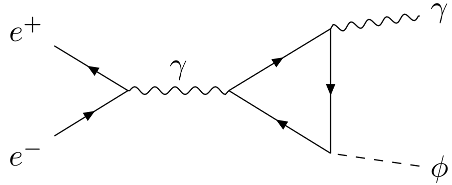


Opening up the pseudoscalar coupling leads to more viable parameter space.

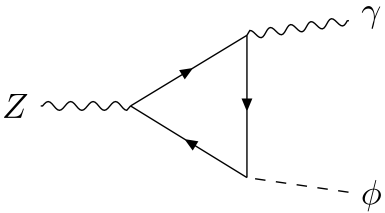
Recall: $(\sigma v)_{\bar{\chi}\chi} \to \alpha^P_\chi + (\alpha^P_\chi + \alpha^S_\chi)v^2 + \mathcal{O}(v^4)$

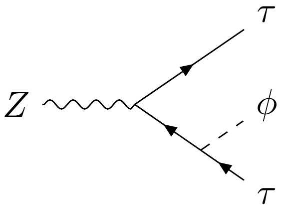
Probing $\tau^+\tau^-$-annihilation at collider experiments

- Monophoton searches at BaBar or Belle-II with $\sqrt{s} = 10.58\,\text{GeV}$ [1709.00009]

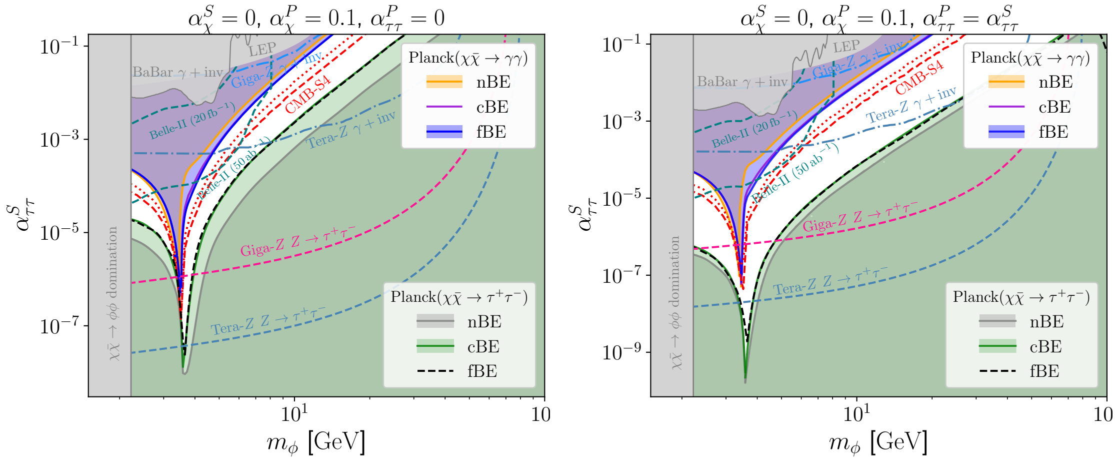


- Production at (future) Z-factories (LEP, FCC-ee or CEPC) [1712.07237]





Exclusion limits - annihilation into taus



Also for annihilation into $\tau^+\tau^-$ a significant reduction of the viable parameter space while the case $\alpha_{\tau\tau}^P = 0$ is less constrained.

Summary

- Light thermal dark matter with direct couplings to leptons is a viable alternative to the WIMP paradigm.

- Almost the entire currently viable parameter space can be probed with CMB-S4, next-generation beam-dump experiments or at a future high-luminosity electron-position collider

- **The relic density calculation based on the full collision term reduces the viable parameter space by up to an order of magnitude.**