Direct detection of self-interacting dark matter

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mostly based on

1707.XXXXX (Kahlhoefer, Kulkarni, SW)

1704.02149 (Kahlhoefer, Schmidt-Hoberg, SW)

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Sudbury, Canada

Self-interacting dark matter (SIDM)

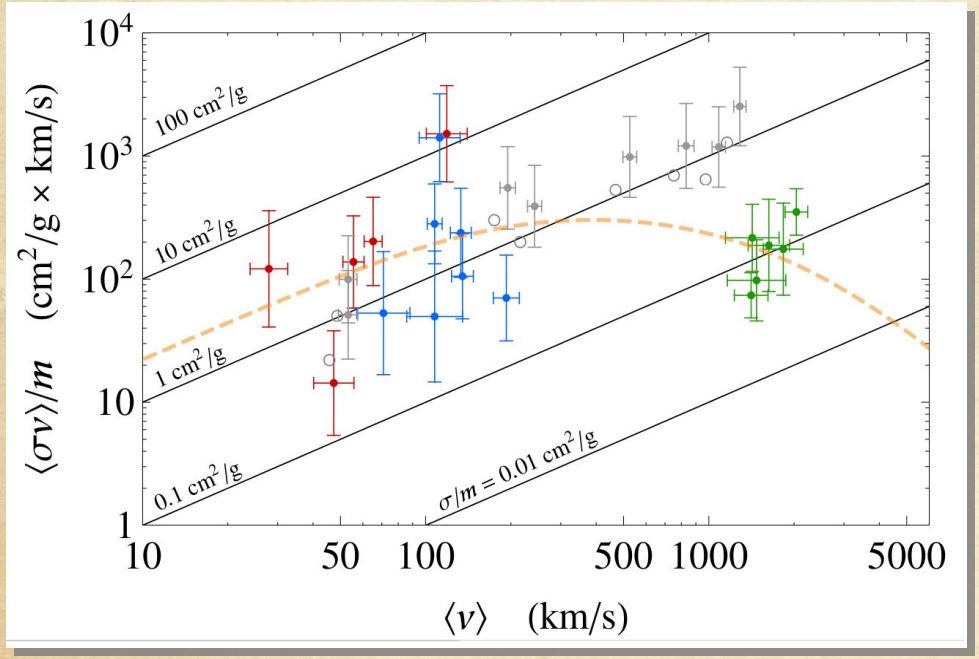
Potential "small-scale crisis" within the cold DM paradigm:

- Too-big-to-fail problem
- Missing-satellites problem
- Cusp-vs-core problem

→ Observational issue? Baryonic physics? **Strong DM self-interactions?**

Spergel+ [astro-ph/9909386]

Kaplinghat+ [1508.03339]



- Observational preference for **velocity-dependent** SIDM:

$$\sigma/m \sim 1 - 10\,\mathrm{cm}^2/\mathrm{g}$$
at dwarf scales $(v \sim 30\ \mathrm{km/s})$

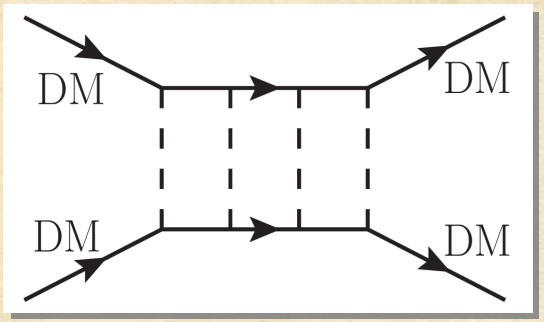
$$\sigma/m \lesssim 0.1 - 1\,\mathrm{cm}^2/\mathrm{g}$$
at cluster scales $(v \sim 1000\ \mathrm{km/s})$

→ How can this be realized in a particle physics model?

SIDM via a light scalar mediator

Feng+ [0905.3039]
Buckley+ [0911.3898]

Dirac WIMP ($m_{\rm DM} \simeq$ GeV $-$ TeV)
+ light scalar mediator ($m_{\rm med} \simeq 1\,{\rm MeV} - 100\,{\rm MeV}$)



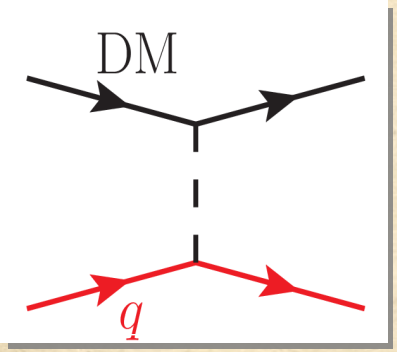
enhanced by
… small $m_{\rm med}$
… non-perturbative effects

Strong DM self-interactions with **weak** couplings!

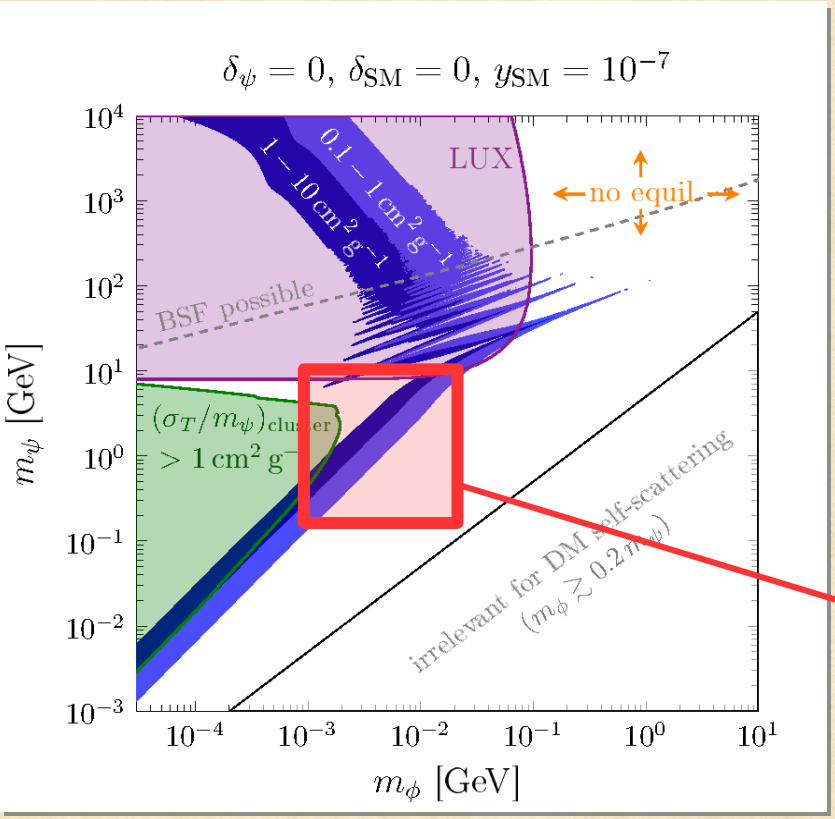
→ Required velocity dependence of self-interaction cross section comes for free!

SIDM via a light scalar mediator

Direct detection is a powerful probe of this scenario:



… enhanced by small m_ϕ



SW+ [1704.02149]

Largely excluded by LUX & Xenon1T for $m_{\rm DM} \gtrsim 5\,{\rm GeV}$

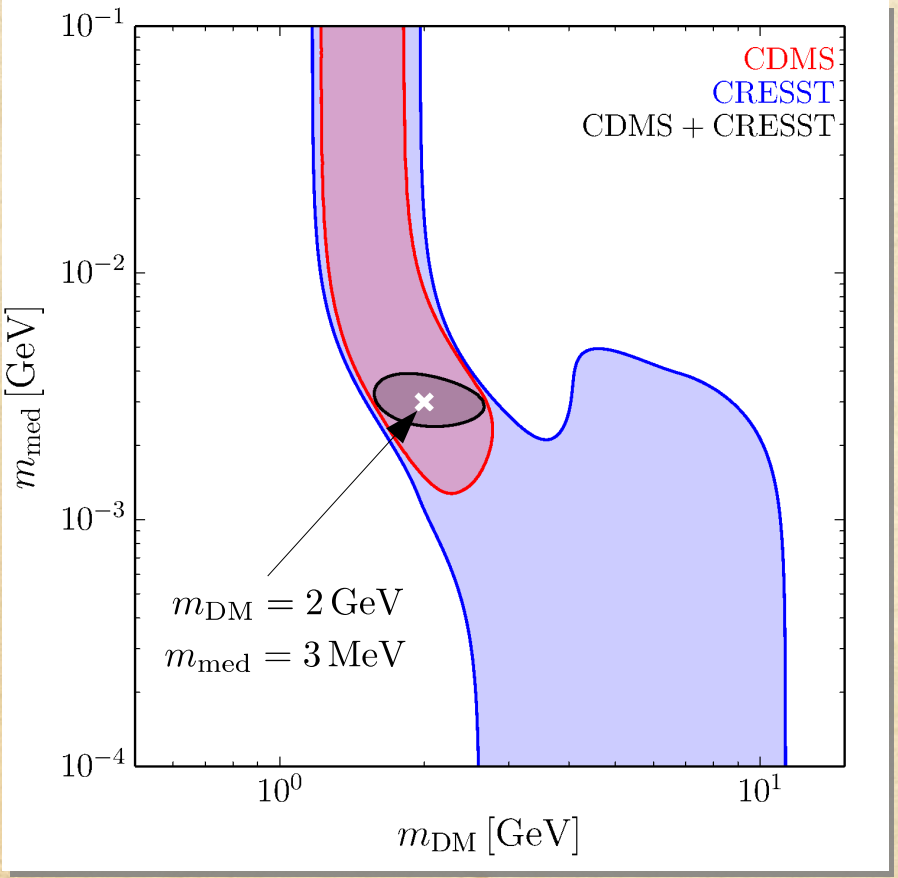
Not excluded by DD:
$m_{\rm DM} \sim {\rm GeV}$,
$m_\phi \sim 1 - 10$ MeV

- **Discovery potential** for future realizations of CRESST, CDMS, EDELWEISS, …
- Non-standard recoil spectrum: ${\rm Rate} \propto \left(q^2 + m_\phi^2\right)^{-2}$ with $m_\phi \sim q \equiv \sqrt{2 m_T E_R}$

Measuring **mediator masses** with direct detection?

Measuring mediator masses with DD

- We conduct the first dedicated **parameter reconstruction study** for CRESST-III + SuperCDMS@SNOLAB in the context of light mediators
- After generating mock data, we perform a **profile likelihood fit** to the energy spectrum.
  → we take into account energy resolution, background uncertainties, astrophysical uncertainties, varying f_n/f_p

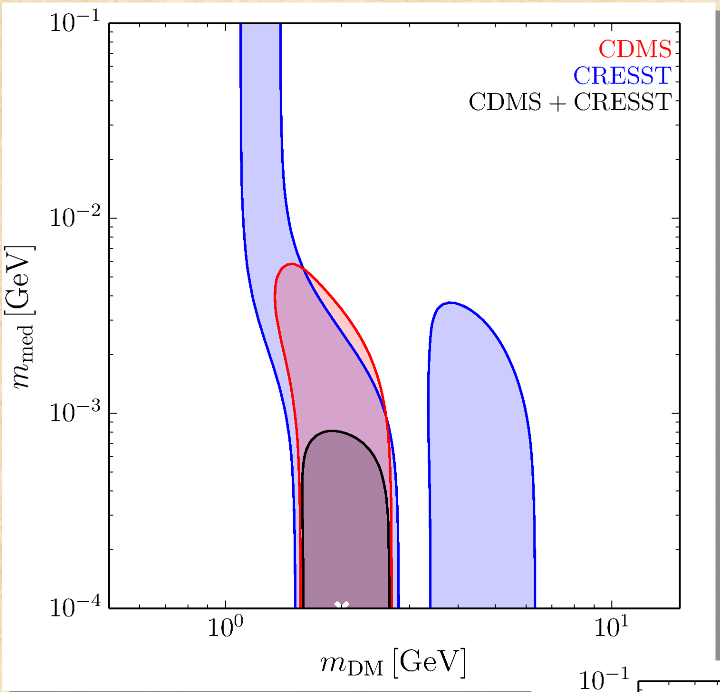


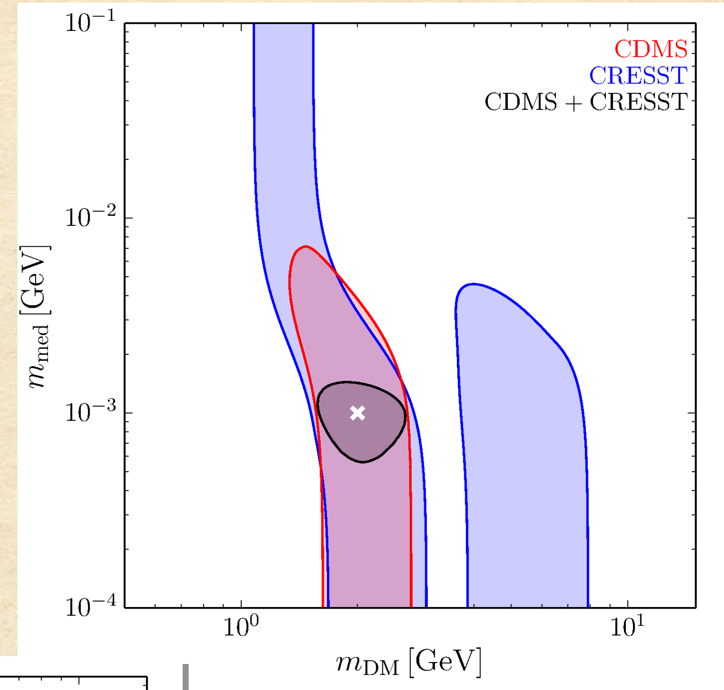
- Strong complementarity of CRESST and CDMS (different targets!)

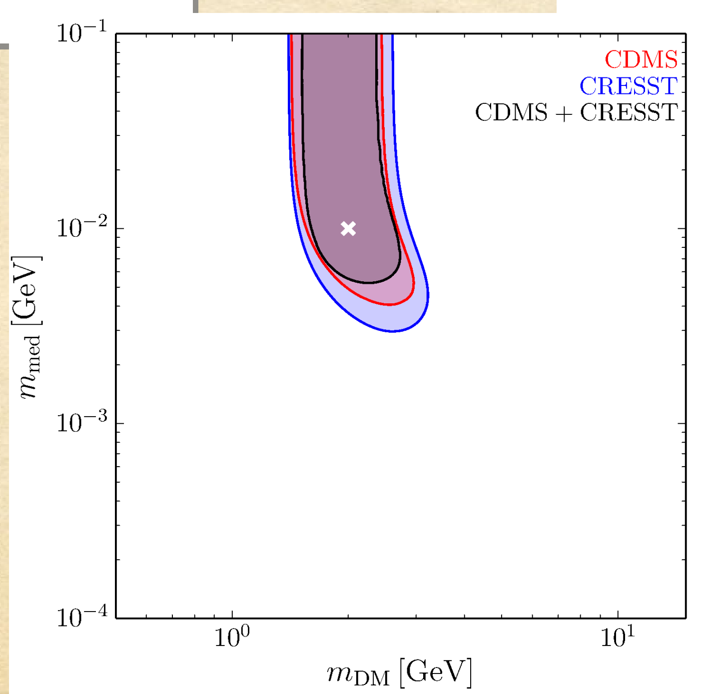
Exciting possibility:
simultaneous measurement of dark matter and mediator masses with low-threshold DD experiments!

SW+ [17XX.XXXXX]

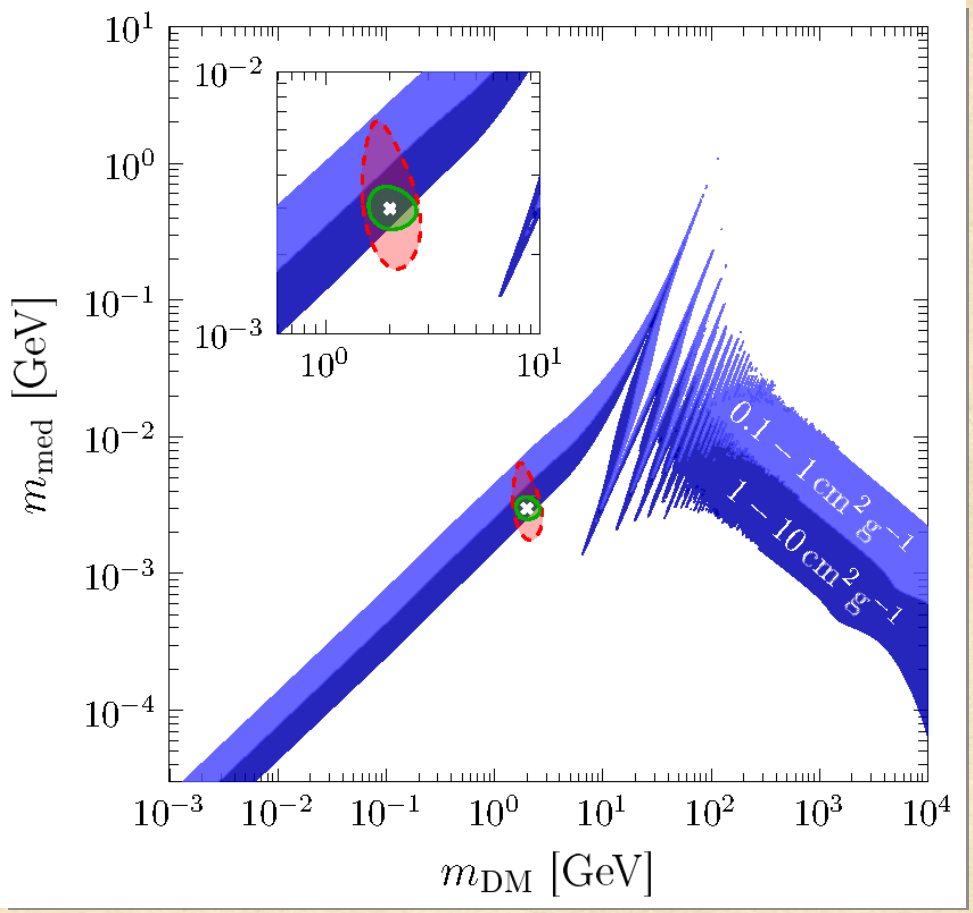
Measuring mediator masses with DD







Interplay: SIDM ←→ direct detection



SW+ [17XX.XXXXX]

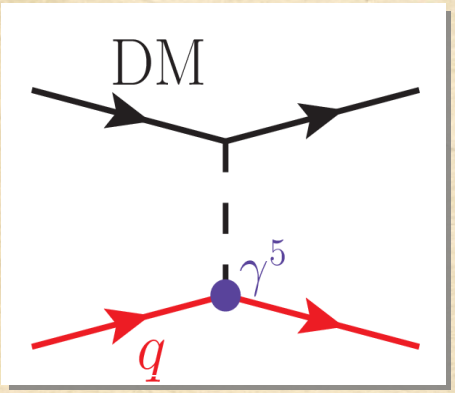
Future low-threshold DD experiments can potentially probe the behaviour of DM on astrophysical scales!

Alternative scenario: CP-violating SIDM

SW+ [1704.02149]

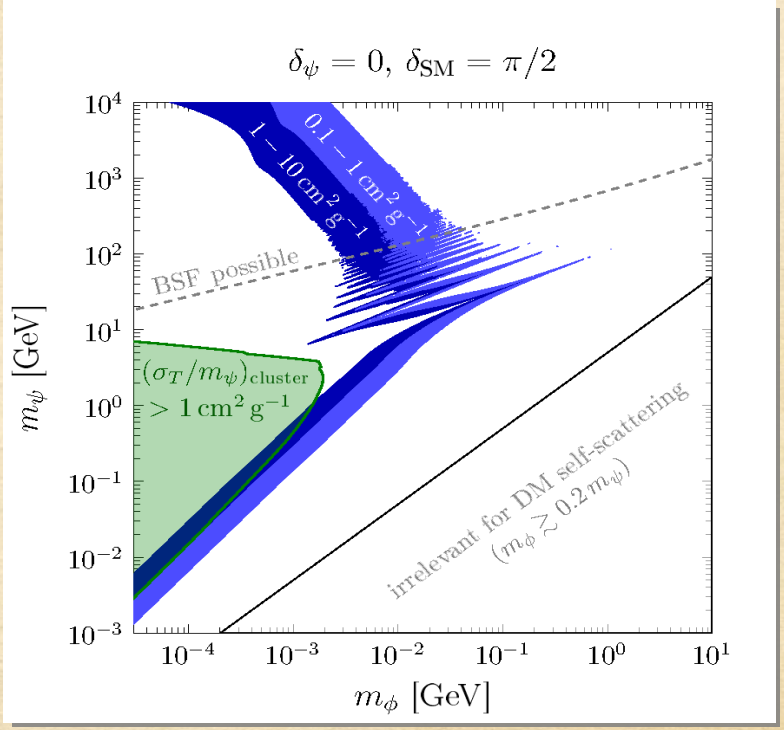
$$\mathcal{L} = -y_\psi \bar{\psi}\psi\phi - i y_{\rm SM} \sum_f \frac{m_f}{v_{\rm EW}} \bar{f}\gamma^5 f \phi$$

Direct detection:

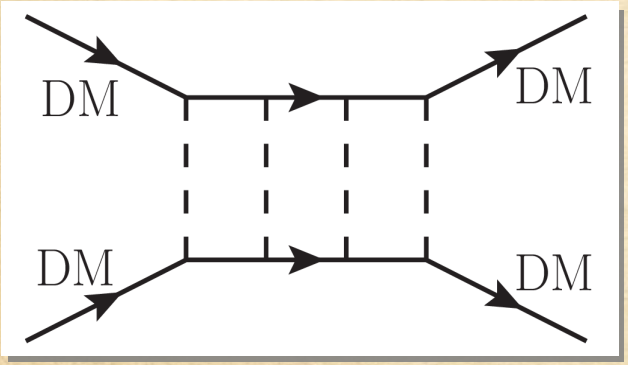


$\propto q^2$ for a mixed scalar/pseudoscalar mediator

→ direct detection constraints are easily evaded



Self-interactions:



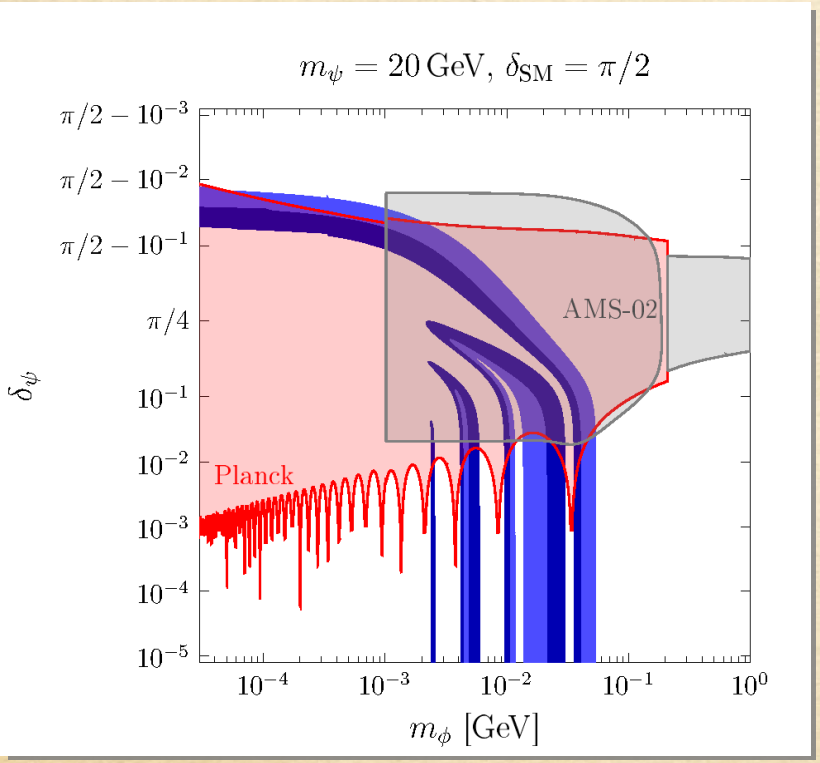
$$V(r) \propto \frac{e^{-m_\phi r}}{r}$$

Phenomenologically viable also for large $m_{\rm DM}$!

CP violating SIDM: general case

- No theoretical reason for maximal CP violation → more general setup:

$$\mathcal{L} = -y_\psi \cos\delta_\psi \bar{\psi}\psi\phi - i y_\psi \sin\delta_\psi \bar{\psi}\gamma^5\psi\phi$$
$$-y_{\rm SM}\sum_f \left[\frac{m_f}{v_{\rm EW}}\cos\delta_{\rm SM}\bar{f}f\phi + i\frac{m_f}{v_{\rm EW}}\sin\delta_{\rm SM}\bar{f}\gamma^5 f\phi\right]$$



- Strong CMB constraints for $\delta_\psi > 0$:

  $(\sigma v)^{\rm CMB}_{\psi\bar{\psi}\to\phi\phi} \propto \sin^2(2\delta_\psi)$

  → CMB requires $\delta_\psi \ll 1$

- For large $m_{\rm DM}$, direct detection strongly constrains the scalar DM-mediator coupling

  → DD requires $\pi/2 - \delta_{\rm SM} \ll 1$

Viable parameter space for SIDM!

- Such a setup can appear **naturally** in models with spontaneous CP violation

Conclusions

- **Self-interacting dark matter** (SIDM) is a potential solution to small-scale problems within the standard cold DM paradigm

- Using **MeV-scale mediators**, this can be realized with "standard" WIMPs

(1) Purely scalar couplings:

- Largely excluded for $m_{\rm DM} \gtrsim 5\,{\rm GeV}$ by direct detection
- **Discovery potential** for future low-threshold experiments!
- Most exciting: direct detection experiments could **simultaneously** probe $m_{\rm DM}$ and $m_{\rm med}$

(2) CP-violating DM (mixed scalar/pseudoscalar couplings)

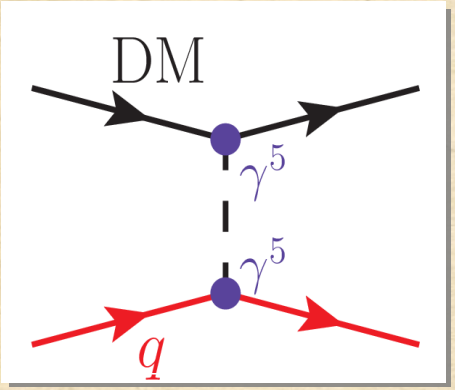
- (Mostly) scalar DM-mediator interactions lead to strong self-interactions
- (Mostly) pseudoscalar SM-mediator interactions suppress direct detection
- Interesting interplay with CMB constraints

Backup material

SIDM with pseudoscalar interactions

$$\mathcal{L} = -iy_\psi \bar{\psi}\gamma^5\psi\phi - iy_{\rm SM}\sum_f \frac{m_f}{v_{\rm EW}}\bar{f}\gamma^5 f\phi$$

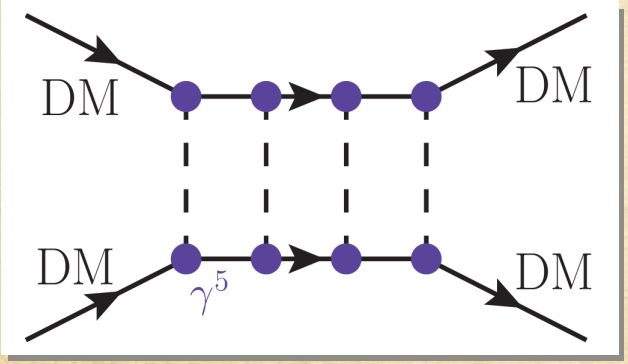
Direct detection:



$\propto q^4$ for a pseudoscalar mediator

→ direct detection constraints are evaded!

BUT:



$$V(r) \propto \frac{m_{\rm med}^2}{m_{\rm DM}^2}\frac{e^{-m_\phi r}}{r} + \mathcal{O}\left(\frac{1}{r^2}\right)$$

→ No significant self-interactions from pseudoscalar exchange

Detailed discussion about this (@tree- and one-loop level) in SW+ [1704.02149]

Spontaneous CP violation

- Starting point: CP-conserving scenario involving a pseudoscalar P:

$$\mathcal{L}_{\rm DM} = \bar{\psi}(i\partial - m_0)\psi - iy_\psi P\bar{\psi}\gamma^5\psi - V(P)$$

- P acquires a vev: $P = v_P + \phi$

$$\Rightarrow\ \mathcal{L}_{\rm DM} = \bar{\psi}\left[i\partial - (m_0 + iy_\psi v_P\gamma^5)\right]\psi - iy_\psi\phi\bar{\psi}\gamma^5\psi - V(\phi)$$

- Chiral rotation $\psi \to \exp(i\gamma^5\alpha/2)\psi$ with $\tan\alpha = y_\psi v_P/m_0$ removes the complex mass term:

$$\mathcal{L}_{\rm DM} = \bar{\psi}(i\partial - m_\psi)\psi - y_\psi\phi\bar{\psi}(\cos\delta_\psi + i\sin\delta_\psi\gamma^5)\psi \qquad (\delta_\psi = \pi/2 - \alpha)$$

→

- Mixed scalar/pseudoscalar interactions of DM
- $\delta_\psi \ll 1$ corresponds to $y_\psi v_P \gg m_0$

Spontaneous CP violation

- Similar story for the mediator-SM coupling:

$$\mathcal{L}_{\text{mass}} \supset -\sum_f \bar{f} \frac{y_f}{\sqrt{2}} (v_{\text{EW}} + i \sin\theta \, v_P \gamma^5) f$$

$$\Rightarrow \quad \mathcal{L}_{\text{mixing}} = -y_{\text{SM}} \sum_f \frac{y_f}{\sqrt{2}} \phi \bar{f} (\cos\delta_{\text{SM}} + i \sin\delta_{\text{SM}} \gamma^5) f$$

with $y_{\text{SM}} = \sin\theta$ and $\delta_{\text{SM}} = \pi/2 - \alpha_{\text{SM}}$

- Crucial point: $\alpha_{\text{SM}} \propto \sin\theta \ll 1 \;\Rightarrow\; \delta_{\text{SM}} \approx 1$

→ Small coupling to SM fermions ensures that the SM-mediator coupling is nearly pseudoscalar after spontaneous CP breaking