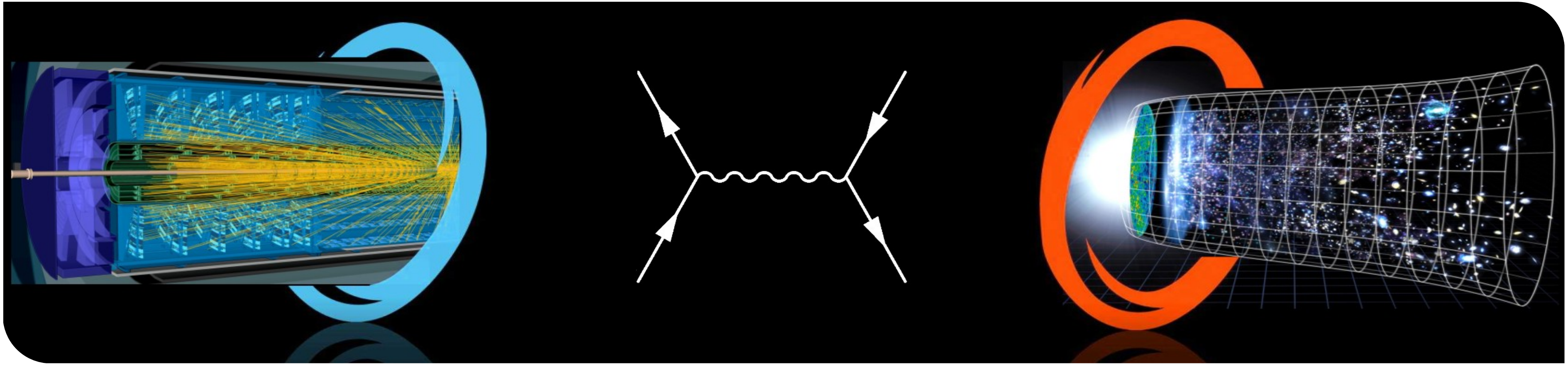
What is the mass scale of self-interacting dark matter?

Felix Kahlhoefer

Workshop on the Small-Scale Structure of the Universe and Self-Interacting Dark Matter, Valencia, 13 June 2025



Back-of-the envelope calculation

- Typical cross section of interest:
  $\sigma / m_{DM} > 0.5\ cm^2 / g \sim 1\ barn / GeV$
- Assume there is only a single mass/energy scale *v* in the dark sector
- Dimensional analysis: $m_{DM} \sim v$ and $\sigma \sim v^{-2}$

➞ Required scale: $v \sim 100$ MeV

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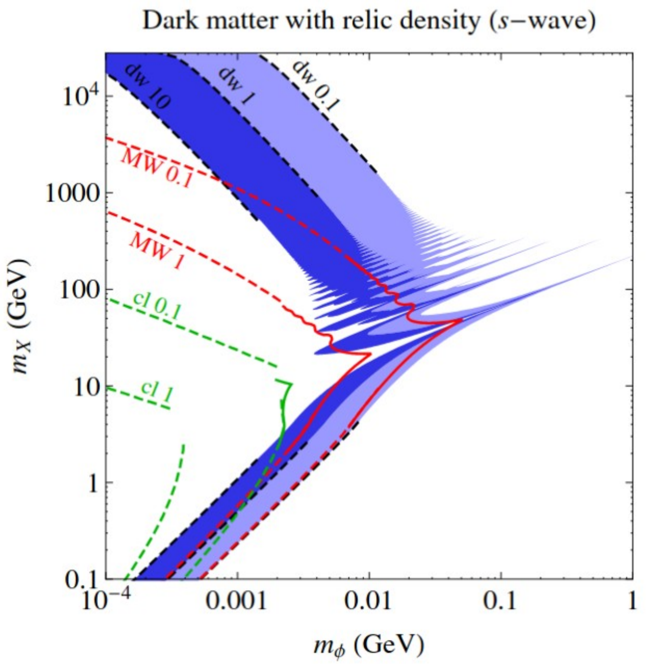
SIDM with several mass scales

- Most popular SIDM model (long-range interaction via light mediator exchange) requires two separate scales: **DM mass and mediator mass**
- Imposing relic density constraint (DM production via freeze-out mechanism) fixes the interaction strength, but neither of the mass scales
  - ➞ DM mass can vary over **many orders of magnitude**
  - ➞ Potentially **large hierarchy** between DM and mediator mas
  - ➞ Large self-interactions **accommodated** but **not predicted**



Tulin et al., arXiv:1302.3898

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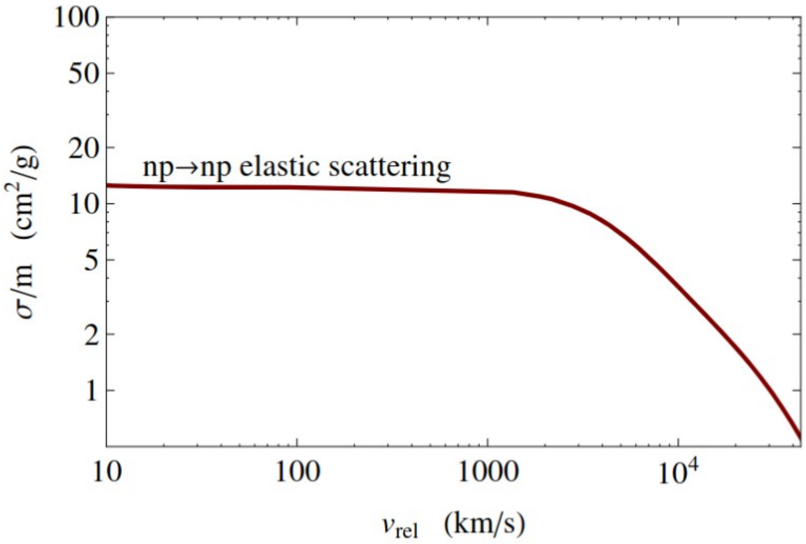
SIDM without a large hierarchy of scales

- **Curious observation:** v ~ 100 MeV is close to QCD confinement scale Λ_{QCD} ~ 200 MeV and to the pion decay constant f_π ~ 92 MeV

- Indeed, 1 barn/GeV is roughly the nucleon-nucleon scattering cross section

  ➞Compelling reason to think about DM particles with interactions similar to QCD

Can we get SIDM from new strong dynamics?



Tulin & Yu, arXiv:1705.02358

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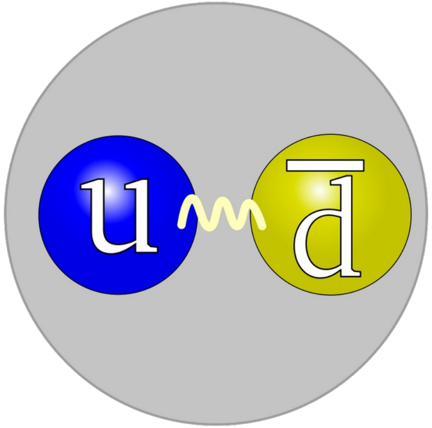
Strongly-interacting dark sectors

- Consider a dark sector that contains dark gluons and dark quarks:

$$\mathcal{L} = -\frac{1}{4} F^a_{\mu\nu} F^{\mu\nu a} + \bar{q}_\mathrm{d} i \not{D} q_\mathrm{d} - \bar{q}_\mathrm{d} M_q q_\mathrm{d}$$

- For energies below some scale Λ_d the dark sector confines, giving rise to dark mesons and dark baryons
- In contrast to the SM, the lightest dark mesons (i.e. the dark pions) may be stable and possible DM candidates



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Chiral symmetry breaking

- In the absence of a mass term for the dark quarks, the dark pions are **Goldstone bosons of chiral symmetry breaking** and therefore massless

- A strongly-interacting dark sector therefore requires two independent mass scales
  - M_q and Λ_d (at high energies)
  - m_π and f_π (at low energies)

- SIDM cross section: $\sigma / m_{DM} \sim m_\pi / f_\pi^4$

- In the Standard Model, m_π and f_π are quite close, but with no fundamental reason

- Can we narrow down the range of m_π / f_π?

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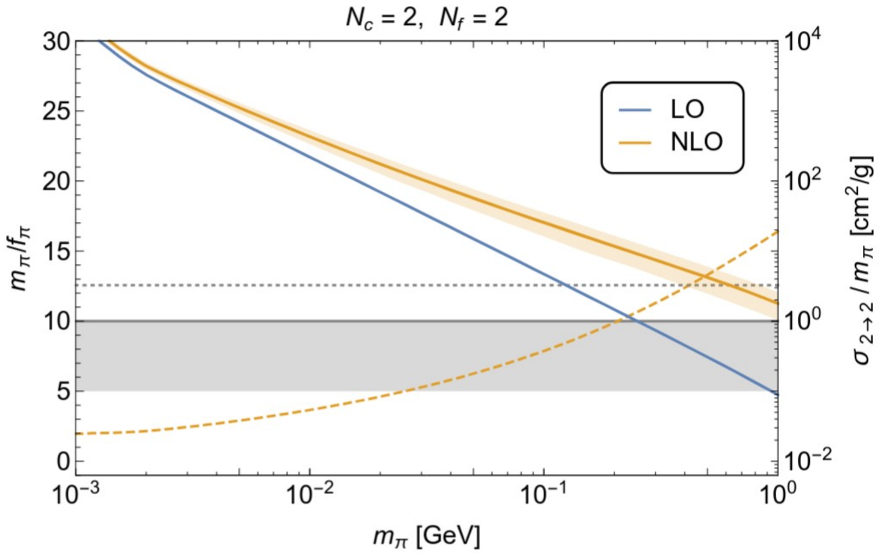
Relic density requirement

- Fix combination of m_π and f_π from the relic density requirement
- **Simplest case:** Consider 3→2 annihilations via Wess-Zumino-Witten anomaly

See Xiaoyong's talk

→ Perturbativity ($m_\pi/f_\pi < 4\pi$) implies $m_\pi < 1$ GeV (dashed line)

→ Predicted self-interaction cross section too large (solid line)

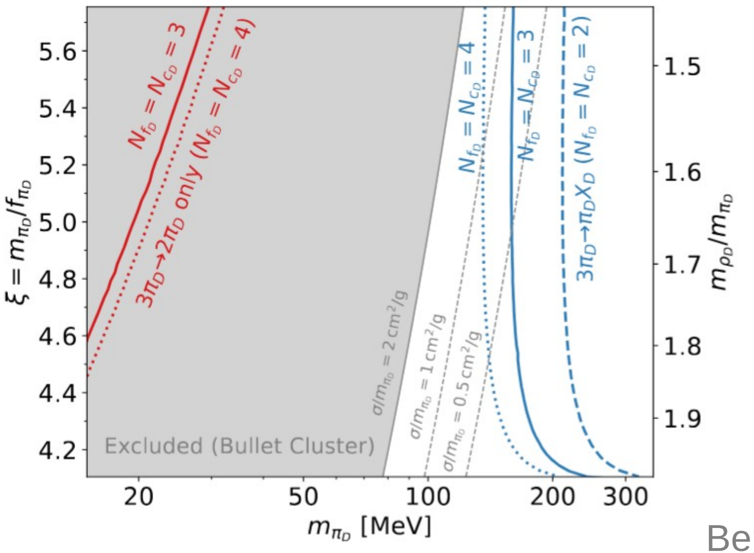


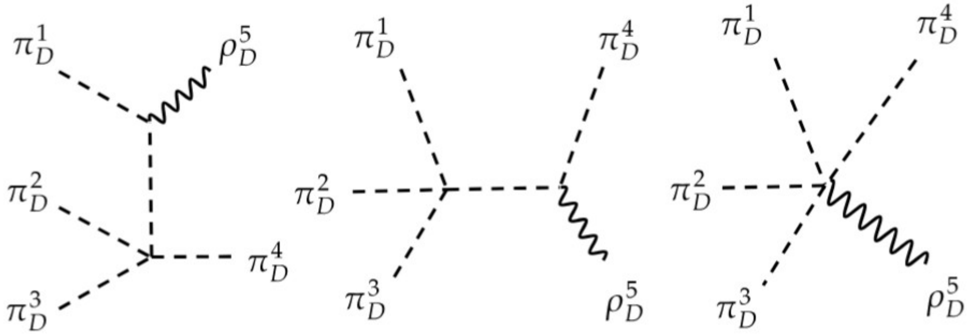
Hansen et al., arXiv:1507.01590

Strongly interacting DM with light vector mesons

- **Lattice simulations:** For $m_\pi/f_\pi > 4$, expect light vector mesons with $m_\rho < 2\, m_\pi$

  → Relevant for relic density calculation





- Relic density requirement points to $m_\pi \sim 200$ MeV
- Predicted self-interaction cross section ~ 1 cm^2 / g

  → Exactly in the interesting range!

- **But:** no significant velocity dependence expected

Bernreuther, FK et al., arXiv:2311.17157

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Dark sectors with only a single mass scale

Key idea: Start with a dark sector without any mass scale

- Consider dark sector with a scalar field Φ and **conformal symmetry**
  - ➞ Invariance under rescaling $x^\mu \to \alpha x^\mu,\ \Phi(x) \to \alpha^{-1}\Phi(\alpha x)$
  - ➞ All mass terms in the Lagrangian forbidden, all particles massless at tree-level

- **But:** Radiative corrections introduce scale dependence
- **Coleman Weinberg mechanism:** effective potential has minimum at non-zero field value

$$V_{\rm eff}(\phi_{\rm b}, T=0) = \sum_a \frac{g_a \eta_a}{64\pi^2} \frac{m_a^4(v)}{v^4} \phi_{\rm b}^4 \left[\log\left(\frac{\phi_{\rm b}^2}{v^2}\right) - \frac{1}{2}\right]$$

- Vacuum expectation value generates mass terms and breaks conformal symmetry

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Connection to dark matter

- Assume dark scalar Φ and fermion fields χ charged under U(1)' gauge symmetry

$$\mathcal{L} = |D_\mu \Phi|^2 - \frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} + \bar{\chi}_1 i \not{D} \chi_1 + \bar{\chi}_2 i \not{D} \chi_2 - \left(\frac{y_1}{2} \Phi \bar{\chi}_1^c \chi_1 + \frac{y_2}{2} \Phi^* \bar{\chi}_2^c \chi_2 + \text{h.c.} \right) - V(\Phi)$$

- Conformal symmetry forbids all mass terms
- All masses must be proportional to vacuum expectation value of dark scalar
  - Gauge interactions: Dark photon mass
  - Yukawa interactions: Dark matter mass
- Interaction terms:

$$\mathcal{L}_{\text{int}} \supset -\lambda v \phi^3 - \frac{\lambda}{4} \phi^4 + g^2 v A'_\mu A'^\mu \phi + \frac{g^2}{2} \phi^2 A'_\mu A'^\mu + \sum_i \frac{g}{2} Q_i \bar{\chi}'_i \gamma^\mu \gamma^5 \chi'_i A'_\mu - \frac{y}{2\sqrt{2}} \phi \bar{\chi}'_i \chi'_i$$

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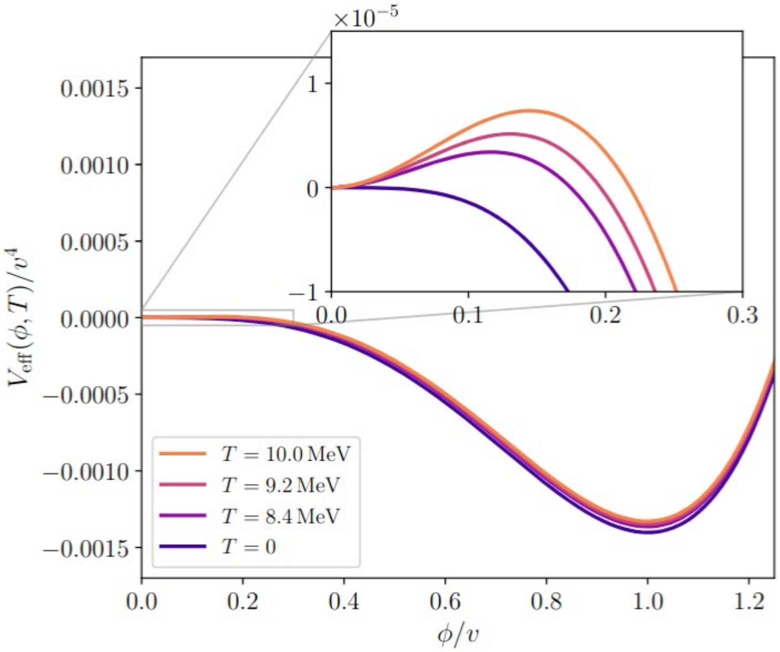
Conformal dark sector at finite temperature

- At high temperatures and densities (early universe), conformal symmetry is restored
- As the universe cools down, symmetric minimum becomes metastable
- Potential barrier prevents transition to energetically favourable ground state

  ➞ Conformal symmetry breaking happens through a (strongly) supercooled first-order phase transition



Balan, FK et al., arXiv:2502.19478

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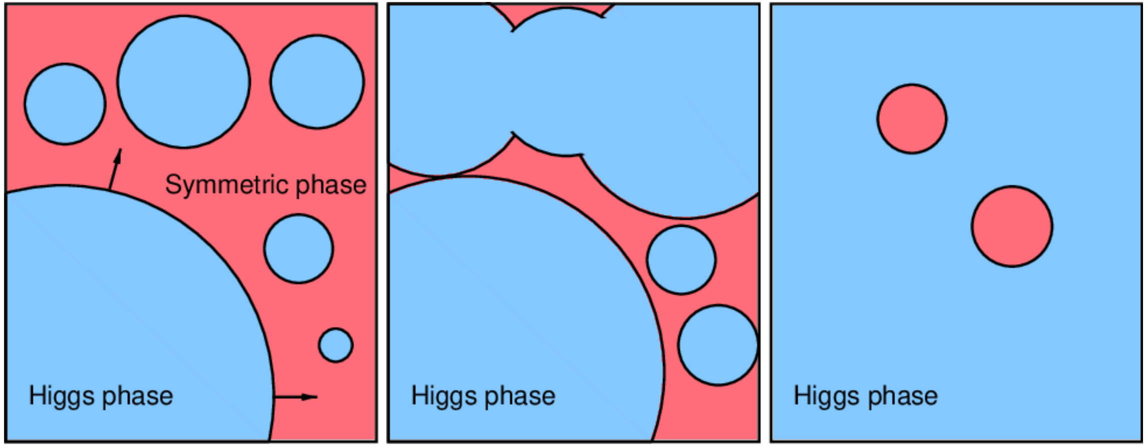
First-order phase transition

- Symmetry breaking occurs through bubble nucleation (local transition to ground state)
- Bubbles expand into symmetric phase and collide
- Expect gravitational waves from sound waves, turbulence and bubble collisions
- Typical peak frequency:



$$f_{\text{peak}} \simeq 10\,\text{mHz} \left(\frac{\beta/H}{100}\right)\left(\frac{T_\text{p}}{1\,\text{TeV}}\right)$$

Phase transition temperature

Phase transition speed

Bringmann, FK et al., arXiv:2311.06346

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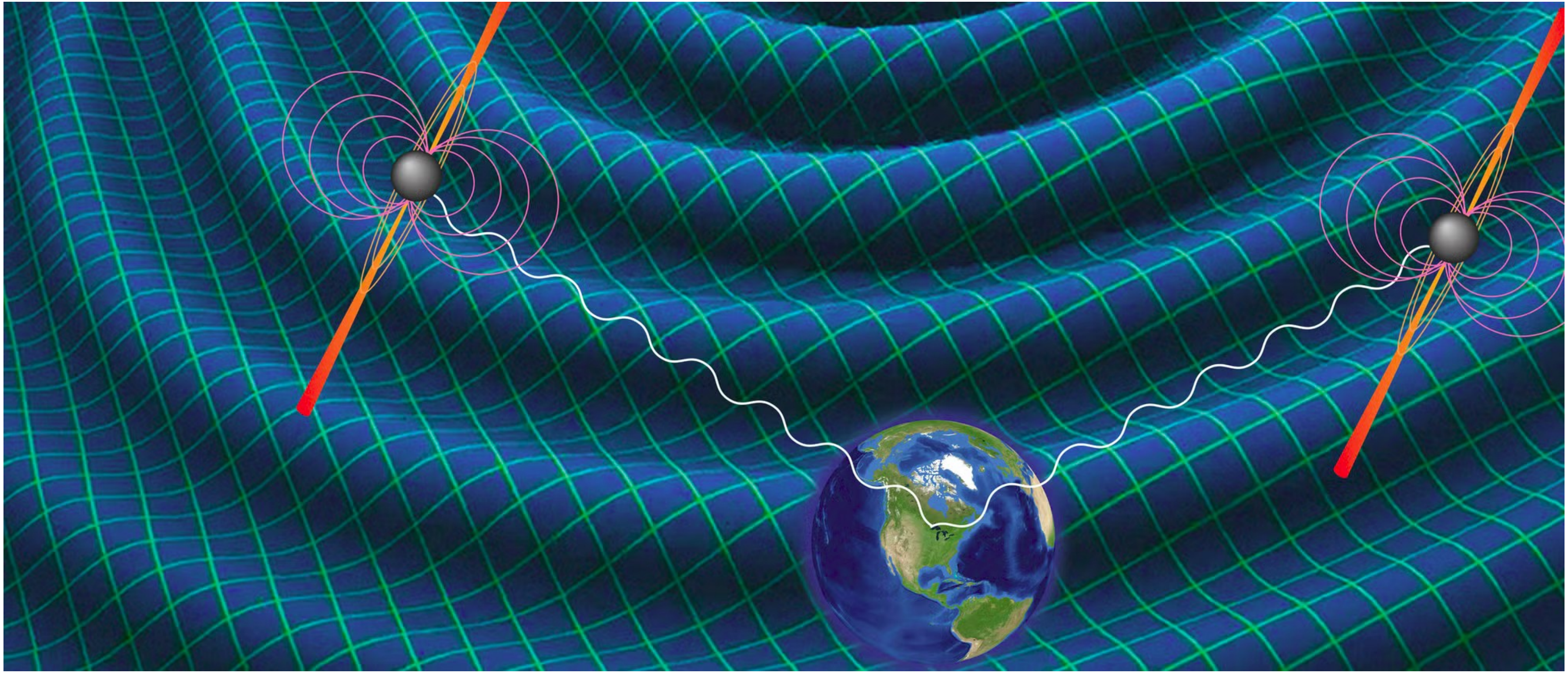
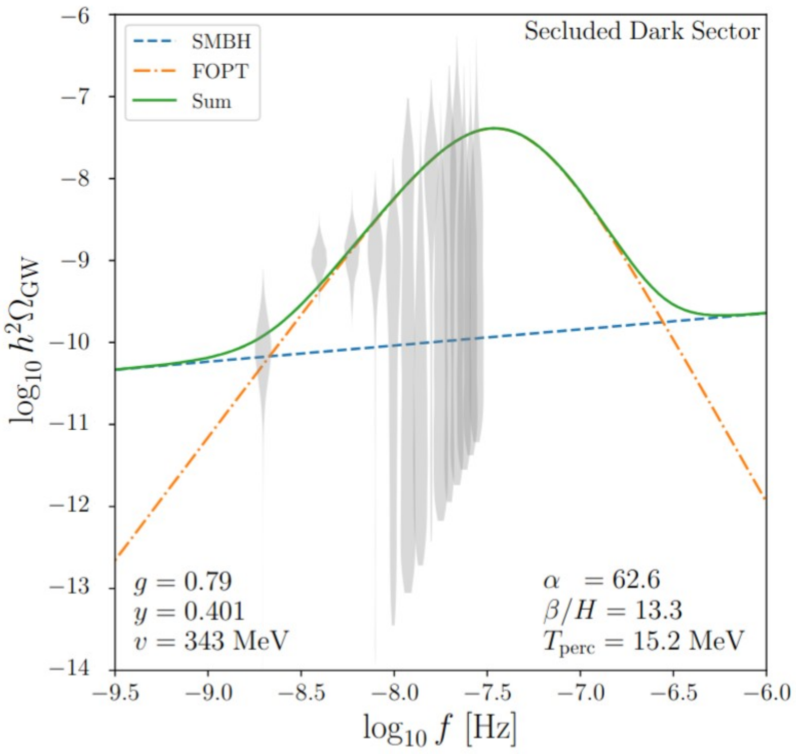
Pulsar Timing Arrays (PTAs)



Stochastic gravitational wave background



- Pulsar timing array data strongly suggests presence of a stochastic GW background
- Peak frequency around 10 nHz
- Typical values:
  - β/H ~ 10
  - T_p ~ 10 MeV
  - ➞ Dark Higgs vev v ~ 100 MeV

PTAs prefer same mass scale as SIDM!

Balan, FK et al., arXiv:2502.19478

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Challenge 1: Portal interactions

- Phase transition requires dark sector in equilibrium with Standard Model
  - → Need "portal" interactions for interactions with SM particles

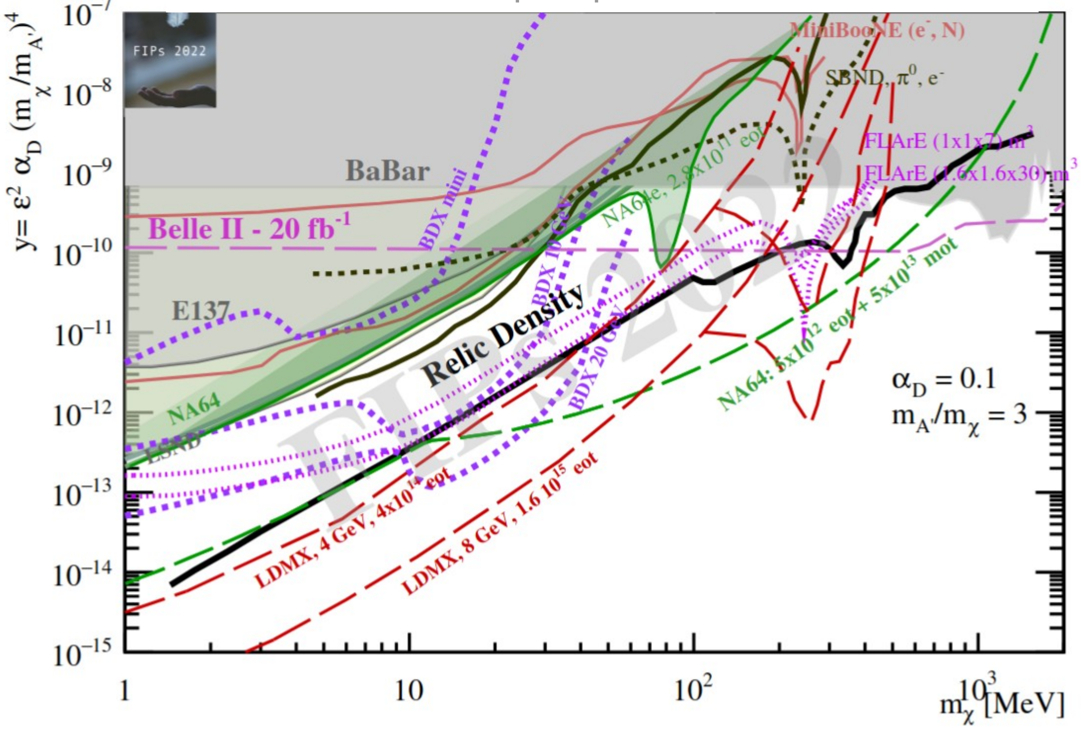
Option 1: Higgs mixing

- → Spoils conformal symmetry after electroweak symmetry breaking

Option 2: Kinetic mixing

- → Subject to strong experimental constraints

FIPs 2022 Workshop Report, arXiv:2305.01715



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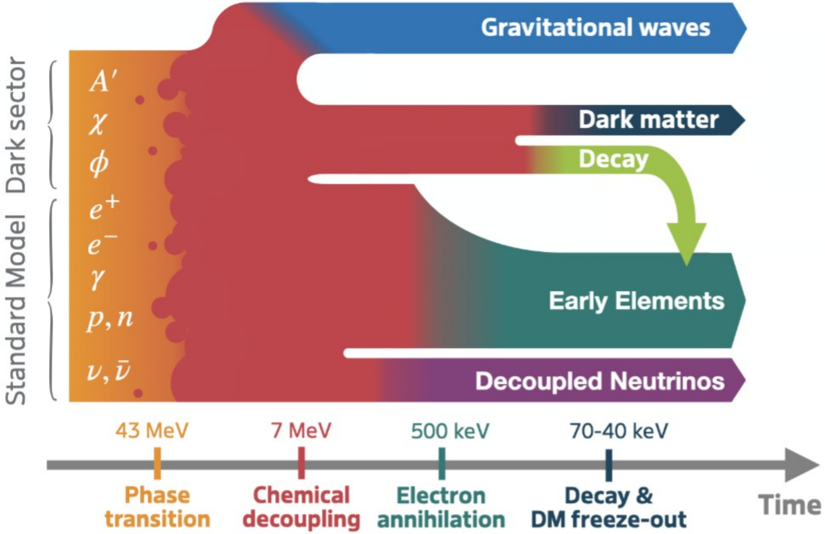
Challenge 1: Portal interactions

- Need to transfer energy density stored in the dark sector back into the Standard Model
- Non-negligible abundance of decoupled dark Higgs bosons remains after BBN
- Decay into e^+e^- via dark-photon loops:

$$\tau_\phi \approx 2500\,\mathrm{s} \left(\frac{\kappa}{10^{-4}}\right)^4 \left(\frac{g}{0.75}\right)^2 \frac{m_\phi}{30\,\mathrm{MeV}} \left(\frac{m_{A'}}{100\,\mathrm{MeV}}\right)^{-2}$$



Balan, FK et al., arXiv:2502.19478

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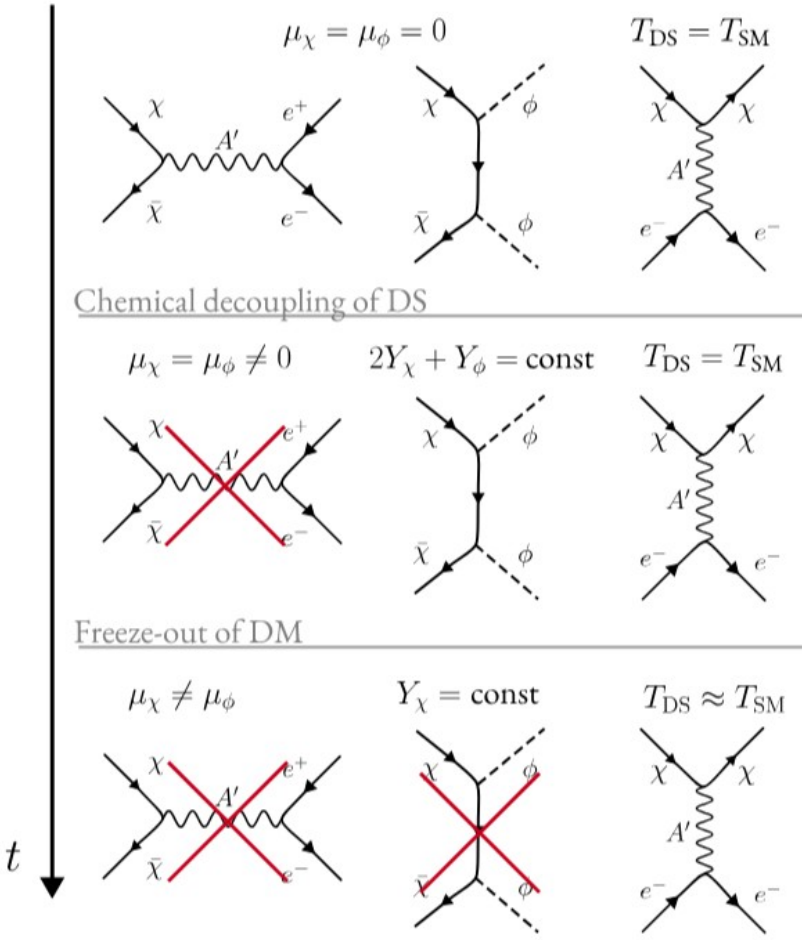
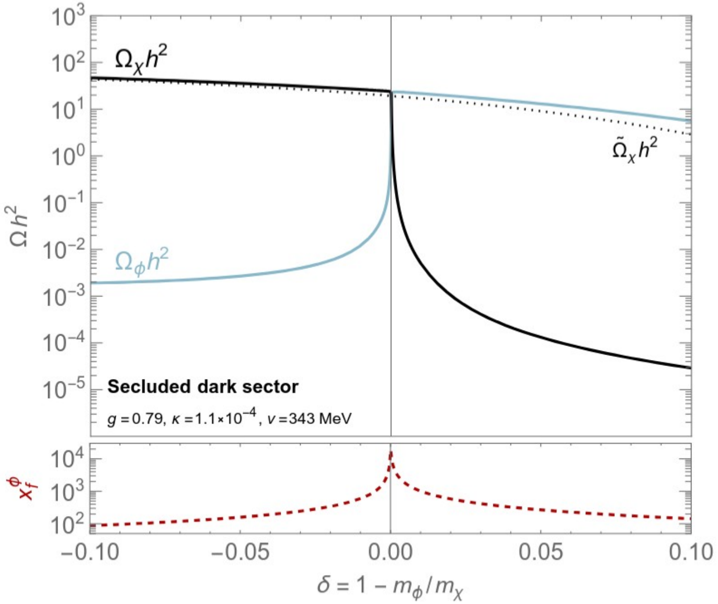
Challenge 2: Dark matter relic density

- Naive estimate of dark matter relic density: $\Omega_{\rm DM} \simeq 0.1 \, \frac{10^{-8}\,\mathrm{GeV}^{-2}}{\langle \sigma_{\rm ann} v \rangle}$
- For direct annihilation of DM into dark Higgs bosons: $\langle \sigma_{\rm ann} v \rangle \sim \frac{y^4}{m_{\rm DM}^2} \sim \frac{y^2}{v_\phi^2}$
- First-order phase transition requires dark sector couplings of order unity
  - ➞ Observed DM relic density implies $v_\Phi \sim$ TeV
  - ➞ Perfect for LISA, but not for pulsar timing arrays
  - ➞ Need to find a way to suppress annihilation cross section



Detailed evolution

- Reproducing DM relic density requires m_χ and m_Φ to be very close



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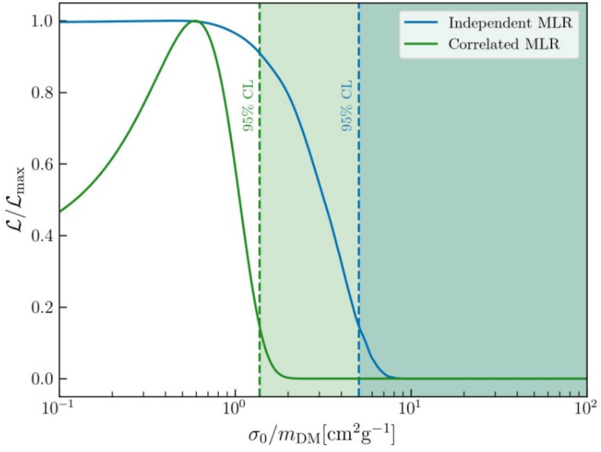
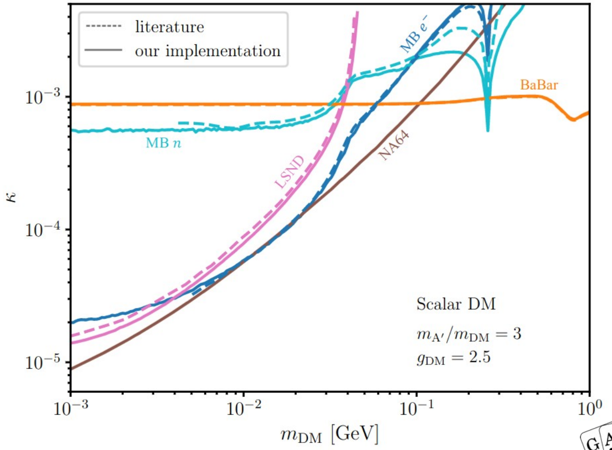
Global fit of a classically conformal dark sector

- Need to take into account many different constraints for global analysis

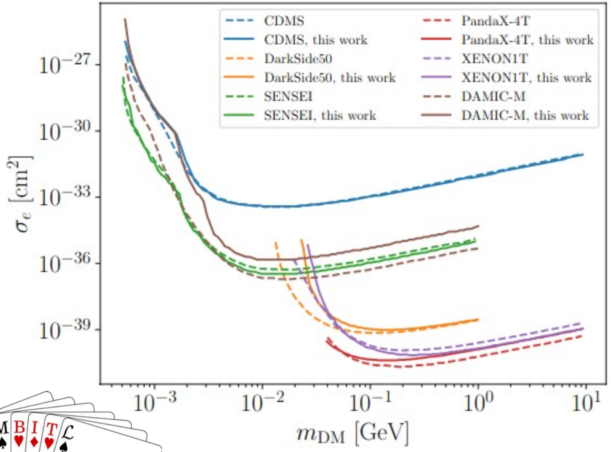
Dark matter self-interactions



Accelerator searches



Scattering off electrons



Balan, FK et al., arXiv:2405.17548

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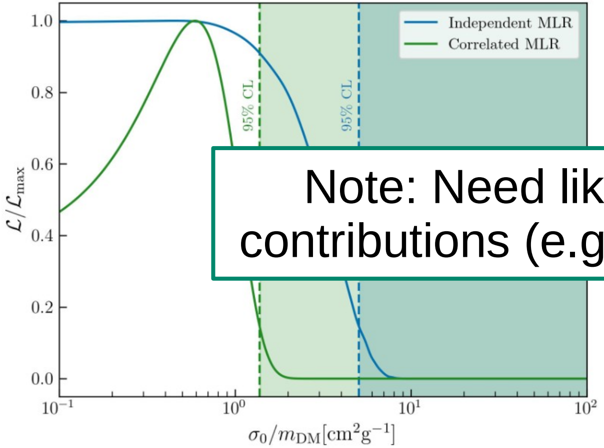
Dark matter self-interactions



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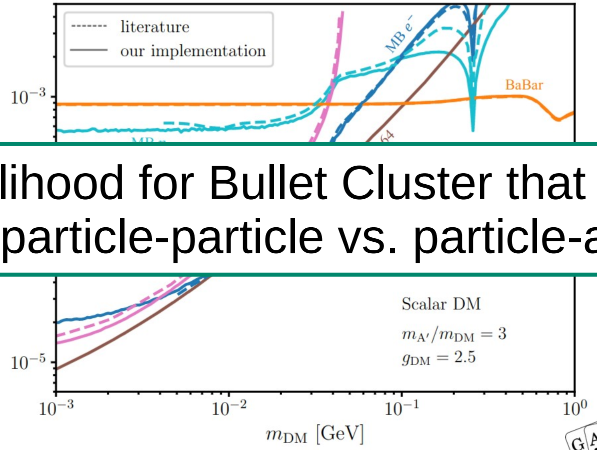

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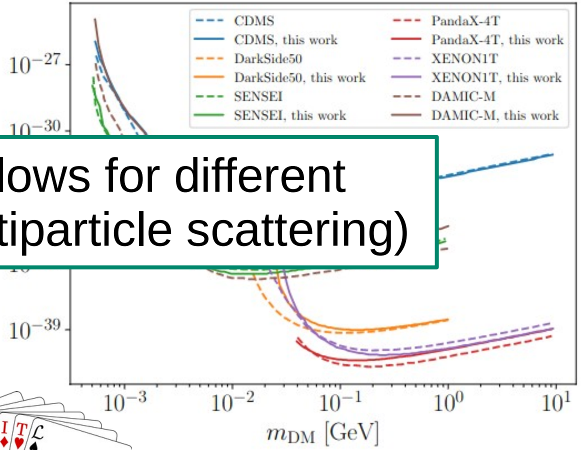

Note: Need likelihood for Bullet Cluster that allows for different contributions (e.g. particle-particle vs. particle-antiparticle scattering)

Balan, FK et al., arXiv:2405.17548

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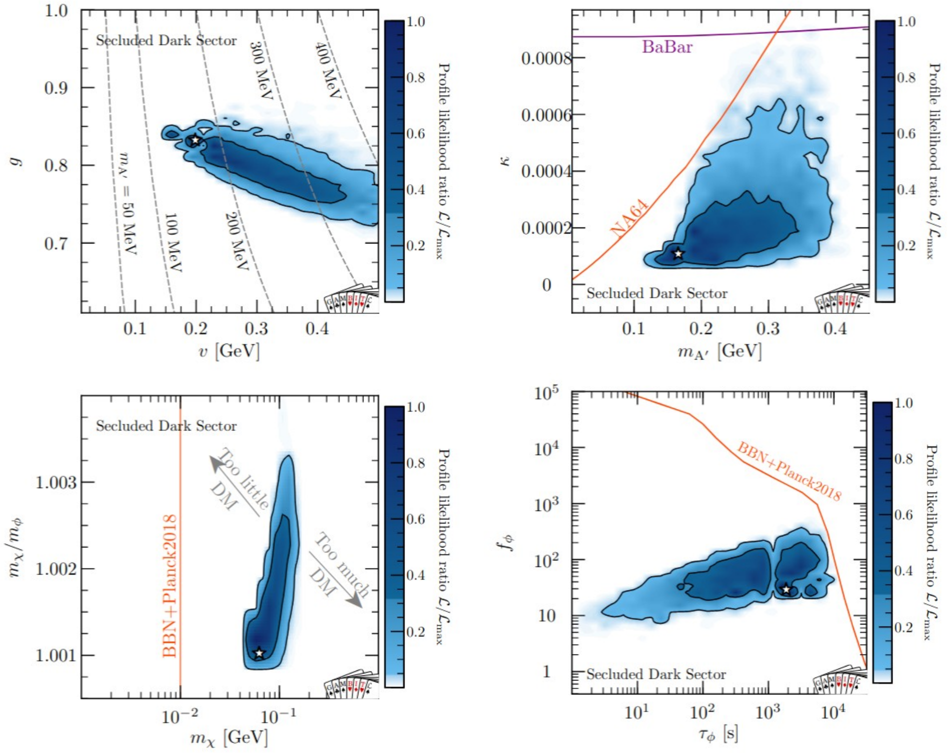
Results

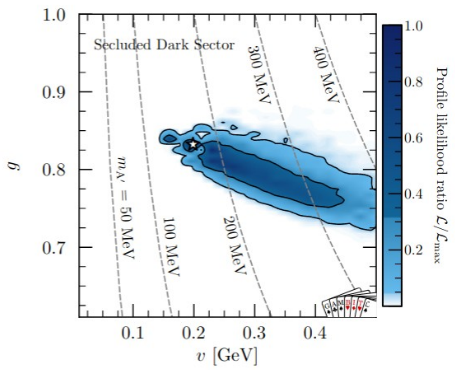


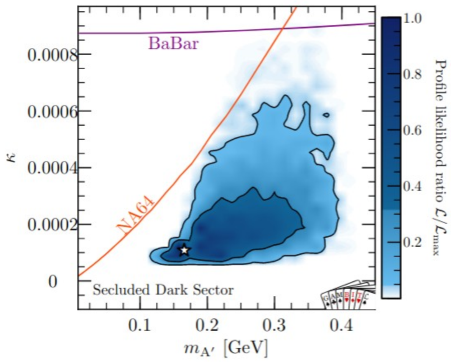
- Possible to fit PTA signal and reproduce observed DM relic abundance while satisfying bounds from dark photon searches
- Abundance and lifetime of dark Higgs bosons small enough to comply with BBN constraints
- Well-defined allowed parameter regions

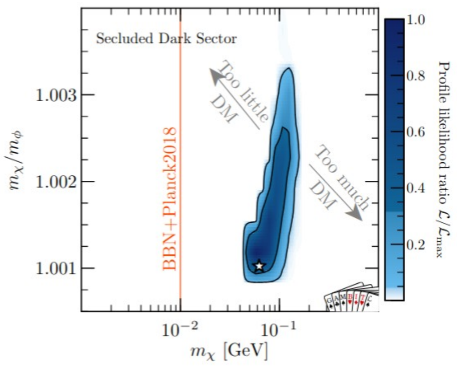
  → Predictions for future searches

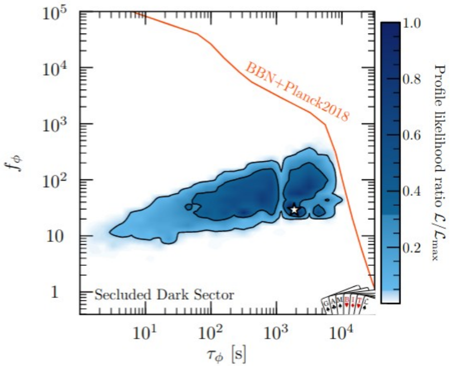
Balan, FK et al., arXiv:2502.19478

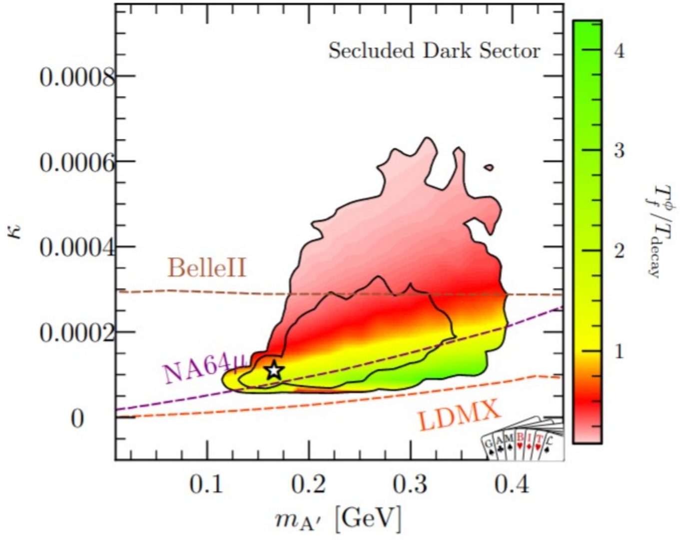
Results











Model can be tested with future searches for invisibly decaying dark photons

Balan, FK et al., arXiv:2502.19478

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Implications for self-interacting dark matter

- Dark matter self-scattering dominated by dark Higgs boson exchange
- Dark photon too heavy to give relevant contribution
- Typical self-interaction cross sections: $\sigma / m_{DM} \sim 0.1\text{–}1\ \text{cm}^2 / \text{g}$
- No velocity dependence…
- Maybe interesting for future improvements on galaxy cluster scales?

$$\sigma_{\chi\chi\to\chi\chi} = \frac{y^2}{256\pi v^2}\left(3 - 4\frac{m_\chi^2}{m_\phi^2}\right)^2$$

$$\sigma_{\chi\bar{\chi}\to\chi\bar{\chi}} = \frac{y^2}{128\pi v^2}\left(7 - 4\frac{m_\chi^2}{m_\phi^2} + 16\frac{m_\chi^4}{m_\phi^4}\right)$$

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Conclusions

- Not all models of self-interacting DM actually **predict** observable effects
- Many models are underconstrained and allow for a wide range of cross sections
- Two notable exceptions:

1. **Self-interacting dark matter from strong dynamics**

   → Two independent mass scales, but additional input from relic density requirement

   → Preferred parameter region: $m_{DM} \sim 200$ MeV, $\sigma / m_{DM} \sim 1\ \mathrm{cm}^2 / \mathrm{g}$

2. **Self-interacting dark matter from spontaneous breaking of conformal symmetry**

   → Mass scale generated dynamically through first-order phase transition

   → PTA signal prefers mDM ~ 100 MeV, $\sigma / m_{DM} \sim 0.1\ \mathrm{cm}^2 / \mathrm{g}$

   → Challenges: Energy transfer and dark matter relic density

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