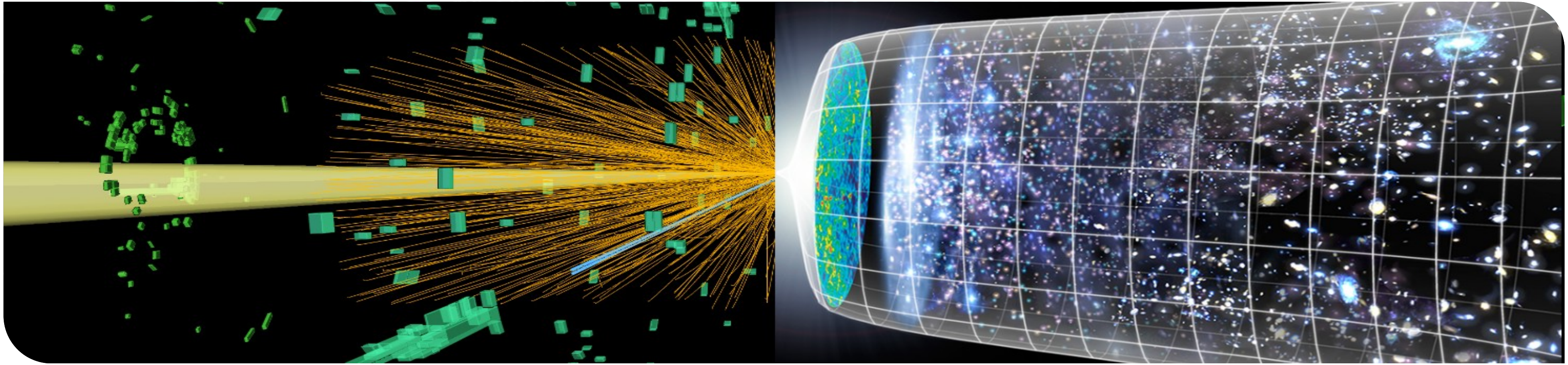
Strongly-interacting dark sectors and dark matter relic density: an overview

Felix Kahlhoefer

Roadmap of Dark Matter Models for Run 3

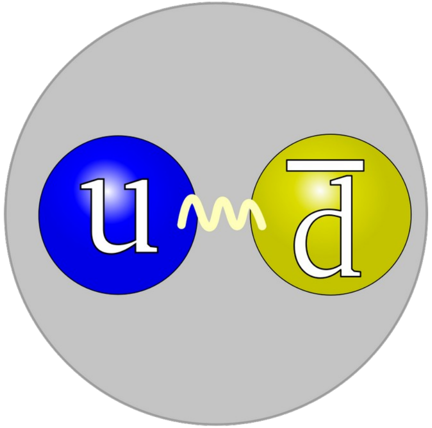


Strongly-interacting dark sectors

- Focus of this talk: QCD-like dark sectors (mostly SU(N) theories with $N_f < 3\,N_c$)
- At high energies: dark sector **contains dark gluons and dark quarks:**

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

- Quark masses small or comparable to confinement scale Λ_d
- At low energies: Confinement into dark mesons and baryons
- In case of particle-antiparticle asymmetry, dark baryons could be DM, otherwise they annihilate away



Cline & Perron, arXiv:2204.00033

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Stable dark pions

- In principle, all dark mesons could be unstable (as in QCD) → no DM candidate
- More appealing: Stabilisation mechanism

  - Option 1: Abelian U(1)' gauge symmetry
    - Different charges for different dark quarks (e.g. +1 for up-type and –1 for down-type quarks)
    - Dark mesons of type $u\bar{d}$ or $d\bar{u}$ carry U(1)' charge
    - Lightest such mesons (dark pions) must be stable

  - Option 2: Global discrete symmetry (G-parity)
    - Also neutral dark pions can be stabilised

u	$\bar{u}$	d	$\bar{d}$	π^0
$-\bar{d}$	$-d$	$\bar{u}$	u	$-\pi^0$

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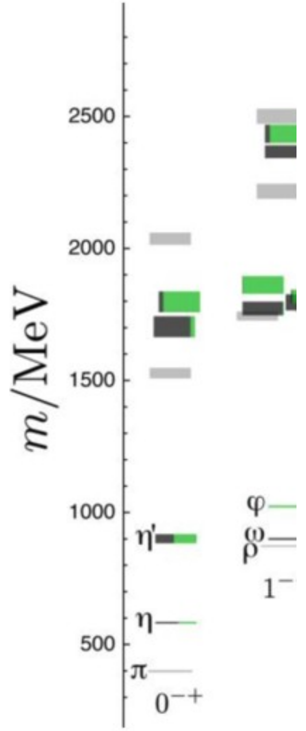
Describing dark mesons

- Low-energy theory features many different states
  - Dark pions (Pseudo-Goldstone bosons of chiral symmetry breaking)
  - Dark rho mesons (spin-1)
  - …
- Apparently many free parameters:
  - Masses of various dark mesons (dark pions, dark rho mesons, …)
  - Interactions between them
  - Interactions with SM particles
- Great complexity! Need some guidance...

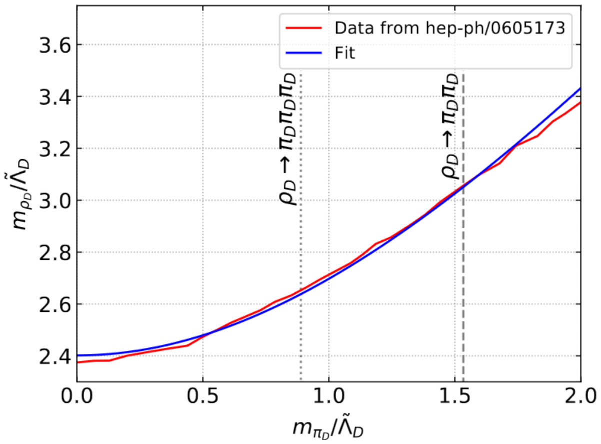


Crucial connections

- But high energy theory has only 3 parameters (for given number of colours and flavours):
  - Dark quark mass (assuming degenerate states)
  - Dark gauge coupling
  - Coupling to mediator (e.g. U(1)' gauge boson)

- Low-energy pheno determined by one dimensionful parameter (e.g. m_π) and one dimensionless ratio (e.g. m_π/Λ_d)
  - Dark rho meson mass determined from lattice simulations
  - Coupling between ρ_d and π_d determined by KSRF relation
  - Couplings to mediator follow from group theory

Dark showers Snowmass report, arXiv:2203.09503



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What constrains the dark pion mass?

- Need input from astrophysics and cosmology

- Bullet Cluster excludes DM self-interaction cross sections larger than ~2 cm²/g (= 4 barn/GeV)

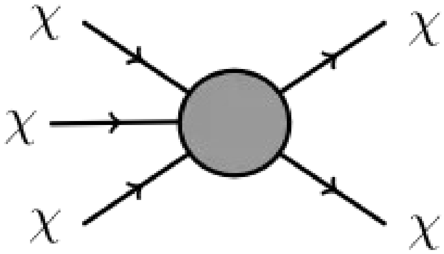
- Dark pions have $\sigma_c = \frac{3}{64\pi} \frac{m_\pi^2}{f_\pi^4} (1 + \mathcal{O}(N_{f_D}^{-2}))$

- Consider sizable dark quark masses, such that m_π and f_π are not too different
  → Dark pion masses below ~100 MeV excluded

Dark pion relic density calculation

- Conceptually simplest way for dark pions to evolve in the early universe:
  Number-changing processes ($3\pi_d \to 2\pi_d$) induced by the Wess-Zumino-Witten term

$$\frac{2N_d}{15\pi^2 f_\pi^5}\epsilon^{\mu\nu\rho\sigma}\mathrm{Tr}\left(\pi\partial_\mu\pi\partial_\nu\pi\partial_\rho\pi\partial_\sigma\pi\right)$$



  - Rest mass converted into kinetic energy
  - Kinetic energy transferred to SM via scattering
  - Relic density determined by freeze-out of number-changing processes

→ **SIMP mechanism**

Hochberg et al., arXiv:1402.5143

Miracle or no miracle?

- Amazingly, the well-known literature result for the SIMP cross section is wrong by a factor of 3
  - Reason: Naive non-relativistic limit leads to an expression that is not Lorentz-invariant

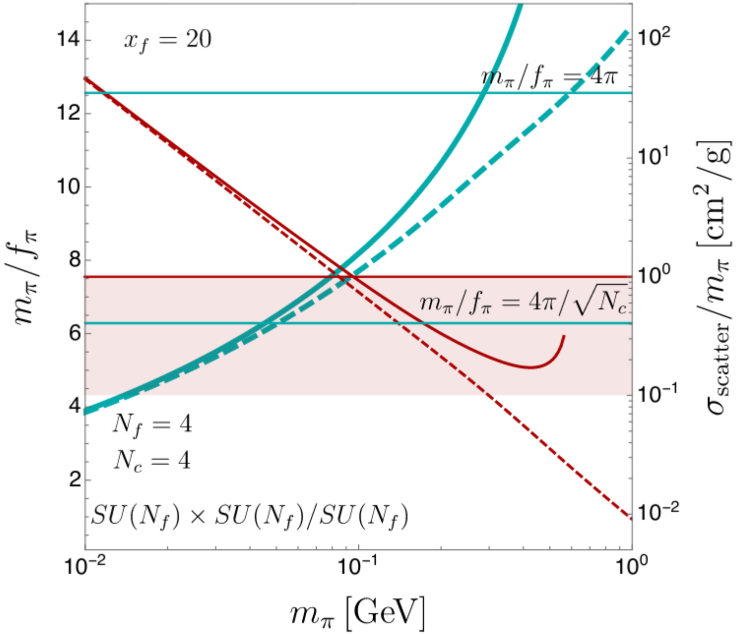
Kamada et al., arXiv:2210.0139…

- (N)NLO corrections can be large → lattice needed!

Hansen et al., arXiv:1507.01590; Dengler et al., arXiv:2405.06506

- General conclusion: SIMP mechanism requires dark pion masses of 10–100 MeV
  - Tension with Bullet Cluster bound
  - Requires m_π / f_π ~ 4π (close to perturbative bound)

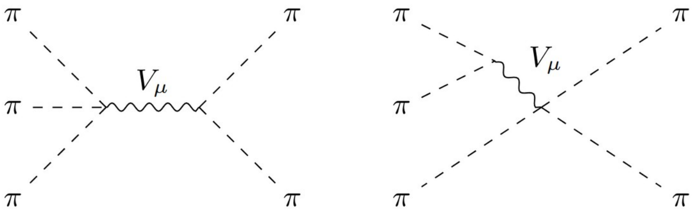
Cyan: m_π/f_π required by relic density
Red: Corresponding cross section



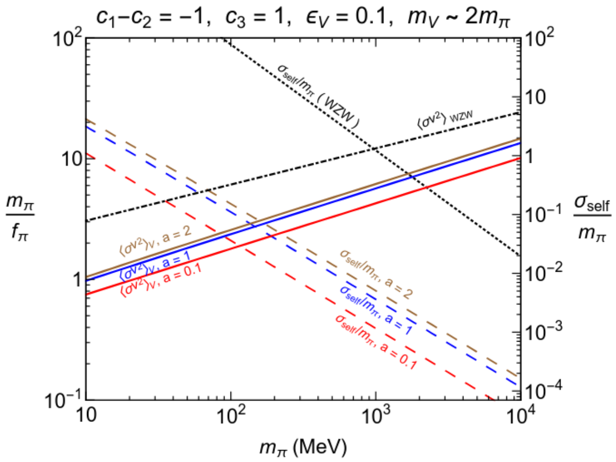
Possible ways forward

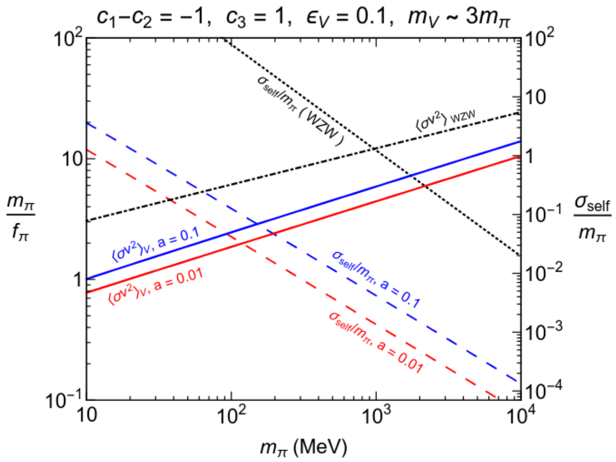
- Assume resonant enhancement of 3 → 2 cross section through exchange of on-shell dark meson

Choi et al., arXiv:1801.07726



- Requires tuning but relaxes Bullet Cluster constraint





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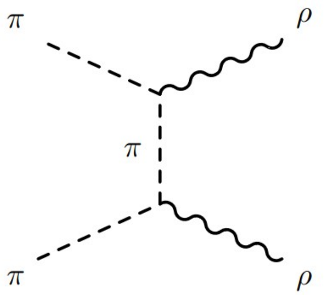
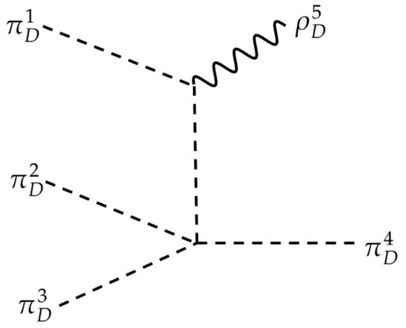
Dark rho mesons in the final state

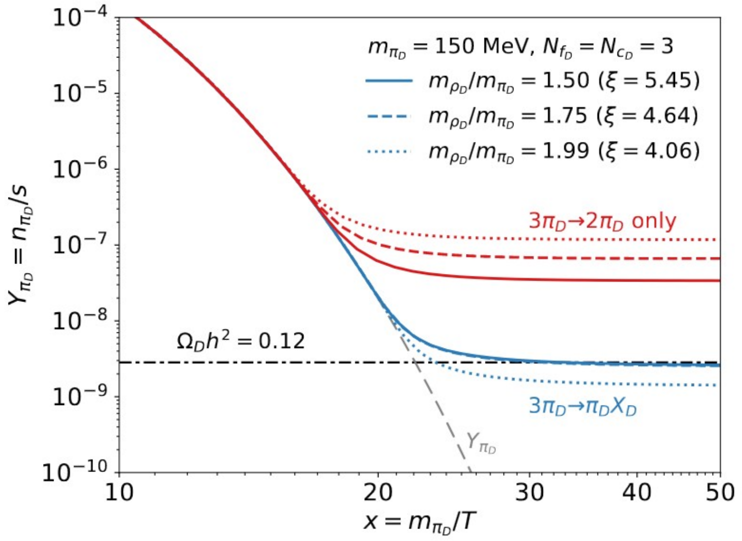
- **$2\pi_d \rightarrow \pi_d+\rho_d$** Berlin et al., arXiv:1801.05805
  - Requires anomalous interaction and violates G-parity
- **$2\pi_d \rightarrow 2\rho_d$** Bernreuther, FK et al., arXiv:1907.04346
  - Requires non-zero kinetic energy in the initial state
  - Annihilation rate exponentially suppressed for small temperatures
  - Requires very small π_d-ρ_d mass difference (problem with chPT validity)
- **$3\pi_d \rightarrow \pi_d+\rho_d$** Berneuther, FK et al., arXiv:2311.17157
  - Kinematically allowed in the non-relativistic limit for $m_\rho < 2\ m_\pi$
  - No momentum suppression (unlike SIMP process)
  - Resonant enhancement for m_ρ close to $2\ m_\pi$

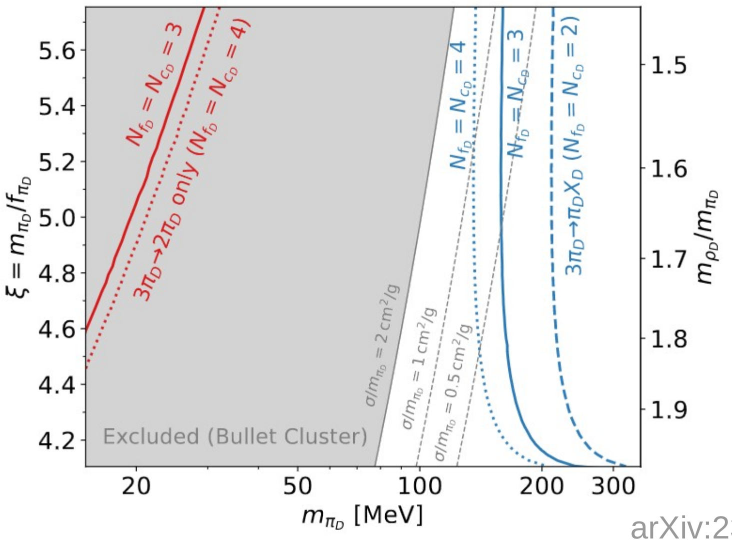




Results

- Including the process $3\pi_d \rightarrow \pi_d + \rho_d$ enhances annihilation rate by orders of magnitude
- Freeze-out delayed, larger masses viable, Bullet Cluster constraint can be evaded





arXiv:2311.17157

Phenomenological implications

- For $m_\rho < 2\, m_\pi$, dark rho mesons cannot decay into pairs of dark pions
- But ρ^0 mesons must couple to SM particles for thermalisation

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Phenomenological implications

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- But ρ^0 mesons must couple to SM particles for thermalisation
- Simple example: Assume U(1)' gauge boson Z' with kinetic mixing κ
  - At energies below Z' mass: Effective interaction between dark quarks and SM fermions

$$\mathcal{L}_\text{eff} \supset \frac{1}{\Lambda^2} \sum_f q_f \bar{f} \gamma^\mu f \bar{q}_\text{d} \gamma_\mu q_\text{d} \qquad \Lambda = \frac{m_{Z'}}{\sqrt{\kappa e e_\text{d}}}$$

  - Dark ρ^0 mesons have the same quantum numbers as the Z' gauge boson
  - Mixing leads to effective coupling $\mathcal{L}_\text{eff} \supset \frac{2}{g} \frac{m_{\rho_\text{d}}^2}{\Lambda^2} \rho_\text{d}^{0\,\mu} \sum_f q_f \bar{f} \gamma_\mu f$

Bernreuther, FK et al., arXiv:2203.08824

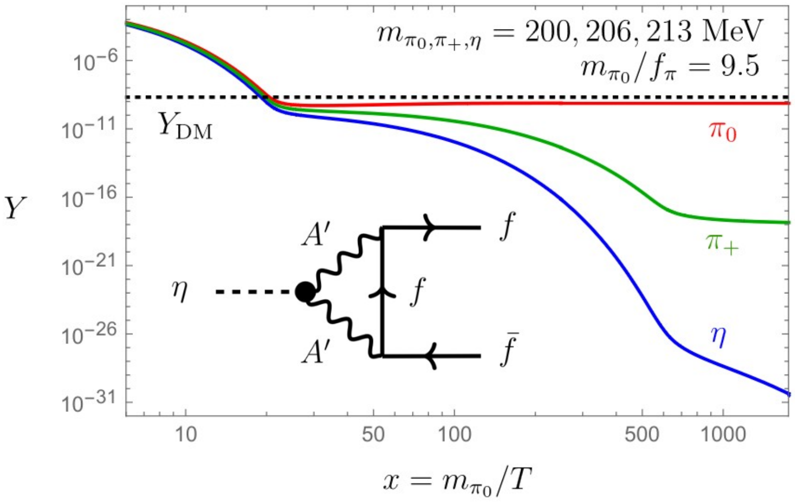
Phenomenological implications

- For $m_\rho < 2\, m_\pi$, dark rho mesons cannot decay into pairs of dark pions
- But ρ^0 mesons must couple to SM particles for thermalisation
  - → Prediction: ρ^0 mesons must decay into SM states
  - → Semi-visible jets!
- Couplings of ρ^0 to SM particles can be very small
  - → Displaced vertices or emerging jets
  - → No guarantee for sizable production cross section
- Preferred mass range for dark mesons (well) below 1 GeV
  - → Dark shower substructure quite similar to QCD except for fraction of invisible particles

Similar mechanisms with other light states

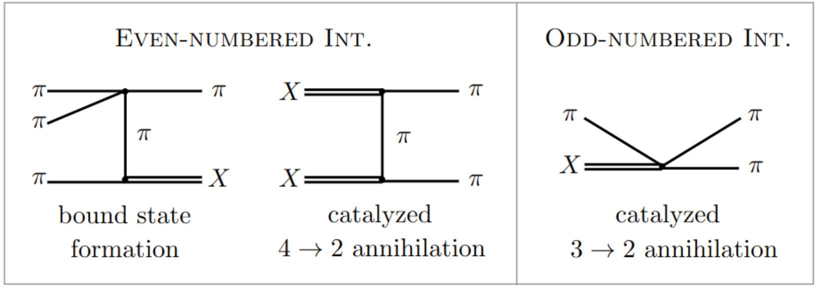
- Dark eta mesons
  - Consider quark flavours with different masses
  - Dark eta meson heavier than dark pions
  - Generally unstable against decays into SM

Katz et al., arXiv:2006.1514{8}



- X = [ππ] bound state (at least in Sp (4))

Chu et al., arXiv:2401.12283

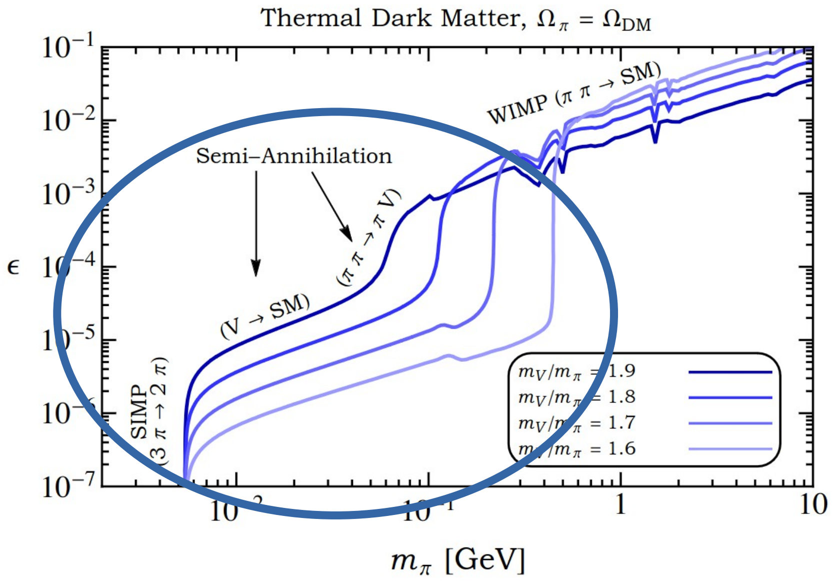


- Dilaton χ arising from breaking of conformal symmetry (not QCD-like any more!)

Appelquist et al., arXiv:2404.07601

SIMPs as WIMPs?

- All scenarios considered so far: relic density requirement places tight constraints on the dark pion mass, but only very weak constraints on the SM couplings



- Couplings vary by many orders of magnitude, while masses vary only slightly
- For the LHC we would prefer the opposite!

Berlin et al., arXiv:1801.05805

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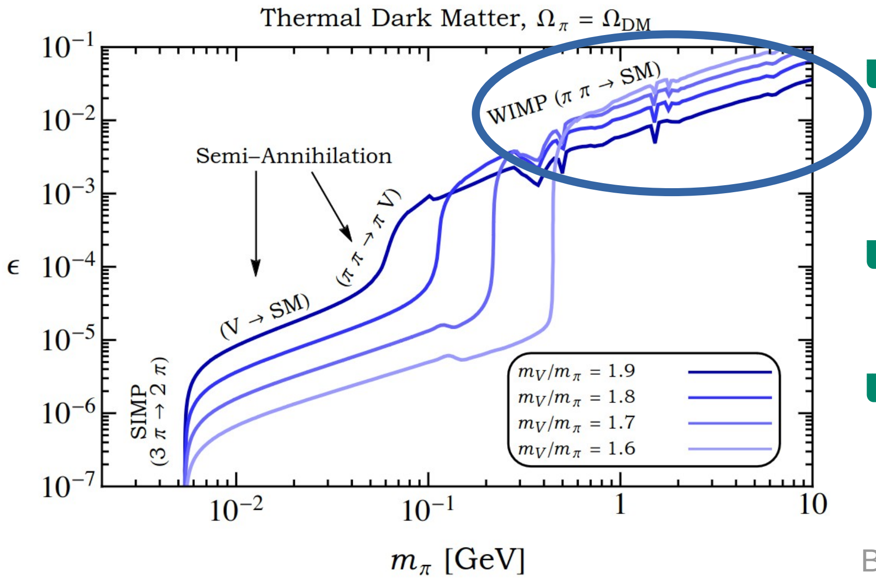

- Couplings vary by many orders of magnitude, while masses vary only slightly
- For the LHC we would prefer the opposite!
- Consider direct annihilations of dark pions into SM particles

Berlin et al., arXiv:1801.05805

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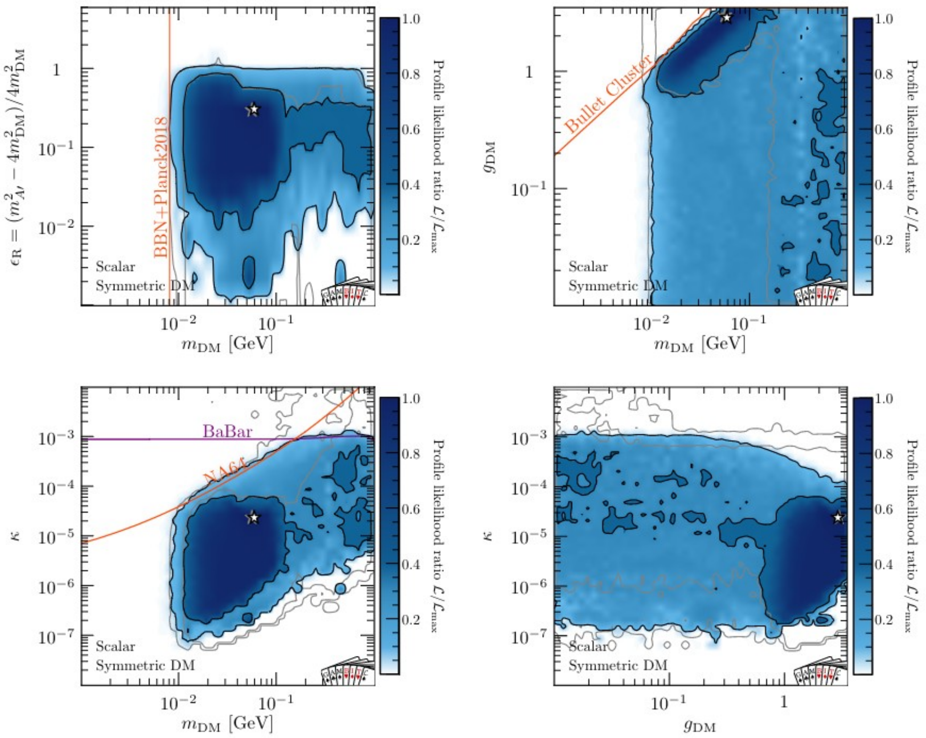
Dark pions as GeV-scale thermal DM

- More flexibility in terms of mass, clearer target in terms of couplings
- Many relevant constraints from missing energy searches, rare meson decays, direct detection etc.
- Viable parameter space for complex scalar DM identified in upcoming global fit

Balan, Gray, FK et al., in preparation

- But: Not all constraints apply to dark pions
- So far no dedicated study (?)



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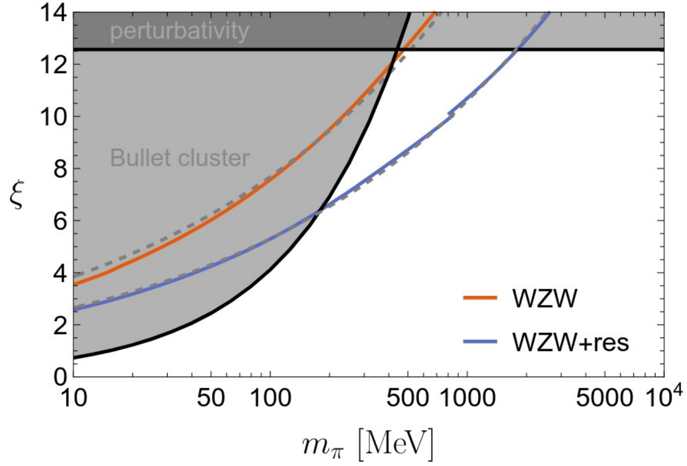
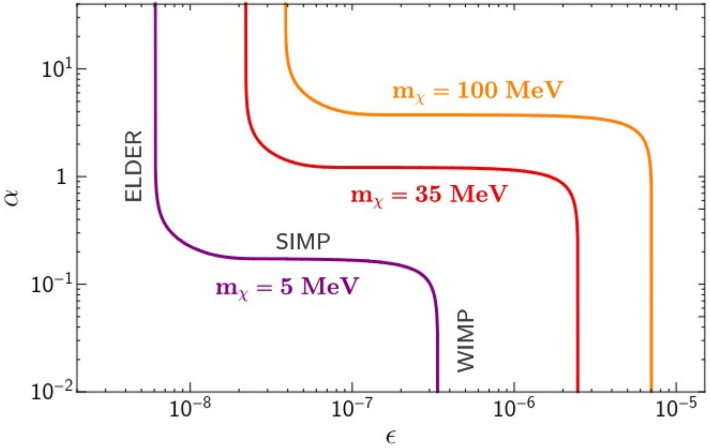
Combination of different interactions

- Combine 3→2 process and (resonantly enhanced) annihilation into SM   Braat & Postma, arXiv:2301.04513

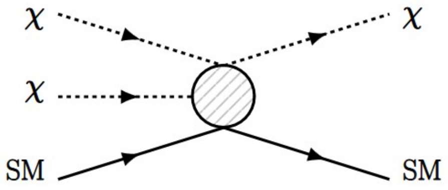
- Relic density set by thermal decoupling of elastic scattering (ELDERs)   Kuflik et al., arXiv:1512.04545





- Consider number-changing processes involving SM particles

Smirnov & Beacom, arXiv:2002.04038



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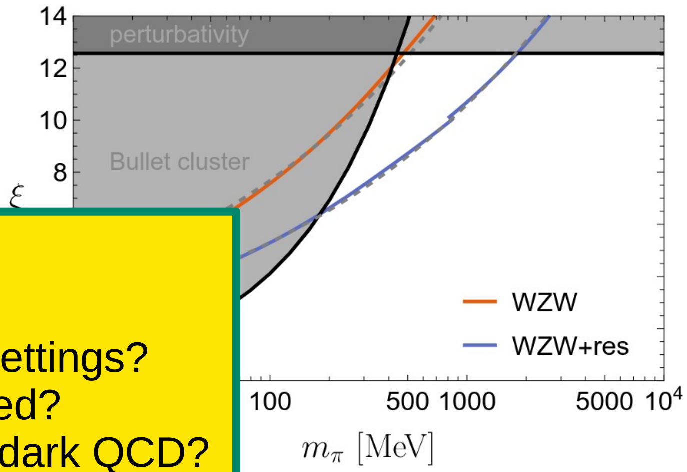

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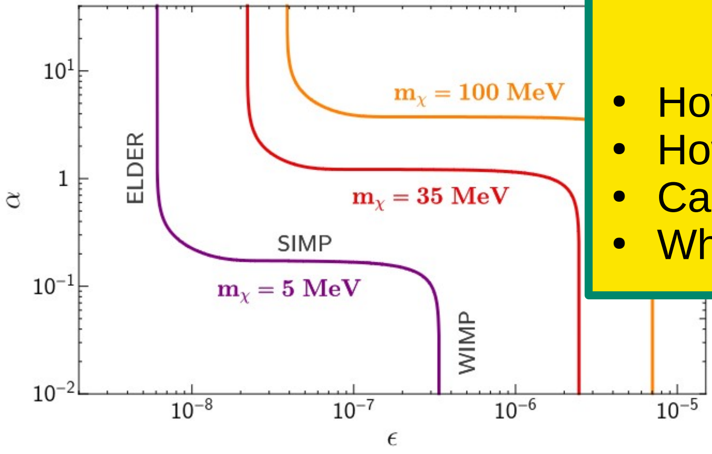
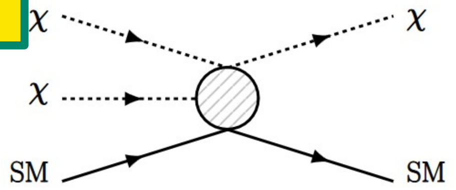


Open questions

- How predictive are these settings?
- How much tuning is required?
- Can they be embedded in dark QCD?
- What is the Bullet Cluster constraint?

- Consider number-changing processes involving SM particles



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Conclusions

- QCD-like strongly interacting DM has exciting implications for cosmology and colliders
- Conventional SIMP mechanism in tension with Bullet Cluster constraints
- Many possible modifications using additional states in the dark sector or new interactions
- Simple solution: Annihilations into dark rho mesons with $m_\rho < 2m_\pi$

  → Dark rho mesons must decay visibly into SM particles
- Interactions between dark and visible sector largely unconstrained
- Interesting to think about alternative relic density mechanisms with tighter connection

  → WIMP-like annihilations? Resonant annihilations? Co-SIMP mechanism?