Karlsruhe Institute of Technology

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Cosmology of strongly interacting dark matter

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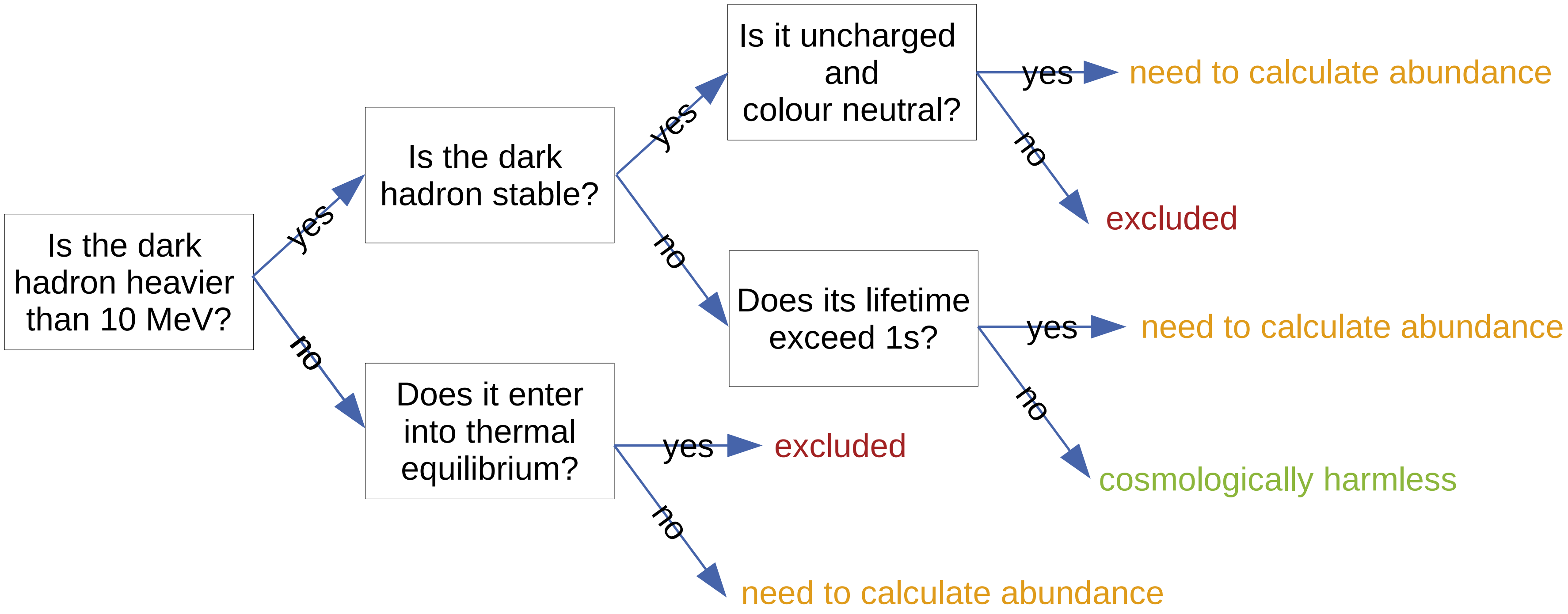
Dark showers SNOWMASS project meeting, 12 May 2022

Many ideas, equations and plots taken from PhD thesis of Elias Bernreuther

Decision tree for dark sector hadrons



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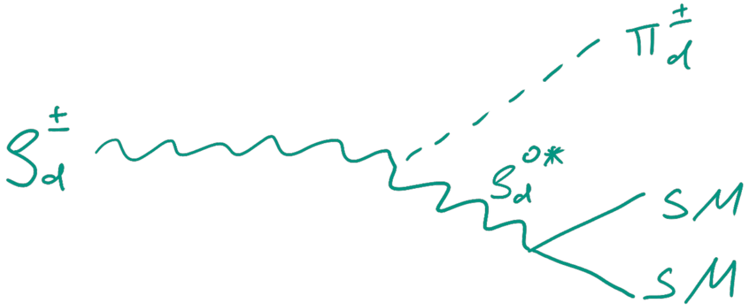
Lifetimes >> 1 second?

- Dark hadrons can be very long-lived if their decays are phase-space suppressed and require an off-shell mediator
- **Example:** dark rho mesons
  - If the decay $\rho_d \rightarrow 2\,\pi_d$ is kinematically forbidden, but $\rho^0_d \rightarrow 2$ SM is allowed, expect $\rho^\pm_d \rightarrow \pi^\pm_d + 2$ SM

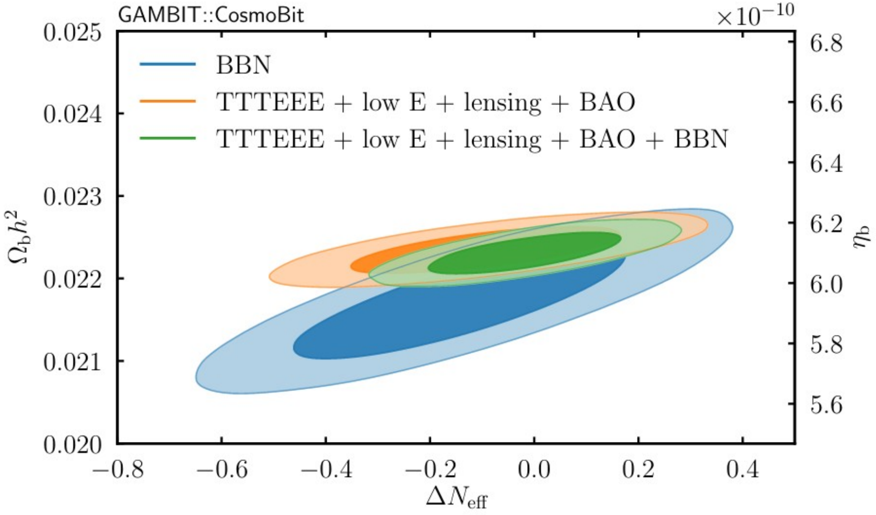


- Many different cosmological constraints depending on dark hadron lifetime

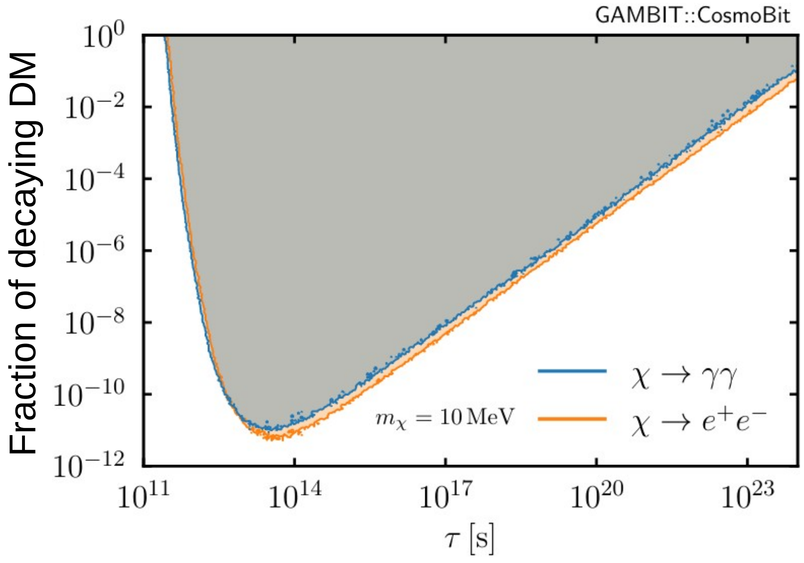
~10^8 s:	Photodisintegration of light elements
~10^{12} s:	CMB spectral distortions
~10^{14} s:	CMB anisotropies
~10^{16} s:	21-cm absorption spectra

Why is the abundance so important?

- For relativistic dark mesons:
  - Need to satisfy bound on ΔN_{eff}



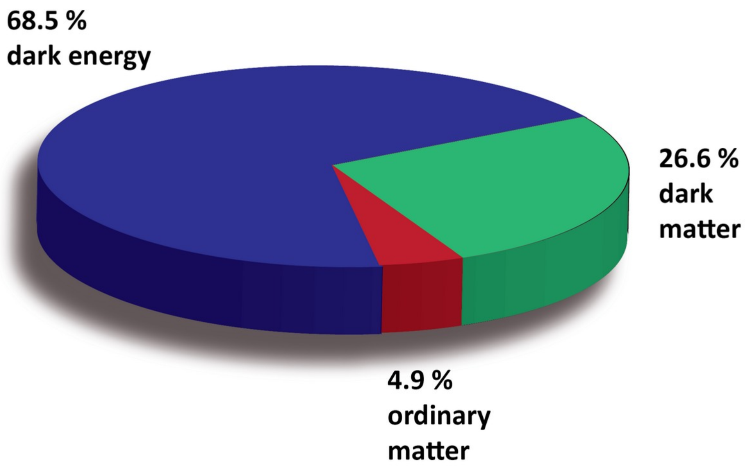
Renk, FK et al., arXiv:2009.03286



- For decaying dark mesons:
  - Need to satisfy bounds on decaying DM

Why is the abundance so important?

- For heavy & stable dark mesons:
  - Need to ensure abundance does not exceed observed DM abundance
  - Identify parameter combinations the reproduce observed DM abundance



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Equilibrium abundances

- Two assumptions:
  - 1. Dark sector hadrons in equilibrium with each other → define dark sector temperature T_d
  - 2. Dark sector tightly coupled to Standard Model → $T_d = T_{SM}$

- Boltzmann suppression of non-relativistic dark hadrons
  - Heavier dark hadrons are more strongly suppressed

$$\left(\frac{n_\rho^{\mathrm{eq}}}{n_\pi^{\mathrm{eq}}}\right)^2 \sim \exp(-2\Delta x)$$

$$x = m_\pi / T \text{ and } \Delta = (m_\rho - m_\pi)/m_\pi$$

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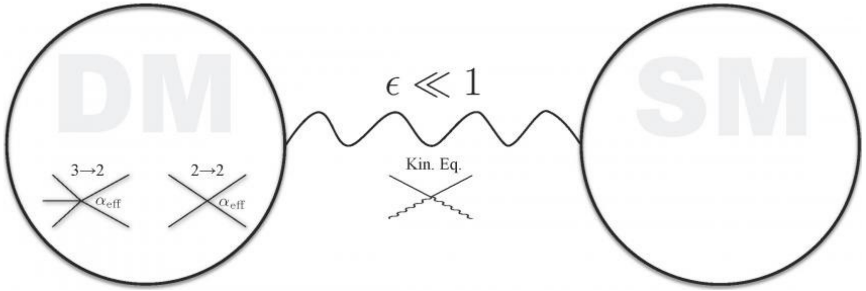
Departure from equilibrium

- Two assumptions:
  - 1. Dark sector hadrons in equilibrium with each other → define dark sector temperature T_d
  - 2. Dark sector tightly coupled to Standard Model → $T_d = T_{SM}$
- Assumption 2 is almost always satisfied (see arXiv:1602.04219 for exceptions)
- Assumption 1 breaks down, when the interaction rate drops below the Hubble rate

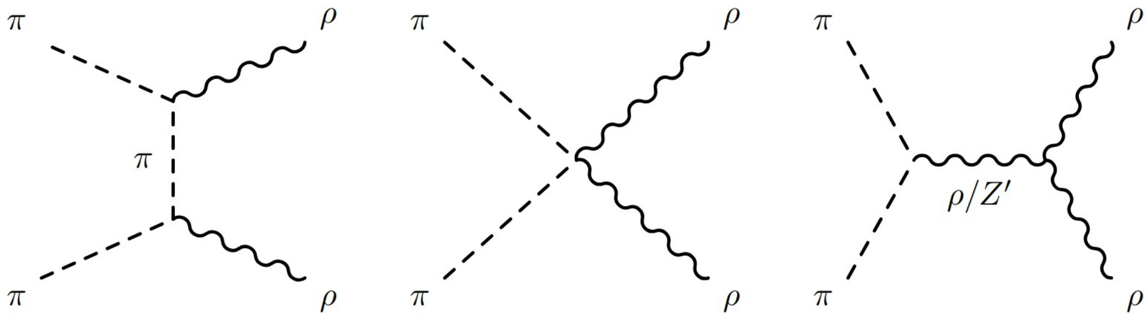
Examples

- **SIMP mechanism:** Dark pion abundance determined by freeze-out of 3π→2π processes



Hochberg et al., arXiv:1402.5143

- **Forbidden annihilations:** Dark pion abundance determined by freeze-out of 2π → 2ρ

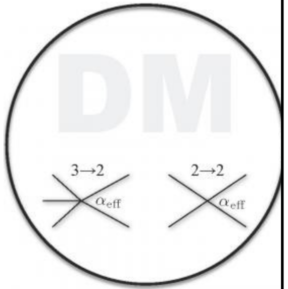


Bernreuther, FK et al., arXiv:1907.04346

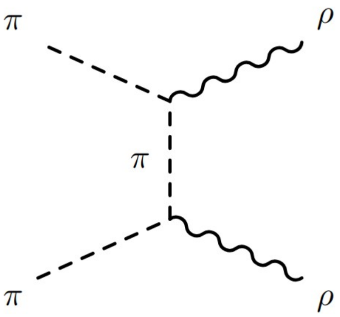
Examples

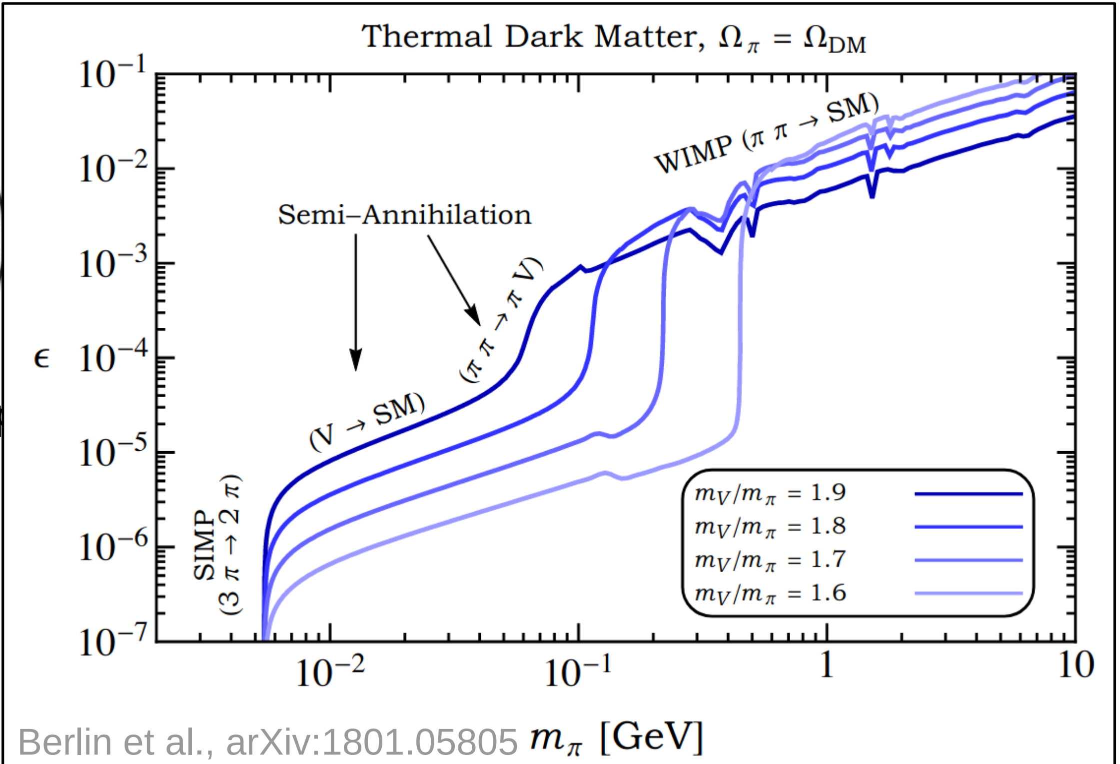
Different processes dominate in different regions of parameter space

- **SIMP mechanism:** Dark pion ab



- **Forbidden annihilations:** Dark





Berlin et al., arXiv:1801.05805

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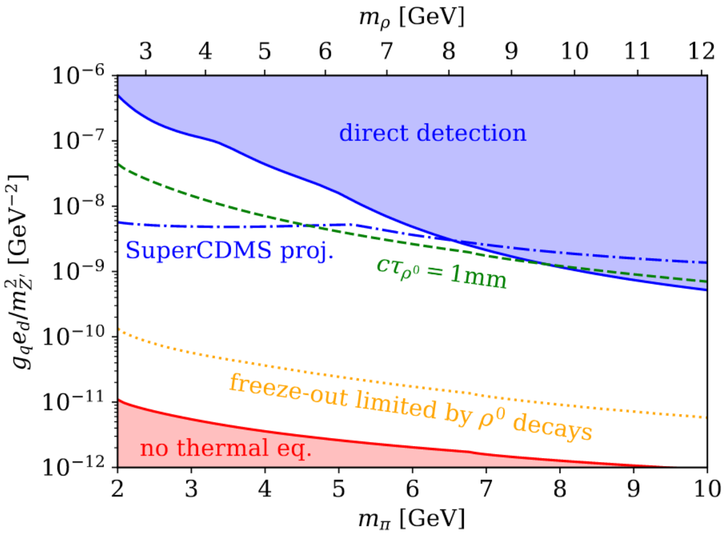
Results

- Requirement of equilibrium between dark and visible sector places lower bound on portal coupling
  - Bound typically quite weak → no implications
- Within dark sector, expect couplings of order unity
- Abundance requirement primarily constrains mass spectrum
  - **SIMP mechanism:** relic density requirement constrains m_π
  - **Forbidden annihilations:** relic density requirement constrains m_π/m_ρ



Bernreuther, FK et al., arXiv:1907.04346

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Stabilising symmetries

- Typically expect very similar masses for π^0_d and $\pi^\pm_d$

  → Abundances also expected to be similar

- Many models: $\pi^\pm_d$ stable, π^0_d unstable

  → Need to ensure that π^0_d decay sufficiently quickly

- Alternative: Ensure π^0_d stability
  - **Example:** G parity
  - Requires even number of quark flavours with degenerate mass

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Summary

- Dark hadrons harmless only if they decay in 1st second of universe
- Otherwise: Need to know their abundance
- Unstable and relativistic dark hadrons must be strongly suppressed
- Stable & neutral dark hadrons may account for observed DM density

- *Cosmological requirements impose conditions on model building and restrictions on parameter space*

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