Electroweak Confinement and $SU(2)_L$ Dark Matter

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Coming soon!

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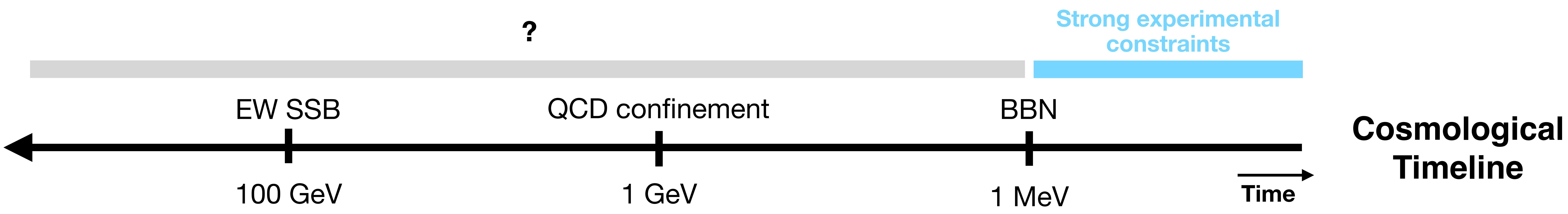
Why consider modified cosmological histories?



- Considering modified cosmological histories is important
  - Experimentally we can, so scientifically we should

- Doing so is also beneficial
  - Might lead to profitable results alleviating current (example of this with WIMPs later)
  - Exploring possibilities will help probe what *actually* happened

Overview

- WIMPs are an attractive model for dark matter (DM)
  - Simple extension of the Standard Model (SM) yields a WIMP miracle
- Experiments have endangered the scenario leading to the WIMP miracle
- However, this assumes a “standard” cosmological history

We find that a period of electroweak confinement contemporary with WIMP freeze-out restores the WIMP miracle

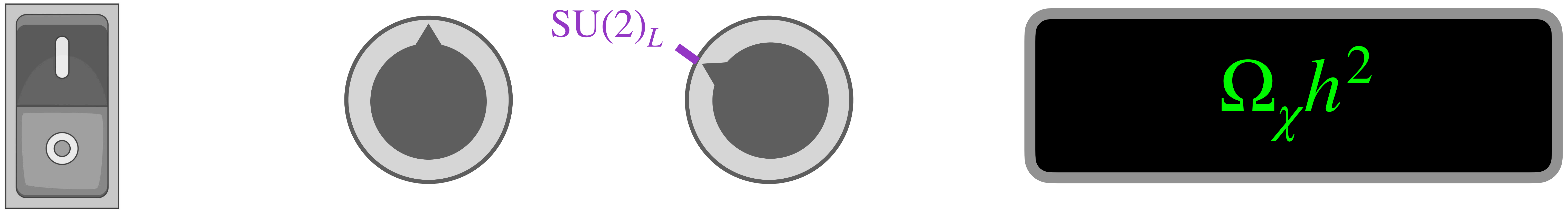
WIMPs and Standard Cosmological History

m_χ **Coupling strength** **DM energy density**

Standard freeze-out knobs

- A classic WIMP model considers DM as an $\mathrm{SU}(2)_L$-charged particle

WIMPs and Standard Cosmological History



Standard cosmology m_χ **Coupling strength** **DM energy density**

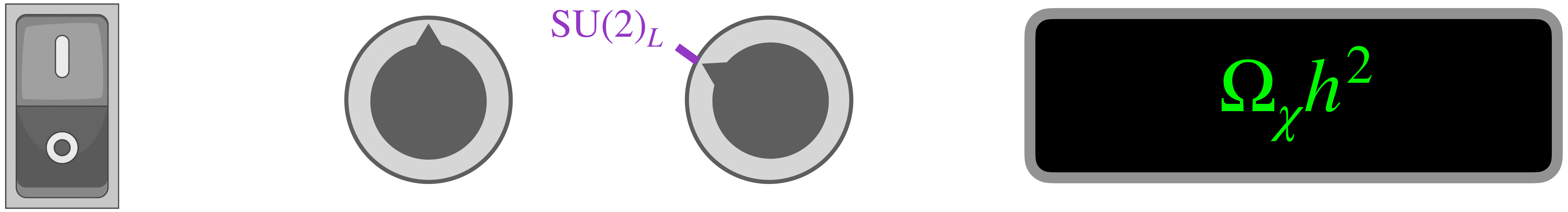
Standard freeze-out knobs

- A classic WIMP model considers DM as an $\mathrm{SU}(2)_L$-charged particle
  - Coupling is uniquely determined by gauge invariance
  - Getting the correct relic abundance uniquely fixes the DM mass

} **Strongly constrained by experiments**

- Are there assumptions which could be modified?
  - One possibility: The cosmological conditions during freeze-out
- Standard assumption:
  - Early universe conditions $\leftrightarrow$ extrapolating the SM to higher energies

WIMPs and Standard Cosmological History



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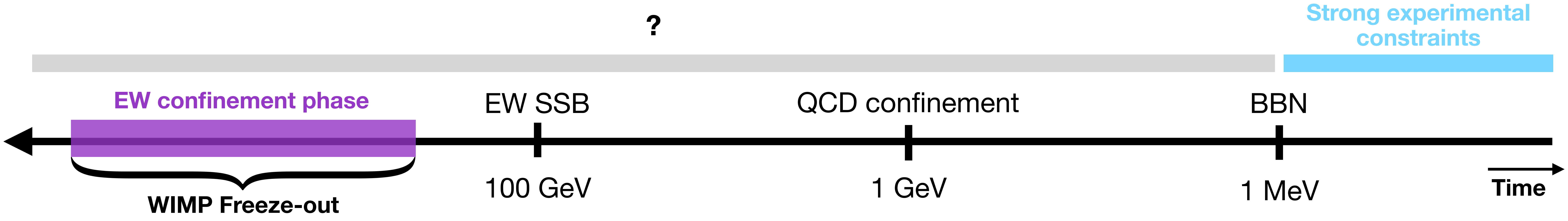
- Are there assumptions which could be modified?
  - One possibility: The cosmological conditions during freeze-out
- Standard assumption:
  - Early universe conditions $\leftrightarrow$ extrapolating the SM to higher energies
- In an alternate cosmological history, this theory might avoid experimental constraints

Modifying Cosmological History



- Experiments have placed strong constraints back to BBN
  - What happened before (including WIMP freeze-out) is more open to creativity
- Recent work has explored modifying cosmological history E.g. arXiv: 1906.05157, arXiv: 1911.01432
- In particular, one work[1] explored a phase of early Electroweak (EW) confinement
  - Coupling strength is linked to the vev of a scalar field, ϕ, undergoing a phase transition in the early universe

$$\mathcal{L} \supset -\frac{1}{2}\frac{1}{g_{eff}^2}\mathrm{Tr}(W_{\mu\nu}W^{\mu\nu}) \qquad \frac{1}{g_{eff}^2} = \left(\frac{1}{g^2} - \frac{\langle\phi\rangle}{M}\right)$$

Energy scale parameter: $M > \mathrm{TeV}$

  - Strong EW force causes particles to confine into pion-like objects

[1] Joshua Berger, Andrew J. Long, Jessica Turner. A phase of confined electroweak force in the early Universe. arXiv: 1906.05157

WIMP Dark Matter in this Scenario

- Our DM candidate is a pair of vector-like $\mathrm{SU}(2)_L$-charged Weyl fermions
  - SM quantum numbers $\mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y = \{1,\ 2,\ \pm 1/2\}$ with mass m_χ
  - Assume a Majorana mass $m_M \ll m_\chi$ to avoid direct detection bounds[1]

χ_1 χ_2

- During EW confinement, DM confines with SM quarks and leptons into “pions”
  - Confinement breaks flavor symmetry $\mathrm{SU}(2N_f) \to \mathrm{Sp}(2N_f)$
  - For one generation $\{l, q^r, q^g, g^b, \chi_1, \chi_2\}$ we have $\mathrm{SU}(6) \to \mathrm{Sp}(6)$ and get 15 pions
    - 5 are pure SM, 8 are a SM/DM mix, and 2 are pure DM
  - We are interested in reactions which deplete the DM density i.e. $\Pi_\chi \Pi_\chi \to \Pi_{SM}\ \Pi_{SM}$

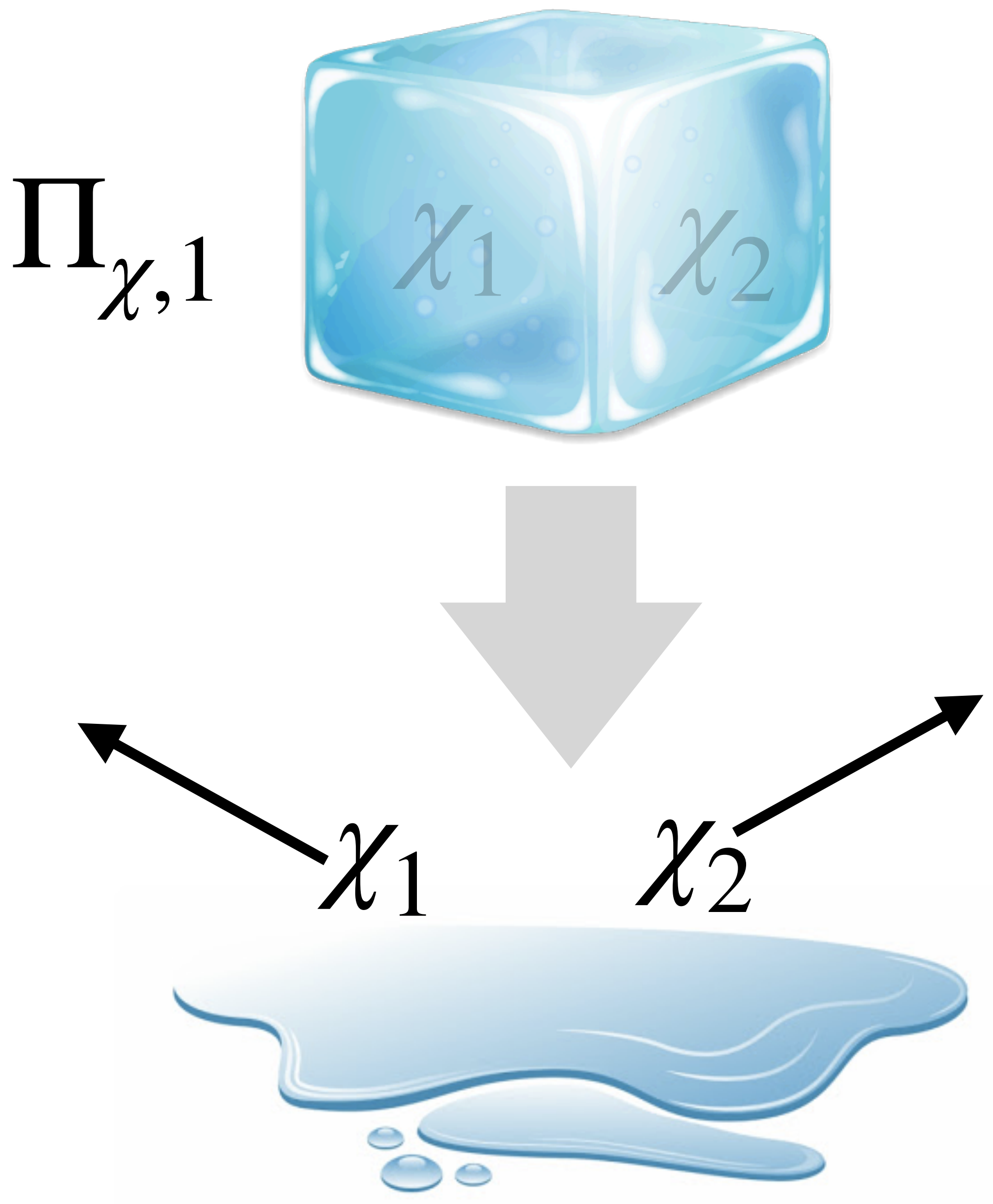
$\Pi_{\chi,1}$

- We derive pion masses and interactions in analogy with chiral perturbation theory
  - See backup slides for more details

[1] David Smith, Neal Weiner. Inelastic Dark Matter. arXiv: hep-ph/0101138

WIMP Freeze-out in this Scenario

- Freeze-out happens while DM is in pion form
  - Lightest pion ($m_{\Pi_{\chi,1}}$) survives freeze-out
  - Calculated $\Omega_{\Pi_{\chi,1}} h^2$ numerically taking into account possible coannihilation



- After freeze-out, EW confined phase ends and pions deconfine
  - Entropy dump is negligible which prevents further freeze-out

- In general, $m_{\Pi_{\chi,1}} > m_\chi$ so we adjust the relic abundance accordingly $\Omega_\chi h^2 = 2 \frac{m_\chi}{m_{\Pi_{\chi,1}}} \Omega_{\Pi_{\chi,1}} h^2$

Preliminary results

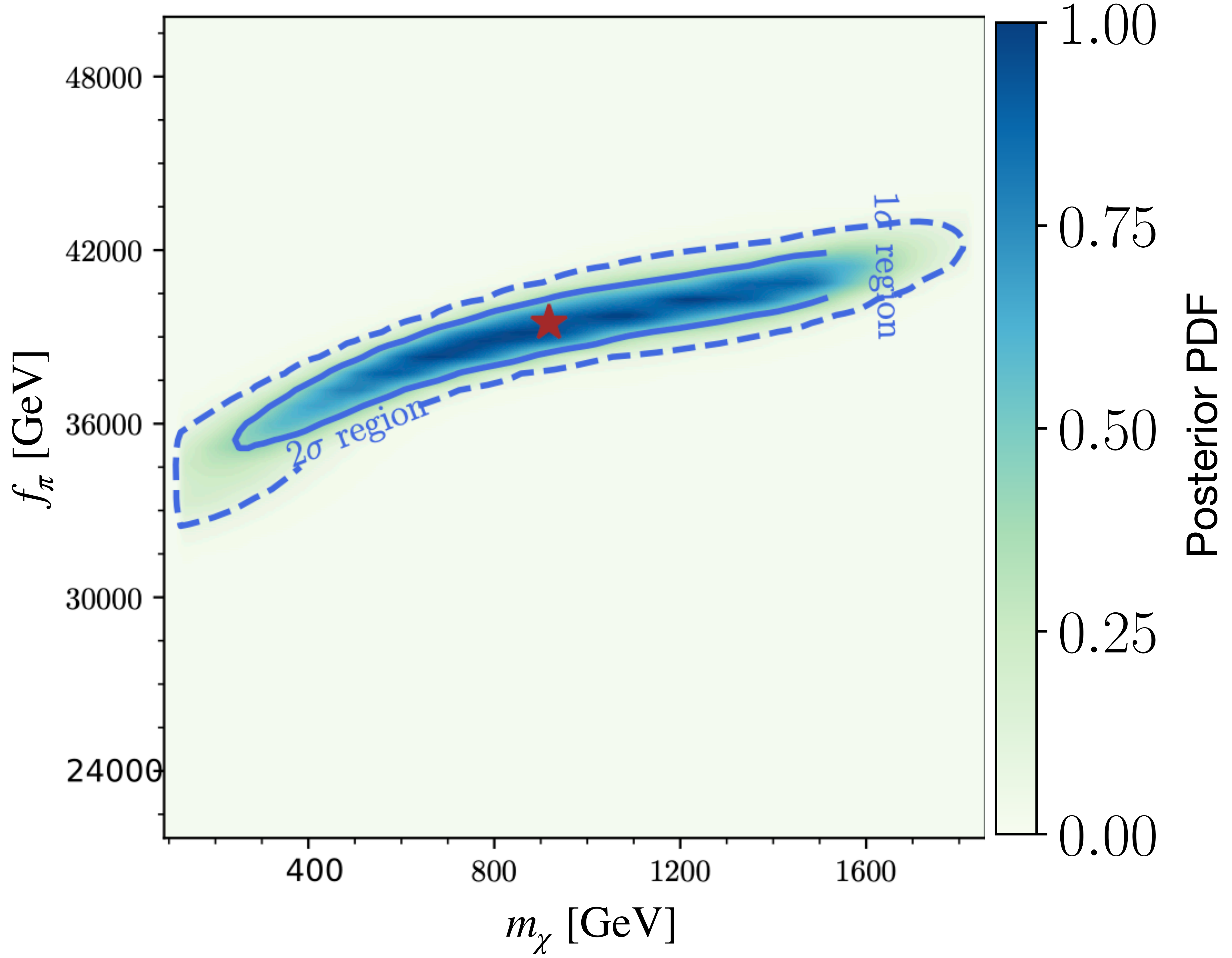
- Performing a scan, we find a region yielding the correct $\Omega_\chi h^2$ that is not ruled out by experiments

Minimal assumptions:

$m_\chi < \Lambda_W \quad f_\Pi = \frac{1}{4\pi}\Lambda_W \quad \Lambda_W =$ **Weak Confinement Scale**

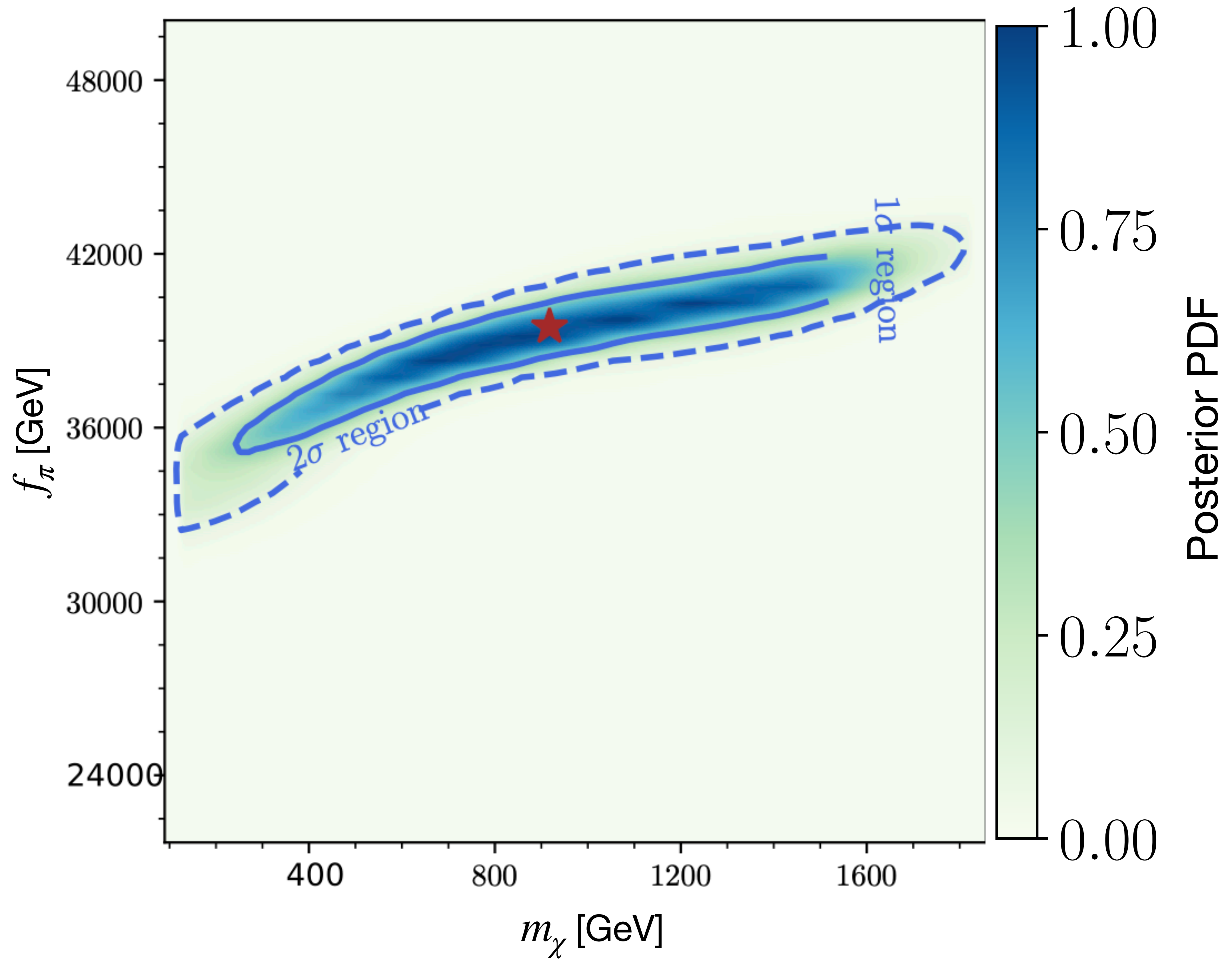
Example point yielding correct $\Omega_\chi h^2$:

Pion decay constant	$f_\Pi = 39.5\ \text{TeV}$
DM candidate mass	$m_\chi = 918\ \text{GeV}$
Mass of lightest DM pion	$m_{\Pi_{\chi,1}} = 268\ \text{TeV}$



Conclusion

- Considering alternate cosmological histories is important and advantageous
- Small modification to cosmological history can restore the WIMP miracle
- Not ruled out by current experiments
- Coming to arXiv soon!



Questions?

Backup Slides

Calculation Details

- After confinement we have the IR Lagrangian

$$\mathcal{L}_{\text{IR}} = \frac{f_\Pi^2}{4}\text{Tr}[D^\mu\Sigma^\dagger D_\mu\Sigma] + \kappa\Lambda_W^2 f_\Pi^2 \text{Re}[\det(\Sigma)] + \Lambda_W^3 \text{Tr}[M\Sigma + \Sigma^\dagger M^T] \qquad \Sigma = exp\left[\frac{i\Pi^0}{\sqrt{N_f}f_\Pi}\right] exp\left[i\frac{2\Pi^a X^a}{f_\Pi}\right]\Sigma_0$$

X^a **broken flavor symmetry generators** $\text{SU}(2N_f)/\text{Sp}(2N_f)$**,** $a: 1,...,2N_f^2 - N_f - 1$ **where** N_f **is the number of flavors**

Σ_0 **is the vev of** Σ **which breaks flavor symmetry**

$M = diag(0_{2x2}, \ldots, 0_{2x2}, M_\chi)$ **is the mass matrix of** χ**, for now we neglect the small Majorana mass** $M_\chi = \frac{1}{2}\begin{pmatrix} 0 & m_\chi \\ -m_\chi & 0 \end{pmatrix}$

- Gauge interactions from the kinetic term introduce loop corrections which lift some of the Goldstone bosons (pions) from massless degeneracy
  - 1 pion remains a true massless Goldstone boson
  - The rest have masses from gauge corrections, DM contributions, or both

Calculation Details

- We extract the relevant $\Pi_a\Pi_b \to \Pi_c\Pi_d$ interaction terms

$$\mathcal{L}_{2\to 2} \quad = \Pi_a\Pi_b\partial^\mu[\Pi_c]\partial_\mu[\Pi_d]F_1(a,b,c,d) + \Pi_a\Pi_b\Pi_c\Pi_d F_2(a,b,c,d)$$

- $F_1(a,b,c,d),\ F_2(a,b,c,d)$ are factors defined for notational convenience and depend on traces of combinations of the broken generators as well as other parameters

- This allows us to calculate the velocity averaged cross-section as a function of $\{a,b,c,d\}$ assuming non-relativistic, s-wave scattering

- We then calculate the effective cross-section, taking into account coannihilation
    - Because of the many possible combinations of $\{a,b,c,d\}$ we perform this calculation numerically in Python (code available upon publication)