Dark Matter Freeze-out during $\mathrm{SU(2)_L}$ Confinement

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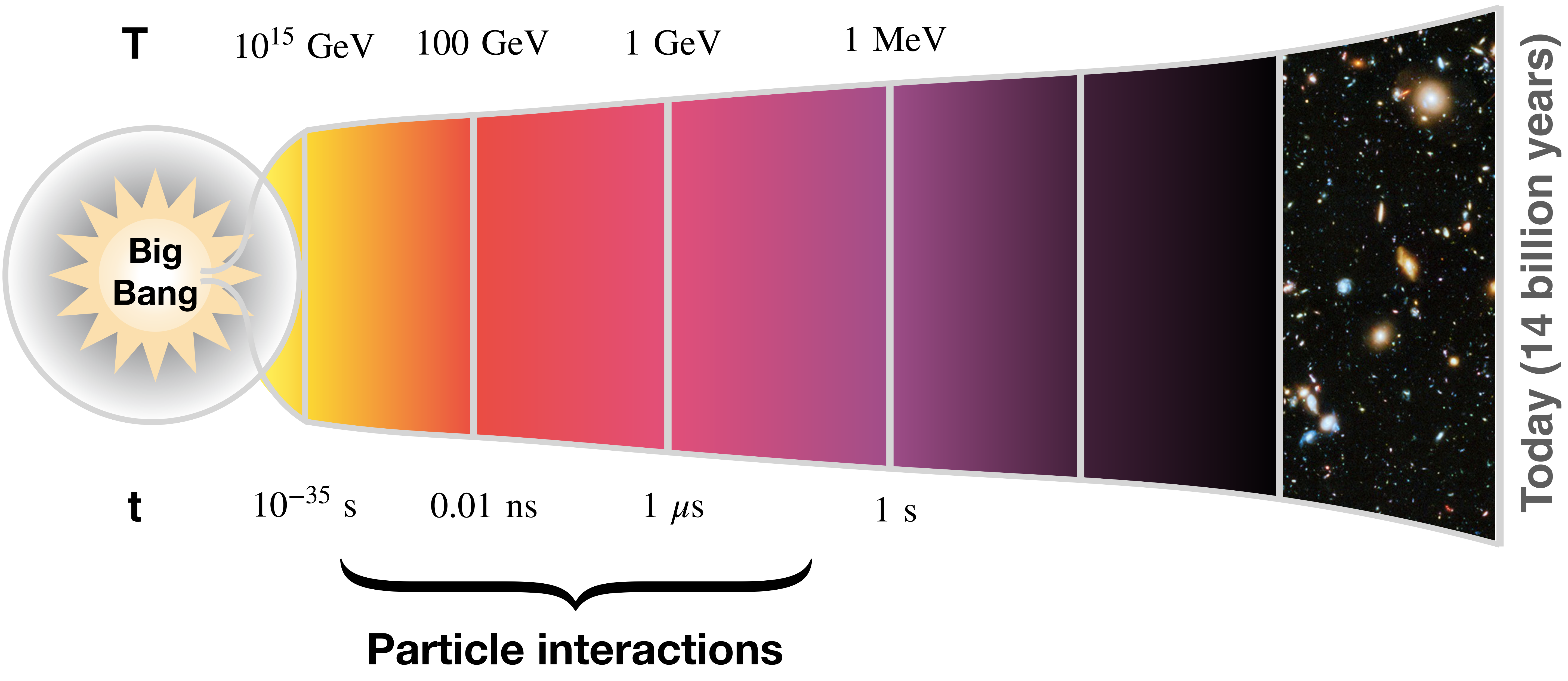
Particle physics and cosmological history



Cosmological Timeline

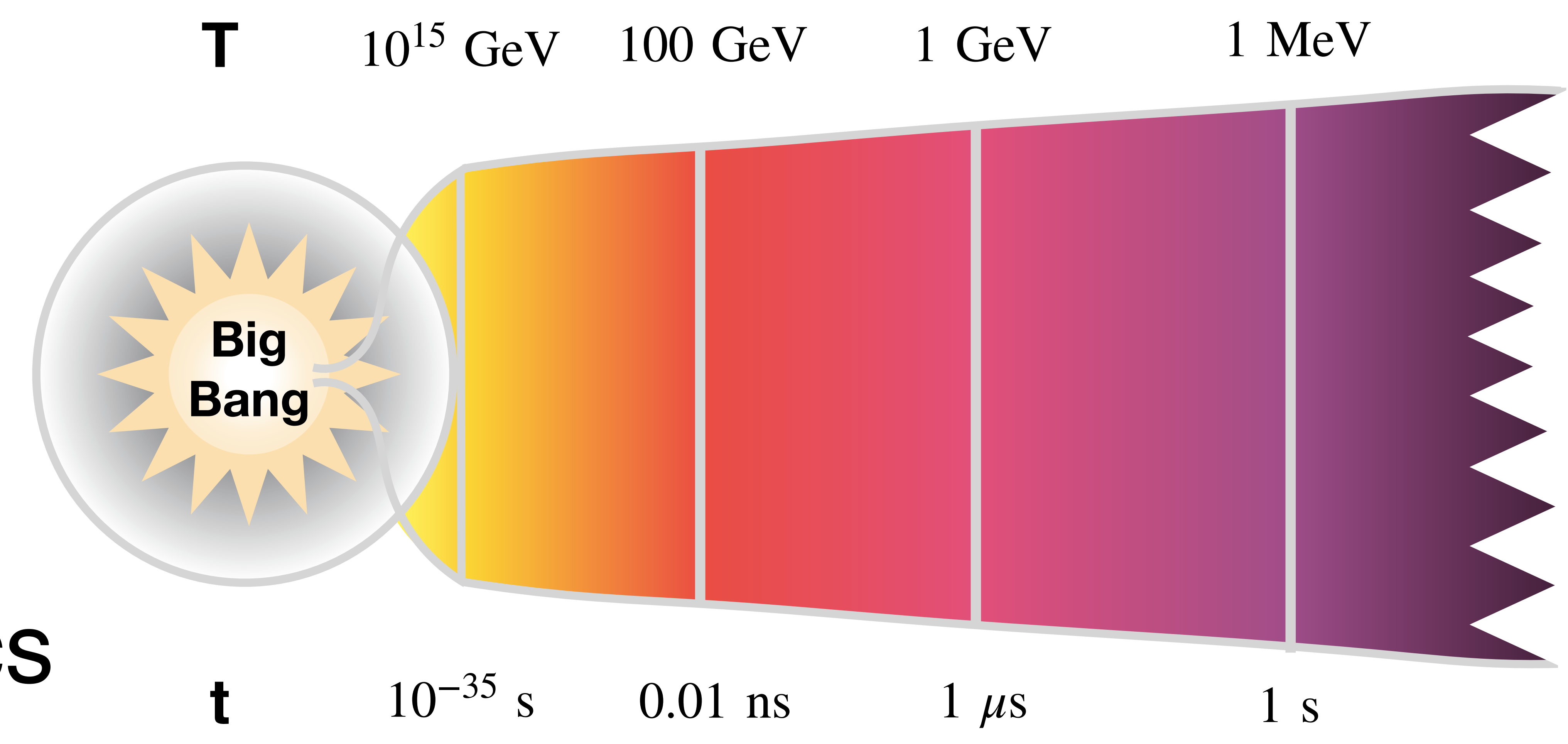
Time (t) →

Temperature (T) ←

- Particles dominated in the early universe
- Particle interactions had profound downstream effects
- Studying particle interactions will help us understand the evolution of our universe

Studying particle interactions

- Studied particle interactions at E ~ 100 GeV
  - Indirectly probes the early universe t ~ 0.01 ns



- Leading to the **Standard Model** of Particle Physics

- Assuming that the early universe particles follow the Standard Model gives us the **Standard Cosmological History**

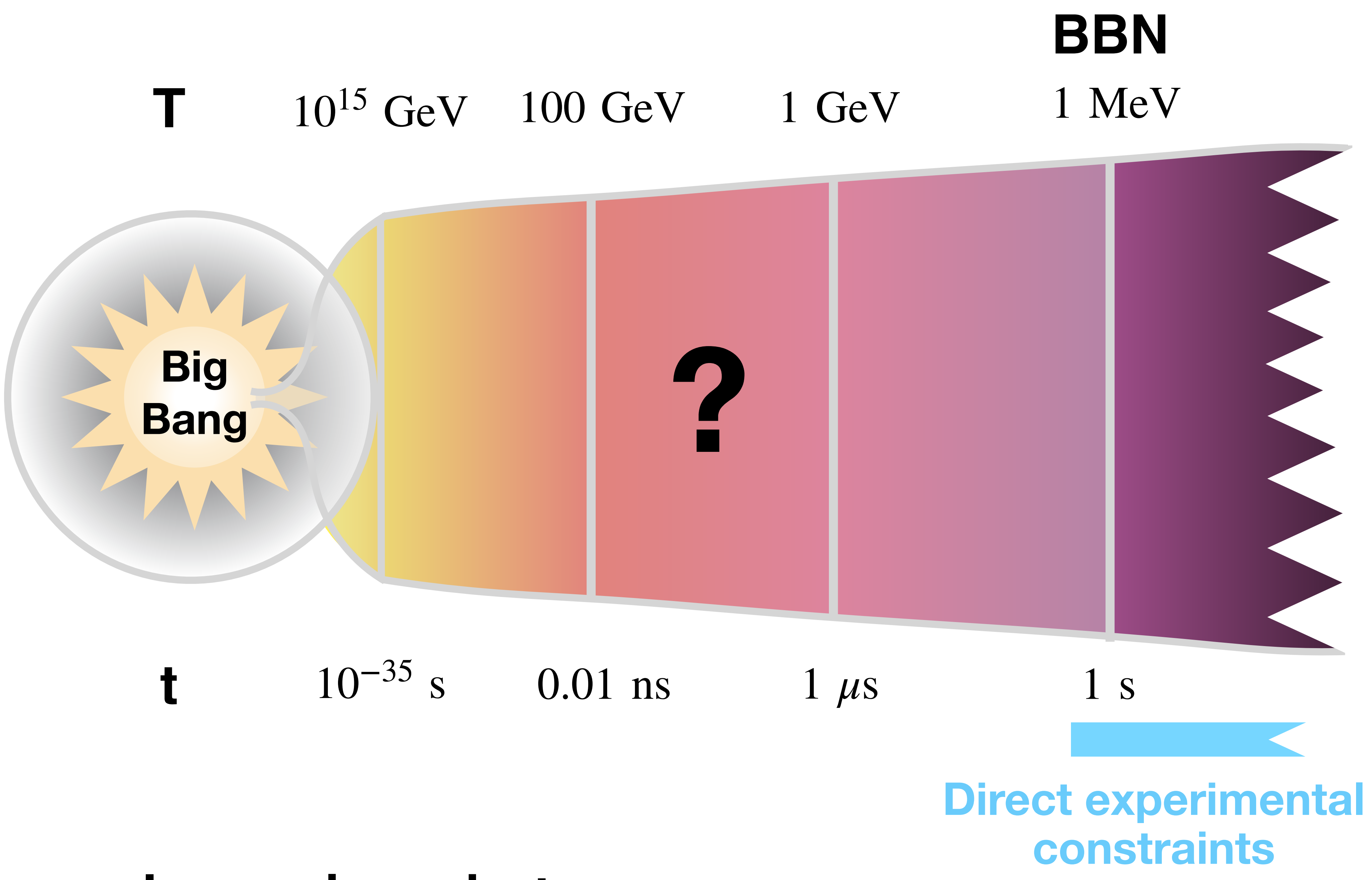
- However, this is only an assumption, the real cosmological history may differ
  - Direct probes are needed to say definitively

Alternate cosmological histories

- We know the Standard Model is incomplete

Matter/Anti-Matter Asymmetry

Dark Matter

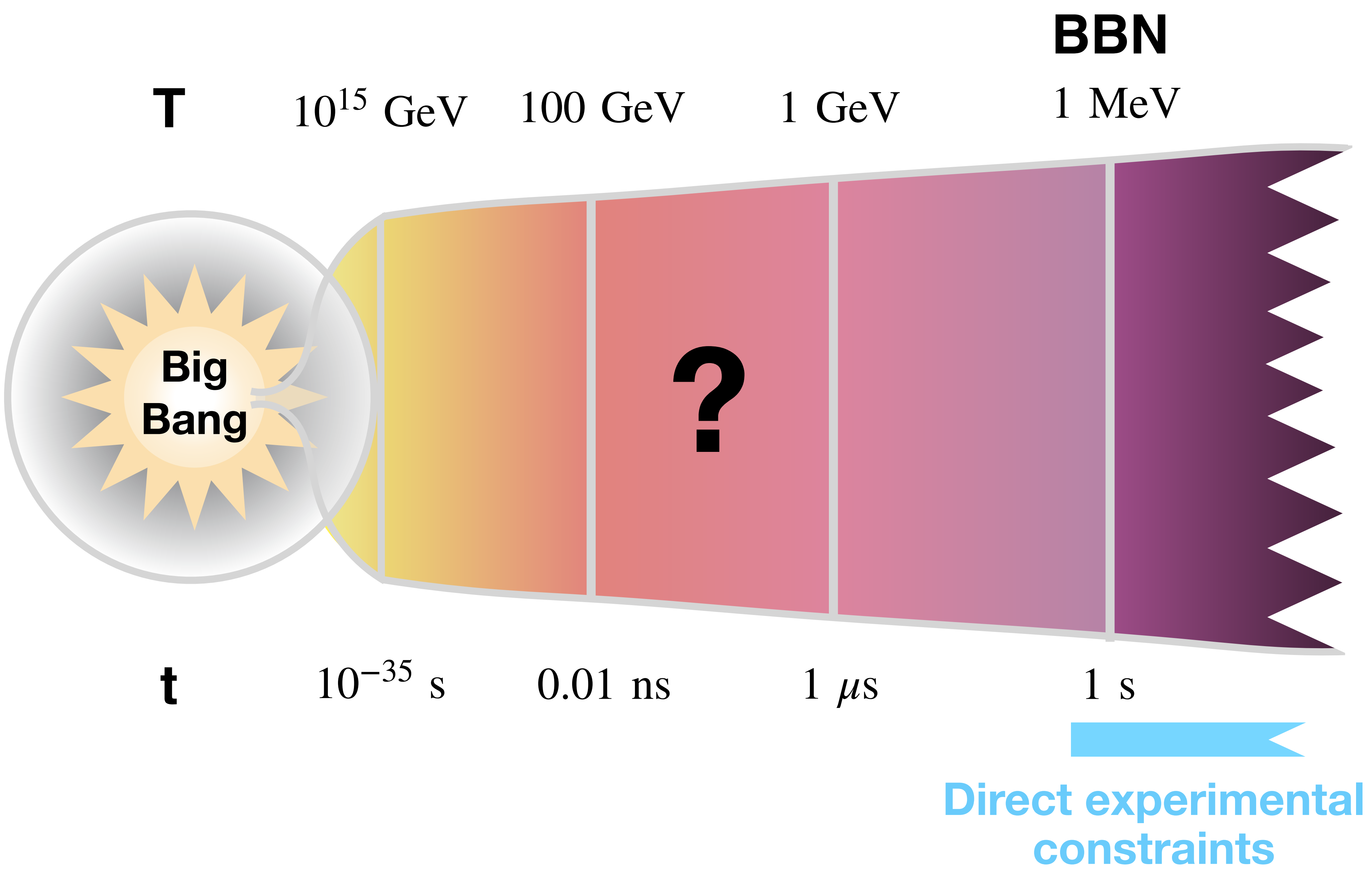


- Direct measurements only confirm a Standard Cosmology back to **Big Bang Nucleosynthesis (BBN)**

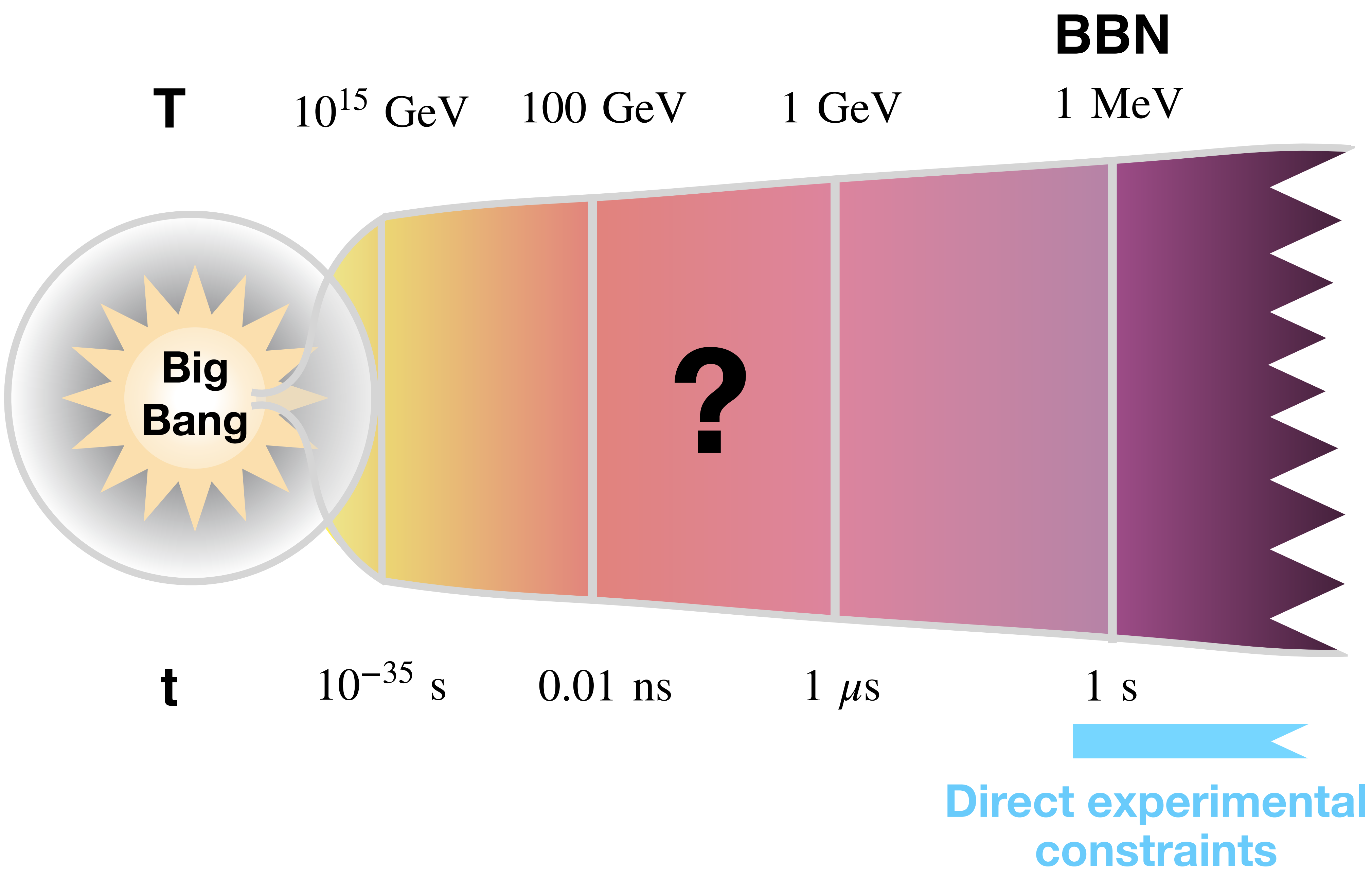
- Alternate cosmological histories may help provide explanations

Why consider alternate cosmological histories?

- Immediate practical benefits
  - Might lead to profitable results alleviating current constraints
- Scientifically important
  - Experimentally we can, so scientifically we should
- Long-term benefits
  - Exploring possibilities will help probe what *actually* happened



How to modify cosmological history?



- **Common example:** Add new particle species
  - Standard WIMP Dark Matter

- **Weirder example:** Modify strengths of forces
  - Features of the early universe caused the strengths of the forces to evolve, eventually settling to what we see today

E.g Joshua Berger, Andrew J. Long, Jessica Turner: 2019.
Djuna Croon, JNH, Seyda Ipek, Timothy M.P. Tait: 2019.

- **This talk:** Modify the Electroweak (EW) force to alleviate WIMP DM constraints

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 helps restore the WIMP miracle

WIMP dark matter (DM) freeze-out

m_χ

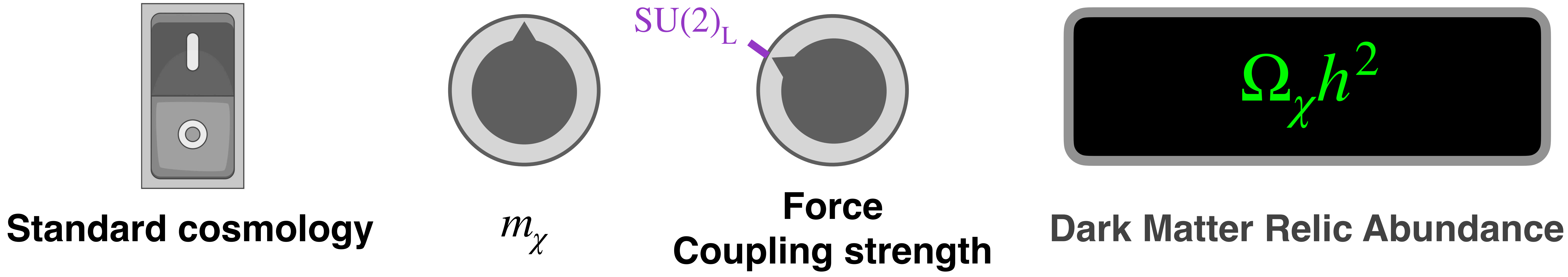
Force Coupling strength

Dark Matter Relic Abundance

Standard freeze-out knobs

- A classic WIMP model considers DM as a Weakly charged particle

WIMP dark matter (DM) freeze-out



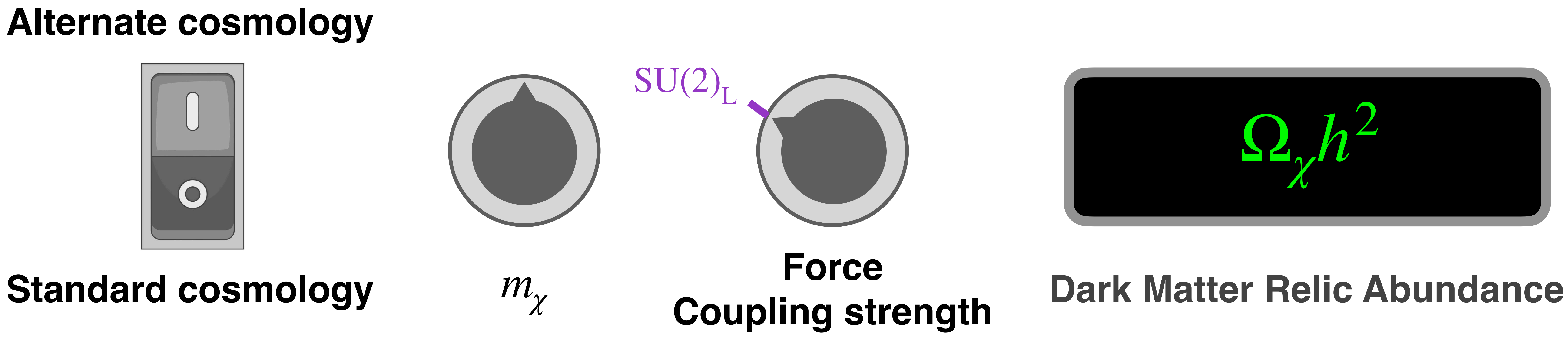
Standard freeze-out knobs

- A classic WIMP model considers DM as a Weakly charged particle
  - Force coupling is uniquely fixed
  - Getting the correct relic abundance uniquely fixes the DM mass

} **Strongly constrained by experiments**

- This was assuming a standard cosmological history

WIMP dark matter (DM) freeze-out



Standard freeze-out knobs

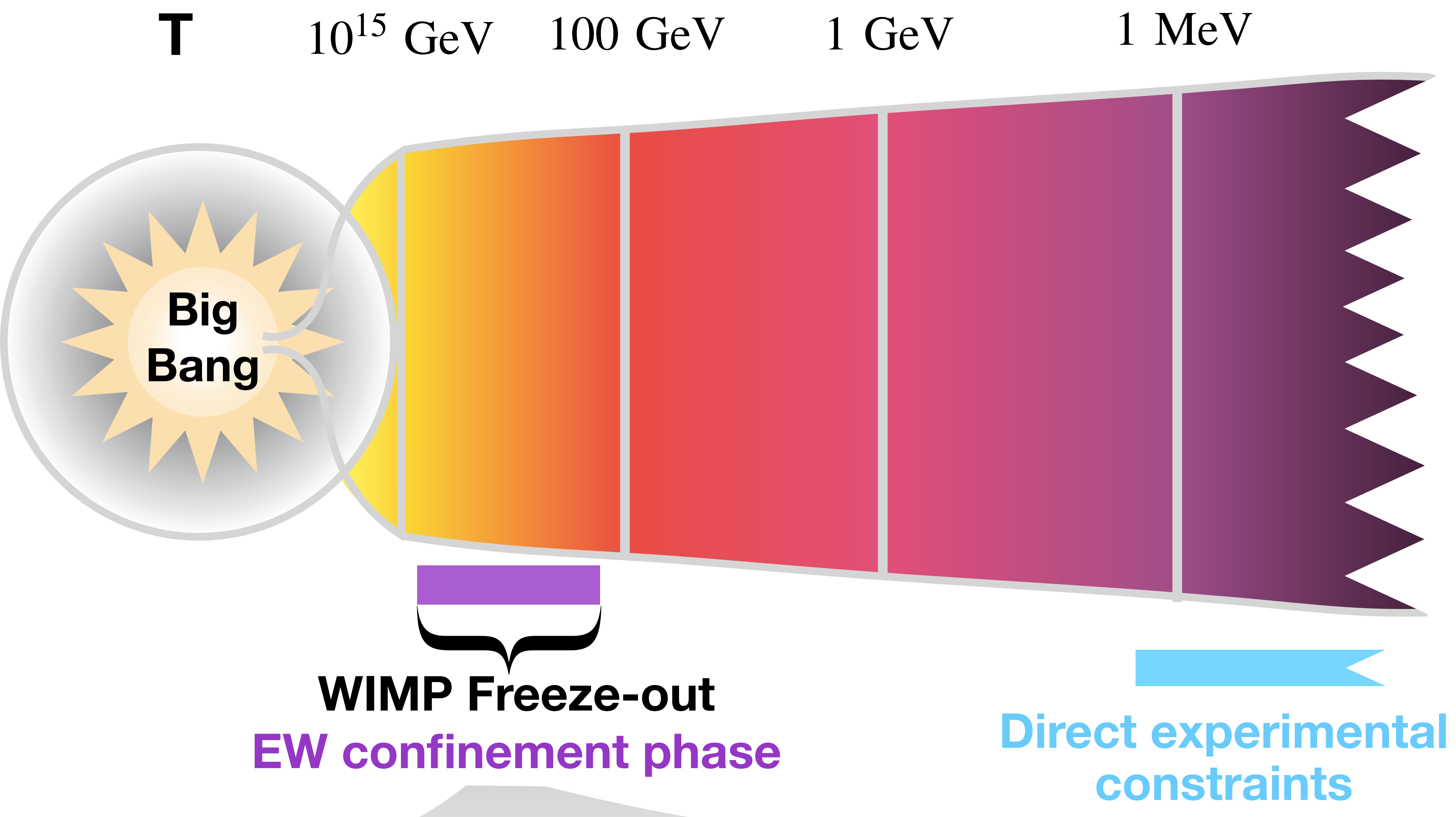
- A classic WIMP model considers DM as a Weakly charged particle
  - Force coupling is uniquely fixed
  - Getting the correct relic abundance uniquely fixes the DM mass

} **Strongly constrained by experiments**

- This was assuming a standard cosmological history

- If instead there was an alternate cosmological history where the Weak force coupling was different during freeze-out, freedom in DM mass would be restored

Schematic outline of calculation



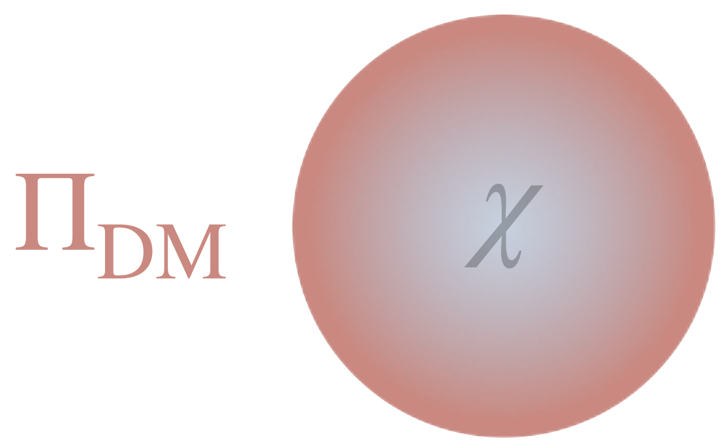
$$\mathcal{L} \supset -\frac{1}{2}\frac{1}{g_{\text{eff}}^2}\text{Tr}(W_{\mu\nu}W^{\mu\nu}) \qquad \frac{1}{g_{\text{eff}}^2} = \left(\frac{1}{g^2} - \frac{\langle\phi\rangle}{M}\right) \qquad M > \text{TeV}$$

$\langle\phi\rangle \ll M/g$ — **Electroweak (EW) Force is at normal strength**

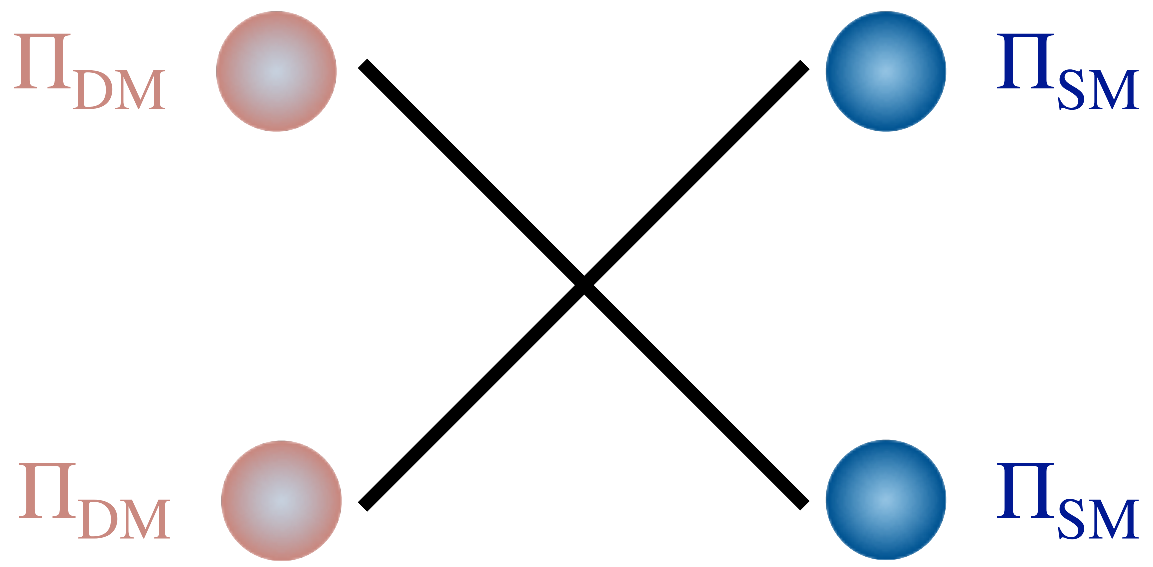
$\langle\phi\rangle \sim M/g$ — **Electroweak (EW) Force is much stronger**

This causes EW confinement (analogous to QCD)

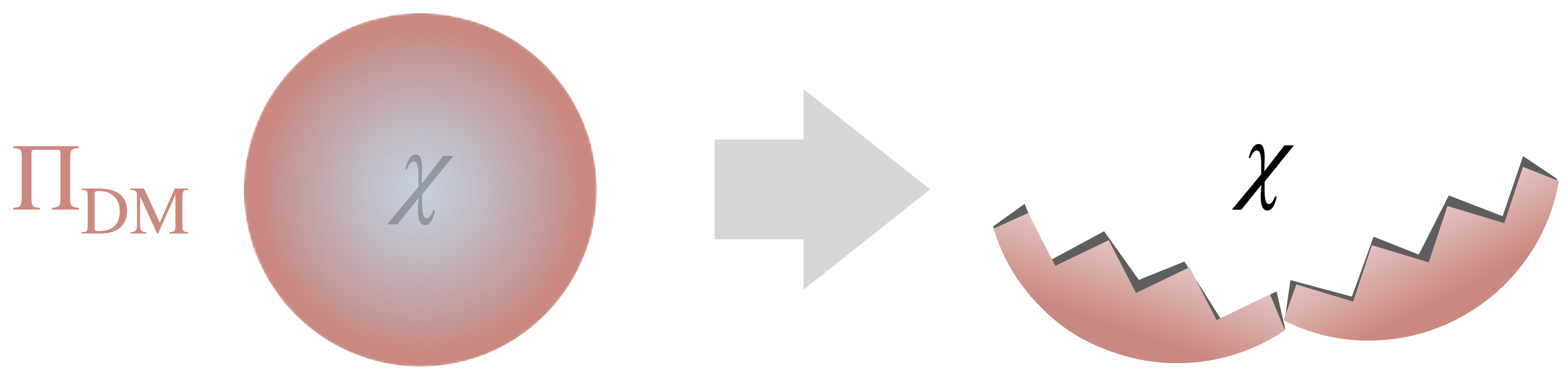
EW Force confines DM into "pions"



DM pions interact / freeze-out



EW confined phase ends, pions deconfine



$\langle\phi\rangle \neq 0$

$\langle\phi\rangle \to 0$

Prior work on EW confinement

- Historical work: L.F. Abbott, E. Farhi: 1981a, 1981b. M. Claudson, E. Farhi, R L. Jaffe: 1986. Gerard 't Hooft: 1998.

- One work[1] explored cosmological implications of an early EW confinement phase
  - Coupling strength is linked to the vev of a scalar field, ϕ, undergoing a phase transition in the early universe

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

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

- Agnostic to phase transition specifics

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

Main takeaways from [1]

- Strong EW force causes quark and lepton doublets to confine into pion-like objects
- Confinement causes spontaneous flavor symmetry breaking: $\mathrm{SU}(2N_f) \to \mathrm{Sp}(2N_f)$ (for SM $N_f = 6$)
  - Massless GSBs*: $(4N_f^2 - 1) - (2N_f^2 + N_f) = 2N_f^2 - N_f - 1 = 65$
  - One massive pseudo-GSB (η' analog)

*Neglecting gauge interactions and Yukawas

- Loop induced corrections from gauge interactions + Yukawas give 58/65 “pions” masses
- Confinement breaks SM gauge symmetry: $\mathrm{SU}(3)_\mathrm{C} \times \mathrm{U}(1)_\mathrm{Y} \to \mathrm{SU}(2)_\mathrm{C} \times \mathrm{U}(1)_\mathrm{Q}$
  - 4 massless gauge bosons + 5 massive gauge bosons

Our work throws a WIMP-like DM particle into the mix

[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

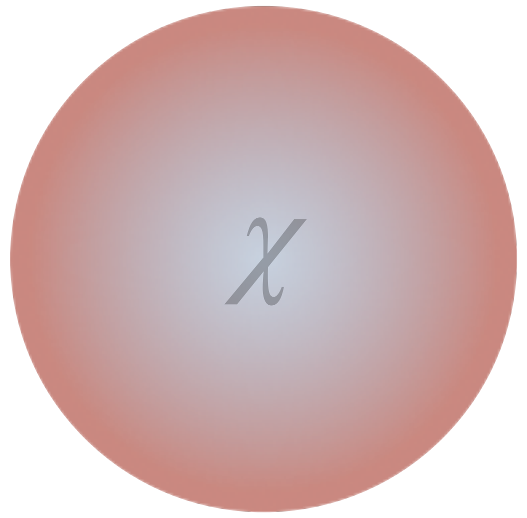
- Our DM candidate is a pair of vector-like $\mathrm{SU(2)_L}$-charged Weyl fermions
  - SM quantum numbers $\mathrm{SU(3)_C} \times \mathrm{SU(2)_L} \times \mathrm{U(1)_Y} = \{1,\ 2,\ \pm 1/2\}$ with mass m_{DM}

$\chi_1 \quad \chi_2$

$$\mathcal{L}_\chi = i\chi_1^\dagger \bar{\sigma}^\mu D_\mu \chi_1 + i\chi_2^\dagger \bar{\sigma}^\mu D_\mu \chi_2 + m_{DM}\chi_1\chi_2 + \mathrm{h.c.}$$

- During EW confinement, χ_1 and χ_2 confine with SM quarks and leptons into bound states
  - These are analogous to mesons and baryons of QCD
  - The lightest of these states are mesons: Π and η'

Π_{DM}



- In analogy with chiral perturbation theory, we collect these into a complex antisymmetric scalar field Σ_{ij} where $i, j = 1, \ldots, 2N_f$ ← **Number of flavors of $\mathrm{SU(2)_L}$ doublets**

Confinement details

- Confinement spontaneously breaks flavor symmetry $\mathrm{SU}(2N_f) \to \mathrm{Sp}(2N_f)$
  - Follows intuition from chiral symmetry breaking in QCD and confirmed with lattice simulations
  - Encoded by Σ_{ij} obtaining a vev $(\Sigma_0)_{ij}$ satisfying $\Sigma_0^\dagger \Sigma_0 = \Sigma_0 \Sigma_0^\dagger = 1$
- Neglecting other SM gauge interactions and Yukawa couplings we get $2N_f^2 - N_f - 1$ massless Goldstone bosons (GSBs) and 1 massive pseudo-GSB, analogous to the η' of QCD.

1 generation

$\{l, q^r, q^g, q^b, \chi_1, \chi_2\}$

$2N_f = 6$

$\Downarrow$

$\mathrm{SU}(6) \to \mathrm{Sp}(6)$

$\Downarrow$

15 mesons

$2N_f$

$\mathrm{SU}(2N_f) \to \mathrm{Sp}(2N_f)$

$2N_f^2 - N_f - 1$ Π**'s and** 1 η'

3 generations

$\{l_1, q_1^r, q_1^g, q_1^b, l_2, q_2^r, q_2^g, q_2^b, l_3, q_3^r, q_3^g, q_3^b, \chi_1, \chi_2\}$

$2N_f = 14$

$\Downarrow$

$\mathrm{SU}(14) \to \mathrm{Sp}(14)$

$\Downarrow$

91 mesons

Confinement details

$$\mathcal{L}_{\text{IR}} \supset \frac{f^2}{4}\text{Tr}\left[D_\mu \Sigma^\dagger D^\mu \Sigma\right] + \Lambda_W^3 \text{Tr}\left[M\Sigma + \Sigma^\dagger M^T\right] + \kappa \Lambda_{\text{W}}^2 f^2 \text{Re}\left[\det \Sigma\right] + \Delta\mathcal{L}$$

$$\Sigma = \exp\left[i\frac{\eta'}{\sqrt{N_f}f}\right]\exp\left[\sum_a 2i\frac{\Pi^a X^a}{f}\right]\Sigma_0$$

$$\Delta\mathcal{L} = C_G \Lambda_W^2 f^2 \frac{g_s^2}{16\pi^2}\sum_{a=1,2,3}\text{Tr}[L^a\Sigma^\dagger L^{aT}\Sigma] + C_A\Lambda_W^2 f^2 \frac{e_Q^2}{16\pi^2}\text{Tr}[Q\Sigma^\dagger Q\Sigma]$$
$$+ C_W \Lambda_W^2 f^2 \frac{g_s^2/2}{16\pi^2}\sum_{\pm}\sum_{i=1,2}\text{Tr}[L^{i\pm}\Sigma^\dagger L^{i\pm}\Sigma] + C_Z\Lambda_W^2 f^2 \frac{e_Q^2/s_Q^2 c_Q^2}{16\pi^2}\text{Tr}[J\Sigma^\dagger J\Sigma]$$

X^a **generators of the broken symmetry**

$\text{SU}(2N_f)/\text{Sp}(2N_f)$, $a: 1, \ldots, 2N_f^2 - N_f - 1$

- $\Delta\mathcal{L}$ gauge corrections from $\text{SU}(3)_\text{C}$ and $\text{U}(1)_\text{Y}$ explicitly break $\text{SU}(2N_f)$ giving some GSBs masses
- Confinement breaks $\text{SU}(3)_\text{C} \times \text{U}(1)_\text{Y} \to \text{SU}(2)_\text{C} \times \text{U}(1)_\text{Q}$ eating some of the massless GSBs

Unbroken χ charge

- $\mathcal{L}_{\rm IR}$ is invariant under an unbroken $\mathrm{U}(1)_\chi$, convenient to organize the pions by their charges

$$\Sigma \xrightarrow{\mathrm{U}(1)_\chi} \Sigma' \approx \Sigma + i\theta_\chi \left(Q_\chi \Sigma + \Sigma Q_\chi\right) + \ldots \qquad Q_\chi = \mathrm{diag}(\,0,\,\ldots,\,0,\,1,\,-1)$$

- Expanding Σ to first order implies

$$\Pi_b \;\to\; \Pi_b + i\theta_\chi \delta\Pi_b \qquad \delta\Pi_b = 2\Pi_a \mathrm{Tr}[[Q_\chi, X_a], X_b]$$

- We can then construct linear combinations of the pion fields with definite $\mathrm{U}(1)_\chi$ charge

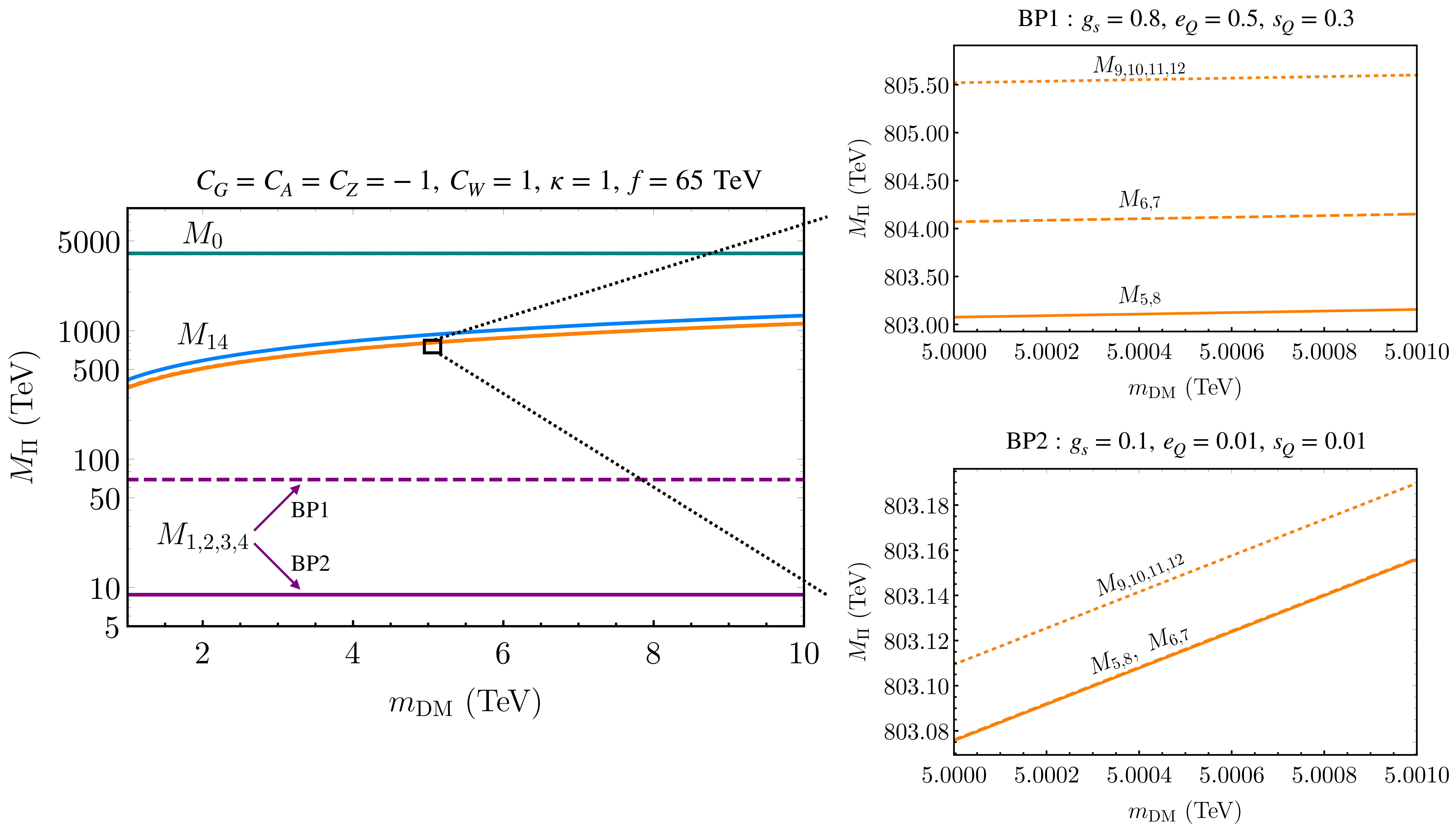
$$\Pi_1^\pm := \frac{1}{\sqrt{2}}(\Pi_5^{\rm mass} \mp i\Pi_8^{\rm mass}) \quad \Pi_2^\pm := \frac{1}{\sqrt{2}}(\Pi_6^{\rm mass} \mp i\Pi_7^{\rm mass}) \quad \Pi_3^\pm := \frac{1}{\sqrt{2}}(\Pi_9^{\rm mass} \mp i\Pi_{12}^{\rm mass}) \quad \Pi_4^\pm := \frac{1}{\sqrt{2}}(\Pi_{10}^{\rm mass} \mp i\Pi_{11}^{\rm mass})$$

Pion masses and remaining gauge symmetries

Gauge charges

	$U(1)_Q$	$SU(2)_C$
η'	0	1
4 SM pions	±1	2
2 SM/DM pions	0	1
2 SM/DM pions	±1	1
4 SM/DM pions	±1	2
1 SM pion	0	1
1 DM pion	0	1

Masses



Deriving pion interactions

- We are interested in reactions which deplete the DM density i.e. $\Pi_{\text{DM}}\Pi_{\text{DM}} \to \Pi_{\text{SM}}\ \Pi_{\text{SM}}$

$$\mathcal{L}_{\text{IR}} \supset \frac{f^2}{4}\text{Tr}\left[D_\mu\Sigma^\dagger D^\mu\Sigma\right] + \Lambda_W^3\text{Tr}[M\Sigma + \Sigma^\dagger M^T] + \kappa\Lambda_{\text{W}}^2 f^2\text{Re}[\det\Sigma] + \Delta\mathcal{L}$$

$$\Downarrow$$

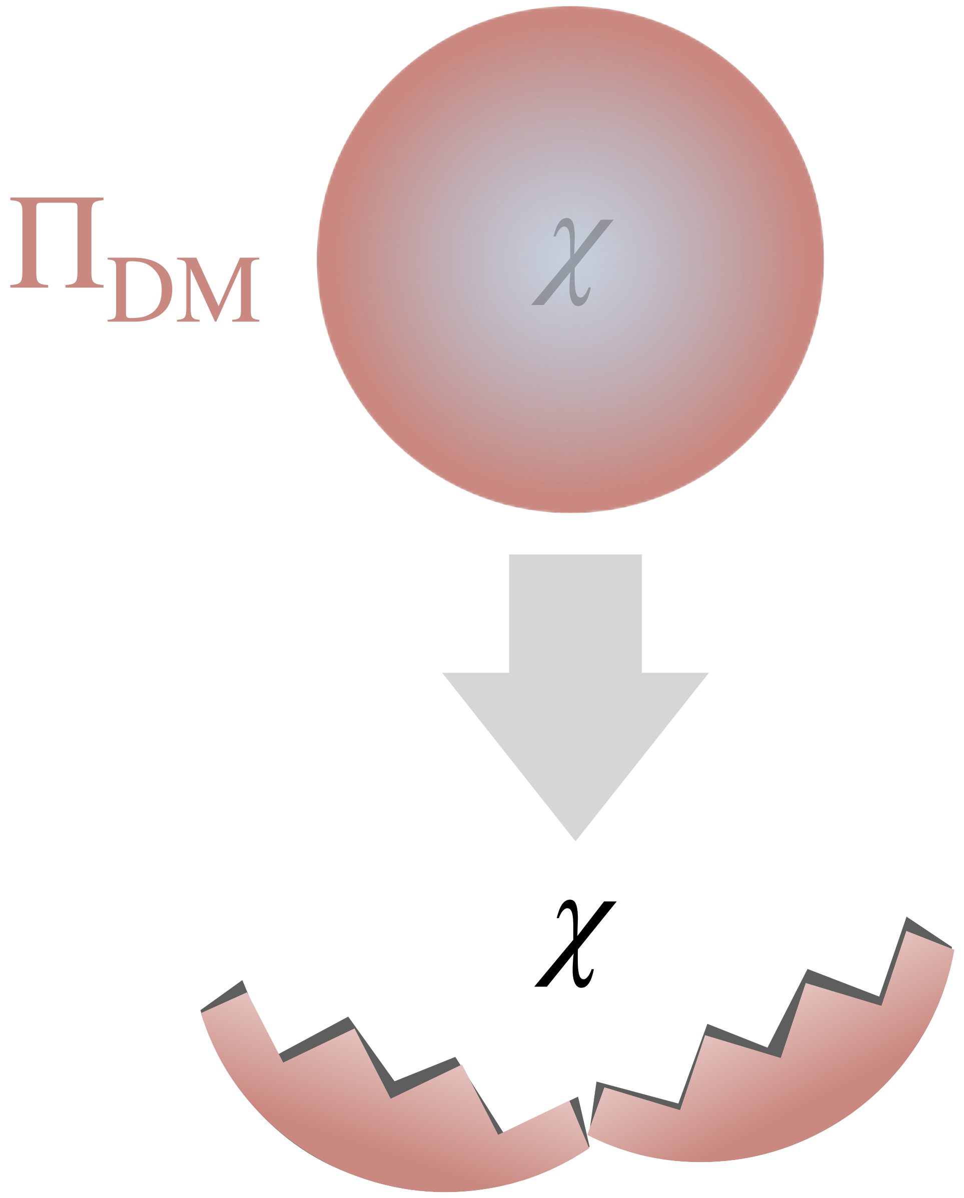
$\Pi_a\Pi_b \to \Pi_c\ \Pi_d$

$$\mathcal{L}_{2\to 2} = \frac{4}{f^2}\text{Tr}_1(a,b,c,d)\ \Pi_a\Pi_b\partial^\mu[\Pi_c]\partial_\mu[\Pi_d] + \frac{2m_{\text{DM}}\Lambda_W^3}{3f^4}\text{Tr}_2(a,b,c,d)\ \Pi_a\Pi_b\Pi_c\Pi_d$$

- Transforming into definite DM charge basis implies we want $\Pi^+\ \Pi^- \to \Pi^0\ \Pi^0$
- For the benchmarks chosen we can safely neglect annihilation to gauge bosons
- We calculate the velocity averaged effective cross-section, taking into account coannihilation
  - We assume non-relativistic, s-wave scattering
- We then use this in solving the Boltzmann equation for the final co-moving number density of Π_{DM}

WIMP freeze-out in this scenario

- Freeze-out happens while χ_1 and χ_2 are confined in pion form
  - Lightest pion containing χ survives freeze-out: $\Pi_{\mathrm{DM},1}$ (mass = m_1)
  - Calculate $\Omega_{\Pi_{\mathrm{DM},1}} h^2$ numerically taking into account possible coannihilation



- After freeze-out, EW confined phase ends and pions deconfine
  - Entropy dump from deconfinement is negligible which prevents further freeze-out of the χ's

- In general, $m_{\Pi_{\mathrm{DM},1}} > m_{\mathrm{DM}}$ so we adjust the relic abundance accordingly

$$\Omega_\chi h^2 = \frac{m_{\mathrm{DM}}}{m_1} \Omega_{\Pi_{\mathrm{DM},1}} h^2$$

Parameter scan

- Under some minimal assumptions: $m_{\mathrm{DM}} < \Lambda_W$ and $f = \frac{1}{4\pi}\Lambda_W$

- Performed a parameter scan in $\left[\log_{10}\left(\frac{m_{\mathrm{DM}}}{\mathrm{GeV}}\right), \log_{10}\left(\frac{f}{\mathrm{GeV}}\right)\right]$

- Using the log-likelihood as the objective function

$$\ln L = -\frac{1}{2}\left[\frac{\Omega_\chi h^2\left(m_{\mathrm{DM}}, f\right) - \Omega_{\mathrm{PDG}}h^2}{\Delta\Omega h^2}\right]$$

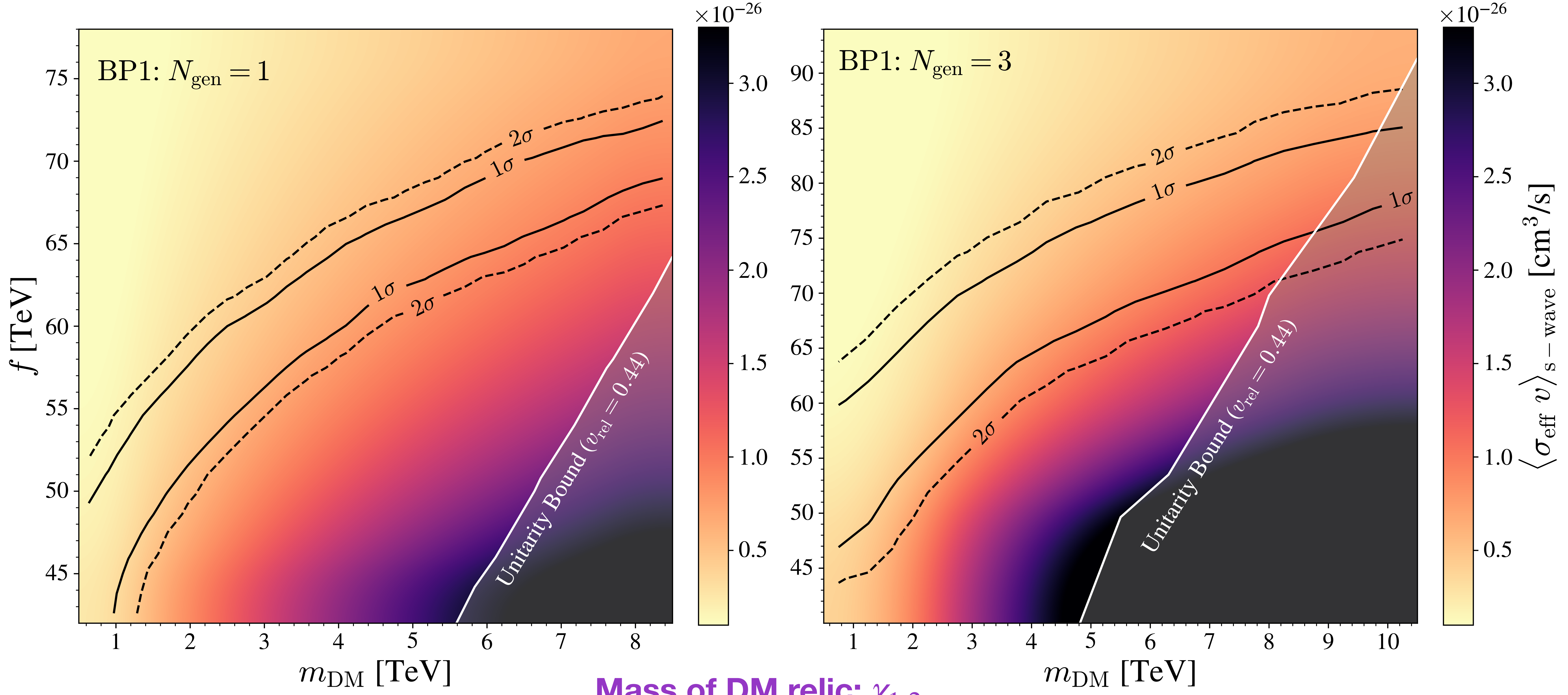
$$\Omega_{\mathrm{PDG}}h^2 \pm \Delta\Omega h^2 = 0.1200 \ \pm \ 0.0012$$ [1]

[1] Planck Collaboration. Planck 2018 results. VI. Cosmological parameters. arXiv: 1807.06209

Results

$$\langle \sigma_{\text{eff}} v \rangle \approx (1.5 \text{ to } 2) \times 10^{-11} \text{ GeV}^{-2} \left(\frac{m_{\text{DM}}}{5 \text{ TeV}} \right) \left(\frac{65 \text{ TeV}}{f} \right)^3$$

Pion decay constant



Effective DM pion cross-section

Mass of DM relic: $\chi_{1,2}$

Experimental constraints: Direct detection

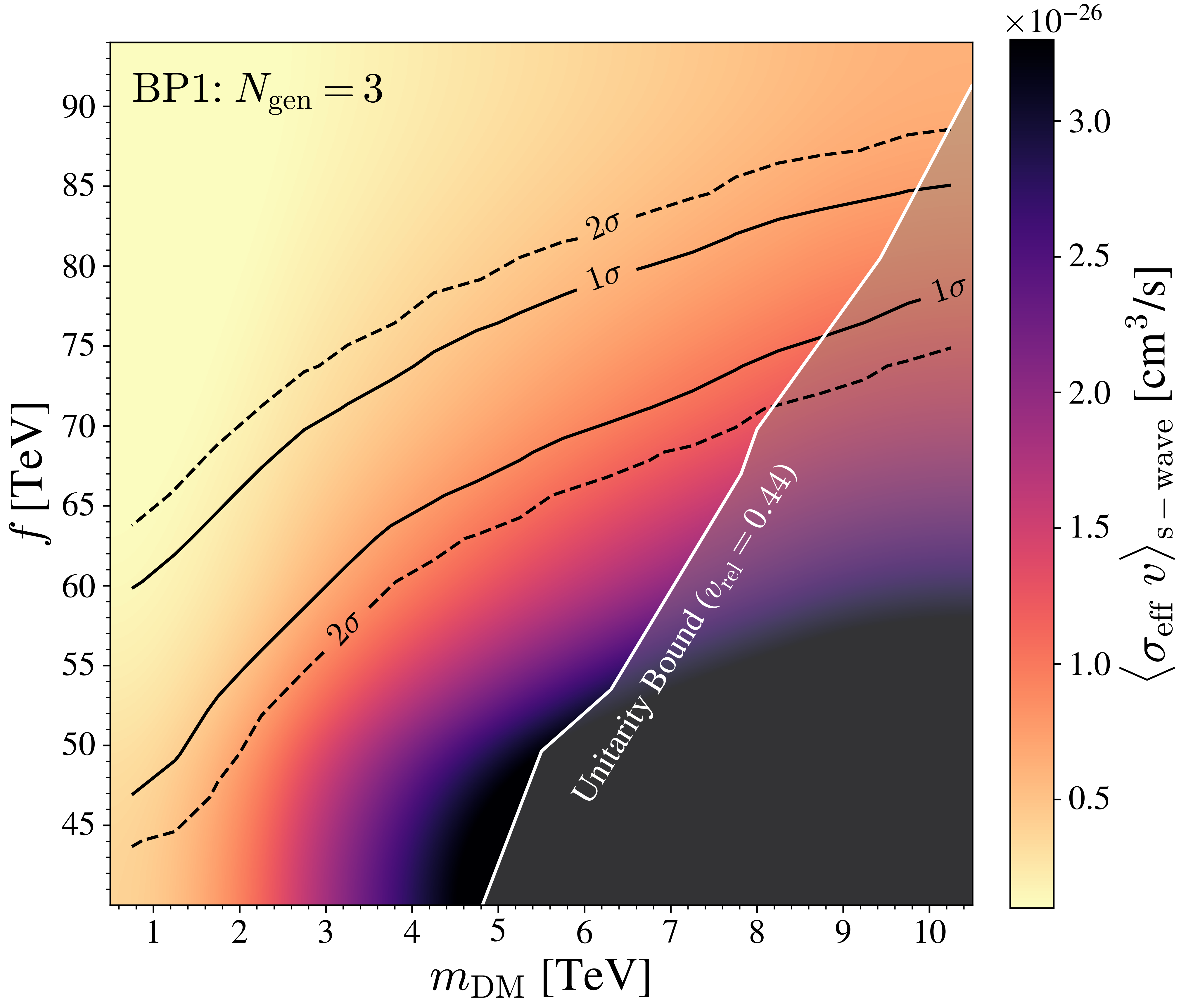
Reminder: $\chi_{1,2}$ are $\mathrm{SU}(2)_\mathrm{L}$-doublets with hypercharge with full strength Z-boson couplings $\Rightarrow$ trouble, but…

- Avoided if there is a small Majorana mass $m_M \ll m_\mathrm{DM}$ today[1]

- Can be induced by a dimension 5 interaction with the Higgs

$$\mathcal{L}_{\Delta M} = \frac{1}{M_1}(H^\dagger \chi_1)(H^\dagger \chi_1) + \frac{1}{M_2}(H\chi_2)(H\chi_2) + \mathrm{h.c.}$$

- No effect on freeze-out for sufficiently large mass scales



Effective DM pion cross-section

Mass of DM relic: $\chi_{1,2}$

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

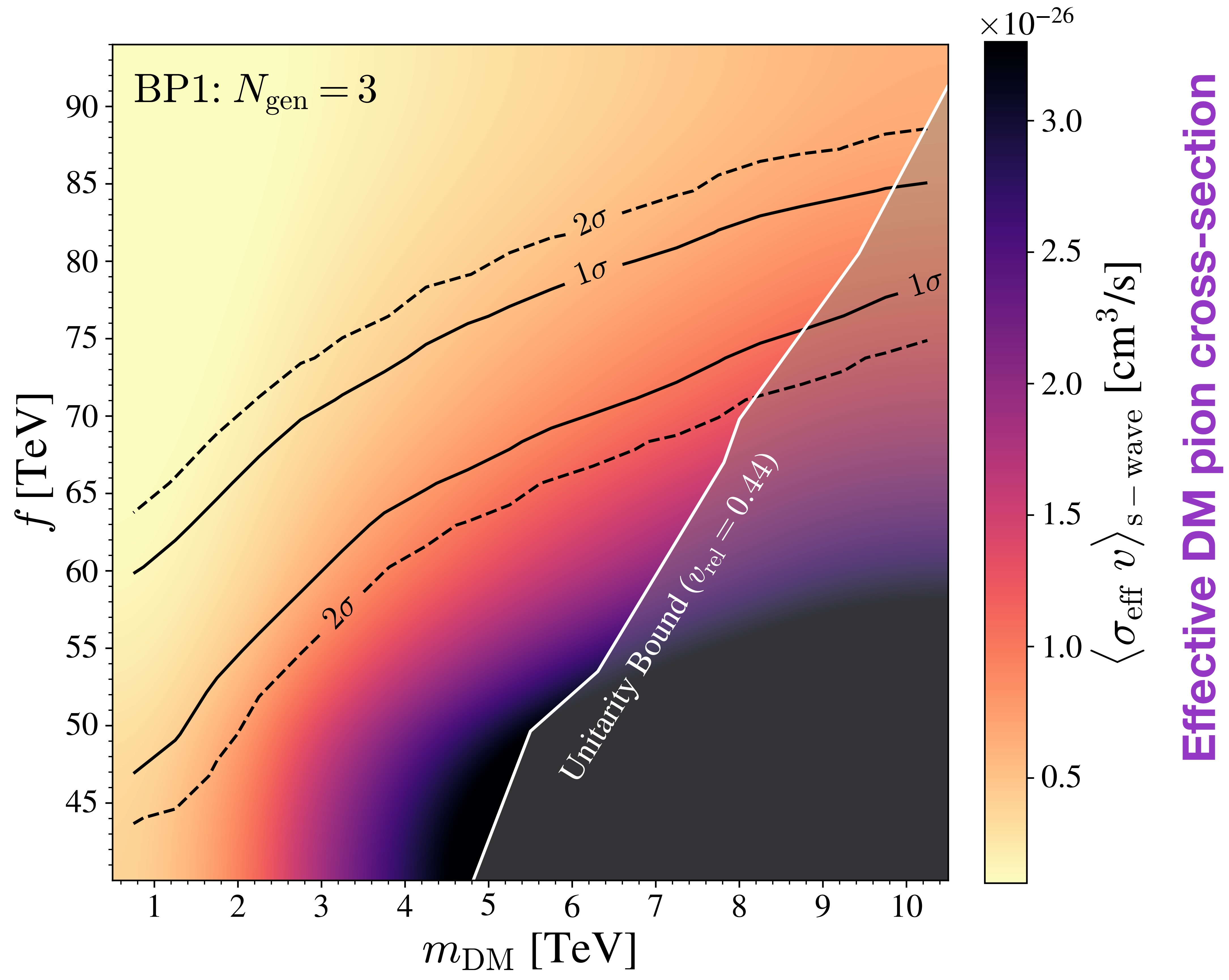
Other experimental constraints

LHC bounds

- Analogous signature to charginos
- No constraints for $m_{\mathrm{DM}} > 420\ \mathrm{GeV}$[1]
- Likely out of reach for future colliders

Indirect detection

- Might be in reach of future gamma ray observatories



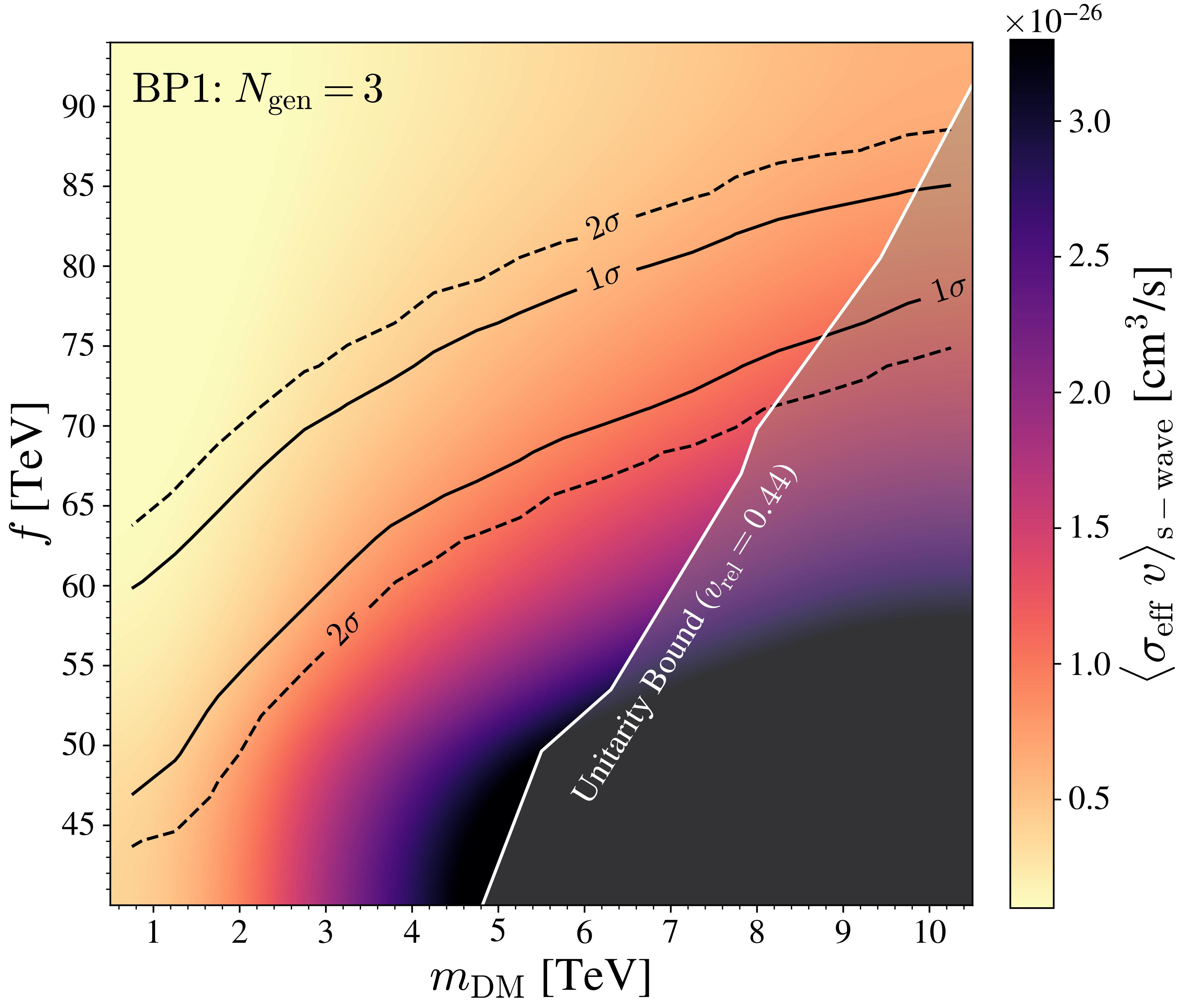
Mass of DM relic: $\chi_{1,2}$

[1] ATLAS: arXiv:1908.08215 and CMS: arXiv: 1807.07799

Main takeaway

What did this alternate cosmological history get us?

- Maintains the correct DM relic abundance
- Increases the possible mass range of DM
- Restores some freedom to WIMP models



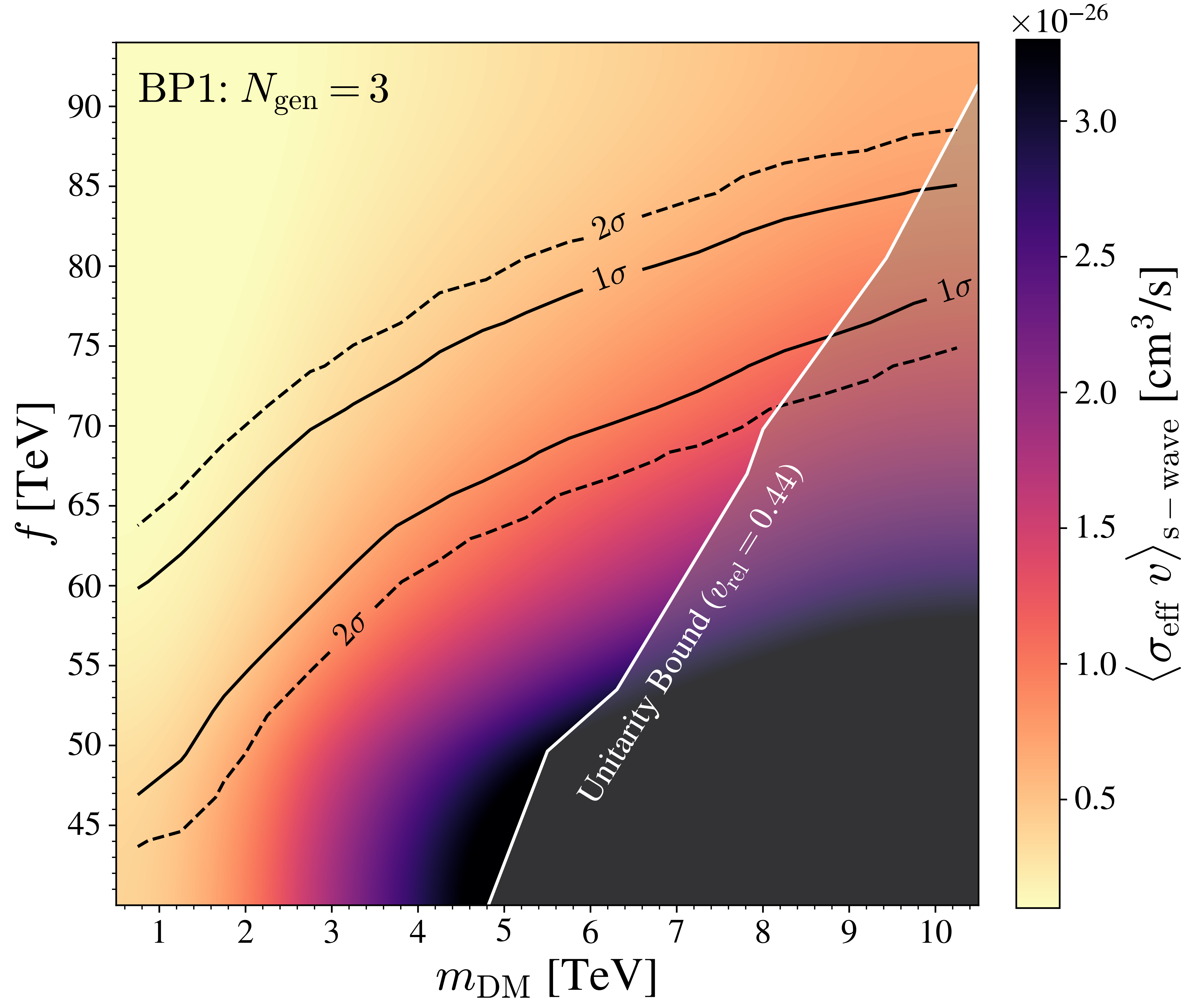
Effective DM pion cross-section

Mass of DM relic: $\chi_{1,2}$

Conclusion

- Considering alternate cosmological histories is important and can be advantageous
- Modification to cosmological history can help restore the WIMP miracle
- Not ruled out by current experiments

Questions?



Effective DM pion cross-section

Mass of DM relic: $\chi_{1,2}$

Backup Slides

Code outline

- Because of the many possible combinations of $\{a, b, c, d\}$ we perform the calculation of $\Pi_a \Pi_b \to \Pi_c\ \Pi_d$ numerically via Python

- The code calculates $\Omega_\chi h^2$ for each parameter space point (f, m_{DM}) and compares it to PDG value

- Parameter scan done with ULYSSES with a PyMultiNest back-end

GitHub: jnhoward/SU2LDM_public
DOI: 10.5281/zenodo.5965537