Bouncing Dark Matter

2208.08453 with Lucas Pütter, Josh Ruderman, Bibhushan Shakya

(2006.08453 with Andrey Katz and Bibhushan Shakya)

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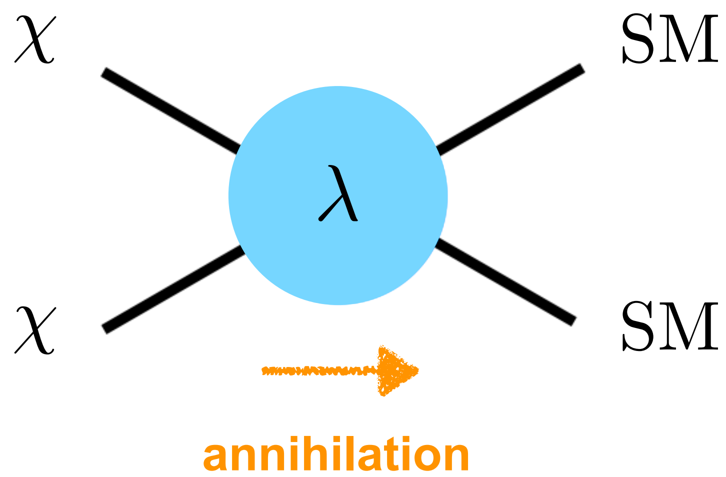
KIAS, 13/10/2022

Thermal freeze-out

A compelling picture for the origin of dark matter:

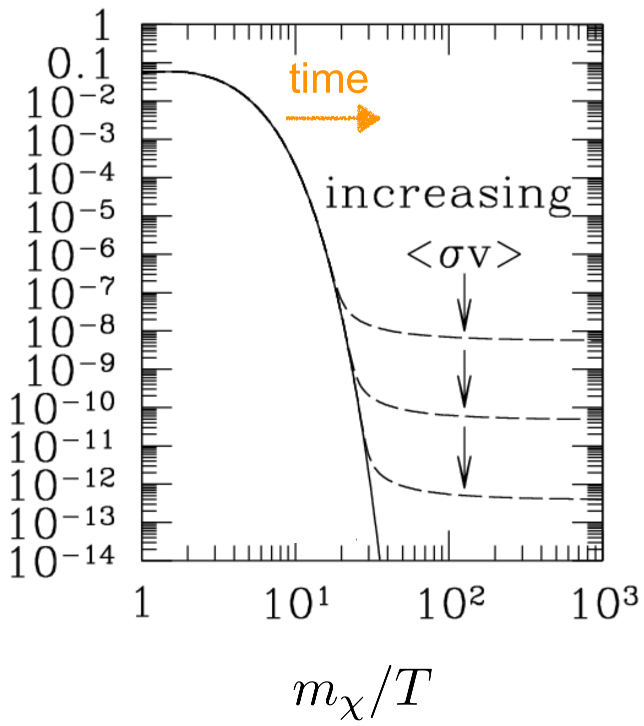


$$\Omega_\chi h^2 \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{\pi m_\chi^2}{\lambda^2} \quad \Rightarrow \quad \frac{\Omega_\chi h^2}{0.1} \sim \left(\frac{0.1}{\lambda}\right)^2 \left(\frac{m_\chi}{100\ \mathrm{GeV}}\right)^2$$

"WIMP miracle"

Thermal freeze-out

$$Y_\chi = \frac{n_\chi}{s}$$



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$$\frac{\Omega_\chi h^2}{0.1} \sim \left(\frac{0.1}{\lambda}\right)^2 \left(\frac{m_\chi}{100\ \mathrm{GeV}}\right)^2$$

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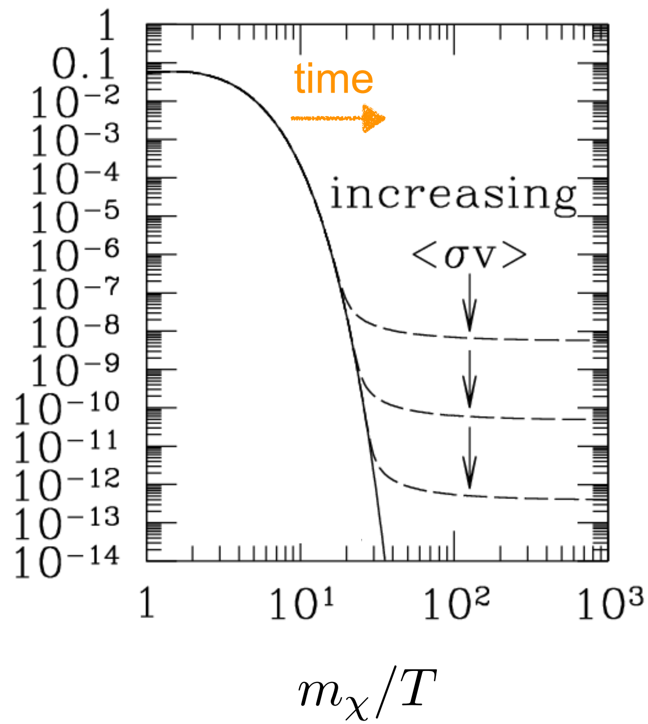
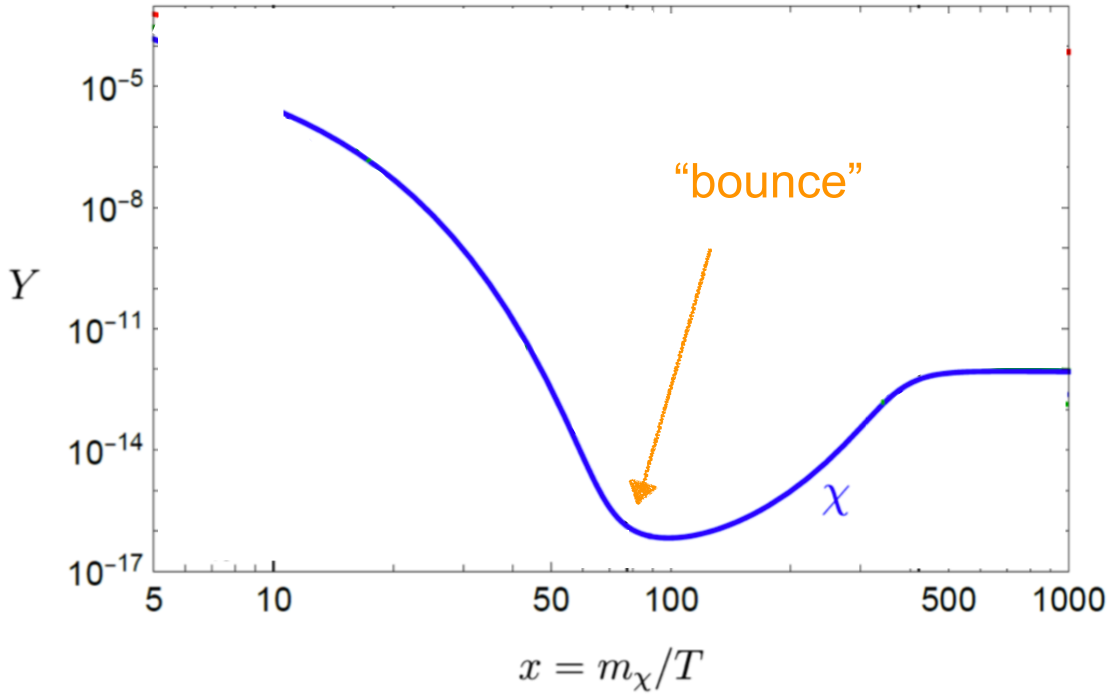


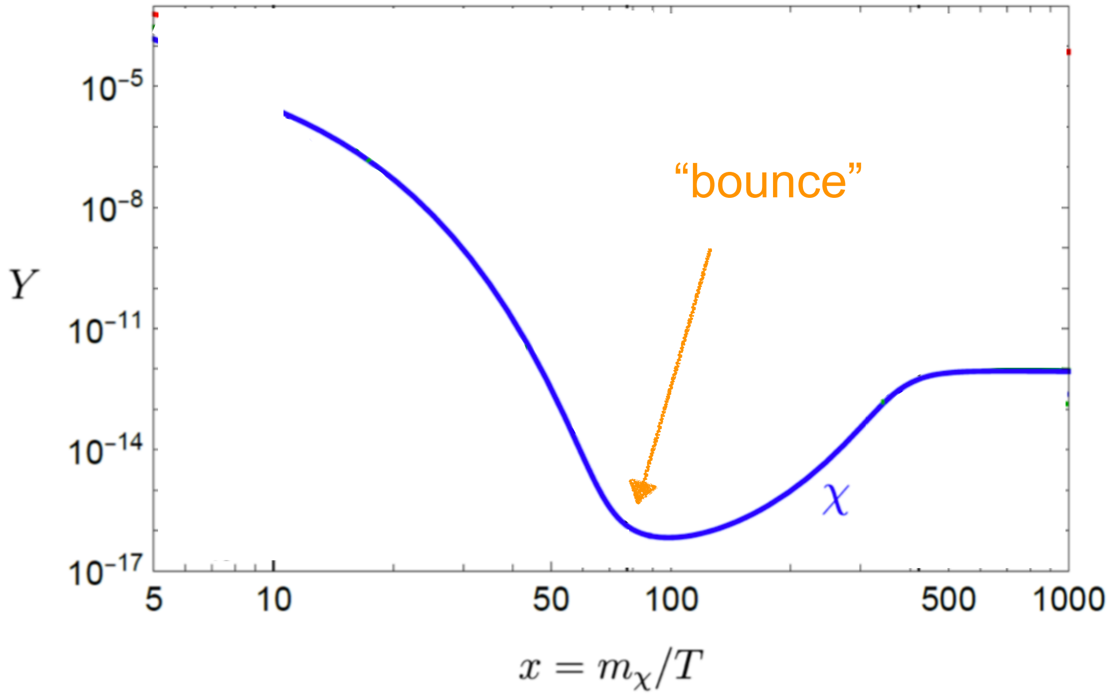
- An extremely well-studied scenario, with many interesting variations
- In all cases, DM abundance decreases exponentially along equilibrium curve, then becomes constant (freezes out)

Bouncing Dark Matter



Dark matter abundance transitions from exponentially falling to exponentially rising curve, while remaining in equilibrium

Bouncing Dark Matter

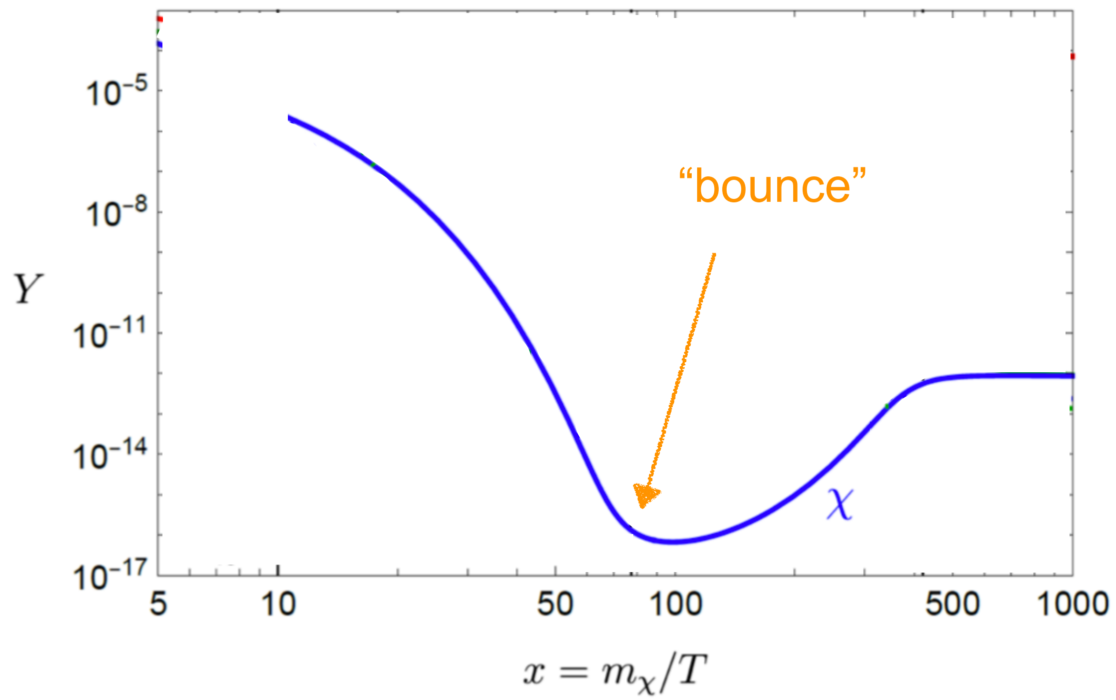


First observed in [Katz, Salvioni, Shakya 2006.15148] for metastable dark states

Then for DM in [Ho, Ko, Lu 2201.06856] and [Ho, 2207.13373]

(see also [Griest, Kolb 1989] in different context; very recent reappraisal in [Bai, Lu, Orlofsky 2208.12290])

Bouncing Dark Matter



In this talk:

- Conditions for bounce to happen
- Explicit realizations in (simplified) models
- Implications for phenomenology

Conditions for the bounce

The bounce takes place in scenarios where DM is accompanied by other states

Track evolution of number densities via chemical potentials μ_i

$$n_i \approx e^{\mu_i/T} n_i^{\rm eq} \qquad\qquad n_i^{\rm eq} = g_i \left(\frac{m_i T}{2\pi}\right)^{3/2} e^{-m_i/T}$$

If a reaction $AB \leftrightarrow CD$ is rapid compared to Hubble,

$$\mu_A + \mu_B = \mu_C + \mu_D$$

This holds until $\Gamma < H$

Conditions for the bounce

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- If DM shares chemical potential with a lighter species A, DM abundance keeps falling exponentially

$$\mu_\chi = \mu_A \quad \longrightarrow \quad n_\chi = \frac{n_\chi^{\rm eq}}{n_A^{\rm eq}} n_A$$

$$\frac{n_\chi^{\rm eq}}{n_A^{\rm eq}} \sim e^{-(m_\chi - m_A)/T}$$

First condition: DM chemical potential needs to deviate from other species'

Conditions for the bounce: summary

The bounce takes place in scenarios where DM is accompanied by other states

Track evolution of number densities via chemical potentials μ_i

$$n_i \approx e^{\mu_i/T} n_i^{\text{eq}} \qquad\qquad n_i^{\text{eq}} = g_i \left(\frac{m_i T}{2\pi}\right)^{3/2} e^{-m_i/T}$$

(1) DM chemical potential needs to deviate from other species'

$$\mu_\chi \neq \mu_A$$

(2) DM chemical potential needs to rise sufficiently fast

$$\mu_\chi(x) + x\frac{d\mu_\chi(x)}{dx} > m_\chi\left(1 - \frac{3}{2x}\right)$$

A simplified model

An example model

Dark sector containing 3 scalars

χ	ϕ_2	ϕ_1
dark matter	possibly stable	long-lived

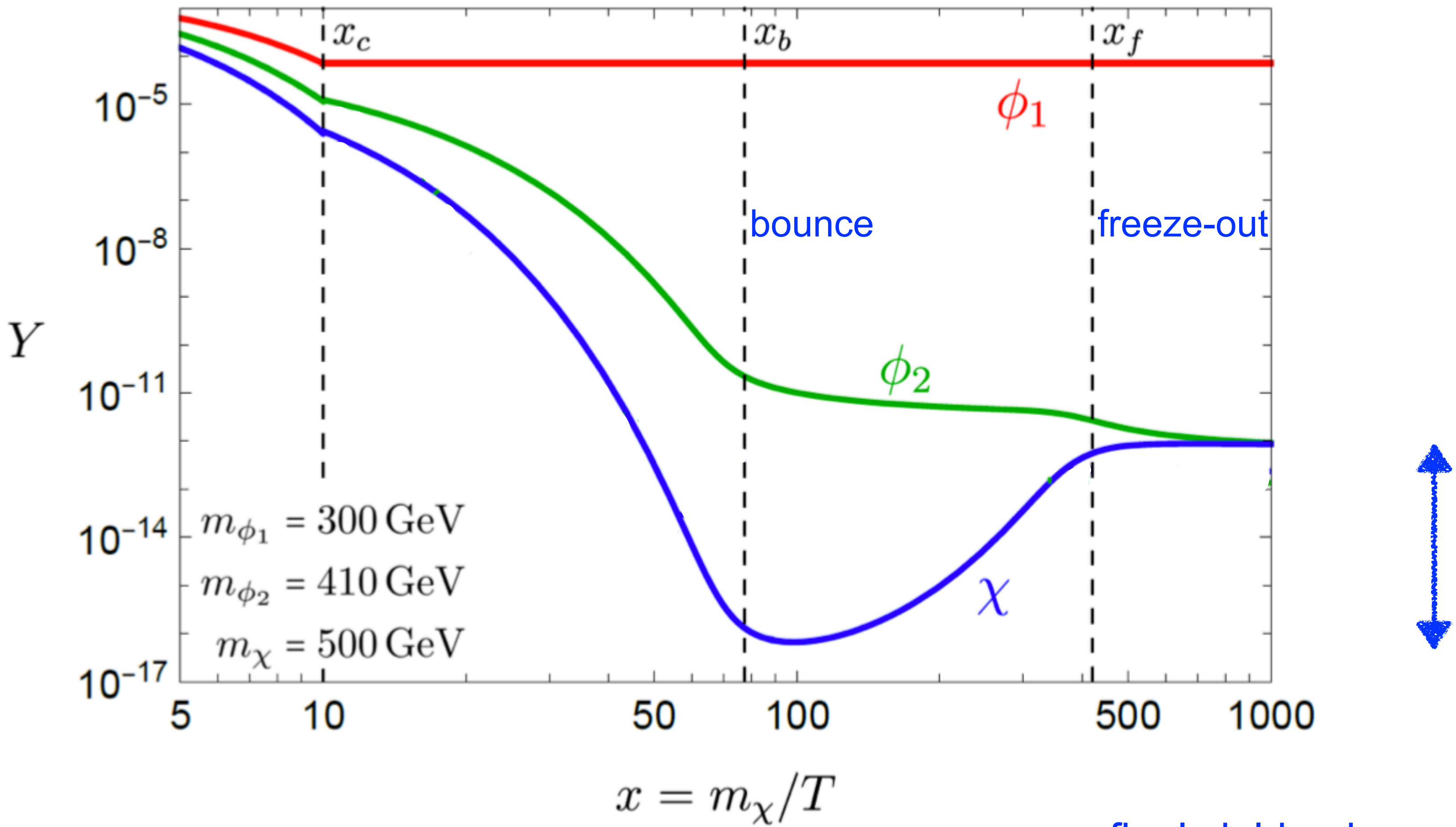
$$m_\chi > m_{\phi_2} > m_{\phi_1}$$

$$-\mathcal{L} \supset \lambda_{\chi 1}\chi^2\phi_1^2 + \lambda_{\chi 2}\chi^2\phi_2^2 + \lambda_{12}\phi_1^2\phi_2^2 + \lambda\phi_2^2\chi\phi_1$$

$$\chi\phi_1 \leftrightarrow \phi_2\phi_2$$

assume $2m_{\phi_2} > m_\chi + m_{\phi_1}$

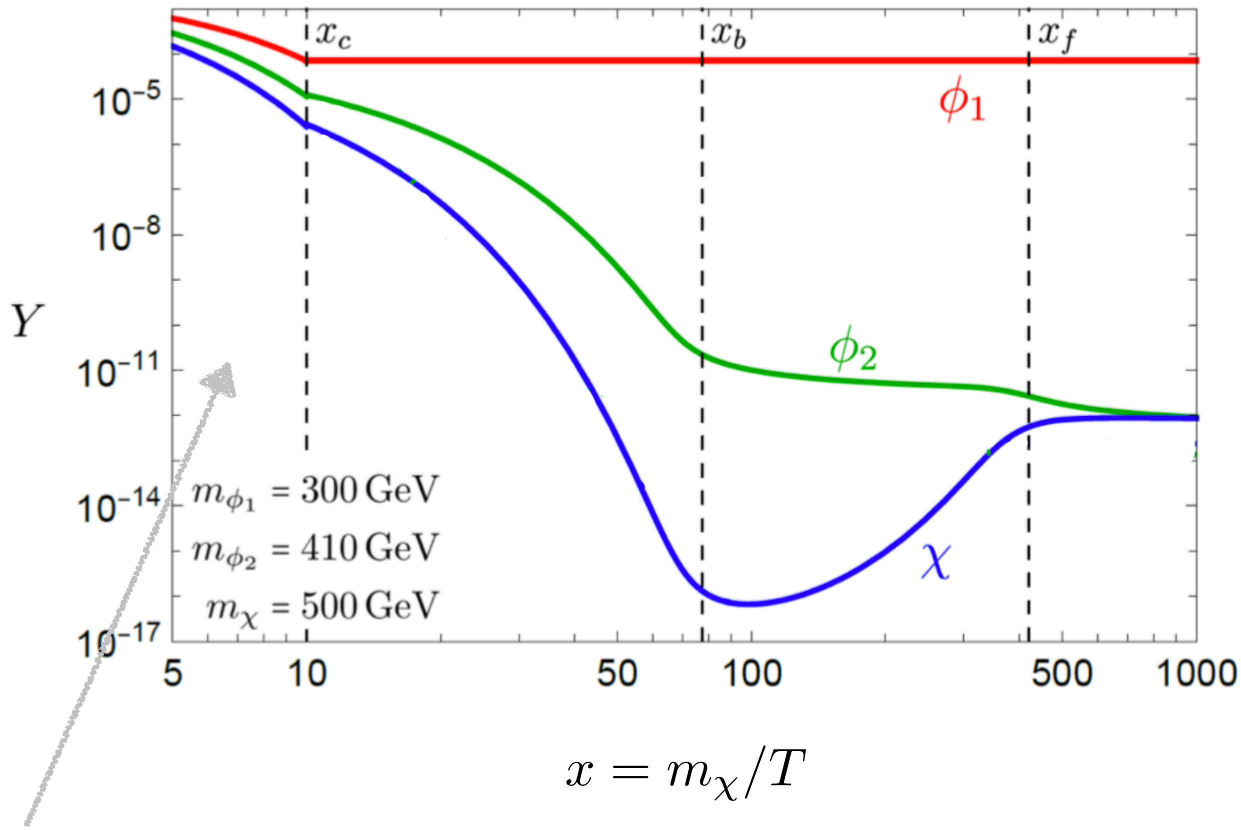
The bounce at work



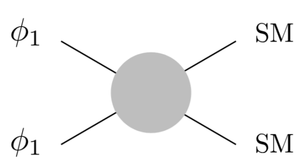
final yield enhanced
by several orders of magnitude

(here, kinetic equilibrium between dark and SM sectors is assumed throughout)

Cosmological history



Equilibrium phase

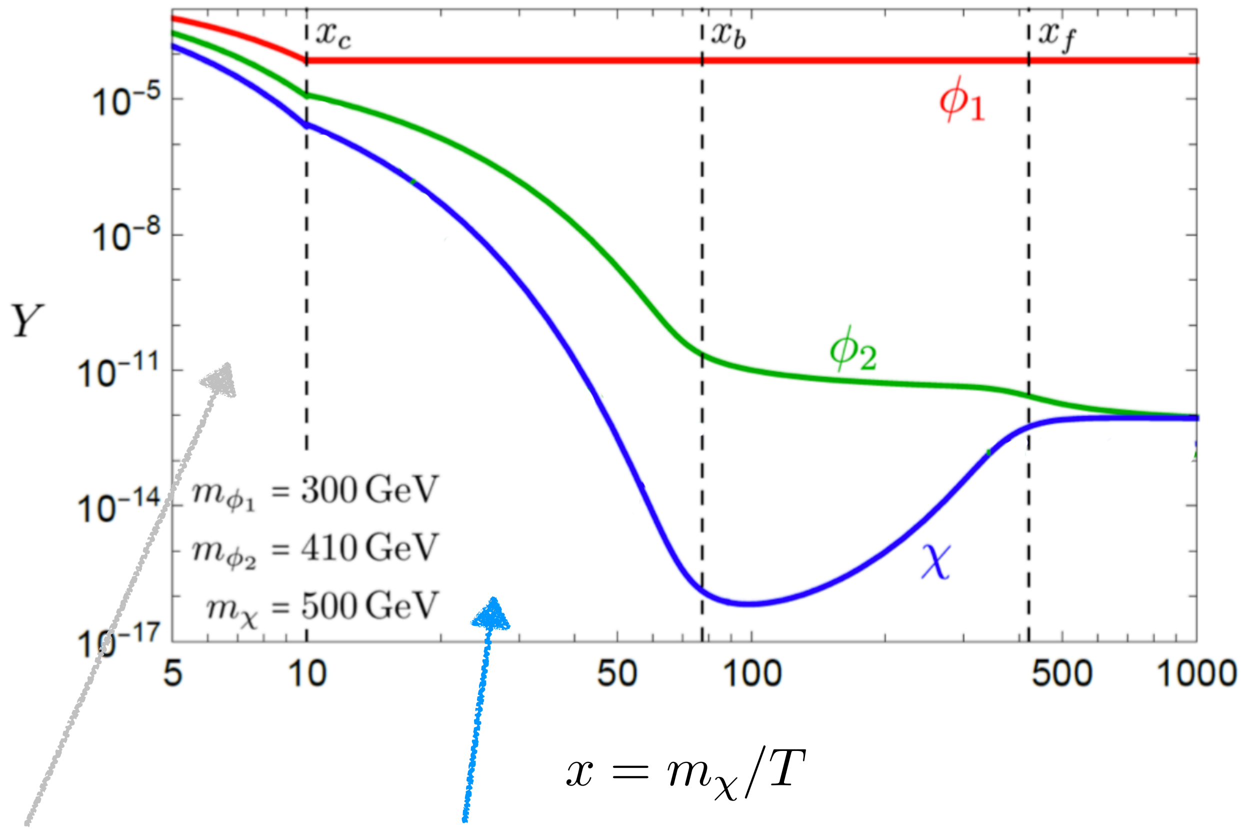


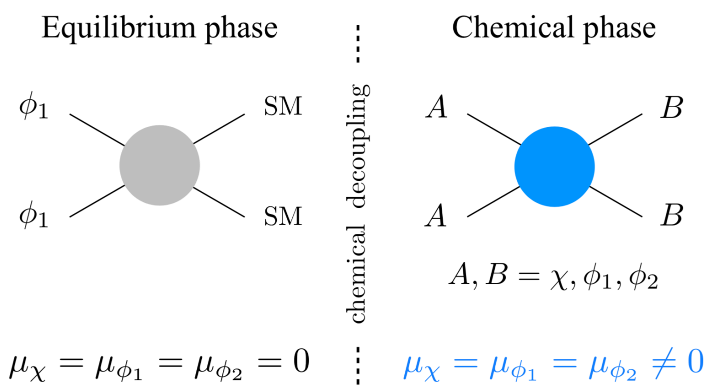
dark sector and SM are kept in thermal equilibrium

by portal interactions

$$\mu_\chi = \mu_{\phi_1} = \mu_{\phi_2} = 0$$

Cosmological history

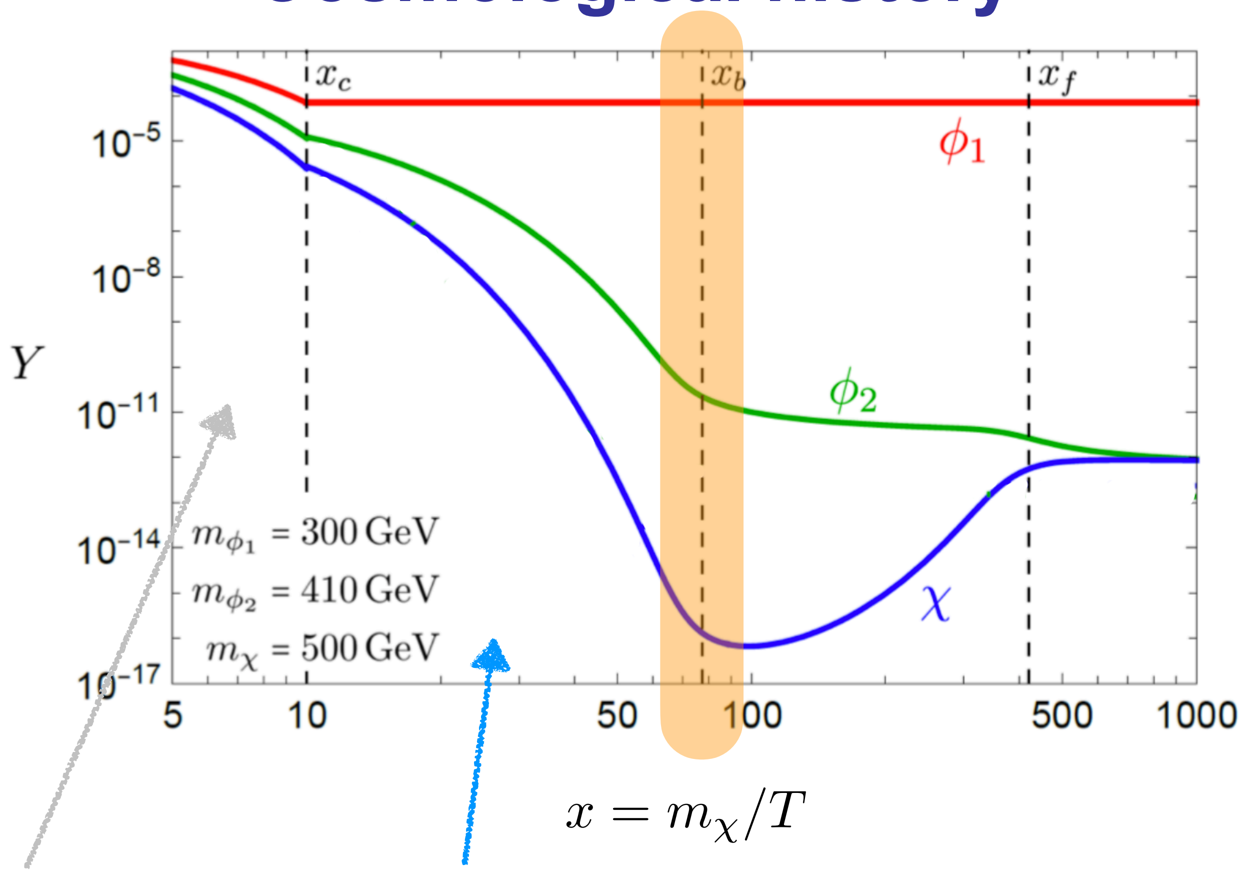


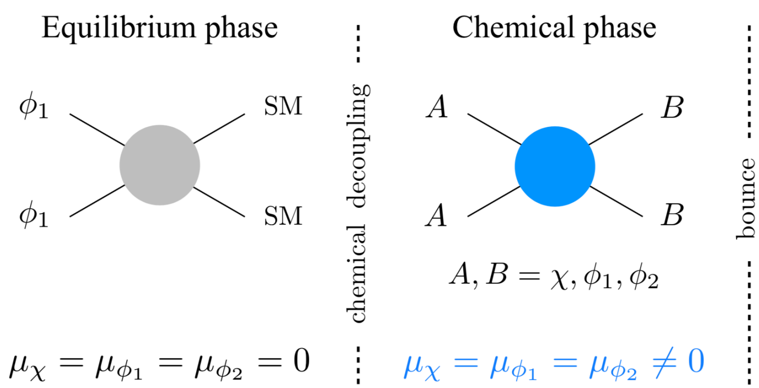


total comoving number density of dark sector is conserved

shifted equilibrium curves

Cosmological history

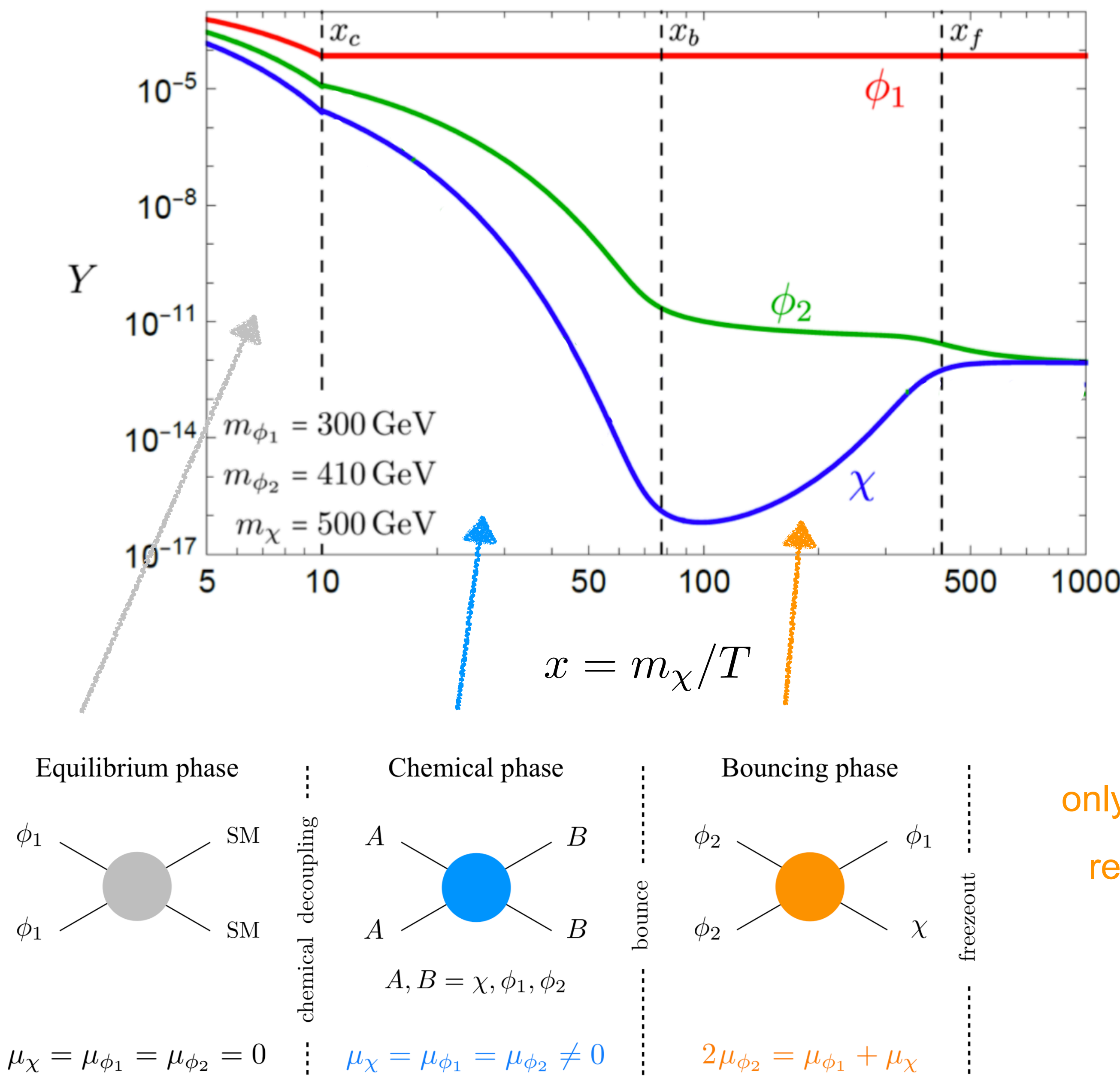




$AA \leftrightarrow BB$ and $\chi\phi_2 \leftrightarrow \phi_1\phi_2$
decouple

bounce

Cosmological history



only $\phi_2 \phi_2 \leftrightarrow \chi \phi_1$

remains active

bouncing phase

Cosmological history

Recall that $2m_{\phi_2} > m_\chi + m_{\phi_1}$

Bouncing phase controlled by

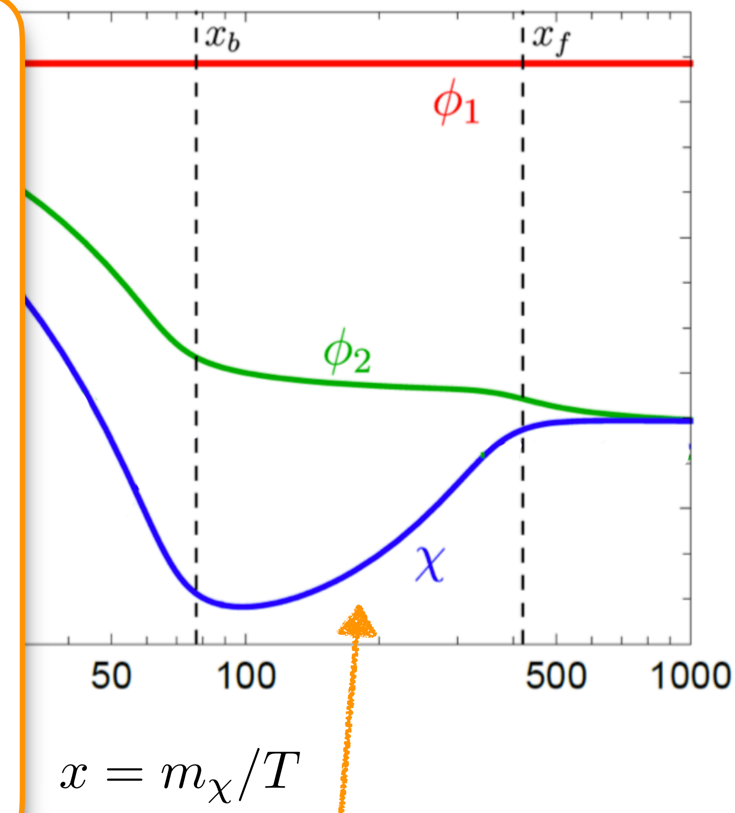
$$\phi_2\phi_2 \leftrightarrow \chi\phi_1$$

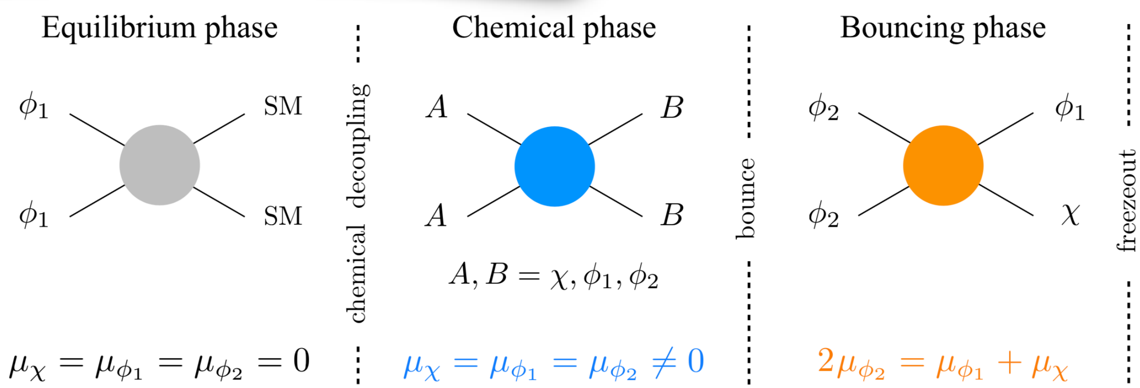
Forward process is kinematically allowed
Backward process needs thermal support

When T drops below mass splitting,
$\chi\phi_1$ is populated preferentially

↓

transition to **exponentially rising** curve





only $\phi_2\phi_2 \leftrightarrow \chi\phi_1$

remains active

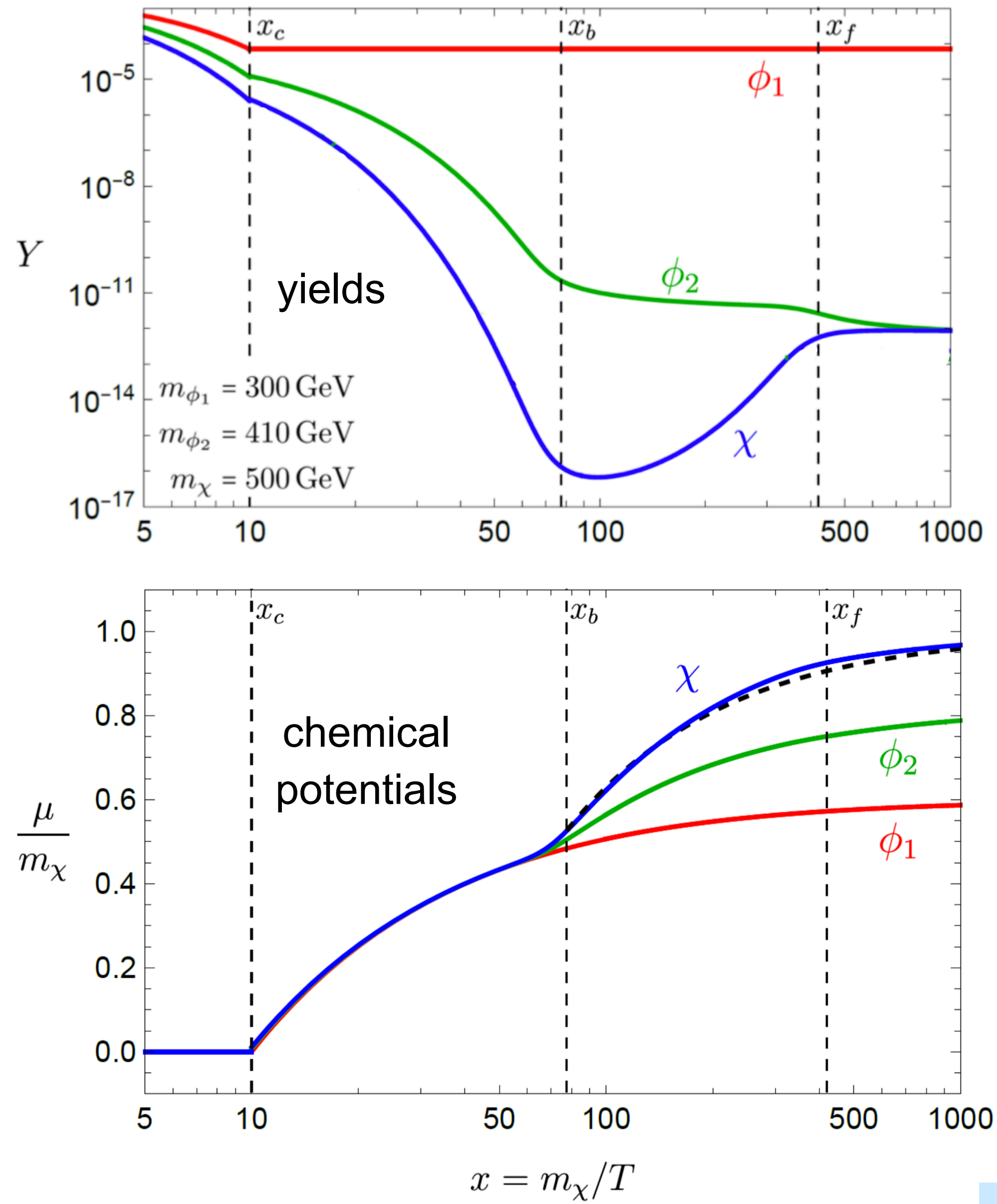
bouncing phase

The chemical potentials

$$\mu_\chi = \mu_{\phi_1} = \mu_{\phi_2}$$

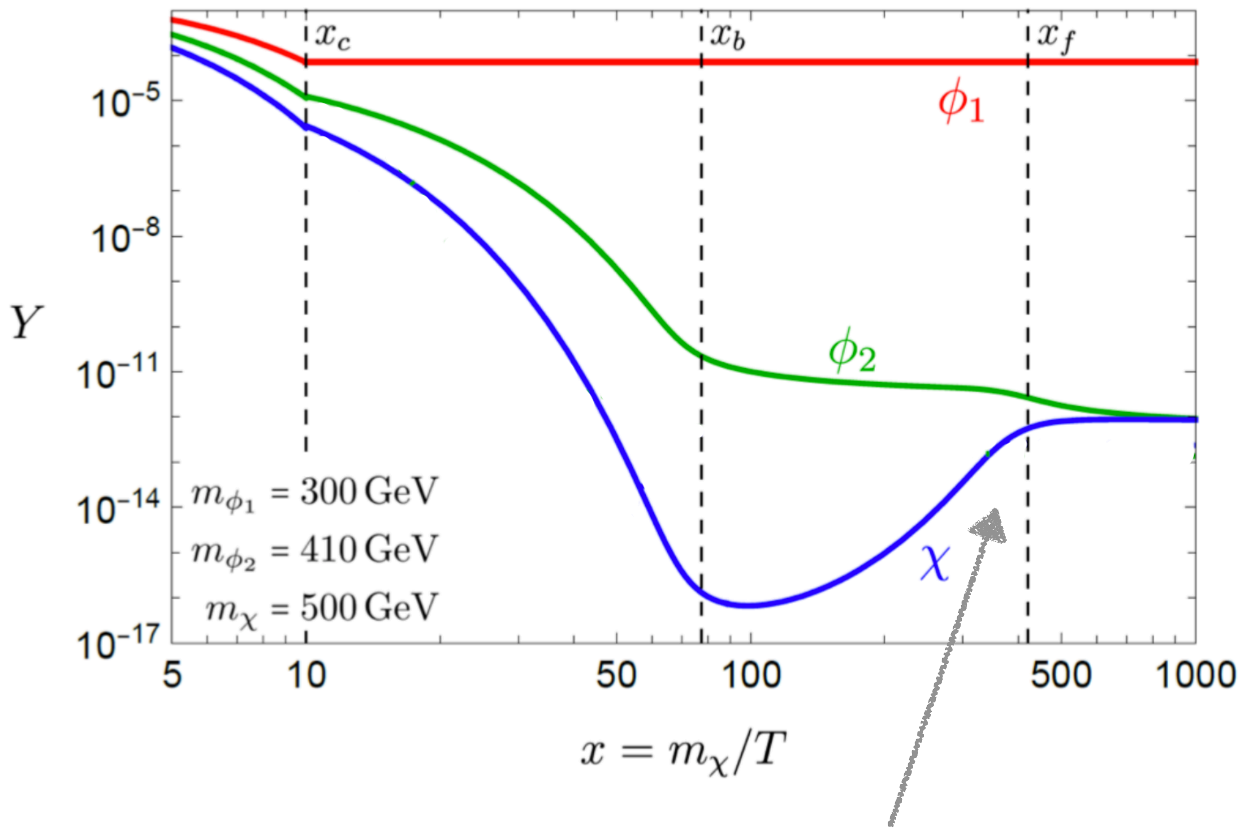
bounce

$$\mu_\chi + \mu_{\phi_1} = 2\mu_{\phi_2}$$



dashed black: constant Y_χ after bounce

Cosmological history



Analytical solution

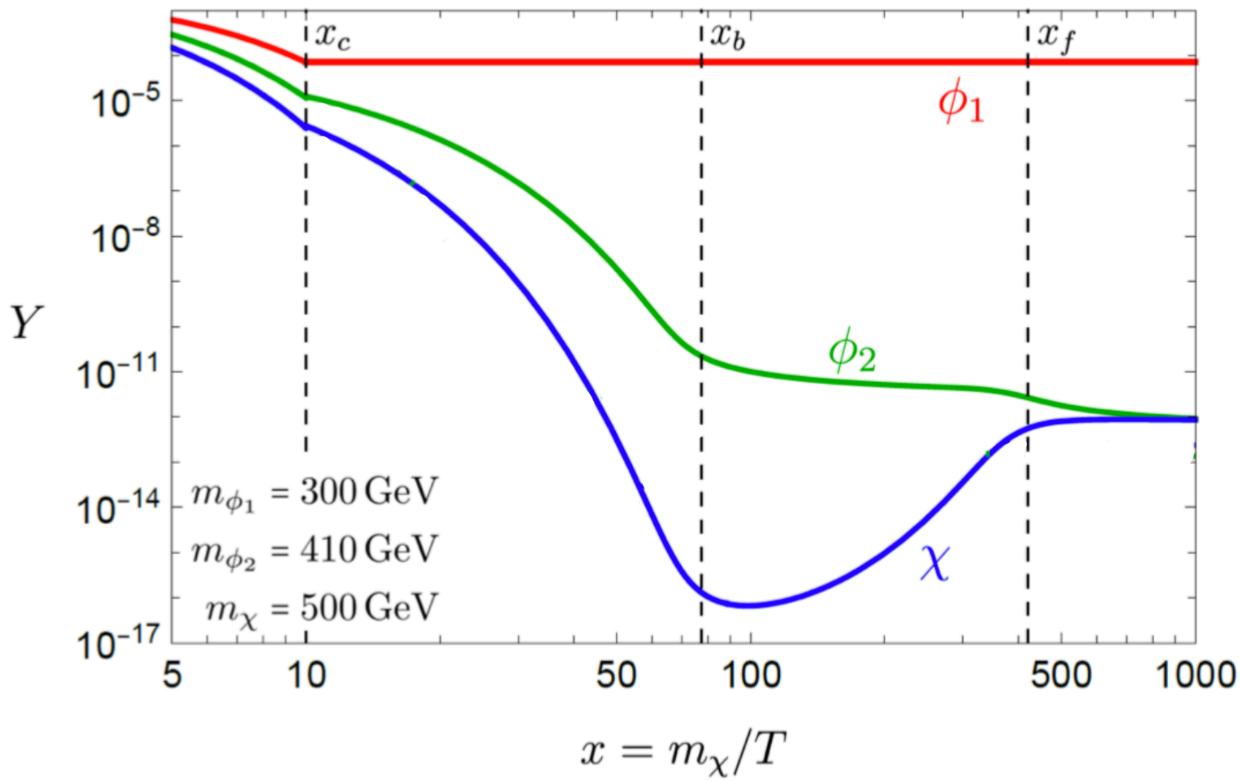
$$Y_\chi \overset{x\to\infty}{\longrightarrow} \frac{1}{2}Y_{\phi_2}^{(b)} + Y_\chi^{(b)}$$

In practice, once $Y_\chi \sim Y_{\phi_2}$

other processes recouple, such as $\chi\phi_2 \to \phi_1\phi_2$

Freezeout abundances are comparable

Cosmological history



- ϕ_2 may be stable (2-component DM) or decay before BBN
- ϕ_1 freezes out with very large abundance, **must** decay before BBN

$$\tau_{\phi_1} \lesssim 1\ \mathrm{s}$$

Impact on phenomenology

Signals of dark matter annihilation (indirect detection):

Canonical thermal target is $\langle \sigma v \rangle_{\rm canonical} \simeq 2 \times 10^{-26}\ {\rm cm^3\, s^{-1}}$

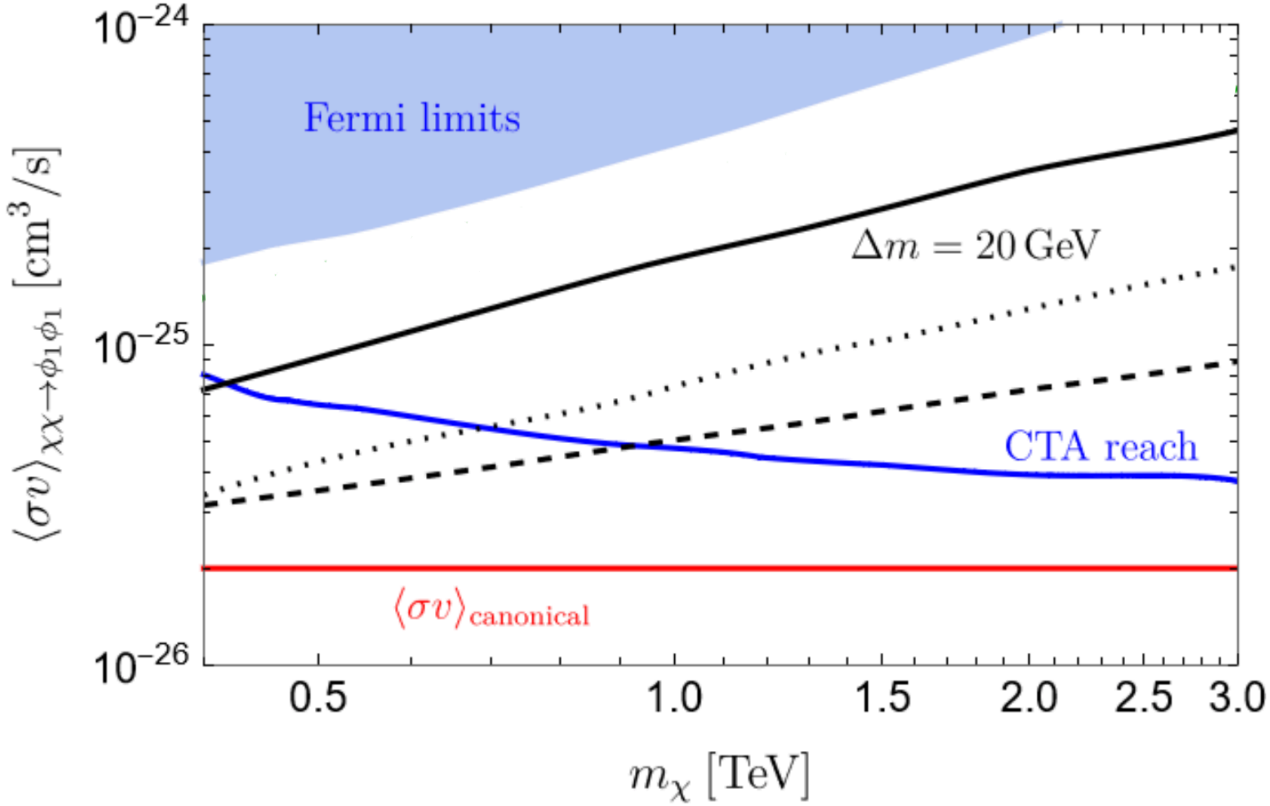
Here, cross sections for $\chi\chi \to \phi_i \phi_i$ can be larger than $\langle \sigma v \rangle_{\rm canonical}$

In standard scenarios, would lead to a too-small freezeout abundance.

But the bounce compensates for this

→ Bouncing dark matter has improved prospects of discovery at indirect detection experiments

Indirect detection



$$m_{\phi_1} = \frac{m_\chi}{2}$$

$$\Delta m \equiv m_{\phi_2} - \frac{m_\chi + m_{\phi_1}}{2}$$

$$\chi\chi \to \phi_1\phi_1$$

$$\phi_1 \to WW$$

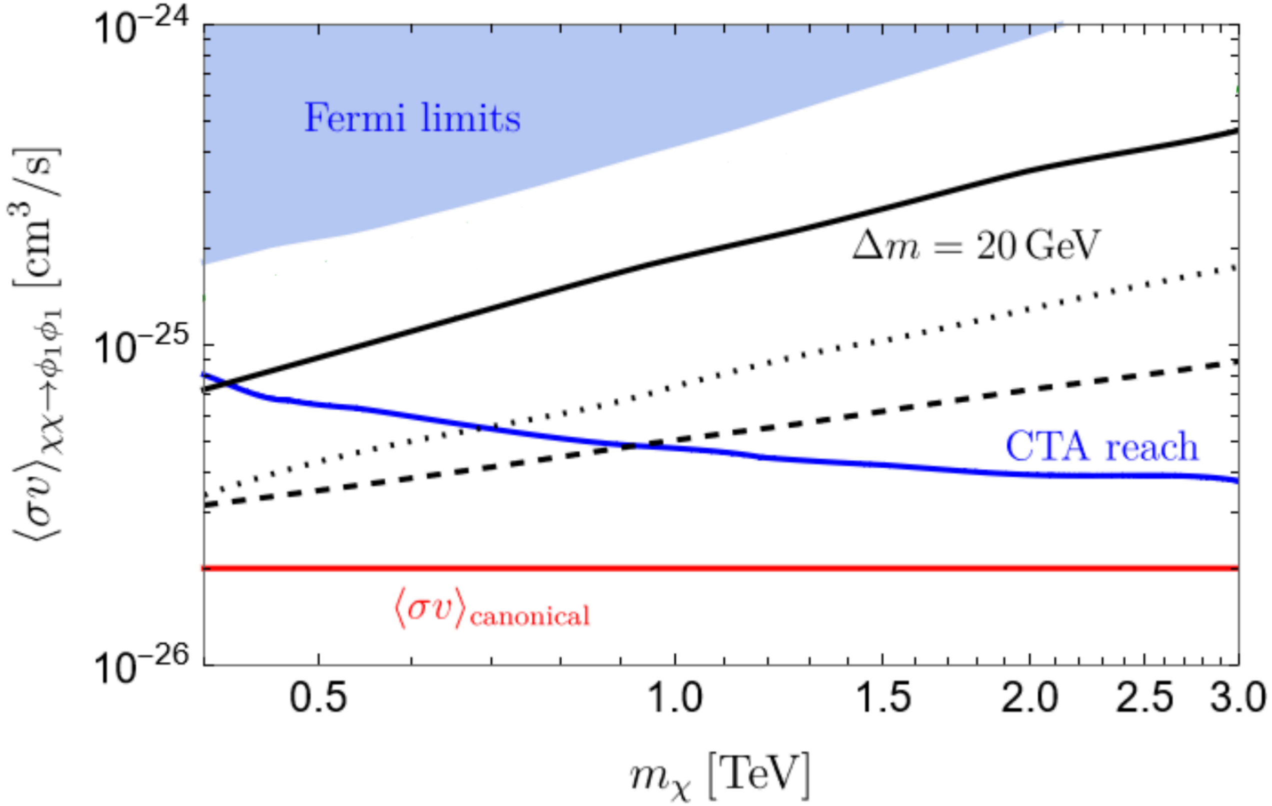
dashed: early kinetic decoupling

dotted: intermediate kinetic decoupling (Higgs portal)

$$\sigma_{ABCD} \equiv \langle\sigma v\rangle_{AB\to CD}$$

$$40\,\sigma_{\chi\chi\phi_2\phi_2} = 200\,\sigma_{\phi_2\phi_2\phi_1\phi_1} = \sigma_{\chi\chi\phi_1\phi_1} = 4\,\sigma_{\phi_2\phi_2\chi\phi_1}$$

Indirect detection



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$$\chi\chi \to \phi_1\phi_1$$

$$\phi_1 \to WW$$

CTA unable to reach canonical thermal target for this cascade process, but will probe bouncing dark matter!

Back to the model

The scalars are charged under a $SU(2) \times U(1) \times Z_2$ symmetry

$$\chi \sim \mathbf{3}_0 \qquad \phi_2 \sim \mathbf{2}_{\pm 1} \qquad \phi_1 \sim \mathbf{1}_0$$

$$-\mathcal{L} \supset \lambda_{\chi 1} \mathrm{Tr}(\chi^2)\phi_1^2 + \lambda_{\chi 2} \mathrm{Tr}(\chi^2)|\phi_2|^2 + \lambda_{12}\phi_1^2|\phi_2|^2 + \lambda \phi_2^\dagger \chi \phi_2 \phi_1 \,, \qquad \chi \equiv \sigma^a \chi^a \,,$$

- All other number-changing quartics automatically forbidden
- Both χ and ϕ_2 are stabilized ($2m_{\phi_2} > m_\chi + m_{\phi_1} > m_\chi$)
- ϕ_1, being a singlet, can easily decay before BBN

Parameter space

For instance, assume the following interactions of ϕ_1 with the SM

$$\mathcal{L} = -\lambda_v \phi_1^2 \mathcal{H}^\dagger \mathcal{H} + \frac{\bar{g}\phi_1}{\Lambda} W^a_{\mu\nu} W^{a\,\mu\nu}$$

Higgs portal keeps thermal eq at early times

small Z_2 breaking, mediates ϕ_1 decay

@ tree-level to transverse modes

@ one loop, tadpole for ϕ_1

$$\langle \phi_1 \rangle \sim \frac{\bar{g}\Lambda^3}{(4\pi)^2 m_{\phi_1}^2}$$

decay to longitudinal modes

→ Require $10^{-6} \lesssim \tau_{\phi_1}/\mathrm{s} \lesssim 1$ (after bounce but before BBN)

Parameter space

For instance, assume the following interactions of ϕ_1 with the SM

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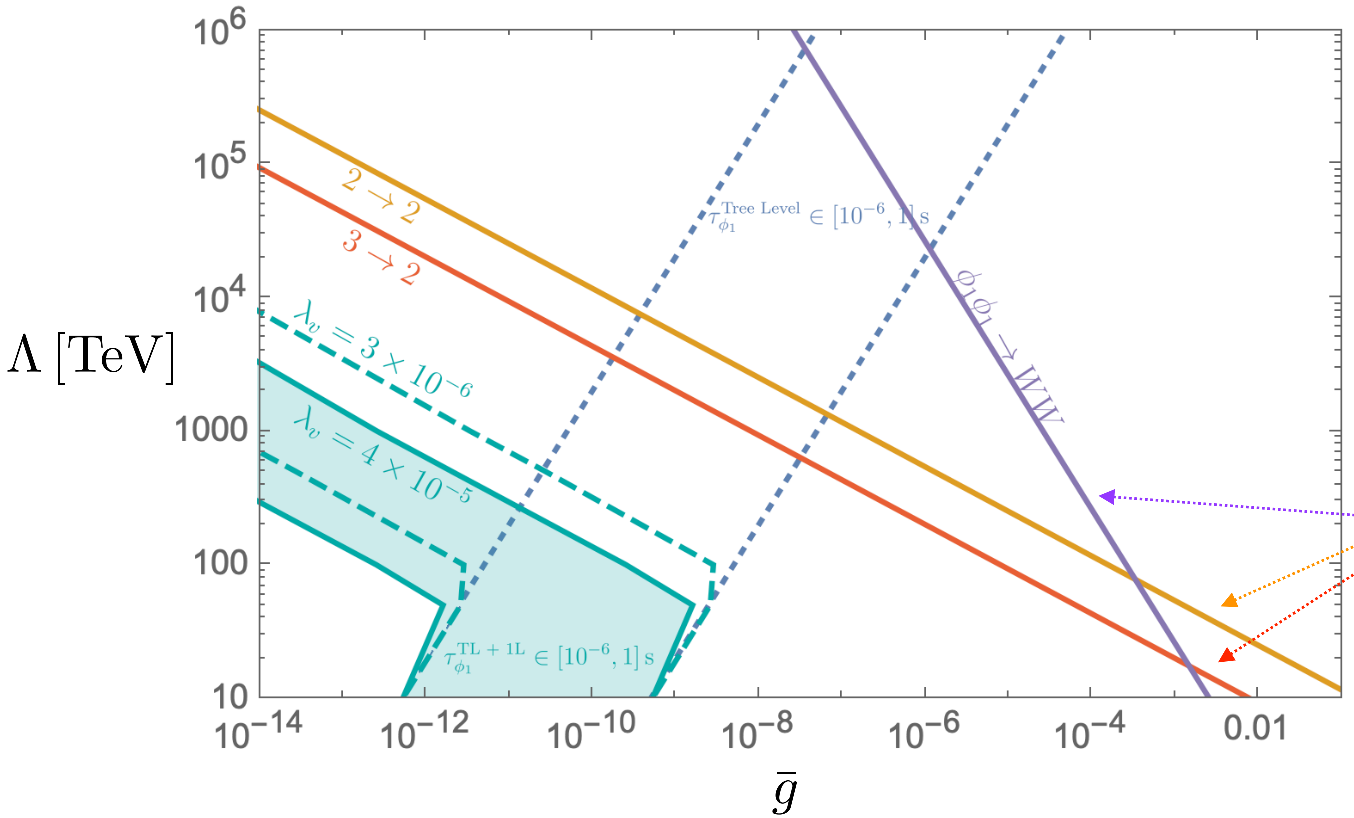

@ one loop

$$\langle \phi_1 \rangle \sim \frac{\bar{g}\Lambda^3}{(4\pi)^2 m_{\phi_1}^2}$$

below the lines, trilinear couplings generated by $\langle \phi_1 \rangle$ do not impact bounce

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Higgs portal keeps thermal eq at early times

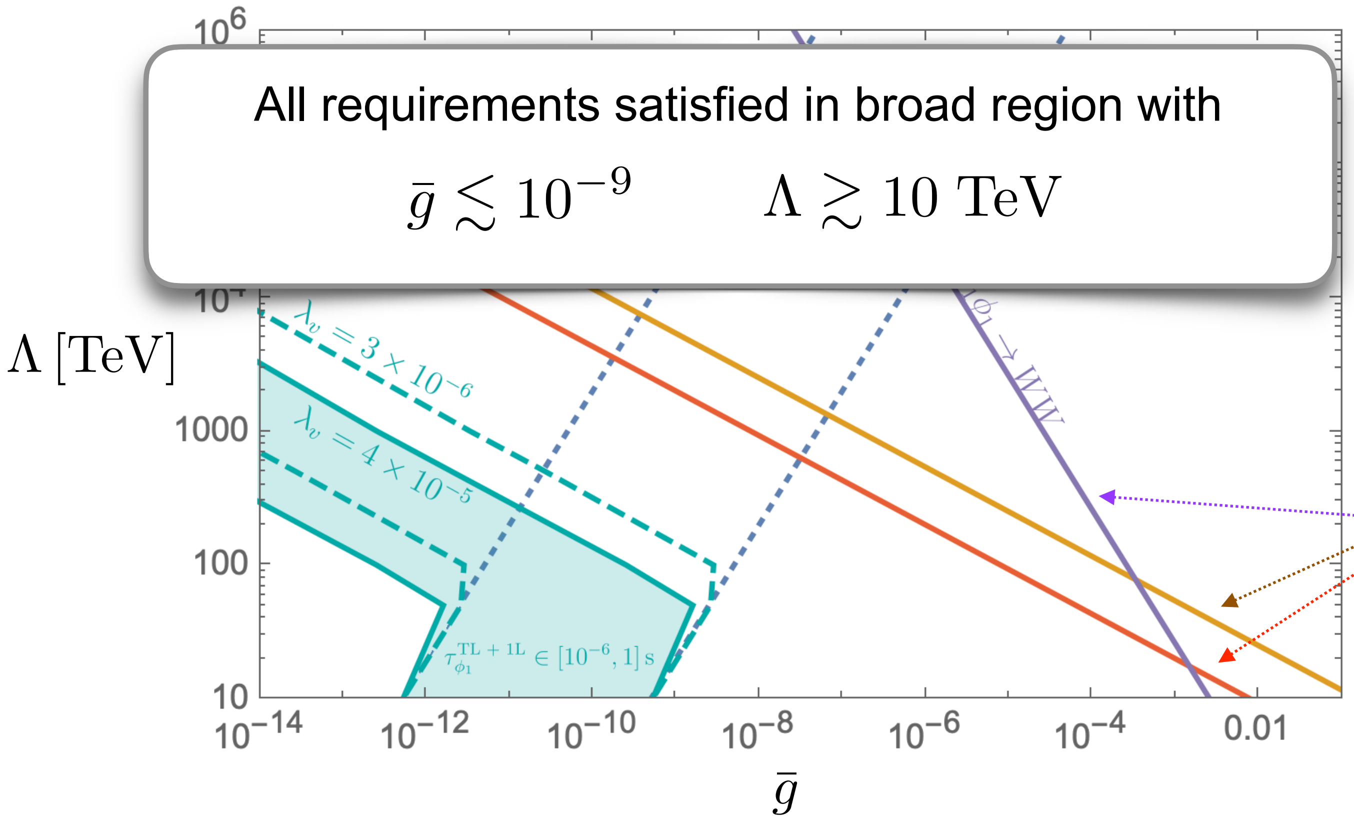
small Z_2 breaking, mediates ϕ_1 decay

All requirements satisfied in broad region with

$$\bar{g} \lesssim 10^{-9} \qquad \Lambda \gtrsim 10\ \mathrm{TeV}$$

@ one loop

$$\langle \phi_1 \rangle \sim \frac{\bar{g}\Lambda^3}{(4\pi)^2 m_{\phi_1}^2}$$



below the lines, trilinear couplings generated by $\langle \phi_1 \rangle$ do not impact bounce

Other bouncing scenarios

Co-annihilation with decaying partner

Same setup as before:

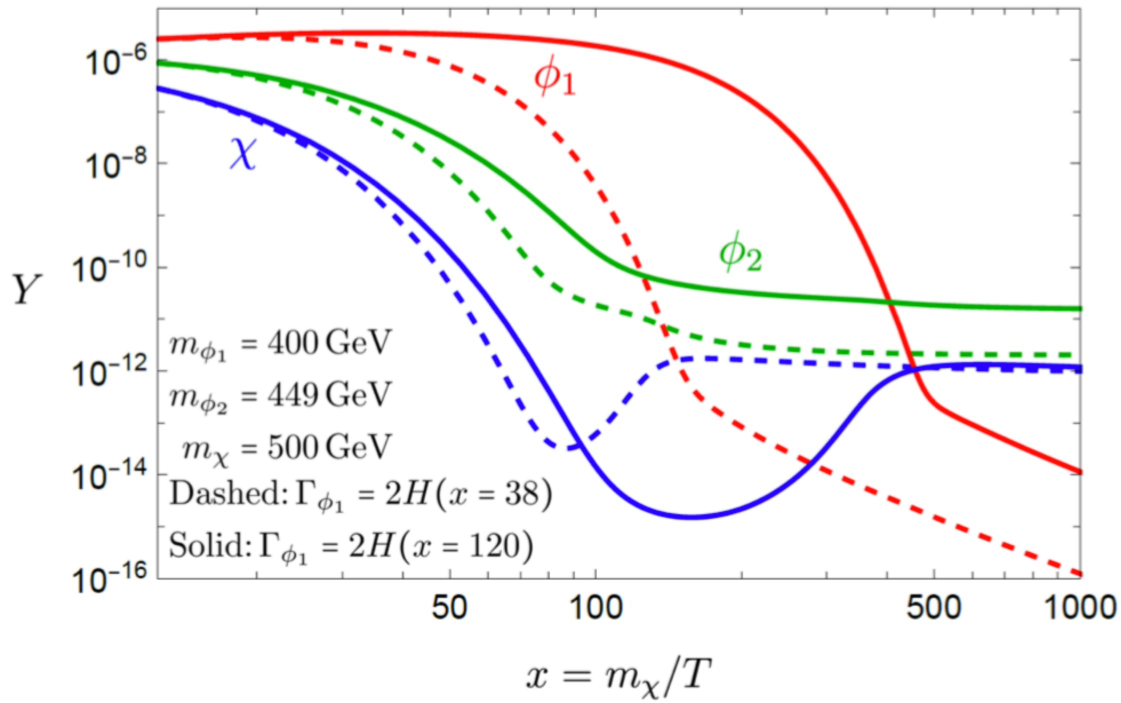
χ	ϕ_2	ϕ_1
dark matter	possibly stable	long-lived

$$-\mathcal{L} \supset \lambda_{\chi 1}\chi^2\phi_1^2 + \lambda_{\chi 2}\chi^2\phi_2^2 + \lambda_{12}\phi_1^2\phi_2^2 + \lambda\phi_2^2\chi\phi_1$$

but two important modifications:

1. Reversed mass condition $2m_{\phi_2} \lesssim m_\chi + m_{\phi_1}$
2. ϕ_1 decays around the time of χ freezeout

Co-annihilation with decaying partner



$$2m_{\phi_2} \lesssim m_\chi + m_{\phi_1}$$

$2\mu_{\phi_2} = \mu_\chi + \mu_{\phi_1}$ still holds, but now μ_{ϕ_1} decreases as ϕ_1 is decaying

→ To compensate, μ_{ϕ_2} decreases and μ_χ increases

$\phi_2\phi_2 \to \chi\phi_1$ wins, despite requiring thermal support

$3 \leftrightarrow 2$ process

A setup with only 2 states:

$$\chi \qquad\qquad\qquad \phi$$

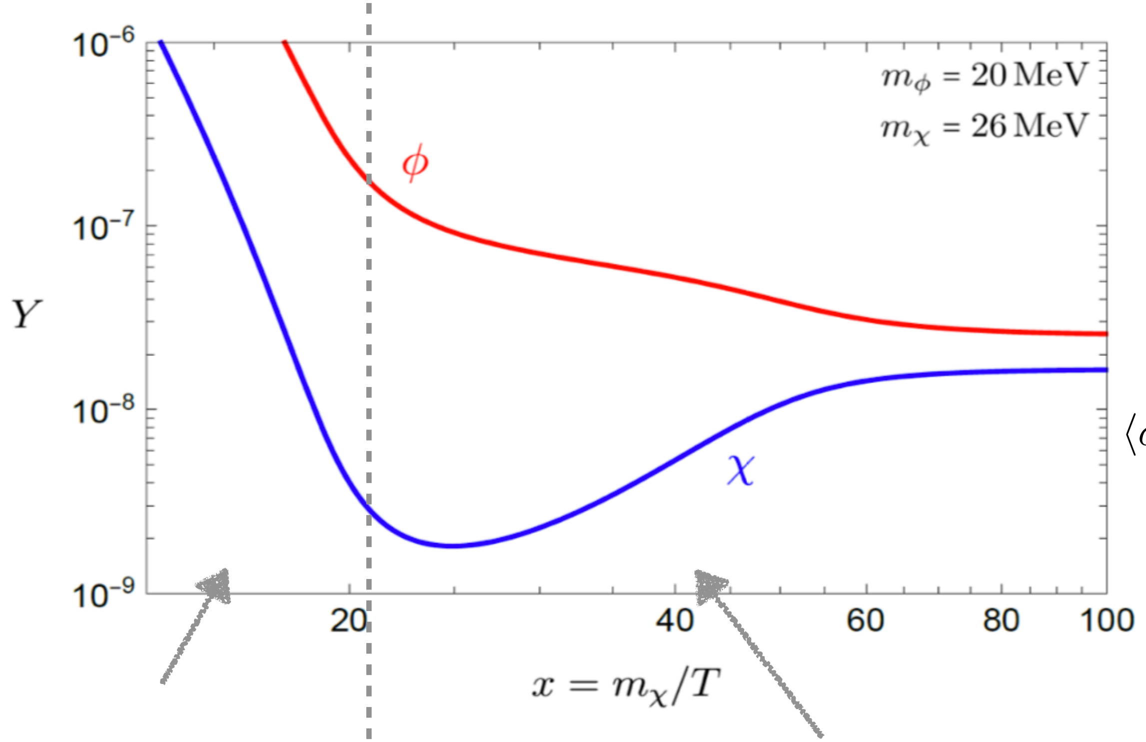
dark matter

Masses: $m_\chi > m_\phi$ but $2m_\chi < 3m_\phi$

Interactions: only $\chi^2\phi^3$

$3 \leftrightarrow 2$ process

A setup with only 2 states:



$$2m_\chi < 3m_\phi$$

$$\langle \sigma v^2 \rangle_{\phi\phi\phi\to\chi\chi} = \frac{\pi^2 \alpha_{\text{eff}}^3}{m_\phi^5}$$

$$\alpha_{\text{eff}} = 0.4$$

$\phi\phi\chi \leftrightarrow \phi\chi$ still rapid

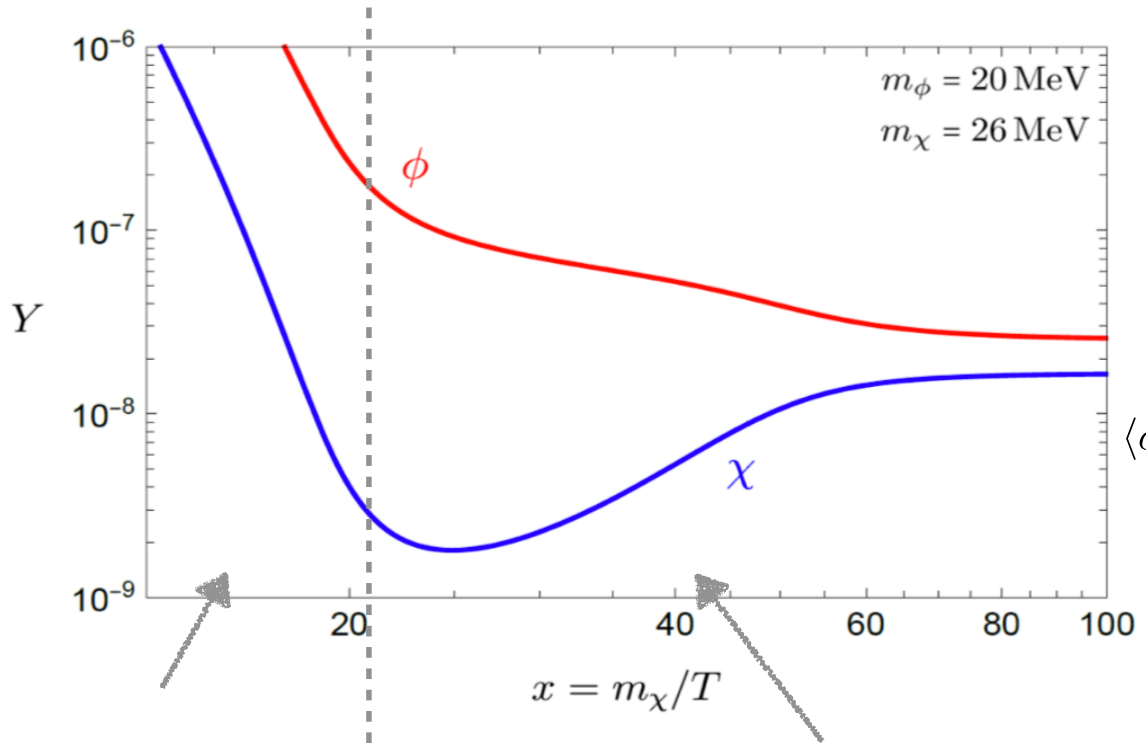
only $\phi\phi\phi \leftrightarrow \chi\chi$ is active

$$\mu_\chi = \mu_\phi = 0$$

$$3\mu_\phi = 2\mu_\chi$$

$3 \leftrightarrow 2$ process

A setup with only 2 states:



$$2m_\chi < 3m_\phi$$

$$\langle \sigma v^2 \rangle_{\phi\phi\phi \to \chi\chi} = \frac{\pi^2 \alpha_{\rm eff}^3}{m_\phi^5}$$

$$\alpha_{\rm eff} = 0.4$$

$\phi\phi\chi \leftrightarrow \phi\chi$ still rapid

$$\mu_\chi = \mu_\phi = 0$$

Approximate solution in bouncing phase:

$$Y_\chi \approx e^{-3c/2}\, e^{-(2m_\chi - 3m_\phi)/(2T)}$$

$$\mu_\phi \approx m_\phi - cT$$

$3 \leftrightarrow 2$ process

Some considerations for embedding into complete model:

$3 \leftrightarrow 2$ process

Some considerations for embedding into complete model:

- Dominance of $\chi^2\phi^3$ over $\chi^2\phi^2$?

  Example: complex scalars

mediator, same quantum numbers as χ

χ $\quad S \quad$ ϕ

$$\chi^* S|\phi|^2 + \epsilon\, \chi^* S\phi$$

breaks ϕ number $\qquad \epsilon \ll 1$

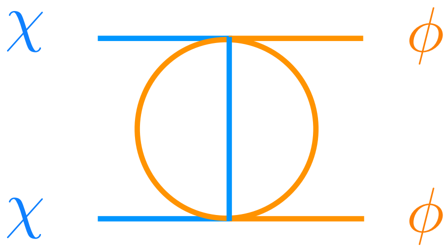
integrate out S

$$\mathcal{L}_{\text{EFT}} \sim \epsilon\, |\chi|^2|\phi|^2\phi + \epsilon^2|\chi|^2|\phi|^2$$

$3 \leftrightarrow 2$ process

Some considerations for embedding into complete model:

- In general, the $\chi^2\phi^3$ interaction generates $2 \leftrightarrow 2$ processes at two loops



which can wash out the bounce

$$\langle \sigma v \rangle_{\chi\chi\to\phi\phi} = \frac{\alpha_{\rm eff}^6}{\pi^3 m_\chi^2}$$ *if s-wave*

[Ho, Ko, Lu 2107.04375]
[Ho, Ko, Lu 2201.06856]

Interesting model-dependent aspect:

- Important numerical coefficients?
- *p*- or higher-wave suppression?
- Symmetry arguments forbidding $2 \leftrightarrow 2$ altogether? (e.g. discrete symmetries)

Summary

- Bouncing DM: new mechanism for thermal production.

  Transition from exponentially falling to exponentially rising equilibrium curve

- Requires DM chemical potential to deviate from other species',

  and rise rapidly enough

- DM annihilation cross sections can be larger than standard thermal target,

  improves prospects for indirect detection

- Presented a few qualitatively different realizations, in simple scenarios.

  Does bouncing DM arise in other non-minimal dark sector models?

Bouncing SIMPs

The bounce in a dark QCD model

- We first observed the bounce while studying a dark QCD SIMP model

[Katz, Salvioni, Shakya 2006.15148]

- Recalling that model can be useful,

  since it inspired the setup with 3 scalars I presented here

A minimal SIMP model

- $SU(N_c)$ confining gauge theory, 3 light flavors $(u, d, s) \rightarrow$ octet of GBs
- EM is gauged by dark photon
- Explicit breaking parametrized by

$$M = \mathrm{diag}\,(m_u, m_d, m_s)$$

$$Q = \mathrm{diag}\,(2/3, -1/3, -1/3)$$

- One of the mesons is always unstable

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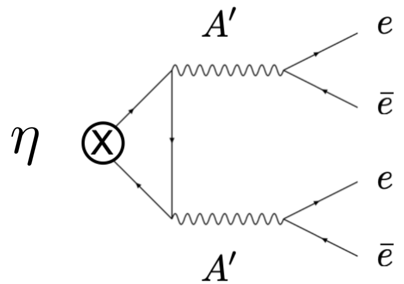
- One of the mesons is always unstable

- Decay through chiral anomaly, $\mathrm{Tr}\,(Q^2 T^\eta) \neq 0$



$$\tau^{(\mathrm{anomaly})}_{\eta \to 4e} \approx 1.9 \times 10^{14}\ \mathrm{s} \left(\frac{10^{-5}}{\varepsilon}\right)^4 \left(\frac{\alpha}{\hat{\alpha}}\right)^2 \left(\frac{m_{A'}}{0.4\ \mathrm{GeV}}\right)^8 \left(\frac{200\ \mathrm{MeV}}{m_\eta}\right)^9 \left(\frac{10}{m_\eta/f_\pi}\right)^2$$

- Comparable to timescale of recombination: EM injection impacts CMB anisotropies

Strong constraints: fraction of decaying species must be $\lesssim 10^{-11}$ for this lifetime

[Poulin, Serpico 2016]
[Slatyer, Wu 2016]

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$$M = \text{diag}\,(m_u, m_d, m_s)$$
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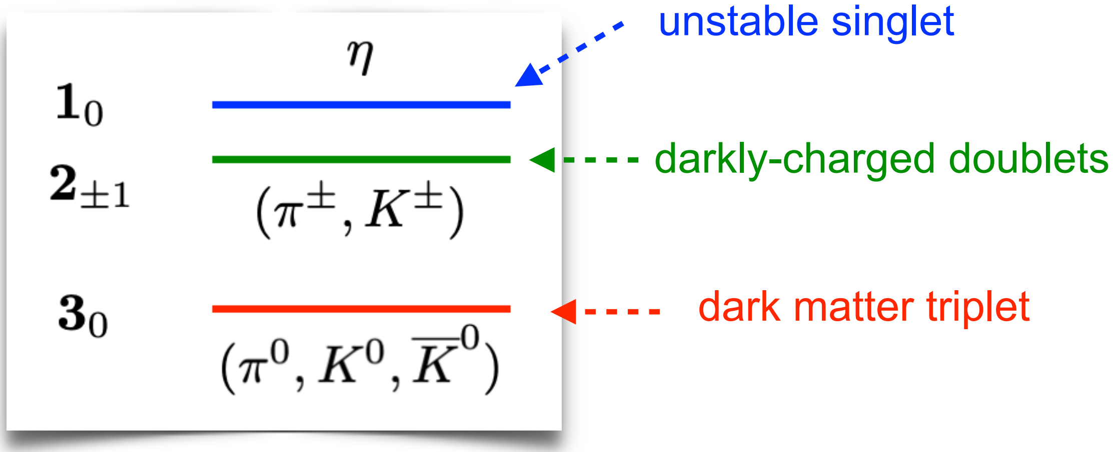
Only viable choice: split the spectrum with $m_u > m_d = m_s$

Exact $SU(2)_U \times U(1)_Q$

"U-spin" in the SM



[Katz, Salvioni, Shakya 2006.15148]

A minimal SIMP model

- Exactly the symmetry structure I presented earlier
- LO chiral Lagrangian predicts crucial mass relation

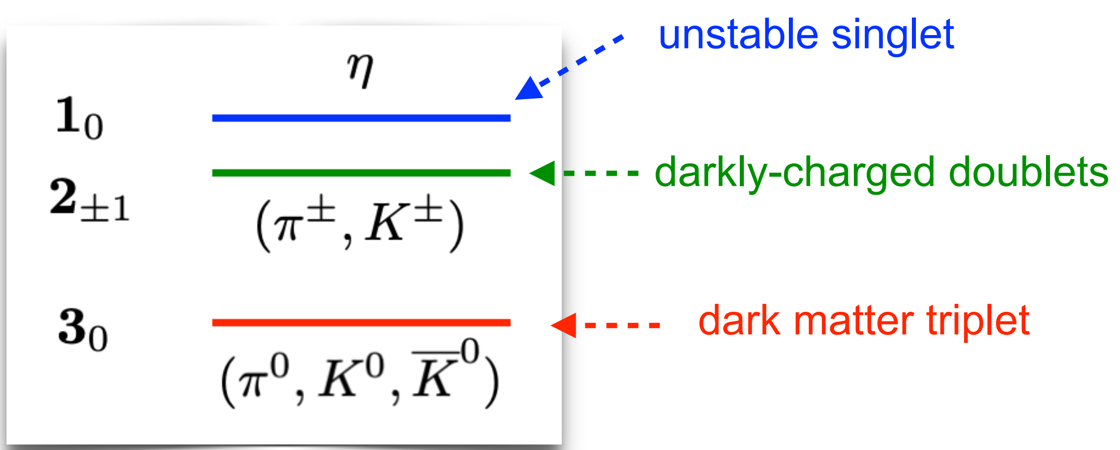
$$2m_{\text{doublets}} > m_{\text{triplet}} + m_{\text{singlet}}$$

- But roles played by states are different: bounce for unstable singlet, not for DM

Only viable choice: split the spectrum with $m_u > m_d = m_s$

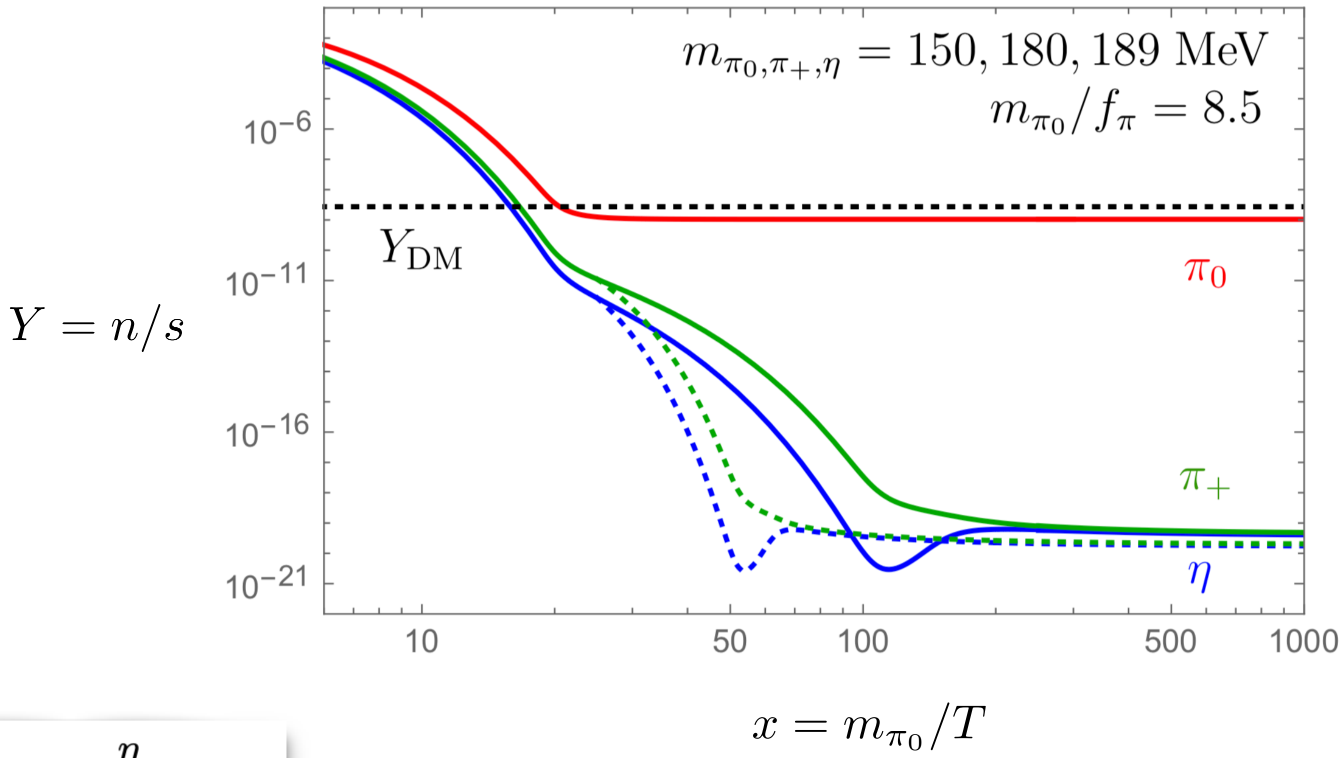
Exact $SU(2)_U \times U(1)_Q$

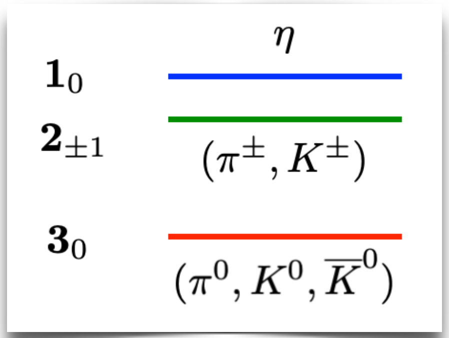
"U-spin" in the SM



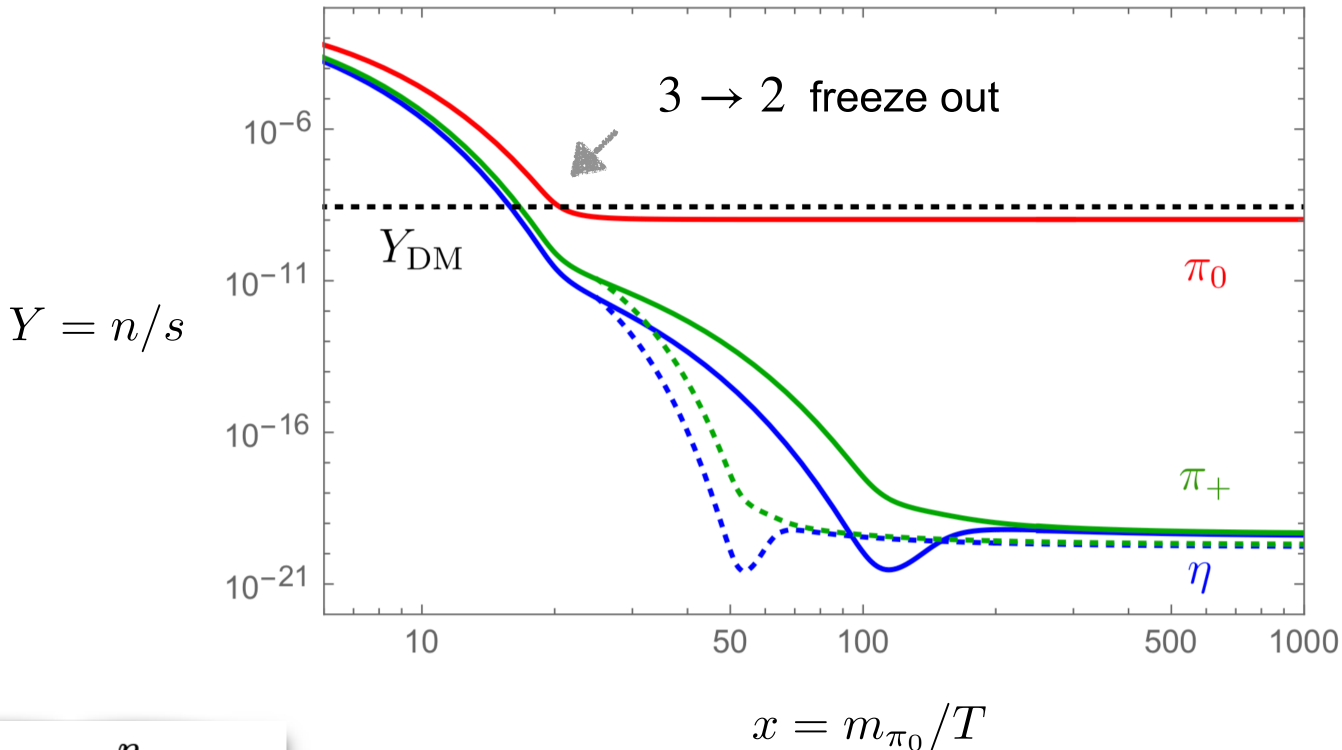
[Katz, Salvioni, Shakya 2006.15148]

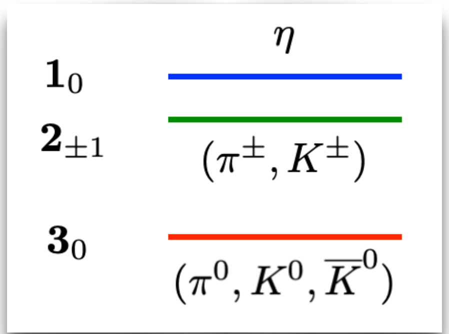
SIMP cosmological history



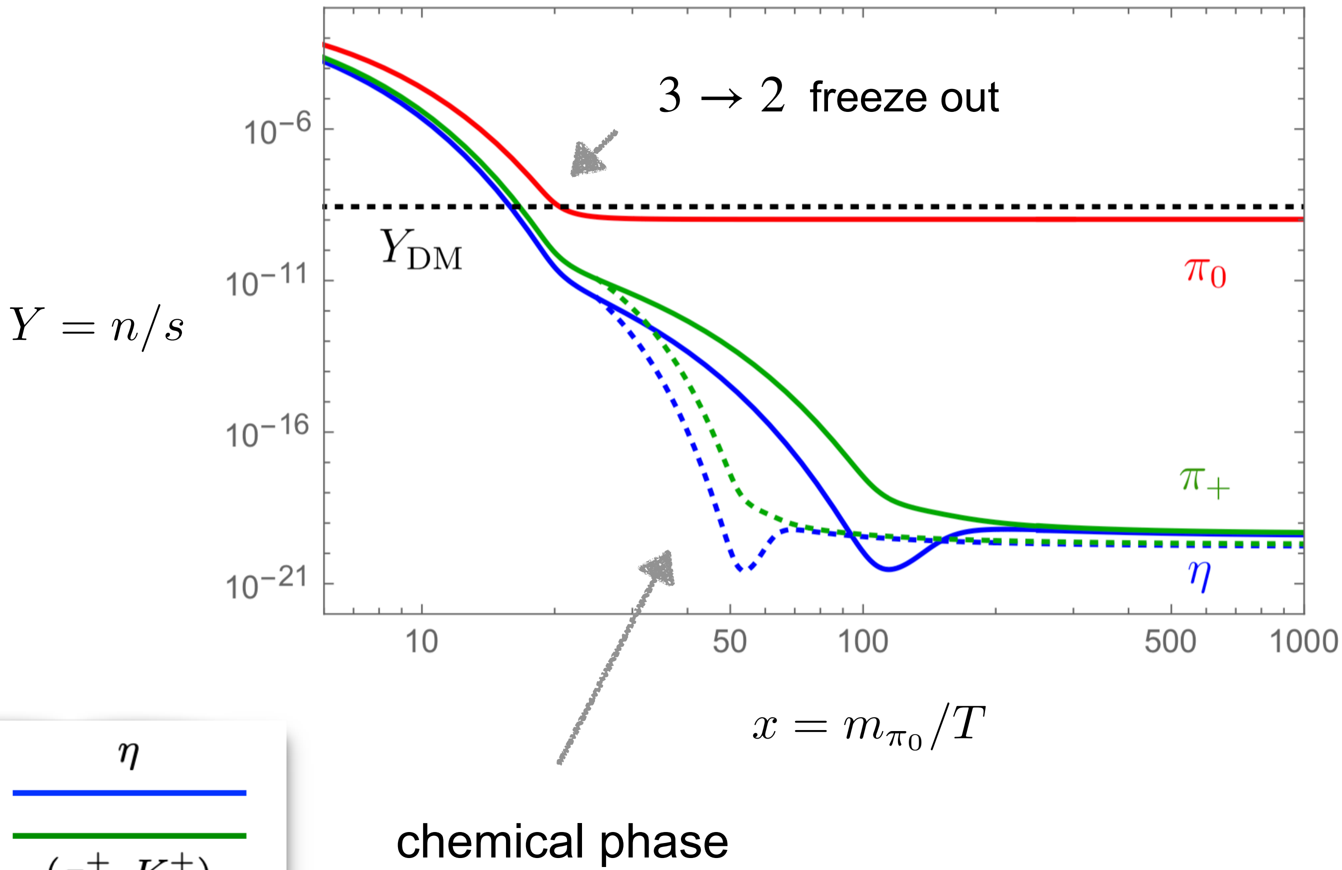


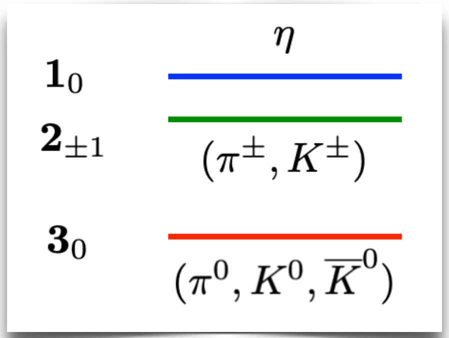
SIMP cosmological history



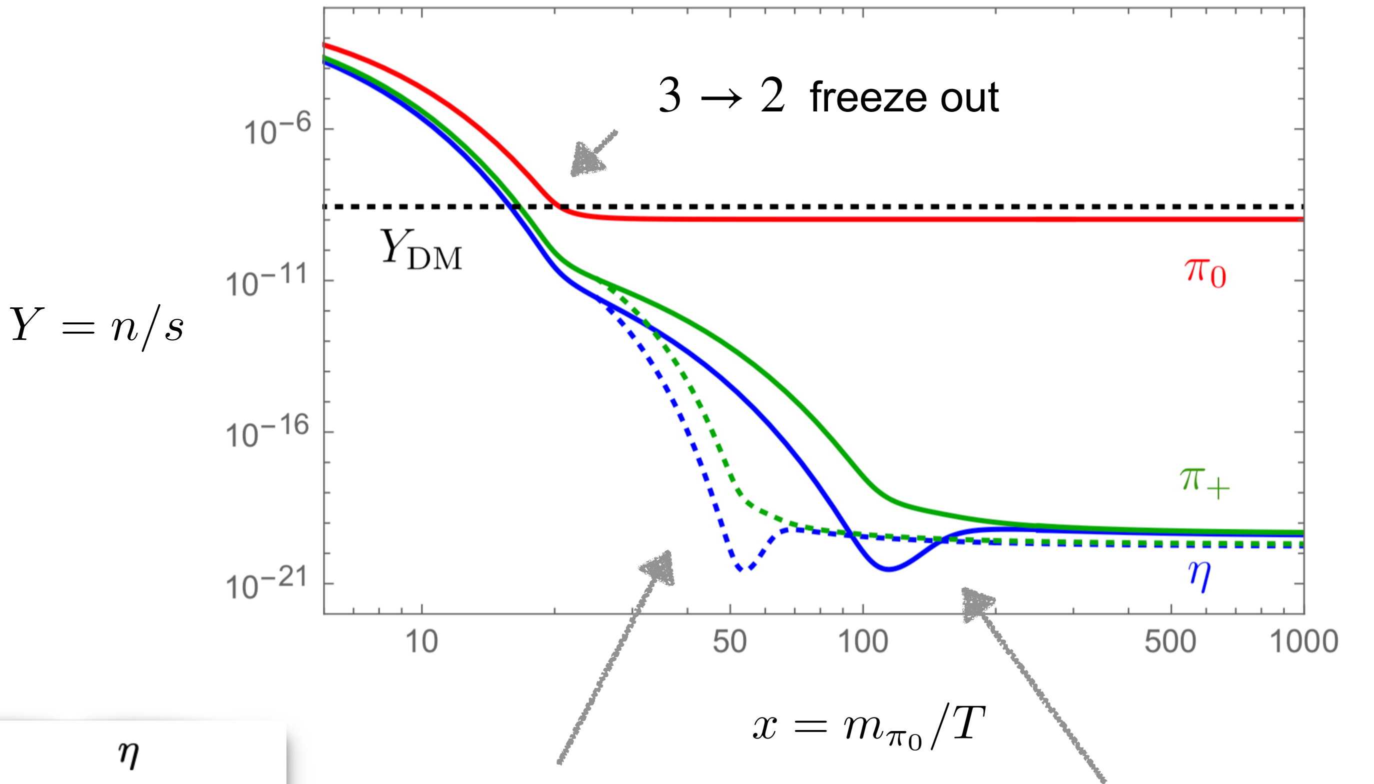


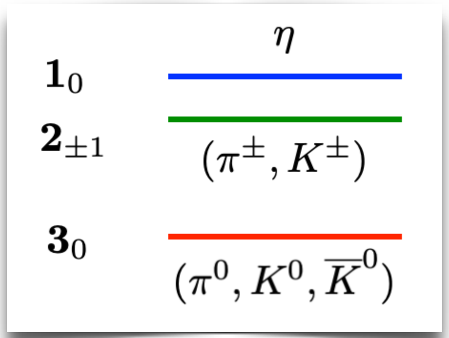
SIMP cosmological history





SIMP cosmological history

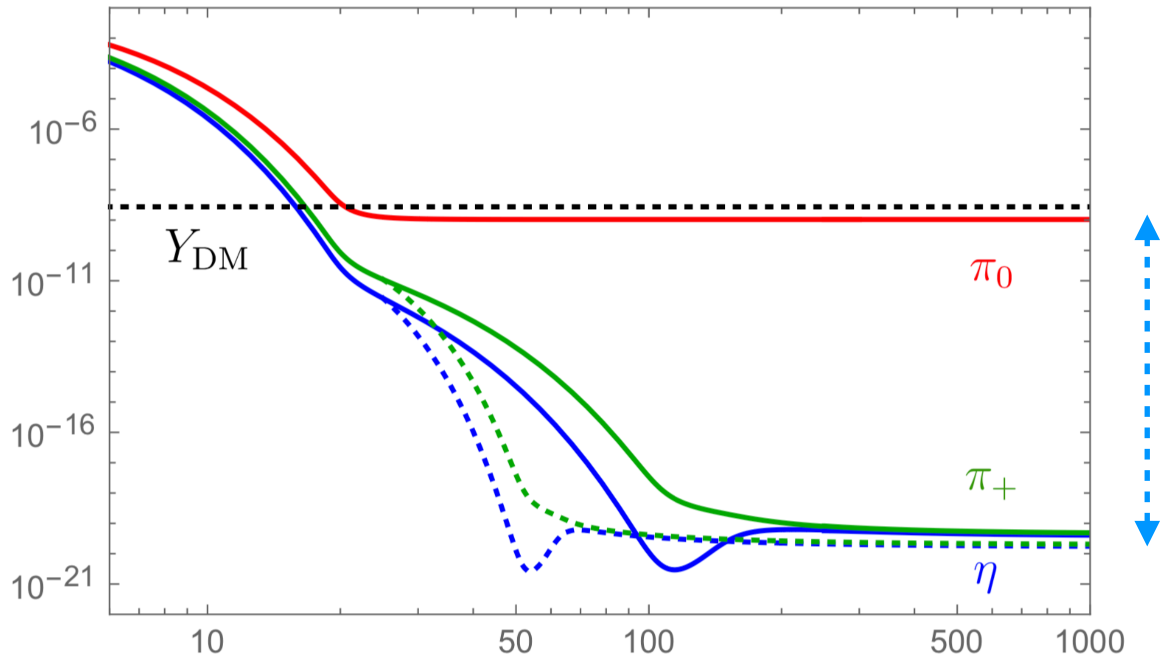




$$\pi^+\pi^- \rightarrow \eta\, \pi^0$$

SIMP cosmological history

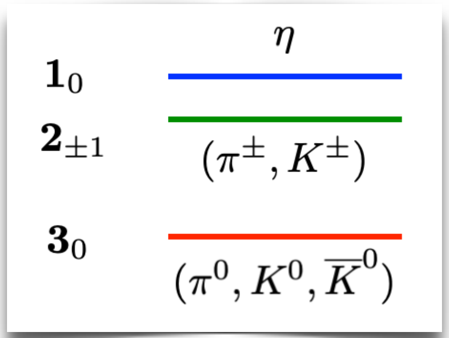
$Y = n/s$



$x = m_{\pi_0}/T$

$$\frac{Y_\eta^{\rm fo}}{Y_{\rm DM}} \approx 10^{-11}$$

CMB ✓



CMB bounds are satisfied
(for splitting $\gtrsim 20\,\%$)

[Katz, Salvioni, Shakya 2006.15148]