BOUNCING DARK MATTER

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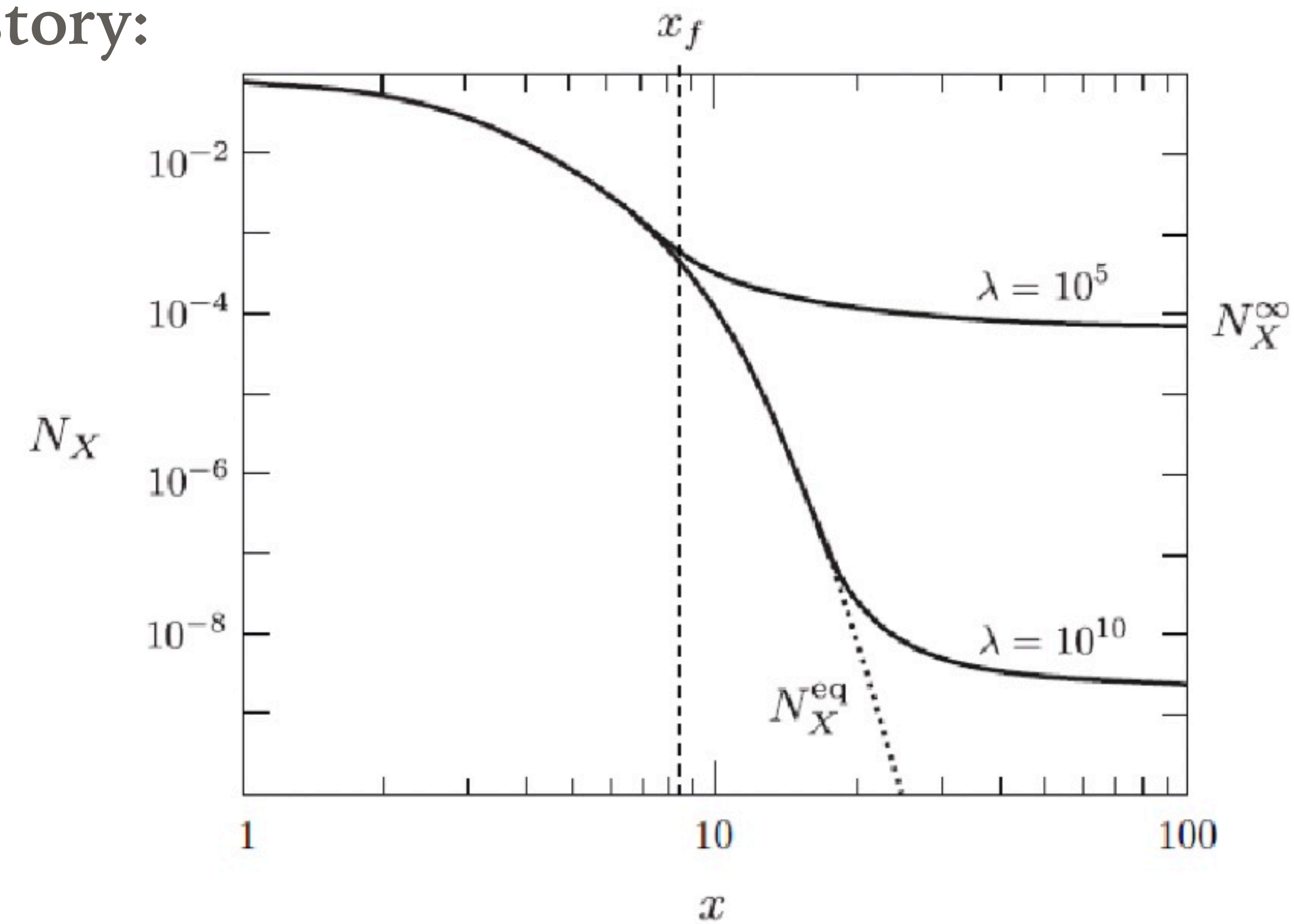
DESY.

BASED ON 2207.XXXXX [HEP-PH] W/ LUCAS PUETTER, JOSHUA RUDERMAN, ENNIO SALVIONI

THERMAL DARK MATTER

A familiar story:

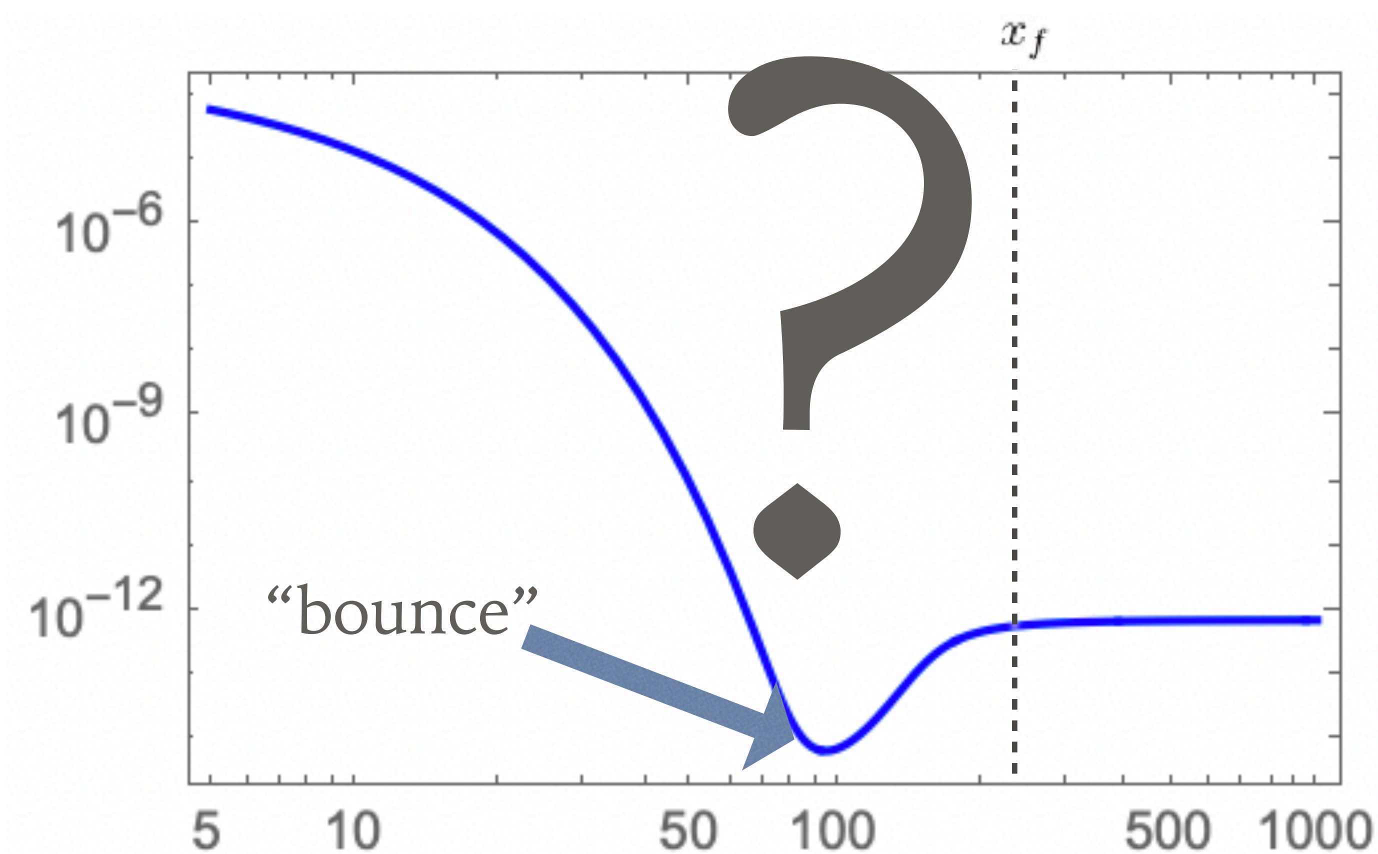


$\psi\,\psi \leftrightarrow X X$

- dark matter traces an **equilibrium (exponentially falling) abundance curve**
- **freeze out** when interactions become slower than the Hubble rate;
  larger cross section→later freezeout, smaller abundance
- Associated with a **"thermal" cross section** that is a well defined target for experiments:
  $3\text{x}10^{-26}\ \text{cm}^3\text{s}^{-1}$

THERMAL DARK MATTER

THIS TALK



Can dark matter abundance depart from the exponentially falling curve **while in equilibrium**?

(and **RISE?**)

* Under what conditions ?
* With what phenomenological implications ?

UNDERSTANDING EQUILIBRIUM DYNAMICS

Track equilibrium abundance of species i in terms of its **chemical potential** μ_i

$$n_i = n_i^{\mathrm{eq}} e^{\mu_i/T} \qquad n_X^{\mathrm{eq}} = g_X \left(\frac{m_X T}{2\pi}\right)^{3/2} e^{-m_X/T}$$

If an interaction $AB \leftrightarrow CD$ is rapid,

the chemical potentials of the species involved are related as

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

Maintained until the interaction goes out of equilibrium (becomes slower than Hubble rate)

UNDERSTANDING EQUILIBRIUM DYNAMICS

Track equilibrium abundance of species i in terms of its **chemical potential** μ_i

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If DM shares the same (nonzero) chemical potential as another light species, remains an exponentially falling distribution

$$\mu_\chi = \mu_A \qquad n_\chi = (n_\chi^{\text{eq}}/n_A^{\text{eq}})\, n_A$$

Condition for DM yield to RISE

$$dY_\chi/dx > 0 \Rightarrow \mu_\chi(x) + x\frac{d\mu_\chi(x)}{dx} > m_\chi\left(1 - \frac{3}{2x}\right)$$

UNDERSTANDING EQUILIBRIUM DYNAMICS

Track equilibrium abundance of species i in terms of its **chemical potential** μ_i

$$n_i = n_i^{\rm eq} e^{\mu_i/T} \qquad n_X^{\rm eq} = g_X \left(\frac{m_X T}{2\pi}\right)^{3/2} e^{-m_X/T}$$

Departure (and rise) from the an exponentially falling curve:
dark matter chemical potential needs to

(i) deviate from those of other particles

(ii) rise sufficiently rapidly (to overcome falling exponential in $n^{\rm eq}$)

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

AN EXAMPLE

A SIMPLIFIED DARK SECTOR

Consider a dark sector with three scalars

χ	ϕ_2	ϕ_1
dark matter	possibly stable	metastable

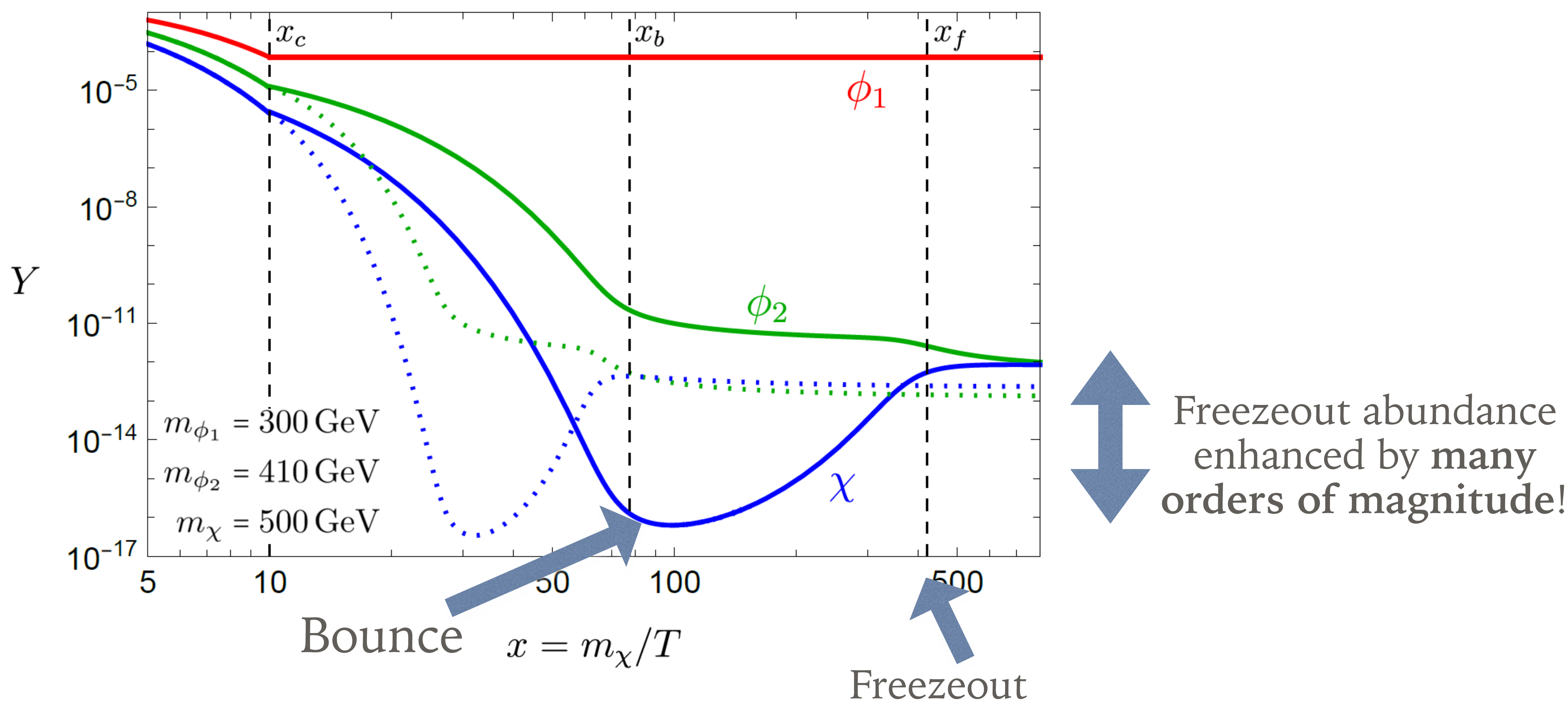
$$m_\chi > m_{\phi_2} > m_{\phi_1}$$

Interactions

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

Consider masses such that $2\,m_{\phi_2} > m_\chi + m_{\phi_1}$

EVOLUTION OF ABUNDANCES:
A BENCHMARK POINT



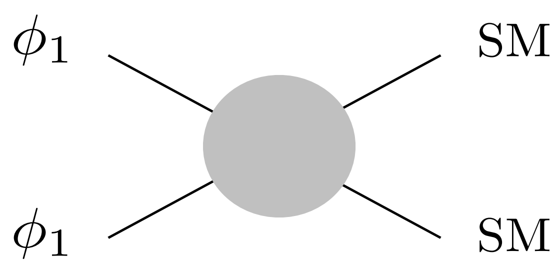
$$10\,\sigma_{\chi\chi\phi_2\phi_2} = 30\,\sigma_{\phi_2\phi_2\phi_1\phi_1} = 10\,\sigma_{\chi\chi\phi_1\phi_1} = \sigma_{\phi_2\phi_2\chi\phi_1} = 2.1\times 10^{-25}\,\mathrm{cm}^3\,\mathrm{s}^{-1}$$

Solid/Dotted: Late/early kinetic decoupling between dark and SM sectors

COSMOLOGICAL HISTORY

Temperature Time

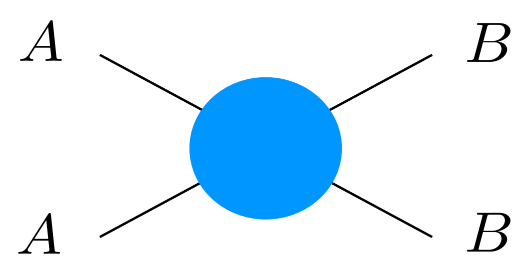
Equilibrium phase



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

chemical decoupling

Chemical phase

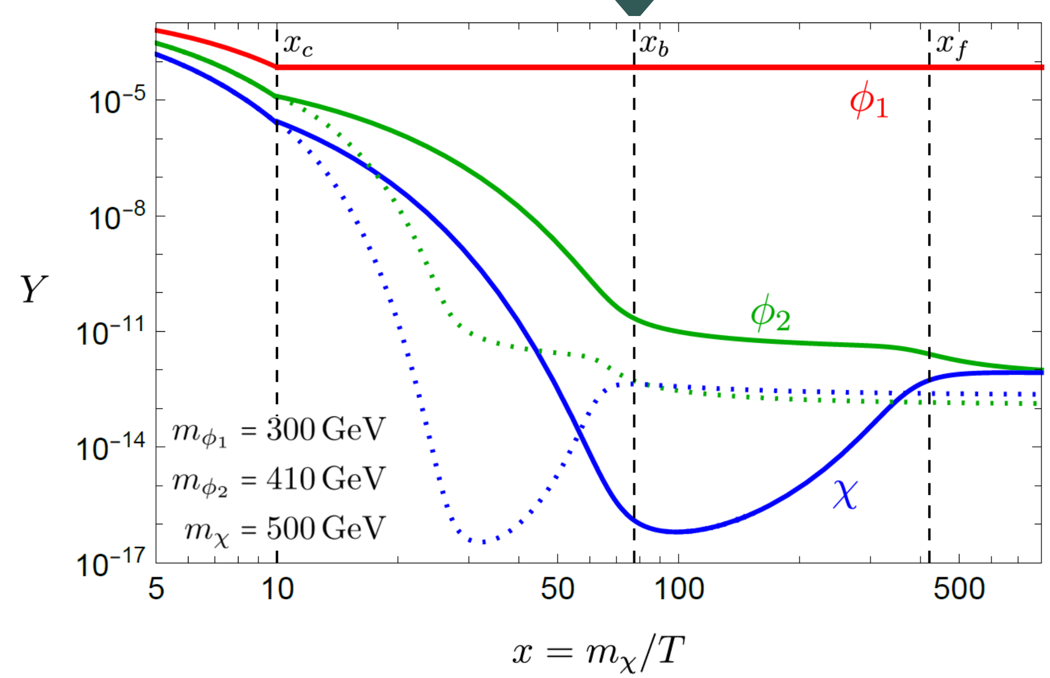


$$A, B = \chi, \phi_1, \phi_2$$

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

bounce

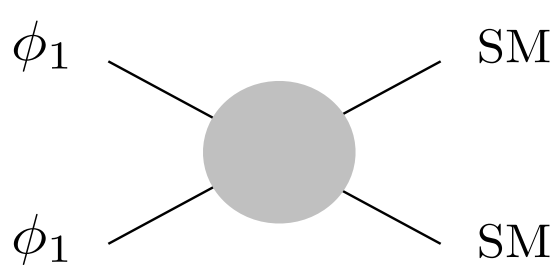
AA ↔ BB type dark sector interactions, as well as $\chi\phi_2 \leftrightarrow \phi_1\phi_2$, decouple



COSMOLOGICAL HISTORY

Temperature ⟷ Time

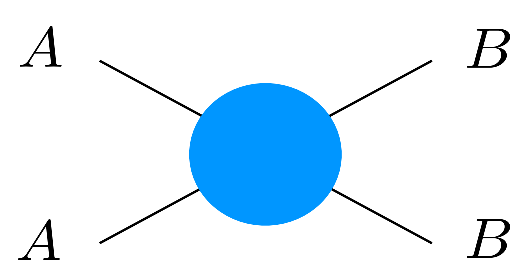
Equilibrium phase



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

chemical decoupling

Chemical phase

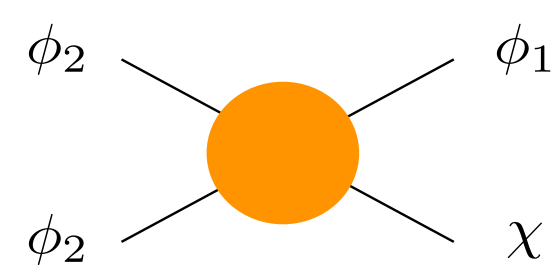


$$A, B = \chi, \phi_1, \phi_2$$

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

bounce

Bouncing phase

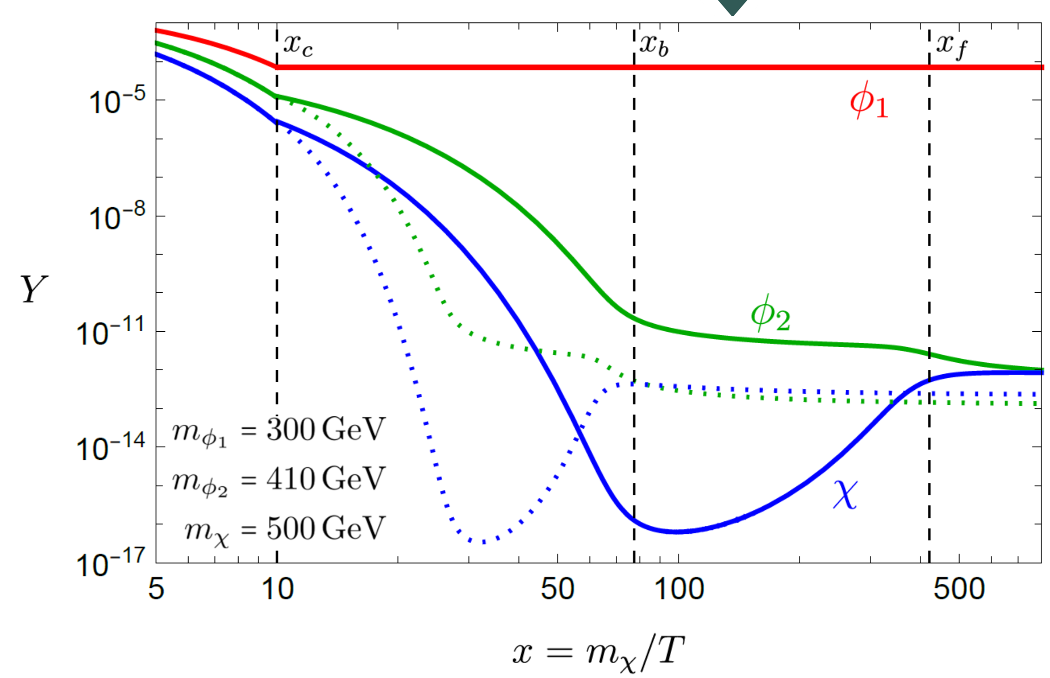


$$\boxed{2\mu_{\phi_2} = \mu_{\phi_1} + \mu_\chi}$$

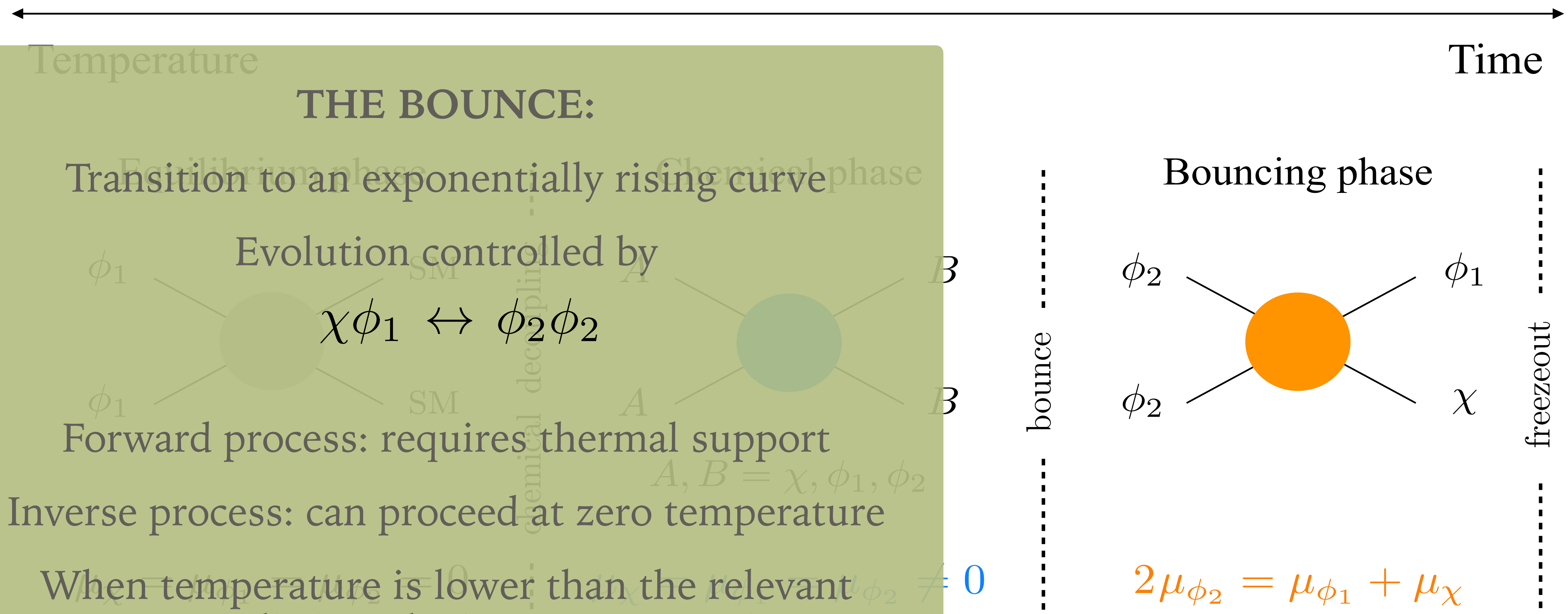
Evolution dominated by the only remaining active process

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

Dark matter abundance **transitions** from an exponentially falling to an **exponentially rising curve**!



THE BOUNCE, INTUITIVELY



THE BOUNCE:

Transition to an exponentially rising curve

Evolution controlled by

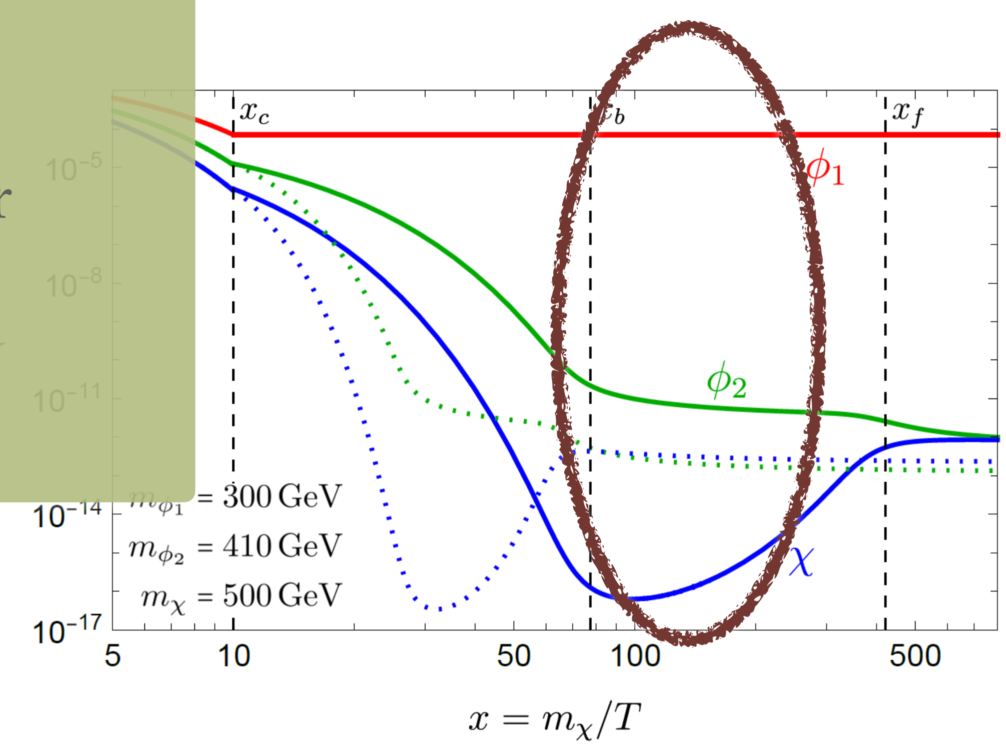
$$\chi\phi_1 \leftrightarrow \phi_2\phi_2$$

Forward process: requires thermal support

Inverse process: can proceed at zero temperature

When temperature is lower than the relevant mass splitting, the inverse process is **exponentially favored: dark matter production rises exponentially**!

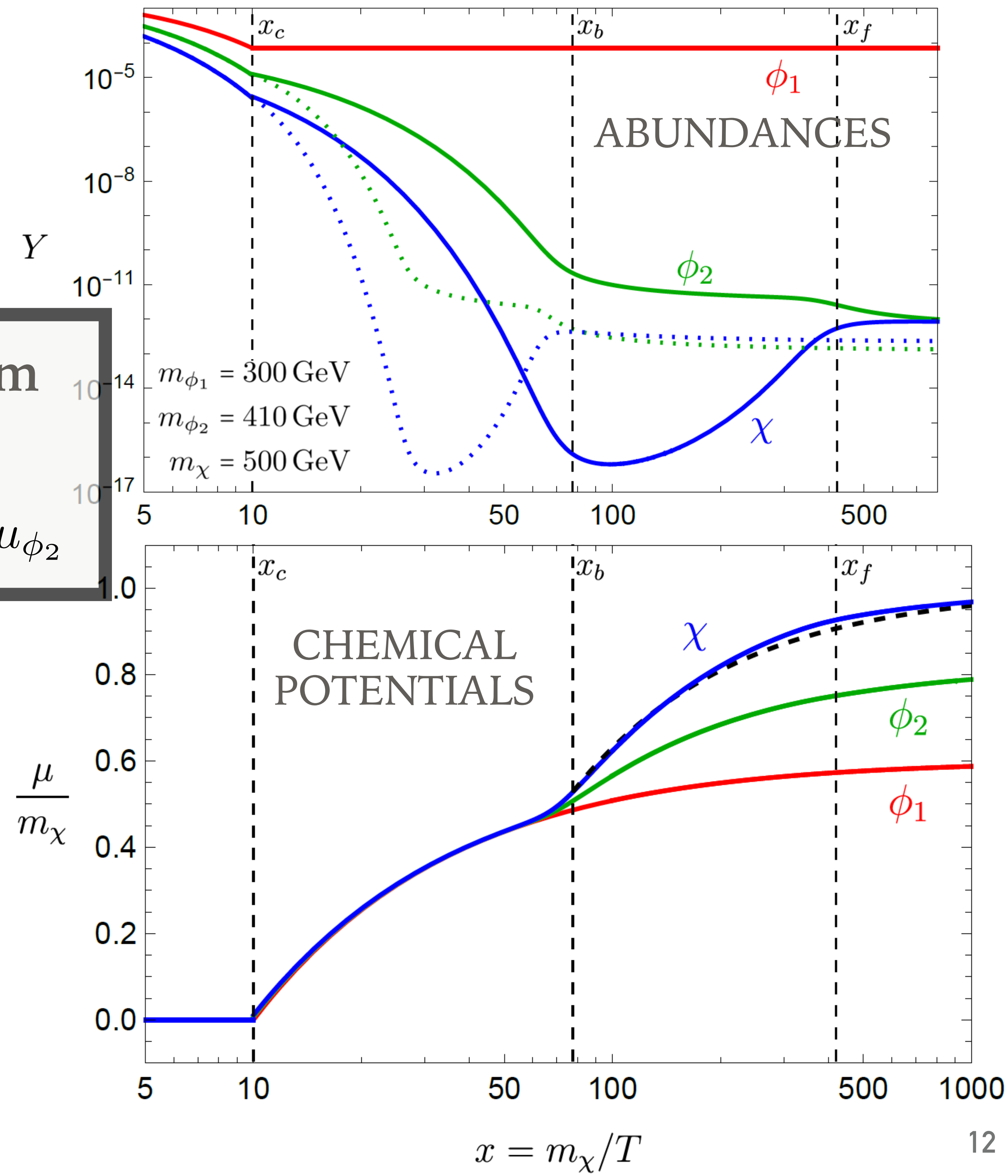
(The **inverse** of the standard dark matter freezeout story)



THE BOUNCE, TECHNICALLY

“Bounce”: from one equilibrium distribution to another

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



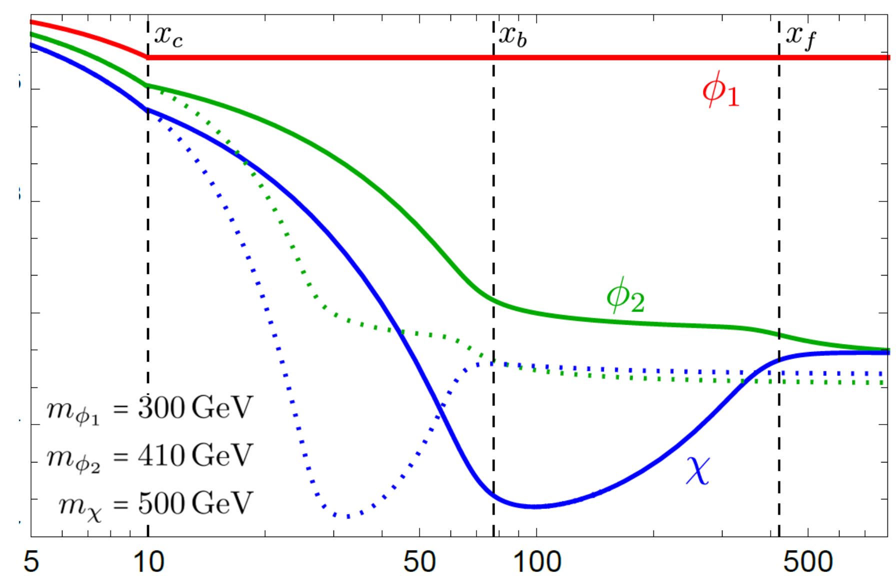
INDIRECT DETECTION SIGNALS

Indirect detection signals from dark matter annihilation:

$$\chi\chi \rightarrow \phi_i\phi_i \rightarrow \text{visible}$$

Annihilation cross sections can be **larger than** the naive thermal target ($3\text{x}10^{-26}\,\text{cm}^3\text{s}^{-1}$)!

(would have led to a later freezeout a smaller than measured abundance of dark matter, but **this gets "fixed" by the bouncing phase!)**

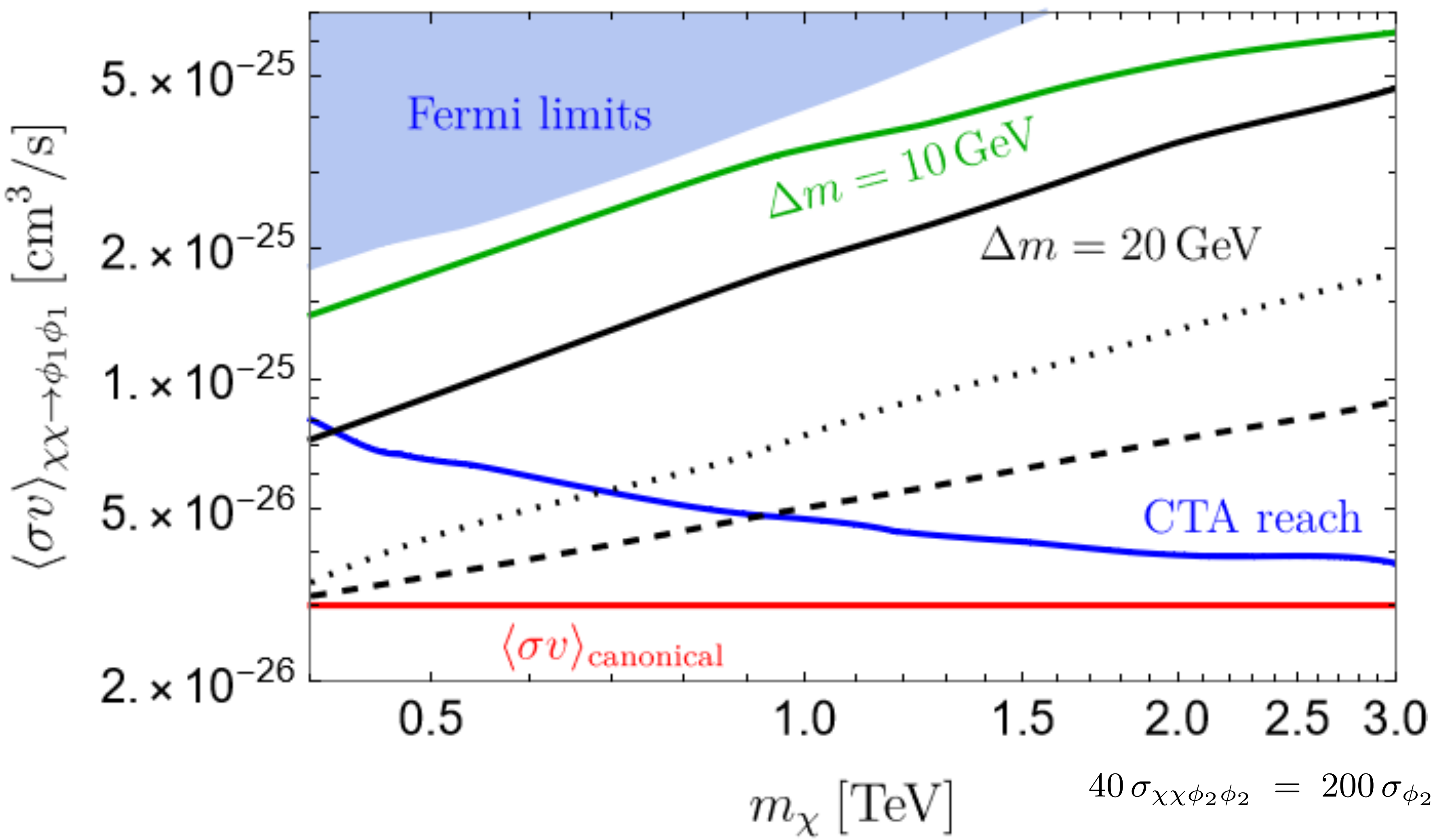


Improves prospects of detection with indirect detection experiments:

can see dark matter signals "above" the thermal target.

The most salient phenomenological aspect of bouncing dark matter

INDIRECT DETECTION SIGNALS



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

$$\phi_1 \to WW$$

$$\Delta m = m_{\phi_2} - (m_\chi + m_{\phi_1})/2$$

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

solid/dotted/dashed: Late/intermediate/early kinetic decoupling between dark and SM sectors

CTA unable to probe the canonical thermal target,

but can discover bouncing dark matter in this case

OTHER BOUNCING DARK MATTER SCENARIOS

COANNIHILATION WITH A DECAYING PARTNER

Consider the **same setup as before**,

$\boxed{\chi}$	ϕ_2	ϕ_1
dark matter	possibly stable	metastable

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

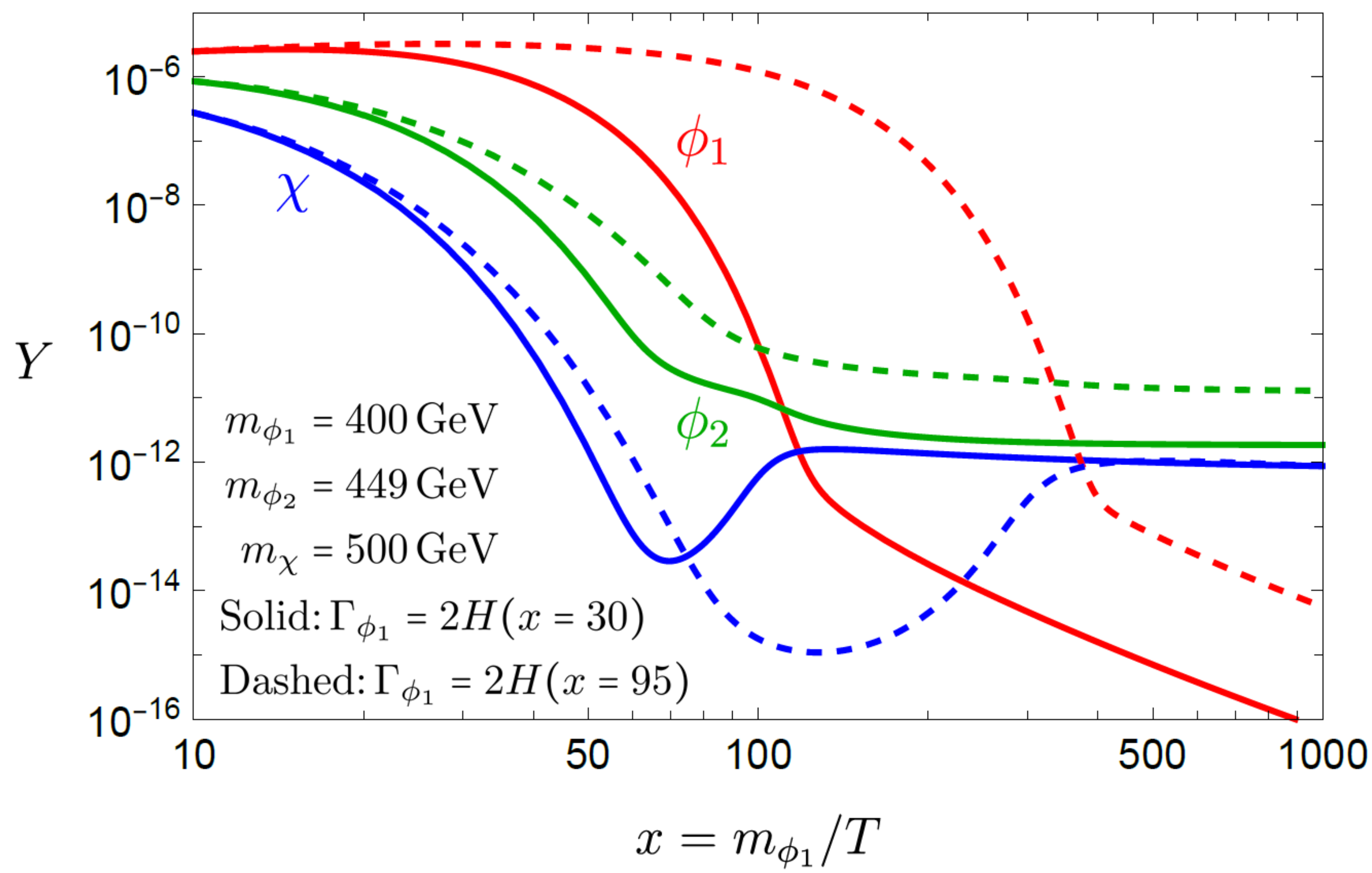
Interactions

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

With two crucial modifications:

1. The reversed condition $2\,m_{\phi_2} \lesssim m_\chi + m_{\phi_1}$;
2. ϕ_1 decays around the time when χ freezes out.

COANNIHILATION WITH A DECAYING PARTNER



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

decays of ϕ_1 cause the chemical potential of ϕ_1 to drop:

To maintain the above relation, this triggers

a decrease in μ_{ϕ_2} and an increase in μ_χ

Freezeout Driven by $2 \to 3$ Process

Consider a 2 particle setup

$$\boxed{\chi}$$

dark matter

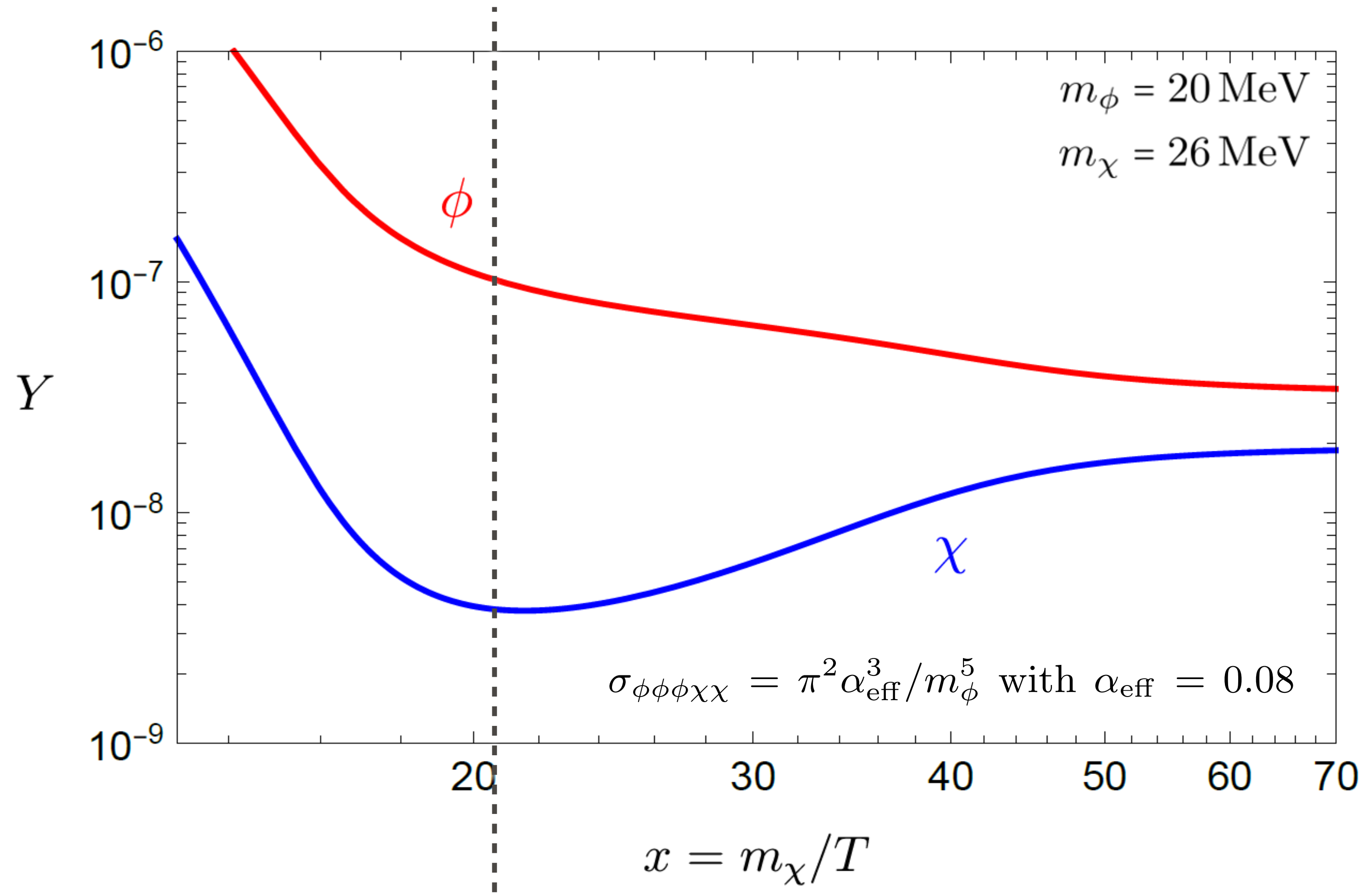
$$\phi$$

metastable

$$m_\chi > m_\phi\,, \qquad 2m_\chi < 3m_\phi$$

only relevant interaction : $\chi^2\phi^3$

Freezeout Driven by $2 \to 3$ Process



Evolution controlled by
$\phi\phi\chi \leftrightarrow \phi\chi$

Relation:

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

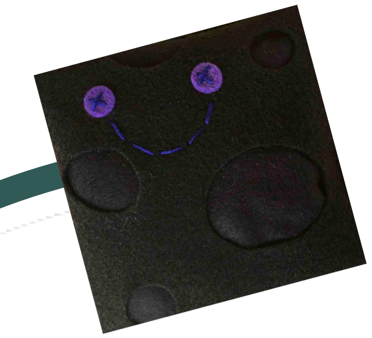
Evolution controlled by
$\phi\phi\phi \leftrightarrow \chi\chi$

Relation:

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

SUMMARY

Bouncing Dark Matter:



- An **exponentially (Boltzmann) suppressed abundance** as a consequence of DM **thermal freezeout: generic, but not necessary**!
- Requires **DM chemical potential to deviate** from those of other species in the bath (and **rise sufficiently rapidly** for abundance to go up)
- Can be realized in **several qualitatively different frameworks**
- Present day dark matter annihilation cross section **larger than standard thermal target, more promising for indirect detection searches**