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AFTER WINTER COMES SPRING

DARK MATTER WITH A BOUNCE

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BASED ON 2106.XXXXX
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DARK MATTER: WHAT SETS ITS ABUNDANCE?

The most popular paradigm: Thermal Freezeout

Standard Picture

- dark matter traces an equilibrium (thermal) abundance curve
- Boltzmann suppressed as temperature drops
- freeze out when interactions become slower than the Hubble rate
DARK MATTER: WHAT SETS ITS ABUNDANCE?

The most popular paradigm: Thermal Freezeout

**Standard Picture**

- Dark matter traces an equilibrium (thermal, abundance curve)
- Boltzmann suppressed as temperature drops
- Freeze out when interactions become slower than the Hubble rate

**THIS TALK**

- Dark matter abundance undergoes the usual suppression, but **bounces up at late times** and freezes out with an **enhanced relic abundance**!
If dark matter primarily annihilates into species $X$ in the bath $\psi \psi \leftrightarrow XX$

Particle $X$ in the bath follows Boltzmann distribution

Only the part of $X$ distribution with $E > m_{\psi}$ can participate in the production of dark matter

The relevant parameters for our discussion are

- $\langle \kappa \rangle$: The strength of the phase transition, generally defined as $\kappa \equiv \frac{\langle \text{vacuum} \rangle}{\langle \text{radiation} \rangle}$, which measures the total energy released in the phase transition relative to the total energy density in the thermal bath at the time of the transition.

- $T_{\ast}$: The temperature (of the SM thermal bath) at which bubbles of true vacuum percolate and the phase transition ends.

Particle $X$ in the bath follows Boltzmann distribution

\[
\frac{dY}{dx} = \frac{-x \langle \sigma v \rangle_{\psi X \rightarrow X X} |v|}{H(m)} (Y^2 - Y_{\text{EQ}}^2)
\]

Only the part of $X$ distribution with $E > m_{\psi}$ can participate in the production of dark matter

\[
Y_{\text{EQ}}(x) = \frac{45}{2\pi^4} \left( \frac{\pi}{8} \right)^{1/2} \frac{g}{g_{\ast} s} x^{3/2} e^{-x}
\]

T decreases $\rightarrow$ a smaller and smaller fraction of $X$ distribution can participate $\rightarrow$ familiar exponential (Boltzmann) suppression
THERMAL FREEZEOUT: A CLOSER LOOK

If dark matter primarily annihilates into species X in the bath $\psi \psi \leftrightarrow XX$

$$\frac{dY}{dx} = \frac{-x(\sigma v^2_{\psi \psi \rightarrow XX})}{H(m)} (Y^2 - Y_{EQ}^2)$$

Particle X in the bath follows Boltzmann distribution

Only the part of X distribution with $E > m_\psi$
can participate in the production of dark matter

T decreases $\rightarrow$ a smaller and smaller fraction
of X distribution can participate $\rightarrow$
familiar exponential (Boltzmann) suppression

Dark matter thermal histories in most models follows this pattern

- Interactions controlling DM freezeout feature lighter particles $\rightarrow$ (Inverse) processes that populate dark matter need thermal support, grow weaker as the temperature falls $\rightarrow$ DM abundance Boltzmann suppressed
- Interactions with heavier particles in the bath generally irrelevant, as these are less abundant than dark matter
A MODIFIED DARK MATTER SETUP

Consider a hidden sector where the aforementioned statements do not hold:

A dark sector with three particles:

- H (heavy; dark matter)
- M (medium)
- L (light)

All four particle interactions allowed, e.g.

\[ HH \leftrightarrow LL, \quad HH \leftrightarrow MM, \quad HM \leftrightarrow ML, \quad HM \leftrightarrow LL, \quad MM \leftrightarrow HL \quad \ldots \]

Key assumption: \[ 2m_M > m_H + m_L \]
COSMOLOGICAL HISTORY

- 200 GeV
- 240 GeV
- 260 GeV
COSMOLOGICAL HISTORY

- Hidden sector out of (chemical) equilibrium from the SM thermal bath
- Comoving number density in the hidden sector (H+M+L) conserved
- Interactions between hidden sector species rapid

Relation between chemical potentials:

\[ \mu_H = \mu_M = \mu_L \]

\[ n_i = n_i^{eq} e^{\mu_i/T} \]
COSMOLOGICAL HISTORY

- Rapid hidden sector interactions interconverting $H \leftrightarrow M \leftrightarrow L$ to familiar Boltzmann suppression of heavier particles relative to the lighter ones

- Relation between chemical potentials:

$$\mu_H = \mu_M = \mu_L$$

$$n_i = n_{i}^{eq} e^{\mu_i / T}$$
COSMOLOGICAL HISTORY

Most processes that destroy H(M) in favor of L (HH → MM, HH → LL, HL → LL, HM → ML) go out of equilibrium

- Relation between chemical potentials:

\[
\mu_H = \mu_M = \mu_L
\]

\[
n_i = n_i^{eq} e^{\mu_i/T}
\]
COSMOLOGICAL HISTORY

Only remaining rapid interaction: \( \text{MM} \leftrightarrow \text{HL} \)

Boltzmann suppression logic reversed:

Thermal bath needs to choose between MM (heavier) and HL (lighter); the latter is (exponentially) more “favored”! Leads to a conversion of M population to HL states
Modified relation for chemical potentials

\[ 2\mu_M = \mu_L + \mu_H \]

Only remaining rapid interaction: \(\text{MM} \leftrightarrow \text{HL}\)

\[ \mu_H = \mu_M = \mu_L \]

is no longer an acceptable solution to the Boltzmann equations
Final relic abundance of dark matter “bounces up” and can be larger by several orders of magnitude!

Corresponds to a “bounce” in its equilibrium distribution

\[ \mu_H = \mu_M = \mu_L \quad \rightarrow \quad 2\mu_M = \mu_L + \mu_H \]
CONTEXT

Can occur in realistic setups

e.g. a dark (“twin”) QCD sector with multiple dark mesons

\[ m_{\pi_0,\pi^+,\eta} = 200, 210, 213 \text{ MeV} \]
\[ m_{\pi_0}/f_\pi = 9.5 \]

“Split SIMPs with Decays”
Andrey Katz, Ennio Salvioni, Bibhushan Shakya
PARTICLE DECAYS

H can be completely stable (if protected by a symmetry)
Or unstable on cosmological timescales (via L (M) loop decays)

Too much L; needs to decay (before BBN)
M might be OK; could be effectively stable and a component of dark matter
INDIRECT DETECTION SIGNALS

ANNIHILATION

Indirect detection signals from dark matter annihilation: HH→MM,LL
Rates larger than “naively” expected from standard freezeout

DECAY

H can decay via loops of L/M
For L/M lifetime ~1s,
H lifetime: ~10^{27} s
Long enough to be dark matter, short enough to see indirect detection signals!
As another illustration of the mechanism, consider a different setup:

A dark sector with two particles:

- H (heavy; dark matter)
- L (light)

Final interaction to decouple:

$$3 \rightarrow 2 \text{ process } 3L \rightarrow 2H$$

Key assumption: $$3m_L > 2m_H$$

Bounce:

$$\mu_H = \mu_L \quad \rightarrow \quad 3\mu_L = 2\mu_H$$
SUMMARY

• An exponentially (Boltzmann) suppressed abundance as a consequence of dark matter thermal freezeout: generic, but not necessary!

• Possible for late stages of DM freezeout to feature a “bounce” in the DM abundance, increasing by several orders of magnitude

• Requires late stages to be driven by an annihilation channel into DM that does not require thermal support

• Present day dark matter annihilation cross section larger than naively expected from standard freezeout processes

• Dark matter can be cosmologically unstable, with decay lifetimes of interest for observable signals