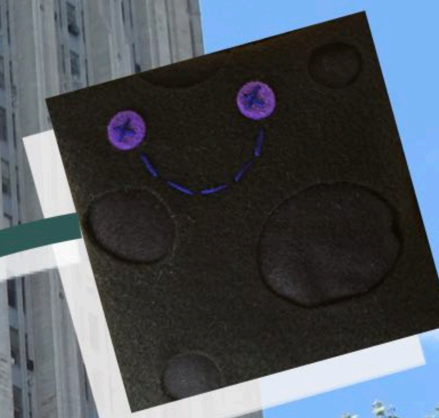
MAY 25, 2021

PHENO 2021

AFTER WINTER COMES SPRING

DARK MATTER WITH A BOUNCE

BIBHUSHAN SHAKYA



DESY.

BASED ON 2106.XXXXX
WITH JOSHUA RUDERMAN, ENNIO SALVIONI

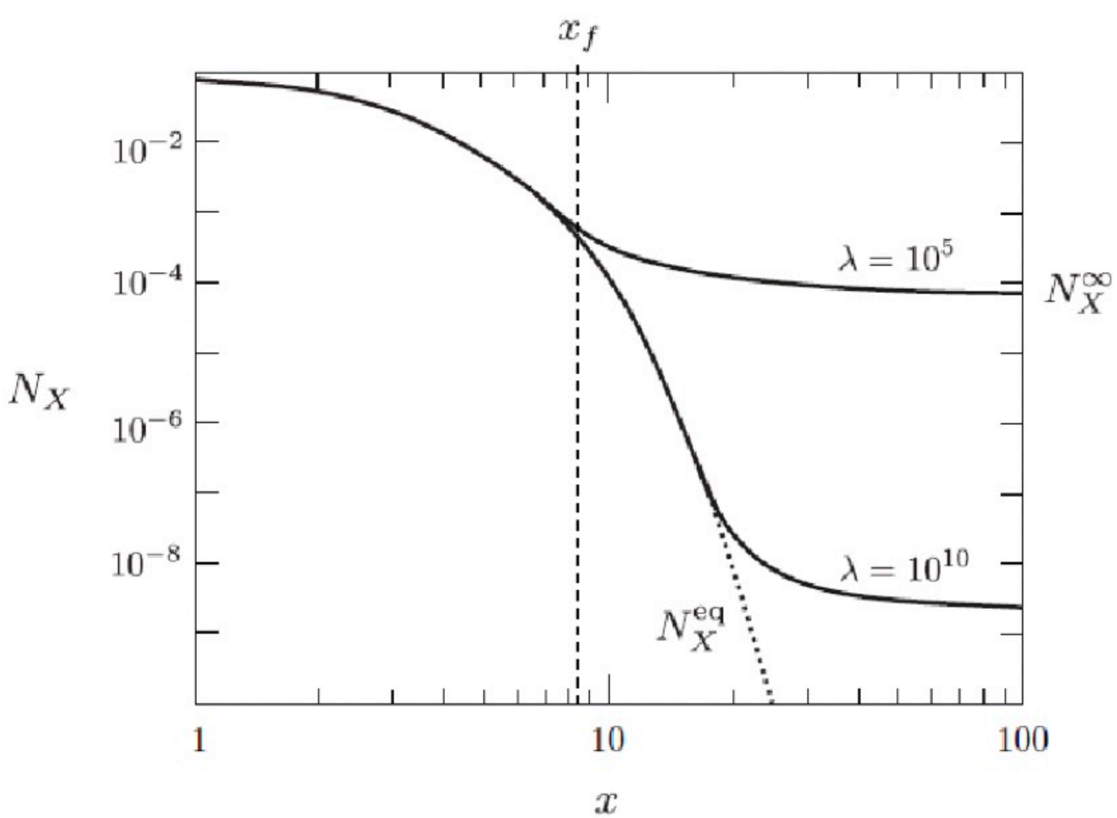
UNIVERSITY OF PITTSBURGH
VERITAS 1787 VIRTUS

PITTPACC
PITTSBURGH PARTICLE PHYSICS ASTROPHYSICS

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

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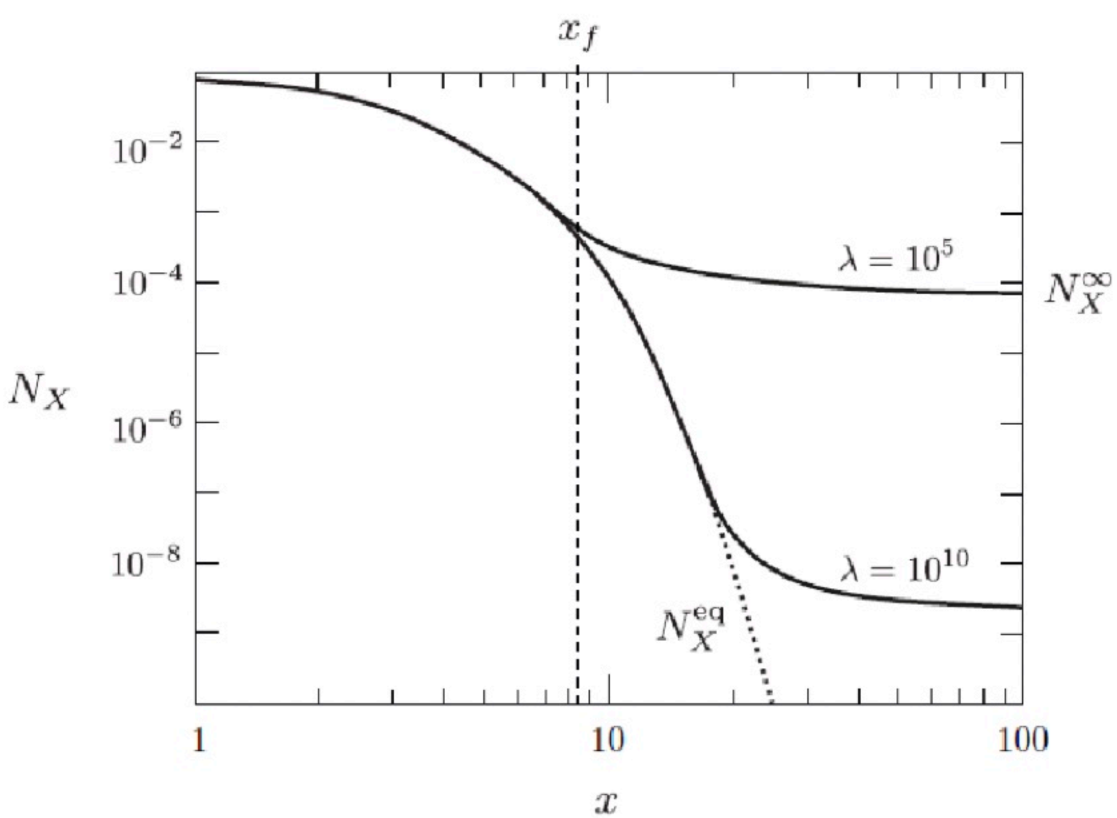

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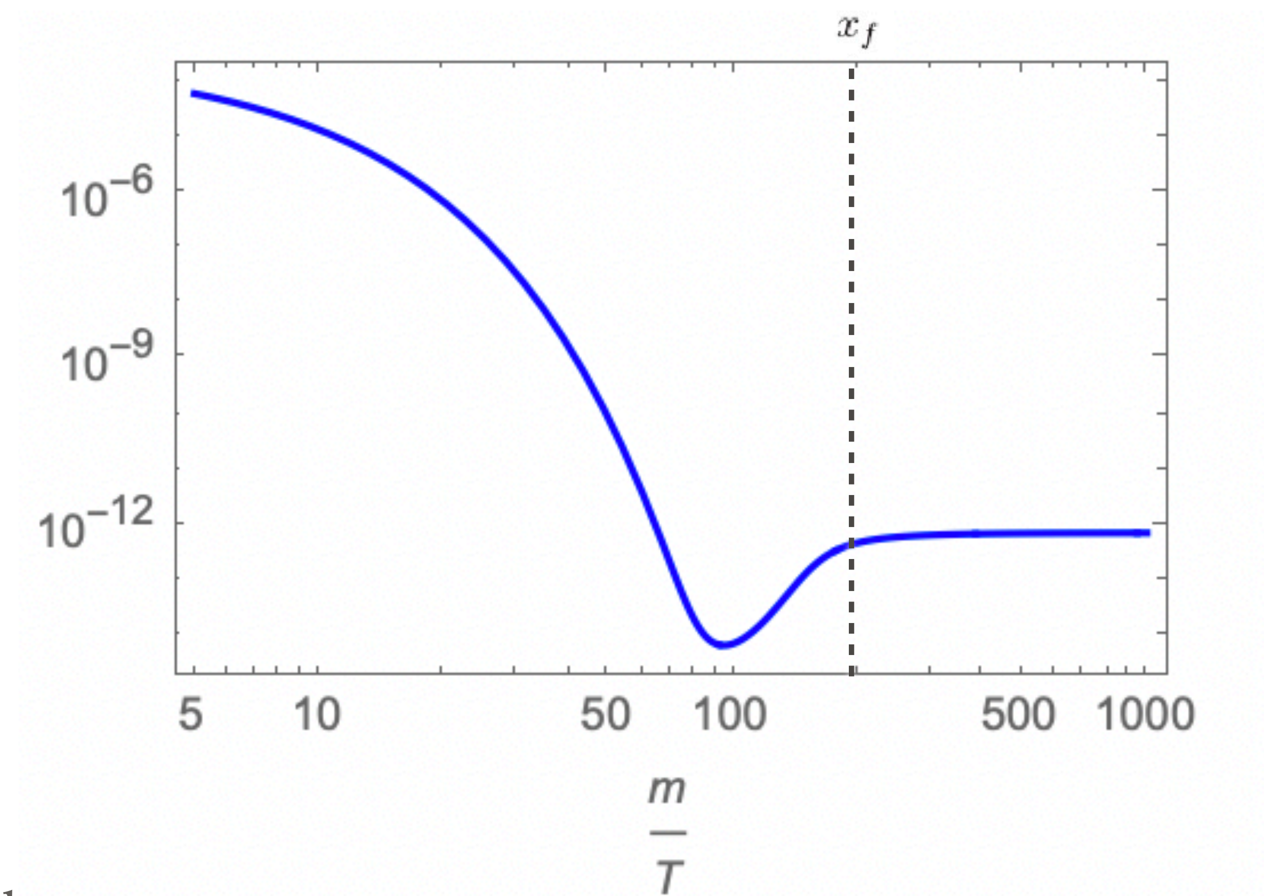
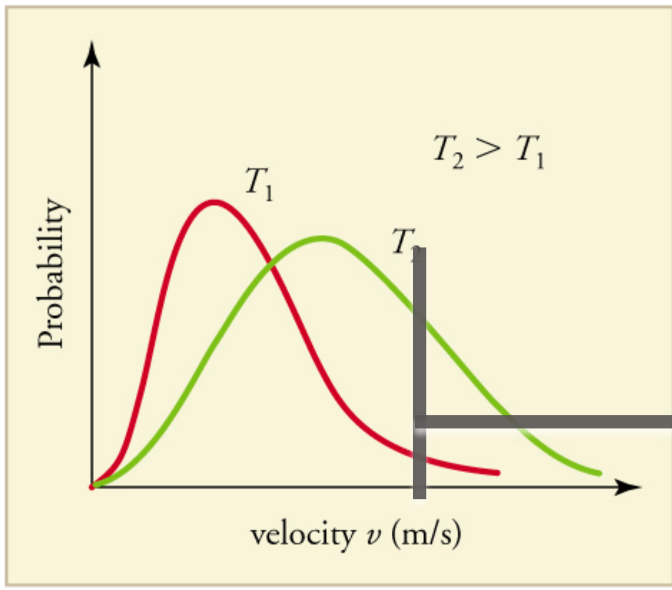
THIS TALK



Dark matter abundance undergoes the usual suppression, but **bounces up at late times** and freezes out with **an enhanced relic abundance**!

THERMAL FREEZEOUT: A CLOSER LOOK

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



$$\frac{dY}{dx} = \frac{-x\langle\sigma_{\psi\bar{\psi}\rightarrow X\bar{X}}|v|\rangle s}{H(m)}(Y^2 - Y_{EQ}^2)$$

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 → a smaller and smaller fraction of X distribution can participate → familiar exponential (Boltzmann) suppression

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

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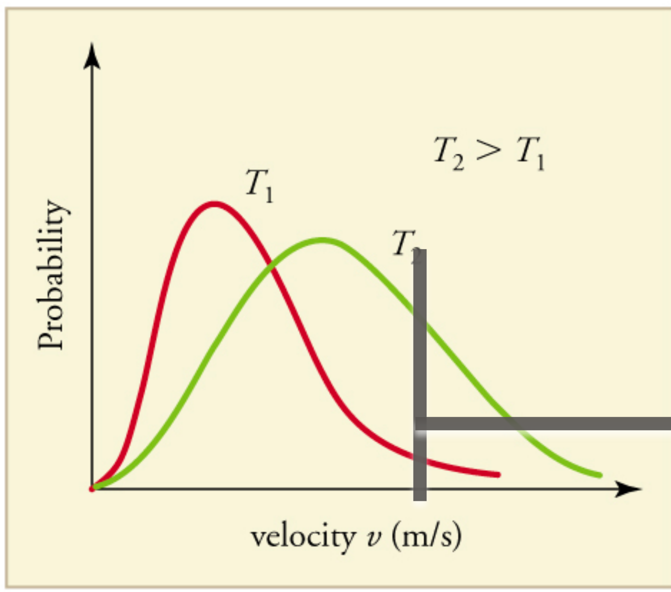

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Dark matter thermal histories in most models follows this pattern

- Interactions controlling DM freezeout feature **lighter particles** → (Inverse) processes that populate dark matter **need thermal support, grow weaker as the temperature falls** → 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)

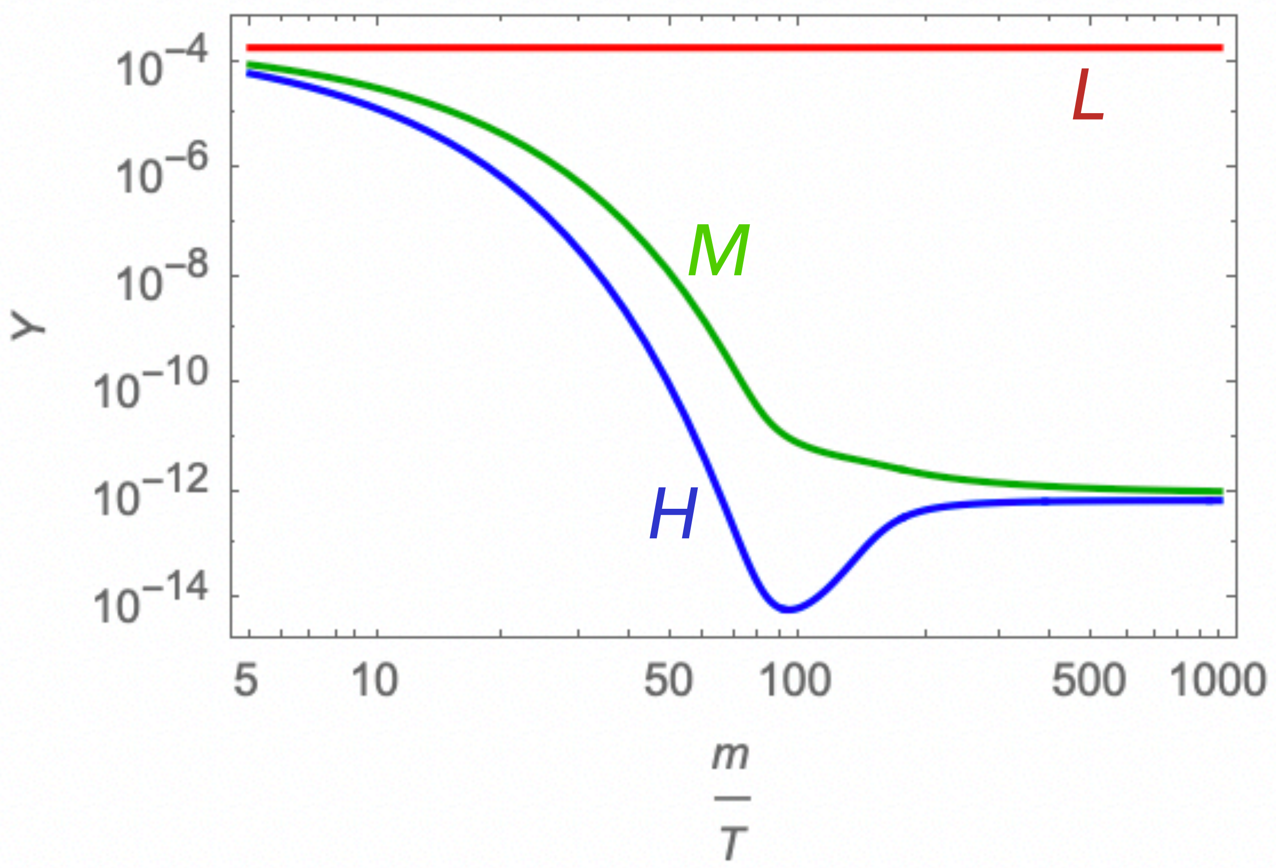
L (light)

All four particle interactions allowed, e.g.

HH↔LL, HH↔MM, HM↔ML, HM↔LL, MM↔HL …

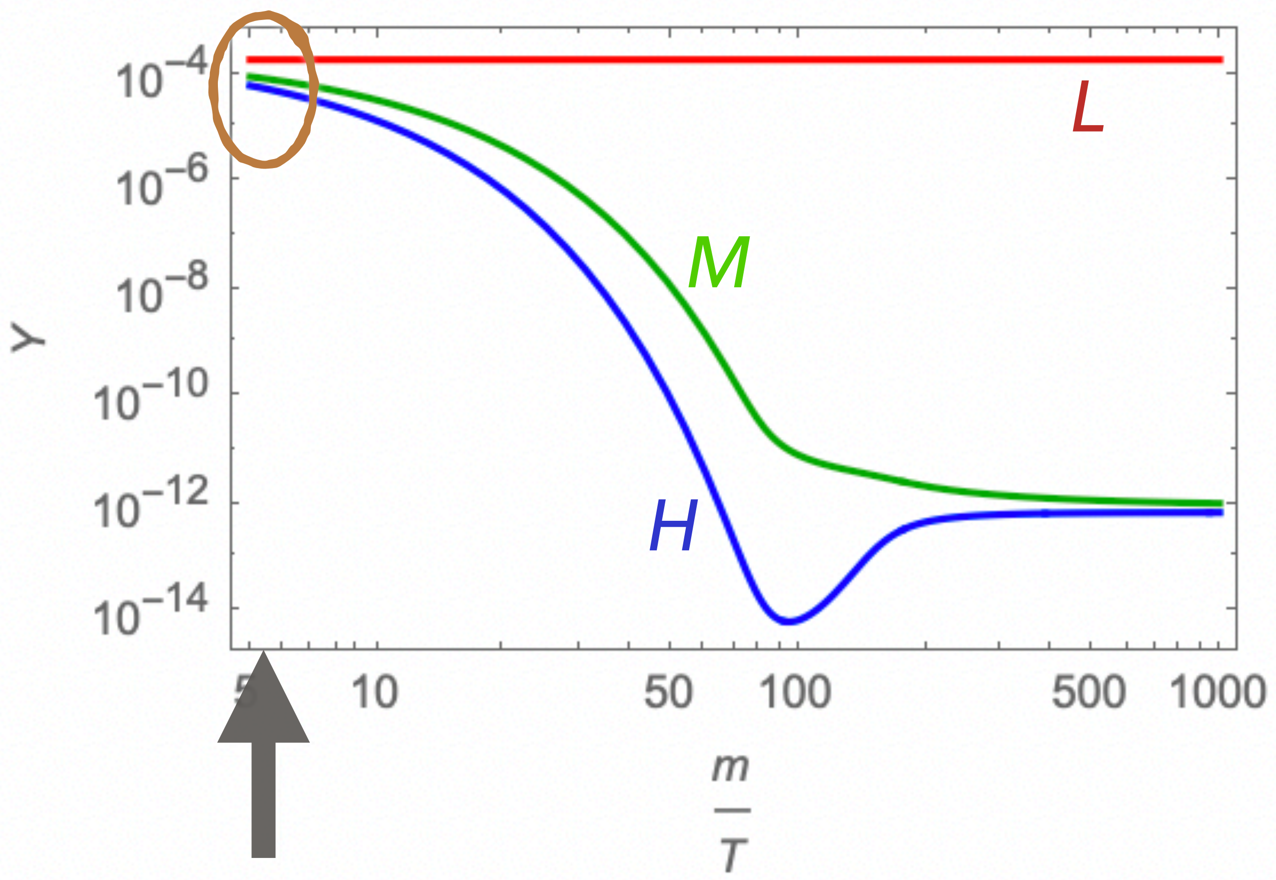
Key assumption: $2m_M > m_H + m_L$

COSMOLOGICAL HISTORY



- 200 GeV
- 240 GeV
- 260 GeV

COSMOLOGICAL HISTORY



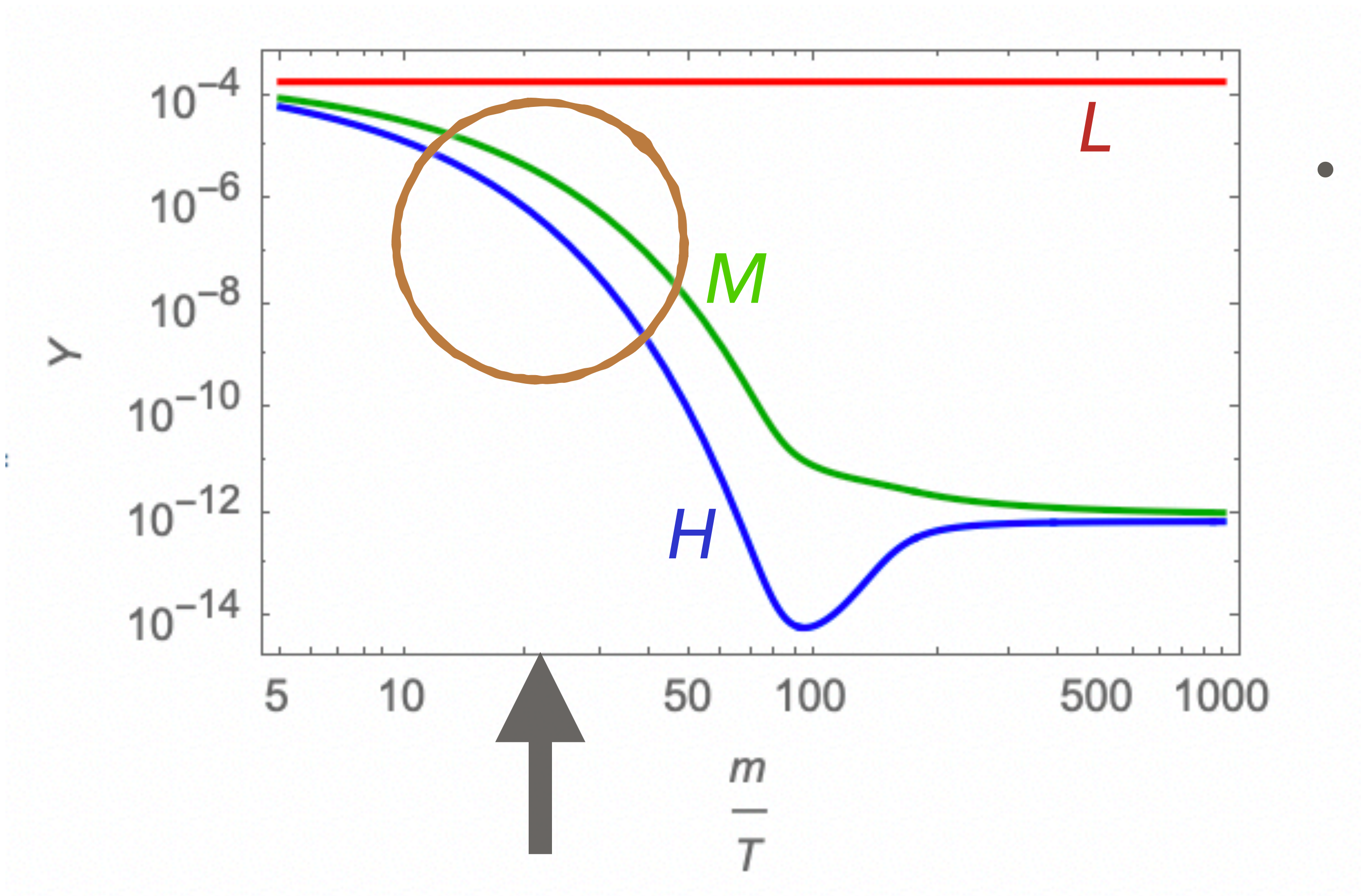
- Hidden sector out of (chemical) equilibrium from the SM thermal bath
- Comoving number density in the hidden sector (H+M+L) conserved
- Interactions between hidden sector species rapid

- 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↔M↔L to familiar Boltzmann suppression of heavier particles relative to the lighter ones

- Relation between chemical potentials:

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

$$n_i = n_i^{eq} e^{\mu_i/T}$$

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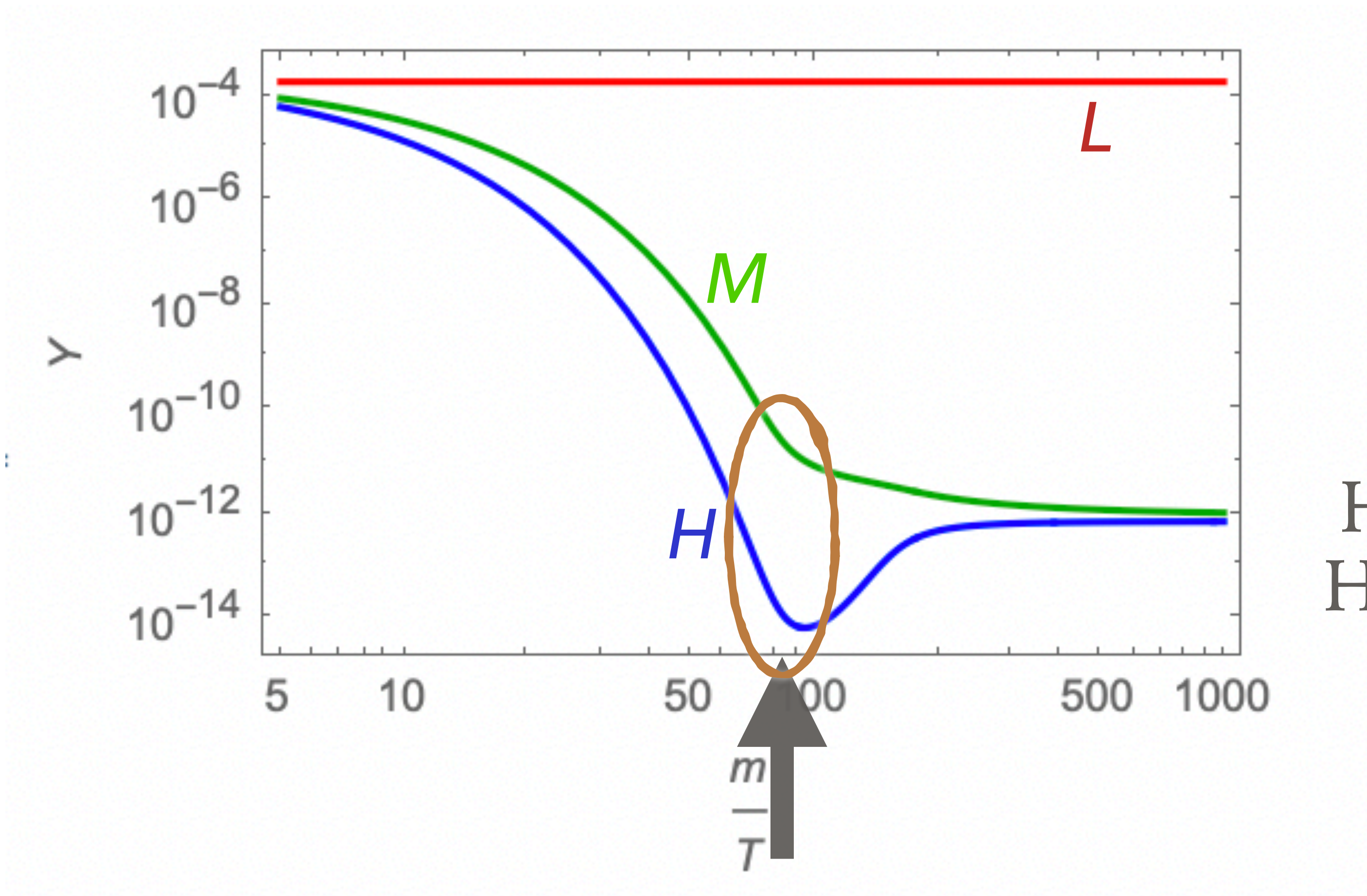


x~60

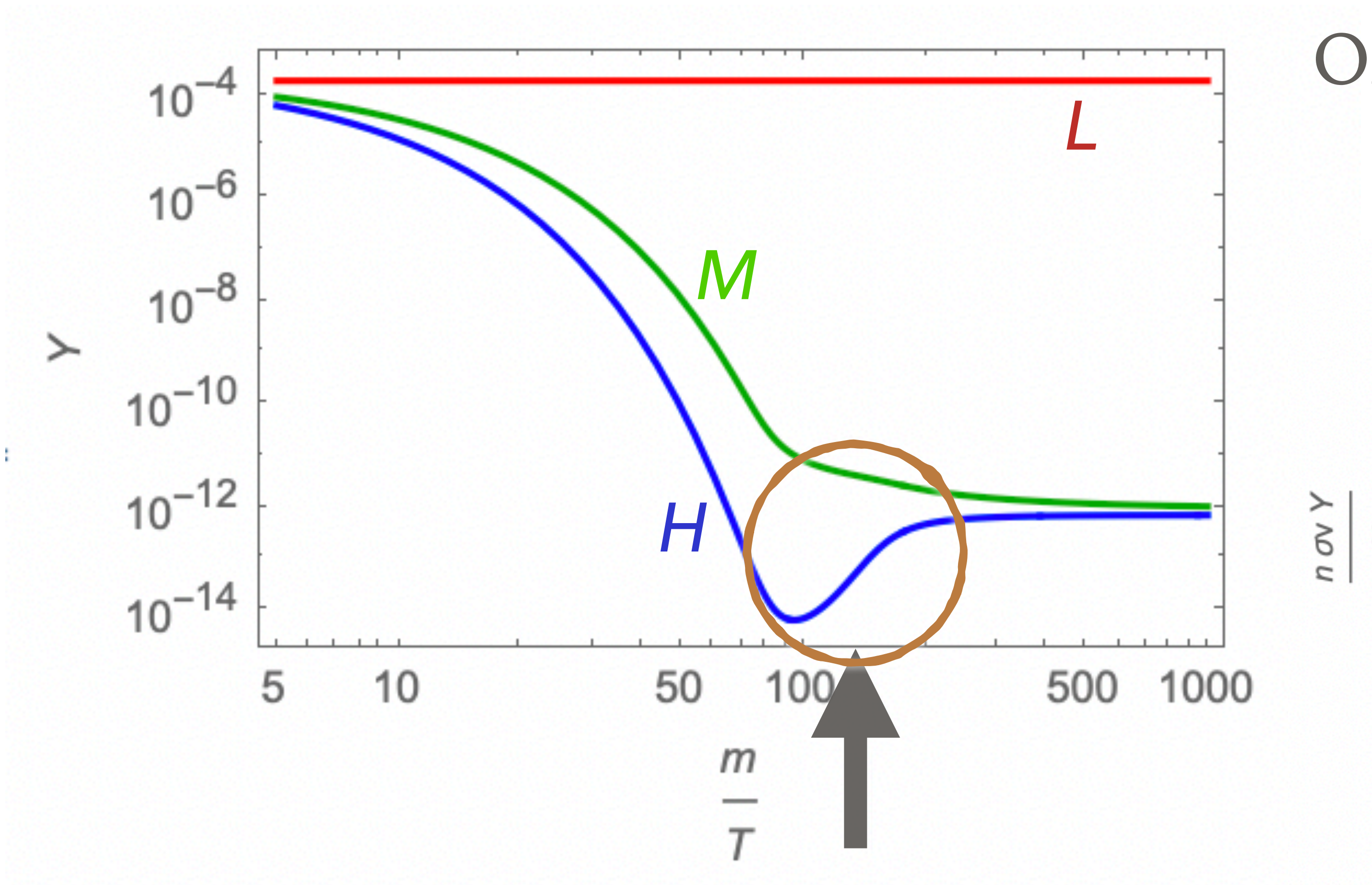
Most processes that destroy H(M) in favor of L (HH → MM, HH → LL, HL → LL, HM → ML) go out of equilibrium

- Relation between chemical potentials:

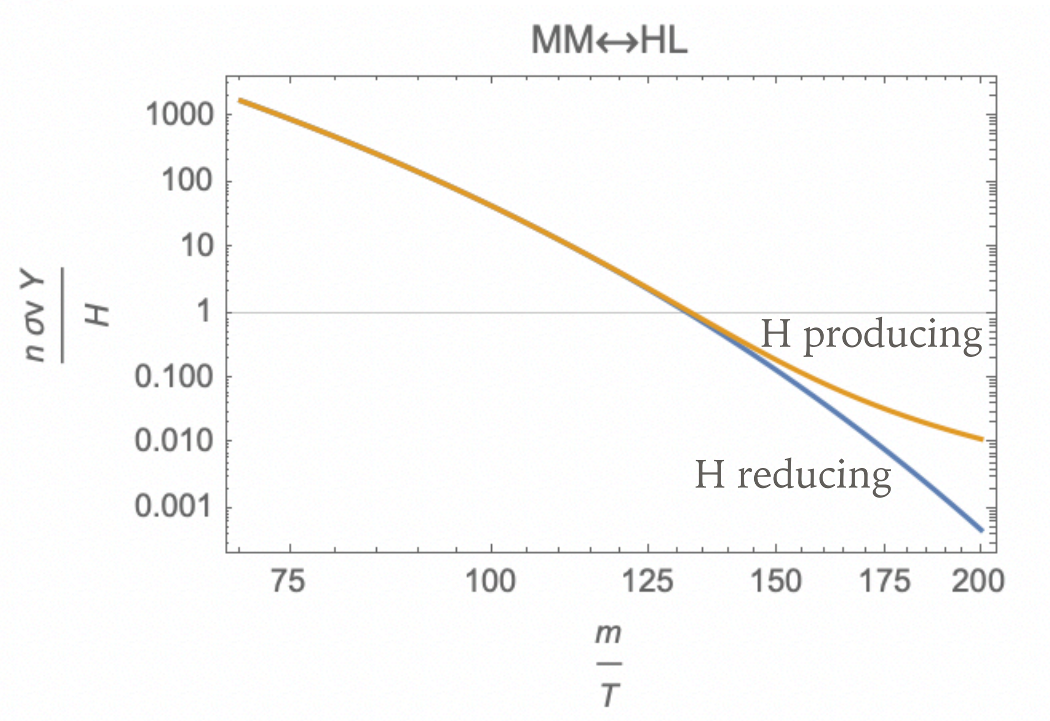
$$\mu_H = \mu_M = \mu_L$$

$$n_i = n_i^{eq} e^{\mu_i / T}$$

COSMOLOGICAL HISTORY



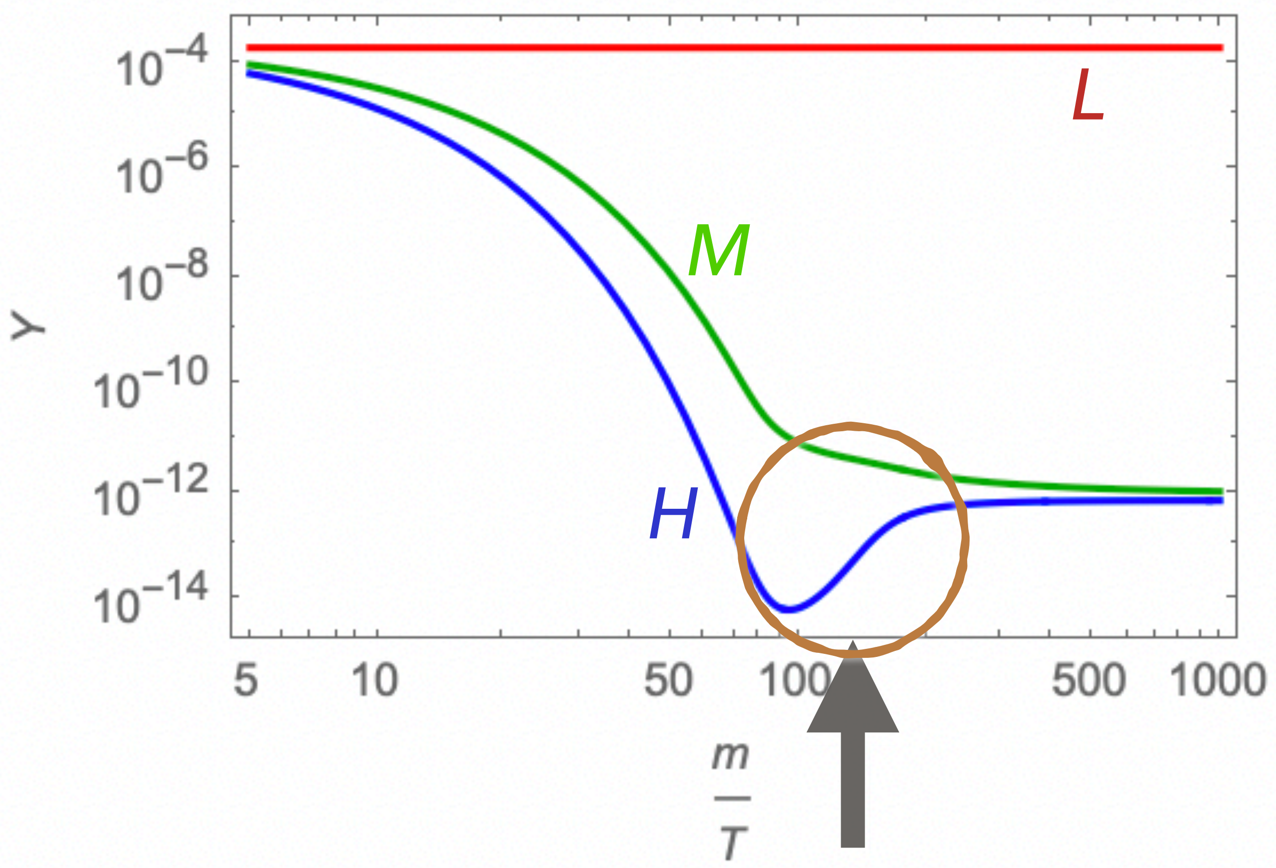
Only remaining rapid interaction:
MM↔HL



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

COSMOLOGICAL HISTORY



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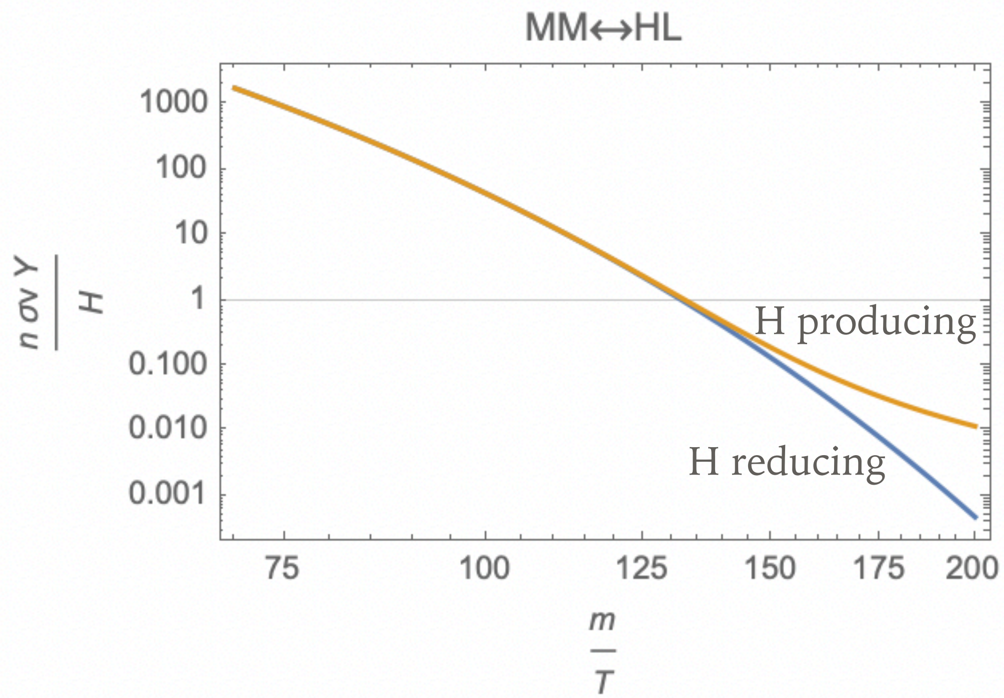


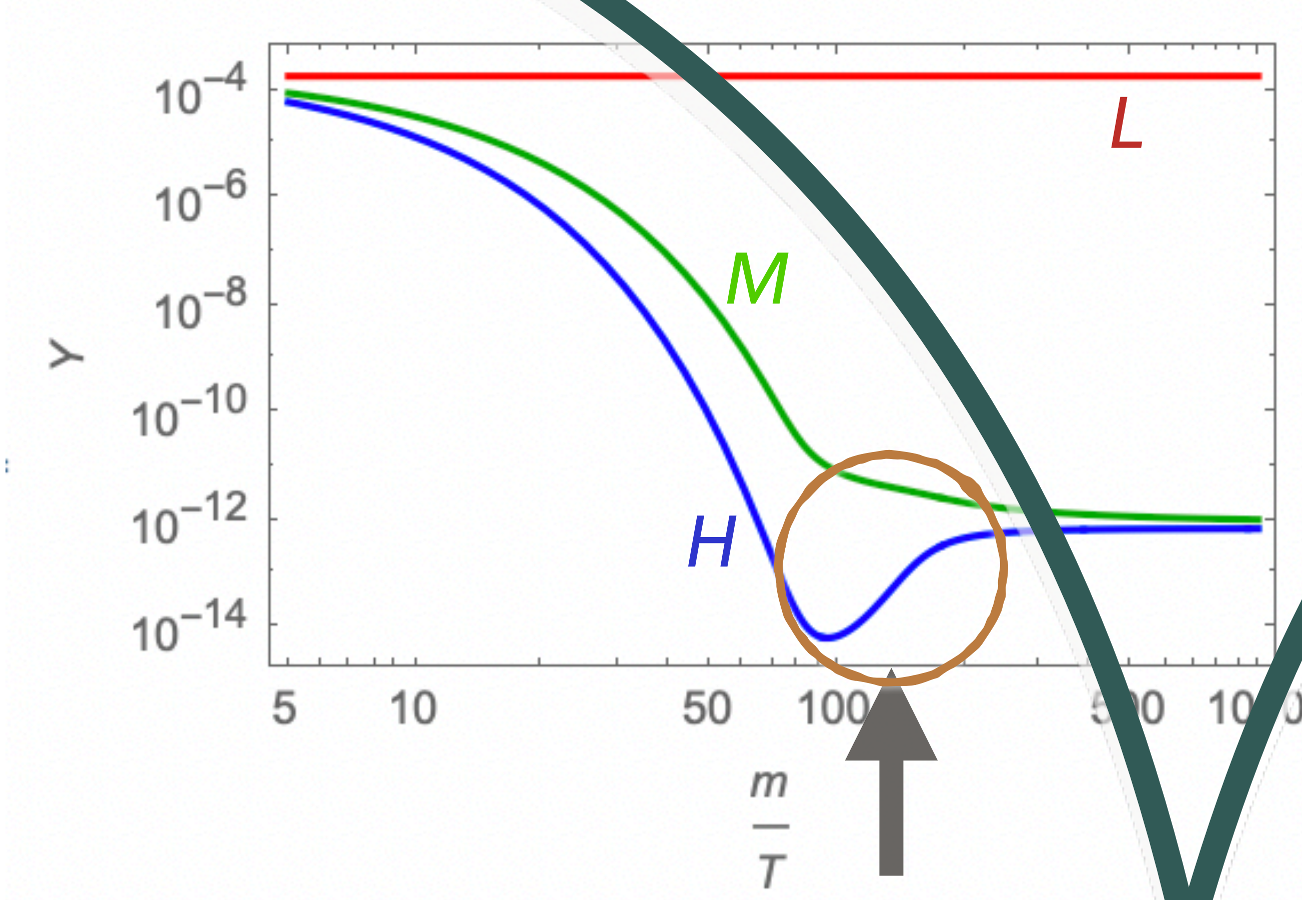
Modified relation for chemical potentials

$$2\mu_M = \mu_L + \mu_H$$

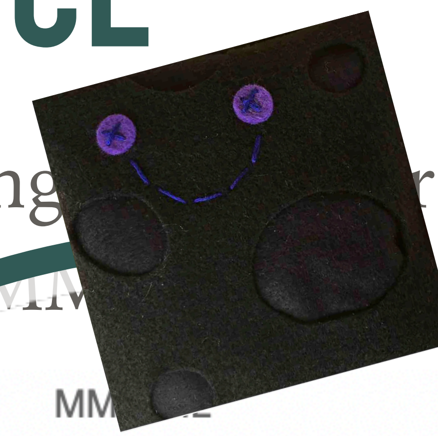
$$\mu_H = \mu_M = \mu_L$$

is no longer an acceptable solution to the Boltzmann equations

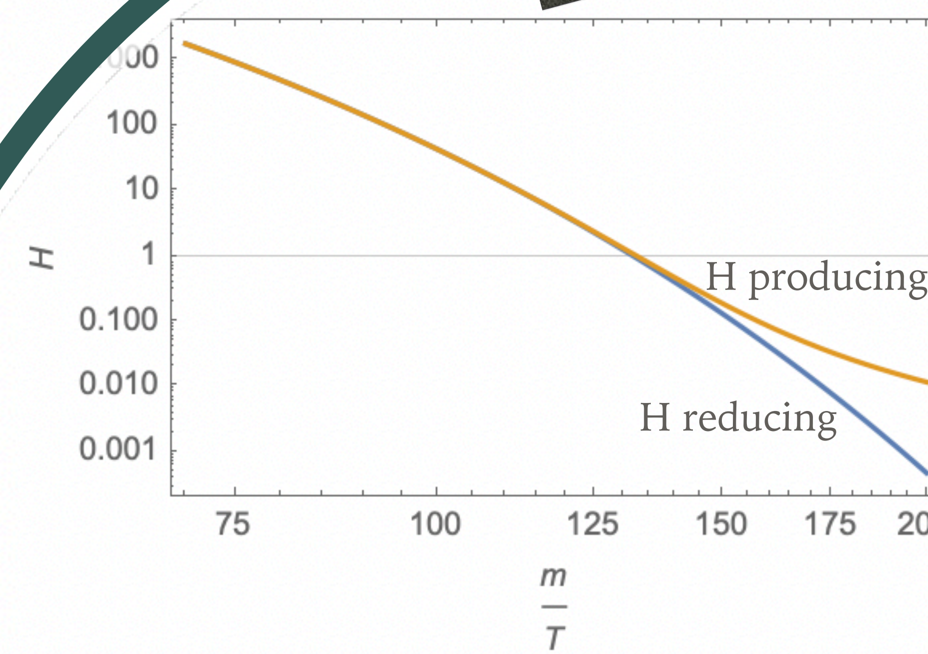
DARK MATTER WITH A BOUNCE



Only remaining … raction:



MM…



Final relic abundance of dark matter "bounces up" and can be larger by several orders of magnitude!

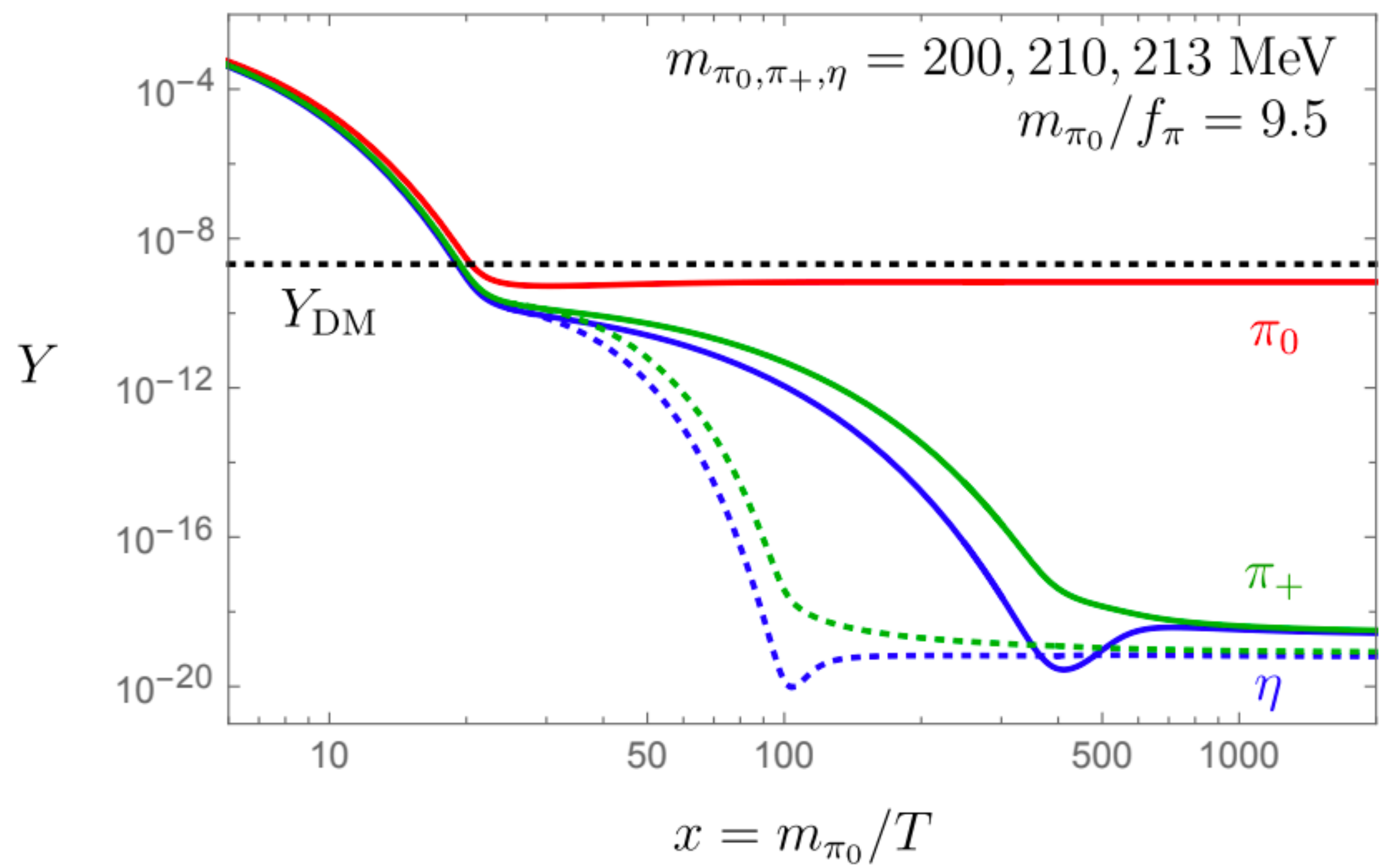
Corresponds to a "bounce" in its equilibrium distribution

$$\mu_H = \mu_M = \mu_L \longrightarrow 2\mu_M = \mu_L + \mu_H$$

CONTEXT

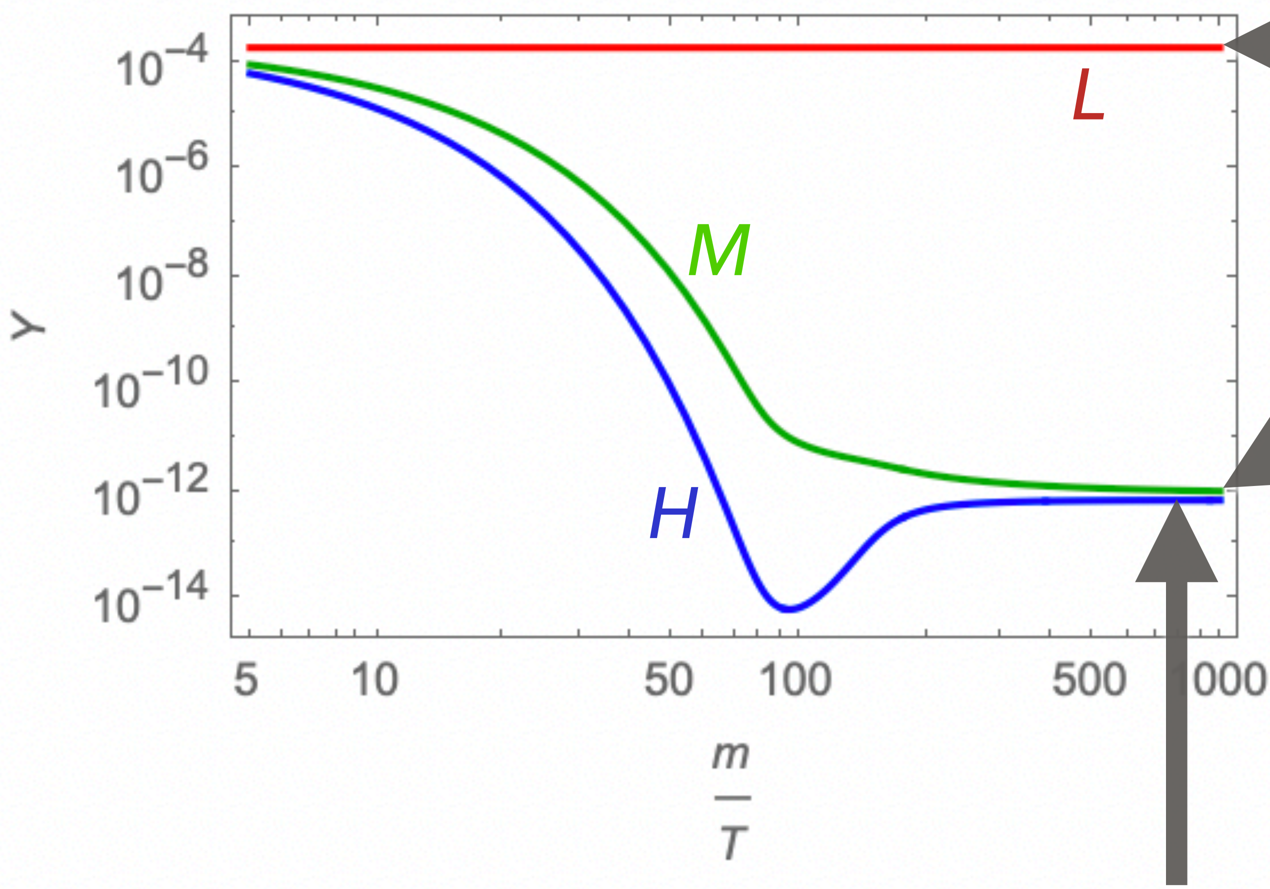
Can occur in realistic setups

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



"Split SIMPs with Decays"
Andrey Katz, Ennio Salvioni, Bibhushan Shakya
arXiv: 2006.15148 [hep-ph]

PARTICLE DECAYS

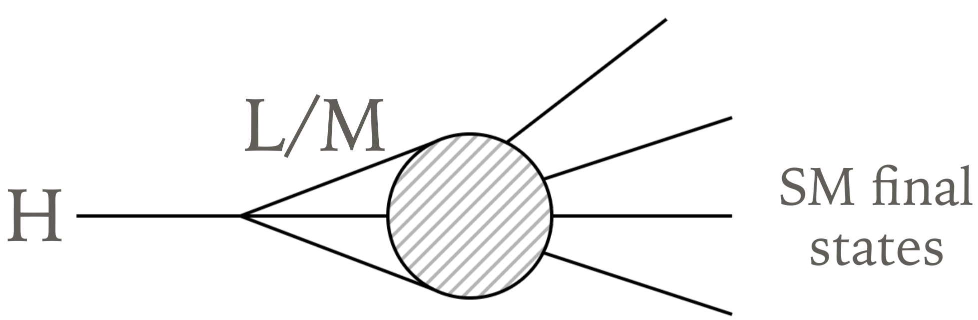


Too much L; needs to decay (before BBN)

M might be OK; could be effectively stable and a component of dark matter

H can be completely stable (if protected by a symmetry)

Or unstable on cosmological timescales (via L (M) loop decays)



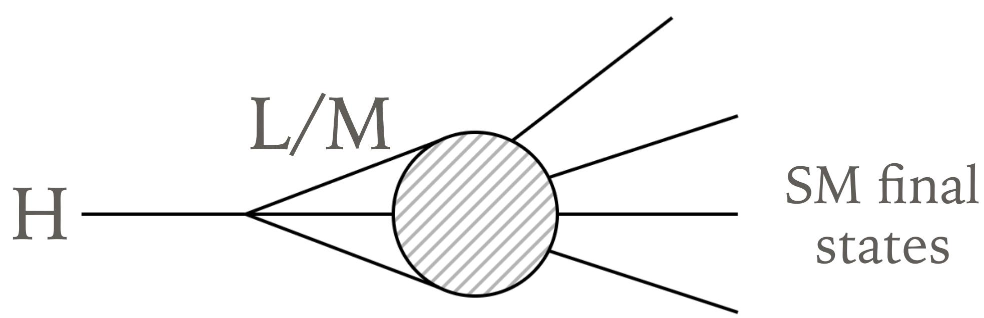
INDIRECT DETECTION SIGNALS

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: $\sim 10^{27}$ s

Long enough to be dark matter, short enough to see indirect detection signals!

ANOTHER EXAMPLE

As another illustration of the mechanism, consider a different setup

A dark sector with two particles:

H (heavy; dark matter)

L (light)

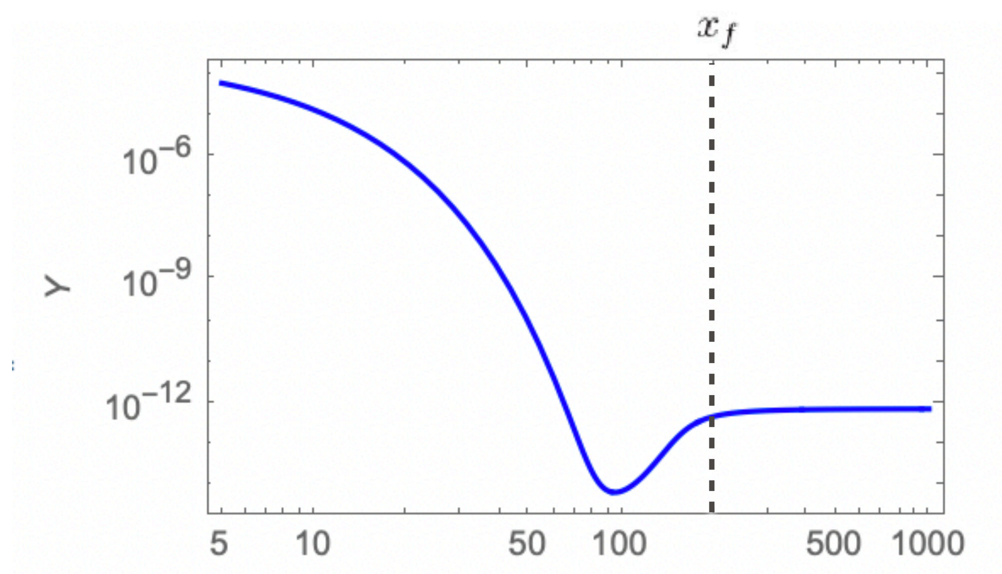
Final interaction to decouple:

$3 \to 2$ process $3L \to 2H$

Key assumption: $3m_L > 2m_H$

Bounce: $\mu_H = \mu_L \longrightarrow 3\mu_L = 2\mu_H$

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**