DARK MATTER WITH A BOUNCE

MARCH 29, 2021

ASPEN CENTER FOR PHYSICS
2021 VIRTUAL WINTER CONFERENCE
A RAINBOW OF DARK SECTORS

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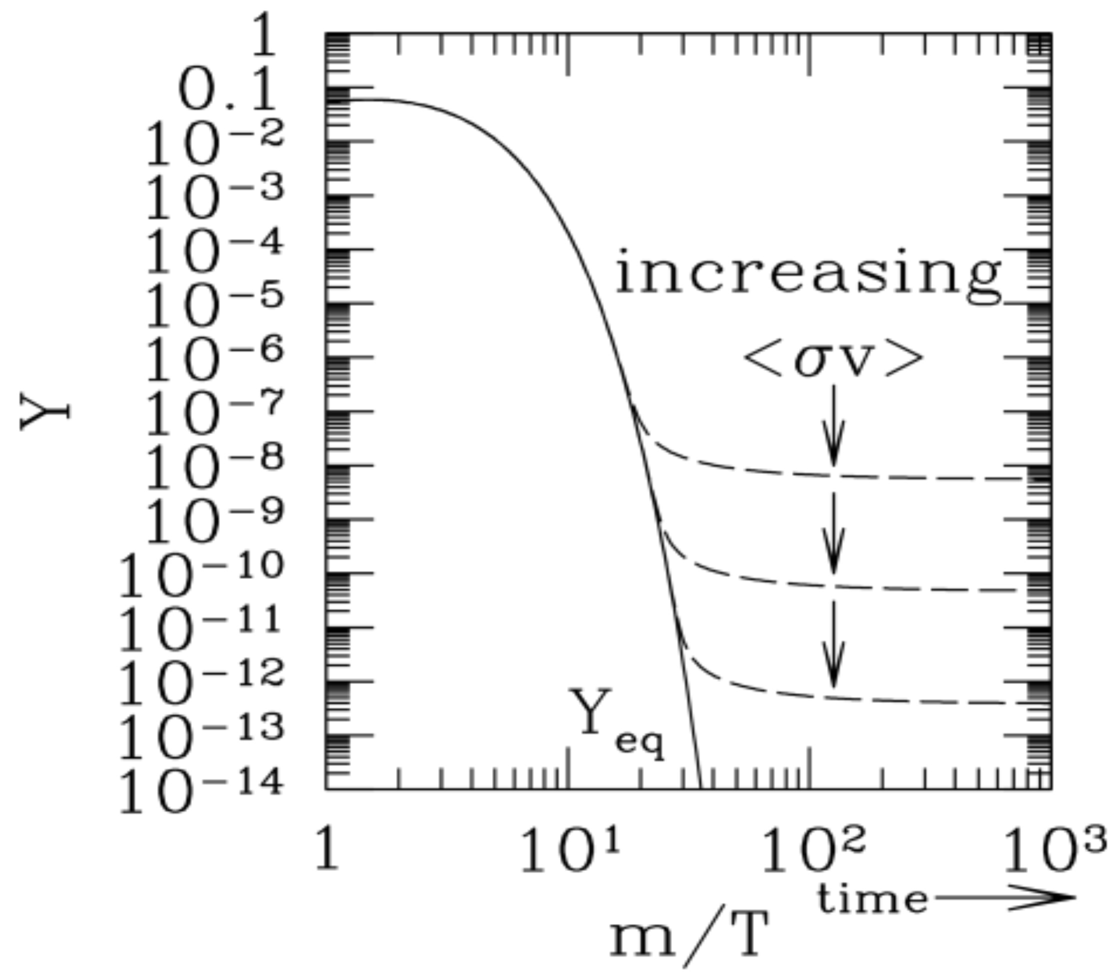
DESY.

BASED ON 2104.XXXXX WITH JOSHUA RUDERMAN, ENNIO SALVIONI

DARK MATTER : HOW DID IT GET HERE?

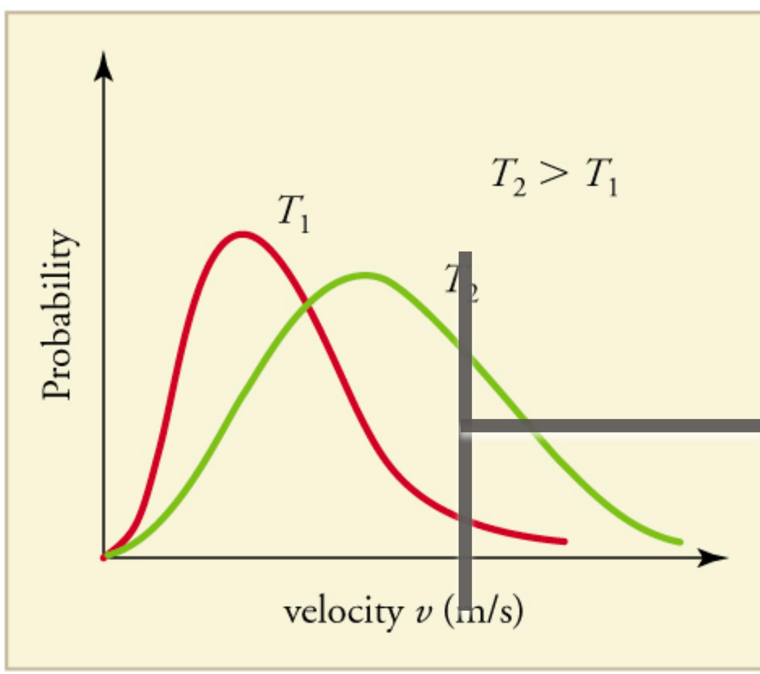


The most popular paradigm: Thermal Freezeout

If significant interactions establish equilibrium with the thermal bath, dark matter traces a thermal abundance, getting Boltzmann suppressed and freezing out when the interactions become slower than the Hubble rate

THERMAL FREEZEOUT: A CLOSER LOOK

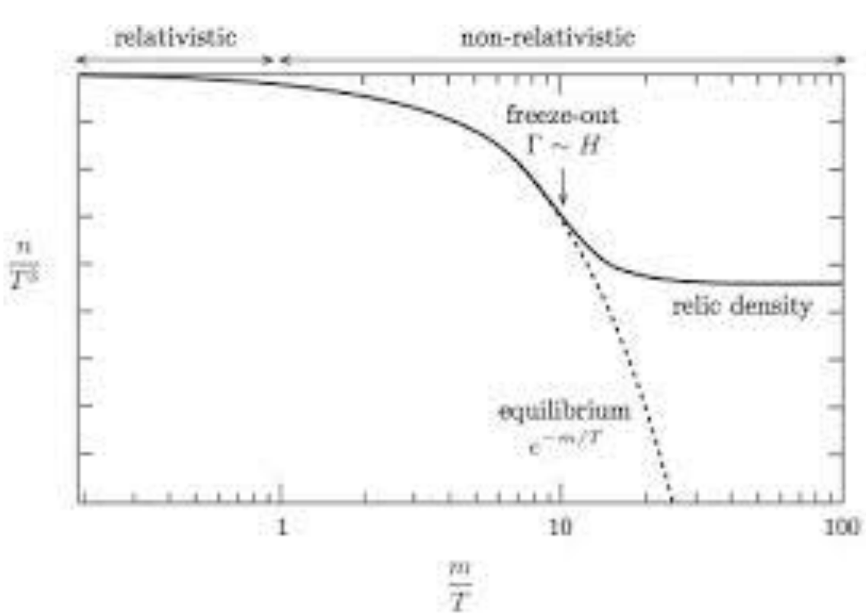
If dark matter primarily annihilates into species X in the bath $\psi\psi \leftrightarrow XX$



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

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



As T decreases, a smaller and smaller fraction of X distribution has enough energy to produce dark matter, hence the dark matter equilibrium abundance gets the familiar exponential (Boltzmann) suppression

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

THERMAL FREEZEOUT: A CLOSER LOOK

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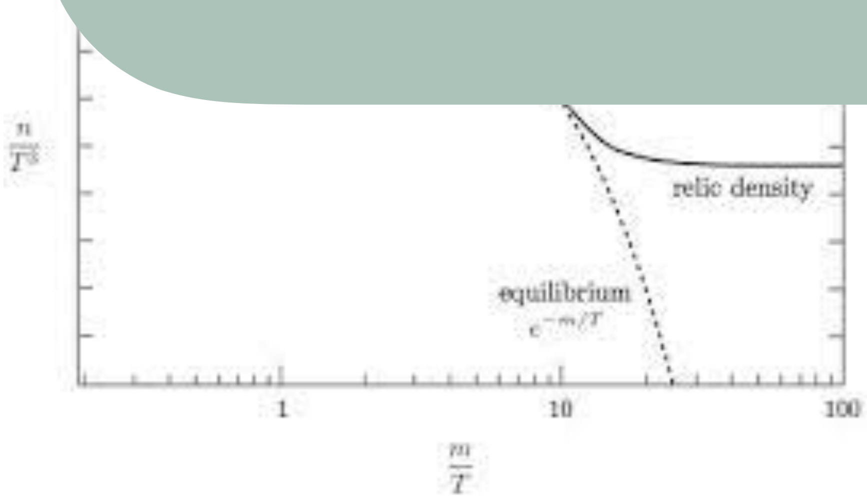
Most variations of a thermal dark matter history share these features:

- Dark matter number changing processes faster than Hubble
- (Inverse) processes that populate dark matter need thermal support, and grow weaker as the temperature falls

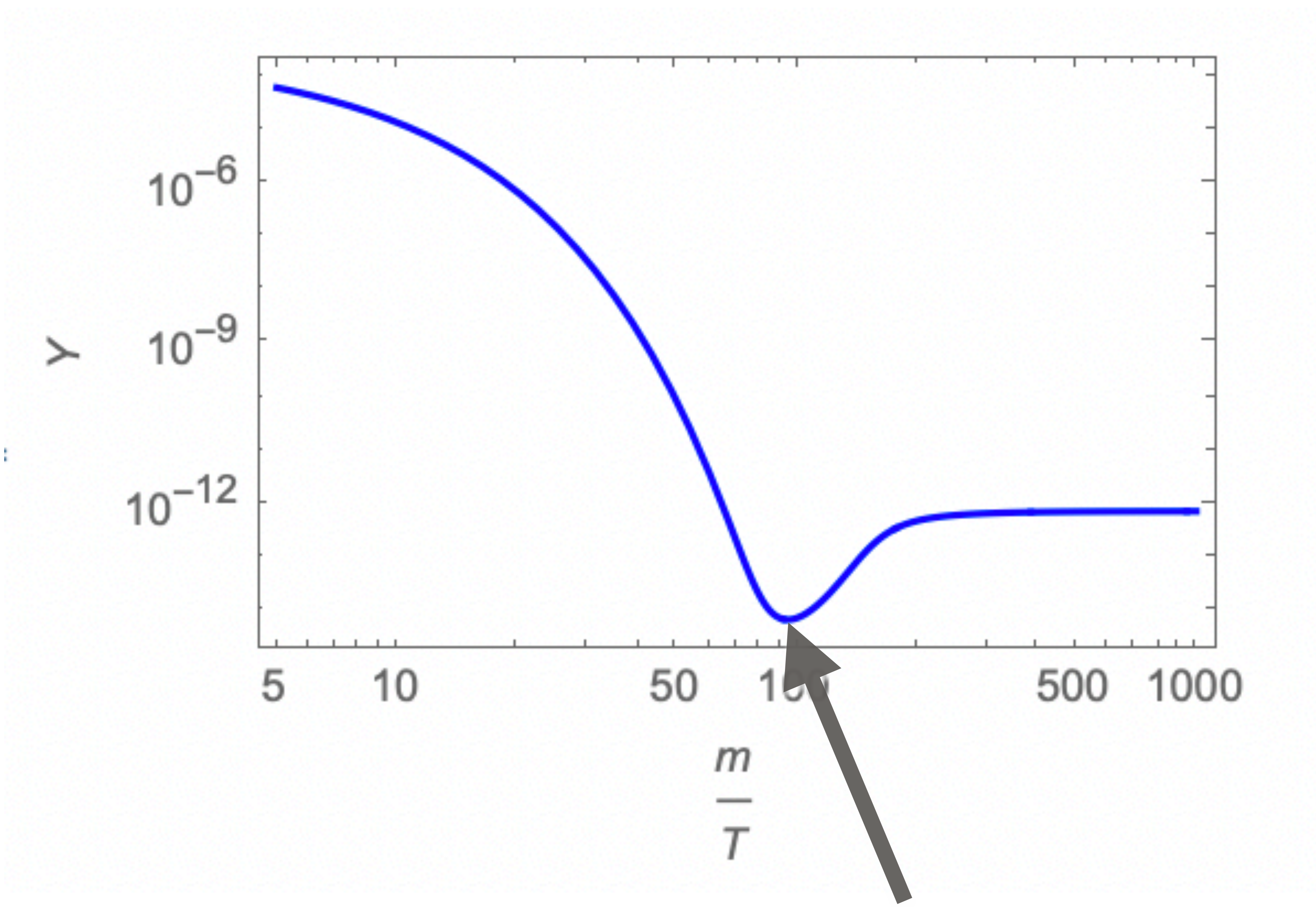
Result: dark matter abundance **follows an exponentially falling curve, freezes out** at some point



(Boltzmann) suppression

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

THIS TALK:



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

A MODIFIED DARK MATTER SETUP

(Unspoken) assumptions in dark matter thermal freezeout frameworks:

- Dark matter carries an **effective Z_2 symmetry**
- Dark matter producing processes require thermal support

Entirely plausible, but not necessary!!!

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)

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HH↔LL, HH↔MM, HM↔ML, HM↔LL, MM↔HL …

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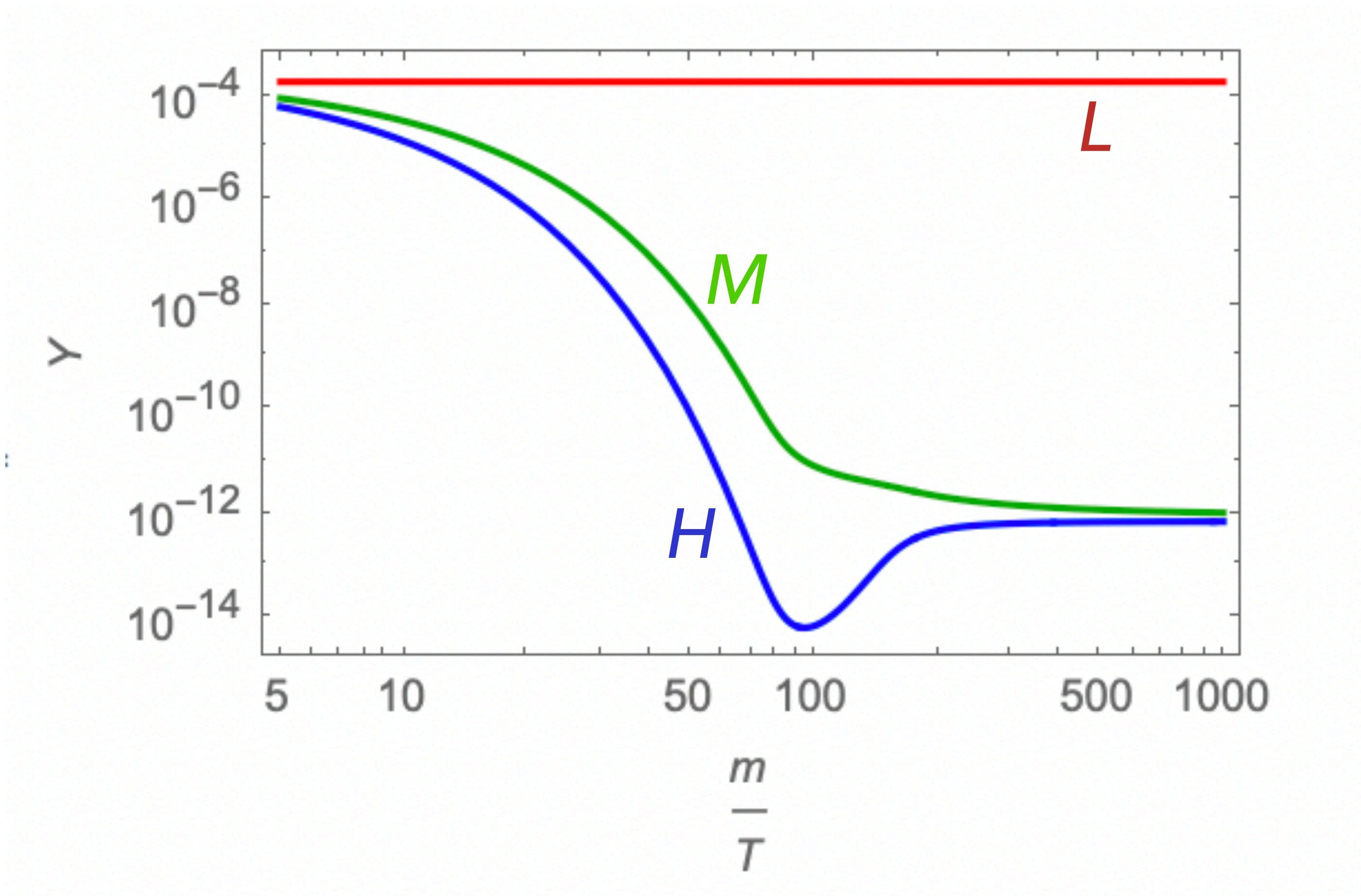
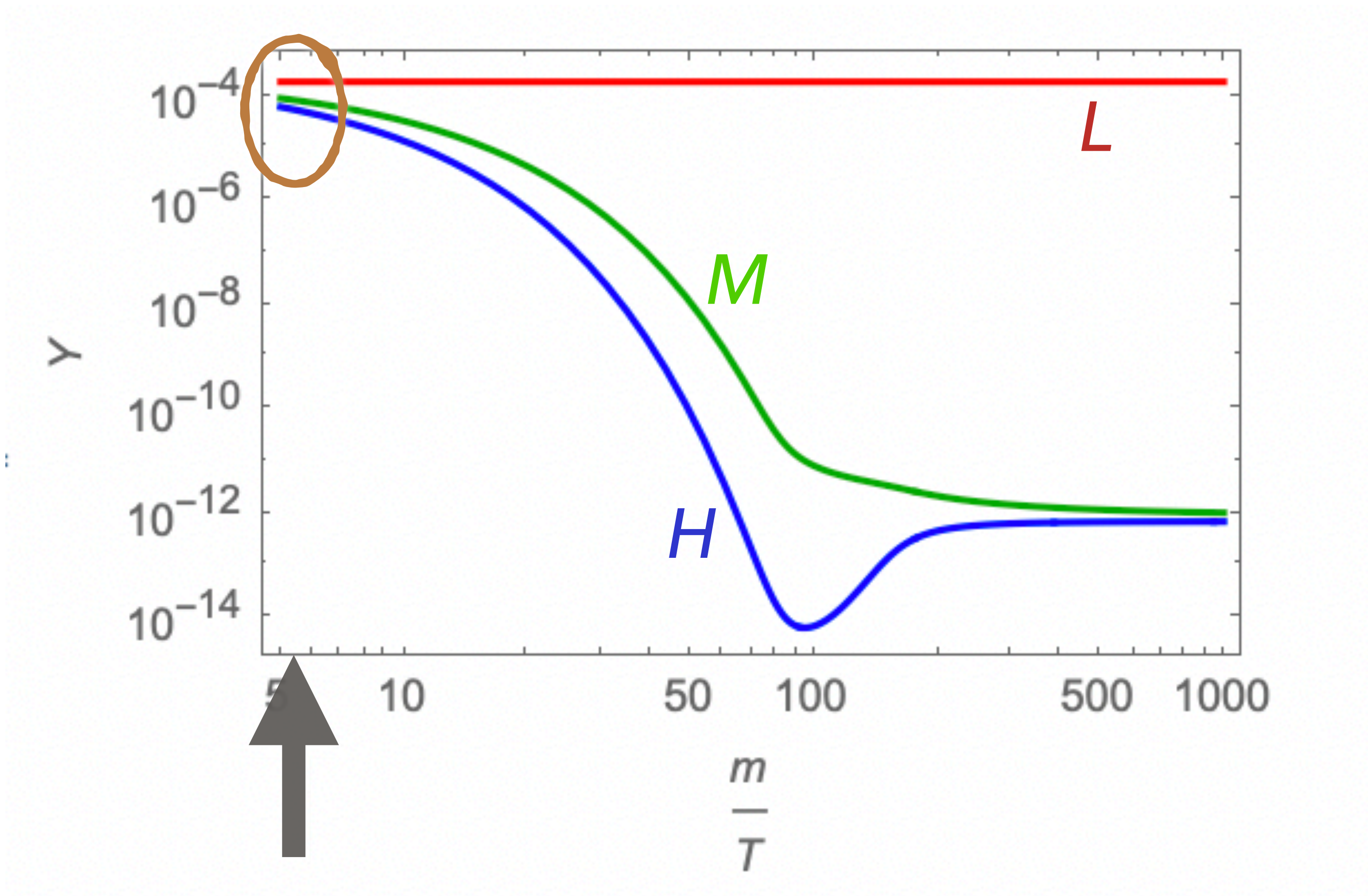
Key assumption: $2m_M > m_H + m_L$

COSMOLOGICAL HISTORY



- 200 GeV
- 240 GeV
- 260 GeV

COSMOLOGICAL HISTORY



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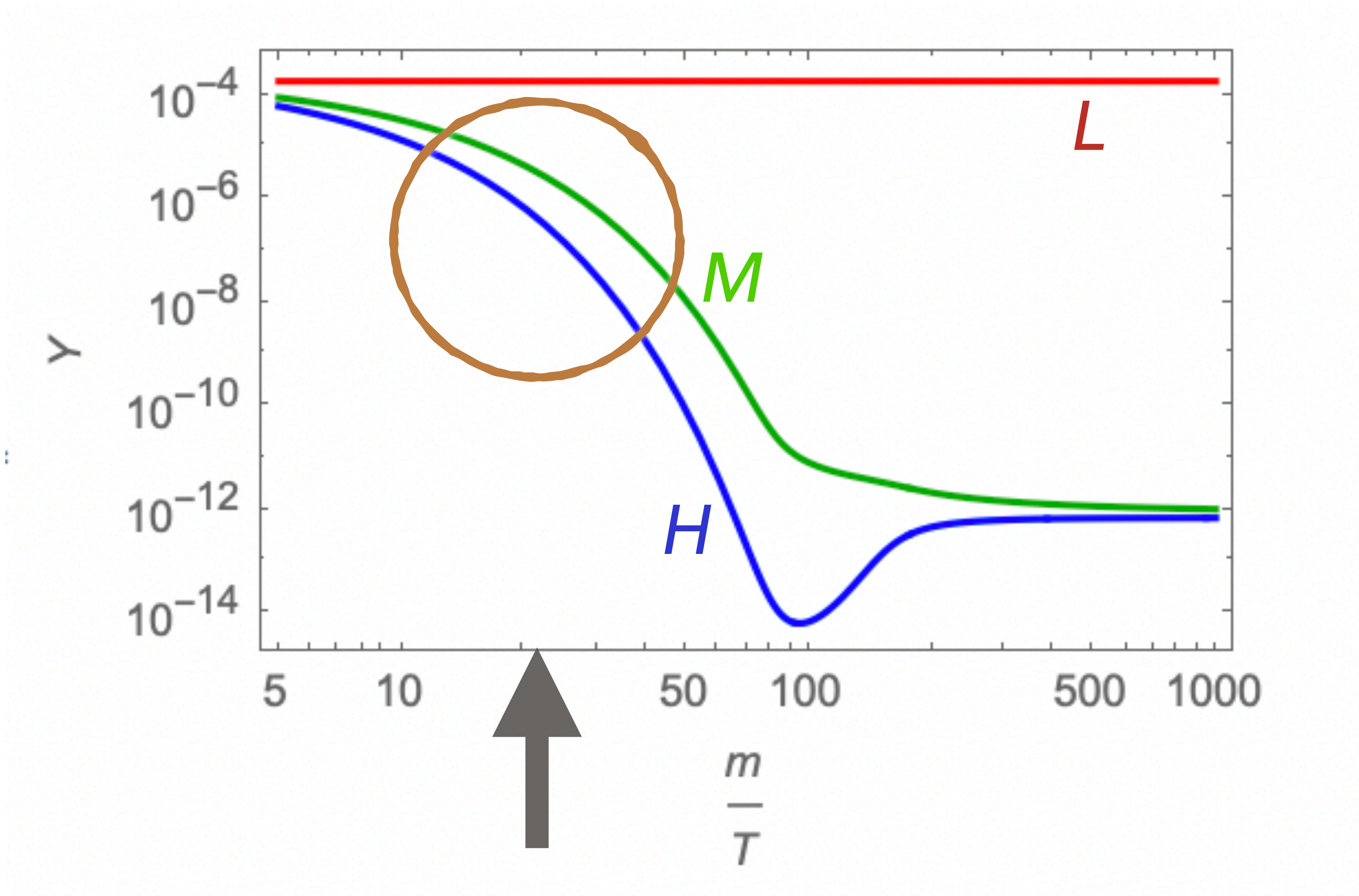
- Hidden sector out of (chemical) equilibrium from the SM thermal bath
- Comoving number density in the hidden sector (H+M+L) conserved
- Interactions between hidden sector species rapid

COSMOLOGICAL HISTORY



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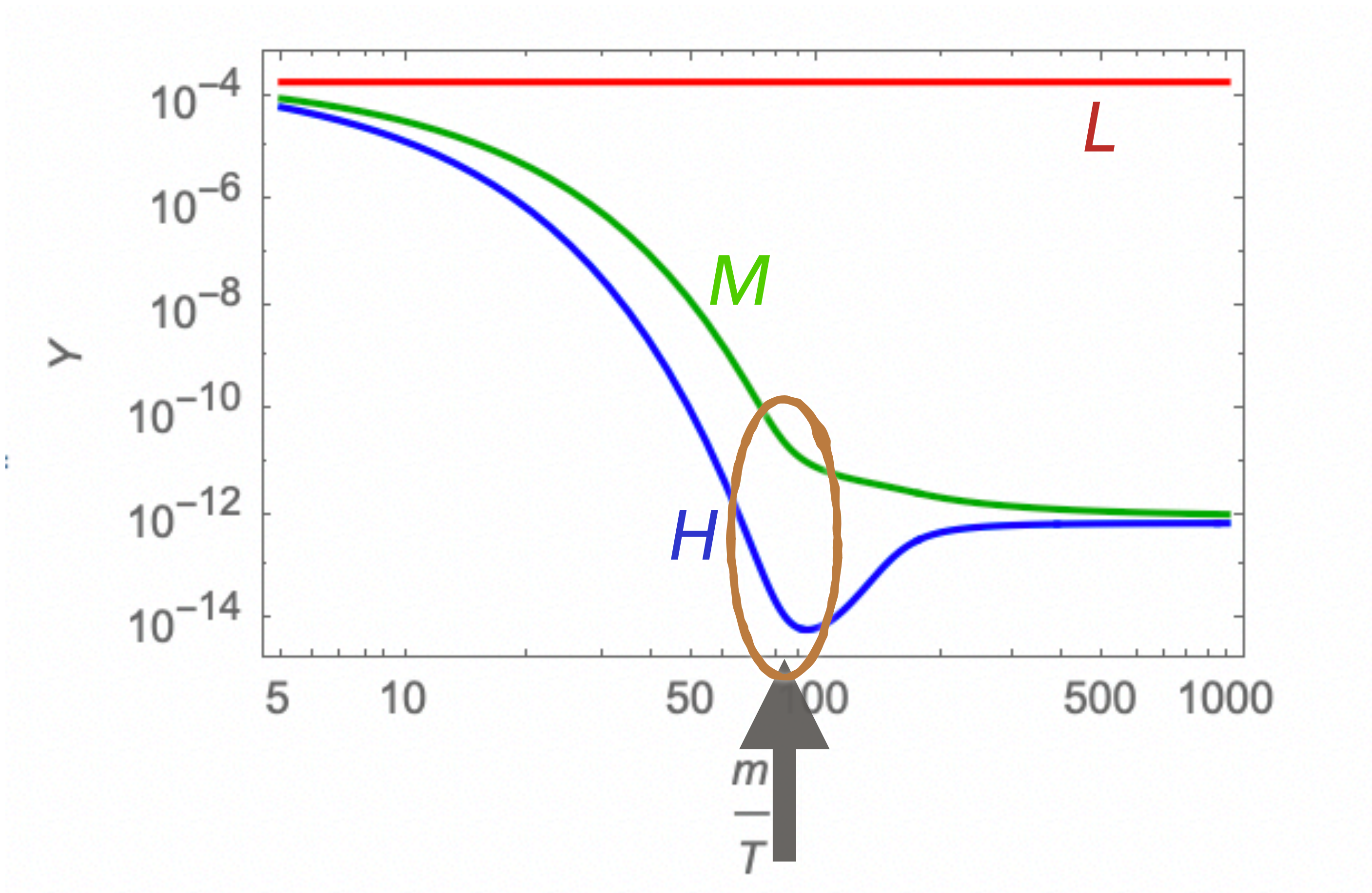
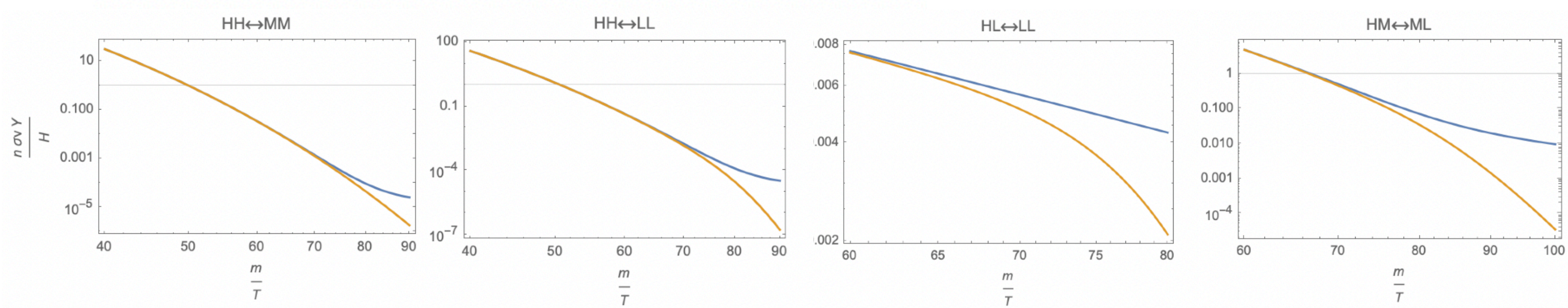
- Rapid hidden sector interactions interconverting H↔M↔L to familiar Boltzmann suppression of heavier particles relative to the lighter ones

COSMOLOGICAL HISTORY



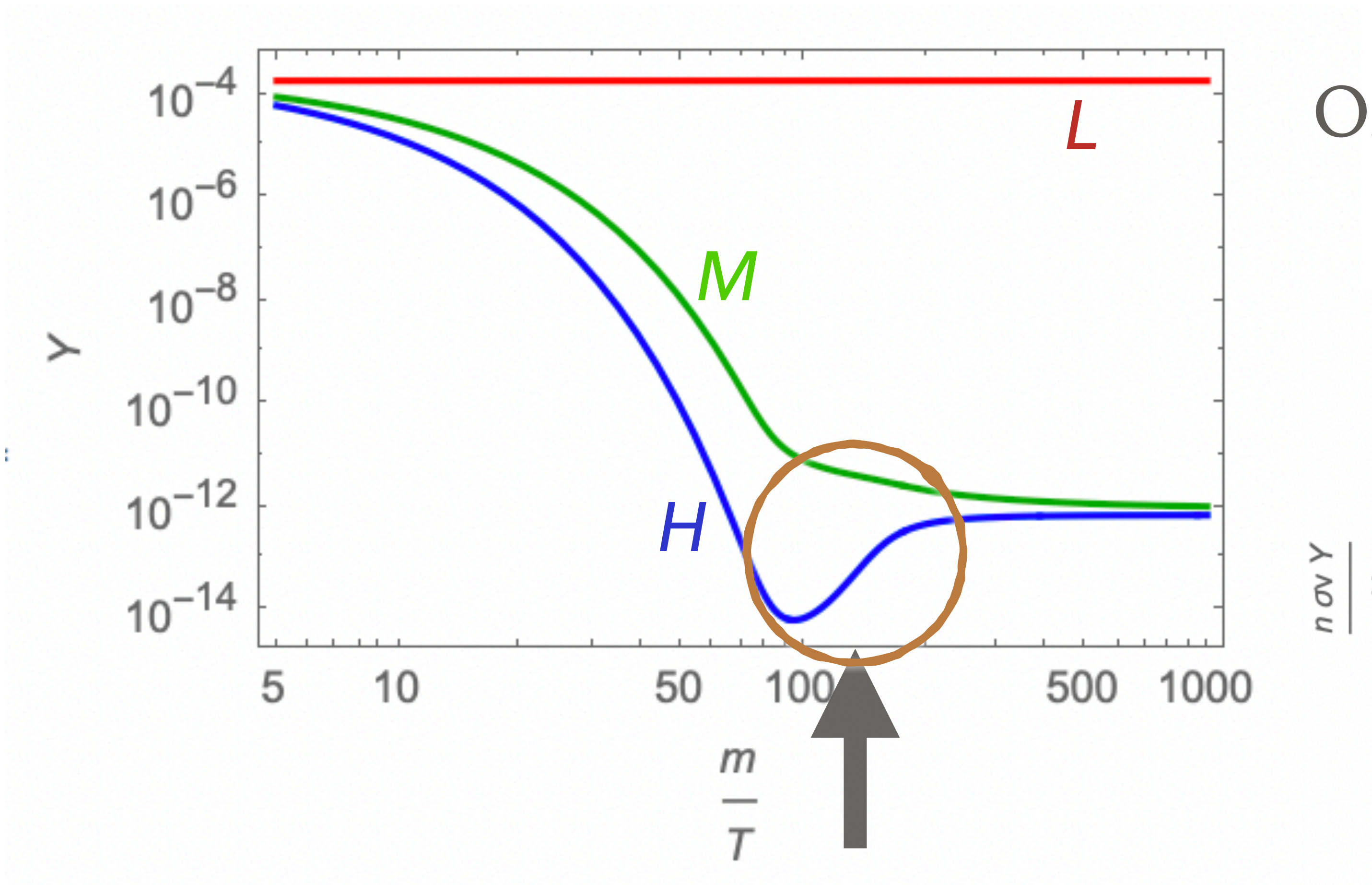
x~60

Most processes that destroy H(M) in favor of L go out of equilibrium

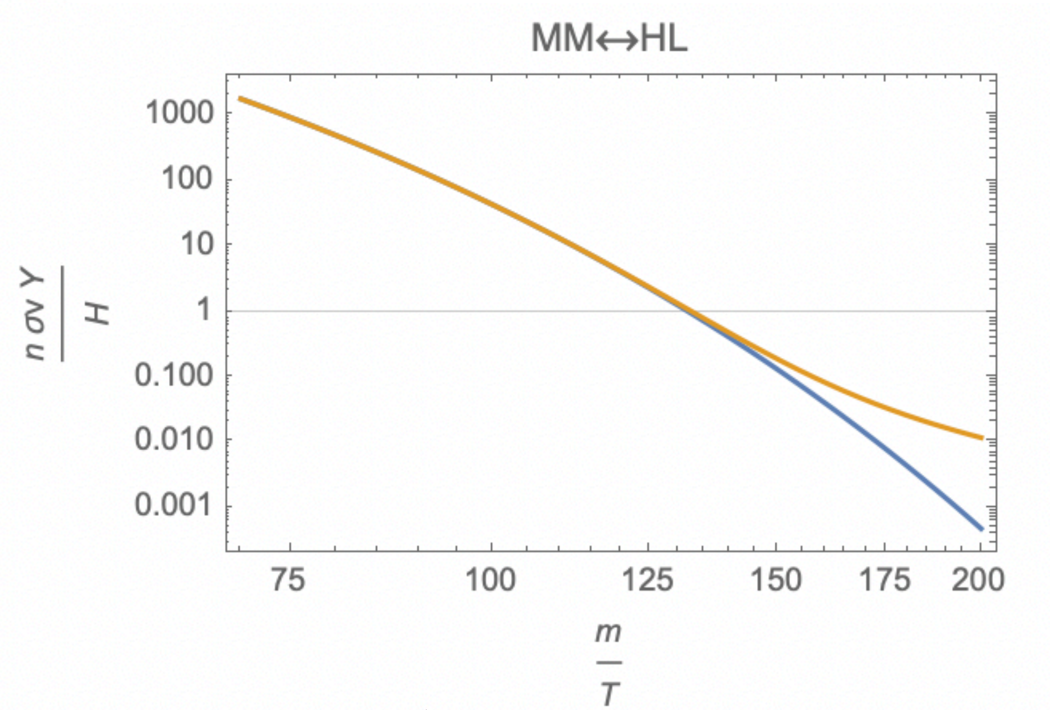


orange(blue): forward (reverse) process

COSMOLOGICAL HISTORY



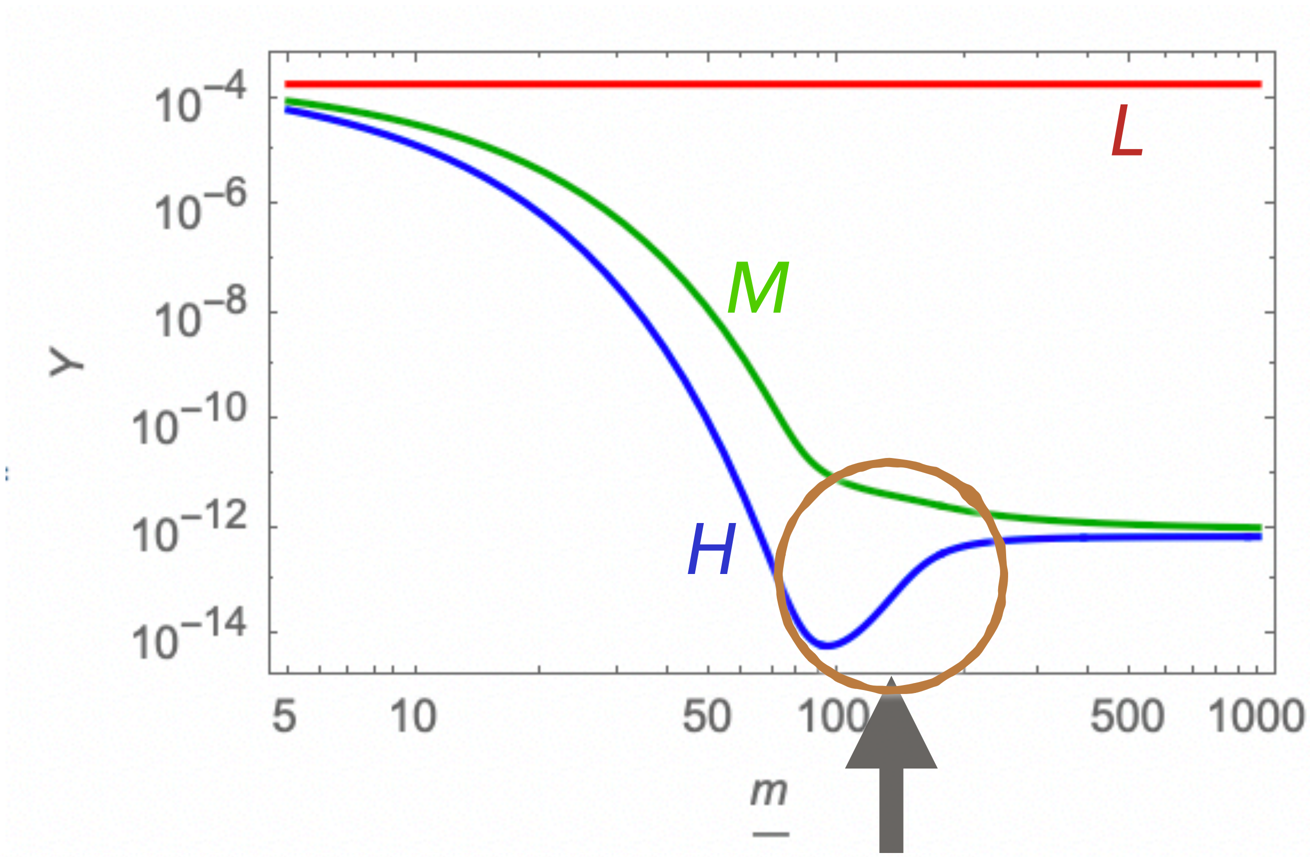
Only remaining rapid interaction:
MM↔HL



Boltzmann suppression logic reversed:

MM ->HL can proceed at zero temperature; the reverse needs thermal support, so the former is more “favored”!

COSMOLOGICAL HISTORY



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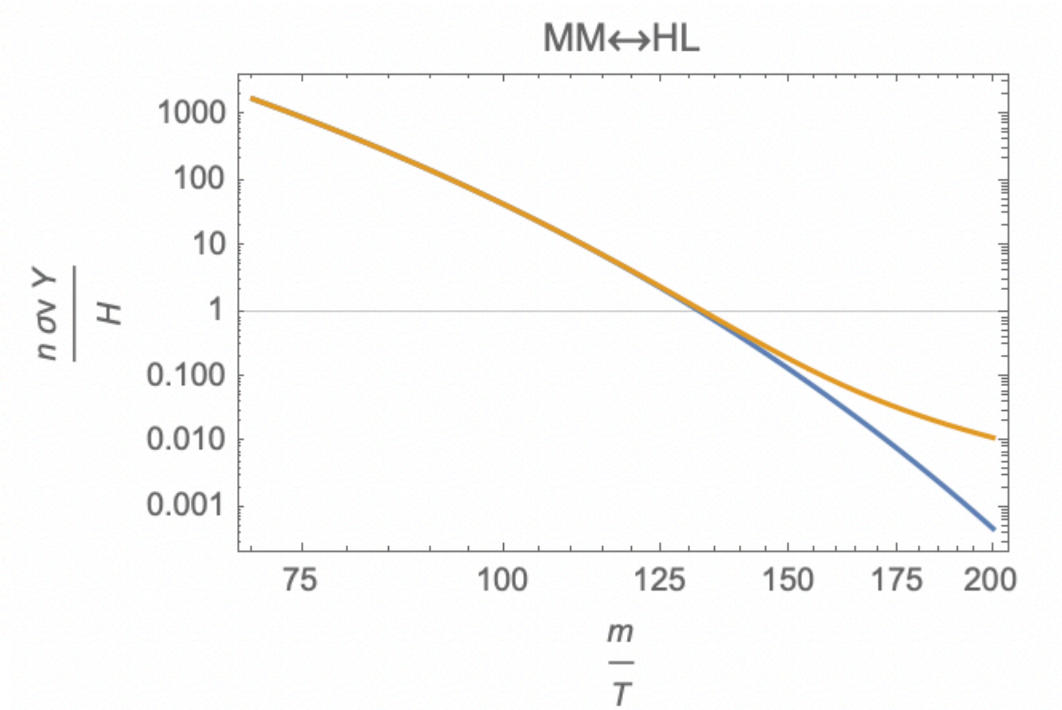
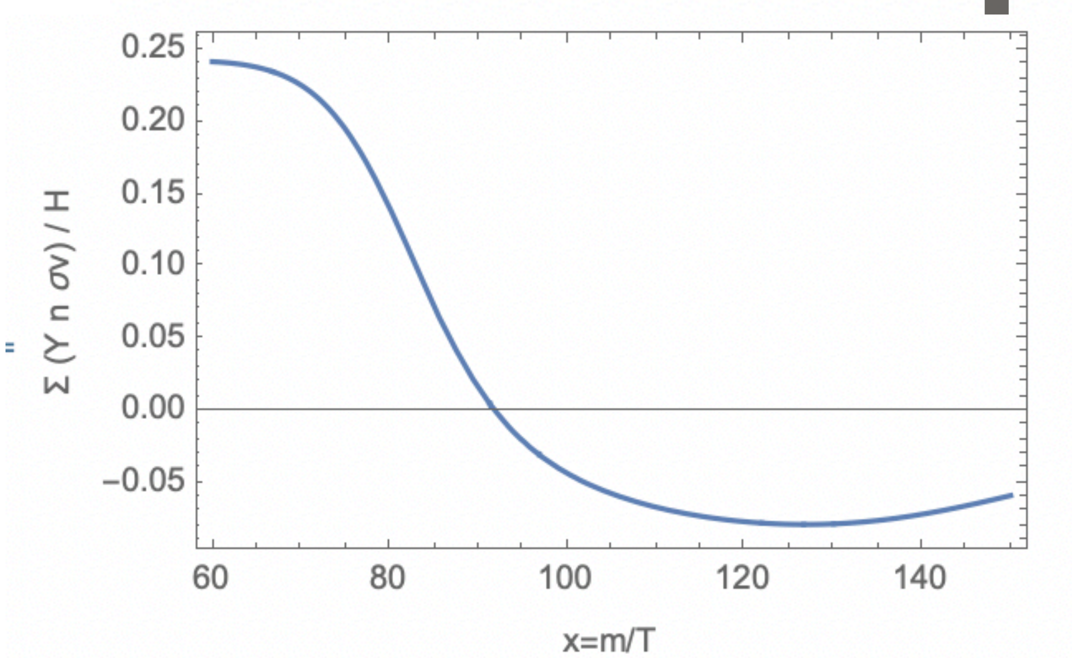
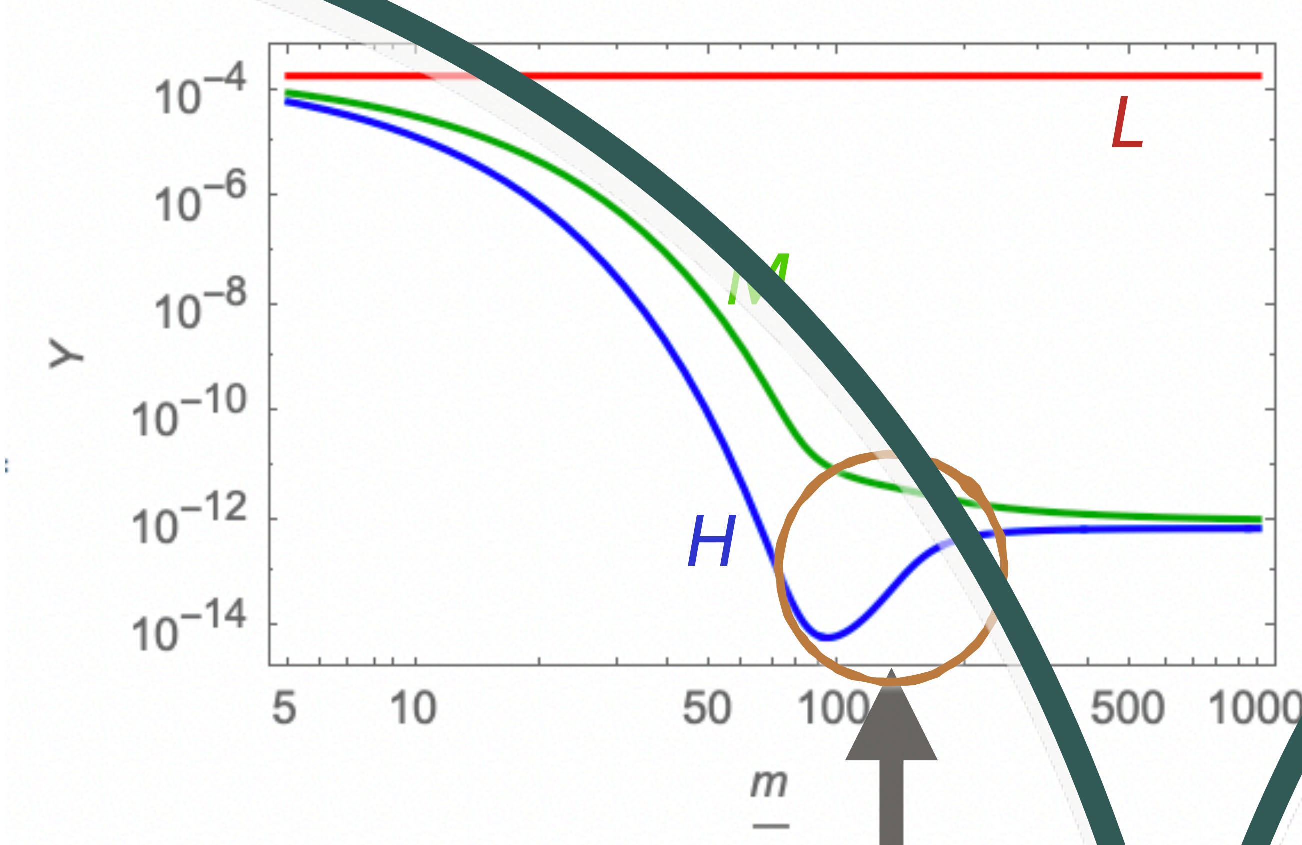




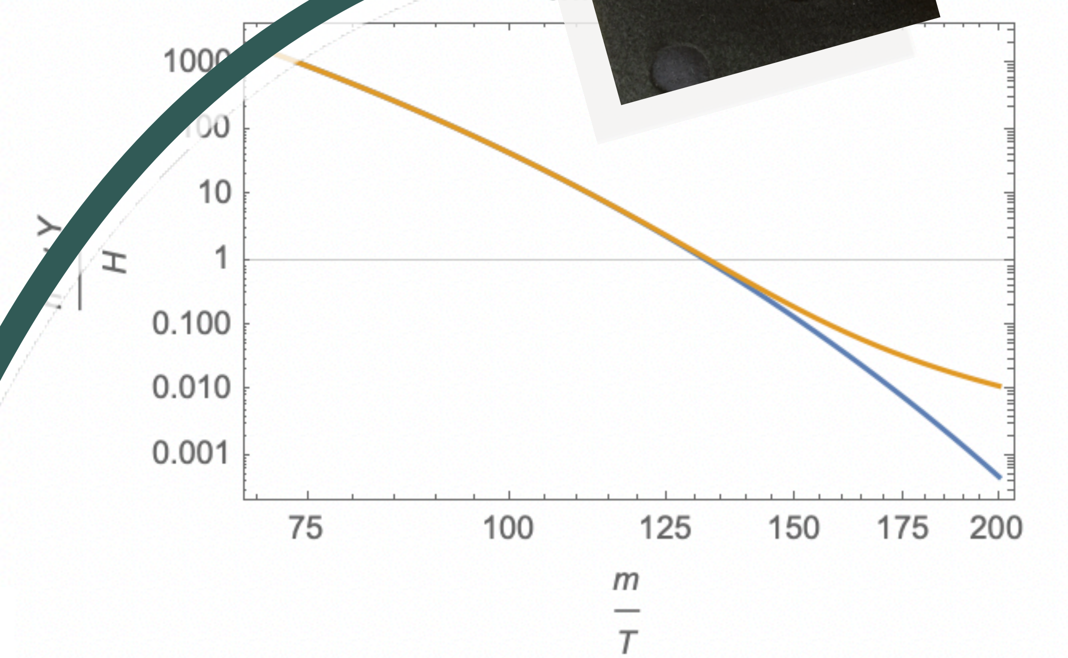
Net collision term for Boltzmann eq for H:
transitions from overall H number
reducing to H number increasing!

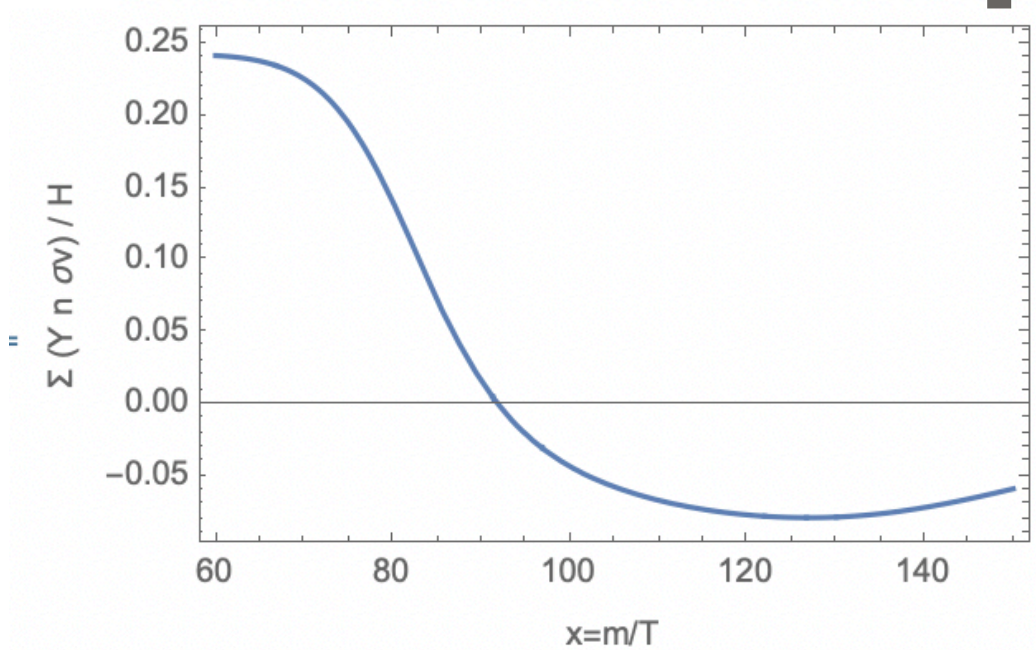
COSMOLOGICAL HISTORY



Only remaining ra eraction:

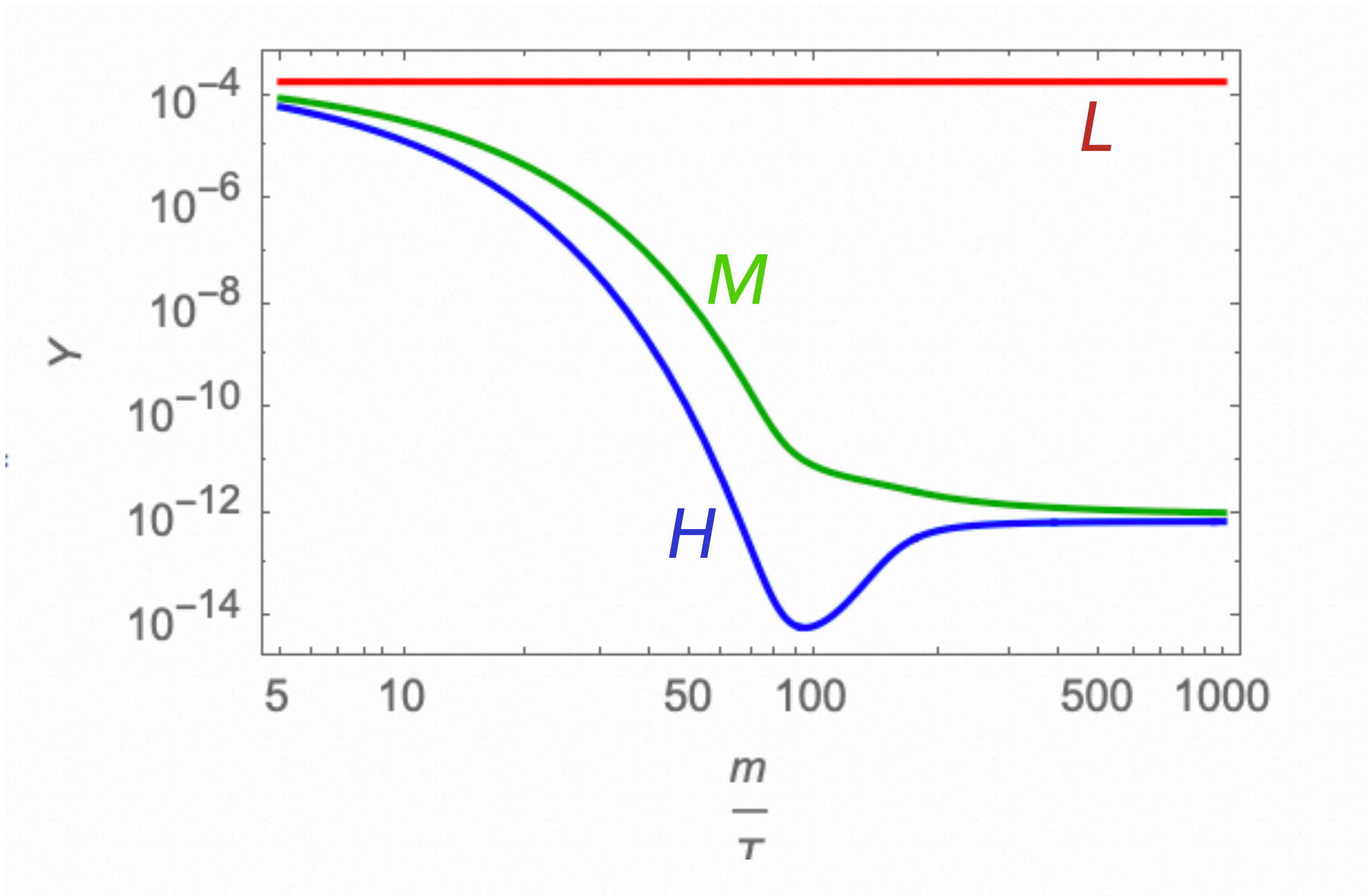
M



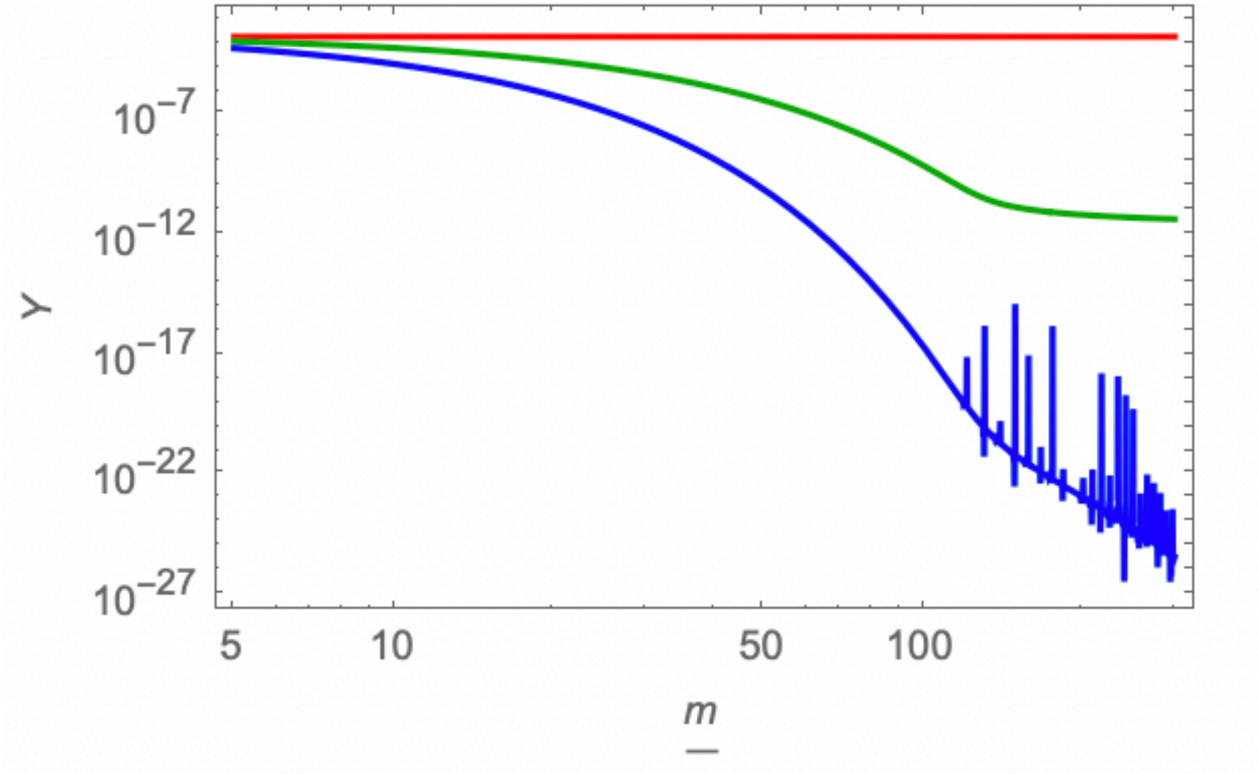


Final relic abundance of dark matter bounces up and can be larger by several orders of magnitude!

A COMPARISON



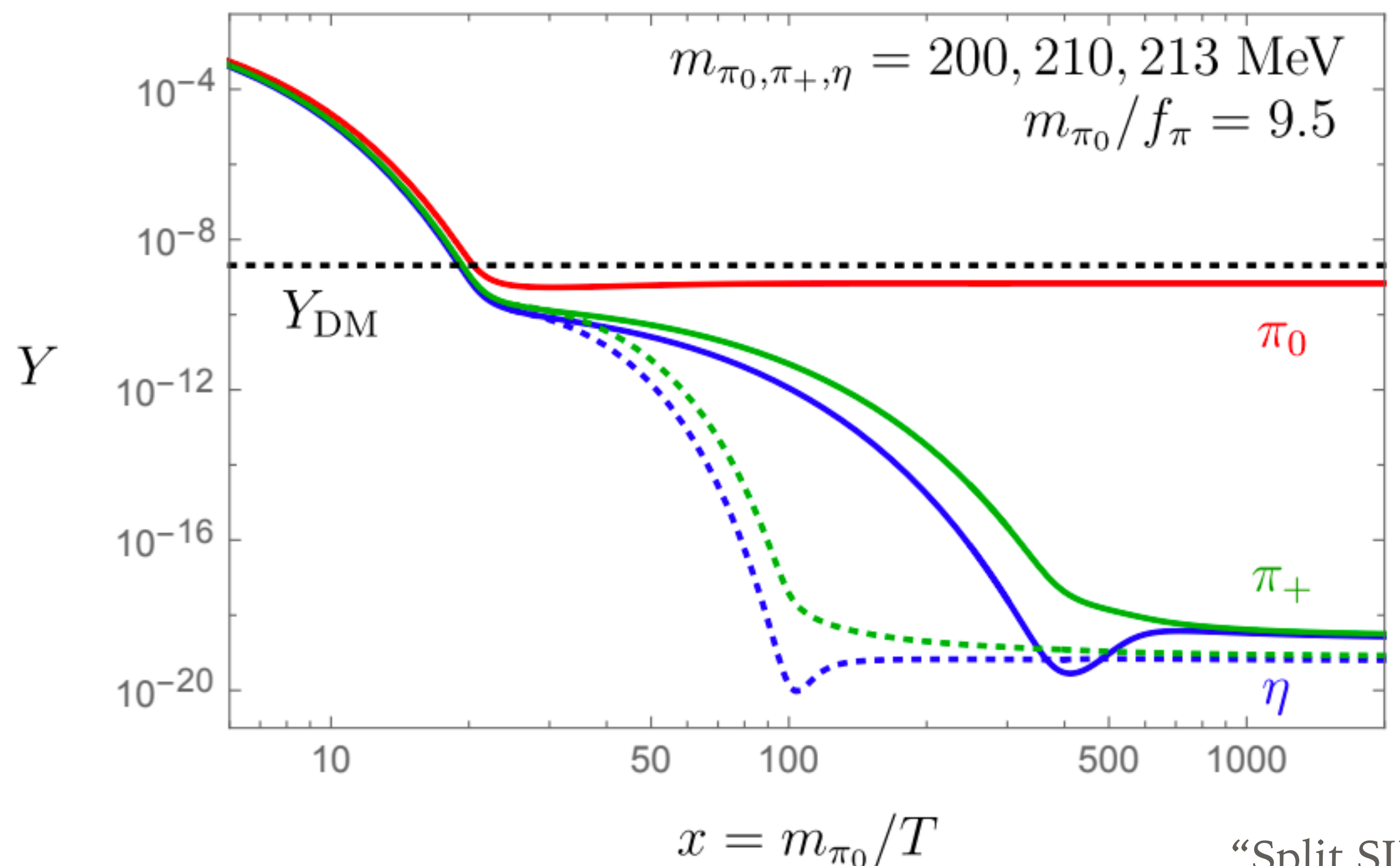
- 200 GeV
- 240 GeV
- 260 GeV



- 200 GeV
- 225 GeV
- 260 GeV

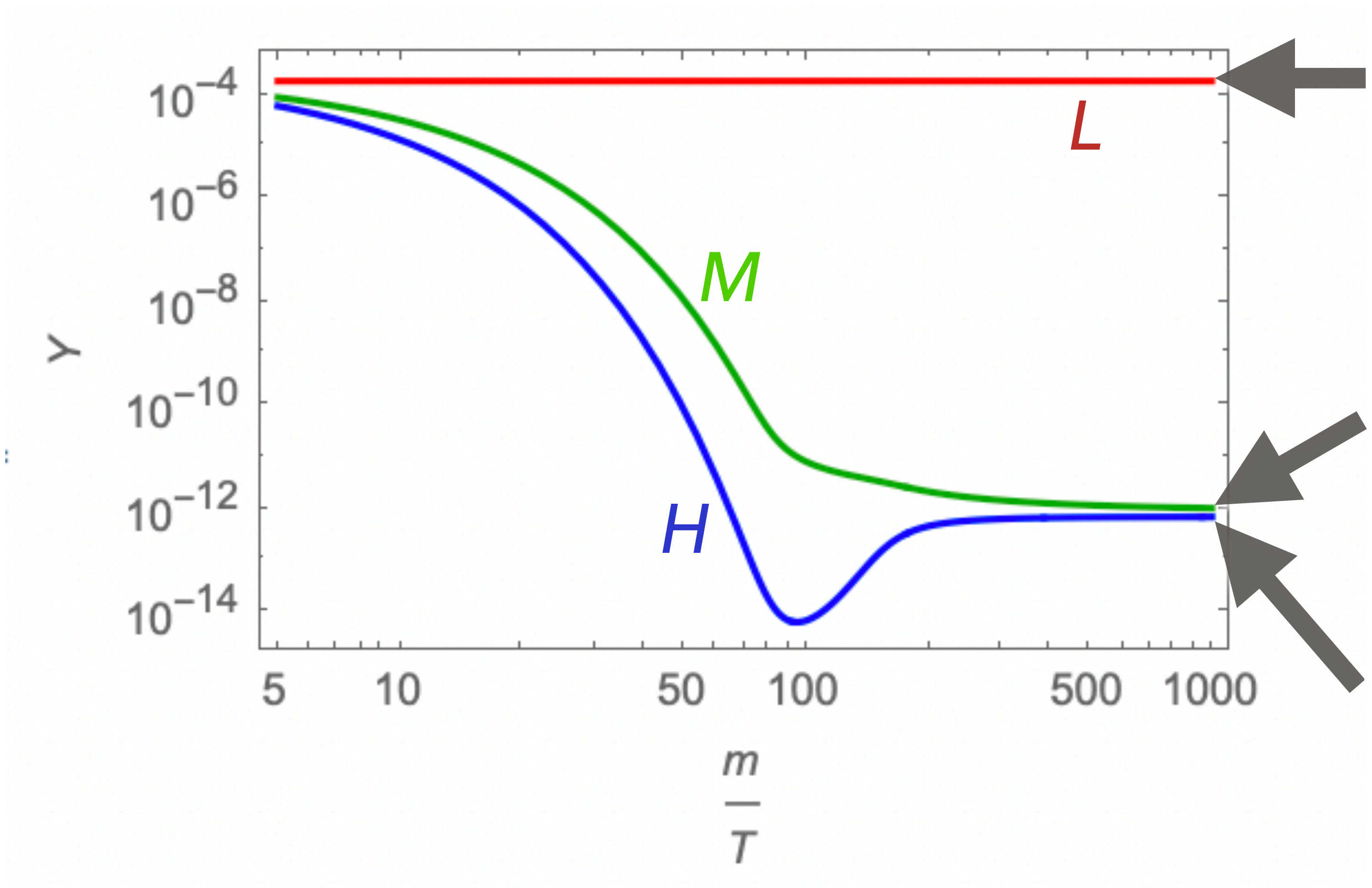
CONTEXT

- Needs: a dark sector with multiple particles, with a process that involves heavier particles annihilating into final states that contains the particle of interest
- 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]

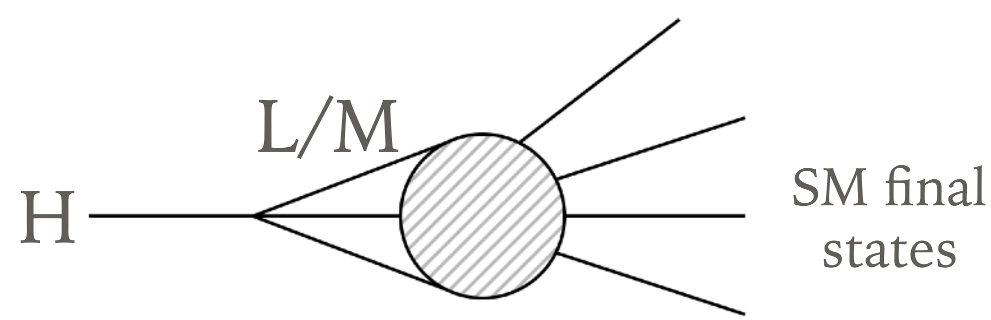
PARTICLE DECAYS



Too much L; needs to decay, otherwise will overclose

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

H will also be unstable and can decay if L (and M) can decay



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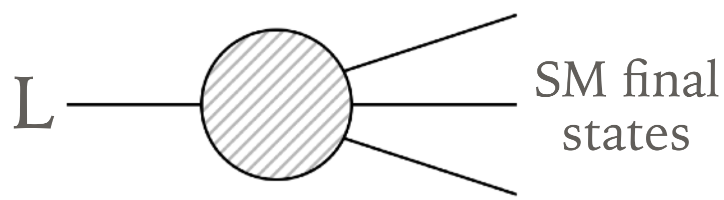
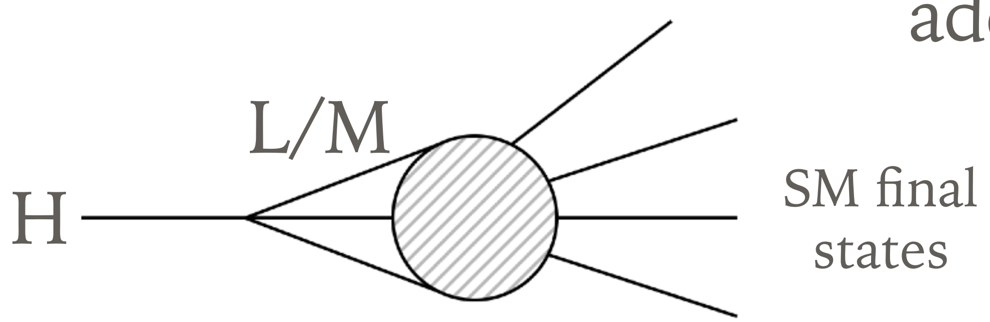


If L (M) decay with effective coupling $\sim g$, ensuring that L decays away before BBN requires roughly $g > 10^{-13}$

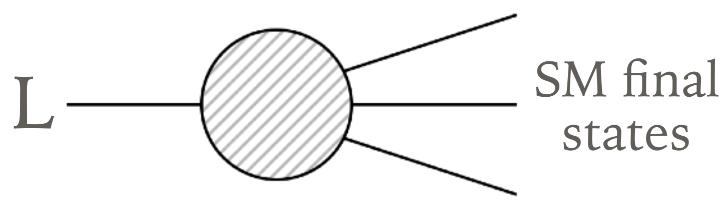


H decays with an effective coupling g^2, plus additional phase space suppression factors

lifetime: $\sim 10^{27}$ s

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

PARTICLE DECAYS



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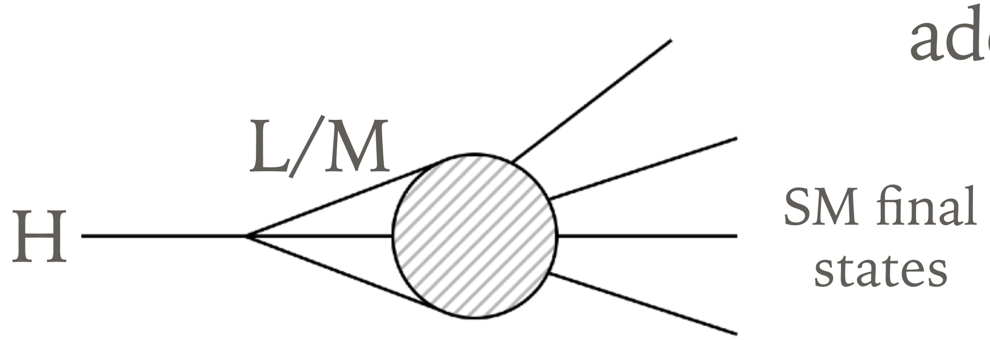

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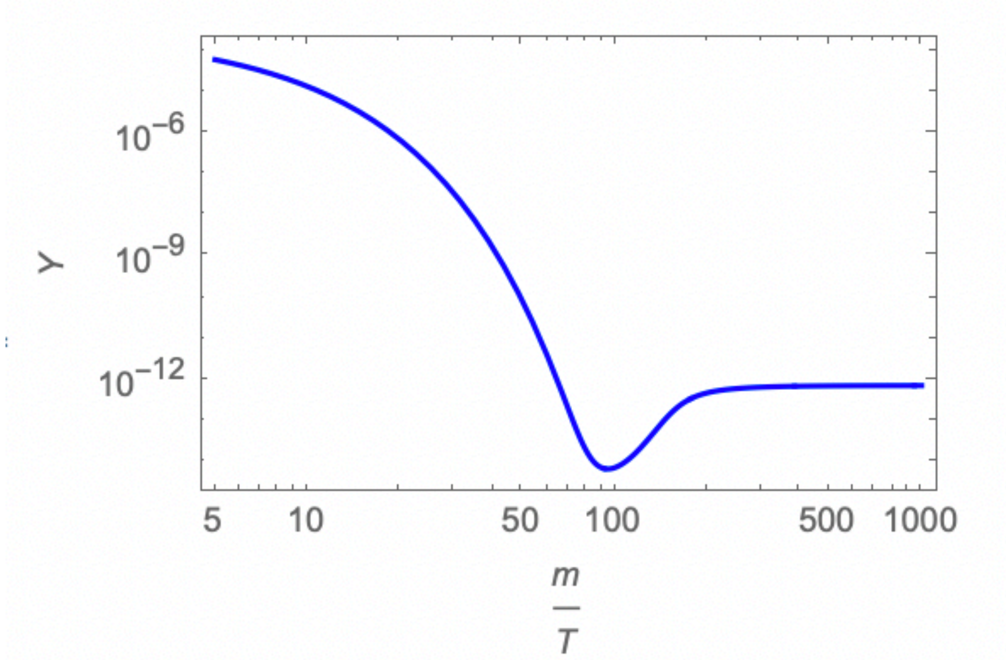
Indirect detection signals from dark matter annihilation: HH->MM,LL

Rates larger than “naively” expected from standard hidden sector freezeout

SUMMARY



- In some scenarios, it is possible for the dark matter freezeout abundance to undergo a “bounce” in the late stages of thermal freezeout, increasing by several orders of magnitude compared to standard freezeout
- Requires multiple species interacting with dark matter, and the presence of an annihilation channel into dark matter that does not require thermal support to control the final stage of freezeout
- Present day dark matter annihilation cross section larger than naively expected from standard freezeout processes
- Dark matter is necessarily unstable, with decay lifetime of interest for signals