Thermal Squeezeout for Strongly Interacting Dark Matter

Tracy Slatyer

HiDDeN Webinar
15 February 2022

Based on arXiv:2103.09822 (PRL '21),
2103.09827 (PRD '21)
with Pouya Asadi, Eric Kramer, Eric Kuflik,
Gregory Ridgway, & Juri Smirnov

Outline

- Introduction to thermal freezeout, the thermal mass window, and the unitarity bound

- Estimating the effects of a first-order dark-sector phase transition on a strongly interacting dark sector with heavy dark quarks

- How a phase transition after initial freezeout leads to a second "squeezeout" phase that can dramatically deplete the DM density

- The accidentally asymmetric limit

- Results for the relic density

- (if time permits) Glueballs, early matter domination, entropy injection, and generalized freezeout

What is dark matter?
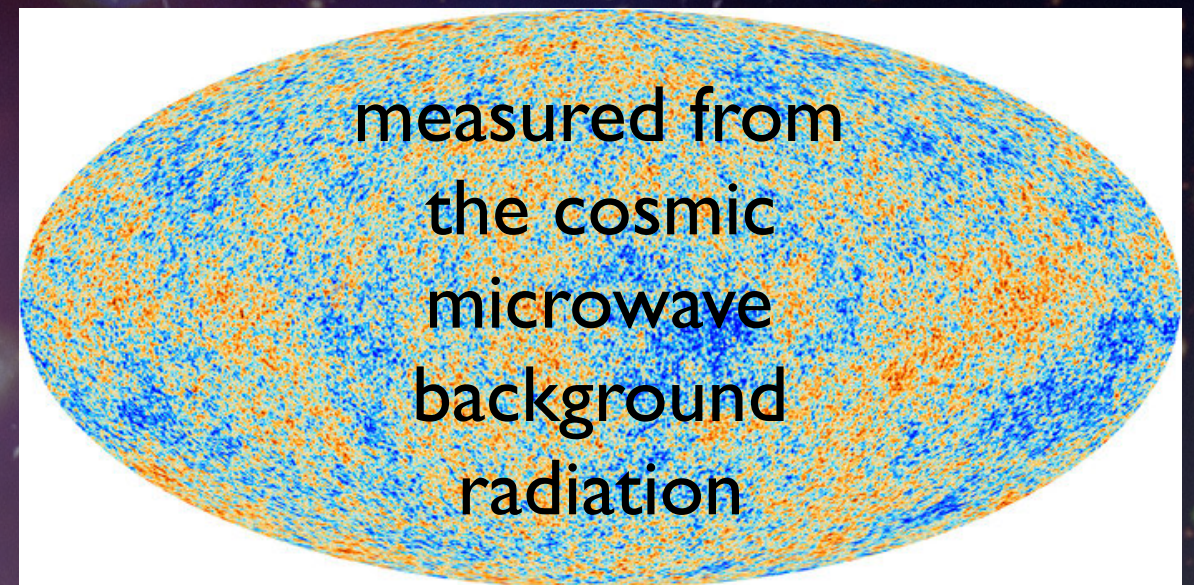
We know it:

What is dark matter?

We know it:

– Doesn't scatter/emit/absorb light (really "transparent matter"!) but does have mass (and hence gravity).

What is dark matter?

We know it:

- Doesn't scatter/emit/absorb light (really "transparent matter"!) but does have mass (and hence gravity).

- Is ~84% of the matter in the universe.

measured from the cosmic microwave background radiation

What is dark matter?

We know it:

– Doesn't scatter/emit/absorb light (really "transparent matter"!) but does have mass (and hence gravity).
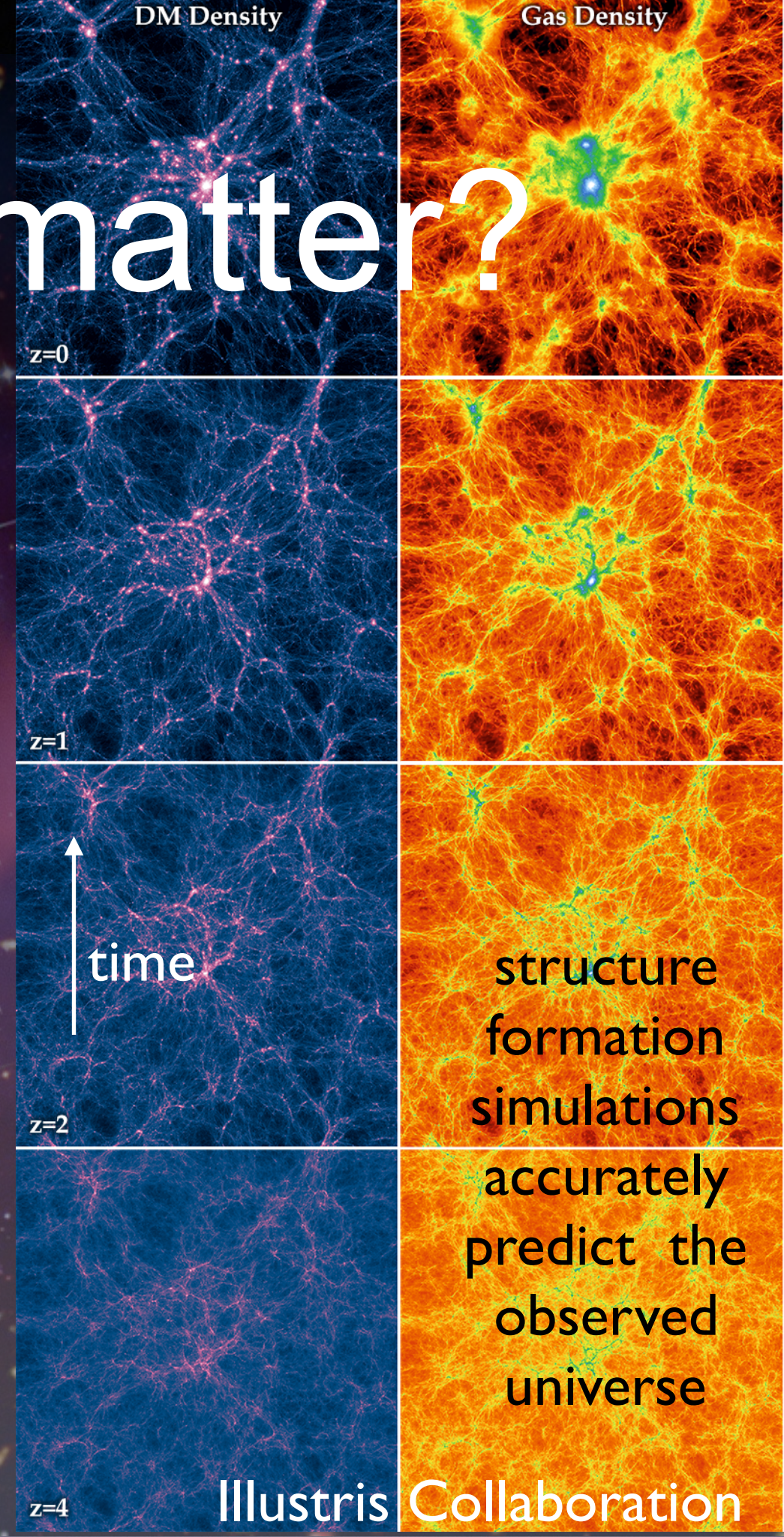
– Is ~84% of the matter in the universe.

– Forms the primordial "scaffolding" for the visible universe.

DM Density   Gas Density

z=0

z=1

time

z=2

structure formation simulations accurately predict the observed universe
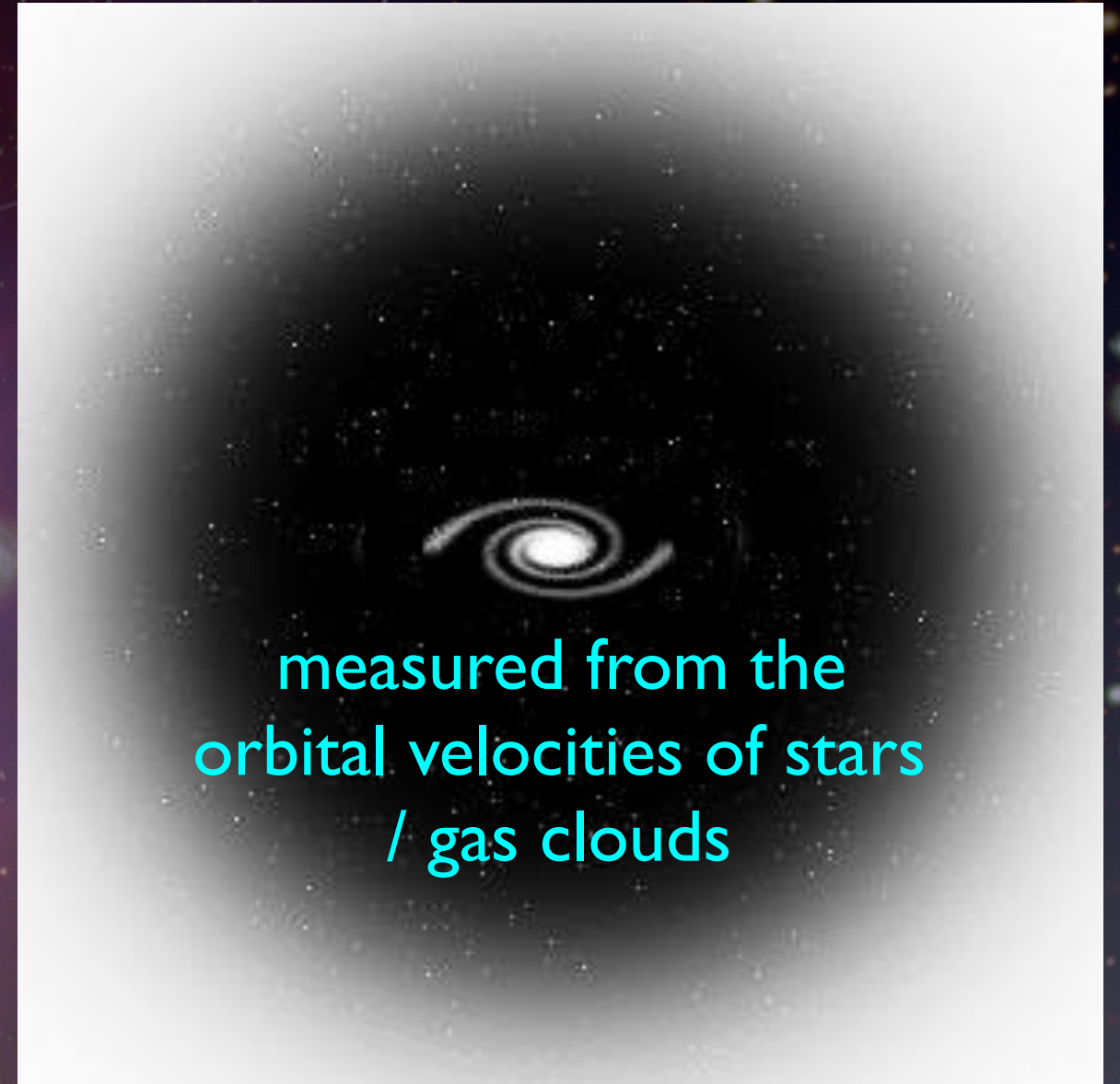
z=4

Illustris Collaboration

What is dark matter?

We know it:

– Doesn't scatter/emit/absorb light (really "transparent matter"!) but does have mass (and hence gravity).

– Is ~84% of the matter in the universe.

– Forms the primordial "scaffolding" for the visible universe.

– Forms large clouds or "halos" around galaxies.

measured from the orbital velocities of stars / gas clouds

What is dark matter?

We know it:

– Doesn't scatter/emit/absorb light (really "transparent matter"!) but does have mass (and hence gravity).

– Is ~84% of the matter in the universe.

– Forms the primordial "scaffolding" for the visible universe.

– Forms large clouds or "halos" around galaxies.

– Interacts with other particles weakly or not at all (except by gravity).

null results of existing searches

What is dark matter?

We know it:

Open questions:

– Consequently, cannot be explained by any physics we currently understand

What is dark matter?

We know it:

Open questions:

– Consequently, cannot be explained by any physics we currently understand

– WHAT IS IT?

What is dark matter?

We know it:

– Consequently, cannot be explained by any physics we currently understand

Open questions:

– What is it made from? e.g. a new particle? Many new particles? Ancient black holes?

What is dark matter?

We know it:

– Consequently, cannot be explained by any physics we currently understand

Open questions:

– What is it made from? e.g. a new particle? Many new particles? Ancient black holes?

– Where did it come from?

What is dark matter?

We know it:

— Consequently, cannot be explained by any physics we currently understand

Open questions:

— What is it made from? e.g. a new particle? Many new particles? Ancient black holes?

— Where did it come from?

— Does it interact with ordinary particles? If so how?

What is dark matter?

We know it:

– Consequently, cannot be explained by any physics we currently understand
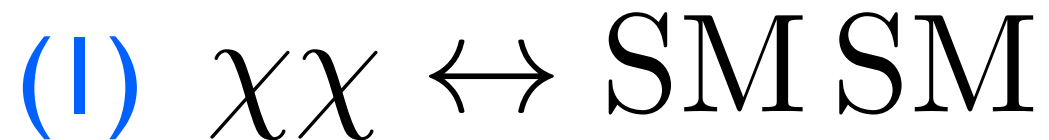
Open questions:

– What is it made from? e.g. a new particle? Many new particles? Ancient black holes?

– Where did it come from?

– Does it interact with ordinary particles? If so how?

– and many more…

Classic thermal freezeout

Suppose there is some interaction that interconverts between dark matter and SM particles and is efficient in the early universe
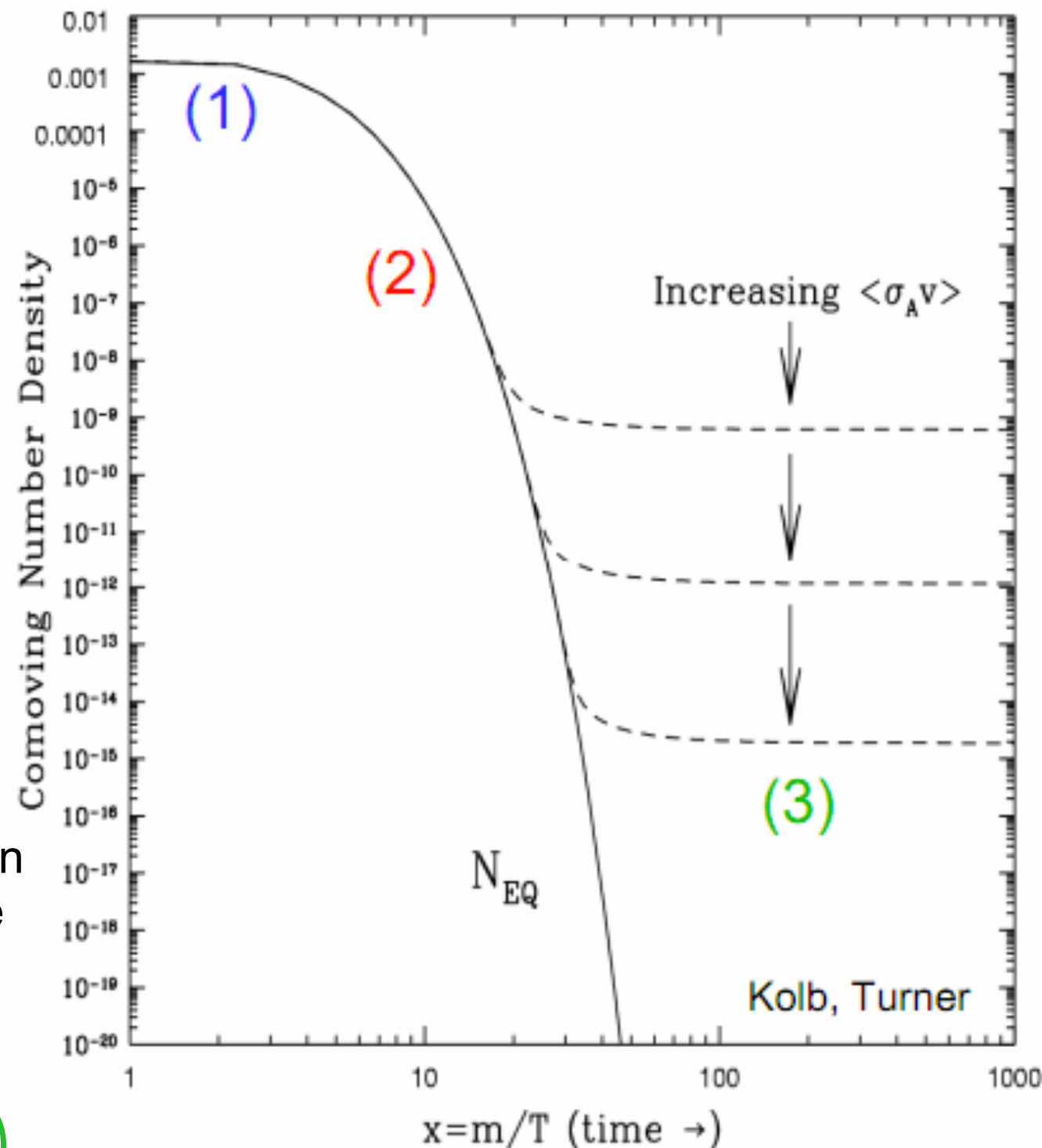
$$(\text{I}) \quad \chi\chi \leftrightarrow \text{SM}\,\text{SM}$$

As the universe expands, it cools down; eventually its temperature drops below the dark matter mass.

At this stage, dark matter particles can efficiently annihilate to visible particles, but not the reverse:

$$(2) \quad \chi\chi \to \text{SM}\,\text{SM} \not\to \chi\chi$$

Dark matter abundance falls exponentially - eventually cuts off when the timescale for collision becomes comparable to the expansion timescale

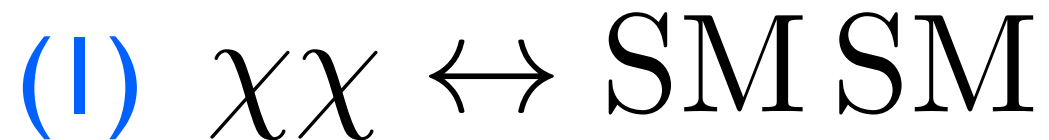At this point we say the annihilation has <u>frozen out</u> and the late-time dark matter abundance is fixed

Classic thermal freezeout

- Suppose there is some interaction that interconverts between dark matter and SM particles and is efficient in the early universe

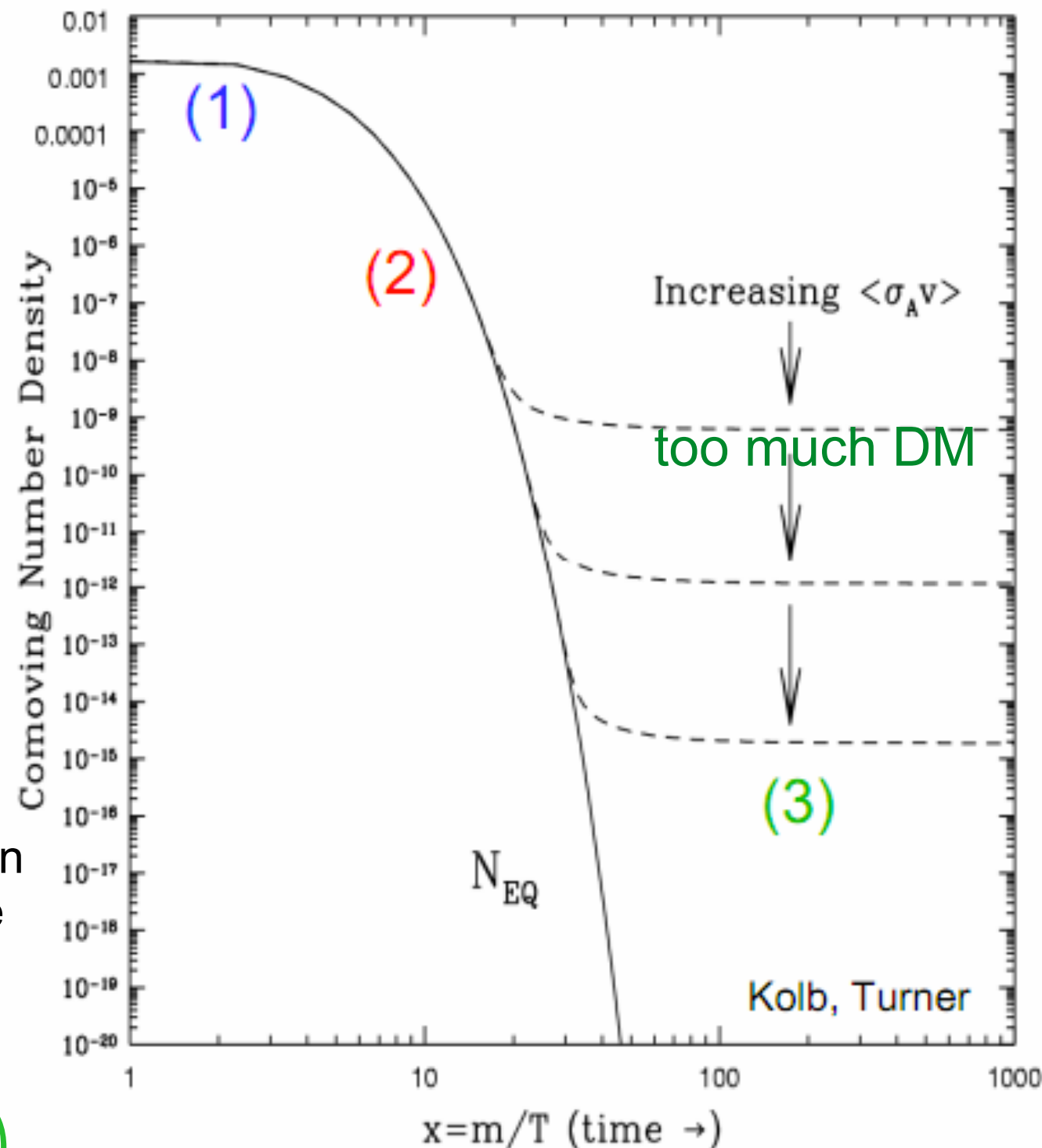(1) $\quad \chi\chi \leftrightarrow \text{SM SM}$

- As the universe expands, it cools down; eventually its temperature drops below the dark matter mass.

- At this stage, dark matter particles can efficiently annihilate to visible particles, but not the reverse:

(2) $\quad \chi\chi \rightarrow \text{SM SM} \nrightarrow \chi\chi$

- Dark matter abundance falls exponentially - eventually cuts off when the timescale for collision becomes comparable to the expansion timescale

- At this point we say the annihilation has <u>frozen out</u> and the late-time dark matter abundance is fixed
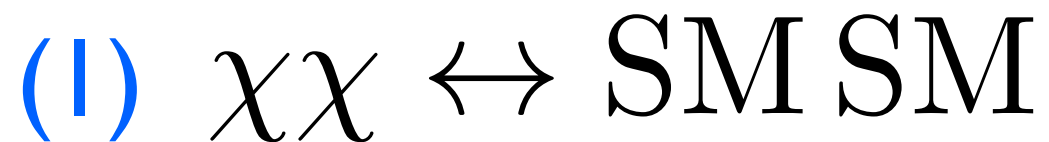
(3)

(1)

(2)

Increasing $\langle \sigma_A v \rangle$

too much DM

(3)

N_{EQ}

Kolb, Turner

$x = m/T$ (time $\rightarrow$)

Comoving Number Density

Classic thermal freezeout

- Suppose there is some interaction that interconverts between dark matter and SM particles and is efficient in the early universe

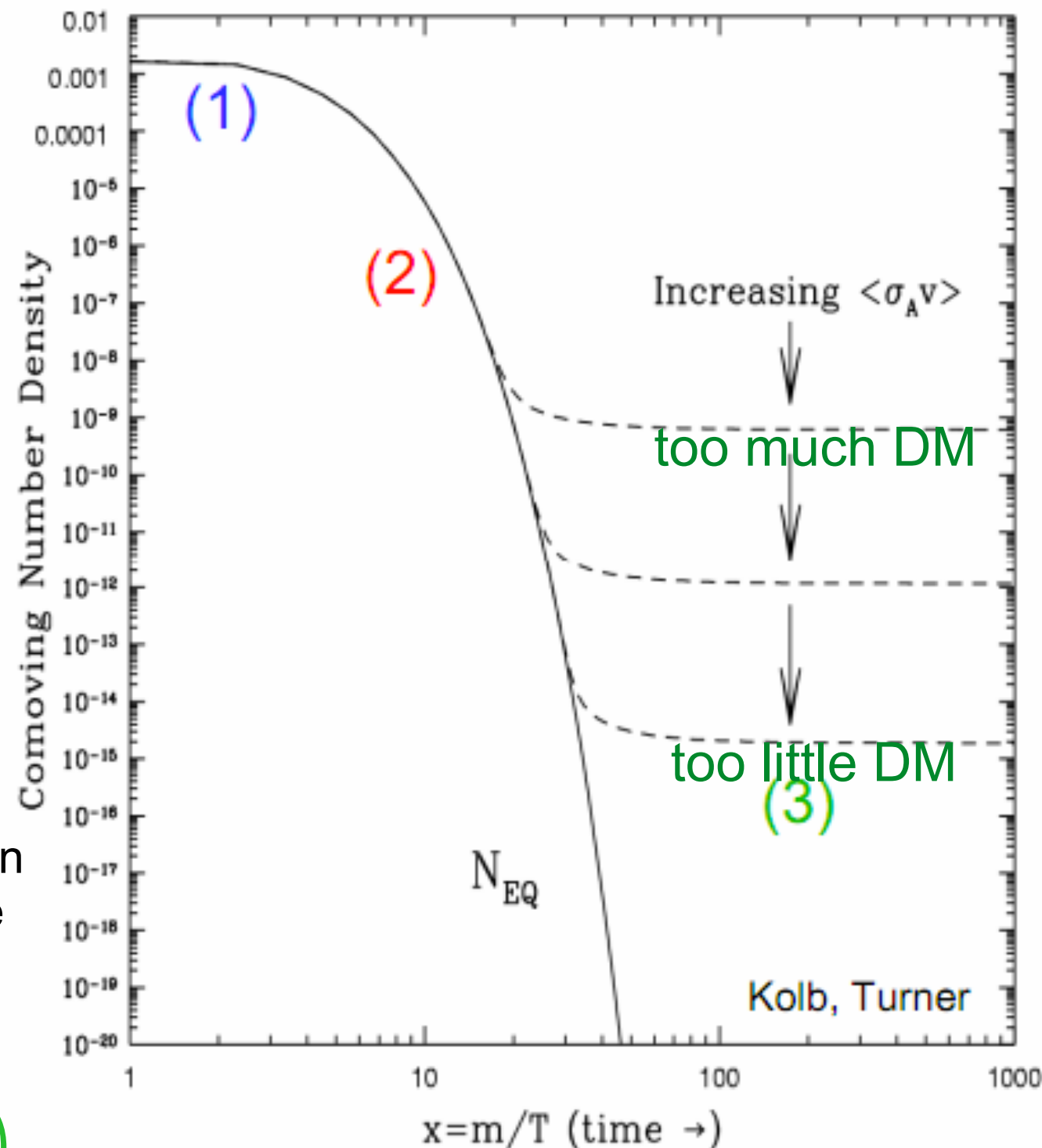$$(1) \quad \chi\chi \leftrightarrow SM\,SM$$

- As the universe expands, it cools down; eventually its temperature drops below the dark matter mass.

- At this stage, dark matter particles can efficiently annihilate to visible particles, but not the reverse:

$$(2) \quad \chi\chi \rightarrow SM\,SM \nrightarrow \chi\chi$$

- Dark matter abundance falls exponentially - eventually cuts off when the timescale for collision becomes comparable to the expansion timescale

- At this point we say the annihilation has <u>frozen out</u> and the late-time dark matter abundance is fixed
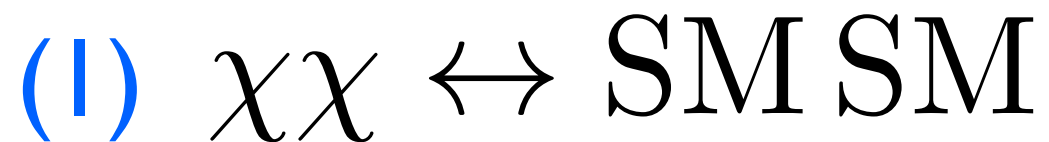
(3)

(1)

(2)

Increasing $\langle \sigma_A v \rangle$

too much DM

too little DM

(3)

N_{EQ}

Kolb, Turner

$x = m/T$ (time →)

Comoving Number Density

Classic thermal freezeout

- Suppose there is some interaction that interconverts between dark matter and SM particles and is efficient in the early universe

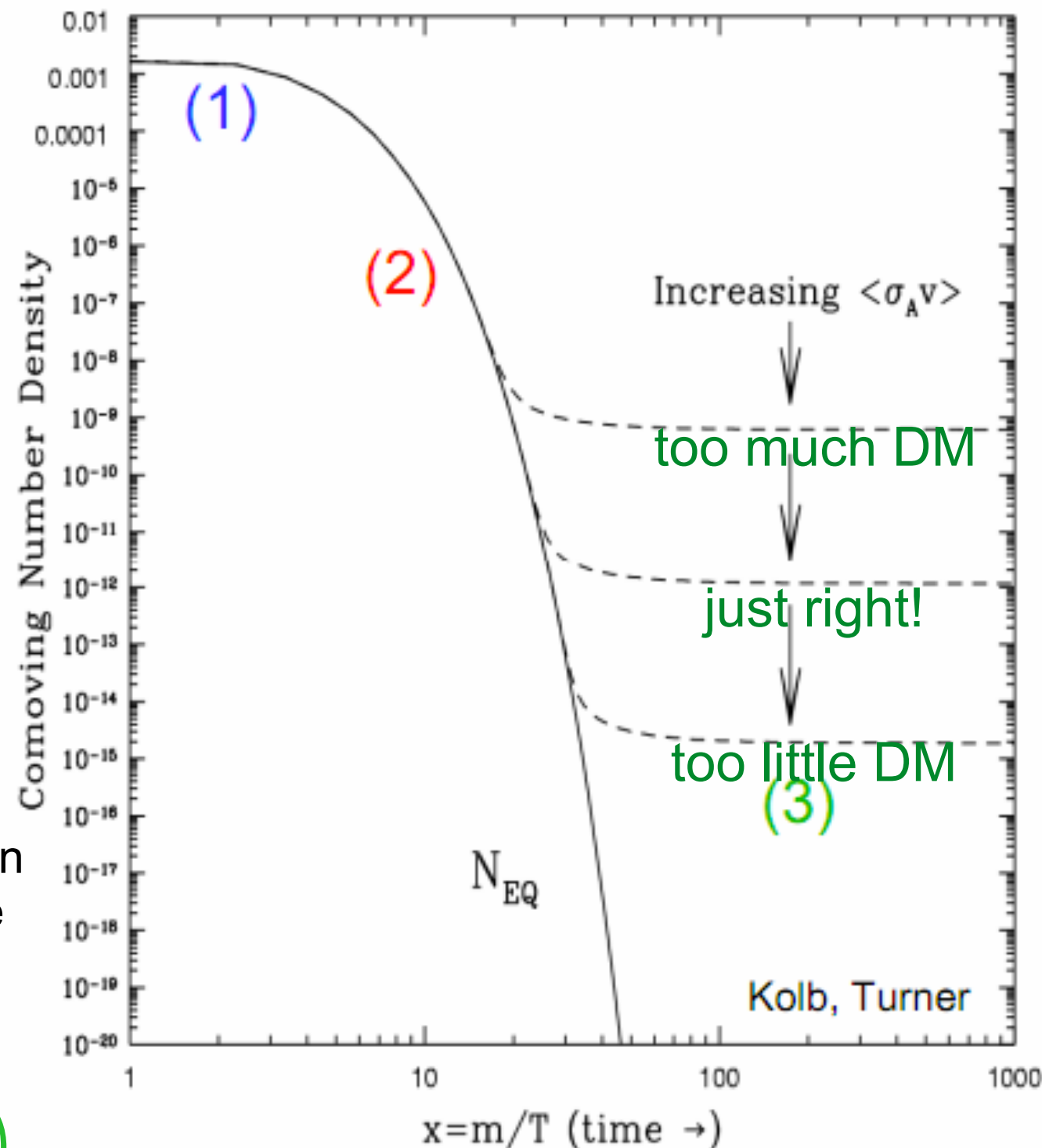$$(1) \quad \chi\chi \leftrightarrow \mathrm{SM}\,\mathrm{SM}$$

- As the universe expands, it cools down; eventually its temperature drops below the dark matter mass.

- At this stage, dark matter particles can efficiently annihilate to visible particles, but not the reverse:

$$(2) \quad \chi\chi \rightarrow \mathrm{SM}\,\mathrm{SM} \nrightarrow \chi\chi$$

- Dark matter abundance falls exponentially - eventually cuts off when the timescale for collision becomes comparable to the expansion timescale

- At this point we say the annihilation has <u>frozen out</u> and the late-time dark matter abundance is fixed

(3)

(1)

(2)

Increasing $\langle \sigma_A v \rangle$

too much DM

just right!

too little DM

(3)

N_{EQ}

Kolb, Turner

$x = m/T$ (time →)

Comoving Number Density

Freezeout implications

- In this scenario, the interaction strength controls the freezeout and hence the late-time ("relic") abundance of dark matter: stronger interactions = longer exponential decrease = lower abundance

- From measuring the relic abundance we can predict the annihilation rate:

$$\langle \sigma v \rangle \approx 2 \times 10^{-26} \mathrm{cm}^3/s \approx \frac{1}{(25 \mathrm{TeV})^2} \sim \frac{1}{m_{\mathrm{Pl}} T_{\mathrm{eq}}}$$

- In the limit of weak interactions, this suggests a characteristic mass scale around $M \sim \alpha_D \times 25 \mathrm{TeV}$, if α_D is the relevant coupling

- Unitarity sets an upper limit on the contribution to the depletion rate from any given partial wave,

$$(\sigma v_{\mathrm{rel}})^J_{\mathrm{total}} < (\sigma v)^J_{\mathrm{max}} = \frac{4\pi(2J+1)}{M^2_{\mathrm{DM}} v_{\mathrm{rel}}}$$

The unitarity bound

- Given a set of partial waves that contribute significantly to depletion (l_{max}) + a velocity scale for freezeout + assumptions of standard cosmology, unitarity bound sets an upper limit on the DM mass in this thermal scenario

- Saturating this unitarity bound typically requires long-range interactions and/or strong couplings [e.g. von Harling & Petraki '14]

- Mass limit often quoted as 100-200 TeV, valid when l_{max} is small, although:

  - for bound states / extended objects higher partial waves may contribute significantly,

  - argument in Smirnov & Beacom '19 that shallowly-bound high-l states will be disrupted by plasma effects before they can annihilate → upper bound on l_{max} depending on $T_{freezeout}$ → upper mass limit of 1 PeV

- Limit can be evaded in non-thermal scenarios or if cosmology is modified

A confining dark sector
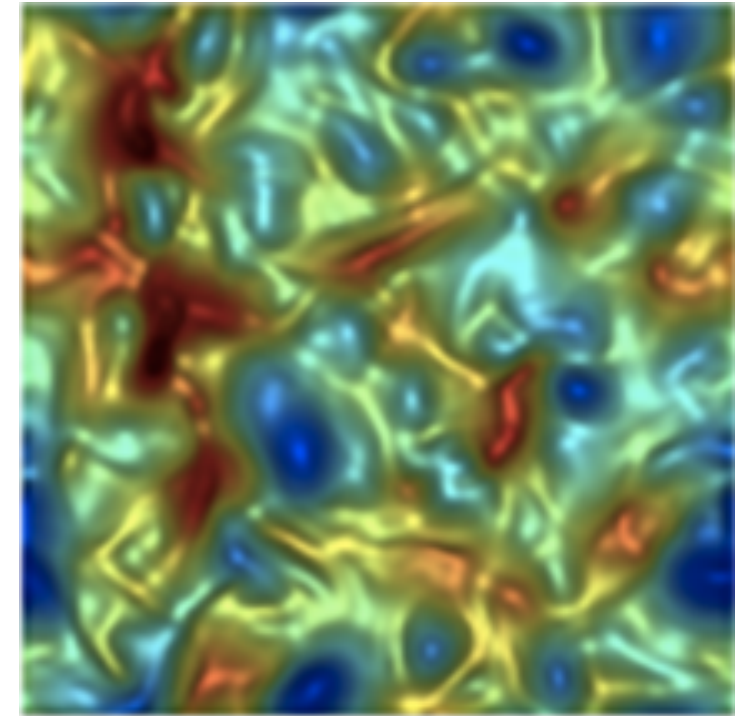
- Consider strongly-interacting DM inhabiting a confining dark sector (like QCD in the Standard Model).

- Today: dark matter comprised of stable dark baryons

- Early in the universe: dark quark-gluon plasma.

- Automatic modification to early-universe cosmology: the confinement phase transition.

- If the dark quarks are sufficiently heavy then plasma is similar to pure Yang-Mills - expect a first-order phase transition for $SU(N \geq 3)$ based on lattice studies [e.g. Lucini et al '03].

- The rest of this talk: a first-order phase transition in a strongly-interacting dark sector naturally strongly dilutes heavy thermal DM and points to a PeV-EeV mass scale.

- Caveat: this will not be a detailed calculation using advanced non-perturbative techniques - many simplifying approximations, aim is to derive a first-pass estimate of relevant physical effects and the resulting evolution.
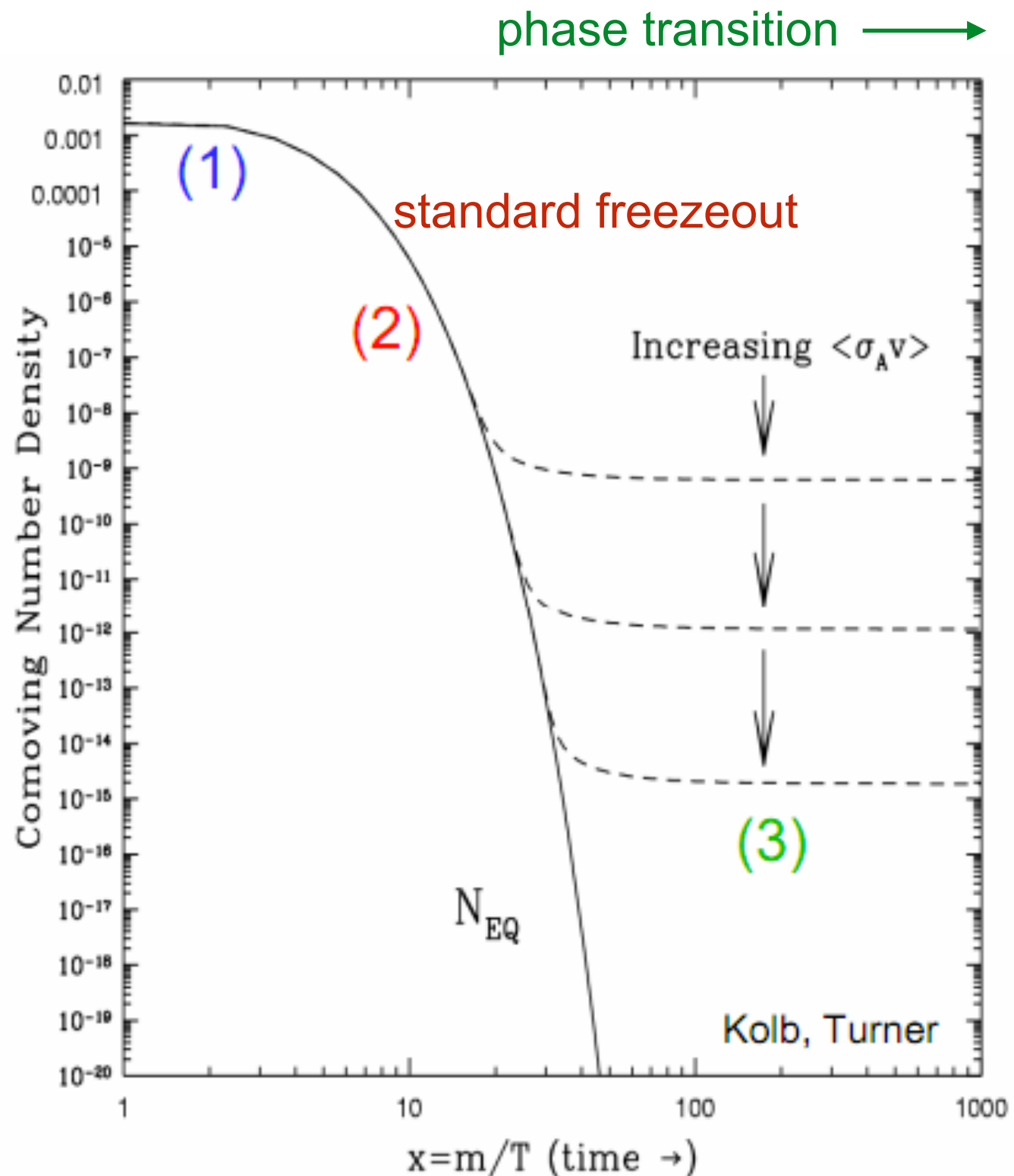
A multi-stage history

- There are two relevant mass scales in the problem:

  - the confinement scale Λ - determines the phase transition temperature and the binding energies post-confinement

  - the quark mass m_q - determines the quark freezeout temperature

- If freezeout happens after confinement, similar to previous cases, with dark matter = dark baryons: annihilations keep the dark baryons/glueballs/other states in equilibrium with the SM, the relic abundance is fixed when the annihilation freezes out

- We will assume $m_q \gg \Lambda$ so freezeout happens BEFORE the confinement phase transition
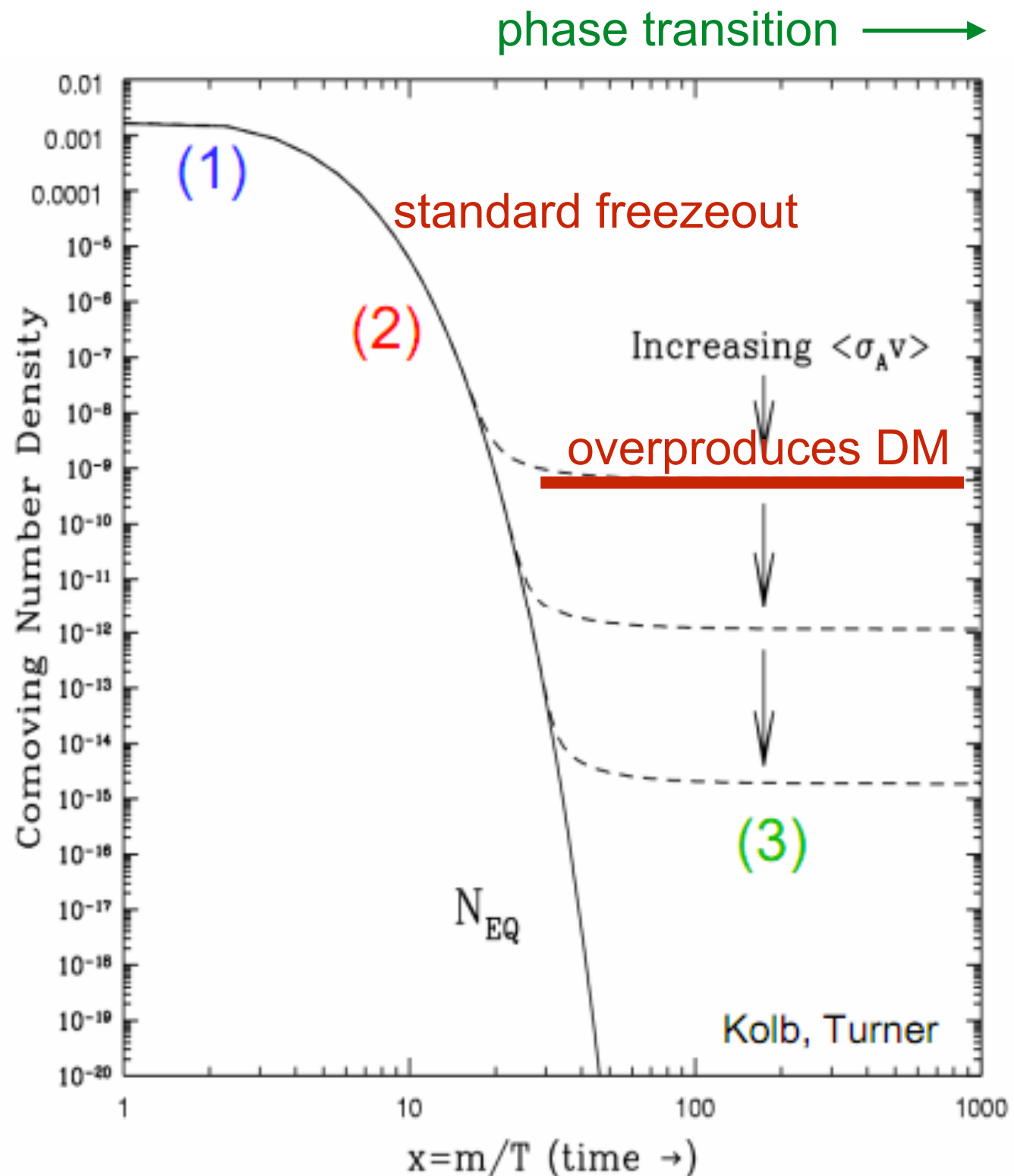
Stage I: freezeout

- Freezeout occurs as usual in the deconfined phase

- Sets initial conditions for the phase transition - stable comoving density of dark quarks + antiquarks

- If dark quarks are heavier than the unitarity bound, this density will be <u>too high</u> to match the relic abundance

phase transition ⟶

(1)

standard freezeout

(2)

Increasing $\langle \sigma_A v \rangle$

(3)

N_{EQ}

Kolb, Turner

Comoving Number Density
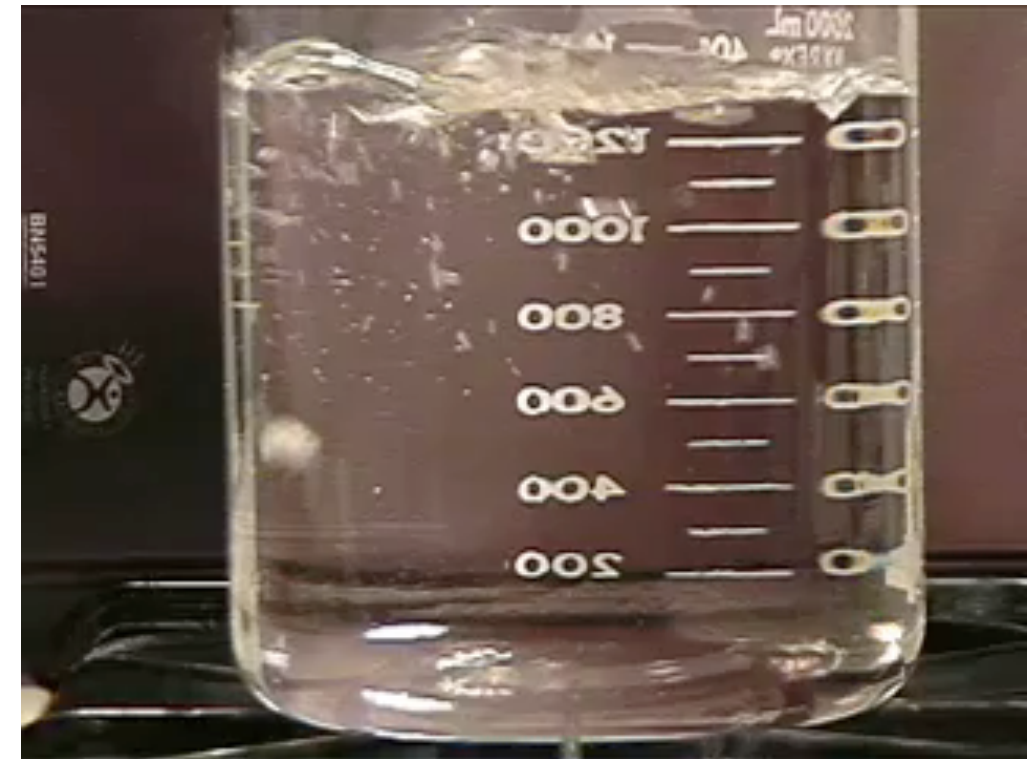
$x = m/T$ (time →)

Stage I: freezeout

- Freezeout occurs as usual in the deconfined phase

- Sets initial conditions for the phase transition - stable comoving density of dark quarks + antiquarks

- If dark quarks are heavier than the unitarity bound, this density will be <u>too high</u> to match the relic abundance
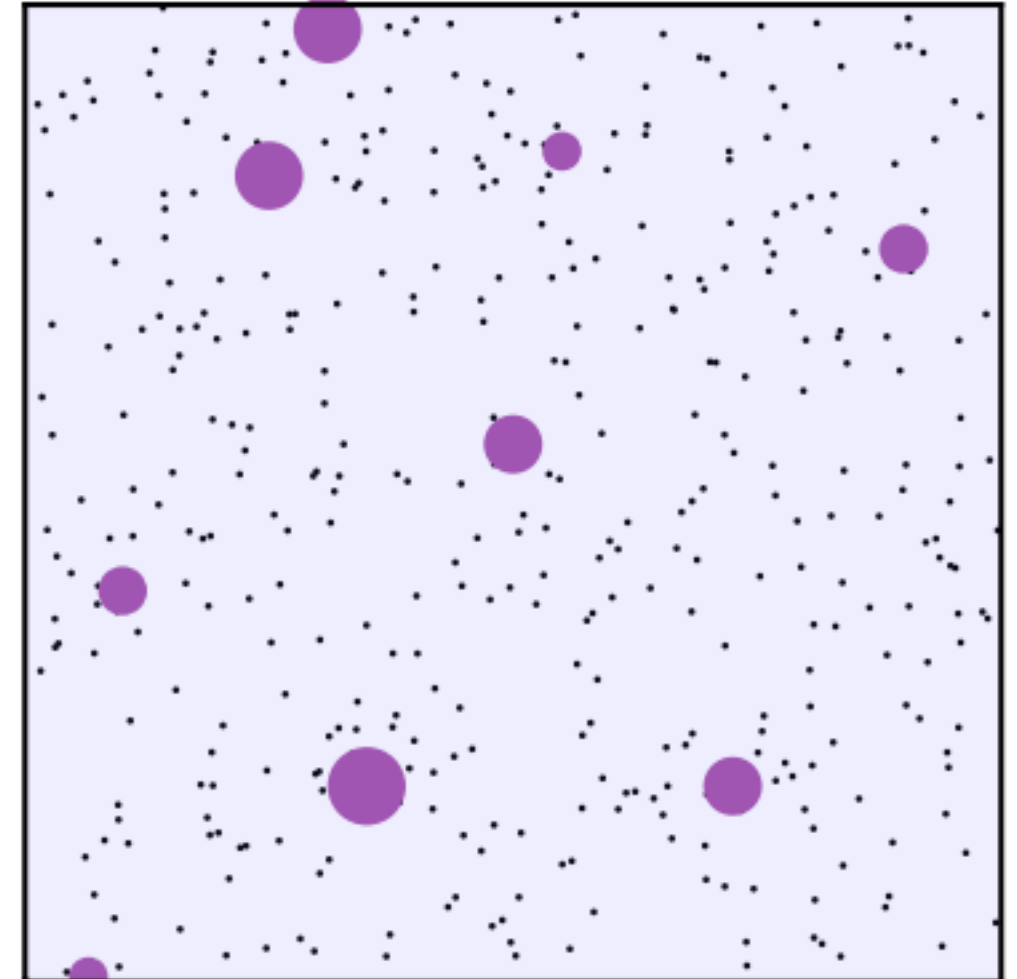
phase transition ⟶

(1)

standard freezeout

(2)

Increasing $\langle \sigma_A v \rangle$

overproduces DM

(3)

N_{EQ}

Kolb, Turner

Comoving Number Density

$x = m/T$ (time →)

Stage 2: bubble growth

ISLE Physics, YouTube

- After freezeout, once the temperature of the universe drops to Λ, bubbles of the confined phase begin to form and grow.

- These bubbles cannot form with free quarks inside, as free quarks cannot exist in the confined phase (requiring too much energy).

- Quarks (& antiquarks) must either quickly form hadrons or be shunted to the outside of the bubbles.

- <u>Note</u>: see also Hong, Jung & Xie '20, which uses similar "herding" of dark matter in a first-order phase transition to generate macroscopic "Fermi-balls" (or even primordial black holes, Kawana & Xie '21).
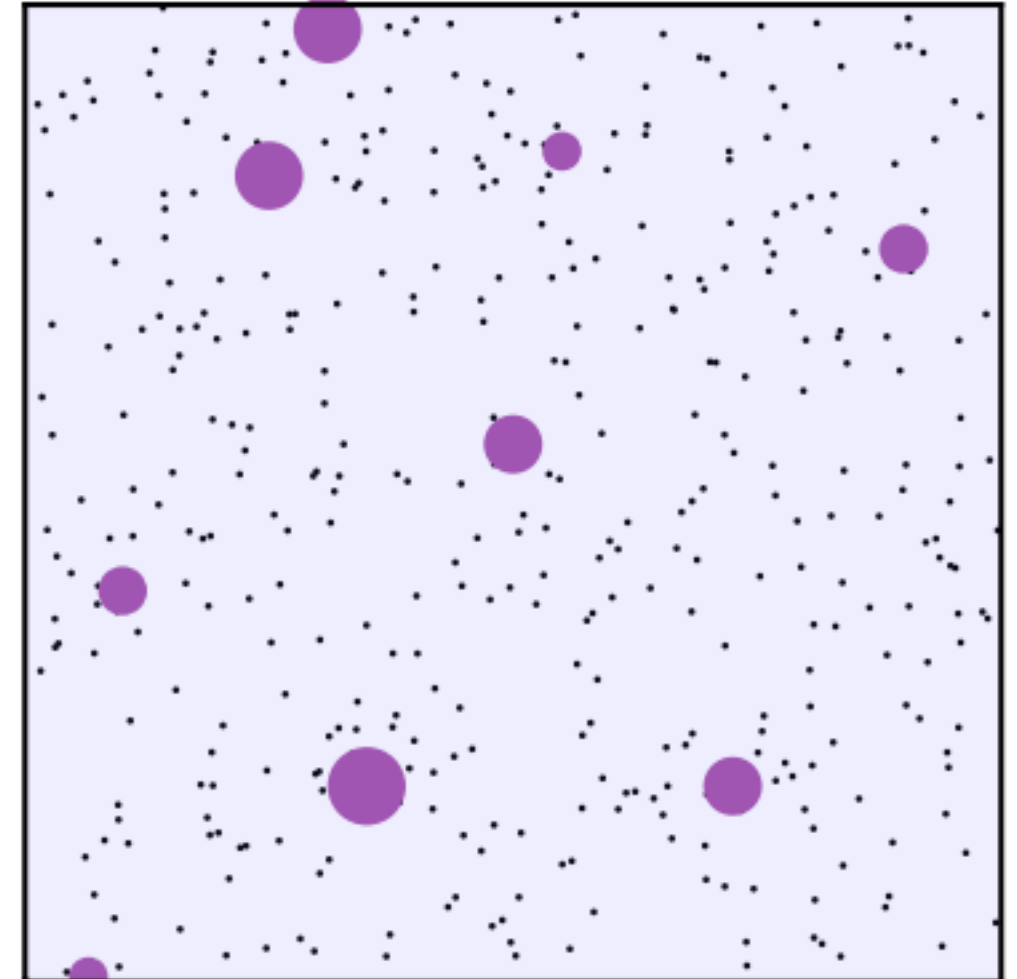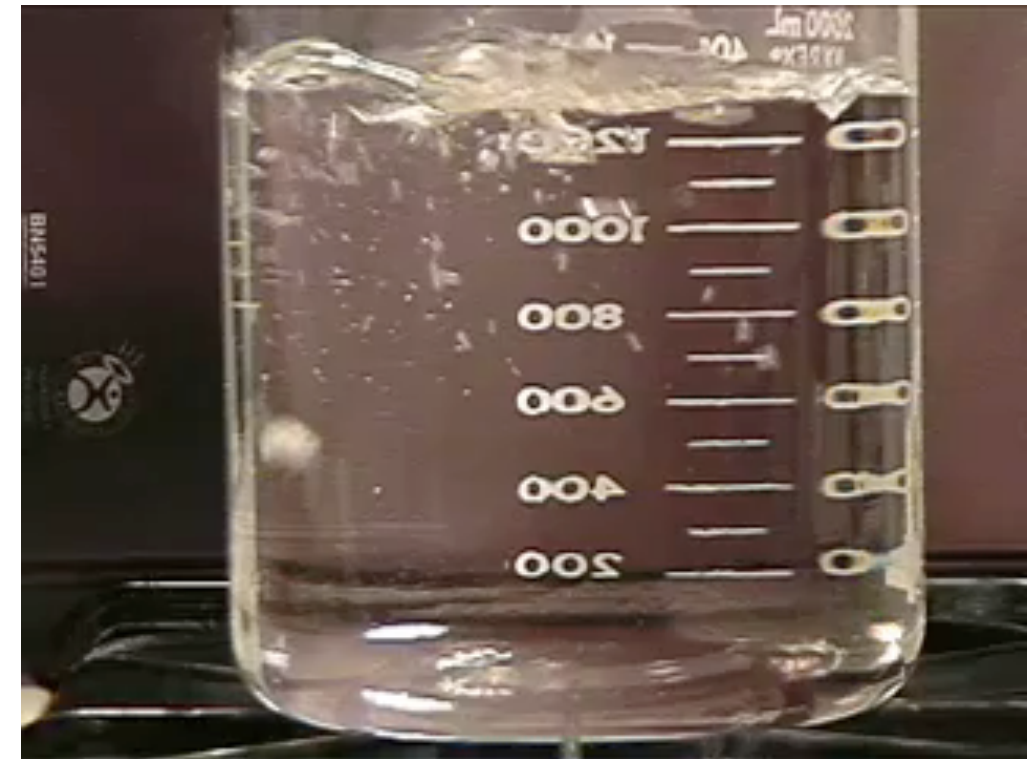
Stage 2: bubble growth

ISLE Physics, YouTube

- After freezeout, once the temperature of the universe drops to Λ, bubbles of the confined phase begin to form and grow.

- These bubbles cannot form with free quarks inside, as free quarks cannot exist in the confined phase (requiring too much energy).

- Quarks (& antiquarks) must either quickly form hadrons or be shunted to the outside of the bubbles.

- <u>Note</u>: see also Hong, Jung & Xie '20, which uses similar "herding" of dark matter in a first-order phase transition to generate macroscopic "Fermi-balls" (or even primordial black holes, Kawana & Xie '21).
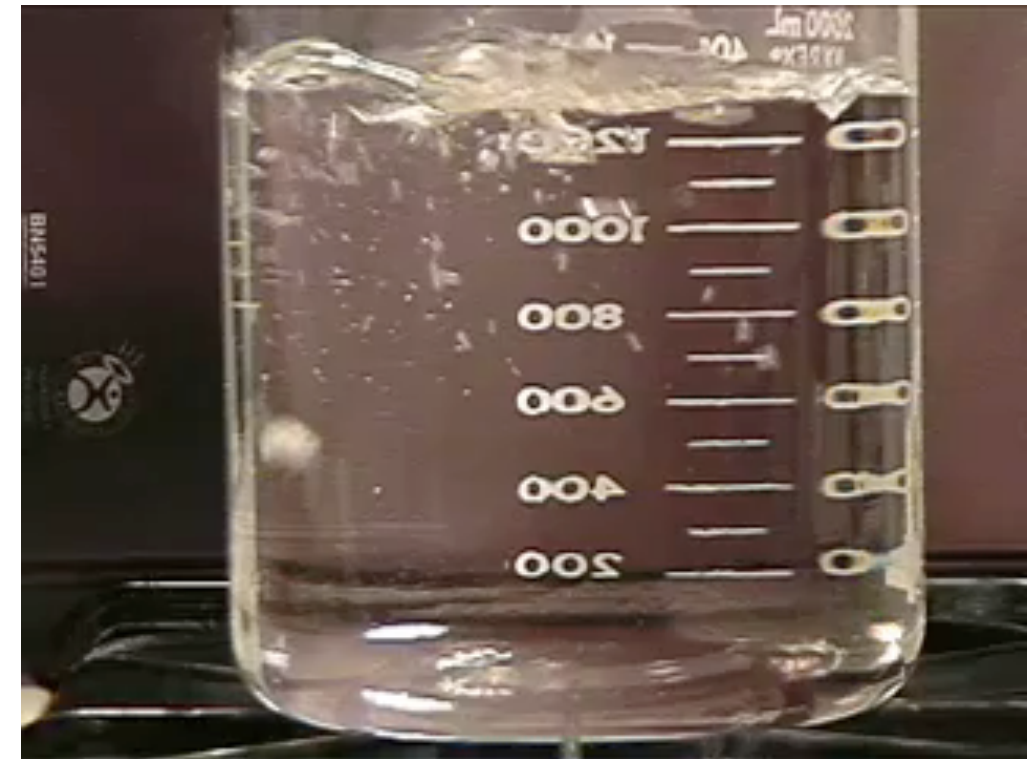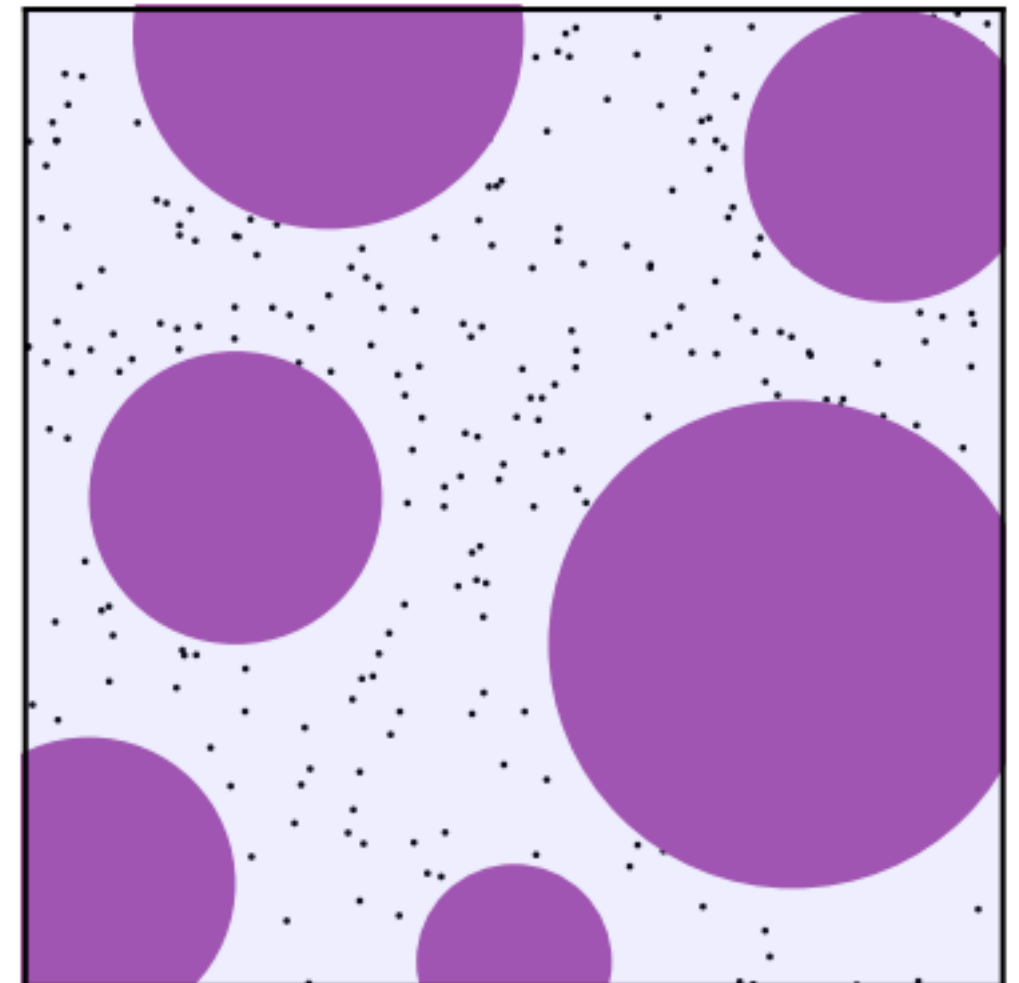
Stage 2: bubble growth

ISLE Physics, YouTube

- After freezeout, once the temperature of the universe drops to Λ, bubbles of the confined phase begin to form and grow.

- These bubbles cannot form with free quarks inside, as free quarks cannot exist in the confined phase (requiring too much energy).

- Quarks (& antiquarks) must either quickly form hadrons or be shunted to the outside of the bubbles.

- Note: see also Hong, Jung & Xie '20, which uses similar "herding" of dark matter in a first-order phase transition to generate macroscopic "Fermi-balls" (or even primordial black holes, Kawana & Xie '21).

Quarks and bubbles

- What happens when a heavy (dark) quark encounters a bubble wall?

- Like a bowling ball hitting a trampoline - initially pushes into the bubble, putting a dent in its surface, but then recoils and bounces off

- We estimated this bounce time and found it to be very fast, $t_{\mathrm{rebound}} \sim \dfrac{v_q}{\dot{v}_q} \sim \dfrac{v_q}{\Lambda^2/m_q} = \sqrt{\dfrac{m_q}{\Lambda}}\dfrac{1}{\Lambda}.$

- Alternatively, the energy from deforming the bubble wall could allow creation of more quarks/antiquarks from the vacuum, so the original quark can form a hadron - very slow/rare if the dark quarks are sufficiently heavy

Quarks and bubbles

- What happens when a heavy (dark) quark encounters a bubble wall?

- Like a bowling ball hitting a trampoline - initially pushes into the bubble, putting a dent in its surface, but then recoils and bounces off
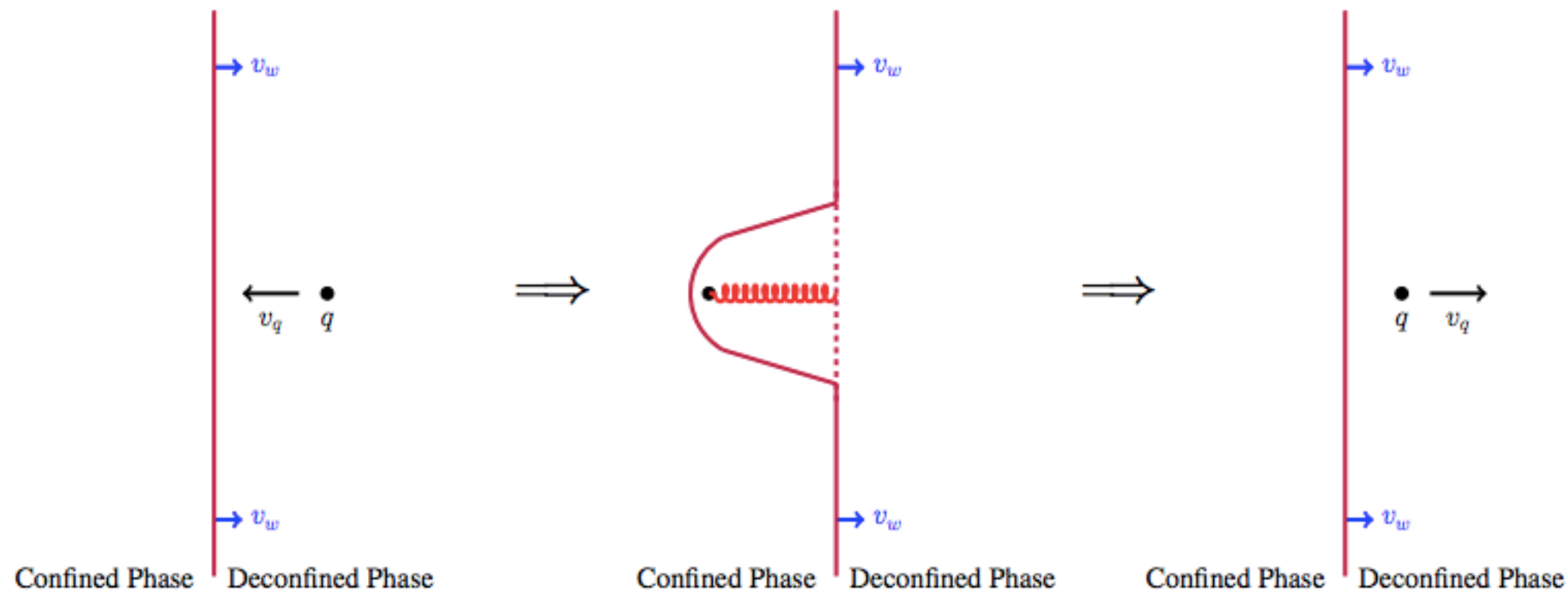

- We estimated this bounce time and found it to be very fast, $t_{\text{rebound}} \sim \dfrac{v_q}{\dot{v}_q} \sim \dfrac{v_q}{\Lambda^2/m_q} = \sqrt{\dfrac{m_q}{\Lambda}} \dfrac{1}{\Lambda}$.

- Alternatively, the energy from deforming the bubble wall could allow creation of more quarks/antiquarks from the vacuum, so the original quark can form a hadron - very slow/rare if the dark quarks are sufficiently heavy
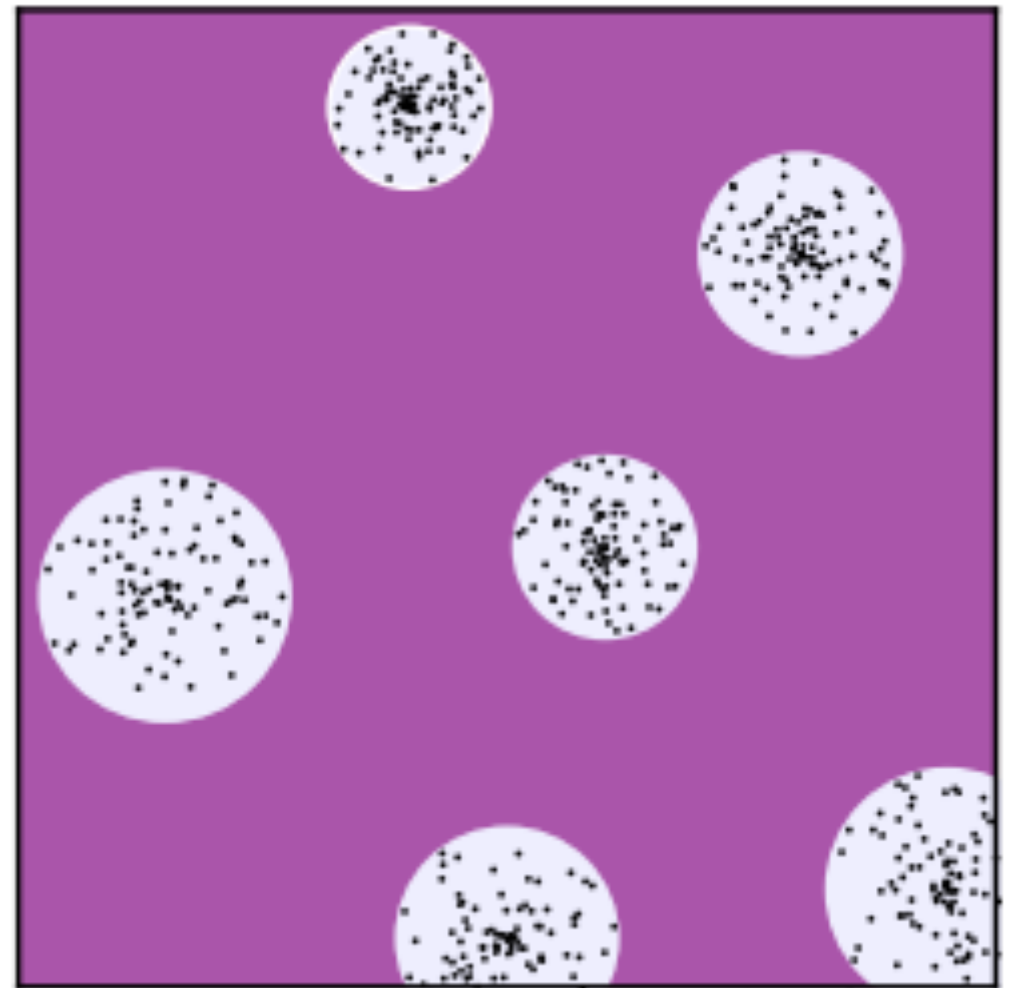
Stage 3: percolation

- As the bubbles continue to grow, eventually they will fill most of the universe - the remaining deconfined phase (gluon "sea" + heavy quarks) will occur only in isolated "pockets"

- All the heavy quarks will have been herded into these pockets by bouncing off the bubble walls

- As these pockets continue to shrink, they compress the heavy quarks to high density
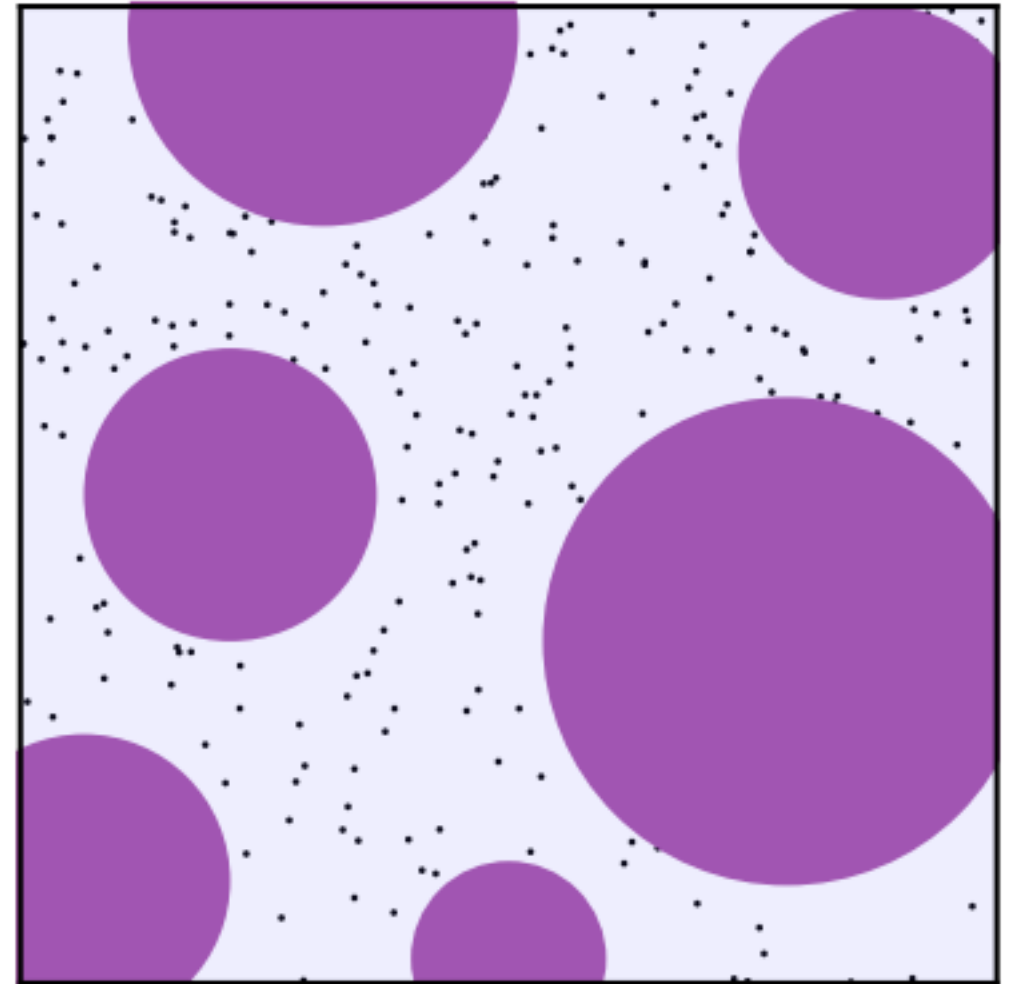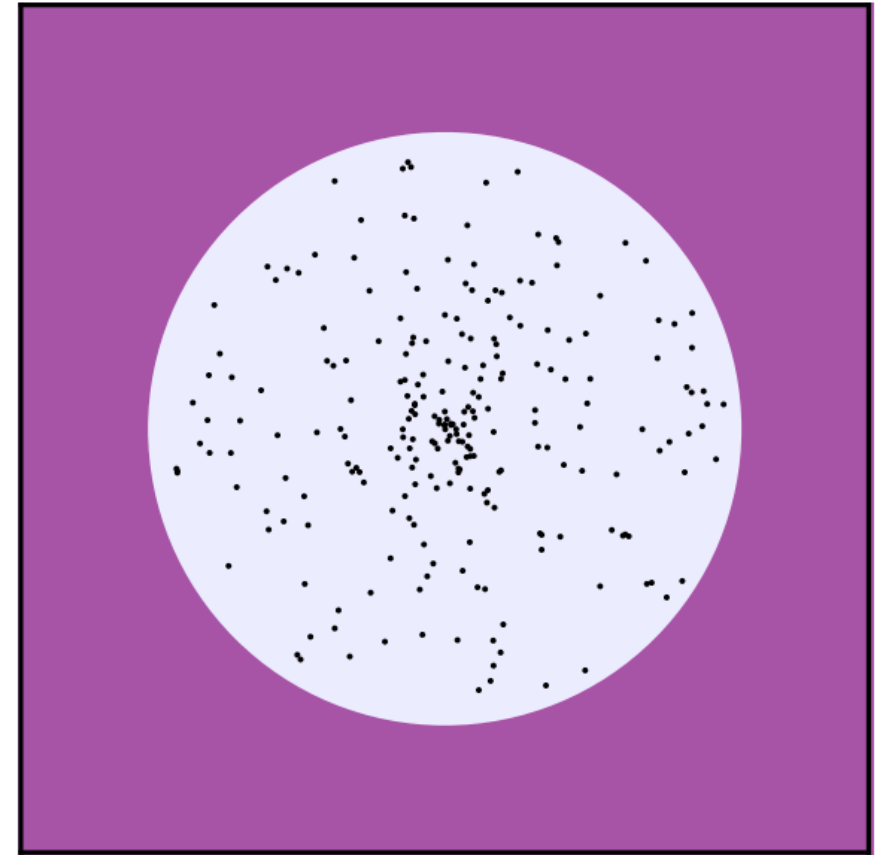
Stage 3: percolation

- As the bubbles continue to grow, eventually they will fill most of the universe - the remaining deconfined phase (gluon "sea" + heavy quarks) will occur only in isolated "pockets"

- All the heavy quarks will have been herded into these pockets by bouncing off the bubble walls

- As these pockets continue to shrink, they compress the heavy quarks to high density

Stage 4: squeezeout

- Previously annihilation had frozen out

- But now the dark quarks are compressed into a much smaller volume, the density is high enough for it to re-start!

- At the same time, at these high densities the dark quarks can bind into dark hadrons

- Dark hadrons can leak through the shrinking pocket walls into the bulk of the universe that is now in the confined phase

- These hadrons form the dark matter at late times - DM is squeezed out of the pockets as they shrink down to zero size
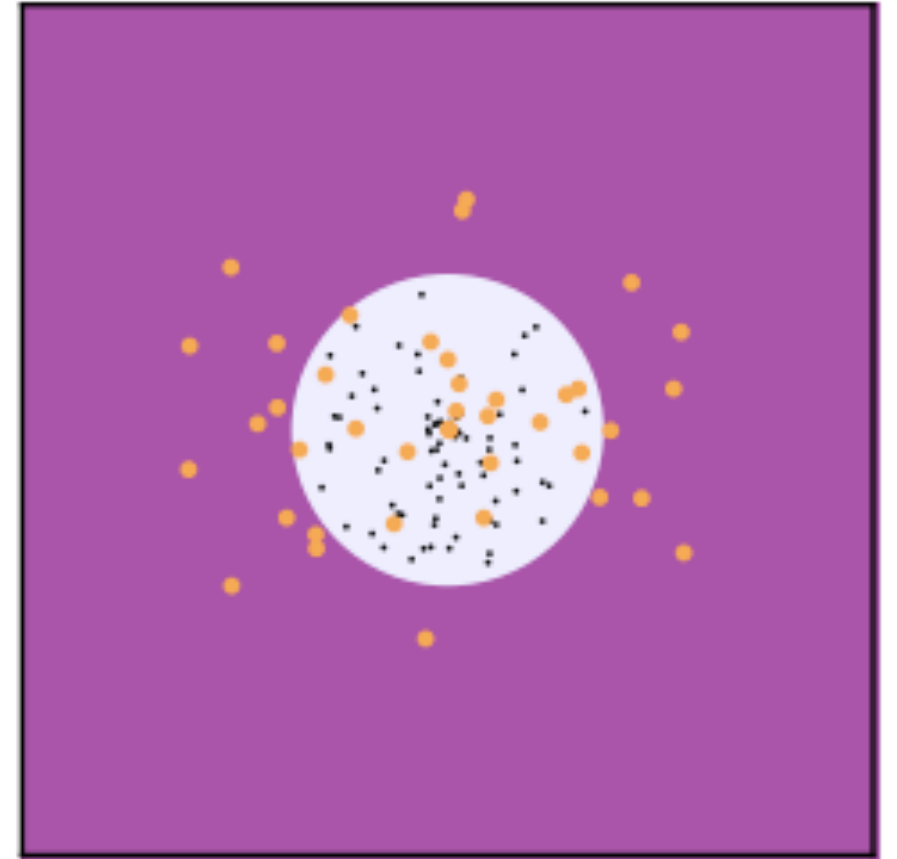
Stage 4: squeezeout

- Previously annihilation had frozen out

- But now the dark quarks are compressed into a much smaller volume, the density is high enough for it to re-start!

- At the same time, at these high densities the dark quarks can bind into dark hadrons

- Dark hadrons can leak through the shrinking pocket walls into the bulk of the universe that is now in the confined phase

- These hadrons form the dark matter at late times - DM is squeezed out of the pockets as they shrink down to zero size
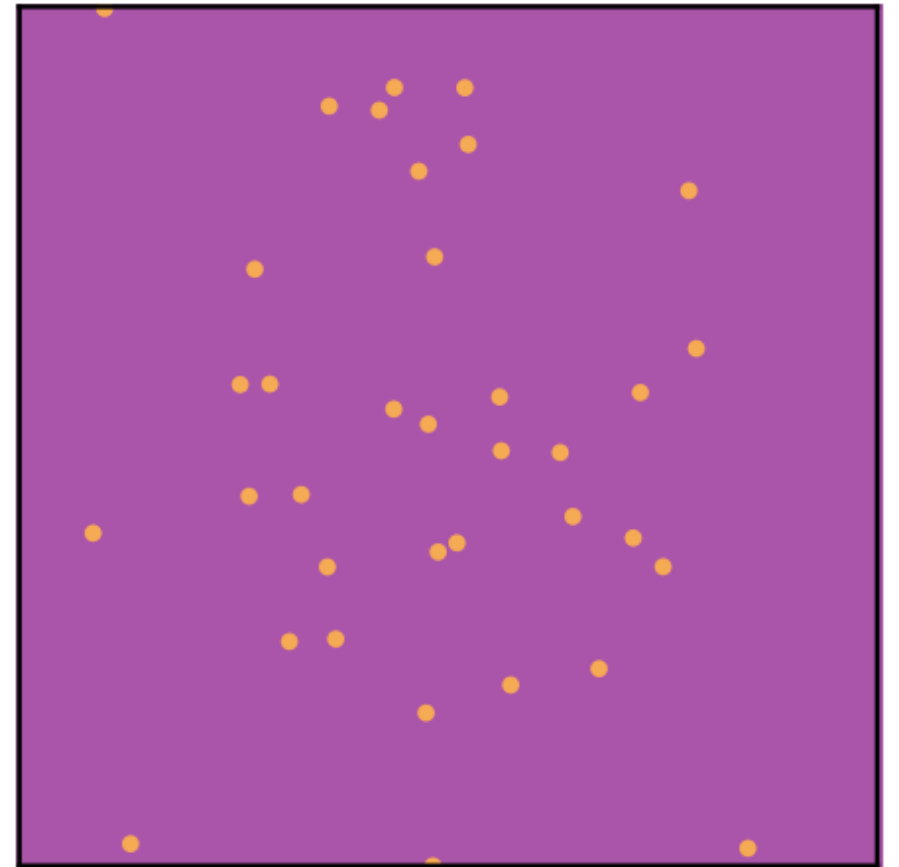
Stage 4: squeezeout

- Previously annihilation had frozen out

- But now the dark quarks are compressed into a much smaller volume, the density is high enough for it to re-start!

- At the same time, at these high densities the dark quarks can bind into dark hadrons

- Dark hadrons can leak through the shrinking pocket walls into the bulk of the universe that is now in the confined phase

- These hadrons form the dark matter at late times - DM is squeezed out of the pockets as they shrink down to zero size
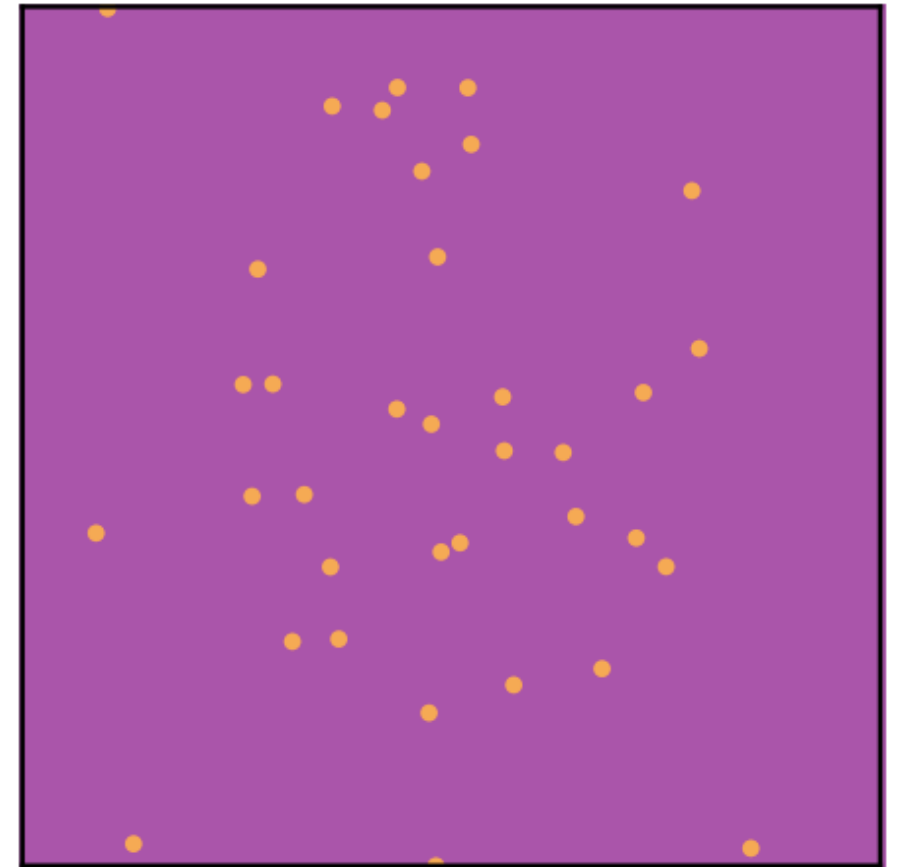
Stage 4: squeezeout

- Previously annihilation had frozen out

- But now the dark quarks are compressed into a much smaller volume, the density is high enough for it to re-start!

- At the same time, at these high densities the dark quarks can bind into dark hadrons

- Dark hadrons can leak through the shrinking pocket walls into the bulk of the universe that is now in the confined phase

- These hadrons form the dark matter at late times - DM is squeezed out of the pockets as they shrink down to zero size
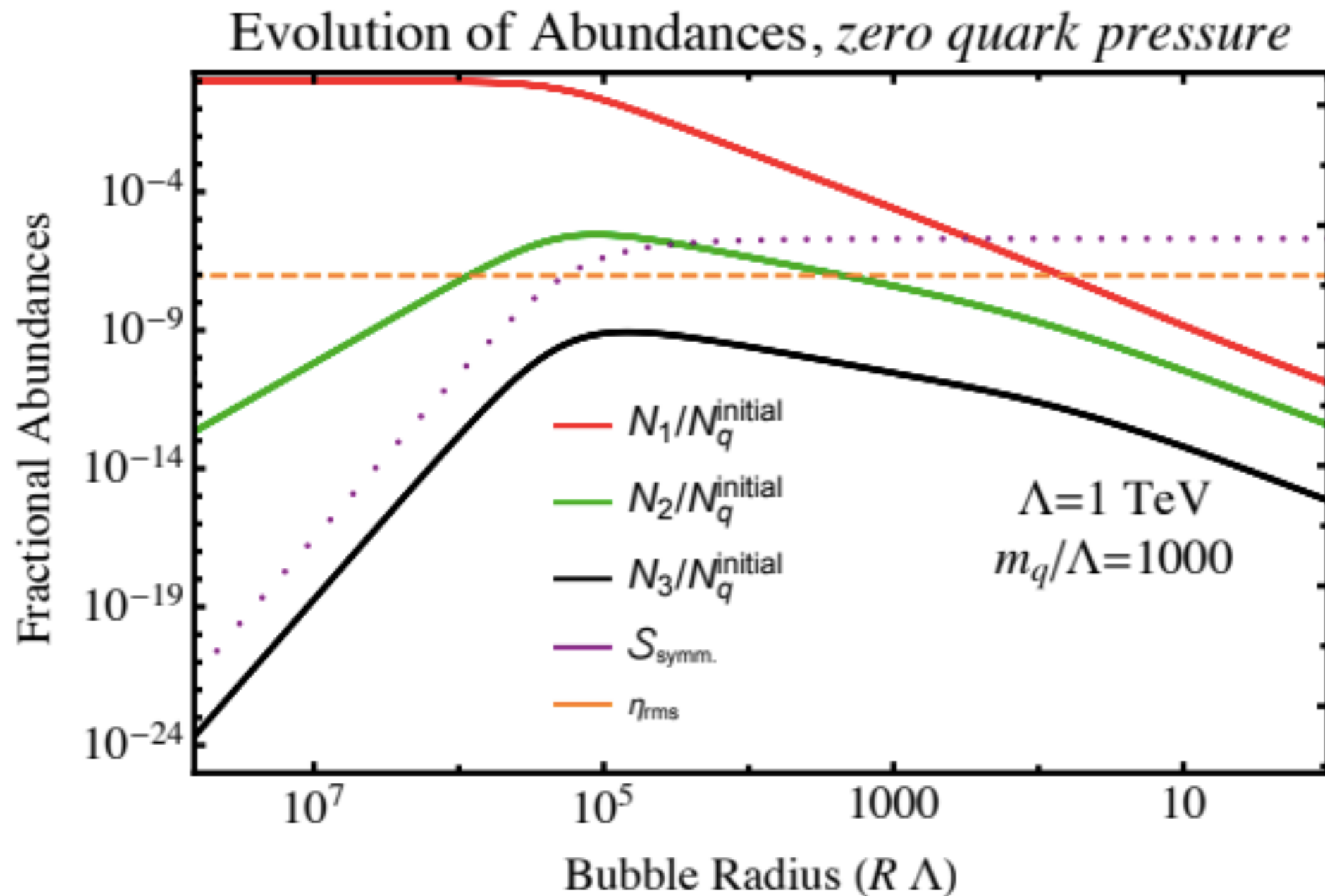
Hadronization vs annihilation?

- In this squeezeout phase, there is a competition between annihilation (destroys dark quarks) and hadronization (makes dark baryons).

- The baryon formation requires multiple steps (quarks → diquarks → baryons).

- Bound states do not necessarily survive to leave the pocket; they can be broken up before escaping.

- The shrinking of the pocket drives the quark density to continually higher values, increasing rates for all processes. Slower shrinkage = more time for annihilation to occur before hadronization+escape becomes efficient = less dark matter survives to be squeezed out.

- Other relevant parameters: initial quark density (set by freezeout), initial pocket size (set by phase transition dynamics, parametric estimate).

- We write down Boltzmann equations for all the processes and solve them numerically, using parametric estimates for the dark-strong-interaction cross sections.

An example simulation

Evolution of Abundances, *zero quark pressure*

$N_1/N_q^{initial}$
$N_2/N_q^{initial}$
$N_3/N_q^{initial}$
$S_{symm.}$
η_{rms}

$\Lambda = 1$ TeV
$m_q/\Lambda = 1000$

- The <u>survival factor S</u> (purple dotted line) is the fraction of dark quarks that survive as baryons, compared to the initial post-freezeout dark quark abundance

The accidentally asymmetric limit

- So far we have assumed every pocket has equal amounts of dark quarks and dark antiquarks

- But even if overall the universe is symmetric, this is clearly not true in detail!

- A pocket with (initially) roughly N_{+q} quarks and N_{-q} antiquarks, summing to $N = N_{+q} + N_{-q}$, will be expected to have an asymmetry due to statistical fluctuations of order $|N_{+q} - N_{-q}| \sim \sqrt{N}$

- This "accidental asymmetry" can cut off the annihilations in the pockets - once all the quarks <u>or</u> antiquarks are eliminated, no further annihilations can occur, and all remaining quarks/antiquarks must hadronize and escape

- In turn this places a lower bound on the average survival factor S, $S \gtrsim 1/\sqrt{N}$

Quark pressure

- The simulation I showed previously made an extra approximation - it ignored the effects of quark pressure

- As the pockets shrink, the (increasingly-high-density) quarks within will exert a pressure on the pocket walls

- This is a strong-interaction, non-equilibrium effect and we do not have an accurate model for it; however, parametric estimates indicate it is likely to be quite large

- We expect the effect will be to slow down the pocket shrinkage velocity (possibly by a lot), which <u>decreases</u> the survival fraction

Is the accidentally-asymmetric limit generic?

- We scanned a wide range of input parameters and found that even when we <u>ignore</u> quark pressure, S generically either saturates the accidentally-asymmetric lower bound or comes close to it.

- Including quark pressure will generically decrease S - under simple estimates, causes saturation of the bound (easily) everywhere.

S with symmetry

accidentally asymmetric limit

Evolution of Abundances, *zero quark pressure*

$N_1/N_q^{initial}$
$N_2/N_q^{initial}$
$N_3/N_q^{initial}$
$S_{symm.}$
η_{rms}

$\Lambda = 1$ TeV
$m_q/\Lambda = 1000$

Fractional Abundances

Bubble Radius ($R\,\Lambda$)
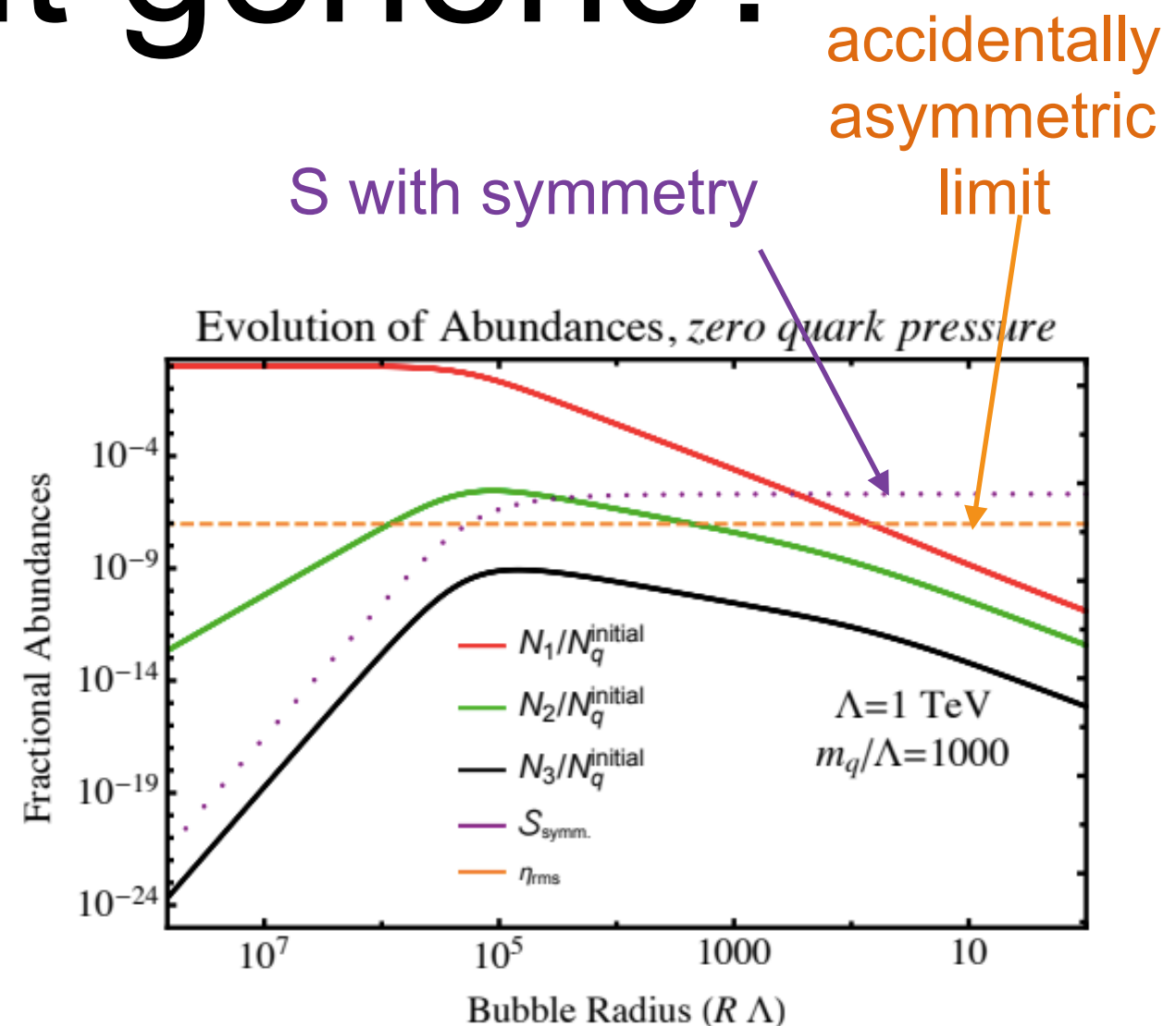
- Consequently, we argue that the accidentally-asymmetric limit is likely to be generically a good approximation.

The relic density

Relic Abundance

- In the accidentally asymmetric limit, the survival factor S is determined entirely by the initial number of quarks per pocket

- Fixed by:

  - post-freezeout number density (depends on quark mass + high-energy couplings, set by Λ)

  - radius of pockets at percolation (estimated as
    $$R_1 \approx \left(\frac{M_{\text{Pl}}}{10^4 \Lambda} \right)^{2/3} \frac{1}{\Lambda}, \text{ from}$$
    Witten 1984)
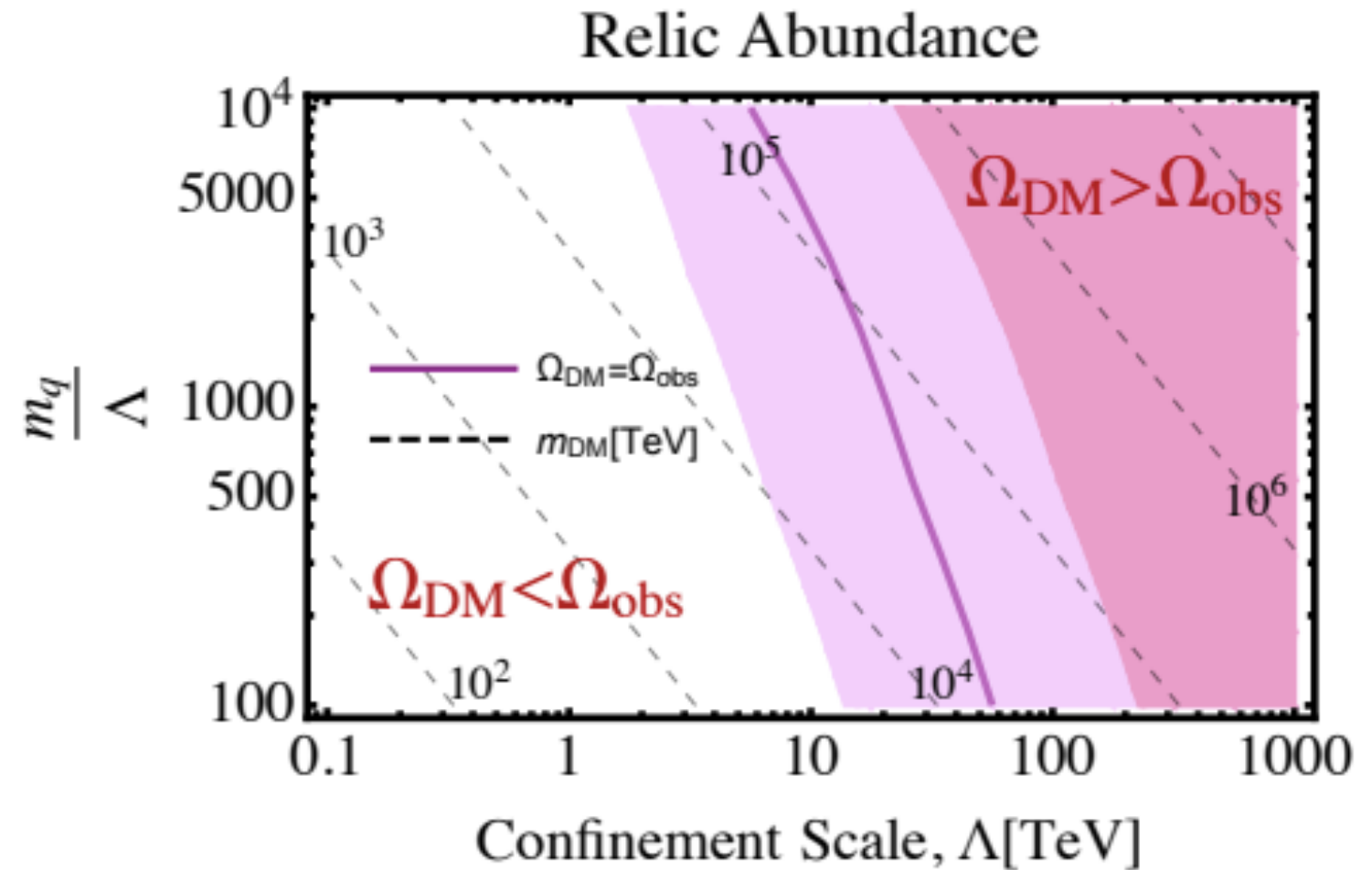
- We can calculate the relic density as a function of m_q and Λ, allowing for an order-of-magnitude variation in the pocket radius around our estimate

- We find preferred DM masses around 1-1000 PeV (also if we assume zero quark pressure)

Summary of cosmic history for this scenario

Freezeout: the dark quark abundance is depleted through annihilation as normal.

Squeezeout: the phase transition triggers a further sharp drop in the abundance, potentially by several orders of magnitude, as the dark quarks are compressed in contracting pockets and many of them annihilate before forming hadrons.

Dark hadrons escape the pockets as the pocket size shrinks to zero, leading to the observed relic abundance for PeV+ DM.

$\Lambda = 1\text{TeV}, m_q = 1000\Lambda$

$T > \Lambda \quad T < \Lambda$

Y_q

Y_q^{eq}

S

Abundance, Y

Mass Ratio, m_q/T
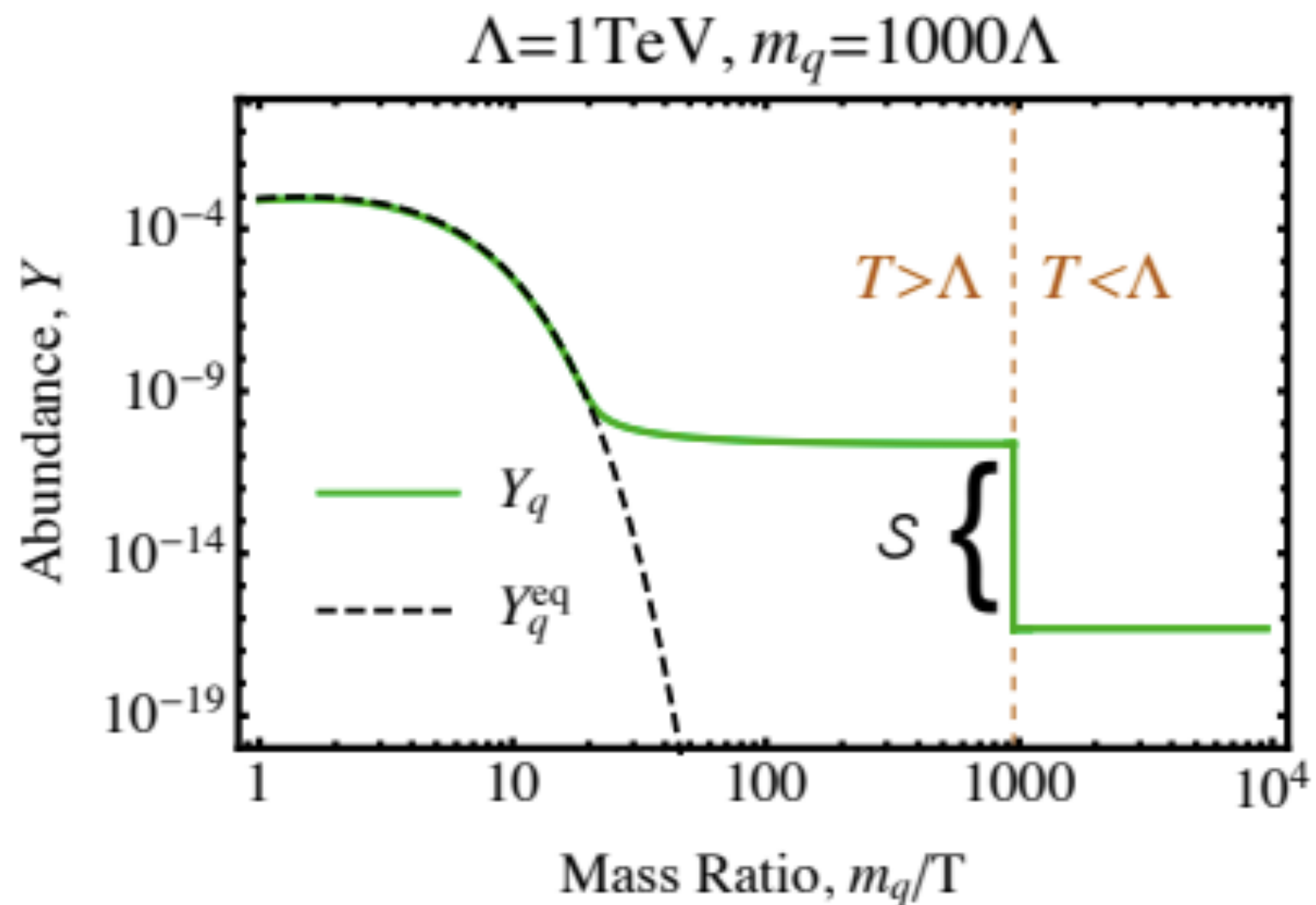
Observational signatures?

- What I have shown you so far depends almost exclusively on the dark-sector physics - most signatures would depend on the details of the portal to the Standard Model (work in progress)

- Any first-order dark sector phase transition could generate a stochastic gravitational wave background that could be seen in future experiments [e.g. Geller et al, PRL 2018]

- This scenario predicts heavy unstable states (mesons + glueballs) lighter than the DM - glueballs might possibly be within reach for future colliders

- Indirect searches are limited by the unitarity upper bound on the annihilation cross-section

- Because the mass scale is so high, rather large interactions with the SM may be viable - interesting for direct detection? [e.g. Cappiello et al, PRD 2021]

The importance of glueballs

PRELIMINARY

- Two reasons for the portal to the SM

  - keep the sectors at the same temperature (simplifies the calculation, may not be essential)

  - provide a decay channel for the glueballs (important - else they may overclose the universe)

- In exploring portals to the SM, we found it is quite generic for some glueballs to be metastable, decaying with a long lifetime

- In parts of parameter space the glueballs are long-lived enough to dominate the energy density before they decay → early matter domination (EMD)

- When they do decay, large entropy injection into the SM → further dilution of the DM abundance

- Can drive (parts of) the allowed parameter space to even heavier DM masses
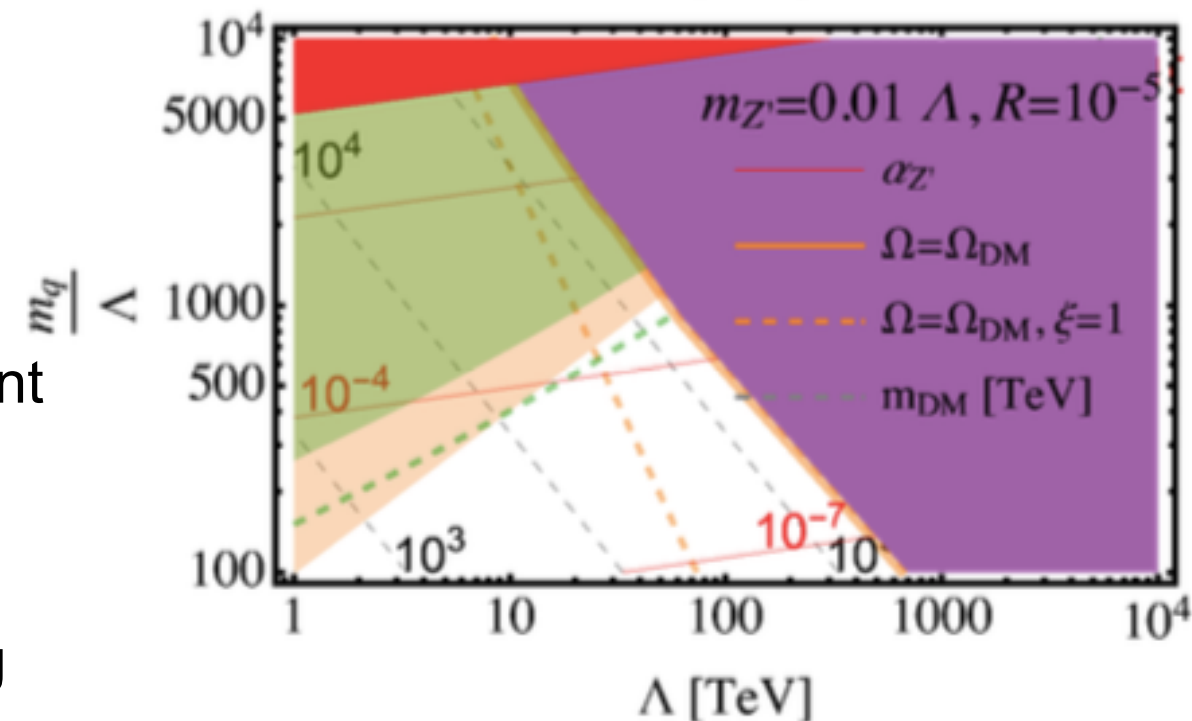
Preliminary work with Asadi, Kramer, Kuflik & Smirnov on Z' portal between dark quarks and SM

Dashed and solid orange lines show shift in parameters yielding correct relic density due to glueballs

Green, orange, purple regions show constraints on model due to direct detection, collider searches for Z', and overclosure

Entropy injection from a partner

- More generally, suppose DM is accompanied by a metastable partner particle, both produced by freezeout

- If the partner decays after it comes to dominate the energy budget, large entropy injection that dilutes DM

- Smaller annihilation xsec for DM & partner increases abundance of both - but increased abundance of partner leads to increased dilution of DM

WIMPs without weakness

[arXiv:2111.11444, Asadi, TRS & Smirnov]

- Wide range of characteristic xsecs yield the correct relic abundance

- Unitarity bound no longer applies due to dilution

- Parameter space limited by requiring metastable species to decay before BBN
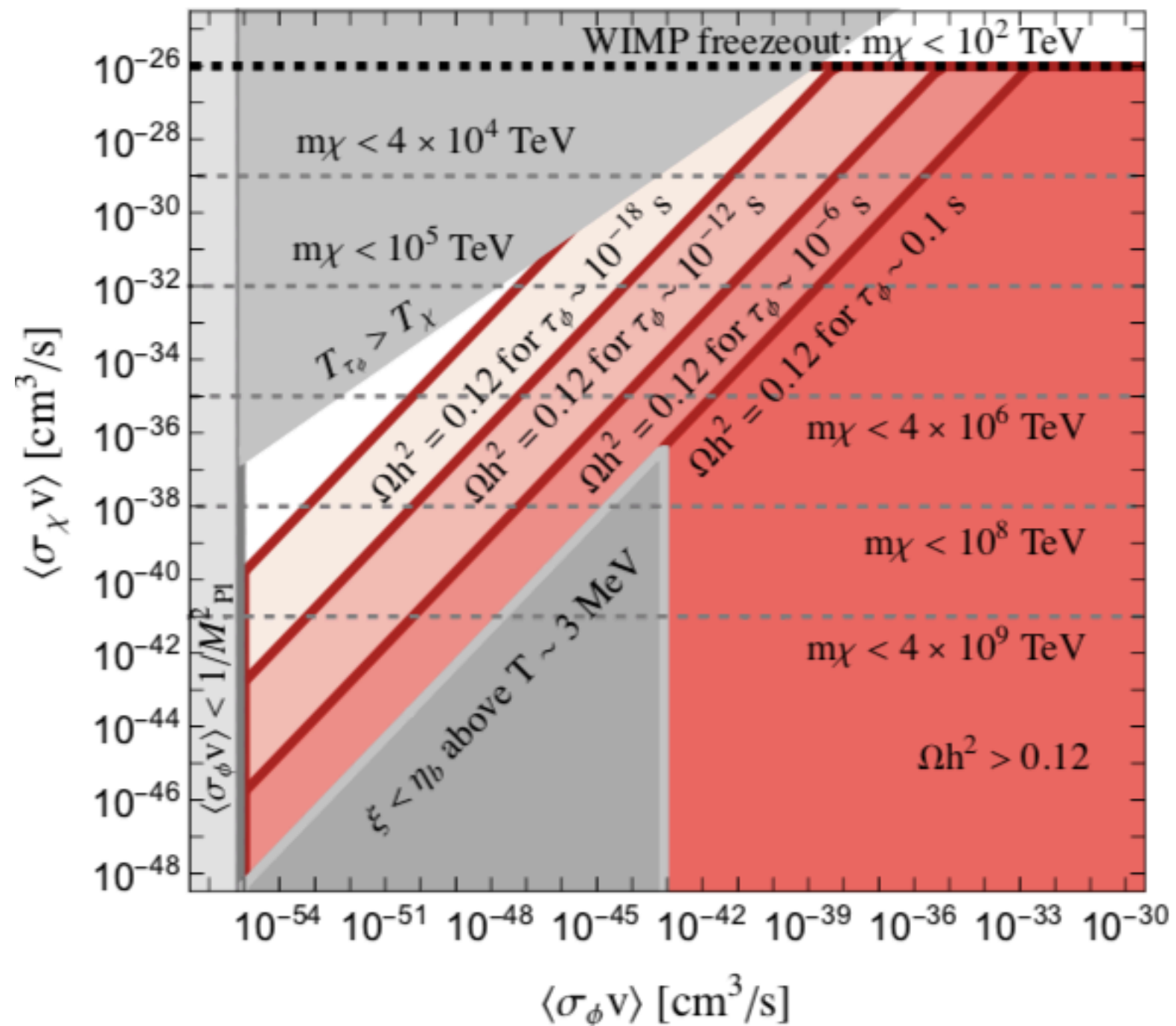
Other implications

- More generally, the annihilation xsecs/processes for the two species may be very different

- We present results for cases where one or both of the annihilations are multi-body (i.e. n>2 DM particles in initial state)

- Dilution also weakens indirect-detection constraints since a smaller xsec is needed to get the correct relic density - opens parameter space at low masses

$\chi : 3 \to 2, \phi : 2 \to 0, l_{\chi,\phi} \to 0, \sigma \to \sigma_{uni.}$

$m_{Z'} = 3/2\, m_\chi$
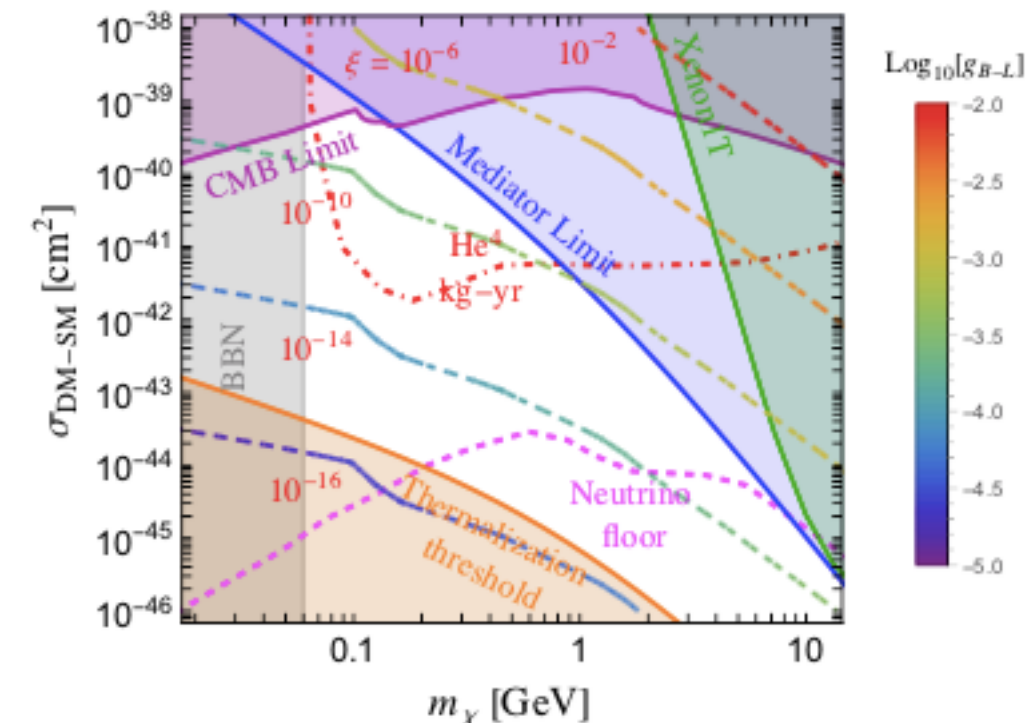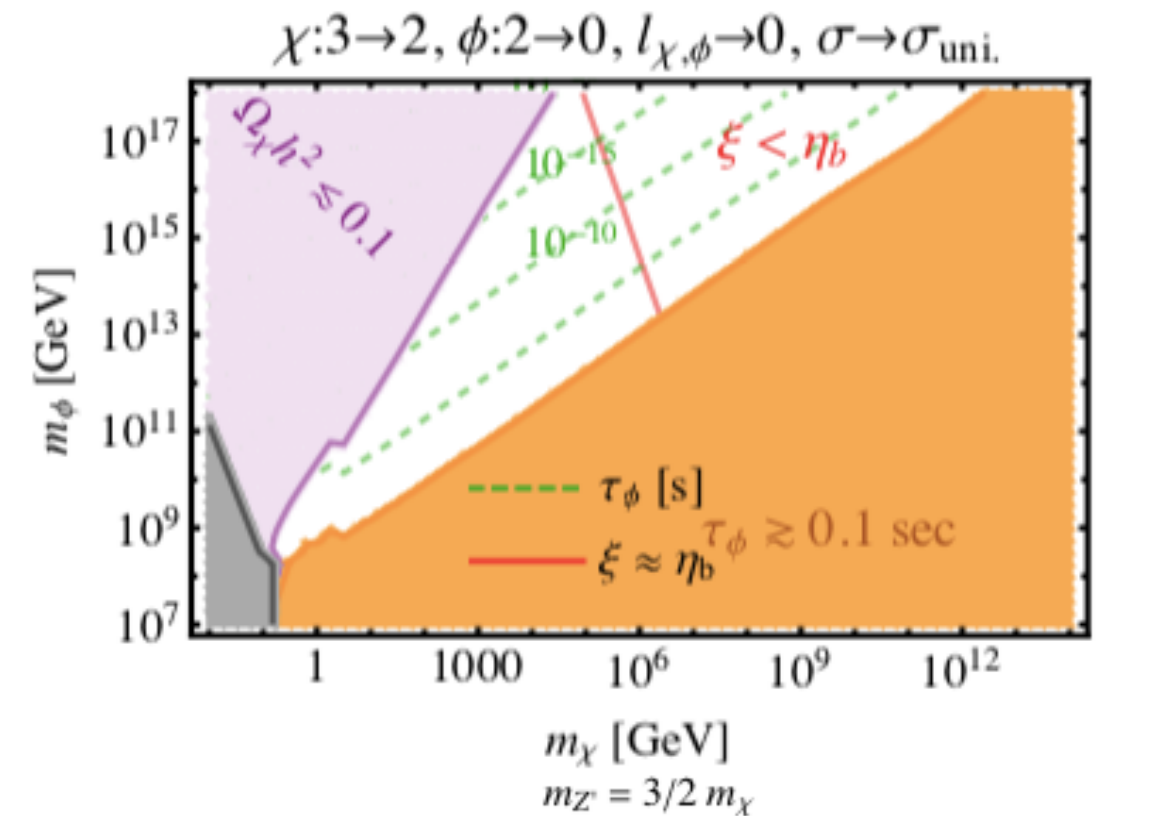
Summary

- A natural possibility for heavy thermal dark matter, beyond the standard unitarity bound at O(100) TeV, is a strongly-interacting dark sector.

- If the dark quark mass is much heavier than the confinement scale, the confinement phase transition is expected to be first-order.

- The interplay between thermal freezeout and a dark phase transition naturally leads to inhomogeneous regions of high dark quark density, a second phase of rapid annihilation during the phase transition, and the correct relic abundance for PeV-EeV DM.

- (preliminary) Long-lived glueball states in such a dark sector can generically give rise to an early matter-dominated epoch prior to BBN

- We have explored the consequences of general scenarios where a thermally-produced metastable partner particle decays away, diluting the DM density, opening up thermal relic parameter space at both low and high masses

BONUS SLIDES

Rates for bound-state formation

- We need the rates to form diquark bound states, and to go from diquarks to baryons

- Simplifying approximations:

  - for mesons, which are expected to decay on a timescale fast relative to annihilations/hadronization, assume they are in equilibrium at the SM temperature (so abundance is very small)

  - ignore heavy tetraquark/pentaquark states for the same reason

  - include only $2 \rightarrow 2$ processes as $3 \rightarrow 2$ and $2 \rightarrow 3$ are suppressed

  - treat gluons as a radiation species in equilibrium in deconfined phase

  - couplings can be evaluated at $m_q \gg \Lambda$

- Notation: label each species by its quark number (gluons = 0, quarks = +1, anti-quarks = -1, diquarks = +2, etc)
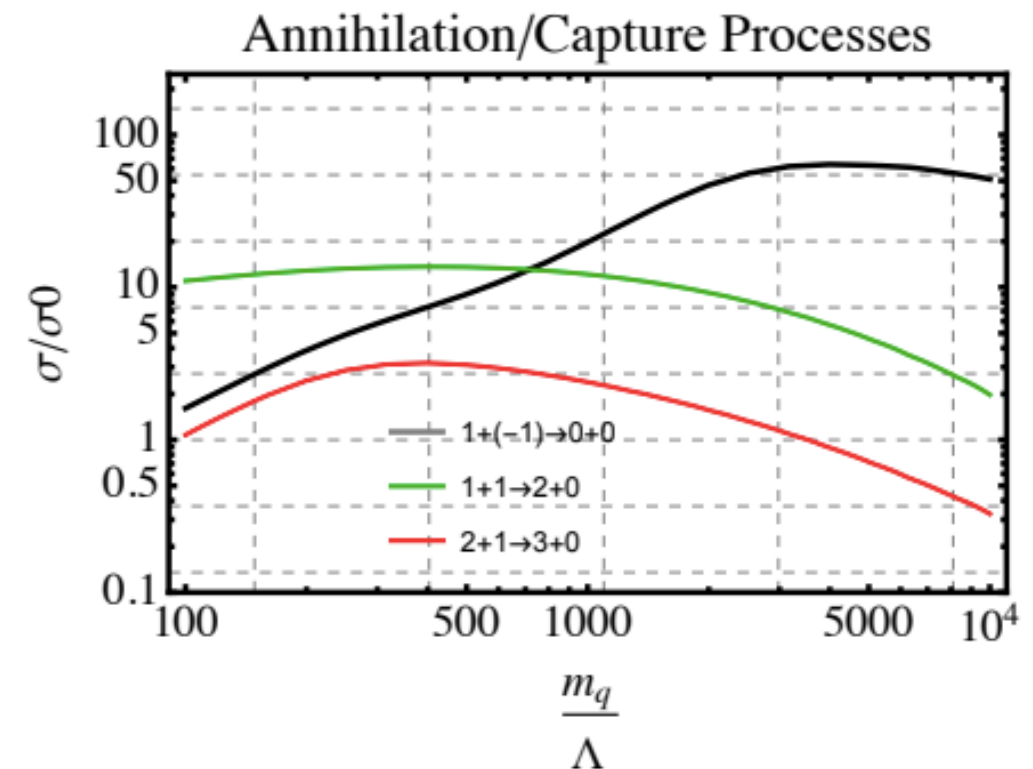
Relevant processes

- <u>Annihilation</u>: particles and antiparticles annihilate directly (and completely) into gluons, e.g. $1 + -1 \rightarrow 0 + 0$

- <u>Capture (and dissociation)</u>: quark number is conserved but a dark gluon is emitted to conserve momentum, e.g. $1 + 1 \rightarrow 2 + 0$

$$\langle \sigma_{\mathrm{ann./cap.}} v \rangle = \zeta \, \frac{\pi \alpha^2}{m_q^2} \equiv \zeta \, \sigma_0$$

- <u>Rearrangement</u>: quark number is conserved and no dark gluon is emitted, e.g. $2 + 2 \rightarrow 3 + 1$

Annihilation/Capture Processes

Legend:
- $1+(-1) \rightarrow 0+0$
- $1+1 \rightarrow 2+0$
- $2+1 \rightarrow 3+0$

Axes: $\sigma/\sigma 0$ vs $\frac{m_q}{\Lambda}$

$$\langle \sigma_{\mathrm{RA}} v \rangle = \frac{1}{C_N \alpha} \frac{\pi}{m_q^2} = \frac{\sigma_0}{C_N \alpha^3},$$

enhancement from finite size of colliding bound states

Boltzmann equations

$$L[i] = C[i], \quad i = 1, 2, 3.$$

$$
\begin{aligned}
C[1] &= -\Big\langle (-3,1) \to (-1,-1) \Big\rangle - \Big\langle (-3,1) \to (-2,0) \Big\rangle + 2\Big\langle (3,-1) \to (1,1) \Big\rangle \\
&\quad + \Big\langle (3,-2) \to (1,0) \Big\rangle - \Big\langle (1,-1) \to (0,0) \Big\rangle + \Big\langle (2,2) \to (3,1) \Big\rangle - 2\Big\langle (1,1) \to (2,0) \Big\rangle \\
&\quad + \Big\langle (-3,2) \to (-2,1) \Big\rangle + \Big\langle (2,-2) \to (1,-1) \Big\rangle + \Big\langle (2,-1) \to (1,0) \Big\rangle \\
&\quad - \Big\langle (2,1) \to (3,0) \Big\rangle - \Big\langle (-2,1) \to (-1,0) \Big\rangle + \Big\langle (3,-3) \to (1,-1) \Big\rangle \quad,
\end{aligned}
$$

$$
\begin{aligned}
C[2] &= \Big\langle (1,1) \to (2,0) \Big\rangle - \Big\langle (-3,2) \to (-1,0) \Big\rangle + \Big\langle (3,-1) \to (2,0) \Big\rangle \\
&\quad - \Big\langle (2,-2) \to (0,0) \Big\rangle + \Big\langle (3,-2) \to (2,-1) \Big\rangle + \Big\langle (3,-3) \to (2,-2) \Big\rangle \\
&\quad - \Big\langle (2,-1) \to (1,0) \Big\rangle - 2\Big\langle (2,2) \to (3,1) \Big\rangle - \Big\langle (2,1) \to (3,0) \Big\rangle \\
&\quad - \Big\langle (-3,2) \to (-2,1) \Big\rangle - \Big\langle (2,-2) \to (1,-1) \Big\rangle \quad,
\end{aligned}
$$

$$
\begin{aligned}
C[3] &= \Big\langle (2,1) \to (3,0) \Big\rangle + \Big\langle (2,2) \to (3,1) \Big\rangle - \Big\langle (3,-3) \to (0,0) \Big\rangle - \Big\langle (3,-1) \to (2,0) \Big\rangle \\
&\quad - \Big\langle (3,-1) \to (1,1) \Big\rangle - \Big\langle (3,-3) \to (1,-1) \Big\rangle - \Big\langle (3,-3) \to (2,-2) \Big\rangle \\
&\quad - \Big\langle (3,-2) \to (2,-1) \Big\rangle - \Big\langle (3,-2) \to (1,0) \Big\rangle
\end{aligned}
$$

$$L[i] = -\frac{v_w}{V} N_i', \quad i = 1, 2,$$

$$L[3] = -\frac{v_w}{V}\left(N_3' - \frac{3}{R}\frac{v_q + v_w}{v_w} N_3 \right),$$

$$\Big\langle (a,b) \to (\alpha,\beta) \Big\rangle = \langle \sigma v \rangle_{ab \to \alpha\beta} \left(n_a n_b - n_\alpha n_\beta \frac{n_a^{eq} n_b^{eq}}{n_\alpha^{eq} n_\beta^{eq}} \right)$$

$$= \frac{\langle \sigma v \rangle_{ab \to \alpha\beta}}{V^2} \left(N_a N_b - N_\alpha N_\beta f_{ab,\alpha\beta} \right),$$

Boltzmann equations

$$L[i] = C[i], \quad i = 1, 2, 3.$$

$$C[1] = -\Big\langle (-3,1) \to (-1,-1) \Big\rangle - \Big\langle (-3,1) \to (-2,0) \Big\rangle + 2\Big\langle (3,-1) \to (1,1) \Big\rangle$$

$$+ \Big\langle (3,-2) \to (1,0) \Big\rangle - \Big\langle (1,-1) \to (0,0) \Big\rangle + \Big\langle (2,2) \to (3,1) \Big\rangle - 2\Big\langle (1,1) \to (2,0) \Big\rangle$$

$$+ \Big\langle (-3,2) \to (-2,1) \Big\rangle + \Big\langle (2,-2) \to (1,-1) \Big\rangle + \Big\langle (2,-1) \to (1,0) \Big\rangle$$

$$- \Big\langle (2,1) \to (3,0) \Big\rangle - \Big\langle (-2,1) \to (-1,0) \Big\rangle + \Big\langle (3,-3) \to (1,-1) \Big\rangle \quad ,$$

$$C[2] = \Big\langle (1,1) \to (2,0) \Big\rangle - \Big\langle (-3,2) \to (-1,0) \Big\rangle + \Big\langle (3,-1) \to (2,0) \Big\rangle$$

$$- \Big\langle (2,-2) \to (0,0) \Big\rangle + \Big\langle (3,-2) \to (2,-1) \Big\rangle + \Big\langle (3,-3) \to (2,-2) \Big\rangle$$

$$- \Big\langle (2,-1) \to (1,0) \Big\rangle - 2\Big\langle (2,2) \to (3,1) \Big\rangle - \Big\langle (2,1) \to (3,0) \Big\rangle$$

$$- \Big\langle (-3,2) \to (-2,1) \Big\rangle - \Big\langle (2,-2) \to (1,-1) \Big\rangle \quad ,$$

$$C[3] = \Big\langle (2,1) \to (3,0) \Big\rangle + \Big\langle (2,2) \to (3,1) \Big\rangle - \Big\langle (3,-3) \to (0,0) \Big\rangle - \Big\langle (3,-1) \to (2,0) \Big\rangle$$

$$- \Big\langle (3,-1) \to (1,1) \Big\rangle - \Big\langle (3,-3) \to (1,-1) \Big\rangle - \Big\langle (3,-3) \to (2,-2) \Big\rangle$$

$$- \Big\langle (3,-2) \to (2,-1) \Big\rangle - \Big\langle (3,-2) \to (1,0) \Big\rangle$$

describes change in particle number with respect to pocket radius

$$L[i] = -\frac{v_w}{V} N_i', \quad i = 1, 2,$$

$$L[3] = -\frac{v_w}{V}\left(N_3' - \frac{3}{R}\frac{v_q + v_w}{v_w} N_3 \right),$$

$$\Big\langle (a,b) \to (\alpha,\beta) \Big\rangle = \langle \sigma v \rangle_{ab \to \alpha\beta} \left(n_a n_b - n_\alpha n_\beta \frac{n_a^{eq} n_b^{eq}}{n_\alpha^{eq} n_\beta^{eq}} \right)$$

$$= \frac{\langle \sigma v \rangle_{ab \to \alpha\beta}}{V^2} \left(N_a N_b - N_\alpha N_\beta f_{ab,\alpha\beta} \right),$$

Boltzmann equations

$$L[i] = C[i], \quad i = 1, 2, 3.$$

$$
\begin{aligned}
C[1] = {}& -\big\langle (-3,1) \to (-1,-1) \big\rangle - \big\langle (-3,1) \to (-2,0) \big\rangle + 2\big\langle (3,-1) \to (1,1) \big\rangle \\
& + \big\langle (3,-2) \to (1,0) \big\rangle - \big\langle (1,-1) \to (0,0) \big\rangle + \big\langle (2,2) \to (3,1) \big\rangle - 2\big\langle (1,1) \to (2,0) \big\rangle \\
& + \big\langle (-3,2) \to (-2,1) \big\rangle + \big\langle (2,-2) \to (1,-1) \big\rangle + \big\langle (2,-1) \to (1,0) \big\rangle \\
& - \big\langle (2,1) \to (3,0) \big\rangle - \big\langle (-2,1) \to (-1,0) \big\rangle + \big\langle (3,-3) \to (1,-1) \big\rangle \ ,
\end{aligned}
$$

$$
\begin{aligned}
C[2] = {}& \big\langle (1,1) \to (2,0) \big\rangle - \big\langle (-3,2) \to (-1,0) \big\rangle + \big\langle (3,-1) \to (2,0) \big\rangle \\
& - \big\langle (2,-2) \to (0,0) \big\rangle + \big\langle (3,-2) \to (2,-1) \big\rangle + \big\langle (3,-3) \to (2,-2) \big\rangle \\
& - \big\langle (2,-1) \to (1,0) \big\rangle - 2\big\langle (2,2) \to (3,1) \big\rangle - \big\langle (2,1) \to (3,0) \big\rangle \\
& - \big\langle (-3,2) \to (-2,1) \big\rangle - \big\langle (2,-2) \to (1,-1) \big\rangle \ ,
\end{aligned}
$$

$$
\begin{aligned}
C[3] = {}& \big\langle (2,1) \to (3,0) \big\rangle + \big\langle (2,2) \to (3,1) \big\rangle - \big\langle (3,-3) \to (0,0) \big\rangle - \big\langle (3,-1) \to (2,0) \big\rangle \\
& - \big\langle (3,-1) \to (1,1) \big\rangle - \big\langle (3,-3) \to (1,-1) \big\rangle - \big\langle (3,-3) \to (2,-2) \big\rangle \\
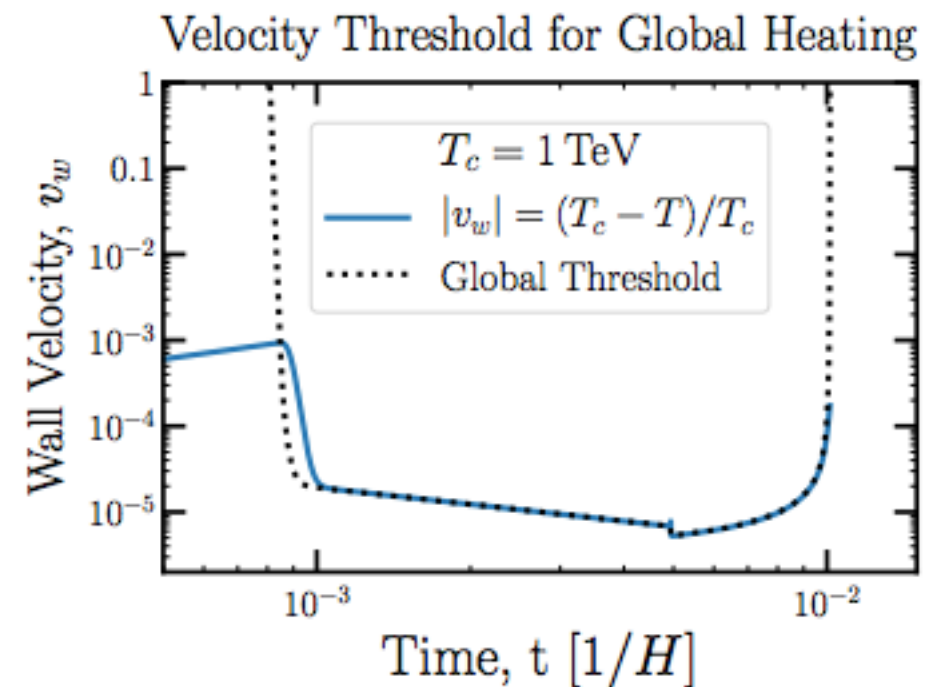& - \big\langle (3,-2) \to (2,-1) \big\rangle - \big\langle (3,-2) \to (1,0) \big\rangle
\end{aligned}
$$

describes change in particle number with respect to pocket radius

$$L[i] = -\frac{v_w}{V} N_i', \quad i = 1, 2, \qquad \big\langle (a,b) \to (\alpha,\beta) \big\rangle = \langle \sigma v \rangle_{ab \to \alpha\beta} \left(n_a n_b - n_\alpha n_\beta \frac{n_a^{eq} n_b^{eq}}{n_\alpha^{eq} n_\beta^{eq}} \right)$$

$$L[3] = -\frac{v_w}{V} \left(N_3' - \frac{3}{R} \frac{v_q + v_w}{v_w} N_3 \right), \qquad = \frac{\langle \sigma v \rangle_{ab \to \alpha\beta}}{V^2} \left(N_a N_b - N_\alpha N_\beta f_{ab,\alpha\beta} \right),$$

describes escape of baryons from pocket

Estimating the pocket wall velocity

Velocity Threshold for Global Heating

Wall Velocity, v_w vs Time, t $[1/H]$

- $T_c = 1\,\text{TeV}$
- $|v_w| = (T_c - T)/T_c$
- Global Threshold

- Important parameter for squeezeout; sets the overall timescale in which quarks must annihilate or hadronize.

- If this velocity is too large, the heat released by phase conversion from pocket shrinkage (or bubble expansion) can raise the local temperature to the point where phase conversion is no longer energetically favorable.

- We require that the rate for the local temperature to fall due to diffusion of injected heat away from the pocket wall matches the rate at which the temperature rises due to phase conversion,

$$\dot{T}_{\text{heat}} \sim \Lambda^2 v_w$$

- Assume that the heat is diffused away through dark gluon bath outside the pocket, diffusion timescale controlled by Λ and by the difference of local & global temperatures:

$$\dot{T}_{\text{cool}} \sim -\Lambda^2 (T_c - T)/T_c.$$

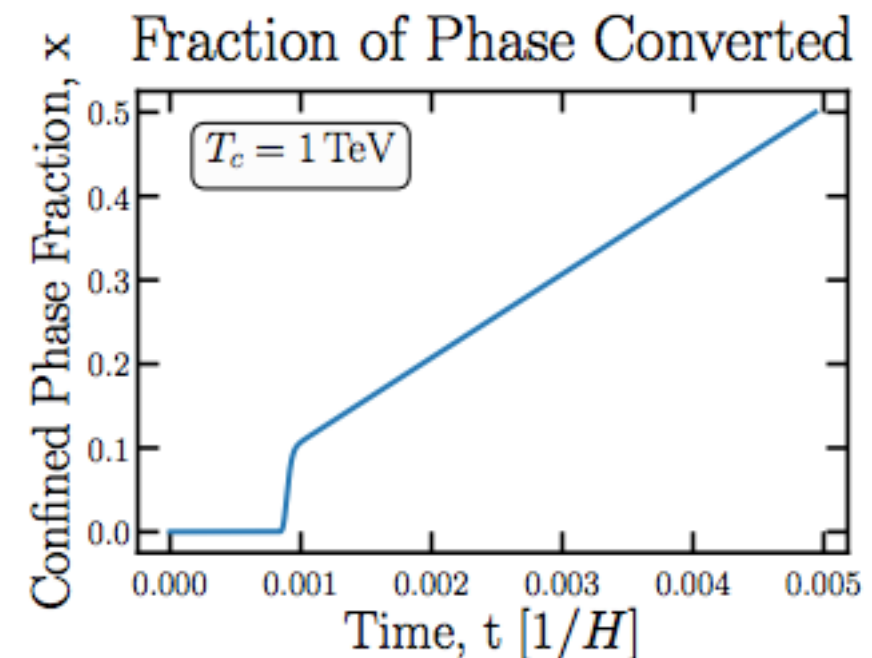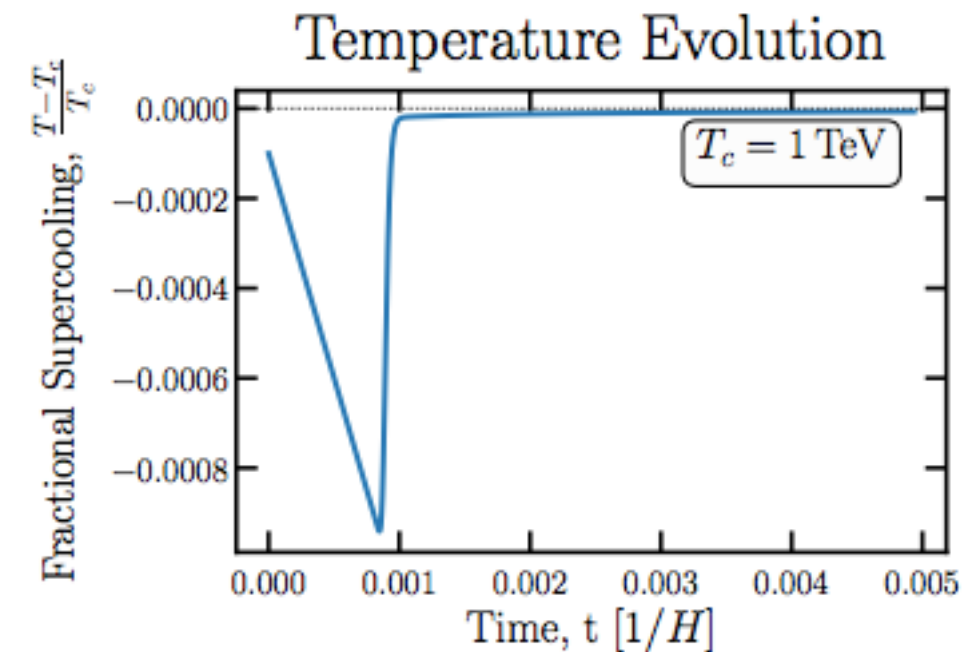- This implies $v_w \sim (T_c - T)/T_c$

Relic density assuming zero quark pressure

Relic Abundance, $f_R \in (0.1, 10), f_v = 1$

Relic Abundance, $f_v \in (0.1, 10), f_R = 1$

- These plots show the effect of varying initial pocket radius and wall velocity

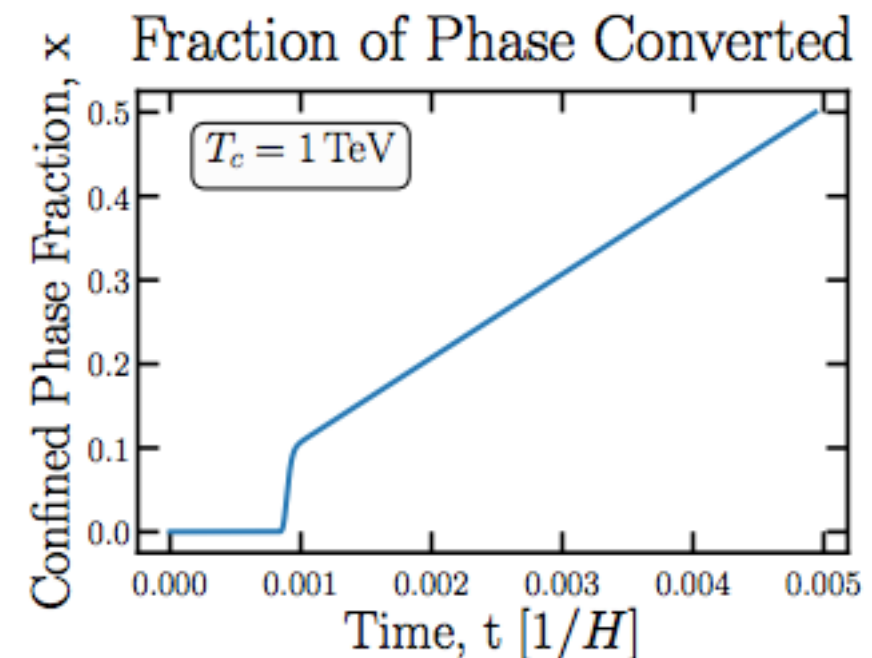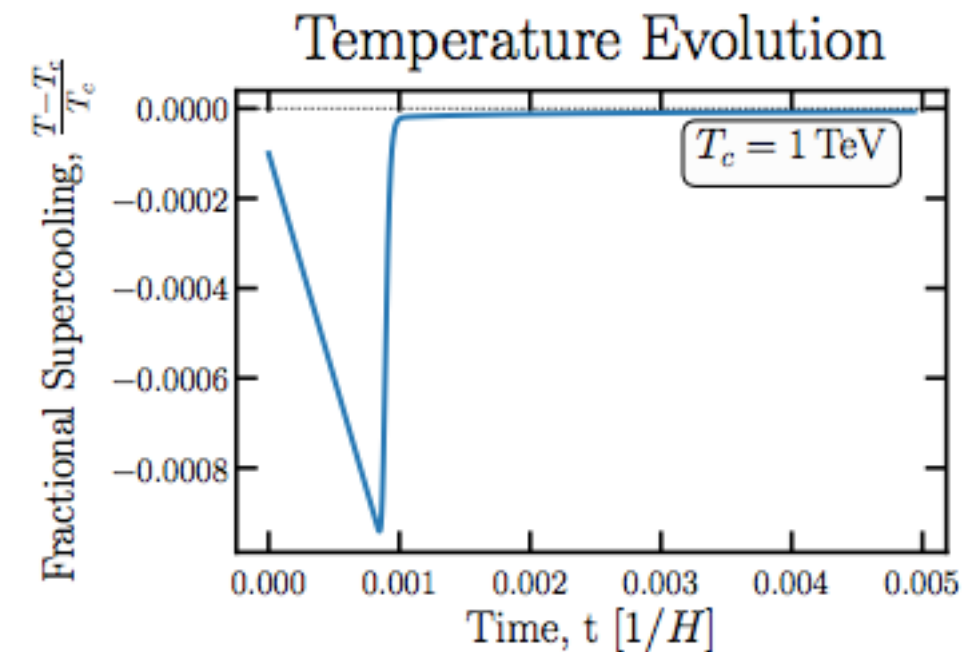- Preferred parameter space is similar to accidental-asymmetry case, 1-100 PeV DM
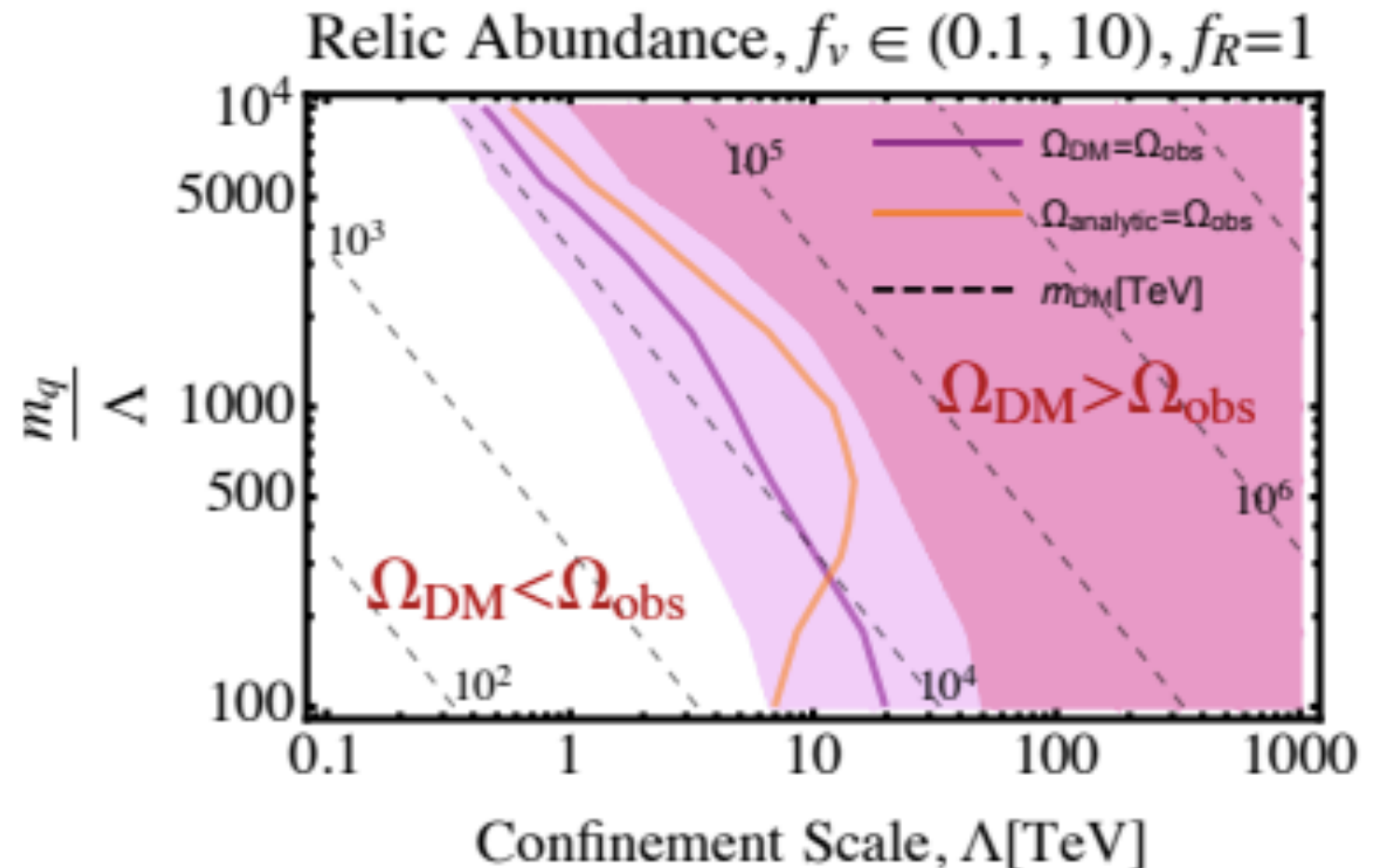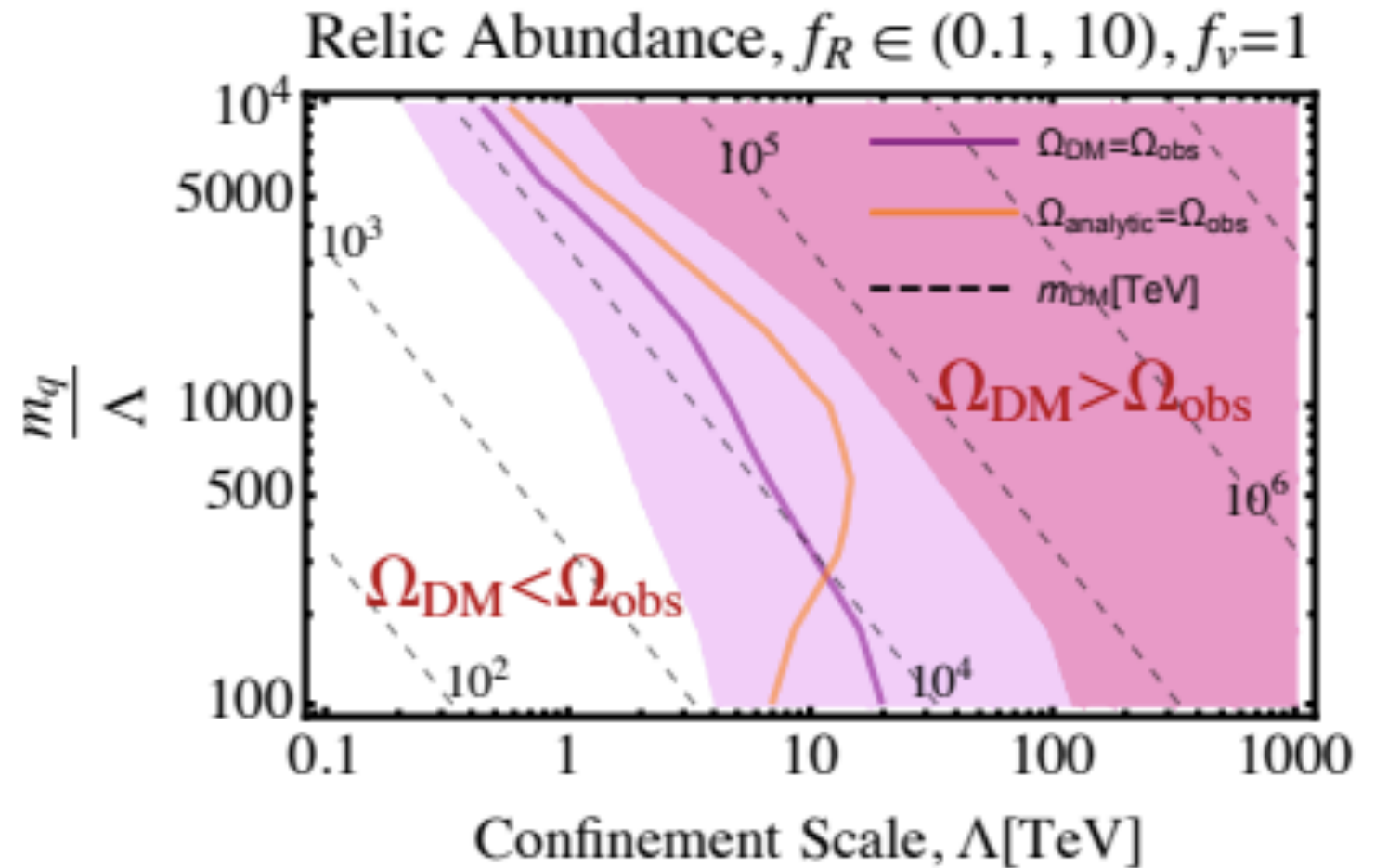
Temperature evolution during the phase transition

Temperature evolution during the phase transition

- The entire phase transition completes very quickly relative to a Hubble time (~0.01/H)

Temperature Evolution, $T_c = 1\,\mathrm{TeV}$

Fractional Supercooling, $\frac{T - T_c}{T_c}$ vs Time, t [1/H]

Fraction of Phase Converted, $T_c = 1\,\mathrm{TeV}$

Confined Phase Fraction, x vs Time, t [1/H]

Temperature evolution during the phase transition
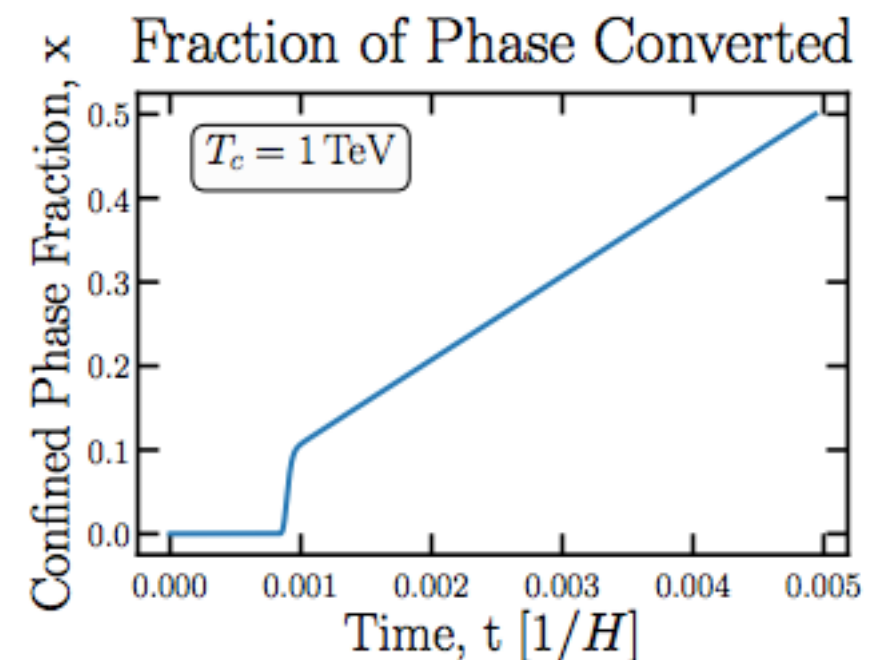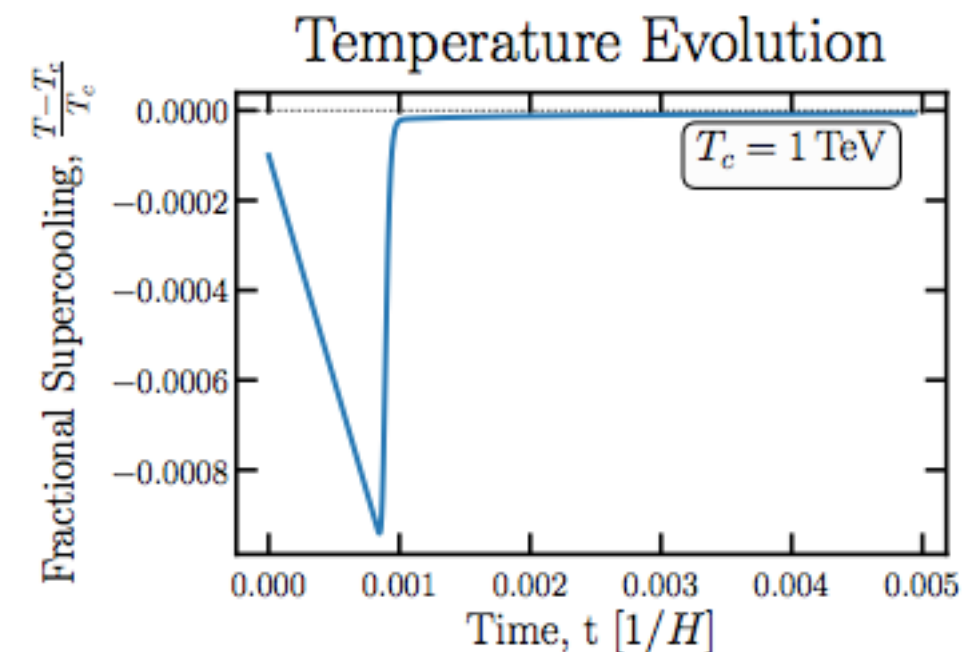
- The entire phase transition completes very quickly relative to a Hubble time (~0.01/H)

- Consequently there is little cooling due to expansion during the transition, but the bubble nucleation rate is very sensitive to any cooling below T_c

Temperature Evolution

$T_c = 1\,\mathrm{TeV}$

Fractional Supercooling, $\frac{T - T_c}{T_c}$

Time, t $[1/H]$

Fraction of Phase Converted

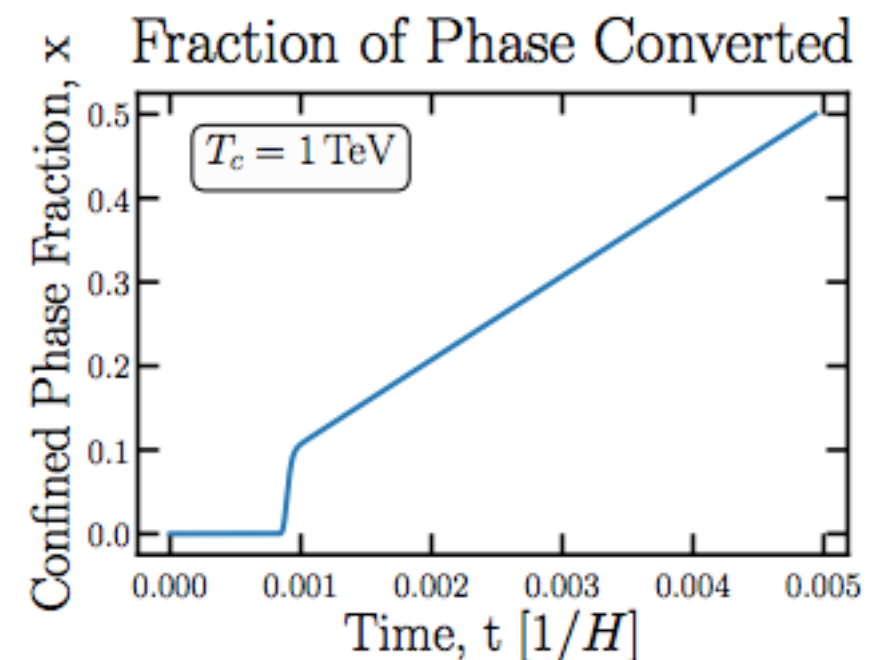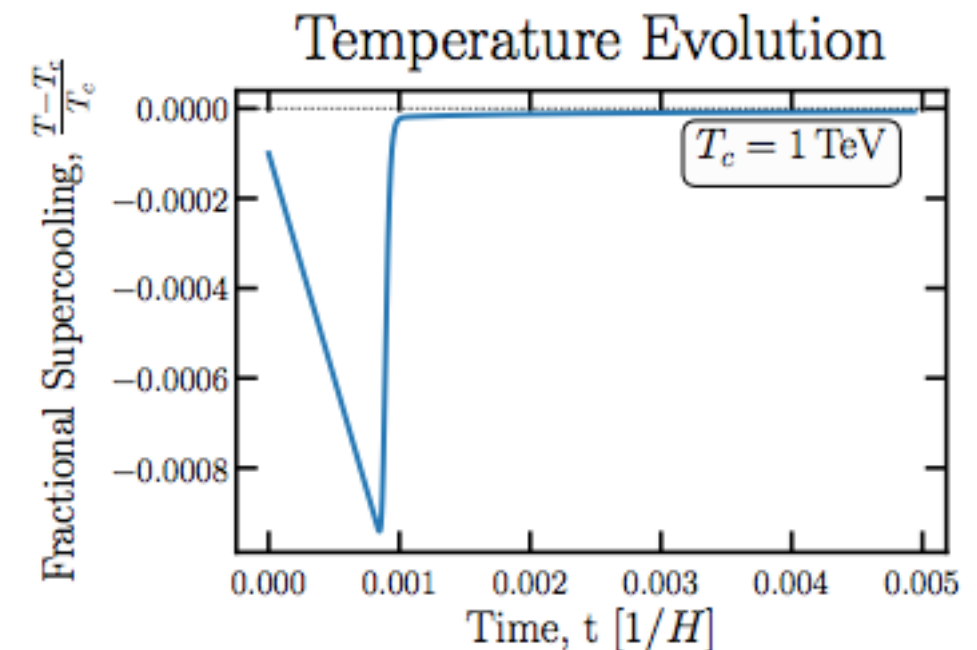$T_c = 1\,\mathrm{TeV}$

Confined Phase Fraction, x

Time, t $[1/H]$

Temperature evolution during the phase transition

- The entire phase transition completes very quickly relative to a Hubble time (~0.01/H)

- Consequently there is little cooling due to expansion during the transition, but the bubble nucleation rate is very sensitive to any cooling below T_c

- Initial slight supercooling due to expansion leads to bubble nucleation → releases heat and reheats the cosmos back almost to T_c as the transition continues

Temperature Evolution

$T_c = 1\,\text{TeV}$

Fractional Supercooling, $\frac{T - T_c}{T_c}$

Time, t $[1/H]$

Fraction of Phase Converted

$T_c = 1\,\text{TeV}$

Confined Phase Fraction, x

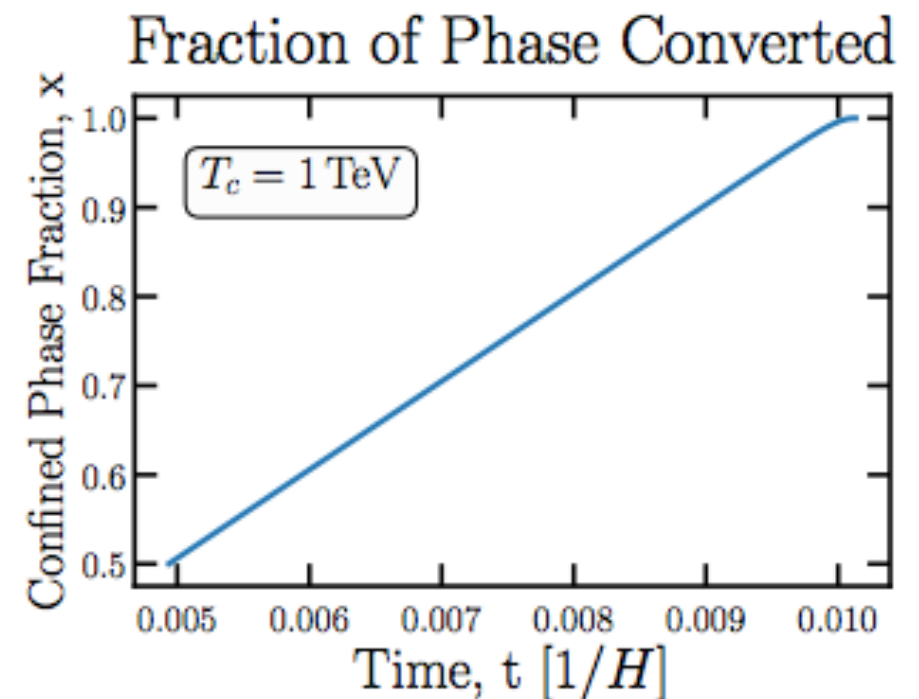Time, t $[1/H]$

Temperature evolution during the phase transition
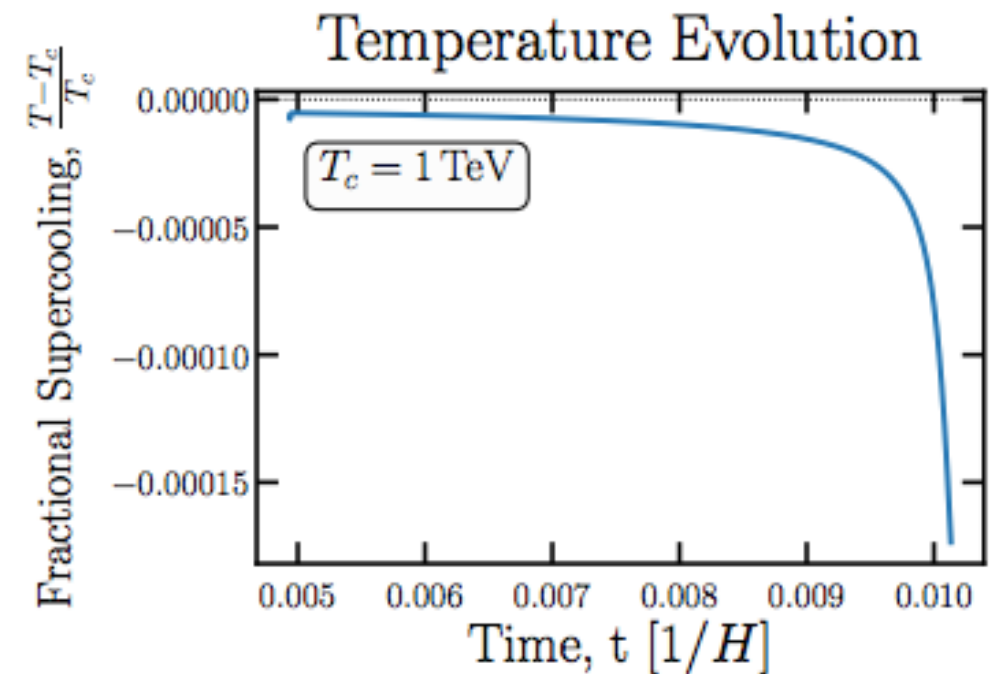
- The entire phase transition completes very quickly relative to a Hubble time (~0.01/H)

- Consequently there is little cooling due to expansion during the transition, but the bubble nucleation rate is very sensitive to any cooling below T_c

- Initial slight supercooling due to expansion leads to bubble nucleation → releases heat and reheats the cosmos back almost to T_c as the transition continues

Temperature Evolution

$\frac{T - T_c}{T_c}$

Fractional Supercooling

$T_c = 1\,\text{TeV}$

Time, t $[1/H]$

Fraction of Phase Converted

Confined Phase Fraction, x

$T_c = 1\,\text{TeV}$

Time, t $[1/H]$
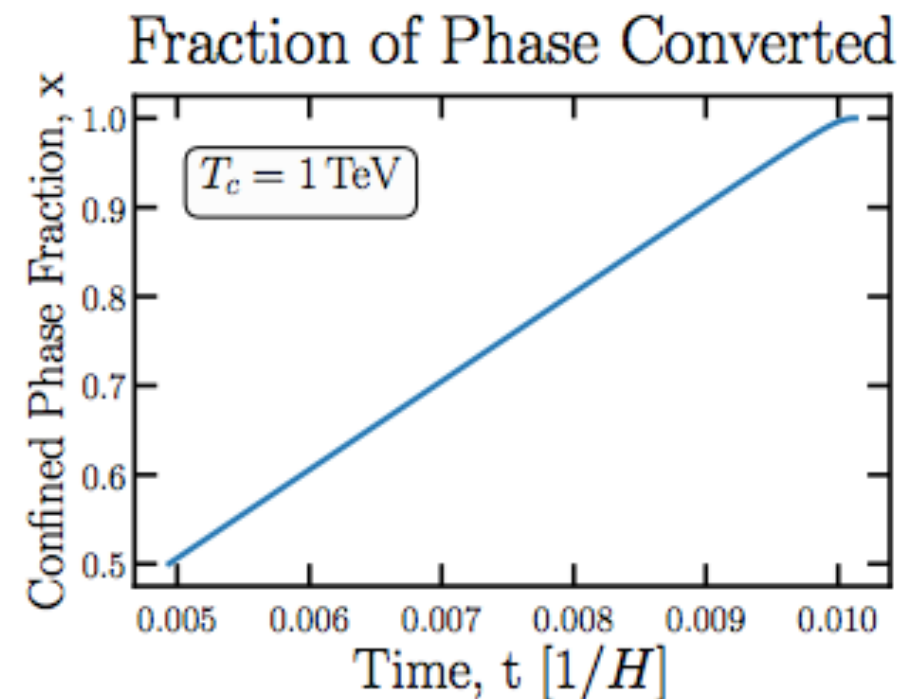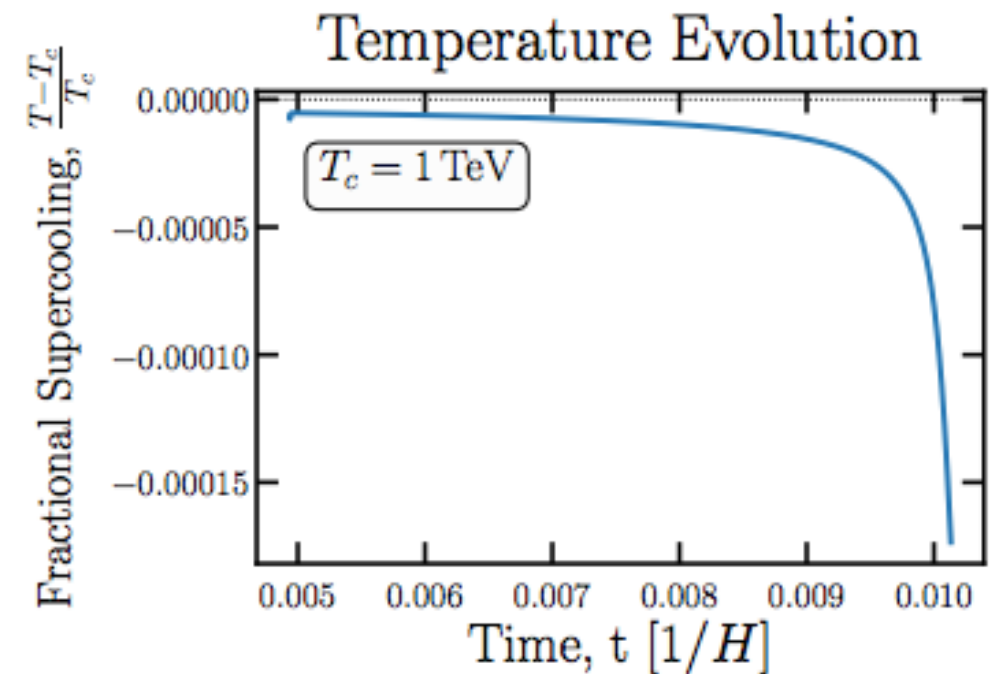
Temperature evolution during the phase transition

- The entire phase transition completes very quickly relative to a Hubble time (~0.01/H)

- Consequently there is little cooling due to expansion during the transition, but the bubble nucleation rate is very sensitive to any cooling below T_c

- Initial slight supercooling due to expansion leads to bubble nucleation → releases heat and reheats the cosmos back almost to T_c as the transition continues

- After percolation, the slowing rate of phase conversion means that Hubble cooling takes over again

Temperature Evolution

$T_c = 1\,\mathrm{TeV}$

Fractional Supercooling, $\frac{T - T_c}{T_c}$

Time, t $[1/H]$

Fraction of Phase Converted

$T_c = 1\,\mathrm{TeV}$

Confined Phase Fraction, x

Time, t $[1/H]$

Equilibrium estimate of quark pressure effects

- Use zero-quark-pressure approximation until quark pressure is large enough to support the bubbles, in mechanical equilibrium with the other forces acting on the bubble wall

- Subsequently assume equilibrium is maintained, the bubbles shrink slowly as the quarks annihilate away and the equilibrium point evolves adiabatically

- Abrupt drop in contraction rate makes quark depletion more efficient with respect to the rate of change of pocket radius

- We find the asymmetric limit is always saturated in this case

Pocket Wall Velocity

Contraction Rate, v_w vs Pocket Radius, $R\,[\Lambda^{-1}]$

$\cdots\cdots$ Neglecting p_q

Evolution of Pocket Abundances

Fractional Abundance, $N_i/N_q^{initial}$ vs Bubble Radius, $R\Lambda$

$\Lambda = 1\,\mathrm{TeV}$
$m_q = 1000\Lambda$

$N_1/N_q^{initial}$
$N_2/N_q^{initial}$
$N_3/N_q^{initial}$