Thermal Squeezeout for Strongly Interacting Dark Matter

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Quarkonia Meet Dark Matter
Kavli IPMU
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Based on arXiv:2103.09822, 2103.09827
with Pouya Asadi, Eric Kramer, Eric Kuflik,
Gregory Ridgway, & Juri Smirnov

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Outline

- Quick recap of 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

Classic thermal freezeout

- Already much-discussed in this workshop!
- DM initially in thermal equilibrium with the SM bath
- Number density is depleted once $m_{DM} > T$, by annihilation, bound state formation, etc
- Requires a sufficiently large depletion rate to deplete the DM density to its observed value
- 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]

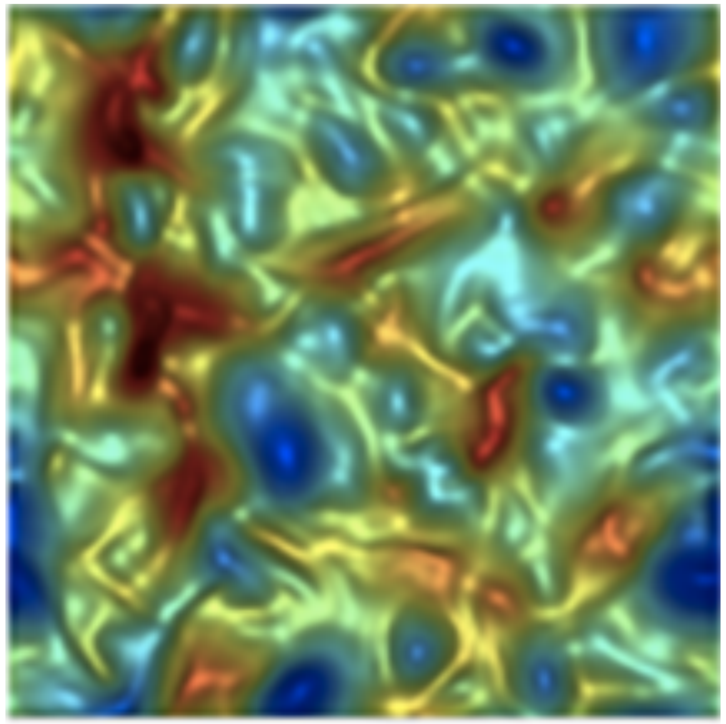
- Mass limit often quoted as 100-200 TeV, valid when l_{max} is small, although:

  - 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



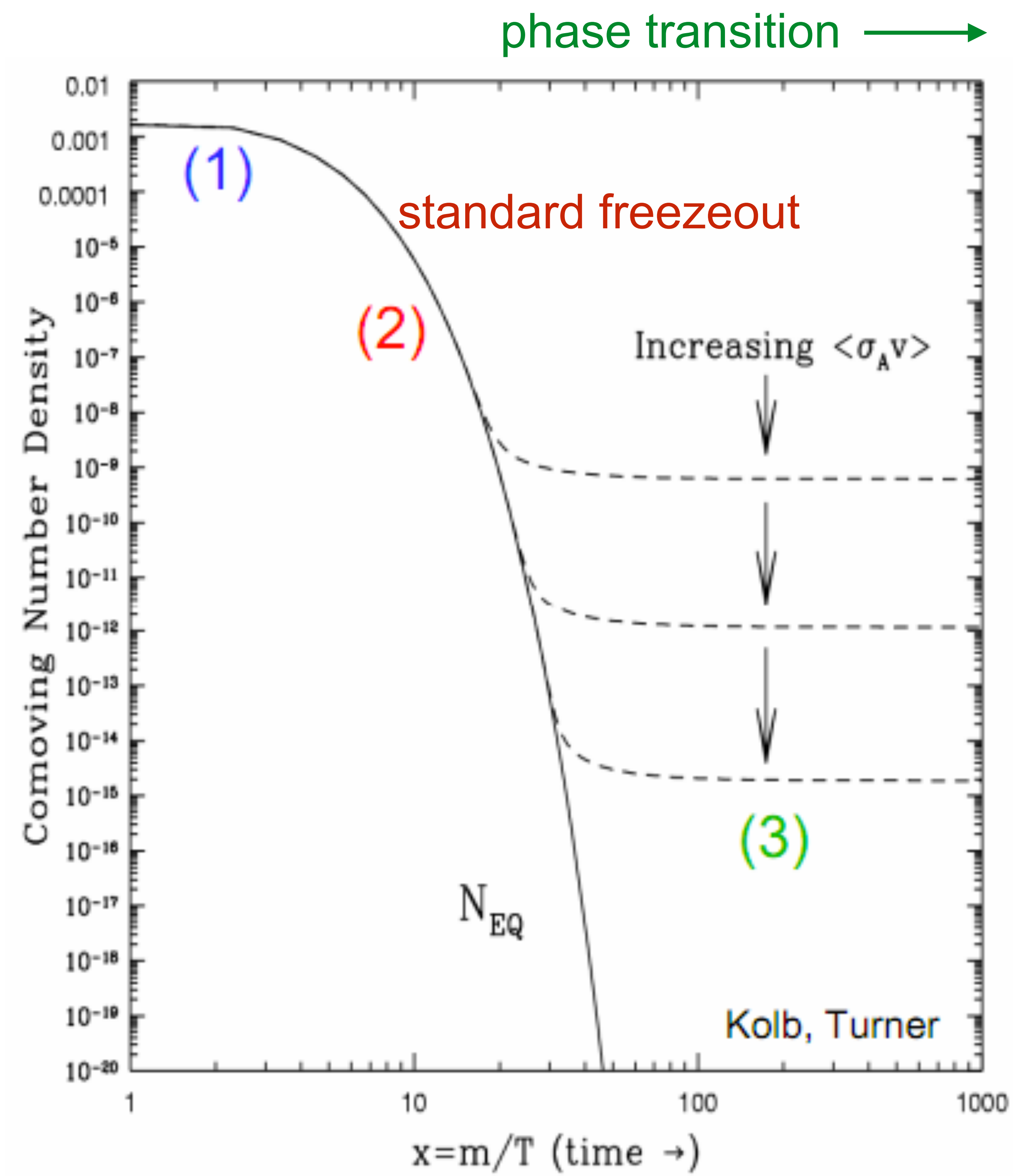
- Consider strongly-interacting DM inhabiting a confining dark sector.
- Today: dark matter comprised of stable dark baryons
- Early in the universe: dark quark-gluon plasma.
- Automatic modification to early-universe cosmology: the confinement phase transition.
- If the dark quarks are sufficiently 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 $m_q >> \Lambda$ 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



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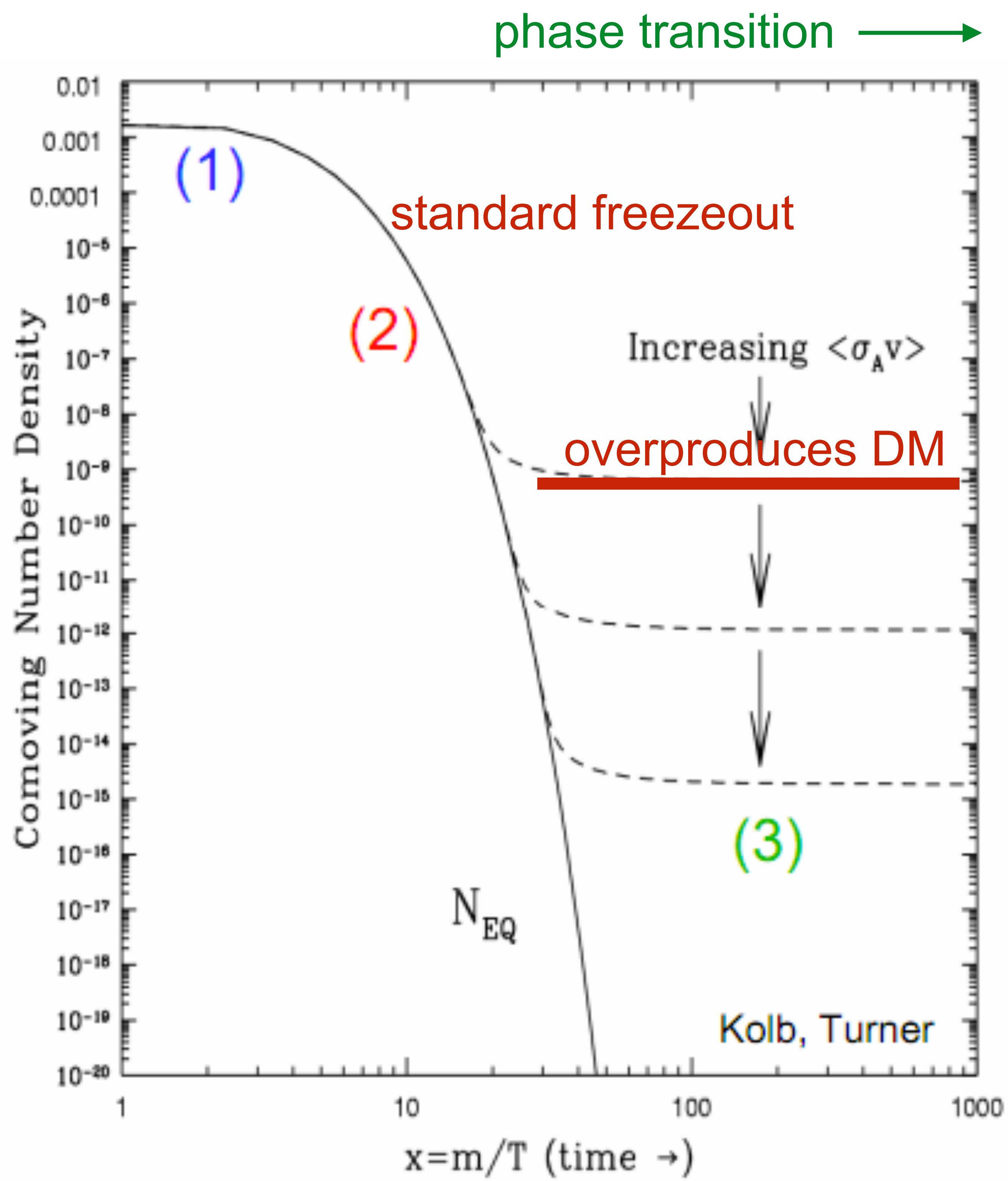


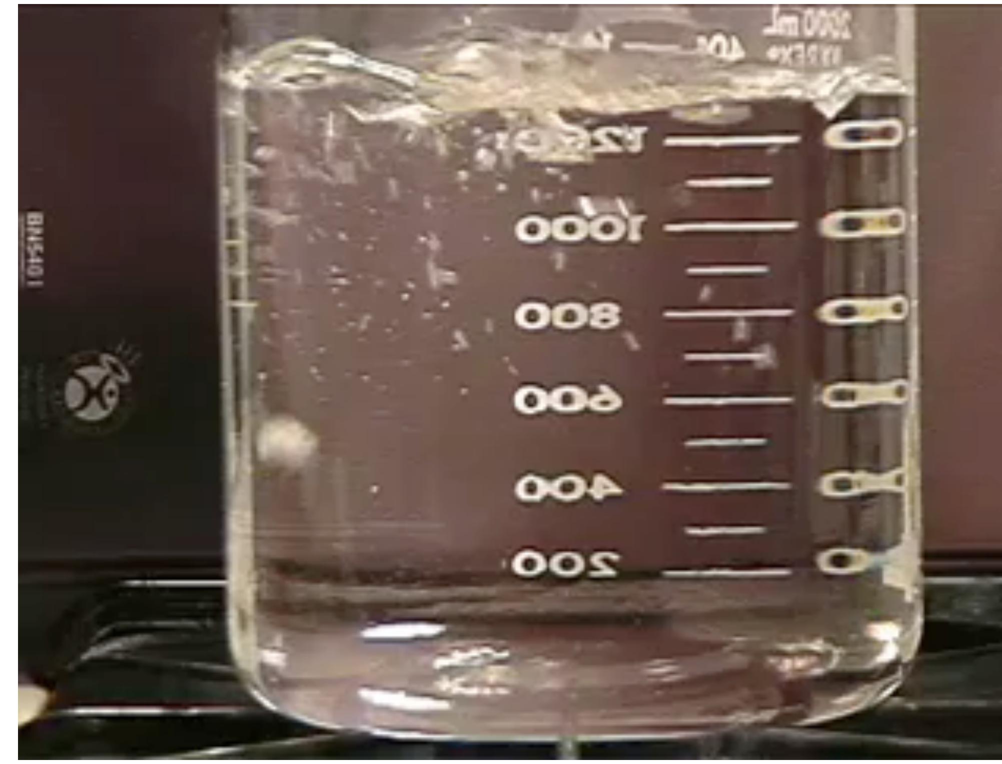
Stage 2: bubble growth

- 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, arXiv: 2008.04430, 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).



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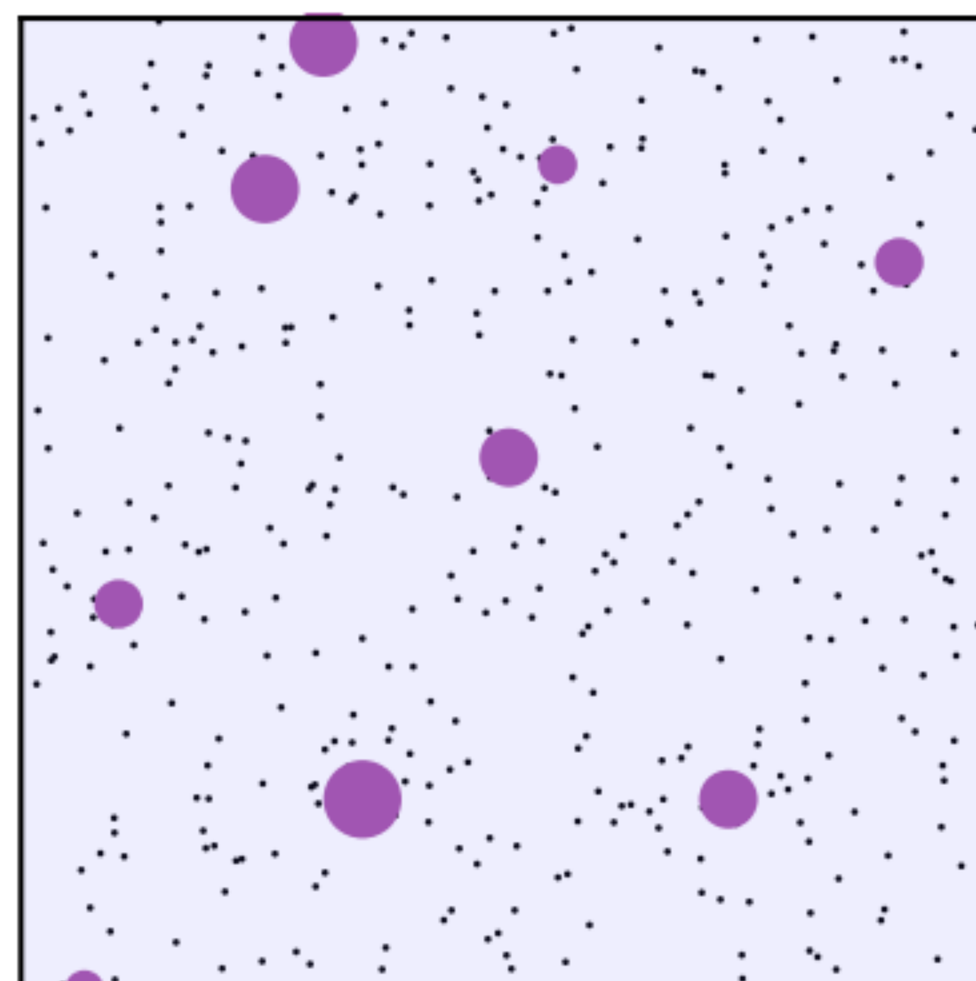

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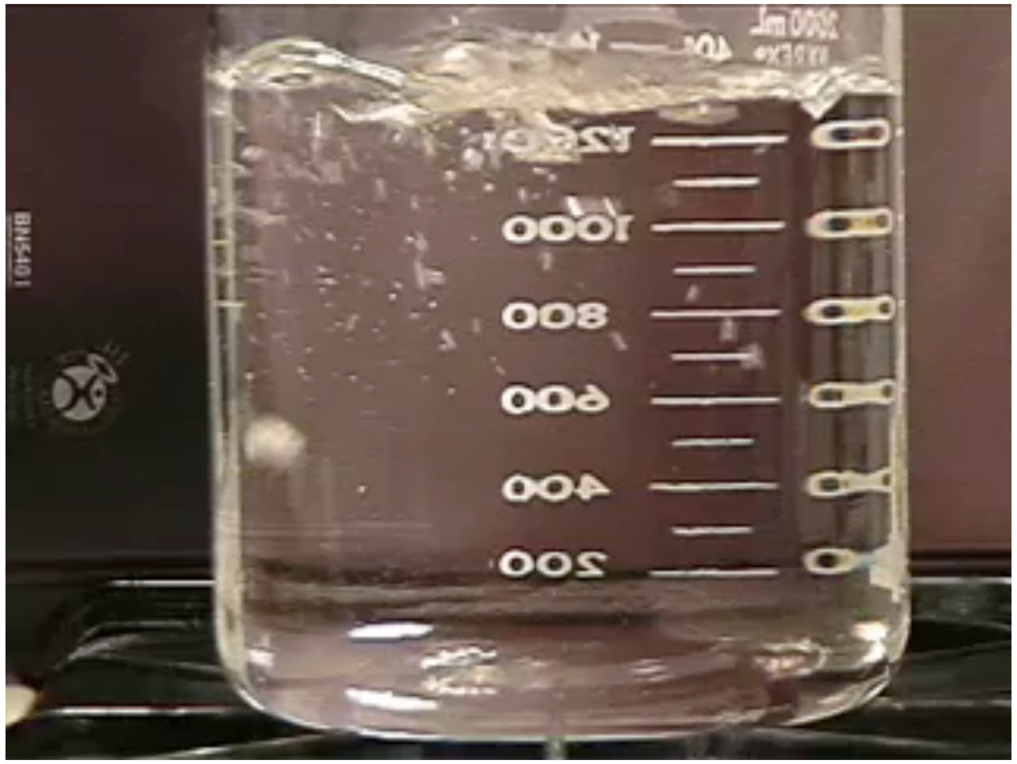

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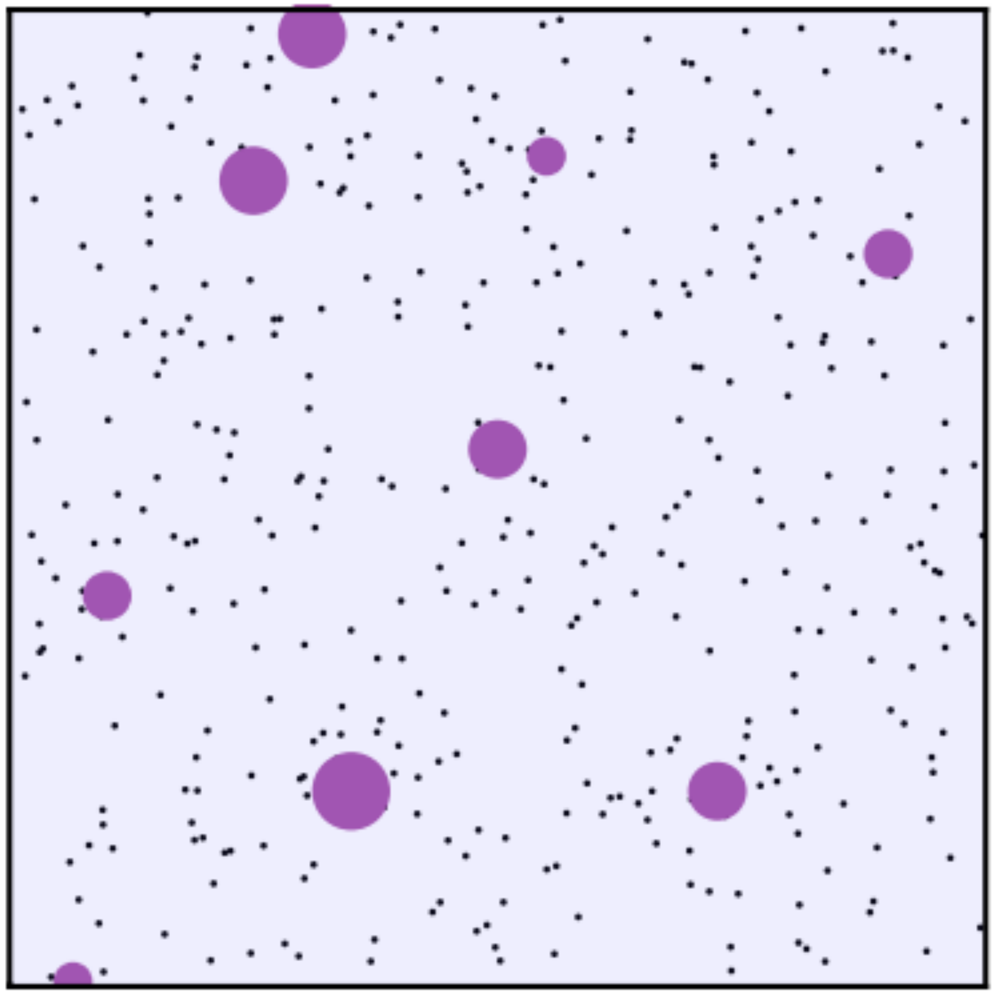

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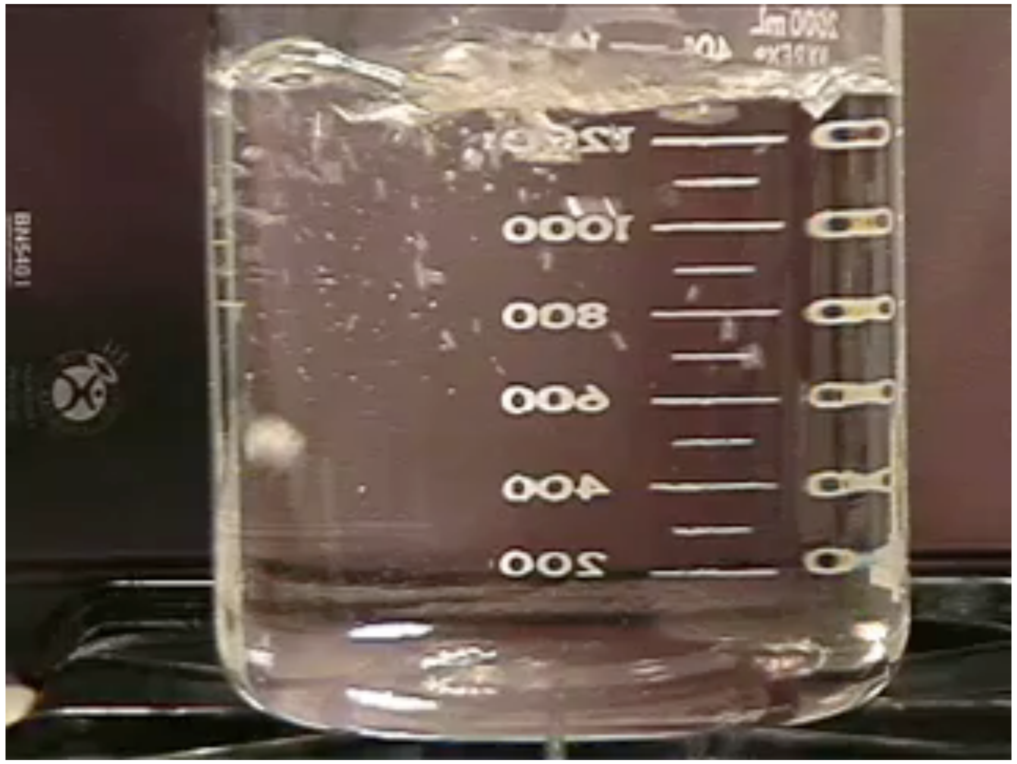

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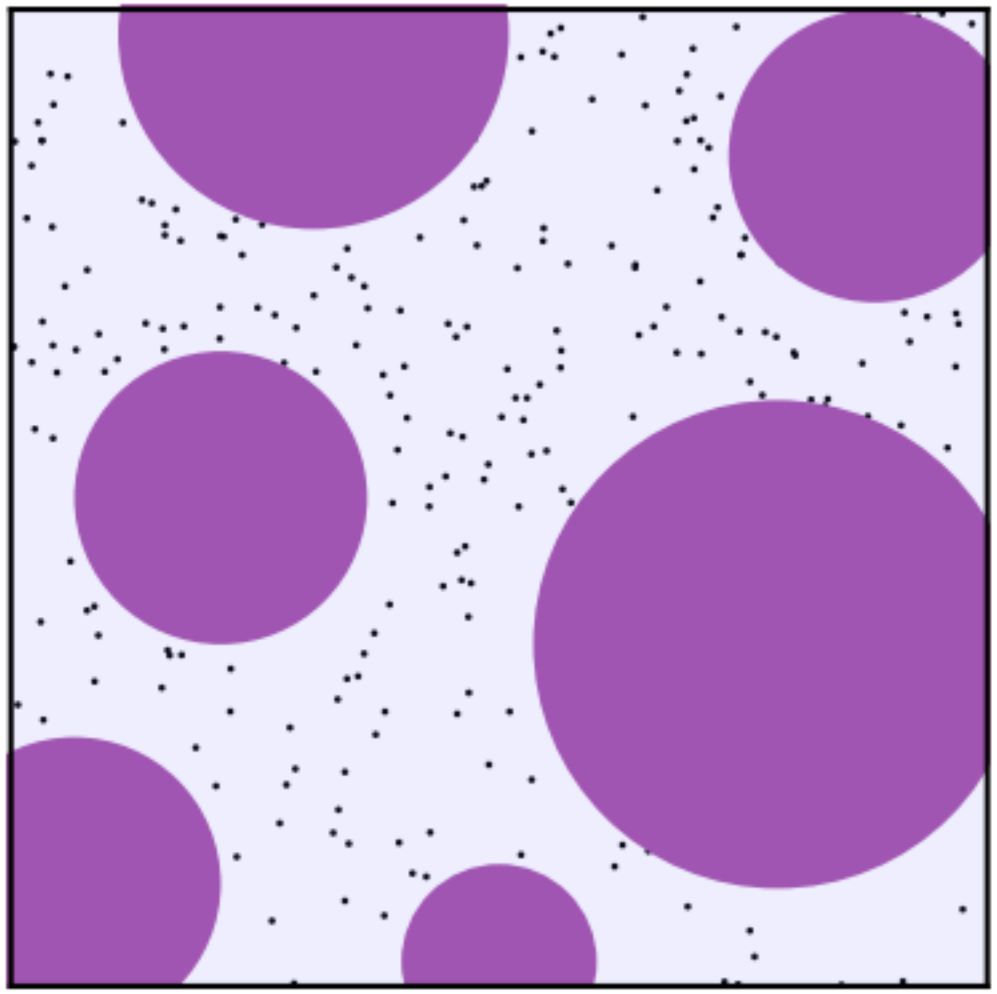

Quarks and bubbles

- 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, $t_{\text{rebound}} \sim \frac{v_q}{\dot{v}_q} \sim \frac{v_q}{\Lambda^2/m_q} = \sqrt{\frac{m_q}{\Lambda}}\frac{1}{\Lambda}$.
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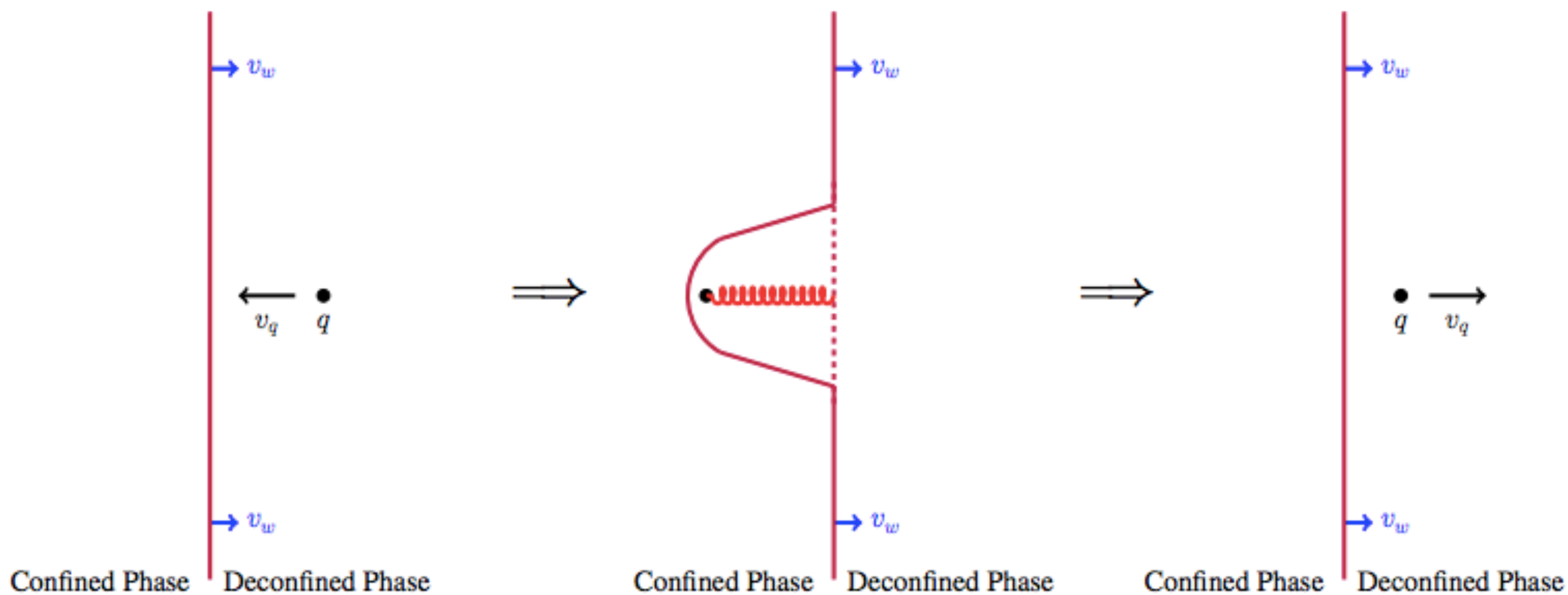

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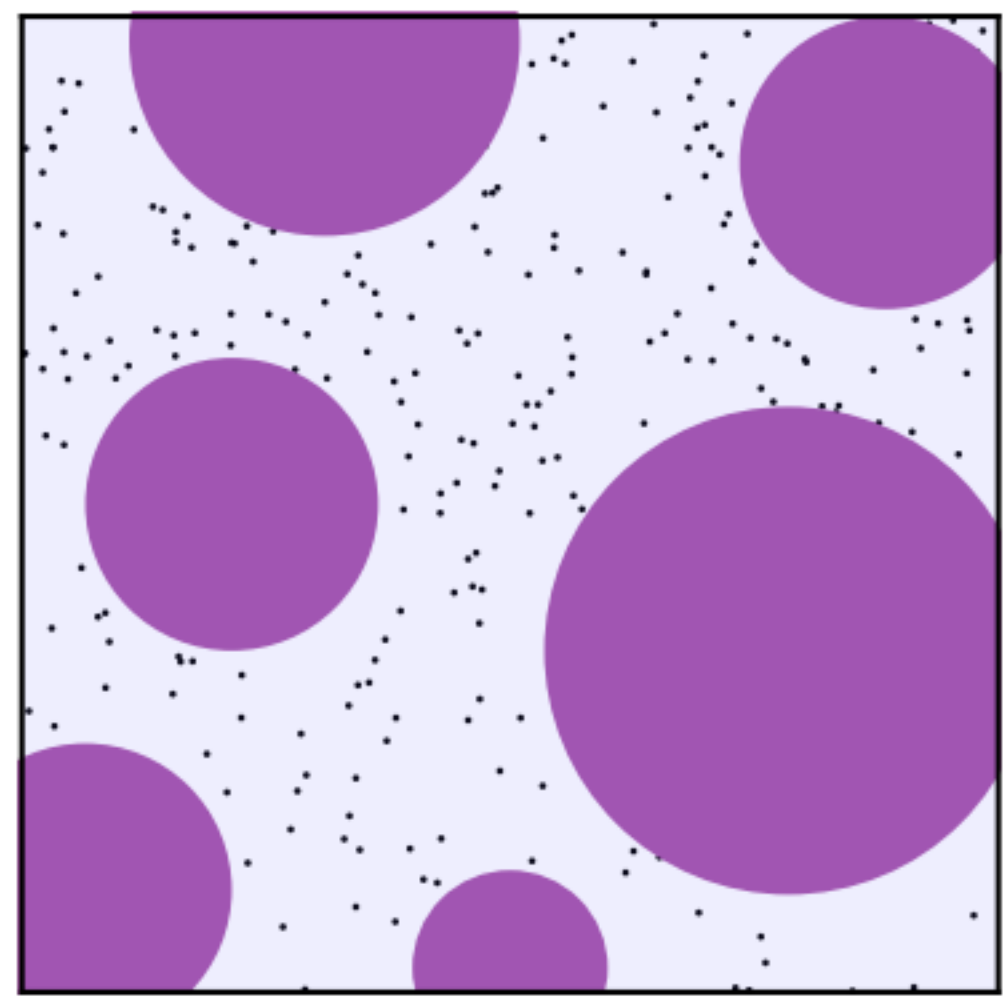
Stage 3: percolation

- 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



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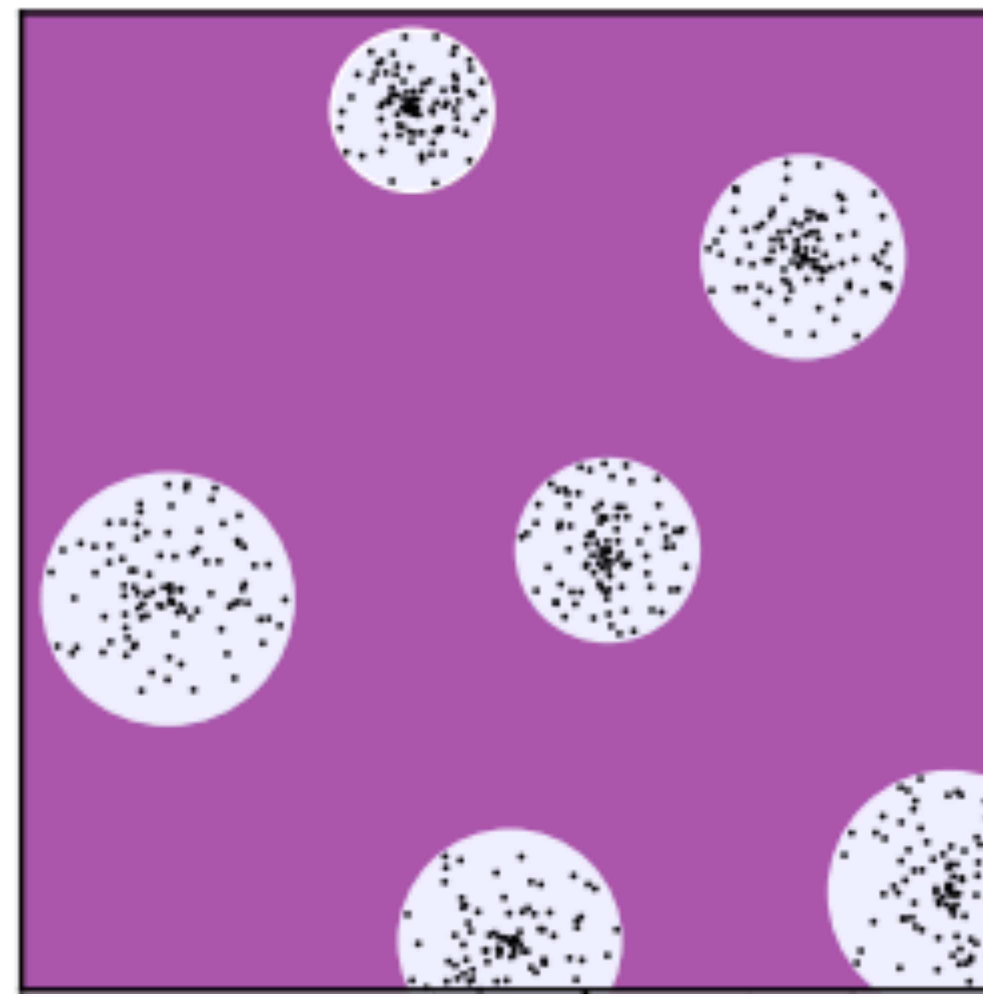
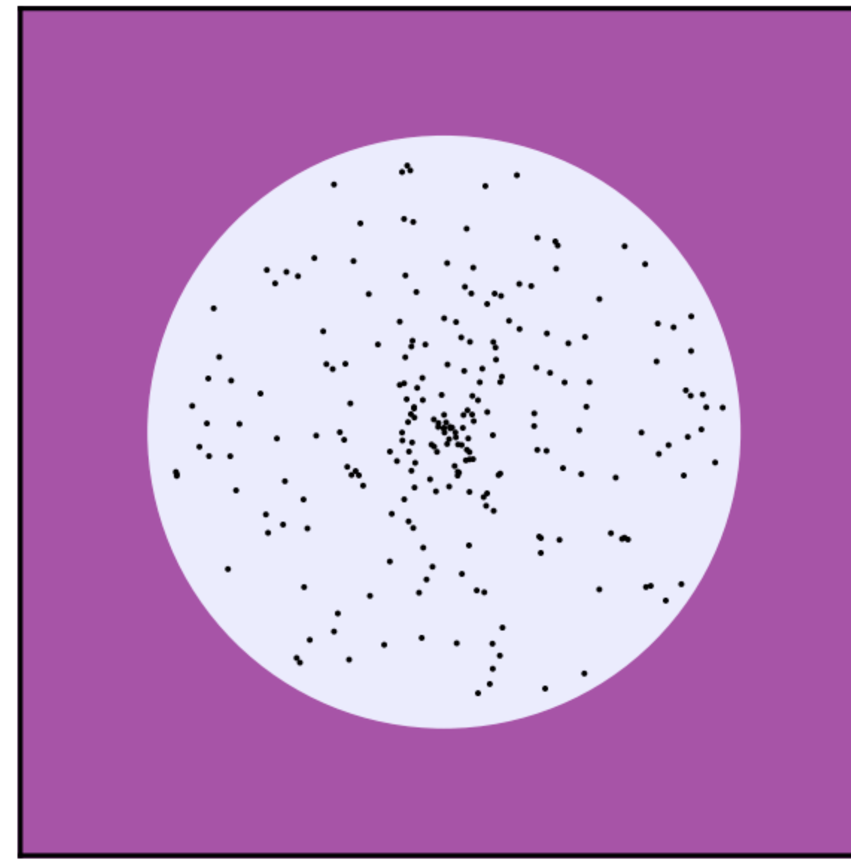


Stage 4: squeezeout

- 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



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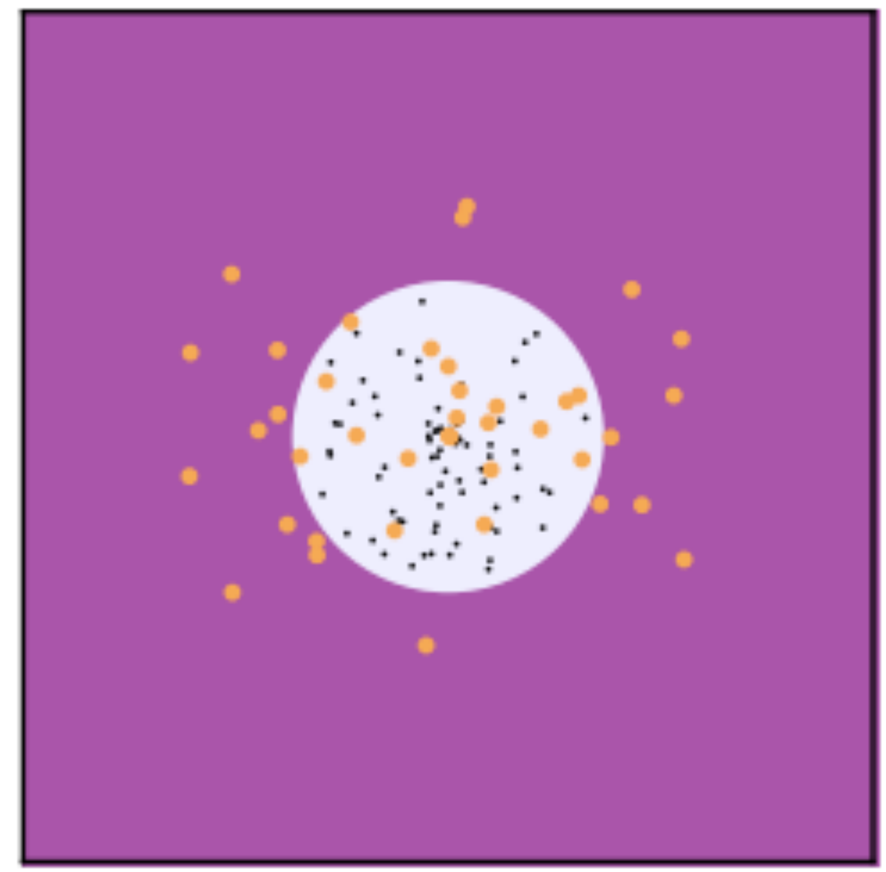

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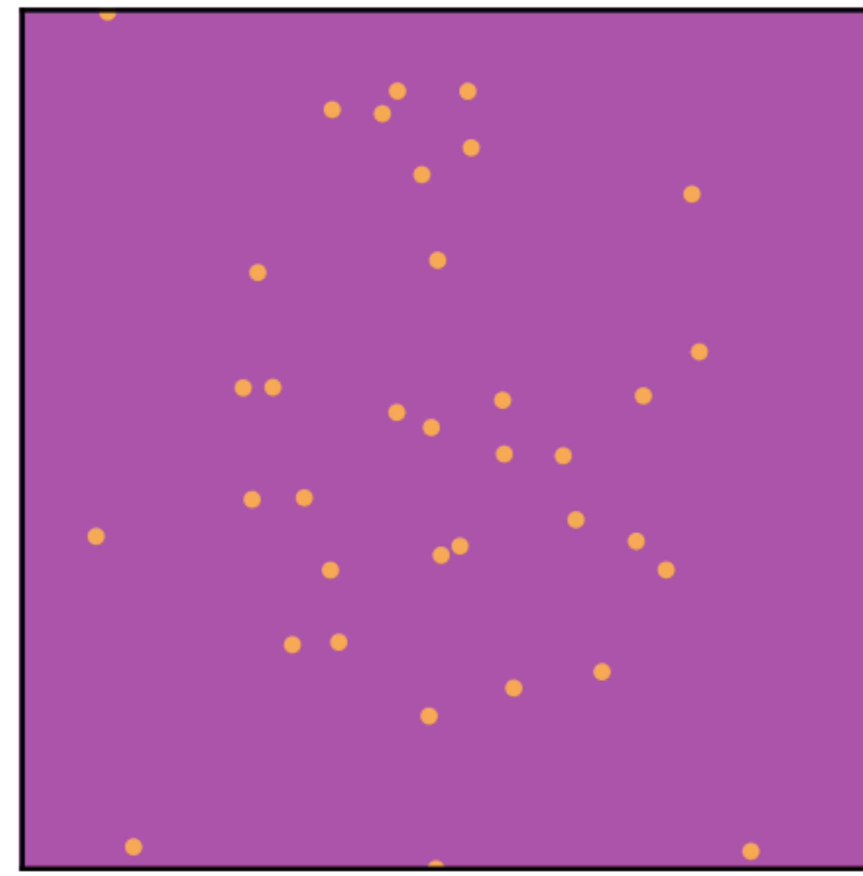

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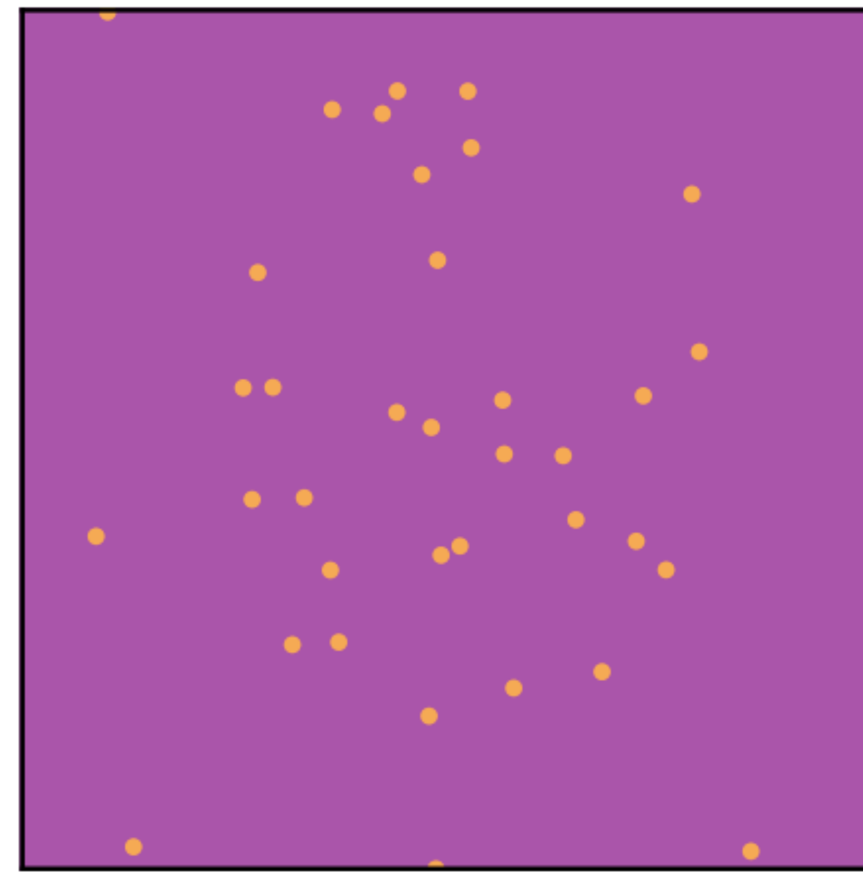


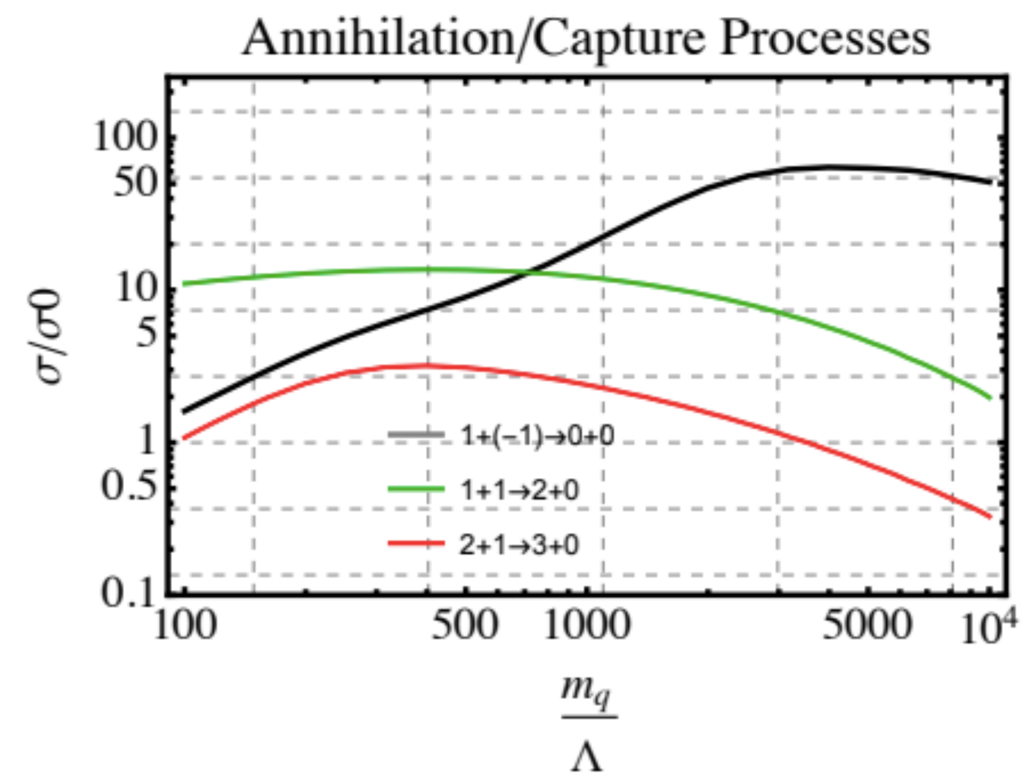
Hadronization vs annihilation?

- 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.

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 $m_q >> \Lambda$
- Notation: label each species by its quark number (gluons = 0, quarks = +1, anti-quarks = -1, diquarks = +2, etc)

Relevant processes



- Annihilation: particles and antiparticles annihilate directly (and completely) into gluons, e.g. 1 + -1 → 0 + 0
- Capture (and dissociation): quark number is conserved but a dark gluon is emitted to conserve momentum, e.g. 1 + 1 → 2 + 0

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

- Rearrangement: quark number is conserved and no dark gluon is emitted, e.g. 2 + 2 → 3 + 1

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

enhancement from finite size of colliding bound states

Boltzmann equations

$$
\begin{aligned}
L[i] &= C[i], \quad i = 1,2,3. \\
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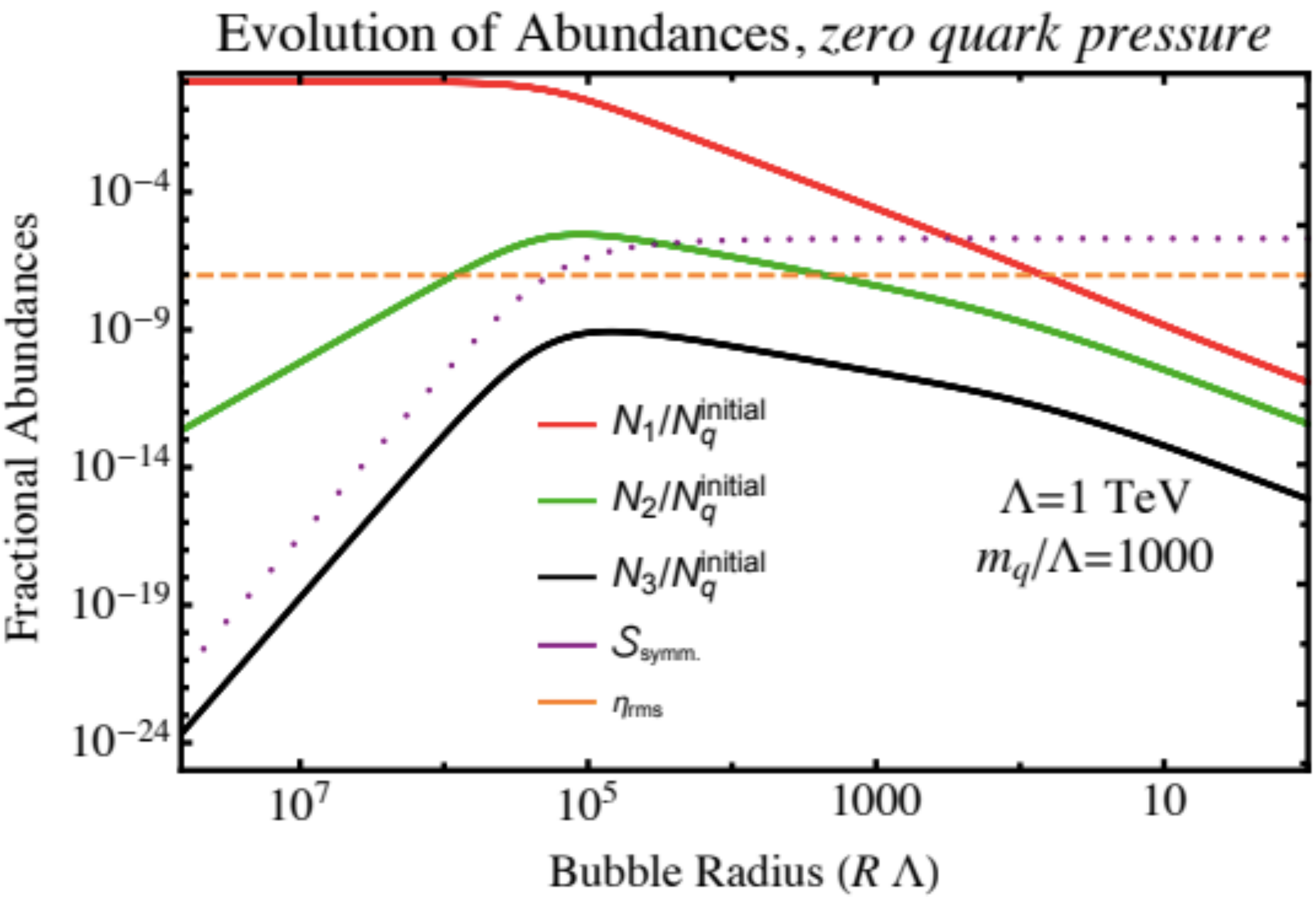
describes escape of baryons from pocket

An example simulation



- The survival factor S (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, $S \gtrsim 1/\sqrt{N}$

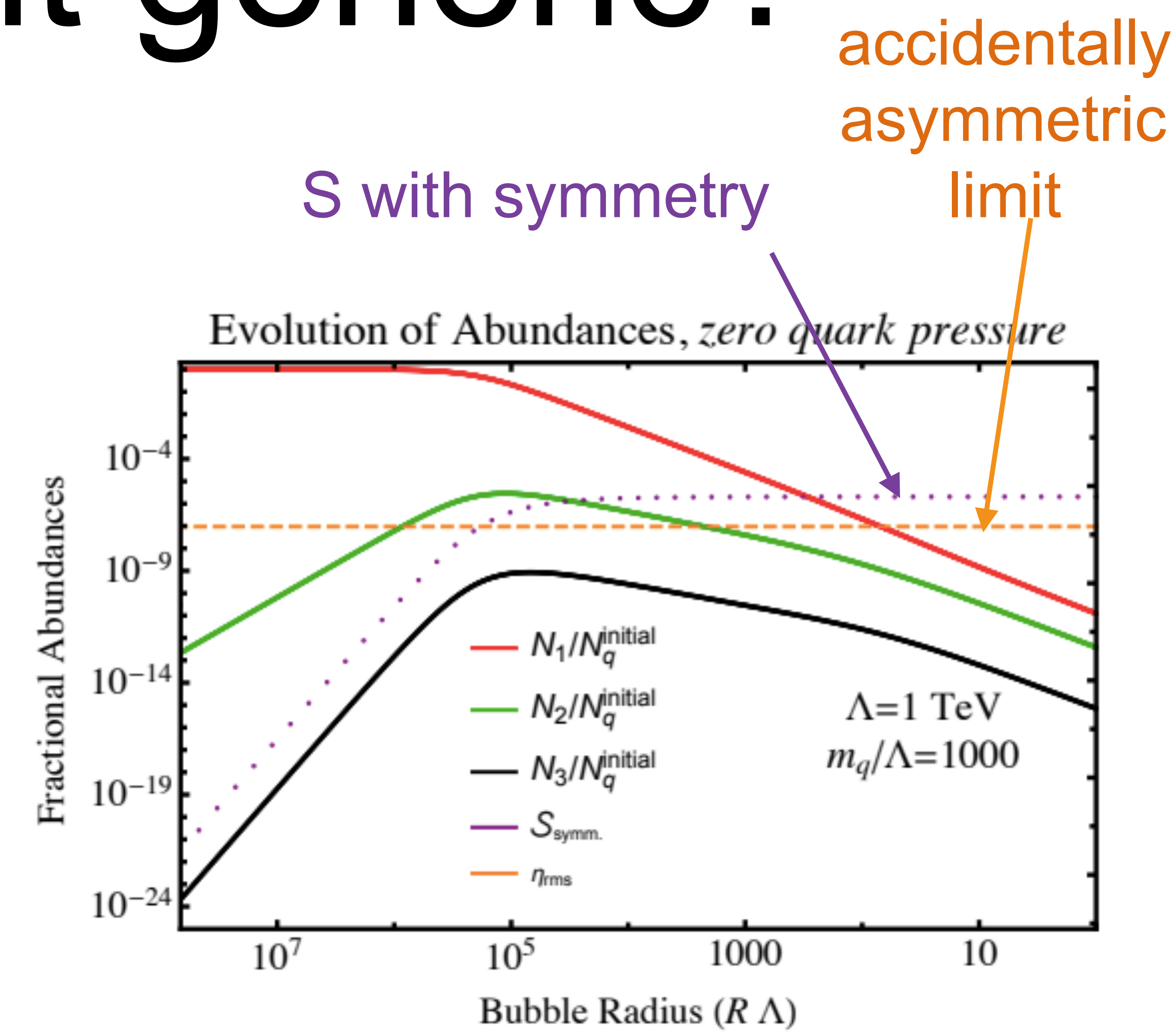
Quark pressure

- 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.

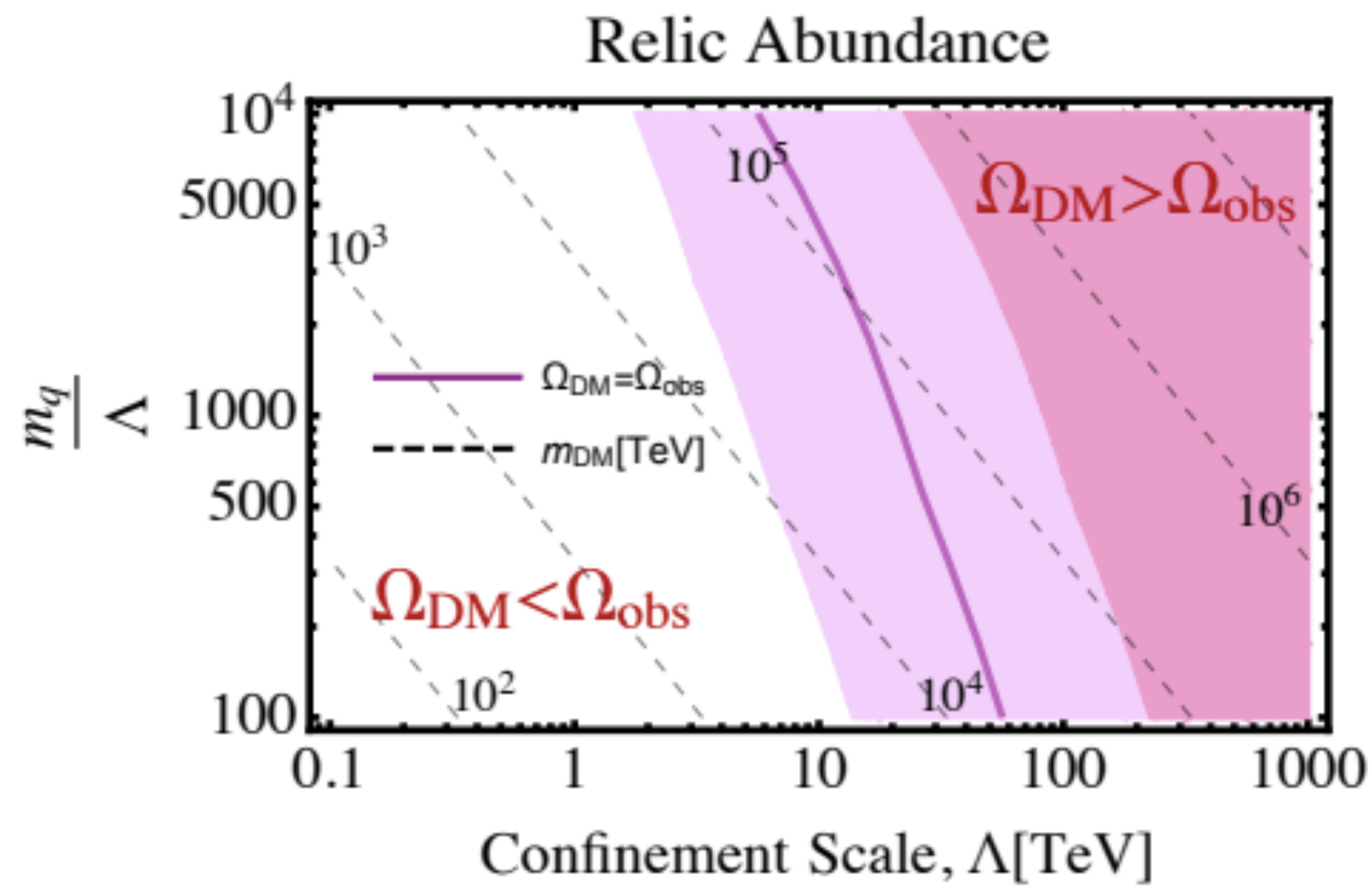
- Including quark pressure will generically decrease S - under simple estimates, causes saturation of the bound (easily) everywhere.



- Consequently, we argue that the accidentally-asymmetric limit is generically a good approximation.

The relic density

- 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 $R_1 \approx \left(\frac{M_{\mathrm{Pl}}}{10^4 \Lambda}\right)^{2/3} \frac{1}{\Lambda}$, from Witten 1984)



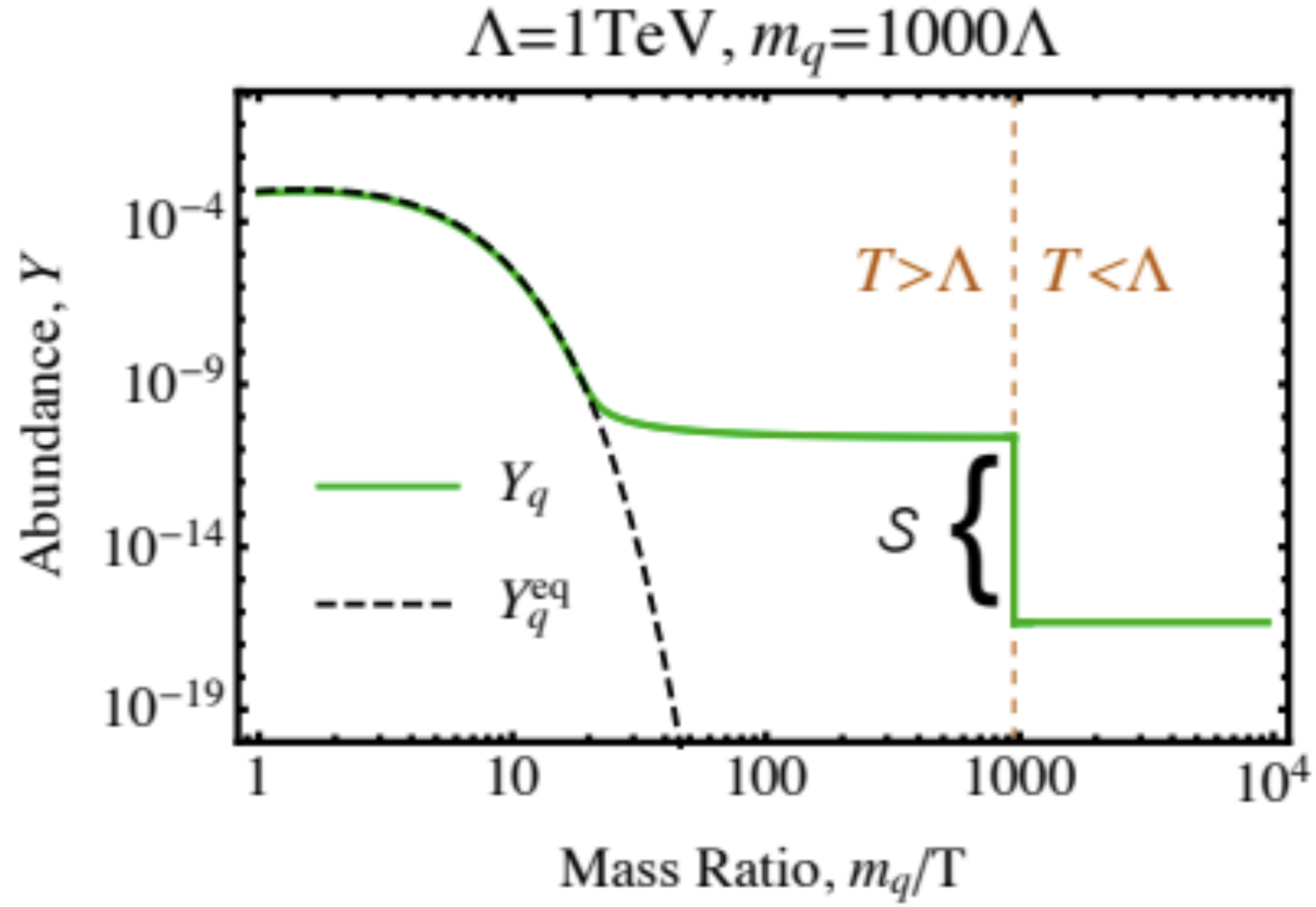
- We can calculate the relic density as a function of m_q and Λ, allowing for an order-of-magnitude variation in the pocket radius around our estimate
- We find preferred DM masses around 1-1000 PeV (also if we assume zero quark pressure)

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.



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

- 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

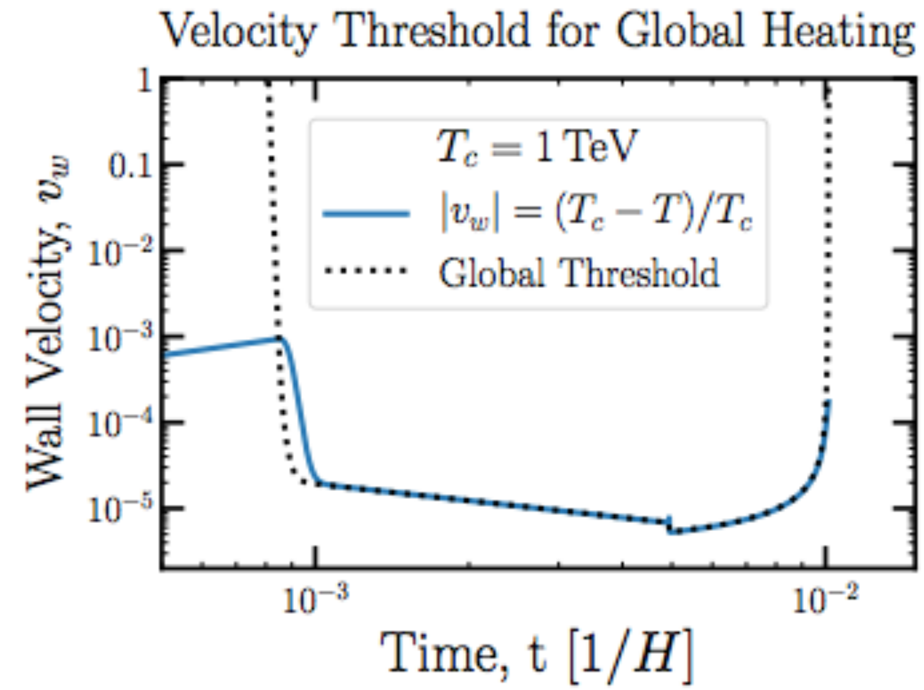
- Because the mass scale is so high, rather large interactions with the SM may be viable - interesting for direct detection? [e.g. Cappiello et al, PRD 2021]

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 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 the correct abundance for PeV-EeV DM due to a second period of rapid annihilation during the phase transition.
- Heavy dark quarks and antiquarks are forced into shrinking pockets of the high-temperature phase, and annihilate away until only a residual *accidentally asymmetric* component (i.e. pure quarks or pure antiquarks) remains.
- This residual component forms dark hadrons which are squeezed out of the pockets as they shrink and vanish, in a process we call *squeezeout*.

BONUS SLIDES

Estimating the pocket wall velocity



- 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,

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

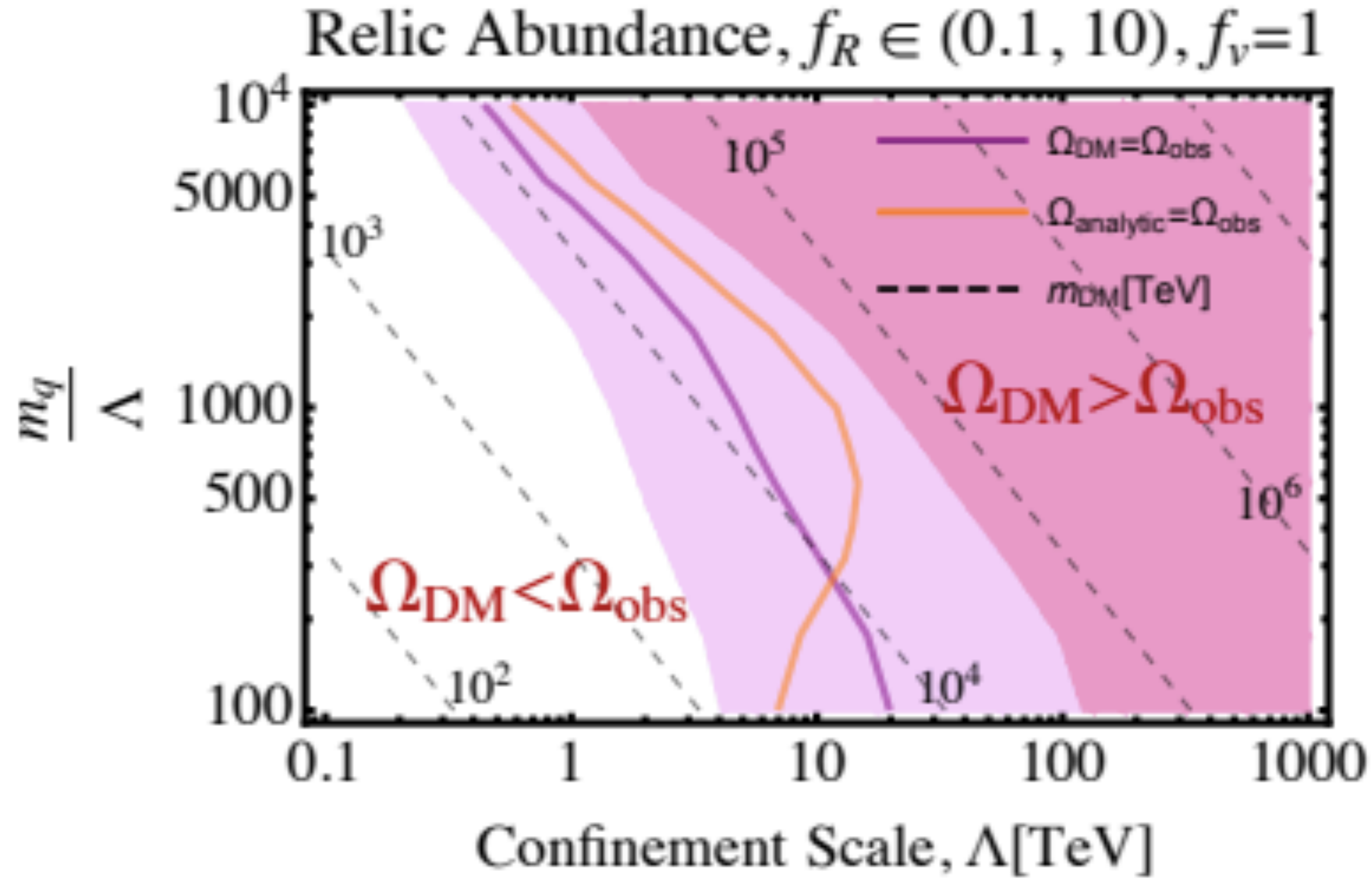
- Assume that the heat is diffused away through dark gluon bath outside the pocket, diffusion timescale controlled by Λ and by the difference of local & global temperatures:

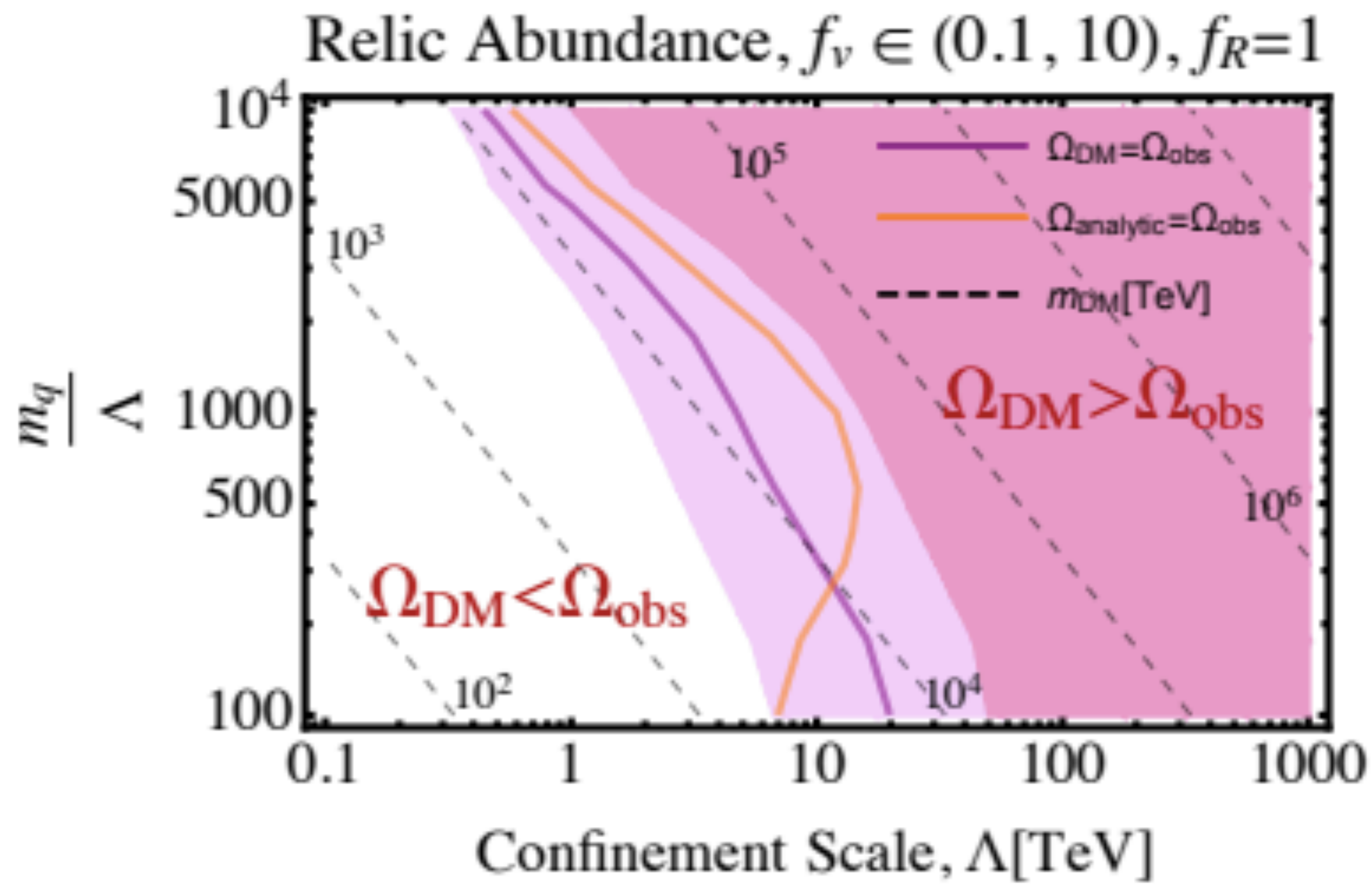
$$\dot{T}_{\rm cool} \sim -\Lambda^2 \left(T_c - T\right)/T_c.$$

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

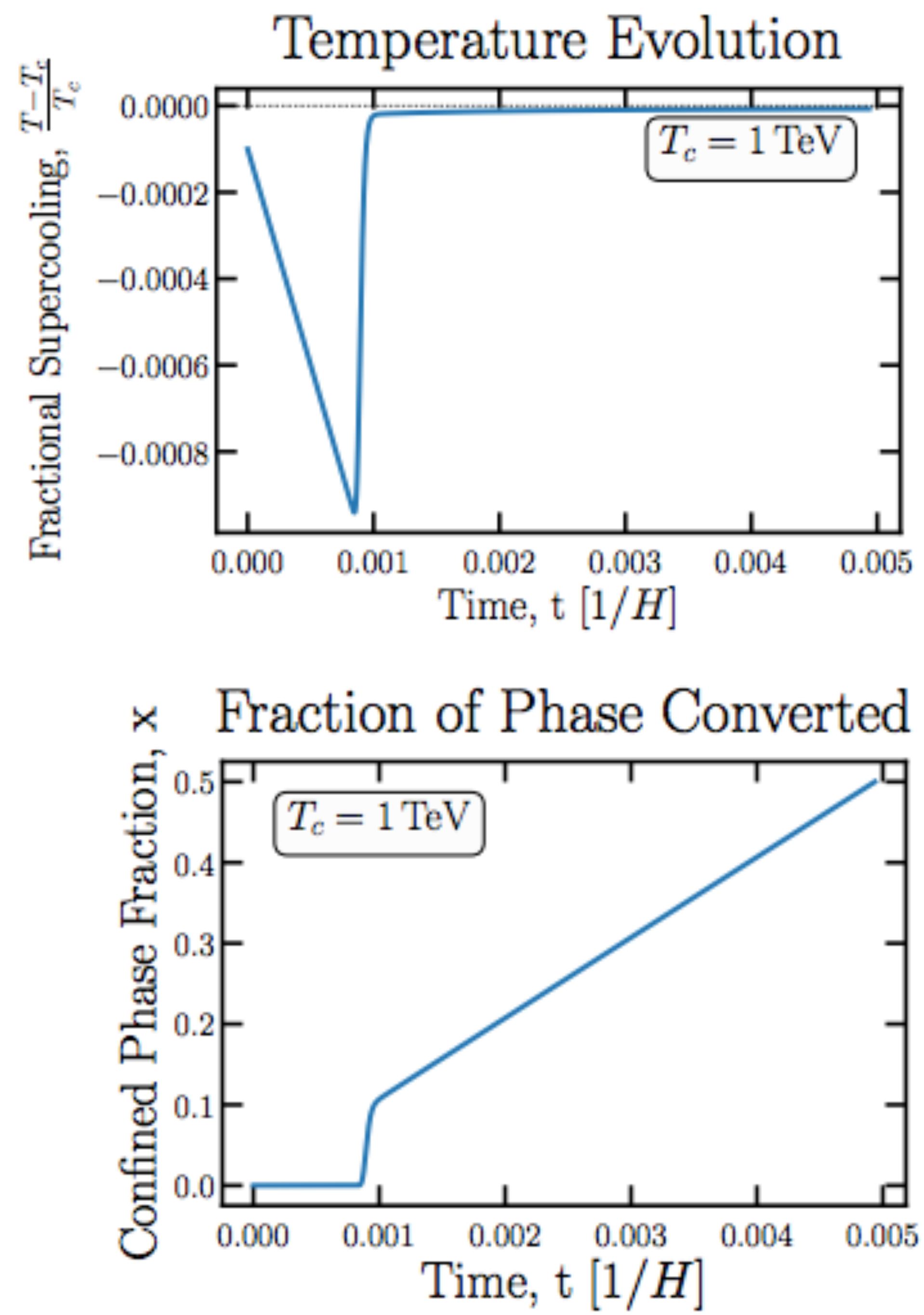
Relic density assuming zero quark pressure

- 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



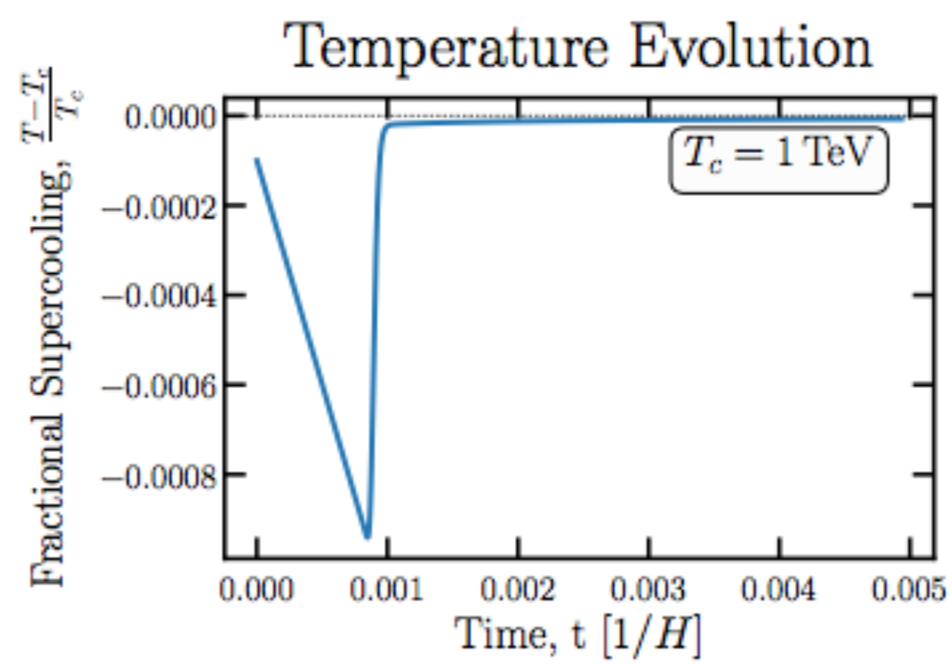


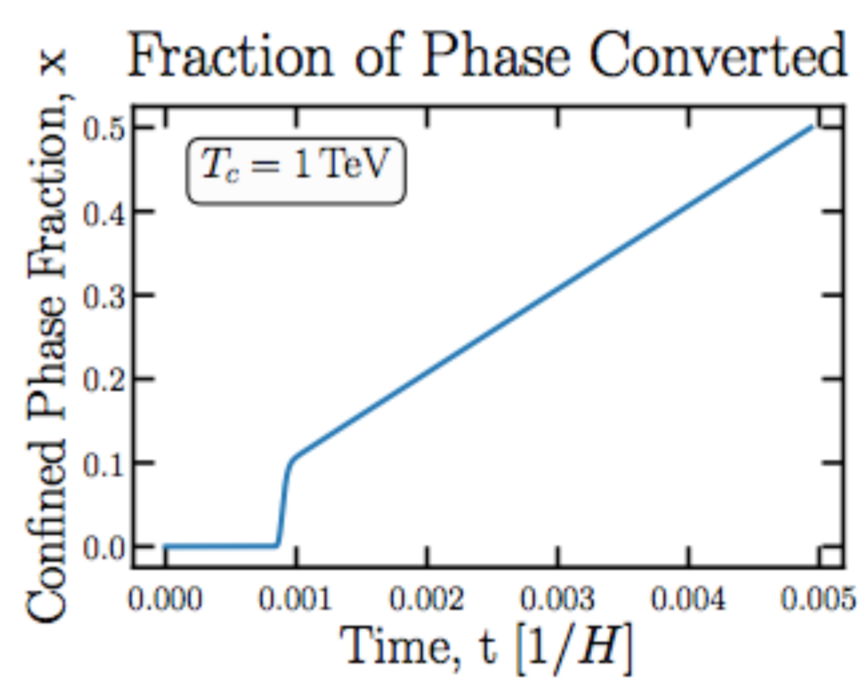
Temperature evolution during the phase transition



Temperature evolution during the phase transition

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





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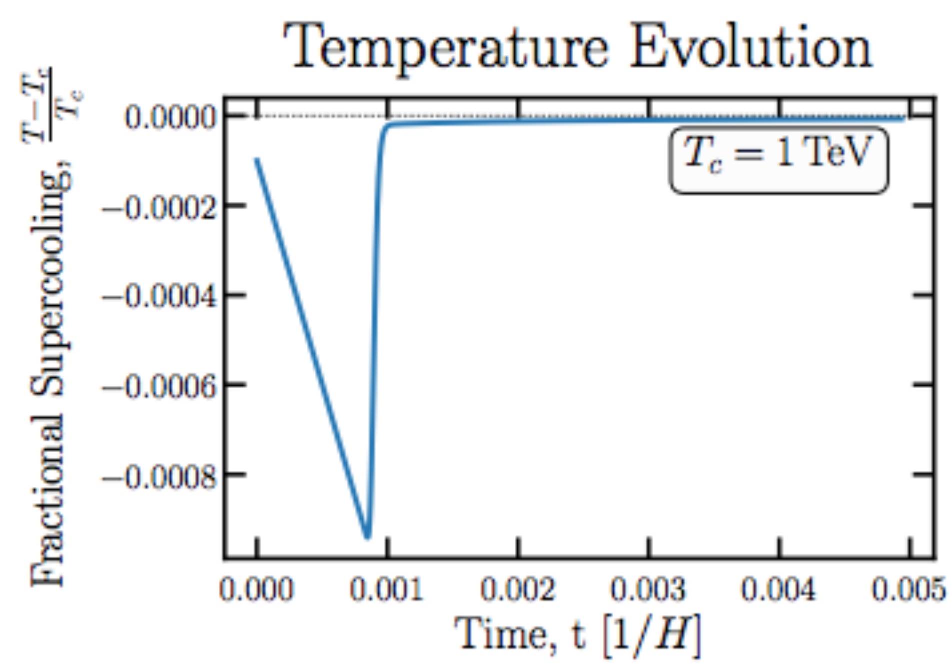
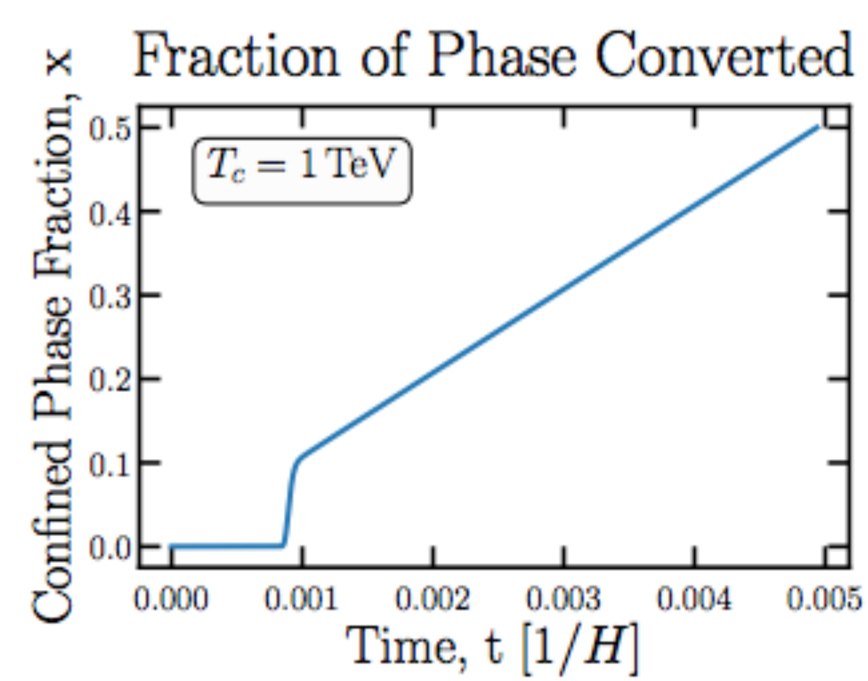
- Consequently there is little cooling due to expansion during the transition, but the bubble nucleation rate is very sensitive to any cooling below T_c





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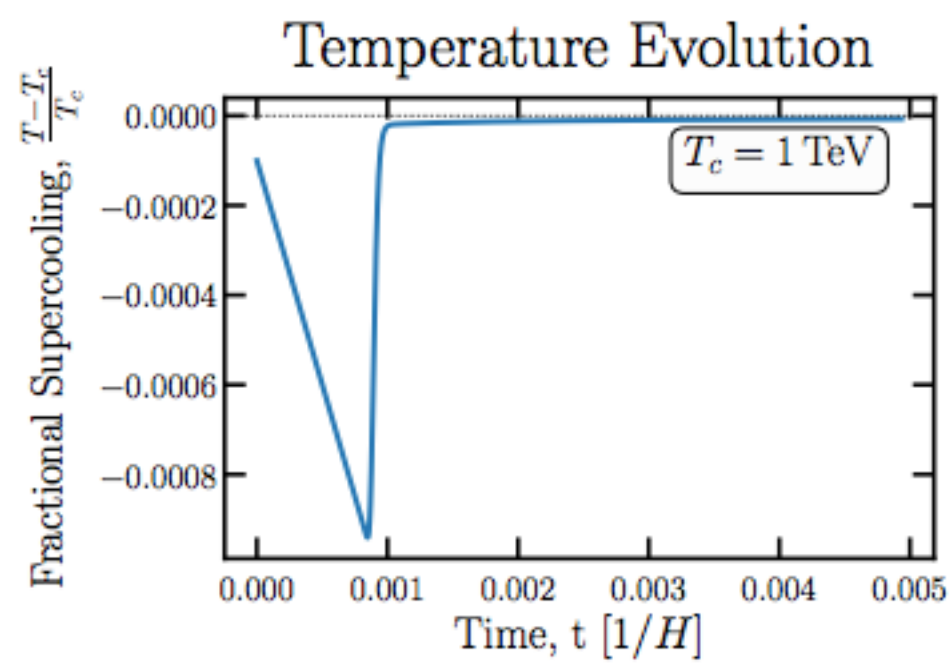
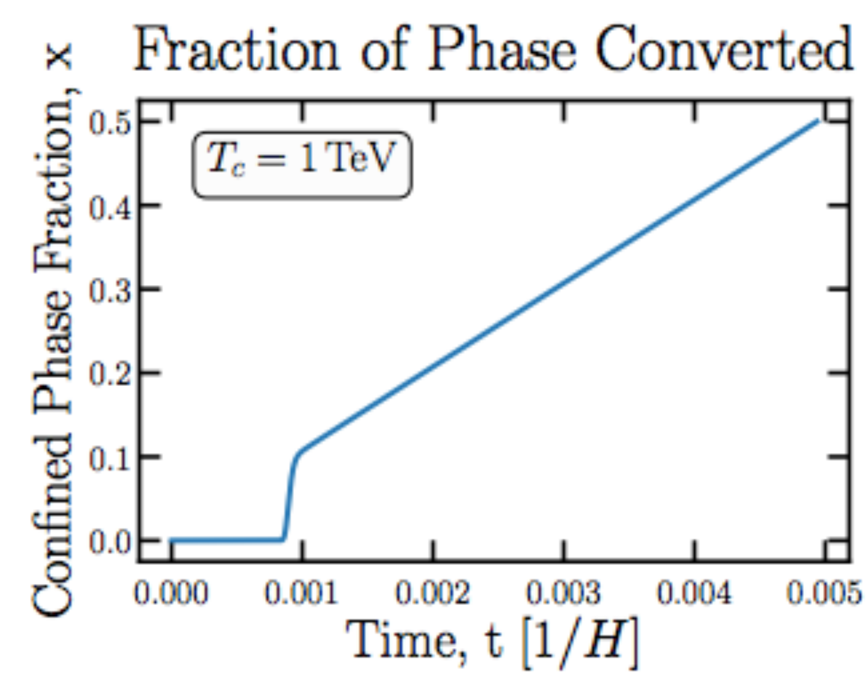
- Consequently there is little cooling due to expansion during the transition, but the bubble nucleation rate is very sensitive to any cooling below T_c
- Initial slight supercooling due to expansion leads to bubble nucleation → releases heat and reheats the cosmos back almost to T_c as the transition continues





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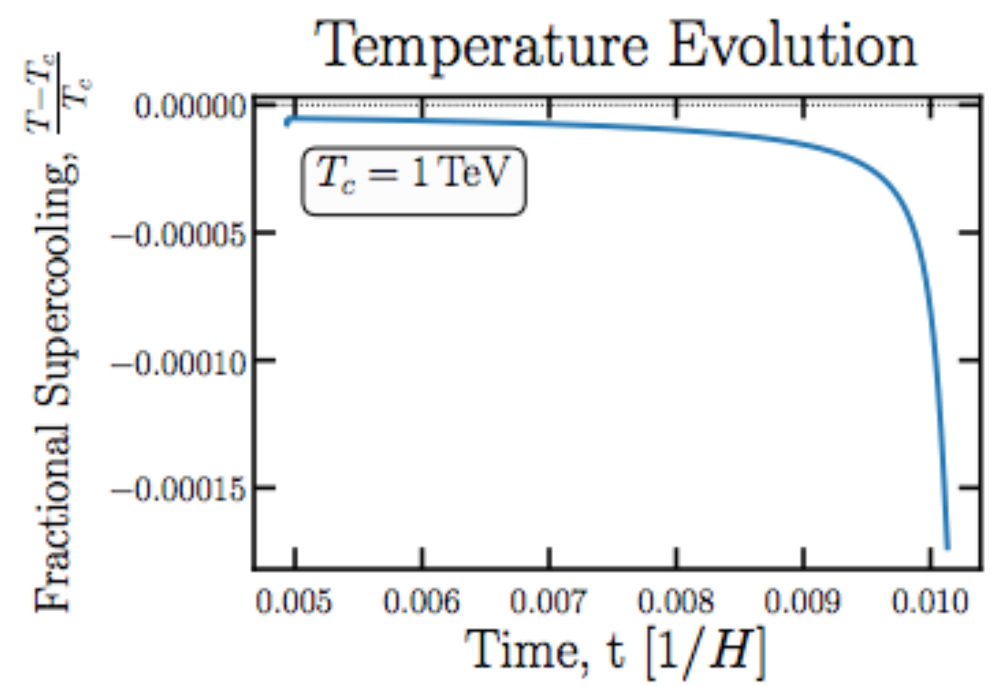

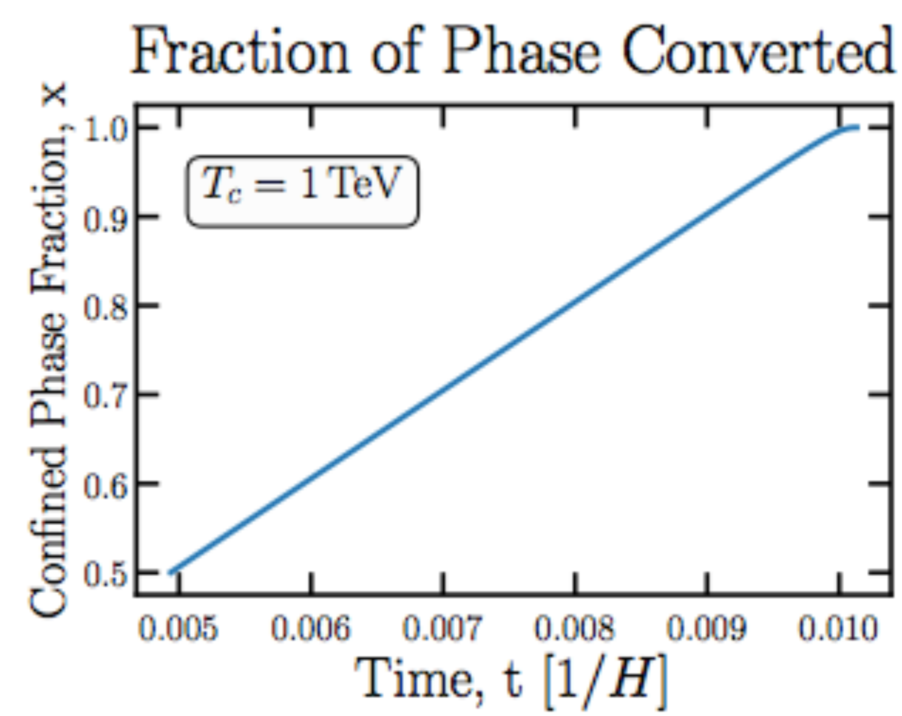

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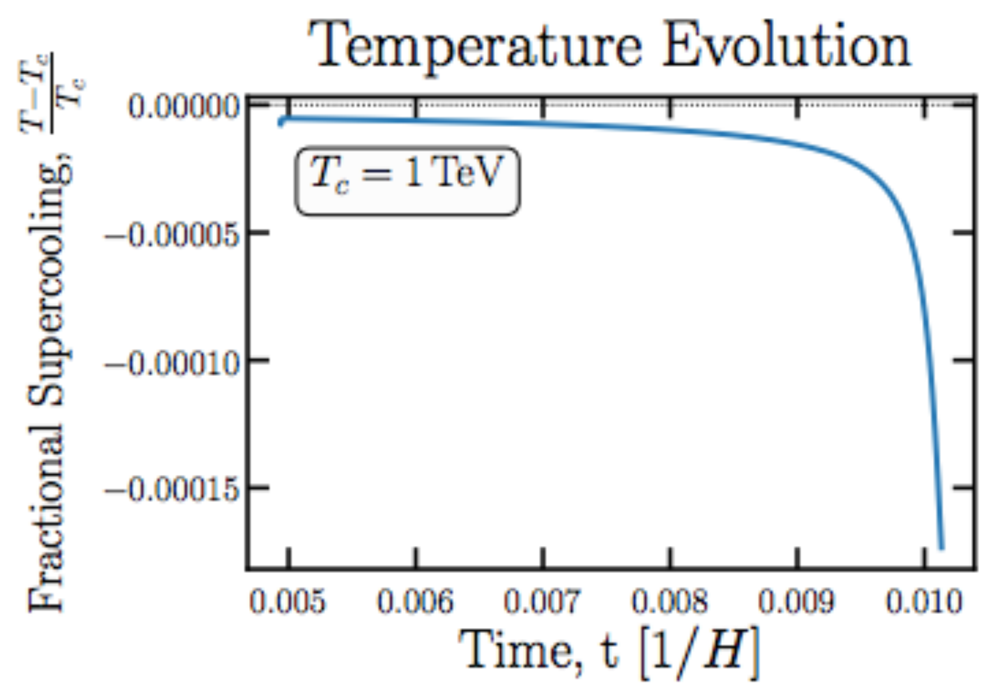
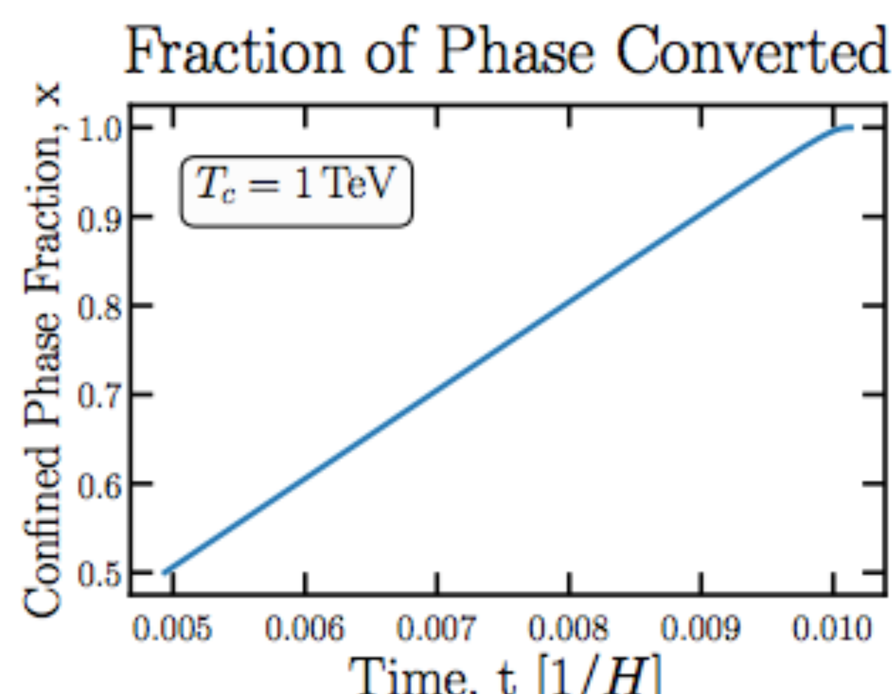
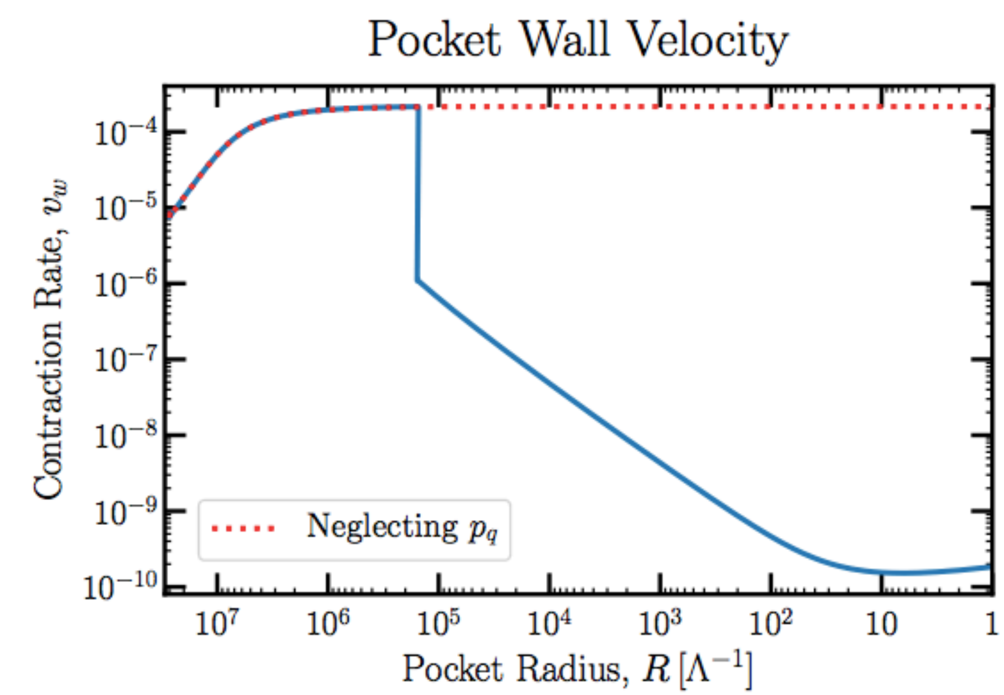
- Initial slight supercooling due to expansion leads to bubble nucleation → releases heat and reheats the cosmos back almost to T_c as the transition continues
- After percolation, the slowing rate of phase conversion means that Hubble cooling takes over again

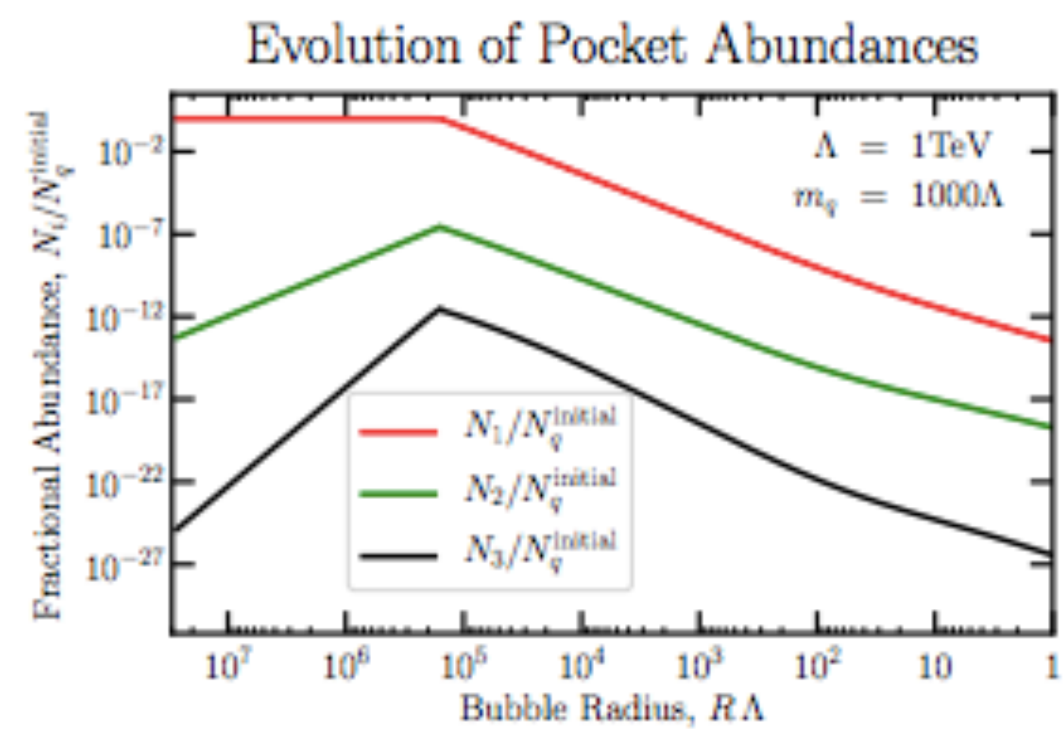




Equilibrium estimate of quark pressure effects

- 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





Classic thermal freezeout

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

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

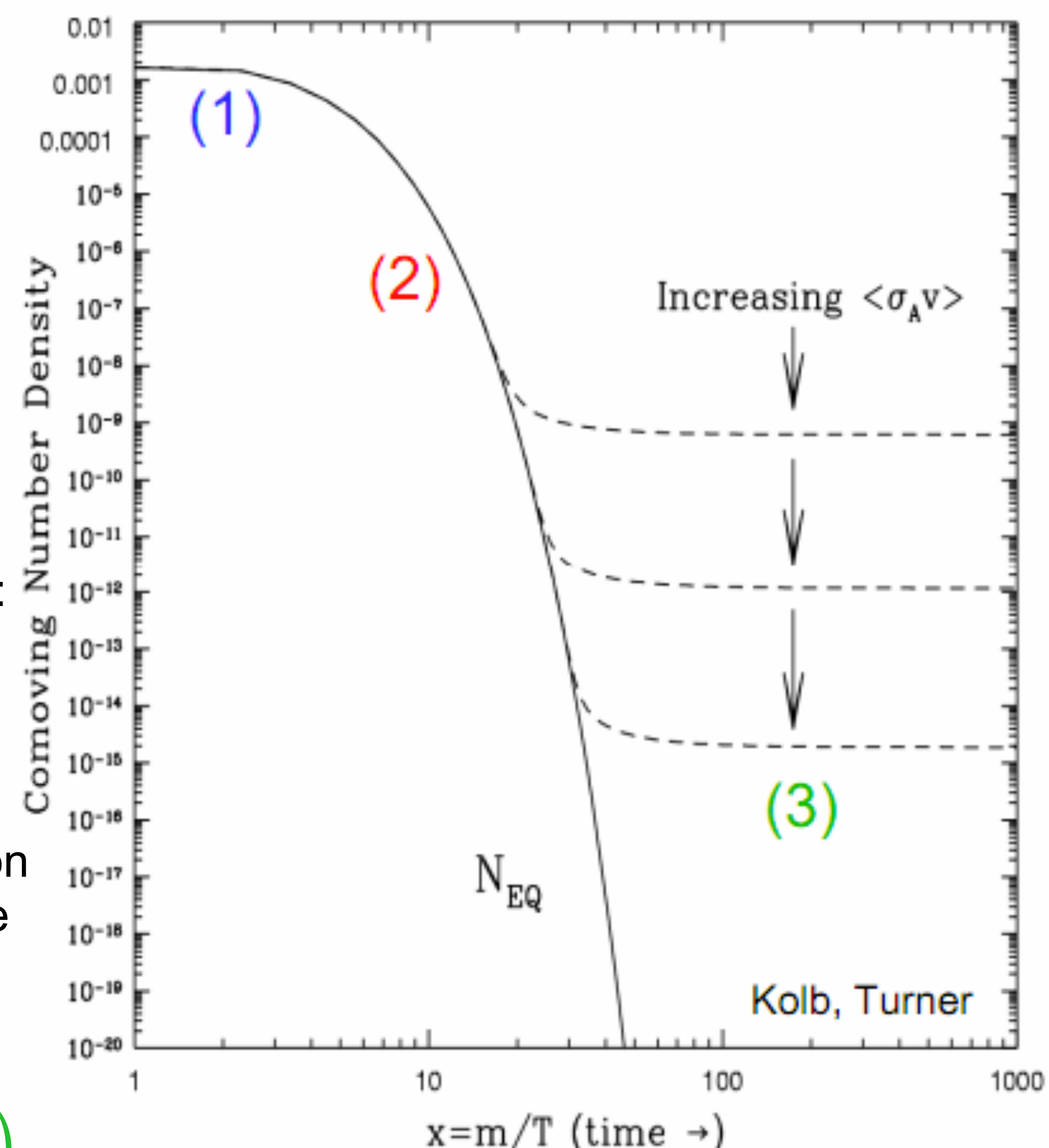
- As the universe expands, it cools down; eventually its temperature drops below the dark matter mass.

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

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

- 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 (3)



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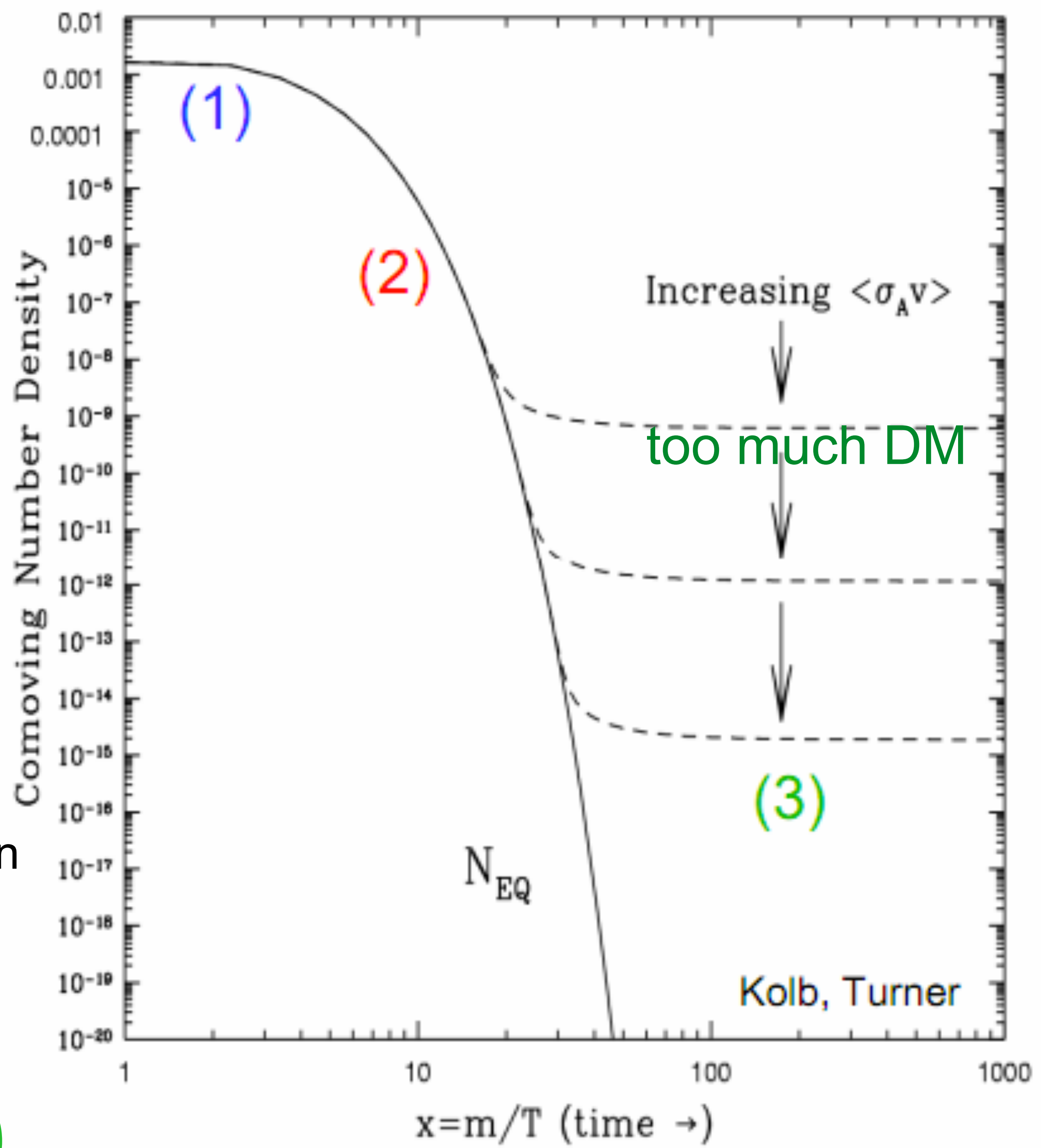

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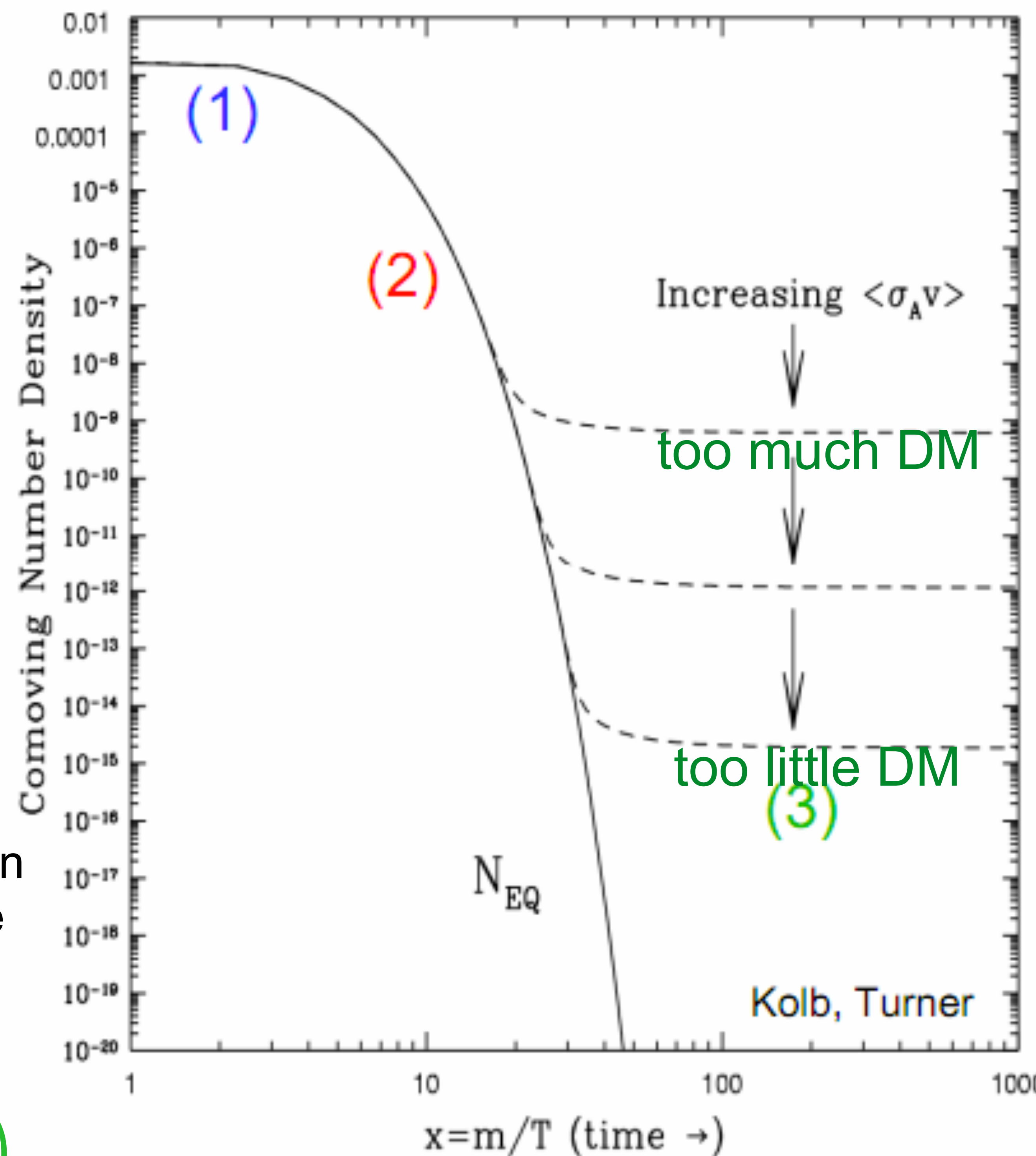

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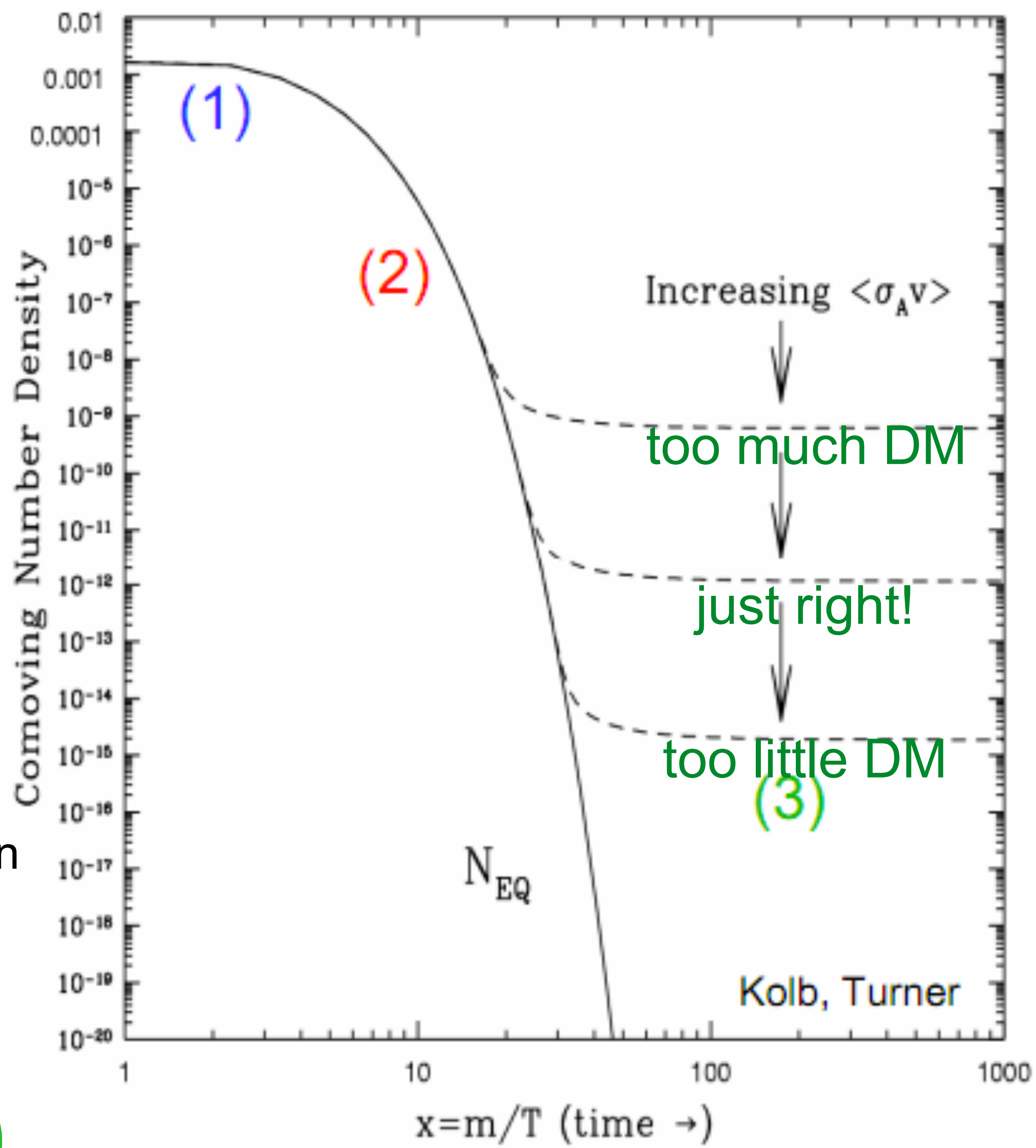

The unitarity bound

- 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

- In the limit of strong interactions, partial-wave unitarity still sets a mass-dependent upper bound on the cross section, which implies a maximum mass scale around 100 TeV if only l=0 contributes:

$$\sigma = \sum_{l=0}^{\infty} \sigma_l, \quad \sigma_l = \frac{4\pi}{k^2}(2l+1)\sin^2\delta_l \leq (2l+1)\frac{4\pi}{k^2}$$