Thermal Squeezeout for Heavy Dark Matter

Tracy Slatyer

Summiting the Unknown
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with Pouya Asadi, Eric Kramer, Eric Kuflik, Gregory Ridgway, & Juri Smirnov

This talk: dark matter, compositeness, phase transitions, early-universe cosmology, model-building…

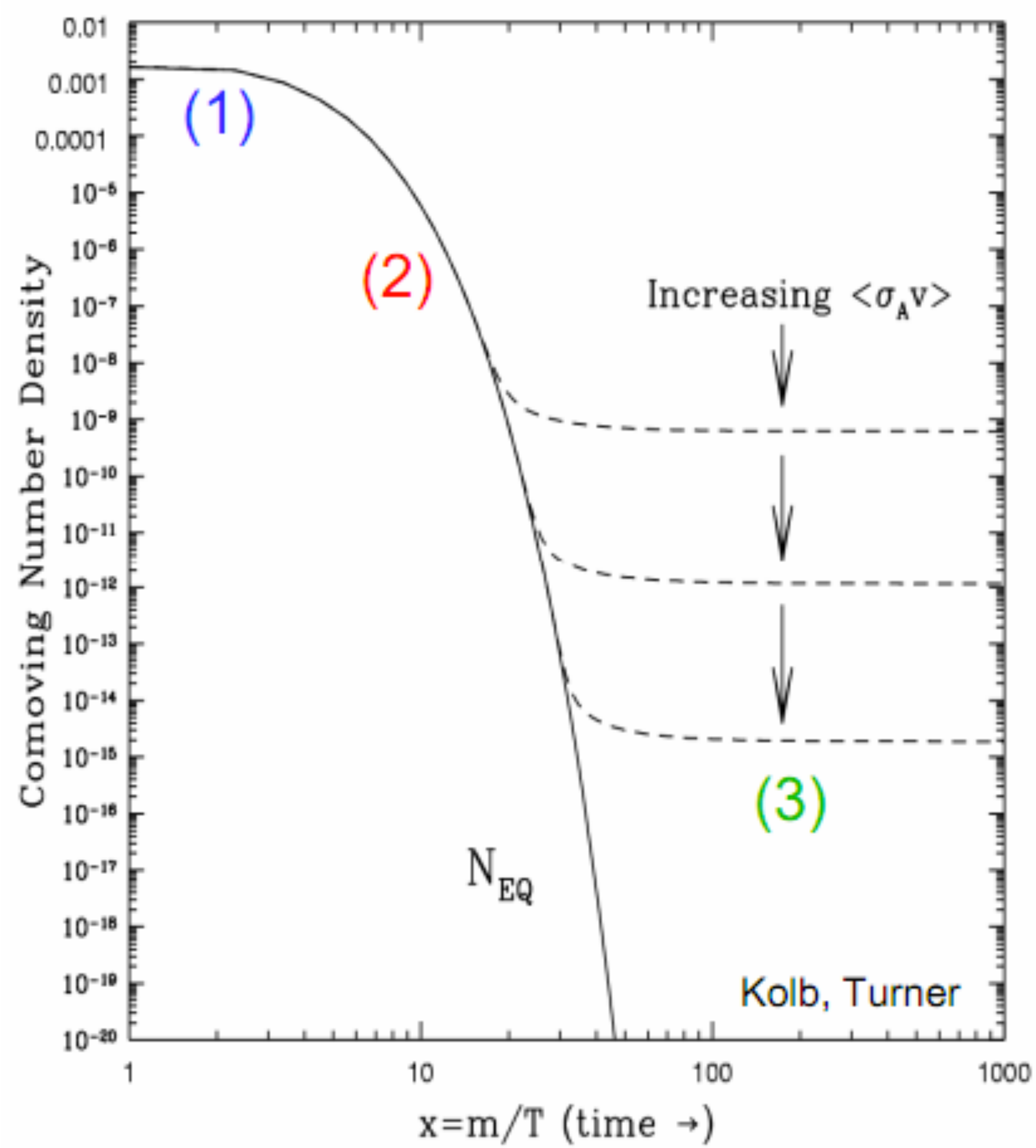
10 years of Ann's paper titles

Outline

- Background: thermal freezeout and the unitarity bound
- Setup: strongly-interacting dark sector with heavy dark quarks
- Calculating the effect of the confinement phase transition on the late-time dark baryon abundance (“squeezeout”)
- Dark matter dilution from dark glueball decay + observational signatures

Thermal freezeout

- Sufficiently strong DM-SM interactions keep the two species in thermal equilibrium in the early universe (1)
- DM density is exponentially depleted once it becomes non-relativistic (2)
- Exponential depletion freezes out when annihilation becomes inefficient relative to cosmic expansion (3)



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 sets a maximum DM mass that allows for a sufficiently large annihilation cross section & hence sufficient depletion of the DM

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

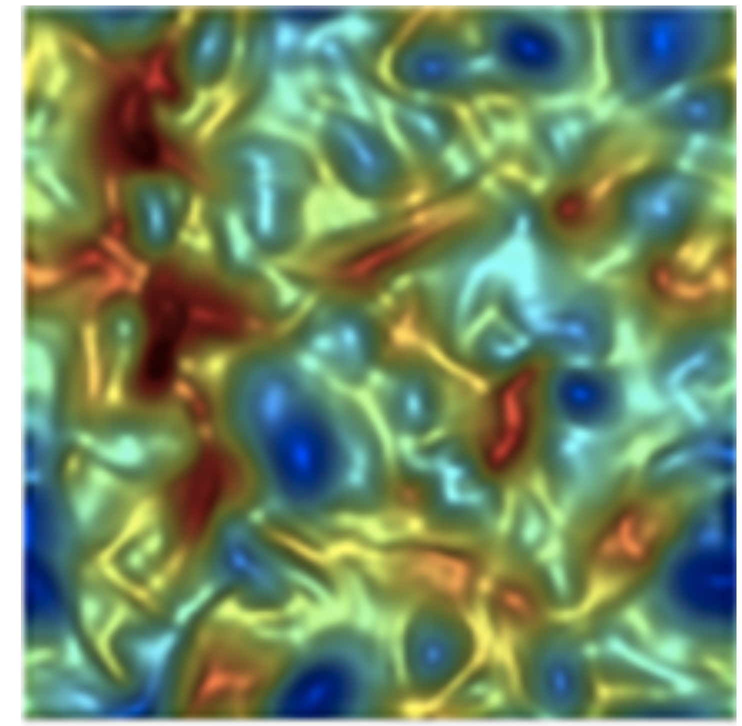
- Mass limit often quoted as 100-200 TeV, valid when l_{max} is small, although:

  - 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



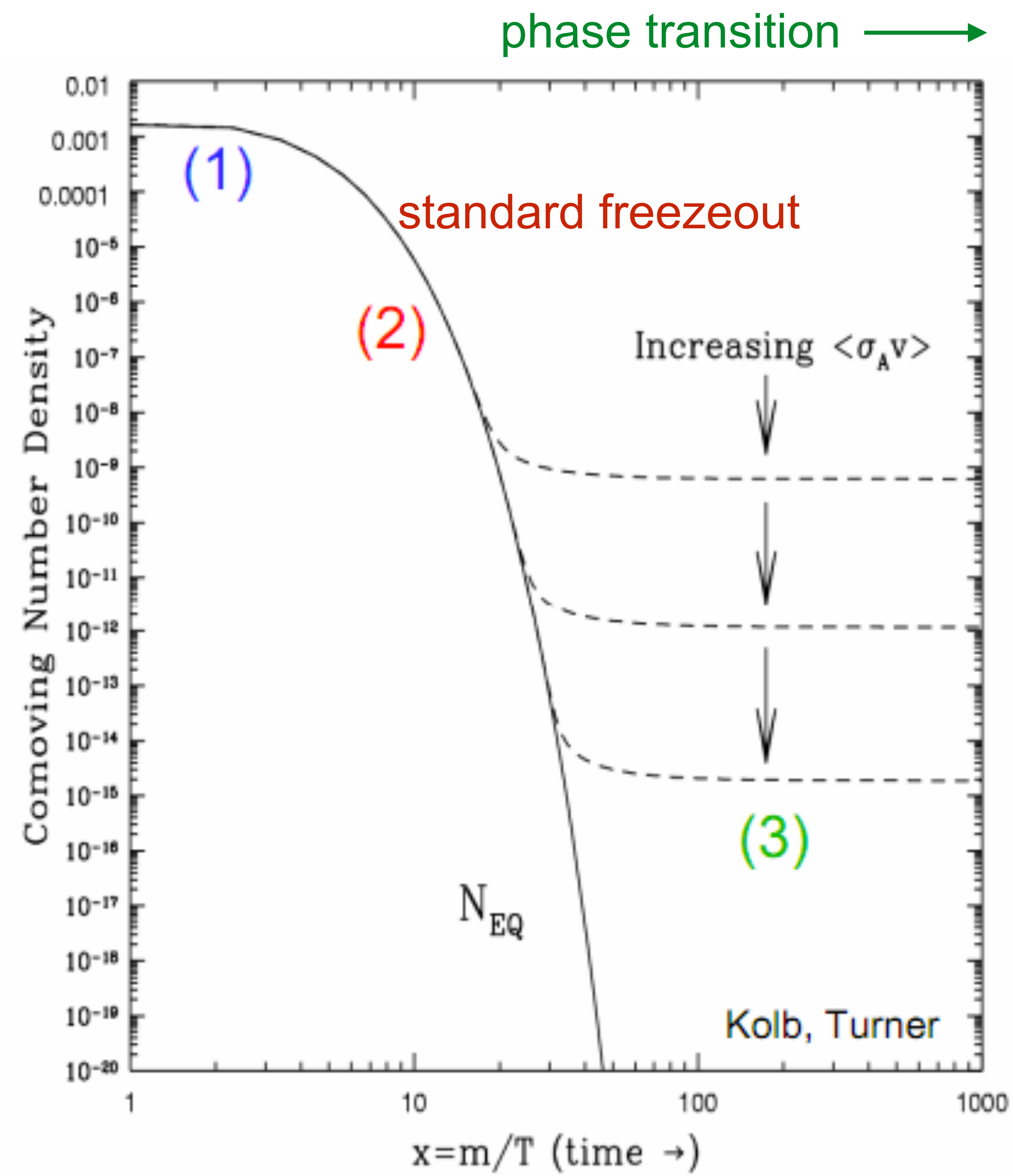
- Consider strongly-interacting DM inhabiting a confining dark sector (like QCD in the Standard Model).
- Today: dark matter comprised of stable dark baryons
- Early in the universe: dark quark-gluon plasma.
- Automatic modification to early-universe cosmology: the confinement phase transition.
- If 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].
- 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.
- <u>Caveat</u>: this will <u>not</u> be a detailed calculation using advanced 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

- Assume dark quarks are much heavier than confinement scale
- 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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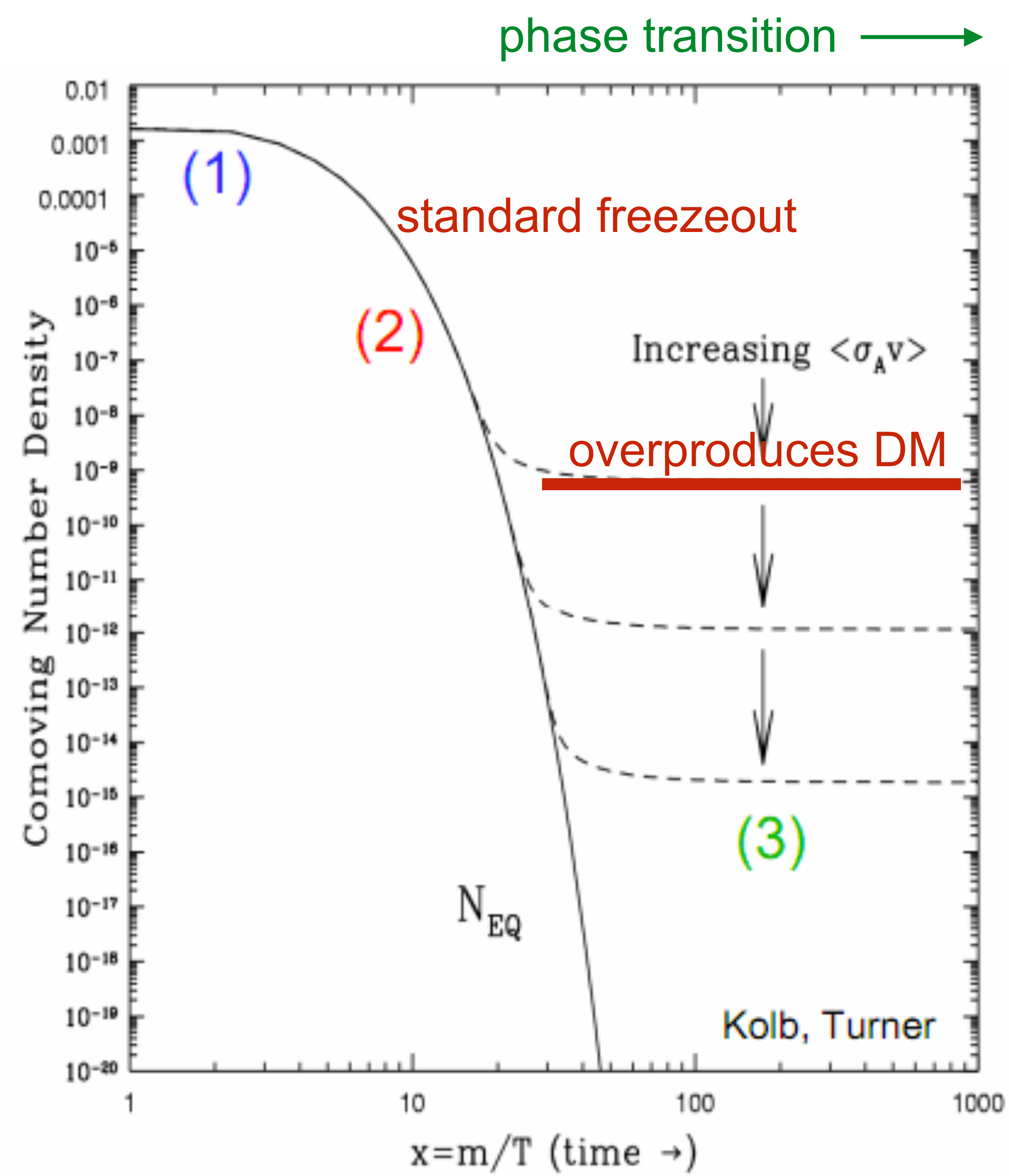
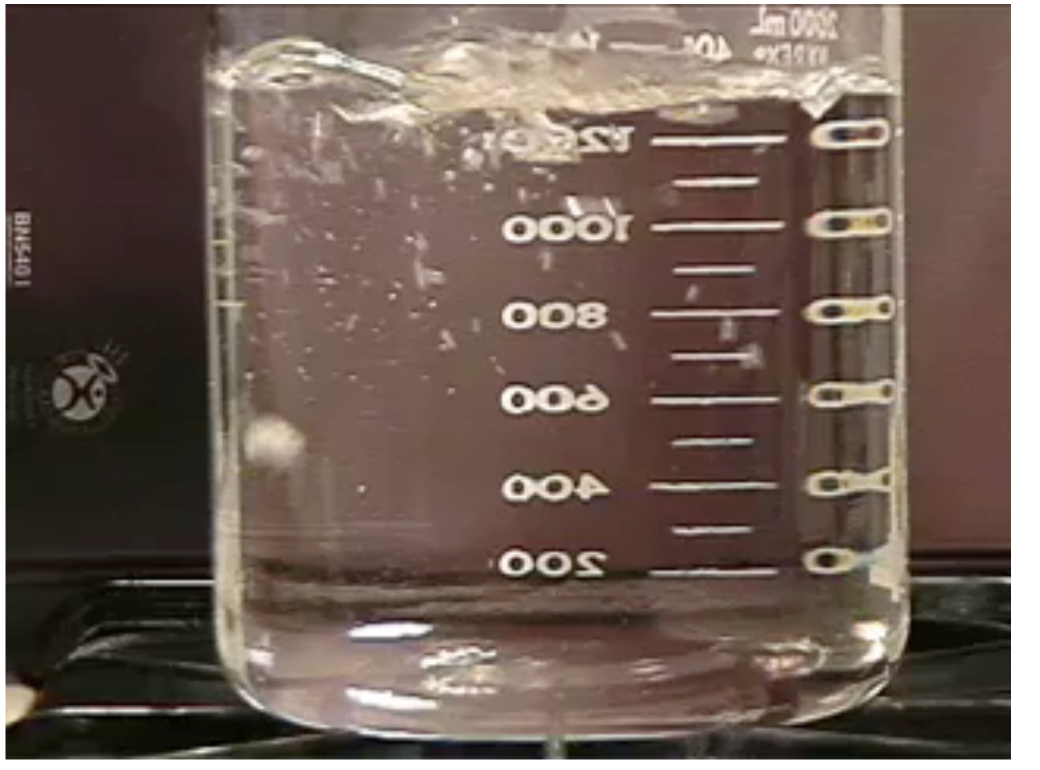


Stage 2: bubble growth

- 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 '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).



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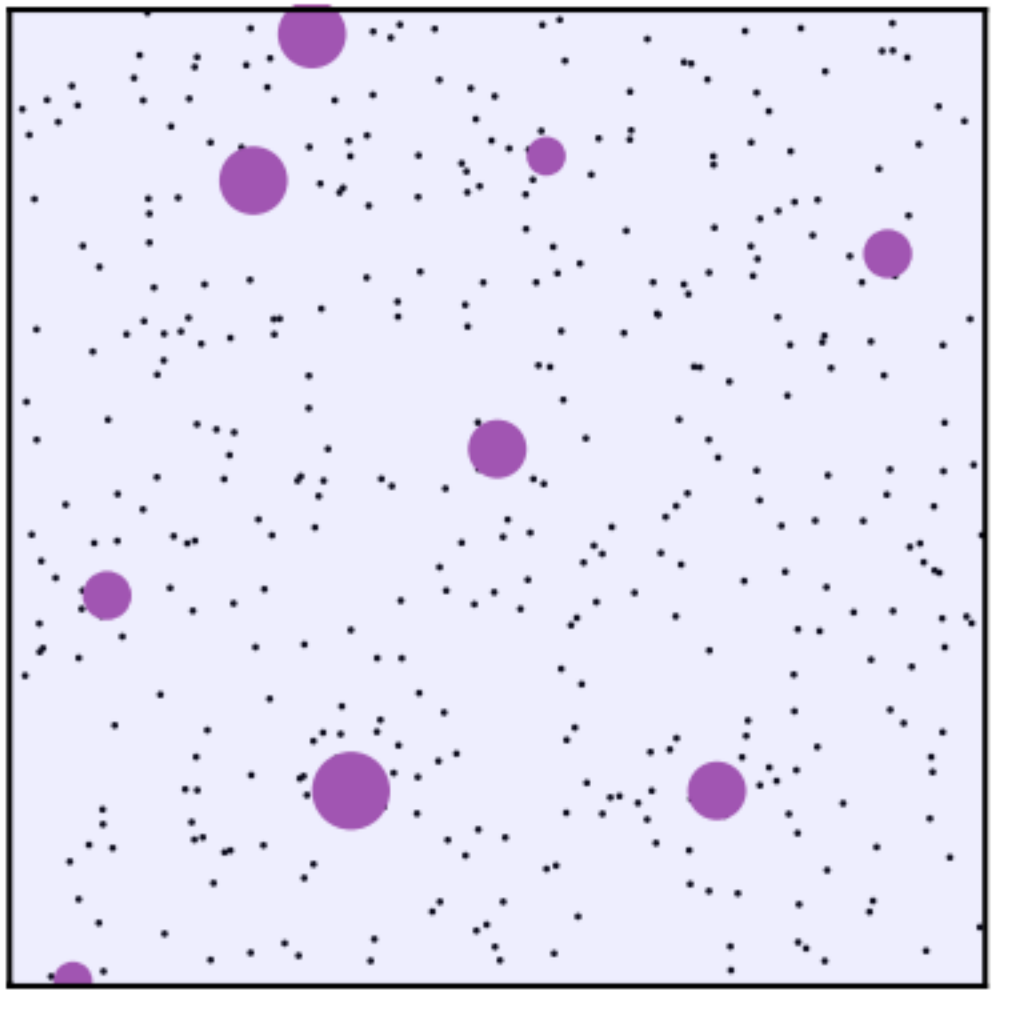

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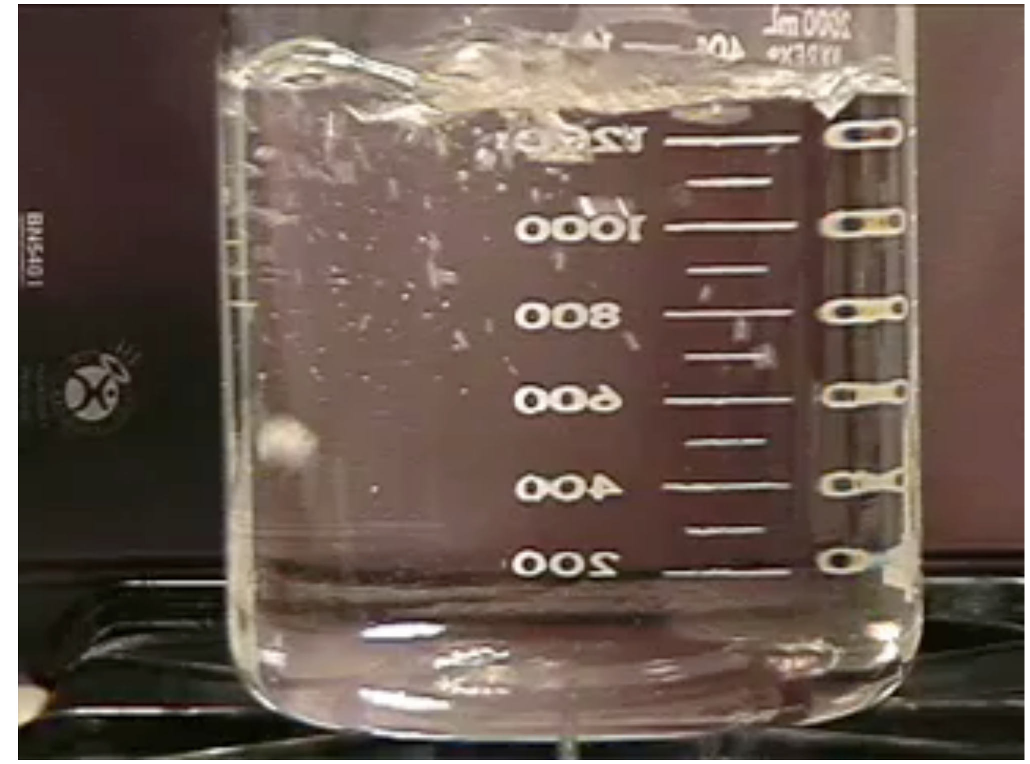

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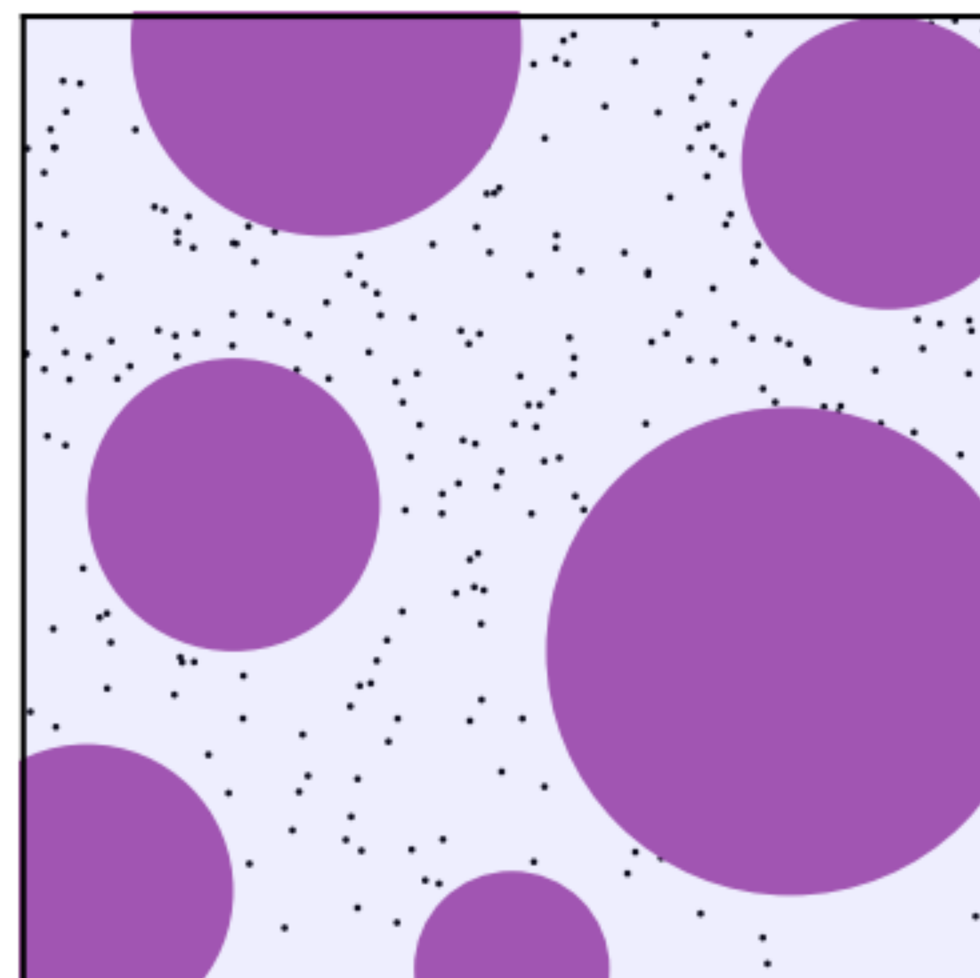

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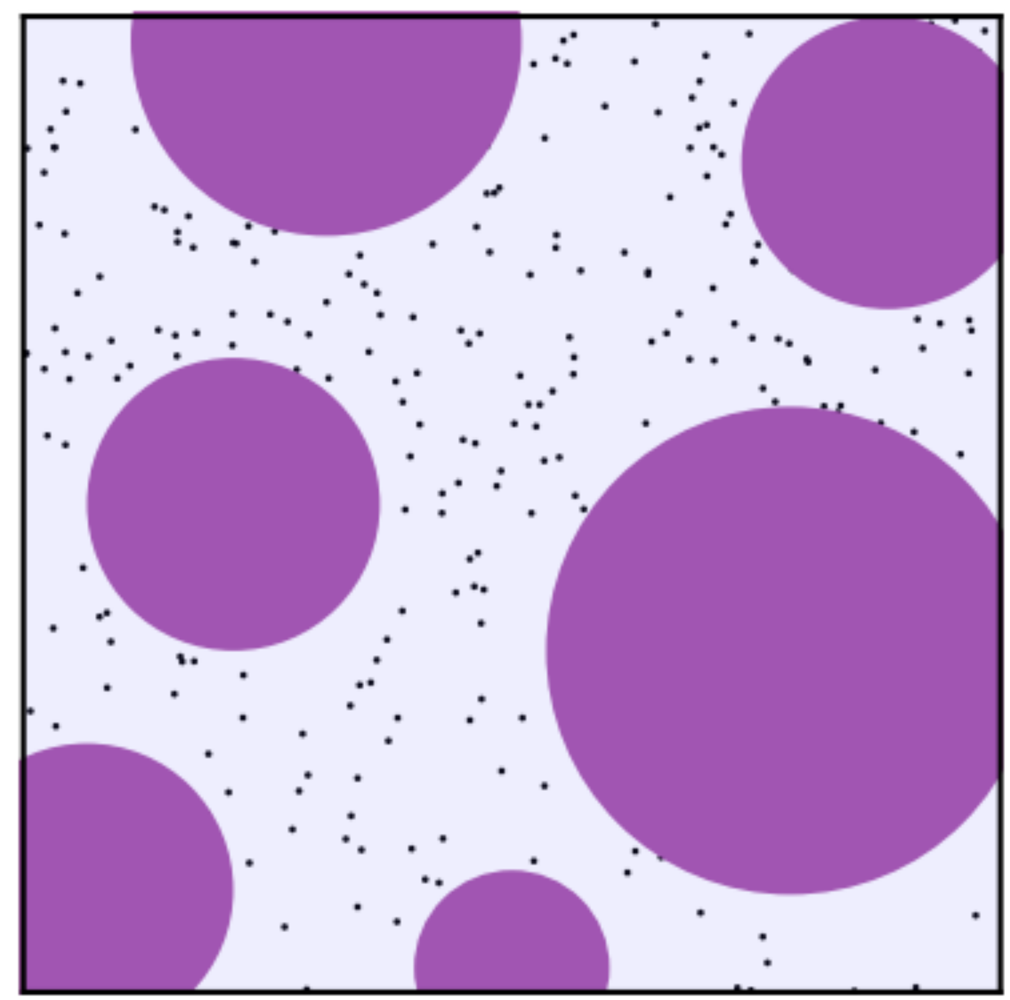
Stage 3: percolation

- 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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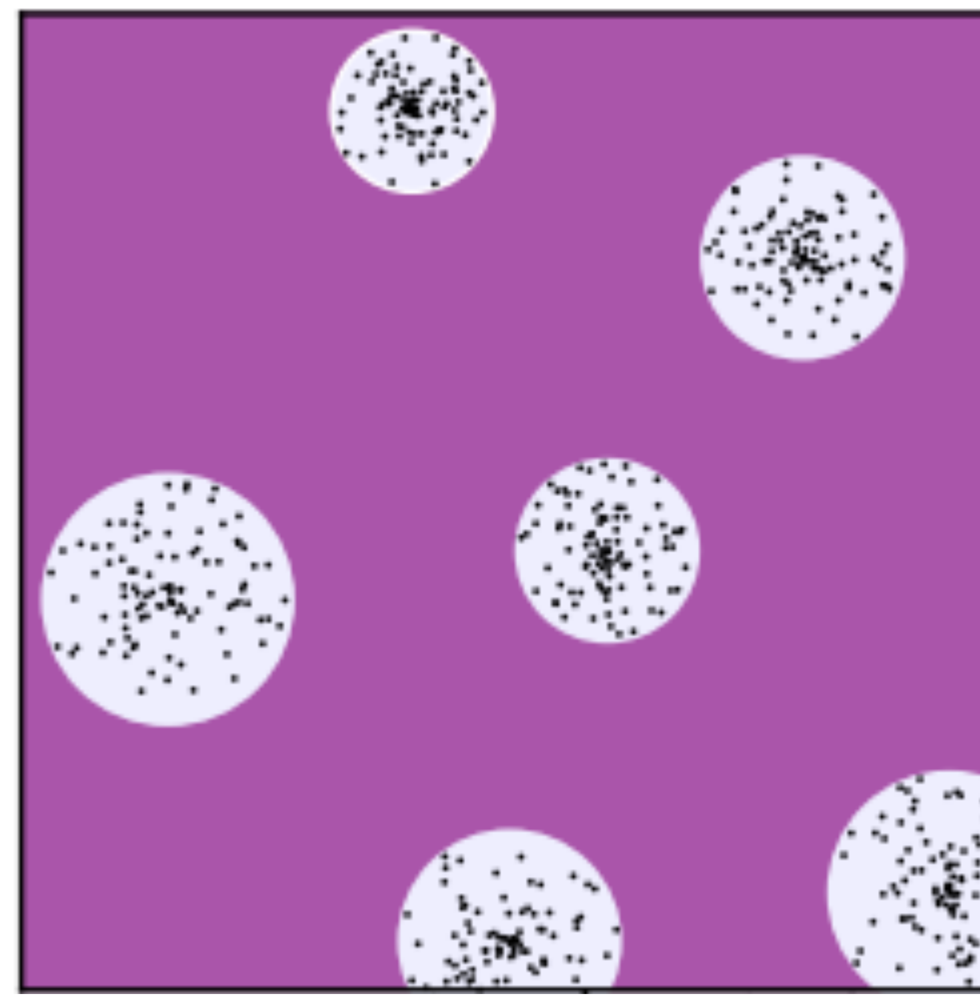
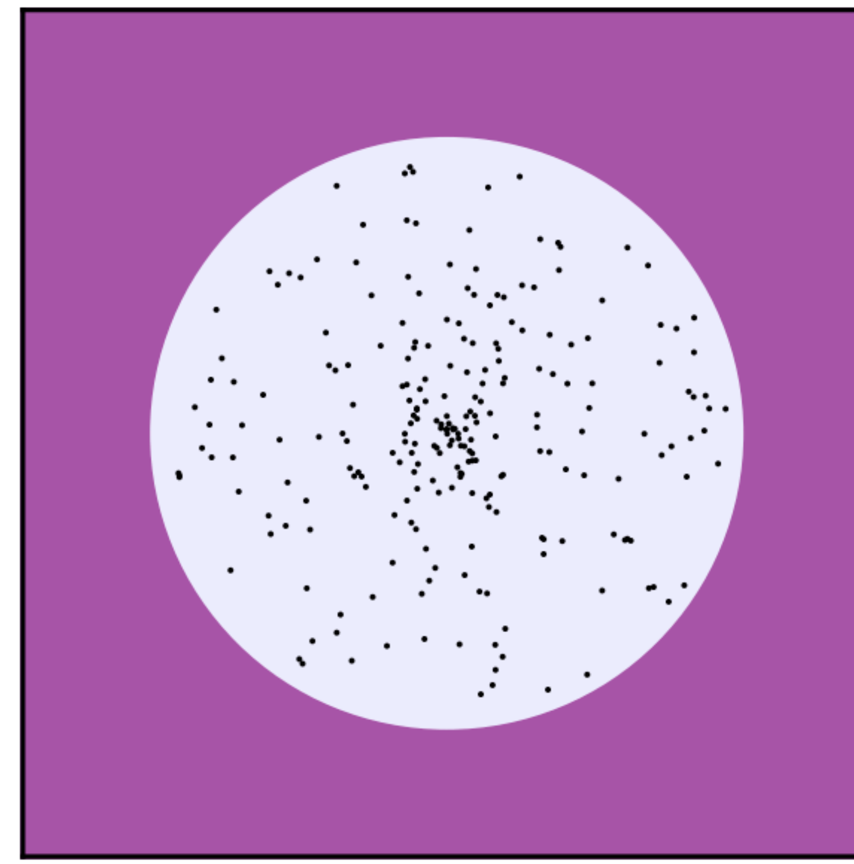


Stage 4: squeezeout

- 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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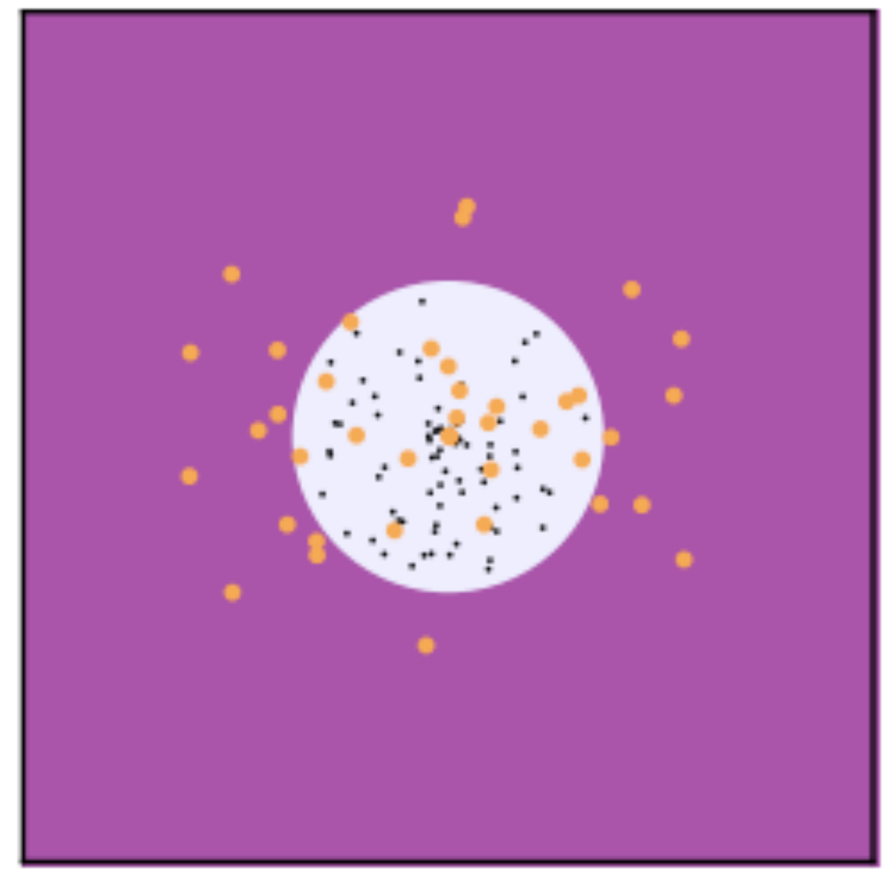

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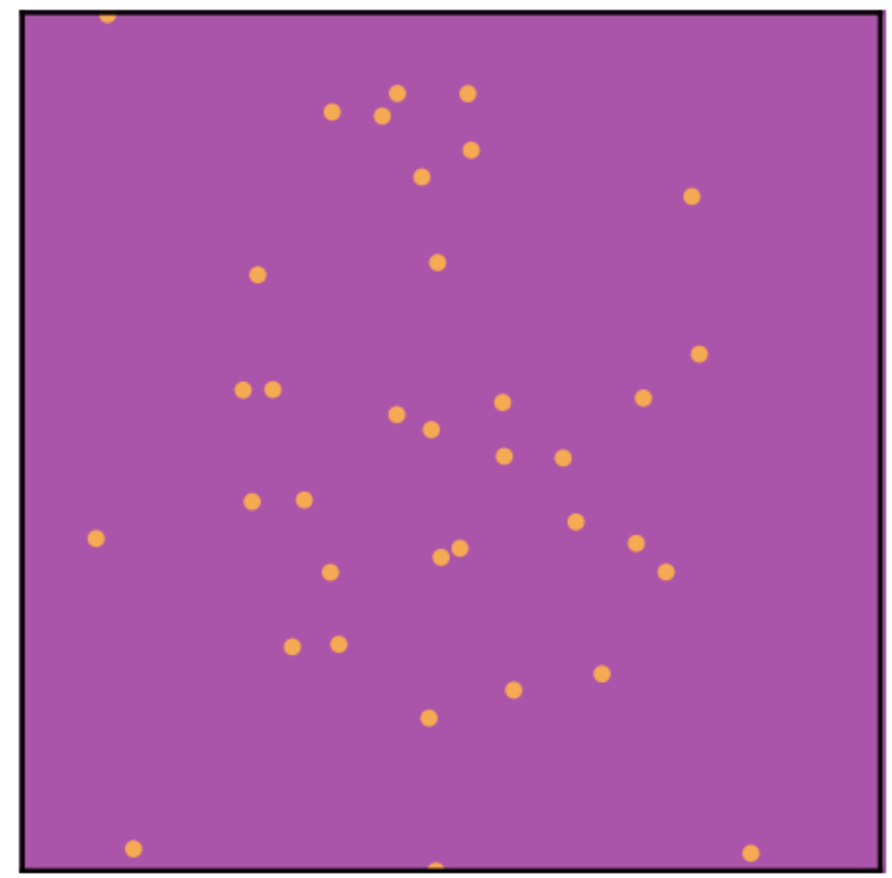

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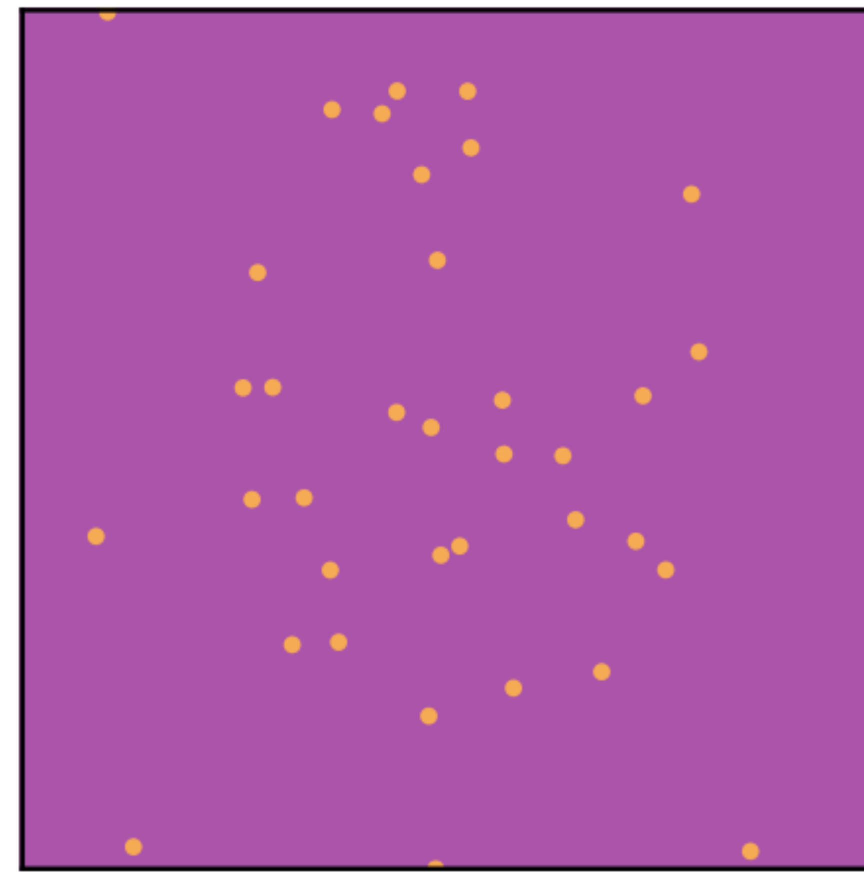
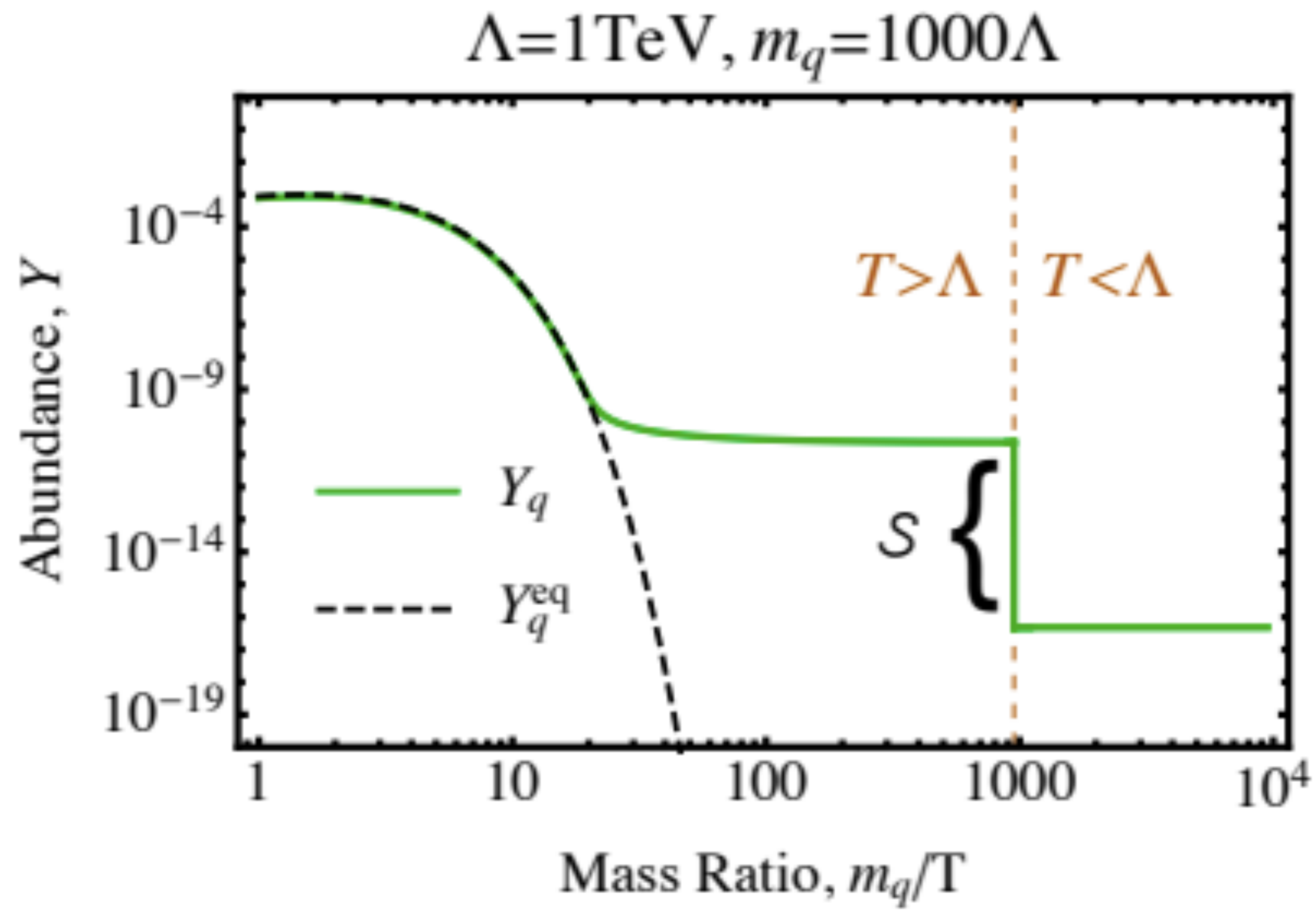


Summary of cosmic history for this scenario

- 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.
- We find this leads to the observed relic abundance for PeV-EeV 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]

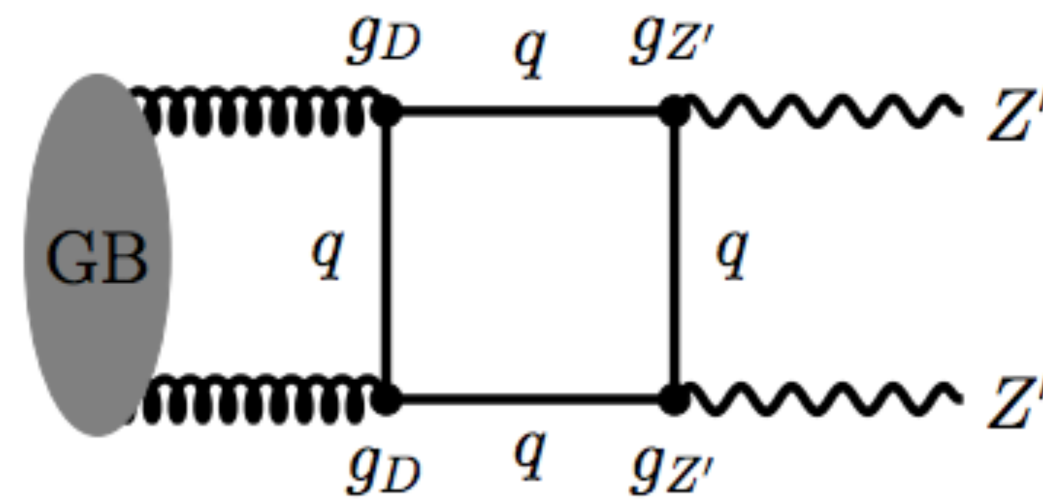
- To explore other signatures, we consider a simple $U(1)_{B-L}$ portal to the Standard Model [2203.15813, Asadi, Kramer, Kuflik, TRS & Smirnov]

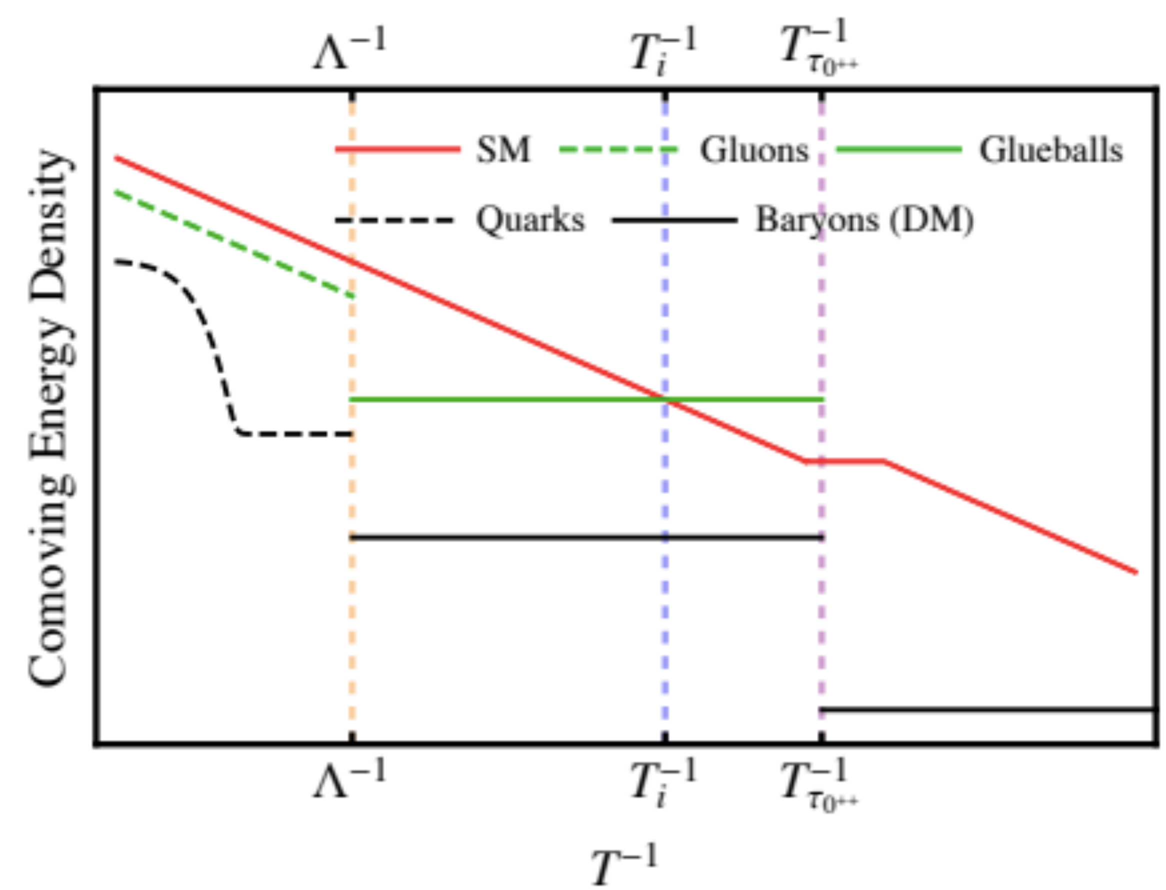
- Gauge B-L symmetry giving rise to a new Z' gauge boson, charge dark quarks under B-L ($q_q=1$)

- Adds two new parameters: the mass of the Z' and the gauge coupling for $U(1)_{B-L}$

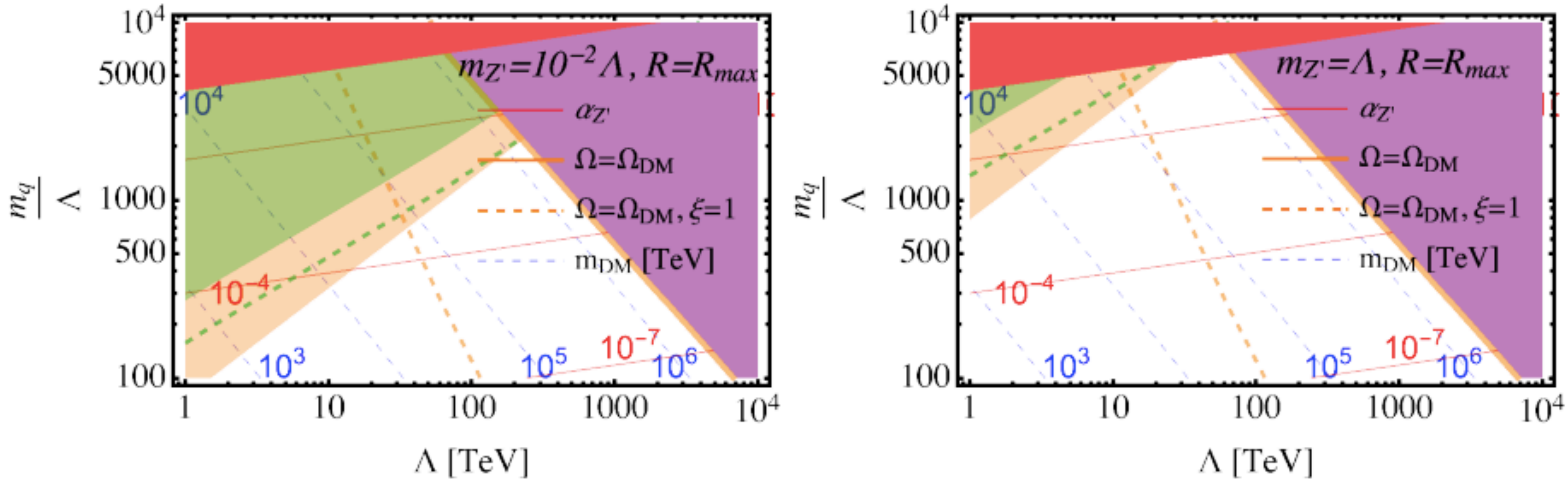
The importance of glueballs

- Dark glueballs = bound states of the dark gluons
- If they are stable, would make up the DM - requires a portal to the Standard Model so they can decay
- But 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
- 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





Constraints on the Z' model



- In this plot we adjust the coupling to the Standard Model the value that allows the maximal glueball lifetime consistent with constraints. In the red region this value becomes nonperturbative.
- Dashed and solid orange lines show the shift in parameters yielding the correct relic density due to glueball decay
- Green, orange, purple regions show constraints on model due to direct detection (dashed green = neutrino floor), collider searches for the Z', and overclosure

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.

- Long-lived glueball states in such a dark sector can generically give rise to an early matter-dominated epoch prior to BBN, and further increase the preferred mass scale.

BONUS SLIDES

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,

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

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)

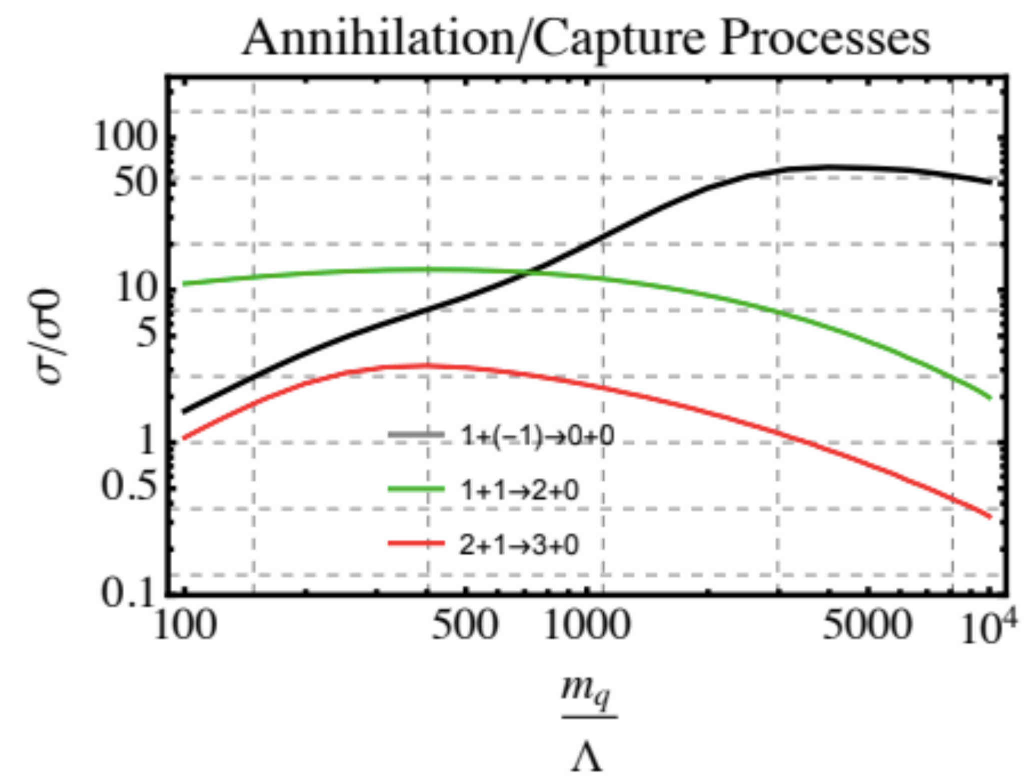
Relevant processes

- 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

$$
\begin{aligned}
L[i] &= C[i], \quad i = 1,2,3. \\
C[1] &= -\Big\langle(-3,1)\to(-1,-1)\Big\rangle - \Big\langle(-3,1)\to(-2,0)\Big\rangle + 2\Big\langle(3,-1)\to(1,1)\Big\rangle \\
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\end{aligned}
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\Big\langle(a,b)\to(\alpha,\beta)\Big\rangle &= \langle\sigma v\rangle_{ab\to\alpha\beta}\left(n_a n_b - n_\alpha n_\beta \frac{n_a^{eq} n_b^{eq}}{n_\alpha^{eq} n_\beta^{eq}}\right) \\
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\end{aligned}
$$

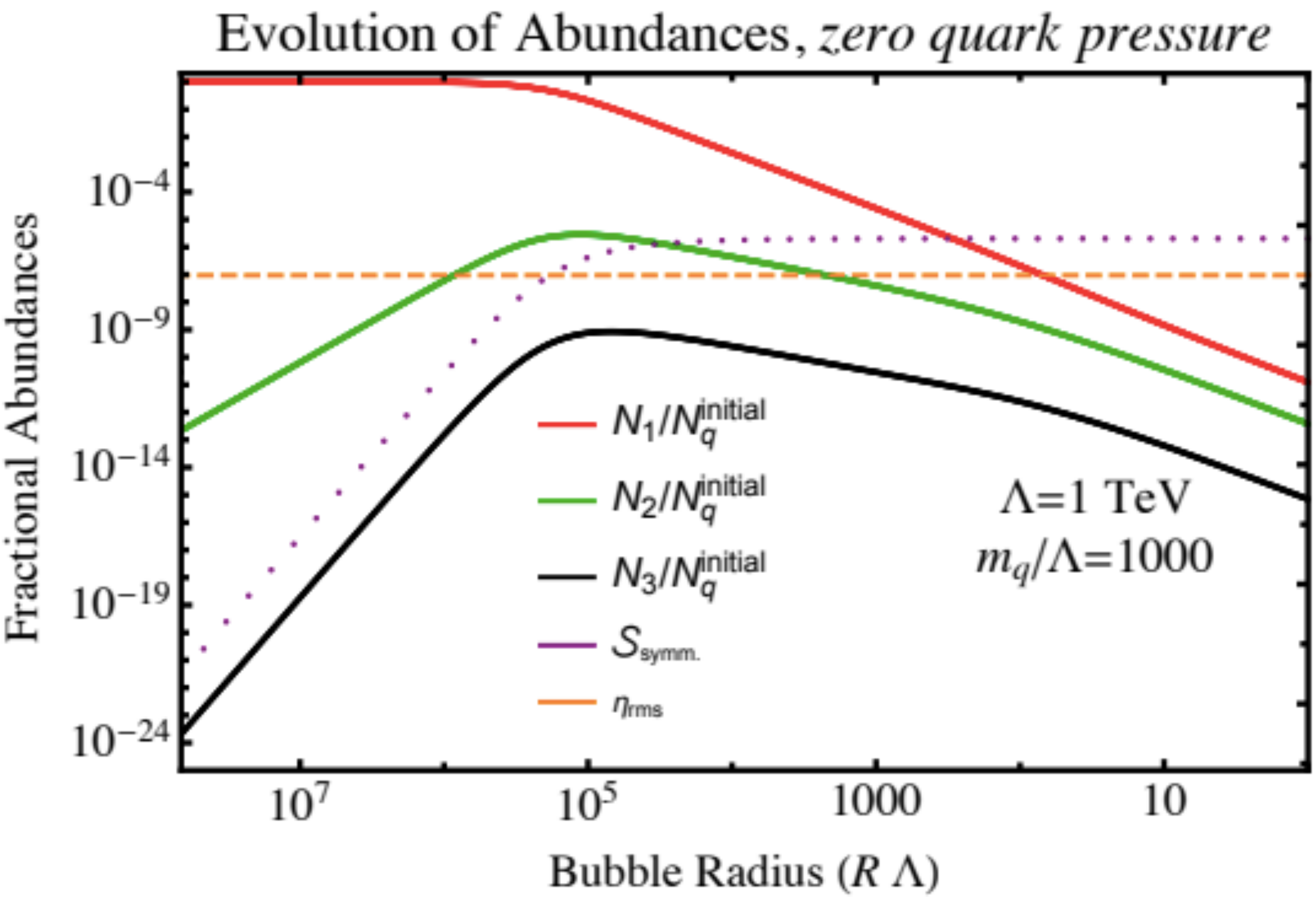
describes change in particle number with respect to pocket radius

$$
\begin{aligned}
L[i] &= -\frac{v_w}{V}N_i', \quad i=1,2, \\
L[3] &= -\frac{v_w}{V}\left(N_3' - \frac{3}{R}\frac{v_q+v_w}{v_w}N_3\right),
\end{aligned}
$$

$$
\begin{aligned}
\Big\langle(a,b)\to(\alpha,\beta)\Big\rangle &= \langle\sigma v\rangle_{ab\to\alpha\beta}\left(n_a n_b - n_\alpha n_\beta \frac{n_a^{eq} n_b^{eq}}{n_\alpha^{eq} n_\beta^{eq}}\right) \\
&= \frac{\langle\sigma v\rangle_{ab\to\alpha\beta}}{V^2}\left(N_a N_b - N_\alpha N_\beta f_{ab,\alpha\beta}\right),
\end{aligned}
$$

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, $S \gtrsim 1/\sqrt{N}$

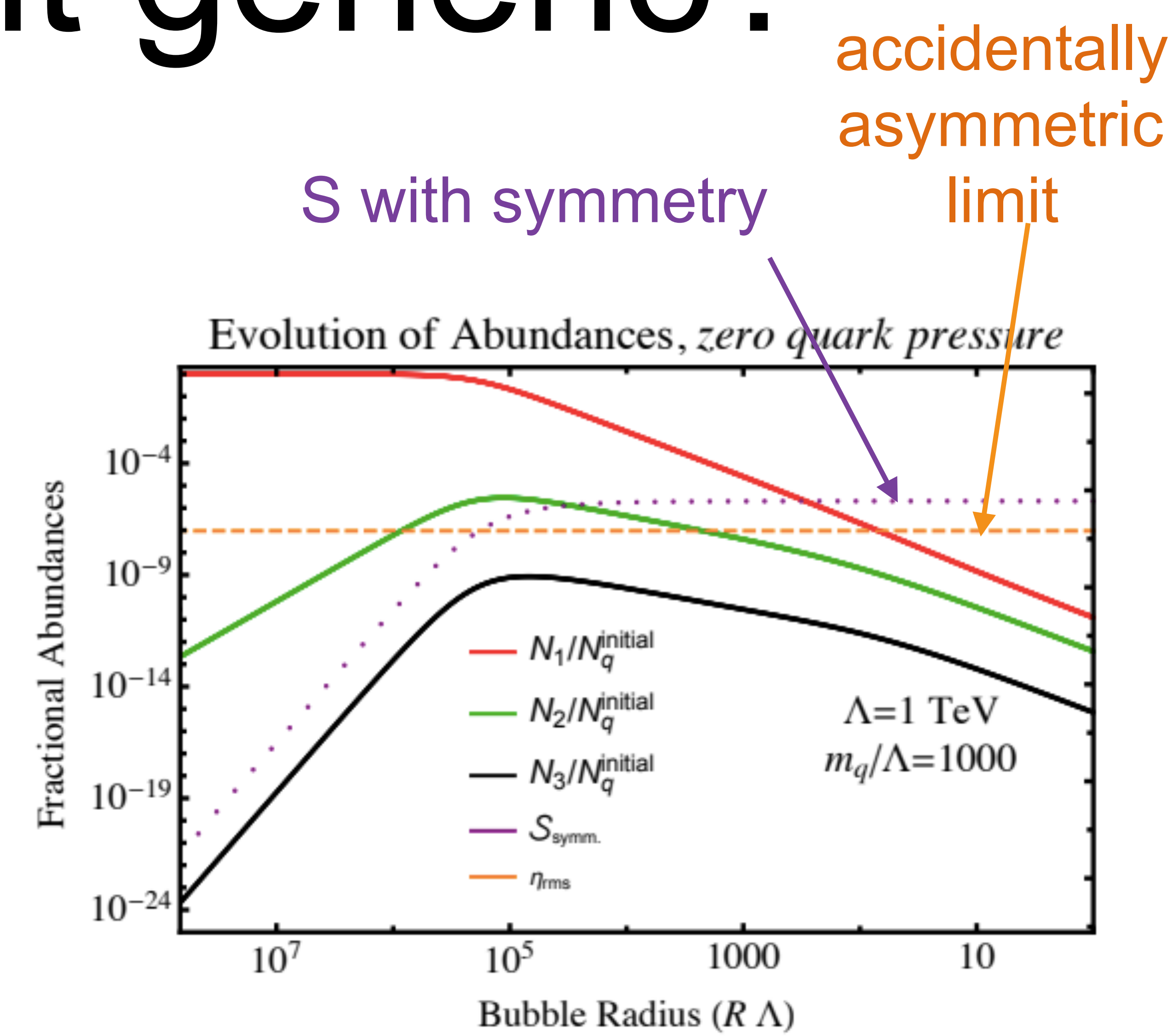
Quark pressure

- 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 ignore quark pressure, S generically either saturates the accidentally-asymmetric lower bound or comes close to it.

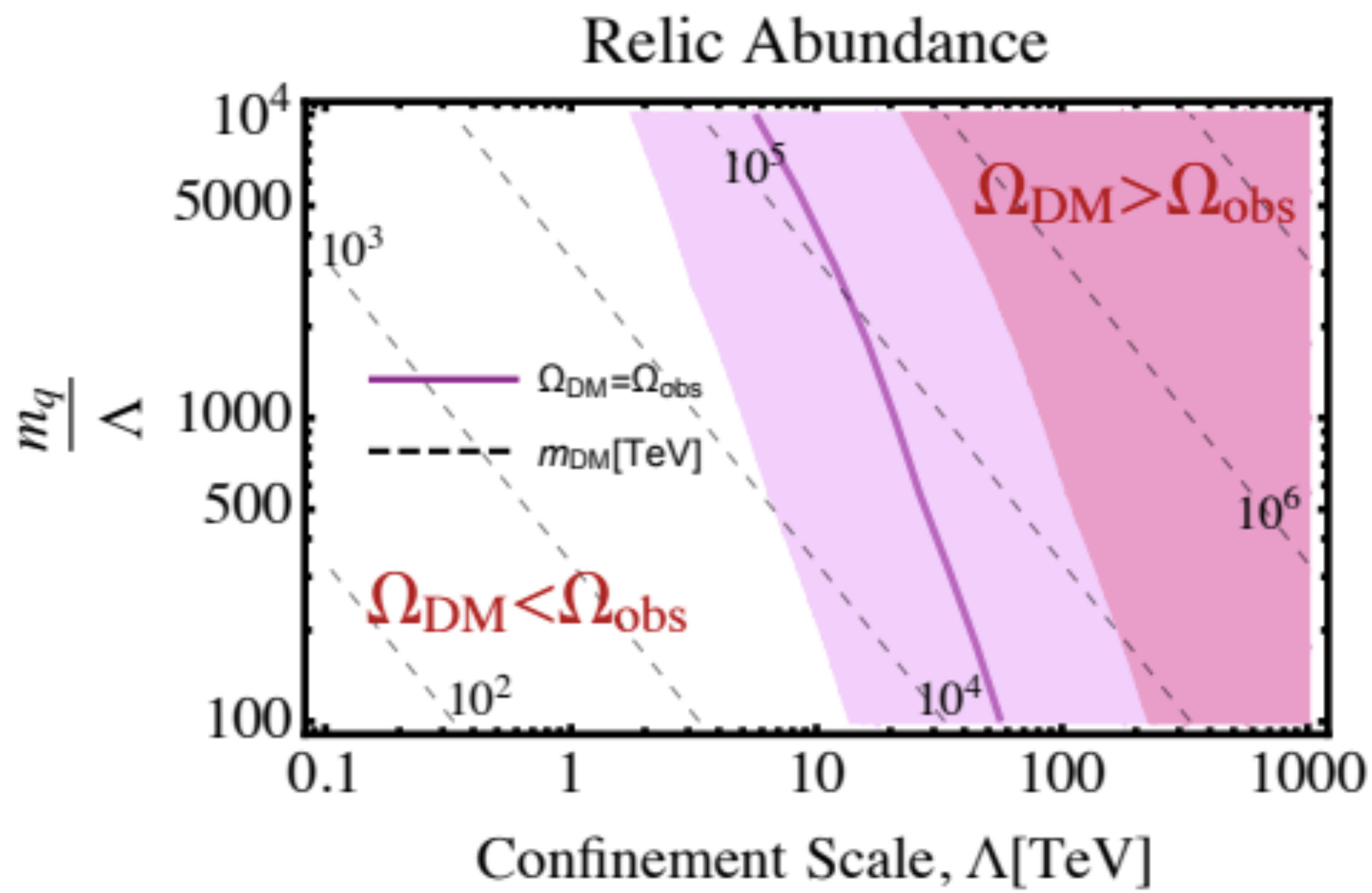
- Including quark pressure will generically decrease S - under simple estimates, causes saturation of the bound (easily) everywhere.



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

The relic density

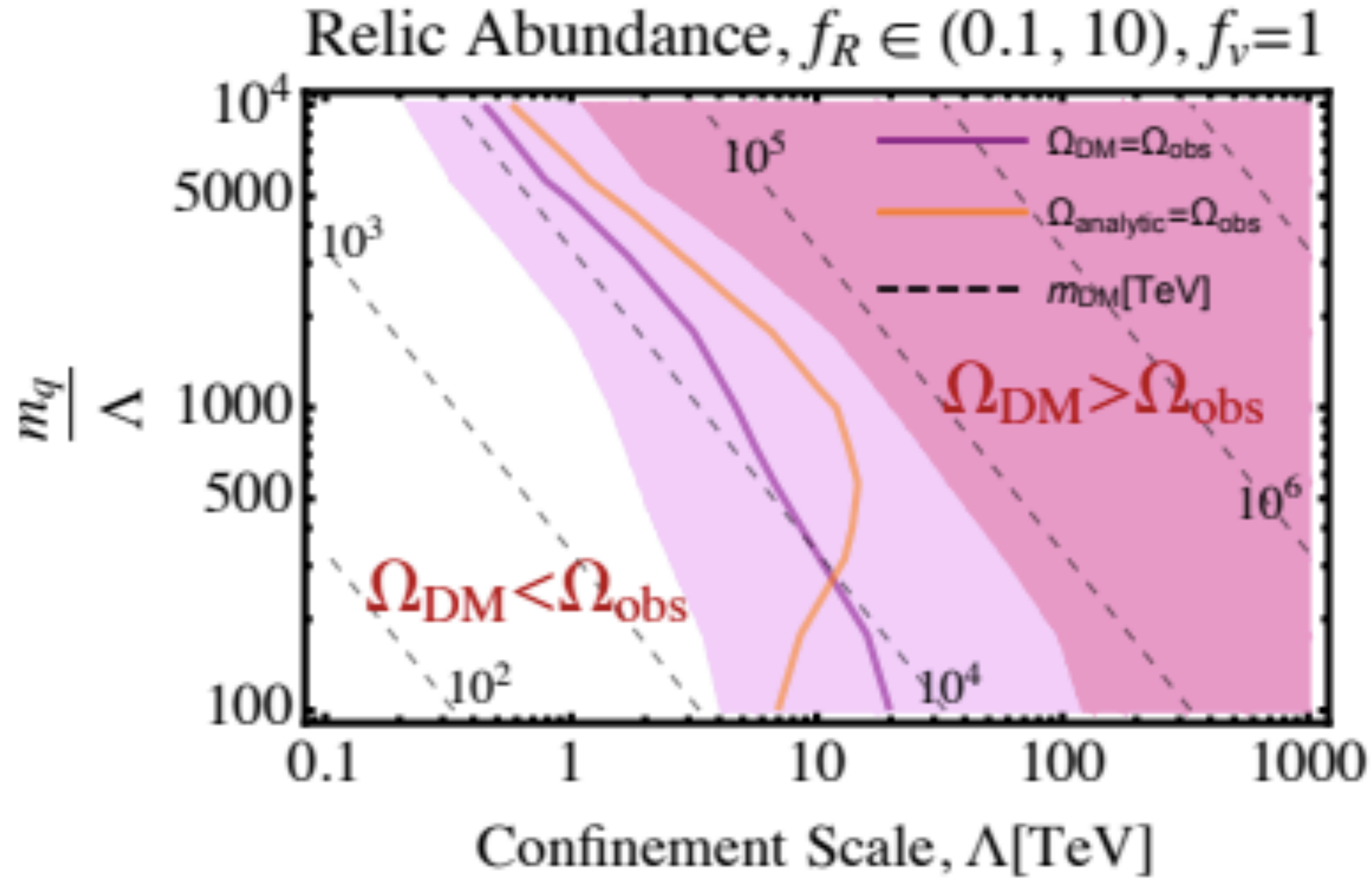
- In the accidentally asymmetric limit, the survival factor S is determined entirely by the initial number of quarks per pocket
- Fixed by:
  - post-freezeout number density (depends on quark mass + high-energy couplings, set by Λ)
  - radius of pockets at percolation (estimated as $R_1 \approx \left(\frac{M_{\mathrm{Pl}}}{10^4 \Lambda}\right)^{2/3} \frac{1}{\Lambda}$, from Witten 1984)

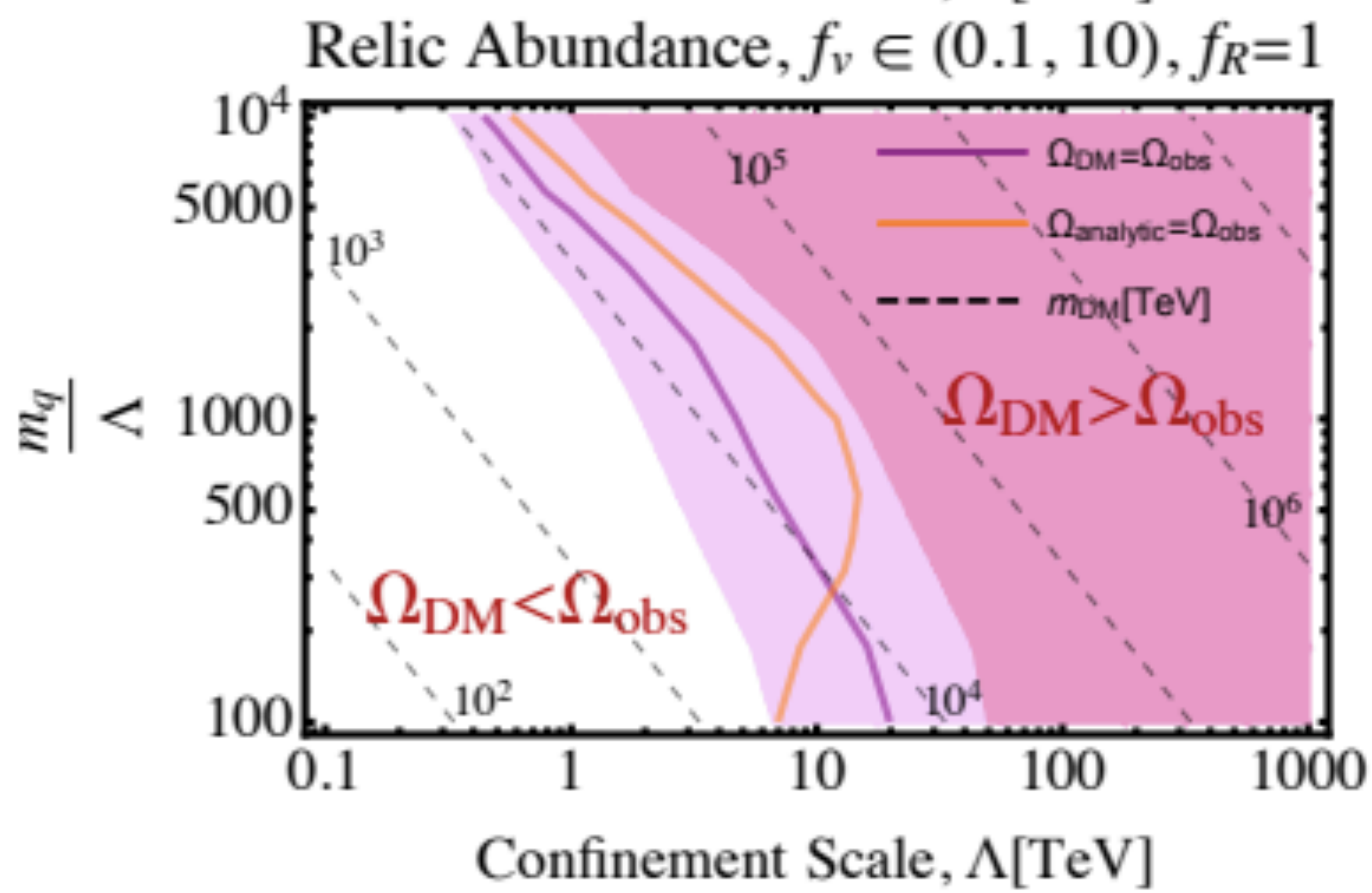


- We can calculate the relic density as a function of m_q and Λ, allowing for an order-of-magnitude variation in the pocket radius around our estimate
- We find preferred DM masses around 1-1000 PeV (also if we assume zero quark pressure)

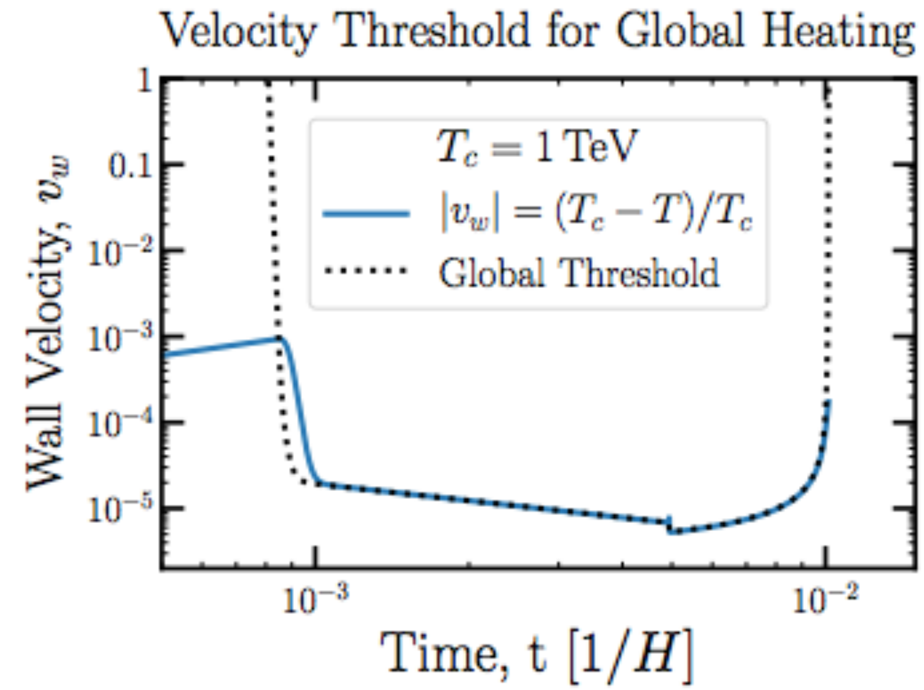
Relic density assuming zero quark pressure

- 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





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,

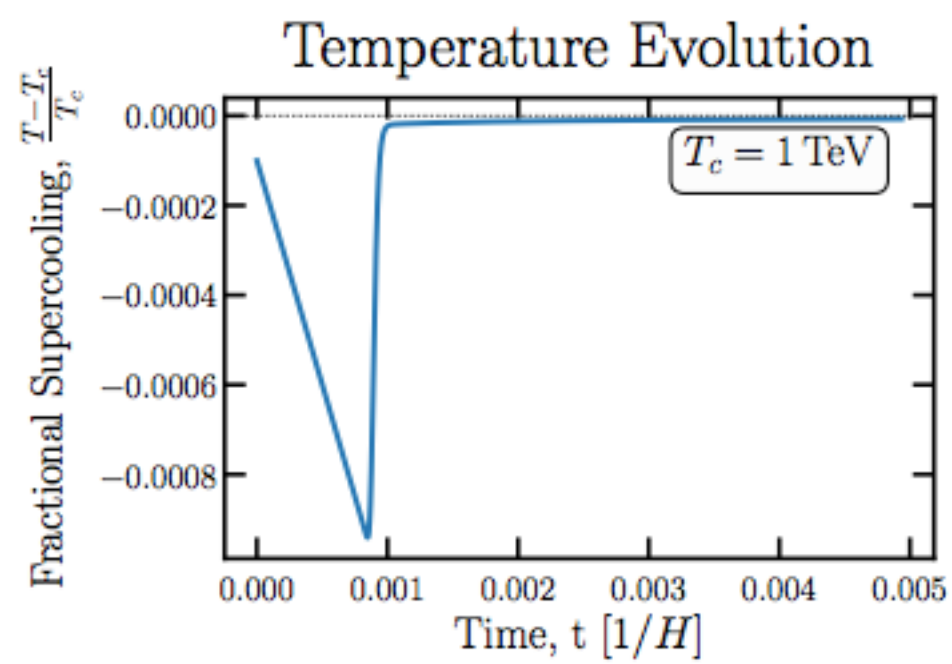
$$\dot{T}_{\mathrm{heat}} \sim \Lambda^2 v_w$$

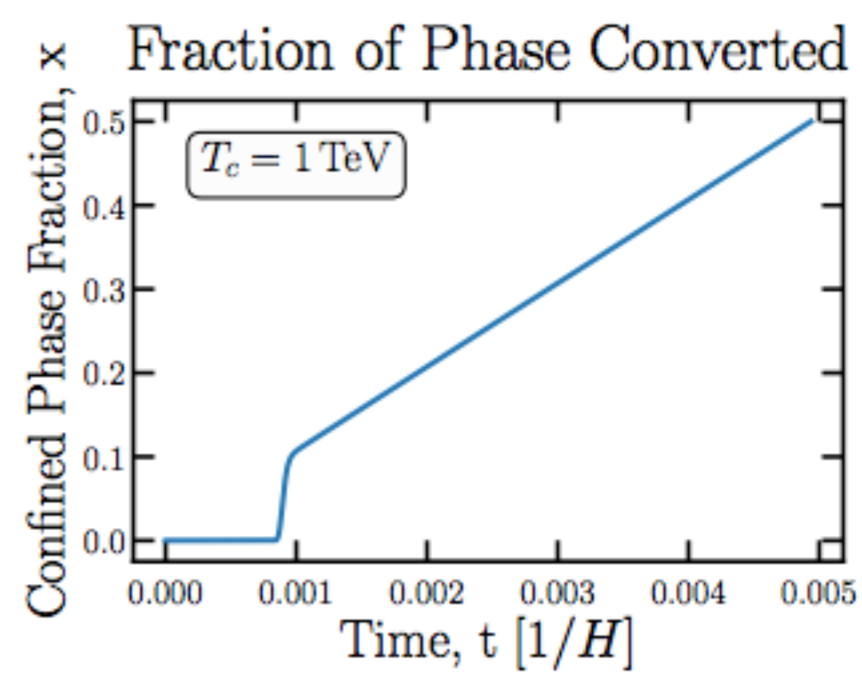
- Assume that the heat is diffused away through dark gluon bath outside the pocket, diffusion timescale controlled by Λ and by the difference of local & global temperatures:

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

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

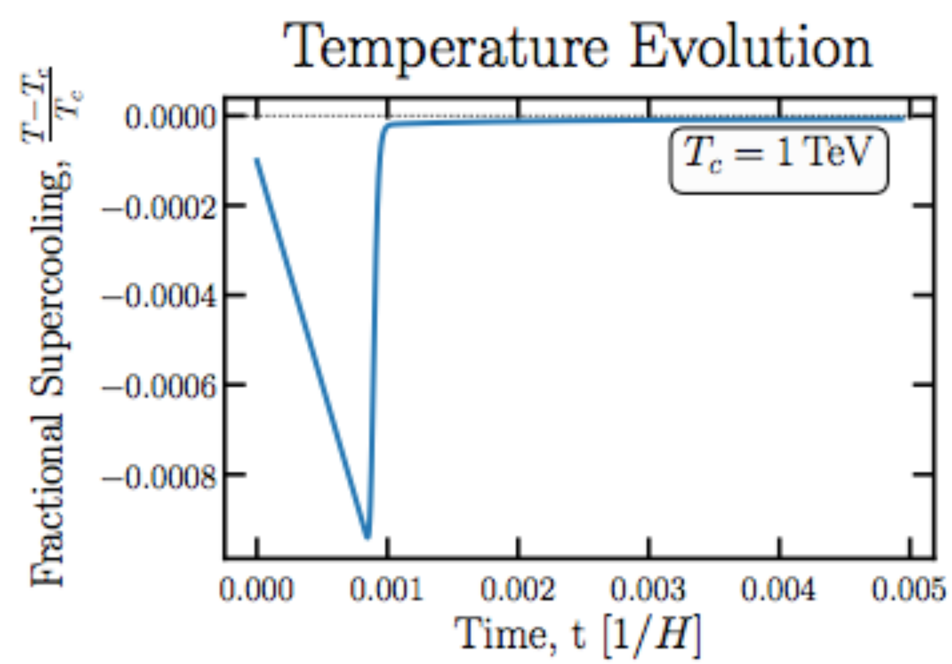
Temperature evolution during the phase transition

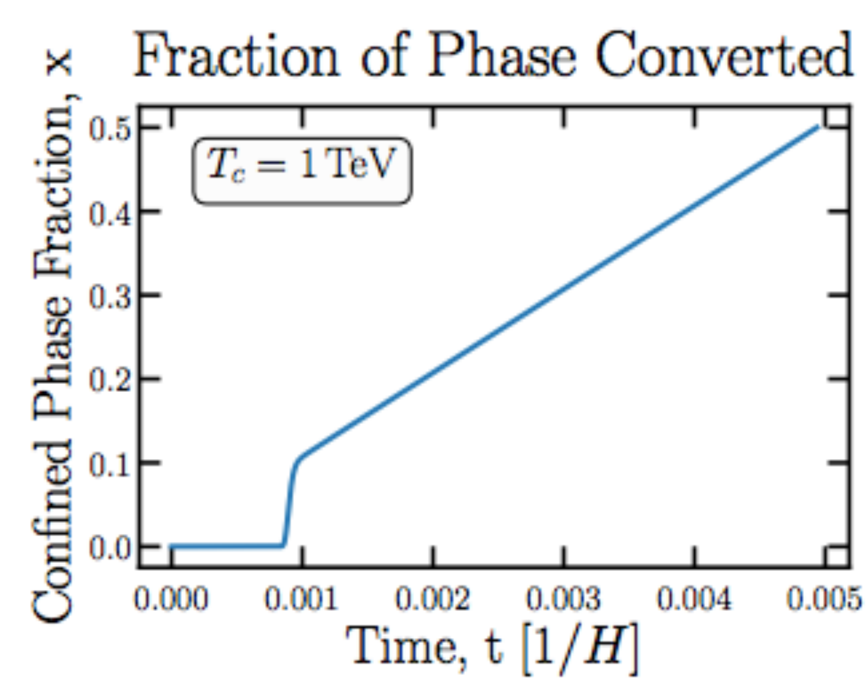




Temperature evolution during the phase transition

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





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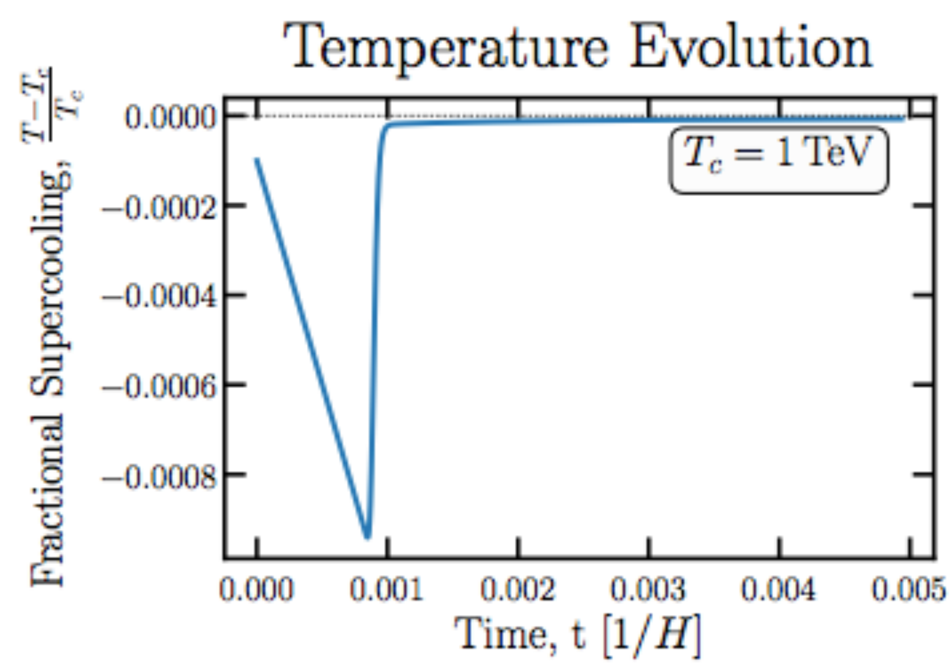
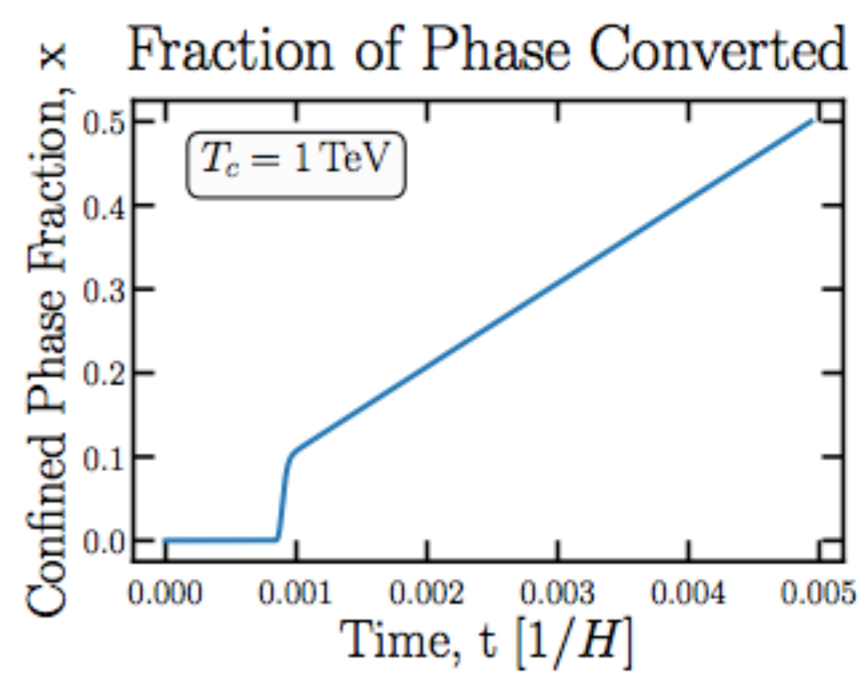
- Consequently there is little cooling due to expansion during the transition, but the bubble nucleation rate is very sensitive to any cooling below T_c





Temperature evolution during the phase transition

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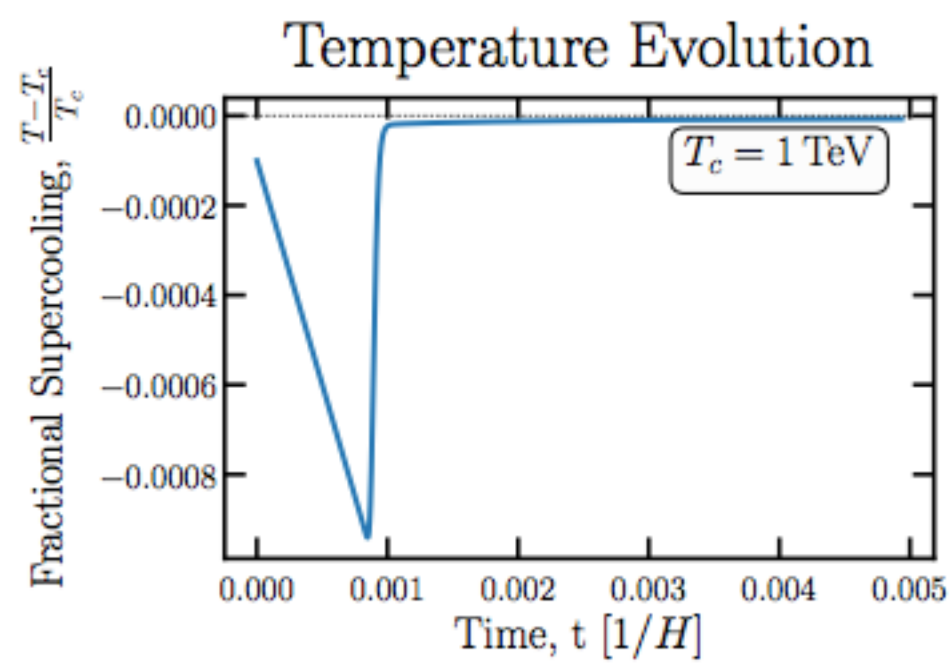
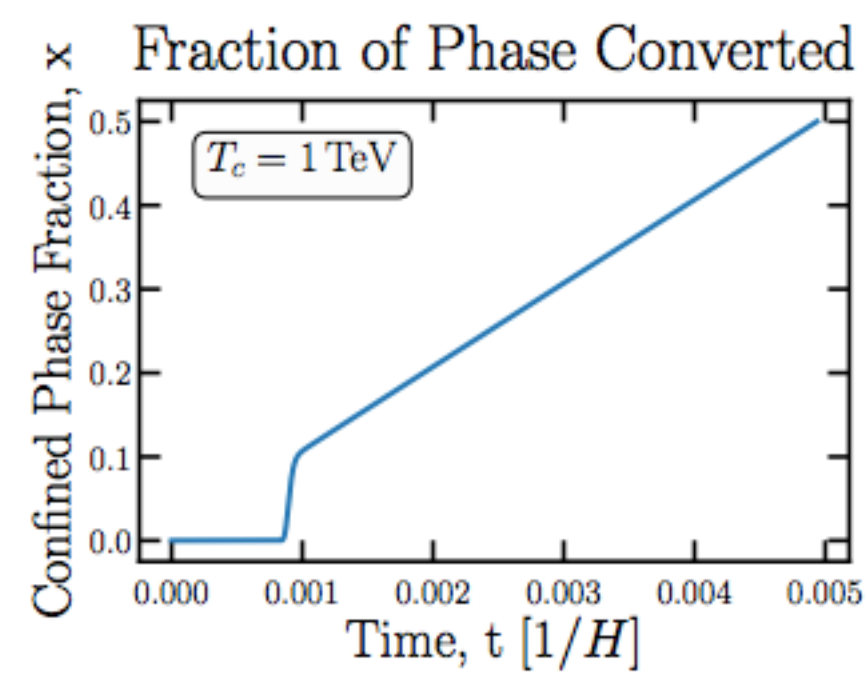
- Consequently there is little cooling due to expansion during the transition, but the bubble nucleation rate is very sensitive to any cooling below T_c
- Initial slight supercooling due to expansion leads to bubble nucleation → releases heat and reheats the cosmos back almost to T_c as the transition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





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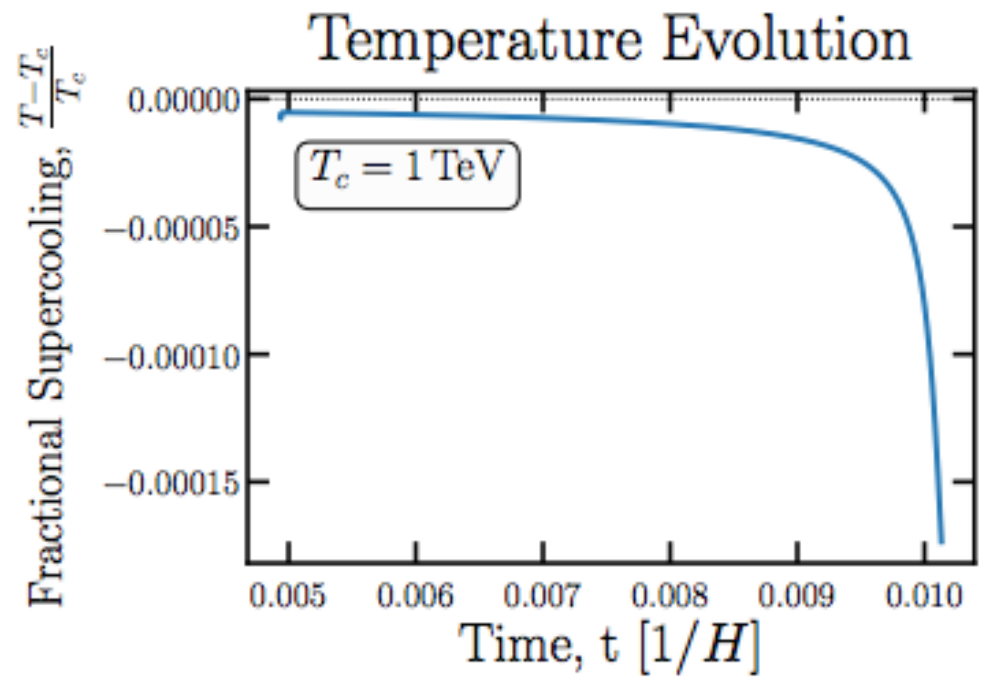

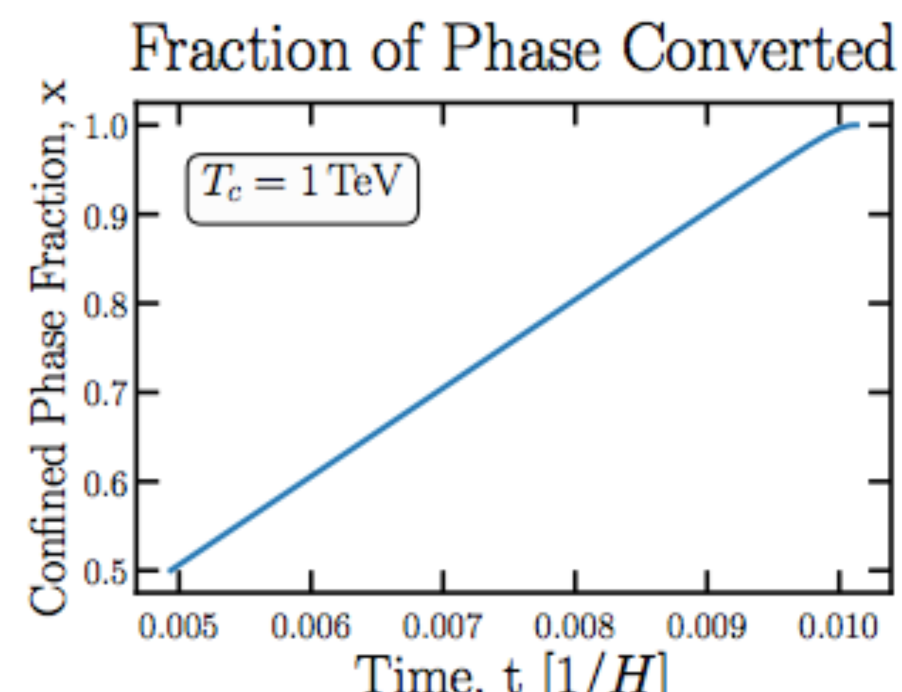

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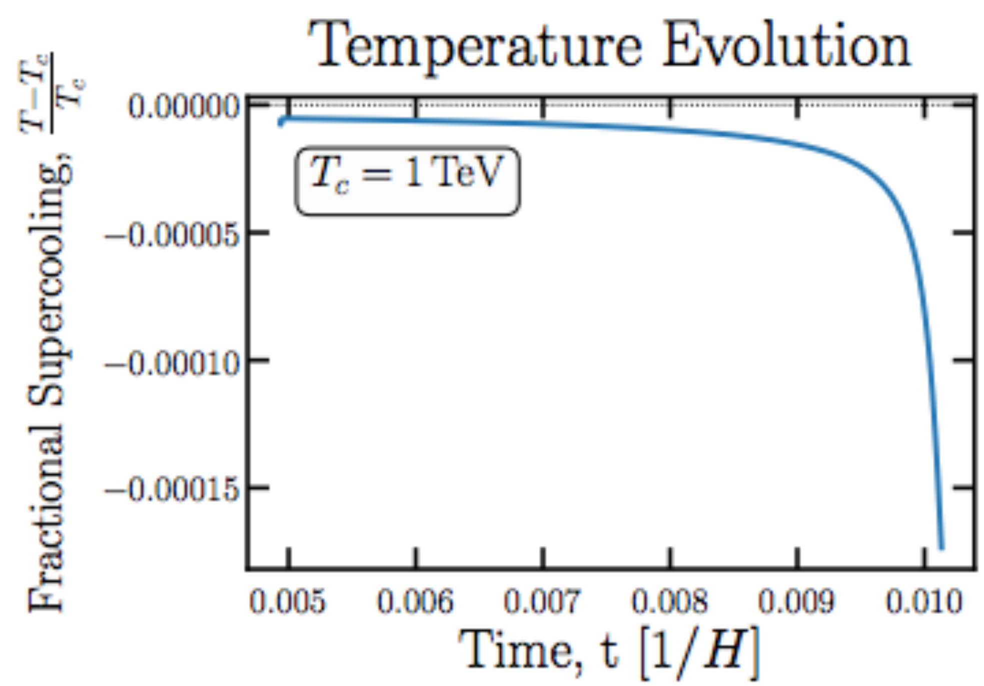
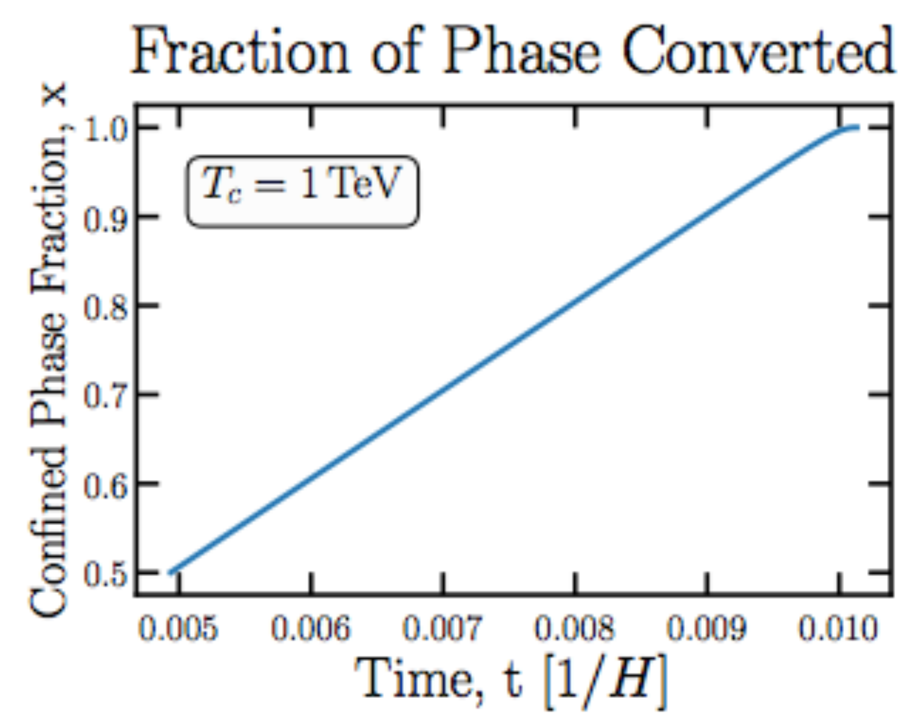
- Initial slight supercooling due to expansion leads to bubble nucleation → releases heat and reheats the cosmos back almost to T_c as the transition continues
- After percolation, the slowing rate of phase conversion means that Hubble cooling takes over again





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