

# Thermal Squeezeout of Dark Matter

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*Based on : 2103.09822, 2103.09827*

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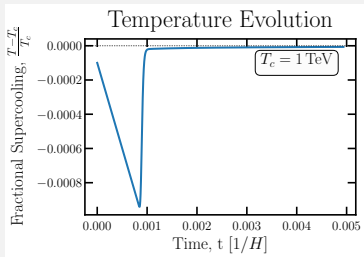
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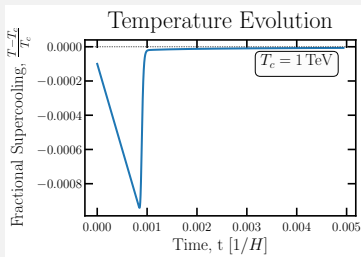
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- These models have been studied in the literature before. But the phase transition effect was (for the most part) overlooked.
- We look more closely at the phase transition epoch.

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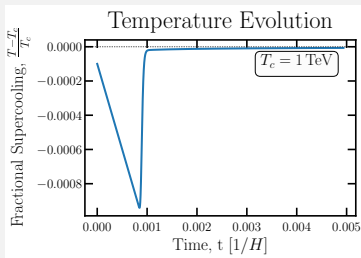


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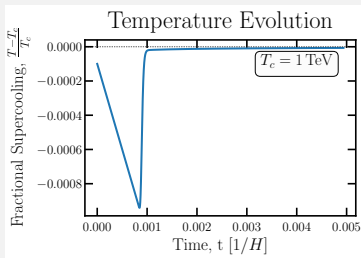
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- The universe slightly supercools; the confined phase becomes energetically favored; bubbles of the confined phase start nucleating.
- The latent heat is large enough that it can heat up the vicinity of the bubble back to  $T = \Lambda$ .

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- Once  $\mathcal{O}(1)$  fraction of the universe converts to the confined phase, the percolation happens.
- After the percolation the table is turned. Now we have isolated pockets of the deconfined phase in a sea of the confined phase.
- The pockets contract and eventually they disappear.

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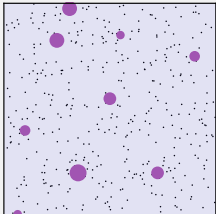
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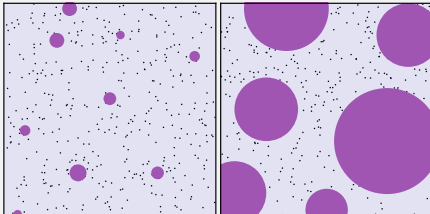
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- Upon running into a confined phase bubble, an isolated source of color feels an infinitely large potential barrier.
- Thus, the quark will always be pushed back into the deconfined phase. They can not enter the confined phase bubbles.

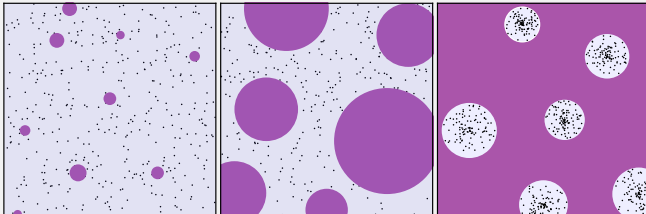
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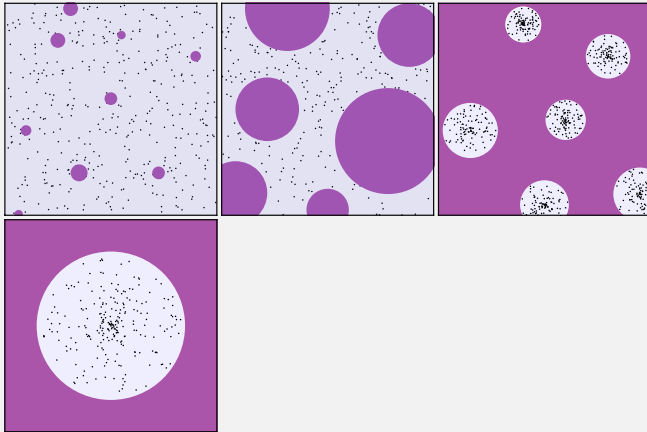
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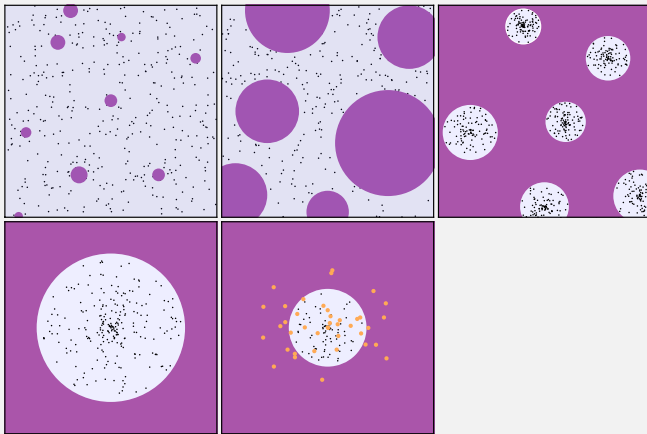
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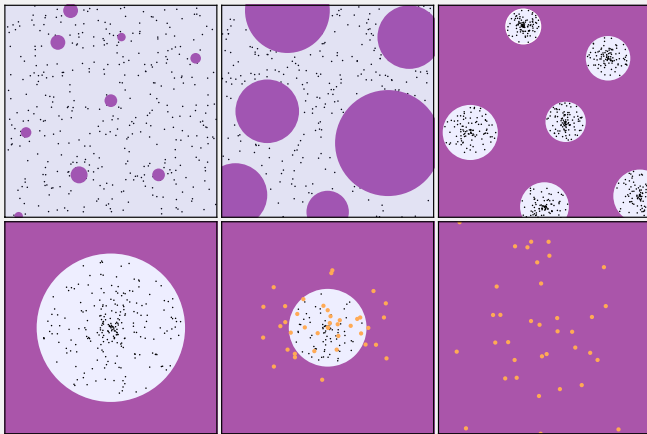


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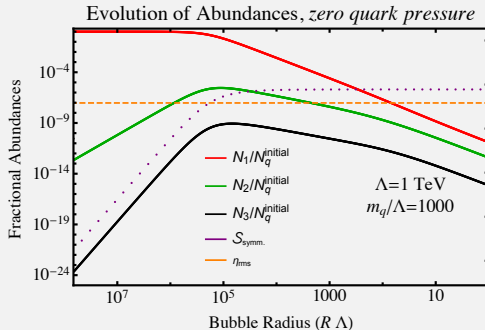
- Quarks either form color-neutral bound states or annihilate.
- Important to calculate the survival rate  $\mathcal{S} \equiv \frac{N_q^{\text{survived}}}{N_q^{\text{initial}}}$ .

## Evolution of the Relics in a Pocket

- We solve a set of Boltzmann equations for the trapped relics in the contracting pockets.

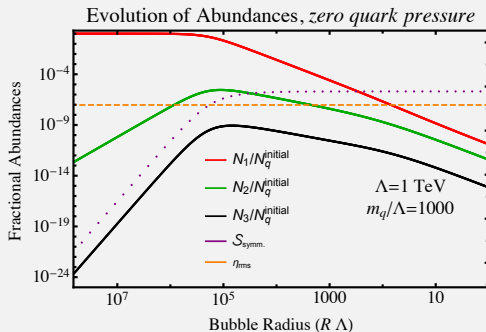
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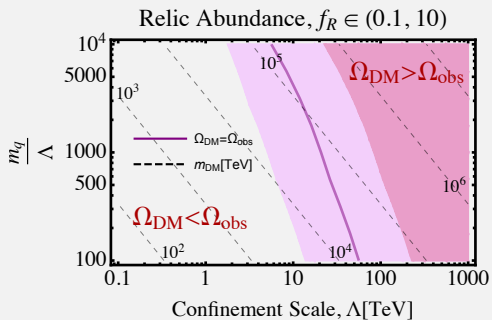
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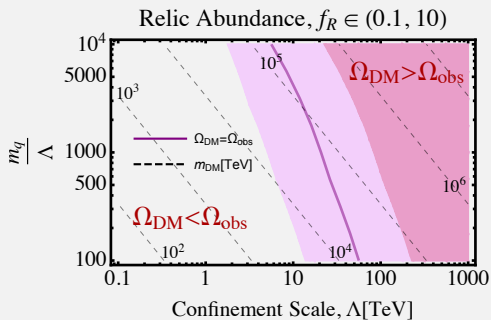
- The solution allows us to calculate the survival factor.

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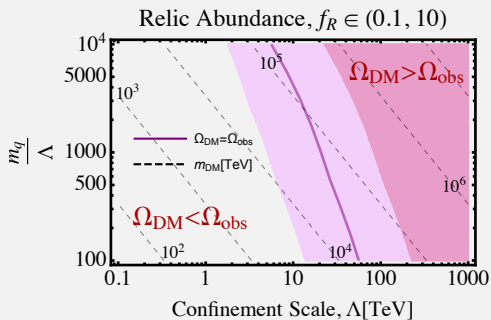


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- All in all,  $\mathcal{O}(\text{PeV}) \lesssim m_{\text{DM}} \lesssim \mathcal{O}(100\text{PeV})$ .

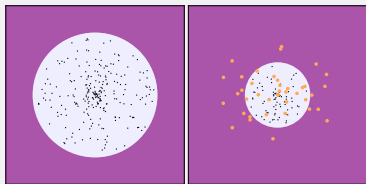
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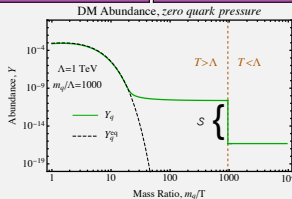
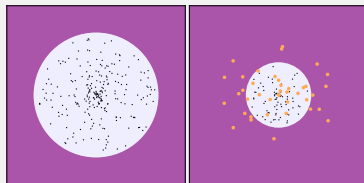
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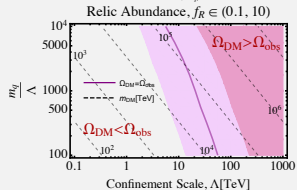
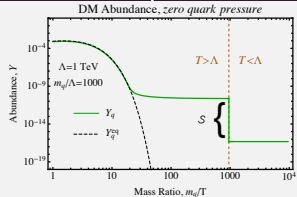
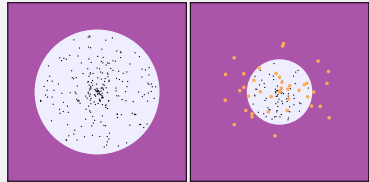
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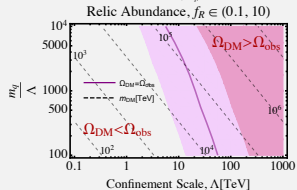
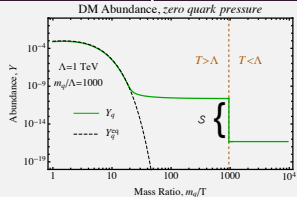
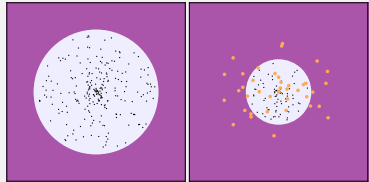
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- A confining dark sectors; heavy quarks; conserved baryon number.
- A second stage of annihilation thanks to the phase transition: DM Squeezeout
- $\mathcal{O}(1) \lesssim \frac{m_{\text{DM}}}{\text{PeV}} \lesssim \mathcal{O}(100)$ .
  - THANK YOU!



# Back up

- Thermodynamical Parameters
- More on  $v \sim \epsilon$
- More on  $R_0, R_1$  and their derivation
- More on the Bubble Dynamics
- Lattice Results on Quark Potential
- String Breaking
- Accidental Pocket Asymmetry
- Full Boltzmann Equations
- Discussing the Results
- Cross Sections
- Analytic Approximation
- Phenomenology

# Thermodynamics of Bubbles

$$f_{\text{deconf}} = f_{\text{conf}}$$

$$f = -p, \quad \rho = Ts - p$$

$$\Delta\rho = T_c \Delta s \equiv l, \quad l = 1.413 T_c^4, \quad \sigma = .02 T_c^3$$

$$\Delta f = l \frac{(T_c - T)}{T_c}$$

Total free energy of bubbles at critical radius:

$$F_c = \frac{16\pi}{3} \left( \frac{\sigma}{T_c^3} \right)^3 \left( \frac{l}{T_c^4} \right)^{-2} \frac{T_c^3}{(T_c - T)^2}$$

$$\Gamma = AT_c^4 e^{-\frac{\kappa T_c^2}{(T_c - T)^2}}$$

$$\kappa = \frac{16\pi}{3} \left( \frac{\sigma}{T_c^3} \right)^3 \left( \frac{l}{T_c^4} \right)^{-2} \sim 7 \times 10^{-5}$$

$v_w$ 

Assuming the wall is at  $T = T_c$ , the cooling rate will be

$$\dot{T}_{\text{cool}} \sim -K \nabla^2 T \sim -\Lambda^2 \frac{T_c - T}{T_c} \sim -\Lambda^2 \epsilon$$

$$\dot{T}_{\text{heat}} \sim \frac{1}{C} \times \frac{dE}{dt} \left( \frac{d\rho}{dT} \right)^3 \times l \Lambda v_w \Lambda^2 v_w$$

$$\dot{T}_{\text{heat}} \sim -\dot{T}_{\text{cool}} \implies v_w \sim \epsilon$$

# $R_i$

When two bubbles merge, they keep their volume fixed but turn into a another spherical bubble. The associated energy difference is:

$$\Delta E \sim 4\pi R^2(2 - 2^{\frac{2}{3}})\sigma = 4\pi R^2(2 - 2^{\frac{2}{3}}) \times .02 T_c^3$$

$$F \sim \Delta E/R \sim Ma \sim MR/t_{\text{coalesce}}^2, \quad M \sim \frac{8\pi}{3} R^3 T_c^4$$

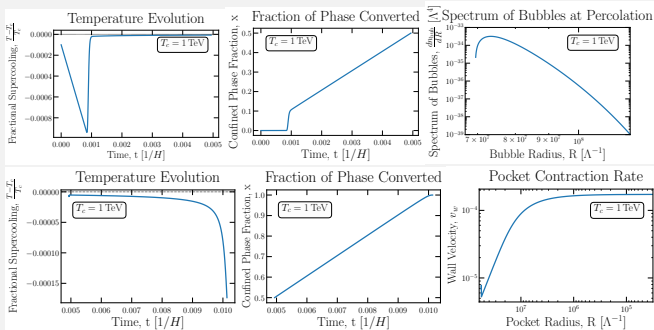
$$t_{\text{perc}} \sim 10^{-3} H^{-1} \sim 10^{-3} \frac{M_{pl}}{\Lambda^2}$$

$$t_{\text{coalesce}} \sim t_{\text{perc}} \implies R_i \Lambda \sim 10^{-8/3} \left( \frac{M_{pl}}{\Lambda} \right)^{2/3}$$

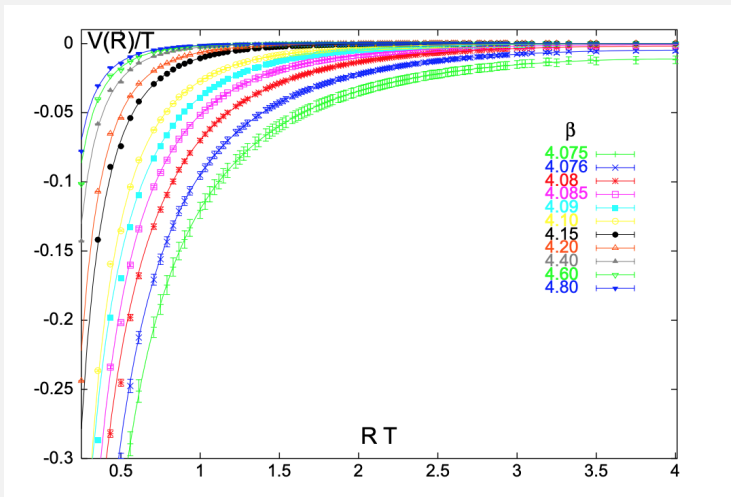
# More on Bubble Dynamics

$$x(t) = \int_{t_c}^t dt' \Gamma(t') \frac{4\pi}{3} R^3(t, t') (1 - x(t'))$$

$$\dot{T} = -HT + 10^{-2} T_c \dot{x}$$

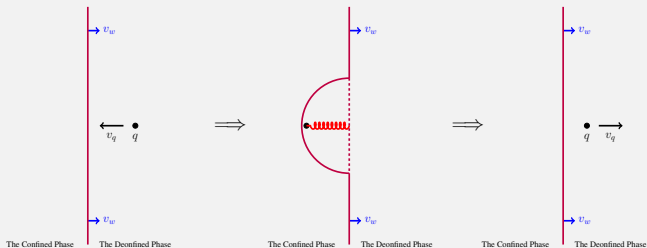


# Quark Potentials at High T



# Quarks and Confinement - String Breaking

- How can quark go inside the confined phase bubble? (1) running into other sources of color; (2) string breaking.



$$(\tau_{\text{string}})^{-1} \sim \frac{m_q}{4\pi^3} e^{-m_q^2/\Lambda^2}$$

- $t_{\text{PT}} \sim 10^{-2}/H$  for the transition to complete.  $t_{\text{PT}} \ll \tau_{\text{string}}$  for masses we will consider.
- Thus, quarks are trapped inside contracting pockets and are brought back into interaction.

# Pockets Accidental Asymmetry

- The wall runs into either particles or anti-particles randomly.
- The net baryon number in each pocket is a Gaussian random variable with zero mean.
- If the total number of particles (quarks + anti-quarks) is  $N_q^{initial}$ , the asymmetry is roughly  $\sqrt{N_q^{initial}}$ .
- This accidental asymmetry puts a lower bound on the survival rate:

$$S \geq \eta_{\text{rms}} \equiv \frac{1}{\sqrt{N_q^{initial}}}$$

- $N_q^{initial}$  can be calculated using the pocket's initial radius after the percolation and the quarks' number density from before confinement.

# Boltzmann Equations Governing the Compression

- The pocket walls only constrain colored relics and modify the their Liouville operators.
- We can list all  $2 \leftrightarrow 2$  collision terms using the conservation of baryon numbers in the interactions.

State	Dark Quark Number	Color Rep.
Gluons	0	8
Quark	1	3
Diquark	2	$\bar{3}$
Baryon	3	1

$$L[i] = - \sum_{a+b=c+d} s_{a,b,c,d}^i \langle \sigma v \rangle_{ab \rightarrow cd} \left( n_a n_b - n_c n_d \frac{n_a^{eq} n_b^{eq}}{n_c^{eq} n_d^{eq}} \right)$$

# Boltzmann Equations

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

$$\begin{aligned}
 L[i] &= -\frac{v_w}{V} N'_i, \quad i = 1, 2, \\
 L[3] &= -\frac{v_w}{V} \left( N'_3 - \frac{3}{R} \frac{v_q + v_w}{v_w} N_3 \right),
 \end{aligned}$$

# Relevant Quantities

- Relevant quantities from the phase transition : pocket wall and quark velocities, pocket radius, initial particle density in the pocket.

$$v_w \sim \epsilon, \quad v_q \sim \sqrt{\frac{\Lambda}{m_q}}, \quad R_1 \Lambda \sim 10^{-8/3} \left( \frac{M_{\text{pl}}}{\Lambda} \right)^{2/3}$$

- Other relevant quantities : cross sections, binding energies.
- These are calculated earlier in the literature. They are calculated accurately enough.
- We can now write down and solve the Boltzmann equations for trapped quarks.

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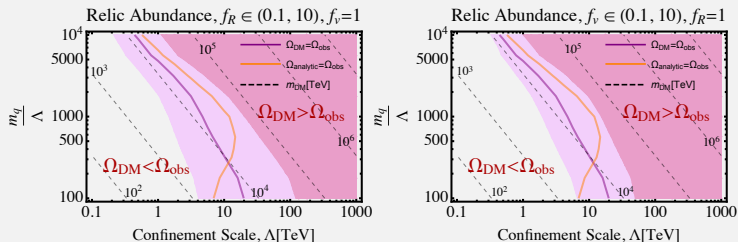
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$$\mathcal{S}_{\text{symm.}} = \frac{3 \int dN_3^{\text{esc}}}{N_q^{\text{initial}}} = \frac{9}{N_1(R_i)} \int dR \frac{v_q + v_w}{v_w R} N_3(R)$$

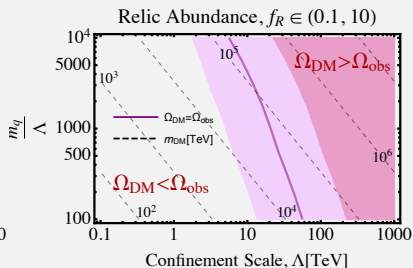
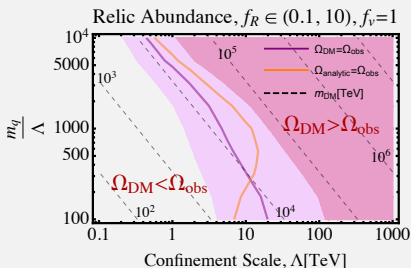
# The Results



- We vary  $R_1$ ,  $v_w$  by an order of magnitude just to parametrize the uncertainties.
- The available parameter space is very similar to the case with saturated asymmetry.

# The Results

- Lower velocity, lower survival factor.
- Including the quark pressure means lowering the velocity, hence lower survival factor.
- The lowest survival factor was given by the asymmetry bound.
- Once quark pressure included, the available parameter space will be between these two cases.



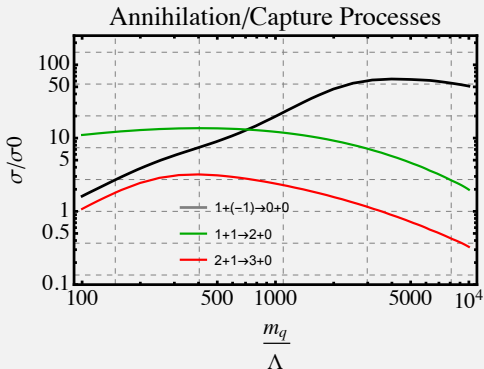
# Cross Sections

Class	Process
Annihilation	$1 + (-1) \rightarrow 0 + 0$
Capture	$1 + 1 \rightarrow 2 + 0$ $2 + 1 \rightarrow 3 + 0$
Rearrangement	$(-3) + 1 \rightarrow (-1) + (-1)$ $(-3) + 1 \rightarrow (-2) + 0$ $(-2) + 1 \rightarrow (-1) + 0$ $3 + (-2) \rightarrow 1 + 0$ $2 + 2 \rightarrow 3 + 1$ $3 + (-2) \rightarrow 2 + (-1)$ $3 + (-3) \rightarrow 2 + (-2)$ $2 + (-2) \rightarrow 1 + (-1)$ $3 + (-3) \rightarrow 1 + (-1)$ $3 + (-3) \rightarrow 0 + 0$ $2 + (-2) \rightarrow 0 + 0$

# Cross Sections

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

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



# Analytic Approximation

$$-\frac{v_w}{V} N_1' = -\langle (1, -1) \rightarrow (0, 0) \rangle - 2\langle (1, 1) \rightarrow (2, 0) \rangle - \langle (2, 1) \rightarrow (3, 0) \rangle \\ + \langle (2, -1) \rightarrow (1, 0) \rangle,$$

$$-\frac{v_w}{V} N_2' = -\langle (2, -2) \rightarrow (0, 0) \rangle - \langle (2, 1) \rightarrow (3, 0) \rangle + 2\langle (1, 1) \rightarrow (2, 0) \rangle.$$

$$-\frac{v_w}{V} N_3' = -\langle (3, -3) \rightarrow (0, 0) \rangle - \langle (3, -1) \rightarrow (2, 0) \rangle + \langle (2, 1) \rightarrow (3, 0) \rangle$$

$$R_{\text{rec}} = \sqrt{\frac{3N_q^{\text{initial}} \langle \sigma v \rangle_{1(-1) \rightarrow \infty}}{(4\pi v_w)}}$$

$$\mathcal{S}_{\text{symm.}} \approx 9 \frac{v_q}{v_w} \frac{4\pi v_w^3}{3\tilde{f}_1^2 N_q^{\text{initial}} \langle \sigma v \rangle_{1(-1) \rightarrow \infty}^3}$$

# Overview of Phenomenology

- Gravitational waves.
- The glueballs and the mesons can give rise to interesting signals if long-lived enough.
- The baryons can give rise to interesting direct and indirect detection signals.
- The de-excitation signal in indirect detection experiments.
- Dark matter trapped in astrophysical objects.
- Further studies are well motivated.