Thermal Squeezeout of Dark Matter

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Based on : 2103.09822, 2103.09827
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- Such a sector has a first order phase transition.
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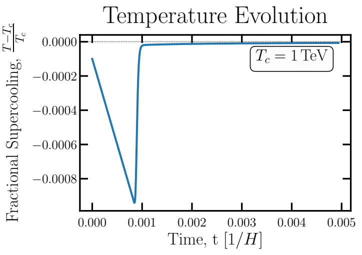
- We look more closely at the phase transition epoch.

Phase Transition - Before Percolation



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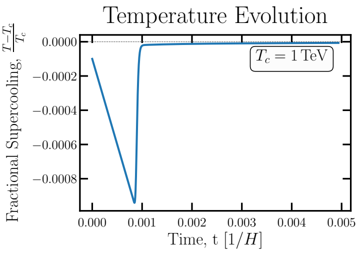

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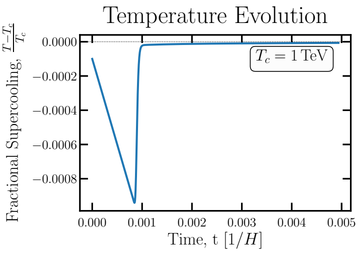

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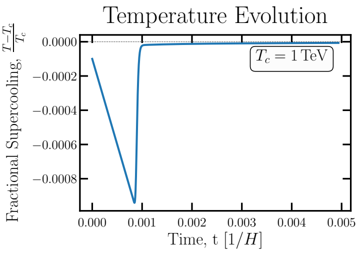

- When we reach $T = \Lambda$, the free energy of the confined and the deconfined phase become equal.
- The universe slightly supercools; the confined phase becomes energetically favored; bubbles of the confined phase start nucleating.
- The latent heat is large enough that it can heat up the vicinity of the bubble back to $T = \Lambda$.

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Phase Transition - After Percolation

- 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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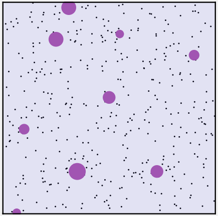
- Lattice studies show that they dont feel each others presence; each quark thinks it's alone in a deconfined universe.
- Upon running into a confined phase bubble, an isolated source of color feels an infinitely large potential barrier.
- Thus, the quark will always be push backed into the deconfined phase. They can not enter the confined phase bubbles.

DM Squeezeout



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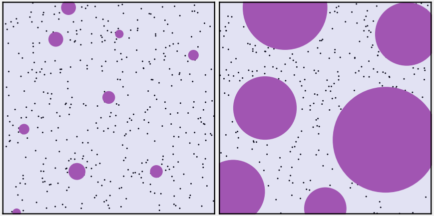

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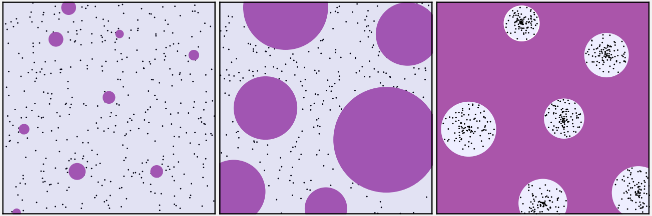

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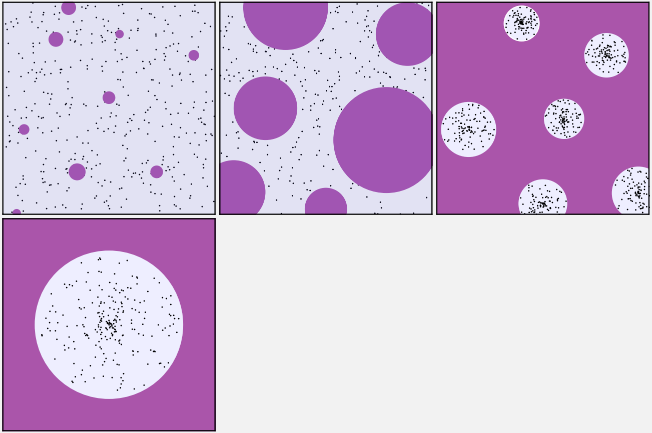

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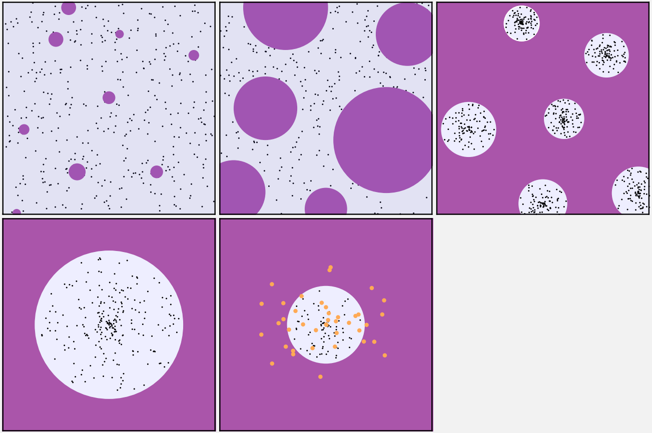

- Quarks either form color-neutral bound states or annihilate.

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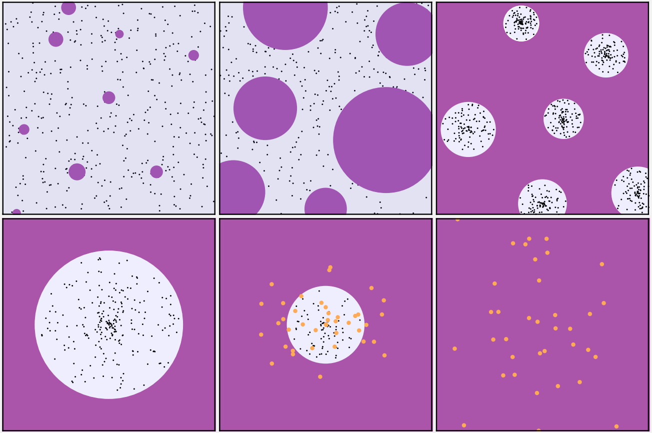

- Quarks either form color-neutral bound states or annihilate.
- Important to calculate the survival rate $\mathcal{S} \equiv \frac{N_q^{\text{survived}}}{N_q^{initial}}$.

Evolution of the Relics in a Pocket

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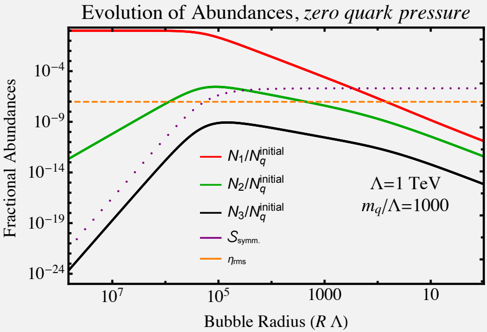

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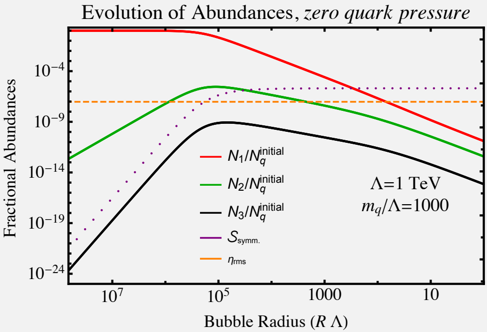

- The solution allows us to calculate the survival factor.

Available Parameter Space

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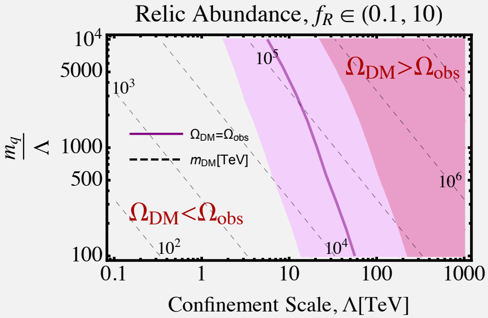

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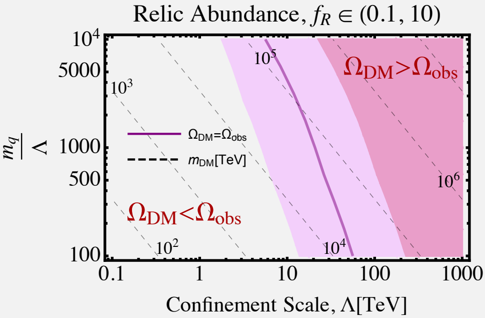

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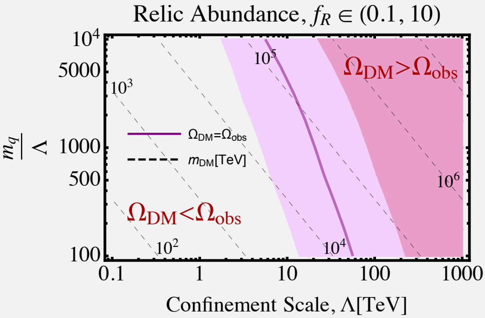

- Purple region characterizes the uncertainty in our results.
- All in all, $\mathcal{O}(\mathrm{PeV}) \lesssim m_{\mathrm{DM}} \lesssim \mathcal{O}(100\mathrm{PeV})$.

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- A confining dark sectors; heavy quarks; conserved baryon number.

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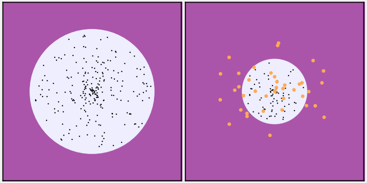

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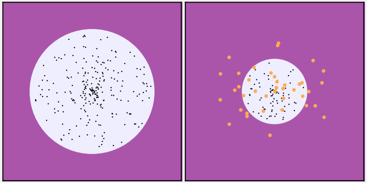

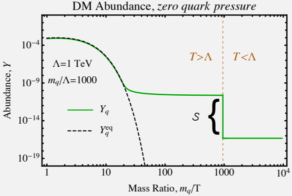

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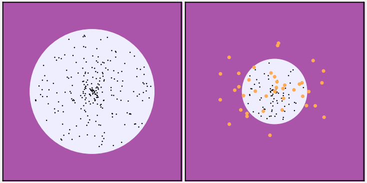
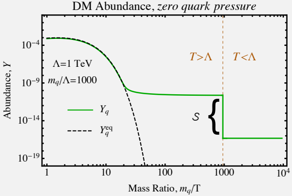
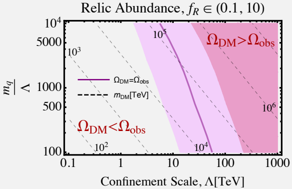
- A confining dark sectors; heavy quarks; conserved baryon number.
- A second stage of annihilation thanks to the phase transition: DM Squeezeout
- $\mathcal{O}(1) \lesssim \frac{m_{\rm DM}}{\rm PeV} \lesssim \mathcal{O}(100)$.







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- A second stage of annihilation thanks to the phase transition: DM Squeezeout
- $\mathcal{O}(1) \lesssim \frac{m_{\rm DM}}{\rm PeV} \lesssim \mathcal{O}(100)$.
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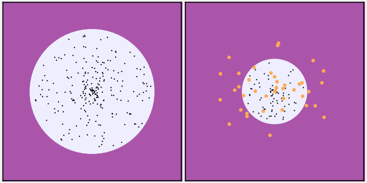
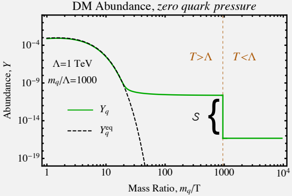
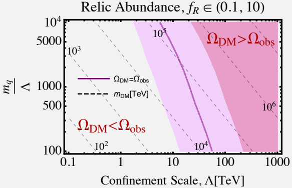






Back up

- 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

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

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

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

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

Total free energy of bubbles at critical radius:

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

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

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

v_w

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

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

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

$$\dot{T}_{\mathrm{heat}} \sim -\dot{T}_{\mathrm{cool}} \Longrightarrow v_w \sim \epsilon$$

R_i

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

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

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

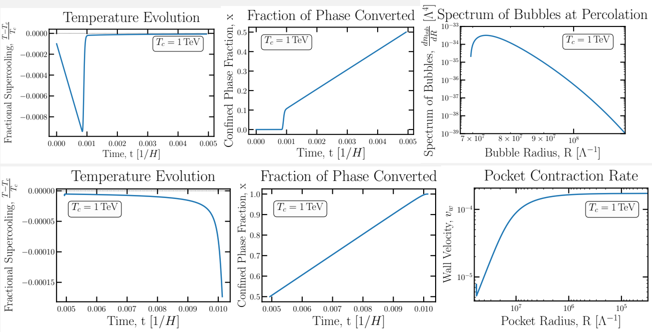
$$t_{\rm perc} \sim 10^{-3} H^{-1} \sim 10^{-3} \frac{M_{pl}}{\Lambda^2}$$

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

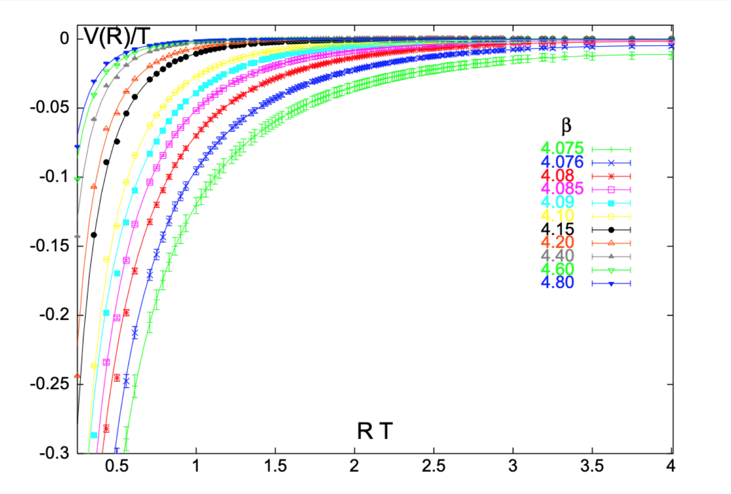
More on Bubble Dynamics

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

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

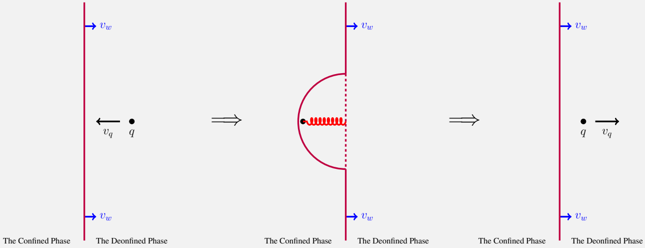


Quark Potentials at High T



Quarks and Confinement - String Breaking

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



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

- $t_{\rm PT} \sim 10^{-2}/H$ for the transition to complete. $t_{\rm PT} \ll \tau_{\rm string}$ 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:

$$\mathcal{S} \geqslant \eta_{\rm rms} \equiv \frac{1}{\sqrt{N_q^{initial}}}$$

- $N_q^{initial}$ can be calculated using the pockets 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

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

Boltzmann Equations

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

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

Relevant Quantities

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

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

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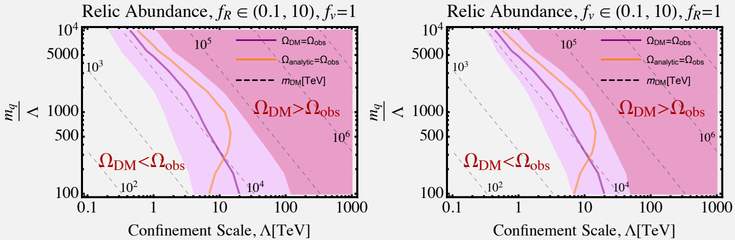
$$\mathcal{S}_{\rm symm.} = \frac{3\int dN_3^{\rm esc}}{N_q^{\rm initial}} = \frac{9}{N_1(R_i)} \int dR \frac{v_q + v_w}{v_w R} N_3(R)$$

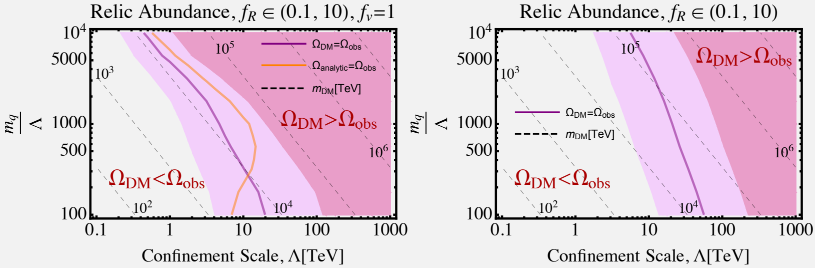
The Results



- 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	$1 + (-1) \to 0 + 0$
Capture	$1 + 1 \to 2 + 0$
	$2 + 1 \to 3 + 0$
Rearrangement	$(-3) + 1 \to (-1) + (-1)$
	$(-3) + 1 \to (-2) + 0$
	$(-2) + 1 \to (-1) + 0$
	$3 + (-2) \to 1 + 0$
	$2 + 2 \to 3 + 1$
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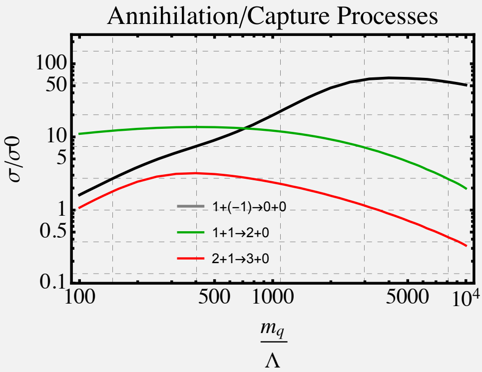
Cross Sections

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

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



Analytic Approximation

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

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

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

$$R_{\rm rec} = \sqrt{\frac{3 N_q^{\rm initial} \langle \sigma v \rangle_{1(-1)\to 00}}{(4\pi v_w)}}$$

$$\mathcal{S}_{\rm symm.} \approx 9 \frac{v_q}{v_w} \frac{4\pi v_w^3}{3 \tilde{f}_1^2 N_q^{\rm initial} \langle \sigma v \rangle^3_{1(-1)\to 00}} .$$

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.