Dark Matter from $SU(N)$ Confinement

The Particle Physics Meeting (RPP), LPTHE Sorbonne, 2024

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LAPTh, Annecy

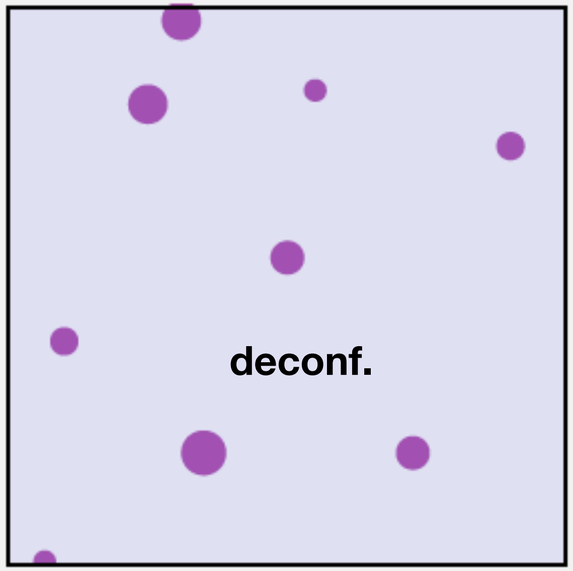
Yann Gouttenoire, Eric Kuflik, DL, arXiv: 2311.00029, PRD (TBA)

Outline:

- **Pure Yang-Mills FOPT**
- **YM+Heavy Quarks**
- **Squeezeout Dark Matter**
- **Boundary Effects**

$SU(N)$ Yang-Miles Phase Transition

$N \geq 3$: **First Order**



$$x \ll 1$$

$$T \sim \Lambda$$

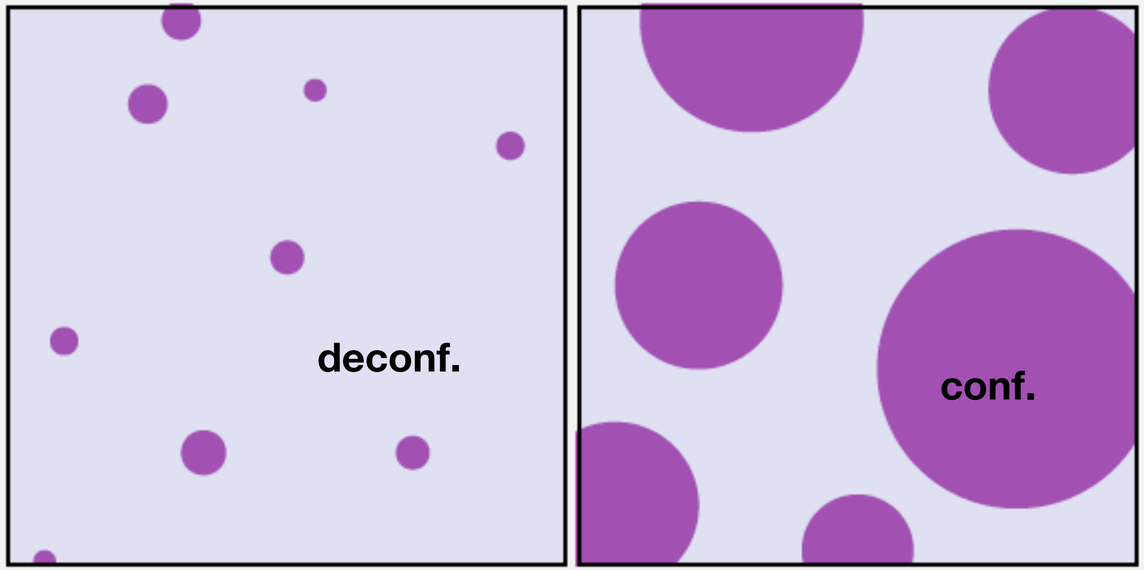
$$x = \frac{V_{\text{conf}}}{V_{\text{tot}}}$$

$$\dot{T} = -HT + \frac{LT}{4\rho}\dot{x}$$

Bubble Expansion: $\dot{R} > 0$

$$v_w = \dot{R} = \frac{\Lambda - T}{\Lambda}$$

$$\frac{dv_w}{dR} = \frac{H}{v_w} - \frac{3LR^2}{8\rho R_i^3}$$



$x \leq 1/2$

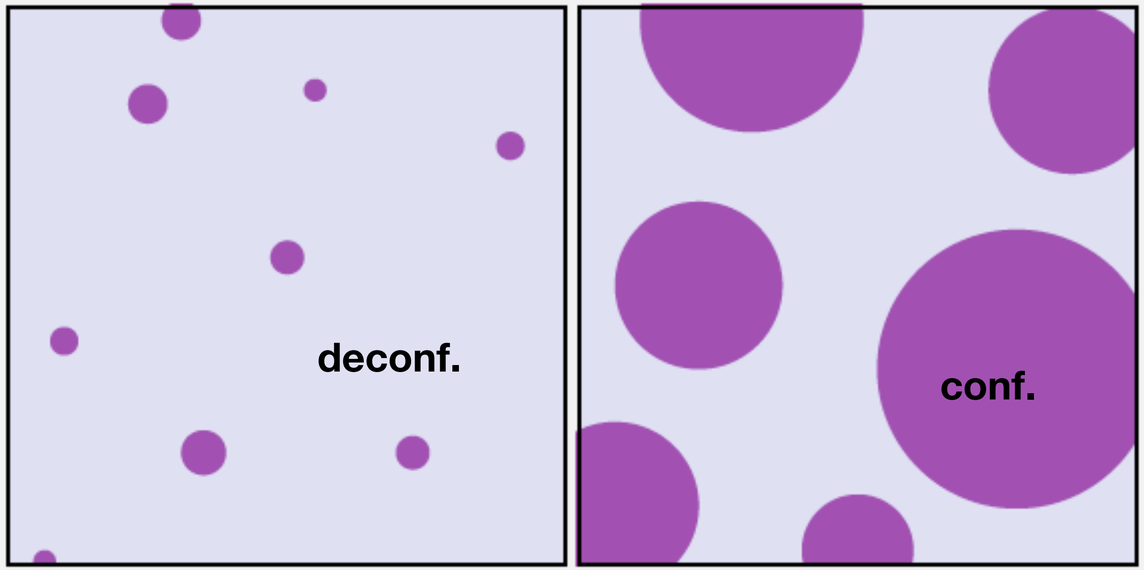
Bubble Expansion: $\dot{R} > 0$

$$v_w = \dot{R} = \frac{T - \Lambda}{\Lambda}$$

Asymptotic value $v_w = \text{const}$

$$\boxed{\frac{dv_w}{dR}} = \frac{H}{v_w} - \frac{3LR^2}{8\rho R_i^3}$$

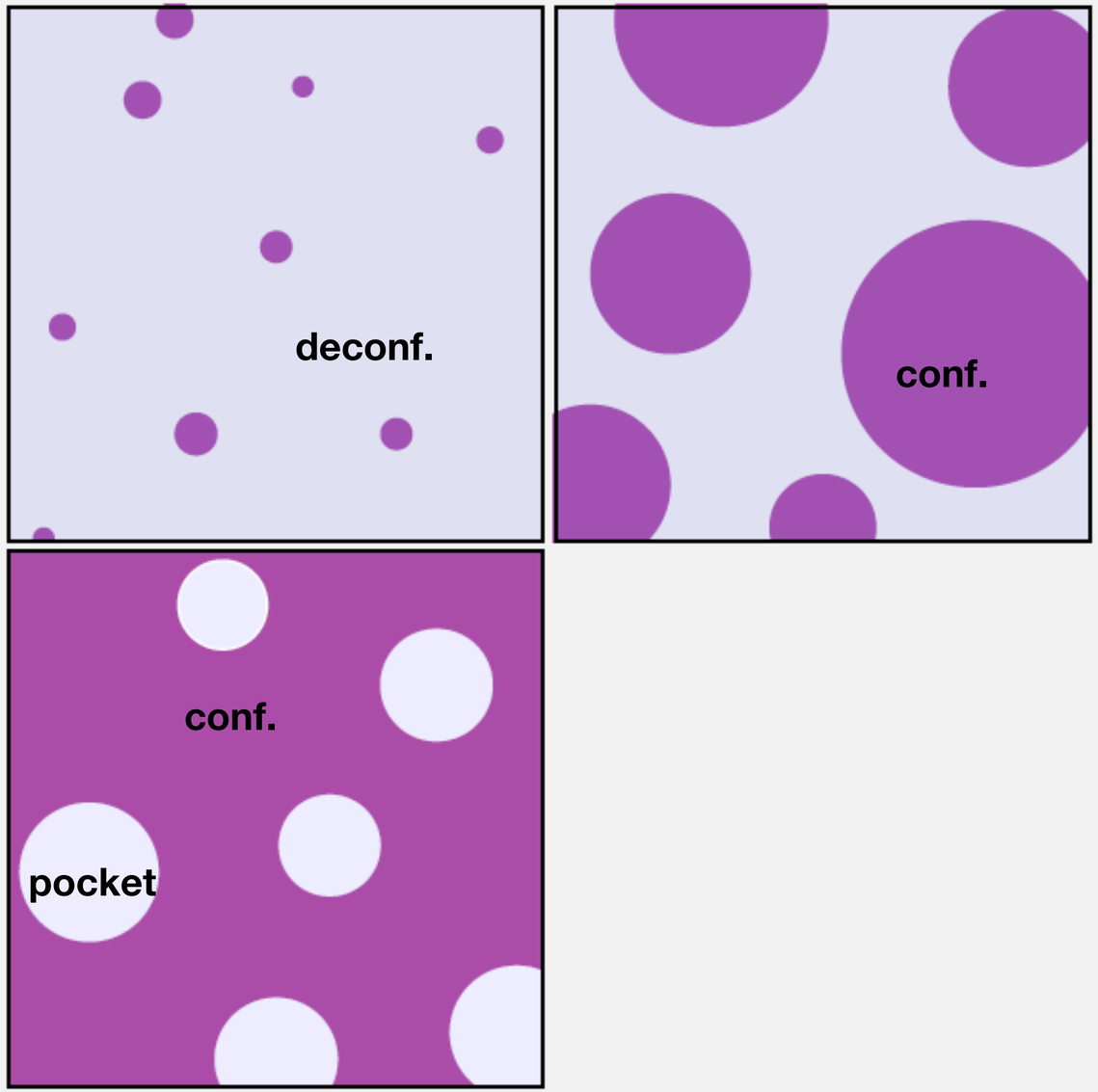
$$\boxed{\frac{dv_w}{dR}} \approx 0$$



$x \leq 1/2$

Pocket Contraction: $\dot{R} < 0$

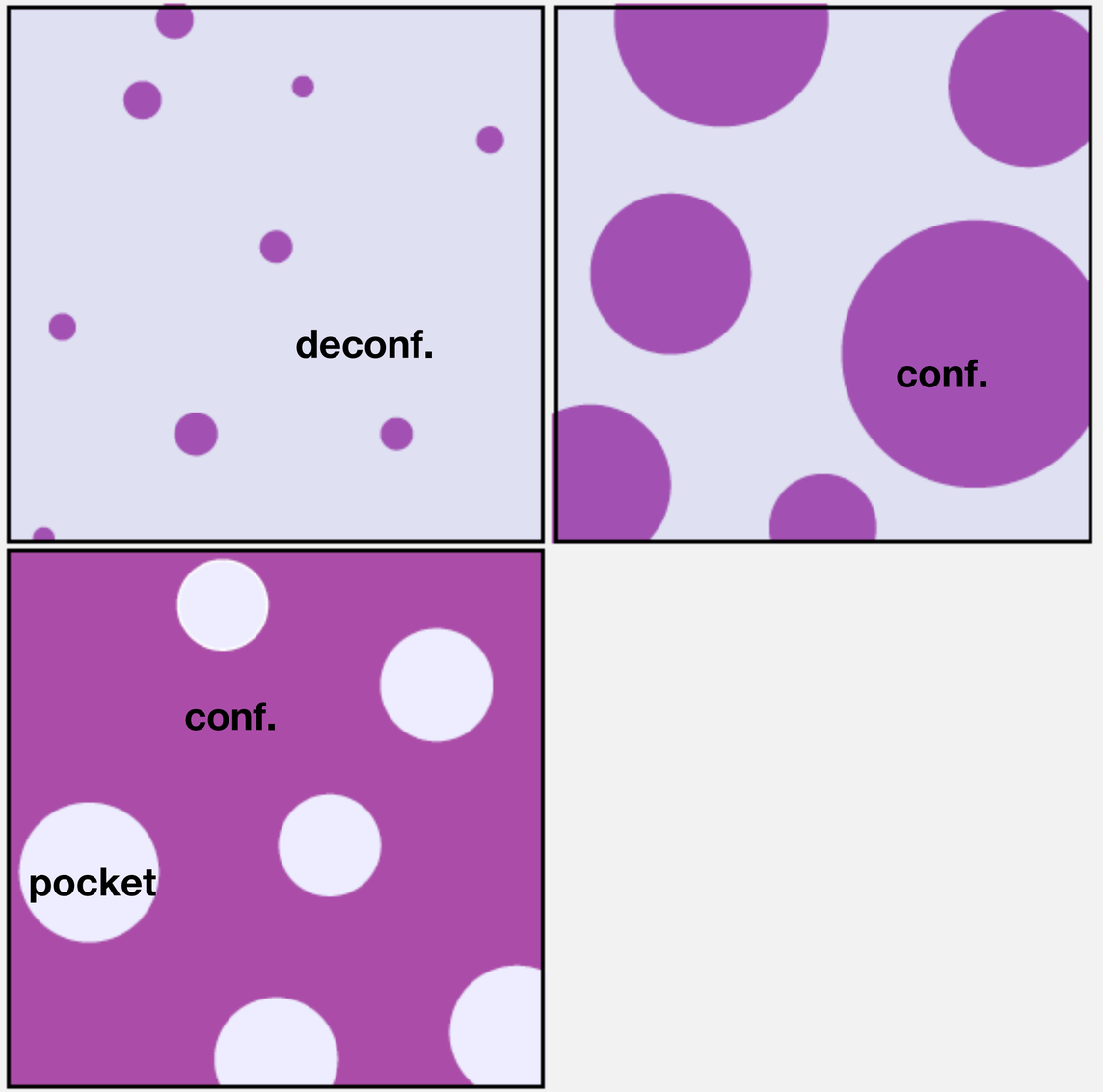
$$\frac{dv_w}{dR} = -\frac{H}{v_w} + \frac{3LR^2}{8\rho R_i^3}$$



$x > 1/2$

Pocket Contraction: $\dot{R} < 0$

$$\frac{dv_w}{dR} = -\frac{H}{v_w} + \boxed{\frac{3LR^2}{8\rho R_i^3}} \approx 0$$



$x > 1/2$

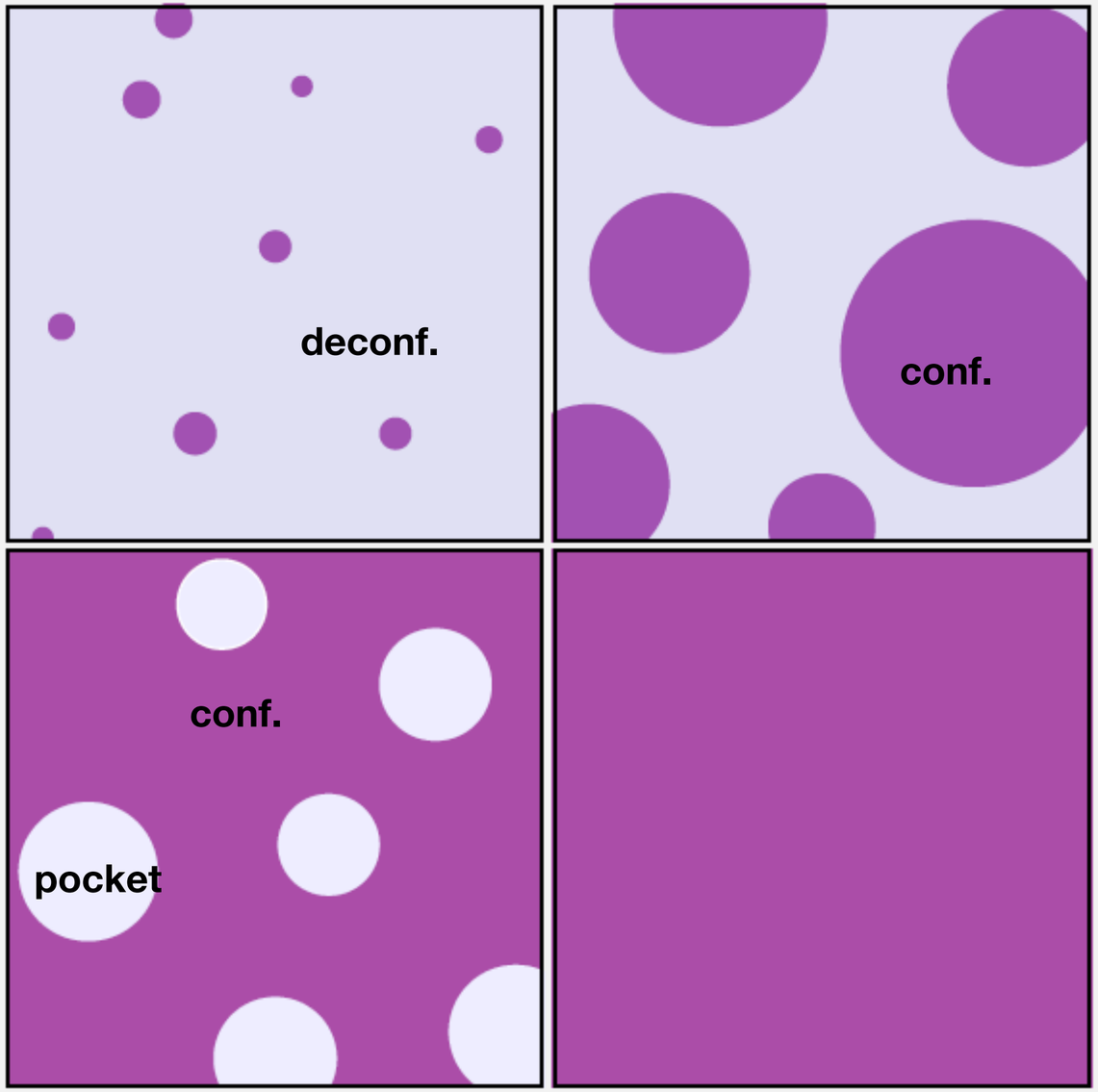
Bubble Expansion, $x \leq 1/2$

$$v_w \simeq 100 H R_i$$

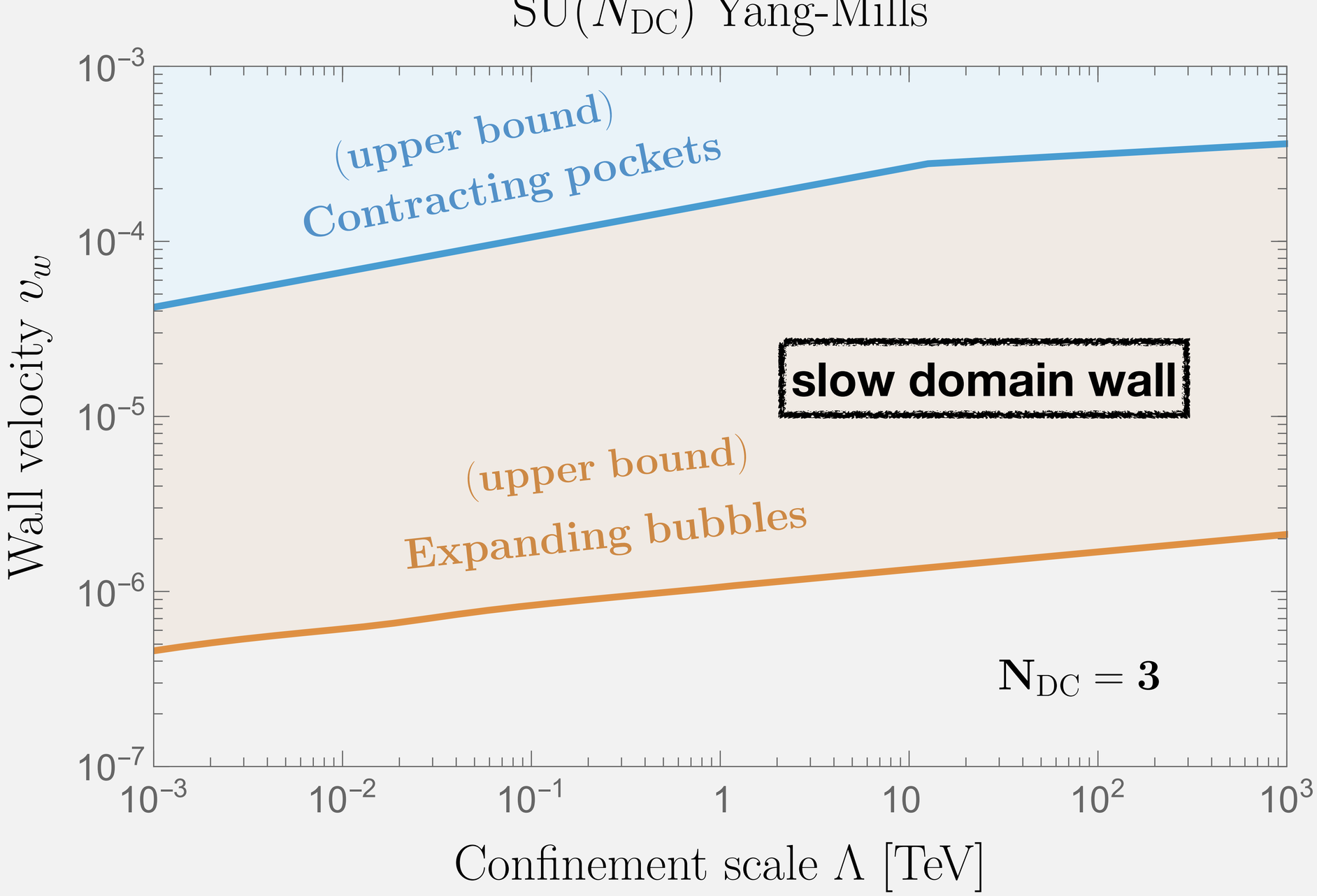
Pocket Contraction , $1/2 < x$

$$v_w \simeq 2\sqrt{2HR_f}$$

$$R_f \simeq 2H^{1/5} R_i^{6/5}$$

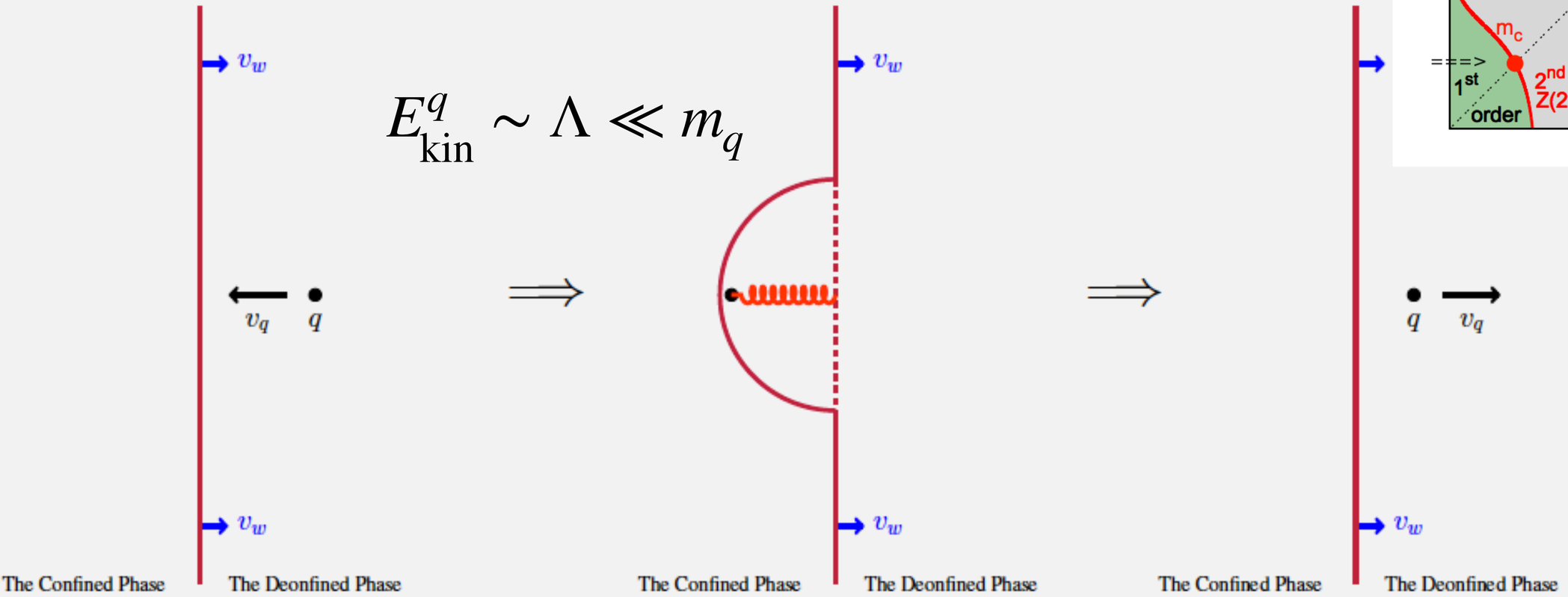


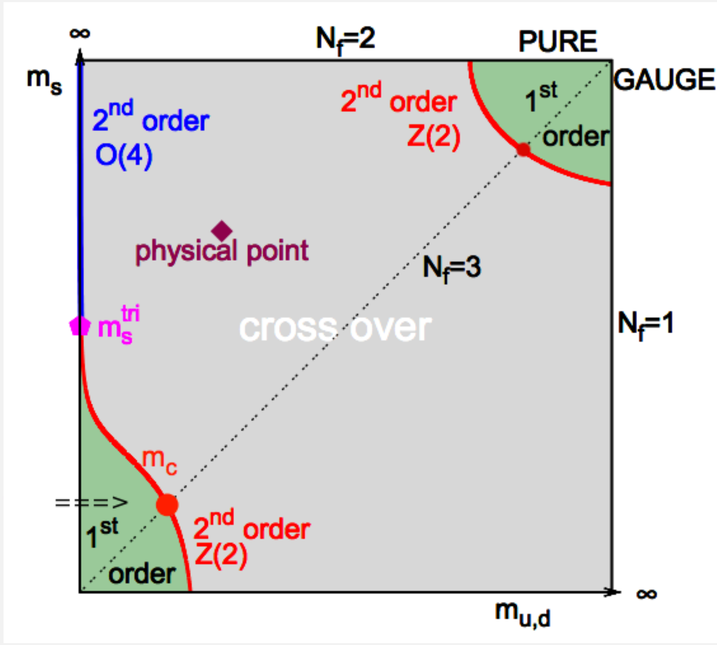
$x = 1$

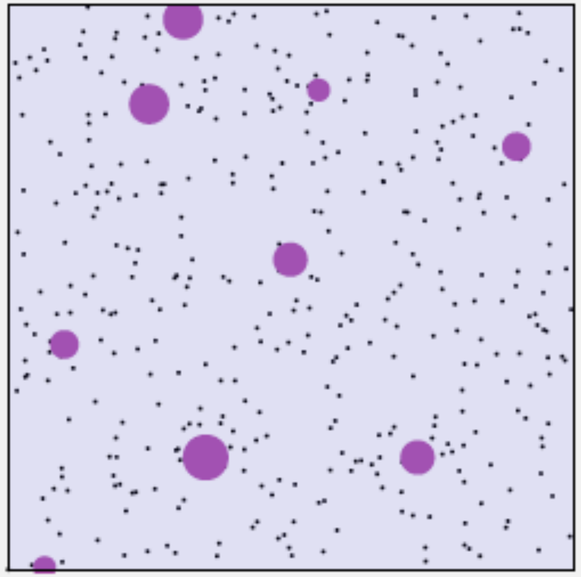

SU($N_{\rm DC}$) Yang-Mills
(upper bound)
Contracting pockets
slow domain wall
(upper bound)
Expanding bubbles
$\mathbf{N_{DC} = 3}$
Wall velocity v_w
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-3}
10^{-2}
10^{-1}
1
10
10^{2}
10^{3}
Confinement scale Λ [TeV]

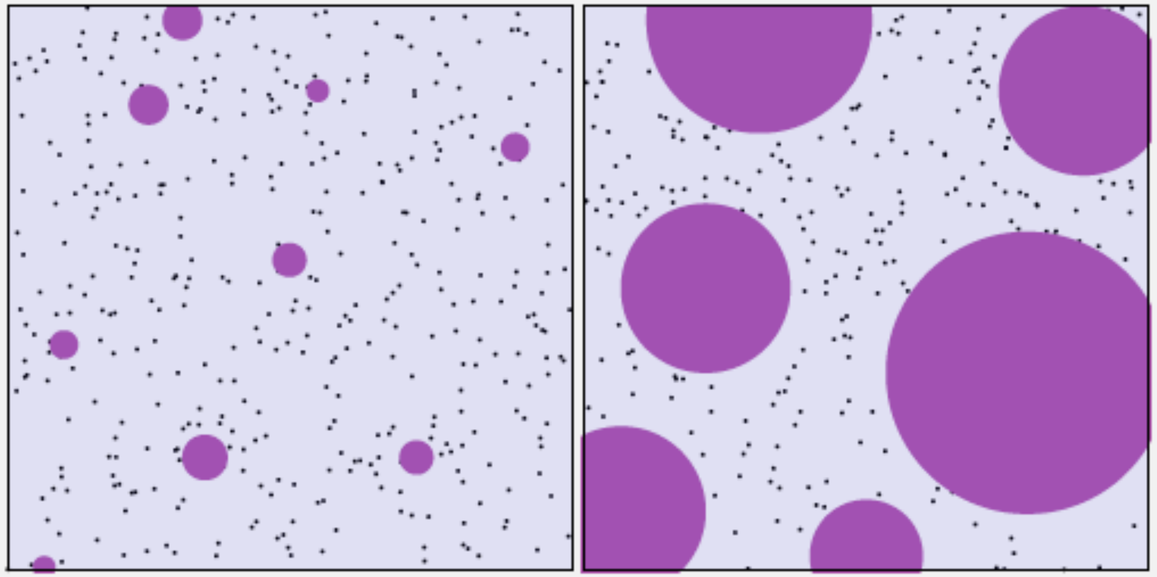
YM + Heavy Quarks:

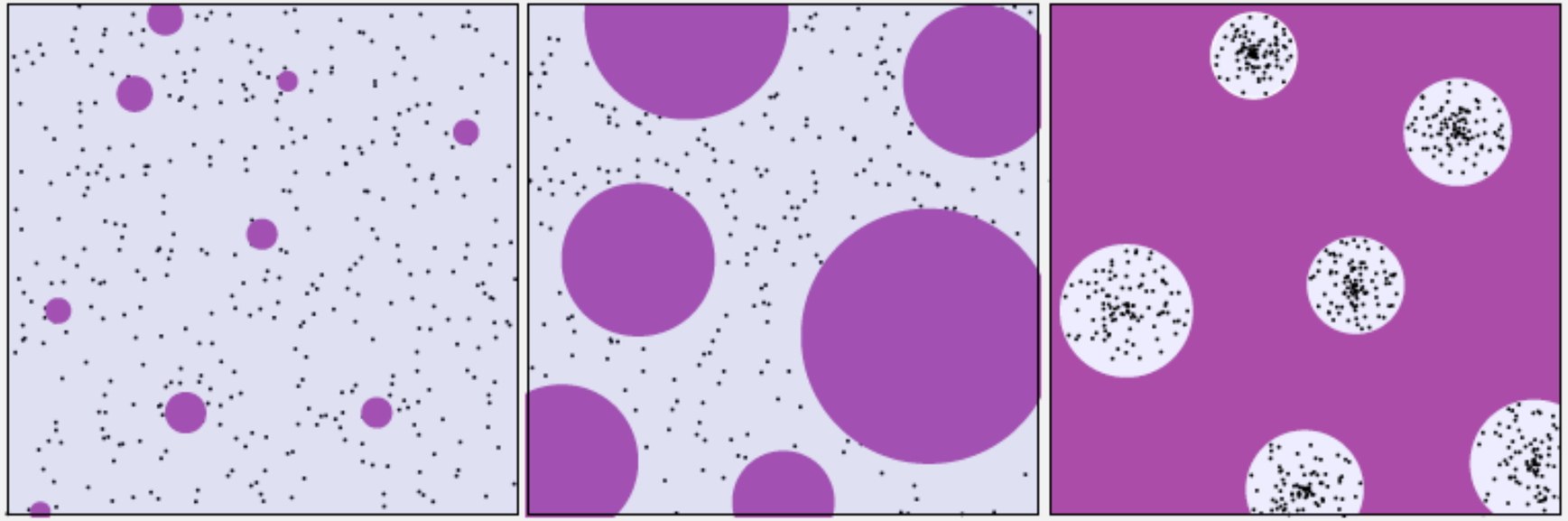
$$m_q > 100\Lambda$$

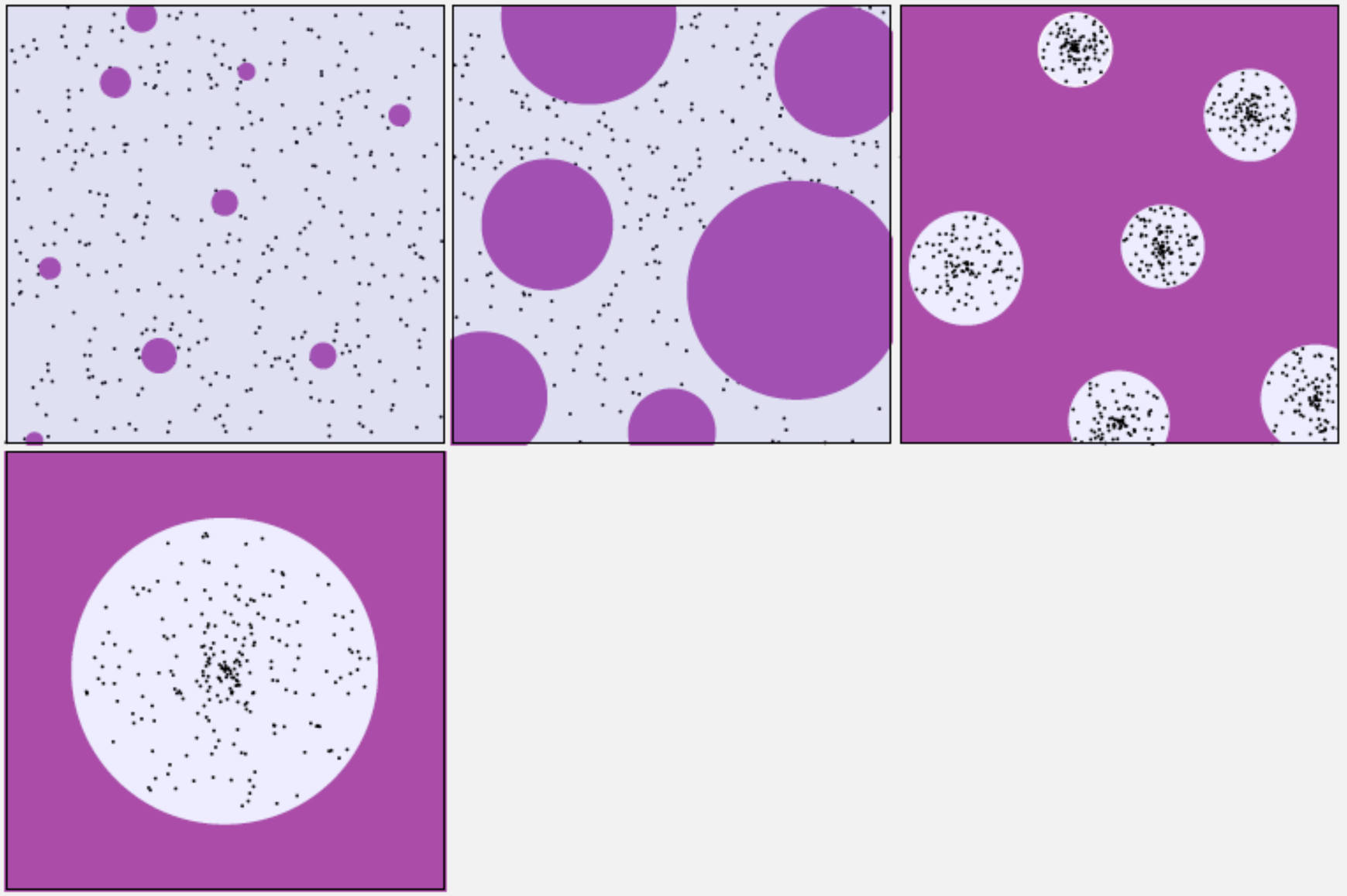


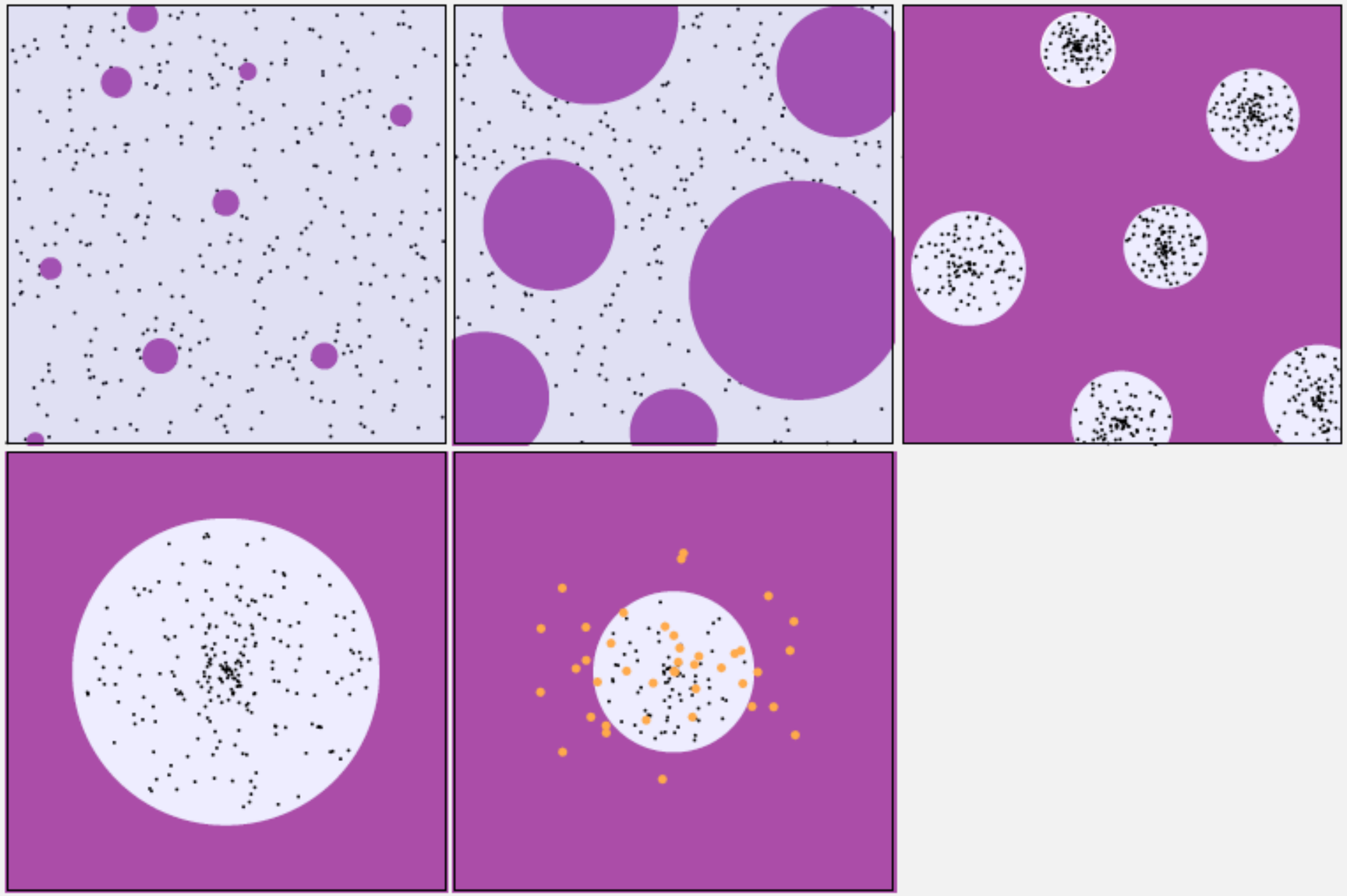




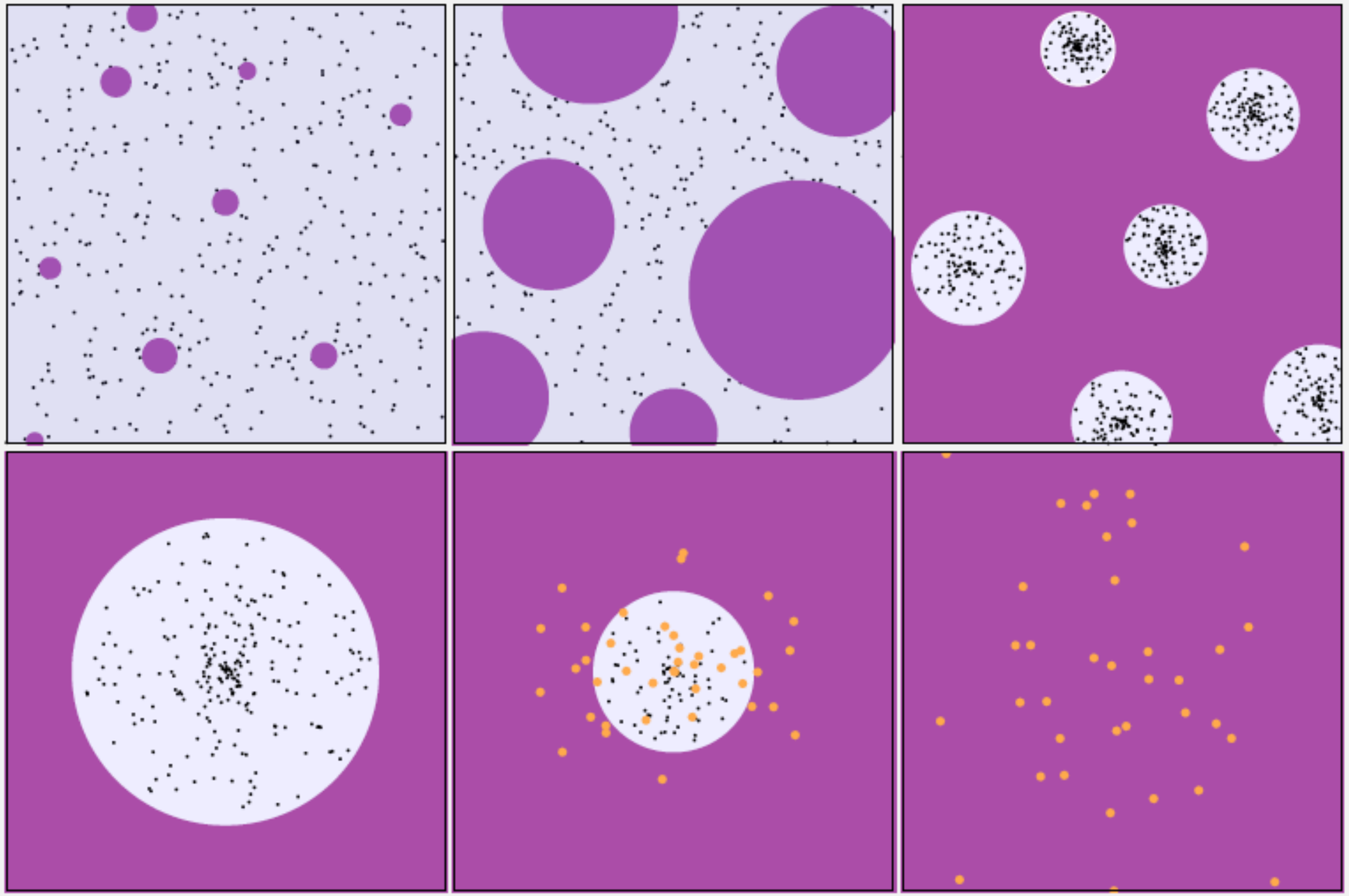






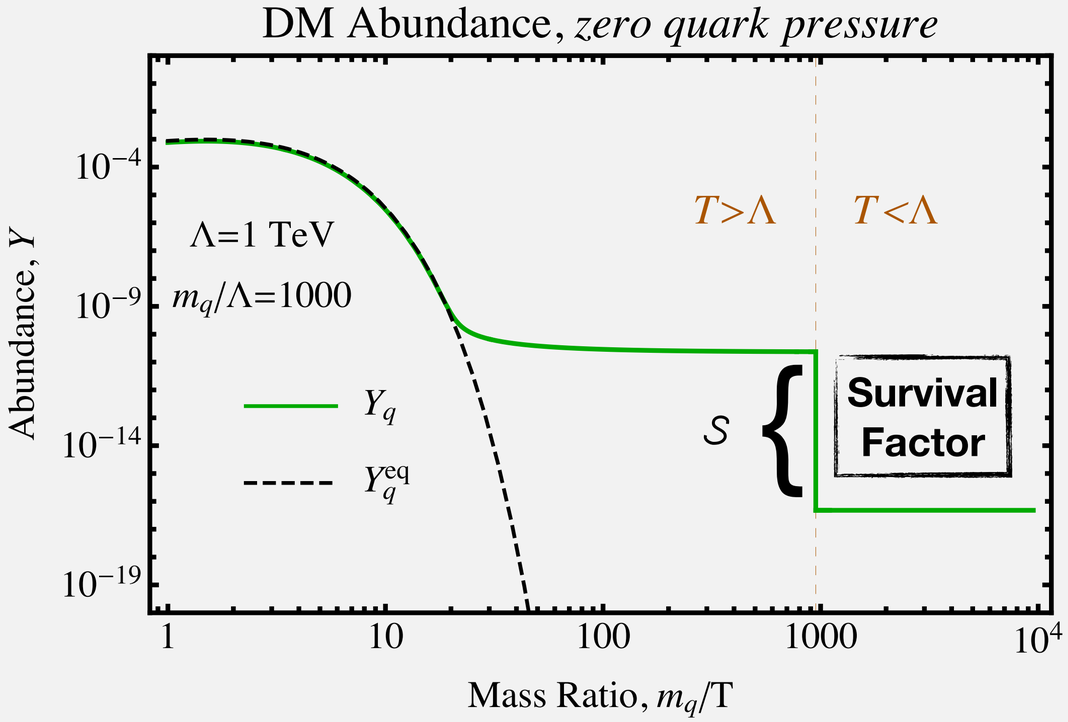


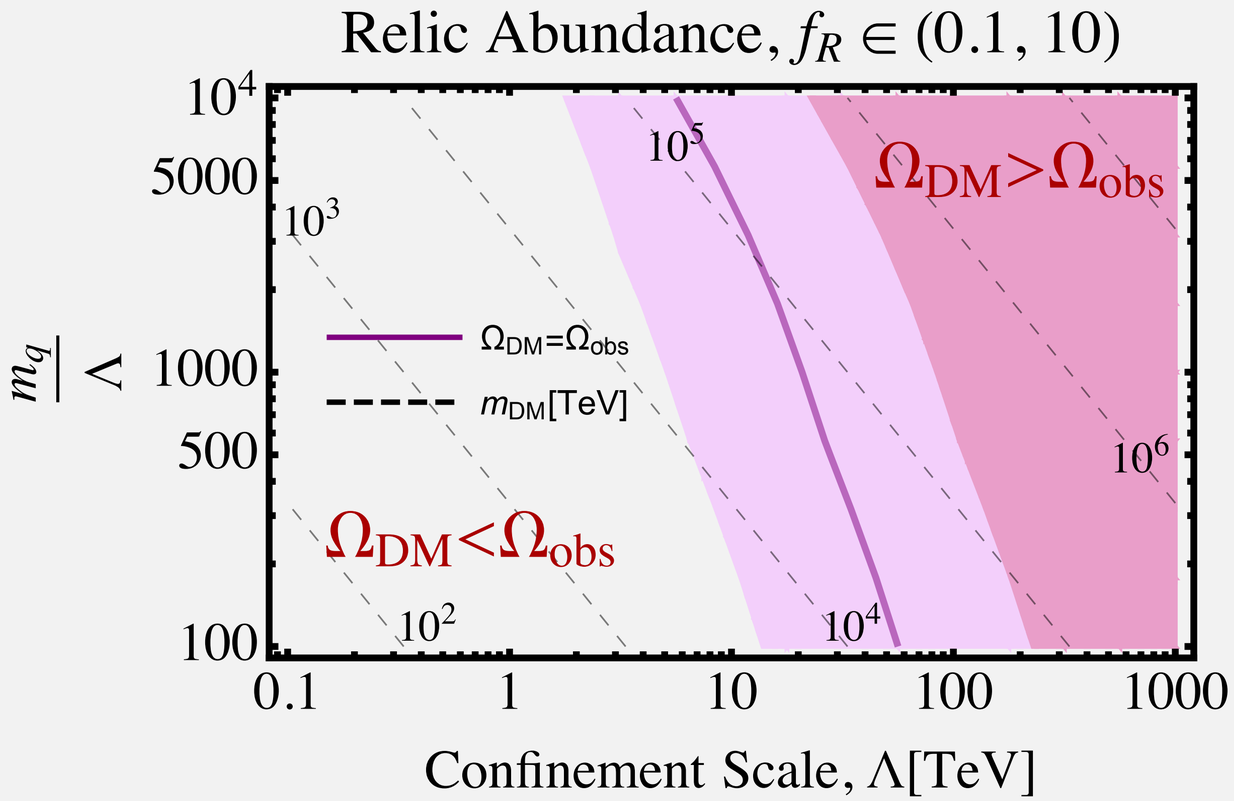
Dark Baryon Dark Matter



- Dark Matter Squezeeout

Thermal Freeze-out



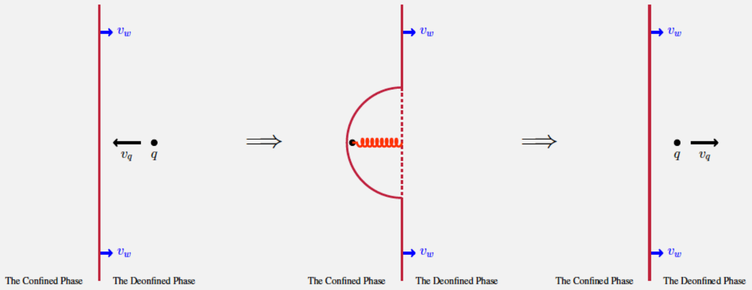


Survival Factor:

$$S = \frac{N_c N_B}{N_i} \ll 1$$

Asadi, Eric, et.al. 2021

Exceeds the Unitarity Bound ($m_{\rm DM} \leq 100$TeV)

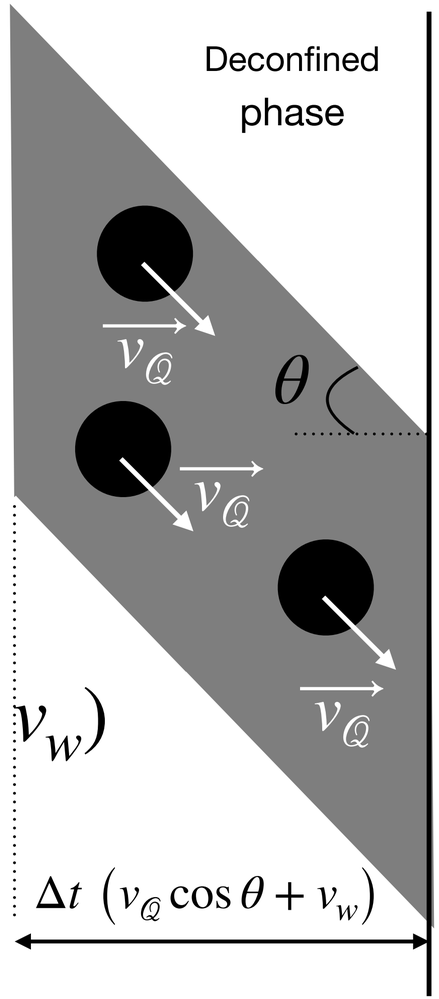


Collective Escaping

Confinement Length

$$\ell = 1/\Lambda$$

$$\Delta t \sim \ell/(v_q + v_w)$$

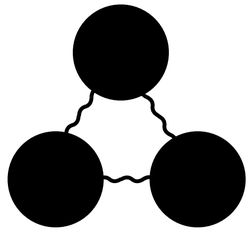


Average particle over Δt

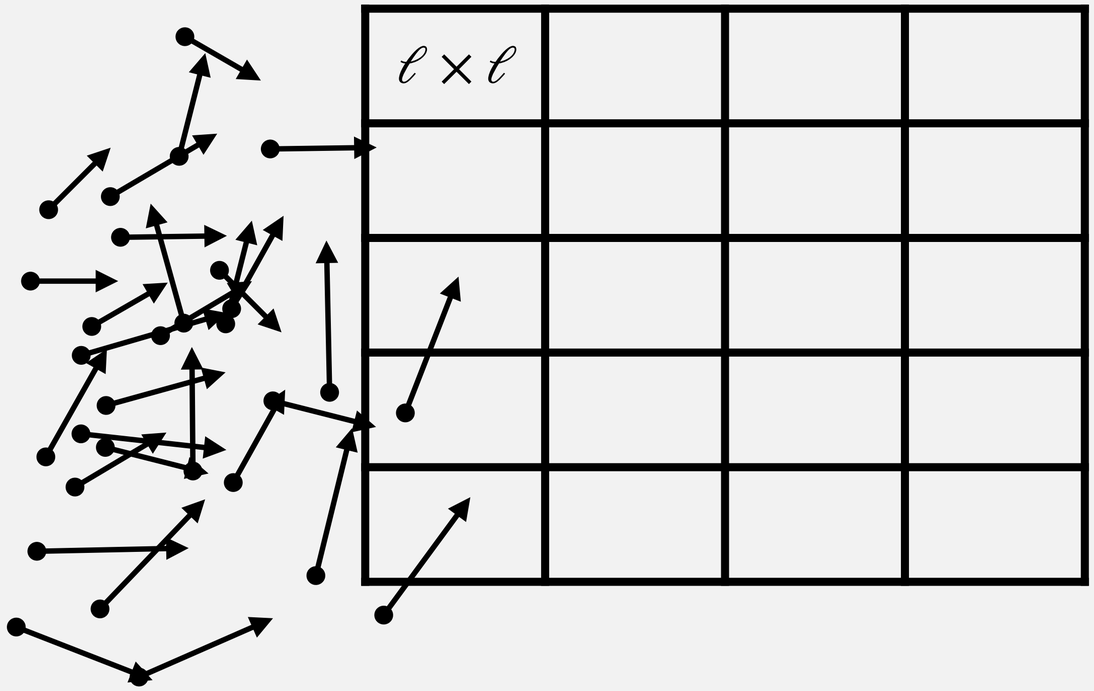
$$\lambda = \Delta t v_\perp n$$

$$\ell^2 \gg \alpha_s / m_q^2$$

$$\sigma \sim \ell^2 \Longrightarrow$$

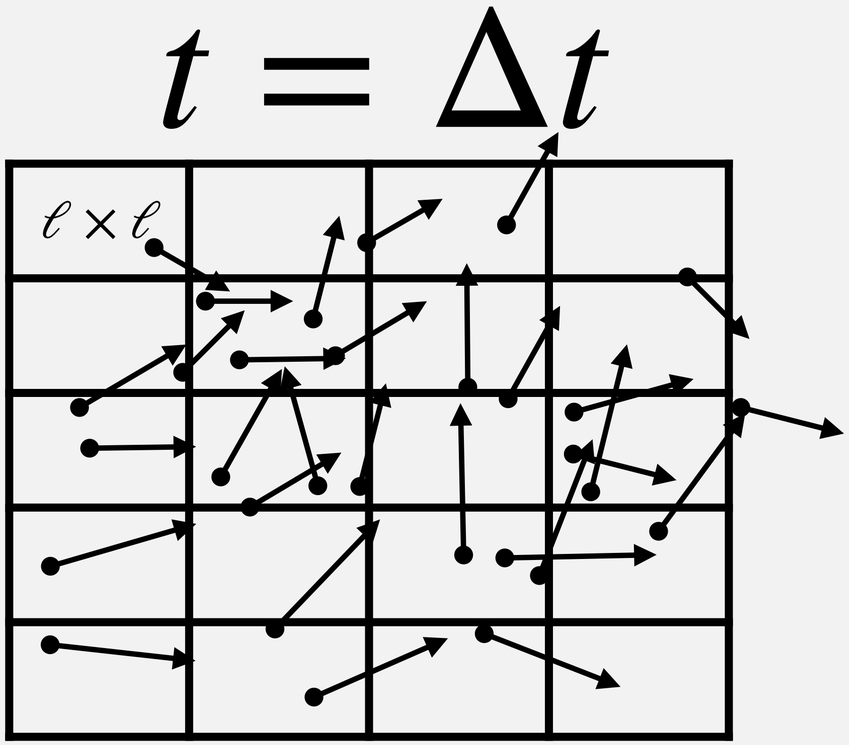


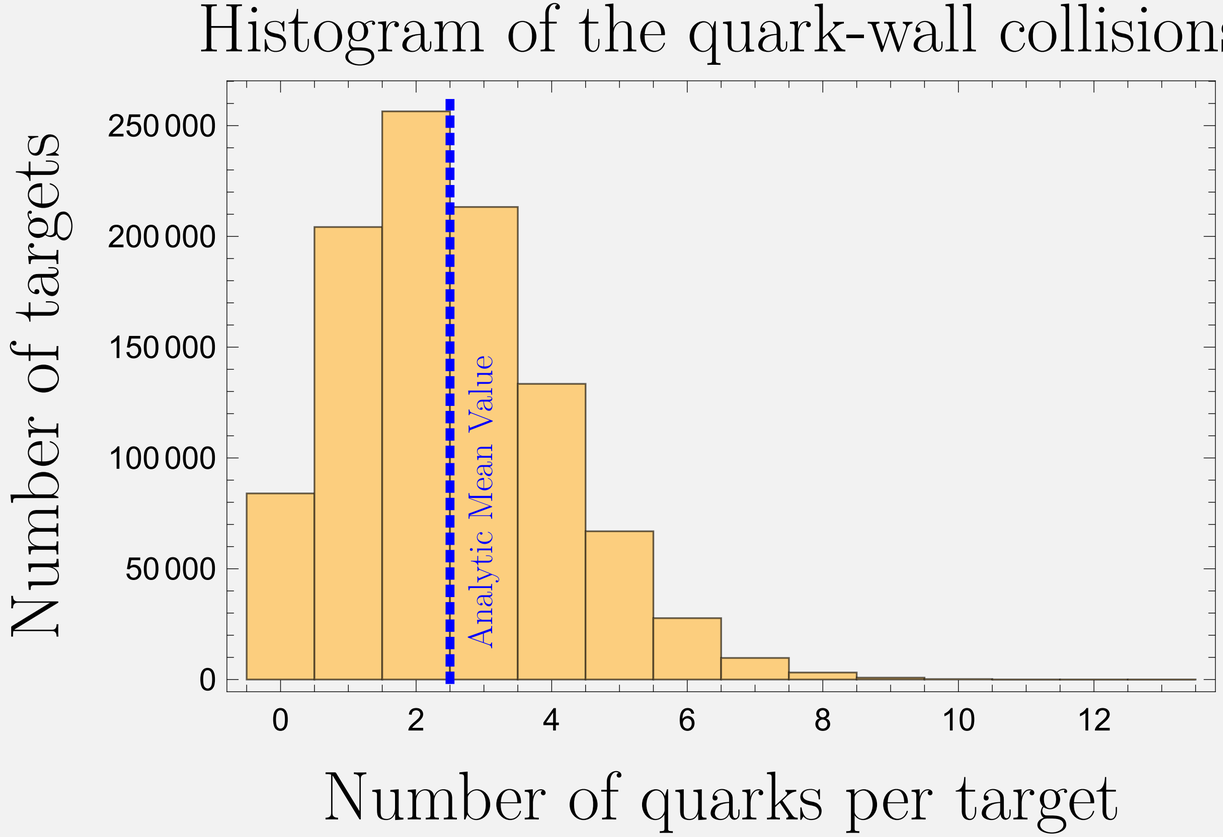
$$t = 0$$



Average particle over Δt

$$\lambda = \Delta t v_{\perp} n \sigma$$





Average particle over Δt

$$\lambda = \Delta t v_{\perp} n \sigma$$

$$P_{\lambda}(k) = \frac{\lambda^{k}}{k!} e^{-\lambda}$$

Quark depletion/BSF rate

Asadi+, 2021

$$\frac{dN_i}{dt} = \Gamma_{\rm bulk}[i]$$

$$\Gamma_{\rm bulk}[i] = -\sum_{\rm a+b=c+d} s^{i}_{\rm ab,cd} \frac{\langle \sigma v \rangle^{\rm bulk}_{abcd}}{V} \left(N_a N_b - N_c N_d f_{abcd} \right)$$

Quark depletion/BSF rate

Asadi+, 2021 | This Work

$$\frac{dN_i}{dt} = \Gamma_{\rm bulk}[i] + \Gamma_{\rm bdy}[i]$$

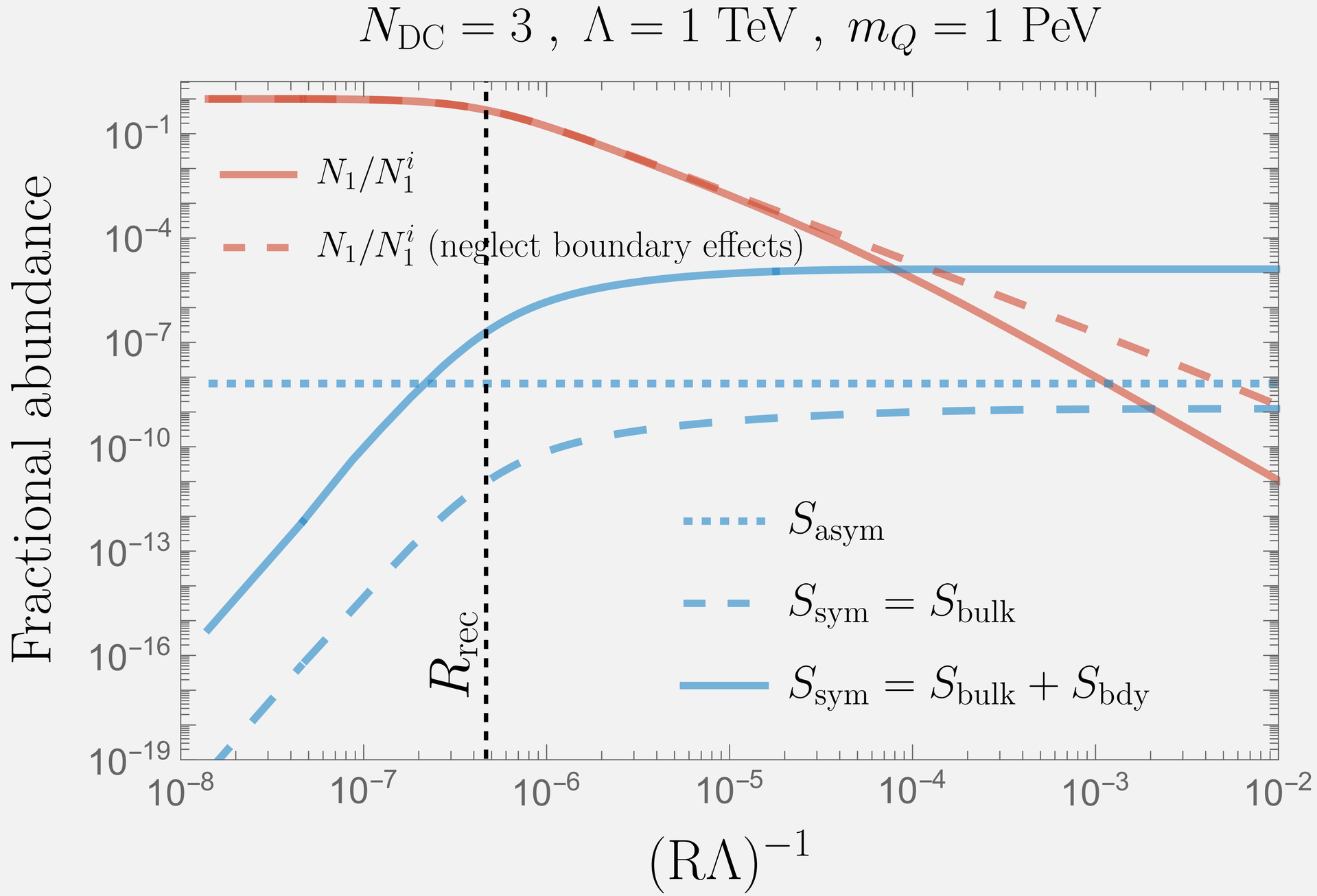
Baryon formation rate via three quarks collisions

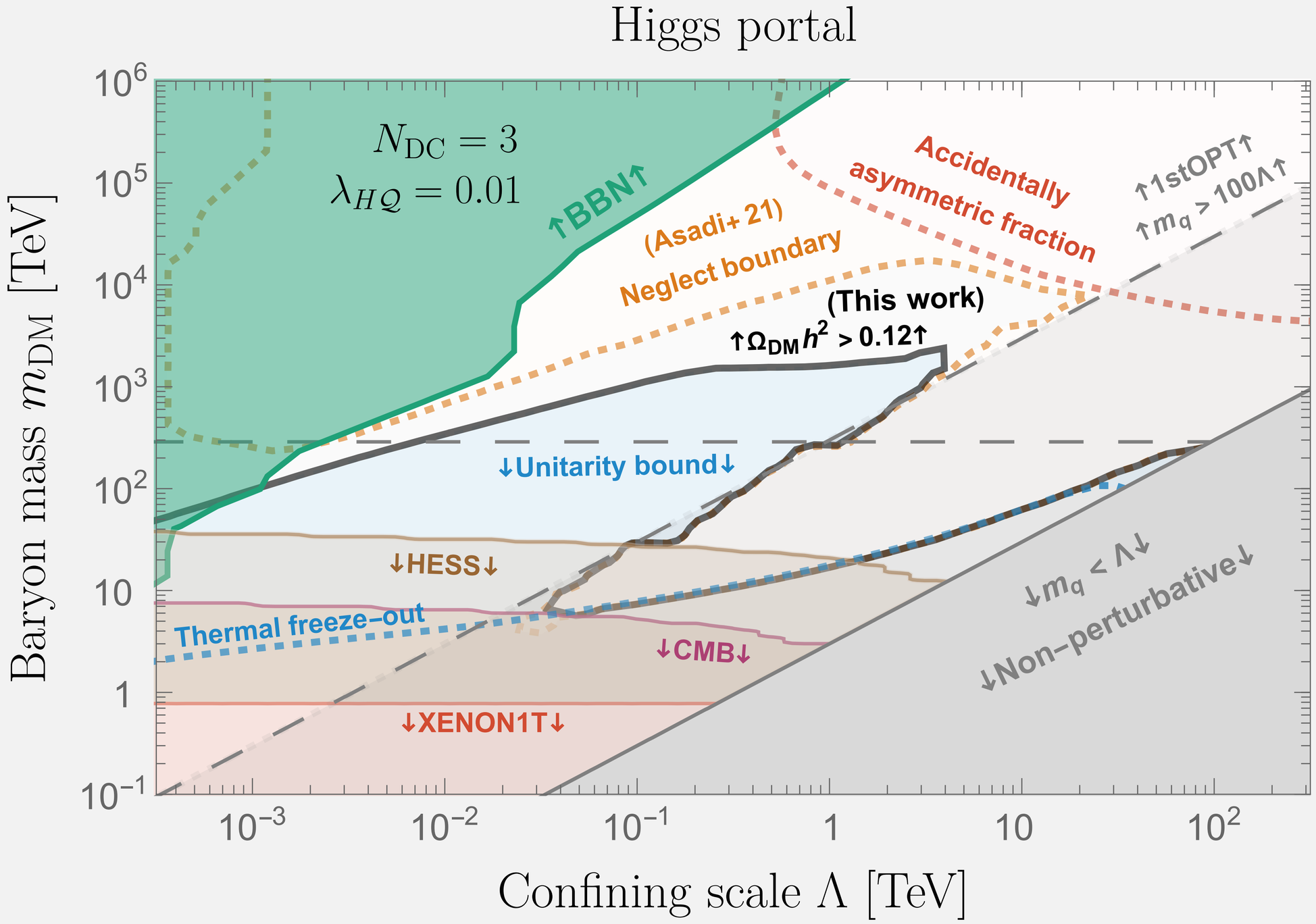
$$\Gamma^{\rm bdy}_{(1,1,1)\to 3} = \oint_{\partial V} \frac{dS}{\sigma \Delta t} \sum_{k=3}^{\infty} P_\lambda\left(k\right)$$

Meson formation rate via quark anti-quark collisions

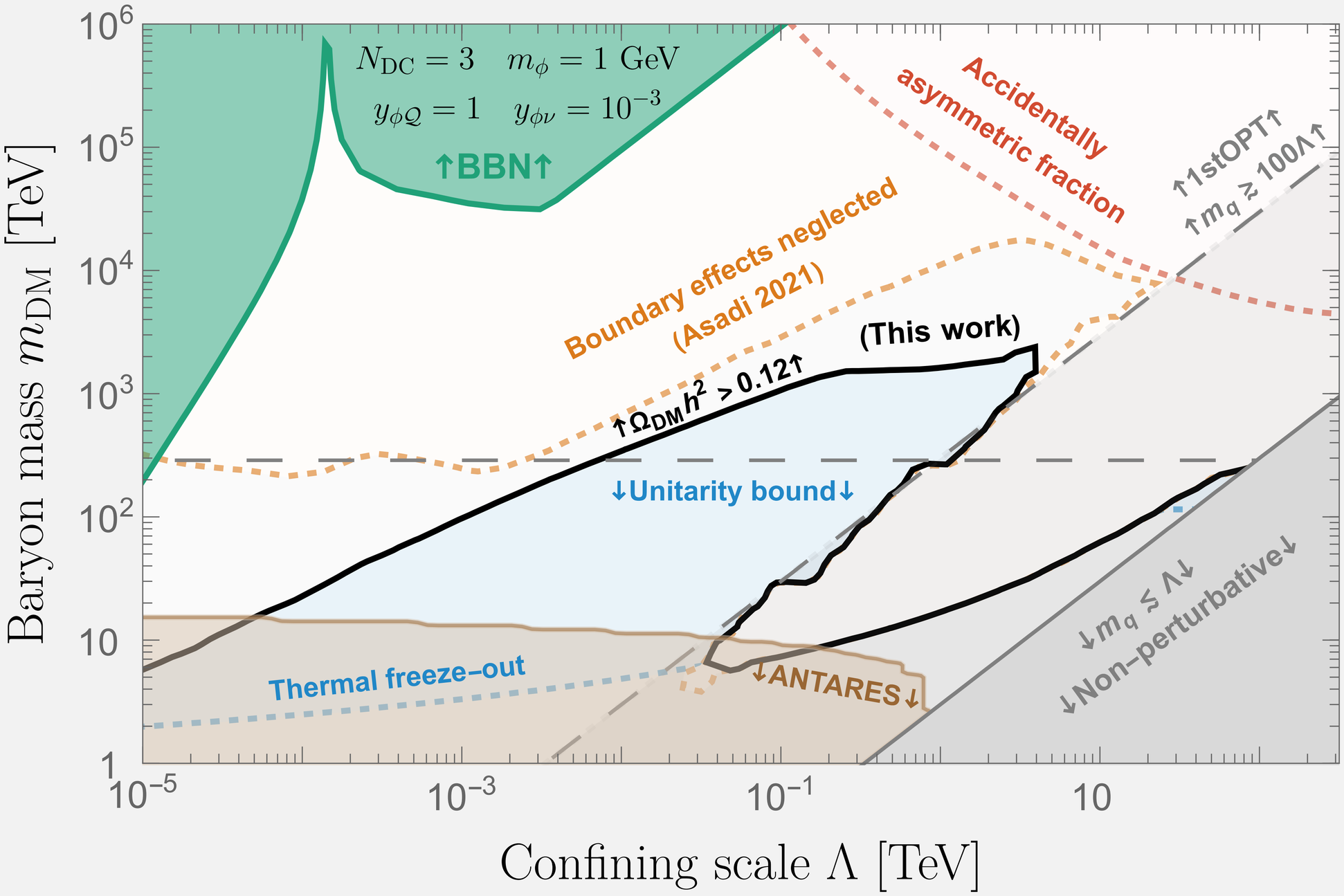
$$\Gamma^{\rm bdy}_{(1,-1)\to \mathscr{M}} = \oint_{\partial V} \frac{dS}{\sigma \Delta t} \left[\sum_{k=1}^{\infty} P_\lambda\left(k\right)\right]^2$$

$$\Gamma_{\rm bulk}[i] = -\sum_{\rm a+b=c+d} s^i_{\rm ab,cd} \frac{\langle \sigma v \rangle^{\rm bulk}_{abcd}}{V} \left(N_a N_b - N_c N_d f_{abcd}\right)$$


$N_{\rm DC} = 3\ ,\ \Lambda = 1\ {\rm TeV}\ ,\ m_Q = 1\ {\rm PeV}$
Fractional abundance
10^{-1}
10^{-4}
10^{-7}
10^{-10}
10^{-13}
10^{-16}
10^{-19}
N_1/N_1^i
N_1/N_1^i (neglect boundary effects)
$R_{\rm rec}$
$S_{\rm asym}$
$S_{\rm sym} = S_{\rm bulk}$
$S_{\rm sym} = S_{\rm bulk} + S_{\rm bdy}$
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
$({\rm R}\Lambda)^{-1}$


Higgs portal
$N_{\rm DC} = 3$
$\lambda_{HQ} = 0.01$
↑BBN↑
(Asadi+ 21)
Neglect boundary
Accidentally
asymmetric fraction
↑1stOPT↑
↑m_q > 100Λ↑
(This work)
↑$\Omega_{\rm DM}h^2$ > 0.12↑
↓Unitarity bound↓
↓HESS↓
Thermal freeze-out
↓CMB↓
↓XENON1T↓
↓m_q < Λ↓
↓Non-perturbative↓
Baryon mass $m_{\rm DM}$ [TeV]
Confining scale Λ [TeV]
10^6
10^5
10^4
10^3
10^2
10
1
10^{-1}
10^{-3}
10^{-2}
10^{-1}
1
10
10^2

Neutrino portal



Conclusion and Outlook

- **Analytical v_w $SU(N)$ FOPT, numerically $v_w \ll 1$: slow domain wall**
- **Boundary Effects of DM Squeeze Out, $S_{\text{bdy}} \gg S_{\text{bulk}}$: heavy quarks mainly collectively escape near the DW.**
- **Generic Finite Volume Boltzmann Equations.**

Thanks For Your Attention

Back Up

Finite Volume Boltzmann equation

$$\int_V L[i]dV = -\int_V \langle \sigma v \rangle_{ij}^{\mathrm{blk}} \left(n_i n_j - n_\alpha n_\beta f_{ij,\alpha\beta} \right) dV$$
$$- \oint_{\partial V} \left(\langle \sigma v \rangle_{\mathbf{2}}^{\mathrm{bdy}} n_i n_j + \langle \sigma v \rangle_{\mathbf{N_c}}^{\mathrm{bdy}} n_i^{N_c} \right) dS$$

paper link