Super Heavy (Thermal) Dark Matter

Eric Kuflik

IAS HEP2022

Kim, **EK** PRL 2019

Kramer, **EK**, Levi, Outmezguine, Ruderman, PRL 2020

Asadi, Kramer, **EK**, Ridgway, Slatyer, Smirnov, PRL, PRD 2021

Work in progress with Yann Gouttenoire and Di Liu 2022

Work in progress with Ronny Frumkin and Itay Lavie 2022

האוניברסיטה העברית בירושלים
THE HEBREW UNIVERSITY OF JERUSALEM

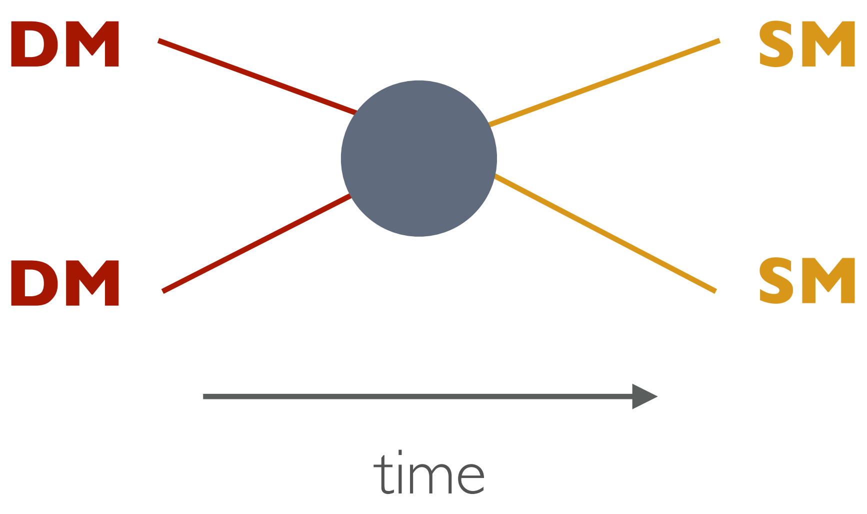
Why?

Past 40 years

WIMP, glorious WIMP*

***Also axions**

WIMP



$$\langle \sigma_{\rm ann} v \rangle = \frac{\alpha^2}{m_{\rm DM}^2}$$

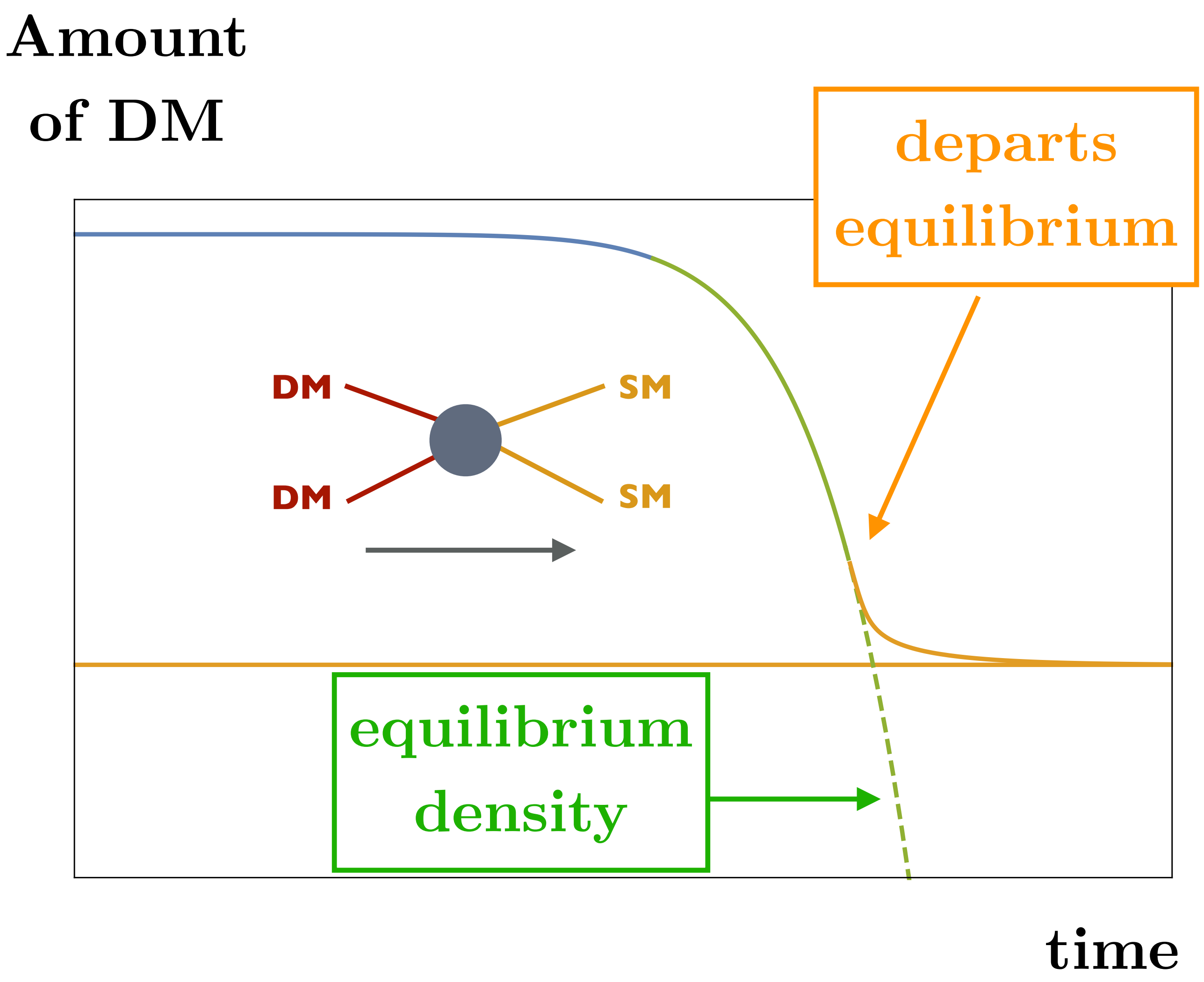
Correct relic abundance for

$$m_{\rm DM} = \alpha \times 30 \text{ TeV}$$

For Weak coupling, Weak scale emerges

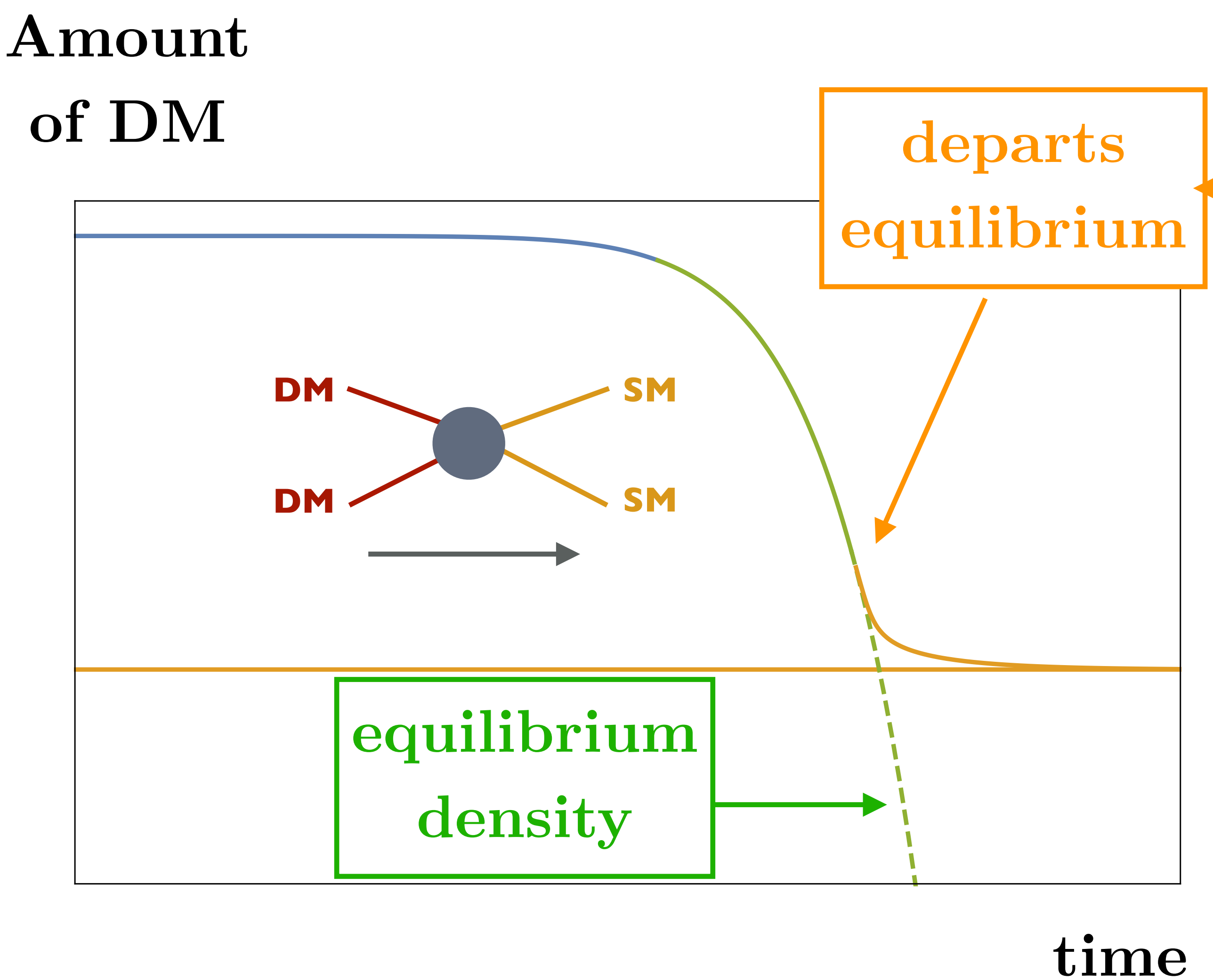
Weakly Interacting Massive Particle (WIMP)

WIMP



Thermal Relic:
Simple and Predictive

WIMP



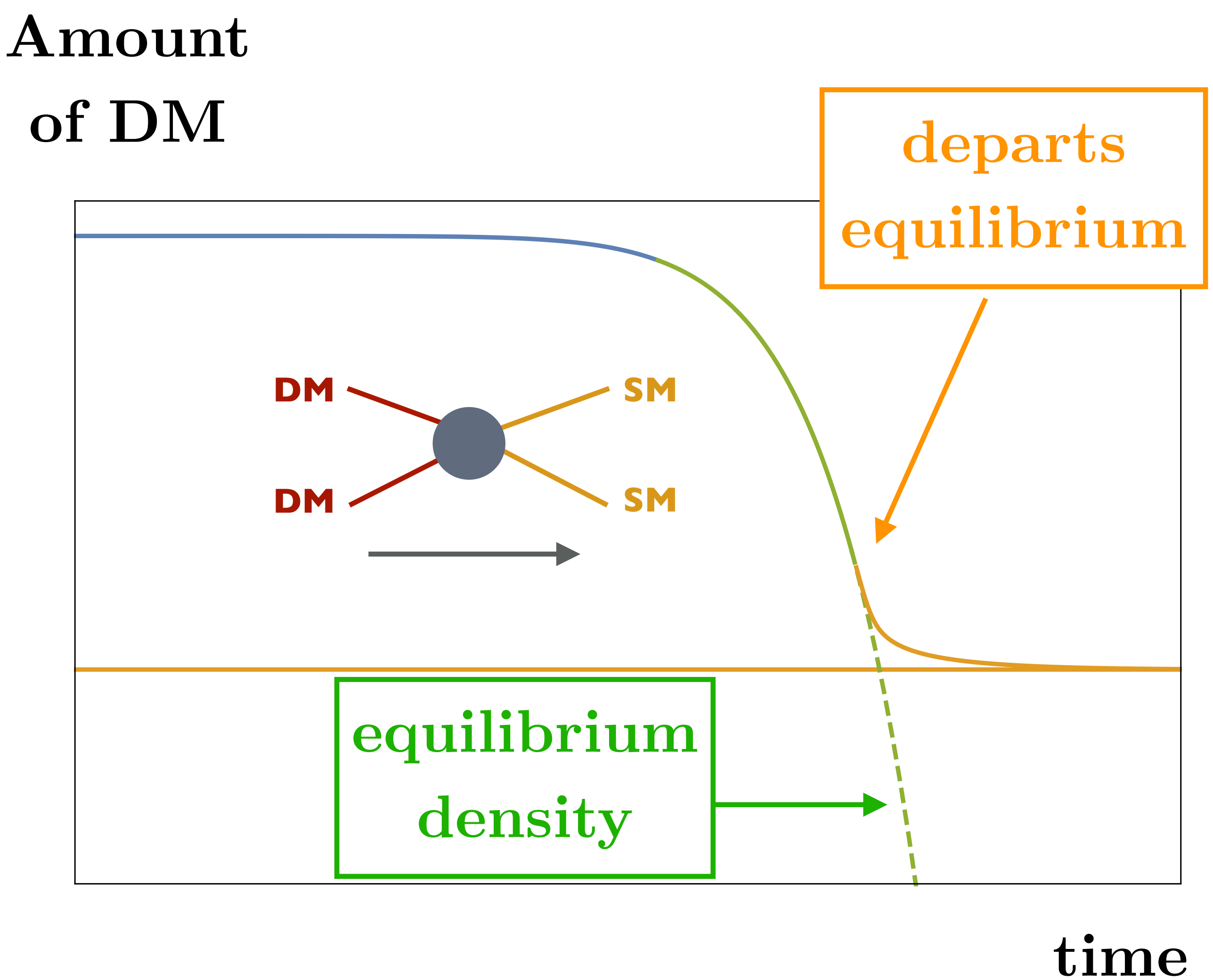
not sensitive to physics before this point

Freezeout:

$$n_{\mathrm{DM}} \langle \sigma_{\mathrm{ann}} v \rangle = H$$

$$n_{\mathrm{DM}} = \frac{H}{\langle \sigma_{\mathrm{ann}} v \rangle}$$

WIMP



Guiding principle
in cosmology

H, He4, D, T, Li abundances from **BBN**

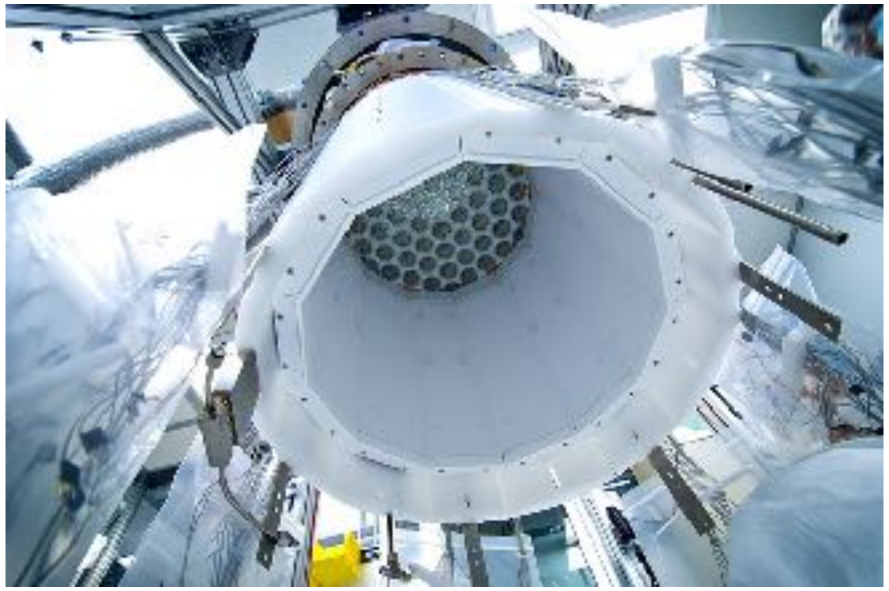
CMB decoupling, free electron fraction from **Recombination**

Searching for WIMPs

Direct Production

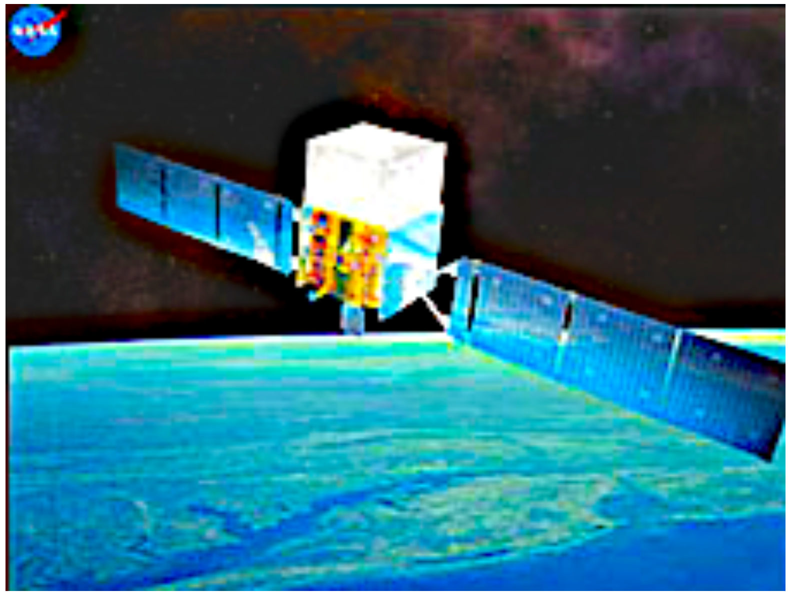
e.g. LHC

Direct Detection



e.g. LUX

Indirect Detection



e.g. FERMI

Experiments are getting increasingly sensitive...

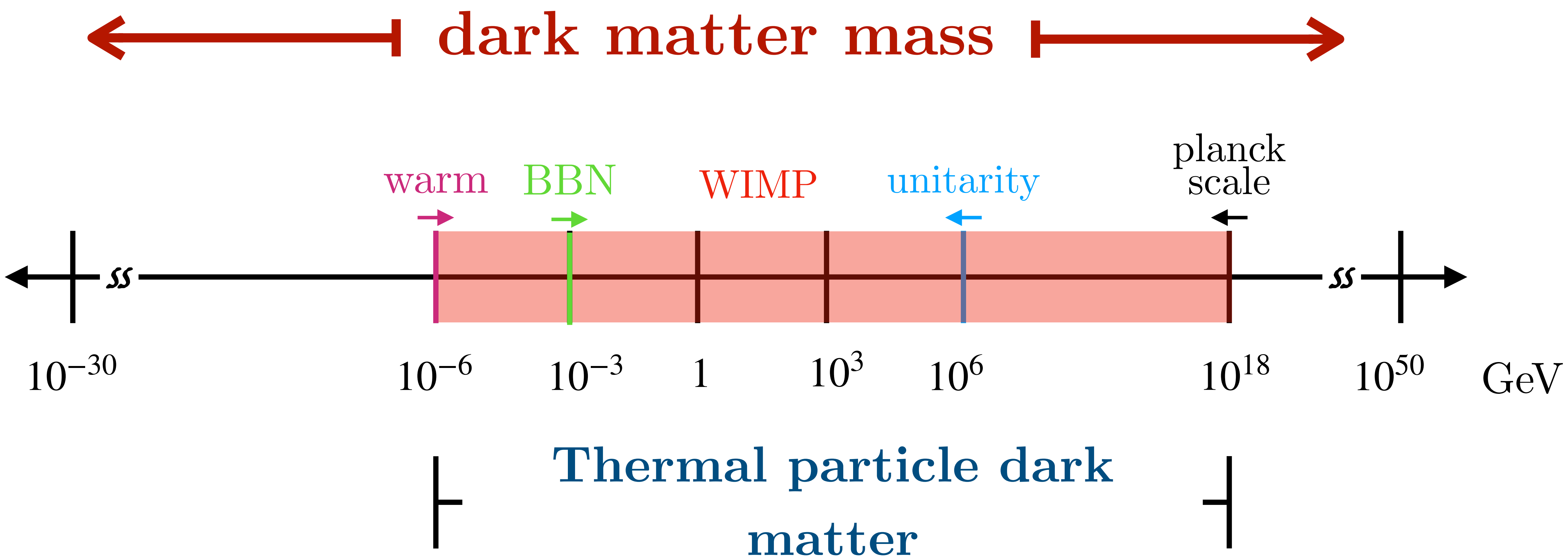
but we still haven't found it

Status in 2022

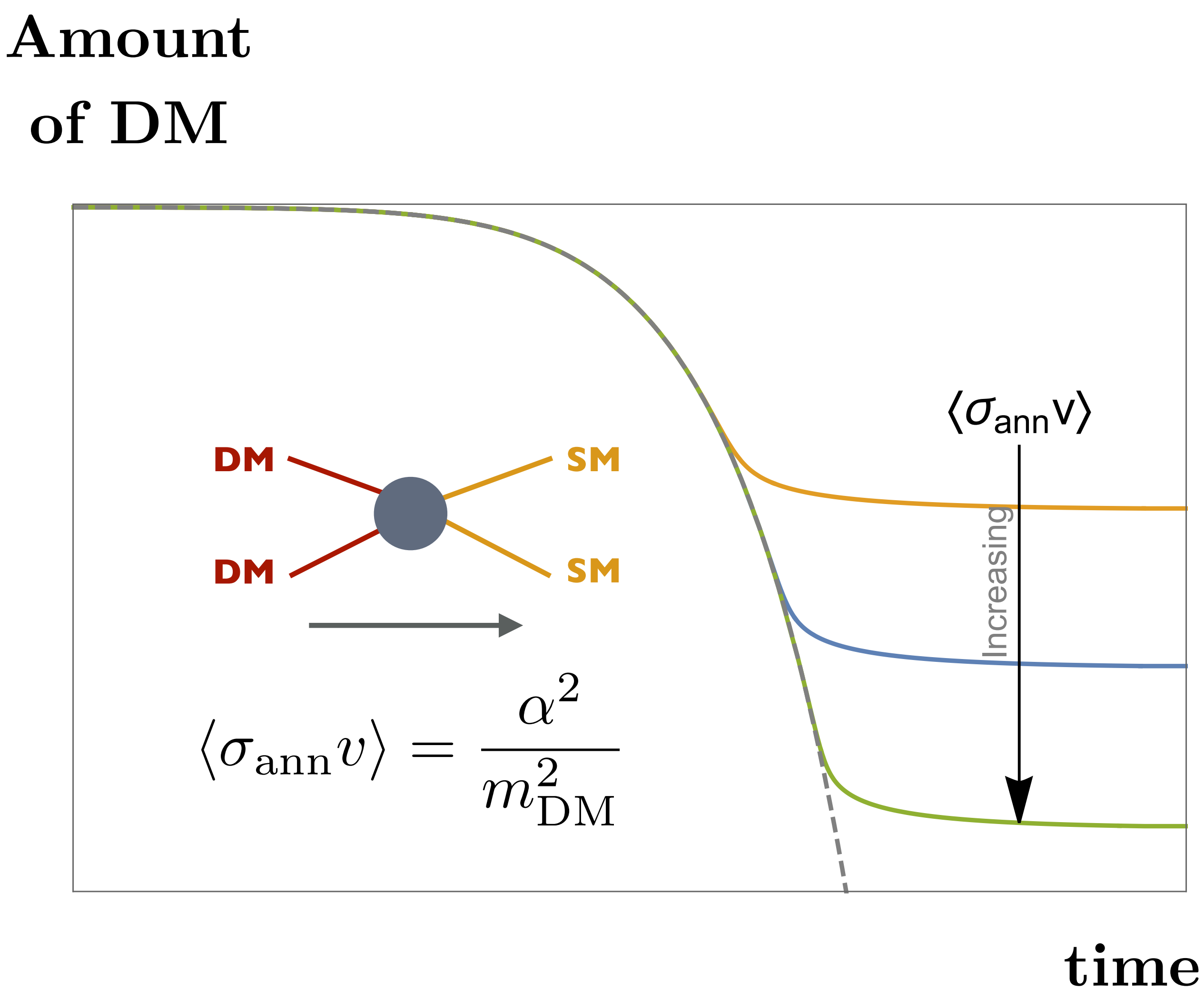
Dominant paradigm being challenged.

Great opportunity for new ideas!

Beyond the WIMP



Unitarity Bound



Correct relic abundance for

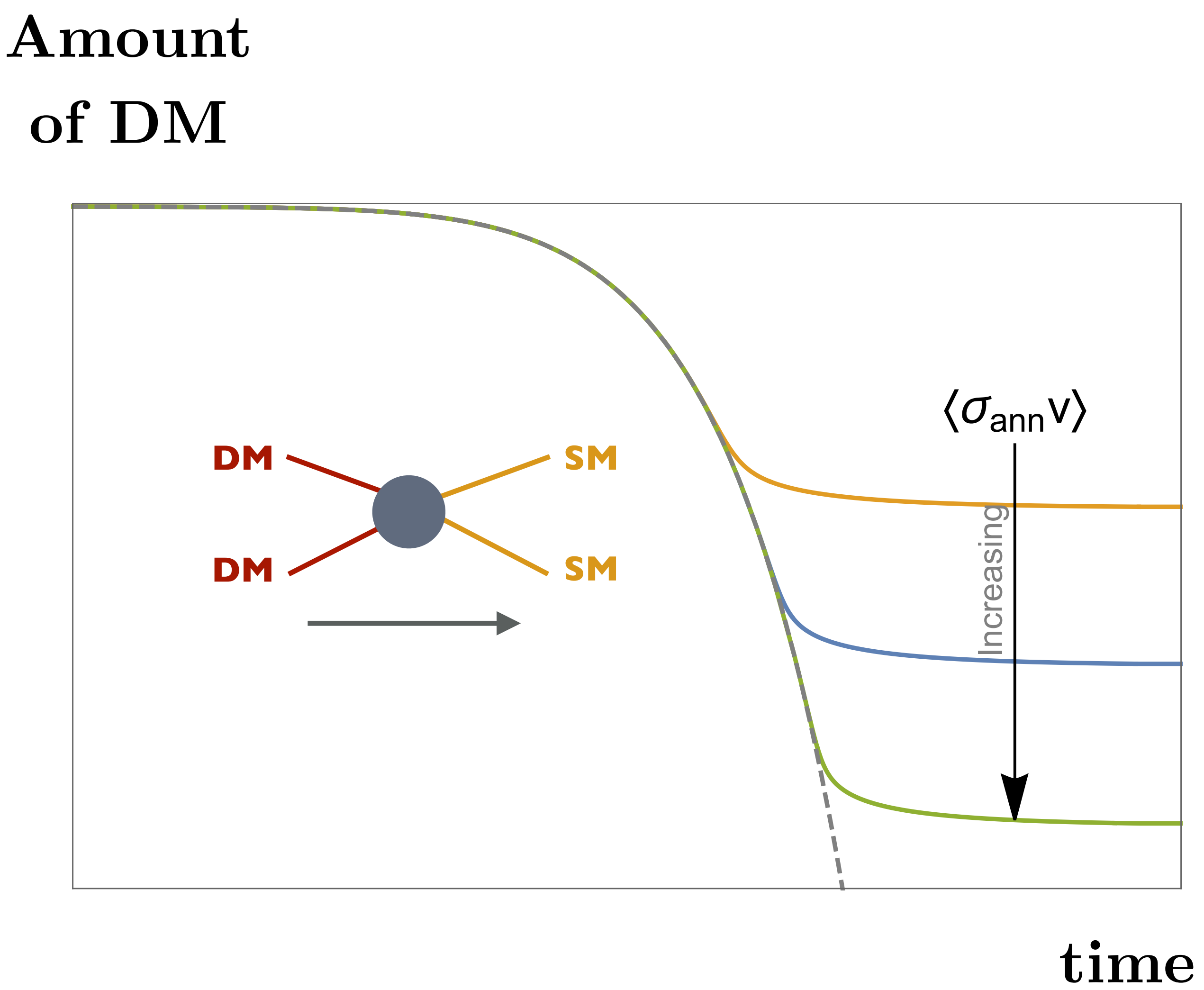
$$m_{\rm DM} \simeq \alpha \times (T_{\rm eq} M_{\rm pl})^{1/2} \simeq \alpha \times 30 \text{ TeV}$$

For perturbative couplings

$$\alpha < 4\pi$$

K. Griest, M. Kamionkowski 1990

Unitarity Bound

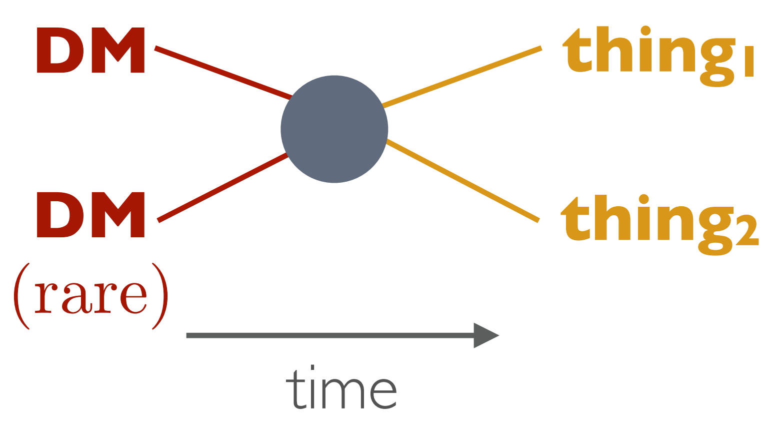


1. Larger cross section
   → DM annihilates away more

2. Fewer dark matter particles
   → must be heavier to give observed energy density

3. Annihilations are never efficient enough to predict very heavier DM

Compare Processes

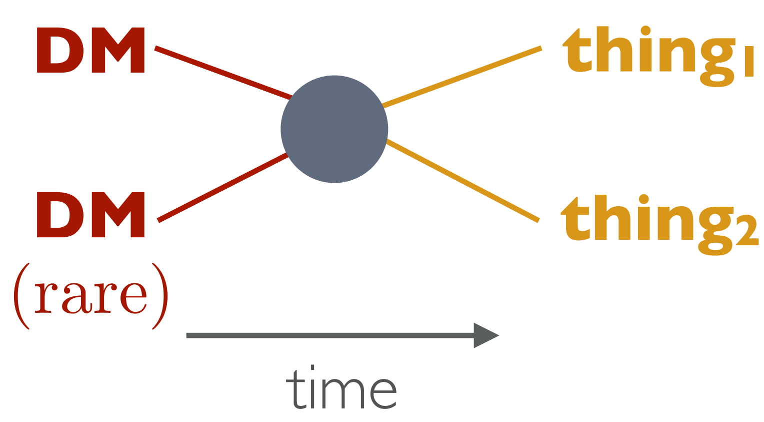


$$\Gamma_{\text{ann}} = n_{\text{DM}} \left\langle \sigma_{\text{ann}} v \right\rangle \propto e^{-m_{\text{DM}}/T}$$

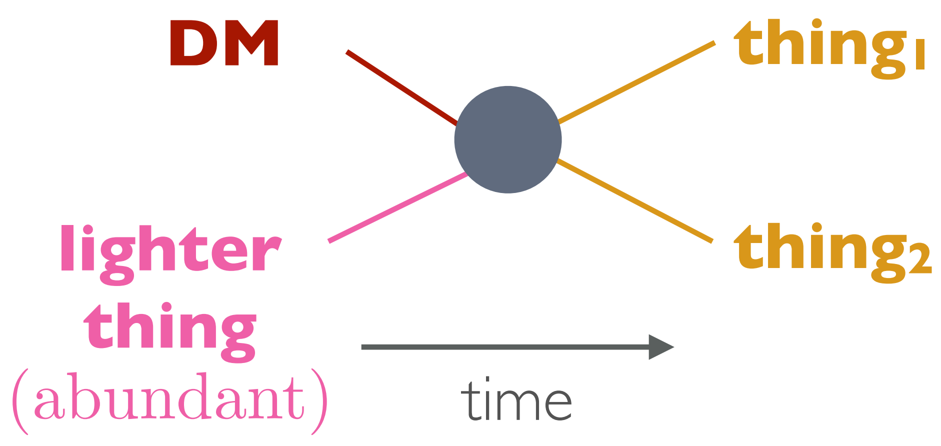
Boltzmann suppressed

Less efficient

Compare Processes



vs.



$$\Gamma_{\rm ann} = n_{\rm DM} \left\langle \sigma_{\rm ann} v \right\rangle \propto e^{-m_{\rm DM}/T}$$

Boltzmann suppressed

Less efficient

$$\Gamma_{\rm ann} = n_{\rm light} \left\langle \sigma_{\rm ann} v \right\rangle$$

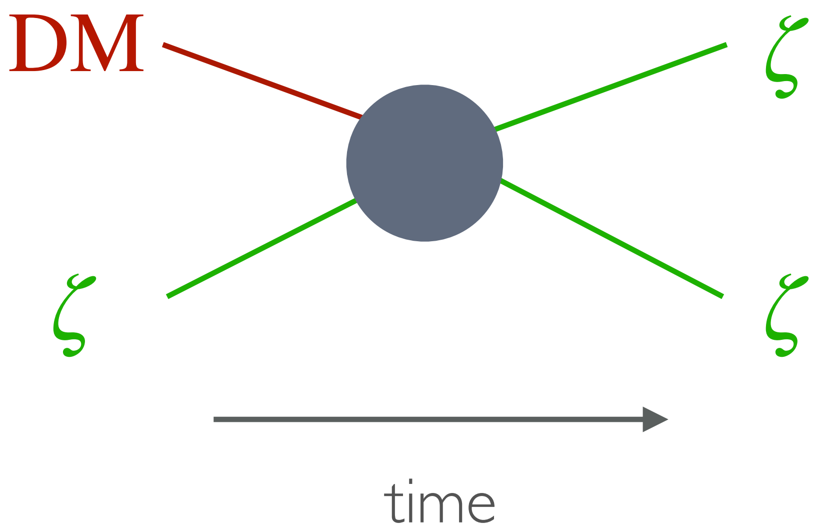
Less (or not) Boltzmann suppressed

Much more efficient!

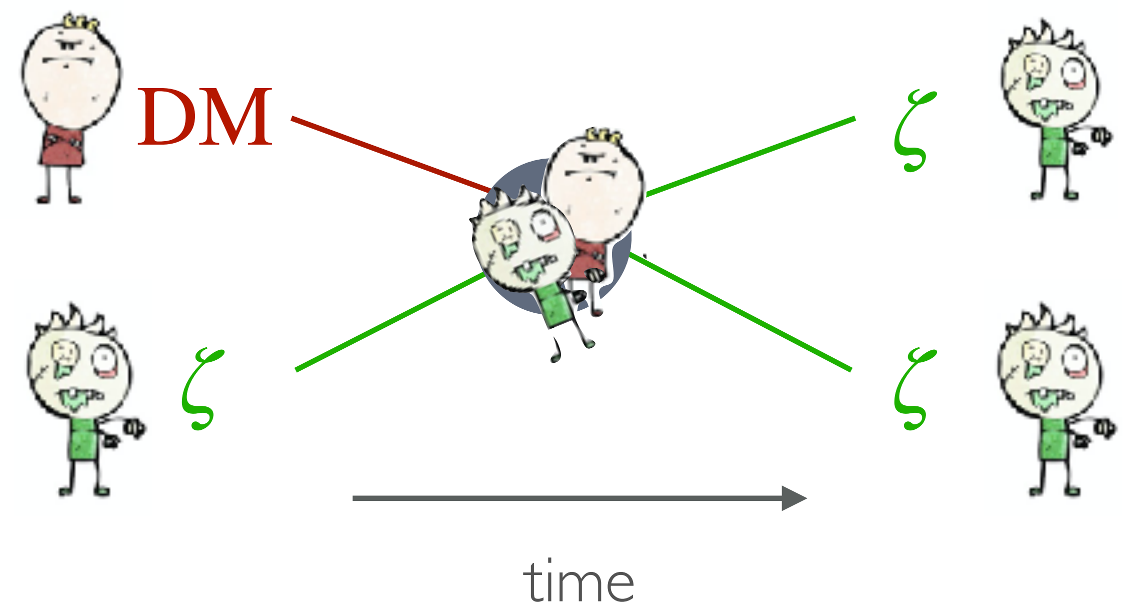
Example #1: Zombies

[Kramer, **EK**, Levi, Outmezguine, Ruderman, PRL 2020]

Zombies

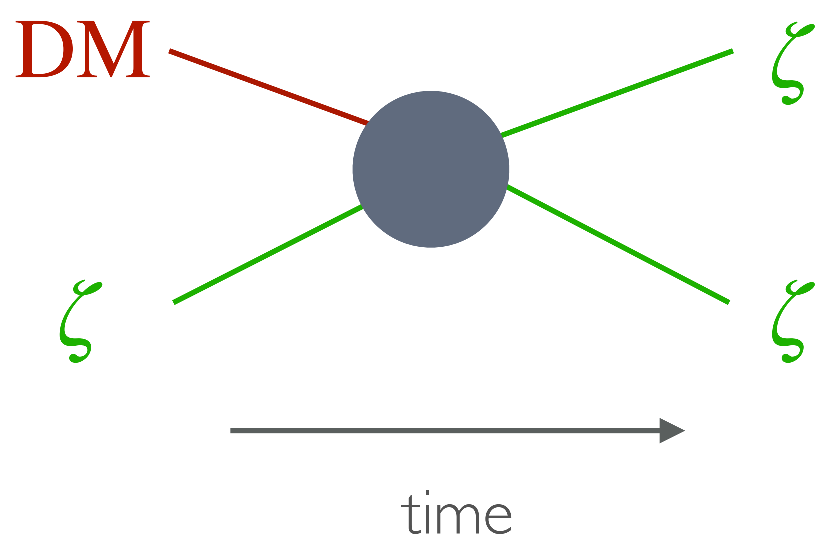


Zombies



1. Dark matter finds a zombie, gets turned into zombie.
2. Some dark matter survives the pandemic until today
3. Zombies eventually decay away

Zombies

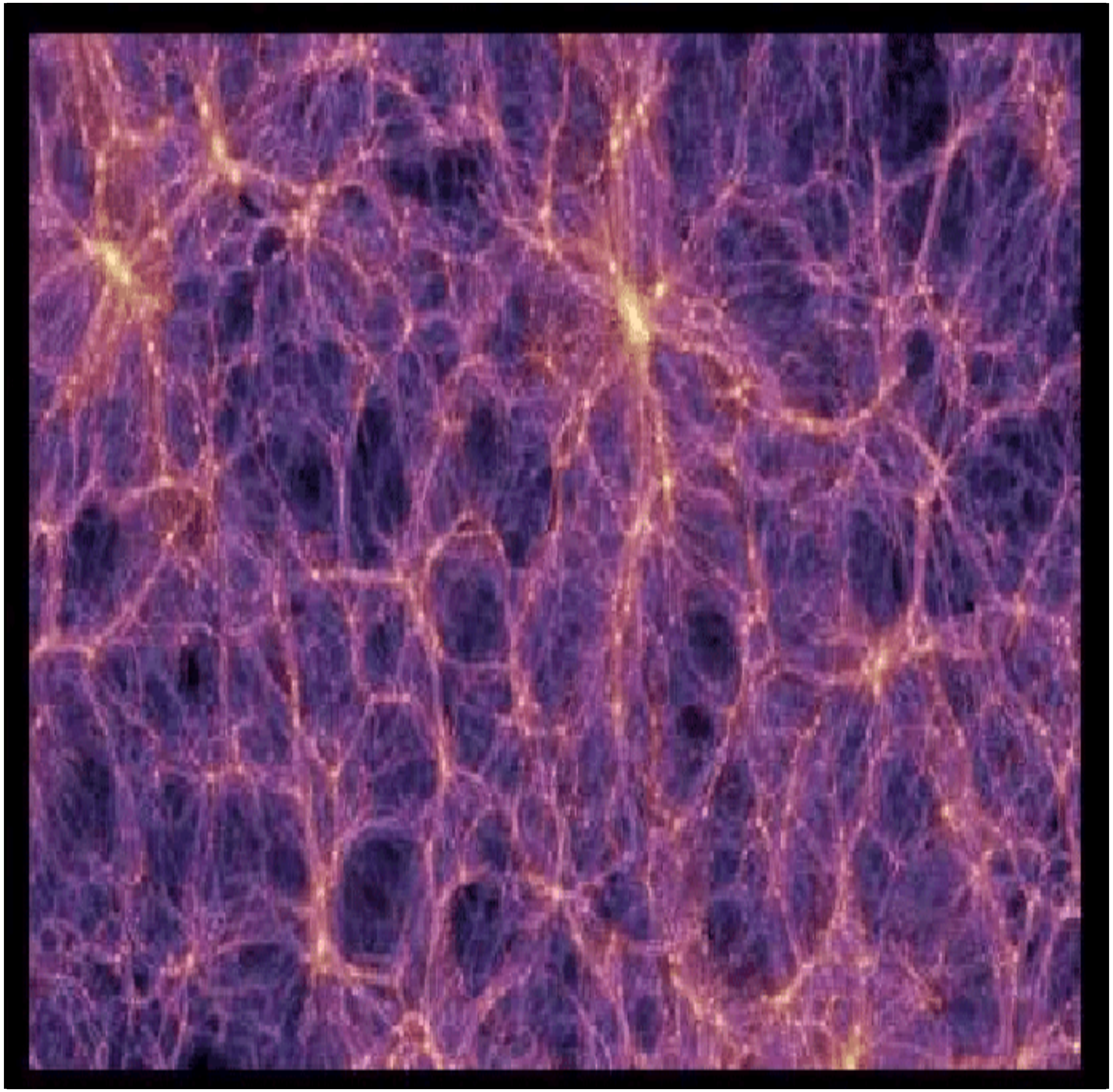


$$m_\zeta < m_{\mathrm{DM}} < 3m_\zeta$$

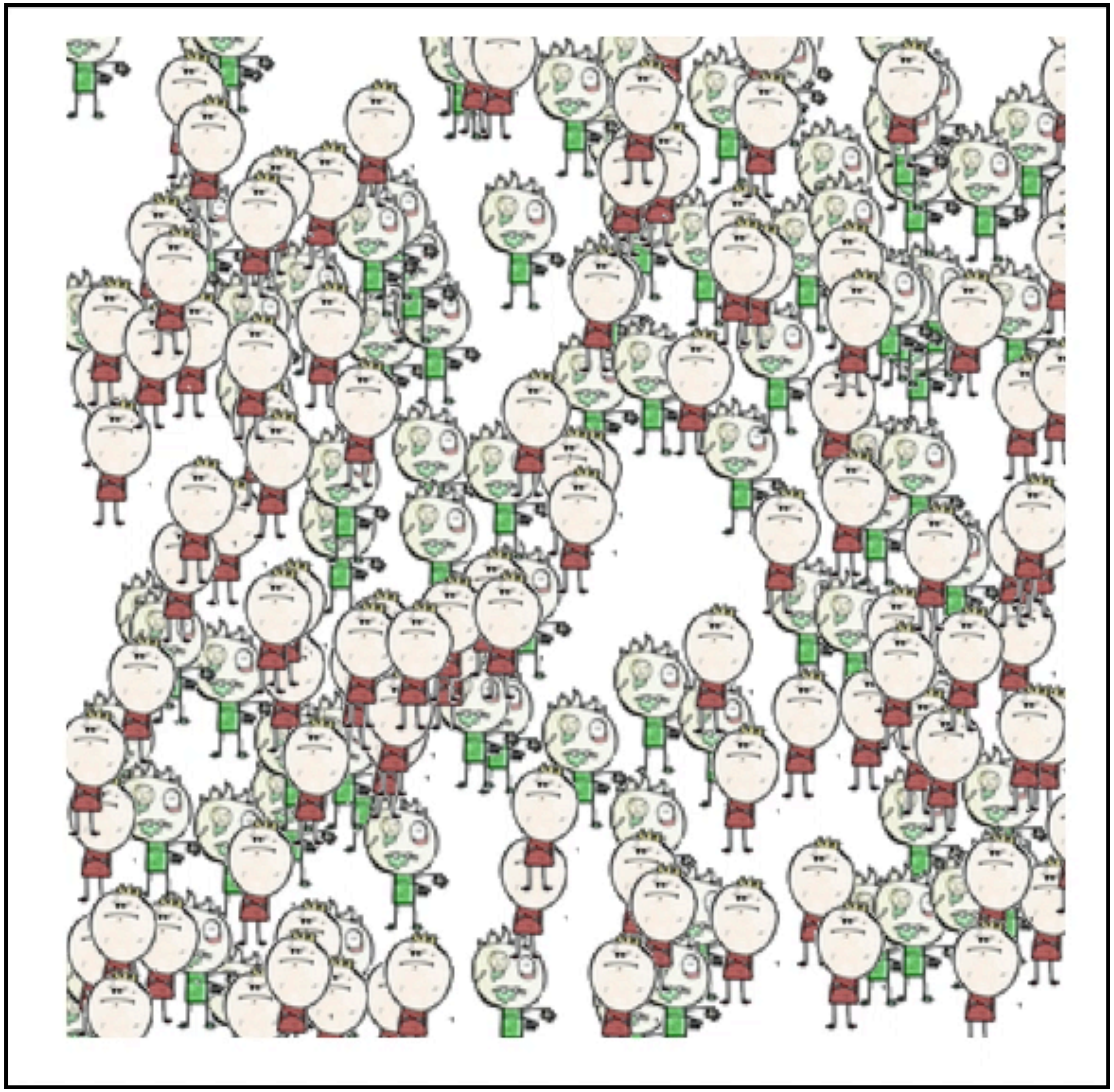
Not forbidden (as $T \to 0$), to get heavy DM

Dark matter should be (meta)stable

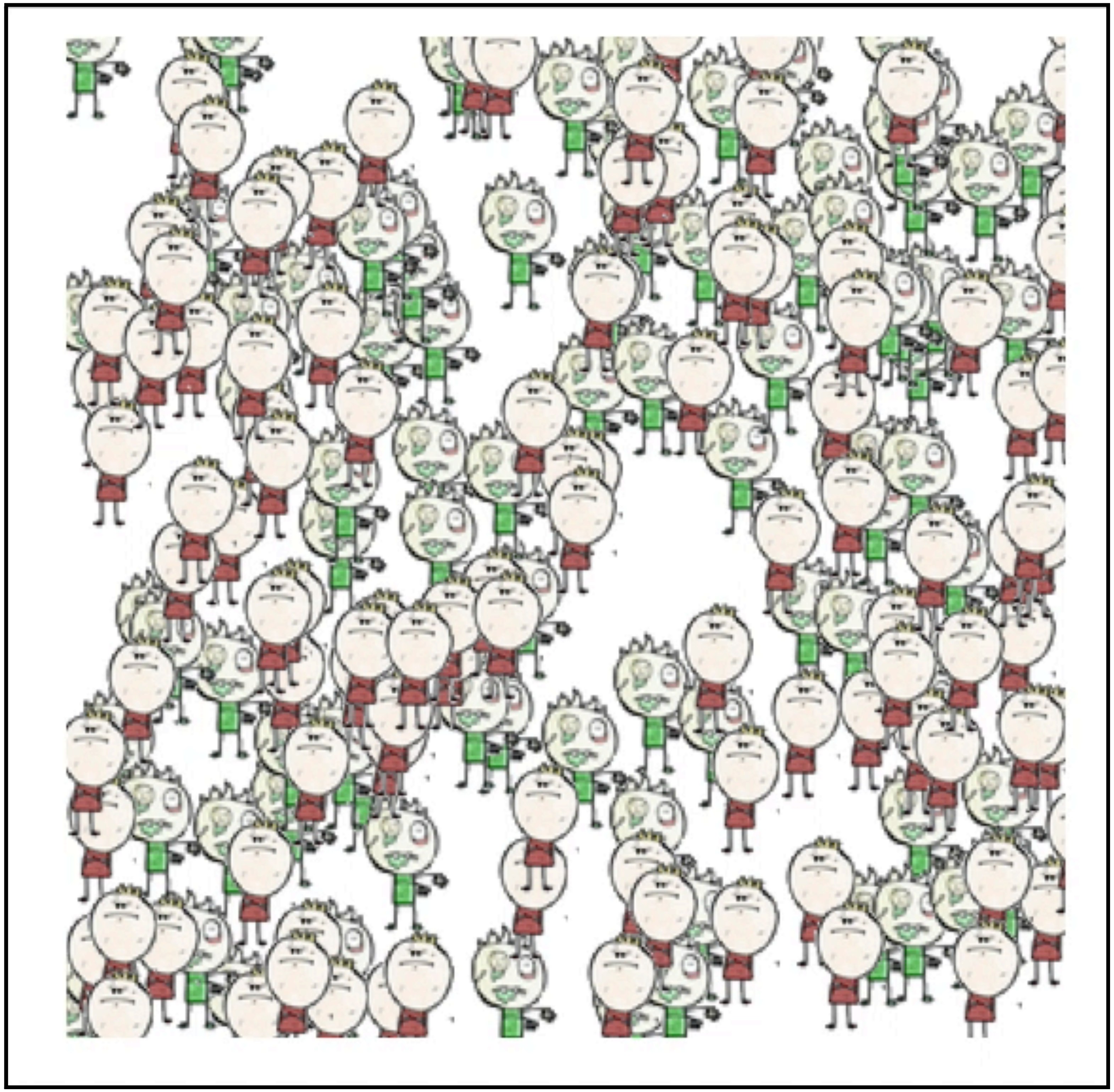
Zombie Simulation



Zombie Simulation



Zombie Simulation

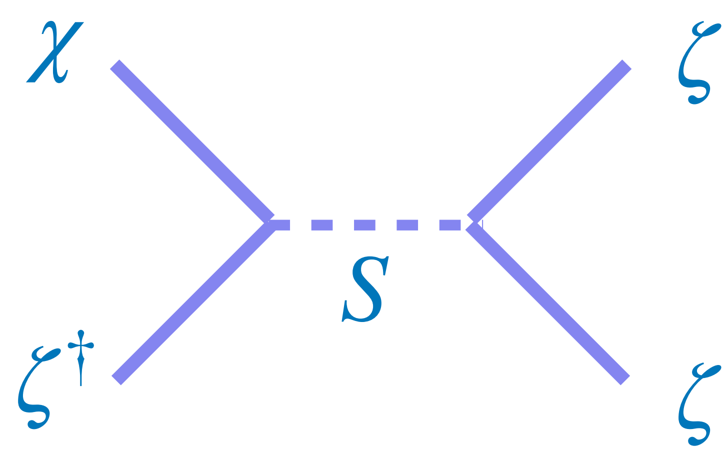


Basic Ingredients

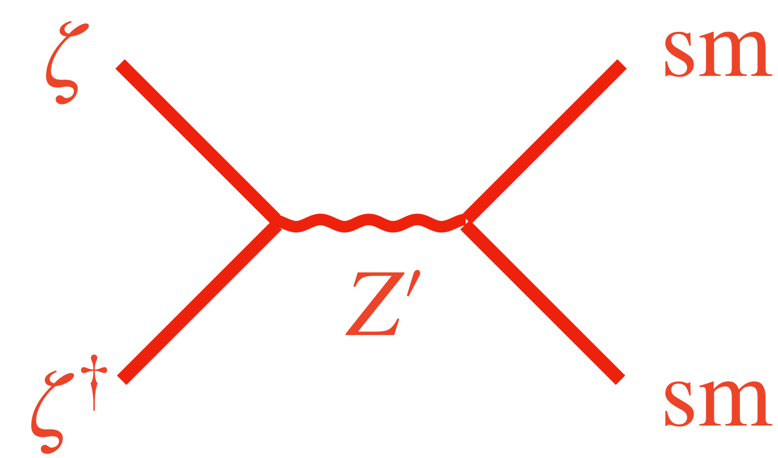
χ : dark matter

ζ : zombie

Zombie process



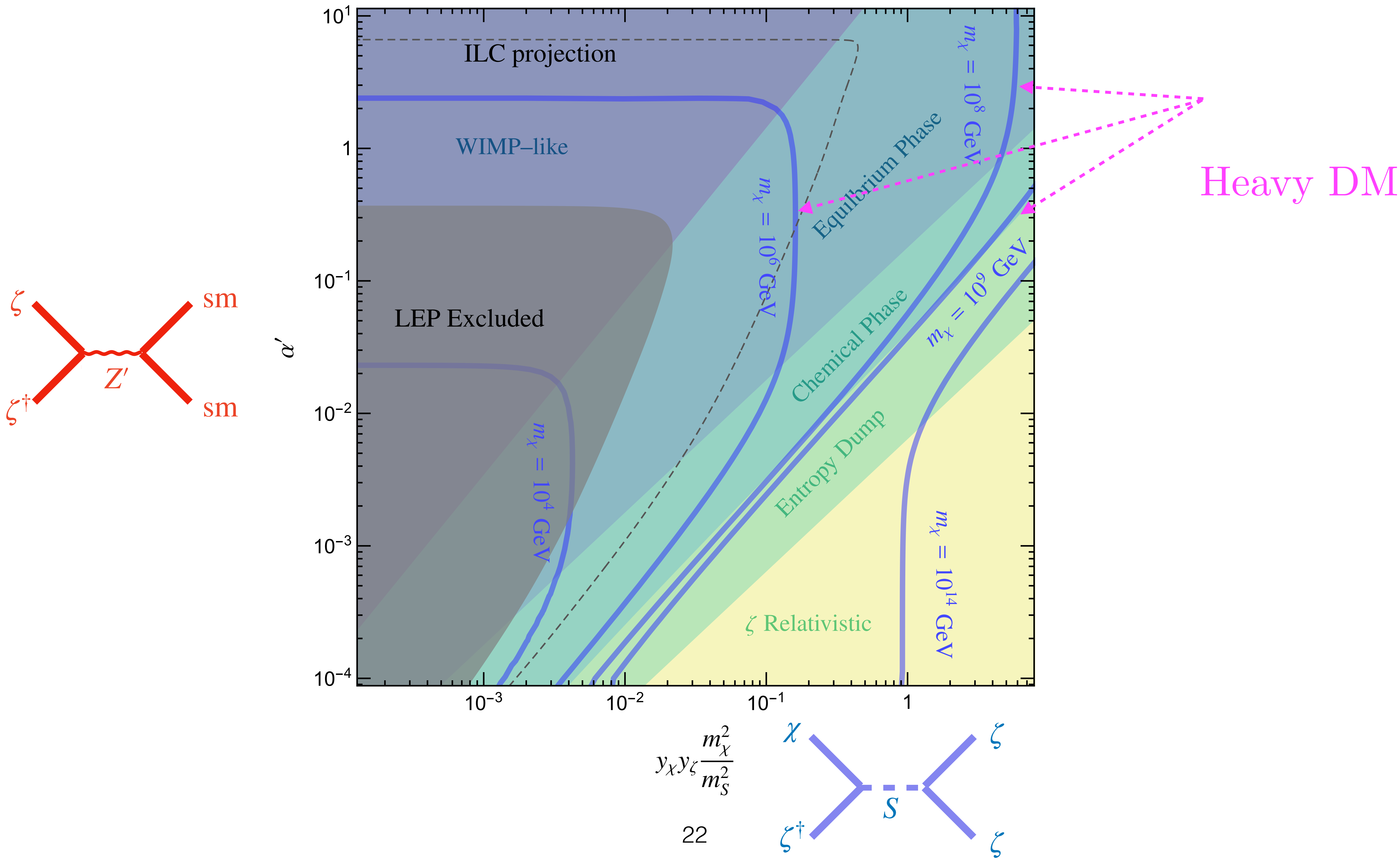
Equilibrium process



	$U(1)_{e-\mu}$
χ	3
ζ	1
S	-2

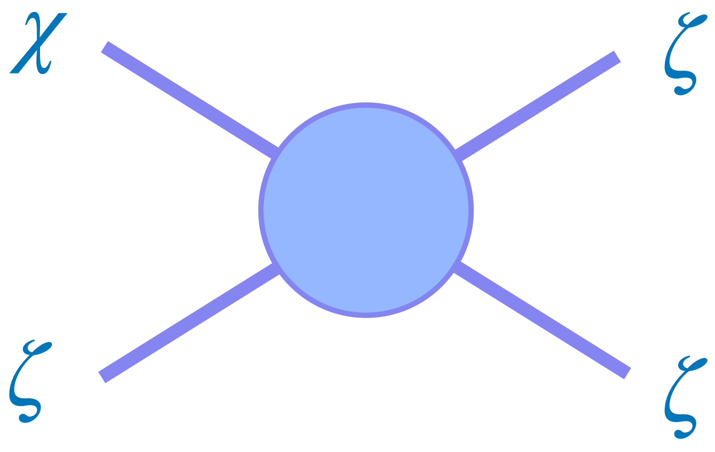
$$\mathcal{L}_{\text{yuk}} = y_\zeta S \bar{\zeta}^c \zeta + y_\chi S \bar{\zeta} \chi + y_e H \bar{\zeta} L_e + y_\mu H \bar{\zeta}^c L_\mu + \text{h.c.}$$

Phase Diagram



Metastable DM

Zombies too abundant
$\rightarrow$ zombies must decay



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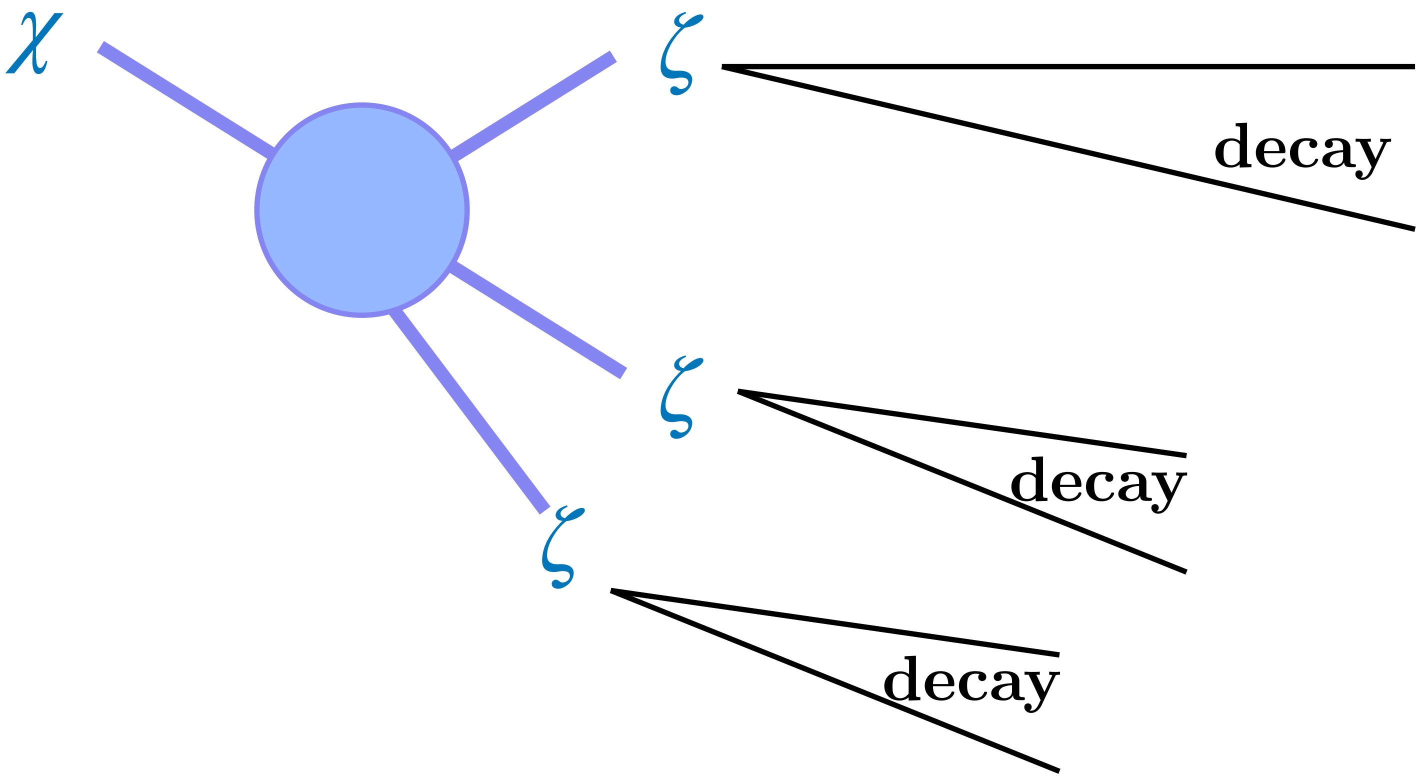
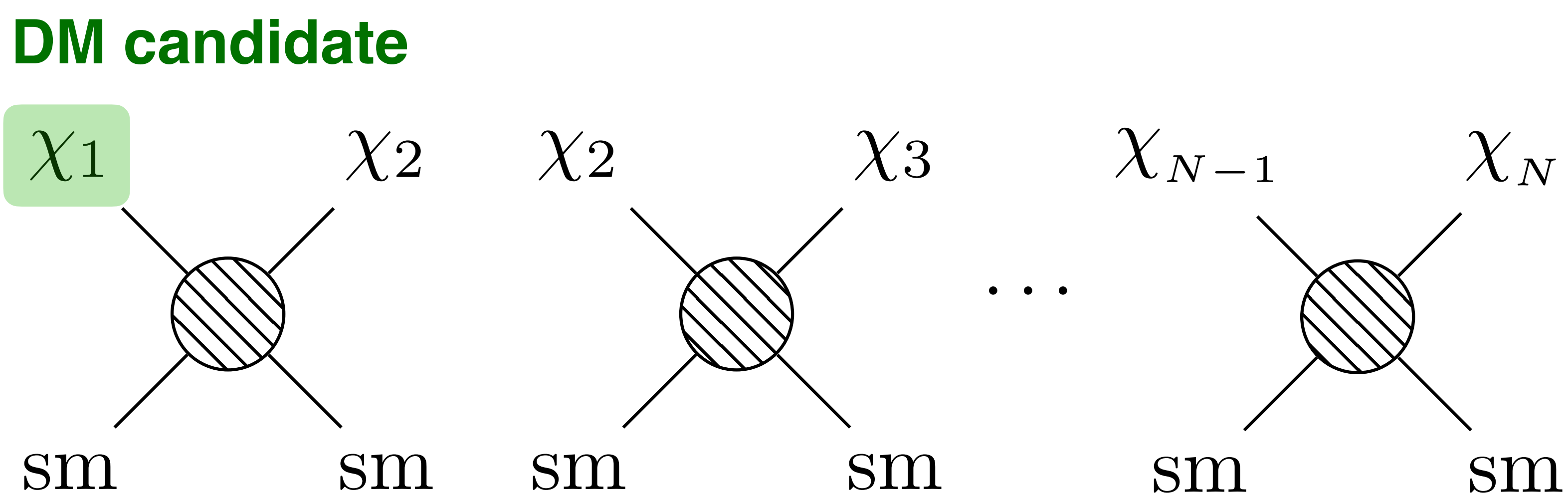


Metastable DM with strong indirect detection signal

Example #2:
Chain Dark Matter

[Kim, **EK** PRL 2019]

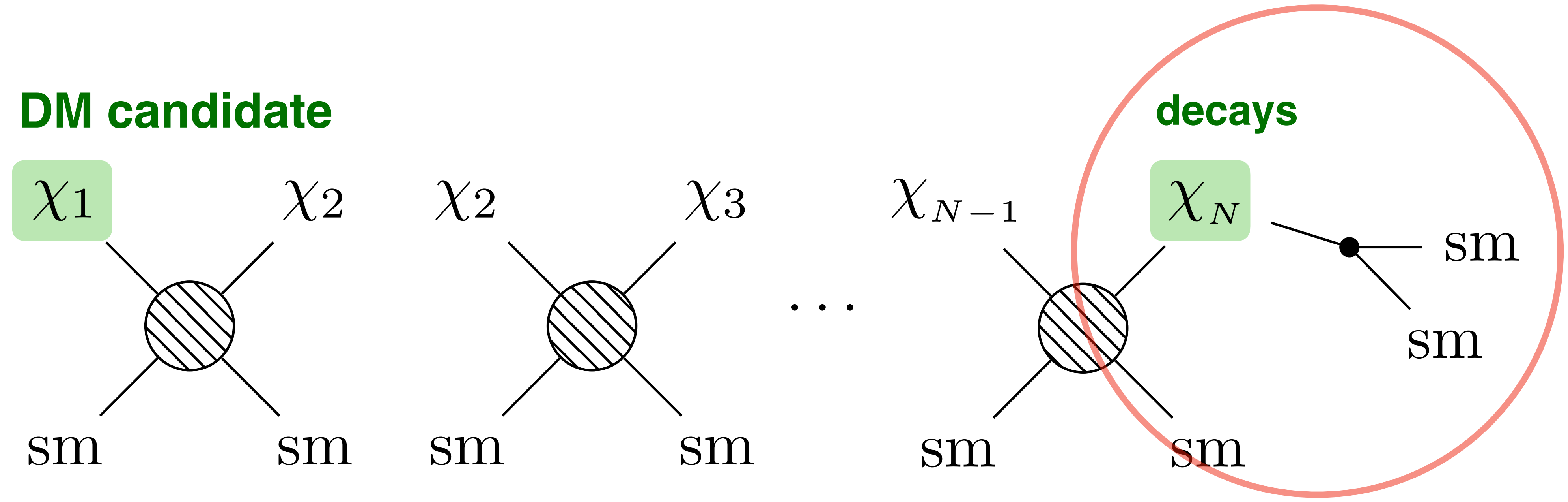
Chain Dark Matter



$$m_{\chi_1} \simeq m_{\chi_2} \simeq \cdots \simeq m_{\chi_N}$$

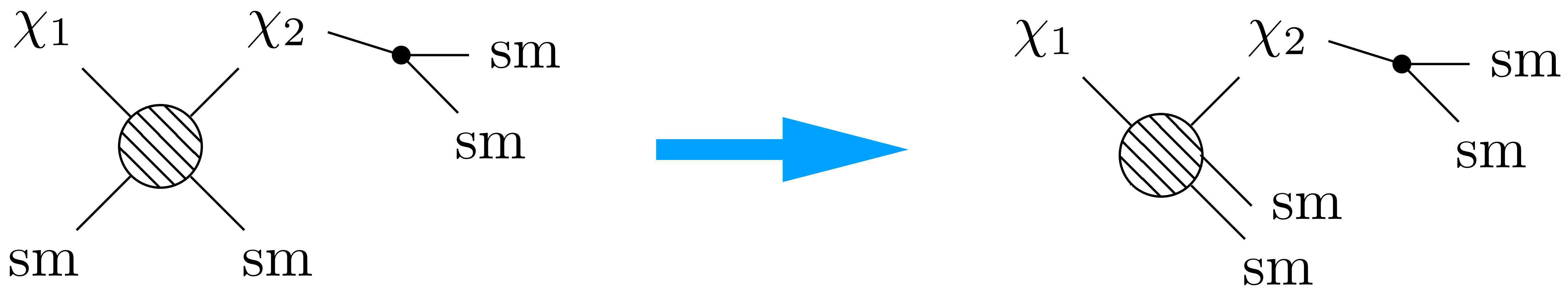
Very efficient because the SM particles are abundant

Chain Dark Matter



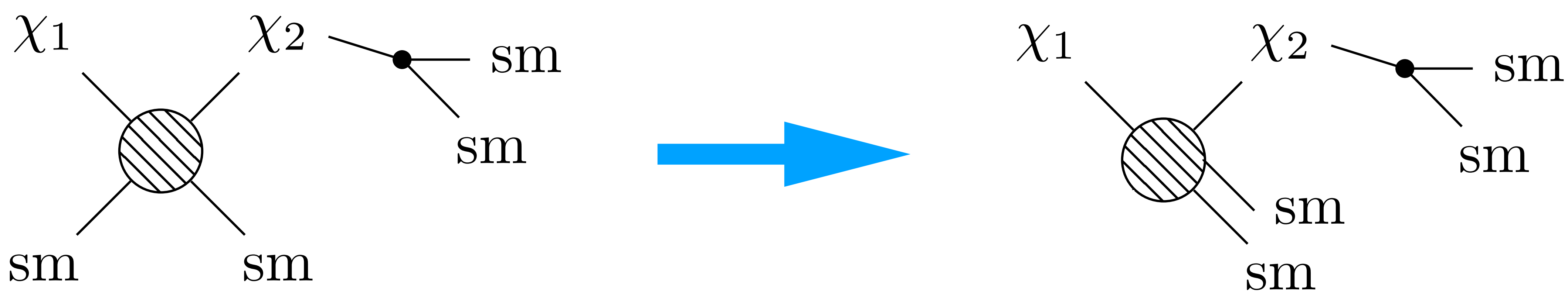
Last particles decays in equilibrium:
system is in chemical equilibrium

Need a chain

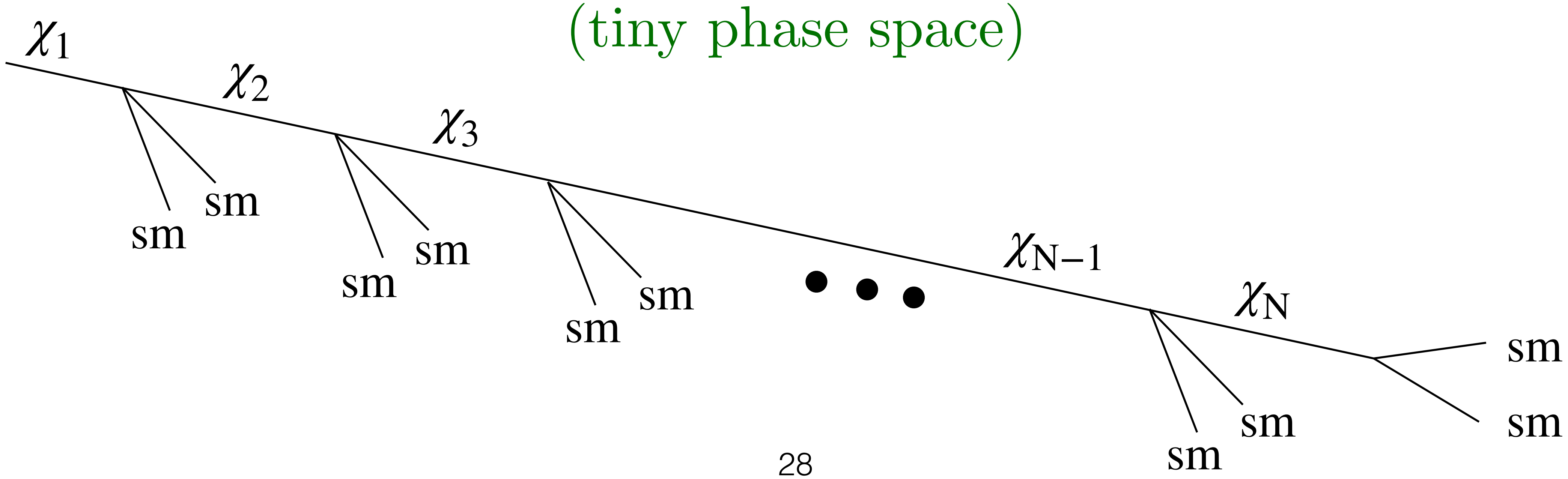


Otherwise DM is too unstable

Metastable DM

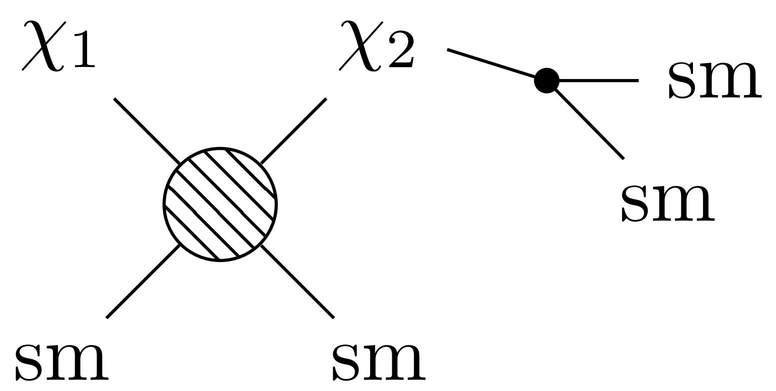


Chain makes DM metastable
(tiny phase space)



Numerics

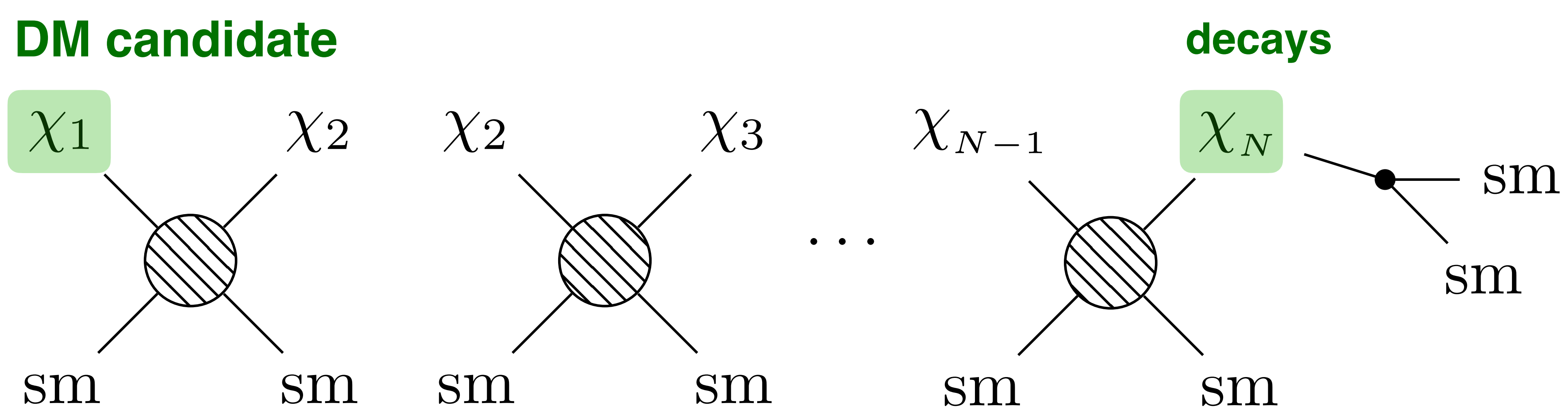
Consider 2-chain first

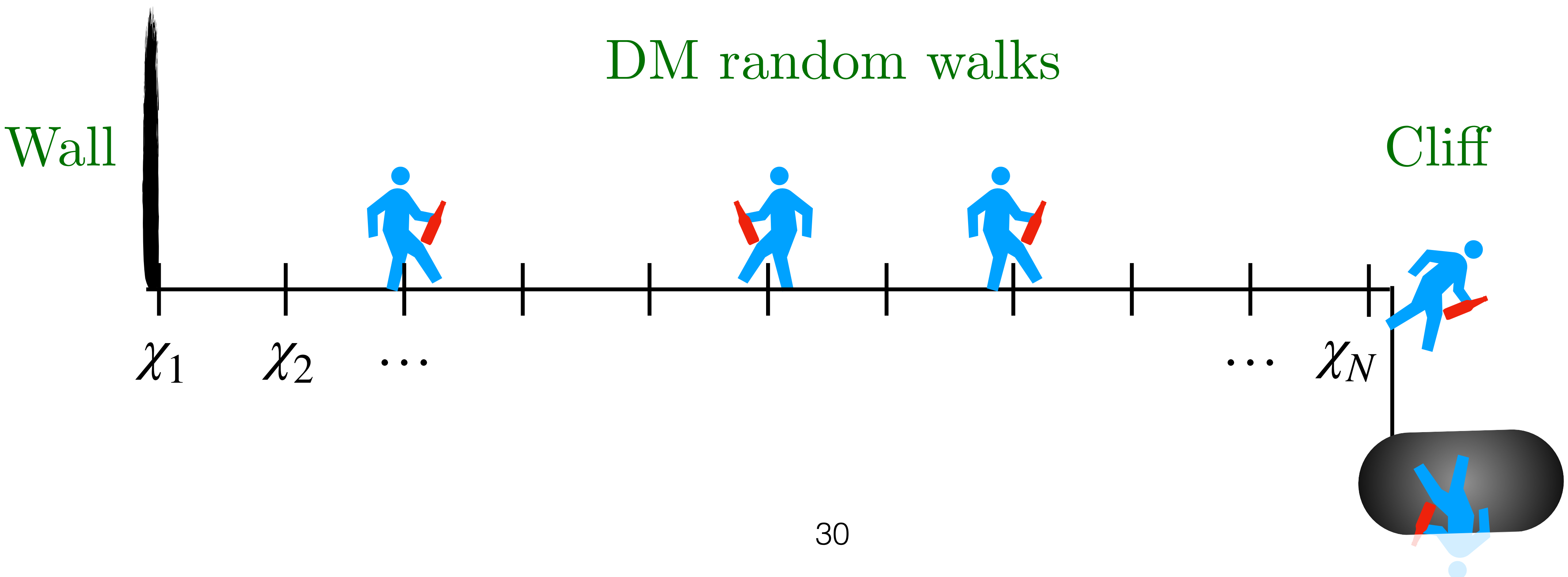


$$\langle \sigma v \rangle = \frac{1}{m_\chi^2} \qquad \rightarrow \qquad m_\chi = 6 \times 10^{14}\ \text{GeV}$$

Very heavy dark matter

Drunk DM


DM candidate
decays
χ_1
χ_2
χ_2
χ_3
χ_{N-1}
χ_N
sm
sm
sm
sm
sm
sm
sm
sm
$\cdots$


DM random walks
Wall
Cliff
χ_1
χ_2
$\cdots$
$\cdots$
χ_N

Numerics

For the N-chain

$$-mT\frac{\partial N_1'}{\partial T} = -\langle \sigma v \rangle n_{\rm sm}(N_1 - N_2)$$

$$-mT\frac{\partial N_j'}{\partial T} = \langle \sigma v \rangle n_{\rm sm}(N_{j-1} - N_j) - \langle \sigma v \rangle n_{\rm sm}(N_j - N_{j+1})$$

$$-mT\frac{\partial N_N'}{\partial T} = \langle \sigma v \rangle n_{\rm sm}(N_{N-1} - N_N) - \Gamma_{\chi_N}(N_N - N_N^{\rm eq})$$

Turn it into a diffusion equation

$$(\partial_\tau - D\partial_\ell^2)N_\ell(\tau) = 0$$

$$\ell = \pi j/[2(N-1)] \qquad \tau = -T/m$$

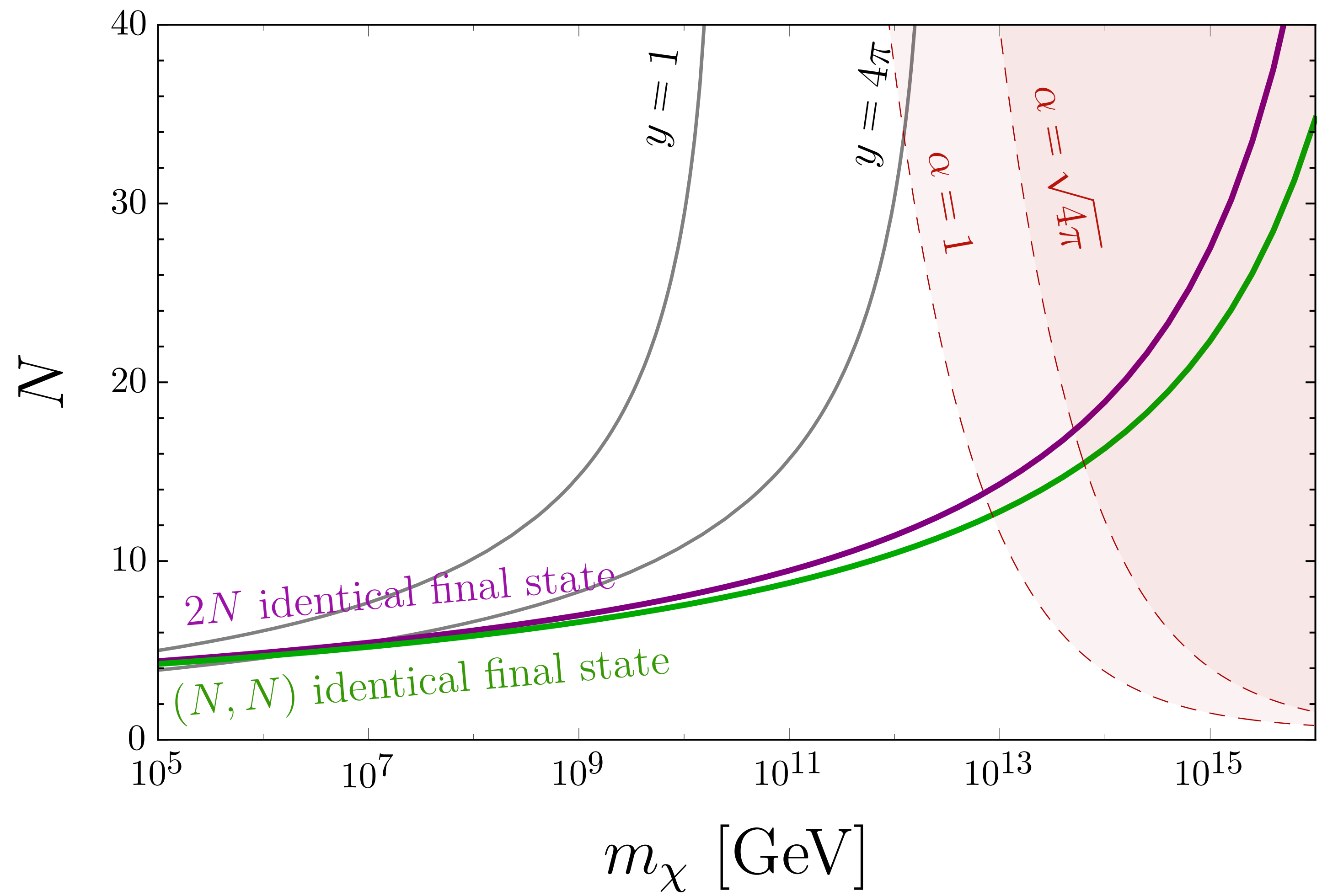
Diffusion coefficient:

$$D = \pi^2\lambda/[4(N-1)^2]$$

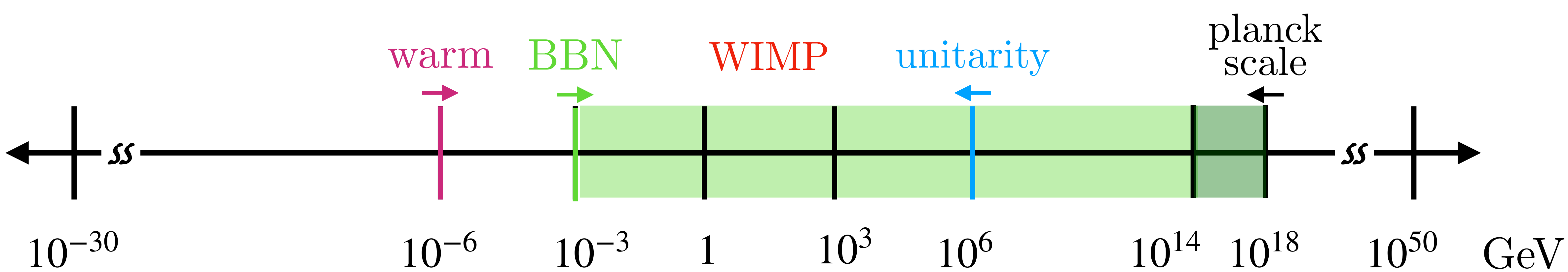
Boundary conditions

$$\partial_\ell N|_{\ell=0} = 0, \qquad N_{\pi/2}(\tau) = N^{\rm eq}(\tau)$$

Chain DM



40
30
20
10
0
N
10^5
10^7
10^9
10^{11}
10^{13}
10^{15}
m_χ [GeV]
$y = 1$
$y = 4\pi$
$\alpha = 1$
$\alpha = \sqrt{4\pi}$
$2N$ identical final state
(N, N) identical final state



warm
BBN
WIMP
unitarity
planck
scale
10^{-30}
10^{-6}
10^{-3}
1
10^3
10^6
10^{14}
10^{18}
10^{50}
GeV

Beyond Thermal Unitarity

Both cases: nearly degenerate dark sector states and metastable dark matter.

Look for cosmic rays up to the Planck scale!

This is generic for going beyond thermal unitarity

Will prove this with students Ronny Frumkin and Itay Lavie

Example #3:
Squeezeout

Asadi, Kramer, **EK**, Ridgway, Slatyer, Smirnov, PRL 2021, PRD 2021

Squeeze-out

Simple theory:

$$SU(3),\ N_F = 1 \qquad m_Q \gg T_C \simeq \Lambda_{\text{confinement}}$$

$$\mathscr{L} \supset -\frac{1}{4} G^{\mu\nu} G_{\mu\nu} + \bar{Q}\left(i\gamma_\mu D^\mu - m_Q\right) Q\,,$$

Asymptotically free with first order phase transition

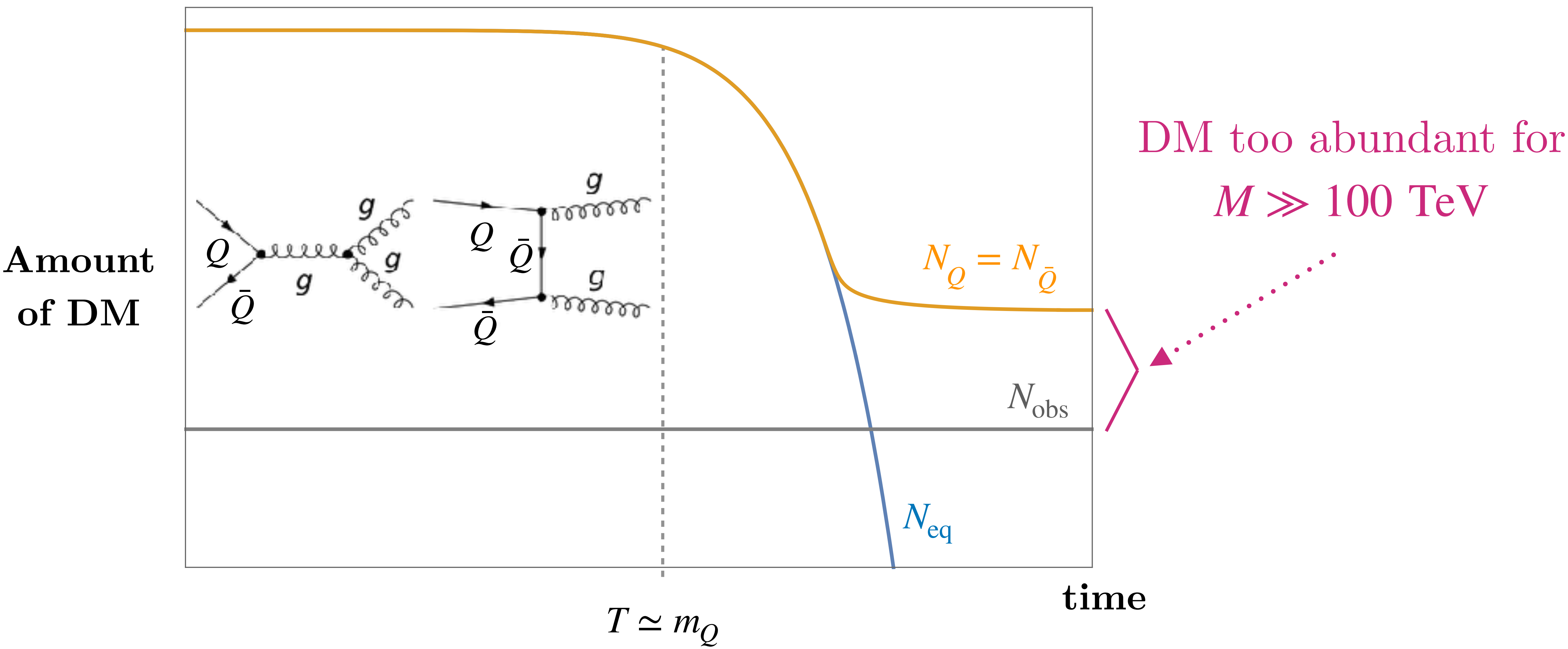
Bounds states:

Mesons $Q\bar{Q}$ → sm

Baryons $QQQ,\ \bar{Q}\bar{Q}\bar{Q}$

stable, DM?

Quark Freezeout



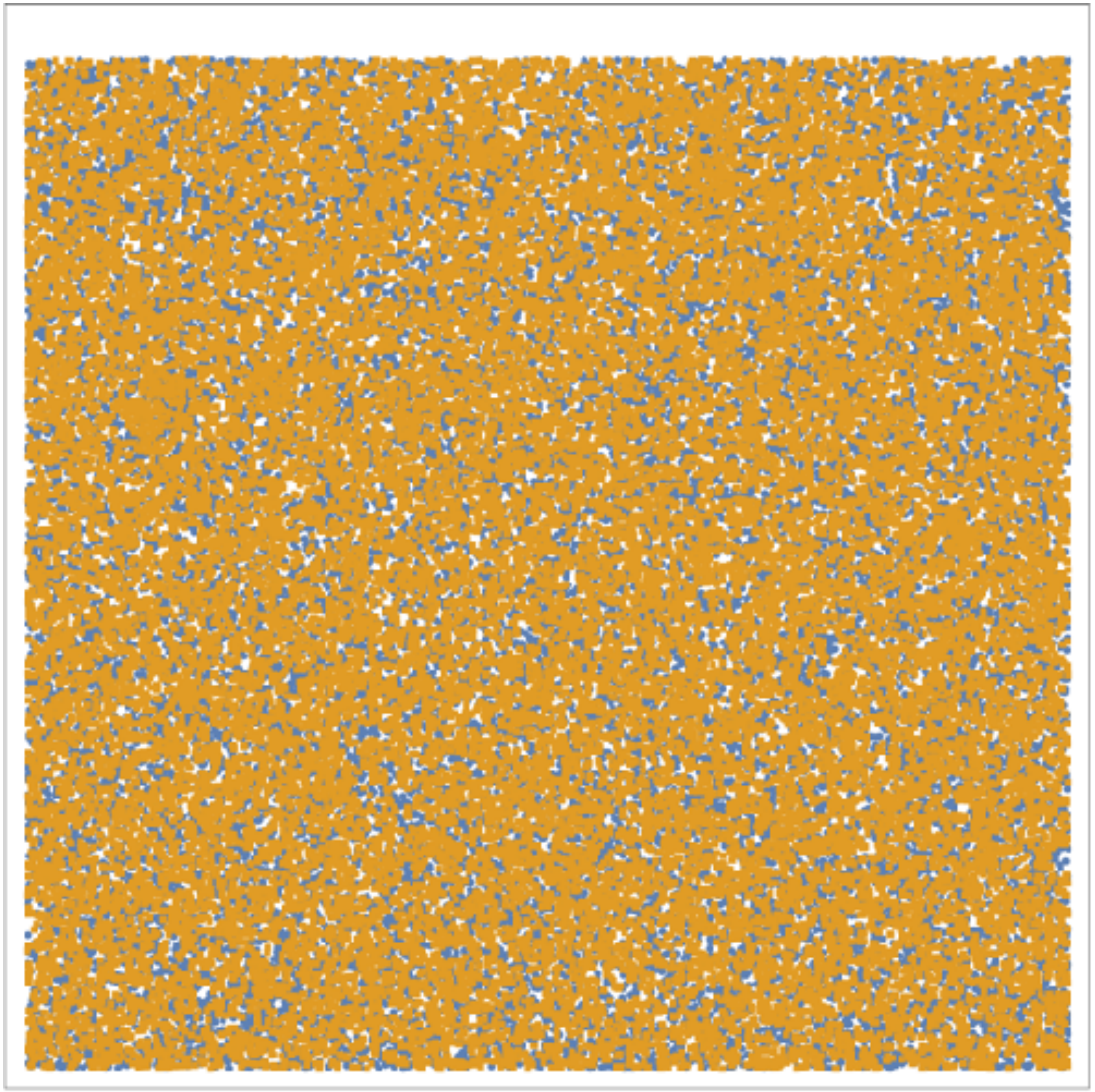
Phase Transition

Not the end of the story

How do these pair up into mesons and baryons?
(only baryons will be DM)

What does the phase transition do?

Stage 1: Freezeout



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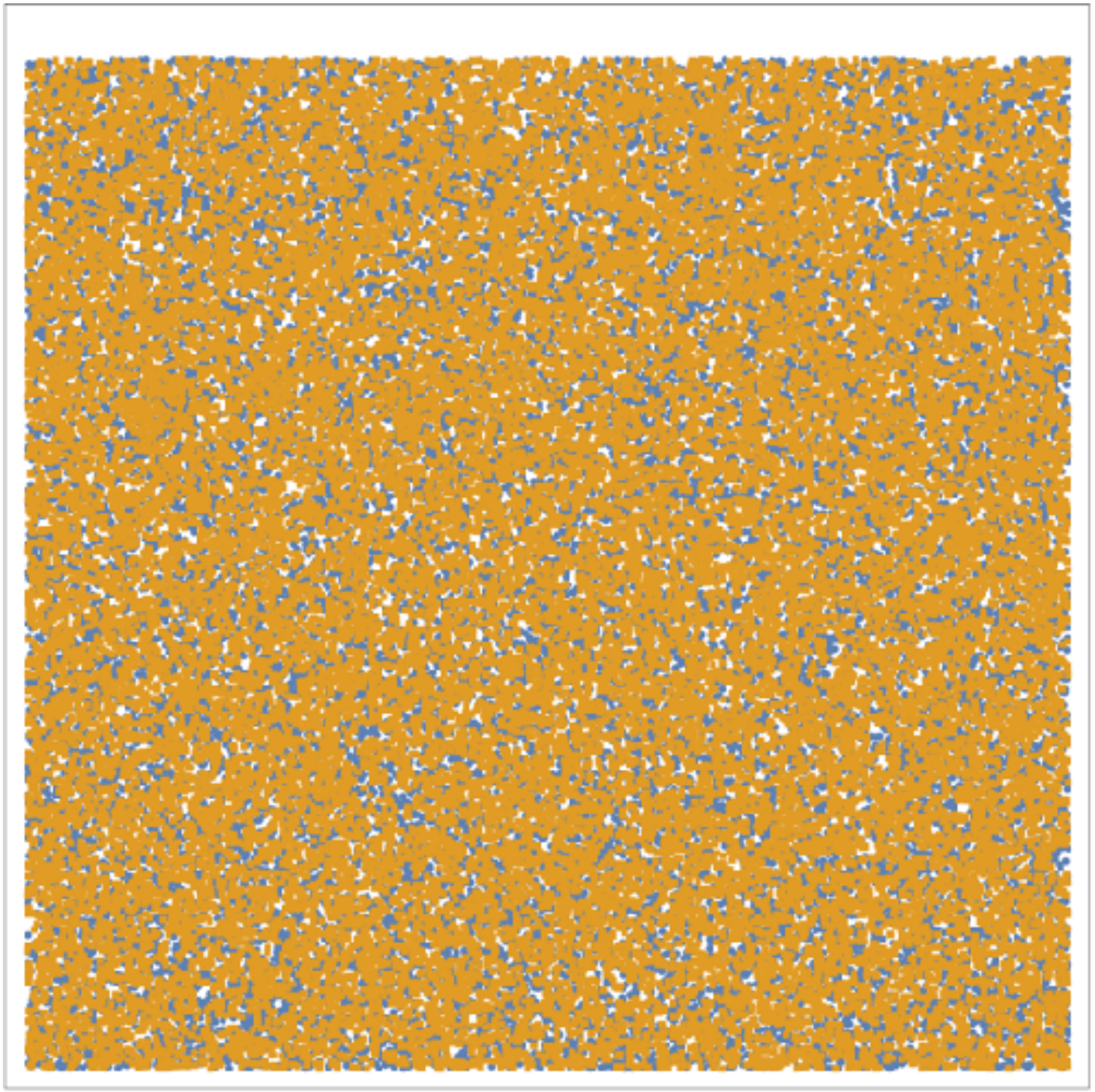

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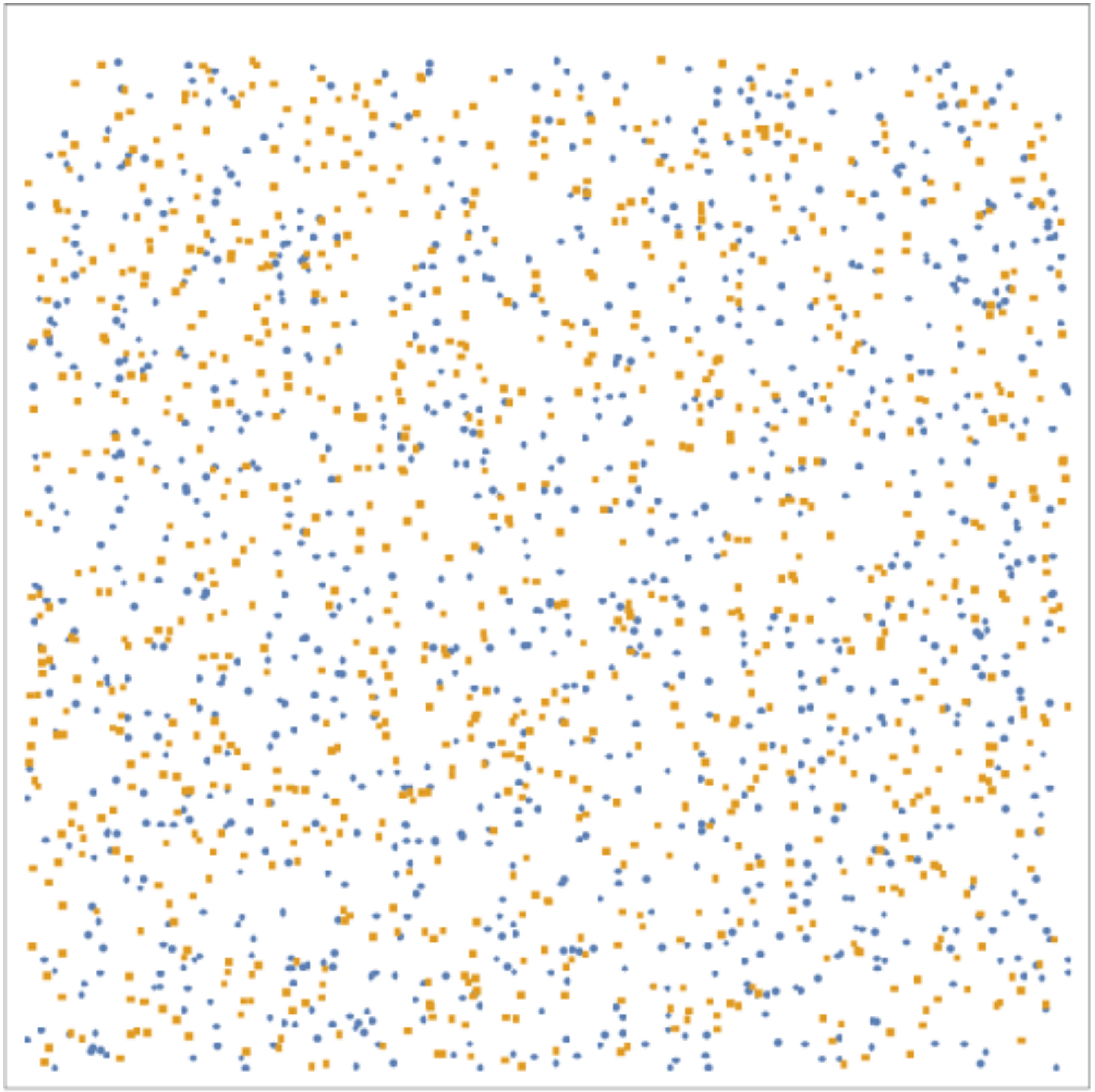
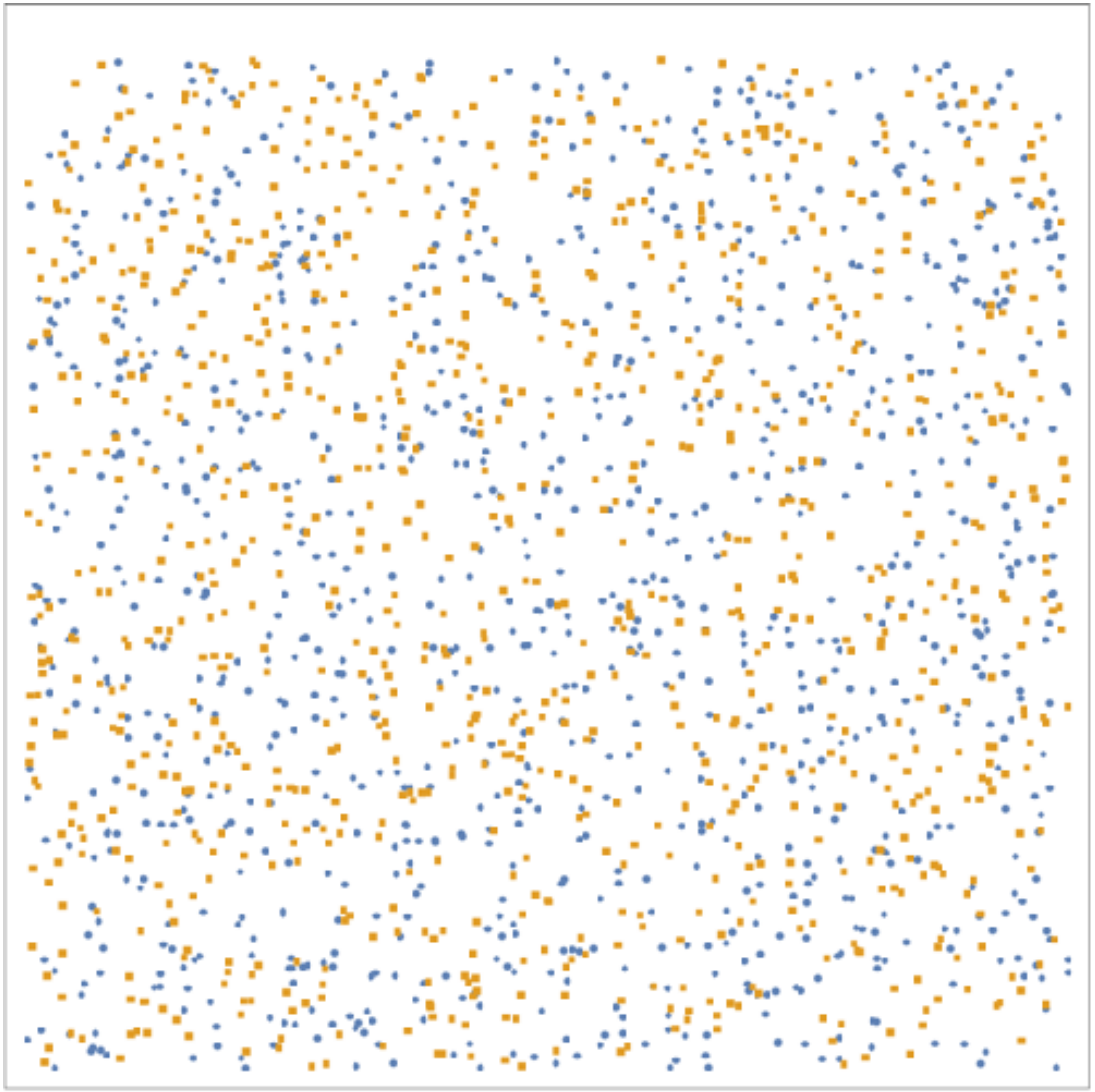


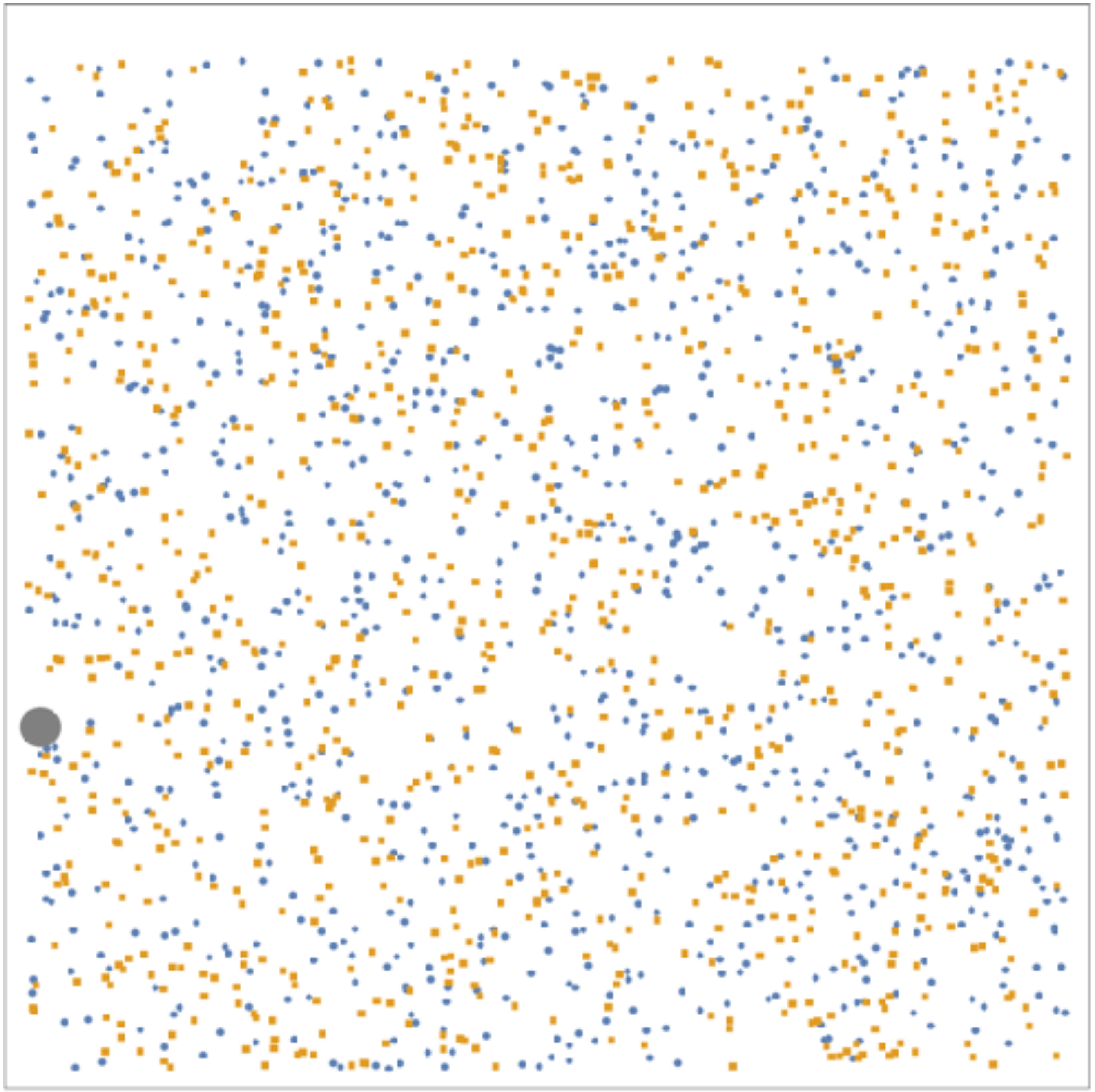
Too far apart to 'recombine'
into hadrons

Stage 1: Freezeout



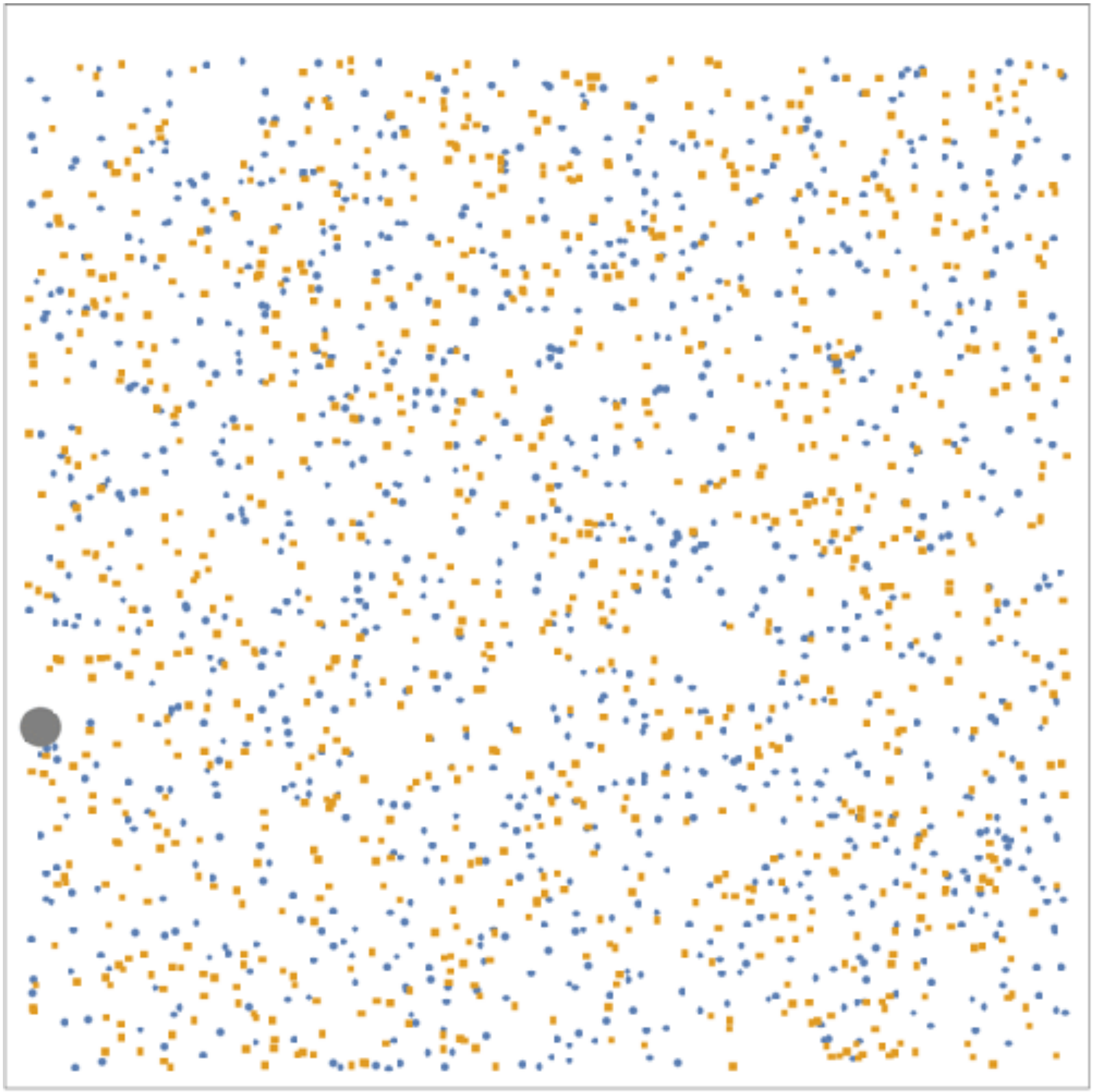
Too far apart to 'recombine' into hadrons

Stage 2: Nucleation



$T \sim T_c$

Stage 2: Nucleation



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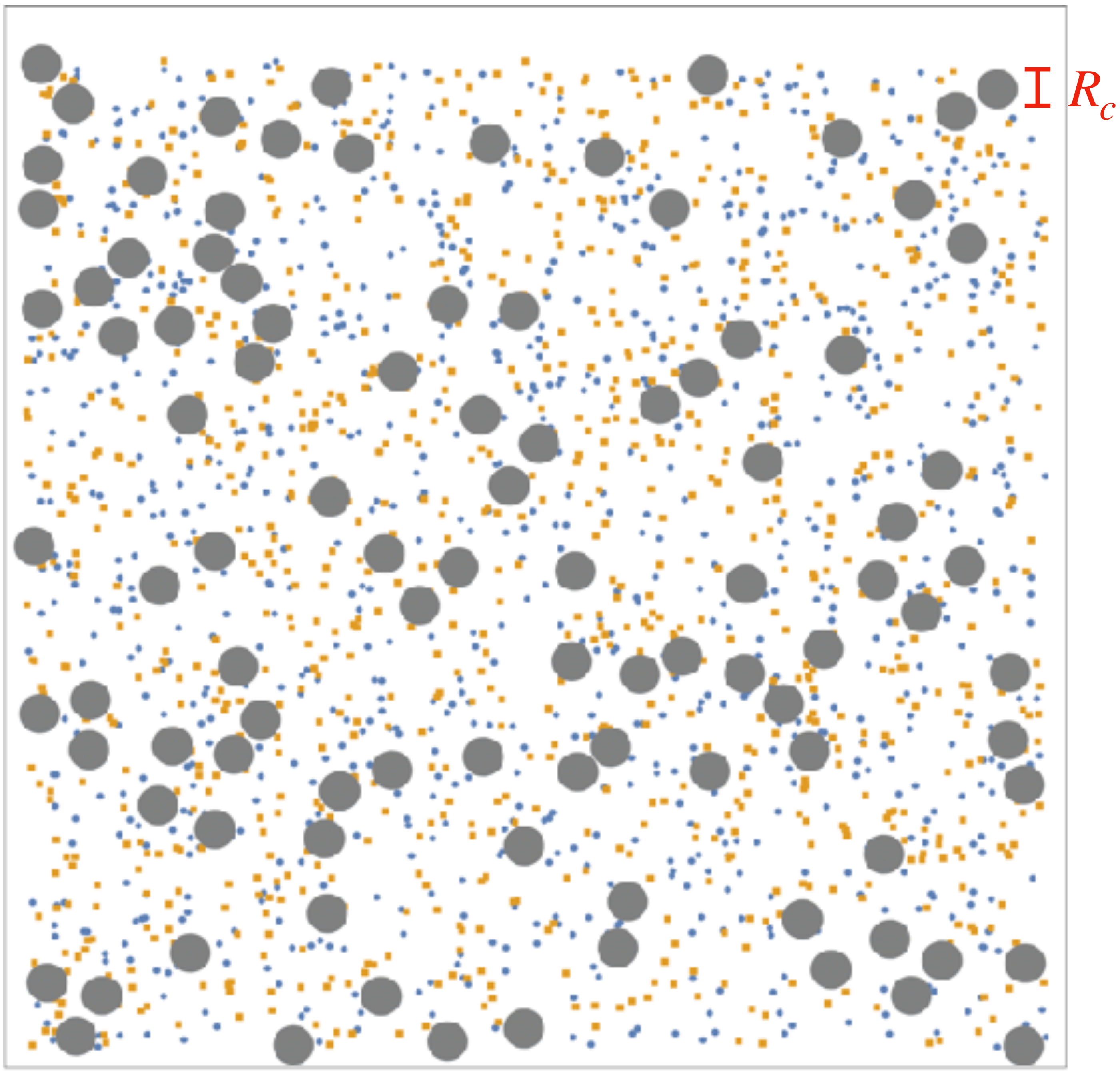


Bubble nucleation

Nucleation rate:

$$\Gamma \simeq T^4 e^{-\frac{F}{T_c}}$$

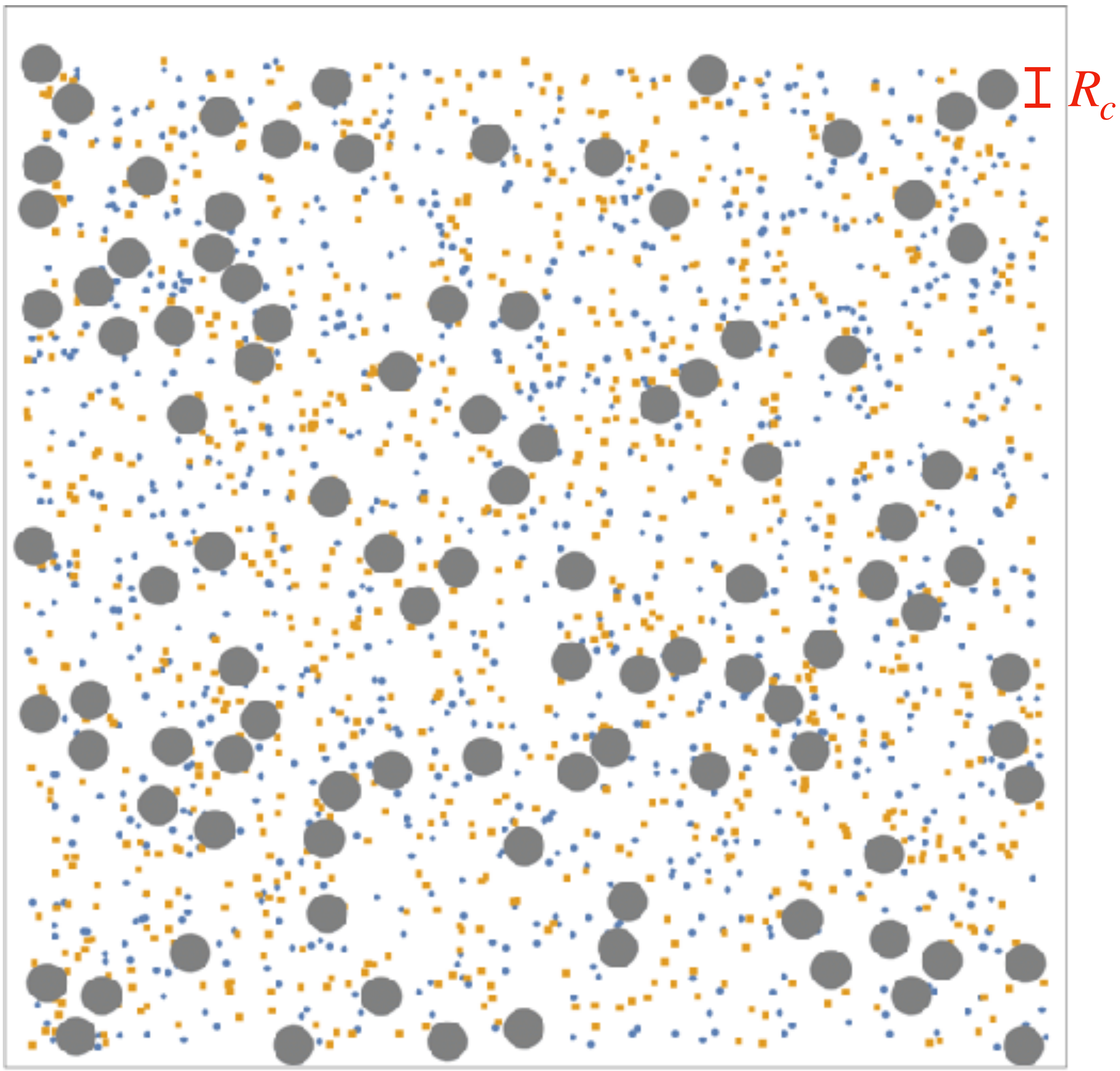
Minimal bubble size

$$R_c = \frac{2\sigma T_c}{l\,(T_c - T)}$$

Free energy at critical size

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

Stage 2: Nucleation



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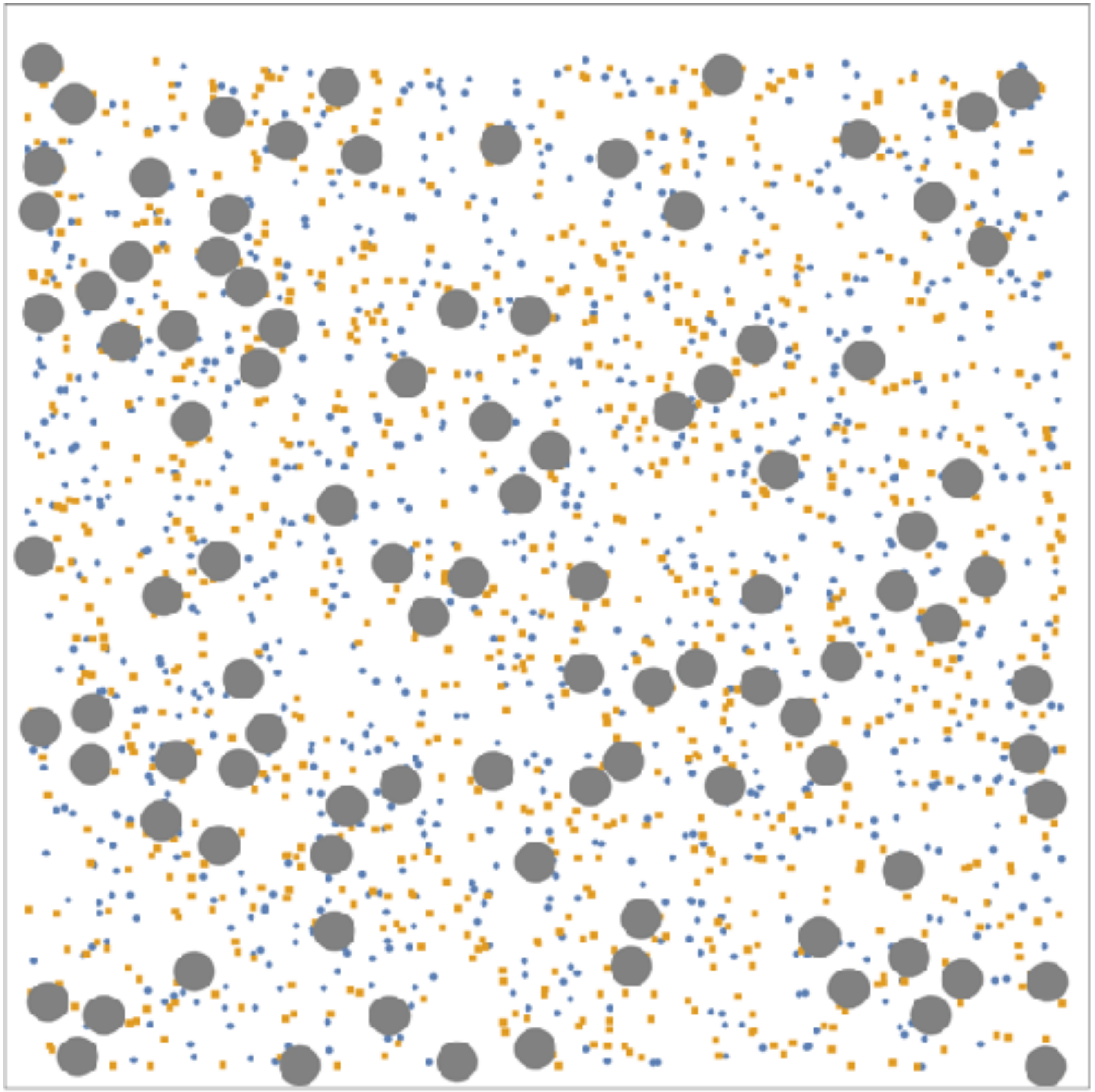
Stage 3: Growth and Coalescing



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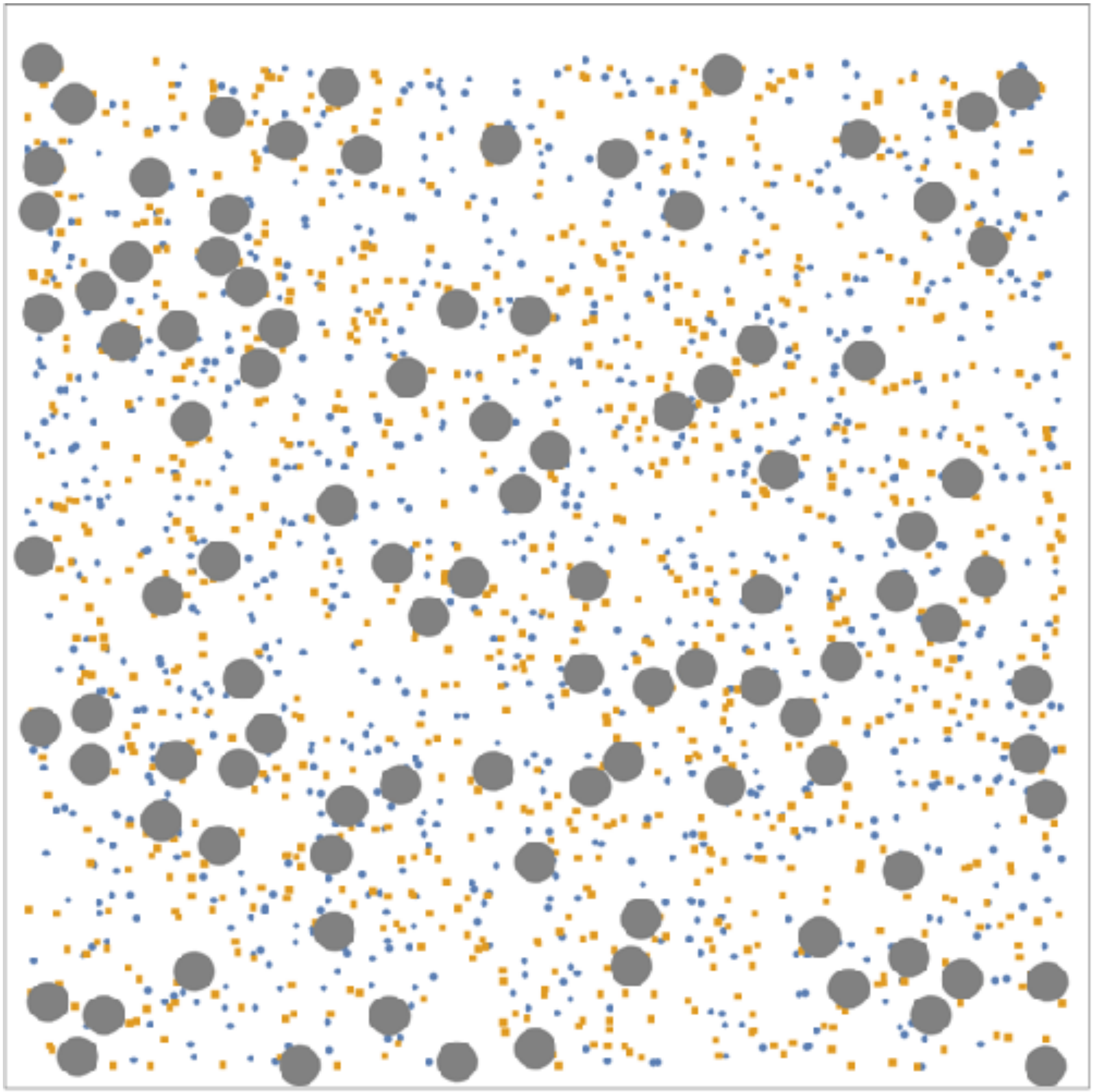

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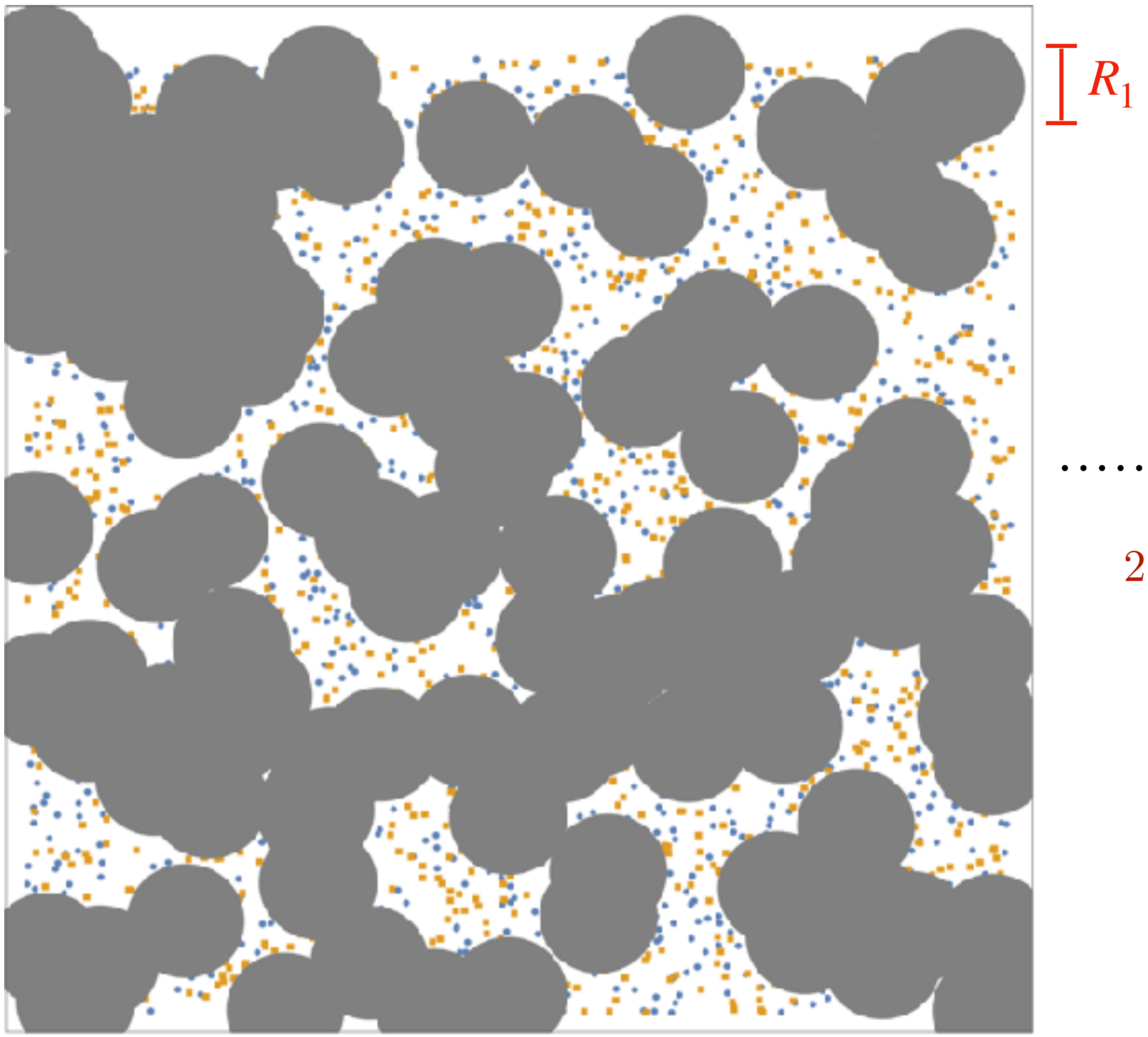


Coalescing

Rate to coalesce fast for

$$R_1 \simeq M_{\rm pl}^{2/3}/T_c^{5/2}$$

Witten 84

2 bubbles radius $R \rightarrow$ bubble radius $2^{2/3}R$

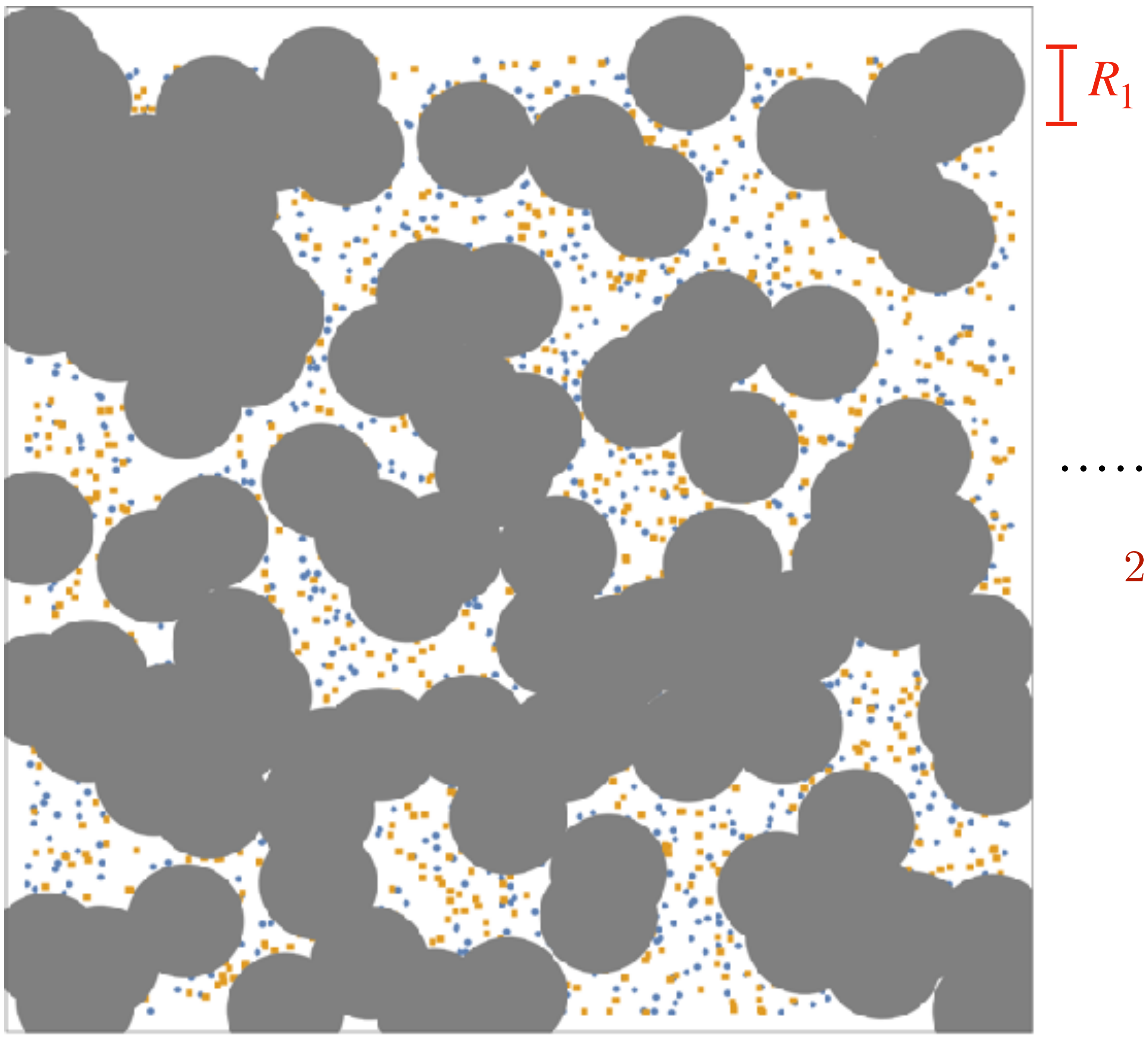
Force and time needed to rearrange

$$\rho\frac{4}{3}\pi^3 R^3 \frac{R}{t^2} \sim Ma = F \sim \frac{\Delta E}{R} \sim 4\pi R^2 \frac{\sigma}{R}$$

Time is faster than Hubble ($t < H^{-1}$)

$$R_1 \lesssim \left(\frac{\sigma}{\rho H^2}\right)^{1/3} \sim M_{\rm pl}^{2/3}/T_c^{5/2}$$

Stage 3: Growth and Coalescing



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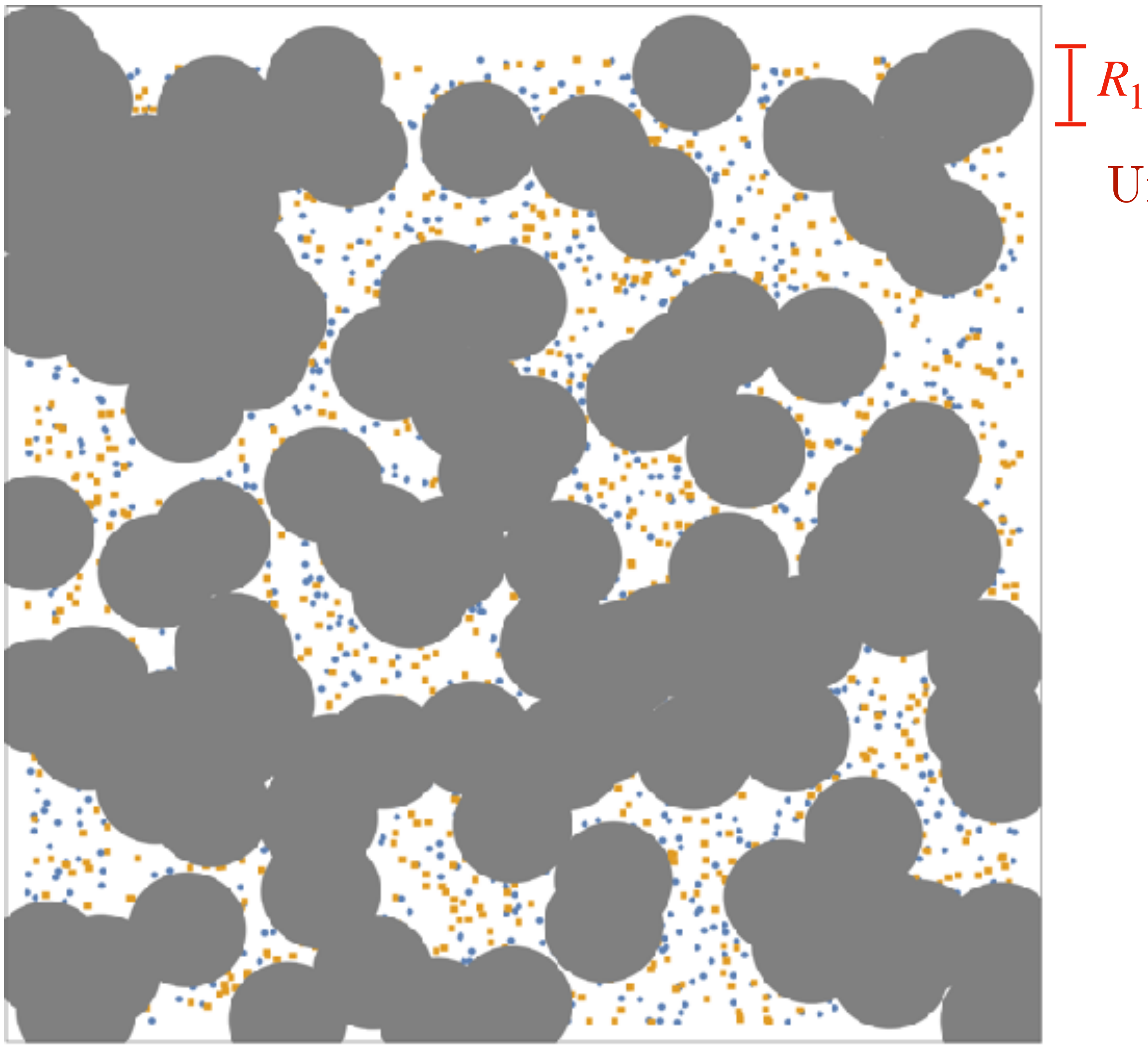
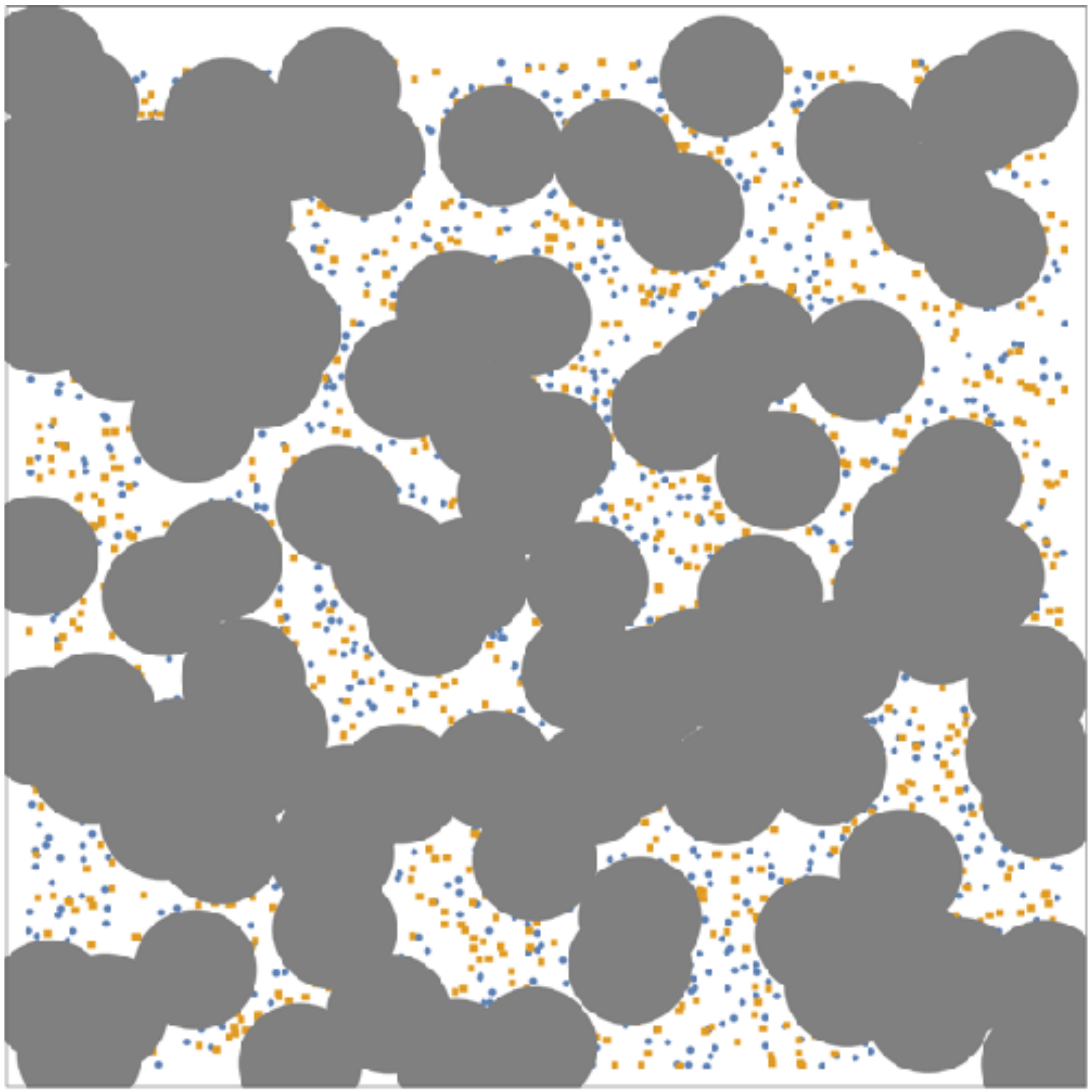


Pessimist

Universe now half full with bubbles with size

$$R_1 \simeq M_{\rm pl}^{2/3}/T_c^{5/2}$$

Stage 3: Growth and Coalescing



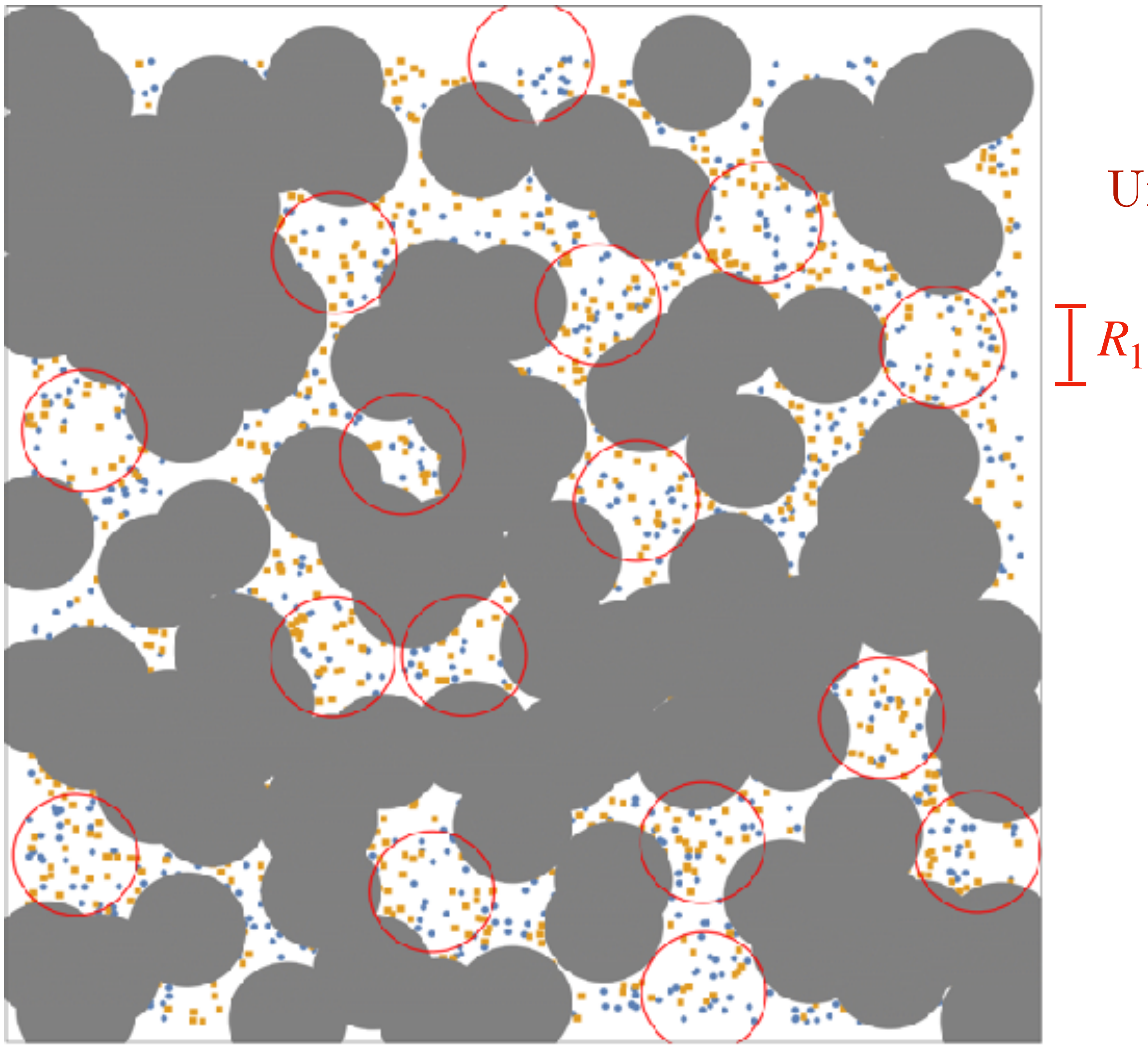
R_1

Pessimist

Universe now half full with bubbles with size

$$R_1 \simeq M_{\rm pl}^{2/3}/T_c^{5/2}$$

Stage 4: Pockets

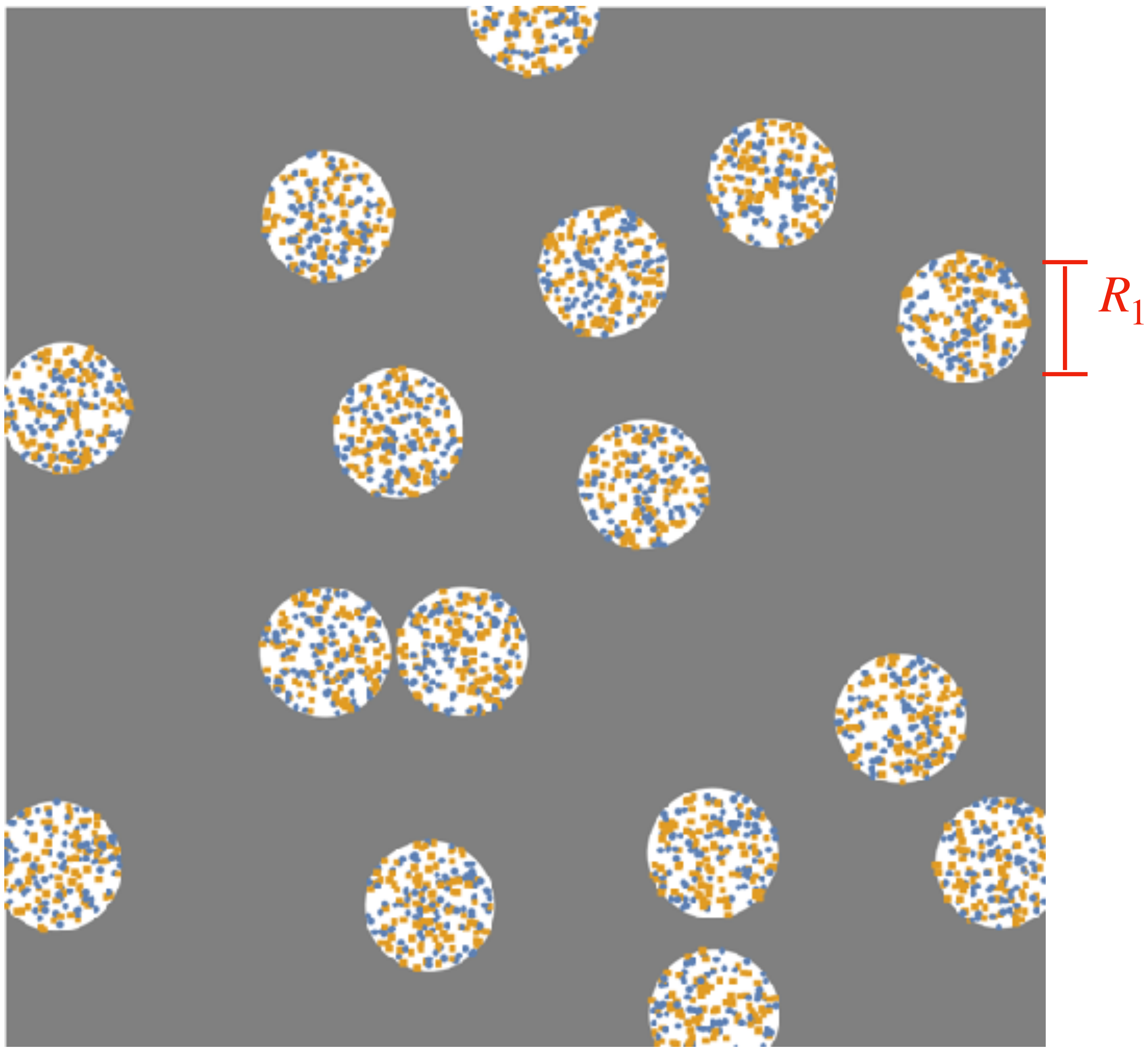


Optimist

Universe now half full with pockets with size

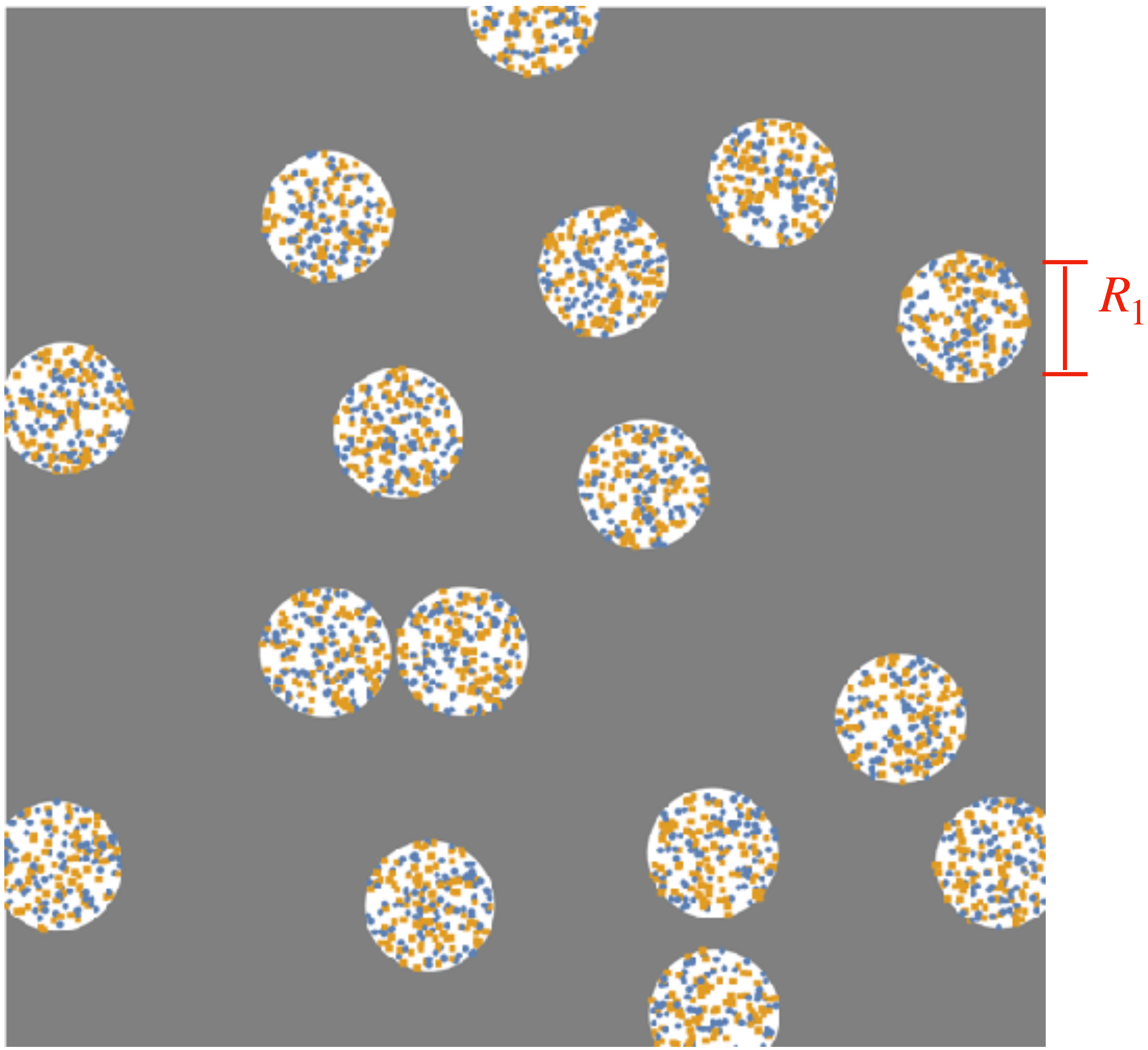
$$R_1 \simeq M_{\rm pl}^{2/3}/T_c^{5/2}$$

Stage 5: Shrinkage



Pockets shrink
condensing quarks and antiquarks

Stage 5: Shrinkage



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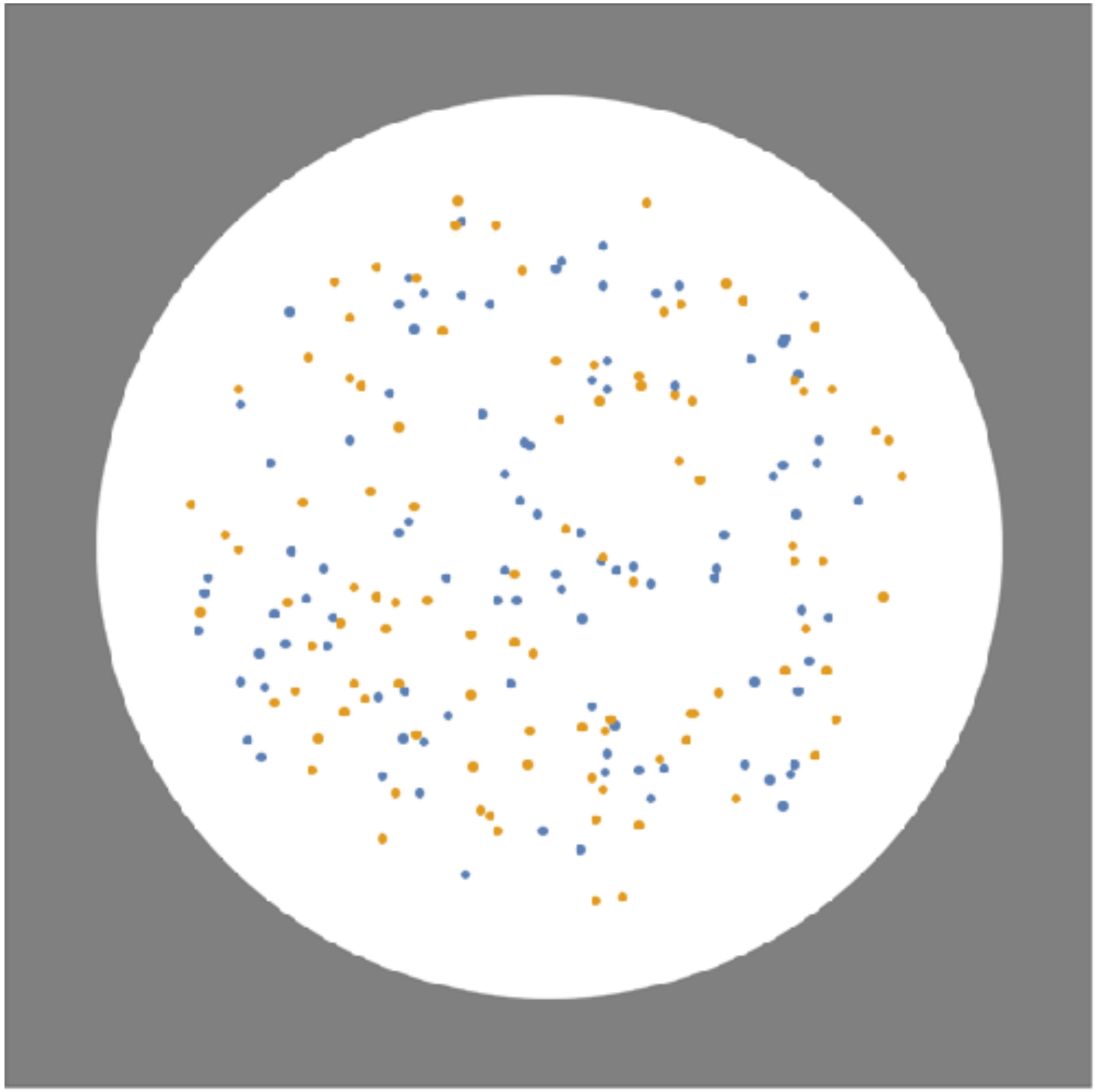

quarks cannot escape

$$\Gamma_{\text{string}} \sim \frac{m_q}{4\pi^3} e^{-m_q^2/\Lambda^2}$$

only hadrons can escape

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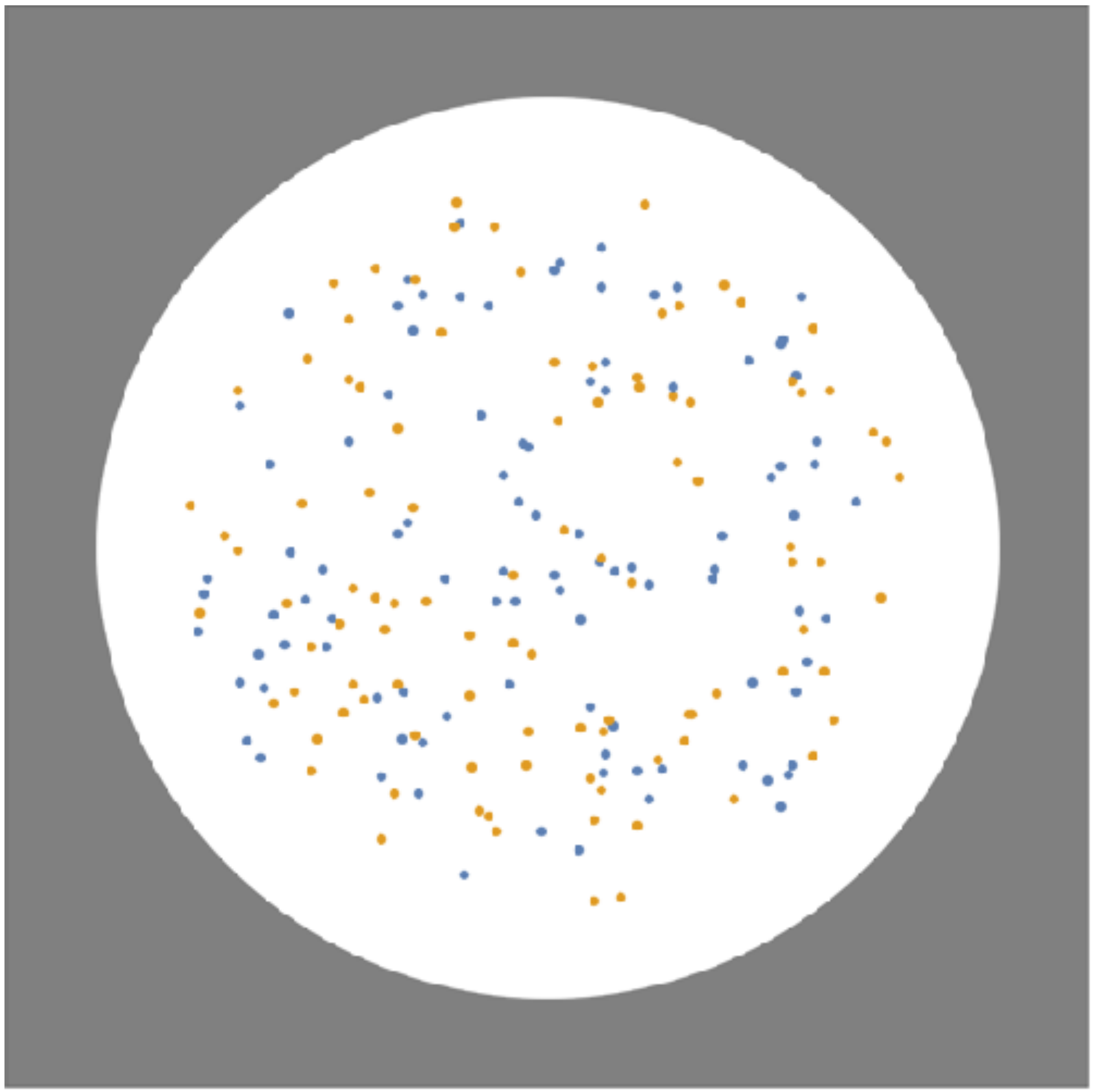

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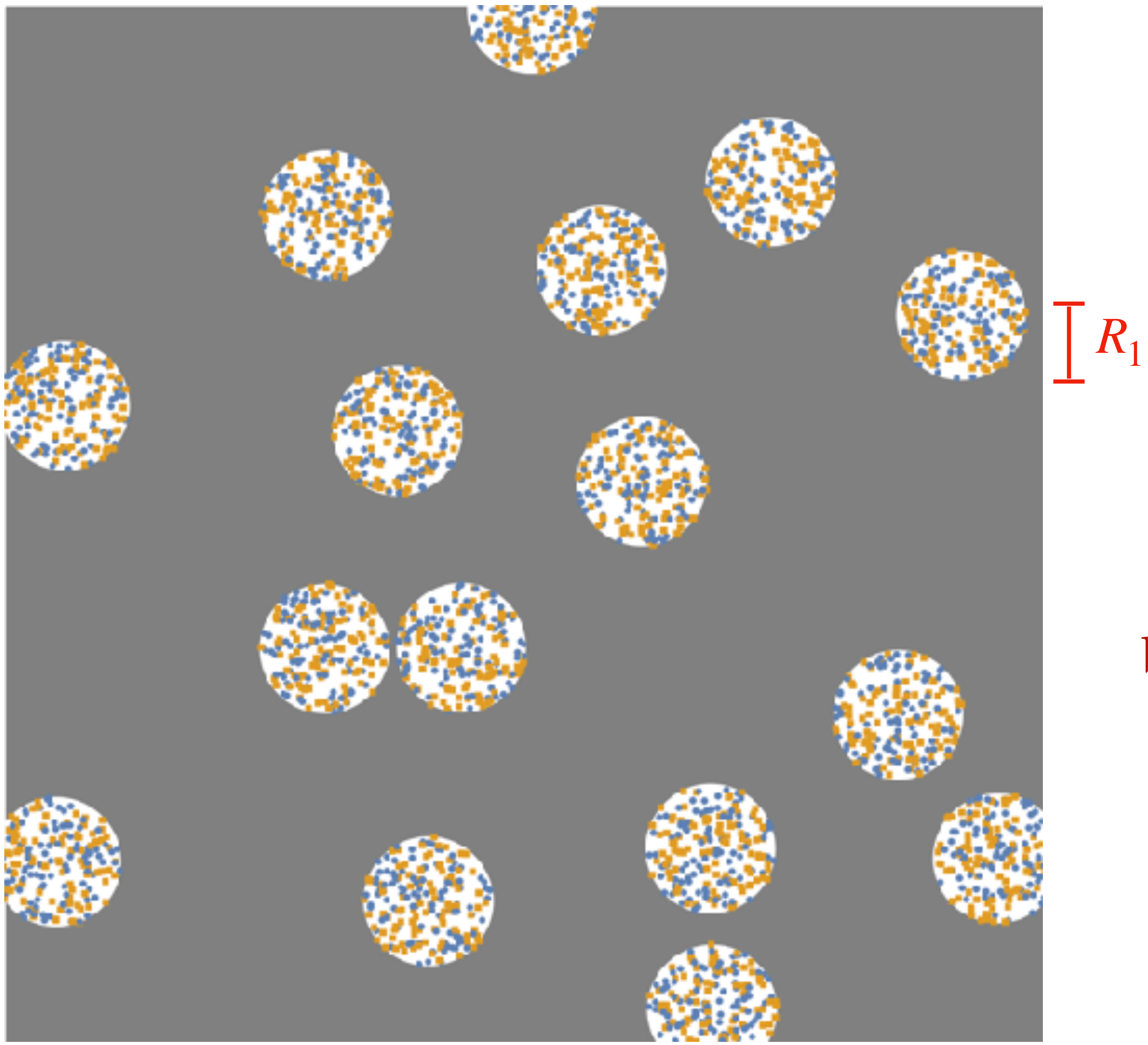
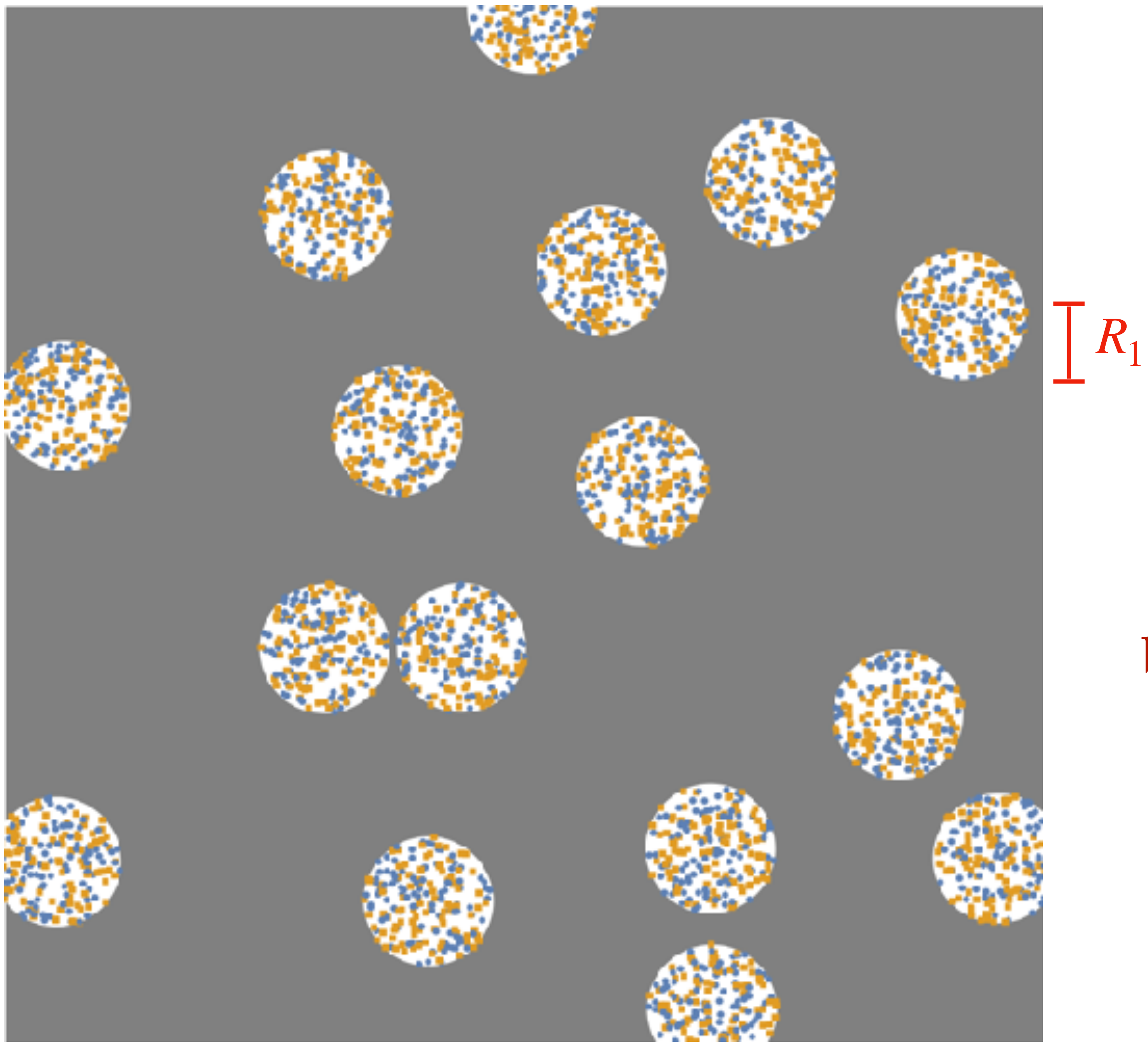
Stage 5: Squeezeout



baryons are formed in the pocket

baryons squeeze out from the pocket

Stage 5: Squeezeout



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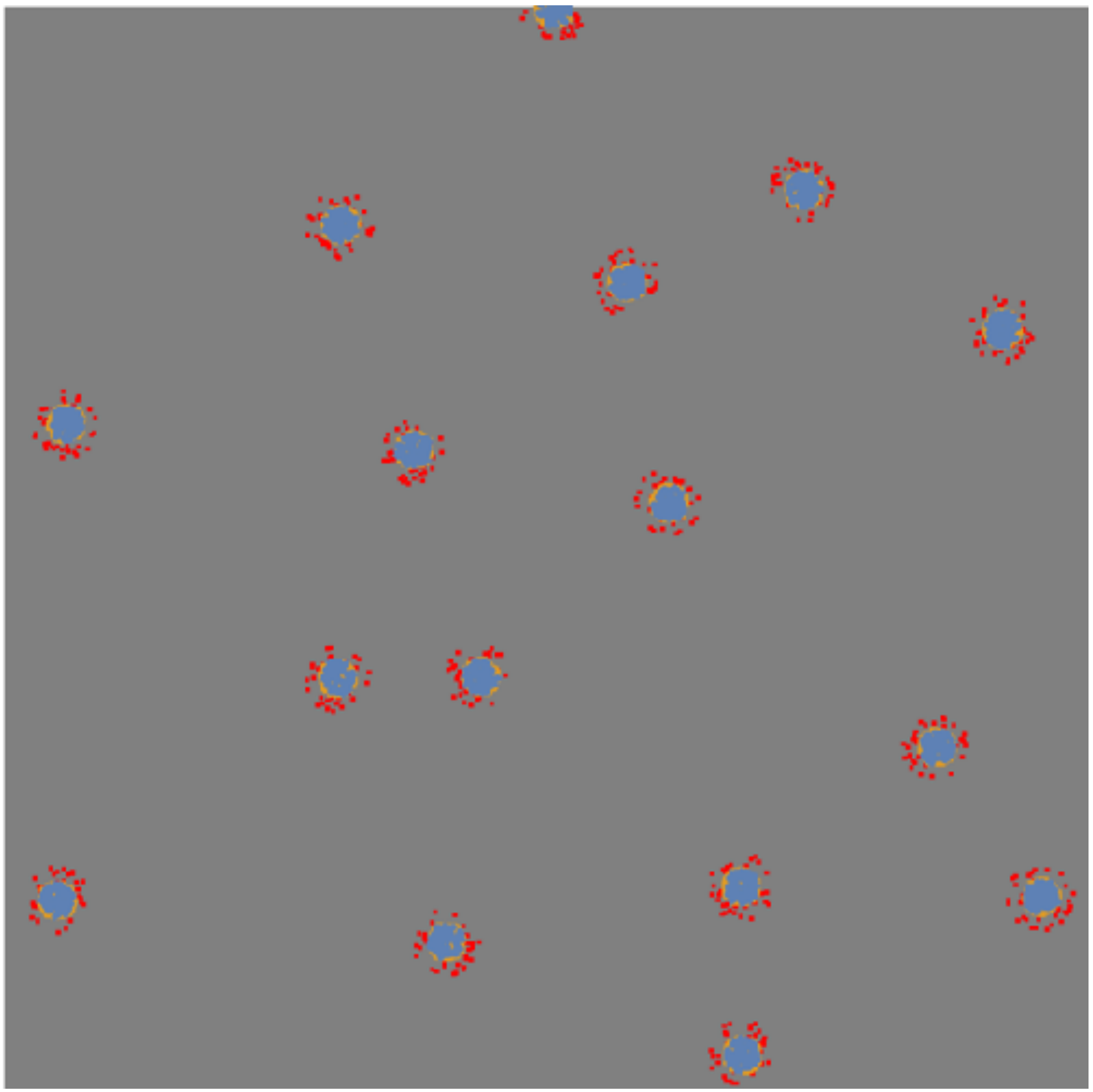
Baryon survival rate



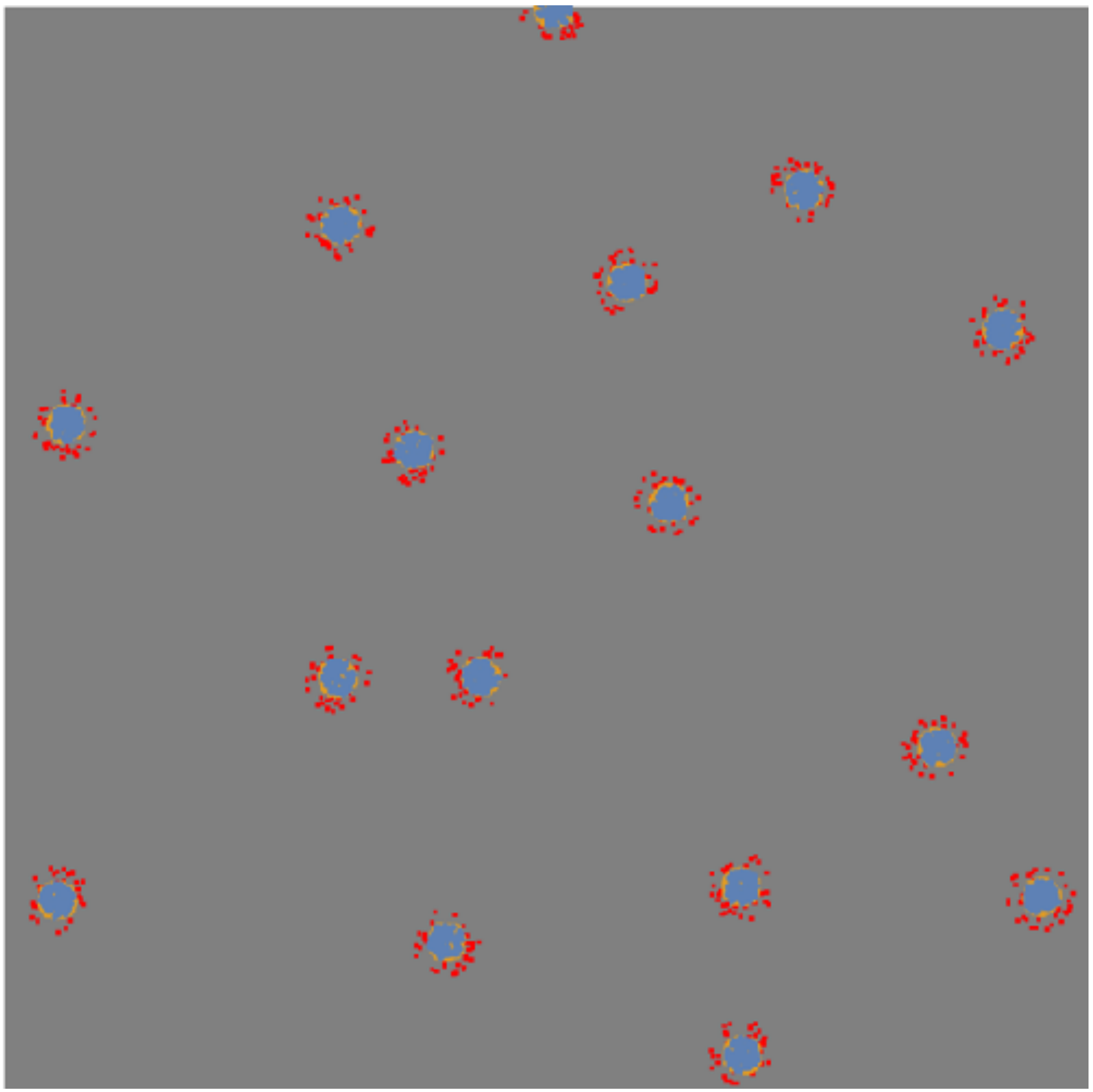
- Complicated physics based on recombination rates, binding energies, quark pressure, wall speed, baryon speed, etc..

- Quarks, mesons and baryons, equilibrate

$$N_B \lll \lll \lll N_M$$

- Mesons decays when formed, depleting all states.

Baryon survival rate



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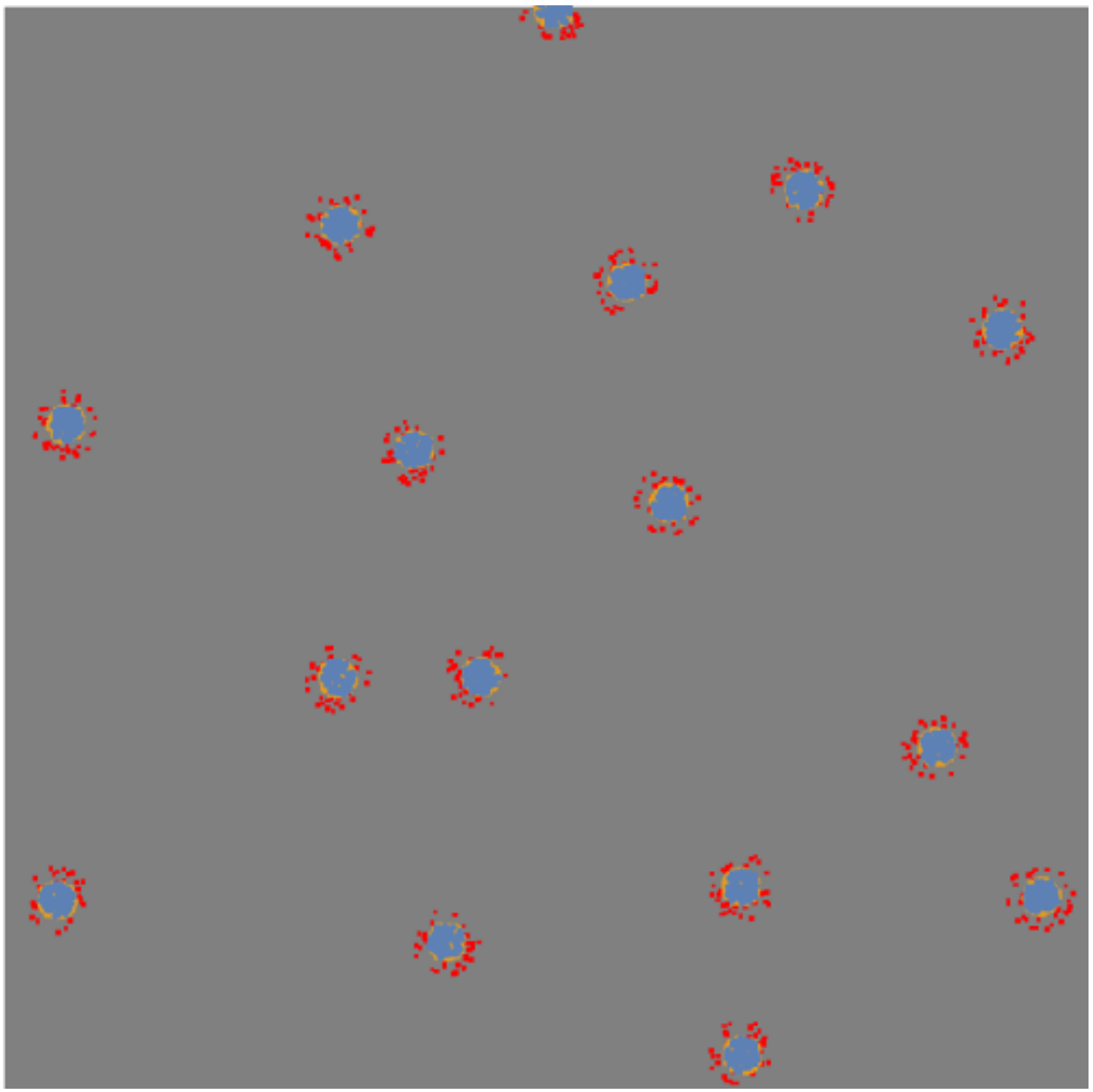
Accidental Asymmetry



- All quarks and anti-quarks are eliminated except for

Asymmetric component!

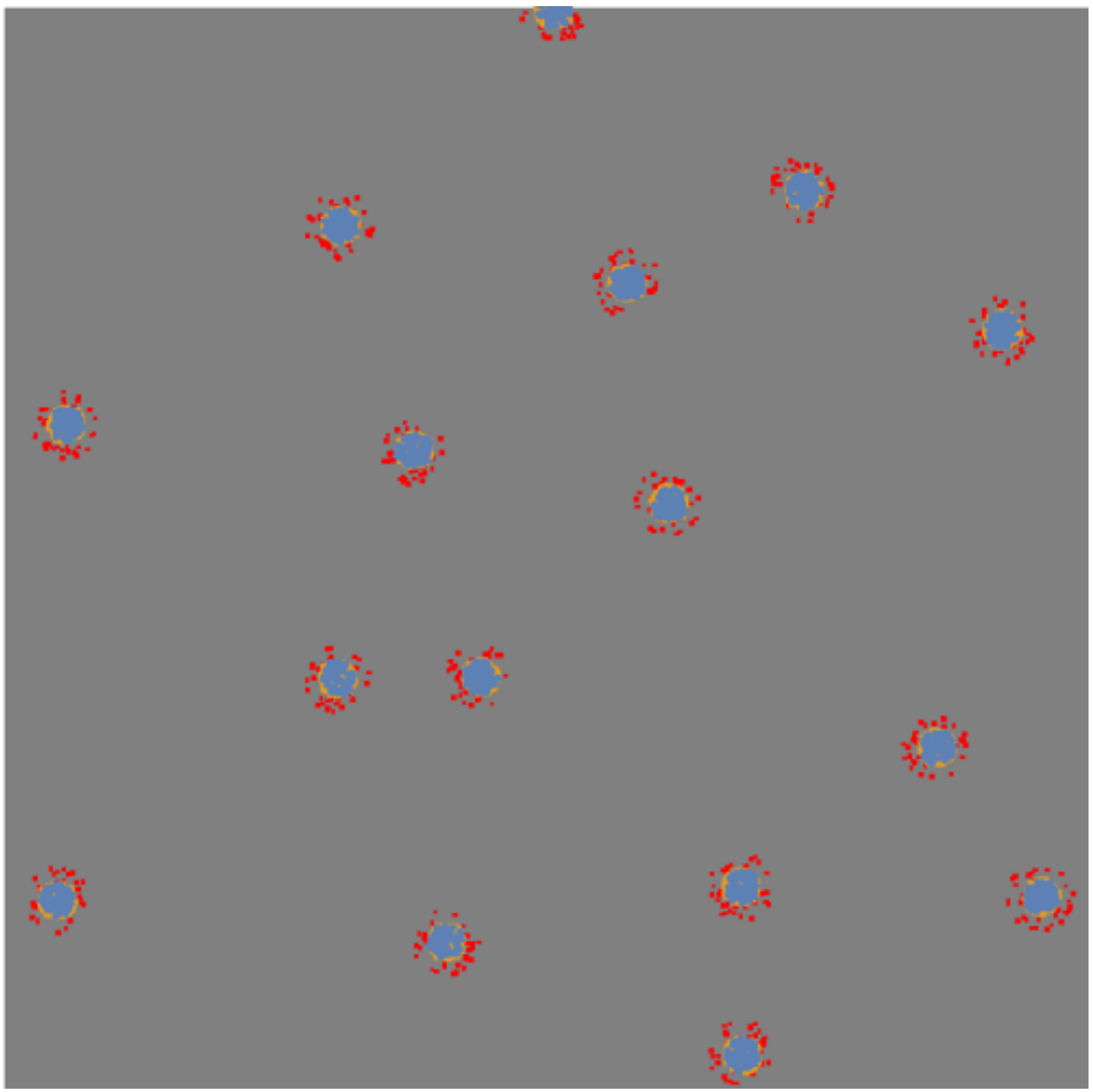
- Accident in each pocket

$$|N_Q - N_{\bar{Q}}| \simeq \sqrt{N_Q}$$

- All we need know is original number in pocket

$$\sqrt{N_Q^{\text{pocket}}} = \sqrt{\frac{4}{3}\pi R_1^3 N_{\bar{Q}}^{\text{freeze-out}}}$$

Accidental Asymmetry



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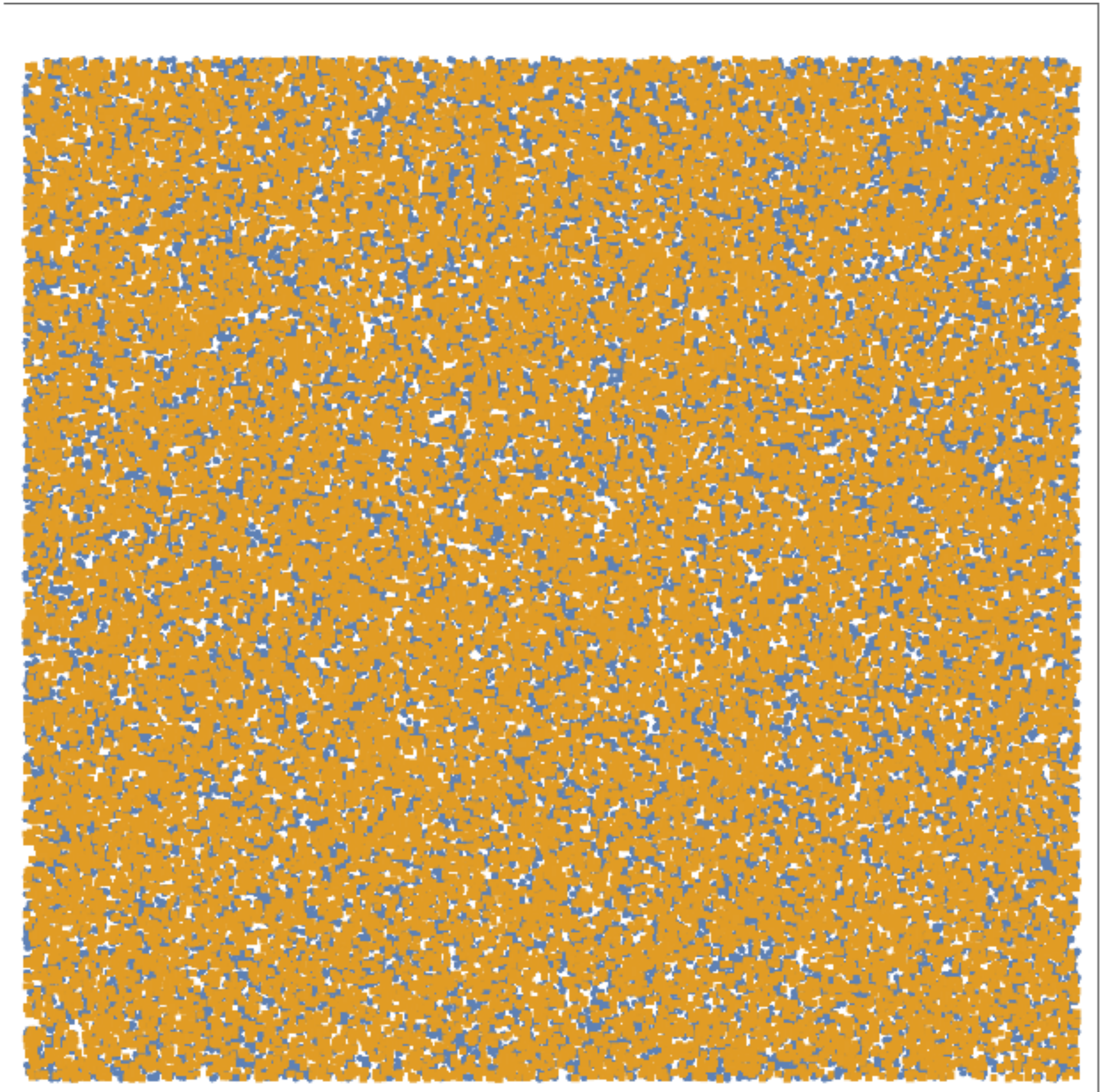
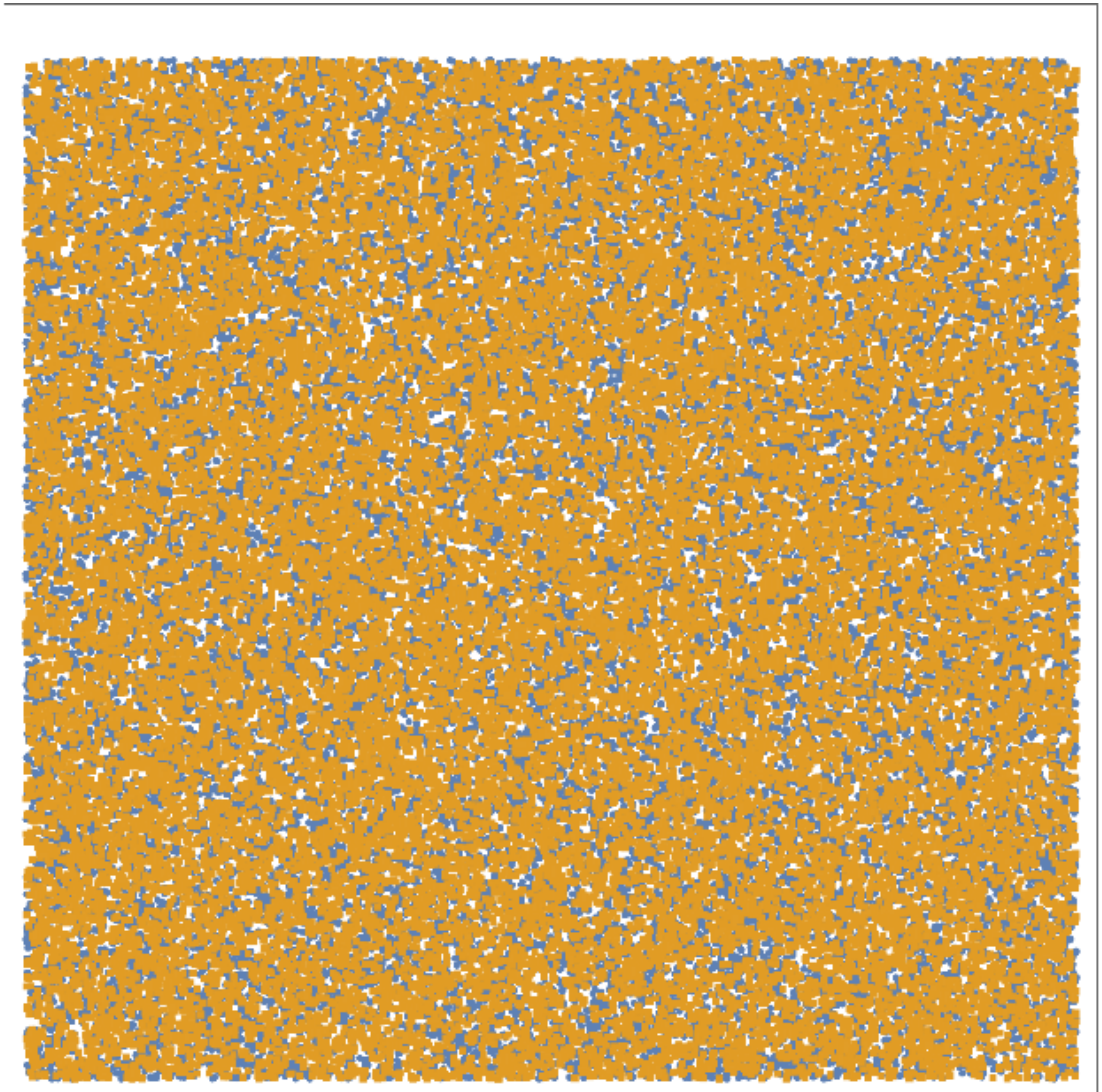
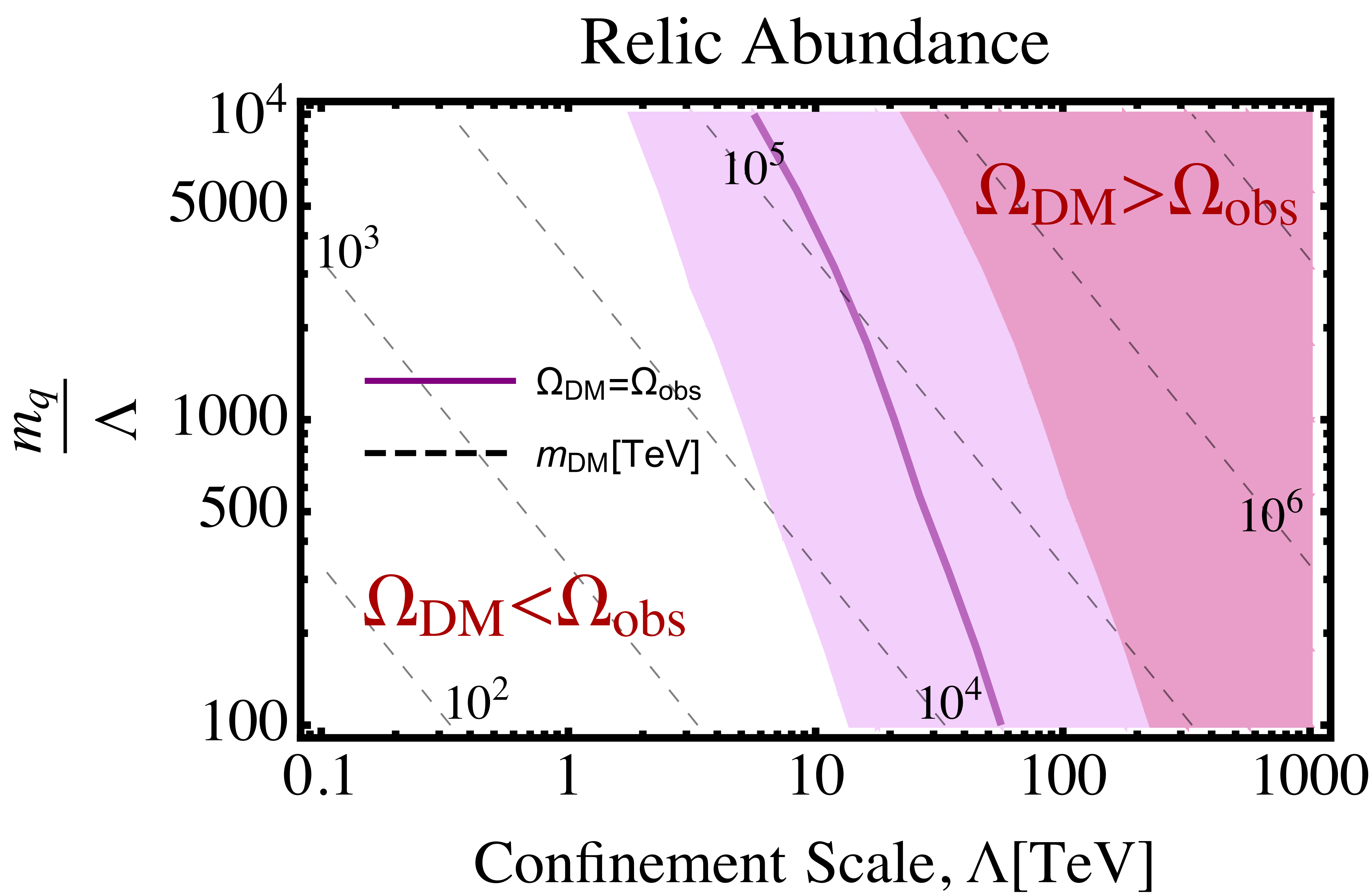
Whole picture



Whole picture



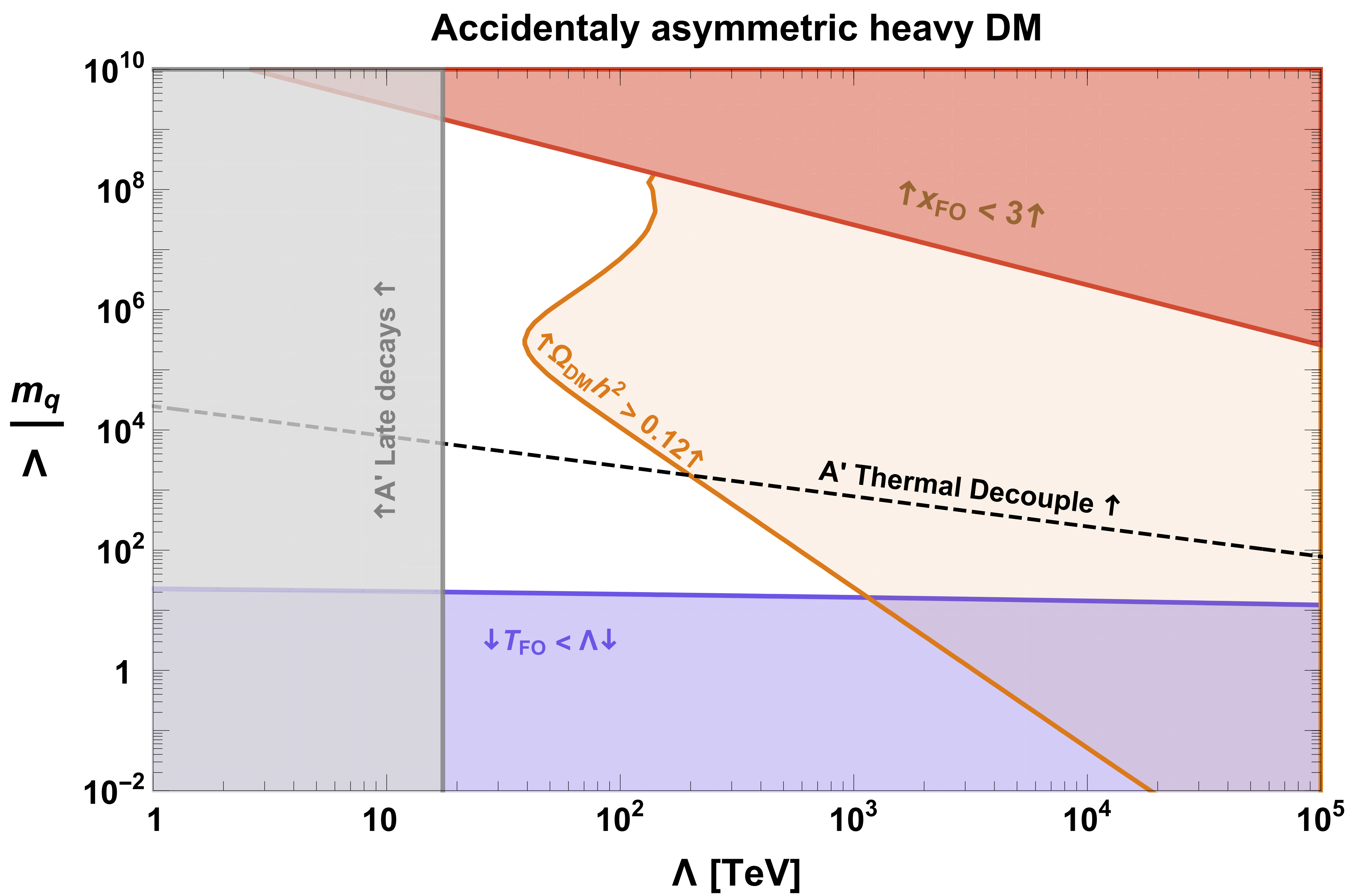
Parameter space



Further squeeze-out

- Consider charged quarks:
  - Long ranged forces wash out asymmetry — much heavier dark matter
  - can lead early matter dominated era
- Consider different mediators to the visible sector.
- Gravitational wave signal.
- More careful escape rate calculation from the walls.

Preliminary



Outlook

- Lots of activity for thermal dark matter.
- Many different interactions, processes, and their relative importance throughout the cosmological history.
- Novel dark matter frameworks.
- Generic.
- Discovery—often point to string indirect detection signal.
- Much more to do.