High Energy Particles from Supercooled Phase Transitions

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Work in progress with
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Heavy Dark Matter

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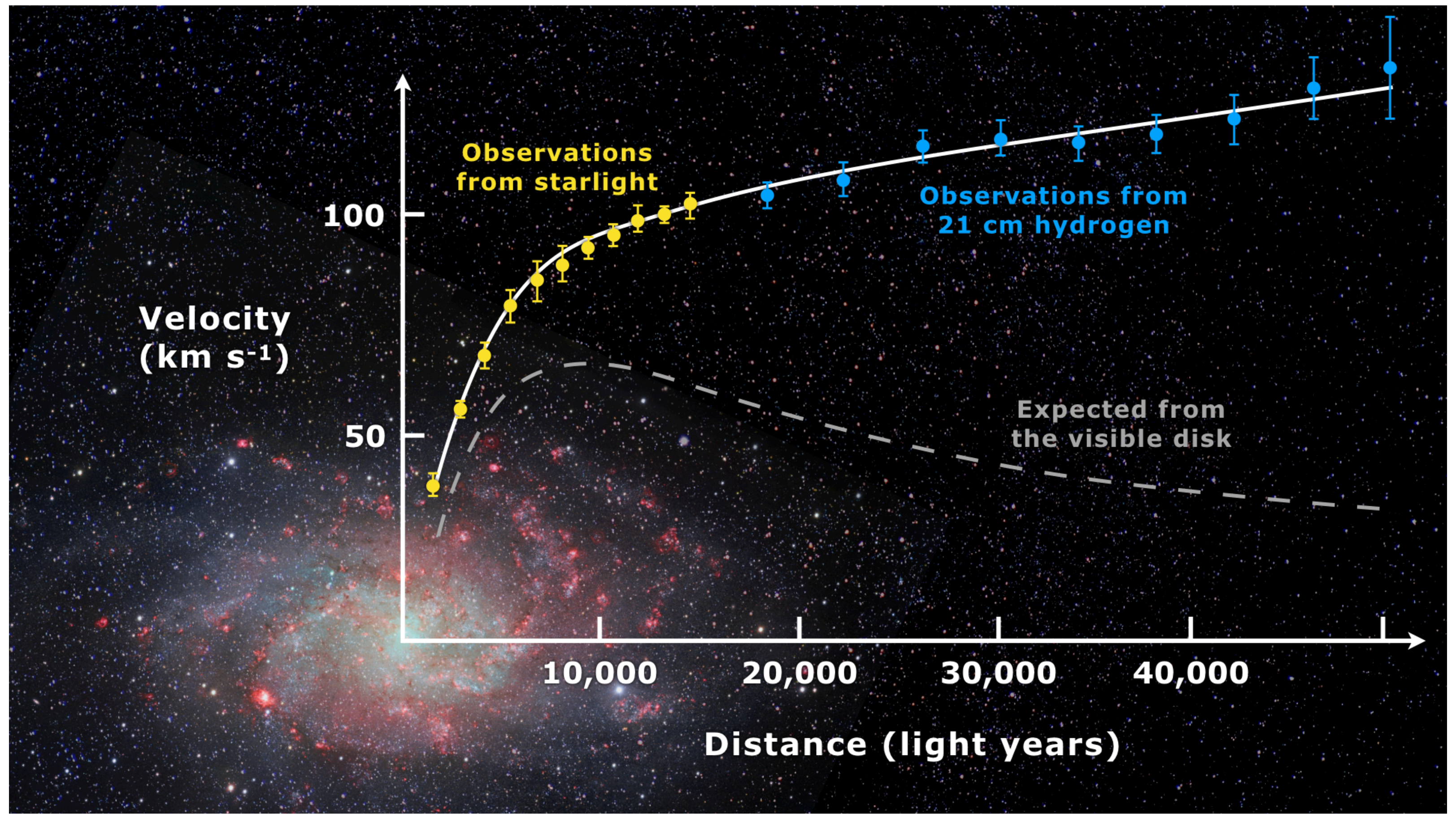
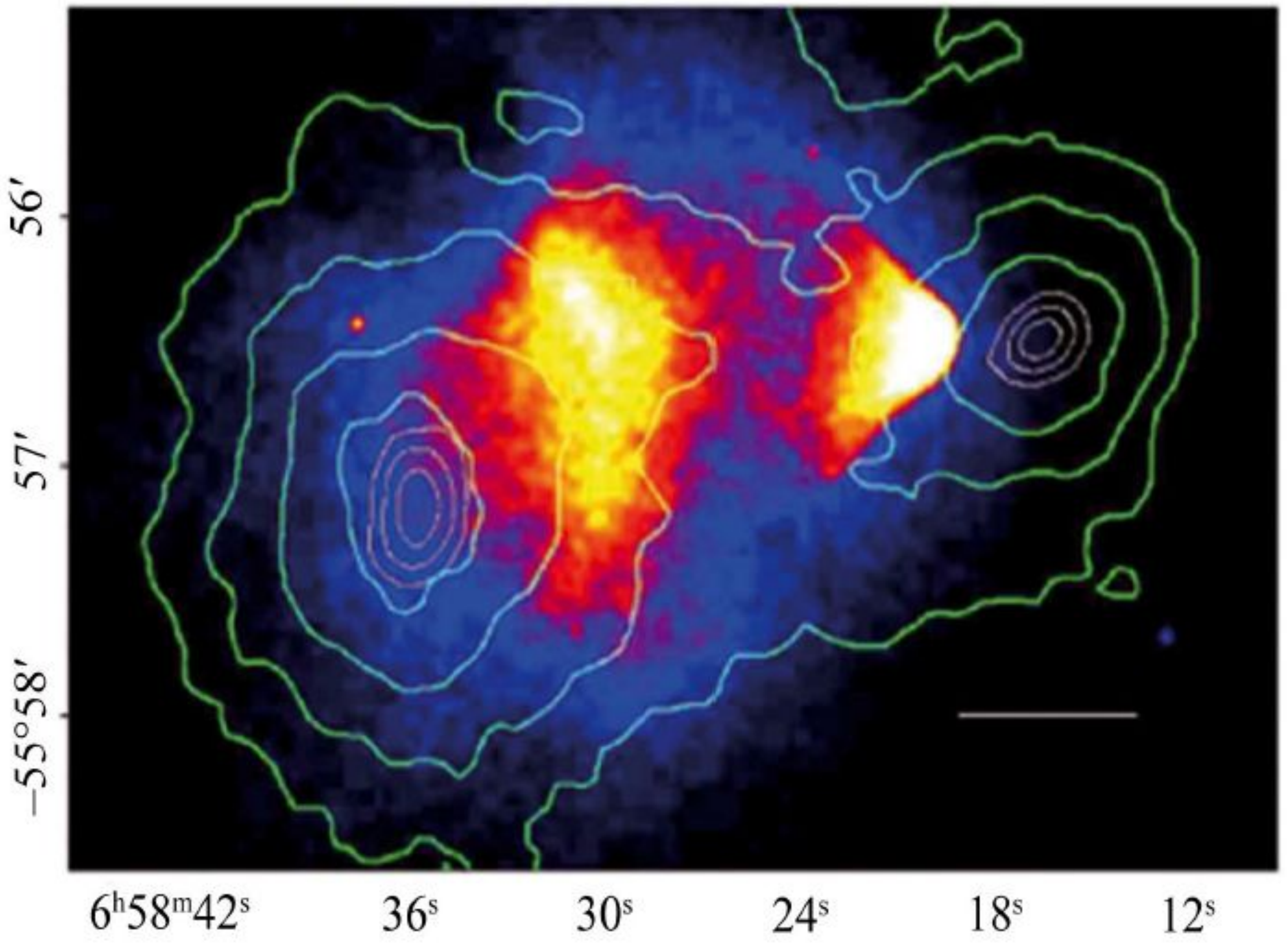
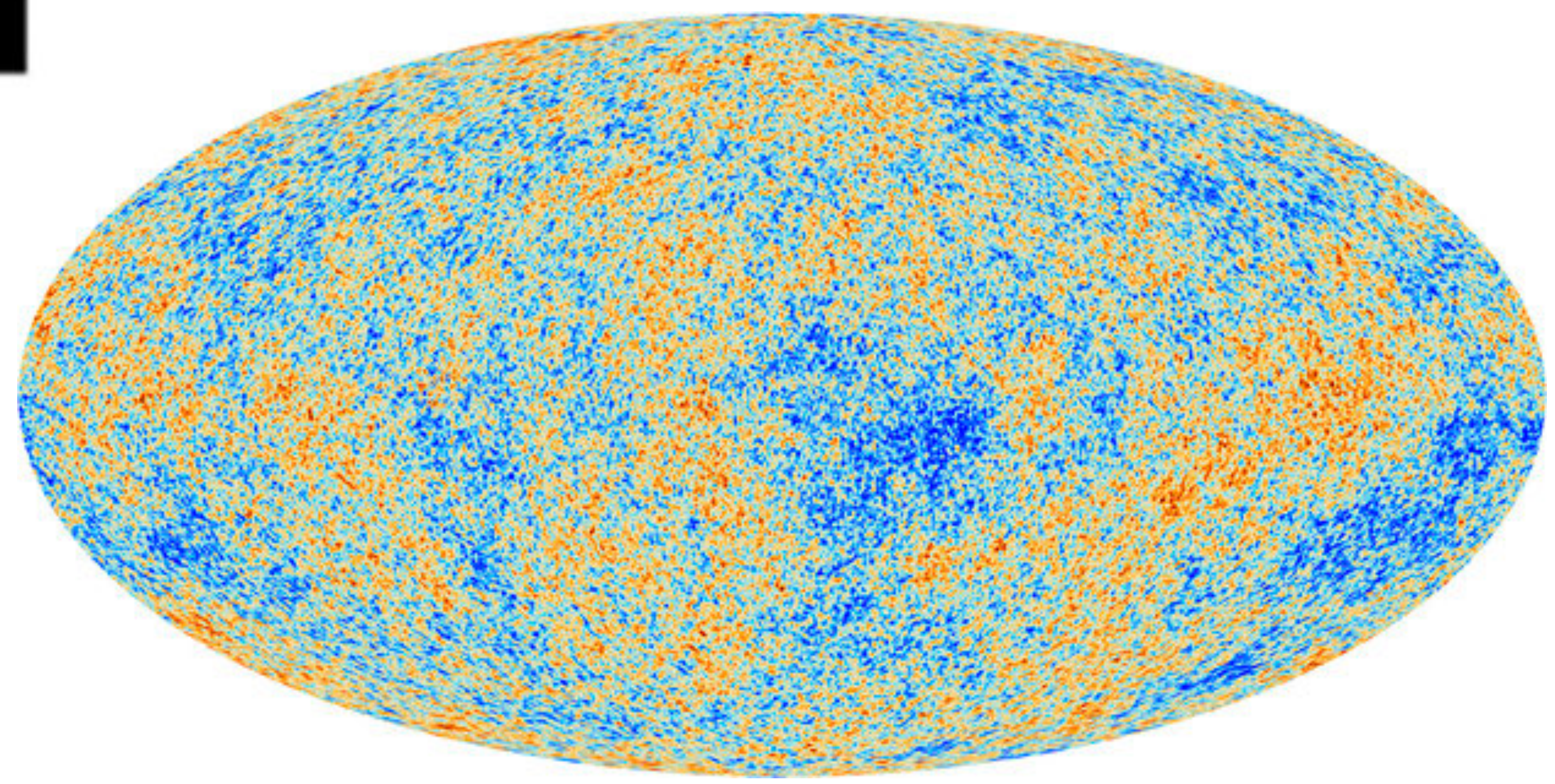
Outline

- What we have done:
  - Supercooled Phase Transitions
  - High Energy Particles
  - Heavy Dark Matter
- What needs to be done

Experimental Evidence for Dark Matter





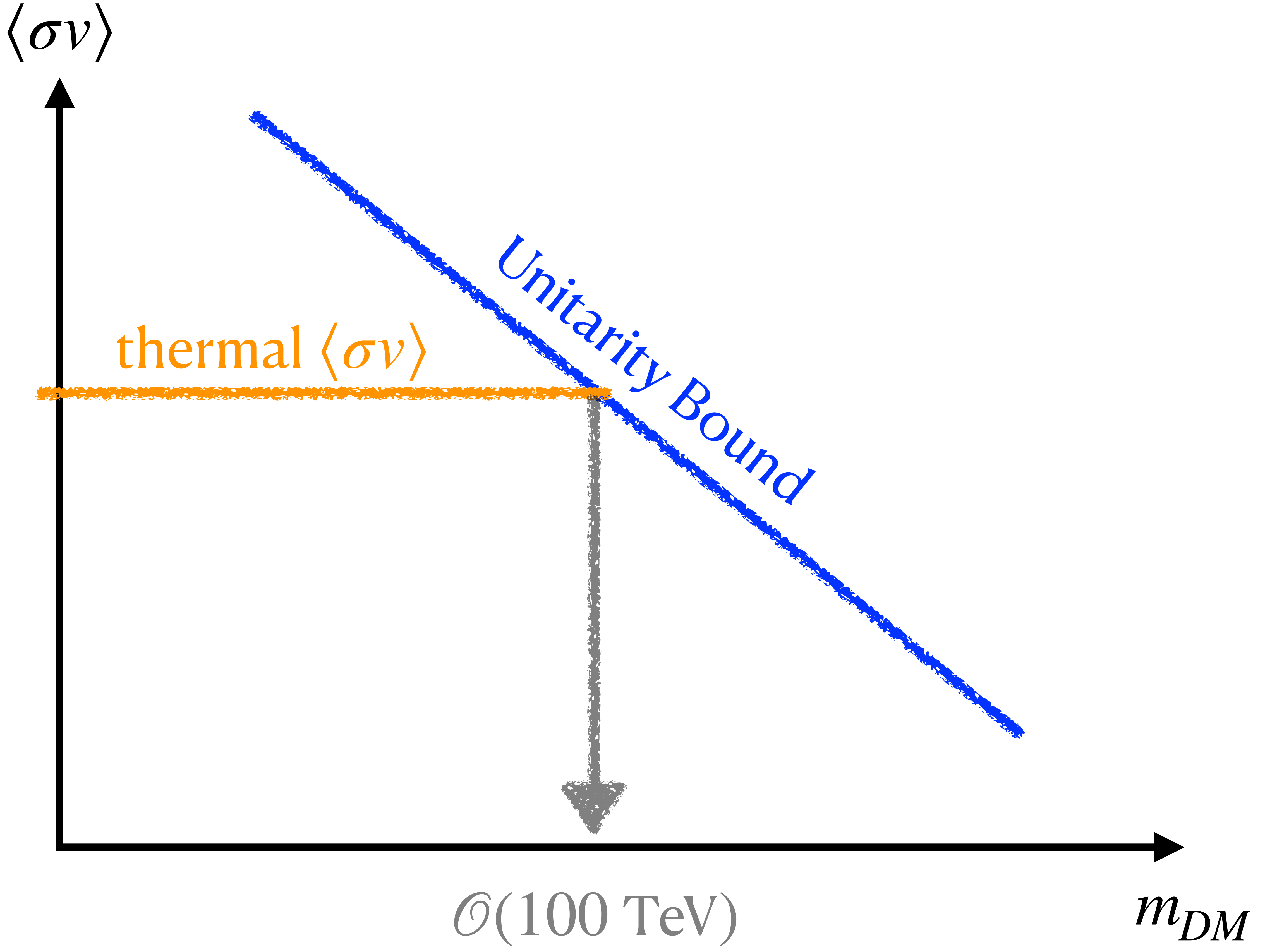


Unitarity Bound

Implication for thermal relic

$$\sigma v \lesssim \frac{4\pi(2J+1)}{v}\frac{1}{m_{DM}^2}$$

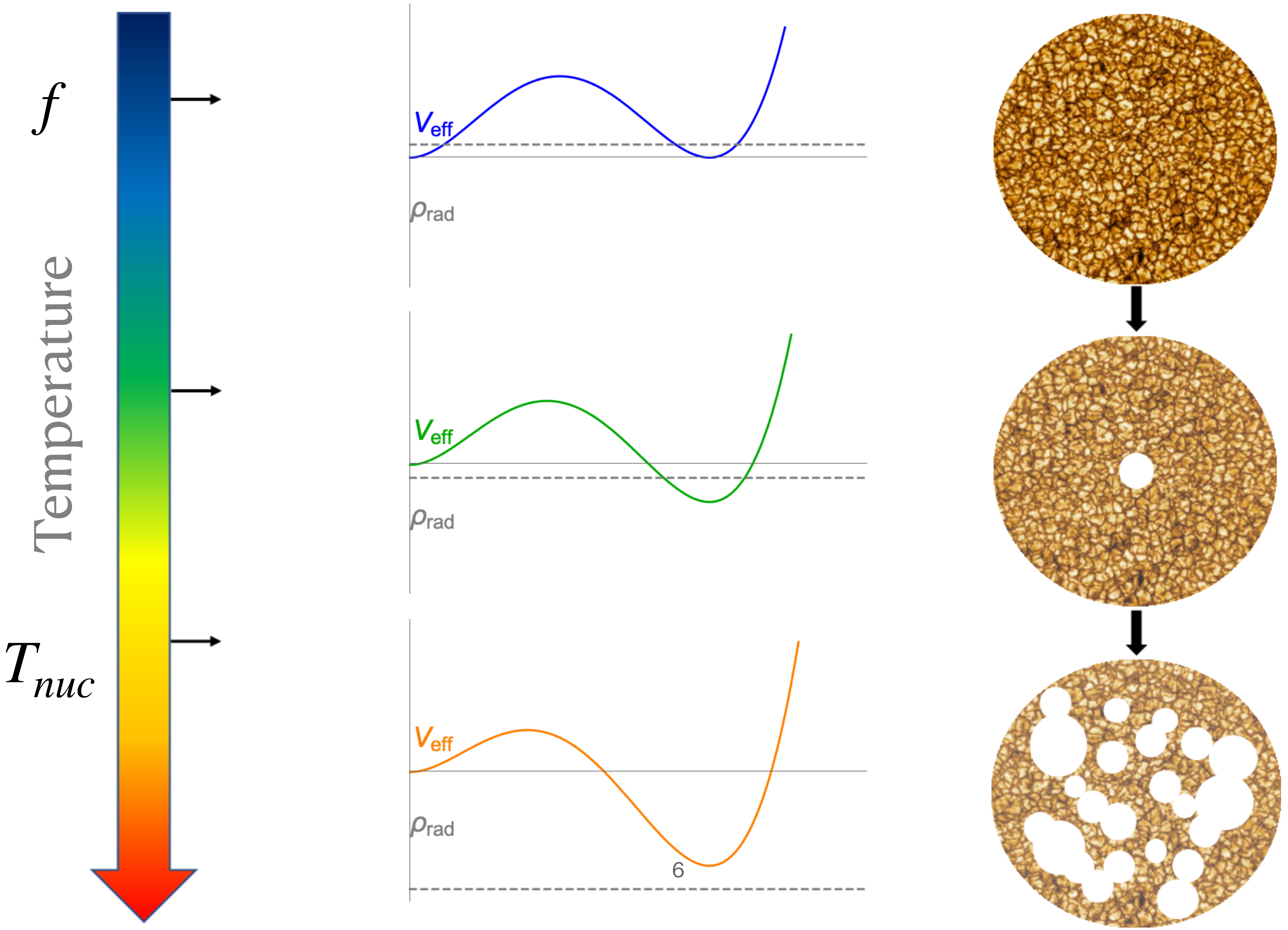
$$\Omega_{DM} \propto \frac{1}{\sigma v}$$



Ways Out

- Non-standard cosmological history before BBN
  - Early phase of matter domination
  - Vacuum Energy Domination
- No thermal contact / Out-of-equilibrium production

Supercooled Phase Transitions



adapted from
Wang+ arXiv:2003.08892

Supercooled Phase Transitions

Main Parameters:

- Energy Scale of the Phase Transition f
- Nucleation Temperature $T_{nuc} \ll f$
- Wall Velocity $\gamma_w(T_{nuc}, f)$

Non-confining

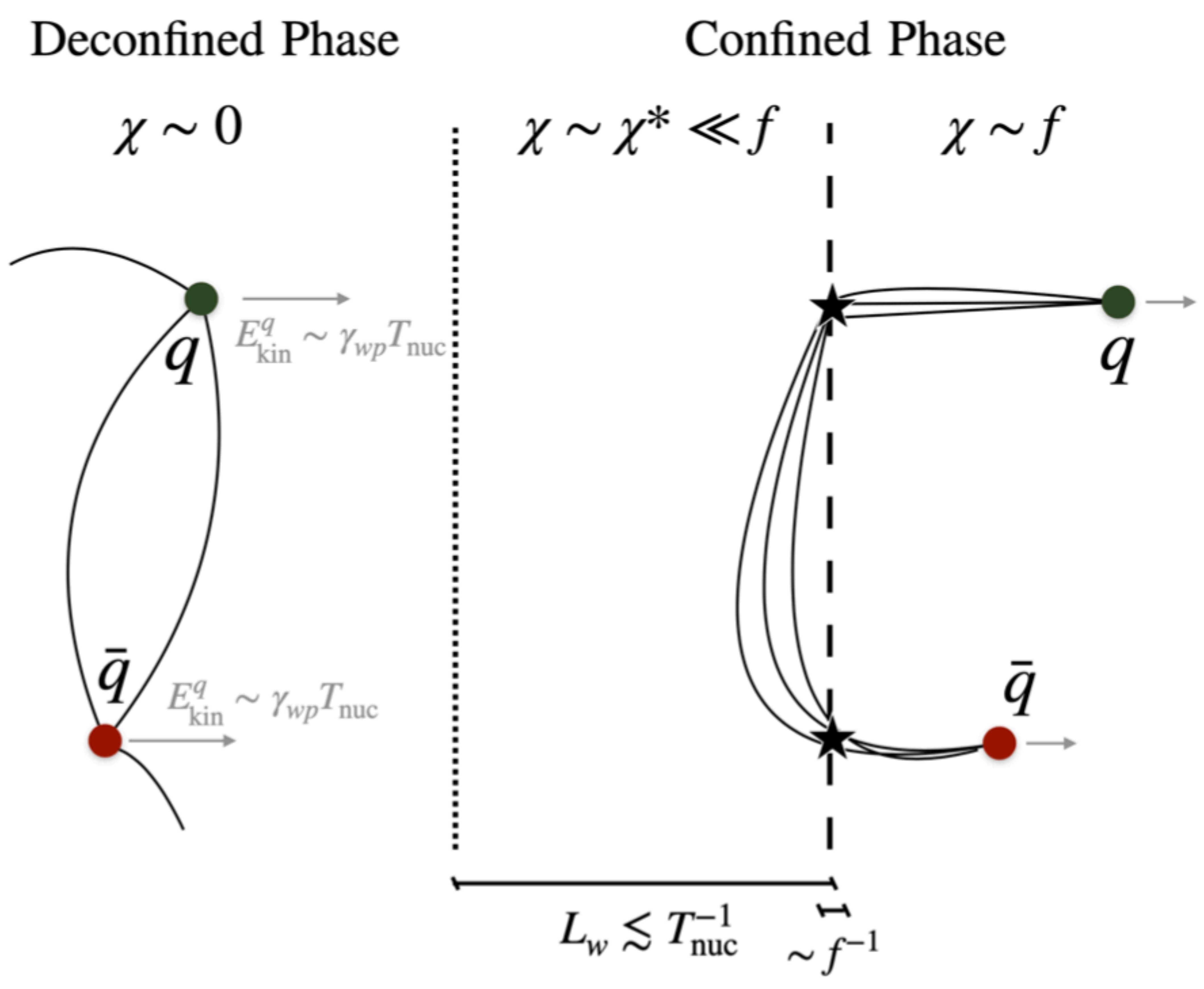
Confining

Non-confining

Confining

String Fragmentation

I.Baldes, Y.Gouttenoire, F.Sala
arXiv:2007.08440



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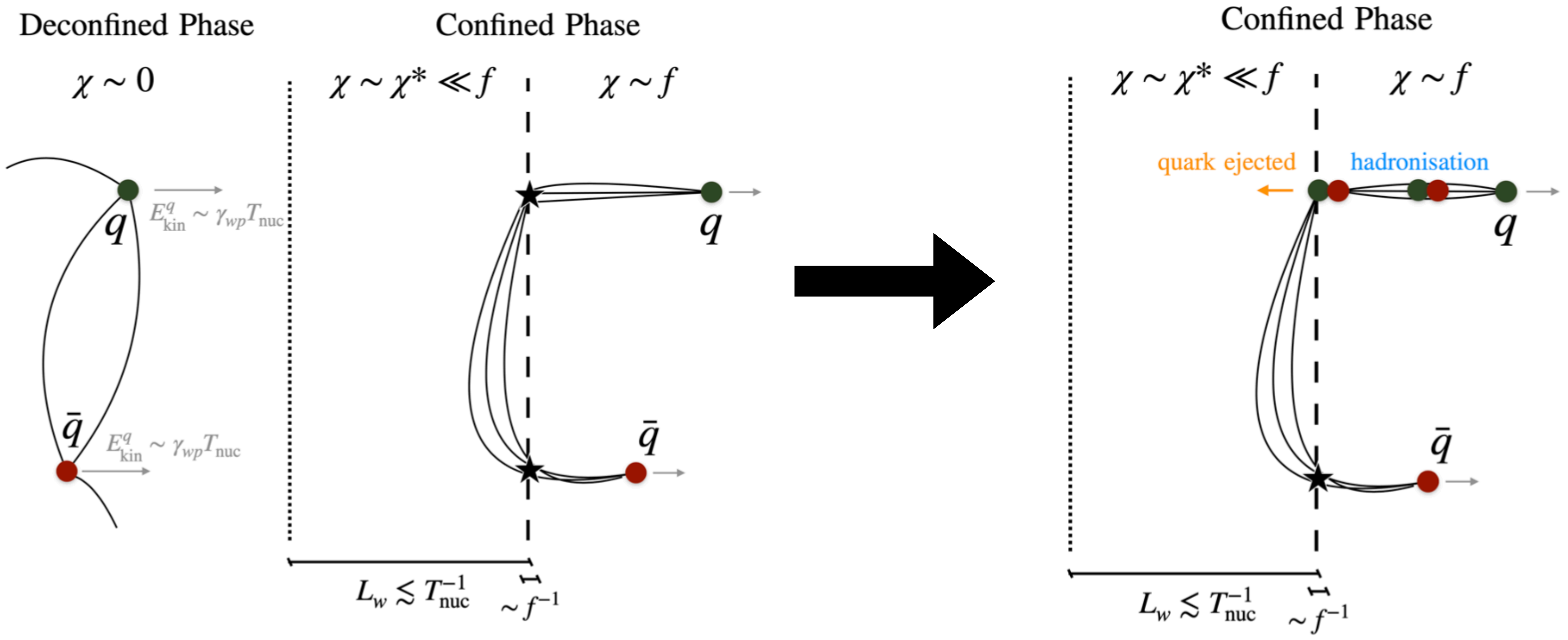
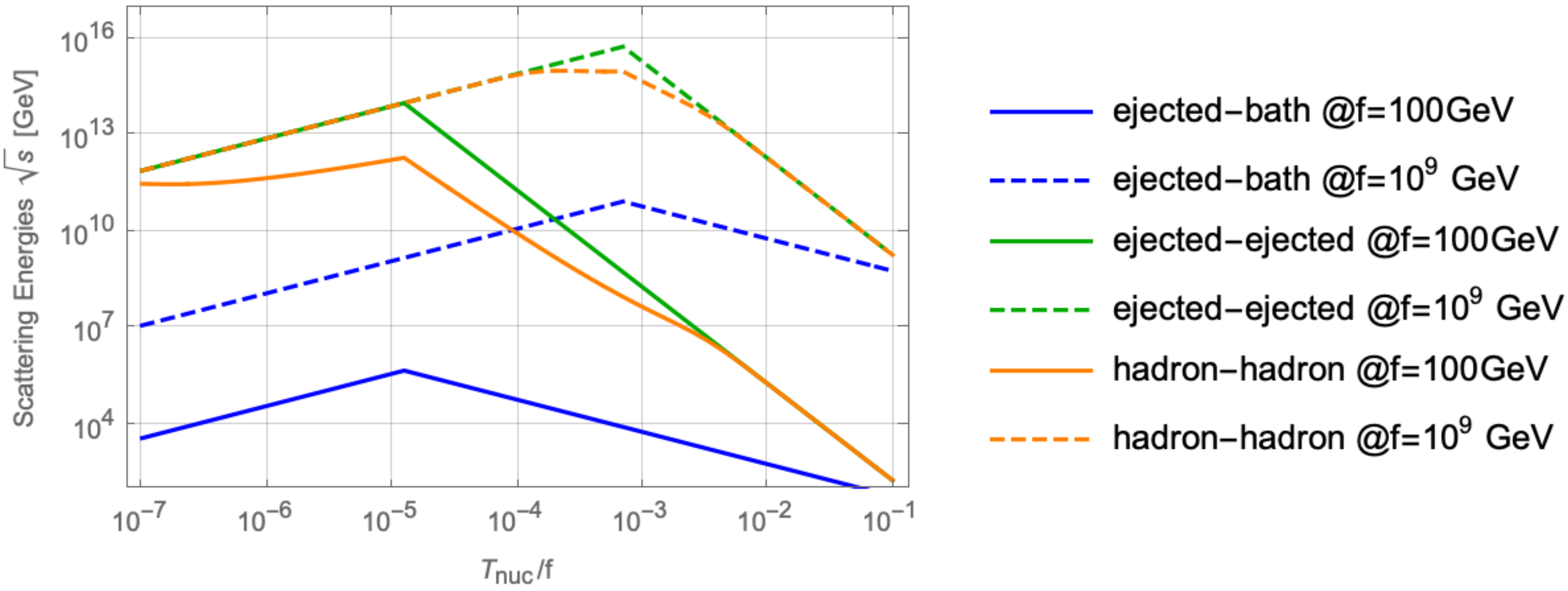


Particle Content

- Bath Particles (typical energies T_{nuc})
- Ejected Particles (typical energies $\gamma_w f$)
- Hadrons (typical energies $\gamma_w f / N_{\text{hadrons}}$)

Typical Scattering Energies



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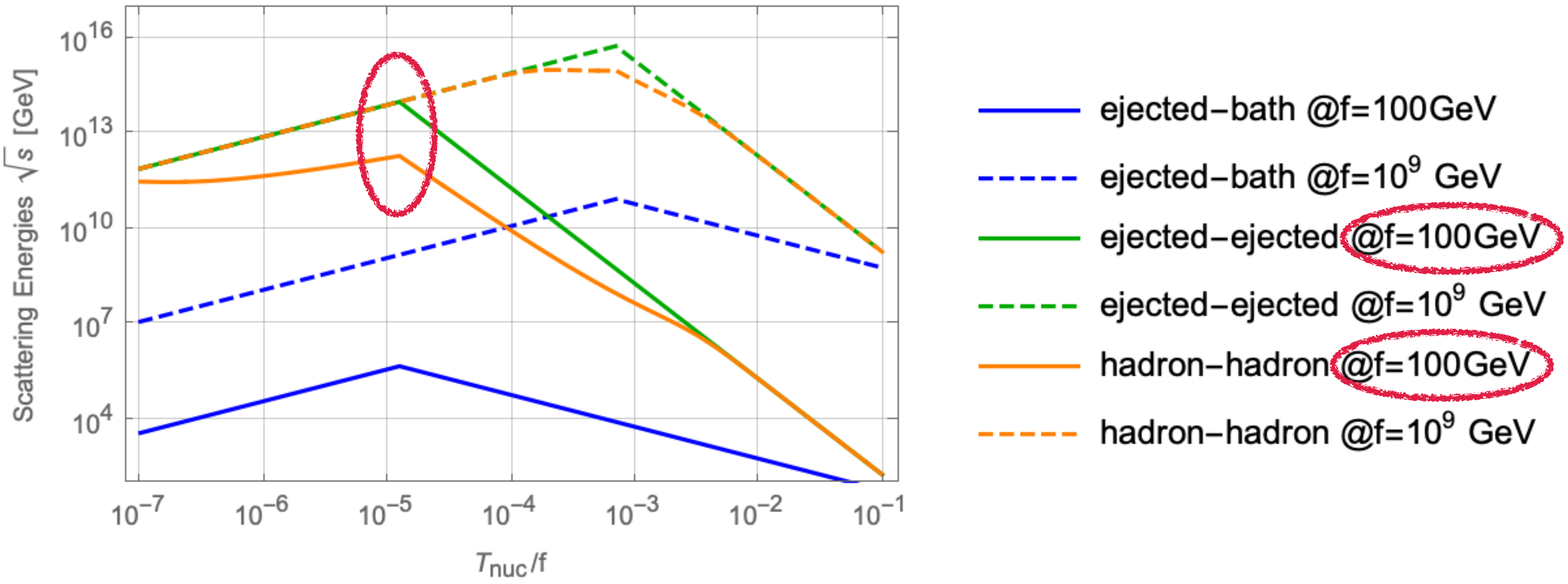
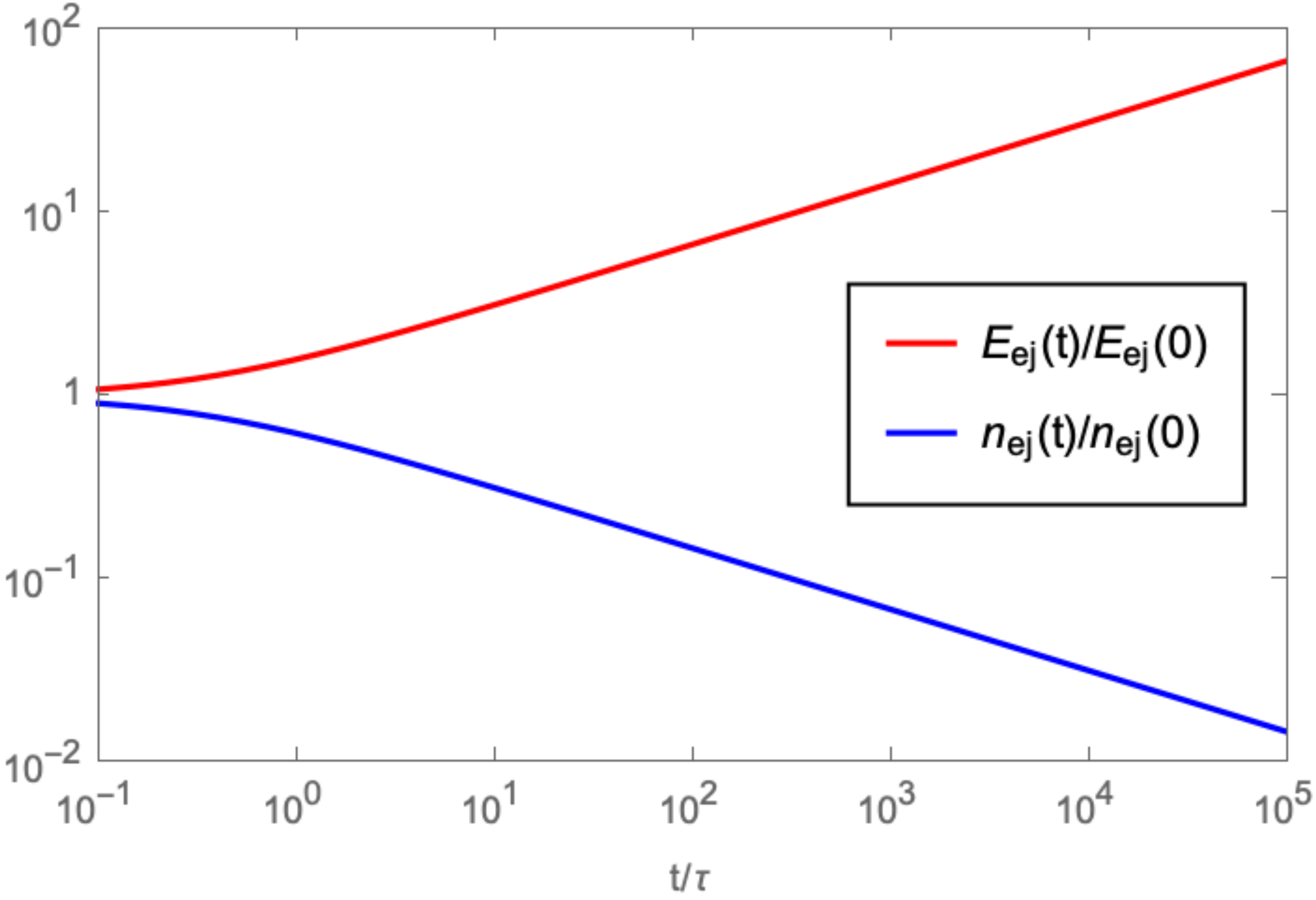


Evolution of High Energy Particles

- Number changing interactions
- Reduce the number of highly energetic particles

Evolution of High Energy Particles



Evolution of High Energy Particles

- Number changing interactions
- Reduce the number of highly energetic particles

Largest contribution to DM production: Last moment production before collision

Heavy Dark Matter

Dark Matter Production

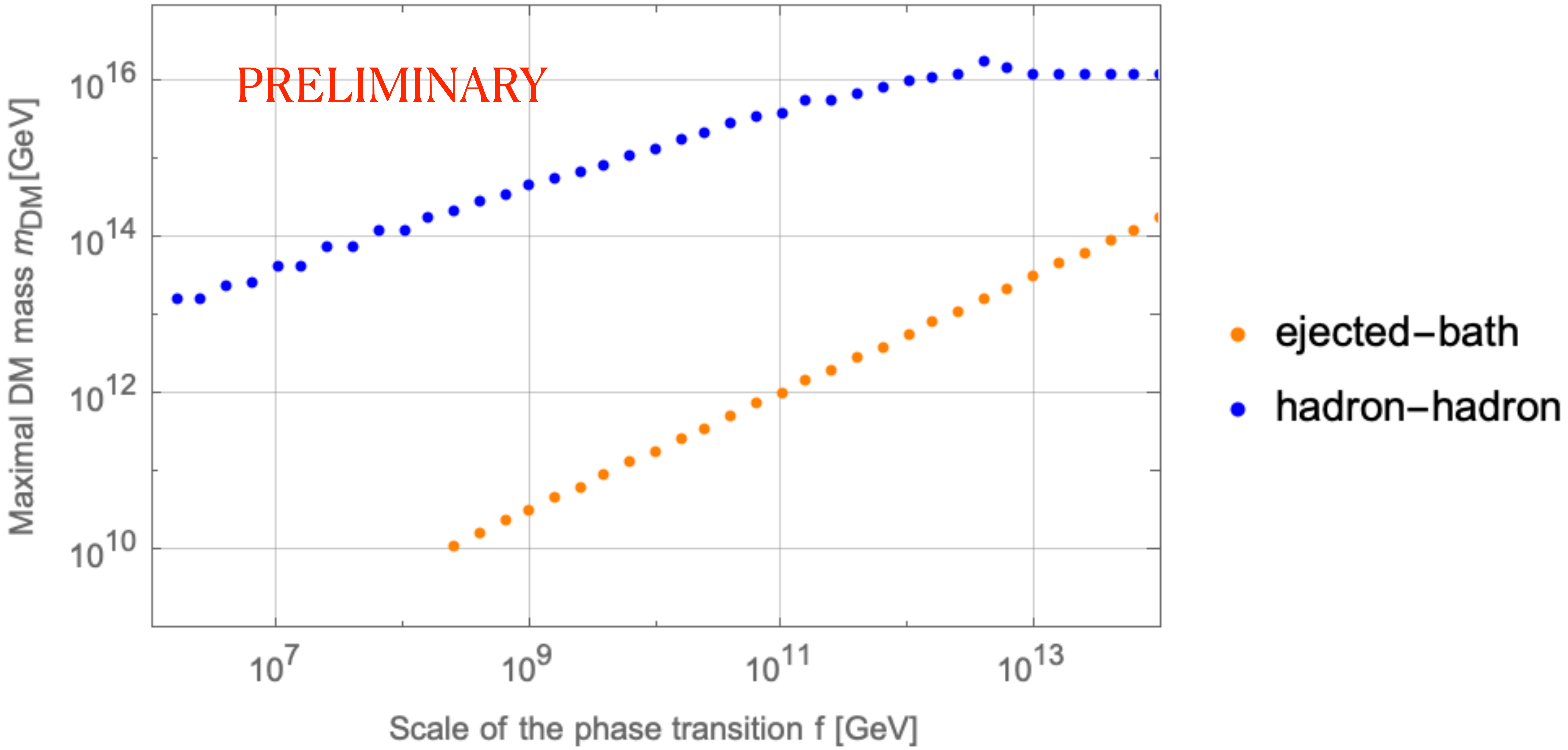
Effective Interacting Theory between

- BSM quarks, and
- Dark Matter

$$\mathcal{O} = \frac{1}{\Lambda^2}(\bar{q}q)(\bar{\Psi}\Psi) \quad , \quad \mathcal{O} = \frac{1}{\Lambda^2}(\bar{q}\gamma^{\mu}q)(\bar{\Psi}\gamma_{mu}\Psi)$$

$$\sigma(\bar{q}q \to \bar{\Psi}\Psi) \simeq \frac{1}{8\pi}\frac{s}{\Lambda^4}$$

Maximal Dark Matter Mass



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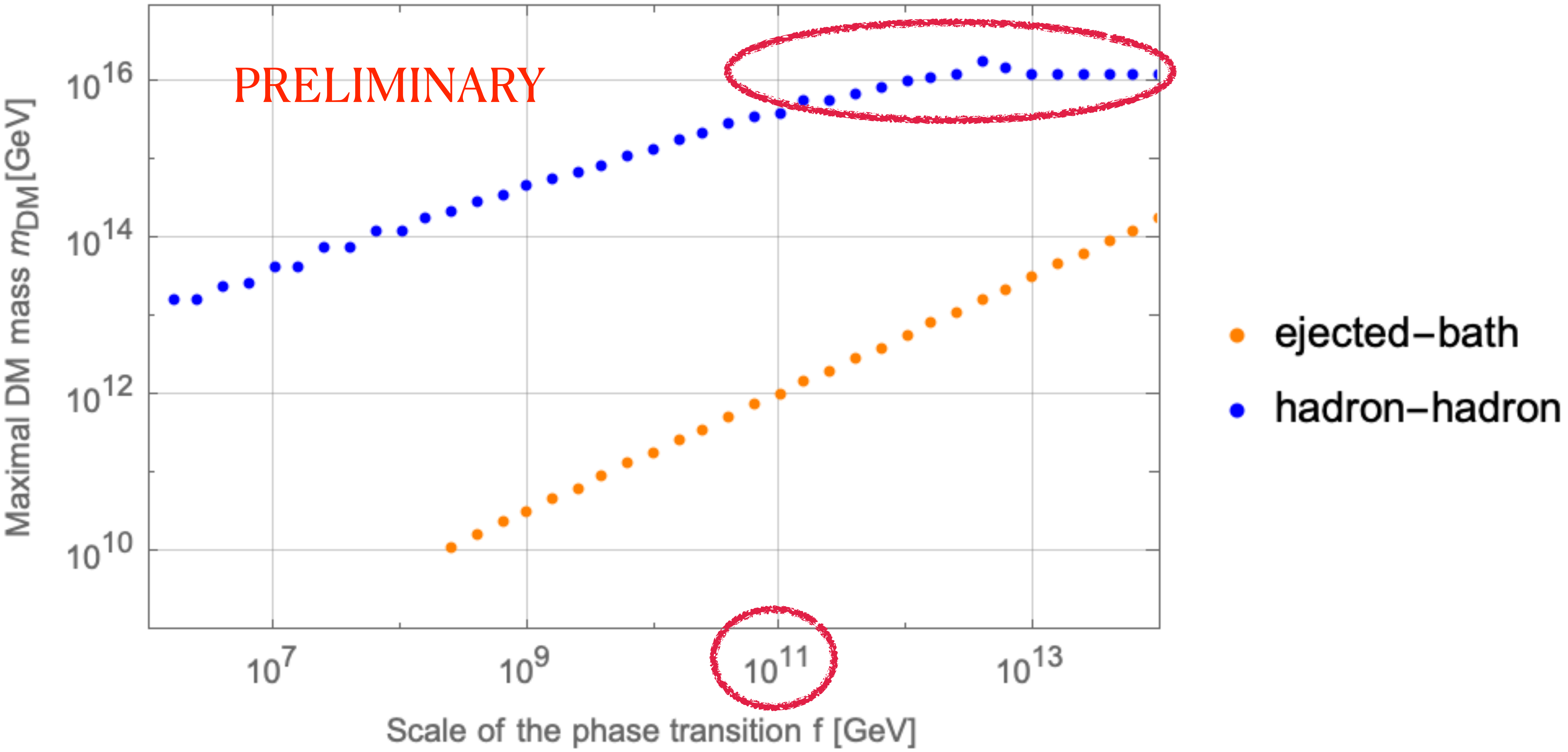

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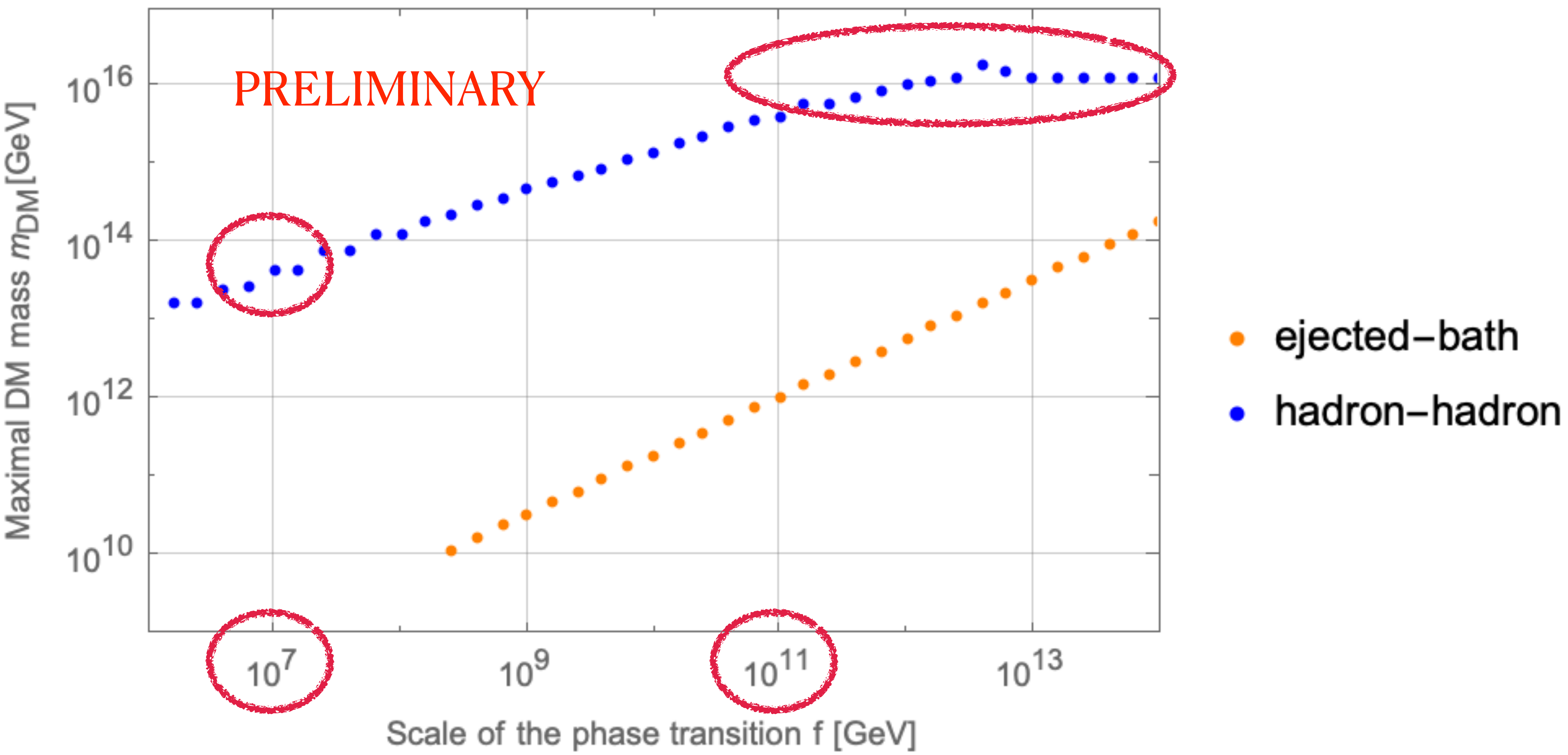

WE NEED YOU

How to handle gluons with a plasma mass?

Problems (1)

- Massless spin-1 polarisation sum in vacuum:

$$\sum_{\lambda=\pm 1} \epsilon_\mu(k)\epsilon_\nu^*(k) = -g_{\mu\nu} + \frac{k_\mu n_\nu + n_\mu k_\nu}{k \cdot n} - \frac{k_\mu k_\nu}{(k \cdot n)^2} \qquad n_\mu = (1,0,0,0)$$

- BRST: $\overline{|M|^2}$ is independent of n_μ

- With thermal mass: depends on n_μ

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Problems (2)

- Massive spin-1 polarisation sum in vacuum:

$$\sum_{\lambda=0,\pm1} \epsilon_\mu(k)\epsilon_\nu^*(k) = -g_{\mu\nu} + \frac{k_\mu k_\nu}{m^2}$$

- No Ward-identities for QCD: Longitudinal modes do not decouple

- $\lim_{m\to0} \sum_{\lambda=0,\pm1} |M|^2 \sim \lim_{m\to0} \frac{1}{m^4} \neq \sum_{\lambda=\pm1} |M|^2$

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Problems (3)

- Pole of propagator = (thermal) mass:

$$\frac{1}{(p_1+p_2)^2} \to \frac{1}{(p_1+p_2)^2+m^2}$$

- On-shell relation $k^2 = m^2$

- E.g. Debye Mass: Higher orders are imaginary (thermal width)
- On-shell relation $k^2 = \mathrm{Re}(m)^2$

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Particle Content: Revisited

- Only (BSM) gluons ($m_{\text{vac}} = 0$)
- Two distributions:
  - Bath Particles
    - Number density $n_b = n_{eq}(T_{nuc})$
    - Typical energies $\langle E_b \rangle = T_{nuc}$
  - Ejected Particles
    - Number density $n_{ej} = \gamma^2 n_b$
    - Typical energies $\langle E_{ej} \rangle = \gamma f$

$3 \to 2$ Boltzmann Equation

$$\frac{dn_1}{dt} = -\int d\Pi_1 d\Pi_2 d\Pi_5 d\Pi_A d\Pi_B \times (2\pi)^4 \delta^{(4)}(p_1 + p_2 + p_3 - p_A - p_B) \times |M|^2 \times f_1 \ f_2 \ f_3$$

Write as

$$\frac{dn_1}{dt} = -\left[\frac{1}{n_1 n_2 n_3}\int d\Pi_1 d\Pi_2 d\Pi_3 \ f_1 f_2 f_3 \left(\int d\Pi_A d\Pi_B \times (2\pi)^4 \delta^{(4)}(p_1 + p_2 + p_3 - p_A - p_B) \times |M|^2\right)\right]$$
$$\times n_1 n_2 n_3$$

Compute cross section:

$$\sigma_{3\to 2} = \int d\Pi_A d\Pi_B \times (2\pi)^4 \delta^{(4)}(p_1 + p_2 + p_3 - p_A - p_B) \times |M|^2$$

$3 \to 2$ Cross Section

$$\sigma_{3\to 2} = \int d\Pi_A d\Pi_B \times (2\pi)^4 \delta^{(4)}(p_1 + p_2 + p_3 - p_A - p_B) \times |M|^2$$

Expect the result to be a function of

$$\gamma \gg 1 \qquad \text{and} \qquad \frac{f}{T_{nuc}} \gg 1$$

We want LO and LLO, to a precision of $\mathcal{O}(10)\ldots\mathcal{O}(100)$

Regulating Collinear Divergences with a Thermal Mass

$$m^2 \sim \int \frac{d^3k}{\omega_k} f(k) \simeq \frac{n_{ej}}{E_{ej}} \simeq \gamma \frac{T_{nuc}^3}{f}$$

$$f^2 \gg m^2 \gg T_{nuc}^2 \qquad \text{but} \qquad \gamma^2 T_{nuc}^2 \gg m^2$$

$$\frac{1}{(p_1 + p_2)^2} \rightarrow \frac{1}{(p_1 + p_2)^2 + m^2}$$

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Summary & Outlook

- Valuable input from SEWM
  - Polarisation sum, thermal mass, …?
- Investigate phenomenology
  - Concrete Models
  - Gravitational Waves
  - Baryogenesis