Maximal temperature of strongly coupled dark sectors

Helena Kolešová (AEC, ITP, University of Bern)

Joint work with Simona Procacci and Mikko Laine

ArXiv: 2303.17973

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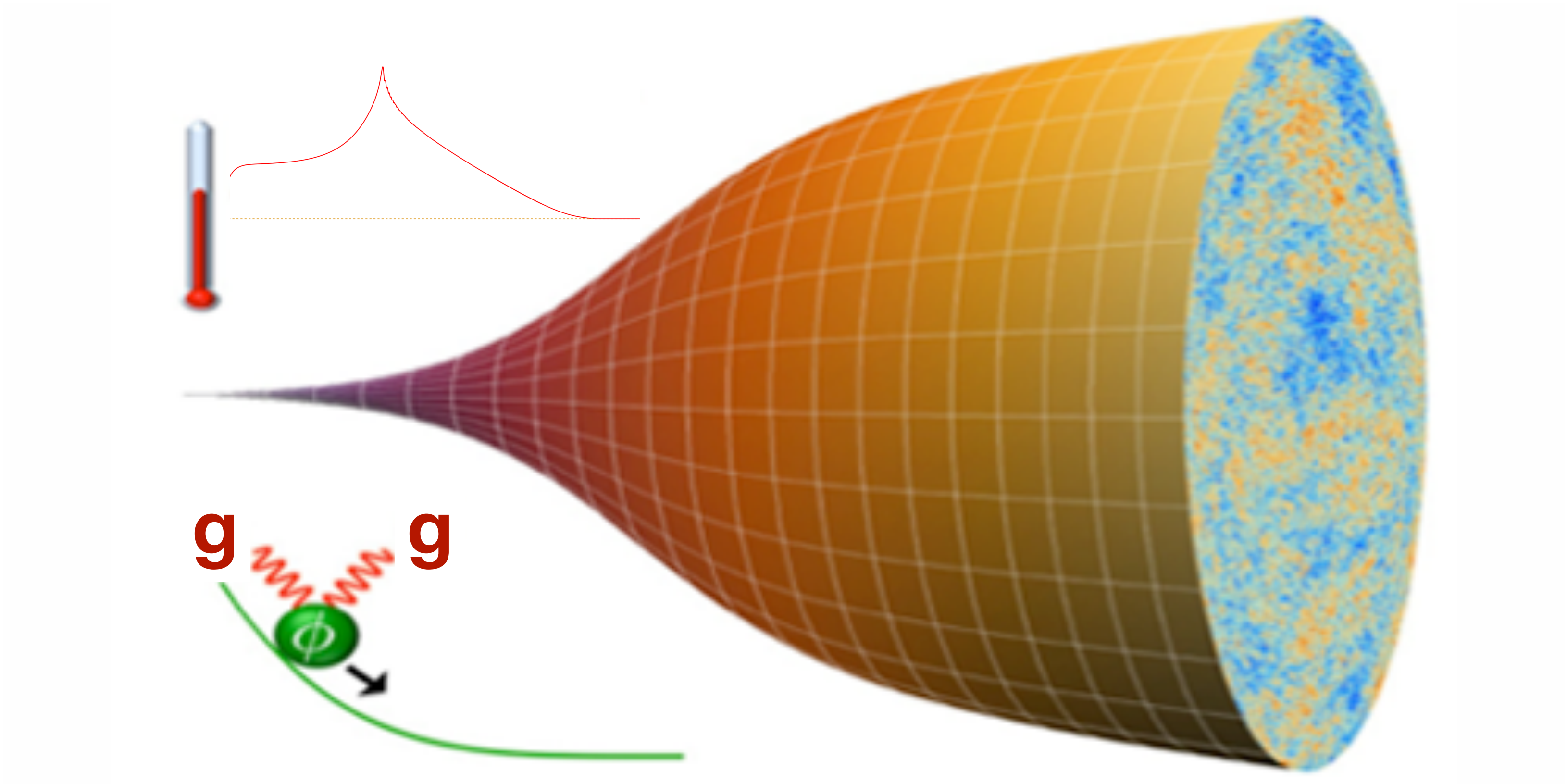
Summary

- Inflaton coupled to non-abelian dark sector (parametrised by confinement scale Λ_{IR})

- Thermal bath present throughout the inflation!

- Working example: Axion inflation coupled to SU(3) gauge sector [Laine, Procacci: 2102.09913] [Klose, Laine, Procacci: 2201.02317] [Klose, Laine, Procacci: 2210.11710]

- [HK, Laine, Procacci: 2303.17973] - evolution of dark sector temperature studied



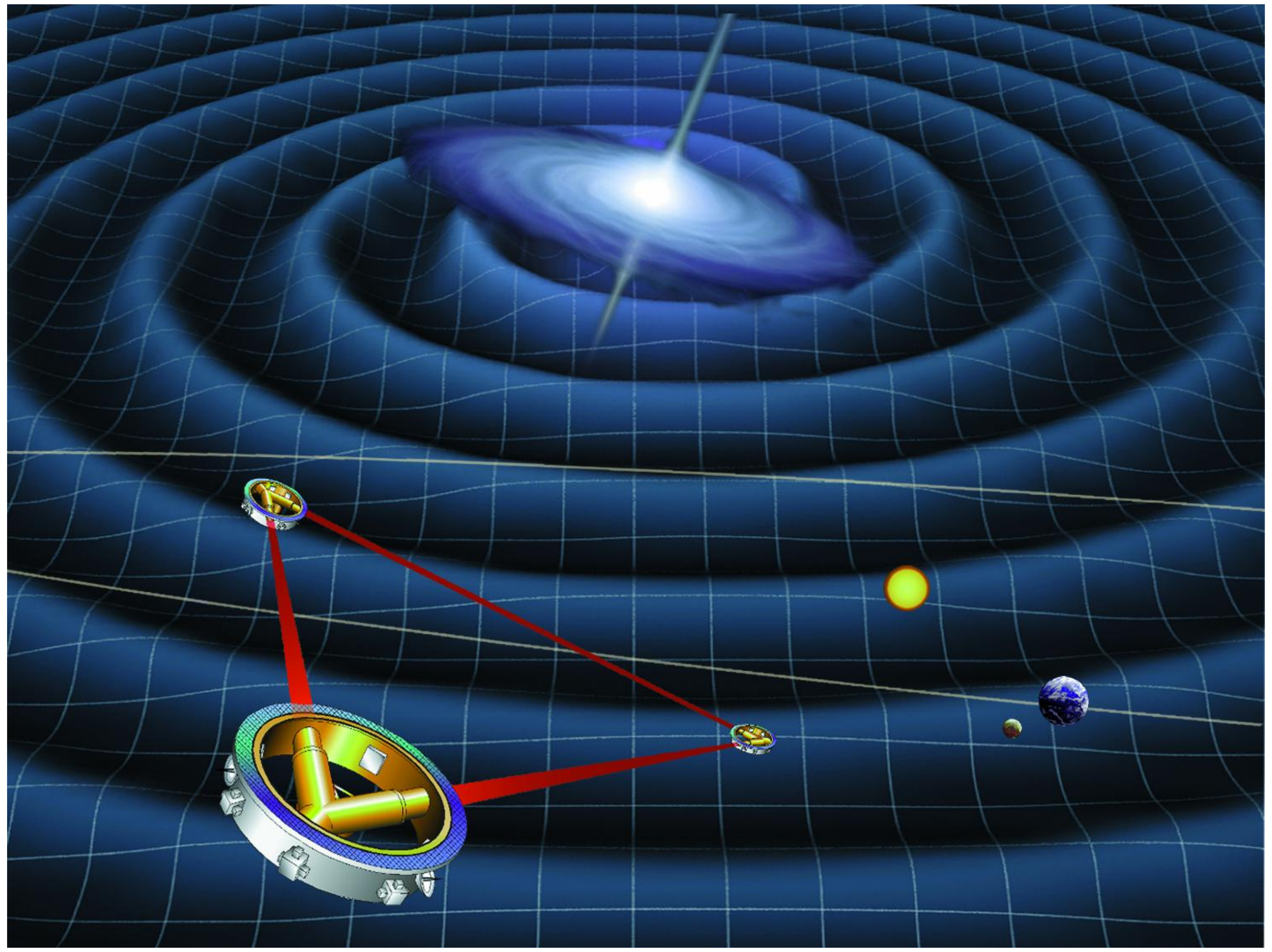
Credit: João G. Rosa/University of Aveiro; ESA and the Planck collaboration

Why is high temperature interesting?

- Possible gravitational wave signal:

  - Thermal fluctuations
    [Ghiglieri, Laine: 1504.02569]
    [Klose, Laine, Procacci: 2201.02317, 2210.11710]

  - Dark sector confinement phase transition
    [Caprini et al.: 1910.13125] [Schwaller:1504.07263]



Credit: http://lisa.jpl.nasa.gov/gallery/lisa-waves.html

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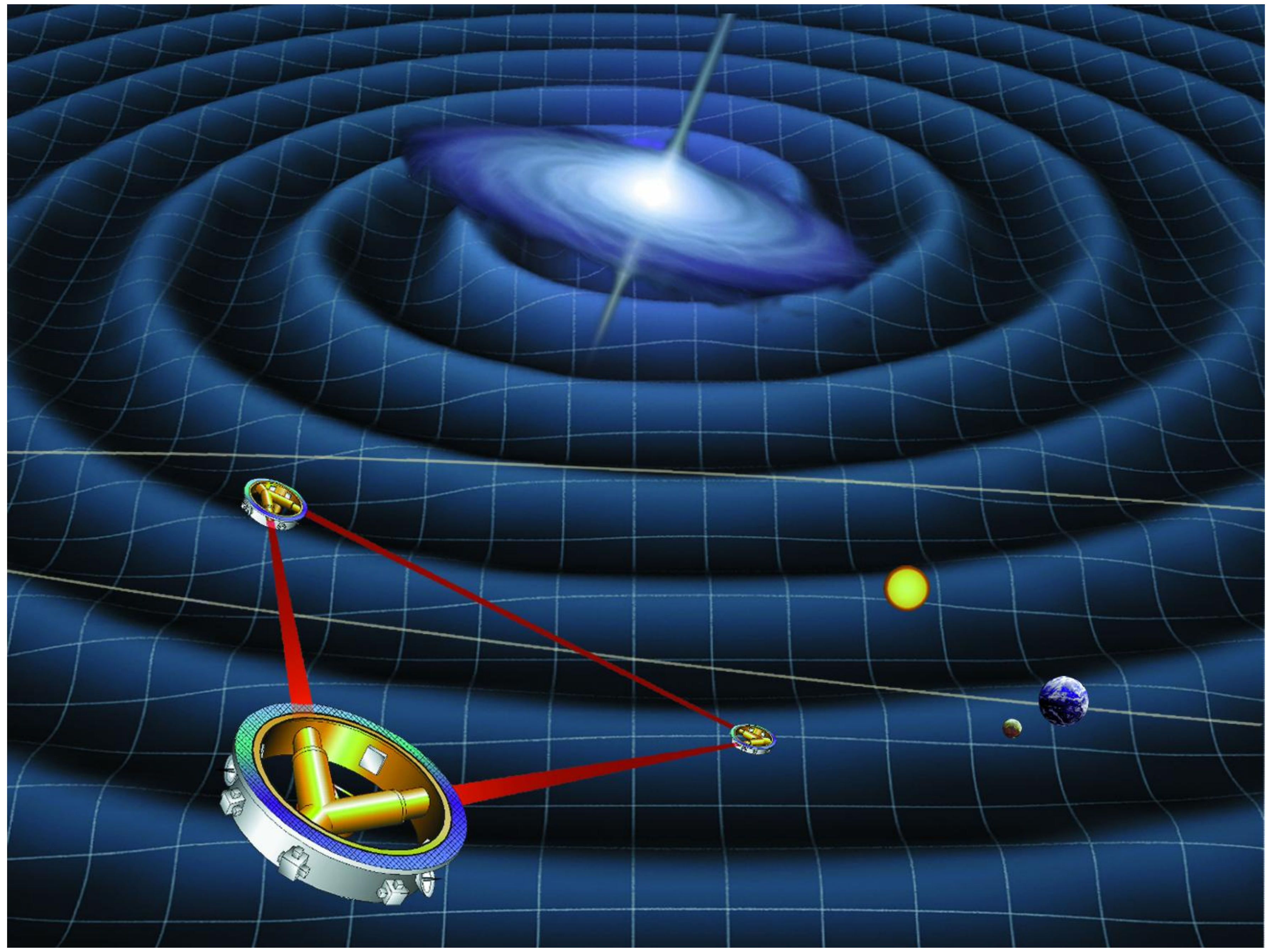
- But has the dark sector heated up above the confinement temperature?



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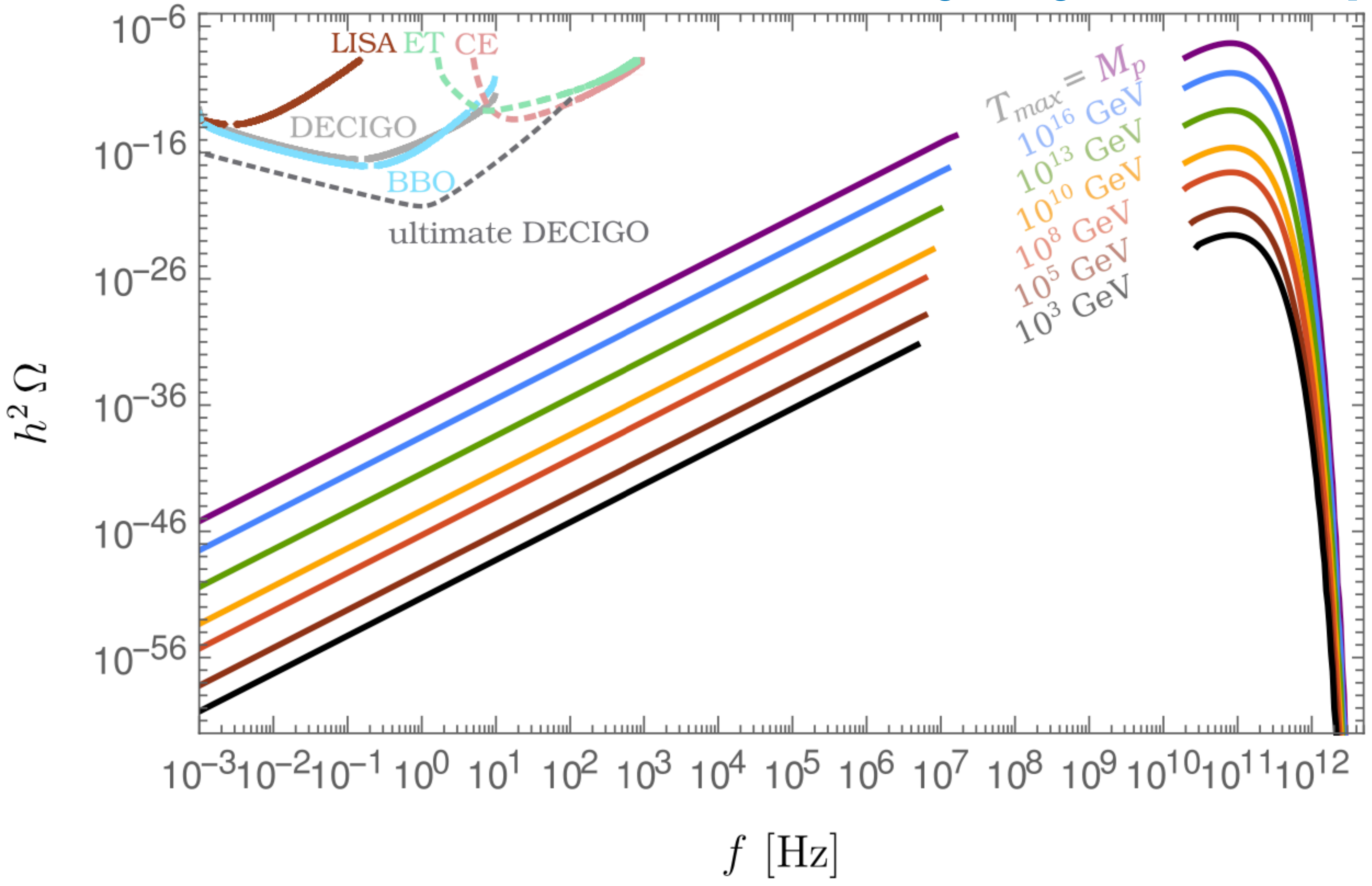
[Ringwald, Schütte-Engel,Tamarit: 2011.04731
Gravitational waves as a big bang thermometer]



- But has the dark sector heated up above the confinement temperature?

- Amplitude of gravitational waves from thermal fluctuations grows significantly with maximum reached temperature!

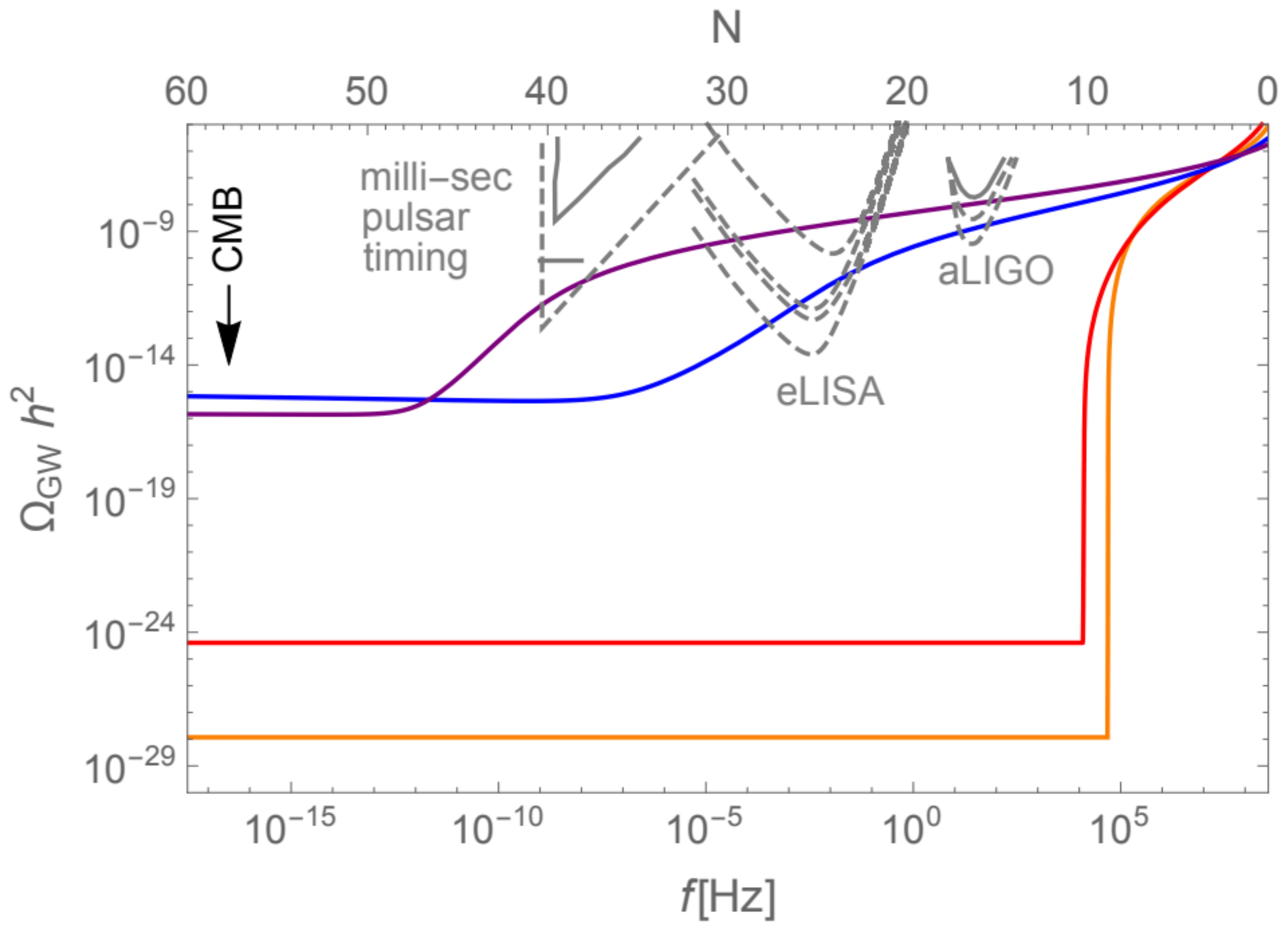
NB: abelian vs non-abelian dark sector

- Pseudoscalar inflaton coupled to gauge fields:

See talks by Juan, Matteo and Martino!

$$\mathscr{L} \supset -\frac{\alpha\, \varphi\, \epsilon^{\mu\nu\rho\sigma} F_{\mu\nu} F_{\rho\sigma}}{16\pi f_a}$$

- Abelian case: exponential growth of one helicity mode of the vector field ⇒ GW, PBH, CMB non-gaussianities… [Sorbo: 1101.1525; Cook, Sorbo: 1101.1525; Barnaby, Pajer, Peloso: 1110.3327; Domcke, Pieroni, Binétruy: 1603.01287…]



[Domcke: 1605.06364; Domcke, Pieroni, Binétruy: 1603.01287]

- Discussion about back-reaction [… Figueroa et al.: 2303.17436]

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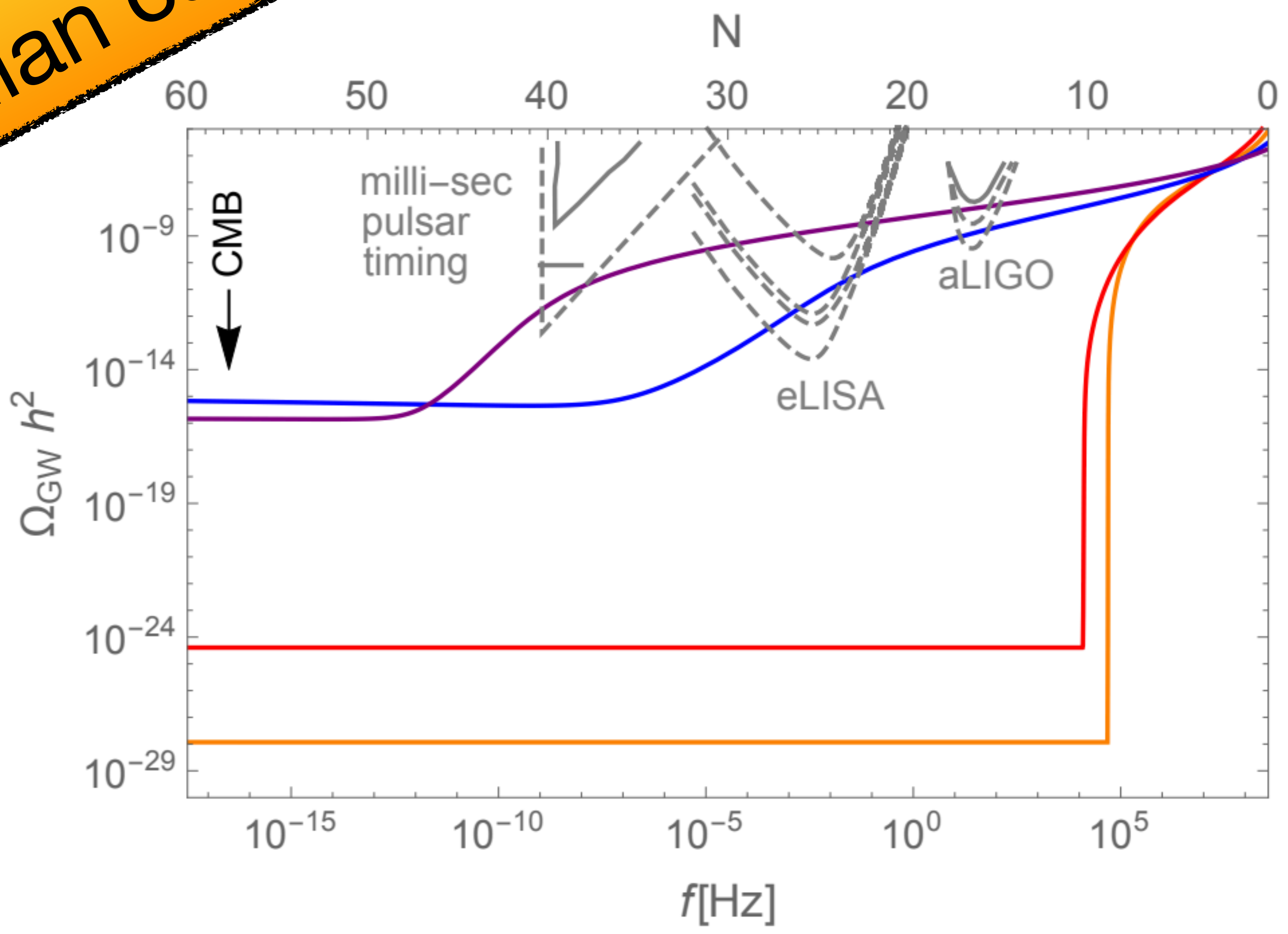
Absent in thermal non-abelian case!



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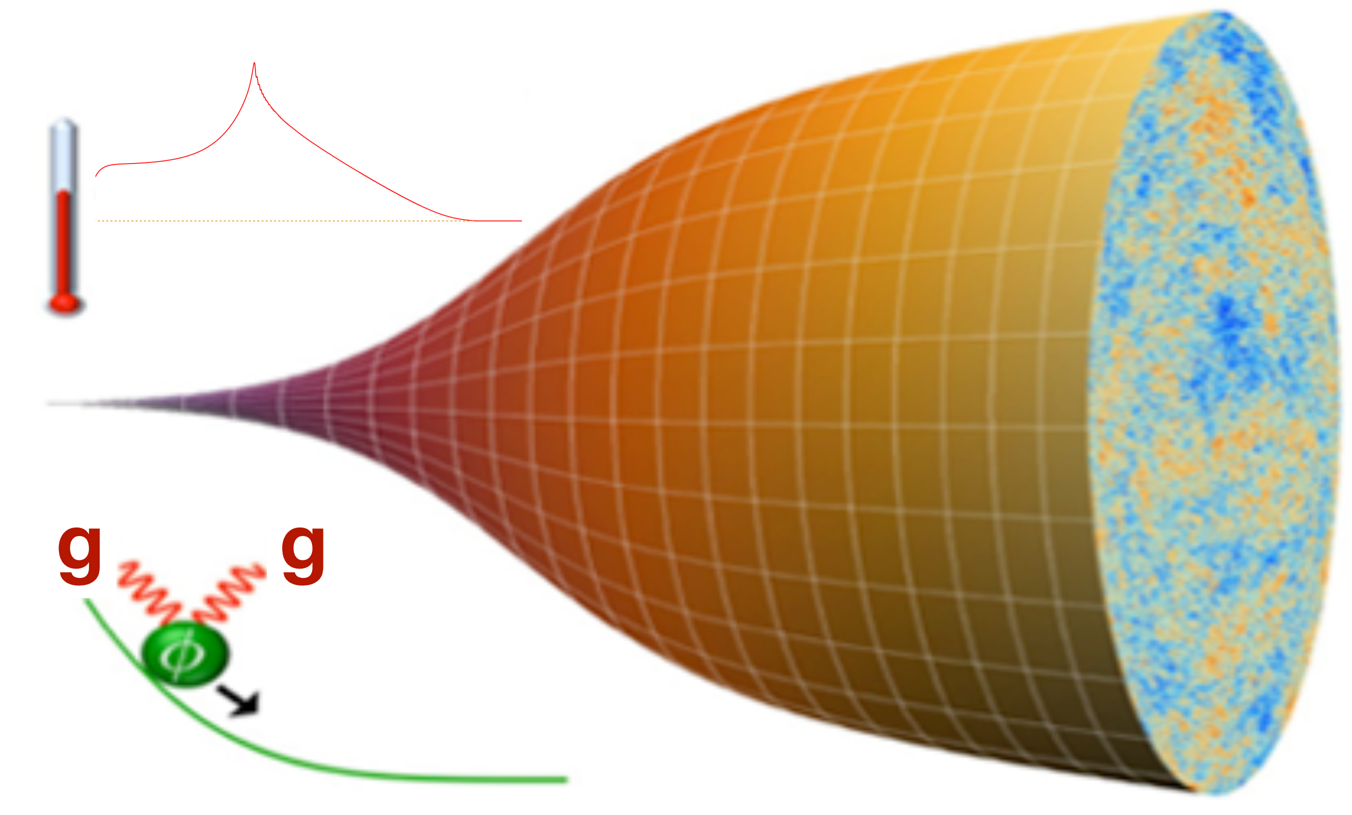
Model setup

- Inflaton coupled to non-abelian dark sector (parametrised by confinement scale Λ_{IR})



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Gauge coupling

Yang-Mills field strength

$$\mathscr{L} \supset \frac{1}{2}\partial^\mu\varphi\,\partial_\mu\varphi - V_0(\varphi) - \frac{\alpha\,\varphi\,\epsilon^{\mu\nu\rho\sigma}F^c_{\mu\nu}F^c_{\rho\sigma}}{16\pi f_a}$$

Inflaton field

Inflaton potential:

Axion decay constant

$$V_0 \simeq m^2 f_a^2\left[1-\cos\left(\frac{\bar{\varphi}}{f_a}\right)\right]$$

“Natural/axion inflation” [Freese, Frieman, Olinto: Phys.Rev.Lett. 65 (1990)]

Model setup

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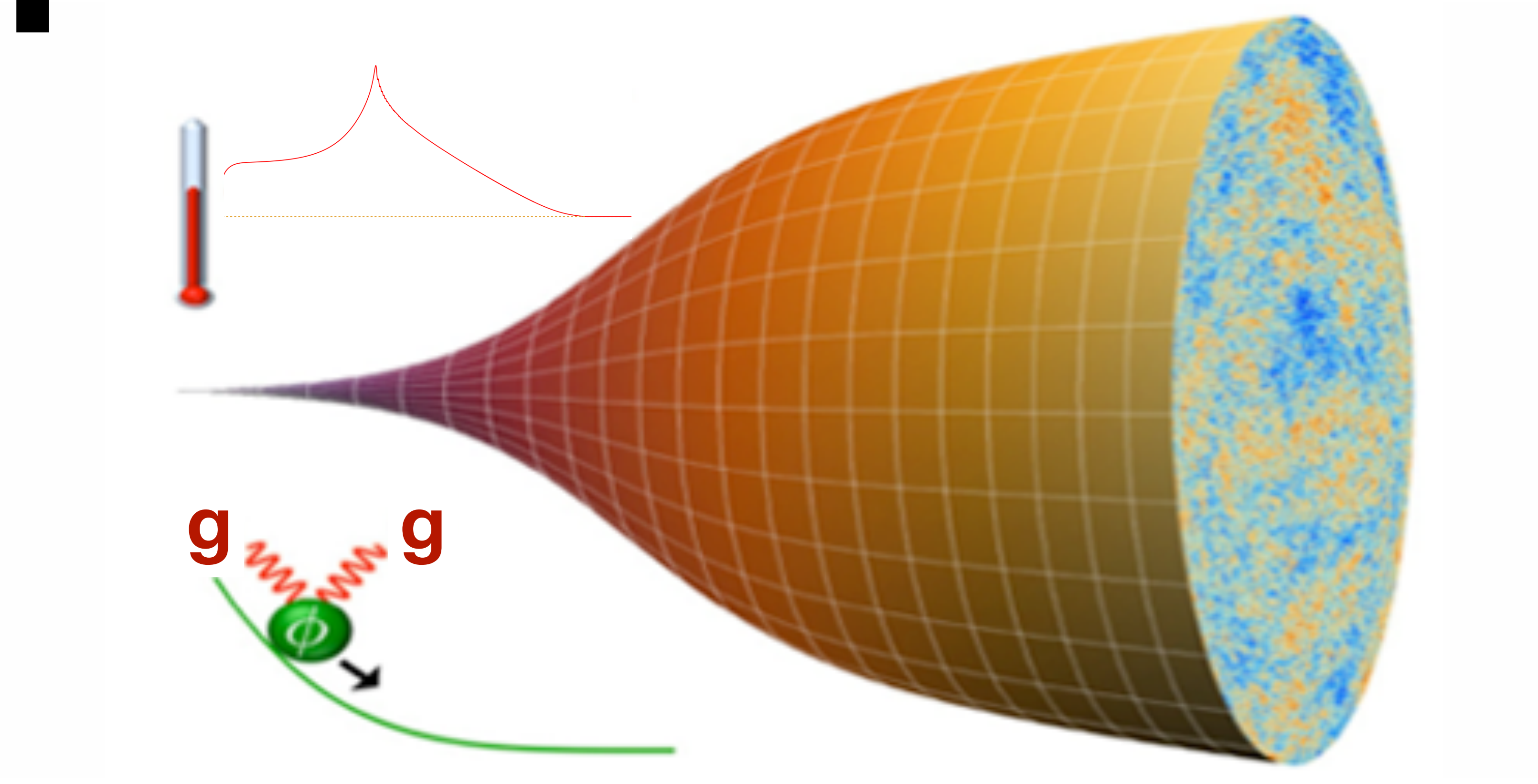

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Hubble rate

Friction due to inflaton coupling to dark sector! [Laine, Niemi, Procacci, Rummukainen: 2209.13804]

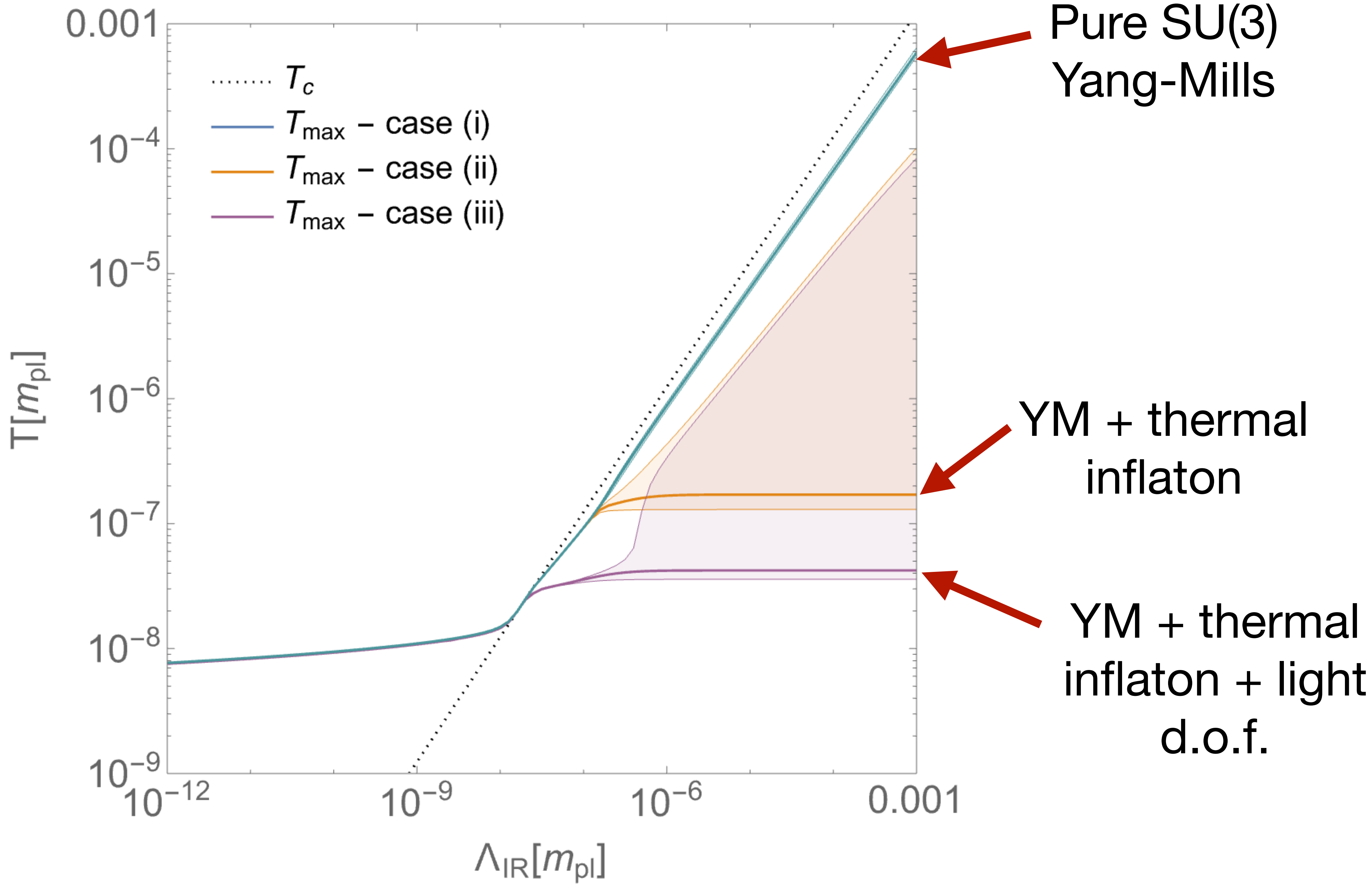
$$\ddot{\bar\varphi} + (3H+\Upsilon)\dot{\bar\varphi} + V_\varphi \simeq 0$$

$$\dot e_r + 3H(e_r+p_r) \simeq \Upsilon\dot{\bar\varphi}^2$$

Dark radiation energy and pressure densities

Results: Maximal temperature of the dark sector

[HK, Laine, Procacci: 2303.17973]



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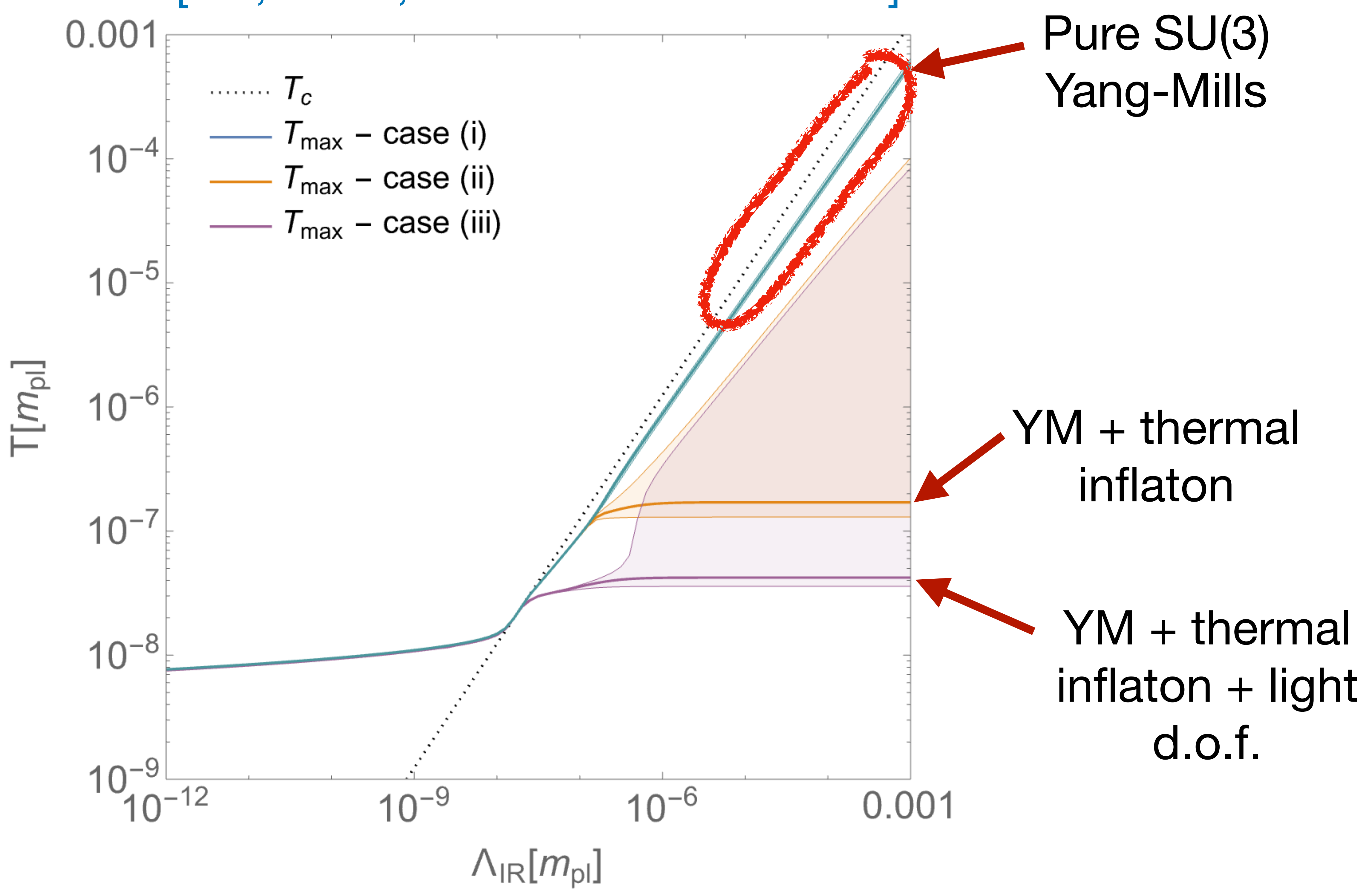

Message 1: Temperatures up to $10^{-3}\, m_{\text{pl}}$ can be reached

- For Λ_{IR} up to $10^{-3}\, m_{\text{pl}}$
- If Yang-Mills plasma not coupled to extra light d.o.f.

$\Rightarrow$ Hope for potentially detectable GW from thermal plasma in ET, LISA frequency range!

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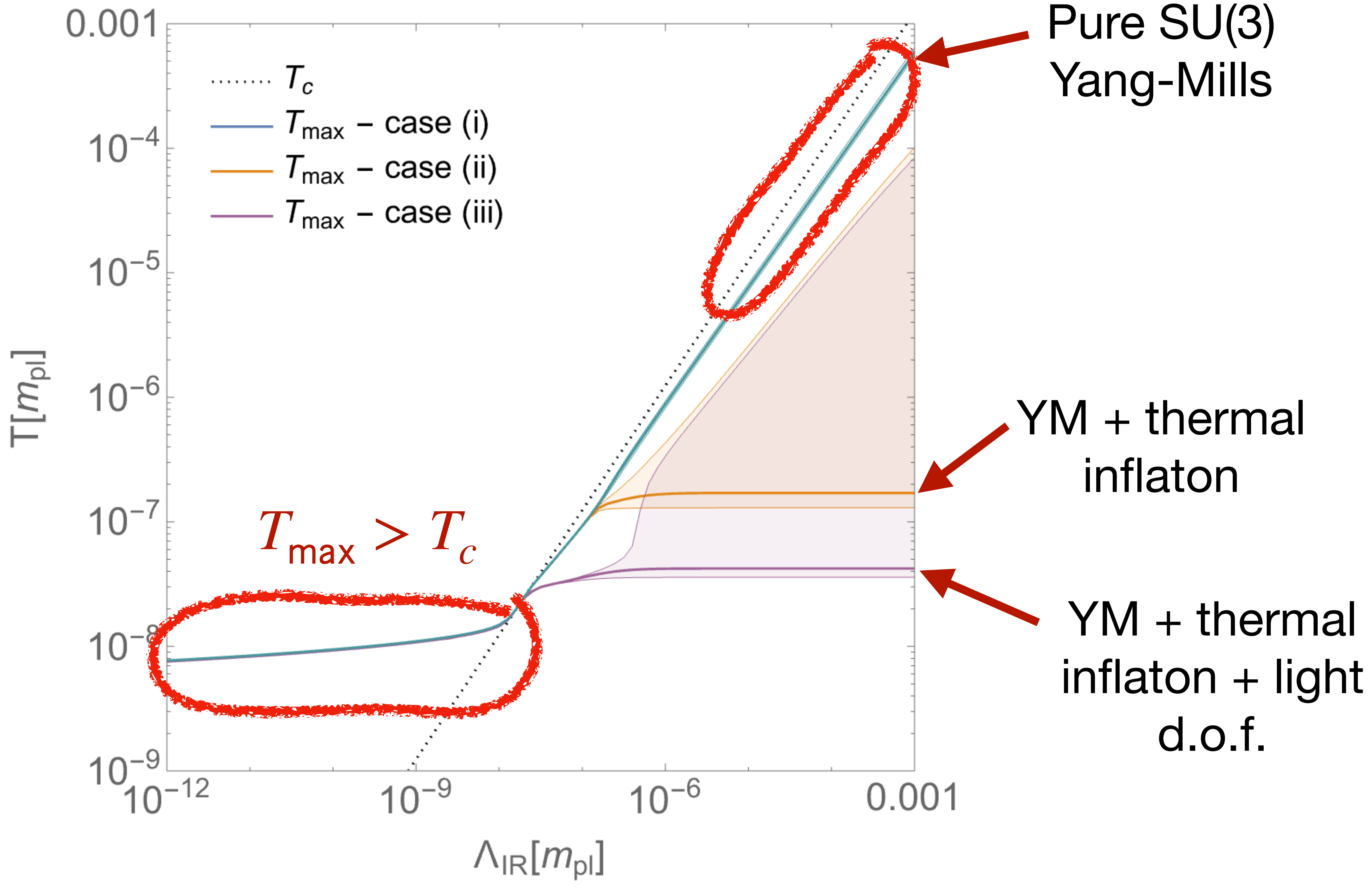

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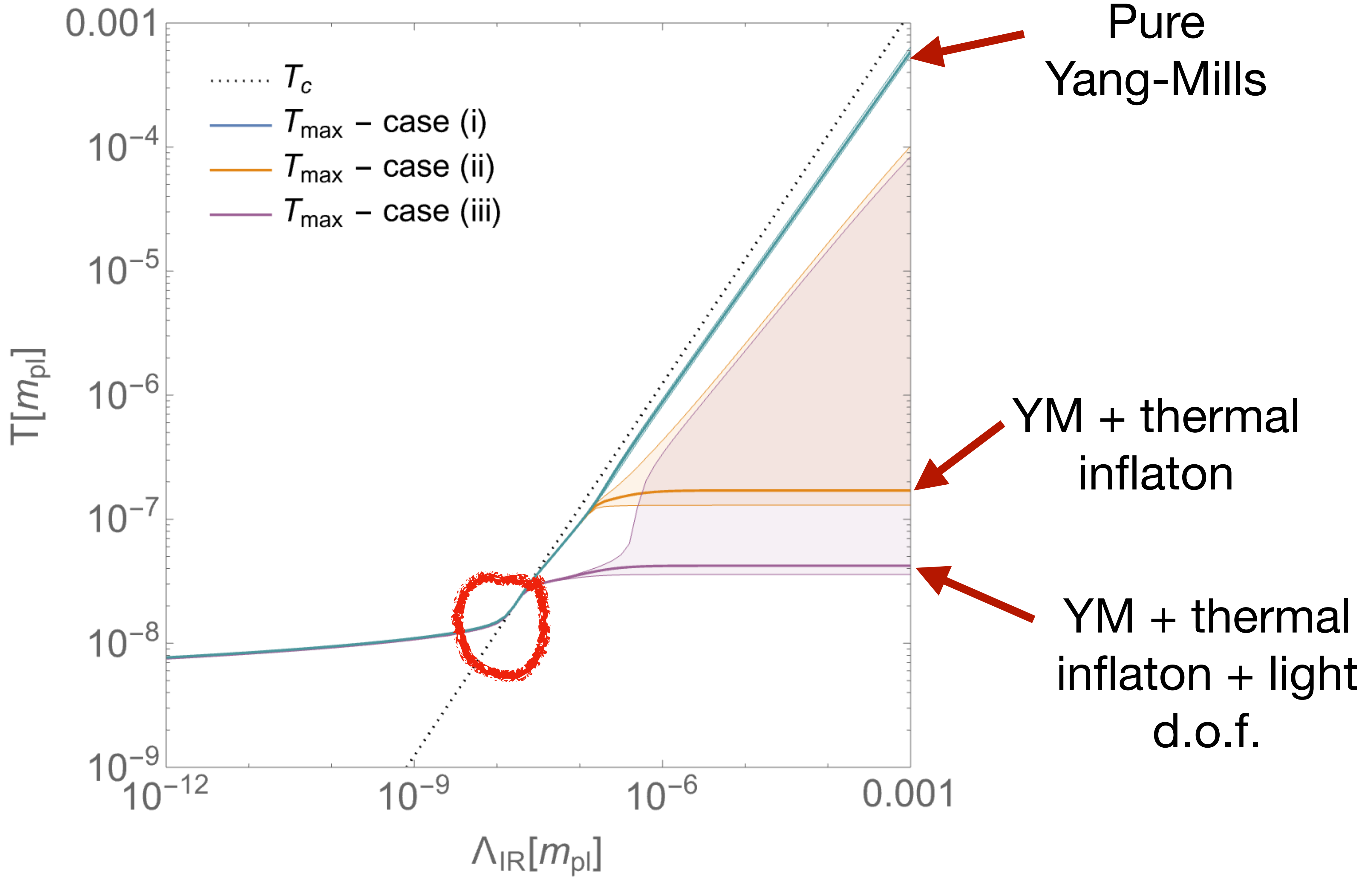
Message 2: For lower Λ_{IR} the dark sector heats up above T_c
⇒ undergoes a phase transition! Possible further GW signal!

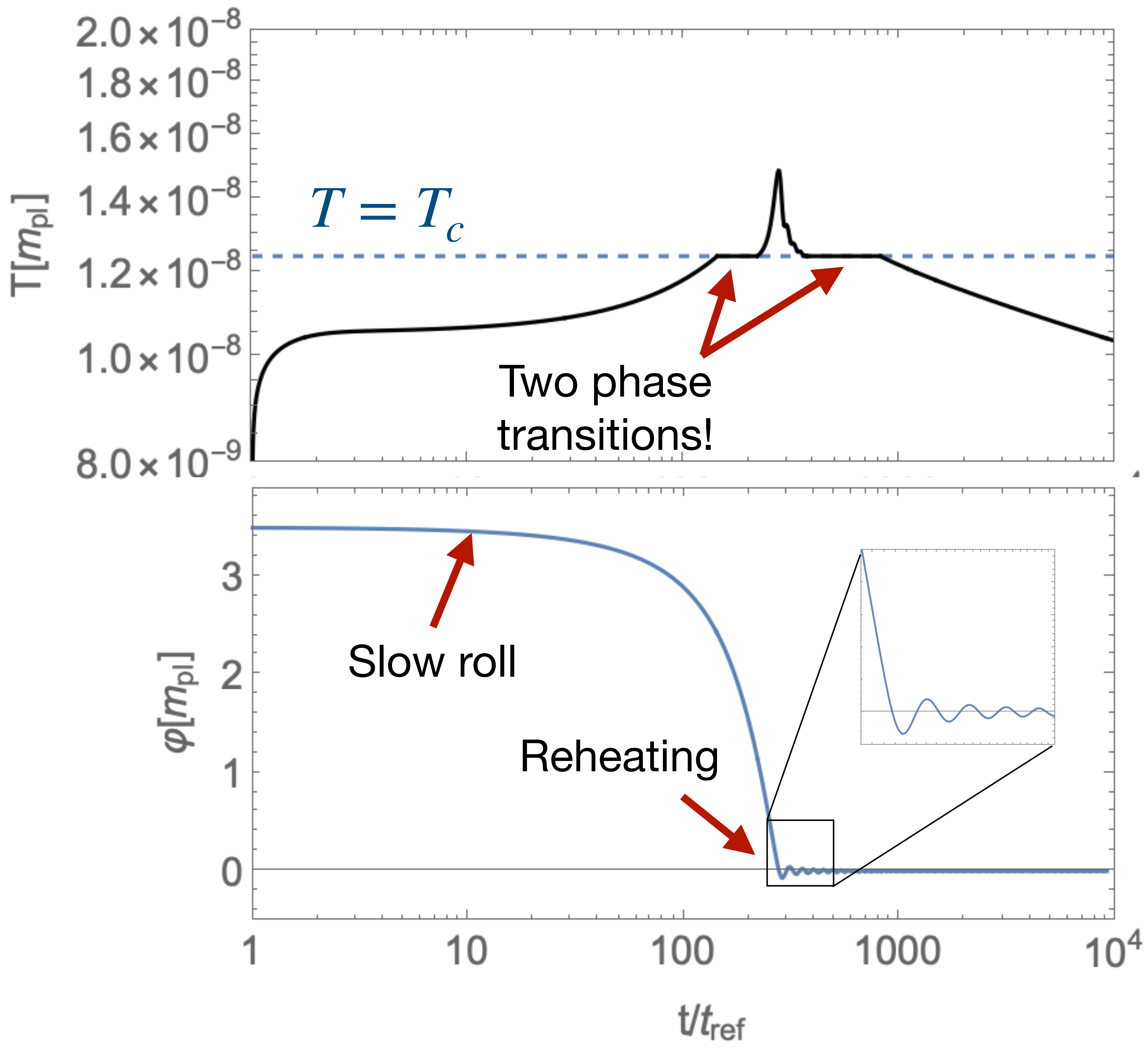
Results: Maximal temperature of the dark sector

[HK, Laine, Procacci: 2303.17973]



Message 3: There can even be two phase transitions!

Example: $\Lambda_{\mathrm{IR}} = 10^{-8} m_{\mathrm{pl}}$



Benchmark parameter choice
(axion inflation consistent with CMB data)
[Klose, Laine, Procacci: 2201.02317]:
axion mass: $m = 1.09 \times 10^{-6}\, m_{\mathrm{pl}}$,
axion decay constant: $f_a = 1.25\, m_{\mathrm{pl}}$,
initial time: $t_{\mathrm{ref}} \sim H_{\mathrm{initial}}^{-1}$

$\Rightarrow \Upsilon \sim 10^{-23} m_{\mathrm{pl}} \ll H_{\mathrm{initial}}$

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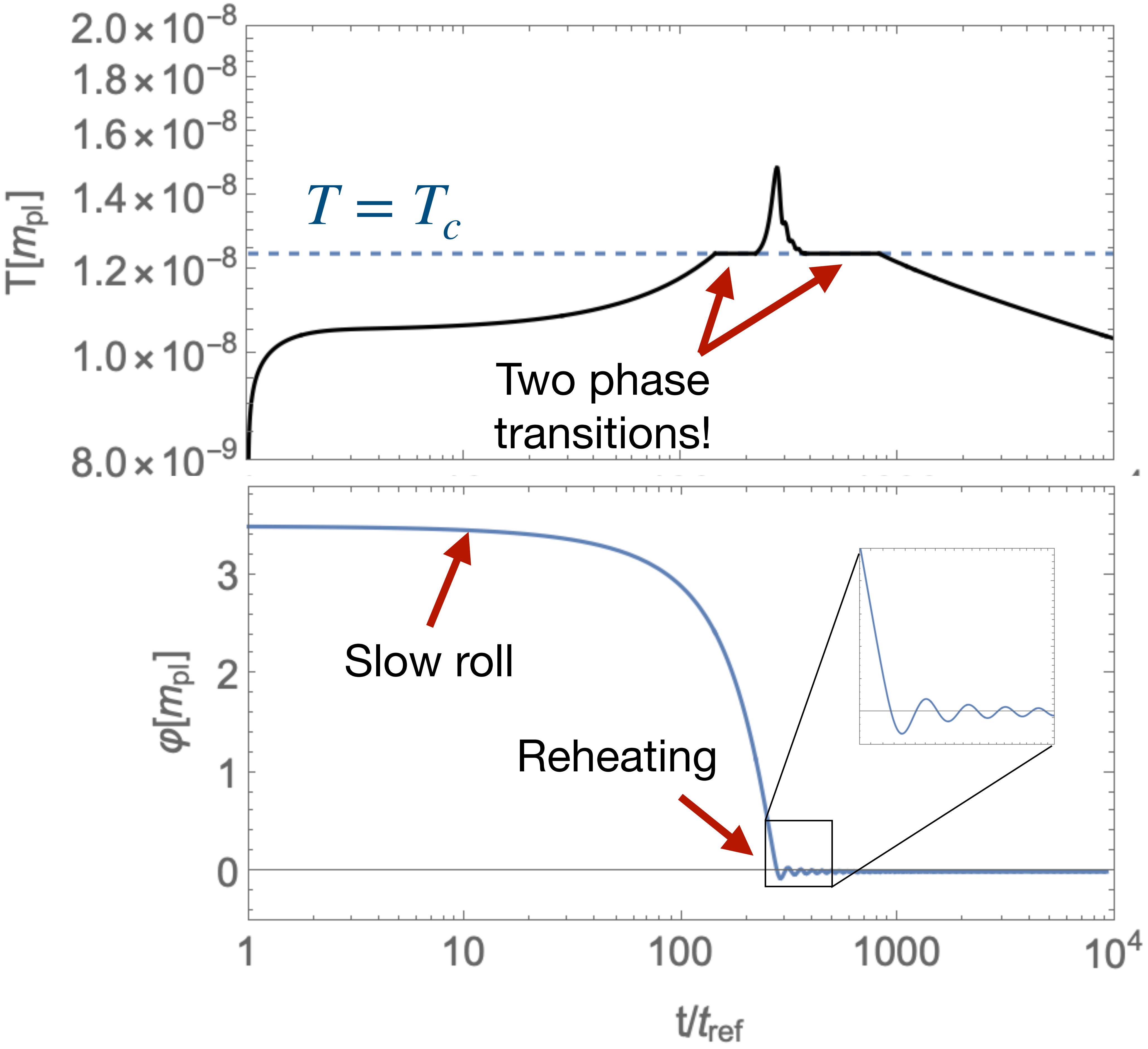

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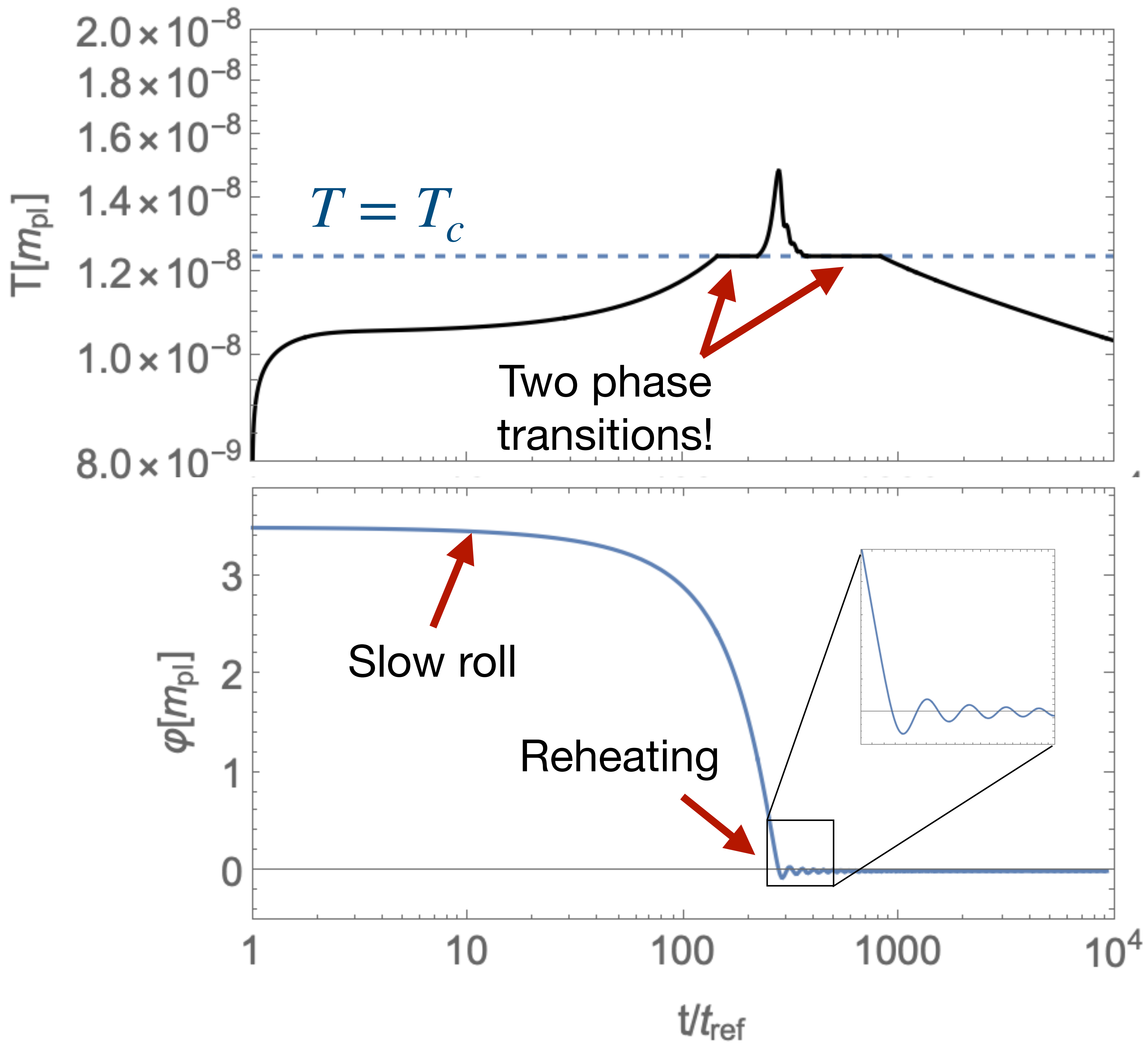

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BUT!

- $\Upsilon \ll H \Rightarrow$ Long inflaton domination $\Rightarrow$ more significant GW dilution

- How and when SM is reheated?

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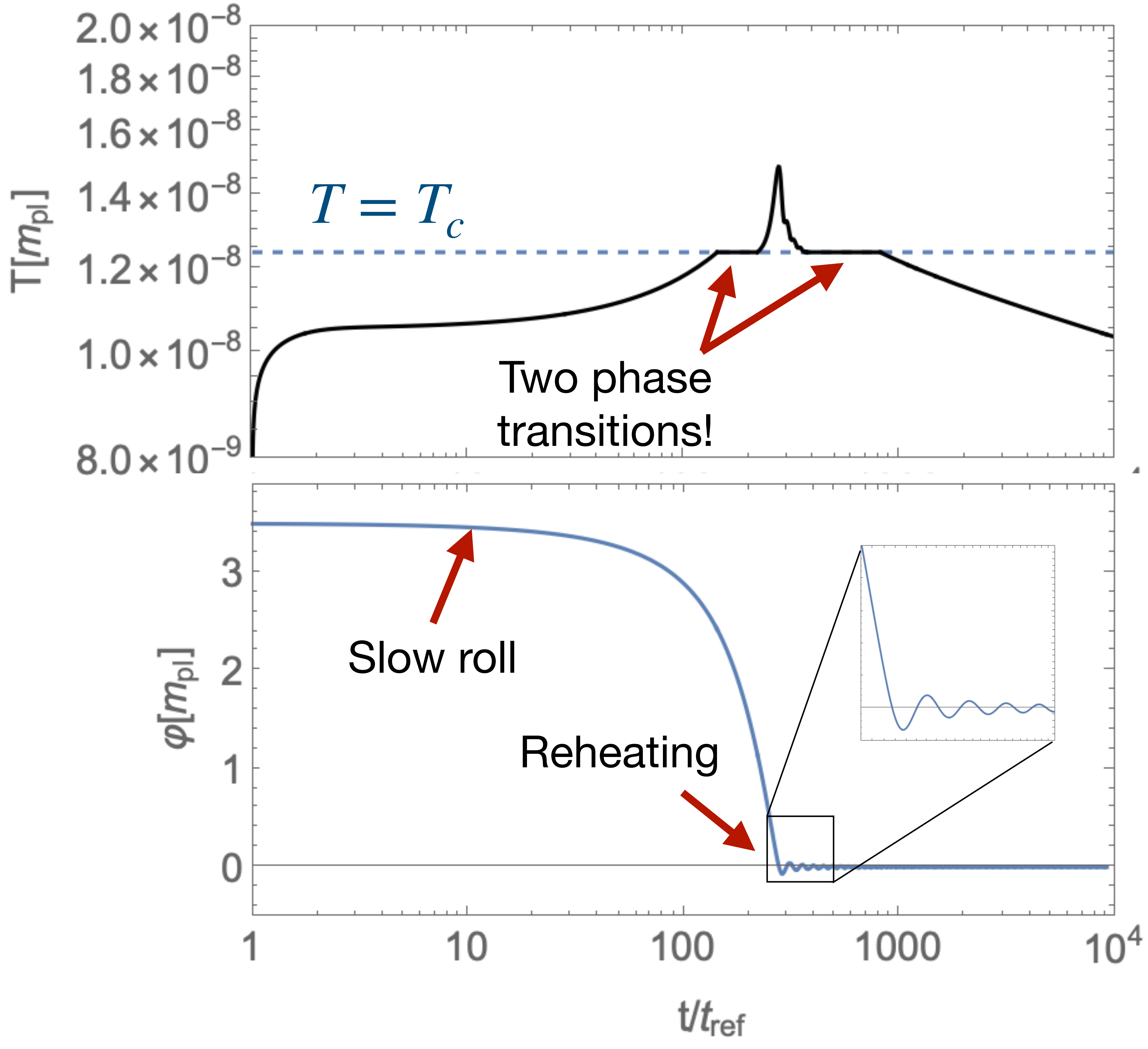

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To be worked out!

Conclusions

- Evolution of a dark Yang-Mills sector coupled to axion inflation studied
- Different qualitative behaviour depending on the dark confinement scale $\Lambda_{\rm IR}$:

$\Lambda_{\rm IR} \lesssim 10^{-8} m_{\rm pl} : T_{\rm max} \sim 10^{-8}\, m_{\rm pl} > T_c \Rightarrow$ Phase transition

$\Lambda_{\rm IR} \gtrsim 10^{-8} m_{\rm pl} : T_{\rm max}$ slightly below $T_c \Rightarrow$ Large temperatures achieved

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Stay tuned :) Thanks for your attention!

Back up

GW from thermal plasma

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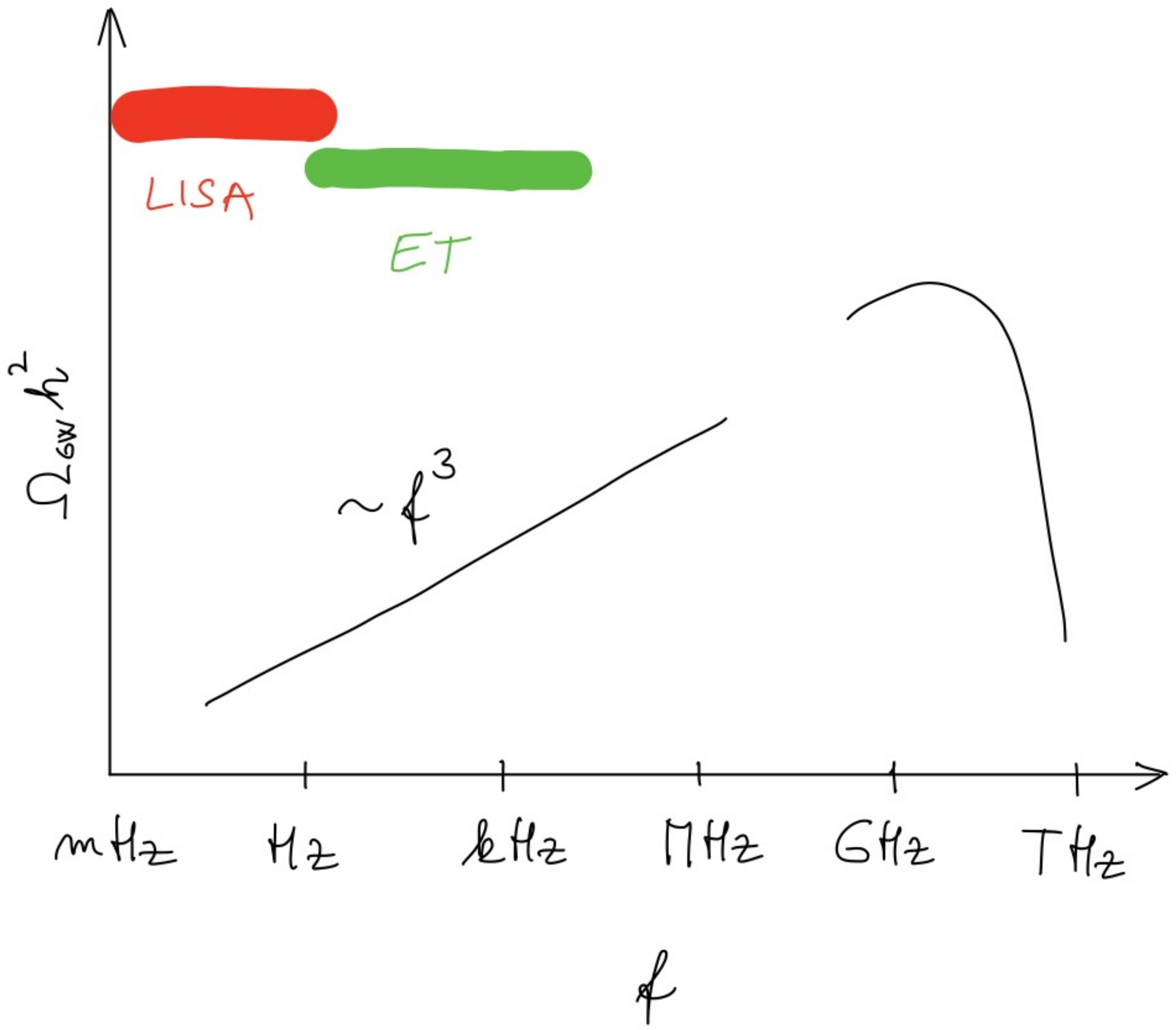

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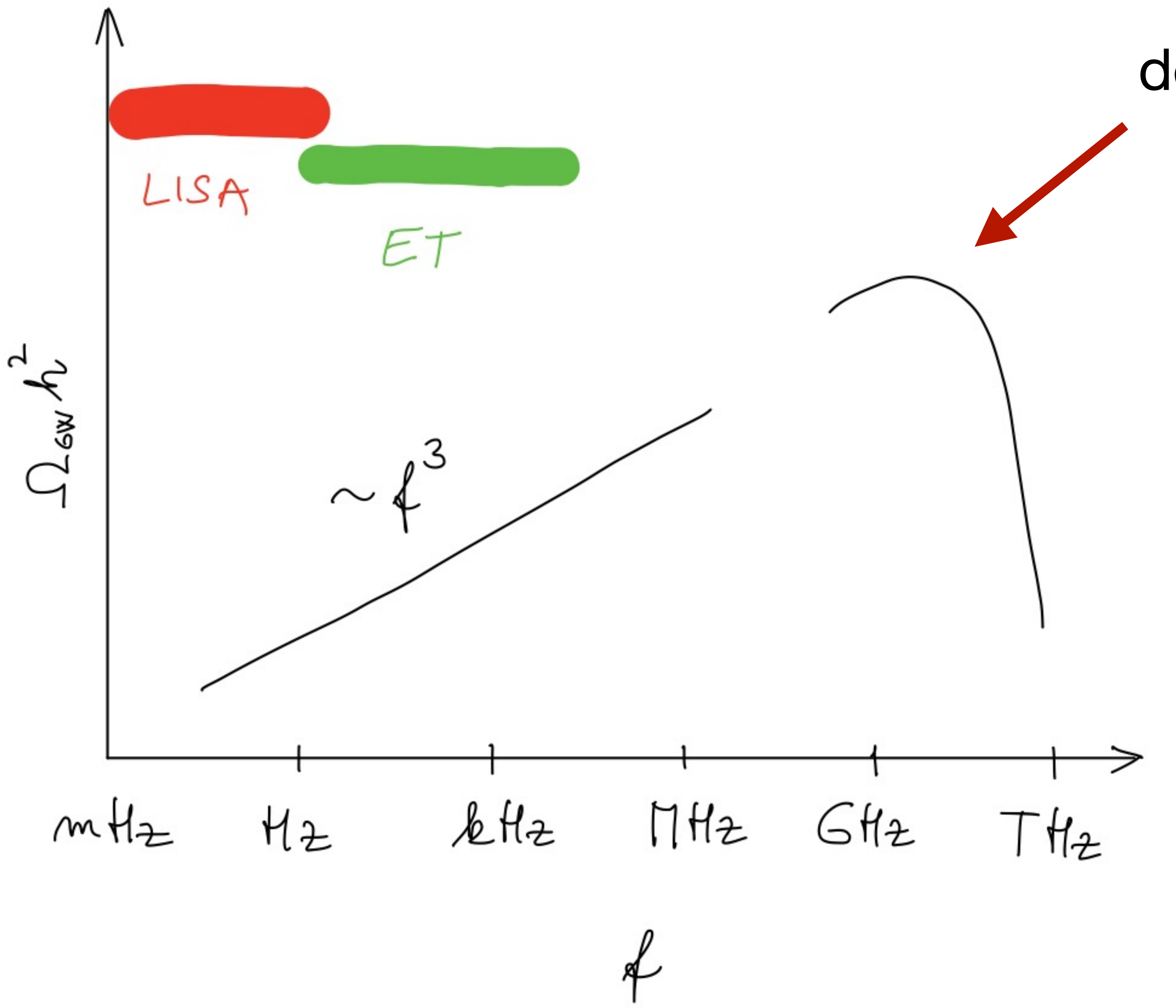

“Boltzmann domain” - determines total energy density in GW ⇔ constraints from $\Delta N_{\rm eff}$ at BBN ($\Delta N_{\rm eff} \lesssim 10^{-3} \Rightarrow T_{\rm max} \lesssim 10^{17}$ GeV)

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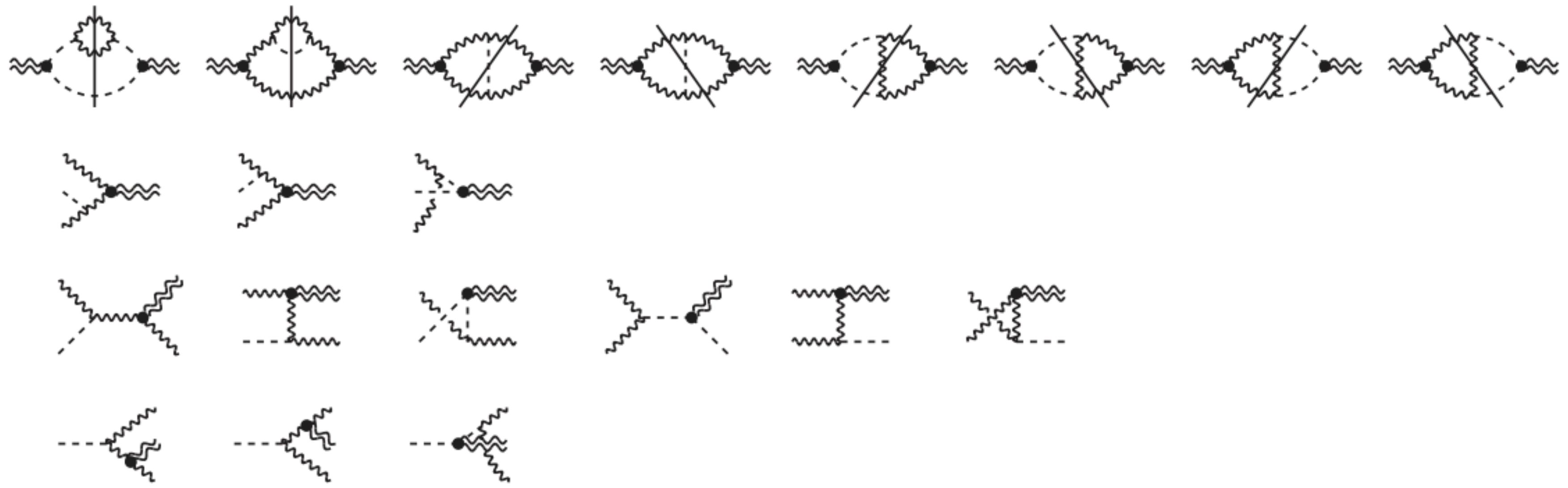

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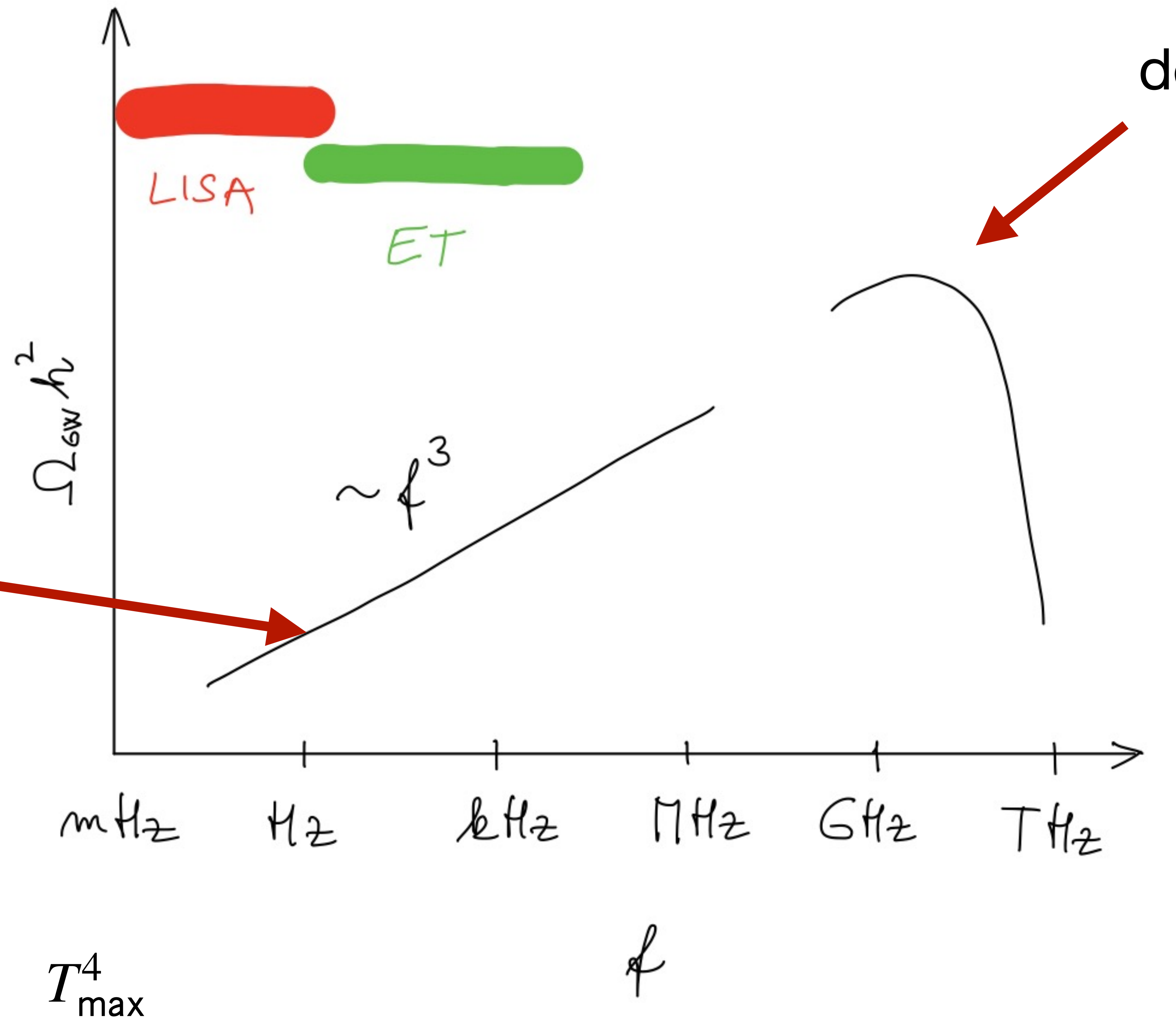

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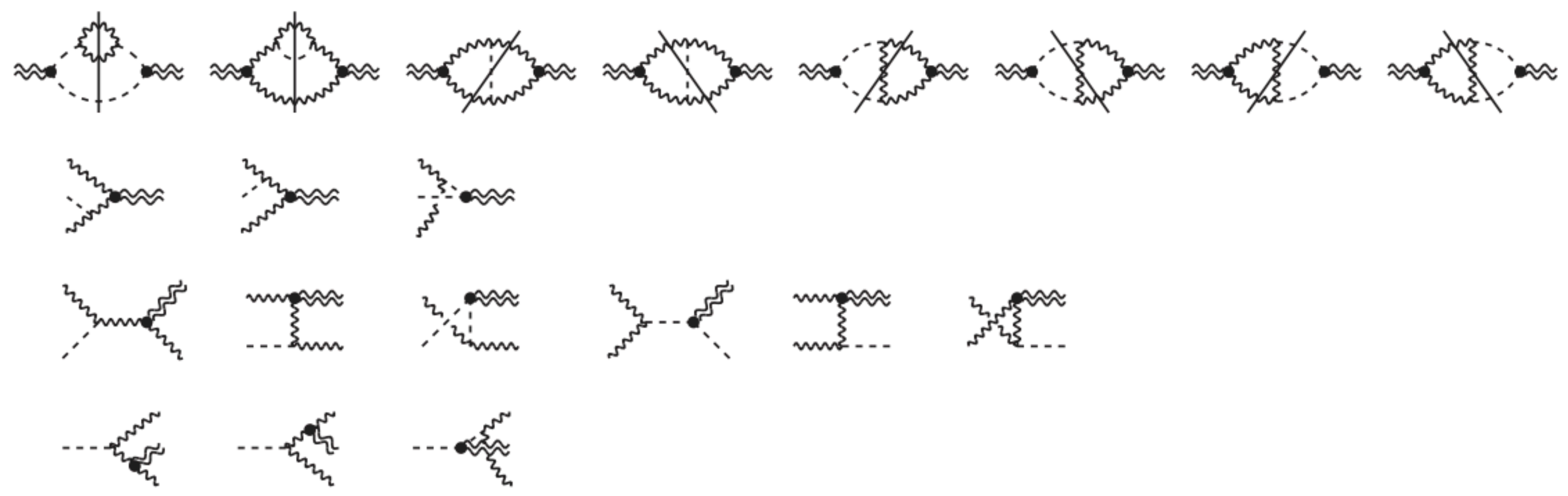
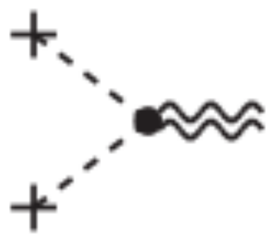


“Hydrodynamic domain”: GW signal driven by shear viscosity η



$$\Omega_{\text{GW}} h^2 \supset A \left(\frac{f}{\text{Hz}}\right)^3 \frac{(T\eta)_{\text{max}}}{m_{\text{pl}}^4}\,, \quad (T\eta)_{\text{max}} \sim \frac{T_{\text{max}}^4}{\alpha_{\text{min}}^2}$$

$A \sim 10^{-9}$ - based on calculation performed for $\Lambda \sim$ GeV

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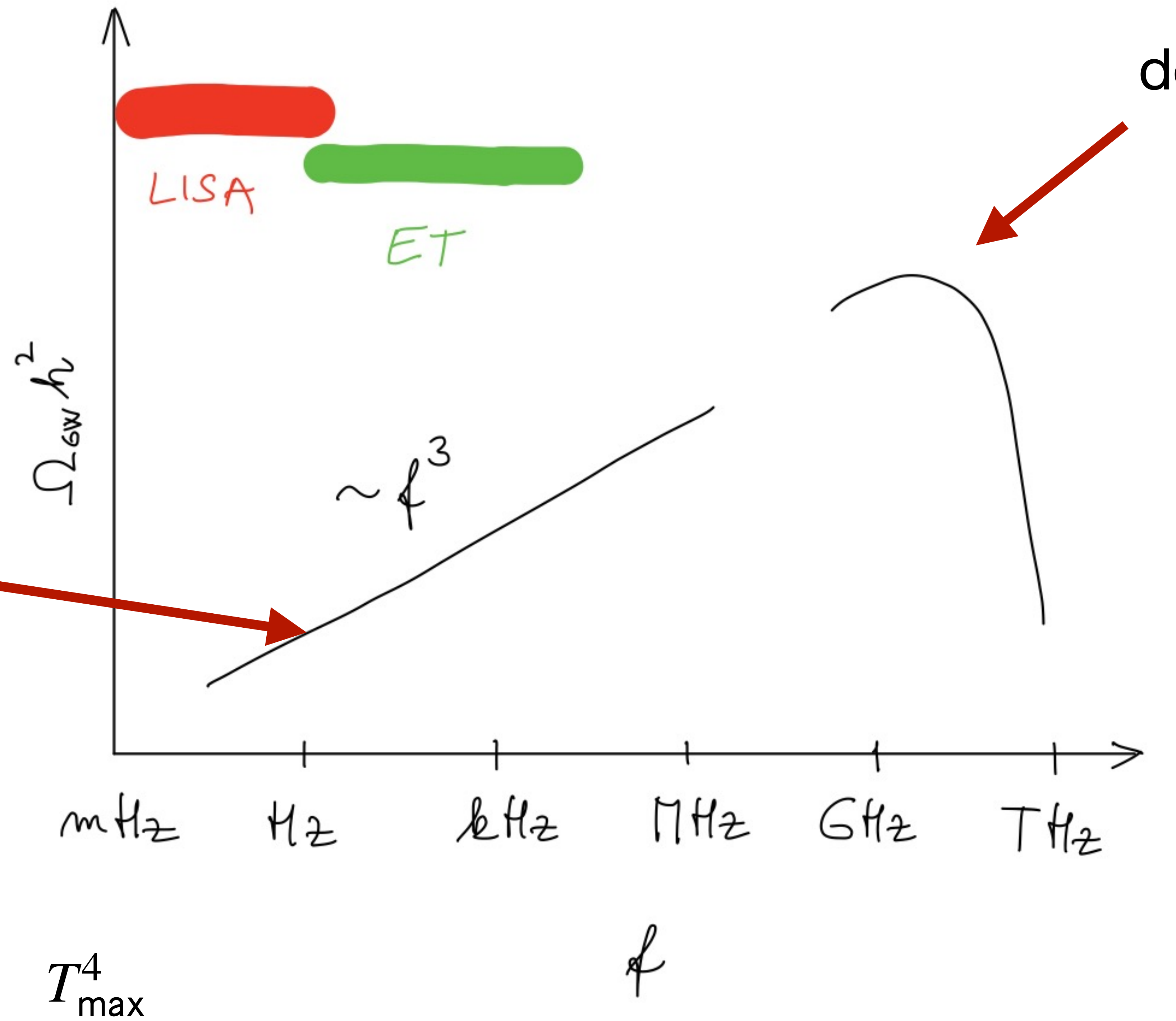

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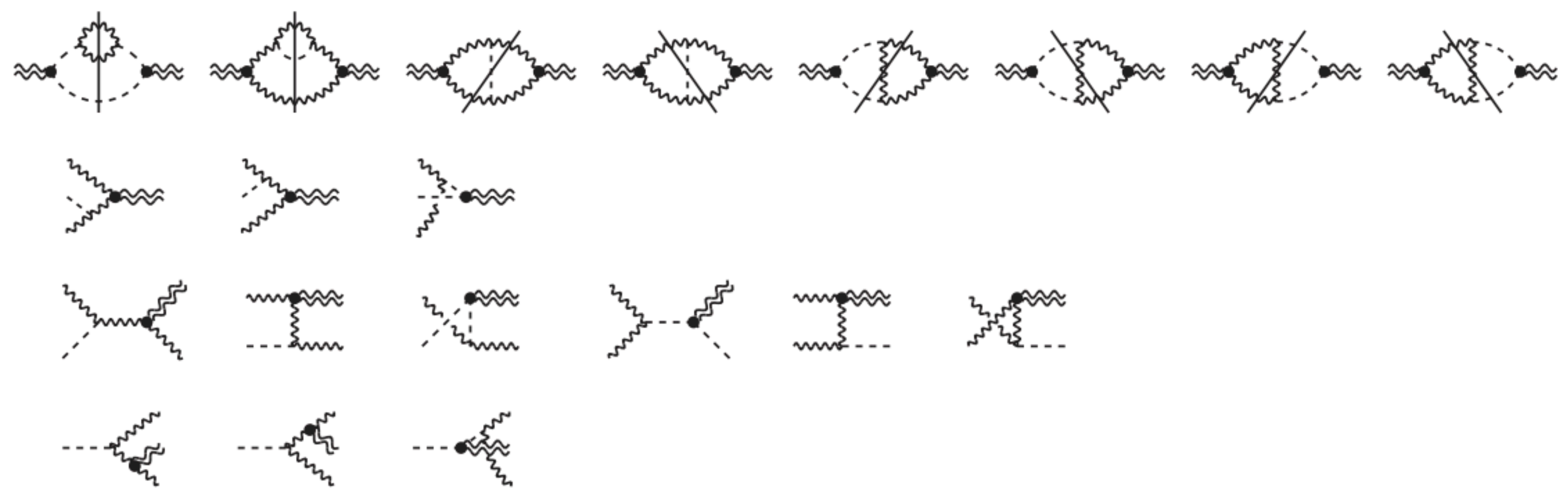

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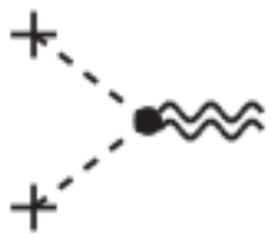

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Might be measurable if $T_{\text{max}} \sim 10^{-3}\, m_{\text{pl}}$ but more detailed calculation needed!

Why large temperatures?

$$\ddot{\varphi} + (3H + \Upsilon)\dot{\varphi} + V_\varphi \simeq 0$$

$$\dot{e}_r + 3H\left(e_r + p_r\right) \simeq \Upsilon\dot{\varphi}^2$$

Parametrize e_r, p_r by T

$$c_r(T)\,\dot{T} + 3H\left[e_r(T) + p_r(T)\right] \simeq \Upsilon\dot{\varphi}^2$$

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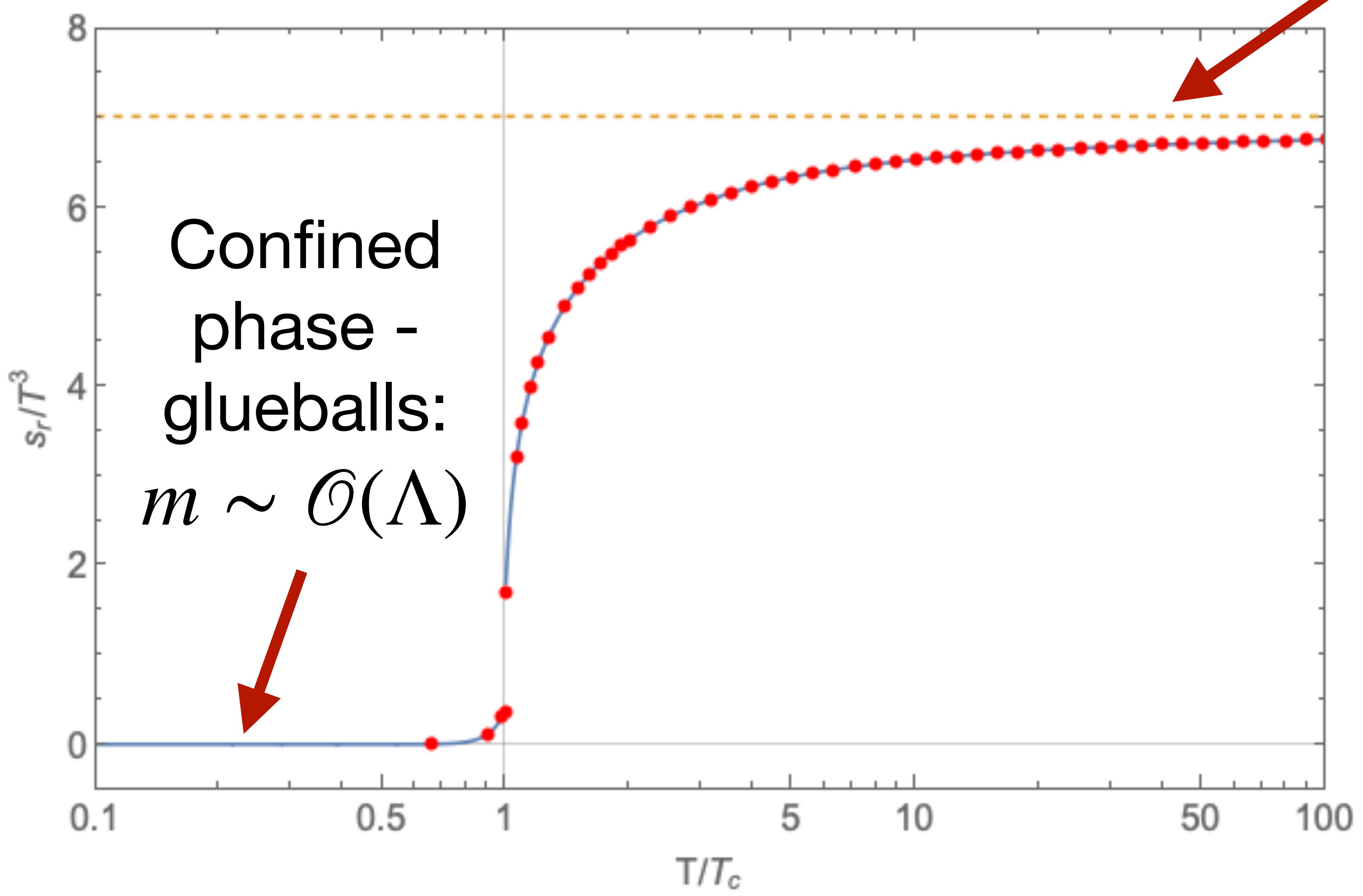
Weakly coupled radiation: $s_r = \frac{2\pi^2 g_*}{45} T^3$



Entropy density of pure $SU(3)$ measured on lattice
[Giusti, Pepe: 1612.00265]

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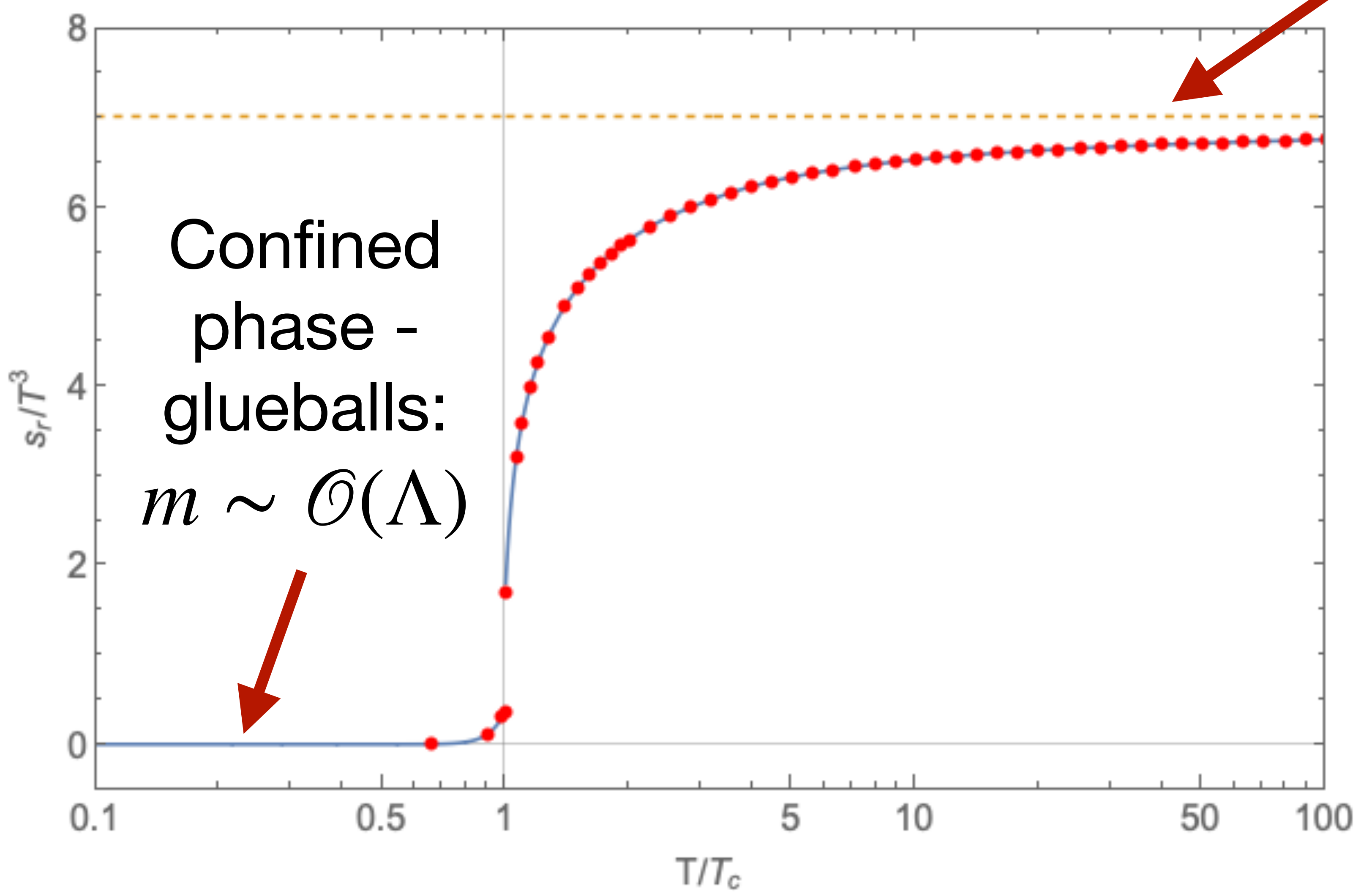

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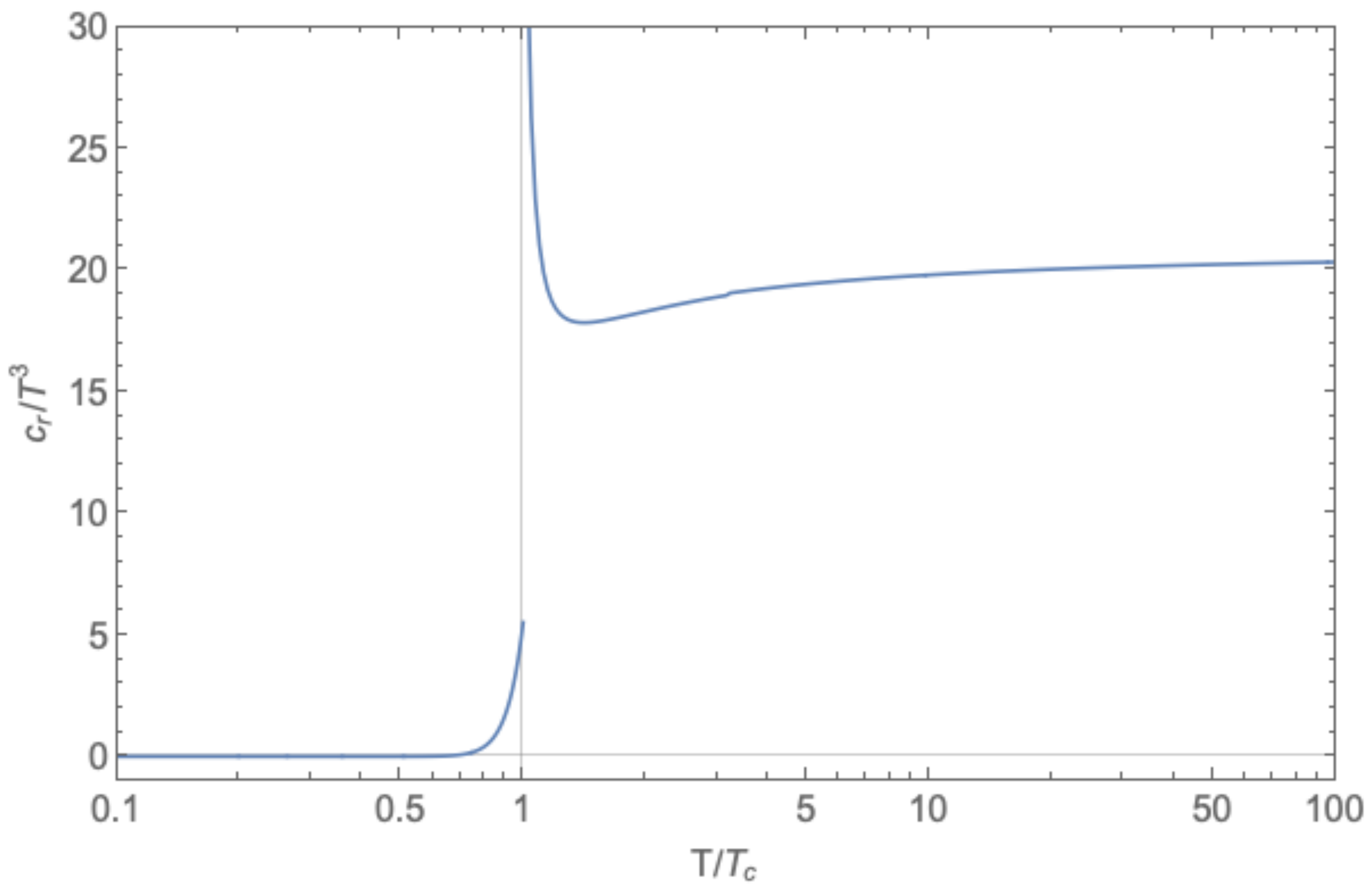

Fit of lattice data for s_r,
$s_r = \partial_T p_r$,
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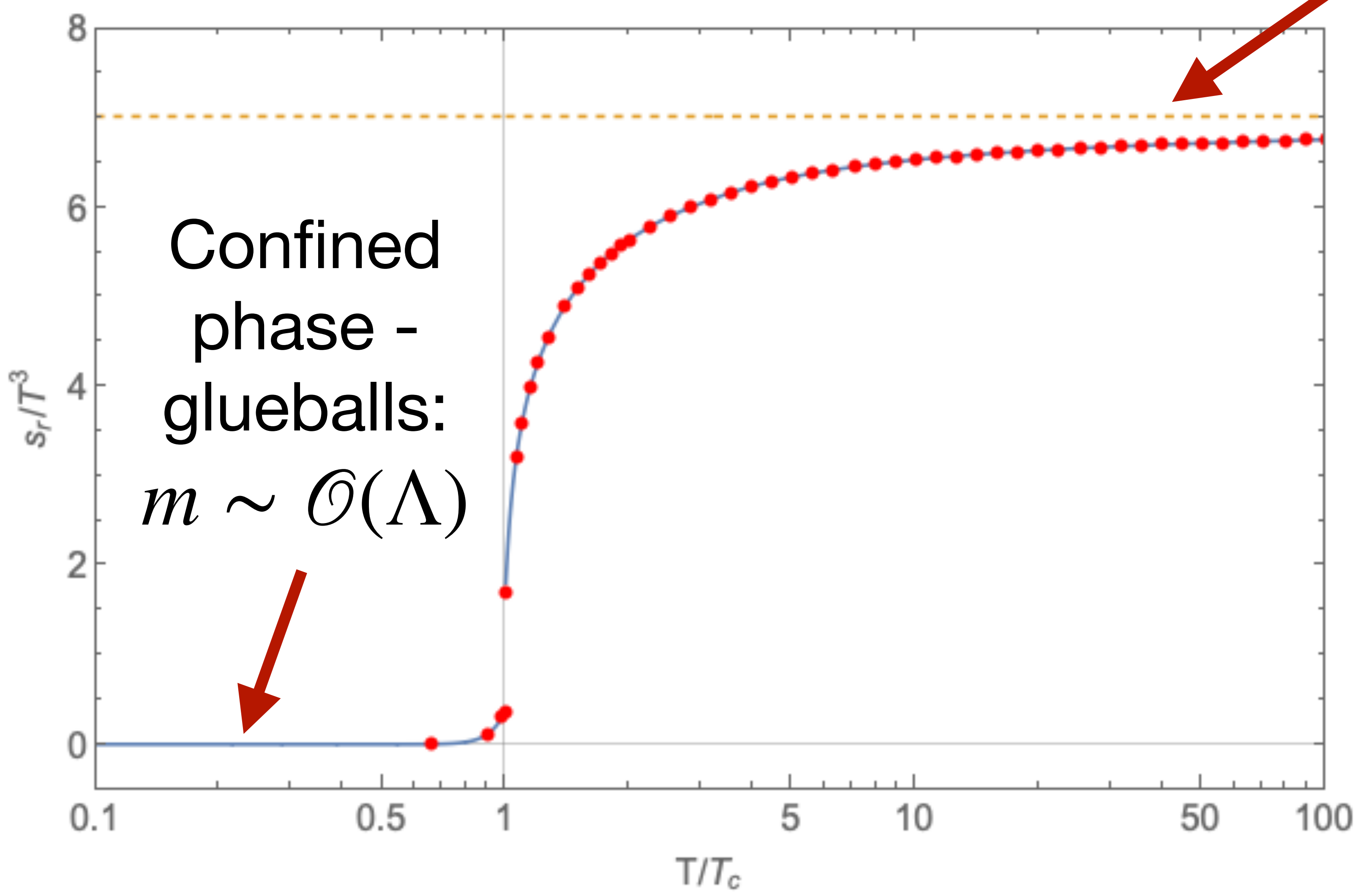
c_r exponentially small well below $T_c \Rightarrow$ rapid temperature growth!



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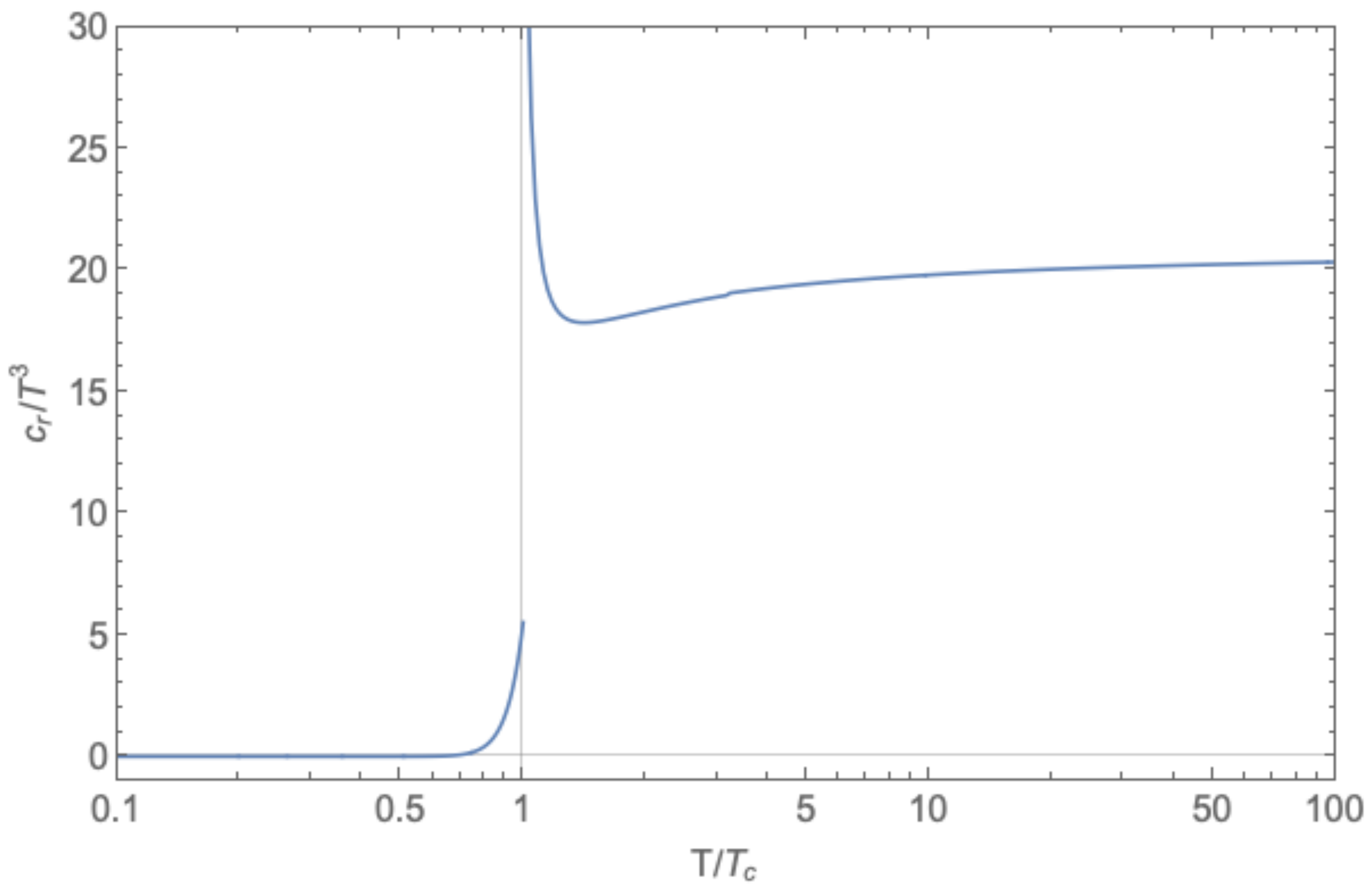

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