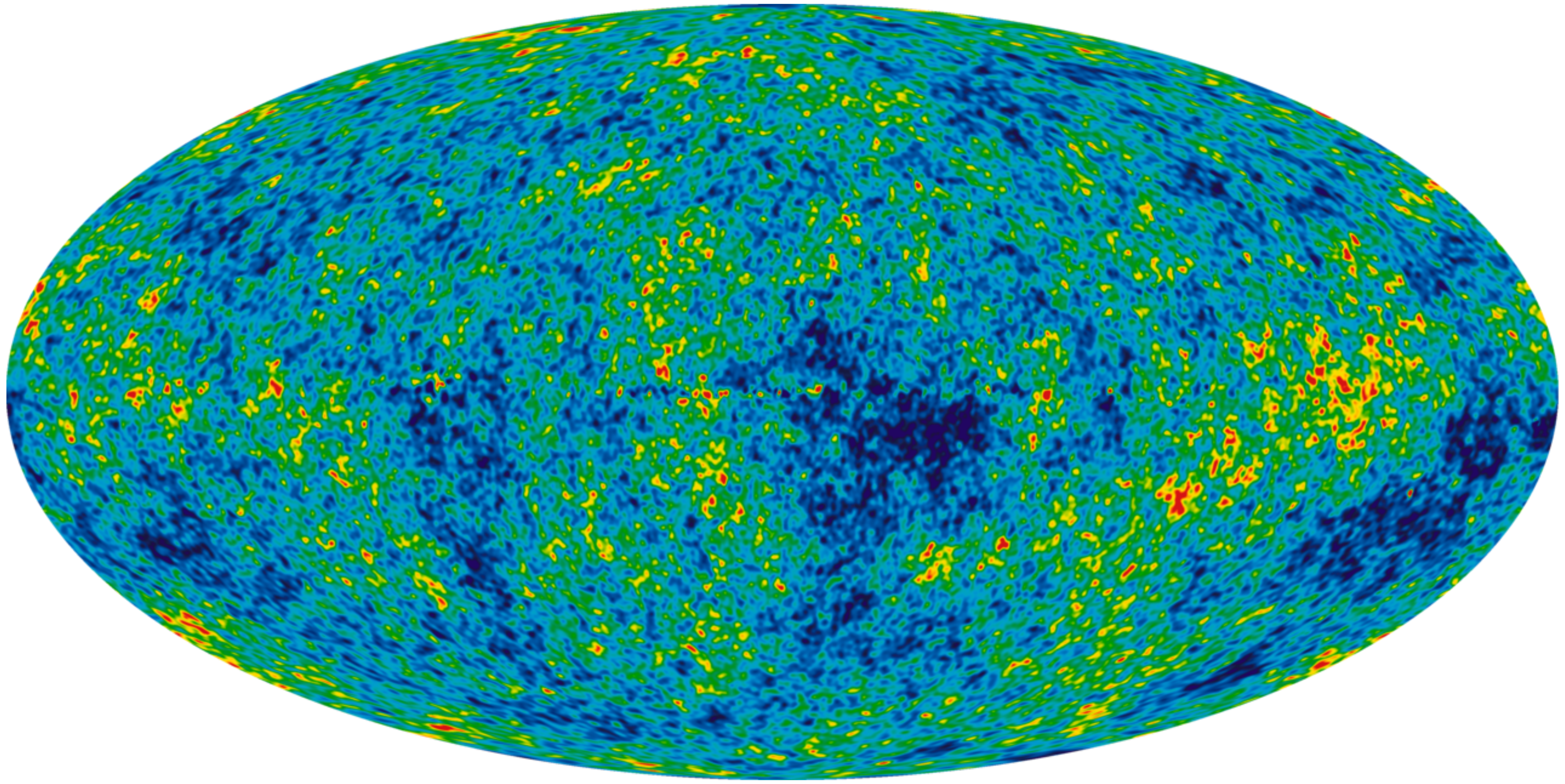
Gravitational waves from a non-abelian dark sector coupled to axion inflation

Helena Kolešová (University of Stavanger)

Joint work with Simone Biondini, Mikko Laine and Simona Procacci
ArXiv: 2303.17973, 2311.03718

Motivation



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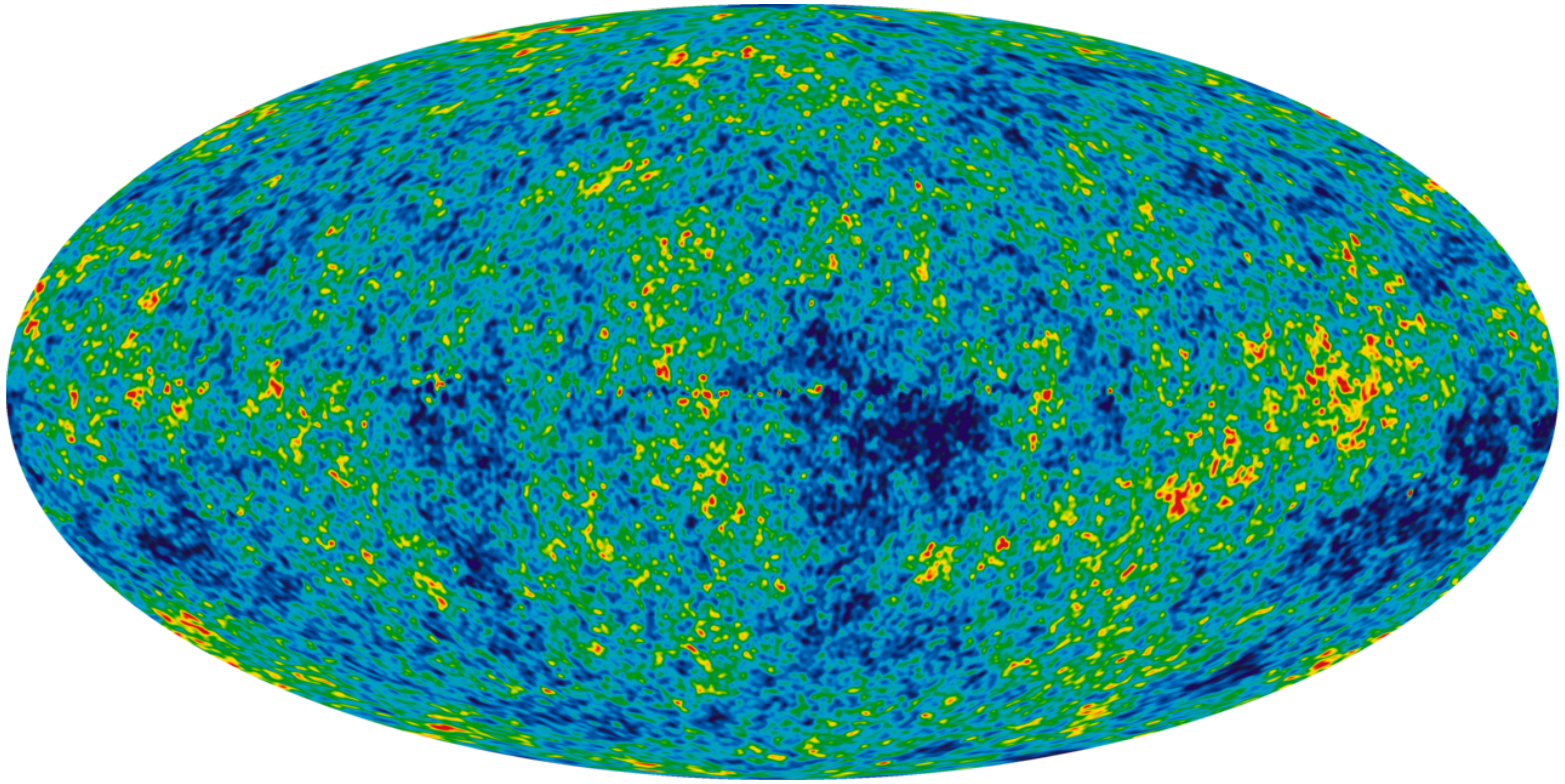

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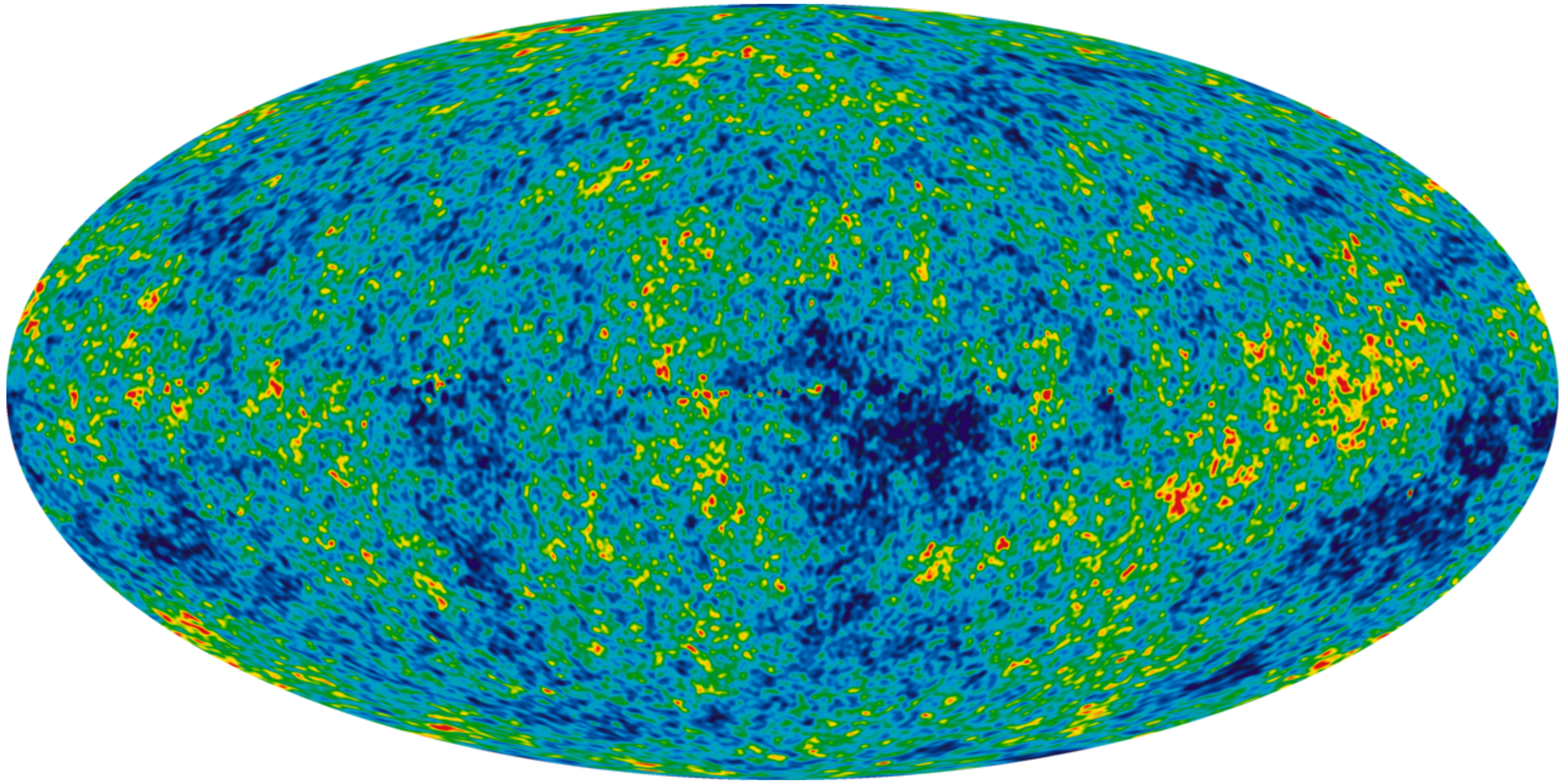

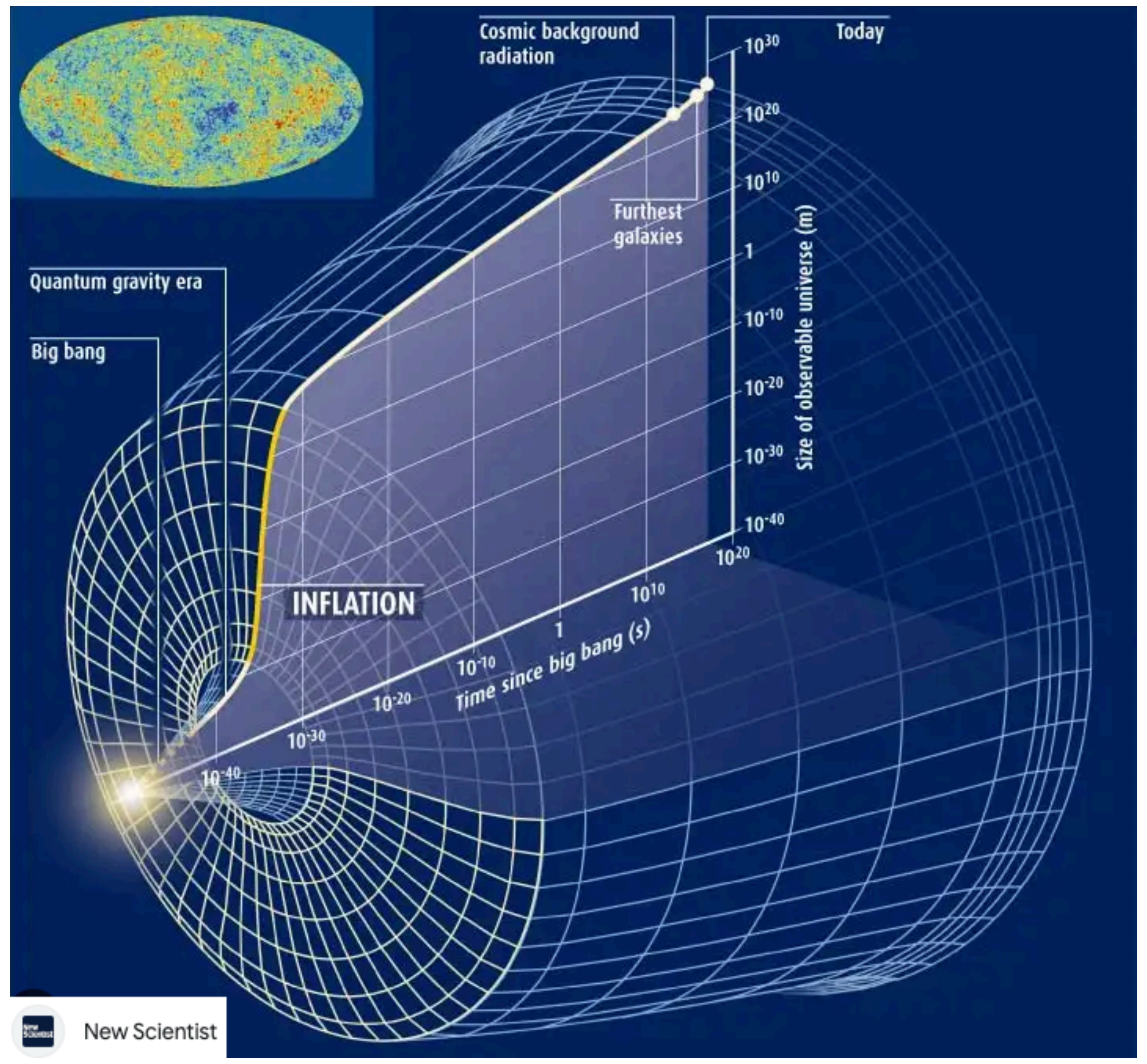

New Scientist

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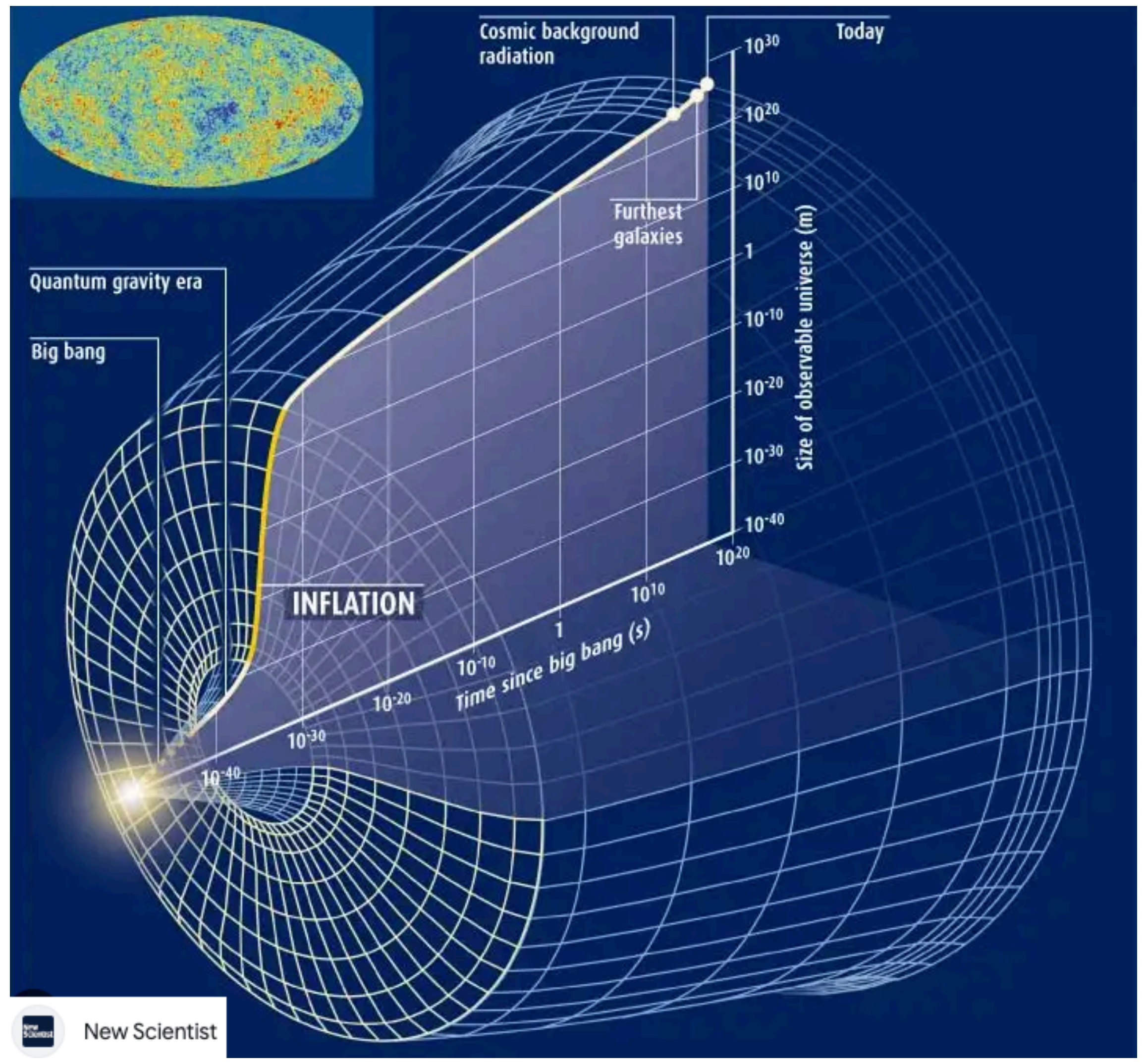
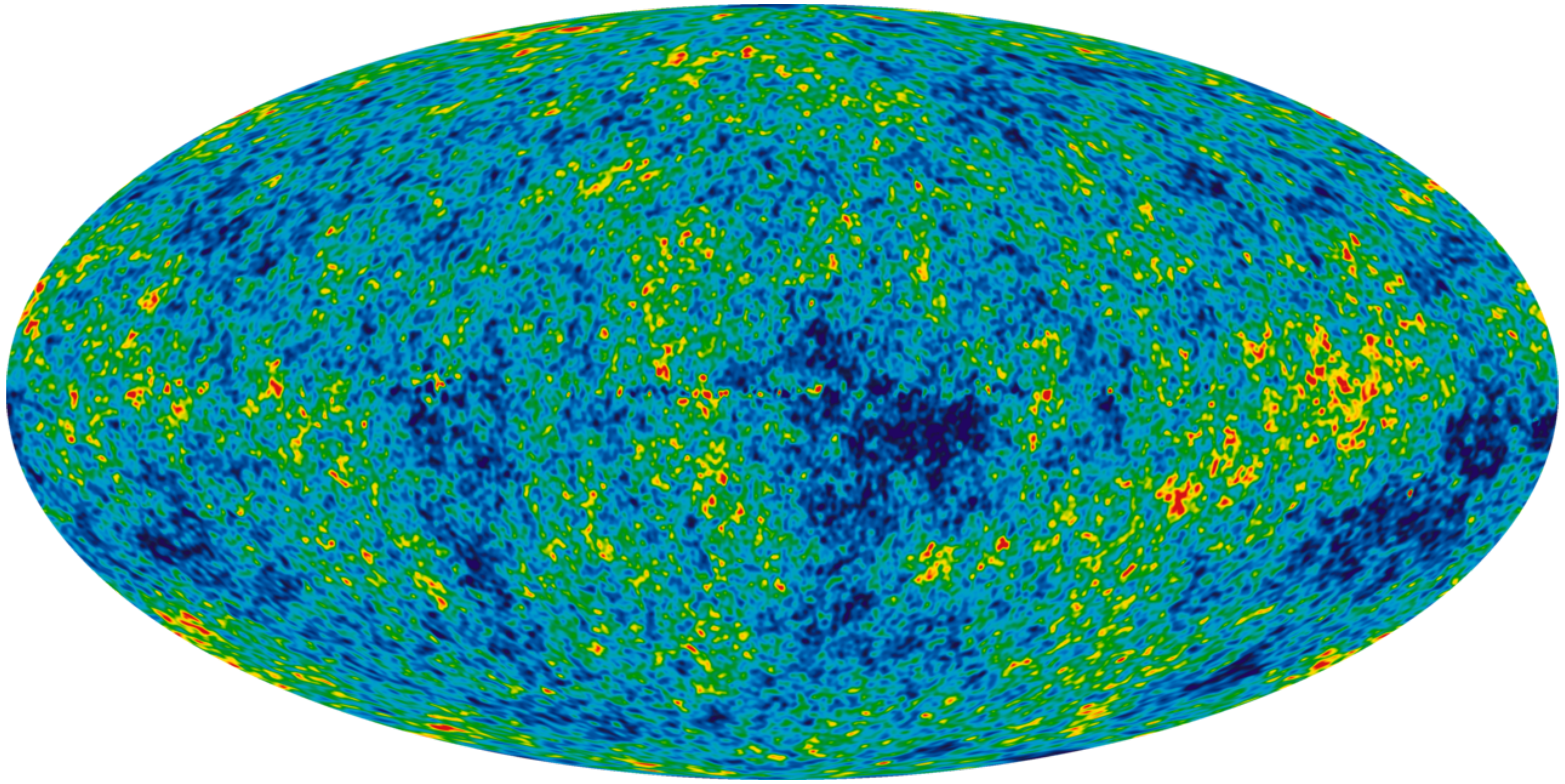
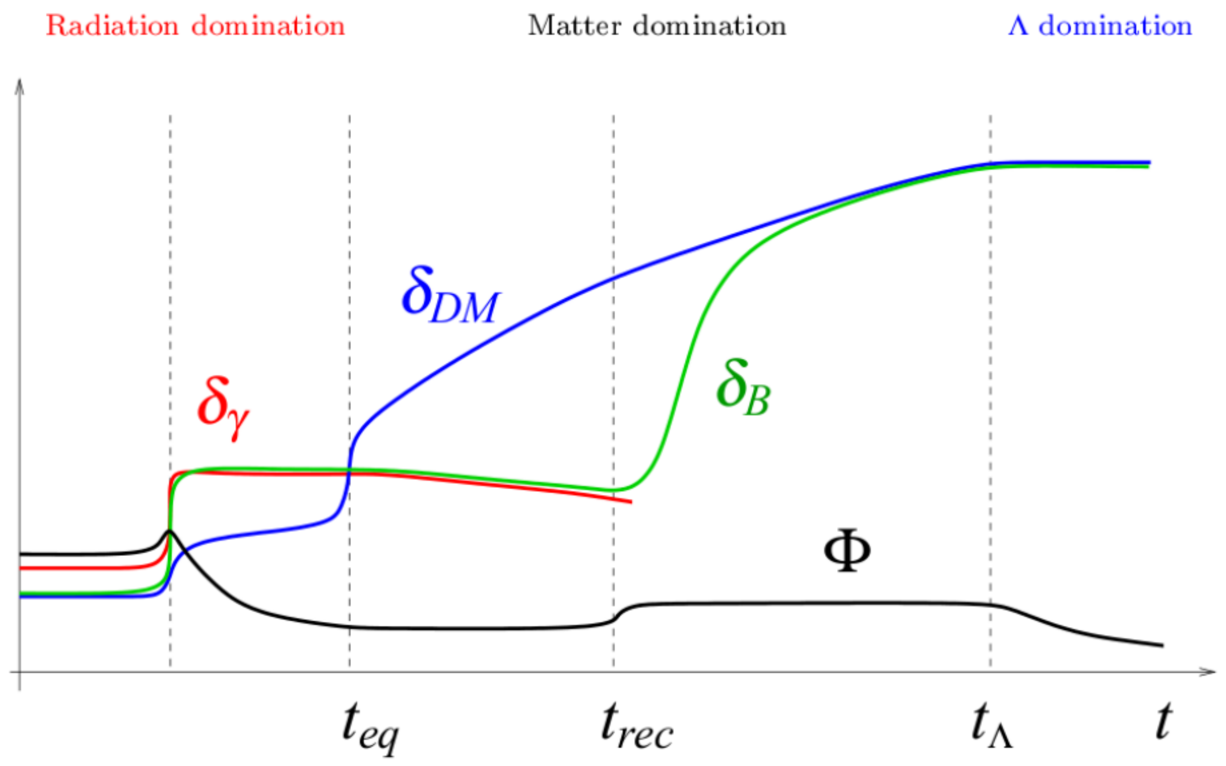




How were the structures in our Universe formed?



[arXiv:1008.1704]

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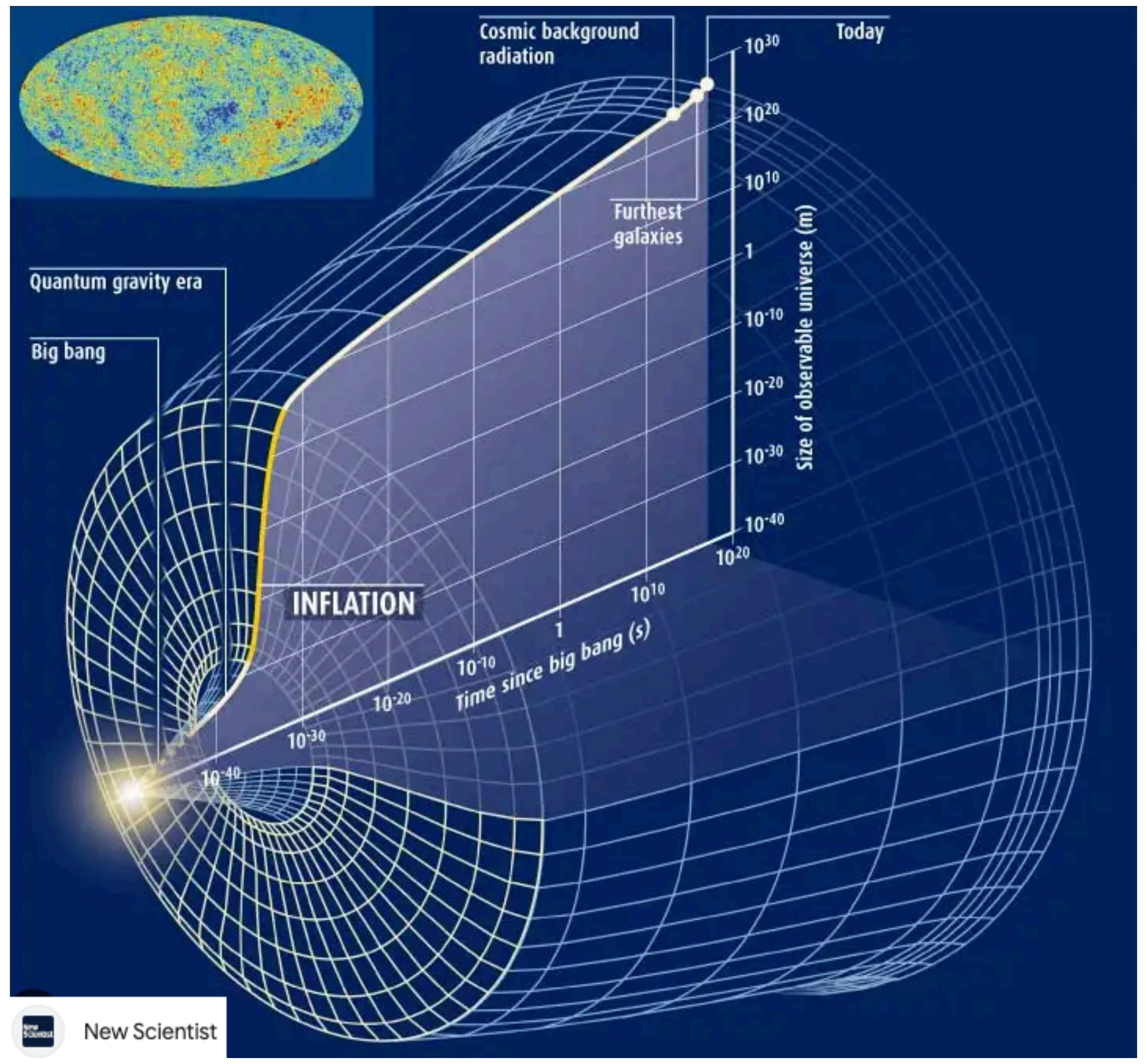

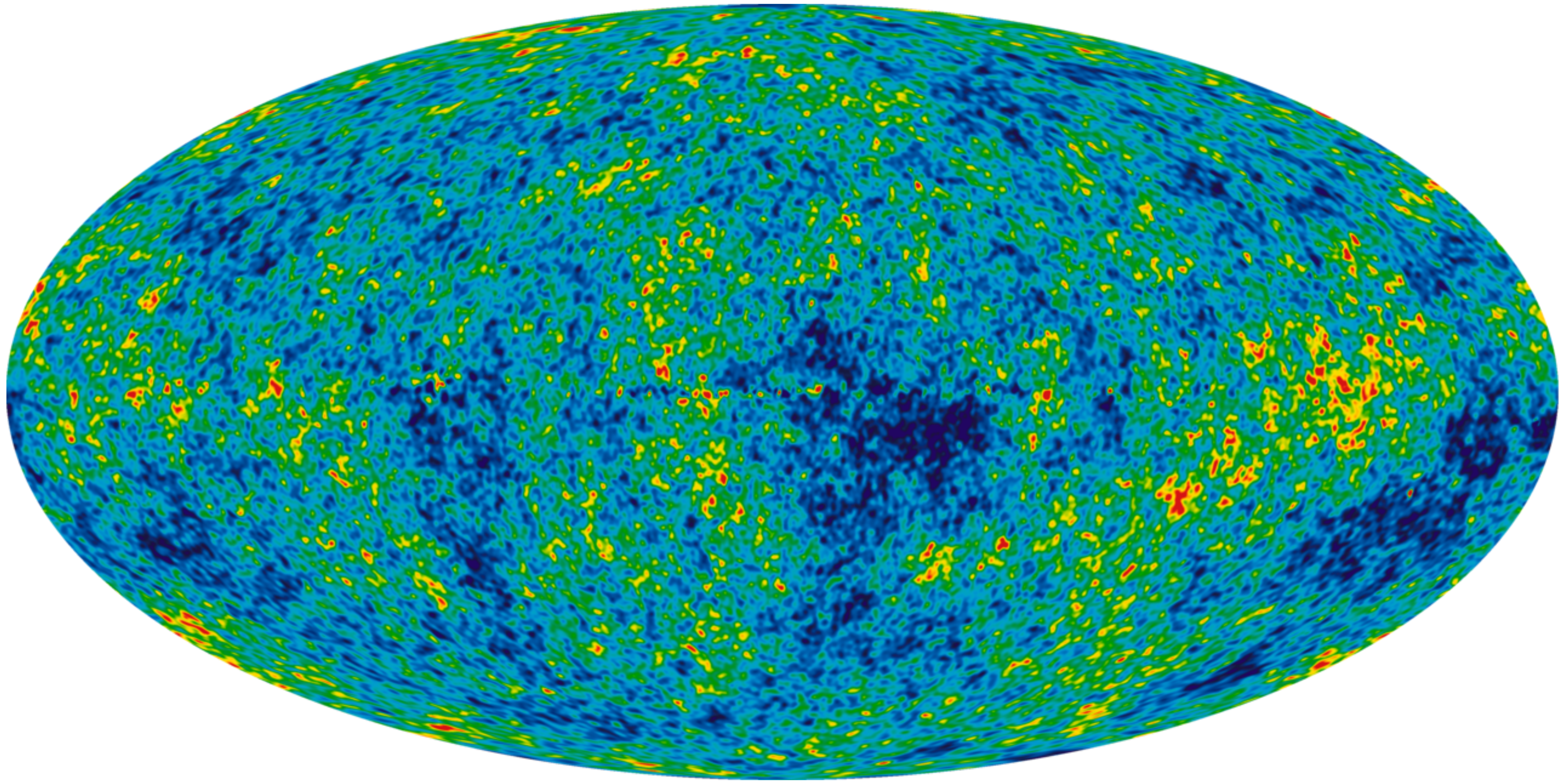

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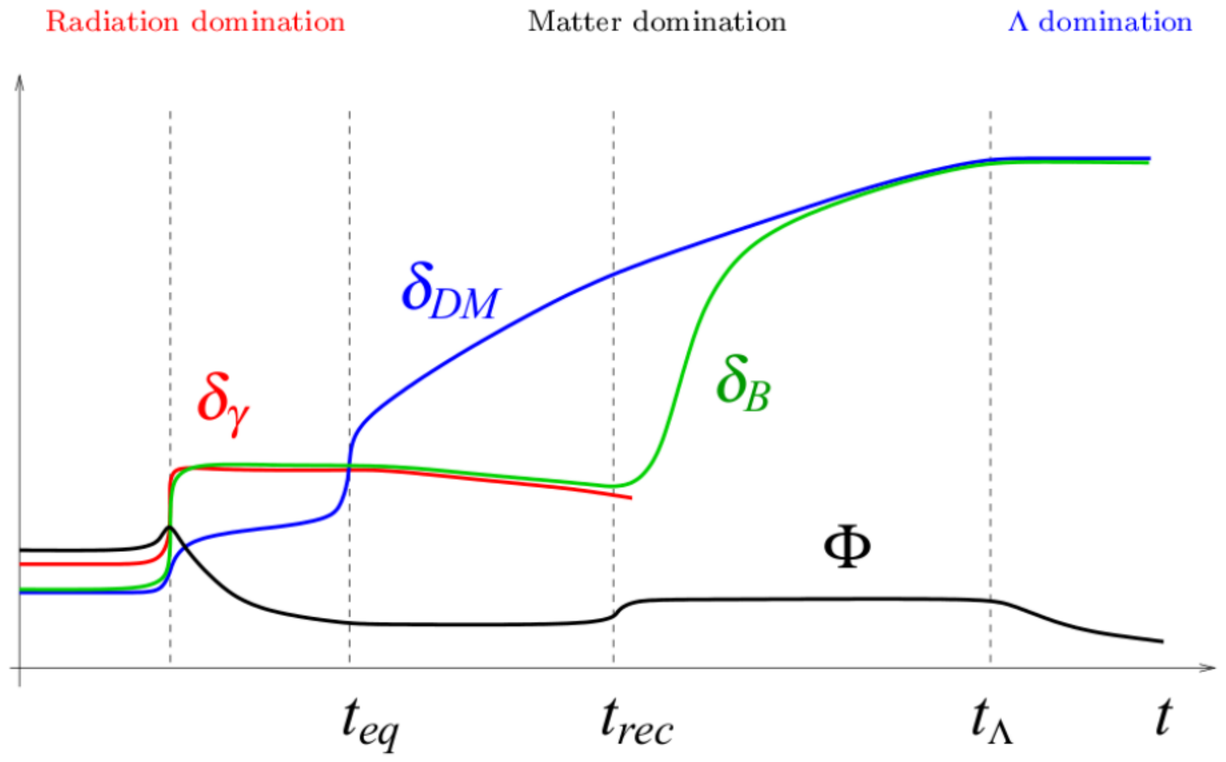

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Dark matter!

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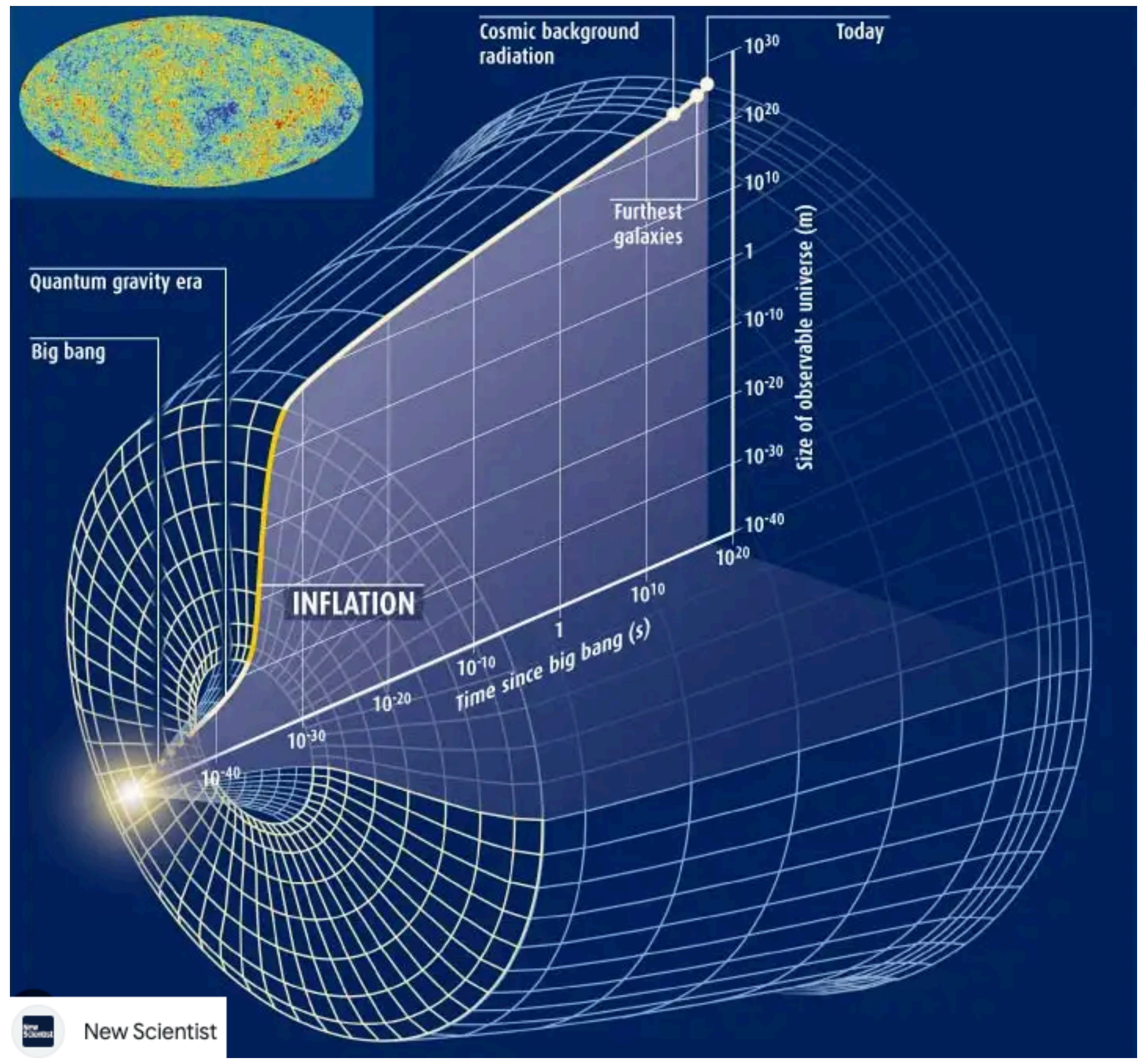

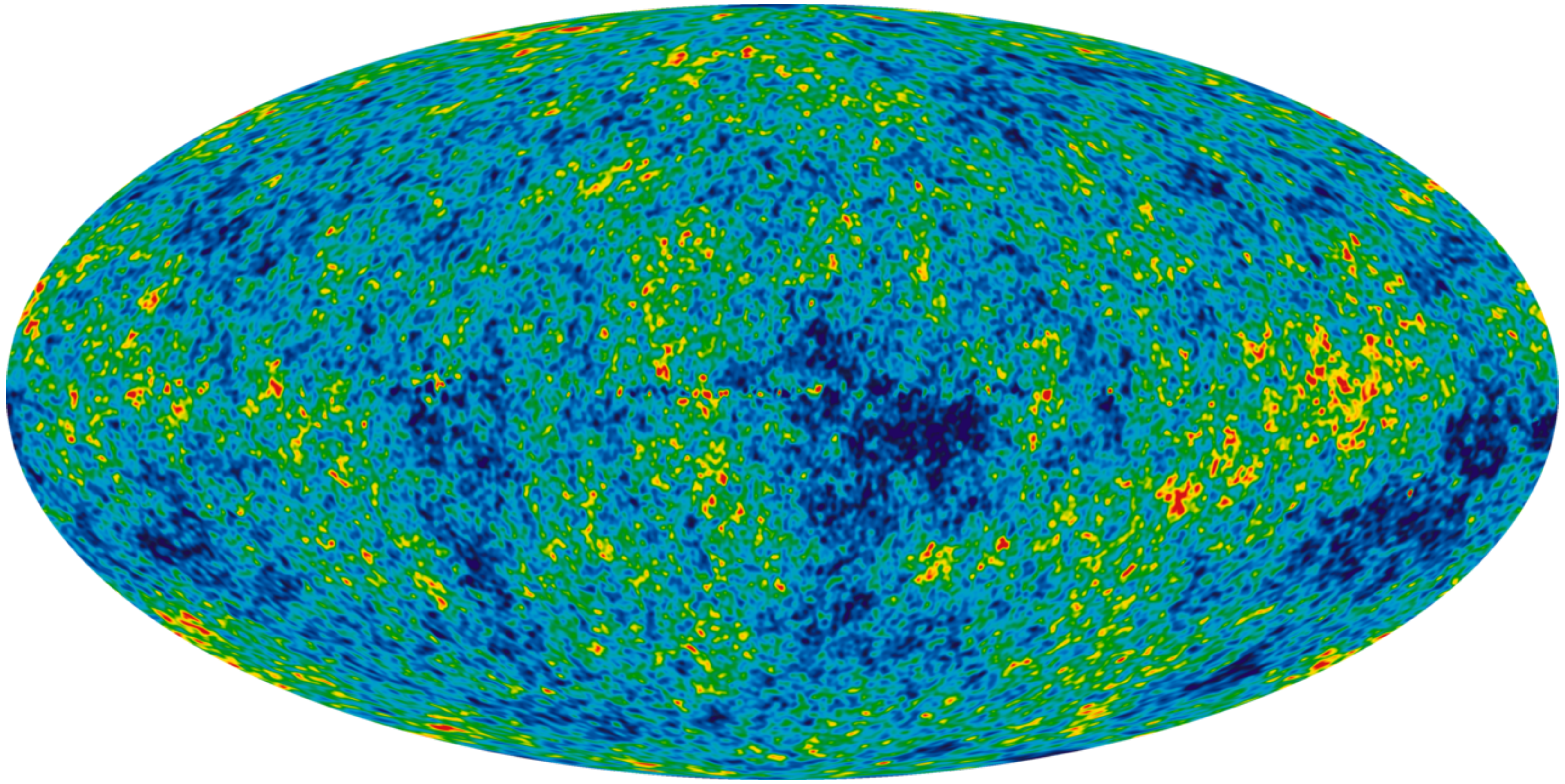

How can we learn more about events before recombination?

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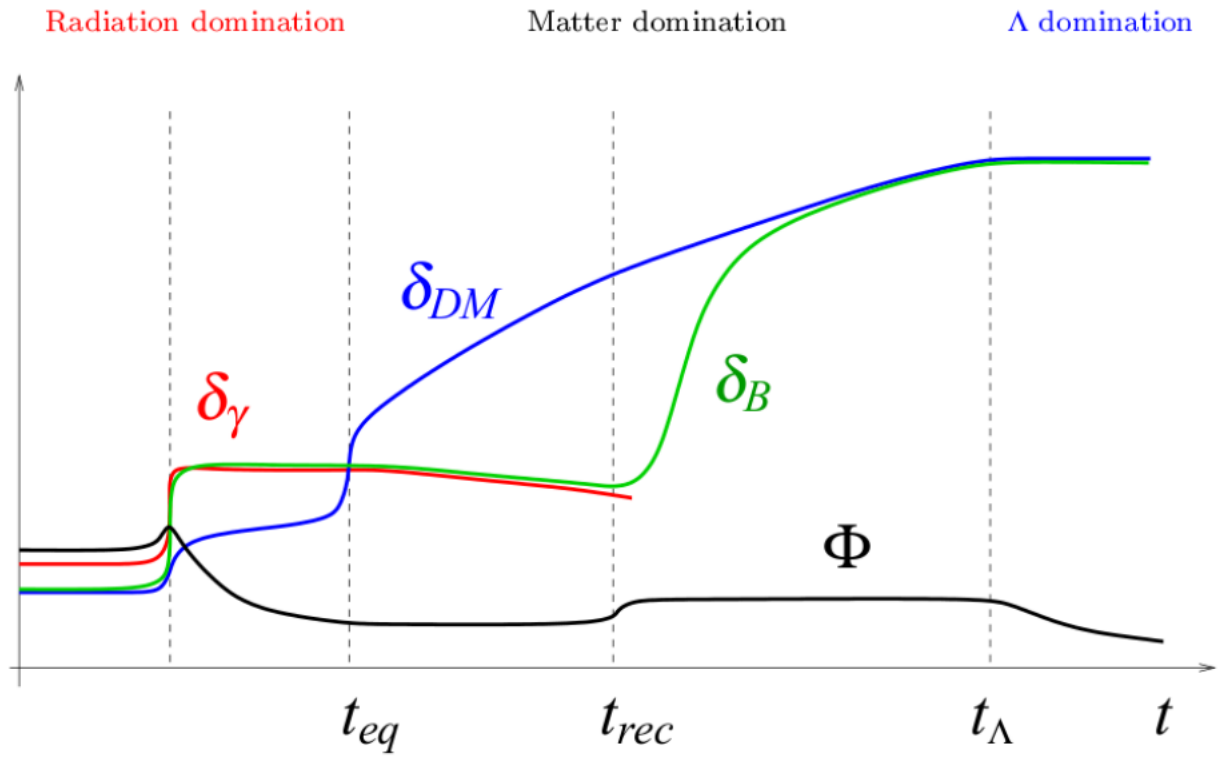

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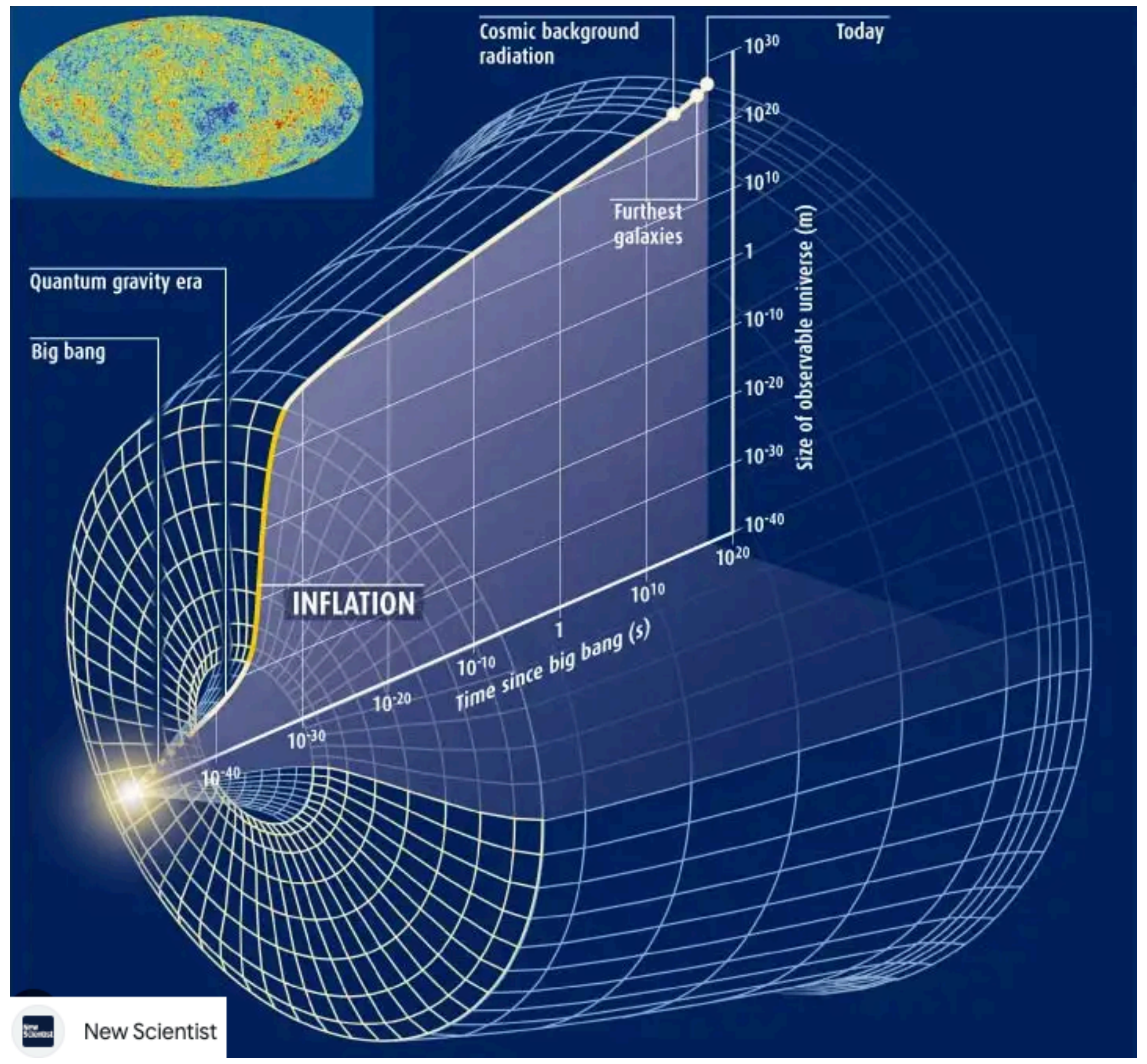

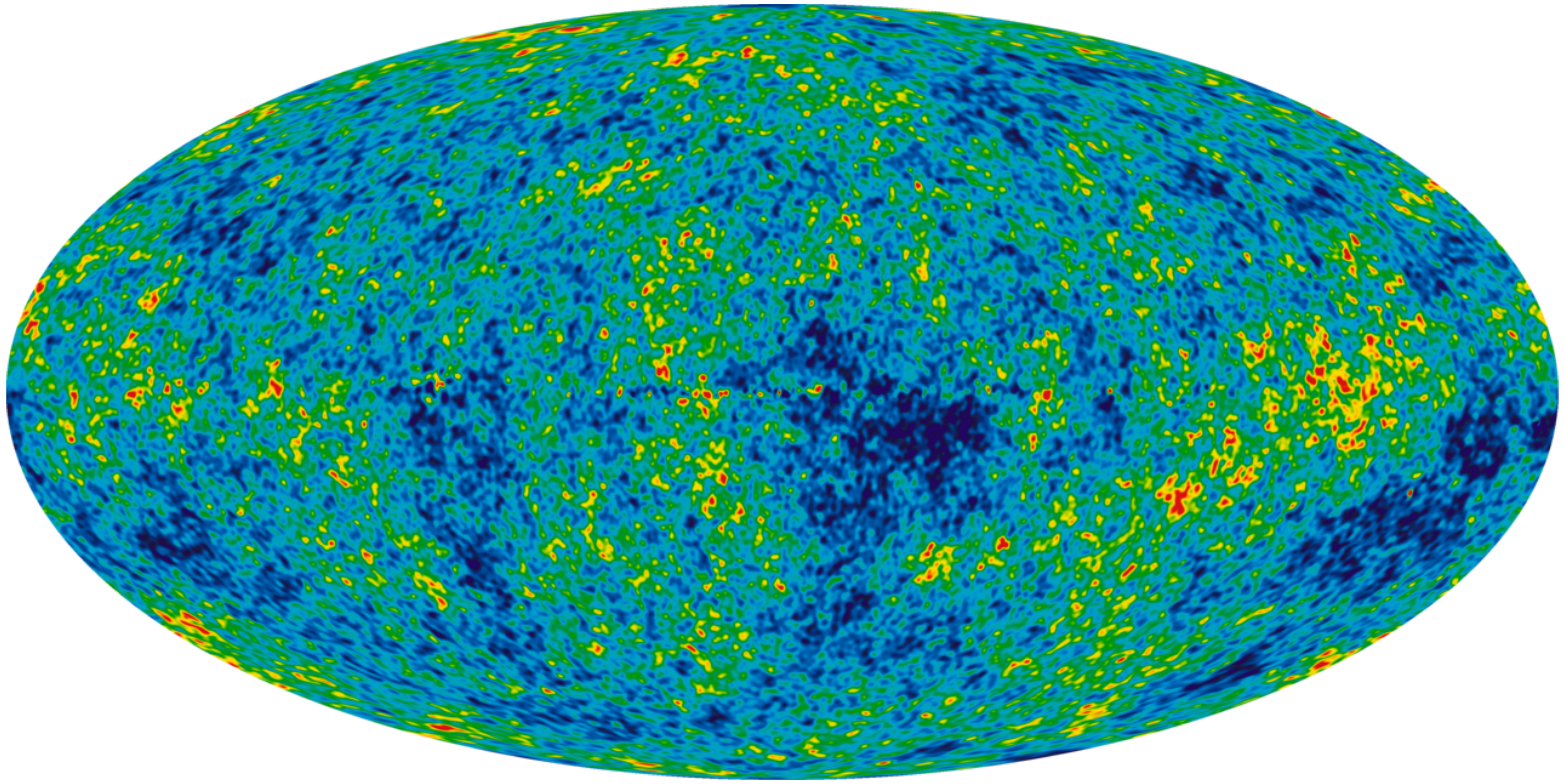

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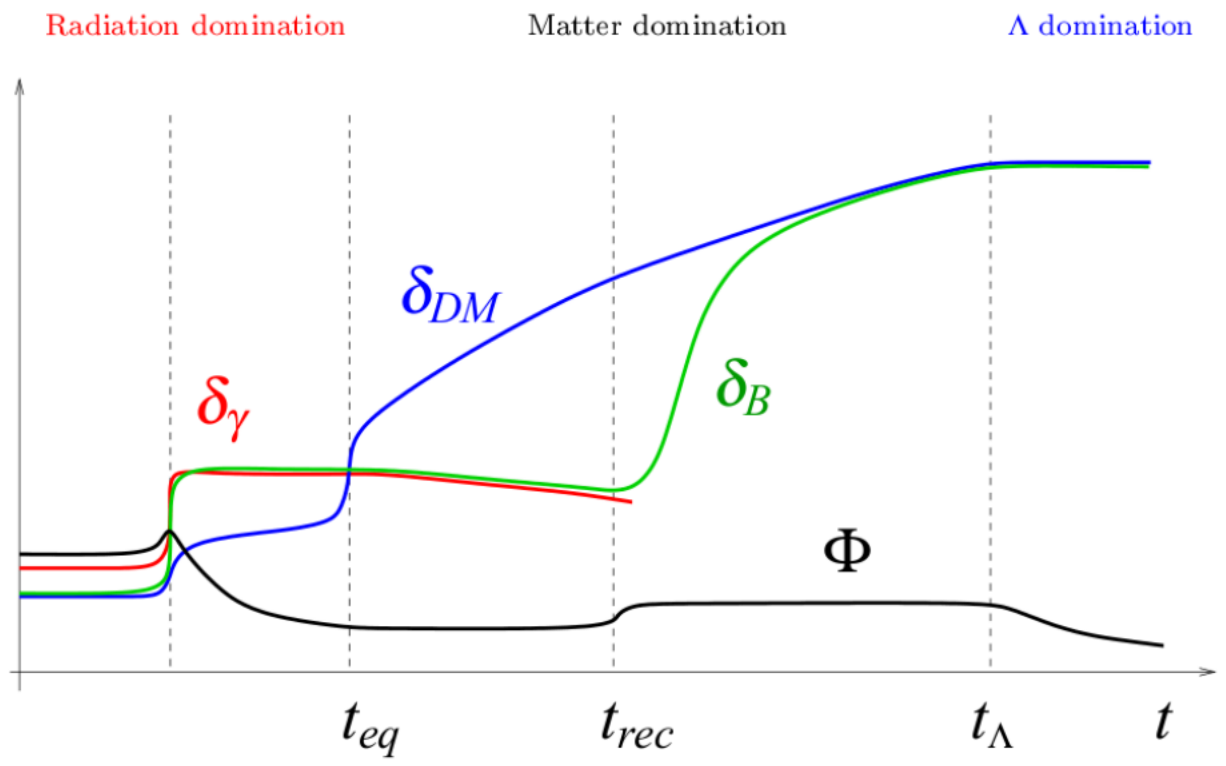

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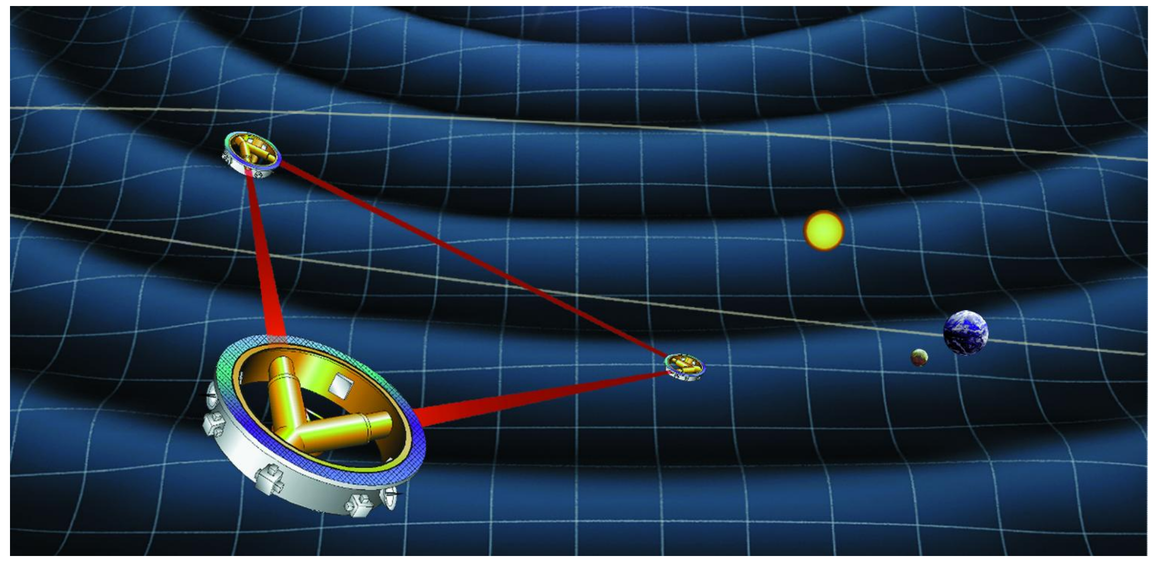


Credit: http://lisa.jpl.nasa.gov/gallery/lisa-waves.html

Dark matter!

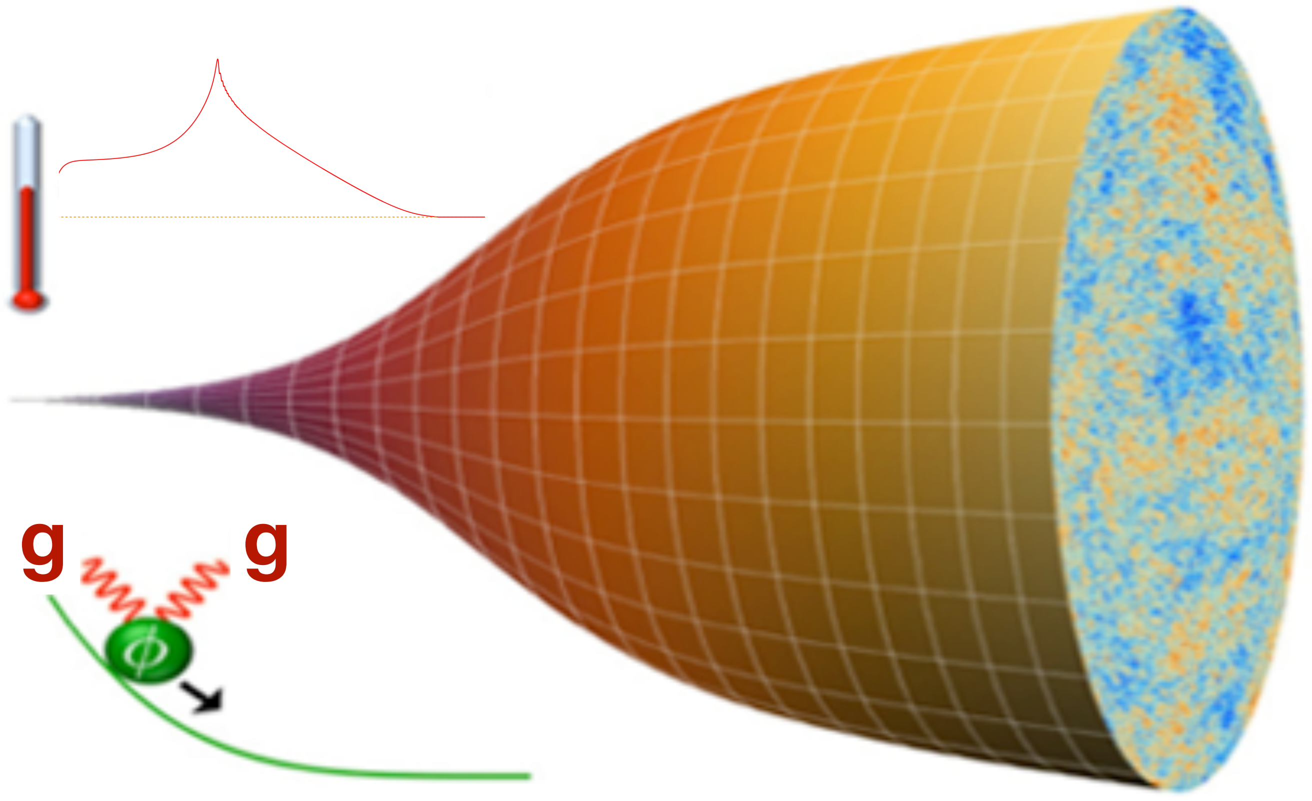
Outline

1. Model setup: Inflaton coupled to non-abelian dark sector

2. Gravitational waves from thermal plasma

3. Gravitational waves from the confinement phase transition

4. Dilution of gravitational wave signals due to early matter domination era



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

Model setup: Example of “warm inflation”

- Axion inflation coupled to non-abelian dark sector

  [Berghaus, Graham, Kaplan: 1910.07525]
  [Laine, Procacci: 2102.09913]
  [Klose, Laine, Procacci: 2201.02317]
  [Klose, Laine, Procacci: 2210.11710]

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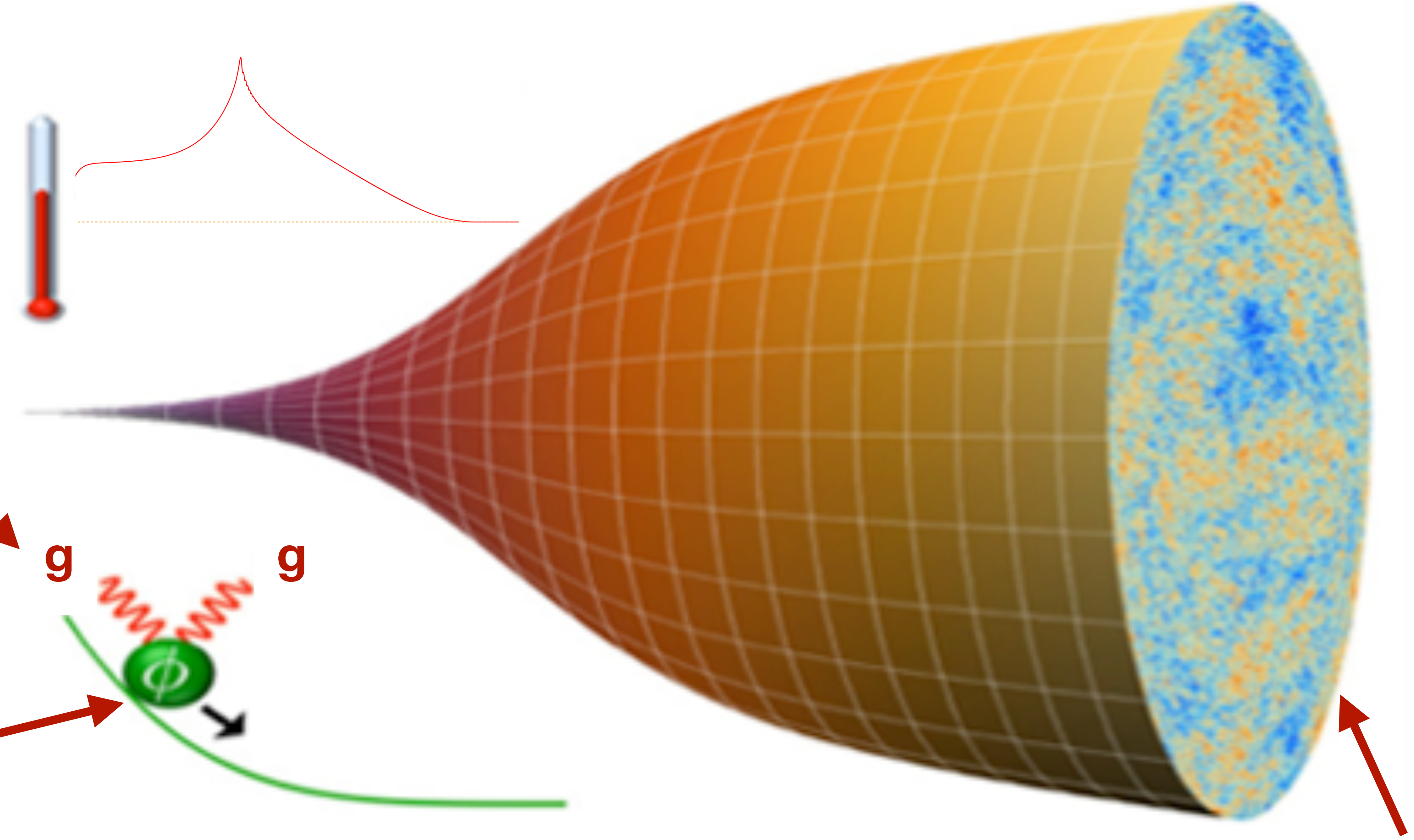

Dark gluons forming thermal bath already during inflation

Inflaton field during “slow roll”:

- Negative pressure density ⇒ accelerated expansion of the Universe
- Additional “friction” related to the interaction with dark gluons

Constraints on the inflaton potential from CMB observations

Model setup: Example of a “warm inflation”

- Axion inflation coupled to non-abelian dark sector

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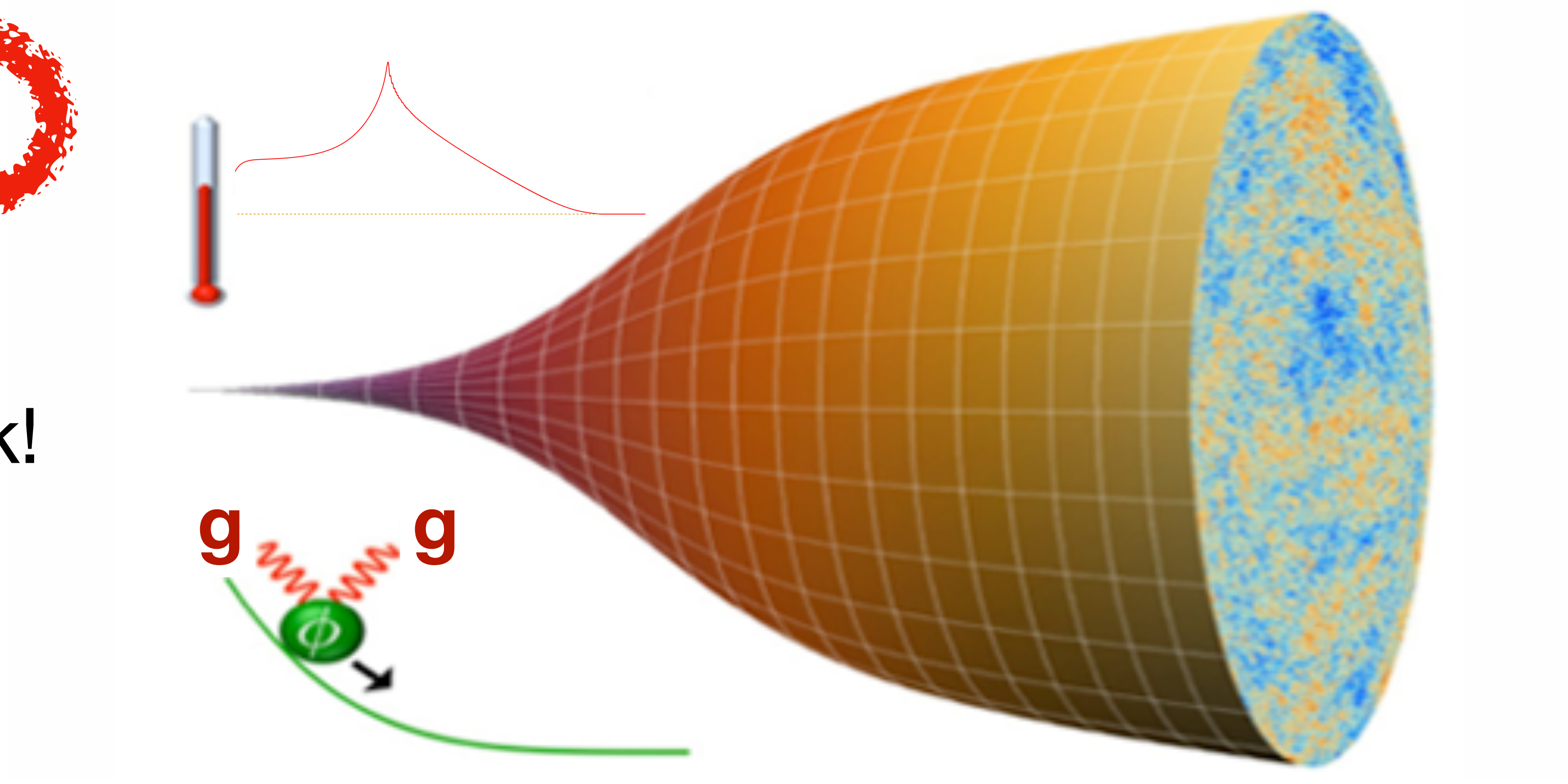
Focus of this talk!



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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:

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

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

Axion decay constant

Hubble rate

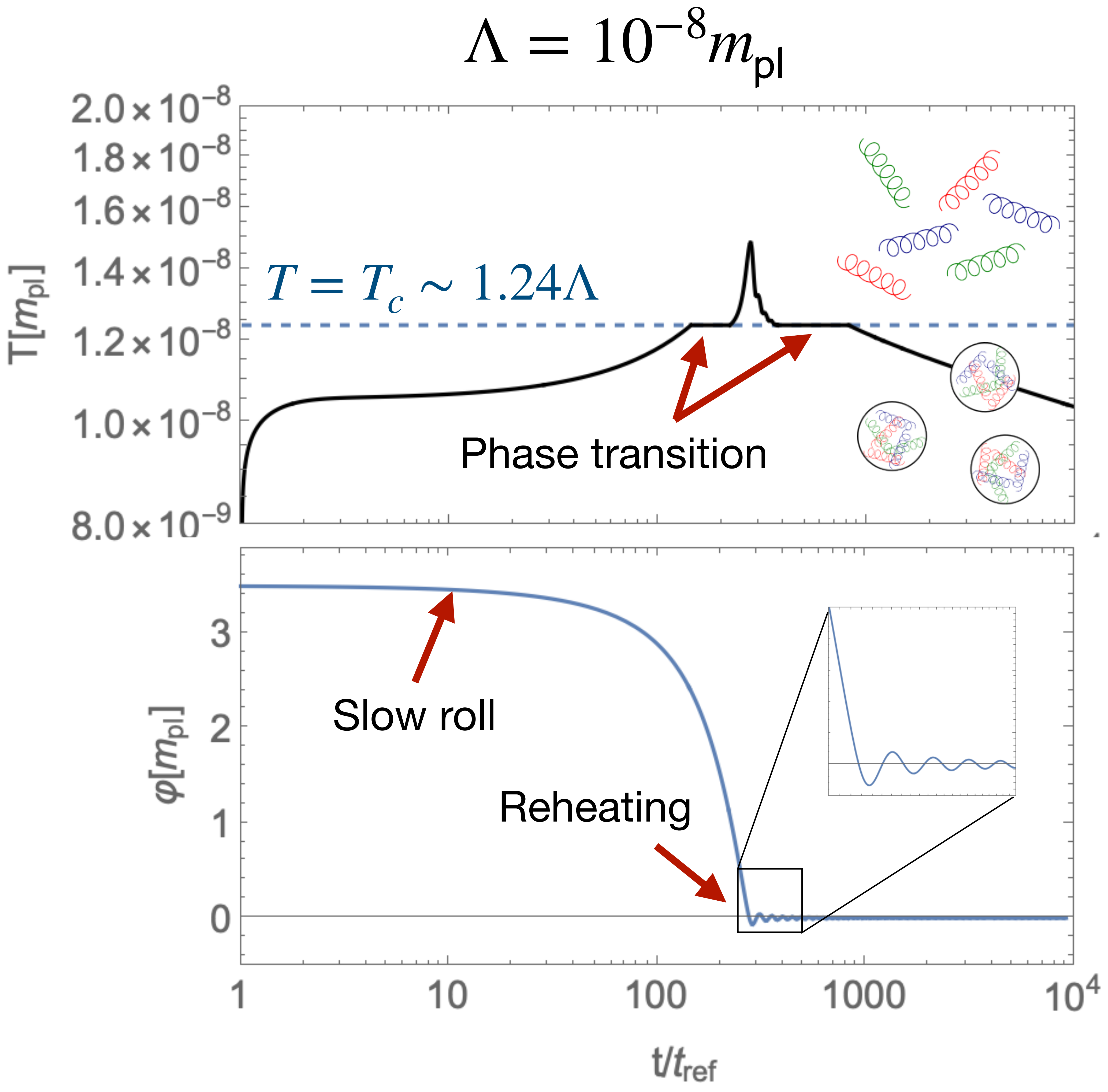
Friction due to inflaton coupling to dark sector

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

$$\dot\rho_D + 3H\left(\rho_D + p_D\right) \simeq \Upsilon\dot{\bar\varphi}^2$$

Dark sector energy and pressure densities

Evolution of the dark sector



$(m_{\rm pl} = 1.22 \times 10^{19}$ GeV)

- Evolution of an SU(3) sector coupled to axion inflation studied for varying confinement scale Λ [HK, Laine, Procacci: 2303.17973]

Friction due to inflaton coupling to dark sector: lattice input available for SU(3) [Moore,Tassler: 1011.1167] [Laine, Niemi, Procacci, Rummukainen: 2209.13804]

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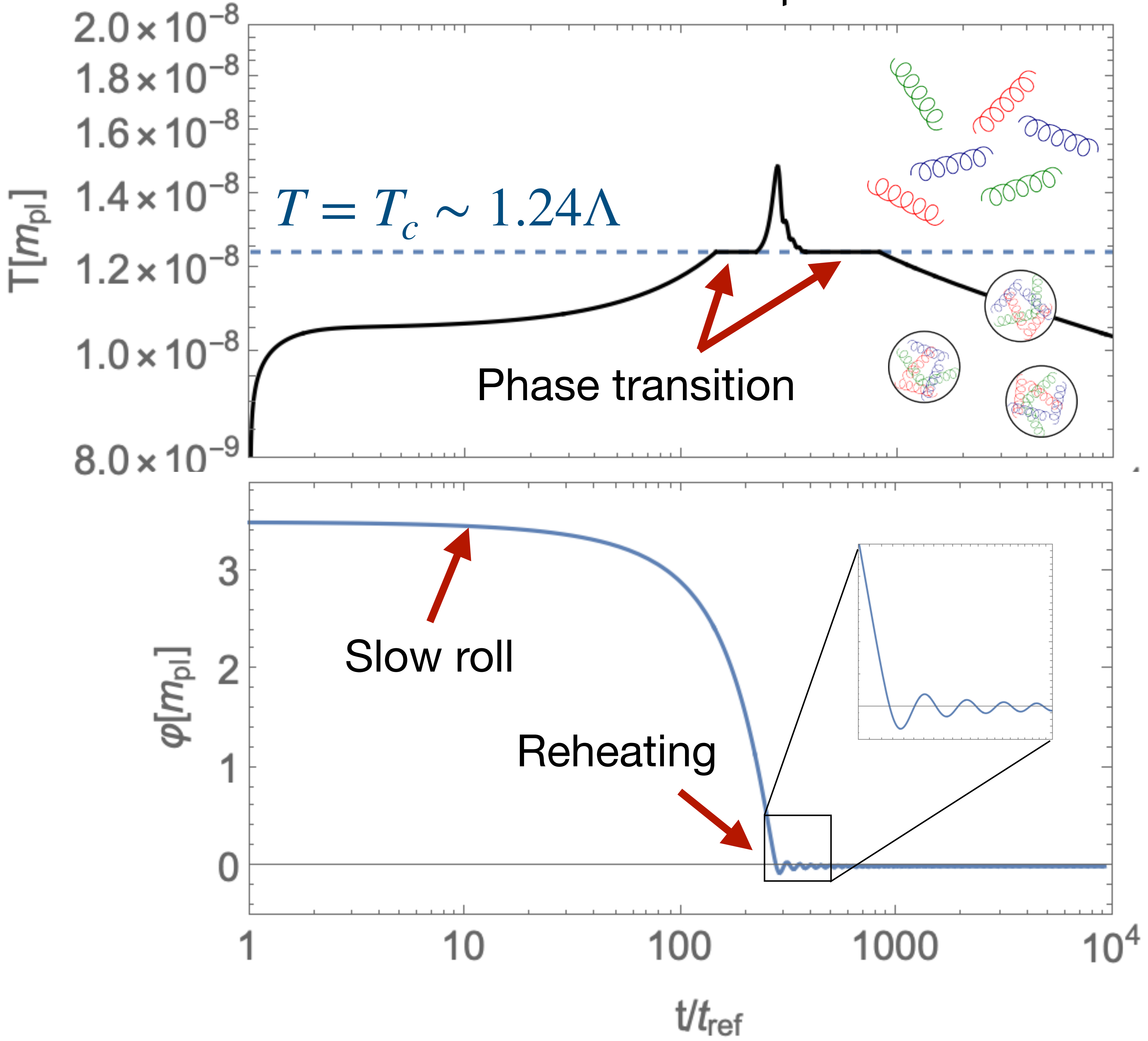
Dark sector energy and pressure densities. SU(3) equation of state: [Giusti, Pepe: 1612.00265] [Meyer: 0905.422]

Evolution of the dark sector

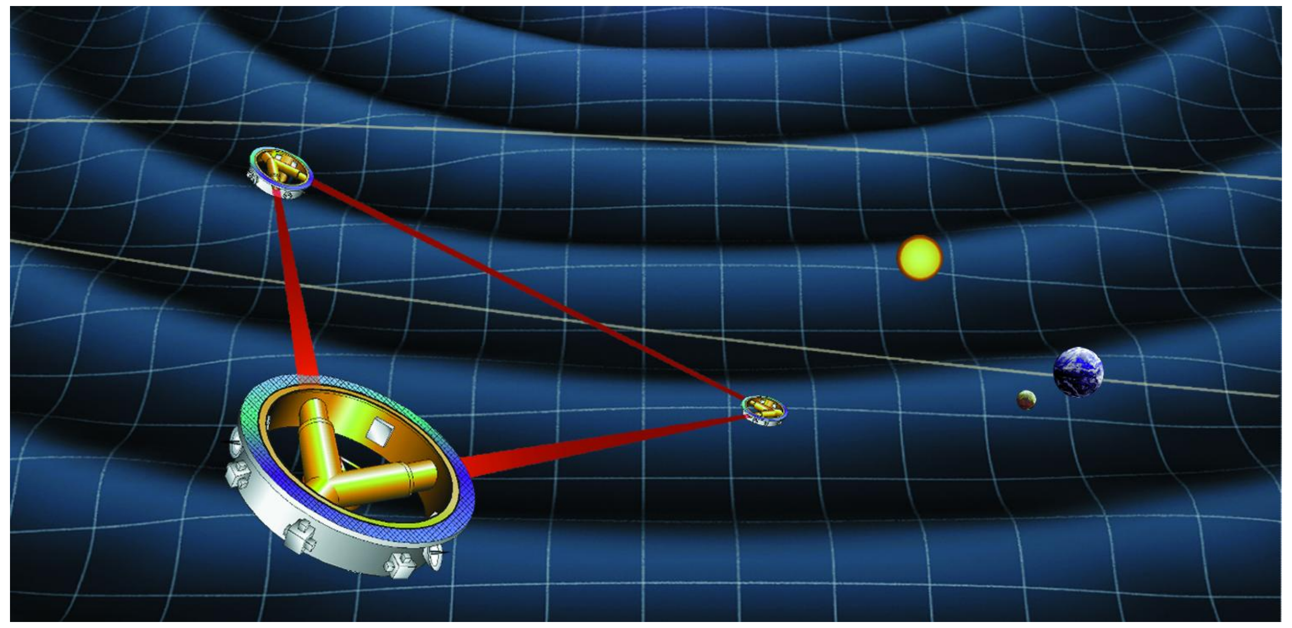
$\Lambda = 10^{-8} m_{\rm pl}$



($m_{\rm pl} = 1.22 \times 10^{19}$ GeV)

Question 1: What is the maximum temperature reached in the dark sector?

Question 2: Did the dark sector undergo a phase transition?



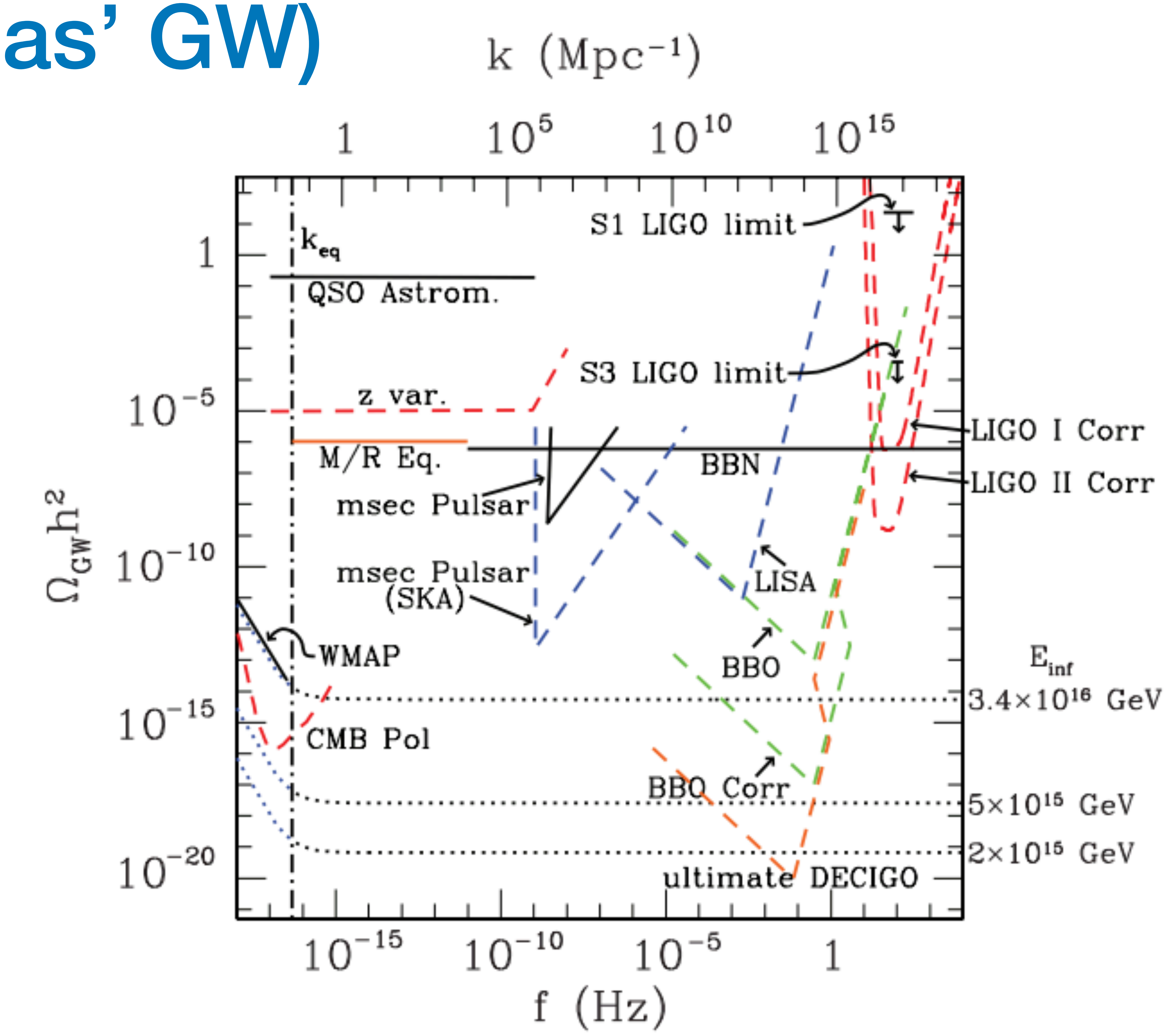
Credit: http://lisa.jpl.nasa.gov/gallery/lisa-waves.html

Both answers are important for the possible gravitational wave signal!

Gravitational waves from inflation I: Vacuum fluctuations of the inflaton during slow roll

(= Jonas’ GW)

- Approximately scale-invariant GW spectrum $(n_t(k) \simeq 2\epsilon \ll 1)$
- For generic (= non-Jonas) inflationary potentials: CMB constraint on tensor-to-scalar ratio ⇒ GW signal not measurable directly by experiments like LISA

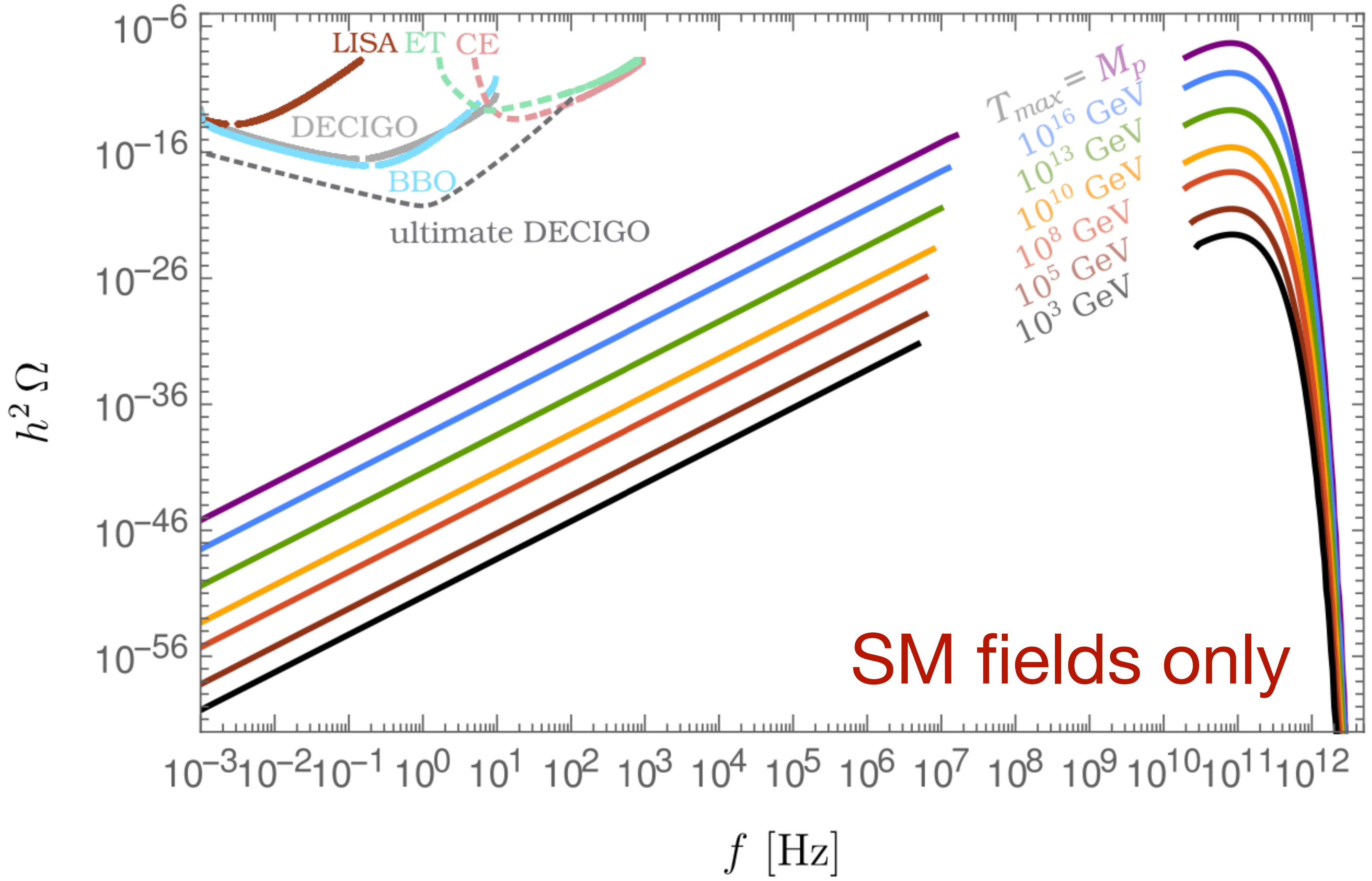


[Smith, Kamionkowski, Cooray: astro-ph/0506422]

Gravitational waves from inflation II: Thermal fluctuations in the hot plasma after reheating

- Thermal fluctuations in a plasma induce production of gravitational waves
  [Ghiglieri, Laine: 1504.02569] [Ghiglieri, Jackson, Laine, Zhu: 2004.11392]
- Peak frequency ~ 80 GHz
- $\Omega_{\text{GW}} h^2 \propto f^3$ at low frequencies
- Constraints from ΔN_{eff} at BBN:
  $\Delta N_{\text{eff}} \lesssim 10^{-3} \Rightarrow T_{\text{max}} \lesssim 10^{17}$ GeV

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



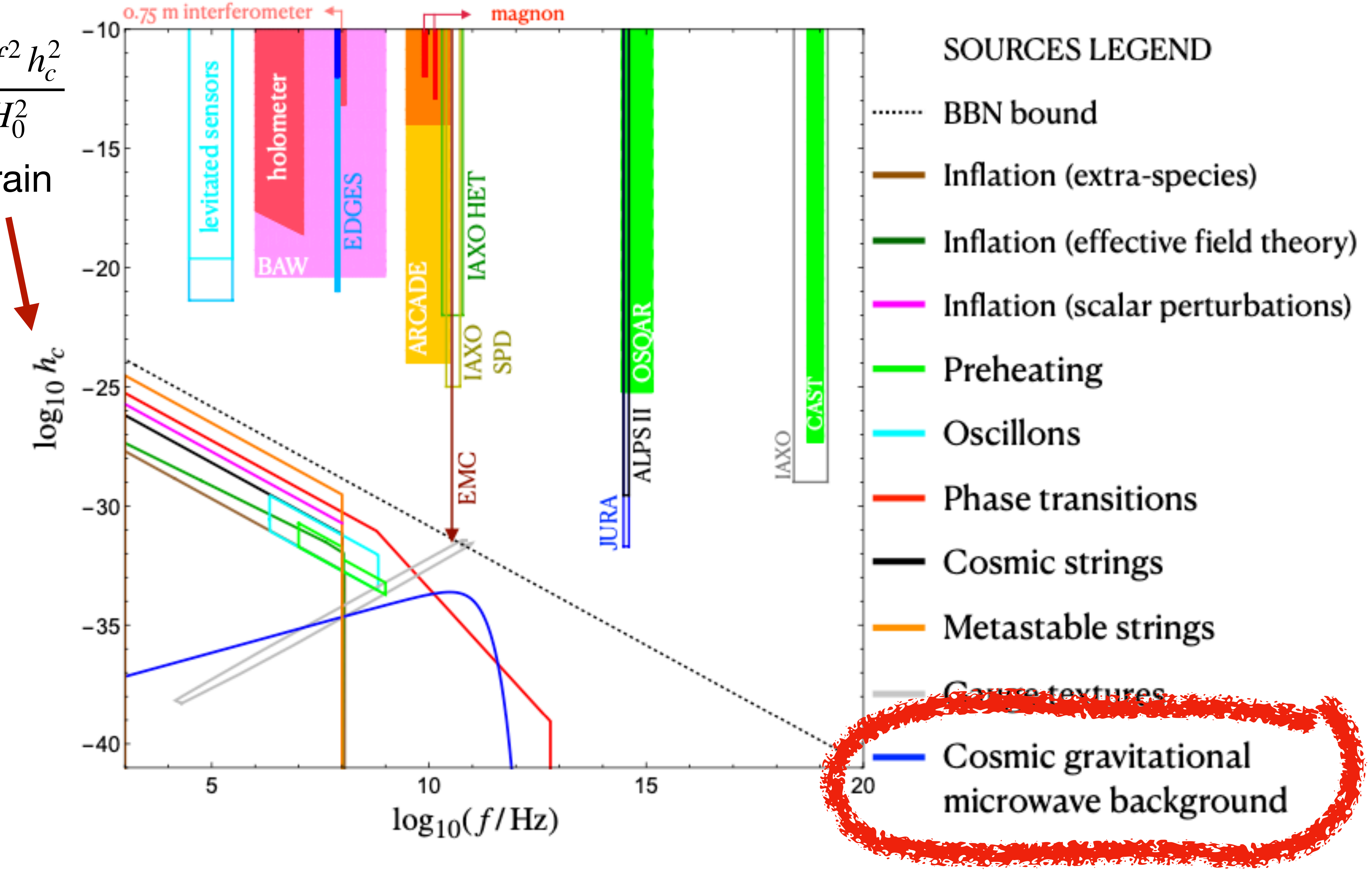
Gravitational waves from inflation II: Thermal fluctuations in the hot plasma after reheating

- Could be in principle measured directly?
- Detection of “ultra-high-frequency” GW is challenging, but new ideas are appearing!
- No known astrophysical sources of GW at MHz to GHz frequencies ⇒unique opportunity to learn about BSM physics!

[Aggarwal et al.: 2011.12414]

$$\Omega_{\rm gw} = \frac{4\pi^2 f^2 h_c^2}{3H_0^2}$$

strain

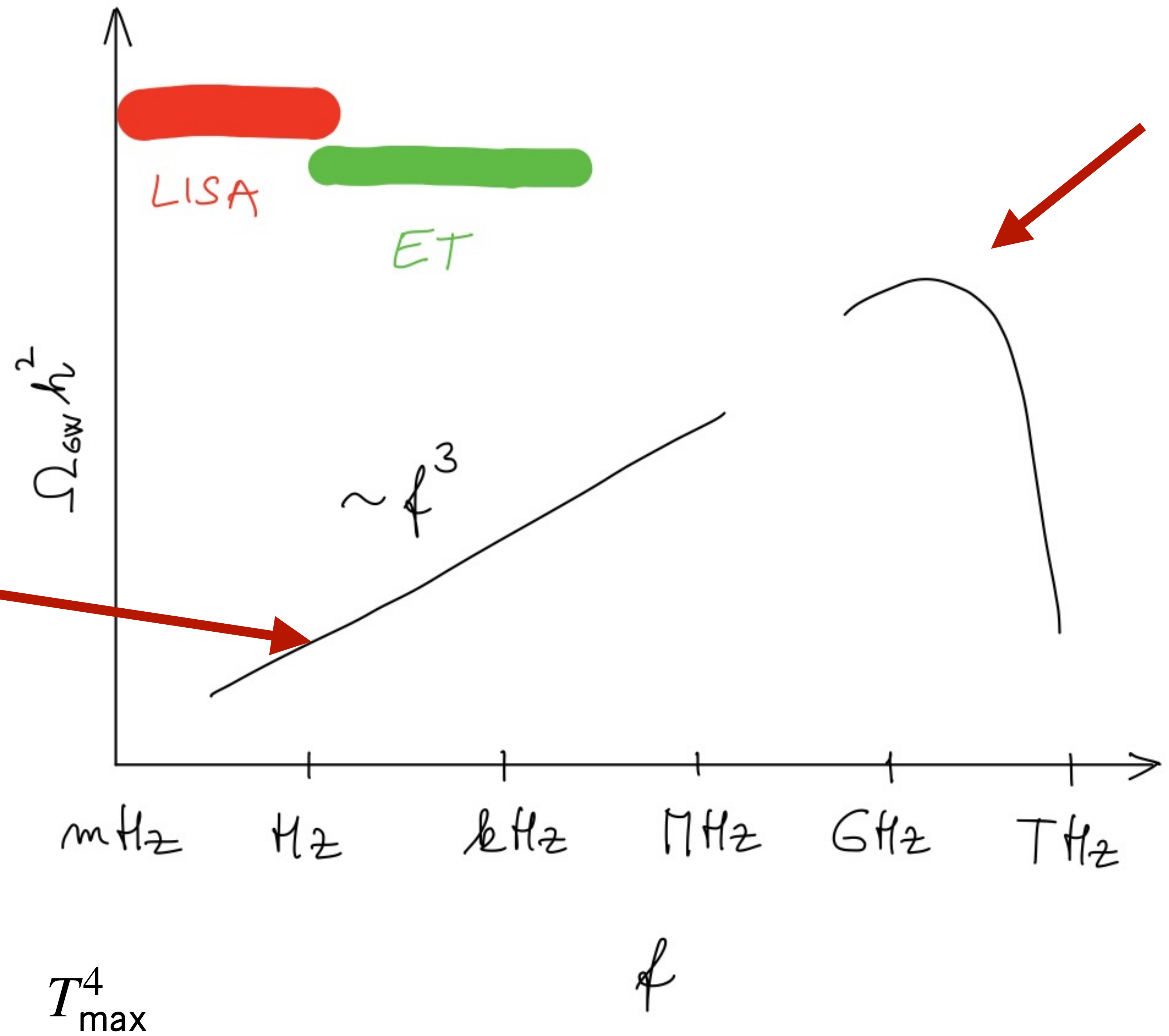


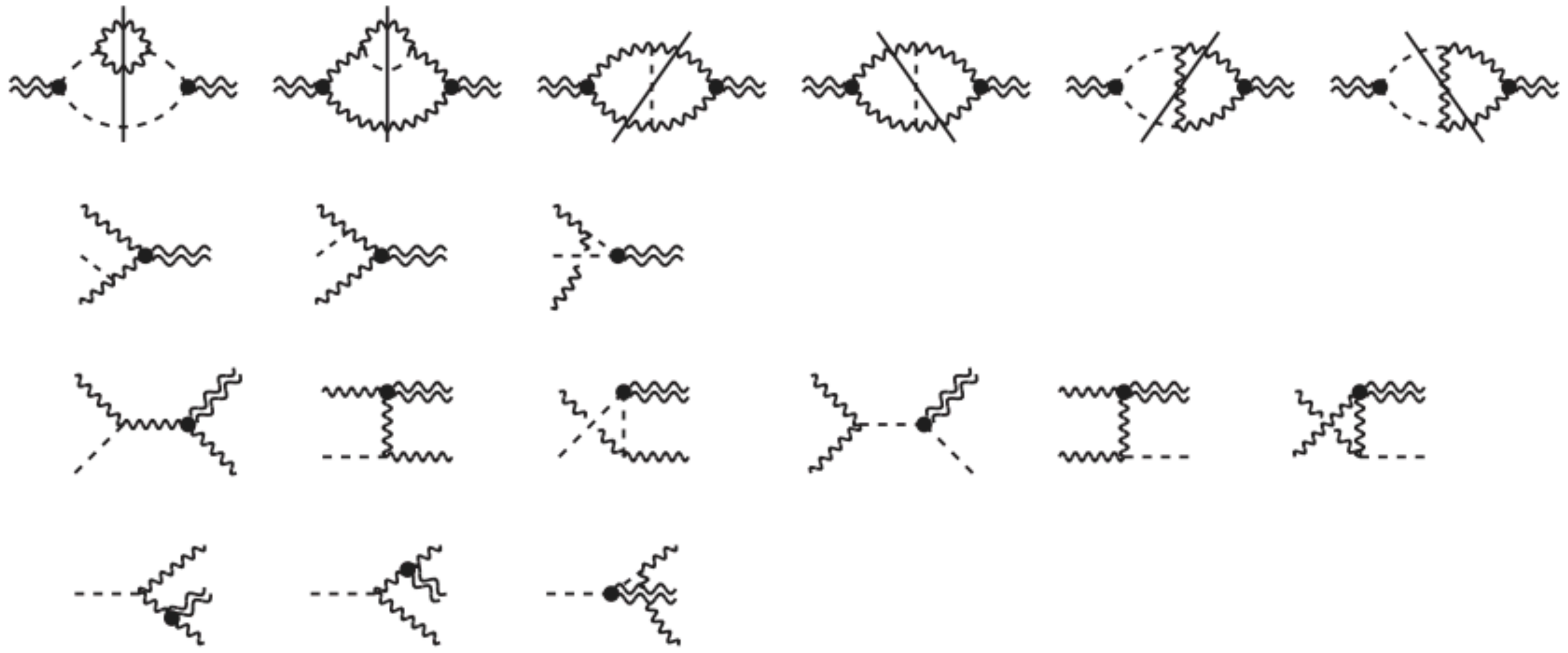
For $T_{\rm max} = 10^{16}$ GeV

GW from warm axion inflation

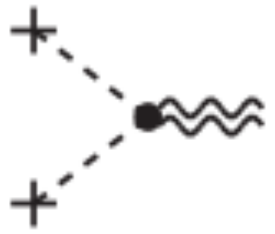
[Klose, Laine, Procacci: 2201.02317]
[Klose, Laine, Procacci: 2210.11710]

“Boltzmann domain” - elementary particle excitations can be resolved. SM contribution dominates (contribution from axion negligible)





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

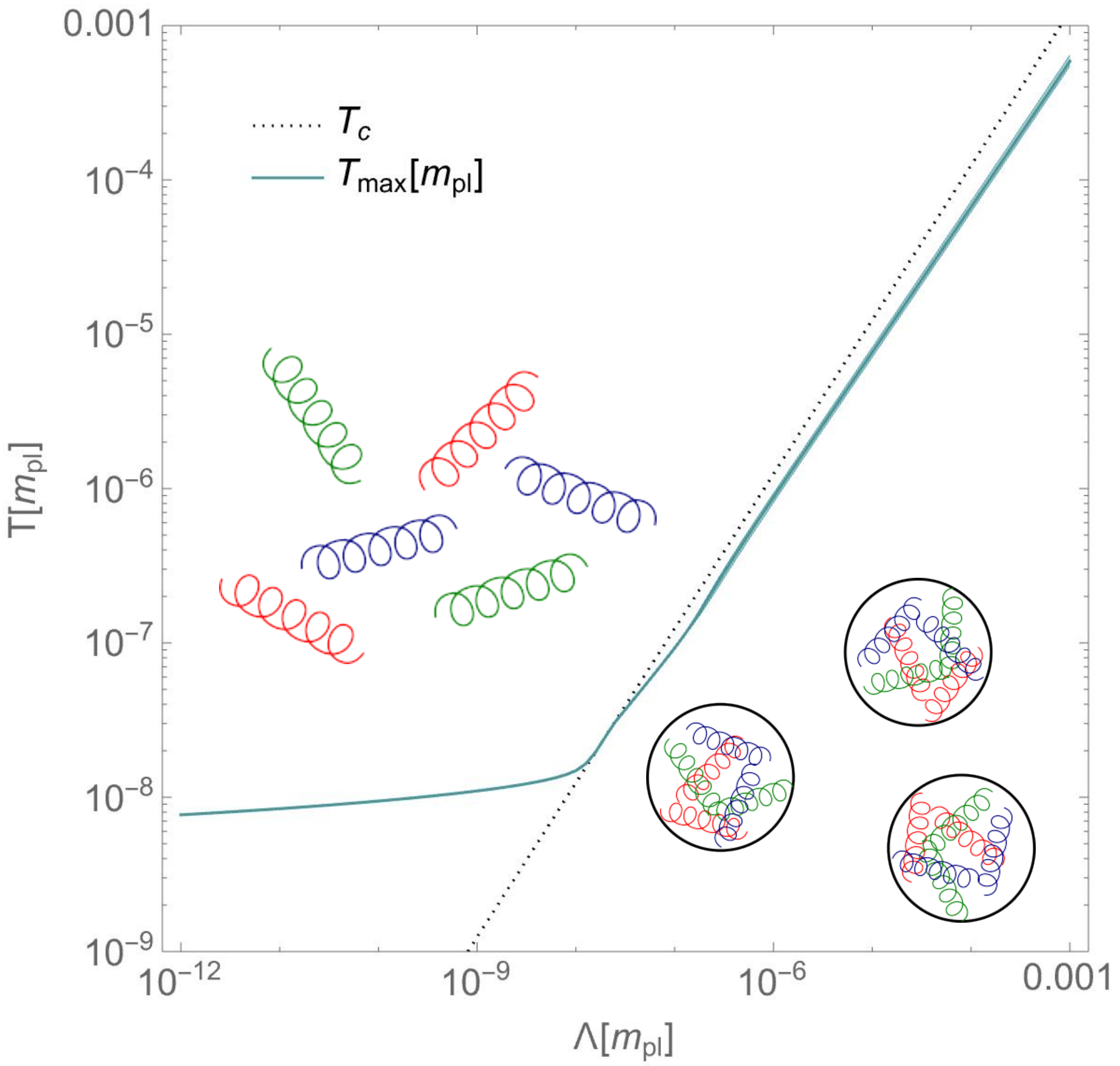


$$\Omega_{\text{GW}}h^2 \supset A\left(\frac{f}{\text{Hz}}\right)^3 \frac{(T\eta)_{\text{max}}}{m_{\text{pl}}^4}, \quad (T\eta)_{\text{max}} \sim \frac{T^4_{\text{max}}}{\alpha^2_{\text{min}}}$$

Contribution due to axion might be substantial!

Sensitive to maximum temperature reached in the YM sector!

Maximum temperature of the dark sector



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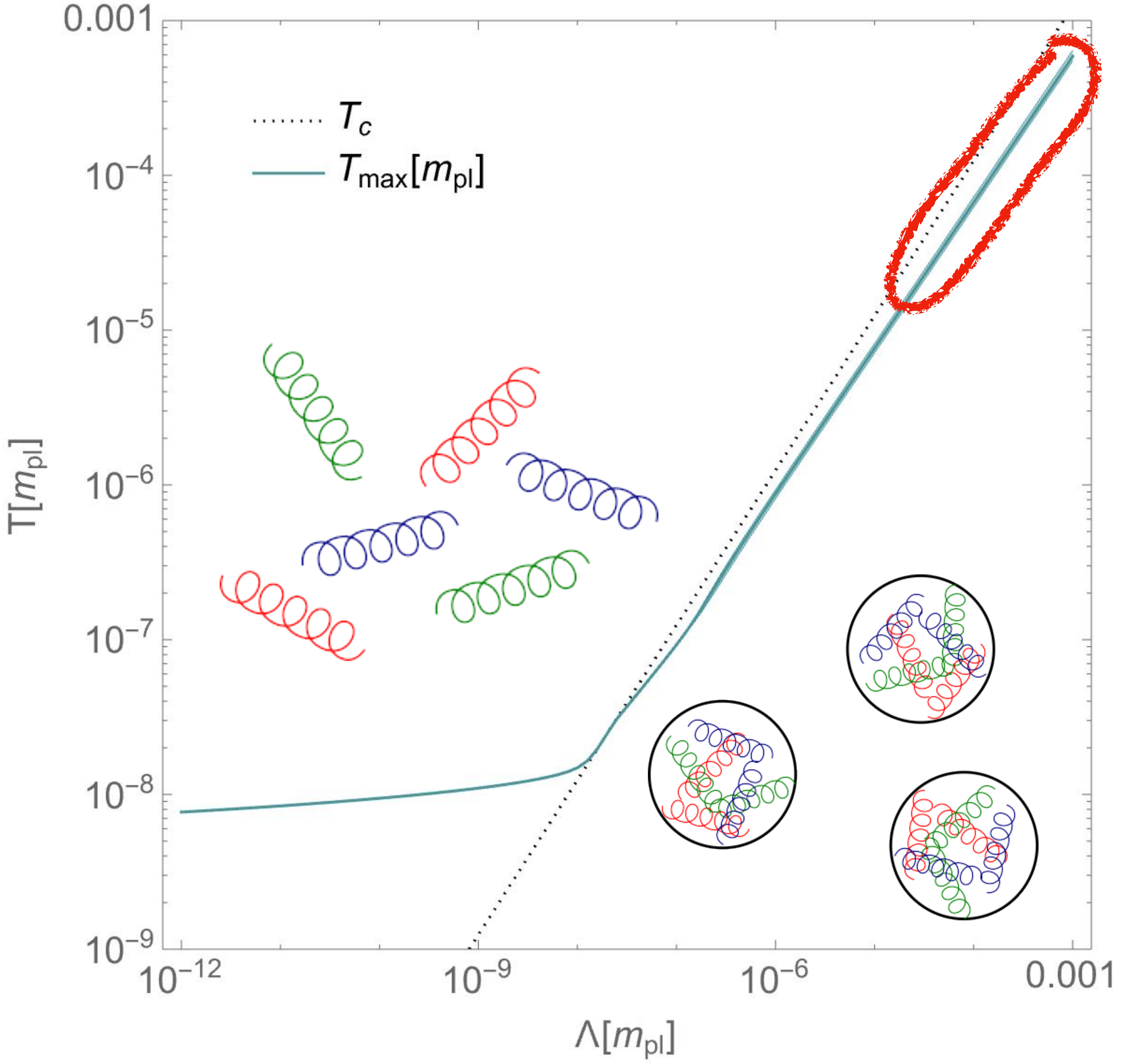

Message 1: Temperatures up to $10^{-3}\,m_{\rm pl}$ can be reached

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

$\Rightarrow$ Enhancement of GW from thermal plasma in ET, LISA frequency range

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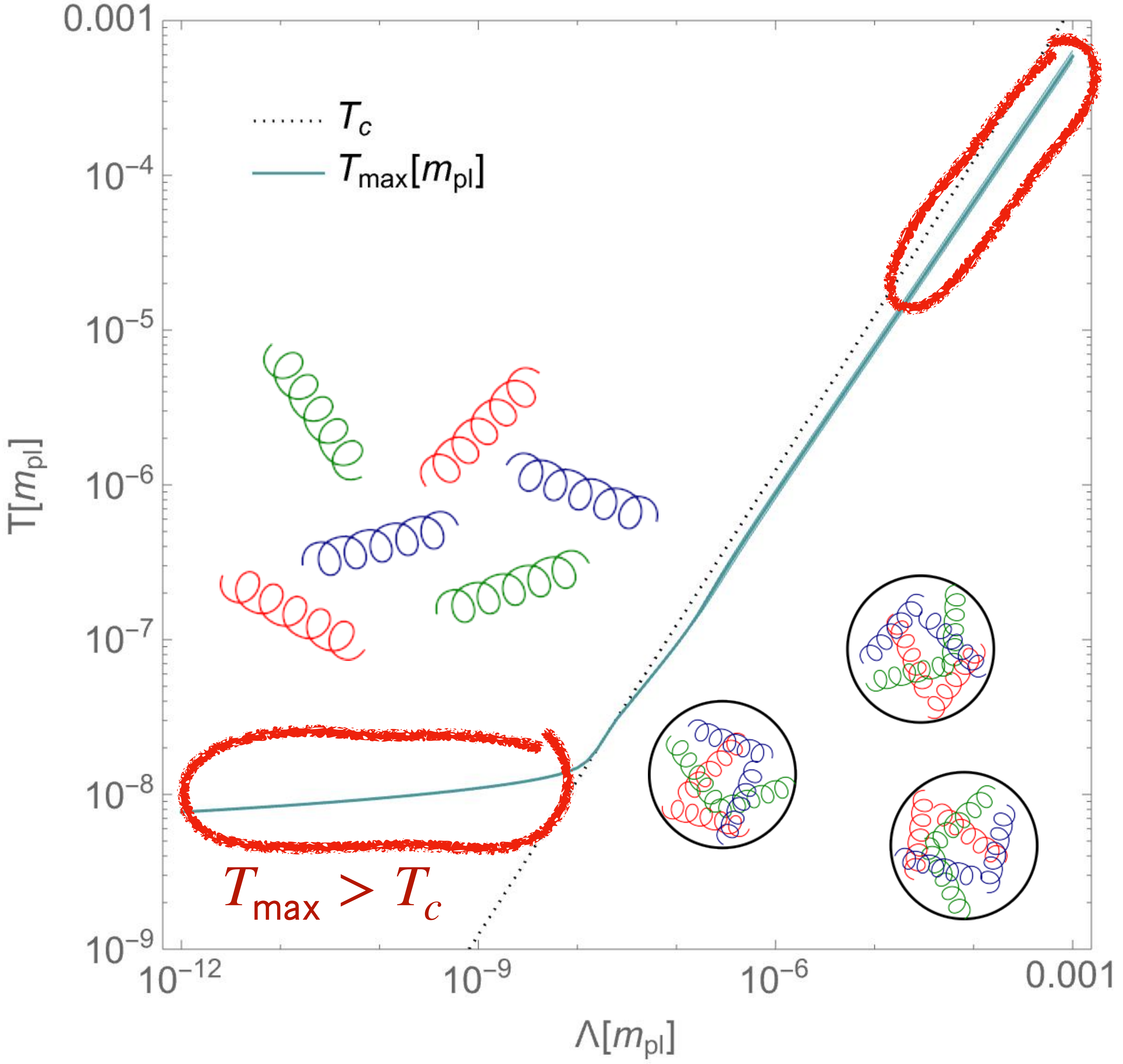

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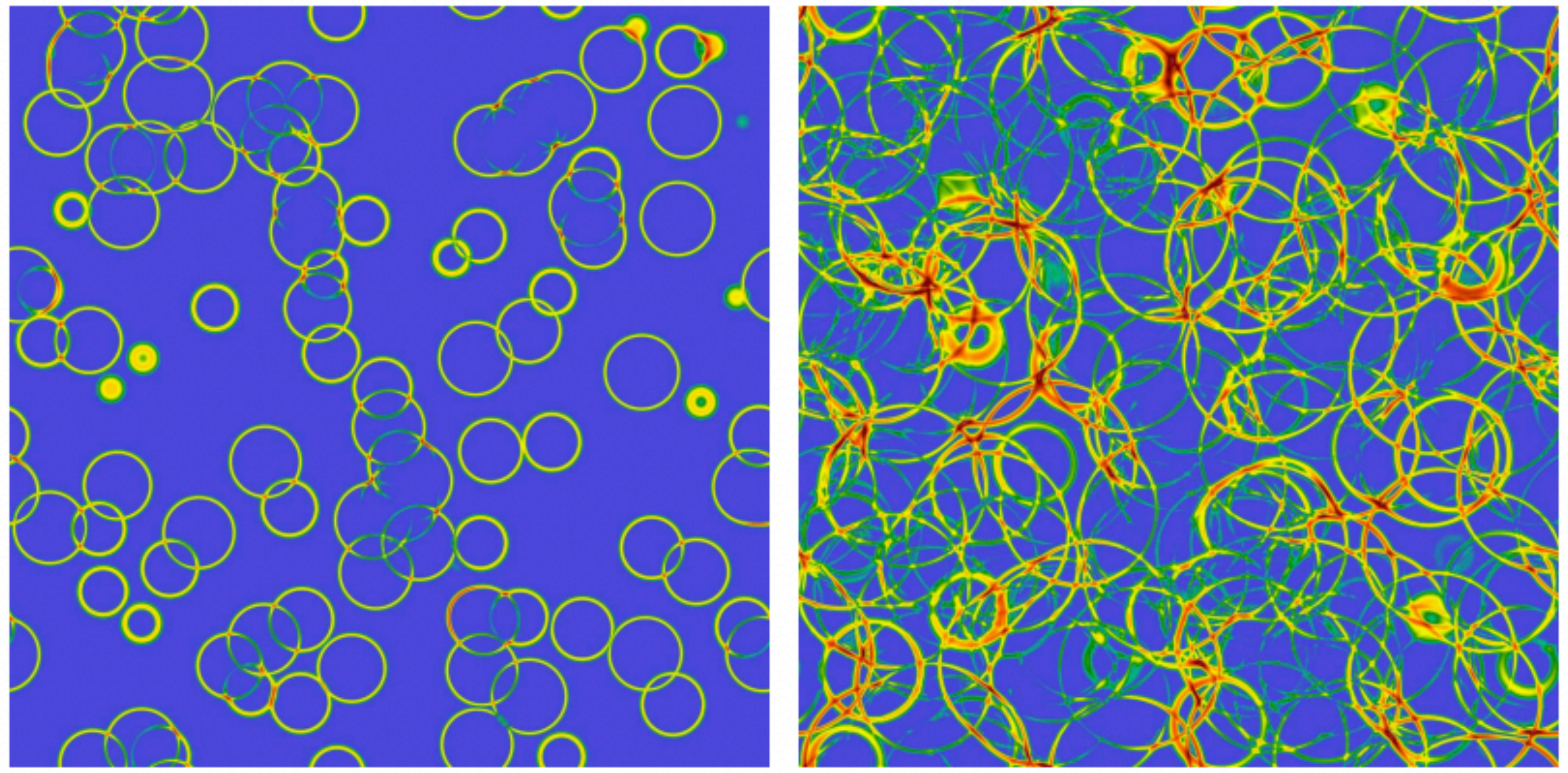
⇒ Enhancement of GW from thermal plasma in ET, LISA frequency range

Message 2: For lower Λ the dark sector heats up above T_c ⇒ undergoes a phase transition ⇒ possible further GW signal

GW from a confinement phase transition?

- Confinement phase transition for SU(3) pure Yang-Mills is of first order ⇒ possible GW signal [Schwaller:1504.07263][Caprini et al.: 1910.13125]…

[Hindmarsh et al.: 1504.03291]



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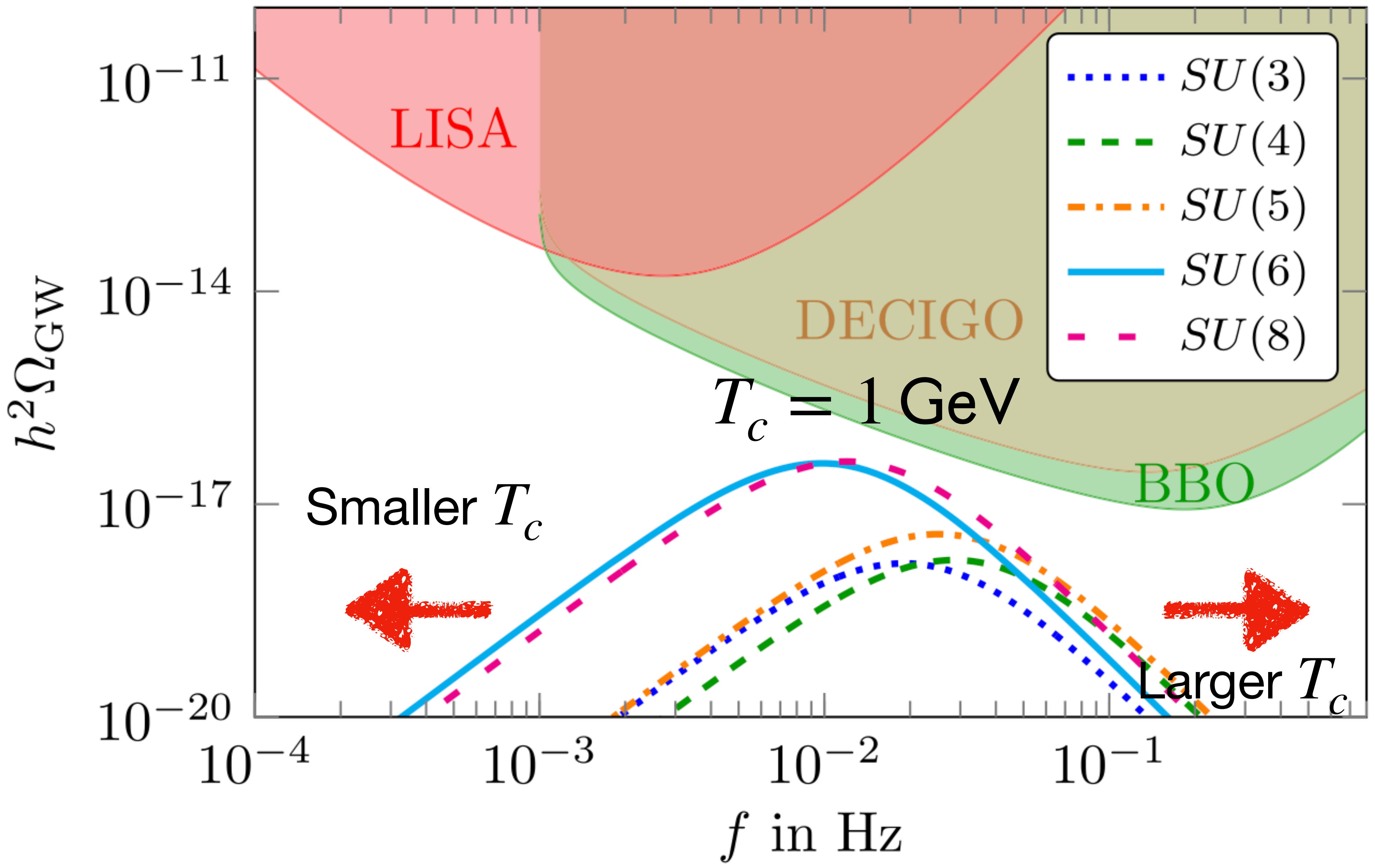
- Open questions: Bubble wall velocity? What if there is no SM plasma (i.e., no relativistic particles) around in the time of the phase transition?

Illustration: GW signal from the confinement phase transition in pure SU(N) theories calculated within PNJL model [Huang, Reichert, Sannino, Wang: 2012.11614]



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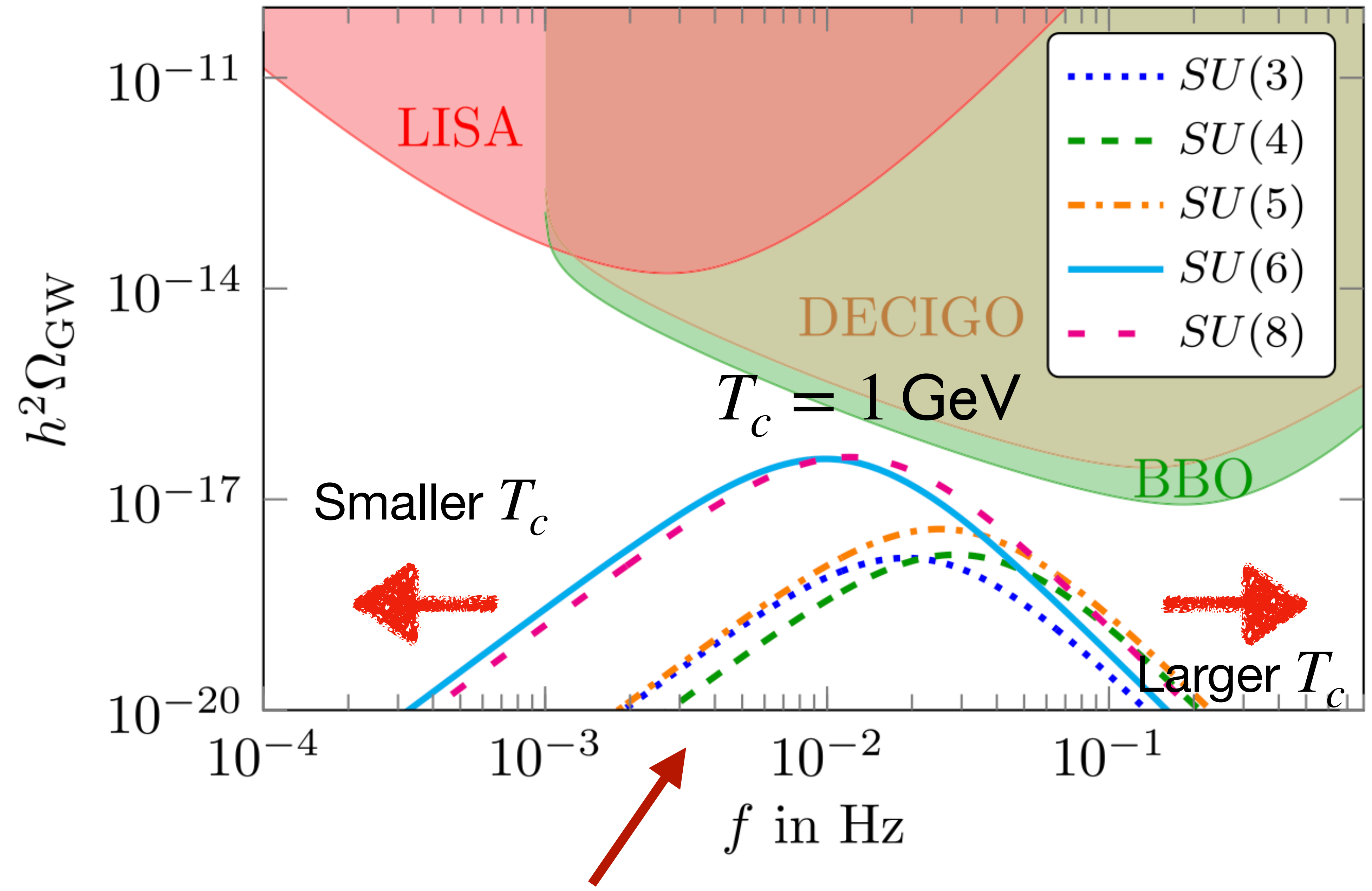


Phase transition assumed to happen during radiation-dominated era!

Dilution of the gravitational wave signal:
I) PT during radiation domination

$$\Omega_{\mathrm{gw},0}\, h^2 = \frac{\rho_{\mathrm{gw},\star}}{\rho_{\mathrm{crit}}} \frac{a_\star^4}{a_0^4} \qquad \& \qquad s_{\mathrm{rad}}\, a^3 = \mathrm{const}\,.$$

$$\Downarrow \qquad s_{\mathrm{rad}} = g_s \frac{2\pi^2}{45} T^3, \quad \rho_{\mathrm{rad}} = g_e \frac{\pi^2}{30} T^4$$

$$\boxed{\Omega_{\mathrm{gw},0}\, h^2 \simeq 1.65 \times 10^{-5} \frac{g_{e,\star}}{g_{s,\star}} \underbrace{\left(\frac{100}{g_{s,\star}}\right)^{1/3}}_{} \frac{\rho_{\mathrm{gw},\star}}{\rho_{\mathrm{rad},\star}}}$$

Between ~1 and ~3 for any phase transition temperature (if SM only)

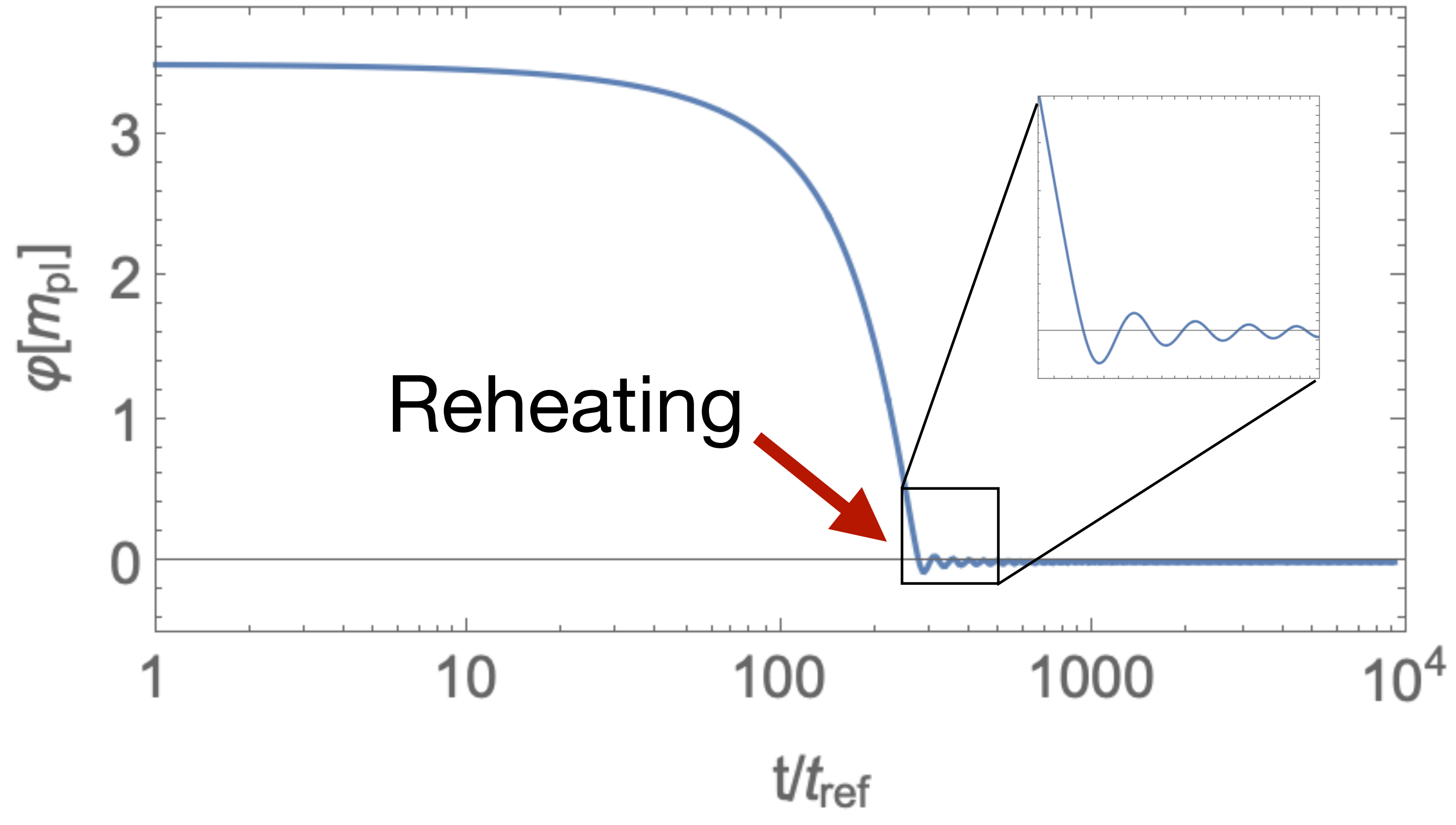
$\Omega_{\mathrm{gw},0}$ depends only mildly on the time when PT happens
(earlier PT ⇔ larger $g_{s,\star}$ ⇔ mildly suppressed GW signal)

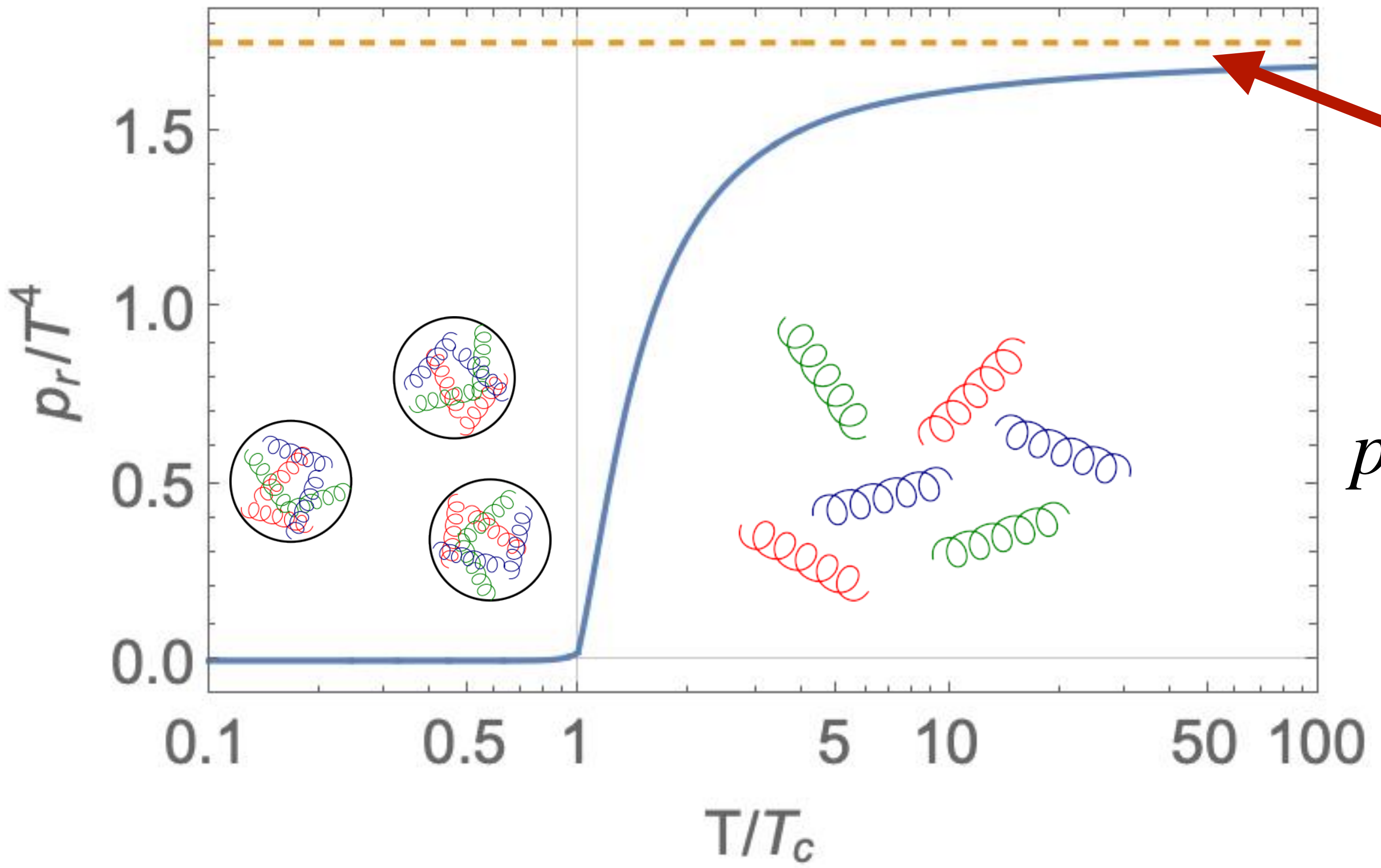
For SU(3) sector coupled to axion inflation, confinement PT may happen in an early matter-dominate era!

- Inflaton oscillations during reheating induce a matter-dominated era for $H \gtrsim \Upsilon$

$$p_\varphi = \frac{\dot{\varphi}^2}{2} - V \text{ ... averages to zero}$$

- Pure Yang-Mills sector below confinement temperature T_c is also matter-like!
(SM fields can be reheated only later, e.g., by the decay of the dark glueballs with rate Γ)





Weakly coupled radiation:

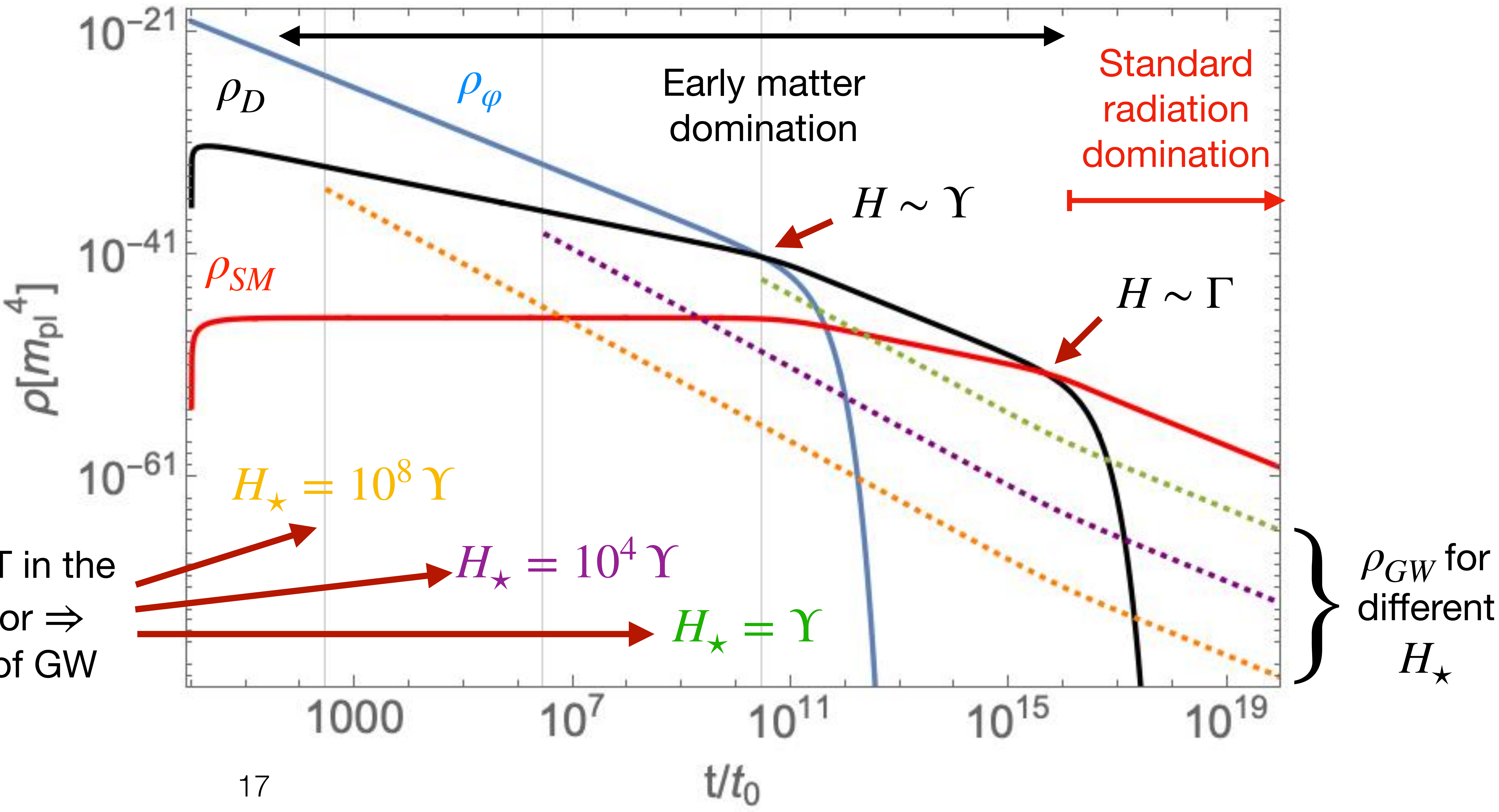
$$p_r = \frac{\pi^2 g_*}{90} T^4$$

How does GW dilution look like if PT happens during matter-dominated era?

Generic model with early matter domination

1. **Oscillations of the inflaton field** dominating the Universe
2. Inflaton decays to **matter-like dark sector** (non-relativistic particles) when $H \sim \Upsilon$
3. Dark sector decays into **SM fields** when $H \sim \Gamma$
4. Standard radiation domination

$$\dot{\rho}_\varphi + 3H\rho_\varphi = -\Upsilon\rho_\varphi$$
$$\dot{\rho}_D + 3H\rho_D = +\Upsilon\rho_\varphi - \Gamma\rho_D$$
$$\dot{\rho}_{SM} + 4H\rho_{SM} = +\Gamma\rho_D$$
$$\dot{\rho}_{\rm gw} + 4H\rho_{\rm gw} = 0$$



Possible PT in the dark sector ⇒ emission of GW

ρ_{GW} for different $H_\star$

Dilution of the gravitational wave signal:
II) PT during matter domination

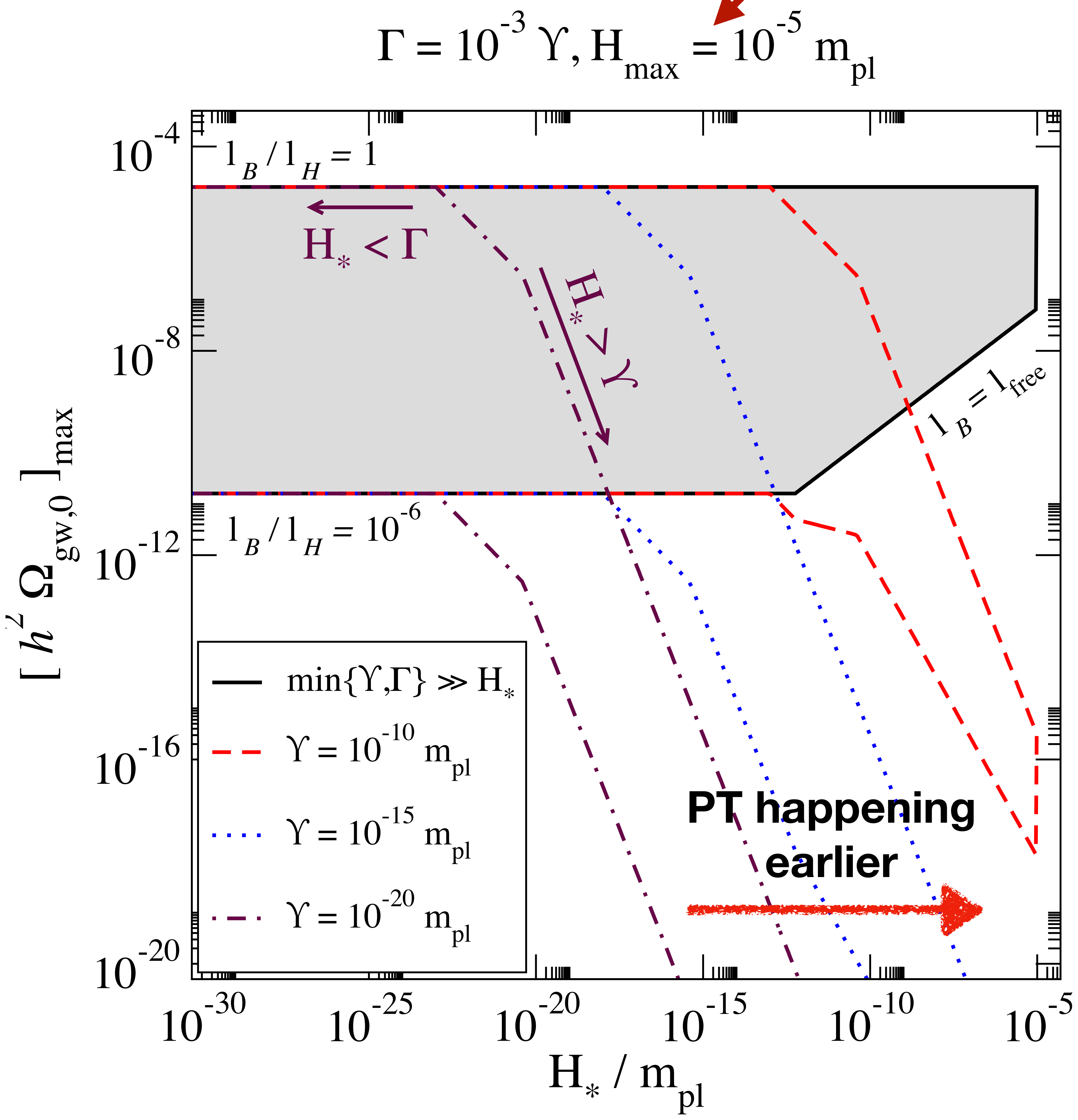
$$\Omega_{\text{gw},0}\,h^2 \simeq 1.65\times 10^{-5}\,\frac{g_{e,r}}{g_{s,r}}\left(\frac{100}{g_{s,r}}\right)^{1/3}\frac{\rho_{\text{gw},\star}}{\rho_{D,\star}}\underbrace{\left(\frac{\Gamma}{H_\star}\right)^{2/3}}_{\substack{\text{Absent if}\\ H_\star<\Gamma}}\;\underbrace{\frac{\Upsilon}{H_\star}}_{\substack{\text{Absent if}\\ H_\star<\Upsilon}}$$

Rough estimate of the maximum possible GW signal:

$$\frac{\rho_{\text{gw},\star}}{\rho_{D,\star}} \sim \frac{l_B}{l_H}\,\theta(l_B - l_{\text{free}}), \qquad \frac{l_B}{l_H} \in (10^{-6}, 1)$$

- $l_B \sim 1/\beta$ … bubble length scale = scale of translation invariance breaking
- $l_H \sim 1/H$ … Hubble length scale
- l_{free} … mean free path = scale of thermal fluctuations ⇒ $l_B \gtrsim l_{\text{free}}$

[Planck: 1807.06211]

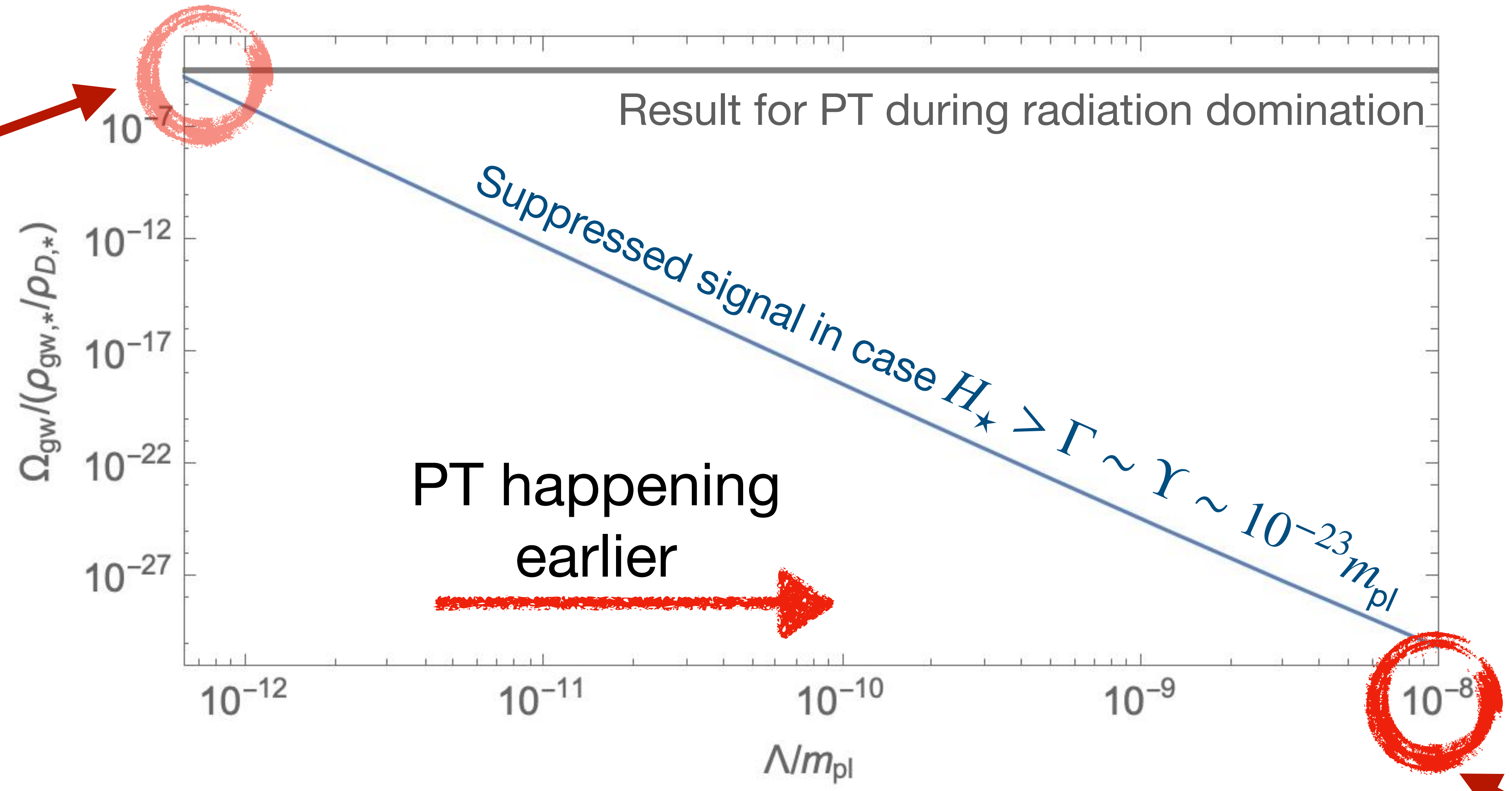


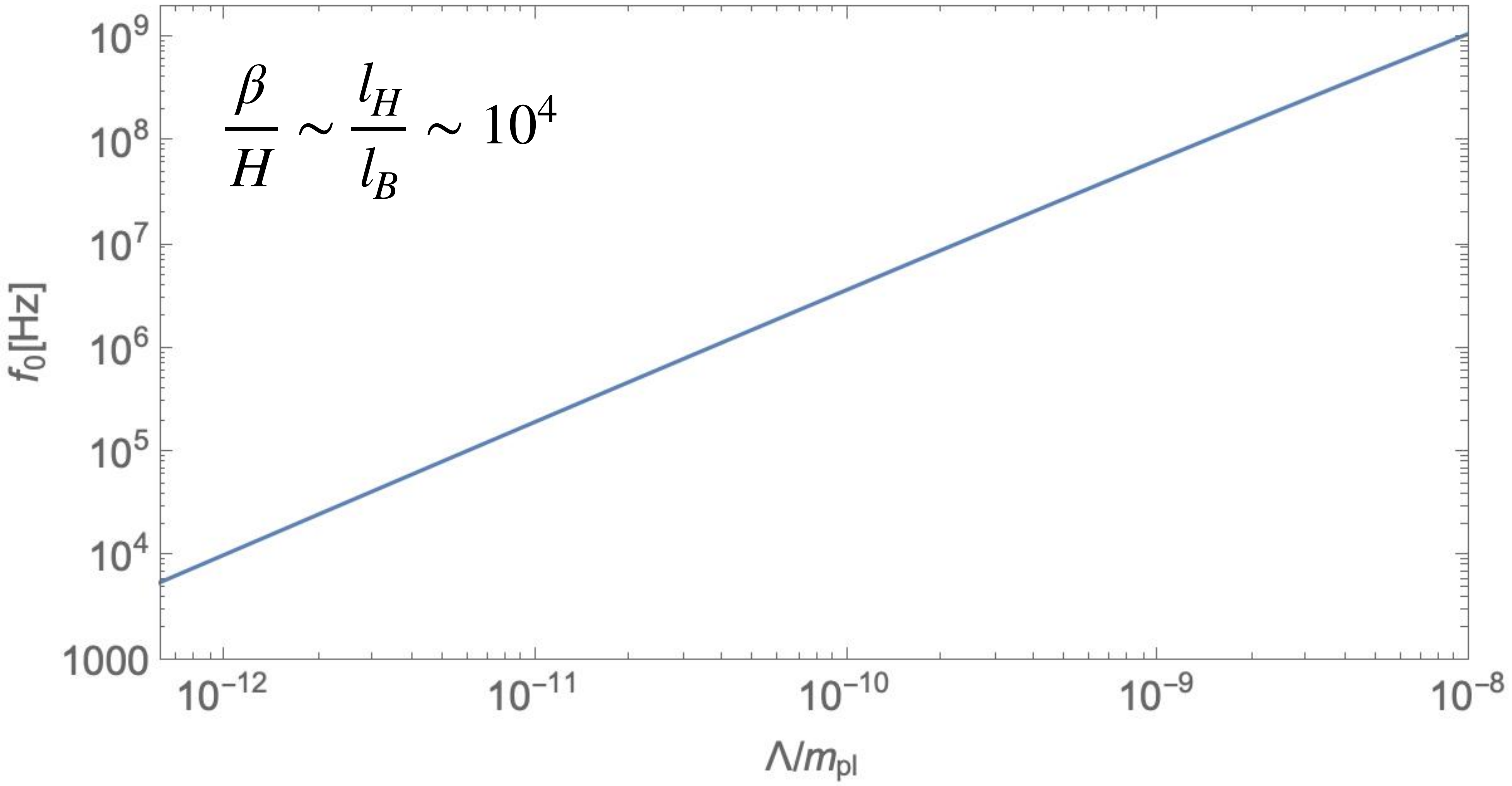
[HK, Laine: 2311.03718]

($m_{\text{pl}} = 1.22\times 10^{19}$ GeV)

Implications for GW from the confinement phase transition in the SU(3) sector coupled to axion inflation

Sizeable signal only if PT happens shortly before radiation domination starts





$\Lambda \sim 10^{-8} m_{\rm pl}$: "interesting" region where two phase transitions occur :(
(Reason why to explore the strong regime of warm axion inflation where Υ can be larger?)

Conclusions

- Evolution of a dark SU(3) sector coupled to axion inflation studied
  - Different qualitative behaviour depending on the dark confinement scale Λ:

$\Lambda \lesssim 10^{-8} m_{\text{pl}} : T_{\text{max}} \sim 10^{-8}\, m_{\text{pl}} > T_c \;\Rightarrow$ Phase transition

$\Lambda \gtrsim 10^{-8} m_{\text{pl}} : T_{\text{max}}$ slightly below $T_c \;\Rightarrow$ Large temperatures achieved

  - Possible gravitational wave signal in both cases, however, it might be diluted due to an early matter dominated era

- Teaser for the NPACT meeting: glueball dark matter for $\Lambda \sim 10^{-12} m_{\text{pl}}$?
  [Biondini, HK, Procacci: in preparation]

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Thanks for your attention!

Back up

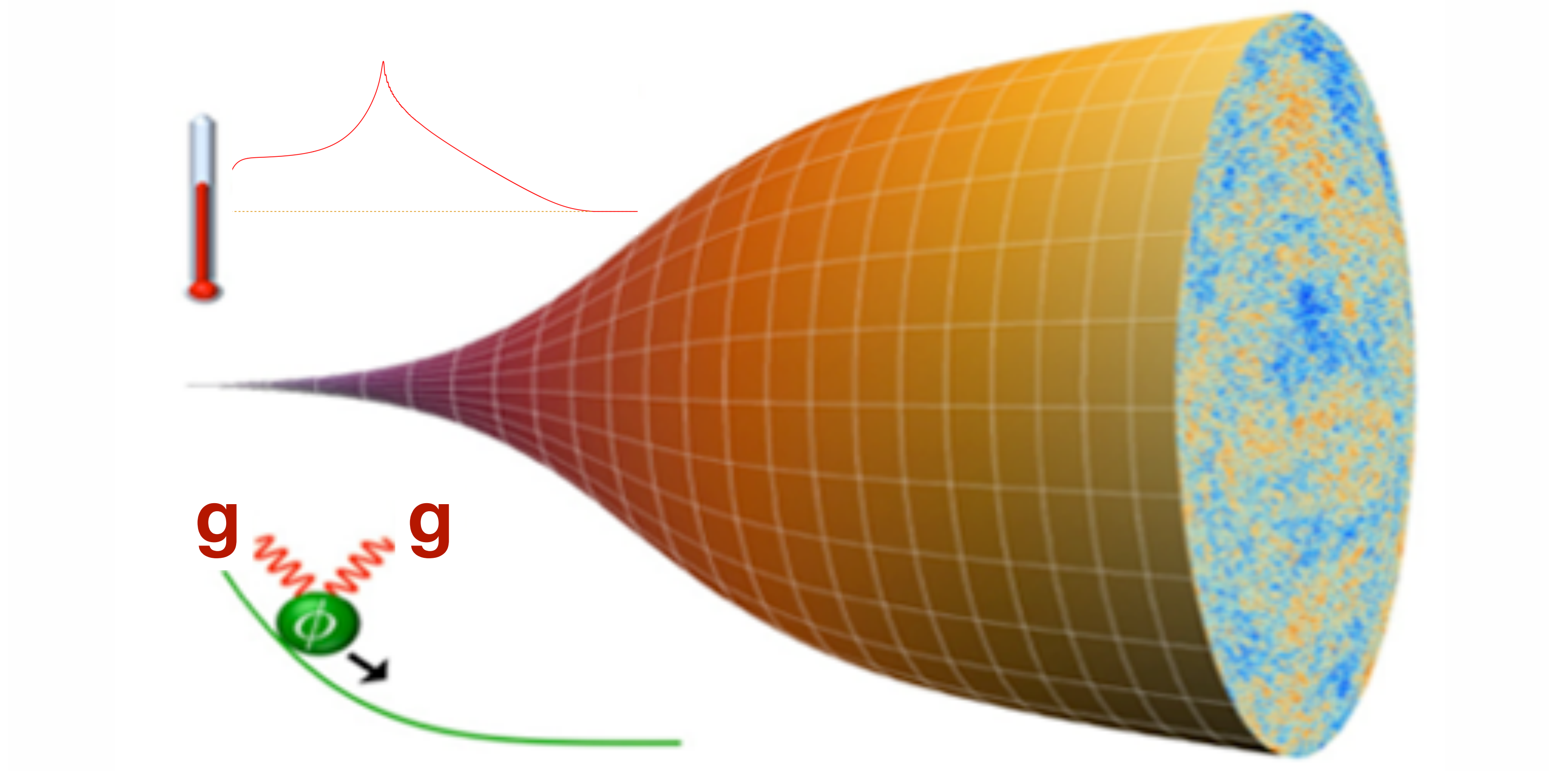
Inspiration: warm inflation

- Inflaton interactions with light particles

  ⇒ Friction term in the inflaton evolution equation

  ⇒ Presence of a thermal bath throughout inflation

[Berera, Fang: astro-ph/9501024; Berera: astro-ph/9509049; Berera, Gleiser, Ramos: hep-ph/9809583], review: [Kamali, Motaharfar, Ramos: 2302.02827]



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

Strong regime: thermal friction dominates

Weak regime: Hubble friction dominates

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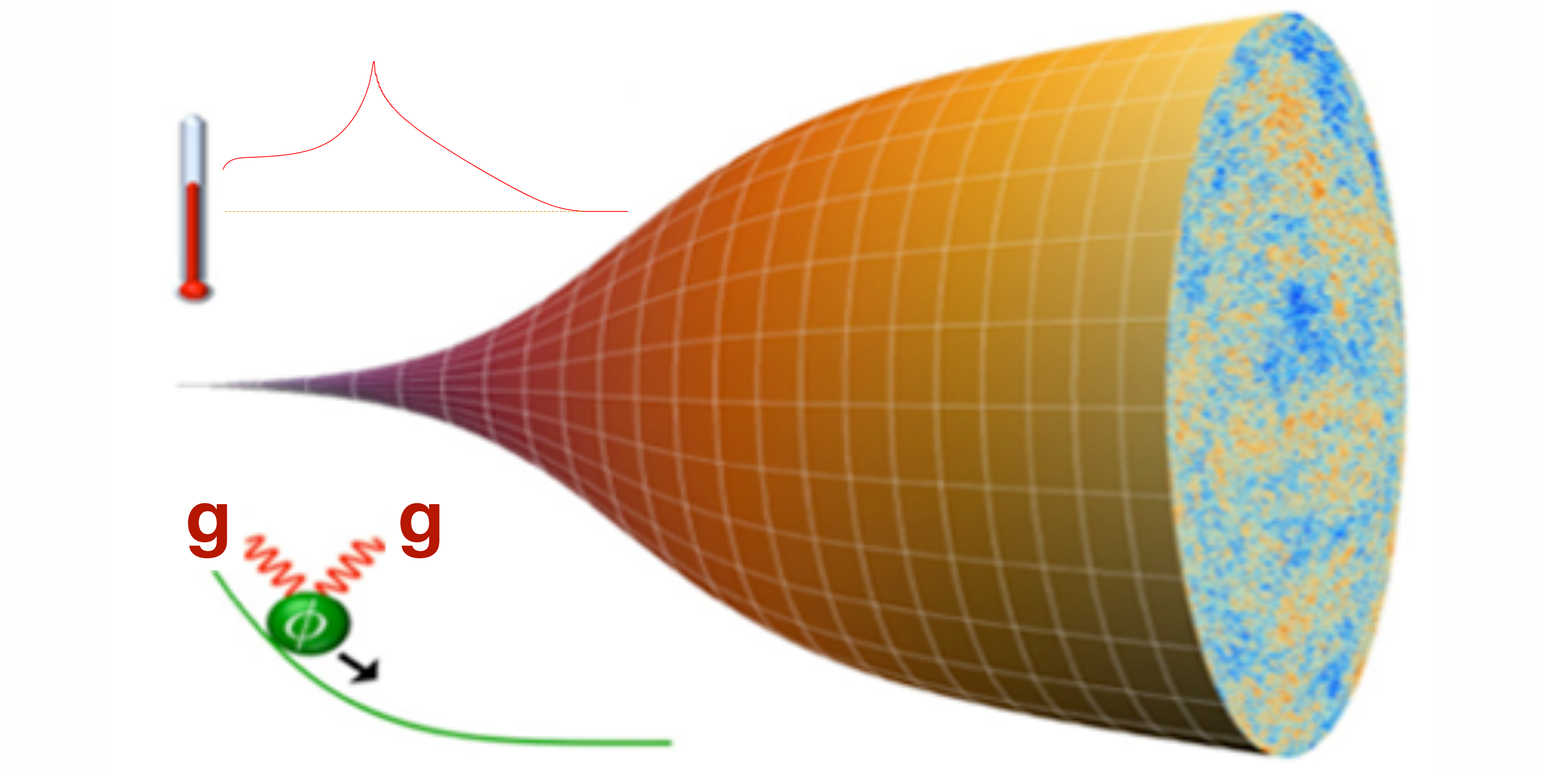

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Strong regime: thermal friction dominates

Weak regime: Hubble friction dominates

- Concrete realisation: warm axion inflation - coupling to non-abelian gauge fields

[Berghaus, Graham, Kaplan: 1910.07525]
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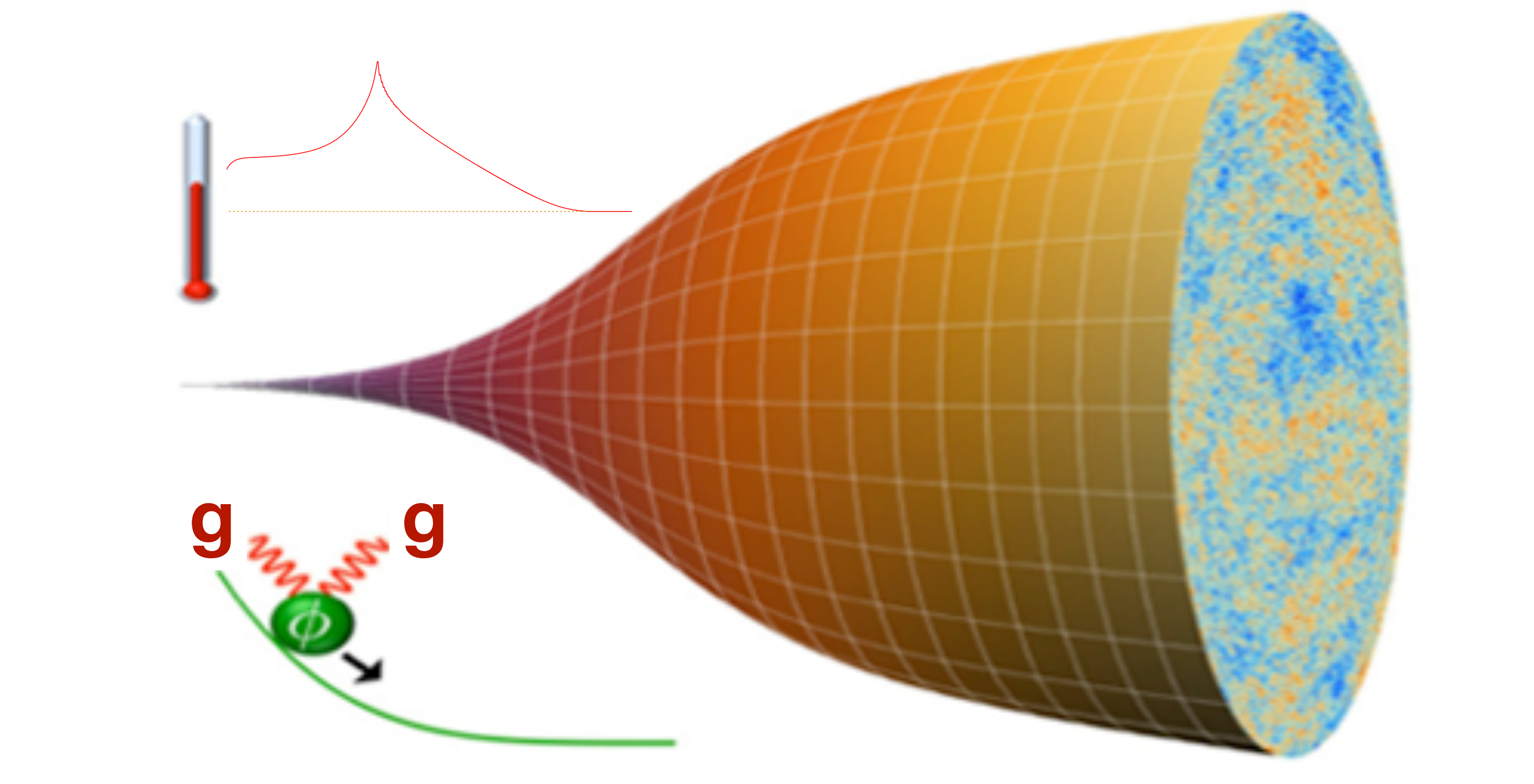

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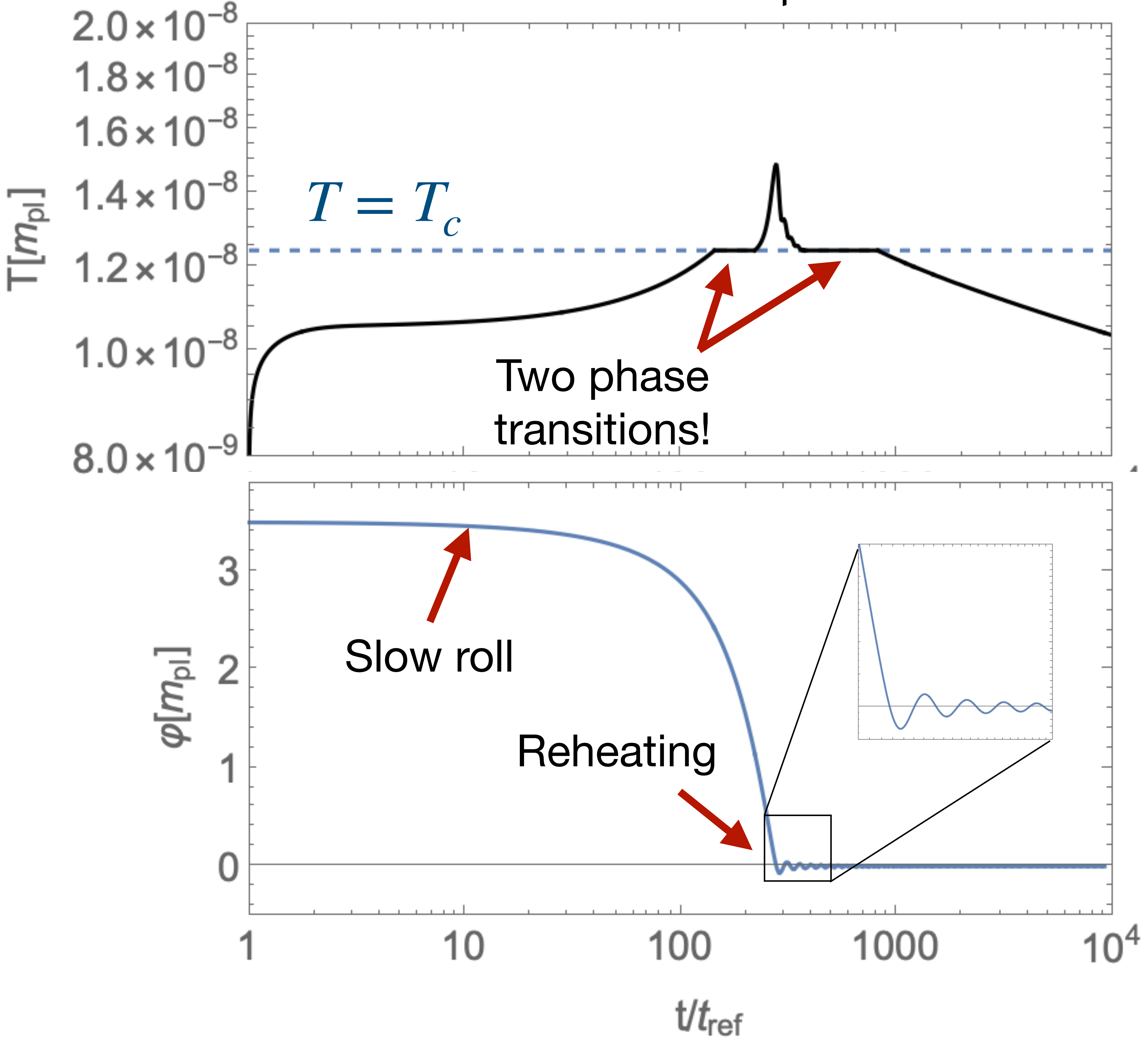
⇒ (Dark) Yang-Mills sector!

Focus of this talk!

There can even be two phase transitions!

$\Lambda = 10^{-8} m_{\rm pl}$



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

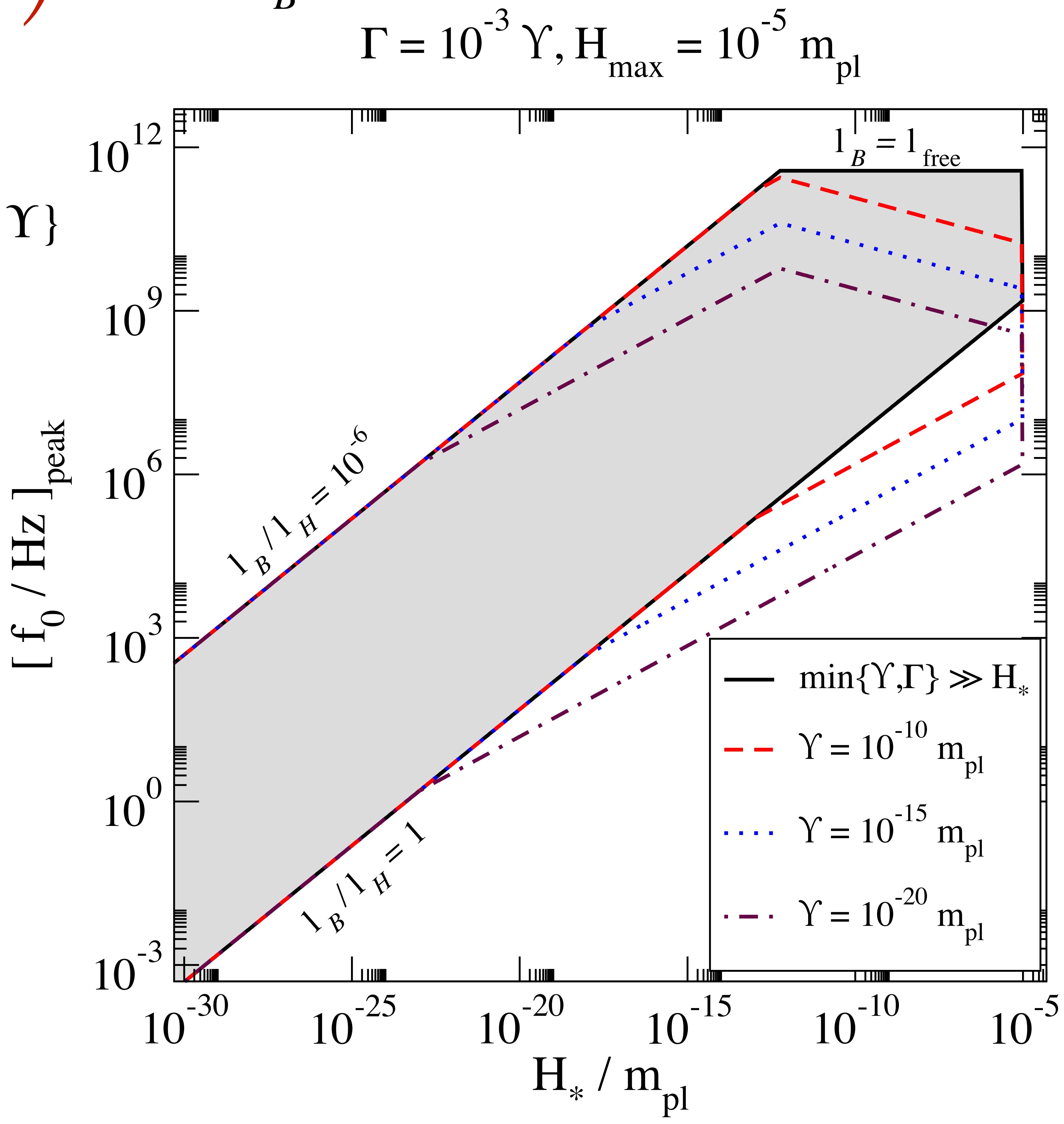
$$\Rightarrow \Upsilon \sim 10^{-23} m_{\rm pl} \ll H_{\rm slow-roll} \sim 10^{-5} m_{\rm pl}$$

- Heating and cooling phase transitions may bring interesting GW signatures!
  [Buen-Abad, Chang, Hook: 2305.09712]

($m_{\rm pl} = 1.22 \times 10^{19}$ GeV)

Dilution of the gravitational wave signal:
II) PT during matter domination

$$f_{0,\text{peak}} \simeq 4.93\times 10^{11}\,\text{Hz}\left(\frac{g_{e,r}}{g_{s,r}}\right)^{1/4}\left(\frac{100}{g_{s,r}}\right)^{1/12}\left(\frac{H_\star}{m_\text{pl}}\right)^{1/2}\underbrace{\left(\frac{\min\{\Gamma,\Upsilon\}}{H_\star}\right)^{1/6}}_{\text{Absent if } H_\star < \min\{\Gamma,\Upsilon\}}\frac{l_H\,\theta(l_B - l_\text{free})}{l_B}$$



- $l_B \sim 1/\beta$ … bubble length scale = scale of breaking of the spherical symmetry
- $l_H \sim 1/H$ … Hubble length scale
- l_free … mean free path = scale of thermal fluctuations
- $l_B \gtrsim l_\text{free} \Rightarrow$ upper bound on peak GW frequency when $H_\star$ close to H_max

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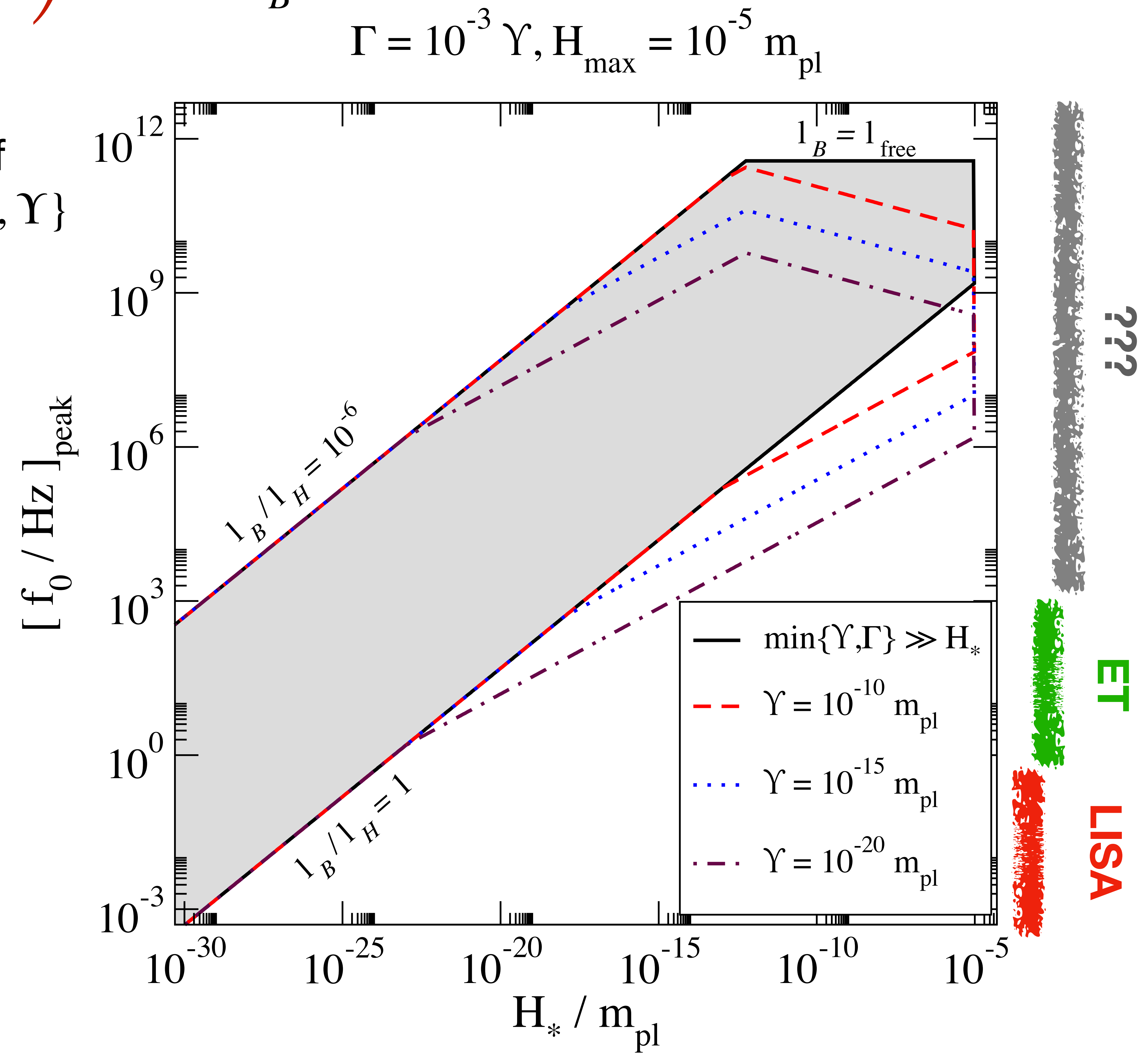
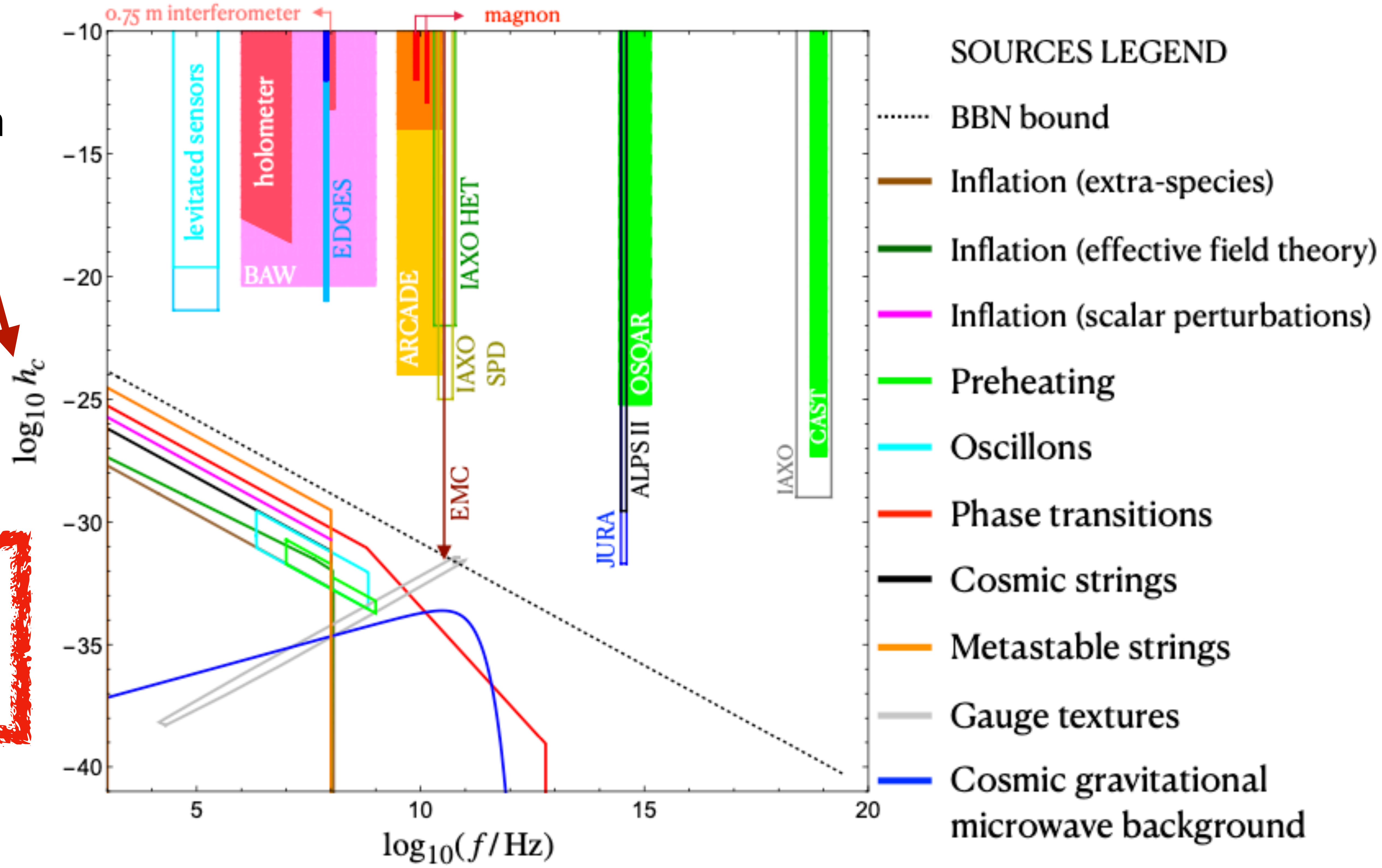


Ultra-high frequency GW

[Aggarwal et al.: 2011.12414]

Experimentally
meaningful
quantity: strain

$$\Omega_{\mathrm{gw},0} = \frac{4\pi^2 f_0^2 h_c^2}{3H_0^2}$$



- No known astrophysical sources of GW at MHz to GHz frequencies ⇒unique opportunity to learn about BSM physics!
- Detection is challenging, but new ideas are appearing!

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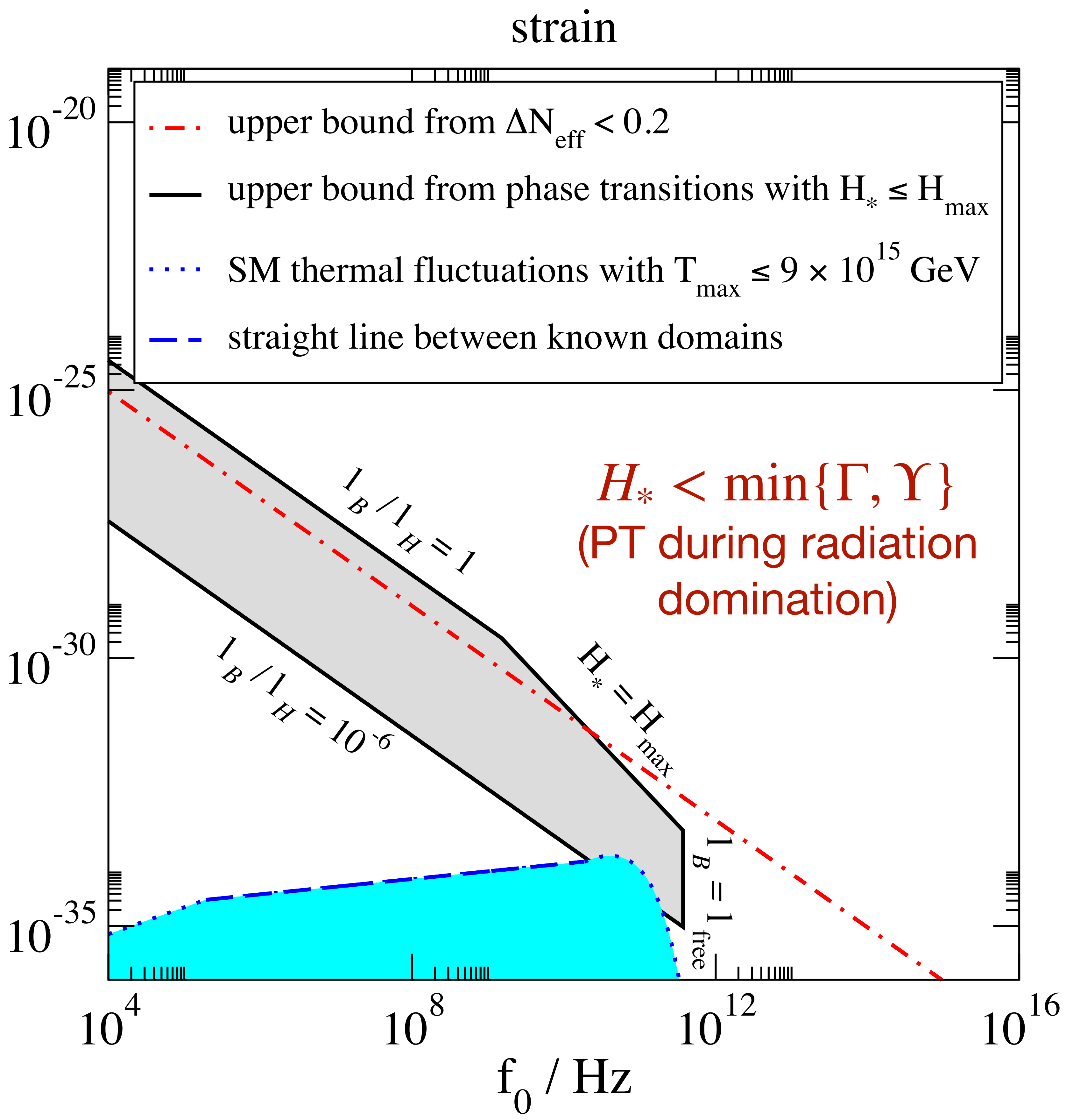
[HK, Laine: 2311.03718]



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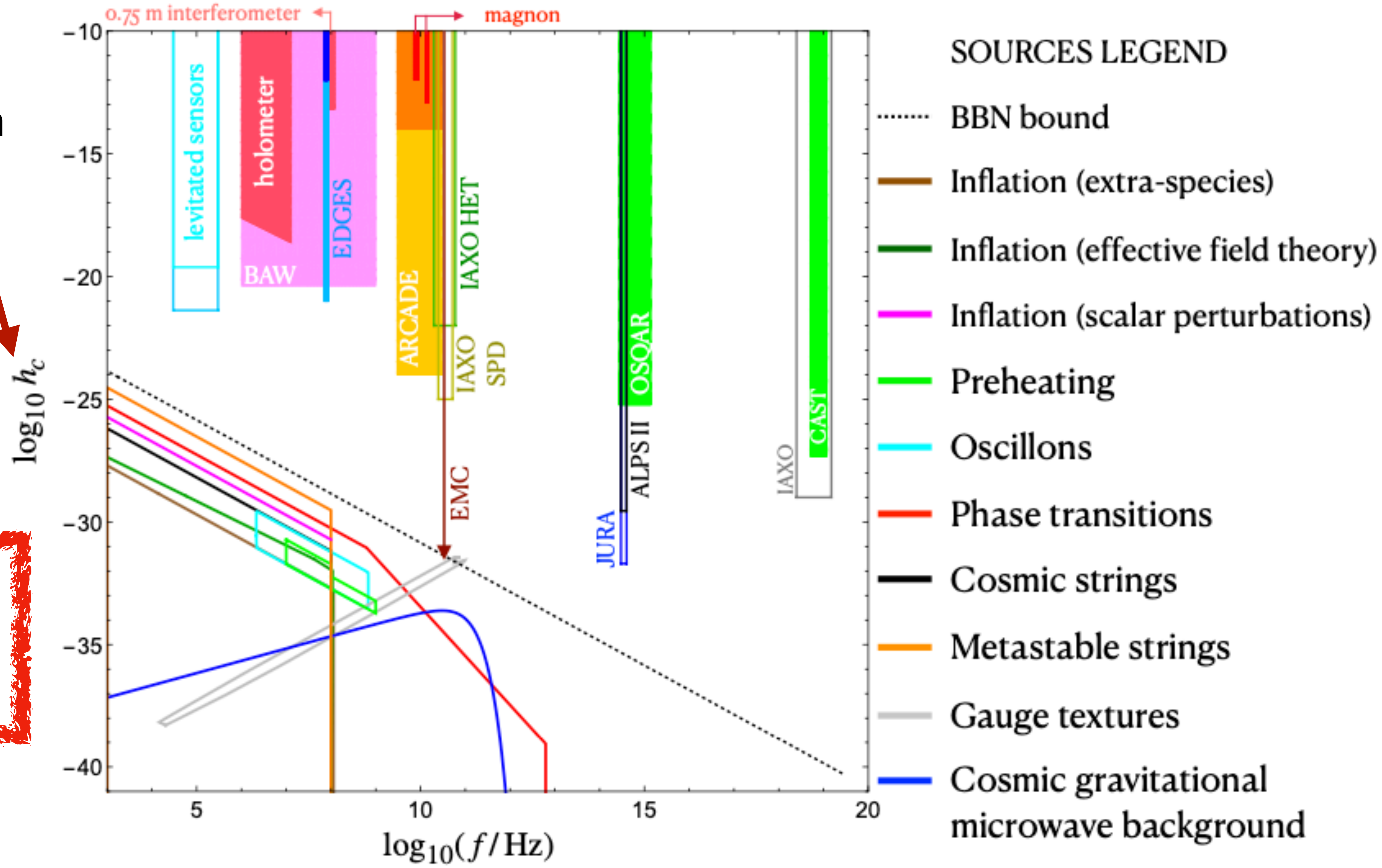

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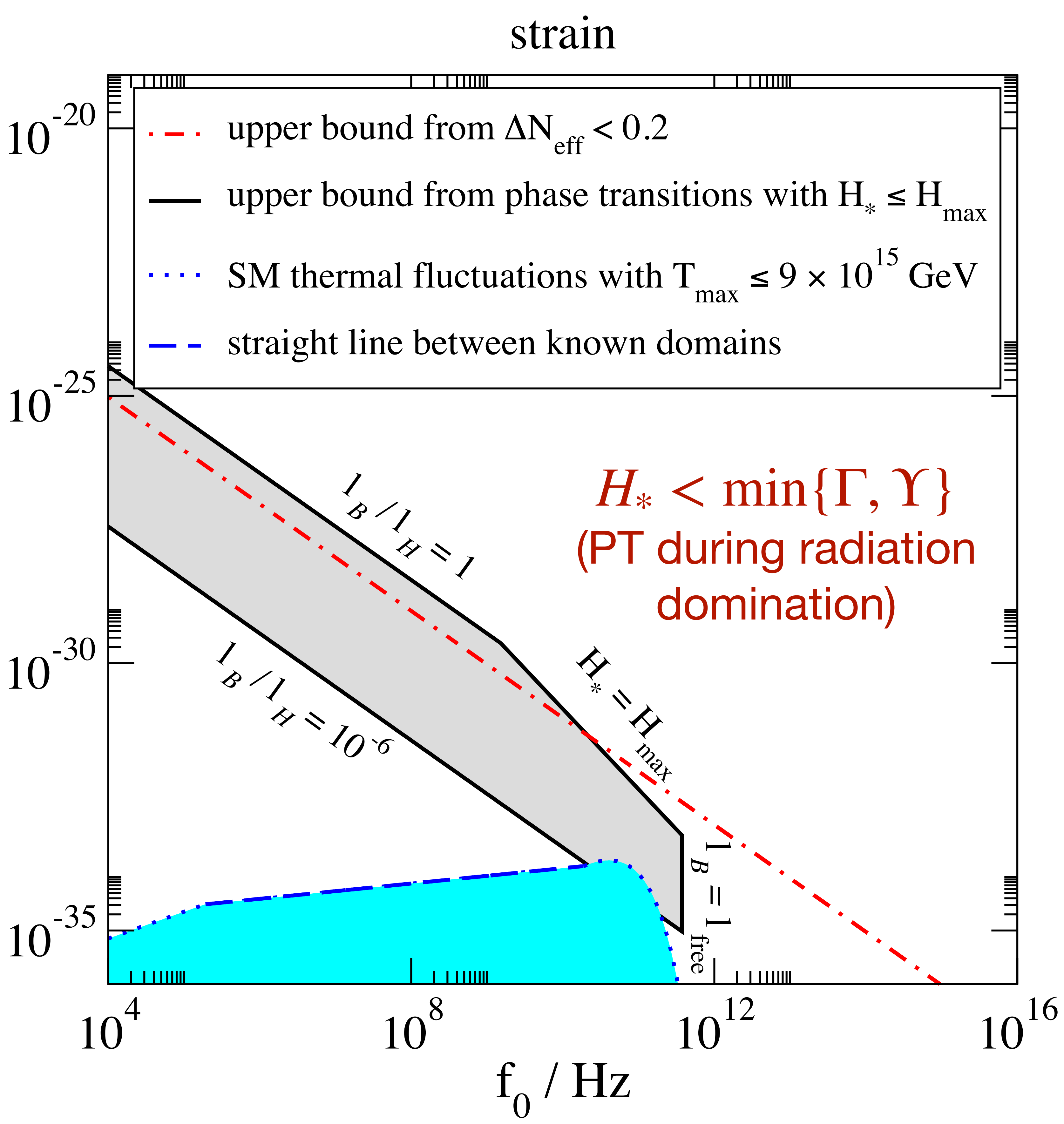

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$H_* < \min\{\Gamma, \Upsilon\}$
(PT during radiation domination)

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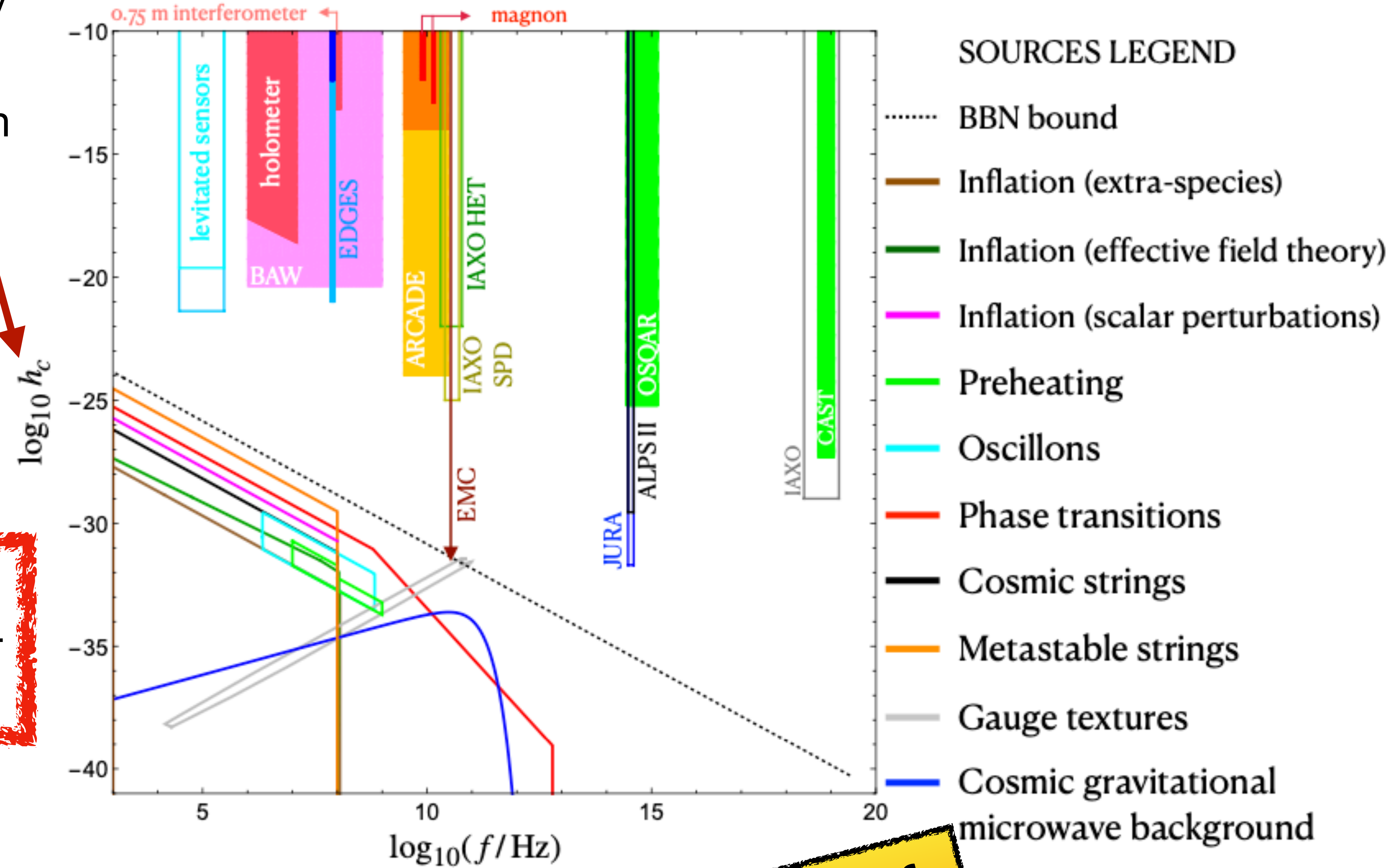

- No known astrophysical sources of GW at MHz to GHz frequencies → tunity to learn about BSM physics!
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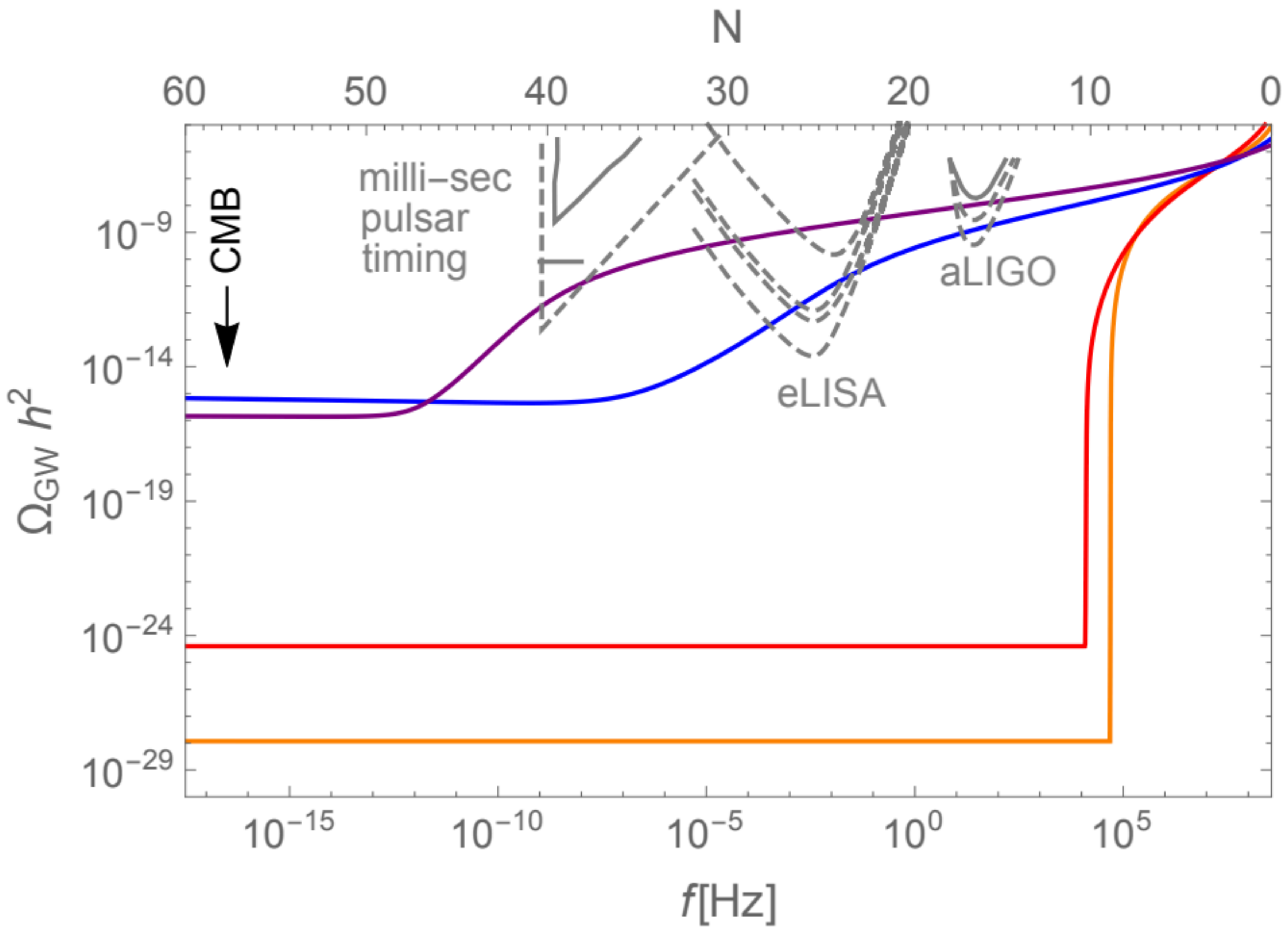
In any case, beware of early matter domination!

NB: abelian vs non-abelian dark sector

- Pseudoscalar inflaton coupled to gauge fields:

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

- 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…]
- Discussion about back-reaction [… Figueroa et al.: 2303.17436]
- Non-Abelian case: thermalisation assumption simplifies the back-reaction modeling!



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Absent in thermal non-abelian case!

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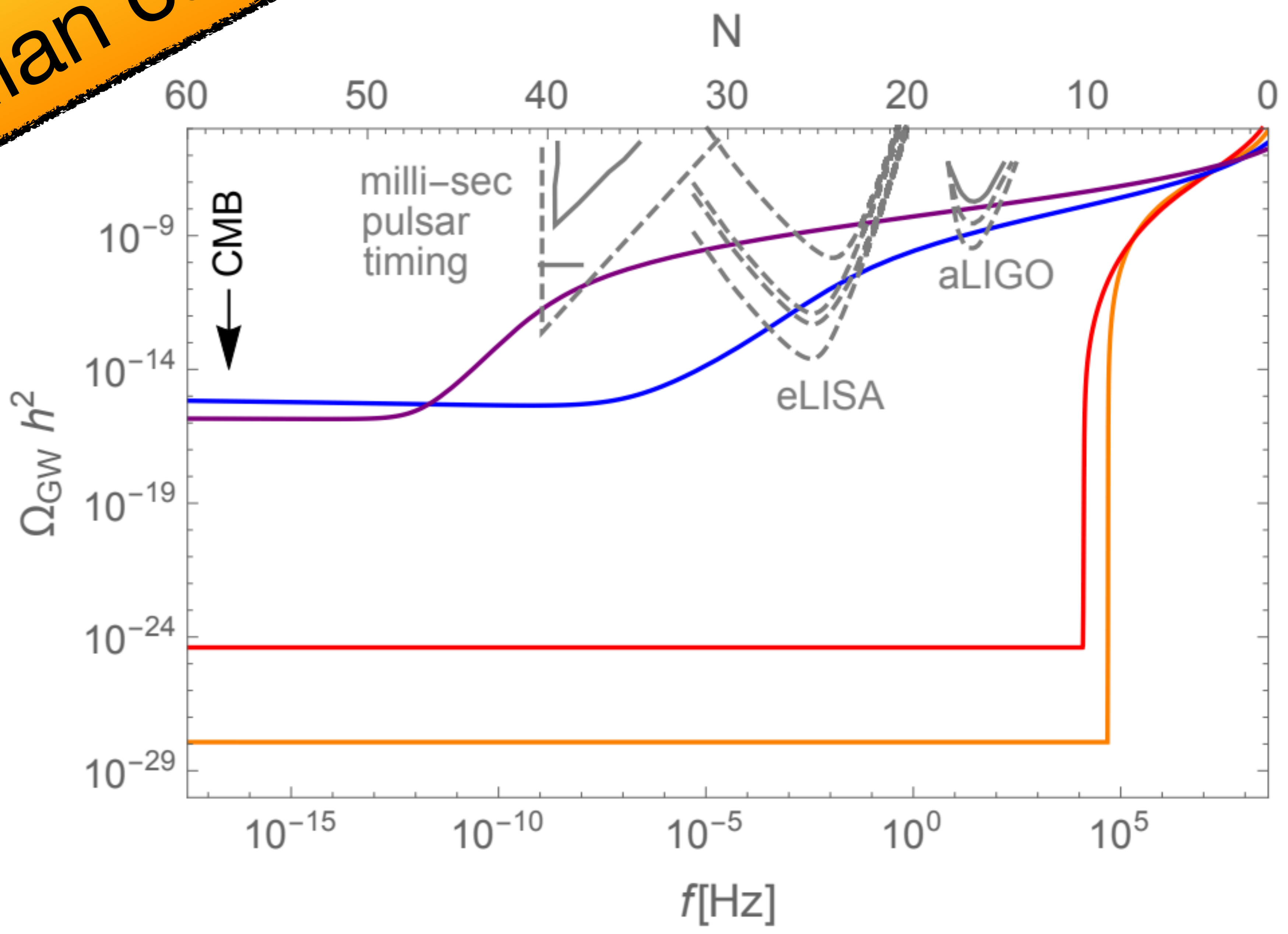

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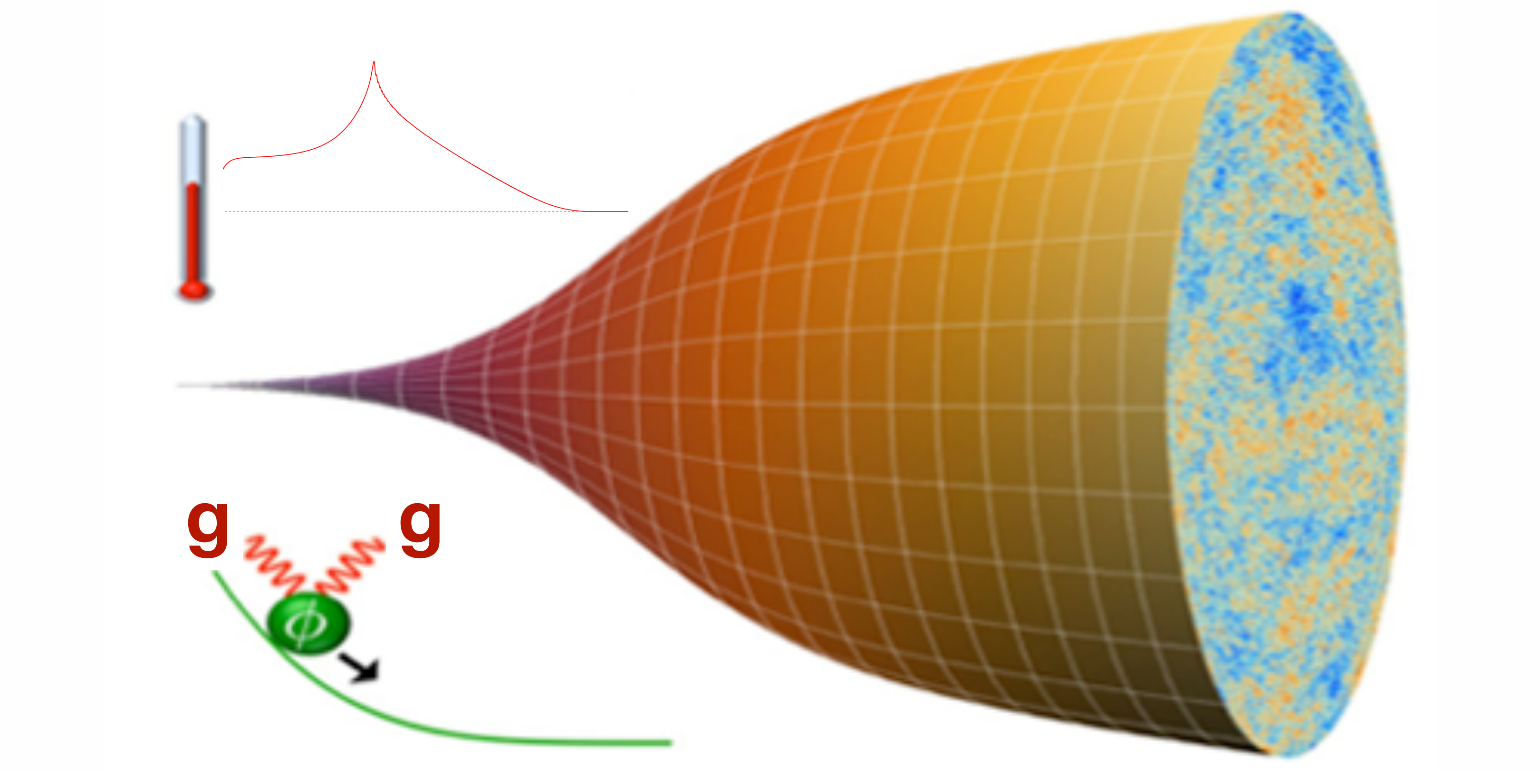
Working example: SU(3) case

[Klose, Laine, Procacci: 2201.02317]
[Klose, Laine, Procacci: 2210.11710]

- Lattice input on the friction coefficient available [Moore,Tassler: 1011.1167] [Laine, Niemi, Procacci, Rummukainen: 2209.13804]

$m \gg T$ - Vacuum inflaton decays: $\Upsilon \propto \frac{\alpha^2 m^3}{f_a^2}$

$m \ll T$ - Plasma scattering: $\Upsilon \propto \frac{\alpha^5 T^3}{f_a^2}$



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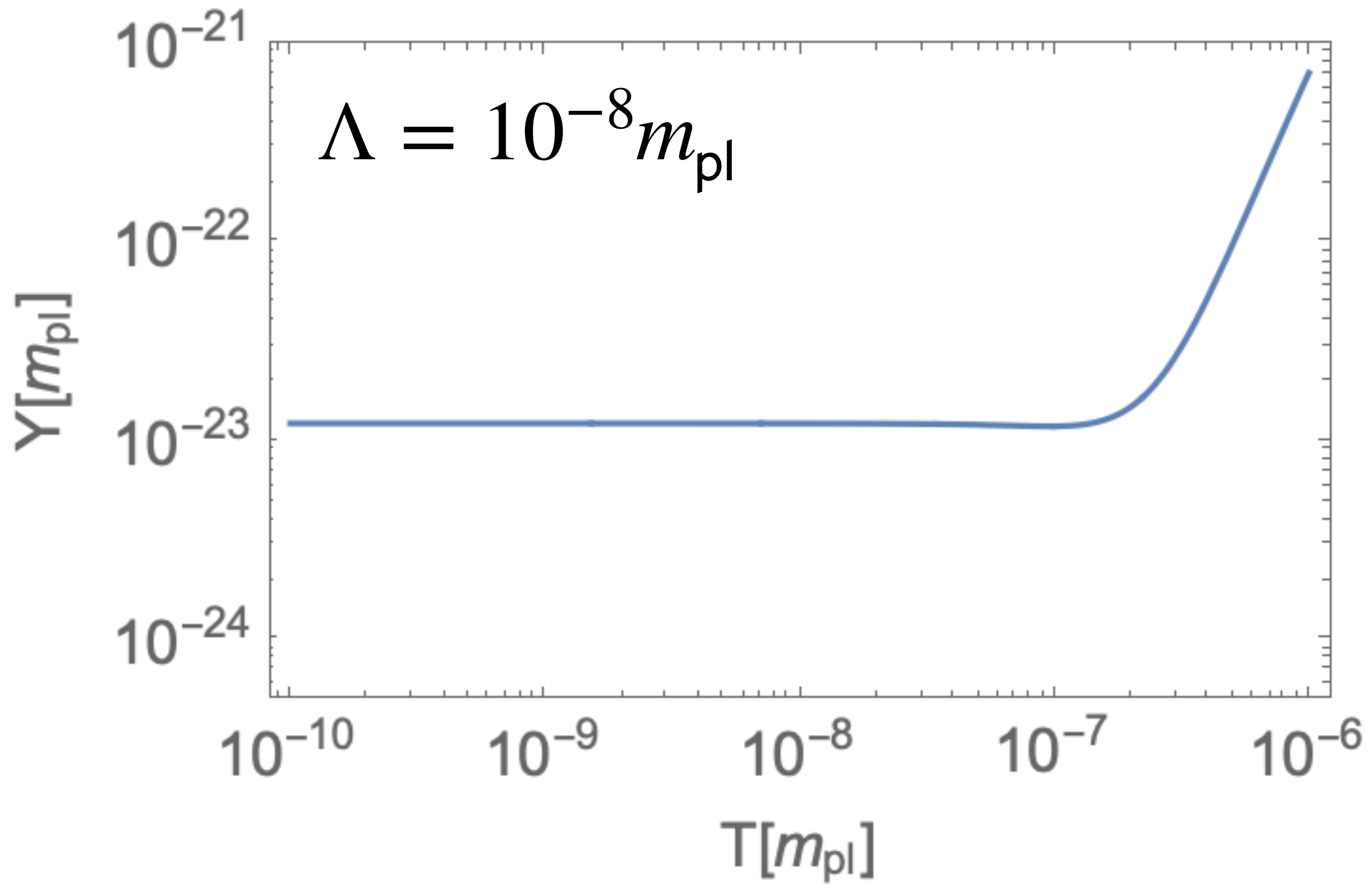

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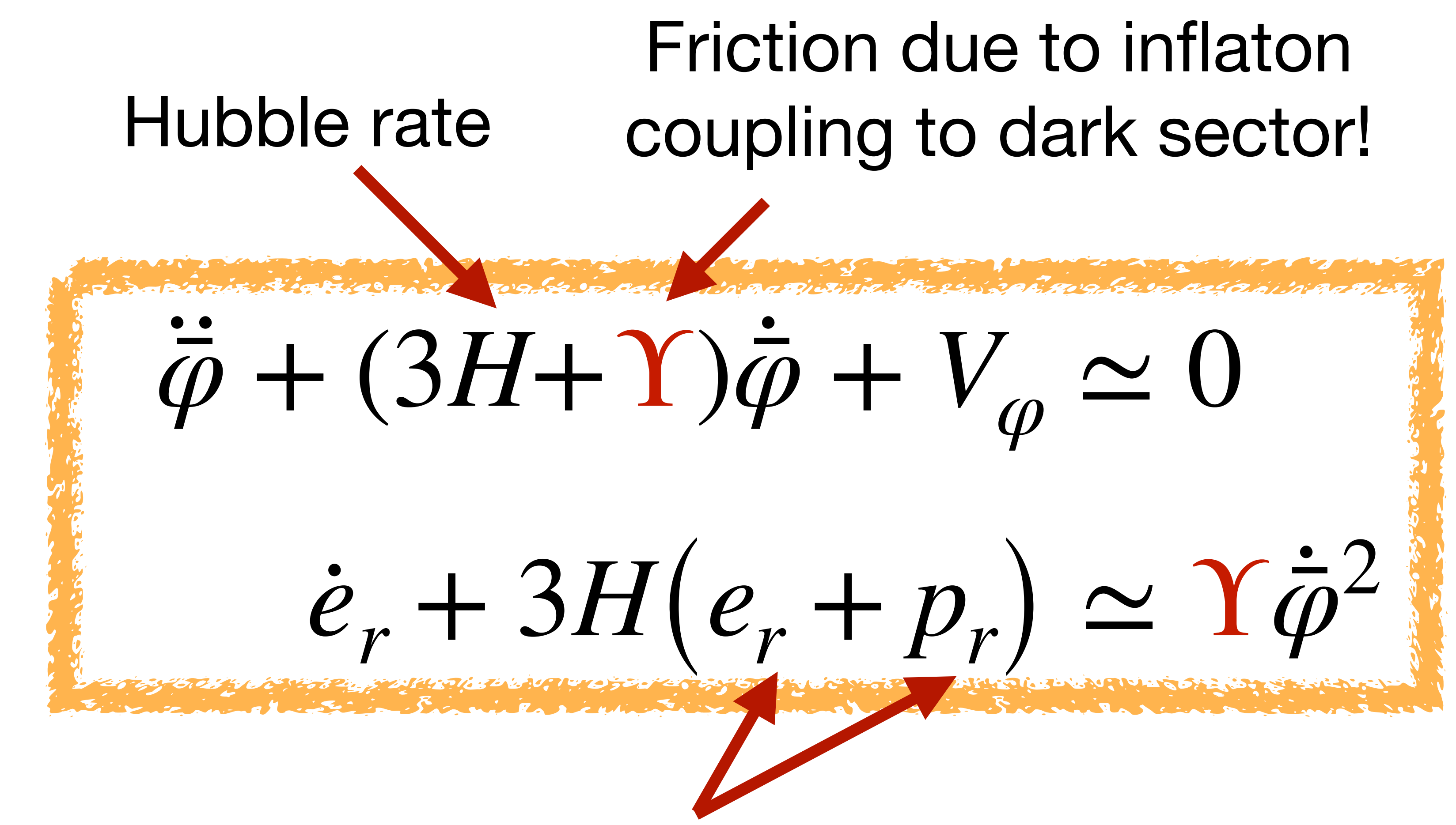


Hubble rate

Friction due to inflaton coupling to dark sector!

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

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

Dark radiation energy
and pressure densities

SU(3) EoS: [Giusti, Pepe: 1612.00265]

Why large temperatures?

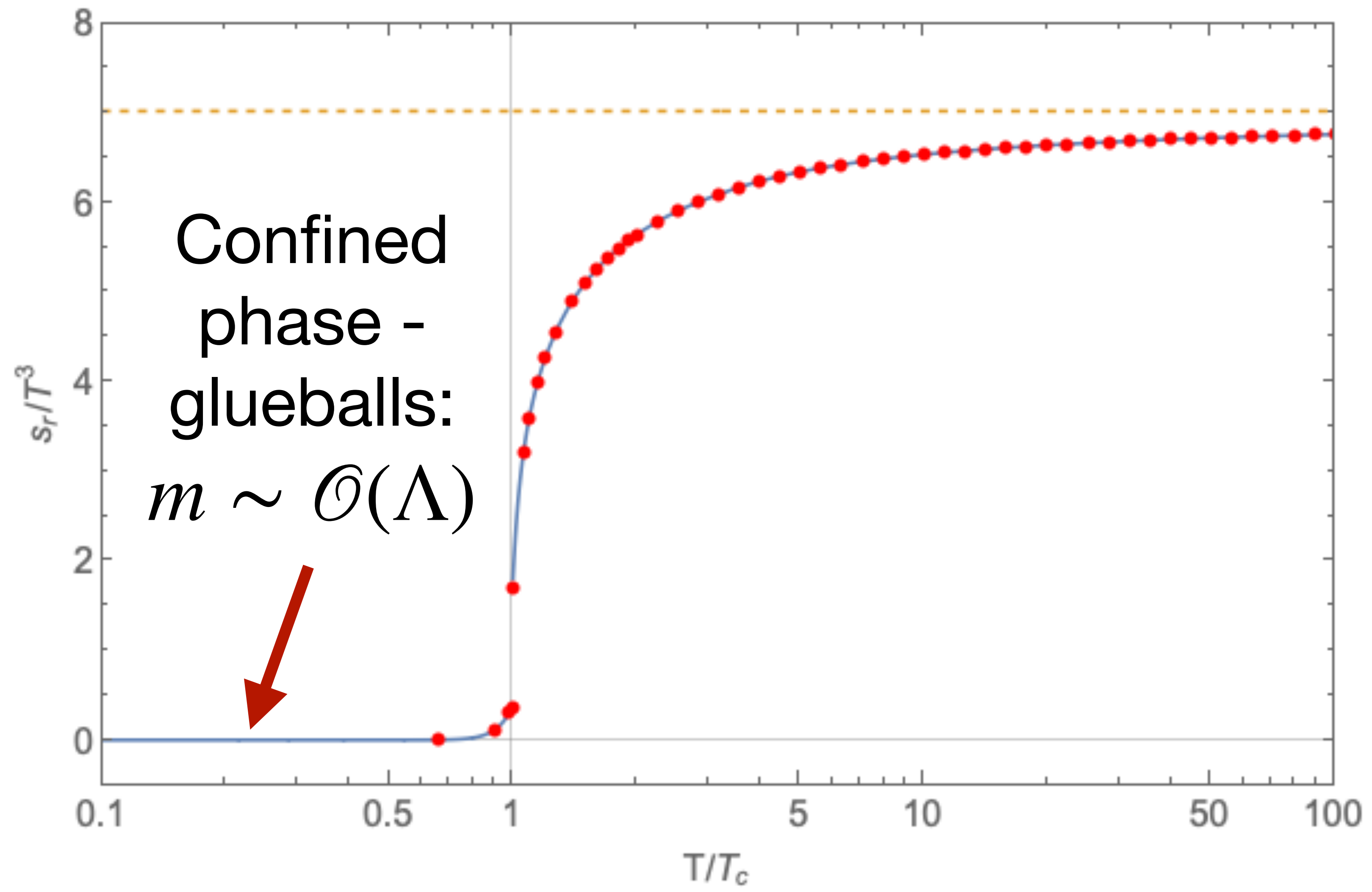
$$\ddot{\varphi} + (3H + \Upsilon)\dot{\varphi} + V_\varphi \simeq 0$$

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

Parametrize

ρ_r, p_r by T

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



Confined phase - glueballs: $m \sim \mathcal{O}(\Lambda)$

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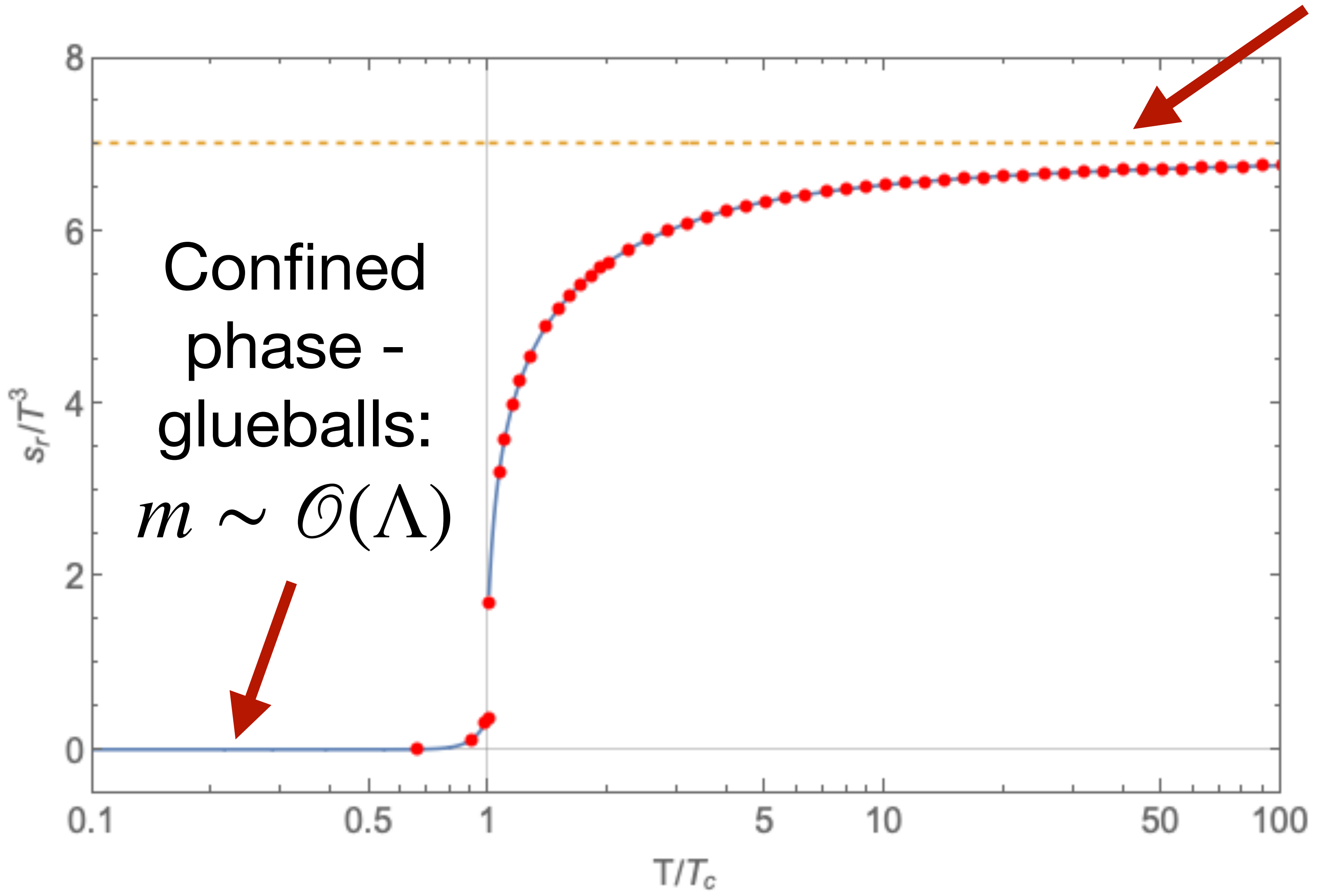

Weakly coupled radiation:

$$s_r = \frac{2\pi^2 g_*}{45}T^3$$

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Entropy density of pure $SU(3)$ measured on lattice

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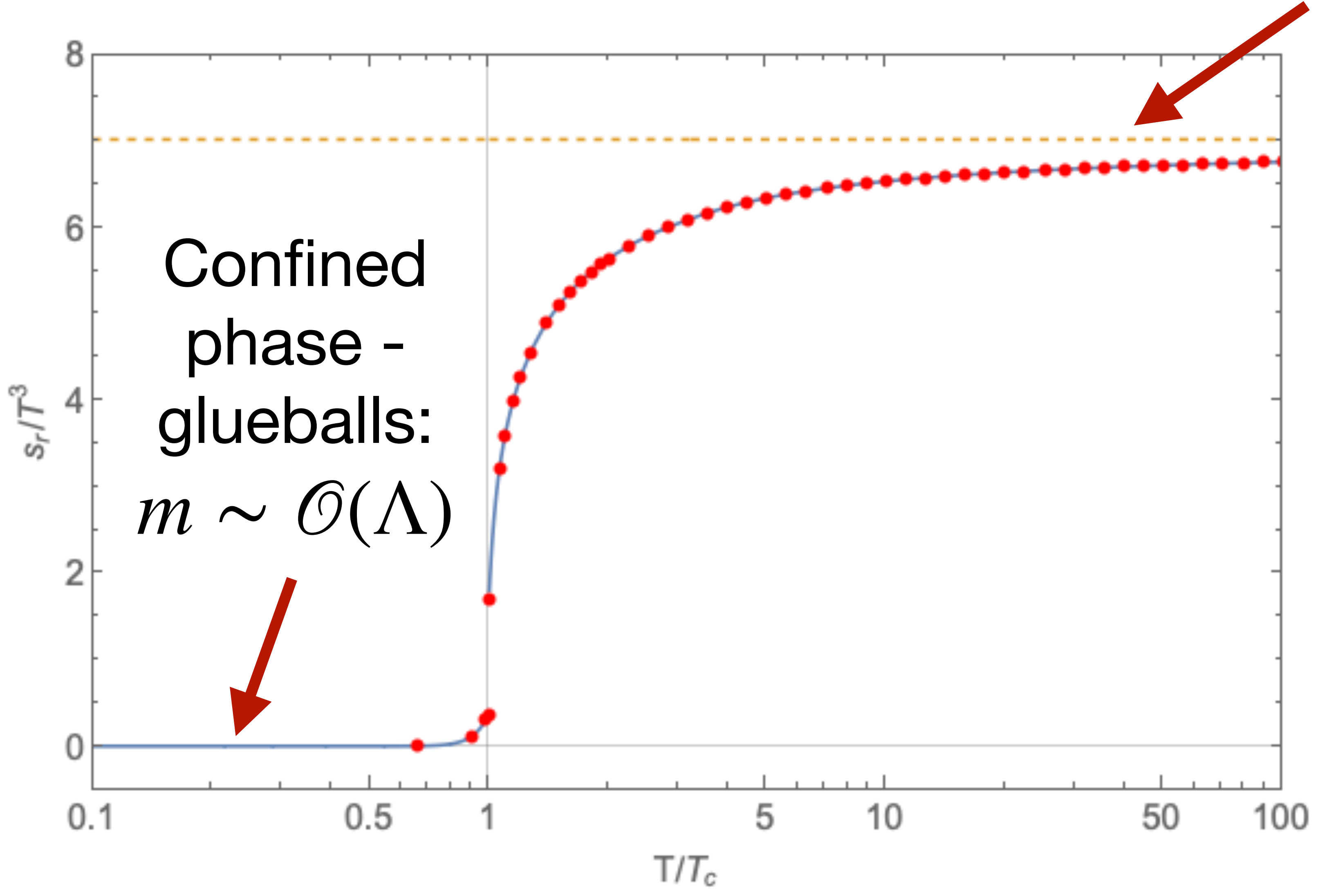

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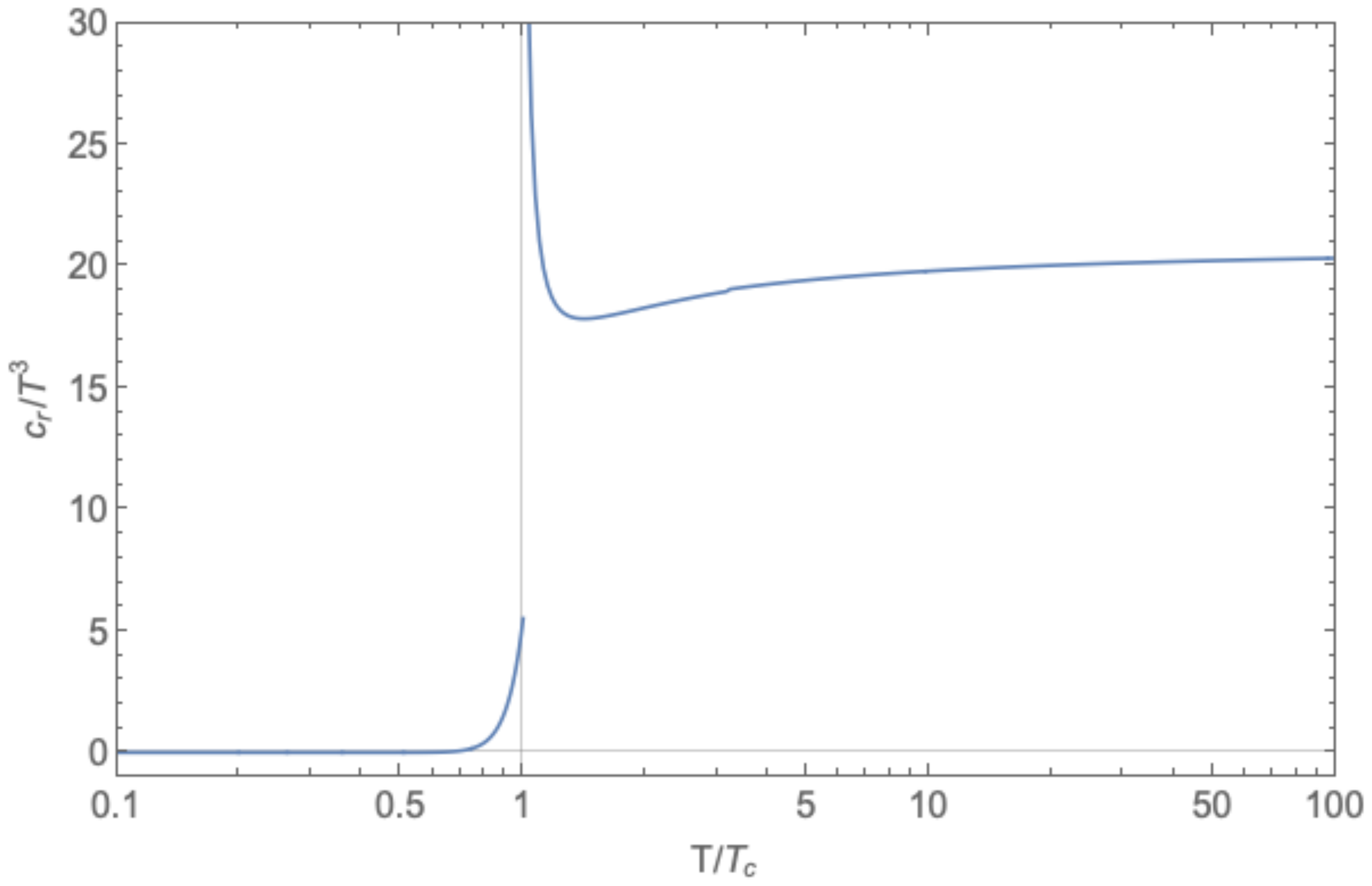

Fit of lattice data for s_r,
$s_r = \partial_T p_r$,
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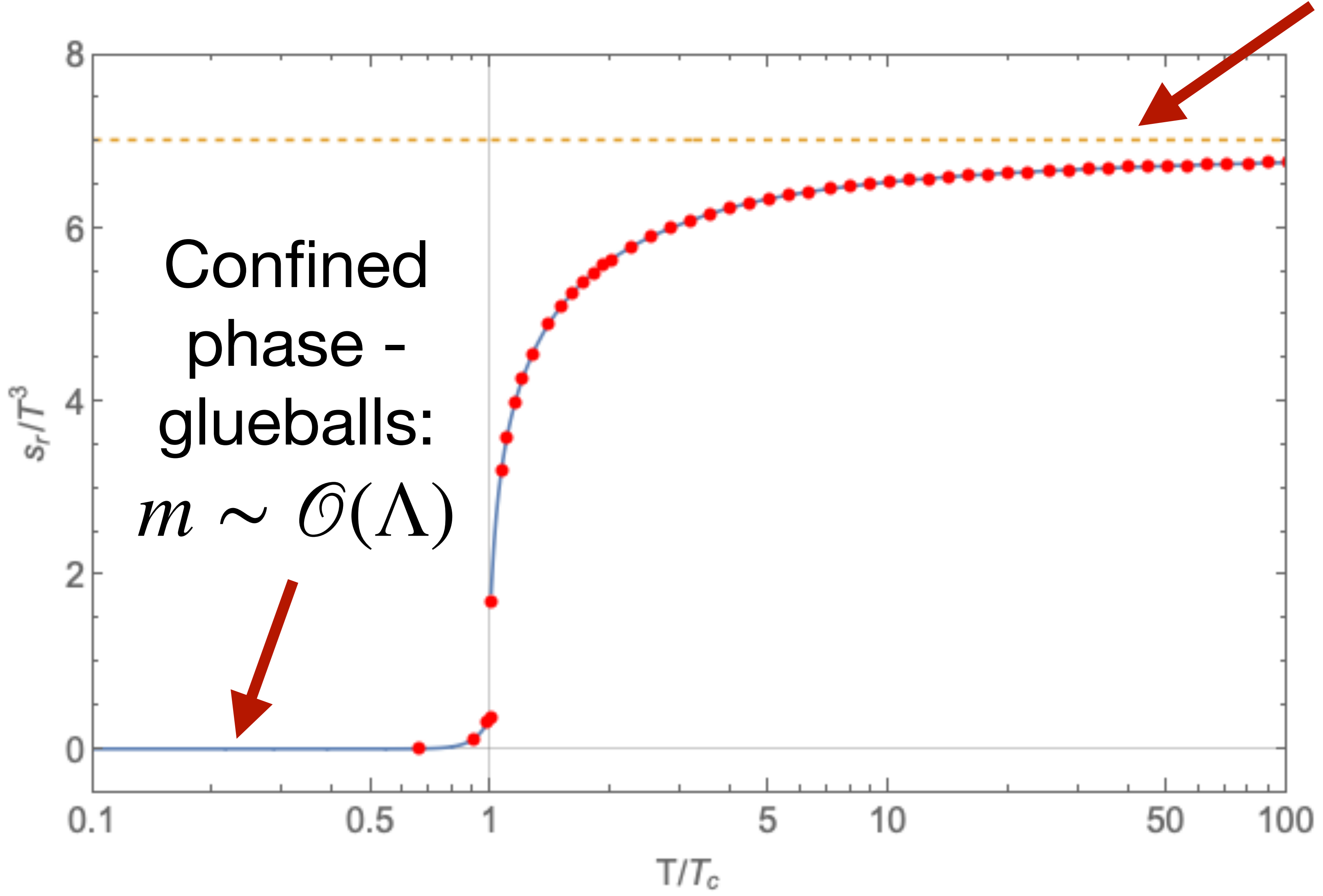
c_r exponentially small well below $T_c \Rightarrow$ rapid temperature growth!



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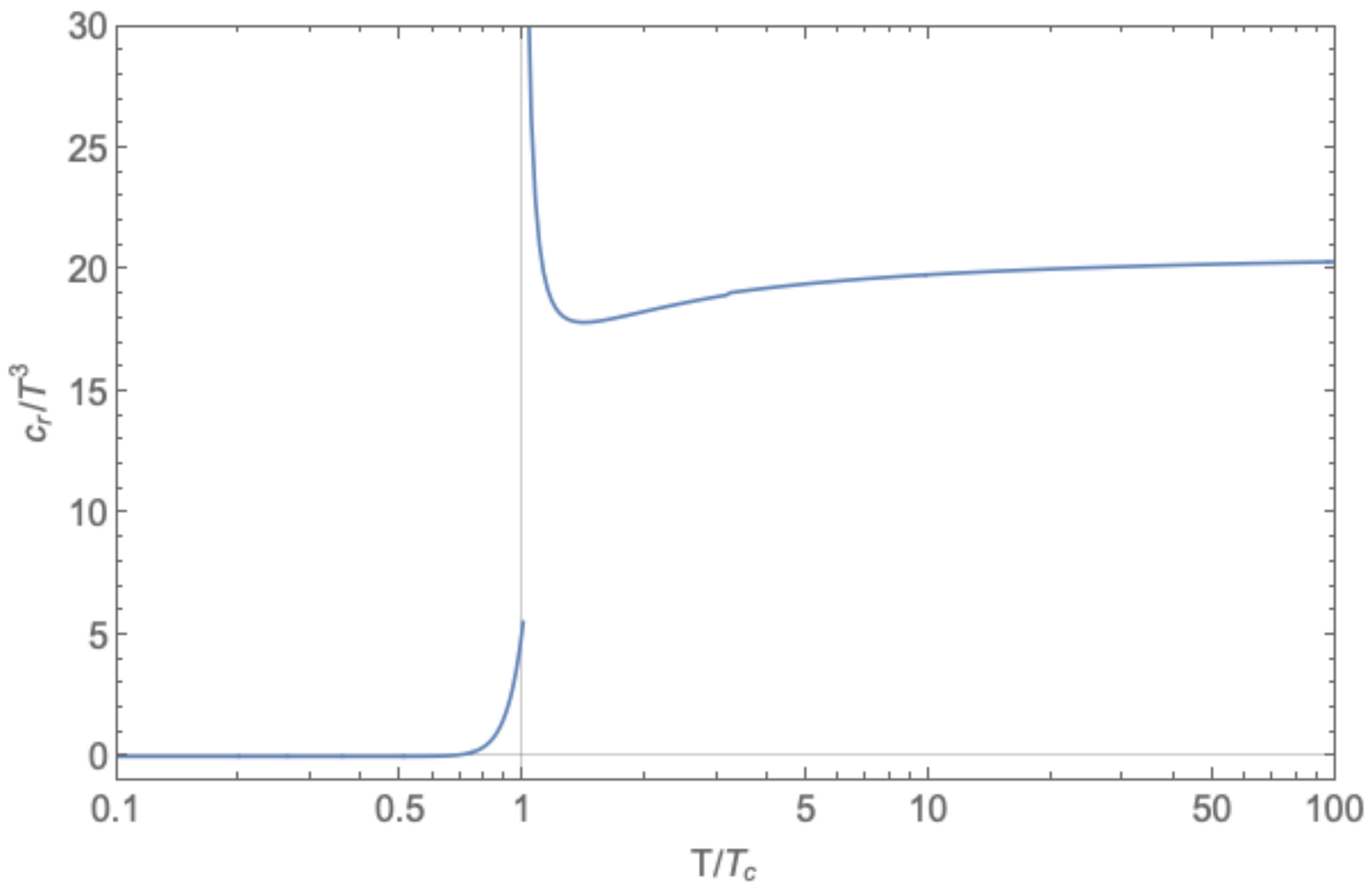
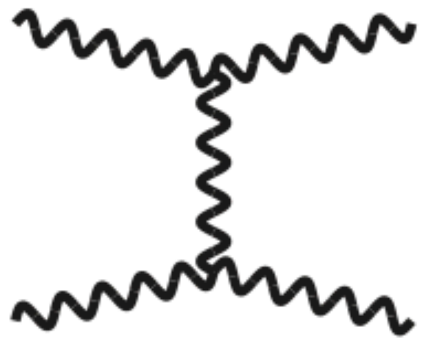
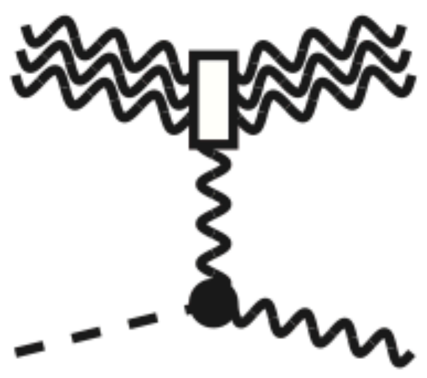


Thermalisation?



(a)



(b)

Thermalisation rate:

$$\Gamma_g \sim \alpha^2 T$$

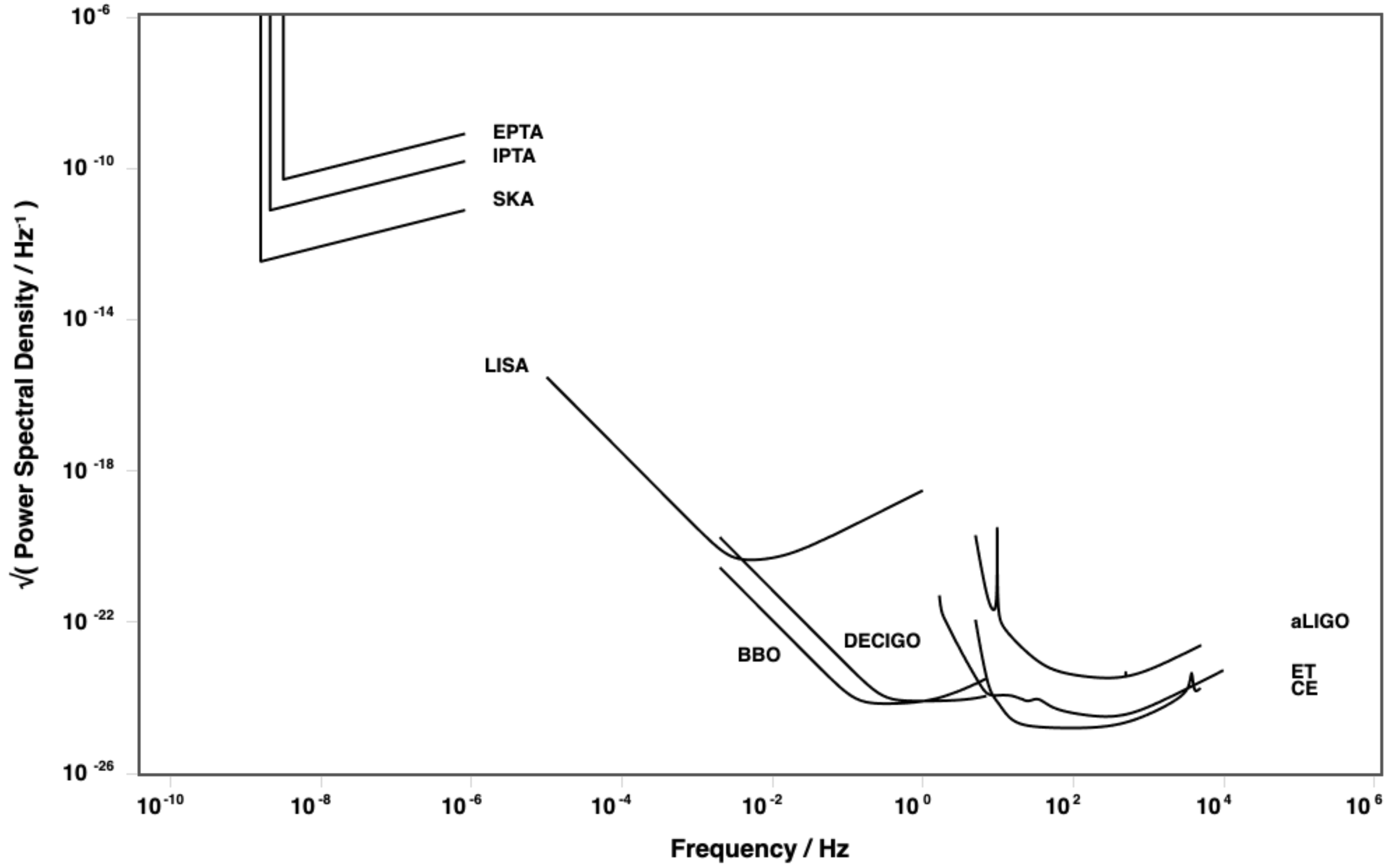
$$\Gamma_a \sim \Upsilon$$

GW from a confinement phase transition?

- In our scenario, energy density dominated by inflaton contribution until $H \sim \Upsilon \Rightarrow$ “matter domination”

$$p_\varphi = \frac{\dot{\varphi}^2}{2} - V \text{ ... averages to zero!}$$

[http://gwplotter.com/]



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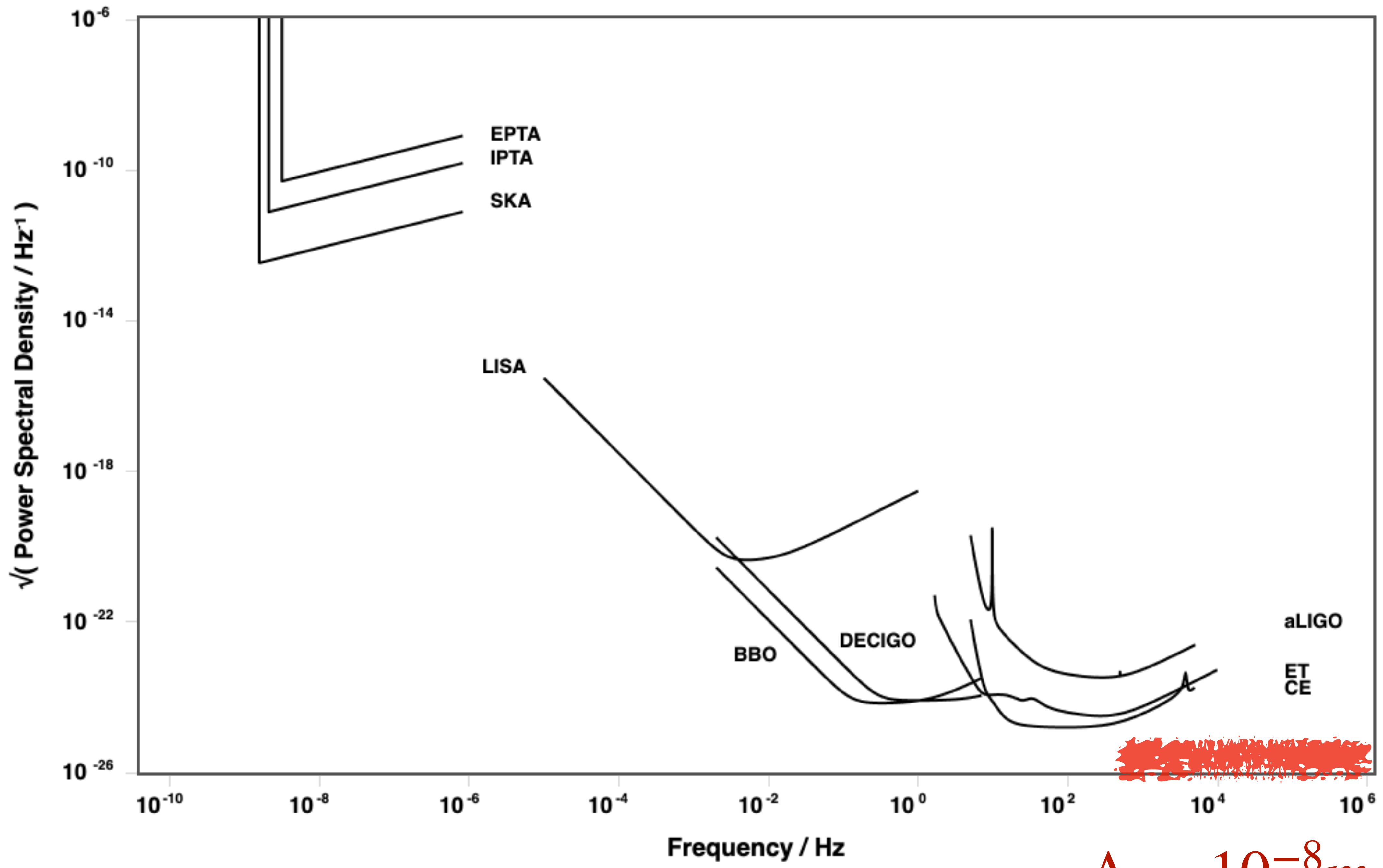
- Necessary ingredient to calculate the GW frequency today: SM temperature when radiation domination starts!

- If $T \equiv T_{\text{dark}} \sim T_{\text{SM}}$ then peak at kHz - MHz frequencies expected for $\Lambda \sim 10^{-8}\, m_{\text{pl}}$

[http://gwplotter.com/]



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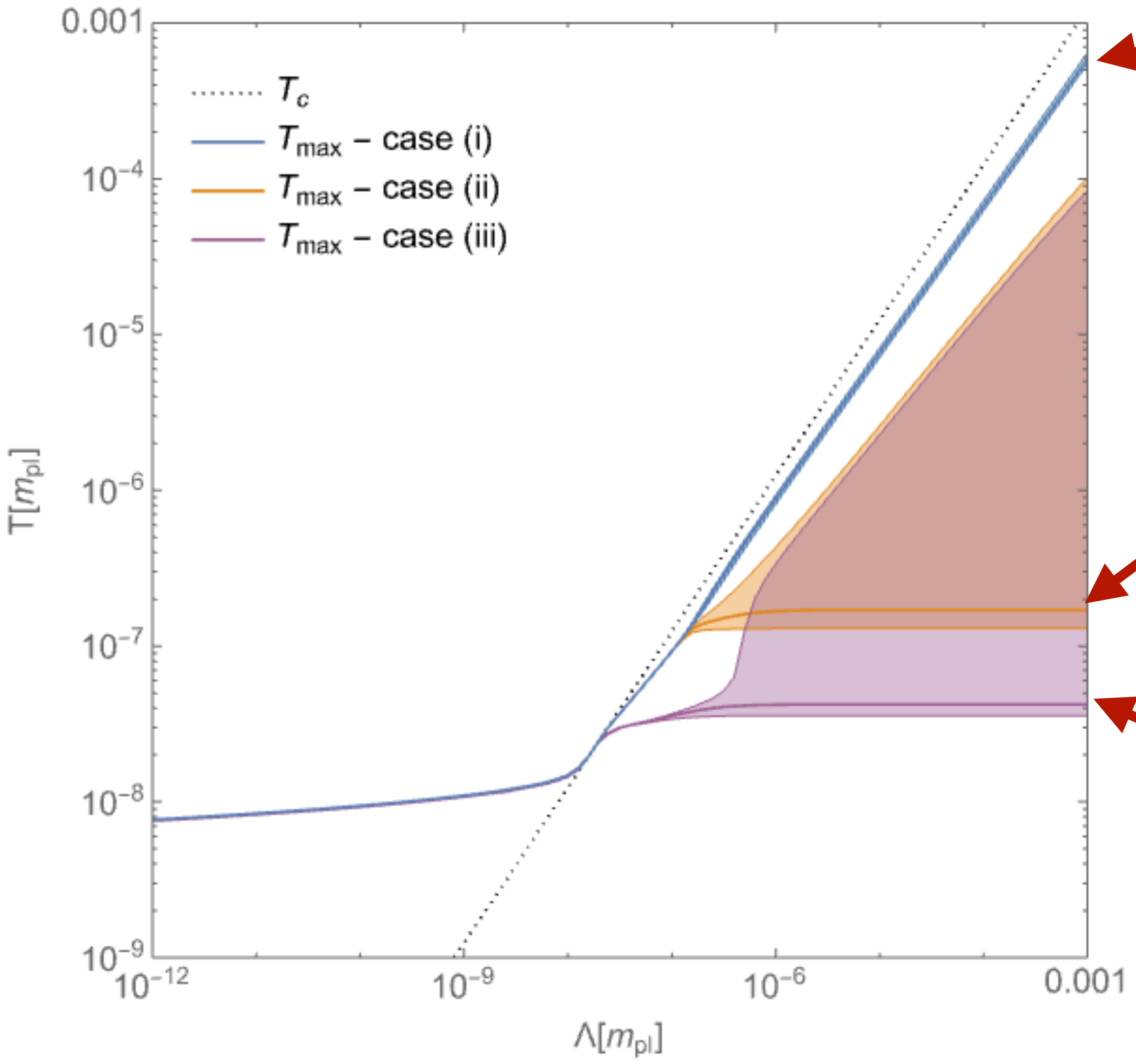
???

Results: Maximal temperature of the dark sector



Pure
Yang-Mills

YM + thermal
inflaton

YM + thermal
inflaton + light
d.o.f.

Why error bars?
Ignorance of Υ below T_c - parametrised
in terms of an IR regulator!

$$\alpha \simeq \frac{6\pi}{11N_c}\log^{-1}\left[\frac{\sqrt{\overbrace{(x\,2\pi\Lambda)}^{\substack{\text{IR regulator}\\ x\in(0.2,2)}}{}^2+(2\pi T)^2+\omega^2}}{\Lambda}\right]$$

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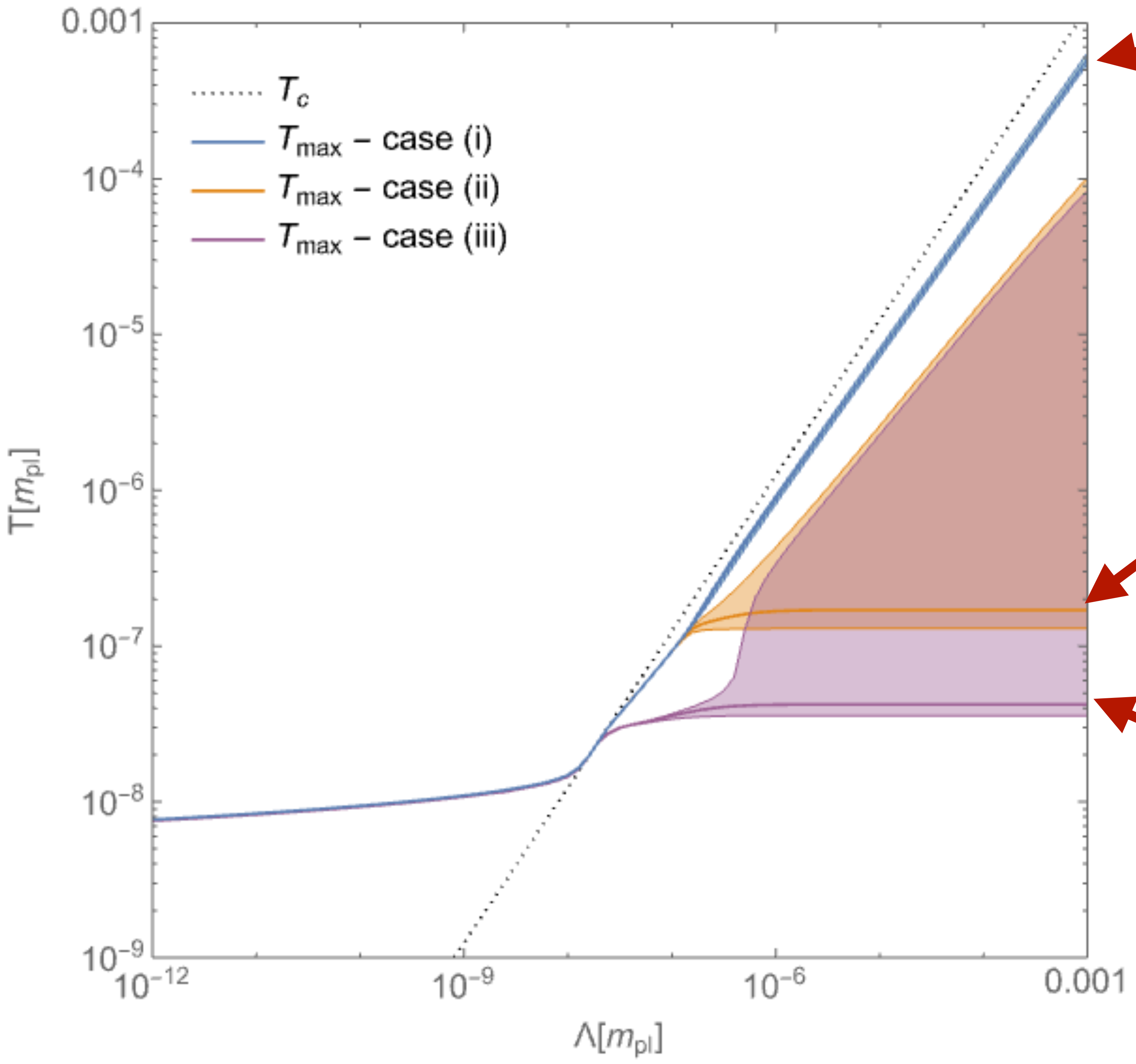

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~Robust!

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Inflaton evolution

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

$$\dot{e}_r + 3H\big(e_r + p_r - TV_T\big) - T\dot{V}_T \simeq \Upsilon\dot{\bar{\varphi}}^2$$

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

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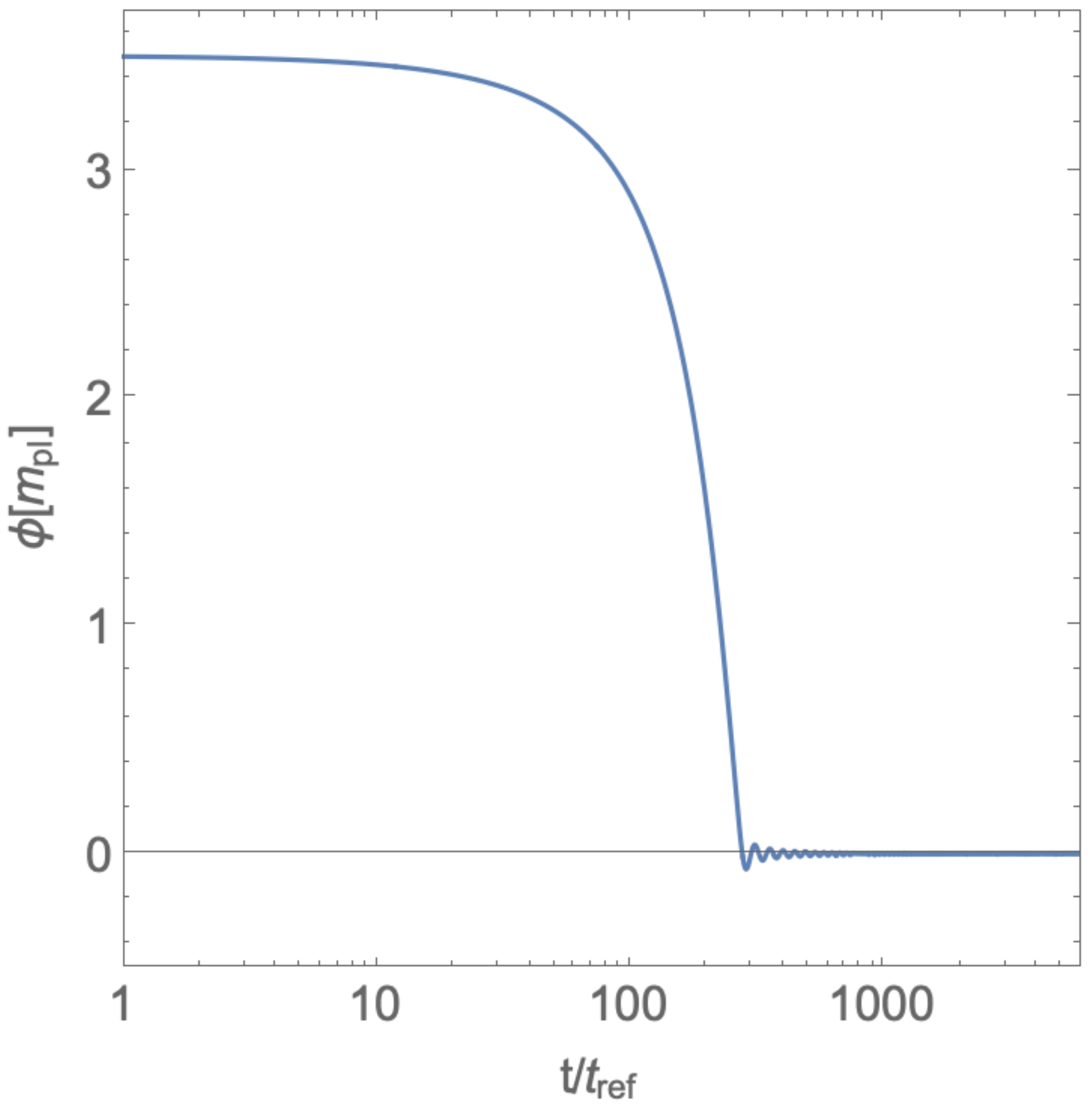
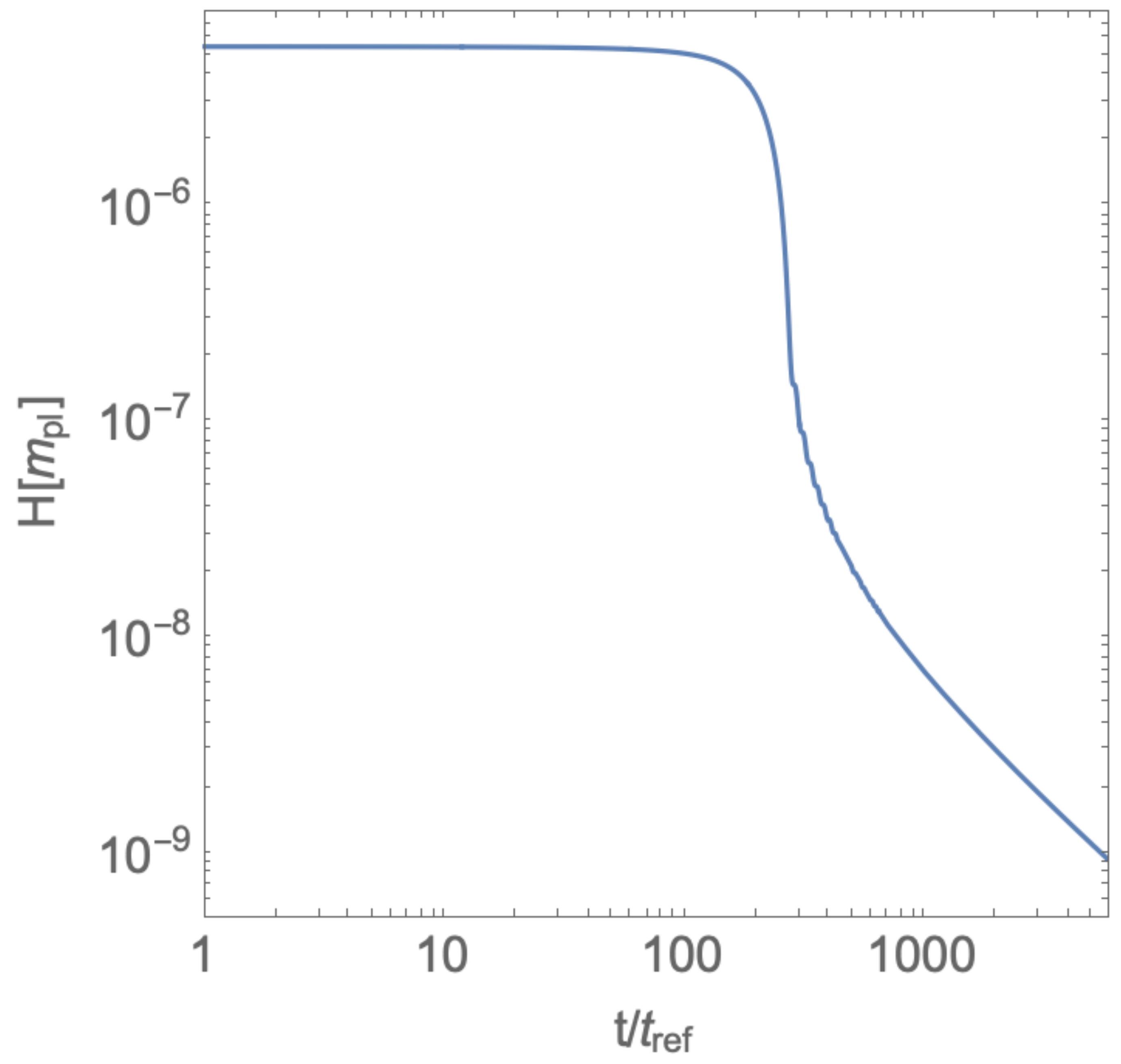
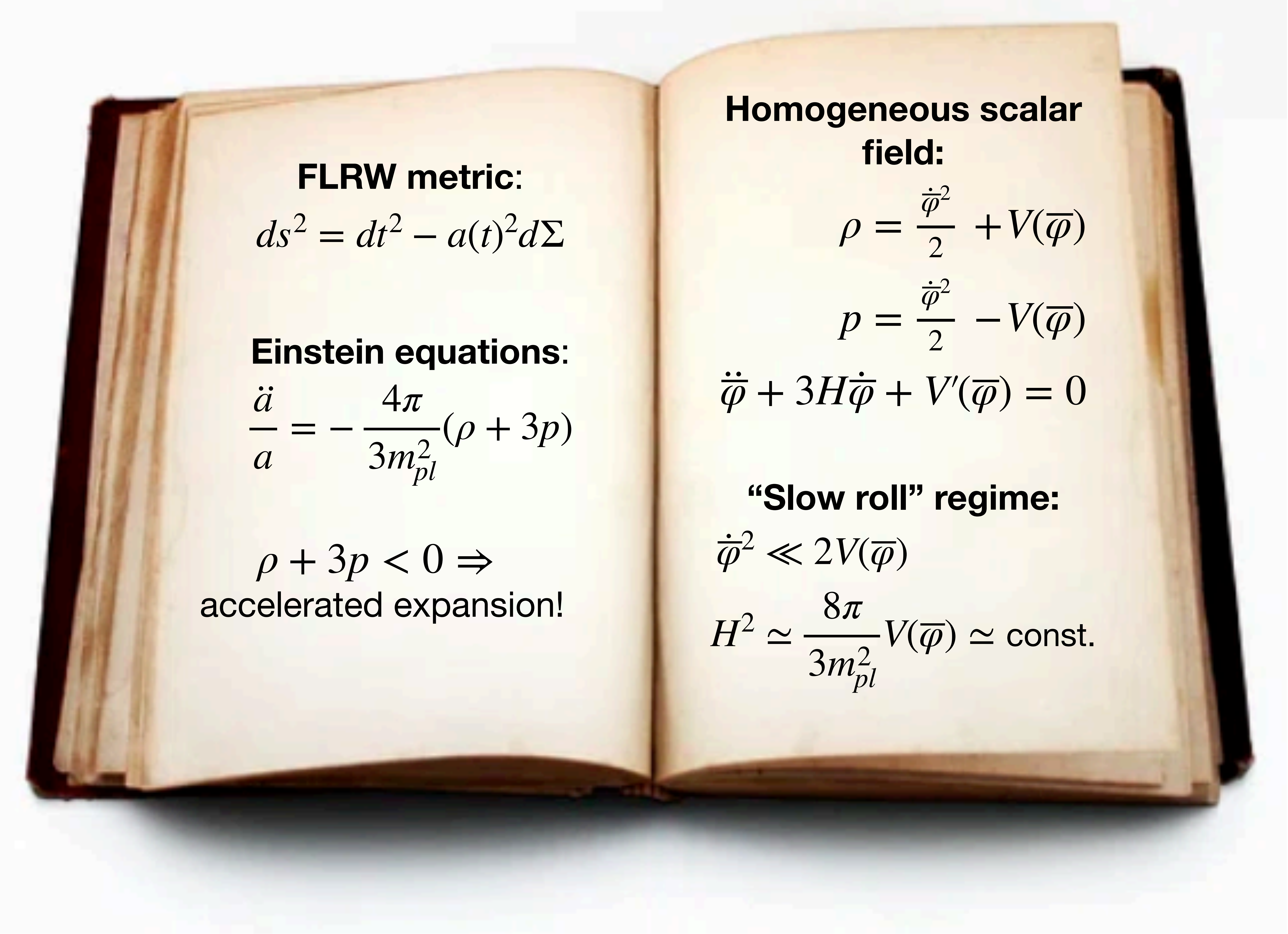
Initial time: $t_{\text{ref}} \sim H^{-1}_{\text{initial}}$

$\Upsilon \ll H \Rightarrow$ Inflaton dynamics unaffected by the evolution of the Yang-Mills sector!





Inflationary cosmology



FLRW metric:

$$ds^2 = dt^2 - a(t)^2 d\Sigma$$

Einstein equations:

$$\frac{\ddot{a}}{a} = -\frac{4\pi}{3m_{pl}^2}(\rho + 3p)$$

$$\rho + 3p < 0 \Rightarrow$$

accelerated expansion!

Homogeneous scalar field:

$$\rho = \frac{\dot{\overline{\varphi}}^2}{2} + V(\overline{\varphi})$$

$$p = \frac{\dot{\overline{\varphi}}^2}{2} - V(\overline{\varphi})$$

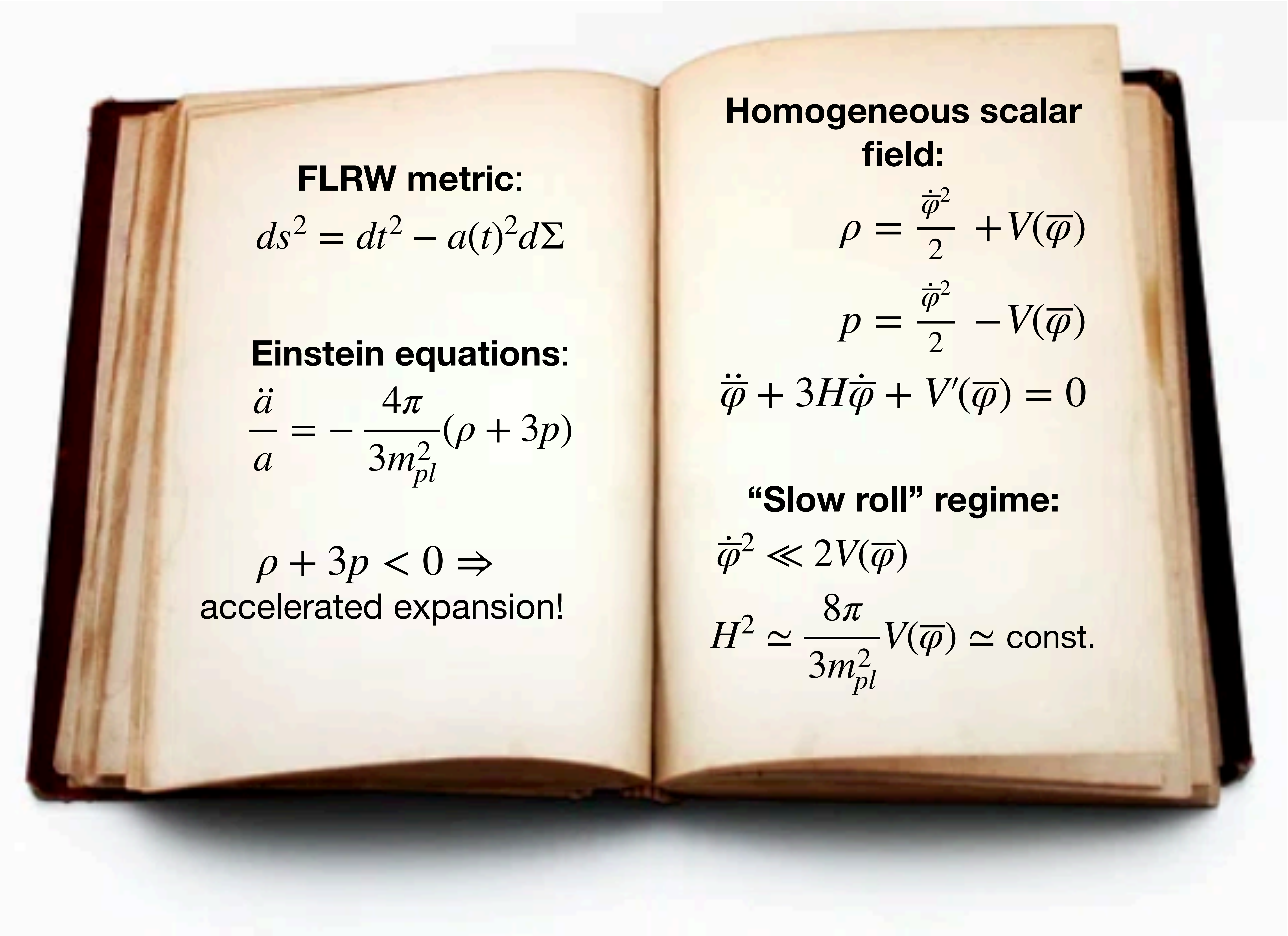
$$\ddot{\overline{\varphi}} + 3H\dot{\overline{\varphi}} + V'(\overline{\varphi}) = 0$$

“Slow roll” regime:

$$\dot{\overline{\varphi}}^2 \ll 2V(\overline{\varphi})$$

$$H^2 \simeq \frac{8\pi}{3m_{pl}^2} V(\overline{\varphi}) \simeq \text{const.}$$

Inflationary cosmology



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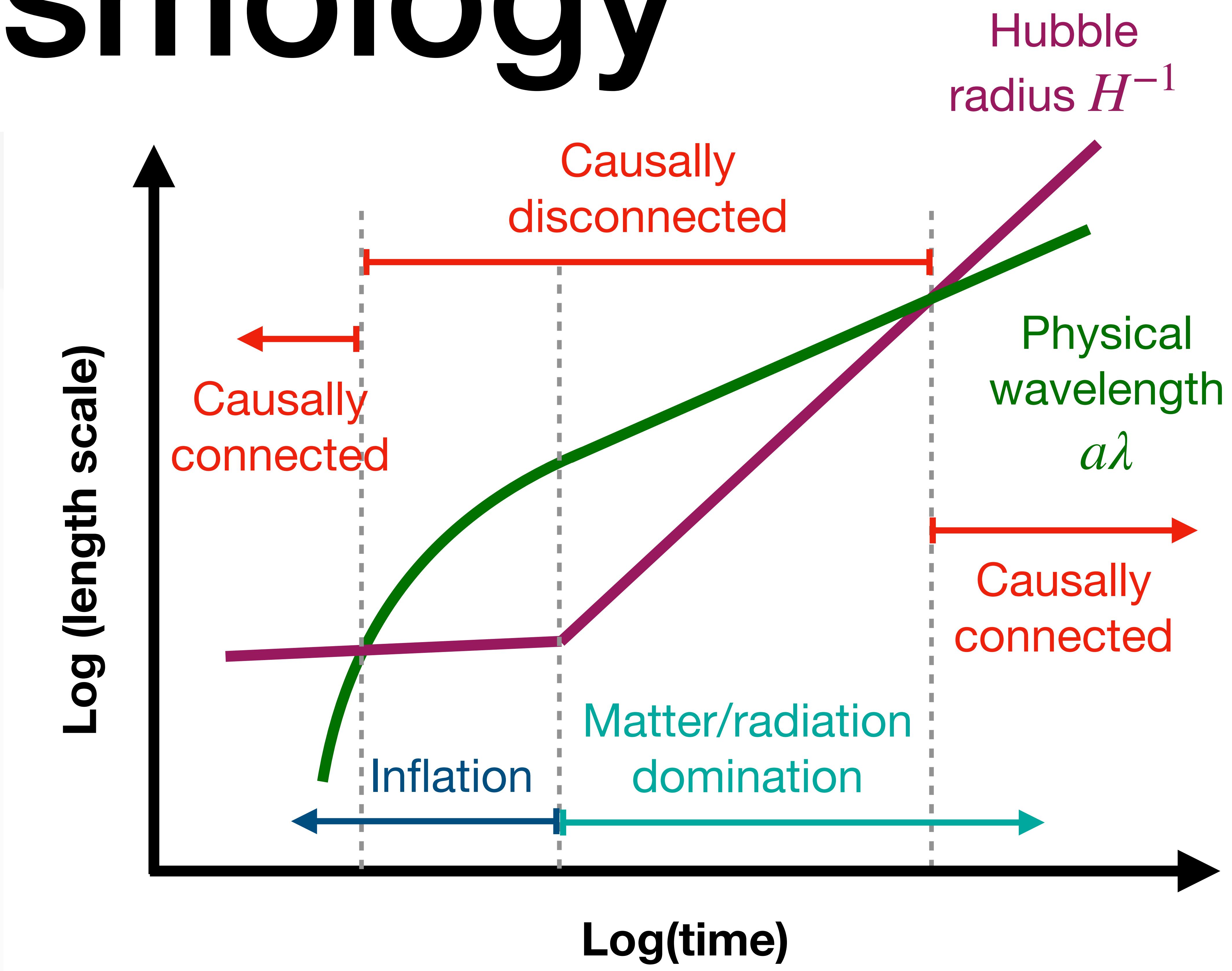
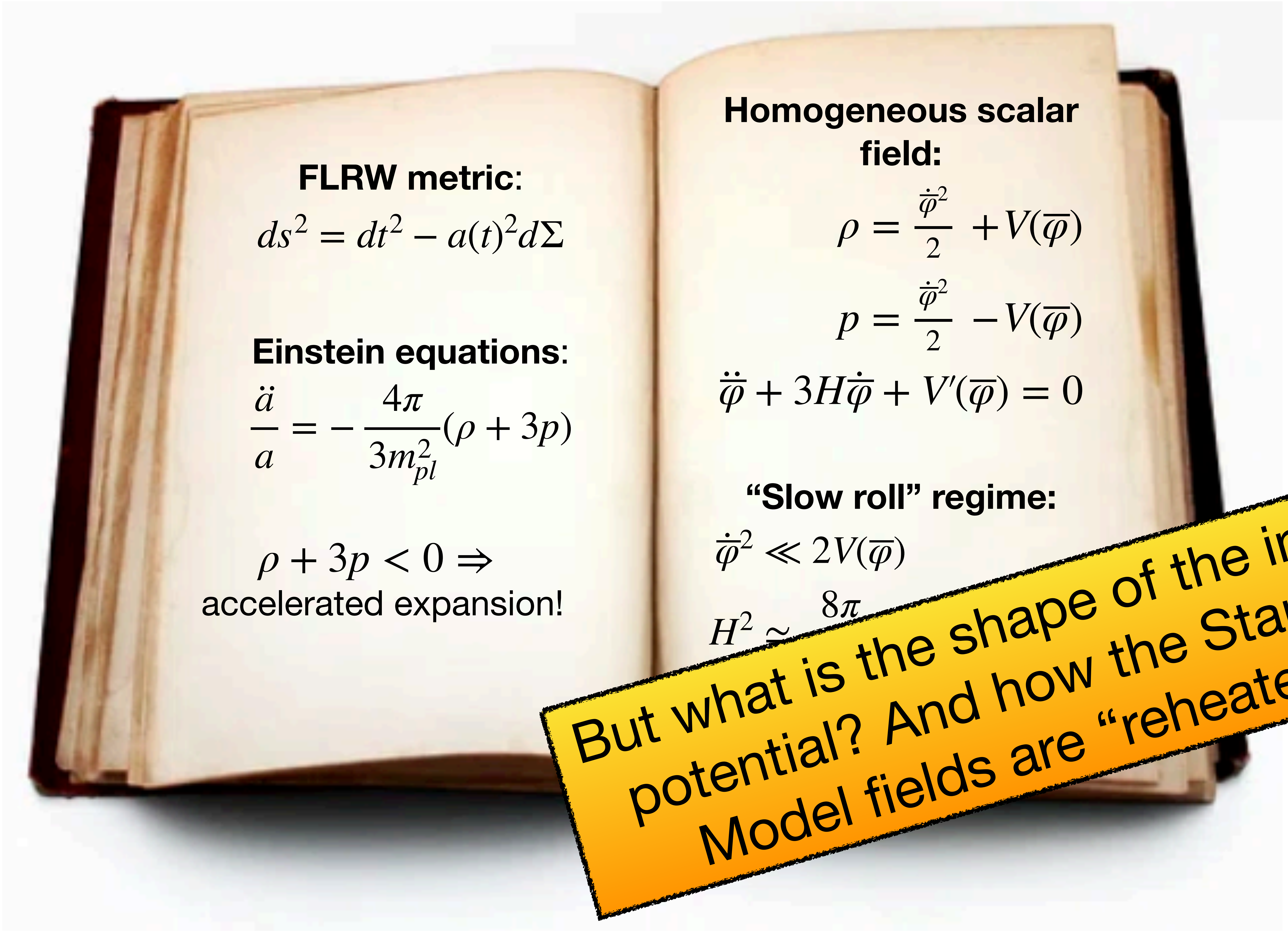


Different regions of CMB sky were causally connected during inflation!

NB: Quantum fluctuations of the inflaton field also give rise to fluctuations in CMB temperature.

Inflationary cosmology



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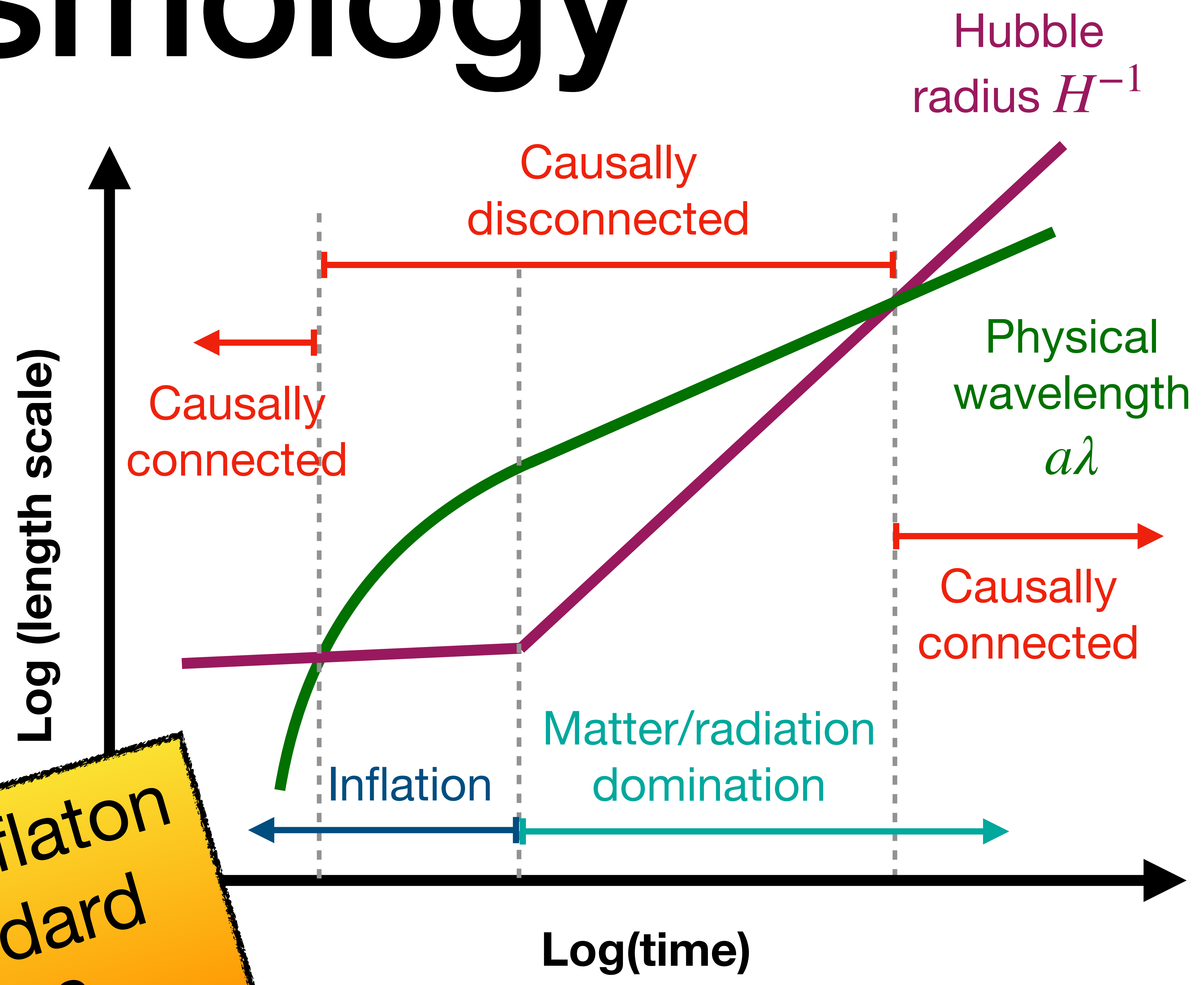
$H^2 \simeq$ 8π

But what is the shape of the inflaton potential? And how the Standard Model fields are "reheated"?



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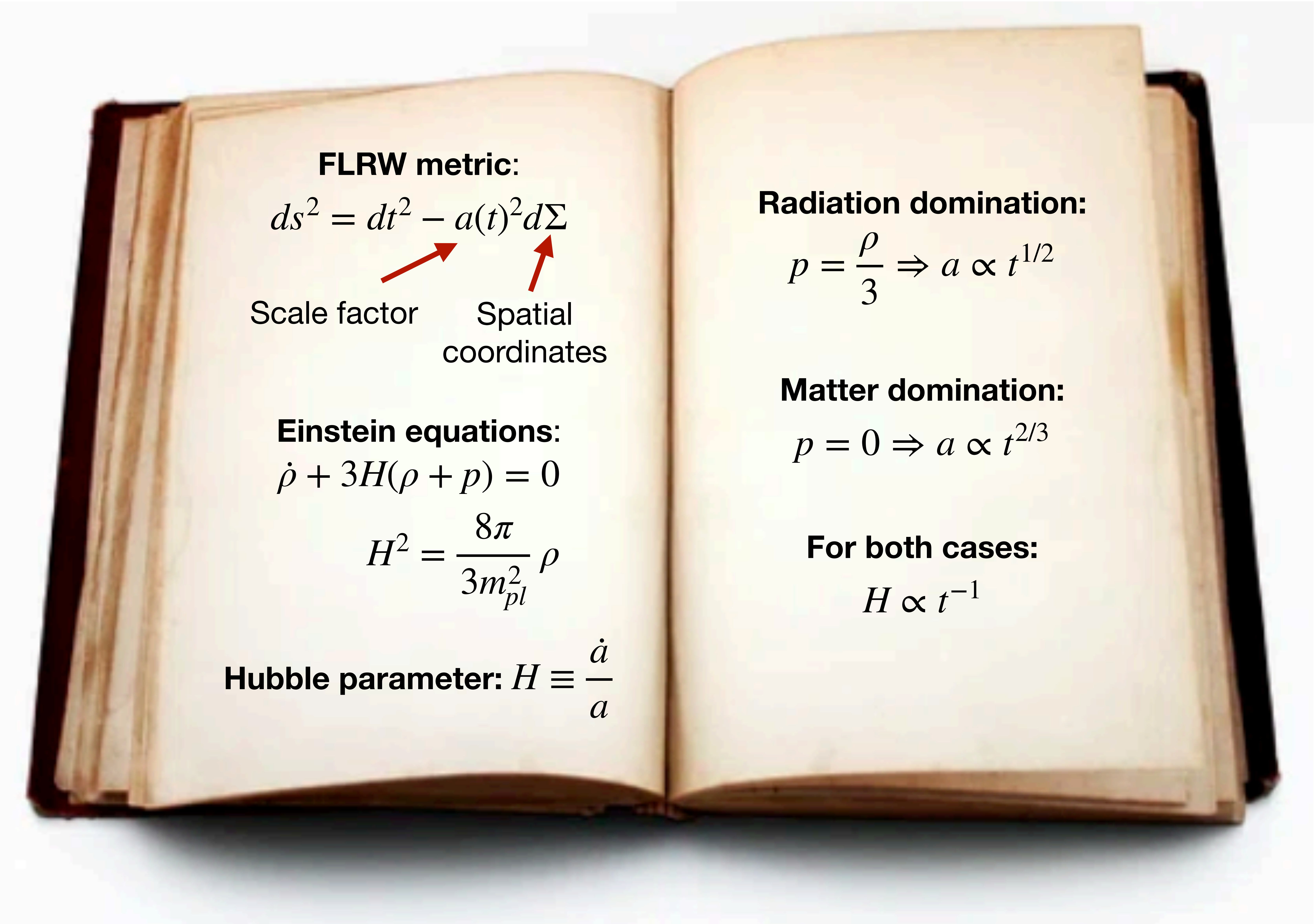
“Standard” cosmology



FLRW metric:

$$ds^2 = dt^2 - a(t)^2 d\Sigma$$

Scale factor

Spatial coordinates

Einstein equations:

$$\dot{\rho} + 3H(\rho + p) = 0$$

$$H^2 = \frac{8\pi}{3m_{pl}^2}\rho$$

Hubble parameter: $H \equiv \frac{\dot{a}}{a}$

Radiation domination:

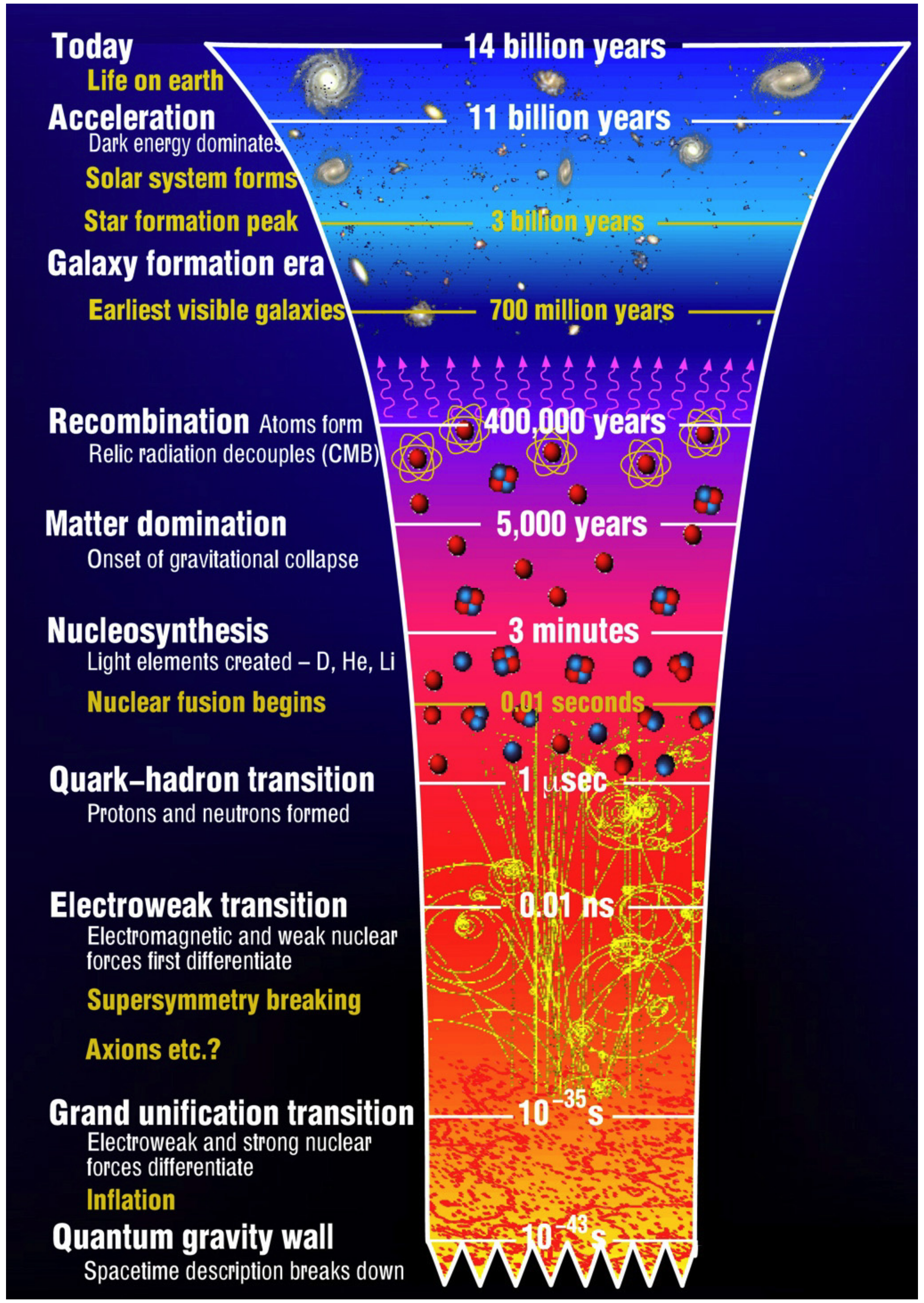
$$p = \frac{\rho}{3} \Rightarrow a \propto t^{1/2}$$

Matter domination:

$$p = 0 \Rightarrow a \propto t^{2/3}$$

For both cases:

$$H \propto t^{-1}$$



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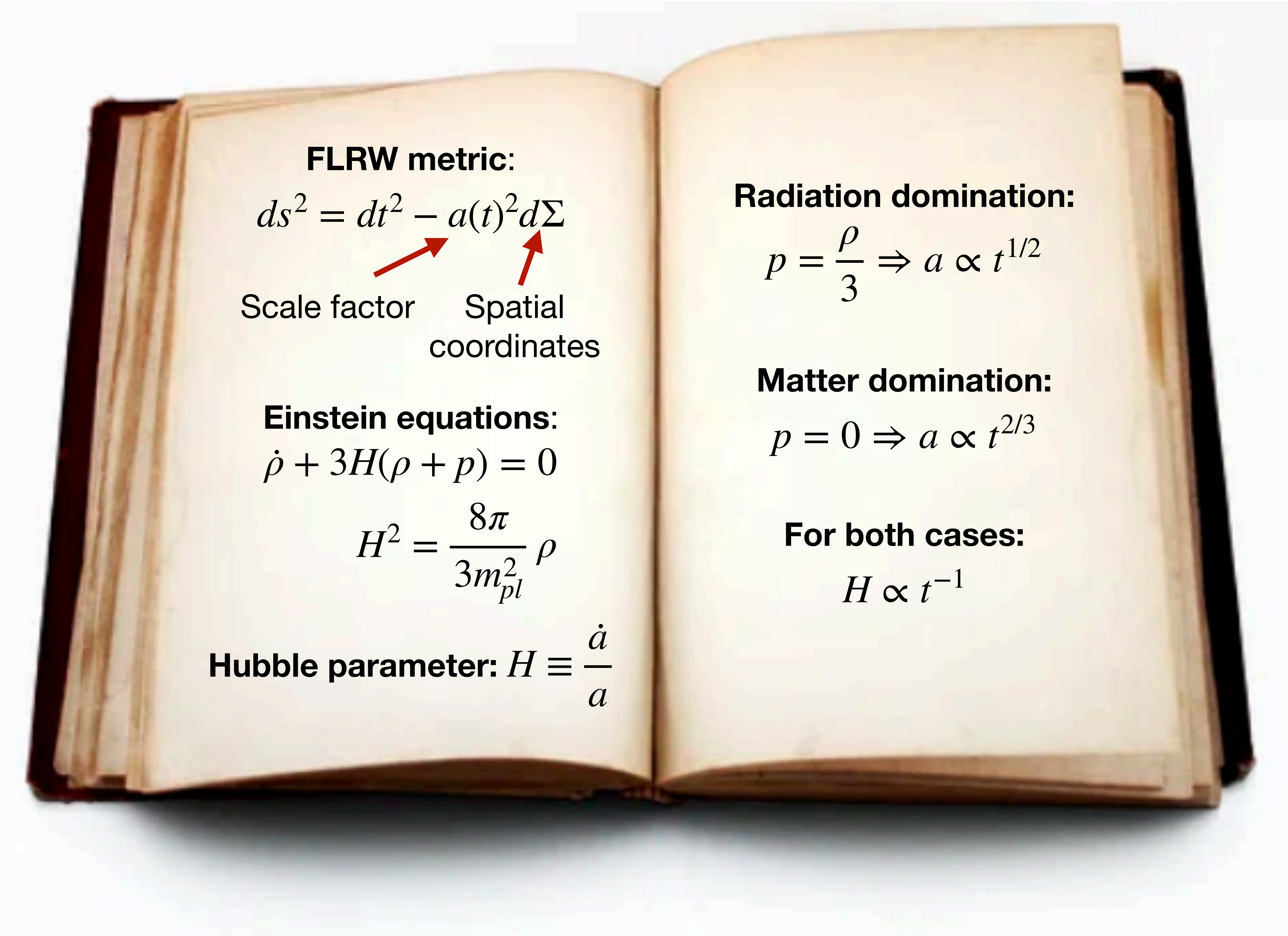

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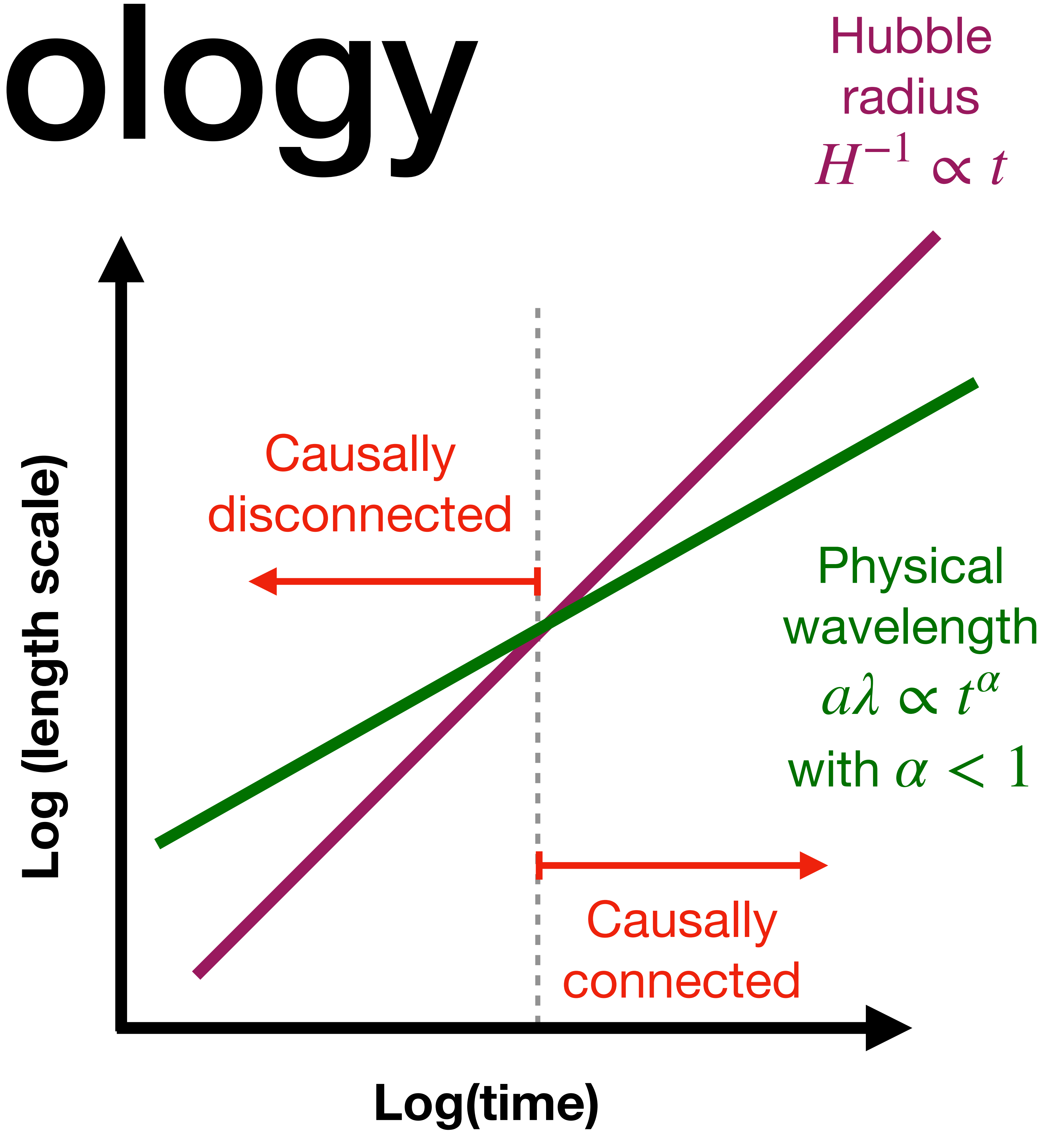


Causally connected regions at the time of CMB formation correspond to O(1°) regions of sky today. But we see all CMB photons thermalised!

“Horizon problem”

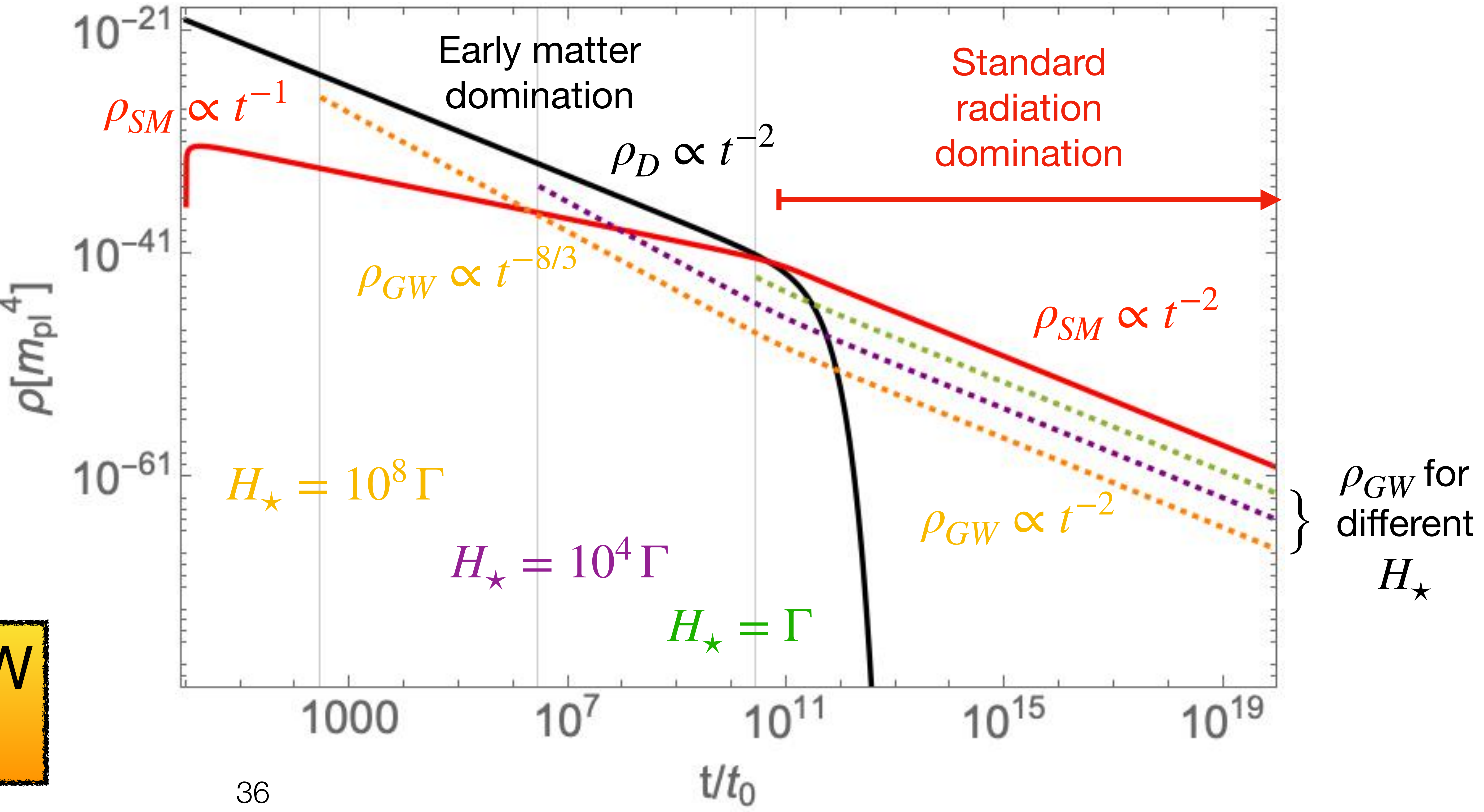
Dilution of the gravitational wave signal: II) PT during matter domination

[Buen-Abad, Chang, Hook: 2305.09712]
[Ertas, Kahlhoefer, Tasillo: 2109.06208]
[Ellis, Lewicki, Vaskonen: 2007.15586]

$$\boxed{\Omega_{\mathrm{gw},0}h^2 \simeq 1.65\times 10^{-5}\,\frac{g_{e,r}}{g_{s,r}}\left(\frac{100}{g_{s,r}}\right)^{1/3}\frac{\rho_{\mathrm{gw},\star}}{\rho_{D,\star}}\left(\frac{\Gamma}{H_\star}\right)^{2/3}}$$

Toy model A:
Dark sector decaying into SM with decay rate Γ, matter-like after a phase transition that happens when $H = H_\star$, $\rho_{\mathrm{gw},\star}/\rho_{D,\star} = 10^{-2}$

$$\dot\rho_D + 3H\rho_D = -\Gamma\rho_D$$
$$\dot\rho_{SM} + 4H\rho_{SM} = +\Gamma\rho_D$$
$$\dot\rho_{\mathrm{gw}} + 4H\rho_{\mathrm{gw}} = 0$$



Sizeable suppression of the GW signal if PT happens earlier!

Dilution of the gravitational wave signal: II) PT during matter domination

$$\boxed{\Omega_{\mathrm{gw},0} h^2 \simeq 1.65 \times 10^{-5} \, \frac{g_{e,r}}{g_{s,r}} \left(\frac{100}{g_{s,r}} \right)^{1/3} \frac{\rho_{\mathrm{gw},\star}}{\rho_{D,\star}} \left(\frac{\Gamma}{H_\star} \right)^{2/3} \frac{\Upsilon}{H_\star}}$$

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Toy model B:
As in toy model A, but the dark sector is reheated by inflaton with equilibration rate $\Upsilon > \Gamma$

$$\dot{\rho}_\varphi + 3H\rho_\varphi = -\,\Upsilon \rho_\varphi$$

$$\dot{\rho}_D + 3H\rho_D = +\,\Upsilon \rho_\varphi - \Gamma \rho_D$$

$$\dot{\rho}_{SM} + 4H\rho_{SM} = +\,\Gamma \rho_D$$

$$\dot{\rho}_{\mathrm{gw}} + 4H\rho_{\mathrm{gw}} = 0$$