

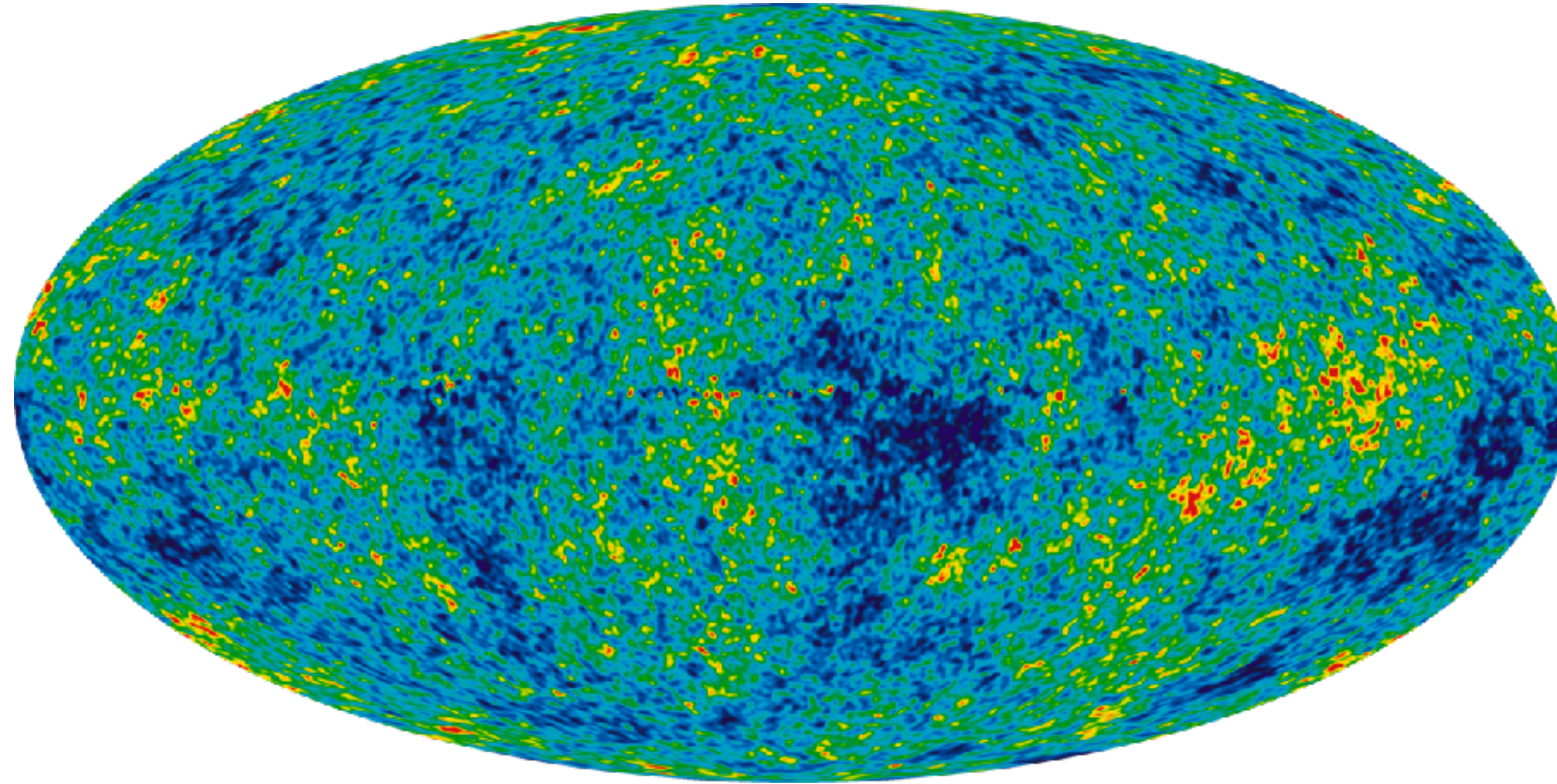
Non-Abelian dark sectors: gravitational waves vs dark matter

Helena Kolešová (University of Stavanger)



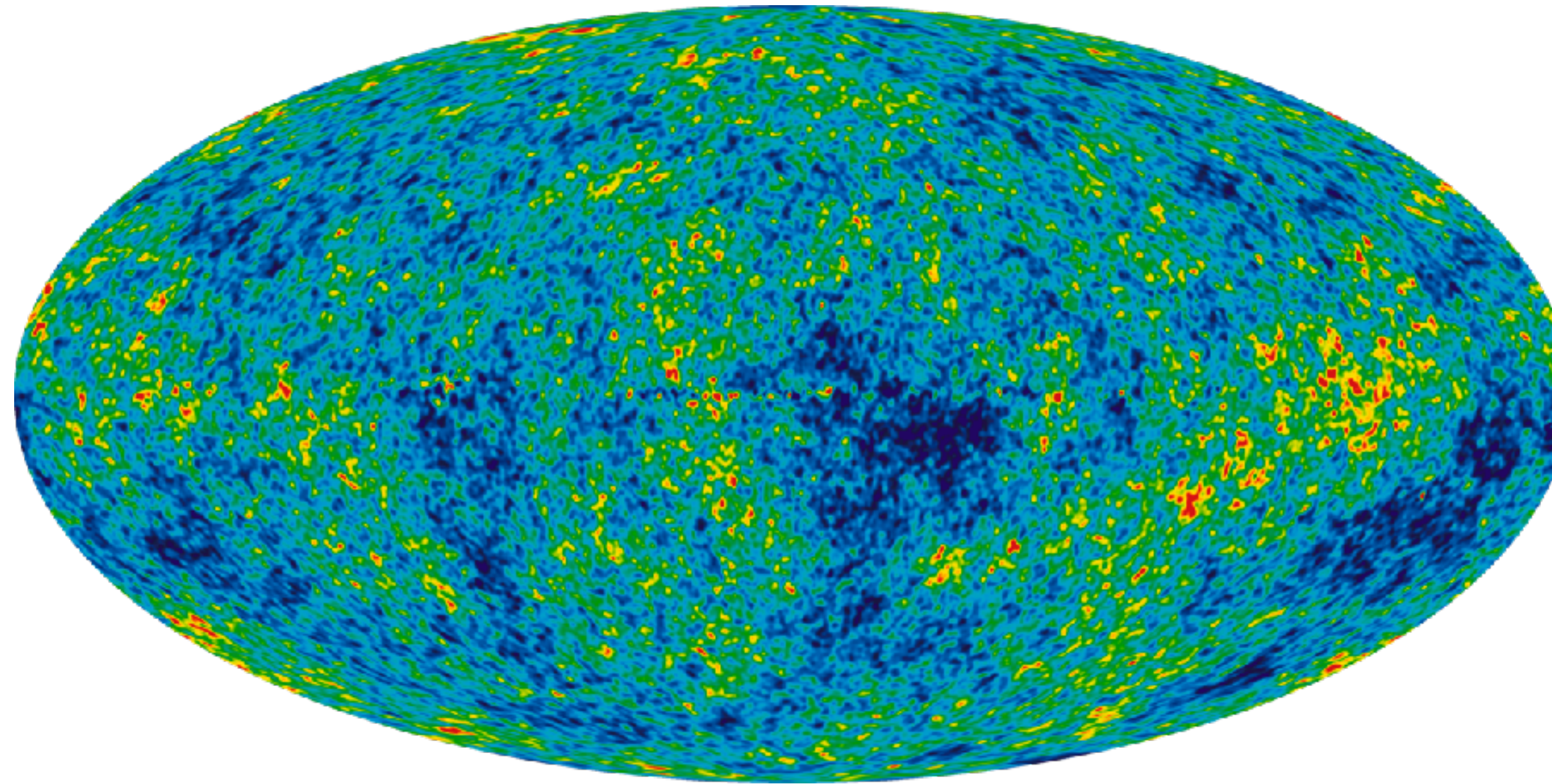
Joint work with Simone Biondini, Mikko Laine and Simona Procacci
ArXiv: 2303.17973, 2311.03718

Motivation



Motivation

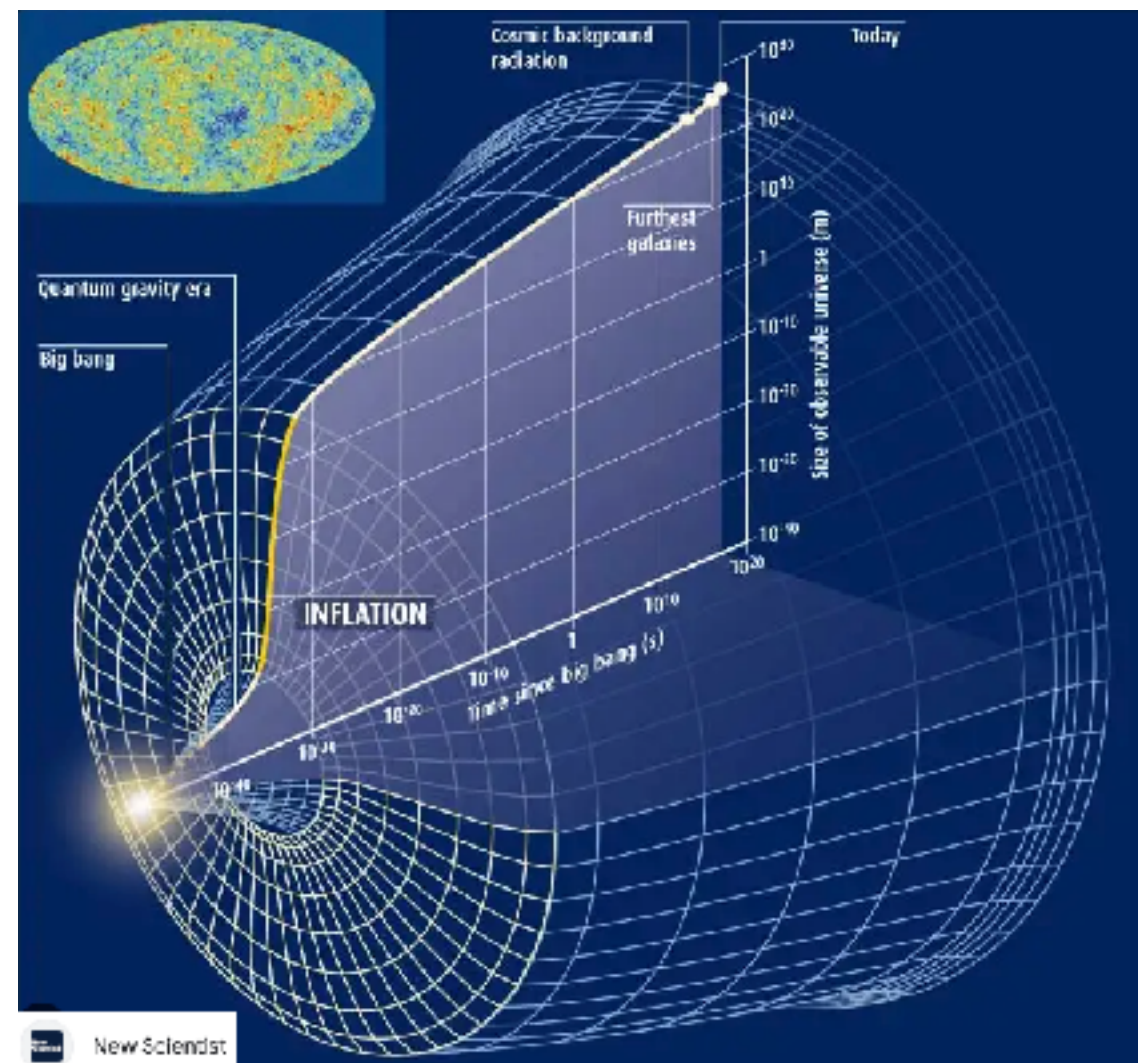
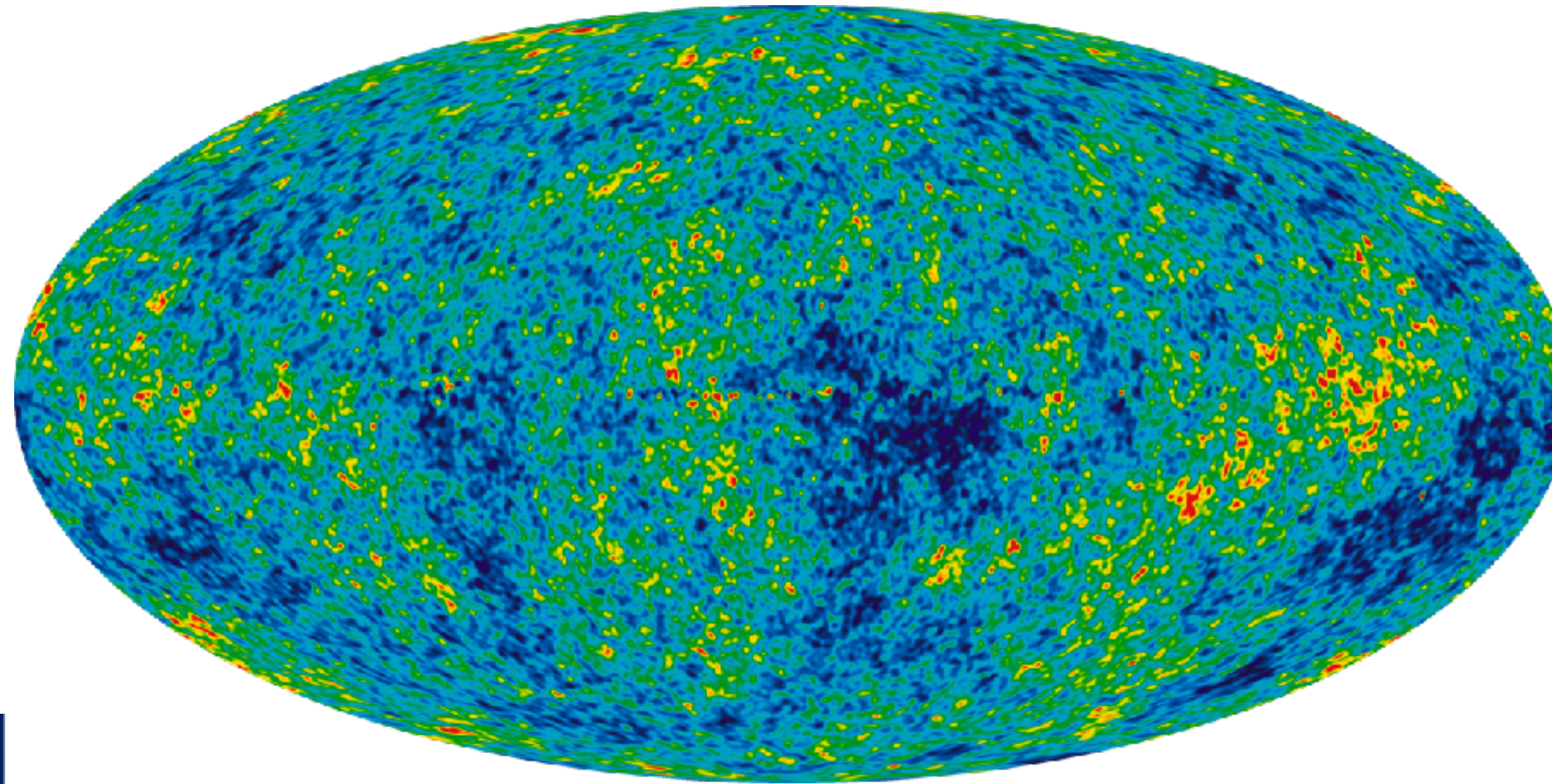
CMB is too
homogeneous!



Motivation

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Inflation?

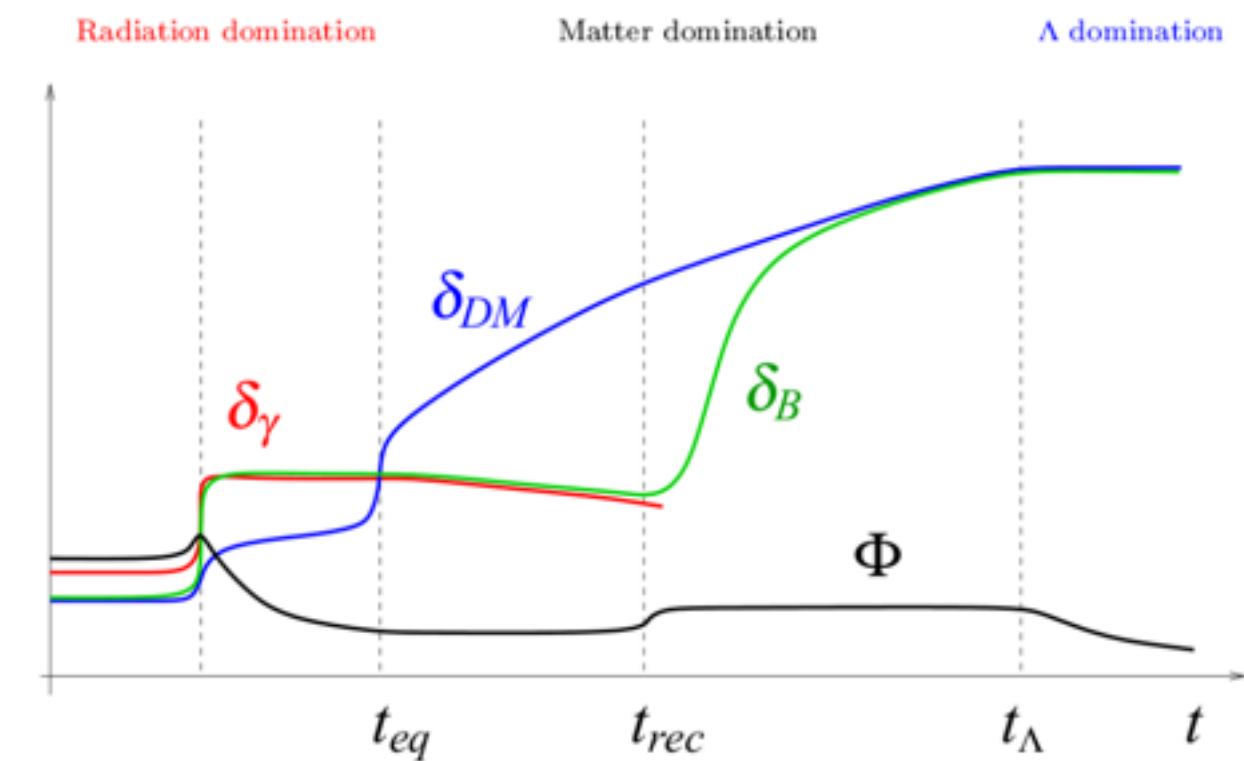
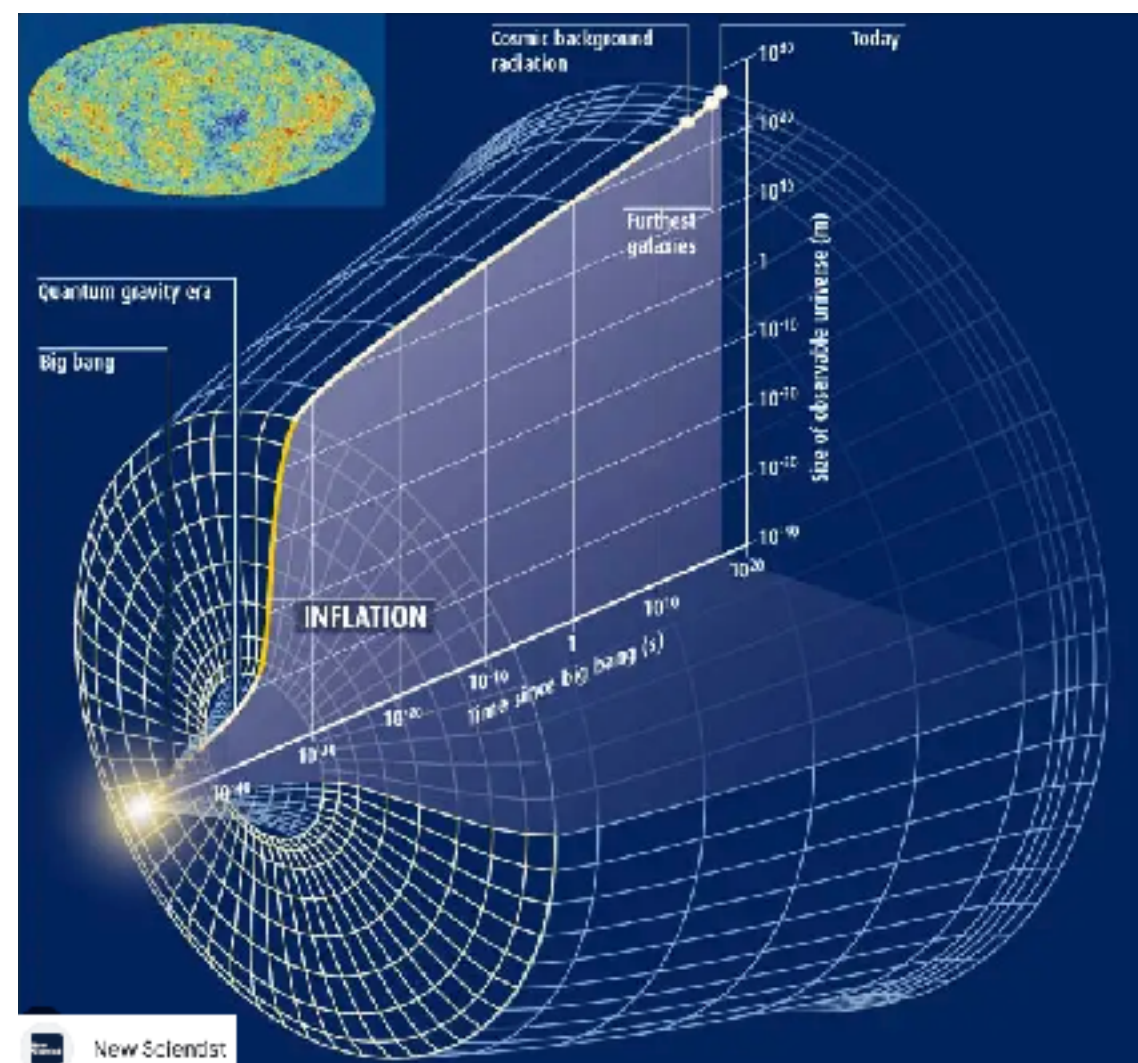
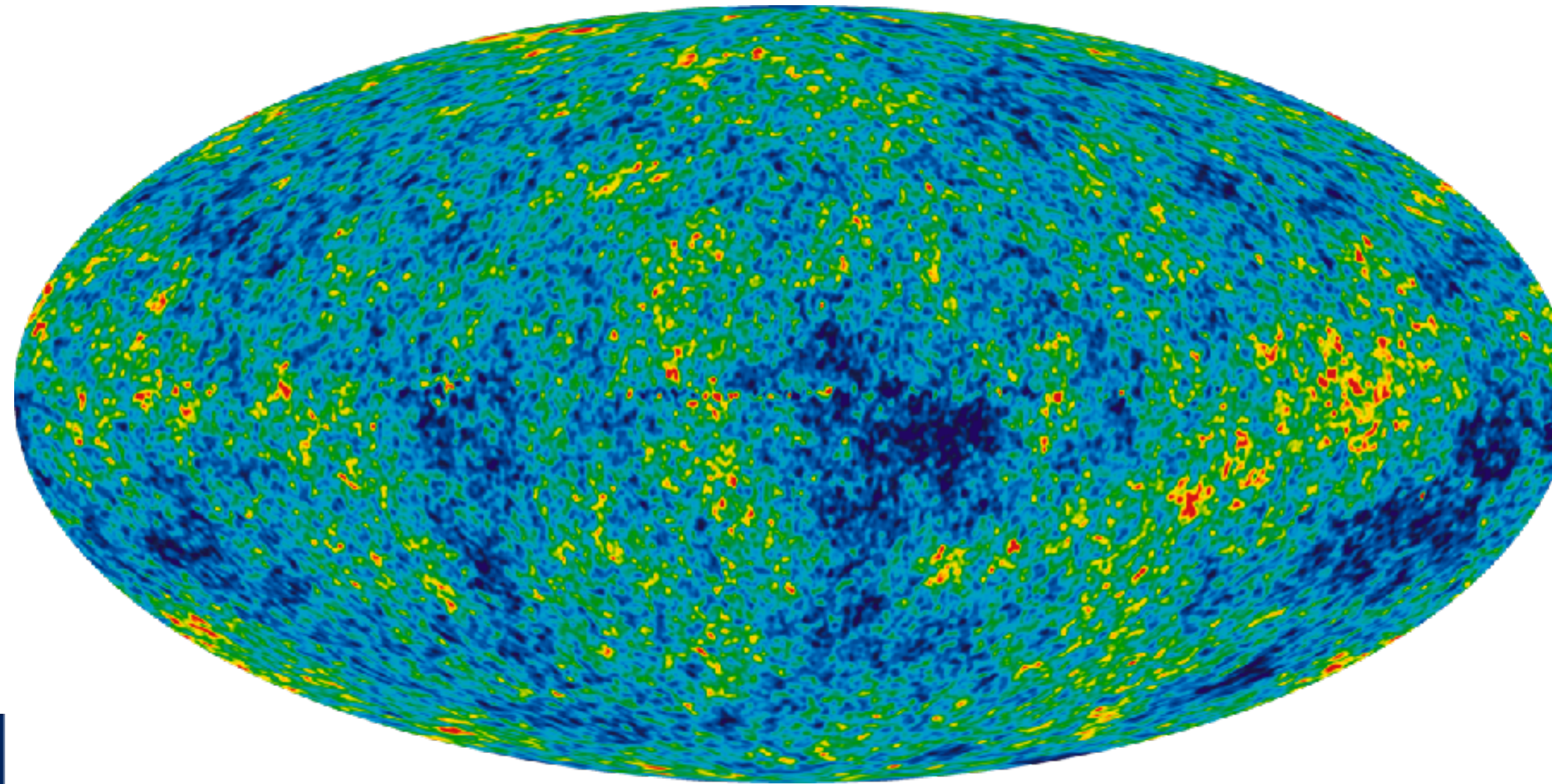


Motivation

How were the structures in our Universe formed?

CMB is too homogeneous!

Inflation?



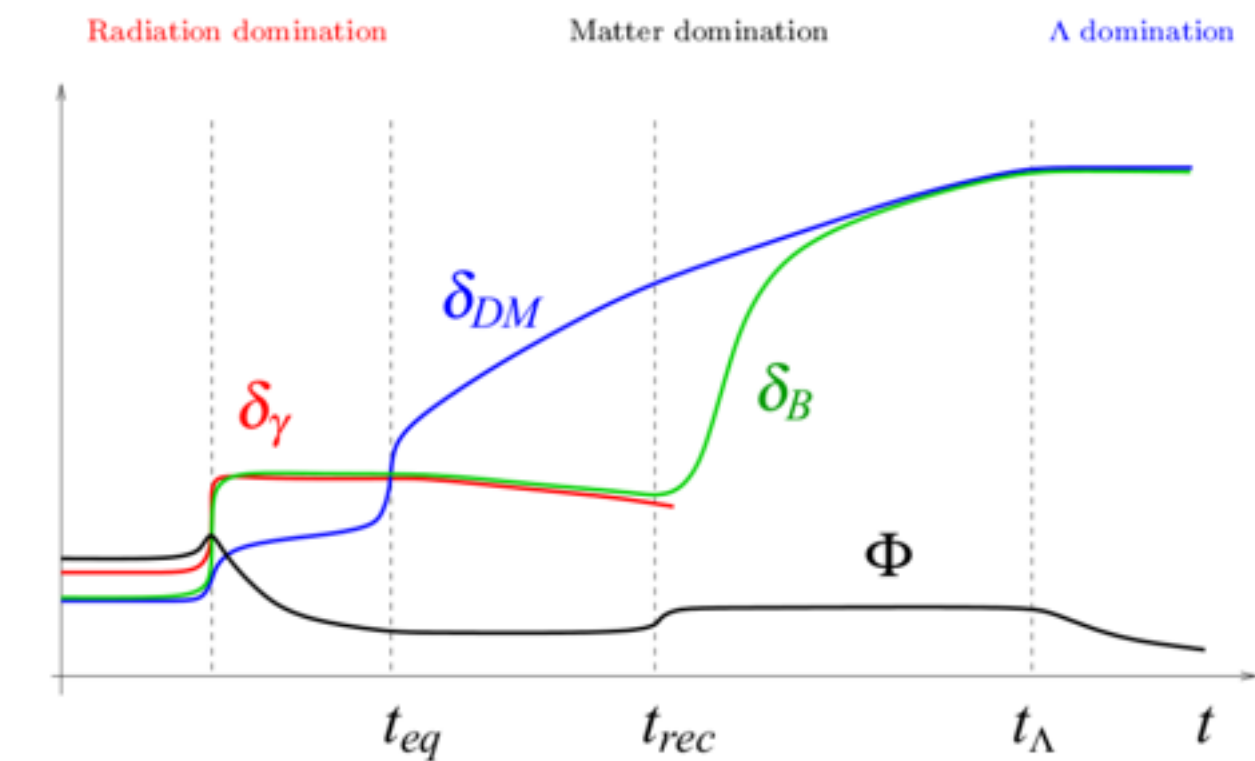
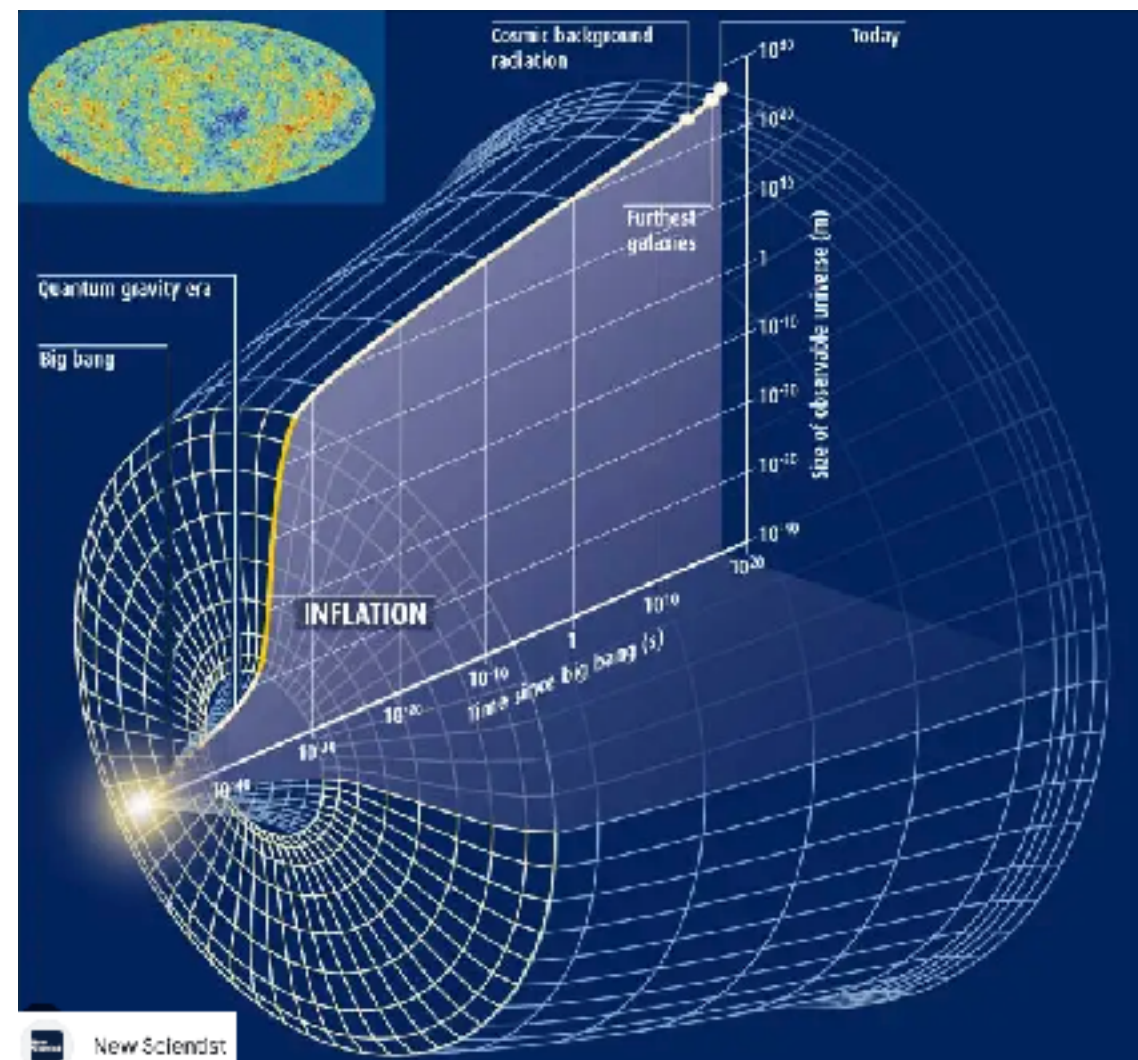
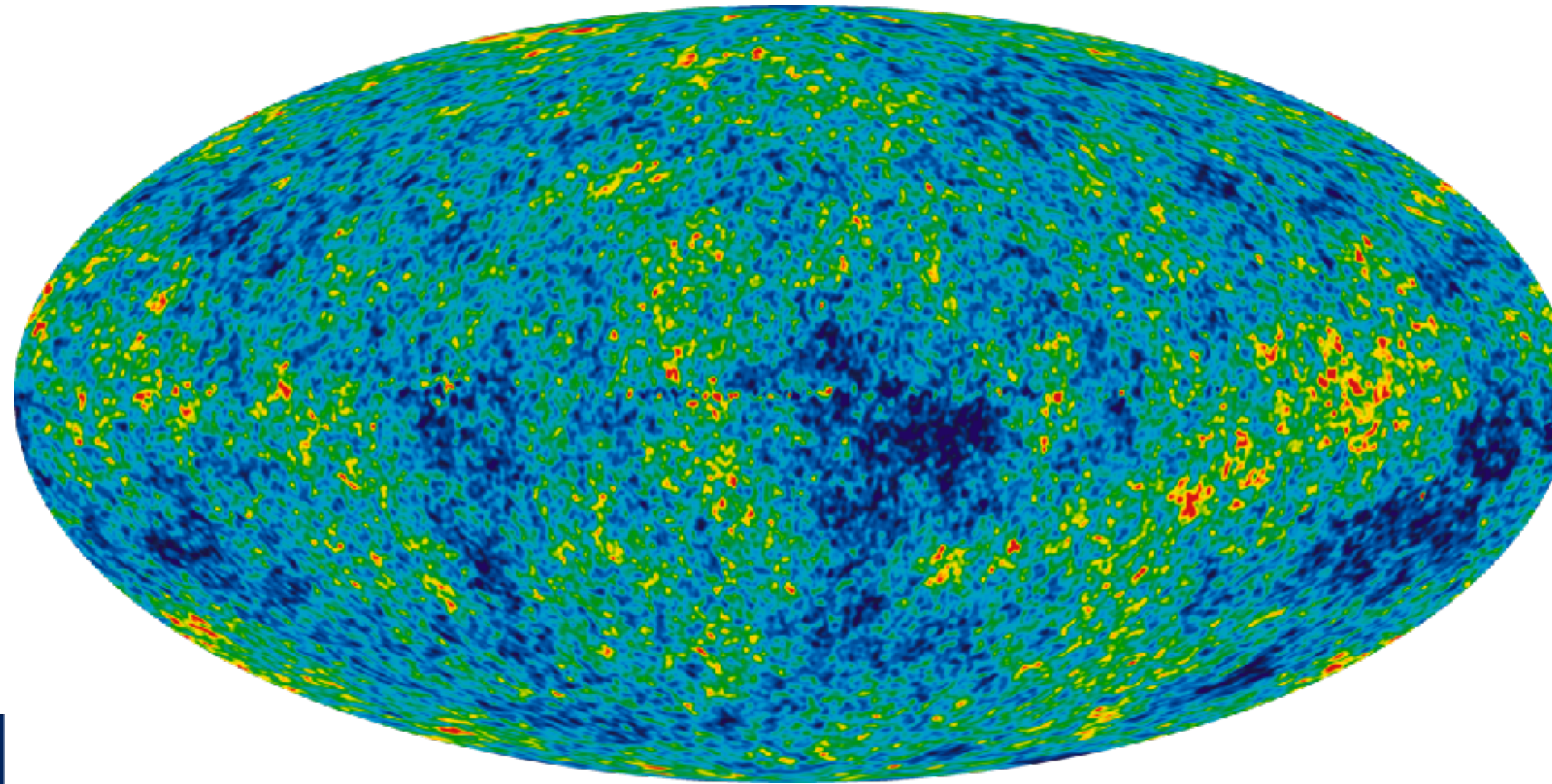
[arXiv:1008.1704]

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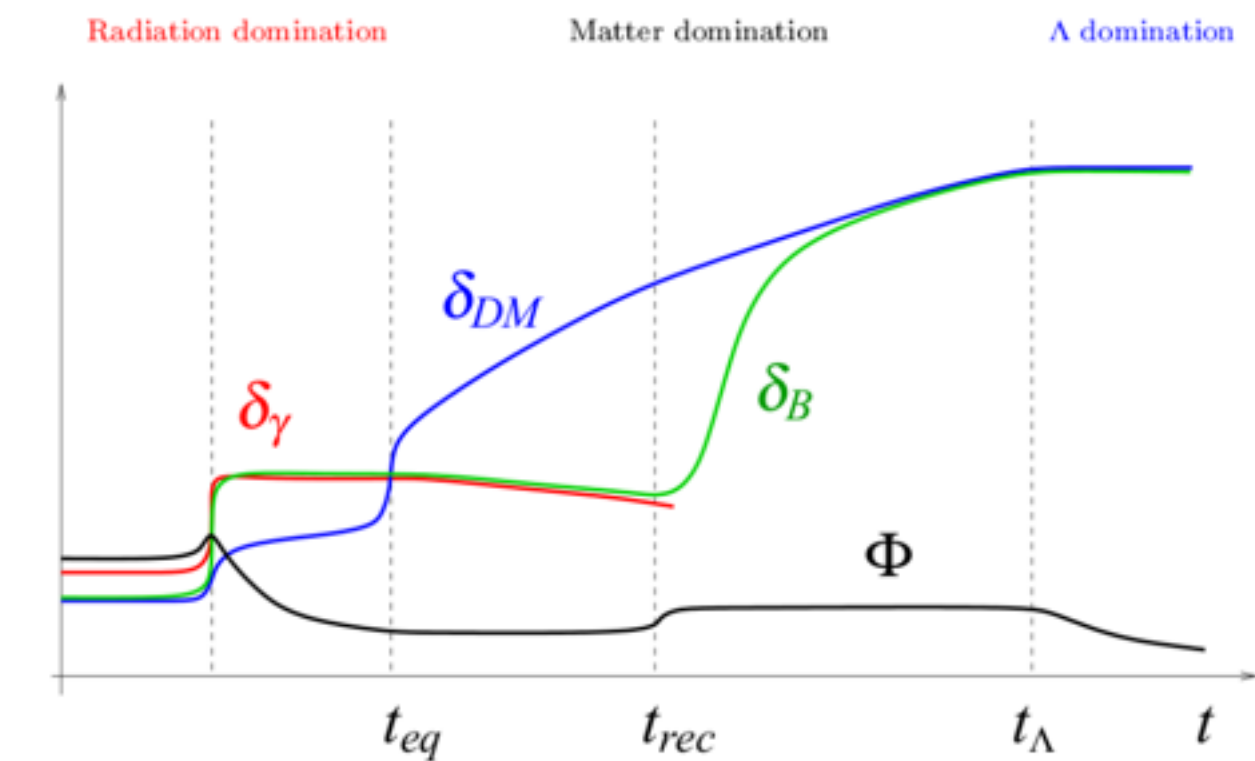
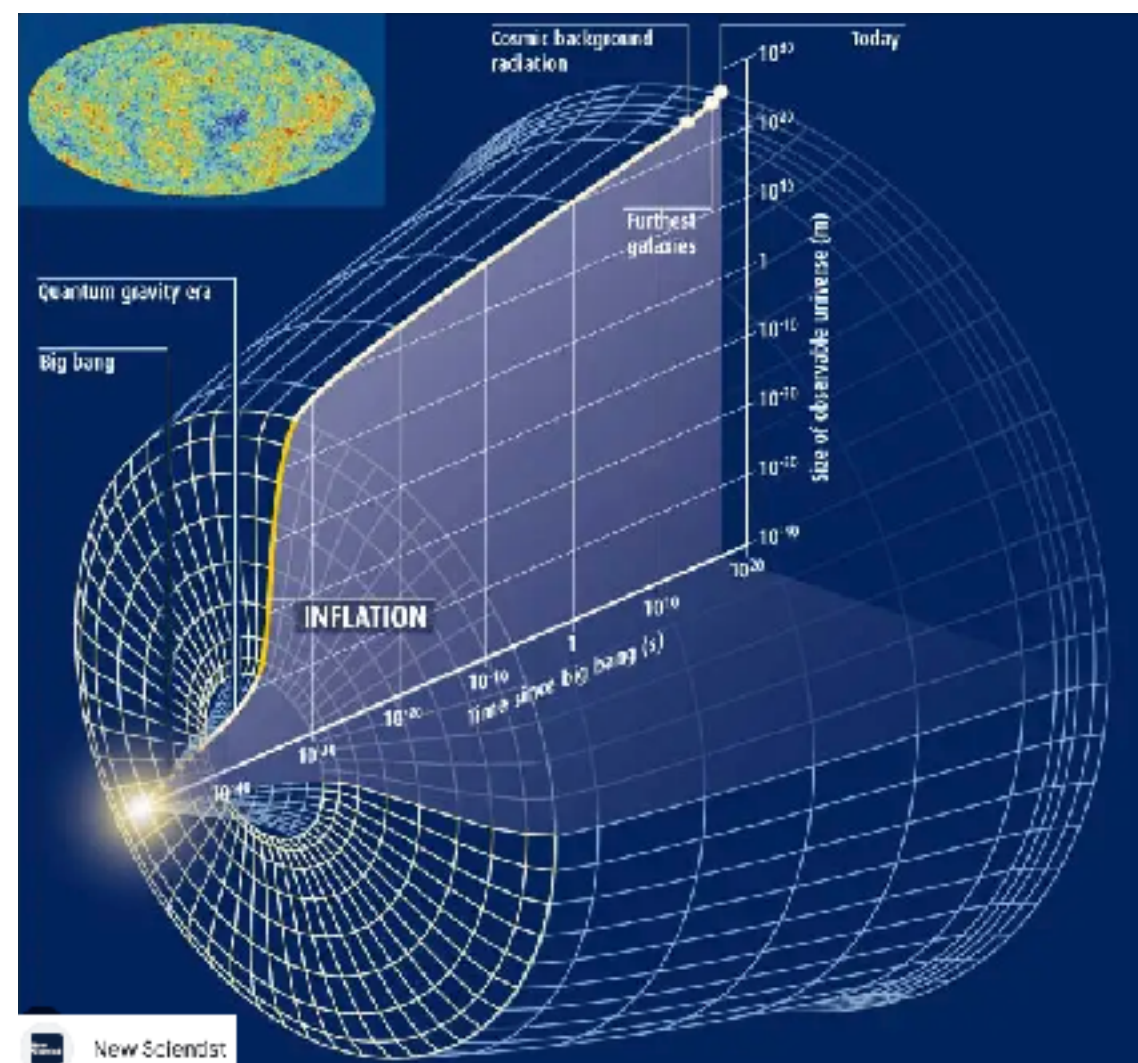
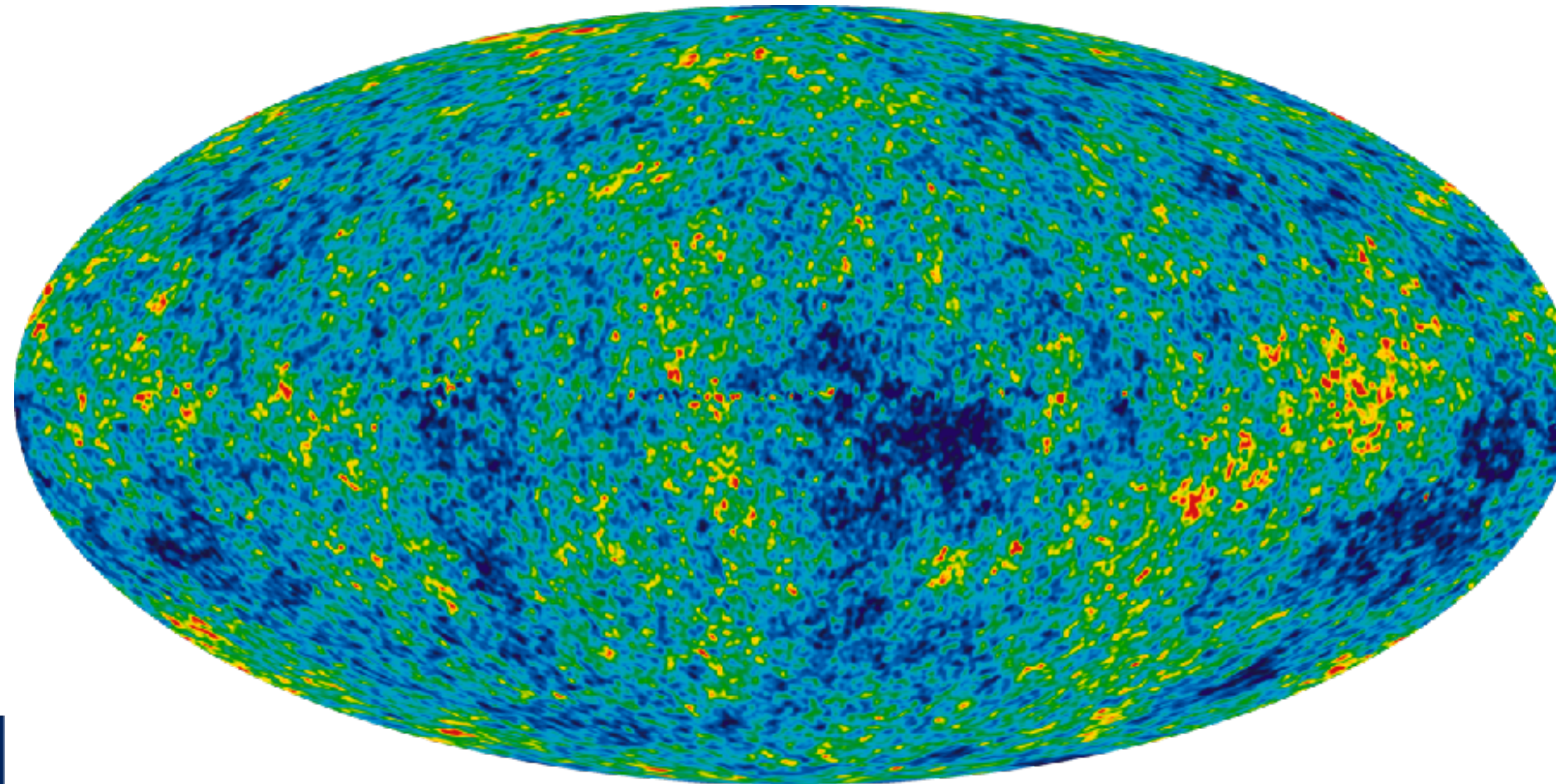
Dark matter!

Motivation

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How were the structures in our Universe formed?



[arXiv:1008.1704]

How can we learn more about events before recombination?

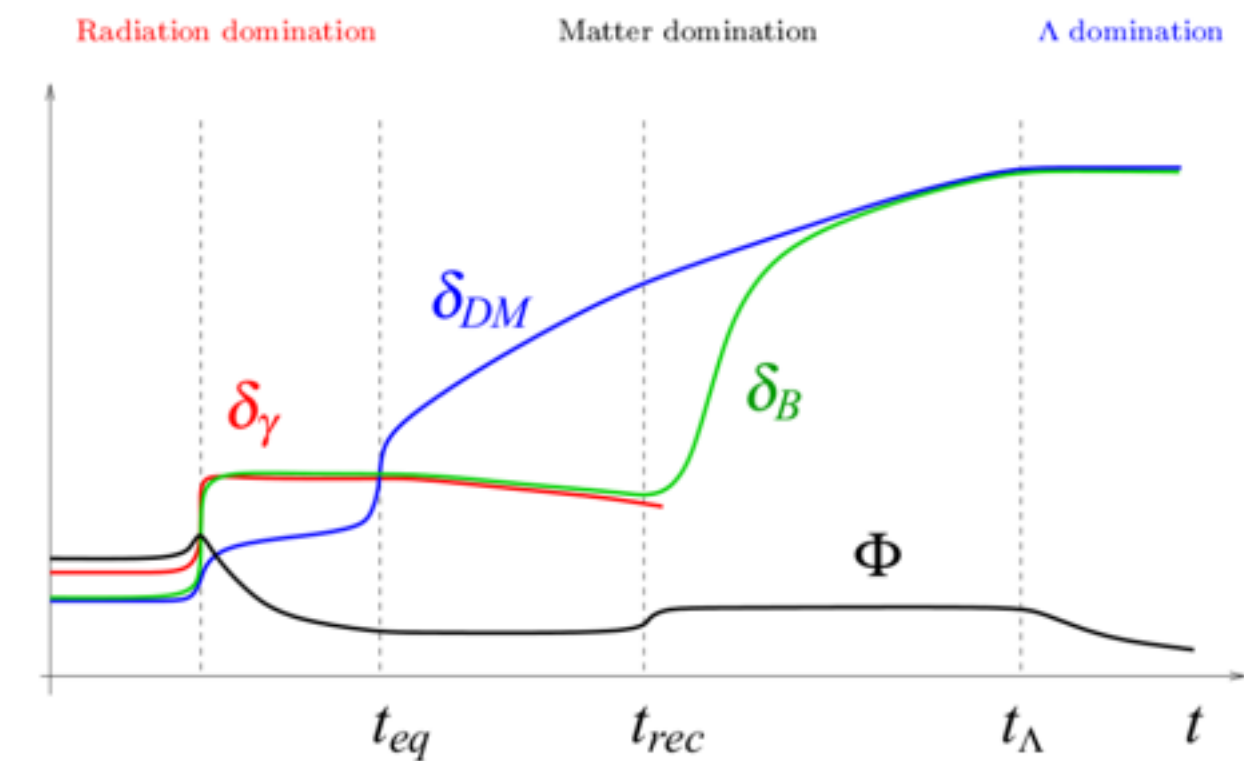
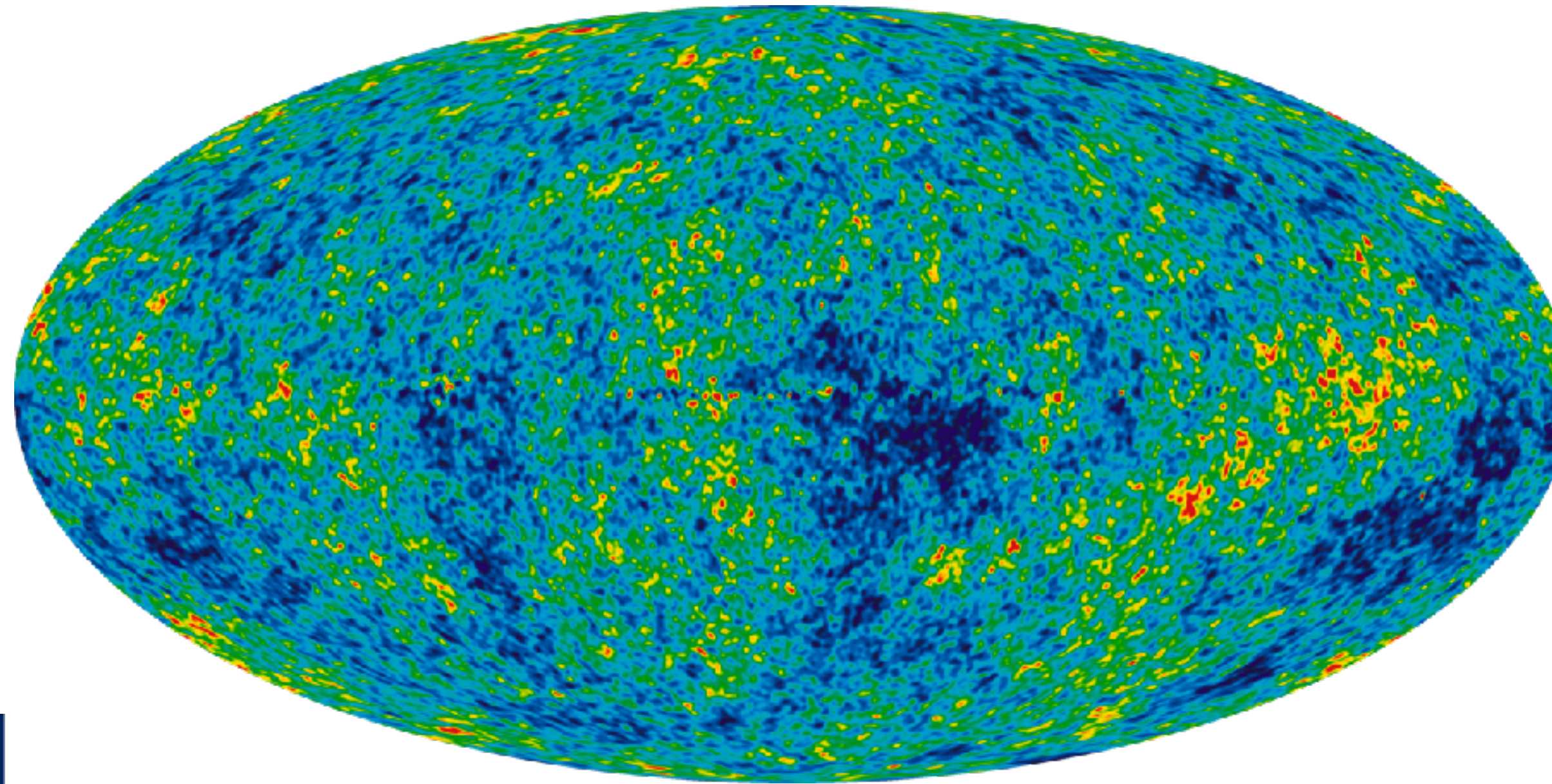
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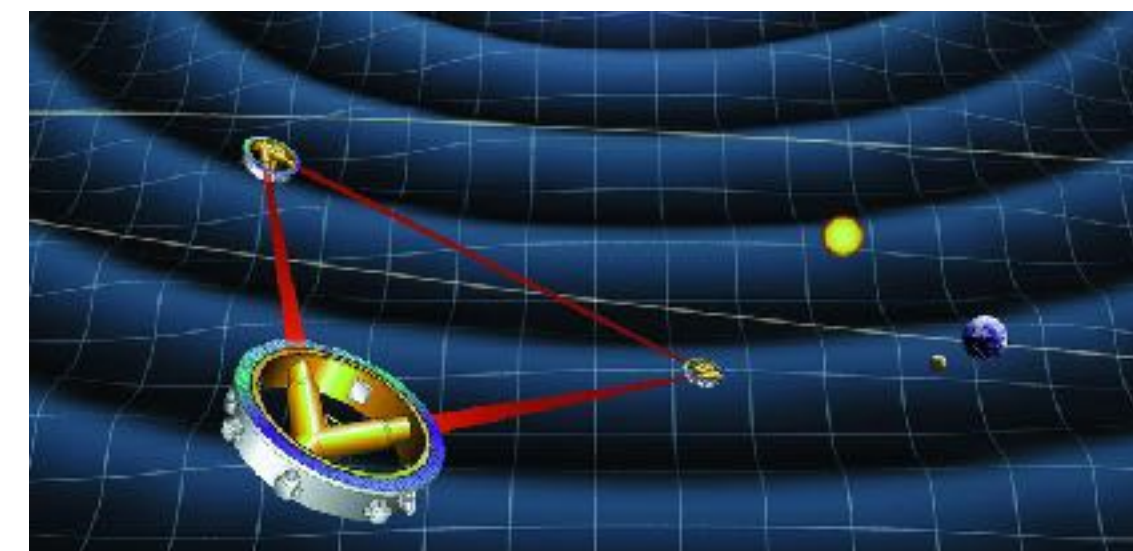
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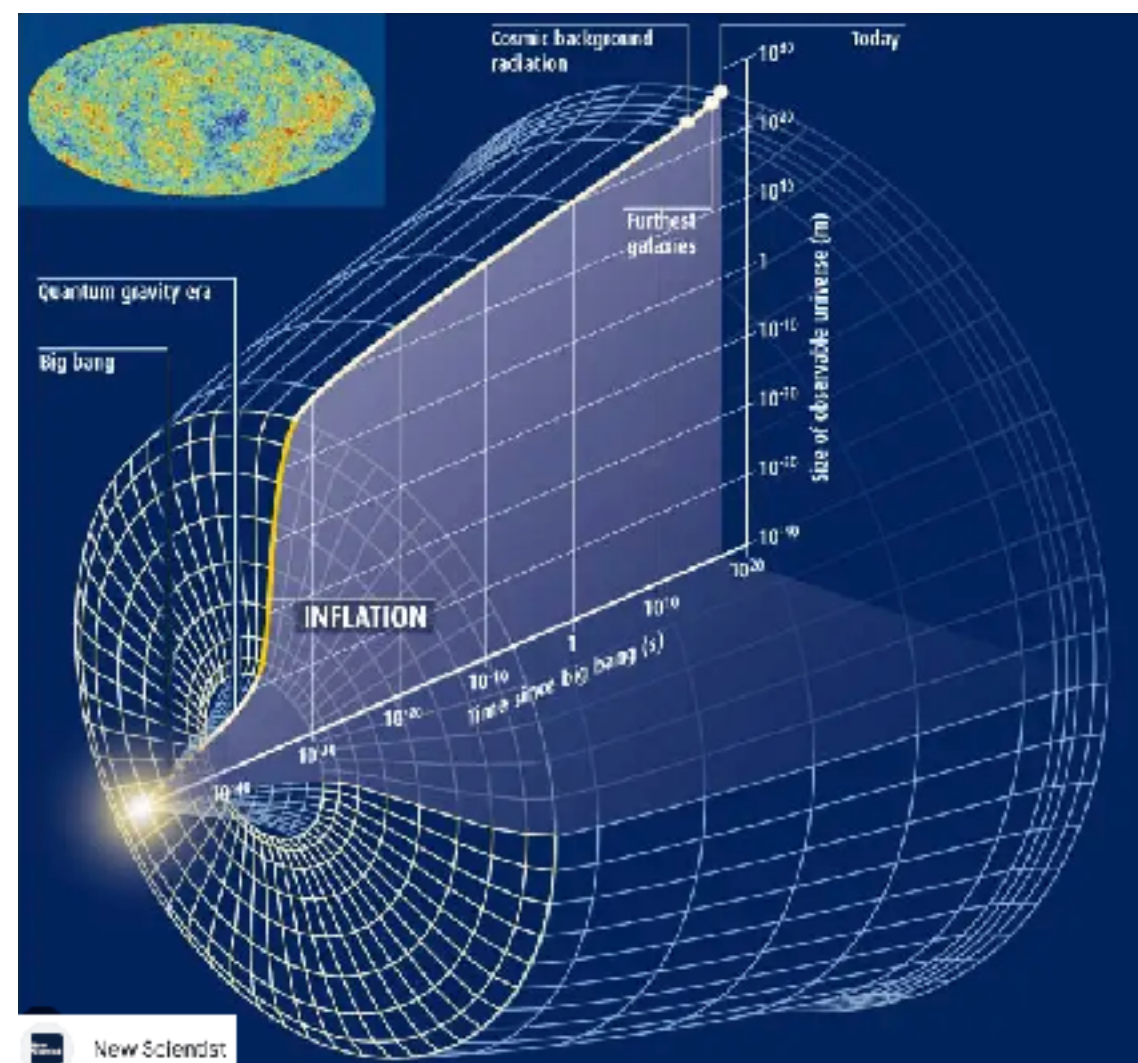
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How can we learn more about events before recombination?



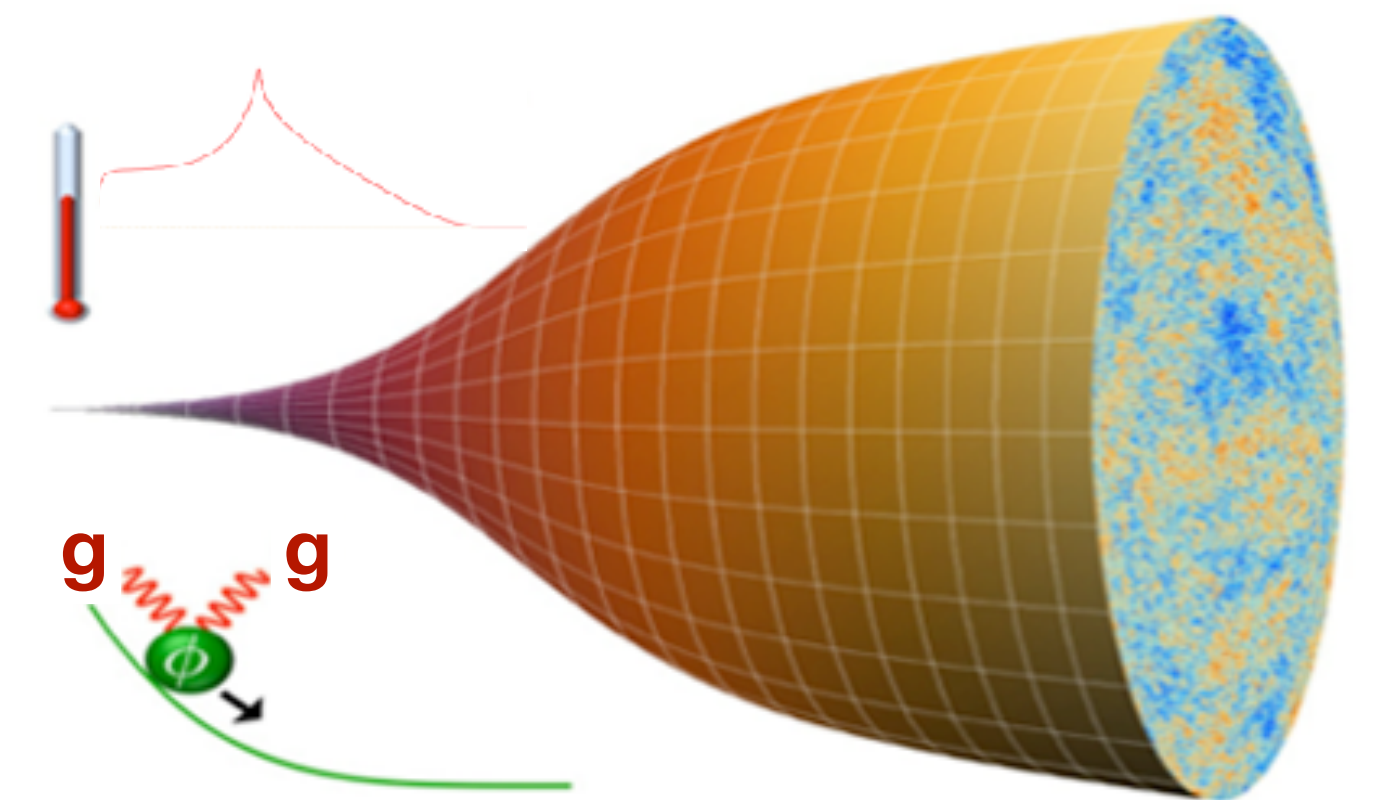
Credit: <http://lisa.jpl.nasa.gov/gallery/lisa-waves.html>

Dark matter!



Outline

1. Introduction to cosmological inflation
2. Model setup: Inflaton coupled to non-abelian dark sector
3. Maximum temperature of the dark sector and possible gravitational wave signals
[HK, Laine, Procacci: 2303.17973]
4. Dilution of gravitational wave signals due to early matter domination era
[HK, Laine: 2311.03718]
5. Glueball dark matter?
[Biondini, HK, Procacci: in preparation]



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

“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:

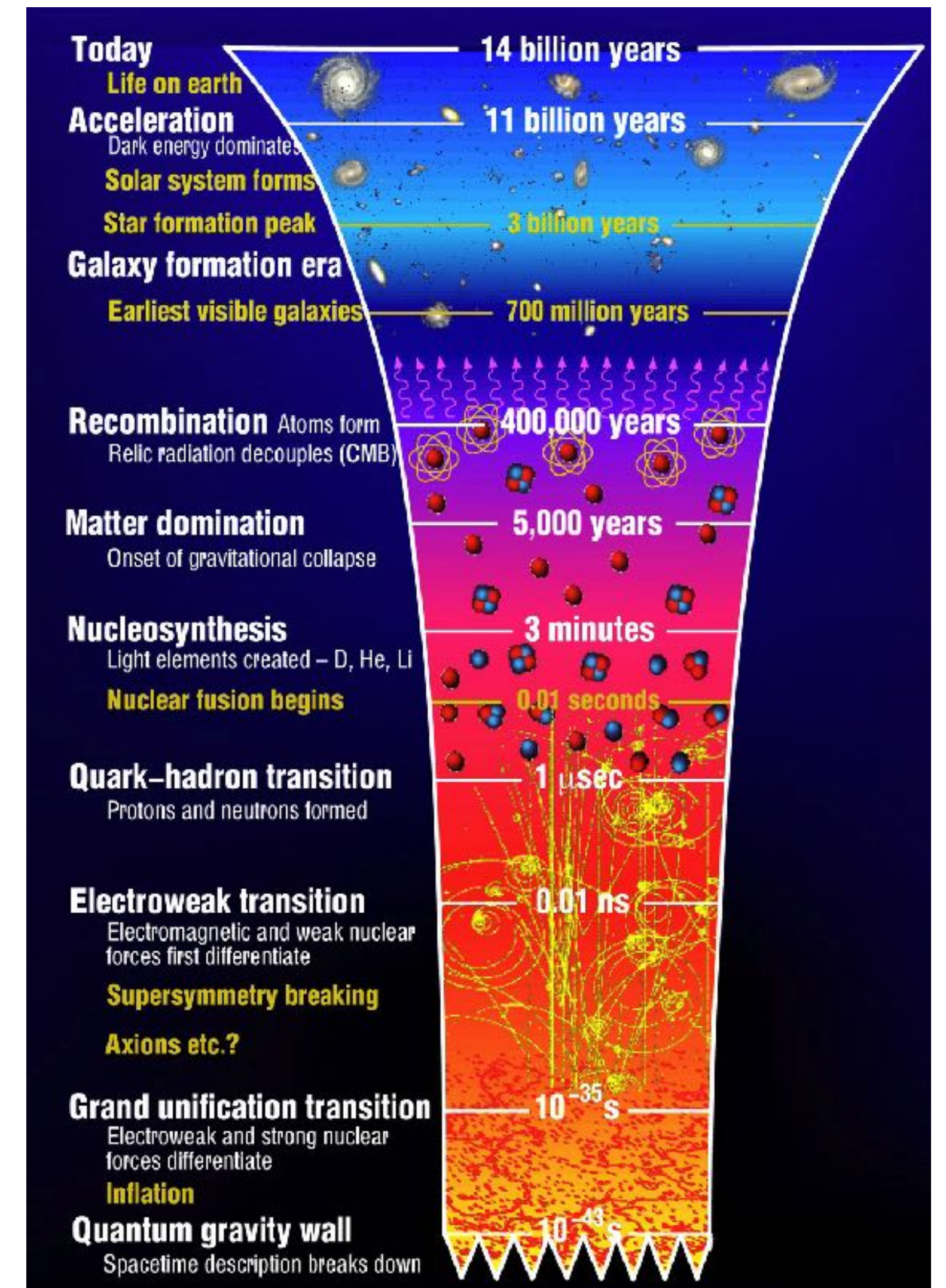
$$p = \frac{\rho}{3} \Rightarrow a \propto t^{1/2}$$

Matter domination:

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

For both cases:

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



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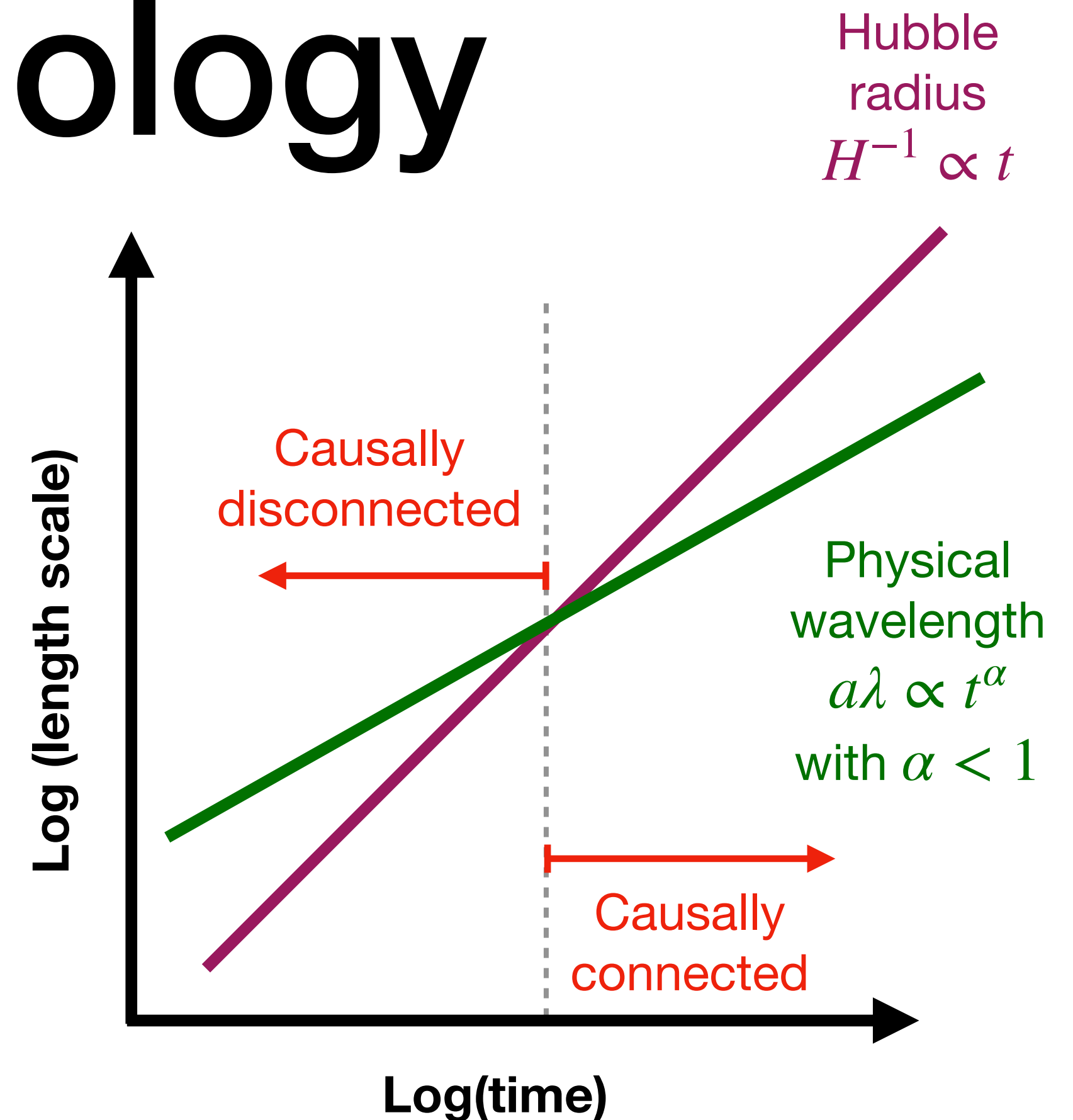
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Causally connected regions at the time of CMB formation correspond to $O(1^\circ)$ regions of sky today. But we see all CMB photons thermalised!

“Horizon problem”

Inflationary cosmology

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

Einstein equations:

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

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

accelerated expansion!

Homogeneous scalar field:

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

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

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

“Slow roll” regime:

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

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

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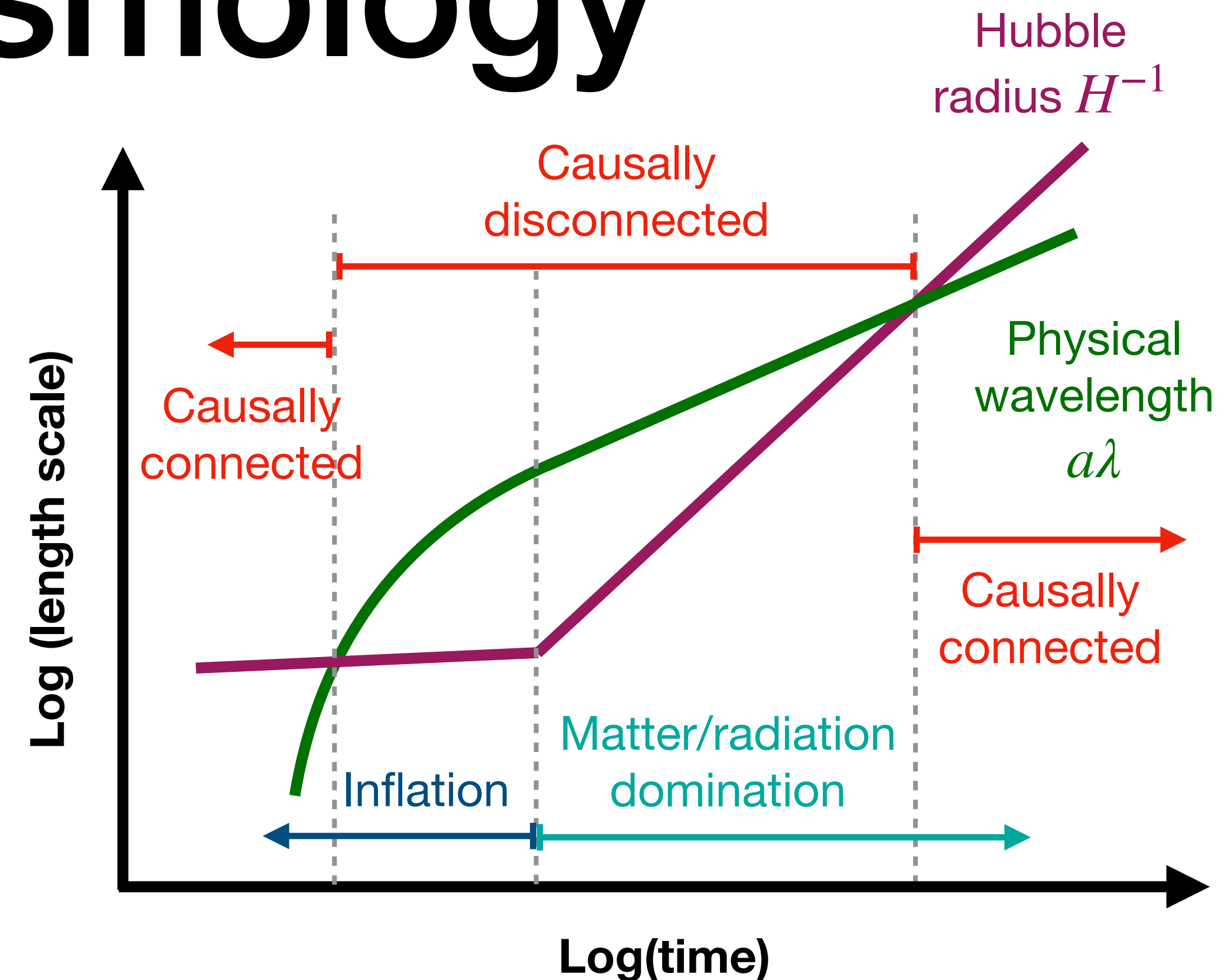
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Different regions of CMB sky were causally connected during inflation!

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

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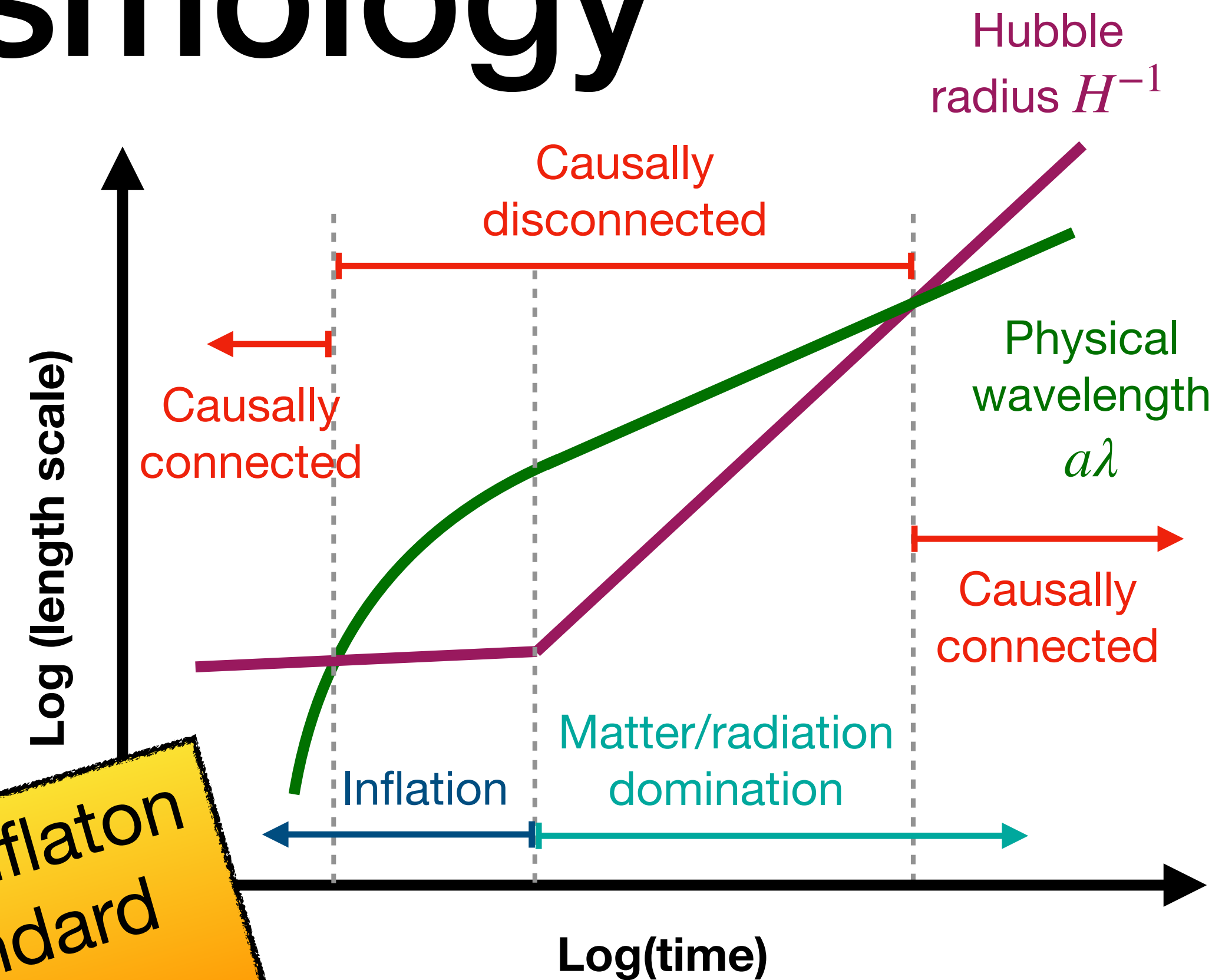
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But what is the shape of the inflaton potential? And how the Standard Model fields are “reheated”?



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Model setup: Example of a “warm inflation”

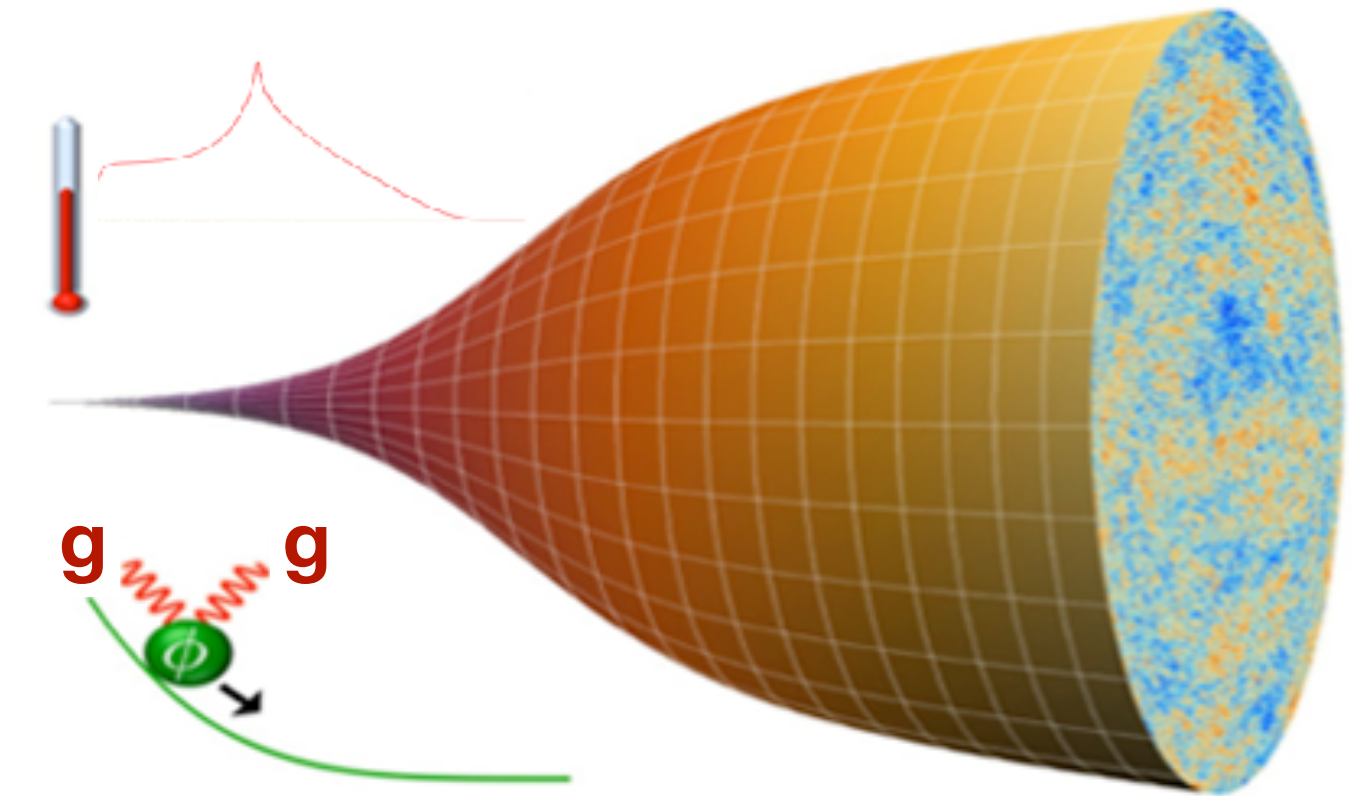
- Axion inflation coupled to non-abelian dark sector

[Berghaus, Graham, Kaplan: 1910.07525]

[Laine, Procacci: 2102.09913]

[Klose, Laine, Procacci: 2201.02317]

[Klose, Laine, Procacci: 2210.11710]



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

$$\mathcal{L} \supset \frac{1}{2} \partial^\mu \varphi \partial_\mu \varphi - V_0(\varphi) - \frac{\alpha \varphi \epsilon^{\mu\nu\rho\sigma} F_{\mu\nu}^c F_{\rho\sigma}^c}{16\pi f_a}$$

Gauge coupling
Yang-Mills field strength

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)]

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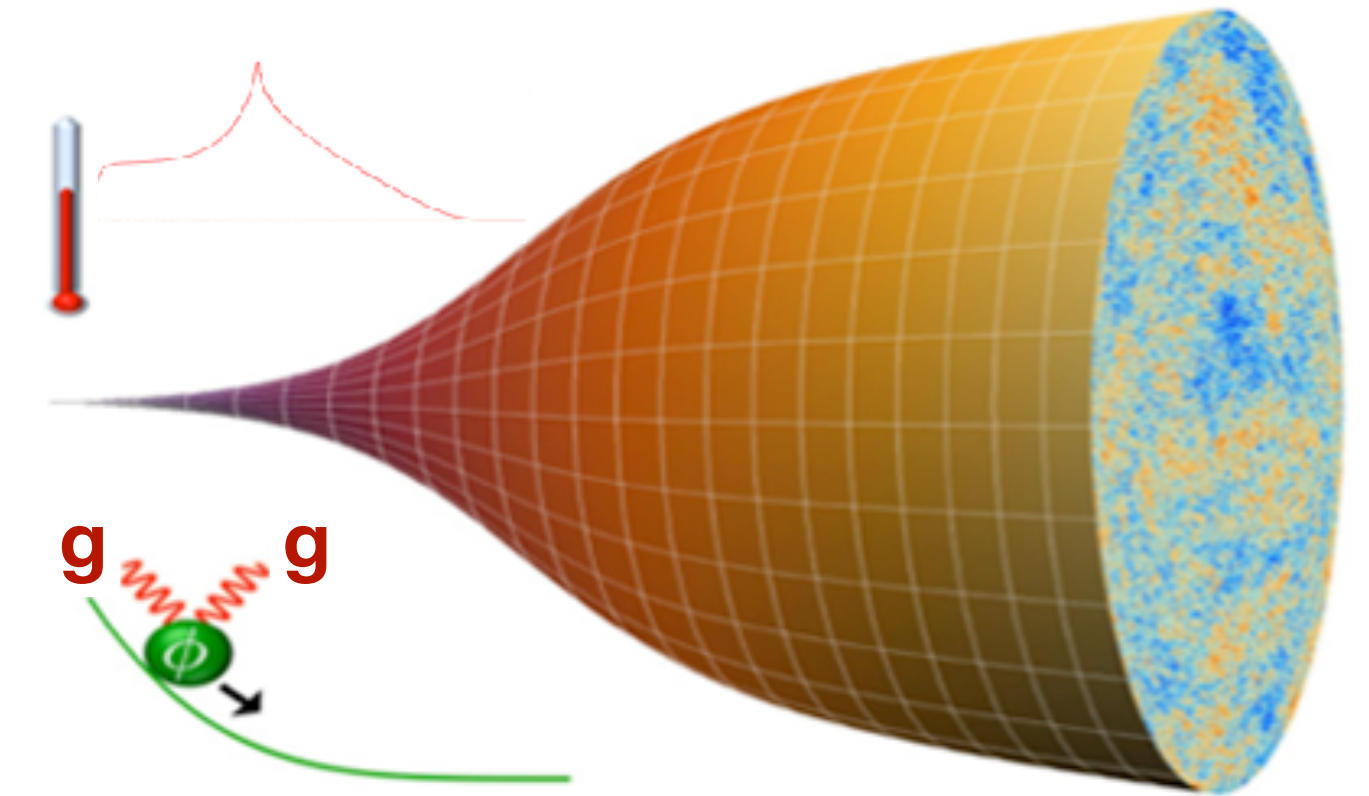
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Inflaton field Inflaton potential: Gauge coupling Yang-Mills field strength Axion decay constant

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Hubble rate Friction due to inflaton coupling to dark sector

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

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

Dark radiation energy and pressure densities

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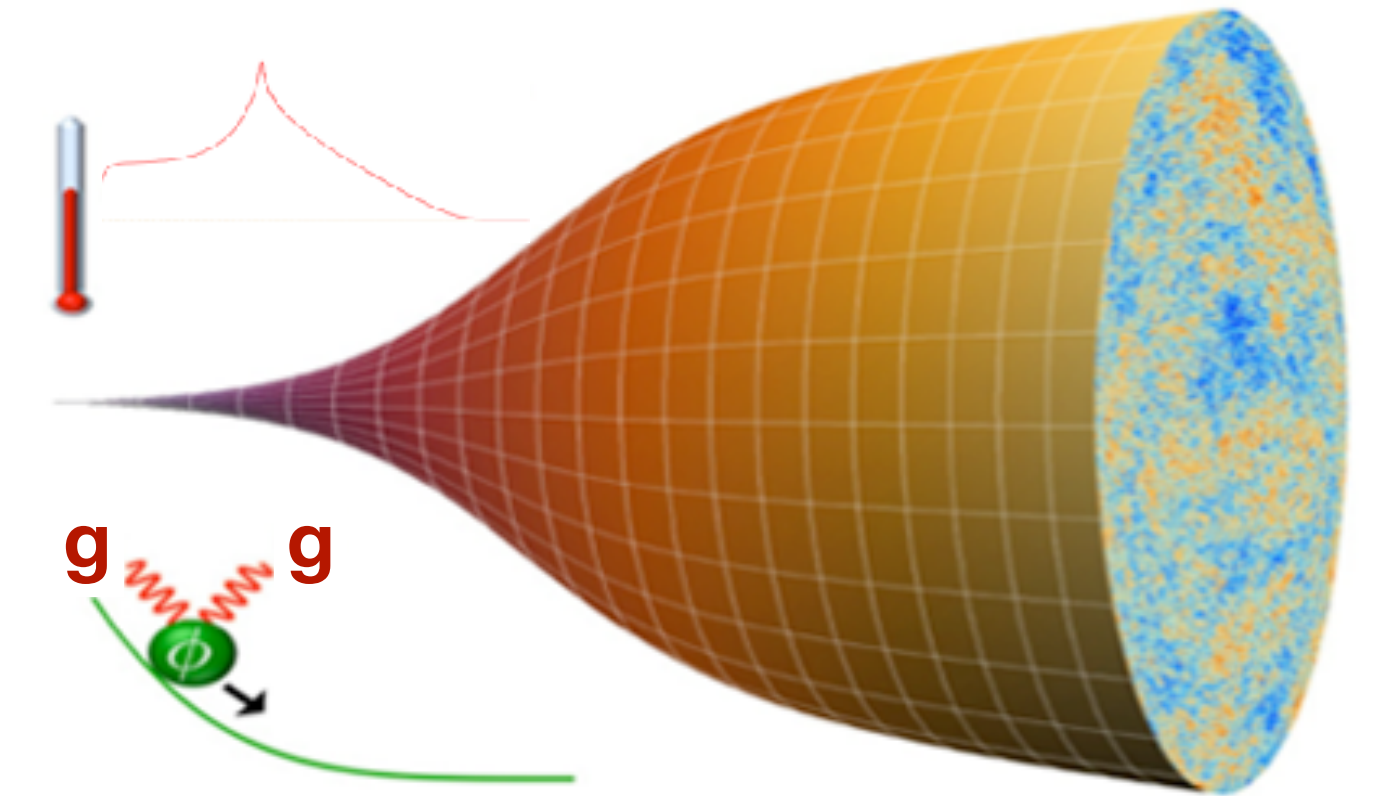
[Klose, Laine, Procacci: 2201.02317]

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Focus of this talk!

Gauge coupling

Yang-Mills
field strength



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Axion decay
constant

Hubble rate

Friction due to inflaton
coupling to dark sector

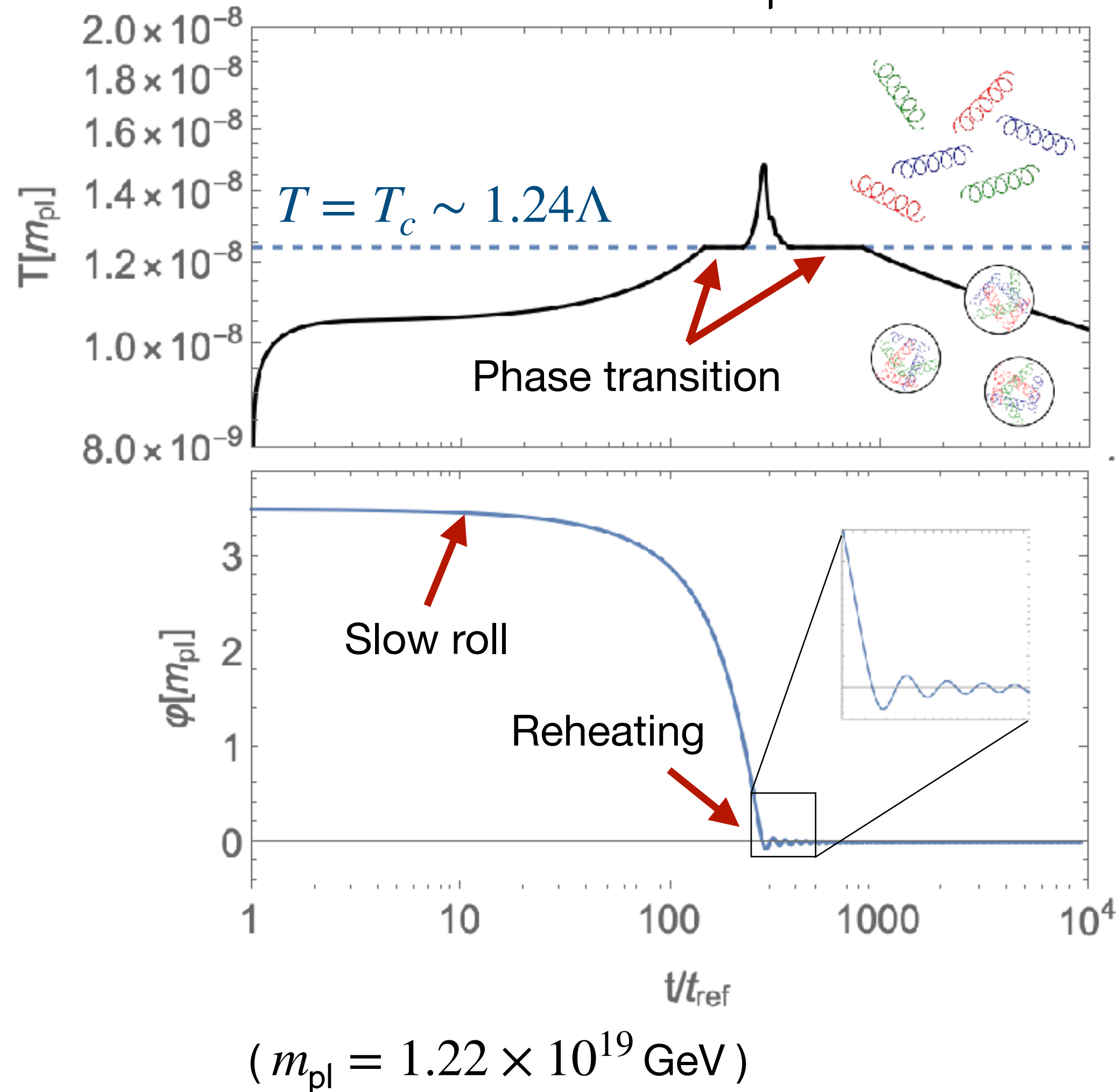
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Dark radiation energy
and pressure densities

Evolution of the dark sector

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



- 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)

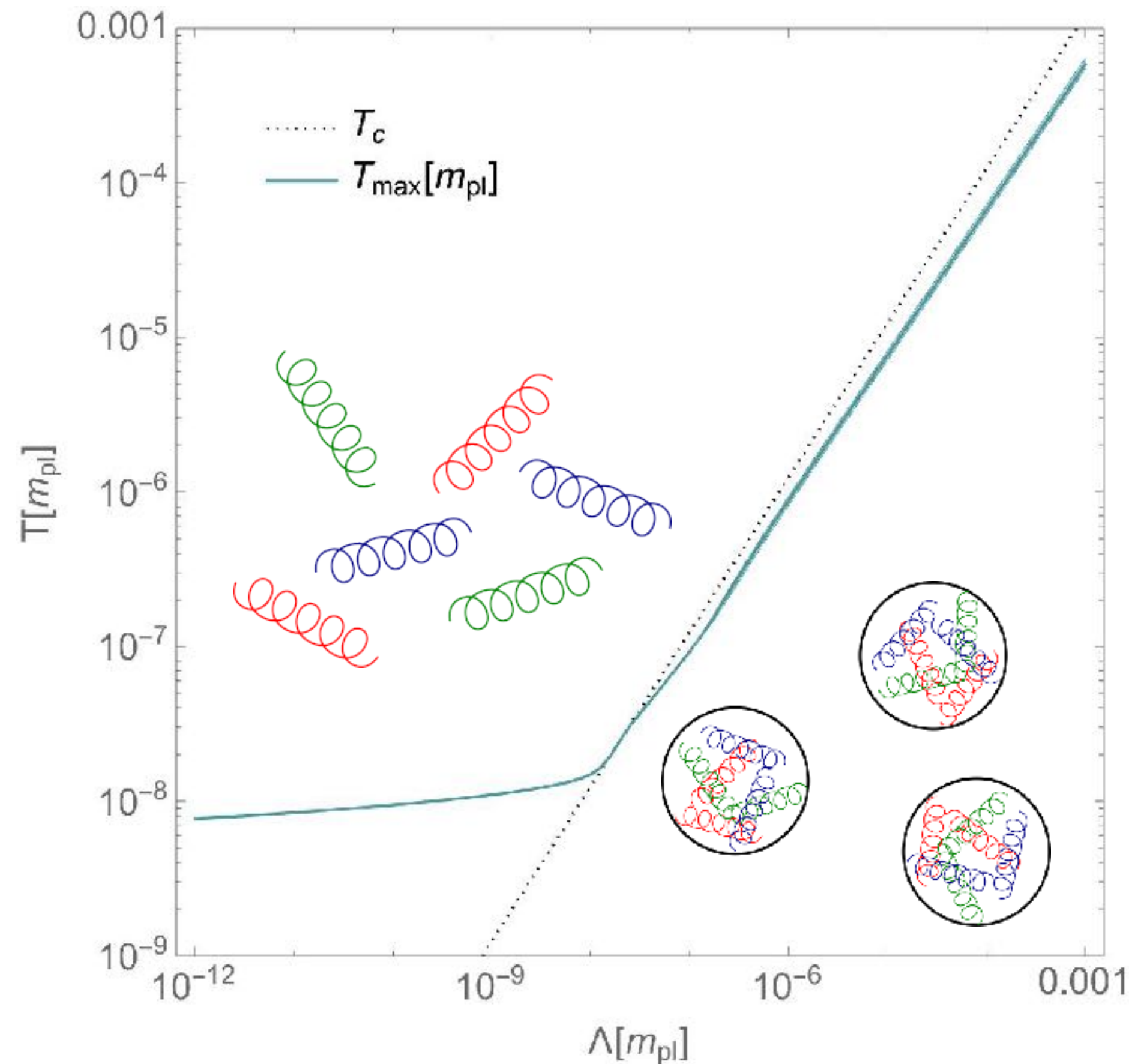
[Moore, Tassler: 1011.1167] [Laine, Niemi, Procacci, Rummukainen: 2209.13804]

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

Maximum temperature of the dark sector



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

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Dark radiation energy and pressure densities
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NB: Gravitational waves from thermal plasma

[Ghiglieri, Laine: 1504.02569]

[Klose, Laine, Procacci: 2201.02317]

[Klose, Laine, Procacci: 2210.11710]

“Boltzmann domain” - determines total energy density in GW $\Leftrightarrow$ constraints from ΔN_{eff} at BBN

$$\Delta N_{\text{eff}} \lesssim 10^{-3} \Rightarrow T_{\text{max}} \lesssim 10^{17} \text{ GeV}$$

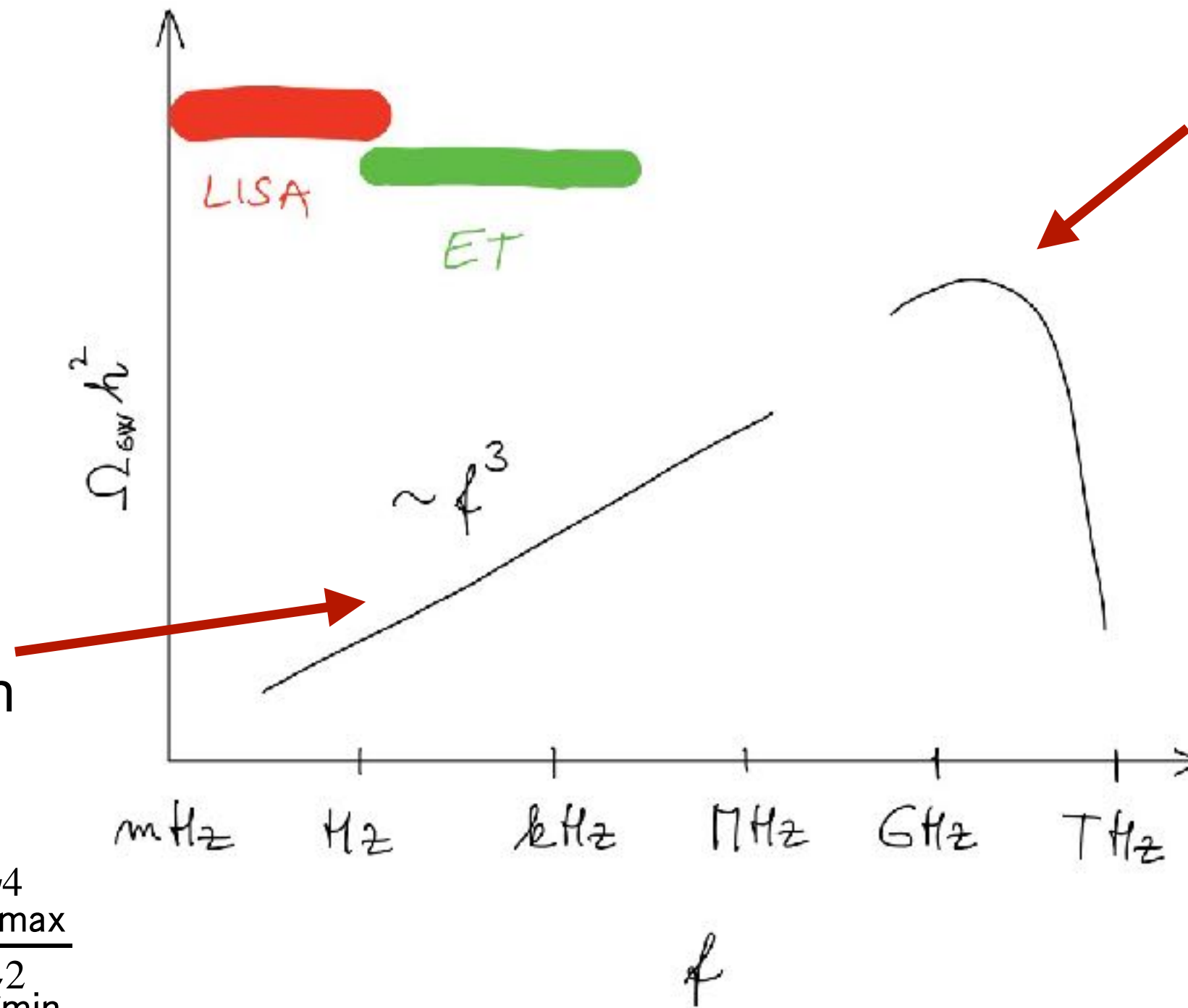
[Ghiglieri, Jackson, Laine, Zhu: 2004.11392]

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

(constraint mainly due to SM plasma, contribution of axion is subdominant)

“Hydrodynamic domain”: GW signal driven by shear viscosity η - contribution due to axion can be substantial

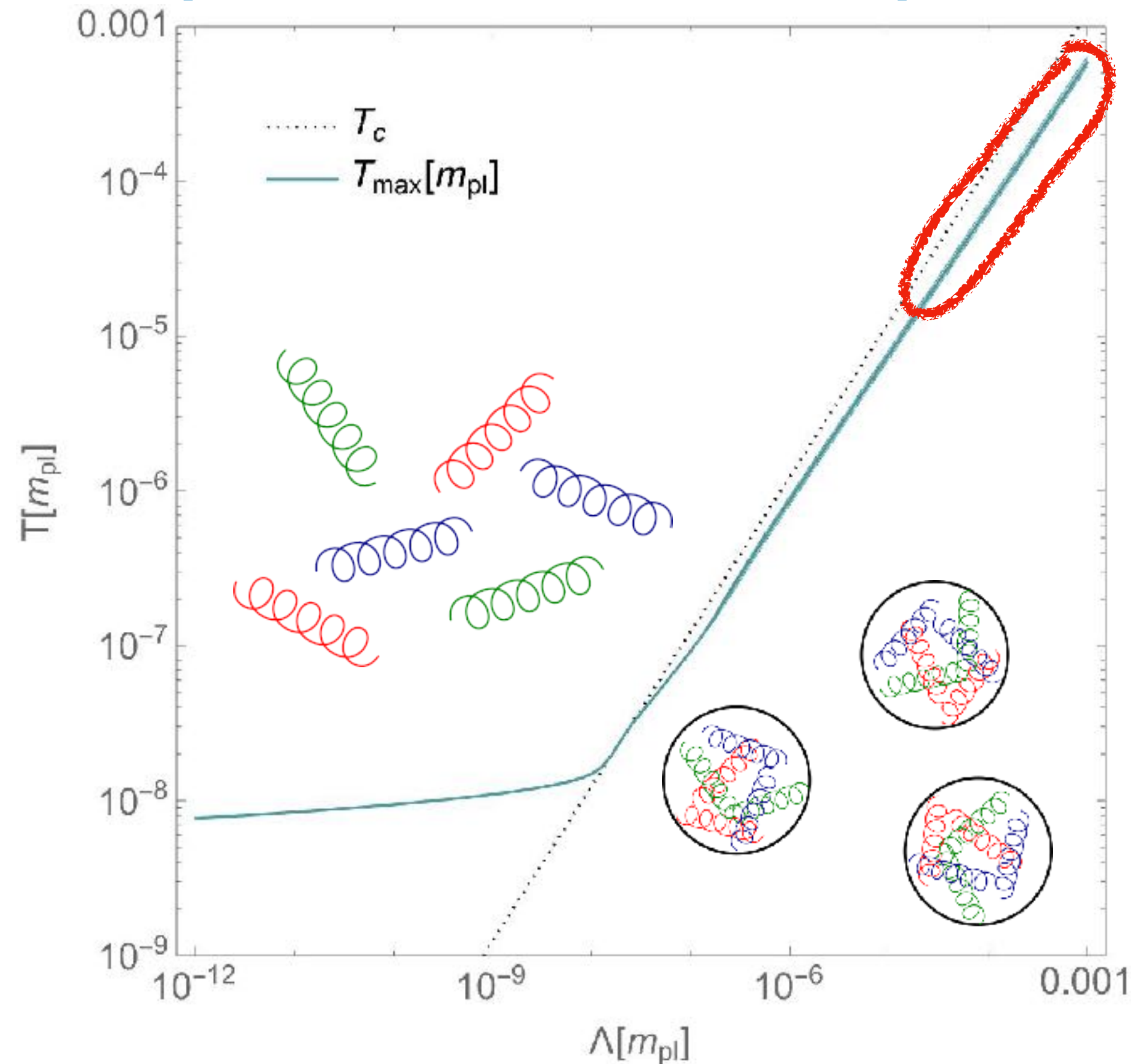
$$\Omega_{\text{GW}} h^2 \supset A \left(\frac{f}{\text{Hz}} \right)^3 \frac{(T\eta)_{\text{max}}}{m_{\text{pl}}^4}, \quad (T\eta)_{\text{max}} \sim \frac{T_{\text{max}}^4}{\alpha_{\text{min}}^2}$$



Sensitive to maximum temperature reached in the YM sector!

Maximum temperature of the dark sector

[HK, Laine, Procacci: 2303.17973]



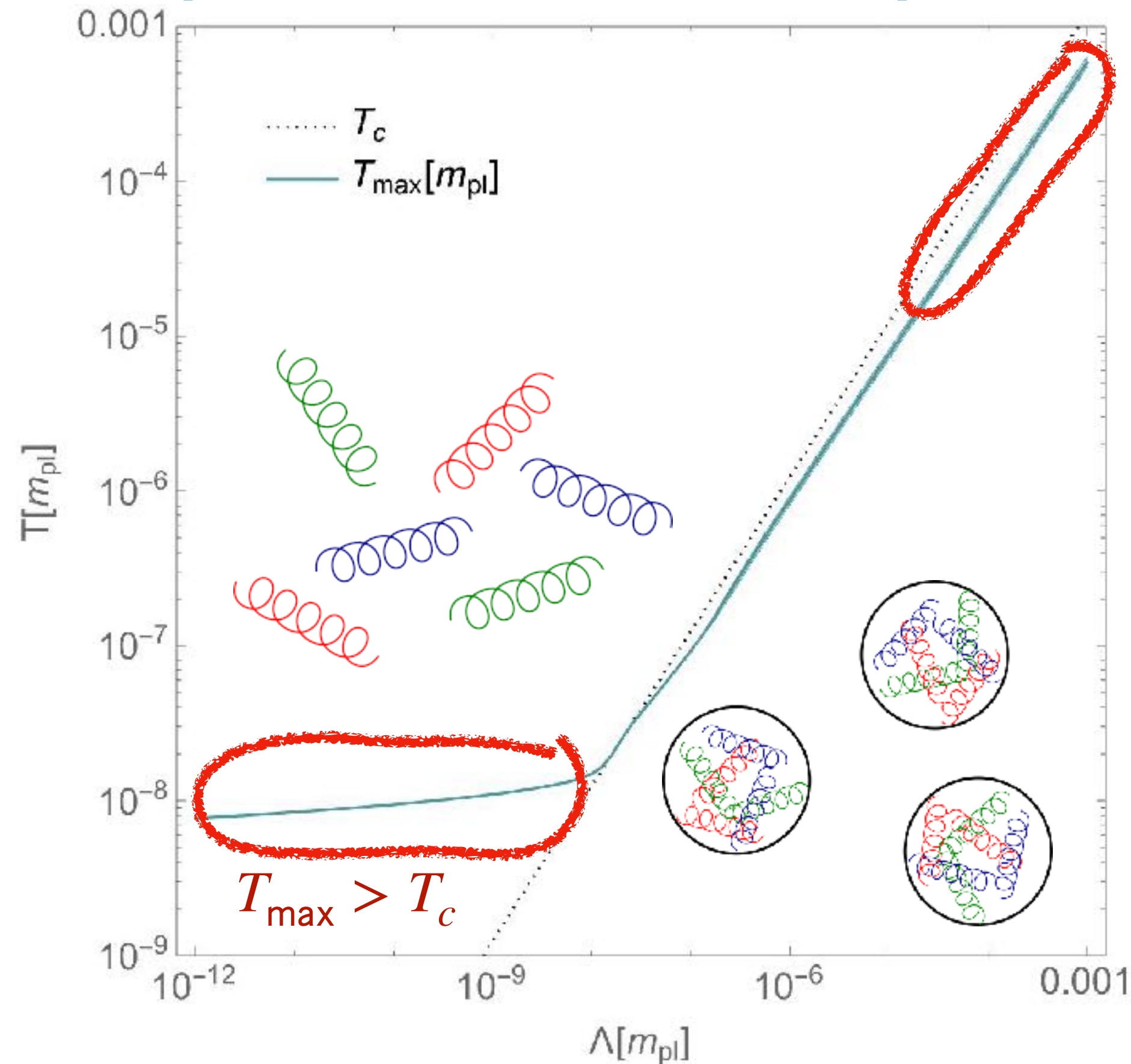
Message 1: Temperatures up to $10^{-3} m_{\text{pl}}$ can be reached

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

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

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

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

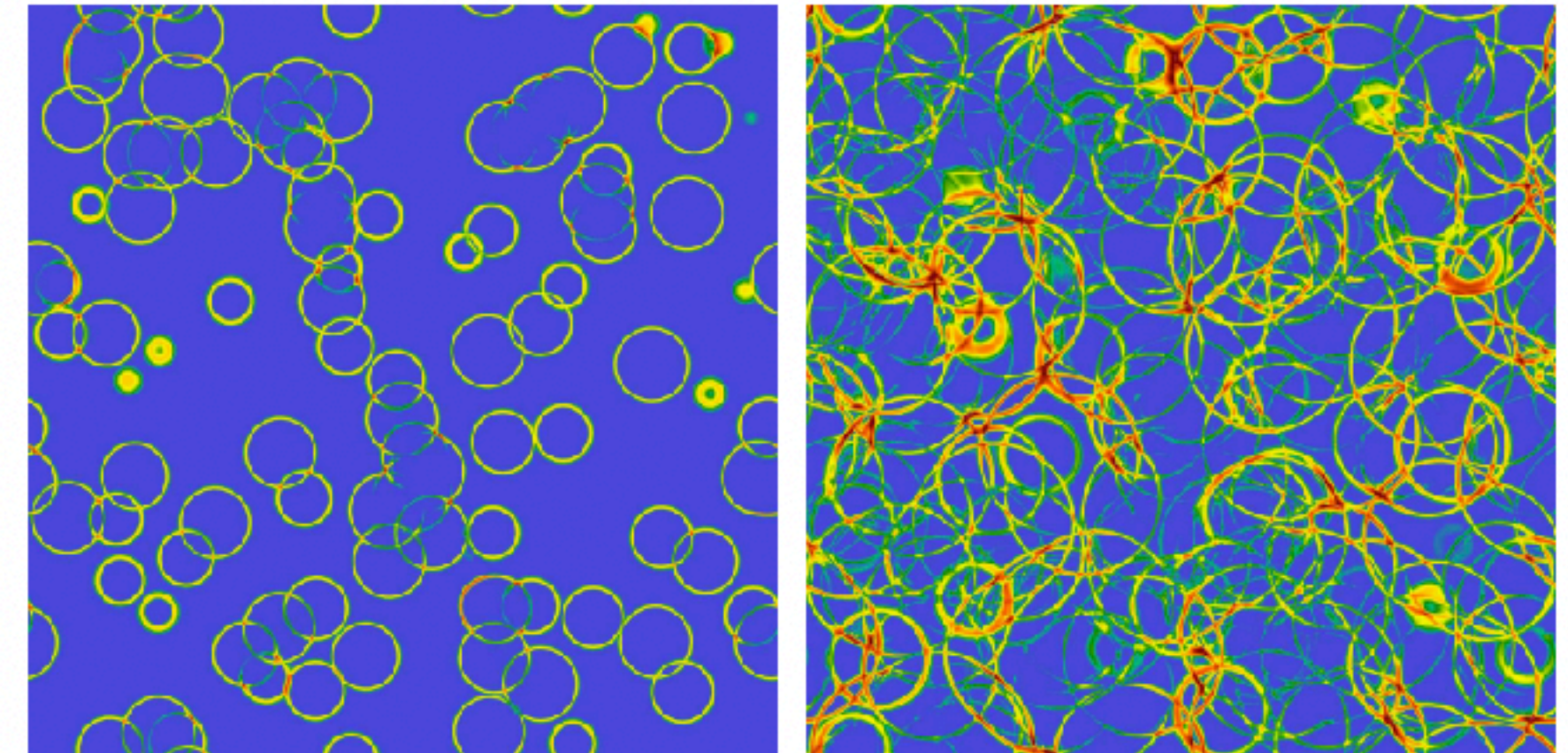
GW from a confinement phase transition?

- 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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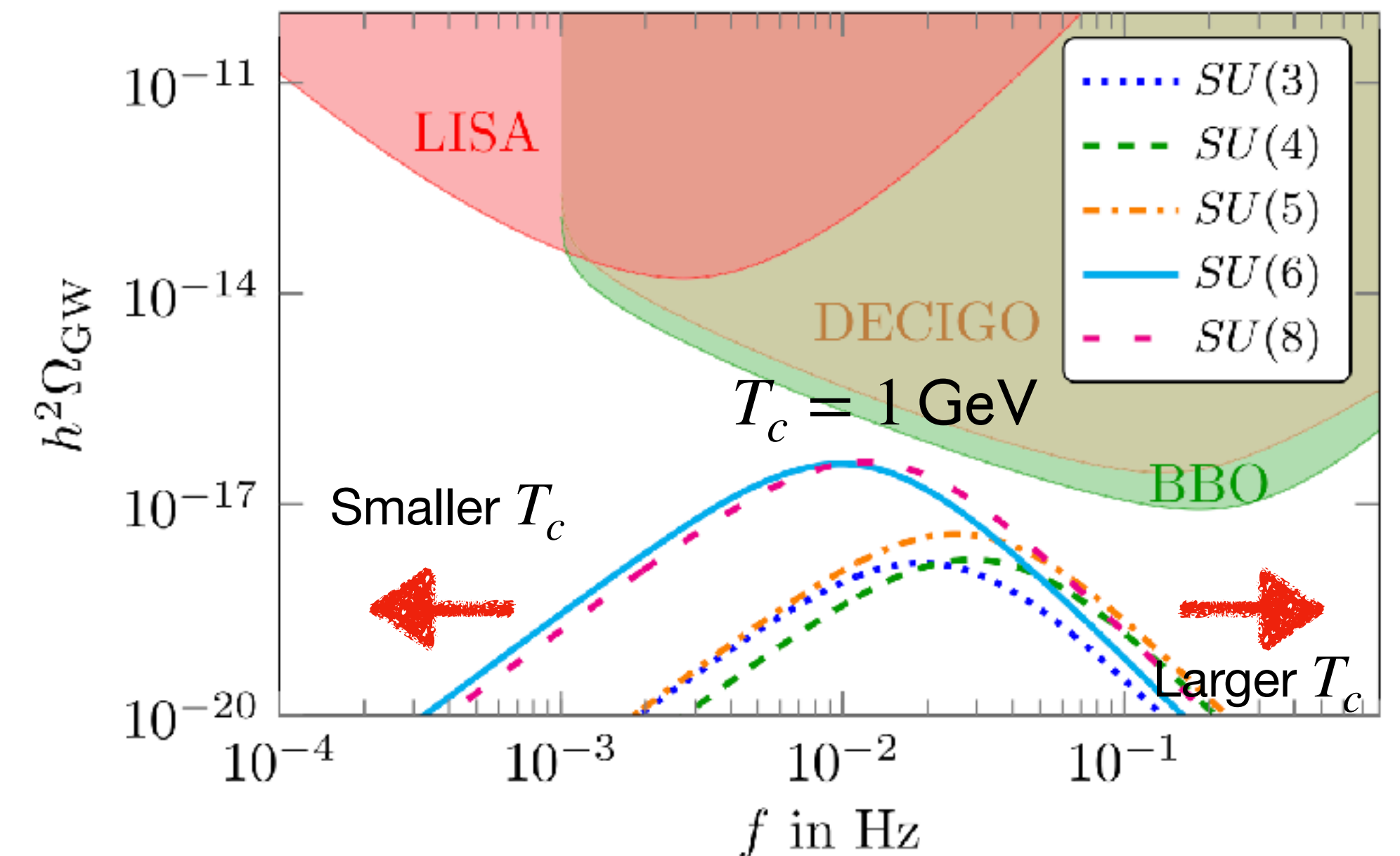
[Schwaller:1504.07263][Caprini et al.: 1910.13125]...

- The signal is relatively weak due to relatively large inverse duration of the phase transition β , but still potentially measurable by future GW experiments

[Huang, Reichert, Sannino, Wang: 2012.11614] [Morgante, Ramberg, Schwaller: 2210.11821]

Illustration: GW signal from the confinement phase transition in pure SU(N) theories calculated within PNJL model

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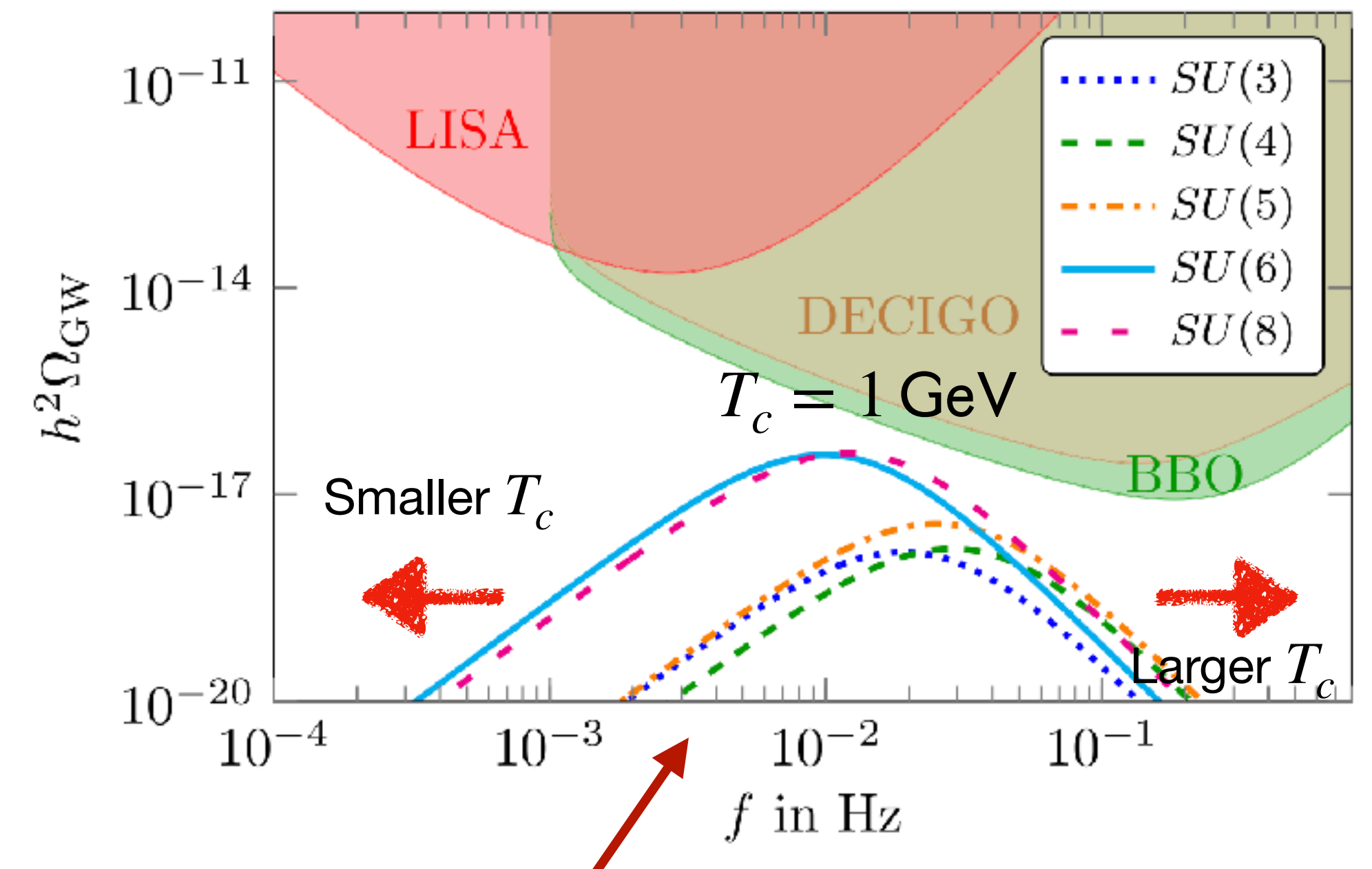
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Phase transition assumed to happen during radiation-dominated era!

Dilution of the gravitational wave signal:

I) PT during radiation domination

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

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

$$\Omega_{\text{gw},0} h^2 \simeq 1.65 \times 10^{-5} \frac{g_{e,\star}}{g_{s,\star}} \underbrace{\left(\frac{100}{g_{s,\star}} \right)^{1/3}}_{\text{Between } \sim 1 \text{ and } \sim 3 \text{ for any phase transition temperature (if SM only)}} \frac{\rho_{\text{gw},\star}}{\rho_{\text{rad},\star}}$$

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

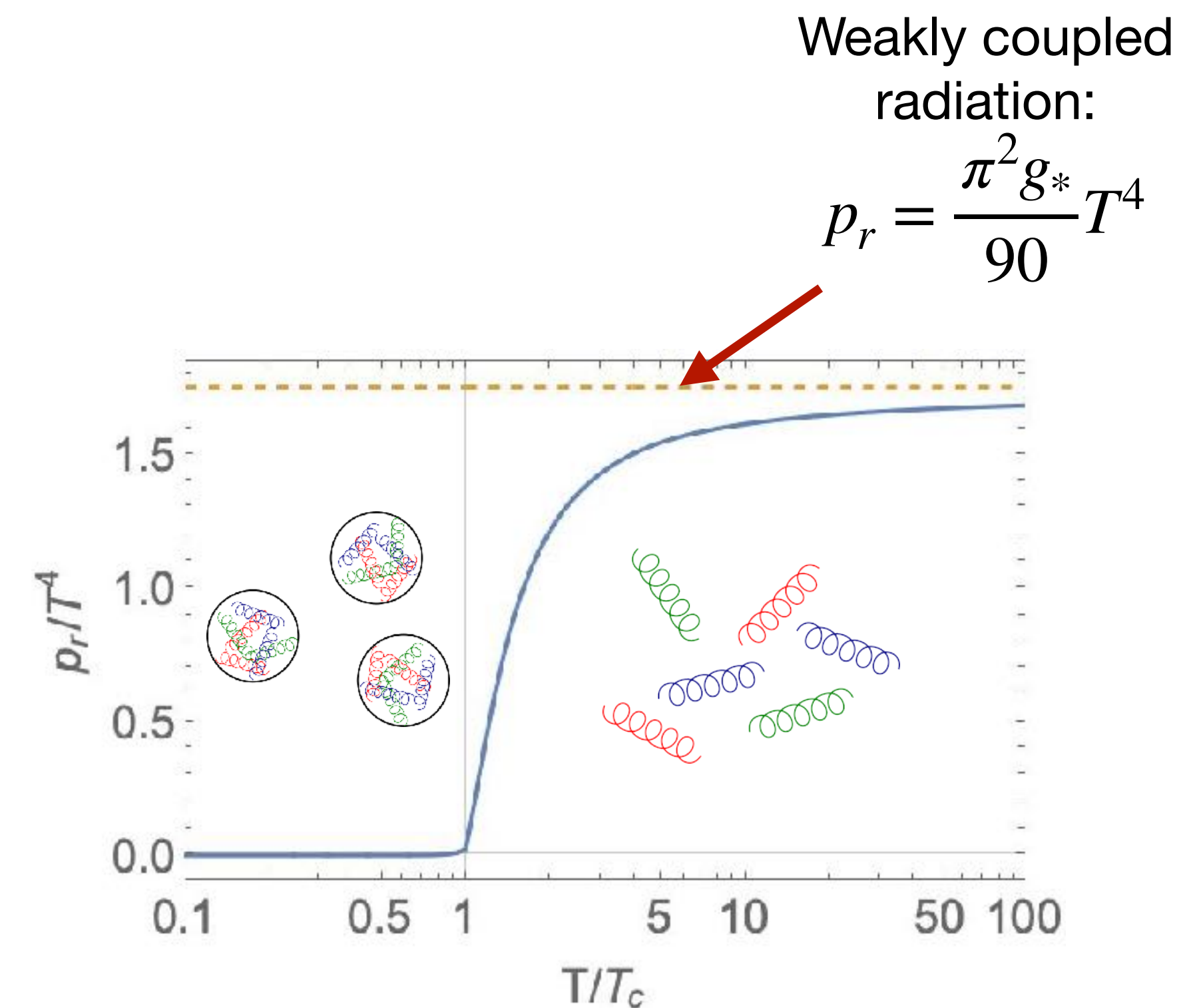
$\Omega_{\text{gw},0}$ depends only mildly on the time when PT happens
(earlier PT $\Leftrightarrow$ larger $g_{s,\star} \Leftrightarrow$ mildly suppressed GW signal)

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

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

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

- The 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)



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

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]

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

Toy model A:

Dark sector decaying into SM with decay rate Γ , matter-like after a phase transition that happens when $H = H_\star$,

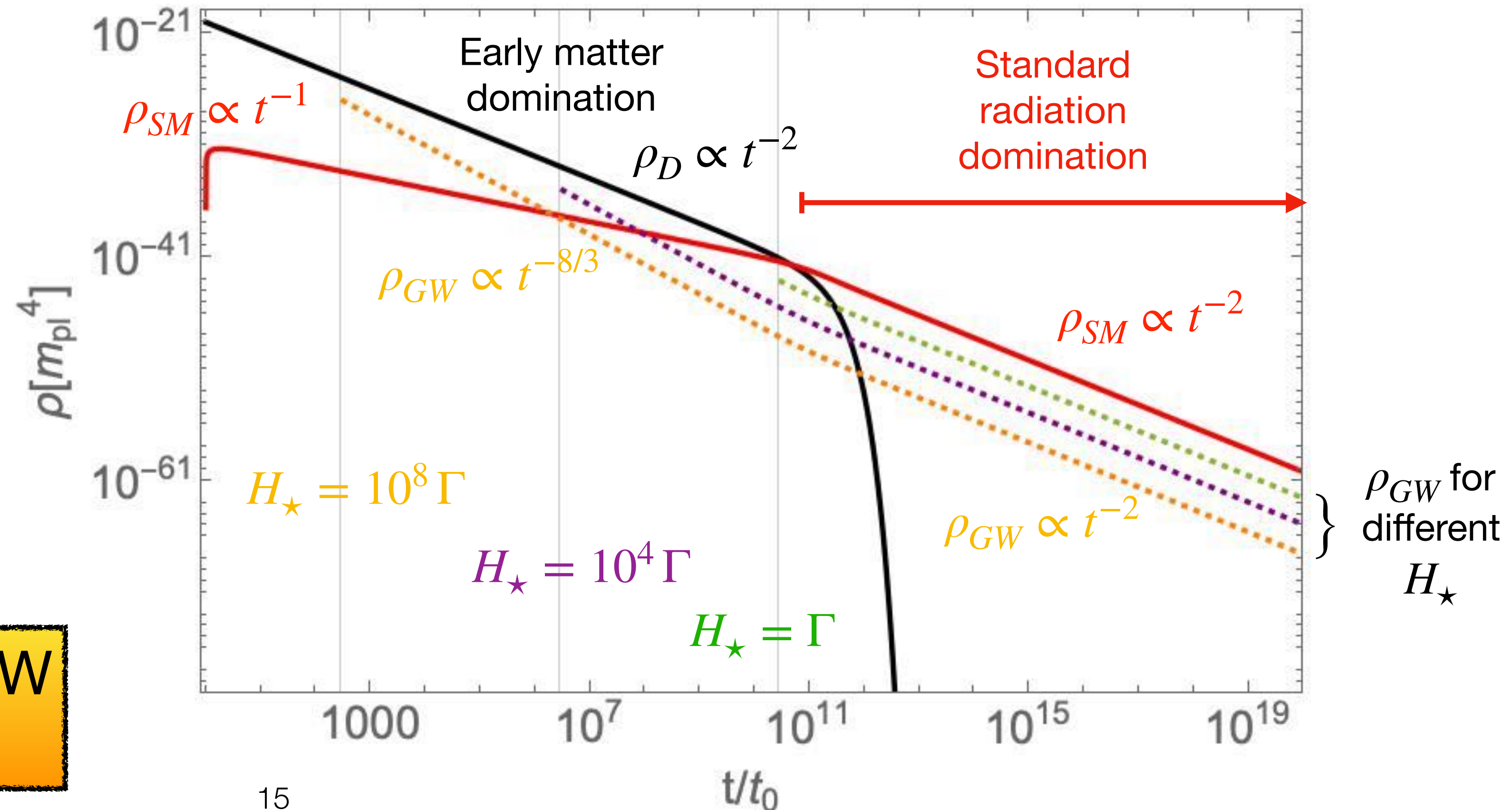
$$\rho_{\text{gw},\star} / \rho_{D,\star} = 10^{-2}$$

$$\dot{\rho}_D + 3H\rho_D = -\Gamma\rho_D$$

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

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

Sizeable suppression of the GW signal if PT happens earlier!



Dilution of the gravitational wave signal:

II) PT during matter domination

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

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Toy model B:

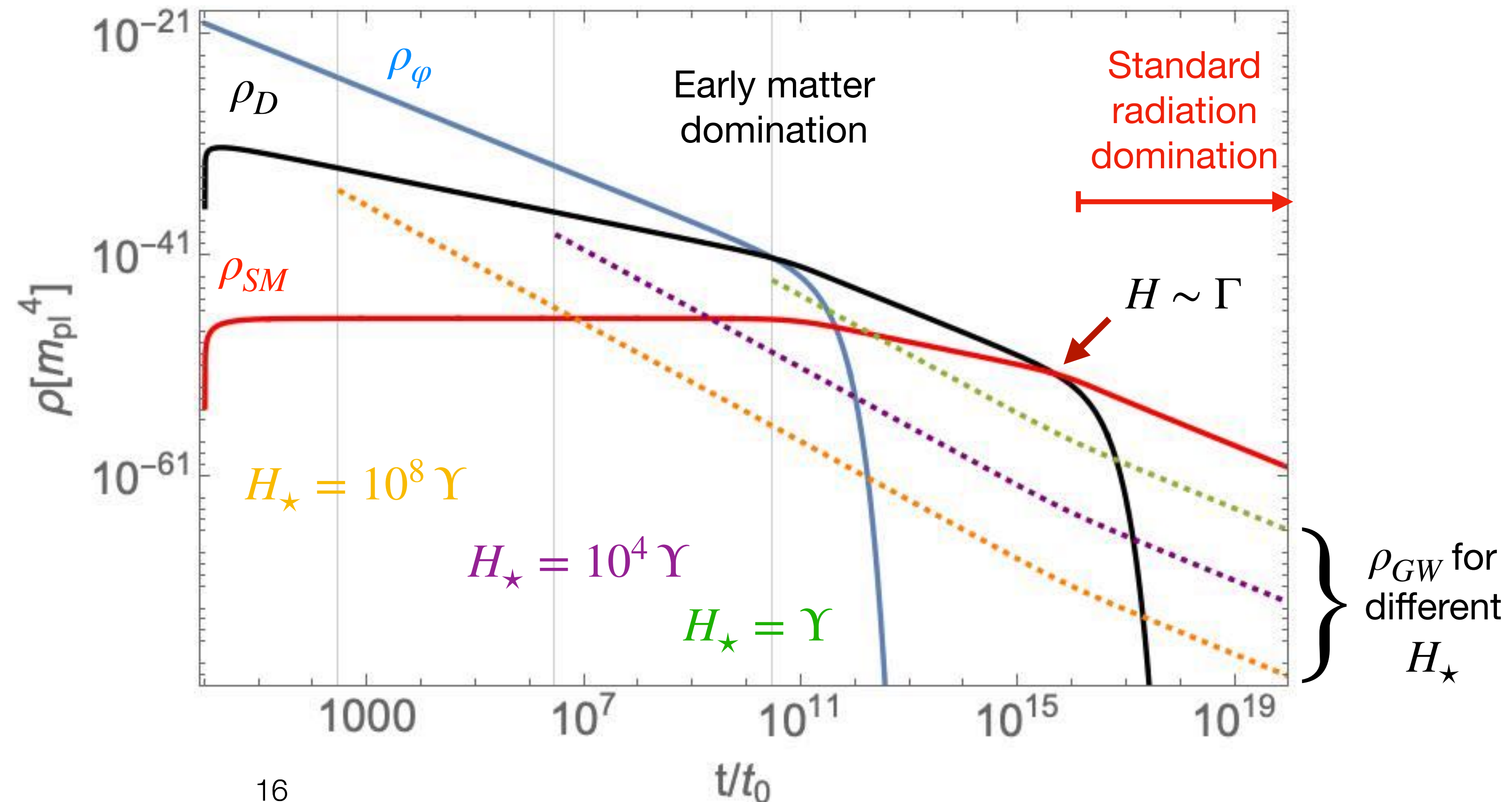
As in toy model A, but the dark sector is reheated by inflaton with equilibration rate $\Upsilon > \Gamma$

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

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

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

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



Dilution of the gravitational wave signal:

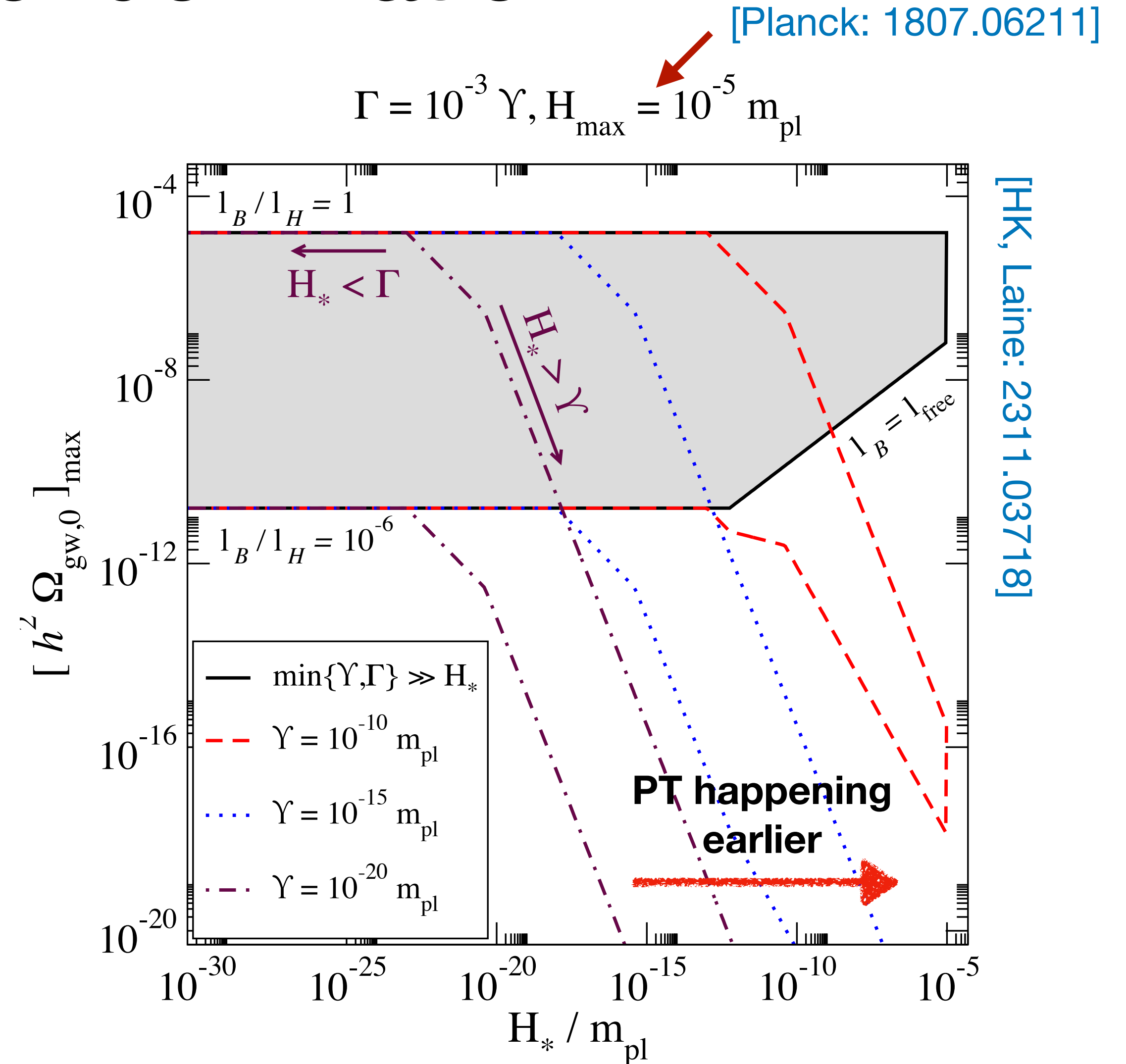
II) PT during matter domination

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

Rough estimate of the maximum possible GW signal:

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

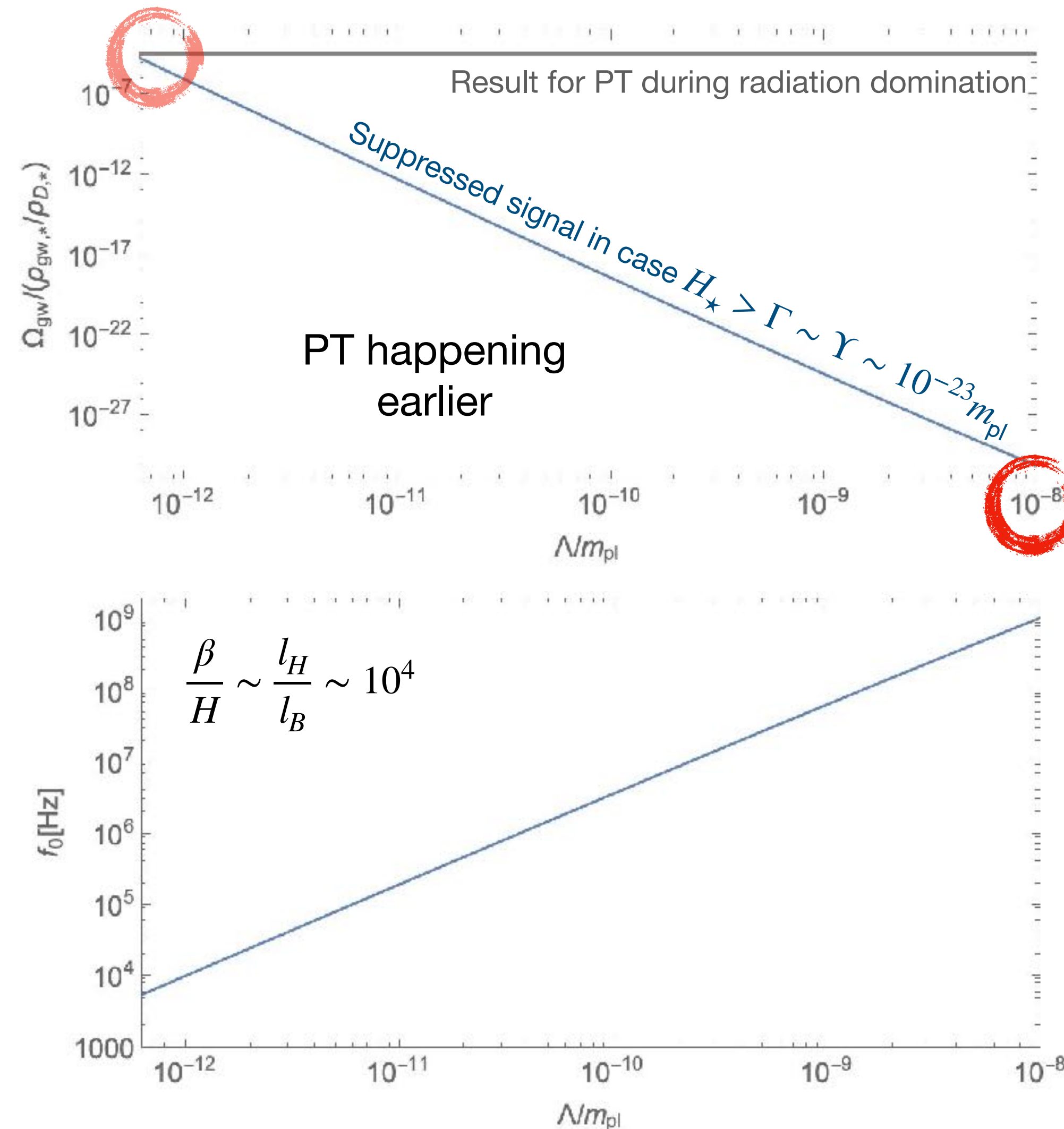
- $l_B \sim 1/\beta$... bubble length scale = scale of translation invariance breaking
- $l_H \sim 1/H$... Hubble length scale
- l_{free} ... mean free path = scale of thermal fluctuations $\Rightarrow l_B \gtrsim l_{\text{free}}$



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

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

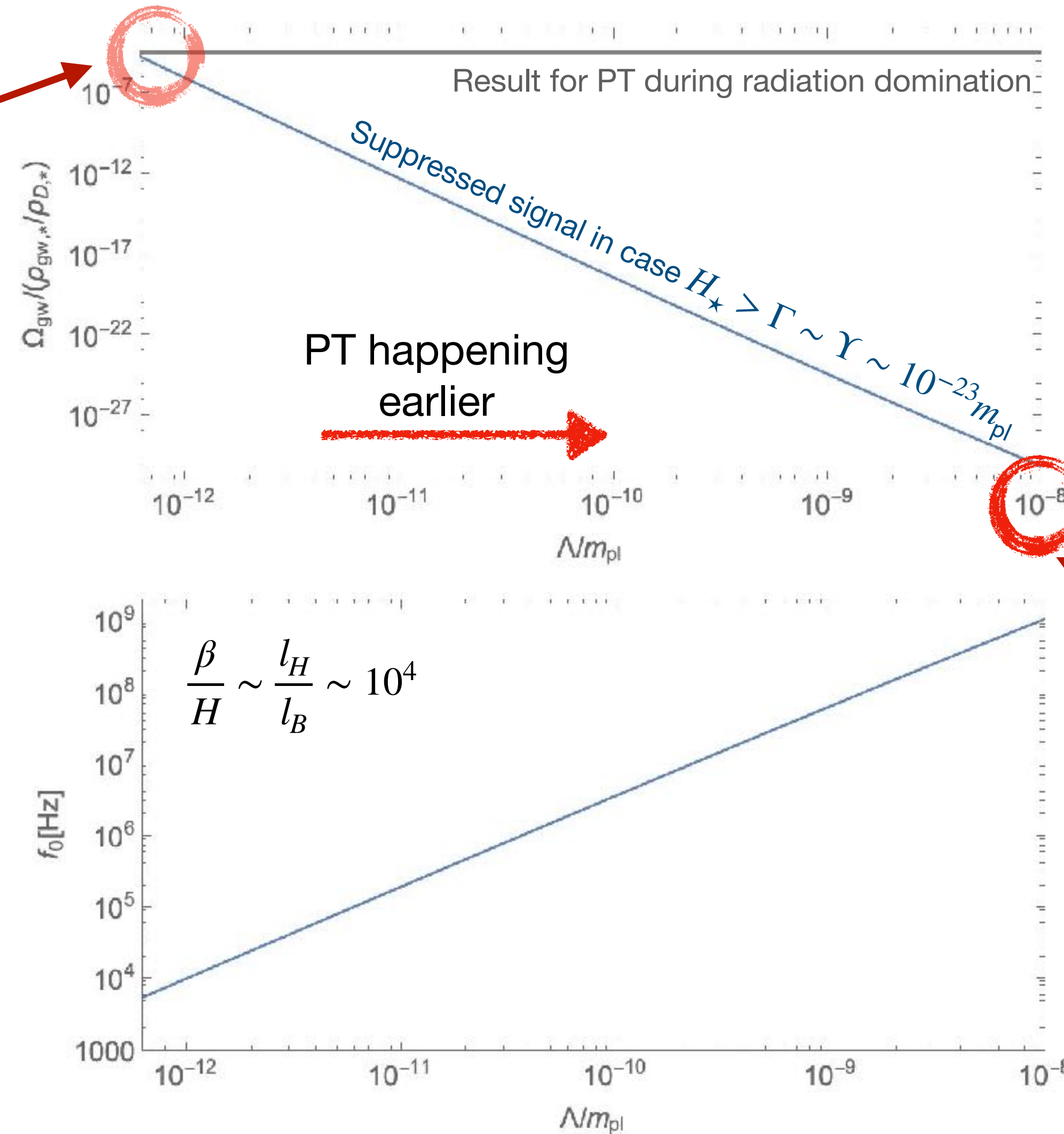
Sizeable signal only if
PT happens shortly
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$\Lambda \sim 10^{-8} m_{\text{pl}}$: “interesting” region
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(Reason why to explore the strong
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 Υ can be larger?)

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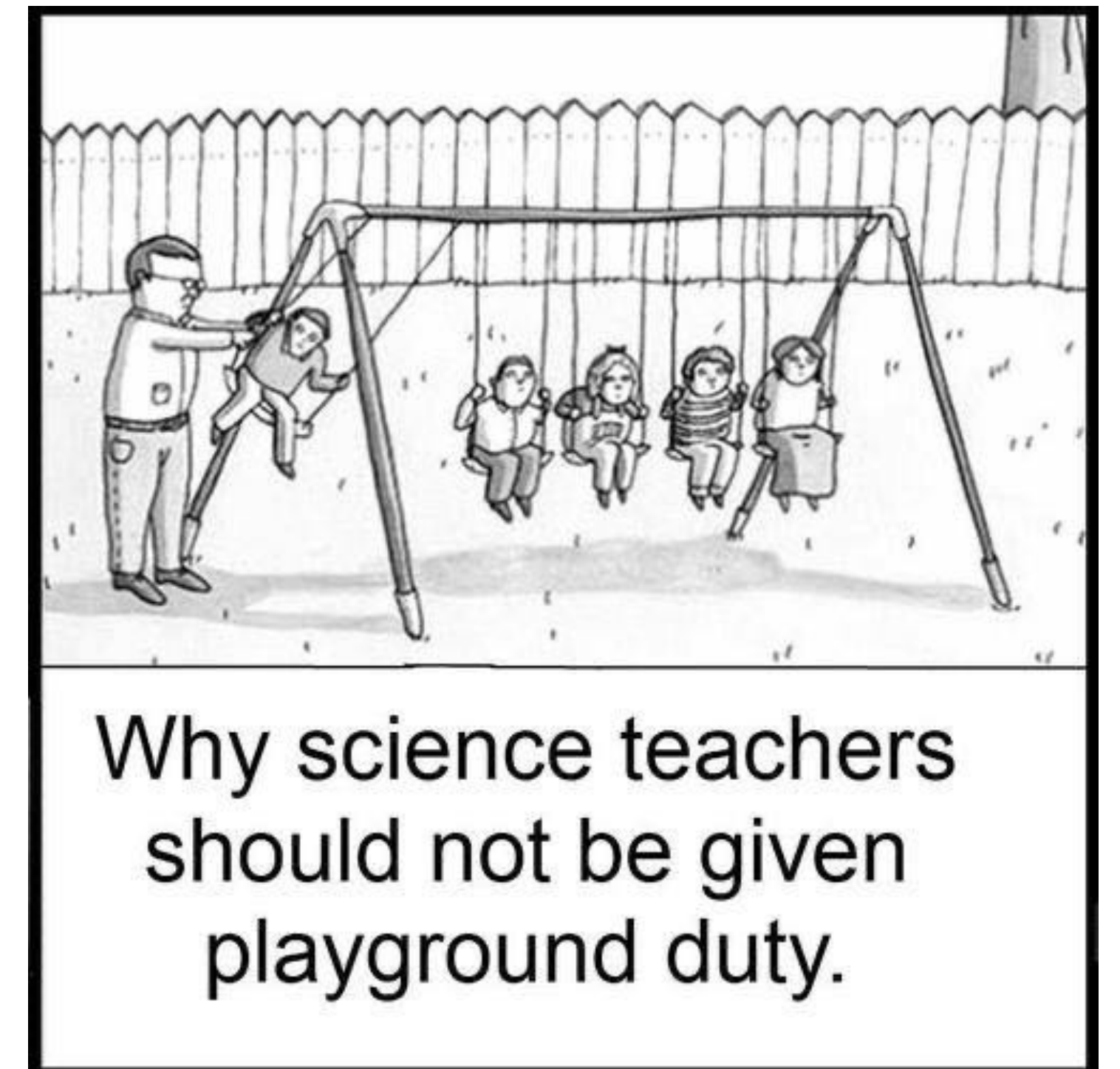
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$\Lambda \sim 10^{-8} m_{\text{pl}}$: "interesting" region where two phase transitions occur : (Reason why to explore the strong regime of warm axion inflation where Υ can be larger?)

Outline

1. Introduction to cosmological inflation
2. Model setup: Inflaton coupled to non-abelian dark sector
3. Maximum temperature of the dark sector and possible gravitational wave signals
[HK, Laine, Procacci: 2303.17973]
4. Dilution of gravitational wave signals due to early matter domination era
[HK, Laine: 2311.03718]
5. Glueball dark matter?
[Biondini, HK, Procacci: in preparation]



Glueball dark matter?

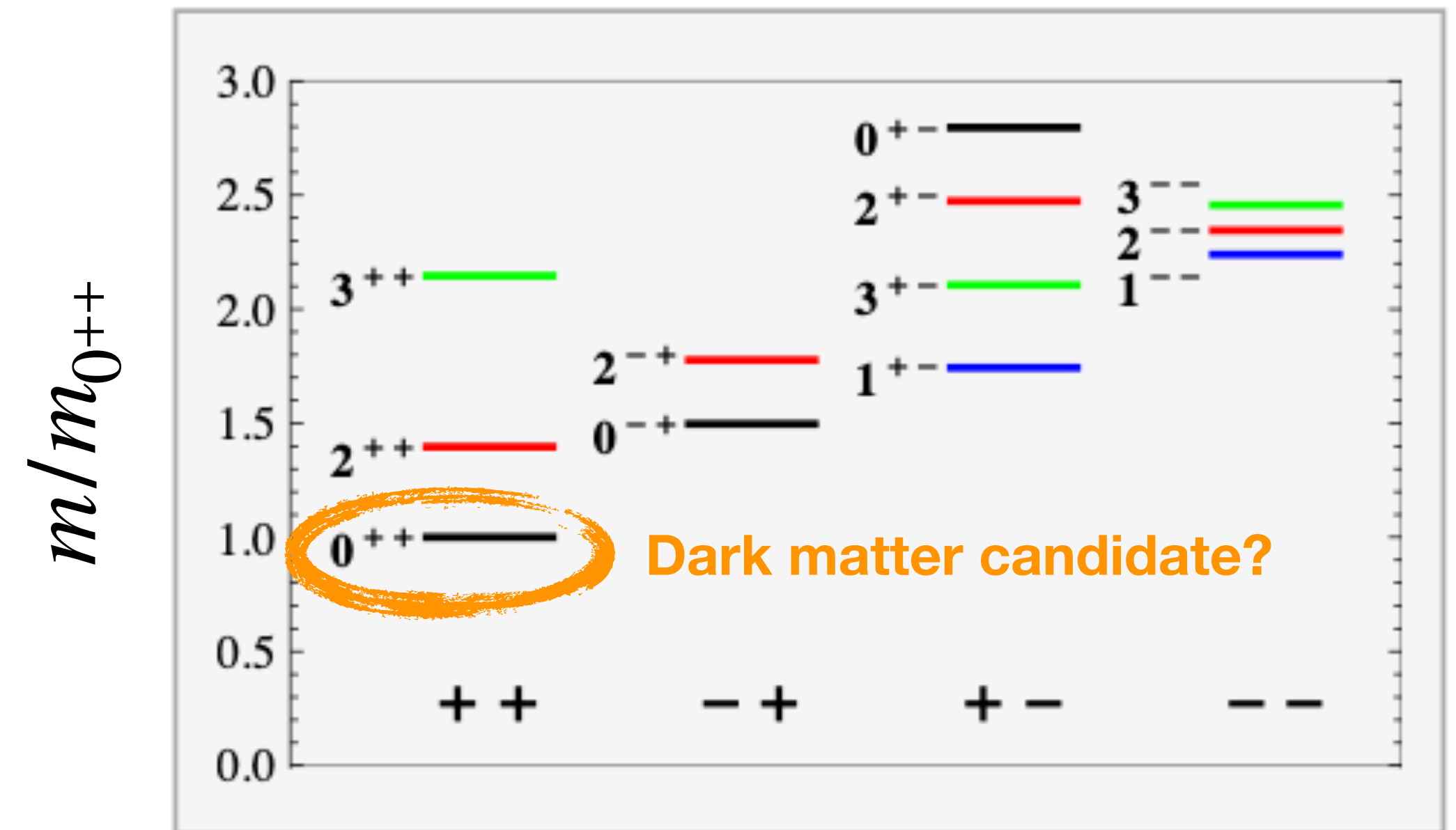
[Boddy et al.:1402.3629] [Soni, Zhang: 1602.00714] [Forestell, Morrissey, Sigurdson: 1605.08048, 1710.06447] [Carenza, Pasechnik, Wang et al.: 2207.13716, 2306.09510]...

- Self-interacting dark matter: $\sigma_{GB} \propto m_{GB}^{-2}$
 $\sigma_{GB}/m_{GB} \sim 1 \text{ cm}^2/\text{g}$ if $\Lambda \sim 100 \text{ MeV}$
- Example of the lowest order effective operator for the decay of the lightest 0^{++} glueball to SM fields:

$$\frac{|H|^2 \text{Tr } G_{\mu\nu} G^{\mu\nu}}{M^2} \Rightarrow \Gamma_{0^{++}} \sim \frac{\Lambda^5}{M^4}$$

- If the lightest glueball forms dark matter: $1/\Gamma_{0^{++}} \gtrsim 10^{26} \text{ s}$
- Even if $M \sim m_{\text{pl}}$ this translates to $\Lambda \lesssim 10^6 \text{ GeV}$

Spectrum of SU(3) glueballs J^{PC}



[Juknevich, Melnikov, Strassler: 0903.0883]

Glueball dark matter?

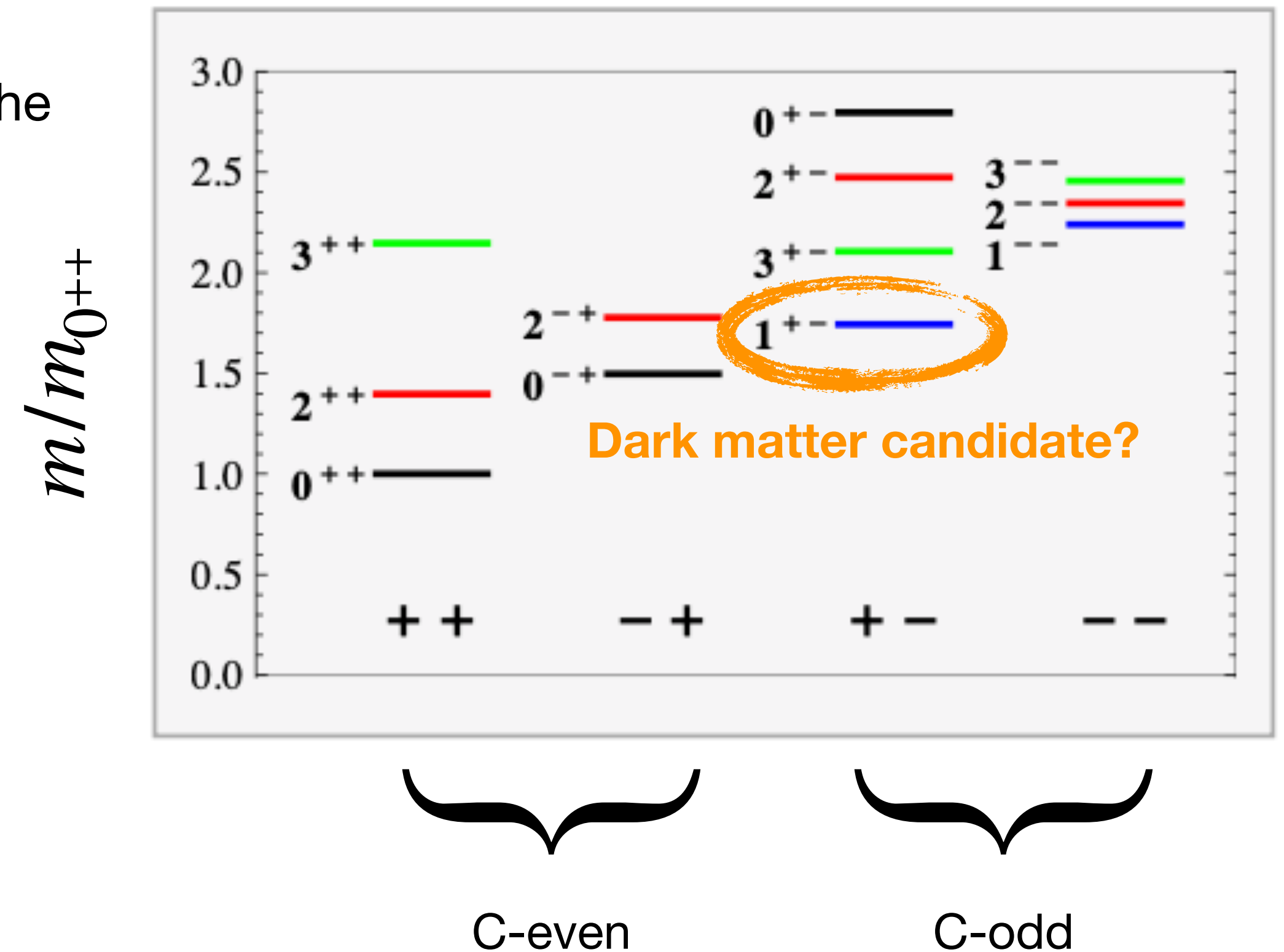
[Gross, Karamitos, Landini, Strumia: 2012.12087]

- C-odd glueballs protected from (co)decay to two C-even glueballs
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$$\frac{B_{\mu\nu} \text{Tr} G^{\mu\nu} G_{\alpha\beta} G^{\alpha\beta}}{M^4} \Rightarrow \Gamma_{\text{odd}} \sim \frac{\Lambda^9}{M^8}$$

- If DM formed by the lightest C-odd glueball 1^{+-} , large Λ is possible!

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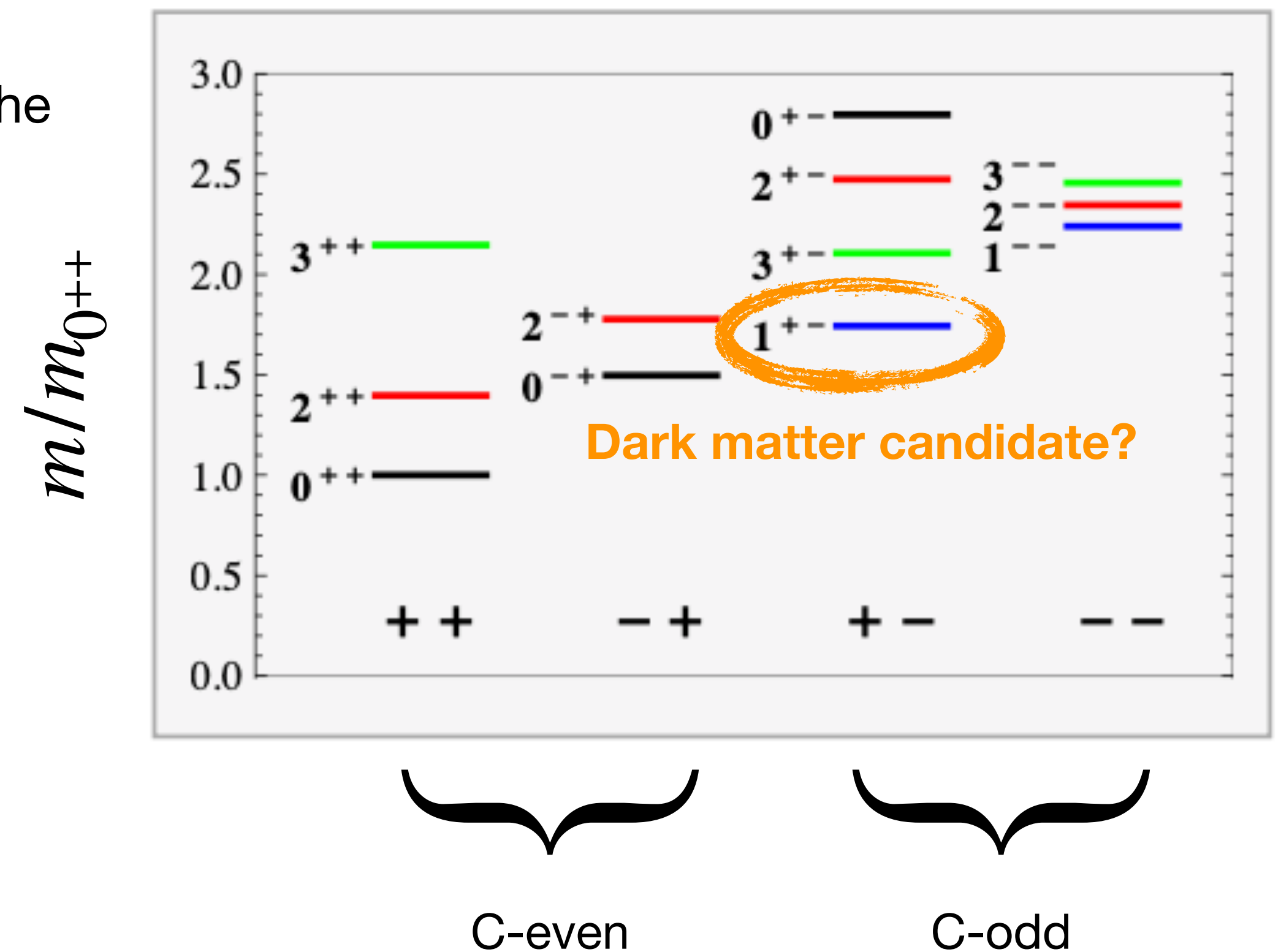
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C-even glueballs could reheat the SM and the C-odd glueballs could form dark matter!

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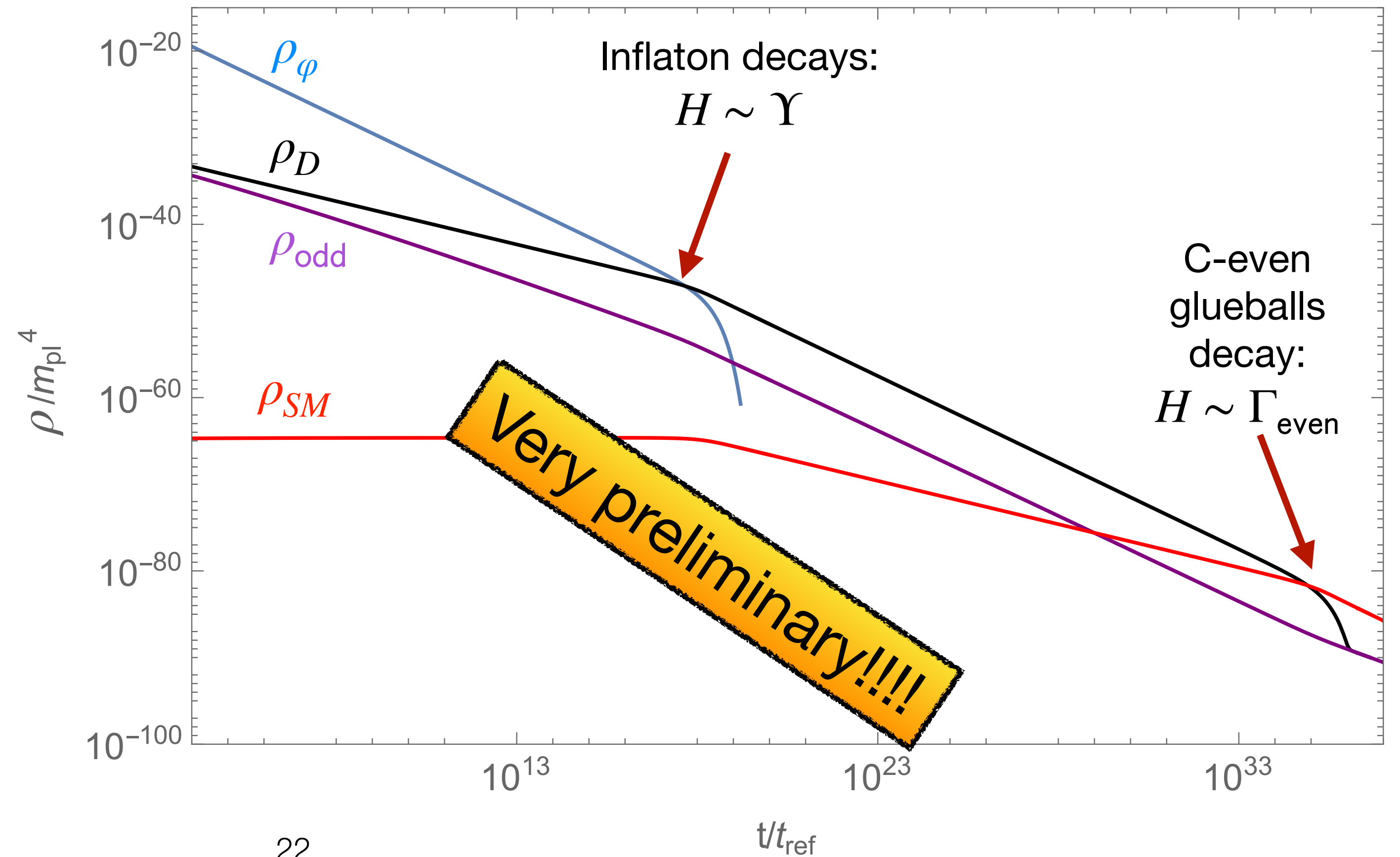
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[Biondini, HK, Procacci: in preparation]



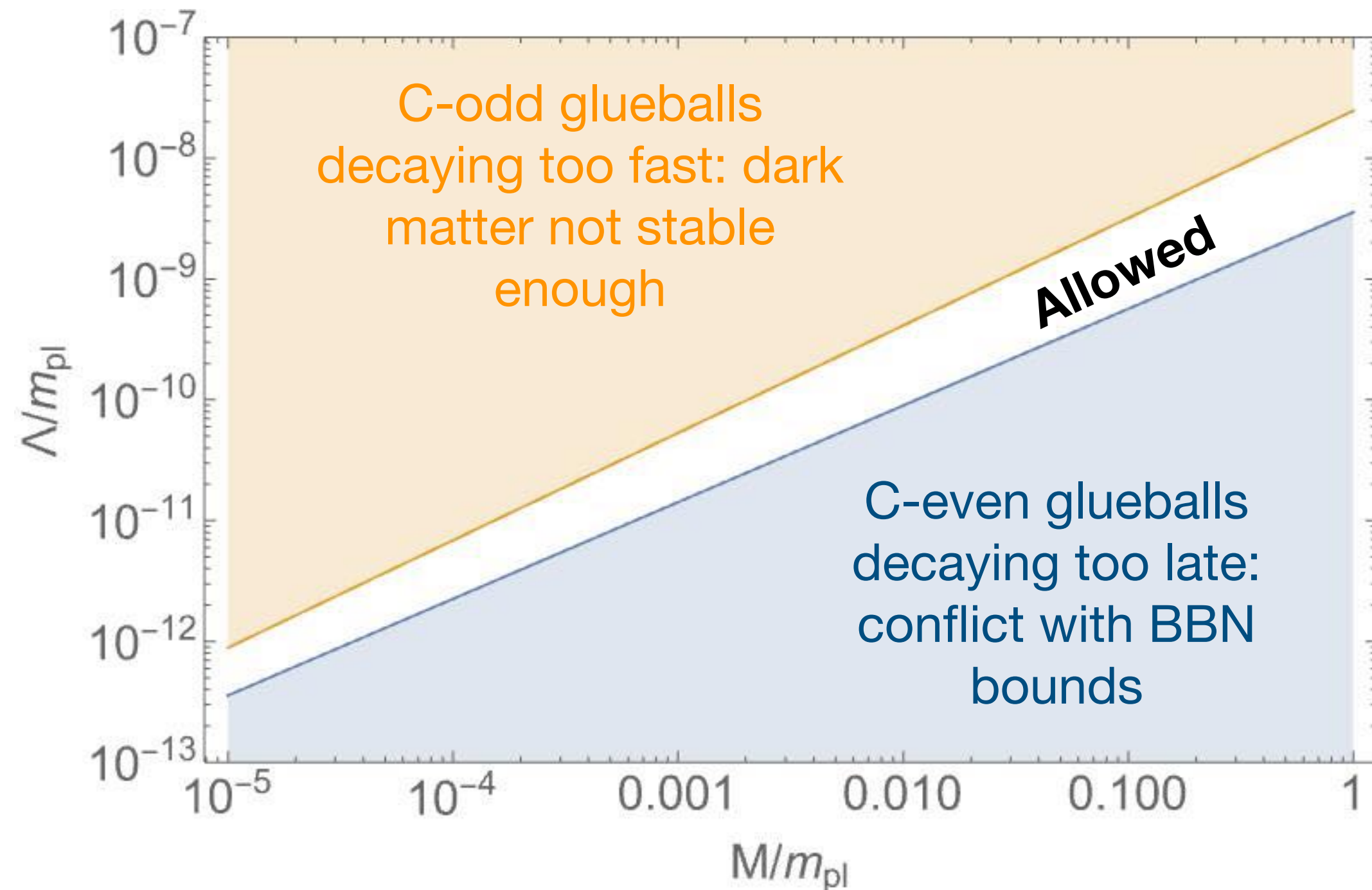
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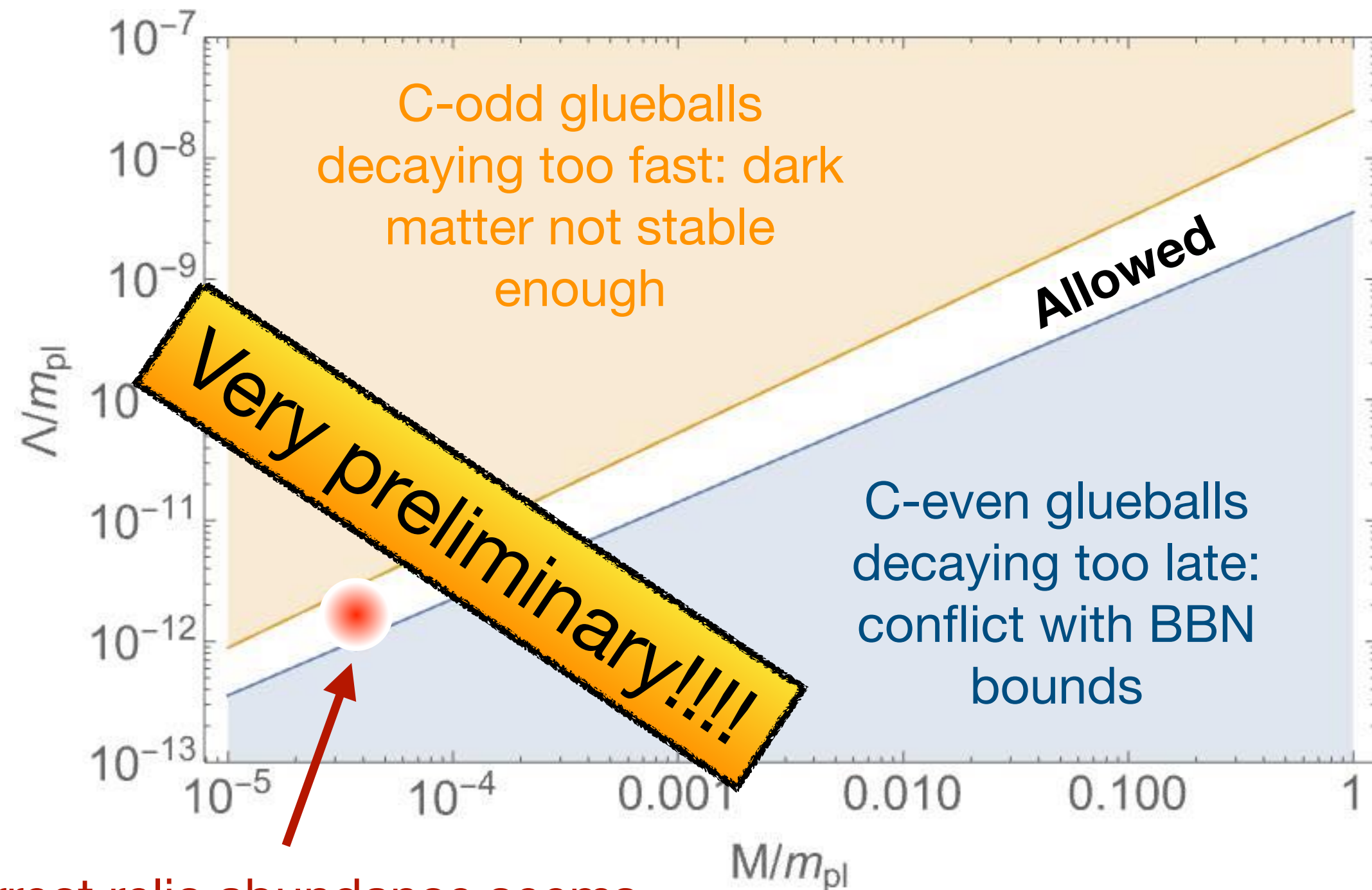
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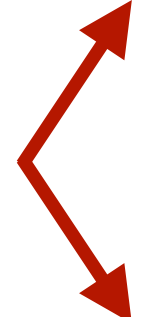


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Correct relic abundance seems to be obtained somewhere here

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
 - Glueball dark matter for $\Lambda \sim 10^{-12} m_{\text{pl}}$?
- **In general**: early matter dominated era can substantially dilute GW signal. On the other hand, this might perhaps rescue some models that seem to be excluded by GW overproduction?

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Stay tuned :) Thanks for your attention!

Back up

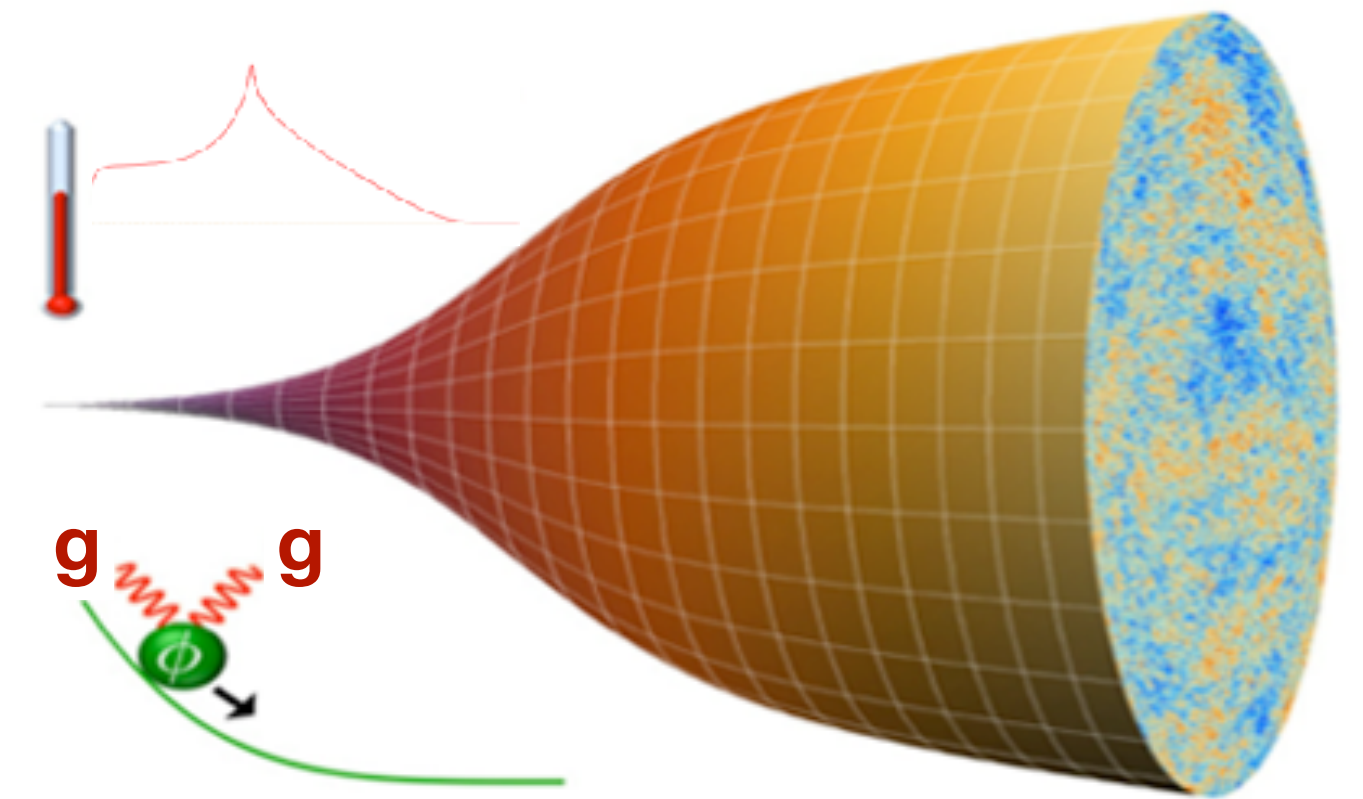
Inspiration: warm inflation

- 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]

Strong regime: thermal friction dominates

Weak regime: Hubble friction dominates

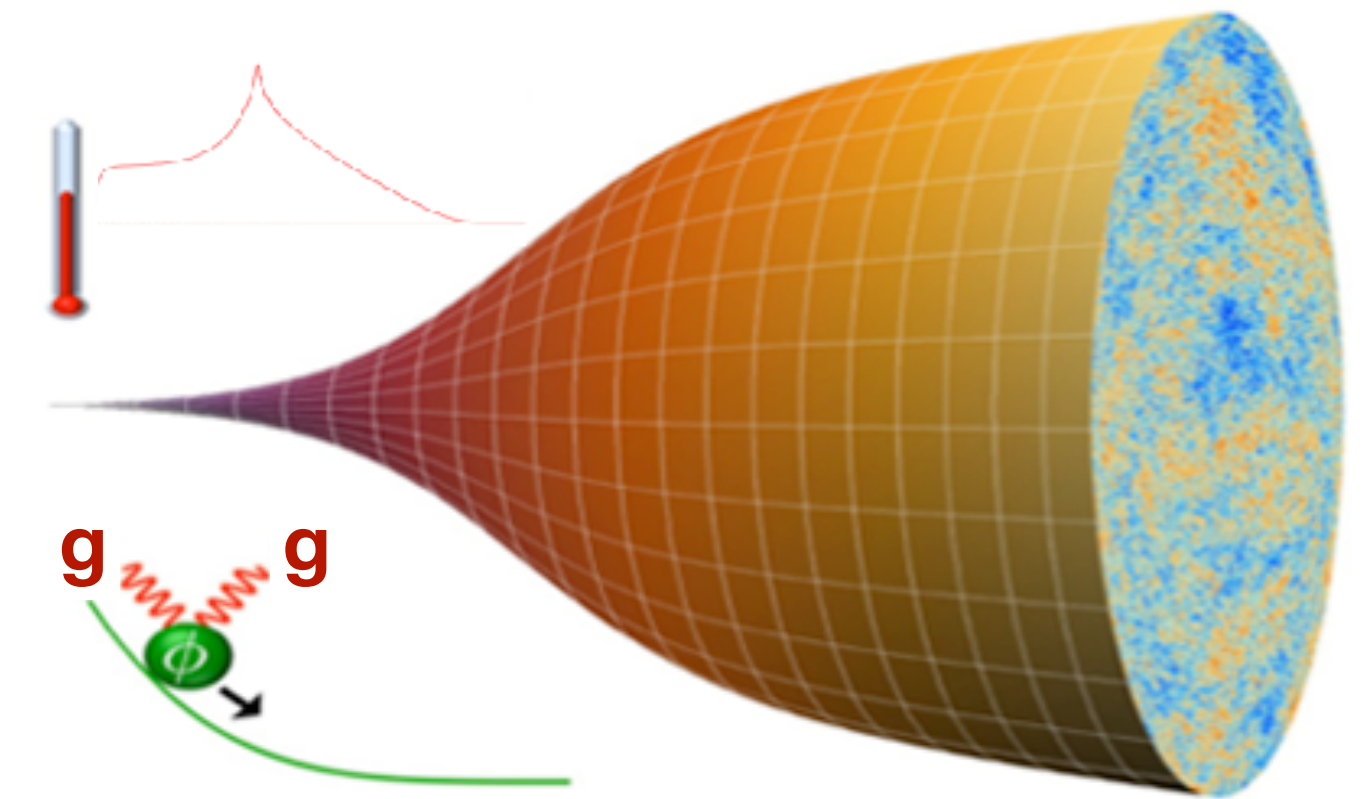


Credit: João G. Rosa/University of Aveiro; ESA and the Planck collaboration

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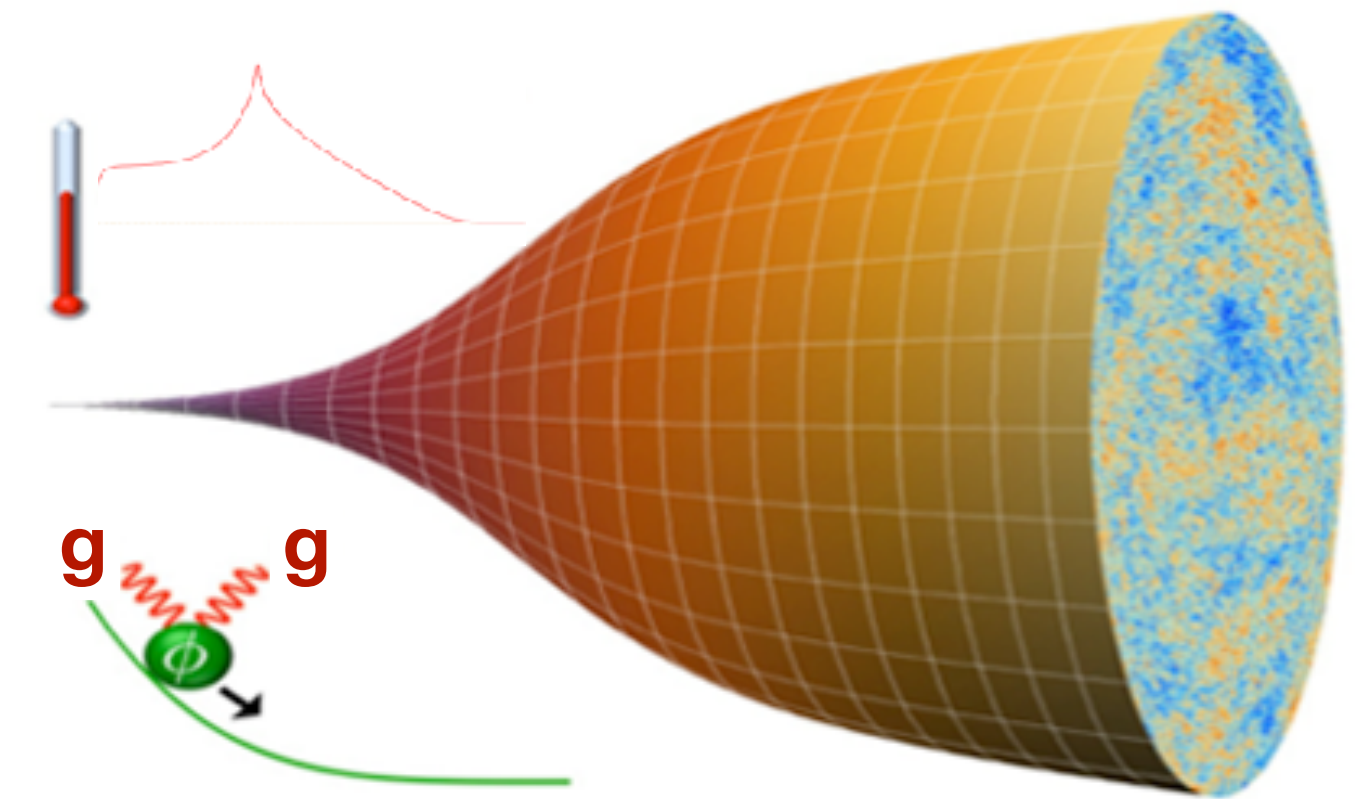
- Concrete realisation: warm axion inflation - coupling to non-abelian gauge fields

[Berghaus, Graham, Kaplan: 1910.07525]
[Laine, Procacci: 2102.09913]
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⇒ (Dark) Yang-Mills sector!

Focus of this talk!

[Berghaus, Graham, Kaplan: 1910.07525]
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Why is high temperature interesting?

- Possible gravitational wave signal:

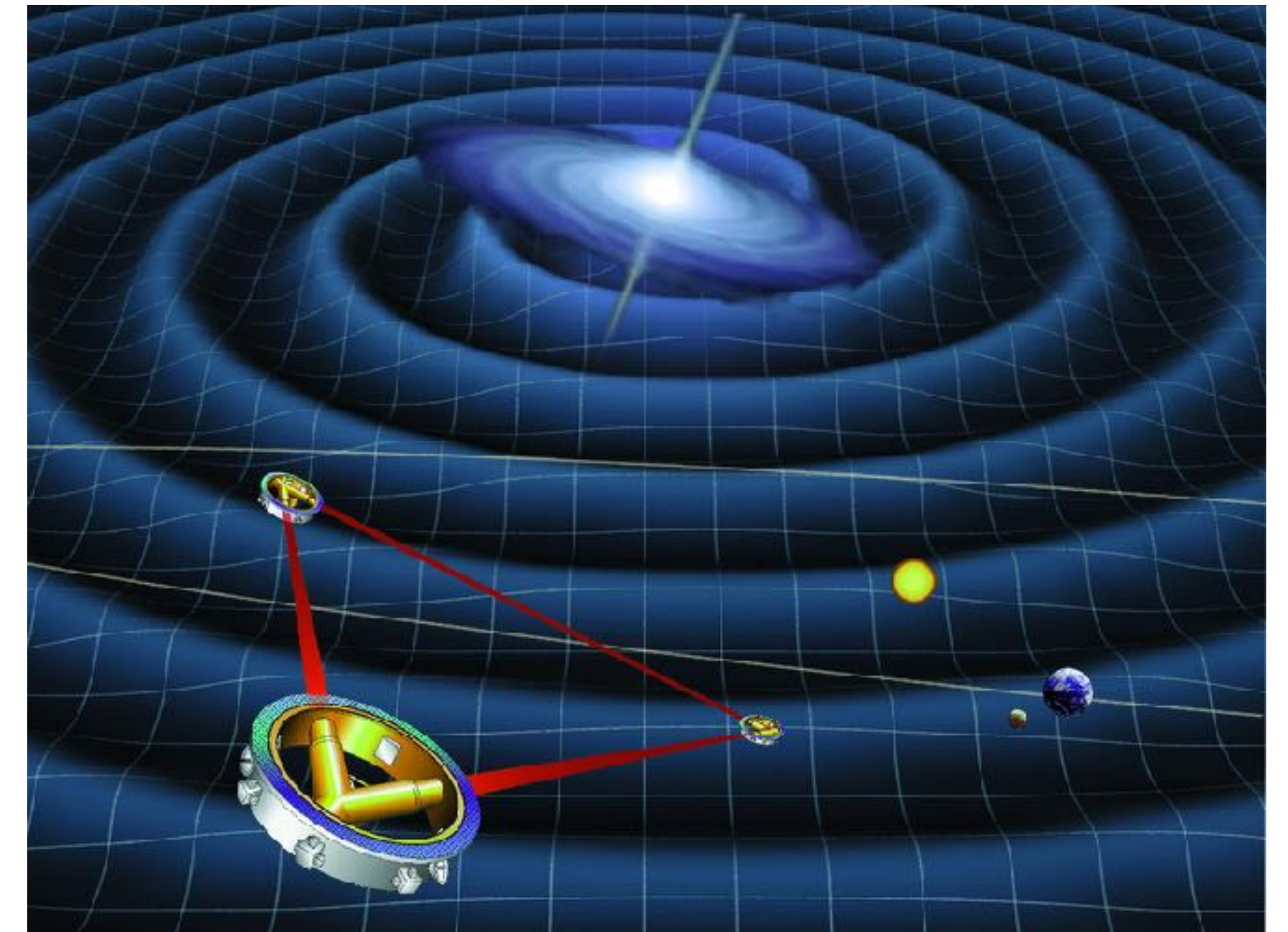
Thermal fluctuations

[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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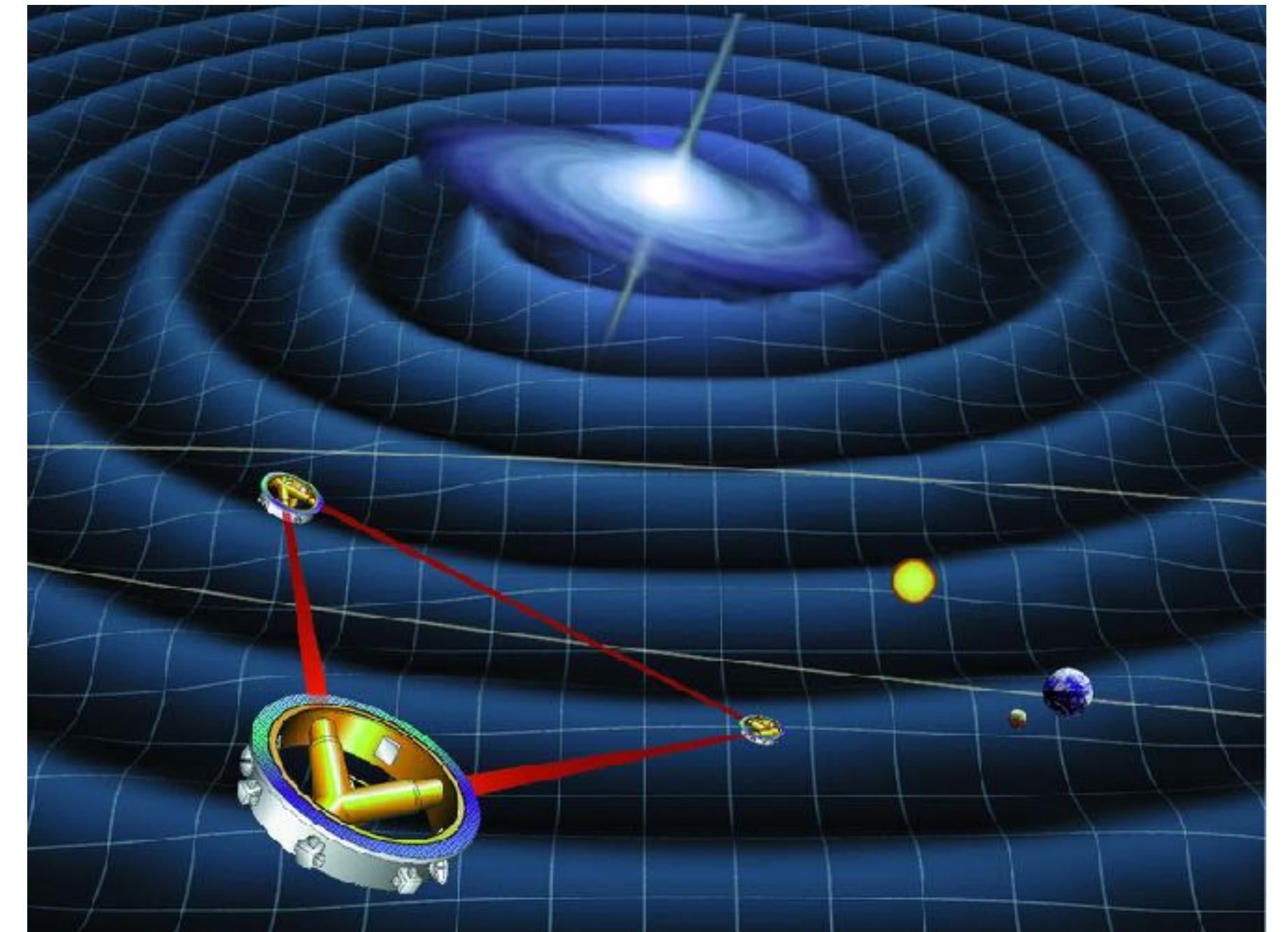
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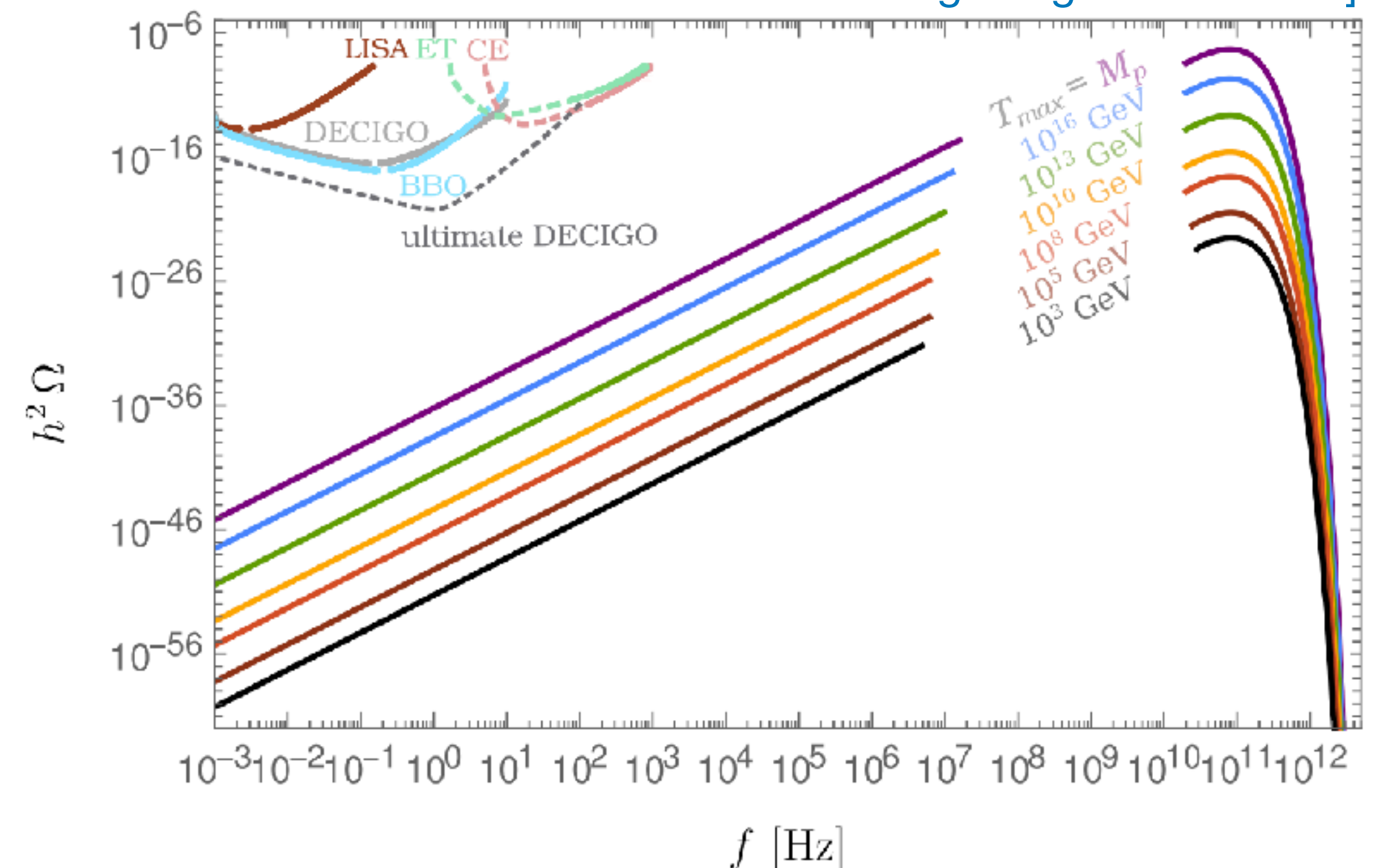
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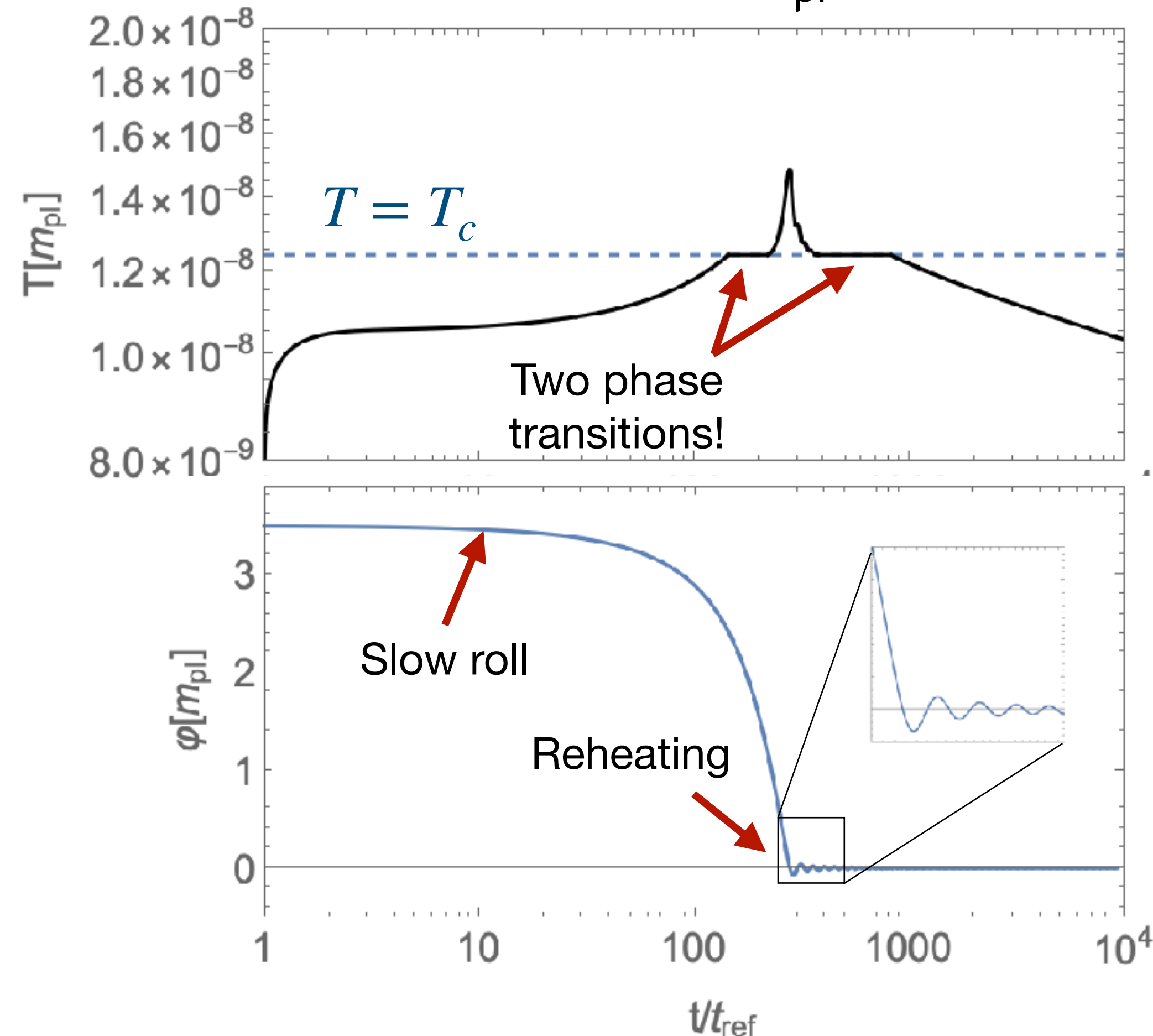
- But has the dark sector heated up above the confinement temperature?
- Amplitude of gravitational waves from thermal fluctuations grows significantly with maximum reached temperature!

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



There can even be two phase transitions!

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



Benchmark parameter choice
(axion inflation consistent with CMB data)

[Klose, Laine, Procacci: 2201.02317]:

axion mass: $m = 1.09 \times 10^{-6} m_{\text{pl}}$,

axion decay constant: $f_a = 1.25 m_{\text{pl}}$,

initial time: $t_{\text{ref}} \sim H_{\text{initial}}^{-1}$

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

- Heating and cooling phase transitions may bring interesting GW signatures!

[Buen-Abad, Chang, Hook: 2305.09712]

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

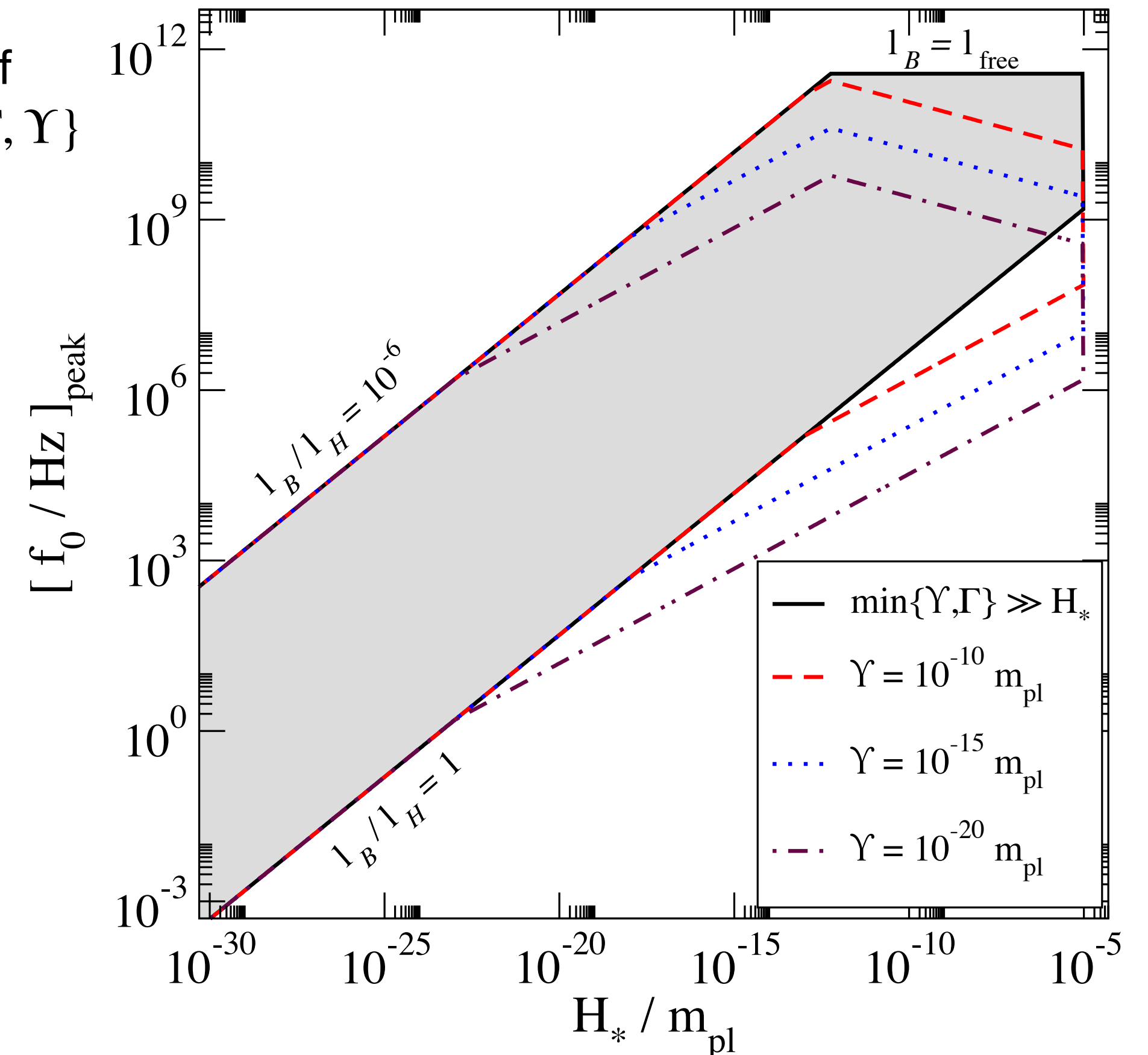
Dilution of the gravitational wave signal:

II) PT during matter domination

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

$$\Gamma = 10^{-3} \Upsilon, H_{\text{max}} = 10^{-5} m_{\text{pl}}$$

- $l_B \sim 1/\beta$... bubble length scale = scale of breaking of the spherical symmetry
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- $l_B \gtrsim l_{\text{free}} \Rightarrow$ upper bound on peak GW frequency when $H_\star$ close to H_{max}



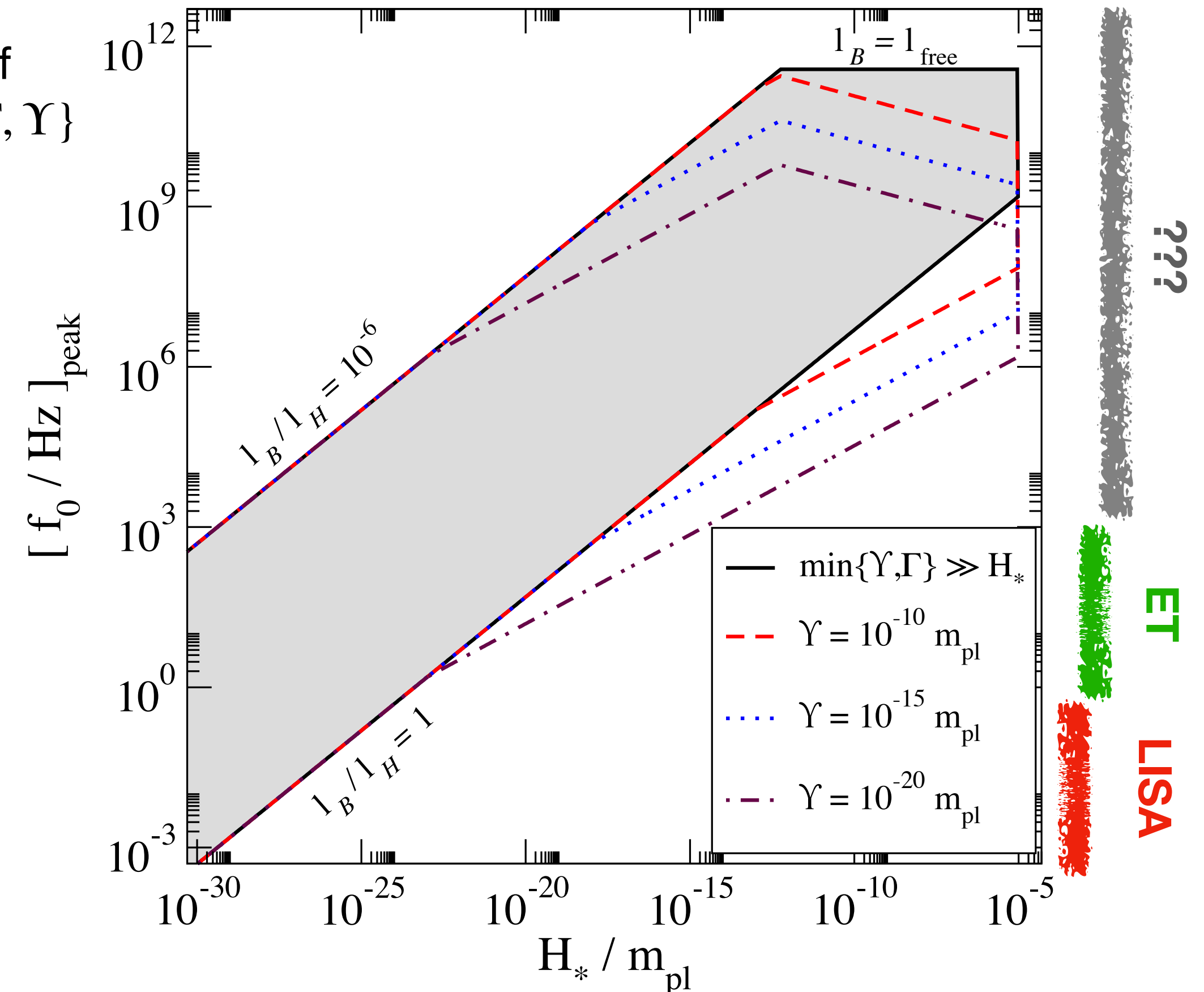
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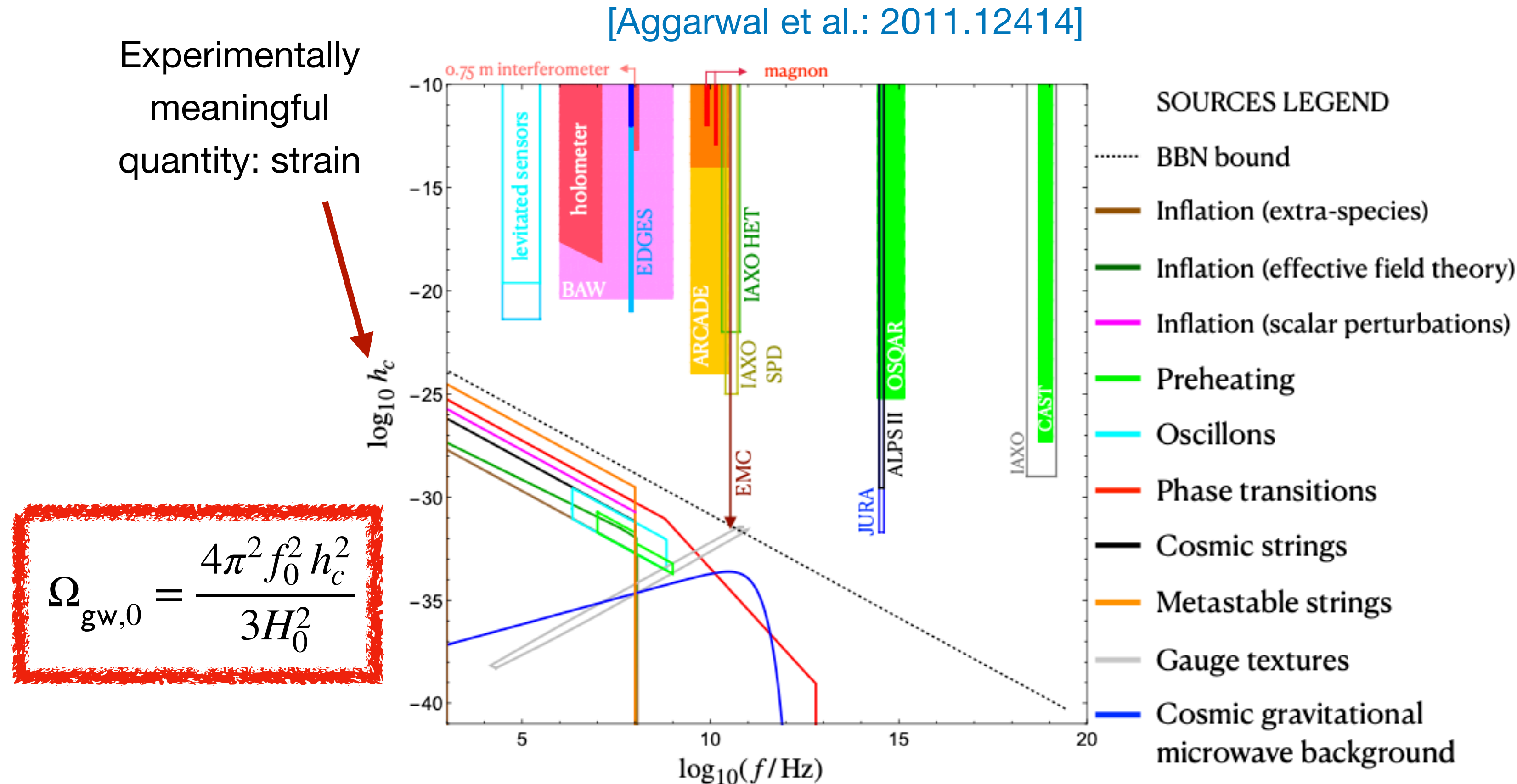
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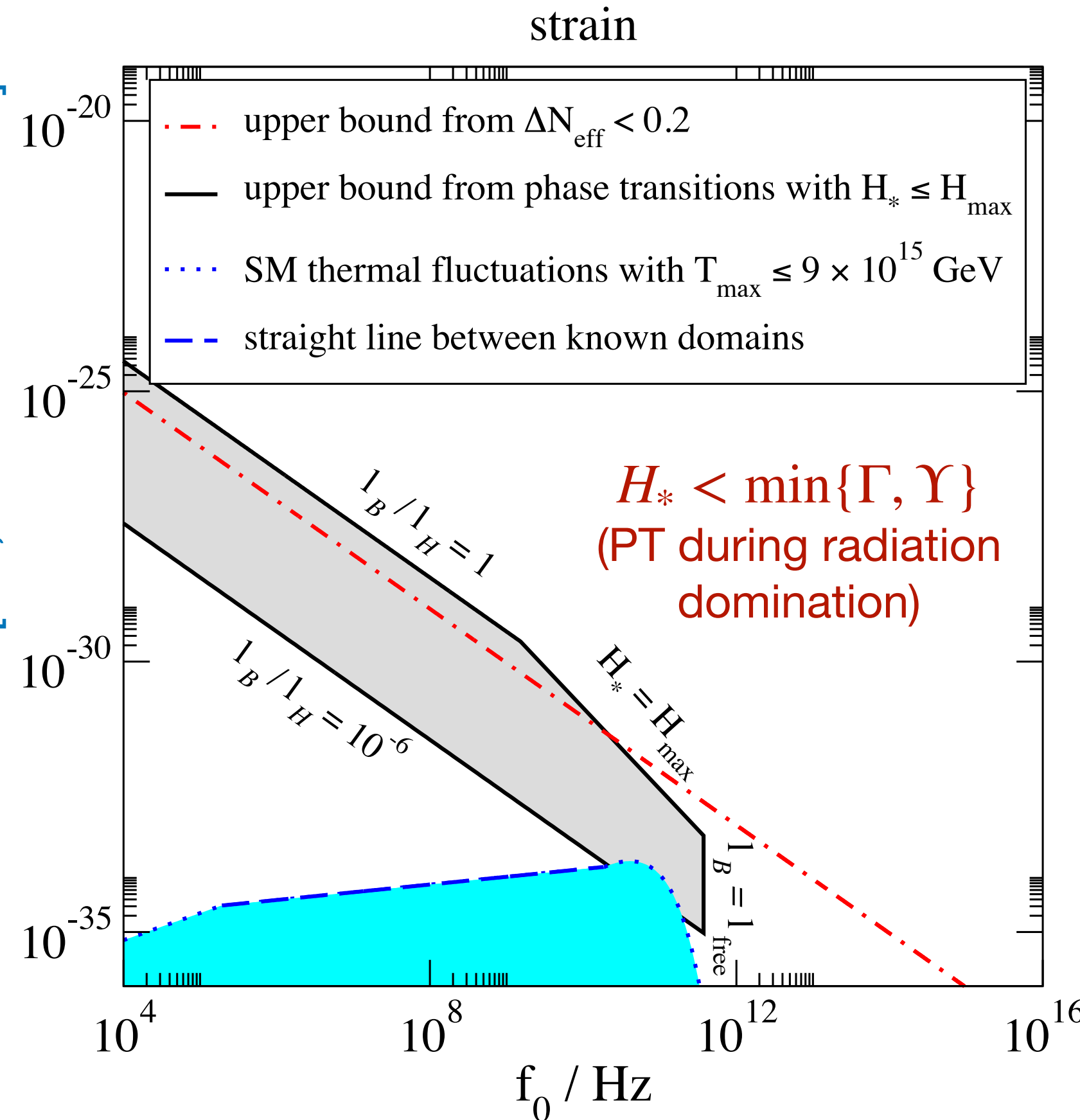
Ultra-high frequency GW



- No known astrophysical sources of GW at MHz to GHz frequencies $\Rightarrow$ unique opportunity to learn about BSM physics!
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Ultra-high frequency GW

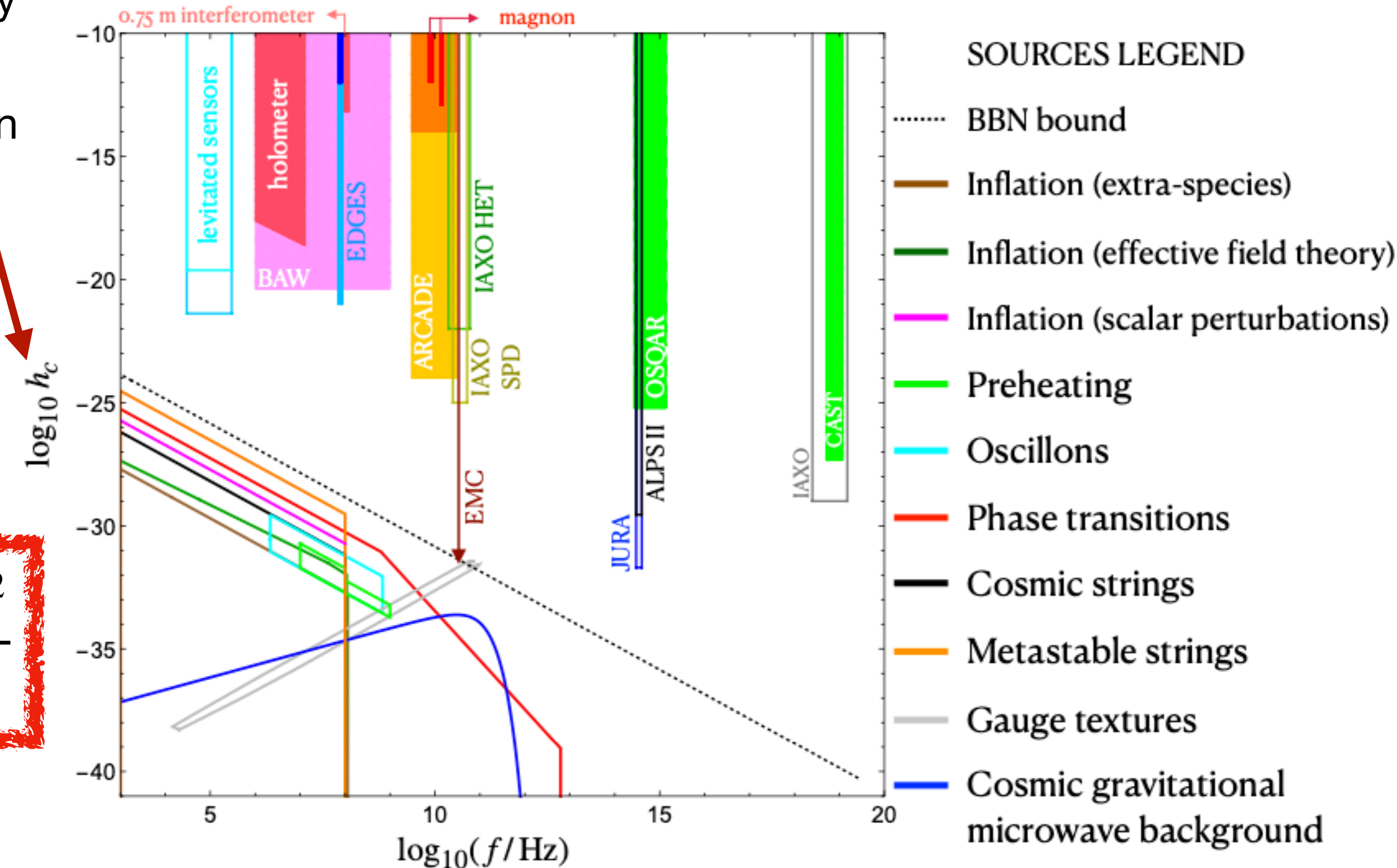
[HK, Laine: 2311.03718]



Experimentally
meaningful
quantity: strain

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

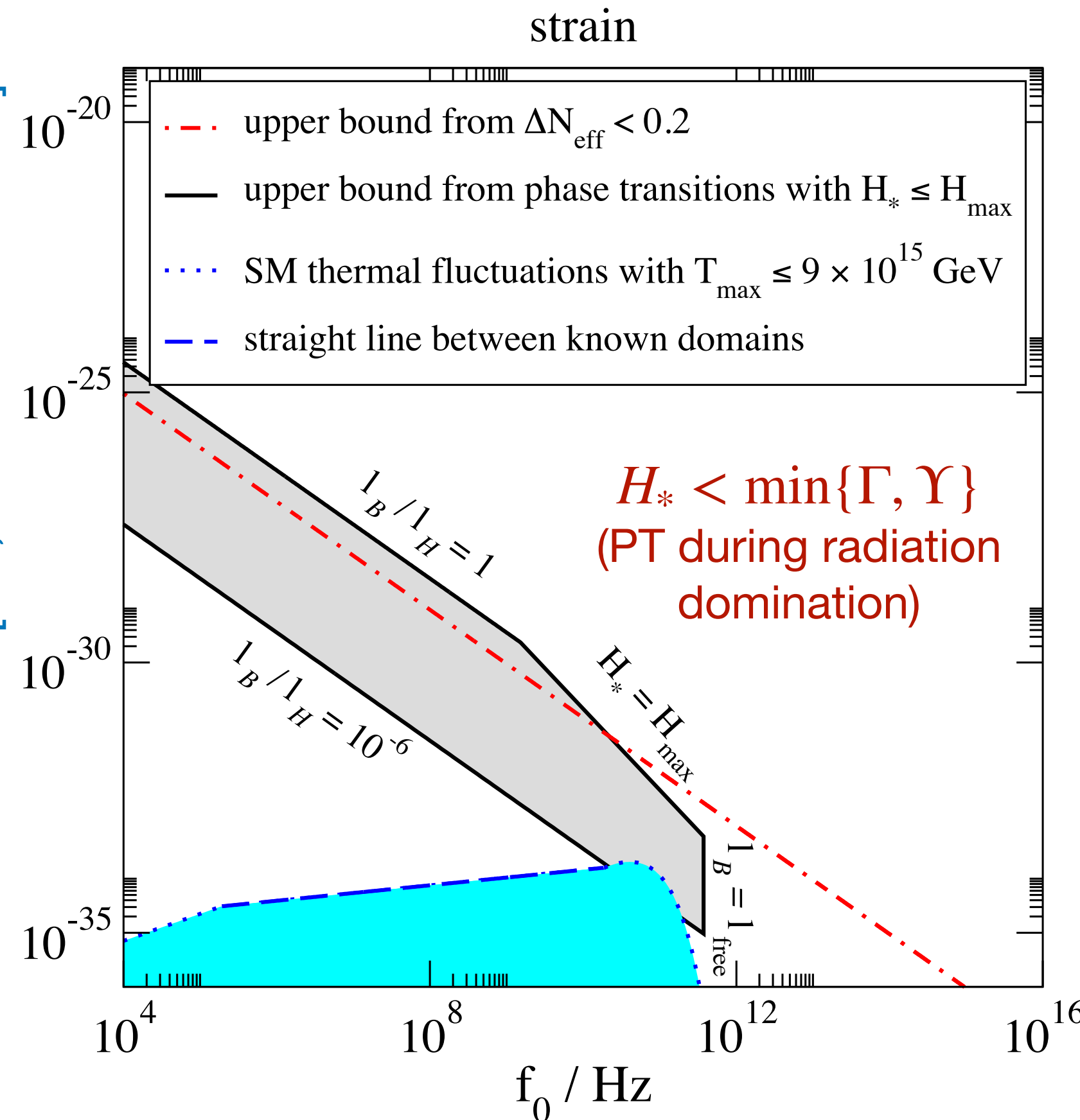
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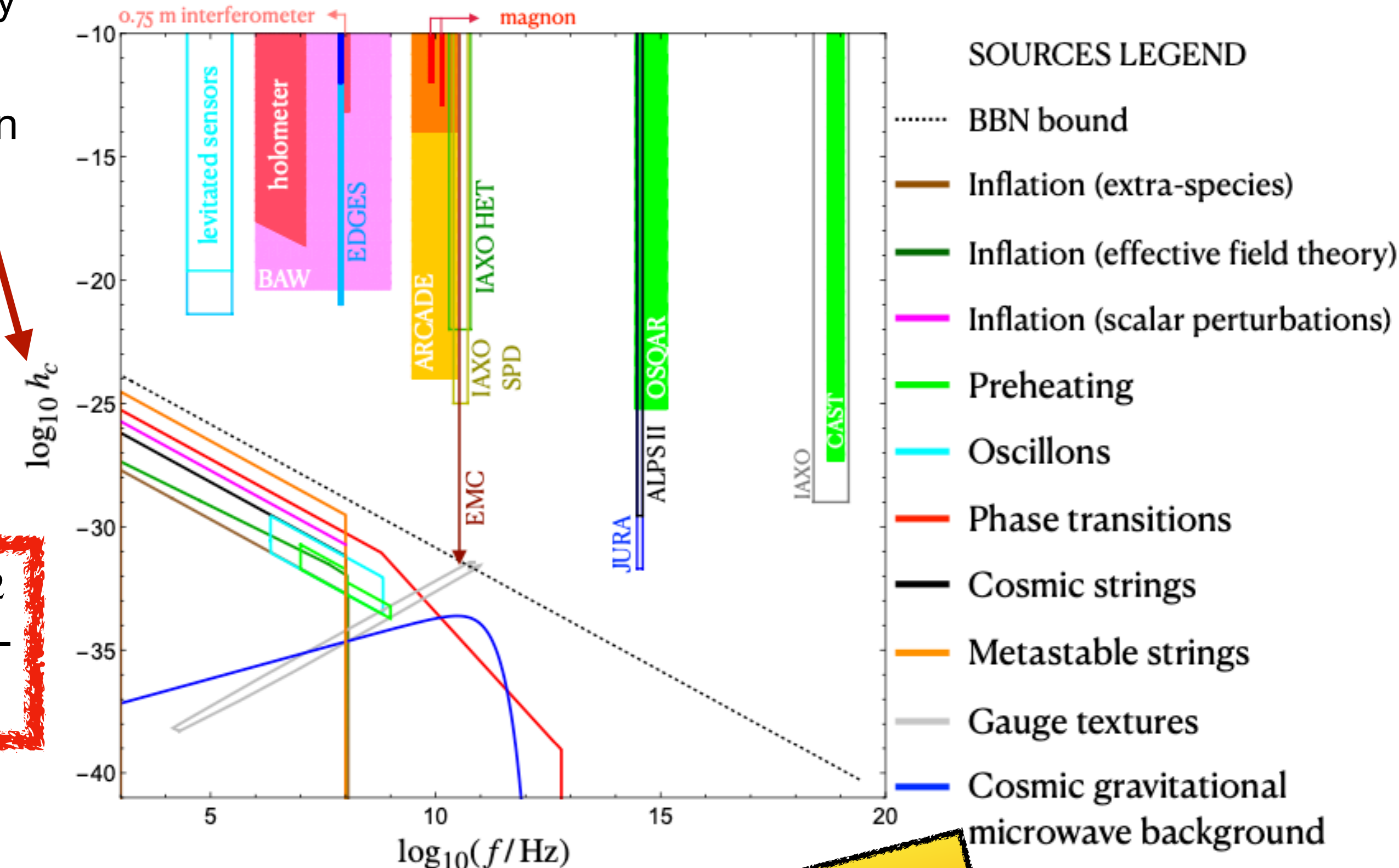
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In any case, beware of early matter domination!

NB: abelian vs non-abelian dark sector

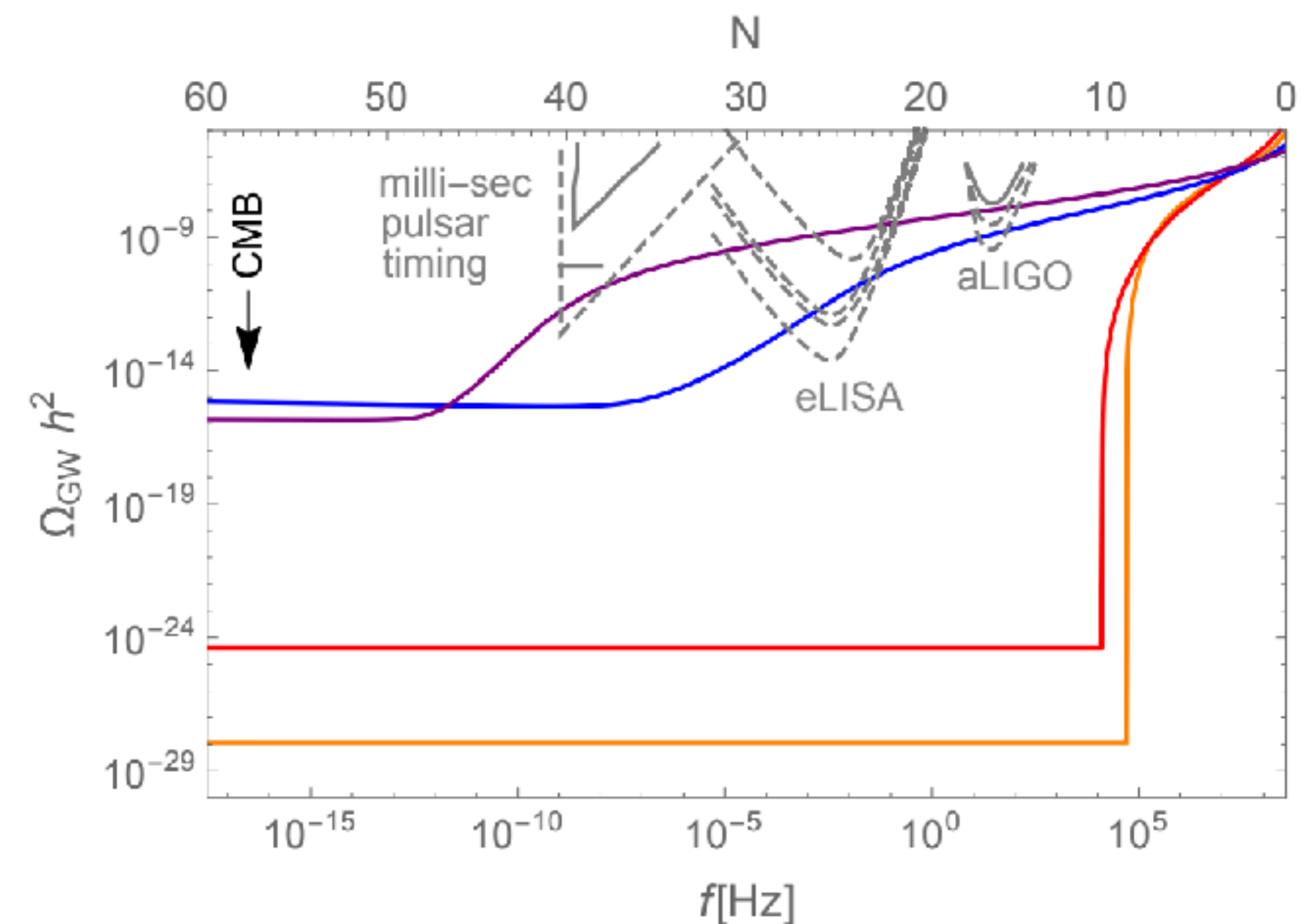
- Pseudoscalar inflaton coupled to gauge fields:

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

- Abelian case: exponential growth of one helicity mode of the vector field $\Rightarrow$ GW, PBH, CMB non-gaussianities...

[Sorbo: 1101.1525;
Cook, Sorbo: 1101.1525;
Barnaby, Pajer, Peloso: 1110.3327;
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- Discussion about back-reaction [... Figueroa et al.: 2303.17436]
- Non-Abelian case: thermalisation assumption simplifies the back-reaction modeling!



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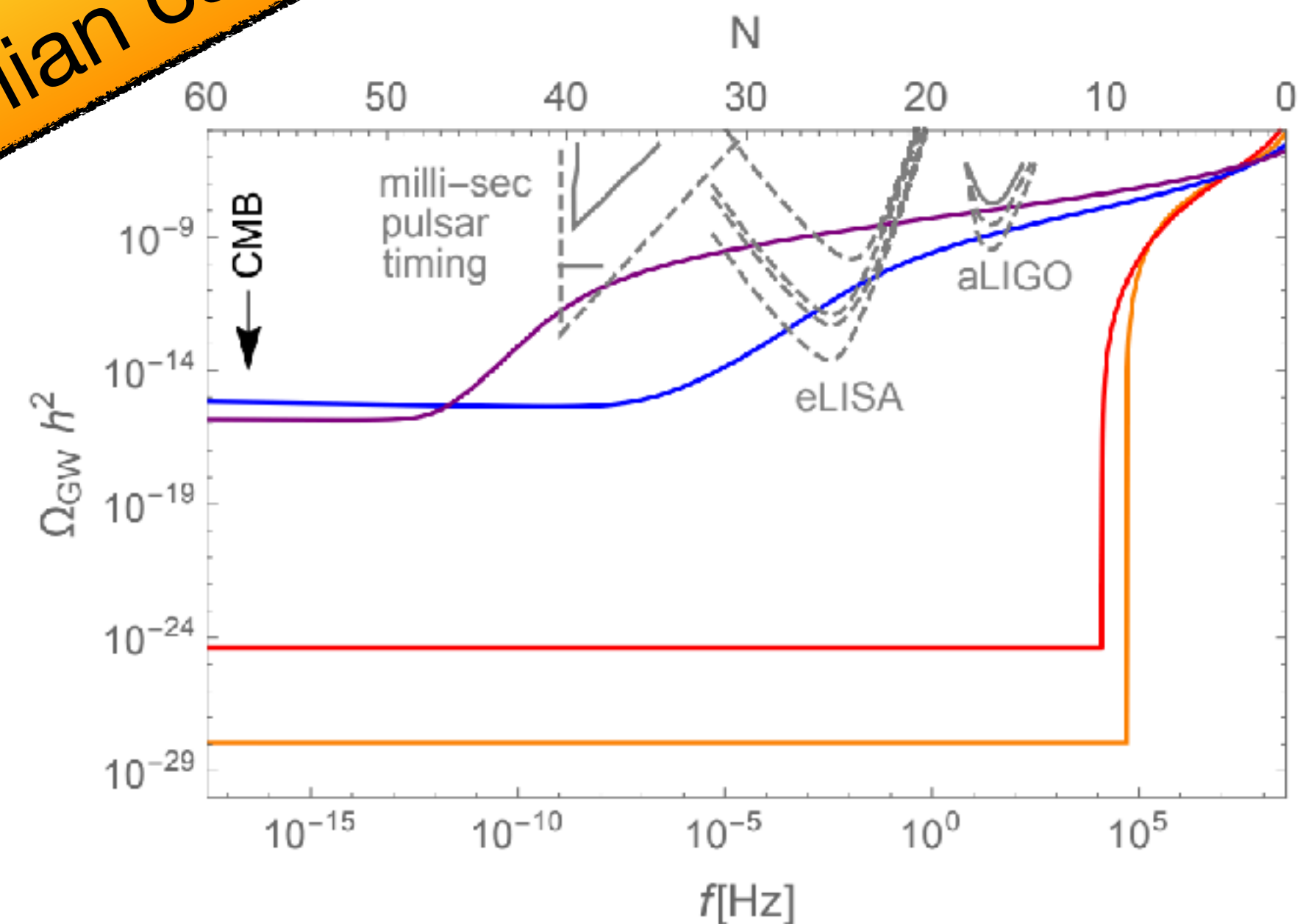
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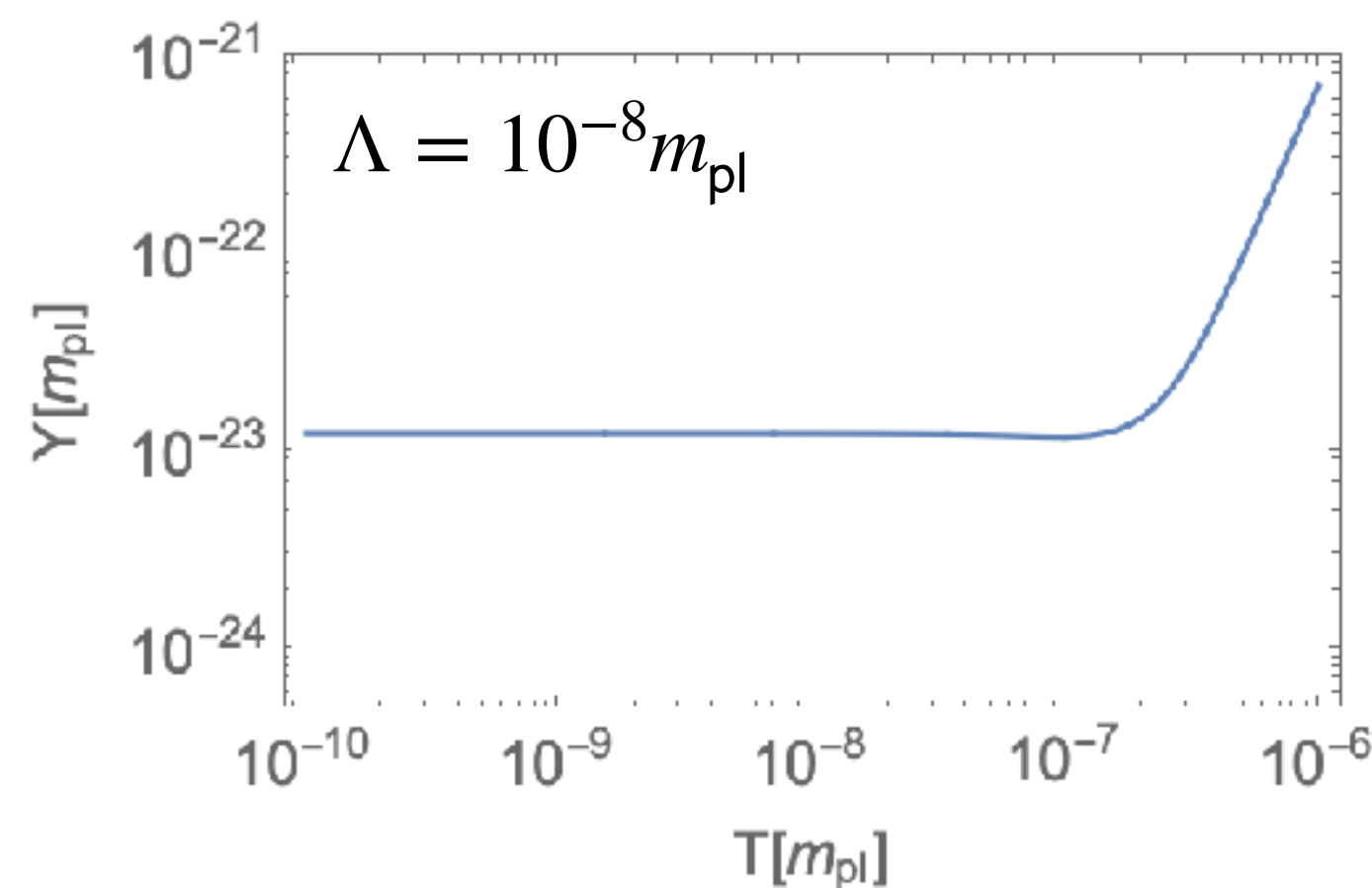
Working example: SU(3) case

[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]

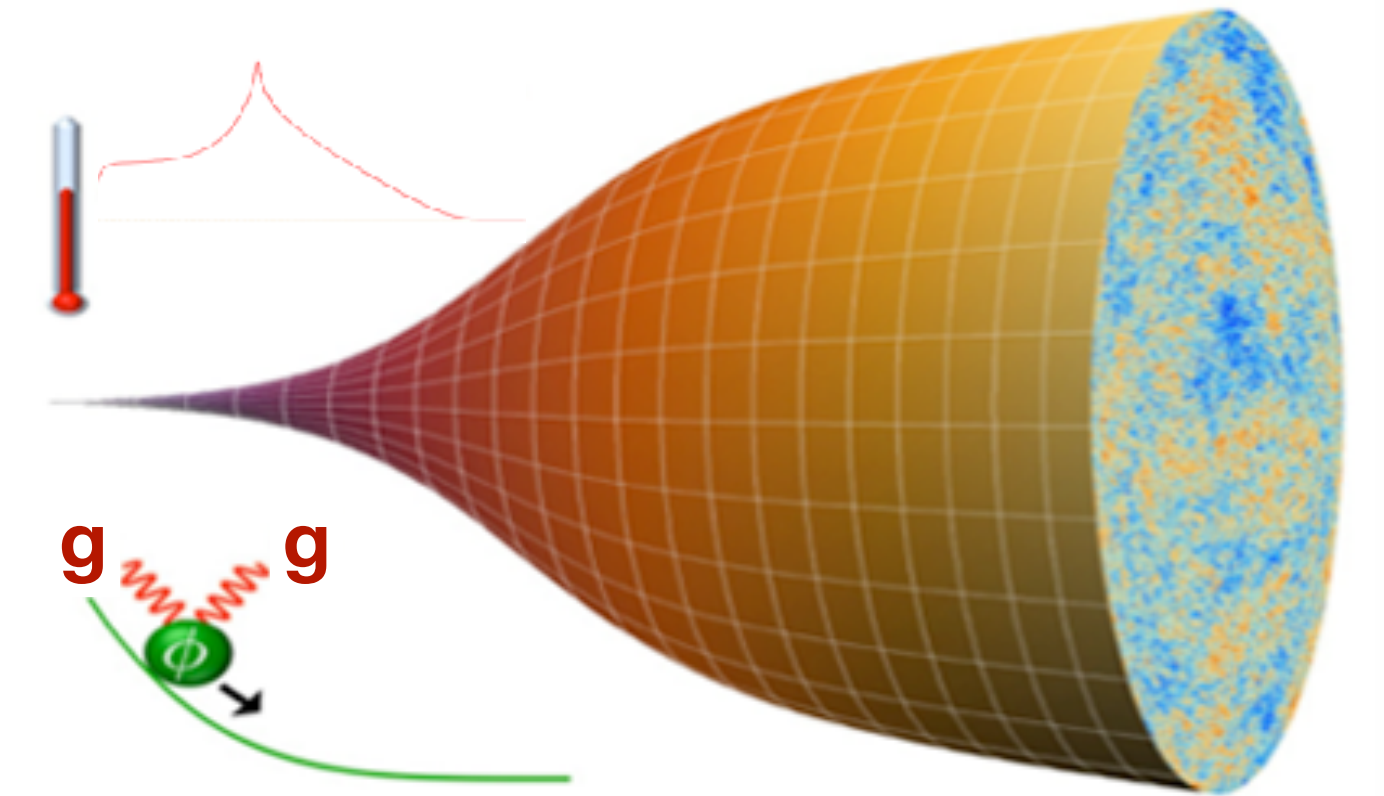
$m \gg T$ - Vacuum inflaton decays: $\Upsilon \propto \frac{\alpha^2 m^3}{f_a^2}$
 $m \ll T$ - Plasma scattering: $\Upsilon \propto \frac{\alpha^5 T^3}{f_a^2}$



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[Klose, Laine, Procacci: 2201.02317]:

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

Hubble rate Friction due to inflaton coupling to dark sector!

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

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

Dark radiation energy
and pressure densities

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

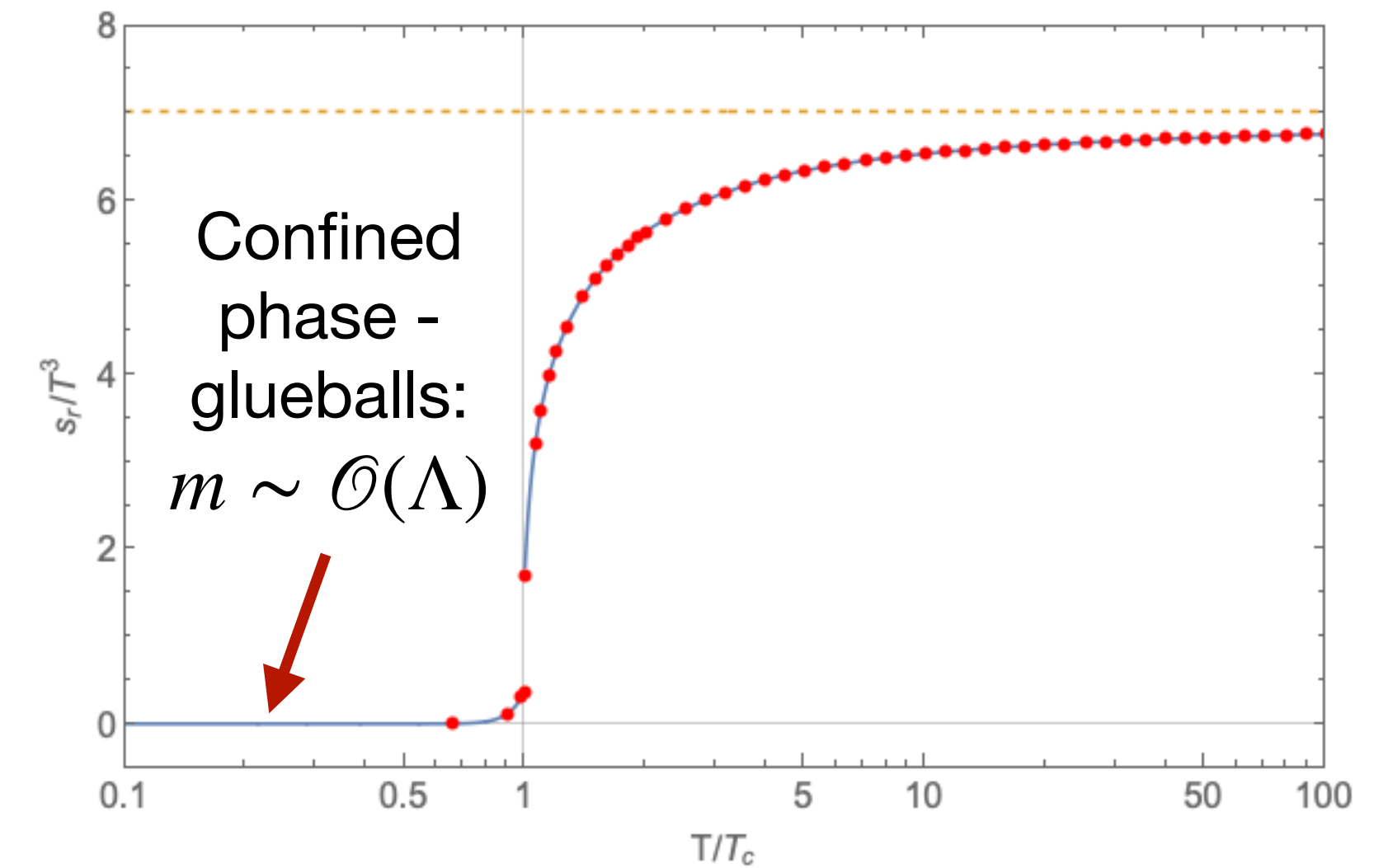
Why large temperatures?

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

$$\dot{\rho}_r + 3H(\rho_r + p_r) \simeq \Upsilon \dot{\tilde{\phi}}^2$$

Parametrize
 ρ_r, p_r by T

$$c_r(T) \dot{T} + 3H[\rho_r(T) + p_r(T)] \simeq \Upsilon \dot{\tilde{\phi}}^2$$



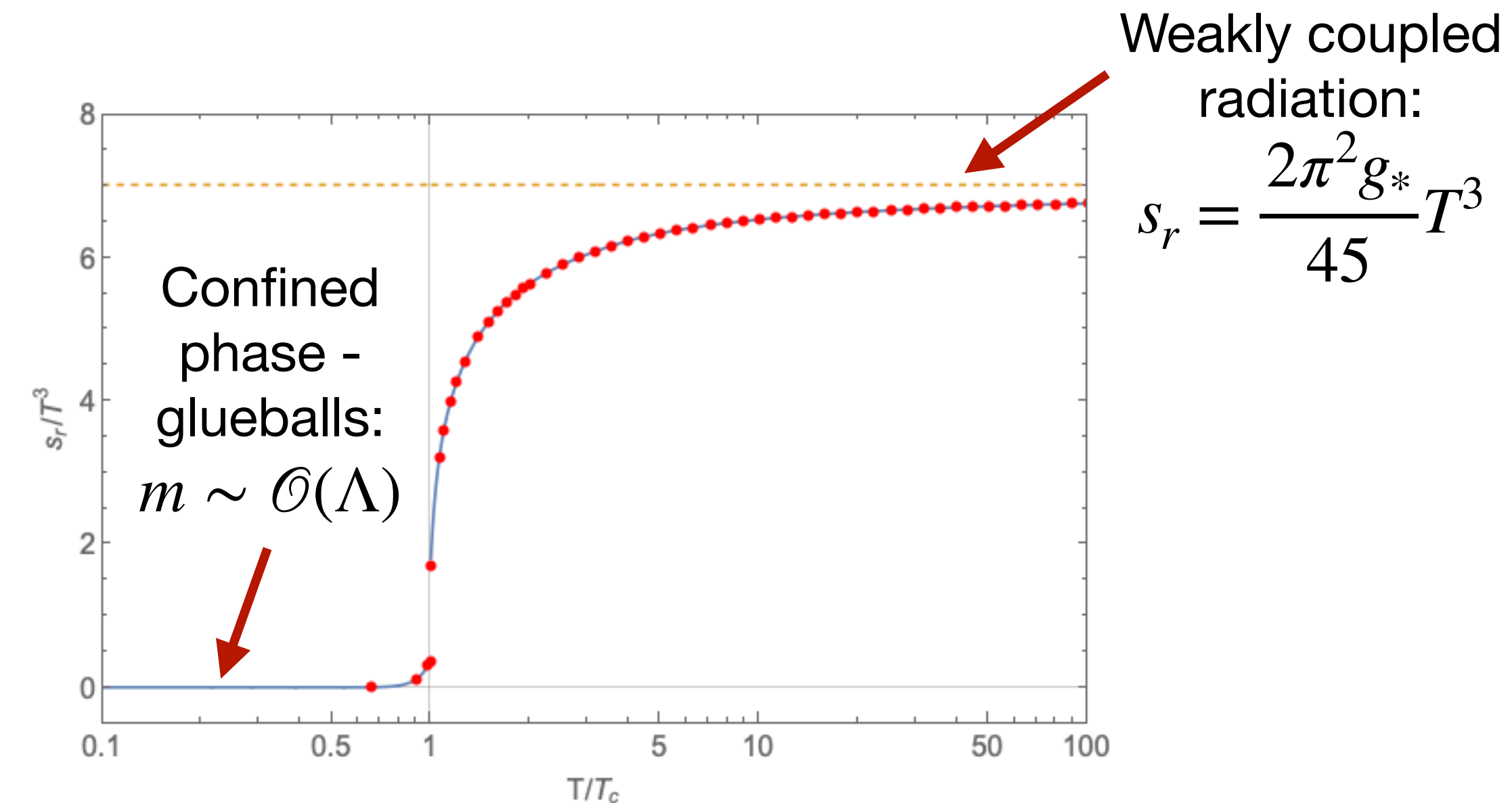
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Parametrize
 ρ_r, p_r by T



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

Why large temperatures?

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

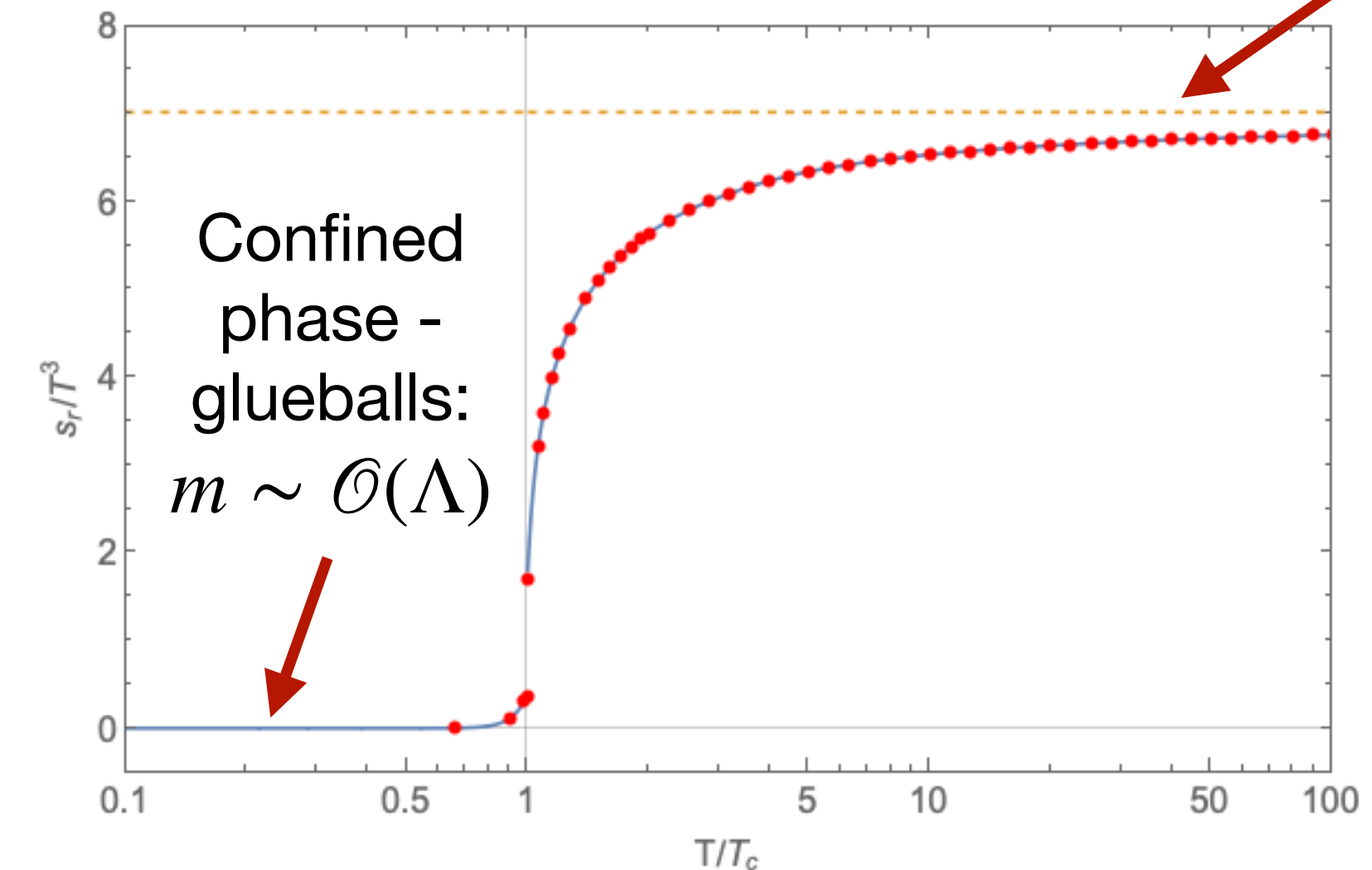
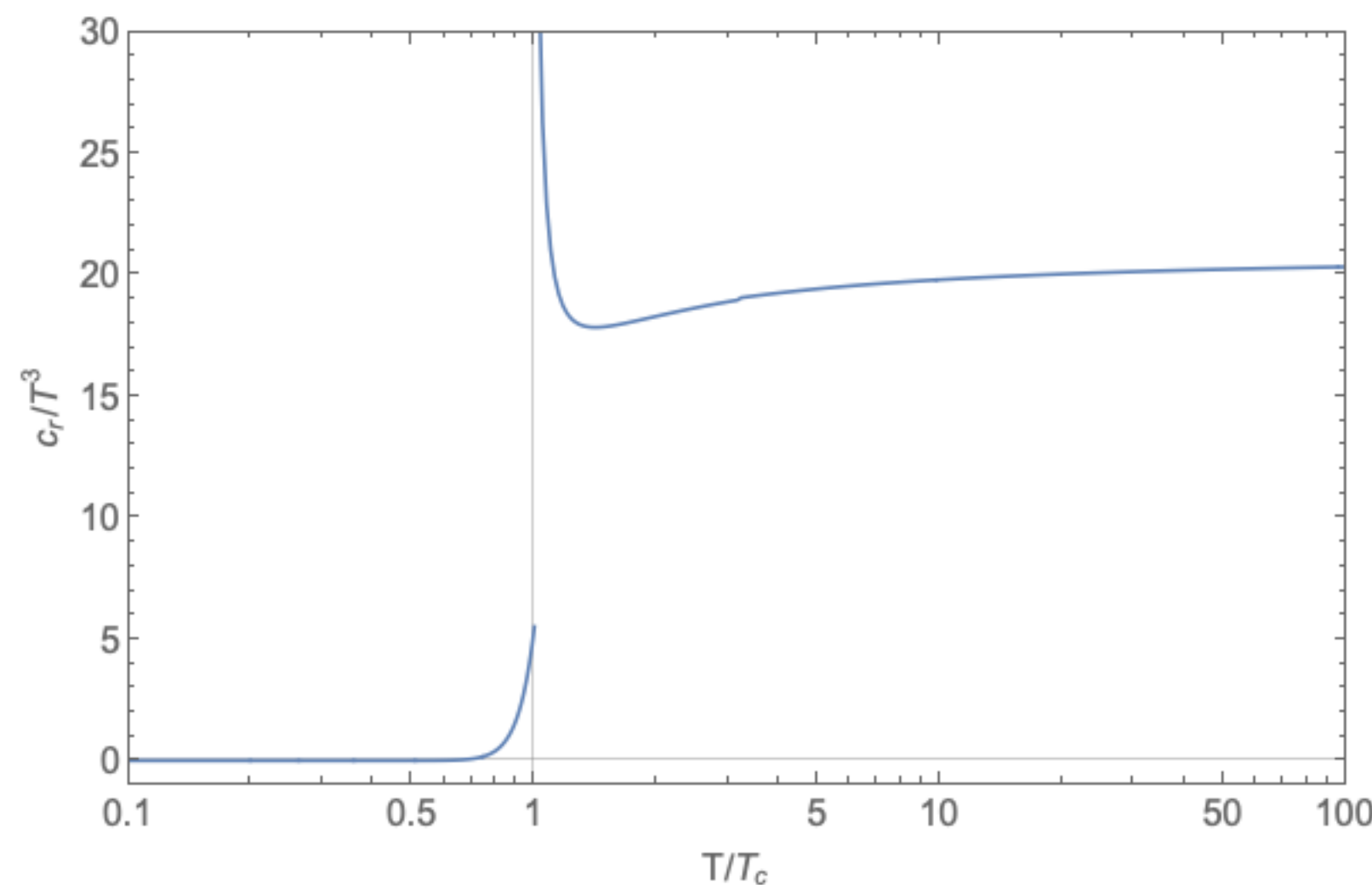
$$\dot{\rho}_r + 3H(\rho_r + p_r) \simeq \Upsilon \dot{\phi}^2$$

Parametrize
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$$c_r(T) \dot{T} + 3H[\rho_r(T) + p_r(T)] \simeq \Upsilon \dot{\phi}^2$$

Heat capacity:

$$c_r = \partial_T e_r$$



Weakly coupled
radiation:

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

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Fit of lattice data for s_r ,

$$s_r = \partial_T p_r,$$

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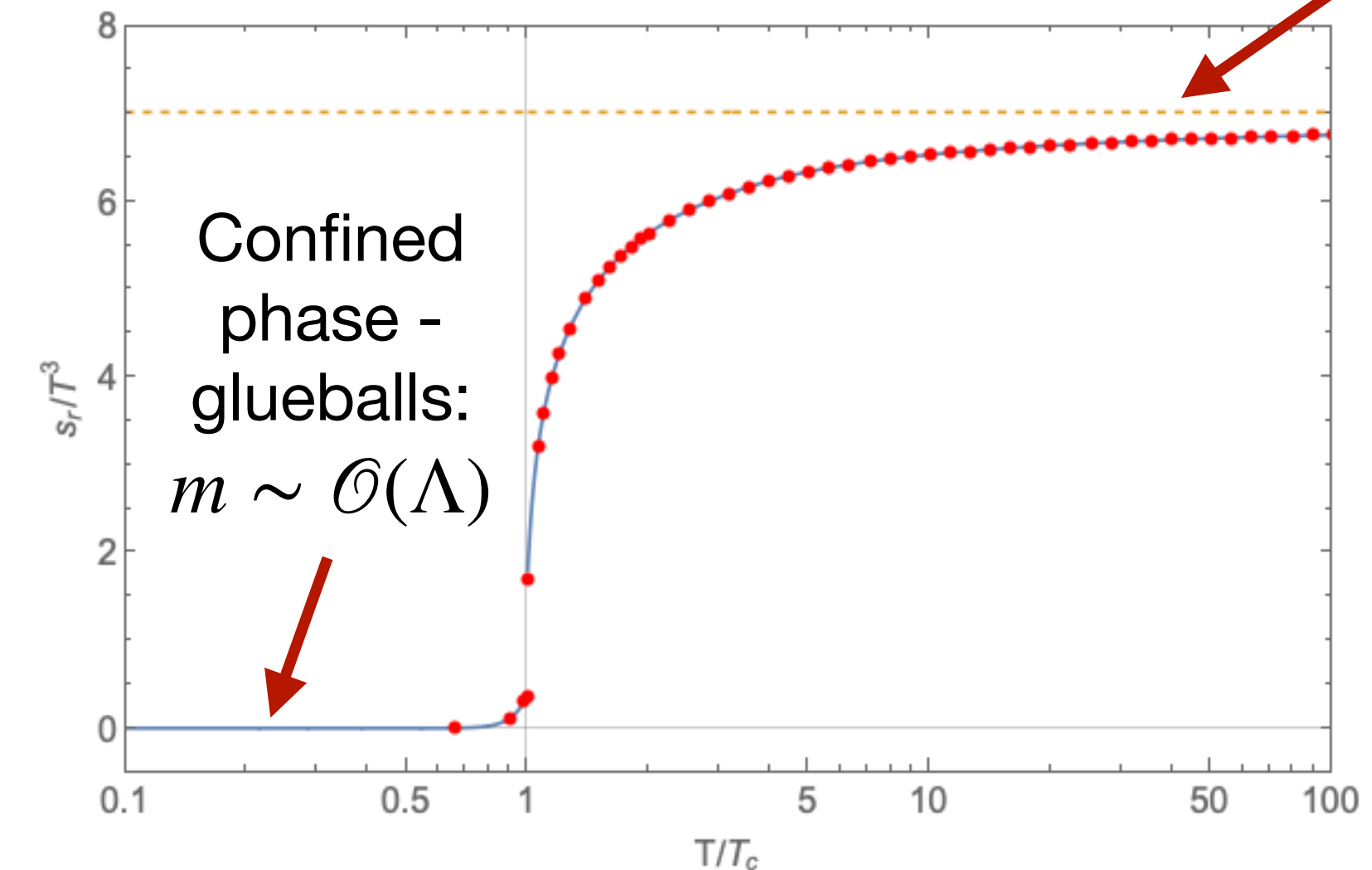
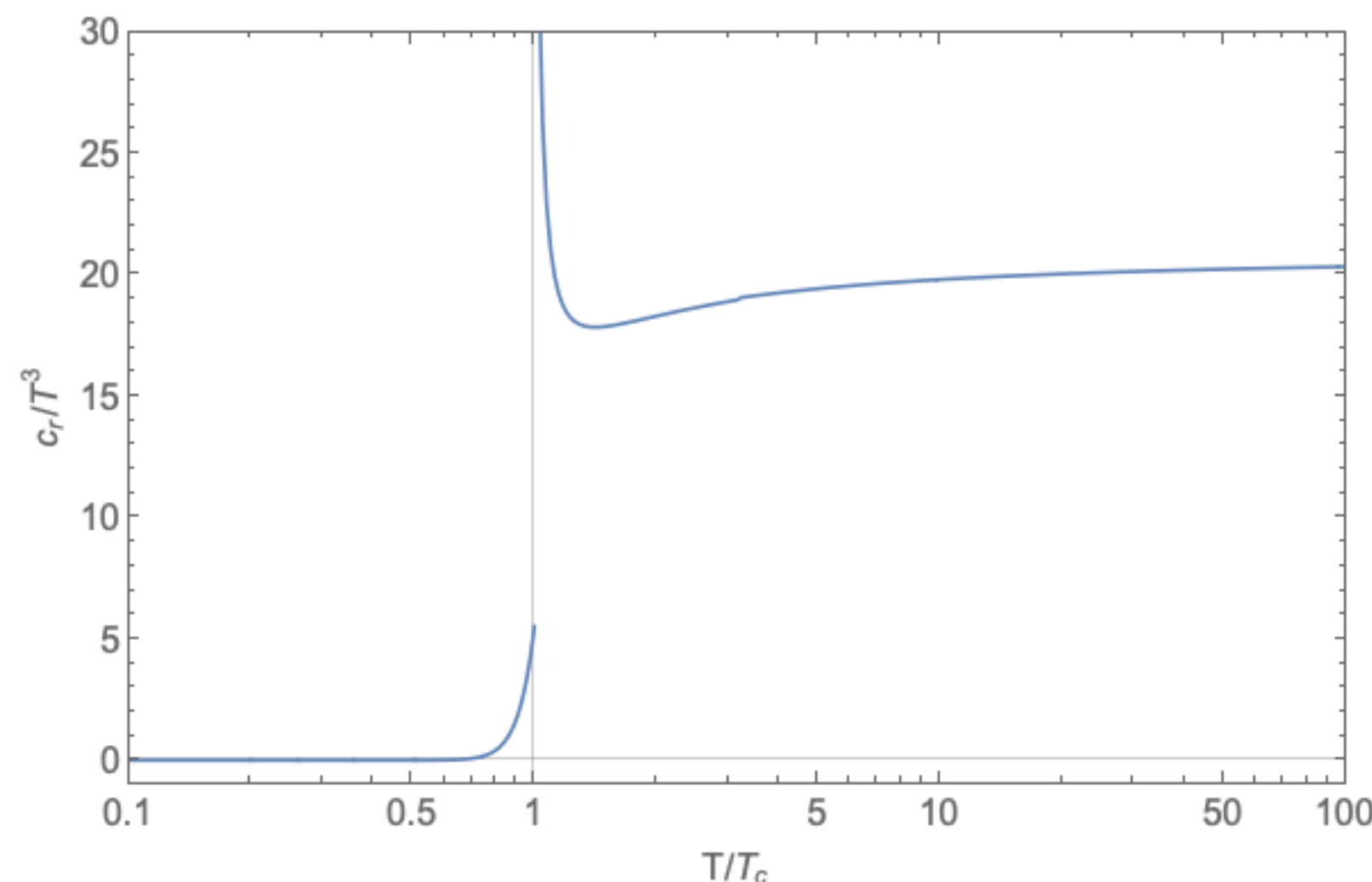
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Heat capacity:

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c_r exponentially
small well below
 $T_c \Rightarrow$ rapid
temperature
growth!



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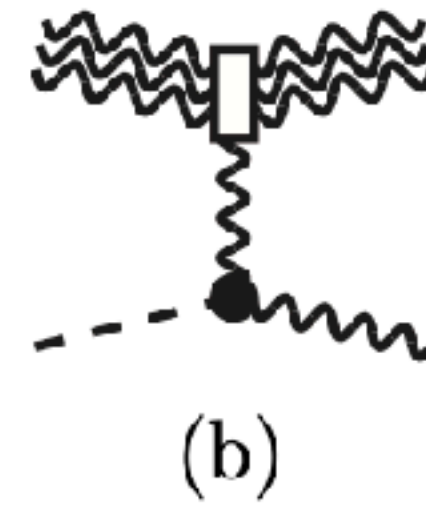
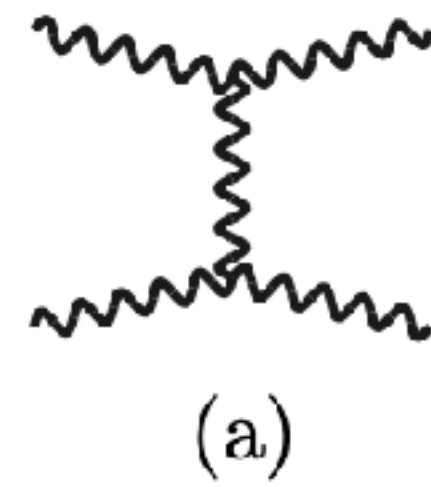
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Thermalisation?



Thermalisation rate:

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

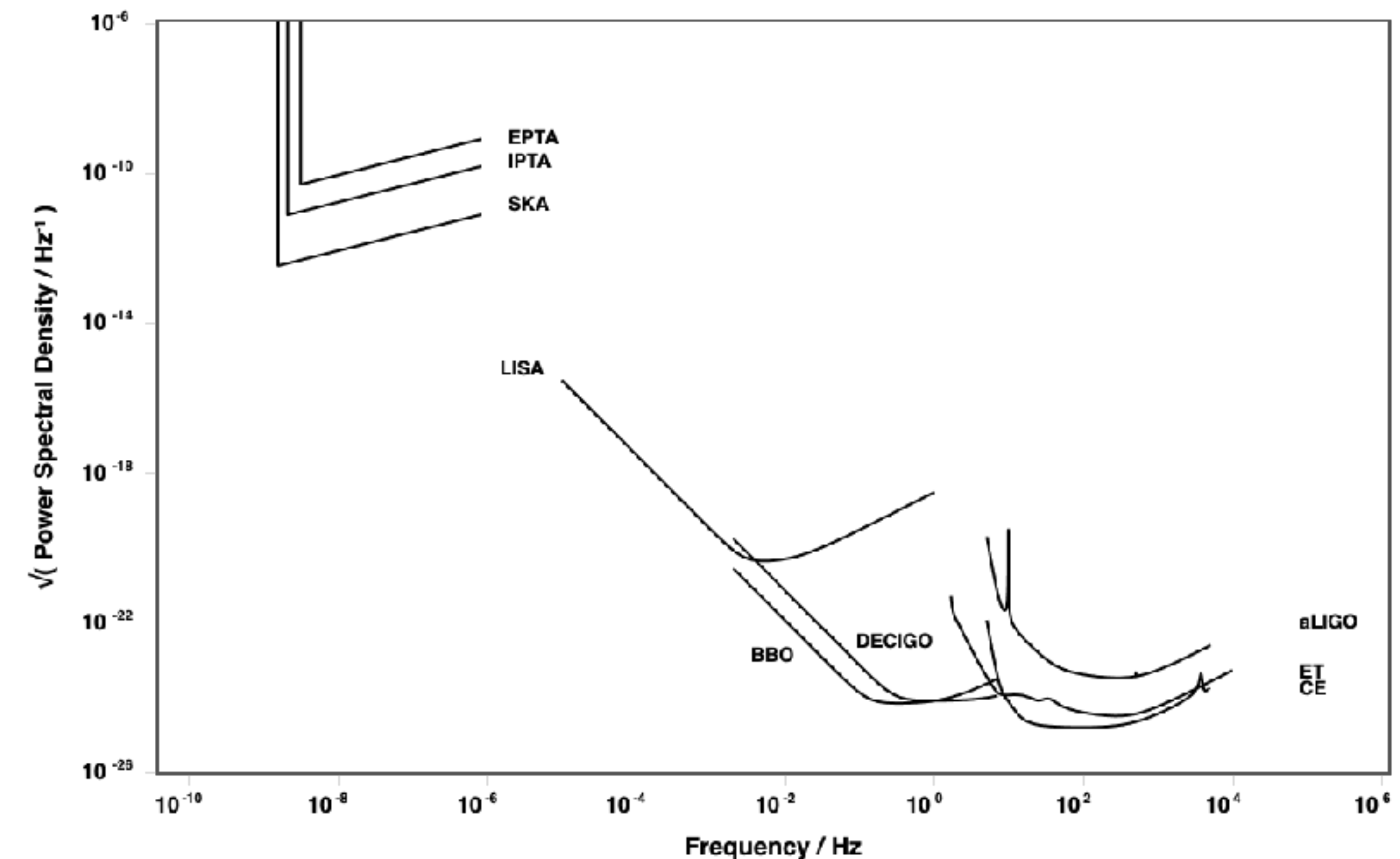
$$\Gamma_a \sim \Upsilon$$

GW from a confinement phase transition?

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

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

[\[http://gwplotter.com/\]](http://gwplotter.com/)



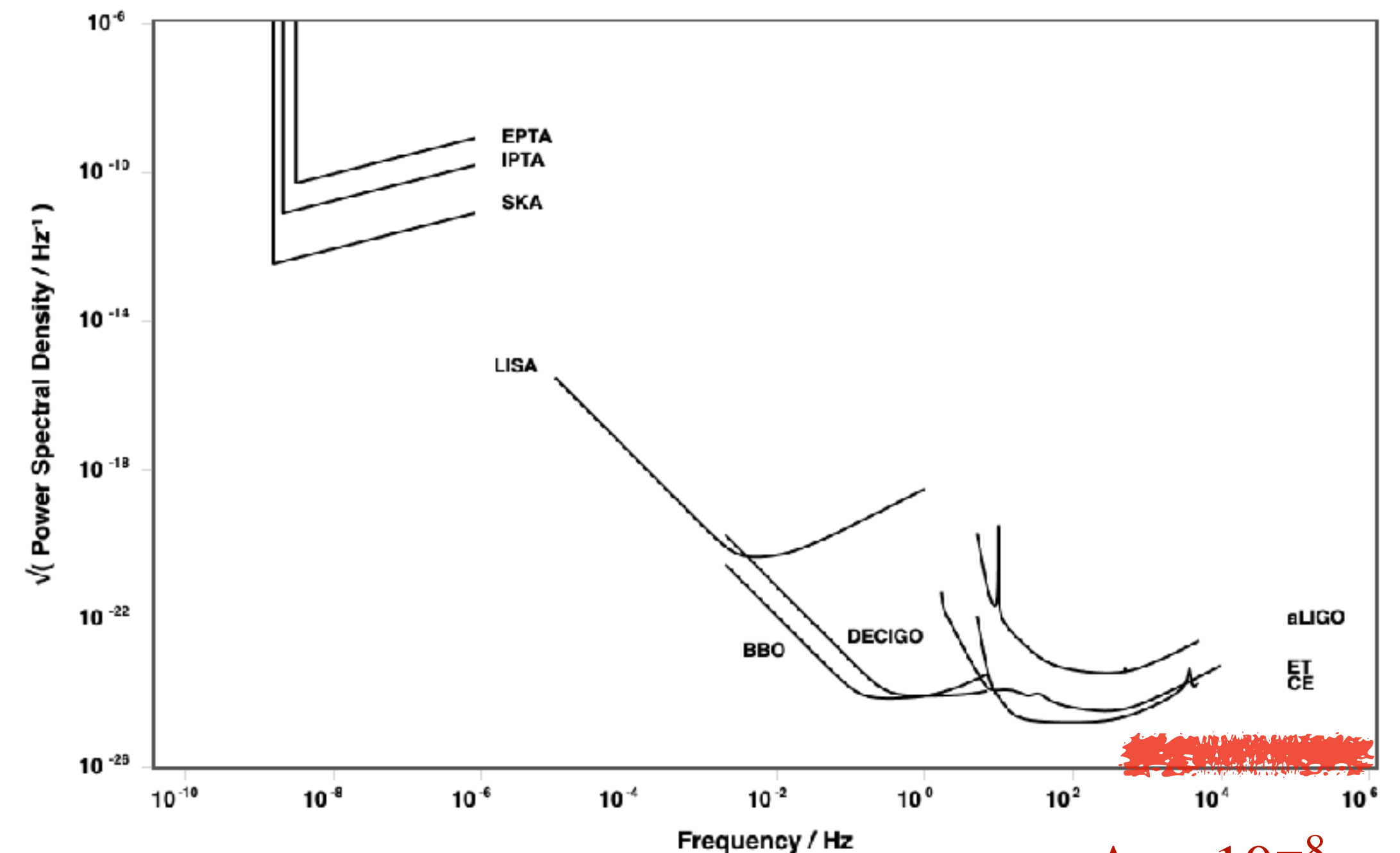
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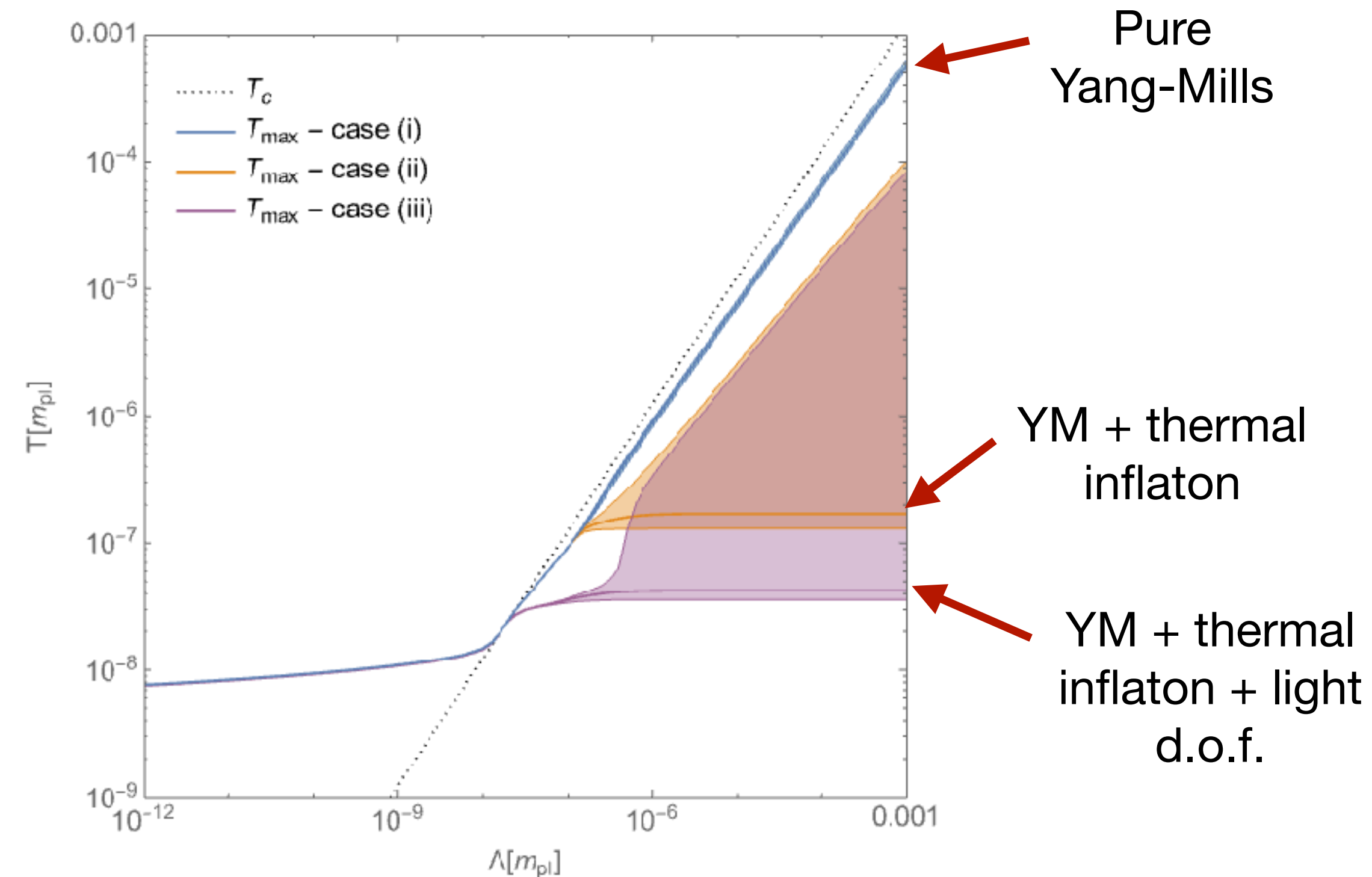
- Necessary ingredient to calculate the GW frequency today: SM temperature when radiation domination starts!
- If $T \equiv T_{\text{dark}} \sim T_{\text{SM}}$ then peak at kHz - MHz frequencies expected for $\Lambda \sim 10^{-8} m_{\text{pl}}$

[\[http://gwplotter.com/\]](http://gwplotter.com/)



$\Lambda \sim 10^{-8} m_{\text{pl}}$
???

Results: Maximal temperature of the dark sector

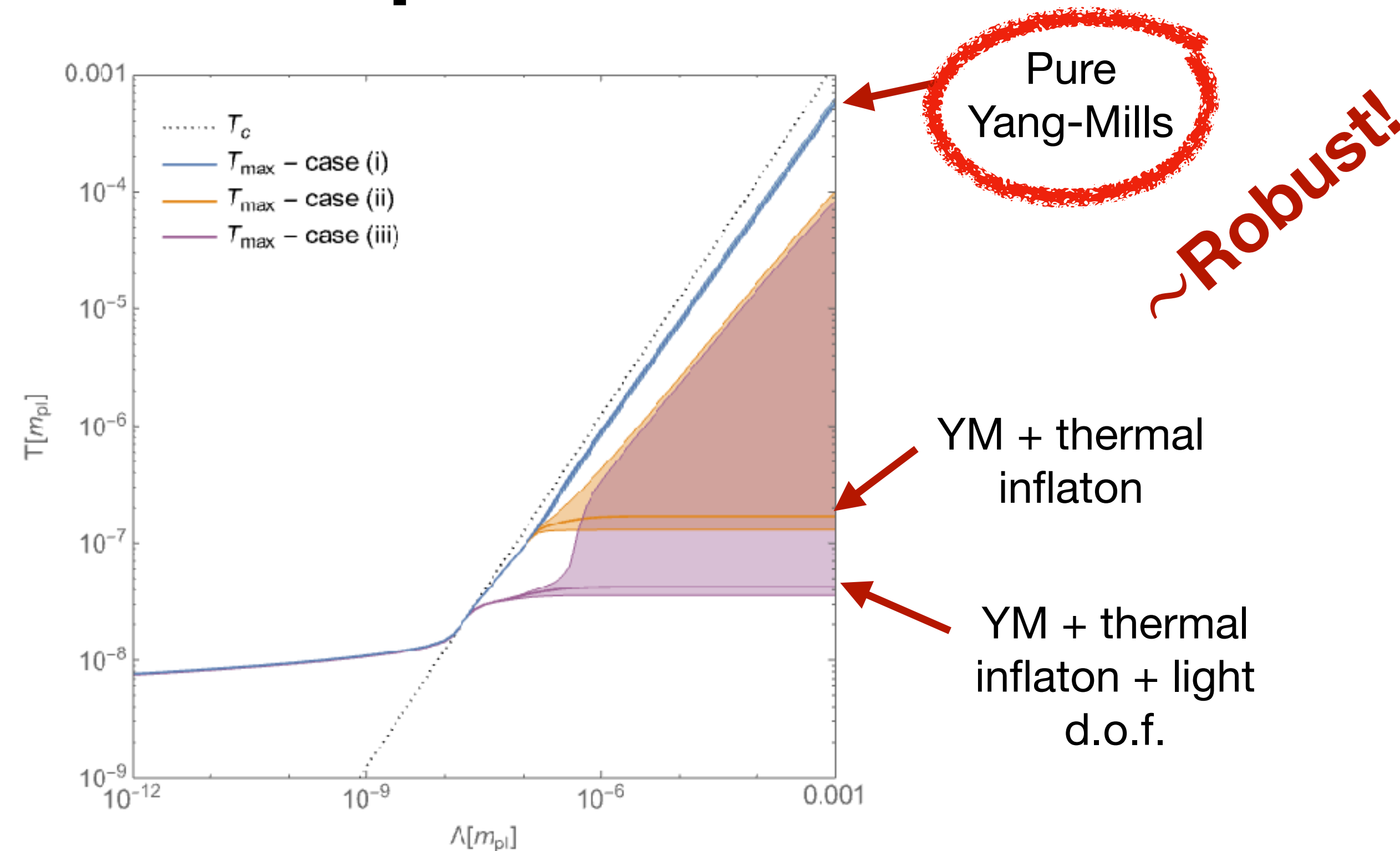


Why error bars?
Ignorance of Υ below T_c - parametrised
in terms of an IR regulator!

IR regulator
 $x \in (0.2, 2)$

$$\alpha \simeq \frac{6\pi}{11N_c} \log^{-1} \left[\frac{\sqrt{(x 2\pi\Lambda)^2 + (2\pi T)^2 + \omega^2}}{\Lambda} \right]$$

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Inflaton evolution

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

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

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

Benchmark parameter choice
(inflation consistent with CMB data)
[Klose, Laine, Procacci: 2201.02317]:

$$m = 1.09 \times 10^{-6} m_{\text{pl}},$$

$$f_a = 1.25 m_{\text{pl}},$$

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

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

