PROBING THE ‘PRIMORDIAL DARK AGE’ WITH GRAVITATIONAL WAVES.

IMPLICATIONS FOR REHEATING

DANIEL G. FIGUEROA

IFIC, Valencia

Inflationary Reheating Meets Particle Physics Frontier, KITP, Santa Bárbara, 3-6 Feb 2020

INCONSISTENCY OF AN INFLATIONARY SECTOR COUPLED ONLY (minimally) TO GRAVITY

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TWO PAPERS / IDEAS*

arXiv:1811.04093 (JCAP 1910 (2019) 10, 050)

Inconsistency of an inflationary sector coupled only to Einstein gravity

arXiv:1905.11960 (JCAP 1908 (2019) 011)

Ability of LIGO & LISA to probe the Eq. of state of the early Universe

*with E. H. Tanin, MsC EPFL (PhD @ J. Hopkins U.)

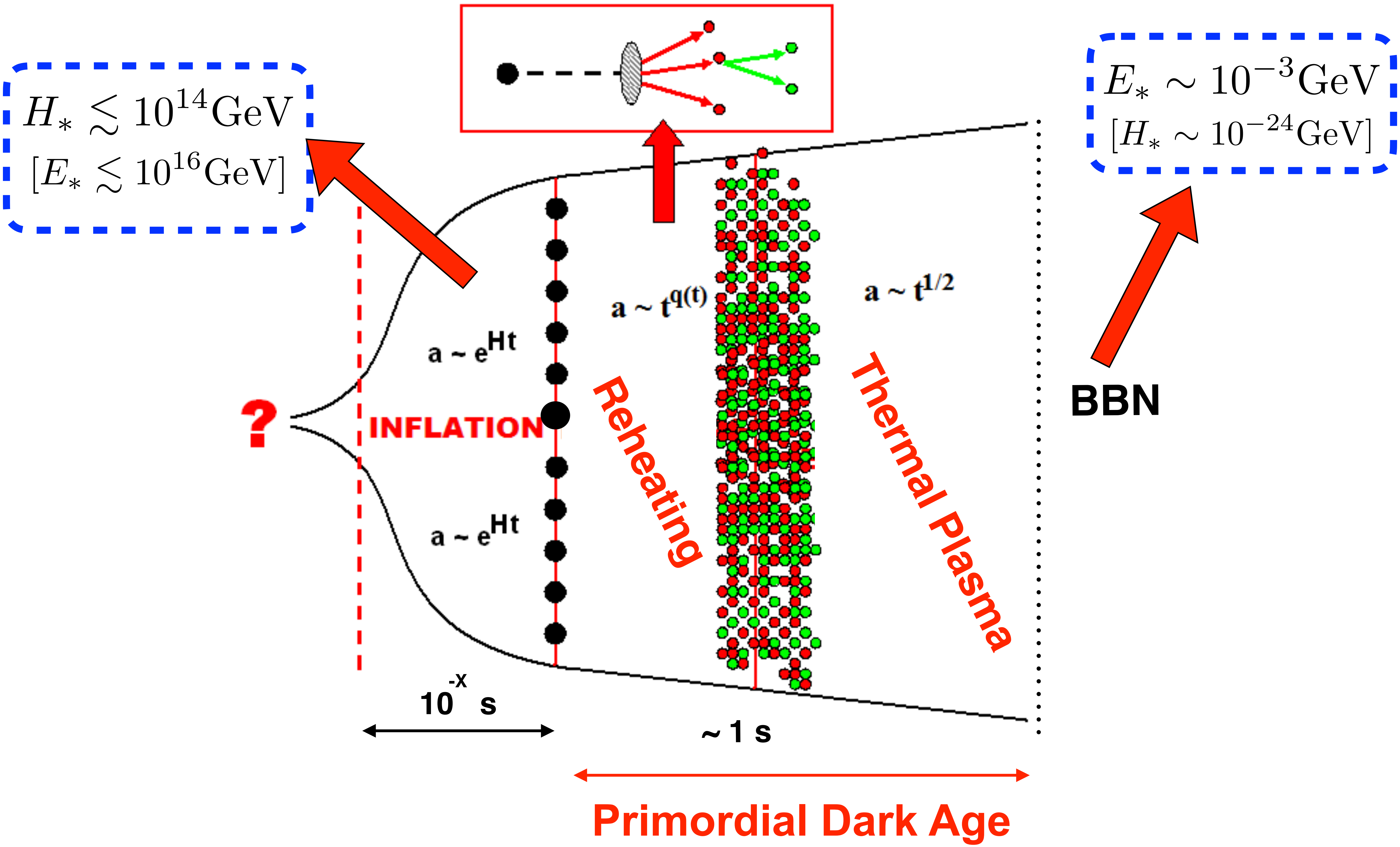
TWO PAPERS / IDEAS

Inconsistency of an inflationary sector coupled only to Einstein gravity

REHEATING / GRAVITATIONAL WAVES

Ability of LIGO & LISA to probe the Eq. of state of the early Universe

The context: The Early Universe



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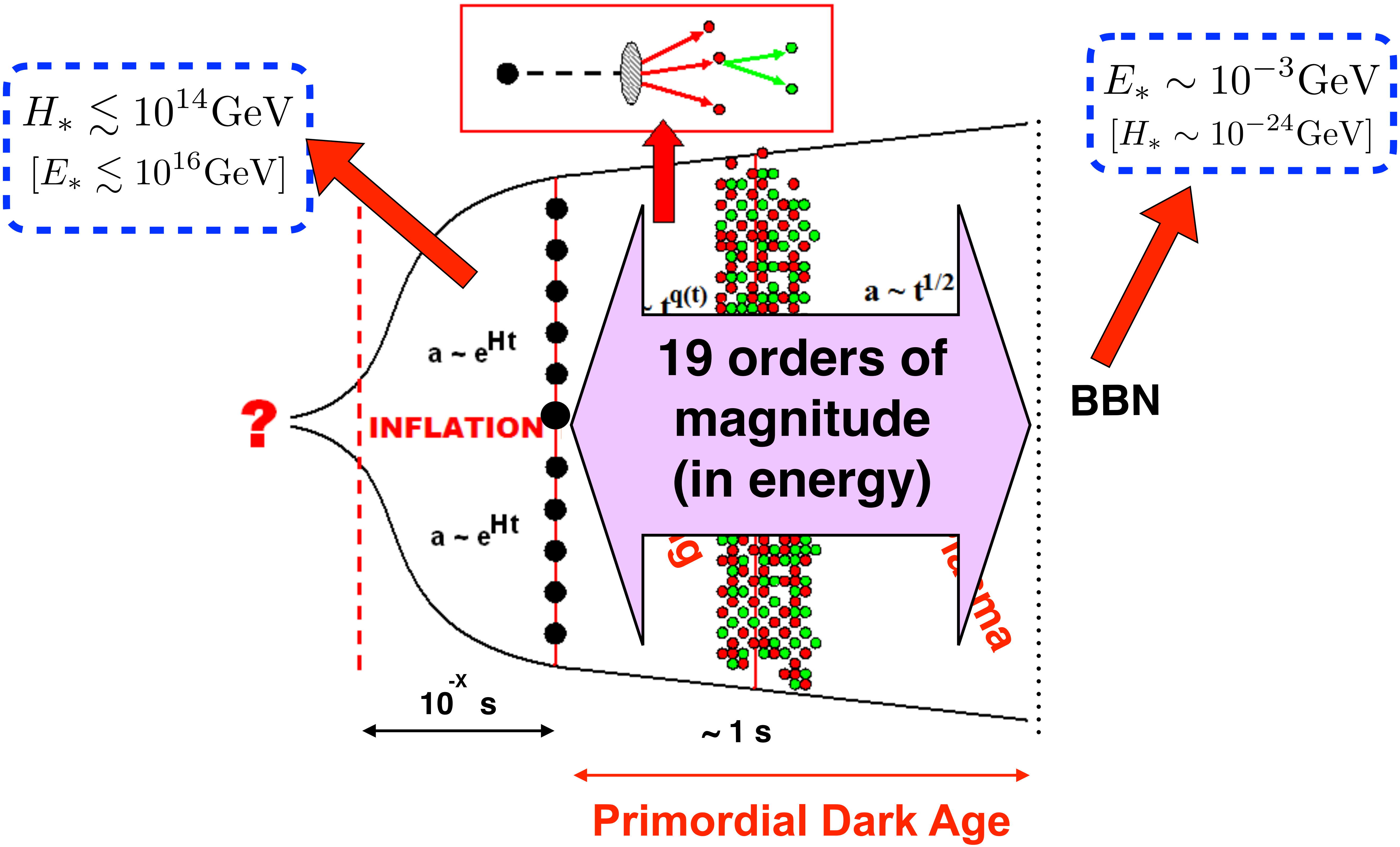
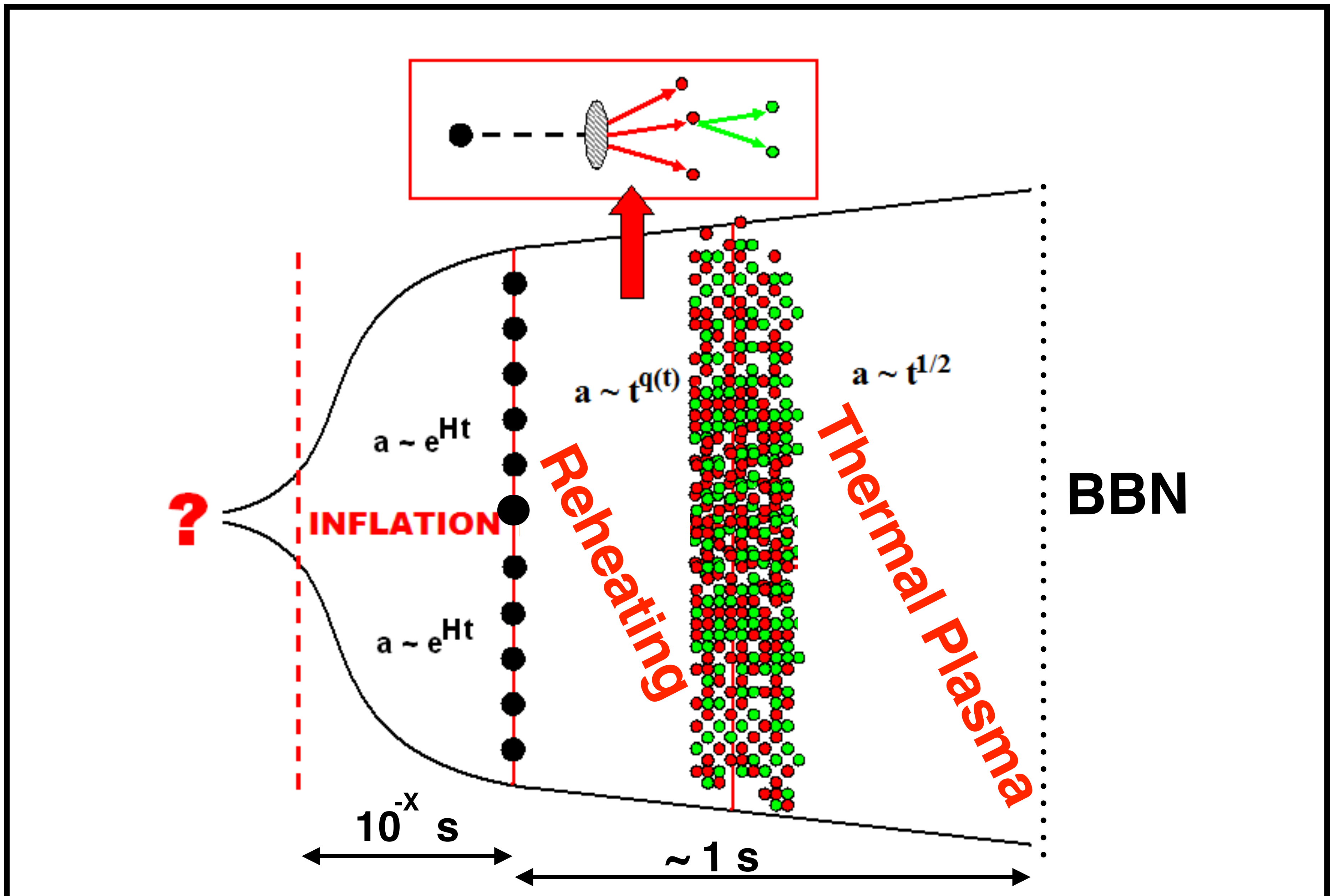


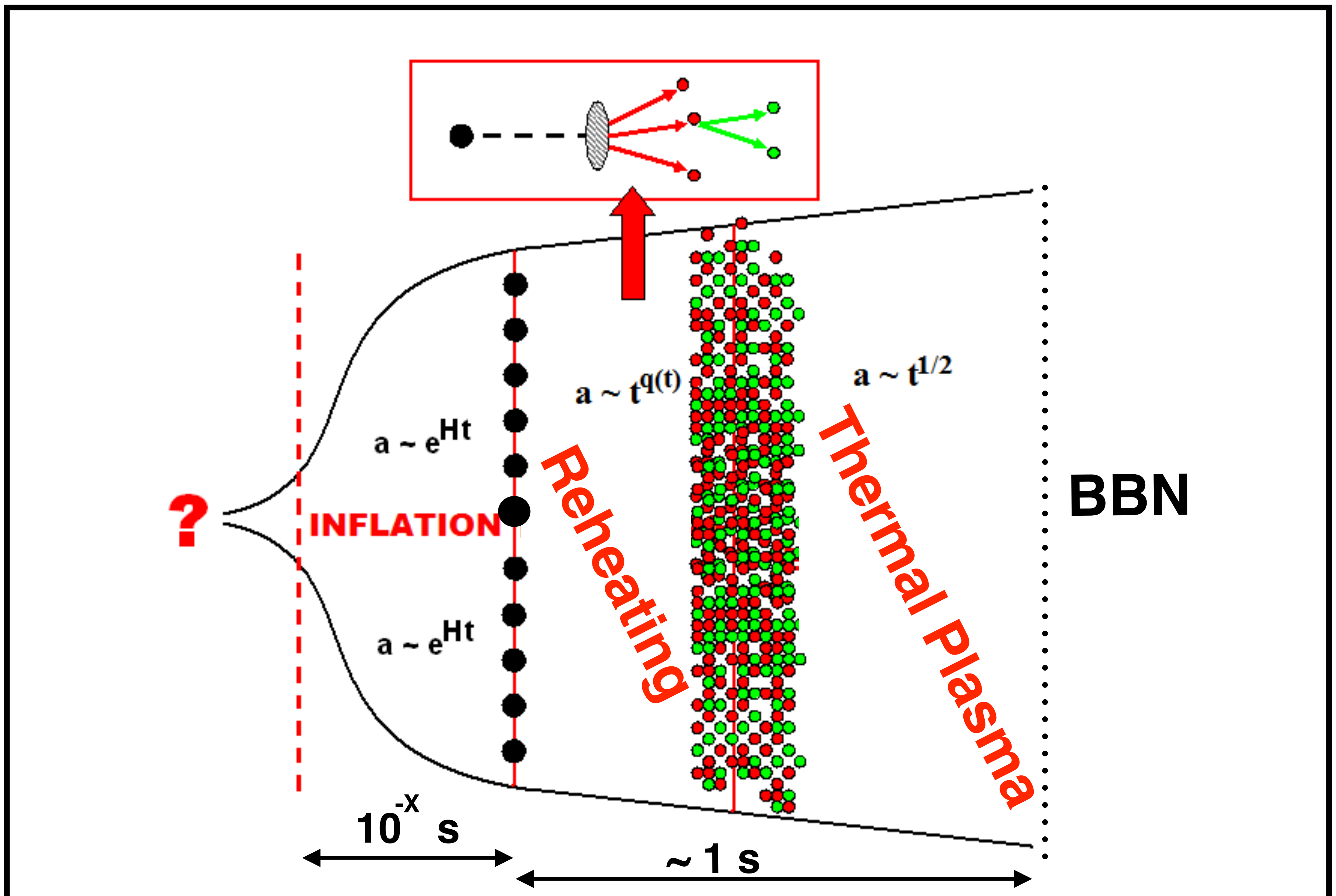
Part 1

(GRAVITATIONAL) REHEATING

Successful Reheating ⟷ Thermal Ensemble of Relativistic Particle Species



Successful Reheating ⟷ Thermal Ensemble of Relativistic Particle Species

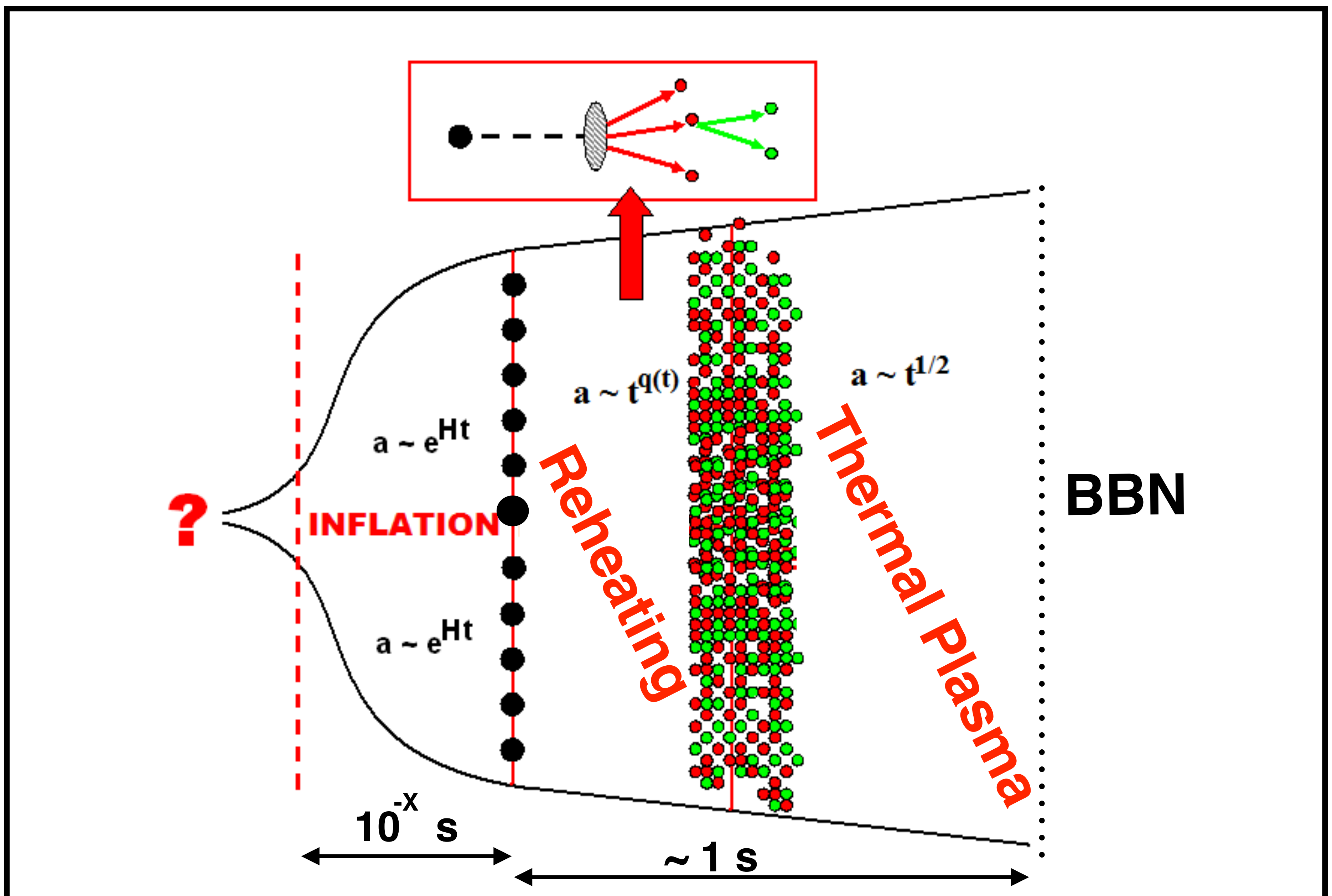


Connection between Particles and Inflationary Sector ?

- SM Portals ?
- Mediator fields ?
- No coupling ?

Successful Reheating

Thermal Ensemble of Relativistic Particle Species



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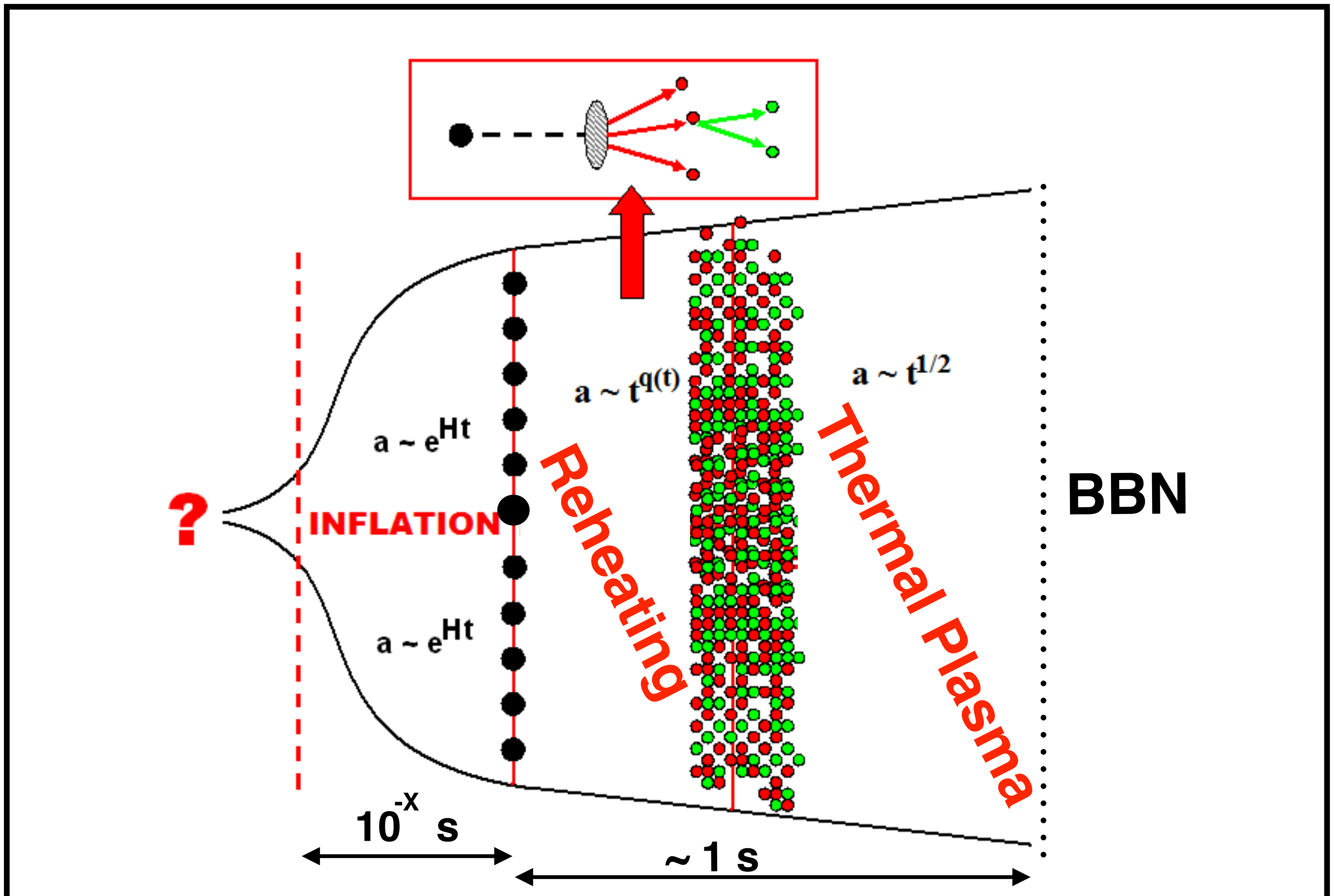

Connection between Particles and Inflationary Sector ?

* SM Portals ?
* Mediator fields ?
* Weak coupling !

INFLATIONARY SECTOR COUPLED ONLY (minimally) TO GRAVITY

$$\mathcal{L} = \frac{1}{\sqrt{g}}\left\{\underbrace{(\partial\phi)^2 - V_{\rm inf}(\phi)}_{\text{inflaton}} + \underbrace{\frac{1}{2}m_{pl}^2 R}_{\substack{\text{gravity}\\ \text{(GR)}}} + \underbrace{(\partial\chi)^2 - V(\chi) - \xi\chi^2 R}_{\text{matter/rad}} - \cancel{g^2\chi^2\phi^2}\right\}$$

Need to excite matter
(to reheat the Universe)

INFLATIONARY SECTOR COUPLED ONLY (minimally) TO GRAVITY

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$$\boxed{\rho_{\rm rad} = \delta \times 10^{-2} H_*^4}$$

Inflation does the job !

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Need to excite matter
(to reheat the Universe)

$$\boxed{\rho_{\rm rad} = \delta \times 10^{-2} H_*^4}\qquad \boxed{\delta \lesssim 1},$$

Inflation does the job !

$$\delta \sim \begin{cases} \mathcal{O}(m^2/H_*^2) & ,\ \text{quantum} - \text{fluct.}\ (\textit{light dof}) \\ \mathcal{O}(1) & ,\ \text{quantum} - \text{fluct.}\ (\textit{self} - \textit{interact.}) \\ \mathcal{O}(1)/\xi & ,\ \text{non} - \text{min grav},\ \xi \gtrsim 1 \\ \mathcal{O}(|1-6\xi|^2) & ,\ \text{non} - \text{min grav},\ |1-6\xi| \ll 1 \end{cases}$$

Linde '83
Starobinsky & Yokoyama '94
Rajantie et al '15
Ford '87

INFLATIONARY SECTOR COUPLED ONLY (minimally) TO GRAVITY

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$$\boxed{\rho_{\rm rad} = \delta \times 10^{-2} H_*^4}\qquad \boxed{\delta \lesssim 1\,,}$$

Inflation does the job !

$$\boxed{\Delta_* \equiv \frac{\rho_{\rm rad}}{3m_p^2 H_*^2} = \frac{\delta}{300}\left(\frac{H_*}{m_p}\right)^2 \ll 1}$$

Fraction energies radiation-to-total

INFLATIONARY SECTOR COUPLED ONLY (minimally) TO GRAVITY

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Need to excite matter
(to reheat the Universe)

$$\boxed{\rho_{\rm rad} = \delta \times 10^{-2} H_*^4} \qquad \boxed{\delta \lesssim 1,}$$

Inflation does the job !

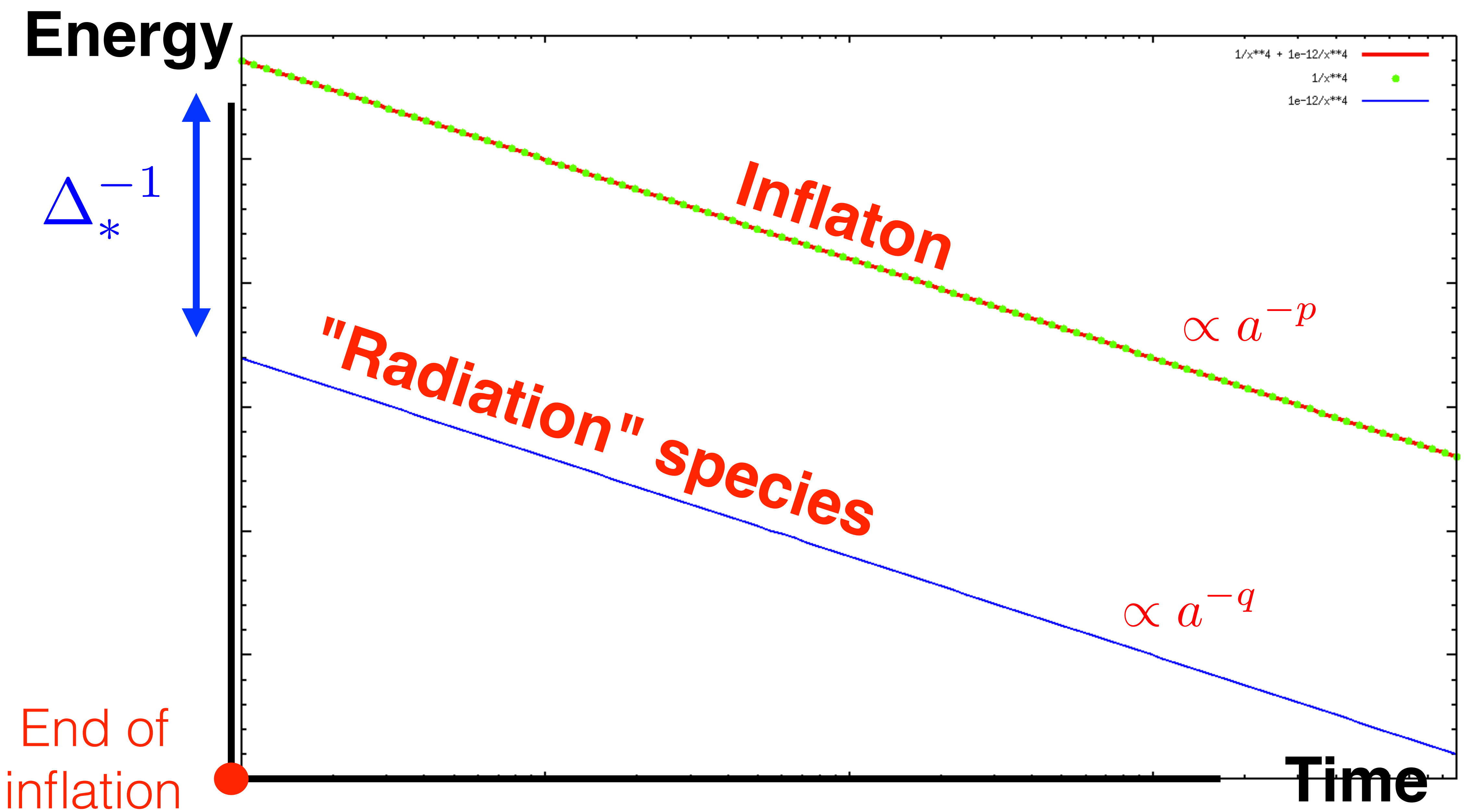
$$\boxed{\Delta_* \sim \delta \cdot 10^{-12} \times \left(\frac{H_*}{H_{\rm max}}\right)^2 \ll 1} \qquad \boxed{\delta \lesssim 1,}$$

Fraction energies radiation-to-total

INFLATIONARY SECTOR COUPLED ONLY (minimally) TO GRAVITY

$$\boxed{\rho^*_{\rm rad} \ll H_*^2 m_{pl}^2}$$

Radiation excited but subdominant



Rad. Excited

$$\rho^*_{\rm rad} \ll H_*^2 m_{pl}^2$$

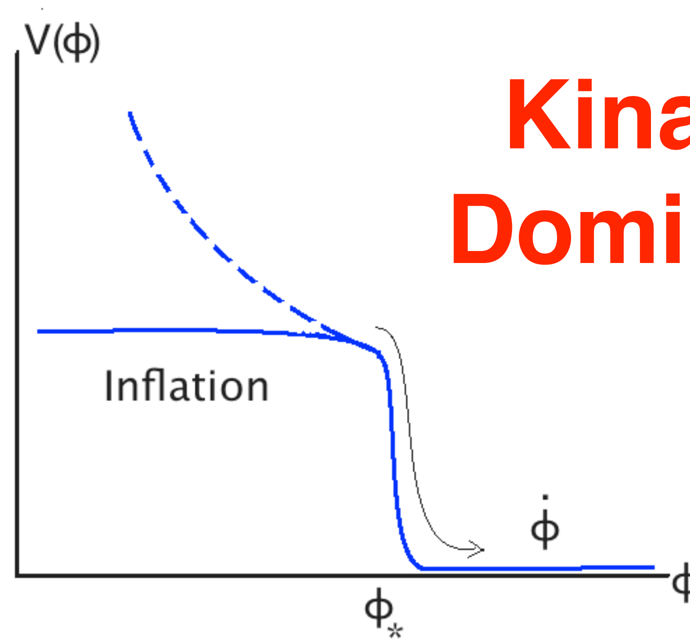
Rad. produced,
but subdominant

?

Rad. Excited

$$\rho^*_{\rm rad} \ll H_*^2 m_{pl}^2$$

Rad. produced,
and dominant !



Kination-Domination

$$\boxed{\text{Energy} \propto \frac{1}{a^6}}$$

[Ford '86, Spokoiny '93]

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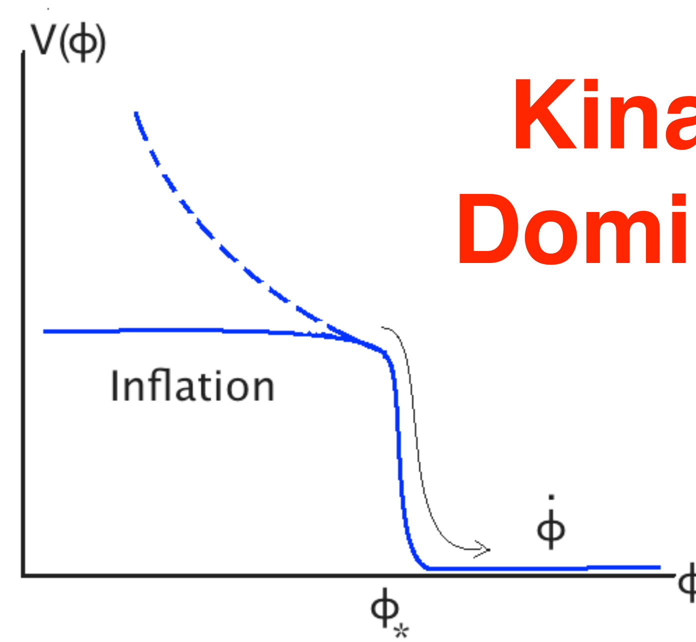

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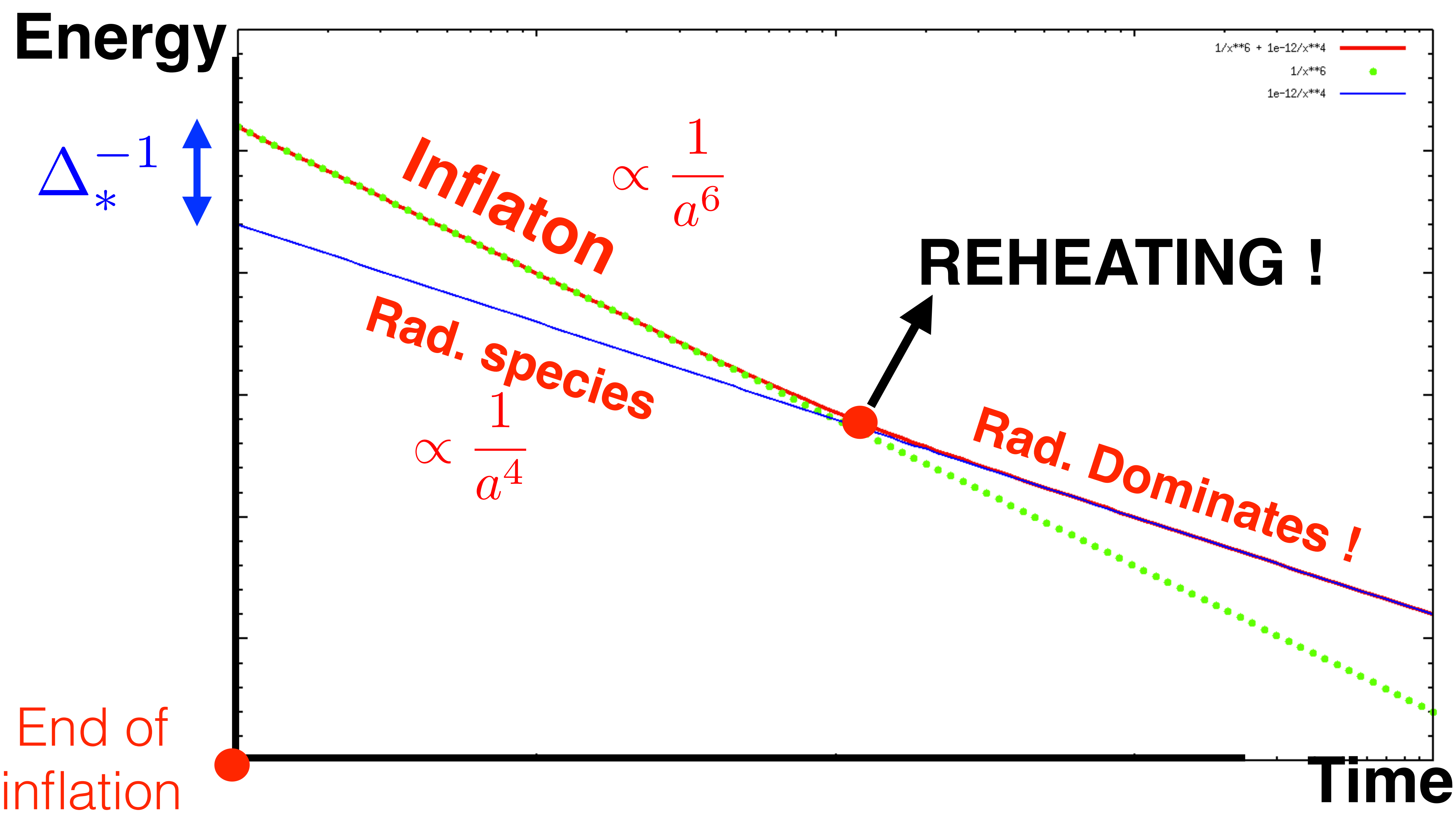
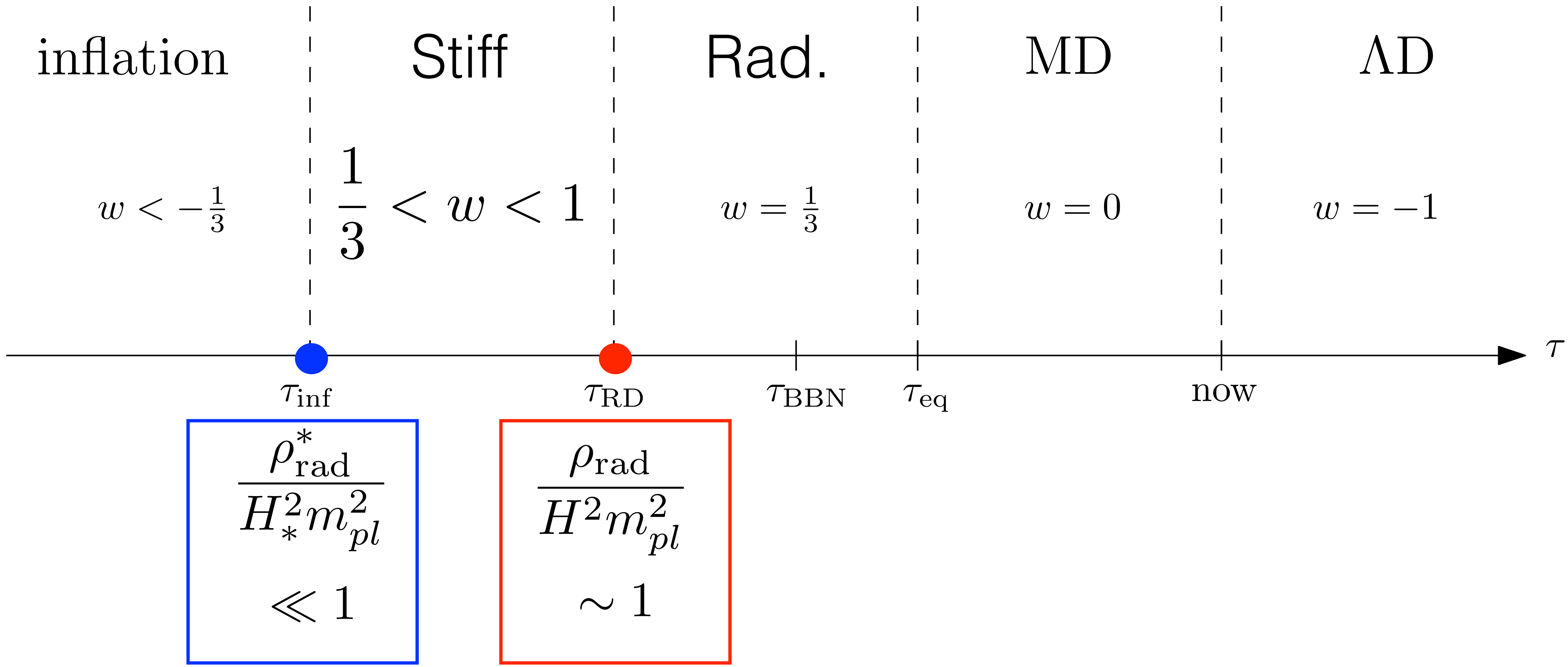


GRAVITATIONAL REHEATING

Ford '86, Spokoiny '93, Joyce '97, Giovannini '98/99, Vilenkin & Damour '95, Peebles & Vilenkin '98, [...], DGF & Tanin '18/19



$$\rho_s \sim m_p^2 H^2 \propto a^{-p(w)}$$

$$(4 < p \lesssim 6)$$

GRAVITATIONAL REHEATING

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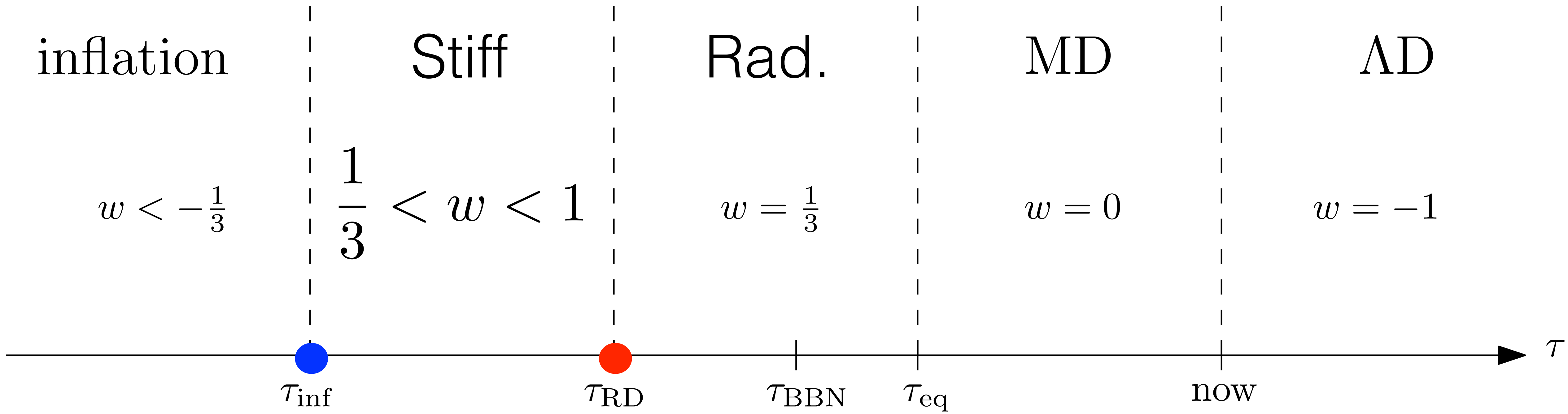

$$\frac{\rho^*_{\rm rad}}{H_*^2 m_{pl}^2} \ll 1$$

$$\frac{\rho_{\rm rad}}{H^2 m_{pl}^2} \sim 1$$

Requisites

- * Control perturbations
- * End before BBN

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$$(4 < p \lesssim 6)$$

GRAVITATIONAL REHEATING

Ford ’86, Spokoiny ’93, Joyce ’97,
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$$\boxed{1/3 < w_s \lesssim 1}$$

Stiff Eq. of State

Requisites

* Control perturbations
* End before BBN

All good… but we are not done !

GRAVITATIONAL REHEATING

Ford '86, Spokoiny '93, Joyce '97,
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$$\boxed{1/3 < w_s \lesssim 1}$$

Stiff Eq. of State

Requisites

* Control perturbations
* End before BBN

✓

All good... but we are not done !

Enhancement of inflationary Gravitational Waves (GW) !

[Giovannini '98/99, ..., Boyle & Buonnano '07, ..., DGF & Tanin '19]

Part 2

GRAVITATIONAL WAVES

(independently of grav. reheating)

Inflationary GW background

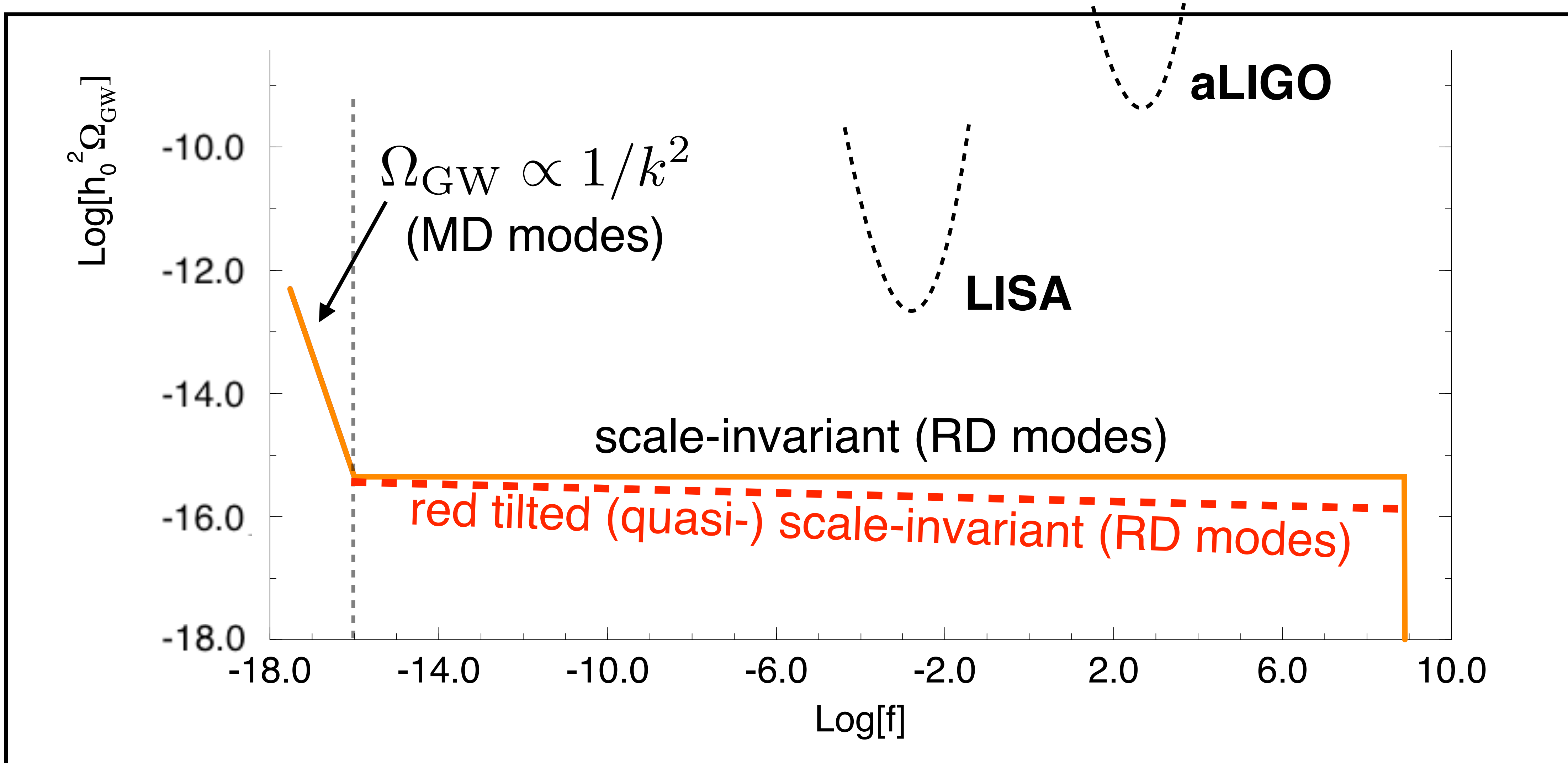
$$\Omega_{\rm GW}^{(o)}(f) \equiv \frac{1}{\rho_c^{(o)}}\left(\frac{d\rho_{\rm GW}}{d\log k}\right)_o = \underbrace{\frac{\Omega_{\rm Rad}^{(o)}}{24}}\Delta_{h_*}^2(k)$$

Transfer Funct.: $T(k) \propto k^0 (\mathrm{RD})$

$$\Delta_h^2(k) = \frac{2}{\pi^2}\left(\frac{H}{m_p}\right)^2\left(\frac{k}{aH}\right)^{n_t}$$

$n_t \equiv -2\epsilon$

energy scale



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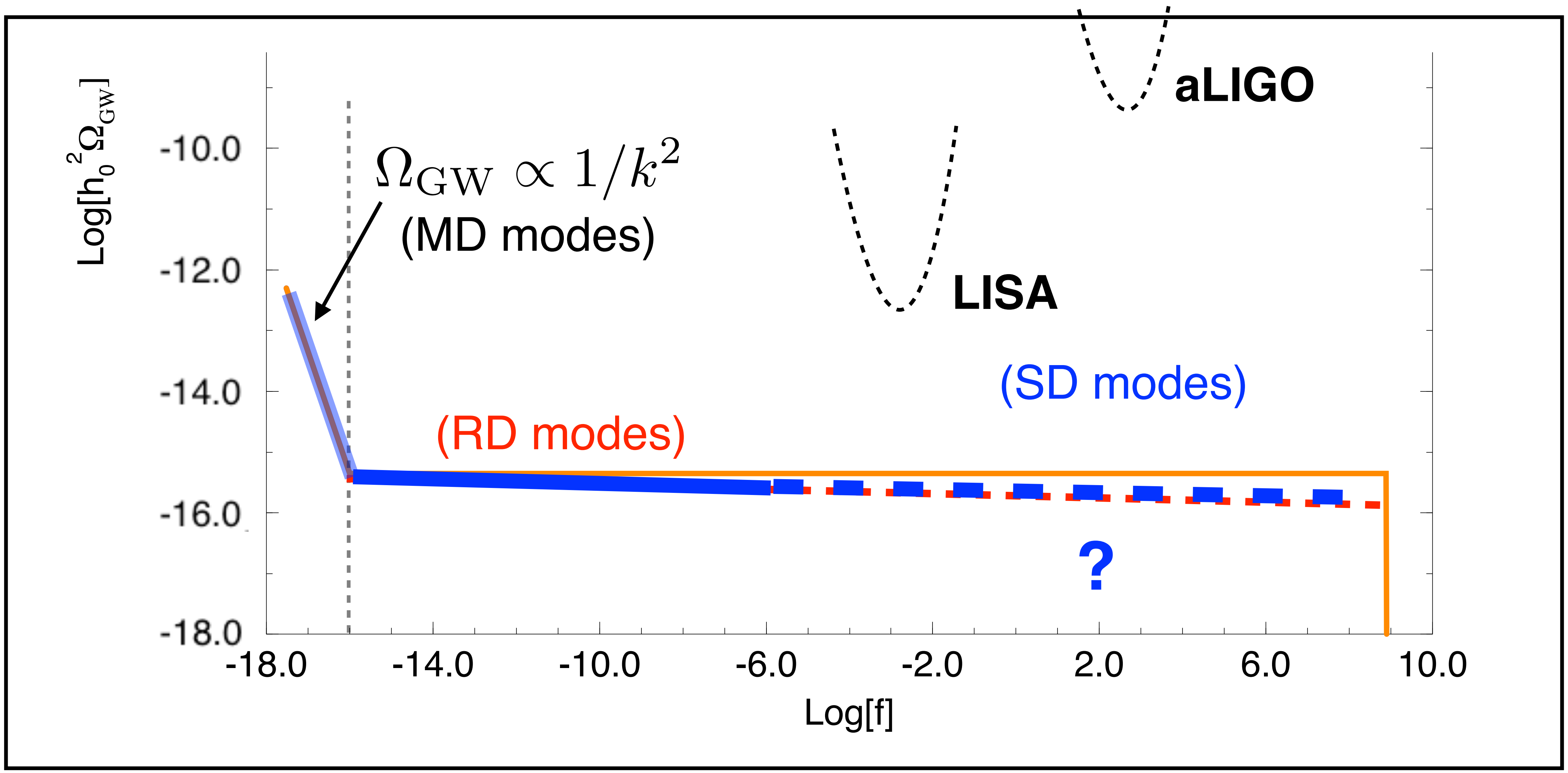
energy scale

Transfer Funct.: $T(k) \propto k^0(\mathrm{RD})$

Stiff Period: $T(k) \propto k^{2\frac{(w_s-1/3)}{(w_s+1/3)}}$



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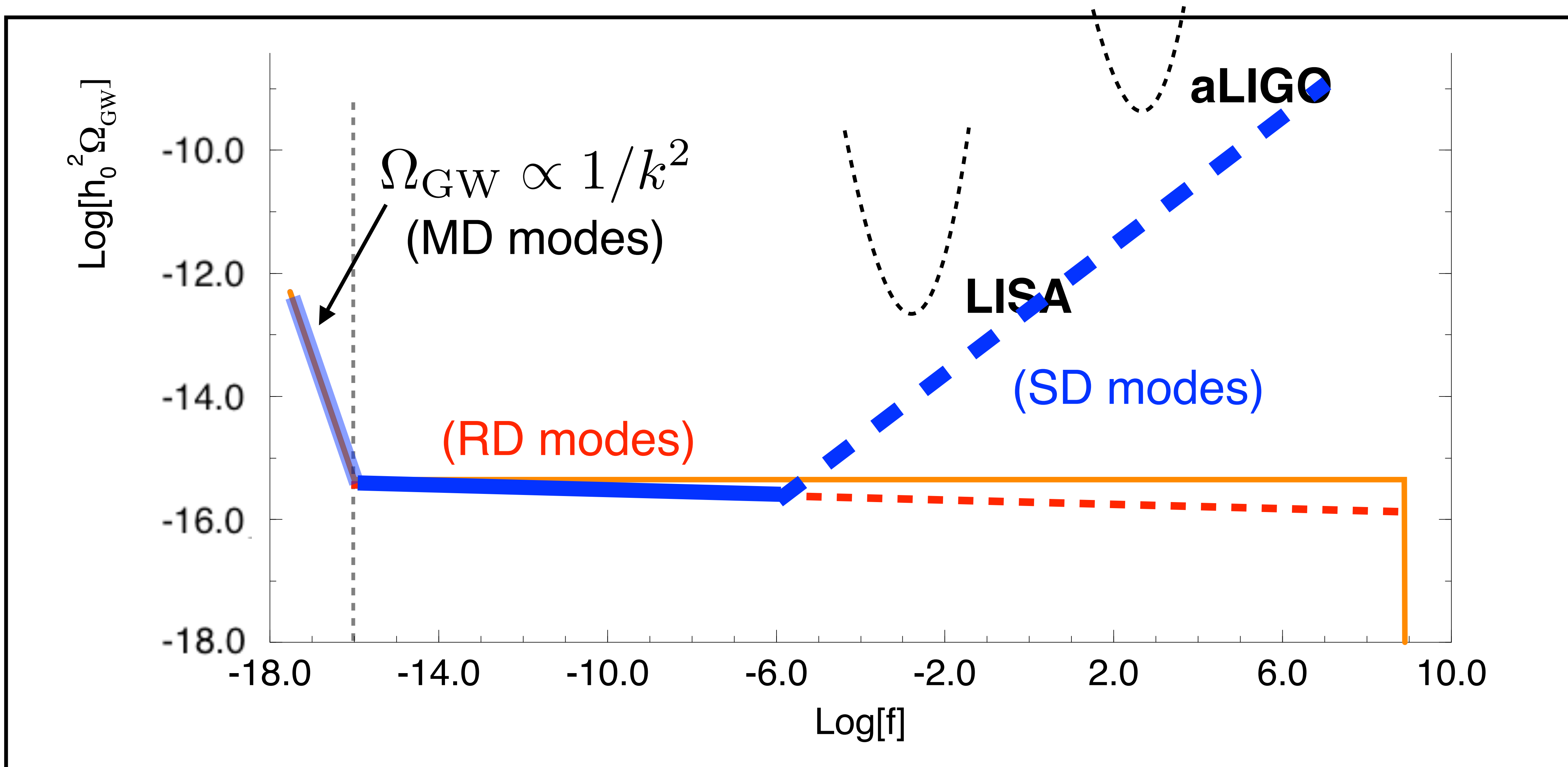

A couple few pages computation of the Transfer function @ Stiff Domination ….

Inflationary GW background

$$\boxed{\Omega_{\rm GW}^{(0)}(f) = \underbrace{\Omega_{\rm GW}^{(0)}\Big|_{\rm plateau}}_{\text{Rad. Plateau}} \times \underbrace{\mathcal{W}(f/f_{\rm RD}) \times \mathcal{A}_{\rm s}\left(\frac{f}{f_{\rm RD}}\right)^{n_t(w_s)}}_{\text{Transfer Funct. Stiff Period}}}\,, \quad \boxed{\Omega_{\rm GW}^{(0)}\Big|_{\rm plateau} \simeq 2\cdot 10^{-16}\left(\frac{H_*}{H_{\rm max}}\right)^2}$$

Window x *power-law*

Inflationary GW background

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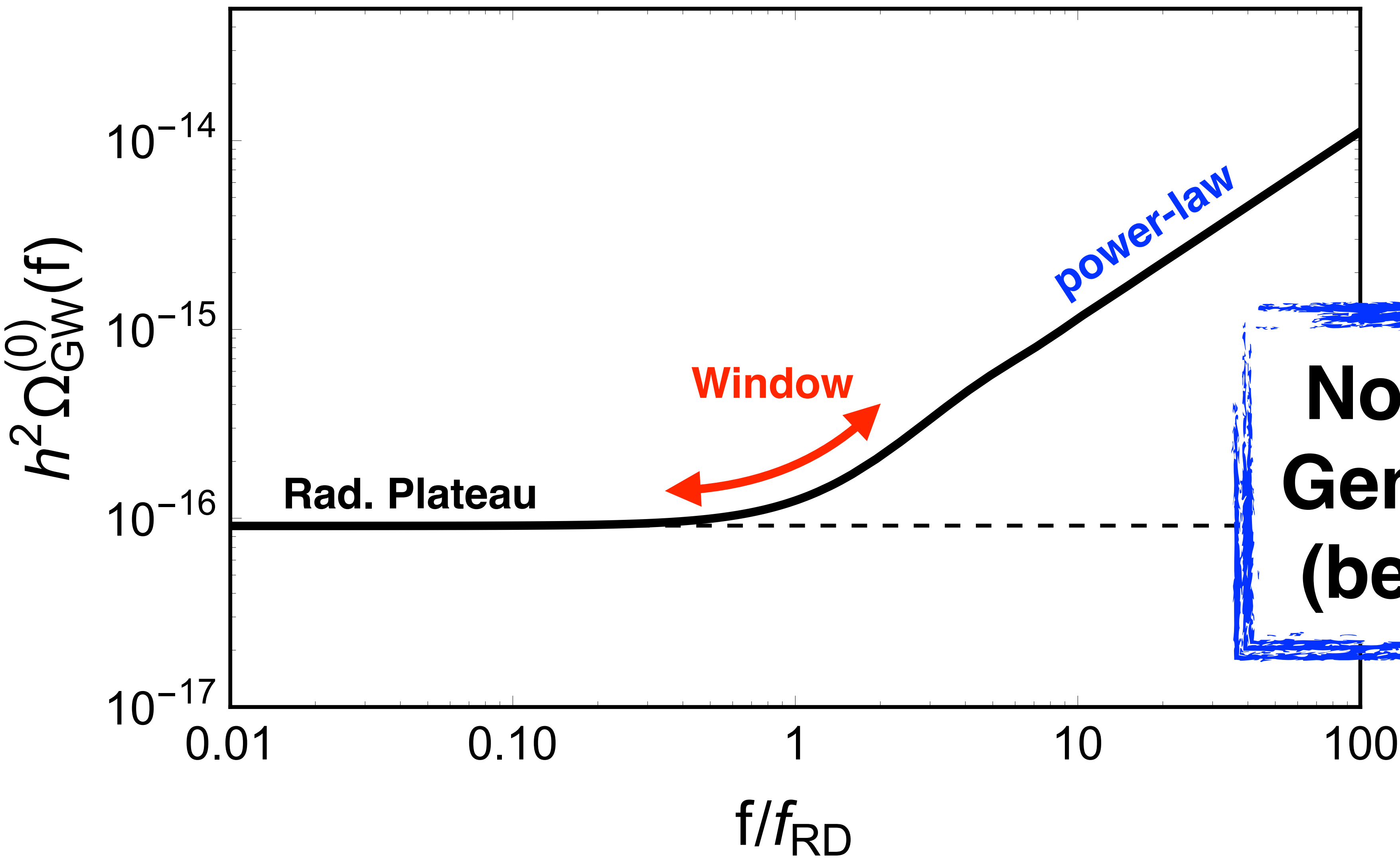

Not just Grav. RH !
Generic for Stiff Era
(before Rad. Dom.)

Inflationary GW background

$$\boxed{\Omega_{\rm GW}^{(0)}(f) = \underbrace{\Omega_{\rm GW}^{(0)}\Big|_{\rm plateau}}_{\text{Rad. Plateau}} \times \underbrace{\mathcal{W}(f/f_{\rm RD}) \times \mathcal{A}_{\rm s}\left(\frac{f}{f_{\rm RD}}\right)^{n_t(w_s)}}_{\text{Transfer Funct. Stiff Period}}}\,, \qquad \boxed{\Omega_{\rm GW}^{(0)}\Big|_{\rm plateau} \simeq 2\cdot 10^{-16}\left(\frac{H_*}{H_{\rm max}}\right)^2}$$

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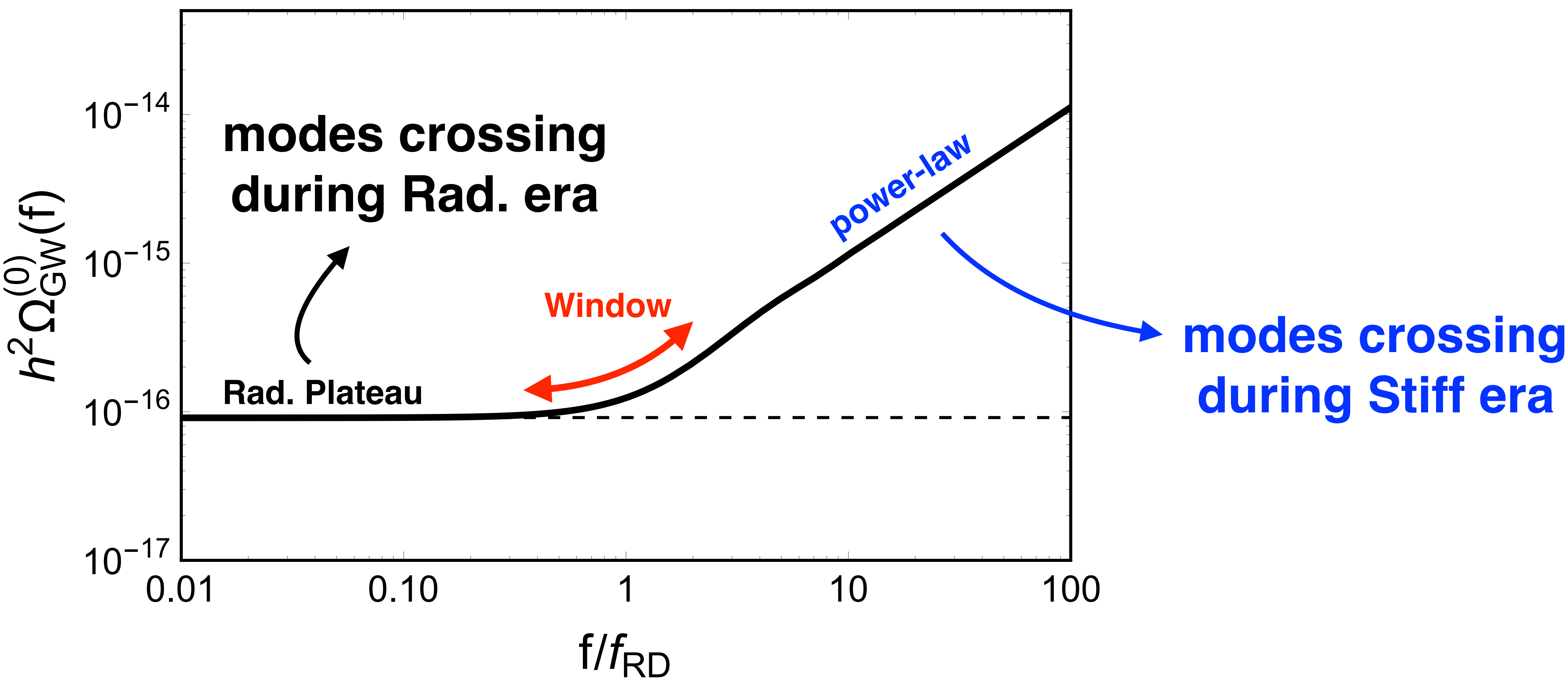

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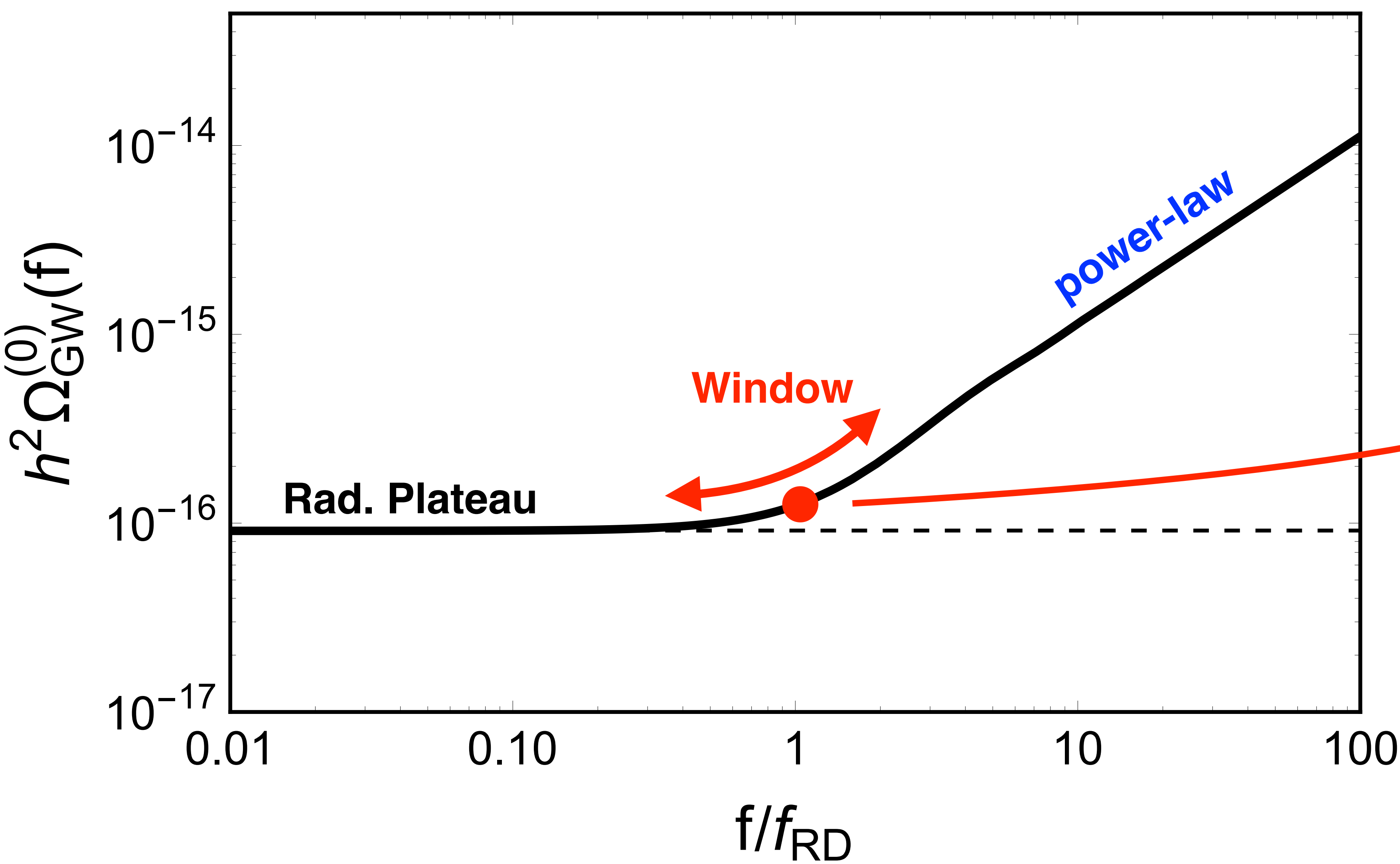
Window x *power-law*

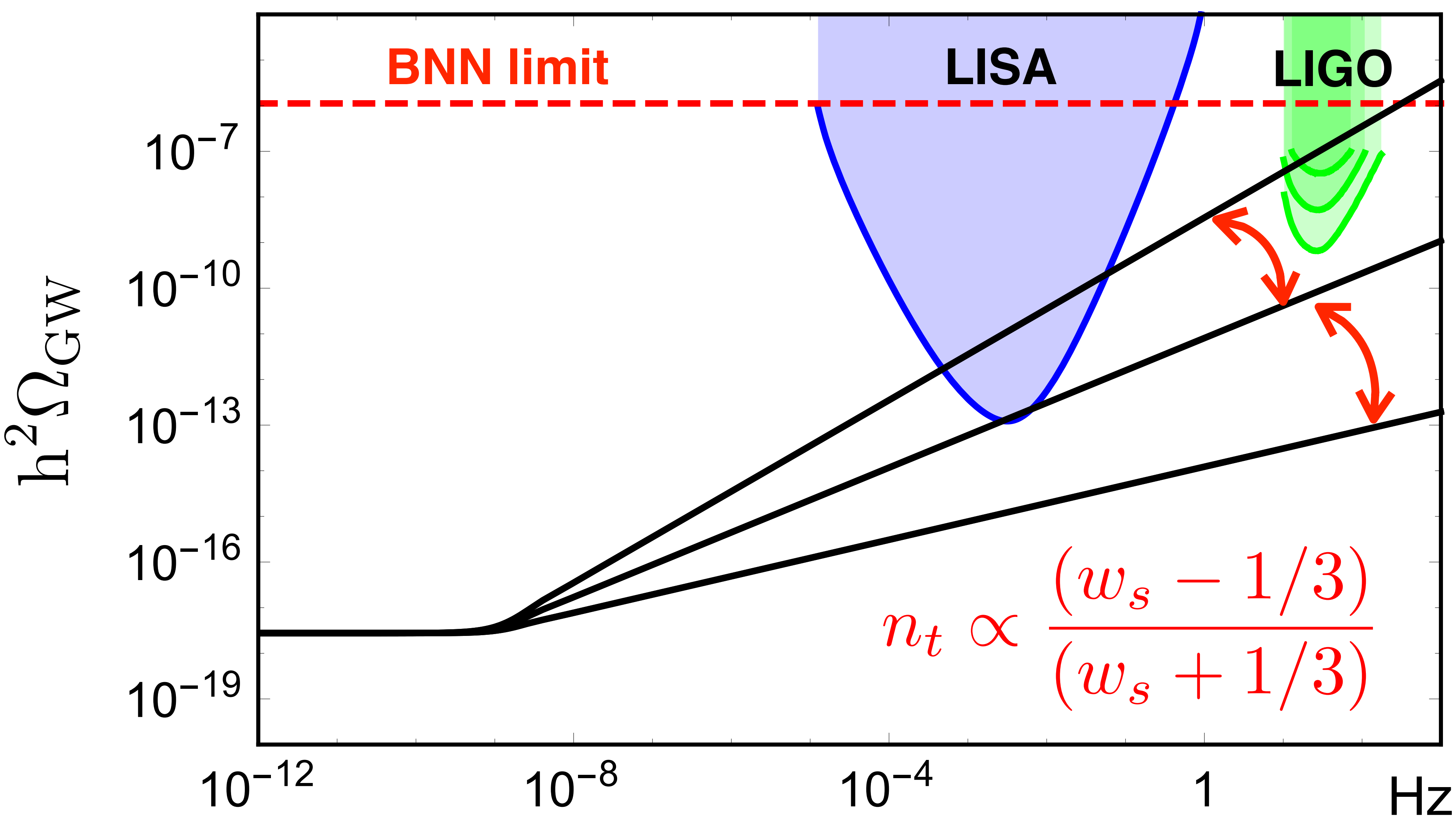


Horizon size @ SD-to-RD transition

Inflationary GW background

$$\boxed{\Omega_{\rm GW}^{(0)}(f) = \underbrace{\Omega_{\rm GW}^{(0)}\Big|_{\rm plateau}}_{\text{Rad. Plateau}} \times \underbrace{\mathcal{W}(f/f_{\rm RD}) \times \mathcal{A}_{\rm s}\left(\frac{f}{f_{\rm RD}}\right)^{n_t(w_s)}}_{\text{Transfer Funct. Stiff Period}}}\,, \quad \boxed{\Omega_{\rm GW}^{(0)}\Big|_{\rm plateau} \simeq 2\cdot 10^{-16}\left(\frac{H_*}{H_{\rm max}}\right)^2}$$

Window x *power-law*



Slope/Tilt
(EoS
Stiff
Period)

Inflationary GW background

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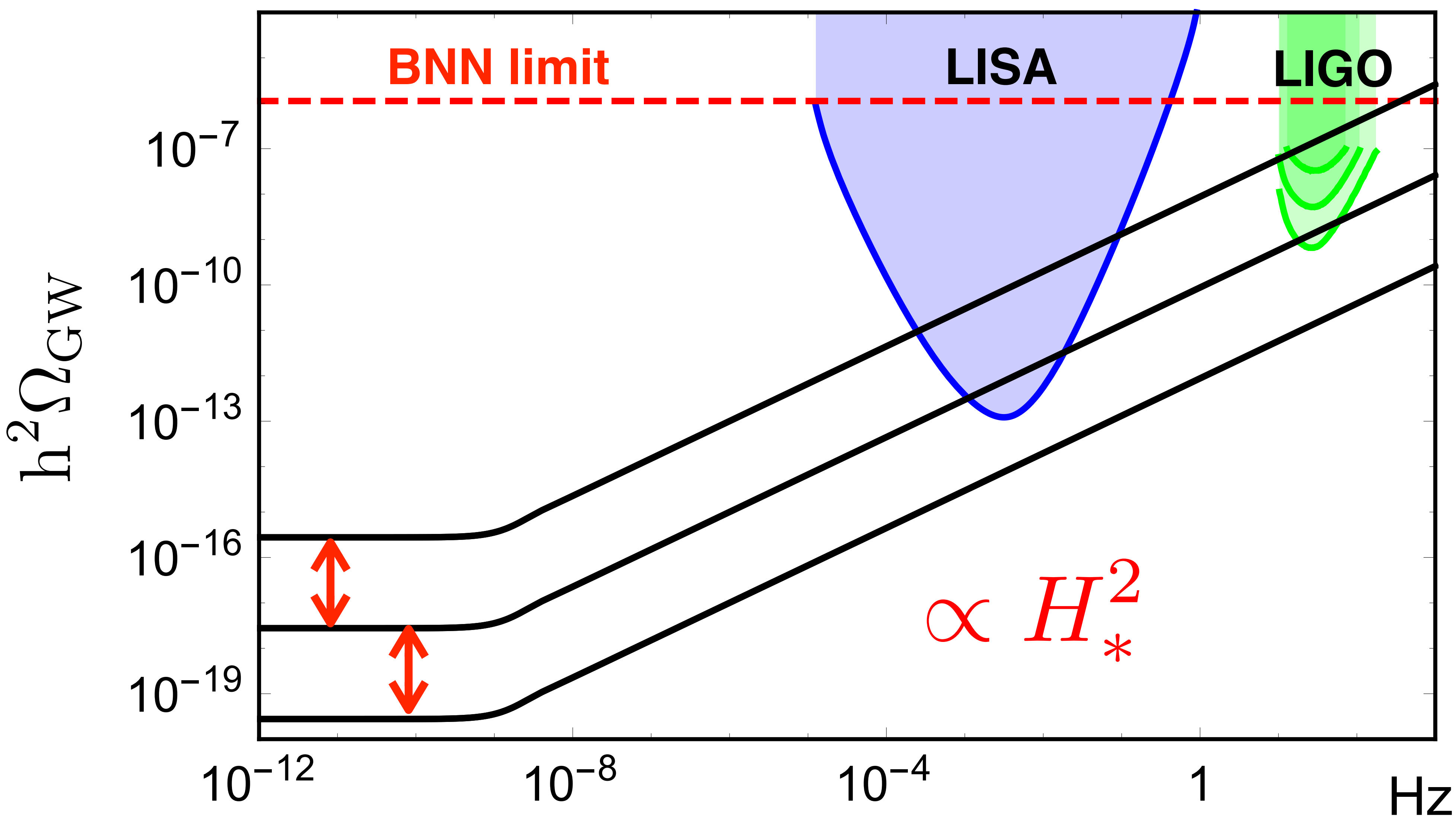
Window x *power-law*

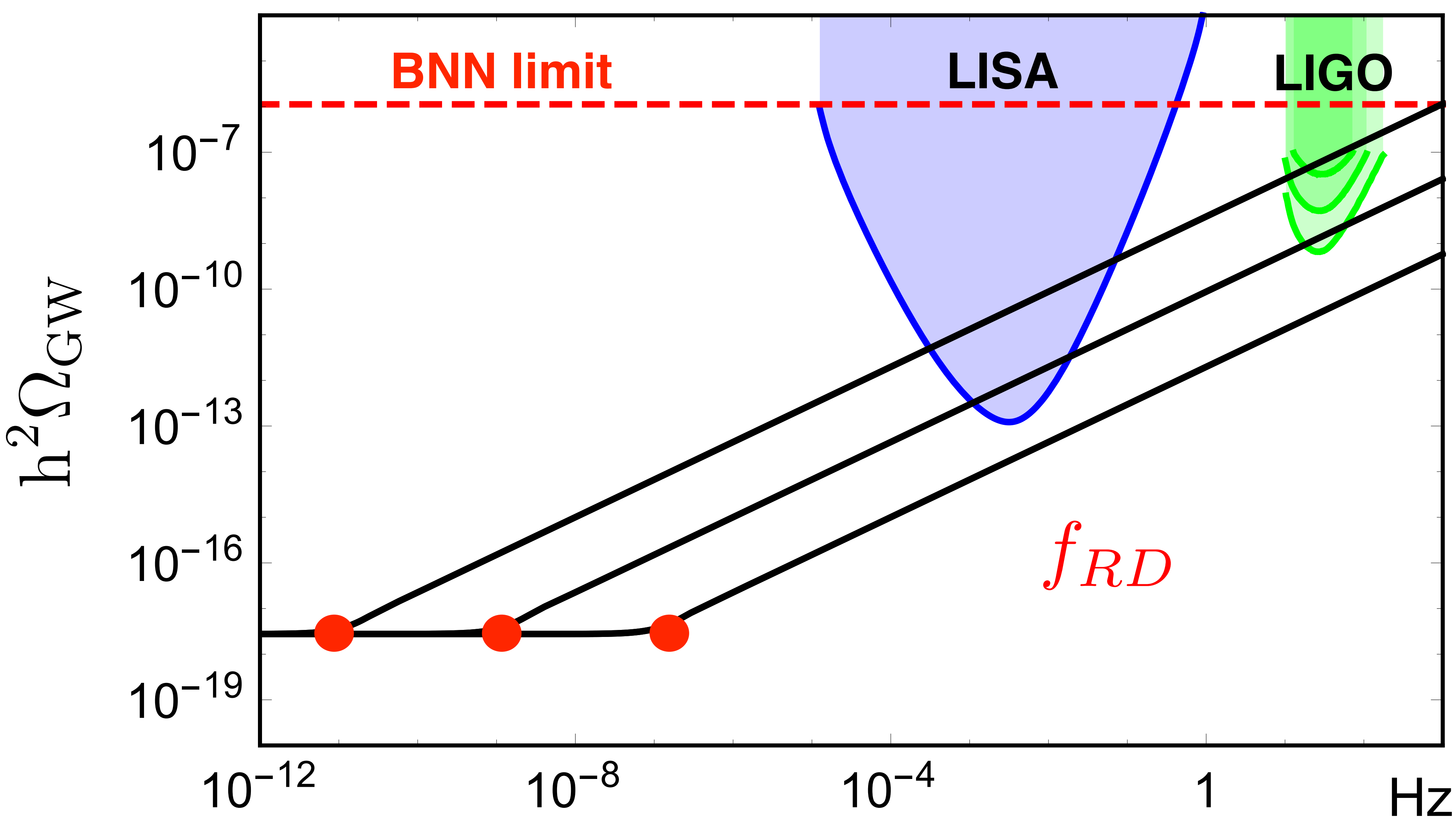


Overall Amplitude (Energy Scale Inflation)

Inflationary GW background

$$\Omega_{\rm GW}^{(0)}(f) = \underbrace{\Omega_{\rm GW}^{(0)}\Big|_{\rm plateau}}_{\text{Rad. Plateau}} \times \underbrace{\mathcal{W}(f/f_{\rm RD}) \times \mathcal{A}_{\rm s}\left(\frac{f}{f_{\rm RD}}\right)^{n_t(w_s)}}_{\text{Transfer Funct. Stiff Period}}\,, \qquad \Omega_{\rm GW}^{(0)}\Big|_{\rm plateau} \simeq 2\cdot 10^{-16}\left(\frac{H_*}{H_{\max}}\right)^2$$

Window x power-law



Freq. RD

$$k_{\rm RD} = a_{\rm RD} H_{\rm RD}$$

$$f_{\rm RD} \equiv k_{\rm RD}/(2\pi a_0)$$

SD-to-RD transition

Inflationary GW background

$$\boxed{\Omega^{(0)}_{\rm GW}(f) = \underbrace{\Omega^{(0)}_{\rm GW}\Big|_{\rm plateau}}_{\textbf{Rad. Plateau}} \times \underbrace{\mathcal{W}(f/f_{\rm RD}) \times \mathcal{A}_{\rm s}\left(\frac{f}{f_{\rm RD}}\right)^{n_t(w_s)}}_{\textbf{Transfer Funct. Stiff Period}}}\,, \quad \boxed{\Omega^{(0)}_{\rm GW}\Big|_{\rm plateau} \simeq 2\cdot 10^{-16}\left(\frac{H_*}{H_{\rm max}}\right)^2}$$

Window x power-law

$$\Omega^{(0)}_{\rm GW}(f; \underline{H_*}, \underline{w_s}, \underline{f_{RD}})$$

Energy Scale Inflation

EoS Stiff Period

Duration Stiff Period

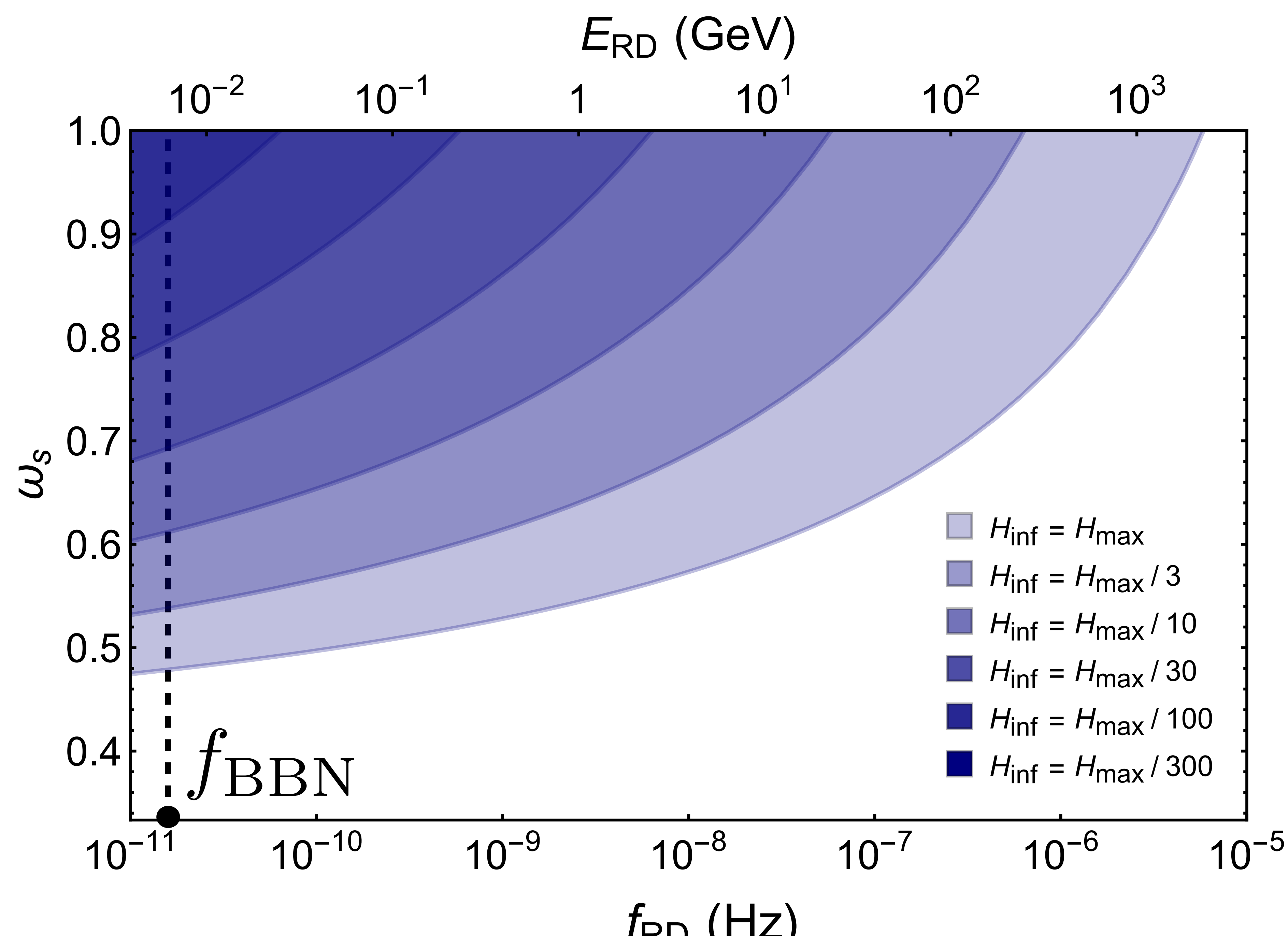
GW background $\Omega^{(0)}_{\rm GW}(f; \underbrace{H_*}_{\text{Energy Scale}}, \underbrace{w_s}_{\text{EoS Stiff}}, \underbrace{f_{RD}}_{\text{Duration Stiff}})$

Observability @ LISA (~ 2034)

GW background $\Omega^{(0)}_{\rm GW}(f; \underline{H_*}, \underline{w_s}, \underline{f_{RD}})$

Energy Scale | EoS Stiff | Duration Stiff

Observability @ LISA (~ 2034)



GW background $\Omega_{\rm GW}^{(0)}(f; \underline{H_*}, \underline{w_s}, \underline{f_{RD}})$

Energy Scale | EoS Stiff | Duration Stiff

Observability @ LISA (~ 2034)

$$9.1 \times 10^{10}\ \text{GeV} < H_{\rm inf} < 6.6 \times 10^{13}\ \text{GeV}$$

$$0.47 < w_{\rm S} < 1$$

$$10^{-11}\ \text{Hz} \lesssim f_{\rm RD} < 4.6 \times 10^{-6}\ \text{Hz}$$

$$10^{-3}\ \text{GeV} \lesssim E_{\rm RD} < 5.91 \times 10^{3}\ \text{GeV}$$

Significant fraction of param. space observable !

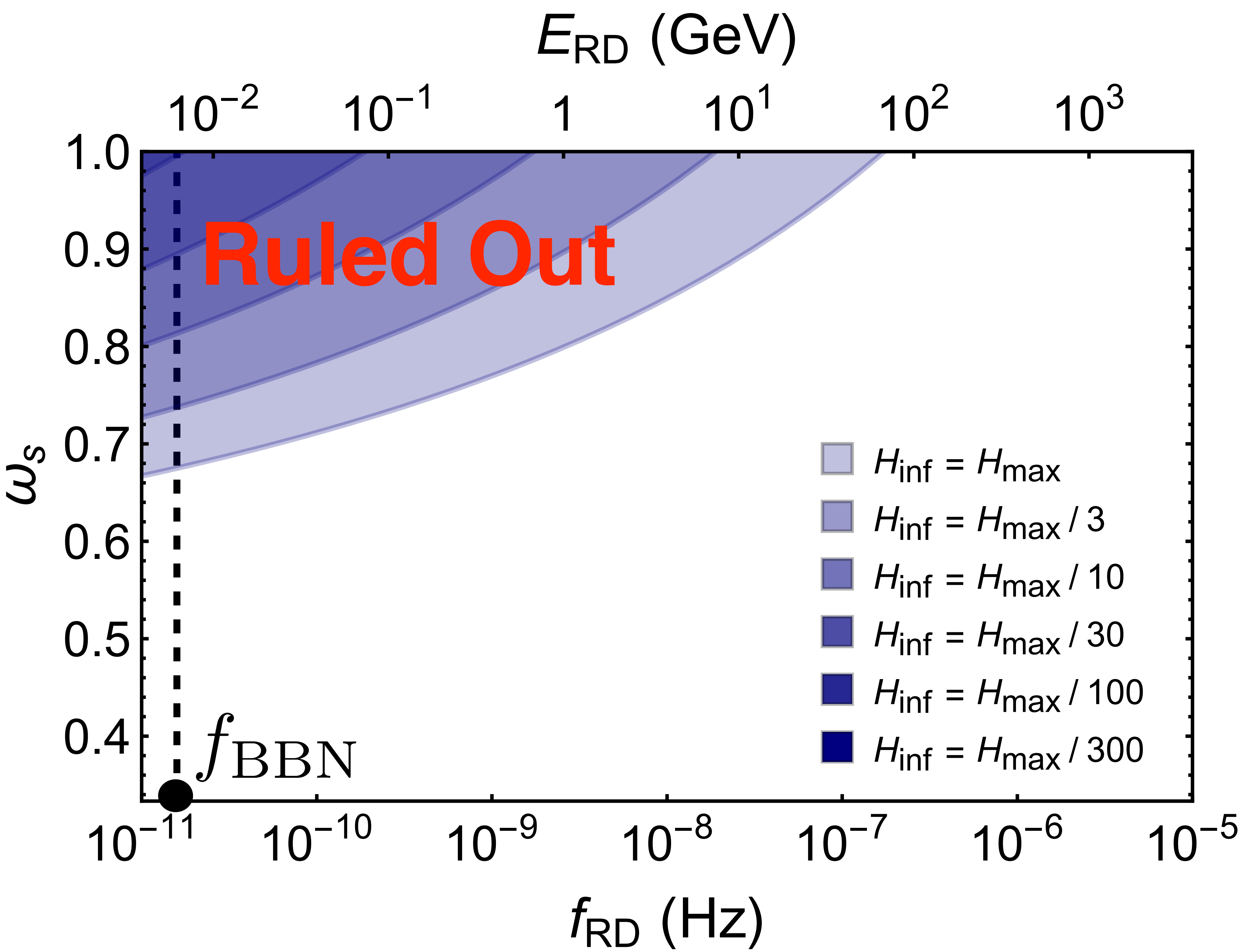
GW background $\Omega^{(0)}_{\rm GW}(f;\underbrace{H_*}_{\text{Energy Scale}},\underbrace{w_s}_{\text{EoS Stiff}},\underbrace{f_{RD}}_{\text{Duration Stiff}})$

Observability @ LIGO (today)

GW background $\Omega^{(0)}_{\rm GW}(f; \underline{H_*}, \underline{w_s}, \underline{f_{RD}})$

Energy Scale | EoS Stiff | Duration Stiff

Observability @ LIGO (today)

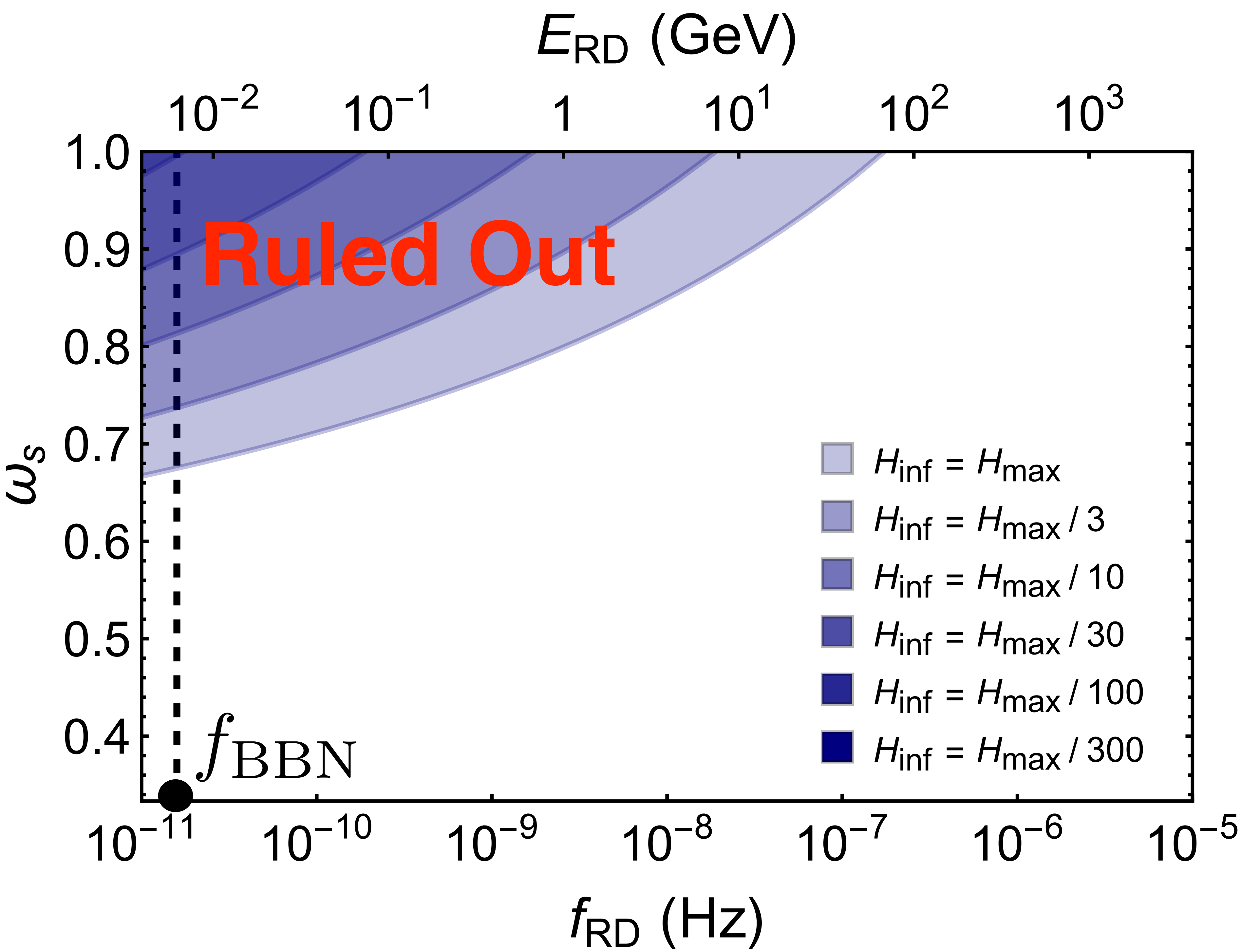


LIGO reduces parameter space probe-able by LISA !

GW background $\Omega^{(0)}_{\rm GW}(f; \underline{H_*}, \underline{w_s}, \underline{f_{RD}})$

Energy Scale | EoS Stiff | Duration Stiff

Observability @ LIGO (today)

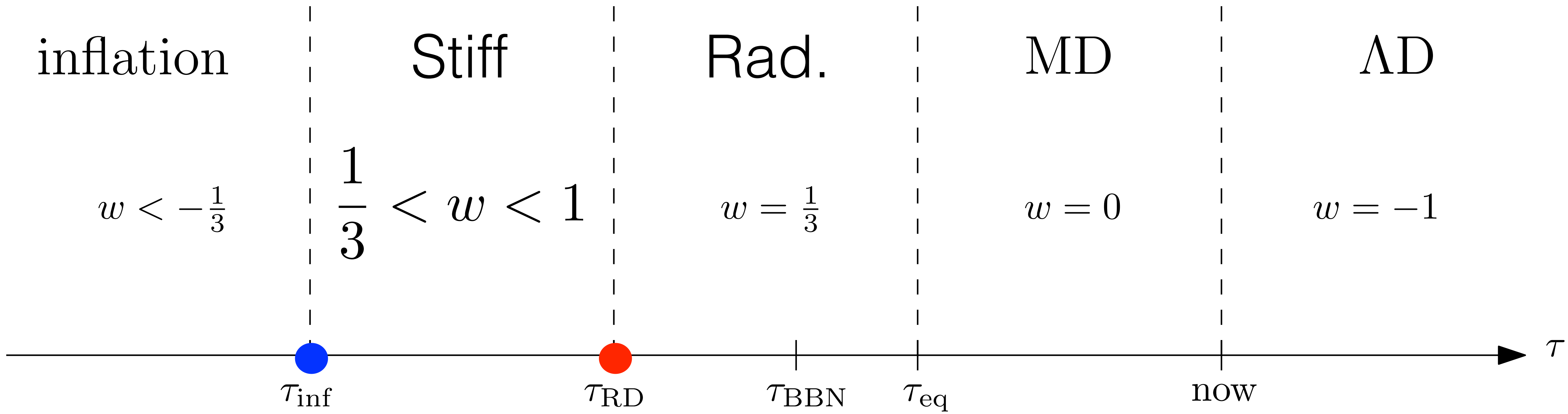


Let's look first at consistency of scenarios

Part 3

The trouble with gravitational reheating

BACK to … GRAVITATIONAL REHEATING



$$\frac{\rho^*_{\rm rad}}{H_*^2 m_{pl}^2} \ll 1$$

$$\frac{\rho_{\rm rad}}{H^2 m_{pl}^2} \sim 1$$

$$\Omega_{\rm GW}^{\rm (TOT)} = \int \left(\frac{d\rho_{\rm GW}}{d\log f}\right) \frac{d\log f}{\rho_c}$$

Requisites

* Control perturbations
* End before BBN
* **Not too many GWs**

BIG BANG NUCLEOSYNTHESIS

Expansion rate (Rad. Dom): ~ Extra relativistic species

$$\int \frac{df}{f}\, h^2\, \Omega_{\rm GW}(f) \leq \; 1.12 \times 10^{-6}$$

$$\Delta N_\nu = 0.2 \; (95\% C.L.)$$ [latest CMB]

BIG BANG NUCLEOSYNTHESIS

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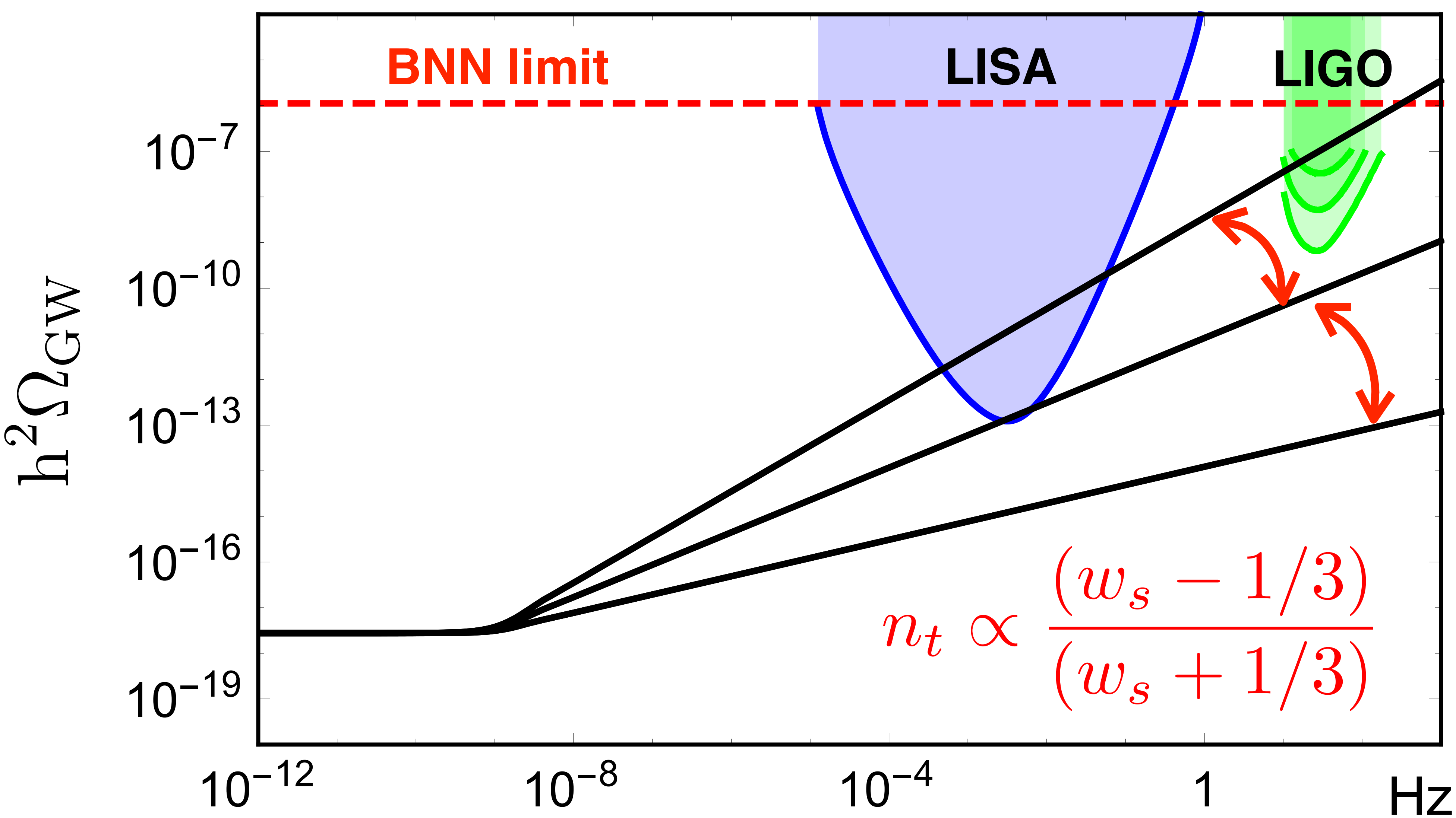
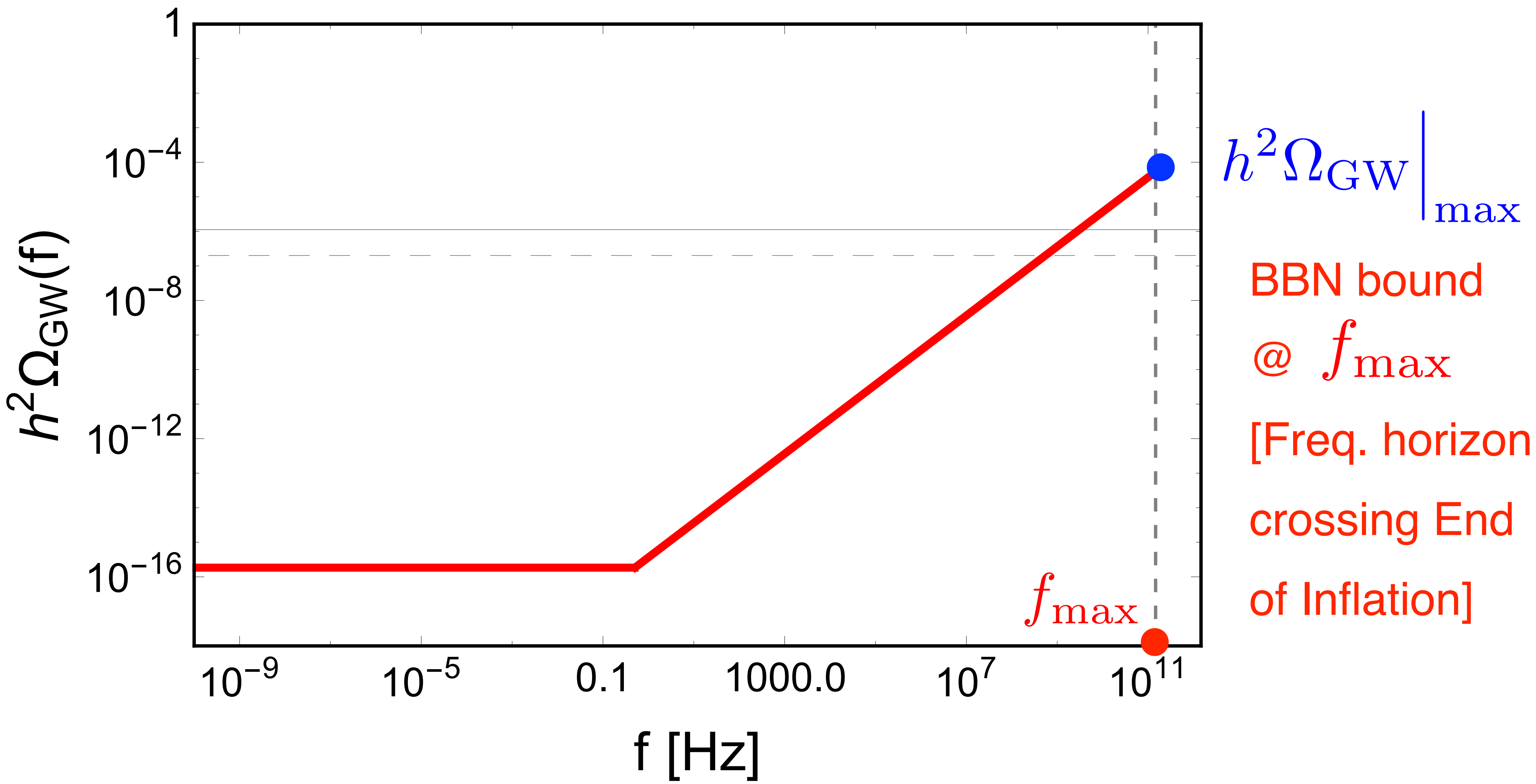


BBN: $\int \frac{df}{f} h^2\,\Omega_{\rm GW}(f) \leq\ 1.12\times 10^{-6}$

Grav. Reheating: $\Omega_{\rm GW}(f) \propto (f/f_{\rm RD})^{2\left(\frac{w_s-1/3}{w_s+1/3}\right)}$

Monotonically growing signal !



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Monotonically growing signal !

BBN bound @ $f_{\rm max}$ [Freq. horizon crossing End of Inflation]

$$h^2\Omega^{(0)}_{\rm GW}\Big|_{\rm max}(H_*, w_s, f_{RD}) \lesssim 10^{-6}$$

BBN: $h^2\Omega_{\rm GW}^{(0)}\Big|_{\rm max}(H_*, w_s, f_{RD}) \lesssim 10^{-6}$

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Grav. Reheating: $$\Delta_* \equiv \frac{\rho_{\rm rad}}{3m_p^2H_*^2} = \frac{\delta}{300}\left(\frac{H_*}{m_p}\right)^2 \,,\quad \delta \lesssim 1\,,$$

$$f_{\rm RD} = f_{\rm RD}(H_*, w_s, \Delta_*) = f_{\rm RD}(H_*, w_s, \delta)$$

$$h^2\Omega_{\rm GW}^{(0)}\Big|_{\rm max}(H_*, w_s, f_{RD}) \lesssim 10^{-6}$$

BBN: $$h^2\Omega_{\rm GW}^{(0)}\Big|_{\rm max}(\,H_*, w_s, f_{RD}) \lesssim 10^{-6}$$

Grav. Reheating: $$h^2\Omega_{\rm GW}^{(0)}\Big|_{\rm max}(H_*, w_s; \delta) \lesssim 10^{-6}, \quad \delta \lesssim 1\,,$$

BBN: $$h^2\Omega^{(0)}_{\rm GW}\Big|_{\rm max}(H_*, w_s, f_{RD}) \lesssim 10^{-6}$$

Grav. Reheating: $$h^2\Omega^{(0)}_{\rm GW}\Big|_{\rm max}(H_*, w_s; \delta) \lesssim 10^{-6}, \quad \delta \lesssim 1\,,$$

However … $$h^2\Omega^{(0)}_{\rm GW}\Big|_{\rm max}(H_*, w_s; \delta) \simeq \underbrace{2.1\cdot 10^{-5}}_{\text{const.}} \times \underbrace{f(w_s)}_{\text{mild dependence}} \times \underbrace{\frac{1}{\delta}}_{\text{initial fraction}}$$

BBN: $$h^2\Omega^{(0)}_{\rm GW}\Big|_{\rm max}(H_*, w_s, f_{RD}) \lesssim 10^{-6}$$

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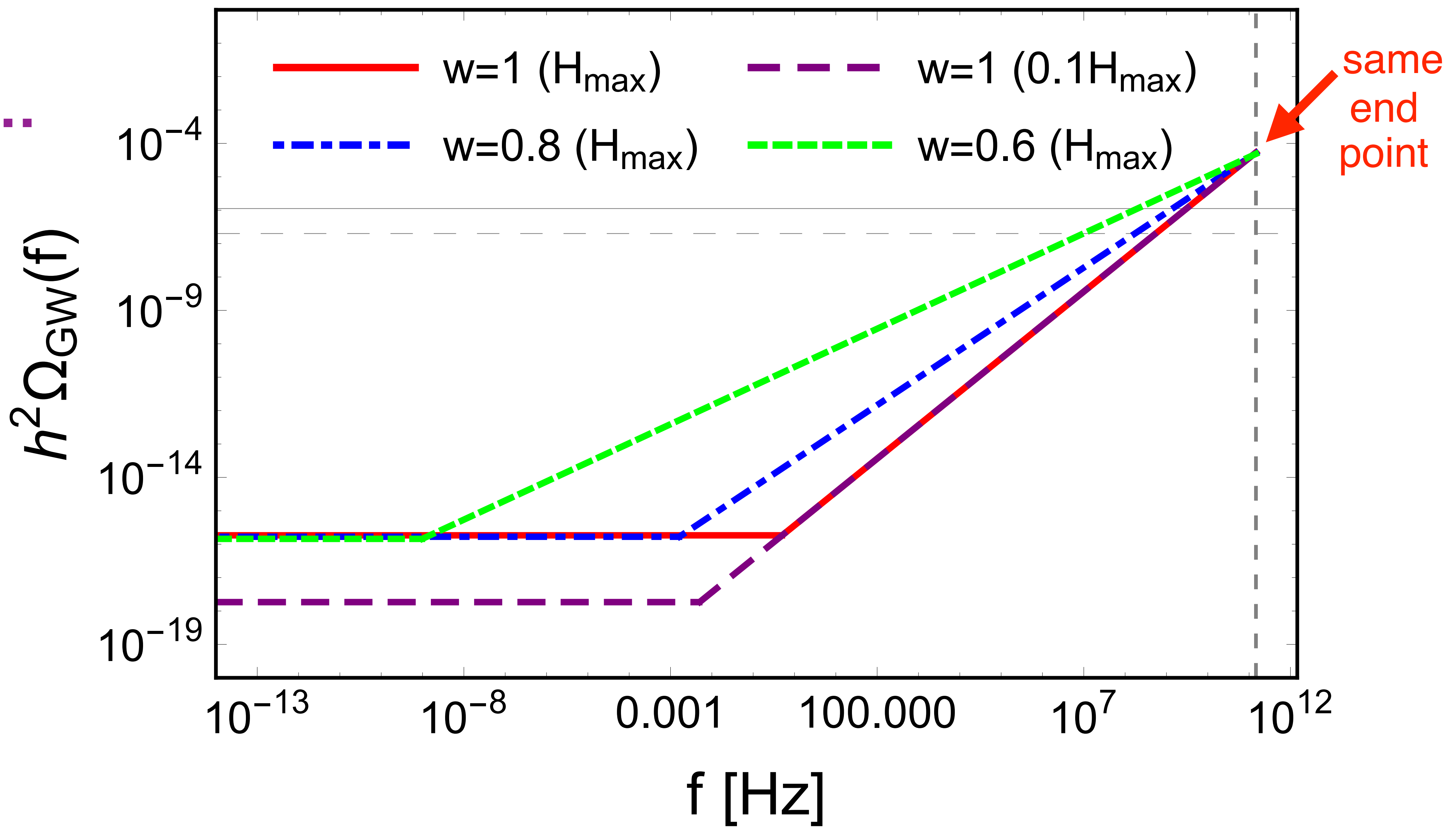
$$\underset{(w_s = 1/3)}{2} \leq f(w_s) \leq \underset{(w_s = 1)}{2.54}$$

$$\boxed{f(w_s) \equiv \frac{2^{\frac{3(1-w_s)}{(1+3w_s)}}\,\Gamma^2\left(\frac{5+3w_s}{2+6w_s}\right)}{\left(\frac{2}{1+3w_s}\right)^{\frac{4}{1+3w_s}}\Gamma^2\left(\frac{3}{2}\right)}}$$

BBN: $$h^2\Omega^{(0)}_{\rm GW}\Big|_{\rm max}(H_*, w_s, f_{RD}) \lesssim 10^{-6}$$

Grav. Reheating: $$h^2\Omega^{(0)}_{\rm GW}\Big|_{\rm max}(H_*, w_s; \delta) \lesssim 10^{-6}, \quad \delta \lesssim 1\,,$$

However …



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Why ?

BBN: $$h^2\Omega_{\rm GW}^{(0)}\Big|_{\max}(H_*, w_s, f_{RD}) \lesssim 10^{-6}$$

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Why ?

$$\left.\begin{aligned} \rho_{\rm rad} &\propto H_*^4 a^{-4} \\ \rho_{\rm GW} &\propto H_*^4 a^{-4} \end{aligned}\right\} \Longrightarrow \frac{\rho_{\rm GW}}{\rho_{\rm rad}} \sim const.$$

BBN: $$h^2\Omega^{(0)}_{\rm GW}\Big|_{\max}(H_*, w_s, f_{RD}) \lesssim 10^{-6}$$

Grav. Reheating: $$h^2\Omega^{(0)}_{\rm GW}\Big|_{\max}(H_*, w_s; \delta) \lesssim 10^{-6}, \quad \delta \lesssim 1,$$

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$$\Delta_* \equiv \frac{\rho_{\rm rad}}{3m_p^2 H_*^2} = \frac{\delta}{300}\left(\frac{H_*}{m_p}\right)^2$$

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So … $$h^2\Omega^{(0)}_{\rm GW}\Big|_{\rm max} \simeq \frac{const.}{\delta} \lesssim 10^{-6} \quad \Leftrightarrow \quad \delta \gtrsim 50$$

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(!)

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So … $$h^2\Omega^{(0)}_{\rm GW}\Big|_{\rm max} \simeq \frac{const.}{\delta} \lesssim 10^{-6} \quad \Leftrightarrow \quad \delta \gtrsim 50$$

(!)

$$\frac{\rho_{\rm GW}}{\rho_{\rm rad}} \sim \underline{const. \gg 1}$$

Universe dominated by GWs!

BBN: $$h^2\Omega_{\rm GW}^{(0)}\Big|_{\rm max}(H_*, w_s, f_{RD}) \lesssim 10^{-6}$$

Grav. Reheating: $$h^2\Omega_{\rm GW}^{(0)}\Big|_{\rm max}(H_*, w_s; \delta) \lesssim 10^{-6}, \quad \delta \lesssim 1,$$

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So … $$h^2\Omega_{\rm GW}^{(0)}\Big|_{\rm max} \simeq \frac{const.}{\delta} \lesssim 10^{-6} \quad \Leftrightarrow \quad \delta \gtrsim 50$$ **(!)**

CMB: $\delta \gtrsim 200$ **(!!)**

(standard) Grav. Reheating incompatible with BBN/CMB !

Therefore…

1) Either we modify Grav. Reheating

2) We use modified gravity in Inflationary Sector

3) We couple the inflaton and reheat via such couplings

(standard) Grav. Reheating incompatible with BBN/CMB !

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Standard (P)reheating

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Therefore…

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2) We use modified gravity in Inflationary Sector

I'm very happy with General Relativity !

(standard) Grav. Reheating incompatible with BBN/CMB !

Therefore…

1) Either we modify Grav. Reheating

2) We use modified gravity in Inflationary Sector

But if you are not …

Y. Watanabe and E. Komatsu, Phys. Rev. **D75**, 061301 (2007), gr-qc/0612120.
Y. Watanabe, Phys. Rev. **D83**, 043511 (2011), 1011.3348.
A. A. Starobinsky, Phys. Lett. **B91**, 99 (1980), [,771(1980)].
A. De Felice and S. Tsujikawa, Living Rev. Rel. **13**, 3 (2010), 1002.4928.

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$\boxed{\textbf{1) Either we modify Grav. Reheating}}$

$$\Delta_* \equiv \frac{\rho_{\rm rad}}{3m_p^2 H_*^2} = \frac{\delta}{300}\left(\frac{H_*}{m_p}\right)^2 \longrightarrow \mathcal{N}_f \Delta_*$$

All $\mathcal{N}_f$ fields
same properties !

$$\delta = \delta_1 \times \mathcal{N}_f \,,$$

$$\mathcal{N}_f \gtrsim \mathcal{O}(10^3)$$

Ad hoc tuning !

(standard) Grav. Reheating incompatible with BBN/CMB !

Therefore…

1) Either we modify Grav. Reheating

Radiation field is the SM Higgs ? We need non-min coupling

$$\mathcal{L}_\chi = (\partial\chi)^2 + \lambda\chi^4 - \xi\chi^2 R$$

(standard) Grav. Reheating incompatible with BBN/CMB !

Therefore…

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Radiation field is the SM Higgs ? We need non-min coupling

$$\mathcal{L}_\chi = (\partial\chi)^2 + \lambda\chi^4 - \xi\chi^2 R$$

Standard Grav. RH ?

(standard) Grav. Reheating incompatible with BBN/CMB !

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Radiation field is the SM Higgs ? We need non-min coupling

$$\mathcal{L}_\chi = (\partial\chi)^2 + \lambda\chi^4 - \xi\chi^2 R$$

Standard Grav. RH wrong !
$m_\chi^2 < 0$ **@ Stiff Period,**

(standard) Grav. Reheating incompatible with BBN/CMB !

Therefore…

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Radiation field is the SM Higgs ? We need non-min coupling

$$\mathcal{L}_\chi = (\partial\chi)^2 + \lambda\chi^4 - \xi\chi^2 R$$

Standard Grav. RH wrong !
$m_\chi^2 < 0$ **@ Stiff Period, but self-interactions regularize**

(standard) Grav. Reheating incompatible with BBN/CMB !

Therefore…

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Radiation field is the SM Higgs ? We need non-min coupling

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Corrected in DGF & Byrnes '16
Phys.Lett. B767 (2017) 272-277
Arxiv: 1604.03905

(standard) Grav. Reheating incompatible with BBN/CMB !

Therefore…

1) Either we modify Grav. Reheating

Radiation field is the SM Higgs ? We need non-min coupling

$$\mathcal{L}_\chi = (\partial\chi)^2 + \lambda\chi^4 - \xi\chi^2 R$$

Standard Grav. RH wrong !

$$\boxed{\delta \sim \mathcal{O}(10^3)\frac{\xi^2}{\lambda} \gg 1}$$

Grav. Reheating OK !

$$\lambda > 0 \ (\text{stability})\,, \quad \xi \gtrsim 1$$

Corrected in DGF & Byrnes '16
Phys.Lett. B767 (2017) 272-277
Arxiv: 1604.03905

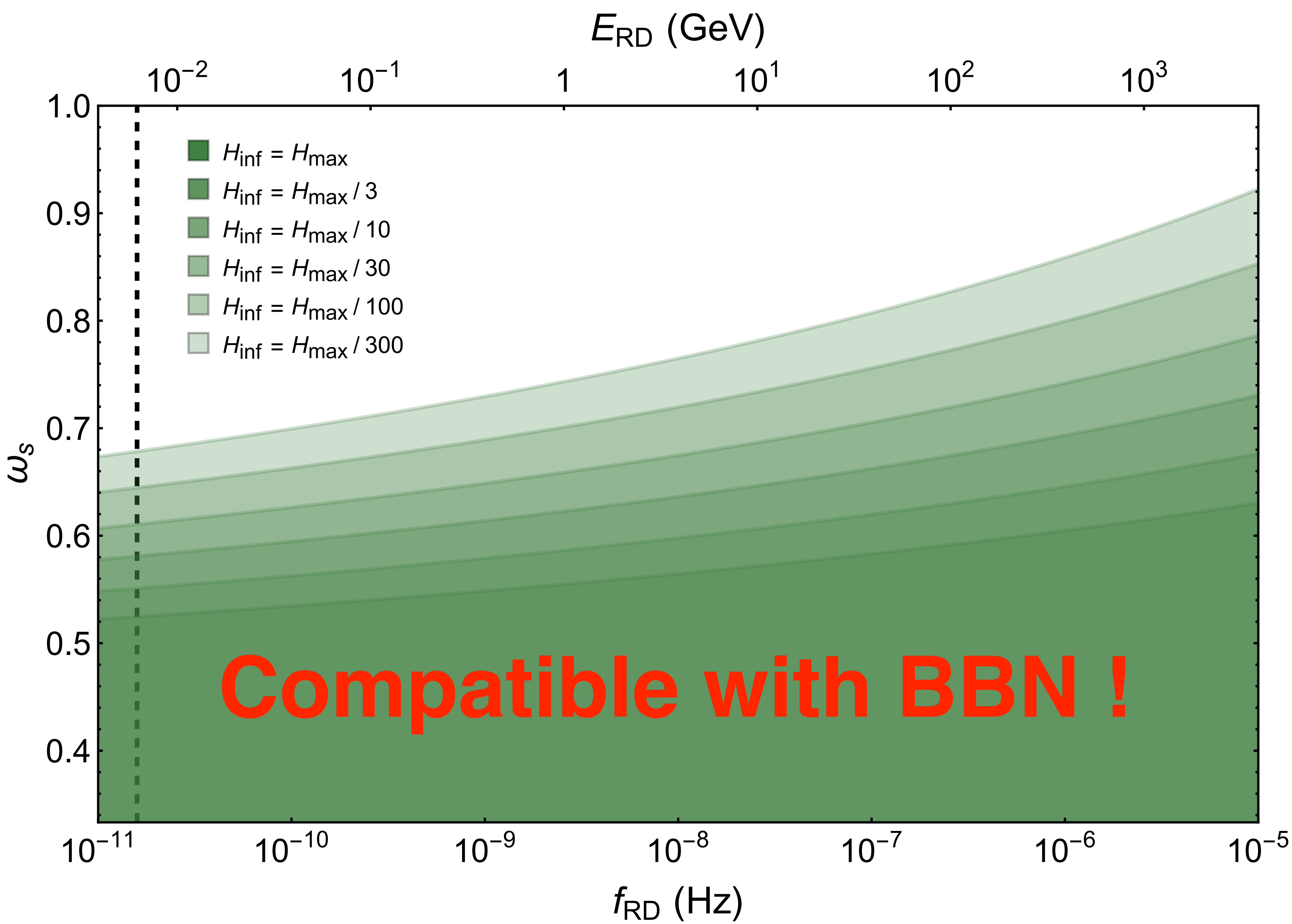
See also **1803.07399** **1905.06823** for generic $\lambda\chi^4$

Part 4

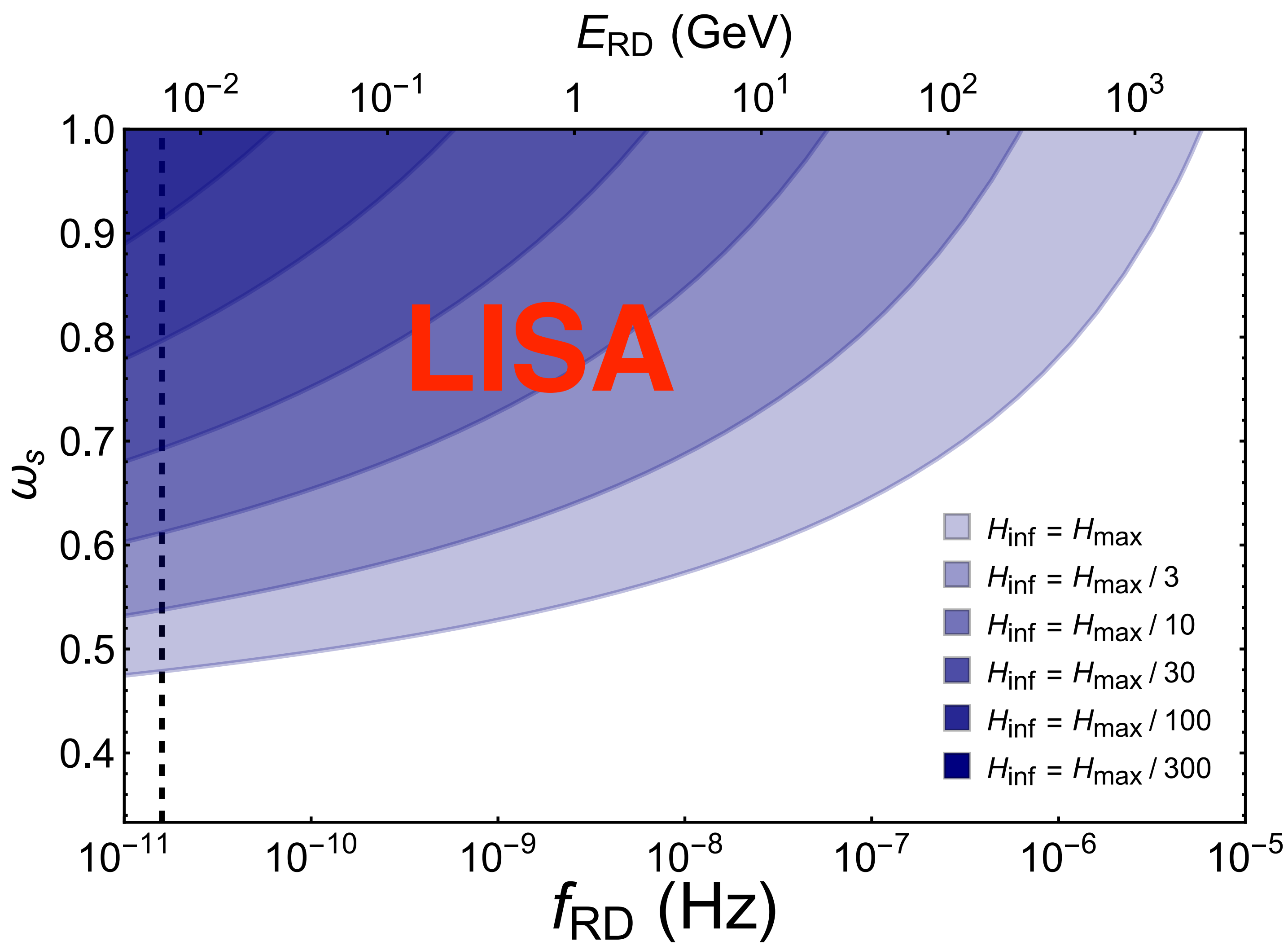
BBN/CMB constraints: further implications

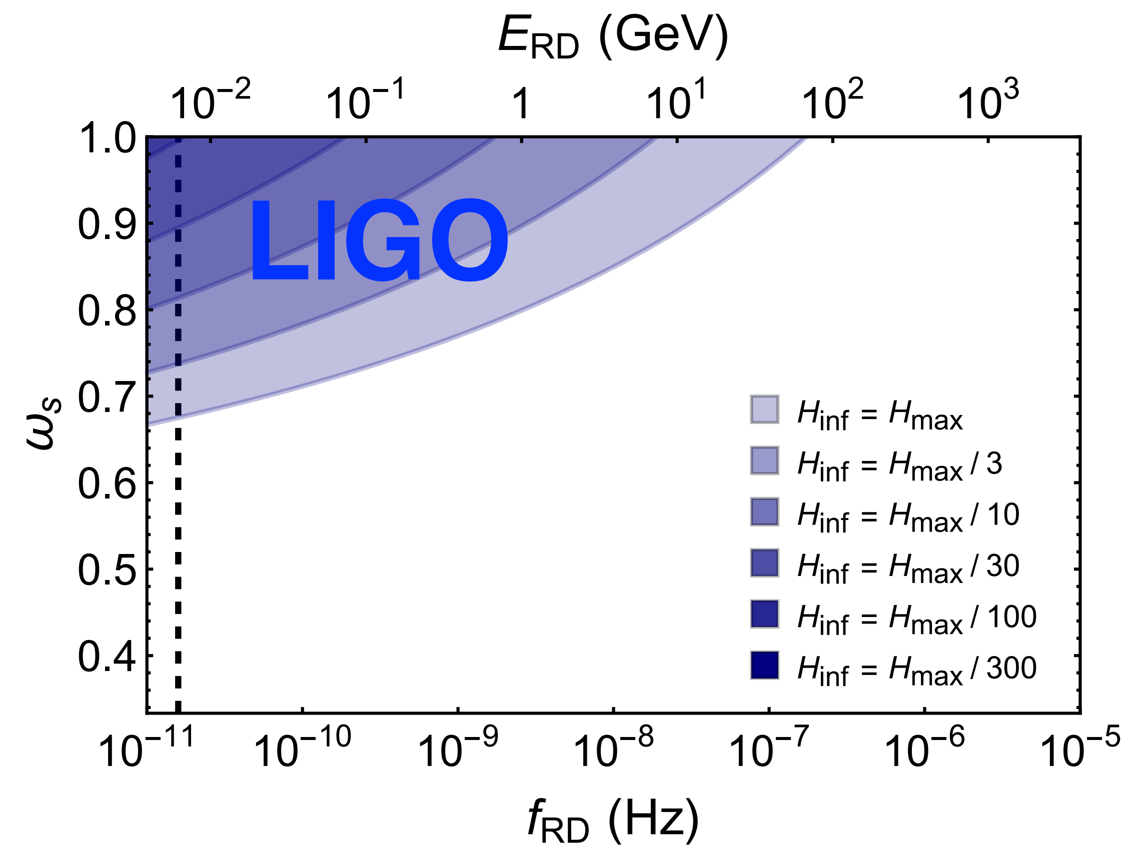
BBN Bound $\Omega_{\rm GW}^{(0)}(f; \underline{H_*}, \underline{w_s}, \underline{f_{RD}}) \lesssim 10^{-6}$

Energy Scale | EoS Stiff | Duration Stiff



BBN Bound $\Omega^{(0)}_{\rm GW}(f; \underbrace{H_*}_{\text{Energy Scale}}, \underbrace{w_s}_{\text{EoS Stiff}}, \underbrace{f_{RD}}_{\text{Duration Stiff}}) \lesssim 10^{-6}$





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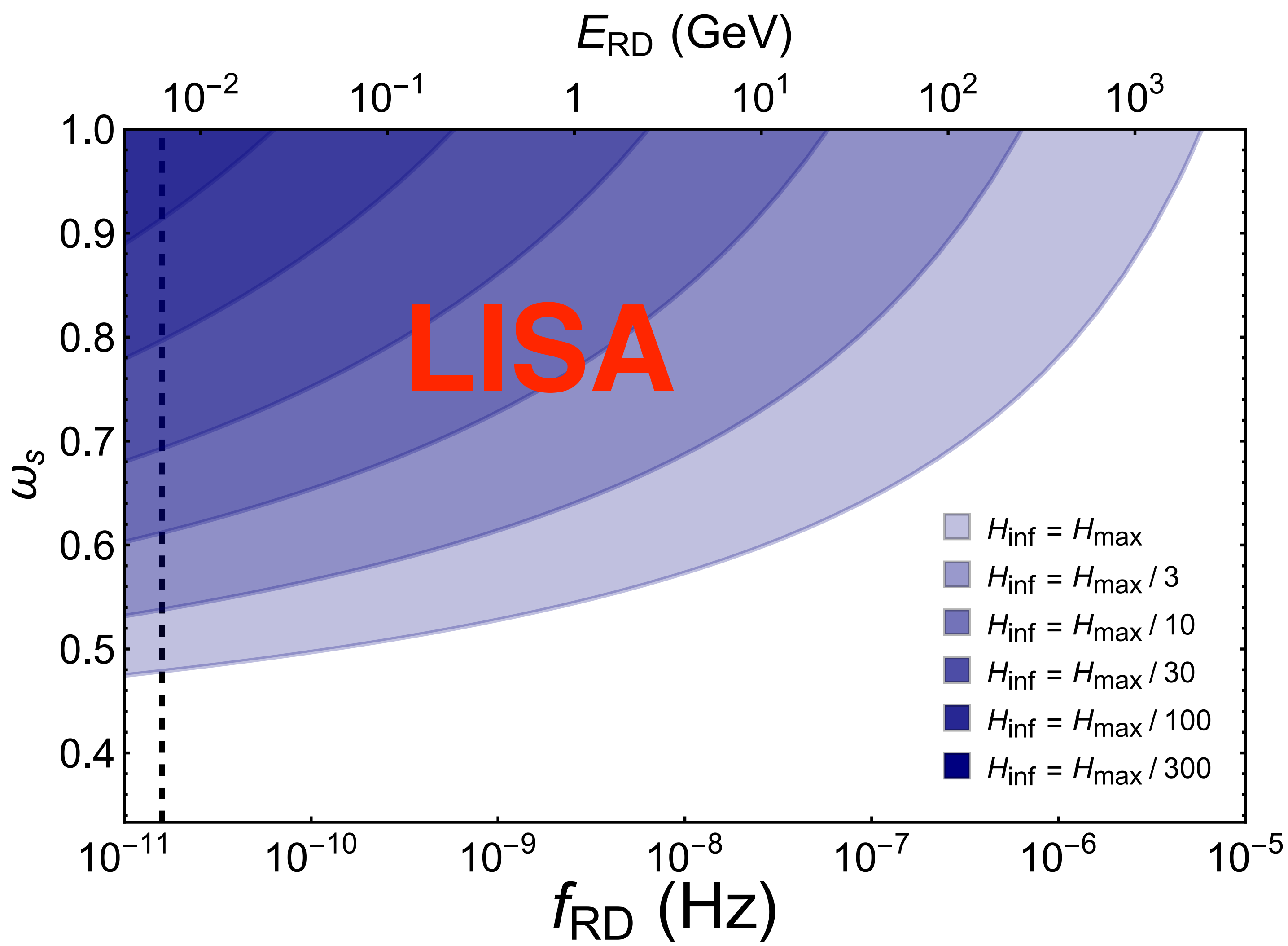
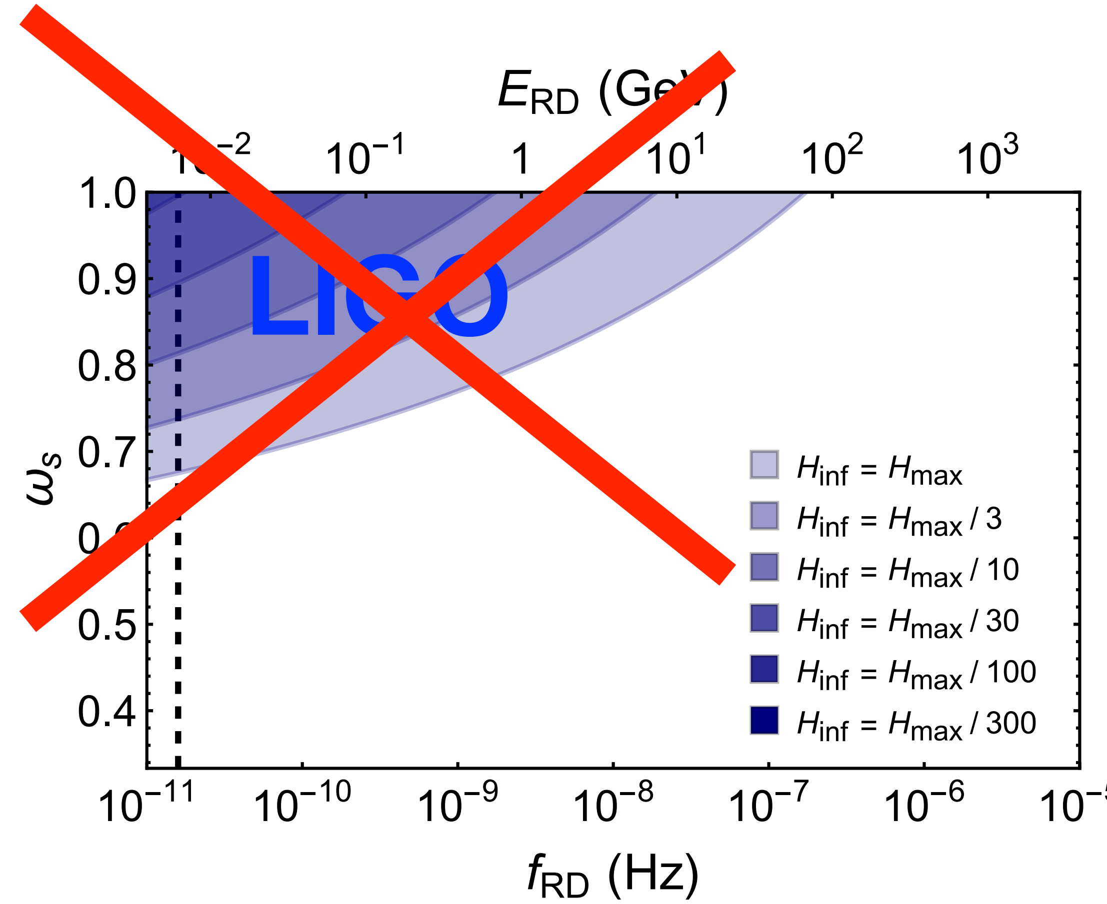


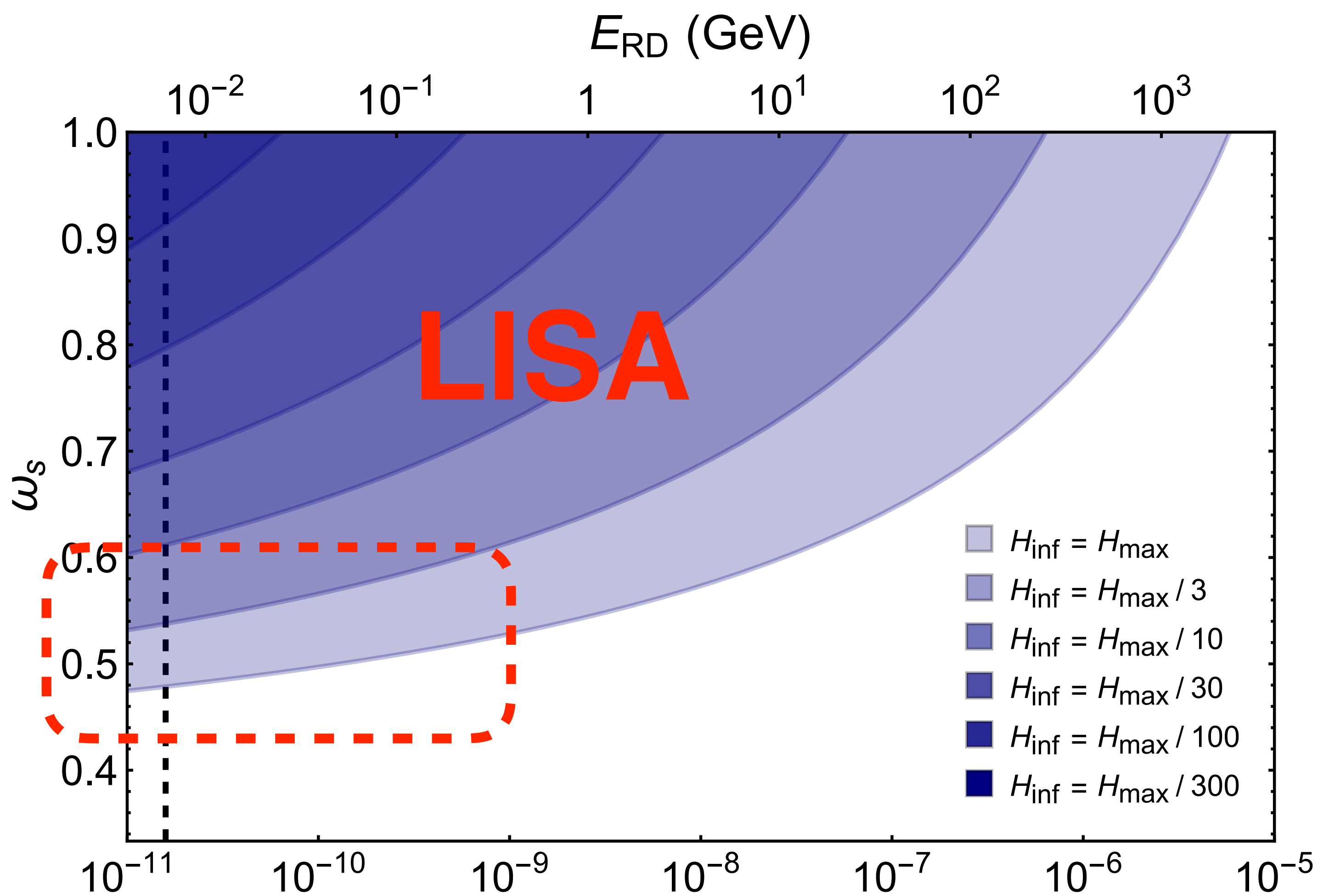


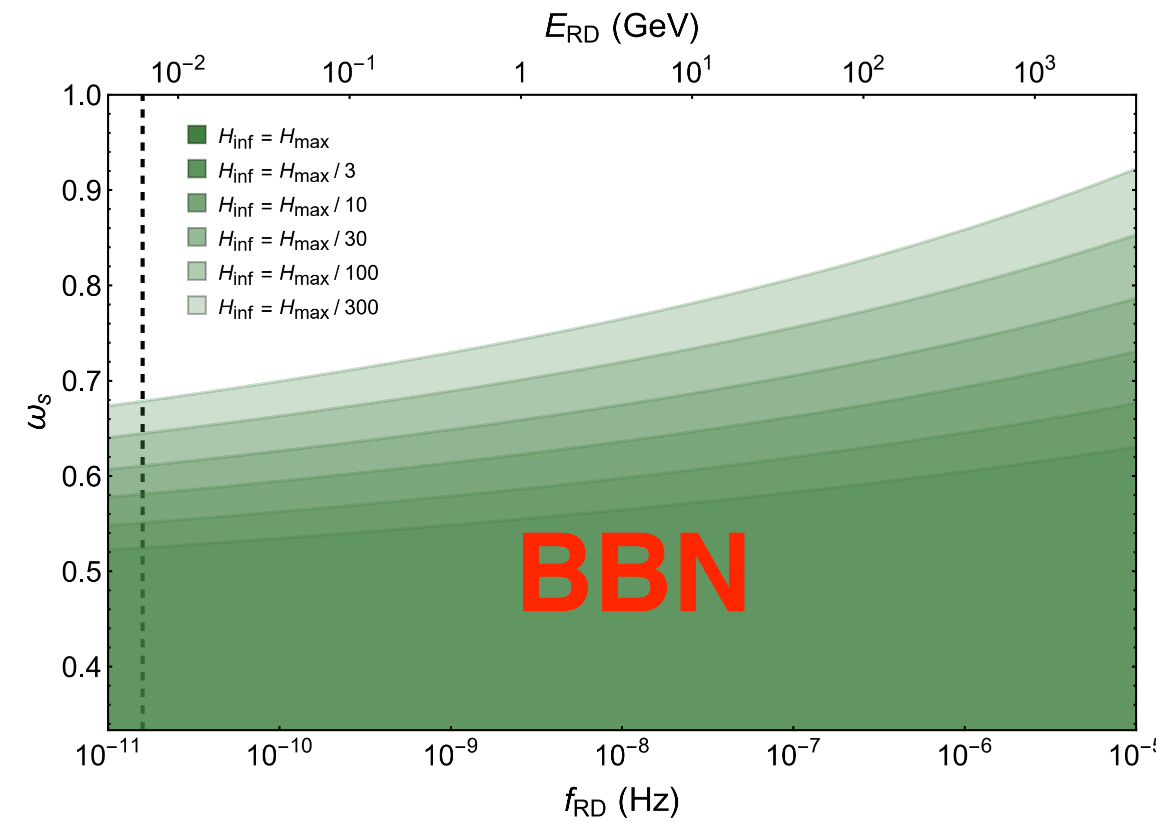
LIGO cannot probe parameter space compatible with BBN !

BBN Bound $\Omega_{\rm GW}^{(0)}(f; \underline{H_*}, \underline{w_s}, \underline{f_{RD}}) \lesssim 10^{-6}$

Energy Scale | EoS Stiff | Duration Stiff

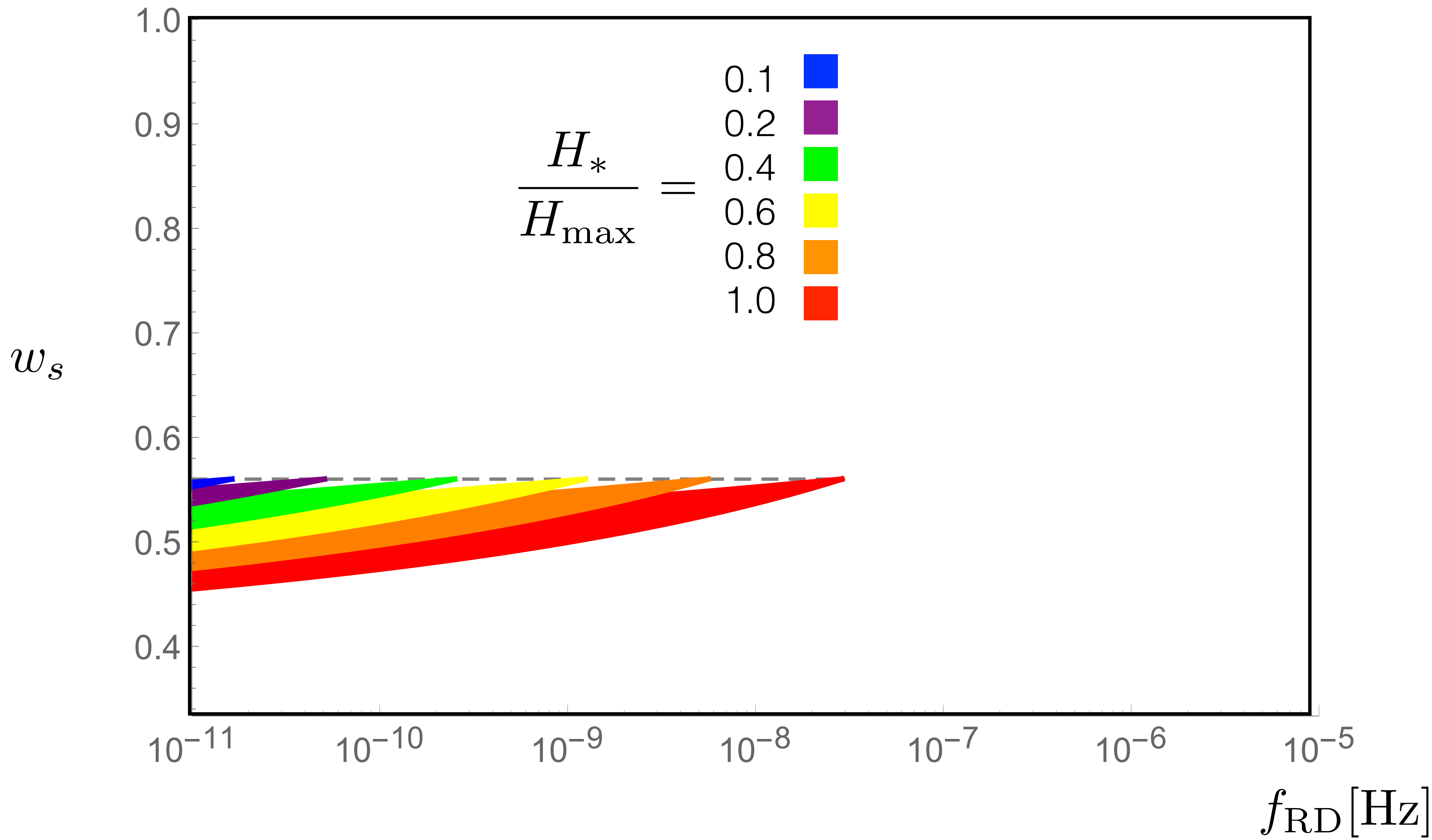
LISA ?





BBN Bound $\Omega_{\rm GW}^{(0)}(f; \underbrace{H_*}_{\text{Energy Scale}}, \underbrace{w_s}_{\text{EoS Stiff}}, \underbrace{f_{RD}}_{\text{Duration Stiff}}) \lesssim 10^{-6}$

LISA ✓



Part 5

Outlook
(+ take-home message)

OUTLOOK

0) Reheating w/o couplings requires imagination:

Grav. Reheating or Modified Gravity

1) (Standard) Grav. Reheating is inconsistent

Too many GWs (violates BBN/CMB bounds)

2) Inf. sectors only (minimally) coupled

to gravity inconsistent unless:

i) Inflation ~ Modify gravity: I don’t want to

ii) O(1000) spectator fields identical: ad hoc tuning

iii) SM Higgs + Non-Min coupling: works (not observable)

3) Stiff Era (in general): not observable @ LIGO, barely @ LISA

TAKE HOME MESSAGE

If you go stiff ...
check LIGO/BBN/CMB

Part 6

Muchas gracias por vuestra atención !

Part 7

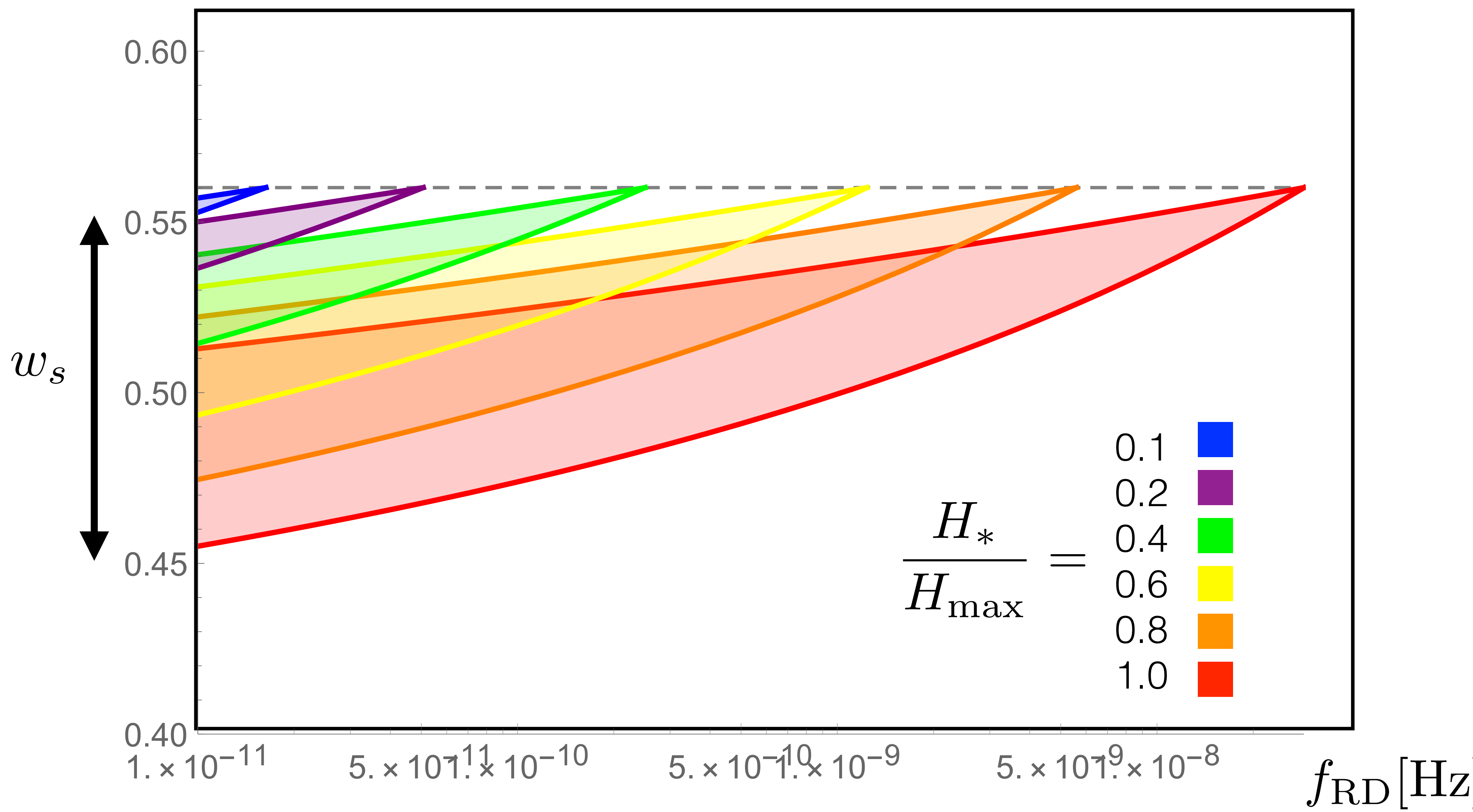
Backslides

BBN Bound $\Omega_{\rm GW}^{(0)}(f; \underline{H_*}, \underline{w_s}, \underline{f_{RD}}) \lesssim 10^{-6}$

Energy Scale | EoS Stiff | Duration Stiff

LISA ✓

ZOOM

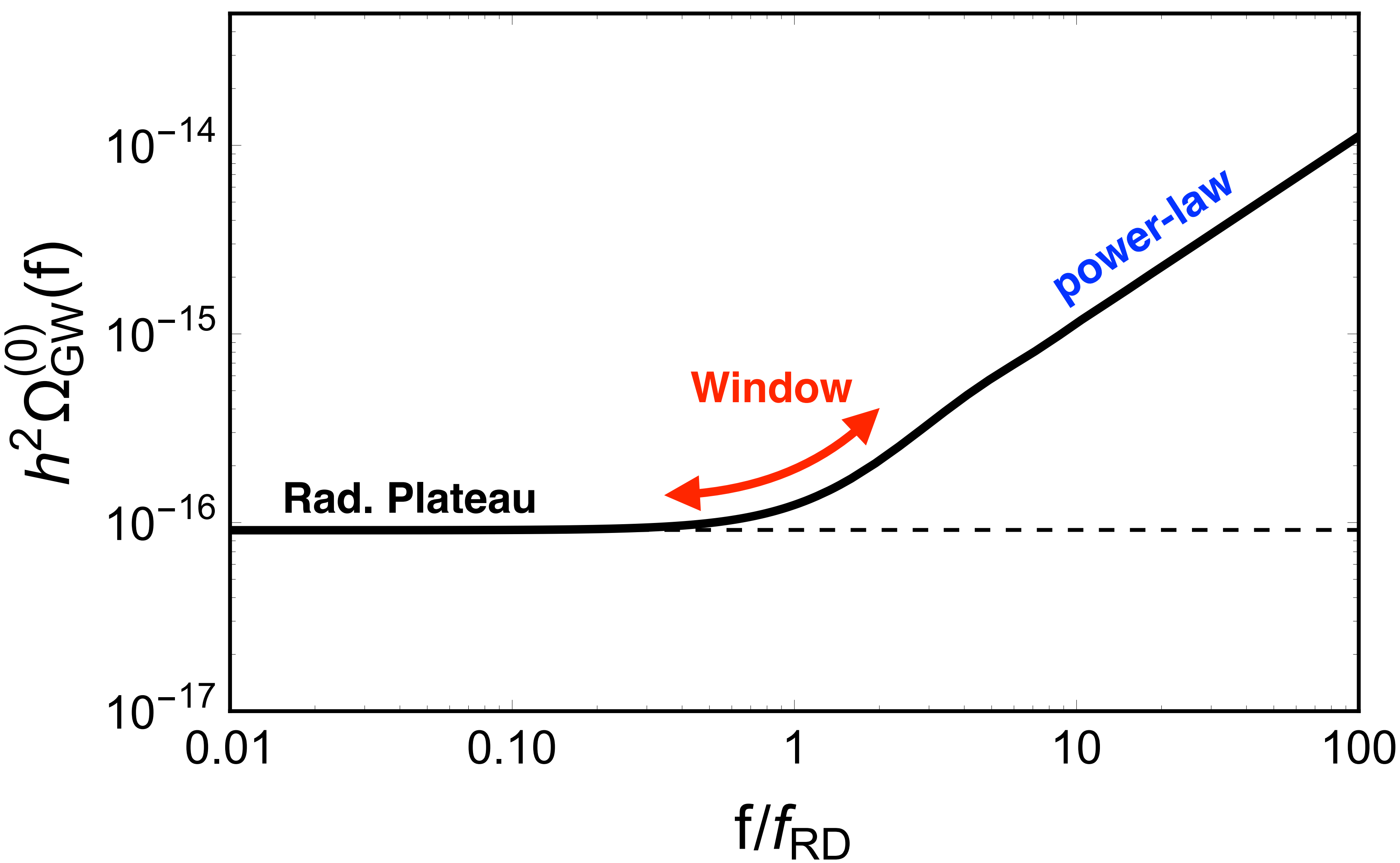


(

Inflationary GW background

$$\Omega^{(0)}_{\rm GW}(f) = \underbrace{\Omega^{(0)}_{\rm GW}\Big|_{\rm plateau}}_{\text{Rad. Plateau}} \times \underbrace{\mathcal{W}(f/f_{\rm RD}) \times \mathcal{A}_{\rm s}\left(\frac{f}{f_{\rm RD}}\right)^{n_t(w_s)}}_{\text{Transfer Funct. Stiff Period}}\,, \qquad \Omega^{(0)}_{\rm GW}\Big|_{\rm plateau} \simeq 2\cdot 10^{-16}\left(\frac{H_*}{H_{\rm max}}\right)^2$$

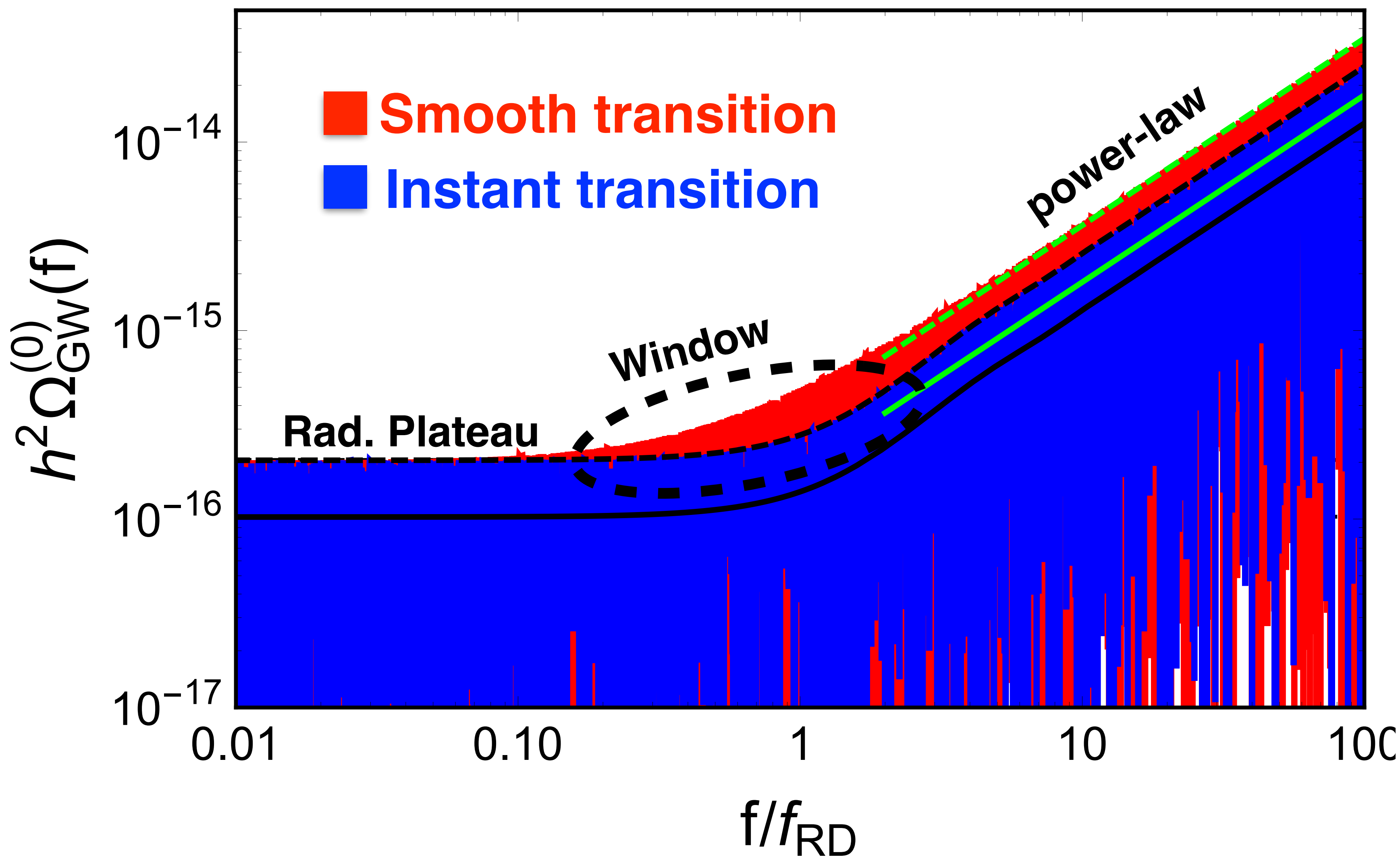
Window x *power-law*



Inflationary GW background

$$\Omega^{(0)}_{\rm GW}(f) = \underbrace{\Omega^{(0)}_{\rm GW}\Big|_{\rm plateau}}_{\substack{\textbf{Rad.}\\ \textbf{Plateau}}} \times \underbrace{\mathcal{W}(f/f_{\rm RD}) \times \mathcal{A}_{\rm s}\left(\frac{f}{f_{\rm RD}}\right)^{n_t(w_s)}}_{\textbf{Transfer Funct. Stiff Period}}\,, \quad \Omega^{(0)}_{\rm GW}\Big|_{\rm plateau} \simeq 2\cdot 10^{-16}\left(\frac{H_*}{H_{\rm max}}\right)^2$$

Window x *power-law*



Real signal: highly oscillatory

Stochastic Signal: average measurement

$$\langle \dot{h}_{ij}(f)\dot{h}_{ij}(f)\rangle = \mathcal{P}_h(f)$$

)