Particle Physics in the Gravitational Wave Era

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25th May 2020

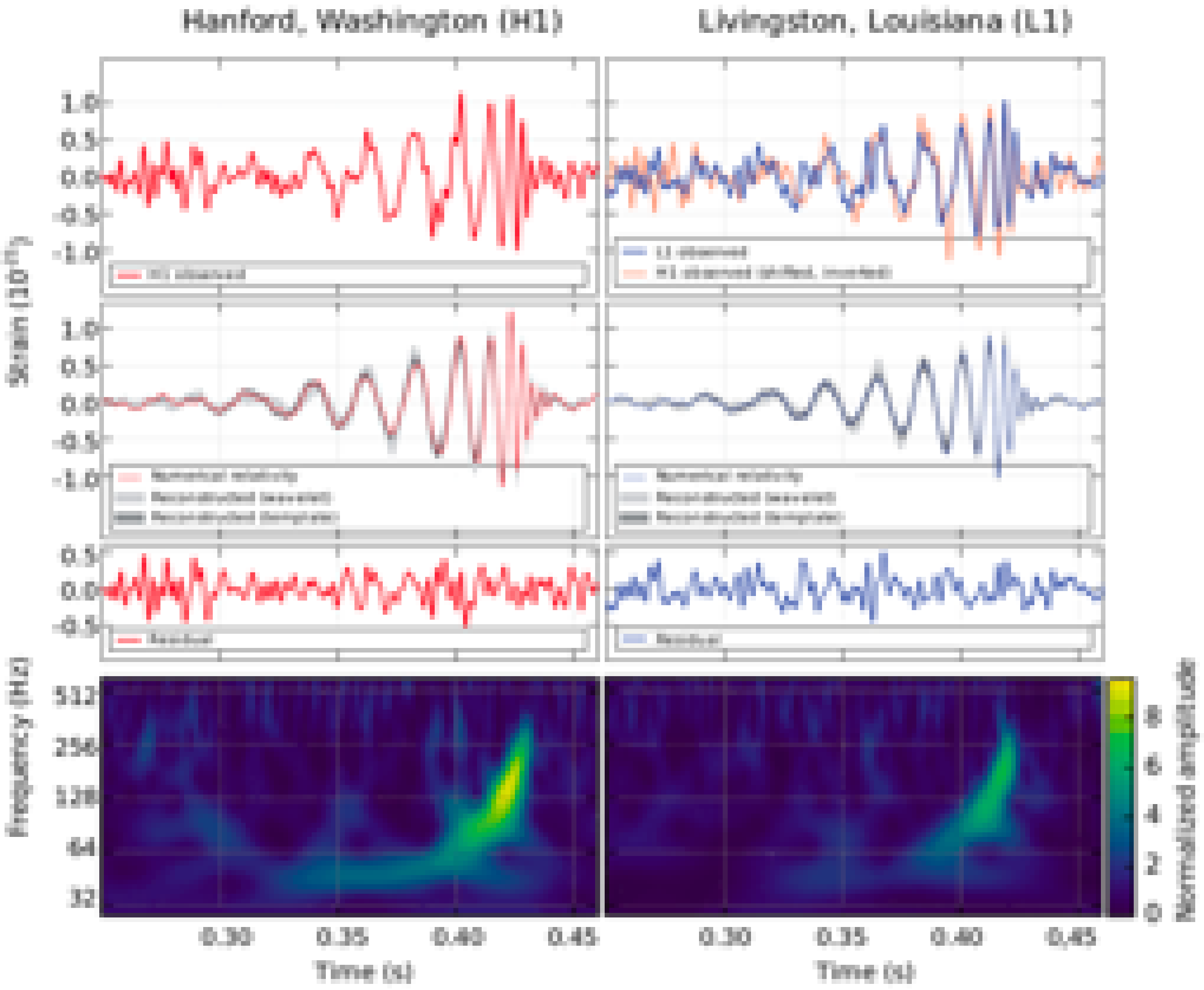
Motivation

Brand new era of observational cosmology and astrophysics

- Unique mediator

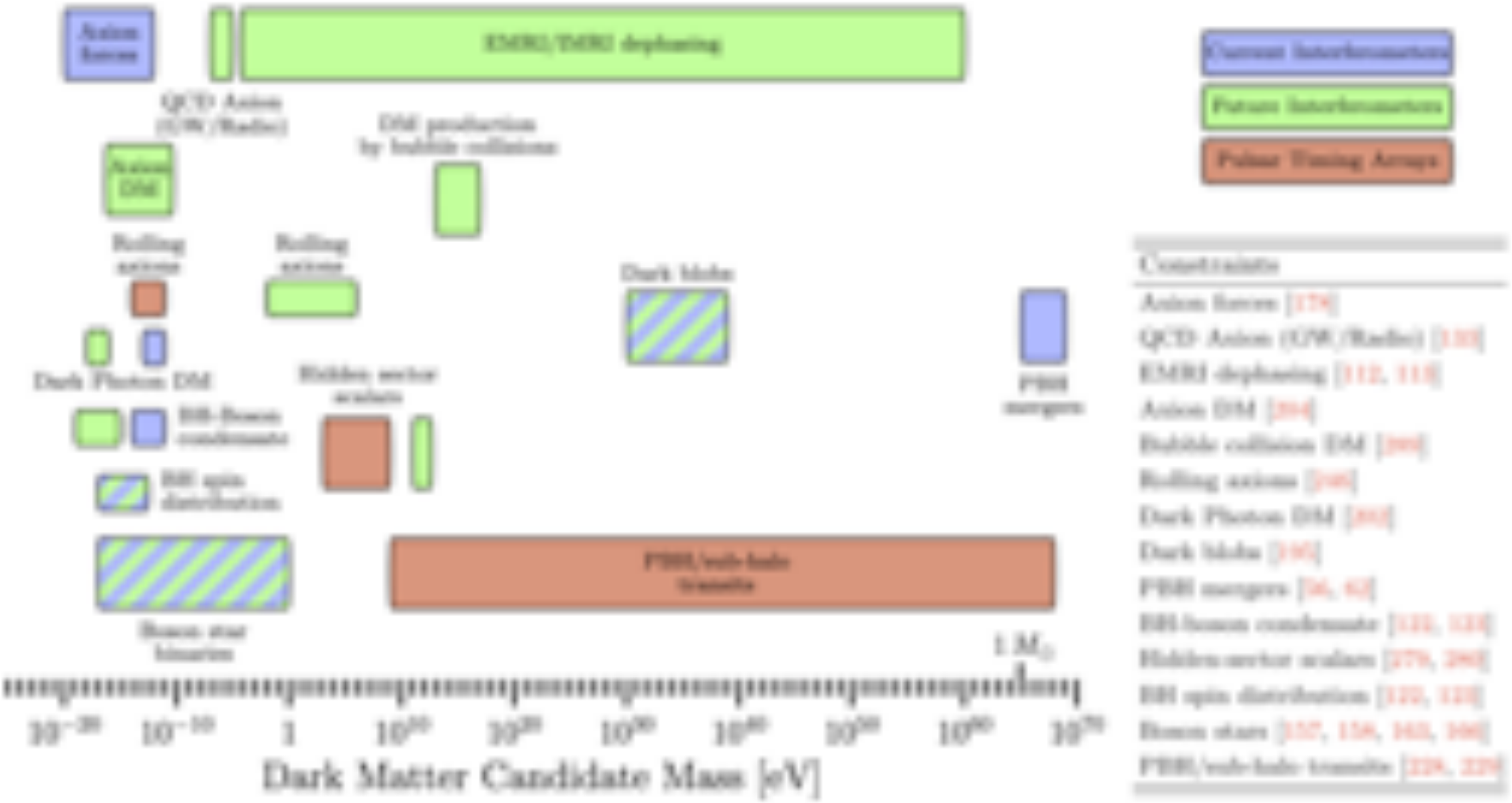
Universe transparent to GWs

Everything couples to gravity



[LIGO/VIRGO collaboration 1602.03837]

Example: GWs and Dark Matter



[Bertone, Croon, Amin, Boddy, Kavanagh, Mack, Natarajan, Opferkuch, Schutz, Takhistov, Weniger, and Yu 1907.10610]

Gravitational Wave Signals

Transient:

- Compact object mergers
  - BH—BH mergers
  - NS—NS mergers
  - NS—BH mergers
  - Extreme mass-ratio inspirals
  - Super-massive BH mergers
  - Exotic compact objects
- GW bursts
  - Binary formation?
  - Highly elliptical binary orbits

Stationary:

- Sum of unresolved transient signals
- Stochastic backgrounds
  - Inflationary background
  - Cosmic strings
  - Cosmological phase transitions
  - Modified cosmological evolution
  - Non-pert. particle production

This is just the very tip of the iceberg!

Gravitational Wave Signals

Transient:

- Compact object mergers
  - ✦ BH—BH mergers
  - ✦ NS—NS mergers
  - ✦ NS—BH mergers
  - ✦ Extreme mass ratio inspirals
  - ✦ Super-massive BH mergers

Part I:
Long-range Forces and Neutron Star Binaries

Part II:
Ricci Reheating

- Stochastic backgrounds
  - ✦ Inflationary background
  - ✦ Cosmic strings
  - ✦ Cosmological phase transitions
  - ✦ Modified cosmological evolution
  - ✦ Non-pert. particle production

This is just the very tip of the iceberg!

Part I:
Long-range Forces and Neutron Star Binaries

Based on:

“Probing Muonic Forces with Neutron Star Binaries"
Jeff Dror, Ranjan Laha and Toby Opferkuch 1909.12845

"Cuckoo’s Eggs in Neutron Stars: Can LIGO Hear Chirps from the Dark Sector?”
Joachim Kopp, Ranjan Laha, Toby Opferkuch and William Shepherd 1807.02527
JHEP 1811 (2018) 096

Motivation

- Post-Newton inspiral phase:

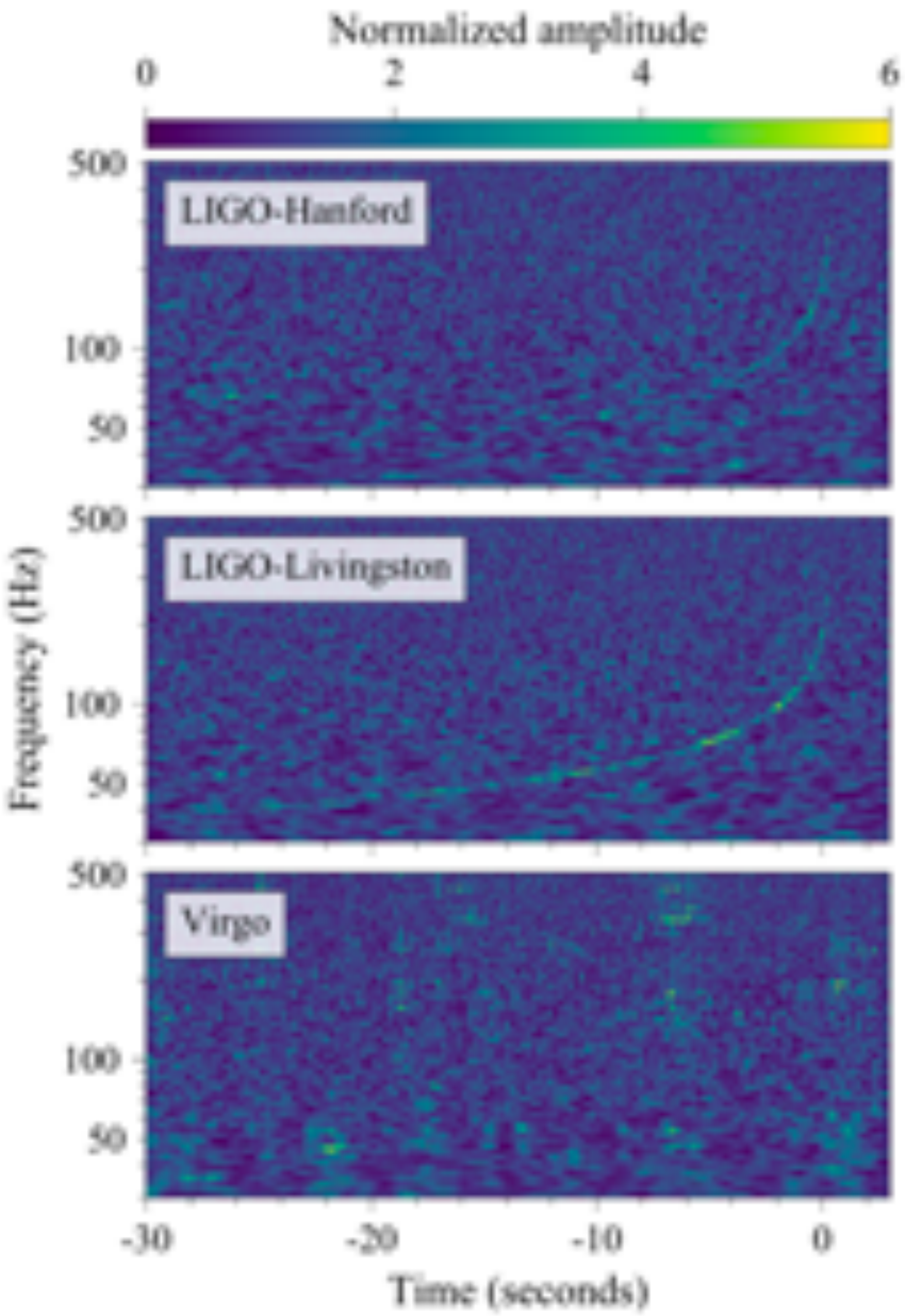
  $\mathcal{O}(.15)$ sec for $30M_\odot$ BH—BH

  $\mathcal{O}(30)$ sec for $1.4M_\odot$ NS—NS

- Sensitivity to:
  - ✦ Modifications of gravity
    [Sagunski et. al. 1709.06634]
  - ✦ Fifth forces (e.g. axionic forces)
    [Hook, Huang 1708.08464]
  - ✦ Forces coupled only to DM *[back-up slides]*
    [Croon et. al. 1711.02096, Alexander et. al. 1808.05286]
    [Fabbrichesi & Urbano 1902.07914]
  - ✦ Muonic Forces *[This talk]*

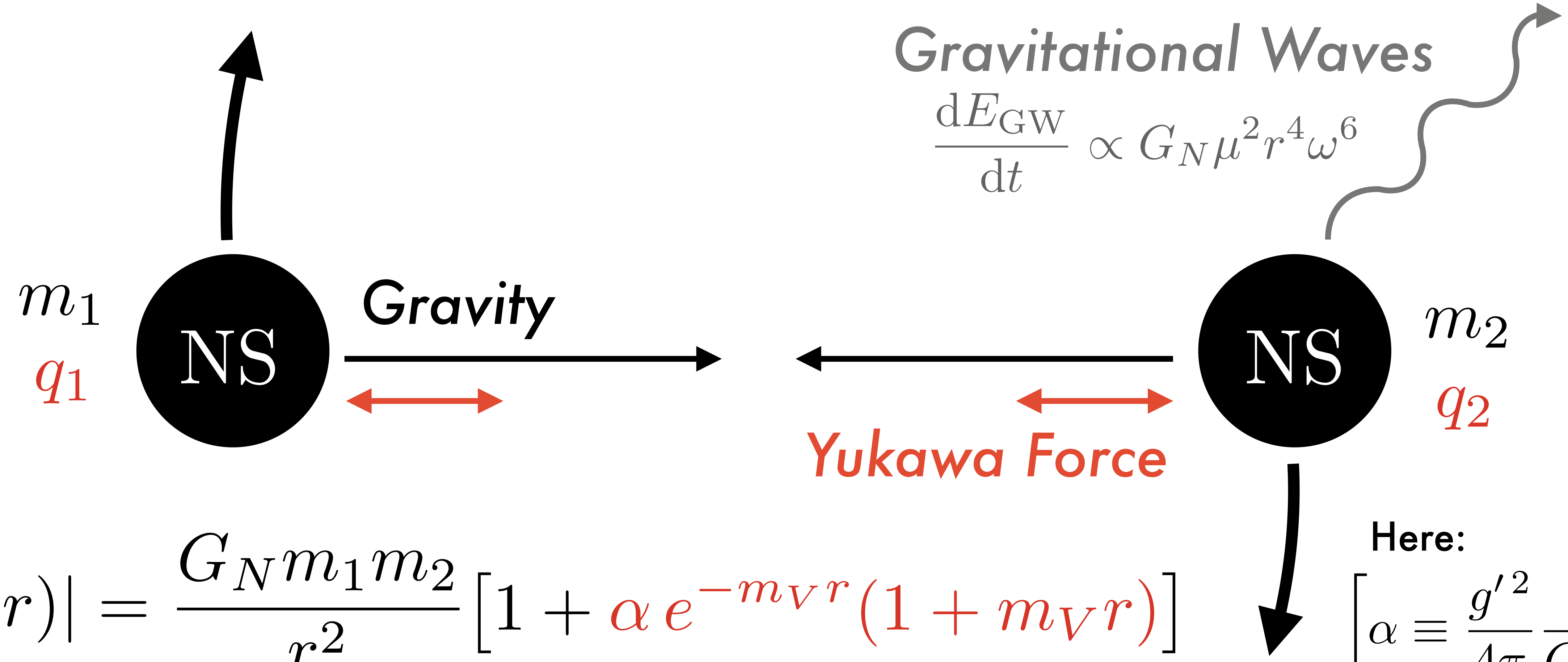
- Two key effects: $m_{\text{med}} \lesssim 10^{-10}\,\text{eV}$

  1. Yukawa force 2. Dipole radiation



[LIGO/VIRGO collaboration 1710.05832]

Yukawa Force



$$\frac{\mathrm{d}E_{\mathrm{GW}}}{\mathrm{d}t} \propto G_N \mu^2 r^4 \omega^6$$

$$|\mathbf{F}(r)| = \frac{G_N m_1 m_2}{r^2}\left[1 + \alpha\, e^{-m_V r}(1 + m_V r)\right]$$

Here:

$$\left[\alpha \equiv \frac{g'^2}{4\pi}\frac{q_1 q_2}{G_N m_1 m_2}\right]$$

Equating: $\dfrac{\mathrm{d}E_{\mathrm{tot}}}{\mathrm{d}t} = -\dfrac{\mathrm{d}E_{\mathrm{GW}}}{\mathrm{d}t}$

$$\underset{m_V \to 0}{\Longrightarrow} \quad \frac{\mathrm{d}\omega}{\mathrm{d}t} = \frac{96}{5}\underbrace{(G_N \mathcal{M}_c)^{5/3}(1+\alpha)^{2/3}}\omega^{11/3}$$

$$\widetilde{\mathcal{M}}_c = \mathcal{M}_c (1+\alpha)^{2/5}$$

Degenerate
[effective shift in chirp mass]

Yukawa Force

- Waveform enters LIGO sensitivity band when $r \sim 750$ km

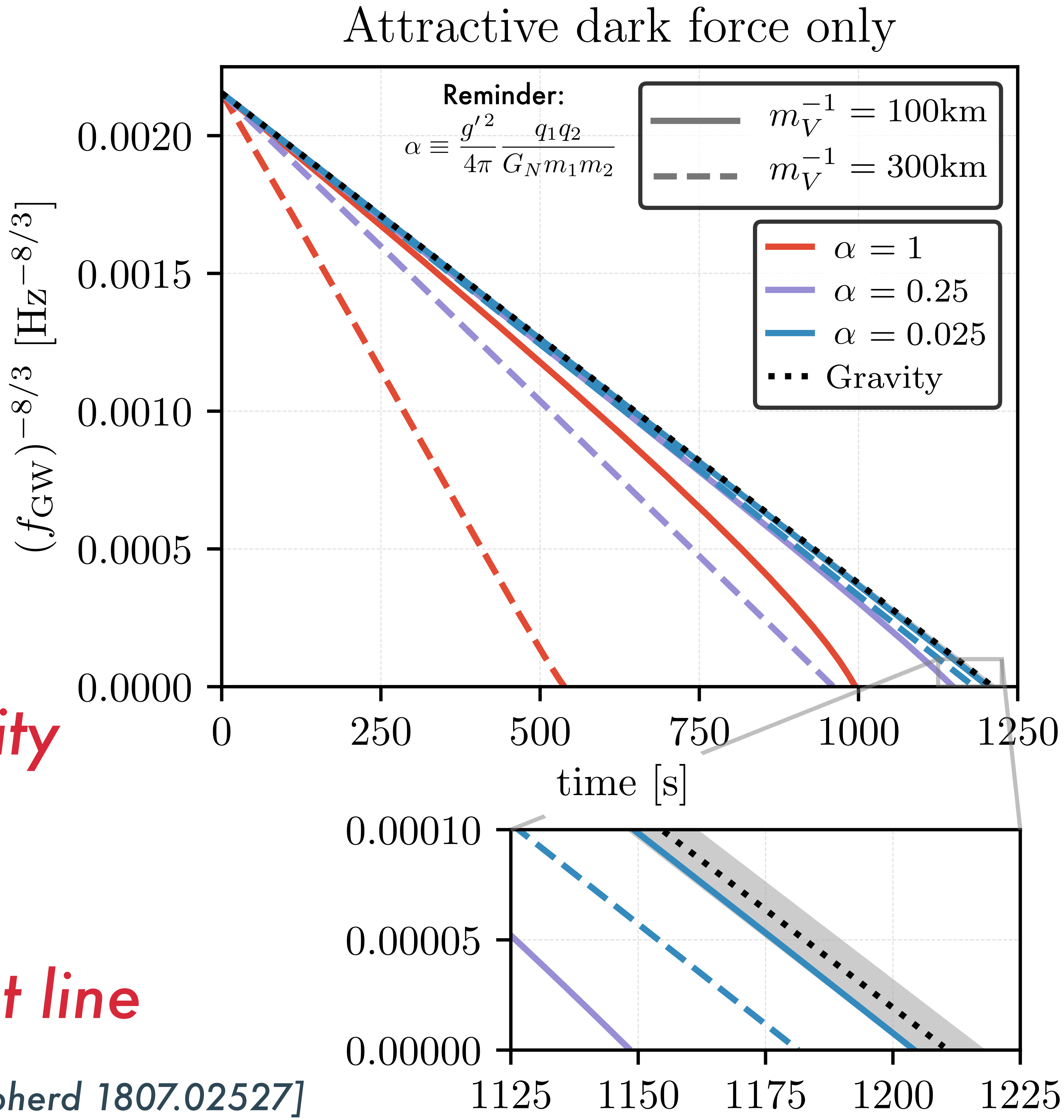
- Two cases:

1. $m_V^{-1} \gtrsim \mathcal{O}(300\text{ km})$

   Degenerate with gravity

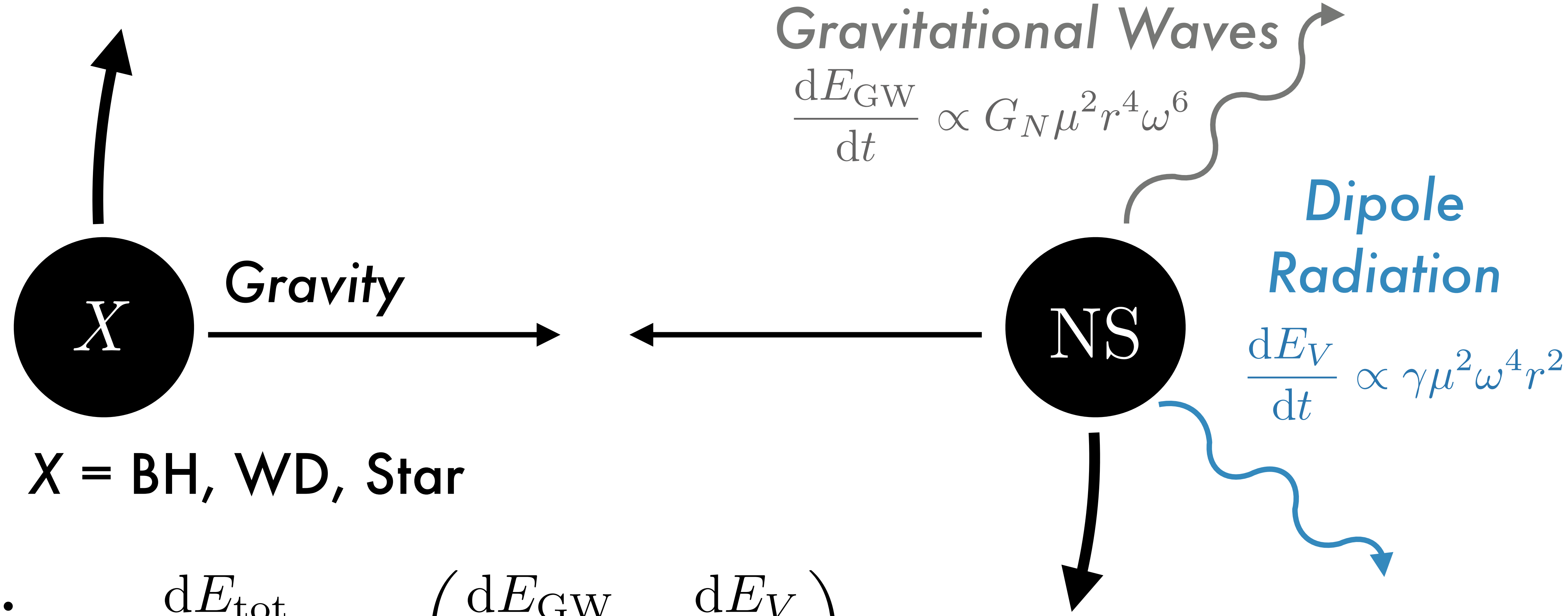
2. $m_V^{-1} \lesssim \mathcal{O}(300\text{ km})$

   Deviation from straight line



[Kopp, Laha, Opferkuch, Shepherd 1807.02527]

Dipole Radiation



Gravitational Waves

$$\frac{\mathrm{d}E_{\mathrm{GW}}}{\mathrm{d}t} \propto G_N \mu^2 r^4 \omega^6$$

Dipole Radiation

$$\frac{\mathrm{d}E_V}{\mathrm{d}t} \propto \gamma \mu^2 \omega^4 r^2$$

X = BH, WD, Star

Equating: $$\frac{\mathrm{d}E_{\mathrm{tot}}}{\mathrm{d}t} = -\left(\frac{\mathrm{d}E_{\mathrm{GW}}}{\mathrm{d}t} + \frac{\mathrm{d}E_V}{\mathrm{d}t}\right)$$

$$\left[\gamma \equiv \frac{g'^2}{(4\pi G_N)}\left(\frac{q_1}{m_1} - \frac{q_2}{m_2}\right)^2\right]$$

$$\frac{\mathrm{d}\omega}{\mathrm{d}t} = \frac{96}{5}\left(G_N \mathcal{M}_c\right)^{5/3}\omega^{11/3} + \frac{1}{2}G_N M \beta \underset{\uparrow}{\omega^3}\mathrm{Re}\left\{\sqrt{1 - \frac{m_V^2}{\omega^2}}\left[1 + \frac{1}{2}\frac{m_V^2}{\omega^2}\right]\right\}$$

Alternate scaling with frequency

$$\left[\beta \equiv \frac{4\gamma\mu^2}{m_1 m_2}\right]$$

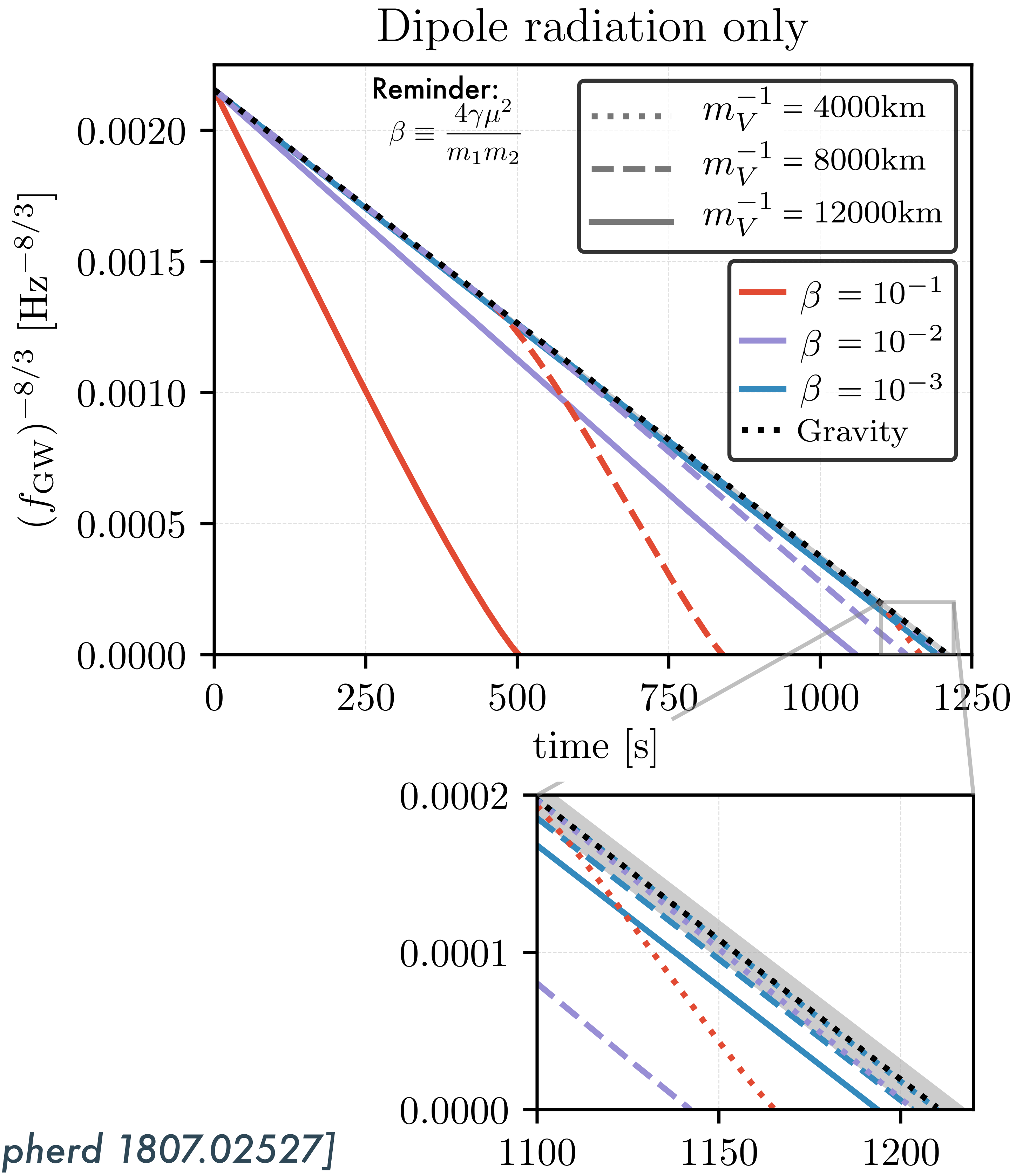
Dipole Radiation

- Waveform enters LIGO sensitivity band when $r \sim 750$ km

- Alternate scaling of the dipole contribution:

  1. *Sensitivity to much lighter masses*

  2. *Easier to distinguish from GR only*



[Kopp, Laha, Opferkuch, Shepherd 1807.02527]

Leptons in Neutron Star Cores

- Leptons described as a non-interacting Fermi-gas

- Determine $n_e(r)$ given nucleon density that minimises the total free energy and the following:

1. Weak processes in equilibrium i.e, n, p, e^- abundance

$$\implies \mu_e(r) + \mu_p(r) + \mu_n(r) = 0$$

NB: neutrinos escape (cold NS)

Reminder: $\mu_i(r) \equiv \sqrt{m_i^2 + k_{F,i}^2}$

for a non-interacting Fermi-gas

2. Local charge neutrality

$$\implies n_e(r) = n_p(r)$$

Leptons in Neutron Star Cores

- As electron density increases: $k_{F,e} = (3\pi^2 n_e)^{\frac{1}{3}} \gtrsim m_\mu$

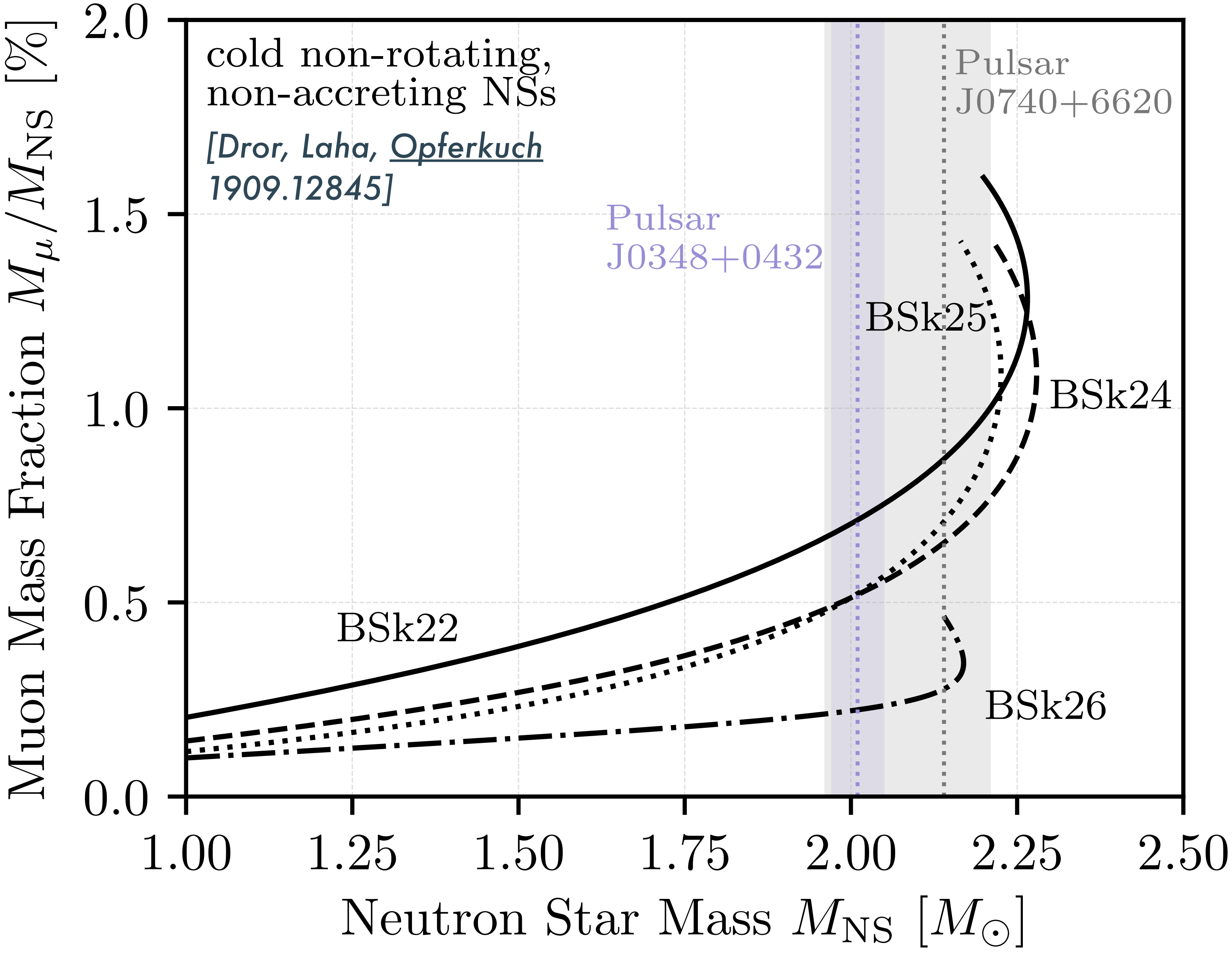
$$\left.\begin{aligned} e^- &\longrightarrow \mu^- + \nu_e + \bar{\nu}_\mu \\ n &\longrightarrow p + \mu^- + \bar{\nu}_\mu \end{aligned}\right\} \text{Kinematically allowed}$$

- In the SM the number density follows:

$$\mu_e(r) + \mu_\mu(r) = 0$$

- Pauli-blocking due to high electron density forbids muon decay

Over 10^{27} kg worth of 'stable' muons



[NS equations of state taken from Pearson et. al. 1903.04981]

Muons & New Forces

- New long-range forces relevant for NS binary mergers induce unscreened self-interactions of the muons

$$\mu_e(r) + \mu_\mu(r) + U_\mu(r) = 0$$

requires solving a non-linear integral equation for $n_\mu(r)$

where

$$U_\mu(r) = \frac{g'^2}{4\pi} \int_\infty^r \mathrm{d}r' \frac{1}{r'^2} \int_0^{r'} \mathrm{d}r'' 4\pi n_\mu(r'')$$

- Effect becomes relevant when

$$\int \mathrm{d}V E_\mu^2 \sim \mu_e N_e \implies N_\mu \propto \frac{1}{g'} \text{ for } g' > 10^{-18}$$

Maximum muonic charge saturated at $g' \sim 10^{-18}$

Constraints on Gauged $L_\mu - L_\tau$

- Prototype example: ultra-light gauged $U(1)_{L_\mu - L_\tau}$

$$\mathcal{L} \supset g' V_\alpha \left(\bar{\mu} \gamma^\alpha \mu - \bar{\tau} \gamma^\alpha \tau + \bar{\nu}_\mu \gamma^\alpha \nu_\mu - \bar{\nu}_\tau \gamma^\alpha \nu_\tau \right)$$

[see for example He, Joshi, Volkas 1991, Altmannshofer, Gori, Pospelov, Yavin 1403.1269]

- Calculate GW waveform (including GR-only PN corrections)

[Requires expanding in α and β]

- Fisher-matrix analysis to determine 1σ upper-limits

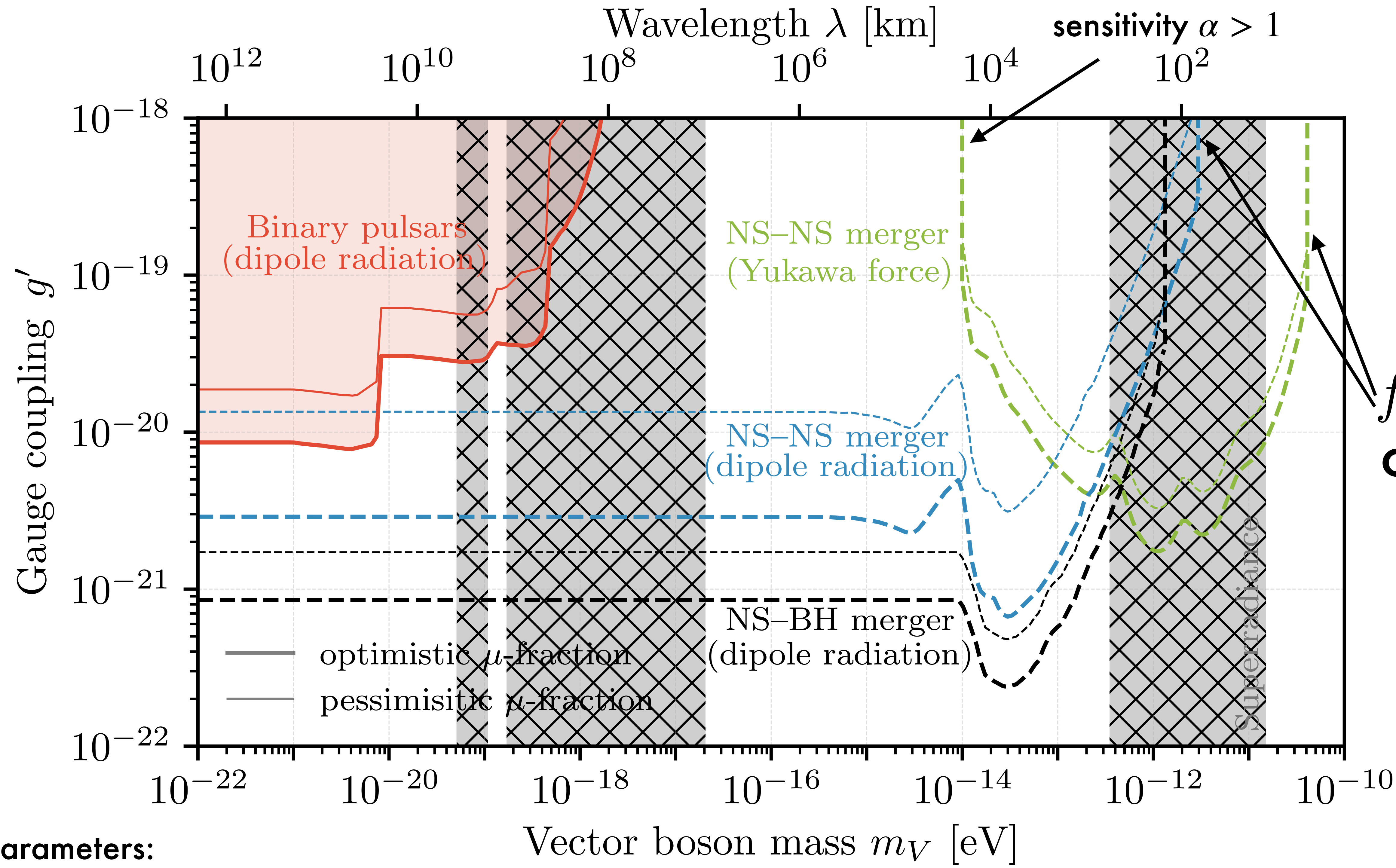
Invert the matrix:

Pred. GW waveform

$$\Gamma_{ab} \equiv \left(\frac{\partial h}{\partial \theta^a} \middle| \frac{\partial h}{\partial \theta^b} \right) \quad \text{with} \quad (h_1 | h_2) \equiv 4 \, \mathrm{Re} \int_{f_\mathrm{low}}^{f_\mathrm{high}} \frac{\tilde{h}_1 \tilde{h}_2^*}{S_n(f')} \mathrm{d}f'$$

Exp. noise curve

Constraints on Gauged $L_\mu - L_\tau$



sensitivity $\alpha > 1$

f_{ISCO}
cut-off

Parameters:

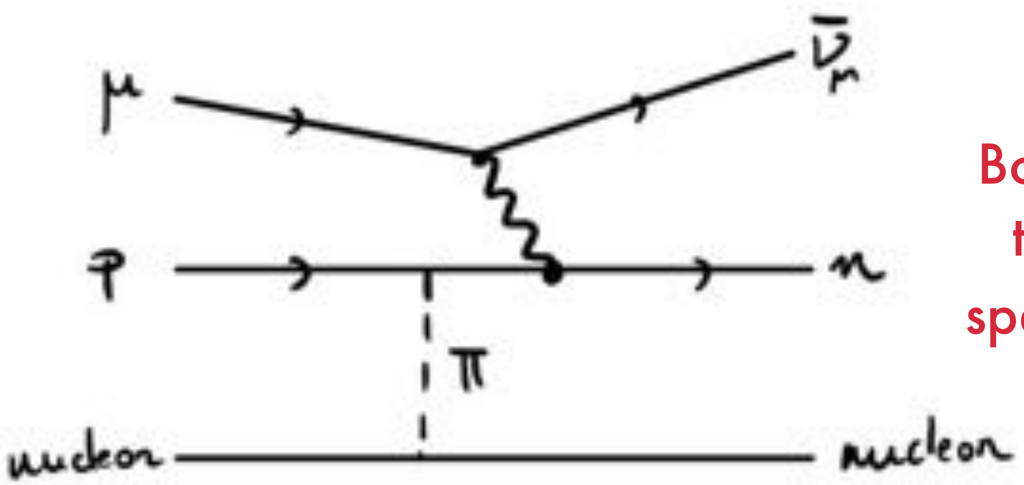
low spin $m_1 = 1.46 M_\odot$
$D_{\text{eff}} = 40\,\text{Mpc}$ $m_2 = 1.27 M_\odot$

[Dror, Laha, Opferkuch 1909.12845]

Neutrinos from NS Muons

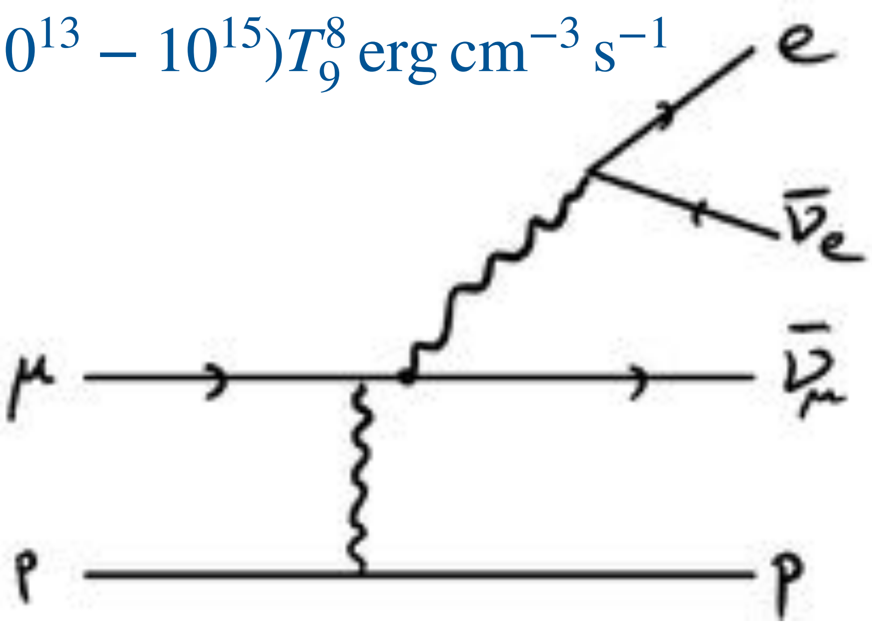
- Large Fermi-energy of electrons and muons implies spectators required for energy and momentum conservation

Rates: $(10^{18} - 10^{21})T_9^8 \, \mathrm{erg \, cm^{-3} \, s^{-1}}$



Both lead to nearly thermal neutrino spectra $T_{\mathrm{NS}} \ll \mathrm{MeV}$

$(10^{13} - 10^{15})T_9^8 \, \mathrm{erg \, cm^{-3} \, s^{-1}}$



[Yakovlev et. al astro-ph/0012122]

- Muon diffusion from Pauli-blocked to free region $(k_{F,e} < m_\mu)$
  1. Non-thermal spectrum $E_\nu \sim 10 - 40 \, \mathrm{MeV}$
  2. Detectable with future neutrino experiments for $t_{\mathrm{NS}} \sim 1 - 15$ years old NS @ 1kpc

[Work in progress - Kopp, Opferkuch]

Part I: Take Home Message

- Neutron stars are fantastic probes of long-range forces *[In particular for cases where fifth-force experiments are not applicable]*

- *Huge inevitable abundance of muons in neutron stars screams out to be used as a new BSM laboratory! [For example NS/SN cooling due to new physics coupled to muons]*

Part II:
Ricci Reheating

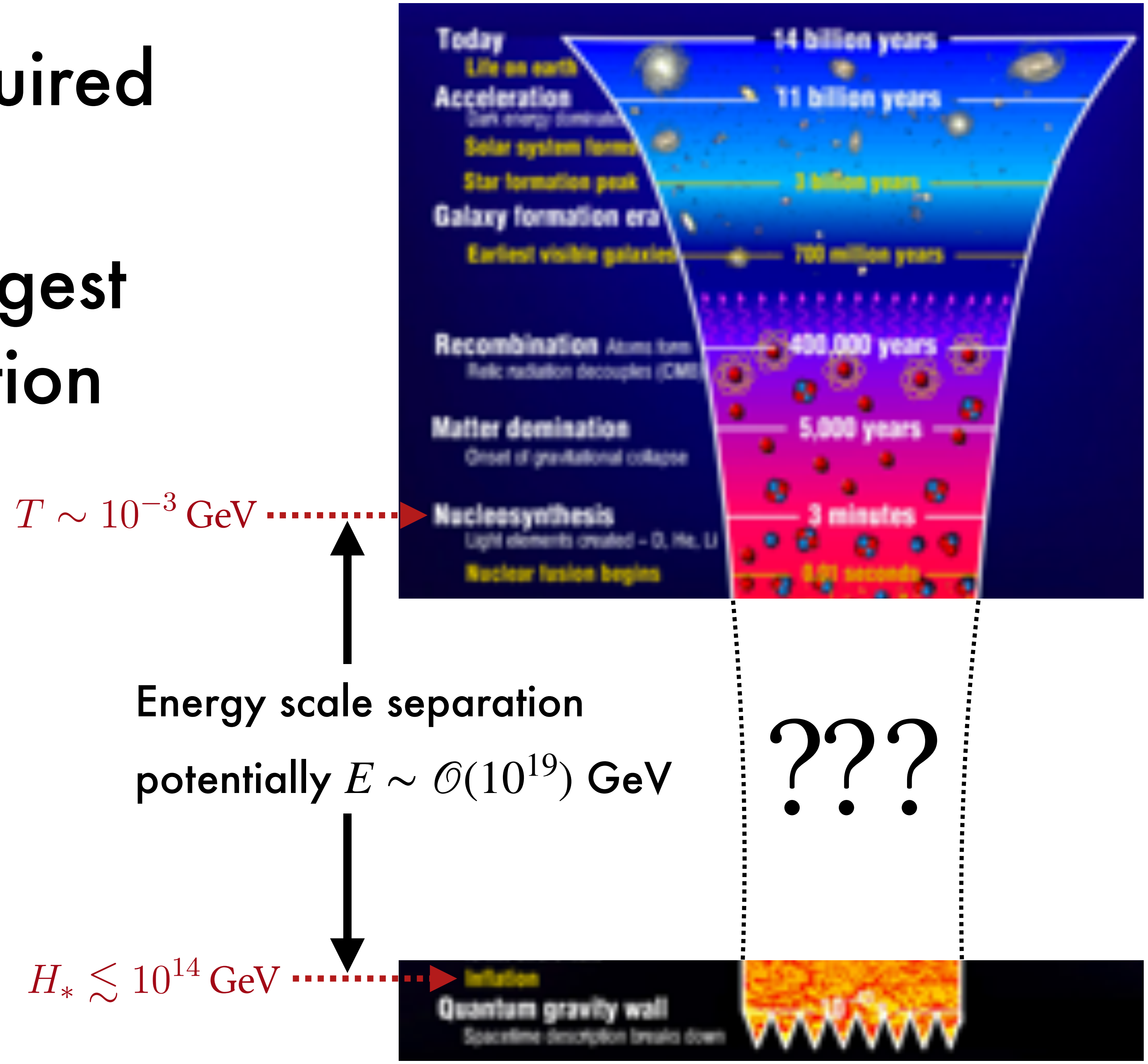
Based on:

"Ricci Reheating"
Toby Opferkuch, Pedro Schwaller and Ben A. Stefanek 1905.06823
JCAP 1907 (2019) 016

What do we know about the Universe?

- Hot thermal plasma required for nucleosynthesis
- CMB measurements suggest a period of cosmic inflation

Possible connections between the SM and the inflationary sector?



$T \sim 10^{-3}$ GeV

Energy scale separation

potentially $E \sim \mathcal{O}(10^{19})$ GeV

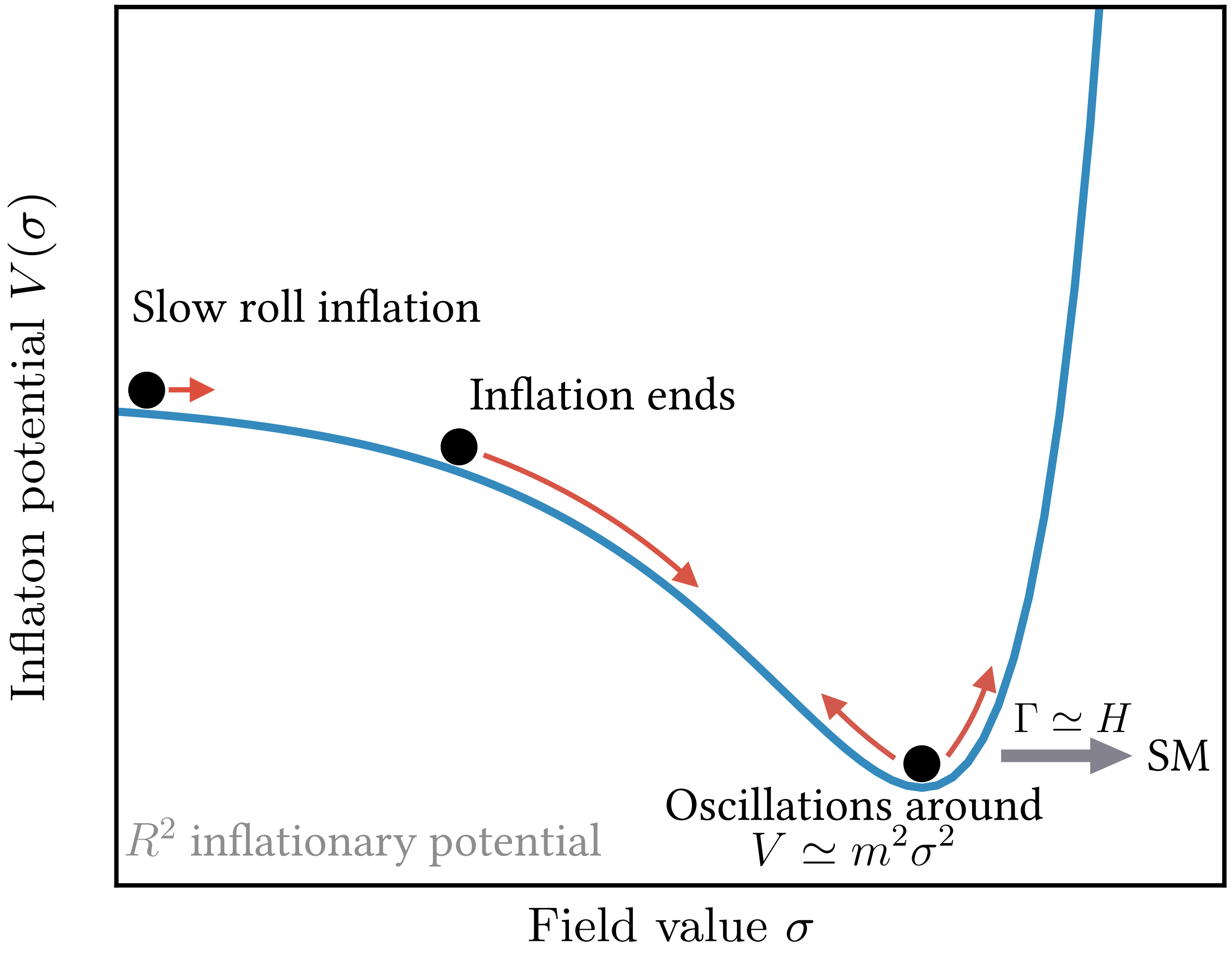
???

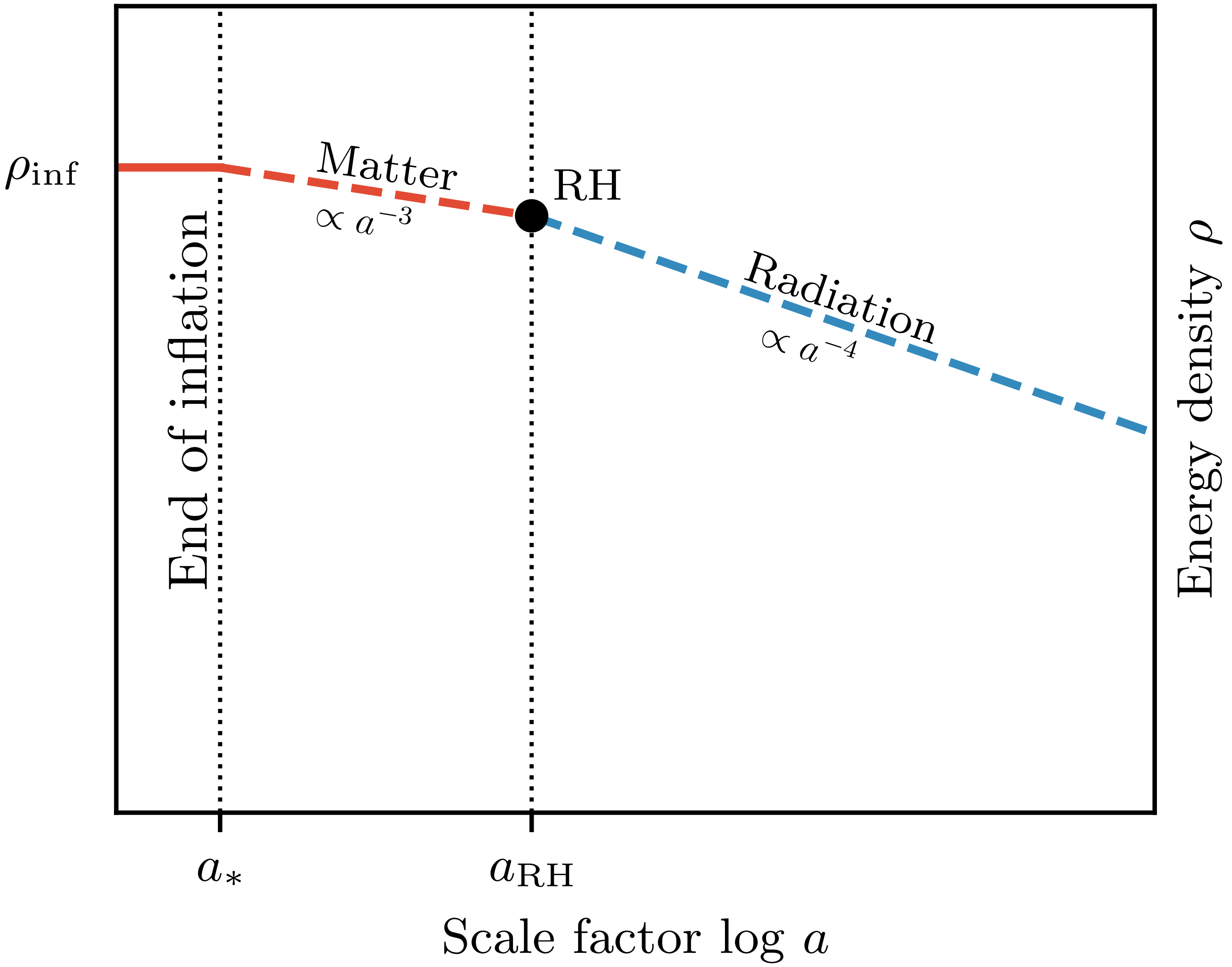
$H_* \lesssim 10^{14}$ GeV

[http://www.ctc.cam.ac.uk]

Can gravitational waves help probe this desert?

Standard Inflation Picture





Couplings between the inflaton and SM sector completely determine reheating temperature and dynamics

$$T_{\rm RH} \propto \sqrt{\Gamma M_P}$$

Does the inflaton require couplings to SM fields?

Gravitational Reheating

[L. H. Ford 87]

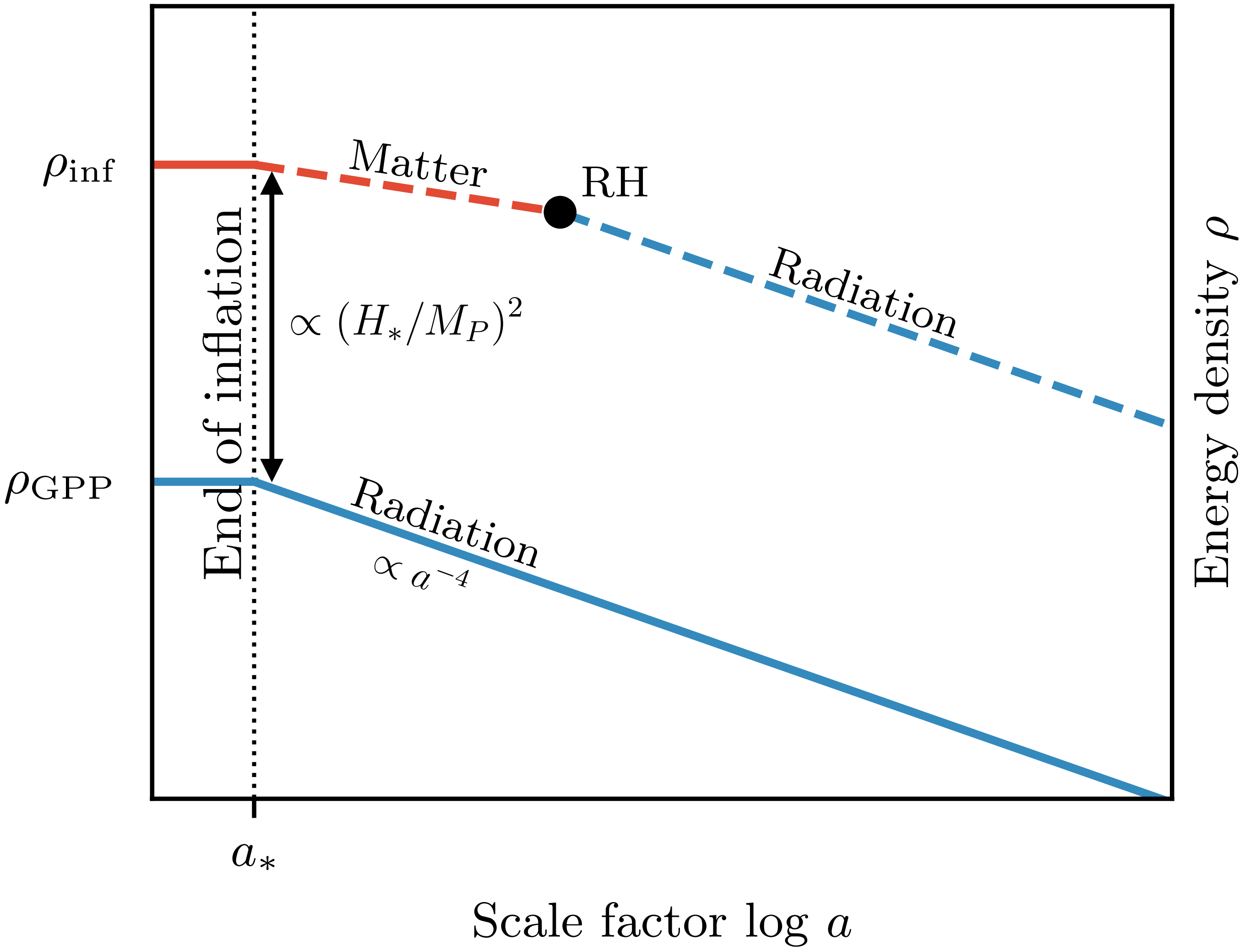
- Time varying background

$$\rho_{\text{GPP}} \sim 10^{-2} H_*^4 \quad \longrightarrow \quad \frac{\rho_{\text{GPP}}}{\rho_{\text{inf}}} \propto \left(\frac{H_*}{M_P}\right)^2$$

*I'll also refer to these as gravitationally produced particles

Need to dilute inflaton energy density (fast)!

Recall: $\rho \propto a^{-3(1+w)}$



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[L. H. Ford 87]

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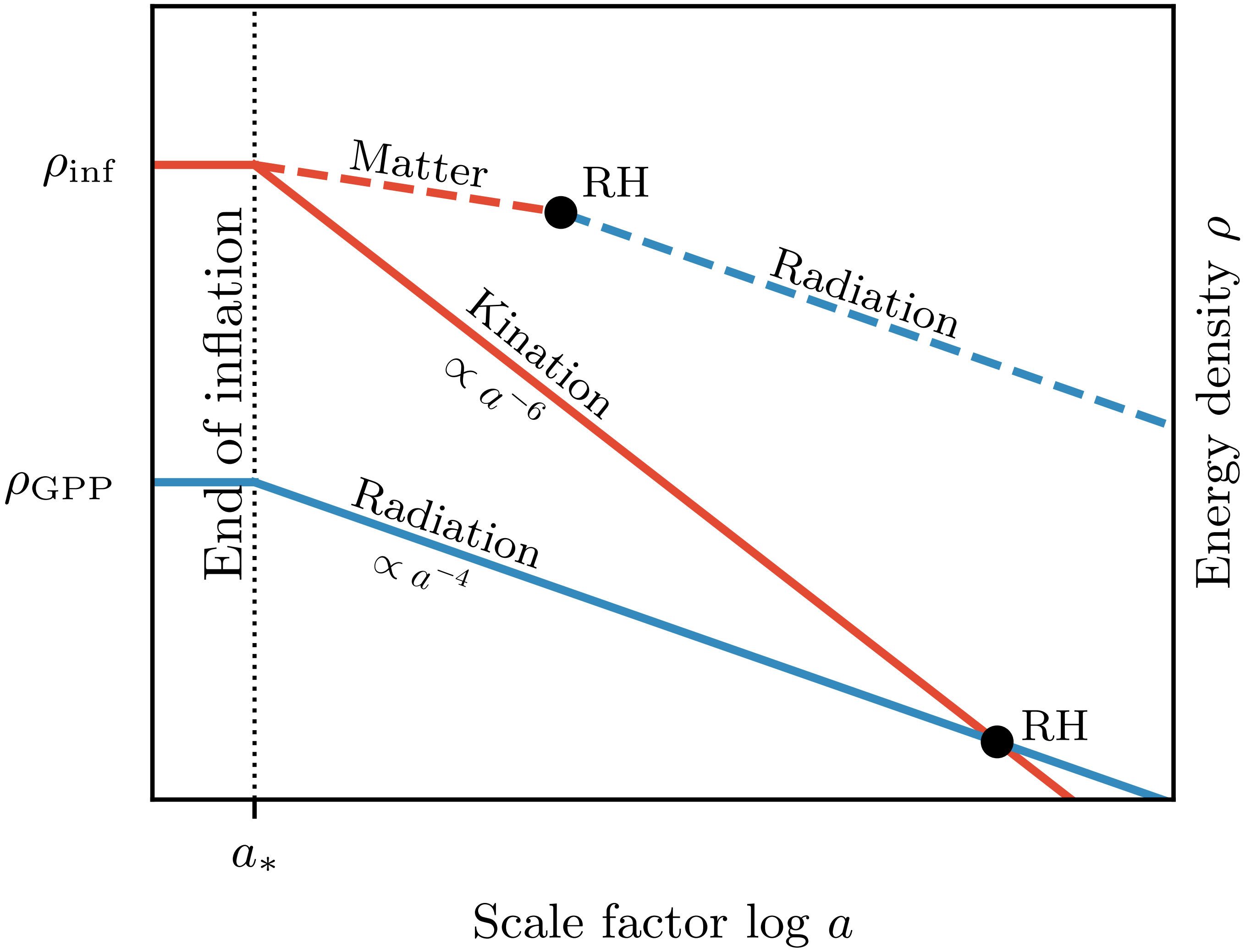

- Require a period with stiff equation of state $1/3 < w \leq 1$

[L. H. Ford 86, Spokoiny 93]

$$w = \frac{K - V}{K + V}$$

Reminder:

$w = -1$ Inflation/CC
$w = 0$ Matter
$w = 1/3$ Radiation
$w > 1/3$ Kination

Gravitational Reheating

[L. H. Ford 87]

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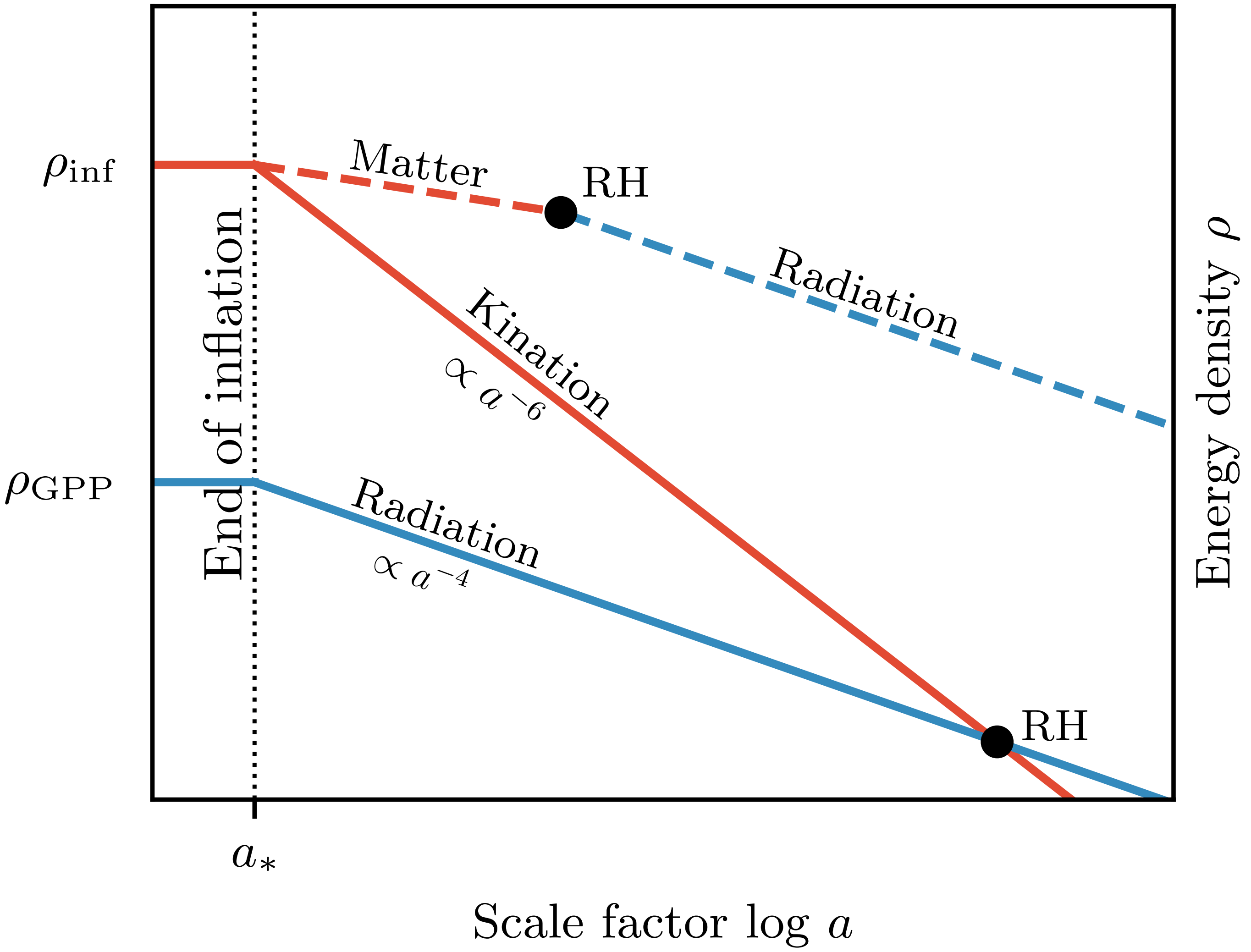


- Require a period with stiff equation of state $1/3 < w \leq 1$

[L. H. Ford 86, Spokoiny 93]

$$w = \frac{K-V}{K+V} \overset{V\to 0}{=} 1$$

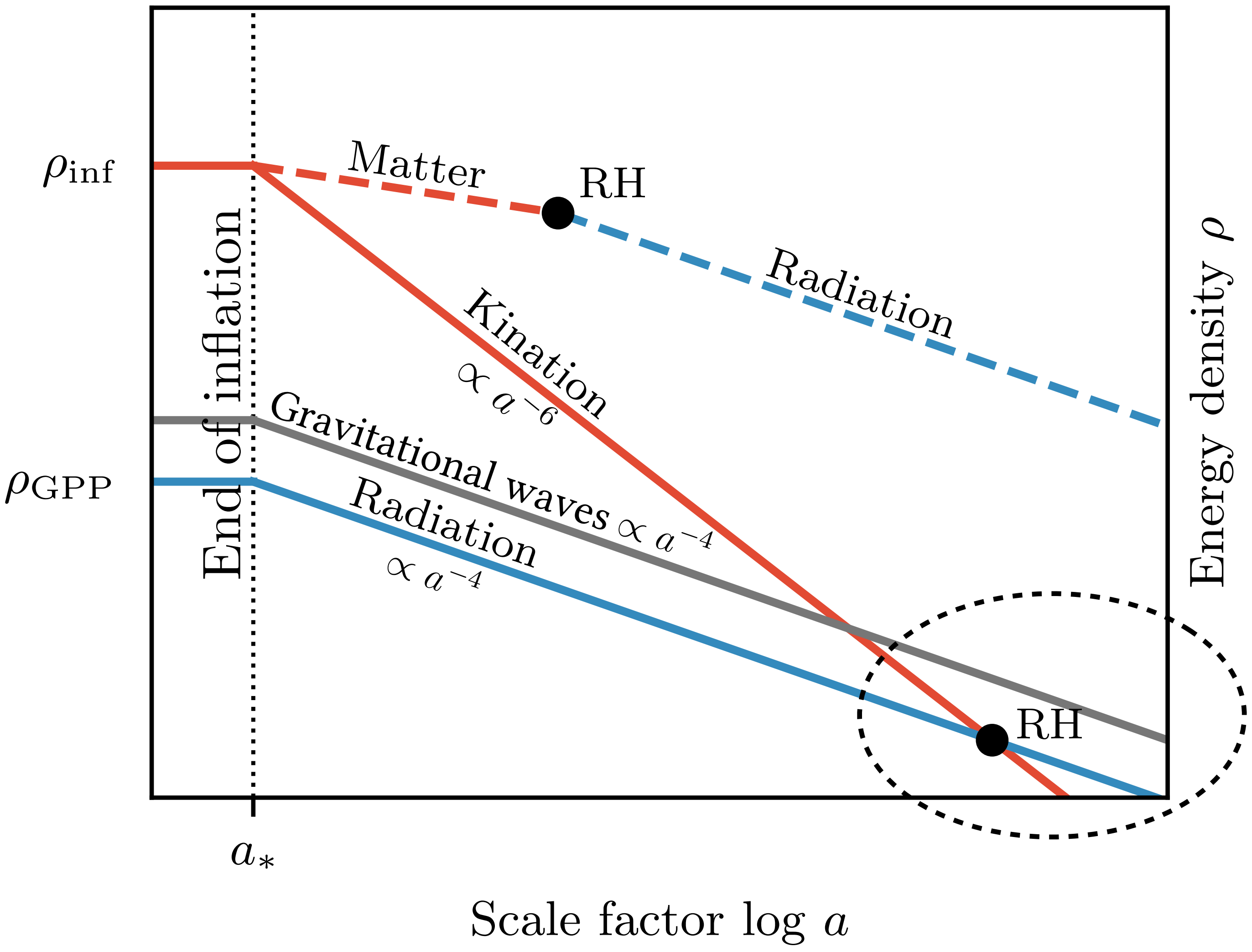
- Example potentials with $w > 1/3$

$\longrightarrow$ $V = \phi^{2n}\,, \quad \text{with} \quad n > 2$

$\longrightarrow$ Non-oscillatory potentials

Inconsistency of Grav. Reheating

[D. Figueroa & E. H. Tanin 1811.04093]



The very same mechanism produces gravitational waves!

- GWs inside the horizon scale as radiation (a^{-4})
- Dominate over radiation produced
- BBN is rather difficult with $\rho_{\rm GW} > \rho_{\rm rad}$

Ways out?

- Additional spectator fields $\mathcal{O}(100)$
- Return to direct coupling of the inflaton
- Modify gravitational reheating

The Ricci Curvature Scalar

Remember:

$\rho_{\text{inf}} \propto a^{-3(1+w)}$

In post-inflationary FRW universe*

$$R = -3(1-3w)H^2$$

$$= \begin{cases} -12H^2\,, & \text{inflation } (w=-1) \\ -3H^2\,, & \text{matter domination } (w=0) \\ 0\,, & \text{radiation domination } (w=1/3) \\ 6H^2\,, & \text{kination domination } (w=1) \end{cases}$$

Ricci scalar changes sign if $w > 1/3$ after inflation

A Non-minimally Coupled Scalar

Consider a real scalar field ‘Reheaton’

Contains other matter fields

$$\mathcal{S} = \int d^4x\sqrt{-g}\left\{\frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - V_{\text{eff}}(\phi) - \frac{M_P^2}{2}R + \mathscr{L}_{\text{mat}}\right\}$$

with

Non-minimal coupling to gravity

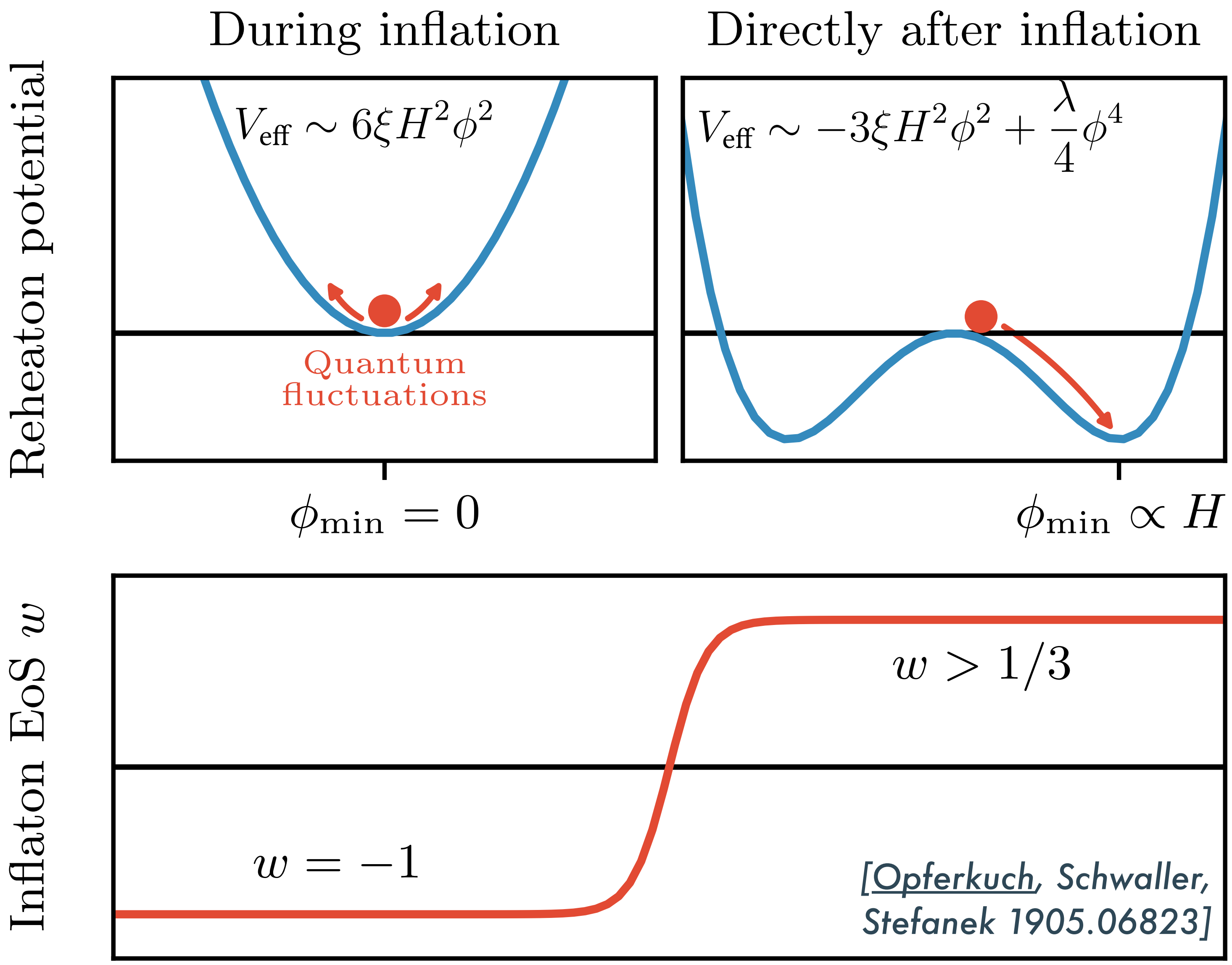
$$V_{\text{eff}} \equiv \frac{1}{2}\left(m^2 - \xi R\right)\phi^2 + \frac{\lambda}{4}\phi^4$$

assuming $m^2 \ll H_*^2$

No inflation sector specified:

Treat inflaton EoS as an order parameter of the theory

[Similar mechanism appears in Dimopoulos, Markkanen 1803.07399]



[Opferkuch, Schwaller, Stefanek 1905.06823]

Energy Extraction by the Reheaton

Numerically solving the full EoM

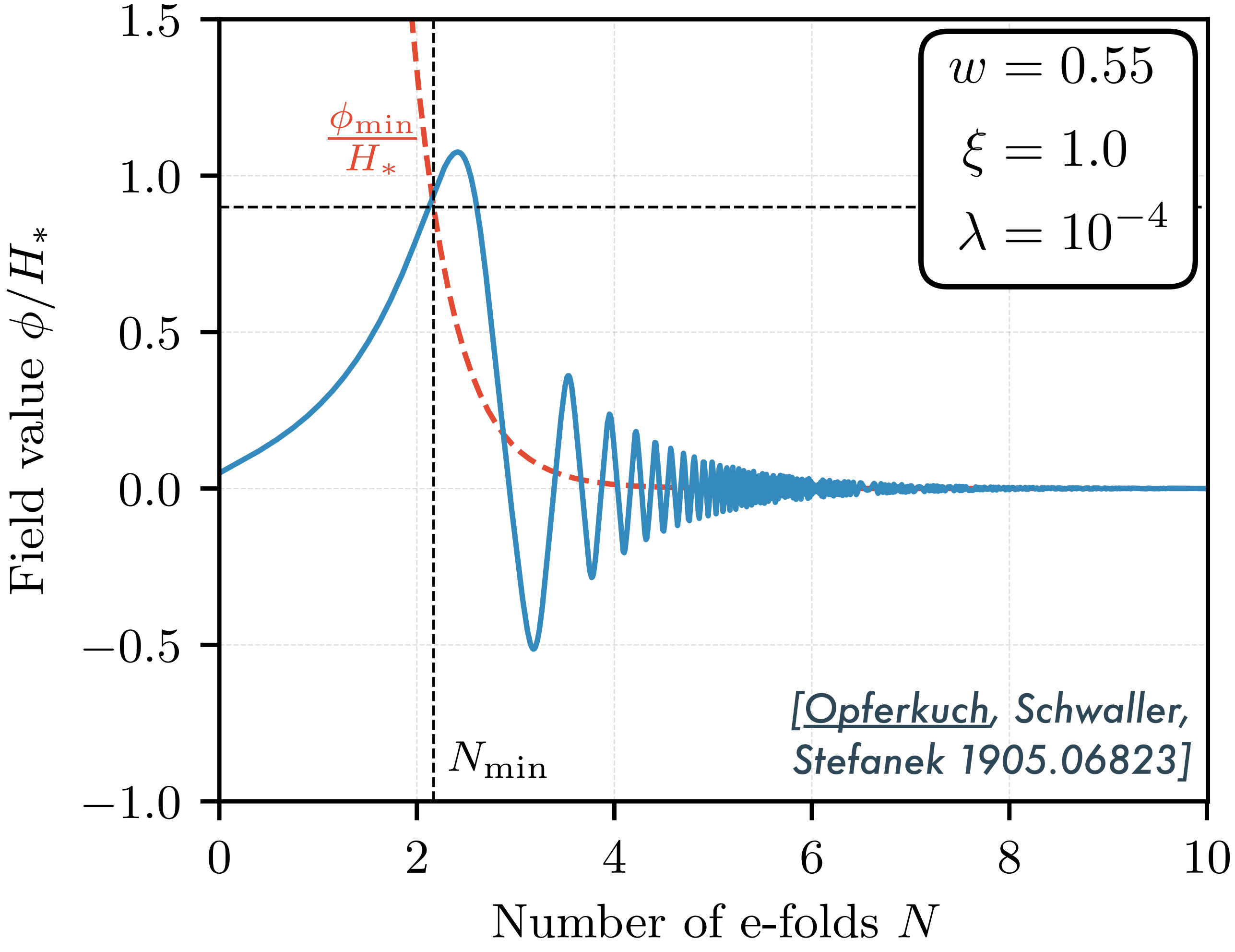
$$\ddot{\phi} + 3H\dot{\phi} + (m^2 - \xi R)\phi + \lambda\phi^3 = 0$$

with $H^2 = \frac{\rho_\mathrm{inf}}{3M_P^2} \simeq H_*^2 e^{-3(1+w)N}$

Alternatively

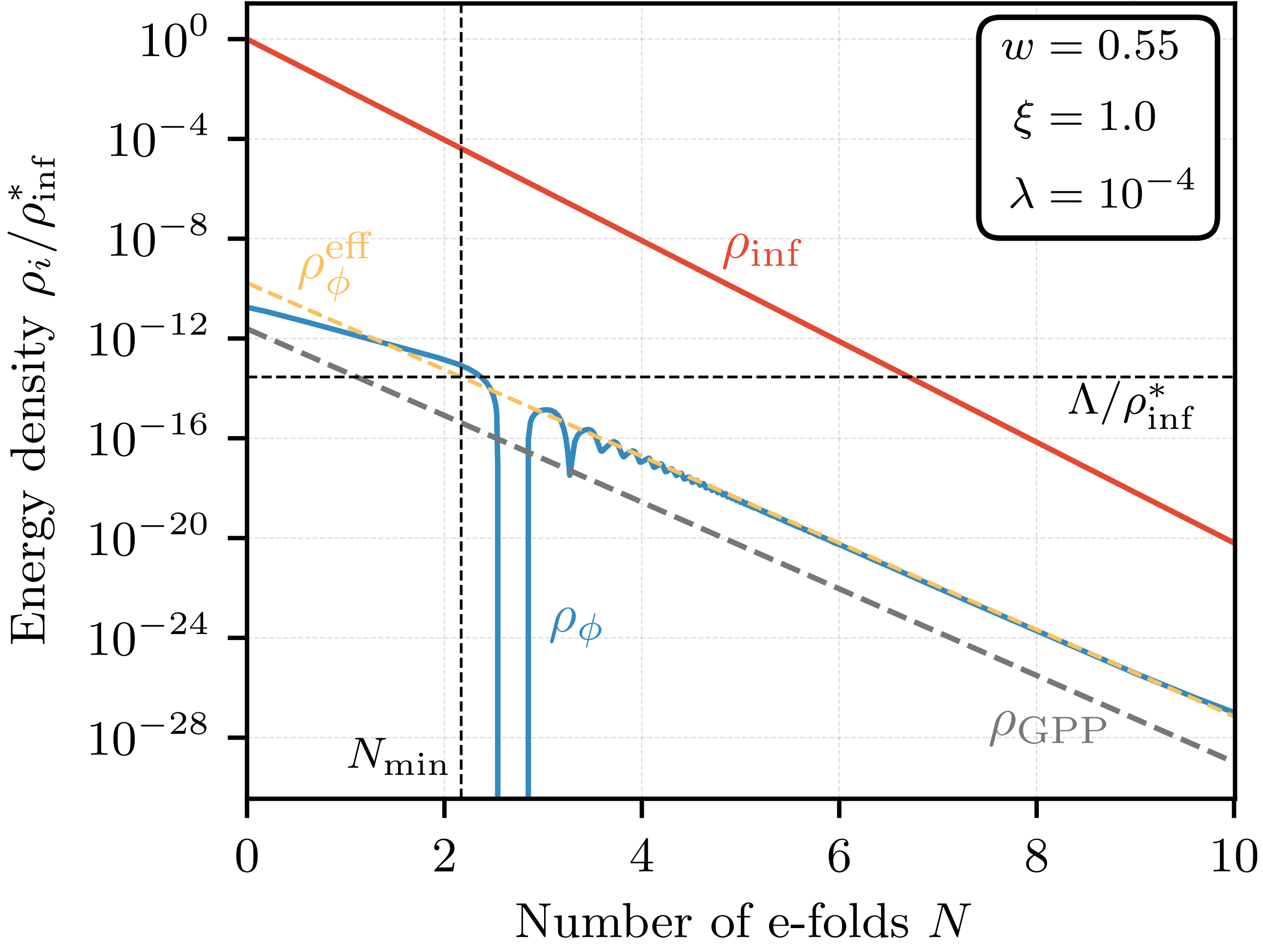
$$\ddot{\phi} + 3H\dot{\phi} + V'(\phi) \simeq \underbrace{\xi(3w-1)\frac{\rho_\mathrm{inf}}{M_P^2}\phi}$$

Inflaton energy density acts as a source for the reheaton

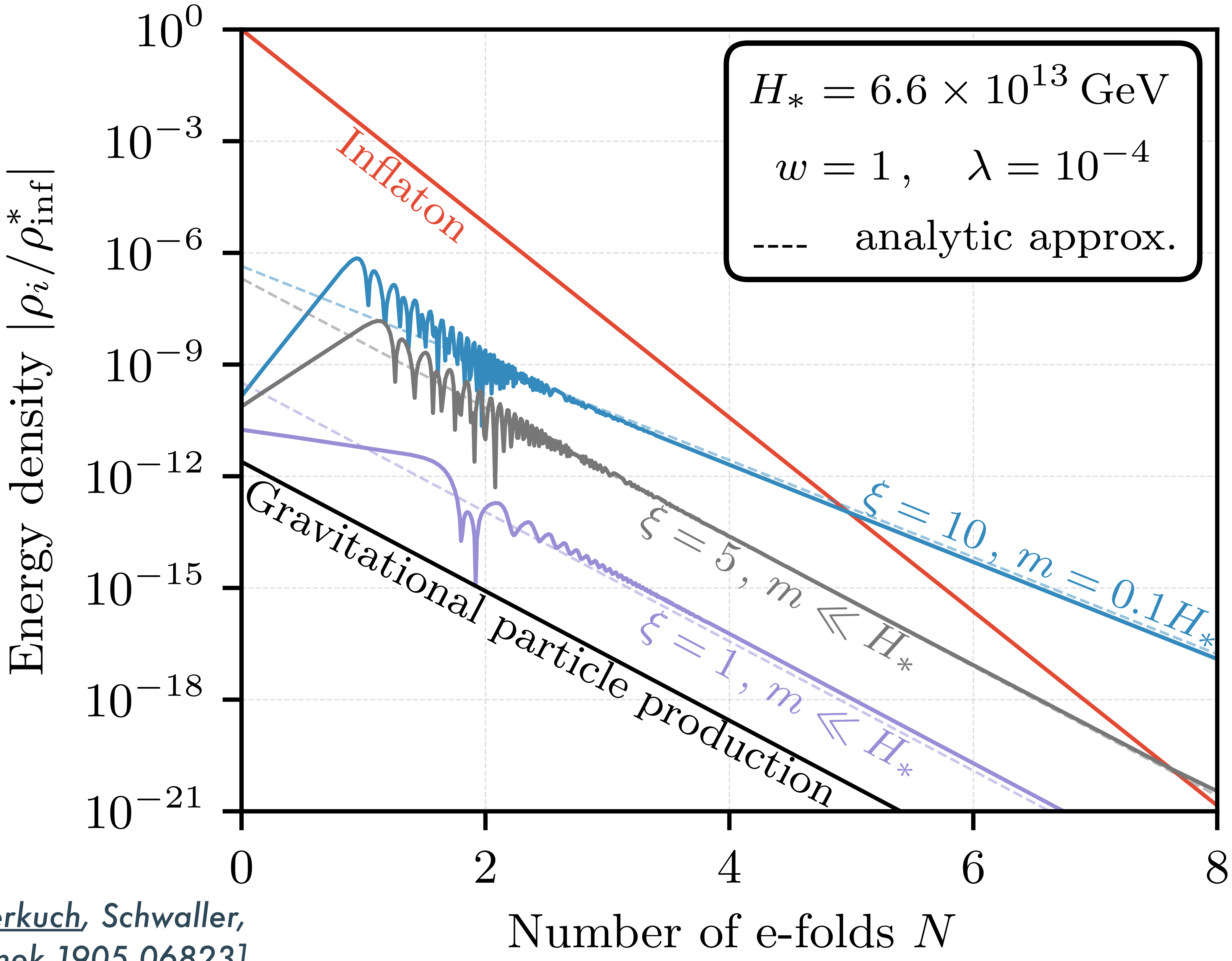


[Opferkuch, Schwaller, Stefanek 1905.06823]

*LISA detectable benchmark point!



Energy Extraction by the Reheaton



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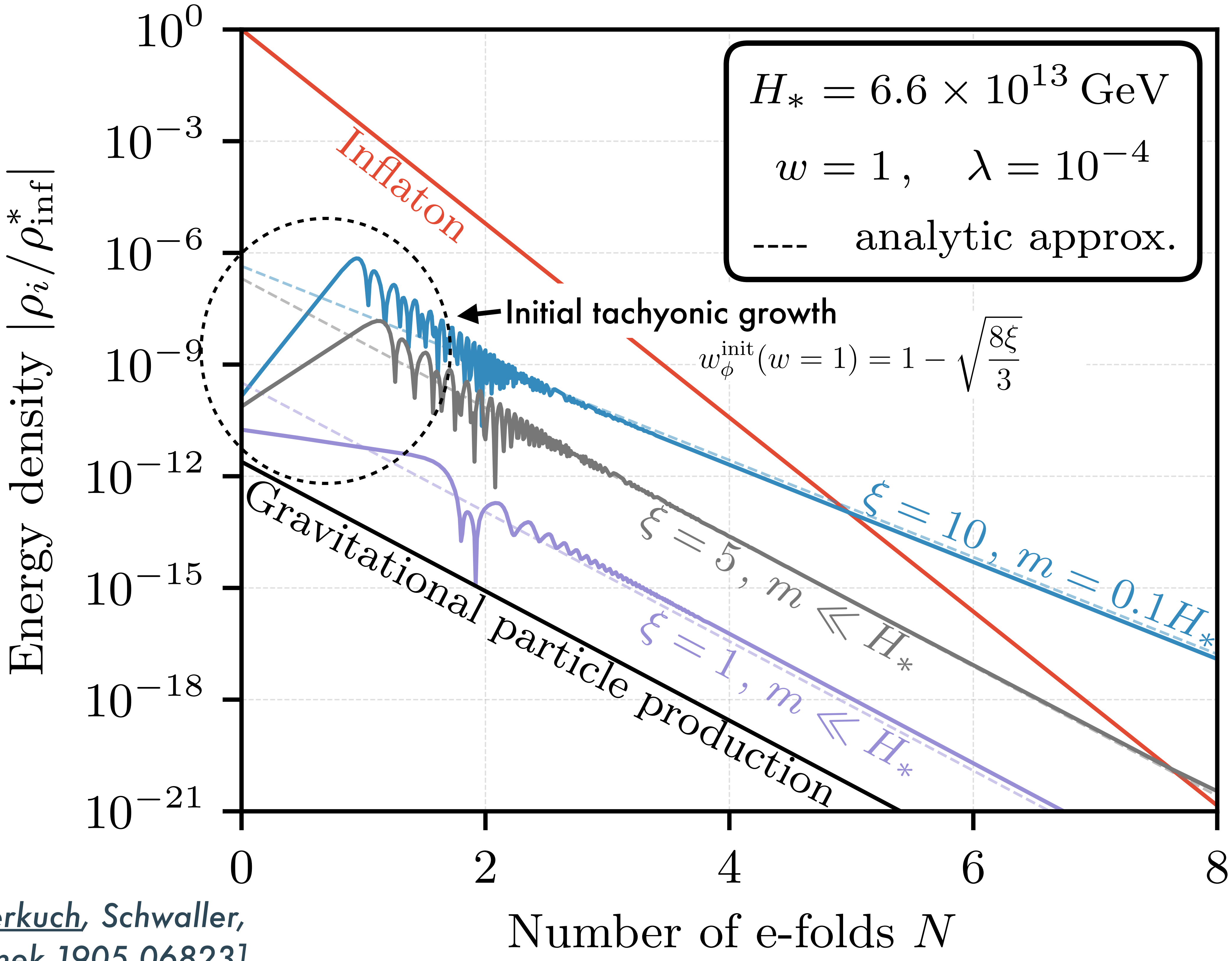
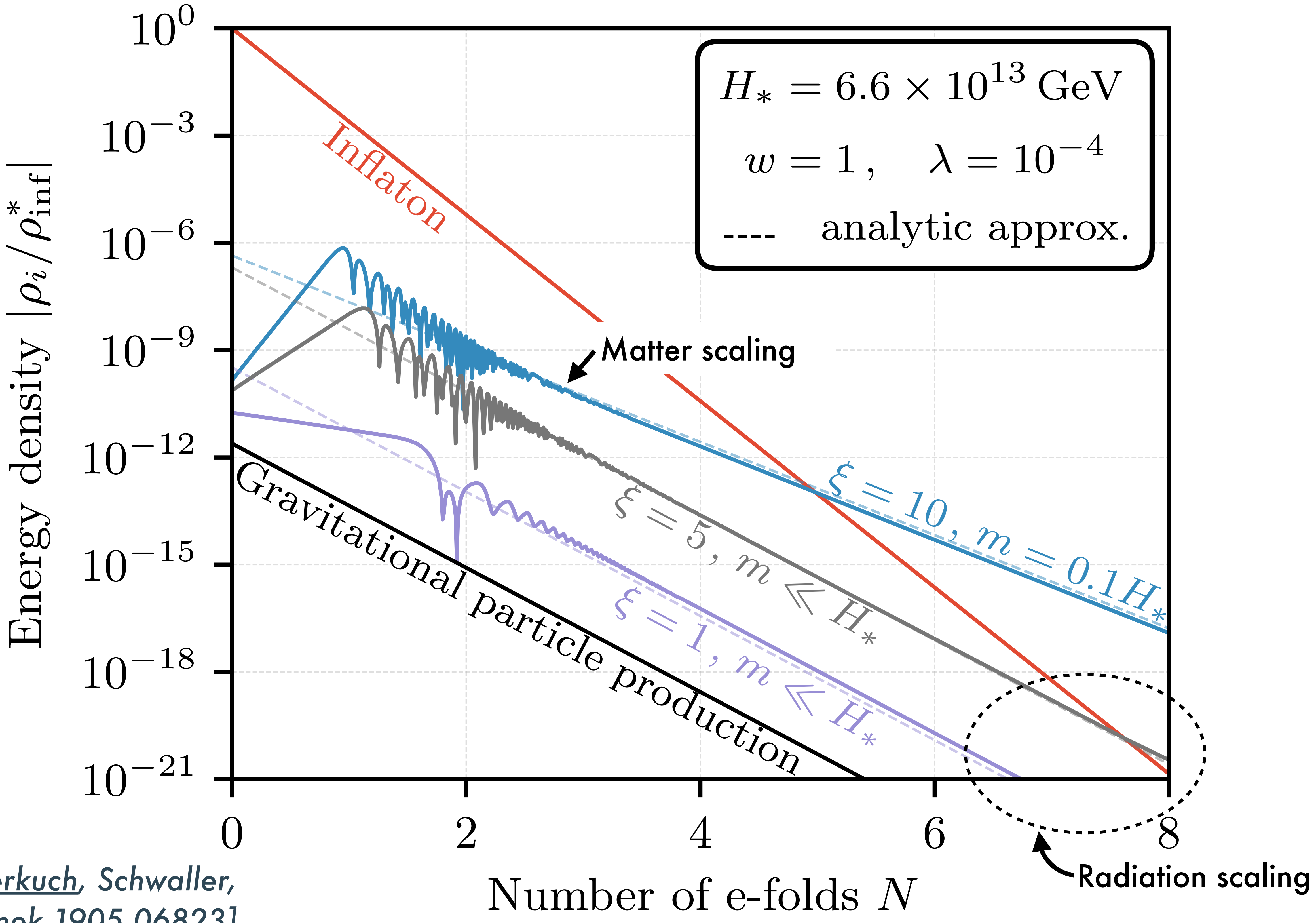


Initial tachyonic growth

$$w_\phi^{\rm init}(w=1) = 1 - \sqrt{\frac{8\xi}{3}}$$

[Opferkuch, Schwaller, Stefanek 1905.06823]

Energy Extraction by the Reheaton



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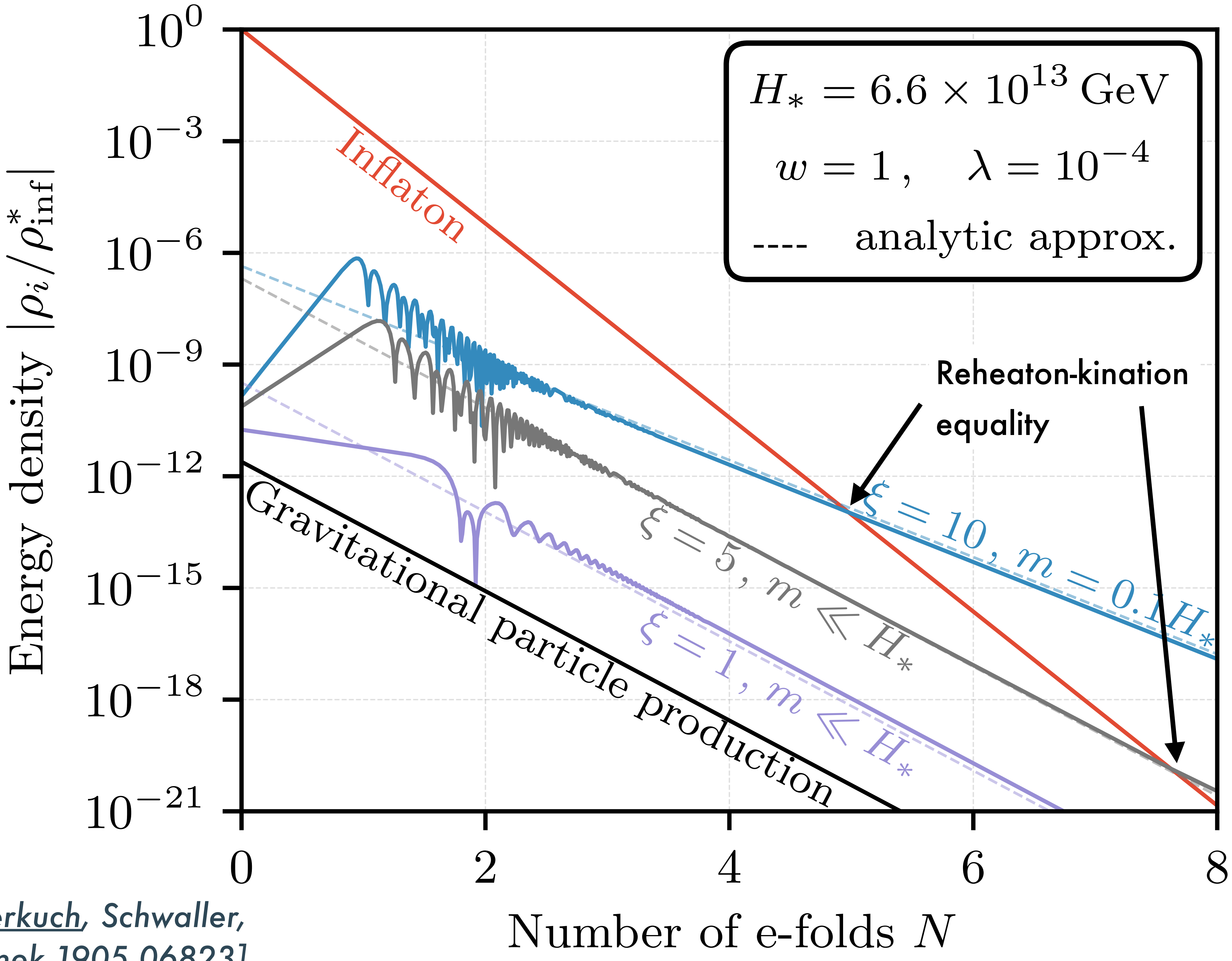

Reheaton-kination equality

[Opferkuch, Schwaller, Stefanek 1905.06823]

Blue-tilting the Infl. GW Background

[M. Giovannini hep-ph/9806329]

Modes re-entering during kination

$$\Omega_{\rm GW}(k) \propto \left(\frac{k}{k_{\rm ke}}\right)^{\frac{2(3w-1)}{3w+1}}$$

Growing function for $w > 1/3$

Can switch to frequency/wave-number through $k = aH$

Arises from mismatch

$$\frac{\rho_{\rm GW}}{\rho_c(k \geq k_{\rm ke})} \propto \frac{a^{-4}}{a^{-3(1+w)}} = a^{3w-1}$$

Blue-tilting the Infl. GW Background

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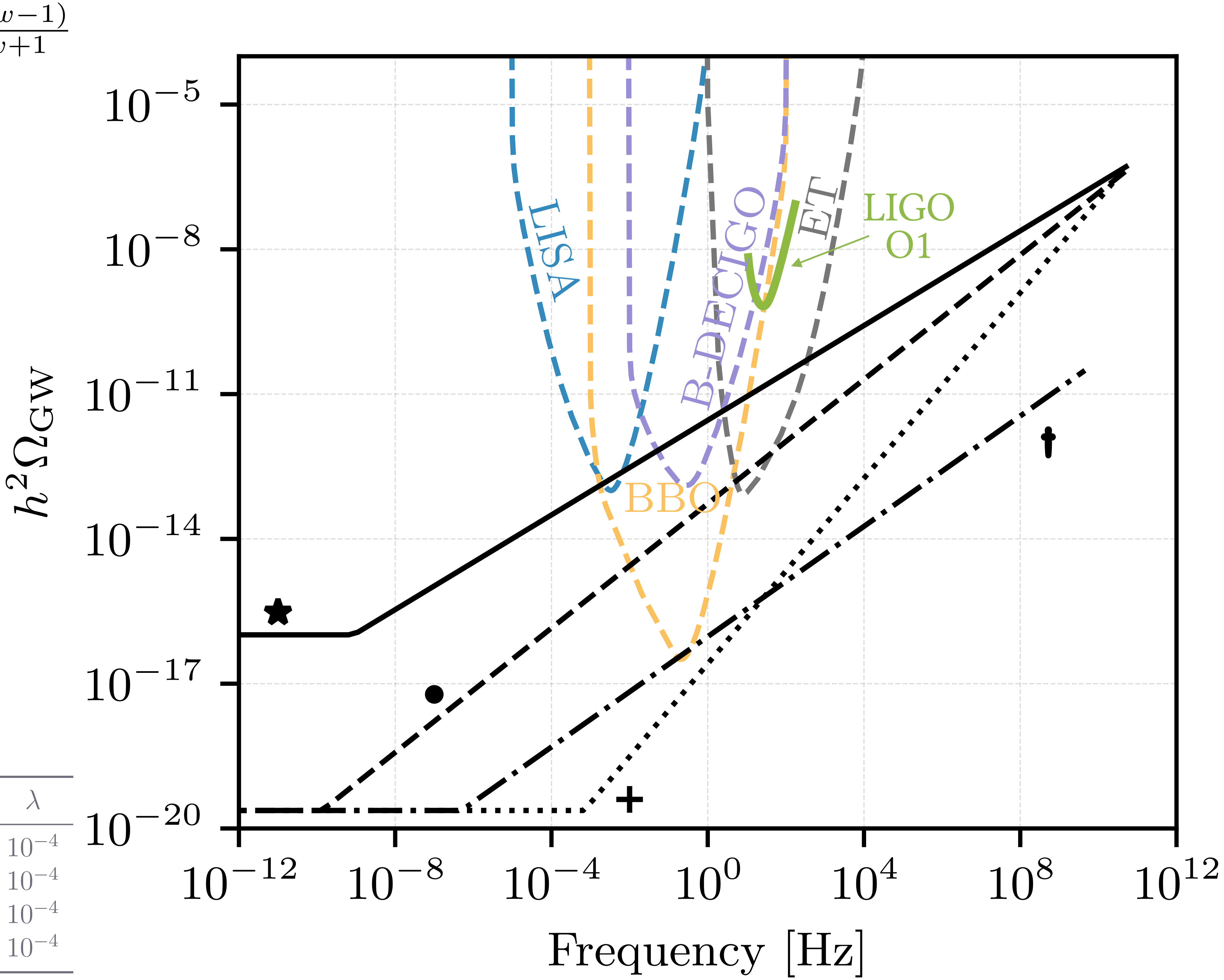


Benchmark point	w	H_* [GeV]	ξ	λ
1. LISA '★'	0.55	6.6×10^{13}	1.0	10^{-4}
2. ET '●'	0.65	10^{12}	1.0	10^{-4}
3. CMB-S4 '+'	0.95	10^{12}	0.8	10^{-4}
4. Large ξ '†'	0.6	10^{12}	15.0	10^{-4}

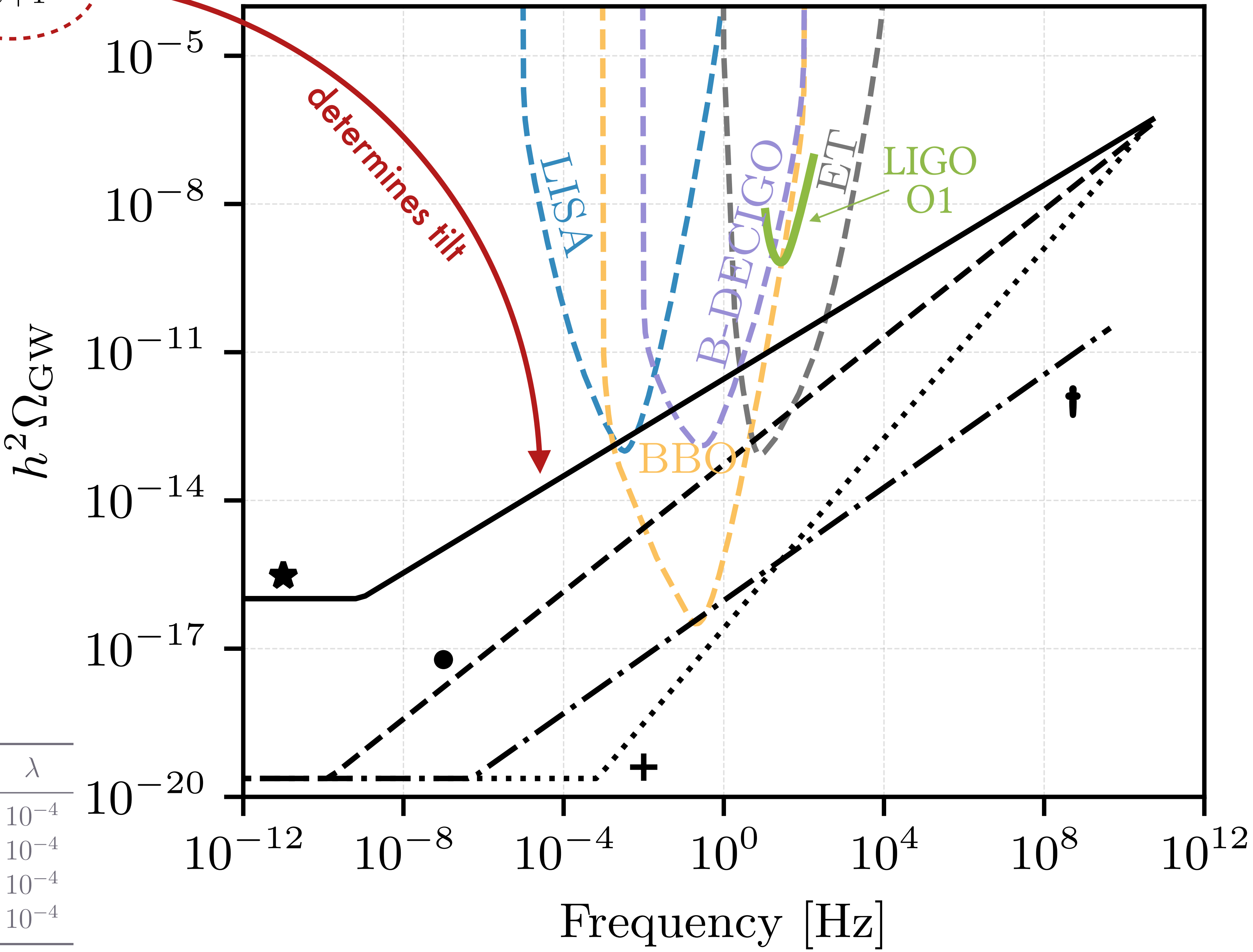
Blue-tilting the Infl. GW Background

Modes re-entering during kination

$$\Omega_{\rm GW}(k) \propto \left(\frac{k}{k_{\rm ke}}\right)^{\frac{2(3w-1)}{3w+1}}$$

Important features:

- Tilt


determines tilt

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4. Large ξ '†'	0.6	10^{12}	15.0	10^{-4}

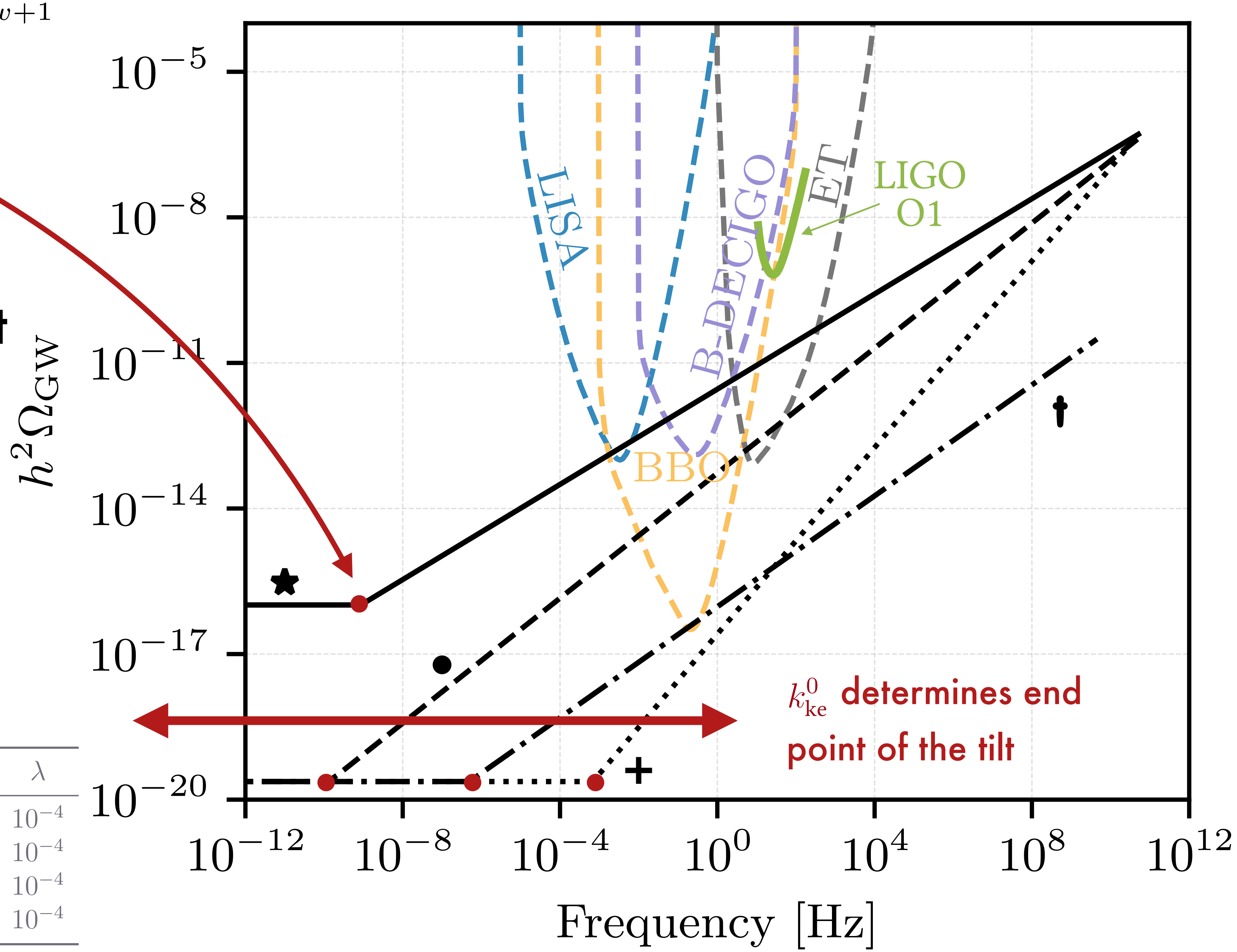
Blue-tilting the Infl. GW Background

Modes re-entering during kination

$$\Omega_{\rm GW}(k) \propto \left(\frac{k}{k_{\rm ke}}\right)^{\frac{2(3w-1)}{3w+1}}$$

Important features:

- Tilt
- Kination end point



$k_{\rm ke}^0$ determines end point of the tilt

Benchmark point	w	H_* [GeV]	ξ	λ
1. LISA '★'	0.55	6.6×10^{13}	1.0	10^{-4}
2. ET '●'	0.65	10^{12}	1.0	10^{-4}
3. CMB-S4 '+'	0.95	10^{12}	0.8	10^{-4}
4. Large ξ '†'	0.6	10^{12}	15.0	10^{-4}

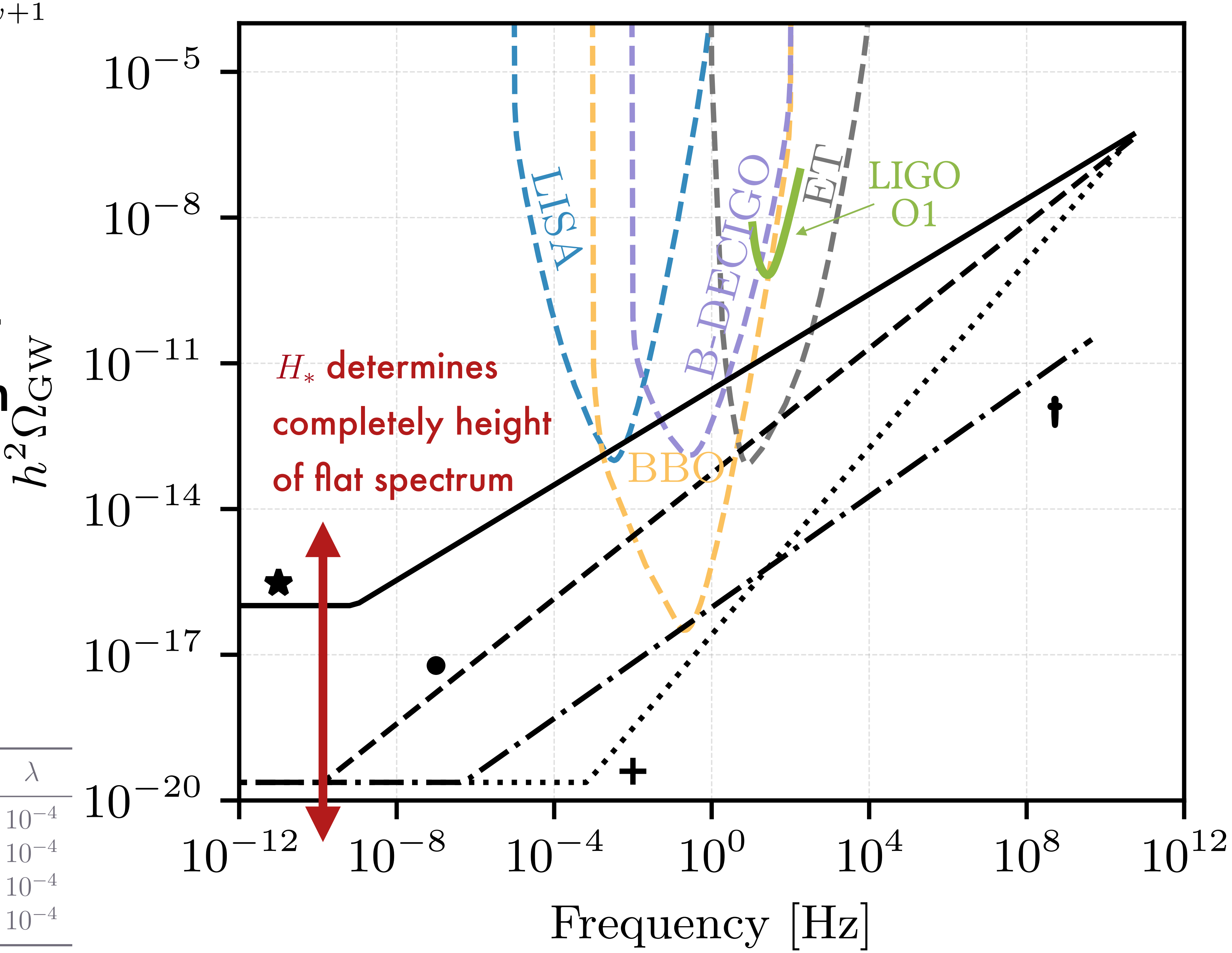
Blue-tilting the Infl. GW Background

Modes re-entering during kination

$$\Omega_{\rm GW}(k) \propto \left(\frac{k}{k_{\rm ke}}\right)^{\frac{2(3w-1)}{3w+1}}$$

Important features:

- Tilt
- Kination end point
- Amp. flat spectrum



H_* determines completely height of flat spectrum

Benchmark point	w	H_* [GeV]	ξ	λ
1. LISA '★'	0.55	6.6×10^{13}	1.0	10^{-4}
2. ET '●'	0.65	10^{12}	1.0	10^{-4}
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4. Large ξ '†'	0.6	10^{12}	15.0	10^{-4}

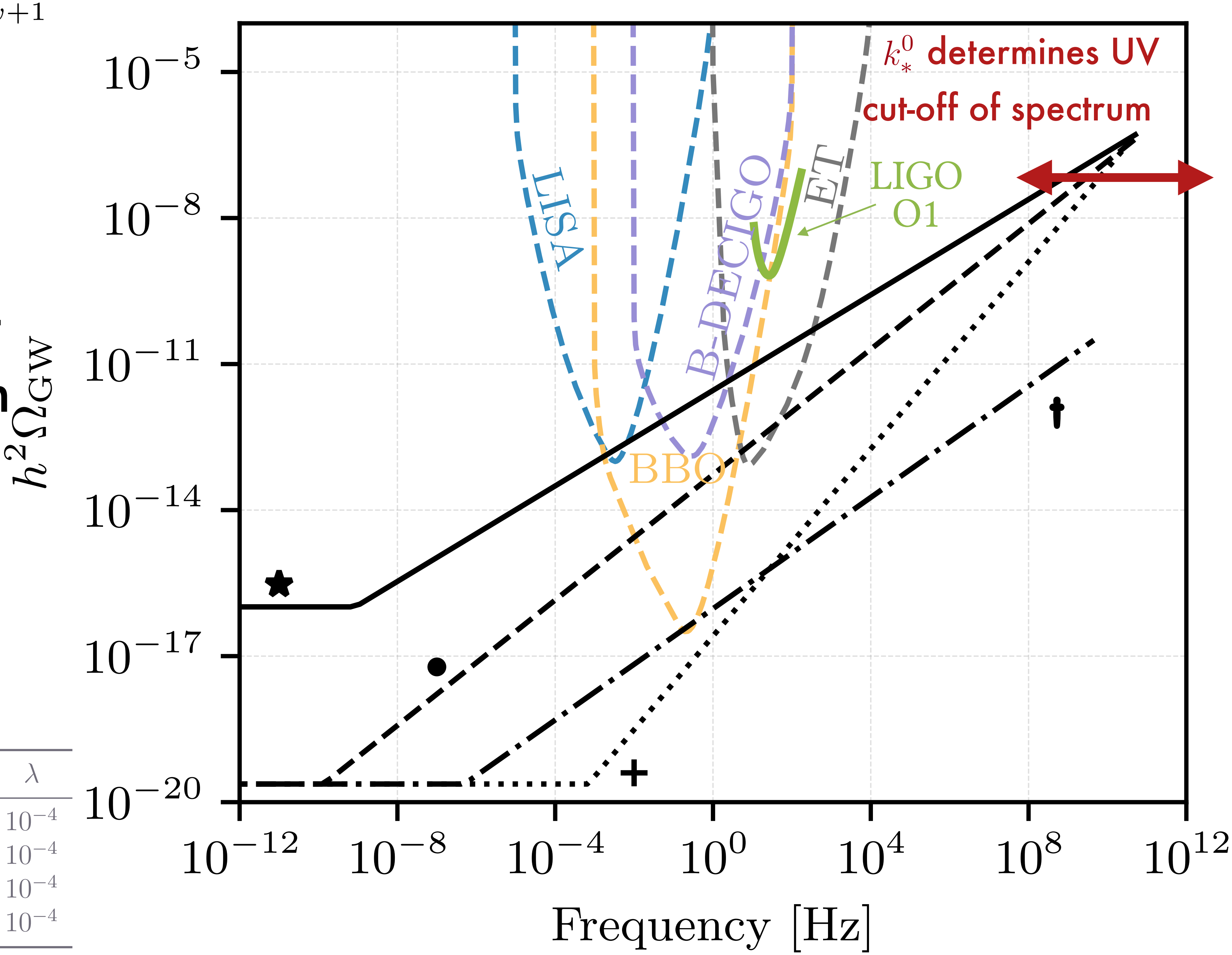
Blue-tilting the Infl. GW Background

Modes re-entering during kination

$$\Omega_{\rm GW}(k) \propto \left(\frac{k}{k_{\rm ke}}\right)^{\frac{2(3w-1)}{3w+1}}$$

Important features:

- Tilt
- Kination end point
- Amp. flat spectrum
- UV cut-off



k_*^0 determines UV cut-off of spectrum

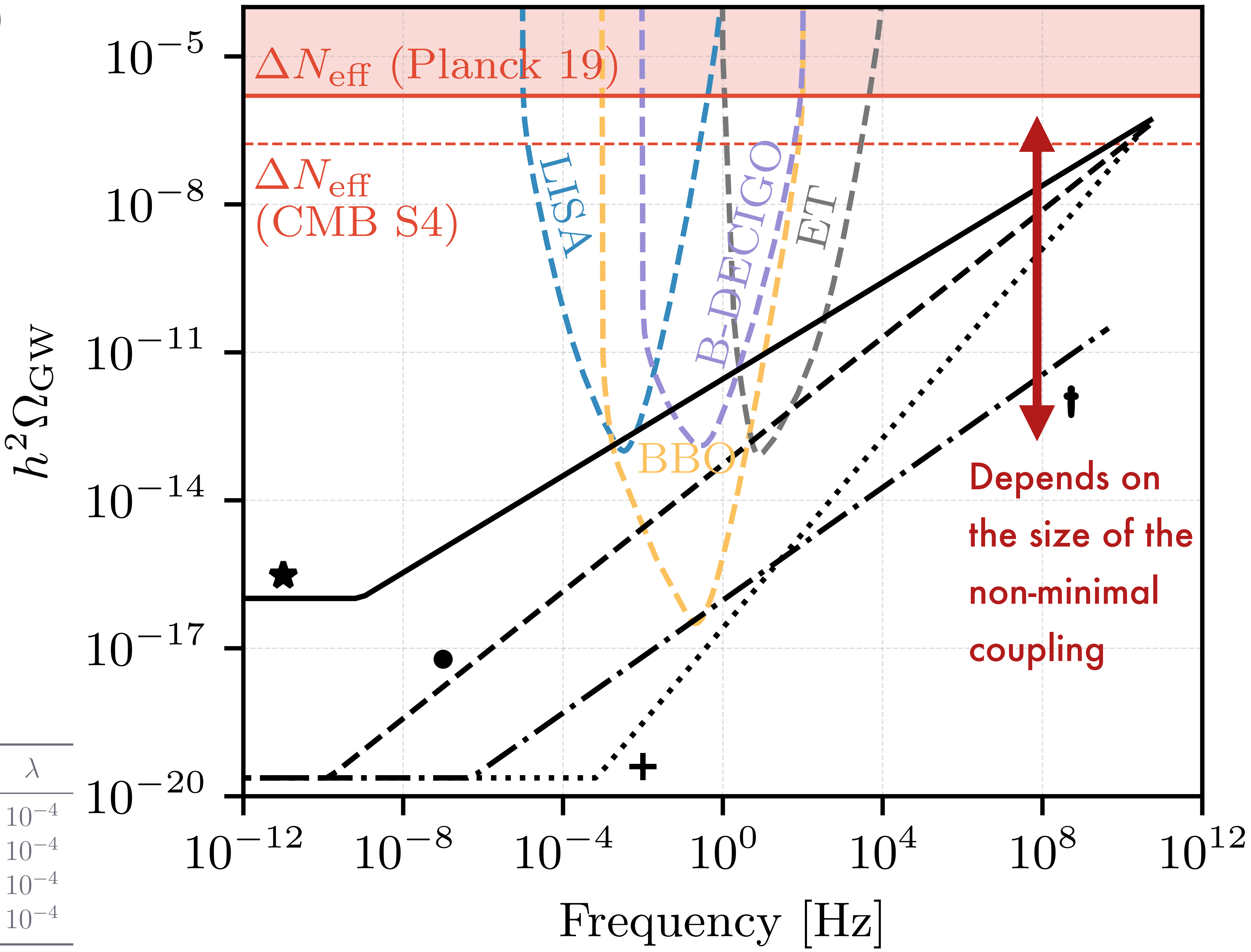
Benchmark point	w	H_* [GeV]	ξ	λ
1. LISA '★'	0.55	6.6×10^{13}	1.0	10^{-4}
2. ET '●'	0.65	10^{12}	1.0	10^{-4}
3. CMB-S4 '+'	0.95	10^{12}	0.8	10^{-4}
4. Large ξ '†'	0.6	10^{12}	15.0	10^{-4}

N_{eff} and Planck

GWs inside the horizon contribute to number of relativistic DOFs

$$\Omega^0_{\text{GW}} = \int \frac{df}{f} \Omega^0_{\text{GW}}(f)$$

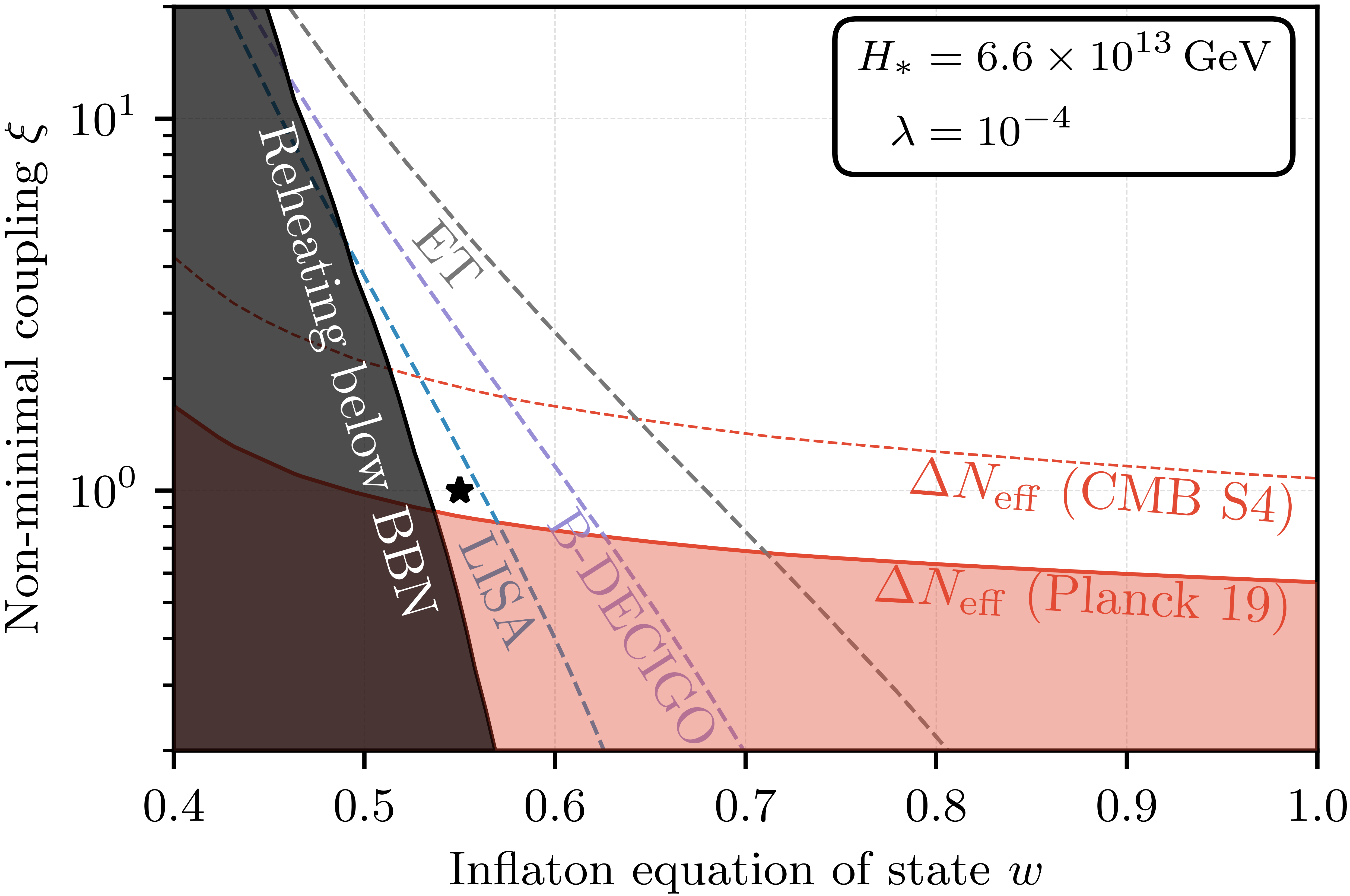
Integral dominated by end point



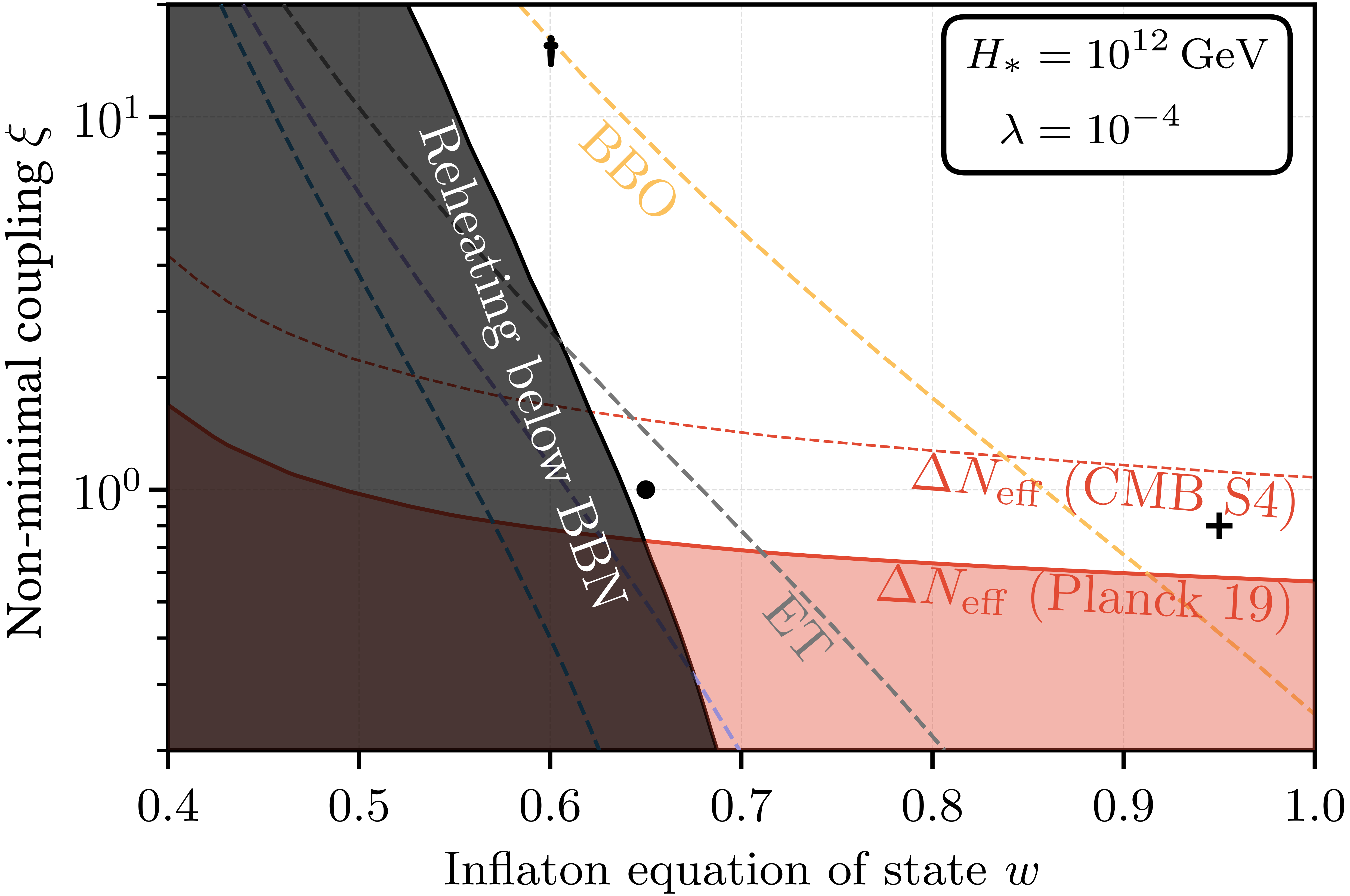
Depends on the size of the non-minimal coupling

Benchmark point	w	H_* [GeV]	ξ	λ
1. LISA '⋆'	0.55	6.6×10^{13}	1.0	10^{-4}
2. ET '•'	0.65	10^{12}	1.0	10^{-4}
3. CMB-S4 '+'	0.95	10^{12}	0.8	10^{-4}
4. Large ξ '†'	0.6	10^{12}	15.0	10^{-4}

Detectability



Detectability



The Higgs as the Reheaton

[See also D. Figueroa & C. Byrnes 1604.03905]

- Replace $\xi\phi^2 R \longrightarrow \xi|H|^2 R$
- Quartic no longer free parameter
- Renormalisation scale & RGEs determine quartic:

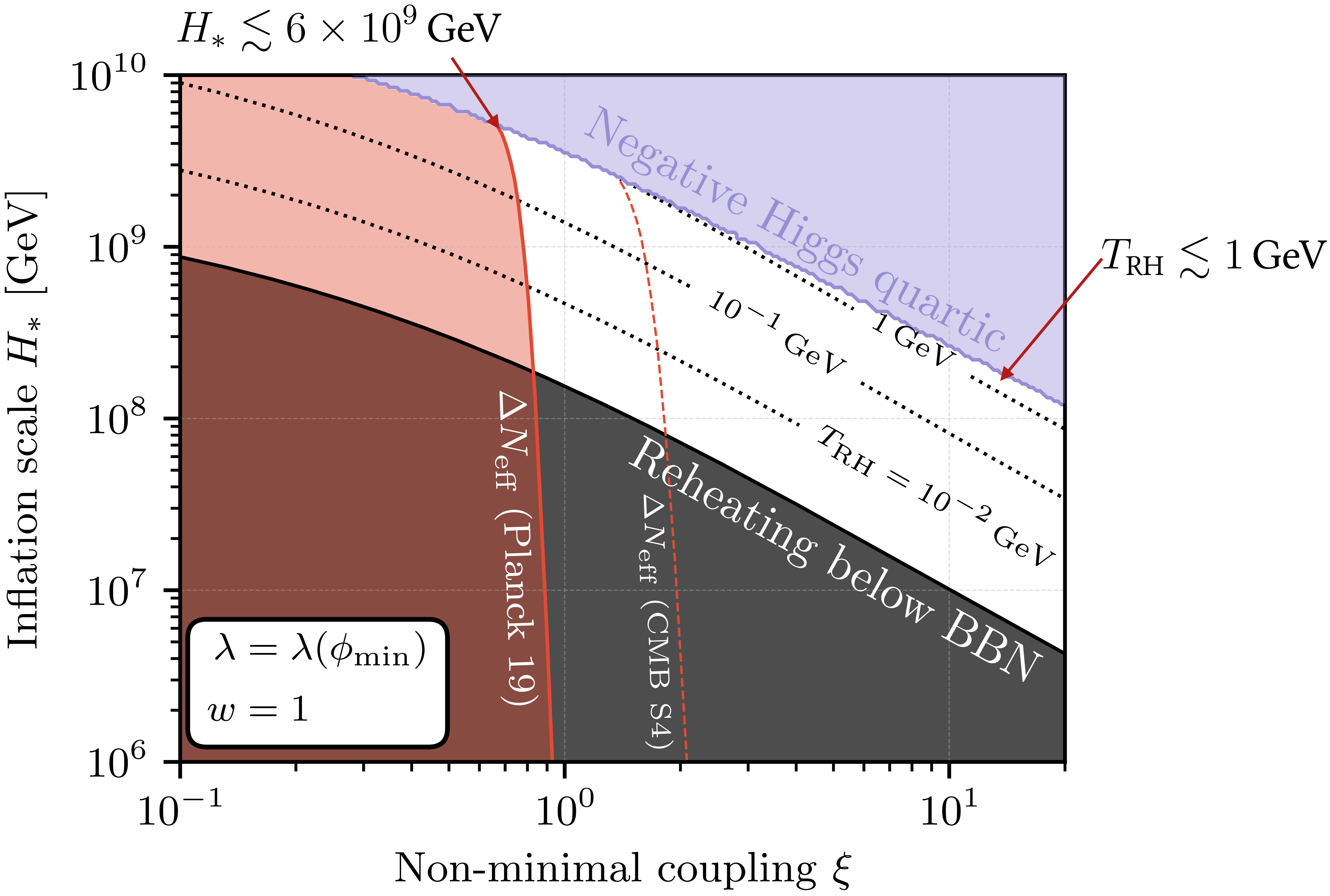
*using results of D. Buttazzo et. al 1307.3536

$$\mu = \phi_{\text{min}} \quad \underset{\text{solve}}{\Longrightarrow} \quad \mu^2 = \frac{3\xi(3w-1)}{\lambda(\mu)} H^2_{\text{min}}(\lambda(\mu))$$

Ending tachyonic growth requires

$$\lambda(\mu = \phi_{\text{min}}) > 0$$

The Higgs as the Reheaton



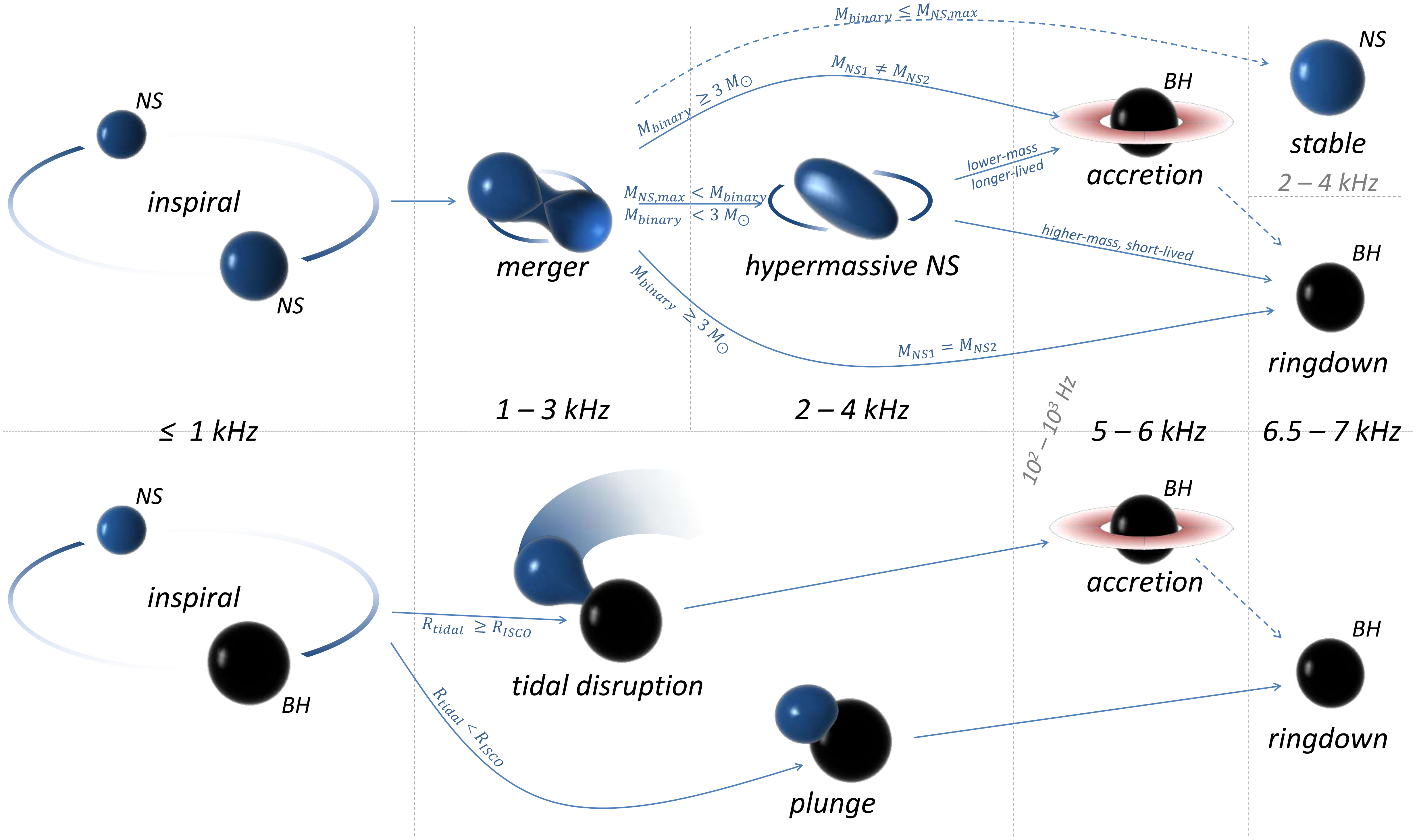
Part II: Take Home Message

- Non-minimally coupled scalar can resolve issues with conventional grav. reheating
- Probed through GWs (direct detection & N_{eff})
- Higgs can be the non-minimally coupled scalar but $T_{\text{RH}} \lesssim 1\,\text{GeV}$

Questions?

Backup Slides

Neutron Star Mergers



NS

inspiral

NS

merger

$M_{binary} \lesssim M_{NS,max}$

$M_{binary} \gtrsim 3\,M_\odot$

$M_{NS1} \neq M_{NS2}$

$M_{NS,max} < M_{binary}$

$M_{binary} < 3\,M_\odot$

hypermassive NS

lower-mass

longer-lived

higher-mass, short-lived

$M_{binary} \gtrsim 3\,M_\odot$

$M_{NS1} = M_{NS2}$

BH

accretion

NS

stable

2 – 4 kHz

BH

ringdown

≤ 1 kHz

1 – 3 kHz

2 – 4 kHz

$10^2 - 10^3$ Hz

5 – 6 kHz

6.5 – 7 kHz

NS

inspiral

BH

$R_{tidal} \geq R_{ISCO}$

tidal disruption

$R_{tidal} < R_{ISCO}$

plunge

BH

accretion

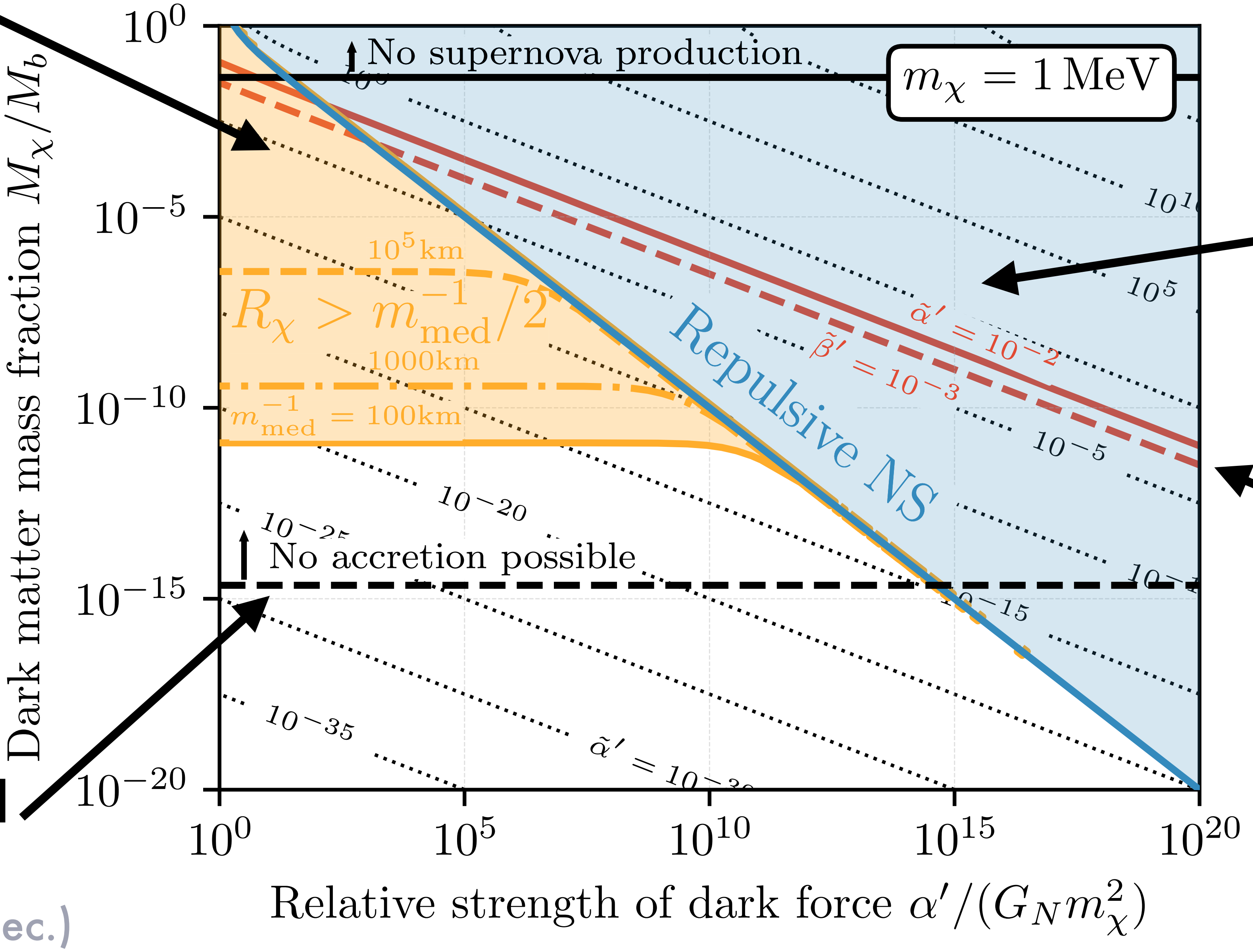
BH

ringdown

[Bartos, Brady and Marka 1212.2289]

What About Dark Matter?

- Asymmetric DM endowed with a repulsive long-range force



Radius of DM core larger similar to range of new force

Accretion bound

(assuming local DM density and geo. X-sec.)

DM is not bound to NS

Approximate LIGO/VIRGO sensitivity

future experiments will probe much deeper into parameter space

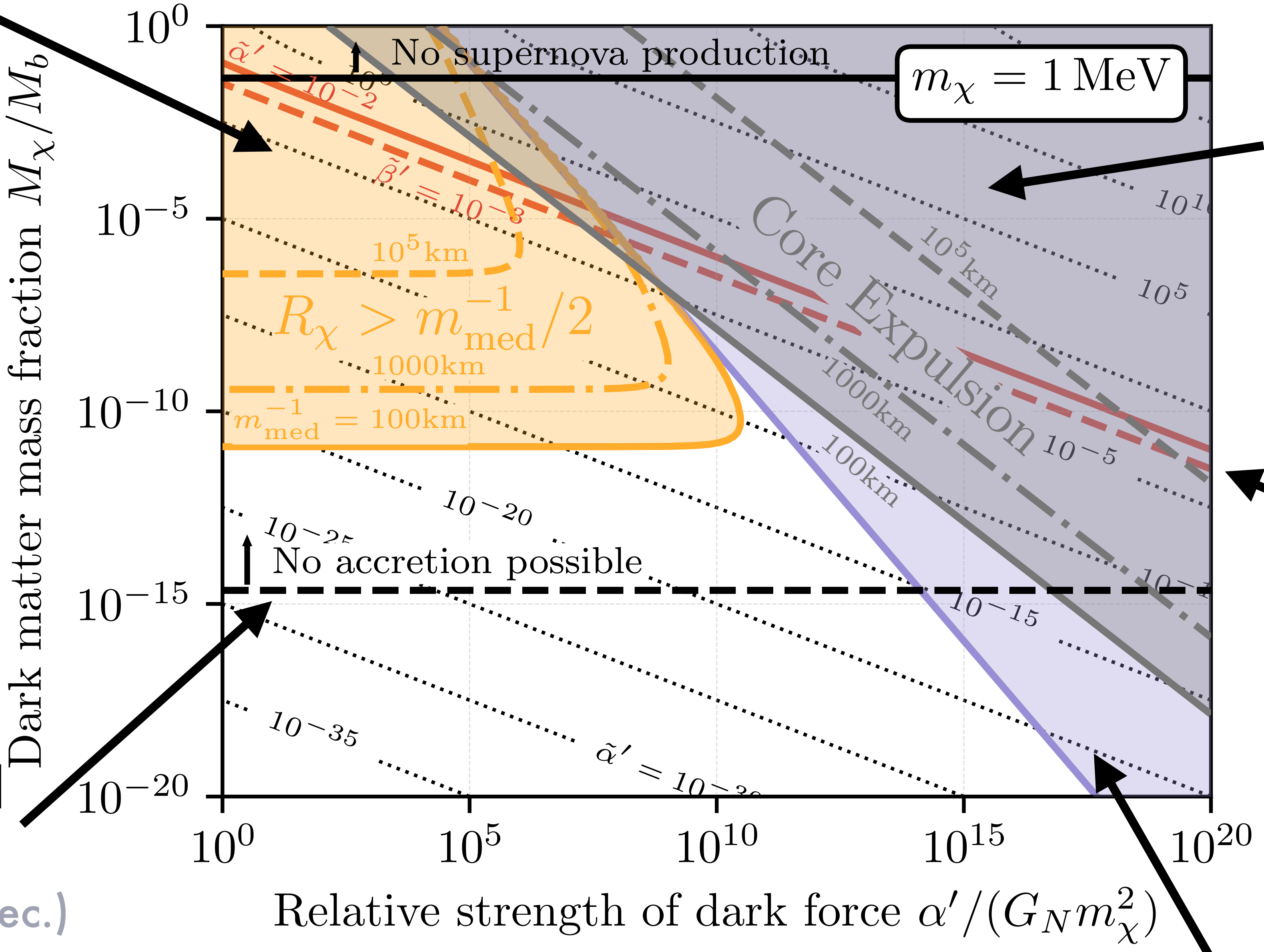
[Alexander et. al. 1808.05286]

Signal only possible with non-standard production mechanism

What About Dark Matter?

- Asymmetric DM endowed with an attractive long-range force

Radius of DM core larger similar to range of new force



DM core expelled from neutron star

Approximate LIGO/VIRGO sensitivity

future experiments will probe much deeper into parameter space

[Alexander et. al. 1808.05286]

Accretion bound

(assuming local DM density and geo. X-sec.)

DM core collapses to black hole

Signal only possible with non-standard production mechanism

Muons in Neutron Stars

- Neutrons produced during stellar collapse: $p + e^- \to n + \nu_e$
- β-equilibrium ensures neutron stability via abundance of protons & electrons
- Electron Fermi energy increases allowing:

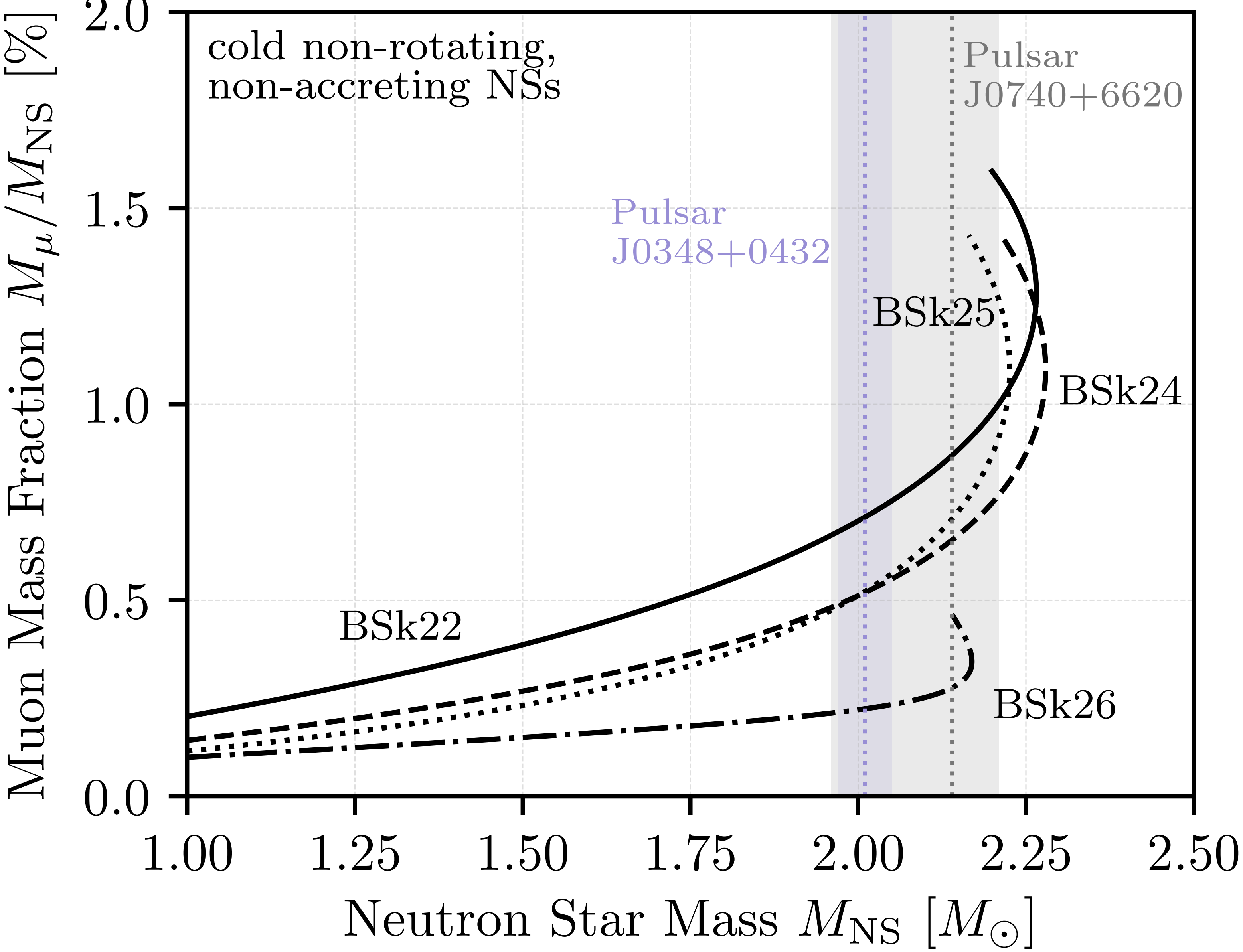
$$n \to p + \mu^- + \bar{\nu}_\mu$$

$$e^- \to \mu^- + \bar{\nu}_\mu + \nu_e$$

- Pauli-blocking due to high electron density forbids muon decay

Over 10^{27} kg worth of 'stable' muons

[Dror, Laha, Opferkuch 1909.12845]



[NS equations of state taken from Pearson et. al. 1903.04981]

Gravitational Waveform

- Expanding to linear order in α and β:

$$\tilde{h}(f) = -\sqrt{\frac{5\pi}{24}} G_N^{5/6} \frac{\mathcal{M}^2}{D_{\text{eff}}} (\pi \mathcal{M} f)^{-7/6} \times \left[\mathcal{A}_{\text{PN}} - \frac{\alpha}{3} C(x) - \frac{5\gamma}{96} (\pi G_N m f)^{-2/3} \Theta\left(\frac{\pi f}{m_V} - 1\right)\right] e^{-i\Psi}$$

**using natural units*

with phase:

$$\Psi \equiv 2\pi f t_0 - 2\phi_0 - \frac{\pi}{4} + \frac{3}{128} (\pi G_N \mathcal{M} f)^{-5/3} \times \left[\frac{20\alpha}{3} F_3(x) - \frac{5\gamma}{84} (\pi G_N m f)^{-2/3} \Theta\left(\frac{\pi f}{m_V} - 1\right)\right] + \Psi_{\text{PN}}$$

and

[PN corrections adapted from S. Kahn et. al. 1508.07253]

$$F_3(x) \equiv \left(\frac{180 + 180x + 69x^2 + 16x^3 + 2x^4}{x^4}\right) e^{-x} + \frac{21\sqrt{\pi}}{2x^{5/2}} \text{erf}(\sqrt{x})$$

$$C(x) \equiv \left(1 + x - 2x^2\right) e^{-x} \qquad m \equiv m_1 + m_2$$

$$x \equiv G_N^{1/3} m\, m_V (\pi m f)^{-2/3} \qquad \mathcal{M} \equiv \mu^{3/5} (m_1 + m_2)^{2/5}$$

Pulsar Constraints

Additional energy loss:

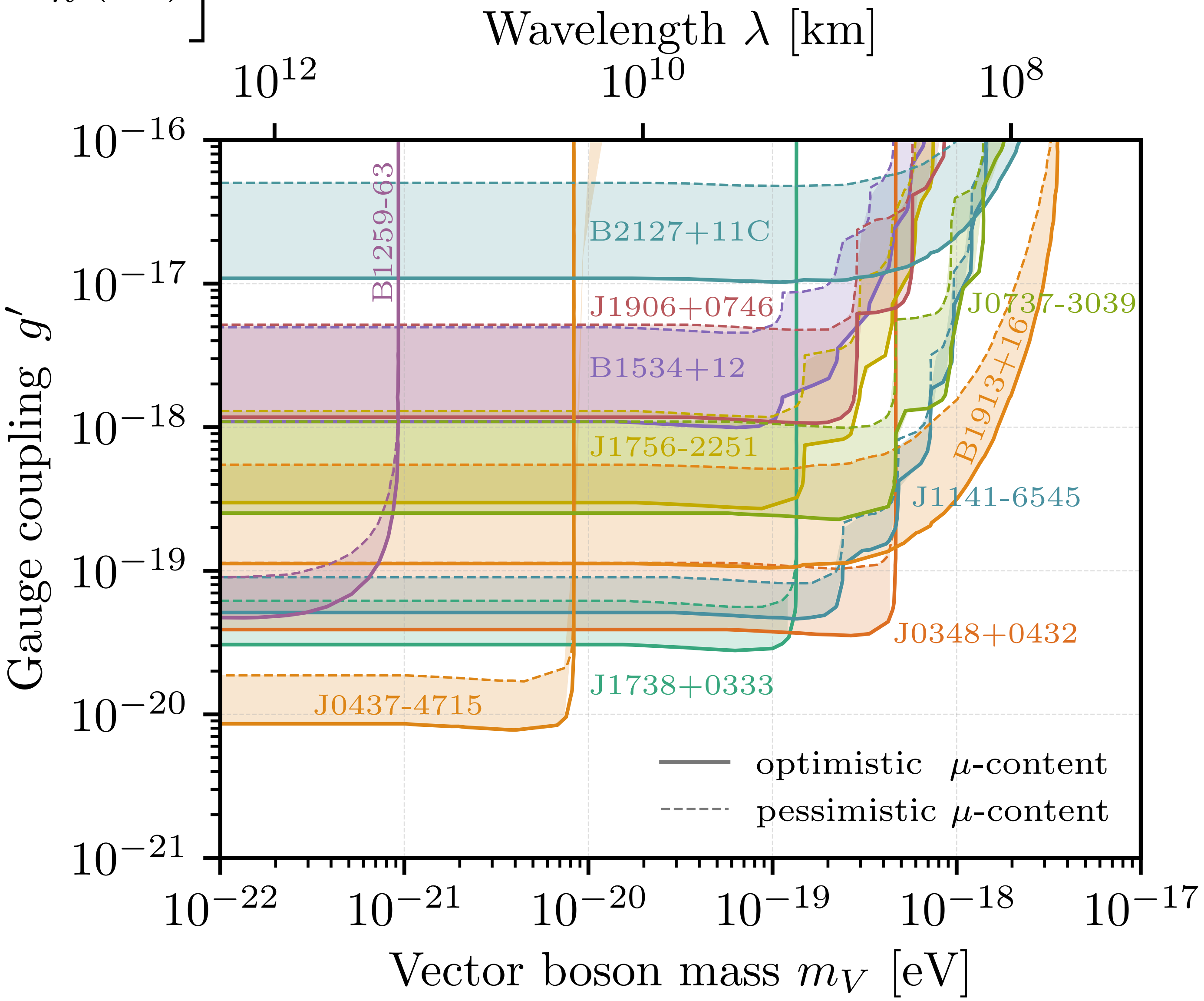
$$\frac{\langle \dot{E}_V \rangle}{\langle \dot{E}_{\rm GW} \rangle} = \frac{5\pi}{12}\gamma \frac{g_V(m_v,\epsilon)}{g_{\rm GR}(\epsilon)} \left(\frac{P_b}{2\pi G_N m}\right)^{2/3}$$

[Krause, Kloor, Fischbach PRD 1994]

$$g_V(m_V,\epsilon) \equiv \sum_{n>n_0} 2n^2 \left[\mathcal{J}_n'^{\,2}(n\epsilon) + \frac{1-\epsilon^2}{\epsilon^2}\mathcal{J}_n^2(n\epsilon)\right] \times \left\{\sqrt{1-\frac{n_0^2}{n^2}}\left(1+\frac{1}{2}\frac{n_0^2}{n^2}\right)\right\}$$

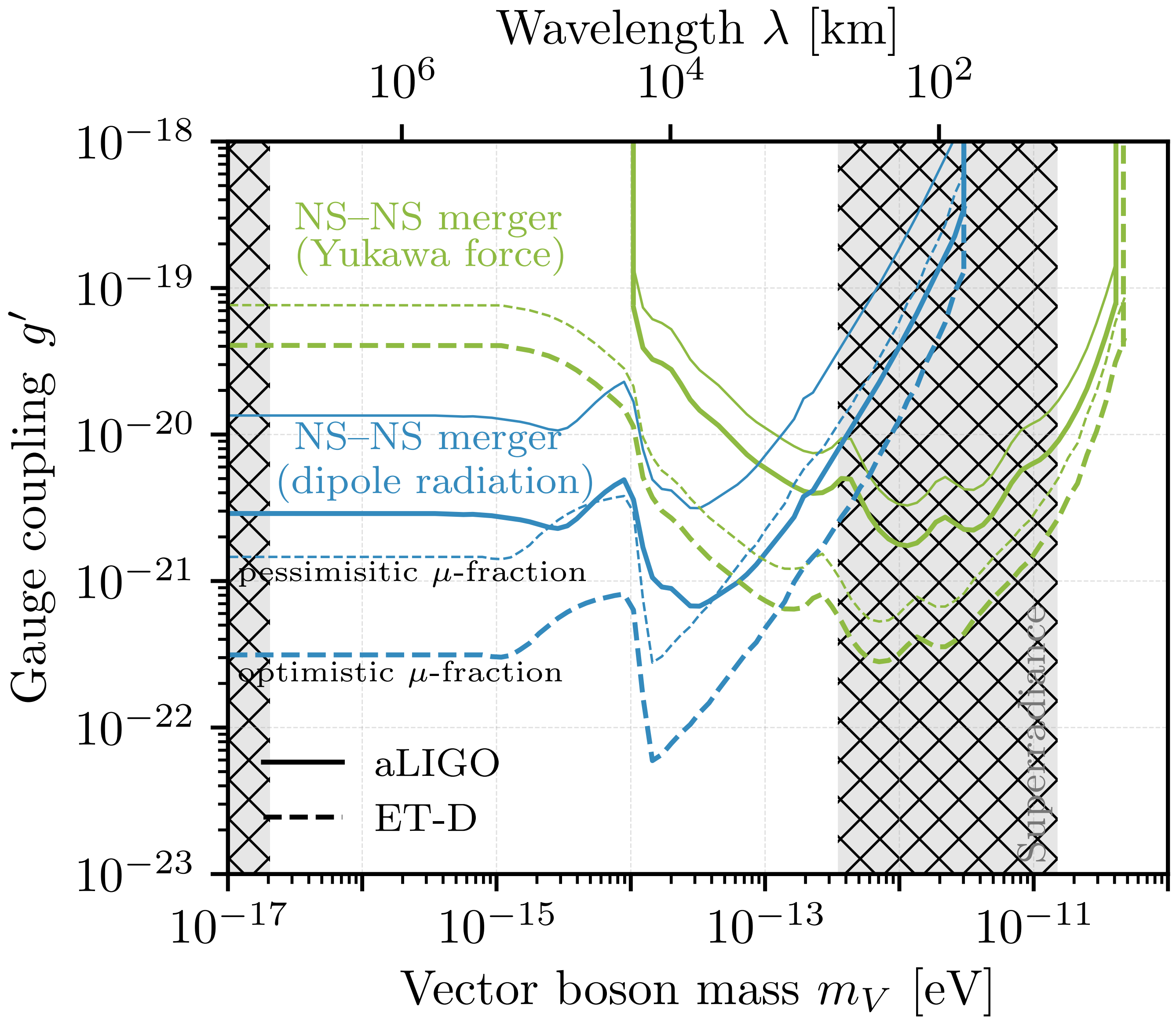
$$n_0 = \frac{m_V P_b}{2\pi}$$

Pulsar	P_b(day)	$\dot{P}_b^{\rm int}/\dot{P}_b^{\rm GR}$	ϵ	$M_1[M_\odot]$	$M_2[M_\odot]$
B1913+16(NS)	0.323	0.9983 ± 0.0016	0.617	1.438	1.390
J0737-3039(P)	0.102	1.003 ± 0.014	0.088	1.3381	1.2489
J0437-4715(WD)	5.74	1.0 ± 0.1	0.00	1.58	0.236
B1534+12(NS)	0.421	0.91 ± 0.06	0.274	1.3452	1.333
B1259-63(O)	1240	1.0 ± 0.5	0.870	1.4	20
J0348+0432(WD)	0.102	1.05 ± 0.18	0.00	2.01	0.172
J1141-6545(WD)	0.198	1.04 ± 0.06	0.172	1.27	1.02
J1738+0333(WD)	0.355	0.94 ± 0.13	0.00	1.46	0.19
J1756-2251(NS)	0.320	1.08 ± 0.03	0.181	1.341	1.230
J1906+0746(NS)	0.166	1.01 ± 0.05	0.085	1.291	1.322
B2127+11C(NS)	0.335	1.00 ± 0.03	0.681	1.358	1.354

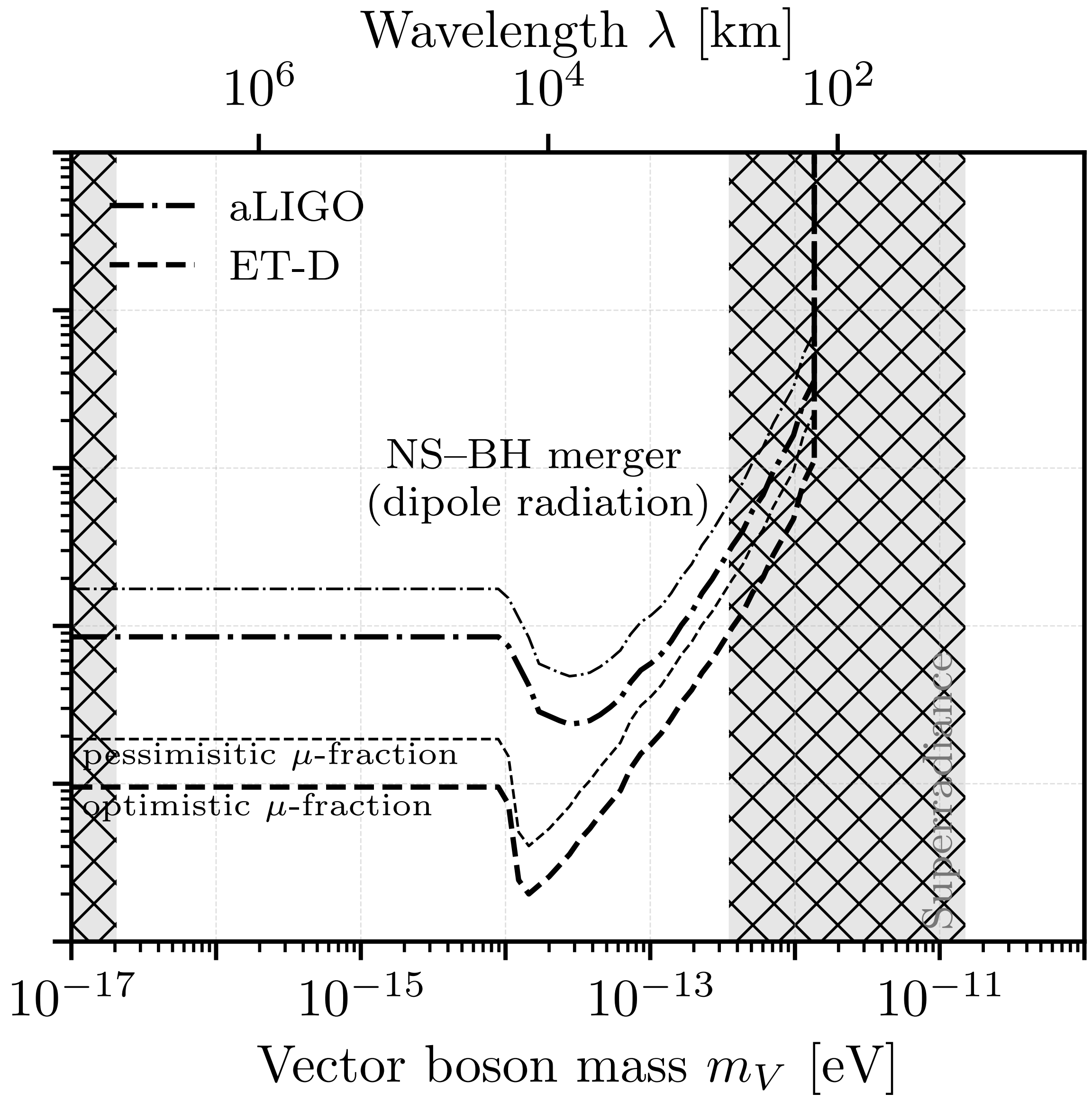


Future Constraints on Gauged $L_\mu - L_\tau$

NS–NS Mergers



NS–BH Mergers



[Dror, Laha, Opferkuch 1909.12845]

Parameters:

low spin $\quad m_1 = 1.46 M_\odot$

$D_{\text{eff}} = 40\,\text{Mpc} \quad m_2 = 1.27 M_\odot$

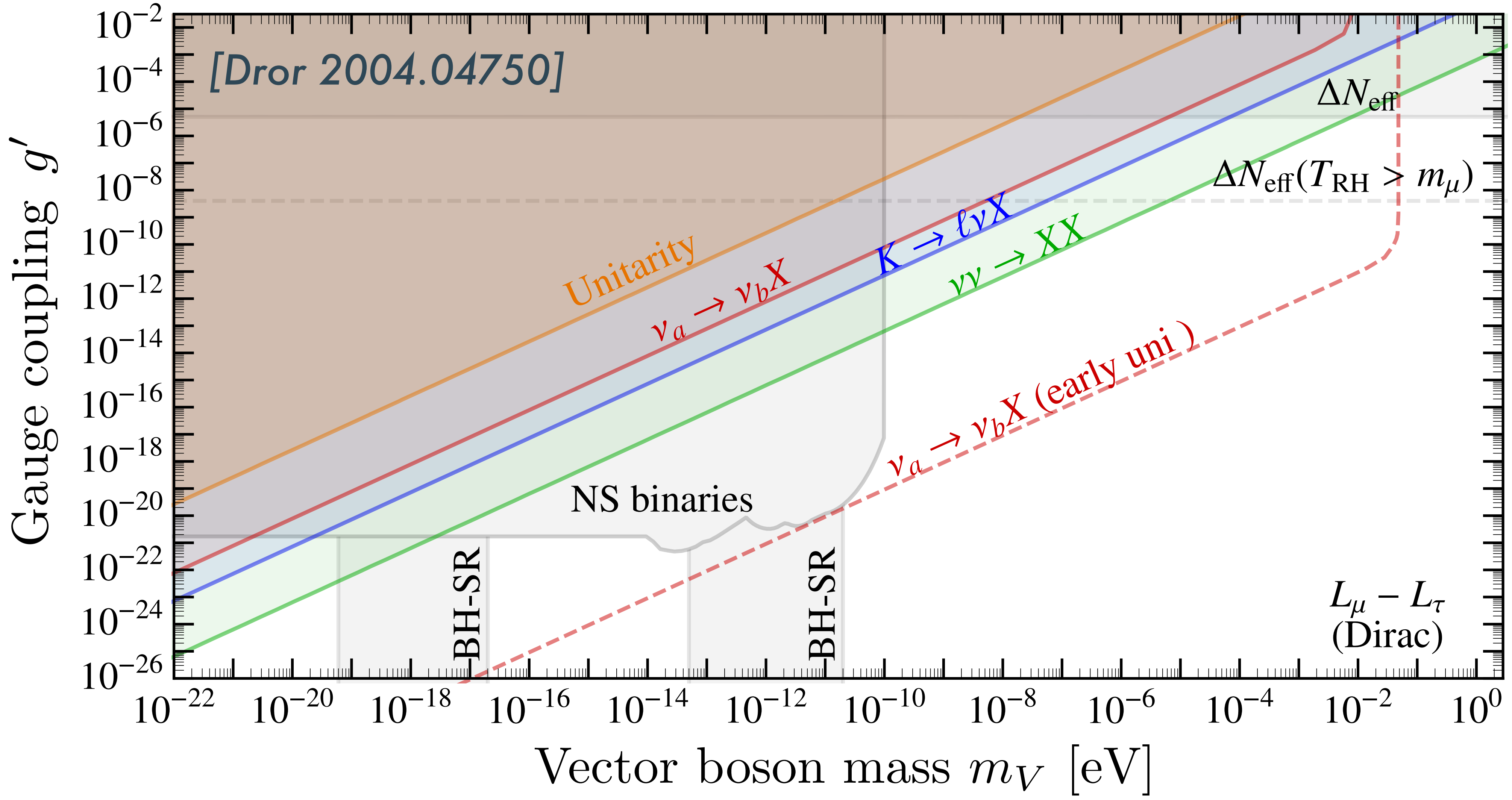
low spin $\quad m_1 = 1.46 M_\odot$

$D_{\text{eff}} = 40\,\text{Mpc} \quad m_2 = 5 M_\odot$

Constraints on Gauged $L_\mu - L_\tau$

- Energy enhanced processes below neutrino masses:

$$X_\mu \bar{\nu}\gamma^\mu \nu \to \frac{g_X m_\nu}{m_X} \varphi \bar{\nu}\nu$$



[Dror 2004.04750]

- Additional constraints in the mass-mixed case

[Heeck, Rodejohann 1007.2655]
[Davoudiasl, Lee, Marciano 1102.5352]

- Stringent $N_{\rm eff}$ constraints for $m_V > 1$ eV

[Kamada,Yu 1504.00711]
[Escudero, et. al 1901.02010]

Non-minimally Coupled Scalars

[L. H. Ford 87]

Energy-momentum tensor of a non-minimally coupled scalar contains additional pieces

$$T^{\phi}_{\mu\nu} = \partial_\mu\phi\partial_\nu\phi - g_{\mu\nu}\left(\frac{1}{2}g^{\rho\sigma}\partial_\rho\phi\partial_\sigma\phi - V(\phi)\right)$$

NMC pieces: $+\xi(G_{\mu\nu} + g_{\mu\nu}\nabla^\sigma\nabla_\sigma - \nabla_\mu\nabla_\nu)\phi^2$

Pressure and energy density for a perfect fluid become

$$\rho_\phi = \frac{1}{2}\dot{\phi}^2 + V(\phi) + \xi\left(3H^2\phi^2 + 6H\phi\dot{\phi}\right)$$

$$p_\phi = \frac{1}{2}\dot{\phi}^2 - V(\phi) + 3\xi\left[w + 2\xi(1-3w)\right]H^2\phi^2$$
$$+2\xi\left(V'\phi + H\phi\dot{\phi} - \dot{\phi}^2\right)$$

Using EoM and and neglecting bare potential:

$$w^{\rm init}_\phi = \frac{8\xi[\gamma + w(1+\gamma-6\xi) + 2\xi] - 3\gamma^2(4\xi-1)(1+w)^2}{8\xi + 3\gamma(1+w)(\gamma + w\gamma + 8\xi)}$$

Energy Extraction by the Reheaton

Energy-momentum tensor of a non-minimally coupled scalar contains additional pieces changing the initial EoS

$$w_\phi^{\text{init}}(w=1) = 1 - \sqrt{\frac{8\xi}{3}} \quad \xrightarrow{\xi \geq 3/2} \quad w_\phi^{\text{init}}(w=1) \leq -1$$

This tachyonic growth turned off when field is turned by the quartic

$$\begin{aligned}\Lambda \equiv \rho_\phi^1 &\overset{\dot\phi = 0}{=} \frac{\lambda}{4}\phi_1^4 + 3\xi H_1^2 \phi_1^2 \\ &\underset{H_1 \sim H_{\text{min}}}{\simeq} (1+w)(3w-1)\frac{27\xi^2}{4\lambda} H_{\text{min}}^4\end{aligned}$$

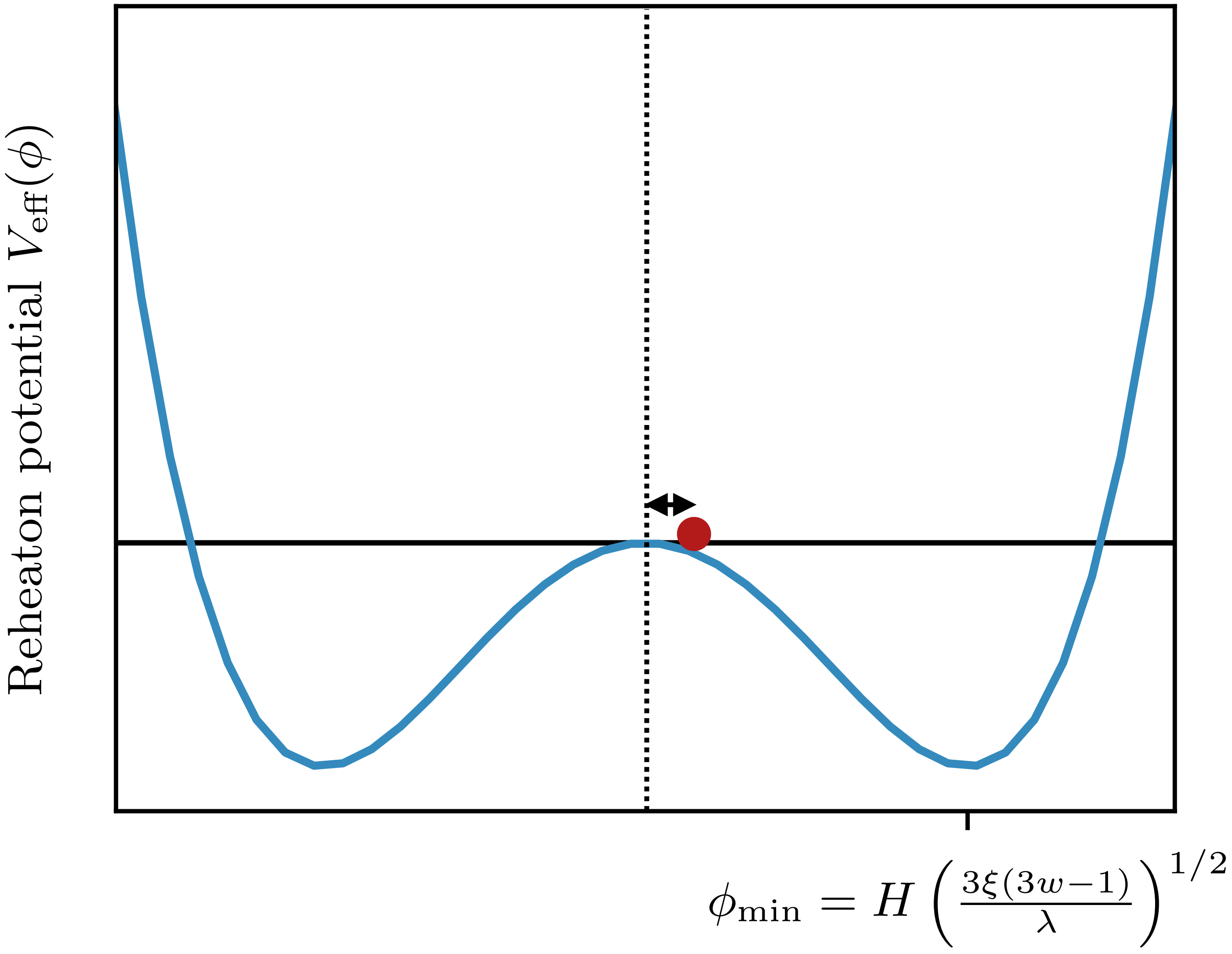
Reheaton Dynamics

Consider the evolution of the $k \leq a_* H_*$ modes of the reheaton:

1.) Fluctuations from inflation give an initial displacement and velocity

Integrate over $k \leq a_* H_*$

$$\langle \hat{\phi}_*^2 \rangle = \int_0^{a_* H_*} \frac{dk}{k} \mathcal{P}(k)$$



$$\phi_* = \sqrt{\langle \hat{\phi}_*^2 \rangle} \approx \frac{H_*}{2\pi} \sqrt{\frac{H_*}{3m_*}}$$

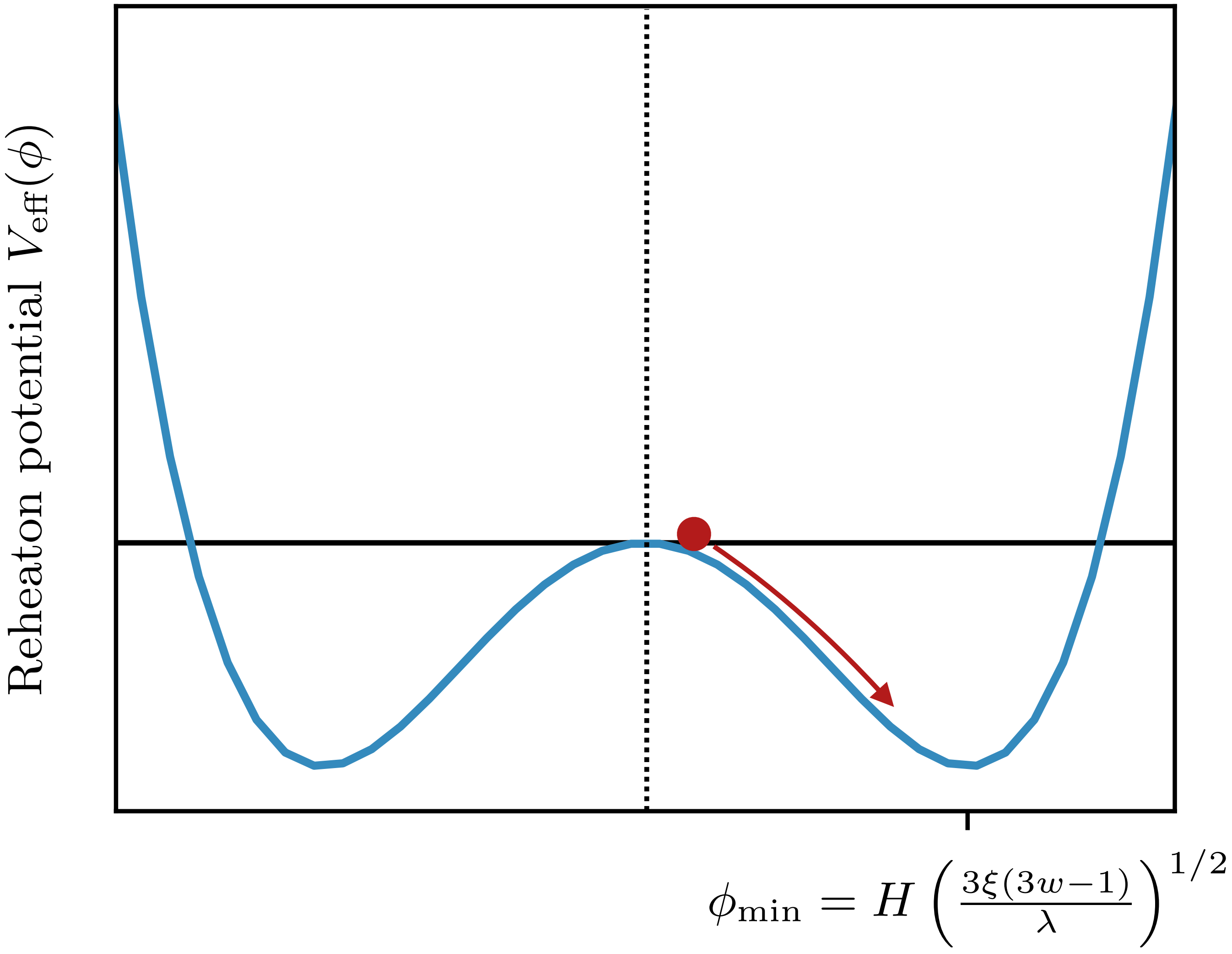
$$m_* = \sqrt{12\xi} H_*$$

$$\dot{\phi}_* = \sqrt{\langle \hat{\phi}_*'^2 \rangle} \approx m_* \phi_*$$

Reheaton Dynamics

Consider the evolution of the $k \leq a_* H_*$ modes of the reheaton:

2.) Field begins to roll off local maximum



Reheaton equation of motion

$$\ddot{\phi} + 3H\dot{\phi} - \xi R \phi \approx 0$$

with solution

$$\phi(t) \approx \frac{\phi_*}{2}\left(1 + \frac{\gamma_*}{\gamma}\right)\left(\frac{H_*}{H}\right)^{\gamma}$$

where

$$\gamma \equiv \sqrt{\xi(3w-1)/3}, \gamma_* \approx \sqrt{12\xi}/3$$

ξ controls how fast field rolls

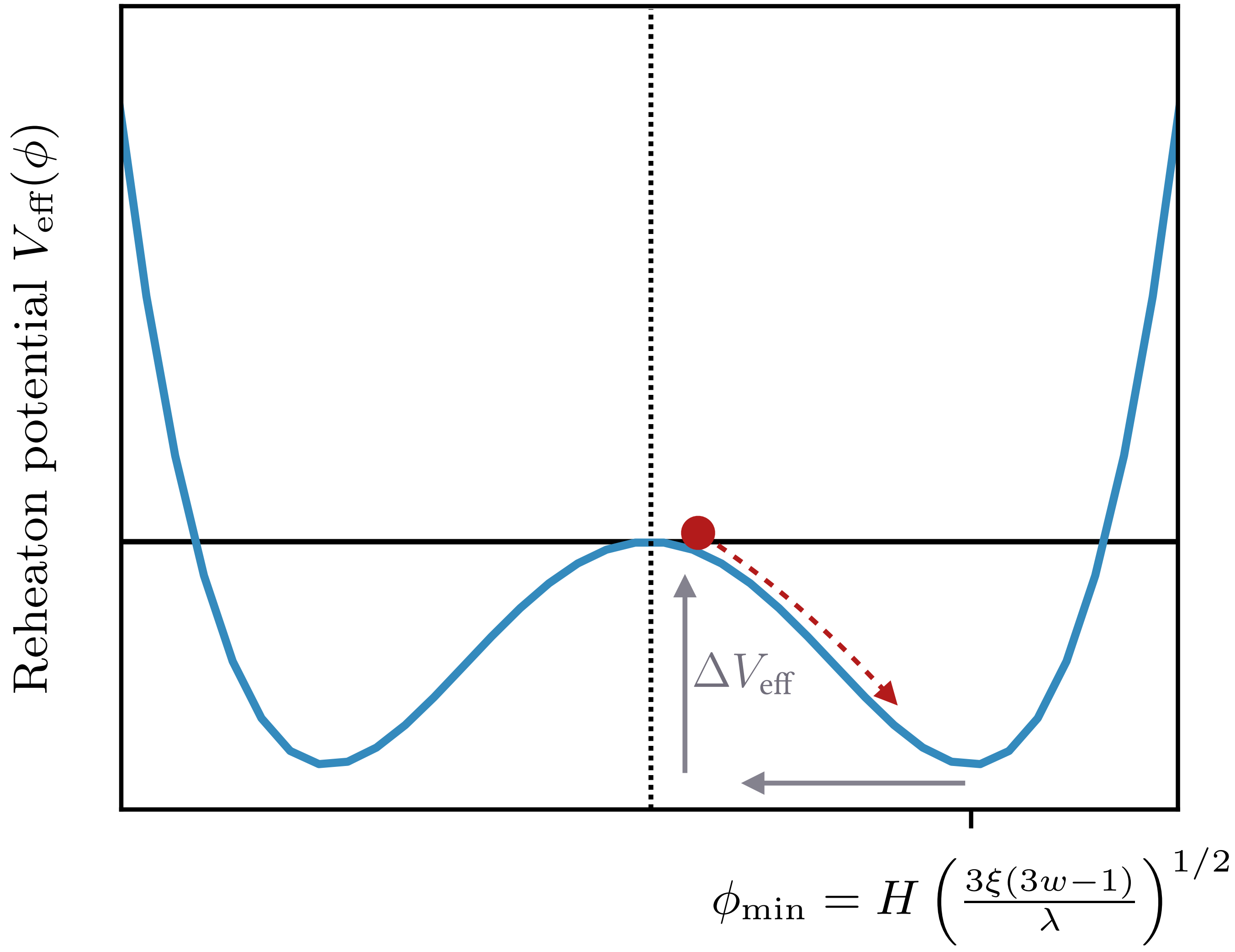
$$\phi(t) \propto H^{-\sqrt{\xi}}$$

Remember H is monotonically decreasing!

Reheaton Dynamics

Consider the evolution of the $k \leq a_* H_*$ modes of the reheaton:

3.) Potential also changes strongly as a function of time (Hubble)



Potential hill decreases as

$$\Delta V_{\text{eff}} = -\frac{9\xi^2}{4\lambda}(3w-1)^2 H^4$$

Field rolls faster to the minimum than the minimum approaches the field if

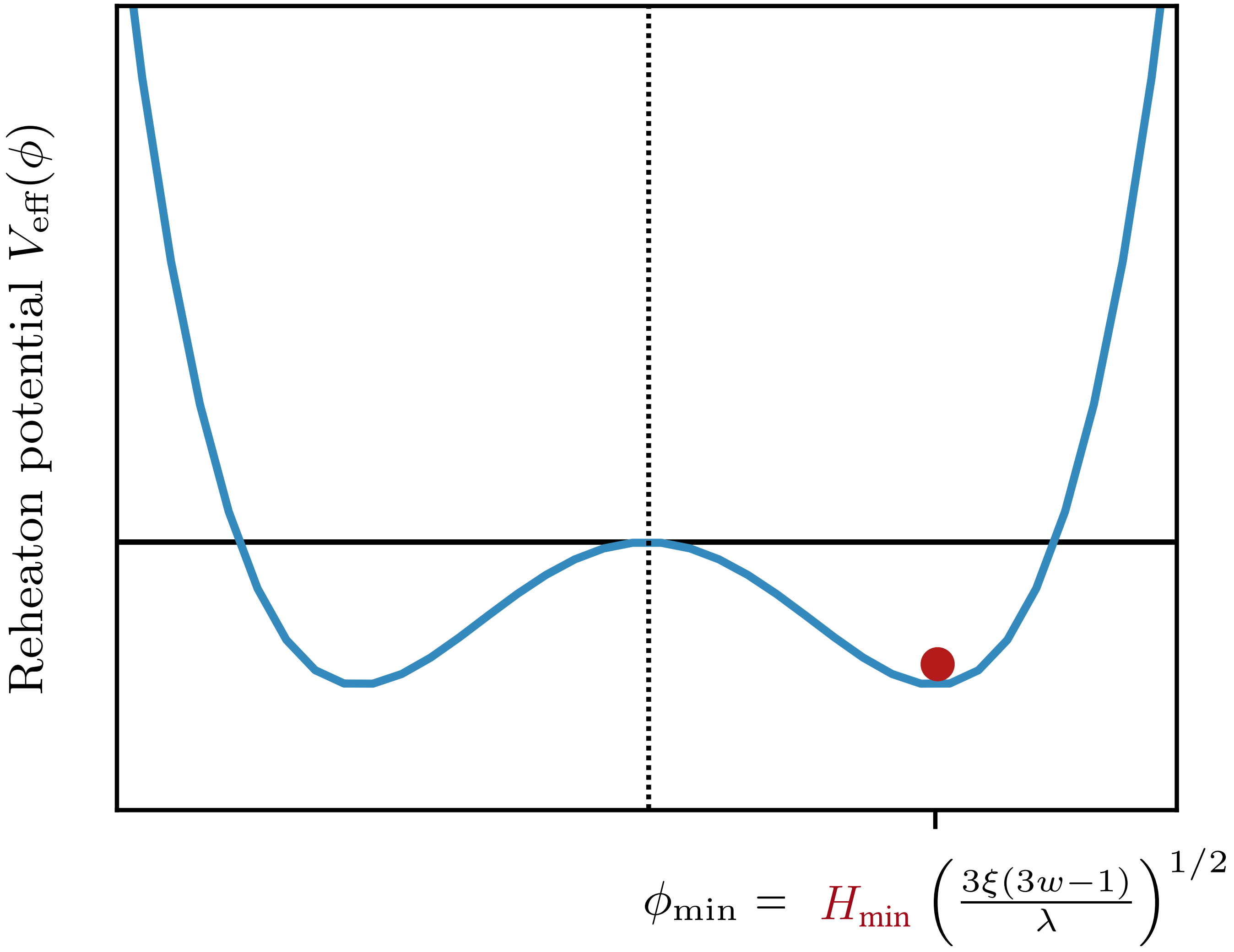
$$\xi > \frac{1}{w - 1/3}$$

Important consequences for energy extraction

Reheaton Dynamics

Consider the evolution of the $k \leq a_* H_*$ modes of the reheaton:

4.) Field reaches the minimum



Solving

$$\phi_{\rm min} = H \left(\frac{3\xi(3w-1)}{\lambda}\right)^{1/2} \overset{!}{=} \phi(t)$$

The Hubble time to the minimum is:

$$\left(\frac{H_{\rm min}}{H_*}\right)^{1+\gamma} \propto \sqrt{\lambda/\xi^{3/2}}$$

$$H_{\rm min} \sim 10^{-2} H_*$$

For $\xi, w \sim \mathcal{O}(1)$
and $10^{-5} \lesssim \lambda \lesssim 10^{-2}$

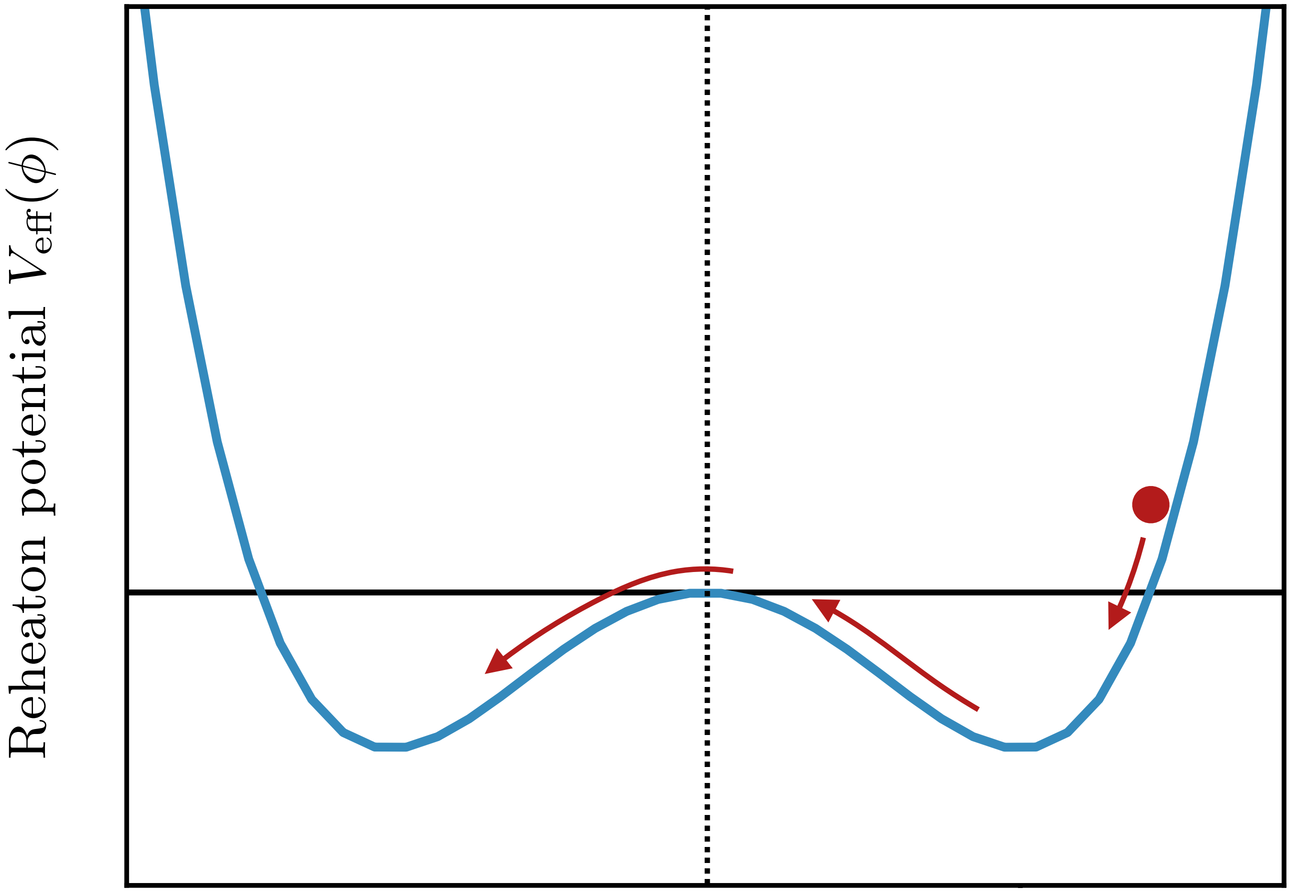
and

$\Delta V_{\rm eff}$ reduced by a factor 10^8

Reheaton Dynamics

Consider the evolution of the $k \leq a_* H_*$ modes of the reheaton:

5.) Field is turned by the quartic coupling



Potential hill decreases by the time the field reaches it again

$\longrightarrow$ oscillates around the quartic

$\longrightarrow$ $\langle w_\phi \rangle = 1/3$ (radiation)

Rad. scaling continues until:

- Bare mass becomes relevant
- Reheaton decays

Tracking the EoS scaling important for GW signal

Energy Extraction by the Reheaton

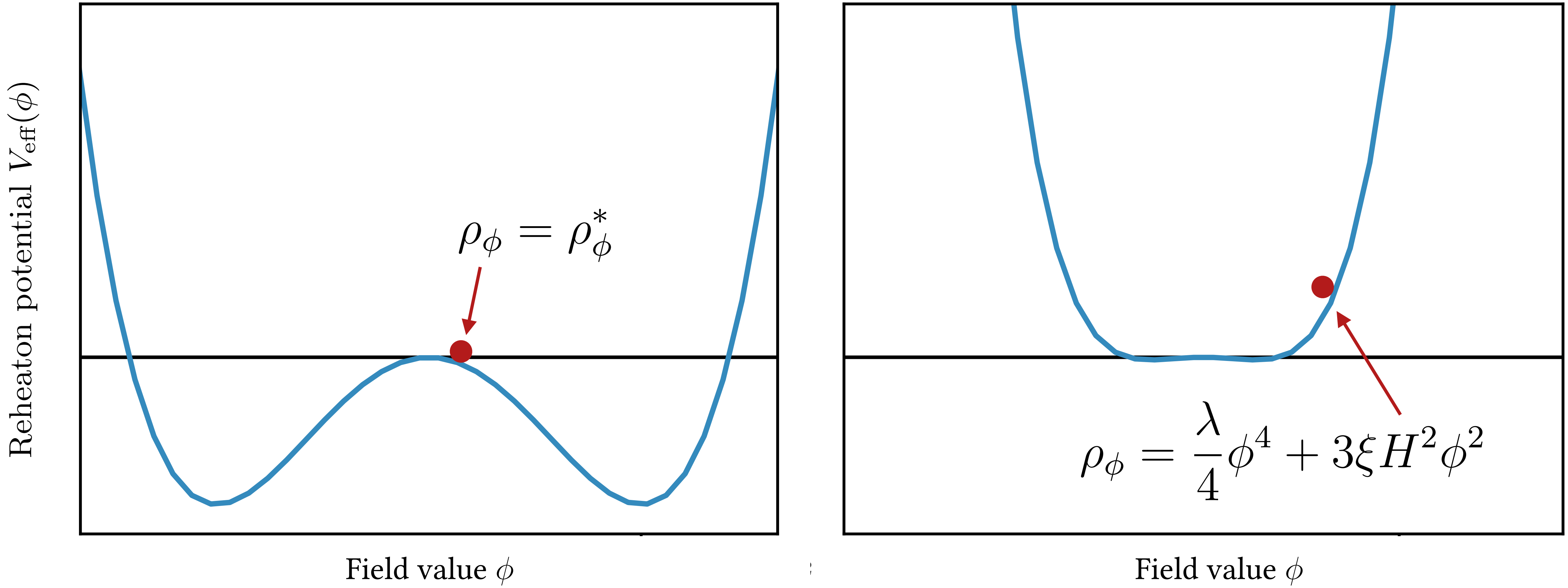
Significant growth in energy density through displacing the field

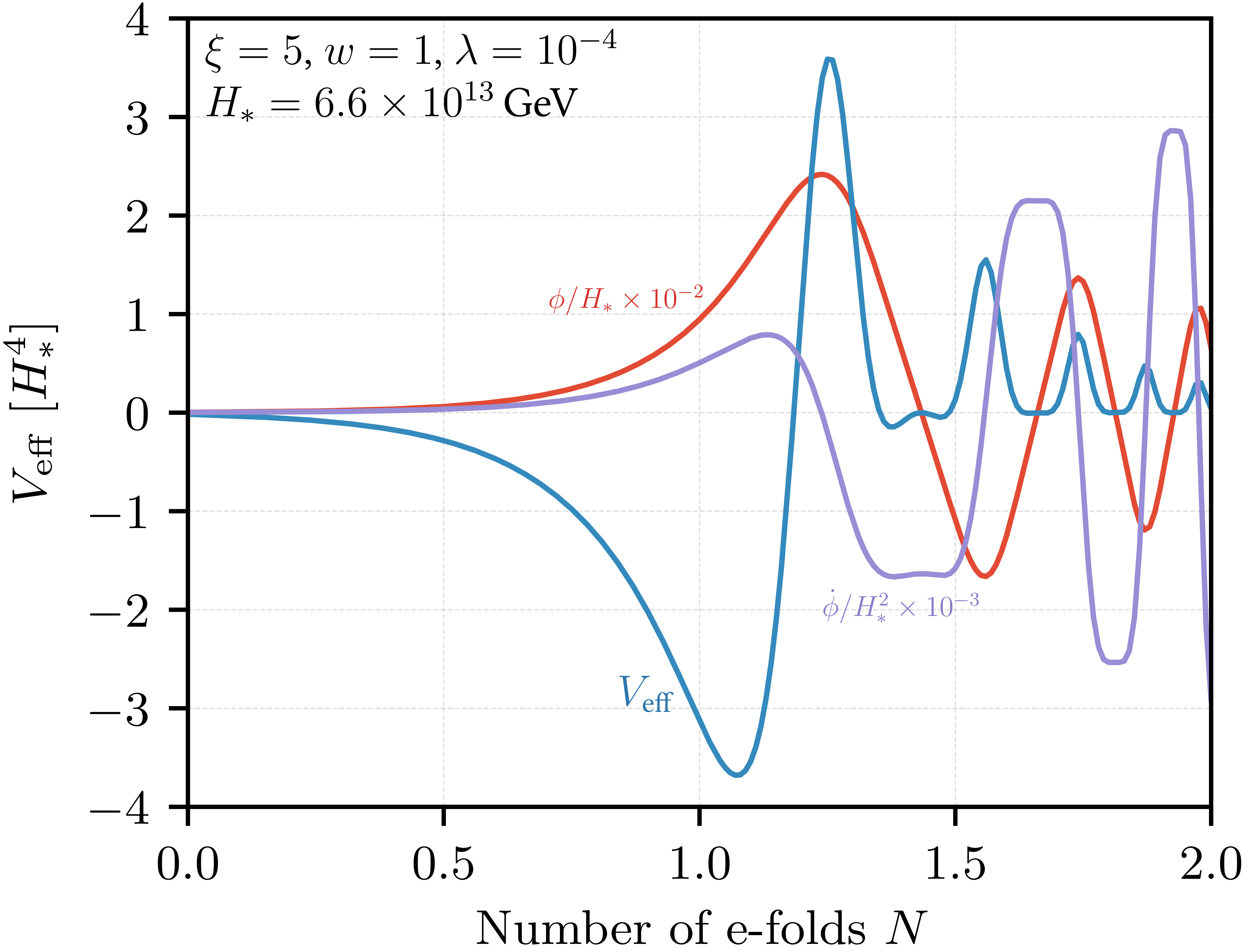
Large ξ gives large field displacements

Alternatively

$$\ddot{\phi} + 3H\dot{\phi} + V'(\phi) \simeq \underbrace{\xi(3w-1)\frac{\rho_{\rm inf}}{M_P^2}\phi}$$

Inflaton energy density acts as a source for the reheaton




$\xi = 5, w = 1, \lambda = 10^{-4}$
$H_* = 6.6 \times 10^{13}$ GeV
$\phi/H_* \times 10^{-2}$
$\dot{\phi}/H_*^2 \times 10^{-3}$
$V_{\rm eff}$
$V_{\rm eff}\ [H_*^4]$
4
3
2
1
0
−1
−2
−3
−4
0.0
0.5
1.0
1.5
2.0
Number of e-folds N

Reheating Constraints

Two options:

- Reheating ***after*** reheaton-kination equality

$$T_{\rm RH} = \left(\frac{90}{\pi^2 g_{\rm RH}}\right)^{1/4} \sqrt{\Gamma M_P}$$

Reheaton decay width determines reheating (exactly the same as textbook reheating case)

- Reheating ***at*** reheaton-kination equality

$$T_{\rm RH} = \left(\frac{45}{\pi^2 g_{\rm RH}}\right)^{\frac{1}{4}} \sqrt{H_{\rm ke} M_P}$$

Hubble at reheaton-kination equality

For remainder of this talk: consider this case ***with only radiation scaling*** ($m^2 \ll H_*^2$)

Inflationary GW Background

[Review: C. Caprini and D. Figueroa 1801.04268]

Unavoidable stochastic background produced during de-Sitter period

$$\rho_{\mathrm{GW}} = T^{00}_{\mathrm{GW}} = \frac{\langle \dot{h}_{ij}(\boldsymbol{x},t)\dot{h}_{ij}(\boldsymbol{x},t)\rangle}{32\pi G_N}$$

For a Fourier transformed, statistically homogeneous, isotropic and unpolarised GW background

$$\langle h'_r(\boldsymbol{k},\tau)h'^*_p(\boldsymbol{q},\tau)\rangle = \frac{8\pi^5}{k^3}\delta^{(3)}(\boldsymbol{k}-\boldsymbol{q})\delta_{rp}\mathcal{P}(k)$$

Power spectrum is flat for perfect de-Sitter*

$$\boxed{\mathcal{P}(k) \simeq \frac{2}{\pi}\frac{H_*^2}{M_P^2}}$$

*Deviations from perfect de-Sitter during inflation lead to the observed spectral tilt in the CMB

Observable is the energy density fraction redshifted to today

$$\Omega^0_{\mathrm{GW}}(k) \equiv \frac{1}{\rho_c}\frac{d\rho_{\mathrm{GW}}}{d\log k} \simeq \frac{k^2}{12H_0^2a_0^2}T^2(k,k_0)\mathcal{P}(k)$$

Transfer function (redshifting & boundary matching)

N_{eff} and Planck

GWs inside the horizon contribute to number of relativistic DOFs

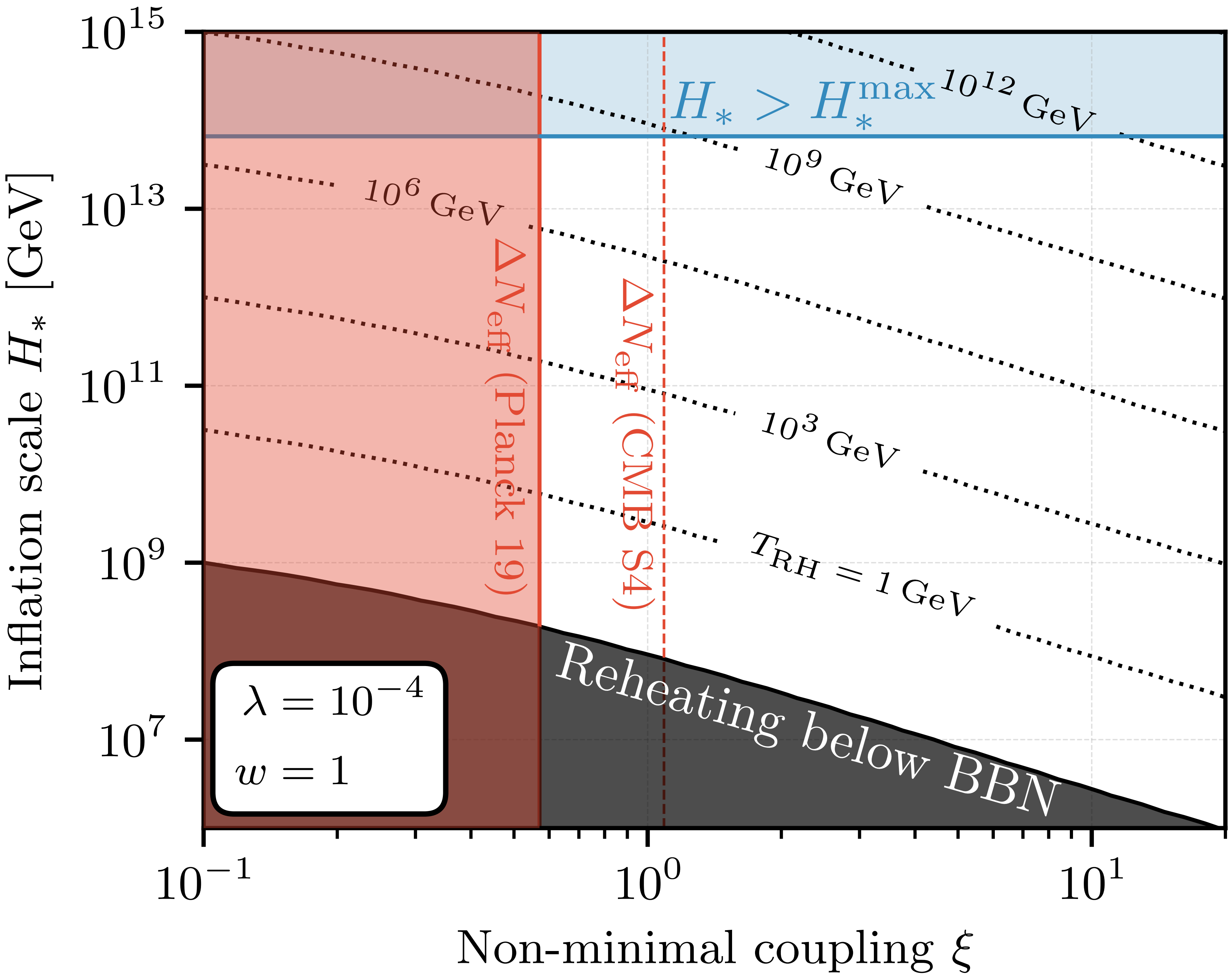
$$\Delta N_{\text{eff}} = \frac{8}{7}\left(\frac{11}{4}\right)^{\frac{4}{3}} \frac{\Omega^0_{\text{GW}}}{\Omega^0_\gamma} \qquad \text{with} \qquad \Omega^0_{\text{GW}} = \int \frac{df}{f}\Omega^0_{\text{GW}}(f)$$

*N_{eff} is sensitive to total energy density not just at a particular frequency

$\Delta N_{\text{eff}} < 0.284$ at 95% C.L. (TT,TE,EE+lowE+lensing+BAO)

[Planck 2018]

Detectability



Caveat:

Reducing λ further increases $T_{\rm RH}$

But $\phi_{\rm min} \simeq M_P$

$\Longrightarrow \lambda \geq 3 \times 10^{-12}$

$\Longrightarrow T_{\rm RH} \leq 6 \times 10^{15}$ GeV

$\xi = 4\pi$, $w = 1$, $H_* = 6.6 \times 10^{13}$ GeV