Stochastic Gravitational Wave Background

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Based on arXiv:1810.11000,
with Rong-gen Cai and Misao Sasaki

Content

- Mechanism of SGWB
- PBH abundances and GWs
- Induced GWs: A probe for non-Gaussianity
- Conclusion

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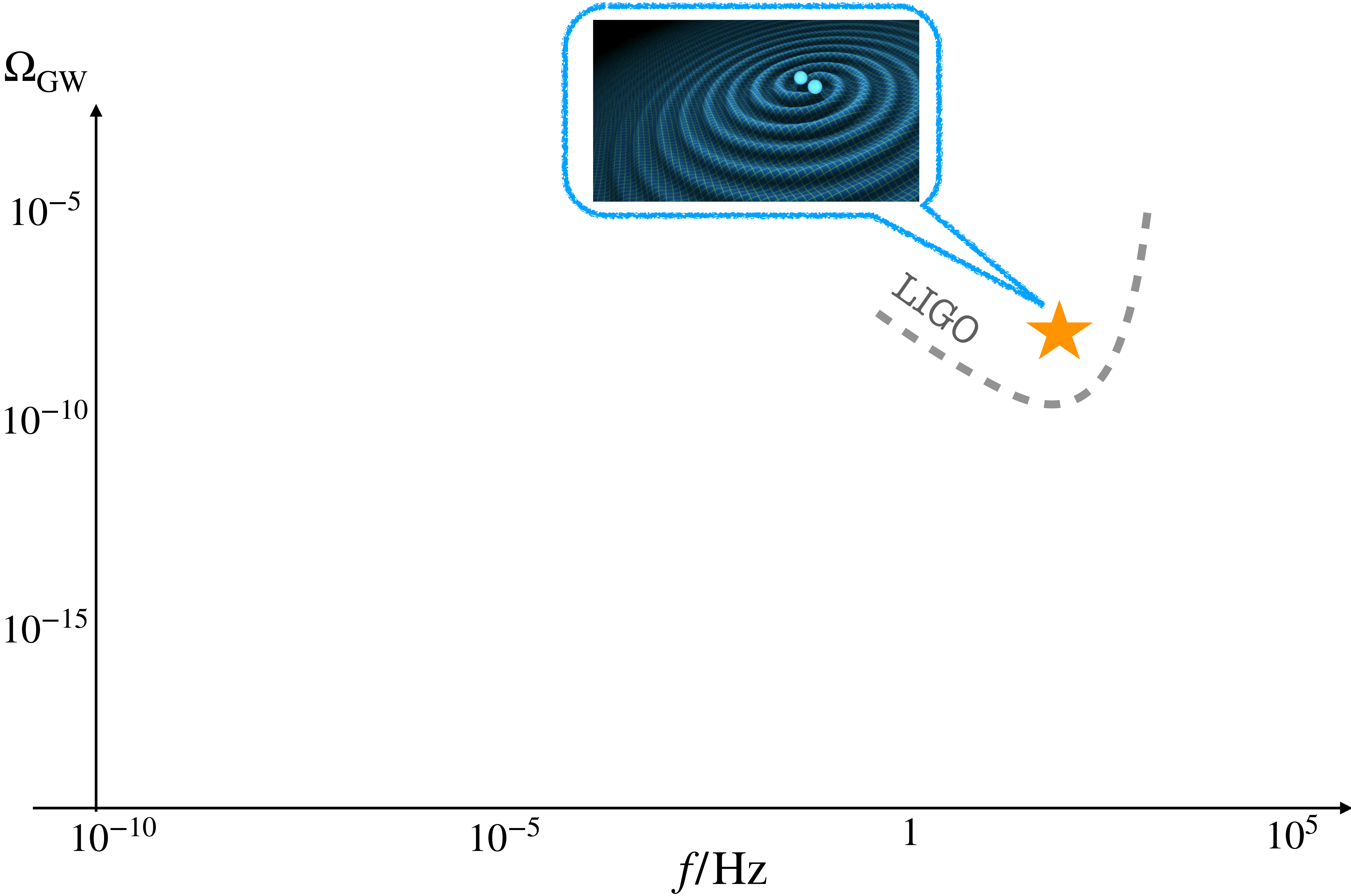
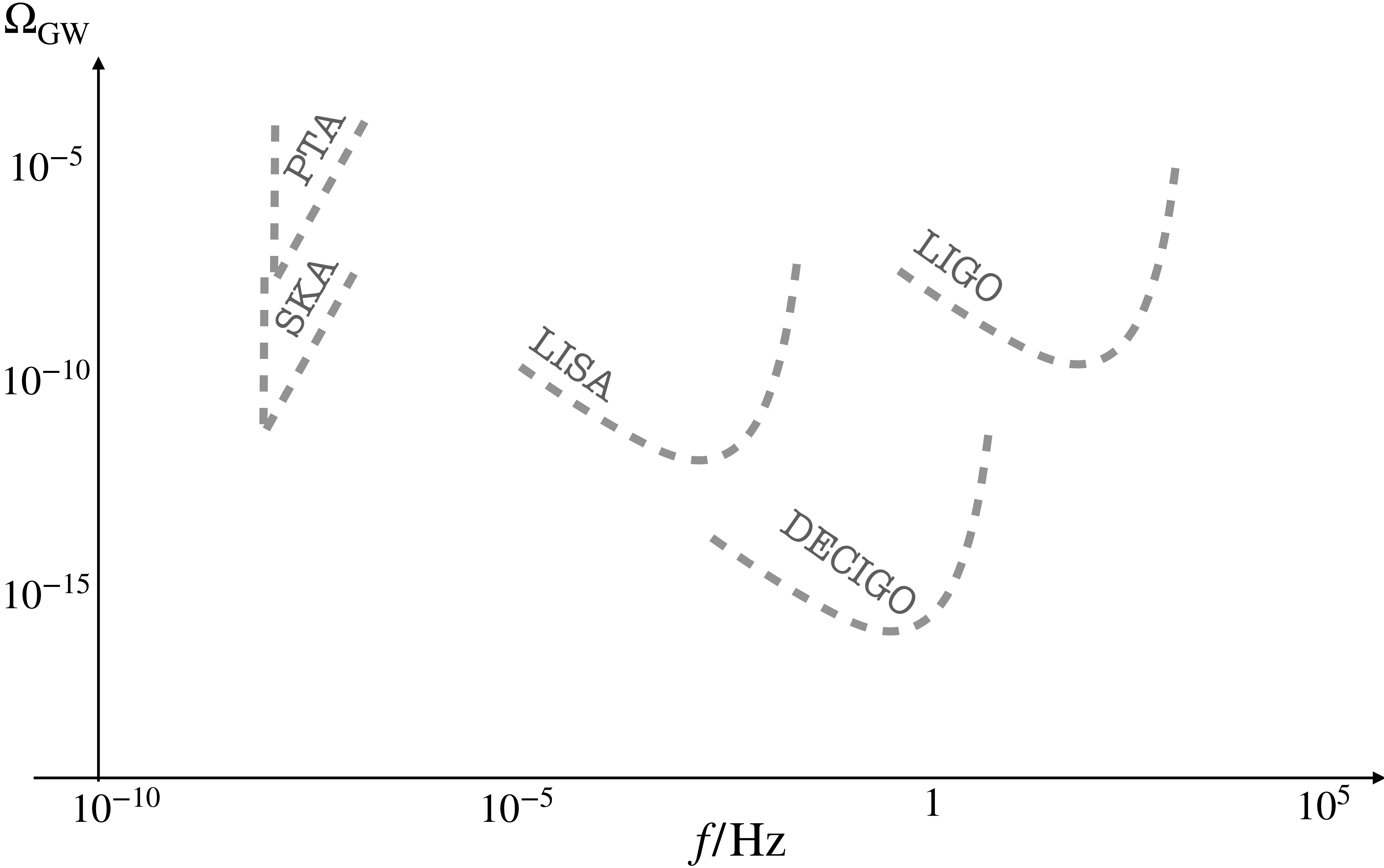
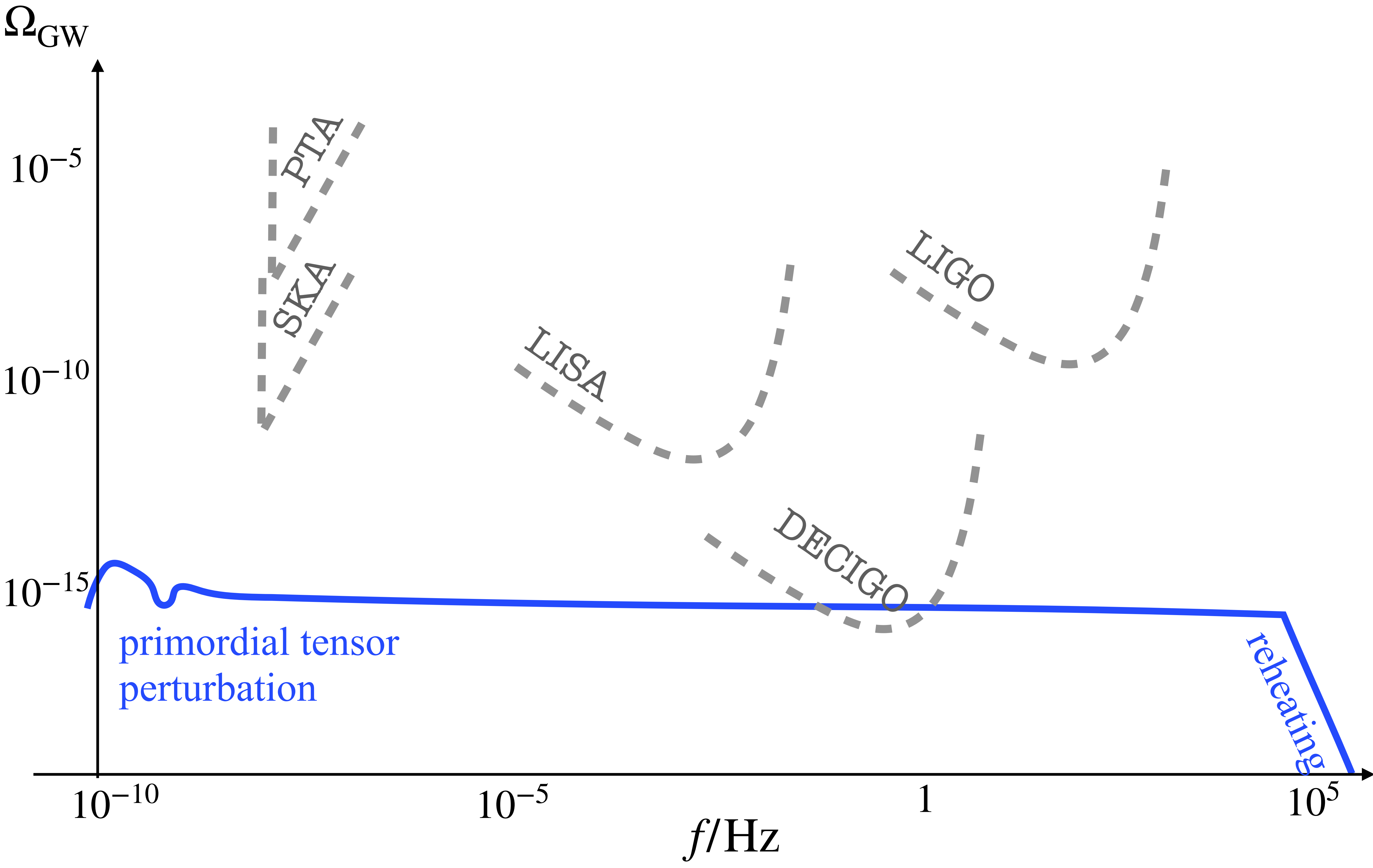
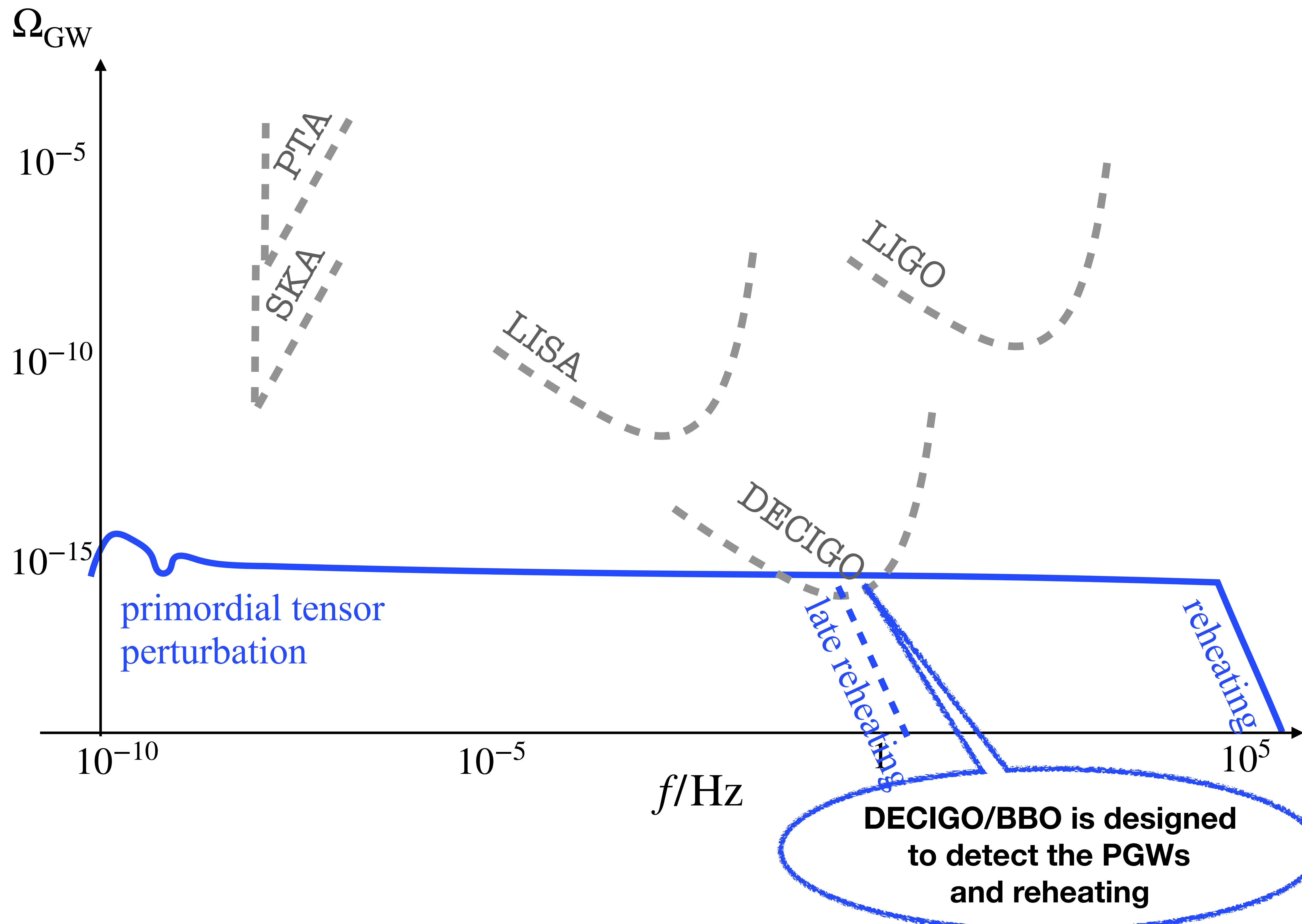

Ω_{GW}
10^{-5}
10^{-10}
10^{-15}
LIGO
10^{-10}
10^{-5}
1
10^{5}
f/Hz

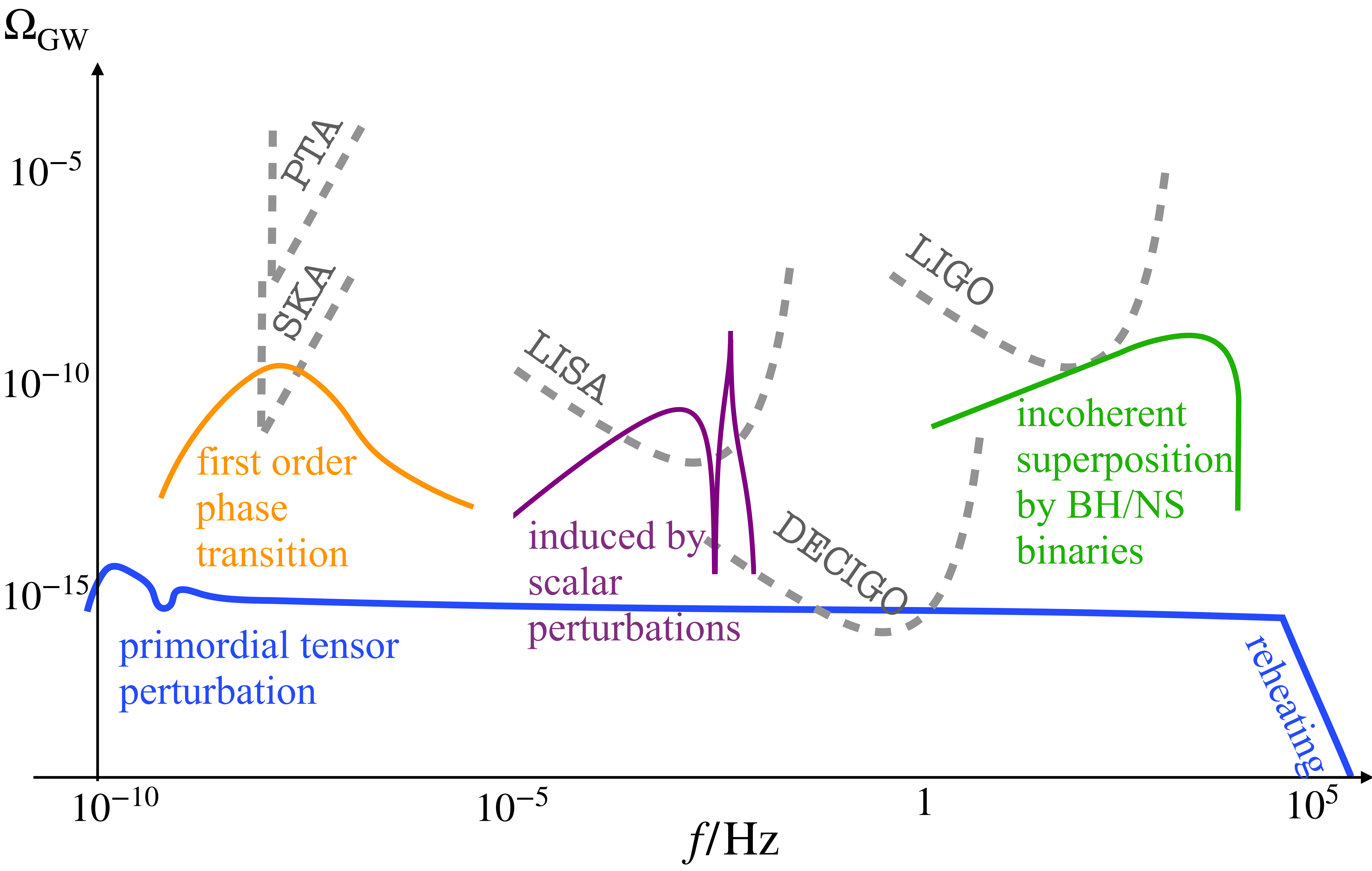


$\Omega_{\rm GW}$
10^{-5}
10^{-10}
10^{-15}
PTA
SKA
LISA
LIGO
DECIGO
10^{-10}
10^{-5}
1
10^{5}
f/Hz

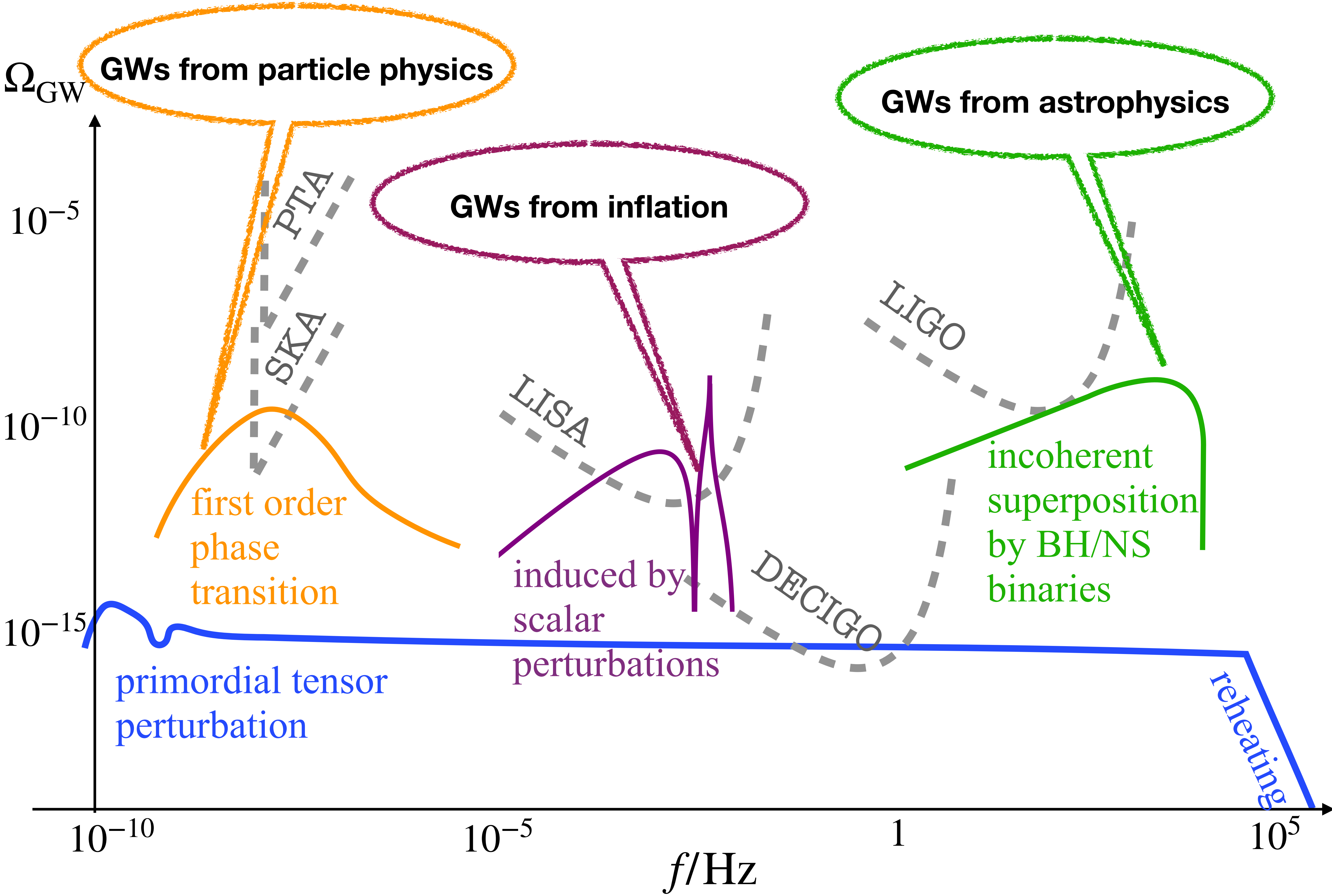

Ω_{GW}
10^{-5}
10^{-10}
10^{-15}
PTA
SKA
LISA
LIGO
DECIGO
primordial tensor
perturbation
reheating
10^{-10}
10^{-5}
1
10^{5}
f/Hz



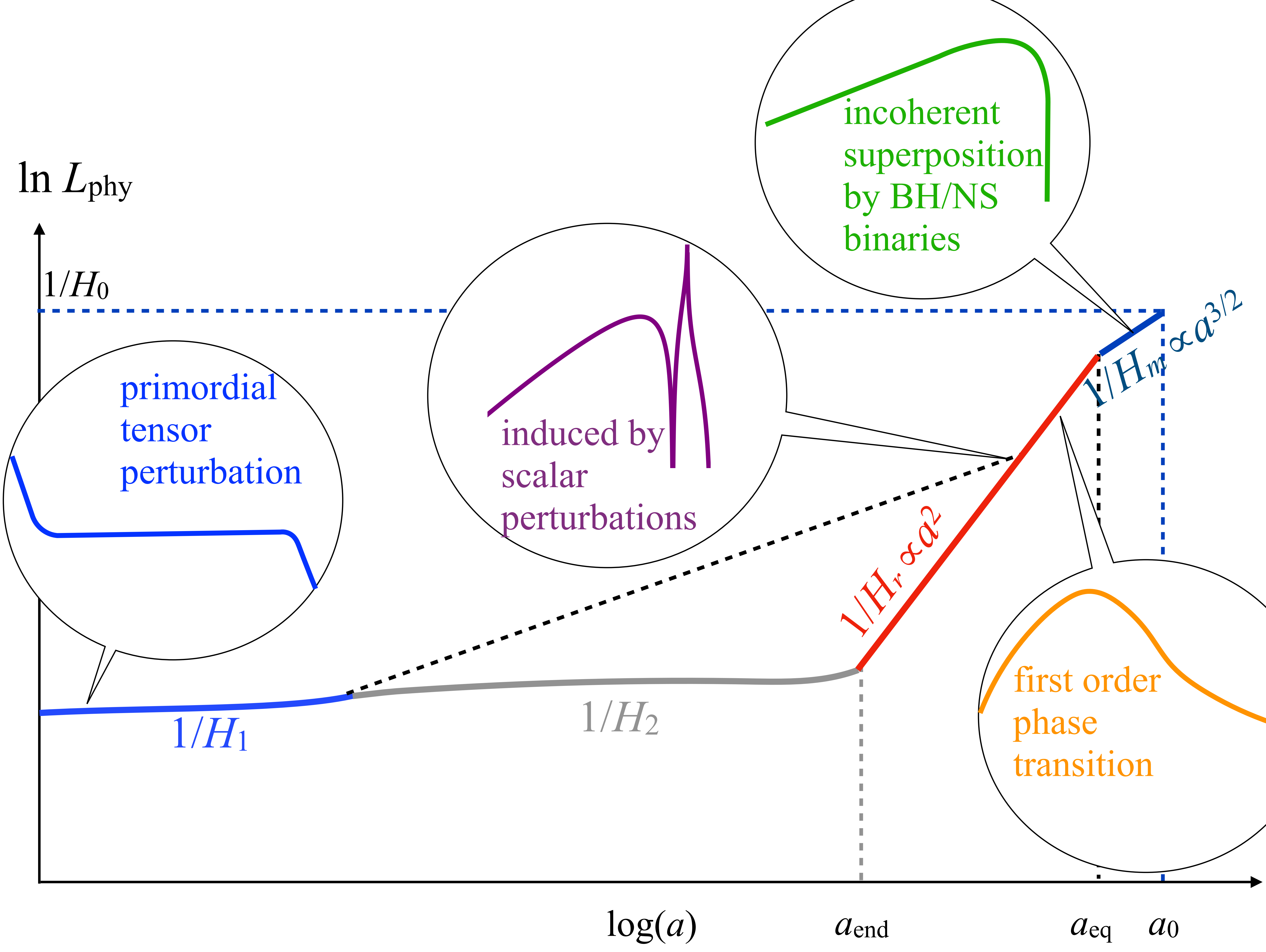
Ω_{GW}
10^{-5}
10^{-10}
10^{-15}
PTA
SKA
LISA
LIGO
DECIGO
primordial tensor perturbation
late reheating
reheating
10^{-10}
10^{-5}
1
10^{5}
f/Hz
DECIGO/BBO is designed to detect the PGWs and reheating



Ω_{GW}
10^{-5}
10^{-10}
10^{-15}
PTA
SKA
LISA
LIGO
DECIGO
first order
phase
transition
induced by
scalar
perturbations
incoherent
superposition
by BH/NS
binaries
primordial tensor
perturbation
reheating
10^{-10}
10^{-5}
1
10^{5}
f/Hz



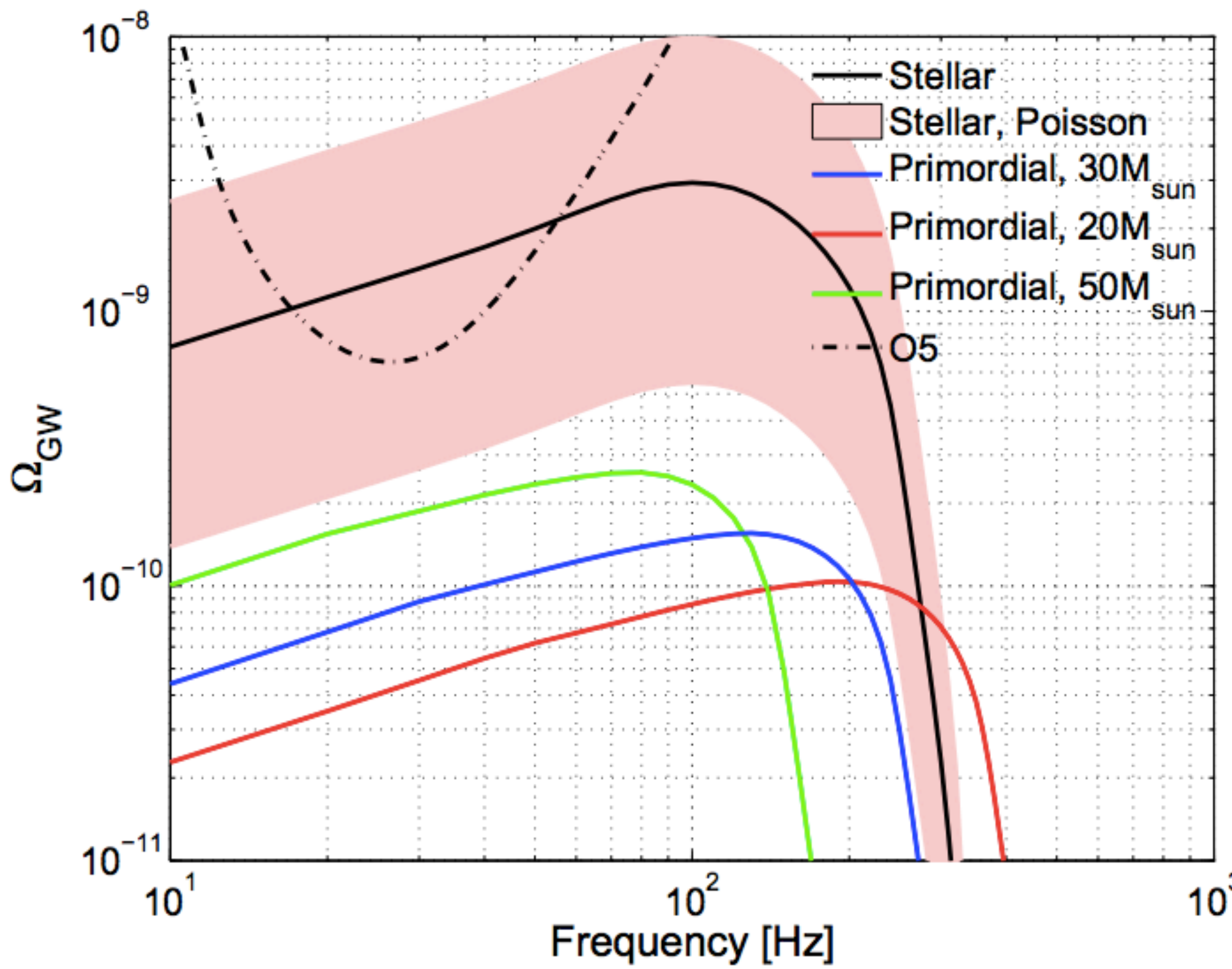
Ω_{GW}
GWs from particle physics
GWs from inflation
GWs from astrophysics
10^{-5}
10^{-10}
10^{-15}
PTA
SKA
LISA
LIGO
DECIGO
first order phase transition
induced by scalar perturbations
incoherent superposition by BH/NS binaries
primordial tensor perturbation
reheating
10^{-10}
10^{-5}
1
10^{5}
f/Hz



ln $L_{\rm phy}$
$1/H_0$
primordial tensor perturbation
induced by scalar perturbations
incoherent superposition by BH/NS binaries
$1/H_m \propto a^{3/2}$
$1/H_r \propto a^2$
first order phase transition
$1/H_1$
$1/H_2$
log(a)
$a_{\rm end}$
$a_{\rm eq}$
a_0

SGWB from binaries

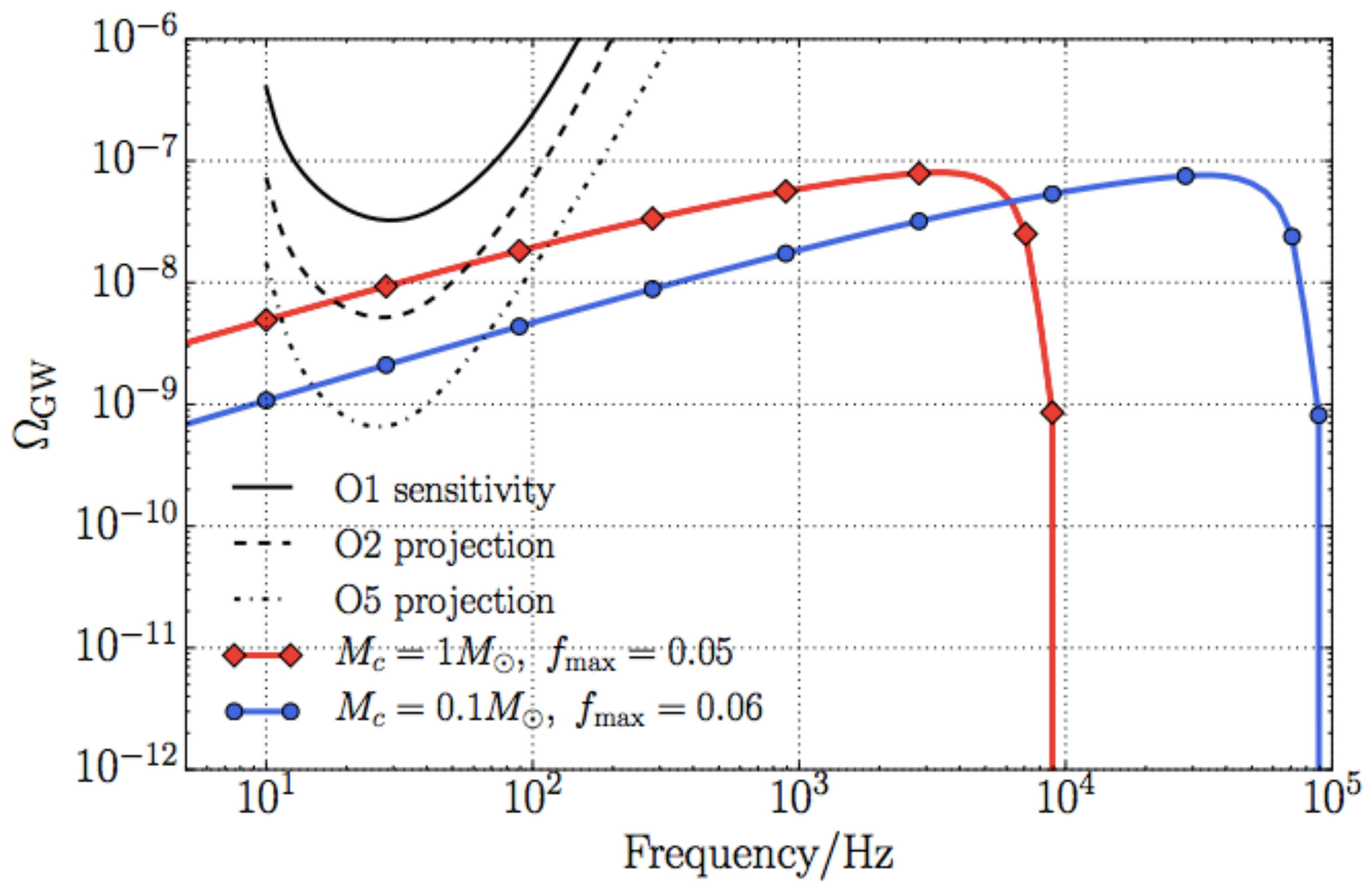
- Origin: incoherent superposition of the GWs emitted by compact star binarys (BH, NS,…)
- Frequencies: 100 Hz(for $10M_\odot$)
- Amplitude: 10^{-9}



1608.06699

SGWB from PBHB

- PBH binaries
- Frequency: 1000Hz (for $1M_\odot$)
- Amplitude: 10^{-9}
- Can be used to constrain PBH abundances



1610.08725

SGWB from 1OPT

- 1st order phase transition
- EW (extended) or beyond
- Dynamics: Bubble nucleation and collision, turbulence, sound waves, ….
- Parameters: α (latent heat) and 1/β (duration of the phase transition)

$$f_{\rm peak} \simeq 10^{-6}{\rm Hz}\left(\frac{\beta}{H_*}\right)\left(\frac{T_*}{100{\rm GeV}}\right)\left(\frac{g_*}{100}\right)^{1/6}$$

$$\Omega_{\rm peak}h^2 \simeq 10^{-4}\left(\frac{\beta}{H_*}\right)^{-2}\left(\frac{g_*}{100}\right)^{-1/3}$$

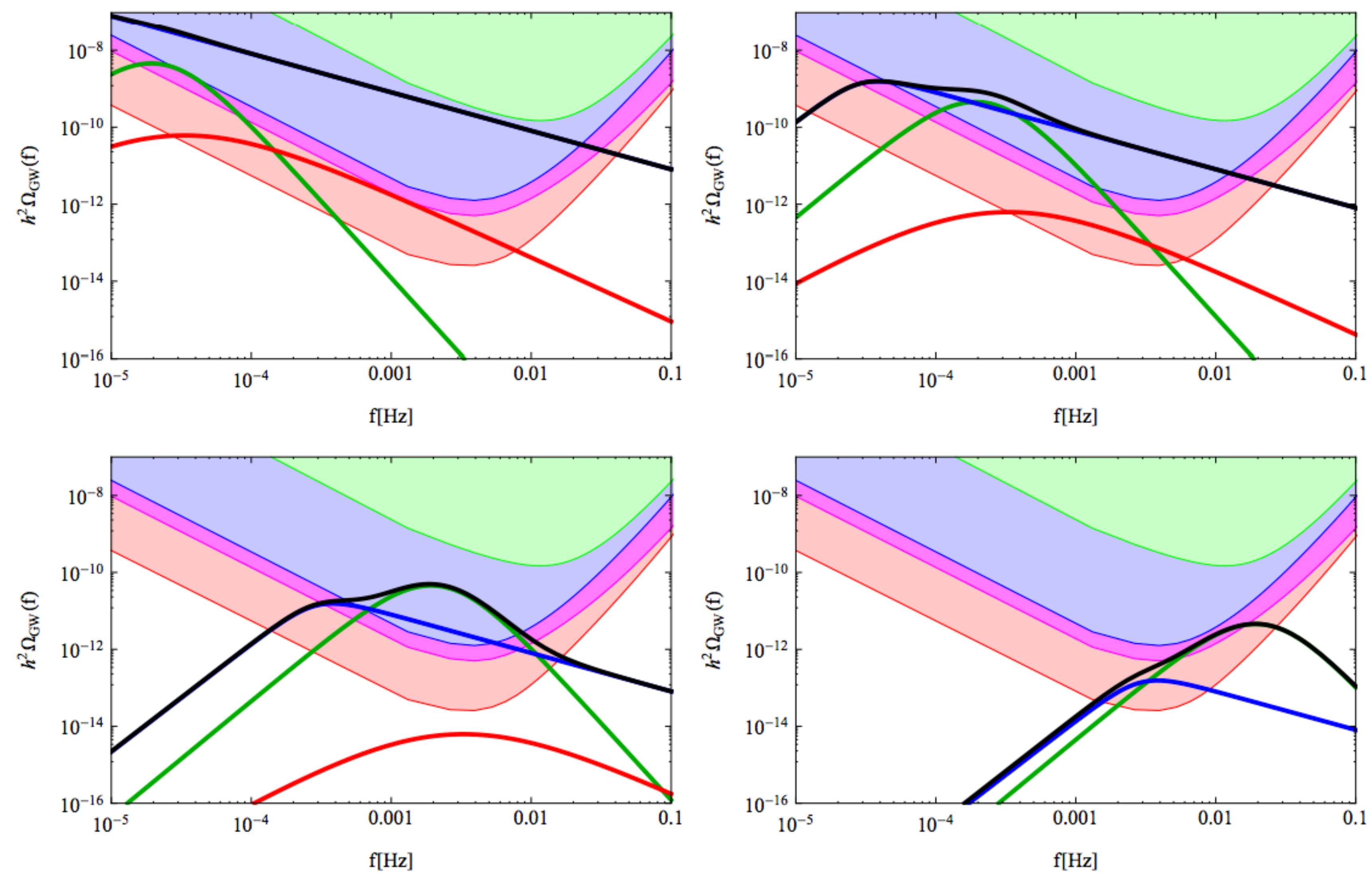
SGWB from 1OPT

$$f_{\text{peak}} \simeq 10^{-6}\text{Hz}\left(\frac{\beta}{H_*}\right)\left(\frac{T_*}{100\text{GeV}}\right)\left(\frac{g_*}{100}\right)^{1/6}$$

$$\Omega_{\text{peak}}h^2 \simeq 10^{-6}\left(\frac{\beta}{H_*}\right)^{-2}\left(\frac{g_*}{}\right)^{-1/3}$$

1512.06239

- Key feature: k^2 increasing, k^{-2} decreasing.
- For $\beta/H_* \sim 100$, frequency is 10^{-4}Hz, in LISA band, but the peak is only 10^{-10}.



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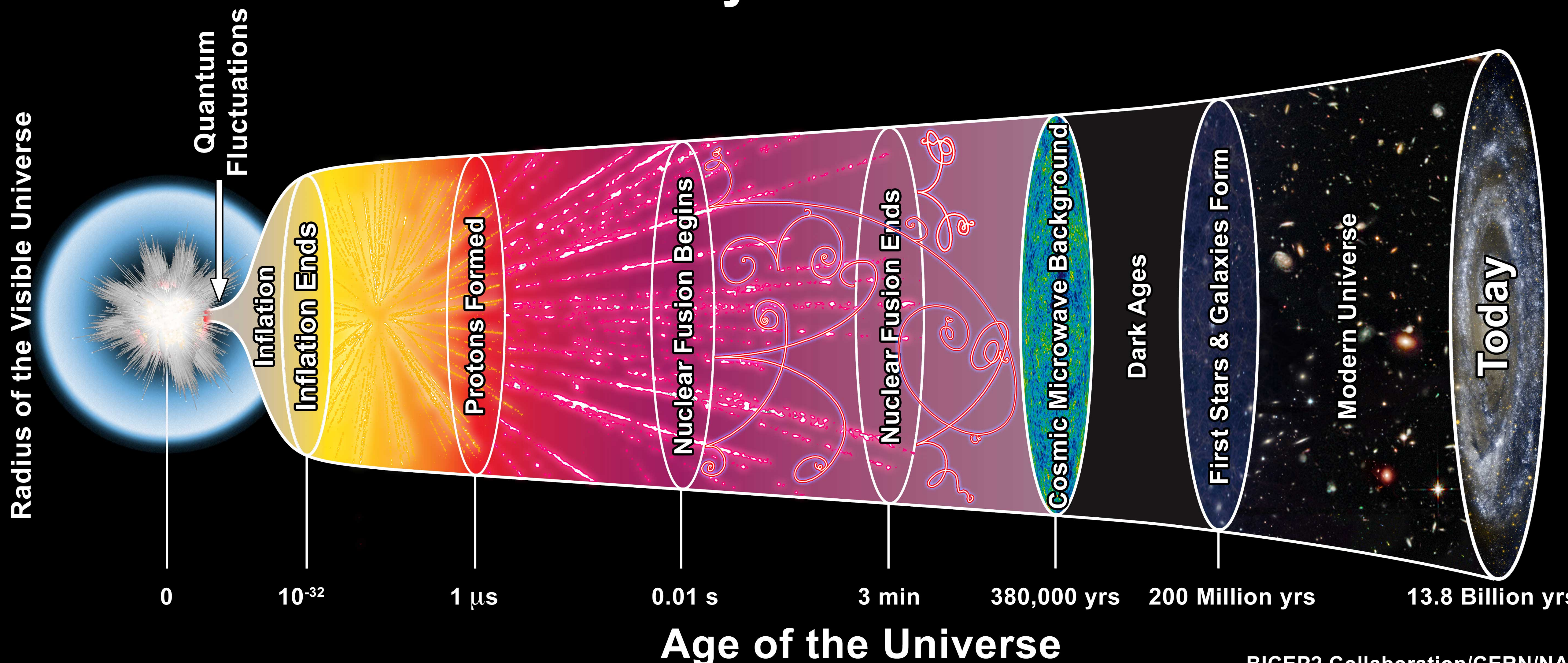
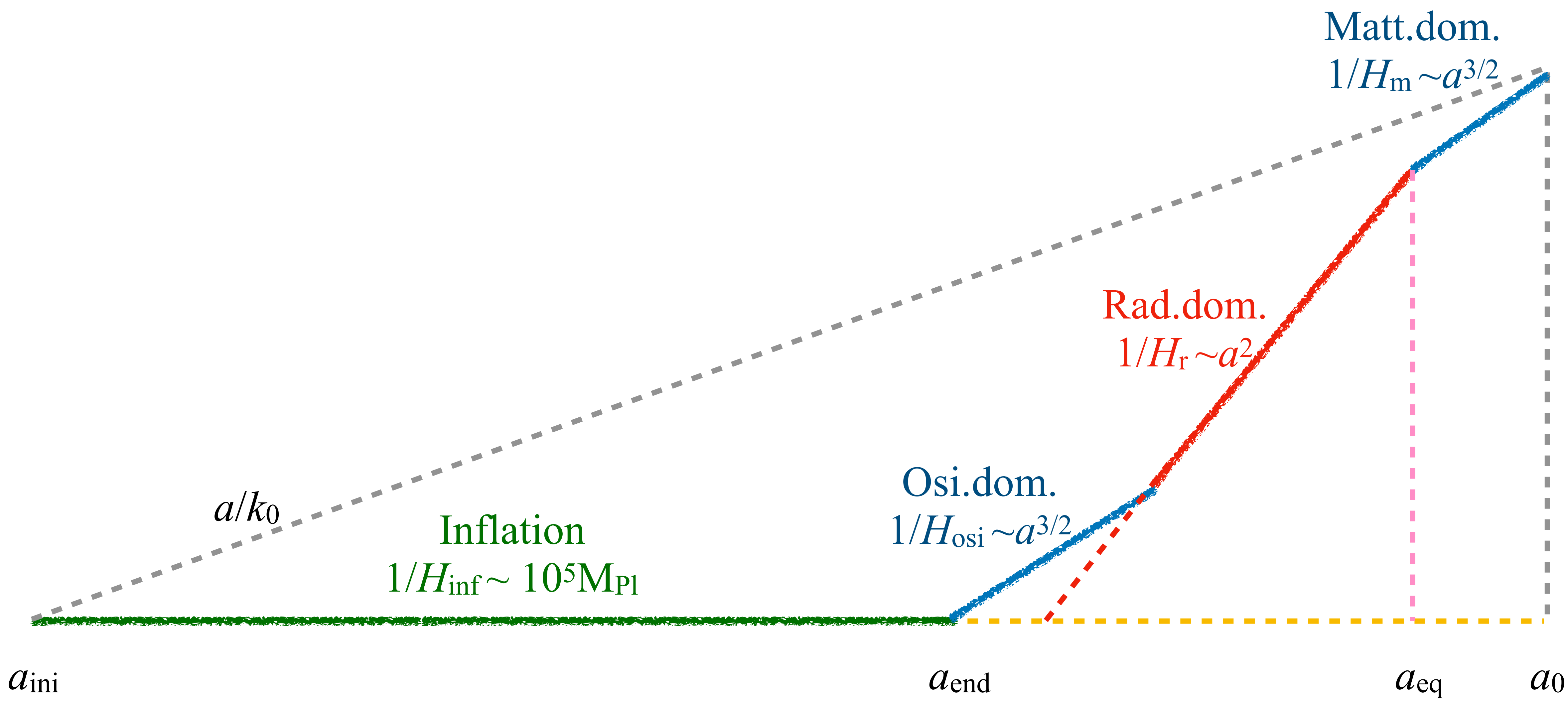
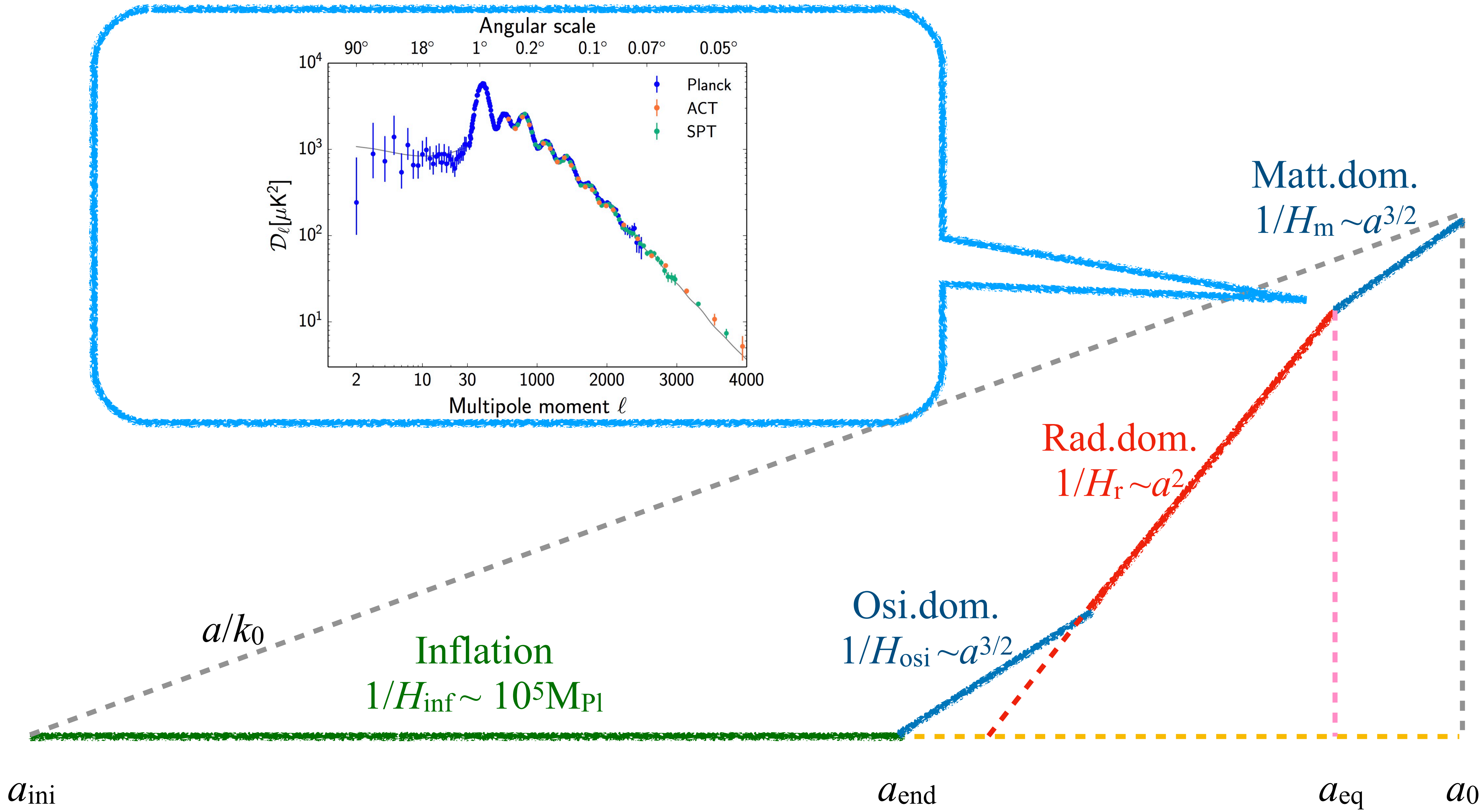
History of the Universe



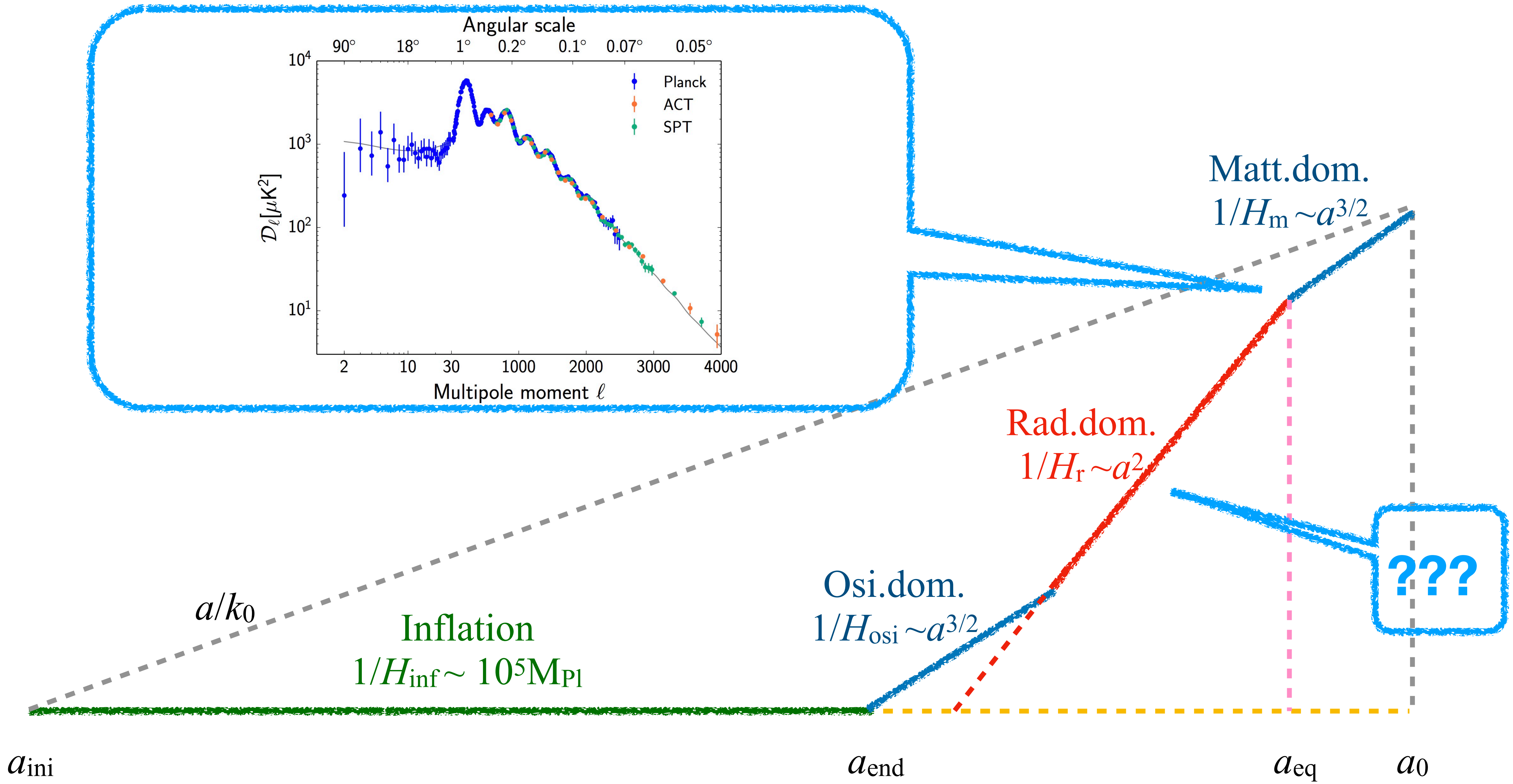
BICEP2 Collaboration/CERN/NASA



Matt.dom.
1/H_m ~a^{3/2}
Rad.dom.
1/H_r ~a^2
Osi.dom.
1/H_osi ~a^{3/2}
a/k_0
Inflation
1/H_inf ~ 10^5 M_Pl
a_ini
a_end
a_eq
a_0



Angular scale
90° 18° 1° 0.2° 0.1° 0.07° 0.05°
10^4 10^3 10^2 10^1
$\mathcal{D}_\ell [\mu K^2]$
Planck
ACT
SPT
2 10 30 1000 2000 3000 4000
Multipole moment ℓ
Matt.dom.
$1/H_{\rm m} \sim a^{3/2}$
Rad.dom.
$1/H_{\rm r} \sim a^2$
Osi.dom.
$1/H_{\rm osi} \sim a^{3/2}$
a/k_0
Inflation
$1/H_{\rm inf} \sim 10^5 M_{\rm Pl}$
$a_{\rm ini}$
$a_{\rm end}$
$a_{\rm eq}$
a_0



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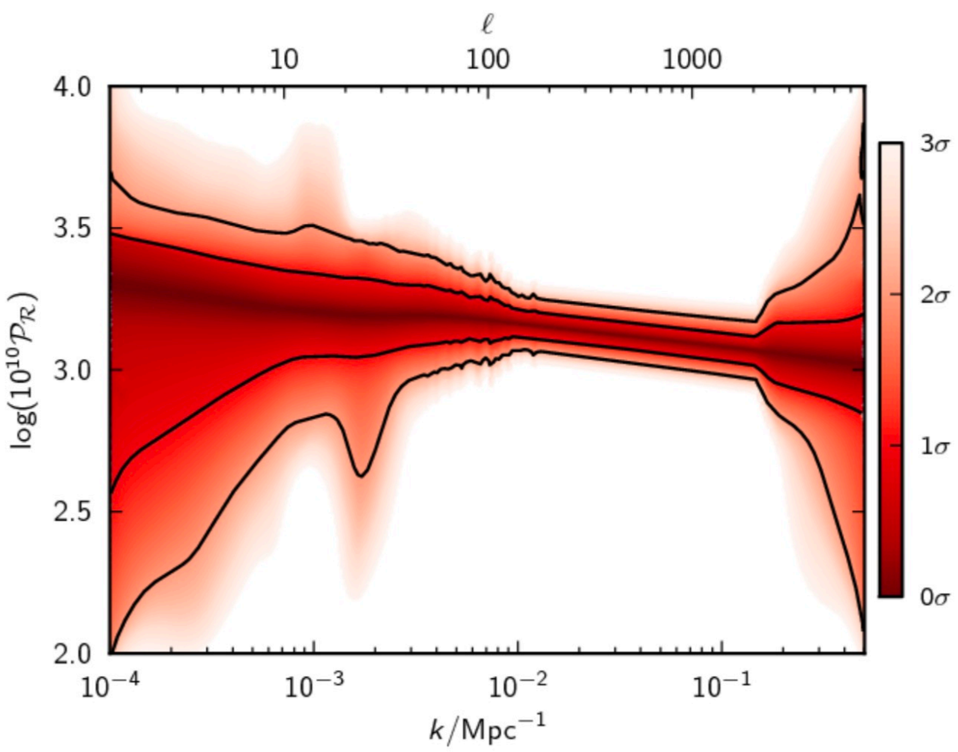
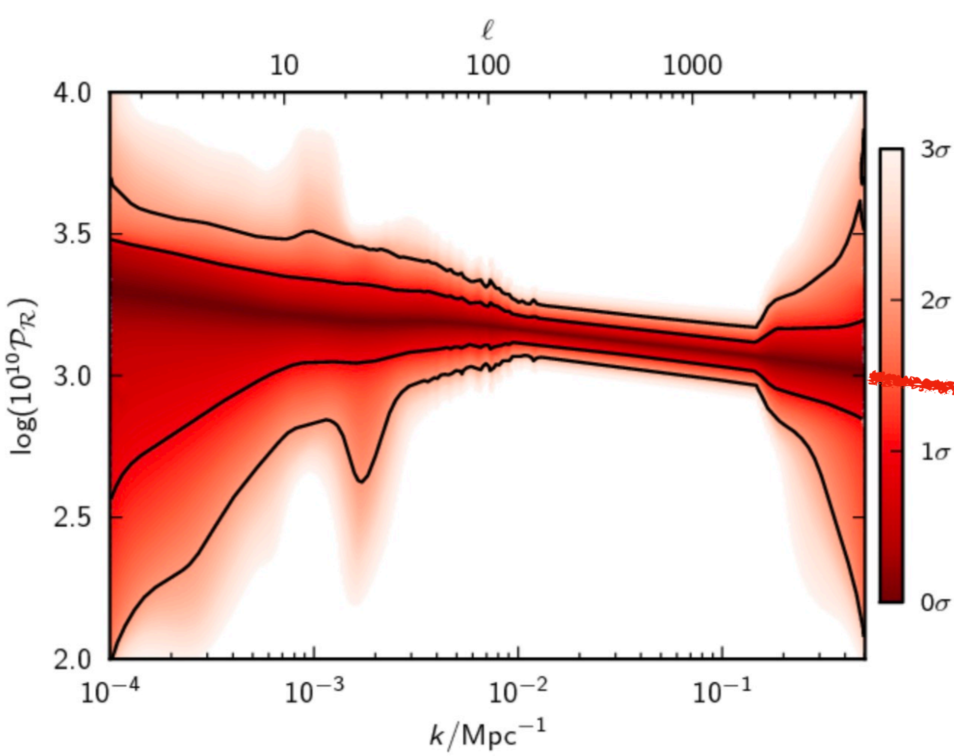
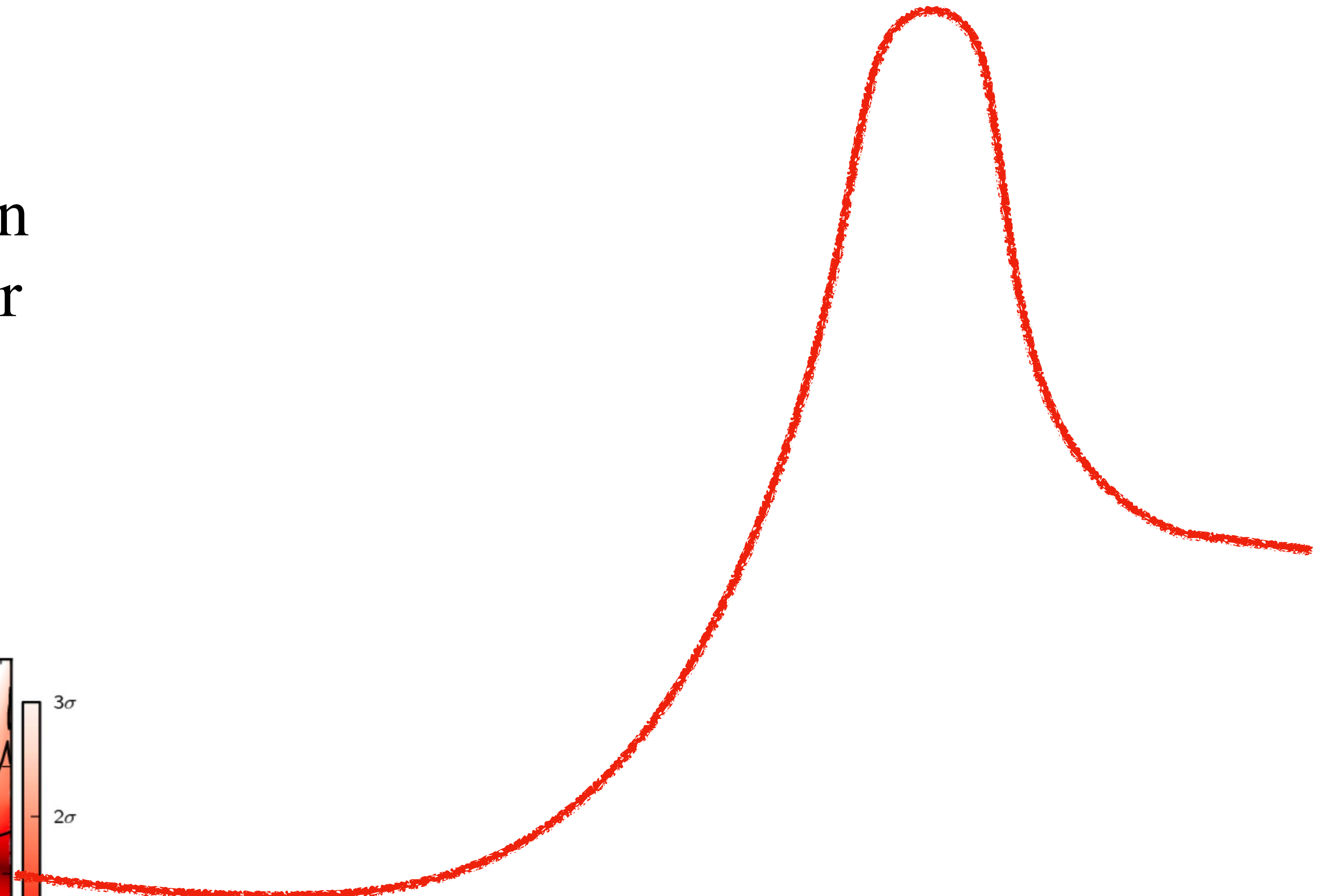
Multipole moment ℓ
Matt.dom.
$1/H_m \sim a^{3/2}$
Rad.dom.
$1/H_r \sim a^2$
???
Osi.dom.
$1/H_{osi} \sim a^{3/2}$
a/k_0
Inflation
$1/H_{inf} \sim 10^5 M_{Pl}$
a_{ini}
a_{end}
a_{eq}
a_0

Bayesian reconstruction of the primordial power spectrum for l<2300. (Planck 2015)

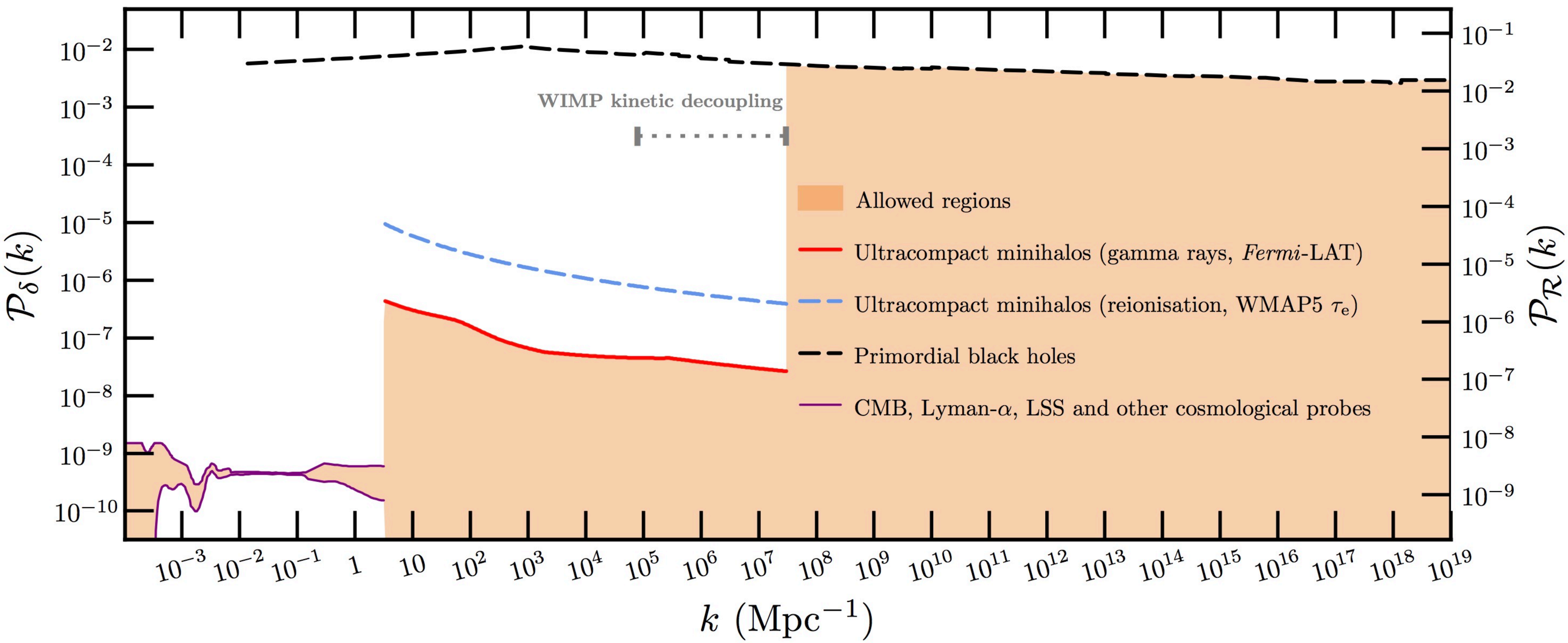


Bayesian reconstruction of the primordial power spectrum for l<2300. (Planck 2015)



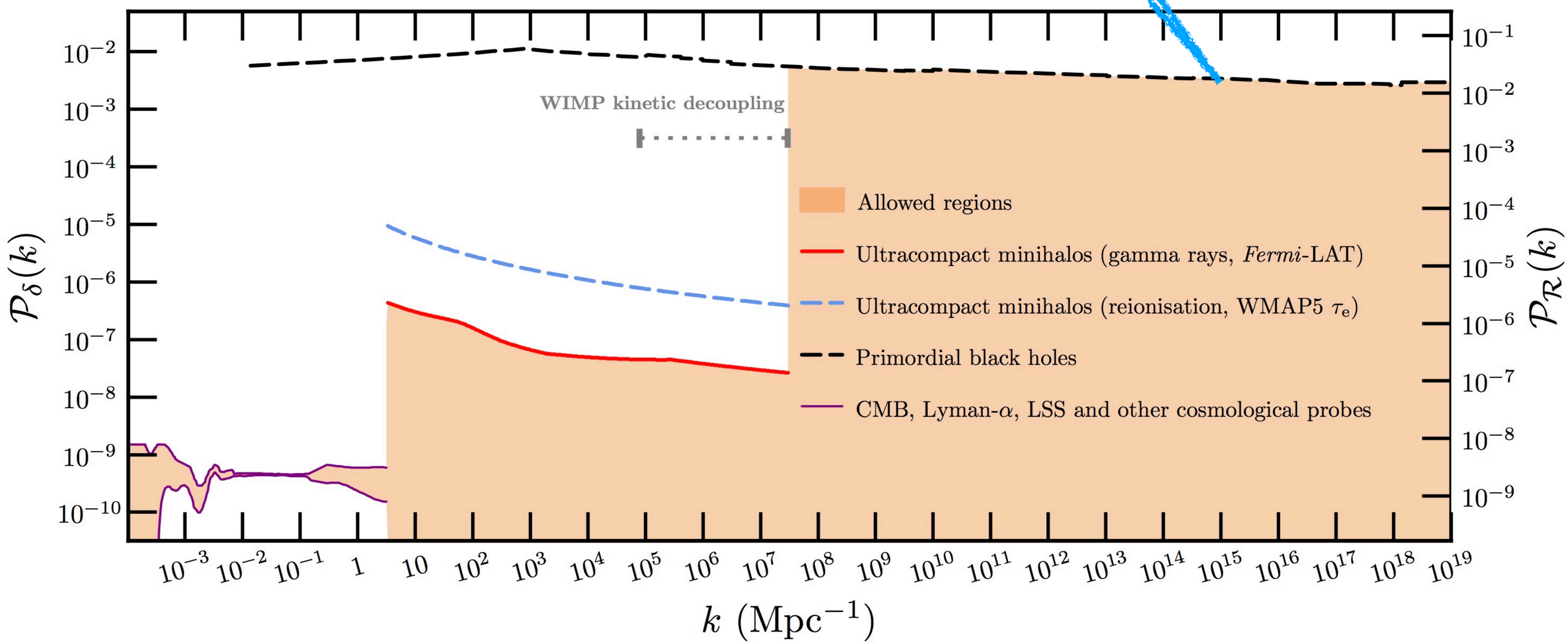


The resolution is lacking to say anything precise about higher l.



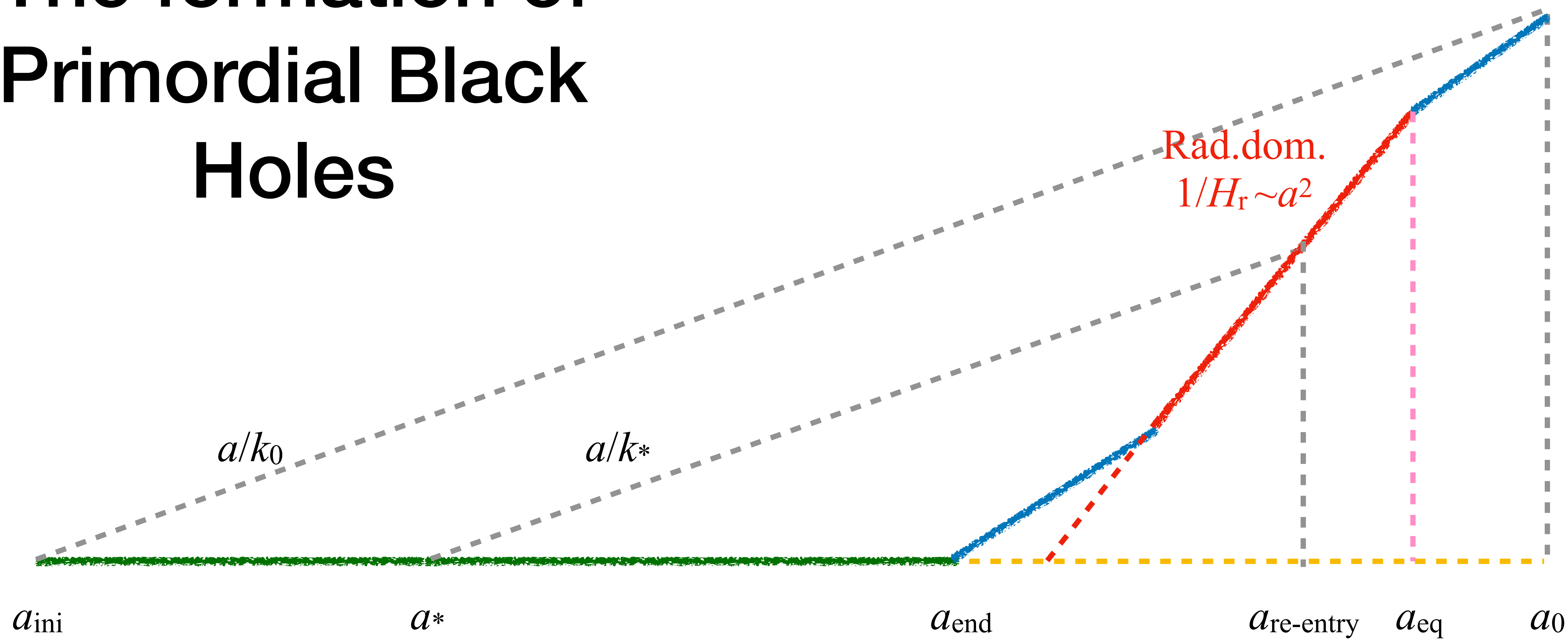
There are some constraints on small scales, but quite loose. (Bringmann et. al. 2011)

The constraints on small scales are mainly from PBHs. (Josan et. al. 2009)

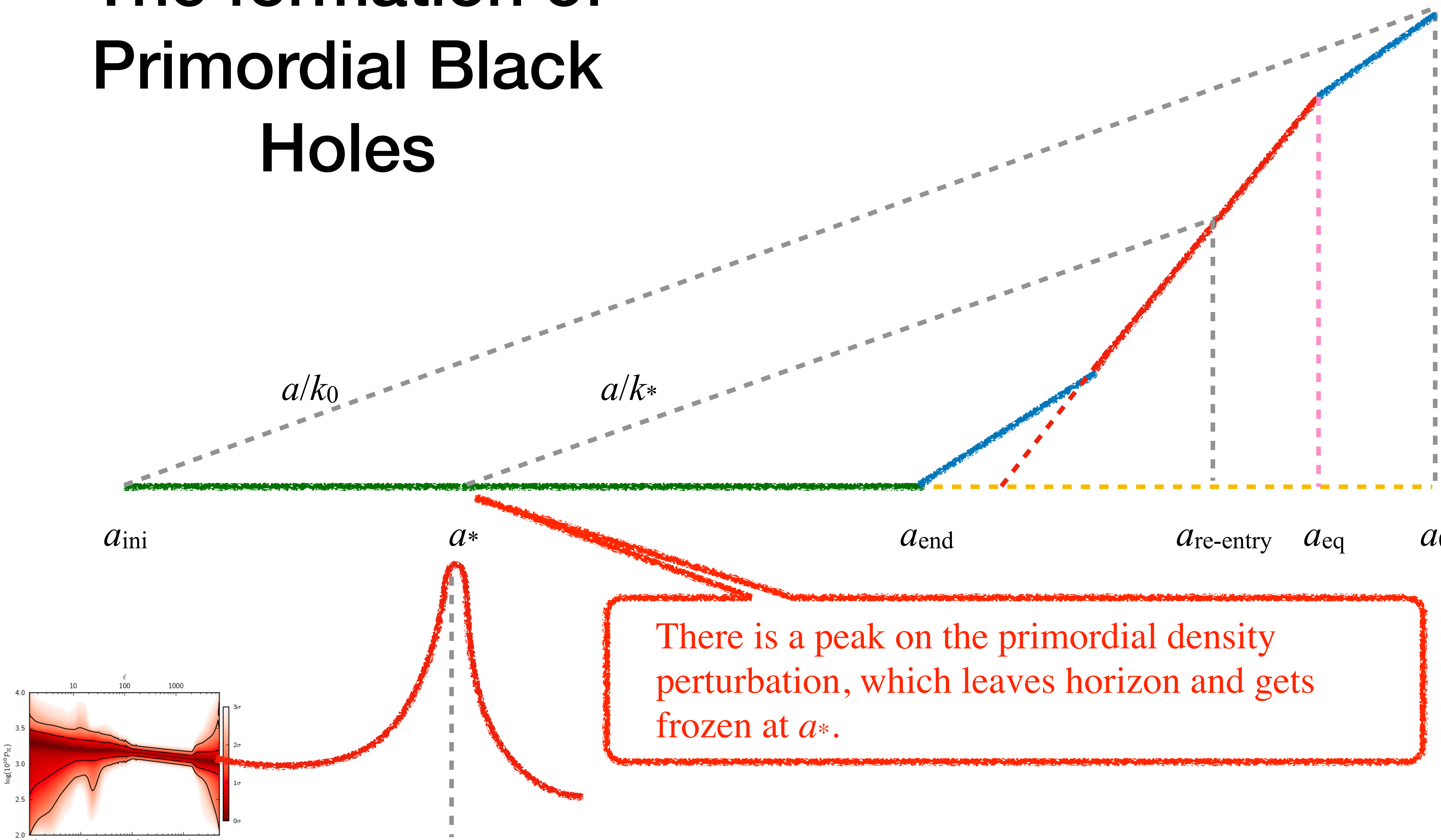


There are some constraints on small scales, but quite loose.

The formation of Primordial Black Holes



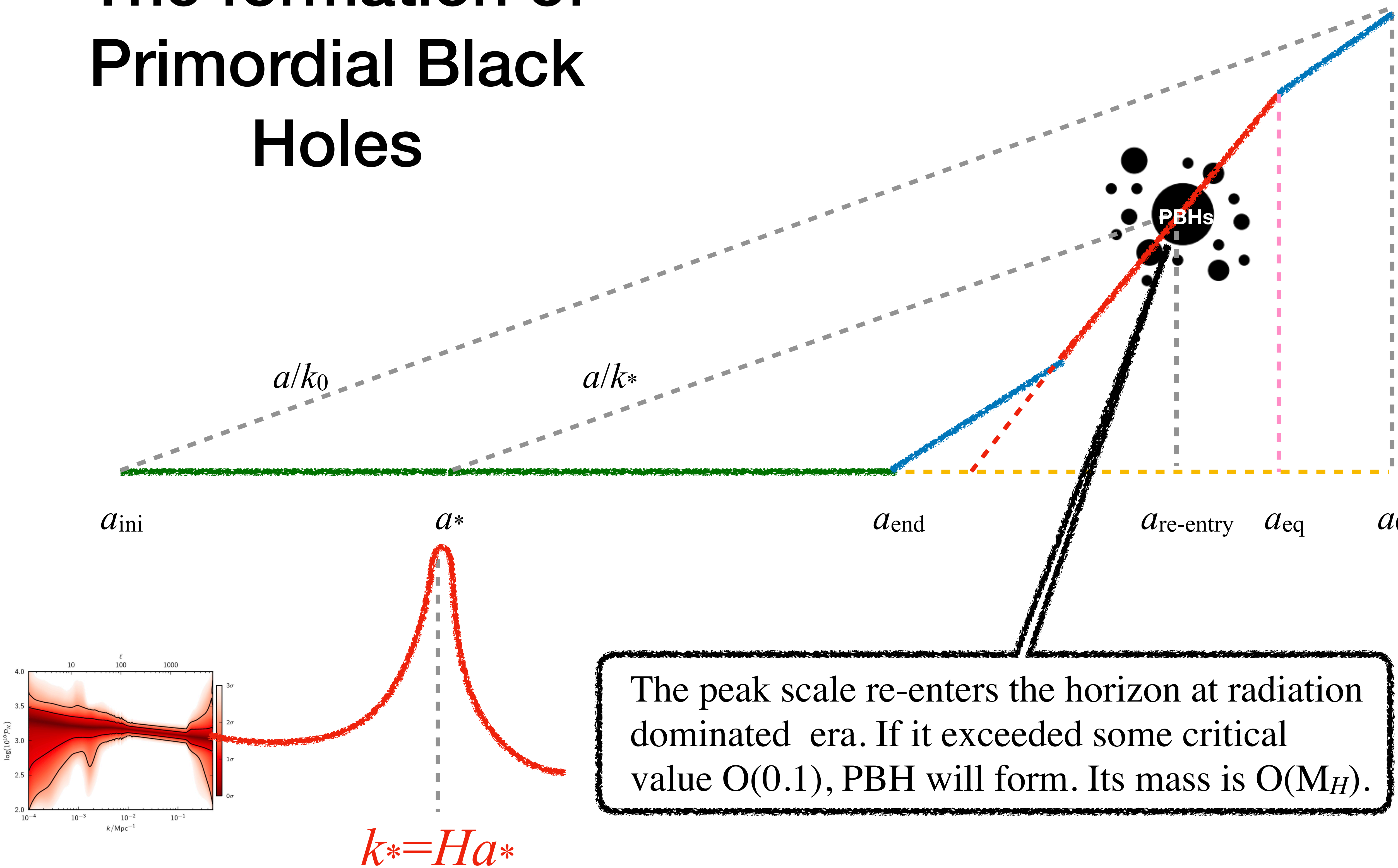
The formation of Primordial Black Holes



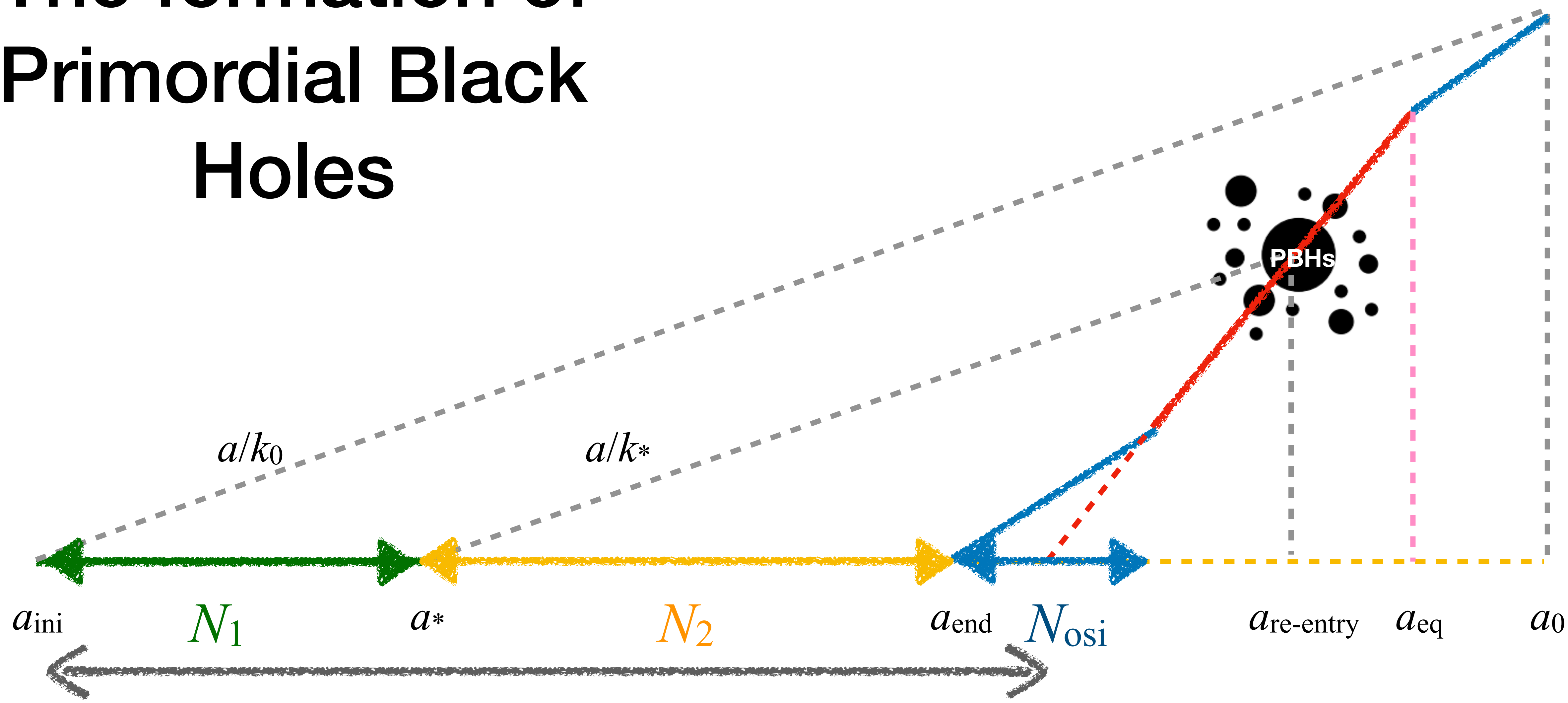
$k_* = Ha_*$

SP, Zhang, Huang & Sasaki 1712.09896

The formation of Primordial Black Holes



The formation of Primordial Black Holes



$N_1 + N_2 + N_{\rm osi}/4 \approx 60$

PBH mass: $M_{\rm PBH} \sim M_H \sim \dfrac{M_{\rm Pl}^2}{H_*} e^{2(N_2 + N_{\rm osi}/4)} = \dfrac{M_{\rm Pl}^2}{H_*} e^{2(60 - N_1)}$

Inverse relation: $N_1 = 44.4 - \dfrac{1}{2} \ln \left(\dfrac{M_{\rm PBH}}{10^{16}\ {\rm g}} \right).$

The Press-Schechter Mass Function

- Press and Schechter assumed the density distribution is Gaussian:

$$P(\delta_M)d\delta_M = \frac{1}{\sqrt{2\pi}\sigma_M}\exp\left(-\frac{\delta_M^2}{2\sigma_M^2}\right)d\delta_M$$

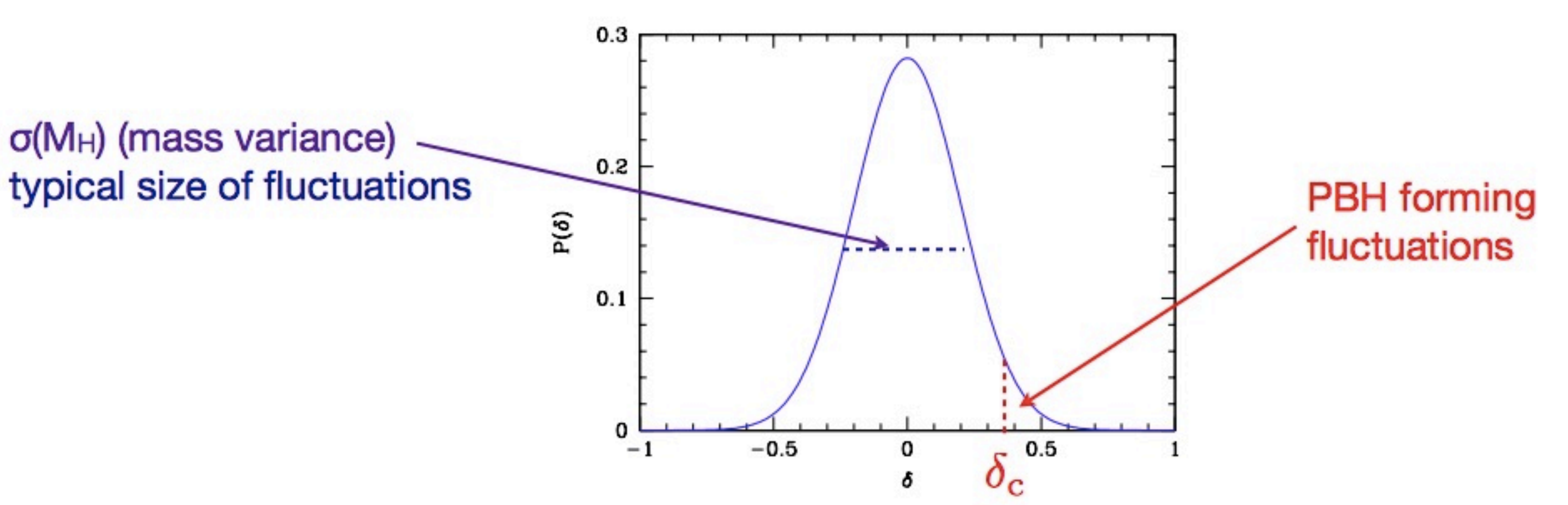
- σ_M is the variance of the density perturbation at mass M.

- The PBH only collapse when $\delta_M > \delta_c$, so the total probability is

$$P_{>\delta_c}(M) = 2\int_{\delta_c}^{\infty} P(\delta_M)d\delta_M = \mathrm{erfc}\left(\frac{\delta_c}{\sqrt{2}\sigma_M}\right)$$

- Ad hoc factor of 2. Highly suppressed when $\sigma_M << \delta_c$. This is the mass fraction at formation, denoted by β.

The Press-Schechter Mass Function



- When $\sigma_M << \delta_c$, β can be approximated by exponential:

$$\beta \approx \sqrt{\frac{2}{\pi}} \frac{\sigma_M}{\delta_c} \exp\left(-\frac{\delta_c^2}{2\sigma_M^2}\right)$$

The Press-Schechter Mass Function

- The current PBH mass measured in critical mass is

$$\Omega_{\rm PBH} = \beta \frac{a_{\rm eq}}{a_{\rm re}} = \beta \frac{a_{\rm eq}}{a_0} \frac{a_0}{a_{\rm re}} \simeq \beta \Omega_r (1 + z_{\rm re}(M))$$

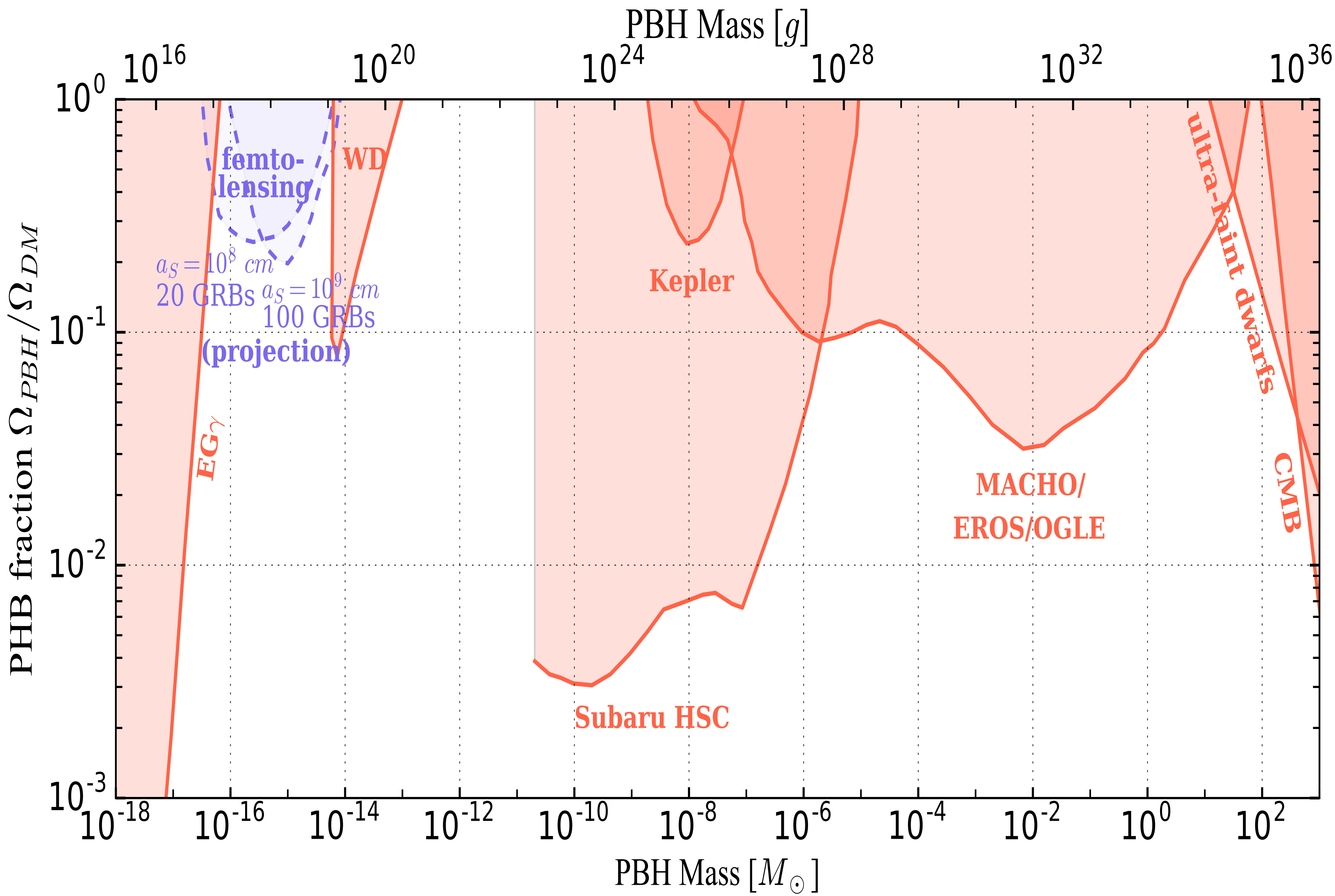
- where "eq" means equality and "re" means re-entry for the peak of the variance of the density perturbation at mass M.

- It is easy to estimate $z(M)$ relation at horizon reentry

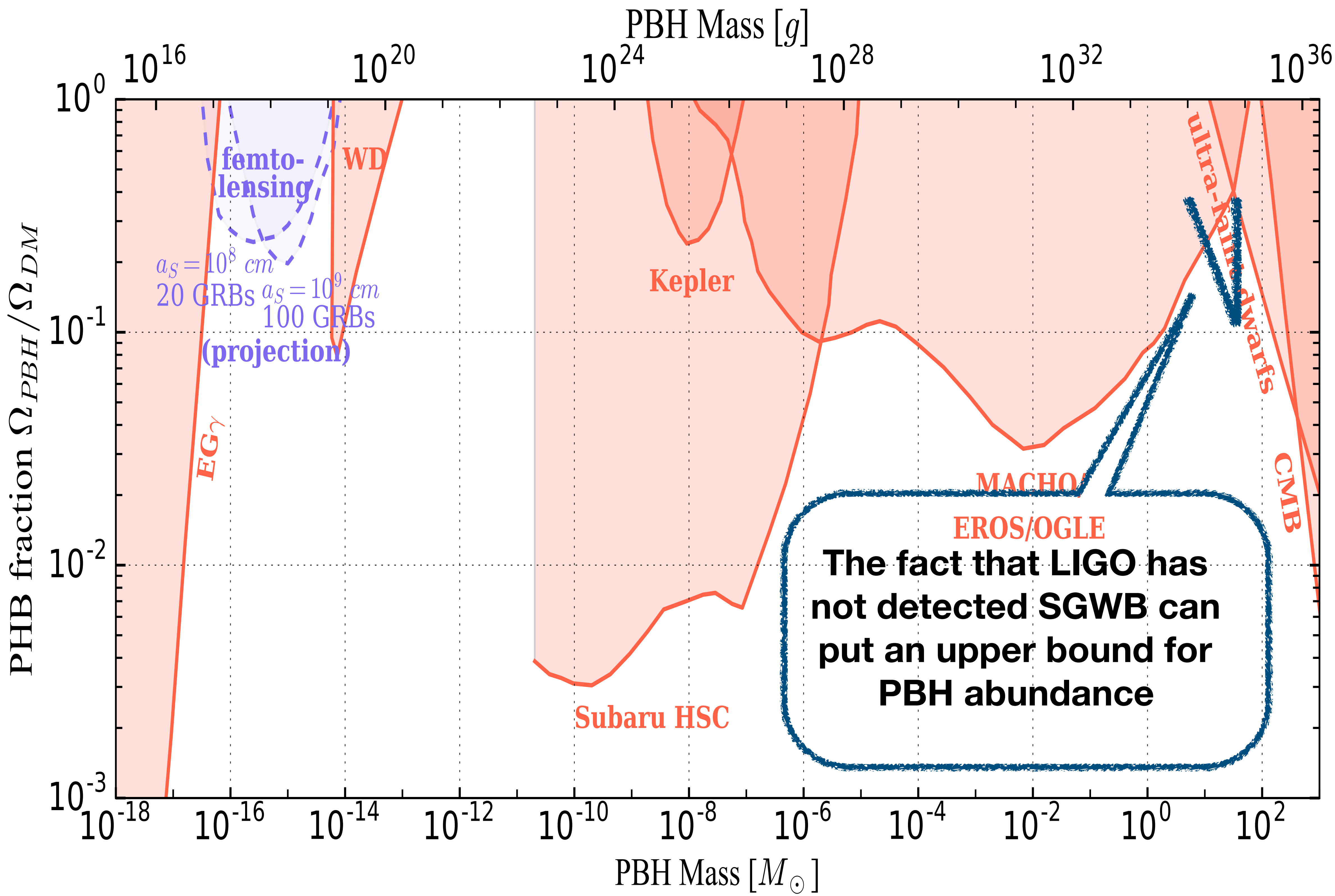
$$M = \frac{c^3}{G H_{\rm re}} = \frac{c^3}{G \Omega_r^{1/2} (1+z)^2 H_0}$$

- Therefore we have

$$f \equiv \frac{\Omega_{\rm PBH}}{\Omega_{\rm CDM}} \approx 4.11 \times 10^8 \beta(M) \left(\frac{M}{M_\odot}\right)^{-1/2}$$


PBH Mass [g]
10^16
10^20
10^24
10^28
10^32
10^36
PHB fraction Ω_PBH/Ω_DM
10^0
10^-1
10^-2
10^-3
femto-
lensing
WD
a_S = 10^8 cm
20 GRBs
a_S = 10^9 cm
100 GRBs
(projection)
EGγ
Kepler
ultra-faint dwarfs
MACHO/
EROS/OGLE
CMB
Subaru HSC
10^-18
10^-16
10^-14
10^-12
10^-10
10^-8
10^-6
10^-4
10^-2
10^0
10^2
PBH Mass [M_⊙]

1807.11495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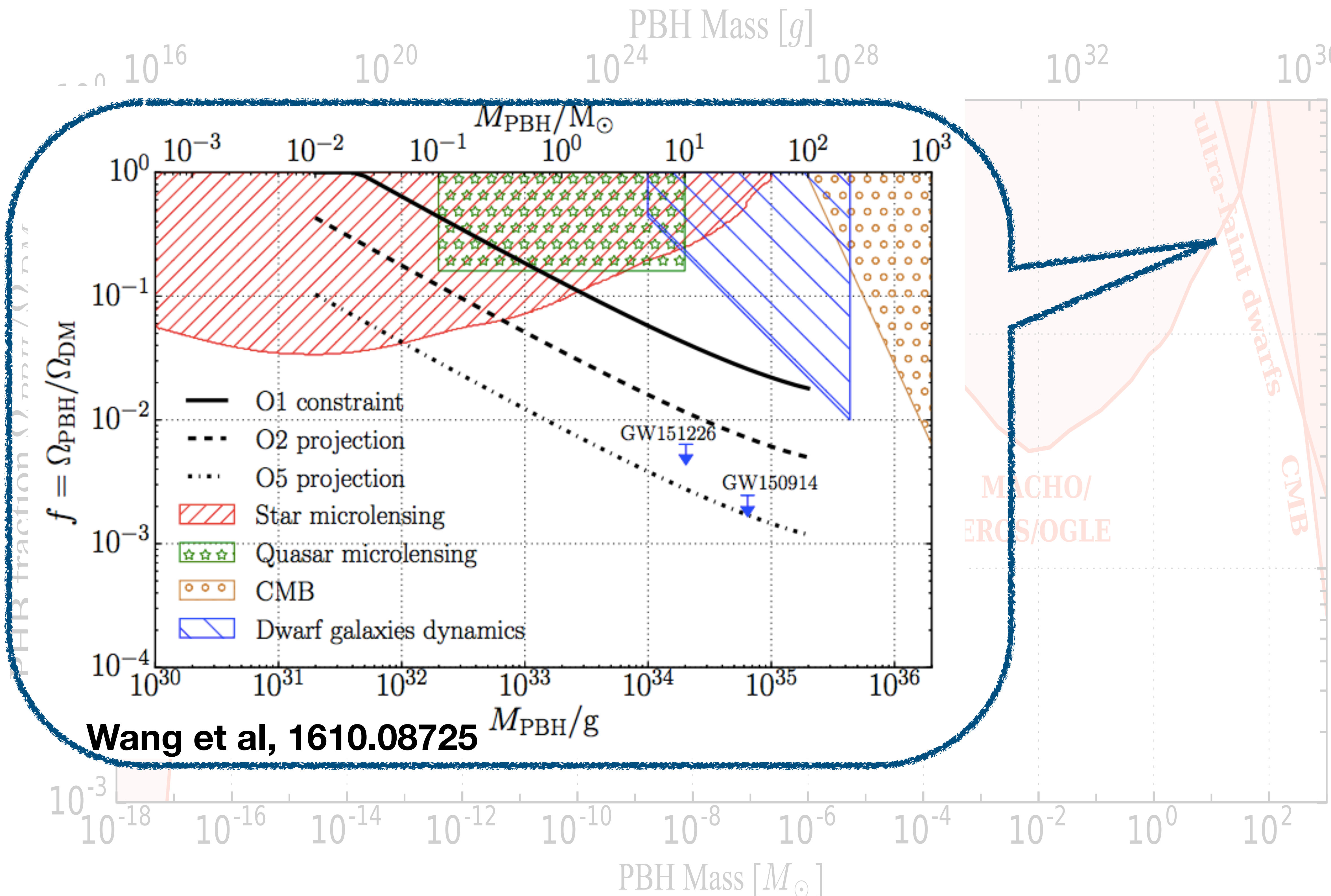
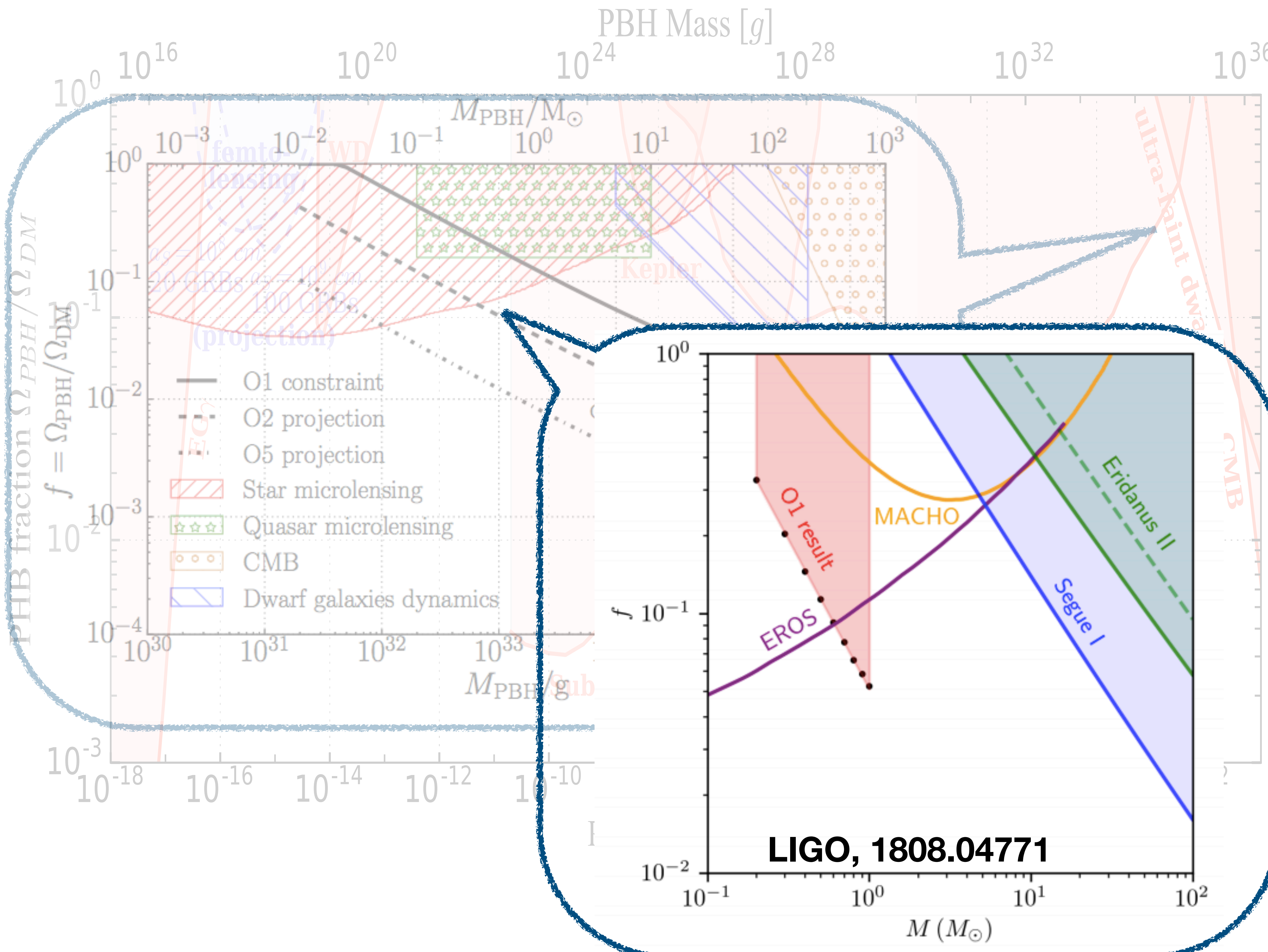
a_S = 10^8 cm
20 GRBs
a_S = 10^9 cm
100 GRBs
(projection)
EGγ
Kepler
Subaru HSC
MACHO/
EROS/OGLE
ultra-faint dwarfs
CMB
The fact that LIGO has not detected SGWB can put an upper bound for PBH abundance
10^-18
10^-16
10^-14
10^-12
10^-10
10^-8
10^-6
10^-4
10^-2
10^0
10^2
PBH Mass [M⊙]

1807.11495



PBH Mass [g]
PBH Mass [$M_\odot$]
ultra-faint dwarfs
CMB
MACHO/
EROS/OGLE
$M_{\rm PBH}/{\rm M}_\odot$
$f = \Omega_{\rm PBH}/\Omega_{\rm DM}$
$M_{\rm PBH}/{\rm g}$
O1 constraint
O2 projection
O5 projection
Star microlensing
Quasar microlensing
CMB
Dwarf galaxies dynamics
GW151226
GW150914
Wang et al, 1610.08725


PBH Mass [g]
PHB fraction Ω_{PBH}/Ω_{DM}
$M_{PBH}/M_\odot$
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O1 constraint
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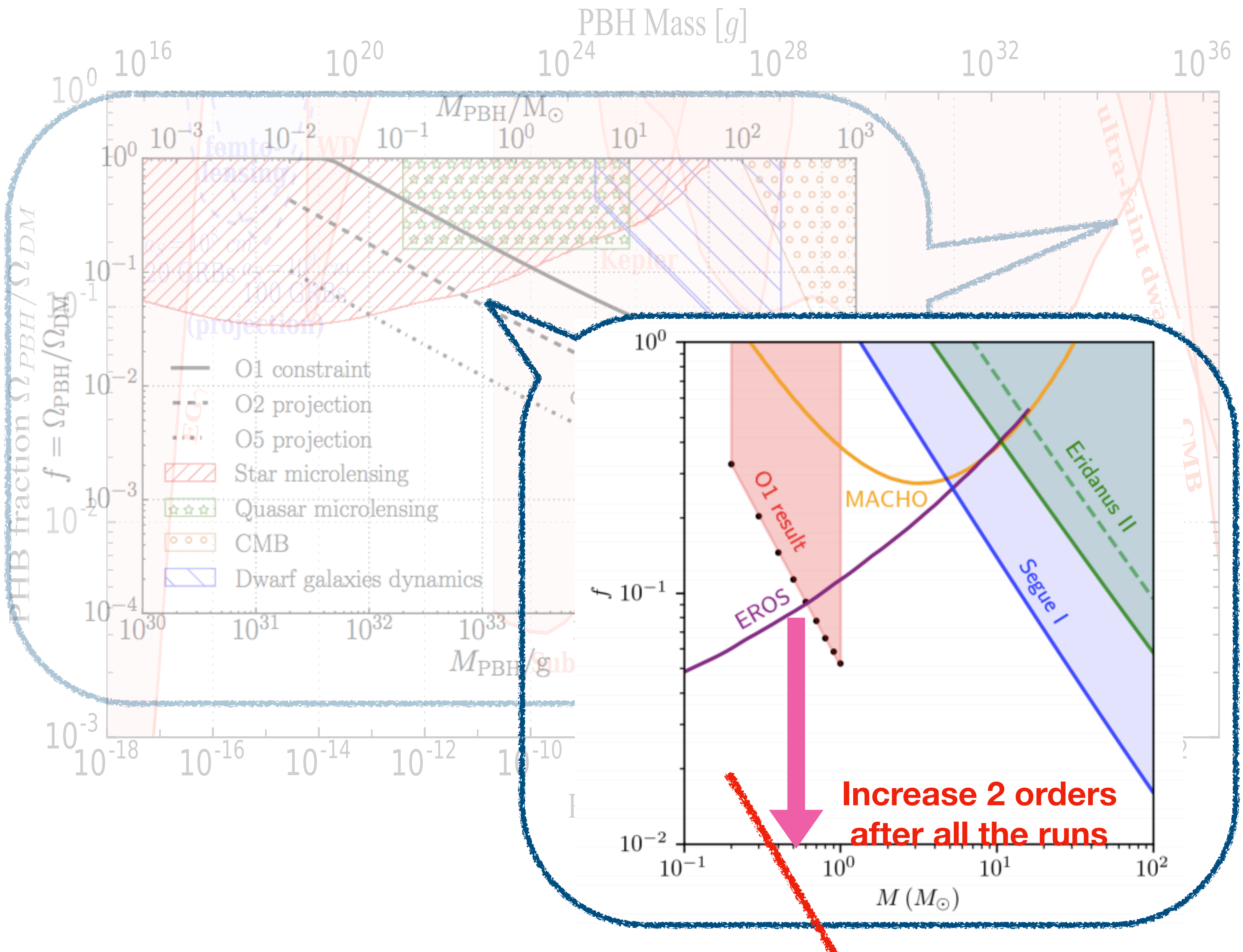
CMB
Dwarf galaxies dynamics
M_{PBH}/g
O1 result
MACHO
EROS
Eridanus II
Segue I
f
$M\ (M_\odot)$
LIGO, 1808.04771


PBH Mass [g]
$M_{PBH}/M_\odot$
$f = \Omega_{PBH}/\Omega_{DM}$
M_{PBH}/g
O1 constraint
O2 projection
O5 projection
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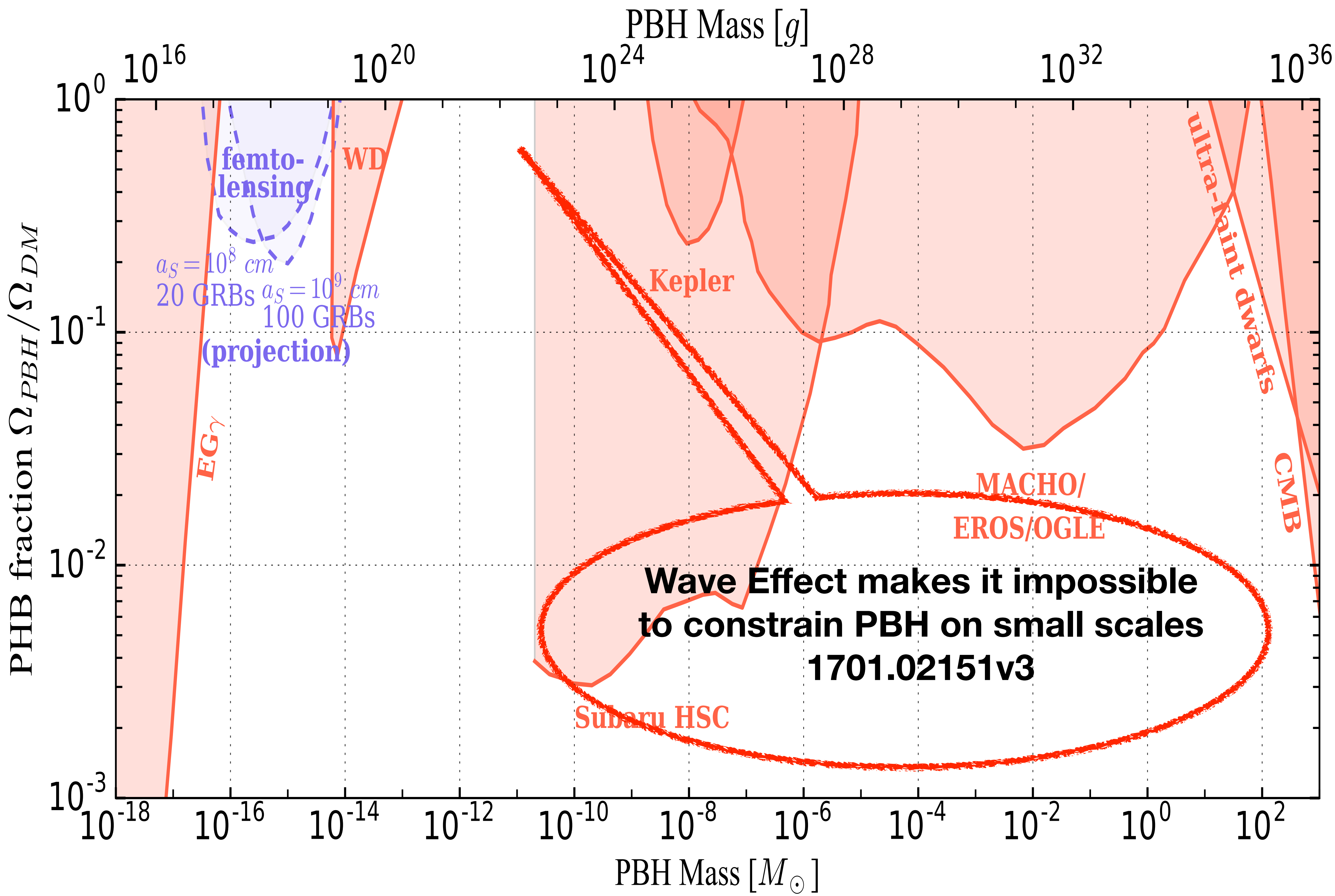
Kepler
ultra-faint dwarfs
O1 result
MACHO
EROS
Eridanus II
Segue I
f
$M\ (M_\odot)$
Increase 2 orders
after all the runs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PBH Mass [$M_\odot$]
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20 GRBs
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100 GRBs
(projection)
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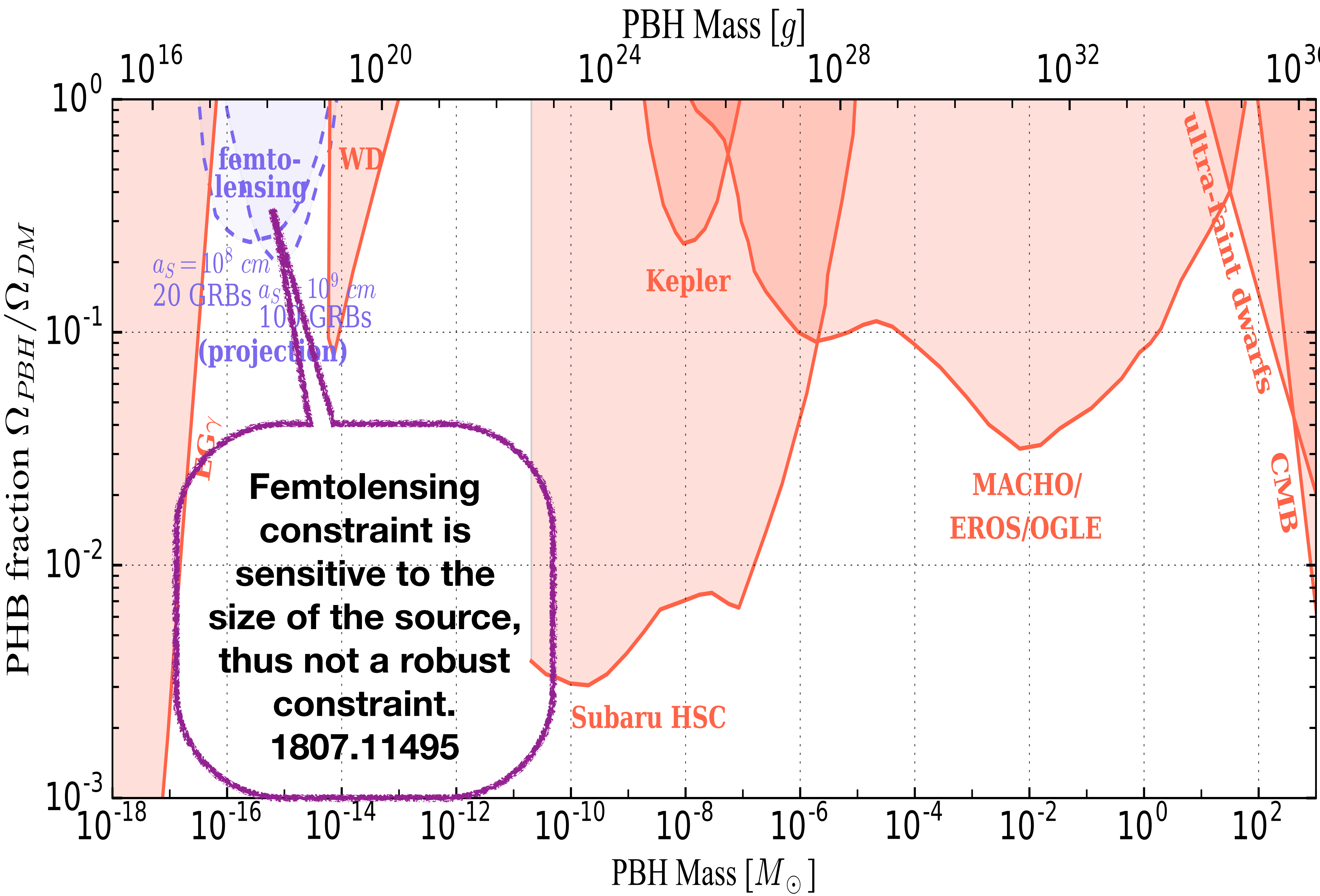
EG_γ
Kepler
Subaru HSC
MACHO/
EROS/OGLE
ultra-faint dwarfs
CMB
Wave Effect makes it impossible
to constrain PBH on small scales
1701.02151v3

1807.11495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100 GRBs
(projection)
WD
Kepler
ultra-faint dwarfs
CMB
MACHO/
EROS/OGLE
Subaru HSC
EGγ
Femtolensing constraint is sensitive to the size of the source, thus not a robust constraint. 1807.11495
10^{-18}
10^{-16}
10^{-14}
10^{-12}
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
10^{0}
10^{2}
PBH Mass [$M_\odot$]

1807.11495

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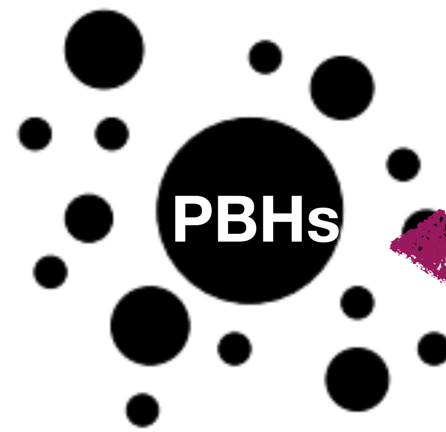
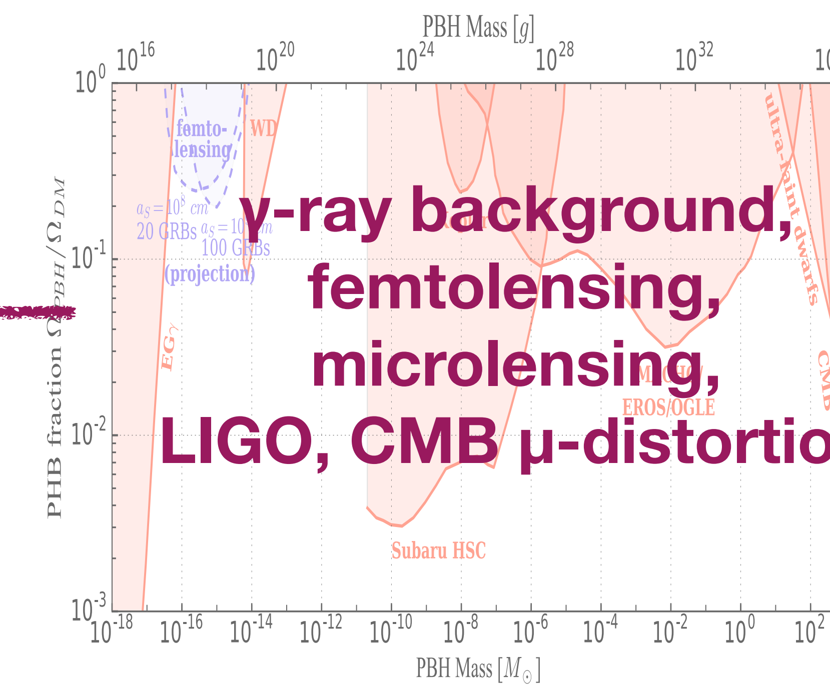
Induced GWs



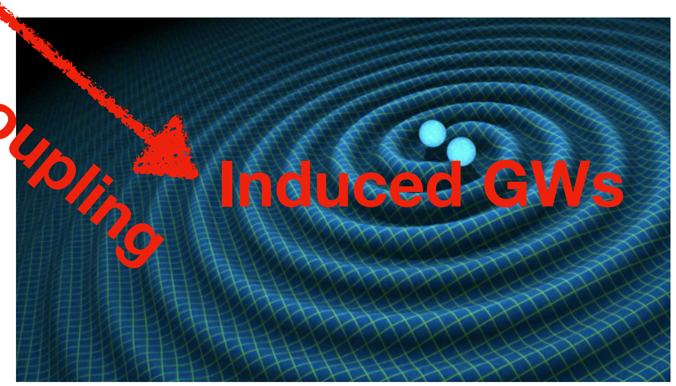


γ-ray background, femtolensing, microlensing, LIGO, CMB μ-distortion

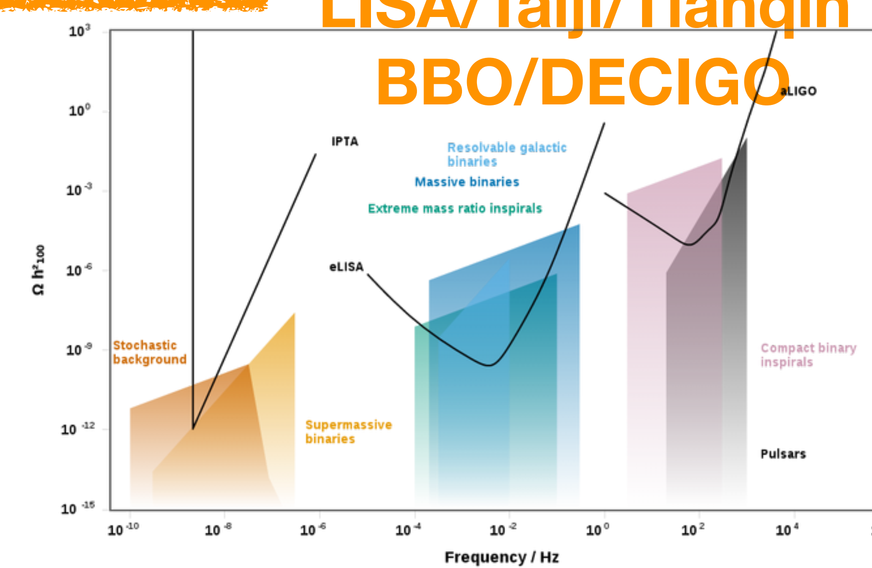
Peak Theory

Peak of scalar perturbation on small scales

secondary coupling

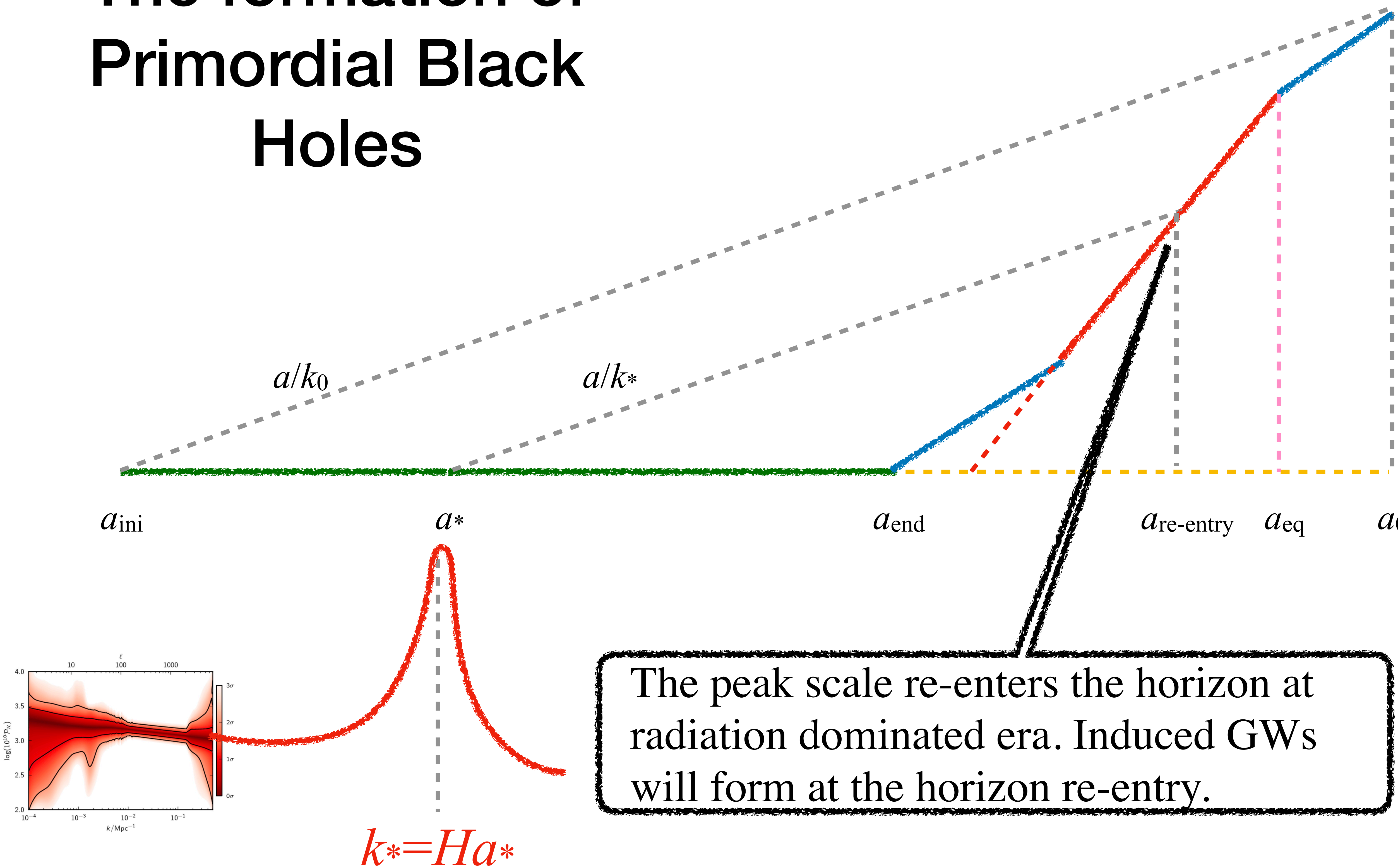


LIGO/VIRGO/KAGRA
LISA/Taiji/Tianqin
BBO/DECIGO



Saito & Yokoyama, 0812.4339

The formation of Primordial Black Holes



Induced GWs

- The metric is

$$ds^2 = a(\eta)^2 \left[-(1-2\Phi)\, d\eta^2 + \left(1 + 2\Phi + \frac{1}{2} h_{ij}\right) dx^i dx^j \right].$$

- From the nonlinear equation of motion for the tensor perturbation

$$h''_{\mathbf{k}} + 2\mathscr{H} h'_{\mathbf{k}} + k^2 h_{\mathbf{k}} = \mathcal{S}(\mathbf{k}, \eta)$$

- where the source term is

$$\mathcal{S}(\mathbf{k}, \eta) = 36 \int \frac{d^3 l}{(2\pi)^{3/2}} \frac{l^2}{\sqrt{2}} \sin^2\theta \begin{pmatrix} \cos 2\varphi \\ \sin 2\varphi \end{pmatrix} \Phi_{\mathbf{l}} \Phi_{\mathbf{k}-\mathbf{l}} \times \left[j_0(ux) j_0(vx) - 2\frac{j_1(ux) j_0(vx)}{ux} - 2\frac{j_0(ux) j_1(vx)}{vx} + 3\frac{j_1(ux) j_1(vx)}{uvx^2} \right].$$

Induced GWs

- The quantity we want to calculate is

$$\Omega_{\mathrm{GW}}(k) \equiv \frac{1}{12}\left(\frac{k}{Ha}\right)^2 \frac{k^3}{\pi^2}\overline{\langle h_{\mathbf{k}}(\eta) h_{\mathbf{k}}(\eta)\rangle}.$$

- Then we know that $\Omega_{GW} \sim <hh> \sim <SS> \sim <\Phi\Phi\Phi\Phi> \sim P_{\Phi}^2$.

- It is naive to believe that Φ stays Gaussian when it becomes very large on small scales.

- Therefore we want to consider the local-type non-Gaussian scalar induced GWs.

- $$\mathscr{R}(\mathbf{x}) = \mathscr{R}_g(\mathbf{x}) + F_{\mathrm{NL}}\left[\mathscr{R}_g^2(\mathbf{x}) - \langle \mathscr{R}_g^2(\mathbf{x})\rangle\right].$$

Induced GWs

- Then the 2pt of Φ is

$$\langle \Phi_{\mathbf{k}} \Phi_{\mathbf{p}} \rangle = (2\pi)^3 \delta^{(3)}(\mathbf{k}+\mathbf{p}) \frac{4}{9} \left(P_{\mathscr{R}}(k) + 2F_{\rm NL}^2 \int d^3l \; P_{\mathscr{R}}(|\mathbf{k}-\mathbf{l}|) P_{\mathscr{R}}(l) \right) .$$

- And we have to specify the power spectrum of the primordial curvature perturbation. As we mentioned, we suppose there is a narrow peak at around k*.

$$P_{\mathscr{R}}(k) = \frac{\mathscr{A}_{\mathscr{R}}}{(2\pi)^{3/2} 2\sigma k_*^2} \exp\left(-\frac{(k-k_*)^2}{2\sigma^2} \right) .$$

- Narrow means σ<<k*. This is for simplicity.

Induced GWs

- Then the result is the integral:

$$\Omega_{\rm GW} = 6\mathcal{A}_{\mathcal{R}}^2 \frac{k^2}{2\pi\sigma^2}\left(\frac{k}{k_*}\right)^4 \int_0^\infty dv \int_{|1-v|}^{1+v} du\, uv\, \mathcal{T}(u,v)$$
$$\times \left(e^{-\frac{(vk-k_*)^2}{2\sigma^2}} + 2\mathcal{A}_{\mathcal{R}} F_{\rm NL}^2 \frac{\sigma}{vk}\sqrt{\frac{\pi}{2}}\Theta(2k_* - vk)\right)$$
$$\times \left(e^{-\frac{(uk-k_*)^2}{2\sigma^2}} + 2\mathcal{A}_{\mathcal{R}} F_{\rm NL}^2 \frac{\sigma}{uk}\sqrt{\frac{\pi}{2}}\Theta(2k_* - uk)\right),$$

$$\mathcal{T}(u,v) = \frac{1}{4}\left(\frac{4v^2-(1+v^2-u^2)^2}{4uv}\right)^2 \left(\frac{u^2+v^2-3}{2uv}\right)^2$$
$$\times \left\{\left(-2 + \frac{u^2+v^2-3}{2uv}\ln\left|\frac{3-(u+v)^2}{3-(u-v)^2}\right|\right)^2 \right.$$
$$\left. + \pi^2\left(\frac{u^2+v^2-3}{2uv}\right)^2 \Theta\left(u+v-\sqrt{3}\right)\right\}.$$

Induced GWs

- Then the result is the integral:

$$\Omega_{\rm GW} = 6\mathcal{A}_{\mathcal{R}}^2 \frac{k^2}{2\pi\sigma^2}\left(\frac{k}{k_*}\right)^4 \int_0^\infty dv \int_{|1-v|}^{1+v} du\, uv\, \mathcal{T}(u,v)$$
$$\times\left(e^{-\frac{(vk-k_*)^2}{2\sigma^2}} + 2\mathcal{A}_{\mathcal{R}} F_{\rm NL}^2 \frac{\sigma}{vk}\sqrt{\frac{\pi}{2}}\Theta(2k_* - vk)\right)$$
$$\times\left(e^{-\frac{(uk-k_*)^2}{2\sigma^2}} + 2\mathcal{A}_{\mathcal{R}} F_{\rm NL}^2 \frac{\sigma}{uk}\sqrt{\frac{\pi}{2}}\Theta(2k_* - uk)\right),$$

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$$\times\left\{\left(-2+\frac{u^2+v^2-3}{2uv}\ln\left|\frac{3-(u+v)^2}{3-(u-v)^2}\right|\right)^2\right.$$
$$\left.+\,\pi^2\left(\frac{u^2+v^2-3}{2uv}\right)^2\Theta\left(u+v-\sqrt{3}\right)\right\}.$$

Kohri & Tareda, 1804.08577

Induced GWs

- Then the result is the integral:

$$\Omega_{\rm GW} = 6\mathcal{A}_{\mathcal{R}}^2 \frac{k^2}{2\pi\sigma^2}\left(\frac{k}{k_*}\right)^4 \int_0^\infty dv \int_{|1-v|}^{1+v} du\, uv\, \mathcal{T}(u,v)$$

$$\times\left(e^{-\frac{(vk-k_*)^2}{2\sigma^2}} + 2\mathcal{A}_{\mathcal{R}} F_{\rm NL}^2 \frac{\sigma}{vk}\sqrt{\frac{\pi}{2}}\Theta(2k_* - vk)\right)$$

$$\times\left(e^{-\frac{(uk-k_*)^2}{2\sigma^2}} + 2\mathcal{A}_{\mathcal{R}} F_{\rm NL}^2 \frac{\sigma}{uk}\sqrt{\frac{\pi}{2}}\Theta(2k_* - uk)\right),$$

Saito & Yokoyama, 0812.4339

$$\mathcal{T}(u,v) = \frac{1}{4}\left(\frac{4v^2-(1+v^2-u^2)^2}{4uv}\right)^2\left(\frac{u^2+v^2-3}{2uv}\right)^2$$

$$\times\left\{\left(-2+\frac{u^2+v^2-3}{2uv}\ln\left|\frac{3-(u+v)^2}{3-(u-v)^2}\right|\right)^2 + \pi^2\left(\frac{u^2+v^2-3}{2uv}\right)^2\Theta\left(u+v-\sqrt{3}\right)\right\}.$$

Kohri & Tareda, 1804.08577

Induced GWs

non-Gaussian contributions

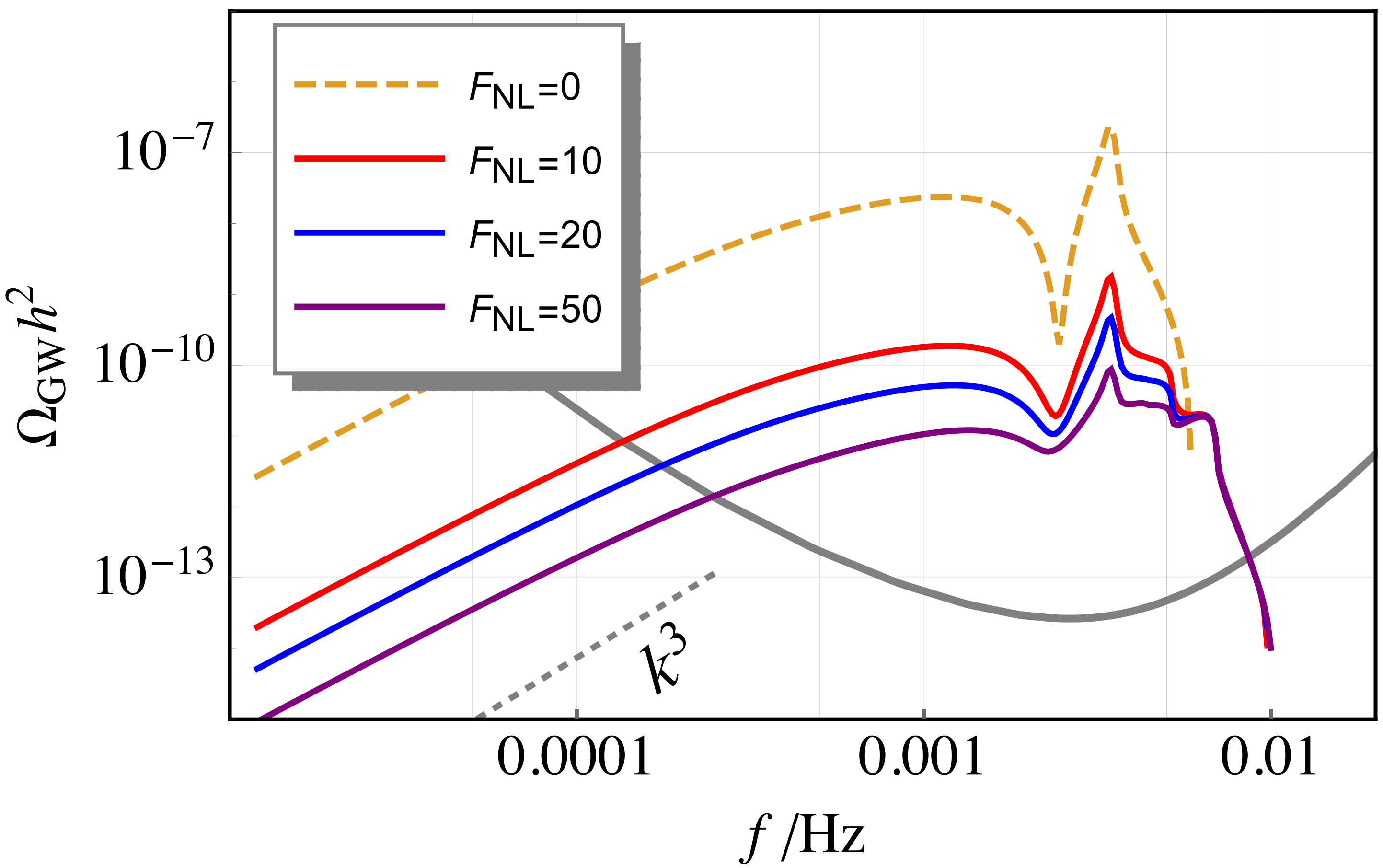
- Then the result is the integral:

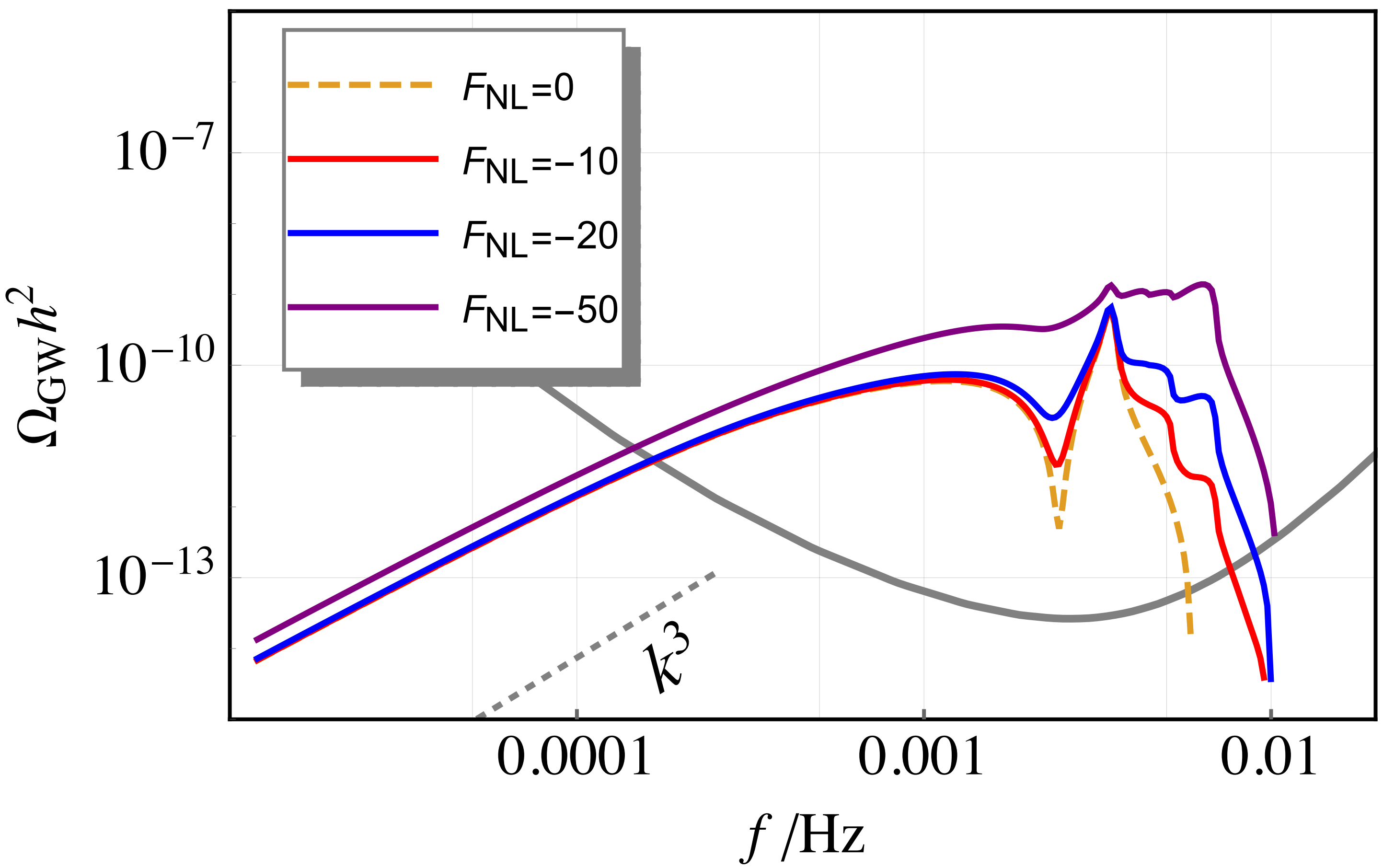
$$\Omega_{\rm GW} = 6\mathcal{A}_{\mathcal{R}}^2 \frac{k^2}{2\pi\sigma^2}\left(\frac{k}{k_*}\right)^4 \int_0^\infty dv \int_{|1-v|}^{1+v} du\, uv\, \mathcal{T}(u,v)$$
$$\times\left(e^{-\frac{(vk-k_*)^2}{2\sigma^2}} + 2\mathcal{A}_{\mathcal{R}} F_{\rm NL}^2 \frac{\sigma}{vk}\sqrt{\frac{\pi}{2}}\Theta(2k_* - vk)\right)$$
$$\times\left(e^{-\frac{(uk-k_*)^2}{2\sigma^2}} + 2\mathcal{A}_{\mathcal{R}} F_{\rm NL}^2 \frac{\sigma}{uk}\sqrt{\frac{\pi}{2}}\Theta(2k_* - uk)\right),$$

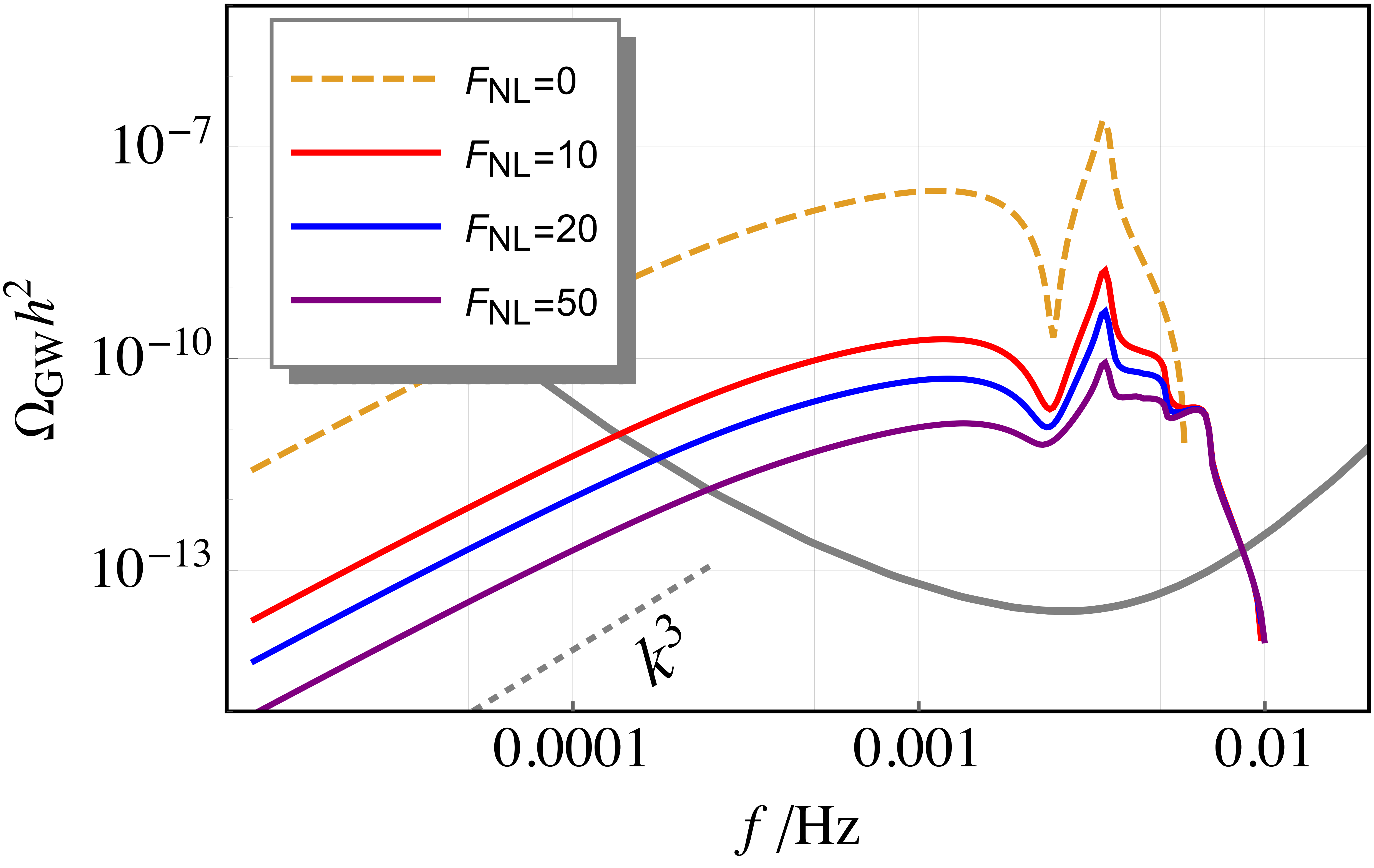
$$\mathcal{T}(u,v) = \frac{1}{4}\left(\frac{4v^2-(1+v^2-u^2)^2}{4uv}\right)^2\left(\frac{u^2+v^2-3}{2uv}\right)^2$$
$$\times\left\{\left(-2+\frac{u^2+v^2-3}{2uv}\ln\left|\frac{3-(u+v)^2}{3-(u-v)^2}\right|\right)^2\right.$$
$$\left.+\,\pi^2\left(\frac{u^2+v^2-3}{2uv}\right)^2\Theta\left(u+v-\sqrt{3}\right)\right\}.$$

Kohri & Tareda, 1804.08577

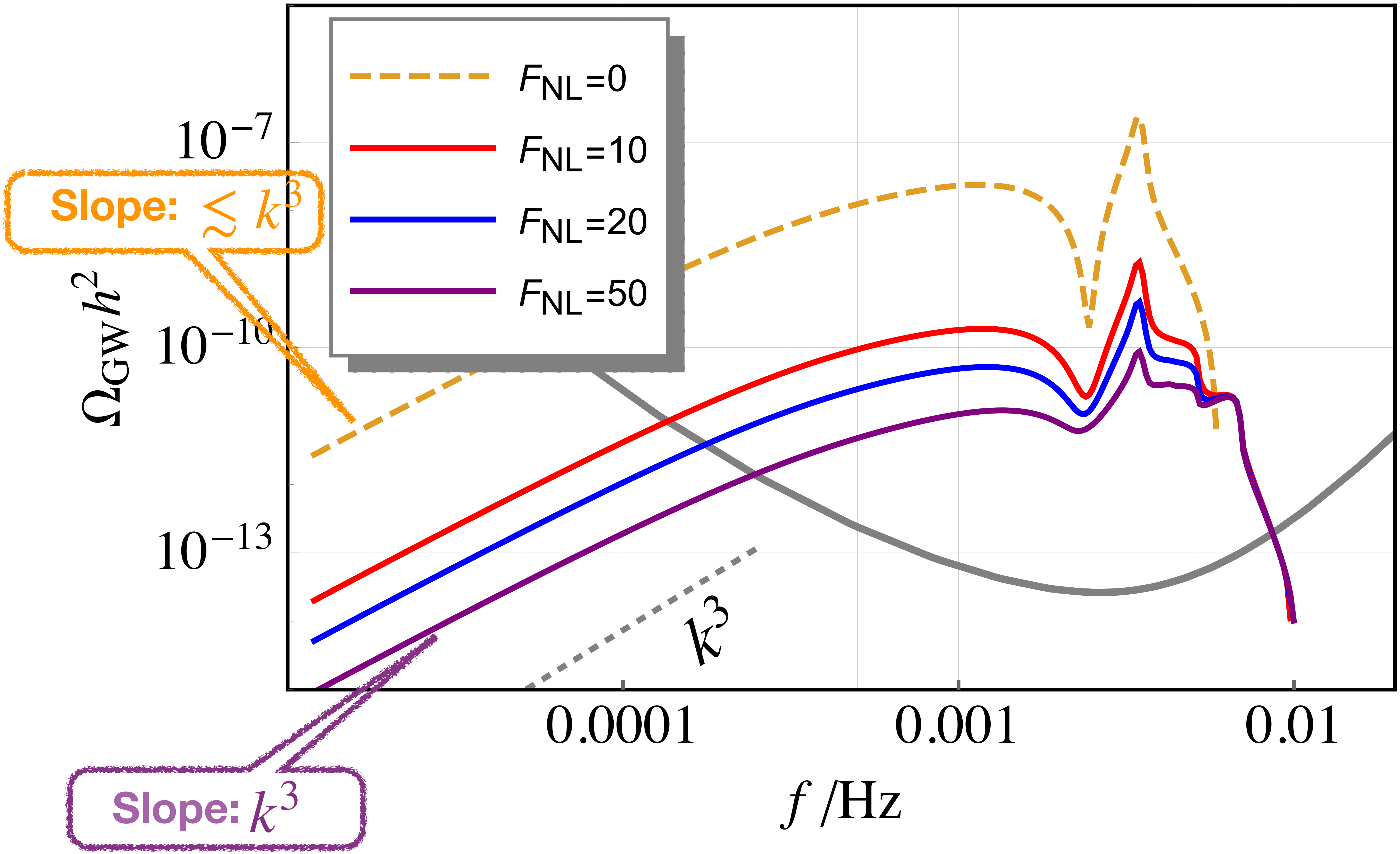
- Up: $F_{NL} > 0$, and we fix the PBH abundance to be 1.
- Down: $F_{NL} < 0$, and we fix the peak amplitude to be $\mathscr{A}_{\mathscr{R}} = 10^{-2}$
- Gray curve: LISA
- Frequency: PBH window <—> LISA band
- Coincidence, but fortunate for our universe.



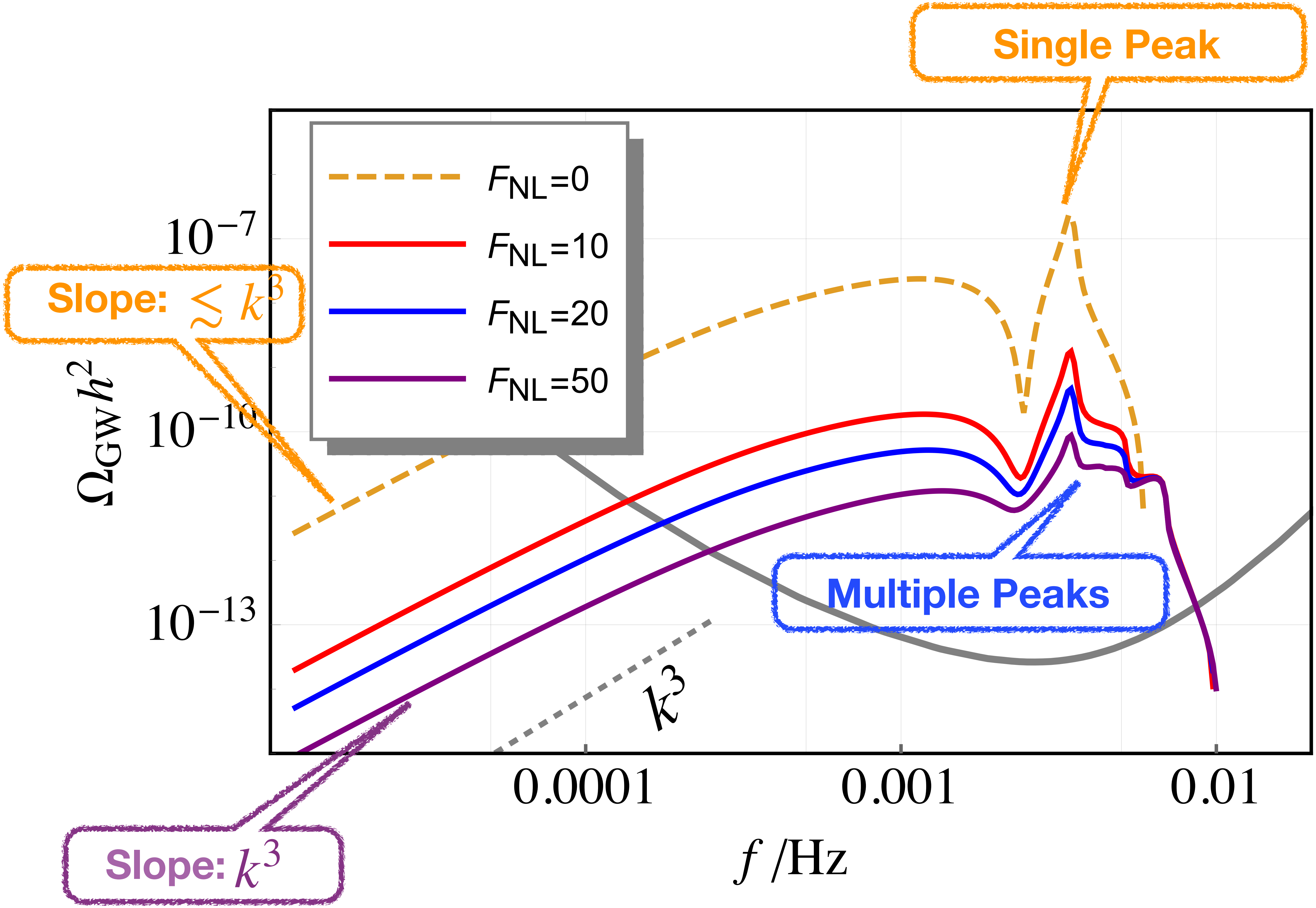




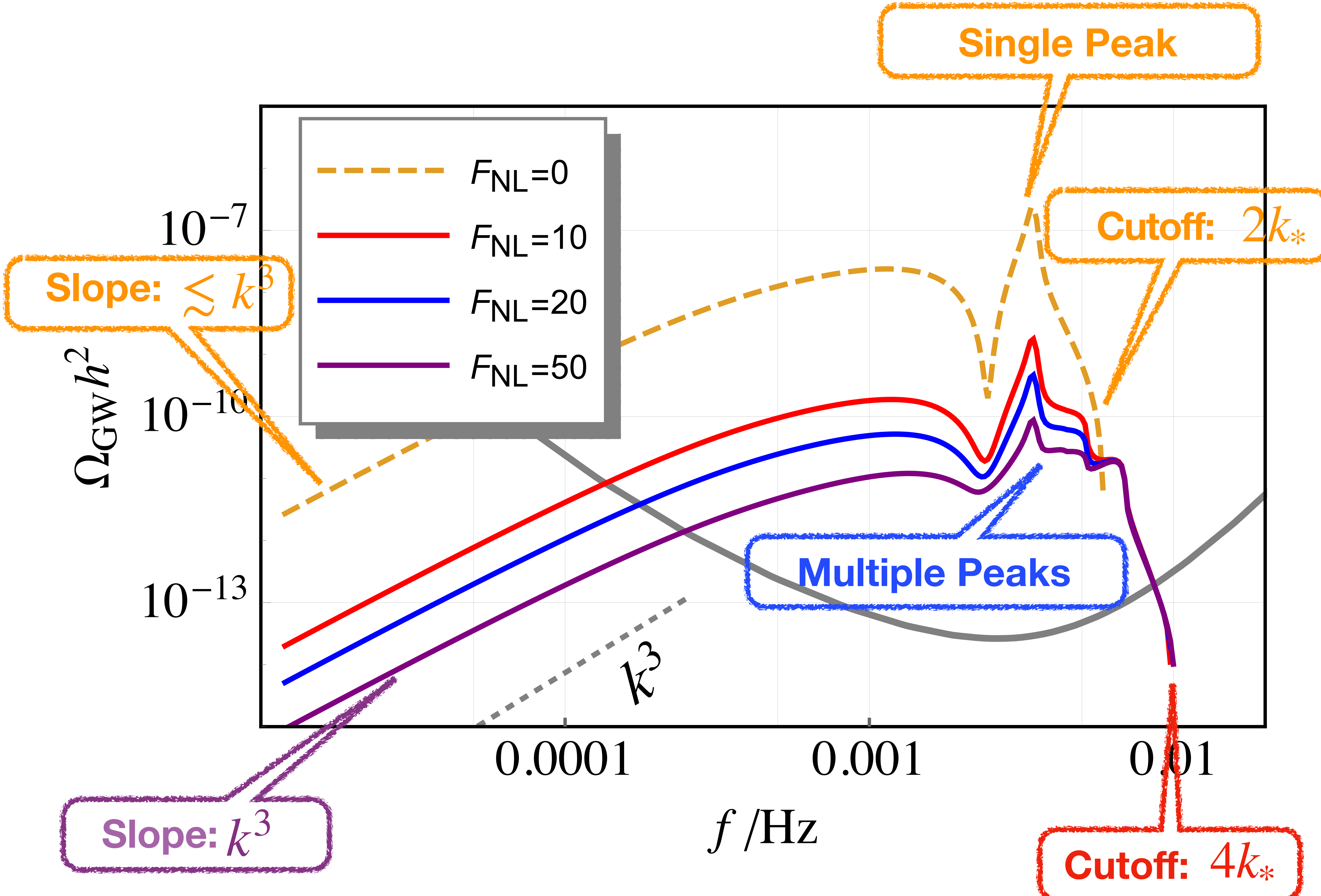
F_{NL}=0
F_{NL}=10
F_{NL}=20
F_{NL}=50
10^{-7}
10^{-10}
10^{-13}
$\Omega_{GW}h^2$
k^3
0.0001
0.001
0.01
f /Hz



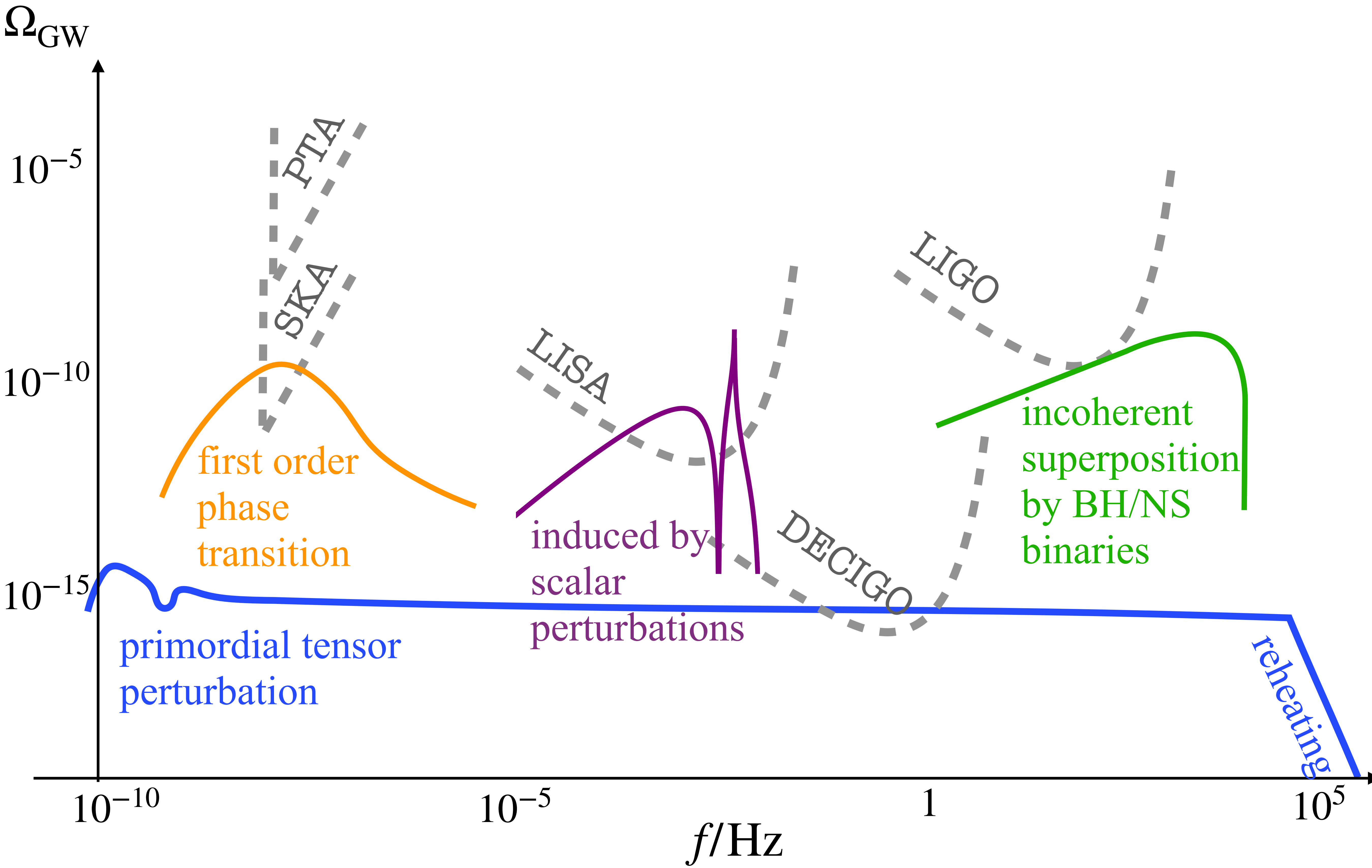
$F_{\rm NL}$=0
$F_{\rm NL}$=10
$F_{\rm NL}$=20
$F_{\rm NL}$=50
10^{-7}
10^{-10}
10^{-13}
$\Omega_{\rm GW} h^2$
Slope: $\lesssim k^3$
k^3
0.0001
0.001
0.01
f /Hz
Slope: k^3



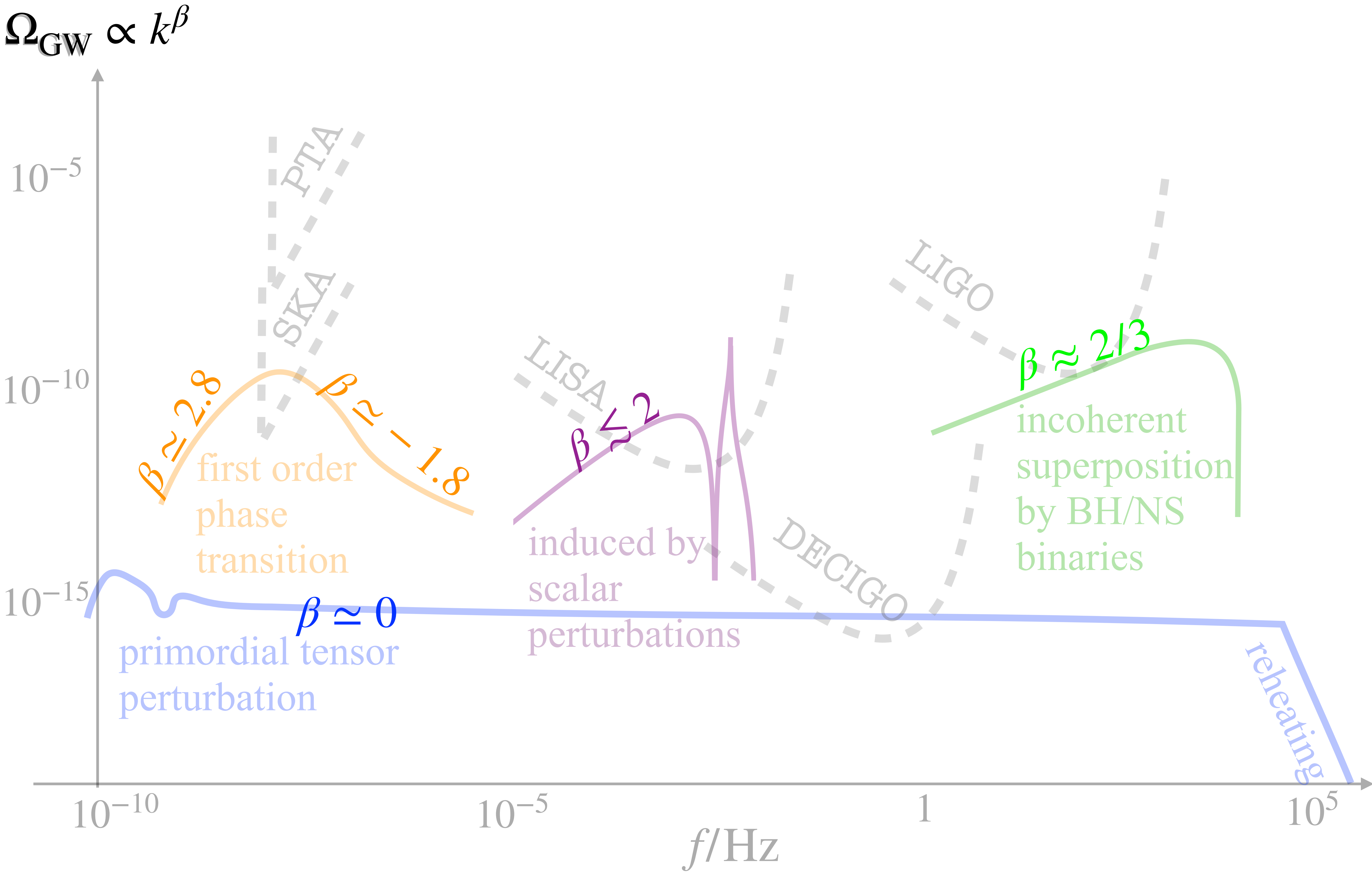
Single Peak
Slope: $\lesssim k^3$
$F_{\rm NL}$=0
$F_{\rm NL}$=10
$F_{\rm NL}$=20
$F_{\rm NL}$=50
10^{-7}
10^{-10}
10^{-13}
$\Omega_{\rm GW} h^2$
Multiple Peaks
k^3
0.0001
0.001
0.01
f /Hz
Slope: k^3



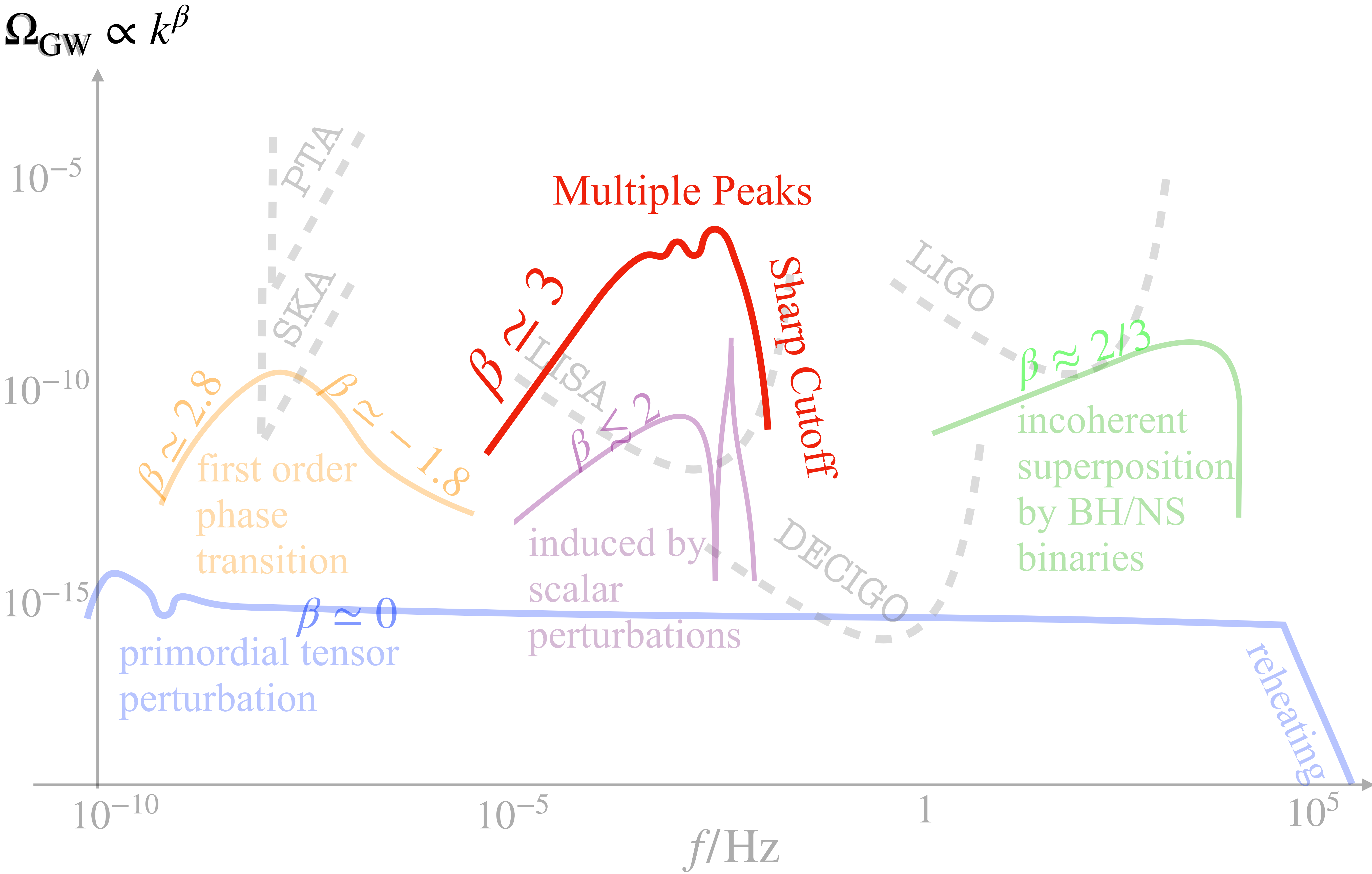
Single Peak
Cutoff: $2k_*$
Slope: $\lesssim k^3$
10^{-7}
10^{-10}
10^{-13}
$\Omega_{\rm GW}h^2$
$F_{\rm NL}$=0
$F_{\rm NL}$=10
$F_{\rm NL}$=20
$F_{\rm NL}$=50
Multiple Peaks
k^3
0.0001
0.001
0.01
f /Hz
Slope: k^3
Cutoff: $4k_*$



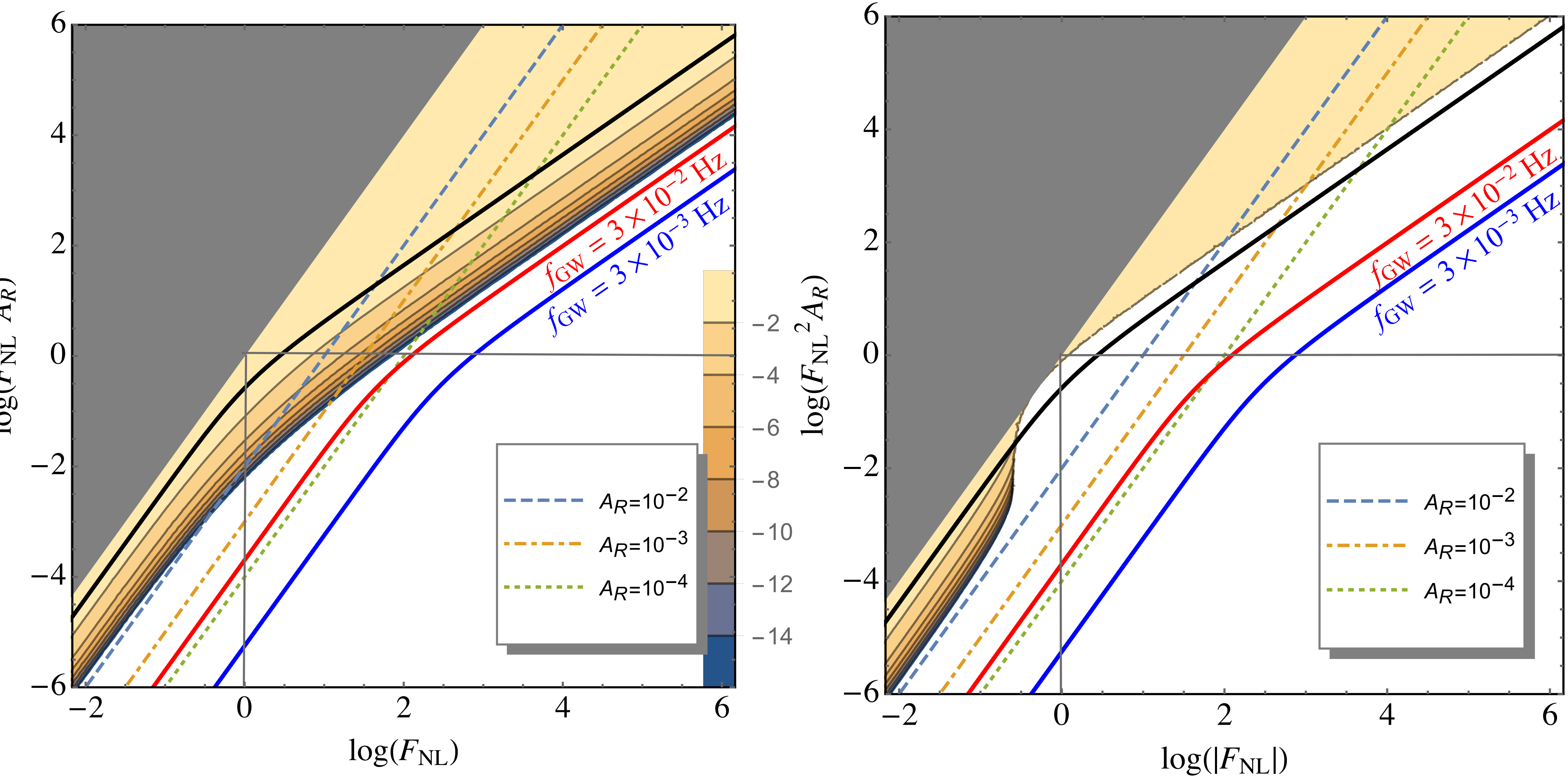
Ω_{GW}
10^{-5}
10^{-10}
10^{-15}
PTA
SKA
LISA
LIGO
DECIGO
first order
phase
transition
induced by
scalar
perturbations
incoherent
superposition
by BH/NS
binaries
primordial tensor
perturbation
reheating
10^{-10}
10^{-5}
1
10^{5}
f/Hz



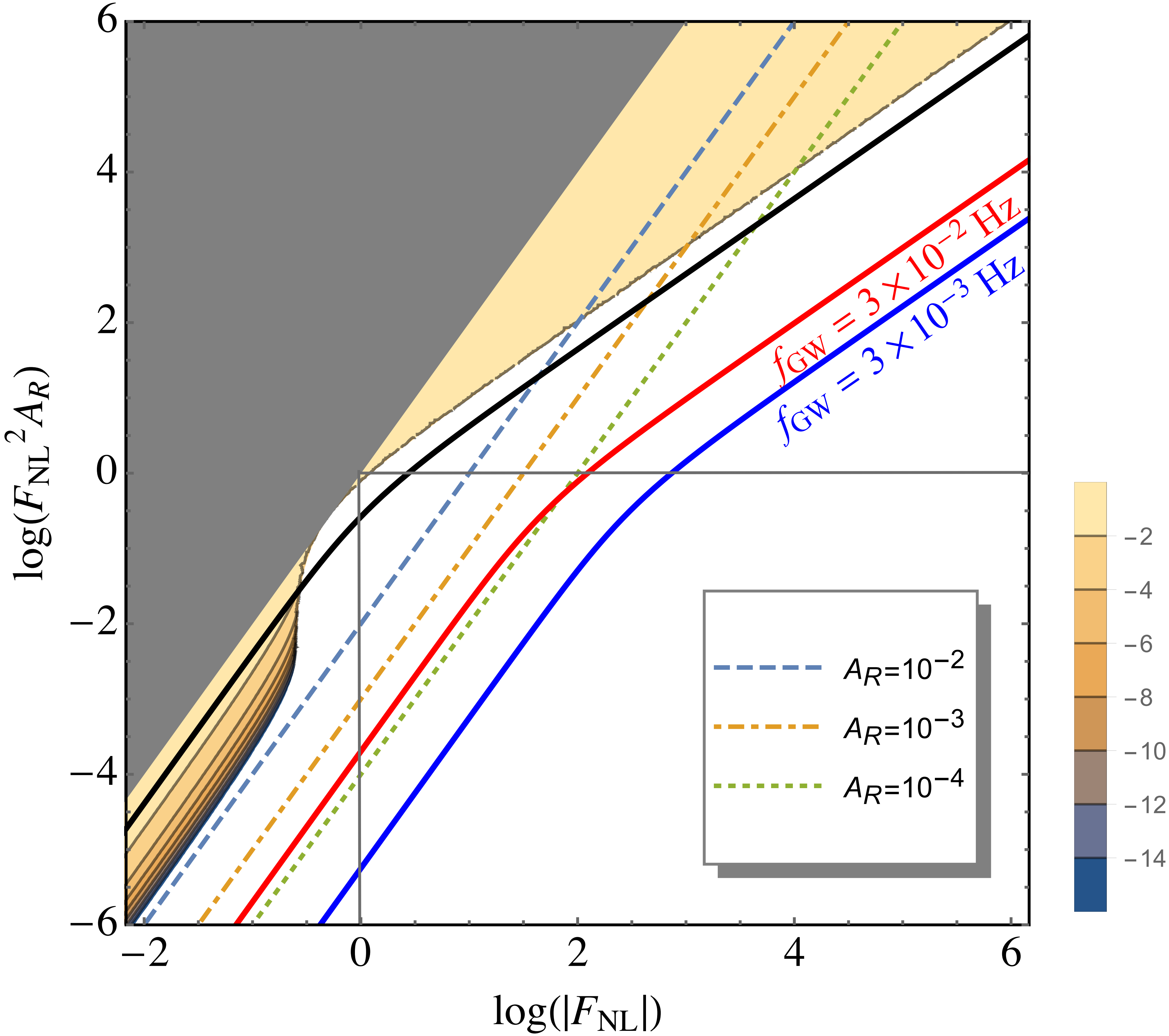
$\Omega_{GW} \propto k^{\beta}$
10^{-5}
10^{-10}
10^{-15}
PTA
SKA
LISA
LIGO
DECIGO
$\beta \simeq 2.8$
$\beta \simeq -1.8$
first order phase transition
$\beta \lesssim 2$
induced by scalar perturbations
$\beta \approx 2/3$
incoherent superposition by BH/NS binaries
$\beta \simeq 0$
primordial tensor perturbation
reheating
10^{-10}
10^{-5}
1
10^{5}
f/Hz



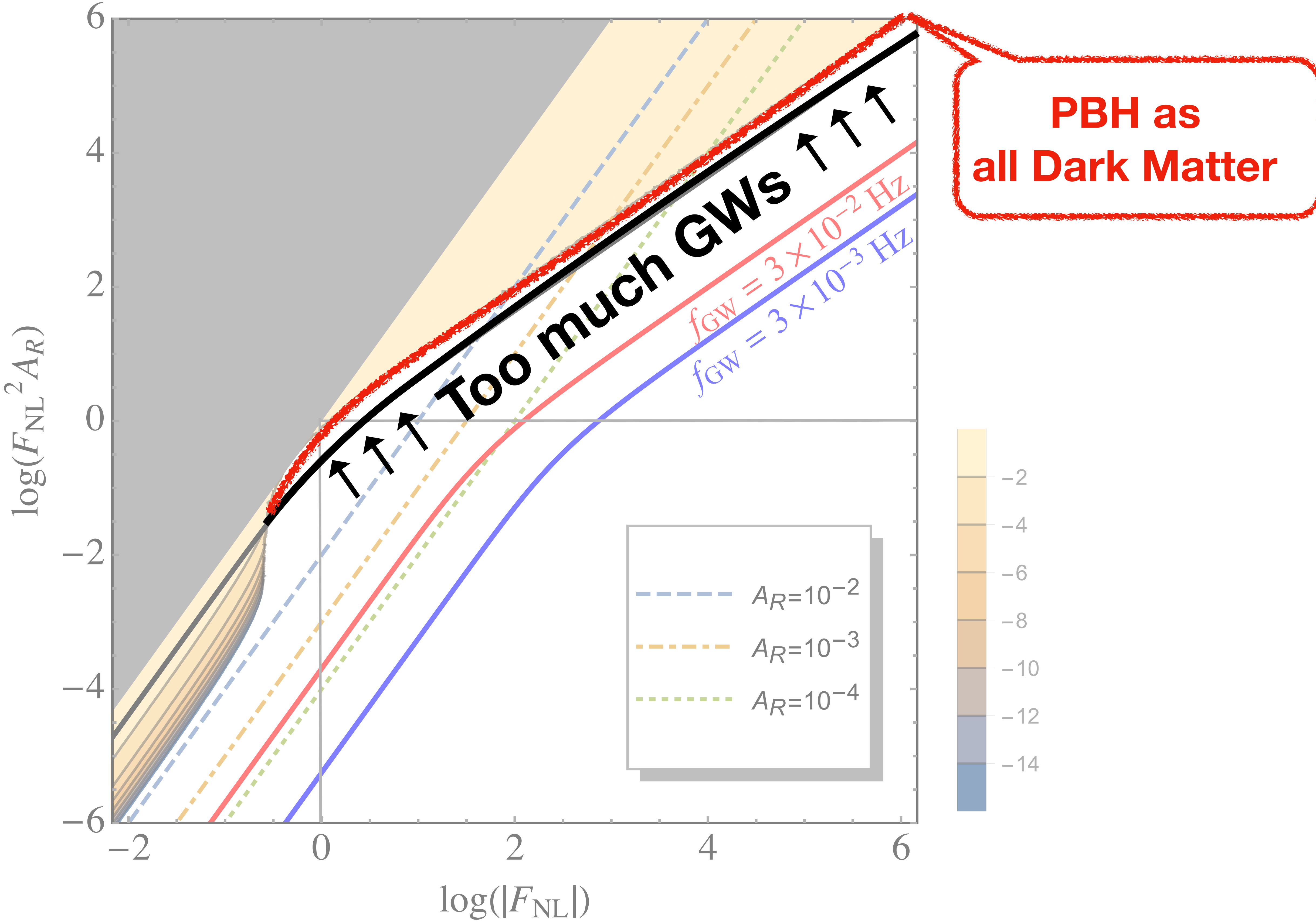
$\Omega_{GW} \propto k^{\beta}$
10^{-5}
10^{-10}
10^{-15}
PTA
SKA
LISA
LIGO
DECIGO
Multiple Peaks
Sharp Cutoff
$\beta \simeq 3$
$\beta \simeq 2.8$
$\beta \simeq -1.8$
first order
phase
transition
$\beta \lesssim 2$
induced by
scalar
perturbations
$\beta \approx 2/3$
incoherent
superposition
by BH/NS
binaries
$\beta \simeq 0$
primordial tensor
perturbation
reheating
10^{-10}
10^{-5}
1
10^{5}
f/Hz

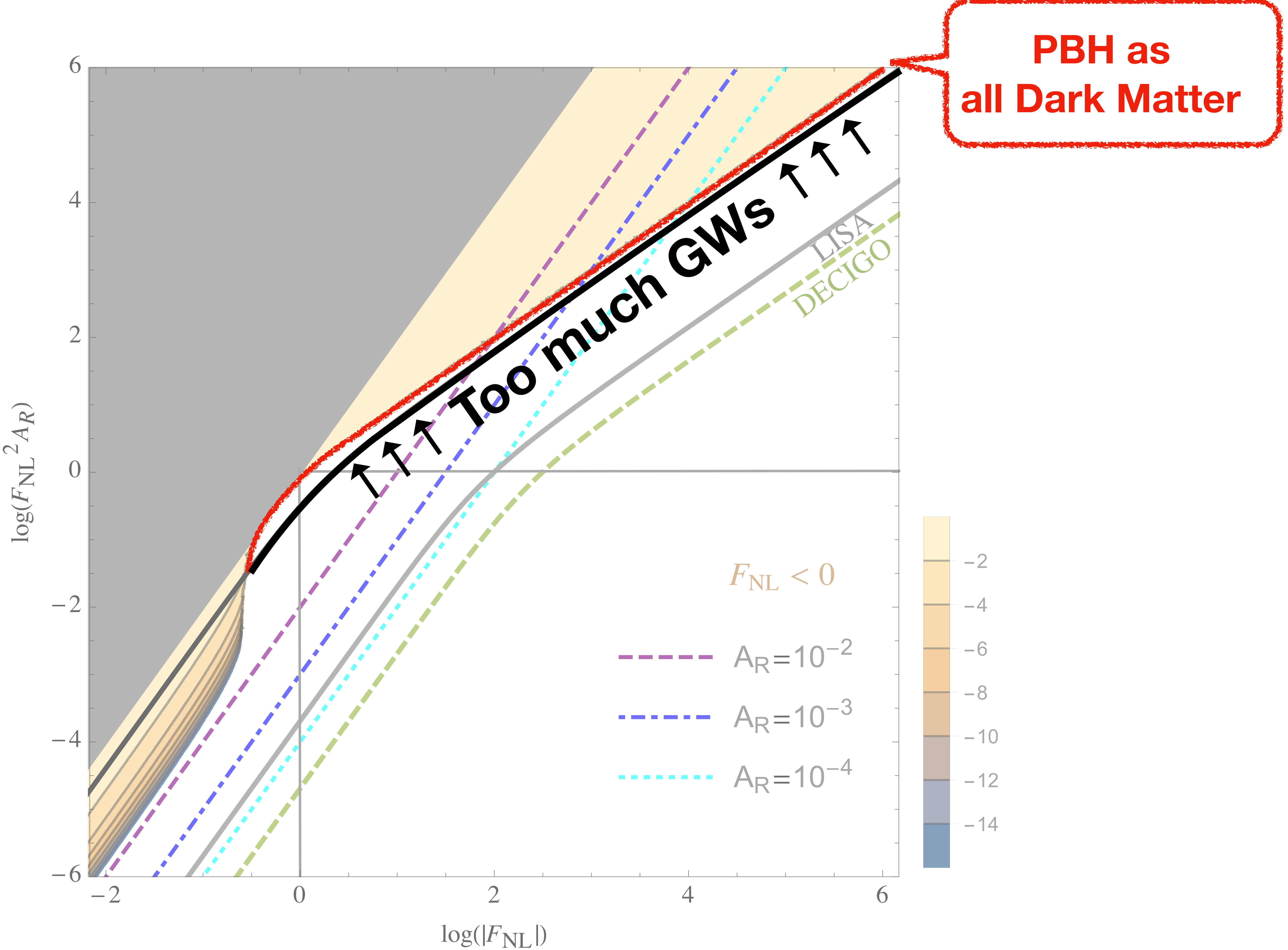


$f_{\rm GW} = 3\times10^{-2}$ Hz
$f_{\rm GW} = 3\times10^{-3}$ Hz
A_R=10^{-2}
A_R=10^{-3}
A_R=10^{-4}
−2
−4
−6
−8
−10
−12
−14
log($F_{\rm NL}$)
log($F_{\rm NL}{}^2 A_R$)
log(|$F_{\rm NL}$|)

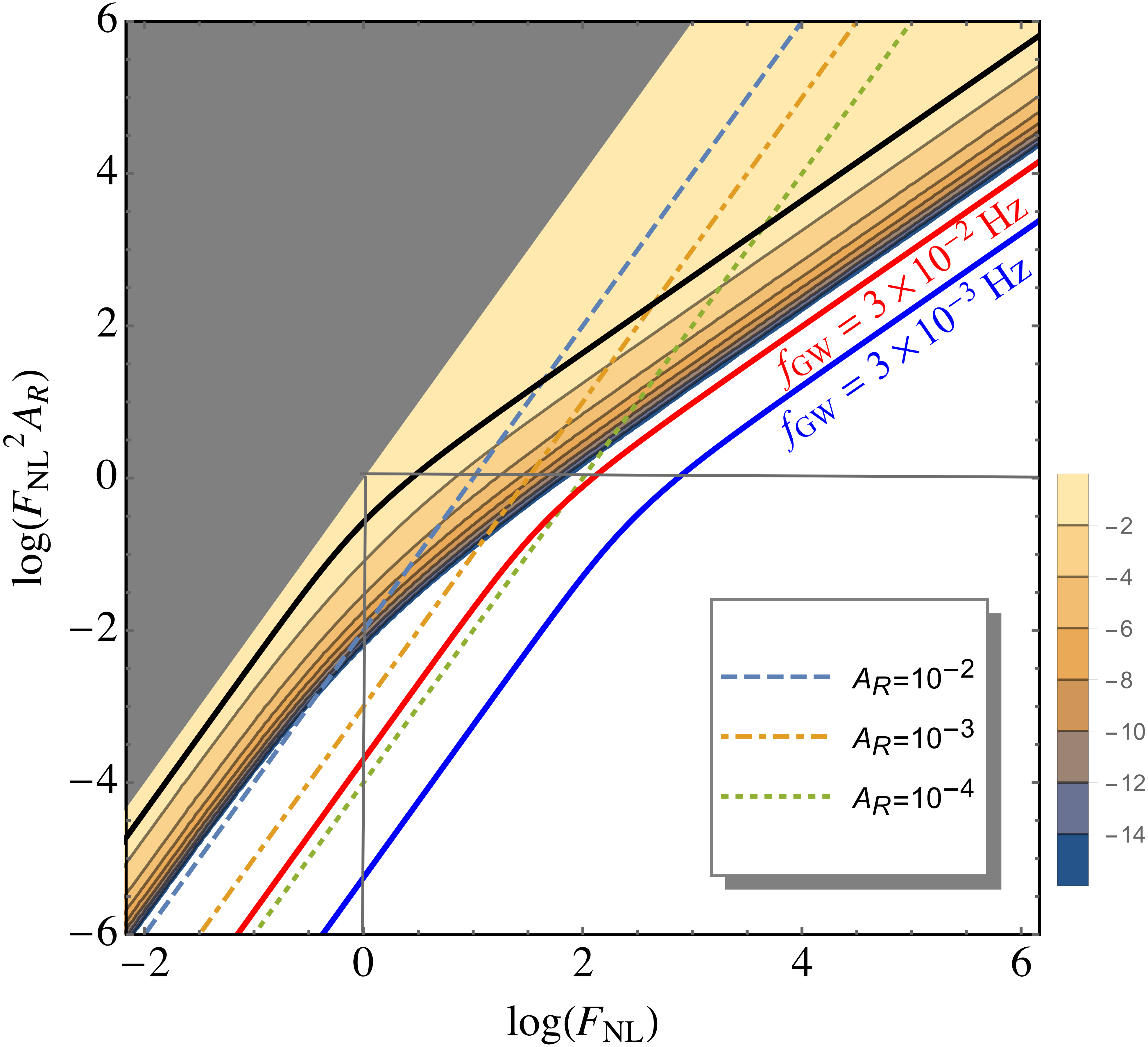


log($F_{\rm NL}{}^2 A_R$)
log($|F_{\rm NL}|$)
$f_{\rm GW} = 3\times10^{-2}$ Hz
$f_{\rm GW} = 3\times10^{-3}$ Hz
A_R=10^{-2}
A_R=10^{-3}
A_R=10^{-4}
6
4
2
0
−2
−4
−6
−2
0
2
4
6
−2
−4
−6
−8
−10
−12
−14

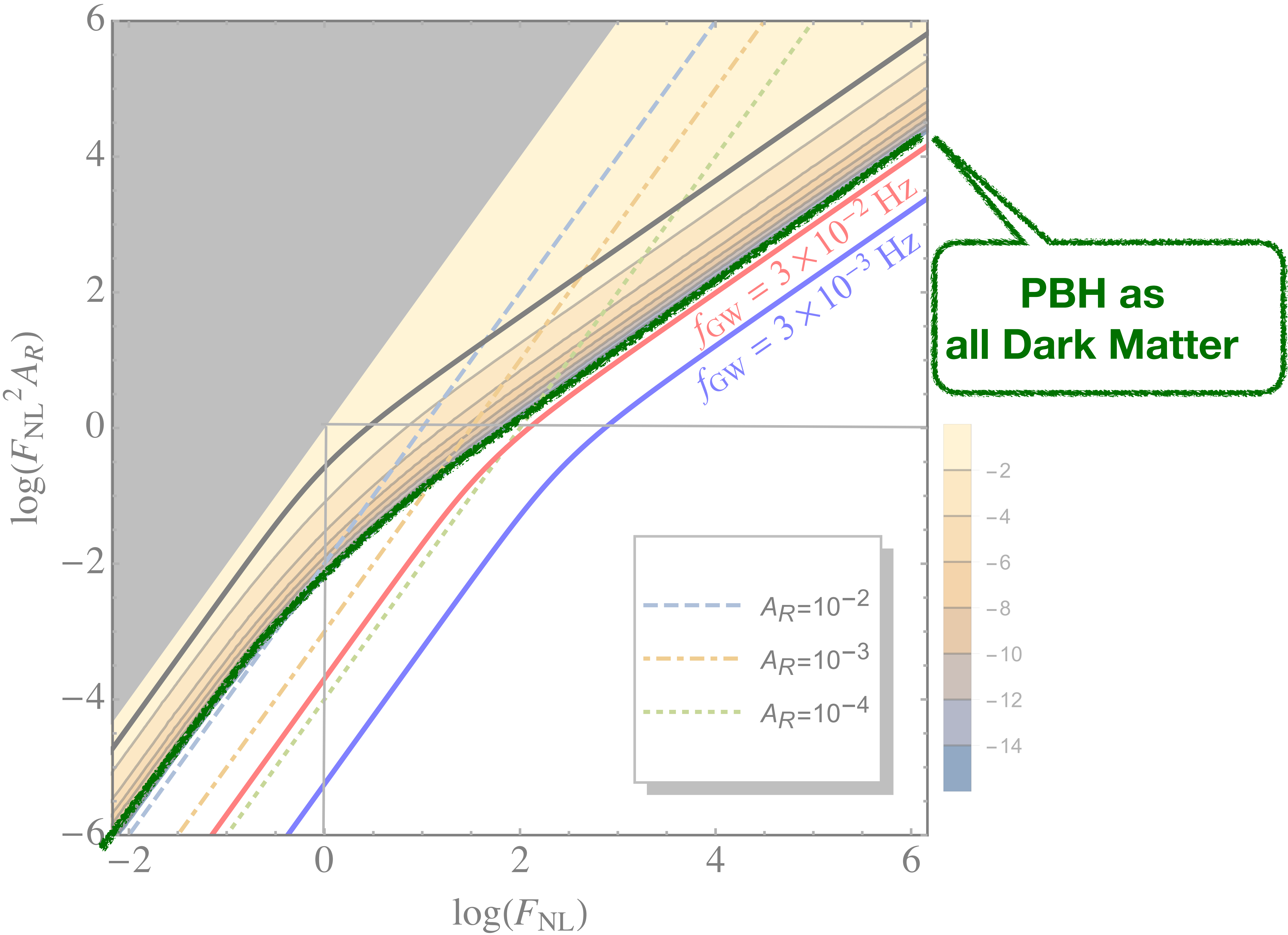

PBH as all Dark Matter
Too much GWs
$f_{GW} = 3\times10^{-2}$ Hz
$f_{GW} = 3\times10^{-3}$ Hz
$A_R=10^{-2}$
$A_R=10^{-3}$
$A_R=10^{-4}$
$\log(F_{NL}{}^2 A_R)$
$\log(|F_{NL}|)$



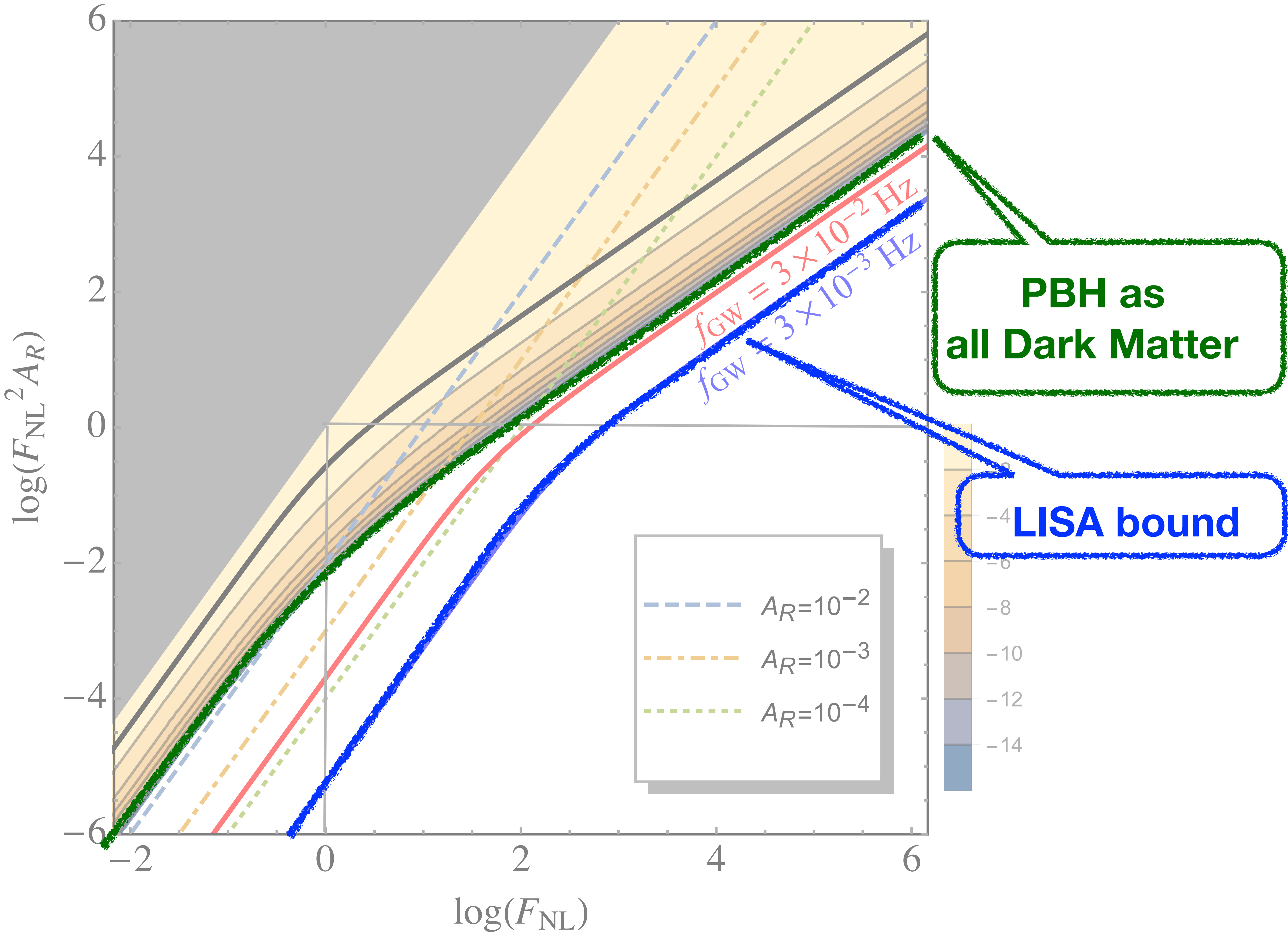
PBH as
all Dark Matter
Too much GWs
LISA
DECIGO
$F_{\rm NL} < 0$
$A_R=10^{-2}$
$A_R=10^{-3}$
$A_R=10^{-4}$
$\log(F_{\rm NL}{}^2 A_R)$
$\log(|F_{\rm NL}|)$
−2
−4
−6
−8
−10
−12
−14



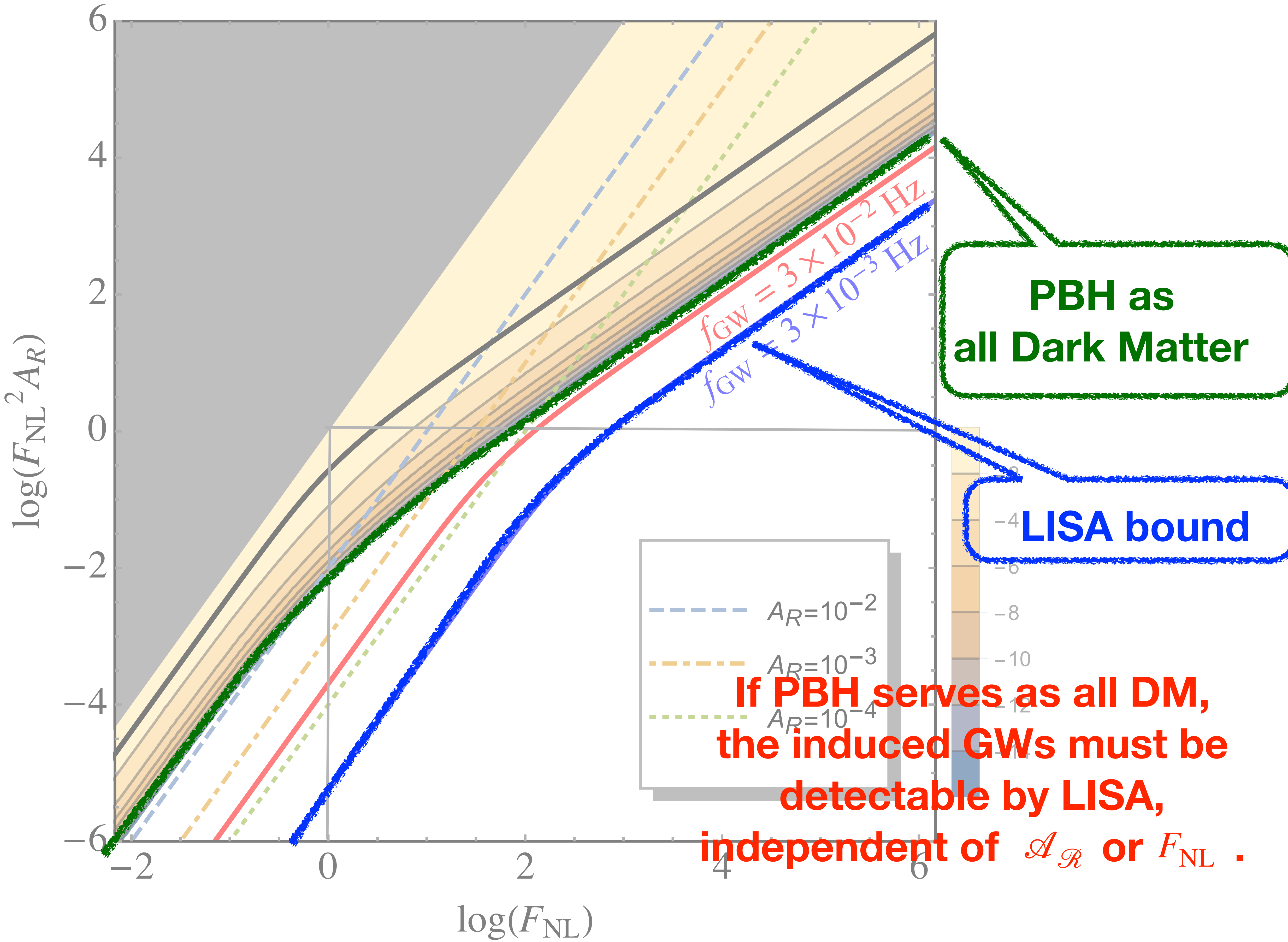
6
4
2
0
−2
−4
−6
−2
0
2
4
6
$\log(F_{\rm NL}{}^2 A_R)$
$\log(F_{\rm NL})$
$f_{\rm GW} = 3\times10^{-2}$ Hz
$f_{\rm GW} = 3\times10^{-3}$ Hz
A_R=10^{-2}
A_R=10^{-3}
A_R=10^{-4}
−2
−4
−6
−8
−10
−12
−14



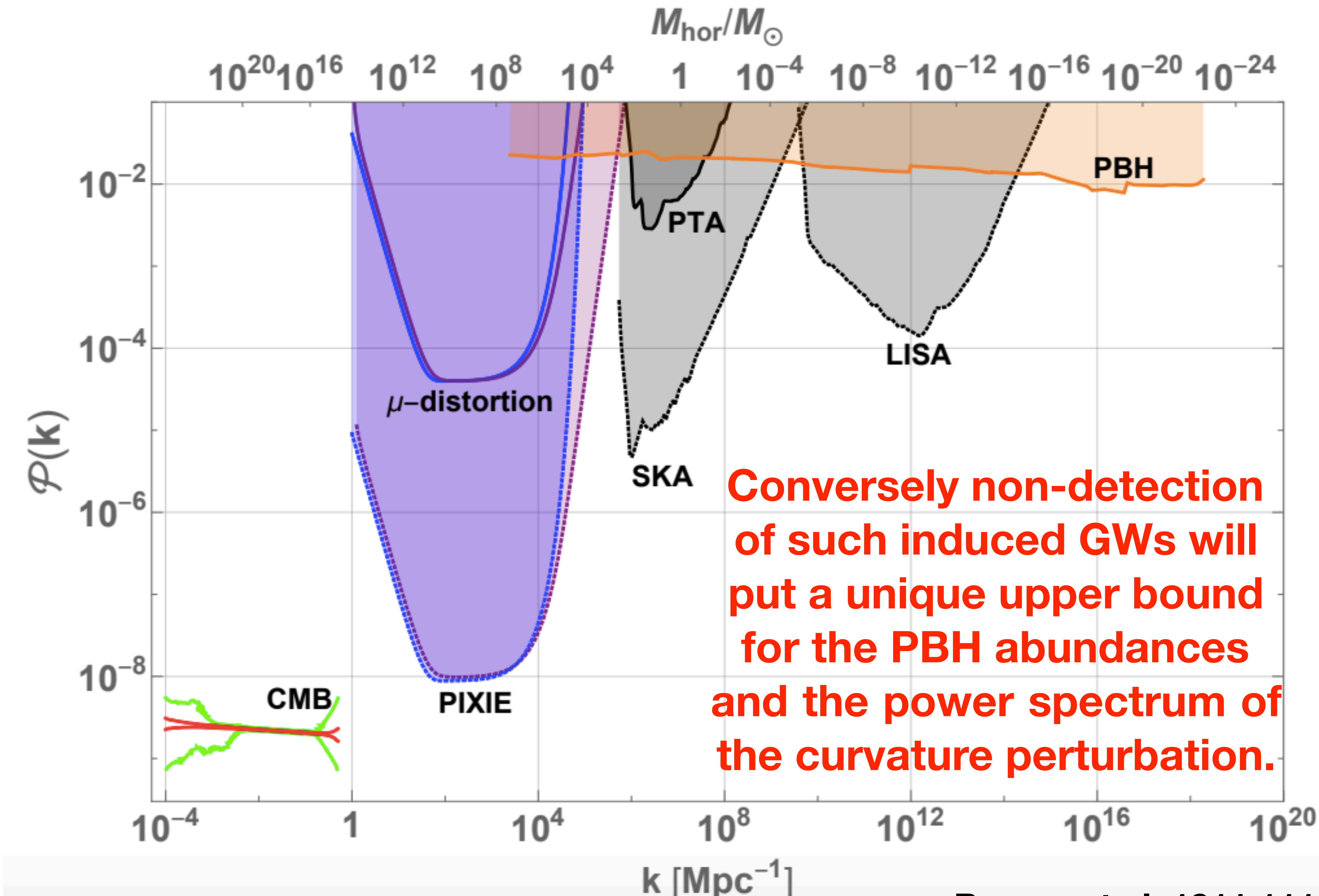
PBH as
all Dark Matter
$f_{GW} = 3\times10^{-2}$ Hz
$f_{GW} = 3\times10^{-3}$ Hz
A_R=10^{-2}
A_R=10^{-3}
A_R=10^{-4}
$\log(F_{NL}{}^2 A_R)$
$\log(F_{NL})$



PBH as all Dark Matter
LISA bound
$f_{GW} = 3\times10^{-2}$ Hz
$f_{GW} = 3\times10^{-3}$ Hz
$A_R=10^{-2}$
$A_R=10^{-3}$
$A_R=10^{-4}$
$\log(F_{NL}{}^2 A_R)$
$\log(F_{NL})$
−4
−6
−8
−10
−12
−14



PBH as
all Dark Matter
LISA bound
$f_{\rm GW} = 3\times10^{-2}$ Hz
$f_{\rm GW} = 3\times10^{-3}$ Hz
A_R=10^{-2}
A_R=10^{-3}
A_R=10^{-4}
$\log(F_{\rm NL}{}^2 A_R)$
$\log(F_{\rm NL})$
6
4
2
0
−2
−4
−6
−2
0
2
4
6
−4
−6
−8
−10
−12
If PBH serves as all DM,
the induced GWs must be
detectable by LISA,
independent of $\mathcal{A}_{\mathcal{R}}$ or $F_{\rm NL}$.



Byrnes et al, 1811.11158

Summary

- Induced GW is a very important source of SGWB.
- LISA detection and crosscheck with PBH abundances.
- Our work shows that induced GW is also a good probe of primordial non-Gaussianity.
- Our work reveals the importance of how to discriminate different sources of SGWB.

Thank you!