Cosmological GWBs

Andrea Mitridate

VIPER GW Summer School | Jul. 12, 2024

DESY.

NANOGrav
Physics Frontiers Center

OUTLINE

what is the fuss all about

general properties of cosmological GWBs

two examples

how to search for them with `PTArcade`

OUTLINE

what is the fuss all about

general properties of cosmological GWBs

two examples

how to search for them with `PTArcade`

OUTLINE

what is the fuss all about

general properties of cosmological GWBs

two examples

how to search for them with `PTArcade`

OUTLINE

what is the fuss all about

general properties of cosmological GWBs

two examples

how to search for them with `PTArcade`

The NANOGrav 12.5-year Data Set: Search For An Isotropic Stochastic Gravitational-Wave Background
Z. Arzoumanian, P.T. Baker, H. Blumer, B. Becsy, A. Brazier, P.R. Brook, S. Burke-Spolaor, S. Chatterjee, S. Chen, J.M. Cordes and 51 more authors
arXiv: 2009.04496 [astro-ph.HE,astro-ph.GA,gr-qc]
my.paperscape: , inSPIRE:
references (27) citations (315) abstract
astro-ph.CO
345
hep-ph
255
high energy experiment (hep-ex)
nuclear experiment (nucl-ex)
high energy lattice (hep-lat)
hep-th
140
gr-co
316


Colouring: category
The NANOGrav 15-year Data Set: Evidence for a Gravitational-Wave Background
G. Agazie, A. Anumarlapudi, A.M. Archibald, Z. Arzoumanian, P.T. Baker, B. Becsy, L. Blecha, A. Brazier, P.R. Brook, S. Burke-Spolaor and 104 more authors
arXiv: 2306.16213 [astro-ph.HE,gr-qc]
my.paperscape: , inSPIRE:
references (0) citations (404) abstract
high energy experiment (hep-ex)
nuclear experiment (nucl-ex)
high energy lattice (hep-lat)
hep-ph 318
astro-ph.CO 420
gr-co 430
hep-th 171

A NEW WINDOW INTO THE UNIVERSE

The NANOGrav 15 yr Data Set: Evidence for a Gravitational-wave Background #1

NANOGrav Collaboration • Gabriella Agazie (Marquette U.) et al. (Jun 28, 2023)

Published in: *Astrophys.J.Lett.* 951 (2023) 1, L8 • e-Print: 2306.16213 [astro-ph.HE]

pdf DOI cite claim reference search 700 citations

Search for an Isotropic Gravitational-wave Background with the Parkes Pulsar Timing Array #2

Daniel J. Reardon (Swinburne U., Ctr. Astrophys. Supercomput. and Australian Natl. U., Canberra (main)), Andrew Zic (Australia, CSIRO, Epping and Macquarie U.), Ryan M. Shannon (Swinburne U., Ctr. Astrophys. Supercomput. and Australian Natl. U., Canberra (main)), George B. Hobbs (Australia, CSIRO, Epping), Matthew Bailes (Swinburne U., Ctr. Astrophys. Supercomput. and Australian Natl. U., Canberra (main)) et al. (Jun 28, 2023)

Published in: *Astrophys.J.Lett.* 951 (2023) 1, L6 • e-Print: 2306.16215 [astro-ph.HE]

pdf DOI cite claim reference search 551 citations

The second data release from the European Pulsar Timing Array - III. Search for gravitational wave signals #3

EPTA and InPTA: Collaborations • J. Antoniadis (Crete U. and IESL, Heraklion and Bonn, Max Planck Inst., Radioastron.) et al. (Jun 28, 2023)

Published in: *Astron.Astrophys.* 678 (2023) A50, *Astron.Astrophys.* 678 (2023) A50 • e-Print: 2306.16214 [astro-ph.HE]

pdf DOI cite claim reference search 549 citations

Searching for the Nano-Hertz Stochastic Gravitational Wave Background with the Chinese Pulsar Timing Array Data Release I #4

Heng Xu (NAOC, Beijing and Beijing, GUCAS), Siyuan Chen (Peking U., Beijing, KIAA and Peking U.), Yanjun Guo (Bonn, Max Planck Inst., Radioastron.), Jinchen Jiang (NAOC, Beijing and Beijing, GUCAS), Bojun Wang (NAOC, Beijing and Beijing, GUCAS) et al. (Jun 28, 2023)

Published in: *Res.Astron.Astrophys.* 23 (2023) 7, 075024 • e-Print: 2306.16216 [astro-ph.HE]

pdf DOI cite claim reference search 522 citations

The NANOGrav 15 yr Data Set: Search for Signals from New Physics #5

NANOGrav Collaboration • Adeela Afzal (Munster U. and Quaid-i-Azam U.) et al. (Jun 28, 2023)

Published in: *Astrophys.J.Lett.* 951 (2023) 1, L11 • e-Print: 2306.16219 [astro-ph.HE]

pdf links DOI cite claim reference search 437 citations evidence papers

The NANOGrav 15 yr Data Set: Evidence for a Gravitational-wave Background #1

NANOGrav Collaboration • Gabriella Agazie (Marquette U.) et al. (Jun 28, 2023)

Published in: *Astrophys.J.Lett.* 951 (2023) 1, L8 • e-Print: 2306.16213 [astro-ph.HE]

pdf DOI cite claim — reference search — 700 citations

Search for an Isotropic Gravitational-wave Background with the Parkes Pulsar Timing Array #2

Daniel J. Reardon (Swinburne U., Ctr. Astrophys. Supercomput. and Australian Natl. U., Canberra (main)), Andrew Zic (Australia, CSIRO, Epping and Macquarie U.), Ryan M. Shannon (Swinburne U., Ctr. Astrophys. Supercomput. and Australian Natl. U., Canberra (main)), George B. Hobbs (Australia, CSIRO, Epping), Matthew Bailes (Swinburne U., Ctr. Astrophys. Supercomput. and Australian Natl. U., Canberra (main)) et al. (Jun 28, 2023)

Published in: *Astrophys.J.Lett.* 951 (2023) 1, L6 • e-Print: 2306.16215 [astro-ph.HE]

pdf DOI cite claim — reference search — 551 citations

The second data release from the European Pulsar Timing Array - III. Search for gravitational wave signals #3

EPTA and InPTA: Collaborations • J. Antoniadis (Crete U. and IESL, Heraklion and Bonn, Max Planck Inst., Radioastron.) et al. (Jun 28, 2023)

Published in: *Astron.Astrophys.* 678 (2023) A50, *Astron.Astrophys.* 678 (2023) A50 • e-Print: 2306.16214 [astro-ph.HE]

pdf DOI cite claim — reference search — 549 citations

Searching for the Nano-Hertz Stochastic Gravitational Wave Background with the Chinese Pulsar Timing Array Data Release I #4

Heng Xu (NAOC, Beijing and Beijing, GUCAS), Siyuan Chen (Peking U., Beijing, KIAA and Peking U.), Yanjun Guo (Bonn, Max Planck Inst., Radioastron.), Jinchen Jiang (NAOC, Beijing and Beijing, GUCAS), Bojun Wang (NAOC, Beijing and Beijing, GUCAS) et al. (Jun 28, 2023)

Published in: *Res.Astron.Astrophys.* 23 (2023) 7, 075024 • e-Print: 2306.16216 [astro-ph.HE]

pdf DOI cite claim — reference search — 522 citations

The NANOGrav 15 yr Data Set: Search for Signals from New Physics #5

NANOGrav Collaboration • Adeela Afzal (Munster U. and Quaid-i-Azam U.) et al. (Jun 28, 2023)

Published in: *Astrophys.J.Lett.* 951 (2023) 1, L11 • e-Print: 2306.16219 [astro-ph.HE]

pdf links DOI cite claim — reference search — 437 citations

The NANOGrav 15 yr Data Set: Evidence for a Gravitational-wave Background #1
NANOGrav Collaboration • Gabriella Agazie (Marquette U.) et al. (Jun 28, 2023)
Published in: *Astrophys.J.Lett.* 951 (2023) 1, L8 • e-Print: 2306.16213 [astro-ph.HE]
pdf DOI cite claim reference search 700 citations

Search for an Isotropic Gravitational-wave Background with the Parkes Pulsar Timing Array #2
Daniel J. Reardon (Swinburne U., Ctr. Astrophys. Supercomput. and Australian Natl. U., Canberra (main)), Andrew Zic (Australia, CSIRO, Epping and Macquarie U.), Ryan M. Shannon (Swinburne U., Ctr. Astrophys. Supercomput. and Australian Natl. U., Canberra (main)), George B. Hobbs (Australia, CSIRO, Epping), Matthew Bailes (Swinburne U., Ctr. Astrophys. Supercomput. and Australian Natl. U., Canberra (main)) et al. (Jun 28, 2023)
Published in: *Astrophys.J.Lett.* 951 (2023) 1, L6 • e-Print: 2306.16215 [astro-ph.HE]
pdf DOI cite claim reference search 551 citations

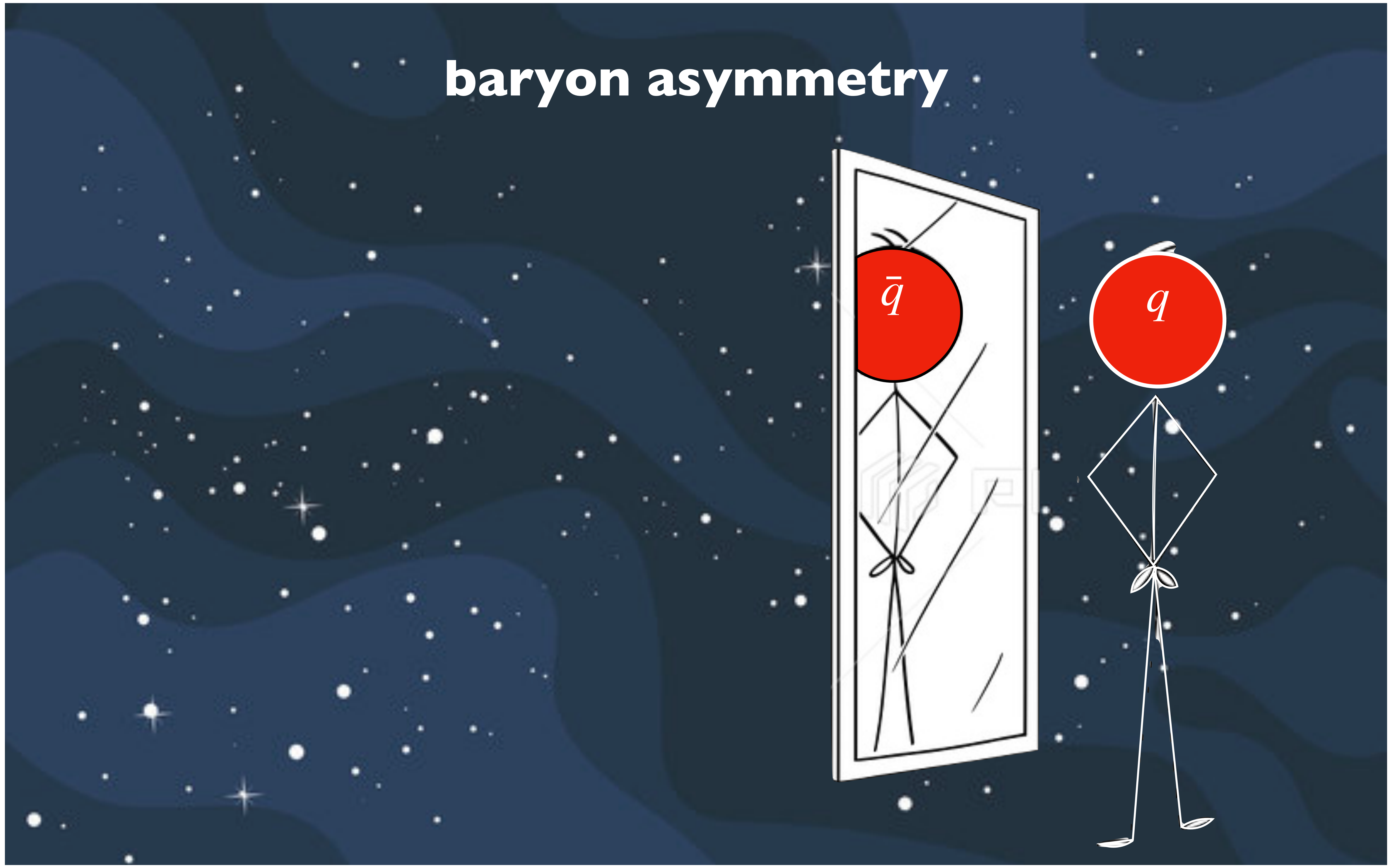
The second data release from the European Pulsar Timing Array - III. Search for gravitational wave signals #3
EPTA and InPTA: Collaborations • J. Antoniadis (Crete U. and IESL, Heraklion and Bonn, Max Planck Inst., Radioastron.) et al. (Jun 28, 2023)
Published in: *Astron.Astrophys.* 678 (2023) A50, *Astron.Astrophys.* 678 (2023) A50 • e-Print: 2306.16214 [astro-ph.HE]
pdf DOI cite claim reference search 549 citations

Searching for the Nano-Hertz Stochastic Gravitational Wave Background with the Chinese Pulsar Timing Array Data Release I #4
Heng Xu (NAOC, Beijing and Beijing, GUCAS), Siyuan Chen (Peking U., Beijing, KIAA and Peking U.), Yanjun Guo (Bonn, Max Planck Inst., Radioastron.), Jinchen Jiang (NAOC, Beijing and Beijing, GUCAS), Bojun Wang (NAOC, Beijing and Beijing, GUCAS) et al. (Jun 28, 2023)
Published in: *Res.Astron.Astrophys.* 23 (2023) 7, 075024 • e-Print: 2306.16216 [astro-ph.HE]
pdf DOI cite claim reference search 522 citations

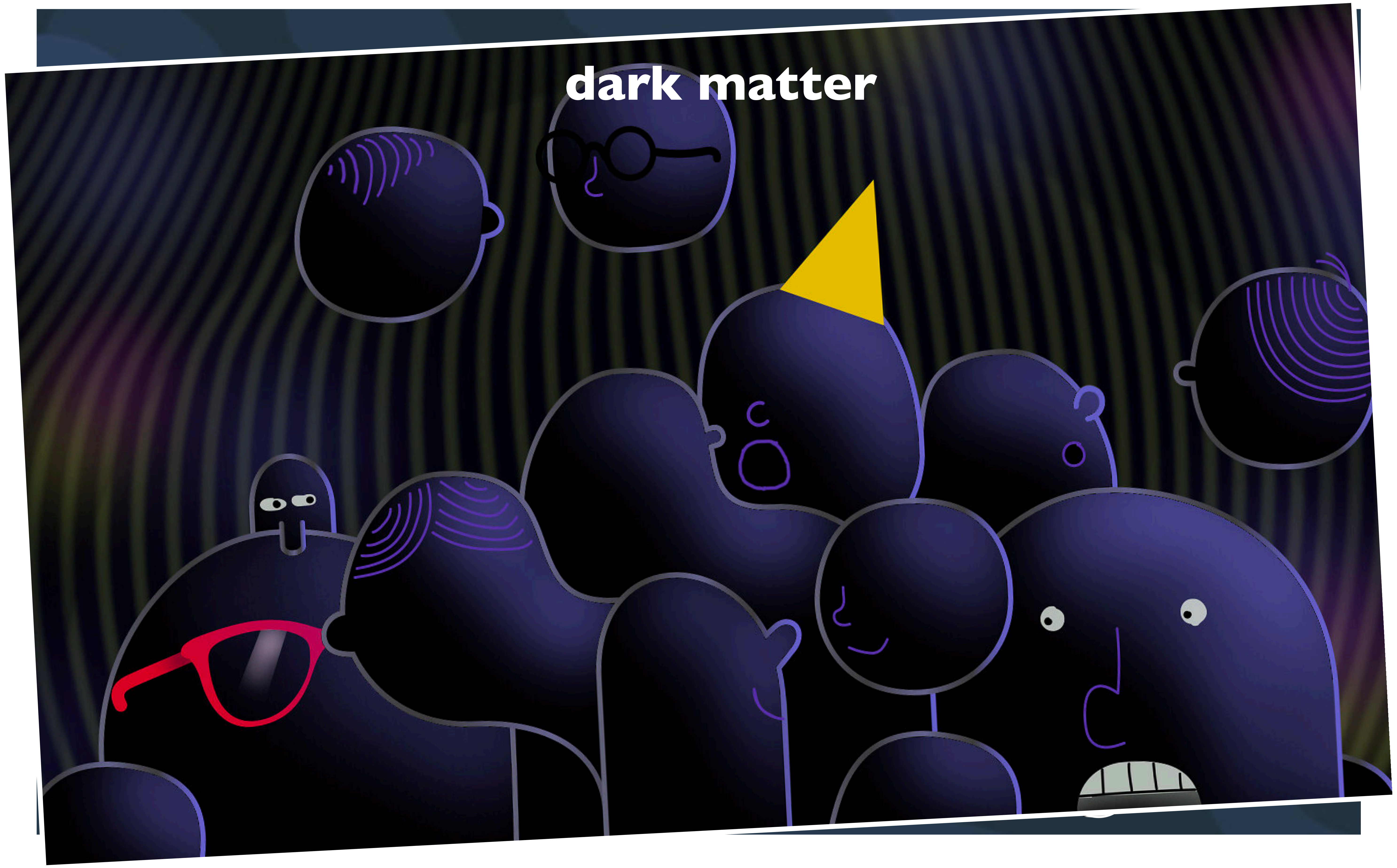
evidence papers

The NANOGrav 15 yr Data Set: Search for Signals from New Physics #5
NANOGrav Collaboration • Adeela Afzal (Munster U. and Quaid-i-Azam U.) et al. (Jun 28, 2023)
Published in: *Astrophys.J.Lett.* 951 (2023) 1, L11 • e-Print: 2306.16219 [astro-ph.HE]
pdf links DOI cite claim reference search 437 citations

NG new physics paper


baryon asymmetry
$\bar{q}$
q

OPEN PROBLEMS IN PARTICLE PHYSICS




dark energy

OPEN PROBLEMS IN PARTICLE PHYSICS

COSMIC ARCHOLOGY

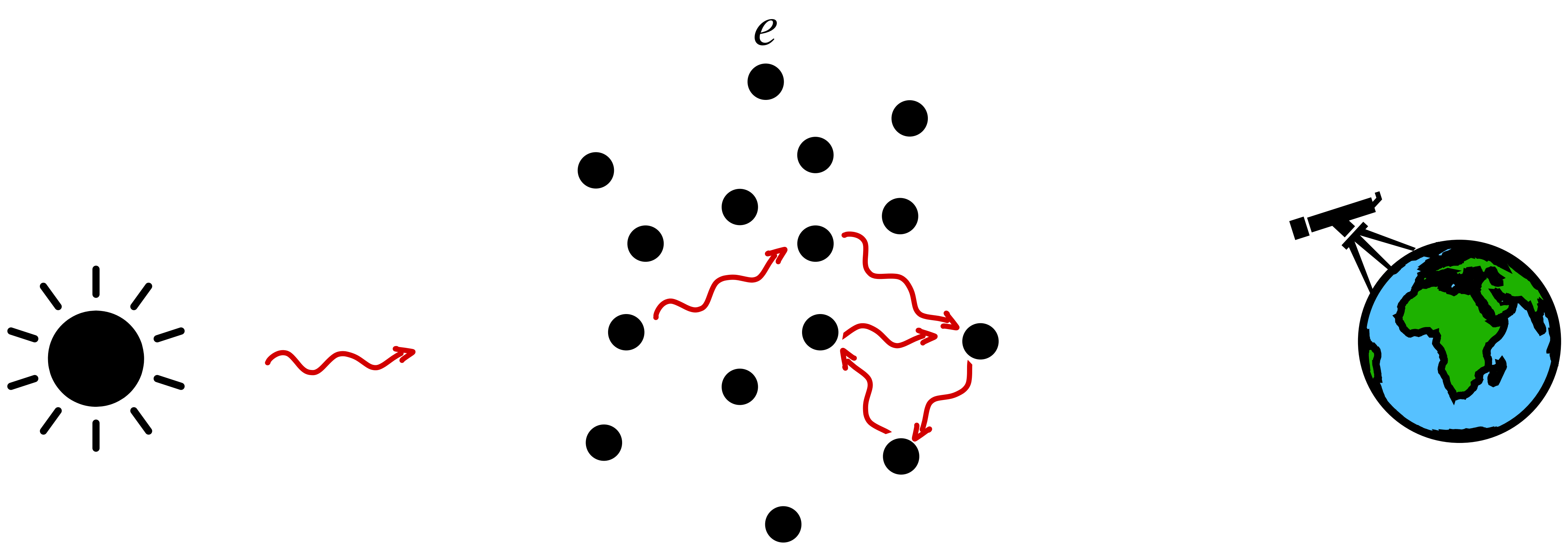
inflation
DM production
baryon asymmetry production

COSMIC ARCHOLOGY

finite speed of light ➜ looking far = looking in the past

THE CMB WALL

photons are not the best messenger in high-density environments

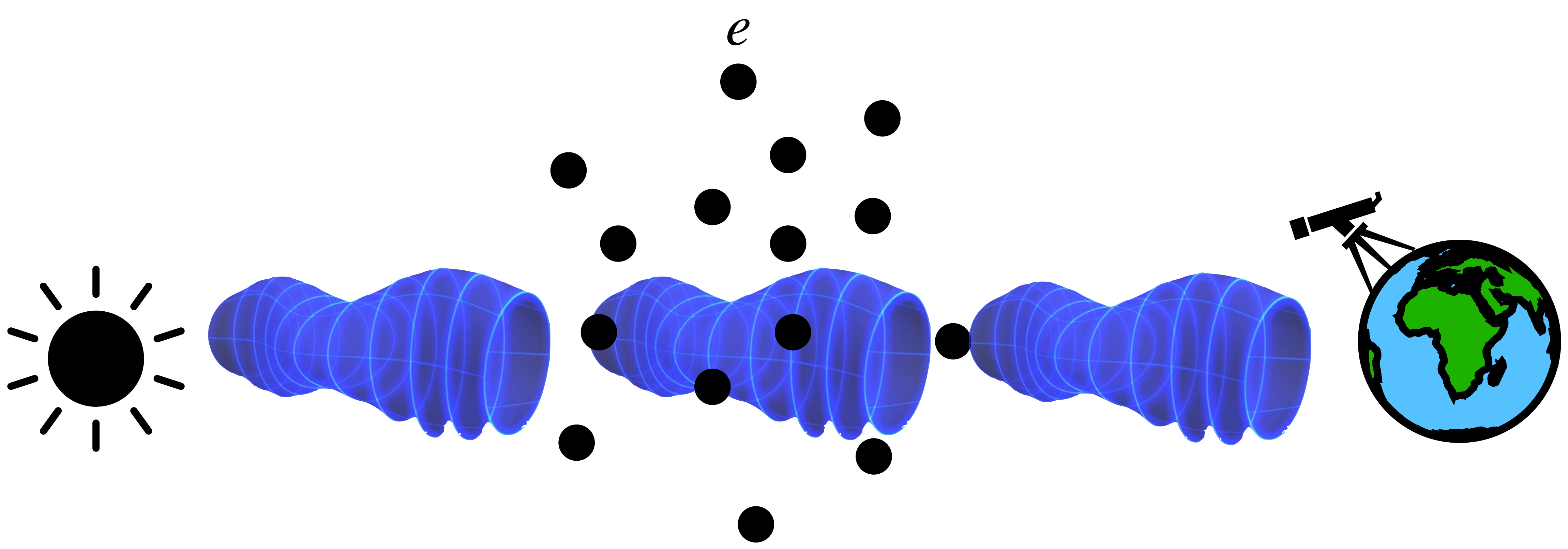


the mean free-path for photons in the primordial plasma is

$$\lambda_\gamma \sim \frac{1}{\sigma_T\, n_e} \sim \mu\mathrm{m} \left(\frac{\mathrm{MeV}}{T}\right)^3$$

any information encoded in EM radiation before recombination is lost in the electron bath

THE CMB WALL



the GW mean free-path in the primordial plasma is

$$\lambda_{\rm GW} \sim \left(\frac{G m_e^2}{\alpha}\right)^2 \lambda_\gamma \sim \frac{1}{\sigma_T\, n_e} \sim 10^{79}\mathrm{m}\left(\frac{\mathrm{MeV}}{T}\right)^3$$

GW do not care about the bath and travel undisturbed trough it

how to describe (stochastic) GWBs

CHARACTERIZING A GWB

$$h_{ij}(t,\vec{x}) = \sum_A \int df \int d\hat{\Omega}\, \underbrace{\tilde{h}_A(f,\hat{\Omega})}_{\text{“Fourier” components}}\, \overbrace{e^{-2\pi i f(t-\hat{\Omega}\cdot\vec{x})}}^{\text{plane waves}}\, \underbrace{e^{A}_{ij}(\hat{\Omega})}_{\text{polarization tensors}}$$

the complex functions $\tilde{h}^A(f,\hat{\Omega})$ are treated as Gaussian random variables

CHARACTERIZING A GWB

$$h_{ij}(t,\vec{x}) = \sum_A \int df \int d\hat{\Omega}\; \underbrace{\tilde{h}_A(f,\hat{\Omega})}_{\text{“Fourier” components}}\; \overbrace{e^{-2\pi i f(t-\hat{\Omega}\cdot\vec{x})}}^{\text{plane waves}}\; \underbrace{e^{A}_{ij}(\hat{\Omega})}_{\text{polarization tensors}}$$

the complex functions $\tilde{h}^A(f,\hat{\Omega})$ are treated as Gaussian random variables

$$\langle \tilde{h}_A(f,\hat{\Omega}) \rangle = 0$$

$$\langle \tilde{h}_A(f,\hat{\Omega})^* \tilde{h}_A(f',\hat{\Omega}') \rangle = \delta_{AA'}\delta(\hat{\Omega},\hat{\Omega}')\delta(f-f')H(f)P(f,\hat{\Omega})$$

CHARACTERIZING A GWB

$$h_{ij}(t,\vec{x}) = \sum_A \int df \int d\hat{\Omega}\, \underbrace{\tilde{h}_A(f,\hat{\Omega})}_{\text{“Fourier” components}}\, \overbrace{e^{-2\pi i f(t-\hat{\Omega}\cdot\vec{x})}}^{\text{plane waves}}\, \underbrace{e^A_{ij}(\hat{\Omega})}_{\text{polarization tensors}}$$

the complex functions $\tilde{h}^A(f,\hat{\Omega})$ are treated as Gaussian random variables

$$\langle \tilde{h}_A(f,\hat{\Omega}) \rangle = 0$$

$$\langle \tilde{h}_A(f,\hat{\Omega})^* \tilde{h}_A(f',\hat{\Omega}') \rangle = \delta_{AA'}\delta(\hat{\Omega},\hat{\Omega}')\delta(f-f')\underbrace{H(f)}_{\text{GWB power spectrum}}\overbrace{P(f,\hat{\Omega})}^{\text{GWB power map}}$$

CHARACTERIZING A GWB

$$h_{ij}(t,\vec{x}) = \sum_A \int df \int d\hat{\Omega}\; \underbrace{\tilde{h}_A(f,\hat{\Omega})}_{\text{“Fourier” components}}\; \overbrace{e^{-2\pi i f(t-\hat{\Omega}\cdot\vec{x})}}^{\text{plane waves}}\; \underbrace{e^{A}_{ij}(\hat{\Omega})}_{\text{polarization tensors}}$$

the complex functions $\tilde{h}^A(f,\hat{\Omega})$ are treated as Gaussian random variables

$$\langle \tilde{h}_A(f,\hat{\Omega}) \rangle = 0$$

$$\langle \tilde{h}_A(f,\hat{\Omega})^* \tilde{h}_A(f',\hat{\Omega}') \rangle = \delta_{AA'}\delta(\hat{\Omega},\hat{\Omega}')\delta(f-f')\underbrace{H(f)}_{\text{GWB power spectrum}}\overset{\text{for isotropic background}}{\cancel{P(\hat{\Omega})}}$$

ONE QUANTITY, MANY NAMES

a Gaussian and isotropic background is fully characterized by its power spectrum

GWB power spectrum

$$\langle \tilde{h}_A^* \tilde{h}_A \rangle = \delta_{AA'} \delta(\hat{\Omega}, \hat{\Omega}') \delta(f - f') H(f)$$

GWB relic density

$$\Omega_{\rm GW}(f) = \frac{1}{\rho_c} \frac{d\rho_{\rm GW}}{d \ln f}$$

$$\Omega_{\rm GW}(f) = \frac{32\pi^3}{3H_0^2} f^3 H(f)$$

characteristic strain

$$\langle h_{ij} h_{ij} \rangle = 2 \int_0^\infty d \log f \, h_c^2(f)$$

$$h_c^2(f) = 16\pi f H(f)$$

ONE QUANTITY, MANY NAMES

a Gaussian and isotropic background is fully characterized by its power spectrum

GWB power spectrum

$$\langle \tilde{h}_A^* \tilde{h}_A \rangle = \delta_{AA'} \delta(\hat{\Omega}, \hat{\Omega}') \delta(f - f') H(f)$$

GWB relic density

$$\Omega_{\rm GW}(f) = \frac{1}{\rho_c} \frac{d\rho_{\rm GW}}{d \ln f}$$

$$\Omega_{\rm GW}(f) = \frac{32\pi^3}{3H_0^2} f^3 H(f)$$

characteristic strain

$$\langle h_{ij} h_{ij} \rangle = 2 \int_0^\infty d \log f \, h_c^2(f)$$

$$h_c^2(f) = 16\pi f H(f)$$

induced TOAs common process

$$\langle \delta t_a(t_1) \delta t_b(t_2) \rangle = \int df \, \Gamma_{ab} \, S(f) \, e^{(2\pi f (t_1 - t_2))}$$

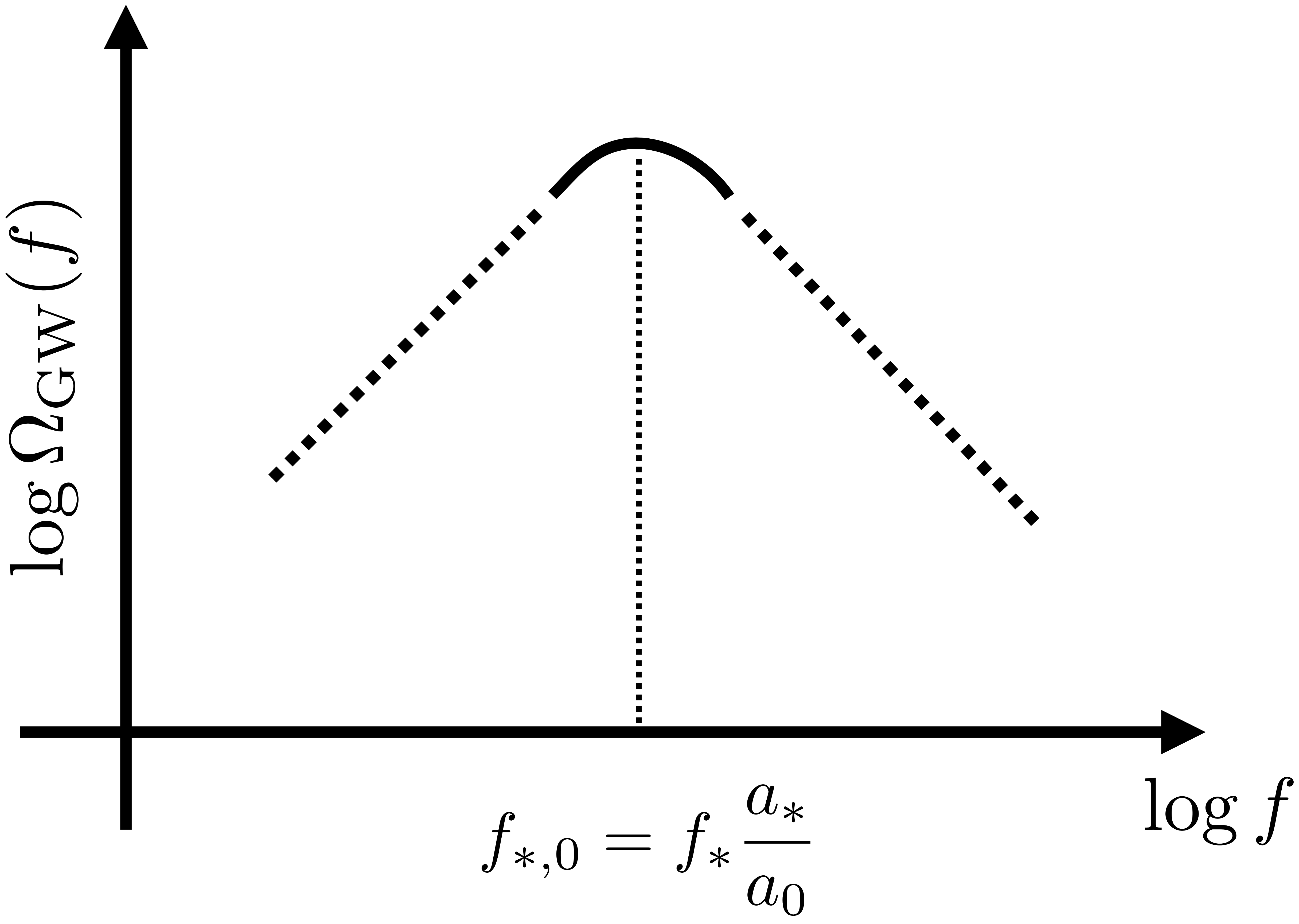
$$S(f) = \frac{H(f)}{(2\pi f)^2}$$

general properties of cosmological GWBs

SPECTRUM: peak frequency

short live sources active at some time $t_* \lesssim H_*^{-1}$

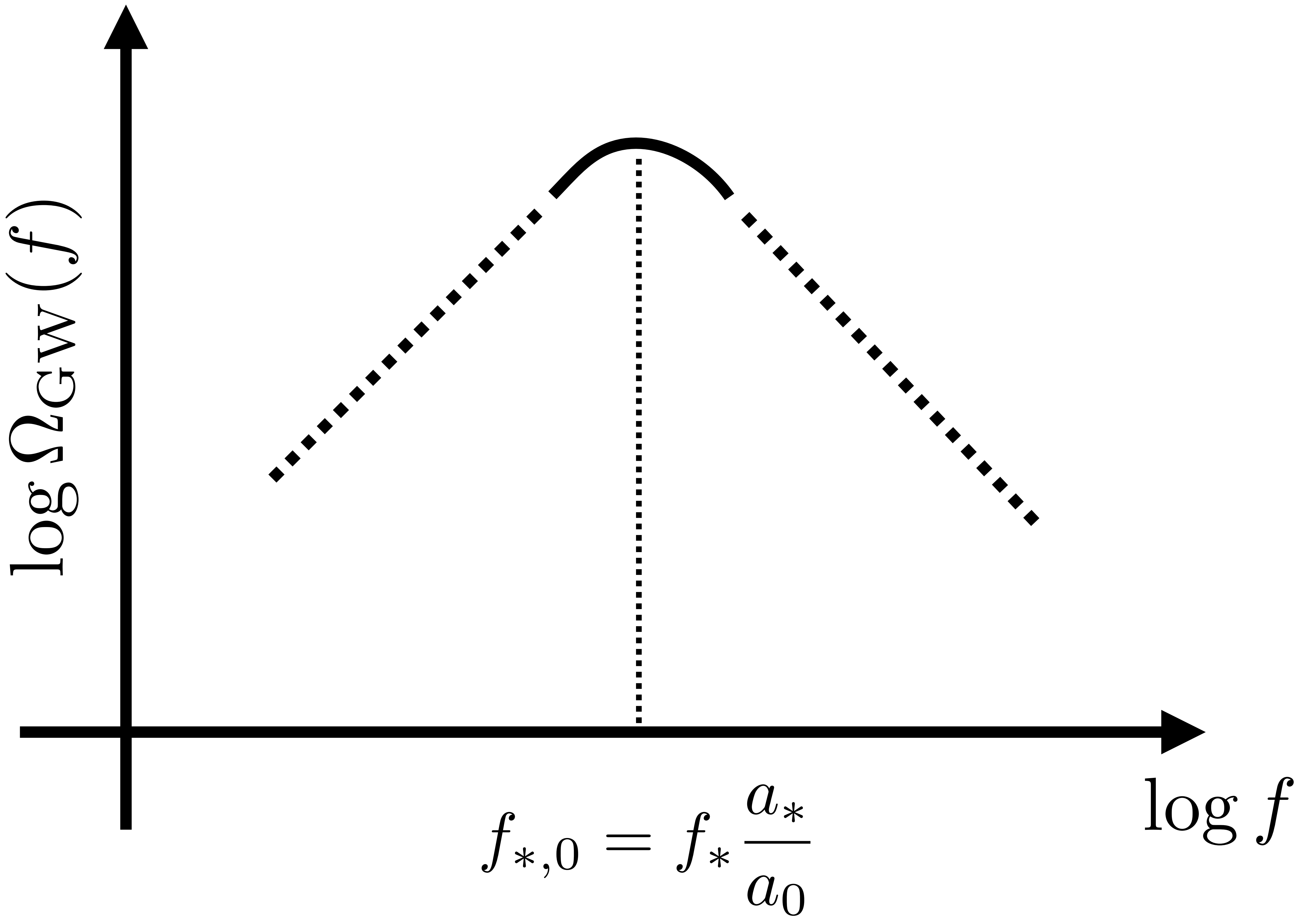
$$f_* = \frac{1}{\text{characteristic length scale}}$$



SPECTRUM: peak frequency

short live sources active at some time $t_* \lesssim H_*^{-1}$

$$f_* = \frac{1}{\text{characteristic length scale}} = \frac{1}{\varepsilon_* H_*^{-1}}$$



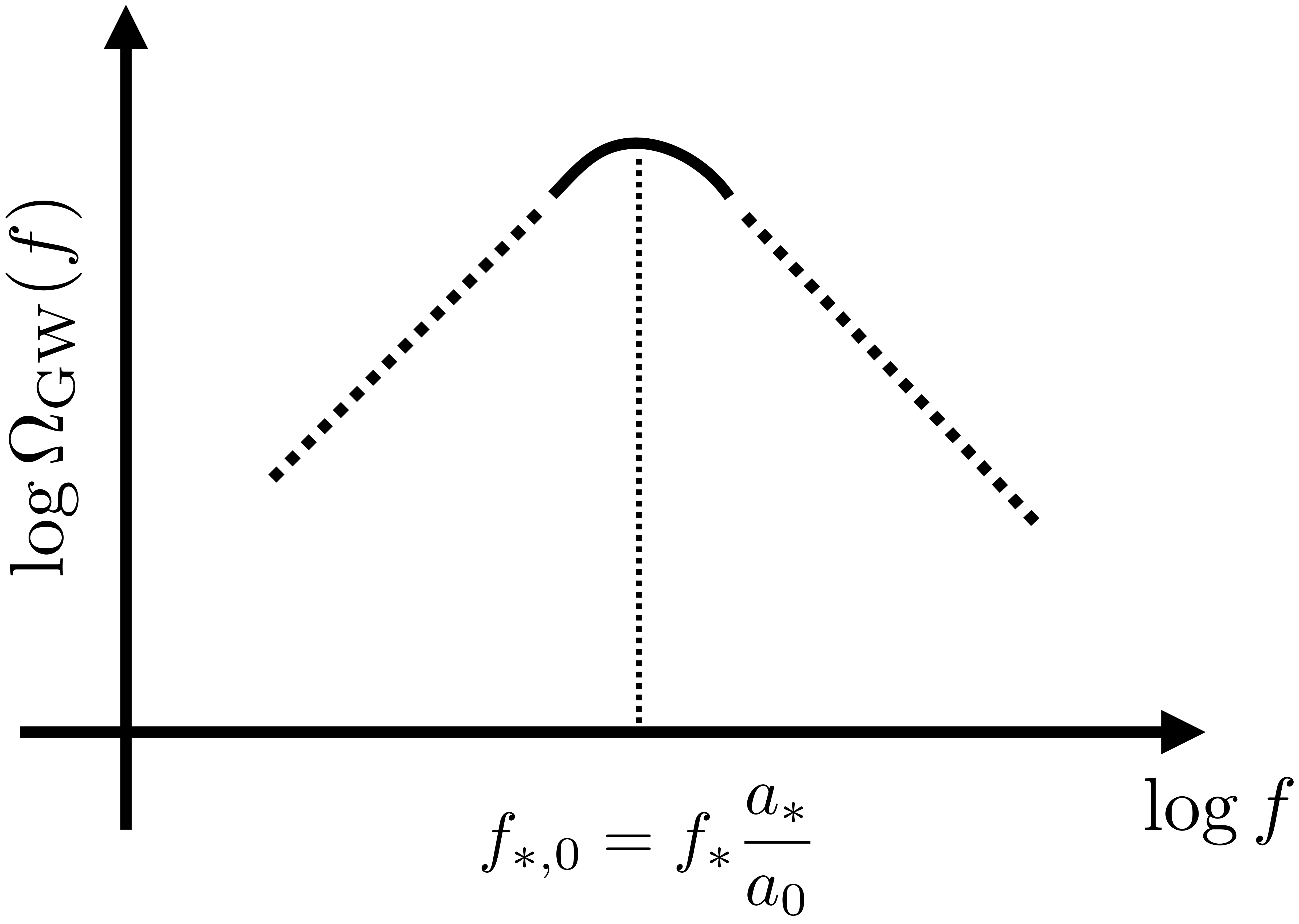
SPECTRUM: peak frequency

short live sources active at some time $t_* \lesssim H_*^{-1}$

$$f_* = \frac{1}{\text{characteristic length scale}} = \frac{1}{\varepsilon_* H_*^{-1}}$$

$\varepsilon_* \lesssim 1$

for casual sources



SPECTRUM: peak frequency

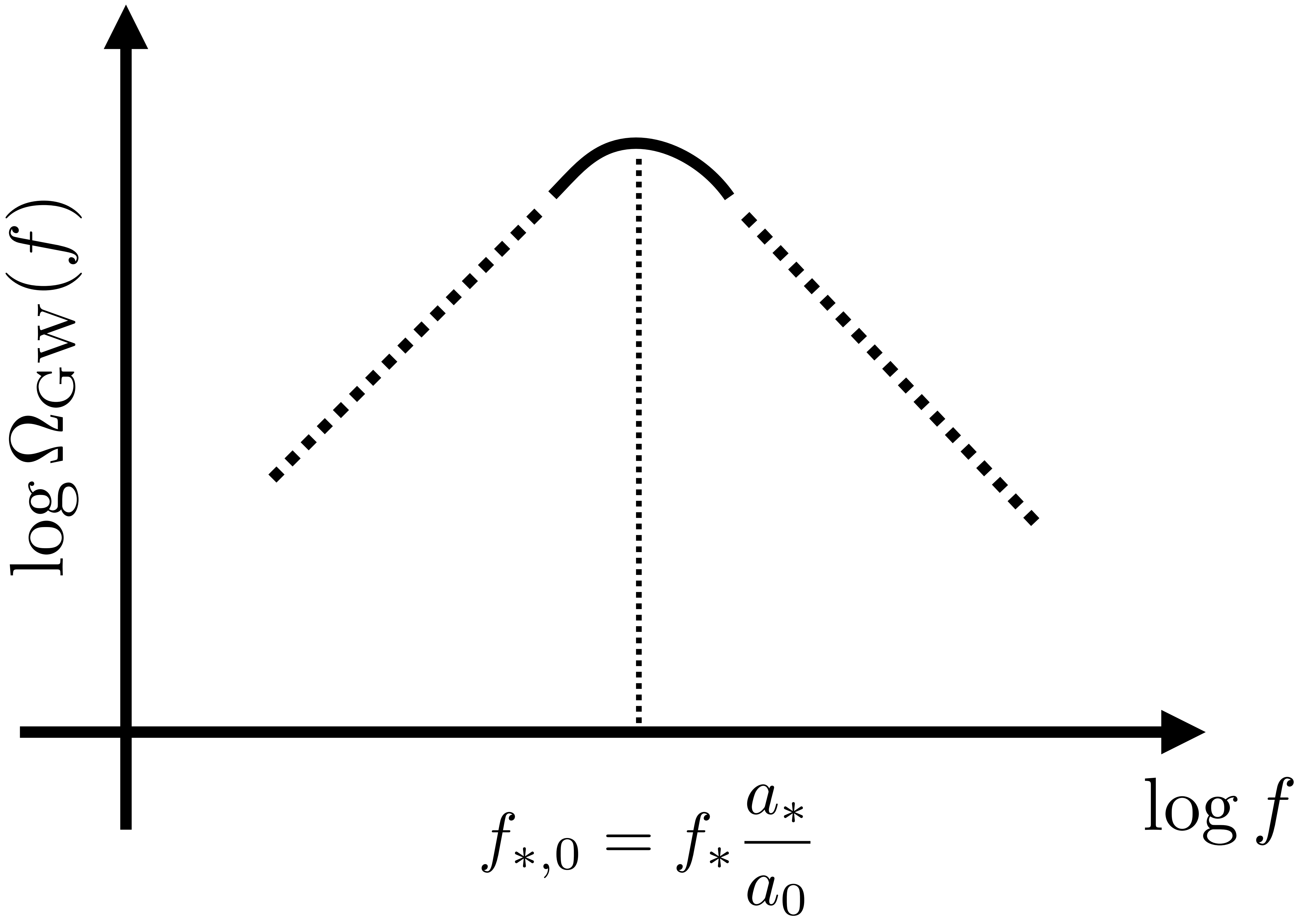
short live sources active at some time $t_* \lesssim H_*^{-1}$

$$f_* = \frac{1}{\text{characteristic length scale}} = \frac{1}{\varepsilon_* H_*^{-1}}$$

$\varepsilon_* \lesssim 1$

for casual sources

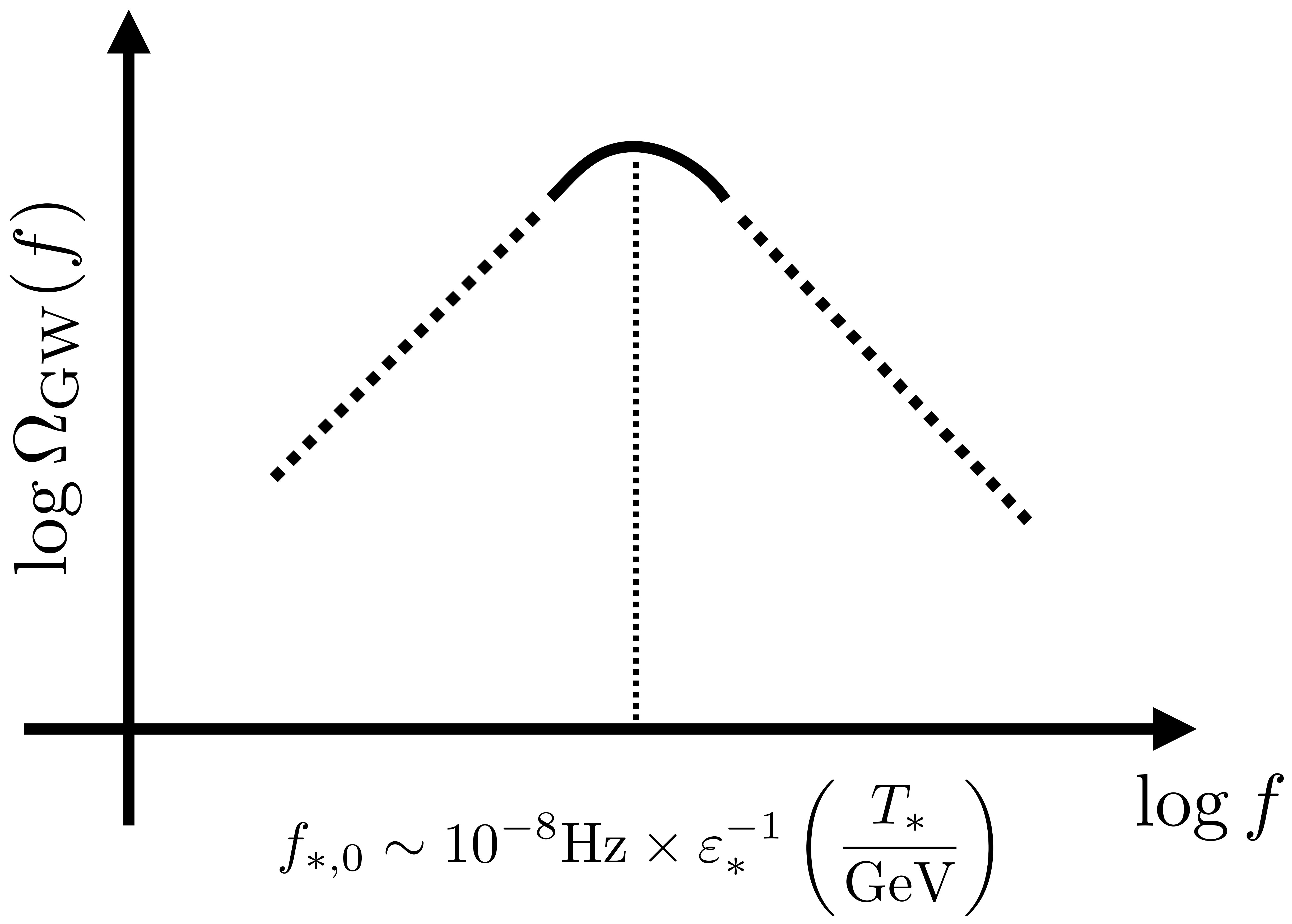
$$\boxed{f_{*,0} \sim 10^{-8}\text{Hz} \times \varepsilon_*^{-1} \left(\frac{T_*}{\text{GeV}}\right)}$$



SPECTRUM: amplitude

primordial GWs contribute to the background expansion as additional radiation

$$H(a)^2 = H_0^2\left[\left(\frac{\rho^0_{\rm GW}}{\rho^0_c}+\Omega^0_{\rm rad}\right)\left(\frac{a_0}{a}\right)^4+\Omega^0_{\rm mat}\left(\frac{a_0}{a}\right)^3+\Omega^0_\Lambda\right]$$



SPECTRUM: amplitude

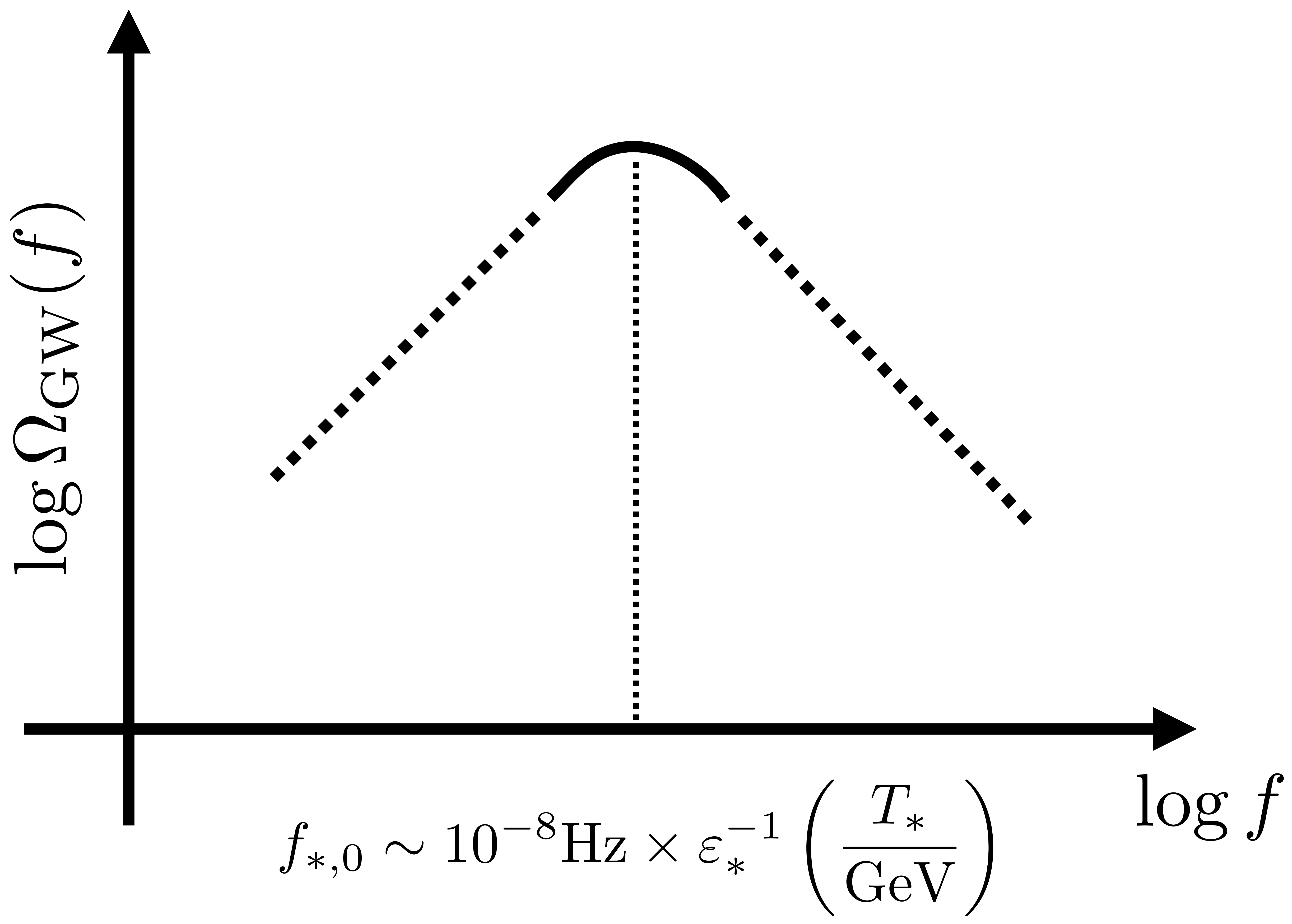
primordial GWs contribute to the background expansion as additional radiation

$$H(a)^2 = H_0^2 \left[\left(\frac{\rho^0_{\rm GW}}{\rho^0_c} + \Omega^0_{\rm rad} \right) \left(\frac{a_0}{a} \right)^4 + \Omega^0_{\rm mat} \left(\frac{a_0}{a} \right)^3 + \Omega^0_\Lambda \right]$$

any observable sensitive to the Universe expansion constraints the energy in GWs

$$\boxed{\int \frac{df}{f}\, h^2 \Omega_{\rm GW}(f) \lesssim 10^{-6}}$$

BBN + CMB



SPECTRUM: amplitude

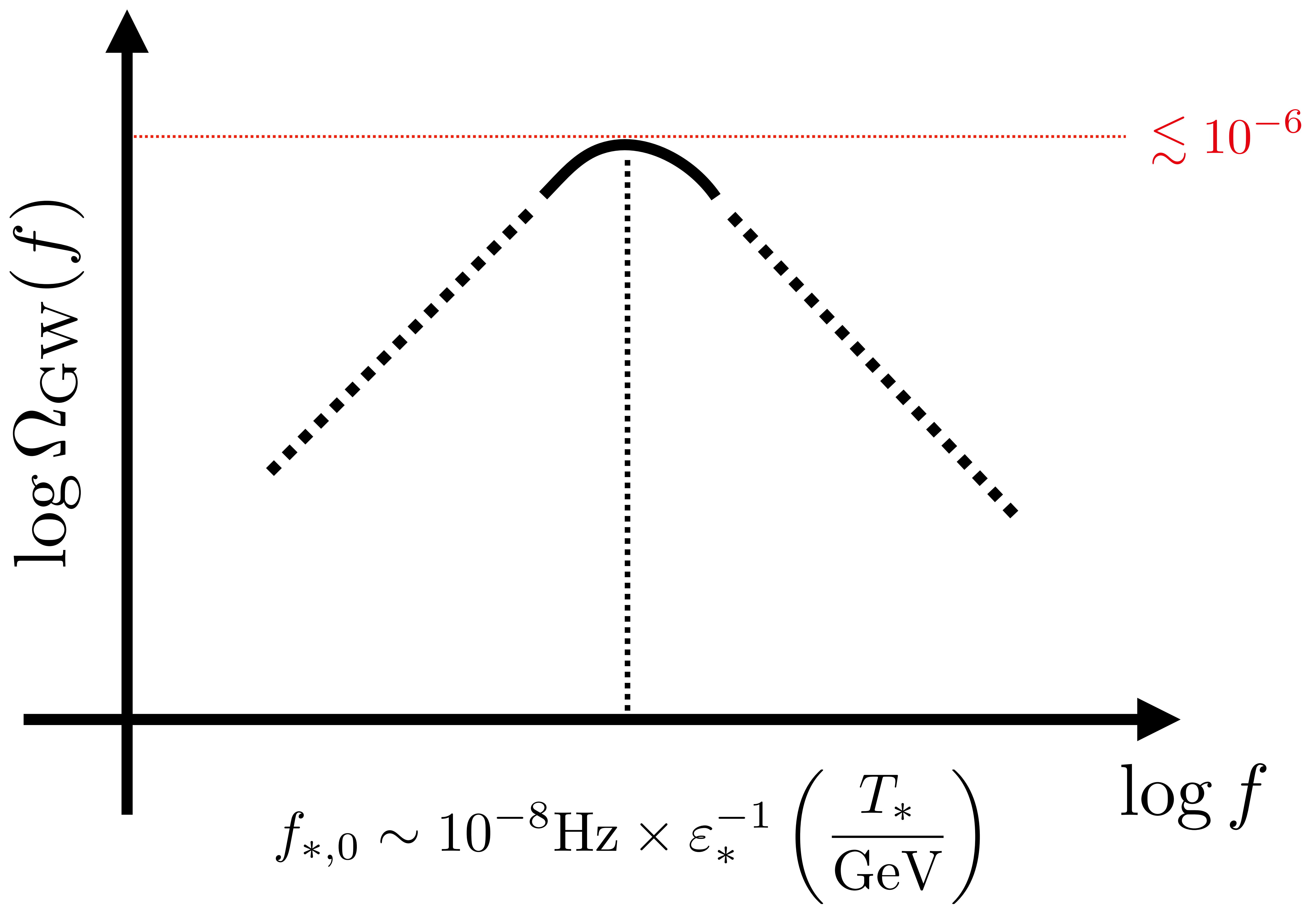
primordial GWs contribute to the background expansion as additional radiation

$$H(a)^2 = H_0^2\left[\left(\frac{\rho^0_{\rm GW}}{\rho^0_c}+\Omega^0_{\rm rad}\right)\left(\frac{a_0}{a}\right)^4+\Omega^0_{\rm mat}\left(\frac{a_0}{a}\right)^3+\Omega^0_\Lambda\right]$$

any observable sensitive to the Universe expansion constraints the energy in GWs

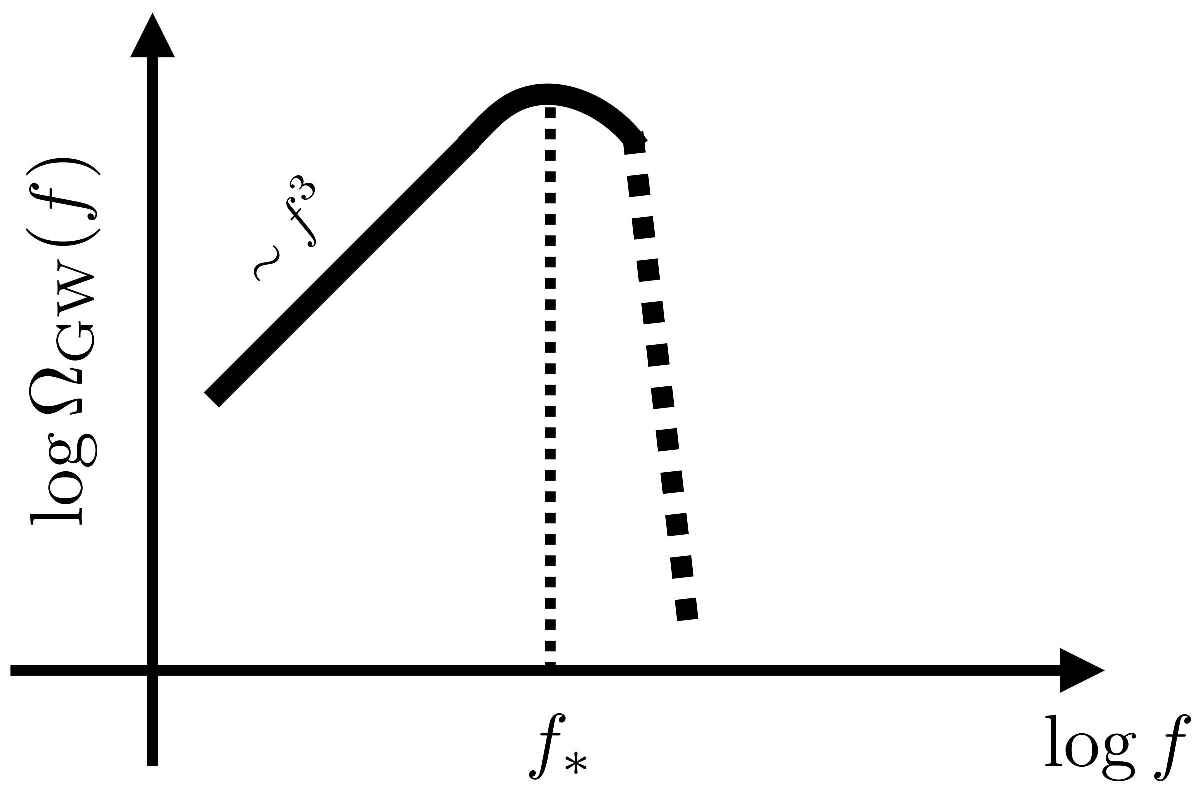
$$\boxed{\int \frac{df}{f}\, h^2\Omega_{\rm GW}(f) \lesssim 10^{-6}}$$

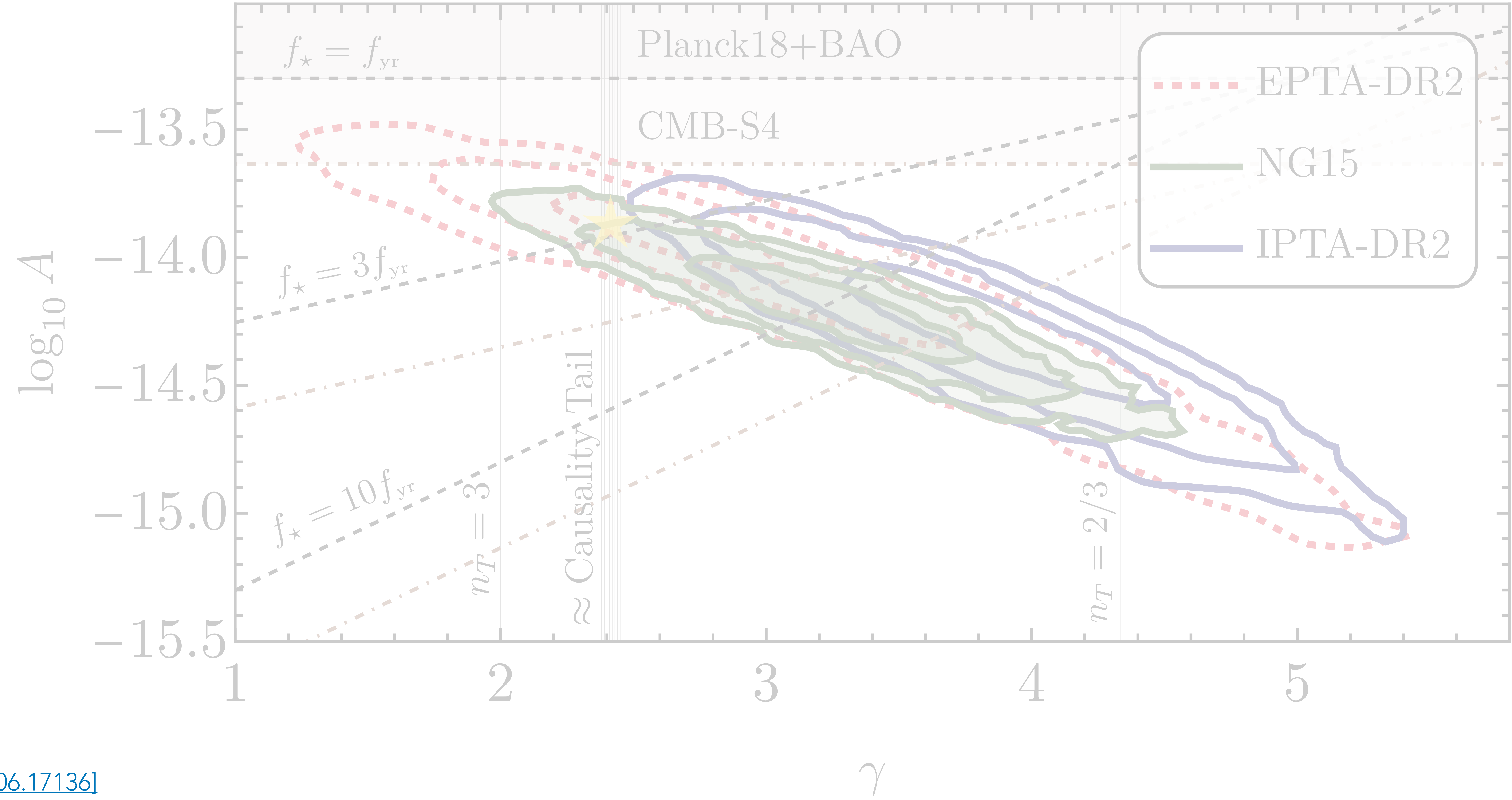
BBN + CMB



SPECTRUM: amplitude

$$h^2\Omega_{\mathrm{GW}} = A^2 \left(\frac{f}{\mathrm{yr}^{-1}}\right)^{5-\gamma} \Theta(f_* - f)$$

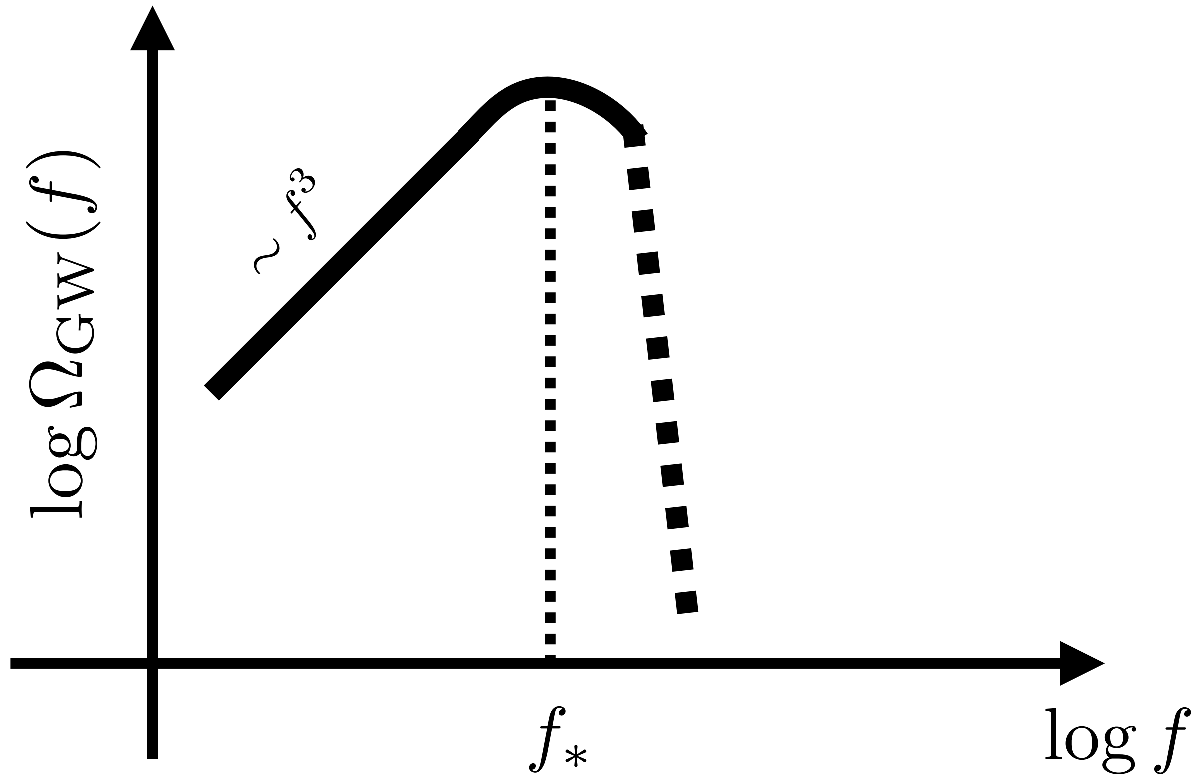


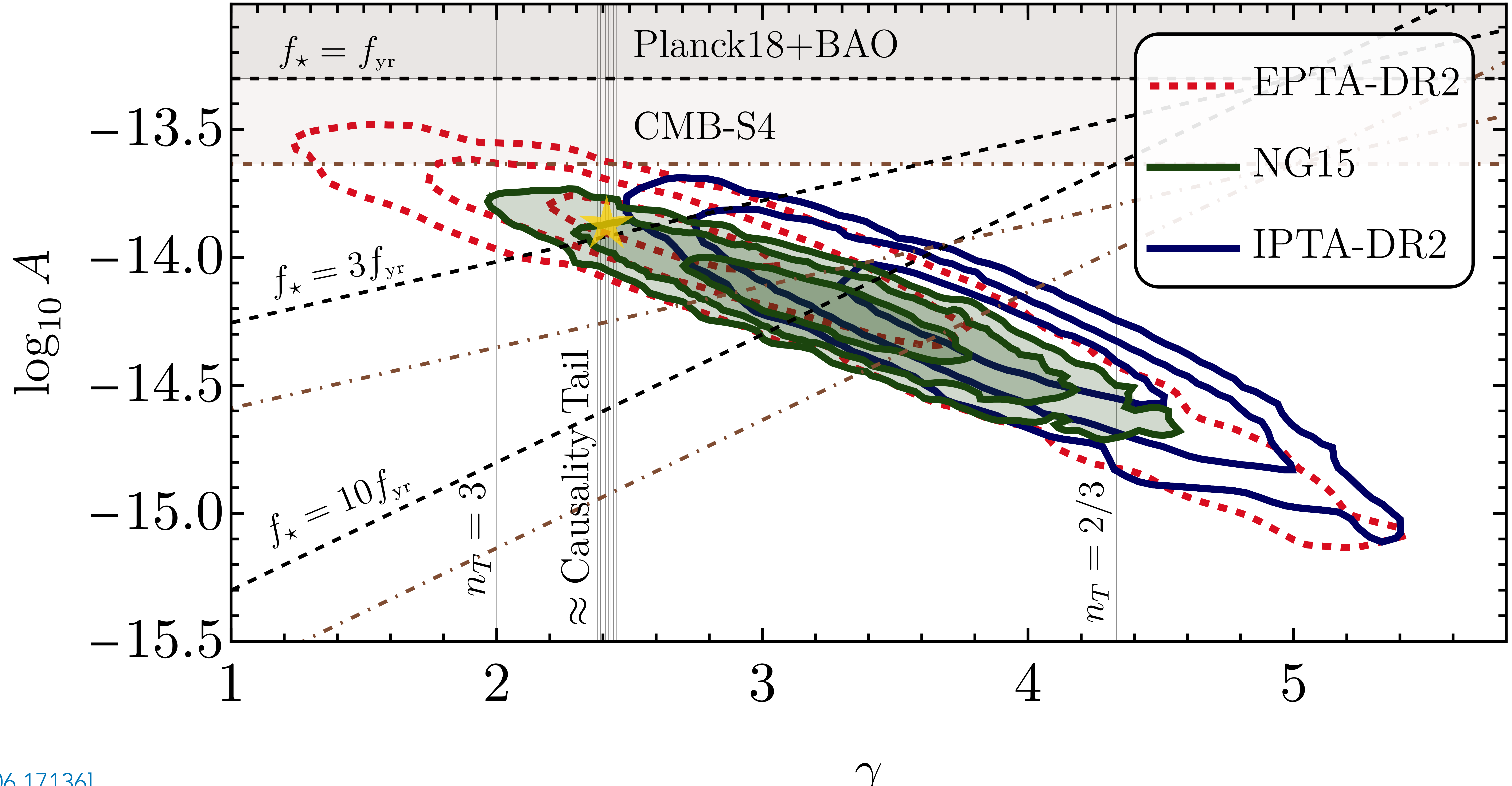


Franciolini et al. [2306.17136]

SPECTRUM: amplitude

$$h^2\Omega_{\rm GW} = A^2 \left(\frac{f}{{\rm yr}^{-1}}\right)^{5-\gamma} \Theta(f_* - f)$$



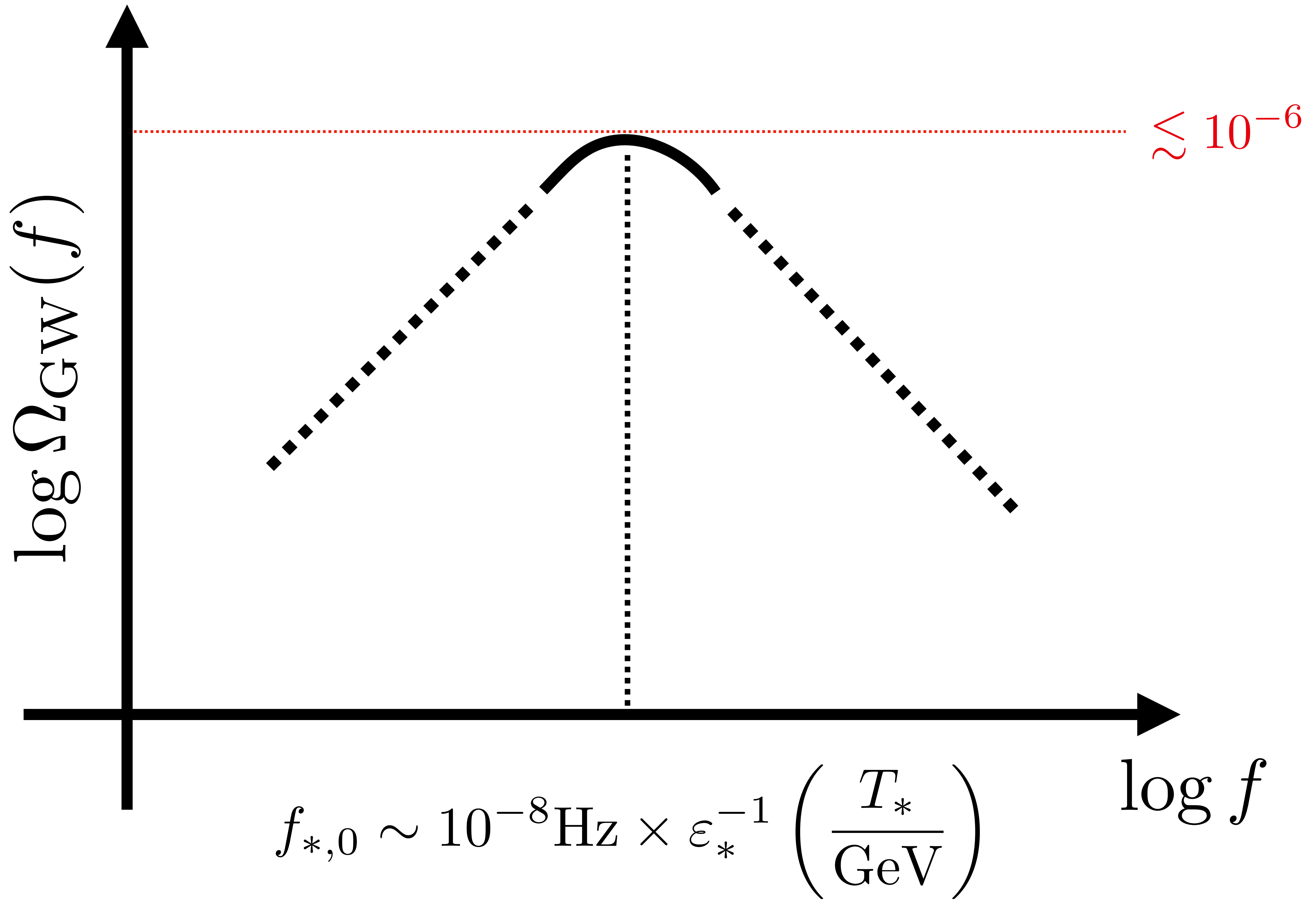


Franciolini et al. [2306.17136]

SPECTRUM: slope

anisotropic stress tensor of the (cosmological) source

$$\ddot{h}_{ij}(\mathbf{x},t) + 3\,H\,\dot{h}_{ij}(\mathbf{x},t) - \frac{\nabla^2}{a^2}\,h_{ij}(\mathbf{x},t) = 16\pi G\,\Pi_{ij}(\mathbf{x},t)$$



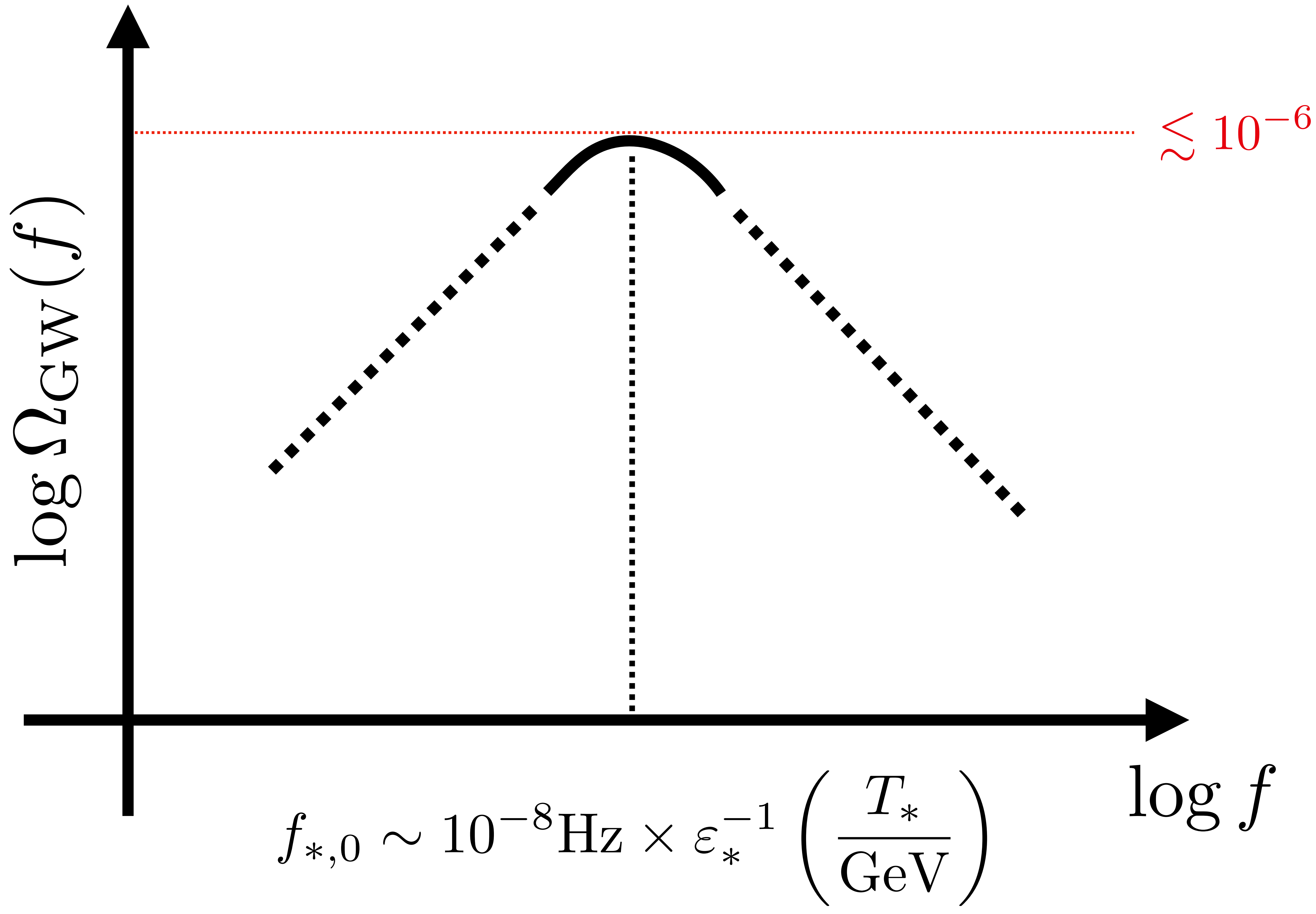
SPECTRUM: slope

anisotropic stress tensor of the (cosmological) source

$$\ddot{h}_{ij}(\mathbf{x},t) + 3\,H\,\dot{h}_{ij}(\mathbf{x},t) - \frac{\nabla^2}{a^2}\,h_{ij}(\mathbf{x},t) = 16\pi G\,\Pi_{ij}(\mathbf{x},t)$$

for homogeneous and isotropic stochastic sources

$$\langle \Pi_{ij}(\mathbf{k},t)\Pi^{ij}(\mathbf{k},t')\rangle = (2\pi)^3\delta(\mathbf{k}-\mathbf{k}')\Pi(\mathbf{k},t,t')$$



SPECTRUM: slope

anisotropic stress tensor of the (cosmological) source

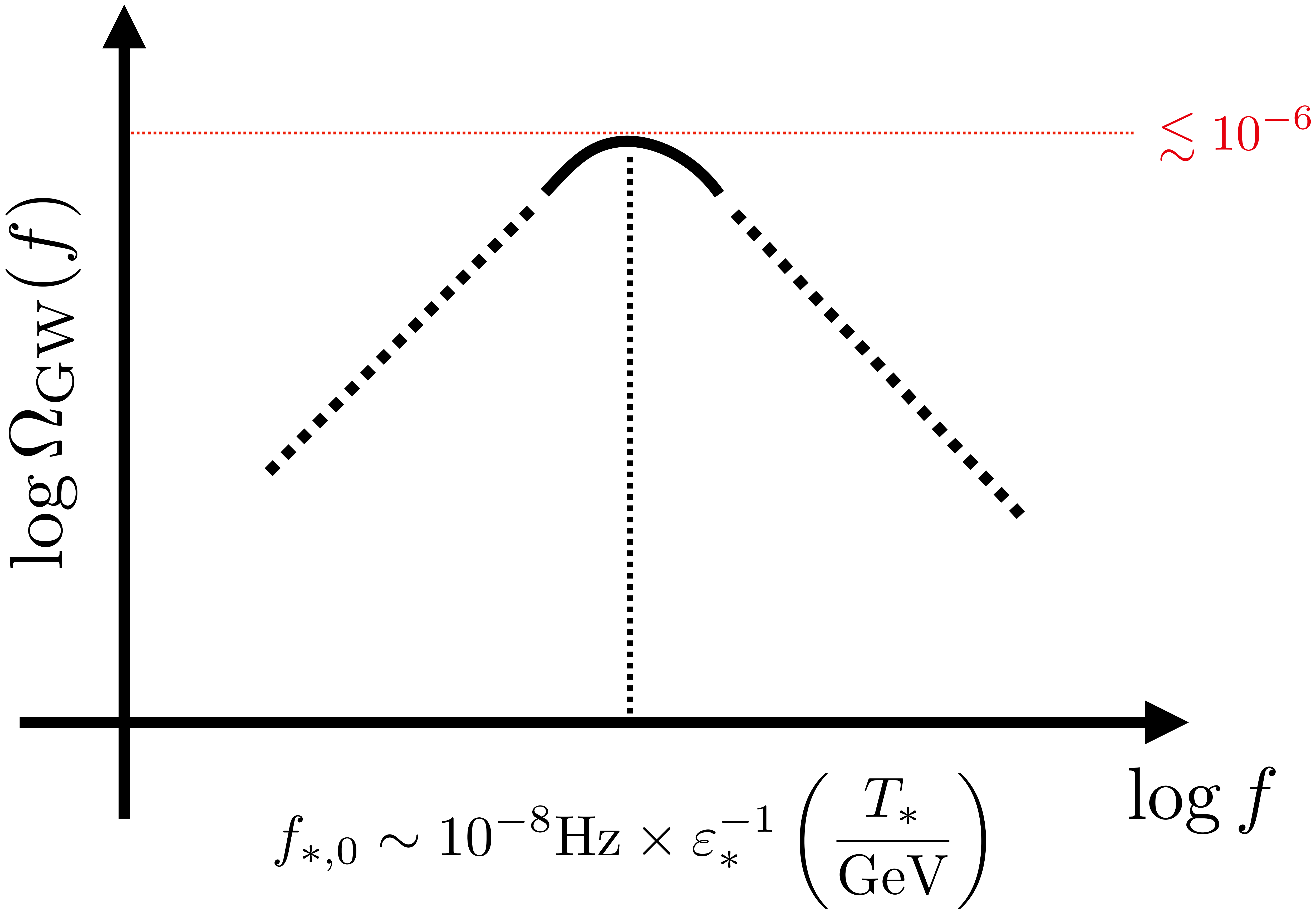
$$\ddot{h}_{ij}(\mathbf{x},t) + 3\,H\,\dot{h}_{ij}(\mathbf{x},t) - \frac{\nabla^2}{a^2}\,h_{ij}(\mathbf{x},t) = \underbrace{16\pi G\,\Pi_{ij}(\mathbf{x},t)}$$

for homogeneous and isotropic stochastic sources

$$\langle \Pi_{ij}(\mathbf{k},t)\Pi^{ij}(\mathbf{k},t')\rangle = (2\pi)^3\delta(\mathbf{k}-\mathbf{k}')\Pi(\mathbf{k},t,t')$$

$$\Downarrow$$

$$\Omega_{\rm GW}(k) = \frac{4G}{\pi}\,k^3\int_{\eta_{\rm in}}^{\eta_{\rm fin}} d\eta\, a^3(\eta)\int_{\eta_{\rm in}}^{\eta_{\rm fin}} d\zeta\, a^3(\zeta)\,\cos[k(\eta-\zeta)]\,\Pi(k,\eta,\zeta)$$



SPECTRUM: slope

anisotropic stress tensor of the (cosmological) source

$$\ddot{h}_{ij}(\mathbf{x},t) + 3\,H\,\dot{h}_{ij}(\mathbf{x},t) - \frac{\nabla^2}{a^2}\,h_{ij}(\mathbf{x},t) = \overline{16\pi G\,\Pi_{ij}(\mathbf{x},t)}$$

for homogeneous and isotropic stochastic sources

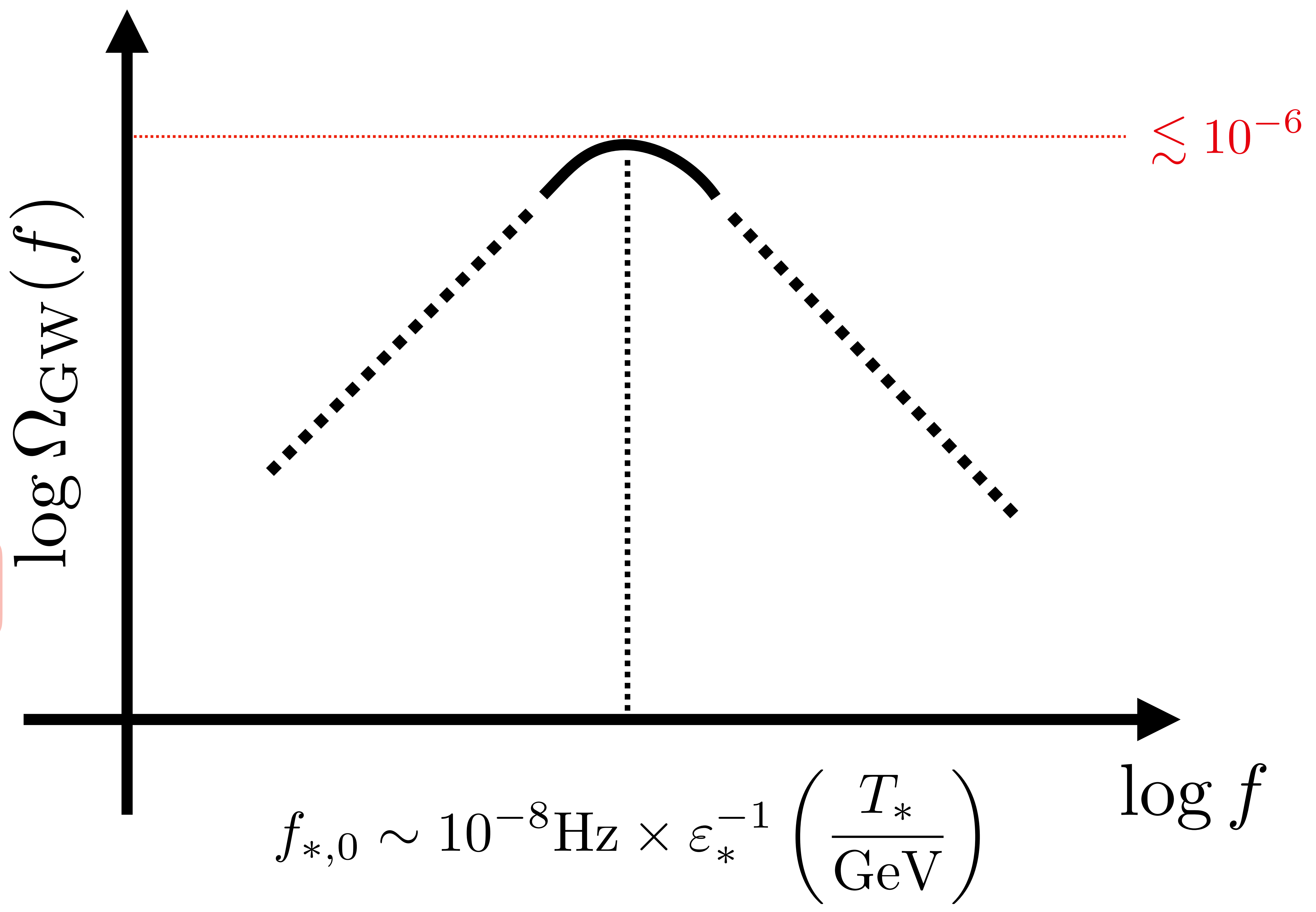
$$\langle \Pi_{ij}(\mathbf{k},t)\Pi^{ij}(\mathbf{k},t')\rangle = (2\pi)^3\delta(\mathbf{k}-\mathbf{k}')\boxed{\Pi(\mathbf{k},t,t')}$$

$$\Downarrow$$

$$\Omega_{\rm GW}(k) = \frac{4G}{\pi}\,k^3\int_{\eta_{\rm in}}^{\eta_{\rm fin}} d\eta\, a^3(\eta)\int_{\eta_{\rm in}}^{\eta_{\rm fin}} d\zeta\, a^3(\zeta)\,\cos[k(\eta-\zeta)]\,\boxed{\Pi(k,\eta,\zeta)}$$

for casual sources

$$\Pi(k,\eta,\zeta) \xrightarrow[k<1/H_*]{} \text{const}$$



SPECTRUM: slope

anisotropic stress tensor of the (cosmological) source

$$\ddot{h}_{ij}(\mathbf{x},t) + 3\,H\,\dot{h}_{ij}(\mathbf{x},t) - \frac{\nabla^2}{a^2}\,h_{ij}(\mathbf{x},t) = \overline{16\pi G\,\Pi_{ij}(\mathbf{x},t)}$$

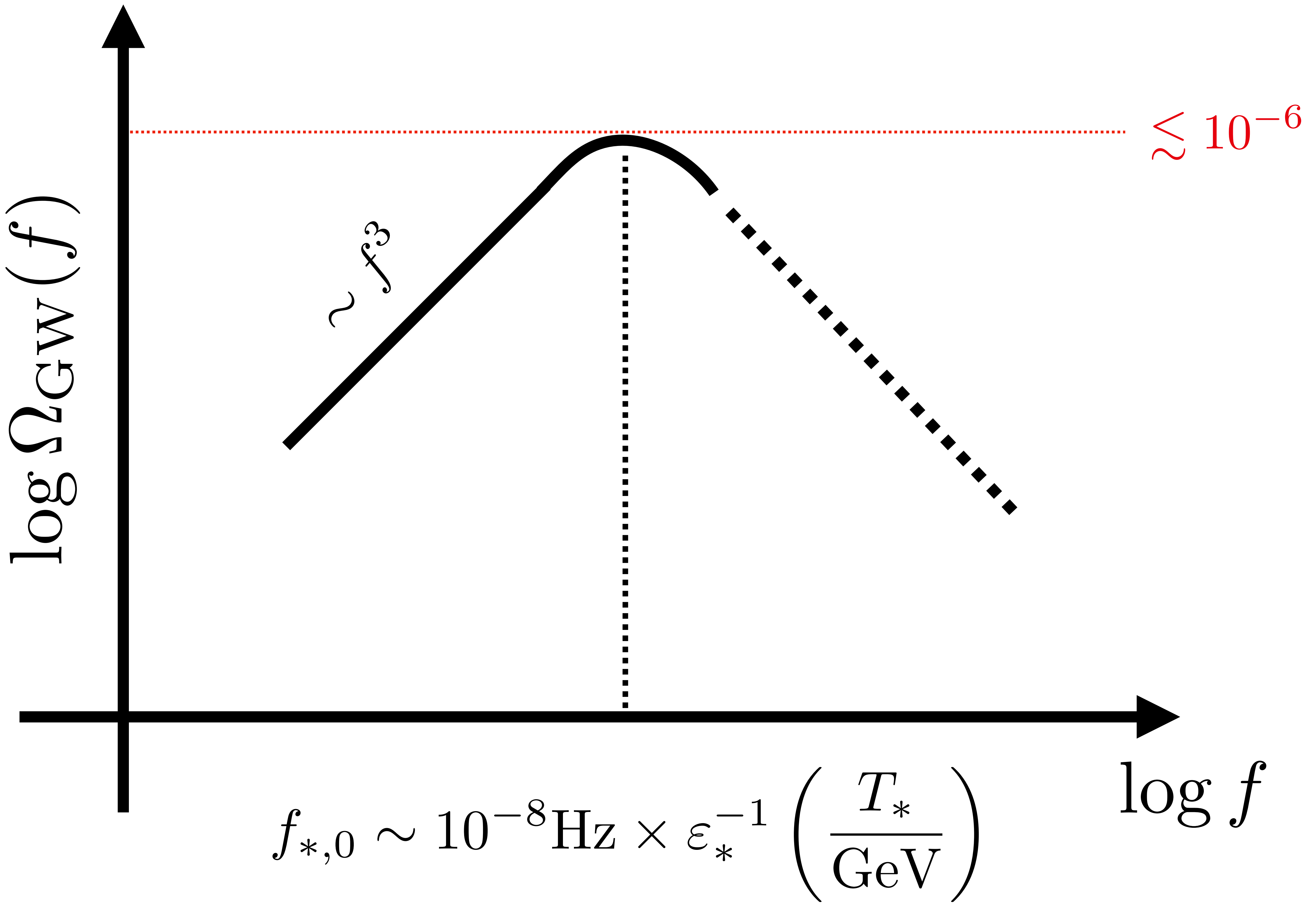
for homogeneous and isotropic stochastic sources

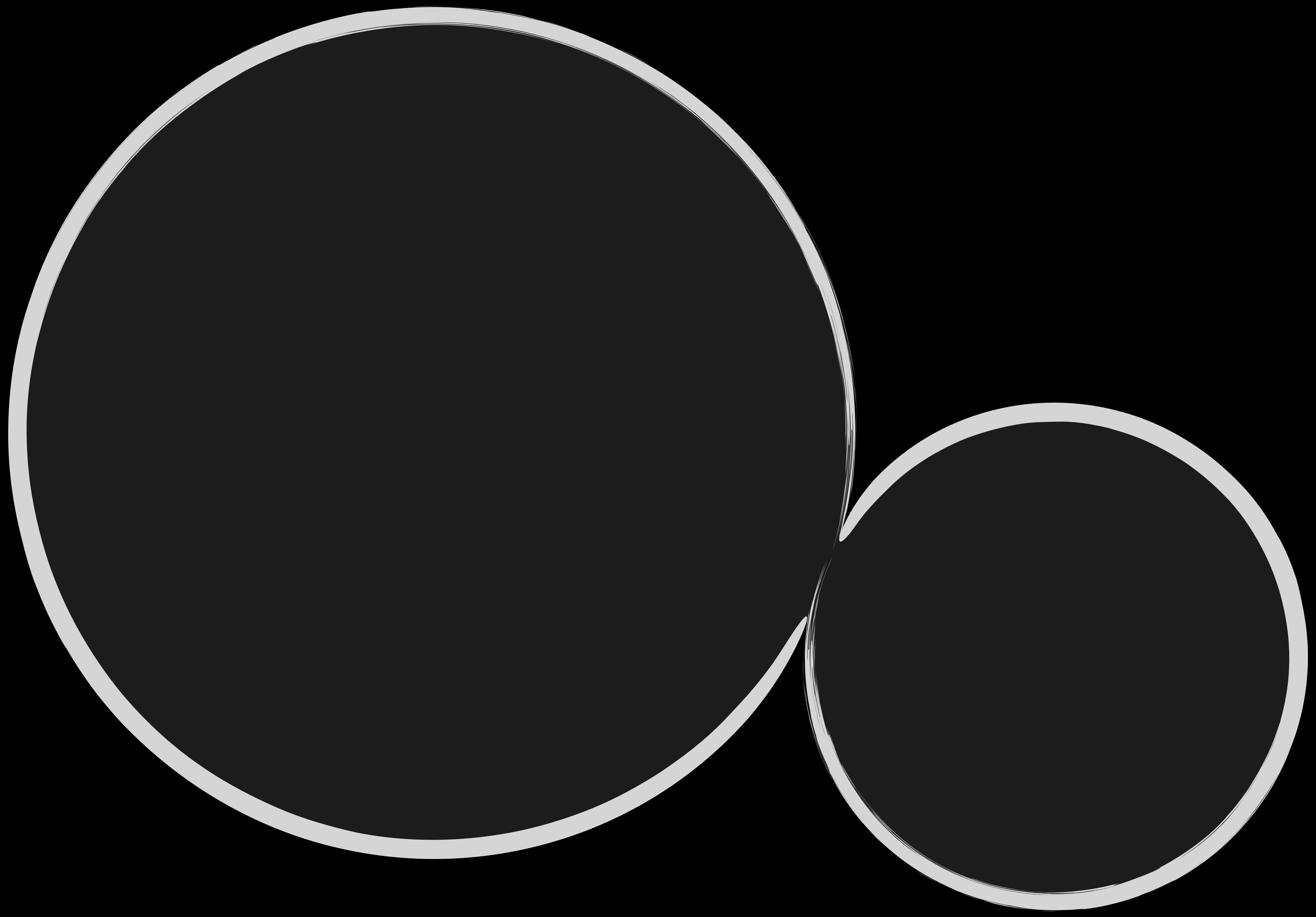
$$\langle \Pi_{ij}(\mathbf{k},t)\Pi^{ij}(\mathbf{k},t')\rangle = (2\pi)^3\delta(\mathbf{k}-\mathbf{k}')\boxed{\Pi(\mathbf{k},t,t')}$$

$$\Omega_{\rm GW}(k) = \frac{4G}{\pi}\,k^3\int_{\eta_{\rm in}}^{\eta_{\rm fin}} d\eta\, a^3(\eta)\int_{\eta_{\rm in}}^{\eta_{\rm fin}} d\zeta\, a^3(\zeta)\,\cos[k(\eta-\zeta)]\,\boxed{\Pi(k,\eta,\zeta)}$$

for casual sources

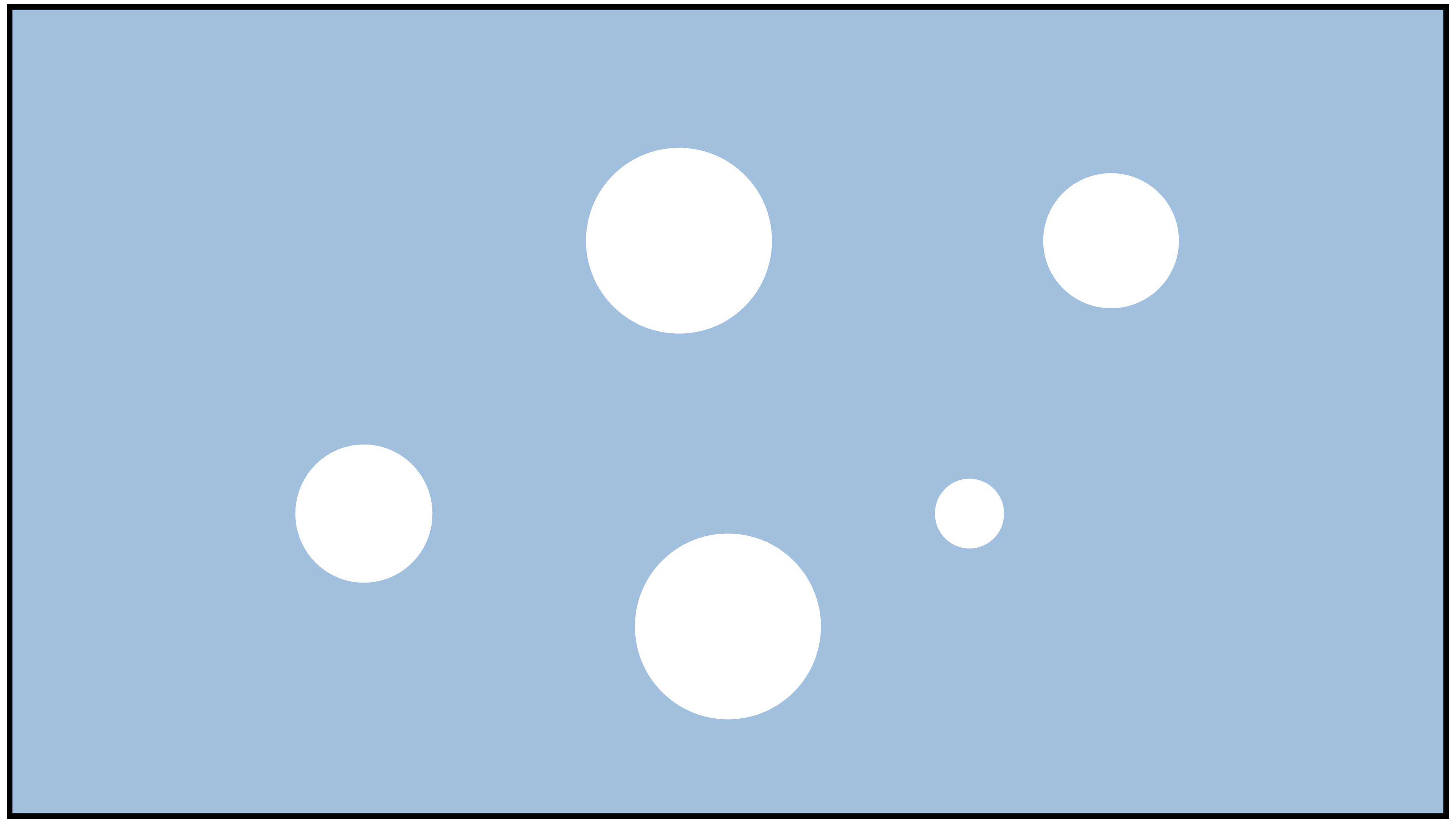
$$\Pi(k,\eta,\zeta)\xrightarrow[k<1/H_*]{}\text{const} \qquad \Omega(f)_{\rm GW}\xrightarrow[k<1/H_*]{} f^3$$



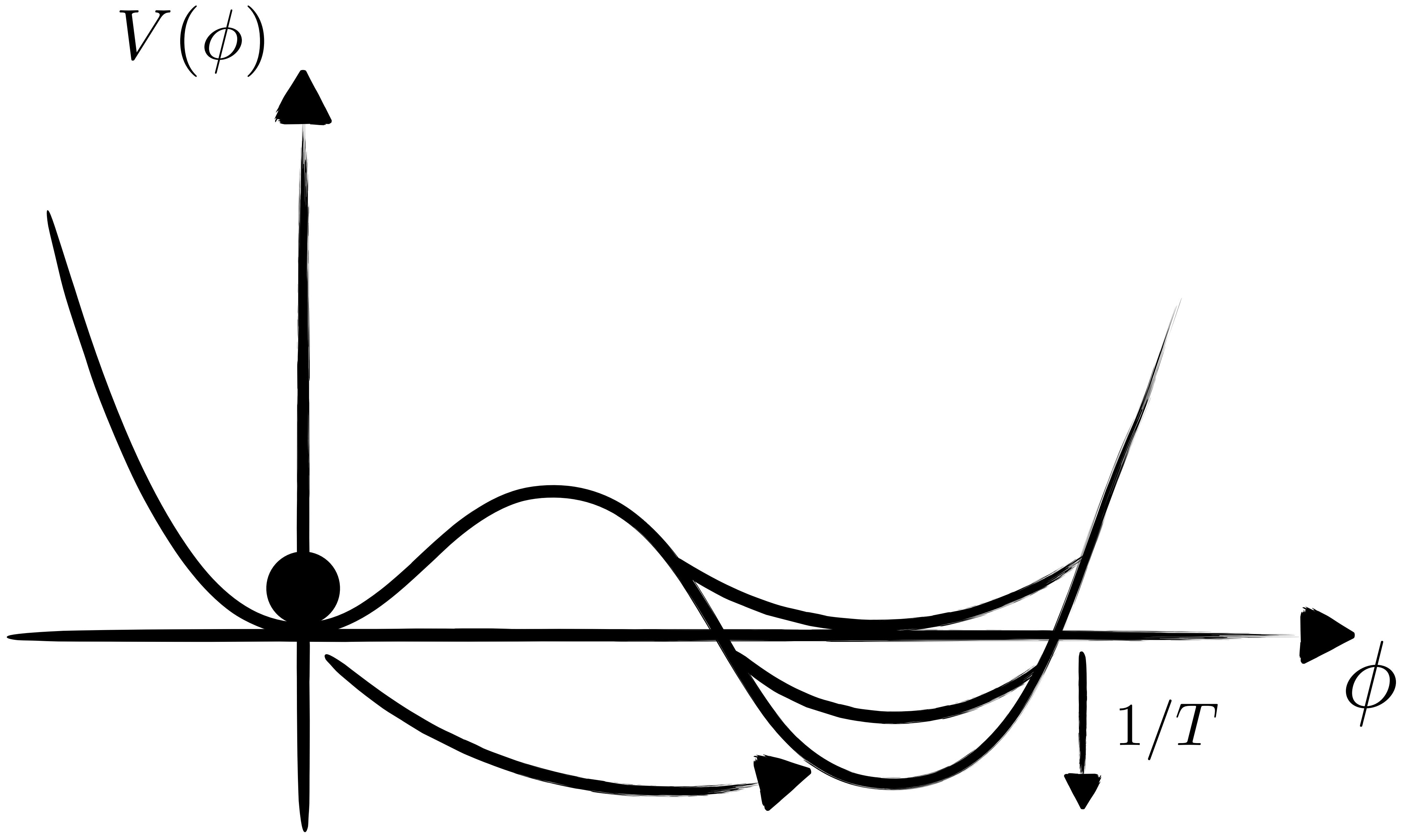


cosmological phase transitions

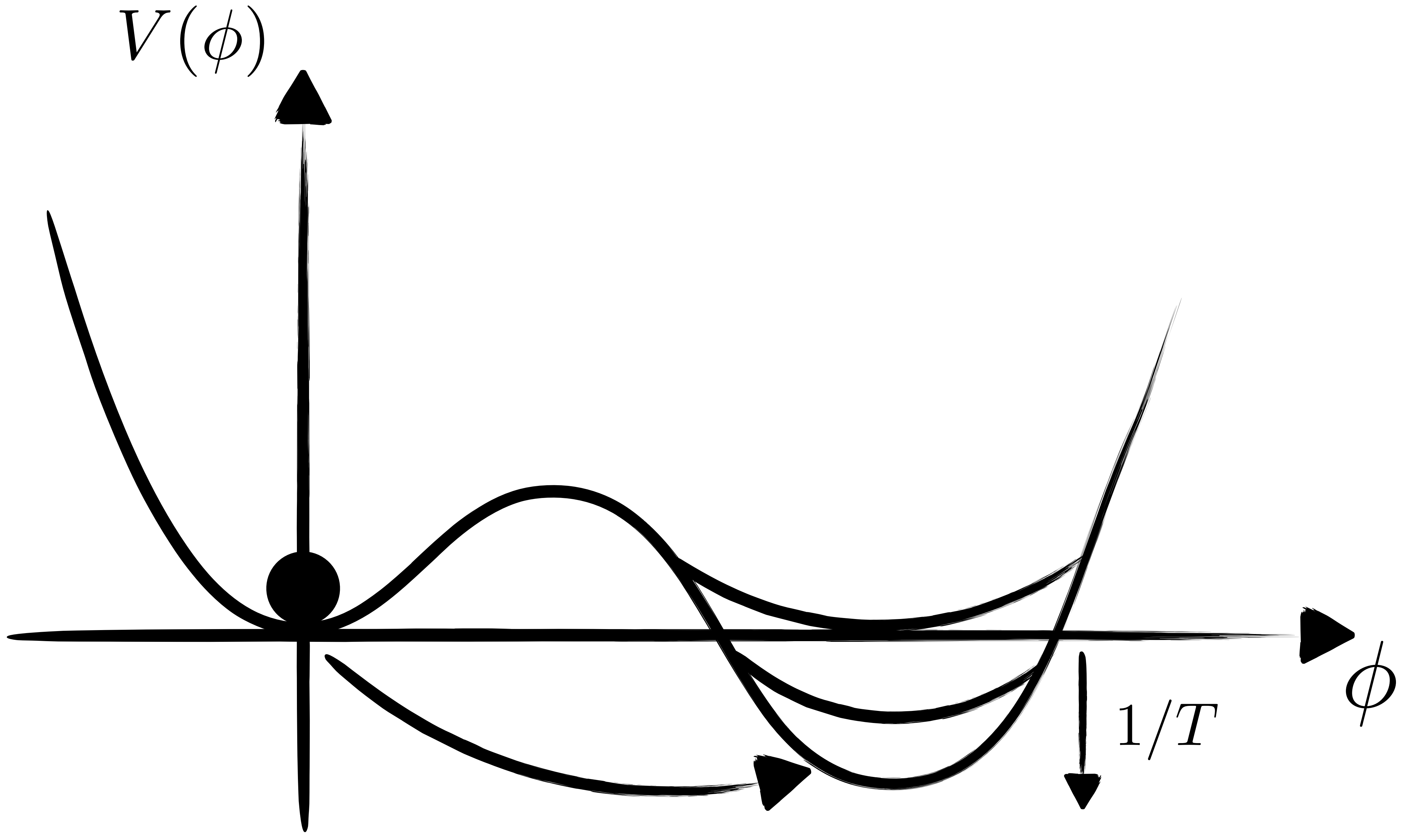
PHASE TRANSITIONS

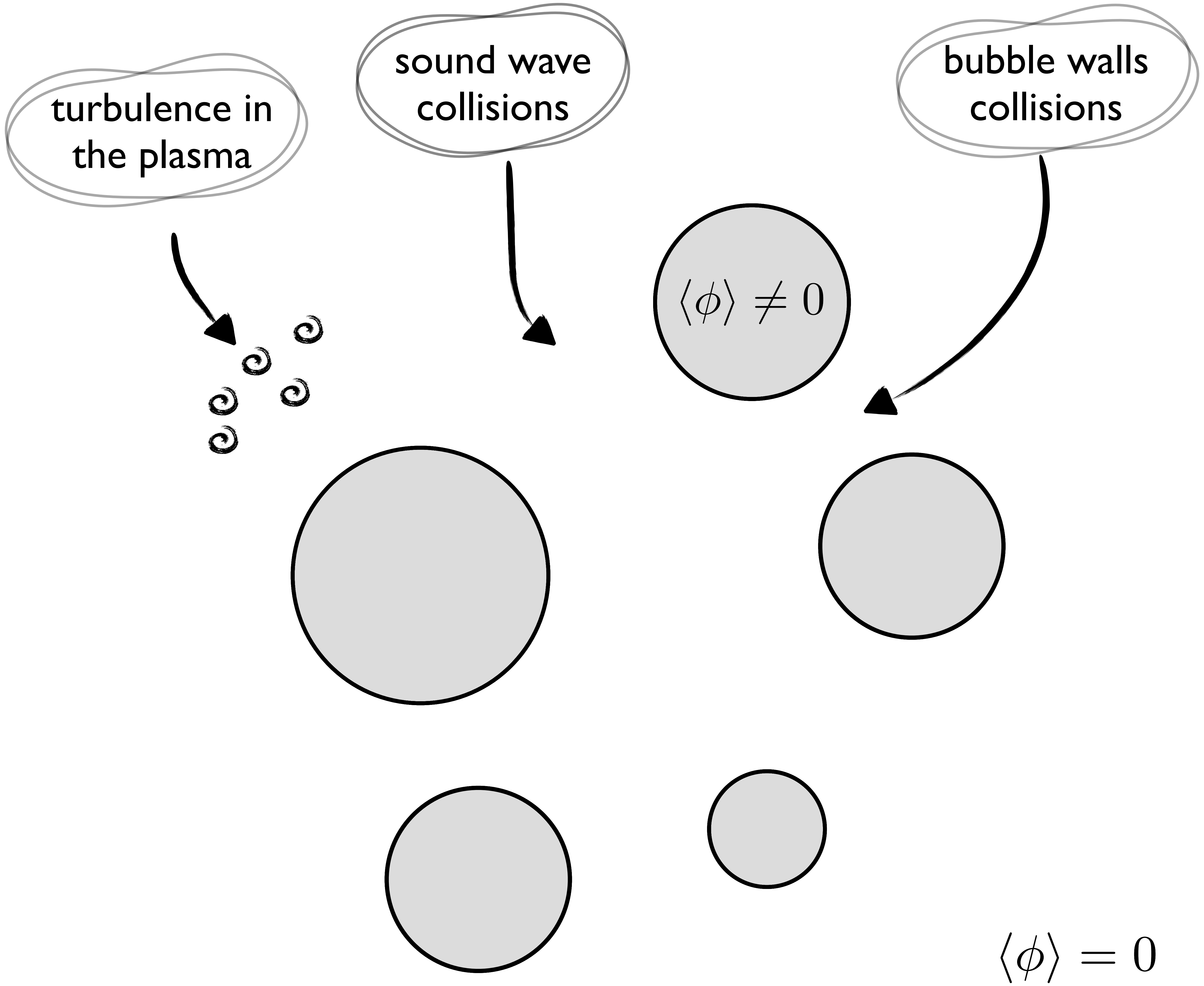


PHASE TRANSITIONS

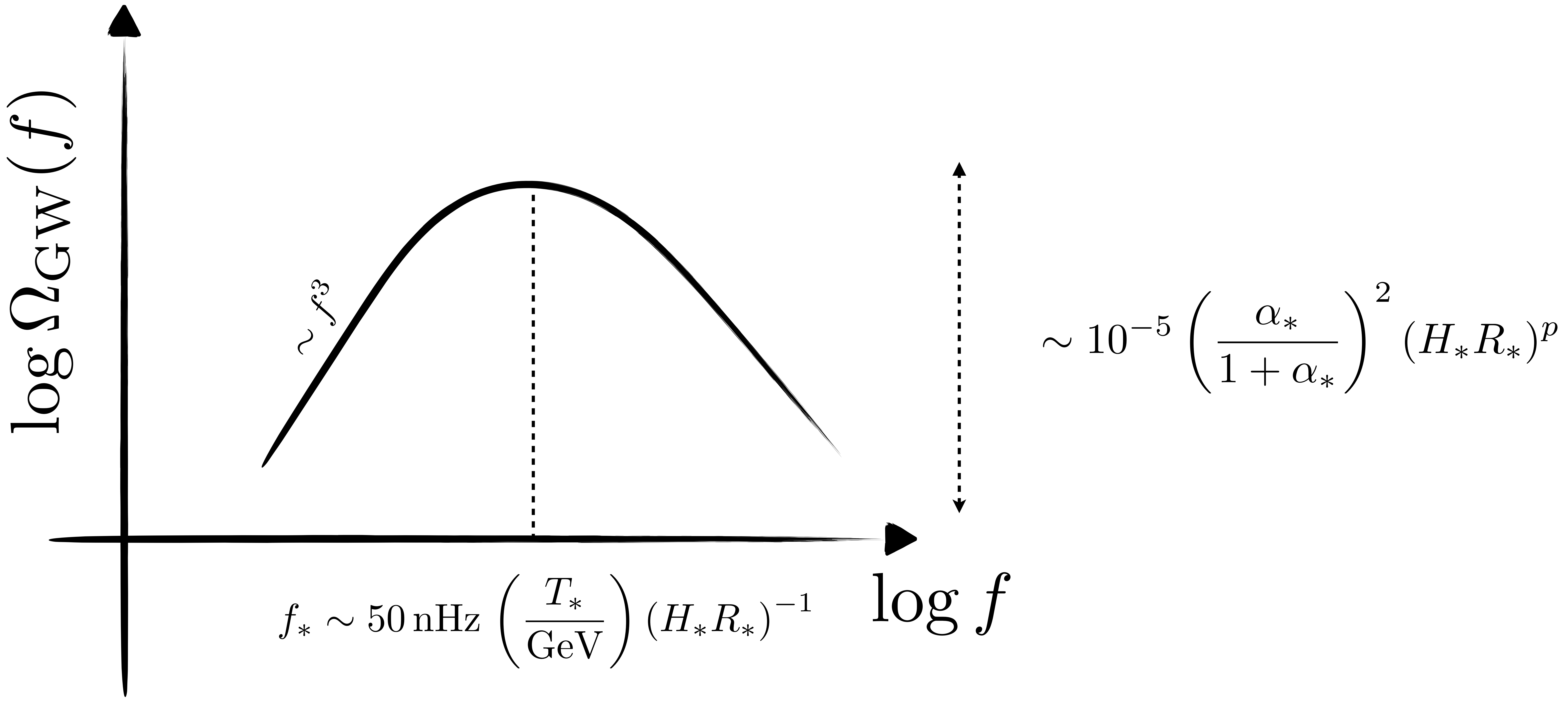


PHASE TRANSITIONS

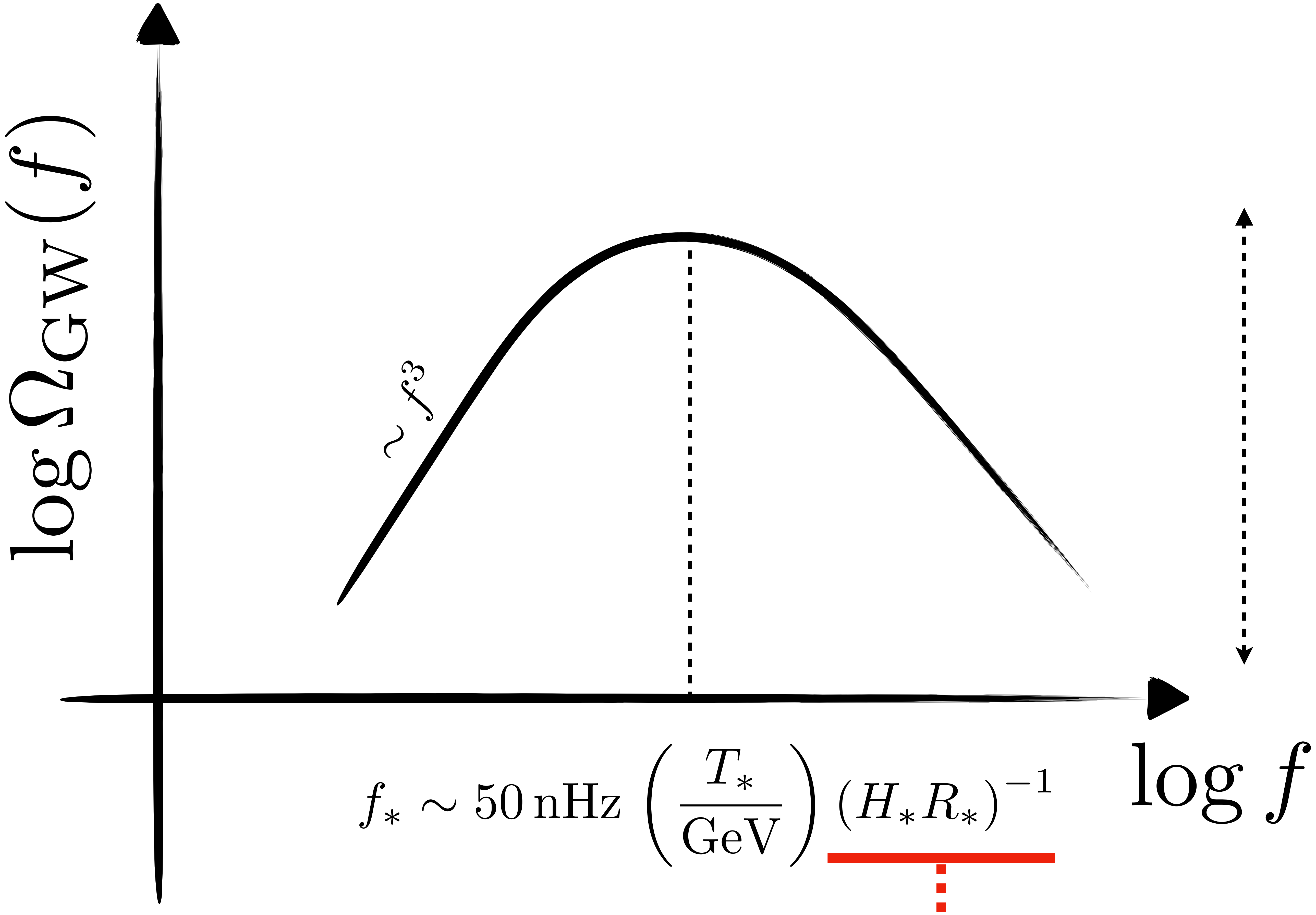




PHASE TRANSITIONS



PHASE TRANSITIONS

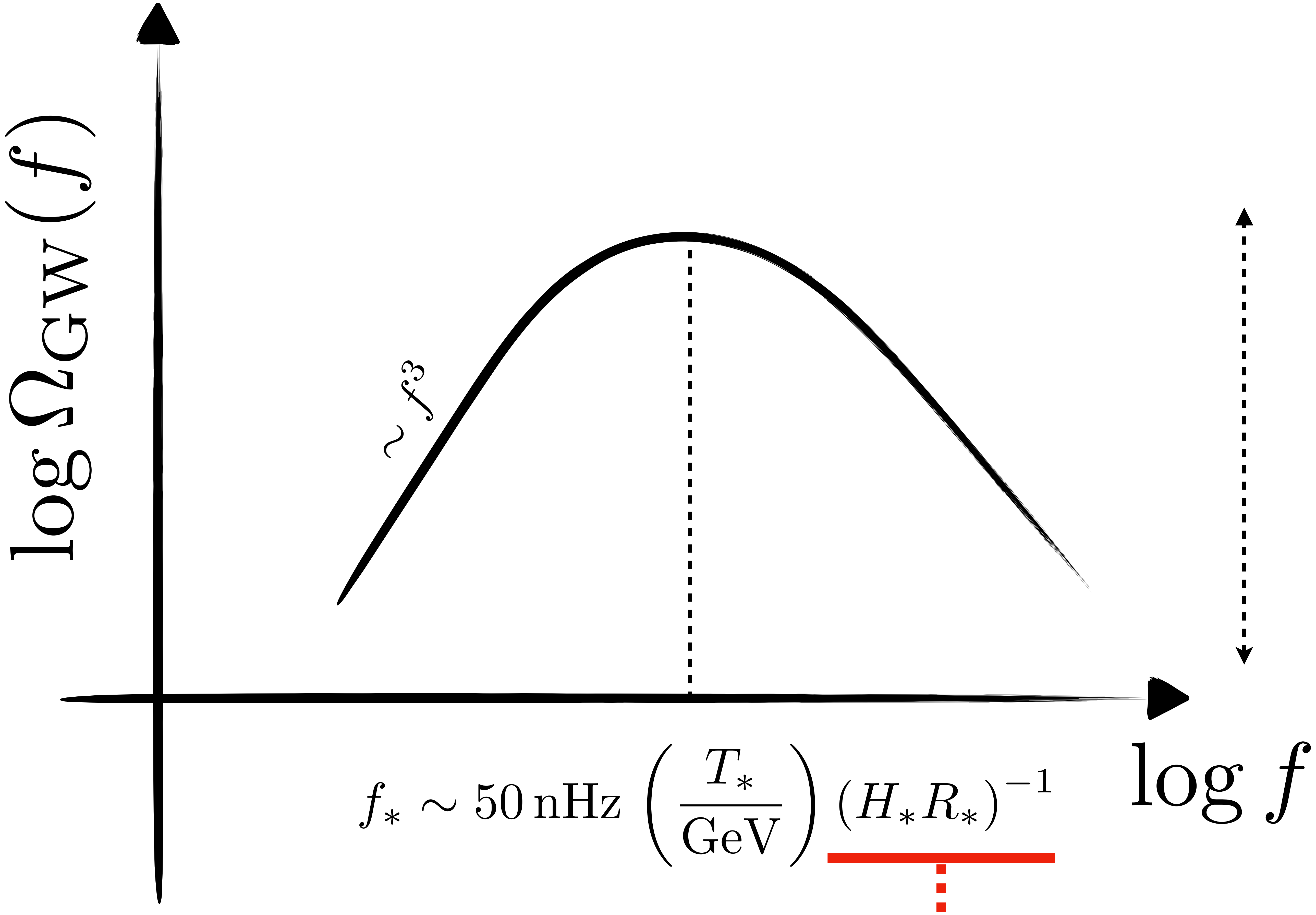


$$\sim 10^{-5} \left(\frac{\alpha_*}{1+\alpha_*} \right)^2 (H_* R_*)^p$$

$$f_* \sim 50\,\mathrm{nHz} \left(\frac{T_*}{\mathrm{GeV}} \right) \underline{(H_* R_*)^{-1}}$$

average bubble separation in unit of Hubble radius

PHASE TRANSITIONS



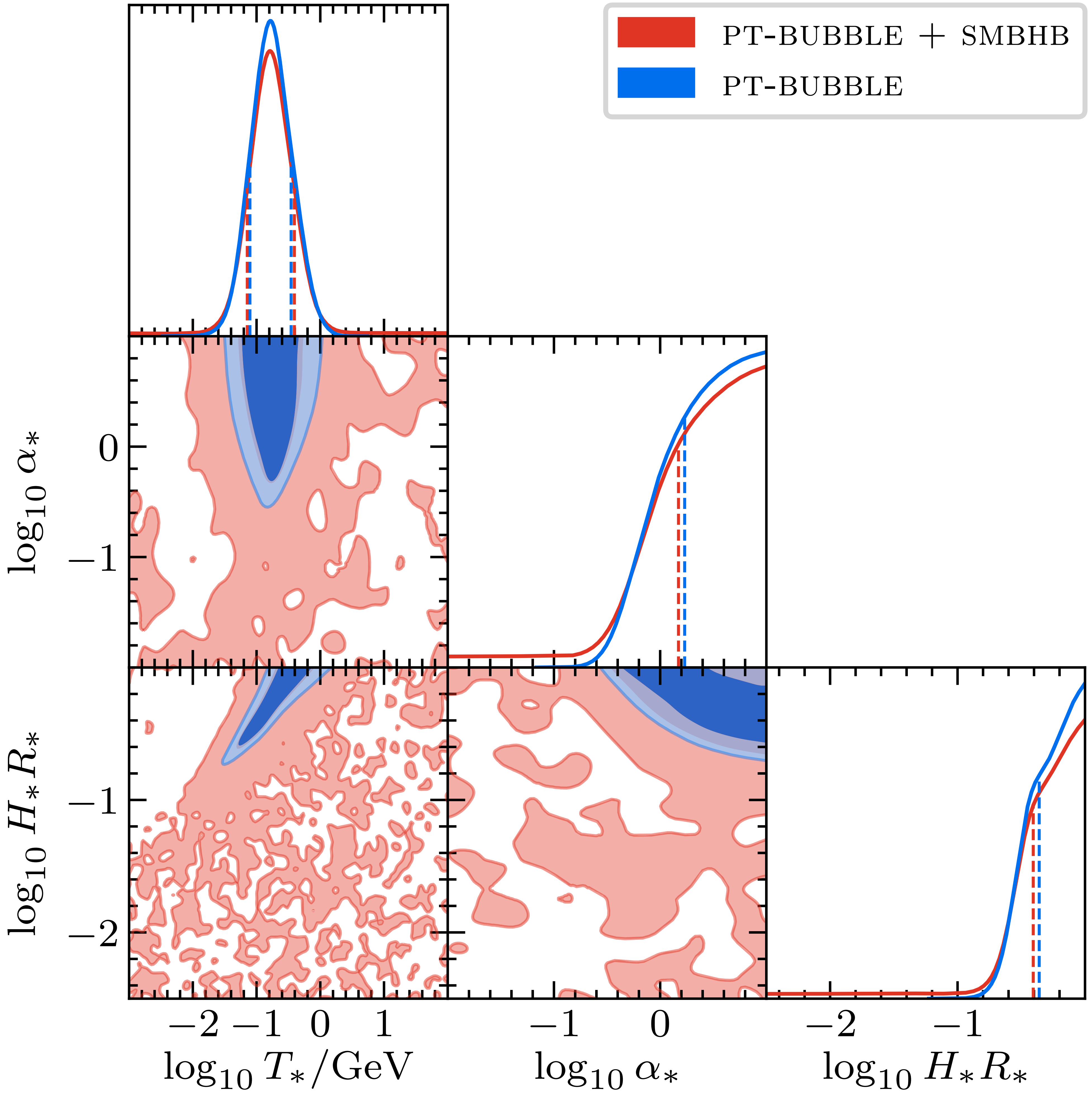
$$\alpha_* \equiv \frac{\rho_V}{\rho_c}$$

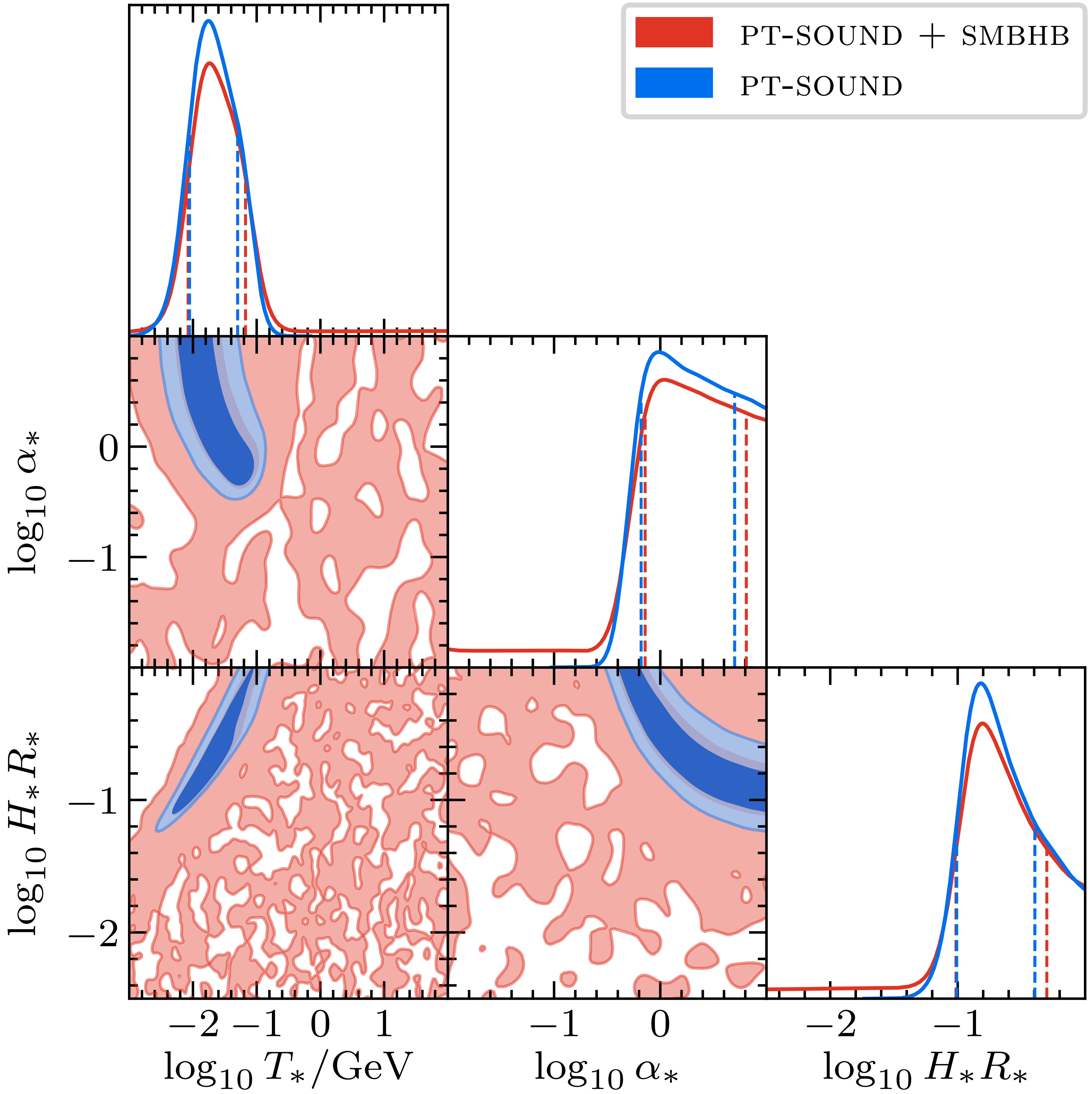
$$\sim 10^{-5} \left(\frac{\alpha_*}{1+\alpha_*}\right)^2 (H_* R_*)^p$$

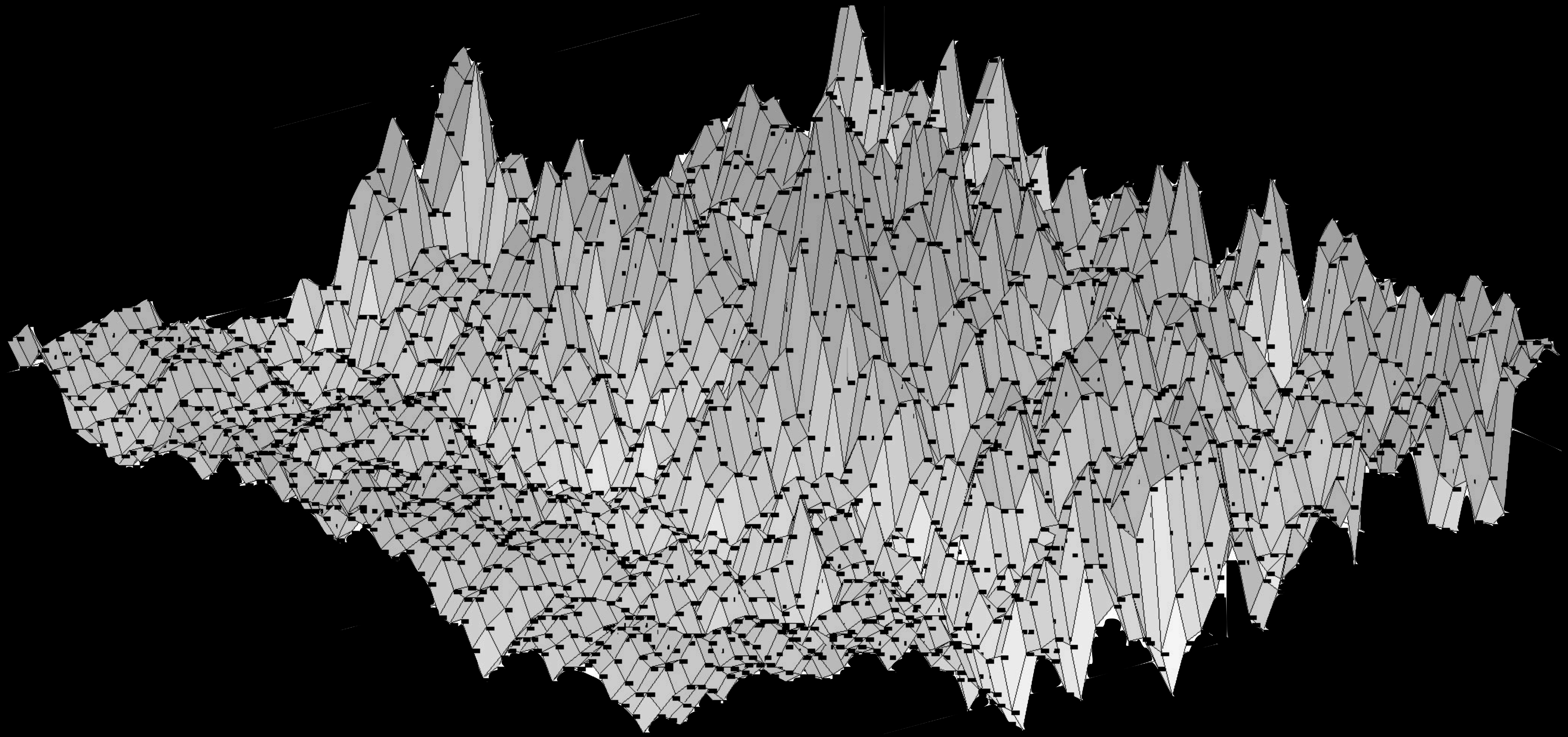
$$f_* \sim 50\,\mathrm{nHz} \left(\frac{T_*}{\mathrm{GeV}}\right) (H_* R_*)^{-1}$$

average bubble separation in unit of Hubble radius

PHASE TRANSITIONS







scalar induced GWs

SCALAR INDUCED GW

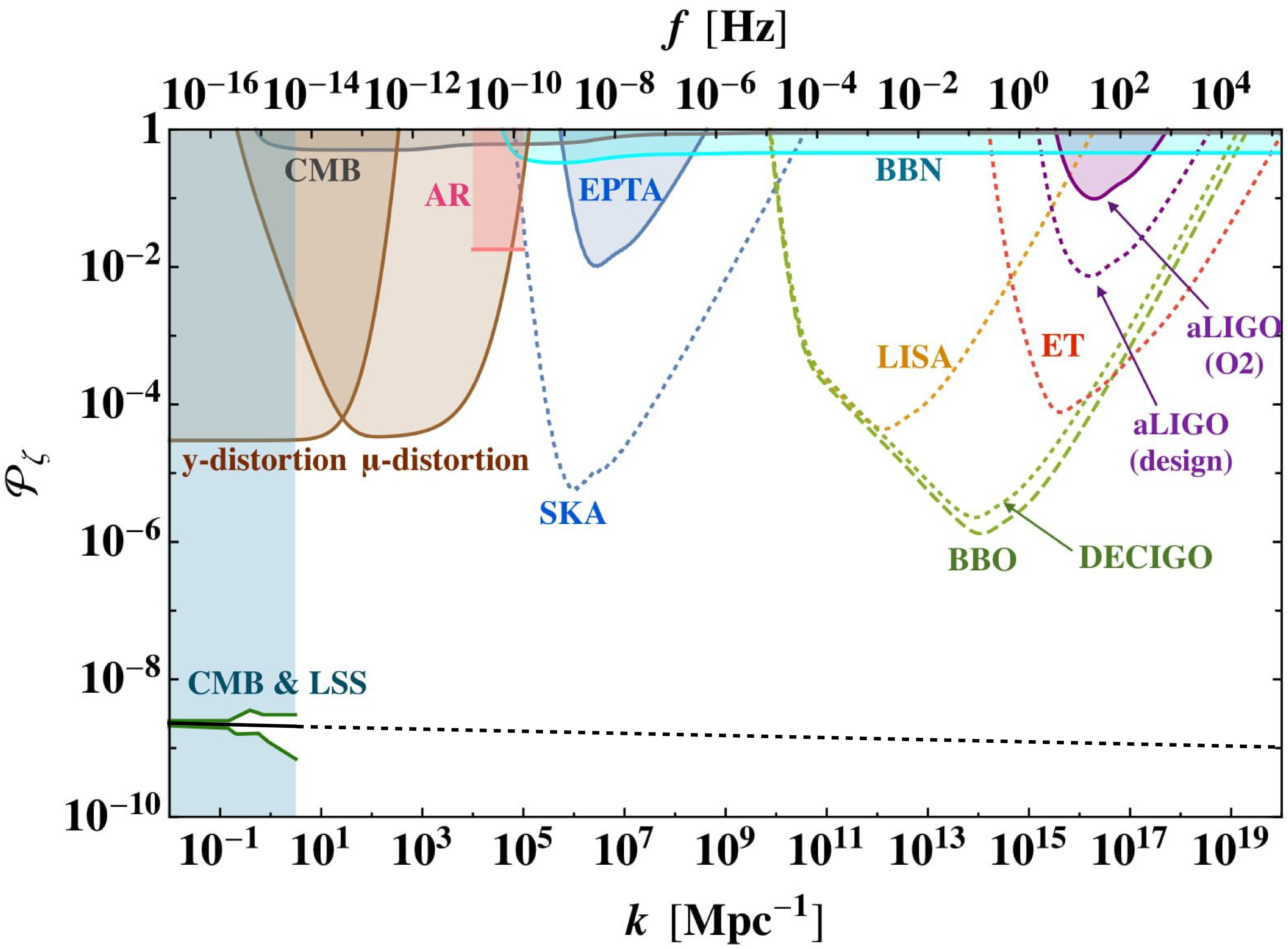


Fig. from Inomata et al. [1812.00674]

SCALAR INDUCED GW

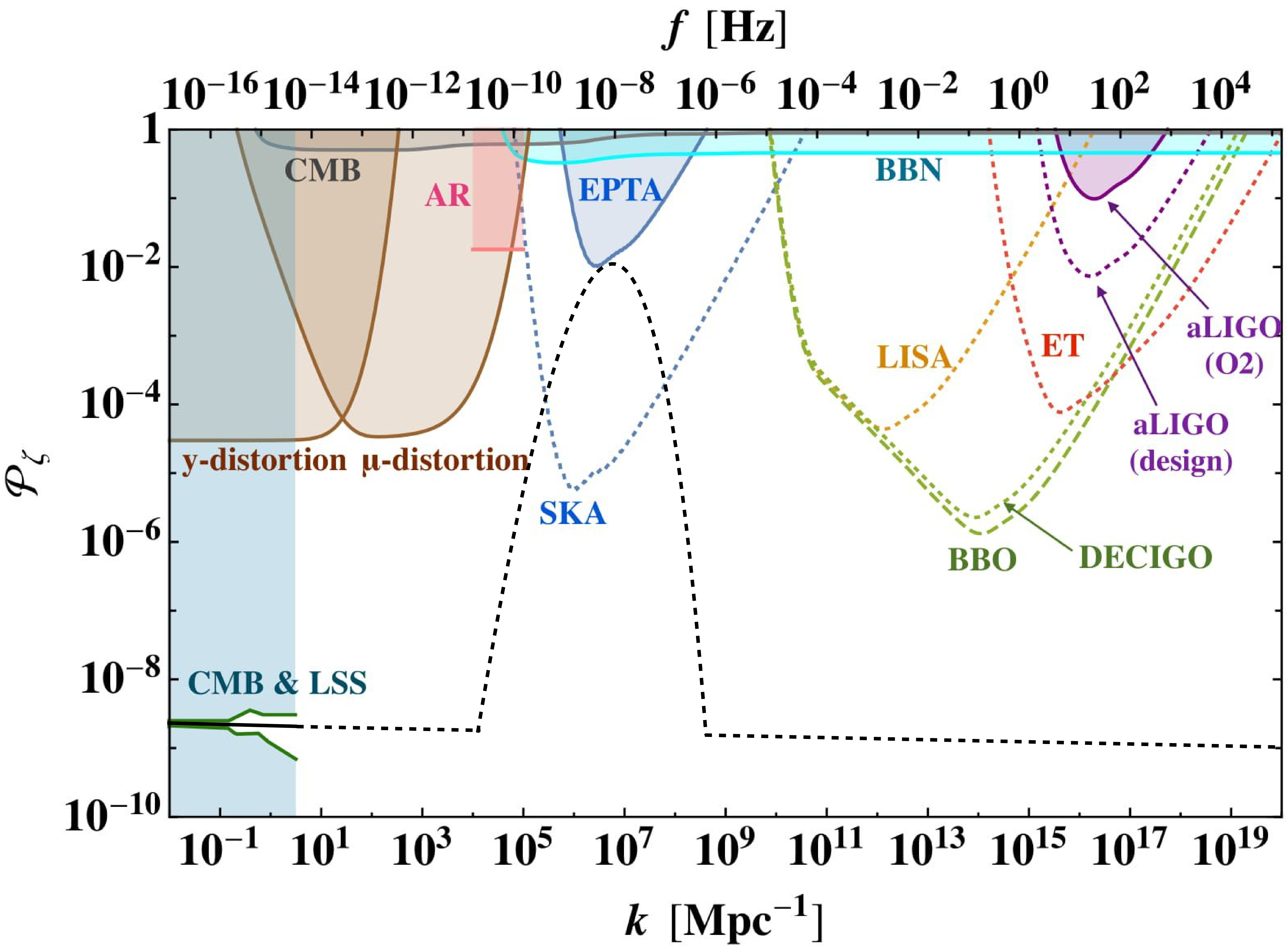


Fig. from Inomata et al. [1812.00674]

SCALAR INDUCED GW

fraction of patches collapsing at horizon re-entry

$$\beta(M) \sim \frac{1}{\sqrt{2\pi}\sigma(M)} \int_{\delta_c}^{\infty} d\delta \exp\left(-\frac{\delta^2}{2\sigma(M)^2}\right)$$

variance of density perturbations

$$\sigma(M)^2 \sim \int \frac{dk}{k} P_\delta(k) W^2(kR(M))$$

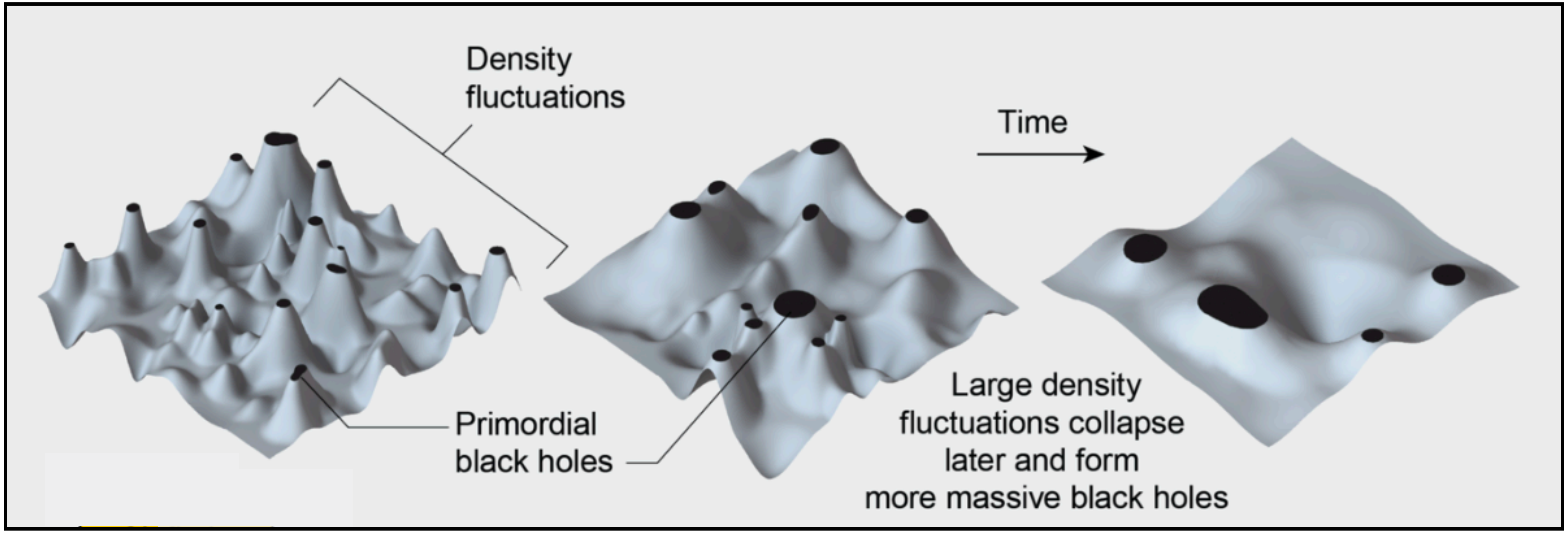
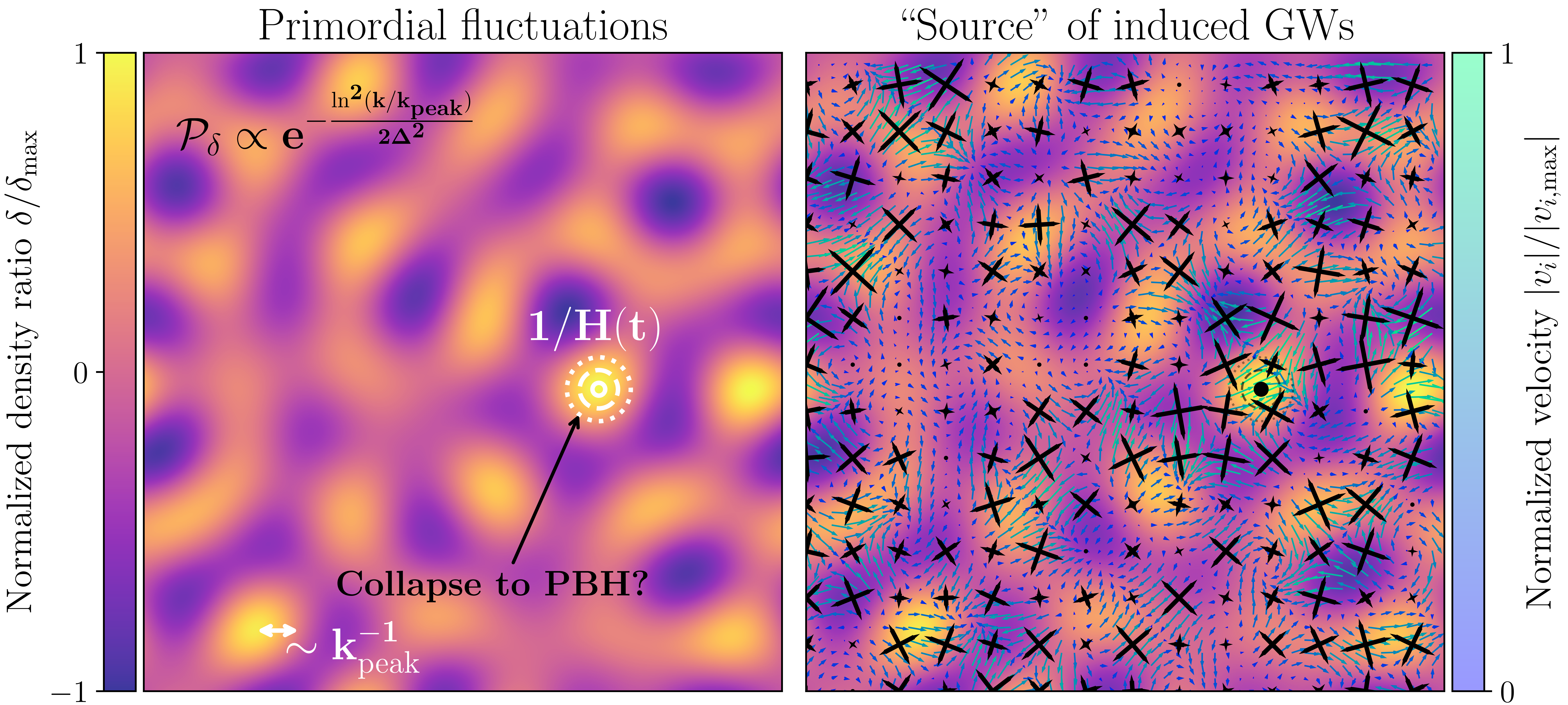


Fig. from Bellido et al.

SCALAR INDUCED GW

$$h''_{ij} + 2Hh'_{ij} - \Delta h_{ij} = \left[4\partial_i\Phi\partial_j\Phi + 2a^2(\rho + P)v_i v_j\right]^{\mathrm{TT}}$$

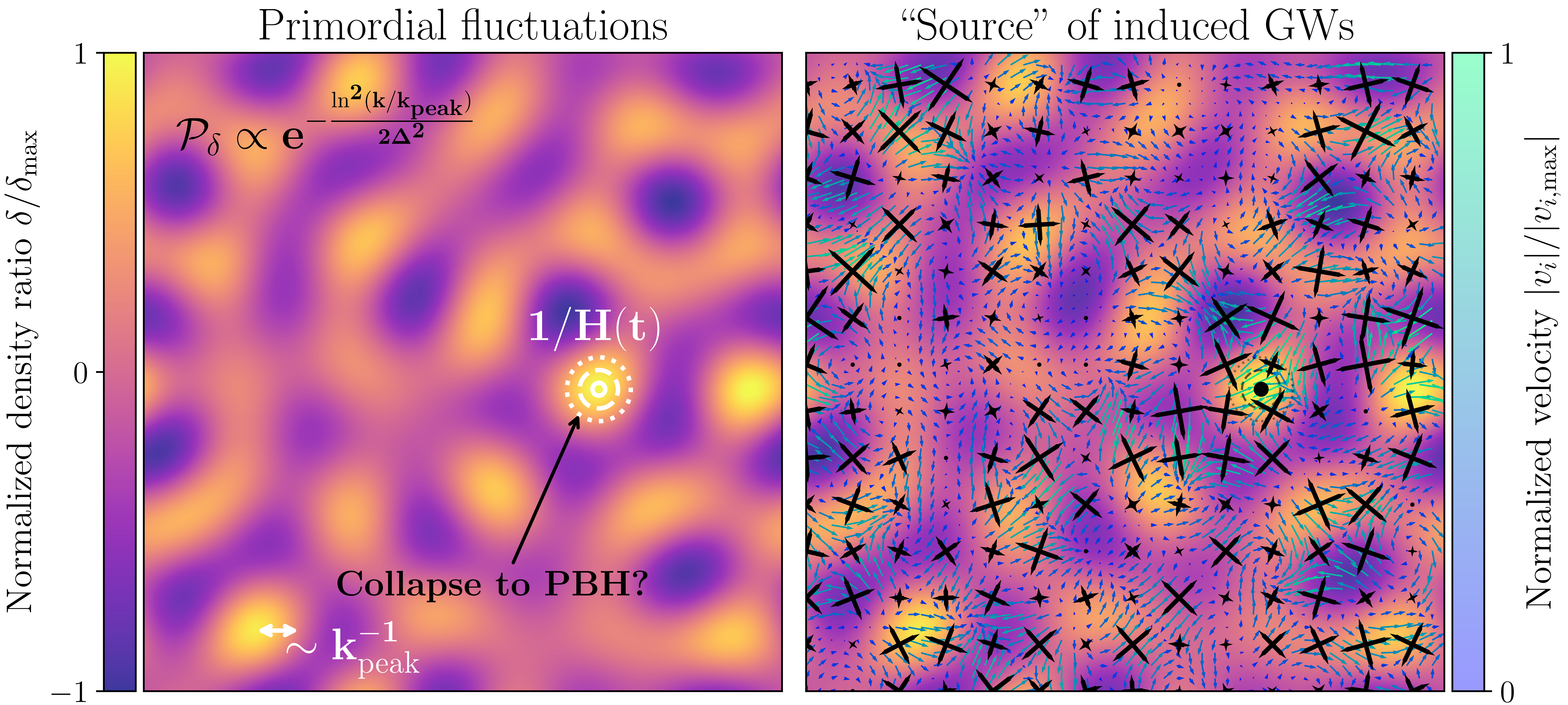


Domenech [2402.17388]

SCALAR INDUCED GW

density fluctuations act as a source for GWs

$$h''_{ij} + 2Hh'_{ij} - \Delta h_{ij} = \left[\boxed{4\partial_i\Phi\partial_j\Phi} + 2a^2(\rho+P)v_iv_j\right]^{\rm TT}$$

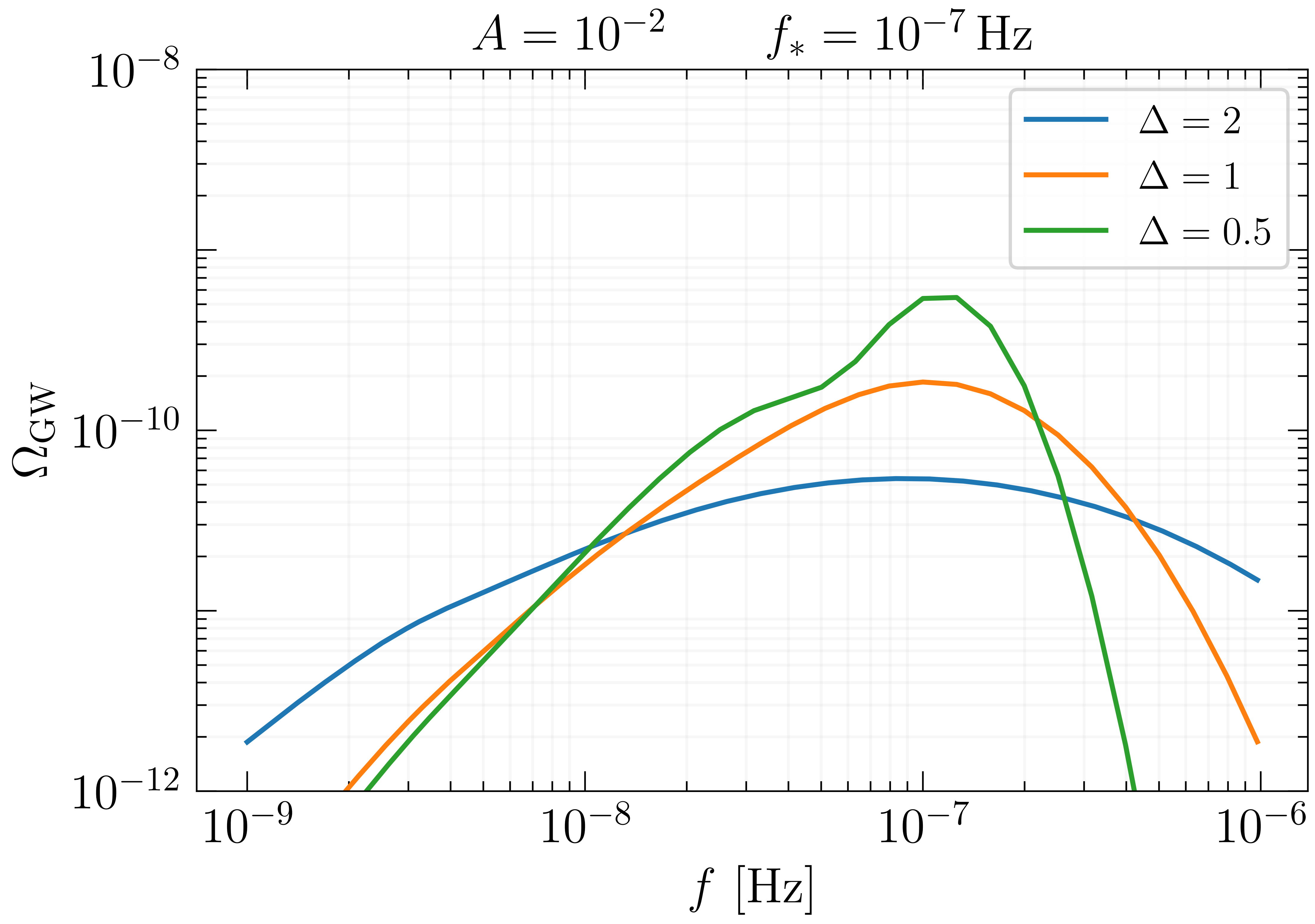


Domenech [2402.17388]

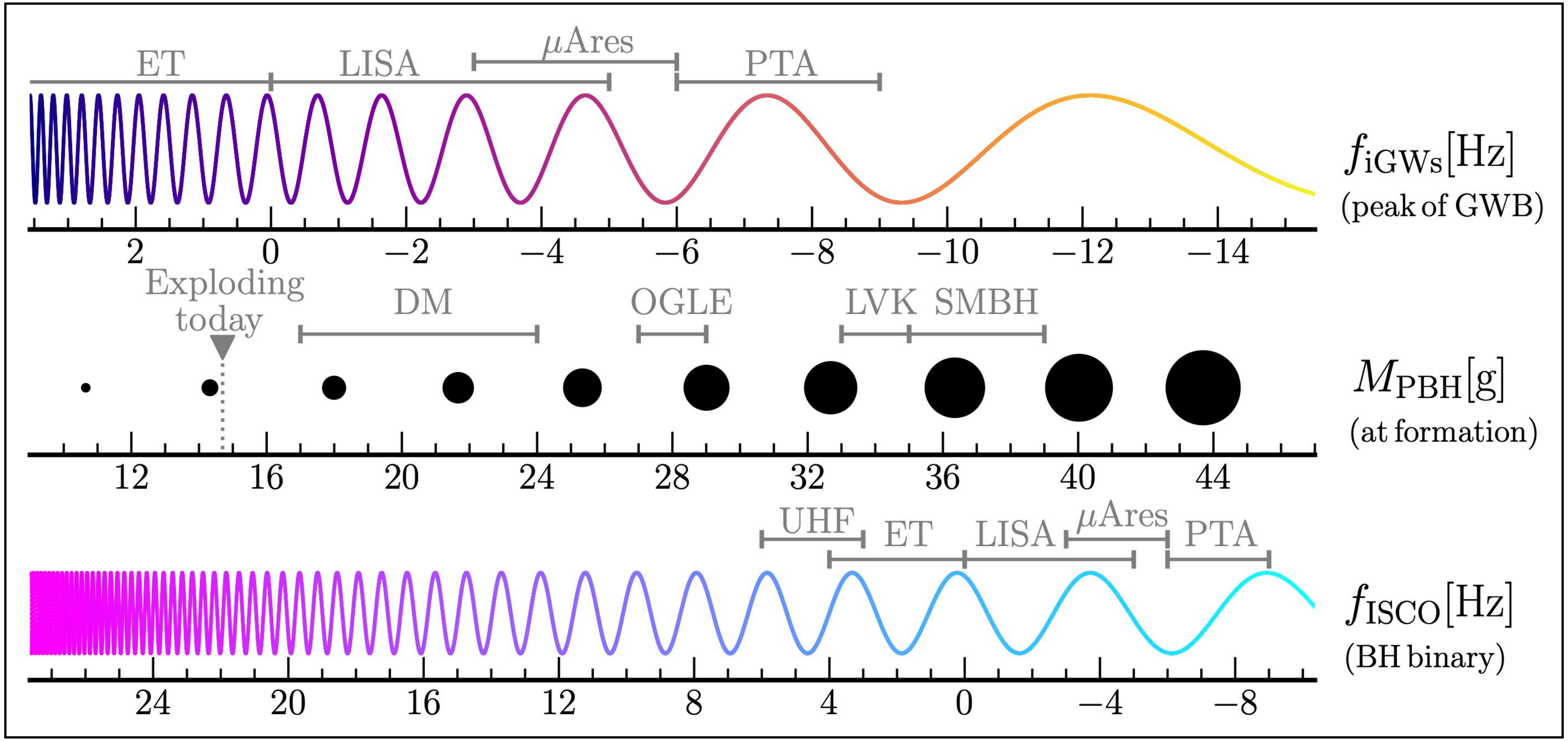
SCALAR INDUCED GW

$$\Omega_{\rm GW}(f) \simeq \Omega_r \int_0^\infty \mathrm{d}v \int_{|1-v|}^{1+v} \mathrm{d}u\, \mathcal{K}(u,v)\, \mathcal{P}_{\mathcal{R}}(uk)\, \mathcal{P}_{\mathcal{R}}(vk)$$

$$P_{\mathcal{R}}(k) = \frac{A}{2\pi\Delta} \exp\left[-\frac{1}{2}\left(\frac{\ln k - \ln k_*}{2\Delta^2}\right)^2\right]$$

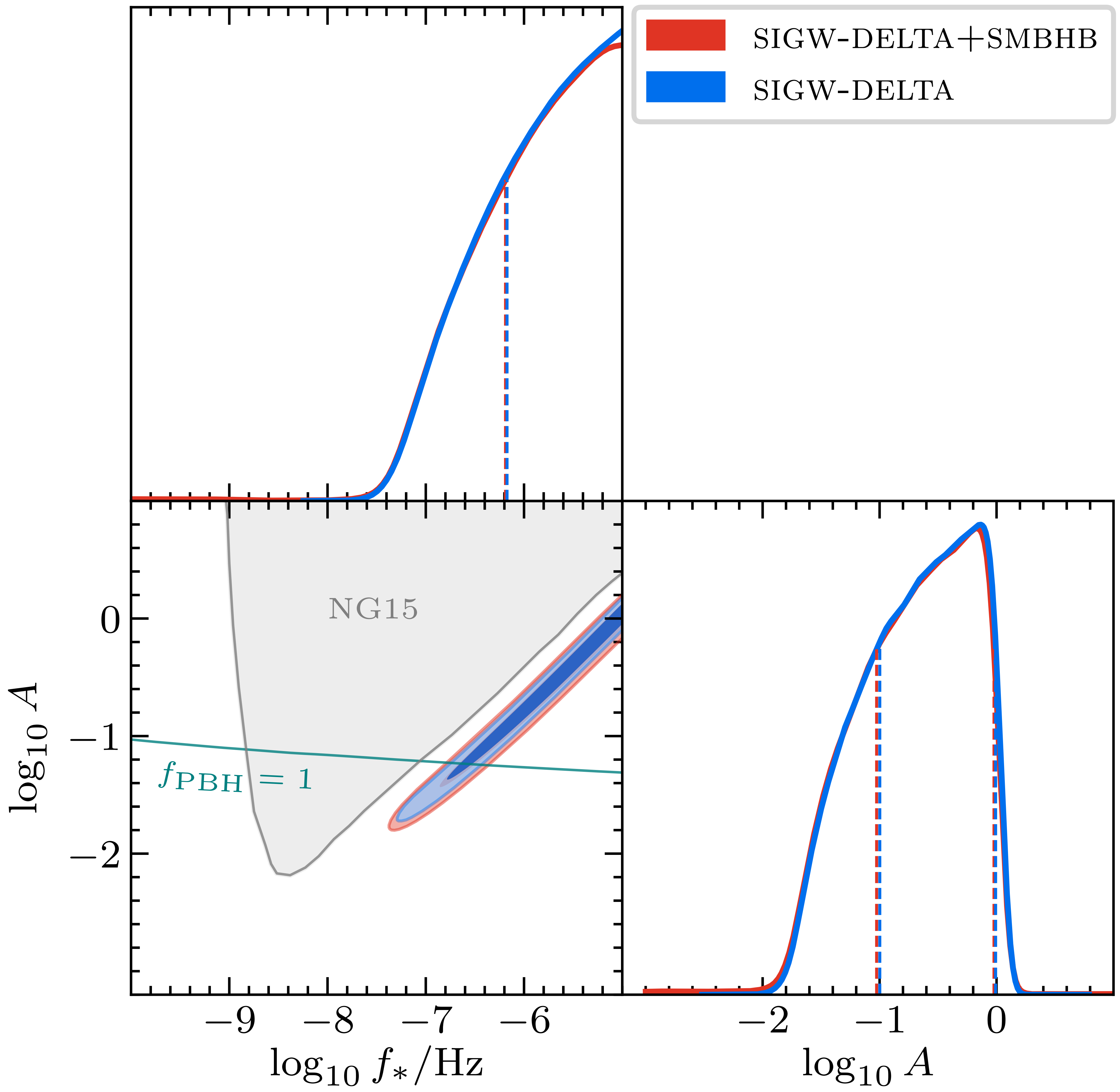


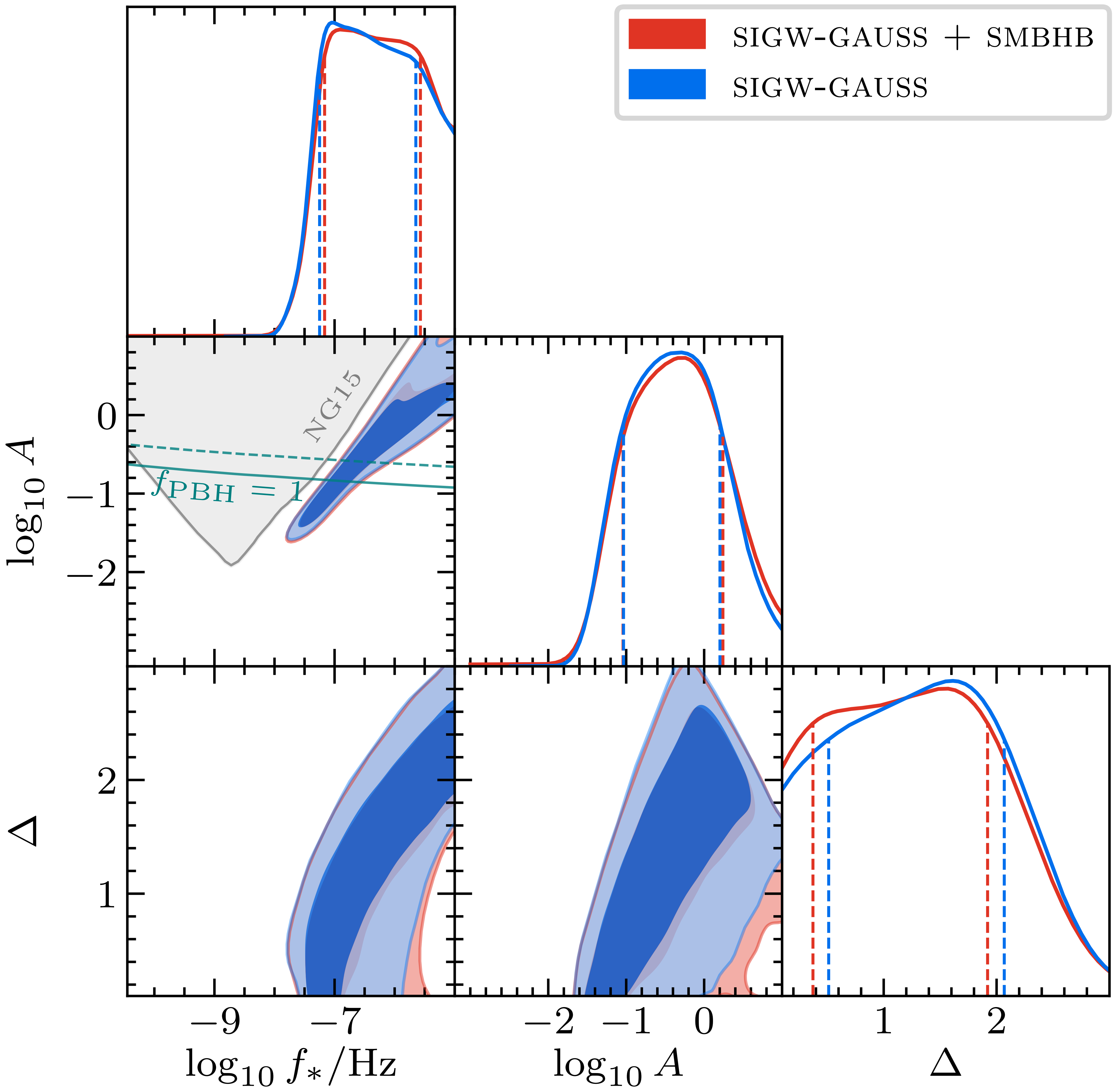
scalar induced GW-PBH connection



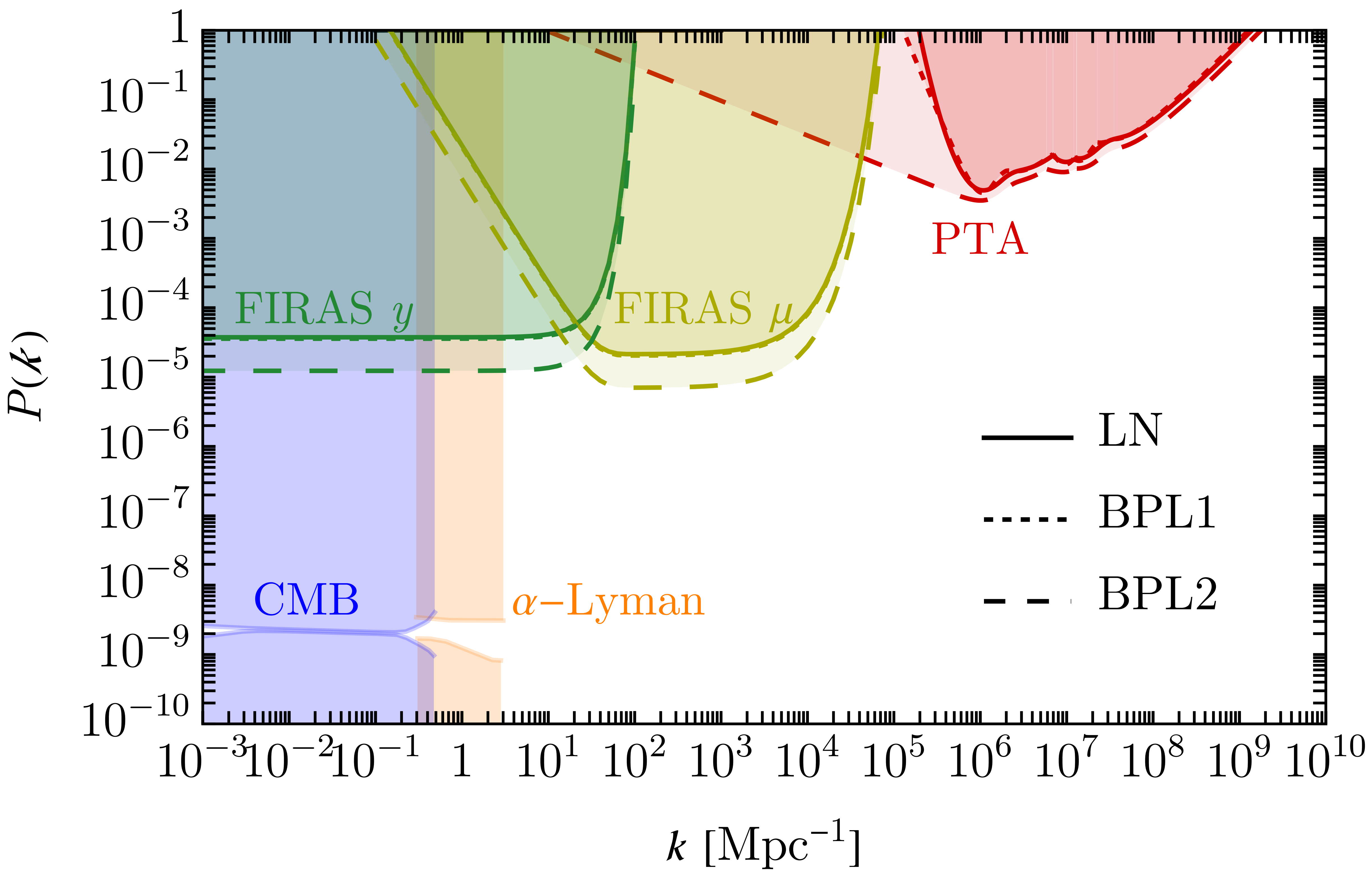
Domenech [2402.17388]

SCALAR INDUCED GW



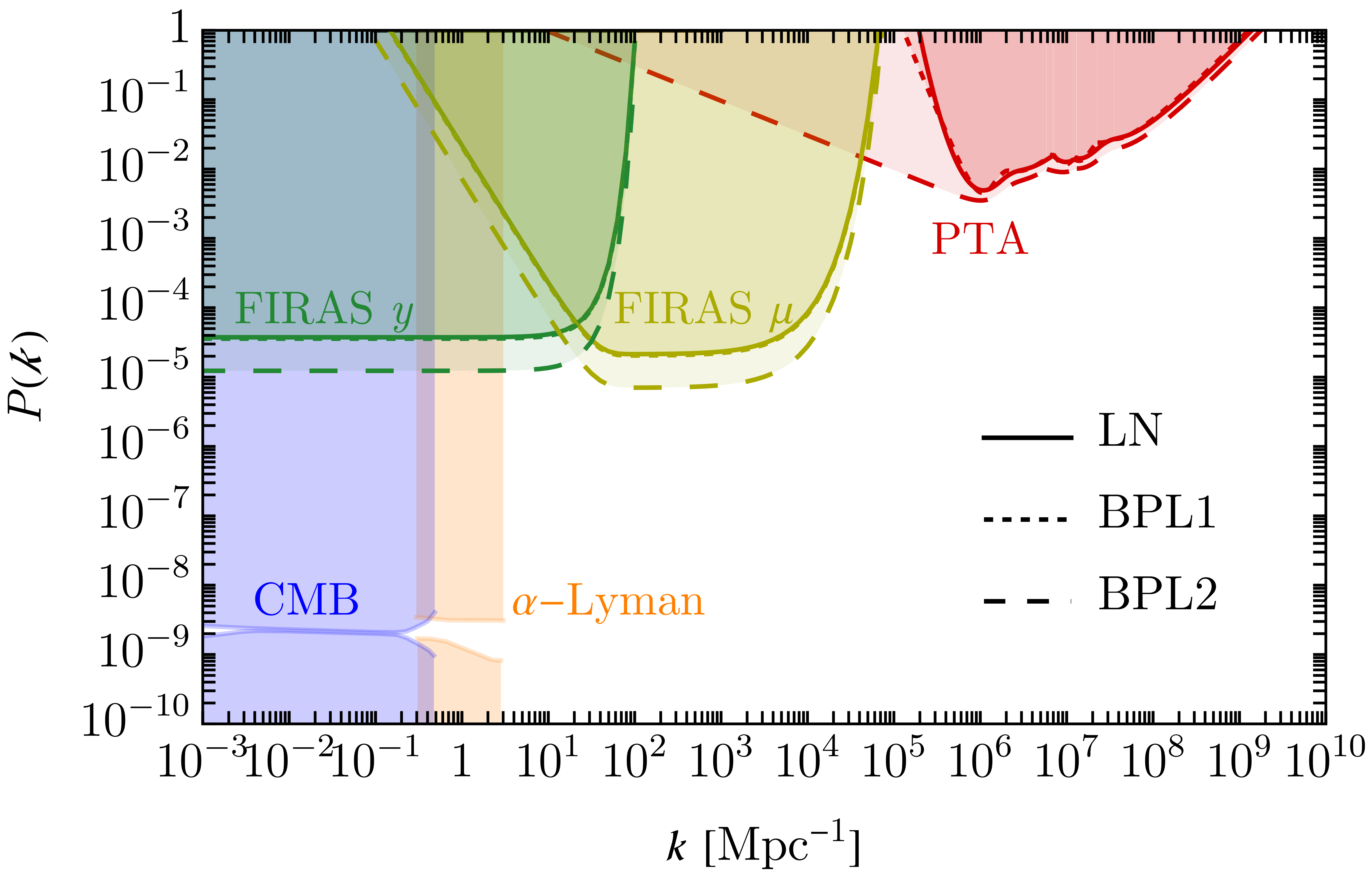


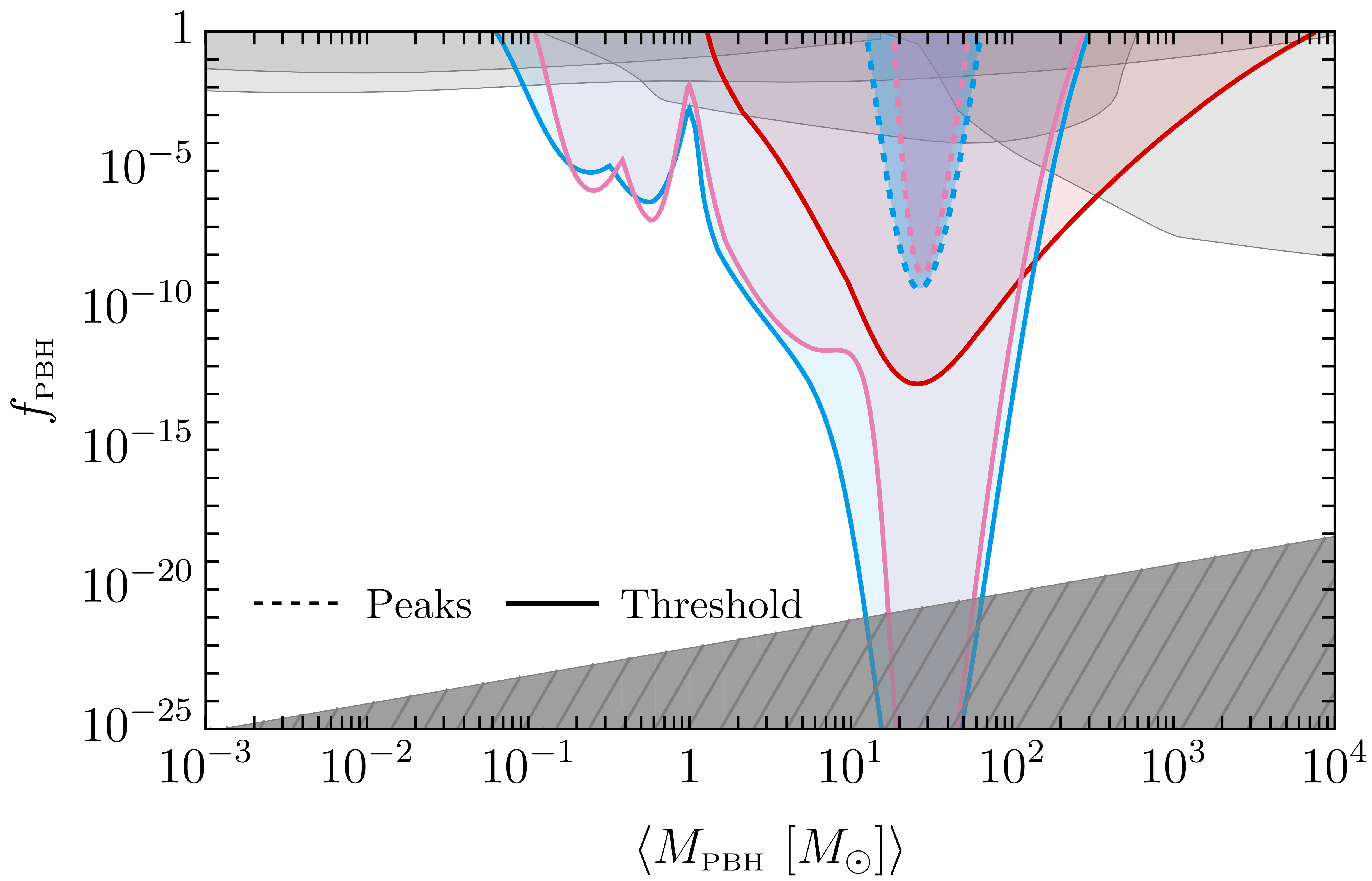
SCALAR INDUCED GW



Jovino et al [2406.20089]

SCALAR INDUCED GW

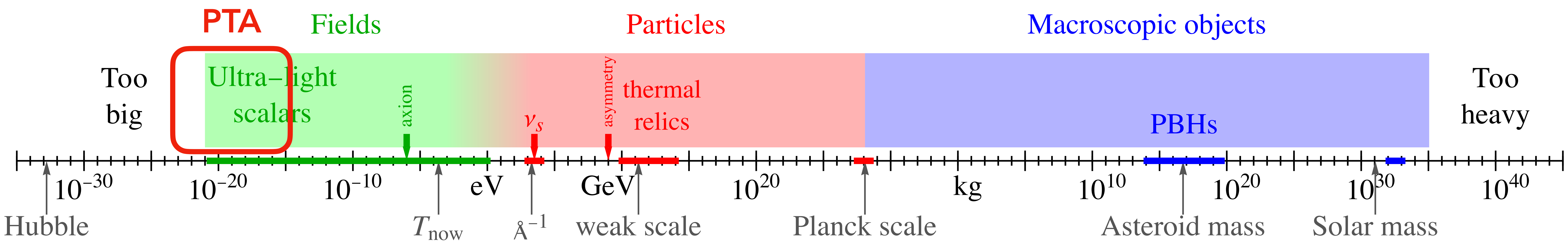




Jovino et al [2406.20089]

not only GWs

ULDM



Cirelli et al. [2406.01705]

ULDM feature **large occupation numbers**

$$N_{\rm occ} \sim \frac{\rho_{\rm DM}}{m}\lambda_{\rm dB}^3 \sim 10^{93}\left(\frac{10^{-20}{\rm eV}}{m}\right)$$

within the Galactic halo, we can treat ULDM as a **classical field**

$$\phi(\vec{x},t) = A(\vec{x})\cos\left(mt + \alpha(\vec{x})\right)$$

Khmelnitsky and Rubakov [1309.5888]

ULDM: GRAVITATIONAL SIGNALS

ULDM density and pressure fluctuations

$$p_\phi \approx -\rho_0 \cos(2mt + \alpha)$$

$$\rho_\phi \approx \rho_0 \left[1 - v^2 \cos(2mt + \alpha)\right]$$

→

source gravitational potentials fluctuations

$$\nabla^2 \Psi = 4\pi G \, \rho_\phi$$

$$6\ddot{\Psi} + 2\nabla^2(\Phi - \Psi) = 24\pi G \, p_\phi$$

→

hence metric fluctuations

$$ds^2 = \Big[1 + 2\Phi(t, \vec{x})\Big] dt^2 - \Big[1 - 2\Psi(t, \vec{x})\Big] dx^2$$

metric fluctuations induce a deterministic timing delay

$$h(t) = A \left[\hat{\phi}_E^2 \sin(2m_\phi t + \gamma_E) - \hat{\phi}_P^2 \sin(2m_\phi t + \gamma_P)\right]$$

ULDM: GRAVITATIONAL SIGNALS

Khmelnitsky and Rubakov [1309.5888]

ULDM density and pressure fluctuations

$$p_\phi \approx -\rho_0 \cos(2mt+\alpha)$$

$$\rho_\phi \approx \rho_0 \left[1 - v^2\cos(2mt+\alpha)\right]$$

$\longrightarrow$

source gravitational potentials fluctuations

$$\nabla^2\Psi = 4\pi G\, \rho_\phi$$

$$6\ddot{\Psi} + 2\nabla^2(\Phi-\Psi) = 24\pi G\, p_\phi$$

$\longrightarrow$

hence metric fluctuations

$$ds^2 = \Big[1 + 2\Phi(t,\vec{x})\Big]dt^2 - \Big[1 - 2\Psi(t,\vec{x})\Big]dx^2$$

metric fluctuations induce a monochromatic and deterministic timing delay

$$h(t) = A\left[\hat{\phi}_E^2 \sin(2m_\phi t + \gamma_E) - \hat{\phi}_P^2 \sin(2m_\phi t + \gamma_P)\right]$$

ULDM: GRAVITATIONAL SIGNALS

Khmelnitsky and Rubakov [1309.5888]

ULDM density and pressure fluctuations

$$p_\phi \approx -\rho_0 \cos(2mt + \alpha)$$

$$\rho_\phi \approx \rho_0 \left[1 - v^2 \cos(2mt + \alpha)\right]$$

→

source gravitational potentials fluctuations

$$\nabla^2 \Psi = 4\pi G\, \rho_\phi$$

$$6\ddot{\Psi} + 2\nabla^2(\Phi - \Psi) = 24\pi G\, p_\phi$$

→

hence metric fluctuations

$$ds^2 = \Big[1 + 2\Phi(t, \vec{x})\Big] dt^2 - \Big[1 - 2\Psi(t, \vec{x})\Big] dx^2$$

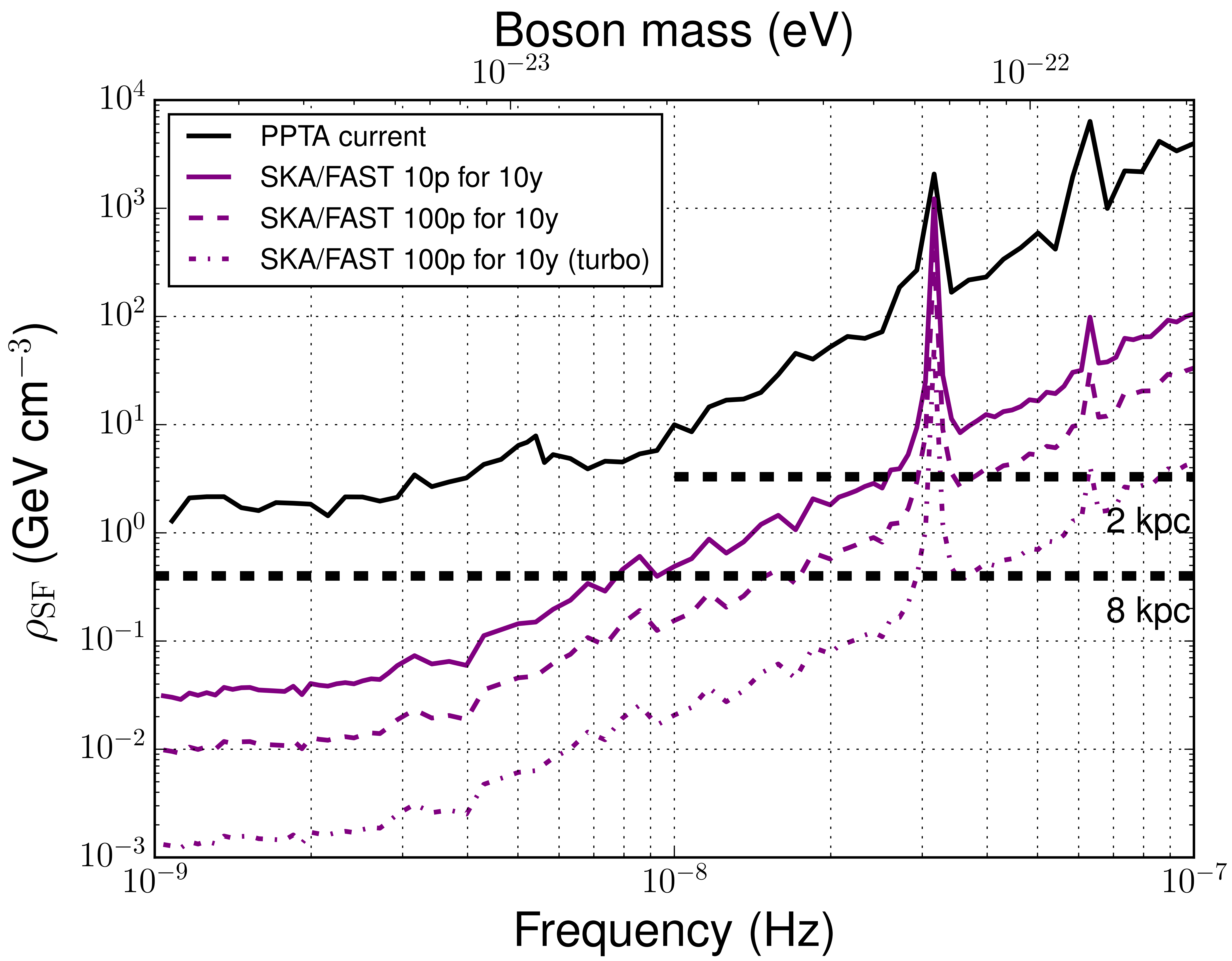
metric fluctuations induce a monochromatic and deterministic timing delay

$$h(t) = A \left[\hat{\phi}_E^2 \sin(2m_\phi t + \gamma_E) - \hat{\phi}_P^2 \sin(2m_\phi t + \gamma_P)\right]$$

$$A \sim \frac{G\rho_\phi}{m_\phi^3}$$

ULDM: GRAVITATIONAL SIGNALS

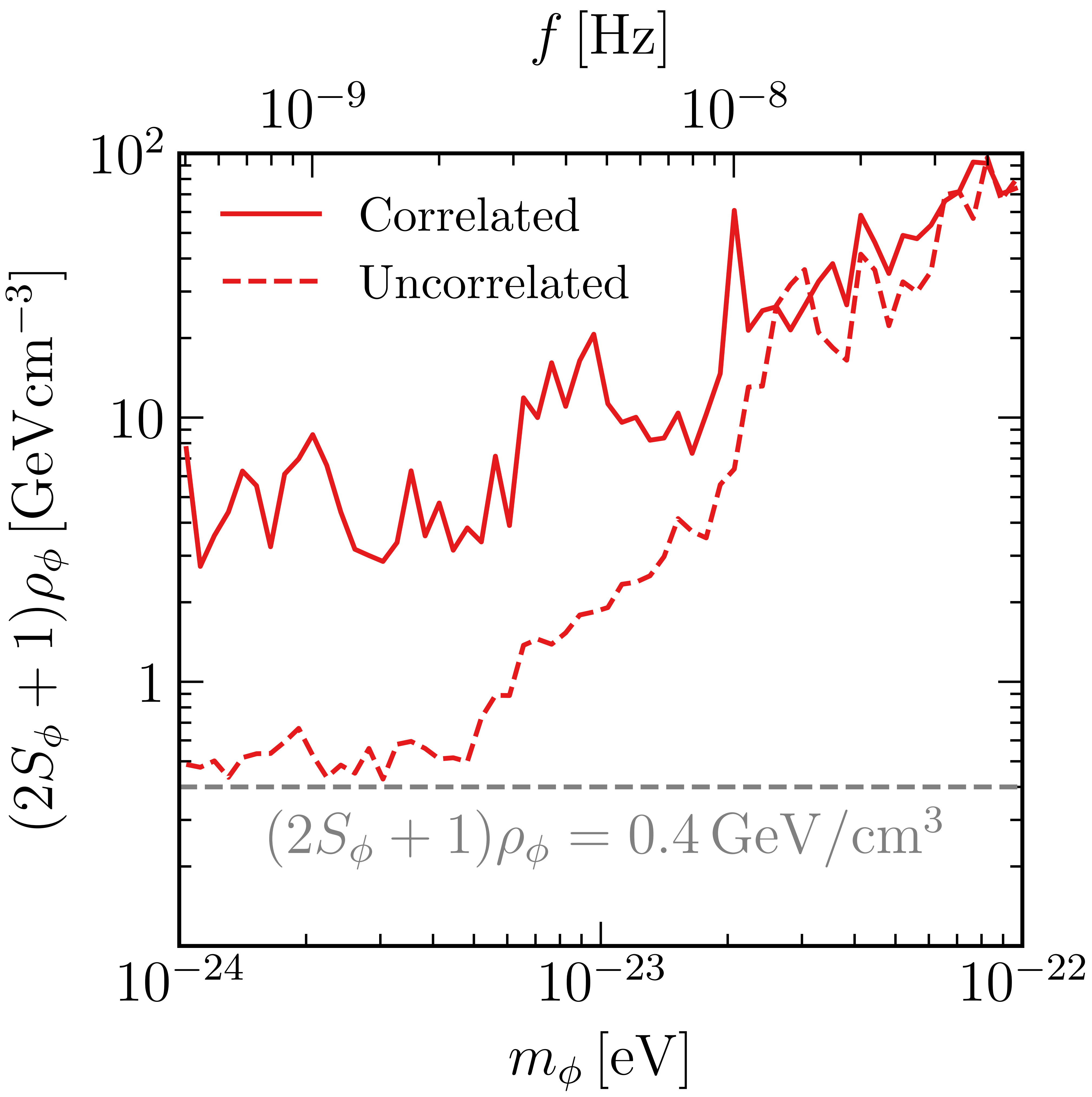
PPTA (2018)
Porayko et al. [1810.03227]



ULDM: GRAVITATIONAL SIGNALS

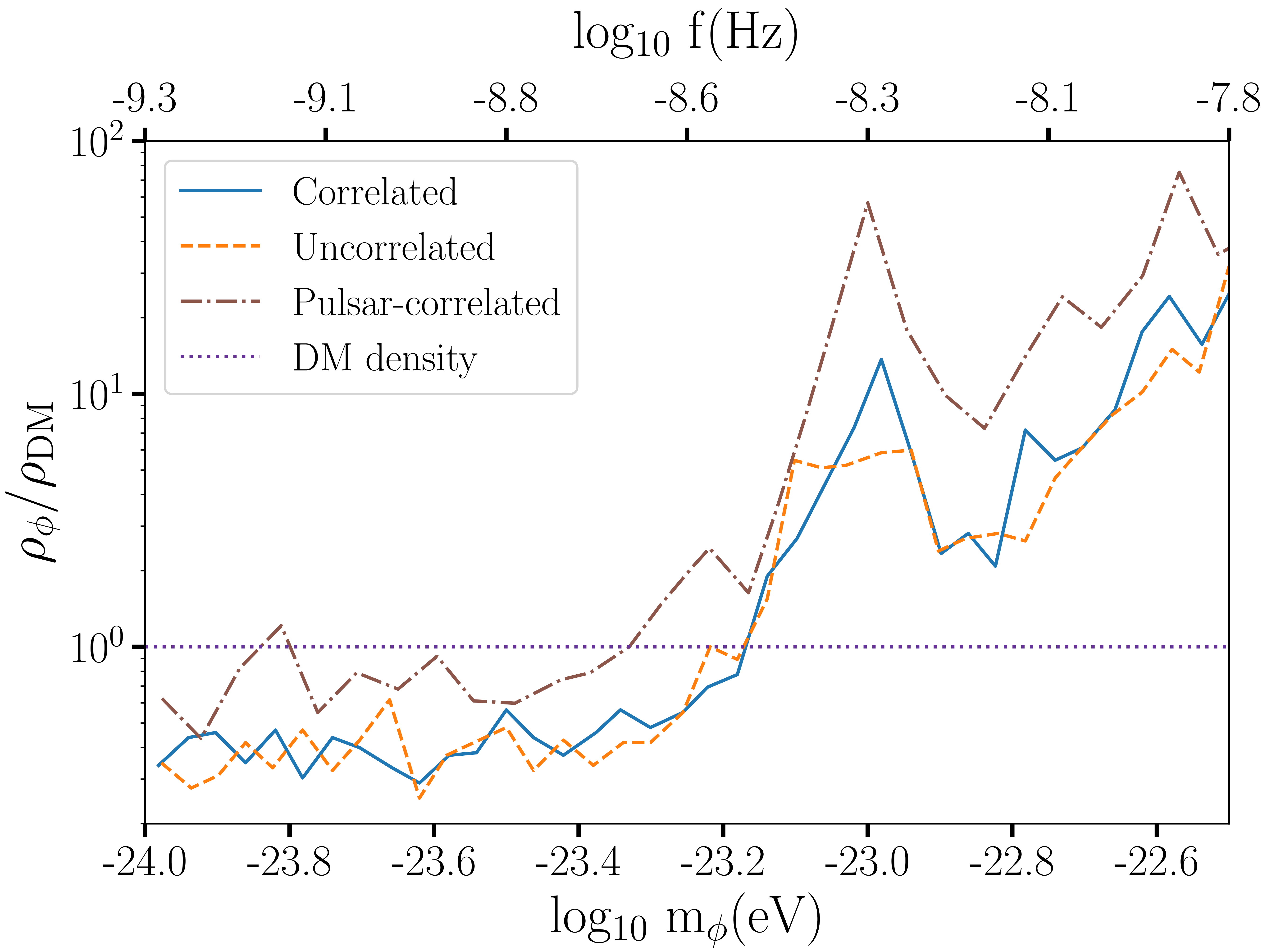
NANOGrav 15-year

Afzal et al. [2306.16219]



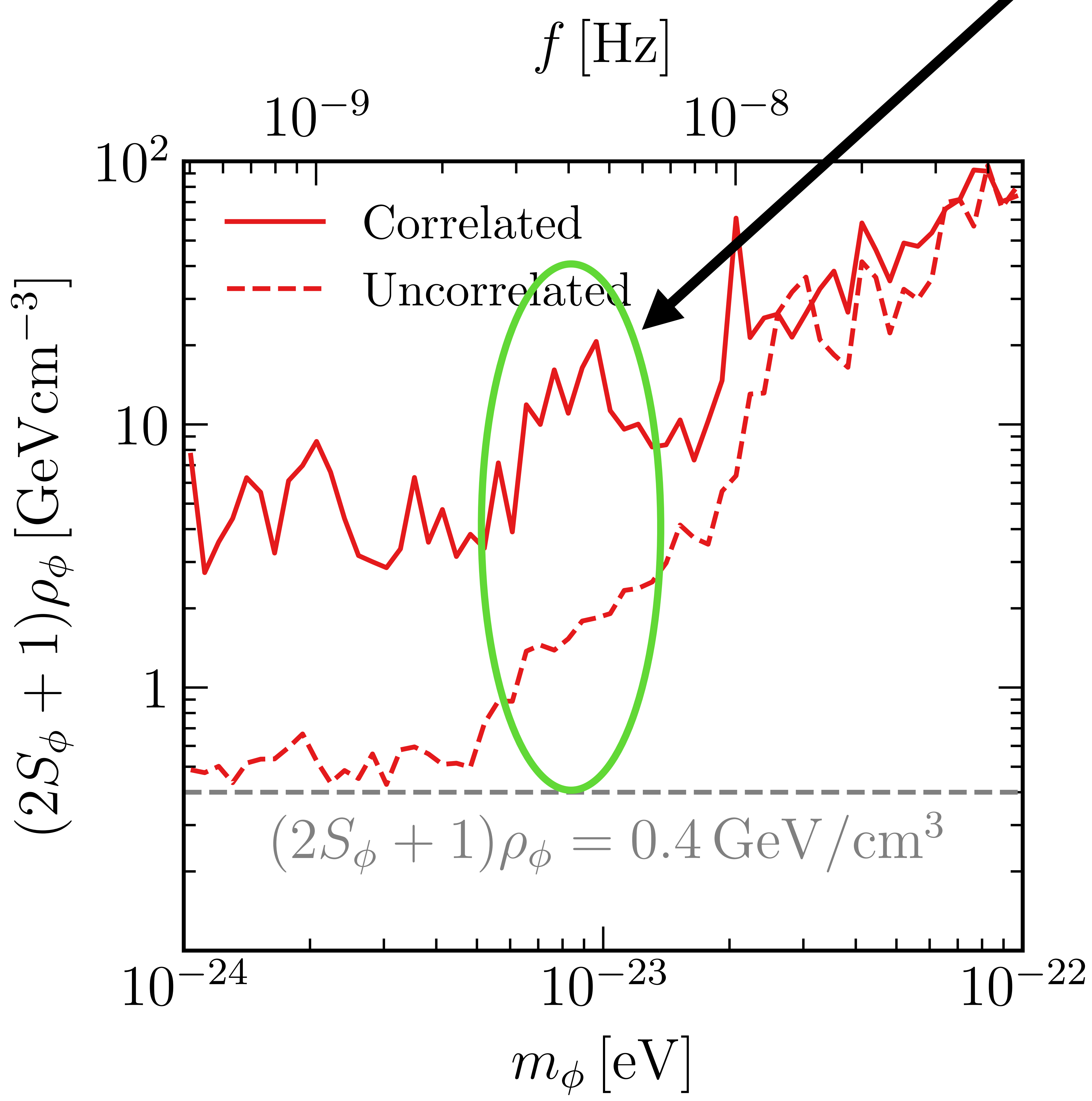
EPTA DR2

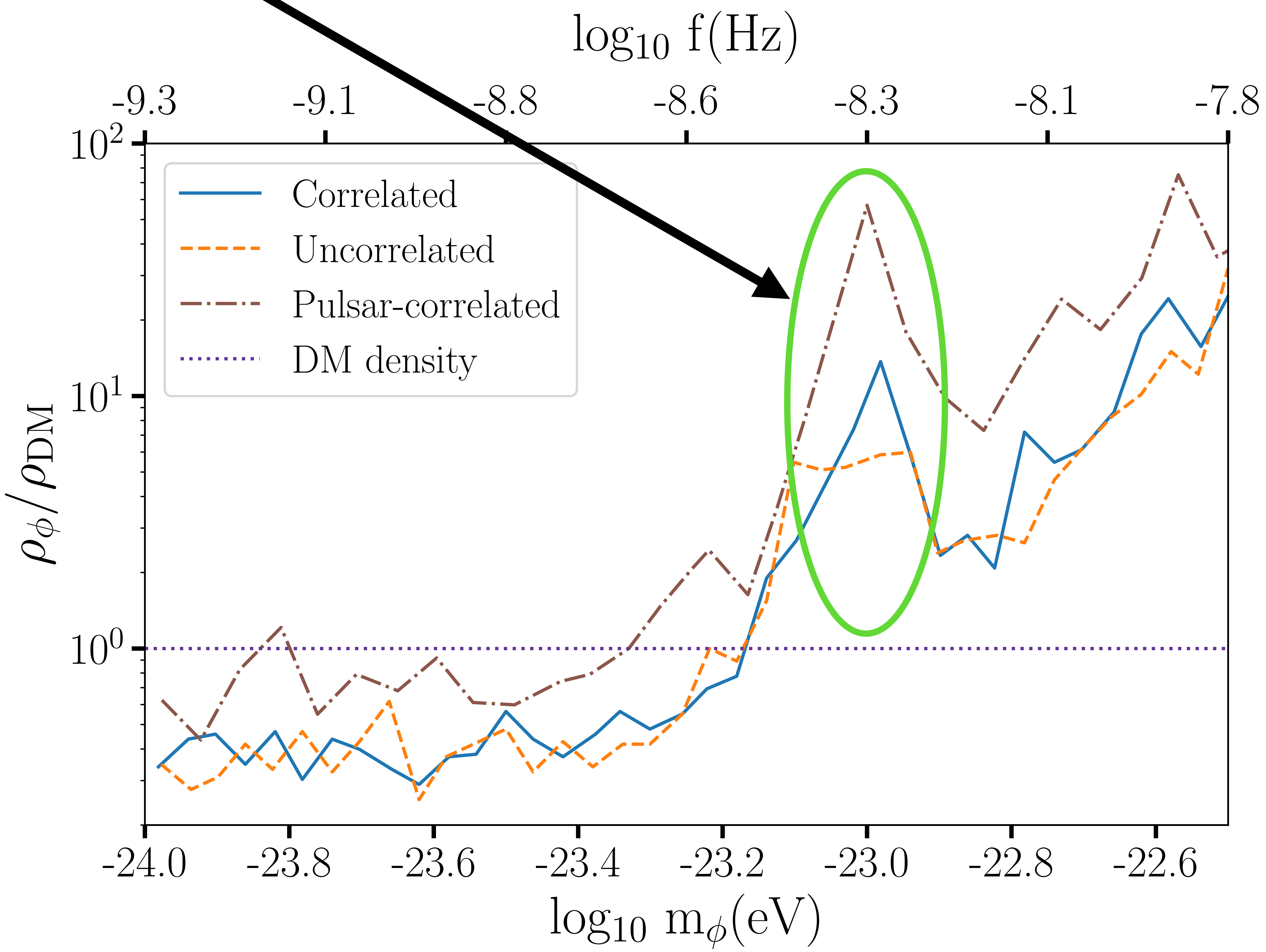
Smarra et al. [2306.16228]



ULDM: GRAVITATIONAL SIGNALS

someone said monopole?





have a model you want to test against PTA data?

say hello to PTArcade

you have a PTA signal

stochastic

$\Omega_{\mathrm{GW}}(f;\,\vec{\theta})$

or

deterministic

$h(t;\,\vec{\theta})$

you want to find the posterior for the signal parameters $\vec{\theta}$

PTArcade

you have a PTA signal

stochastic

$\Omega_{\mathrm{GW}}(f;\,\vec{\theta})$

or

deterministic

$h(t;\,\vec{\theta})$

you want to find the posterior for the signal parameters $\vec{\theta}$

downloads PTA datasets (NG12, NG15, IPTA DR2…)

PTArcade

you have a PTA signal

stochastic

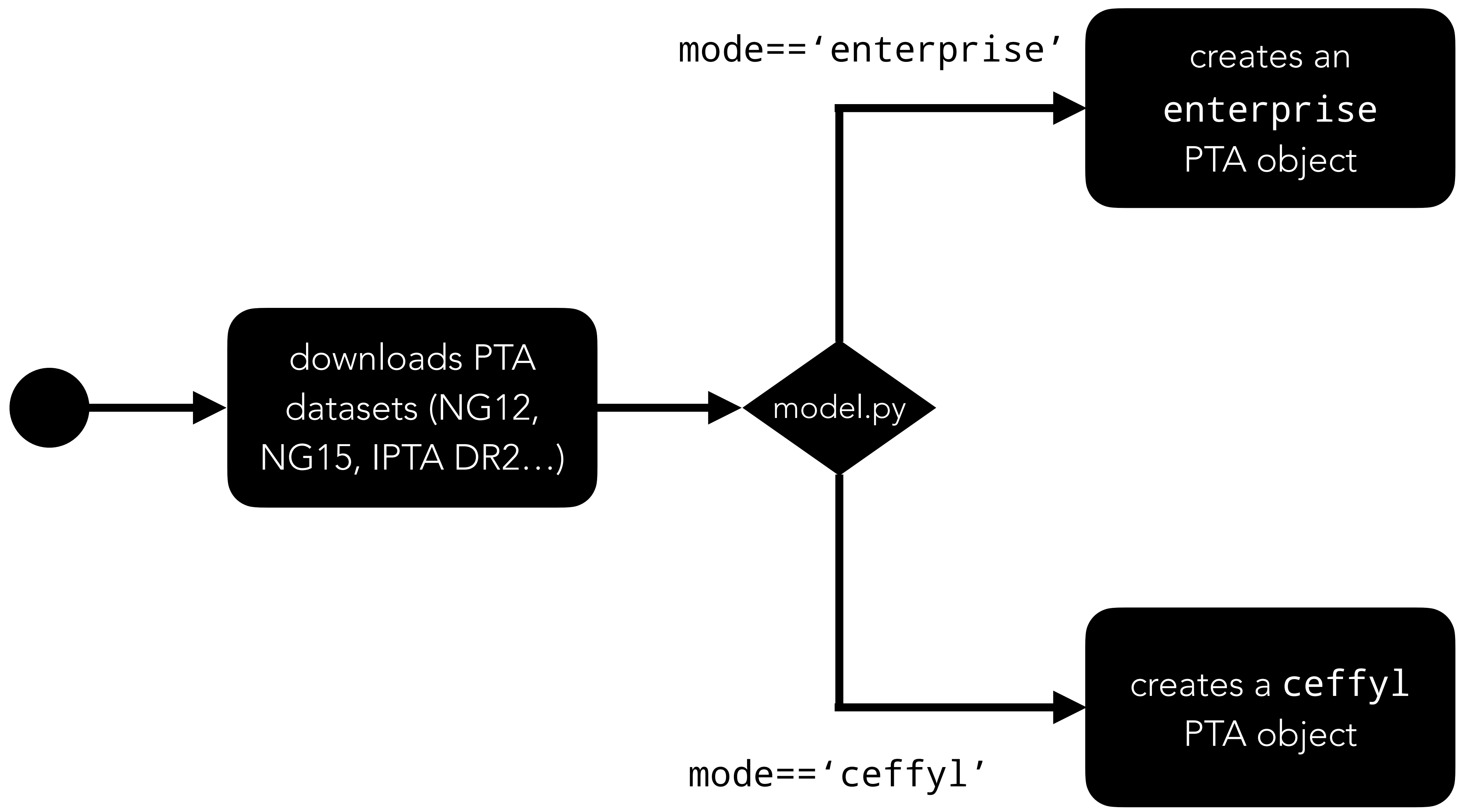
$$\Omega_{\mathrm{GW}}(f;\, \vec{\theta})$$

or

deterministic

$$h(t;\, \vec{\theta})$$

you want to find the posterior for the signal parameters $\vec{\theta}$



PTArcade

you have a PTA signal

stochastic

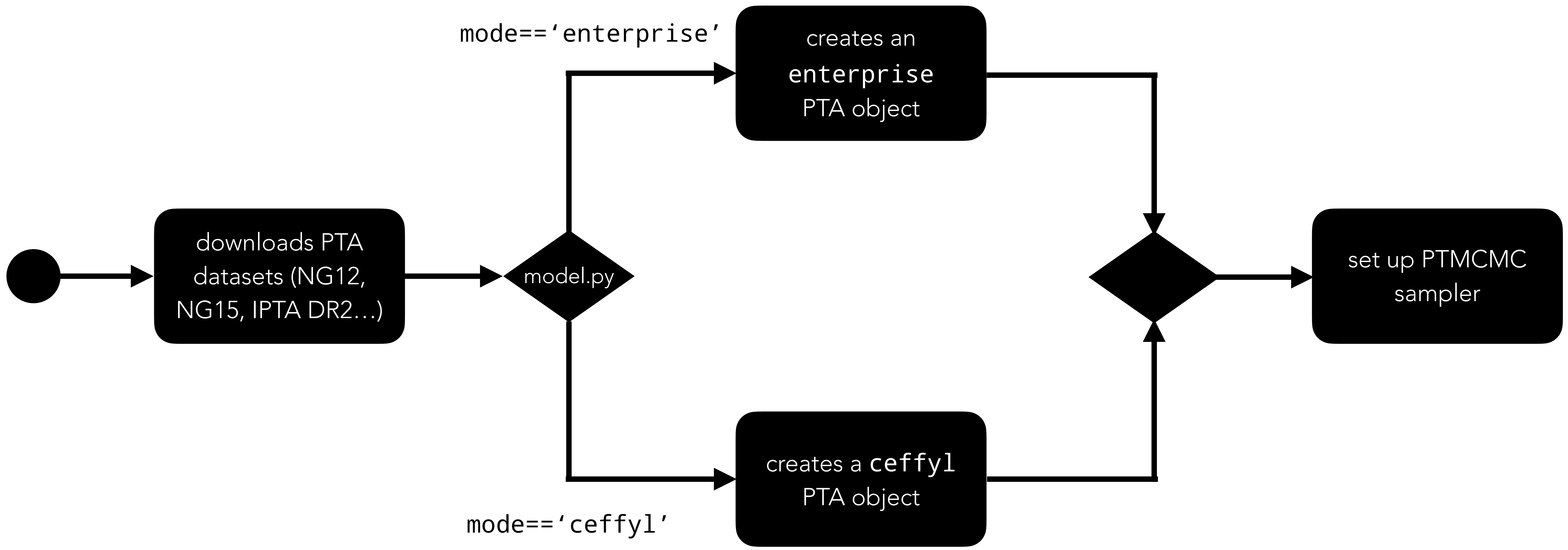
$$\Omega_{\rm GW}(f;\,\vec{\theta})$$

or

deterministic

$$h(t;\,\vec{\theta})$$

you want to find the posterior for the signal parameters $\vec{\theta}$



PTArcade

you have a PTA signal

stochastic

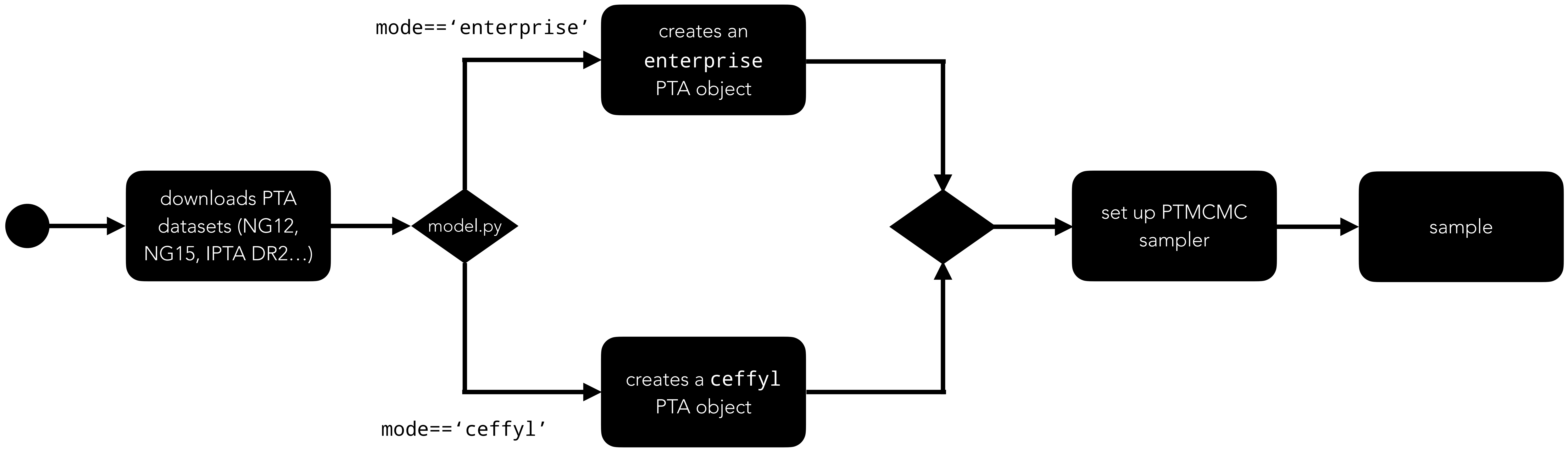
$\Omega_{\rm GW}(f;\,\vec{\theta})$

or

deterministic

$h(t;\,\vec{\theta})$

you want to find the posterior for the signal parameters $\vec{\theta}$



PTArcade

you have a PTA signal

stochastic

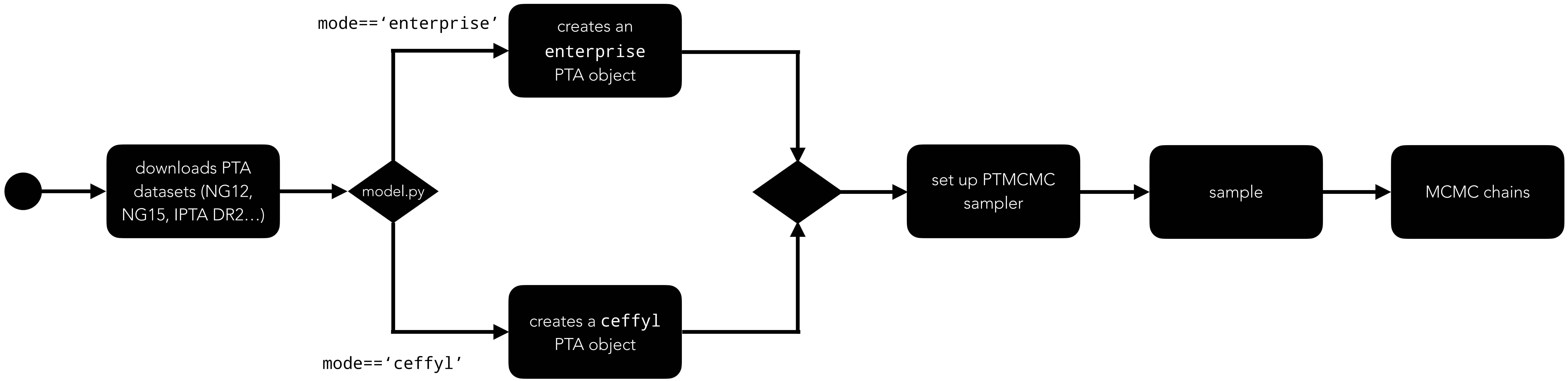
$\Omega_{\rm GW}(f;\,\vec{\theta})$

or

deterministic

$h(t;\,\vec{\theta})$

you want to find the posterior for the signal parameters $\vec{\theta}$



STEP I: installation

on linux and iOS (with intel chips)

```
conda install -c conda-forge ptarcade
```

on iOS (with apple silicon chips)

```
conda create -n ptarcade --platform osx-64 -c conda-forge python=3.10 ptarcade
```

STEP II: model file

$$h^2\Omega_{GW}(f) = \frac{A_*}{f/f_* + f_*/f}$$

REQUIRED CONTENT

- parameter priors
- signal function
  - power spectrum (for stochastic signals)
  - time series (for deterministic ones)

OPTIONAL CONTENT

- modified ORF
- model name
- if add SMBHB signal on top

`model.py`

```python
from ptarcade.models_utils import prior

parameters = {
            'log_A_star' : prior("Uniform", -14, -6),
            'log_f_star' : prior("Uniform", -10, -6)
            }

def S(x):
    return 1 / (1/x + x)

def spectrum(f, log_A_star, log_f_star):
    A_star = 10**log_A_star
    f_star = 10**log_f_star

    return A_star * S(f/f_star)
```

STEP II: model file

$$h^2\Omega_{GW}(f) = \frac{A_*}{f/f_* + f_*/f}$$

REQUIRED CONTENT

- **parameter priors**
- signal function
  - power spectrum (for stochastic signals)
  - time series (for deterministic ones)

OPTIONAL CONTENT

- modified ORF
- model name
- if add SMBHB signal on top

`model.py`

```
from ptarcade.models_utils import prior

parameters = {
            'log_A_star' : prior("Uniform", -14, -6),
            'log_f_star' : prior("Uniform", -10, -6)
            }

def S(x):
    return 1 / (1/x + x)

def spectrum(f, log_A_star, log_f_star):
    A_star = 10**log_A_star
    f_star = 10**log_f_star

    return A_star * S(f/f_star)
```

STEP II: model file

$$h^2\Omega_{GW}(f) = \frac{A_*}{f/f_* + f_*/f}$$

REQUIRED CONTENT

- parameter priors
- **signal function**
  - power spectrum (for stochastic signals)
  - time series (for deterministic ones)

OPTIONAL CONTENT

- modified ORF
- model name
- if add SMBHB signal on top

`model.py`

```python
from ptarcade.models_utils import prior

parameters = {
              'log_A_star' : prior("Uniform", -14, -6),
              'log_f_star' : prior("Uniform", -10, -6)
              }

def S(x):
    return 1 / (1/x + x)

def spectrum(f, log_A_star, log_f_star):
    A_star = 10**log_A_star
    f_star = 10**log_f_star

    return A_star * S(f/f_star)
```

STEP II: model file

$$h^2\Omega_{GW}(f) = \frac{A_*}{f/f_* + f_*/f}$$

REQUIRED CONTENT

- parameter priors
- signal function
  - power spectrum (for stochastic signals)
  - time series (for deterministic ones)

OPTIONAL CONTENT

- **modified ORF**
- model name
- if add SMBHB signal on top

model.py

```
from ptarcade.models_utils import prior

parameters = {
            'log_A_star' : prior("Uniform", -14, -6),
            'log_f_star' : prior("Uniform", -10, -6)
            }

def S(x):
    return 1 / (1/x + x)

def spectrum(f, log_A_star, log_f_star):
    A_star = 10**log_A_star
    f_star = 10**log_f_star

    return A_star * S(f/f_star)

def orf(f, pos1, pos2, log_A_star, log_f_star):
    cos_ab = np.dot(pos1, pos2)

    return cos_ab**2

name = 'choose_your_model_name'
smbhb = True
```

STEP II: model file

$$h^2\Omega_{GW}(f) = \frac{A_*}{f/f_* + f_*/f}$$

REQUIRED CONTENT

- parameter priors
- signal function
  - power spectrum (for stochastic signals)
  - time series (for deterministic ones)

OPTIONAL CONTENT

- modified ORF
- **model name**
- if add SMBHB signal on top

model.py

```python
from ptarcade.models_utils import prior

parameters = {
             'log_A_star' : prior("Uniform", -14, -6),
             'log_f_star' : prior("Uniform", -10, -6)
             }

def S(x):
    return 1 / (1/x + x)

def spectrum(f, log_A_star, log_f_star):
    A_star = 10**log_A_star
    f_star = 10**log_f_star

    return A_star * S(f/f_star)

def orf(f, pos1, pos2, log_A_star, log_f_star):
    cos_ab = np.dot(pos1, pos2)

    return cos_ab**2

name = 'choose_your_model_name'
smbhb = True
```

STEP II: model file

$$h^2\Omega_{GW}(f) = \frac{A_*}{f/f_* + f_*/f}$$

REQUIRED CONTENT

- parameter priors
- signal function
  - power spectrum (for stochastic signals)
  - time series (for deterministic ones)

OPTIONAL CONTENT

- modified ORF
- model name
- if add SMBHB signal on top

`model.py`

```
from ptarcade.models_utils import prior

parameters = {
             'log_A_star' : prior("Uniform", -14, -6),
             'log_f_star' : prior("Uniform", -10, -6)
             }

def S(x):
    return 1 / (1/x + x)

def spectrum(f, log_A_star, log_f_star):
    A_star = 10**log_A_star
    f_star = 10**log_f_star

    return A_star * S(f/f_star)

def orf(f, pos1, pos2, log_A_star, log_f_star):
    cos_ab = np.dot(pos1, pos2)

    return cos_ab**2

name = 'choose_your_model_name'
smbhb = True
```

STEP III: run

```
ptarcade -m model.py
```

output structure

```
out_dir/
└── model_name/
    └── chain_0/
        ├── chain_1.txt
        ├── pars.txt
        ├── priors.txt
        └── ...
```

STEP III: run

```
ptarcade -m model.py
```

output structure

```
out_dir/
└── model_name/
    └── chain_0/
        ├── chain_1.txt
        ├── pars.txt
        ├── priors.txt
        └── ...
```

STEP III: run

```
ptarcade -m model.py
```

output structure

```
out_dir/
└── model_name/
    └── chain_0/
        ├── chain_1.txt
        ├── pars.txt
        ├── priors.txt
        └── ...
```

usual enterprise/ceffyl output

OPTIONAL CONFIGURATIONS

TUNABLE PARAMETERS

- **enterprise or ceffyl mode**
- PTA data set
- include or not cross correlations
- # of frequency components for GWB
- # of frequency components for iRN
- resume old chains
- output directory
- # MCMC samples
- model comparison option
- SMBHB parameter priors

config.py

```
mode = 'ceffyl'

pta_data = 'NG15'

corr = False
gwb_components = 14

red_components = 30

resume = False
out_dir = './chains/'
N_samples = int(2e6)

mod_sel = False
bhb_th_prior = True
A_bhb_logmin = None
A_bhb_logmax = None
gamma_bhb = None
```

ceffyl mode can only be used for stochastic signals

OPTIONAL CONFIGURATIONS

TUNABLE PARAMETERS

- enterprise or ceffyl mode
- **PTA data set**
- include or not cross correlations
- # of frequency components for GWB
- # of frequency components for iRN
- resume old chains
- output directory
- # MCMC samples
- model comparison option
- SMBHB parameter priors

`config.py`

```
mode = 'ceffyl'

pta_data = 'NG15'

corr = False
gwb_components = 14

red_components = 30

resume = False
out_dir = './chains/'
N_samples = int(2e6)

mod_sel = False
bhb_th_prior = True
A_bhb_logmin = None
A_bhb_logmax = None
gamma_bhb = None
```

options are: `'NG12'`, `'NG15'`, `'IPTA2'`

coming soon: `'EPTA2_full'`, `'EPTA2_new'`

OPTIONAL CONFIGURATIONS

TUNABLE PARAMETERS

- enterprise or ceffyl mode
- PTA data set
- **include or not cross correlations**
- # of frequency components for GWB
- # of frequency components for iRN
- resume old chains
- output directory
- # MCMC samples
- model comparison option
- SMBHB parameter priors

`config.py`

```
mode = 'ceffyl'

pta_data = 'NG15'

corr = False
gwb_components = 14

red_components = 30

resume = False
out_dir = './chains/'
N_samples = int(2e6)

mod_sel = False
bhb_th_prior = True
A_bhb_logmin = None
A_bhb_logmax = None
gamma_bhb = None
```

OPTIONAL CONFIGURATIONS

TUNABLE PARAMETERS

- enterprise or ceffyl mode
- PTA data set
- include or not cross correlations
- **# of frequency components for GWB**
- # of frequency components for iRN
- resume old chains
- output directory
- # MCMC samples
- model comparison option
- SMBHB parameter priors

`config.py`

```
mode = 'ceffyl'

pta_data = 'NG15'

corr = False
gwb_components = 14

red_components = 30

resume = False
out_dir = './chains/'
N_samples = int(2e6)

mod_sel = False
bhb_th_prior = True
A_bhb_logmin = None
A_bhb_logmax = None
gamma_bhb = None
```

OPTIONAL CONFIGURATIONS

TUNABLE PARAMETERS

- enterprise or ceffyl mode
- PTA data set
- include or not cross correlations
- # of frequency components for GWB
- **# of frequency components for iRN**
- resume old chains
- output directory
- # MCMC samples
- model comparison option
- SMBHB parameter priors

`config.py`

```
mode = 'ceffyl'

pta_data = 'NG15'

corr = False
gwb_components = 14

red_components = 30

resume = False
out_dir = './chains/'
N_samples = int(2e6)

mod_sel = False
bhb_th_prior = True
A_bhb_logmin = None
A_bhb_logmax = None
gamma_bhb = None
```

OPTIONAL CONFIGURATIONS

TUNABLE PARAMETERS

- enterprise or ceffyl mode
- PTA data set
- include or not cross correlations
- # of frequency components for GWB
- # of frequency components for iRN
- **resume old chains**
- output directory
- # MCMC samples
- model comparison option
- SMBHB parameter priors

`config.py`

```
mode = 'ceffyl'

pta_data = 'NG15'

corr = False
gwb_components = 14

red_components = 30

resume = False
out_dir = './chains/'
N_samples = int(2e6)

mod_sel = False
bhb_th_prior = True
A_bhb_logmin = None
A_bhb_logmax = None
gamma_bhb = None
```

OPTIONAL CONFIGURATIONS

TUNABLE PARAMETERS

- enterprise or ceffyl mode
- PTA data set
- include or not cross correlations
- # of frequency components for GWB
- # of frequency components for iRN
- resume old chains
- **output directory**
- # MCMC samples
- model comparison option
- SMBHB parameter priors

`config.py`

```
mode = 'ceffyl'

pta_data = 'NG15'

corr = False
gwb_components = 14

red_components = 30

resume = False
out_dir = './chains/'
N_samples = int(2e6)

mod_sel = False
bhb_th_prior = True
A_bhb_logmin = None
A_bhb_logmax = None
gamma_bhb = None
```

OPTIONAL CONFIGURATIONS

TUNABLE PARAMETERS

- enterprise or ceffyl mode
- PTA data set
- include or not cross correlations
- # of frequency components for GWB
- # of frequency components for iRN
- resume old chains
- output directory
- **# MCMC samples**
- model comparison option
- SMBHB parameter priors

`config.py`

```
mode = 'ceffyl'

pta_data = 'NG15'

corr = False
gwb_components = 14

red_components = 30

resume = False
out_dir = './chains/'
N_samples = int(2e6)

mod_sel = False
bhb_th_prior = True
A_bhb_logmin = None
A_bhb_logmax = None
gamma_bhb = None
```

OPTIONAL CONFIGURATIONS

TUNABLE PARAMETERS

- enterprise or ceffyl mode
- PTA data set
- include or not cross correlations
- # of frequency components for GWB
- # of frequency components for iRN
- resume old chains
- output directory
- # MCMC samples
- **model comparison option**
- SMBHB parameter priors

config.py

```
mode = 'ceffyl'

pta_data = 'NG15'

corr = False
gwb_components = 14

red_components = 30

resume = False
out_dir = './chains/'
N_samples = int(2e6)

mod_sel = False
bhb_th_prior = True
A_bhb_logmin = None
A_bhb_logmax = None
gamma_bhb = None
```

$$\Omega_{\rm GW} \propto A^2_{\rm BHB} \left(\frac{f}{\rm year^{-1}}\right)^{5-\gamma_{\rm BHB}} \rm year^{-2}$$

OPTIONAL CONFIGURATIONS

TUNABLE PARAMETERS

- enterprise or ceffyl mode
- PTA data set
- include or not cross correlations
- # of frequency components for GWB
- # of frequency components for iRN
- resume old chains
- output directory
- # MCMC samples
- model comparison option
- **SMBHB parameter priors**

config.py

```
mode = 'ceffyl'

pta_data = 'NG15'

corr = False
gwb_components = 14

red_components = 30

resume = False
out_dir = './chains/'
N_samples = int(2e6)

mod_sel = False
bhb_th_prior = True
A_bhb_logmin = None
A_bhb_logmax = None
gamma_bhb = None
```

$$\Omega_{\mathrm{GW}} \propto A_{\mathrm{BHB}}^2 \left(\frac{f}{\mathrm{year}^{-1}}\right)^{5-\gamma_{\mathrm{BHB}}} \mathrm{year}^{-2}$$

CONCLUSIONS

strong evidence for a GWB

if cosmological origin it will provide the first glimpse into the early Universe

independently from the origin of the GWB, PTA can be used to set complementary constraints on new physics models

have a model that you want to test? PTArcade comes to rescue