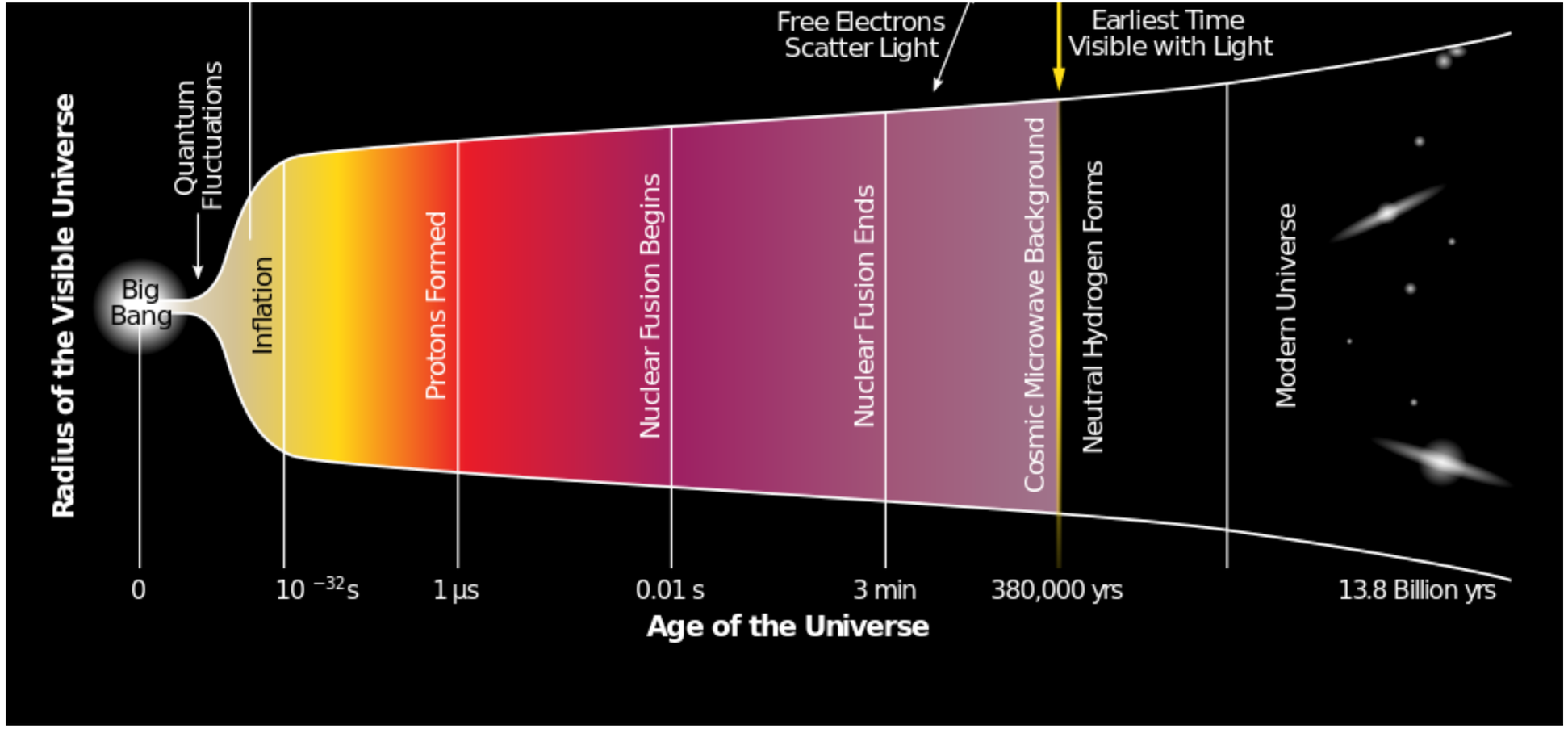
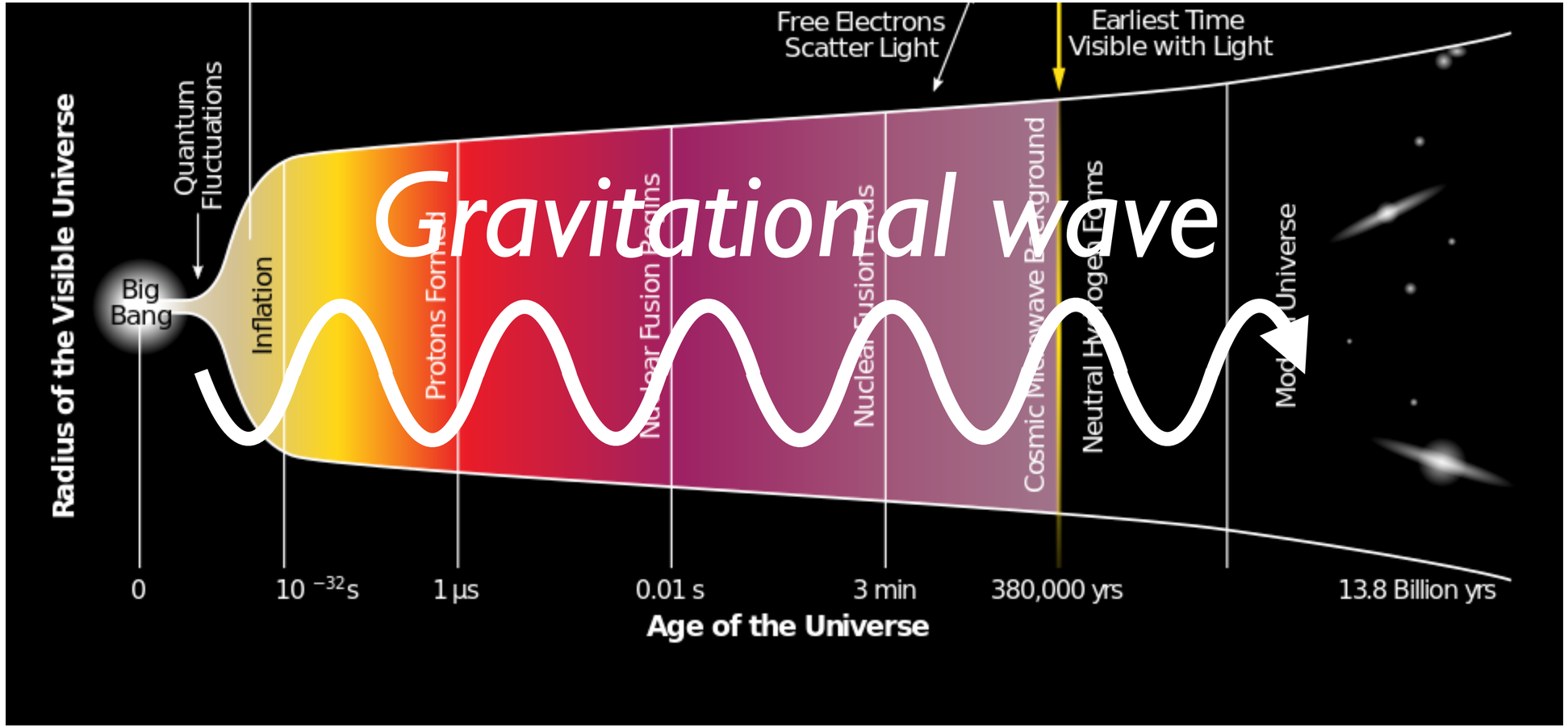
High frequency gravitational waves from reheating

Kazunori Nakayama (Tohoku University)

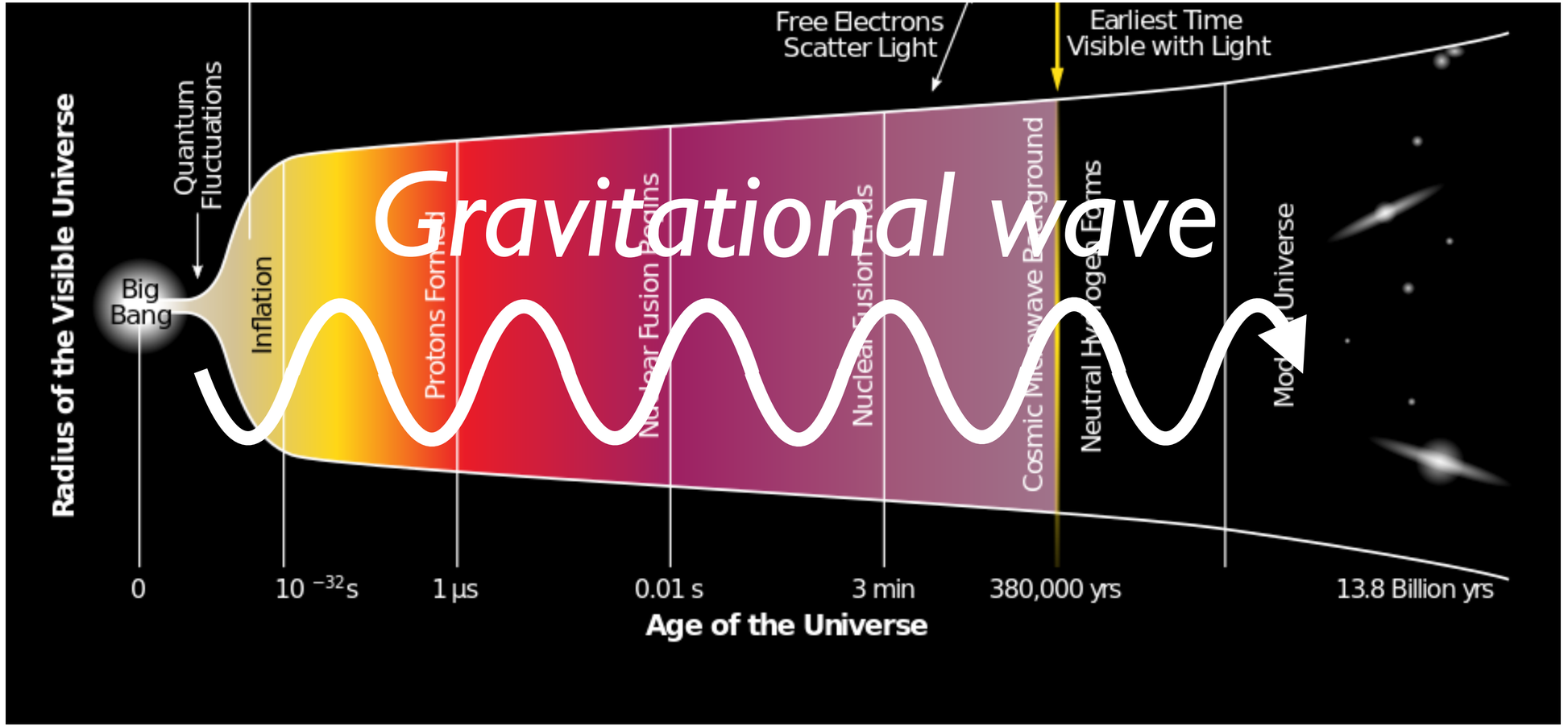
2026/3/13 @ Nagoya University



[figure from wikipedia "inflation"]



[figure from wikipedia "inflation"]



[figure from wikipedia "inflation"]

GW is a direct probe of the early universe physics!

GWs from early universe

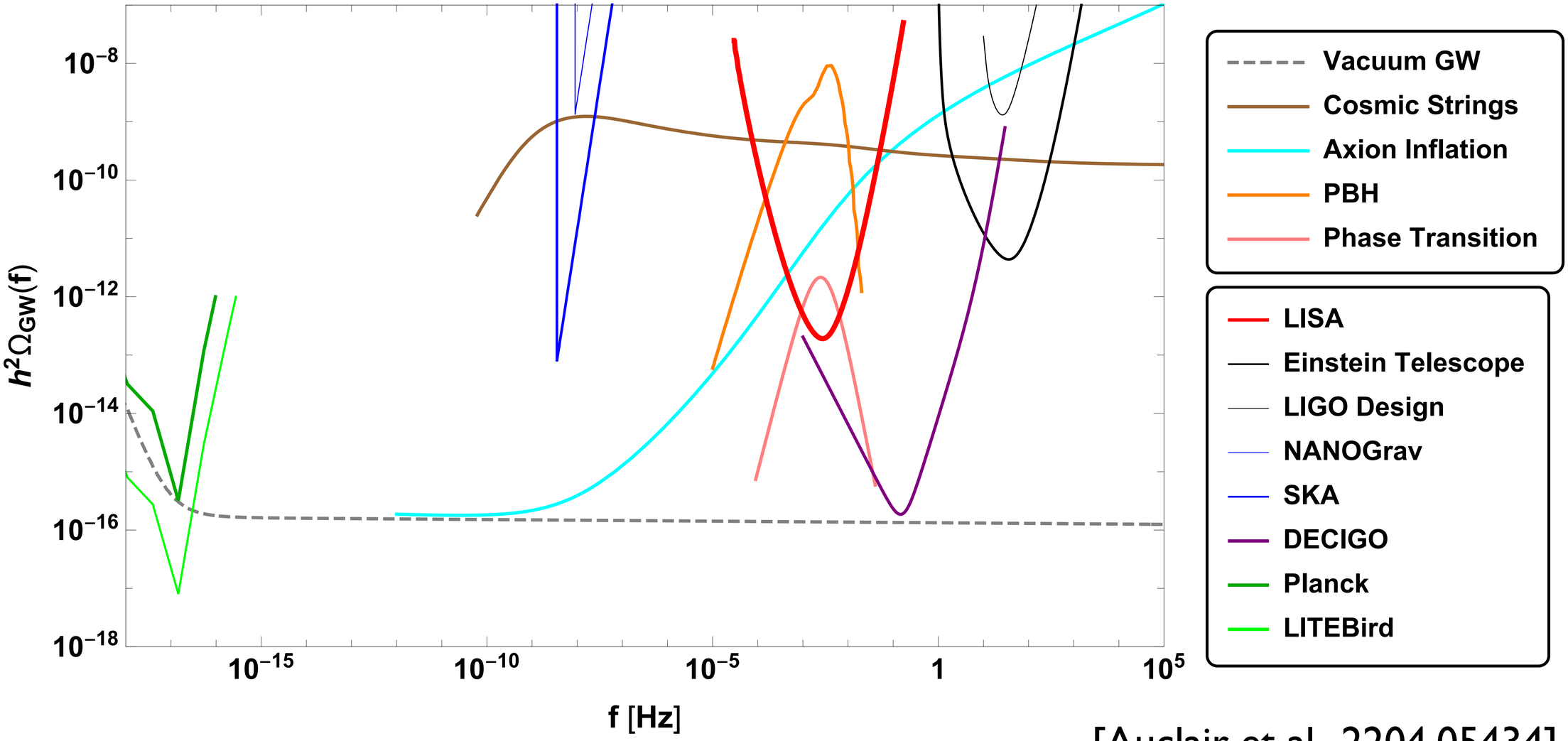
- Primordial GW (inflationary GW)
- GWs from preheating
- GWs from phase transition

  cosmic strings, domain walls, bubble collisions, …
- GWs from second order scalar perturbation

  [Kohri-san's talk yesterday]

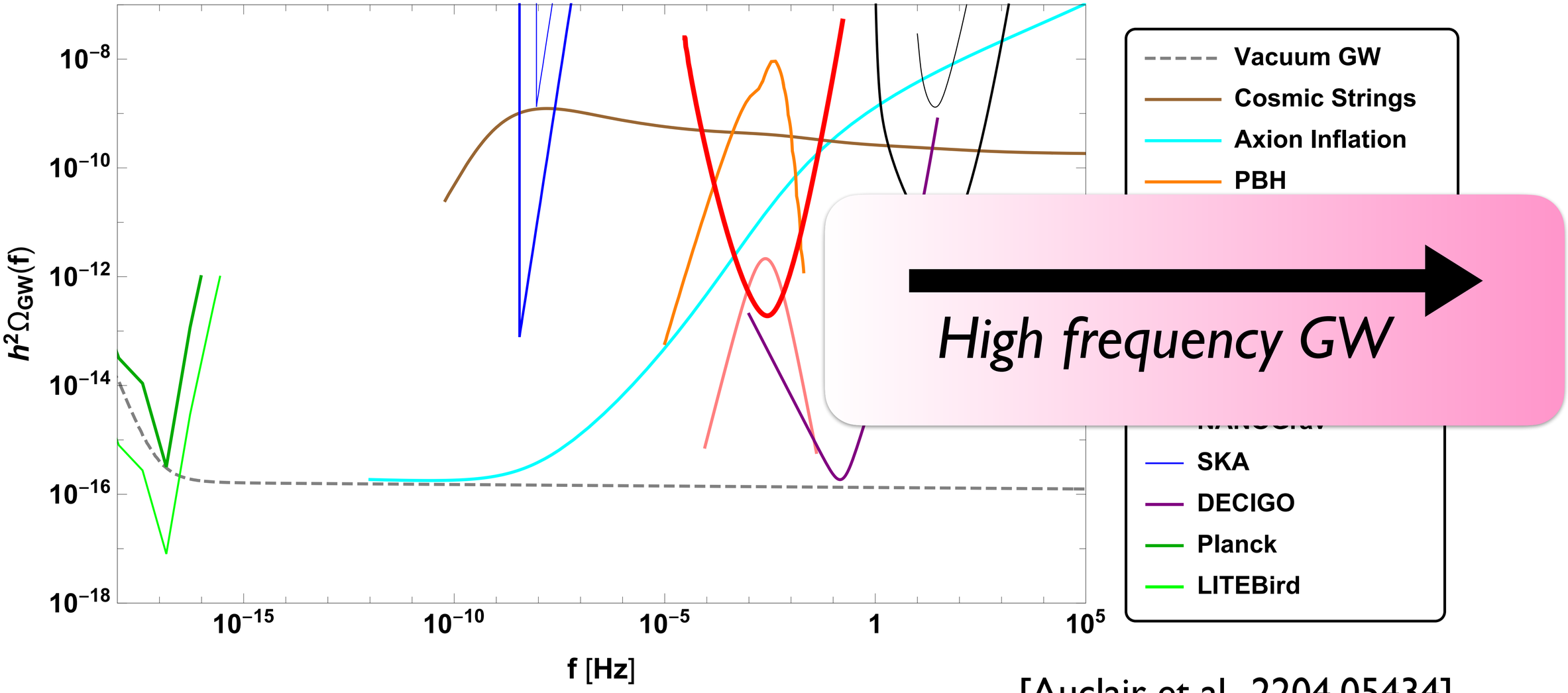
…

GWs from early universe



[Auclair et al., 2204.05434]

GWs from early universe



[Auclair et al., 2204.05434]

“New” GW sources

(1) Gravitons from thermal bath

[Ghiglieri, Laine (2015), Ghiglieri et al. (2020)]

(2) Inflaton annihilation to gravitons

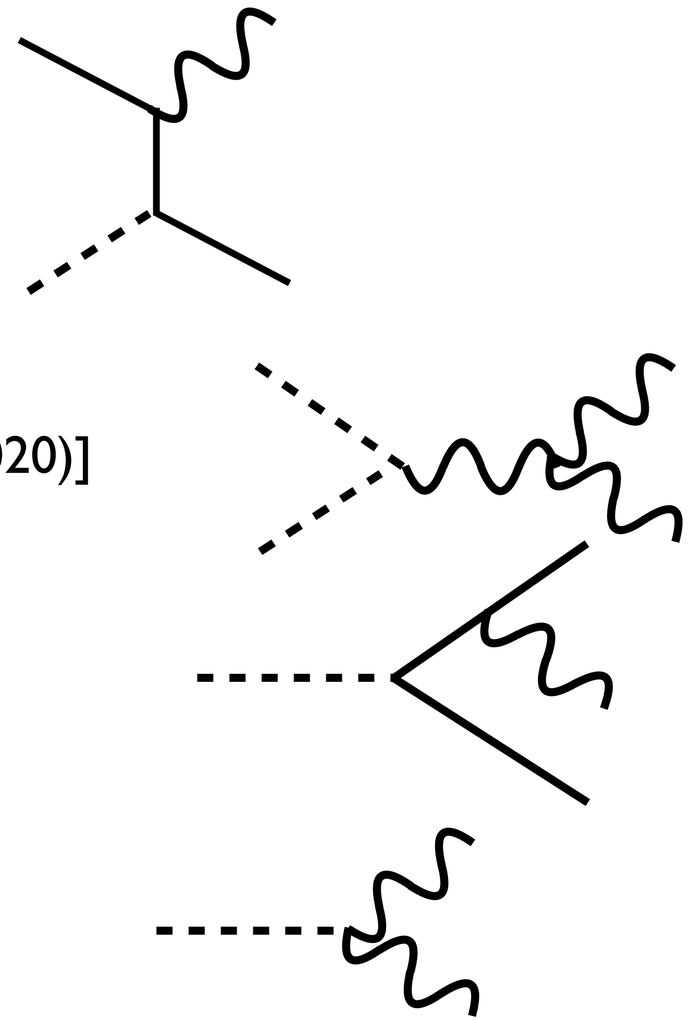
[Ema, Jinno, Mukaida, KN (2015); Ema, Jinno, KN (2020)]

(3) Bremsstrahlung from inflaton decay

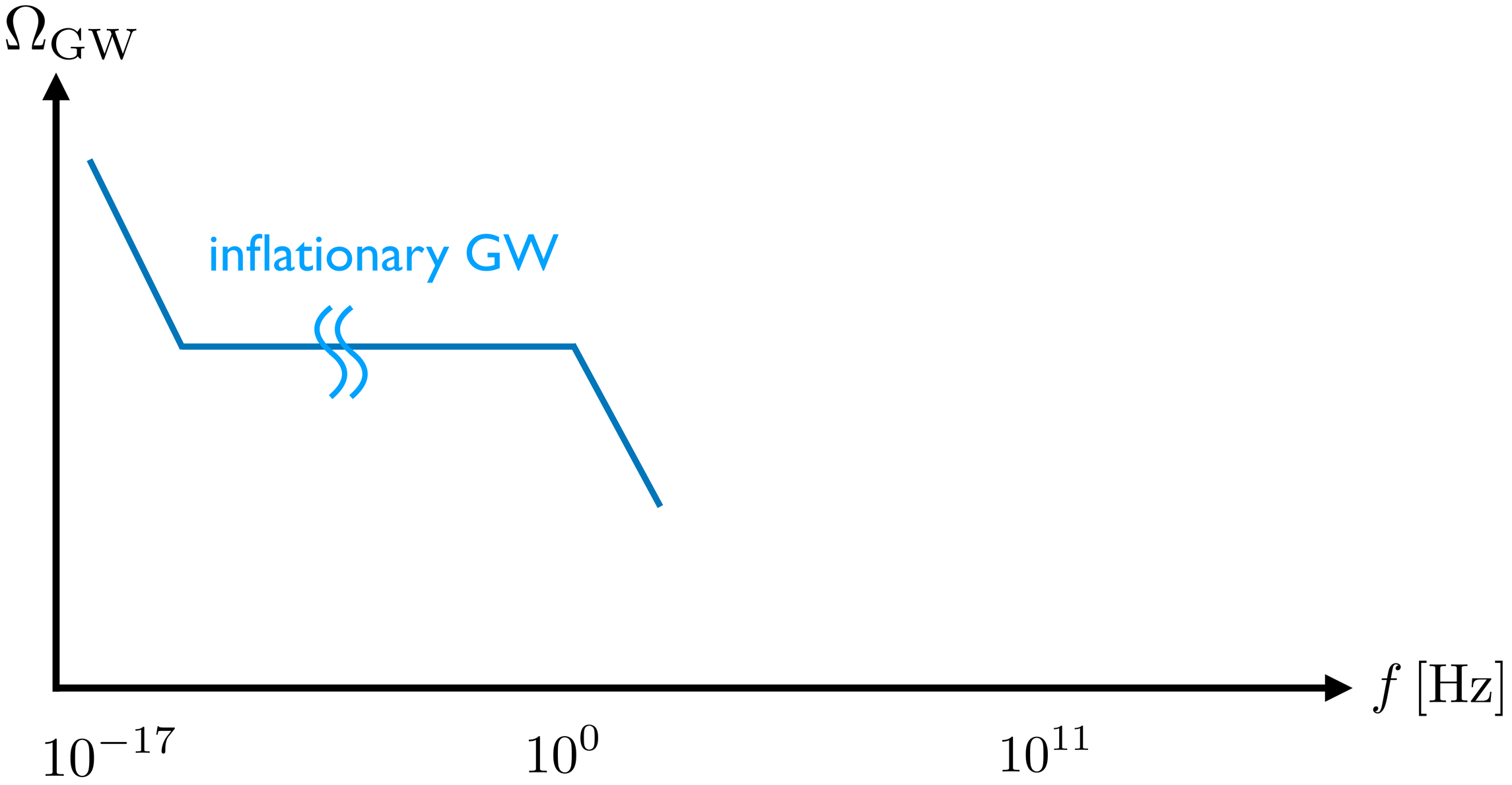
[KN, Tang (2018)]

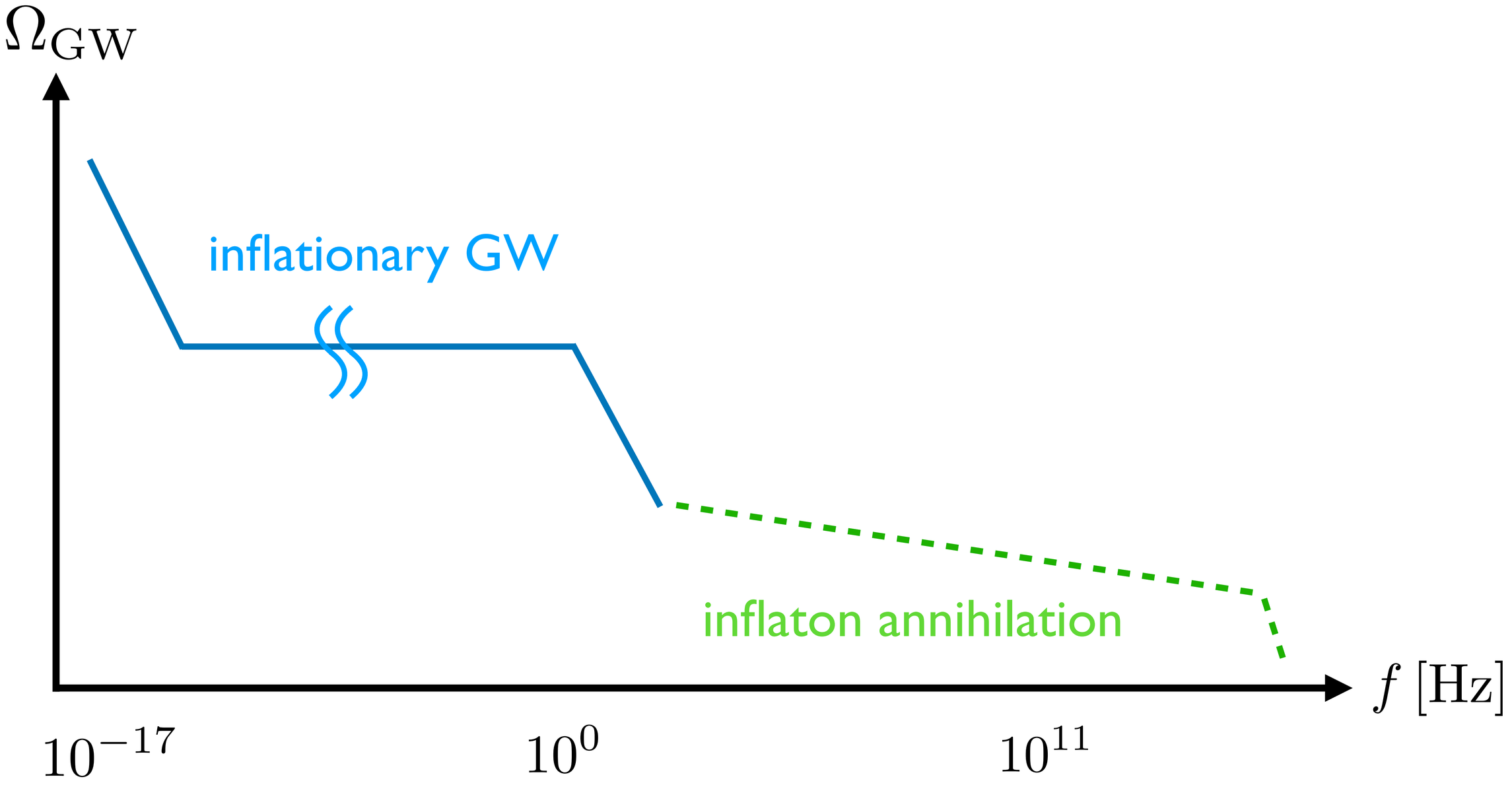
(4) Inflaton decay to gravitons

[Ema, Mukaida, KN (2021); Mudrunka, KN (2023)]



All of them are *perturbative graviton production*


$\Omega_{\rm GW}$
inflationary GW
f [Hz]
10^{-17}
10^{0}
10^{11}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inflationary GW
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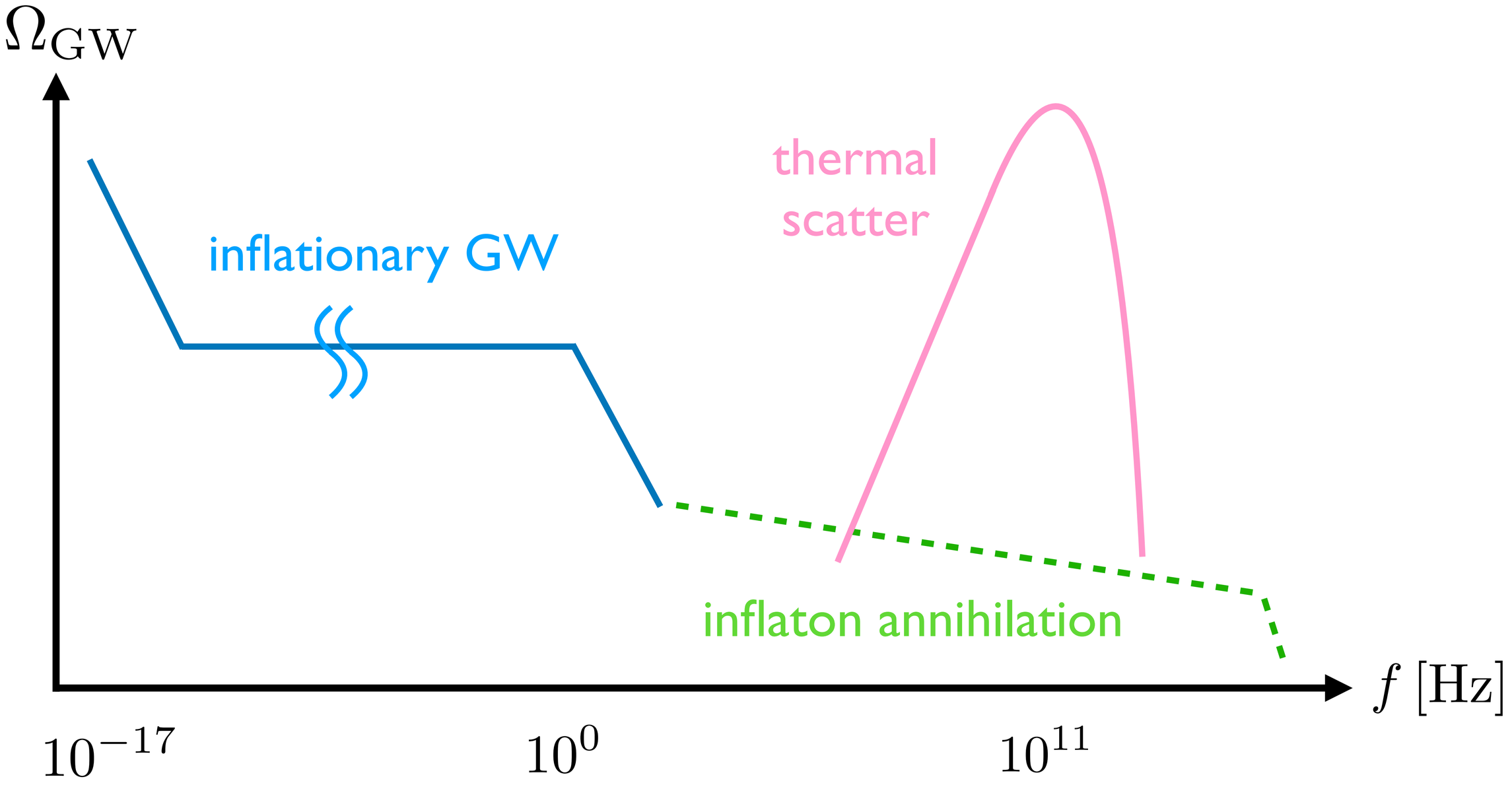
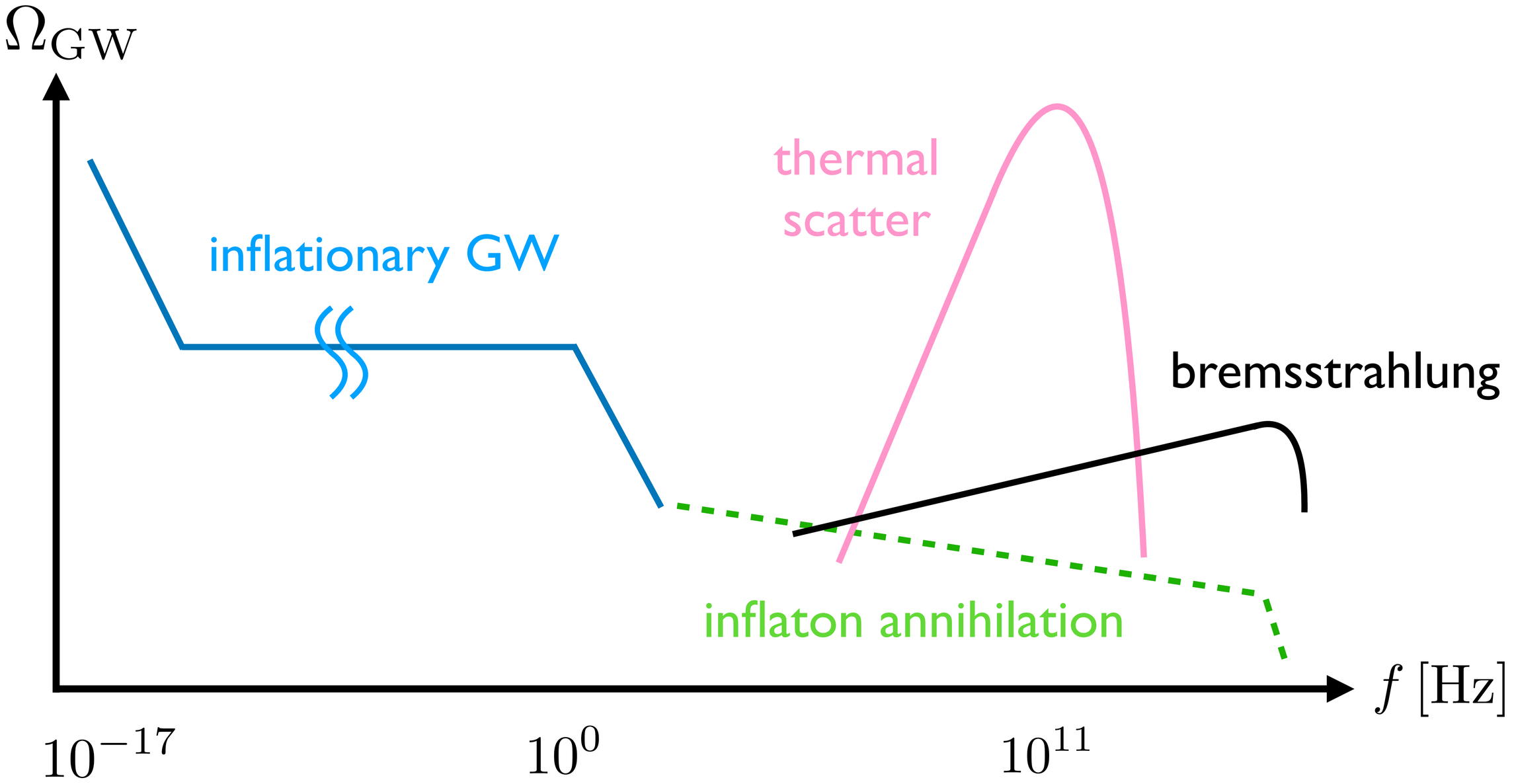

$\Omega_{\rm GW}$
inflationary GW
thermal
scatter
inflaton annihilation
f [Hz]
10^{-17}
10^{0}
10^{11}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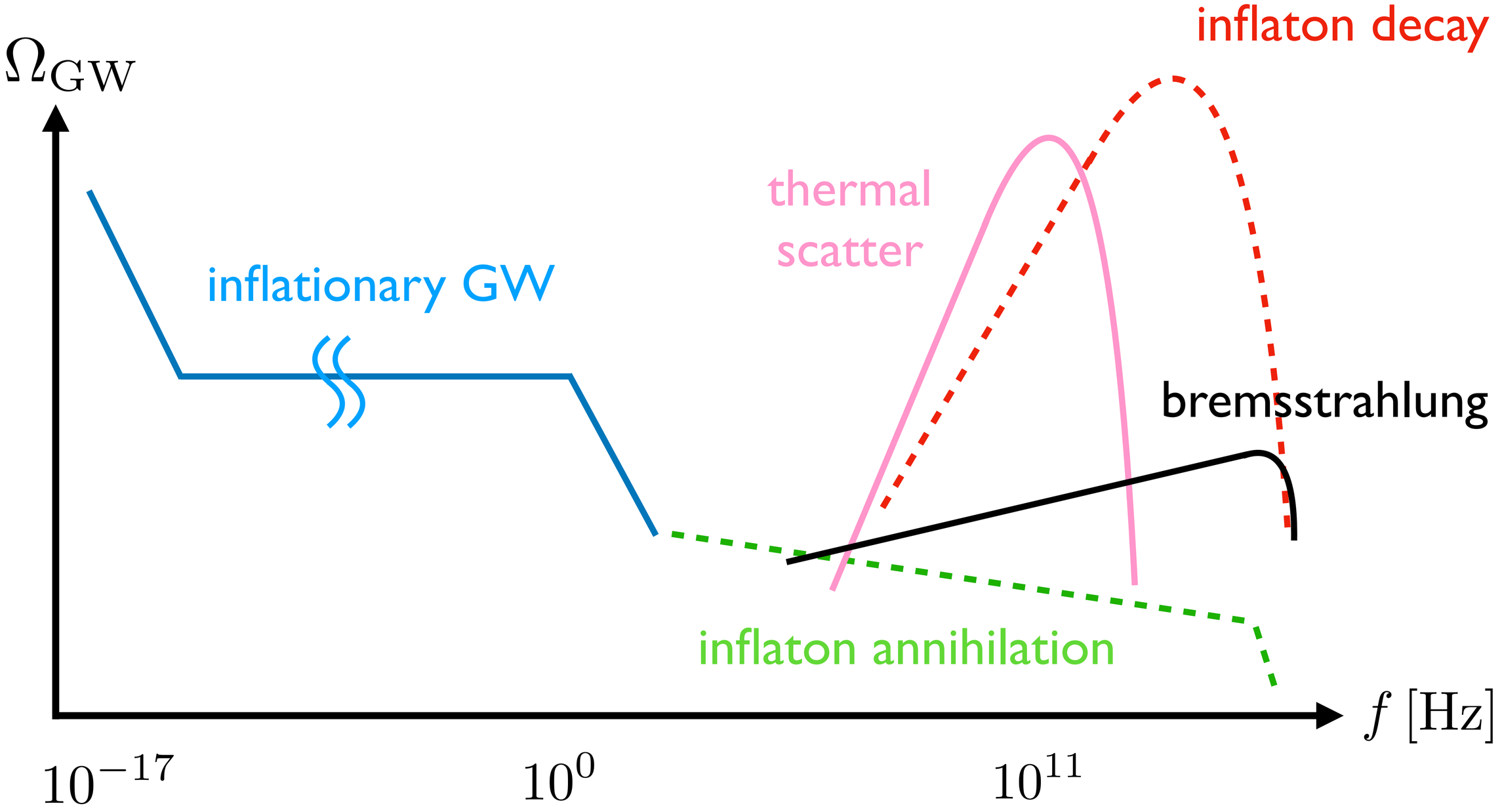
$\Omega_{\rm GW}$
inflaton decay
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10^{-17}
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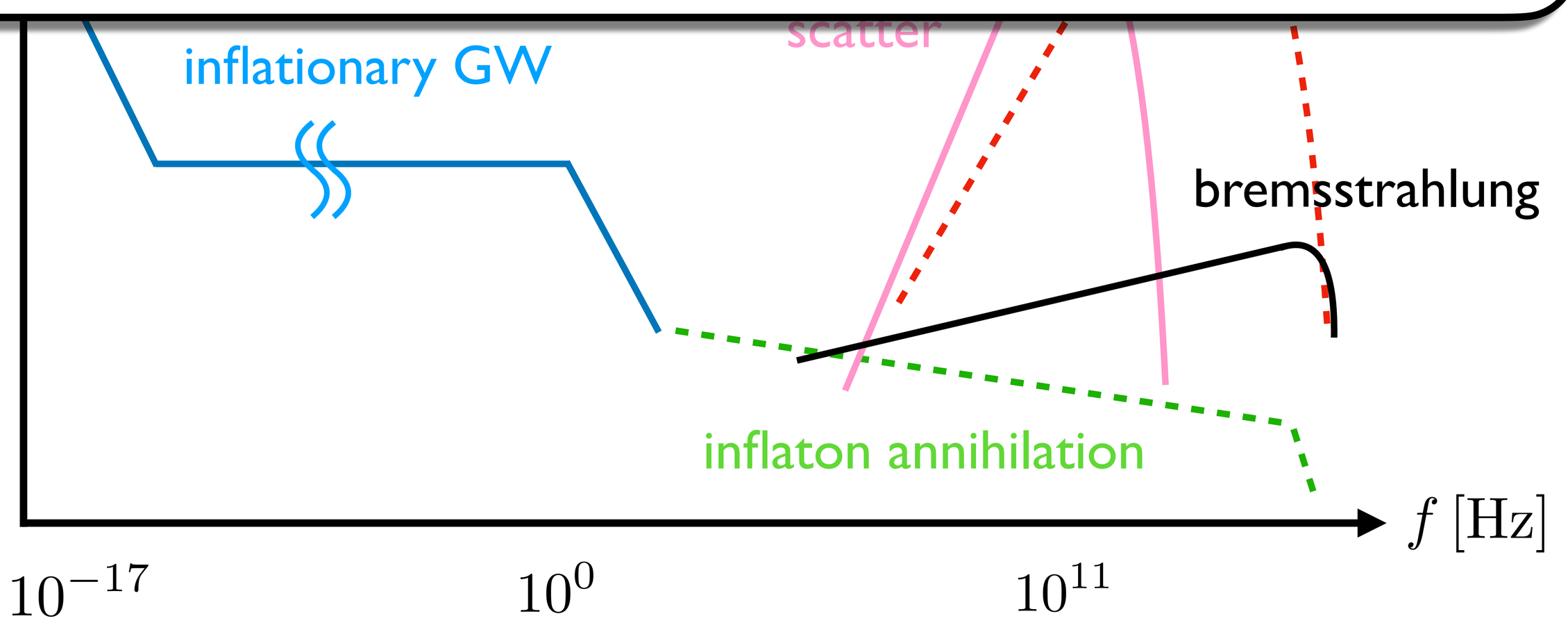
High frequency GW spectrum contain very rich information !!



(1) GW from thermal bath

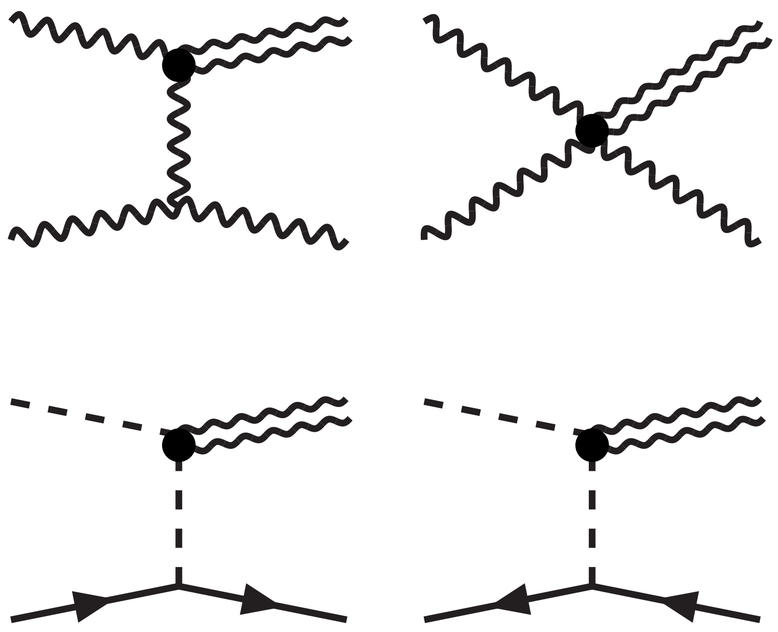
[Ghiglieri, Laine (2015), Ghiglieri et al. (2020)]

- Graviton abundance

$$\langle \sigma v \rangle \, n_{\rm SM}^2 \sim \frac{T^6}{M_P^2}$$

$$\longrightarrow \quad \frac{n_h}{s} \sim \frac{T^6}{M_P^2} \frac{H^{-1}}{s} \sim \frac{T}{M_P}$$

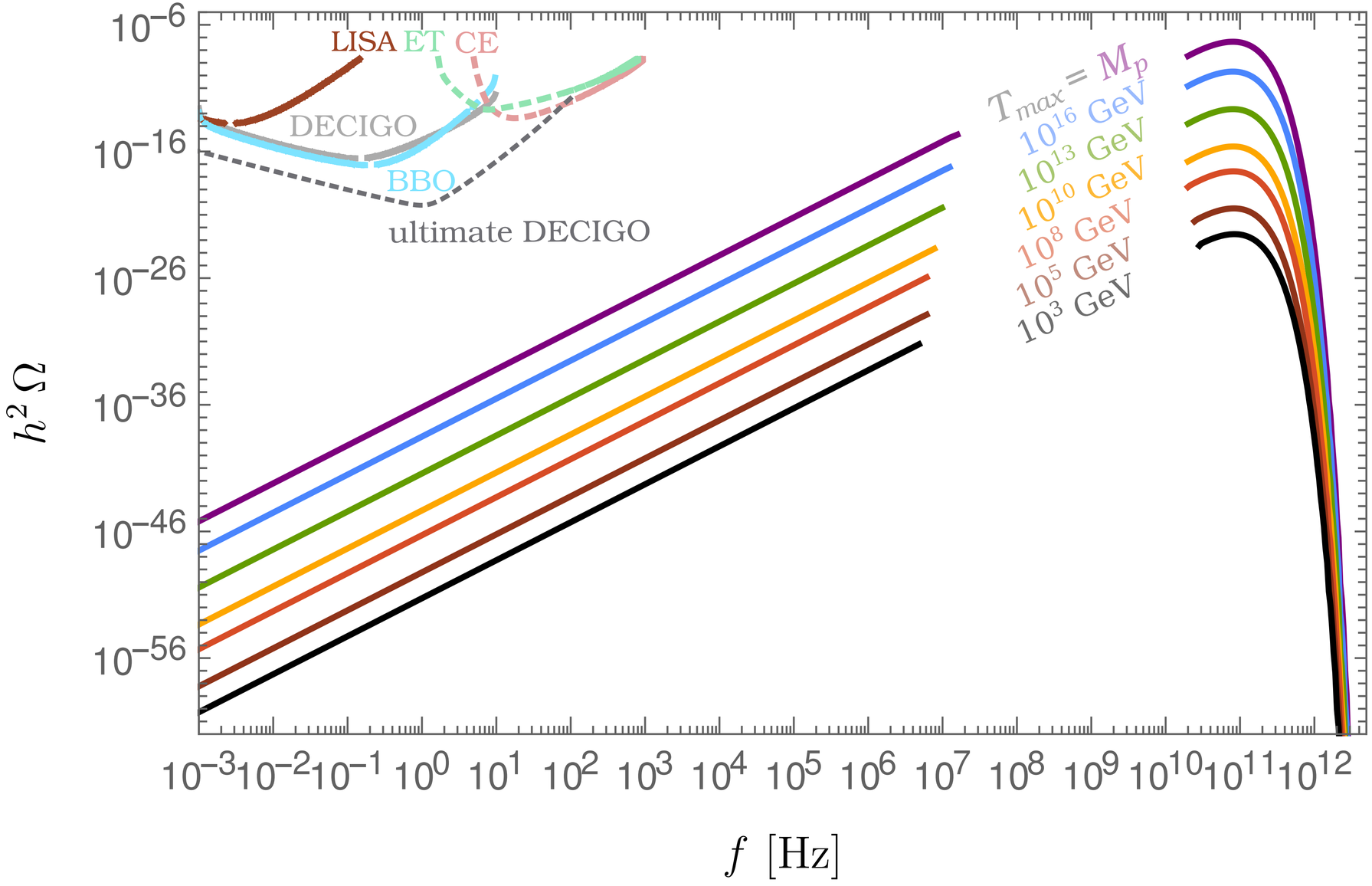
high-T contribution is dominant



(many other diagrams …)

- Typical frequency

$$\sim T_R \times \frac{a(T_R)}{a_0}$$ ~ CMB frequency (~100GHZ)



[Ringwald, Schutte-Engel, Tamarit (2020)]

(2) GW from inflaton annihilation

[Ema, Jinno, Mukaida, KN (2015), Ema, Jinno, KN (2020)]

- Graviton EoM in FLRW background $h_k'' + \left(k^2 - \frac{a''}{a}\right) h_k = 0$
- During inflation $\frac{a''}{a} \simeq \frac{2}{\tau^2}$ enhancement of low-k modes

  ⟶ inflationary GWs for wide frequency range
- During reheating $a(t) \simeq \langle a(t) \rangle \left(1 - \frac{\phi^2(t) - \langle \phi^2 \rangle}{8M_P^2}\right) \sim \frac{\phi^2}{M_P^2} \cos^2(m_\phi t)$

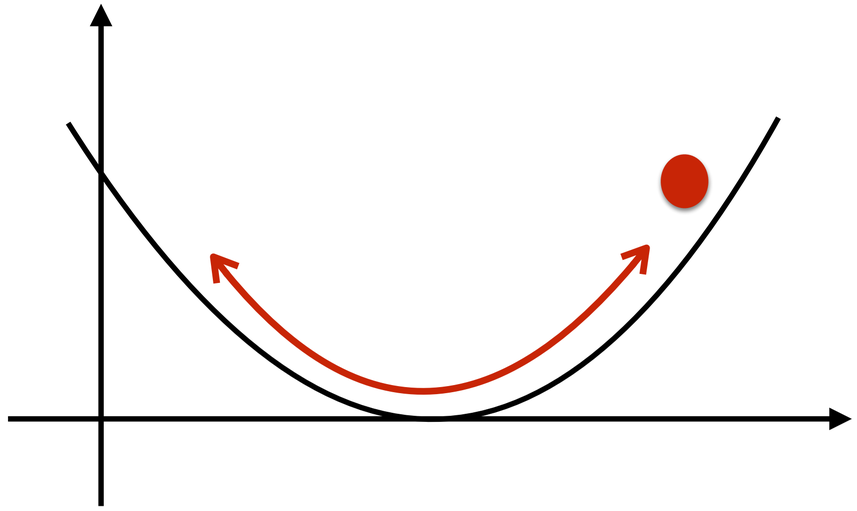
  ⟶ enhancement of $k = a m_\phi$ modes

(2) GW from inflaton annihilation

[Ema, Jinno, Mukaida, KN (2015), Ema, Jinno, KN (2020)]

- Graviton EoM during reheating

$$h_k'' + \left(k^2 + \frac{a^2 m_\phi^2 \phi^2}{M_p^2} \cos^2(m_\phi t) \right) h_k = 0$$



Same as Mathieu eq. for reheating analysis

- Graviton production from inflaton oscillation

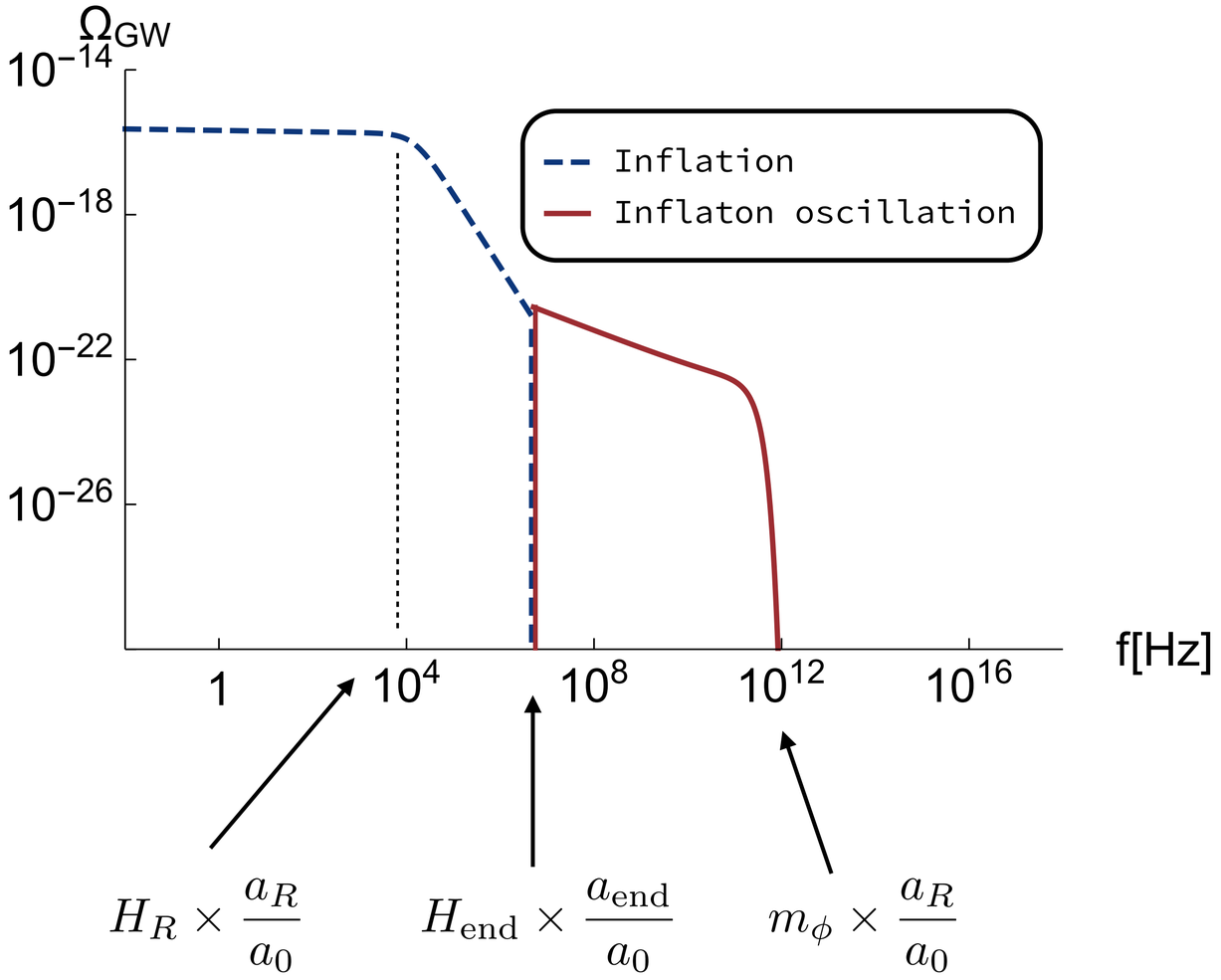
  ~ inflaton "annihilation" to graviton pair

$$\Gamma_{\phi\phi \to hh} \sim \frac{m_\phi^3 \phi^2}{M_P^4}$$

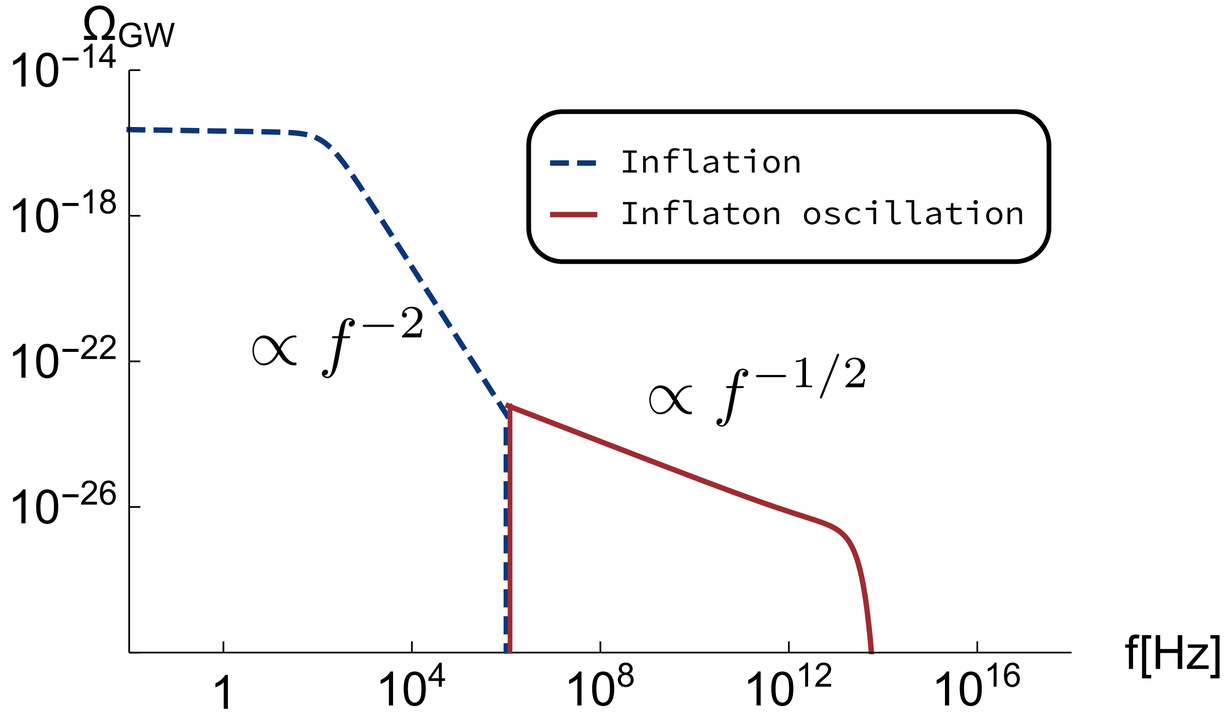
⟶ High frequency tail of primordial GWs.

There exists high frequency tail of primordial GW!

$H_{\rm inf} = 10^{13}\,{\rm GeV},\ T_{\rm R} = 10^{12}\,{\rm GeV}$



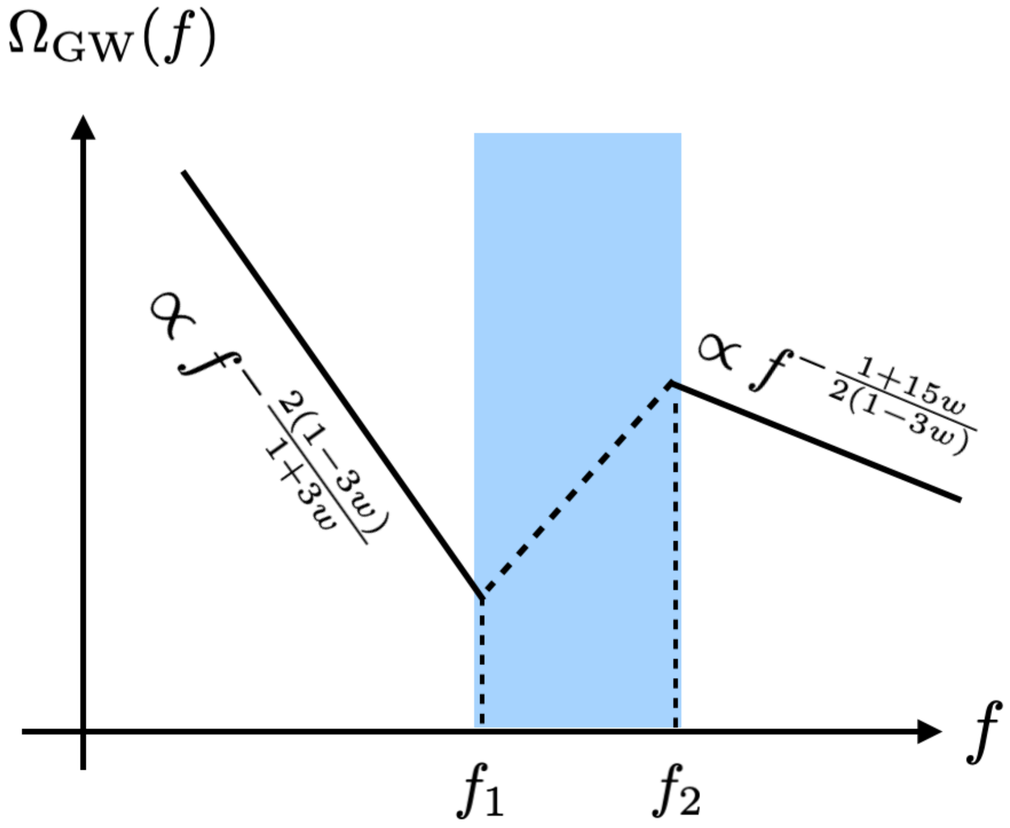
$H_{\rm inf} = 10^{13}\,{\rm GeV},\ T_{\rm R} = 10^{10}\,{\rm GeV}$

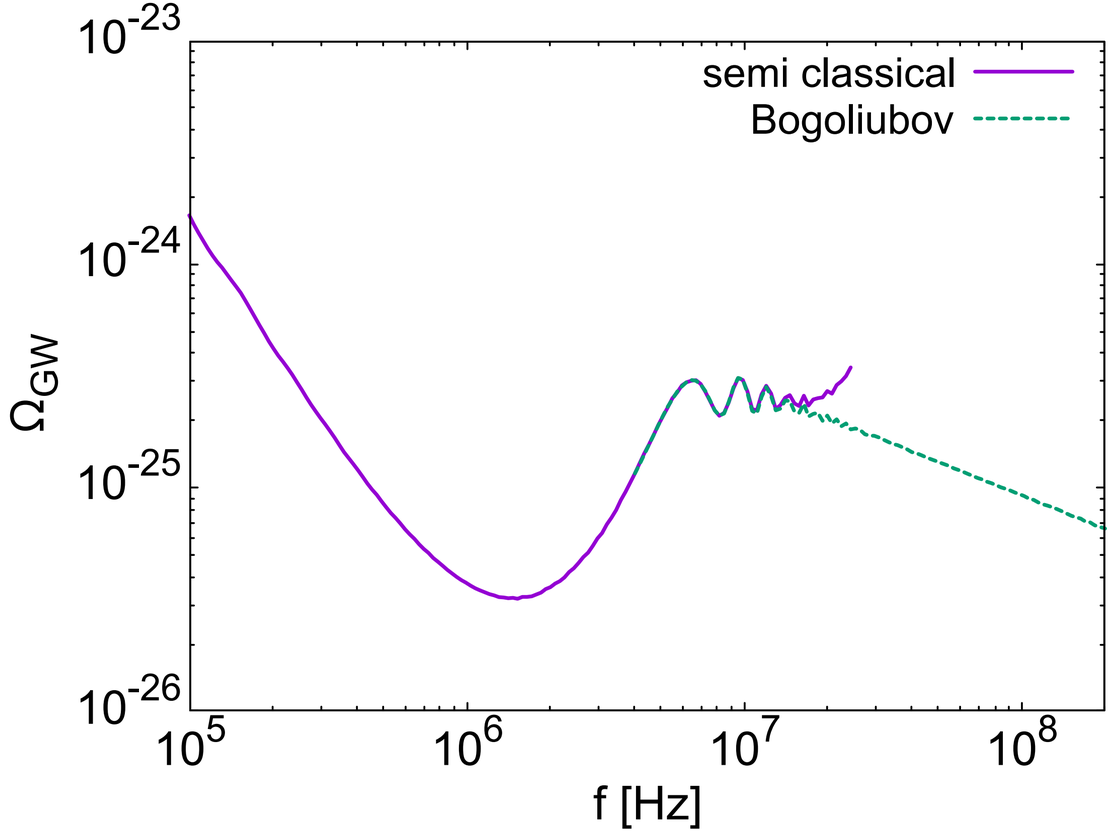


[Ema, Jinno, KN (2020)]

Nontrivial structure for low scale inflation models

[Mudrunka, KN (2026)]



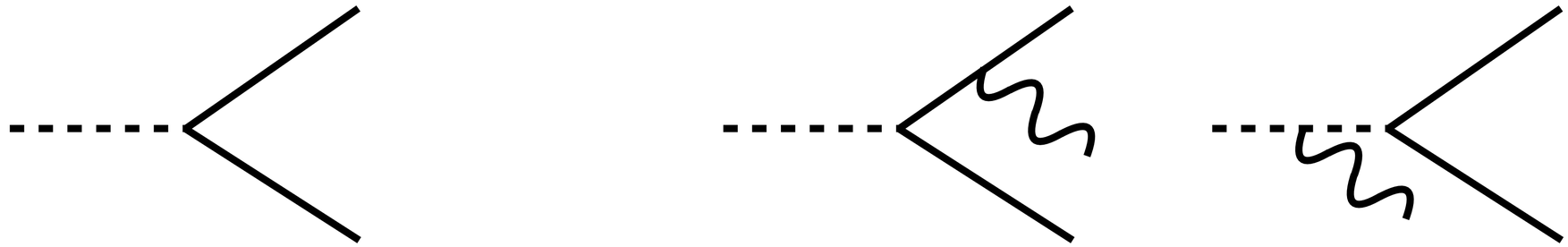


Next talk

(3) GW from bremsstrahlung

[KN, Tang (2018); Barman, Bernal, Xu, Zapata (2023)]

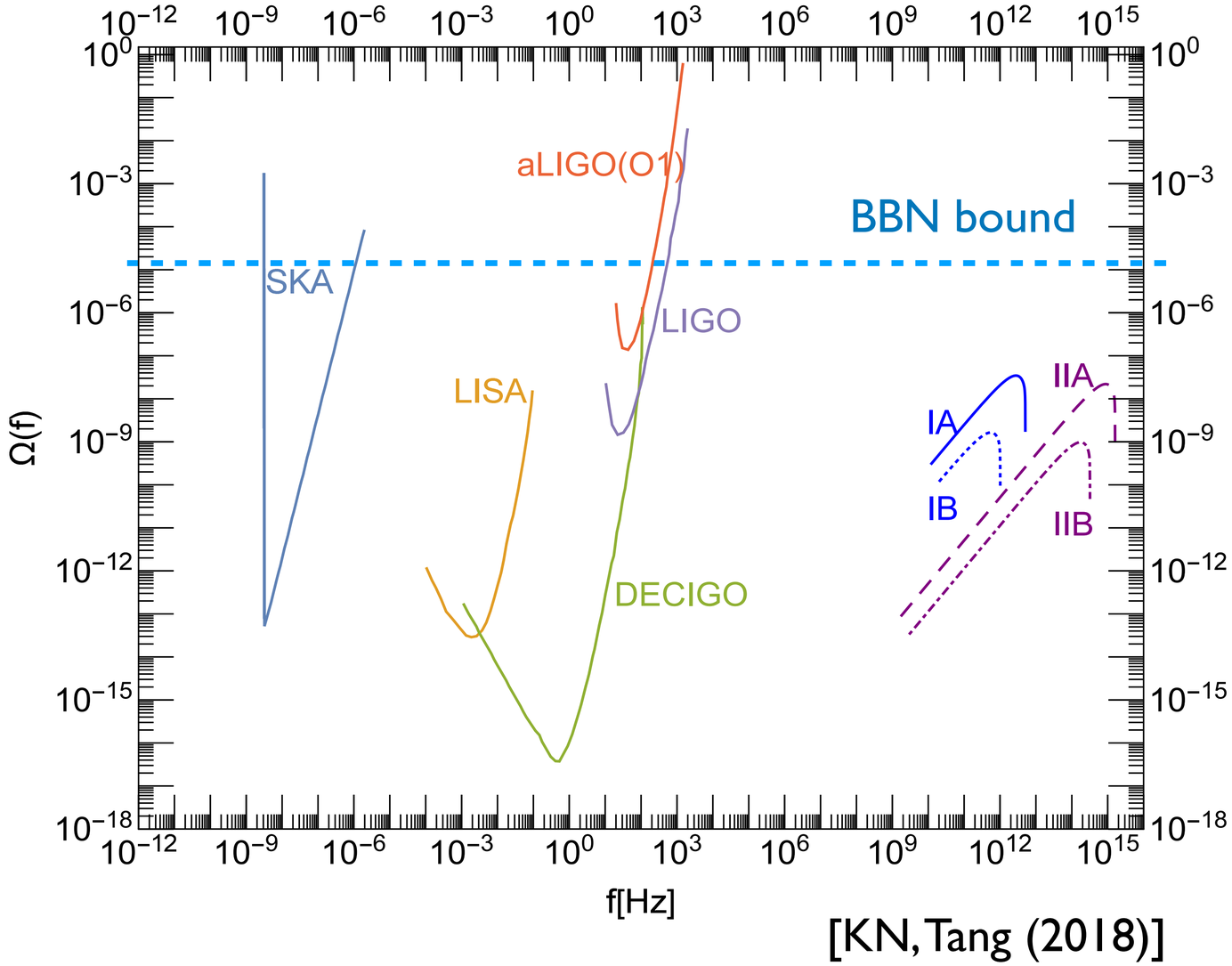
- Perturbative inflaton decay necessarily produces brems graviton



$$\Gamma_{\phi\to\psi\bar{\psi}} = \frac{y^2 m_\phi}{8\pi} \qquad E\frac{d\Gamma_{\phi\to\psi\bar{\psi}h}}{dE} = \frac{y^2 m_\phi^3}{64\pi^3 M_P^2}(1-2x)(1-2x+2x^2) \qquad x = \frac{E}{m_\phi}$$

- Branching ratio depends only on the inflaton mass

$$\mathrm{Br}_{\phi\to\psi\bar{\psi}h} \simeq \frac{1}{8\pi^2}\frac{m_\phi^2}{M_P^2} \qquad \Omega_{\mathrm{GW}} \sim 10^{-5}\mathrm{Br}_{\phi\to\psi\bar{\psi}h}$$



[KN, Tang (2018)]

$$\text{IA: } M = 0.5M_P, \Gamma = 10^{-5}M_P,$$

$$\text{IB: } M = 0.1M_P, \Gamma = 10^{-5}M_P,$$

$$\text{IIA: } M = 0.5M_P, \Gamma = 10^{-10}M_P,$$

$$\text{IIB: } M = 0.1M_P, \Gamma = 10^{-10}M_P,$$

However, typical inflaton mass is

$$m \sim 10^{13}\,\mathrm{GeV}$$

$$\longrightarrow \quad \mathrm{Br} \sim 10^{-11}$$

$$\longrightarrow \quad \Omega_{\mathrm{GW}} \sim 10^{-16}$$

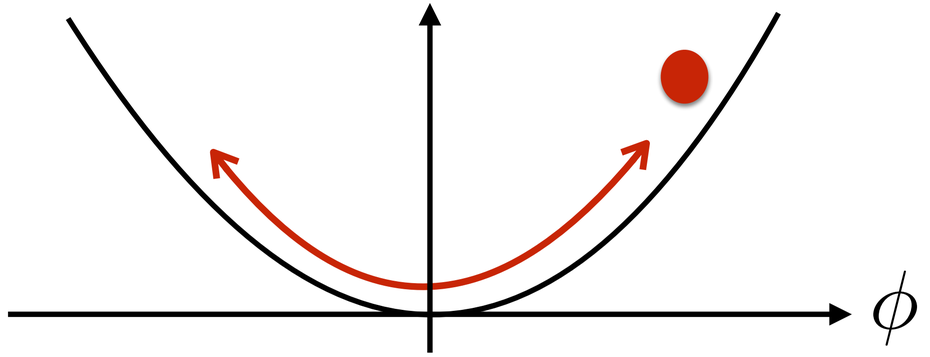
Some of recent studies :

[Huang, Yin (2019), Barman et al. (2023), Bernal et al. (2024), Inui, Mikura, Yokoyama (2024), Jiang, Suyama (2024), Murayama et al. (2025)]

Instant preheating [Felder, Kofman, Linde (1998)]

- A simple model:

$$\mathcal{L} \supset -\frac{1}{2}m_\phi^2\phi^2 - \frac{1}{2}\lambda^2\phi^2\chi^2 + y\chi\bar{\psi}\psi$$



- Non-perturbative production of χ

$$n_\chi \sim k_*^3, \quad k_* \sim \sqrt{\lambda m_\phi \Phi}$$ [Kofman, Linde, Starobinsky (1997)]

- Mass of χ : $m_\chi(t) \sim \lambda\Phi\sin(m_\phi t) \sim \lambda M_{\rm Pl}$ Production of superheavy particle!
- Decay of χ : $\Gamma_\chi \sim y^2 m_\chi(t) \quad (\gg m_\phi)$ Decay almost instantaneously

$\mathrm{Br}_{\chi\to\psi\bar{\psi}h} \sim 0.1$ may be possible in instant preheating!

Examples of instant preheating

- A simple model:

$$\mathcal{L} \supset -\frac{1}{2}m_\phi^2\phi^2 - \frac{1}{2}\lambda^2\phi^2\chi^2 + y\chi\bar{\psi}\psi$$

- **Higgs inflation** [Bezrukov, Shaposhnikov (2007)] [Bezrukov, Gorbunov, Shaposhnikov (2008), Garcia-Bellido, Figueroa, Rubio (2008)]

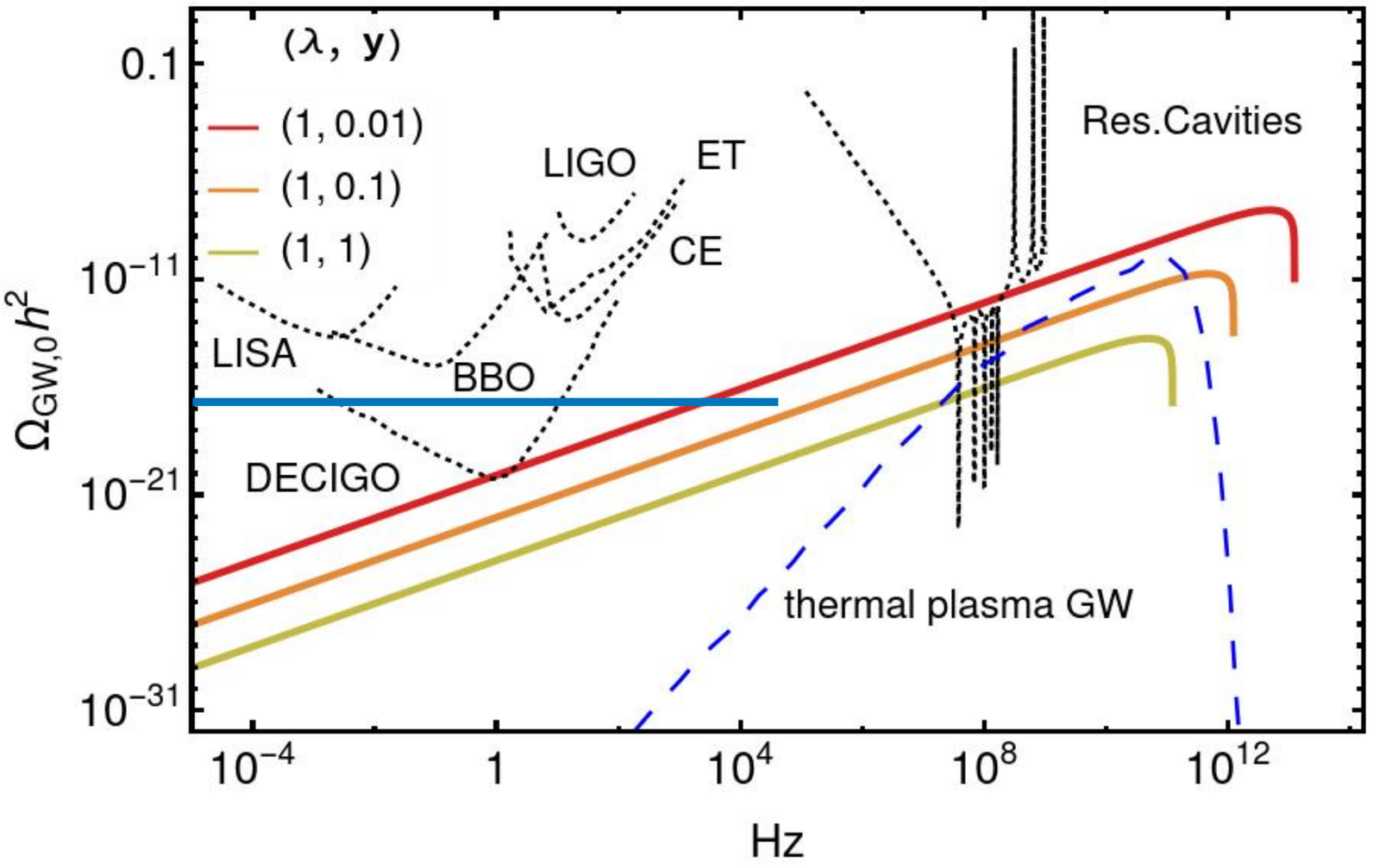
ϕ : Higgs χ : W boson ψ : quarks

- **Sneutrino inflation** [KN, Takahashi, Yanagida (2014)]

ϕ : RH sneutrino χ : slepton/up-Higgs ψ : lepton/down-Higgs(ino)

Instant preheating naturally happens if inflaton is directly related to SM sector.

- GWs from instant preheating [Hu, KN, Takhistov, Tang (2024)]



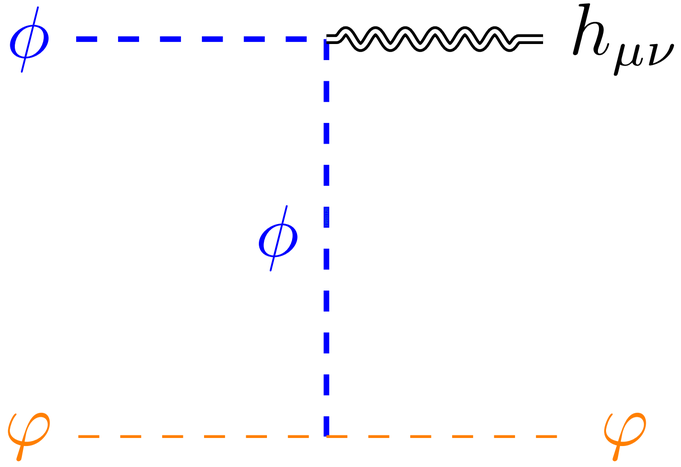
Instant preheating can maximize bremsstrahlung GWs!

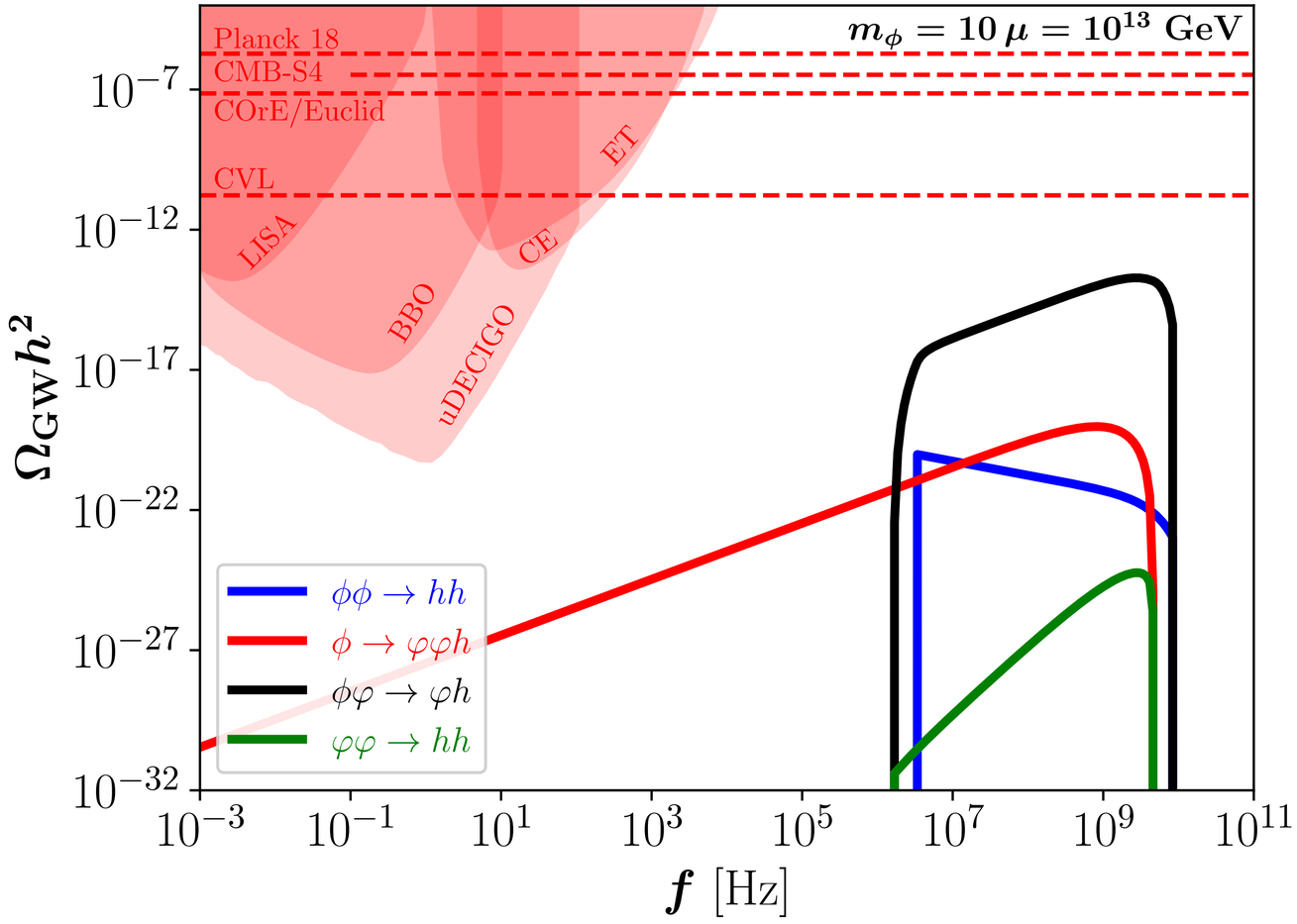
GWs from inflaton rescattering

[Xu, (2024), Bernal, Wu, Xu, Xu (2025)]

$$\mathcal{L}_{\phi\varphi} \supset \frac{1}{2}\,\mu\,\phi\,\varphi^2 \qquad \phi \to \varphi\varphi$$

Scattering $\varphi\phi \to \varphi h$
produce large GWs

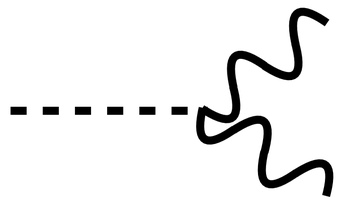




(4) Inflaton decay to gravitons

- Question: does scalar decay into graviton pair? [Ema, Mukaida, KN (2021)]

⟶ In Einstein gravity there is no such process.



$$S = \int d^4x\sqrt{-g}\left[\frac{M_{\rm Pl}^2}{2}R - \frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - V(\phi)\right]$$

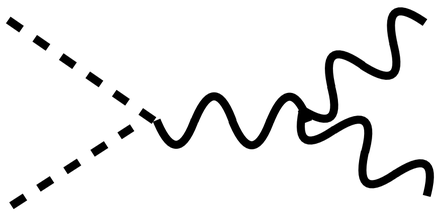
h_{ij}

h, h^2, h_{ij}^2 $\quad \Box h, (\partial h_{ij})^2, h(\partial h_{ij})^2$ $\quad \sim m^2\phi^2$ around potential minimum

No ϕh mixing, No $\phi(\partial h_{ij})^2$ term

- Note: scalar annihilation to graviton is possible.

[Ema, Jinno, Mukaida, KN (2015)]



(4) Inflaton decay to gravitons

[Ema, Mukaida, KN (2021)]

- Operators beyond Einstein:

$$\mathcal{L} \sim c_1 \phi R + c_2 \phi R^2 + c_3 \phi R_{\mu\nu} R^{\mu\nu} + c_4 \phi R_{\mu\nu\rho\sigma} R^{\mu\nu\rho\sigma}$$

- Inflaton decay rate : $c_4 = \dfrac{1}{\Lambda}$

$$\Gamma(\phi \to 2h) = \frac{1}{4\pi} \frac{m_\phi^7}{\Lambda^2 M_{\rm Pl}^4}$$

(4) Inflaton decay to gravitons

[Ema, Mukaida, KN (2021)]

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$$\sim \phi (\partial h)^2$$

After solving mixing between scalar and graviton, it vanishes.

In short, go to Einstein frame!

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(4) Inflaton decay to gravitons

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$\sim \phi (\partial h)^2$

After solving mixing between scalar and graviton, it vanishes.

In short, go to Einstein frame!

$R = R_{\mu\nu} = 0$

for on-shell graviton.

- Inflaton decay rate : $c_4 = \dfrac{1}{\Lambda}$

$$\Gamma(\phi \to 2h) = \frac{1}{4\pi} \frac{m_\phi^7}{\Lambda^2 M_{\rm Pl}^4}$$

(4) Inflaton decay to gravitons

[Ema, Mukaida, KN (2021)]

- Operators beyond Einstein:

$$\mathcal{L} \sim c_1 \phi R + c_2 \phi R^2 + c_3 \phi R_{\mu\nu} R^{\mu\nu} + c_4 \phi R_{\mu\nu\rho\sigma} R^{\mu\nu\rho\sigma}$$

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After solving mixing between scalar and graviton, it vanishes.

In short, go to Einstein frame!

$R = R_{\mu\nu} = 0$

for on-shell graviton.

Only this term induces decay to gravitons!

- Inflaton decay rate : $c_4 = \dfrac{1}{\Lambda}$

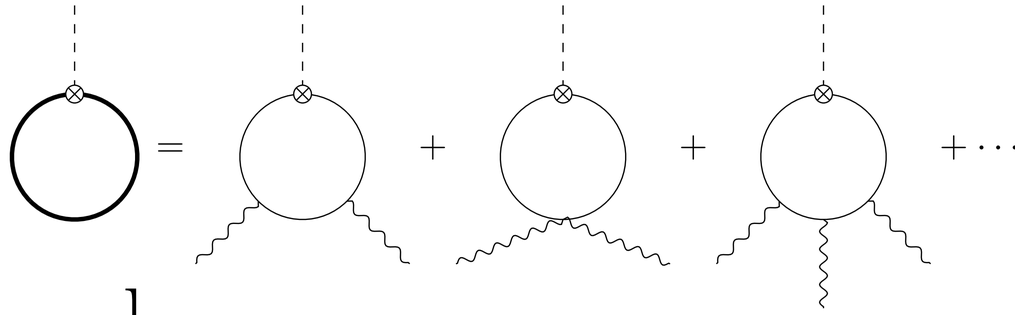
$$\Gamma(\phi \to 2h) = \frac{1}{4\pi} \frac{m_\phi^7}{\Lambda^2 M_{\rm Pl}^4}$$

(4) Inflaton decay to gravitons

[Ema, Mukaida, KN (2021)]

- Such operator appears by integrating out heavy field

$$S = \int \mathrm{d}^4x\sqrt{-g}\,\bar{\psi}\left[i\nabla\!\!\!/ - m - \lambda\phi\right]\psi$$



$$\longrightarrow \quad \mathscr{L}_{\rm eff} = \frac{1}{16\pi^2}\frac{\lambda\phi}{m}\left[\frac{1}{72}R^2 - \frac{1}{45}R_{\mu\nu}R^{\mu\nu} - \frac{7}{360}R_{\mu\nu\rho\sigma}R^{\mu\nu\rho\sigma}\right]$$

- Scalar can even dominantly decay into gravitons!

[Ema, Mukaida, KN (2021); Strumia, Landini (2025); KN, Takahashi, Wada (2025)]

Dark matter may decay into graviton. [Dunsky, Krnjaic, Pinetti (2025)]

New GW probe of inflation

[Mudrunka, KN (2023)]

- String effective theory often contains Gauss-Bonnet correction term
- Inflation with Gauss-Bonnet term

$$S = \int d^4x\sqrt{-g}\left[\frac{1}{2}M_{\rm pl}^2 R - \frac{1}{2}\partial^\mu\phi\partial_\mu\phi - V(\phi) - \frac{1}{16}\xi(\phi)\,R^2_{\rm GB}\right]$$

$$R^2_{\rm GB} = R^{\mu\nu\alpha\beta}R_{\mu\nu\alpha\beta} - 4R^{\mu\nu}R_{\mu\nu} + R^2$$

- Prediction on scalar spectral index & tensor-to-scalar ratio change

[Satoh, Soda (2008), Guo, Schwarz (2010)]

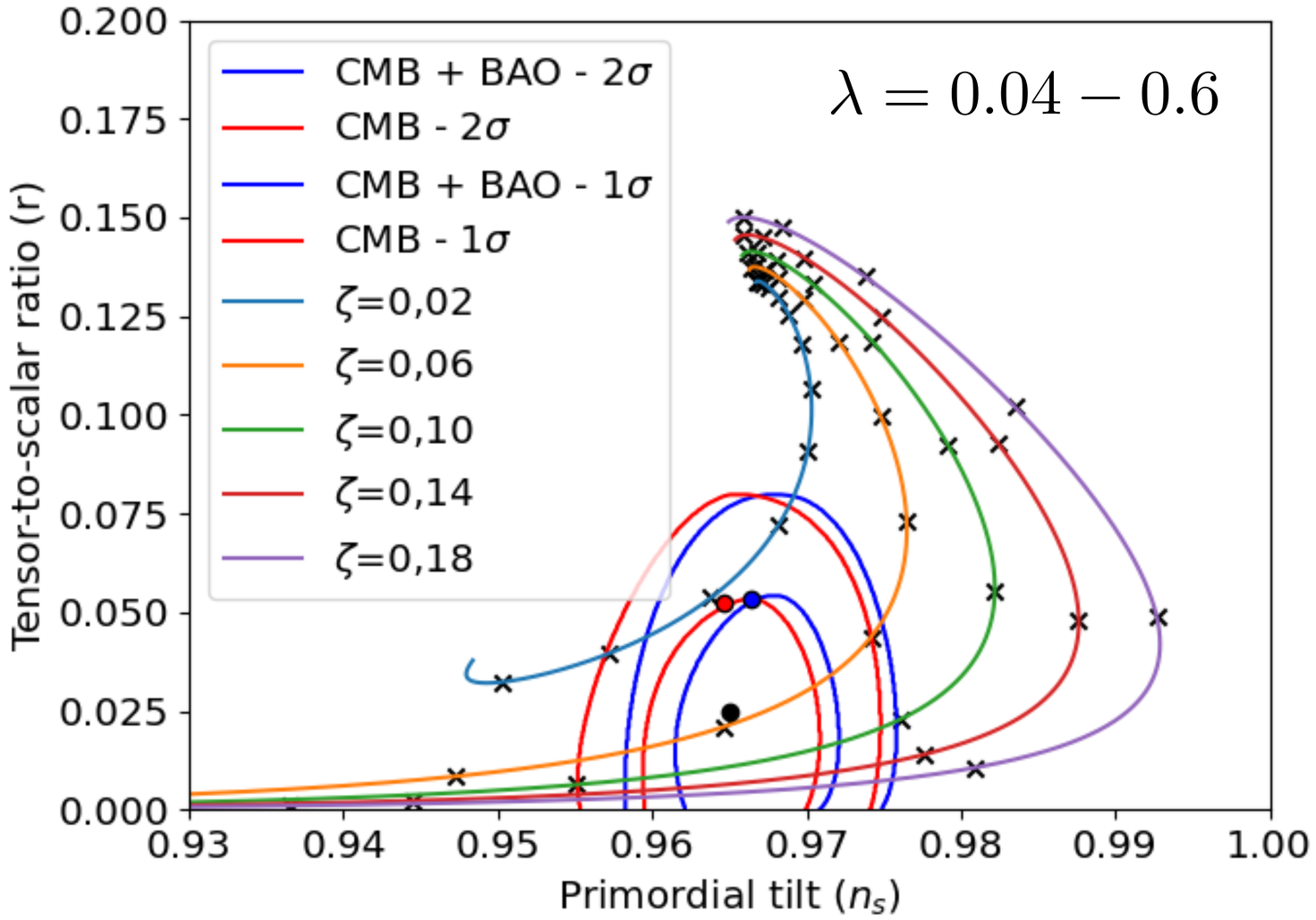
- Gauss-Bonnet term induces inflaton decay to gravitons!

[Mudrunka, KN (2023)]

$$V(\phi) = \frac{1}{2} m^2 \phi^2$$

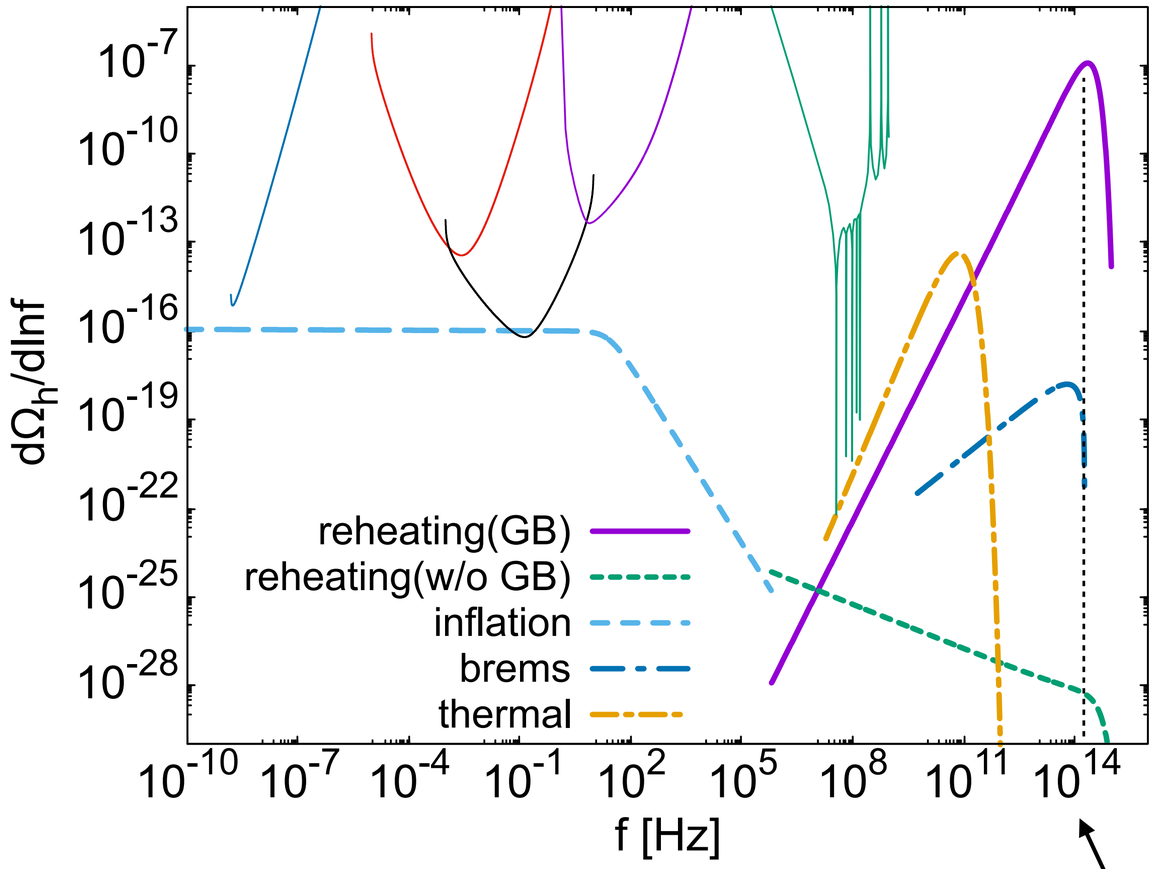
$$\xi(\phi) = 8\xi_0 e^{-\lambda\phi/M_{\mathrm{pl}}}$$

$$\zeta \equiv \frac{2m^2\xi_0}{3M_{\mathrm{pl}}^2}$$



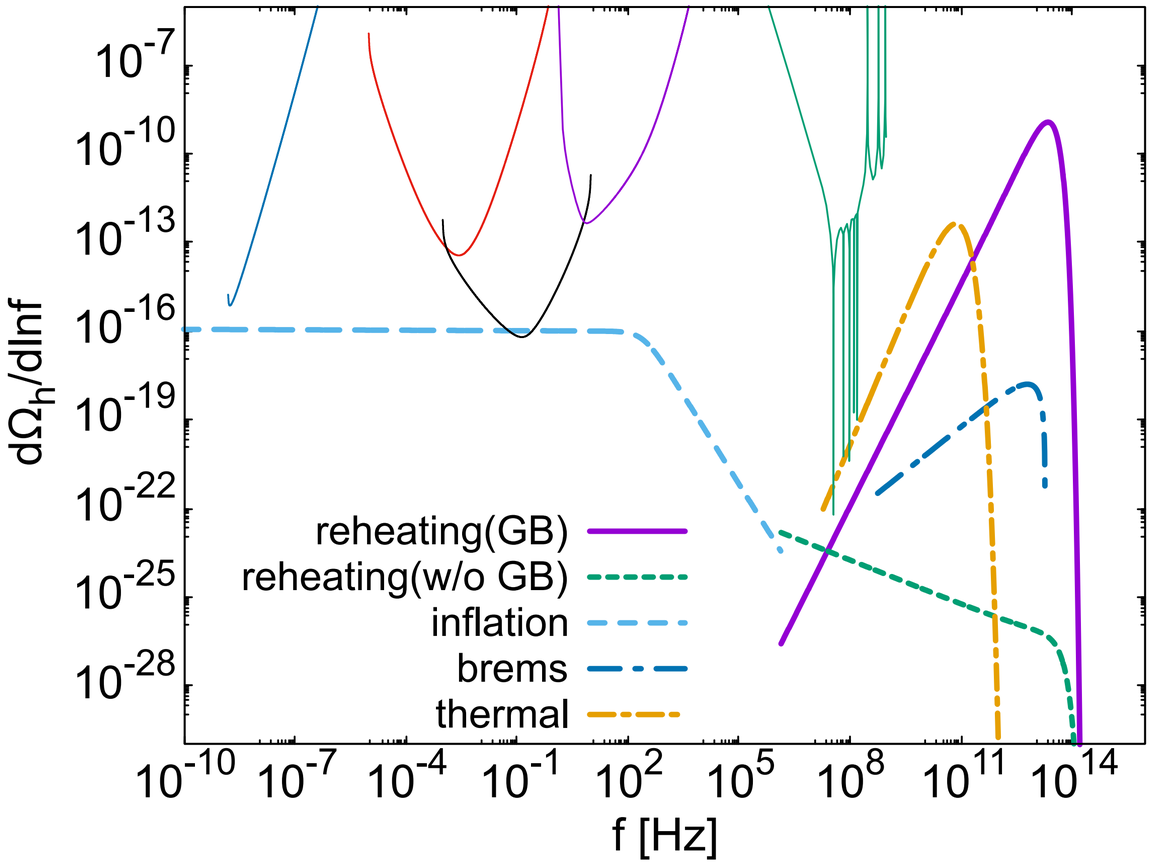
Consistent with Planck observation

$T_{\rm R} = 10^9\,{\rm GeV}$



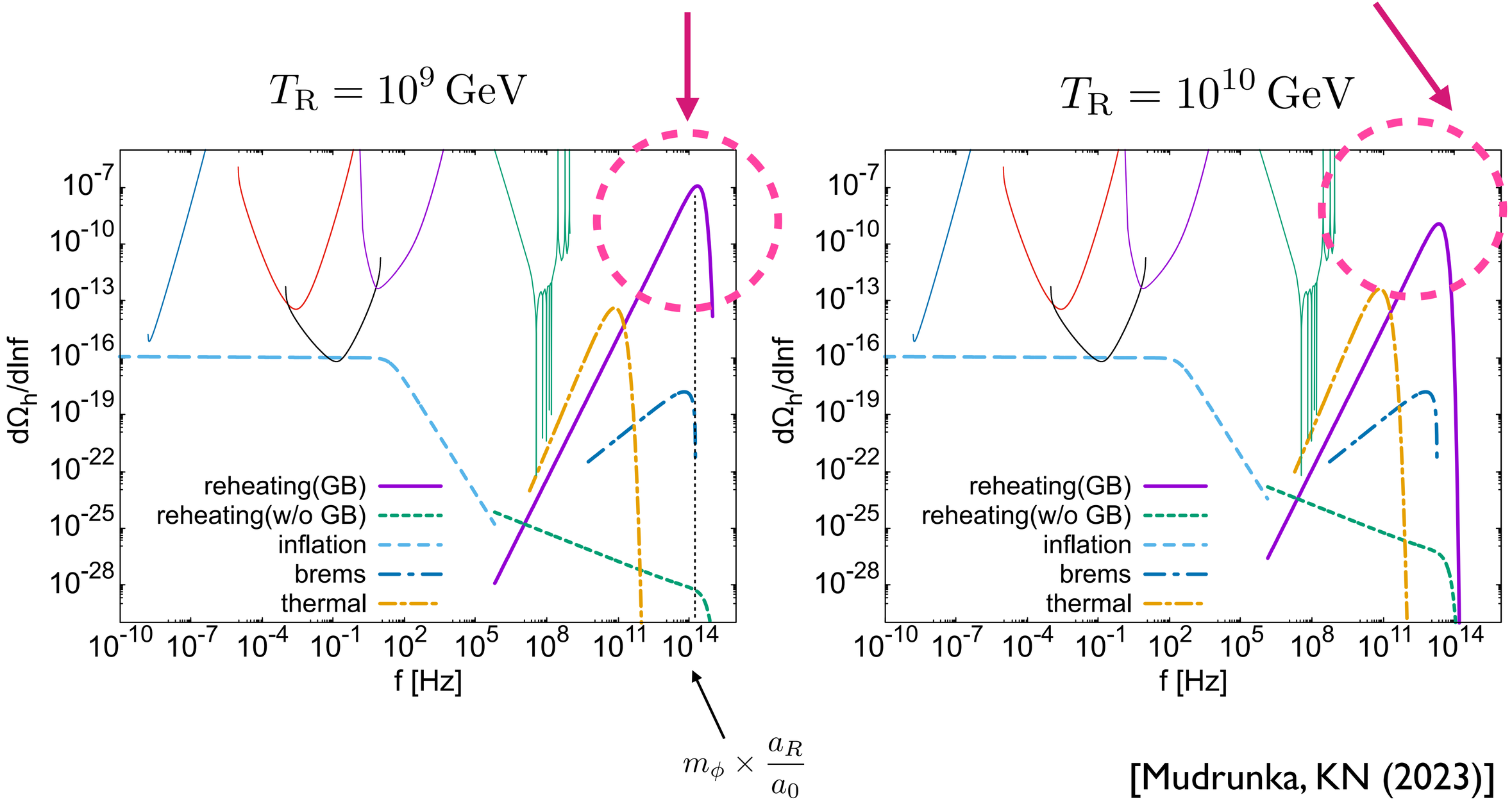
$m_\phi \times \dfrac{a_R}{a_0}$

$T_{\rm R} = 10^{10}\,{\rm GeV}$



[Mudrunka, KN (2023)]

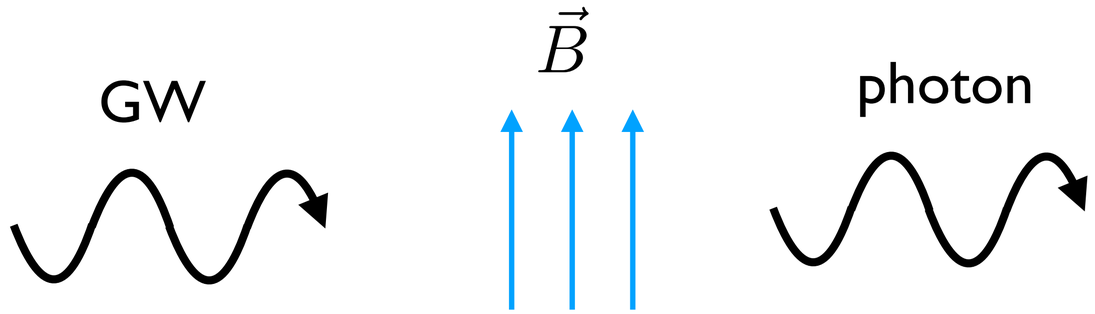
Huge GW background from inflaton decay to gravitons!



[Mudrunka, KN (2023)]

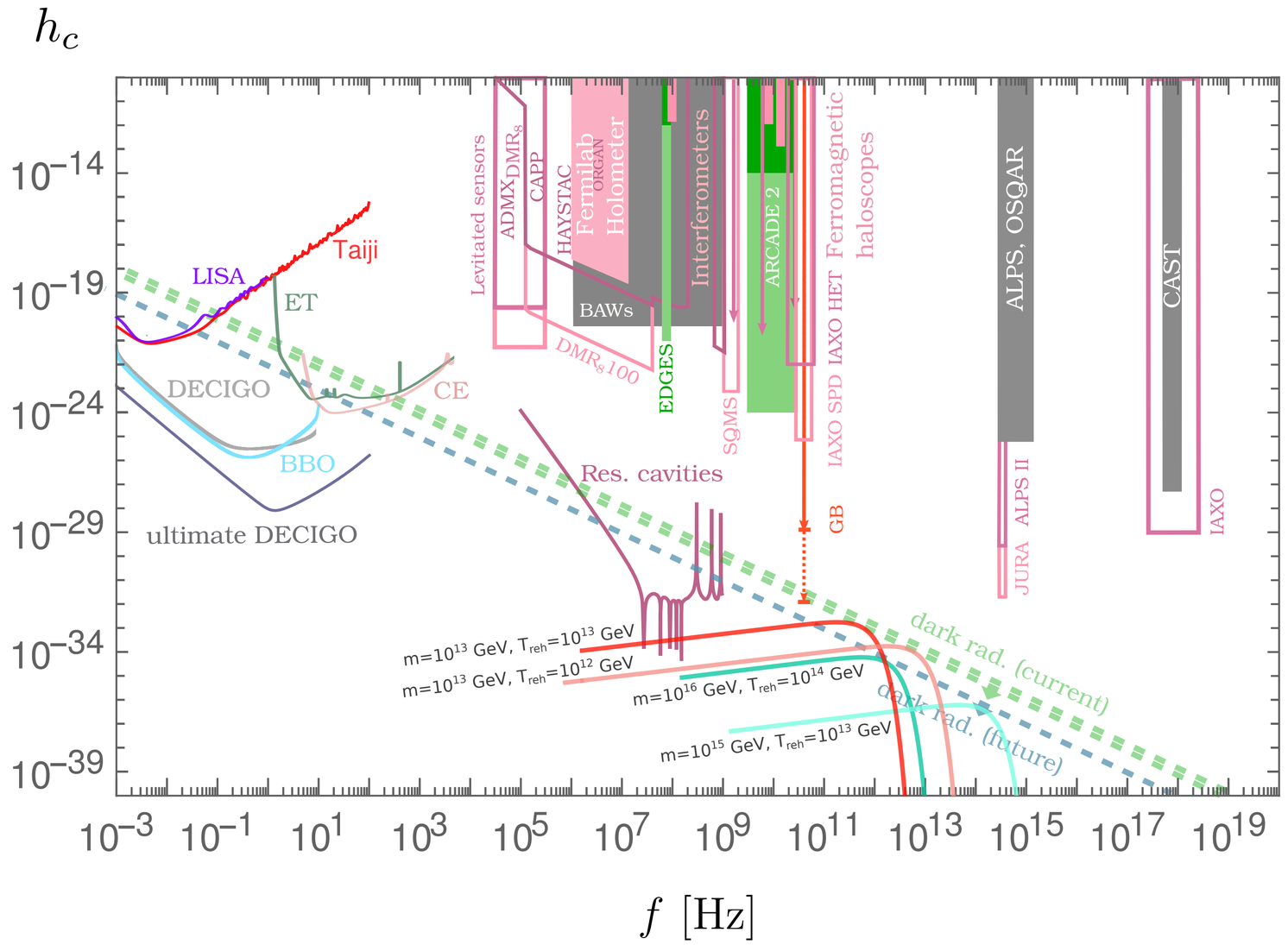
Toward detection of high-f GWs

- Graviton-photon conversion under magnetic field
  (inverse Gertsenshtein effect)
  - Astrophysical observations with telescopes
  - Use of axion experiments (cavity haloscope, helioscope, etc.)

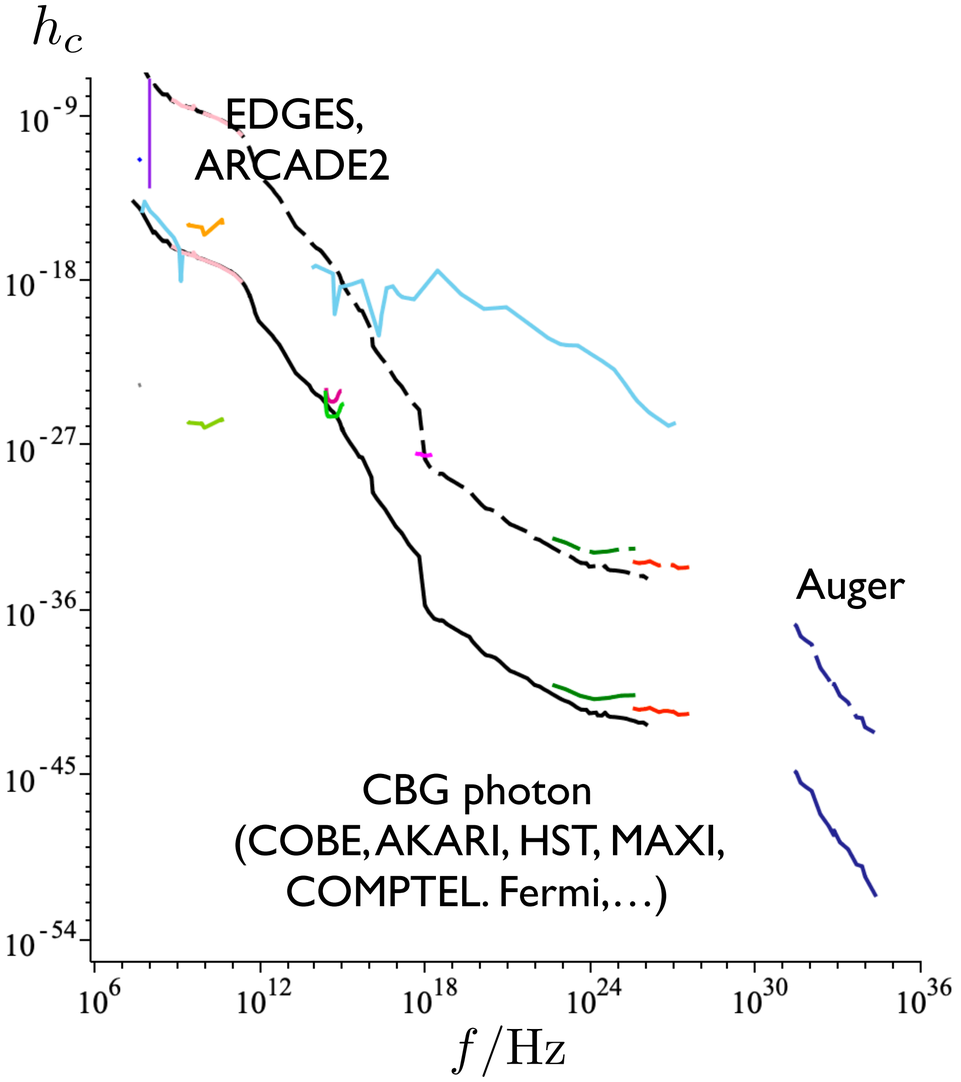


  - GW interaction with materials, qubits, etc.

Radio ~ gamma ray telescopes



[Tokareva (2023)]



[Ito, Kohri, KN (2023)]

Summary

- Many high frequency GW sources are found recently.
- They are directly related to inflaton properties.

New probes of inflation !

- Experimental efforts for high-f GW detection are on-going.