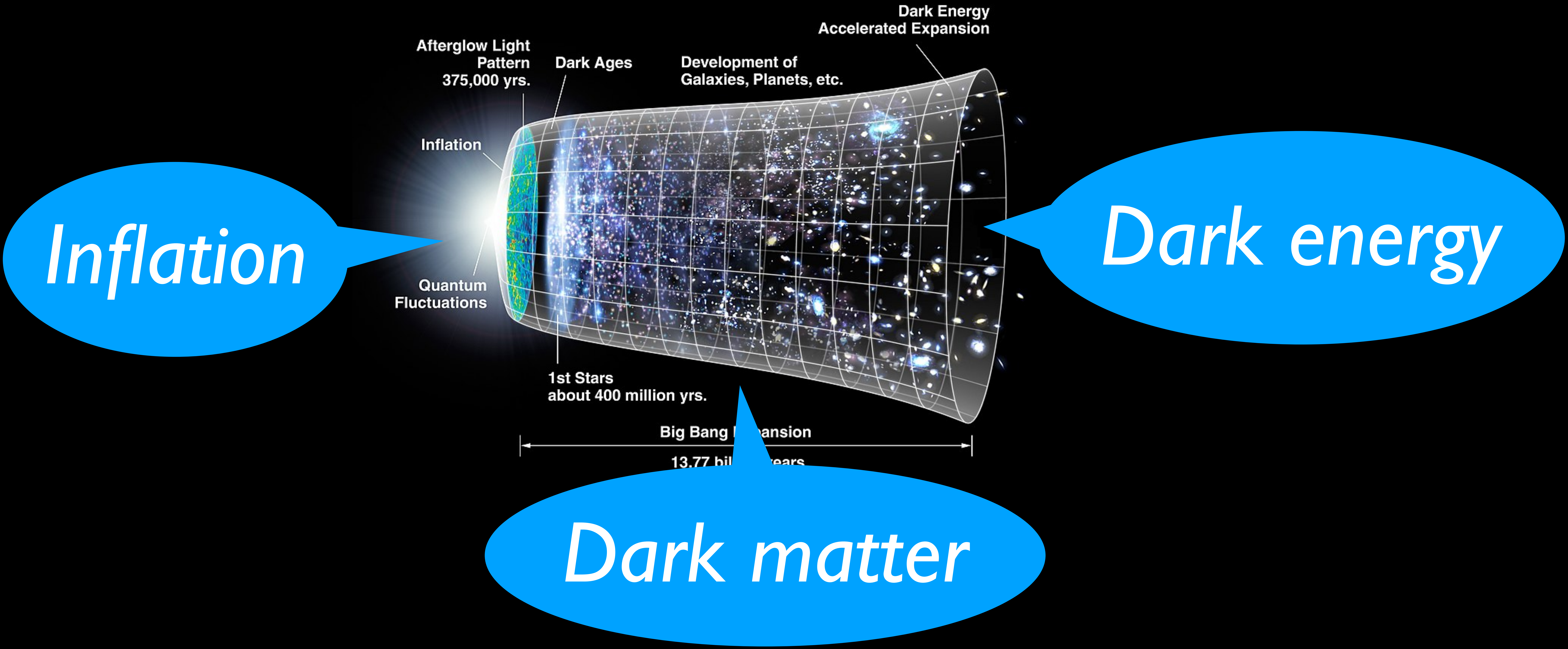
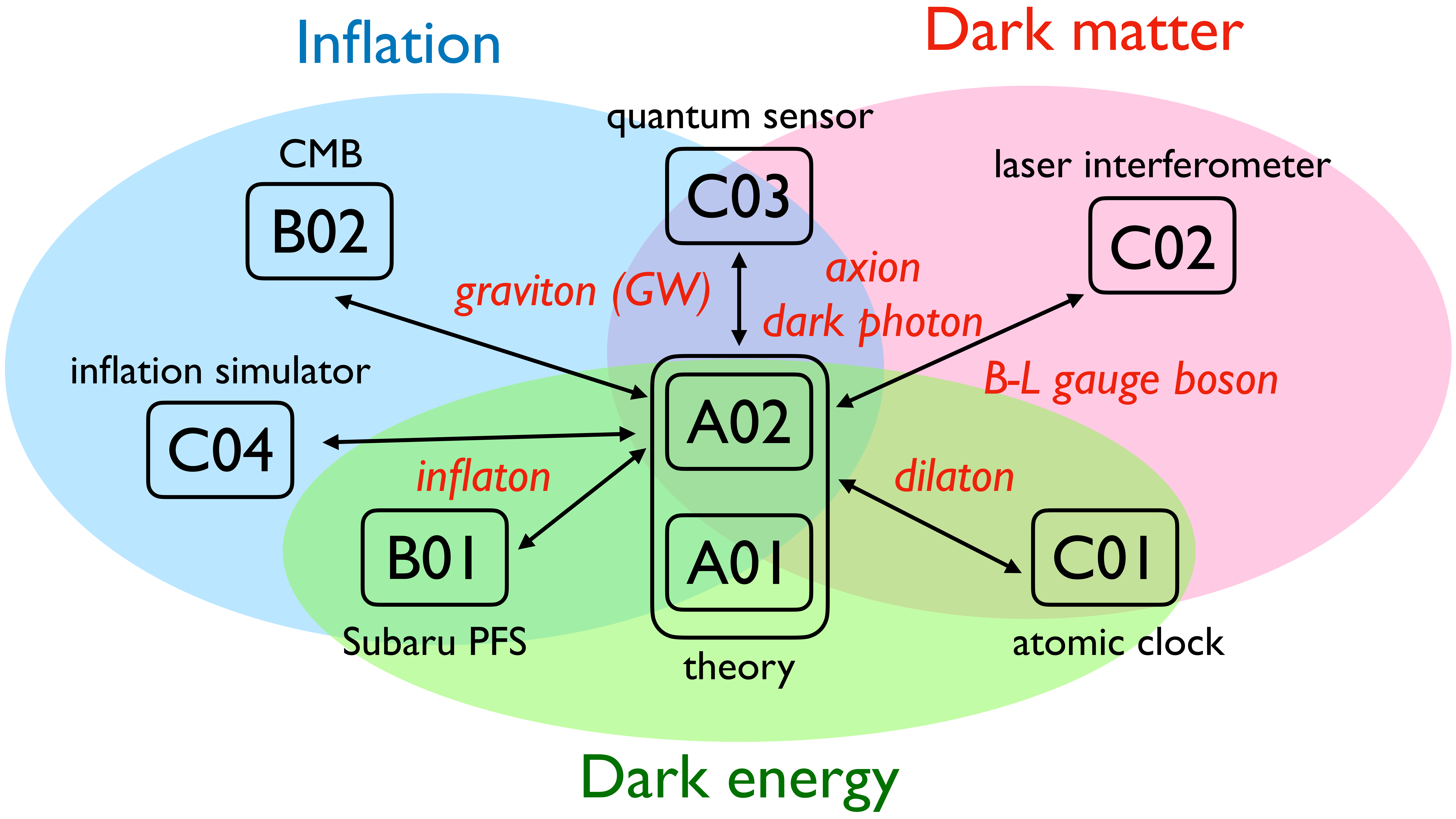
A02: particle theory

Kazunori Nakayama (Tohoku University)

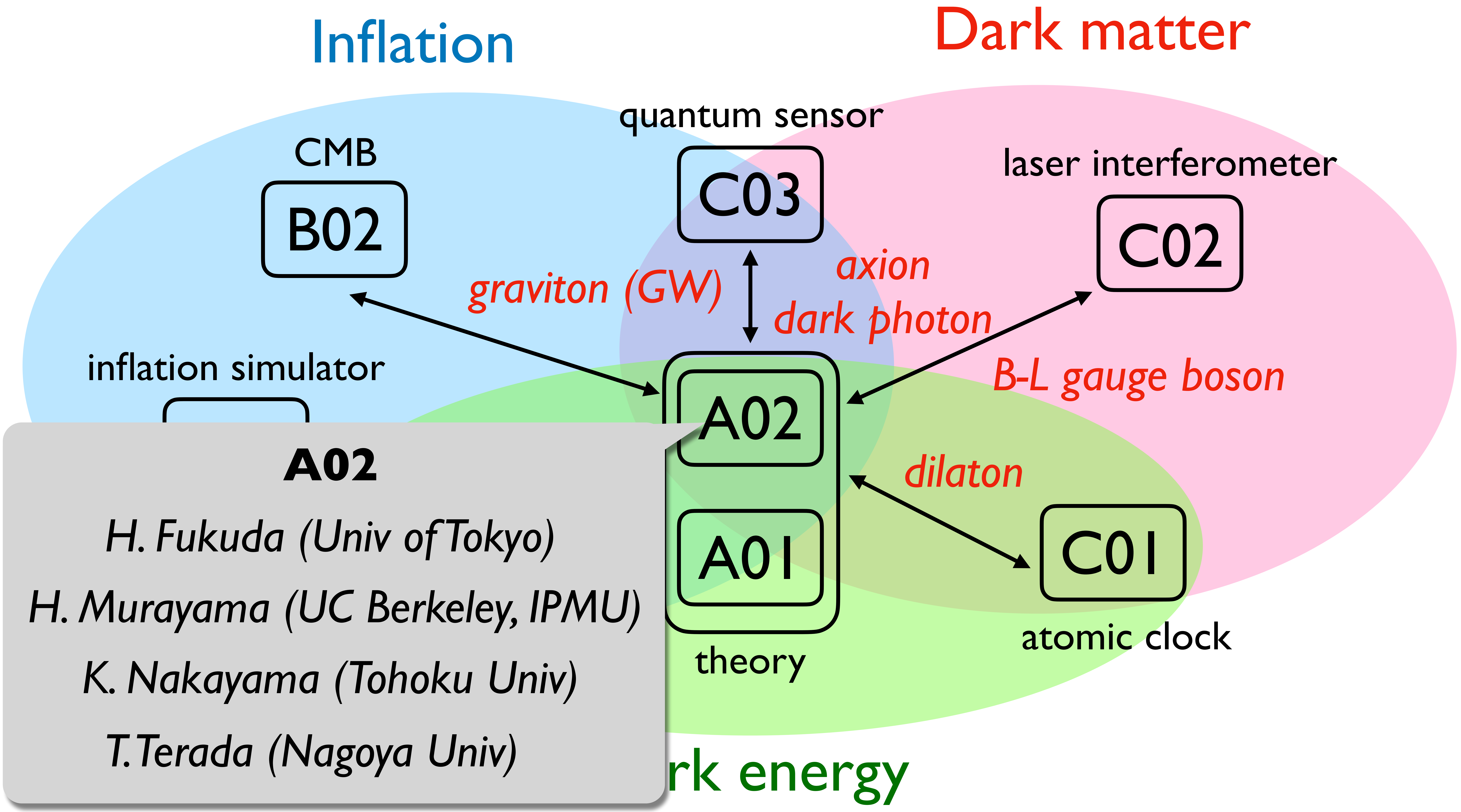
2026/7/7

Big Mysteries





Inflation
Dark matter
quantum sensor
CMB
C03
laser interferometer
B02
C02
axion
graviton (GW)
dark photon
inflation simulator
B-L gauge boson
A02
C04
inflaton
dilaton
B01
A01
C01
Subaru PFS
atomic clock
theory
Dark energy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Quantum technology

Quantum sensor
Quantum computing
…

Dark matter

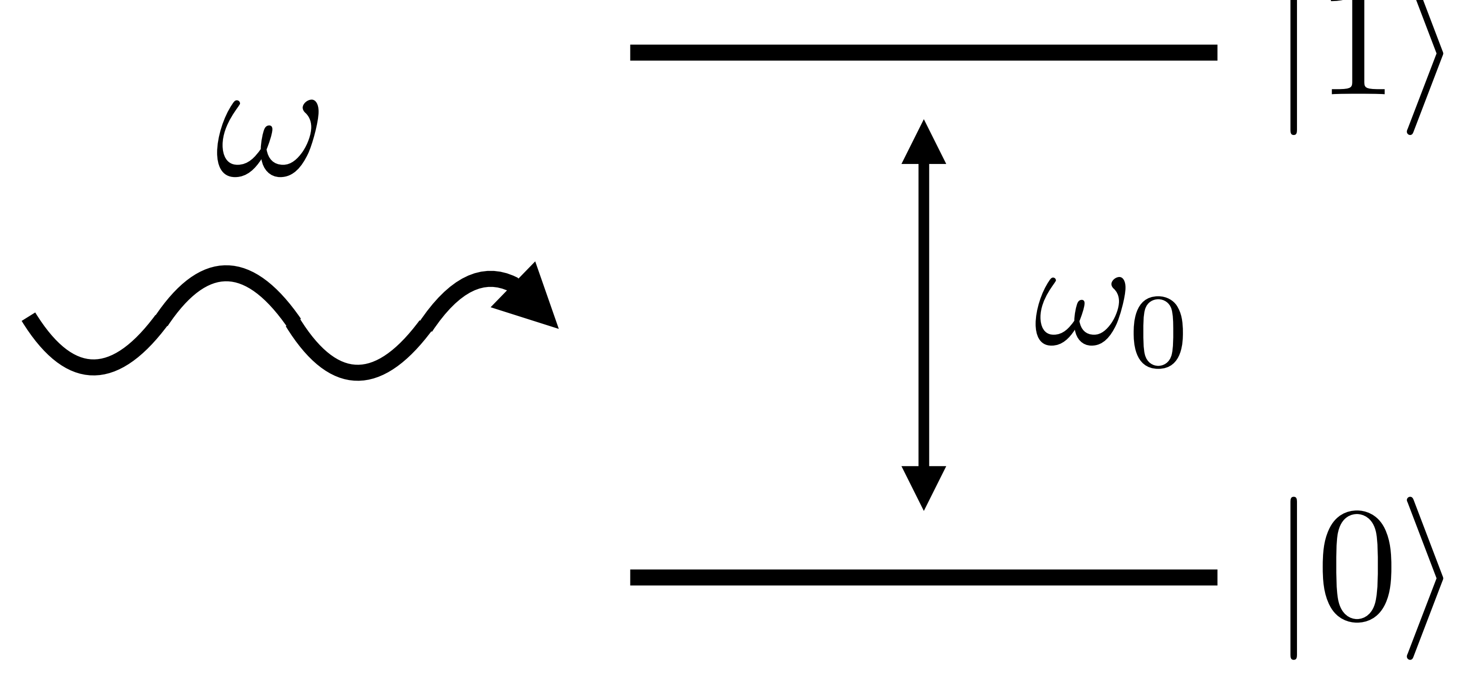
Wave-like dark matter
(axion, dark photon, …)

Inflation

High-frequency GWs

Qubit interaction with dark matter

- Qubit : 2-level system



- Interaction with external field

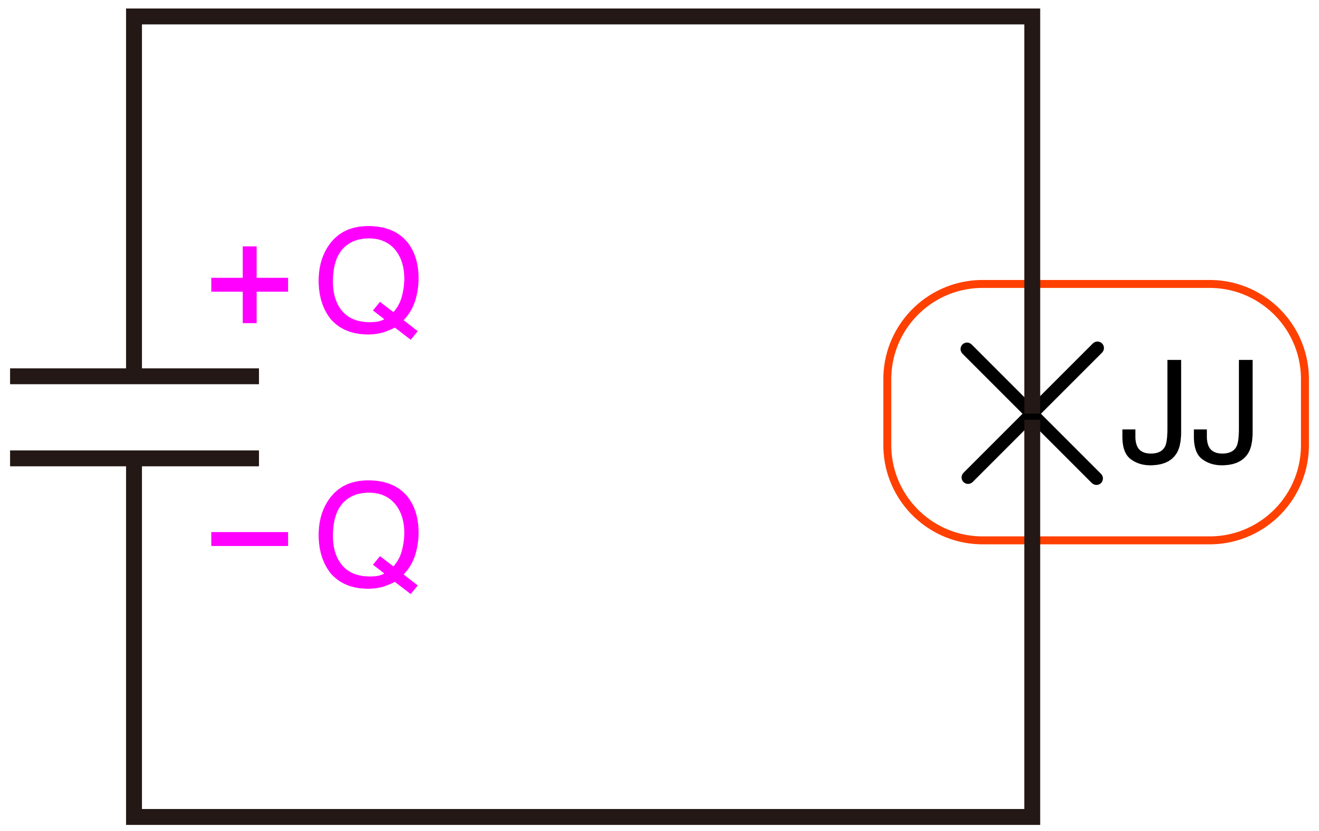
  (electro-magnetic field, dark matter, GW, …)

$$H = -\frac{\omega_0}{2}\sigma_z + \sum_{i=x,y,z} g_i \sigma_i \cos(\omega t)$$

- Time evolution of states induced by dark matter

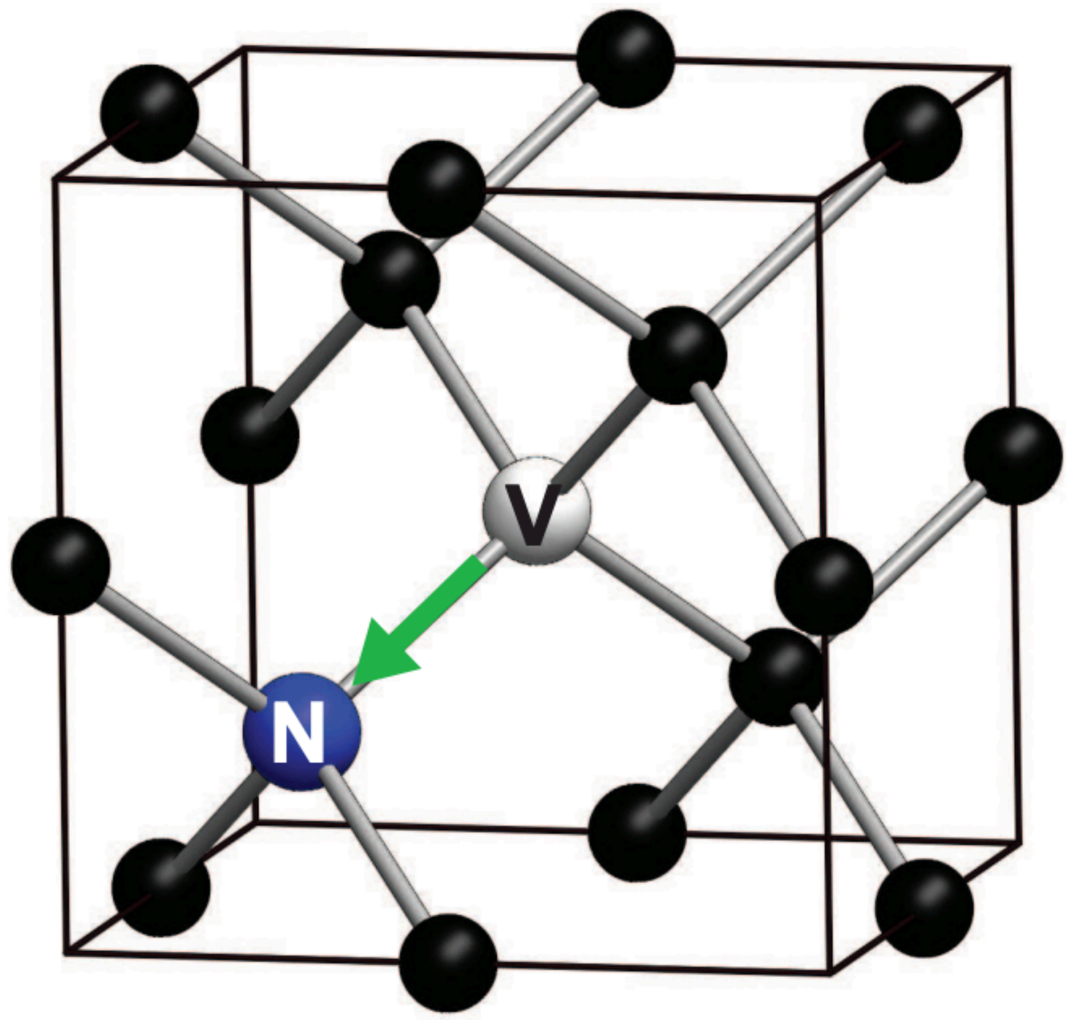
  e.g.) Rabi oscillation: $\left|\widetilde{\psi}(t)\right\rangle = \left[\cos\left(\frac{g_x t}{2}\right) - i\sigma_x \sin\left(\frac{g_x t}{2}\right)\right]\left|\widetilde{\psi}(0)\right\rangle$

Superconducting qubit



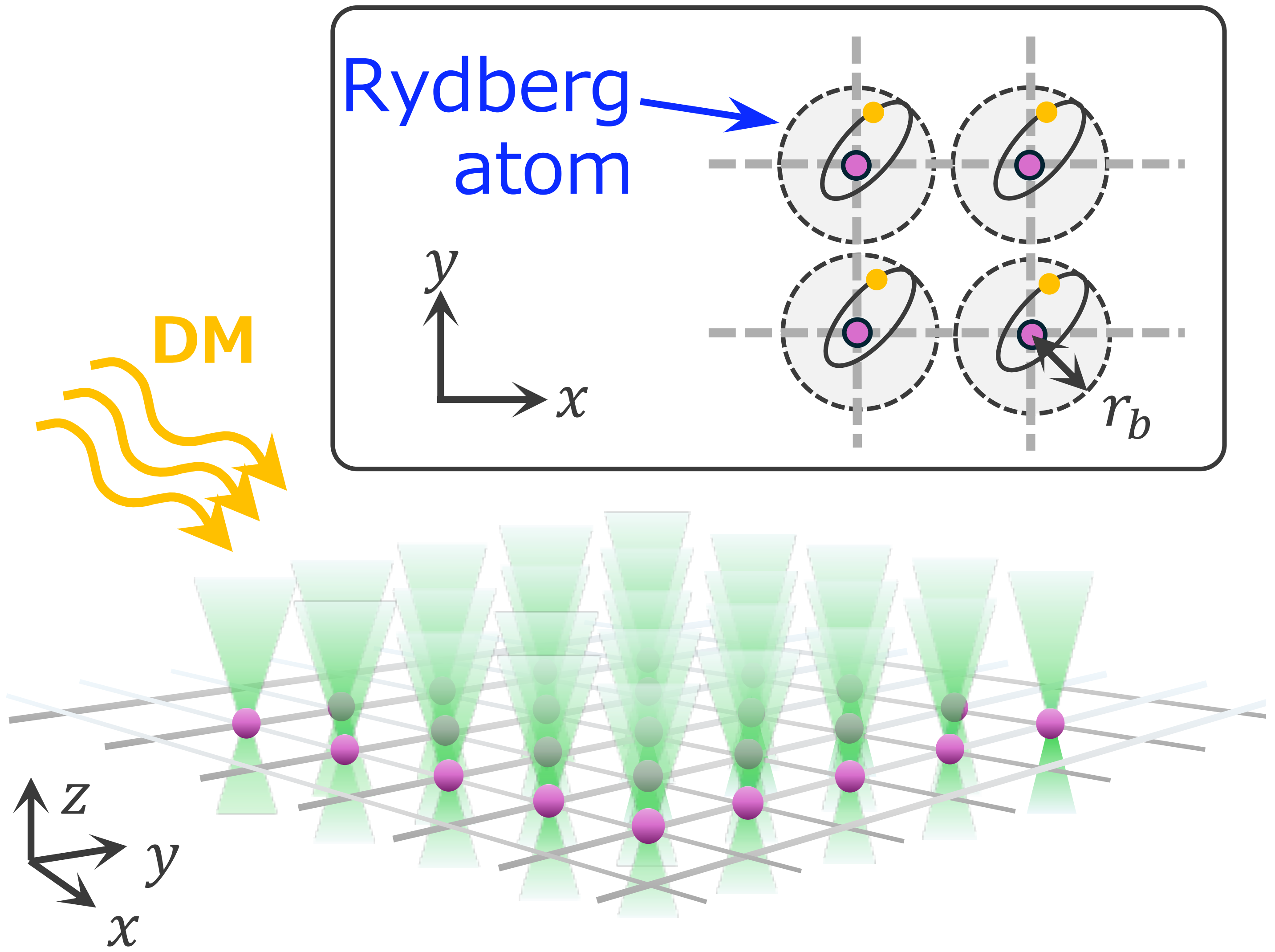
[Chen, Fukuda, Inada, Moroi, Nitta, Sichanugrist (2022)]

NV center in diamonds



[Chigusa, Hazumi, Herbschleb, Mizuochi, KN (2023)]

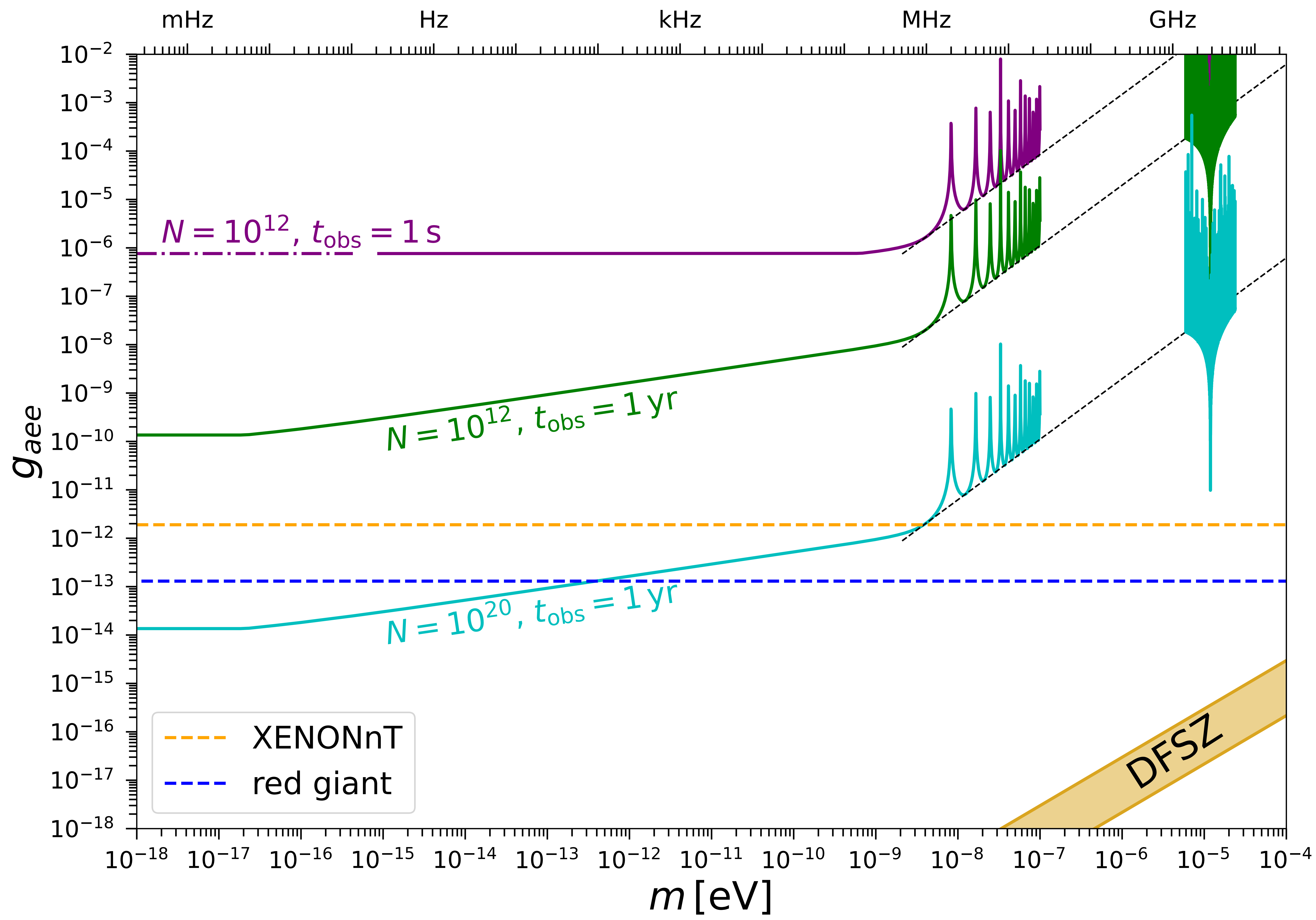
Cold neutral atoms



[Chigusa, Kasamaki, Kusano, Moroi, KN, Ozawa, Umemoto, Takahashi, Vutha (2025)]

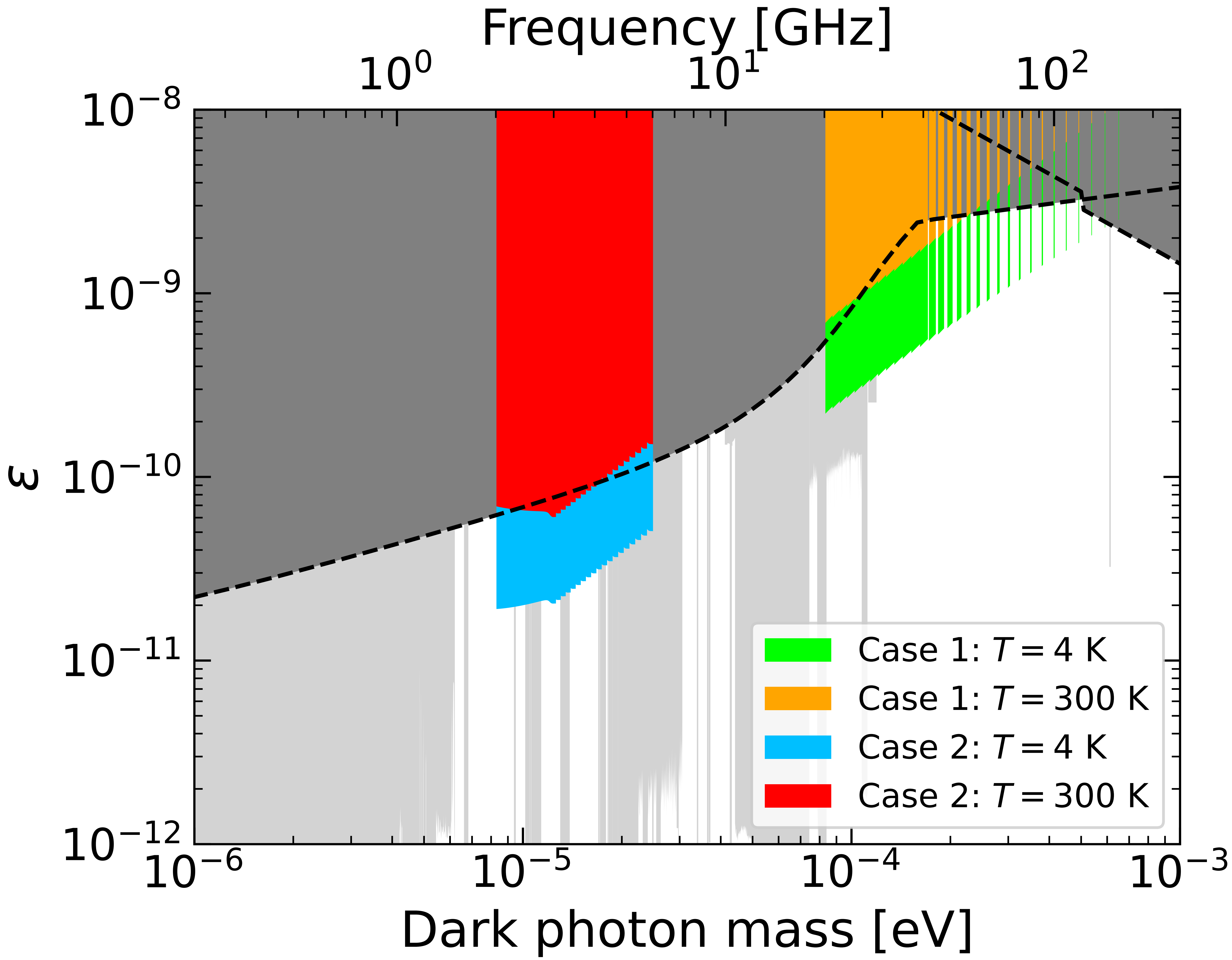
different types of qubits interact differently with dark matter

Projected sensitivity of NV diamond for axion-electron coupling



[Chigusa, Hazumi, Herbschleb, Mizuochi, KN (2023)]

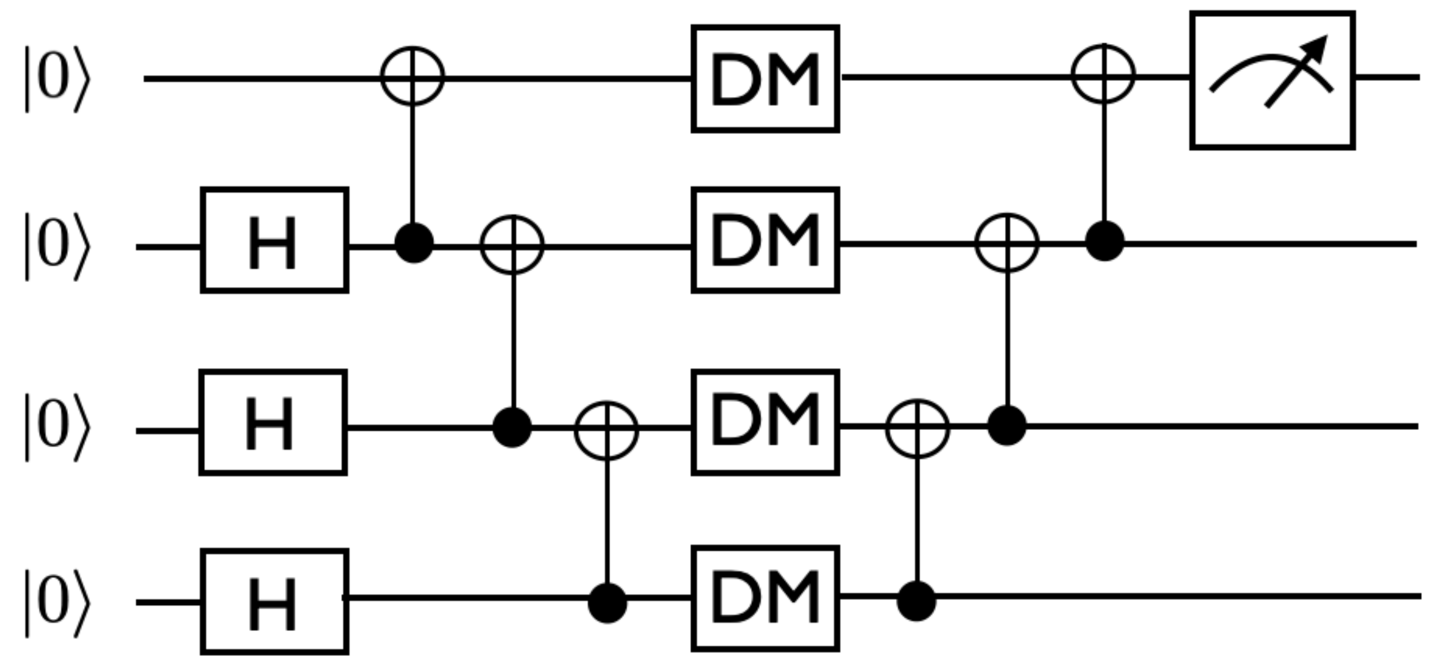
Projected sensitivity of Rydberg atom for dark photon



[Chigusa, Kasamaki, Kusano, Moroi, KN, Ozawa, Umemoto, Takahashi, Vutha (2025)]

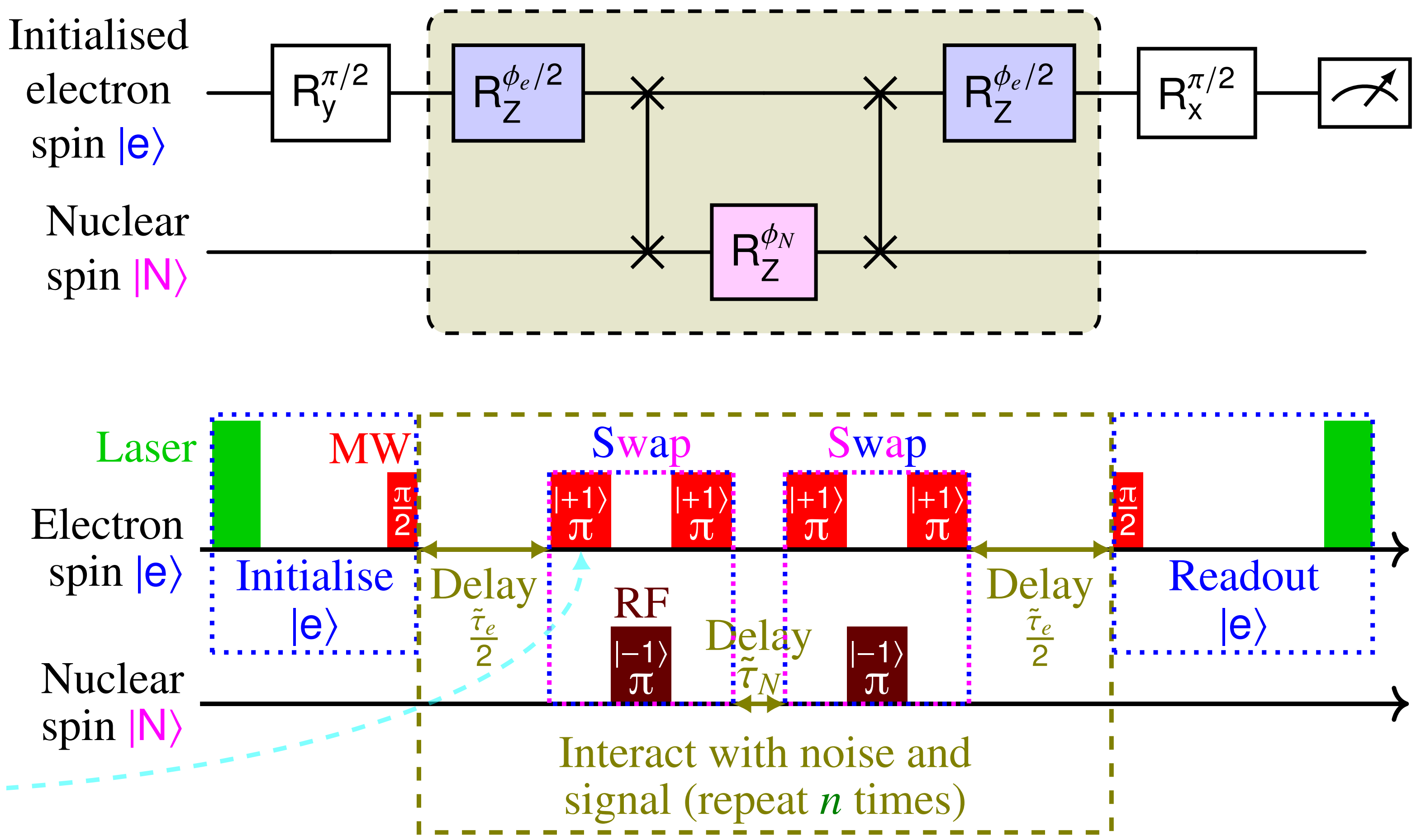
- Quantum circuit & related issues for dark matter search

Entanglement-enhancement



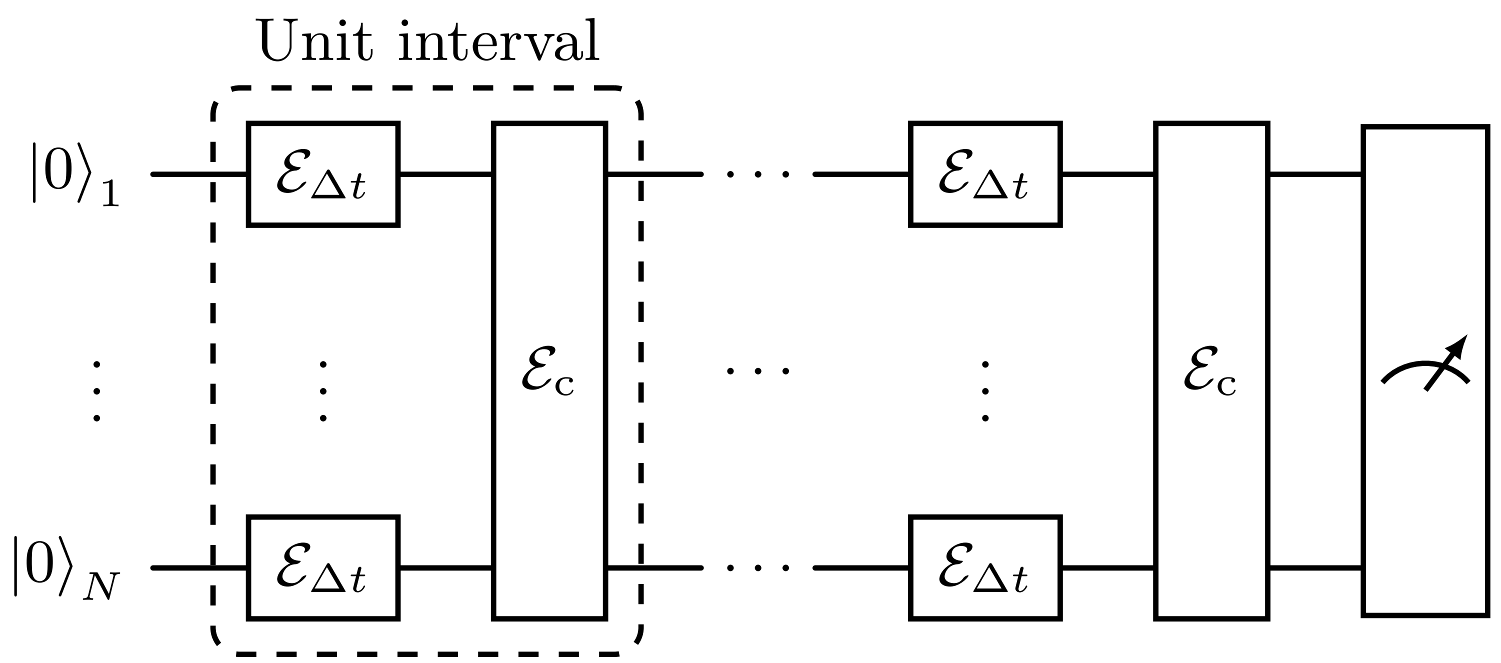
[Sichanugrist, Fukuda, Moroi, KN, Chigusa, Mizuochi, Hazumi, Matsuzaki (2024)]

Hybrid-spin decoupling



[Chigusa, Hazumi, Herbschleb, Matsuzaki, Mizuochi, KN (2025)]

Error correction-like



[Fukuda, Moroi, Sichanugrist (2025)]

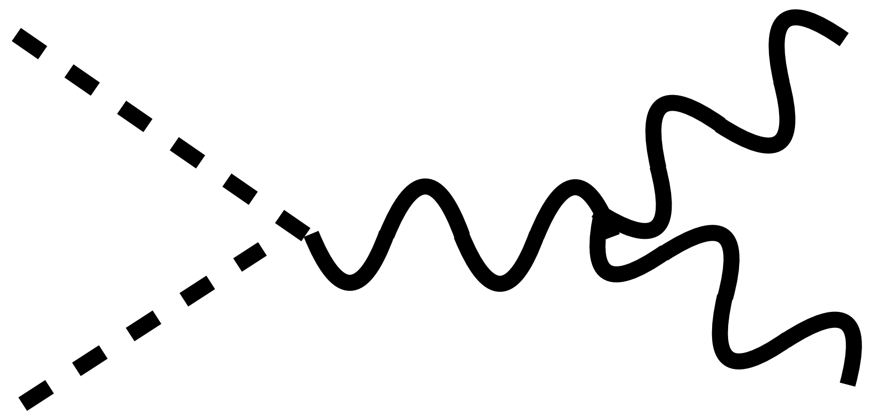
- Quantum sensing/computing may open new window for dark matter

⟶ *Next talk by H.Fukuda*

High frequency gravitational waves

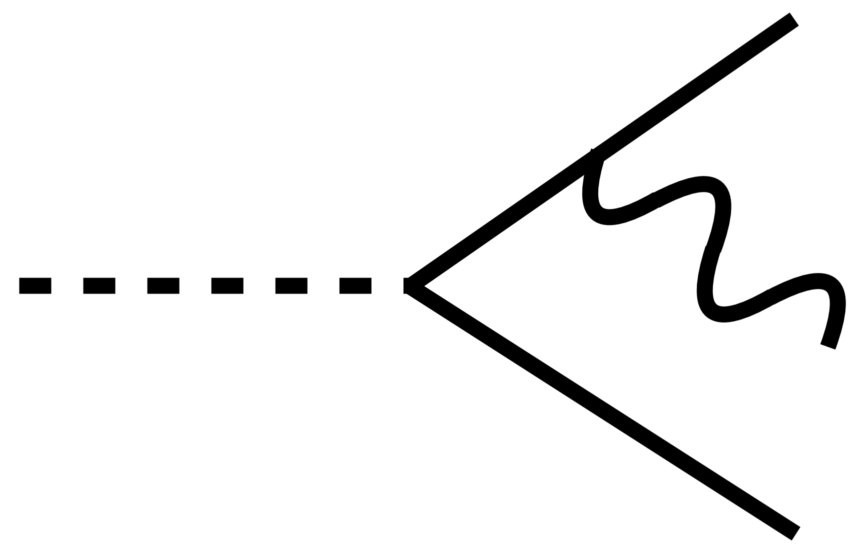
- Recent findings of high-frequency GW sources:

<u>*Inflaton annihilation*</u>



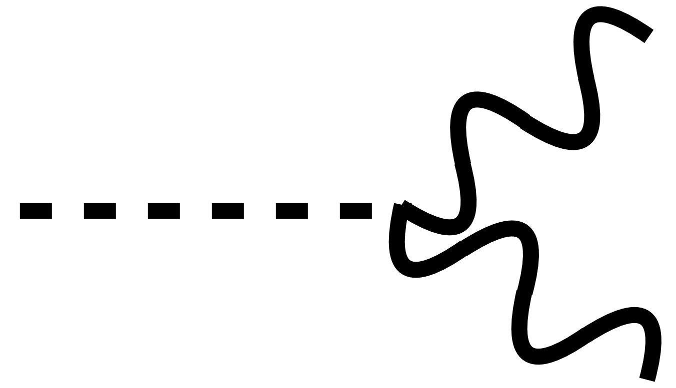
[Ema, Jinno, Mukaida, KN (2015);
Ema, Jinno, KN (2020)]

<u>*Bremsstrahlung*</u>



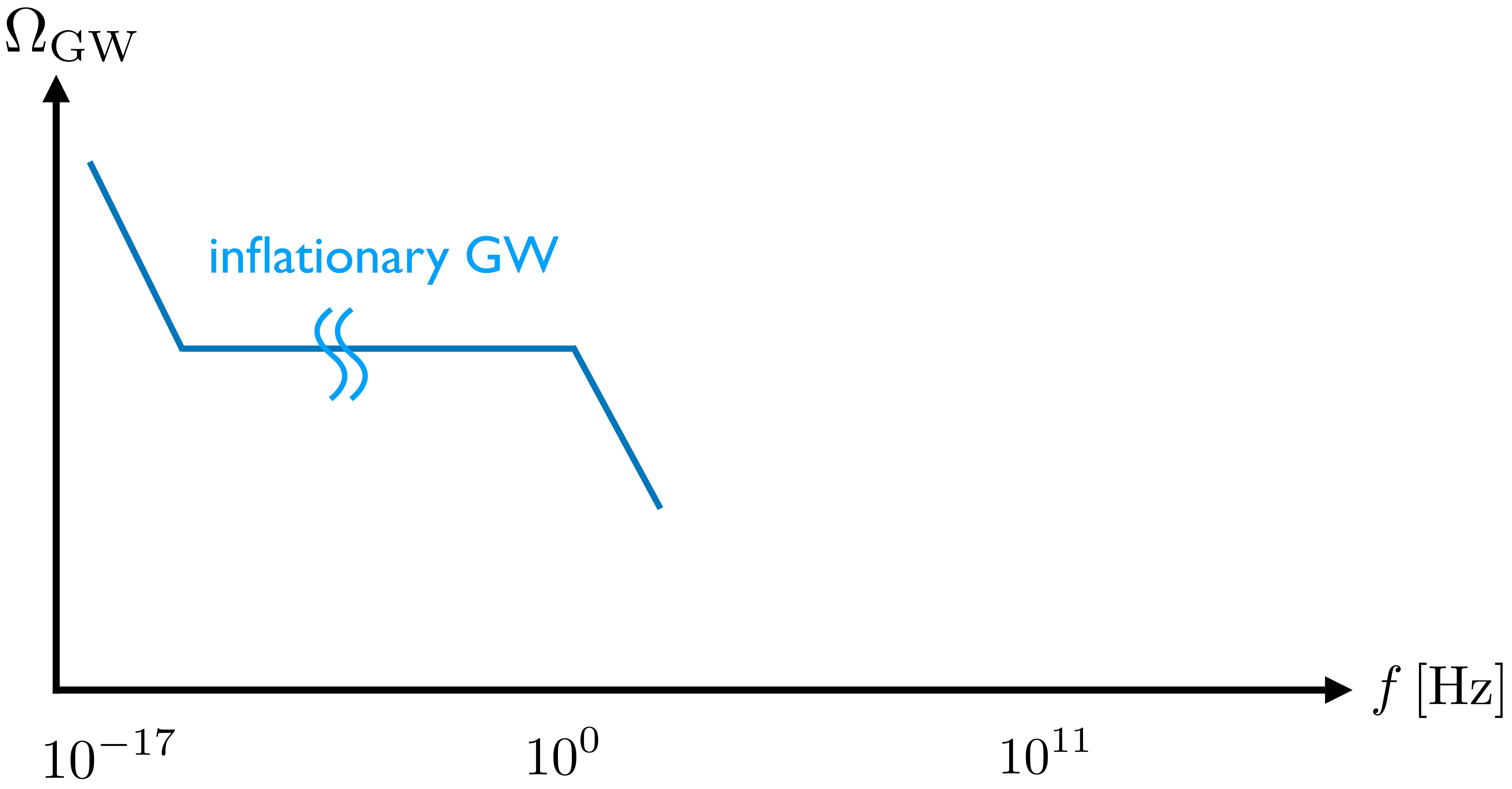
[KN, Tang (2018)]

<u>*Inflaton decay*</u>

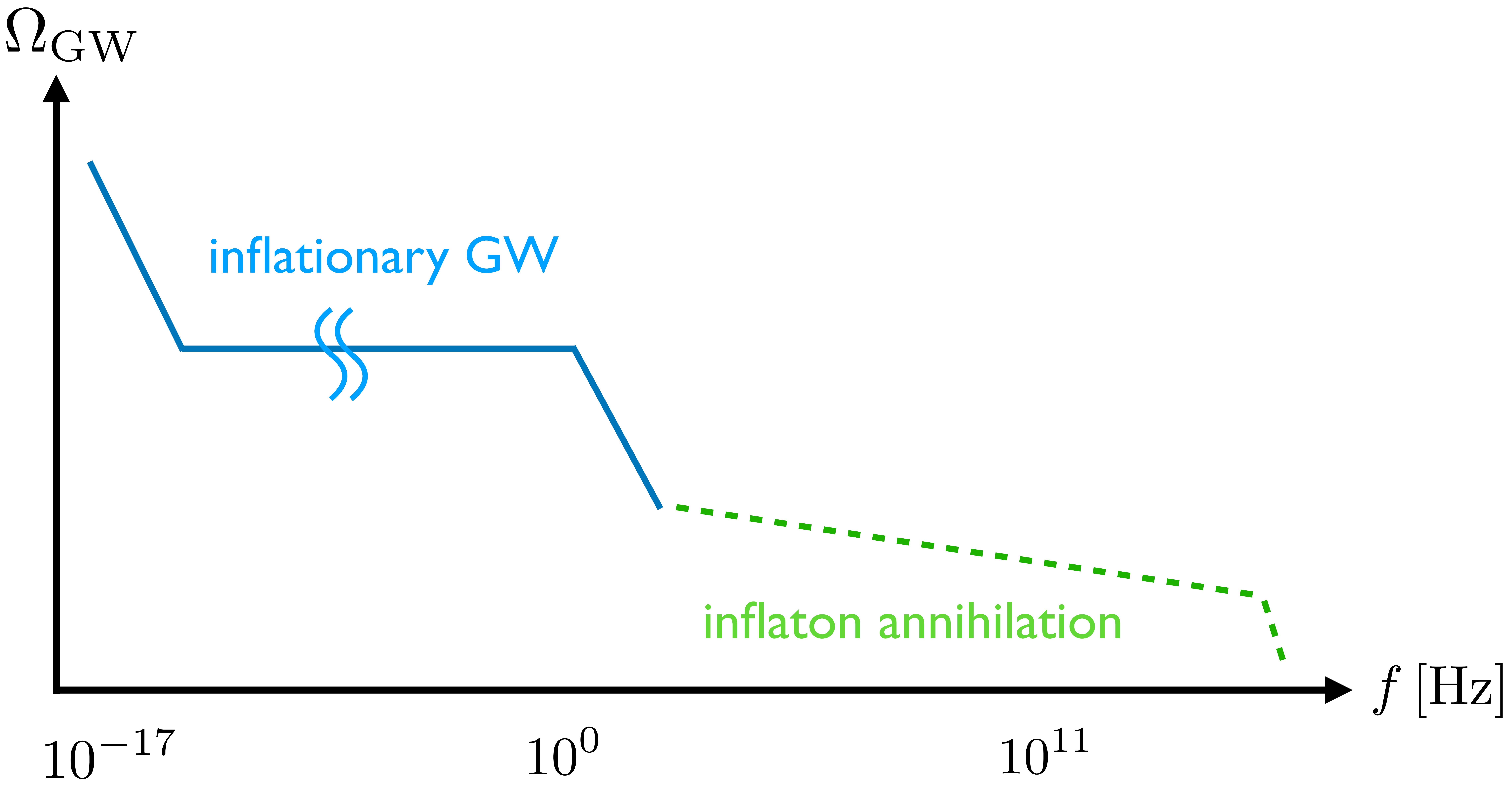


[Ema, Mukaida, KN (2021)]

- High-frequency GWs are keys for identifying inflaton!



Ω_{GW}
inflationary GW
f [Hz]
10^{-17}
10^{0}
10^{11}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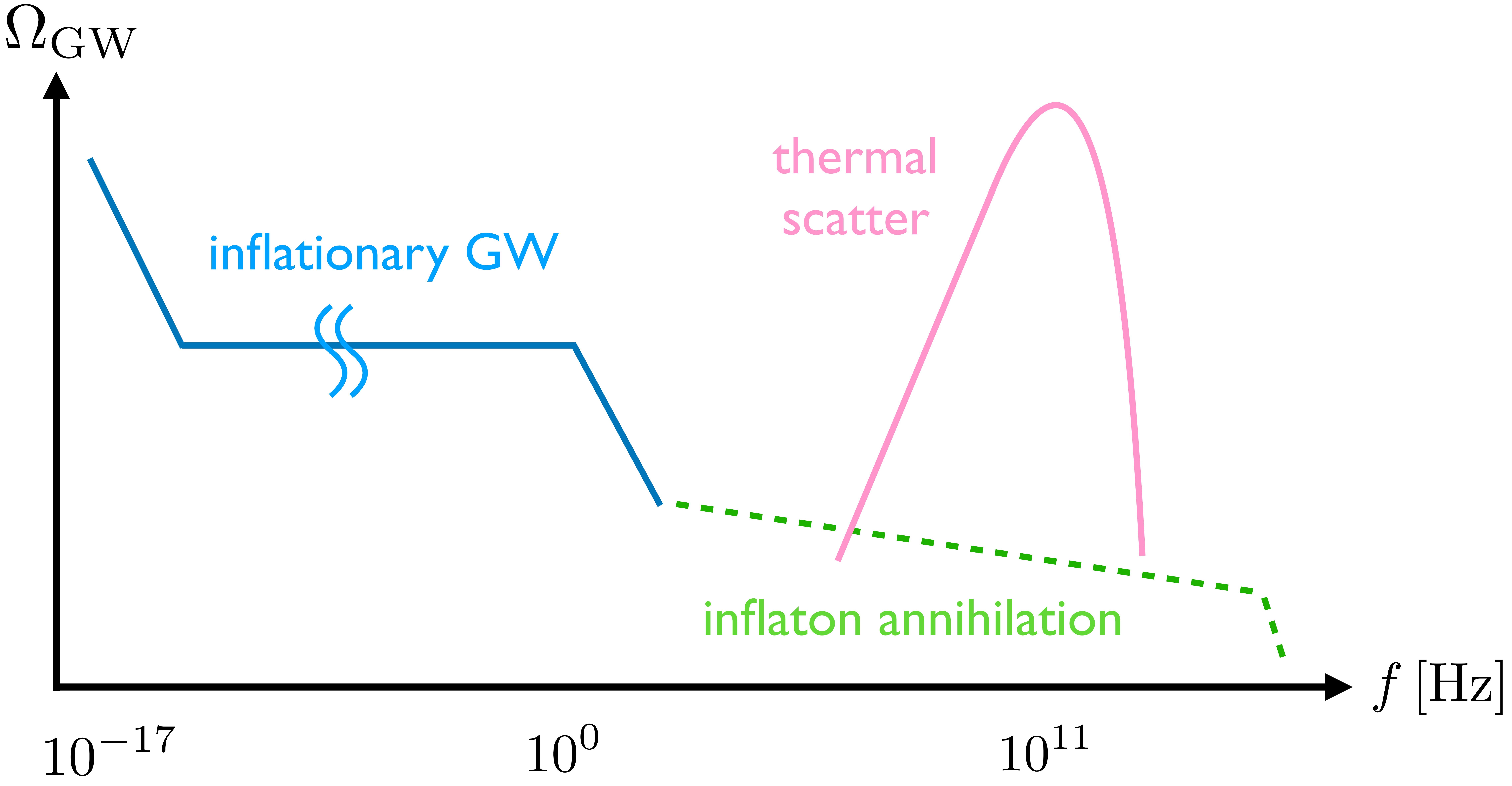
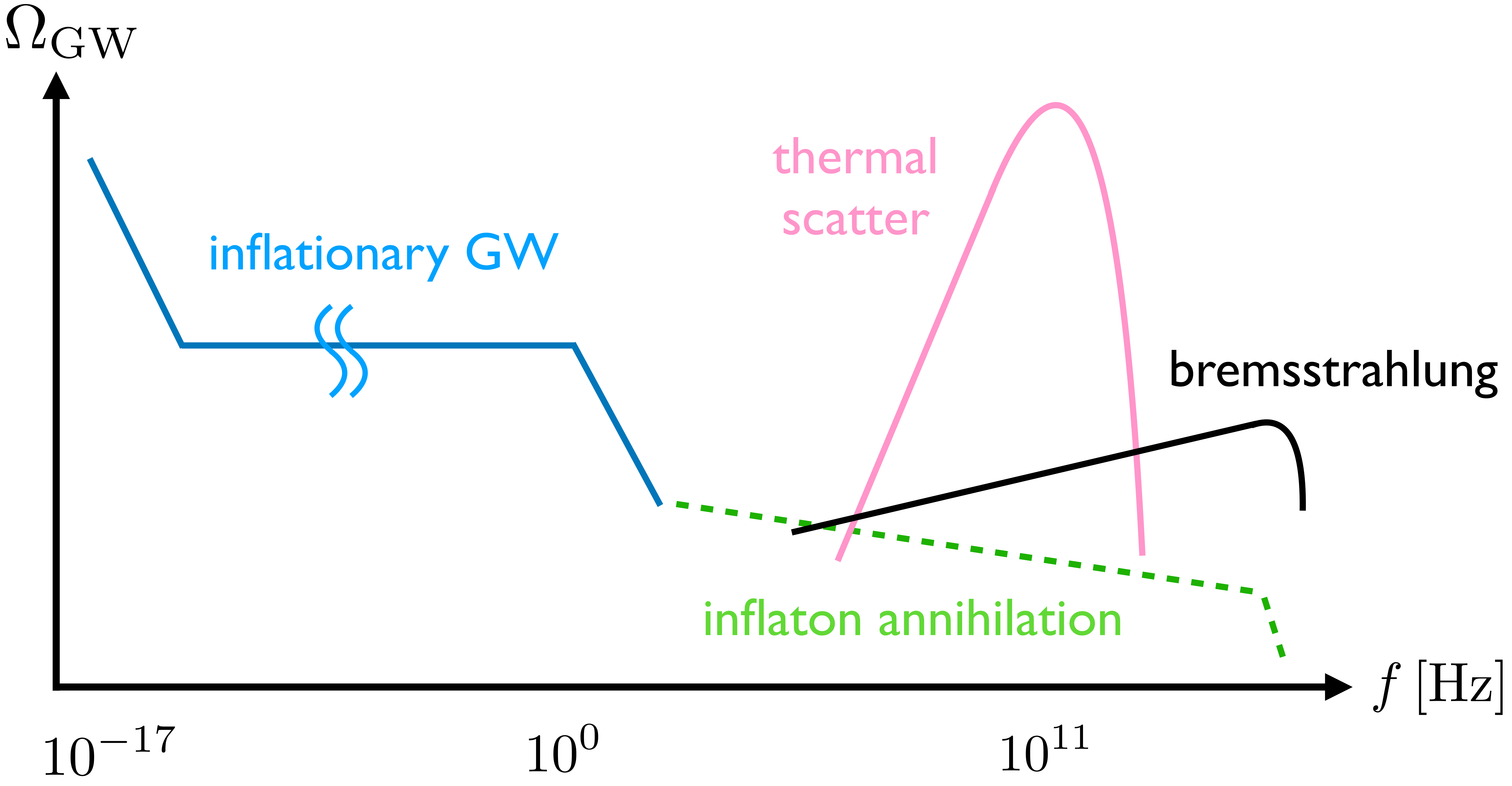


Ω_{GW}
thermal
scatter
inflationary GW
inflaton annihilation
f [Hz]
10^{-17}
10^{0}
10^{11}



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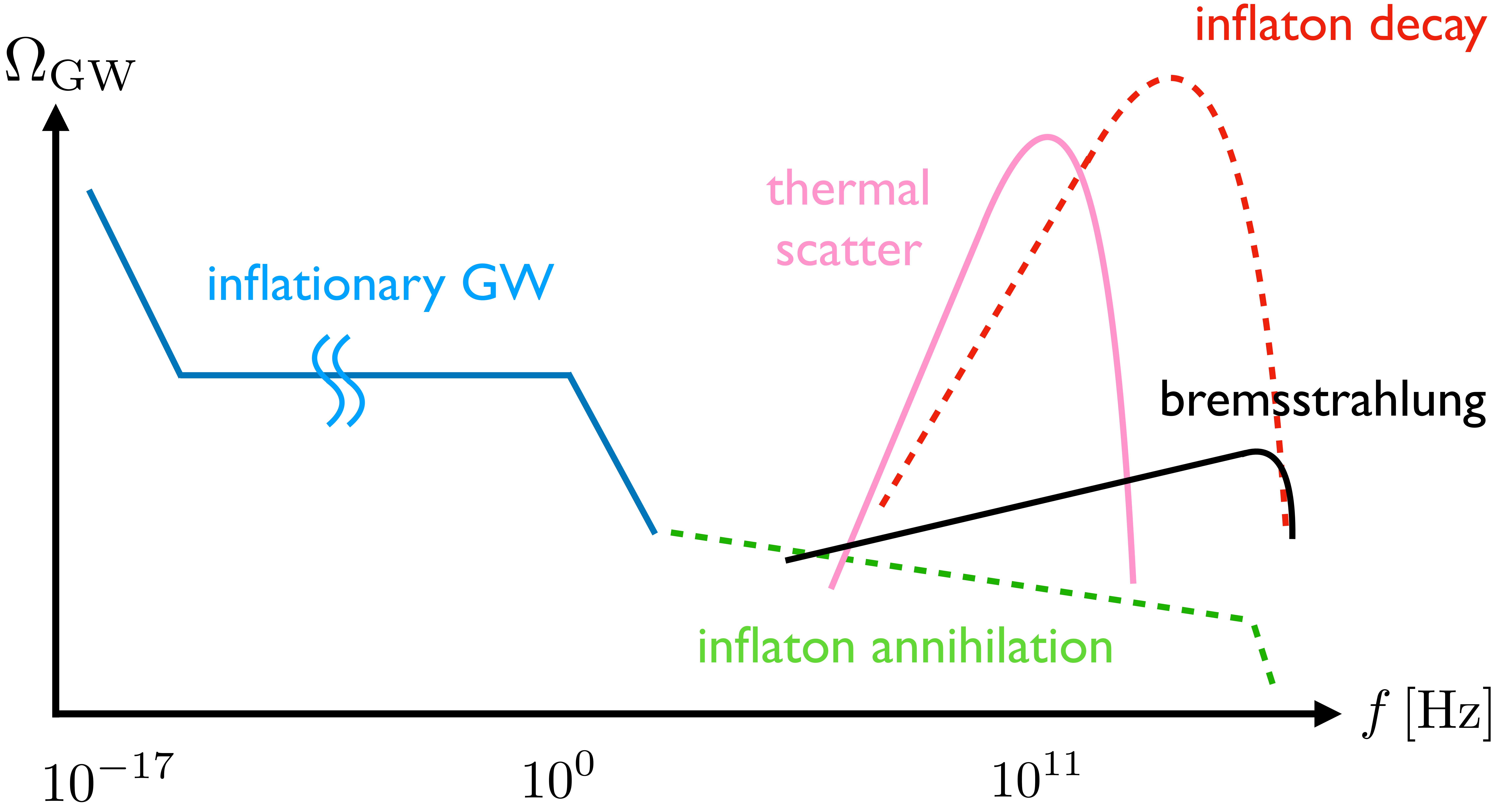

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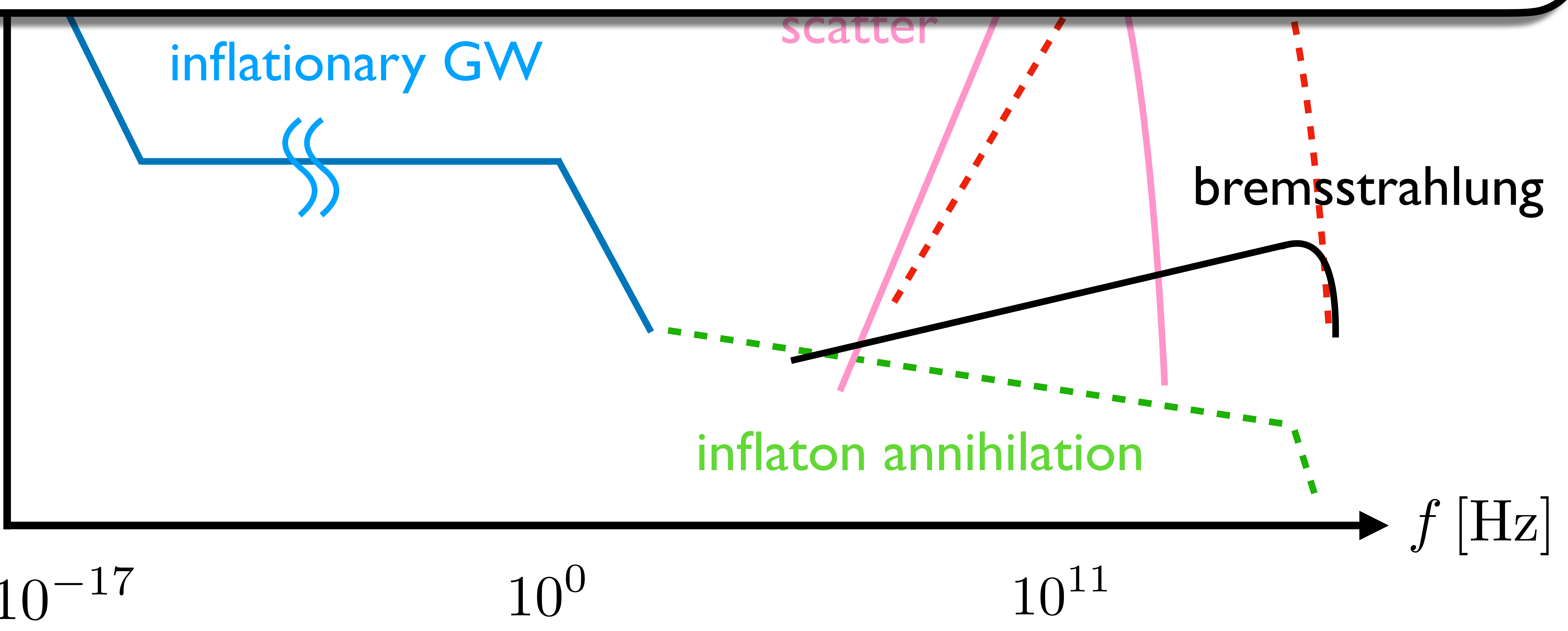
High frequency GW spectrum contain very rich information !!

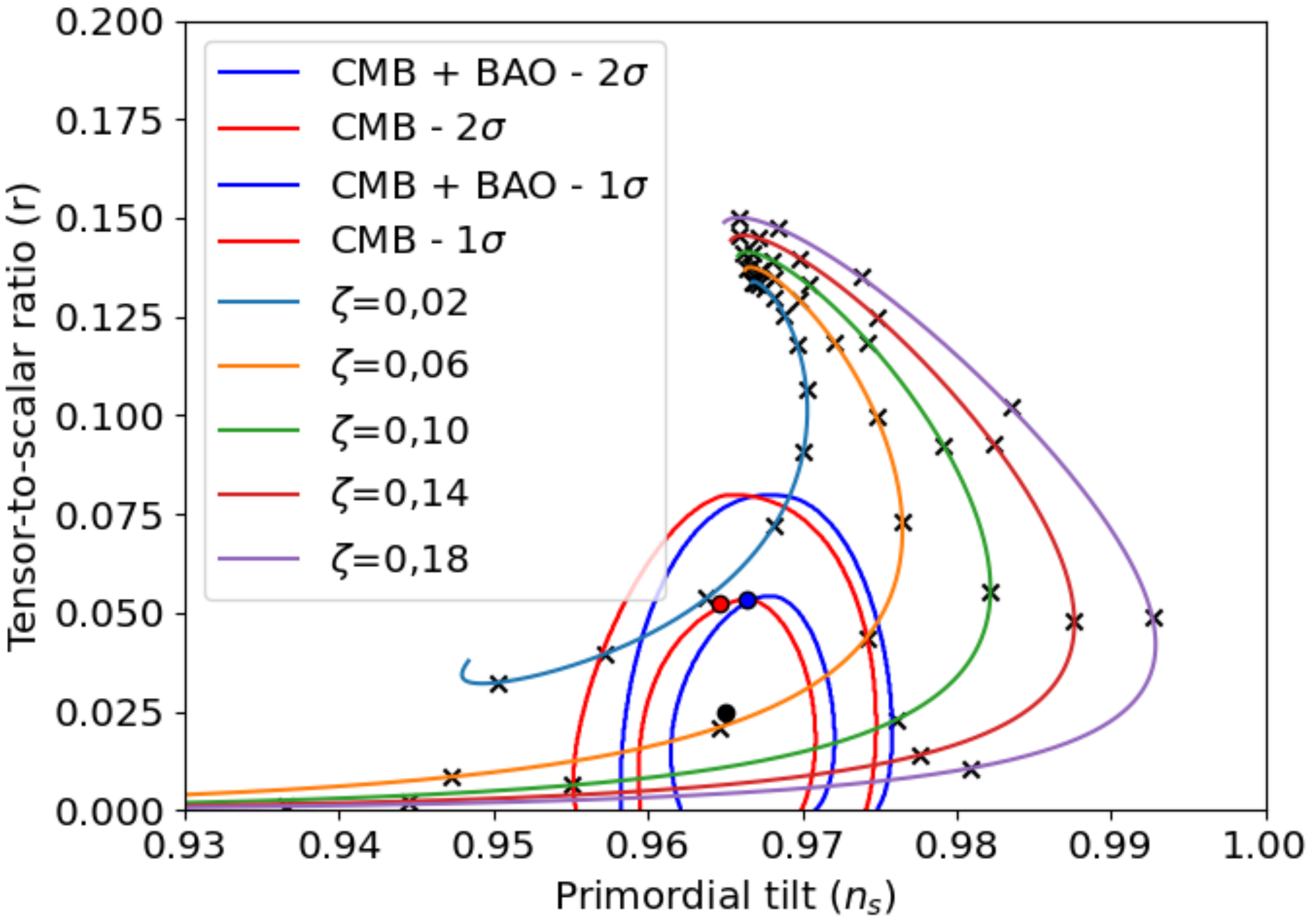


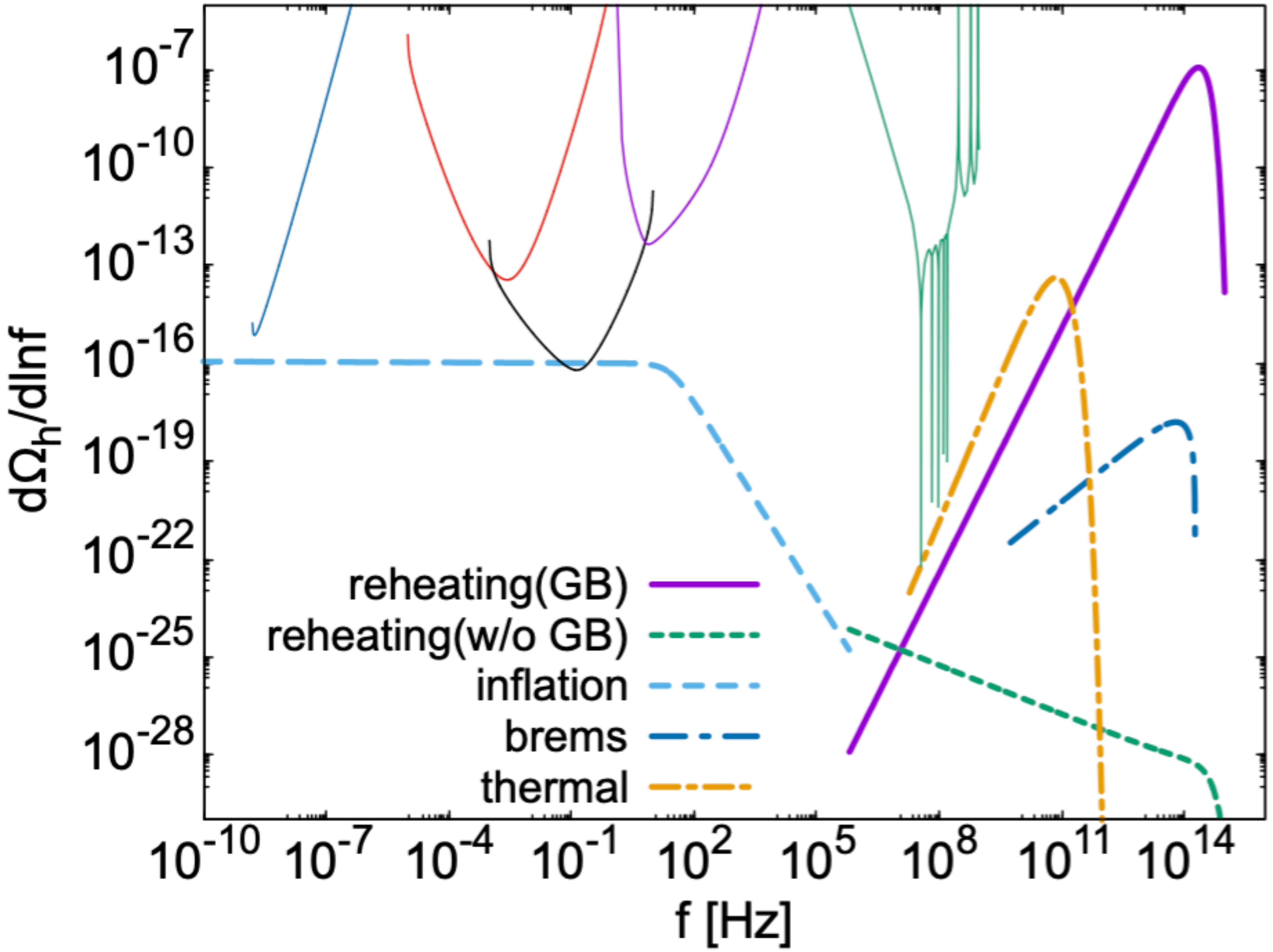
Ex) Inflation with Gauss-Bonnet correction

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

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

$$\xi(\phi)=8\xi_0e^{-\lambda\phi/M_{\rm pl}}$$





[Mudrunka, KN (2023)]

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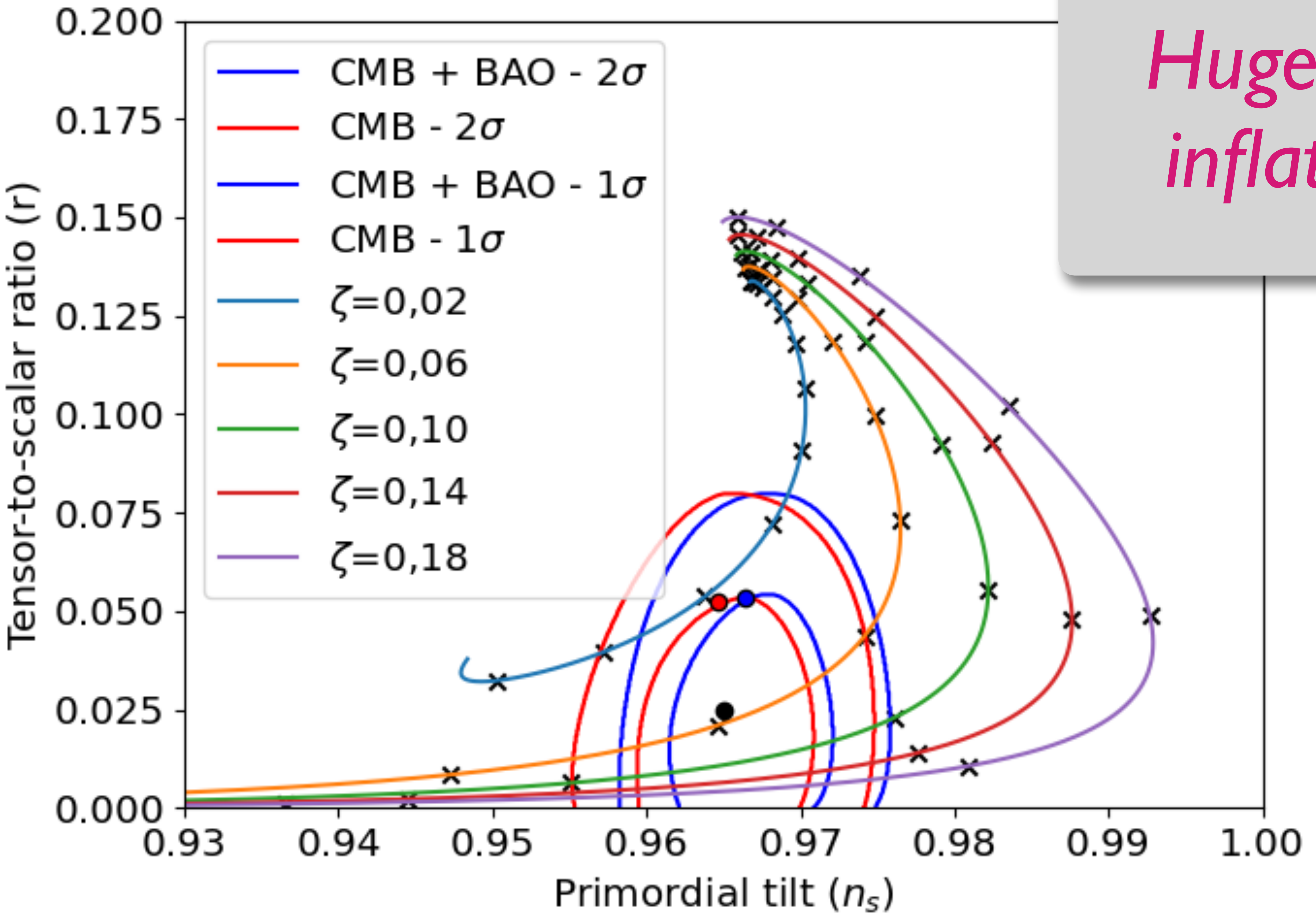
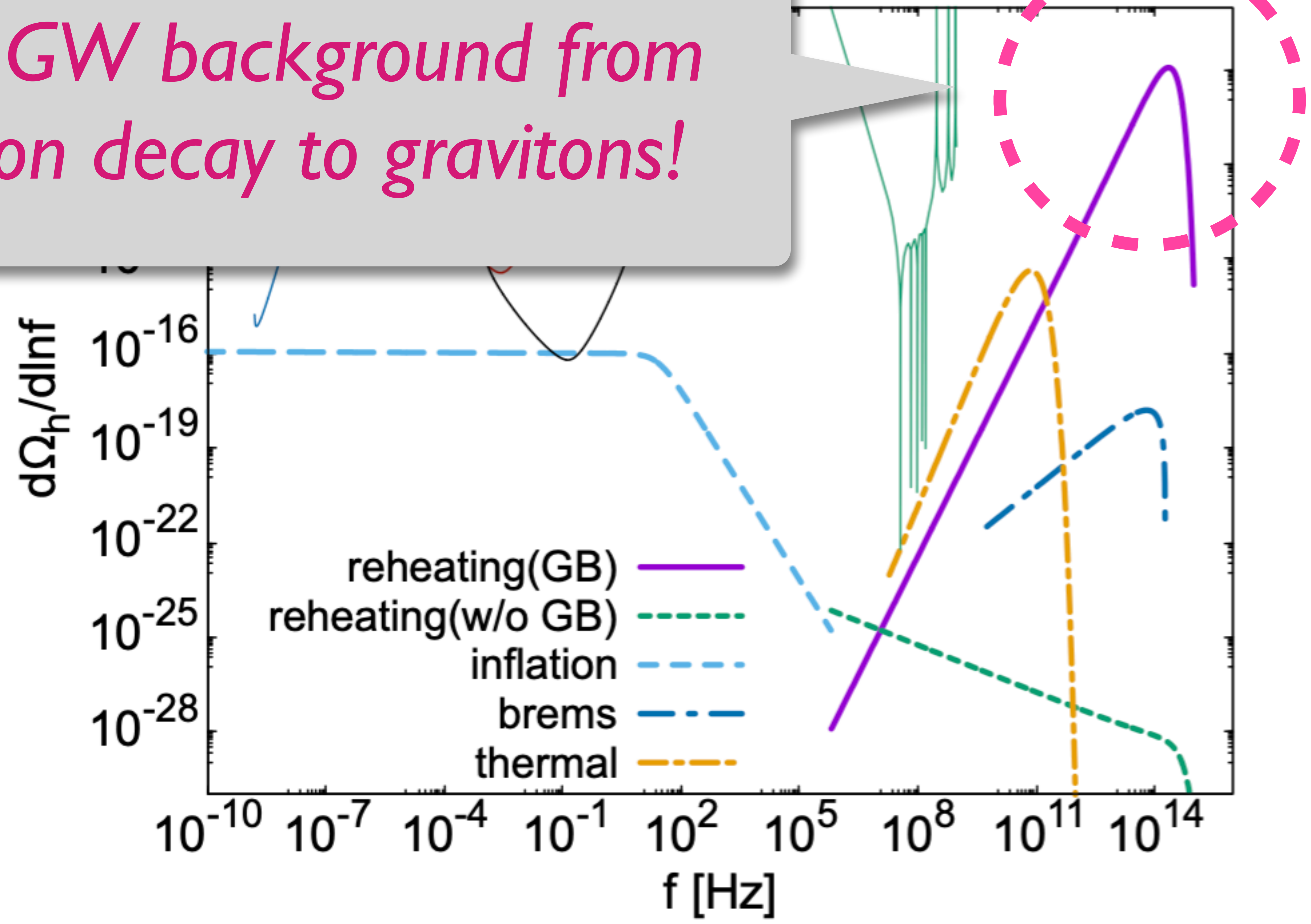




Huge GW background from inflaton decay to gravitons!

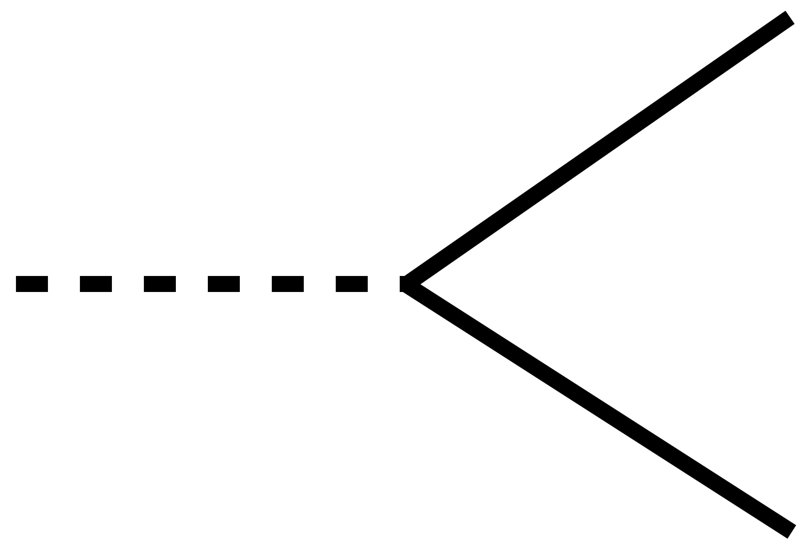
[Mudrunka, KN (2023)]

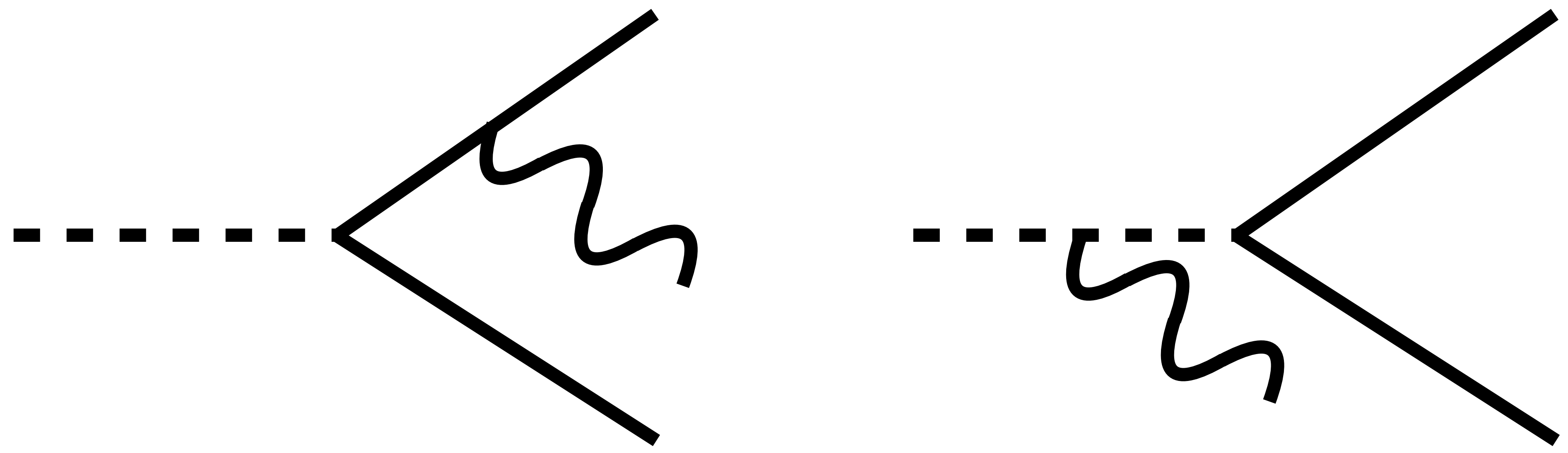
GW as a probe of reheating

- Bremsstrahlung GW is ubiquitous when inflaton decays

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

(See [Murayama, Noether, Schutte-Engel (2025)] for fermion decay)





$$\Gamma_{\phi\to\psi\bar{\psi}} = \frac{y^2 m_\phi}{8\pi}$$

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

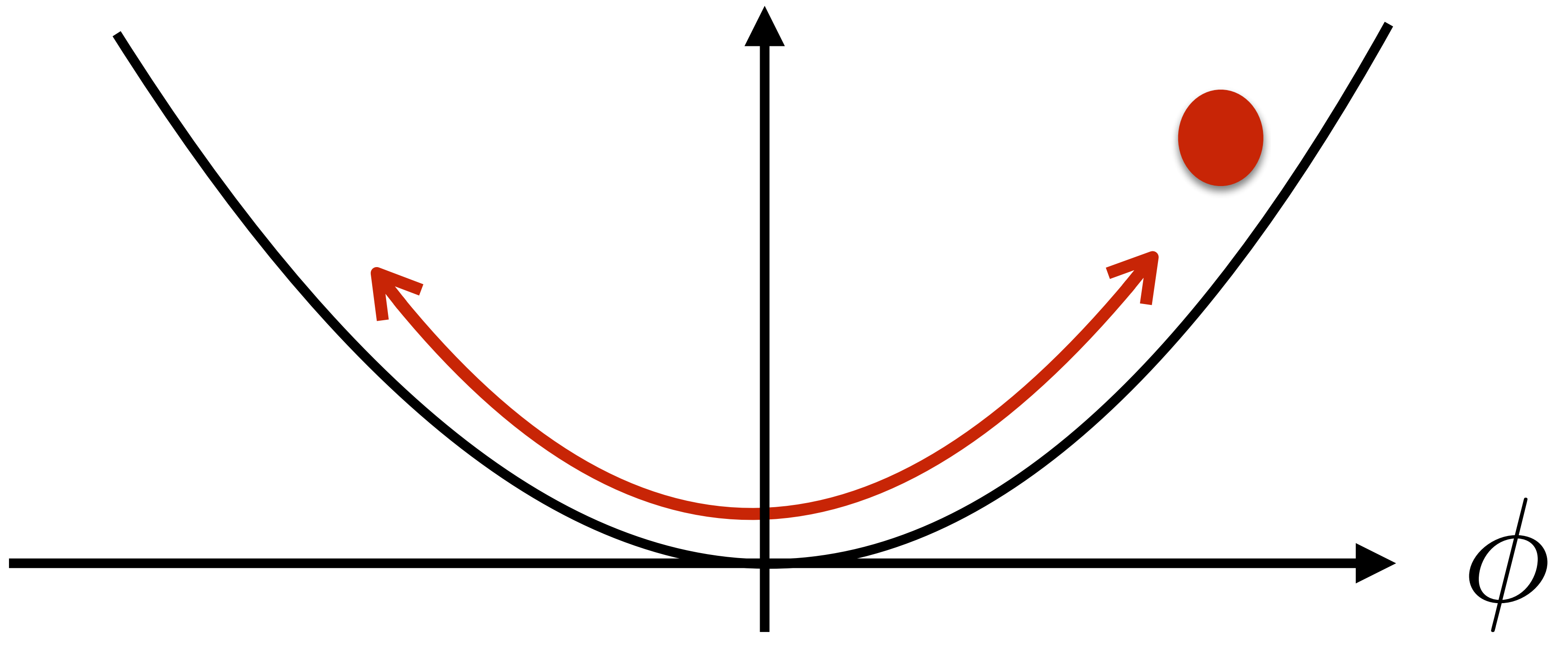
$$\boxed{\mathrm{Br}_{\phi\to\psi\bar{\psi}h} \simeq \frac{1}{8\pi^2}\frac{m_\phi^2}{M_P^2} \qquad \Omega_{\mathrm{GW}} \sim 10^{-5}\mathrm{Br}_{\phi\to\psi\bar{\psi}h}}$$

- Superheavy particles are produced by instant preheating

[Felder, Kofman, Linde (1998)]

- A simple model:

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



- Example:

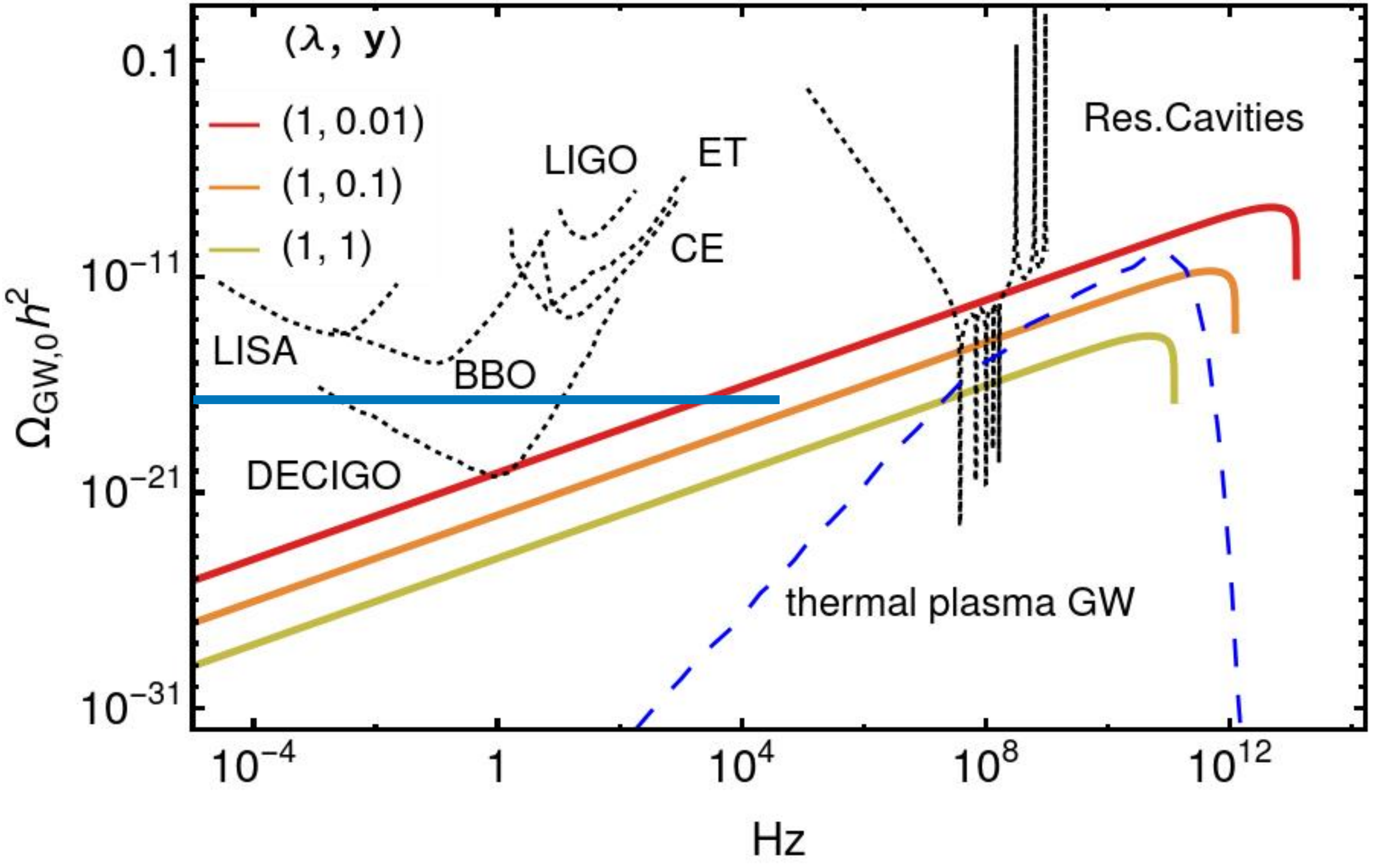
Higgs inflation [Bezrukov, Shaposhnikov (2007)]

Sneutrino inflation [Murayama, KN, Takahashi, Yanagida (2014)]

- Produced particles can be as heavy as Planck scale

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

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



High frequency GWs tell us what is inflaton!

A02 tasks

Try to reveal big mysteries: dark matter, dark energy, inflation

- New method for dark matter/energy detection

  $\longleftrightarrow$ Quantum techniques, atomic clocks, laser interferometer, …

- New method for high-frequency GW detection

- Theoretical background for them