Gravitational wave search through electromagnetic telescopes

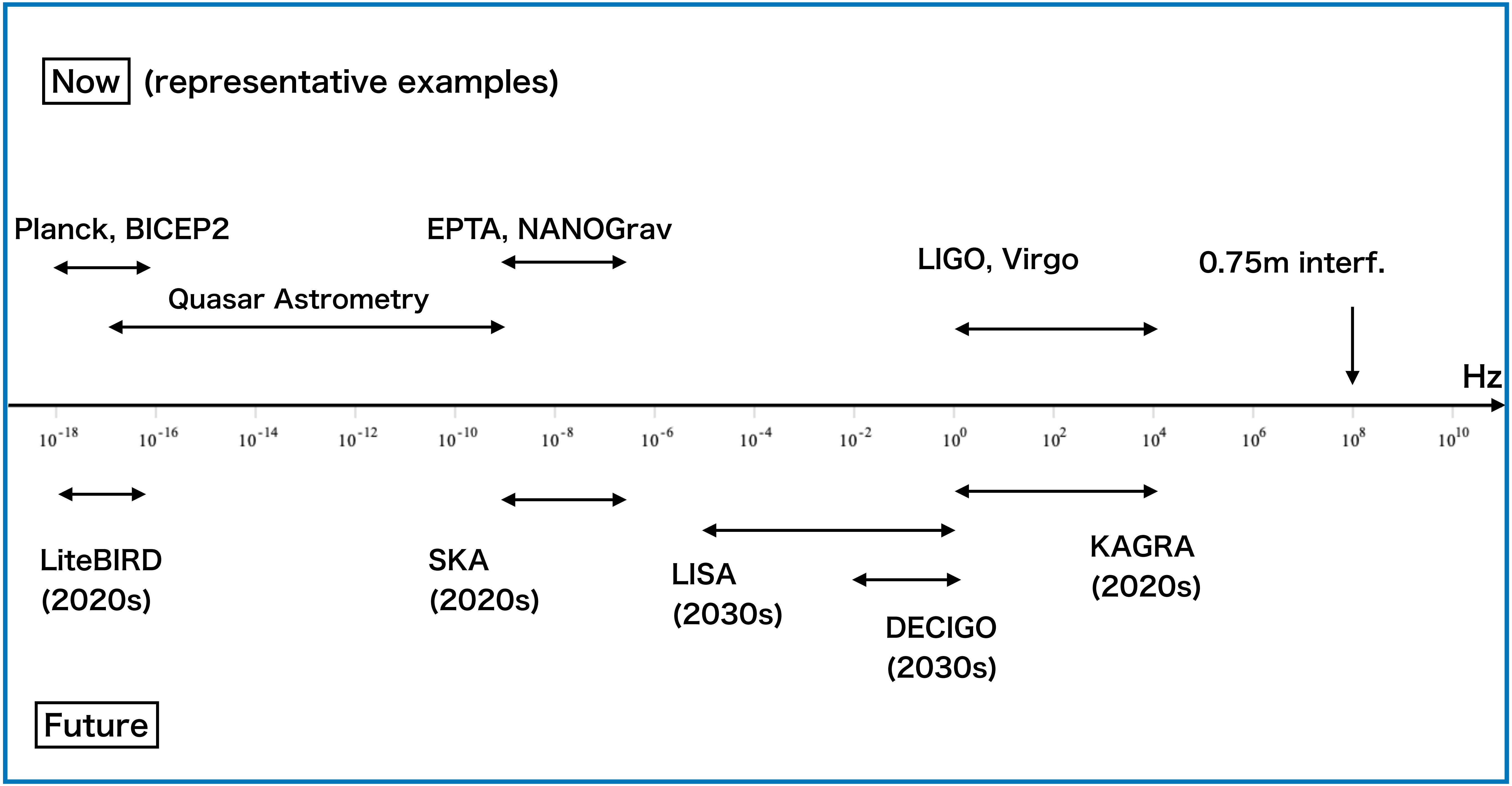
Asuka Ito

from QUP in KEK

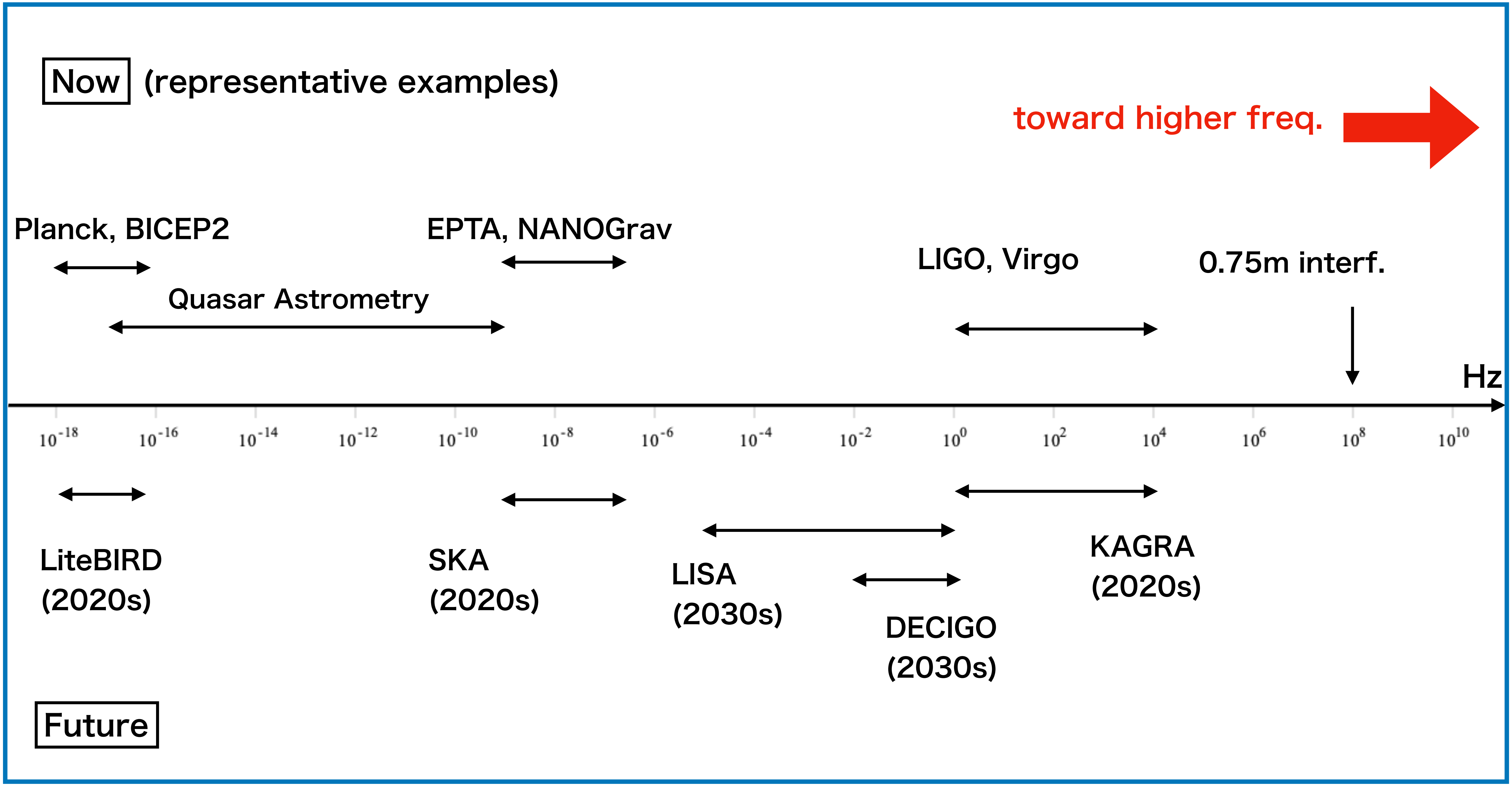
(International Center for Quantum-field Measurement Systems
for Studies of the Universe and Particles)

Refs: AI, K.Kohri, K.Nakayama, (arXiv: 2305.13984 [gr-qc]).
AI, K.Kohri, K.Nakayama, (arXiv: 2309.14765 [gr-qc]).

Multi-frequency GW observations



Multi-frequency GW observations



Multi-frequency GW observations have started.

In this talk, we consider GWs in very high frequency range beyond GHz.

Why?

High-frequency GWs

There are interesting sources of high frequency gravitational waves beyond GHz as below,

- Primordial gravitational waves from like inflation and reheating
  (A cut off or a peak may be around GHz)

- Gravitational waves from thermal scatterings
  [A. Ringwald, et al. (2021), P. Gubler, et al. (2022)]

- Light black hole binaries, $f \sim 10^3 \times \left(\frac{M_\odot}{m_1 + m_2} \right) \mathrm{Hz}$
  LBHs of $10^{14}\mathrm{g} \sim 10^{18}\mathrm{g}$ can be DM

- Superradiance from bosonic fields like axion

→ In order to probe the above high-frequency GW sources,
we utilize telescopes

GW detection with telescopes

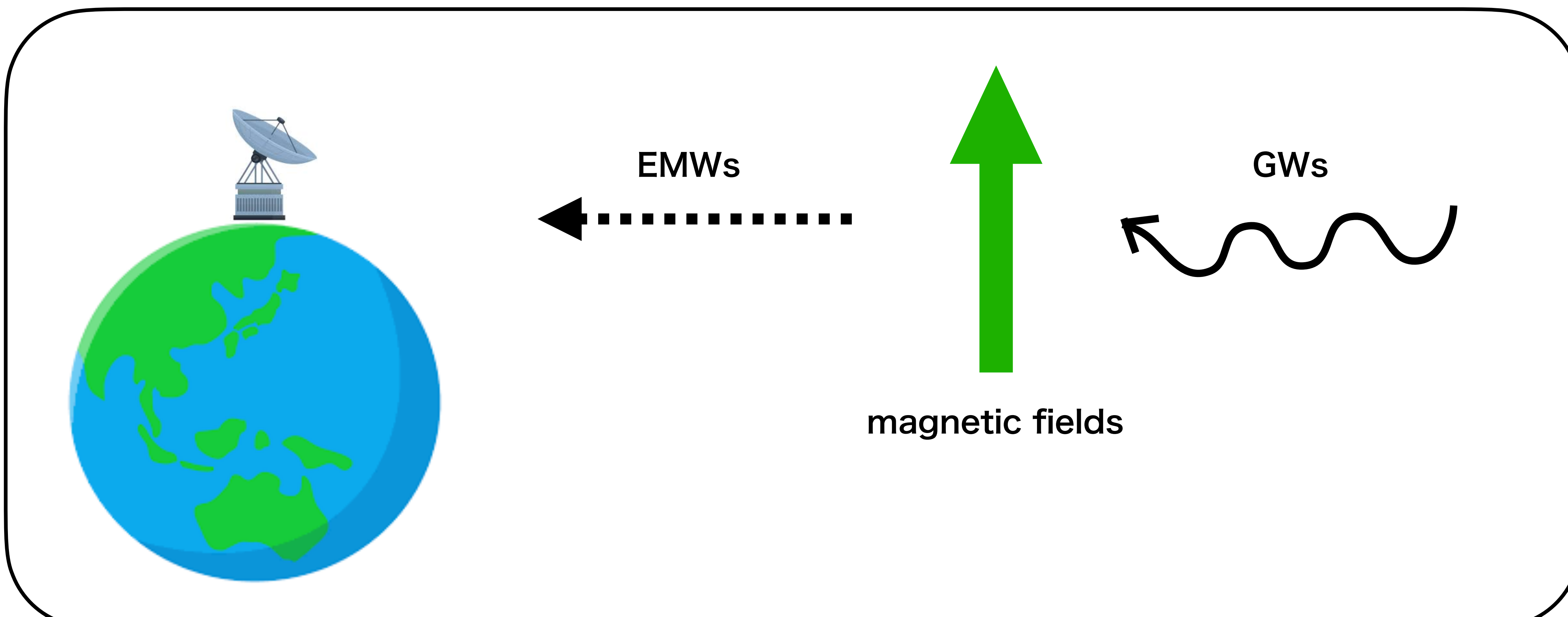
Graviton-photon conversion occurs within magnetic fields in the universe.

ex.) around the Earth, pulsars, in our galaxy, in intergalaxies

→ Converted photons can be detected with telescopes [M.S.Pshirkov, D.Baskaran, (2009).]

$10^8\mathrm{Hz} \sim 10^{35}\mathrm{Hz}$

→ We can potentially observe GWs in the range of $10^8\mathrm{Hz} \sim 10^{35}\mathrm{Hz}$



Graviton-photon conversion

Lagrangian: $$\mathcal{L} = \frac{M_{\rm pl}^2}{2} R - \frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

We consider a background magnetic field $\bar{B}^i = \epsilon^{ijk}\partial_j \bar{A}_k$, and GWs on Minkowski spacetime:

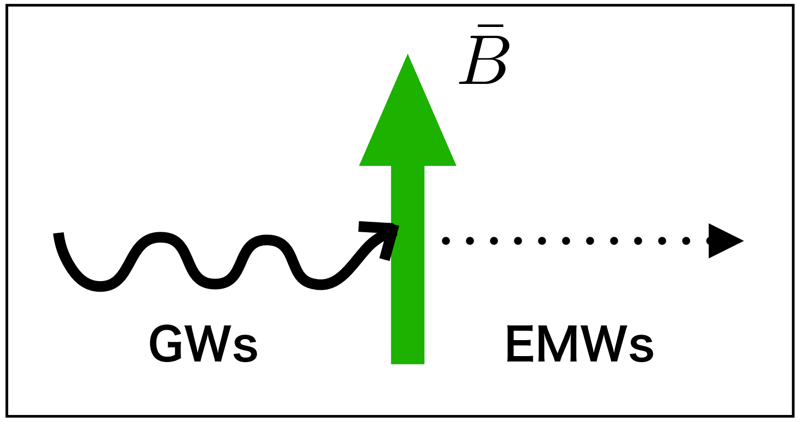
$$\begin{cases} \mathcal{A}_\mu(x) = \bar{A}_\mu + A_\mu(x), \\ g_{\mu\nu}(x) = \eta_{\mu\nu} + \dfrac{2}{M_{\rm pl}} h_{\mu\nu}(x). \end{cases}$$

The Lagrangian is reduced to

$$\mathcal{L} \to -\frac{1}{2}\left(\partial_\mu h_{ij}\right)^2 - \frac{1}{2}\left(\partial_\mu A_i\right)^2 + \underline{\frac{2}{M_{\rm pl}} \epsilon_{ijk} \bar{B}^k h^{jl} \partial_i A^l}$$

graviton-photon mixing

In the presence of a magnetic field, gravitons (photons) can convert into photons (gravitons)



Graviton-photon conversion

$$\mathcal{L} \to -\frac{1}{2}(\partial_\mu h_{ij})^2 - \frac{1}{2}(\partial_\mu A_i)^2 + \frac{2}{M_{\rm pl}}\epsilon_{ijk}\bar{B}^k h^{jl}\partial_i A^l$$

the strength of mixing is $\sim \frac{\bar{B}}{M_{\rm pl}}$

→ conversion would be effective when $\bar{B}$ is large

	Earth	our galaxy	inter galaxies	pulsars
$\bar{B}$	$\sim 1\mathrm{G}$	$\sim 1\mu\mathrm{G}$	$\sim 10^{-17} - 10^{-10}\mathrm{G}$	$\sim 10^{12}\mathrm{G}$

effective conversion is expected?

We need to take into account of ① plasma effects on graviton-photon conversion.
Moreover, ② the Euler-Heisenberg term (higher order terms in QED) must be considered.

① Plasma effect

The EOM of a charged particle in a background magnetic fields is

$$m_{(i)} \frac{\partial \boldsymbol{v}_{(i)}}{\partial t} = e_{(i)} \left(\boldsymbol{E} + \boldsymbol{v}_{(i)} \times \bar{\boldsymbol{B}} \right),$$

(i : electron or proton)

Then, the current of plasma is defined by $\boldsymbol{j} = e n_{(i)} \boldsymbol{v}_{(i)}$.

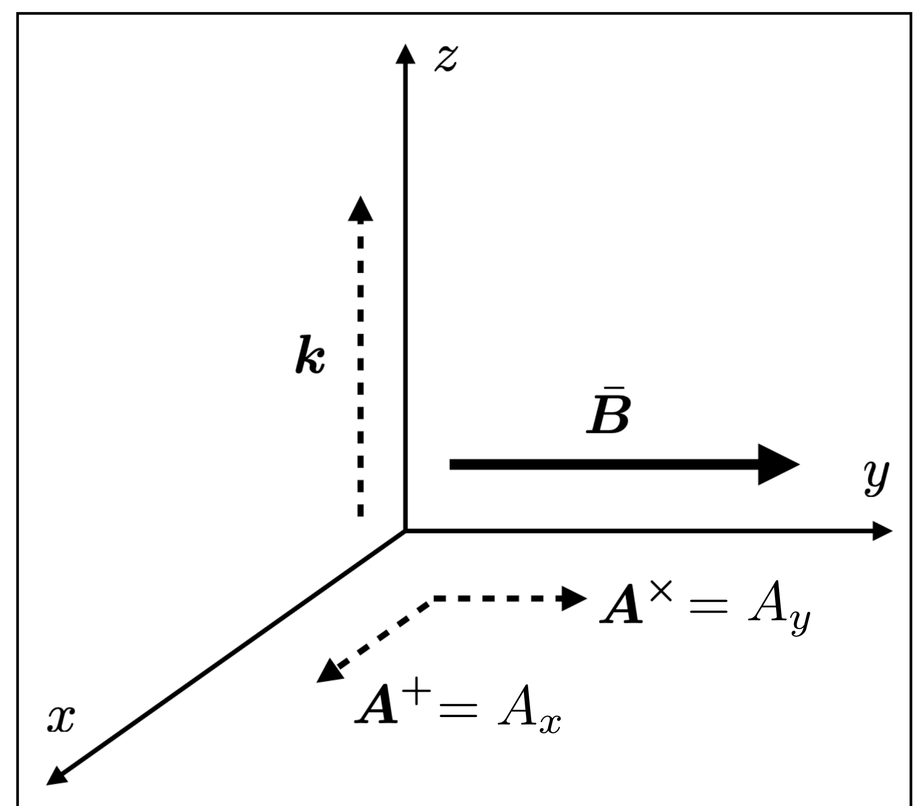
Thus, in the presence of plasma, the Maxwell eq. is

$$\begin{cases} \mathrm{rot}\boldsymbol{E} = -\dfrac{\partial \boldsymbol{B}}{\partial t}, \\ \mathrm{rot}\boldsymbol{B} = \boldsymbol{j} + \dfrac{\partial \boldsymbol{E}}{\partial t}. \end{cases}$$

Using the equations, one can obtain the dispersion relation of photons:

$$\begin{pmatrix} \omega^2 - \dfrac{\omega^2 \omega_{p,(i)}^2}{\omega^2 - \omega_{c,(i)}^2} - k^2 & 0 \\ 0 & \omega^2 - \omega_{p,(i)}^2 - k^2 \end{pmatrix} \begin{pmatrix} A_x \\ A_y \end{pmatrix} = 0.$$

$$\left(\begin{array}{ll} \omega_{p,(i)} = \sqrt{\dfrac{4\pi\alpha n_{(i)}}{m_{(i)}}} & \text{: plasma frequency} \\ \omega_{c,(i)} = \dfrac{e\bar{B}}{m_{(i)}} & \text{: cyclotron frequency} \end{array} \right)$$

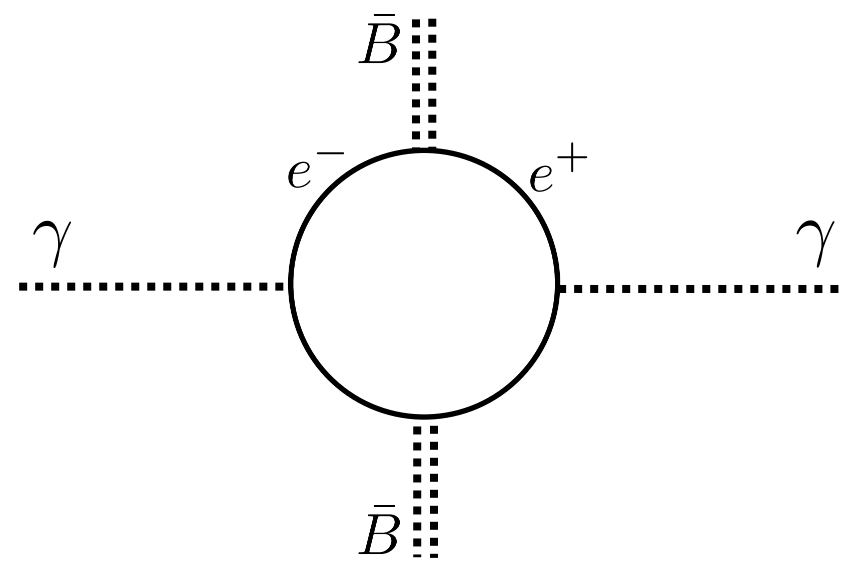


② Euler-Heisenberg term

$$S = \int d^4x \sqrt{-g}\left[\frac{M_{\rm pl}^2}{2}R - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{\alpha^2}{90 m_e^4}\left((F_{\mu\nu}F^{\mu\nu})^2 + \frac{7}{4}(F_{\mu\nu}\tilde{F}^{\mu\nu})^2\right)\right]$$

Euler-Heisenberg term

On a background magnetic field,
an effective mass of photon appears



$$\begin{pmatrix} \omega^2 + \frac{16\alpha^2 \bar{B}^2 \omega^2}{45 m_e^4} - k^2 & 0 \\ 0 & \omega^2 + \frac{28\alpha^2 \bar{B}^2 \omega^2}{45 m_e^4} - k^2 \end{pmatrix} \begin{pmatrix} A_x \\ A_y \end{pmatrix} = 0.$$

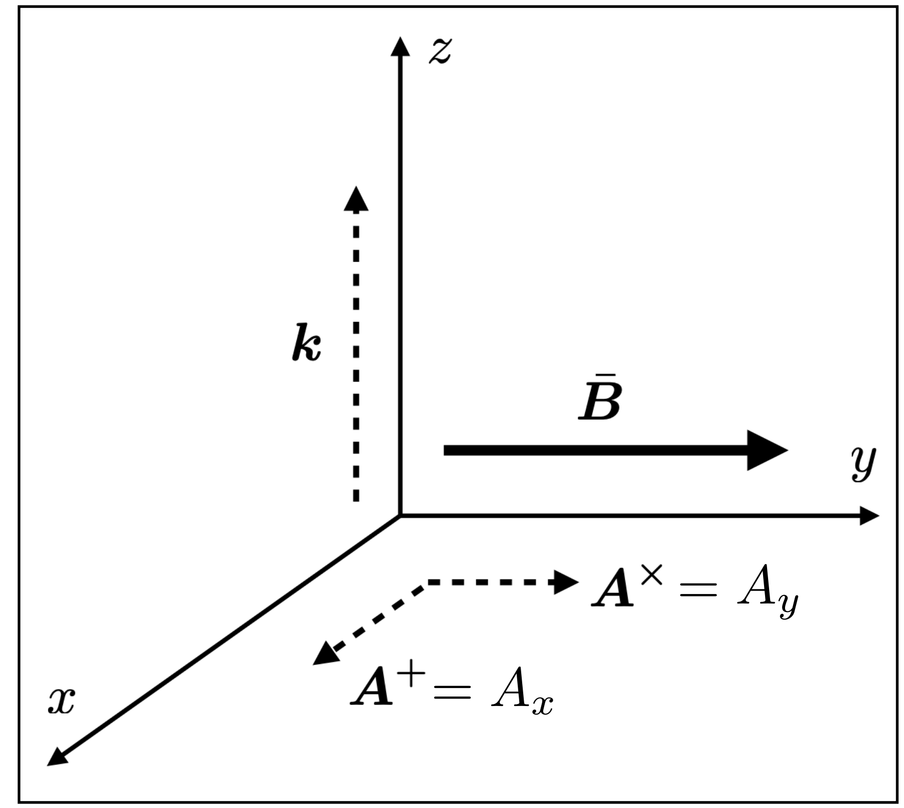
Graviton-photon conversion

Photons obtain effective masses due to plasma (and magnetic fields) and the Euler-Heisenberg term.
On the other hand, graviton is massless. They mix as

$$\left[i\partial_z + \begin{pmatrix} -\frac{1}{2\omega}\frac{\omega^2\omega_{p,(i)}^2}{\omega^2-\omega_{c,(i)}^2} + \frac{1}{2\omega}\frac{16\alpha^2\bar{B}^2\omega^2}{45m_e^4} & i\frac{B}{\sqrt{2}M_{\rm pl}} \\ -i\frac{B}{\sqrt{2}M_{\rm pl}} & 0 \end{pmatrix} \right] \begin{pmatrix} A^+(z) \\ h^+(z) \end{pmatrix} \simeq 0,$$

$$\left[i\partial_z + \begin{pmatrix} -\frac{\omega_{p,(i)}^2}{2\omega} + \frac{1}{2\omega}\frac{28\alpha^2\bar{B}^2\omega^2}{45m_e^4} & i\frac{B}{\sqrt{2}M_{\rm pl}} \\ -i\frac{B}{\sqrt{2}M_{\rm pl}} & 0 \end{pmatrix} \right] \begin{pmatrix} A^\times(z) \\ h^\times(z) \end{pmatrix} \simeq 0.$$

where $\begin{cases} A_i = e^{-i(\omega t - kz)} A^\sigma(z) e_i^\sigma \\ h_{ij} = e^{-i(\omega t - kz)} h^\sigma(z) \epsilon_{ij}^\sigma \end{cases}$

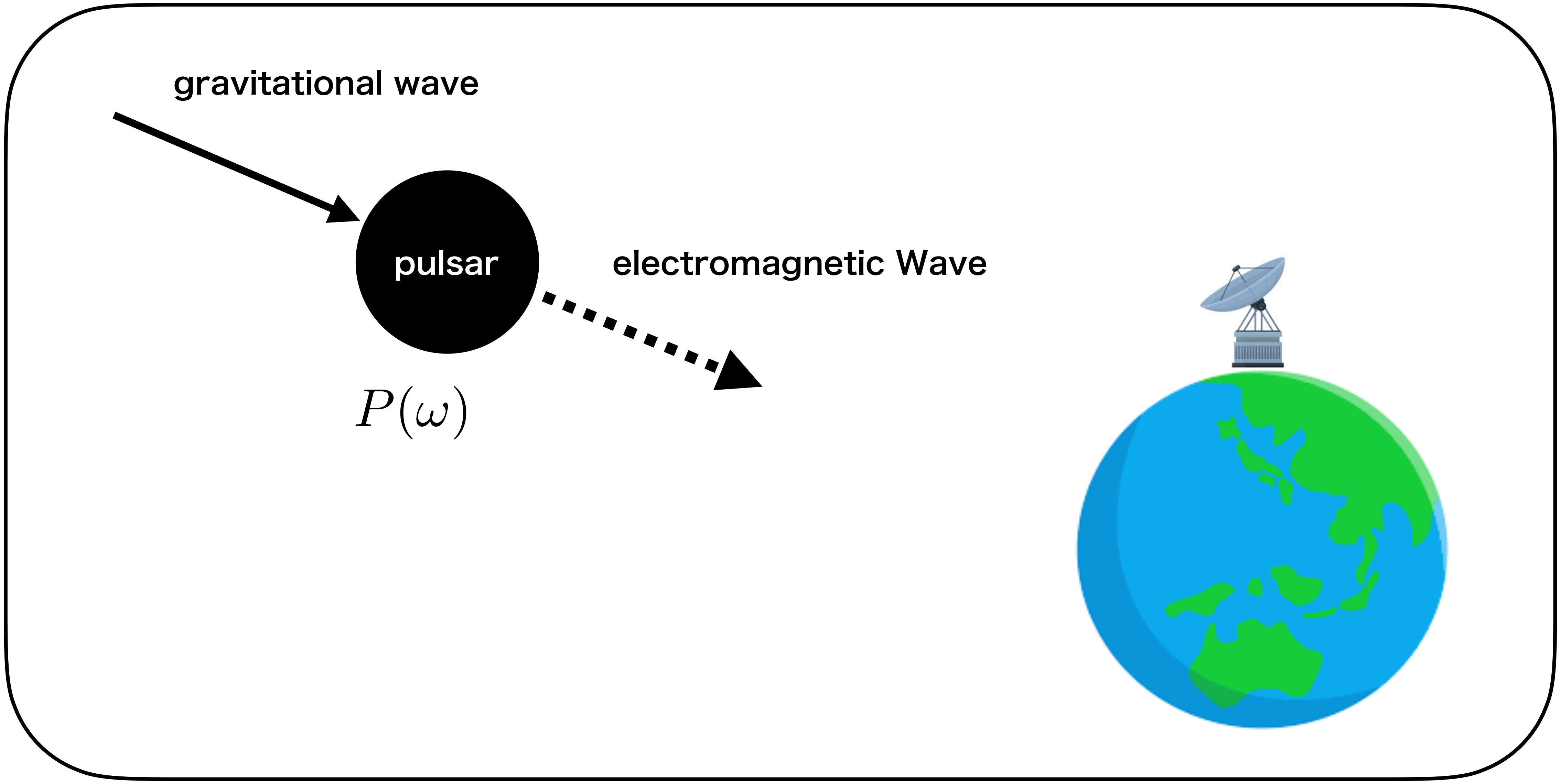


	Earth	our galaxy	inter galaxies	pulsars
$\bar{B}$	$\sim 1\mathrm{G}$	$\sim 1\mu\mathrm{G}$	$\sim 10^{-17} - 10^{-10}\mathrm{G}$	$\sim 10^{12}\mathrm{G}$

effective conversion is expected?

Let us first consider the graviton-photon conversion within magnetosphere of pulsars.

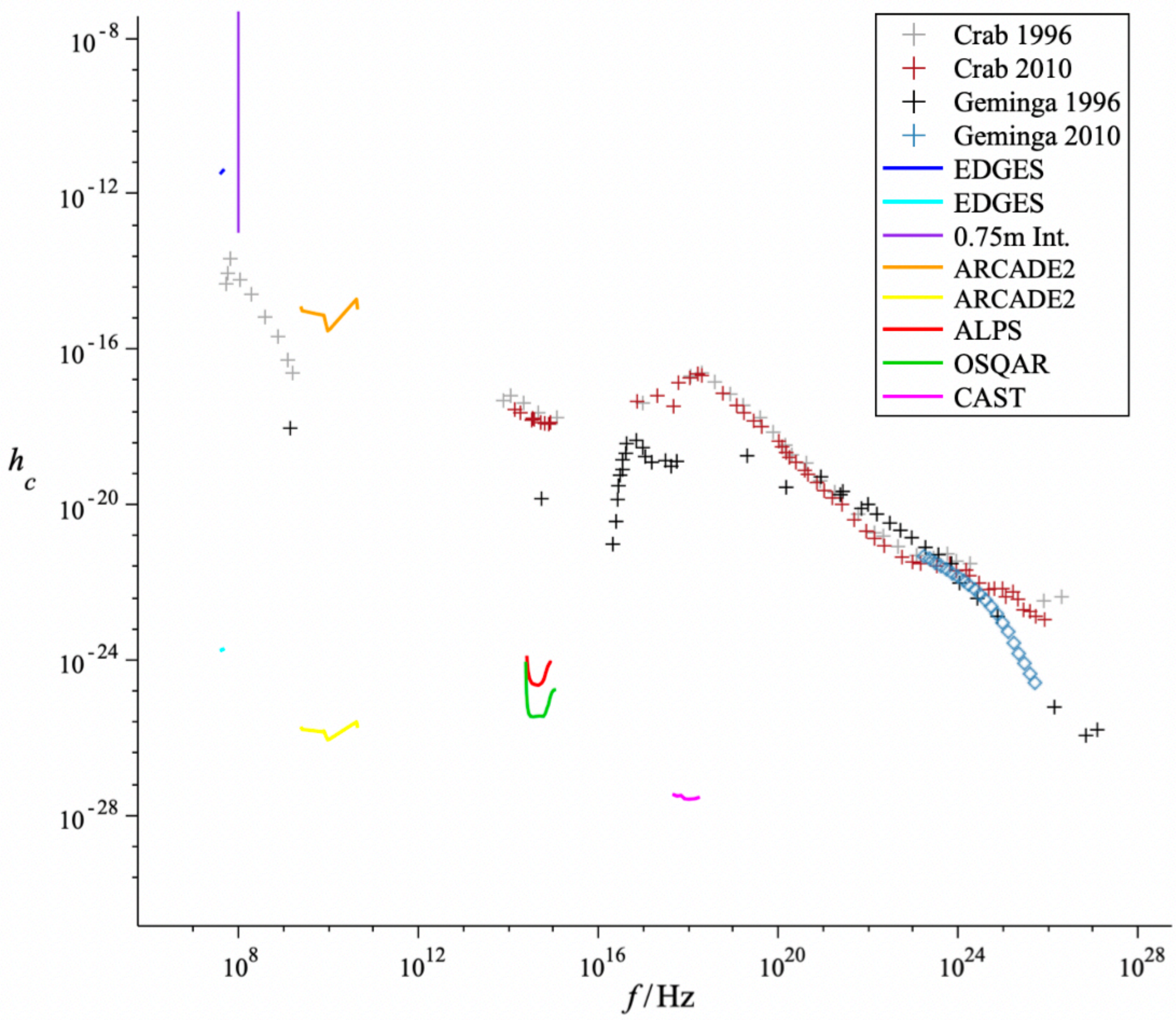
Graviton-photon conversion around a pulsar



1. We numerically calculated the conversion probability $P(\omega)$ around the Crab and the Geminga pulsars.
2. We calculated photon flux converted from stochastic GWs by using $P(\omega)$.
3. Requiring that the photon flux does not exceed the observations of the Crab and the Geminga pulsars with telescopes, we derived upper limits on stochastic GWs.

[AI, K.Kohri, K.Nakayama, arXiv: 2309.02992.]

Limits on stochastic GWs



Detecting HFGWs with telescopes

We found that pulsars are not so useful to search for high frequency gravitational waves, because

- The size of magnetosphere is not so large (~ 1000km)
- Since the distance from a pulsar to the Earth is far ($\sim 1\mathrm{kpc} \sim 10^{14}\mathrm{m}$), the photon flux decreases
- The effective photon mass from the Euler Heisenberg term prevents the graviton-photon conversion

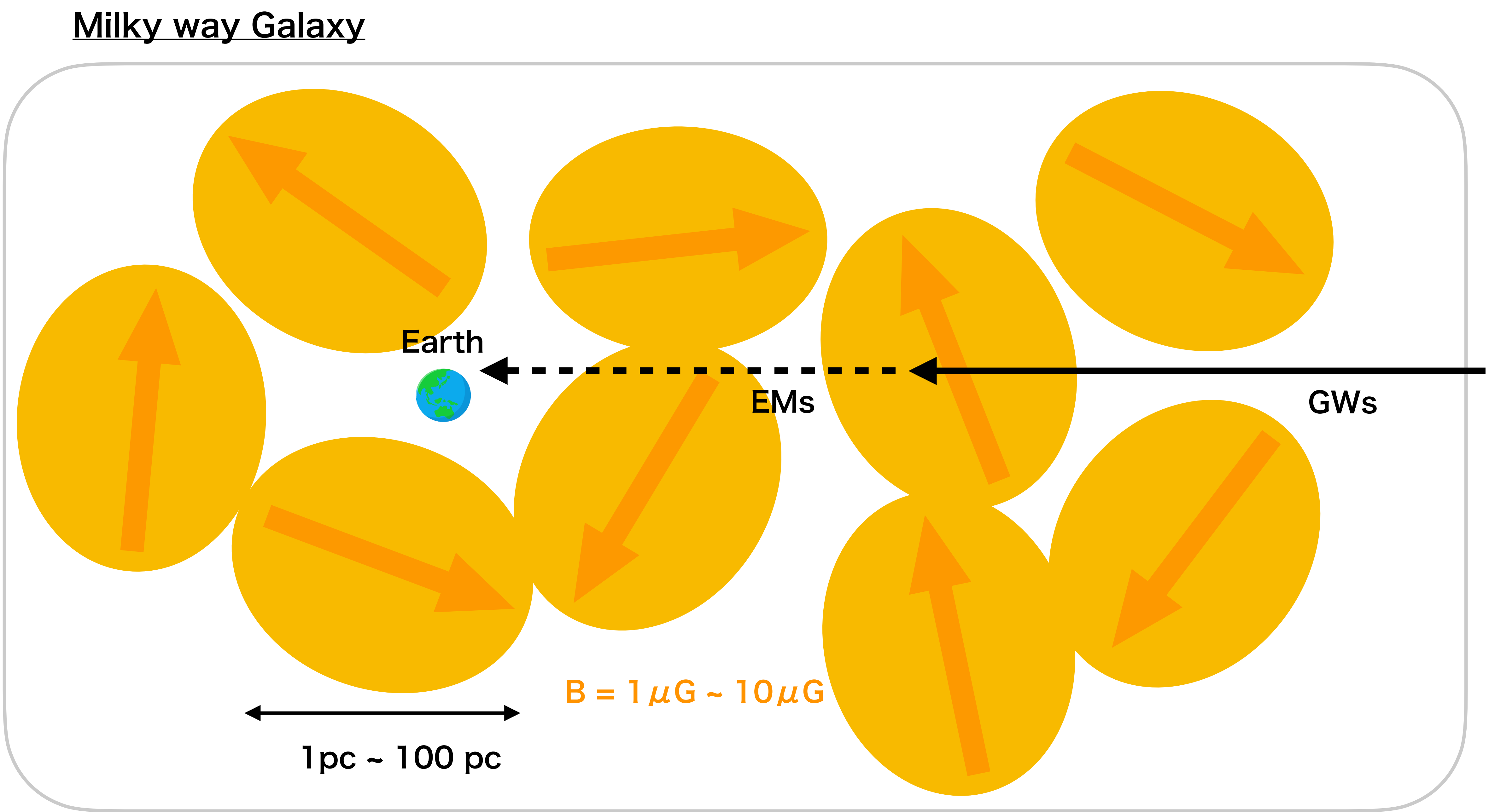
  $\propto \bar{B}^2$

	Earth	our galaxy	inter galaxies	pulsars
$\bar{B}$	$\sim 1\mathrm{G}$	$\sim 1\mu\mathrm{G}$	$\sim 10^{-17} - 10^{-10}\mathrm{G}$	$\sim 10^{12}\mathrm{G}$
size of magnetic field	$\sim 10^{4}\mathrm{km}$	$\sim 10\mathrm{kpc}$	$\lesssim 4000\mathrm{Mpc}$	$\sim 10^{3}\mathrm{km}$
distance	0	~ 0	~ 0	$\sim 1\mathrm{kpc}$

Let us consider the graviton-photon conversion in magnetic fields of the Earth, the Milky Way Galaxy, and intergalactic regions to search for high frequency gravitational waves.

A.Ito, K.Kohri, K.Nakayama, (arXiv: 2309.14765 [gr-qc]).

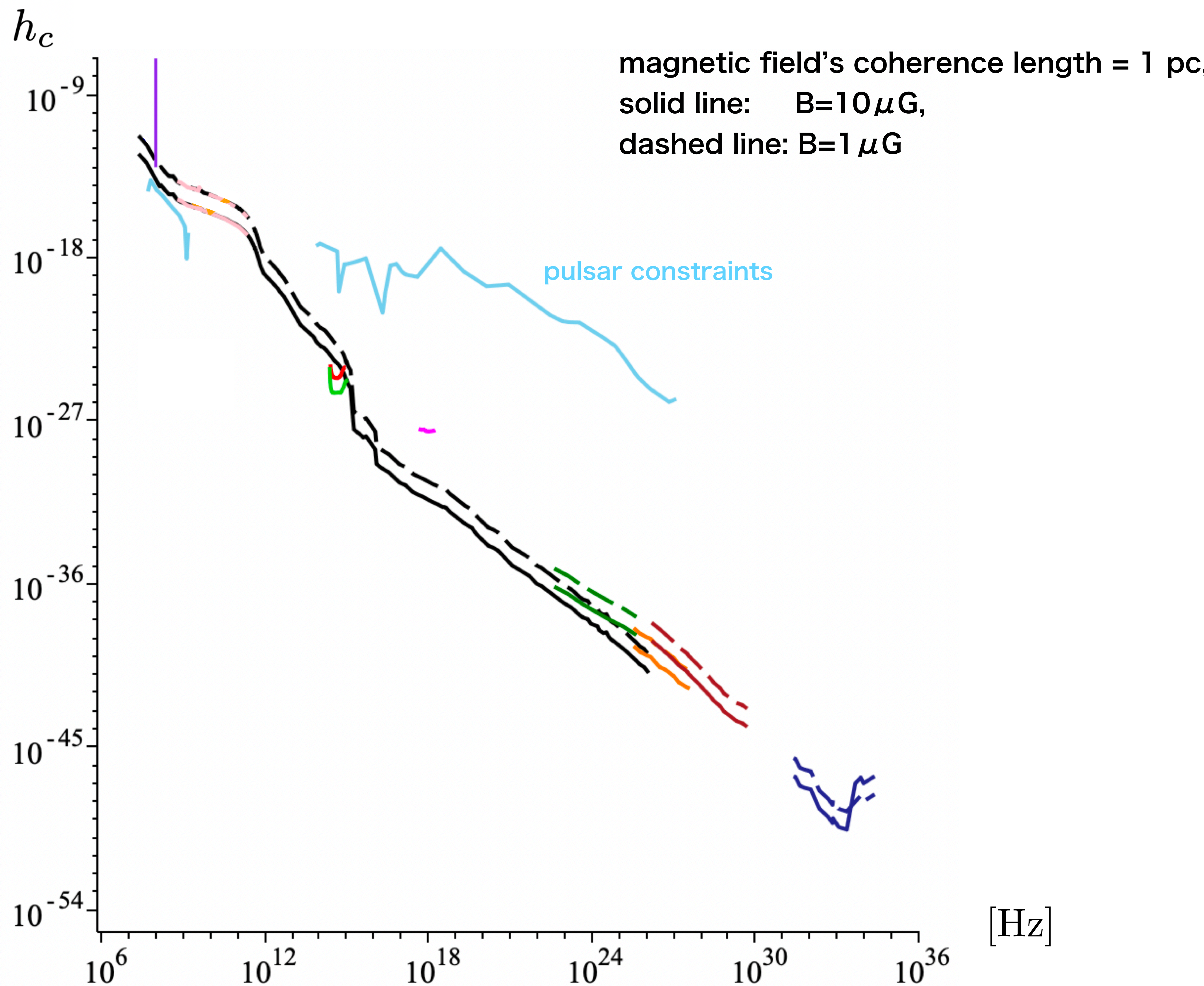
Distribution of magnetic fields in the Milky way



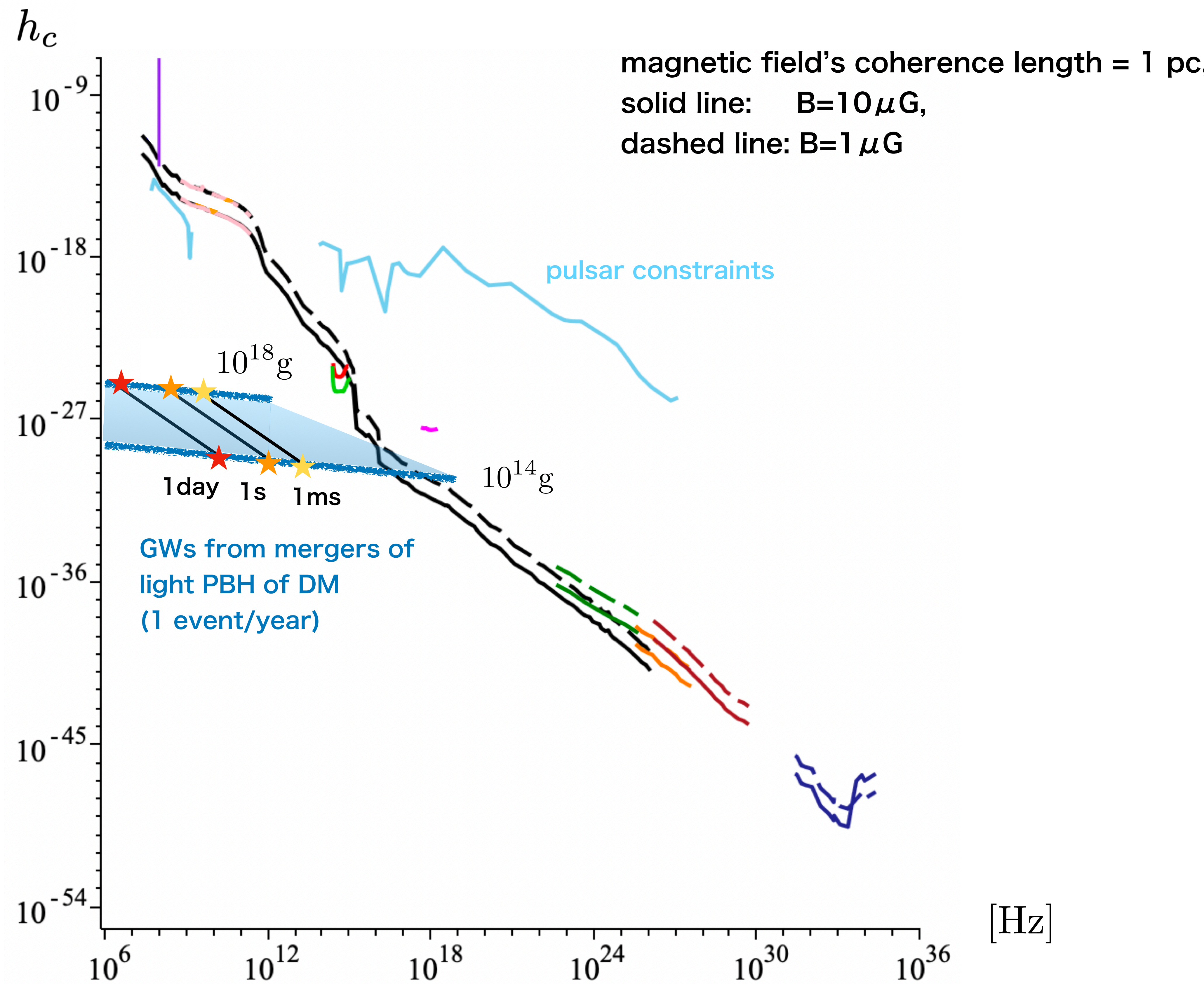
It has been observed that there are many small scale random magnetic fields.
The magnitude is about 1 μG ~ 10 μG and the coherent length is 1pc ~ 100 pc.

We calculated the conversion probability in the Milky way Galaxy and imposed constraints on stochastic GWs. AI, K.Kohri, K.Nakayama, arXiv: 2309.14765.

Constraints on GWs using the Milky way's magnetic fields



Constraints on GWs using the Milky way's magnetic fields



Conclusion

- High frequency gravitational waves are interesting to probe new physics

  ex.) Light primordial black holes as DM

- We explored the possibility to search for high frequency GWs with telescopes

- We studied the graviton-photon conversion within the magnetic fields of pulsars, the Earth, our galaxy, and intergalactic region.

  → We gave upper limits on stochastic gravitational waves with various telescope observations in frequency range of $10^8\mathrm{Hz} \sim 10^{35}\mathrm{Hz}$.

  [AI, K.Kohri, K.Nakayama, arXiv: 2309.02992.]
  [AI, K.Kohri, K.Nakayama, arXiv: 2309.14765.]

The GW search with telescopes would open up a new avenue for high frequency GW observations. However, more ideas/efforts are needed to search for realistic sources like light PBHs as DM.