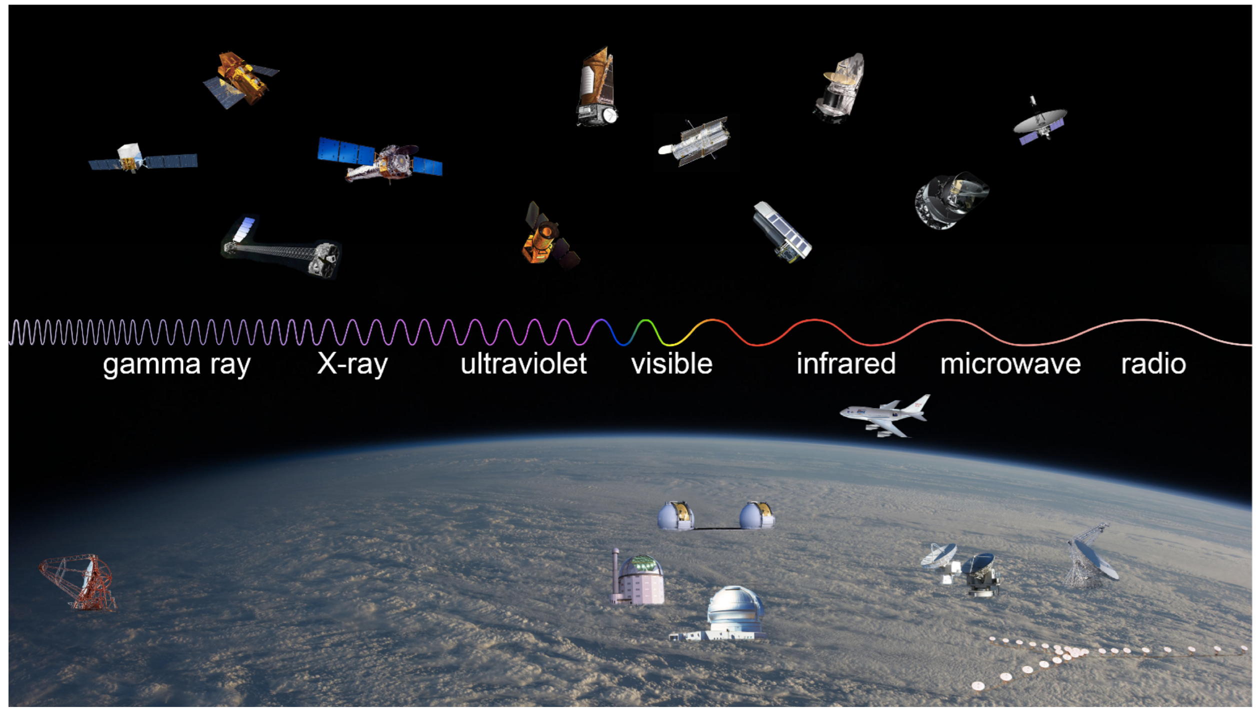
Workshop on Multi-front Exotic phenomena in Particle and Astrophysics (MEPA 2023), Hefei

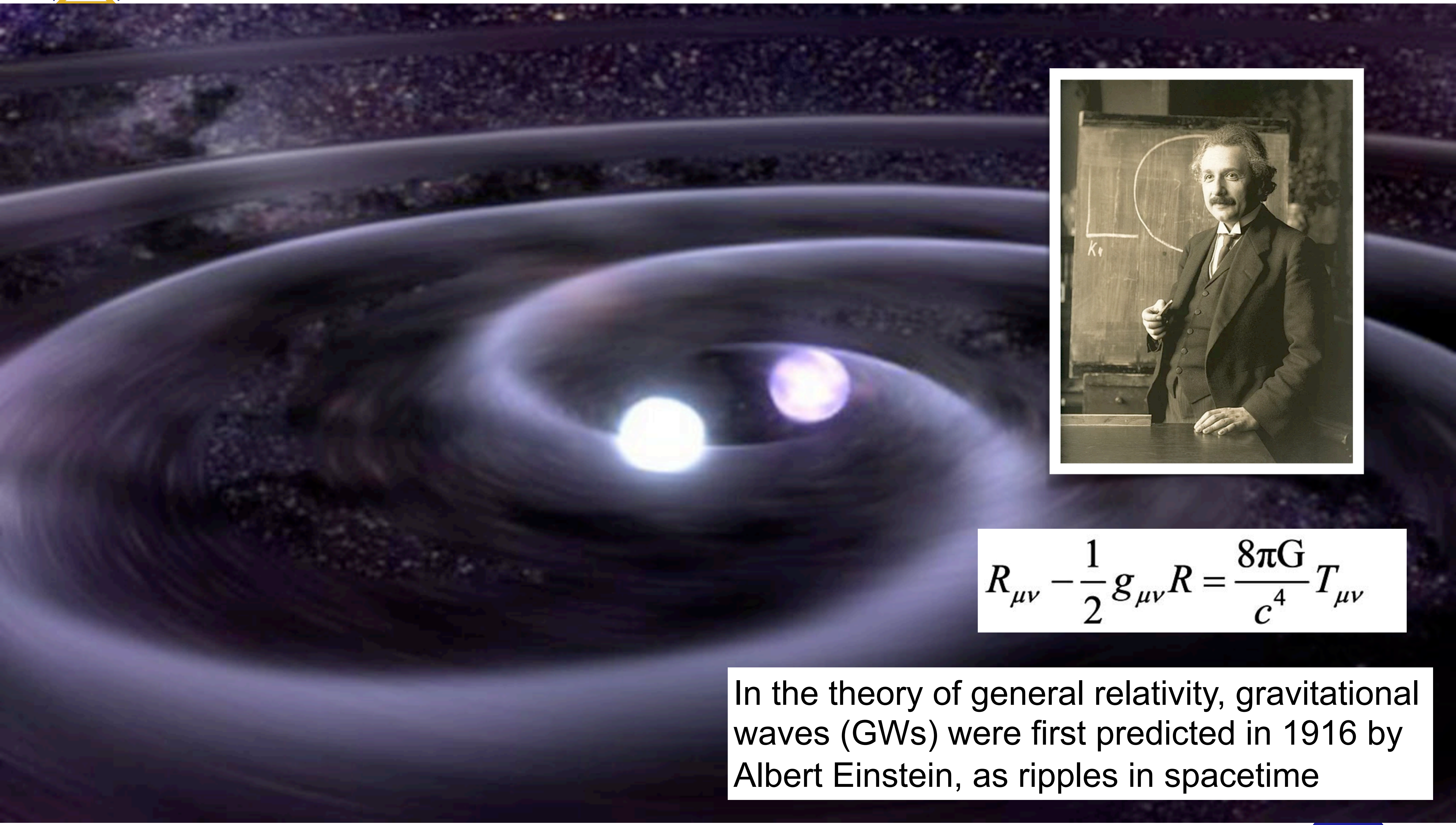


Detecting High-Frequency GWs in Planetary Magnetosphere

Tao Liu (HKUST)

ArXiv: 2305.01832, with Jing Ren and Chen Zhang

Gravitational Waves

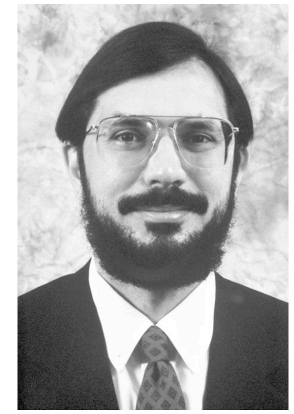


$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{8\pi G}{c^4} T_{\mu\nu}$$

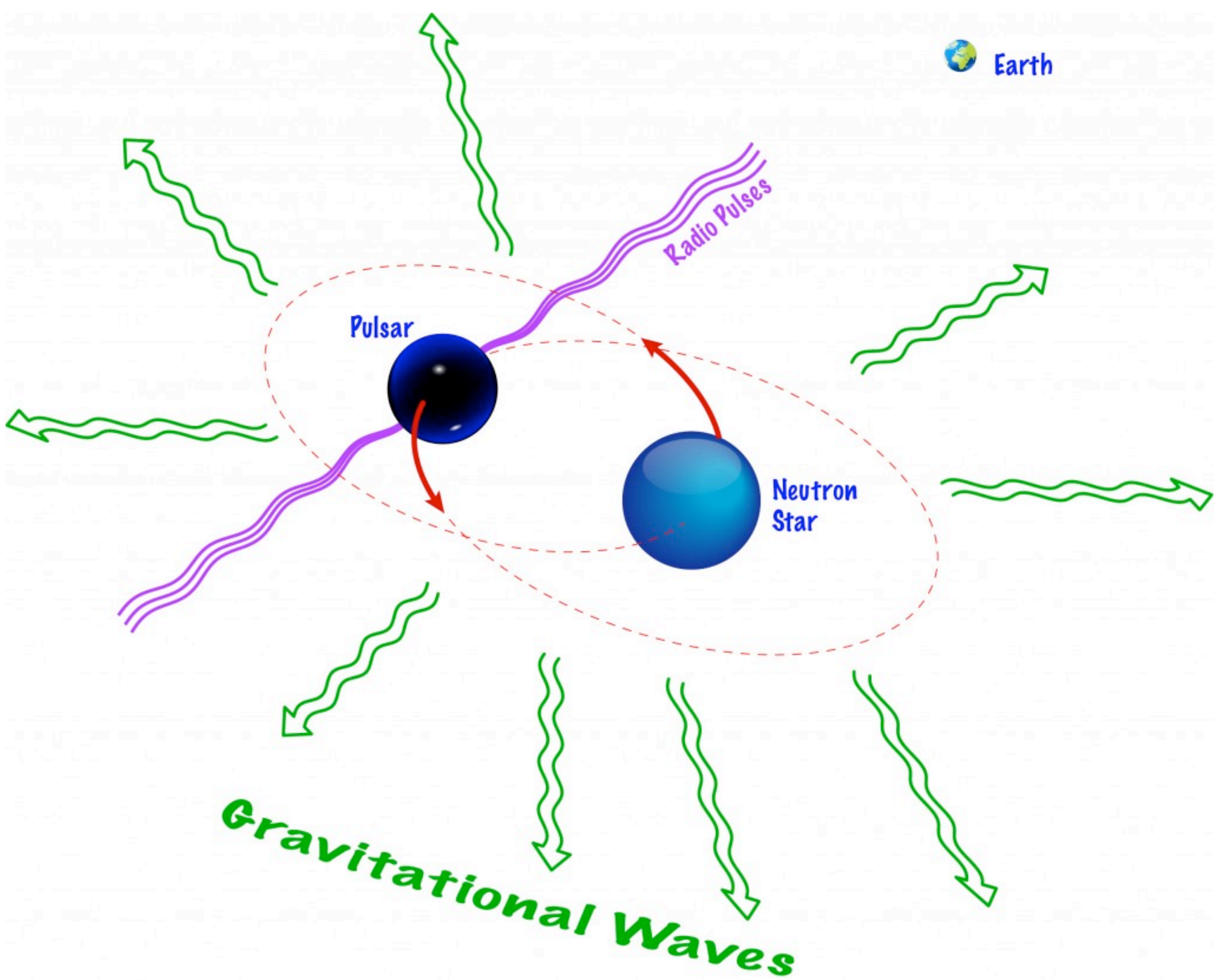
In the theory of general relativity, gravitational waves (GWs) were first predicted in 1916 by Albert Einstein, as ripples in spacetime

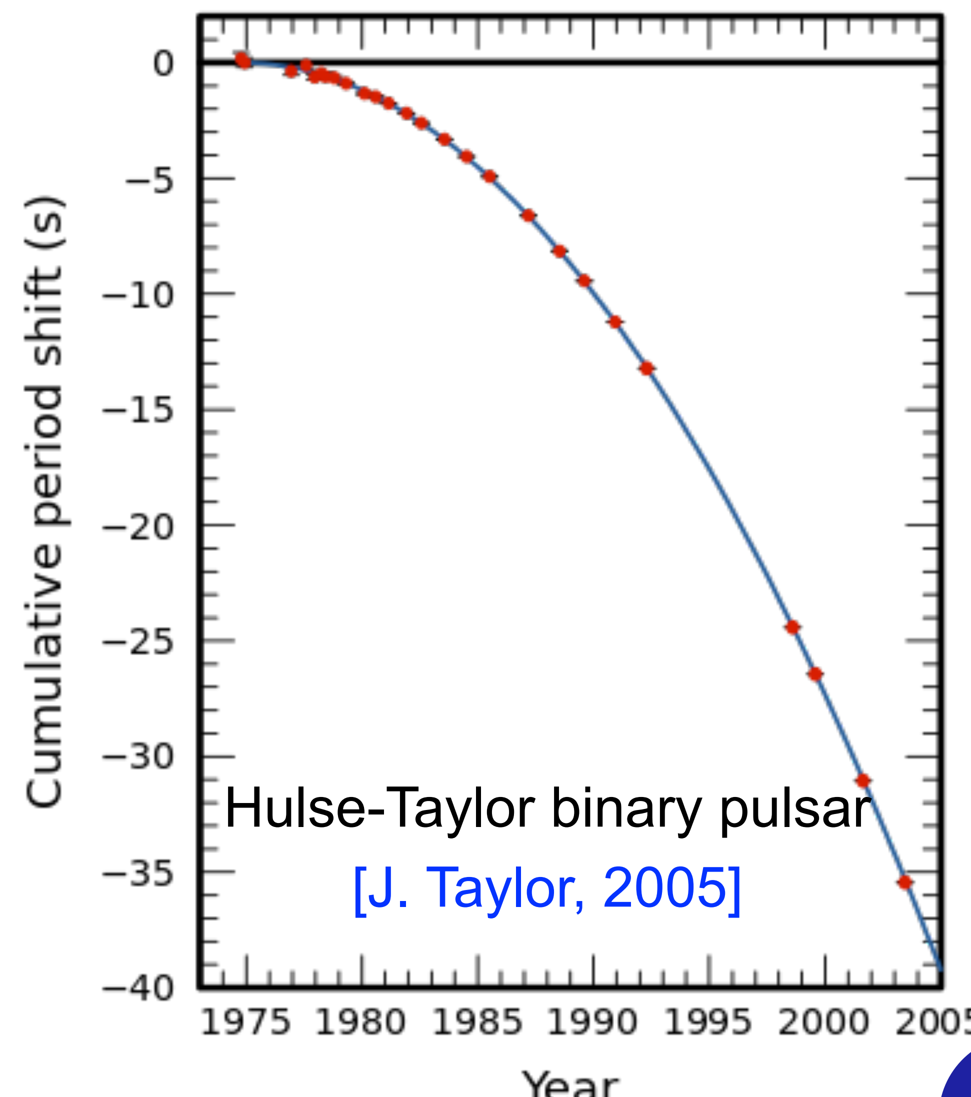
First Indirect Evidence (1974)

Hulse-Taylor binary pulsar (PSR B1913+16) and its orbital decay

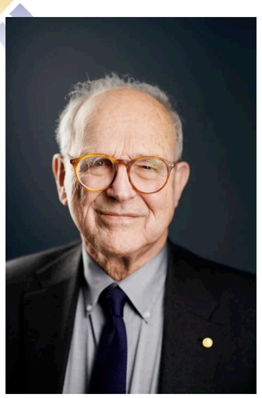


(Physics, 1993)

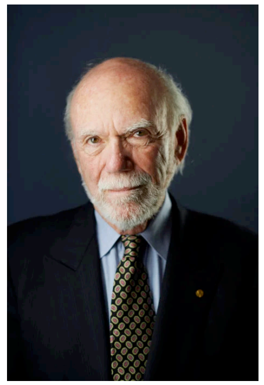




First Direct Evidence (2015)



Weiss



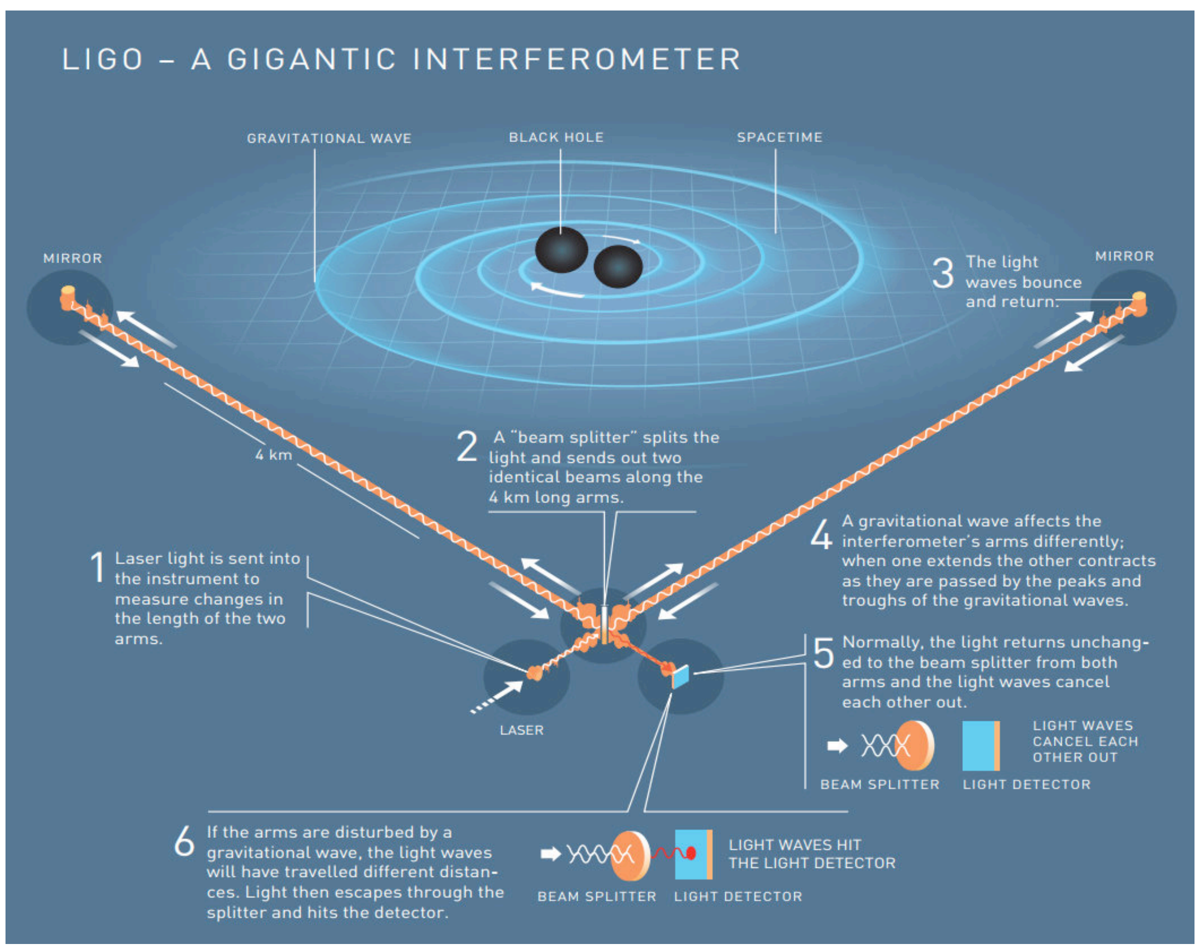
Barish

Thorne

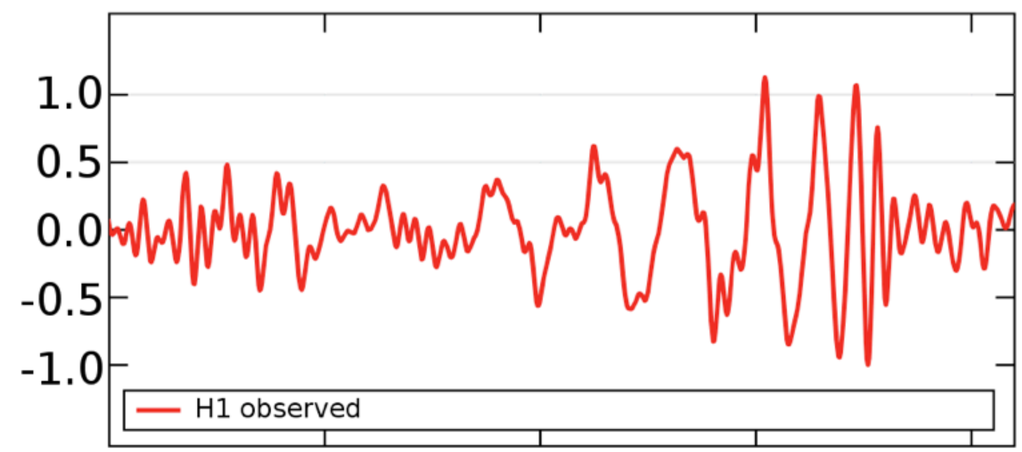
(Physics, 2017)

GW150914

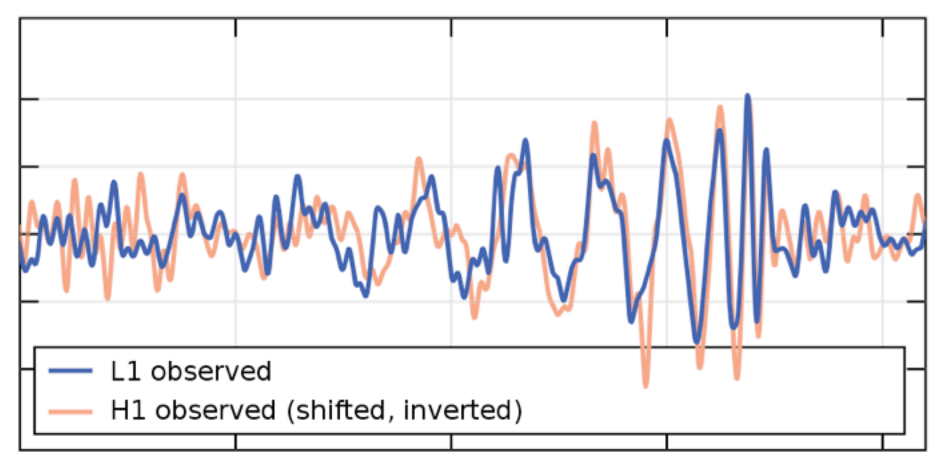
[B.P. Abbott *et. al.*,
PRL 116, 061102 (2016)]



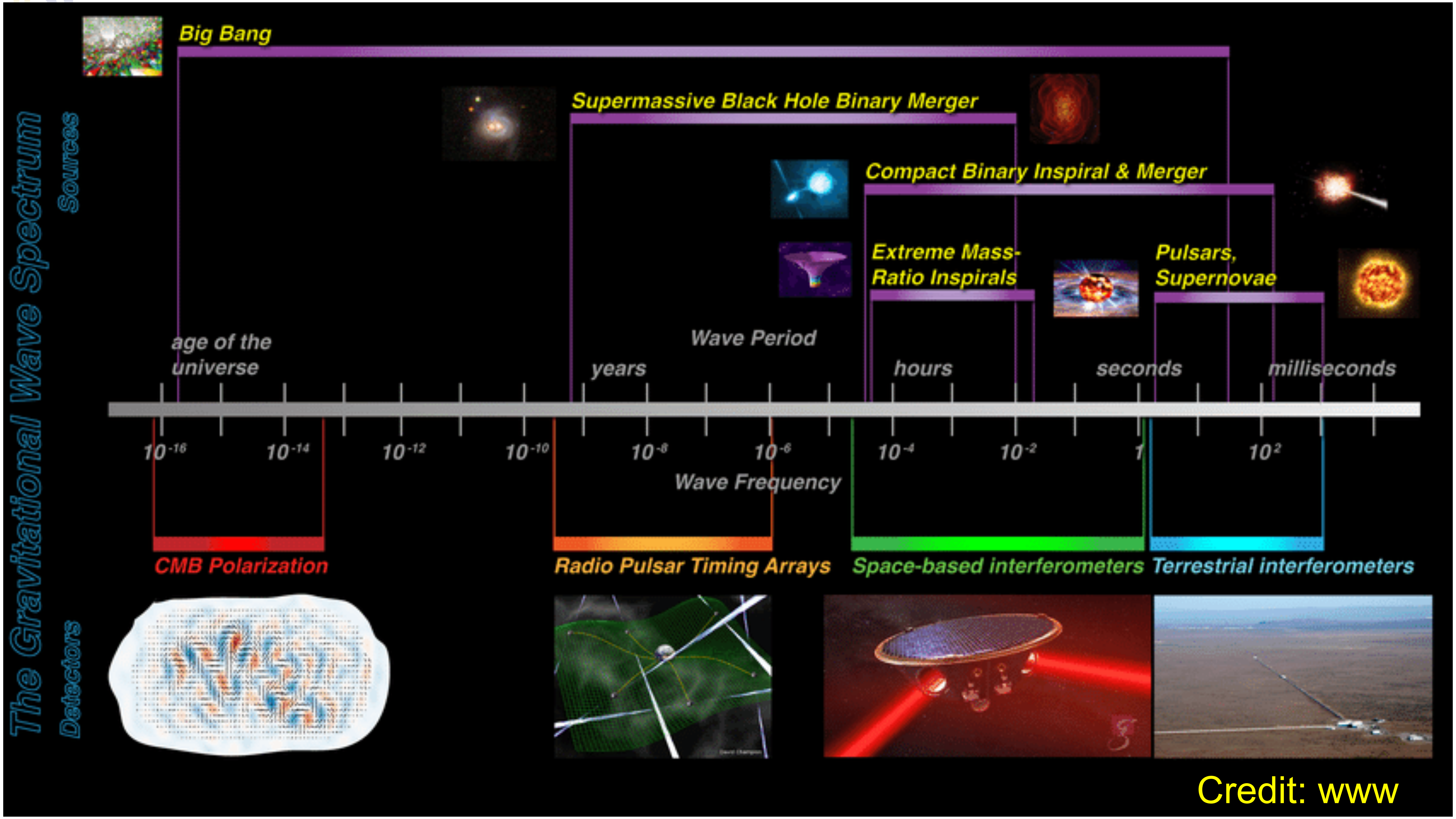
Hanford, Washington (H1)



Livingston, Louisiana (L1)



Detection of LFGWs



Sources for HFGWs

[For a review, see, e.g., N. Aggarwal et. al., Living Rev.Rel. 24 (2021)]

- Early Universe
  - High-scale first order cosmological phase transition:

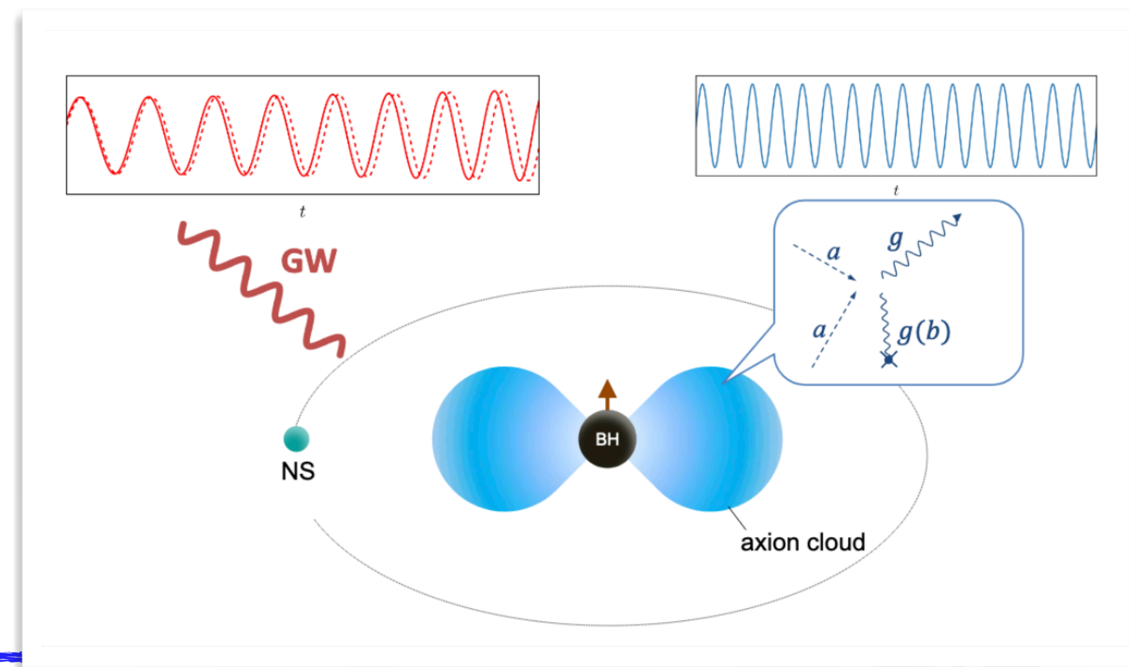
$$f \simeq 26 \left(\frac{1}{H_* R_*}\right) \left(\frac{T_*}{10^5\,\mathrm{GeV}}\right) \left(\frac{g_*(T_*)}{100}\right)^{1/6} \mathrm{mHz}$$

  - Cosmic gravitational microwave background (CGMB): $f \sim (1 - 100)\,\mathrm{GHz}$
- Late Universe
  - Light PBH/compact star mergers

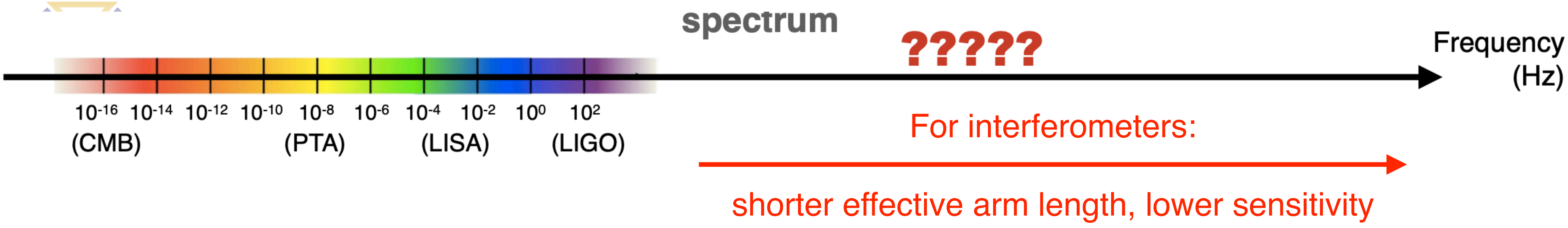
$$f_{\mathrm{ISCO}} \simeq C^{3/2} \left(\frac{6\times 10^{-3}\,M_\odot}{M}\right) 10^6\,\mathrm{Hz}$$

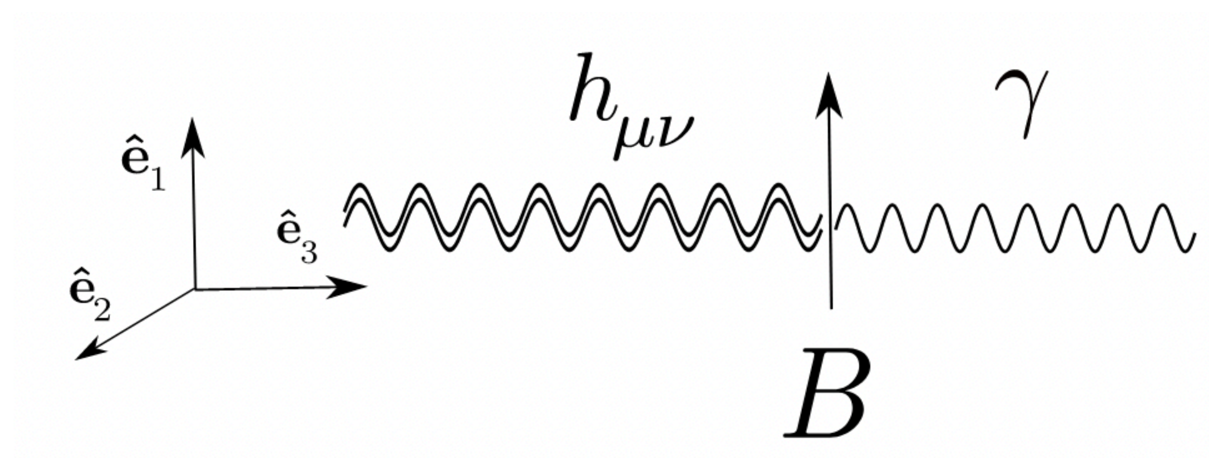
  - Axion cloud: annihilation and decay

$$f = 2\left(\frac{m_a}{10^{-9}\,\mathrm{eV}}\right) 10^6\,\mathrm{Hz} \qquad f = \frac{1}{2}\left(\frac{m_a}{10^{-9}\,\mathrm{eV}}\right) 10^6\,\mathrm{Hz}$$



Inverse Gertsenshtein Effect (Gertsenshtein, 1962)



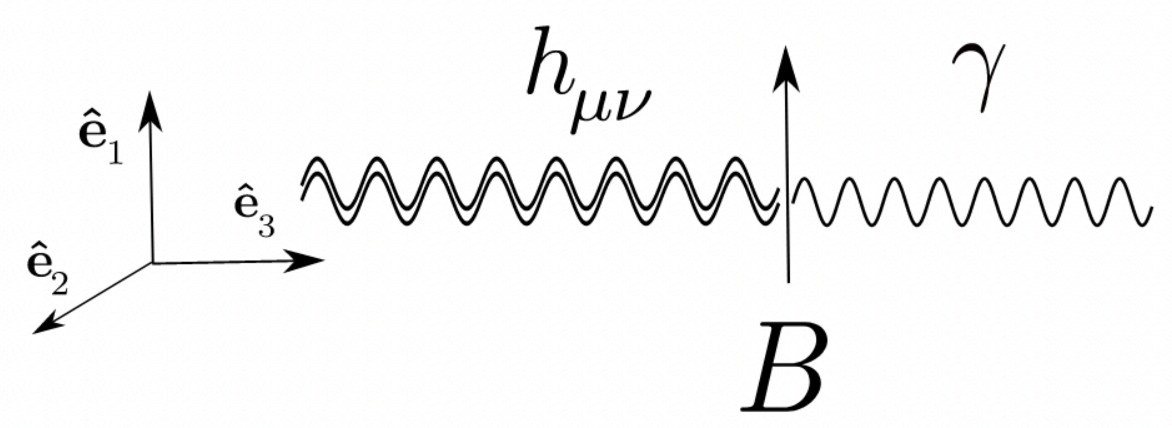


Alternative methodology - Inverse Gertsenshtein effect

While propagating in an external magnetic field, the GWs could oscillate into photons due to a state mixing.

$$S = -\frac{1}{4}\int d^4x\sqrt{-g}g^{\mu\alpha}g^{\nu\beta}F_{\mu\nu}F_{\alpha\beta}$$

Inverse Gertsenshtein Effect (Gertsenshtein, 1962)



$$\begin{pmatrix} \Delta_\gamma & \Delta_M \\ \Delta_M & 0 \end{pmatrix}$$

$\Delta_M = \frac{1}{2}\kappa B_t$ Encodes the GW-photon mixing

$\Delta_\gamma \approx \Delta_{vac} + \Delta_{pla}$ Eff photon mass without GW-photon mixing

$$\Delta_{vac} = 7\alpha\omega/(90\pi)(B_t/B_c)^2 \qquad \Delta_{pla} = -m_{pla}^2/(2\omega)$$

Conversion probability in a homogeneous magnetic field. Can be qualitatively used to guide experimental design

$$P = \sin^2(2\Theta)\sin^2\left(\frac{L}{l_{osc}}\right) = (\Delta_M L)^2 \mathrm{sinc}^2\left(\frac{L}{l_{osc}}\right)$$

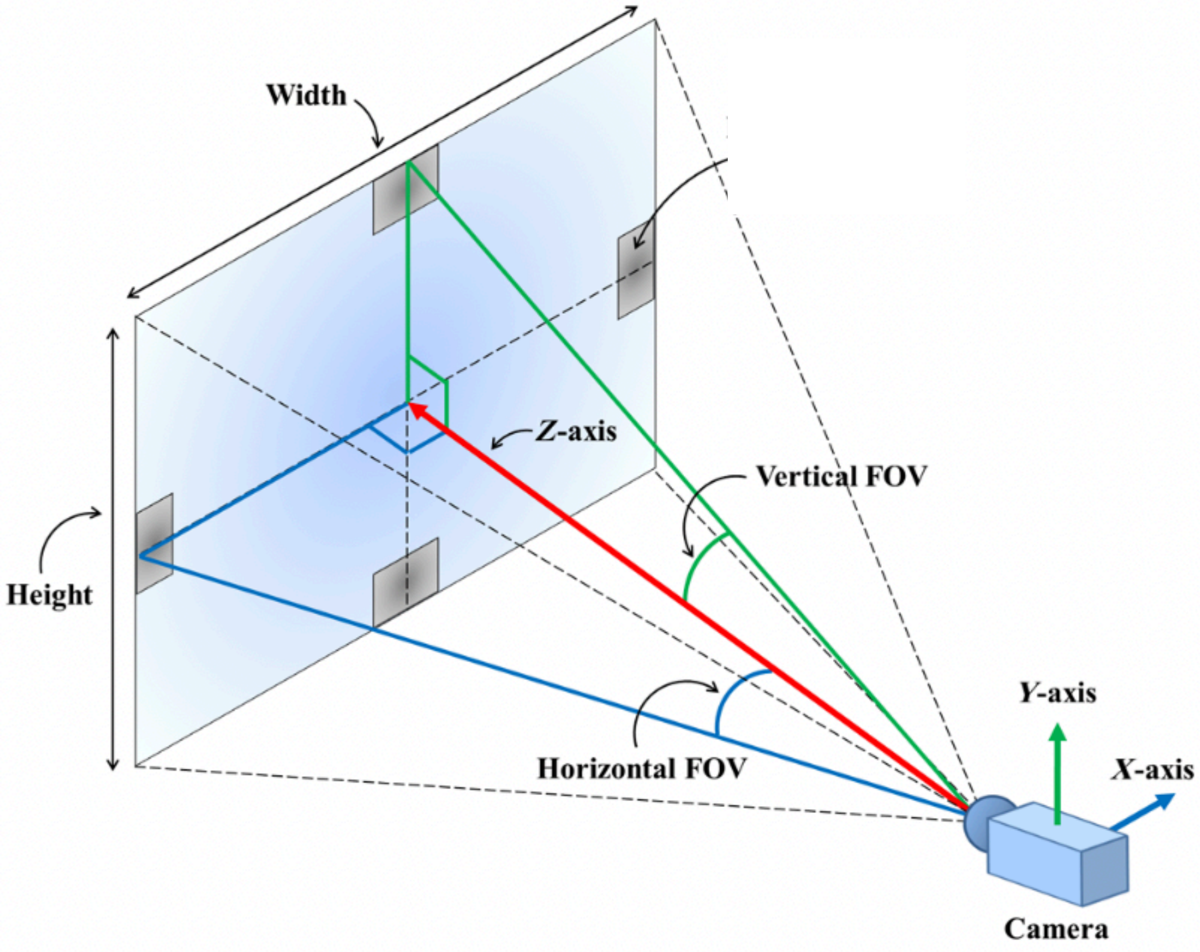
Coherence conversion: sinc -> 1 or large l_osc

L: effective travel distance of GWs in the magnetic field

$l_{osc} = 2/(4\Delta_M^2 + \Delta_\gamma^2)^{1/2}$: GW-photon oscillation length

Sensitivity Analysis

$$\Phi_\gamma = \int_{\Delta\Omega} d\Omega' \int d\omega \frac{1}{\omega} \frac{d}{d\omega} \frac{d\rho_{\rm GW}}{d\Omega} P(\Omega')$$



$$s \approx \Phi_\gamma A\,\Delta t \approx \frac{h_c^2}{4\pi\kappa^2}\langle P\rangle_{\rm det} A\,\Delta t \Delta\omega\Delta\Omega\,,$$

$$b \approx \Phi_b A\,\Delta t \approx \phi_b A\,\Delta t\Delta\omega\Delta\Omega\,,$$

$$h_{c,95\%} \approx 4.5\kappa \left(\frac{\phi_b}{A\,\Delta t\Delta\omega\Delta\Omega}\right)^{1/4} \left(\frac{1}{\langle P\rangle_{\rm det}}\right)^{1/2}$$

Field of view (FOV).

P average over FOV.

Artificial Magnetic Field

Key features: intermediate magnetic field strength (B ~ O(1)T) with a limited size (L ~ O(10)m)

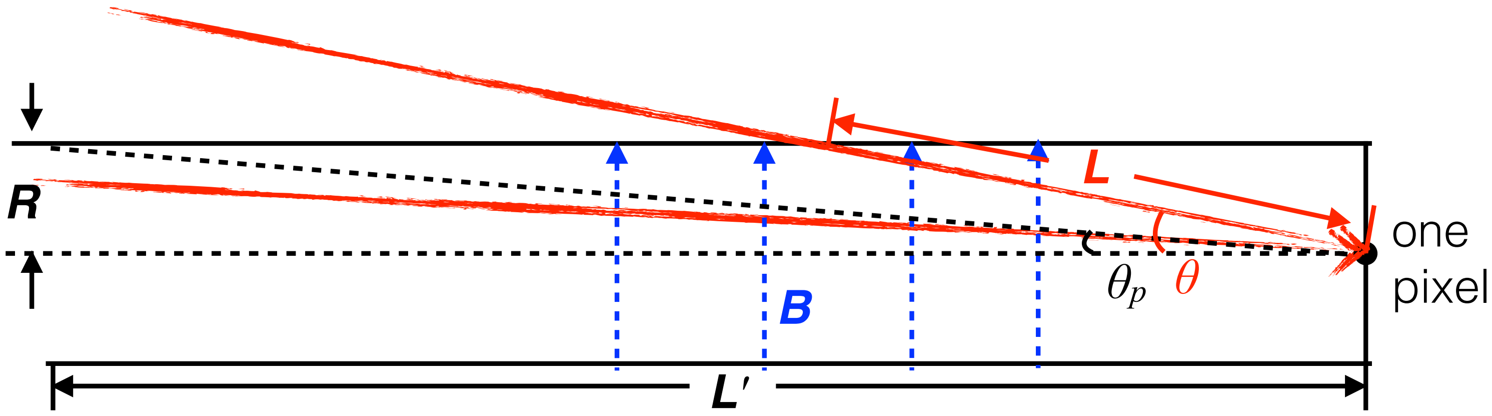
- Axion helioscope (above THz or GHz)
  - Ejlli, et al., EPJC 79 (2019)
  - Franciolini, et al., PRD 106 (2022)
  - narrow angular distribution of signal flux
- Resonant cavity experiments (MHz-GHz)
  - Berlin, et al. PRD 105 (2022)
  - Domcke, et al., PRL 129 (2022)
  - Schmieden and Schott, arXiv:2209.12024 [gr-qc]
  - enhanced sensitivity at the cost of a narrow band

CAST, CERN

$$P = \sin^2(2\Theta)\sin^2\left(\frac{L}{l_{\rm osc}}\right) = (\Delta_{\rm M} L)^2 {\rm sinc}^2\left(\frac{L}{l_{\rm osc}}\right)$$

$$h_{c,95\%} \approx 4.5\kappa\left(\frac{\phi_b}{A\,\Delta t \Delta\omega\Delta\Omega}\right)^{1/4}\left(\frac{1}{\langle P\rangle_{\rm det}}\right)^{1/2}$$

	$N_{\rm exp}$ (mHz)	A (m^2)	L_0 (m)	B_0 (T)	Δf (Hz)
CAST	0.15	0.0029	9.3	9	10^{18}



- Small effective FOV (due to narrow angular distribution of signal photon flux)
- Short GW-photon coherent conversion path (limited by exp facility geometry)

Cosmo/Astro Magnetic Field

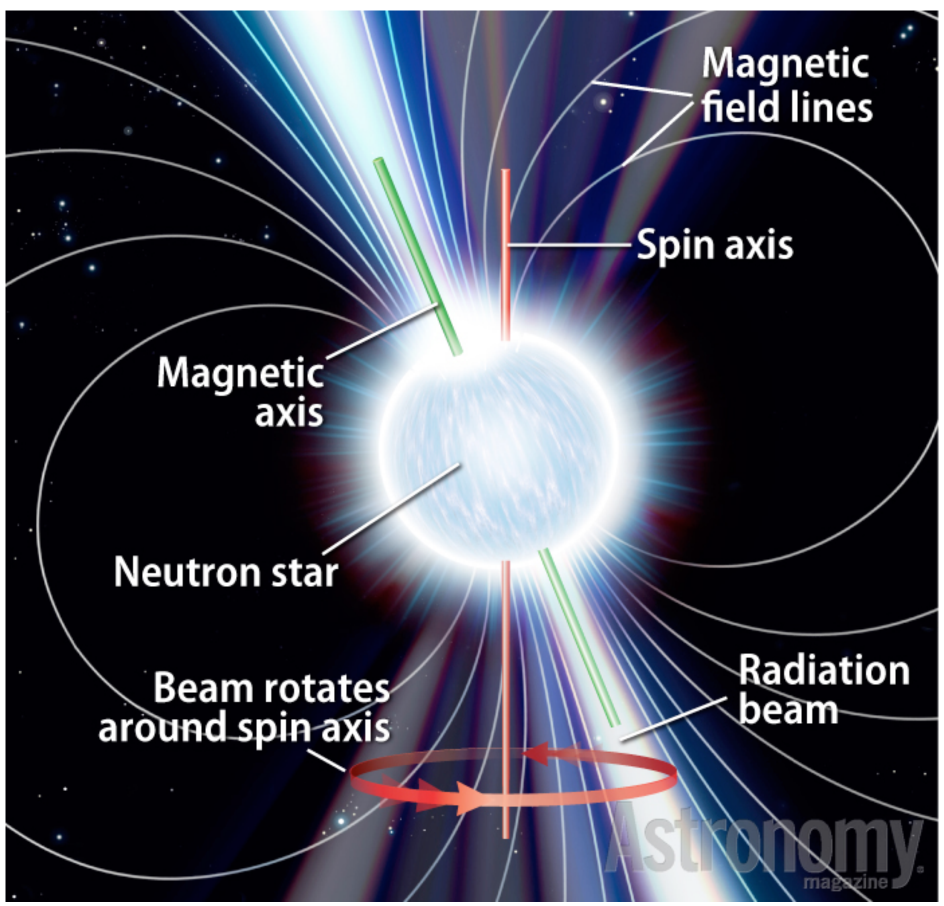
Key features: more extremal (either much stronger or much weaker) magnetic field with a cosmo/astro scale

- Cosmic magnetic field (Rayleigh-Jeans tail of CMB, radio)
  - Chen, PRL 74 (1995)
  - Domcke and Garcia-Cely, PRL 126 (2021)
  - Large uncertainties of cosmic magnetic field
- Neutron stars (frequency bands for NS observation)
  - Raffelt and Stodolsky, PRD 37 (1988)
  - Ito et. al., arXiv: 2305.13984 [gr-qc]
  - Suppressed oscillation length and extremely tiny angular distribution of signal flux

Neutron Stars

$$P = \sin^2(2\Theta)\sin^2\left(\frac{L}{l_{\rm osc}}\right) = (\Delta_{\rm M}L)^2 {\rm sinc}^2\left(\frac{L}{l_{\rm osc}}\right)$$

$$h_{c,95\%} \approx 4.5\kappa\left(\frac{\phi_b}{A\,\Delta t\Delta\omega\Delta\Omega}\right)^{1/4}\left(\frac{1}{\langle P\rangle_{\rm det}}\right)^{1/2}$$

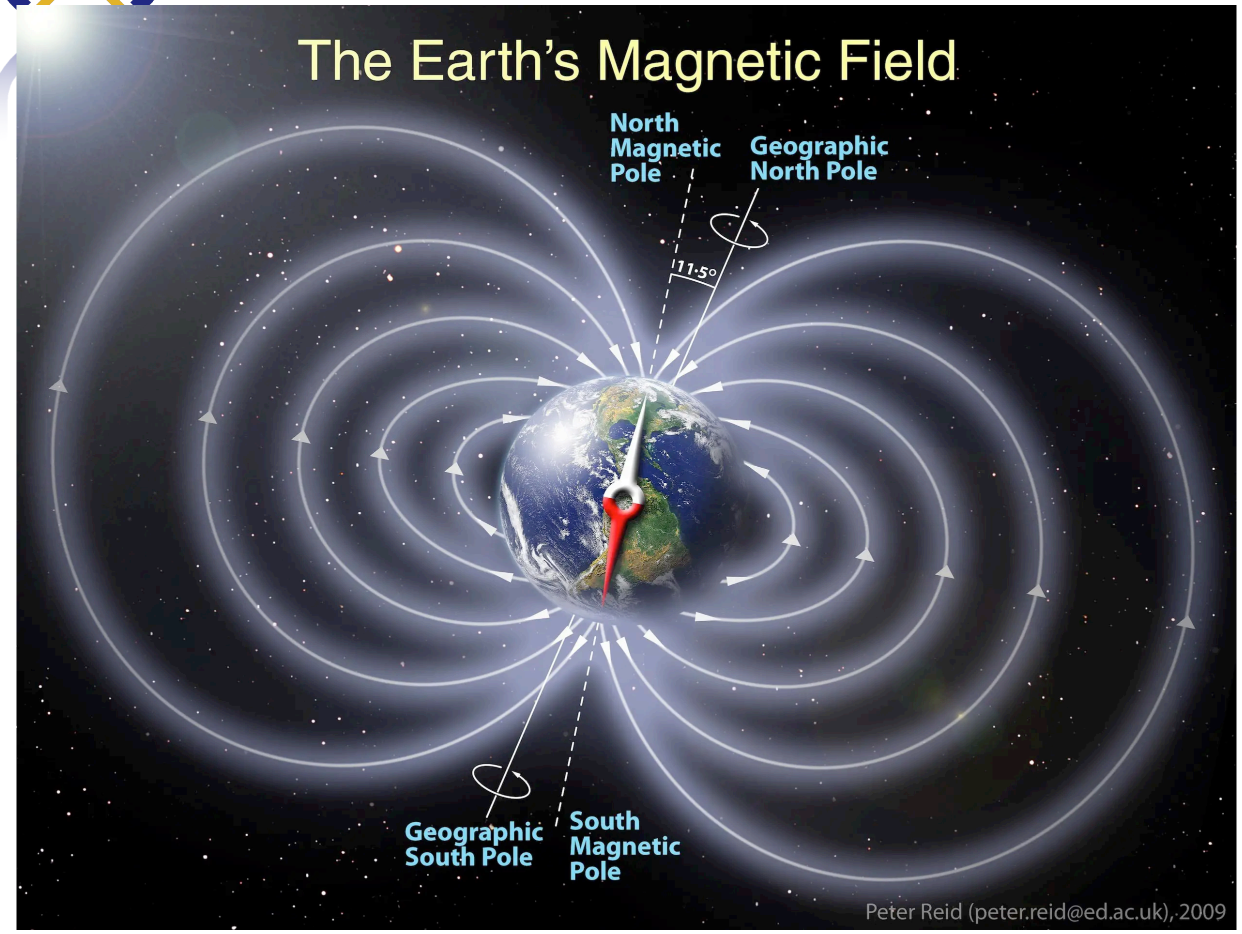


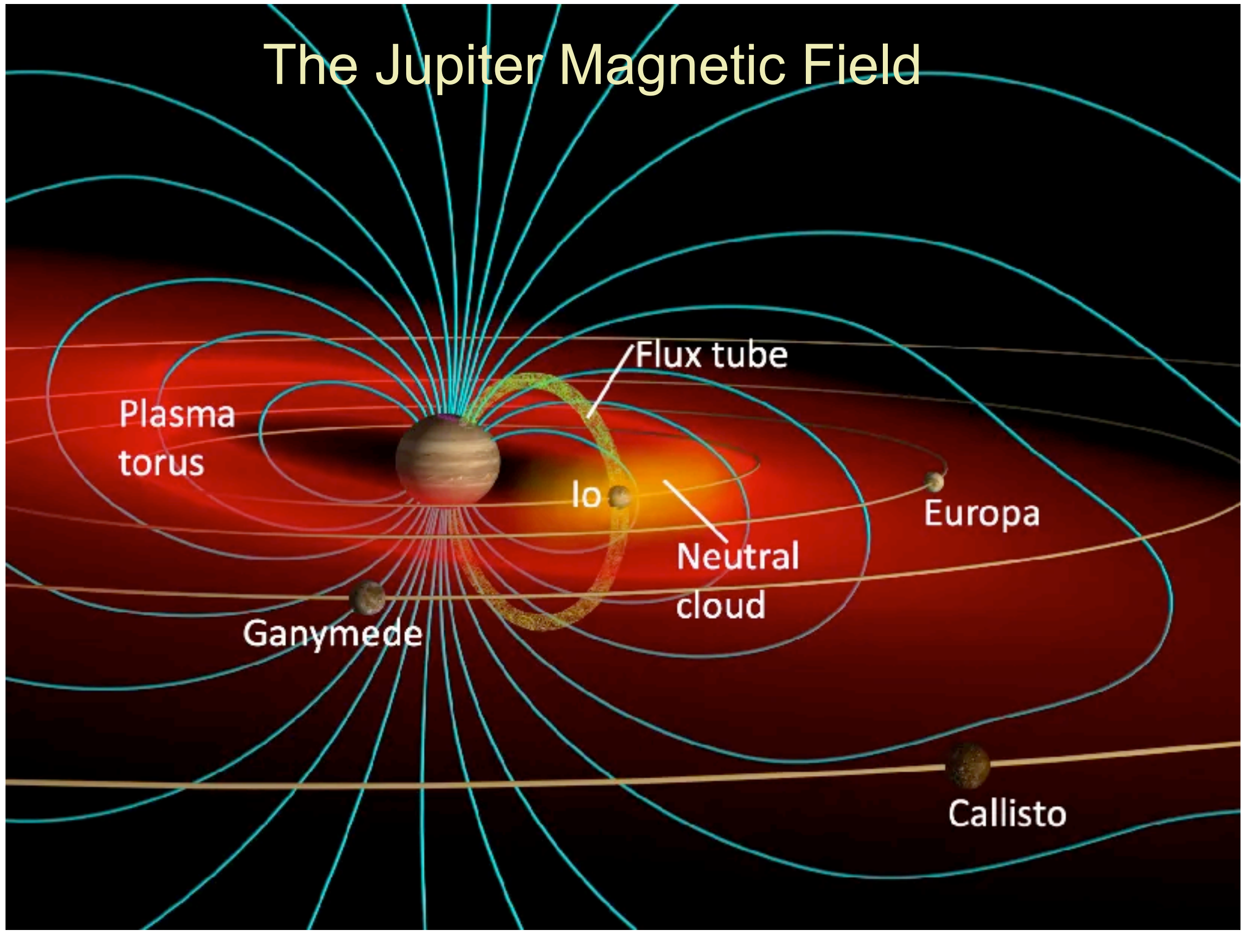
- Collapsed core of a massive star, with a radius ~10km and strong surface magnetic field ~ 10^8 - 10^15 Gauss
- Overall enhancement by strong B: $\Delta_M \propto B$
- Difficult to achieve coherent conversion for its short l_osc [G. Raffelt and L. Stodolsky, Phys.Rev.D 37 (1988)]

$$l_{\rm osc} = 2/(4\Delta_{\rm M}^2 + \Delta_\gamma^2)^{1/2}$$

- Limited by the extremely tiny angular distribution of signal flux, the effective FOV is tiny.

Our Proposal - Planet Magnetic Field

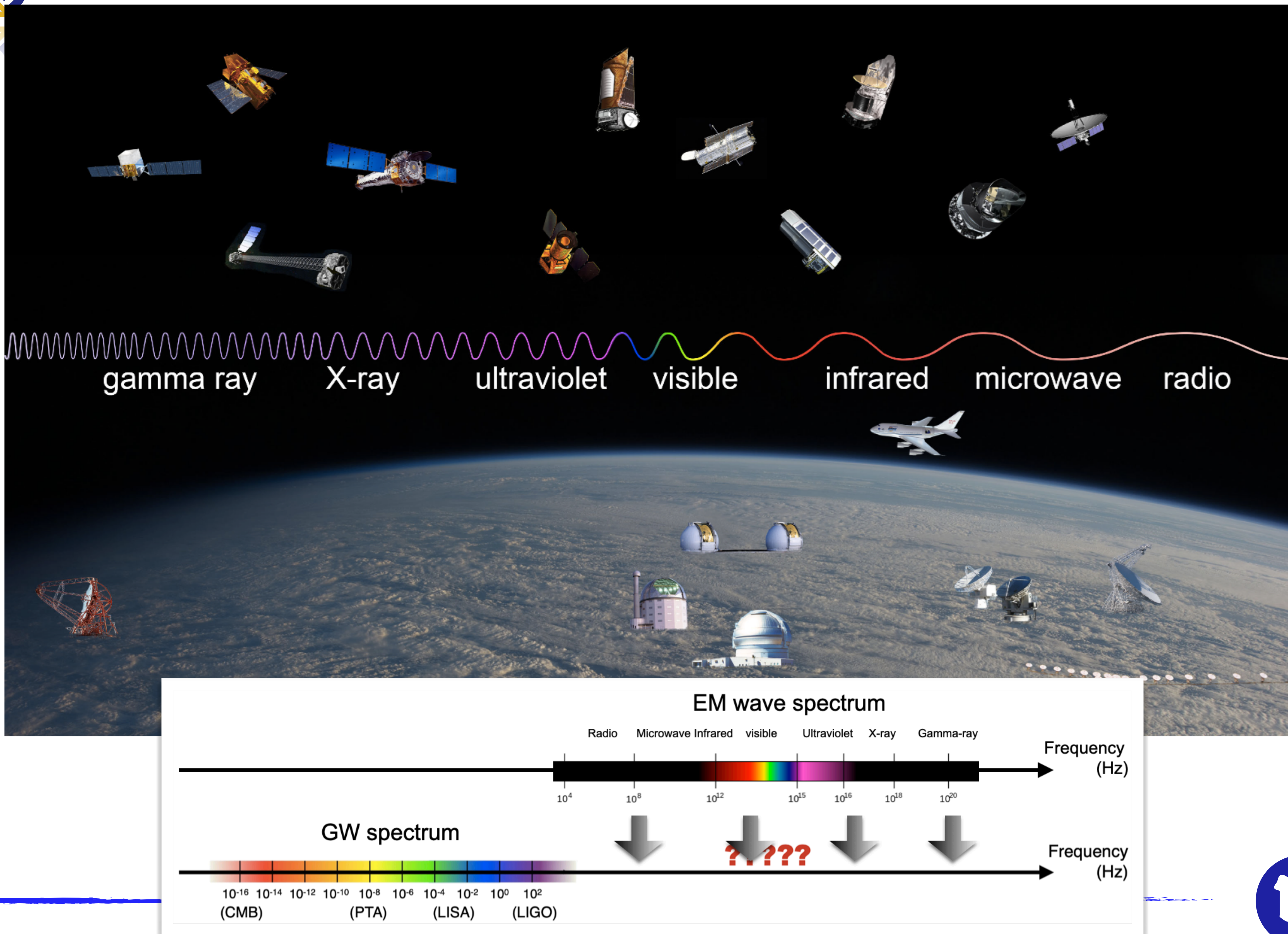




Earth: radius ~ 6000 km and surface magnetic field ~ 0.5 Gauss
Jupiter: radius ~ 70000 km and surface magnetic field ~ 10 Gauss

- Relatively weak B: $\Delta_M \propto B$
- Not difficult to achieve coherent conversion: $l_{\rm osc} = 2/(4\Delta_{\rm M}^2 + \Delta_\gamma^2)^{1/2}$
- Wide angular distribution of signal flux (although technology constraints for FOV need to be considered)

Our Proposal - Planet Magnetic Field



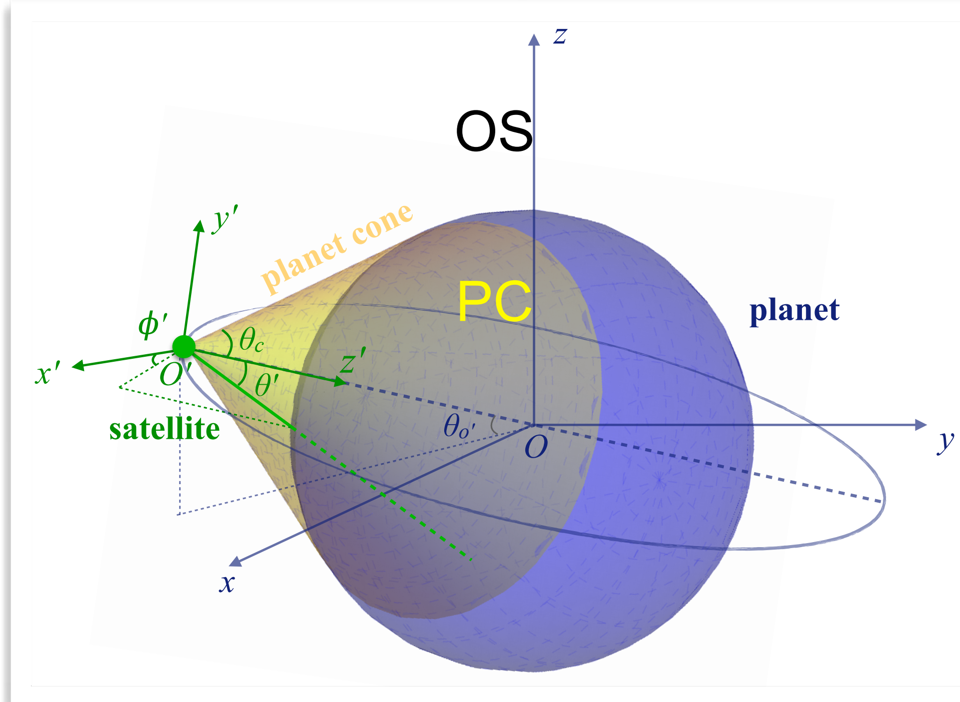
Satellite-Based Detector

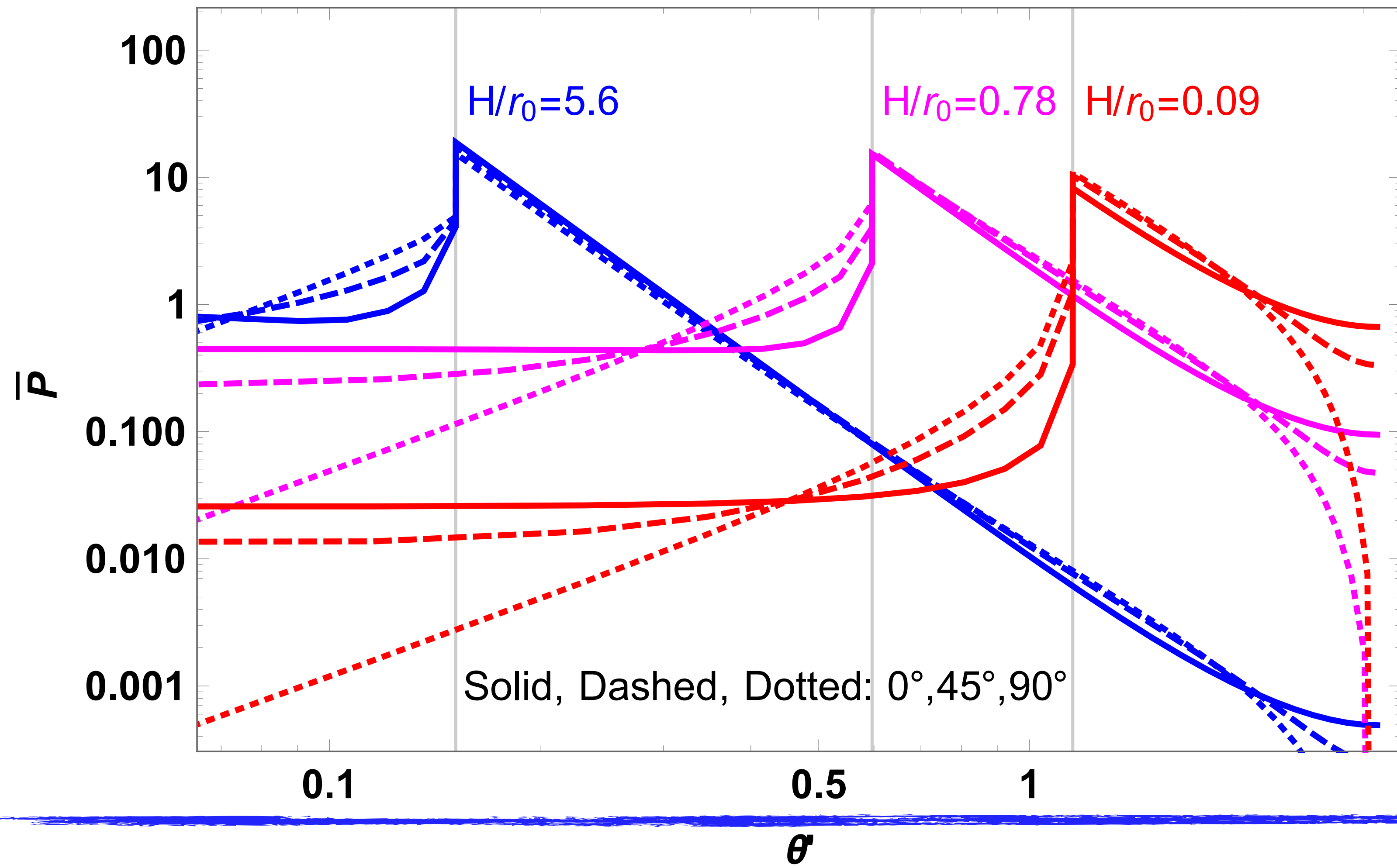
$$\bar{P}(\theta') = \frac{1}{P_0}\frac{1}{2\pi}\int_0^{2\pi} P(\Omega')d\phi'$$

(P average along azimuthal angle, with polar angle fixed)

$$\langle P\rangle_{\rm det} = \frac{1}{\Delta\Omega}\int_{\Delta\Omega} P(\Omega')d\Omega' = P_0\frac{\int_{\Delta\Omega}\bar{P}(\theta')\sin\theta' d\theta'}{\int_{\Delta\Omega}\sin\theta' d\theta'}$$

(P average over FOV)





- Peaks sharply at the boundary between planet cone (PC) and outer space (OS)
- As H/r0 increases, $\bar{P}$ increases along the PC central axis and decreases in opposite direction

Two benchmark Scenarios for Sensitivity Analysis

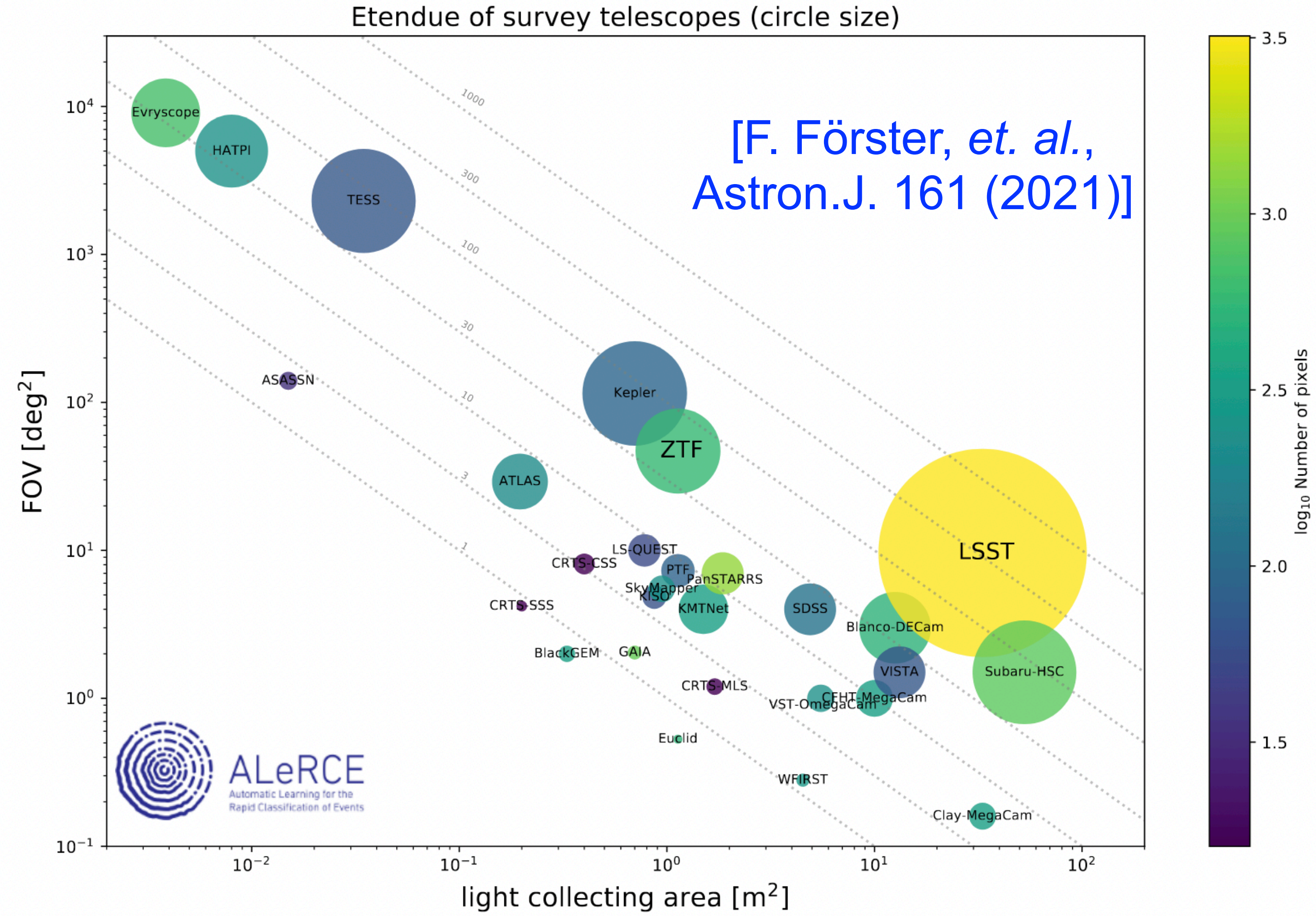
SUZAKU-like

Nimbus Hubble Voyager SUZAKU Fermi-LAT

	Satellite orbit			Detector properties					
	H (km)	$\theta_{\rm inc}$	$T_{\rm dark}$ (s)		IR	UV-Optical	EUV	X-ray	γ-ray
Conservative	600	31.4°	10^7	$\Delta\Omega$ (sr)	1.6×10^{-2}	10^{-6}	10^{-5}	3×10^{-5}	2.4
				A (cm^2)	0.1225	4.5×10^4	1	250	8000
Optimistic	800	98°	10^8	$\Delta\Omega$ (sr)	3.4	3.4	3.4	3.4	3.4
				A (cm^2)	0.1	10^2	10^2	10^2	10^4

SAFIR 2-like

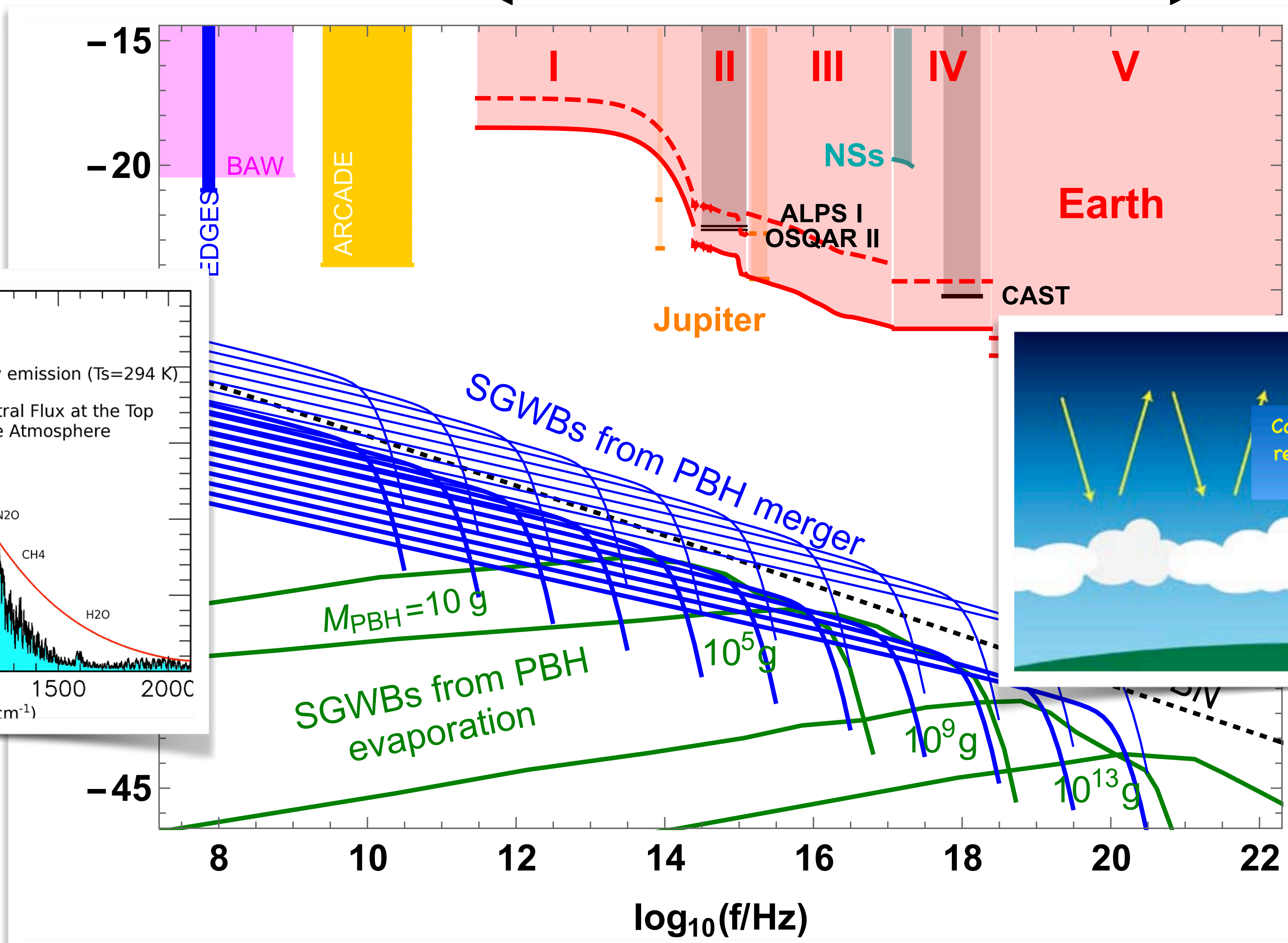
- Operate at low-Earth orbit
- Observe in dark side
- Take a bird view

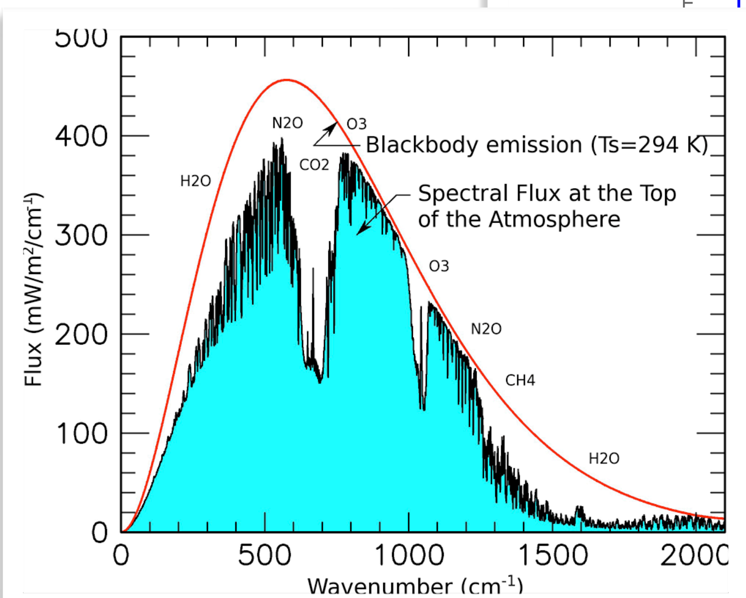


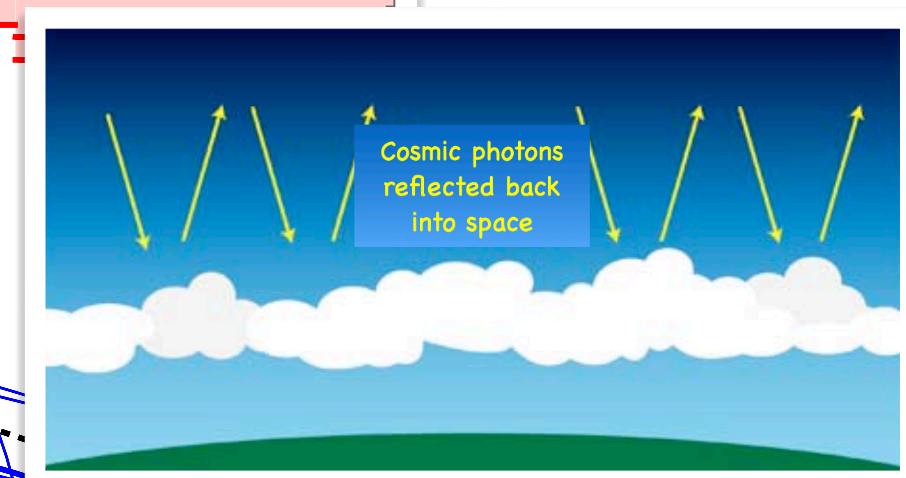
[F. Förster, *et. al.*, Astron.J. 161 (2021)]

Sensitivity Demonstration

Atmospheric thermal emission ← → Albedo reflection of cosmic photons

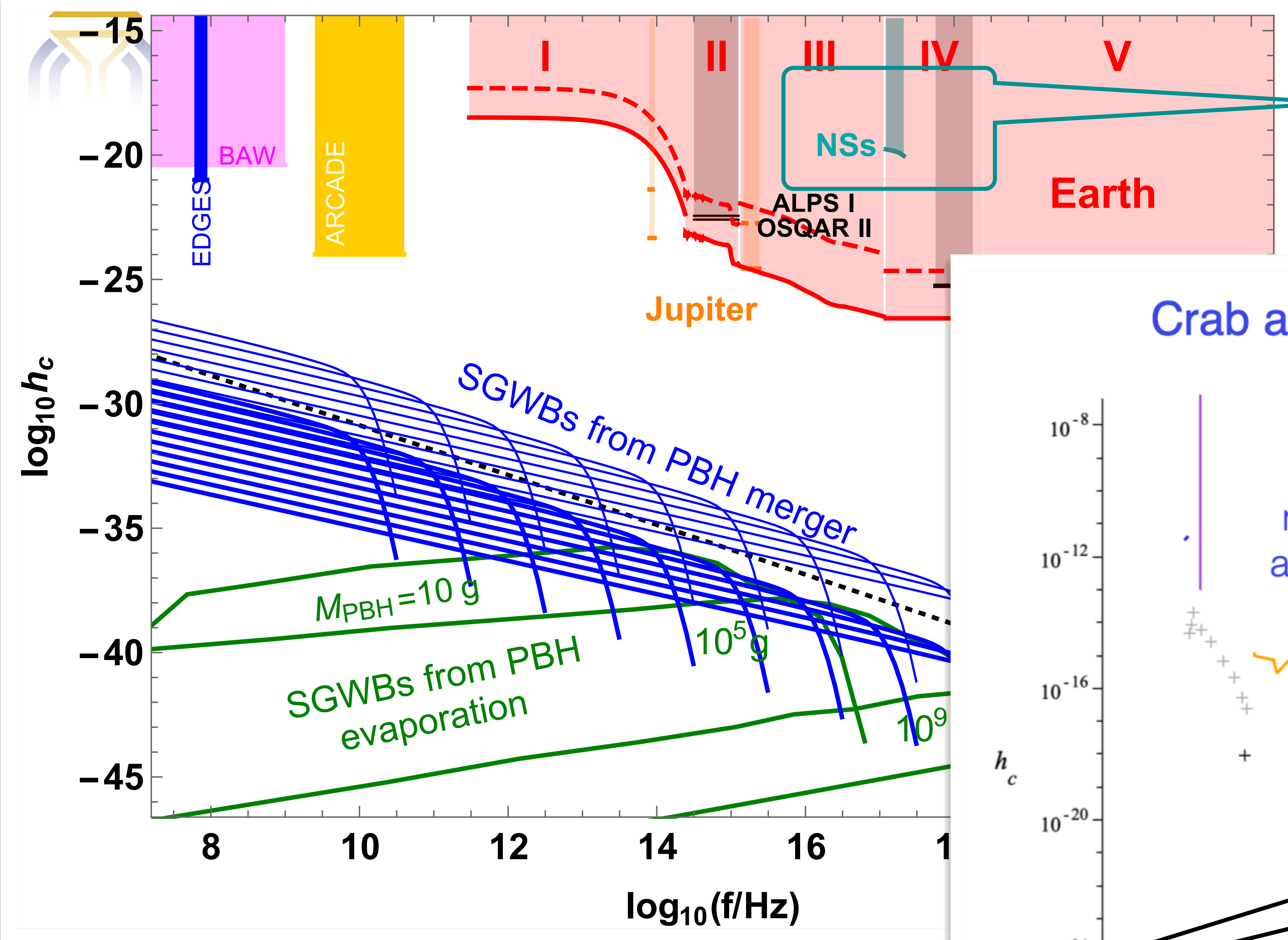




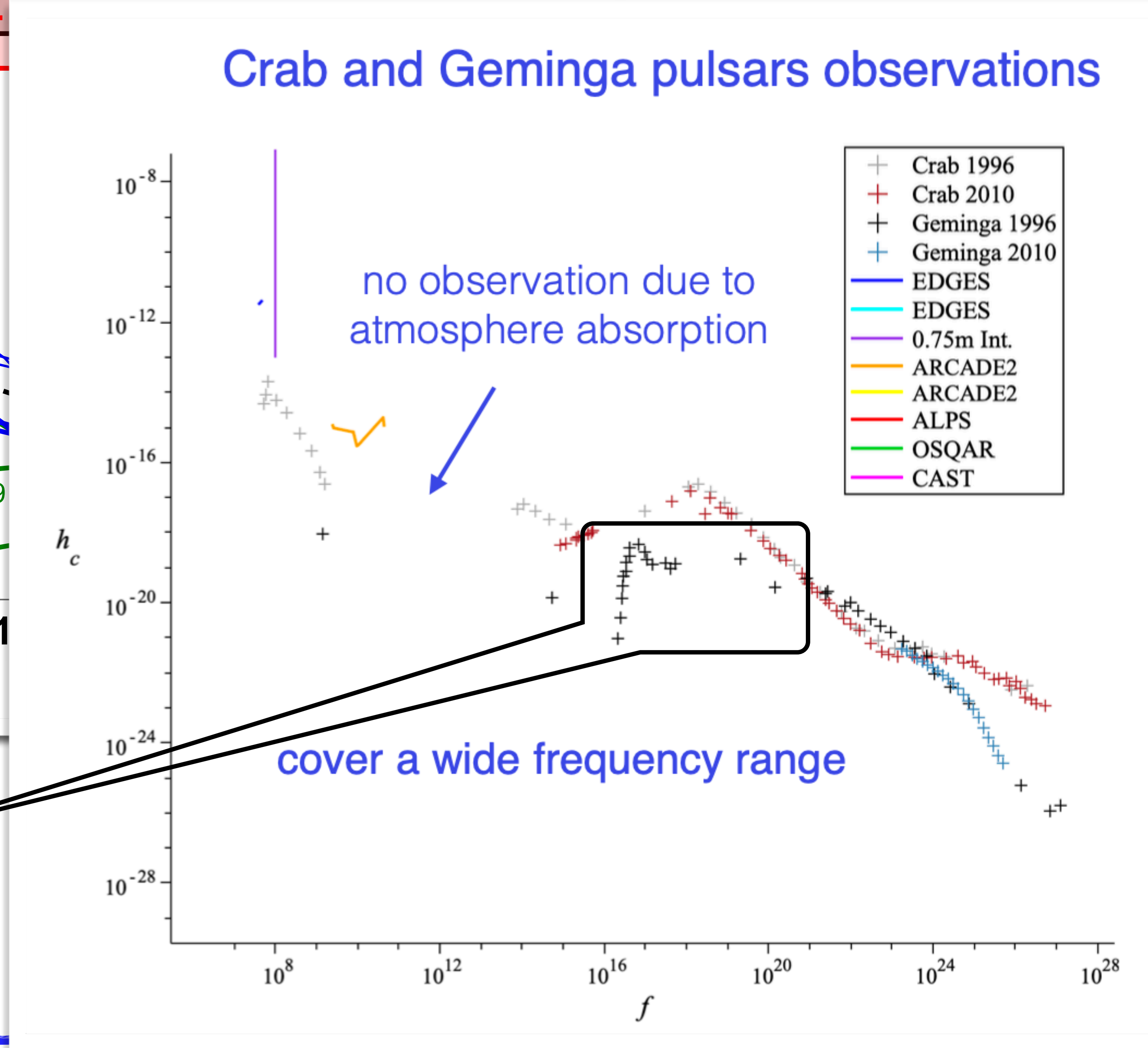


$$h_{c,95\%} \approx 1.0\times10^{-27}\left(\frac{\phi_b}{10^{-8}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{keV}^{-1}\mathrm{arcmin}^{-2}}\right)^{\frac{1}{4}}\left(\frac{100\mathrm{cm}^2}{A}\right)^{\frac{1}{4}}\left(\frac{10^7\mathrm{s}}{\Delta t}\right)^{\frac{1}{4}}\left(\frac{10\mathrm{keV}}{\Delta\omega}\right)^{\frac{1}{4}}\left(\frac{\mathrm{sr}}{\Delta\Omega}\right)^{\frac{1}{4}}\left(\frac{10^{-34}}{\langle P\rangle_{\mathrm{det}}}\right)^{\frac{1}{2}}$$

A Sensitivity Comparison: NS Case



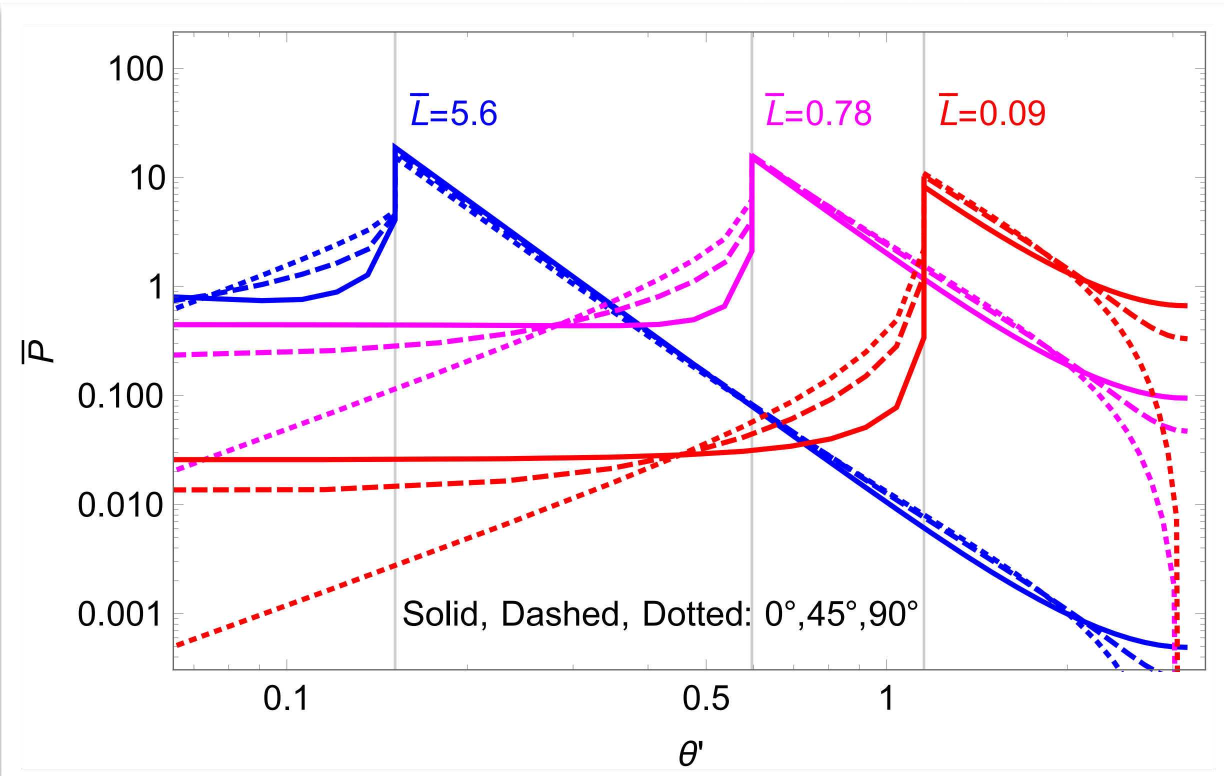
Based on the M7 X-ray dim isolated NSs

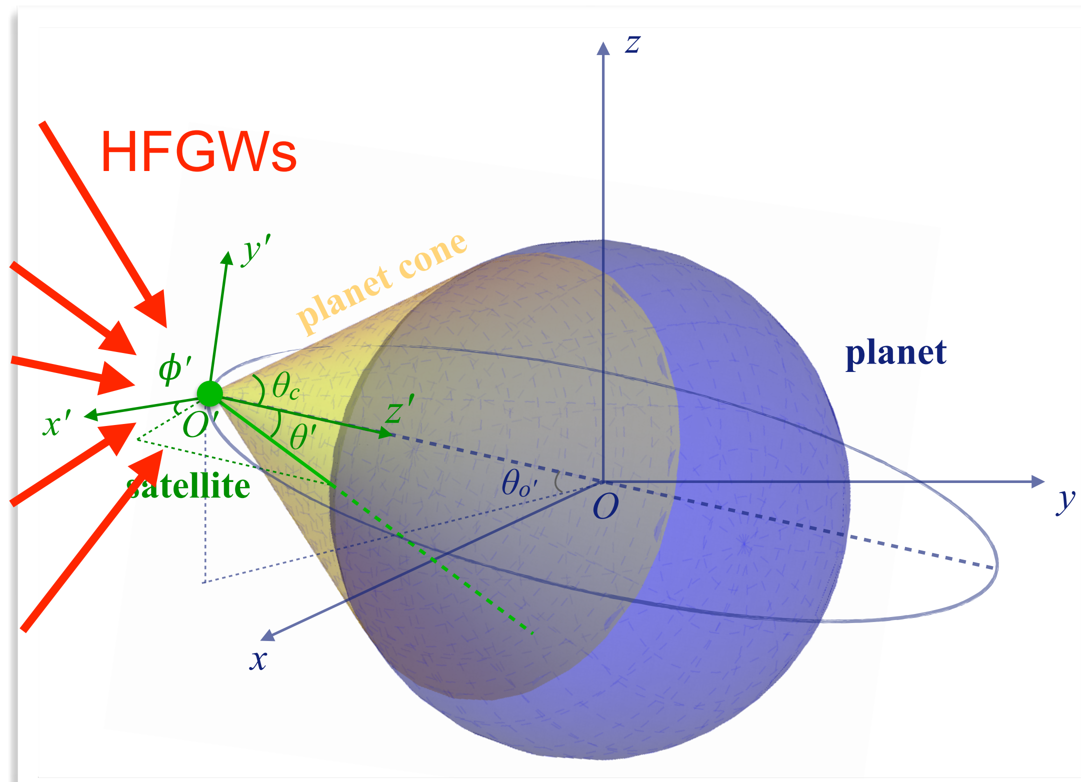


Comparable sensitivities are obtained in the X-ray band in

[Ito et. al., arXiv: 2305.13984]

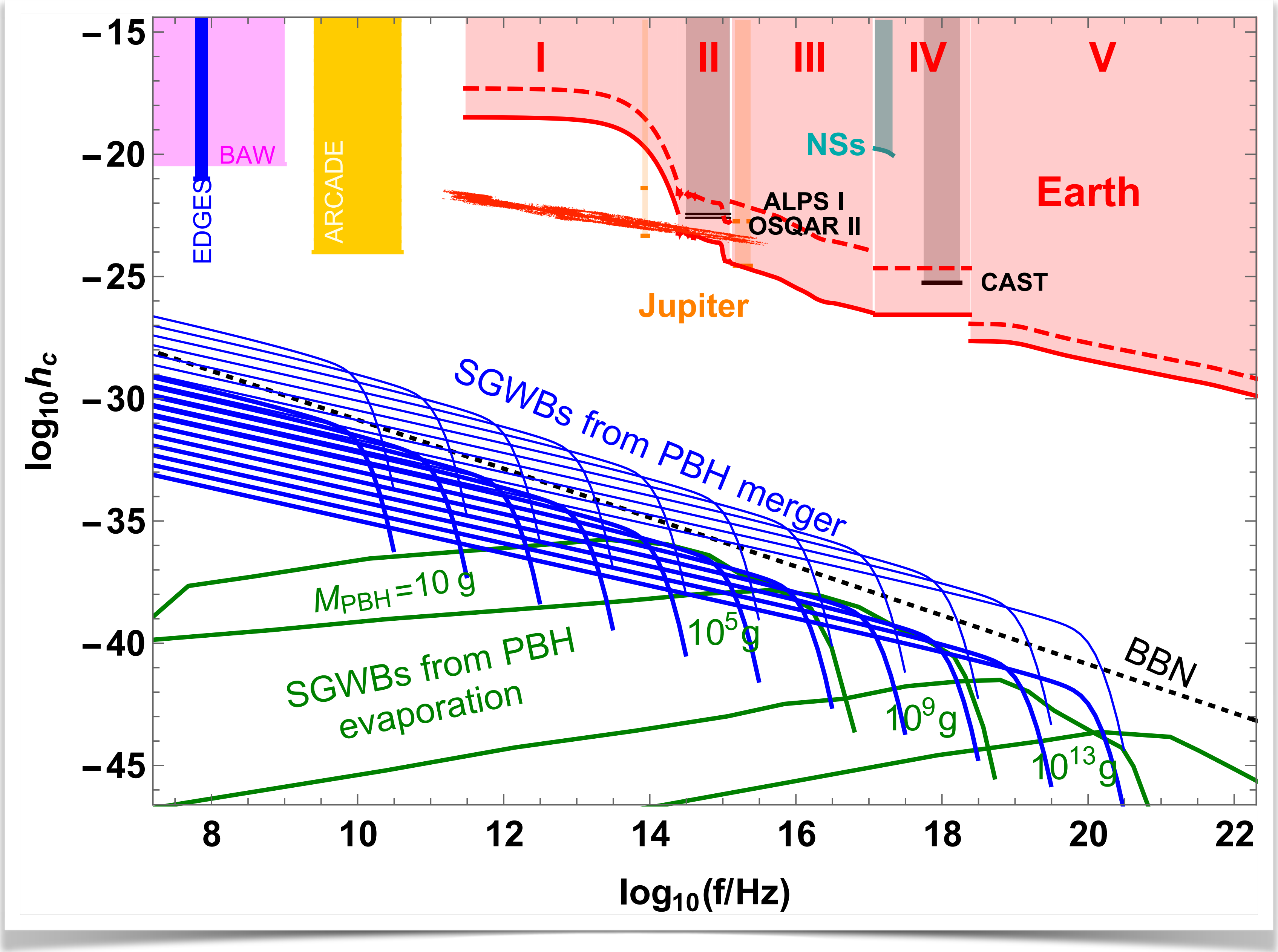
Outlook I - Look into Outer Space





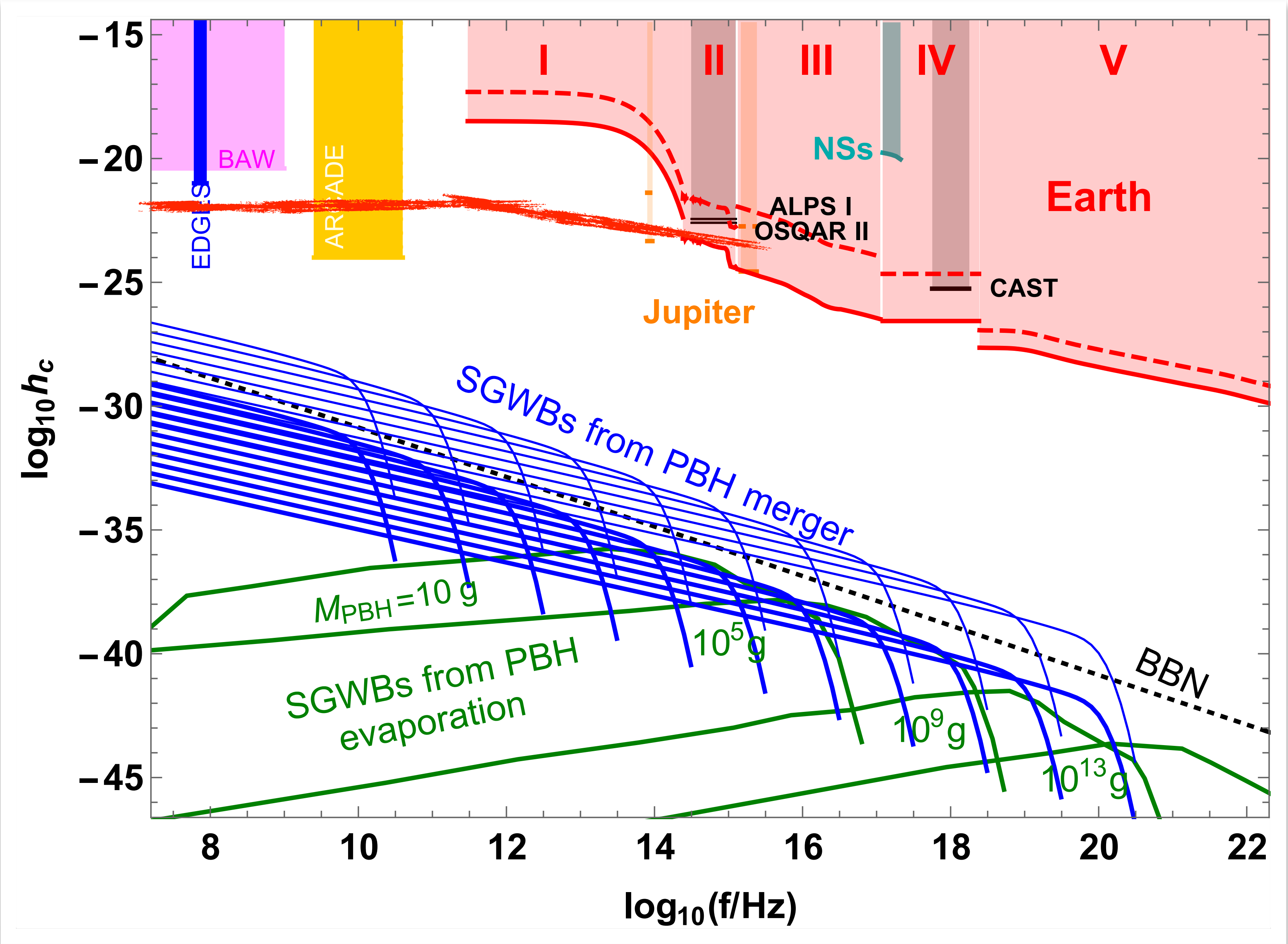
- Higher GW-photon conversion probability
- Suppressed impacts from atmospherical thermal radiation

Outlook I - Look into Outer Space



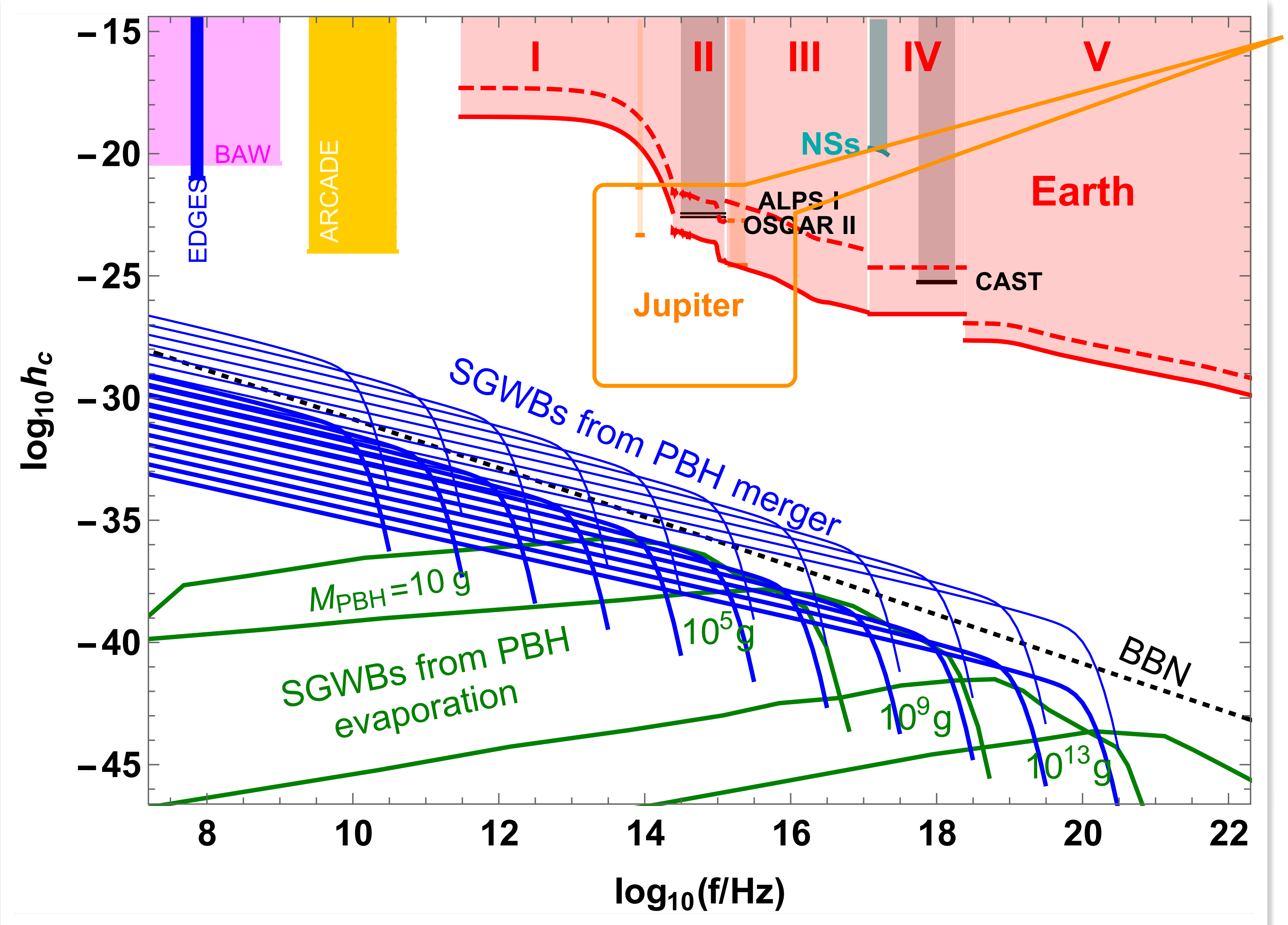
May bring up the sensitivities by orders of magnitude (especially for the infrared band)

Outlook II - Extend to Radio Band

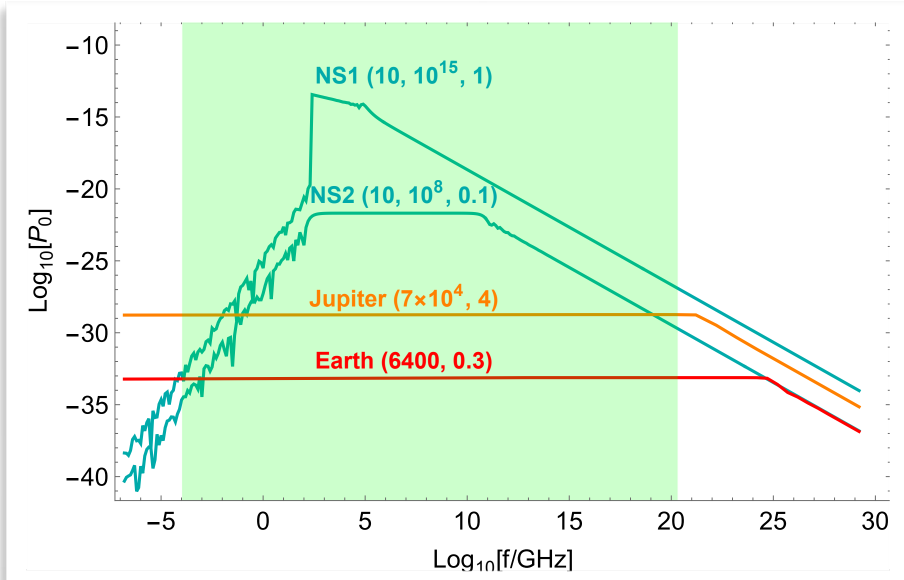


Ground-based observation (mainly for radio telescopes)

Outlook III - Jupiter and Solar Missions



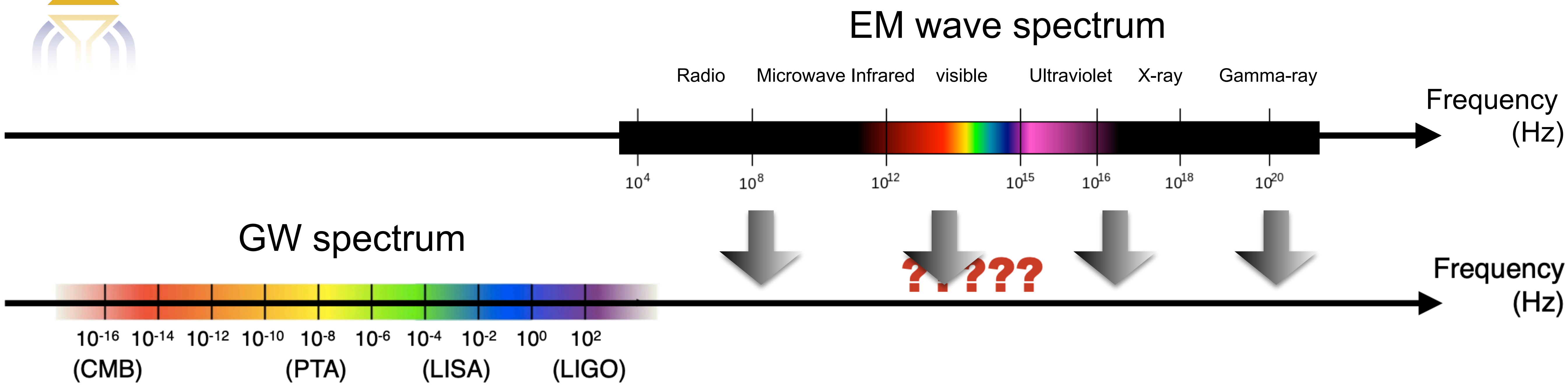
- Conservative (based on JUNO observation): aurora emissions by JIRAM and UV emissions by UVS
- Optimistic: 4sr/100cm^2/10^5s



Compared to the Earth, Jupiter and Sun

- Stronger surface magnetic field
- Longer GW-photon conversion path
- More complex background fluxes

Take-home Messages



- The detection of HFGWs represents a high-scientific-value task in GW astronomy
- For high-frequency bands, however, efficient detection methodologies are strongly demanded
- With long GW-photon conversion path and wide angular distribution of signal fluxes, the proposal of detecting HFGWs in planet magnetosphere opens a new operation space, with encouraging sensitivities projected for a wide coverage of frequencies.
- For some specific frequency bands, the first constraints from the existing data are obtained.
- More comprehensive study, with a refined analysis, is expected. Stay tuned …

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