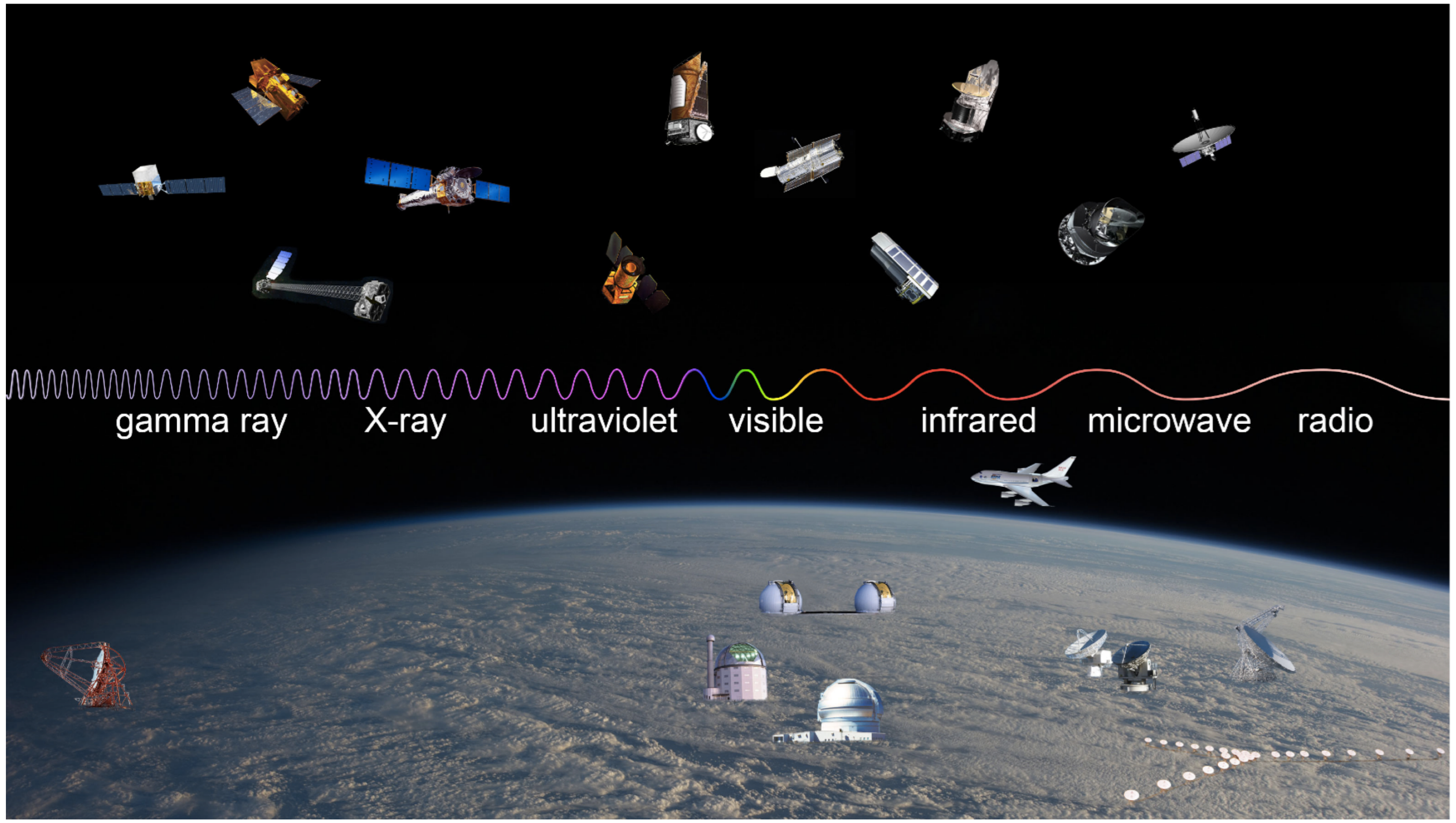
International Workshop on New Opportunities for Particle Physics 2024
Institute for High Energy Physics, CAS, July 2024

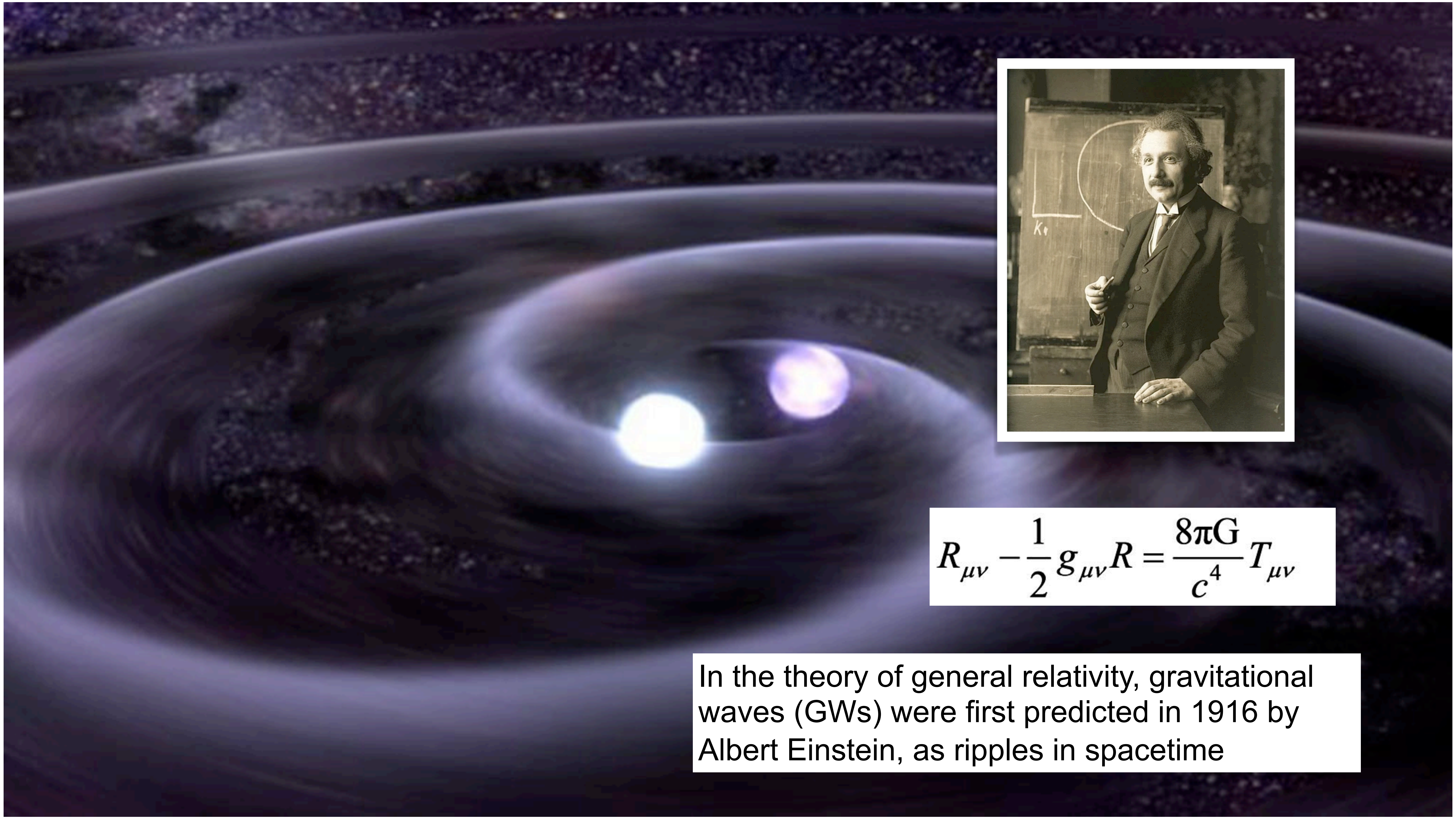


DETECTING HIGH-FREQUENCY GWS IN PLANETARY MAGNETOSPHERE

Tao Liu

Hong Kong University of Science and Technology

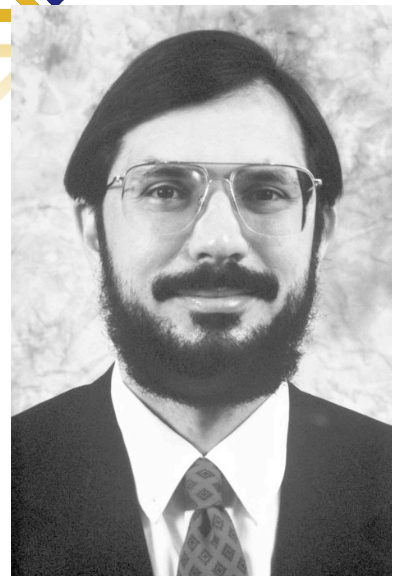
Gravitational Waves



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

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

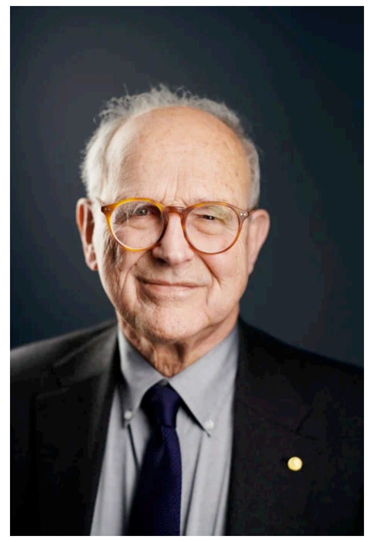
First Indirect Evidence (1974) + First Direct Evidence (2015)



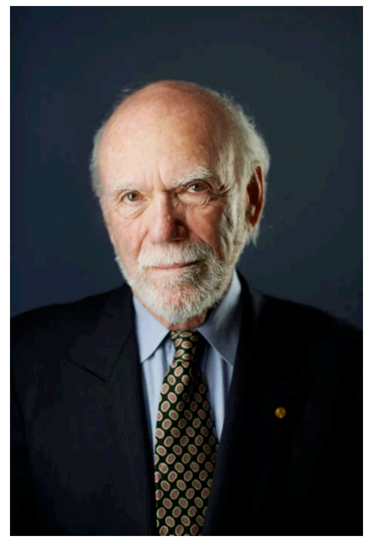
Hulse

Tylor

(Physics, 1993)



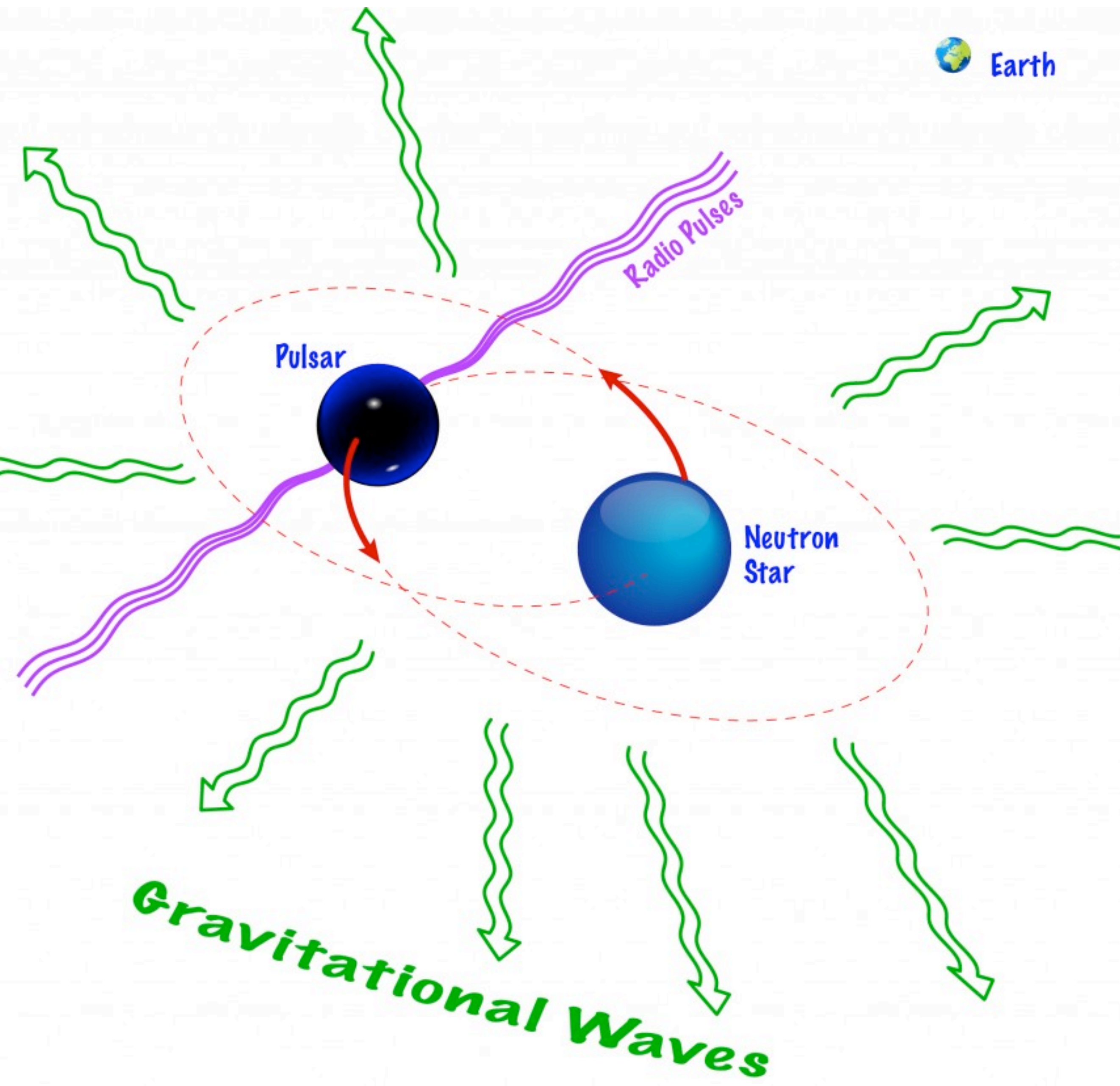
Weiss

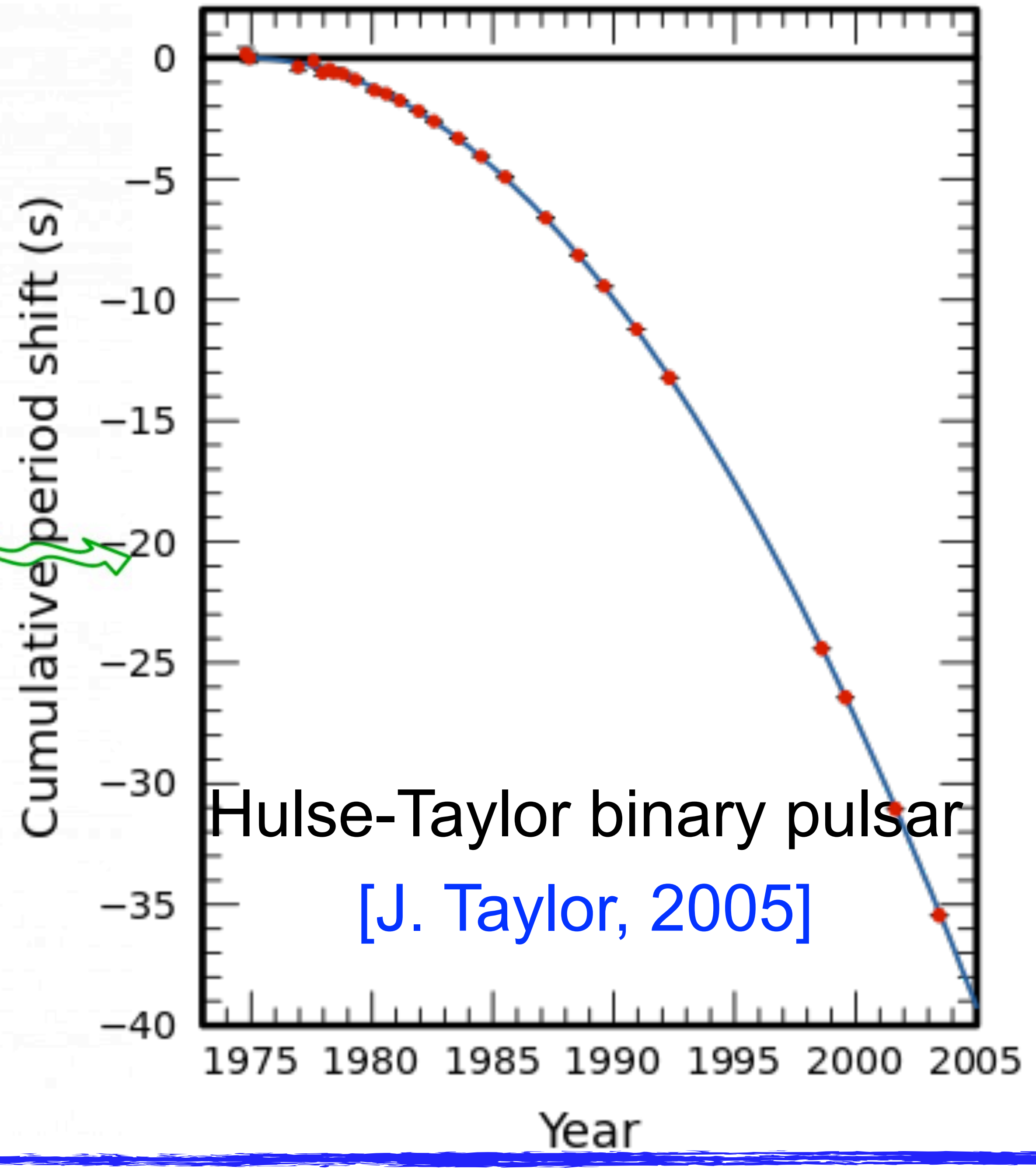


Barish

Thorne

(Physics, 2017)



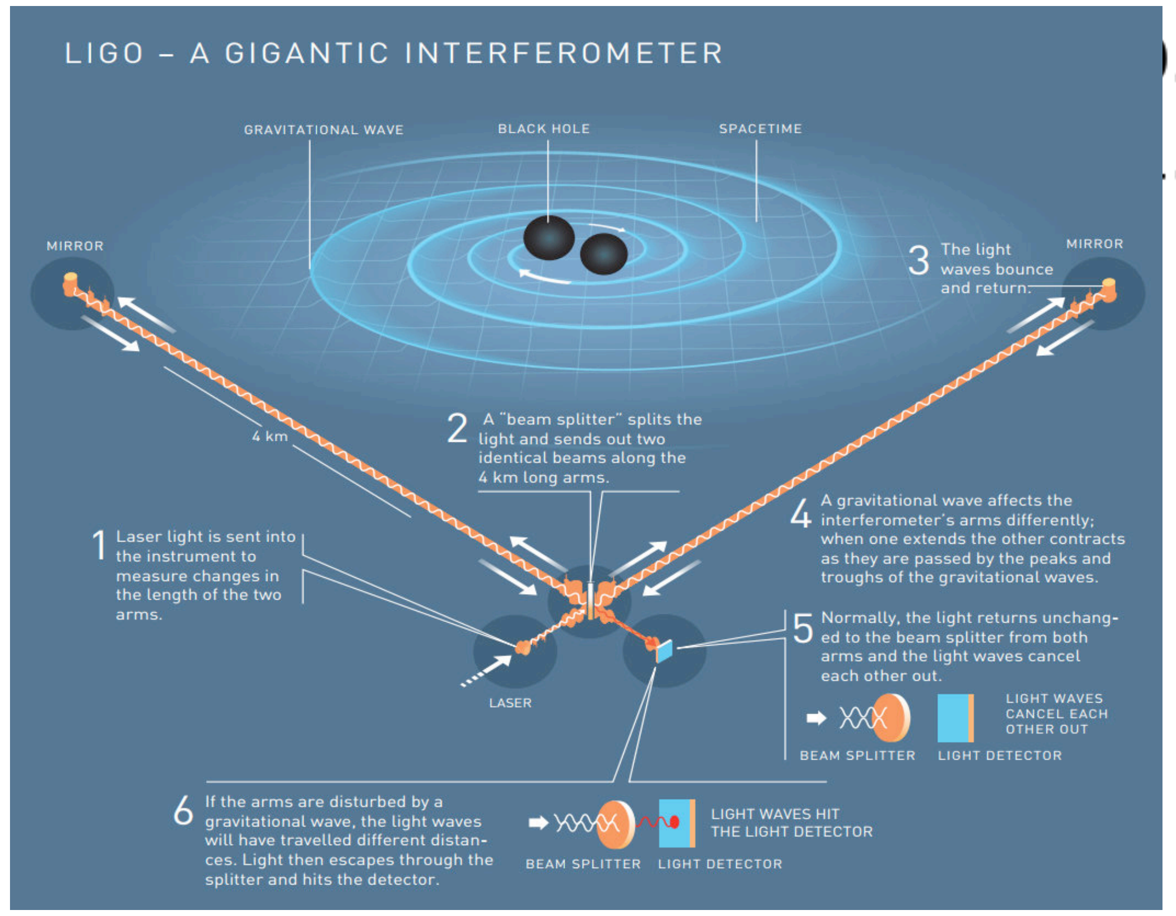


Hulse-Taylor binary pulsar

[J. Taylor, 2005]

GW150914

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



LIGO – A GIGANTIC INTERFEROMETER

1 Laser light is sent into the instrument to measure changes in the length of the two arms.

2 A "beam splitter" splits the light and sends out two identical beams along the 4 km long arms.

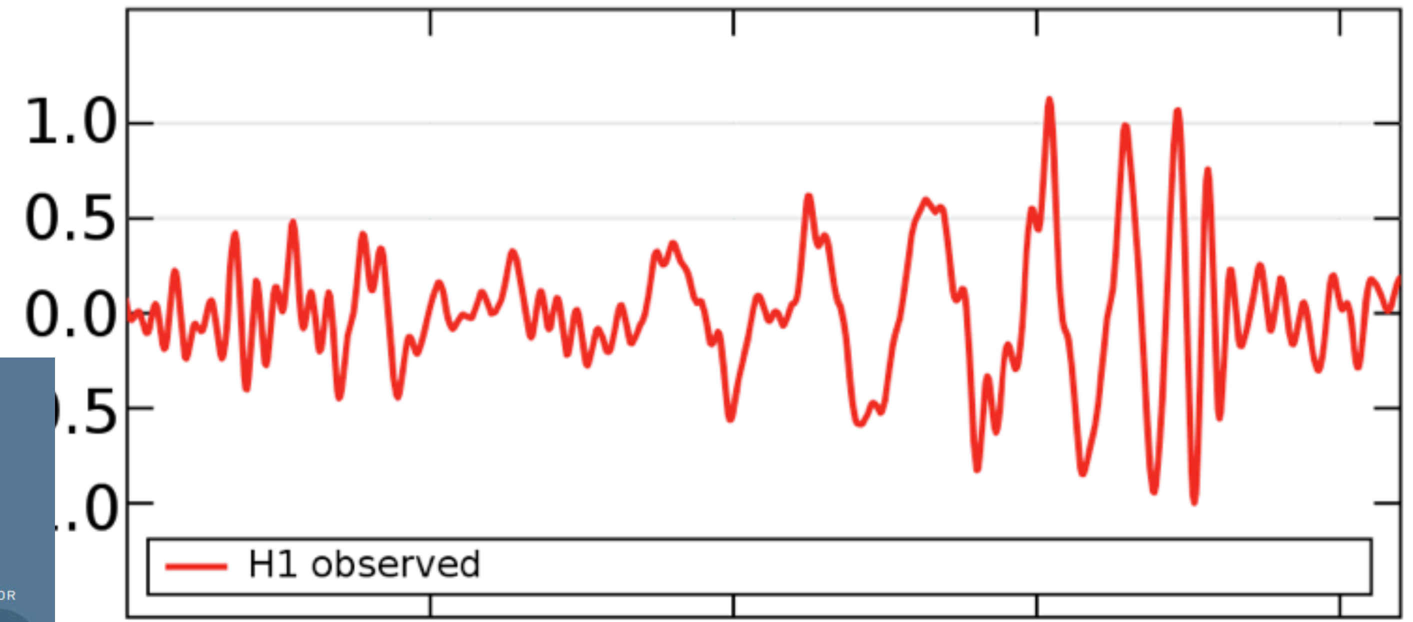
3 The light waves bounce and return.

4 A gravitational wave affects the interferometer's arms differently; when one extends the other contracts as they are passed by the peaks and troughs of the gravitational waves.

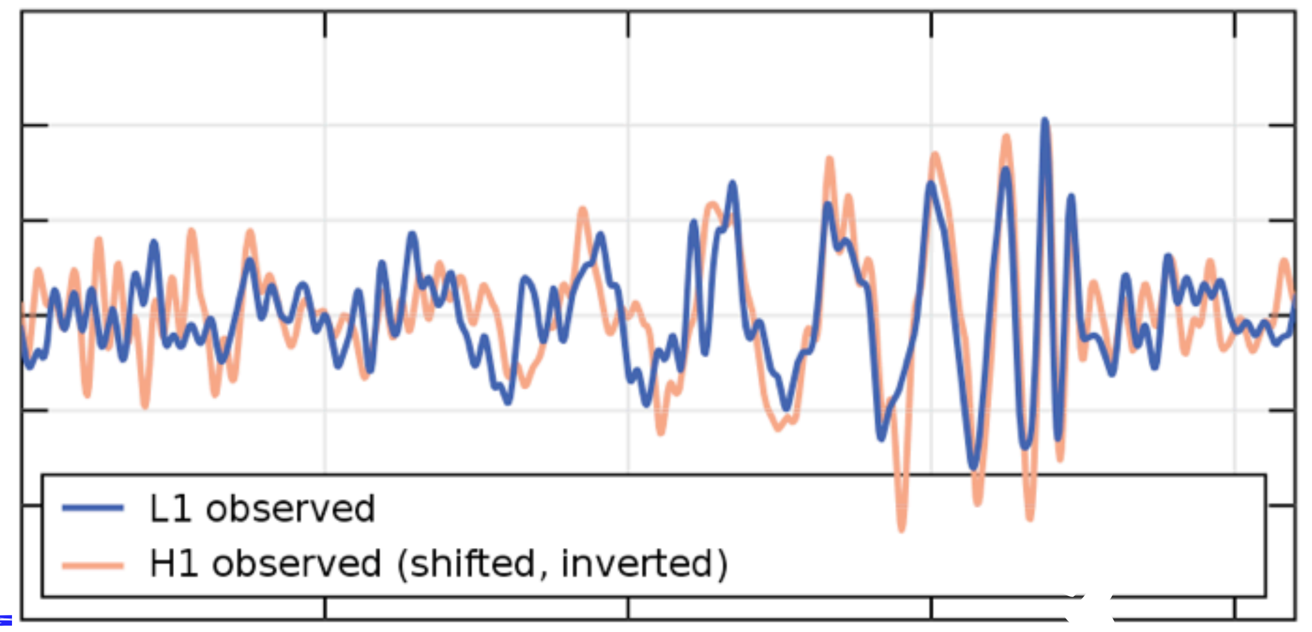
5 Normally, the light returns unchanged to the beam splitter from both arms and the light waves cancel each other out.

6 If the arms are disturbed by a gravitational wave, the light waves will have travelled different distances. Light then escapes through the splitter and hits the detector.

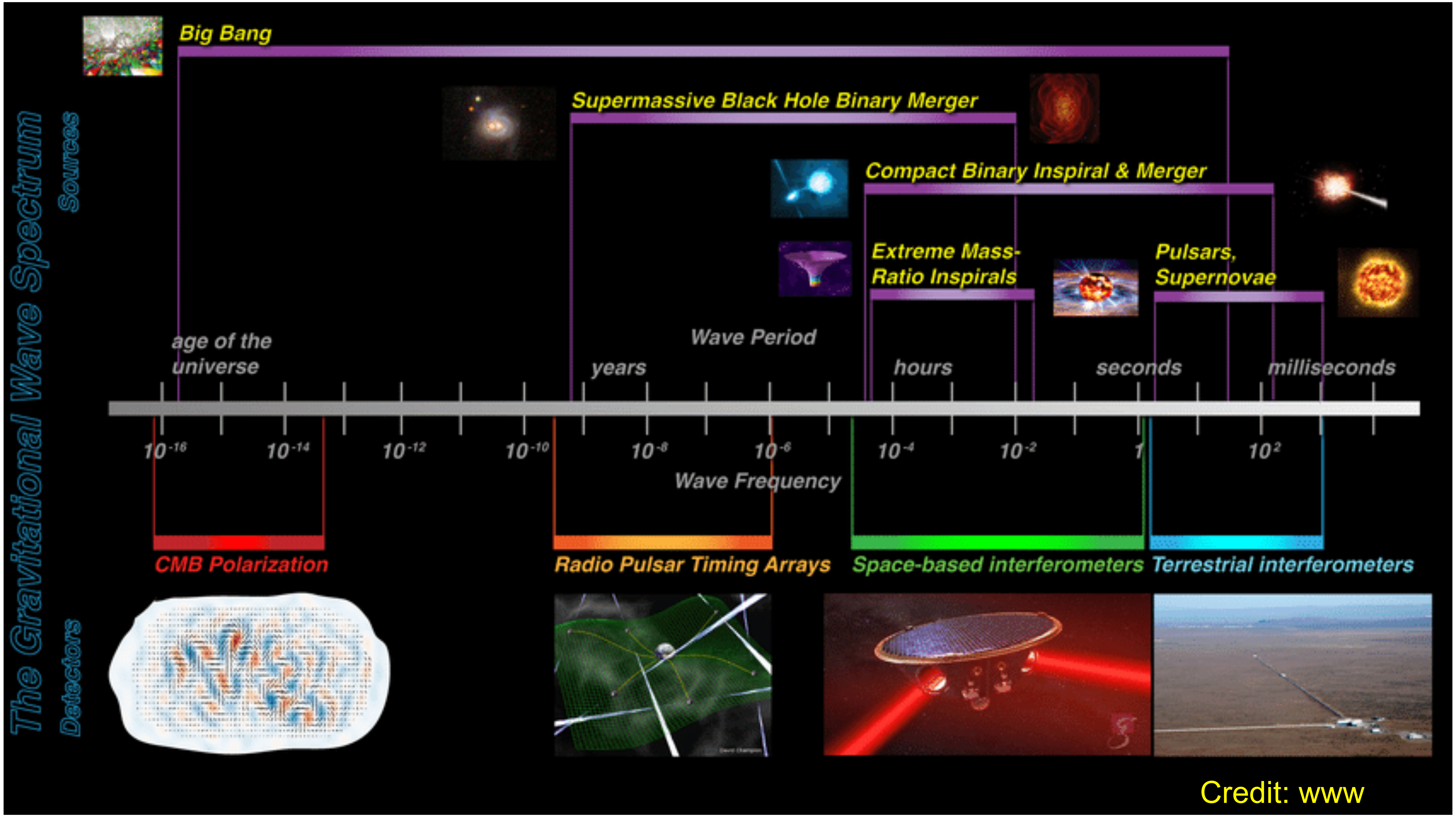
Hanford, Washington (H1)



Livingston, Louisiana (L1)

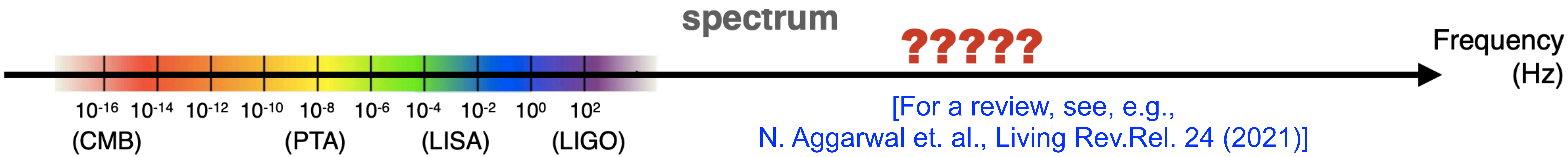


Detection of GWs - A General View

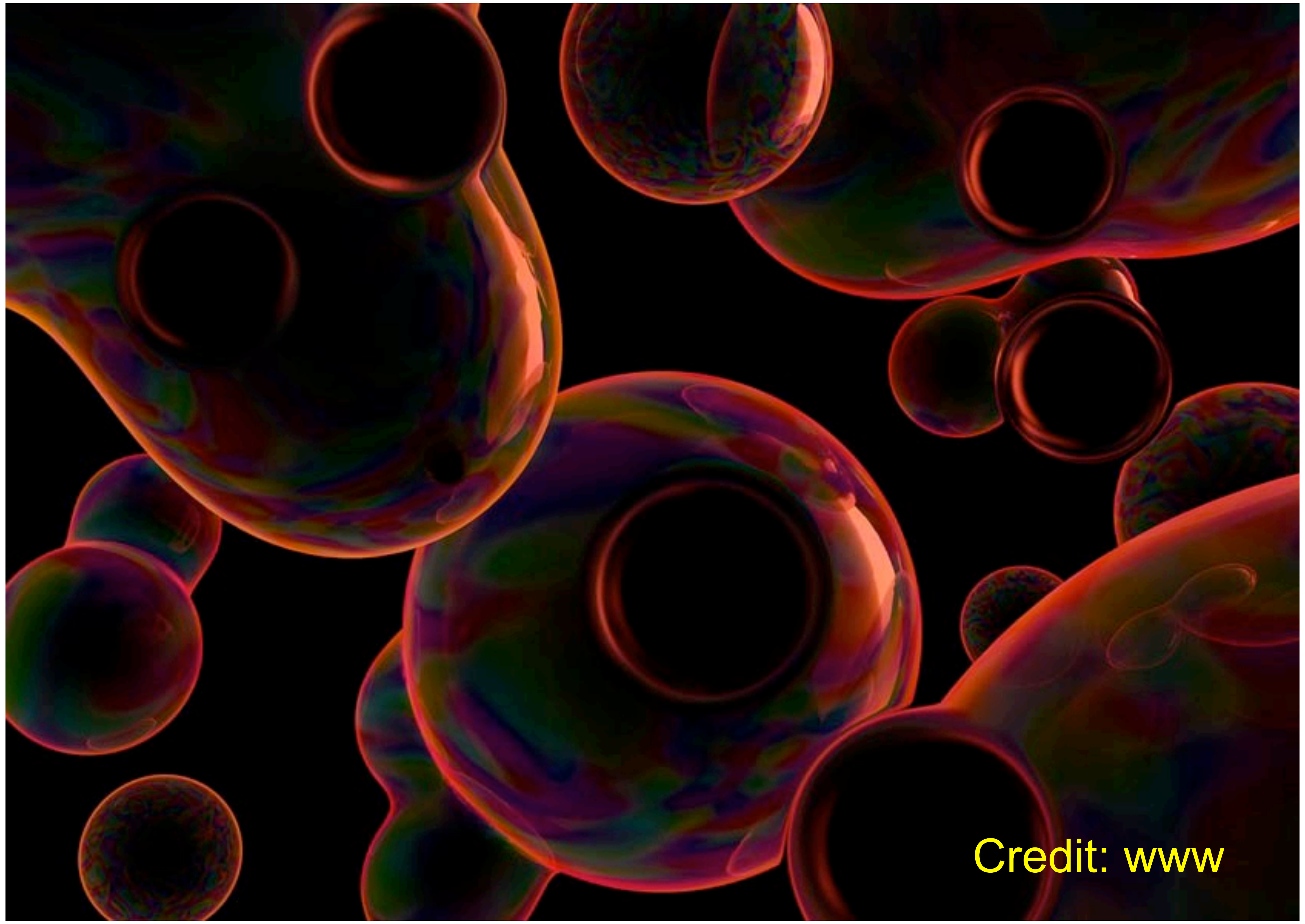


Credit: www

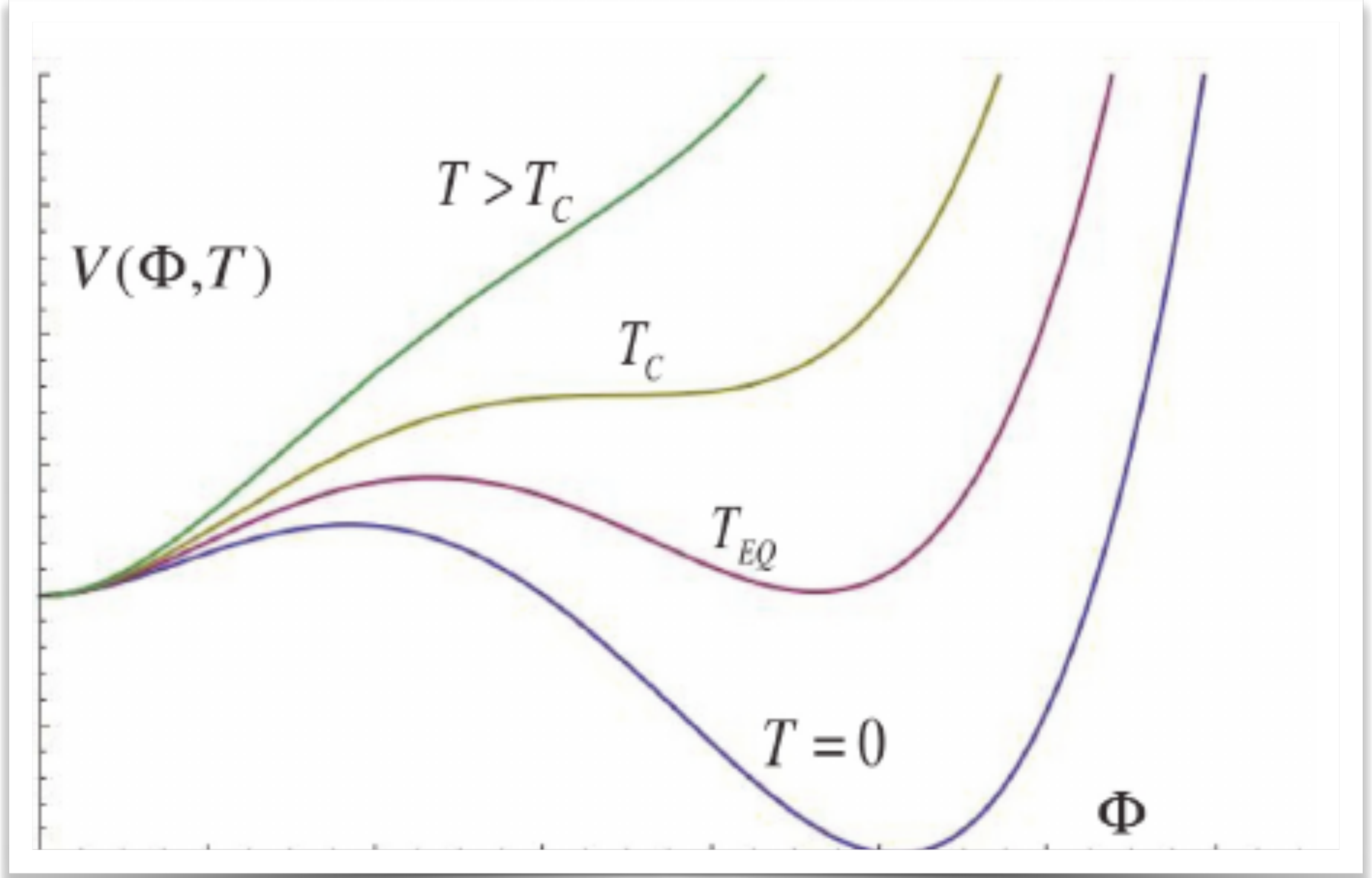
Sources for HFGWs - 1st Order Cosmological Phase Transition



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

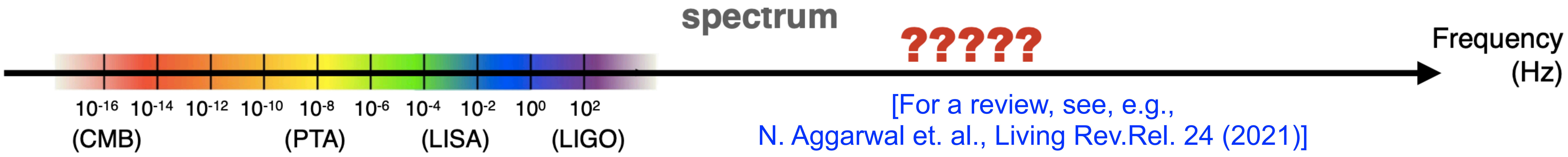


Credit: www

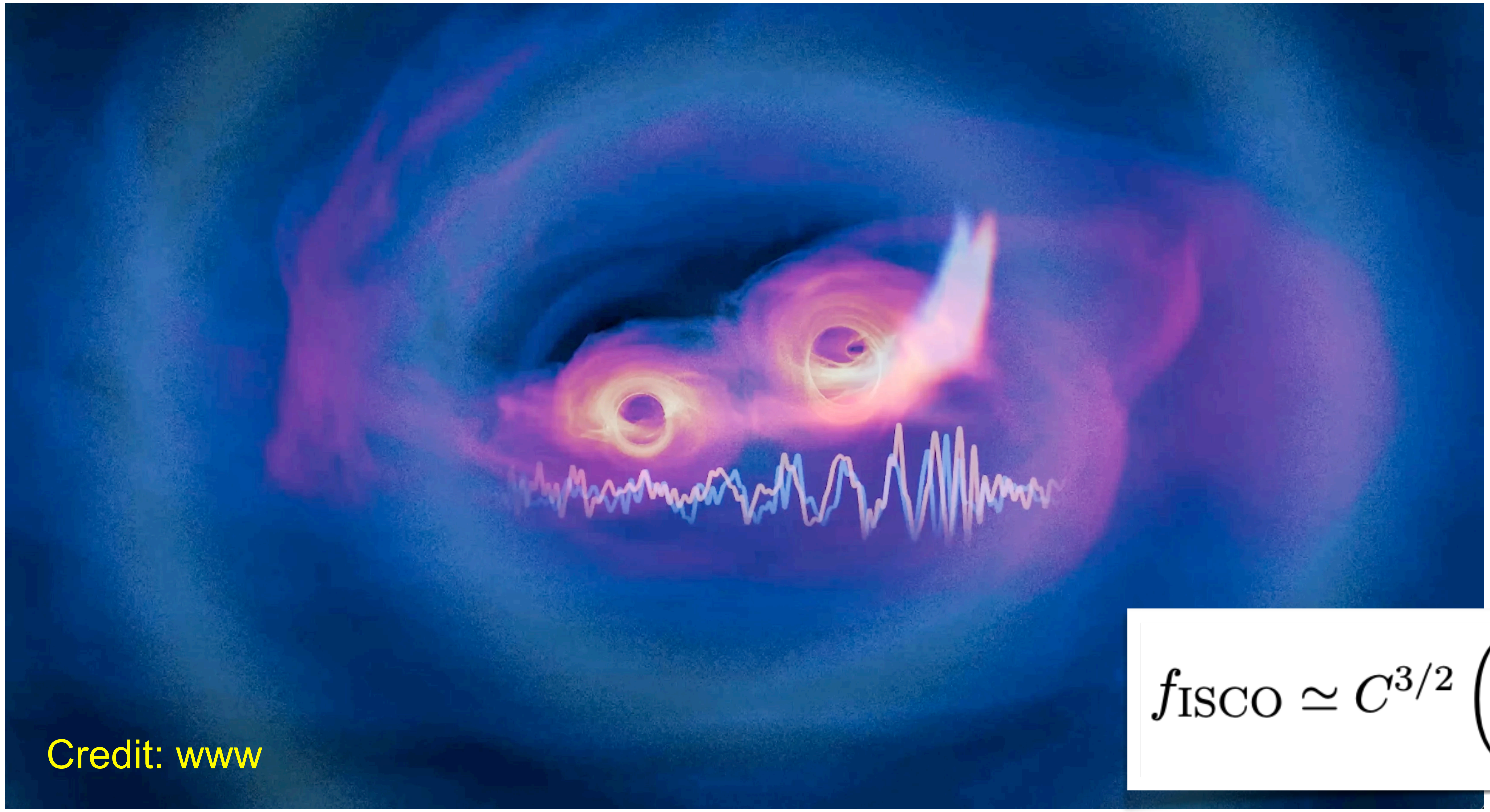


$$f \simeq 26 \left(\frac{1}{H_* R_*}\right) \left(\frac{T_*}{10^5\,\mathrm{GeV}}\right) \left(\frac{g_*(T_*)}{100}\right)^{1/6} \mathrm{mHz}$$

Sources for HFGWs - Light PBH/Compact Star Mergers



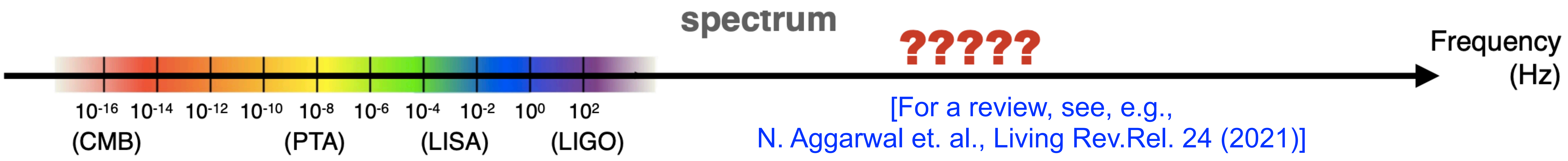
[For a review, see, e.g.,
N. Aggarwal et. al., Living Rev.Rel. 24 (2021)]



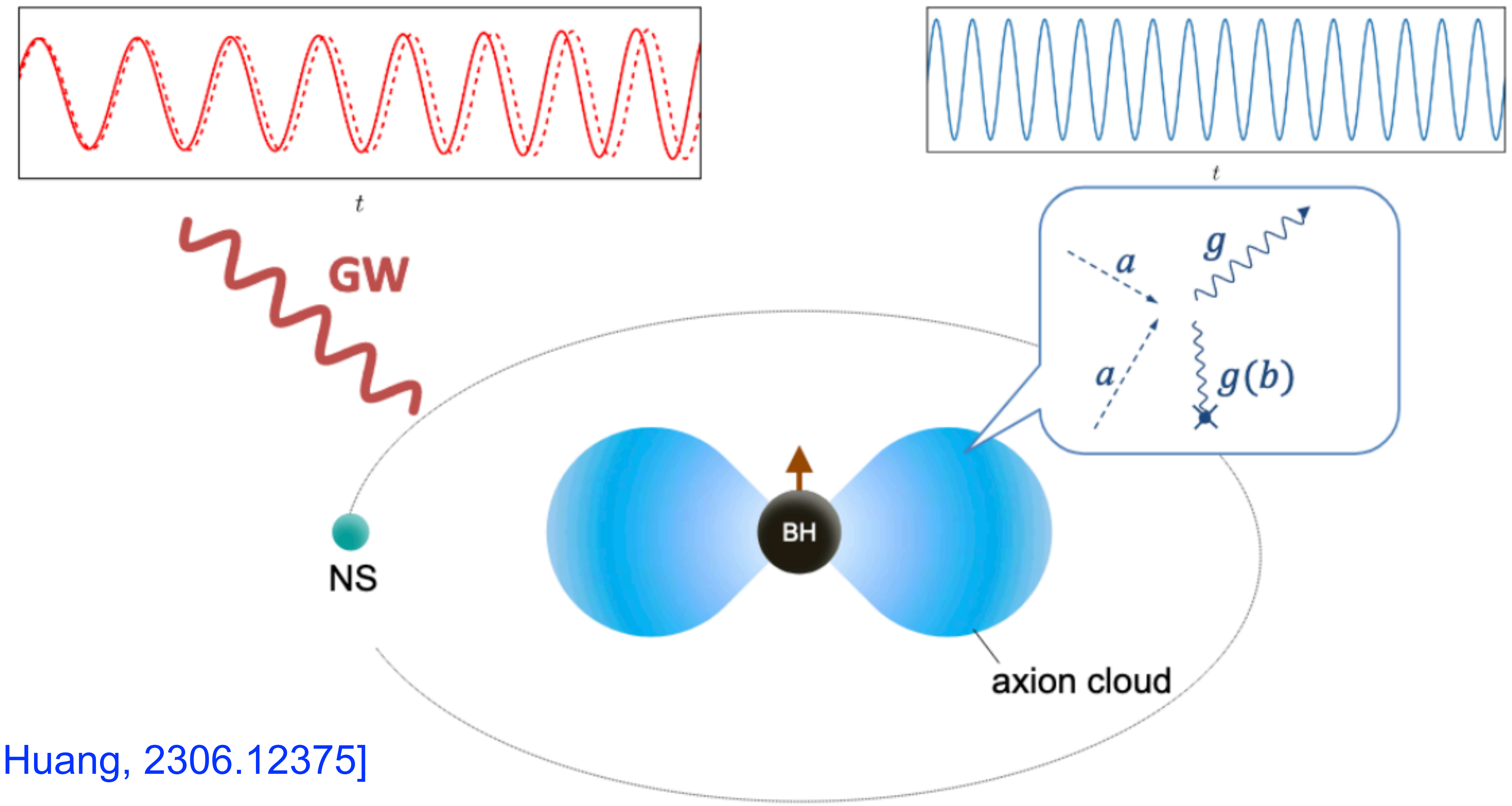
Credit: www

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

Sources for HFGWs - Axion Cloud (Annihilation and Decay)



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

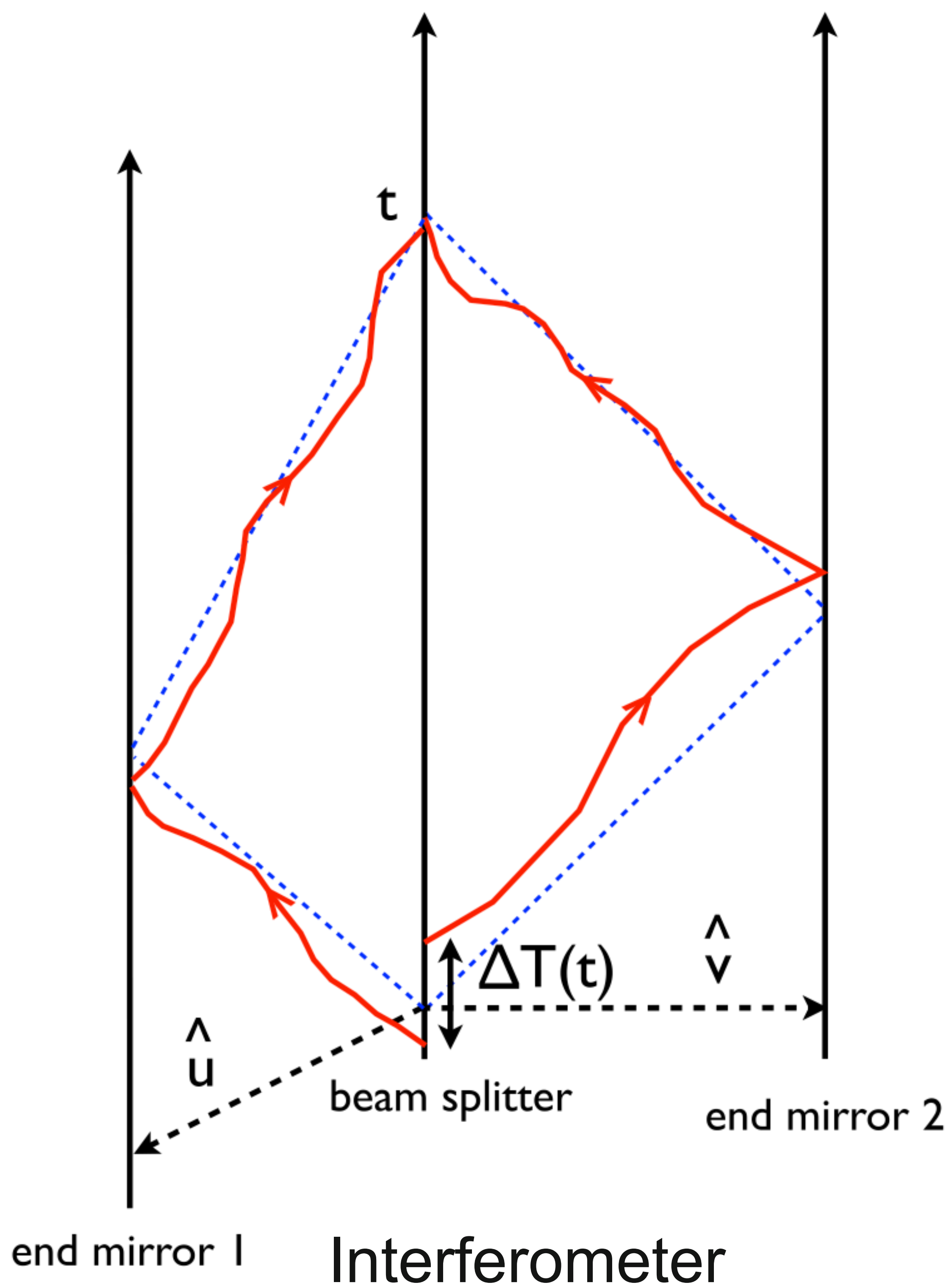


$$f \sim \left(\frac{m_a}{10^{-9}\mathrm{eV}}\right) 10^6 \mathrm{Hz}$$

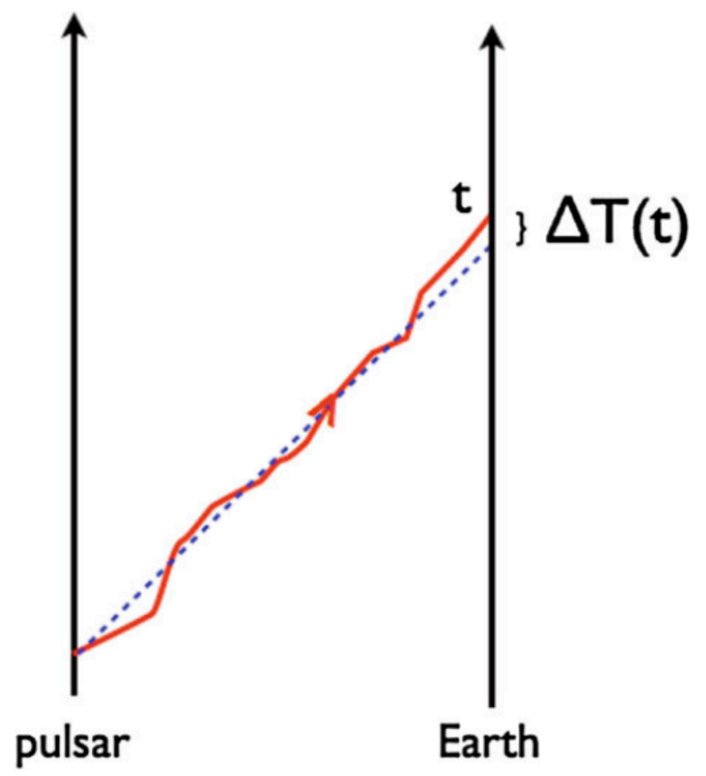
[Yang and Huang, 2306.12375]

Beam Detectors - Weak at High Frequencies

[J. Romano and N. Cornish, Living Rev.Rel. 20 (2017)]



Interferometer



Pulsar timing

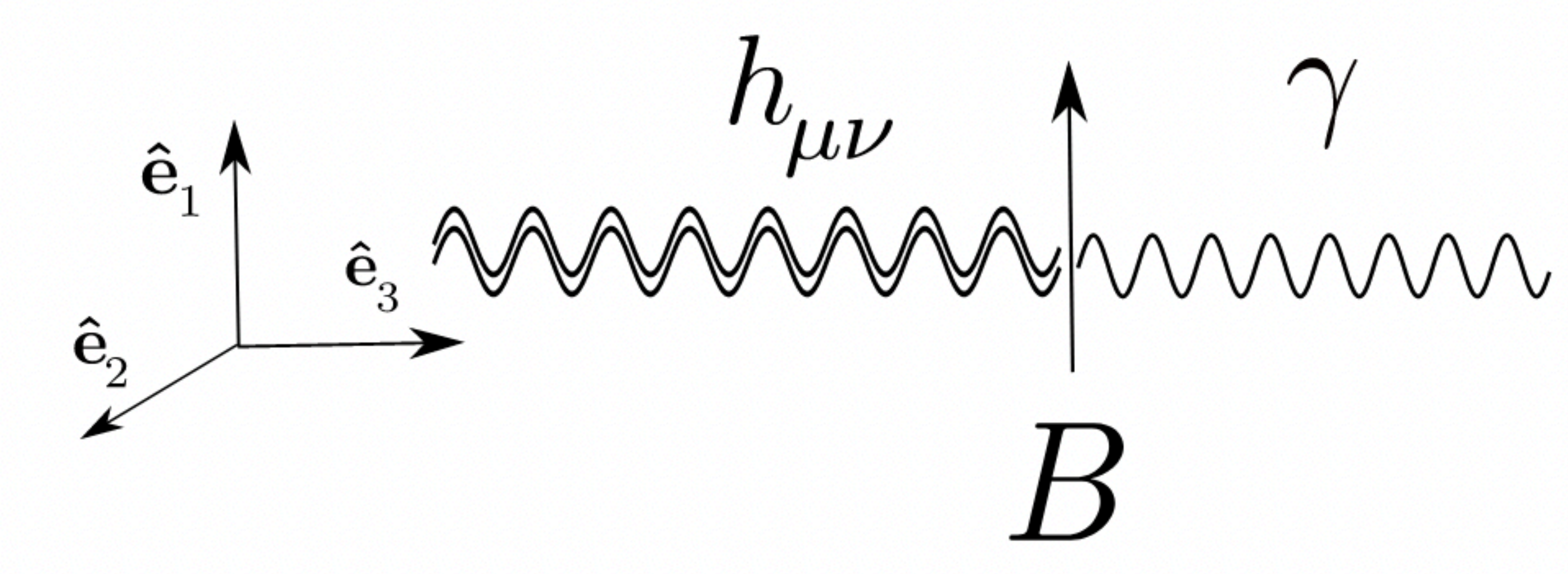
$$\Delta T(t) = \int_{-\infty}^{\infty} df \, \frac{1}{2} u^a u^b h_{ab}(f,\hat{n}) \, \frac{1}{i2\pi f} \, \frac{1}{1+\hat{n}\cdot\hat{u}} \left[e^{i2\pi f (t_2+\hat{n}\cdot\vec{r}_2/c)} - e^{i2\pi f (t_1+\hat{n}\cdot\vec{r}_1/c)} \right]$$

Suppressed at high-frequency

Detector characteristic size influences phase difference

Inverse Gertsenshtein Effect (Gertsenshtein, 1962)

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



$$\begin{pmatrix} \Delta_\gamma & \Delta_{\rm M} \\ \Delta_{\rm M} & 0 \end{pmatrix} \quad \begin{aligned} \Delta_{\rm M} &= \tfrac{1}{2}\kappa B_t \\ \Delta_\gamma &\approx \Delta_{\rm vac} + \Delta_{\rm pla} \end{aligned}$$

Encodes the GW-photon mixing

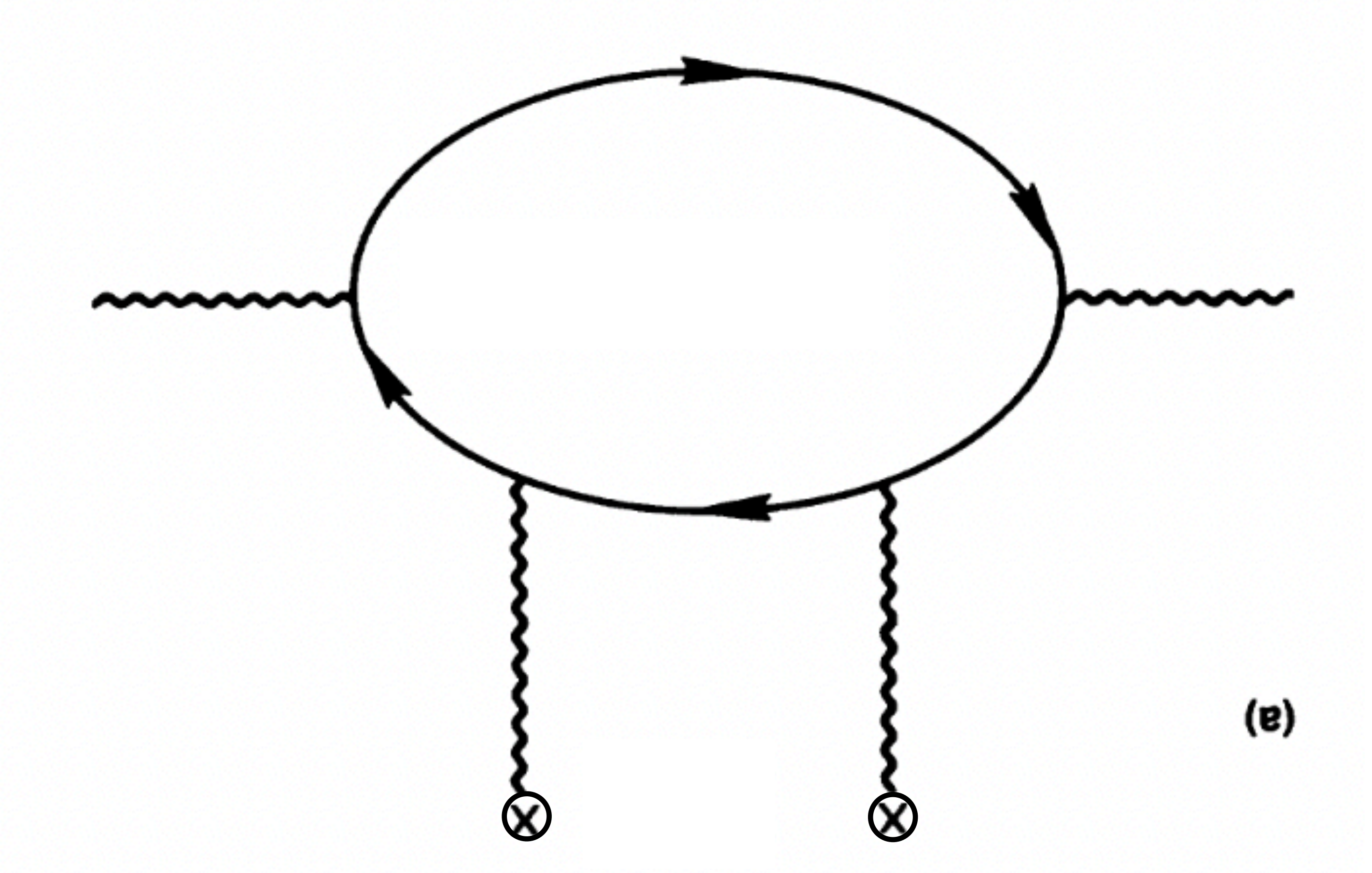
Photon diagonal mass

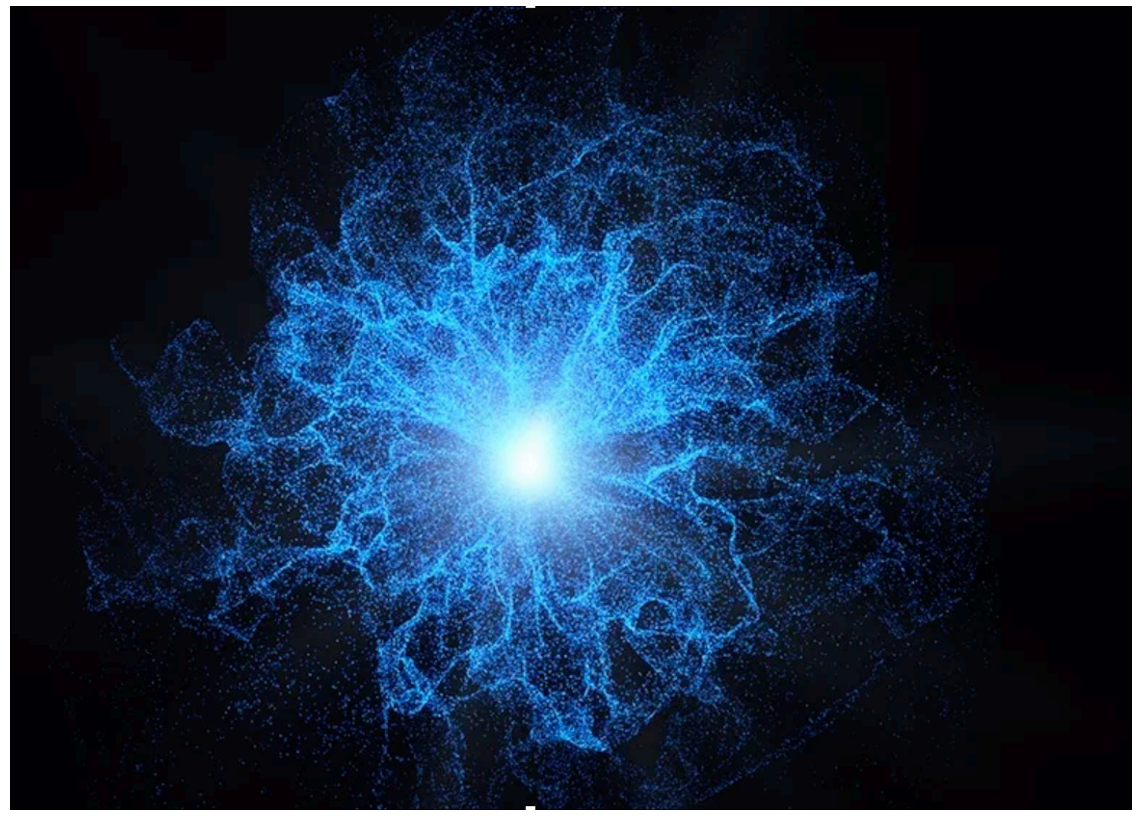
$$\Delta_{\rm pla} = -m_{\rm pla}^2/(2\omega)$$

$$\Delta_{\rm vac} = 7\alpha\omega/(90\pi)(B_t/B_c)^2$$

(Vacuum effect)

(Plasma effect)

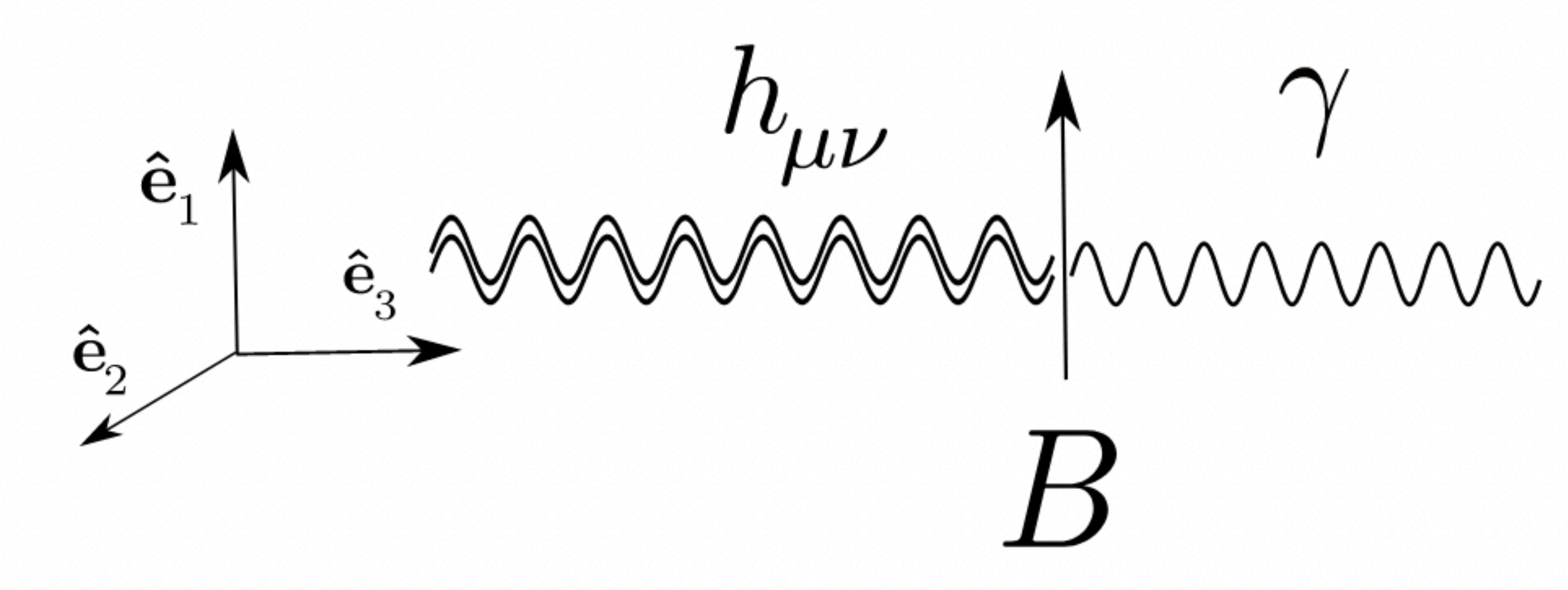




In an external magnetic field, the GWs could be converted into electromagnetic waves or photons with the same frequency.

Inverse Gertsenshtein Effect (Gertsenshtein, 1962)

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



General magnetic field

[Raffelt and Stodolsky, Phys.Rev.D 37 (1988)]

$$P = \left| \int_{\ell_0}^{\ell_1} d\ell\ \Delta_{\mathrm{M}}(\ell)\exp\left(-i\int_{\ell_0}^{\ell} d\ell'\ \Delta_\gamma(\ell')\right)\right|^2$$

L: characteristic travel distance of GWs in the magnetic field

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

GW-photon oscillation length

Homogeneous magnetic field

[Mirizzi and Montanino, JCAP 12, 004 (2009); Kartavtsev, et. al., JCAP 01, 024 (2017)]

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

Determined by the profile of exp setup

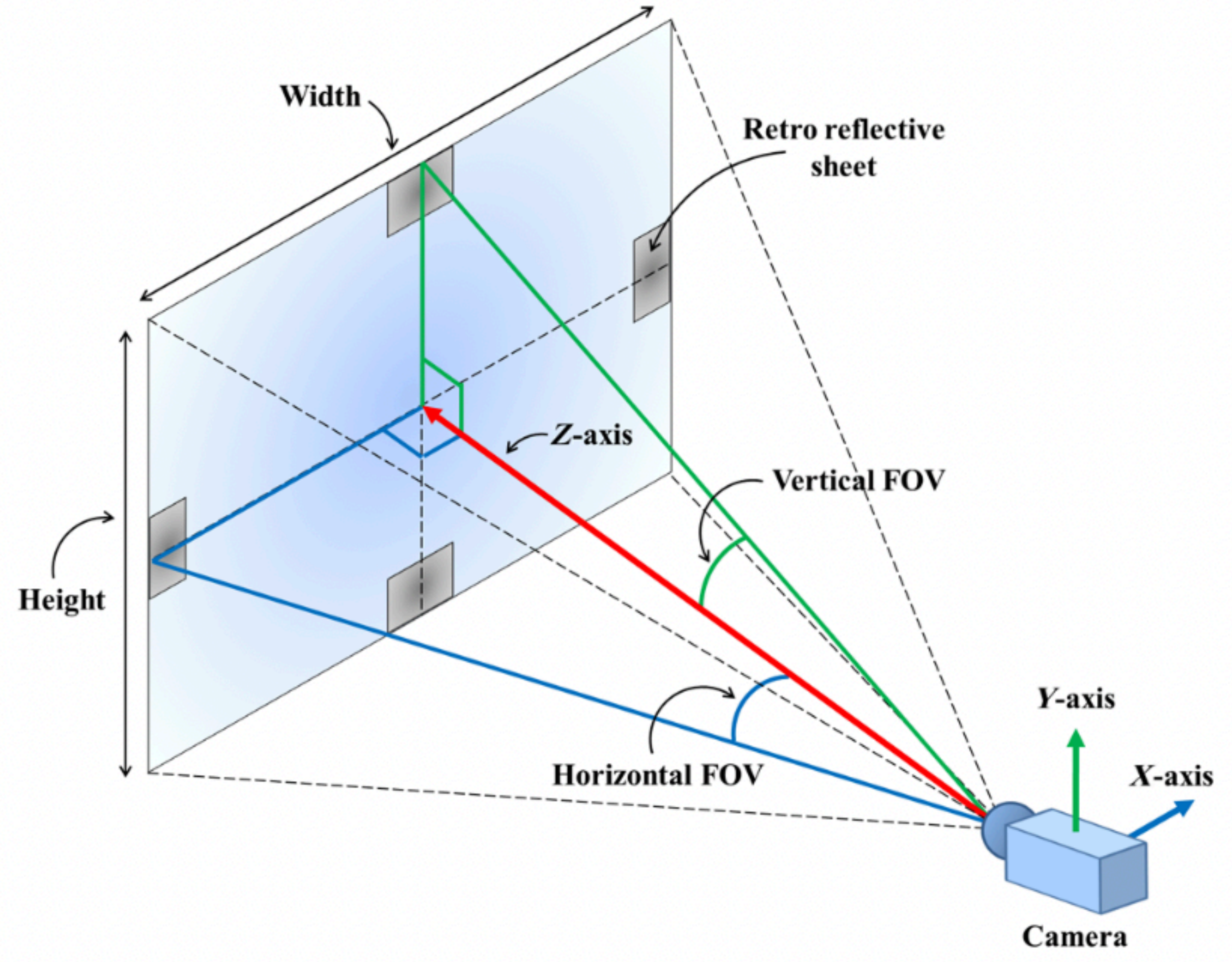
Coherence conversion: sinc -> 1 or large l_osc

Sensitivity Analysis

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

- Angular distribution of GW-converted photons is encoded in P (Ω')
- Photons falling into the detector FOV (ΔΩ) will contribute to Φ_γ

$$\begin{aligned} s &\approx \Phi_\gamma A\,\Delta t \approx \frac{h_c^2}{4\pi\kappa^2} \langle P \rangle_{\rm det} A\,\Delta t \Delta\omega \Delta\Omega\,, \\ b &\approx \Phi_b A\,\Delta t \approx \phi_b A\,\Delta t \Delta\omega \Delta\Omega\,, \end{aligned}$$

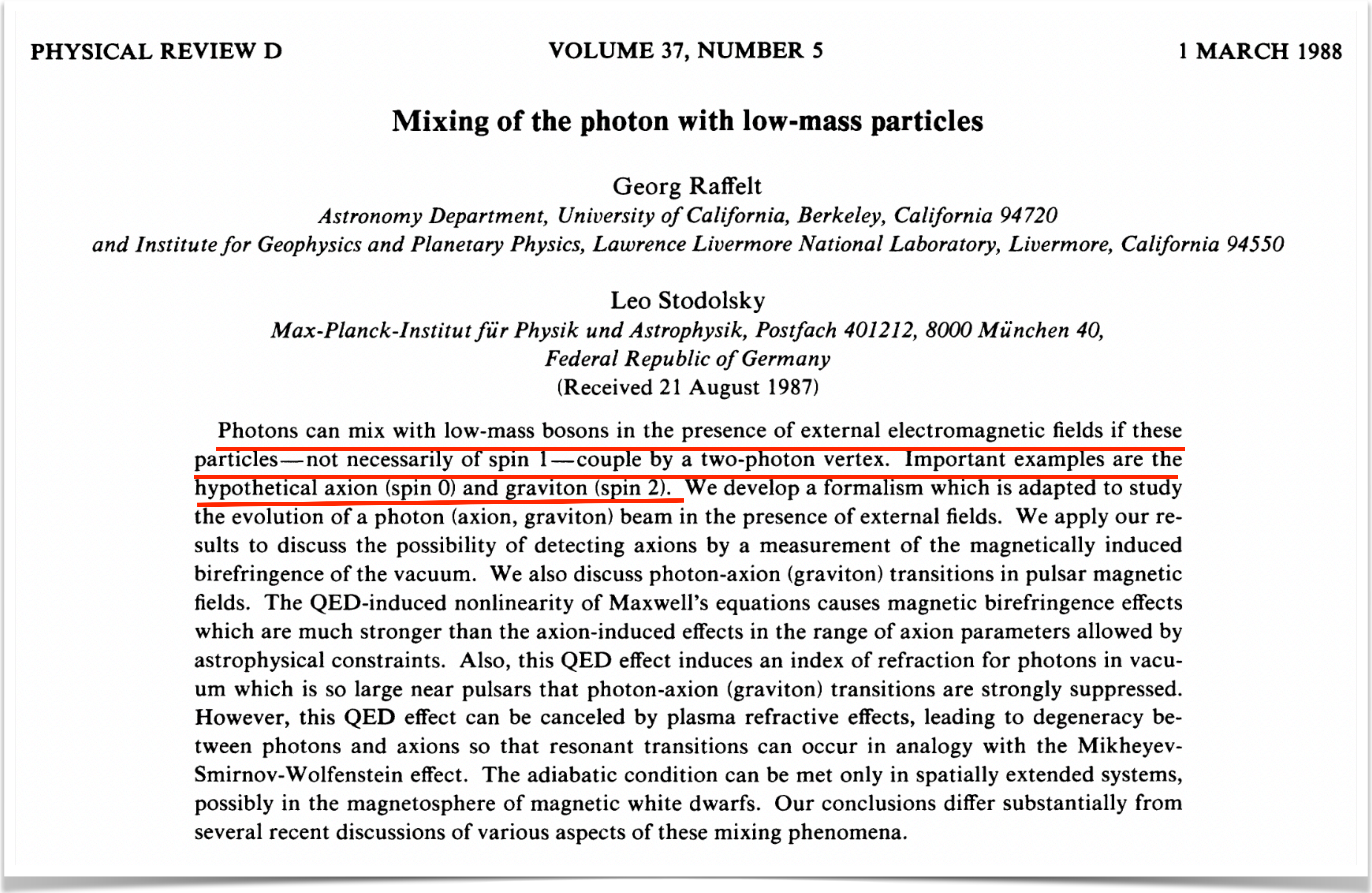


$$\boxed{h_{c,95\%} \approx 4.5\kappa \left(\frac{\phi_b}{A\,\Delta t \Delta\omega \Delta\Omega} \right)^{1/4} \left(\frac{1}{\langle P \rangle_{\rm det}} \right)^{1/2}}$$

Two Representative Cases in Astronomy

	Neutron Star	Earth
Surface magnetic field (SMF)	Extremely strong ~ 10^8 - 10^15 Gauss	Very weak ~ 0.5 Gauss
Plasma density	Goldreich-Julian model	Barometric model
Plasma density (analytical formula)	$n_c = \frac{2\mathbf{\Omega} \cdot \mathbf{B}}{e} \frac{1}{1 - \Omega^2 r^2 \sin^2 \theta}$	$n_c^{\mathrm{Bar}} = n_{c,0} \exp\left(-\frac{r - r_0}{H_{\mathrm{cor}}}\right)$
Distance	Distant ~ O(100-1000) parsecs	Nearby

Magnetosphere Conversion - Neutron Star



PHYSICAL REVIEW D VOLUME 37, NUMBER 5 1 MARCH 1988

Mixing of the photon with low-mass particles

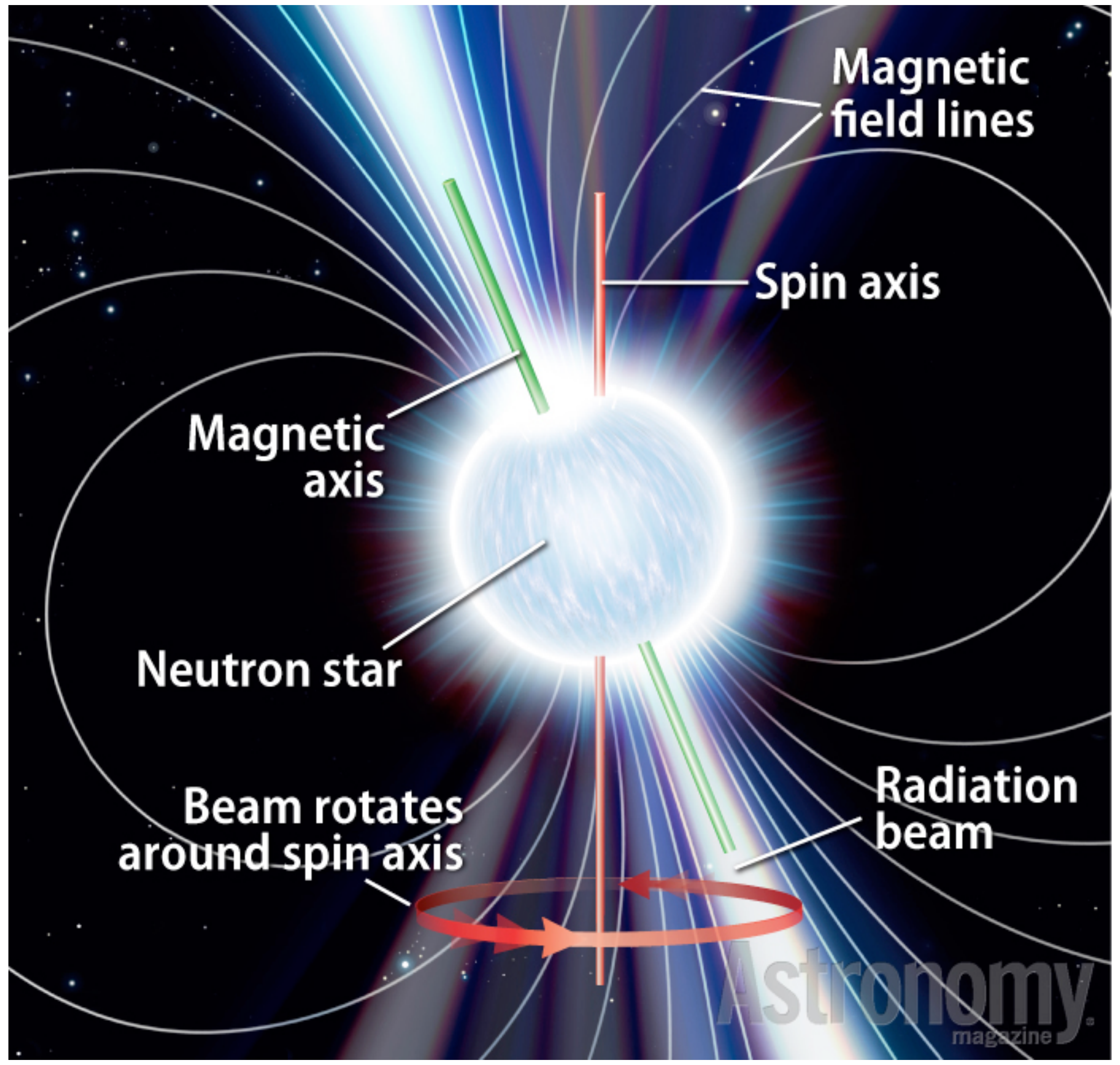
Georg Raffelt
Astronomy Department, University of California, Berkeley, California 94720
and Institute for Geophysics and Planetary Physics, Lawrence Livermore National Laboratory, Livermore, California 94550

Leo Stodolsky
Max-Planck-Institut für Physik und Astrophysik, Postfach 401212, 8000 München 40,
Federal Republic of Germany

(Received 21 August 1987)

Photons can mix with low-mass bosons in the presence of external electromagnetic fields if these particles—not necessarily of spin 1—couple by a two-photon vertex. Important examples are the hypothetical axion (spin 0) and graviton (spin 2). We develop a formalism which is adapted to study the evolution of a photon (axion, graviton) beam in the presence of external fields. We apply our results to discuss the possibility of detecting axions by a measurement of the magnetically induced birefringence of the vacuum. We also discuss photon-axion (graviton) transitions in pulsar magnetic fields. The QED-induced nonlinearity of Maxwell's equations causes magnetic birefringence effects which are much stronger than the axion-induced effects in the range of axion parameters allowed by astrophysical constraints. Also, this QED effect induces an index of refraction for photons in vacuum which is so large near pulsars that photon-axion (graviton) transitions are strongly suppressed. However, this QED effect can be canceled by plasma refractive effects, leading to degeneracy between photons and axions so that resonant transitions can occur in analogy with the Mikheyev-Smirnov-Wolfenstein effect. The adiabatic condition can be met only in spatially extended systems, possibly in the magnetosphere of magnetic white dwarfs. Our conclusions differ substantially from several recent discussions of various aspects of these mixing phenomena.

Magnetosphere Conversion - Neutron Star



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

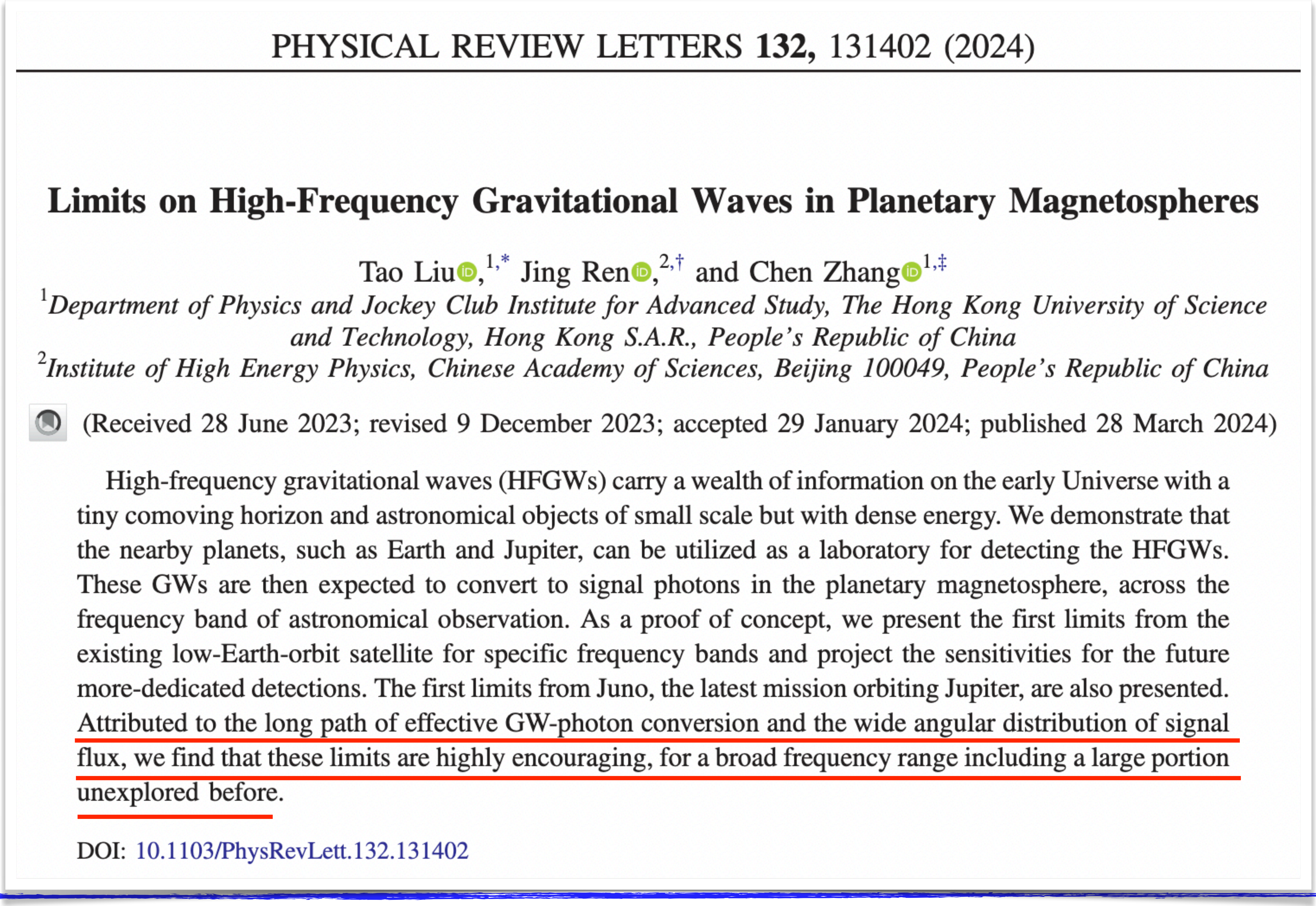
$$\boxed{h_{c,95\%} \approx 4.5\kappa\left(\frac{\phi_b}{A\,\Delta t\Delta\omega\Delta\Omega}\right)^{1/4}\left(\frac{1}{\langle P\rangle_{\rm det}}\right)^{1/2}}$$

- **Strong magnetic field** => large $\Delta_M \propto B$
  - Overall enhancement for the factor of conversion probability: $(\Delta_M L)^2$
  - Difficult to achieve coherent conversion [Raffelt and Stodolsky, Phys.Rev.D 37 (1988)]

$$l_{\rm osc} = 2/(4\Delta_{\rm M}^2 + \Delta_\gamma^2)^{1/2} \qquad \Delta_{\rm pla} = -\frac{m_{\rm pla}^2}{2\omega} \propto \frac{n_c}{\omega}$$

- **G-J model** => Even worse for low-frequency regime (suppressed losc in the magnetosphere):
- **Distant** => Angular distribution of signal photon flux is extremely narrow

Magnetosphere Conversion - Earth



PHYSICAL REVIEW LETTERS **132,** 131402 (2024)

Limits on High-Frequency Gravitational Waves in Planetary Magnetospheres

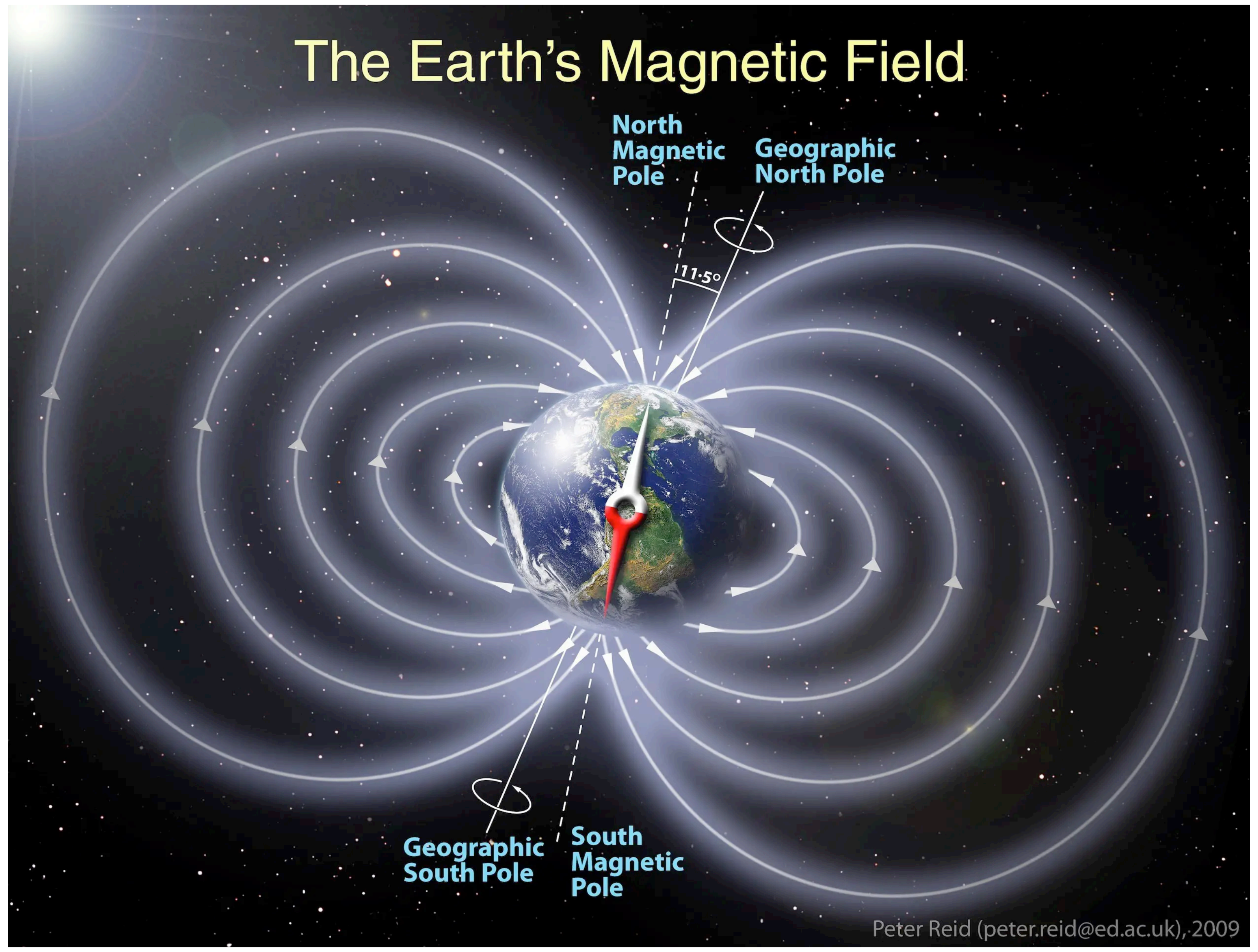
Tao Liu,[1,*] Jing Ren,[2,†] and Chen Zhang[1,‡]
[1]*Department of Physics and Jockey Club Institute for Advanced Study, The Hong Kong University of Science and Technology, Hong Kong S.A.R., People's Republic of China*
[2]*Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, People's Republic of China*

(Received 28 June 2023; revised 9 December 2023; accepted 29 January 2024; published 28 March 2024)

High-frequency gravitational waves (HFGWs) carry a wealth of information on the early Universe with a tiny comoving horizon and astronomical objects of small scale but with dense energy. We demonstrate that the nearby planets, such as Earth and Jupiter, can be utilized as a laboratory for detecting the HFGWs. These GWs are then expected to convert to signal photons in the planetary magnetosphere, across the frequency band of astronomical observation. As a proof of concept, we present the first limits from the existing low-Earth-orbit satellite for specific frequency bands and project the sensitivities for the future more-dedicated detections. The first limits from Juno, the latest mission orbiting Jupiter, are also presented. Attributed to the long path of effective GW-photon conversion and the wide angular distribution of signal flux, we find that these limits are highly encouraging, for a broad frequency range including a large portion unexplored before.

DOI: 10.1103/PhysRevLett.132.131402

Magnetosphere Conversion - Earth



Peter Reid (peter.reid@ed.ac.uk), 2009

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

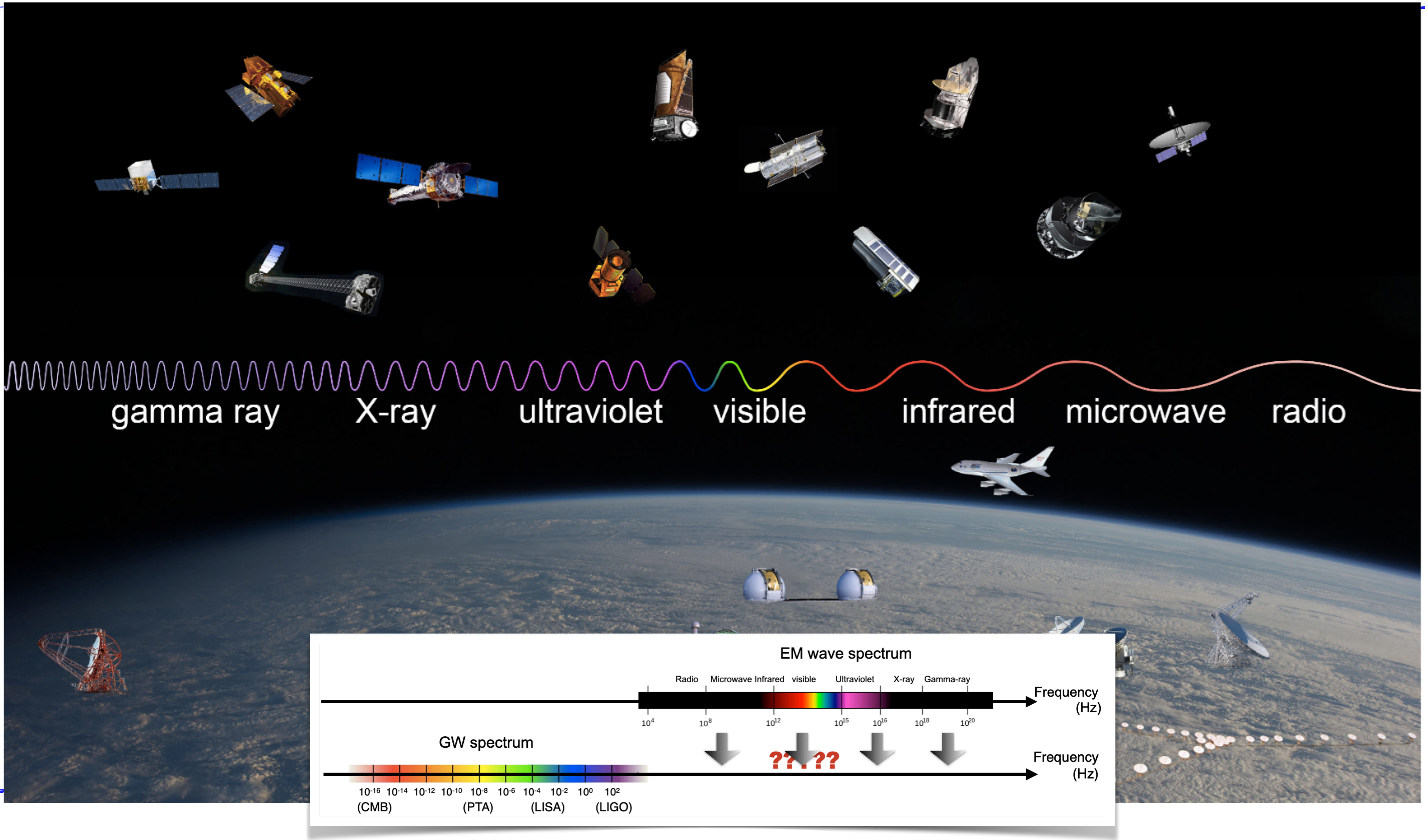
$$h_{c,95\%} \approx 4.5\kappa\left(\frac{\phi_b}{A\,\Delta t \Delta\omega \Delta\Omega}\right)^{1/4}\left(\frac{1}{\langle P\rangle_{\rm det}}\right)^{1/2}$$

- **Weak magnetic field** => small $\Delta_M \propto B$
  - Despite of smallness of $(\Delta_M L)^2$, coherent conversion is easy to achieve

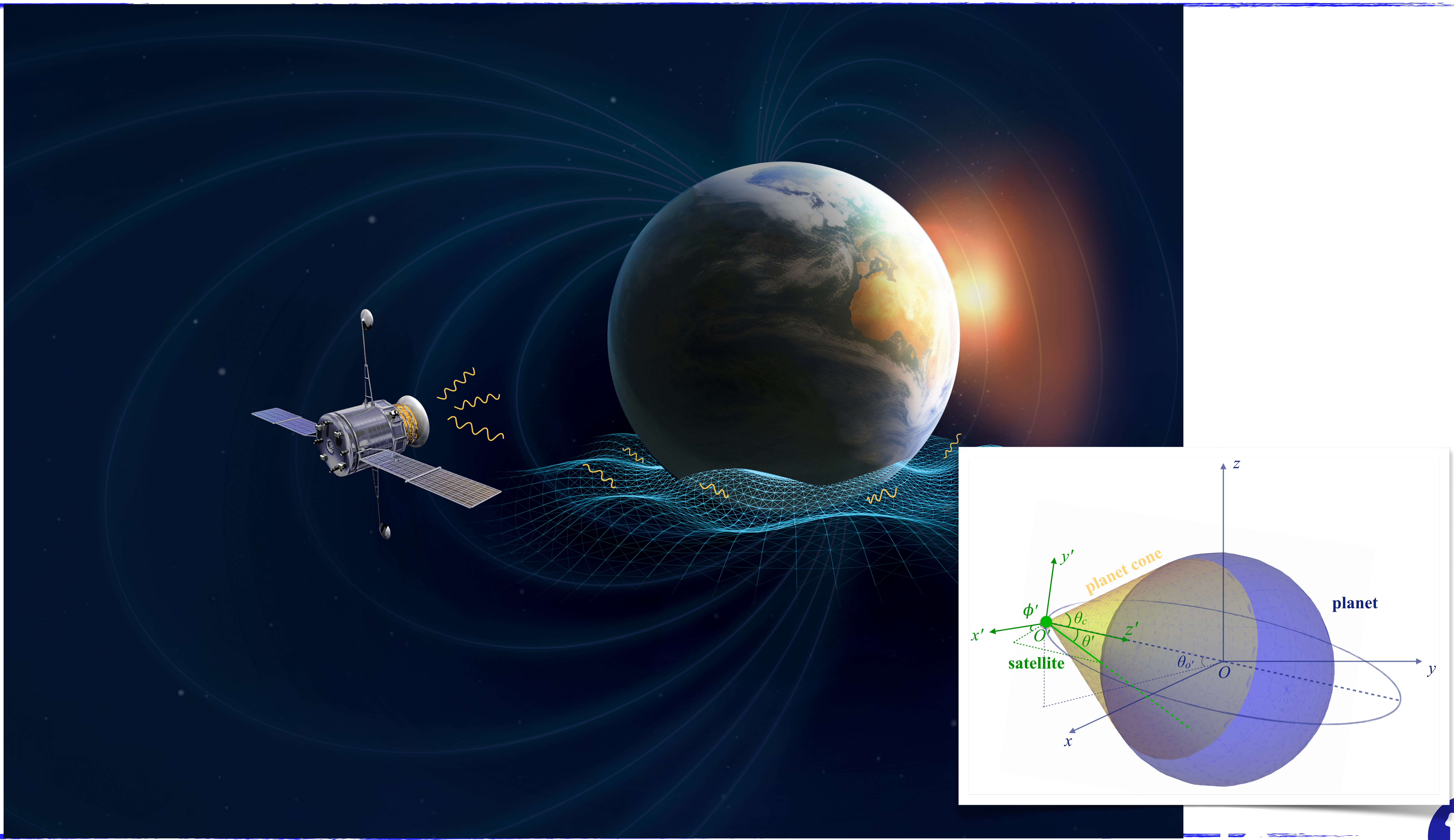
$$l_{\rm osc} = 2/(4\Delta_{\rm M}^2 + \Delta_\gamma^2)^{1/2} \qquad \Delta_{\rm pla} = -\frac{m_{\rm pla}^2}{2\omega} \propto \frac{n_c}{\omega}$$

- **Barometric model** => n_c suppresses l_{osc} significantly only for low frequency and at low altitude
- **Nearby** => Wide angular distribution of signal photon flux (subject to technology constraints for FOV)

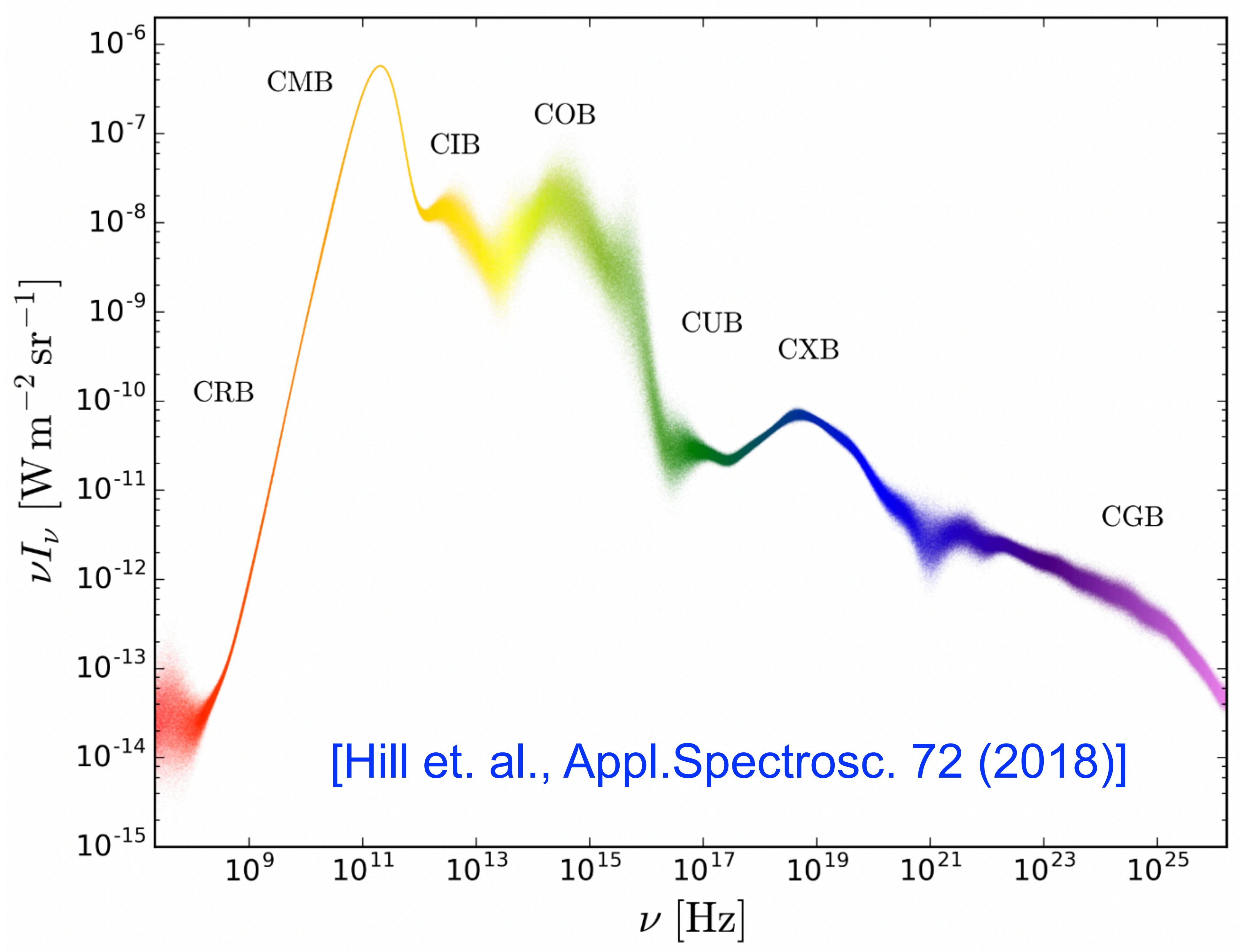
Electromagnetic Telescopes - New Scientific Values



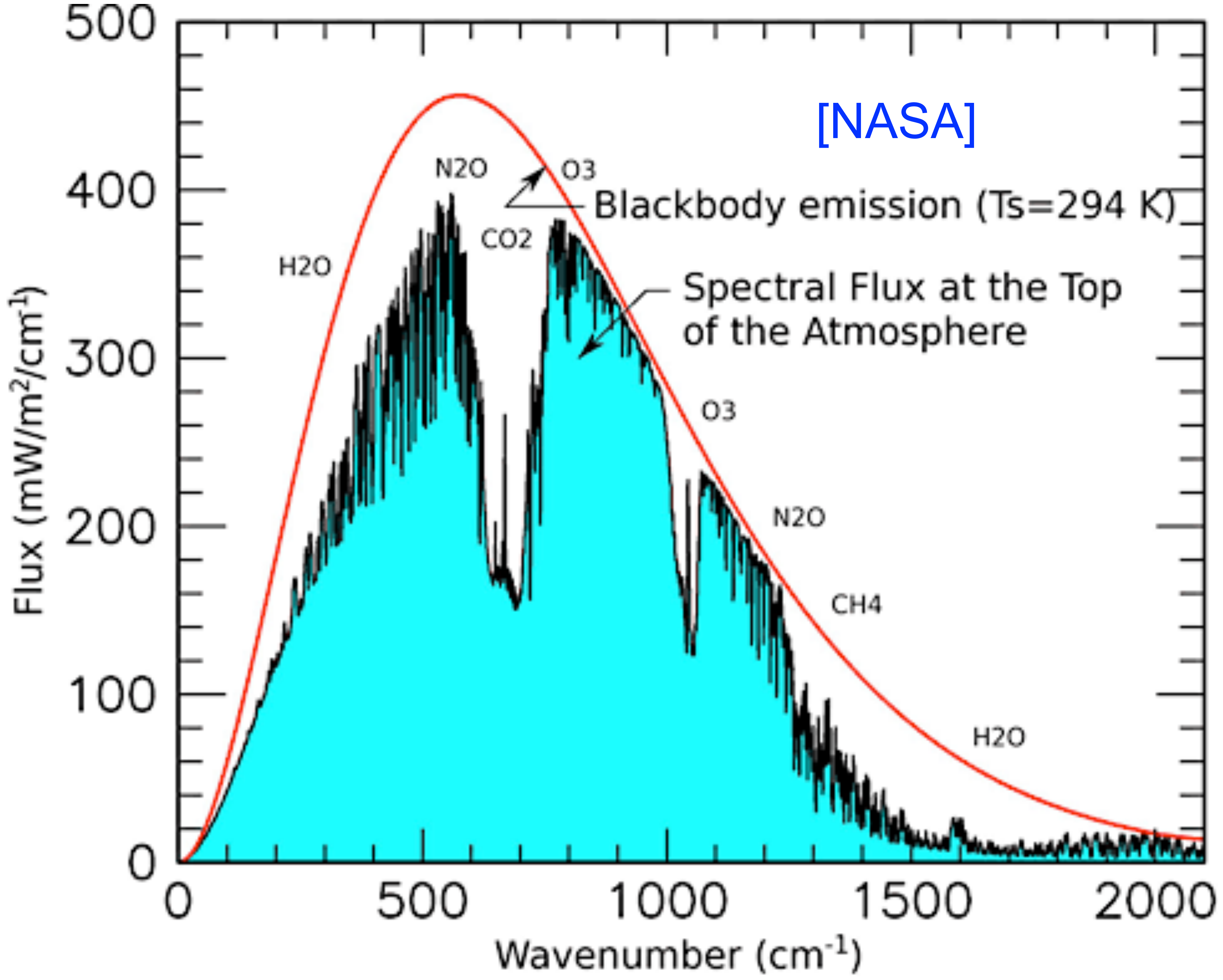
Low-Orbit Satellite with a Birdview in Earth's Dark Side



Main Backgrounds



[Hill et. al., Appl.Spectrosc. 72 (2018)]



[NASA]

Albedo reflection of cosmic photons

Atmospheric thermal emission

Two Benchmark Scenarios

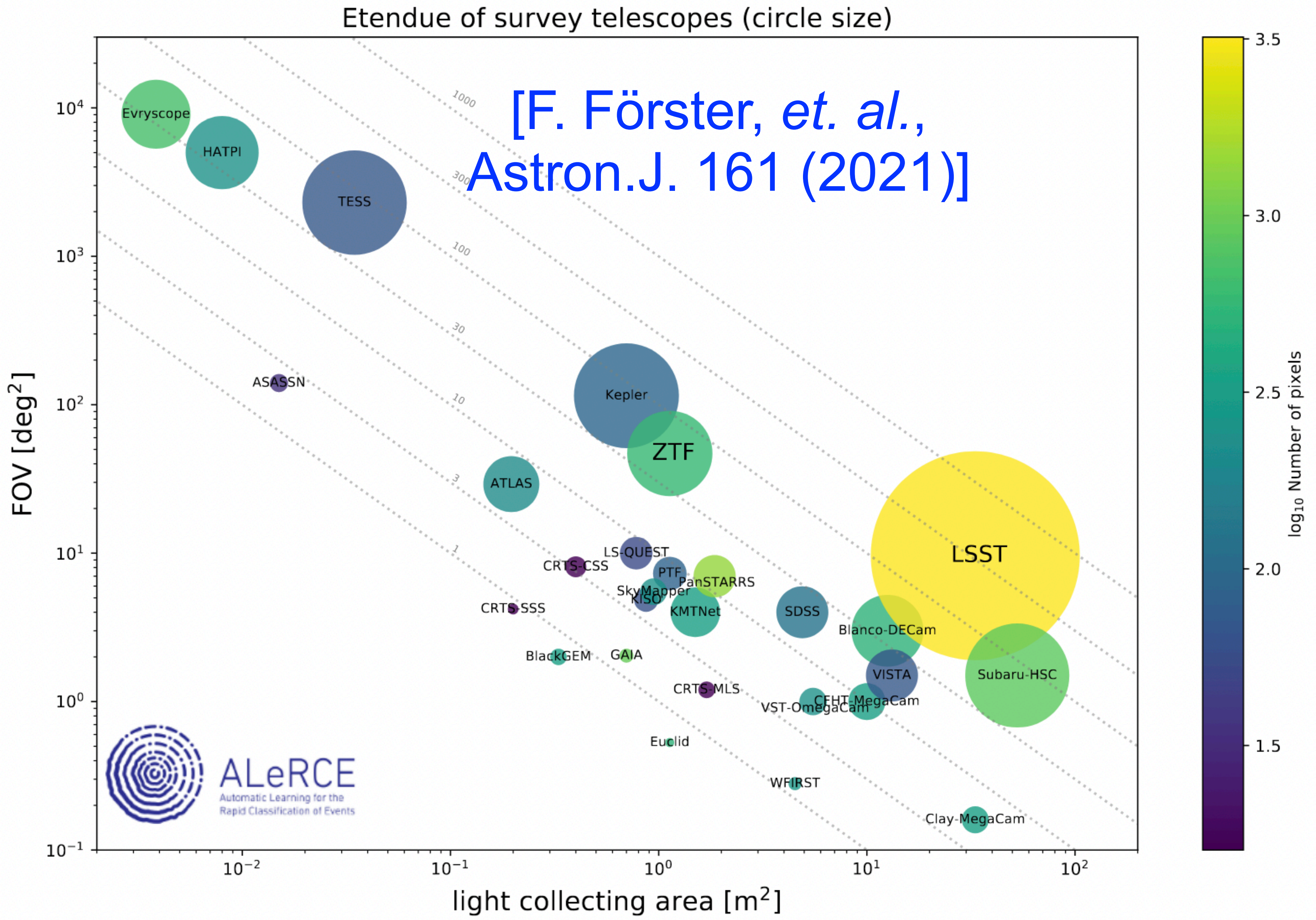
SUZAKU-like

Nimbus Hubble Voyager SUZAKU Fermi-LAT

	Satellite orbit			Detector properties					
	H (km)	θ_{inc}	T_{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

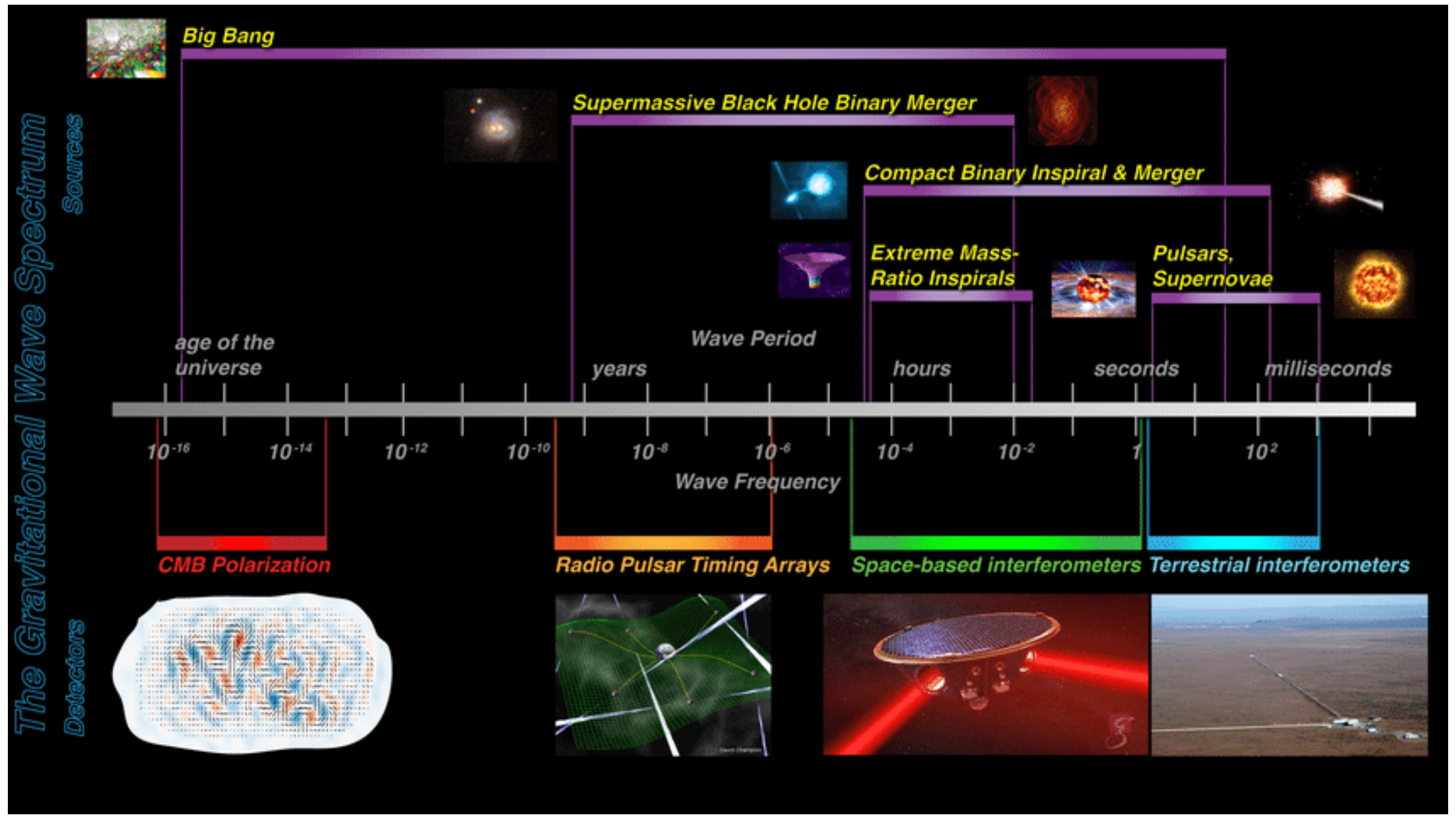
SAFIR 2-like

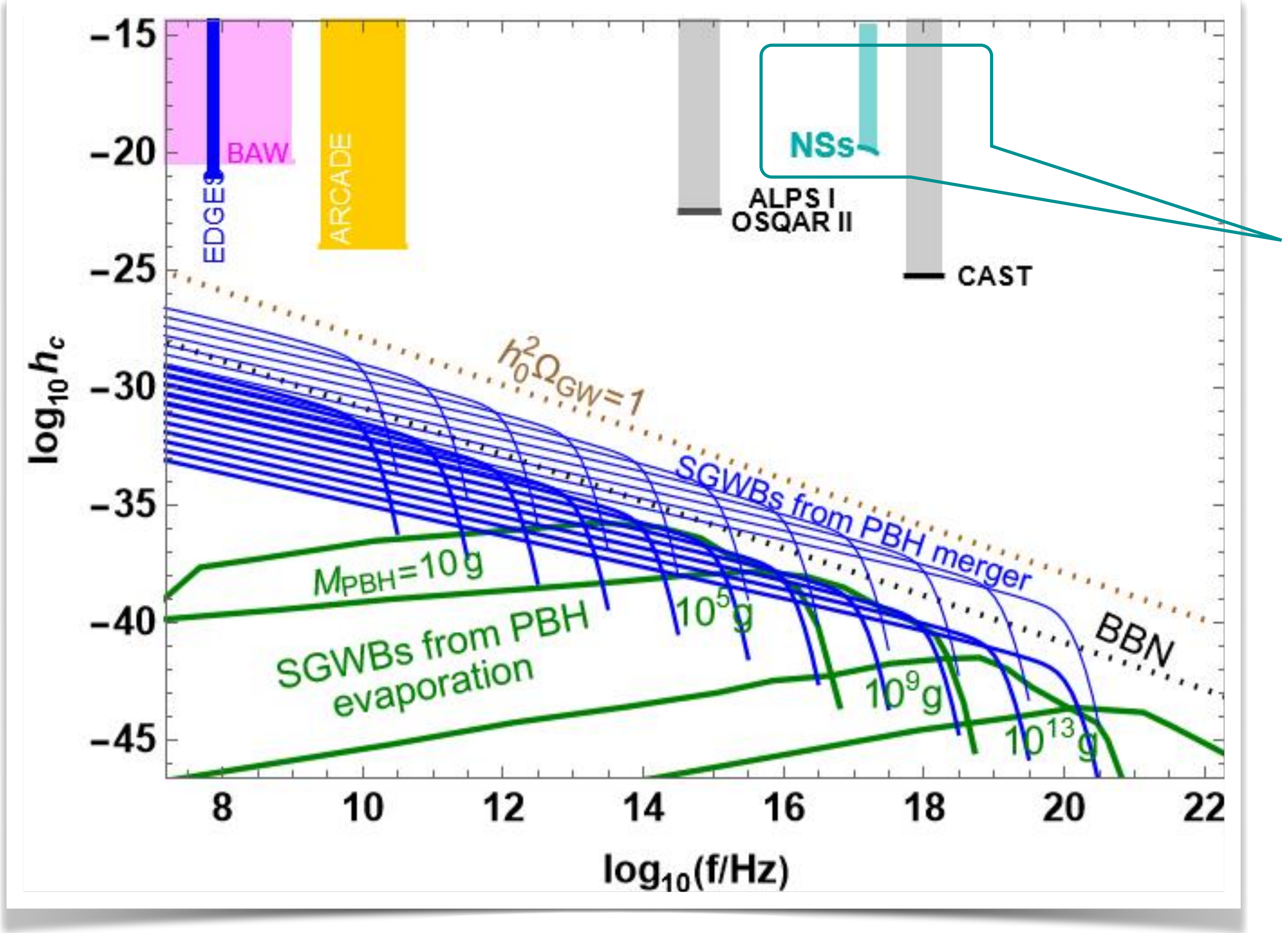
- Detect isotropic stochastic background of HFGWs
  - Conservative scenario: follow the etendue profile of existing missions
  - Optimistic scenario: follow the etendue profile of future telescopes



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

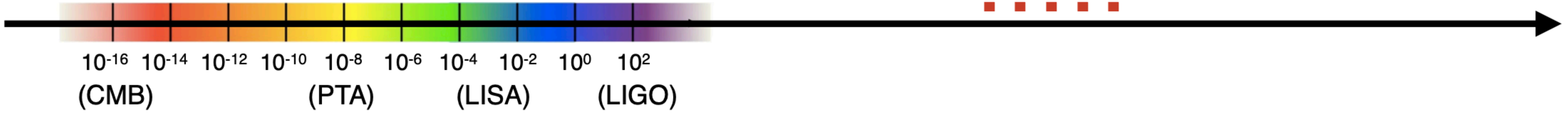
Sensitivities Demonstration





Based on the M7 X-ray dim isolated NSs

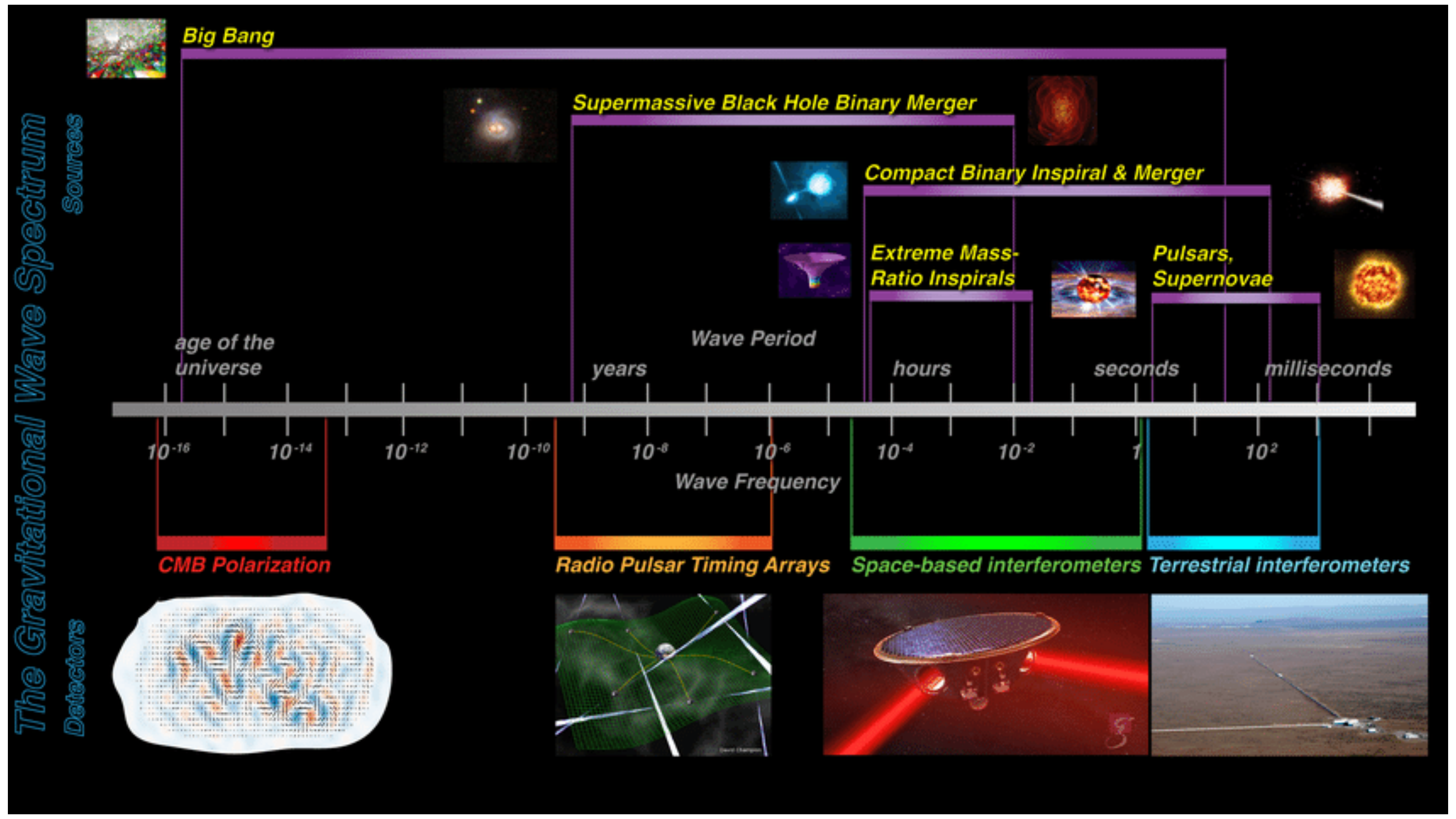
spectrum

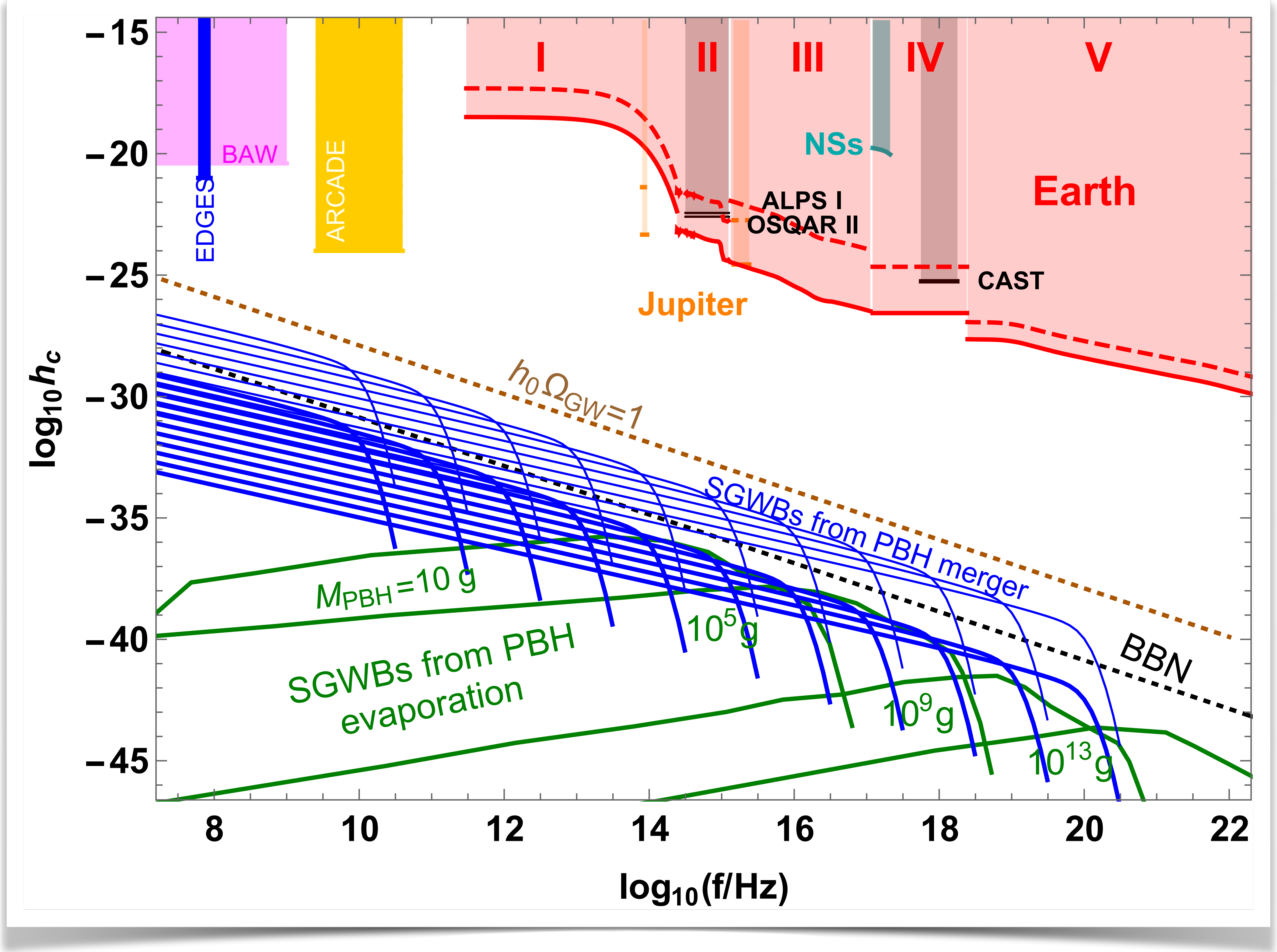


?????

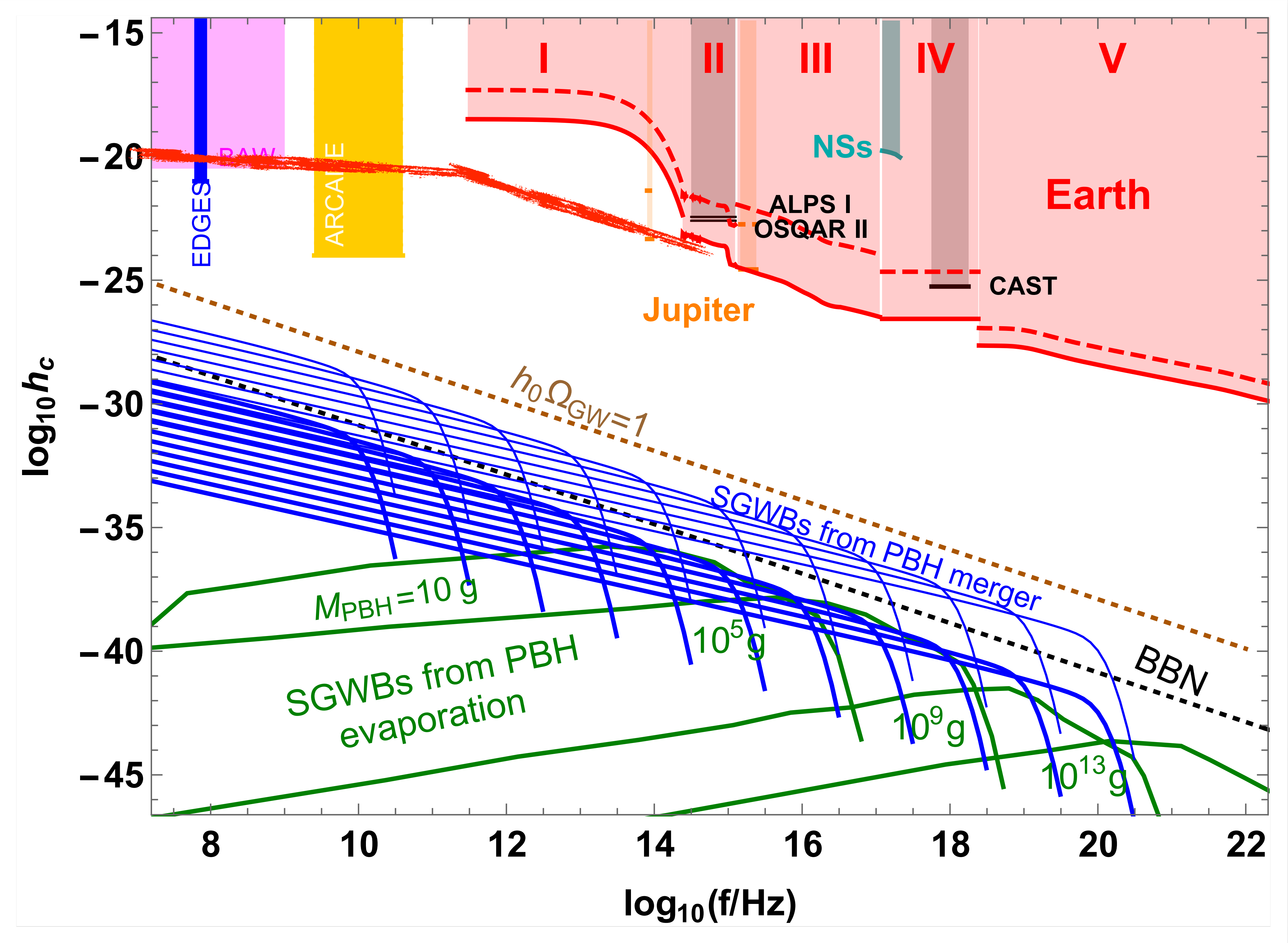
Frequency (Hz)

Sensitivities Demonstration



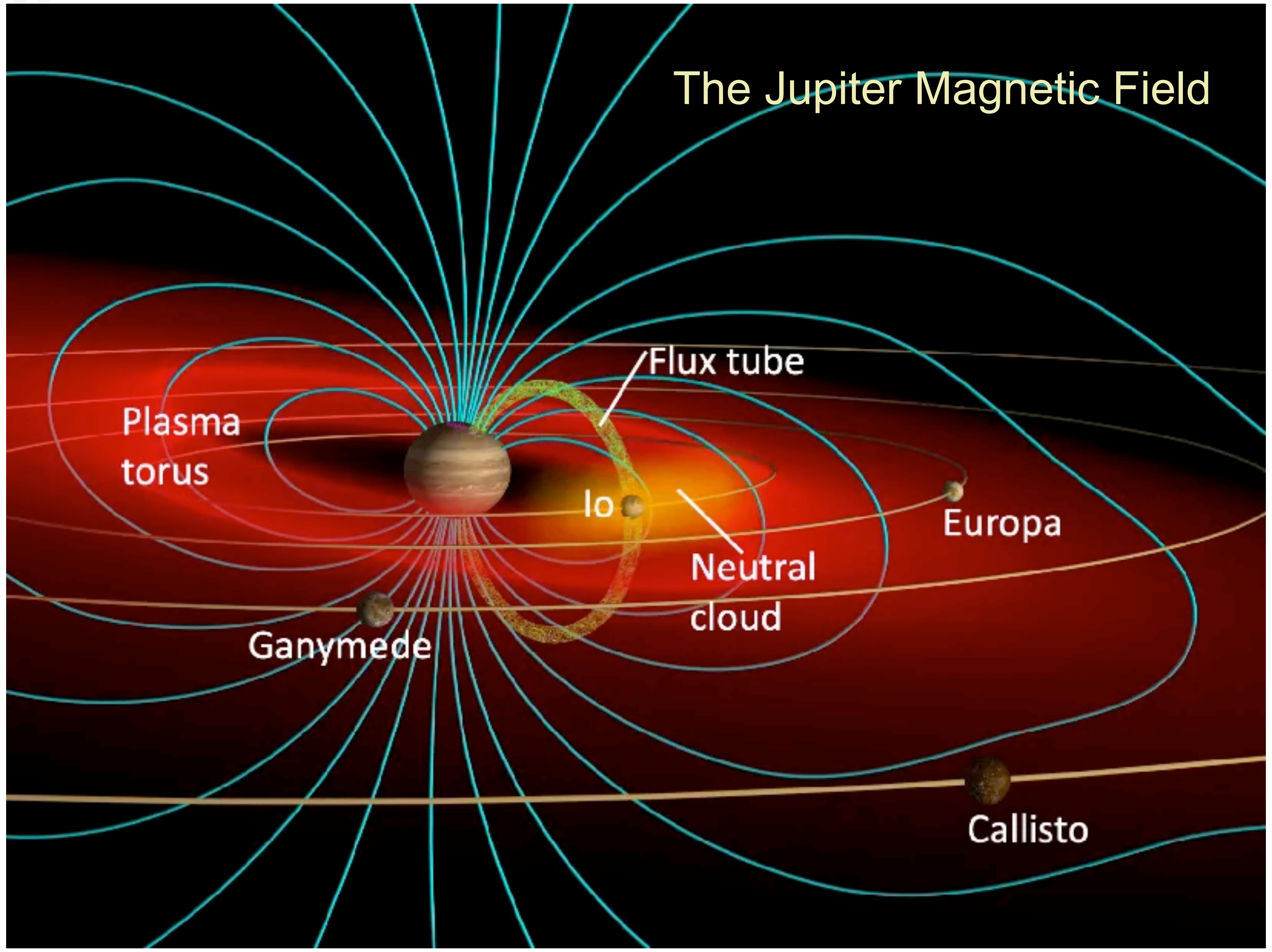


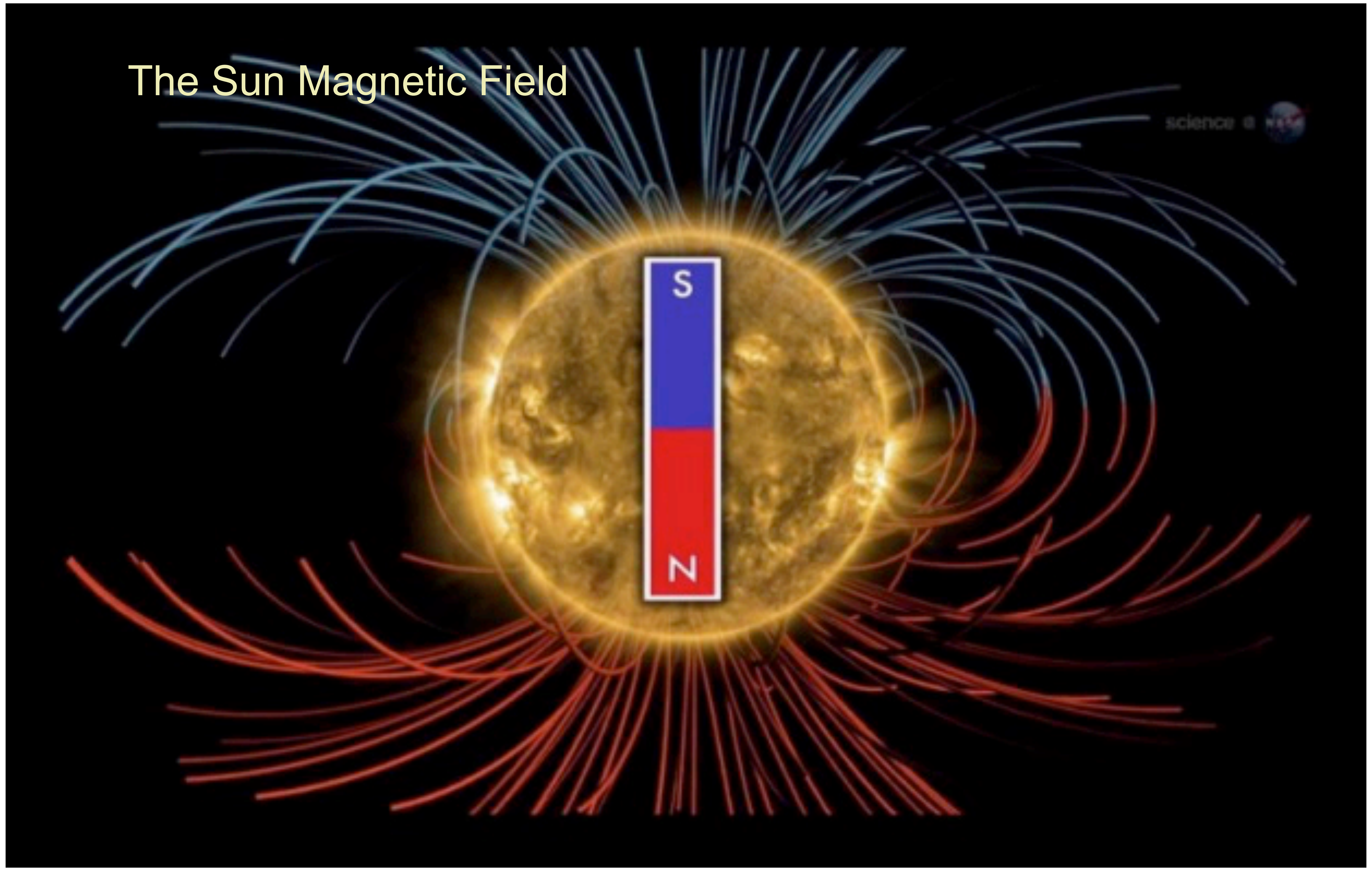
Outlook I



spectrum

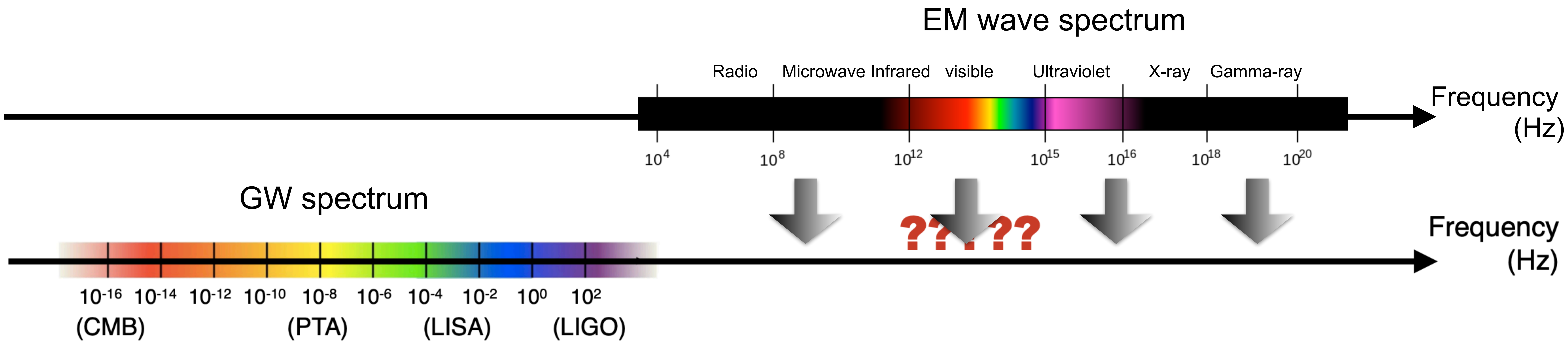
Outlook II - Other Nearby Astronomical Systems



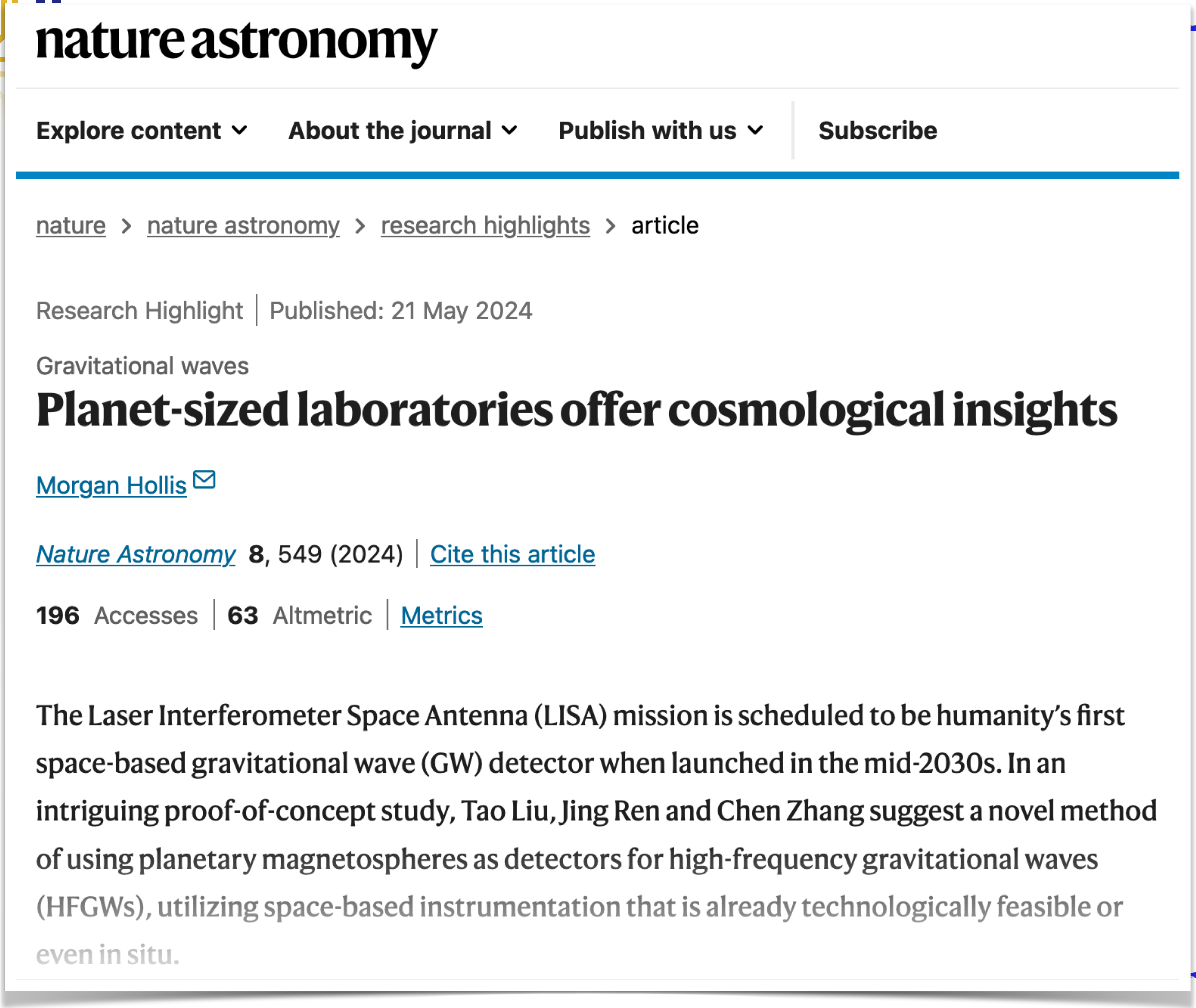


- Jupiter: radius ~ 70,000 km and SMF ~ 10 Gauss; nearby
- Sun: radius ~ 700,000 km and SMF ~ O(1) Gauss; nearby

Take-home Messages



- The detection of HFGWs represents a task in GW astronomy with extremely high scientific significance
- For this task, 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 planetary magnetosphere opens a new operation space, with encouraging sensitivities projected for a wide coverage of frequencies.



Research Highlight | Published: 21 May 2024

Gravitational waves

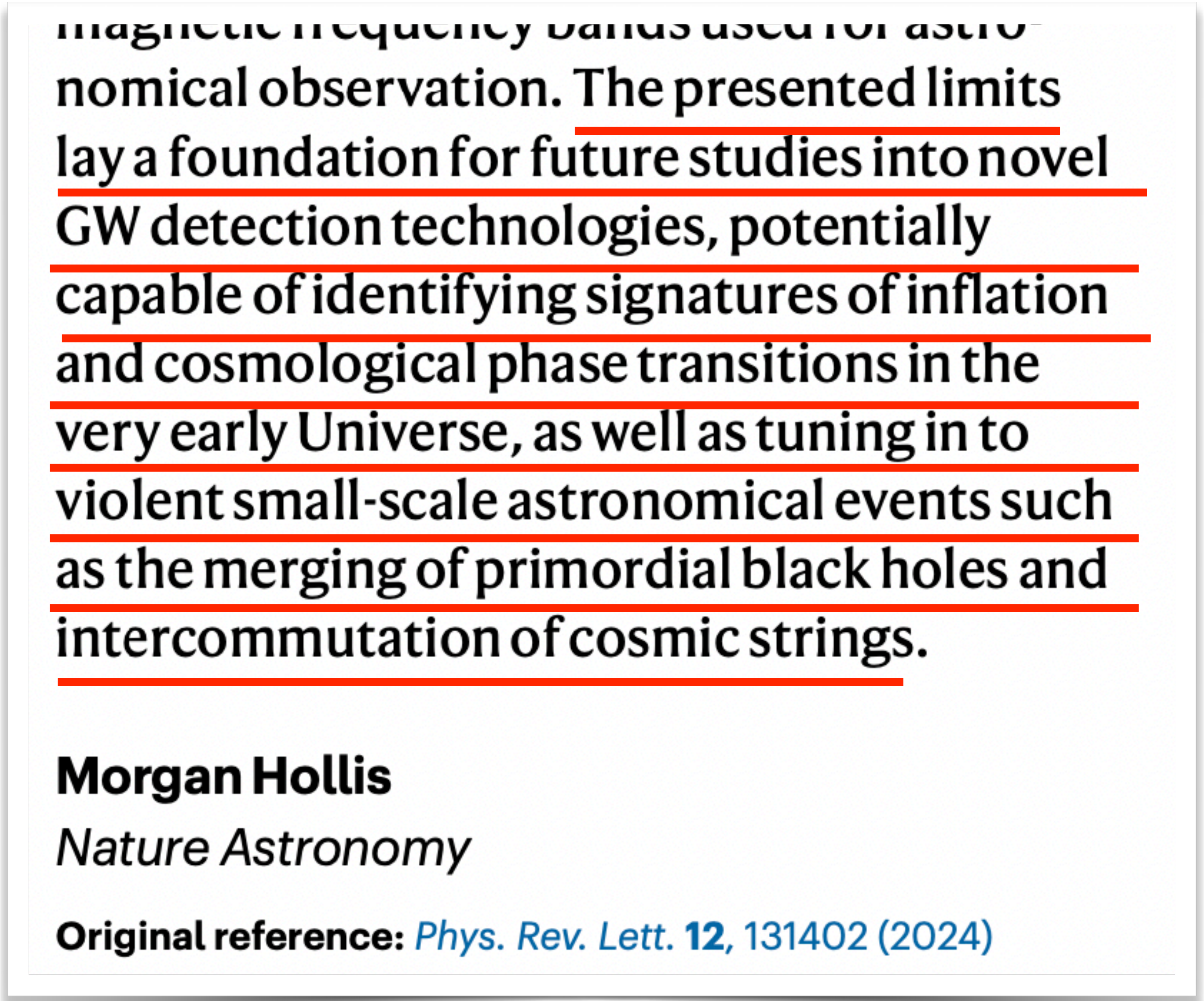
Planet-sized laboratories offer cosmological insights

Morgan Hollis

Nature Astronomy **8**, 549 (2024) | Cite this article

196 Accesses | **63** Altmetric | Metrics

The Laser Interferometer Space Antenna (LISA) mission is scheduled to be humanity's first space-based gravitational wave (GW) detector when launched in the mid-2030s. In an intriguing proof-of-concept study, Tao Liu, Jing Ren and Chen Zhang suggest a novel method of using planetary magnetospheres as detectors for high-frequency gravitational waves (HFGWs), utilizing space-based instrumentation that is already technologically feasible or even in situ.



nomical observation. The presented limits lay a foundation for future studies into novel GW detection technologies, potentially capable of identifying signatures of inflation and cosmological phase transitions in the very early Universe, as well as tuning in to violent small-scale astronomical events such as the merging of primordial black holes and intercommutation of cosmic strings.

Morgan Hollis
Nature Astronomy

Original reference: *Phys. Rev. Lett.* **12**, 131402 (2024)

大學教育資助委員會
University Grants Committee

CRF under Grant No. C6017-20G

Thank you!