Detecting Planetary-mass Primordial Black Holes with Resonant Electromagnetic Gravitational Wave Detectors

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Gravitational waves

~ Interferometry : from nHZ to kHZ

~ Several interests in high-frequency (MHz to THz)

~ Possible astrophysical sources : arXiv:2011.12414

- Transient signals or stochastic background
- Early Universe : preheating, inflation, phase transitions,…
- Late Universe : NS mergers, exotic compact objects or

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  PRIMORDIAL BLACK HOLE MERGERS

Primordial black holes

~ Dark matter candidate (at least part of)

~ Interest in sub-solar detection to point to a primordial origin

~ Two mechanisms : primordial binaries or dense PBH halos

~ Link between frequency and masses $f_{\rm ISCO} = \frac{4400\,{\rm Hz}}{(m_1 + m_2)/M_\odot}$

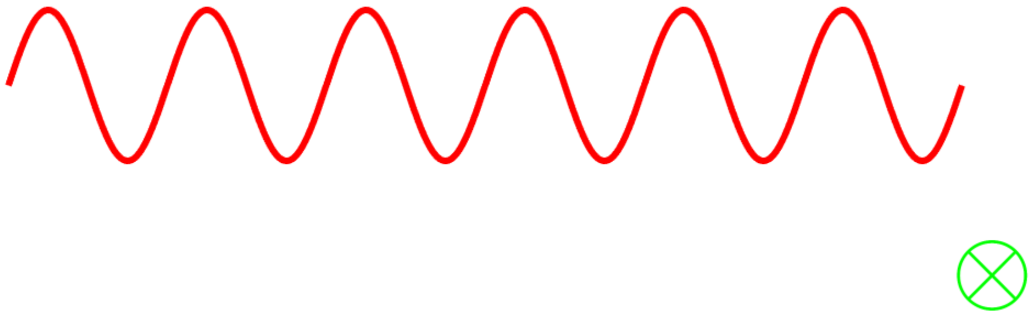
Electromagnetic waves and GW coupling

~ 1962 Gertsenshtein : wave resonance mechanism

~ 1970s Grischuck et al. : Using resonant cavities as detectors

~ 2019 Ejlli, Cruise et al. : Graviton-photon conversion

GW generation with wave resonance



~ Direct Gersentshtein Effect 1962

~ Amplitude of the generated GW

$$\frac{4GB_0E_0L^2}{c^5\mu_0}$$

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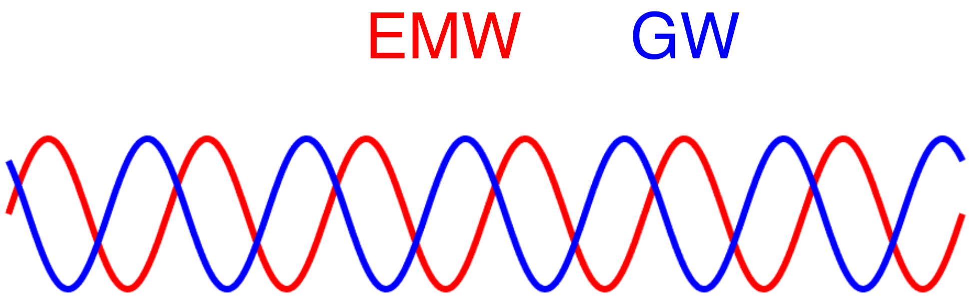

Constant transverse magnetic field

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Direct and inverse Gertsenshtein effects

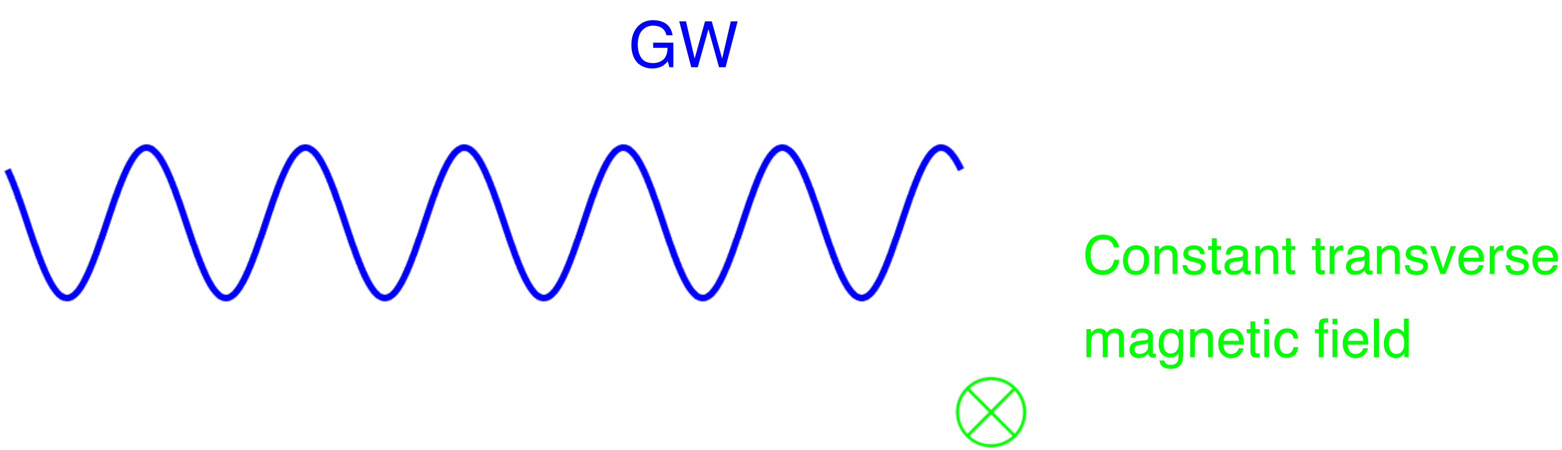
~ Tiny coupling in GW generation $\frac{4G}{c^5\mu_0} \approx 10^{-46}\,(T.V.m)^{-1}$

~ Generating a strain of $h \approx 10^{-21}$, with $B_0 = 10\,\mathrm{T}$ and $E_0 = 1\,\mathrm{MV/m}$, needs $L \approx 120\,\mathrm{lyr}$!!

~ Astrophysical application (Zeldovich, 1973)

~ Inverse Gertsenshtein Effect

A GW passing through a transverse constant magnetic field produces a faint EM wave



~ Application to the GW detection !

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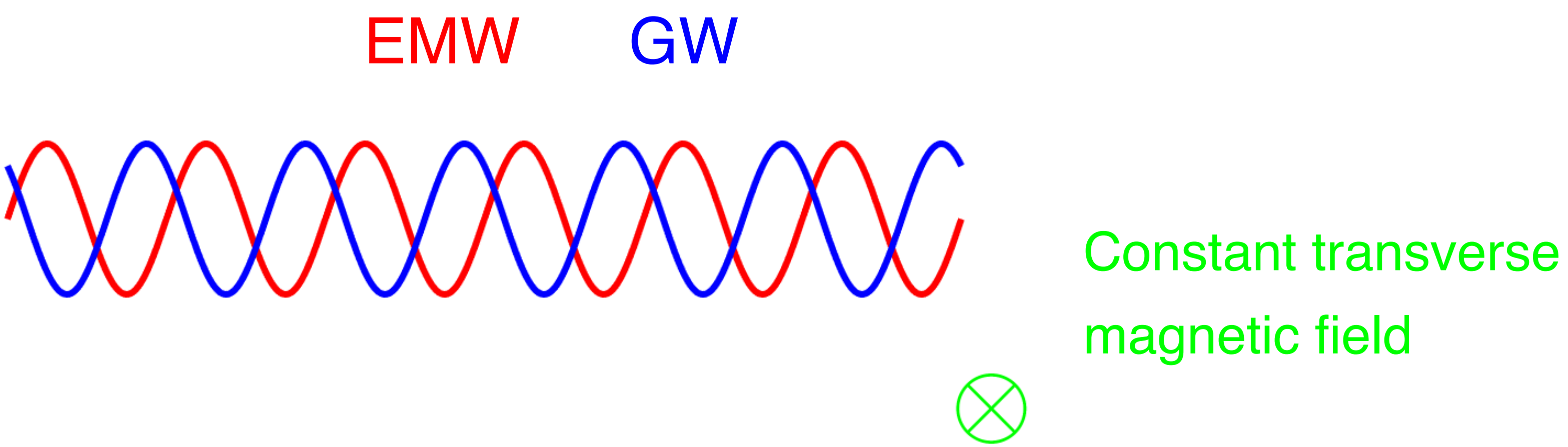

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Inverse Gertsenshtein Effect

~ Maxwell equations in curved space ⇒ EM wave equation

$$g^{\alpha\beta}\nabla_\alpha\nabla_\beta F_{\mu\nu} + R_{\mu\nu\alpha\beta}F^{\alpha\beta} + R^\alpha{}_\mu F_{\nu\alpha} + R^\alpha{}_\nu F_{\alpha\mu} = 0$$

~ Background + perturbations

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

$$\partial_\mu h^{\mu\alpha} = 0$$

Static external field

First order induced field (wave)

$$F_{\mu\nu} = F^{(0)}{}_{\mu\nu} + F^{(1)}{}_{\mu\nu}$$

~ Modified Maxwell equations for EM field at first order, with static field hypothesis $\nabla^{(\eta)}_\gamma F^{(0)}{}_{\alpha\beta} = 0$

$$g^{\alpha\beta}\nabla_\alpha\nabla_\beta F^{(1)}{}_{\mu\nu} = -\partial_\alpha\left(\partial_\mu h_{\beta\nu} - \partial_\nu h_{\beta\mu}\right)F^{(0)\,\alpha\beta}$$

Inverse Gertsenshtein Effect

~ Magnetic field transverse to a passing GW

~ theorem by Choquet-Bruhat using plane wave approximation

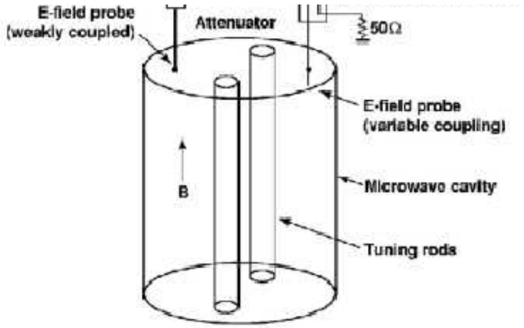
$$S_{\mu\nu} = 0 \Leftrightarrow J_{\mu}^{\text{eff}} = 0 \Leftrightarrow \Phi_{\alpha} F^{\alpha\mu\,(0)} = q\,\Phi^{\mu}$$

~ same frequency content in the response of the detector

=> suitable for HFGW signals (like PBH mergers)

=> different bandwidth than LIGO, LISA, etc.

~ problem with ADMX



arXiv:hep-ex/0701025

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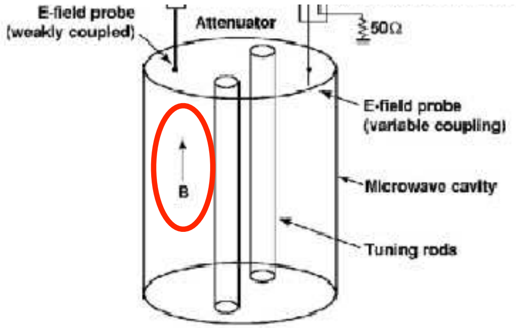

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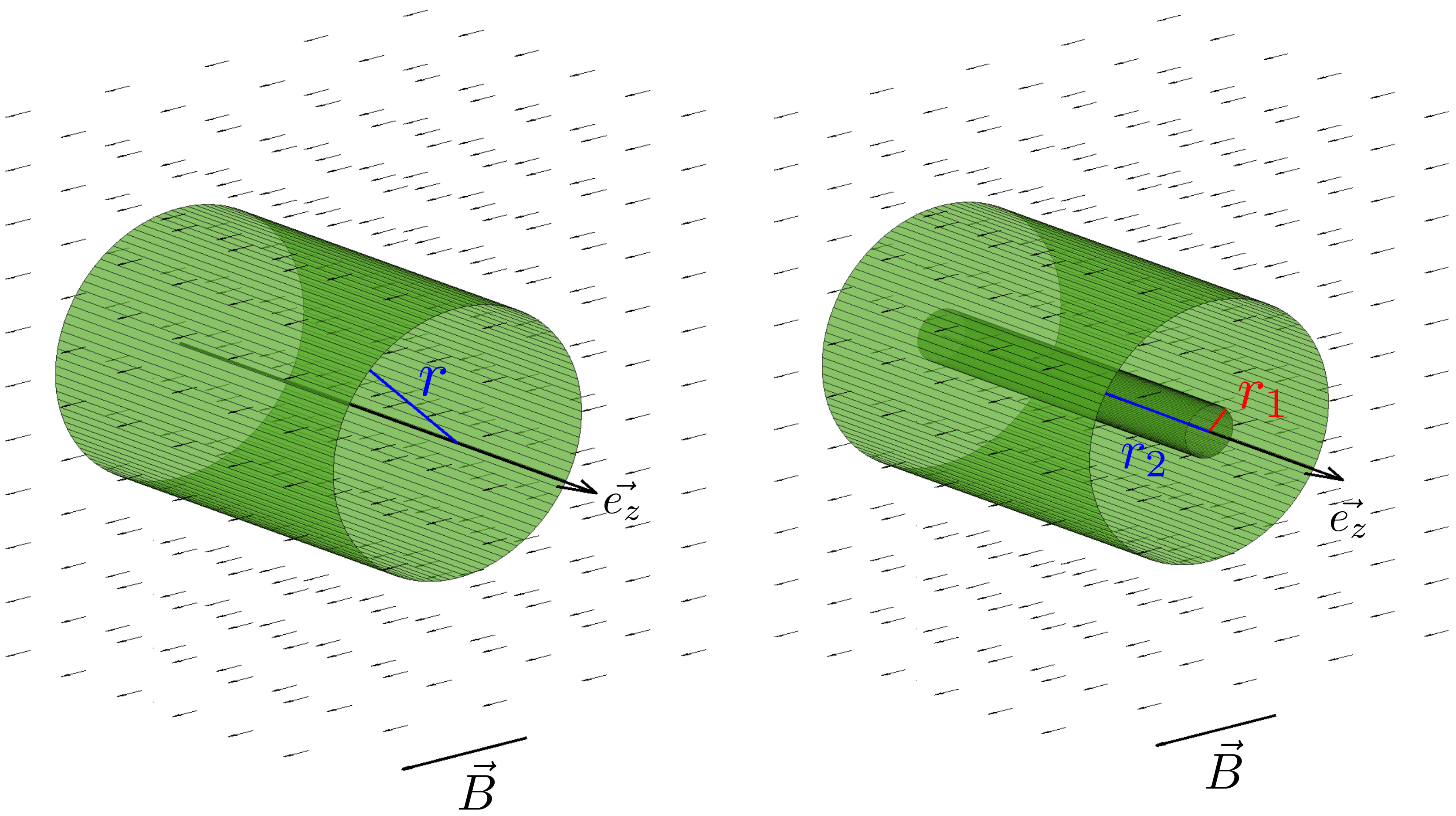
Case study of two EM GW detectors

~ Two cylindrical cavities : TM (hollow) and TEM (coaxial)

Based on patents PCT/EP2018/086758 & PCT/EP2018/086760



Case study of two EM GW detectors

~ Projection on proper functions of Laplacian

$$\frac{d^2\hat{b}^{r,\phi}_{k,m,n}}{dt^2} + \Omega^2_{kn}\hat{b}^{r,\phi}_{k,m,n} = \hat{s}^{r,\phi}_{k,m,n}(t)$$

~ Variation of energy inside the cavity at first order

$$\Delta\mathcal{E} = E_{\text{tot}} - E^{(0)} \approx \frac{1}{\mu_0}\int_V \left(\vec{B}^{(0)} \bullet \vec{B}^{(1)}\right) dV$$

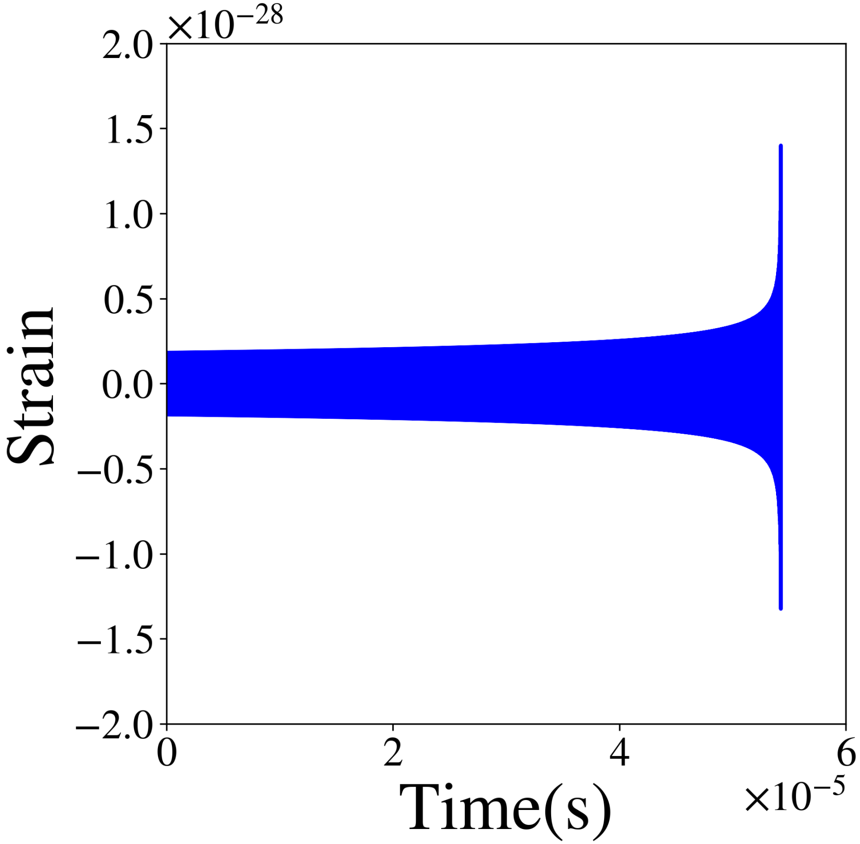
$$\Delta\mathcal{E} \approx \frac{2\pi B_0}{\mu_0} \cdot \sum_k \mathcal{I}_k \hat{b}_{k,1,0}(t)$$

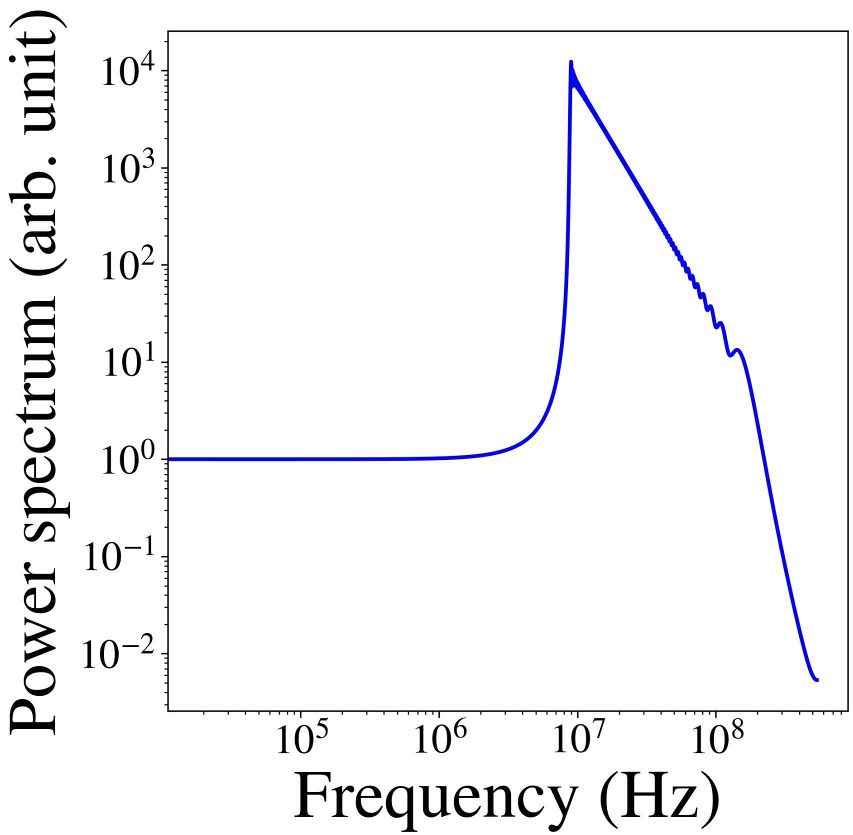
$$\hat{s}^{r,\phi}_{k,1,0}(z,t) = \pi B_0 L^2 \mathcal{I}_k \int_{-L/2}^{L/2} \frac{\partial^2 h_+(z,t)}{\partial z^2} dz$$

Generation of PBH mergers signals

~ Using LALSimulation (PN expansion), start. freq. = $f_{ISCO}/25$

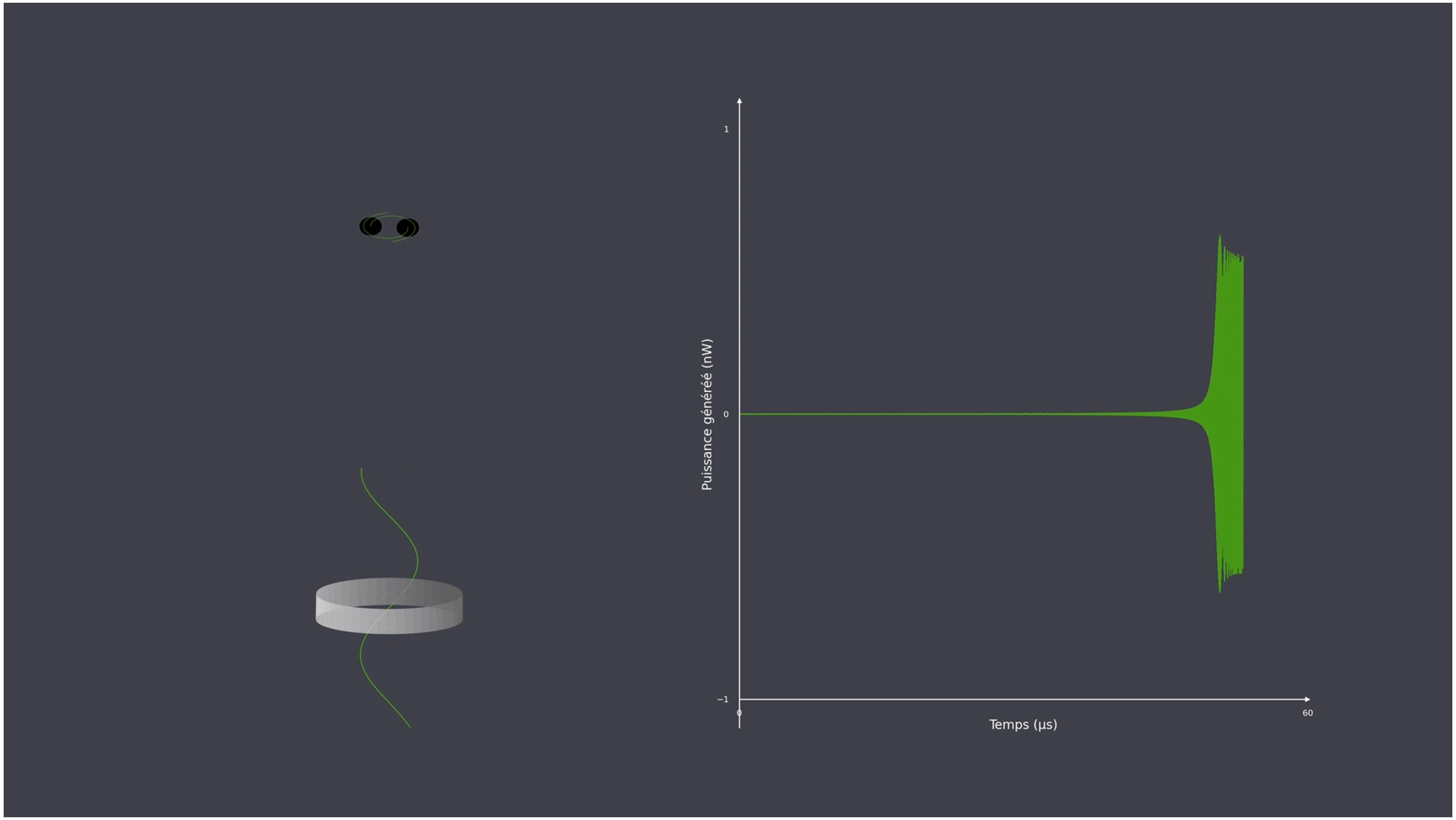
~ Planetary mass : first signal 10^{-5} $M_\odot$





Resonant response of the detectors 10^{-5} M⊙

B=5T   L=1m   r=5m r_1=0.1m



Other simulation

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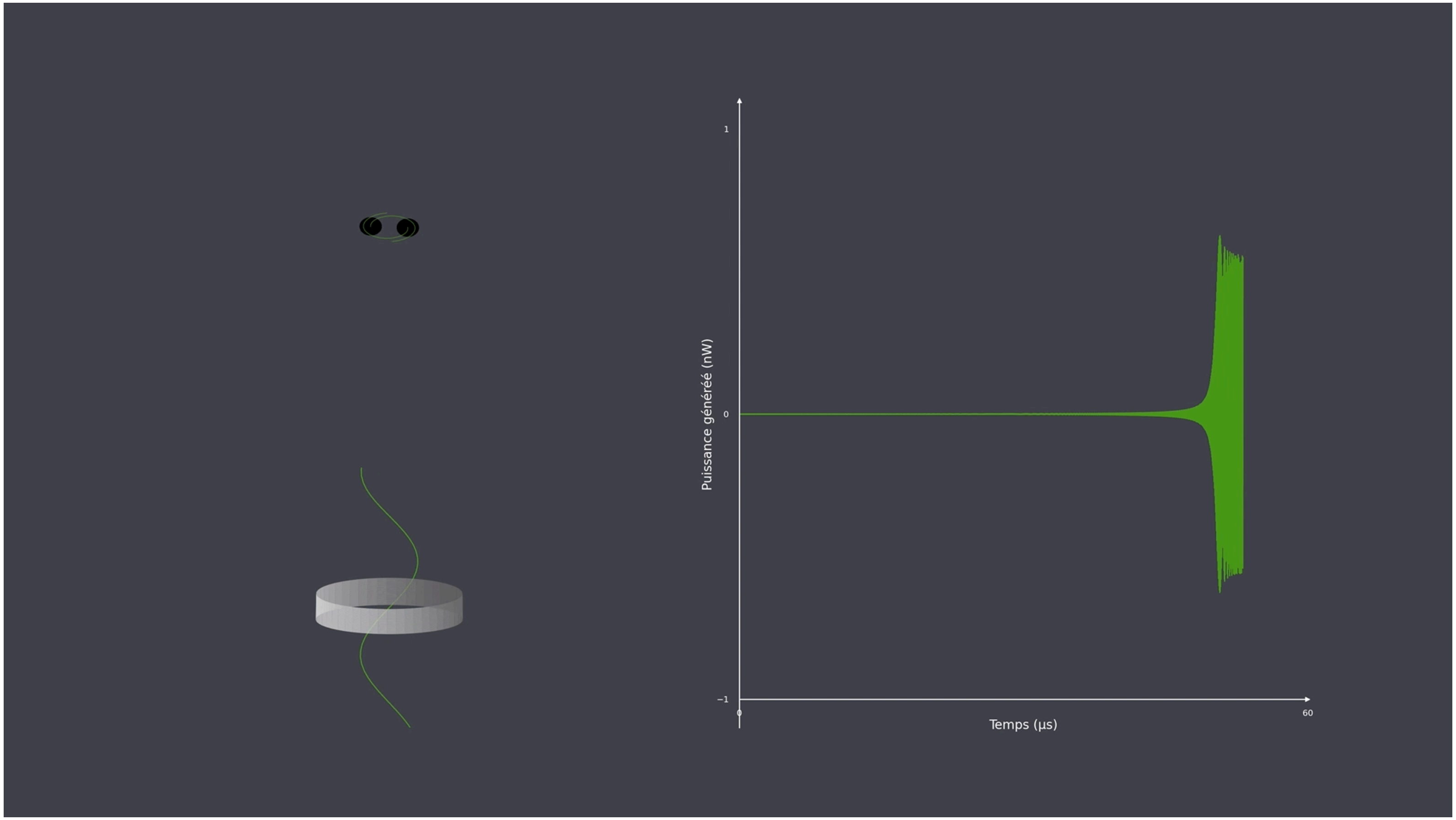

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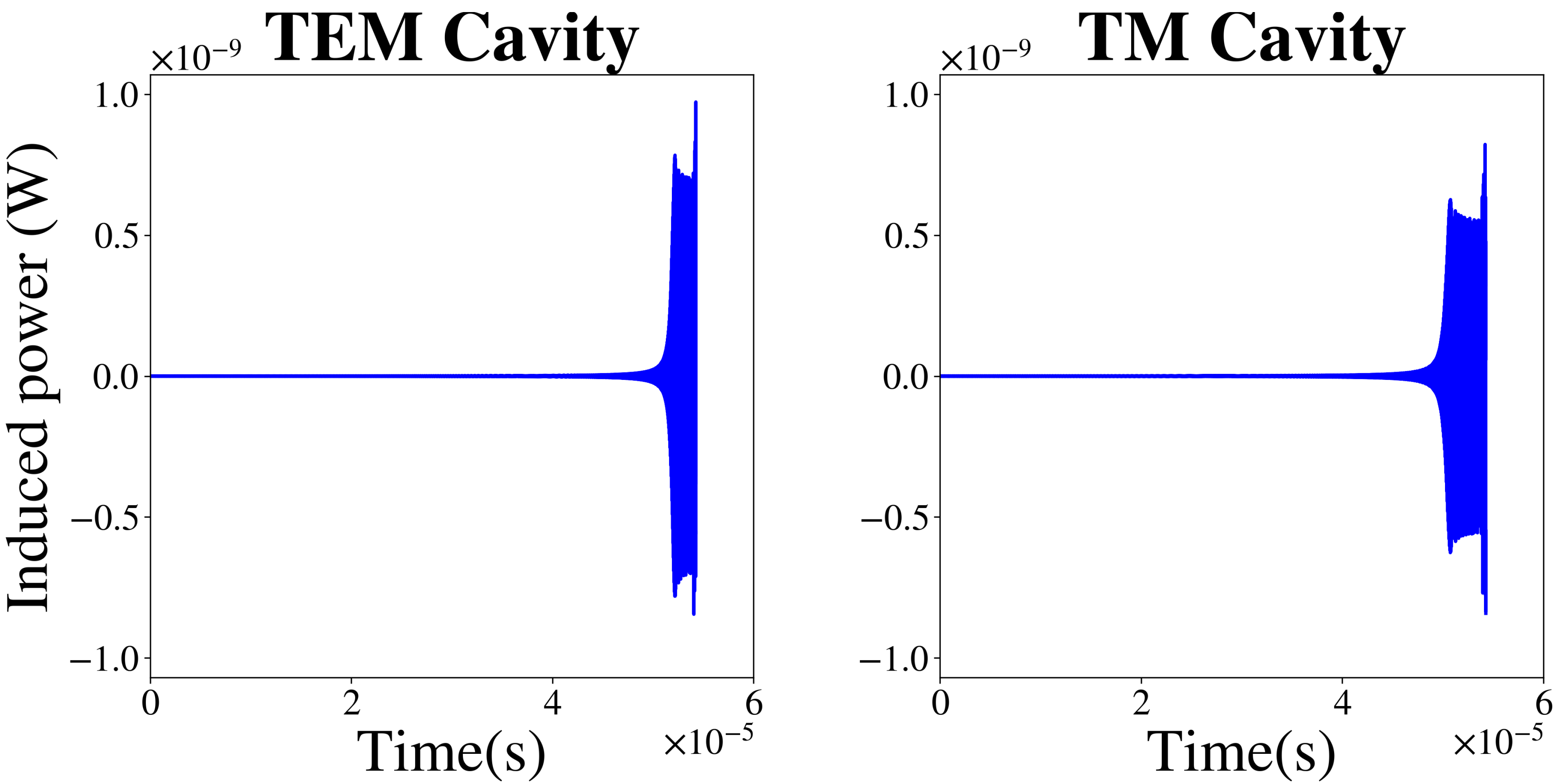

RMS induced power of order 10^{-10} W

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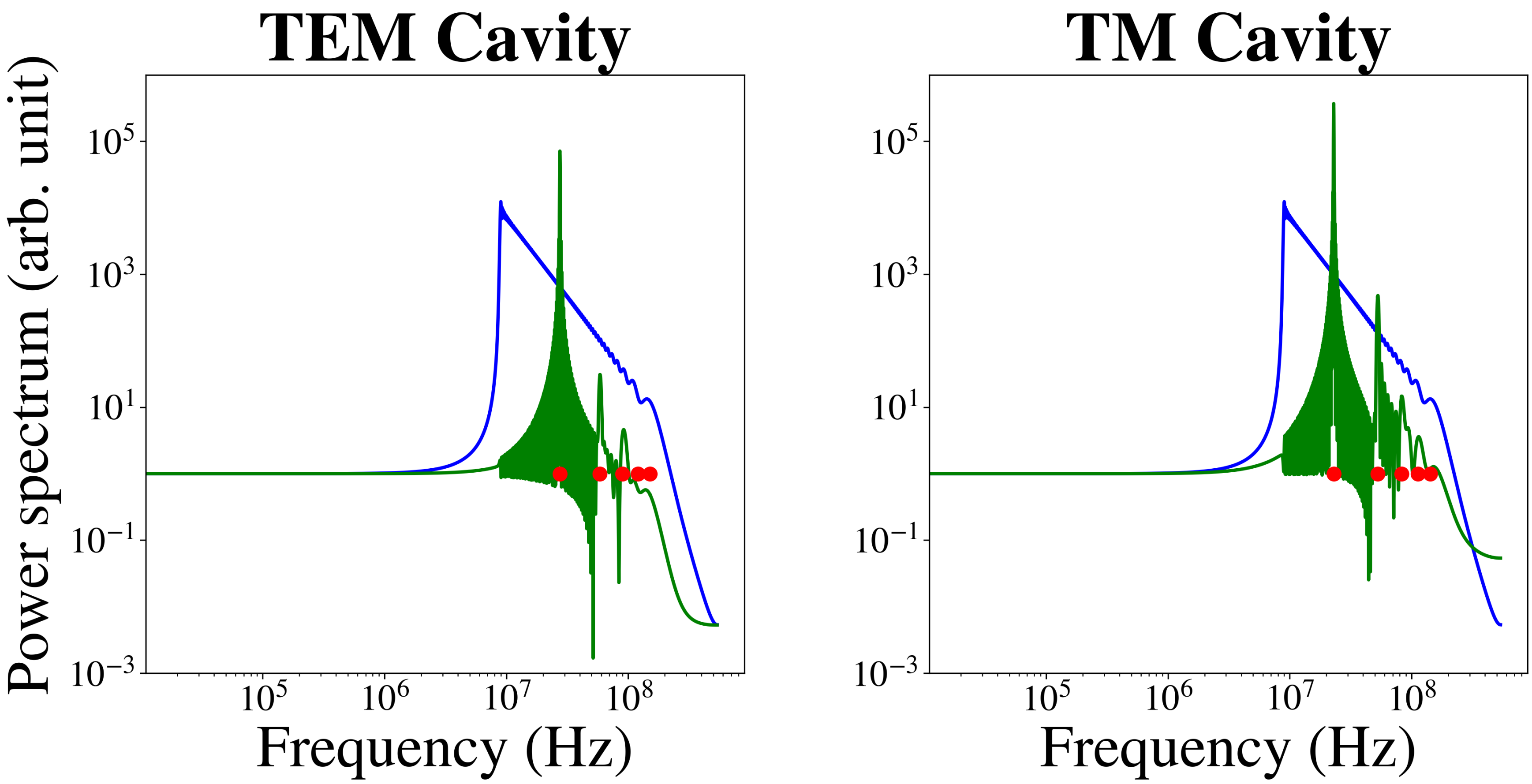
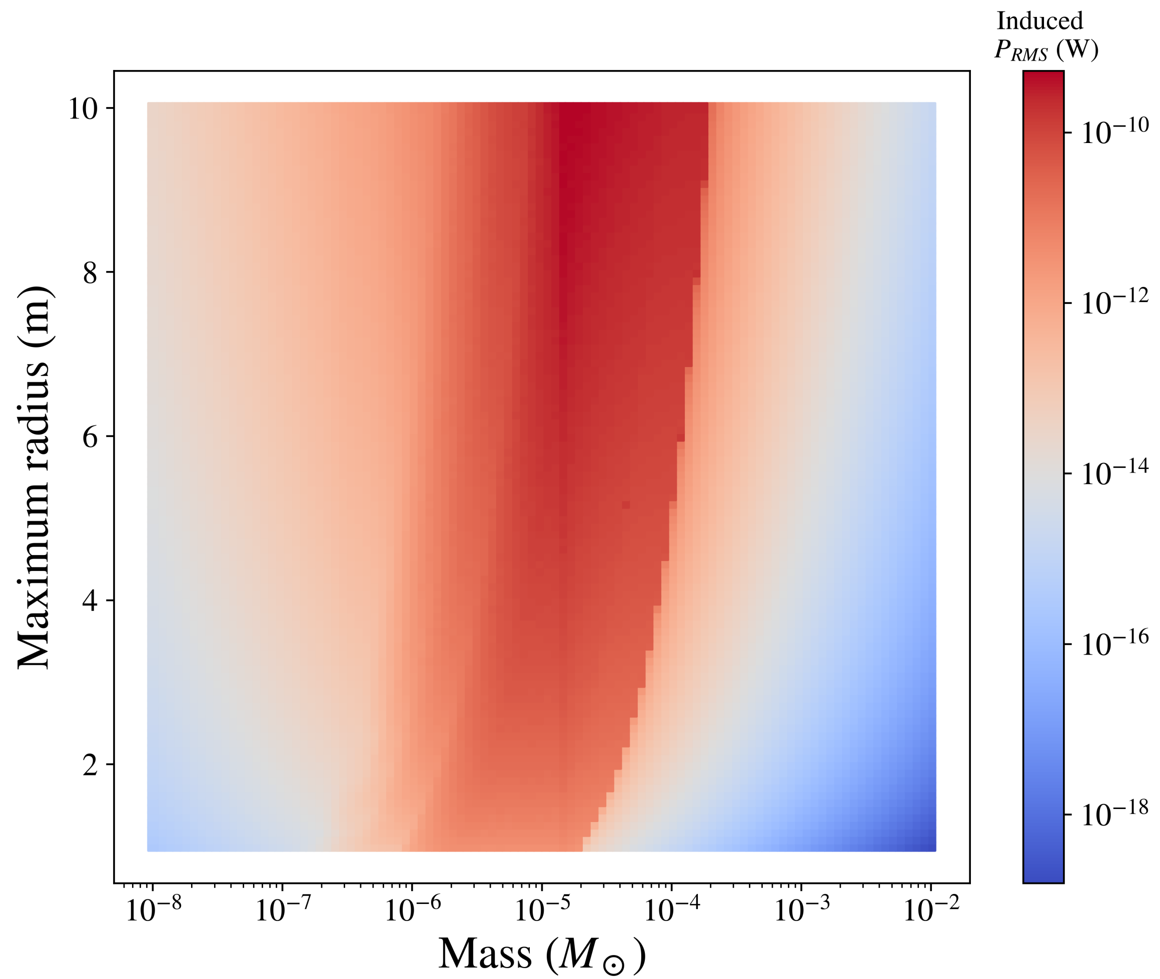
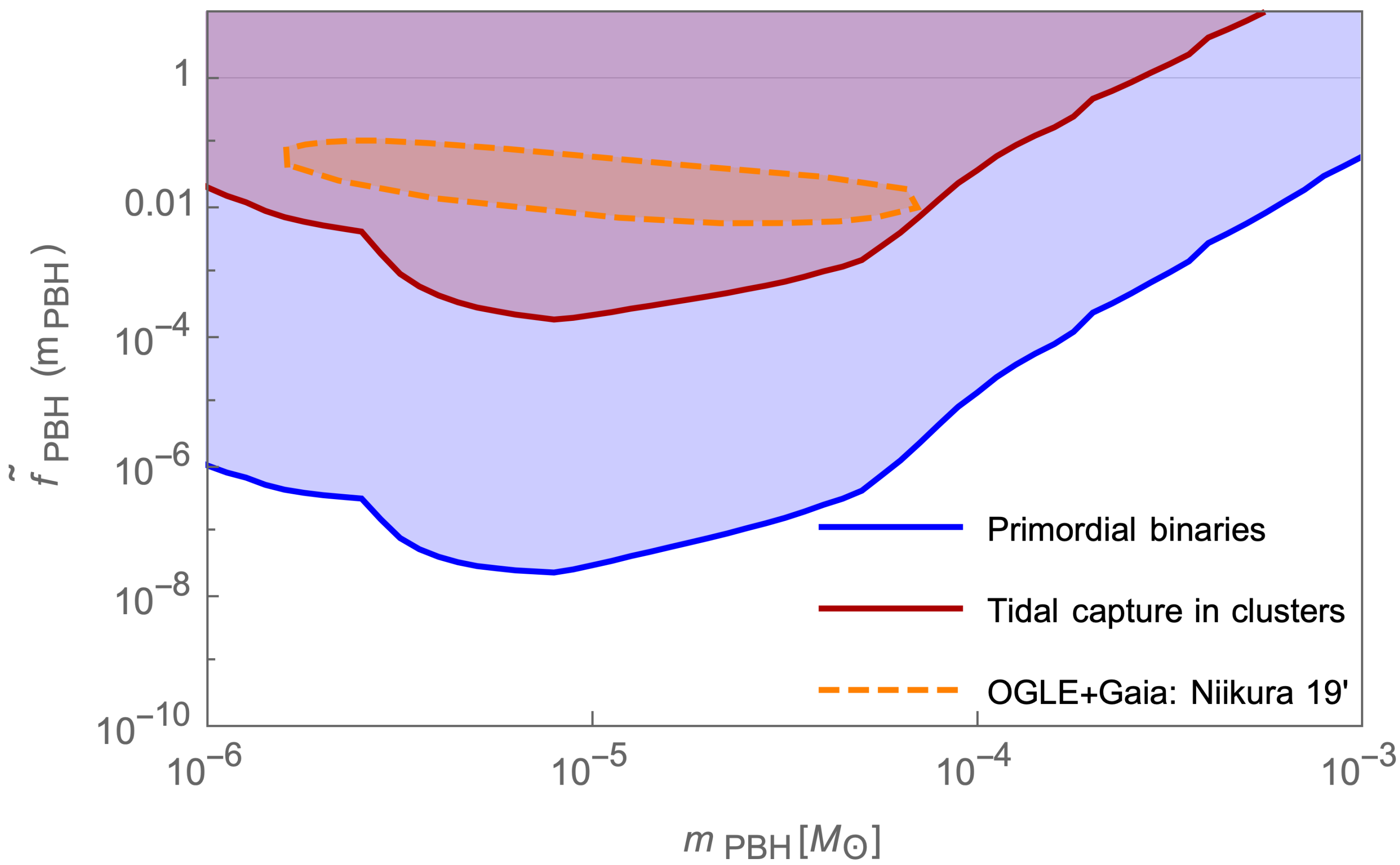


RMS induced power of order 10^{-10} W

Study of the response in function of the mass of the PBH mergers



Study the fraction of DM made of light PBH



Conclusion and perspectives

~ Complementary GW detectors

~ Study the fraction of DM made of light PBH

~ Cosmological GW stochastic background

~ Fundamental physics, from early Universe cosmology to exotic compact objects

~ Our goal : motivations for experimental development

Thanks for your attention 😊

Bode diagram