Electromagnetic detection of ultra high frequency GWs

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Summary

1) Short introduction on ultra high GW frequencies (> MHz)

2) Presentation of the paper :

a) Motivations and objectives

b) GW - EM waves conversion

c) Proposition of experimental set up

d) Results of the simulations (+ undergoing results)

3) Conclusion and perspectives

Why UHF GWs are interesting ?

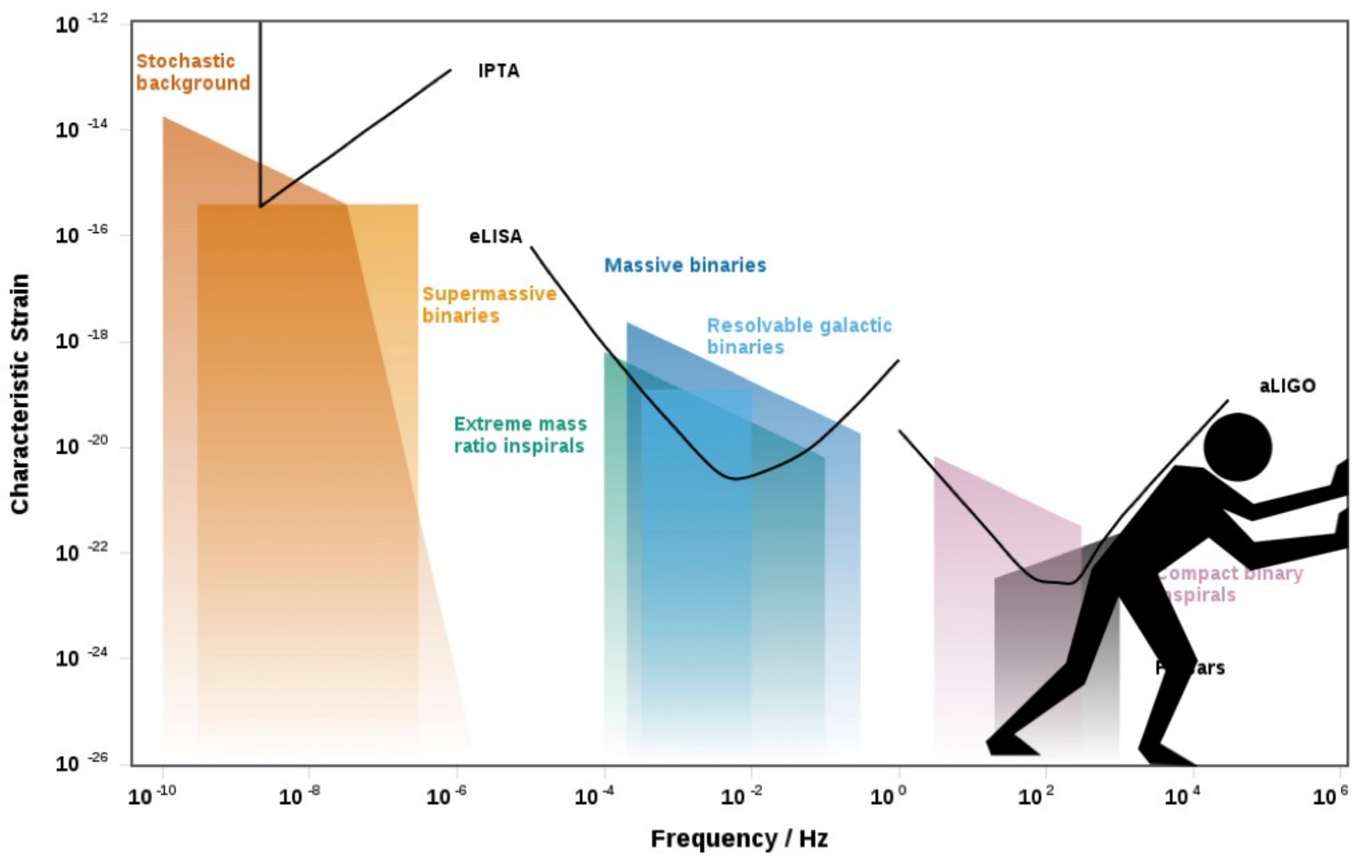
- Interferometry : nHz - kHz (LIGO, Virgo, LISA, NanoGrav)

- Theoretical sources of UHF GWs :

  - Mergers of Primordial Black Holes (PBHs)
  - Univers primordial : inflation, preheating, transitions de phases … (SGWB)

Ultra-High-Frequency GW initiative

The Stephen Hawking
Centre for Theoretical Cosmology



2019 work shop review

Challenges and Opportunities of Gravitational Wave Searches at MHz to GHz Frequencies

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Abstract

The first direct measurement of gravitational waves by the LIGO and Virgo collaborations has opened up new avenues to explore our Universe. This white paper outlines the challenges and gains expected in gravitational wave searches at frequencies above the LIGO/Virgo band, with a particular focus on the MHz and GHz range. The absence of known astrophysical sources in this frequency range provides a unique opportunity to discover physics beyond the Standard Model operating both in the early and late Universe, and we highlight some of the most promising gravitational sources. We review several detector concepts which have been proposed to take up this challenge, and compare their expected sensitivity with the signal strength predicted in various models. This report is the summary of the workshop *Challenges and opportunities of high-frequency gravitational wave detection* held at ICTP Trieste, Italy in October 2019.

The PRD paper

PHYSICAL REVIEW D
covering particles, fields, gravitation, and cosmology

Detecting planetary-mass primordial black holes with resonant electromagnetic gravitational-wave detectors

Nicolas Herman, André Füzfa, Léonard Lehoucq, and Sébastien Clesse
Phys. Rev. D **104**, 023524 – Published 19 July 2021

ABSTRACT

The possibility to detect gravitational waves (GW) from planetary-mass primordial black hole (PBH) binaries with electromagnetic (EM) detectors of high-frequency GWs is investigated. We consider two patented experimental designs, based on the inverse Gertsenshtein effect, in which incoming GWs passing through a static magnetic field induce EM excitations inside either a TM cavity or a TEM waveguide. The frequency response of the detectors is computed for post-Newtonian GW waveforms. We find that such EM detectors based on current technology may achieve a strain sensitivity down to $h \sim 10^{-30}$, which generates an EM induced power of $10^{-10}\,\mathrm{W}$. This allows the detection of PBH binary mergers of mass around $10^{-5} M_{\odot}$ if they constitute more than 0.01 percent of the dark matter, as suggested by recent microlensing observations. We envision that this class of detectors could also be used to detect cosmological GW backgrounds and probe sources in the early Universe at energies up to the grand unified theory scale.

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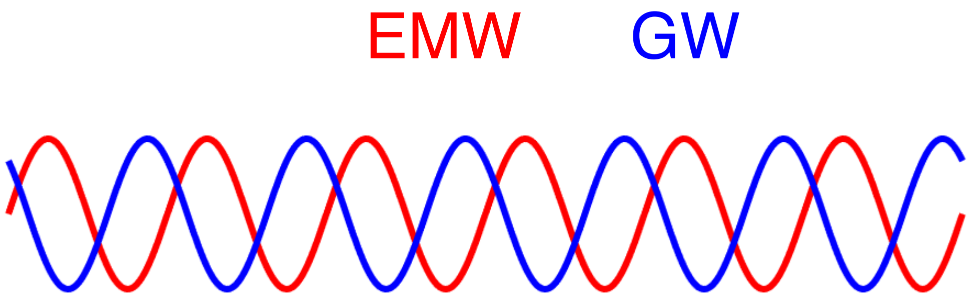
Main goal of the paper

- Propose a detector for UHF GWs
- Study of the GW-EM wave conversion
- Proposition and simulation of an experimental set up based on GW-EM wave conversion and resonant EM cavities
- Study of the detectability of PBHs mergers and of the SGWB with the proposed detector
- Find optimum configuration and parameters for the detector

GW-EM wave coupling



~ Gersentshtein effect 1962

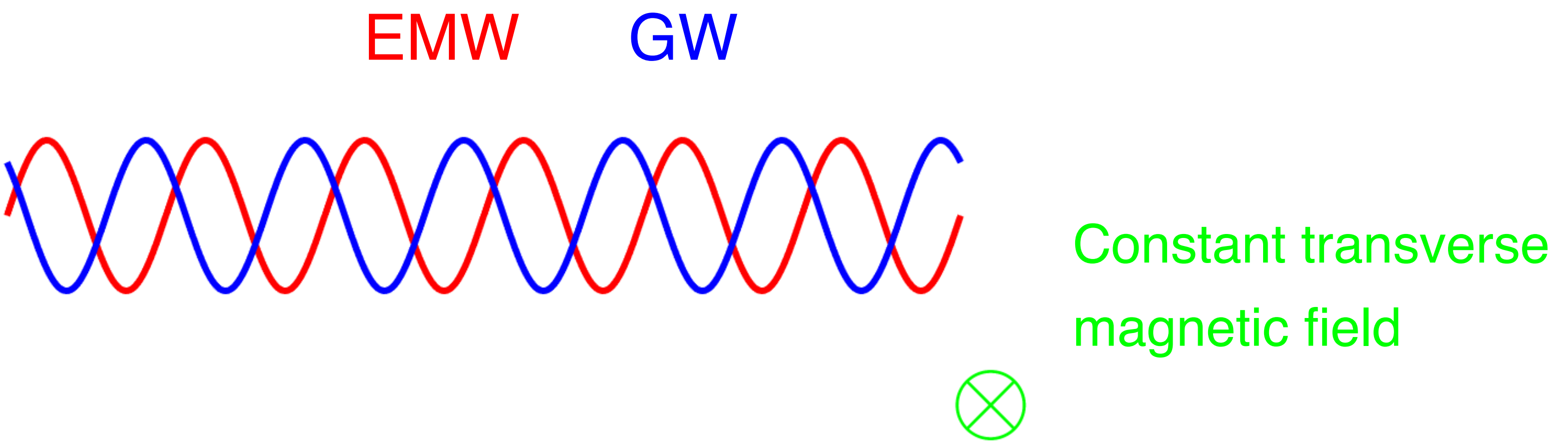
~ Amplitude of the GW induced : $$h_{\mu\nu} \sim \frac{4GB_0E_0L^2}{c^5\mu_0}$$

~ Weak coupling with direct effect : $\frac{4G}{c^5\mu_0} \approx 10^{-46}\,(T.V.m)^{-1}$

~ Strain generated : $h \approx 10^{-21}$, with $B_0 = 10\,\mathrm{T}$ and $E_0 = 1\,\mathrm{MV/m}$, one need $L \approx 120\,\mathrm{lyr}$!!

GW-EM wave coupling

~ Inverse Gertsenshtein effect :



GW → ΔF magnetic field → EM wave

GW-EM wave coupling

~ Maxwell equations in curved space ⇒ EMW 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 magnetic field ↖ induced field (EM wave) ↗

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

~ Linearisation of the Maxwell equations with a static external magnetic field : $\nabla^{(\eta)}_\gamma F^{(0)}{}_{\alpha\beta} = 0$

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

GW-EM wave coupling

~ Transverse magnetic field :

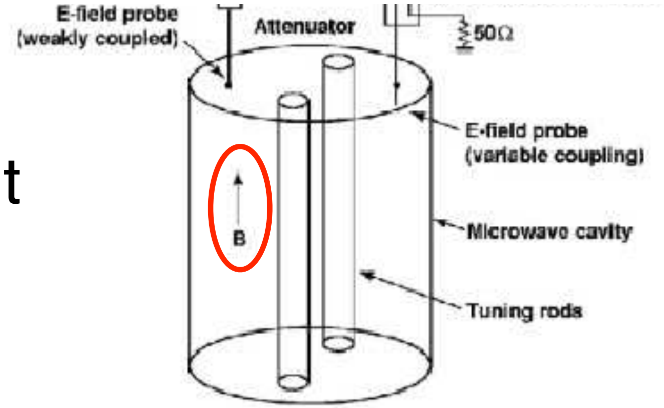
~ Adaptation of Choquet-Bruhat theorem with plane GW :

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

~ ADMX discussion

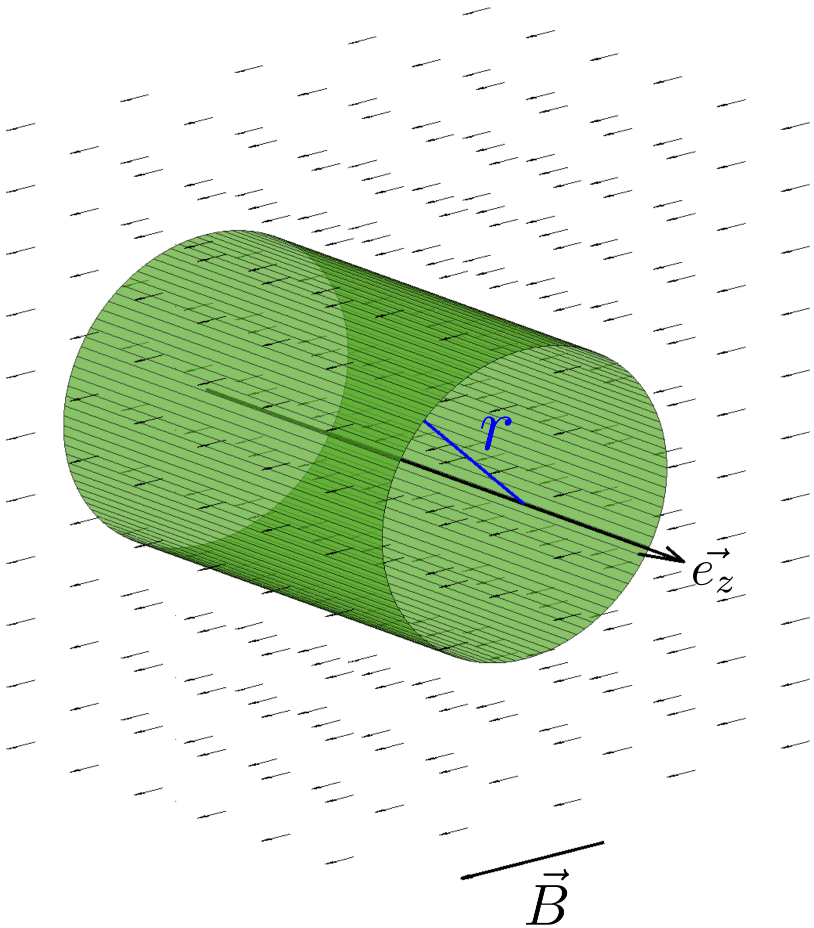
Axion Dark Matter eXperiment

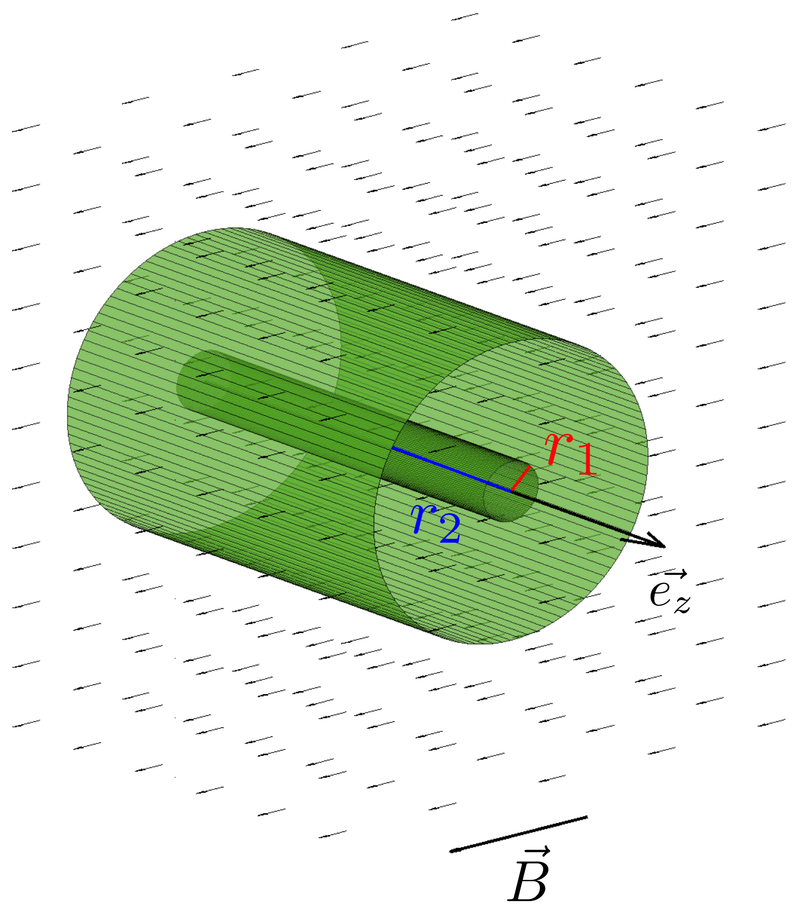
arXiv:hep-ex/0701025



Study of two resonant cavities

- Two cylindrical cavities : TM and TEM (coaxiale)
- Based on patents PCT/EP2018/086758 & PCT/EP2018/086760





Case study of two EM GW detectors

~ Projection on proper functions of Laplacian

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

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

~ Variation of energy inside the cavity at first order

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

$$\Delta\mathcal{E} \approx \frac{2\pi B_0^2 L^3 \mathcal{H}_{\rm GW}}{\mu_0}\mathcal{F}$$

Primordial Black Holes (PBH)

~ DM candidates (at least part of)

~ Bump in the mass distribution at ~ 10^{-5} $M_\odot$

~ Potential seeds for heavier BH

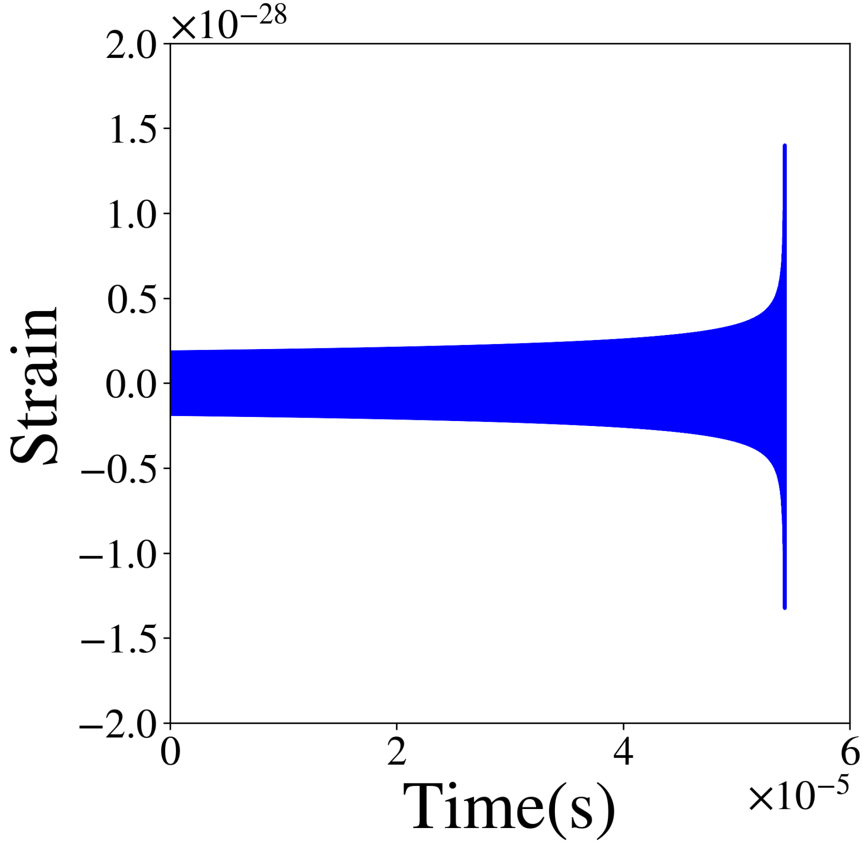
~ Like between mass and frequency

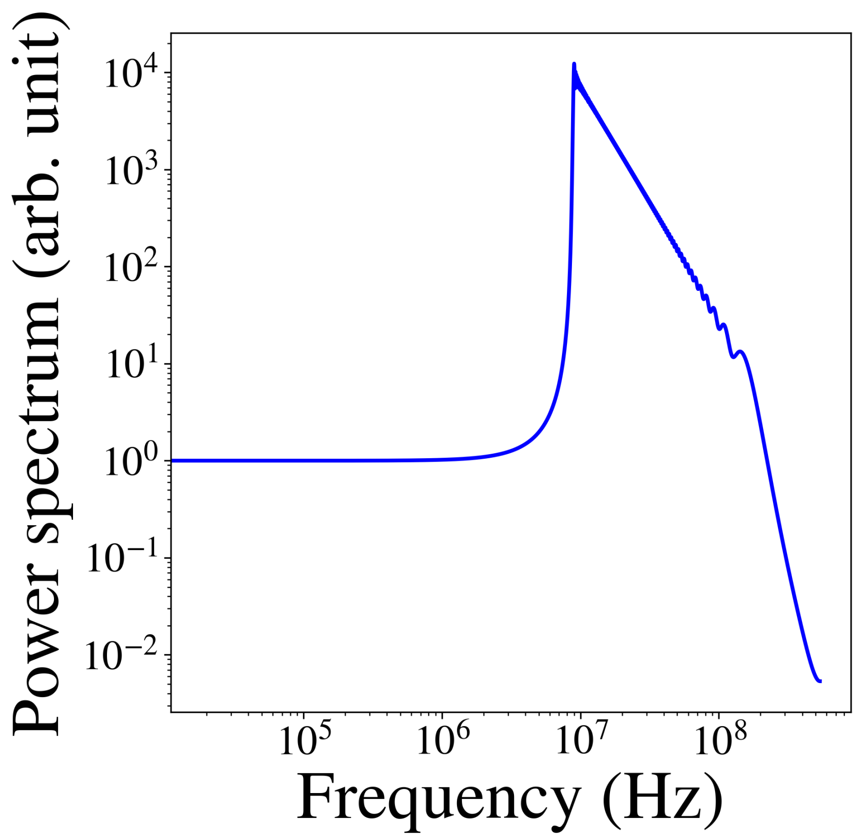
$$f_{\mathrm{ISCO}} = \frac{4400\,\mathrm{Hz}}{(m_1 + m_2)/M_\odot}$$

GWs from PBH mergers

~ PBH: close work with S.Clesse (ULB)

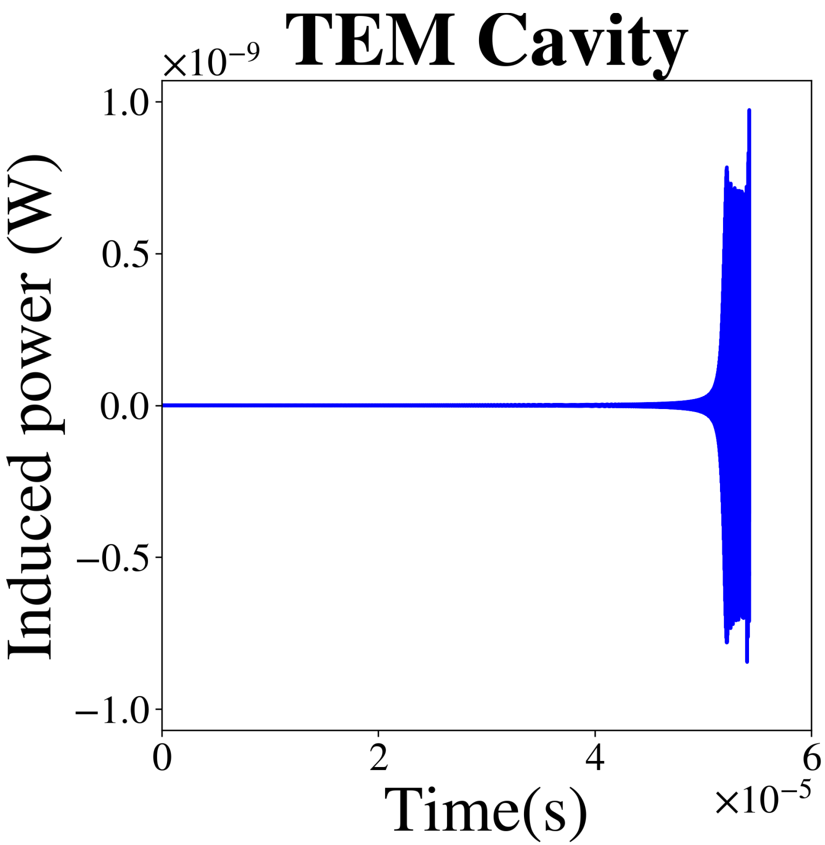
~ LALSimulation (Post-Newtonian), freq. initial = $f_{ISCO}/25$

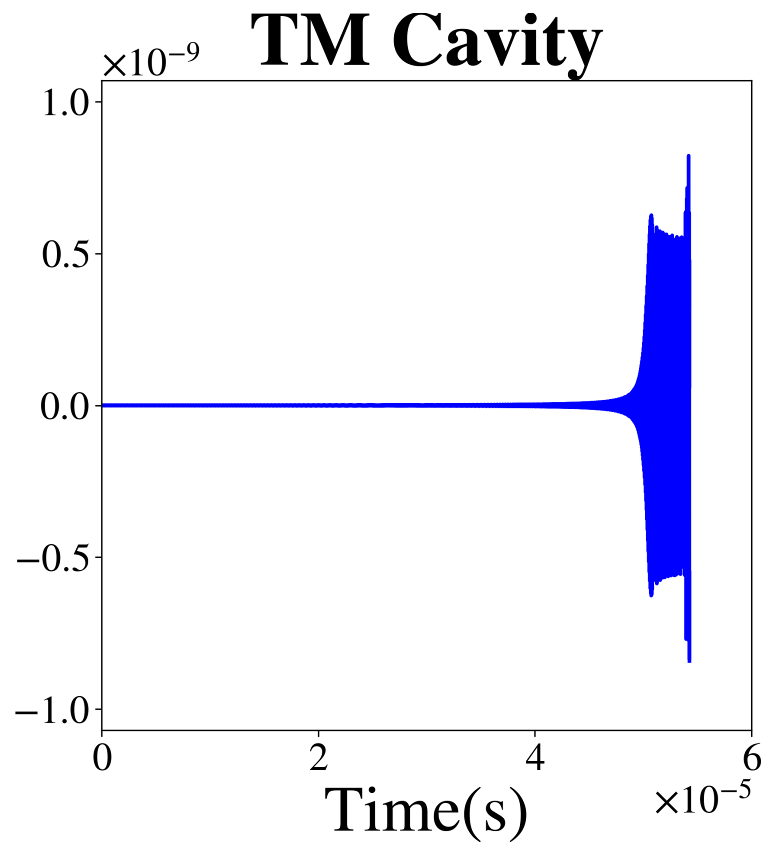




Output of the detector

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

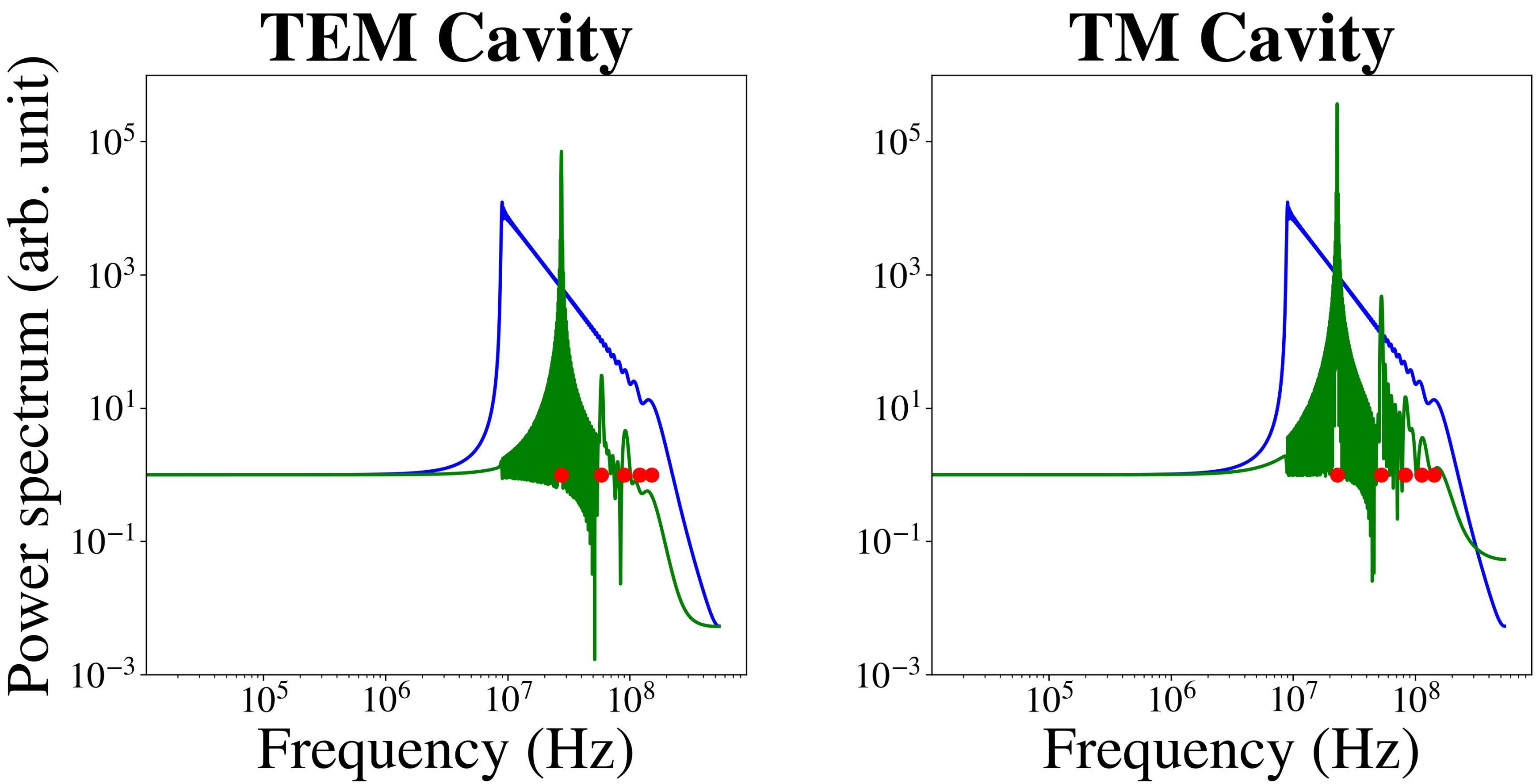




RMS power induced ~ 10^{-10} W

Output of the detector

$B = 5T \quad L = 1m \quad r = 5m \quad r_1 = 0.1m$



RMS power induced ~ 10^{-10} W

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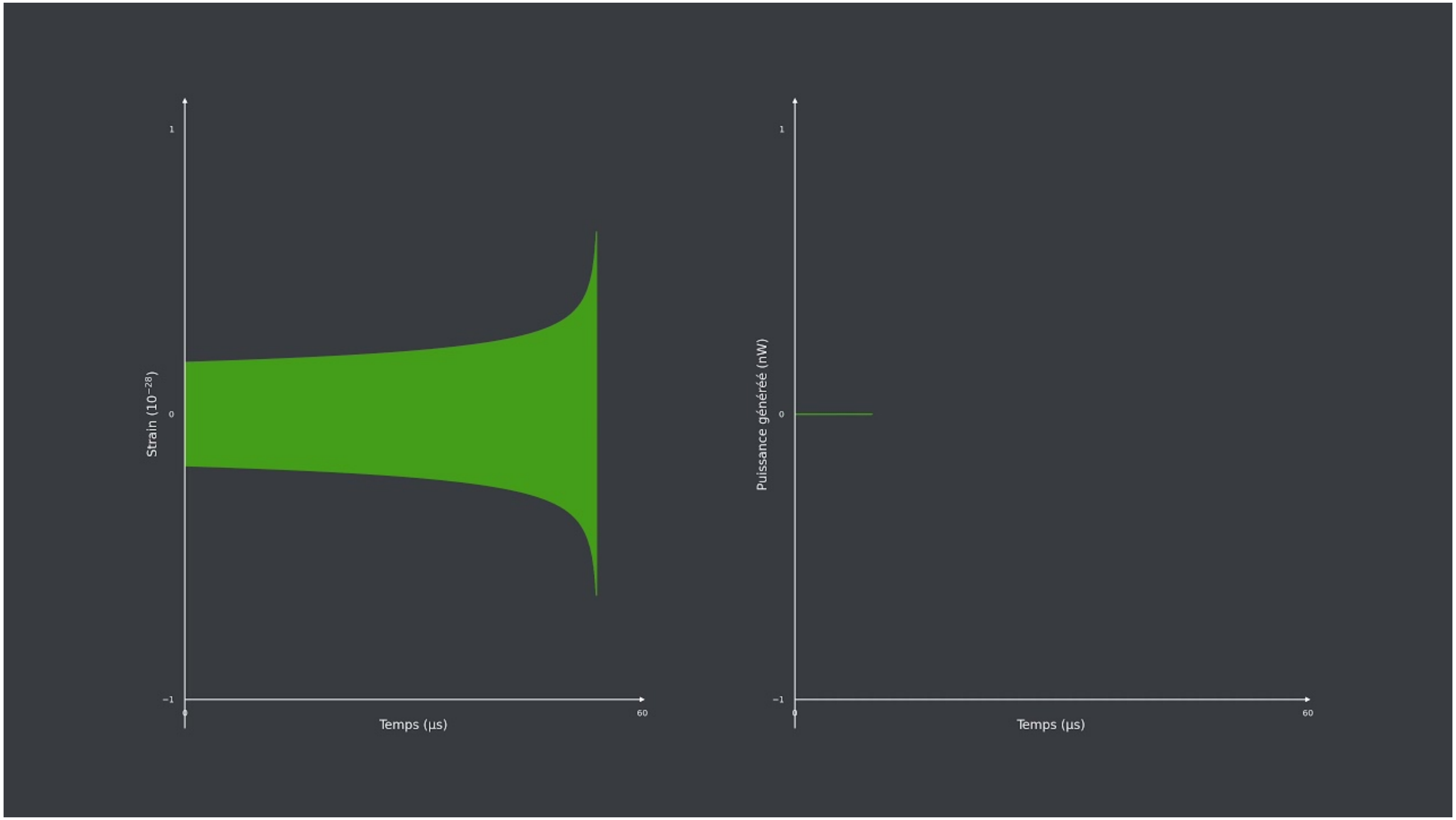
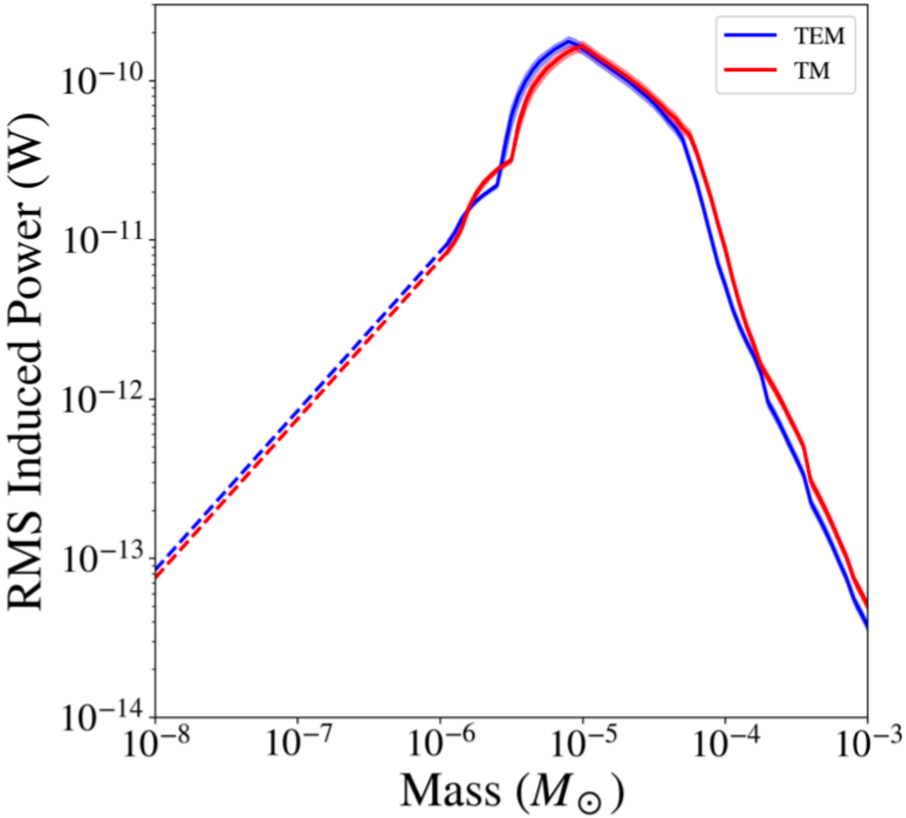
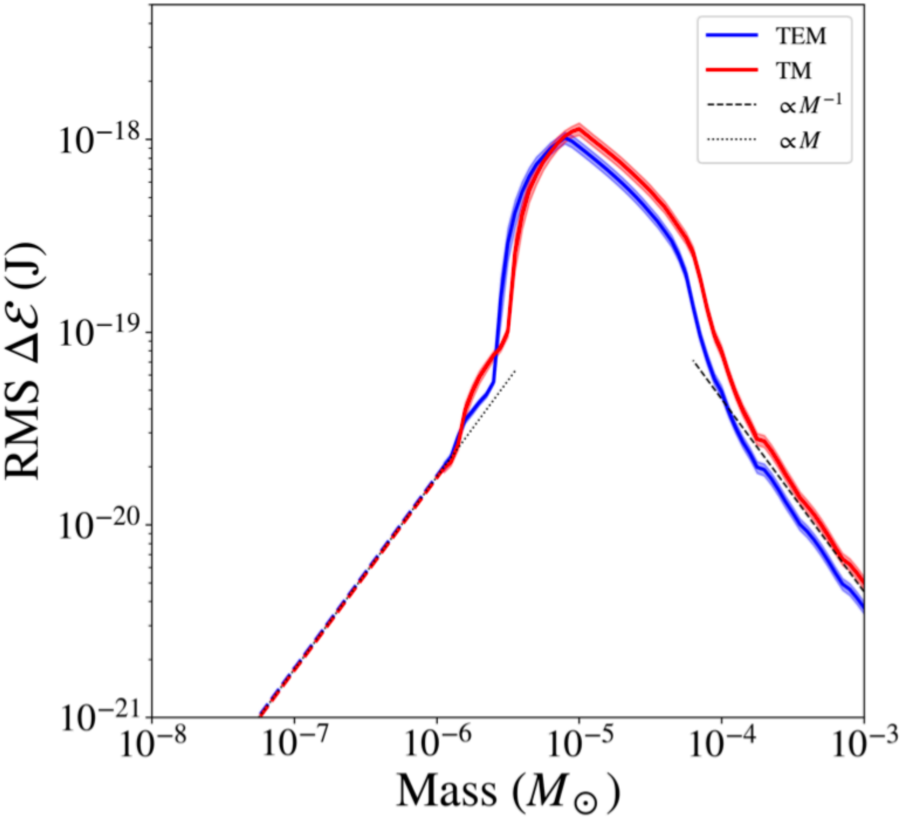


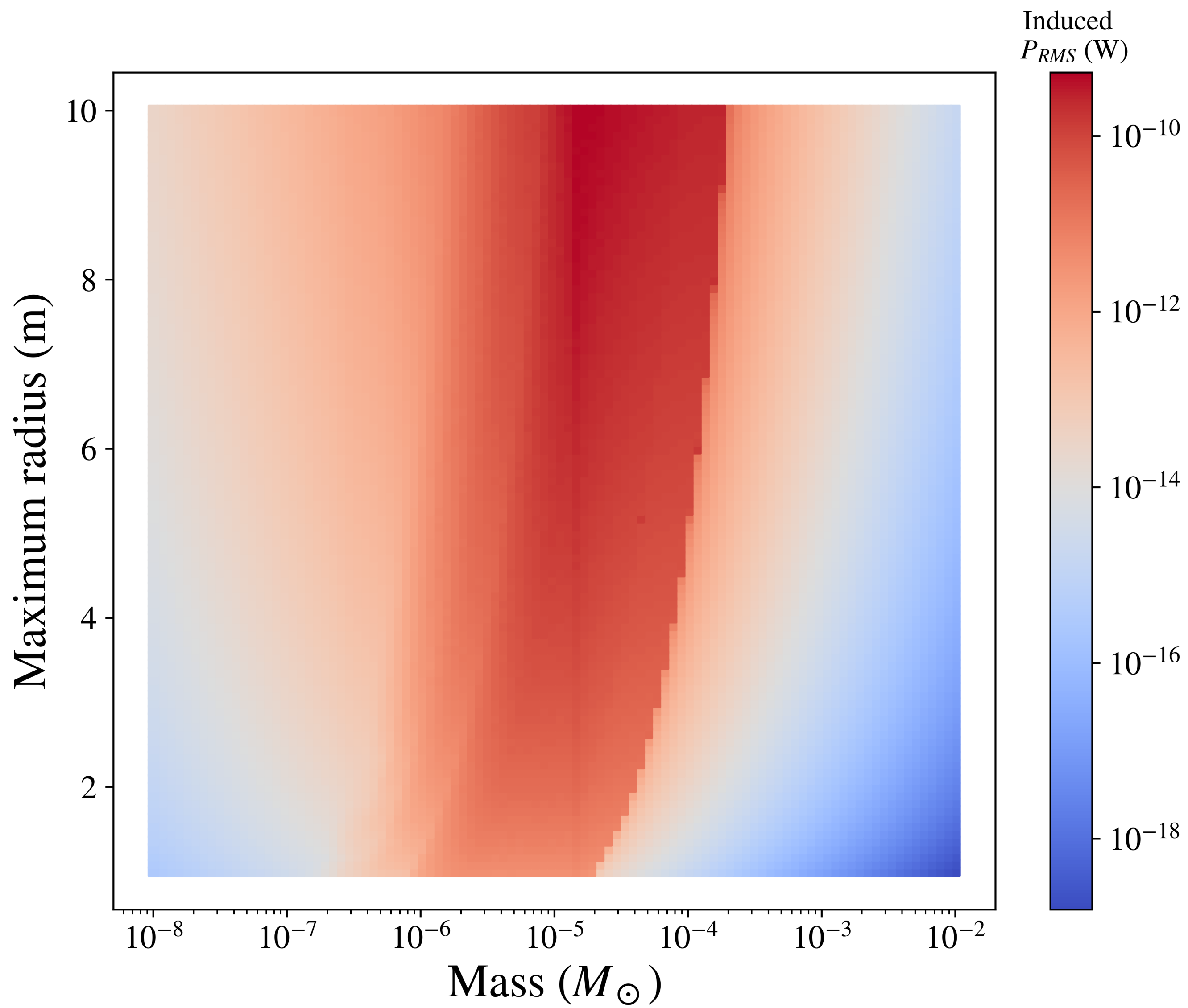
Resonance of the cavity

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





Cavity response map



Merging rate and DM made out of PBHs

4PN approximation

$$h \approx \frac{2}{D}\left(\frac{G\mathcal{M}}{c^2}\right)^{5/3}\left(\frac{\pi f_{\mathrm{GW}}}{c}\right)^{2/3}$$

Maximum distance to detect the merger

$$D_{\max} \approx 1.6 \times \frac{(m_{\mathrm{PBH}}/M_{\odot})}{h_{\mathrm{det}} \times 10^{20}}\mathrm{Mpc}$$

Merging rate

$$R^{\mathrm{prim}}(m_{\mathrm{PBH}}) \approx \frac{3.1 \times 10^6}{\mathrm{Gpc^3 yr}}\tilde{f}^2_{\mathrm{PBH}}\left(\frac{m_{\mathrm{PBH}}}{M_{\odot}}\right)^{-0.86}$$

L. Liu, Z.K. Guo, and R.G. Cai, PhysRevD 2019

Merging rate and DM made out of PBHs

Radius of the sphere for an event per year

$$D_1^{\rm prim} = \left(\frac{4\pi}{3} R^{\rm prim}\right)^{-1/3} \approx 4.2\,{\rm Mpc} \times \tilde{f}_{\rm PBH}^{-2/3} \left(\frac{m_{\rm PBH}}{M_\odot}\right)^{0.29}$$

Strain sensitivity to detect this event

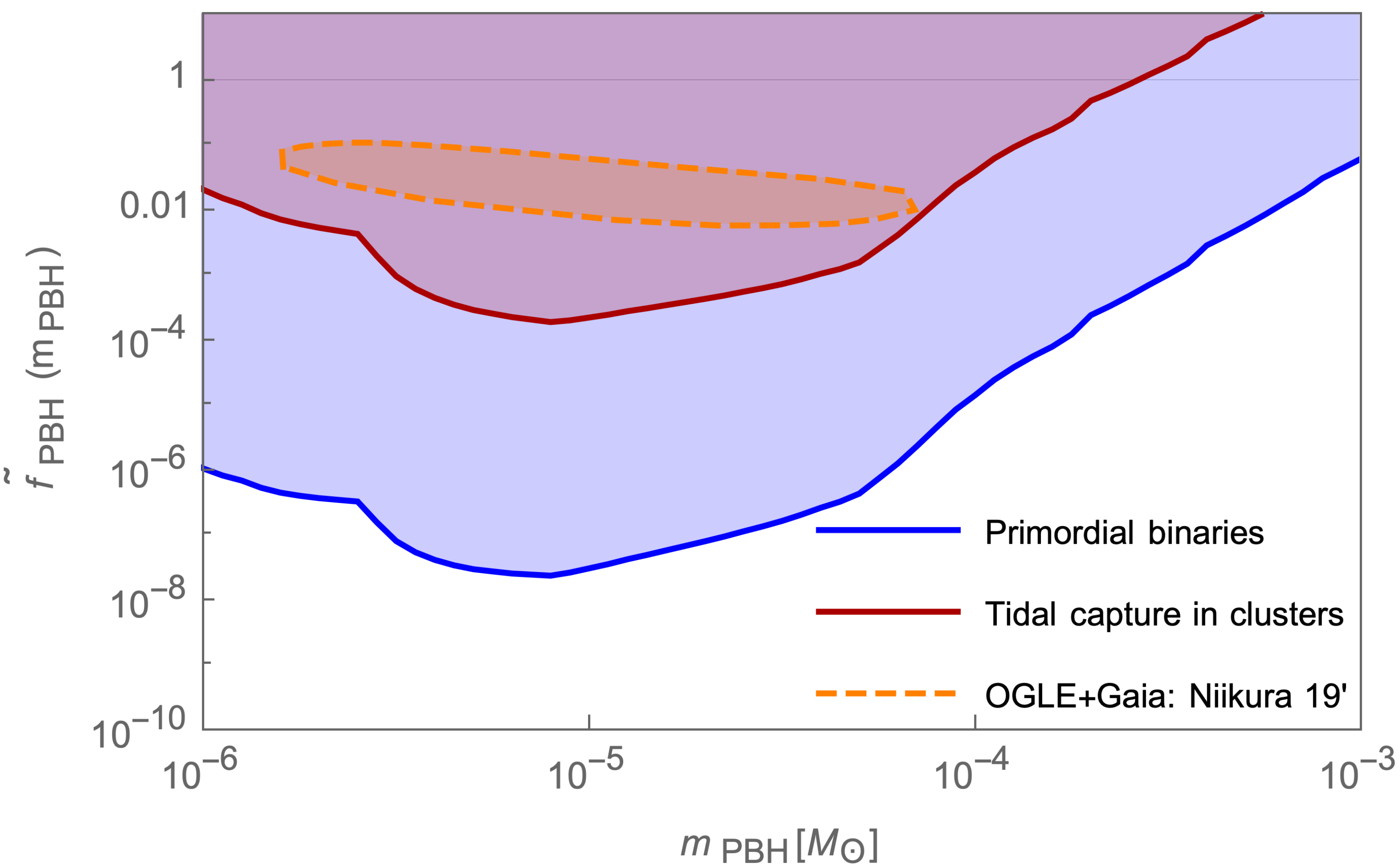
$$h_1^{\rm prim} \approx 3.8 \times 10^{-21}\, \tilde{f}_{\rm PBH}^{2/3} \left(\frac{m_{\rm PBH}}{M_\odot}\right)^{0.7}$$

$$\approx 8.3 \times 10^{-19}\, \tilde{f}_{\rm PBH}^{2/3} \left(\frac{\rm Hz}{f}\right)^{0.7},$$

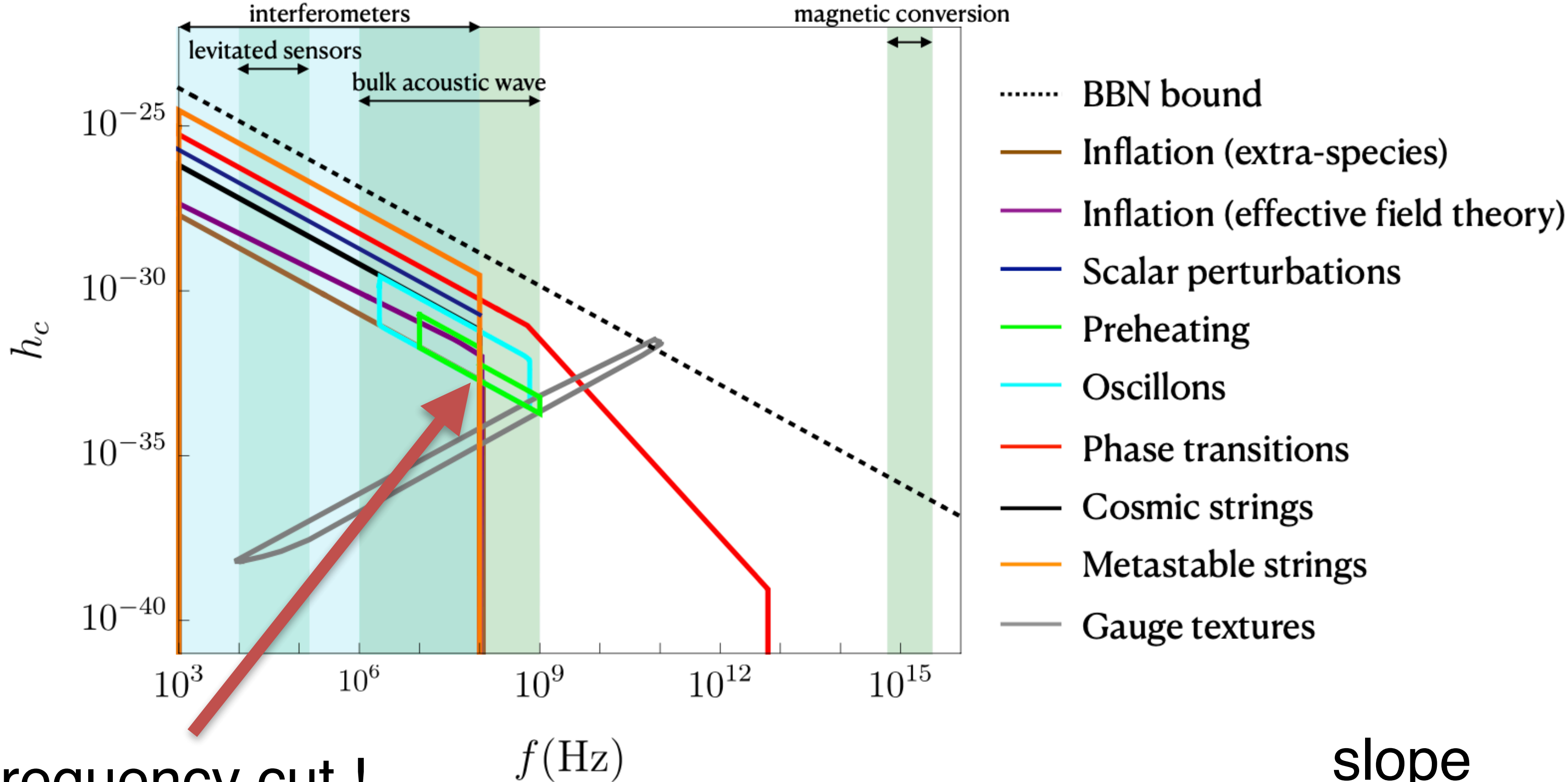
Limit on $f_{\rm PBH}$ in case of null detection

$$\tilde{f}_{\rm PBH} \lesssim 9.1 \left[\frac{h_{\rm det}}{10^{-20}}\right]^{3/2} \left(\frac{m_{\rm PBH}}{M_\odot}\right)^{-1.07}$$

Expected limits on f_{PBH}



SGWB, characteristics and interests



Frequency cut !

slope

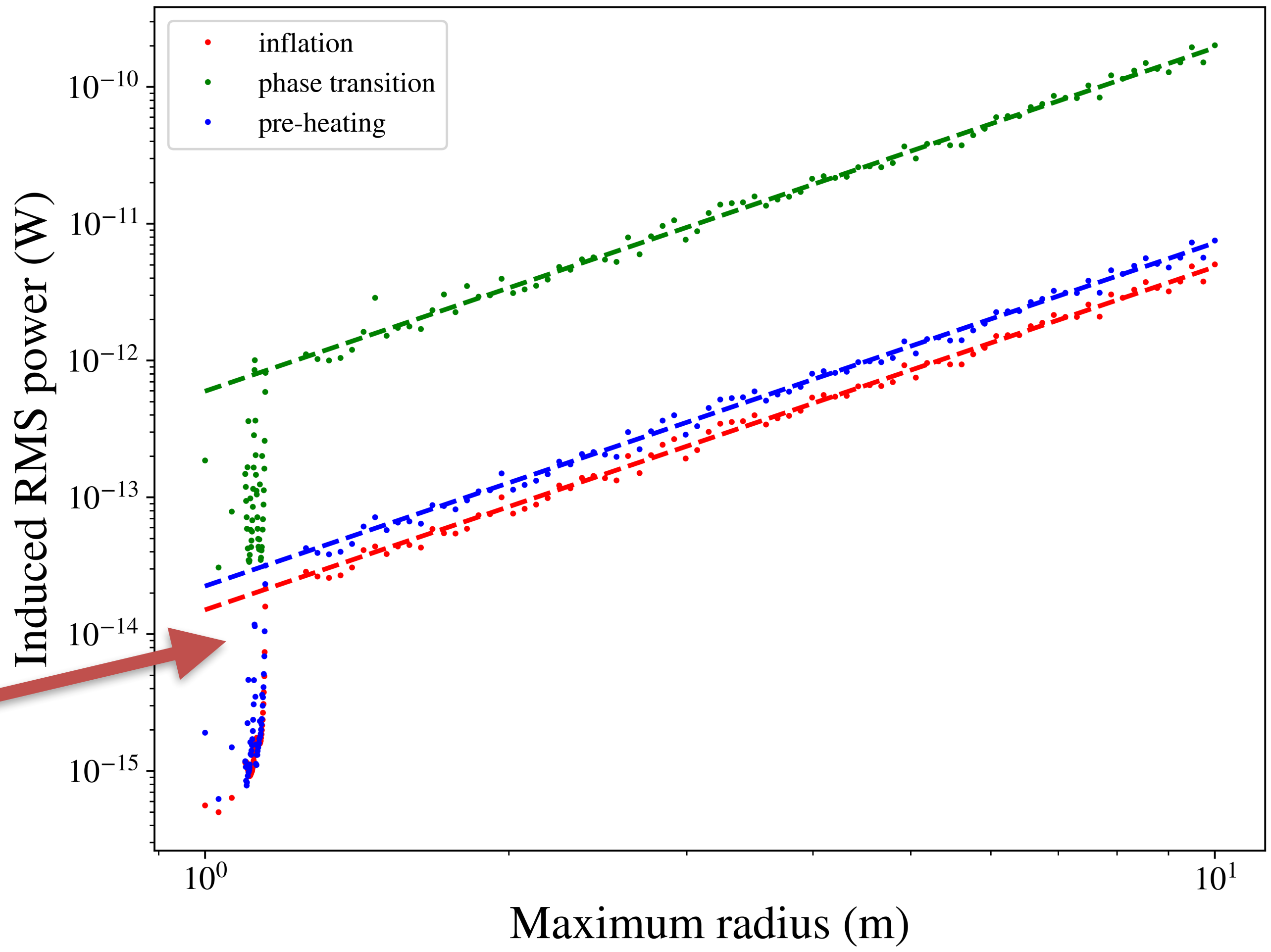
$$f_0 \simeq 2.65 \times 10^{-8} \frac{1}{\epsilon_*} \left(\frac{T_*}{1\,\mathrm{GeV}}\right) \left(\frac{g_*}{106.75}\right)^{1/6} \mathrm{Hz}$$

$$h_c = A \left(\frac{f}{f_{yr}}\right)^{\alpha}$$

Simulation of the detection of the SGWB

$$S = 2 - \frac{2\alpha + 1}{2}$$

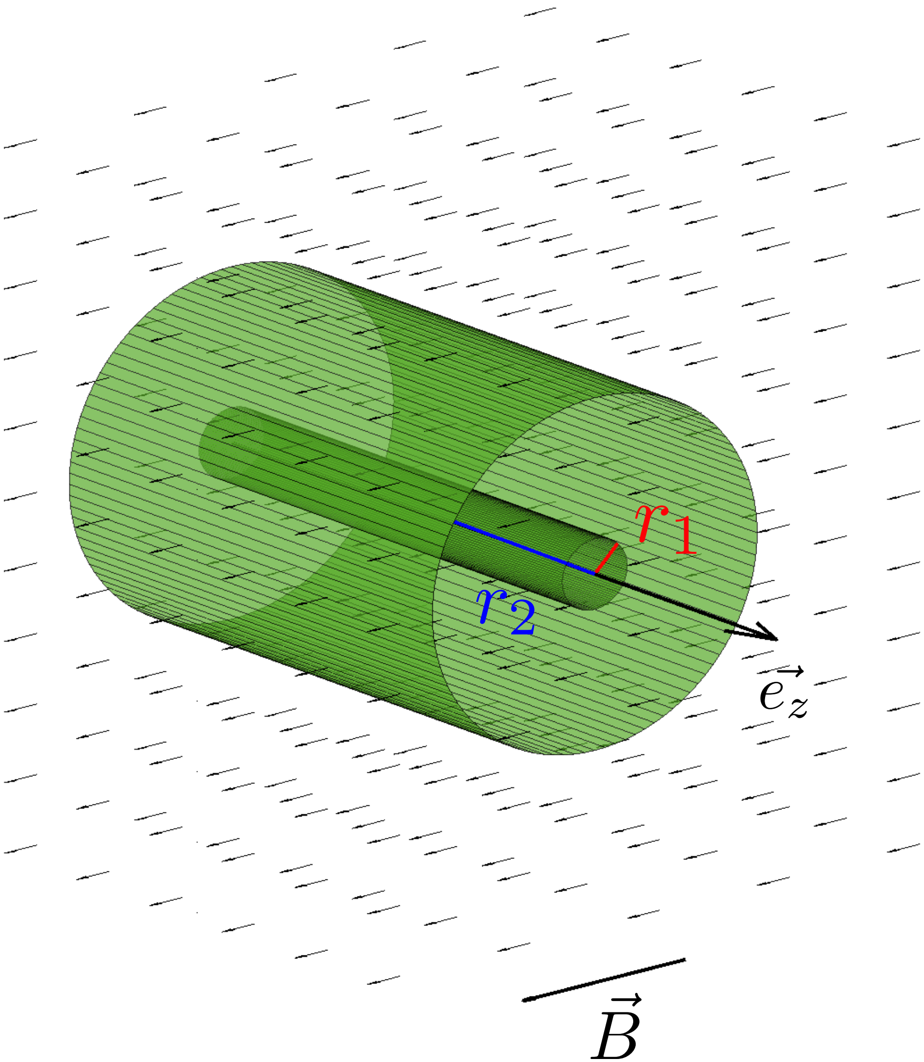
Detection of the frequency cut



Parameters of the detector

- ~ B ≥ 5 T and L ≥ 1 m (B transverse)
- ~ TEM cavity encased (frequency combing)
- ~ 0.5 m ≤ R ≤ 1.5 m

PBHs SGWB



Conclusions

~ UHF GW open up a new window on the univers

~ DM candidates

~ Test for cosmological models

~ A detection method accessible with current technology

~ Theoretical motivation for experimental development

Perspectives

~ Need of experimental development

~ In-depth study of the SGWB

~ PRL article in progress

~ Construction of a prototype

~ Plan of an ERC !