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

Nicolas Herman (speaker)
André Füzfa, Léonard Lehoucq, Sébastien Clesse

https://arxiv.org/abs/2012.12189
accepted in Physical Review D

nicolas.herman@unamur.be
Gravitational waves

~ Interferometry : from nHz to kHz

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

~ Possible astrophysical sources :  
  • 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 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 \( f_{\text{ISCO}} = \frac{4400 \text{ Hz}}{(m_1 + m_2)/M_\odot} \)
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

EMW

\[ \sim \text{Direct Gersentshtein Effect 1962} \]

\[ \sim \text{Amplitude of the generated GW} \]

\[ \frac{4GB_0E_0L^2}{c^5\mu_0} \]
GW generation with wave resonance

EMW \quad GW

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Direct and inverse Gertsenshtein effects

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

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

~ Astrophysical application (Zeldovich, 1973)

~ Inverse Gertsenshtein Effect

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

GW

Constant transverse magnetic field

~ Application to the GW detection!
Direct and inverse Gertsenshtein effects

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\[ \text{EMW} \quad \text{GW} \]

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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

\[ g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu} \]
\[ \partial_\mu h^{\mu\alpha} = 0 \]

~ 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

\[ S_{\mu\nu} = 0 \iff J_{\mu}^{\text{eff}} = 0 \iff \Phi_\alpha F^{\alpha\mu} (0) = q \Phi^\mu \]
~ 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
Inverse Gertsenshtein Effect

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Case study of two EM GW detectors
~ Two cylindrical cavities : TM (hollow) and TEM (coaxial)

Case study of two EM GW detectors

\[ \dot{\hat{b}}_{k,m,n}^r,\phi + \Omega_{kn}^2 \hat{b}_{k,m,n}^r,\phi = \hat{s}_{k,m,n}^r,\phi (t) \]

\sim \text{Projection on proper functions of Laplacian}

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

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

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

- Using LALSimulation (PN expansion), start. freq. = $f_{\text{ISCO}}/25$
- Planetary mass : first signal $10^{-5} M_\odot$
Resonant response of the detectors $10^{-5} \, \text{M} \odot$

$B=5 \, \text{T} \quad L=1 \, \text{m} \quad r=5 \, \text{m} \quad r_1=0.1 \, \text{m}$

Other simulation
Resonant response of the detectors $10^{-5} \text{ M⊙}$

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TEM Cavity

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\times 10^{-9}
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TM Cavity

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RMS induced power of order \(10^{-10} \, \text{W}\)
Resonant response of the detectors $10^{-5}$ M☉

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

TEM Cavity

TM Cavity

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 😊