INFN Bari Theory Group
Xmas Workshop
Bari, 17 December 2024

High-frequency GWs shining in photons in Galactic magnetic fields

Based on: AL., F. Calore, P. Carenza, A. Mirizzi, 2406.17853 [hep-ph]
Phys.Rev.D 110 (2024) 8, 083042

Alessandro Lella
Physics Department of «Aldo Moro» University in Bari
Istituto Nazionale di Fisica Nucleare

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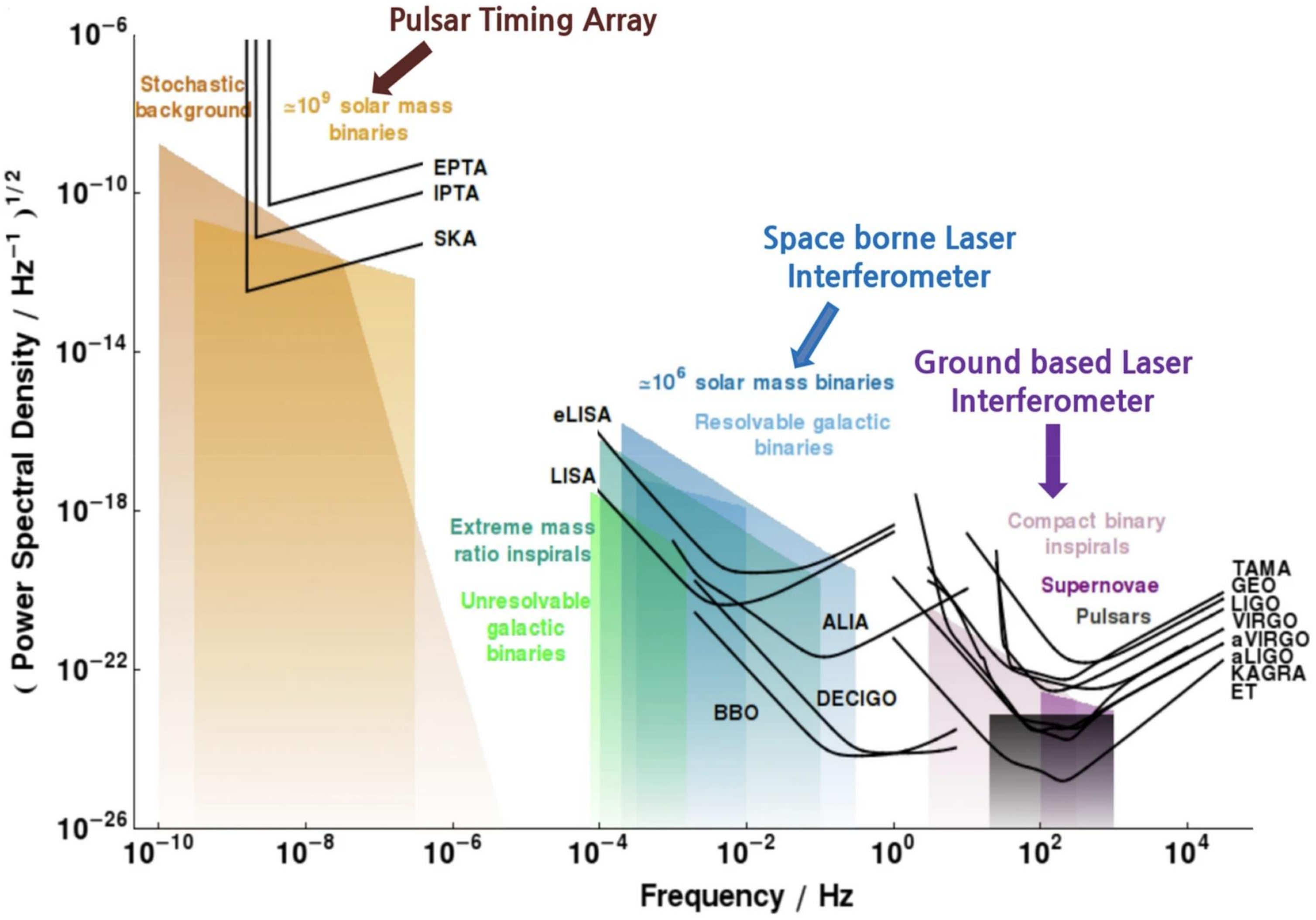
COSMIC WISPERS CA21106

GWs from known sources



Gravitational waves arise from the linearization of Einstein equations

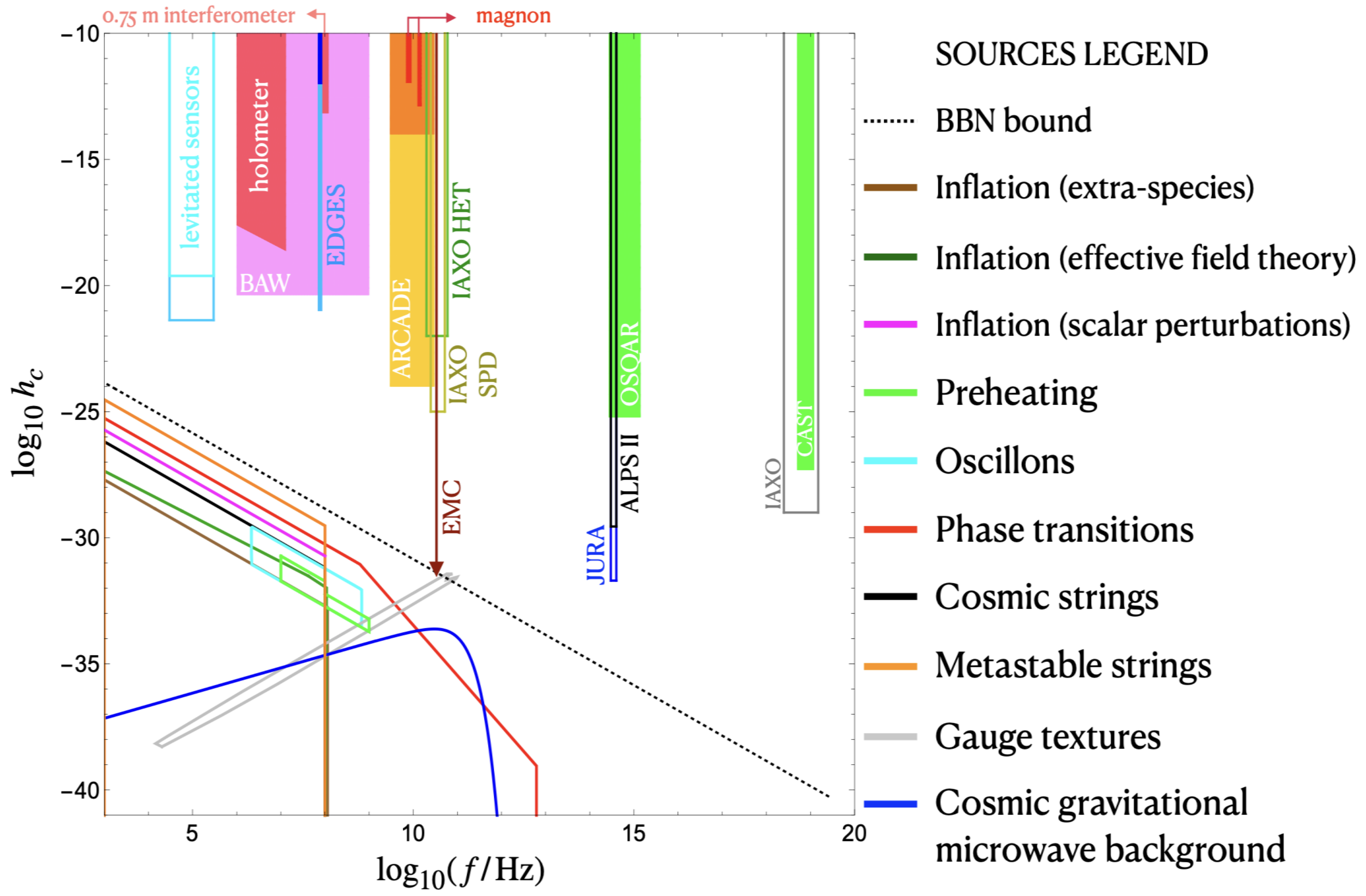
$$g_{\mu\nu}(x) = \eta_{\mu\nu} + \frac{2}{M_{\rm P}} h_{\mu\nu}(x)$$

$$\Box h_{\mu\nu} = \frac{16\pi G}{c^4} S_{\mu\nu}$$

→ Since 2015, detection of ~90 transient sources!
+
Stochastic GW Background

High-frequency GWs

Exotic sources in the early universe could produce a GW background at high frequencies $f \gtrsim \mathrm{MHz}$



Properties of the GW background:

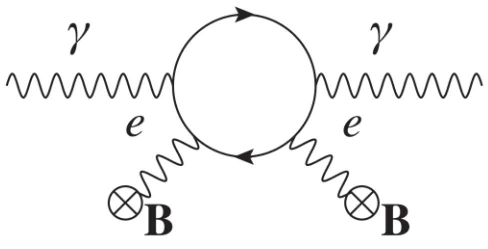
- Isotropic
- Stationary
- Stochastic
- Subject to cosmological constraints

[Aggarwal et al., Living Rev. Rel. 24 (2021) 1, 4]

Graviton-photon conversions

Electromagnetism in a curved space-time couples the photon and the gravitational fields

$$\mathcal{L}_{\rm em} = -\frac{1}{4} g^{\mu\alpha} g^{\nu\beta} F_{\mu\nu} F_{\alpha\rho} + \int d^4x' A_\mu(x) \Pi^{\mu\nu}(x,x') A_\nu(x')$$



Photon polarization tensor in the Euler-Heisenberg limit ($B \ll B_{\rm cr} \sim 10^{13}$ G)

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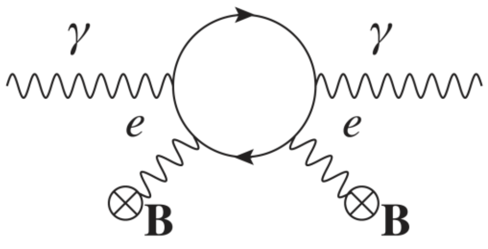

Photon polarization tensor in the Euler-Heisenberg limit ($B \ll B_{\rm cr} \sim 10^{13}$ G)

Deriving the EoM, in the limit $\omega \simeq k$ *[Raffelt & Stodolsky, Phys.Rev.D 37 (1988) 1237]*

$$\left(i\frac{d}{dz} - \omega\right) \begin{pmatrix} h_+ \\ h_\times \\ A_x \\ A_y \end{pmatrix} = H \begin{pmatrix} h_+ \\ h_\times \\ A_x \\ A_y \end{pmatrix}$$

$$H = \begin{pmatrix} 0 & \mathcal{H}_{g\gamma} \\ \mathcal{H}_{g\gamma} & \mathcal{H}_{\gamma\gamma} \end{pmatrix}$$

Mixing term

Photon dispersion relation

Graviton-photon conversions

- Photon dispersion relation:

$$\mathcal{H}_{\gamma\gamma} = \begin{pmatrix} \Delta_x c_\phi^2 + \Delta_y s_\phi^2 & [\Delta_y - \Delta_x] c_\phi s_\phi \\ [\Delta_y - \Delta_x] c_\phi s_\phi & \Delta_y c_\phi^2 + \Delta_x s_\phi^2 \end{pmatrix}$$

$$\Delta_\lambda = \Delta_{\rm pl} + \Delta_{\rm QED}^\lambda + \Delta_{\rm CMB},$$

$$\Delta_{\rm pl} = -\frac{\omega_{\rm pl}^2}{2\,\omega} \simeq -1.1\times 10^{-3}\left(\frac{\omega}{1\ {\rm MeV}}\right)^{-1}\left(\frac{n_e}{10^{-2}\ {\rm cm}^{-3}}\right)\ {\rm kpc}^{-1},$$

$$\Delta_{\rm QED}^\lambda = \kappa_\lambda \frac{4\,\alpha^2 B_T^2\,\omega}{45\, m_e^4} \simeq 4.5\times 10^{-12}\,\kappa_\lambda\left(\frac{\omega}{1\ {\rm MeV}}\right)\left(\frac{B_T}{1\mu{\rm G}}\right)^2\ {\rm kpc}^{-1},$$

$$\Delta_{\rm CMB} = \frac{44\pi^2\,\alpha^2\,T_{\rm CMB}^4\,\omega}{2025\, m_e^4} \simeq 8.7\times 10^{-11}\left(\frac{\omega}{1\ {\rm MeV}}\right)\ {\rm kpc}^{-1},$$

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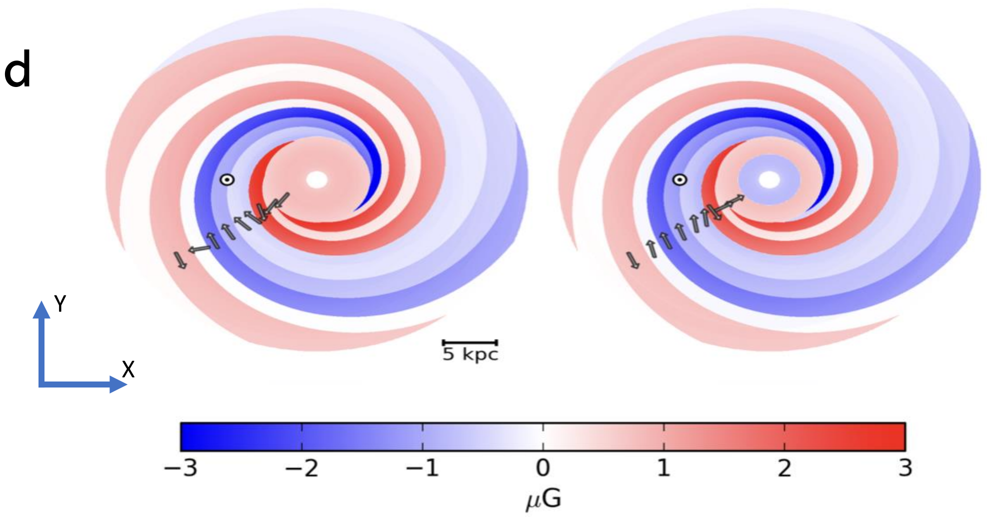
- Mixing terms:

$$\mathcal{H}_{g\gamma} = \begin{pmatrix} \Delta_{g\gamma} s_\phi & \Delta_{g\gamma} c_\phi \\ \Delta_{g\gamma} c_\phi & -\Delta_{g\gamma} s_\phi \end{pmatrix}$$

$$\Delta_{g\gamma} = \frac{B_{\rm T}}{\sqrt{2}\, M_{\rm P}} \simeq 8.8 \times 10^{-10} \left(\frac{B_{\rm T}}{1\ \mu \rm G}\right) \rm kpc^{-1}$$

Large-Scale Galactic Magnetic Field

Jansson-Farrar model for the large-scale Galactic magnetic field
[Jansson & Farrar, Astrophys.J. 757 (2012) 14] .



- $|B| \sim 1\ \mu G$
- Correlated over scales $l_{\rm corr} \sim 1$ kpc
- Disk field + a large halo field
- Reproduces Galactic synchrotron emission

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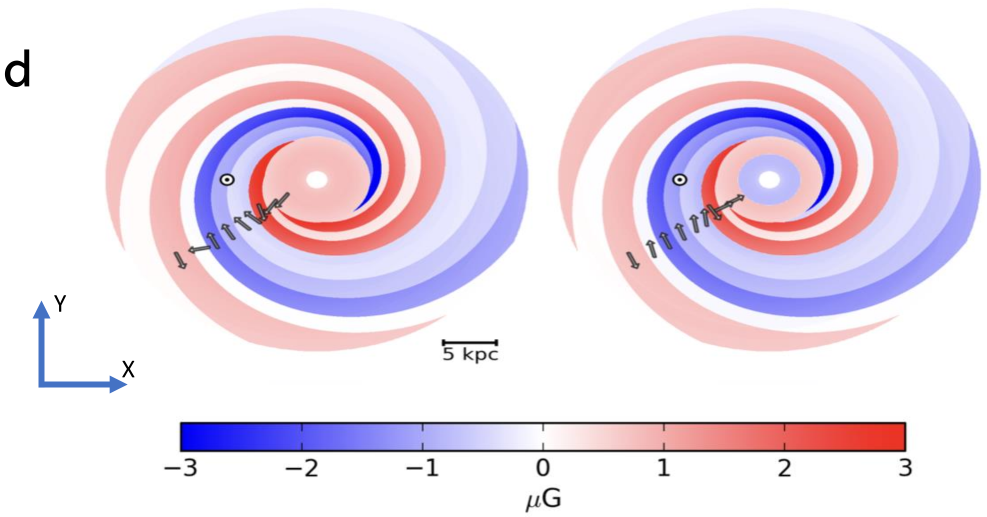
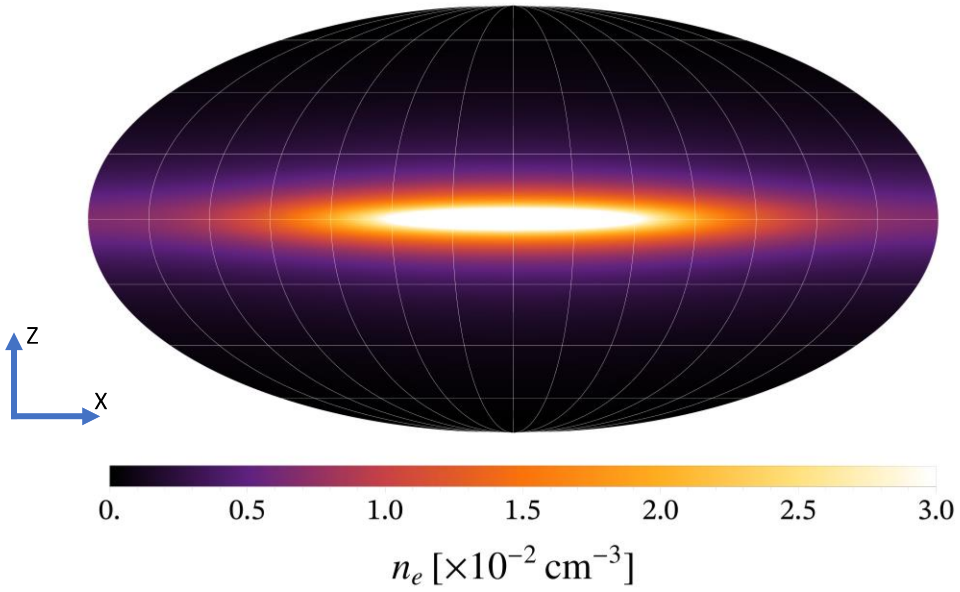


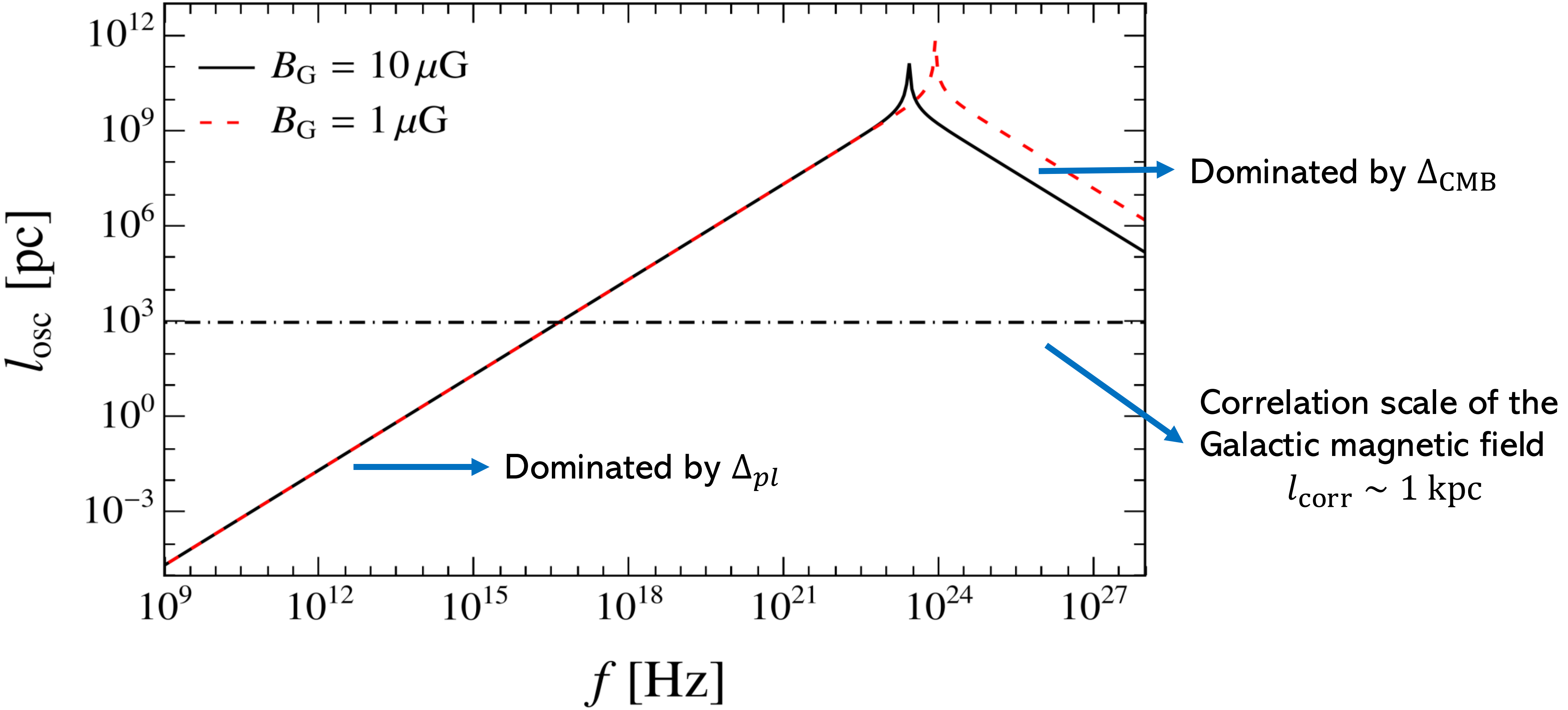
Model for the electron number density from *[Cordes & Lazio, astro-ph/0207156]*.

- $n_e \sim 10^{-3} - 10^{-2}\ cm^{-3}$
- Correlated over scales $l_{\mathrm{corr}} \sim 1\ \mathrm{kpc}$
- Describes large-scale fluctuations in electron density



Graviton-photon conversions

The typical graviton photon oscillation length is given by $l_{\rm osc} \sim \Delta_{\rm osc}^{-1} = \left(\Delta^2 + 4\Delta_{g\gamma}^2\right)^{-\frac{1}{2}}$



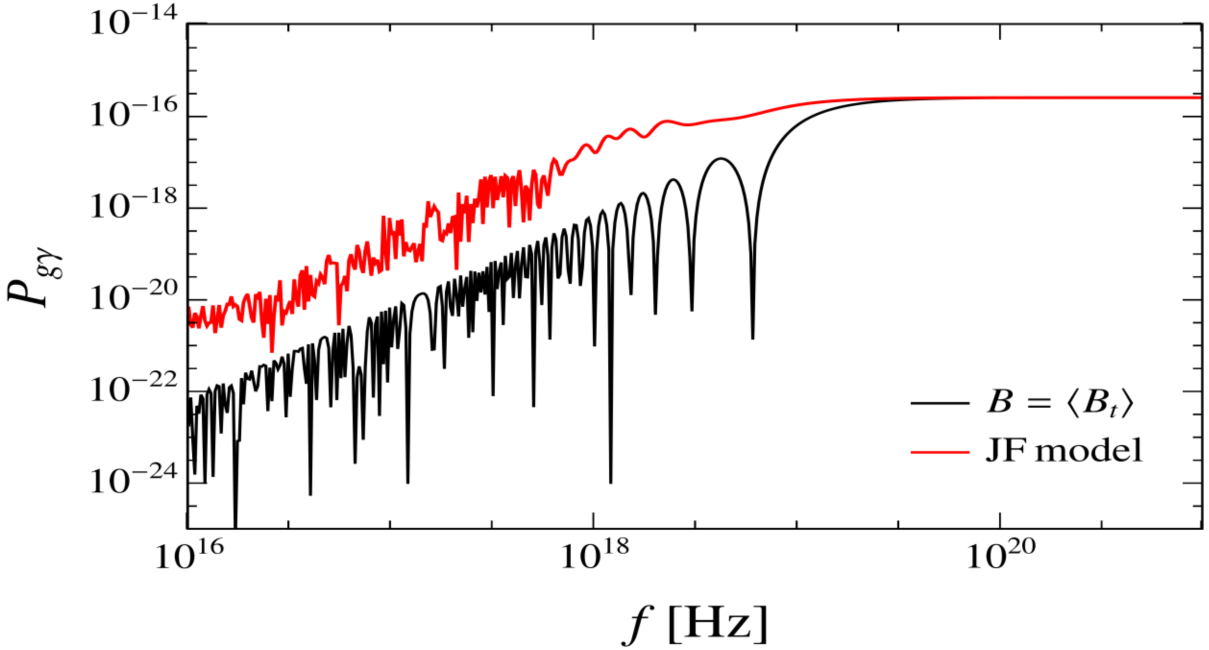
Conversion Probability

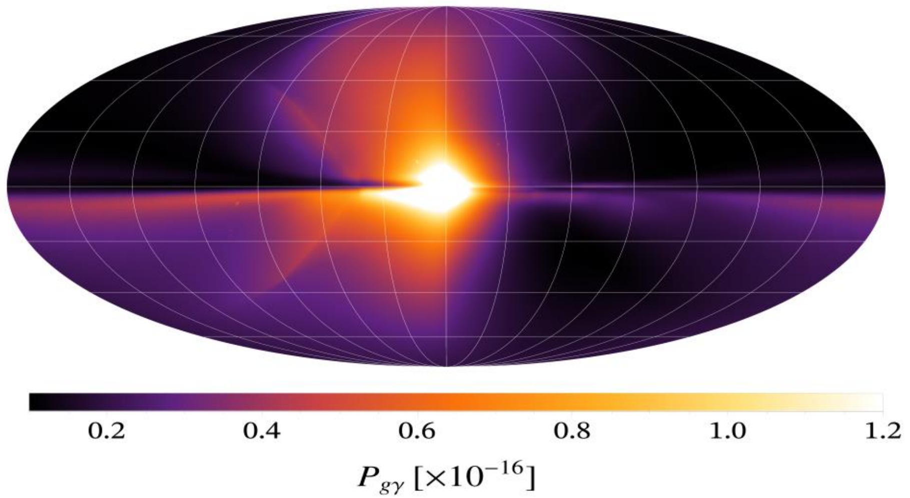
- The oscillation probability can be obtained by solving numerically the EoM

- Assuming a constant and homogenous field along the line of sight

$$\langle B_T \rangle^2 = \frac{1}{L^2}\left(\left|\int_0^L B_x(z,l,b)dz\right|^2 + \left|\int_0^L B_y(z,l,b)dz\right|^2\right)$$

$$P_{g\gamma} = \frac{4\Delta_{g\gamma}^2}{\Delta_{\rm osc}^2}\sin^2\left(\frac{\Delta_{\rm osc}\, z}{2}\right)$$





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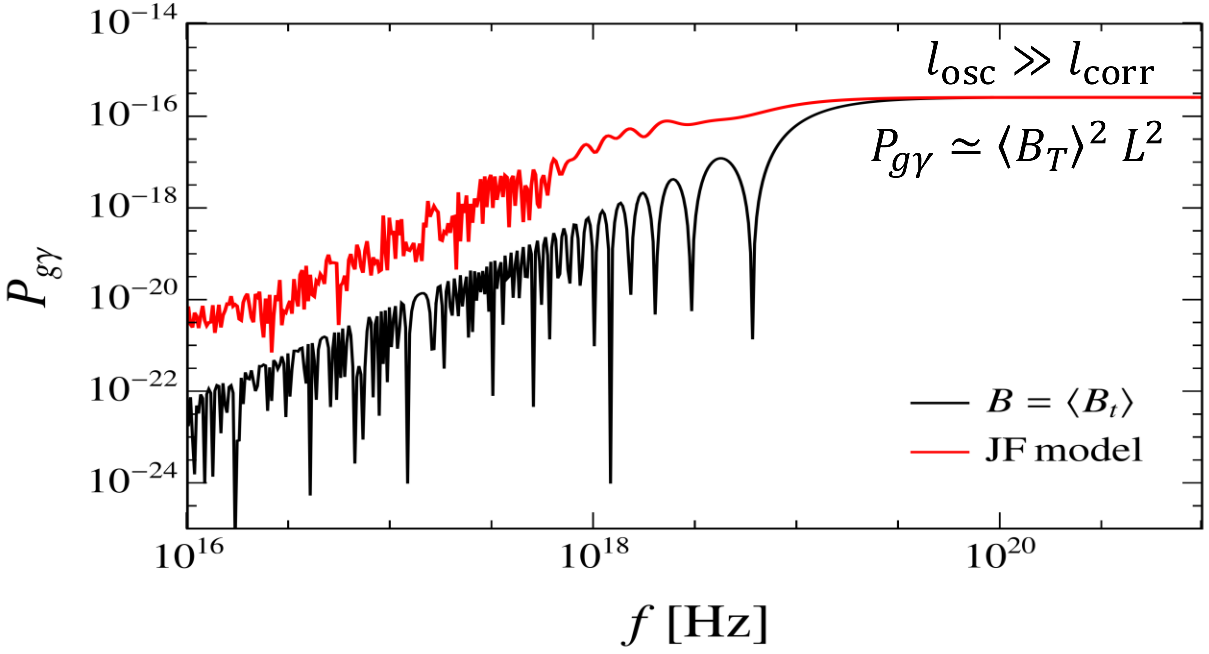
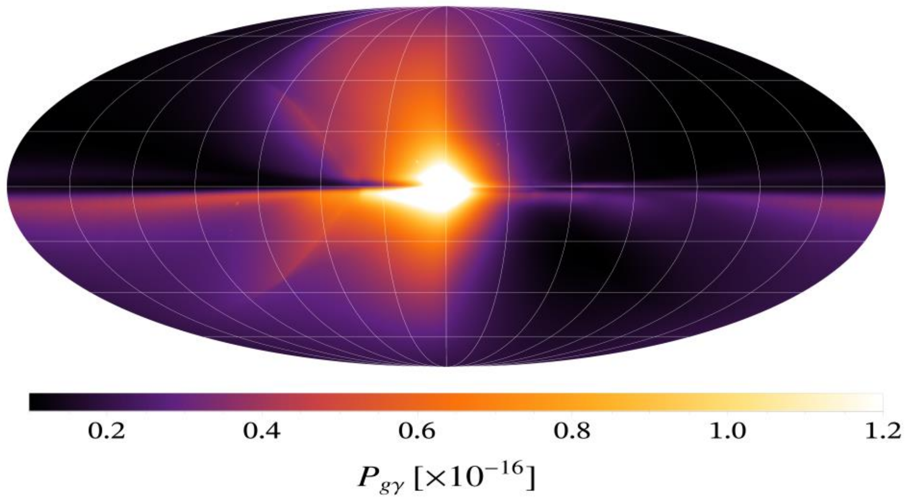
- The two approaches match when $l_{\rm osc} \gg l_{\rm corr}$





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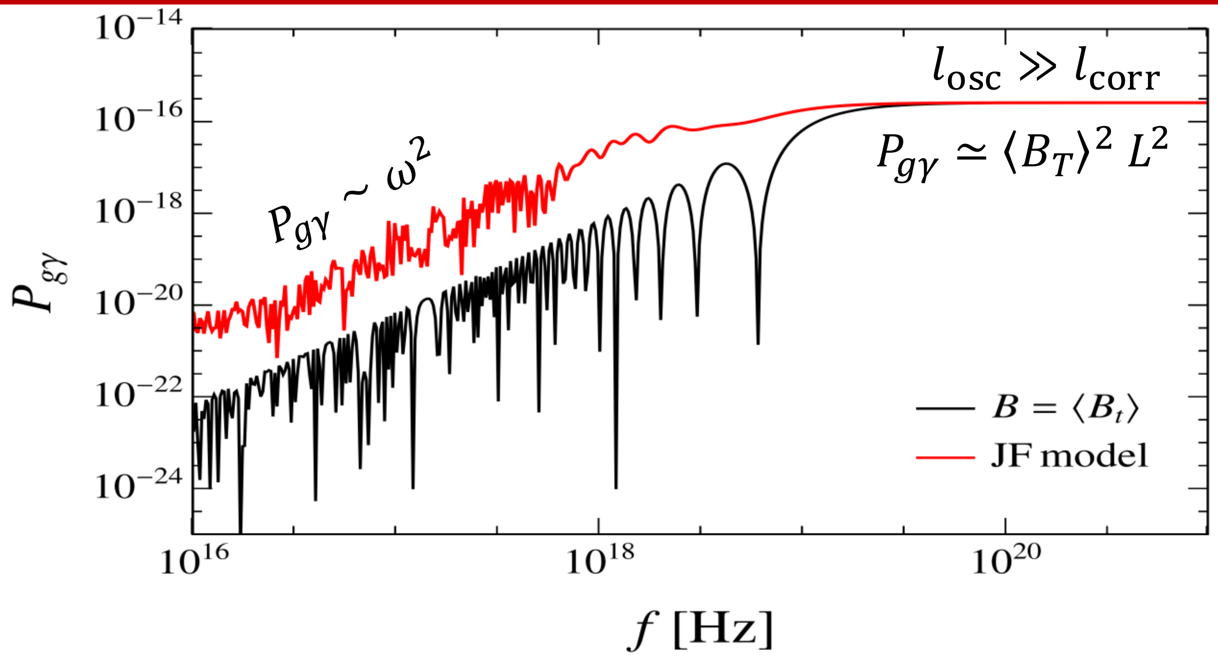
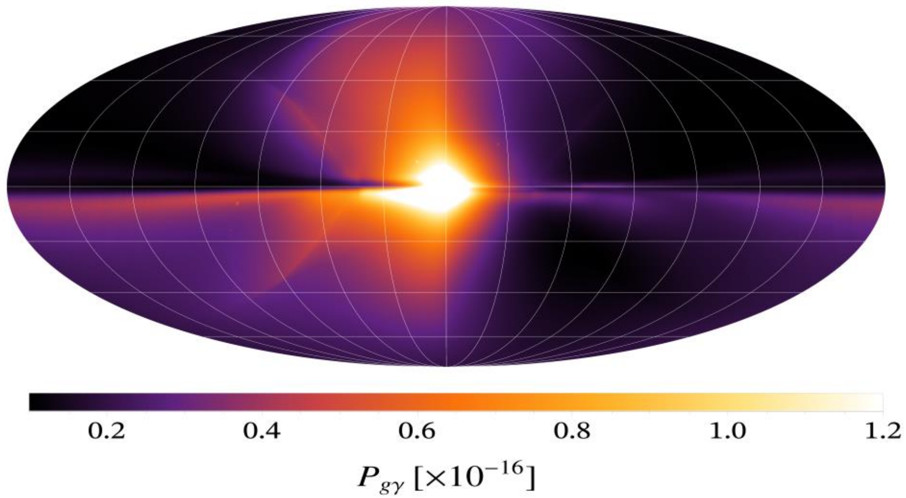
- The two approaches match when $l_{osc} \gg l_{corr}$

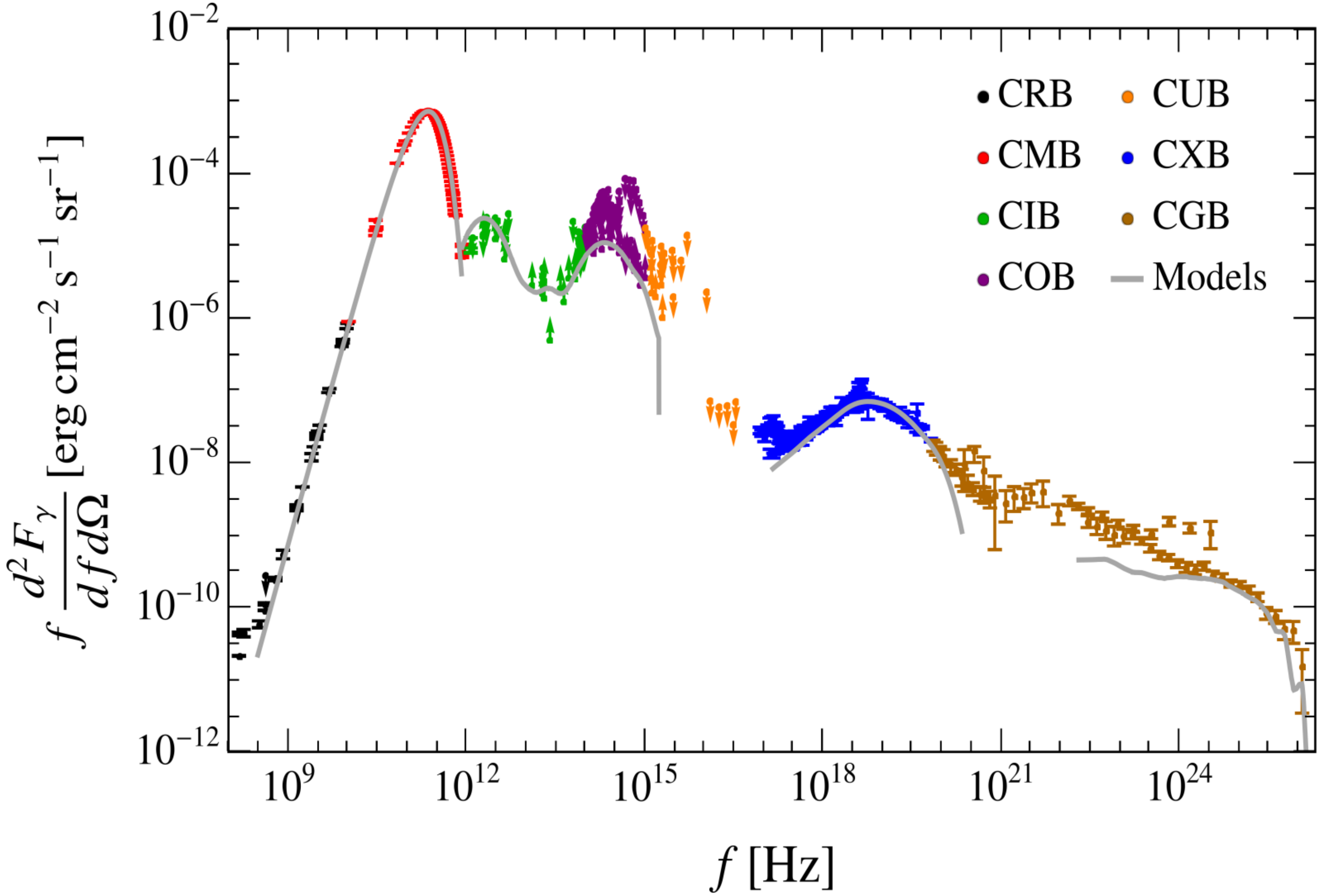
- Dramatic loss of precision in the numerical approach at $l_{osc} \ll l_{corr}$





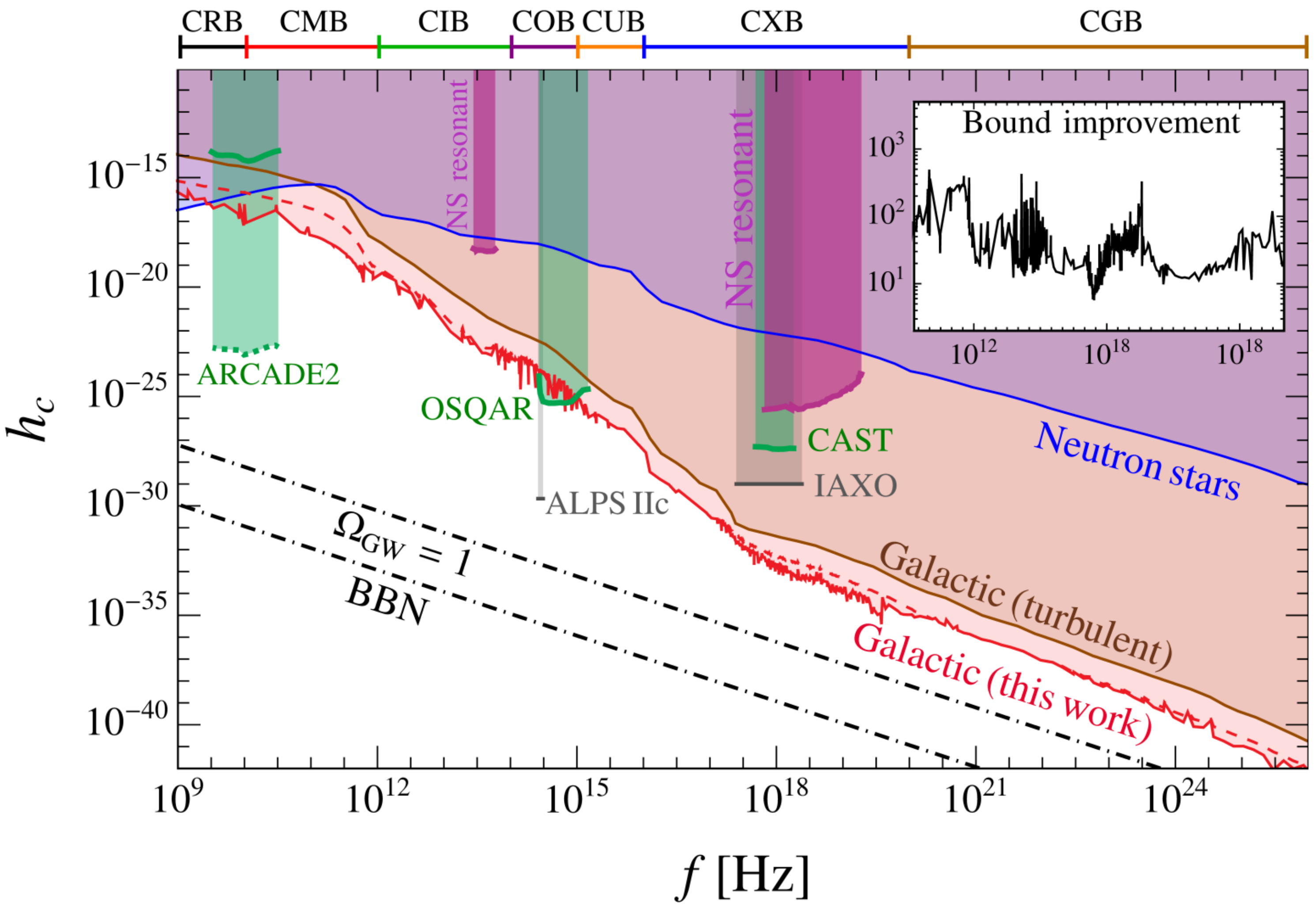
Observation of the CPB

Measurements of the Cosmic Photon Background from *[R. Hill et al., Appl. Spectrscop. 72 (2018) 663]*



- **CRB-CMB**: blackbody spectrum at $T_{\rm CMB} \simeq 2.73$ K *[D. J. Fixsen, Astrophys. J. 707 (2009) 916]*
- **CIB-COB-CUB**: EBL emission *[Dominguez et al., Mon. Not. Roy. Astron. Soc. 410 (2011) 2556]*
- **CXB**: AGN accretion disk emission *[Comastri et al., Astron. Astrophys. 296 (1995) 1]*
- **CGB**: Blazar emission *[M. Fornasa et al., Phys. Rept. 598 (2015)1]*

Constraints on the GW background



To avoid an excess in the CPB we must require:

$$\frac{1}{4\pi}\frac{dF_{g\to\gamma}}{df}\bigg|_{f=f_i} \gtrsim \left|\frac{d^2F^{\rm exp}_{\gamma,i}}{df\,d\Omega} - \frac{d^2F^{\rm th}_{\gamma,i}}{df\,d\Omega}\right|$$

- Constraints comparable to axion experiments sensitivities

  [Ejlli et al., Eur. Phys J. C79 (2019)]

  [Domcke & Garcia-Cely, PRL 126 (2019)]

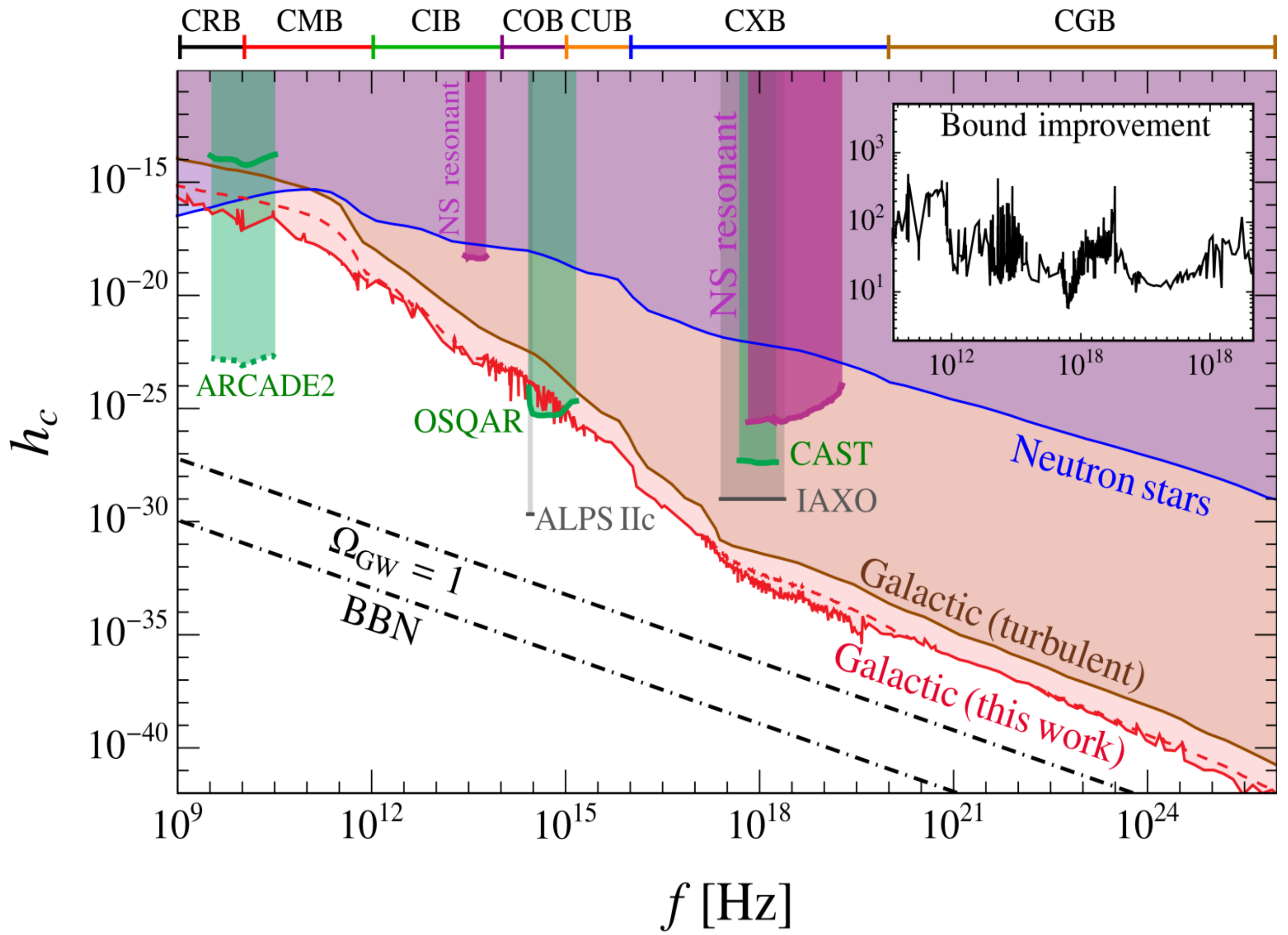
- Improvement of 1-2 orders of magnitude with respect to previous Astro bounds

  [Ito et al., PTEP 2024 (2024)]
  [Dandoy et al., arXiv:2402.14092]

  [Ellis & McDonald, arXiv: 2406.18634]

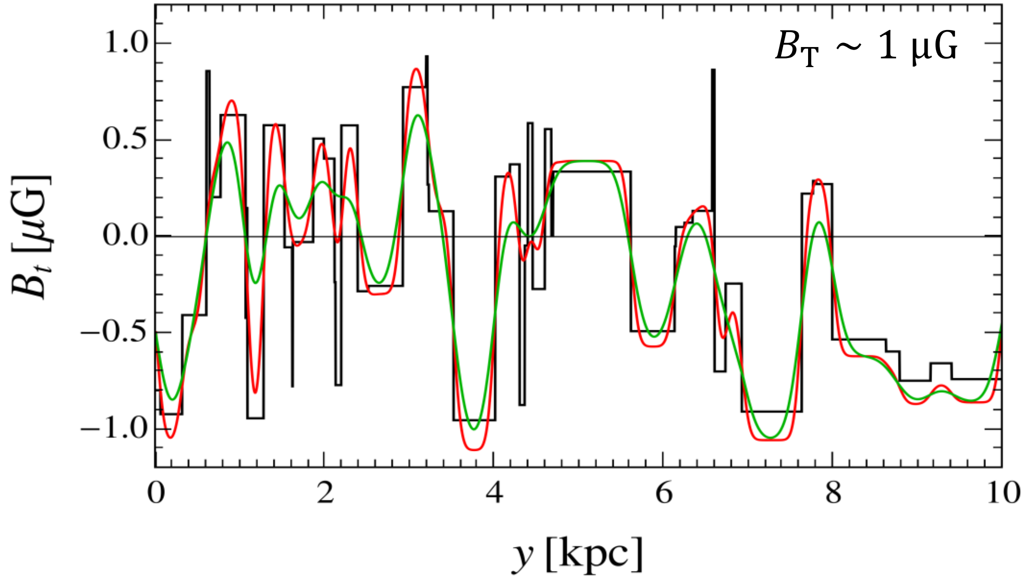
Summary and conclusions

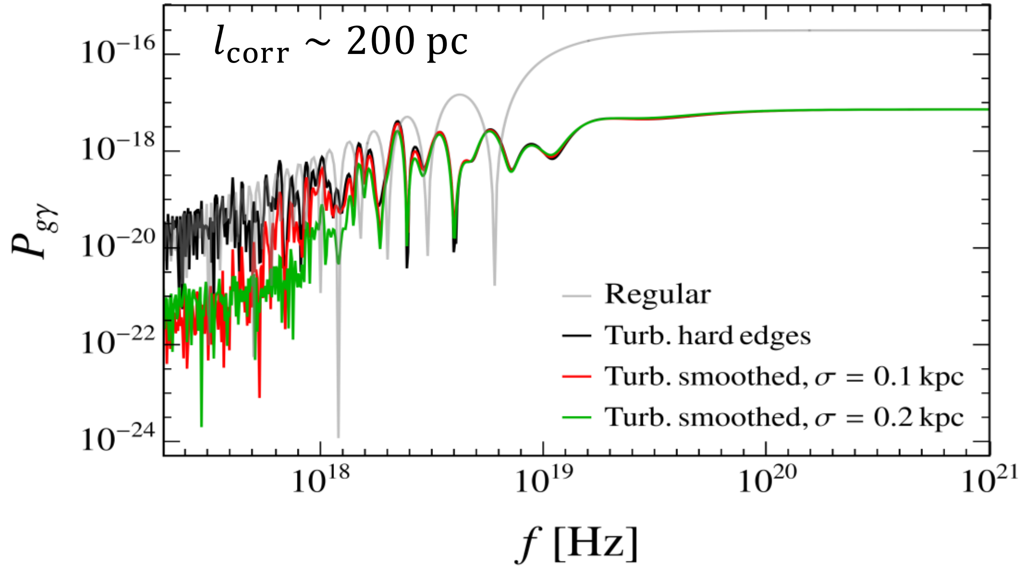
- High-frequency GW backgrounds are a smoking gun for new physics
- Graviton-photon conversion could probe the ultra-high frequency range
- Graviton-photon mixing in the Galactic magnetic field provides strong constraints on high-frequency GW backgrounds.
- Still far away from cosmological constraints. What's next?




Thank you for your attention

Turbulent magnetic field





The Galactic magnetic field shows evidences for a turbulent component with $l_{corr} \sim 20 - 200$ pc

[Iacobelli eta al., Astron. Astrophys. 556 (2013) A72]

- For $l_{osc} \gg l_{corr}$ cell approximation with hard edges holds

$$P_{turb} \simeq N \, \Delta P = \langle B_T \rangle^2 \, L \, l_{corr}$$

→ Suppression of a factor $\sim N$ with respect to the regular component

- For $l_{osc} \ll l_{corr}$ oscillations sensible to fine structure of the field

→ Strong dependency on the field power spectrum