Quantum (and classical) detection of gravitational waves: scope and limitations

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Short talk

BSM odyssey: turns and twists in particle theory (Cargèse, France)

31/07/2025

Based on: C. Beadle, PB, R.T. D'Agnolo, S.A.R. Ellis, arXiv:25XX.XXXXX

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Question and conclusions

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Preceding work: Classical and quantum heuristics for gravitational-wave detection [S.A.R. Ellis, R.T. D'Agnolo, arXiv:2412.17897]

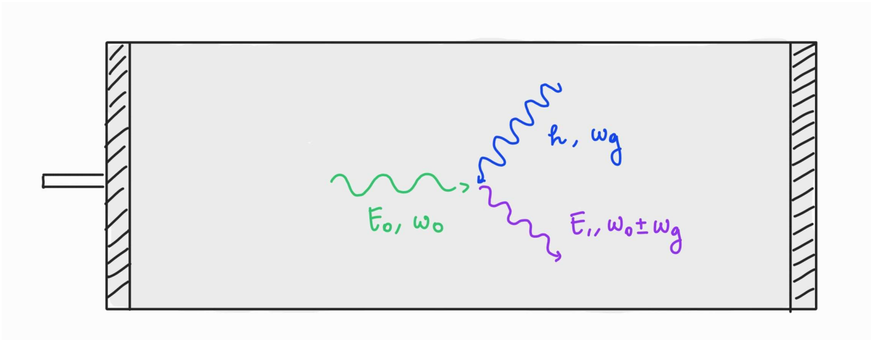
↳ *Bound on signal strength for detection of GWs coming from primordial backgrounds* [M. Maggiore, *Physics Reports* 331 (2000), 283-367]

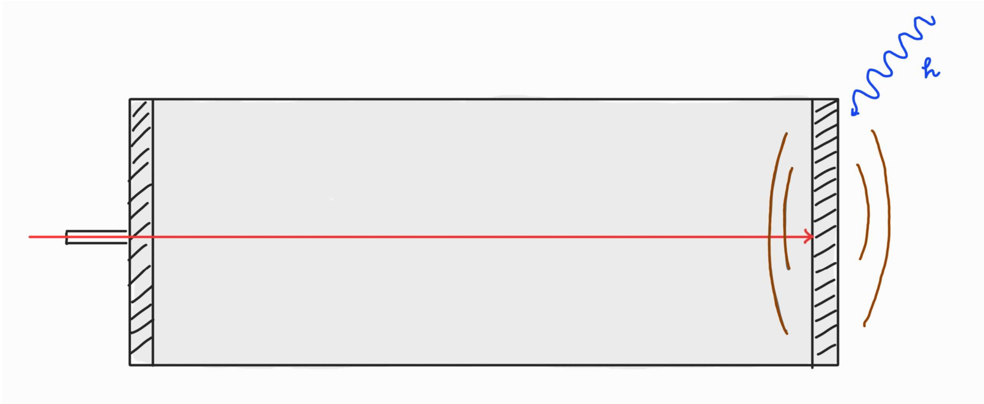
$$\int d\log\omega\; h_{\rm eff}^2 \Omega_g(\omega) \lesssim 5\times 10^{-6}\Delta N_{\rm eff}$$

"BBN bound"

Can we analytically confirm this statement?

Two toy models to describe (almost) any detector





EM resonators

- Large static magnetic field
- **Readout:** $\omega_1 \approx \omega_g$

- **MADMAX** [arXiv:2409.06462], **CAST** [arXiv:1705.02290], **IAXO** [*Eur. Phys. J. C* **79** (2019) 1032]

- Transition mode 0 (loaded) → 1 (readout)
- **Readout:** $\omega_1 = \omega_0 \pm \omega_g$

- **Resonant EM microwave cavities** [*Physical Review* D **105** 116011 (2022)], **Lumped LC resonators** [*Phys. Rev. Lett.* **129** (2022) 041101], **MAGO** [*Phys. Rev. D* **108** (2023) 084058]

Mechanical resonators

- Like test masses. Their position is measured through an **EM readout**

- **Interferometers** (**LVK**, **Holometer**), **Optomechanical sensors** (**levitating sphere** [A. Arvanitaki, A. A. Gercai, *Phys. Rev. Lett.* **110** (2013) 071105]), **Magnetic Weber bars** (**AURIGA** [M. Cerdonio *et al., Classical and Quantum Gravity* **14** (1997) 1491])

Signal vs. Noise: a never-ending duel

- **Power Spectral Density:** $$\langle A(t)B^\dagger(t')\rangle = \int_{-\infty}^{\infty} \frac{\mathrm{d}\omega}{2\pi} e^{i\omega(t-t')} S_{AB}(\omega) \longrightarrow \Omega_g(\omega) = \frac{\omega^3 S_{hh}(\omega)}{24\pi H_0^2}$$

Relation between the h-PSD and the GW energy density

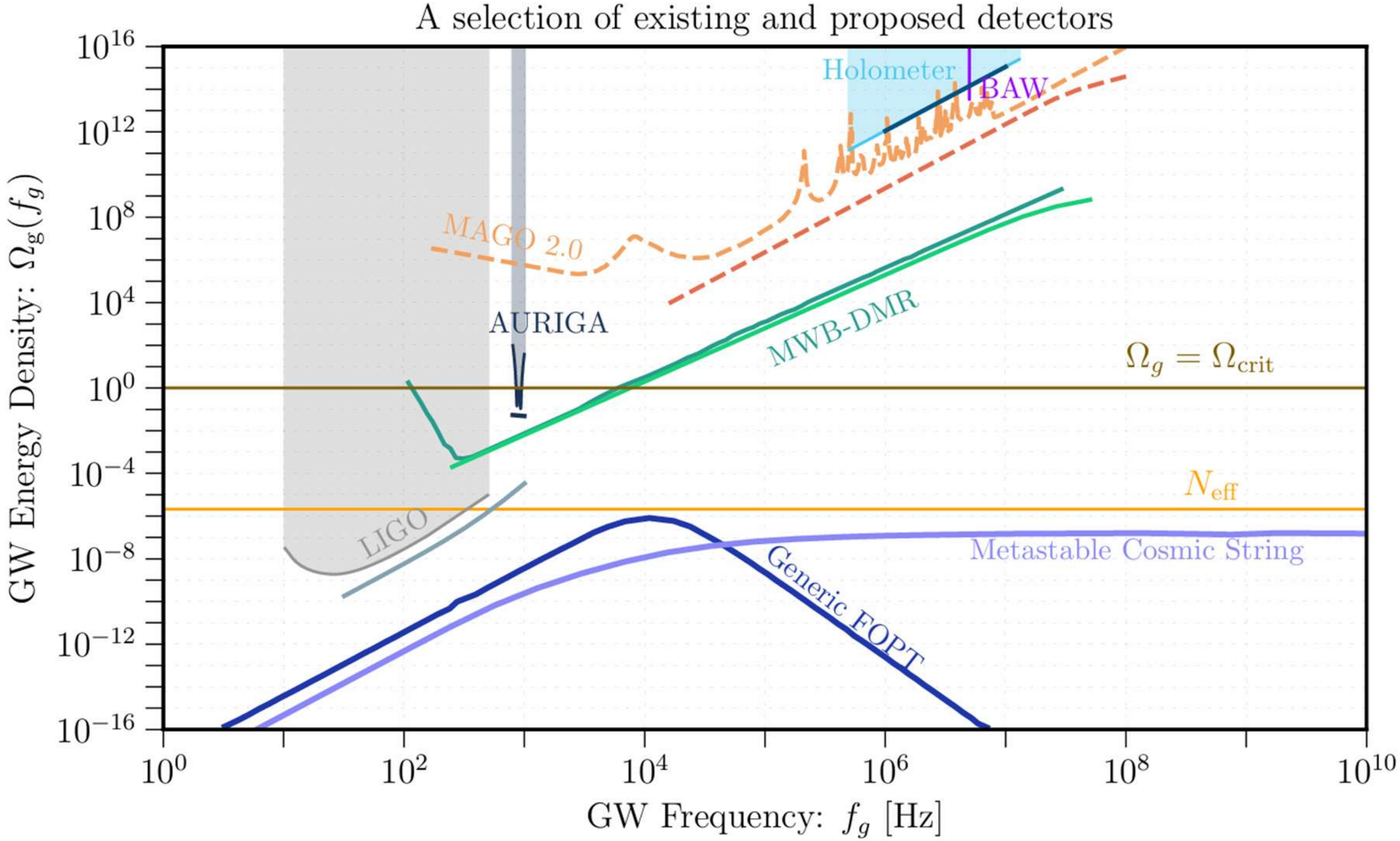
- **Out PSD:** $$\begin{aligned} S^{\text{out}}_{Y_mY_m}(\omega) &= \sum_\Lambda \Big[|\chi_{Y_mY_\Lambda}(\omega)|^2 S^{\text{in}}_{Y_\Lambda Y_\Lambda}(\omega) + |\chi_{Y_mX_\Lambda}(\omega)|^2 S^{\text{in}}_{X_\Lambda X_\Lambda}(\omega)\Big] \\ &+ \sum_\Lambda \Big[\chi_{Y_mX_\Lambda}(\omega)\chi_{Y_mY_\Lambda}(\omega)^* S^{\text{in}}_{Y_\Lambda X_\Lambda}(\omega) + \chi_{Y_mY_\Lambda}(\omega)\chi_{Y_mX_\Lambda}(\omega)^* S^{\text{in}}_{X_\Lambda Y_\Lambda}(\omega)\Big] \\ &+ \sum_I |\chi_{Y_mF_I}(\omega)|^2 S_{F_IF_I}(\omega) \supset S_{hh}(\omega) \end{aligned}$$

Noise (first two lines)

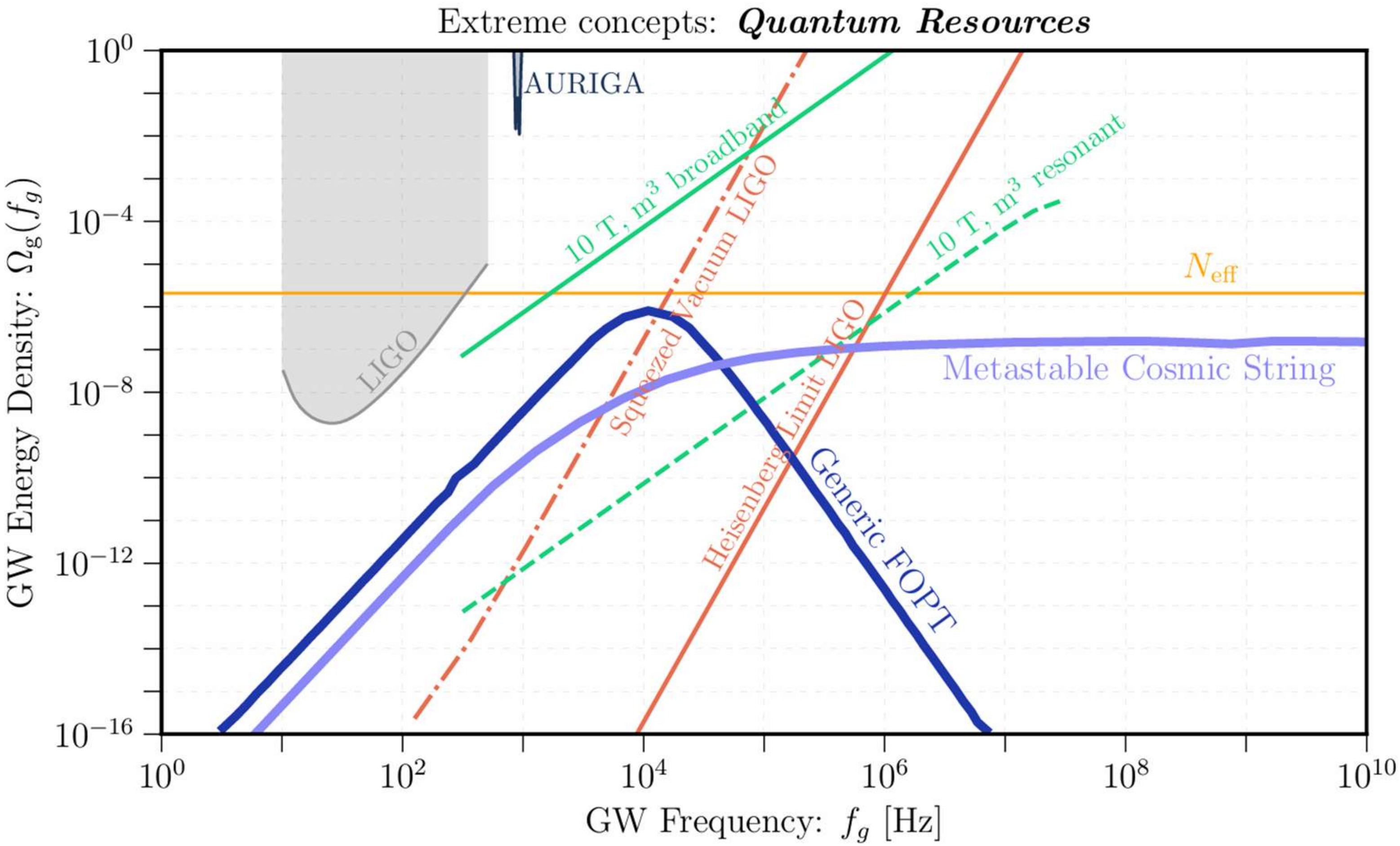
Signal (third line)

- **Minimal detectable signal**

$$\text{SNR} = \left(t_{\text{int}} \int \frac{\mathrm{d}\omega}{2\pi} \frac{S_{hh}(\omega)^2}{S_{nn}(\omega)^2}\right)^{\frac{1}{2}} \simeq 1$$



[S.A.R. Ellis, R.T. D'Agnolo, arXiv:2412.17897]



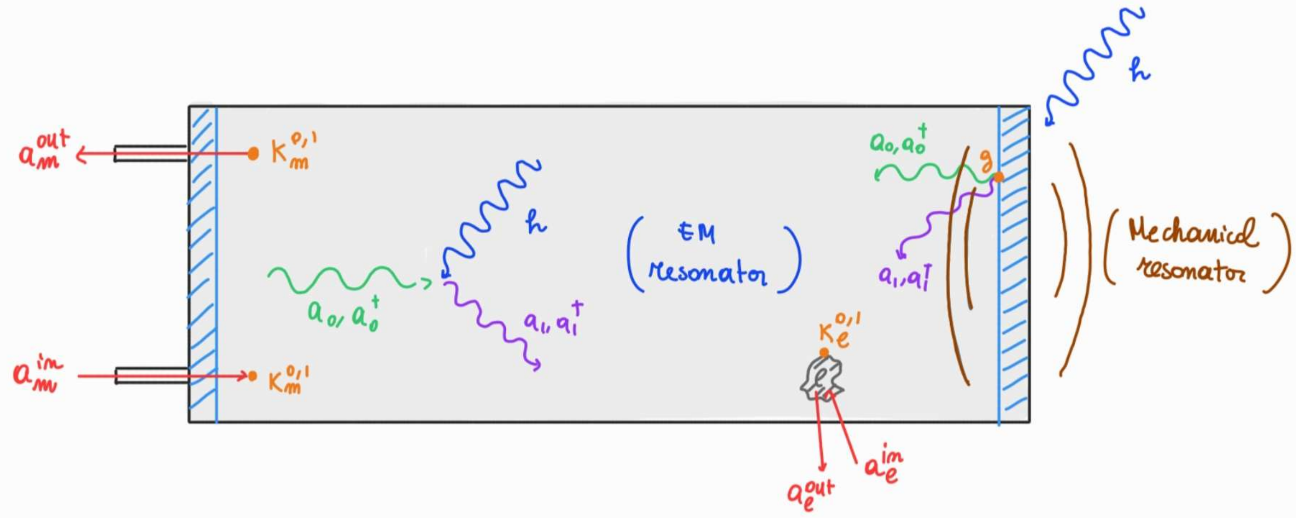
[S.A.R. Ellis, R.T. D'Agnolo, arXiv:2412.17897]

Thank you!

Backup slides

Set-up

$$H(t) = H_0(t) + H_{G+OM}(t) + H_R(t)$$



Free $$H_0(t) = \sum_{n,r} \Delta_n a^\dagger_{n,r} a_{n,r} + \int_V d^3x |B_0|^2 + \omega_m d^\dagger d$$

Int. $$H_{G+OM}(t) = \int_V \mathrm{d}^3x h_{\mu\nu} T^{\mu\nu} = h(t) \left\{ \sum_{jj'} C_{jj'} a^\dagger_j(t) a_{j'}(t) + \sum_j \left[D_j a_j(t) + D^*_j a^\dagger_j(t) \right] + \sum_{jj'} \left[G_{jj'} a_j(t) a_{j'}(t) + G^*_{jj'} a^\dagger_j(t) a^\dagger_{j'}(t) \right] \right\} + gxX_1$$

Readout $$H_R(t) = \sum_{j=0}^{1} \sum_l \int \mathrm{d}\omega \left\{ \omega\, b^\dagger_l(\omega) b_l(\omega) + i g^j_l \left[b^\dagger_l(\omega) a_j(t) - b_l(\omega) a^\dagger_j(t) \right] \right\}$$