UPPER LIMITS ON THE AMPLITUDE OF ULTRA-HIGH-FREQUENCY GRAVITATIONAL WAVES FROM GRAVITON TO PHOTON CONVERSION

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EPS-HEP – Virtual conference, July 26, 2021

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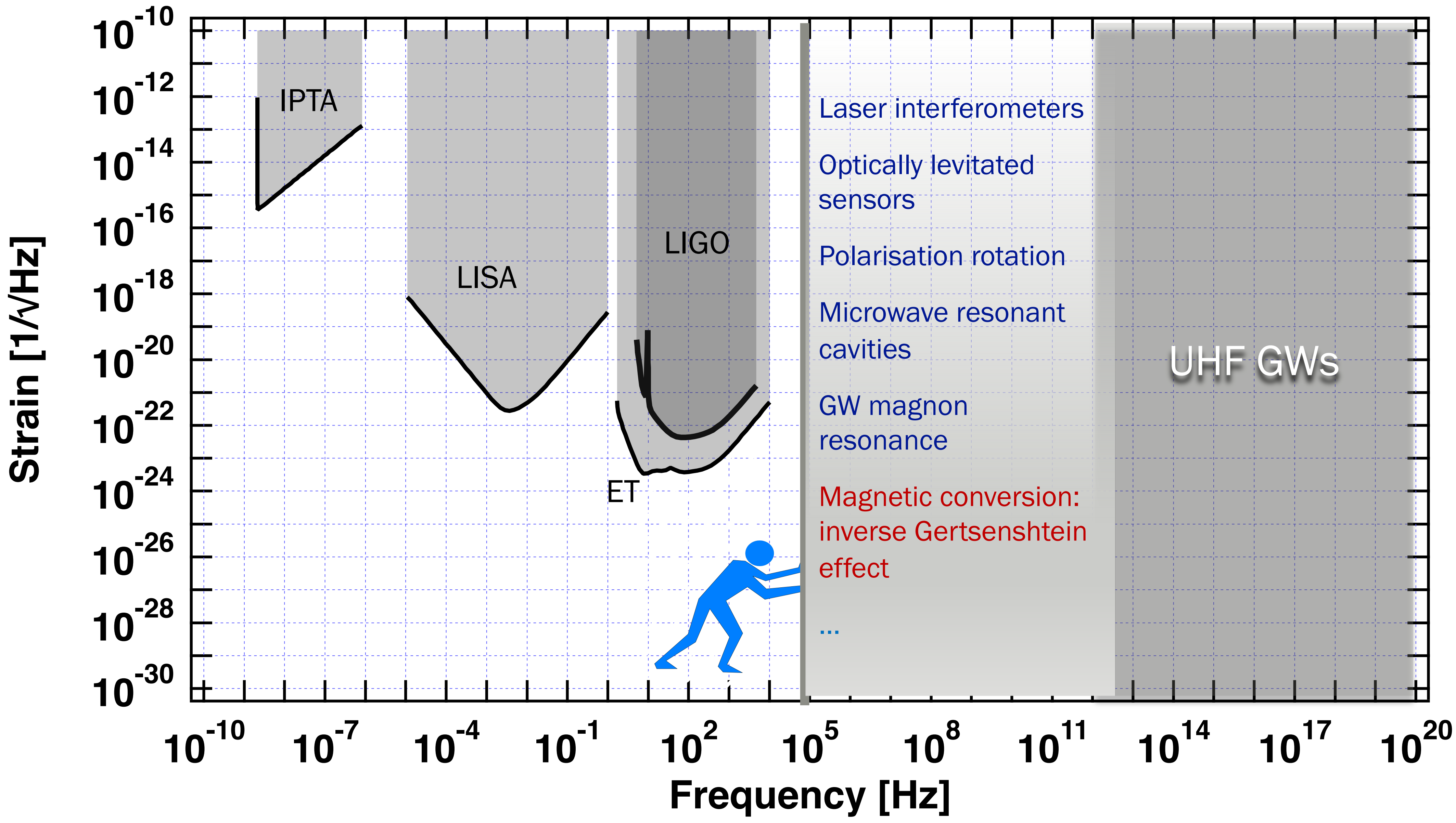


Strain [1/√Hz]
10-10
10-12
10-14
10-16
10-18
10-20
10-22
10-24
10-26
10-28
10-30
IPTA
LISA
LIGO
ET
Laser interferometers
Optically levitated sensors
Polarisation rotation
Microwave resonant cavities
GW magnon resonance
Magnetic conversion: inverse Gertsenshtein effect
...
UHF GWs
10-10
10-7
10-4
10-1
102
105
108
1011
1014
1017
1020
Frequency [Hz]

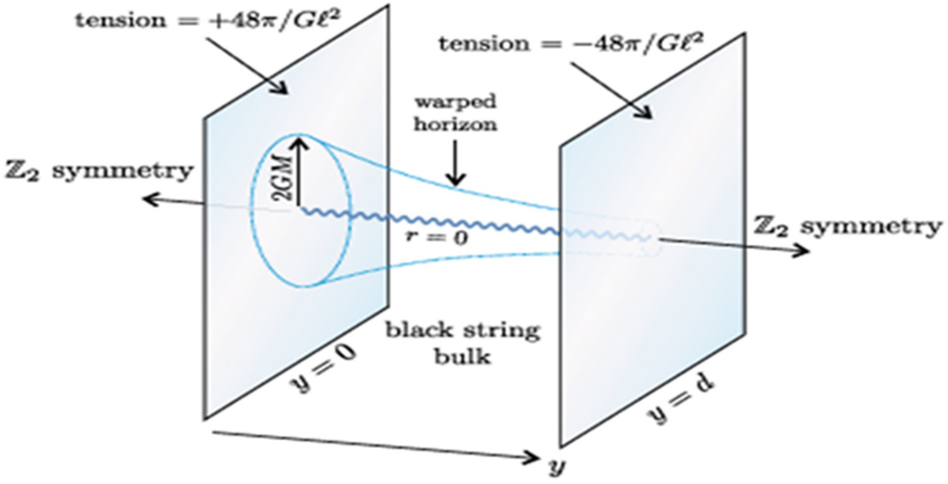
UHF GW sources

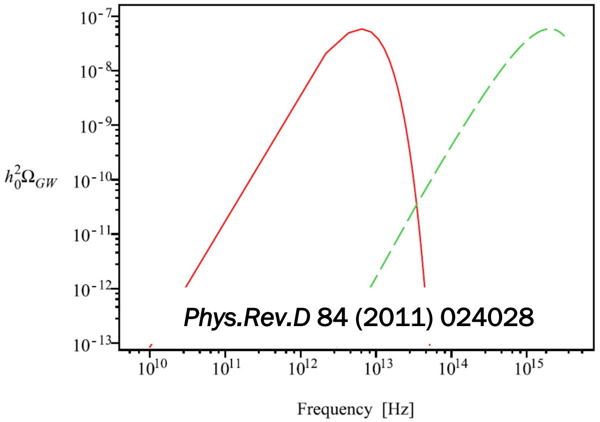
Inevitably speculative at this moment

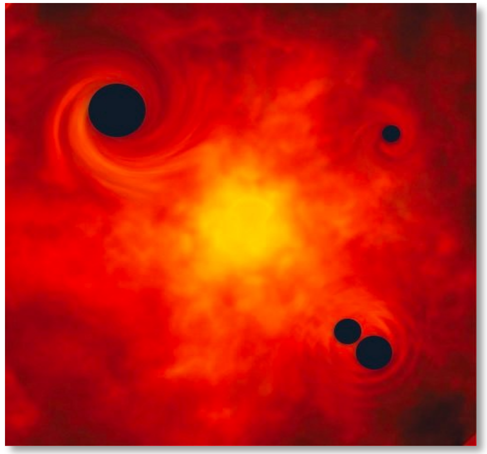
- BH-BH collisions in higher dimensional gravity
- Primordial BH collisions and evaporations
- Early Universe cosmological sources
- Thermal activity of the sun
- Laboratory sources
- ....

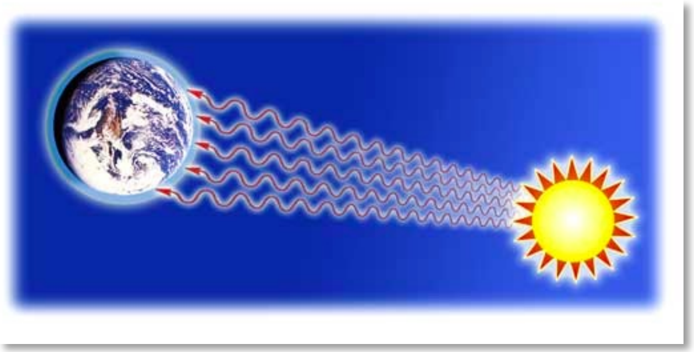
However

We may use UHF GW upper limits to detect or discount new, proposed particles, fields, etc.









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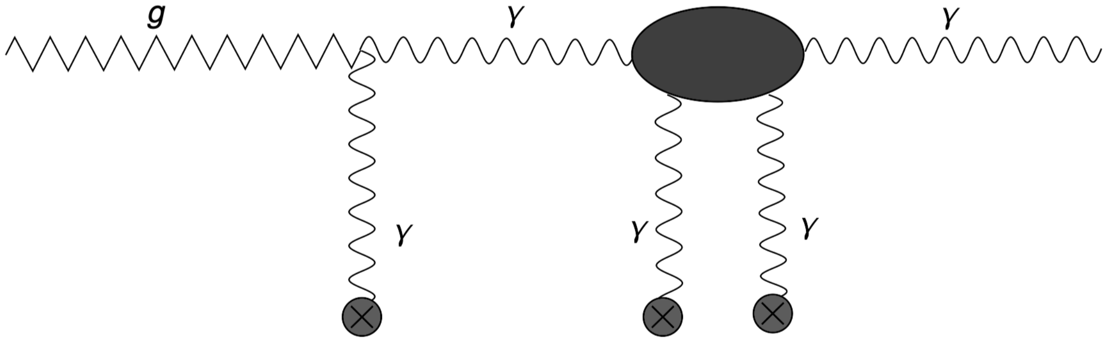
GWs propagating in transverse static magnetic fields

$$\mathcal{L} = \mathcal{L}_{\mathrm{gr}} + \mathcal{L}_{\mathrm{em}}$$



Converted EMWs stochastic flux

$$\Phi_\gamma^{\mathrm{graph}}(z, \omega_f; t) \simeq \int_{\omega_i}^{\omega_f} \frac{B^2\, z^2\, h_c^2(0,\omega)\,\omega}{4} d\omega$$

Measured EMWs flux from the CCD

$$\Phi_\gamma^{\mathrm{CCD}}(z, \omega_f; t) = \int_{\omega_i}^{\omega_f} \frac{1}{A(z)} \frac{N(\omega, t)\,\omega}{\epsilon_\gamma(\omega)} d\omega$$

$$N(\omega, t) = N_{\mathrm{exp}}/\Delta\omega$$

$$h_c^{\mathrm{min}}(0,\omega) \simeq \sqrt{\frac{4\, N_{\mathrm{exp}}}{A\, B^2\, L^2\, \epsilon_\gamma(\omega)\, \Delta\omega}} \simeq 1.6 \times 10^{-16} \sqrt{\left(\frac{N_{\mathrm{exp}}}{1\ \mathrm{Hz}}\right)\left(\frac{1\ \mathrm{m}^2}{A}\right)\left(\frac{1\ \mathrm{T}}{B}\right)^2\left(\frac{1\ \mathrm{m}}{L}\right)^2\left(\frac{1\ \mathrm{Hz}}{\Delta f}\right)\left(\frac{1}{\epsilon_\gamma(\omega)}\right)}$$

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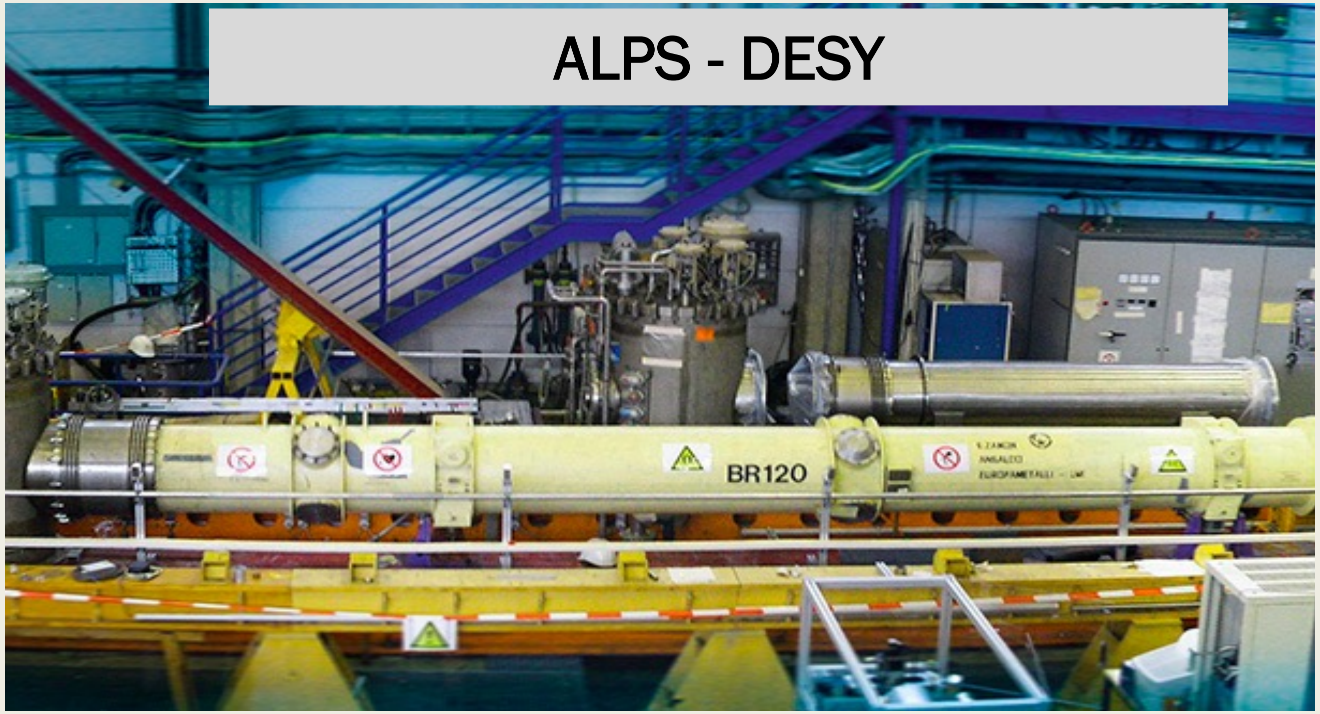
AXION-LIKE PARTICLE SEARCH EXPERIMENTS

CAST - CERN



ALPS - DESY

OSQAR - CERN

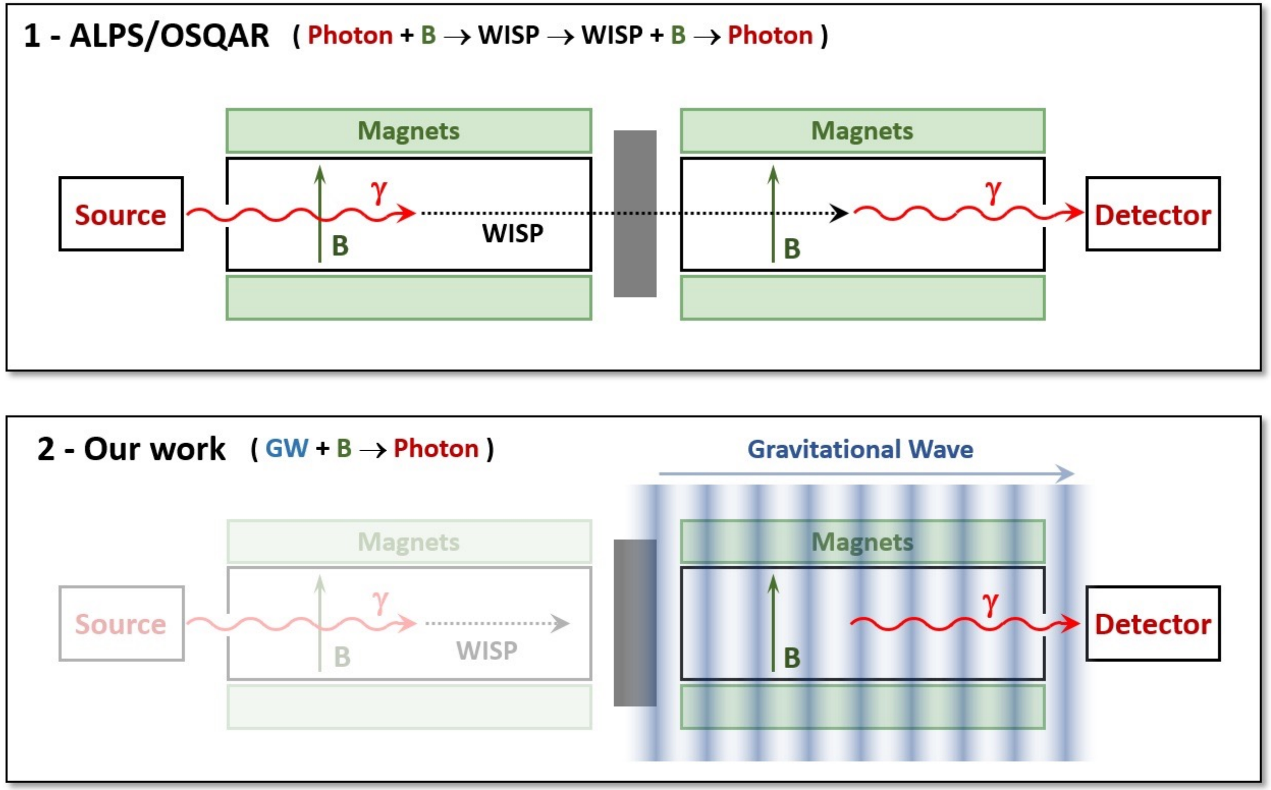
GWs upper limits: ALPS, OSQAR, CAST

Detectors

- Cannot point deliberately to the emitting sources, except CAST
- GWs upper limits at Ultra-High-Frequencies (UHF): optical 5×10^{14} Hz and X-ray 10^{18} Hz

Suited sources

- The cosmological sources: stochastic, isotropic, stationary, and Gaussian gravitational-waves.
- UHF GWs candidates: Primordial black holes (PHB), thermal GWs from the Sun.



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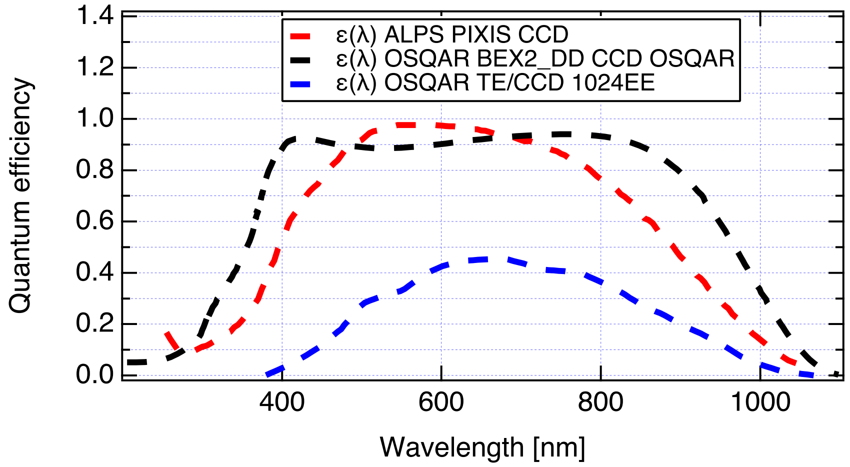
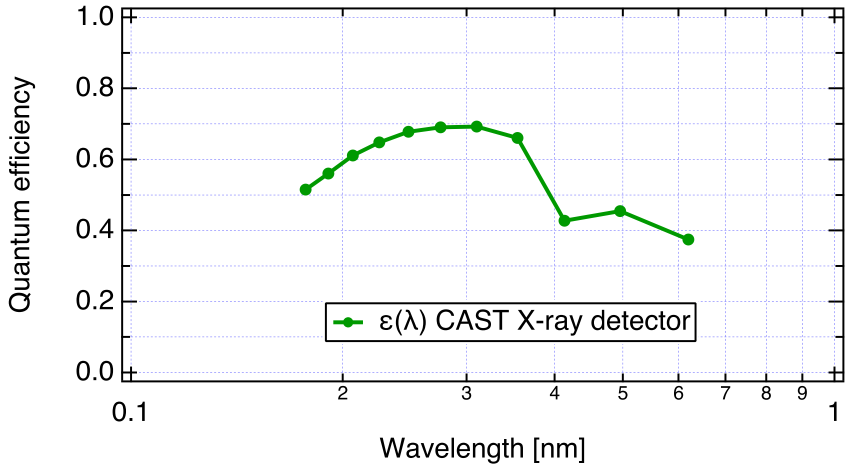
Parameters necessary to compute the characteristic amplitude

$$h_c^{\mathrm{min}}(0,\omega) \simeq \sqrt{\frac{4\,N_{\mathrm{exp}}}{A\,B^2\,L^2\,\epsilon_\gamma(\omega)\,\Delta\omega}} \simeq 1.6\times10^{-16}\sqrt{\left(\frac{N_{\mathrm{exp}}}{1\ \mathrm{Hz}}\right)\left(\frac{1\ \mathrm{m}^2}{A}\right)\left(\frac{1\ \mathrm{T}}{B}\right)^2\left(\frac{1\ \mathrm{m}}{L}\right)^2\left(\frac{1\ \mathrm{Hz}}{\Delta f}\right)\left(\frac{1}{\epsilon_\gamma(\omega)}\right)}$$

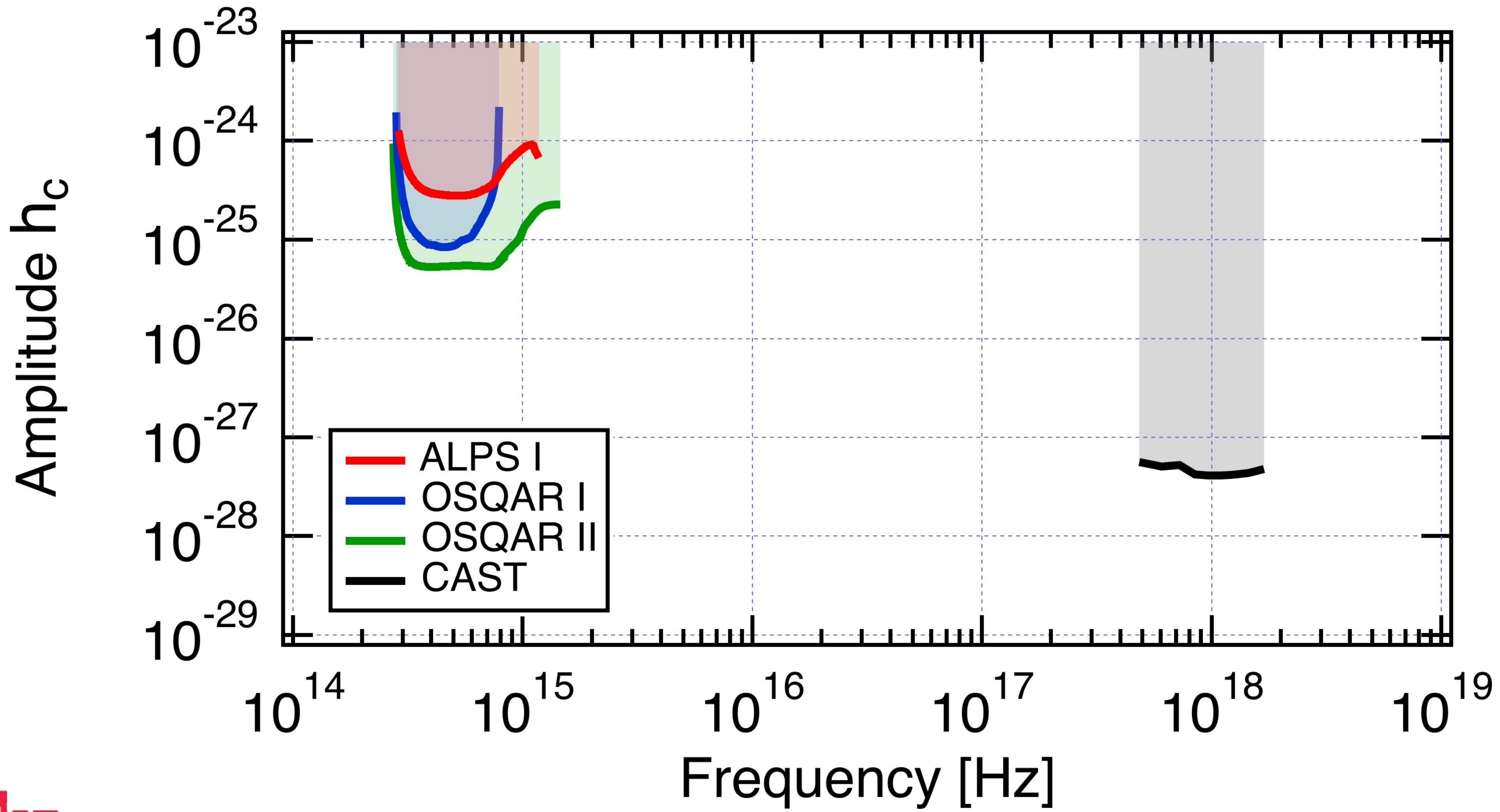
- N_{exp} - detected number of photons per second,
- A - cross-section of the detector,
- B - magnetic field amplitude,
- L - distance extension of the magnetic field,
- $\epsilon_\gamma(\omega)$ - quantum efficiency of the detector,
- Δf - operation frequency of the CCD.



	$\epsilon_\gamma(\omega)$	N_{exp} (mHz)	A (m^2)	B (T)	L (m)	Δf (Hz)
ALPS I	see Fig 2	0.61	0.5×10^{-3}	5	9	9×10^{14}
OSQAR I	see Fig 2	1.76	0.5×10^{-3}	9	14.3	5×10^{14}
OSQAR II	see Fig 2	1.14	0.5×10^{-3}	9	14.3	1×10^{15}
CAST	see Fig 2	0.15	2.9×10^{-3}	9	9.26	1×10^{18}

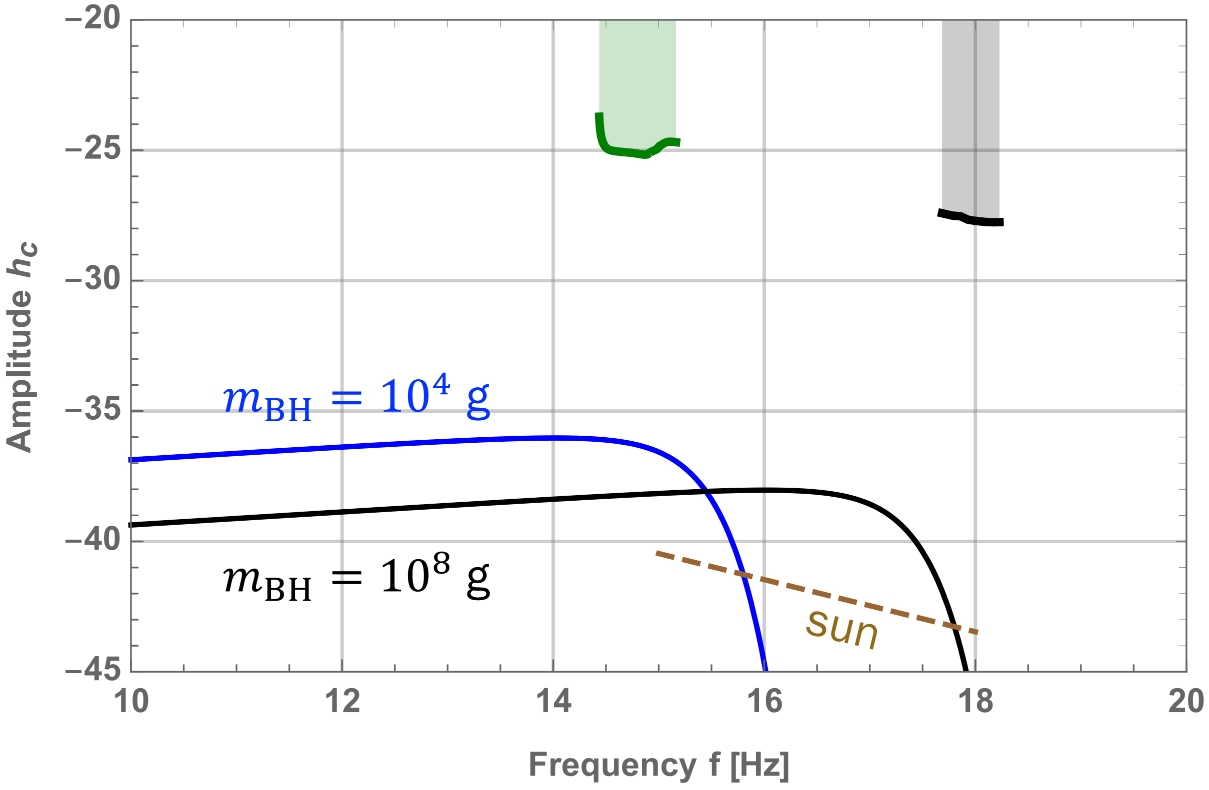


UHF GW characteristic amplitude upper limits

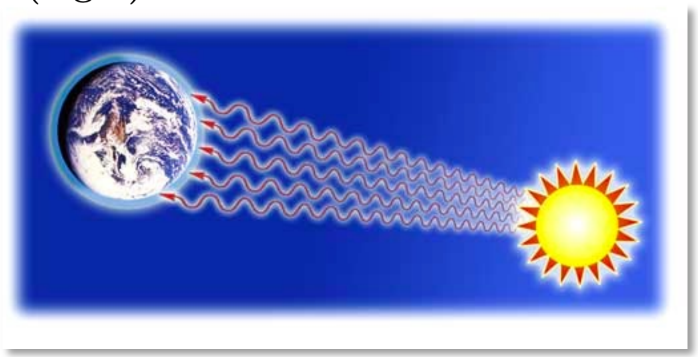


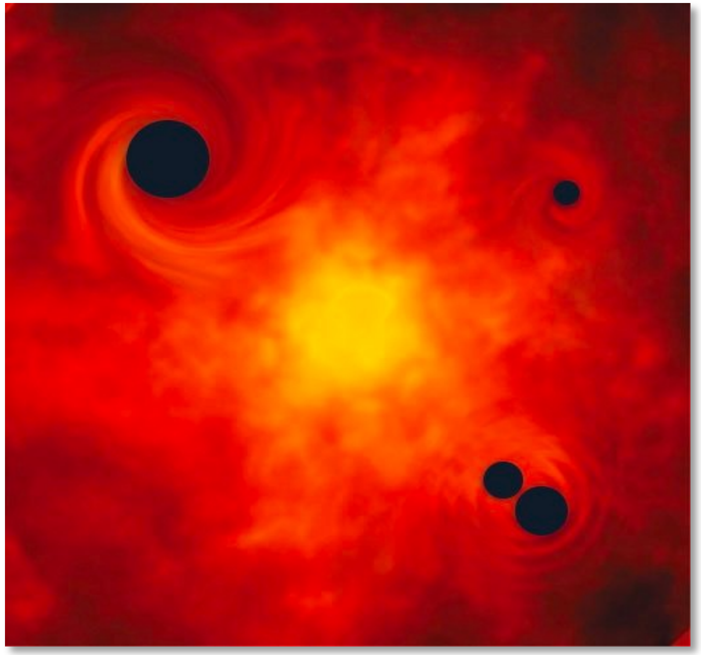
Primordial black hole evaporation and upper limits

- PBH evaporation: predicted stochastic isotropic UHF GWs background
- Sun: thermal activity generates UHF GWs.



$$\frac{d\rho_\gamma^{\mathrm{Sun}}}{d(\log \omega)} \approx 5.7 \times 10^{-62}\ \mathrm{GeV}^4 \text{ @ Earth}$$





WHERE TO NEXT?

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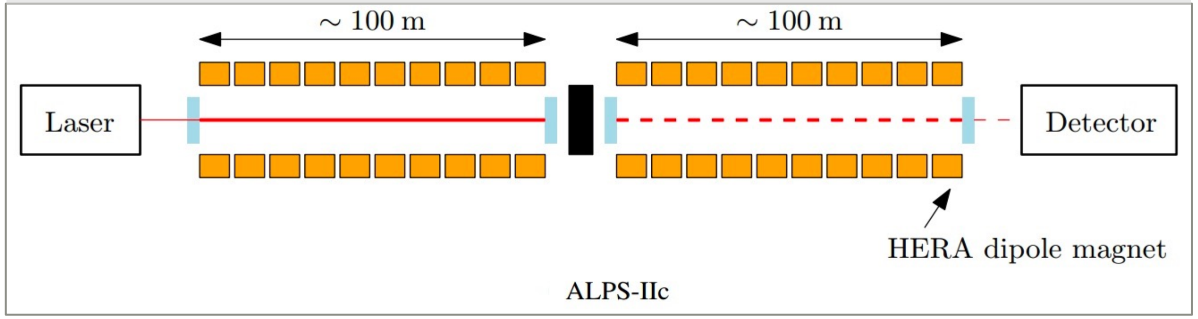
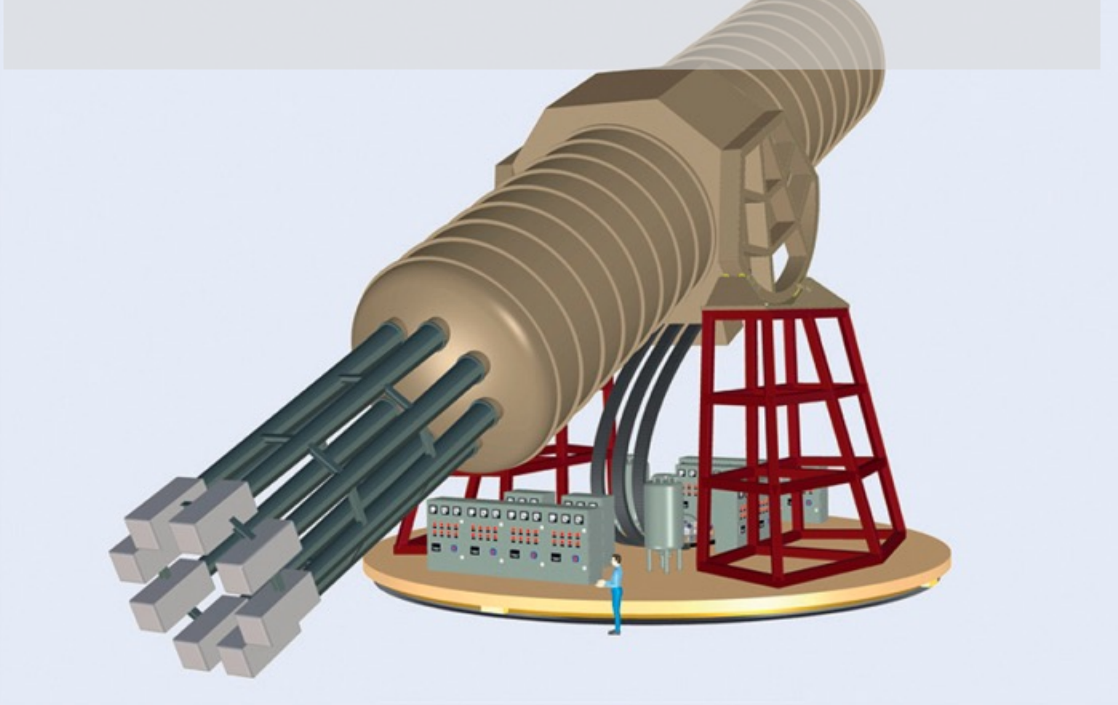
Graviton to photon mixing and future laboratory axion experiments
ALPS II, JURA, IAXO

ALPS II (successor JURA)



ALPS II under construction as of October 2020 (Credit: DESY)

IAXO (*Armengaud et al. JINST 9 T05002 (2014)*)



	ϵ_γ	N_{dark} (Hz)	A (m^2)	B (T)	L (m)	$\mathcal{F}$
ALPS IIc	0.75	$\approx 10^{-6}$	$\approx 2 \times 10^{-3}$	5.3	120	40 000
JURA	1	$\approx 10^{-6}$	$\approx 8 \times 10^{-3}$	13	960	100 000
IAXO	1	$\approx 10^{-4}$	≈ 21	2.5	25	-

Graviton-to-photon in resonant Fabry-Perot cavity

$$\vec{E}^{\rm circ}_{x,y}(z,t) = \vec{E}^{\rm graph}_{x,y}(z,t)\left(1 + Re^{-i2\phi(\omega,L)} + \left(Re^{-i2\phi(\omega,L)}\right)^2 + \cdots\right)$$

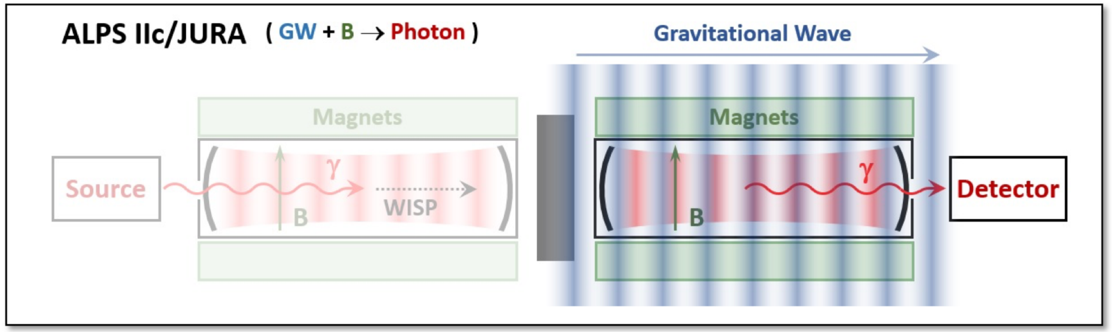
$$= \vec{E}^{\rm graph}_{x,y}(z,t)\sum_{n=0}^{\infty}\left(Re^{-i2\phi(\omega,L)}\right)^n$$

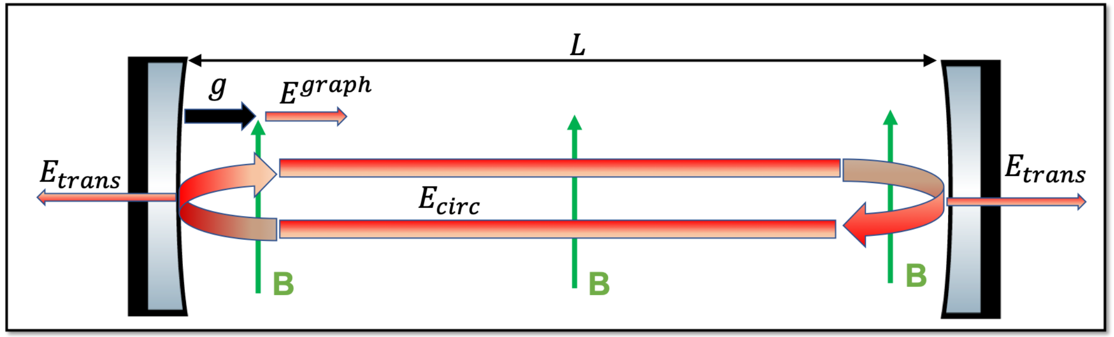
$$= \vec{E}^{\rm graph}_{x,y}(z,t)\,\frac{1}{1 - R\,e^{-i2\phi(\omega,L)}}$$

$$\Phi^{\rm trans}_{\gamma}(L,\omega_f;t) = \int_{\omega_i}^{\omega_f}\frac{B_x^2L^2h_c(0,\omega)^2}{4}\,\frac{1-R}{(1-R)^2 + 4R\,\sin^2\left[\phi(\omega,L)\right]}\,\omega\,d\omega.$$

$$\frac{B_x^2L^2h_c(0,\omega)^2}{4}\,\frac{\mathcal{F}}{\pi}\,\omega \qquad \text{for} \qquad \phi(\omega,L_R) = n\pi$$

$$h_c^{\rm min}(0,\omega^*) \simeq 2.8{\times}10^{-16}\sqrt{\left(\frac{1}{\mathcal{F}}\right)\left(\frac{N_{\rm dark}}{1\ \rm Hz}\right)\left(\frac{1\ \rm m^2}{A}\right)\left(\frac{1\ \rm T}{B}\right)^2\left(\frac{1\ \rm m}{L}\right)^2\left(\frac{1\ \rm Hz}{\Delta f}\right)\left(\frac{1}{\epsilon_\gamma(\omega)}\right)}$$





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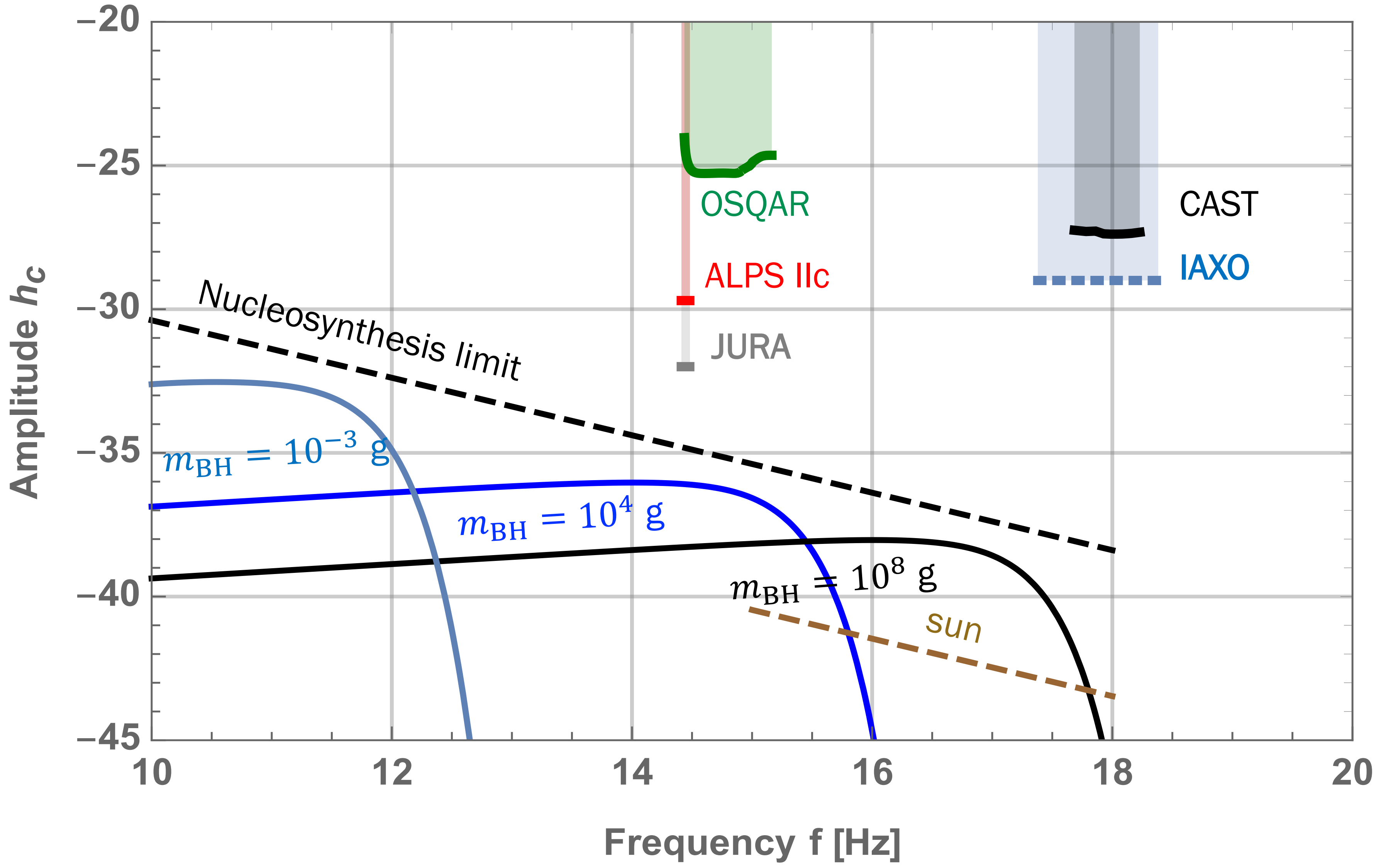
$$h_c^{\rm min}(0,\omega^*) \simeq 2.8{\times}10^{-16}\sqrt{\left(\frac{1}{\mathcal{F}}\right)\left(\frac{N_{\rm dark}}{1\ \rm Hz}\right)\left(\frac{1\ \rm m^2}{A}\right)\left(\frac{1\ \rm T}{B}\right)^2\left(\frac{1\ \rm m}{L}\right)^2\left(\frac{1\ \rm Hz}{\Delta f}\right)\left(\frac{1}{\epsilon_\gamma(\omega)}\right)}$$

Prospects



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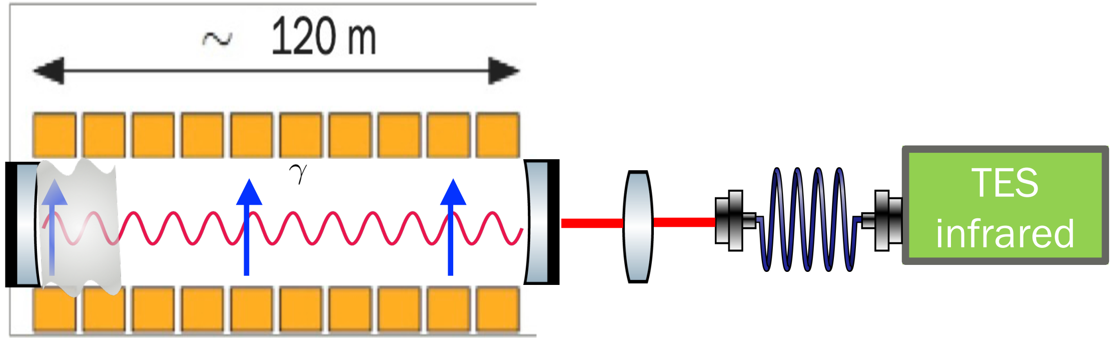
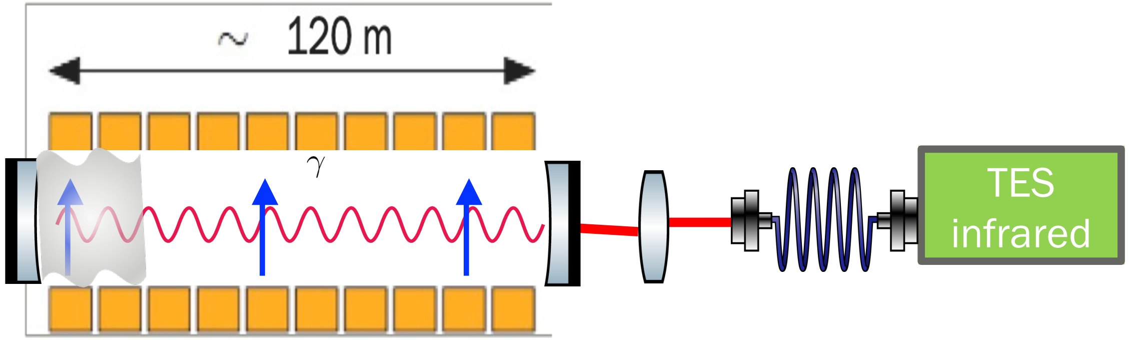
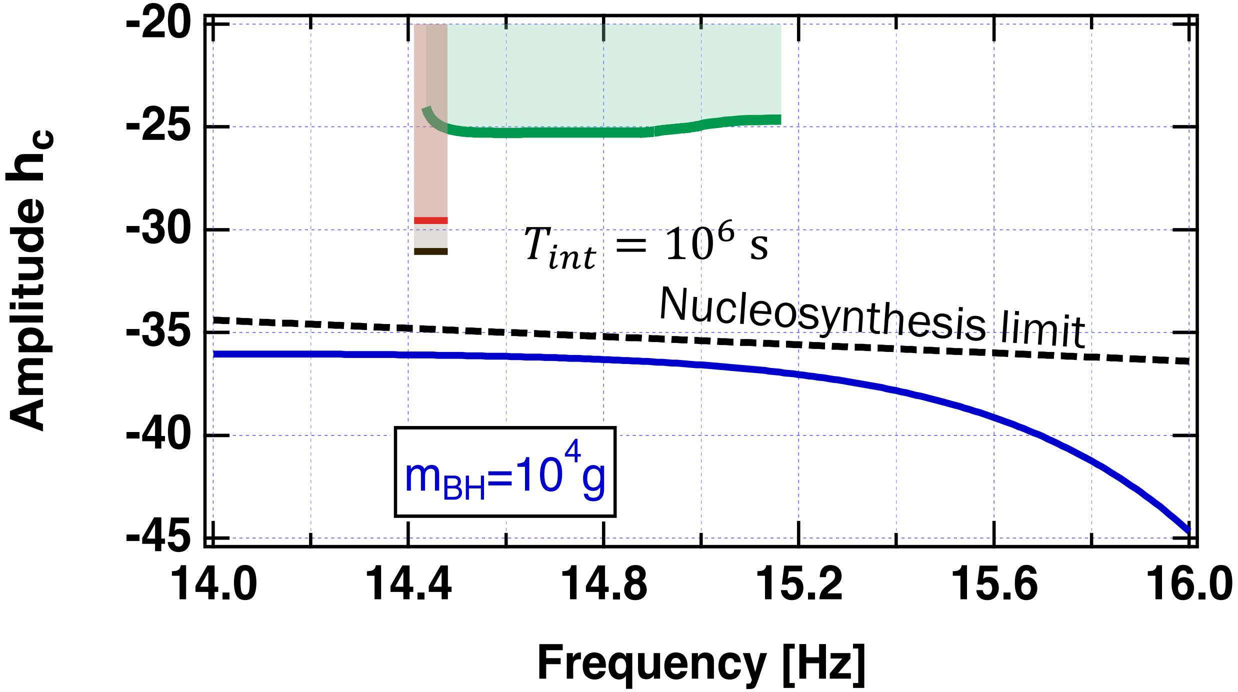
Work in collaboration with: Mike Cruise, Damian Ejlli, Giampaolo Pisano, and Hartmut Grote

ALPS II cross correlation





- Reduction background noise
- Possible identification of GW's transients



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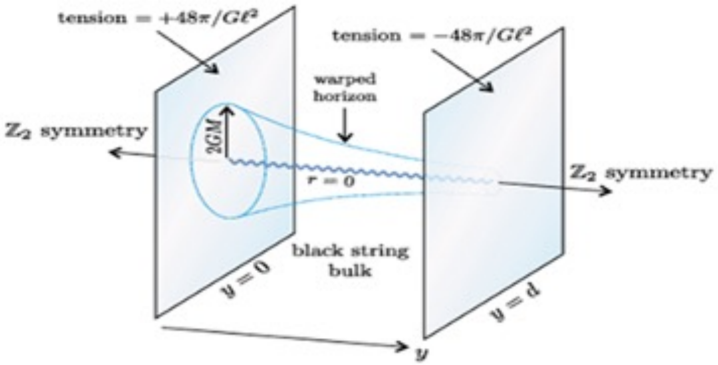
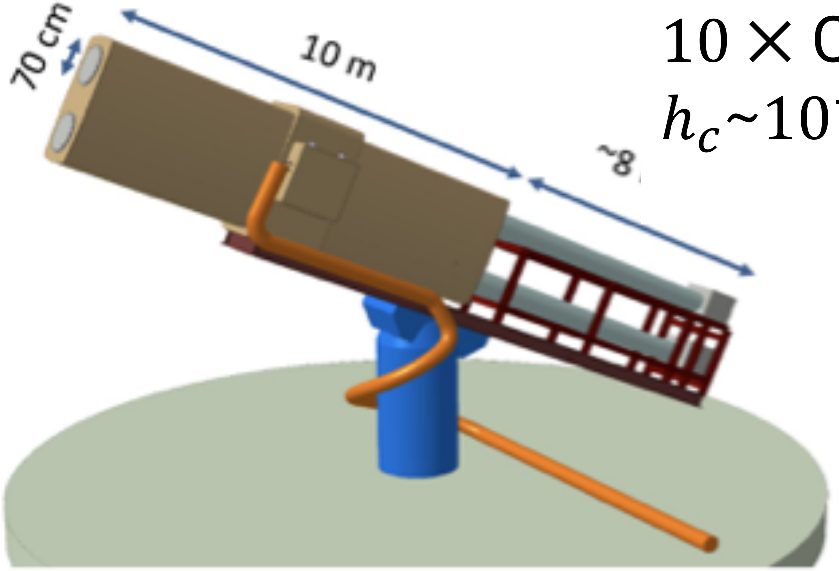
Baby IAXO, IAXO

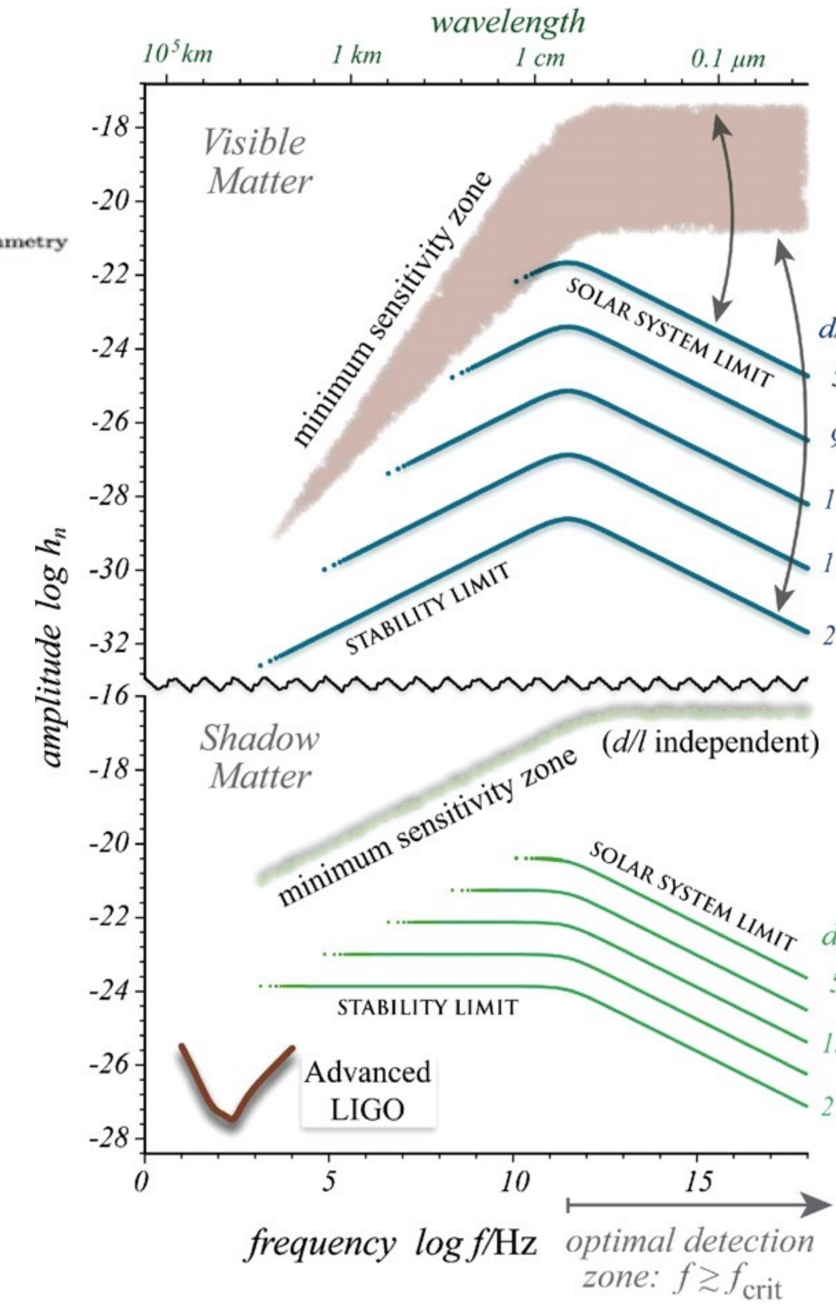


- Pointing: rotatable platform
- BH-BH collisions in higher dimensional gravity



$10 \times$ CAST (B^2L^2A)

$h_c \sim 10^{-28}$ @ $10^{17} - 10^{18}$ Hz



Chris Clarkson and Sanjeev S Seahra
2007 *Class. Quantum Grav.* **24** F33

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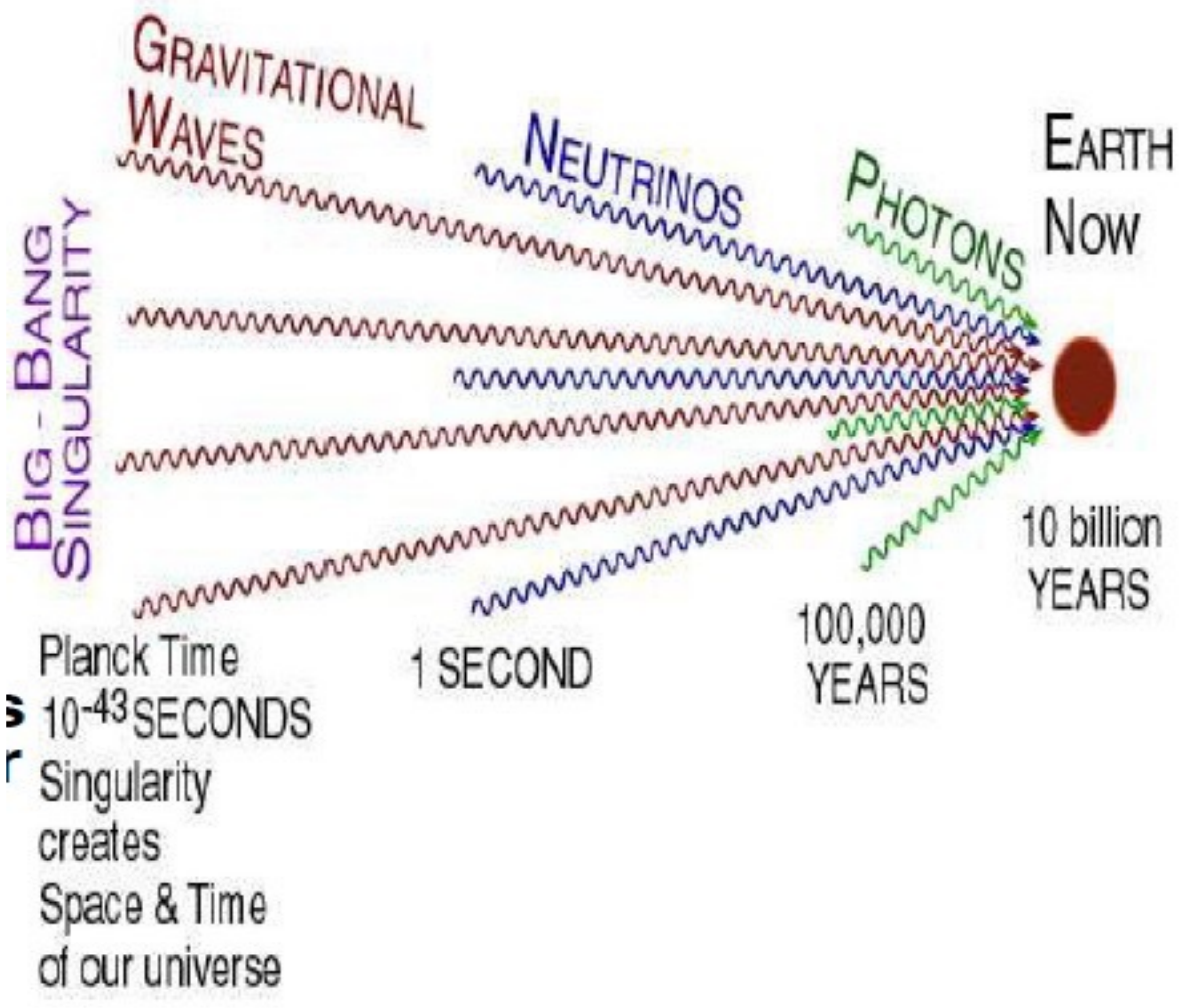
Conclusions

- We set upper limits on stochastic UHF GWs using data of laboratory axion search experiments ALPS I, OSQAR and CAST.
- The upgraded ALPS II, Baby-IAXO/IAXO, are potential infrastructure to improve the existing upper limits for stochastic UHF GWs.
- New source possibilities and new detector developments are being identified by UHF GW.



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Thank you for your attention