# MAGNETIC CONVERSION DETECTORS

Aldo Ejlli

Ultra-High-Frequency GWs: A Theory and Technology Roadmap

13/10/2021

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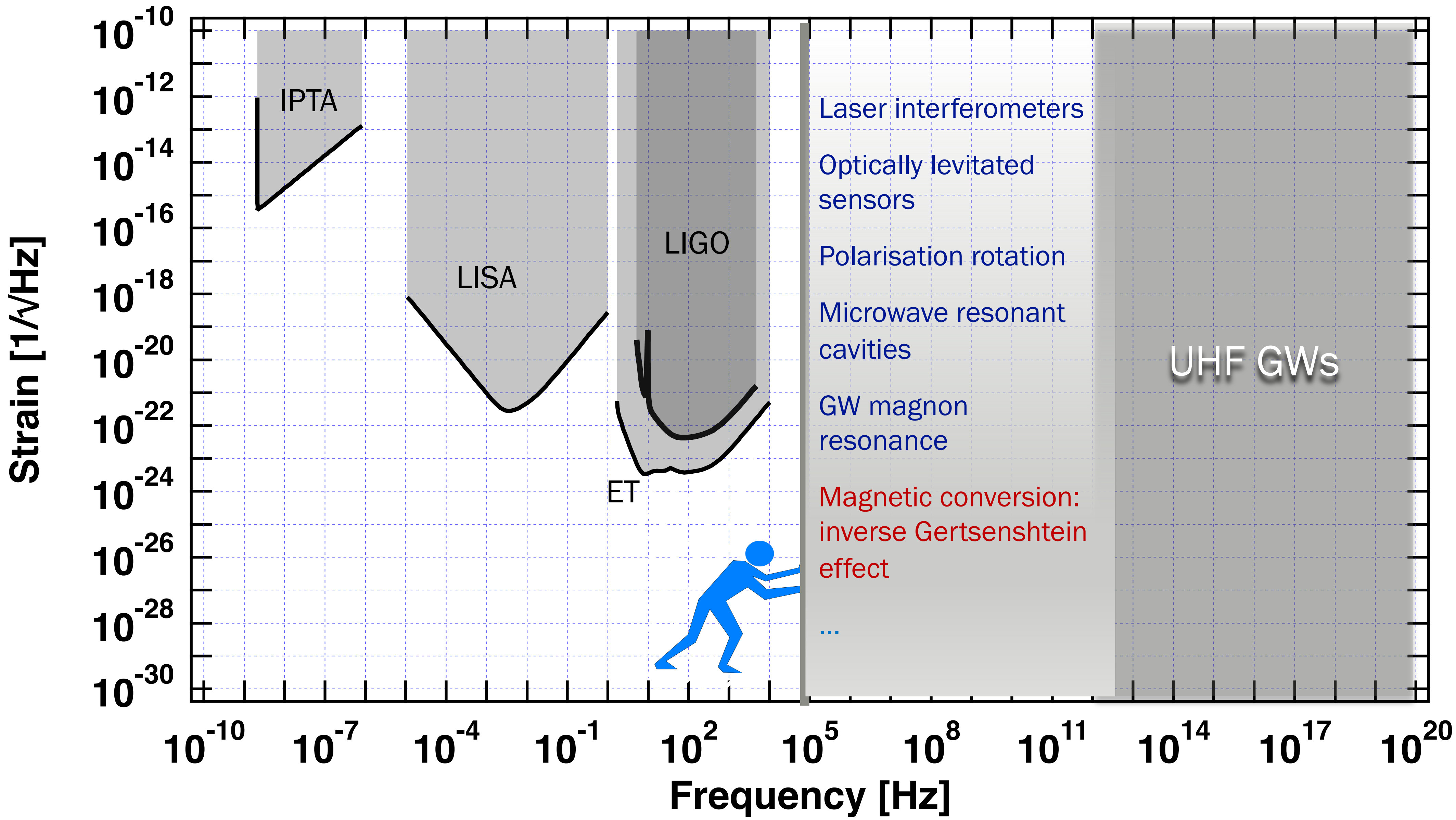
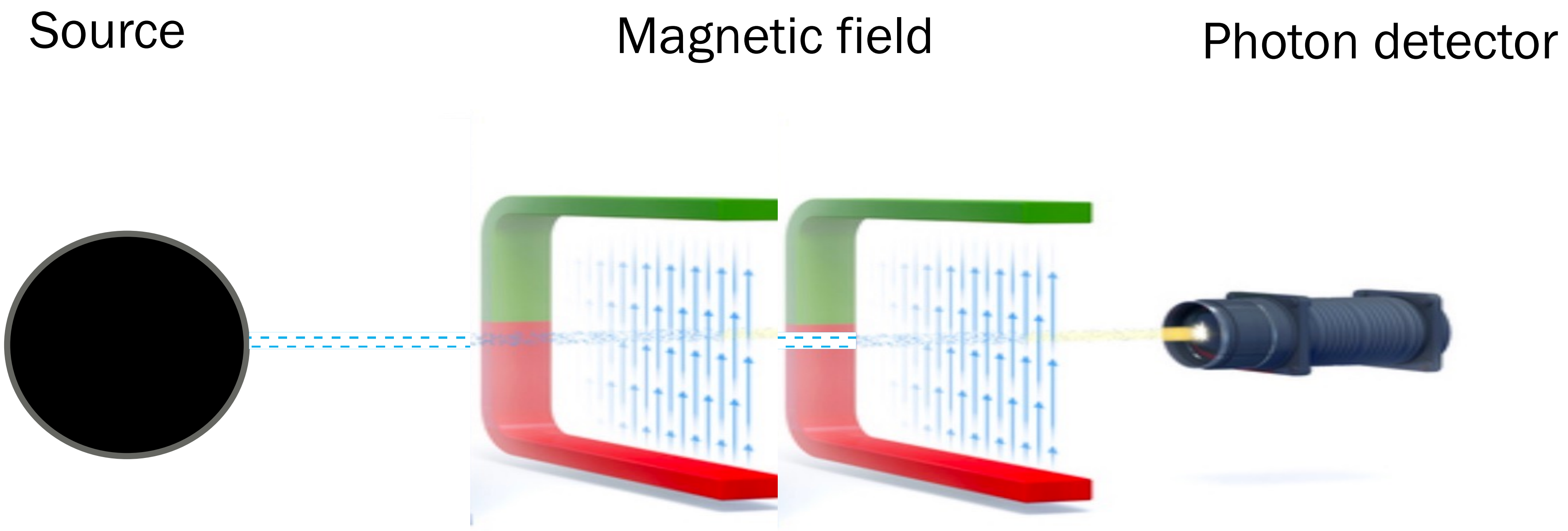


$10^{-10}$
$10^{-12}$
$10^{-14}$
$10^{-16}$
$10^{-18}$
$10^{-20}$
$10^{-22}$
$10^{-24}$
$10^{-26}$
$10^{-28}$
$10^{-30}$
Strain [1/√Hz]
IPTA
LISA
LIGO
ET
Laser interferometers
Optically levitated sensors
Polarisation rotation
Microwave resonant cavities
GW magnon resonance
Magnetic conversion: inverse Gertsenshtein effect
...
UHF GWs
$10^{-10}$ $10^{-7}$ $10^{-4}$ $10^{-1}$ $10^{2}$ $10^{5}$ $10^{8}$ $10^{11}$ $10^{14}$ $10^{17}$ $10^{20}$
Frequency [Hz]

# Magnetic conversion (Inverse Gertsenshtein effect)

- Gravitational-wave propagating in magnetic fields convert into photons.
  *Gertsenshtein, Sov. Phys., JETP 14, 84 (1962), G. A. Lupanov JETP 25, 76 (1967)*



# 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
- ….

However

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

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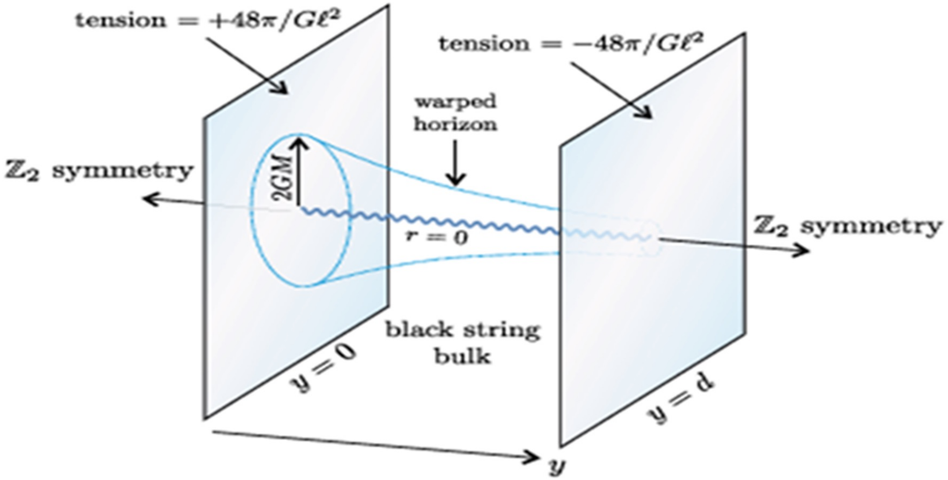
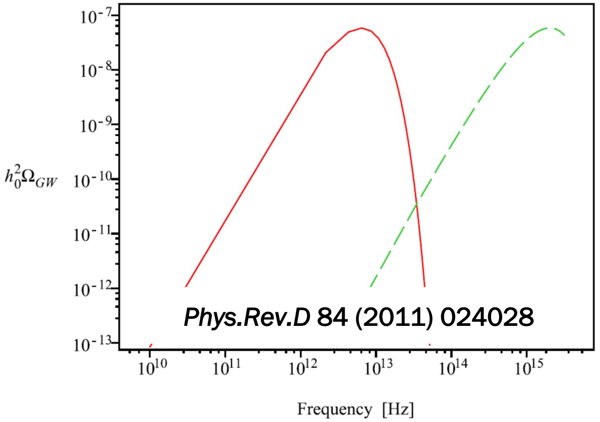
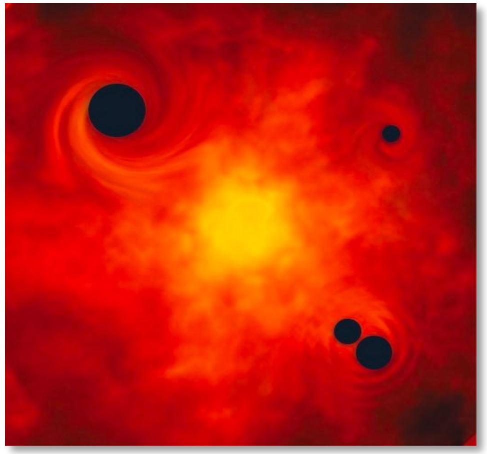
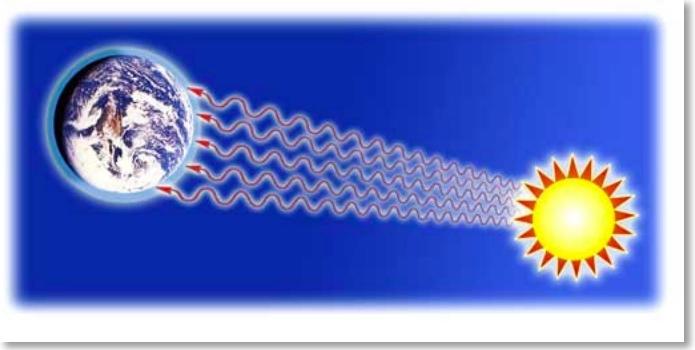


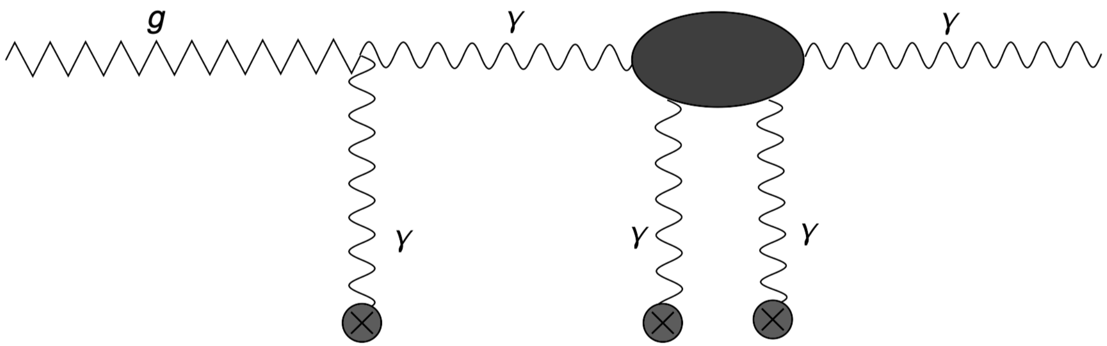





# GWs propagating in transverse static magnetic fields

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




$$\mathcal{L}_{\rm gr} = \frac{1}{\kappa^2} R, \quad \mathcal{L}_{\rm em} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{1}{2} \int d^4x' A_\mu(x) \Pi^{\mu\nu}(x, x') A_\nu(x')$$

**Converted EMWs stochastic flux**

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

**Measured EMWs flux from the CCD**

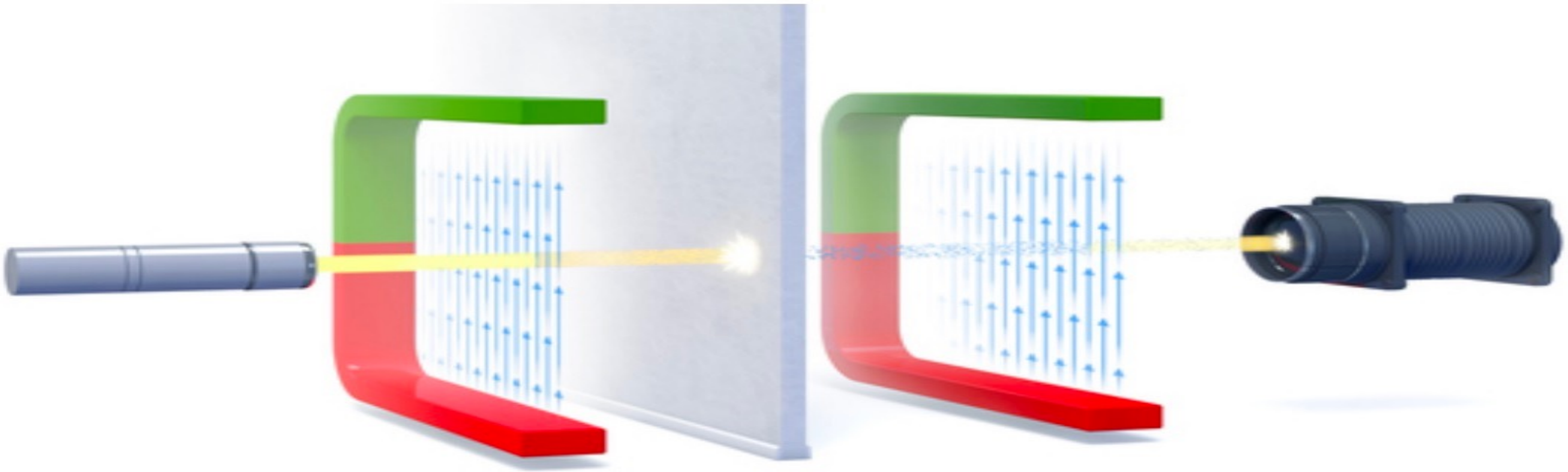
$$\Phi_\gamma^{\rm CCD}(z, \omega_f; t) = \int_{\omega_i}^{\omega_f} \frac{1}{A(z)} \frac{N(\omega, t)\, \omega}{\epsilon_\gamma(\omega)} d\omega$$

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

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

# Axion search using laboratory static magnetic fields

- Axions are generated in the magnetic field coupled to two photons.
- Axions, in the second region of the magnetic field, decay into photons.



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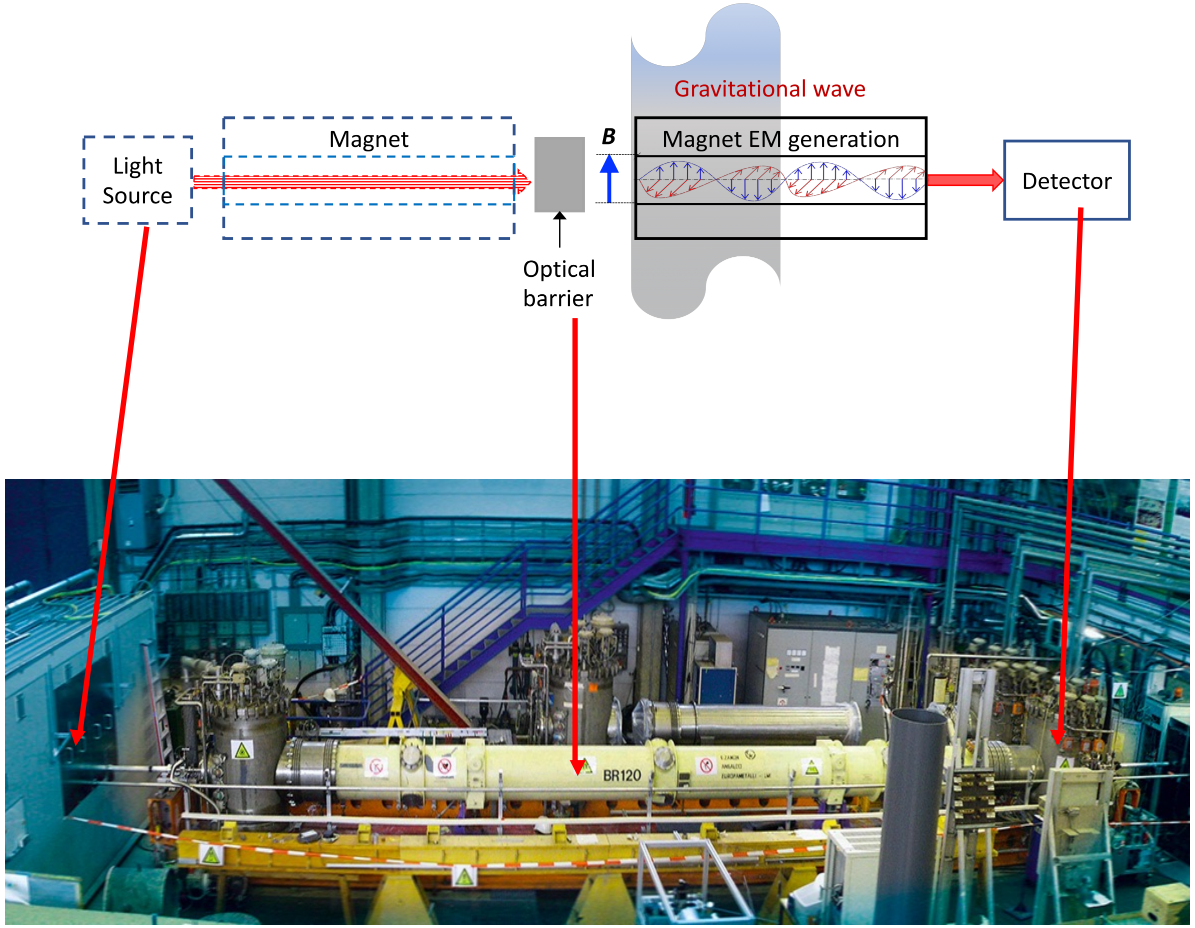
# ALPS (Axion-Like Particle Search) DESY Germany

- Magnet provided form HERA particle accelerator working at liquid helium (4 K).
- Magnetic field: $B$=5 T.
- Length: $L$=2×4.3 m.
- Photodetector @ $\lambda = 532$ nm PIXIS CCD.
- Data acquisition 2009-2010.
- They excluded detection of any physical signal @ 95% confidence interval.

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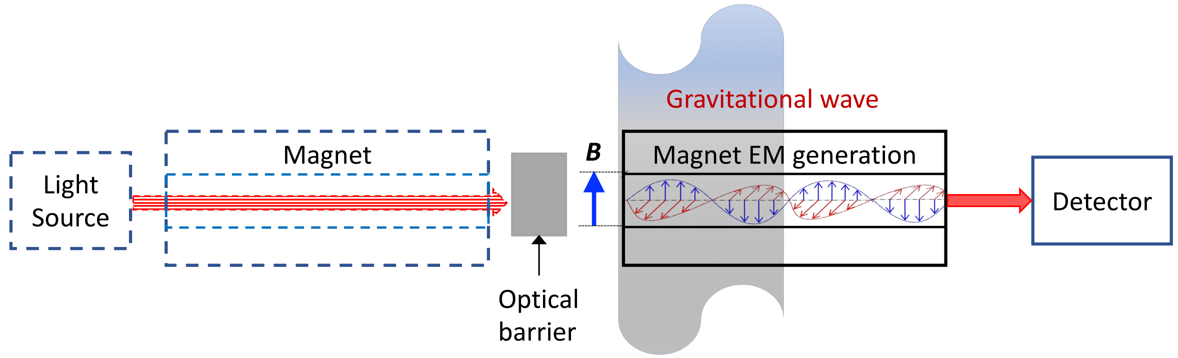
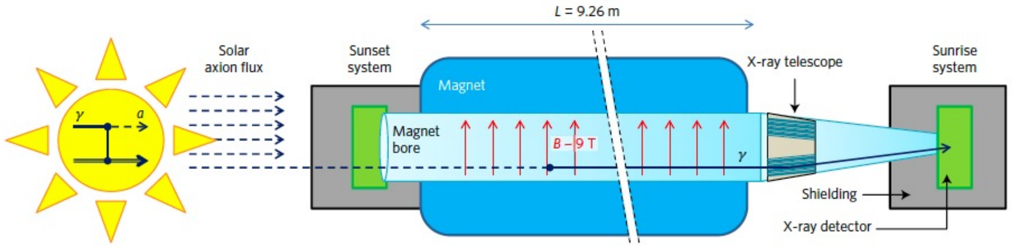
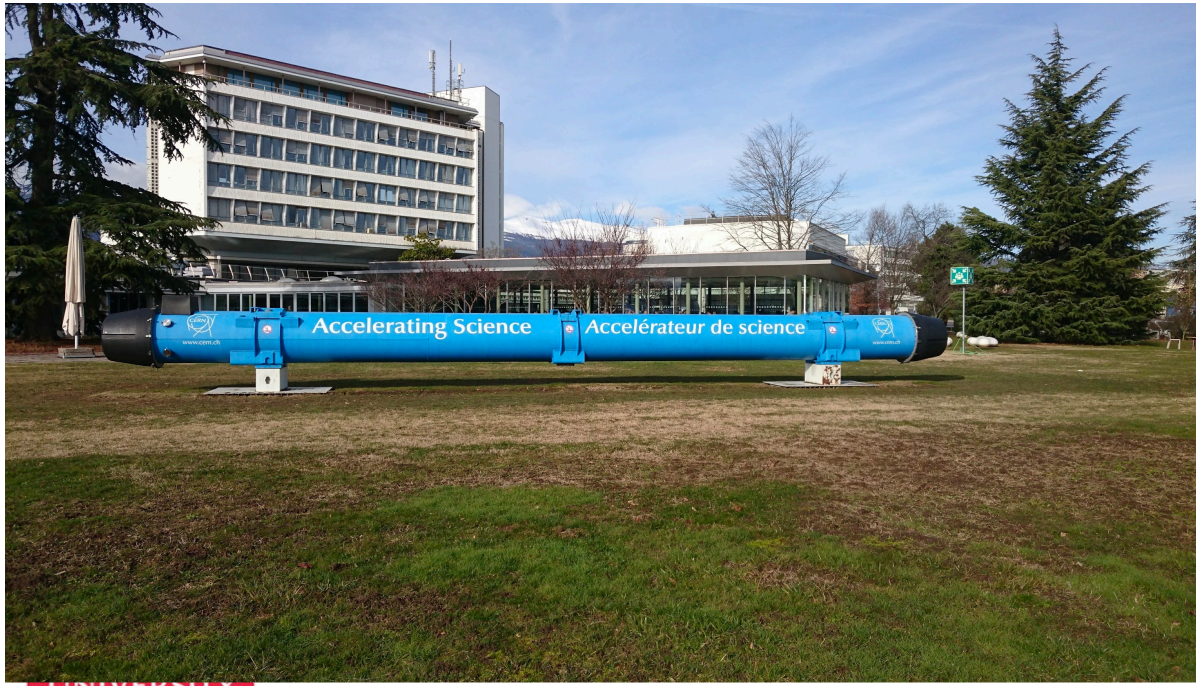
# OSQAR and CAST CERN Switzerland

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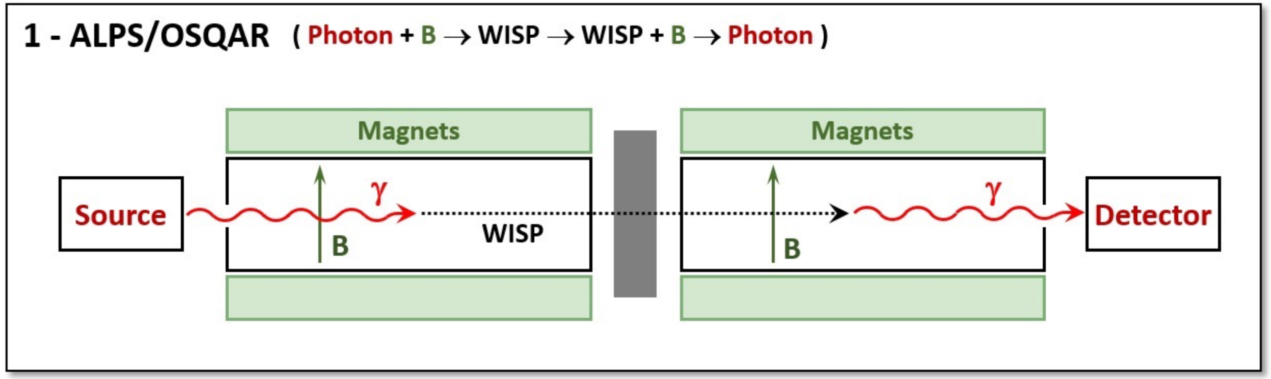
# GWs upper limits: ALPS, OSQAR, CAST

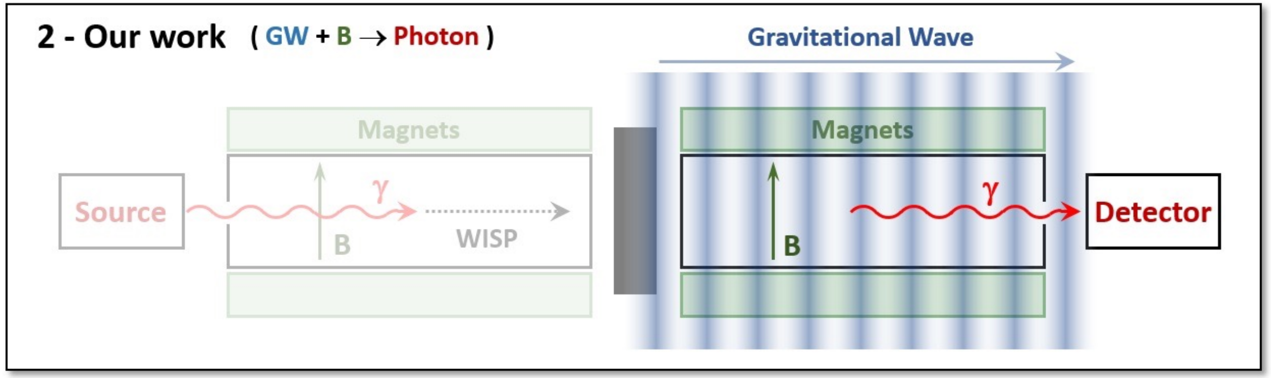
### Detectors

- Cannot point deliberately to the emitting sources, except CAST
- GWs upper limits at Ultra-High-Frequencies (UHF): optical $5\times10^{14}$ 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.



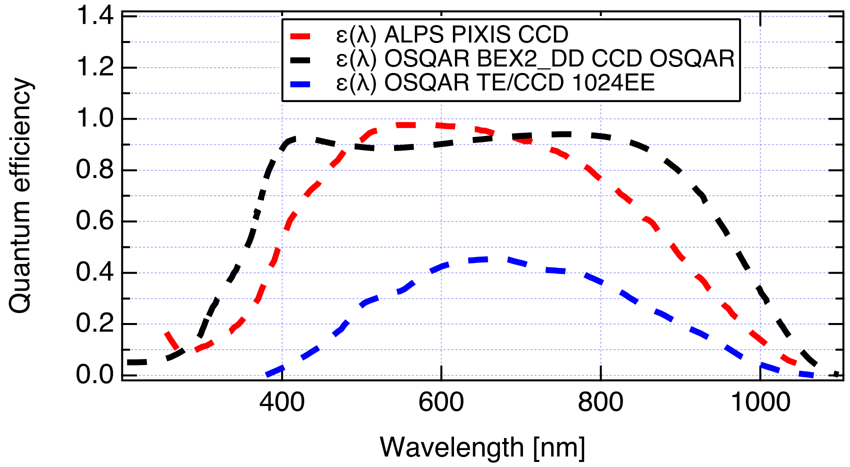



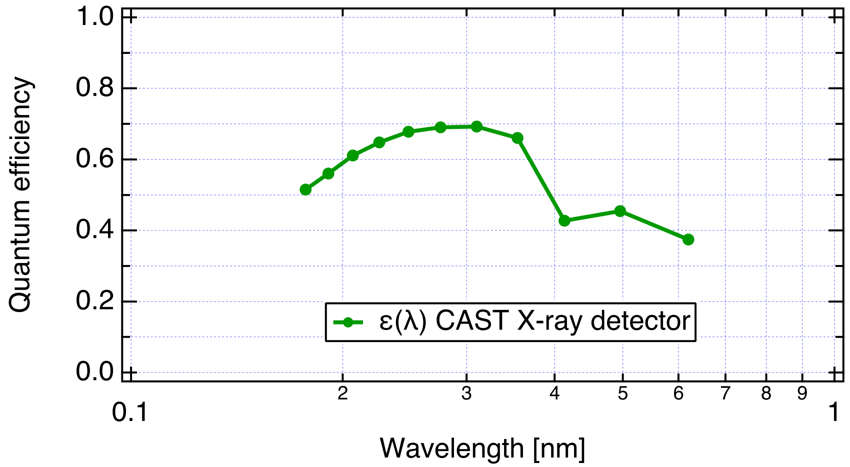
# Parameters necessary to compute the characteristic amplitude

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

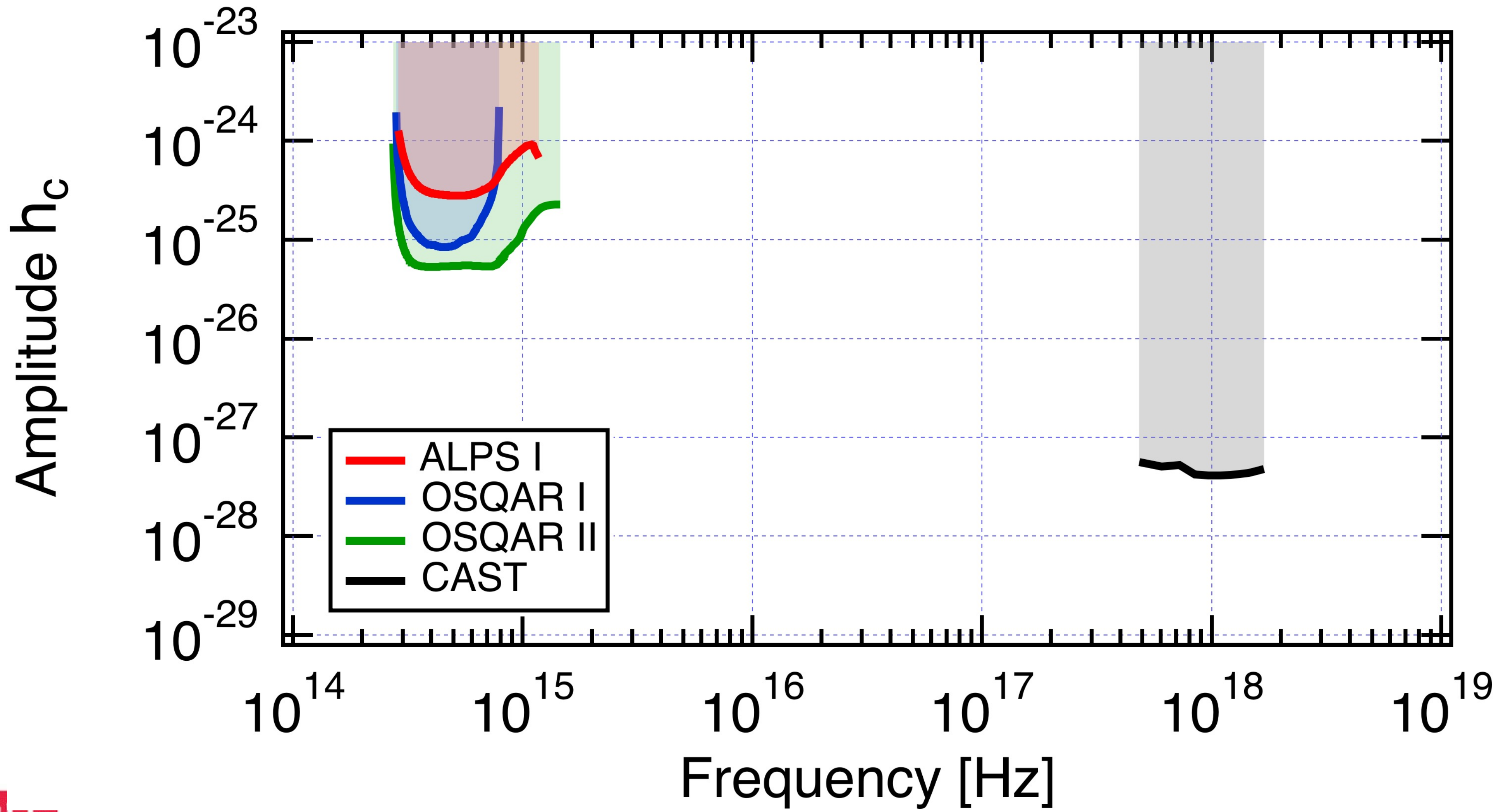
- $N_{exp}$ - detected number of photons per second,
- $A$ - cross-section of the detector,
- $B$ - magnetic field amplitude,
- $L$ - distance extension of the magnetic field,
- $\epsilon_\gamma(\omega)$ - quantum efficiency of the detector,
- $\Delta f$ - operation frequency of the CCD.

| | $\epsilon_\gamma(\omega)$ | $N_{\rm exp}$ (mHz) | $A$ (m$^2$) | $B$ (T) | $L$ (m) | $\Delta f$ (Hz) |
|---|---|---|---|---|---|---|
| ALPS I | see Fig 2 | 0.61 | $0.5\times10^{-3}$ | 5 | 9 | $9\times10^{14}$ |
| OSQAR I | see Fig 2 | 1.76 | $0.5\times10^{-3}$ | 9 | 14.3 | $5\times10^{14}$ |
| OSQAR II | see Fig 2 | 1.14 | $0.5\times10^{-3}$ | 9 | 14.3 | $1\times10^{15}$ |
| CAST | see Fig 2 | 0.15 | $2.9\times10^{-3}$ | 9 | 9.26 | $1\times10^{18}$ |



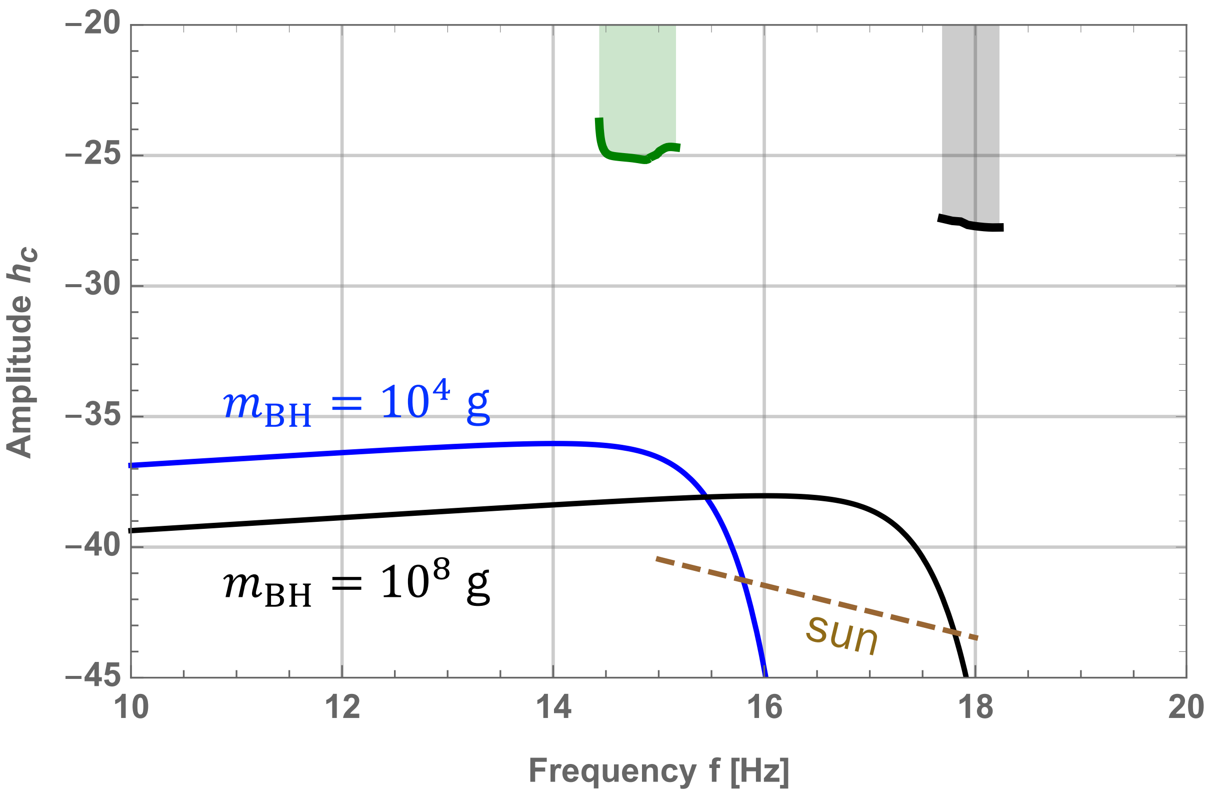
# UHF GW characteristic amplitude upper limits

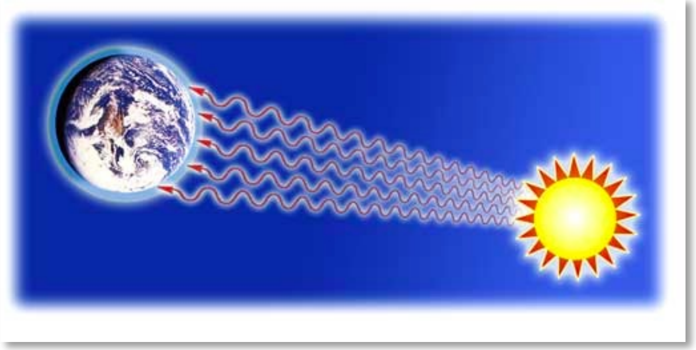


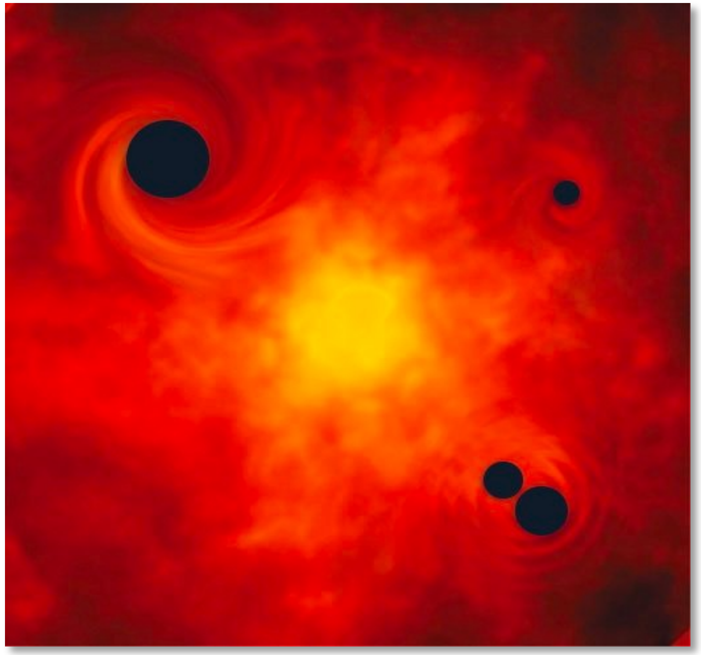
# Primordial black hole evaporation and upper limits

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

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



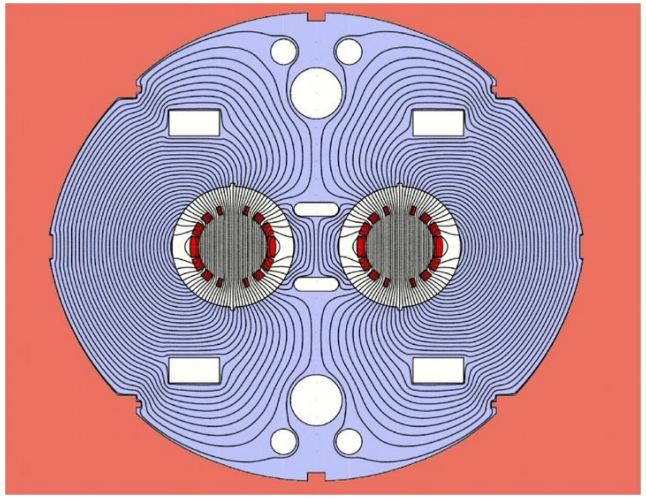


# WHERE TO NEXT?

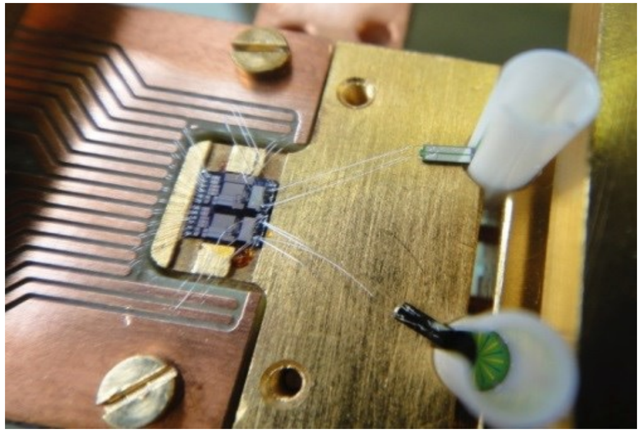
# Characteristic amplitude graviton-to-photon conversion

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

- $N_{exp}$ - 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
- $\Delta f$ - operation frequency of the CCD



TES



Synergies to axion search experiments

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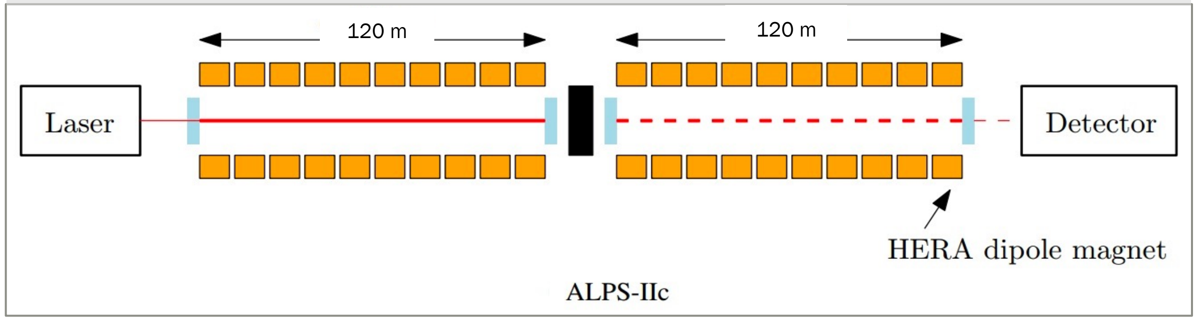
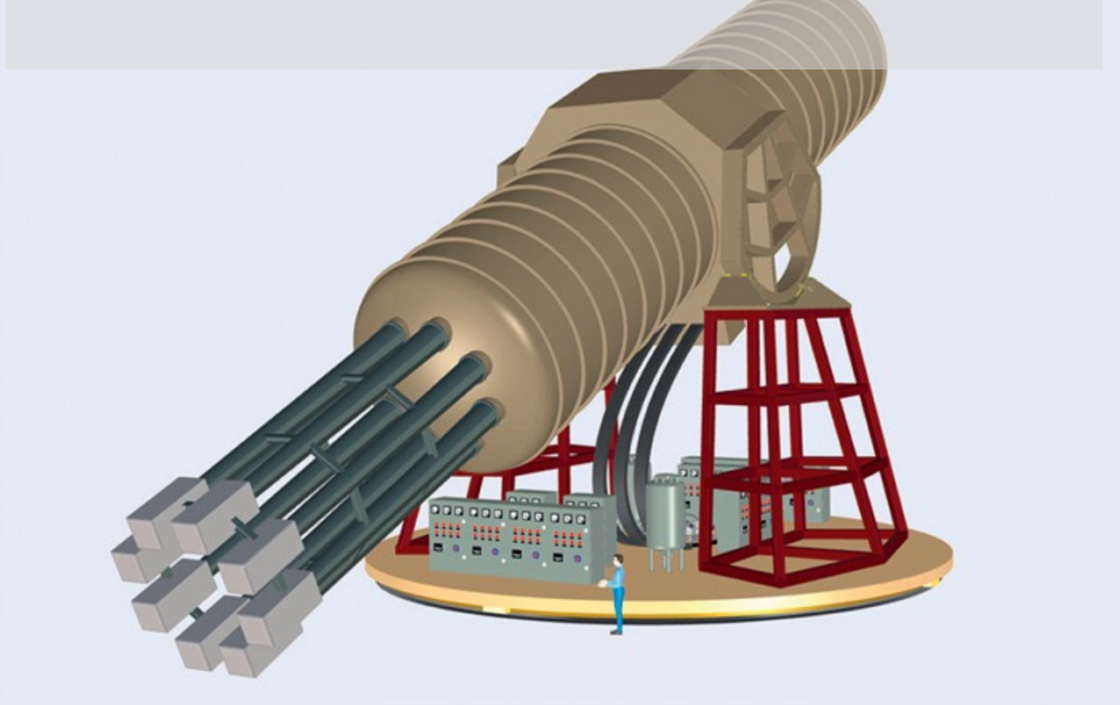
# Graviton to photon mixing and future laboratory axion experiments ALPS II, JURA, IAXO

## ALPS II



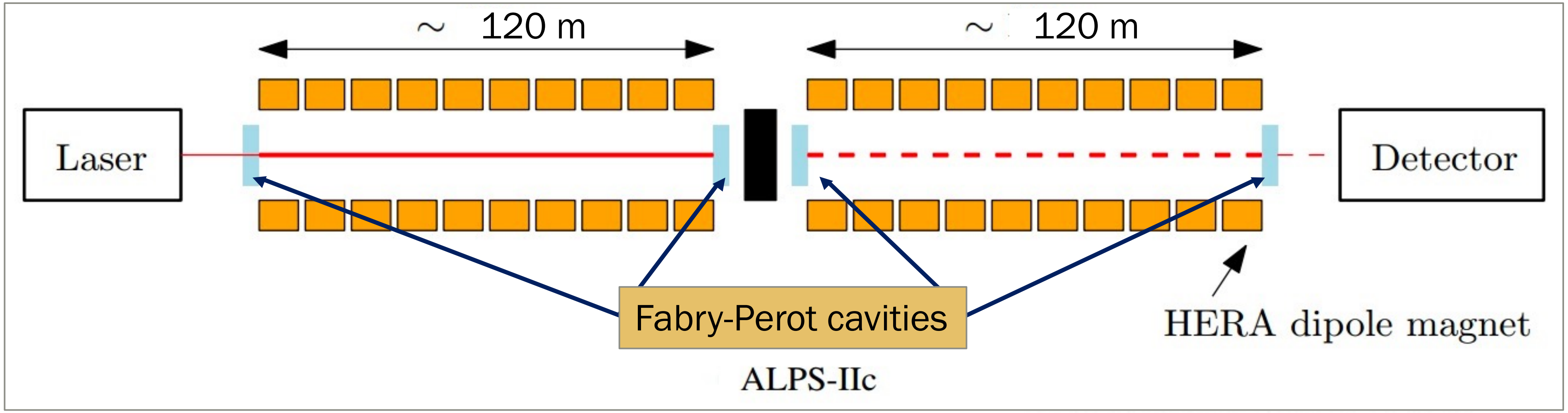

ALPS II under construction as of October 2020 (Credit: DESY)

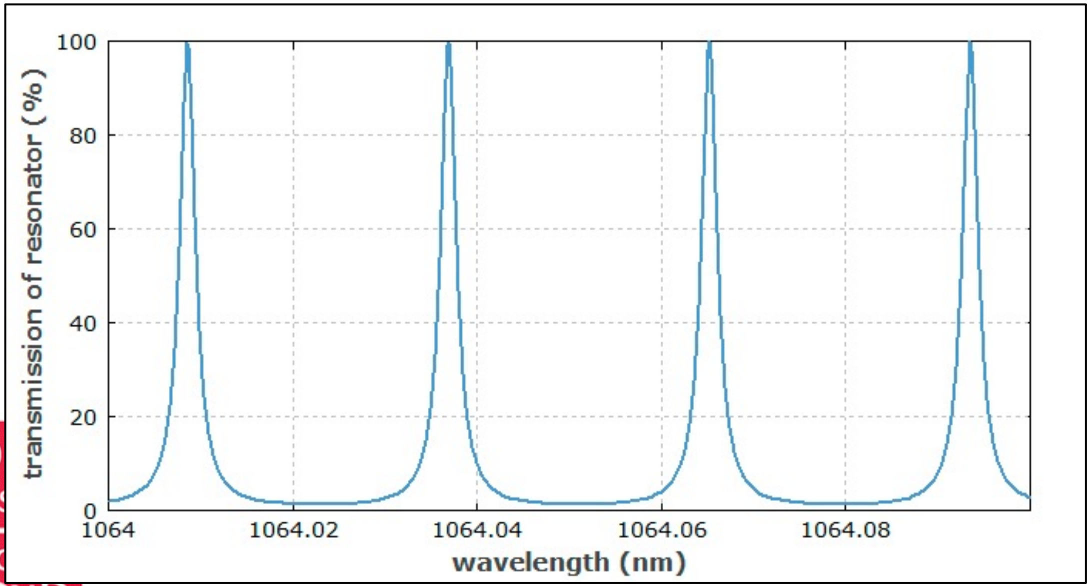
## IAXO (*Armengaud et al. JINST 9 T05002 (2014)*)

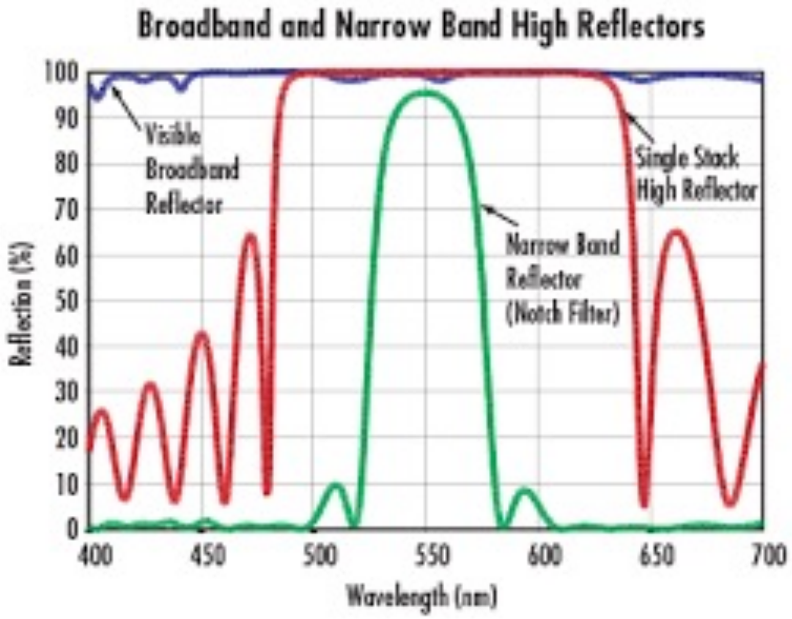


| | $\epsilon_\gamma$ | $N_{\rm dark}$ (Hz) | $A$ (m$^2$) | $B$ (T) | $L$ (m) | $\mathcal{F}$ |
|---|---|---|---|---|---|---|
| ALPS IIc | 0.75 | $\approx 10^{-6}$ | $\approx 2 \times 10^{-3}$ | 5.3 | 120 | 40 000 |
| JURA | 1 | $\approx 10^{-6}$ | $\approx 8 \times 10^{-3}$ | 13 | 960 | 100 000 |
|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

# ALPS II


~ 120 m
~ 120 m
Laser
Detector
Fabry-Perot cavities
HERA dipole magnet
ALPS-IIc


transmission of resonator (%)
wavelength (nm)
100
80
60
40
20
0
1064
1064.02
1064.04
1064.06
1064.08

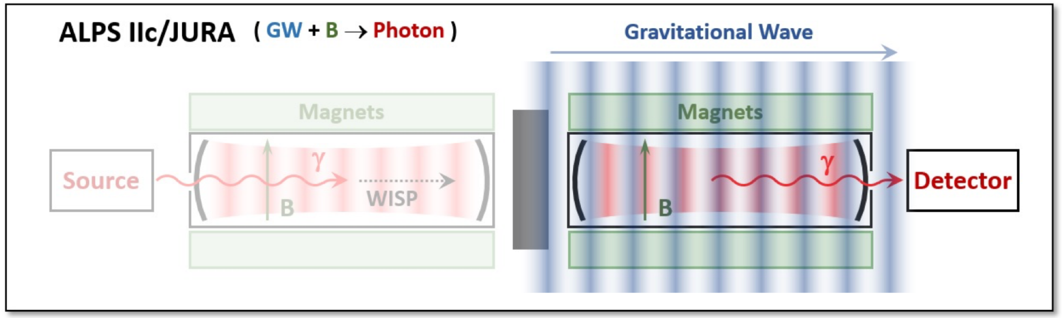

Broadband and Narrow Band High Reflectors
Reflection (%)
Wavelength (nm)
Visible Broadband Reflector
Single Stack High Reflector
Narrow Band Reflector (Notch Filter)
100
90
80
70
60
50
40
30
20
10
0
400
450
500
550
600
650
700

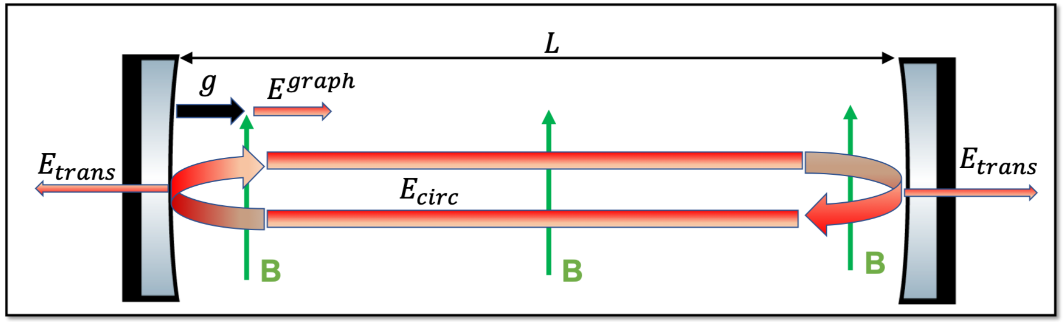
# Graviton-to-photon in the conversion Fabry-Perot cavity

$$\begin{aligned}
\vec{E}^{\rm circ}_{x,y}(z,t) &= \vec{E}^{\rm graph}_{x,y}(z,t)\left(1 + Re^{-i2\phi(\omega,L)} + \left(Re^{-i2\phi(\omega,L)}\right)^2 + \cdots\right) \\
&= \vec{E}^{\rm graph}_{x,y}(z,t)\sum_{n=0}^{\infty}\left(Re^{-i2\phi(\omega,L)}\right)^n \\
&= \vec{E}^{\rm graph}_{x,y}(z,t)\frac{1}{1 - R\,e^{-i2\phi(\omega,L)}}
\end{aligned}$$

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

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




$$h_c^{\rm min}(0,\omega^*) \simeq 2.8\times10^{-16}\sqrt{\left(\frac{1}{\mathcal{F}}\right)\left(\frac{N_{\rm dark}}{1\ {\rm Hz}}\right)\left(\frac{1\ {\rm m}^2}{A}\right)\left(\frac{1\ {\rm T}}{B}\right)^2\left(\frac{1\ {\rm m}}{L}\right)^2\left(\frac{1\ {\rm Hz}}{\Delta f}\right)\left(\frac{1}{\epsilon_\gamma(\omega)}\right)}$$

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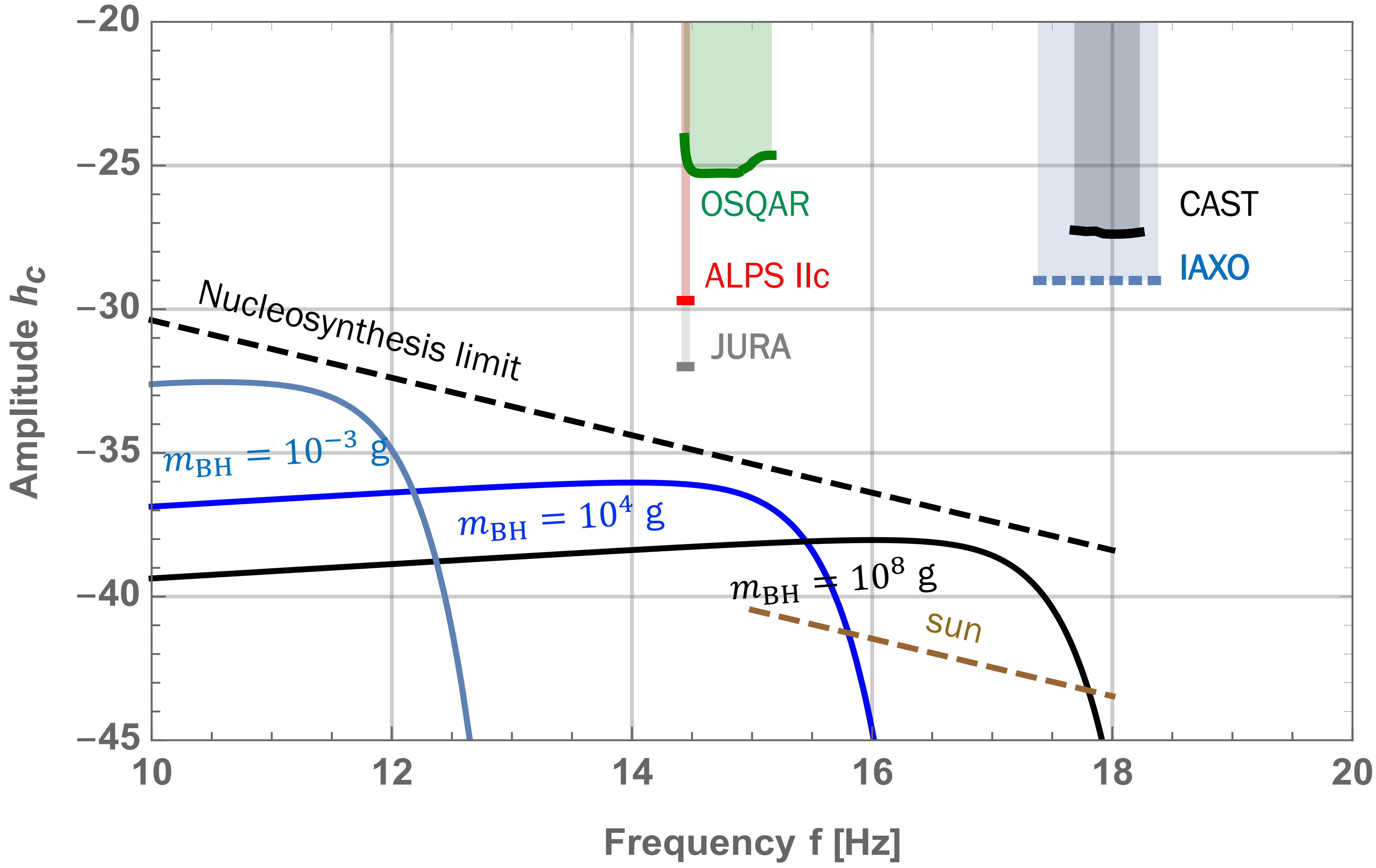
# Prospects

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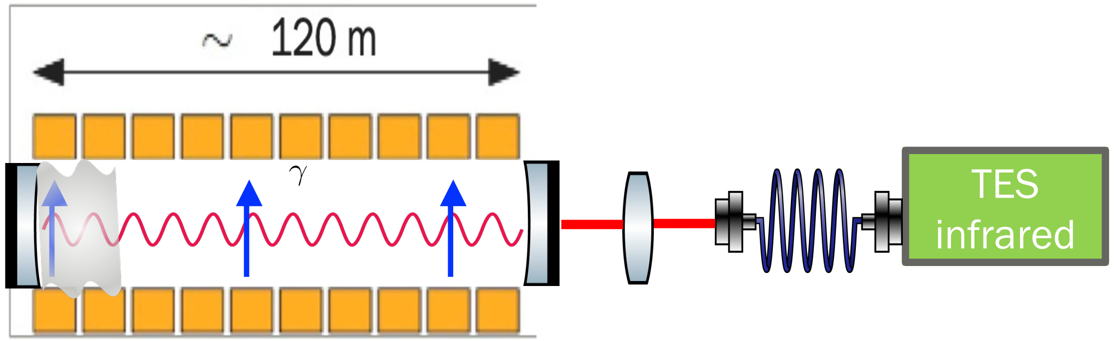
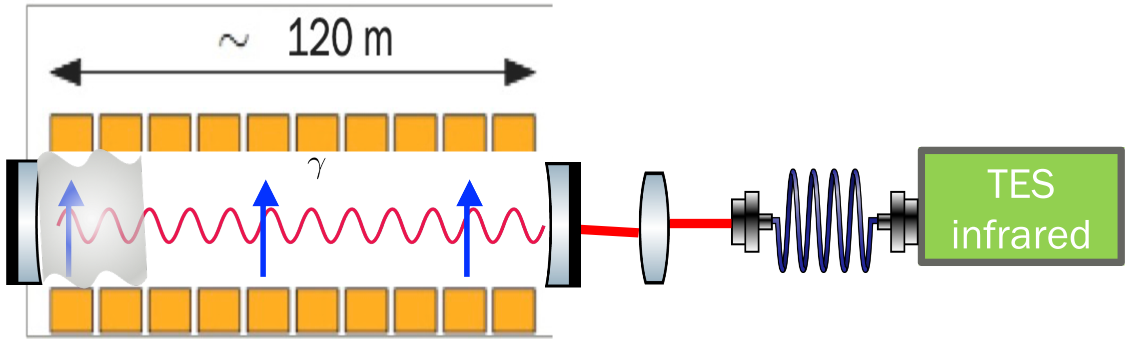
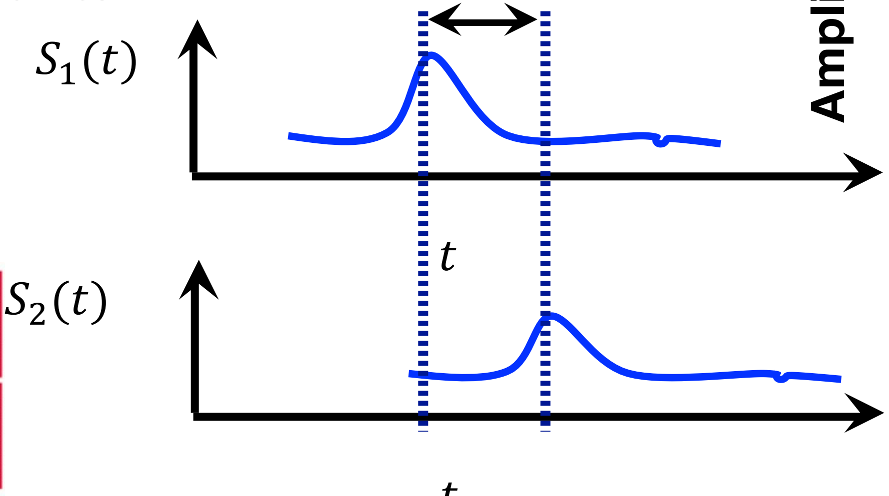
*Work in collaboration with: Mike Cruise, Damian Ejlli, Giampaolo Pisano, and Hartmut Grote*

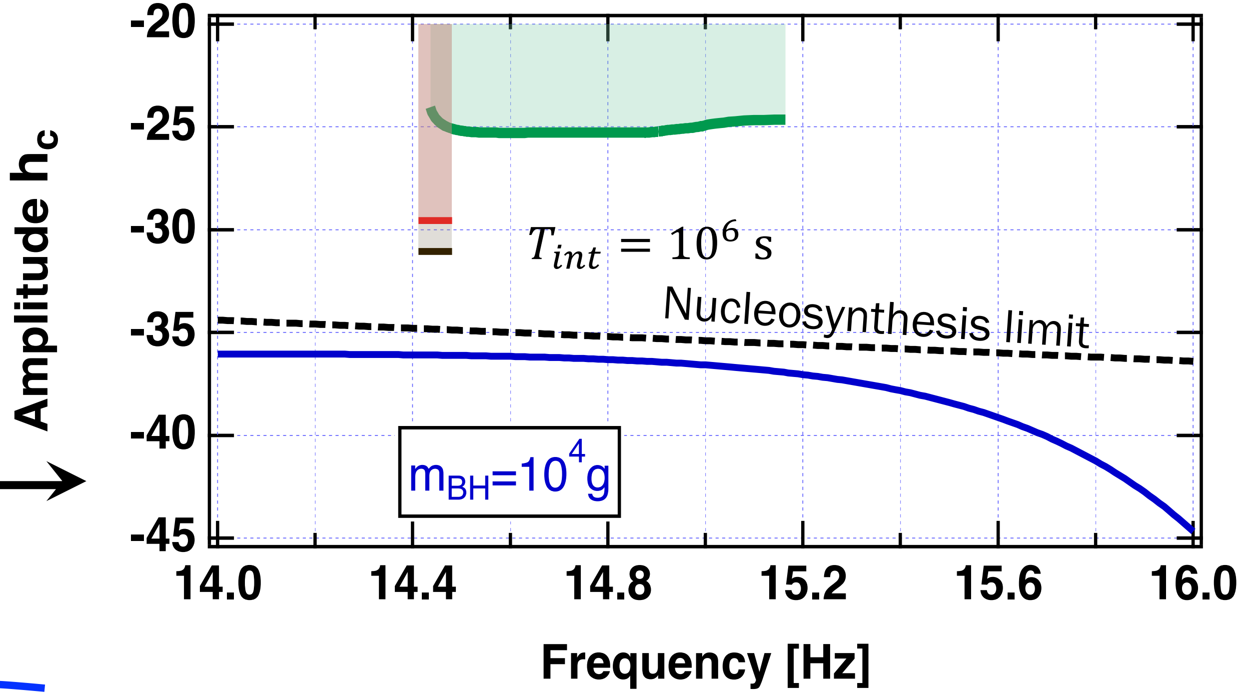
# ALPS II cross correlation




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

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# Gravitational Hertz experiment?

IOP Publishing | Royal Swedish Academy of Sciences Physica Scripta

Phys. Scr. **90** (2015) 074059 (7pp) doi:10.1088/0031-8949/90/7/074059

## Gravitational Hertz experiment with electromagnetic radiation in a strong magnetic field

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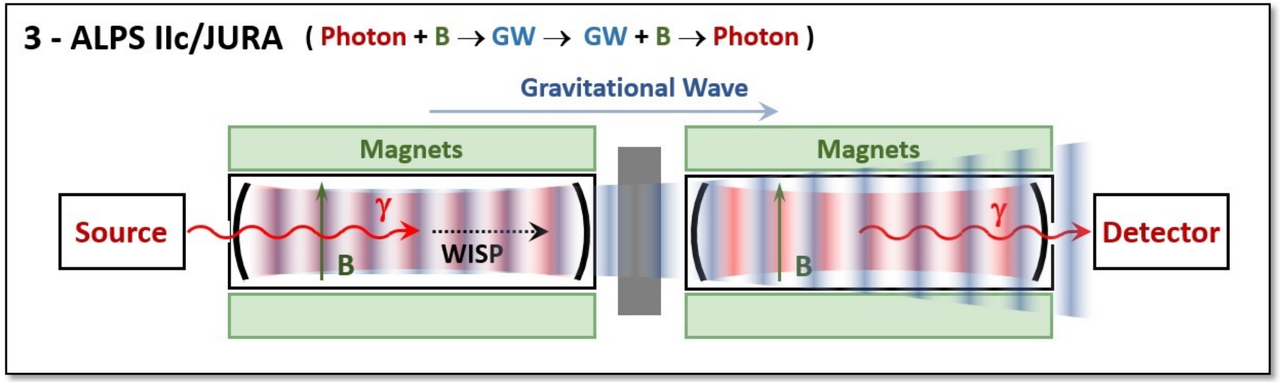
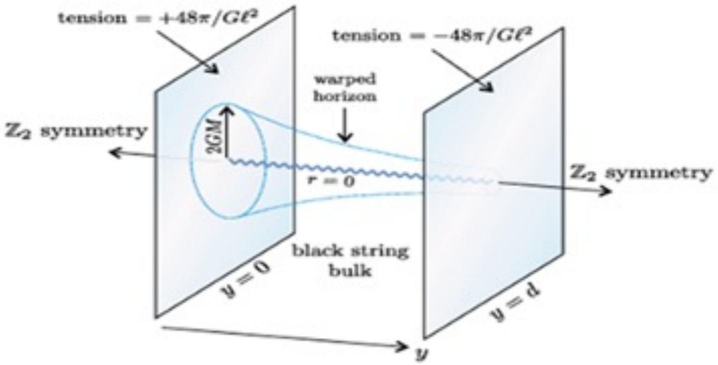
[2] Sternberg Astronomical Institute of Lomonosov Moscow State University (MSU), Universitetskii pr. 13, Moscow 119234, Russia
[3] Institute of Nuclear Researches RAS, str. 60-Letiya Oktyabrya 7a, Moscow 117312, Russia

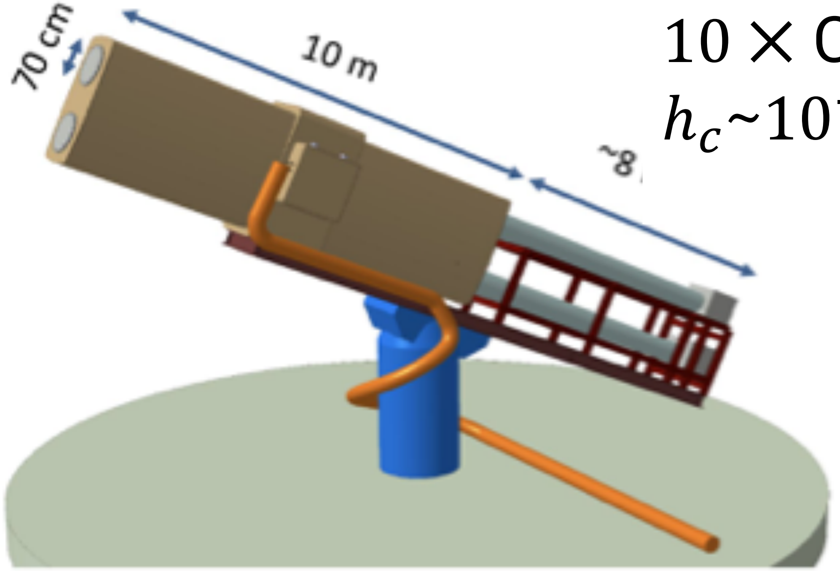
$$\max\ h_{\alpha\beta} = \frac{G}{c^4 k} H_0 \tilde{H}_0 \frac{2L}{1 - r_1 r_2} = \frac{G H_0 \tilde{H}_0 L \lambda_{em}}{c^4 \pi^2} F.$$



# Baby IAXO, IAXO

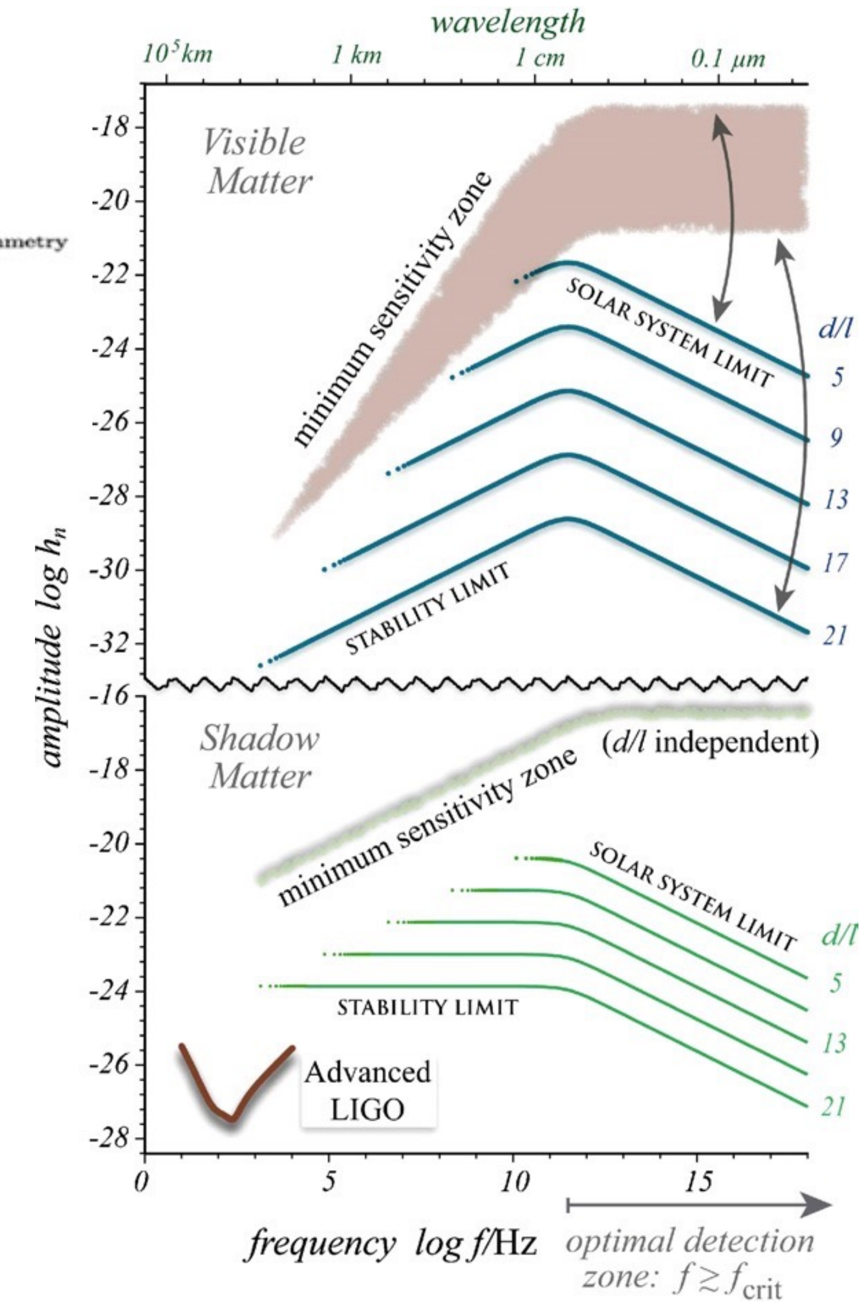



- Pointing: rotatable platform
- BH-BH collisions in higher dimensional gravity




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

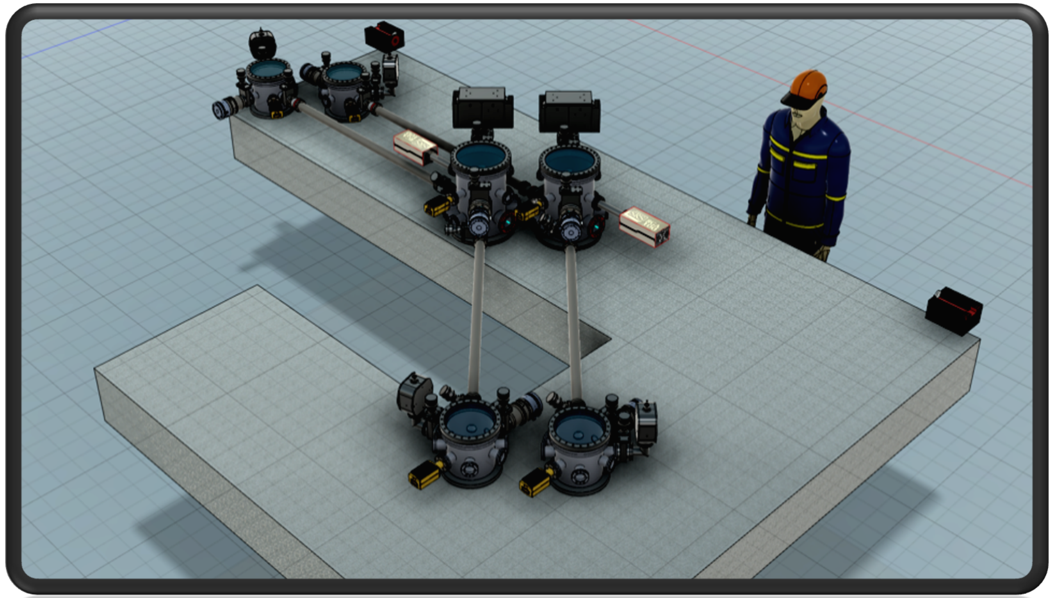
$h_c \sim 10^{-28}$ @ $10^{17} - 10^{18}$ Hz




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

# Co-located interferometry up to 250 MHz

- Quantization of space-time
- Dark matter searches
- High-frequency gravitational waves (1 - 250 MHz)



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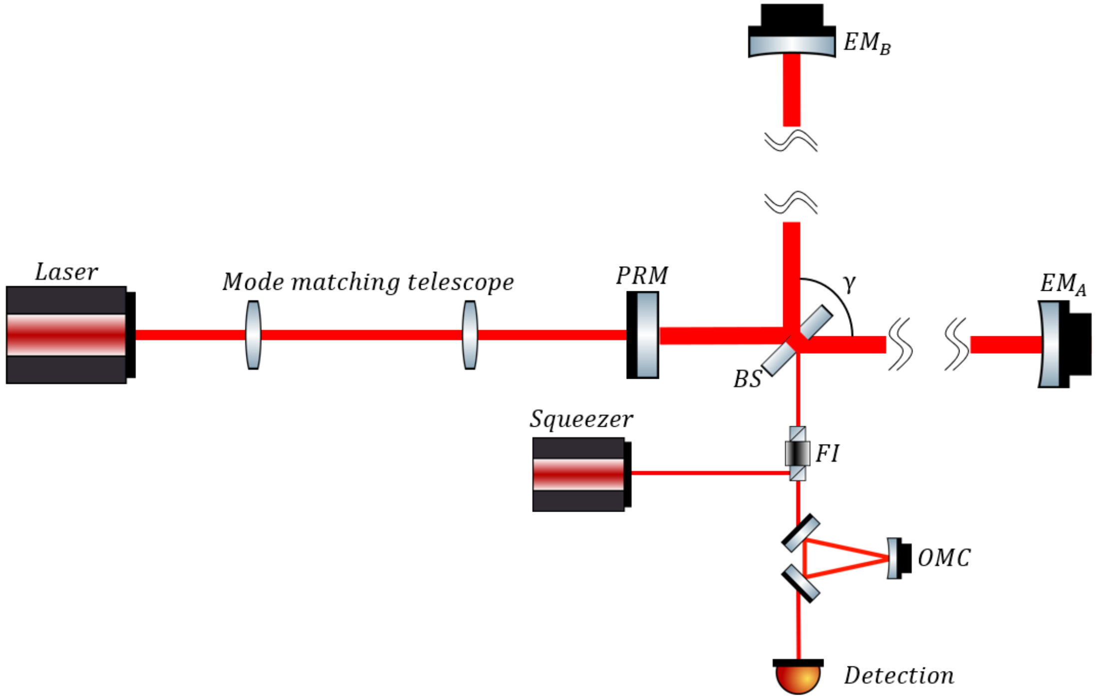
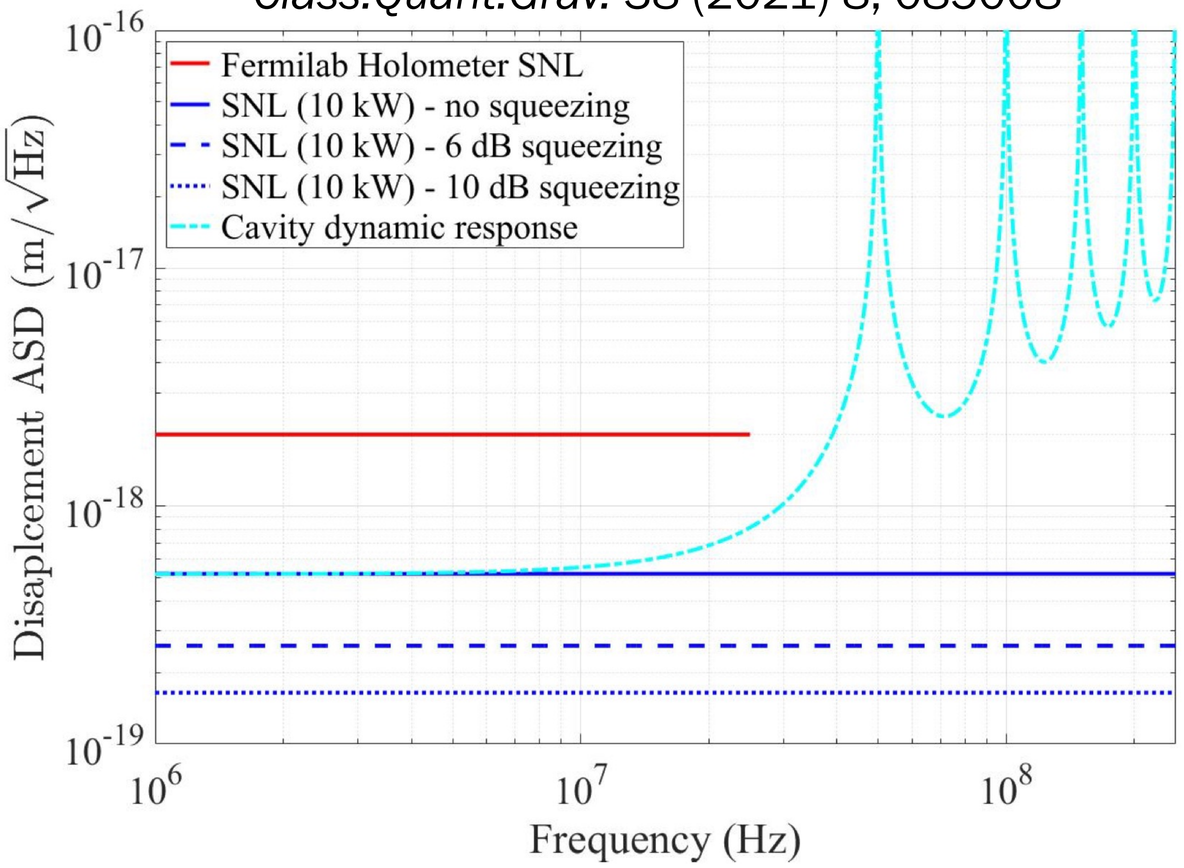
QI
Quantum-enhanced Interferometry for New Physics

# Co-located interferometry up to 250 MHz




*Class.Quant.Grav.* 38 (2021) 8, 085008

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QI
Quantum-enhanced Interferometry for New Physics

# Conclusions

- Axion search experiments ALPS I, OSQAR and CAST, set first upper limits on stochastic UHF GWs.
- The upgraded ALPS II, Baby-IAXO/IAXO, provide infrastructure to improve the existing upper limits for stochastic UHF GWs.
- Minor modifications of axion experiments could improve their sensitivity to UHF GWs.
- Axion search experiments are also being identified as novel UHF GW detectors.

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# Thank you for your attention