UPPER LIMITS ON HFGW FROM GRAVITON TO PHOTON CONVERSION

Aldo Ejlli

Physics Opportunities at 100-500 MHz Haloscopes

17/02/2022

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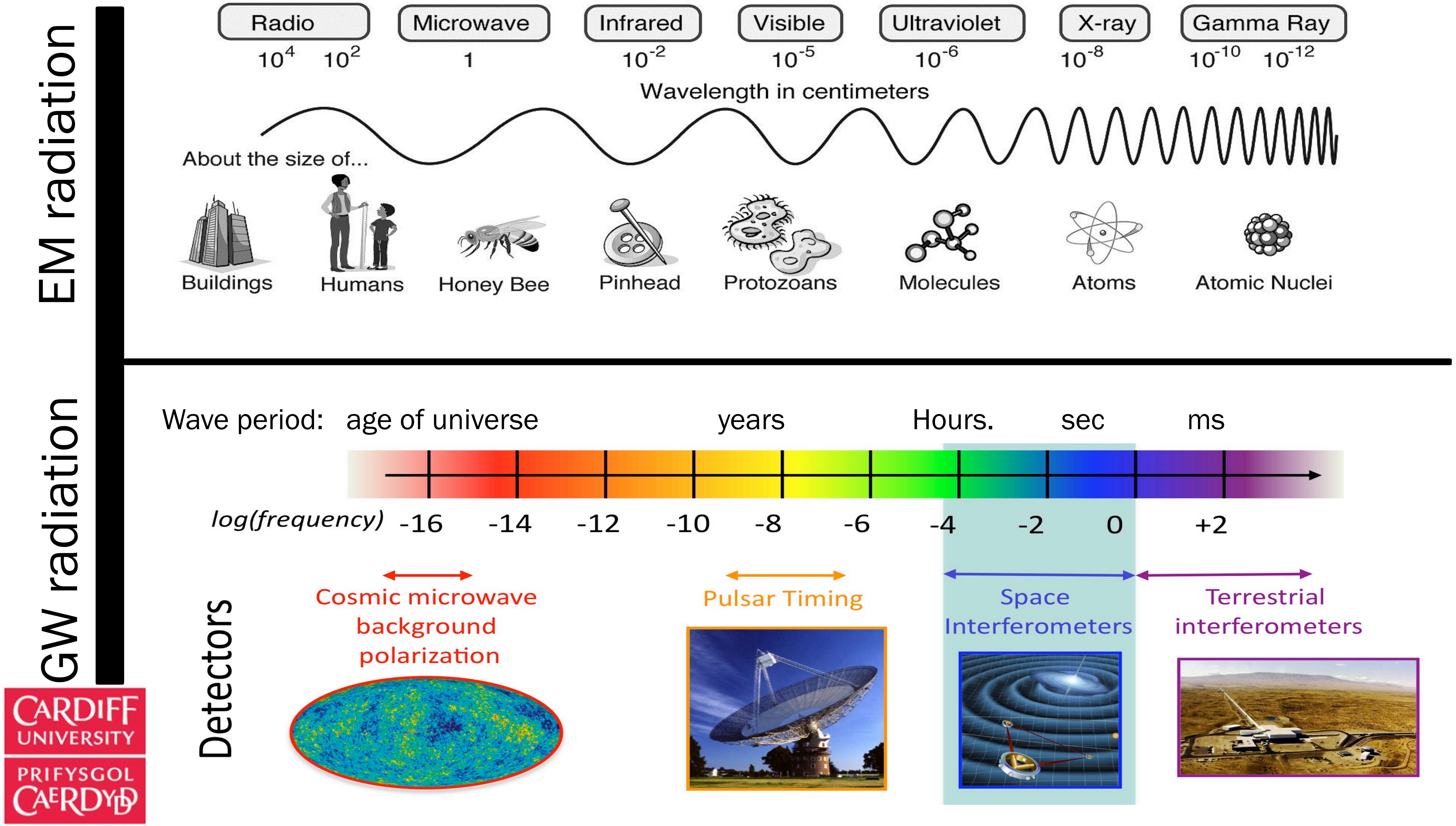

EM radiation
Radio
Microwave
Infrared
Visible
Ultraviolet
X-ray
Gamma Ray
10^4 10^2 1 10^{-2} 10^{-5} 10^{-6} 10^{-8} 10^{-10} 10^{-12}
Wavelength in centimeters
About the size of...
Buildings
Humans
Honey Bee
Pinhead
Protozoans
Molecules
Atoms
Atomic Nuclei
GW radiation
Wave period: age of universe
years
Hours.
sec
ms
log(frequency) -16 -14 -12 -10 -8 -6 -4 -2 0 +2
Detectors
Cosmic microwave background polarization
Pulsar Timing
Space Interferometers
Terrestrial interferometers
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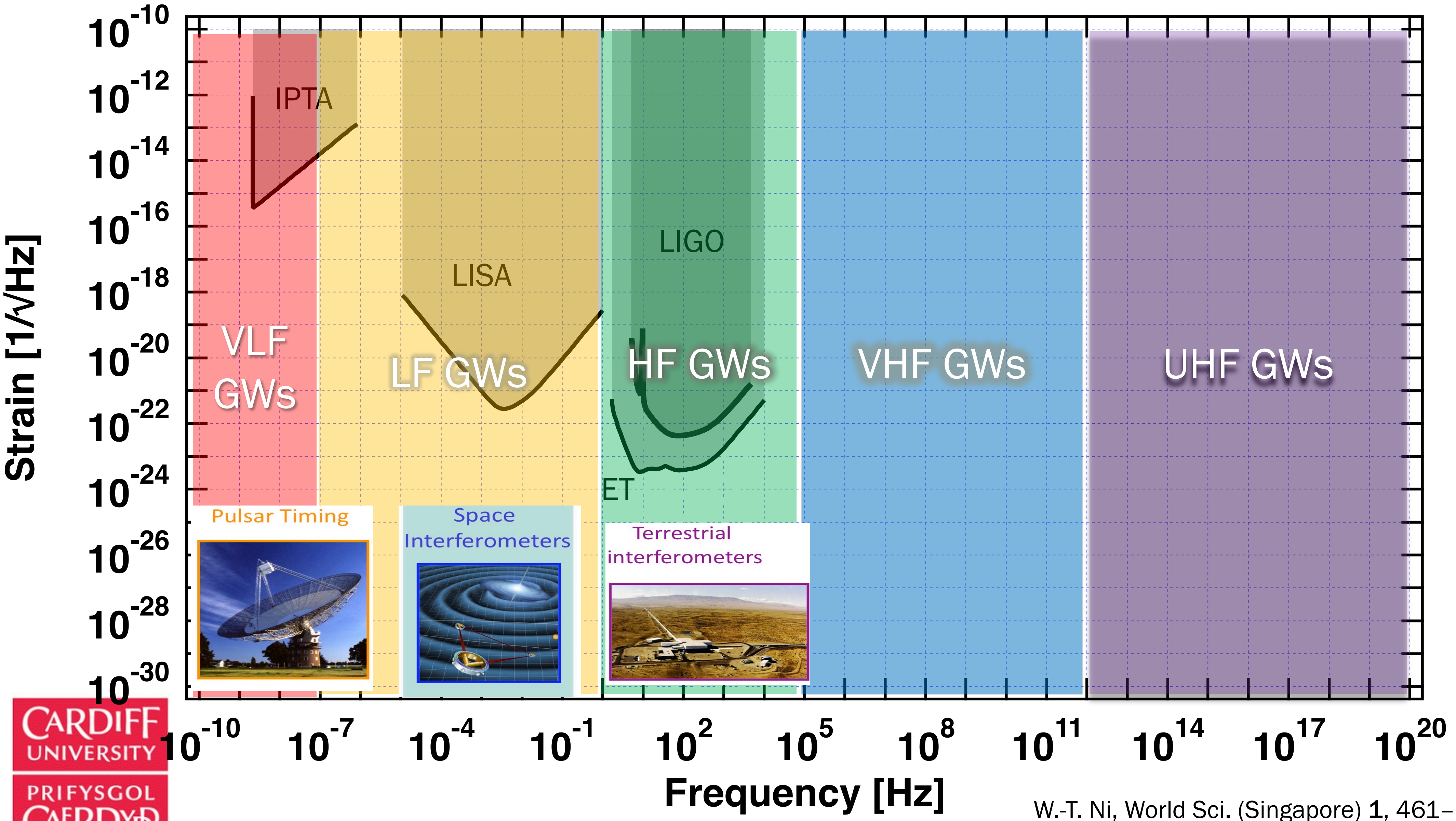
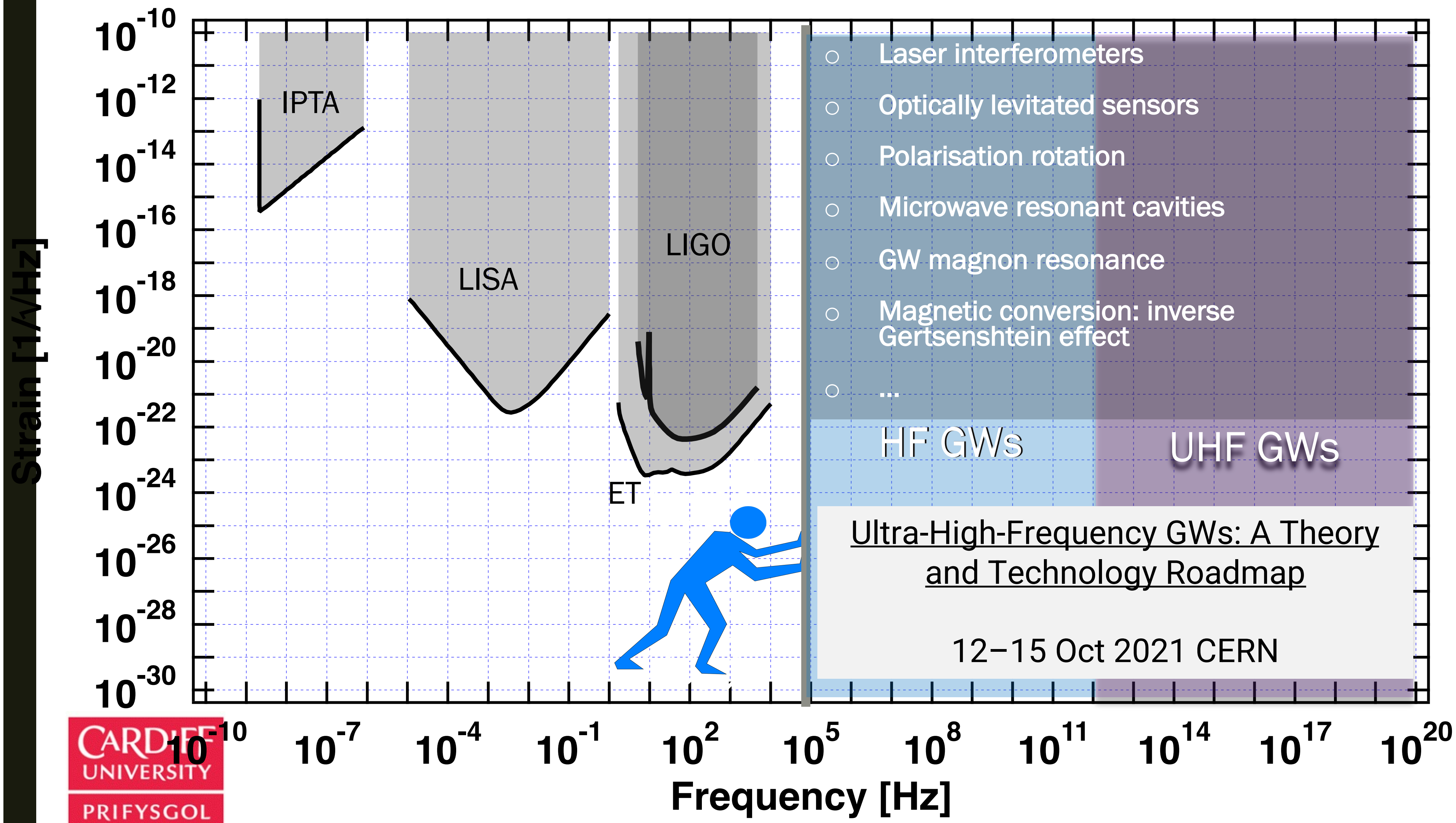
Definition



W.-T. Ni, World Sci. (Singapore) 1, 461–464 (2016)

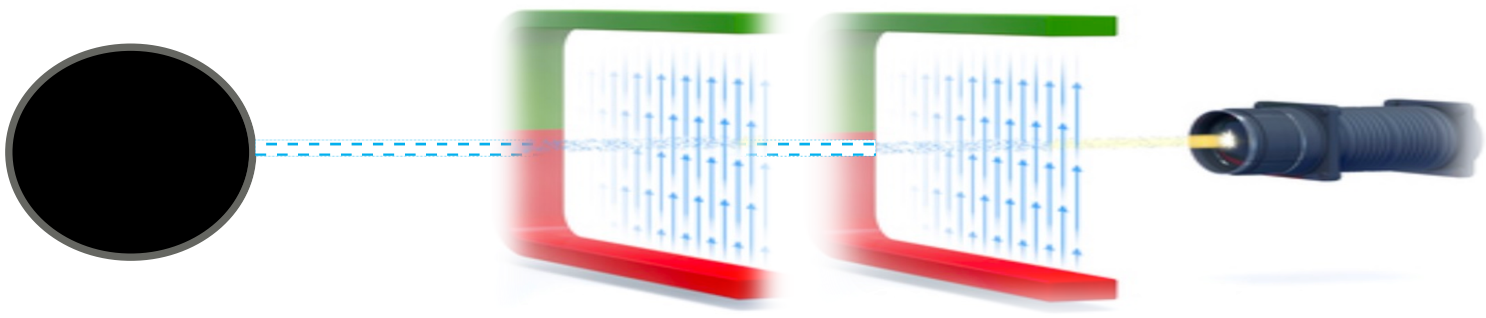

Strain [1/√Hz]
10^-10
10^-12
10^-14
10^-16
10^-18
10^-20
10^-22
10^-24
10^-26
10^-28
10^-30
IPTA
LISA
LIGO
ET
Laser interferometers
Optically levitated sensors
Polarisation rotation
Microwave resonant cavities
GW magnon resonance
Magnetic conversion: inverse Gertsenshtein effect
...
HF GWs
UHF GWs
Ultra-High-Frequency GWs: A Theory and Technology Roadmap
12–15 Oct 2021 CERN
10^-10
10^-7
10^-4
10^-1
10^2
10^5
10^8
10^11
10^14
10^17
10^20
Frequency [Hz]

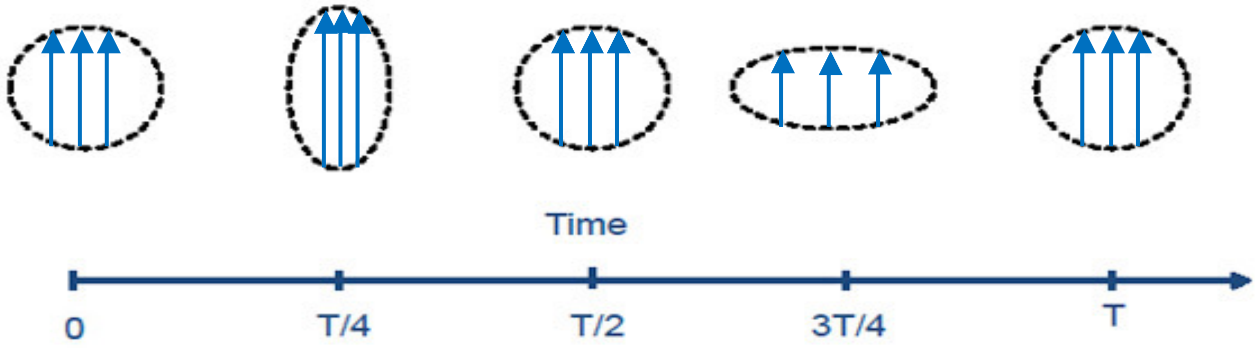
MAGNETIC CONVERSION?

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)

Source — Magnetic field — Photon detector





$$|h_{ij}|\mathbf{B}_{ext}$$

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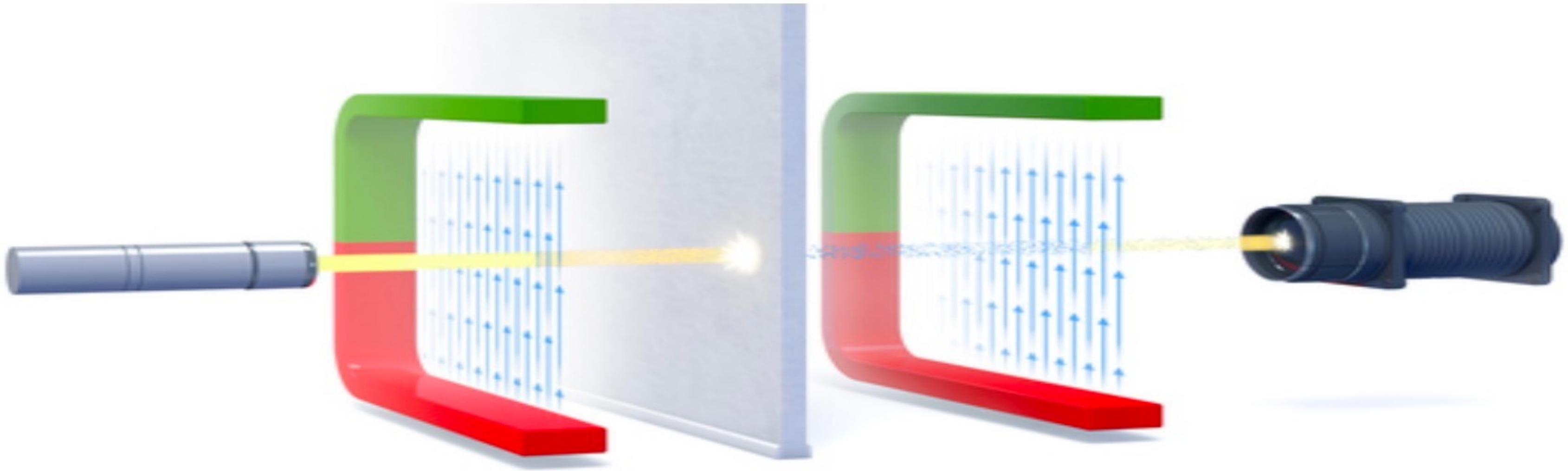
Axion search using laboratory static magnetic fields

- 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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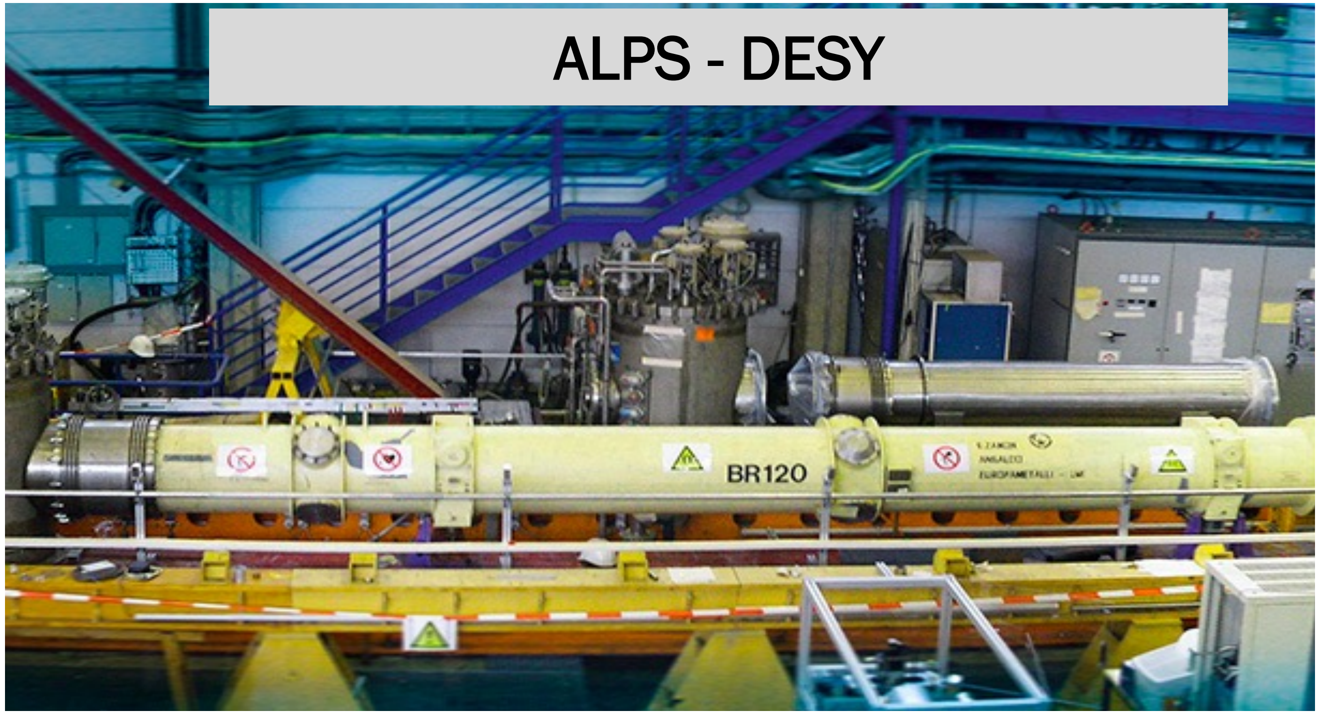
CAST - CERN

ALPS - DESY



AXION-LIKE PARTICLE EXPERIMENTS

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OSQAR - CERN

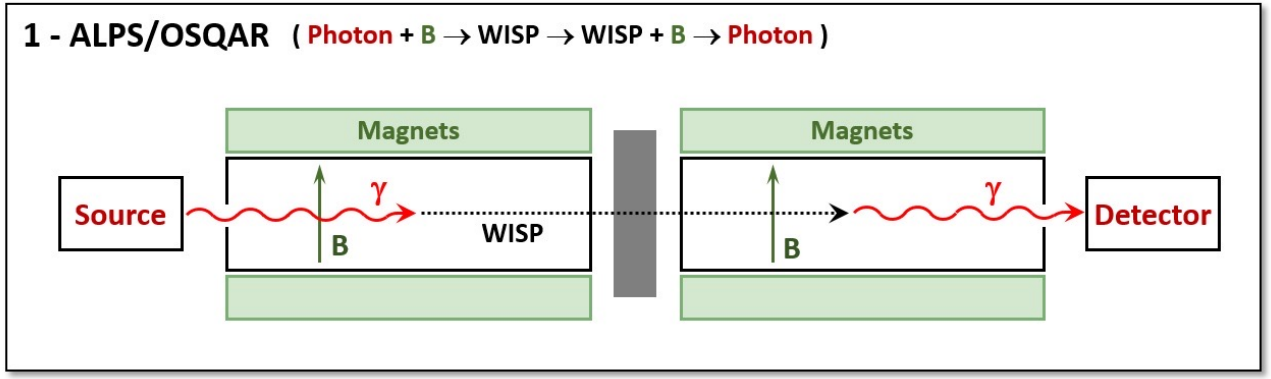
GWs upper limits: ALPS, OSQAR, CAST

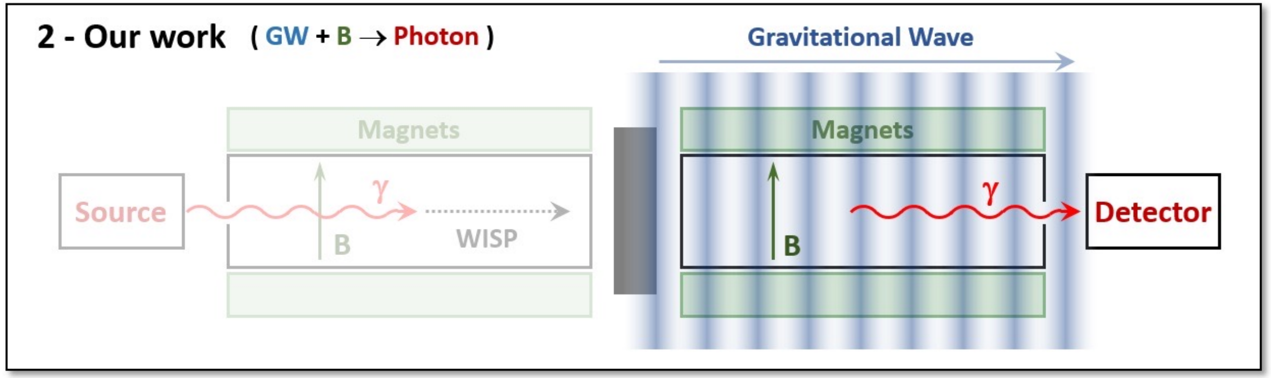
Detectors

- 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

- Stochastic, isotropic, stationary, and Gaussian gravitational-waves.





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UHF GW sources

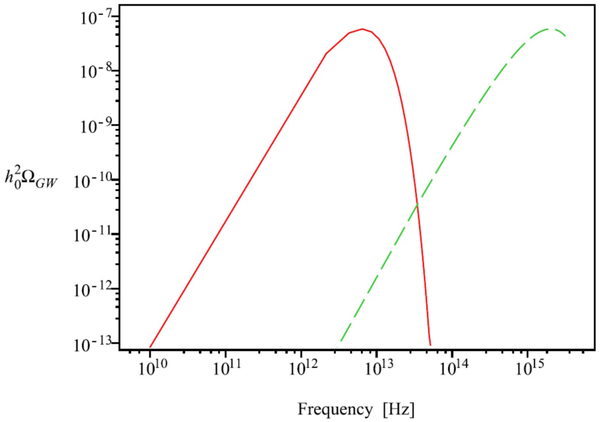
Inevitably speculative at this moment

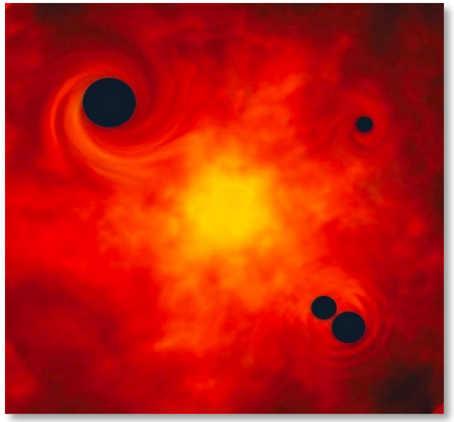
- Early Universe cosmological sources: primordial BH collisions and evaporations
- BH-BH collisions in higher dimensional gravity
- Thermal activity of the sun
- ....

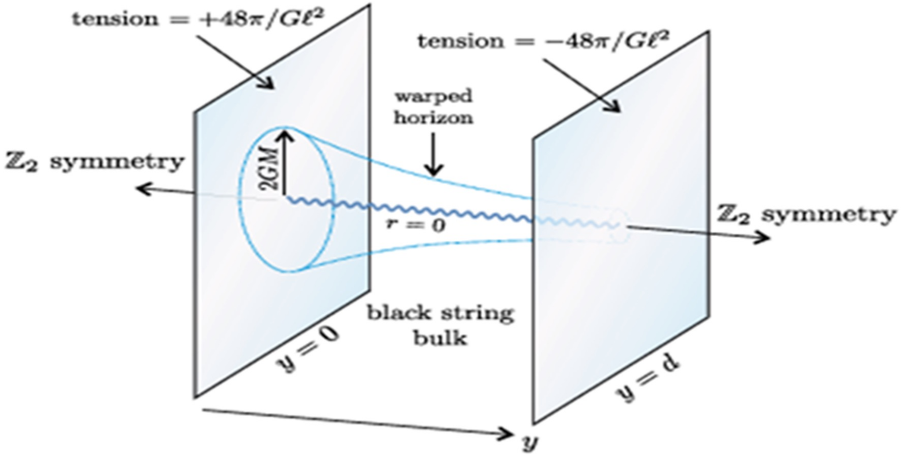
However

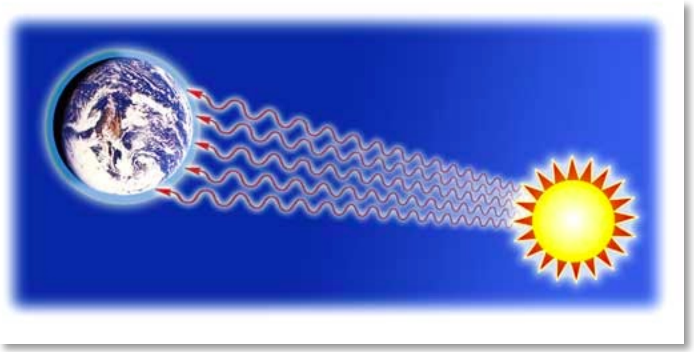
We may use UHF GW upper limits to detect or discount new, proposed particles, fields, etc.

Phys.Rev.D 84 (2011) 024028

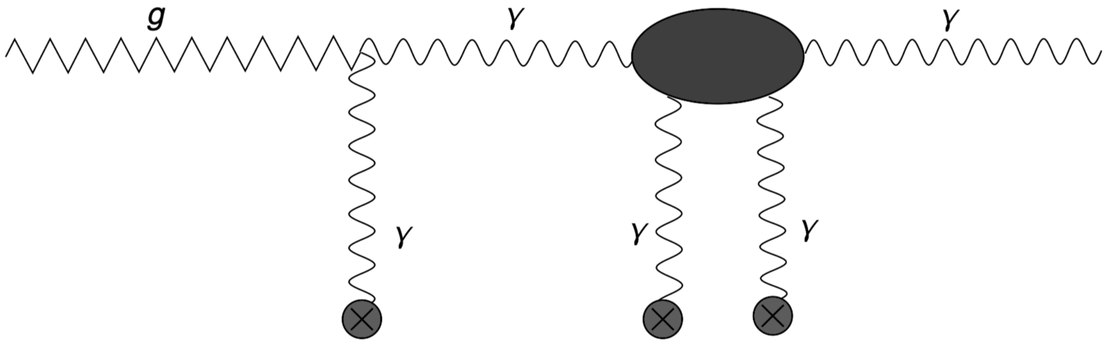








GWs propagating in transverse static magnetic fields



$$S = \int d^4x \sqrt{-g}\mathcal{L}$$

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

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

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

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

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

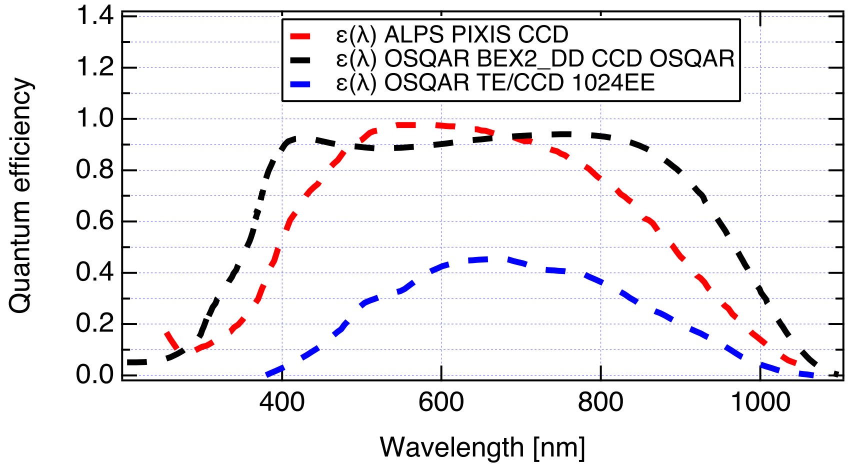
$$h_c^{\rm min}(0, \omega) \simeq \sqrt{\frac{4\, N_{\rm exp}}{A\, B^2\, L^2\, \epsilon_\gamma(\omega)\, \Delta\omega}} \simeq 1.6\times 10^{-16} \sqrt{\left(\frac{N_{\rm exp}}{1\ {\rm Hz}}\right) \left(\frac{1\ {\rm m}^2}{A}\right) \left(\frac{1\ {\rm T}}{B}\right)^2 \left(\frac{1\ {\rm m}}{L}\right)^2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

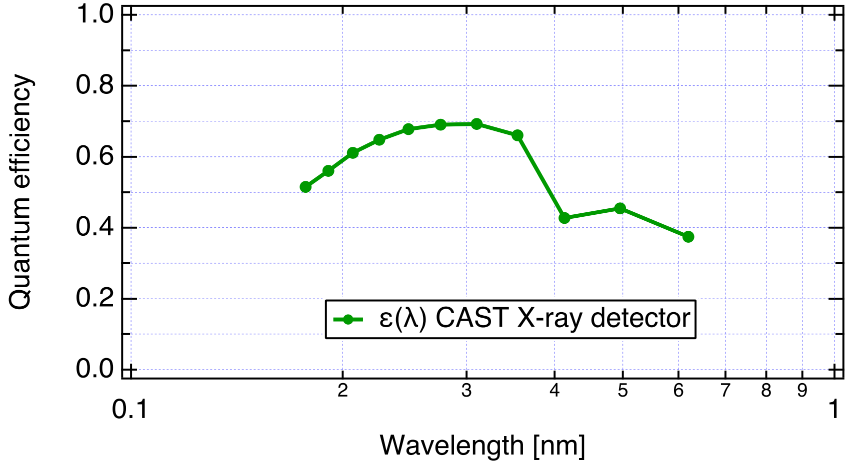
Parameters necessary to compute the characteristic amplitude

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

- 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,
- Δf - operation frequency of the CCD.

	$\epsilon_\gamma(\omega)$	$N_{\rm exp}$ (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}

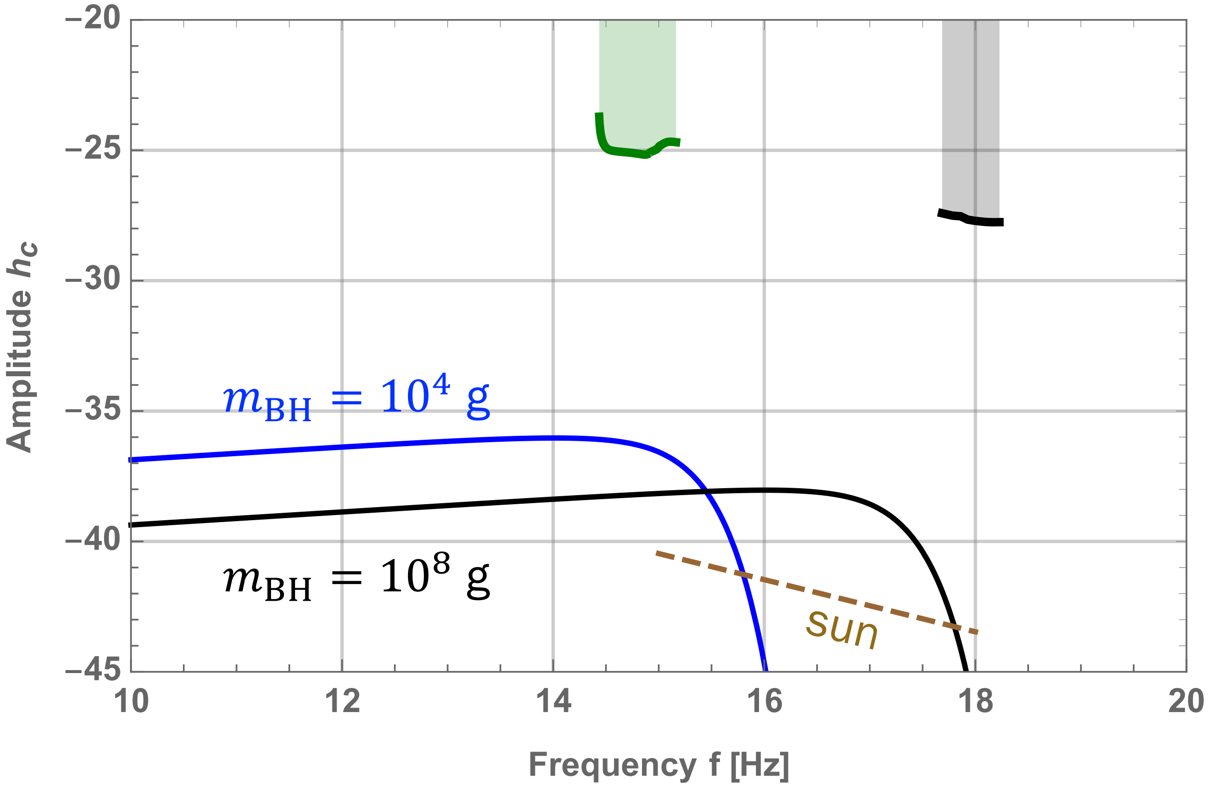


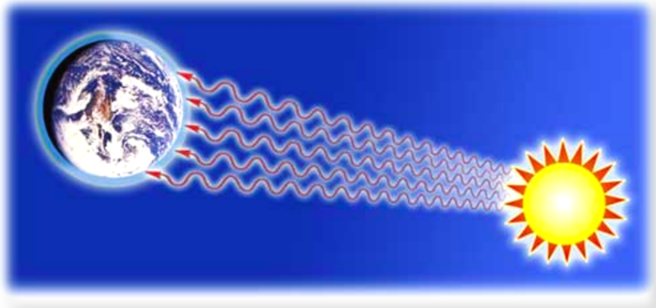


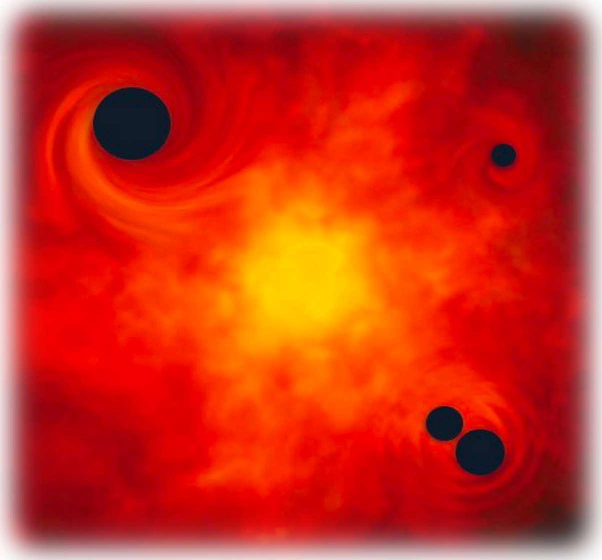
Primordial black hole evaporation and upper limits

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

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





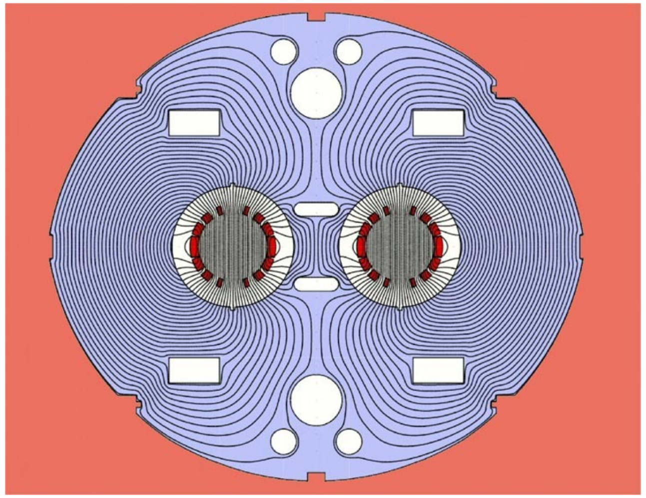


WHERE TO NEXT?

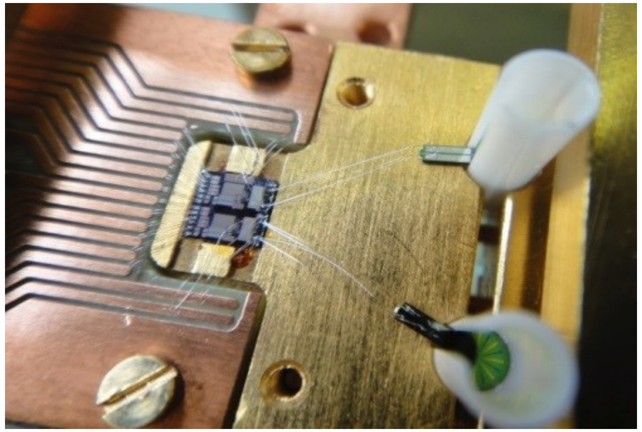
Graviton to photon conversion and synergies with future axion search experiments

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

- 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



TES



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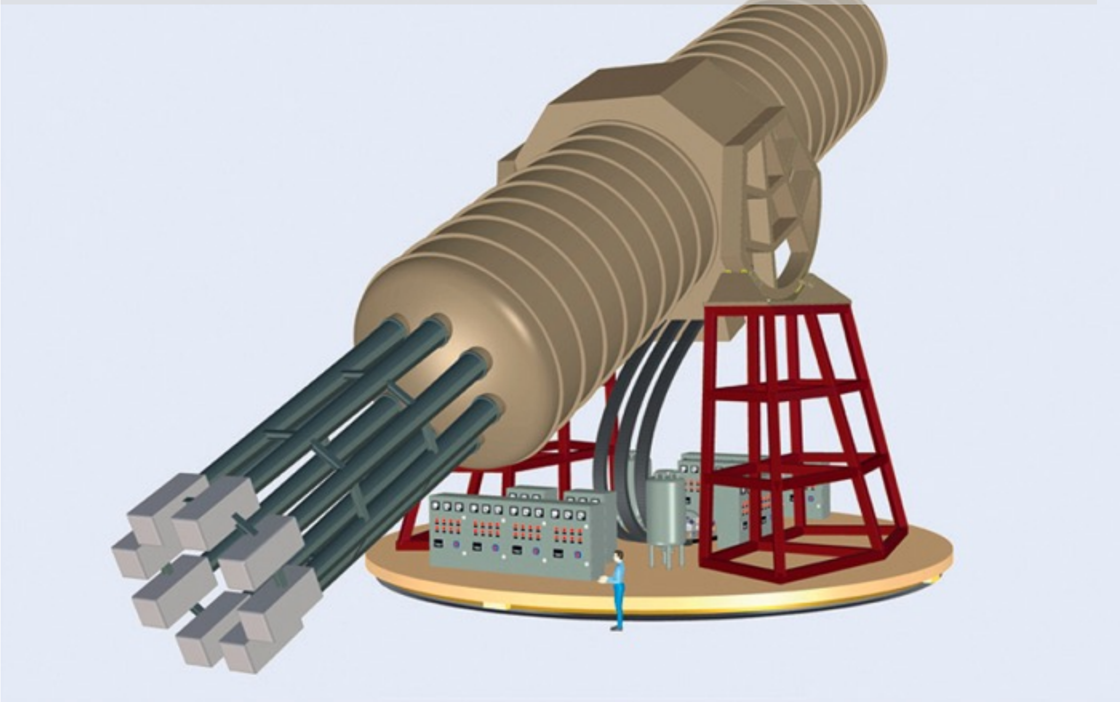
Future laboratory axion experiments: ALPS II, JURA, IAXO.

ALPS II

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

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



	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	-

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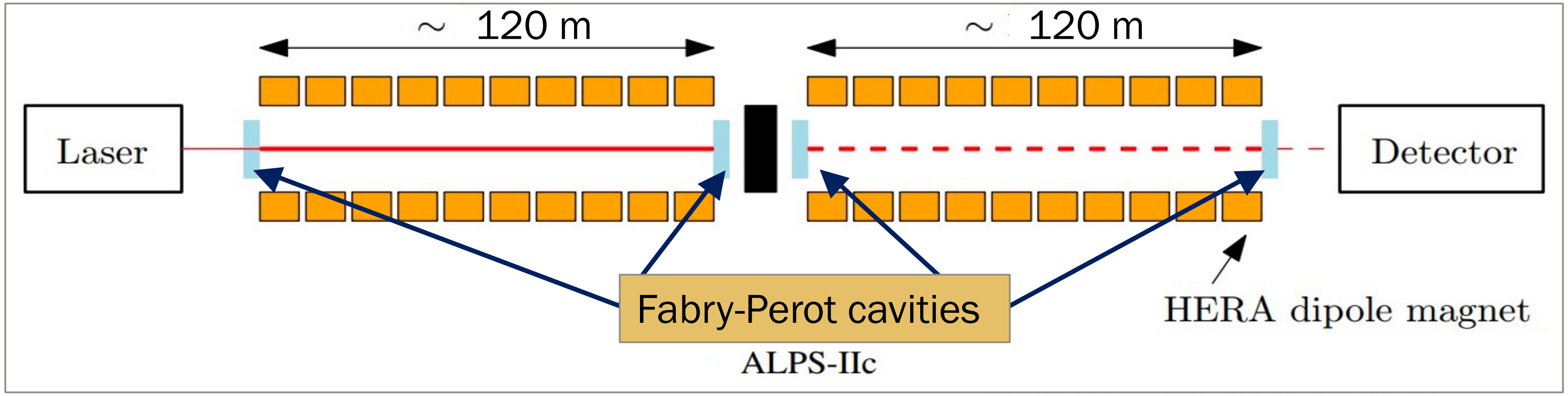
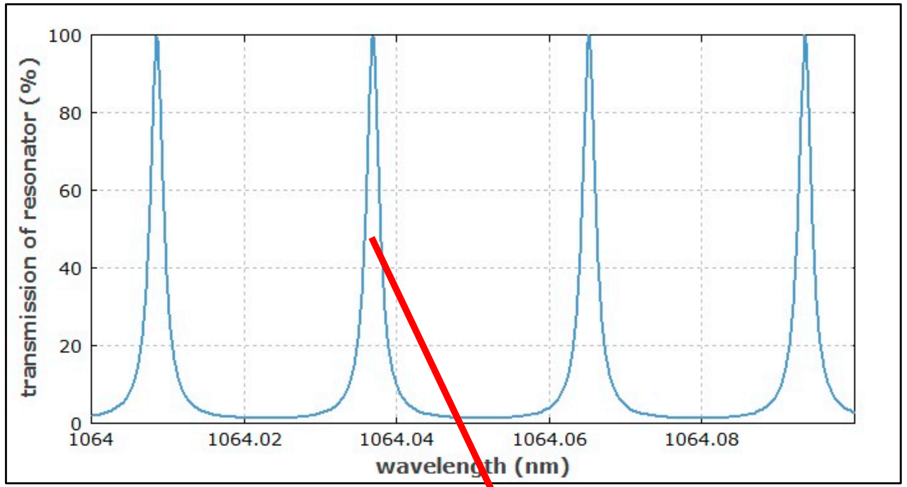
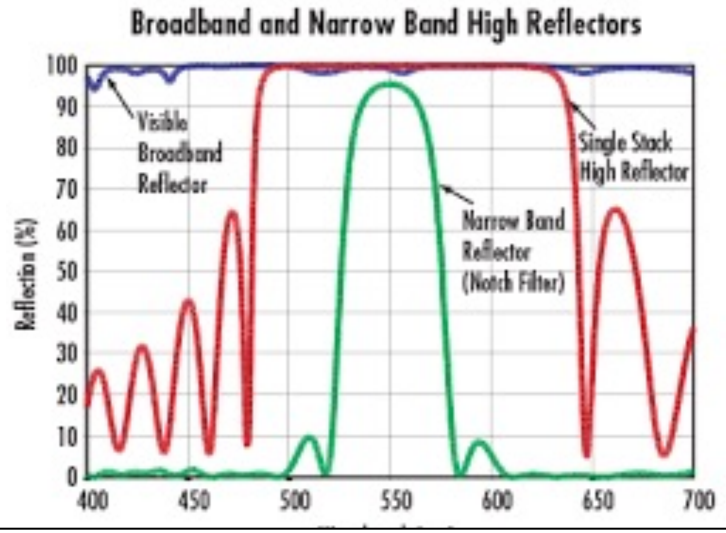
ALPS II: Fabry-Perot cavities

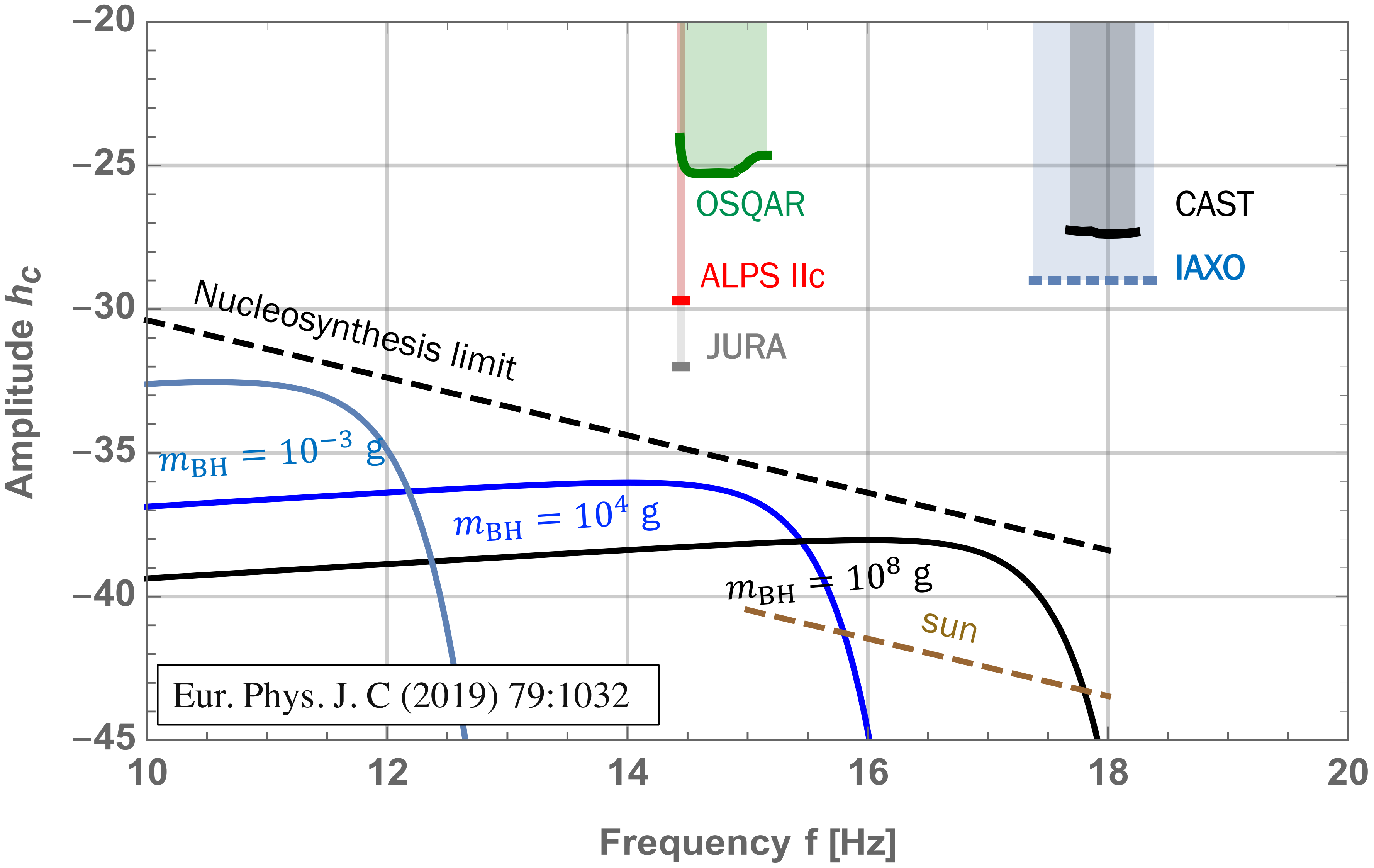






$$h_c^{\mathrm{min}}(0,\omega^*) \simeq 2.8\times 10^{-16}\sqrt{\left(\frac{1}{\mathcal{F}}\right)\left(\frac{N_{\mathrm{dark}}}{1\ \mathrm{Hz}}\right)\left(\frac{1\ \mathrm{m}^2}{A}\right)\left(\frac{1\ \mathrm{T}}{B}\right)^2\left(\frac{1\ \mathrm{m}}{L}\right)^2\left(\frac{1\ \mathrm{Hz}}{\Delta f}\right)\left(\frac{1}{\epsilon_\gamma(\omega)}\right)}$$

Prospects



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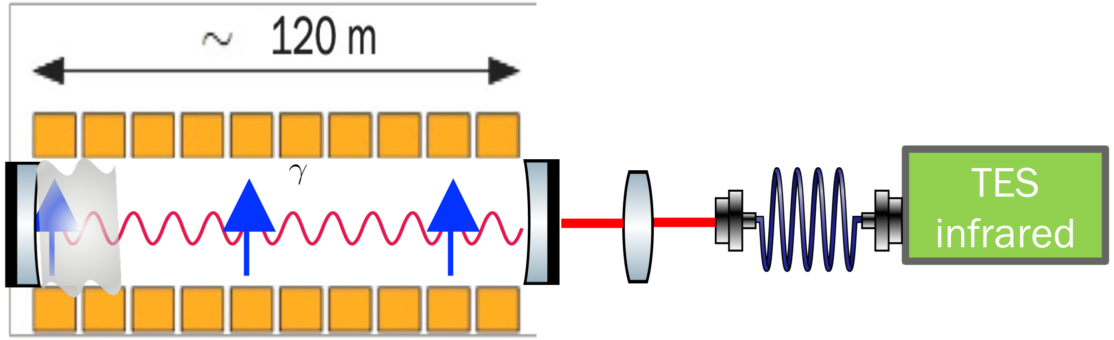
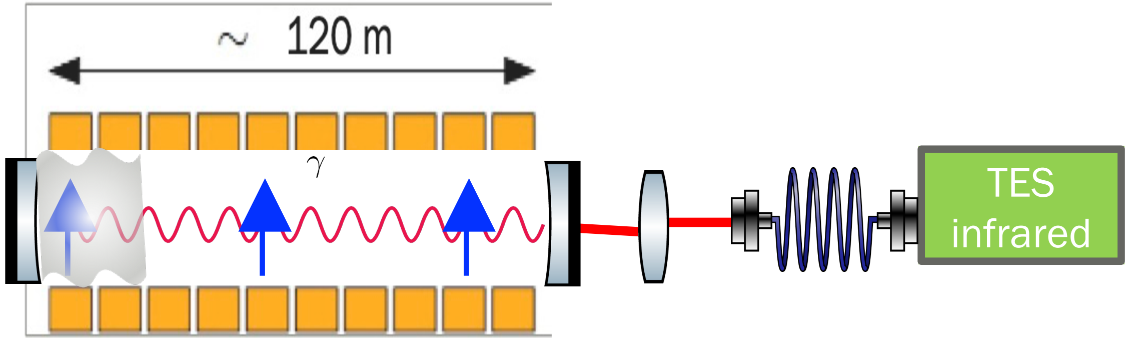
Work in collaboration with: Mike Cruise, Damian Ejlli, Giampaolo Pisano, and Hartmut Grote

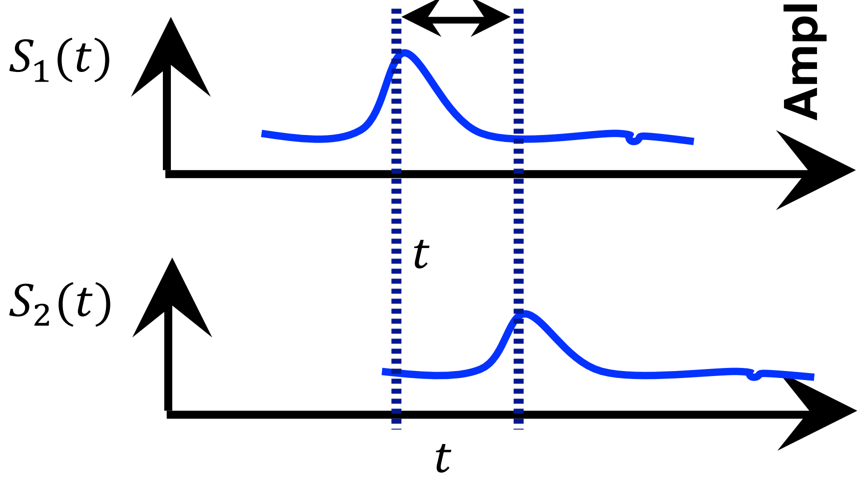

UPGRADES?

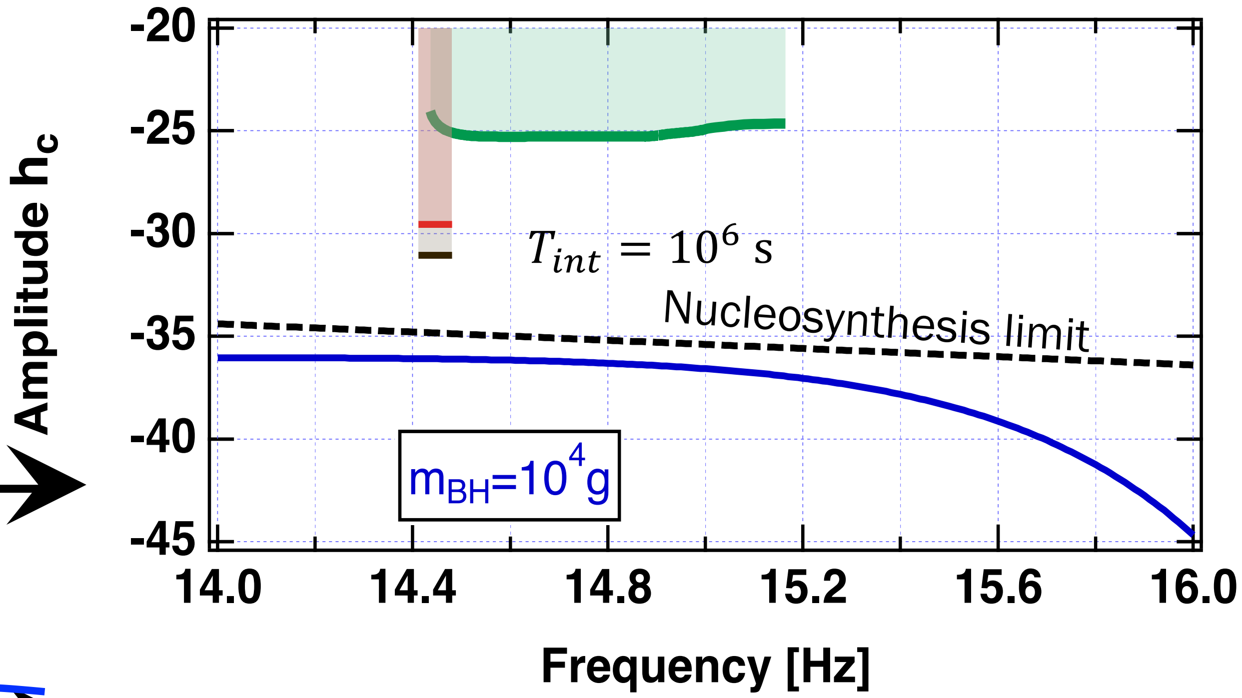
ALPS II: cross correlation





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





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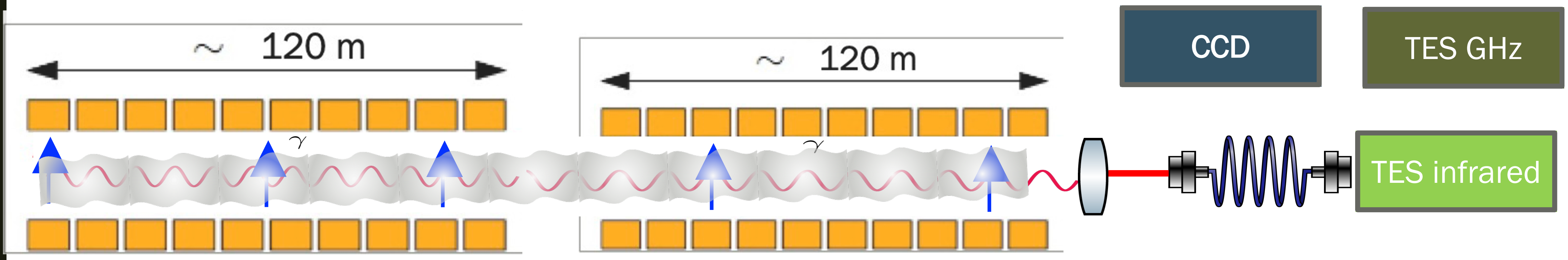
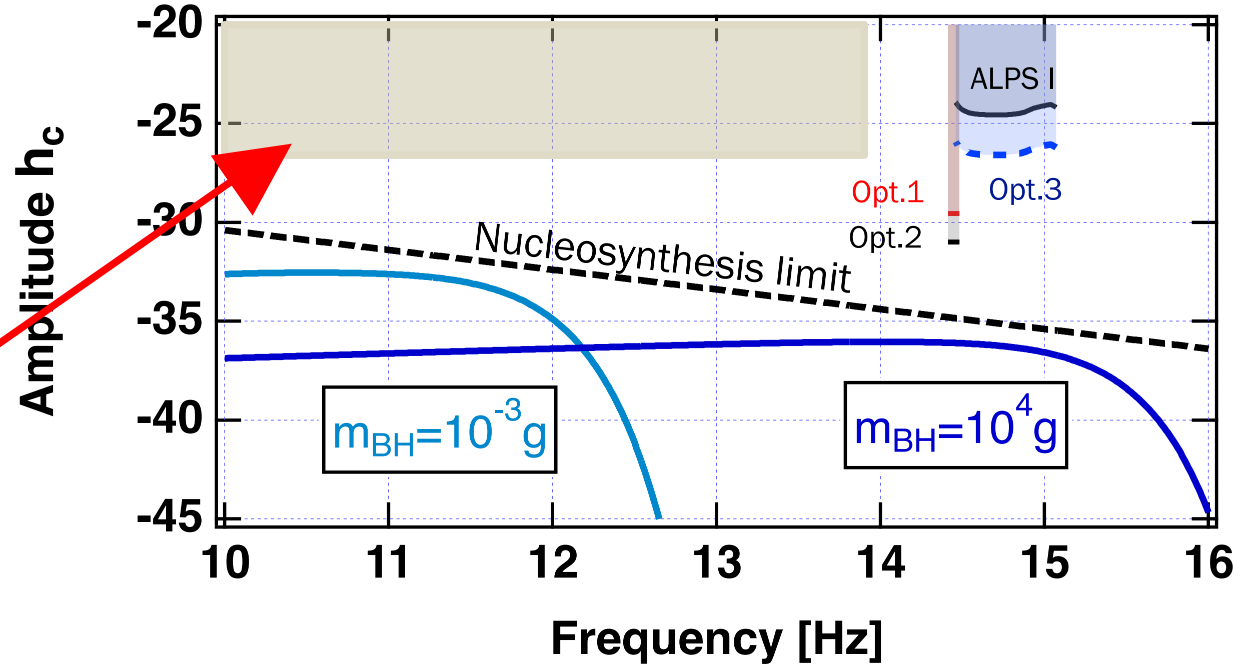
ALPS II without FP cavities



- Double length 2x106 m of the magnetic field.
- Possibility to investigate new frequency regions
- Interesting region in the GHz!



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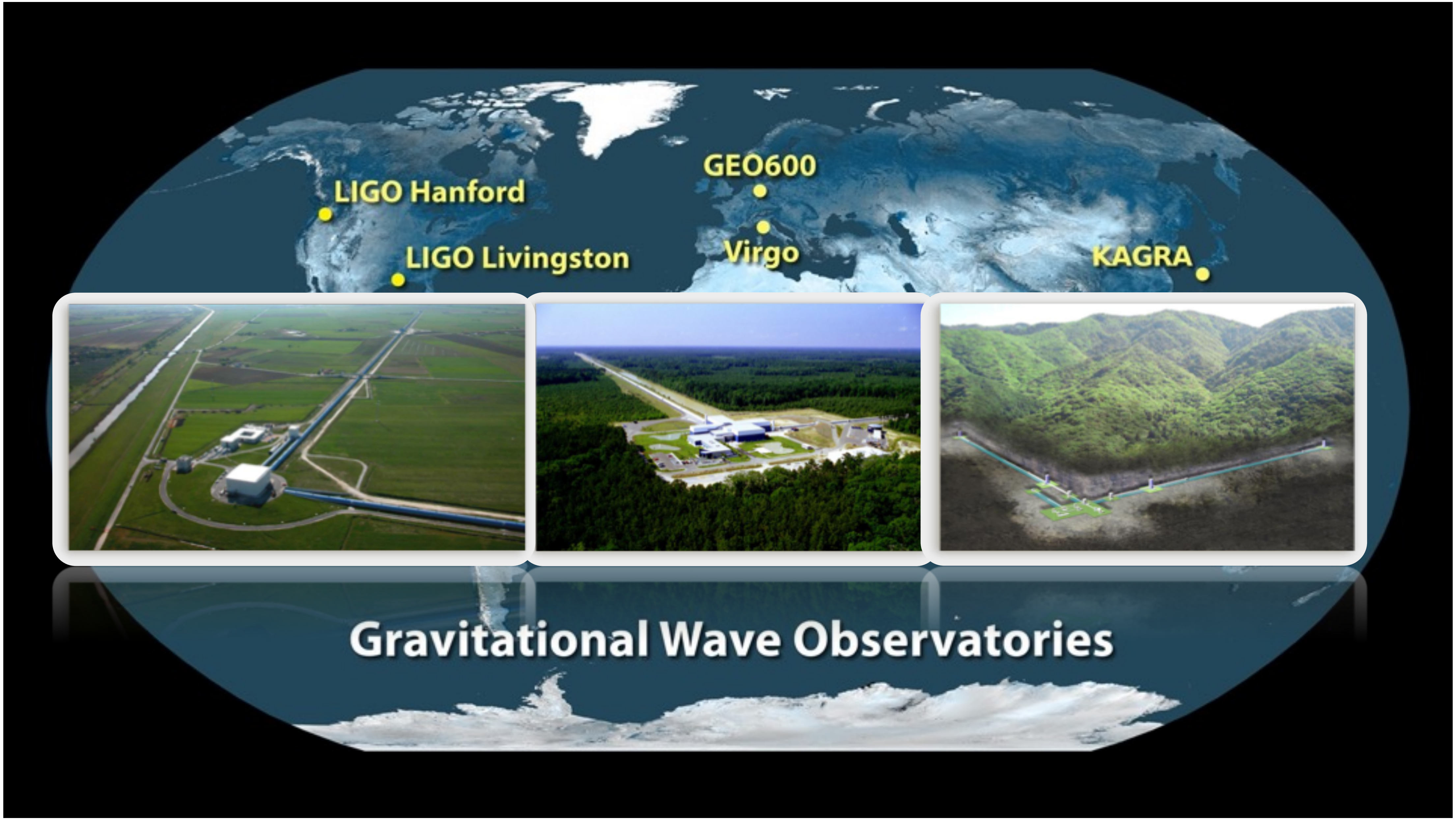
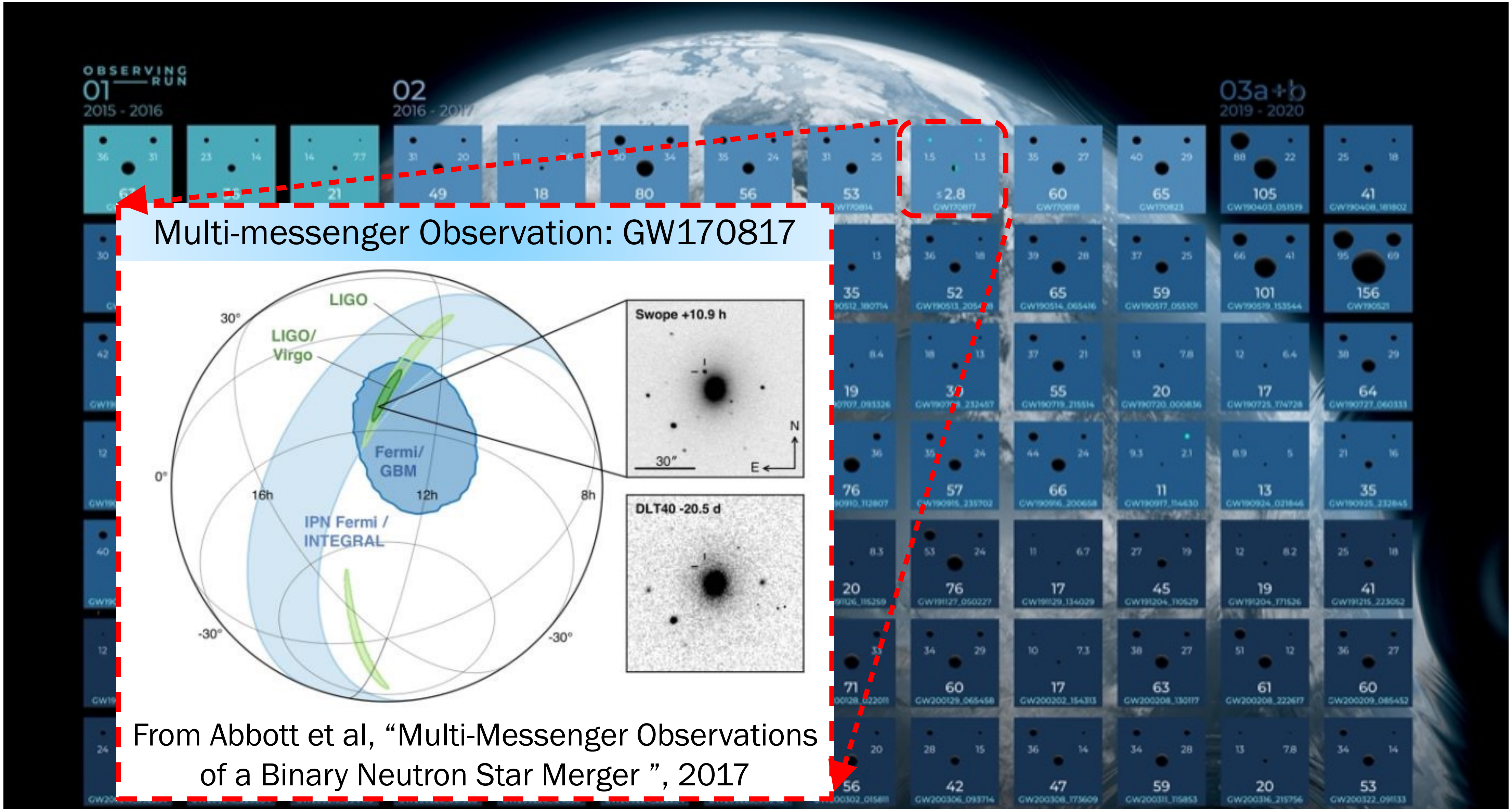
POINTING


GEO600
LIGO Hanford
LIGO Livingston
Virgo
KAGRA
Gravitational Wave Observatories

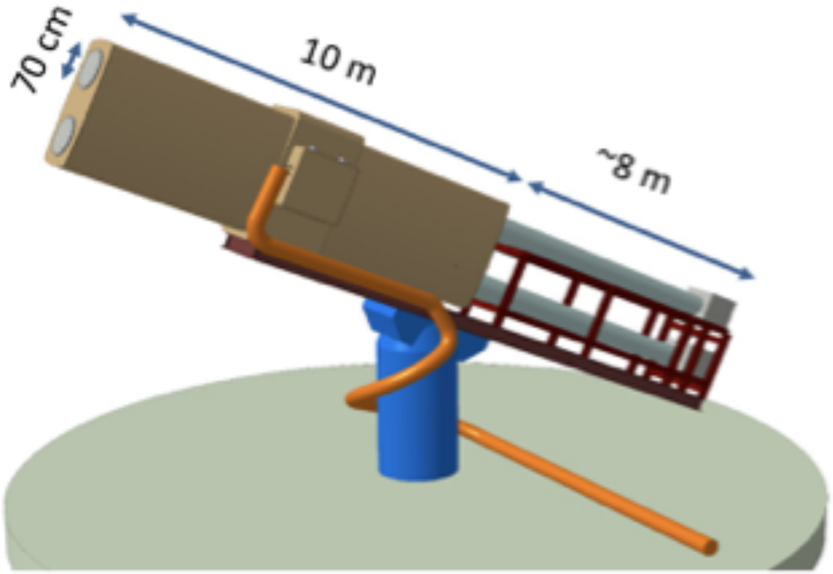


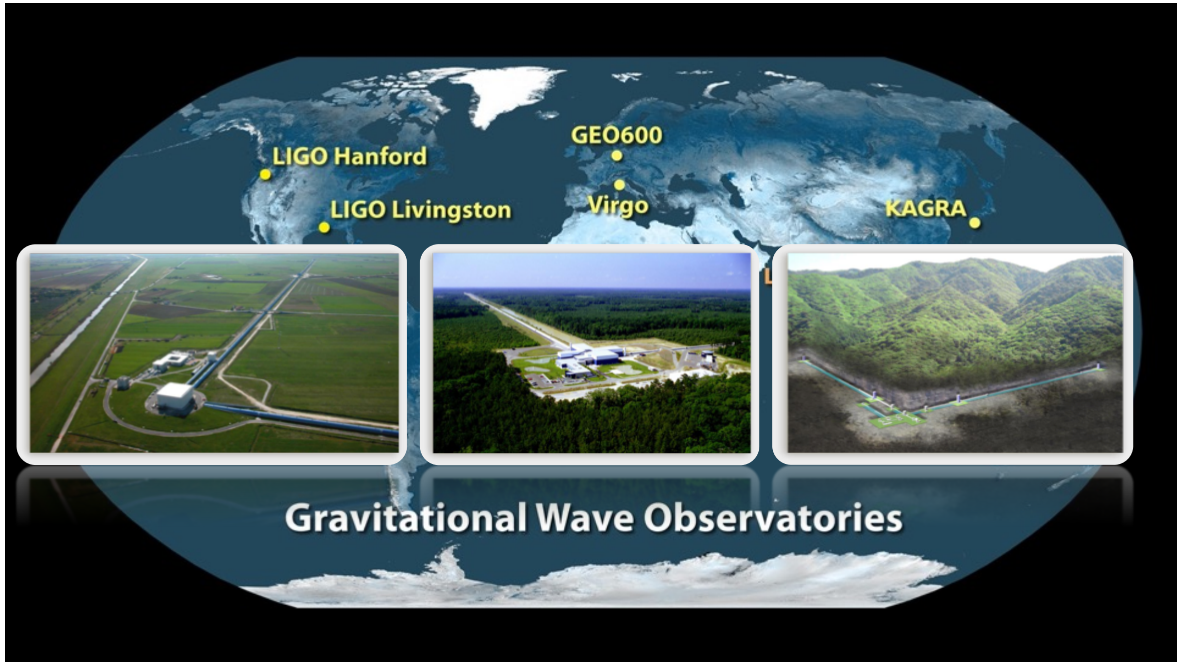
Multi-messenger Observation: GW170817

From Abbott et al, “Multi-Messenger Observations of a Binary Neutron Star Merger ”, 2017

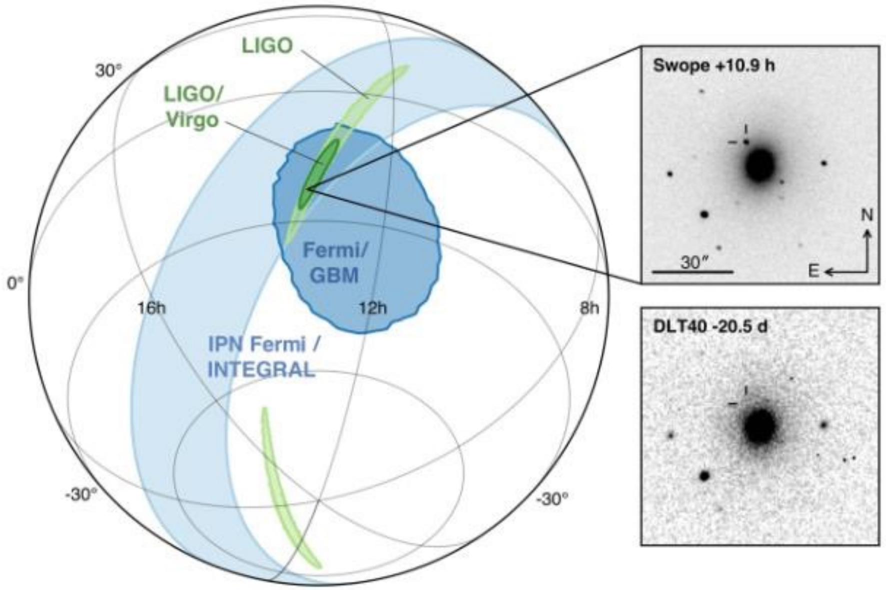
Image credit "Carl Knox (OzGrav, Swinburne University of Technology)"

Baby IAXO, IAXO





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



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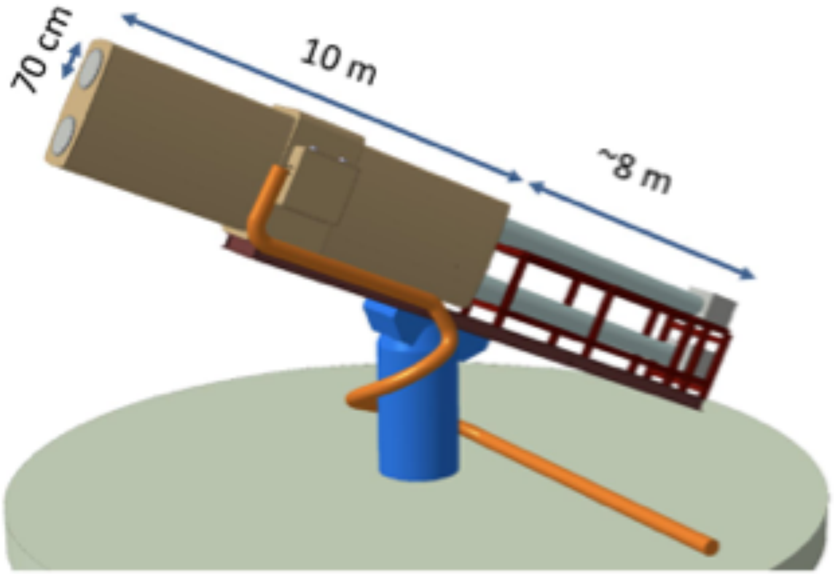
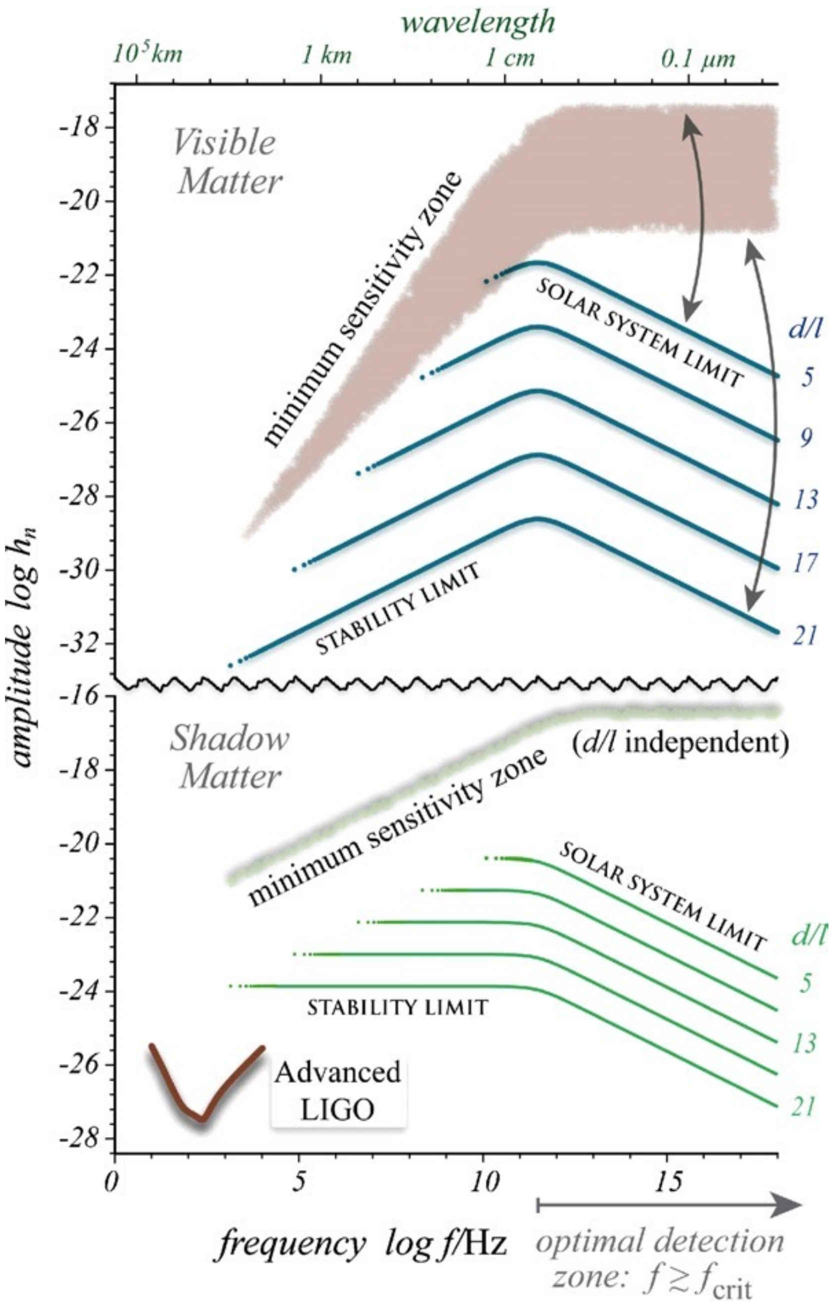
Baby-IAXO/IAXO BH-BH collisions in higher dimensional gravity

Galactic centre





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

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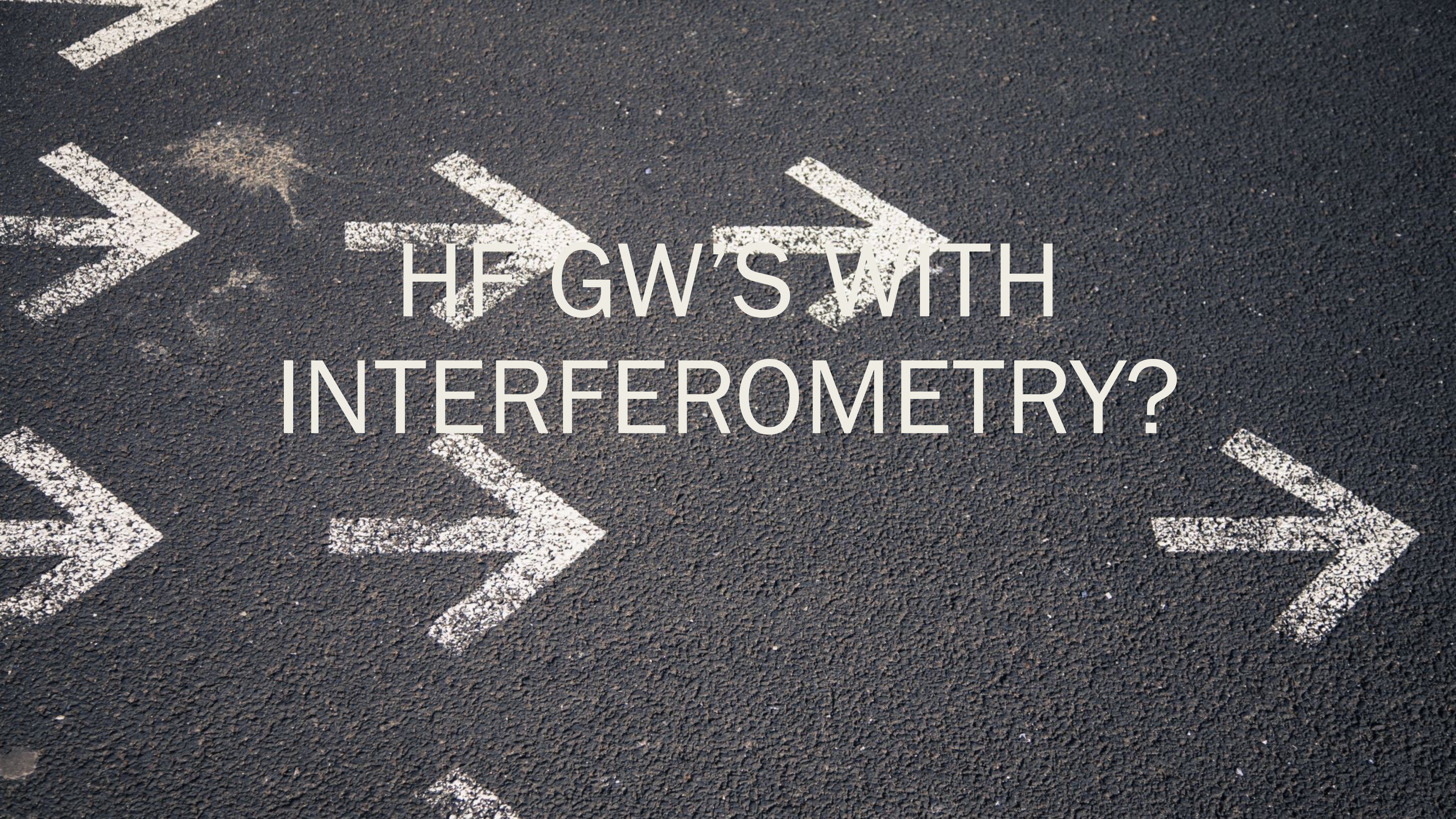
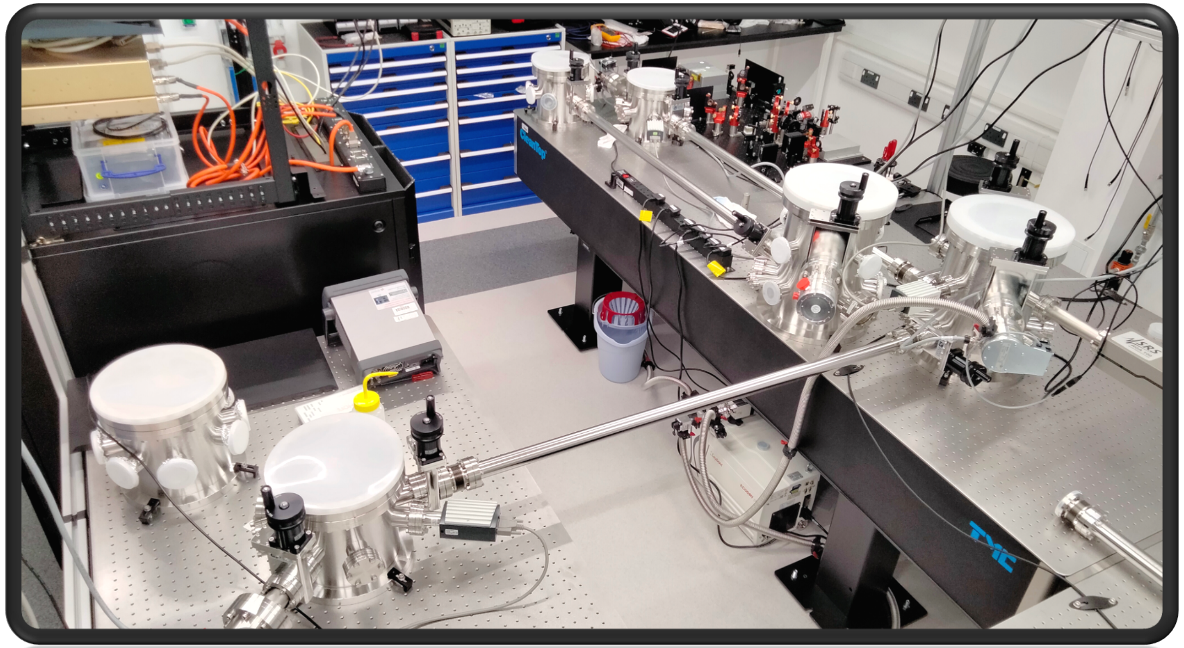
$10 \times$ CAST (B^2L^2A)

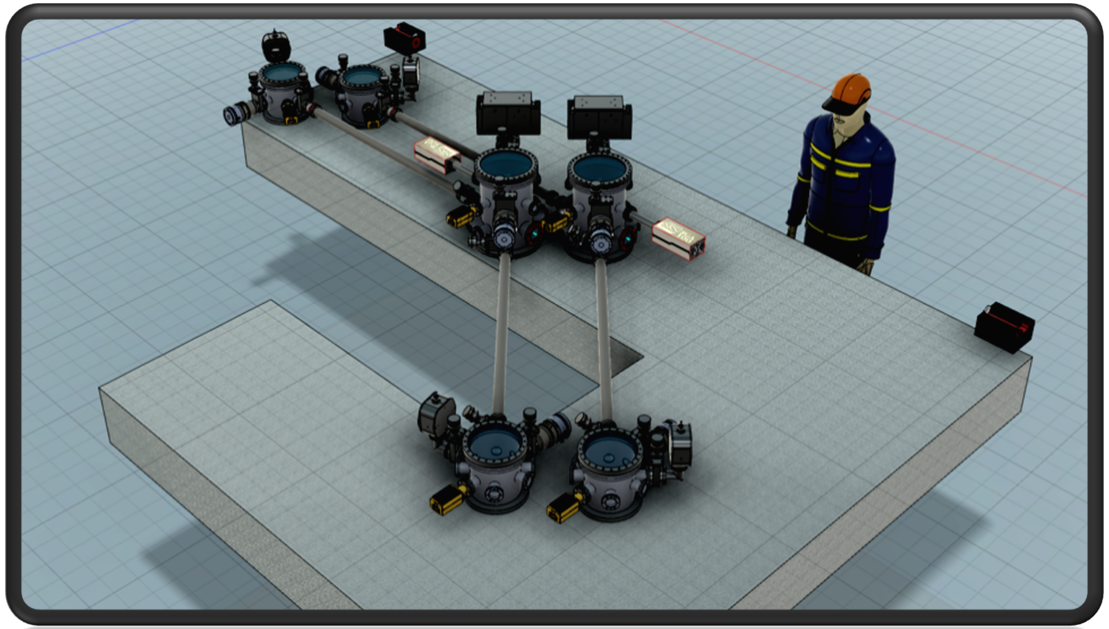
$h_c \sim 10^{-28}$ @ $10^{17} - 10^{18}$ Hz


HF GW'S WITH
INTERFEROMETRY?

Co-located interferometry up to 250 MHz at Cardiff University

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





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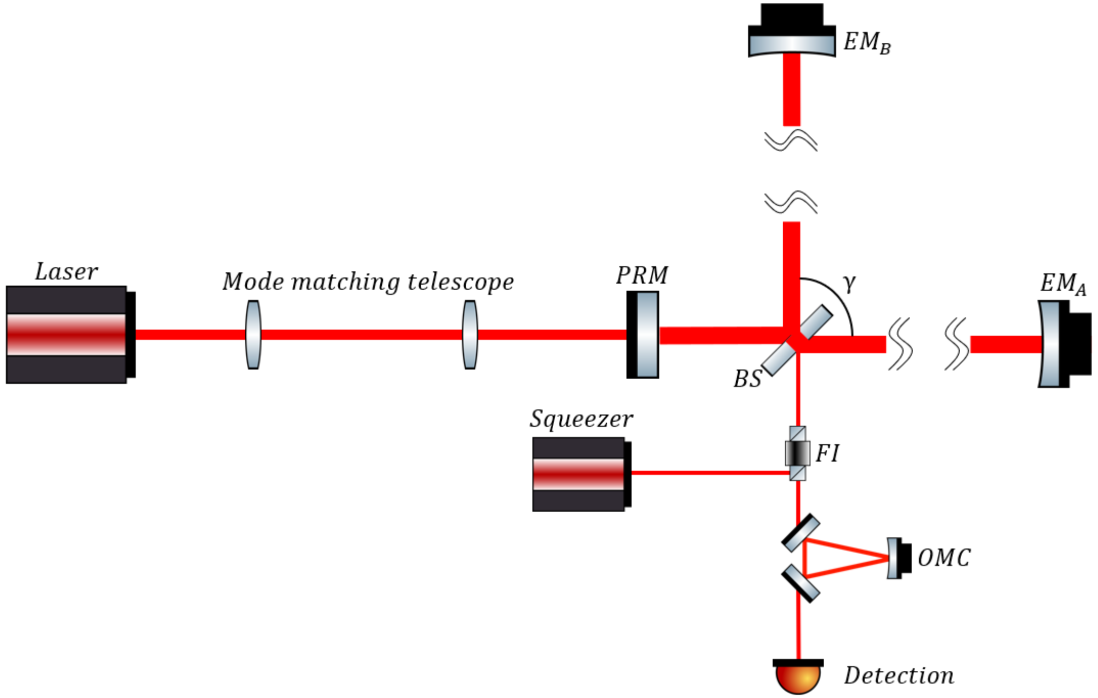
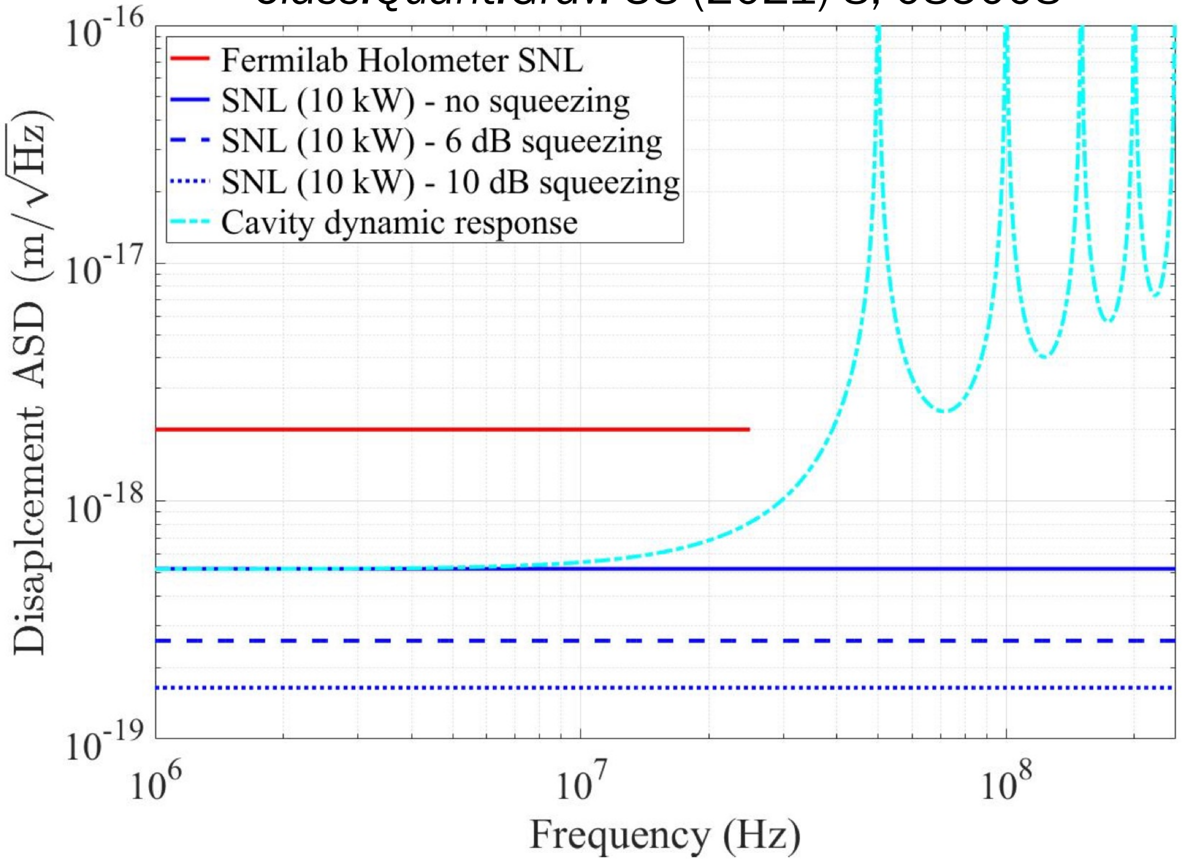
QI
Quantum-enhanced Interferometry for New Physics

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 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