Universität Hamburg
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CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

DESY.

High Frequency Gravitational Wave Detection With SRF Cavities

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with

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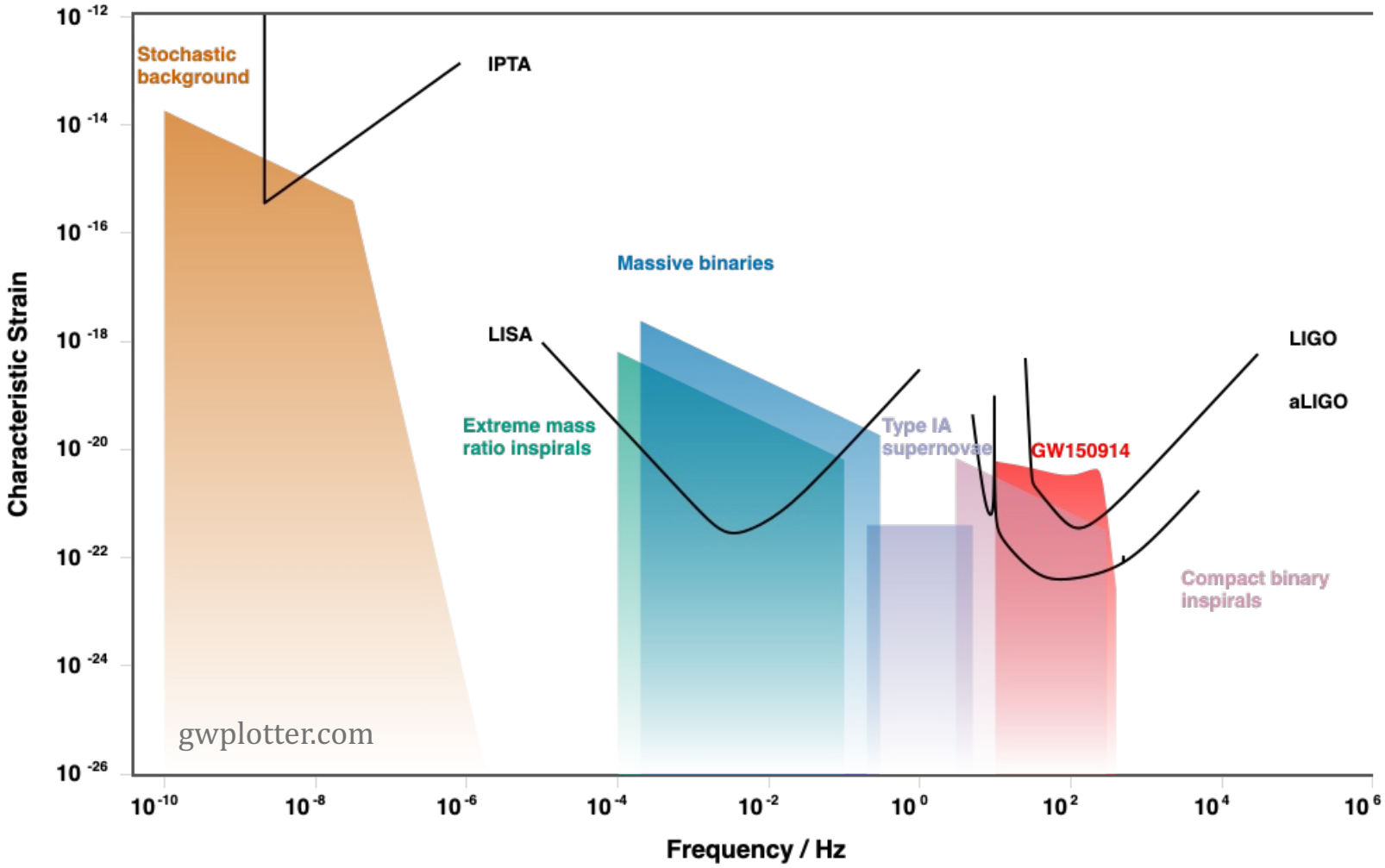
Andreas Ringwald and Marc Wenskat

Outline

- Why care about high frequency gravitational waves?
- RF cavities for gravitational wave detection
- Our project in Hamburg

Why Bother With High Frequency Gravitational Waves?

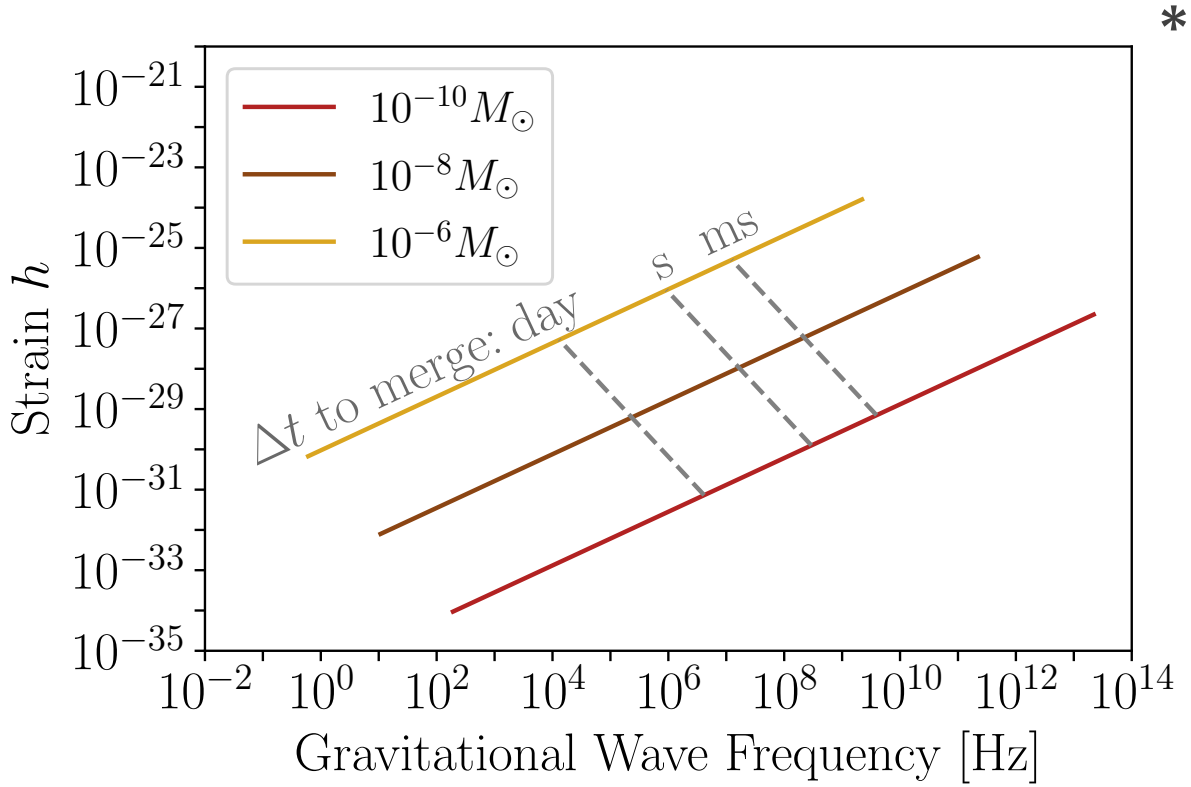


?

High Frequency Compact Binaries

Primordial Black Holes (PBHs)

- Often too **light** to originate from star
- Created by **density fluctuations** in the early universe
- Can solve **Dark Matter** Problem with Standard Model particles
- Hypothetical!

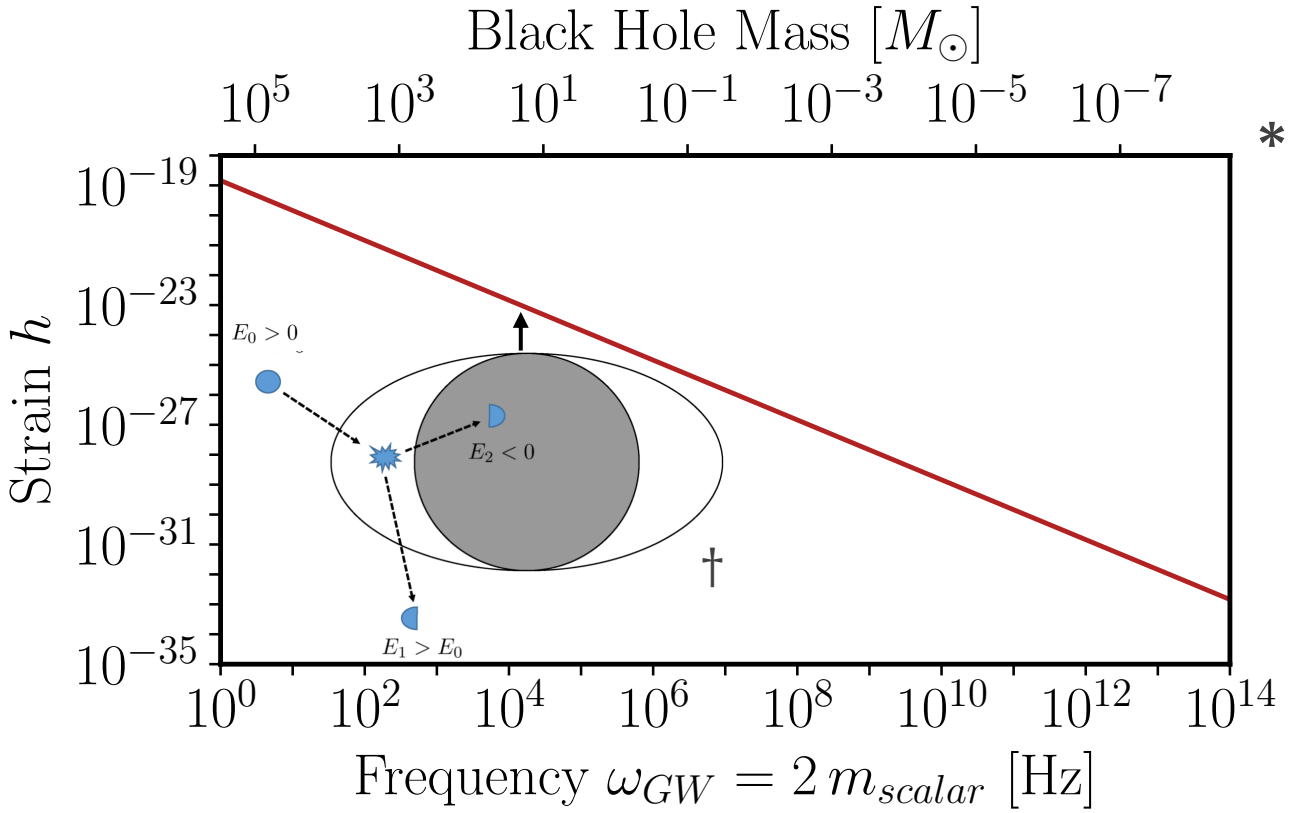


* *Assumes distance $\mathcal{O}(kpc)$ s.t. observing one merger per year is expected (see Muia 2022: 2205.02153)*

Continuous HF Gravitational Waves

Black Hole Superradiance

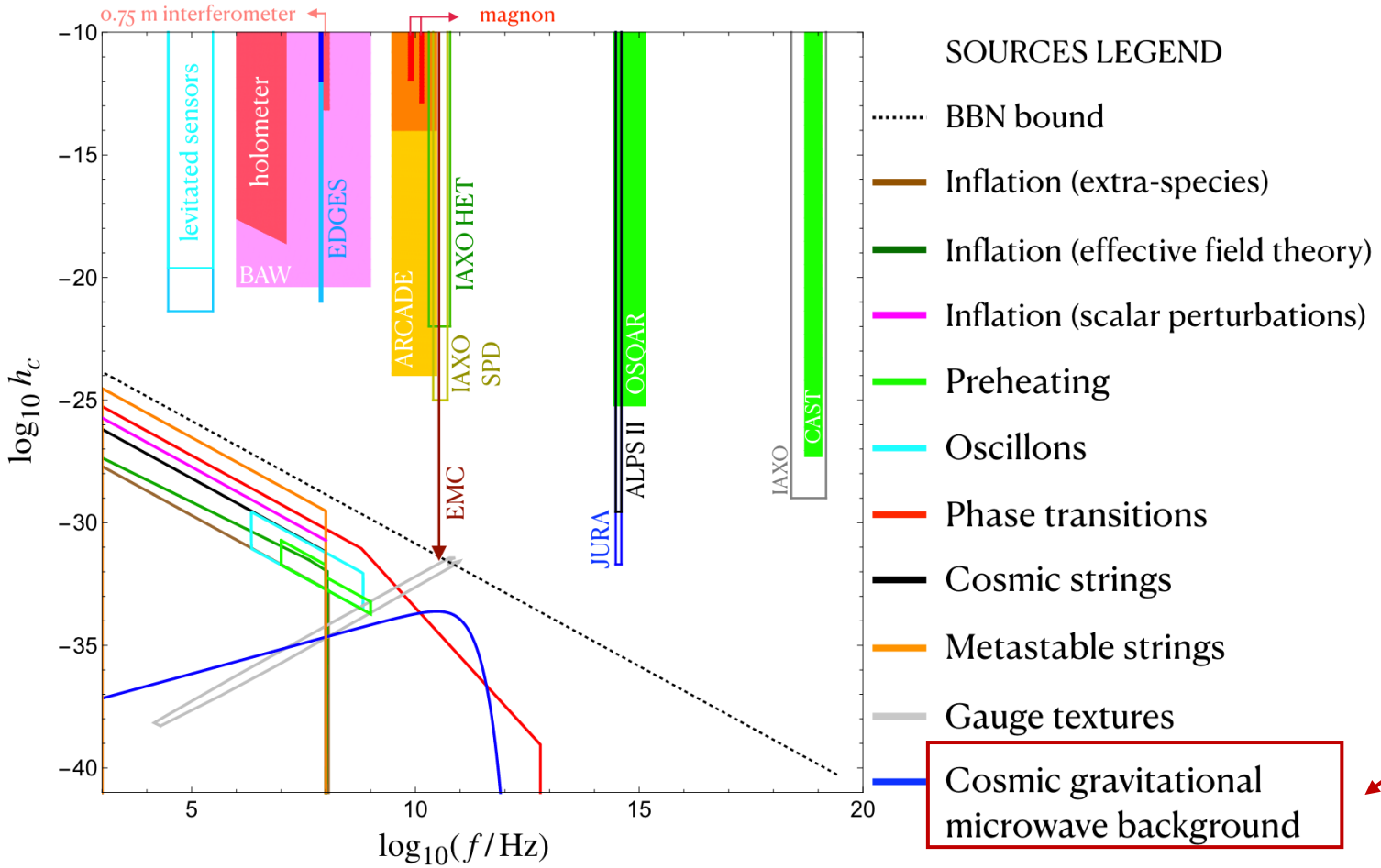
- Created by **light bosonic cloud** (e.g. axions) around **spinning black holes**
  $\phi + \phi + \mathrm{BH} \rightarrow h_{GW}$
- Frequency tied to black hole mass**:**
  $\omega_{GW} = 0.3\ \mathrm{MHz}\ {}^{M_\odot}/_{M}$
  $\Rightarrow \gtrsim 0.1$ MHz GWs requires primordial BHs
- **Coherent** signal for many years
- Hypothetical!



† *Superradiance: New Frontiers in Black Hole Physics. Springer, 2020*

* *Same distance assumption as last slide + further assumptions about e.g. spin of black hole (see Berlin 2023: 2303.01518)*

The Future of HFGWs: Cosmological Backgrounds

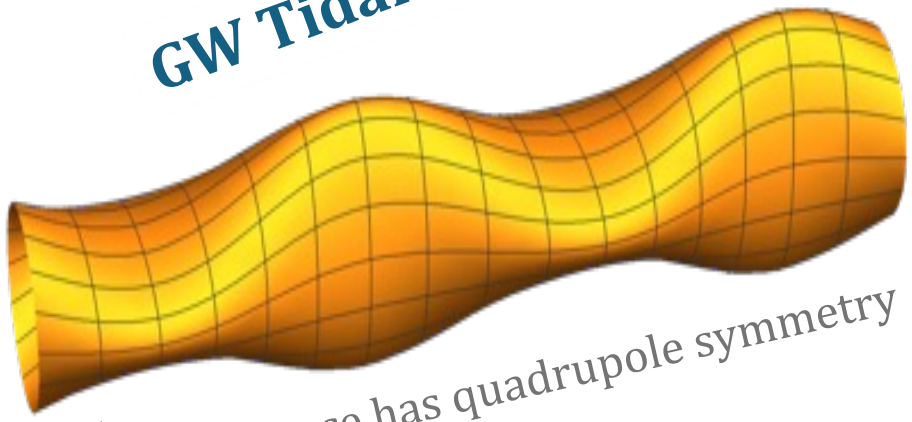


→ Aggarwal et al. 2011.12414

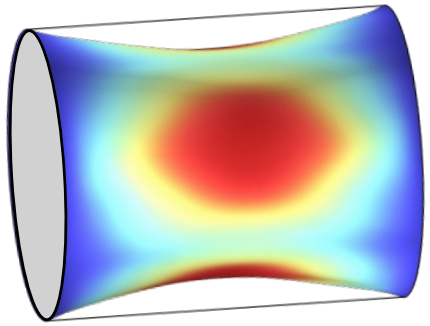
Standard Model Prediction!
→ Ringwald et al. 2011.04731

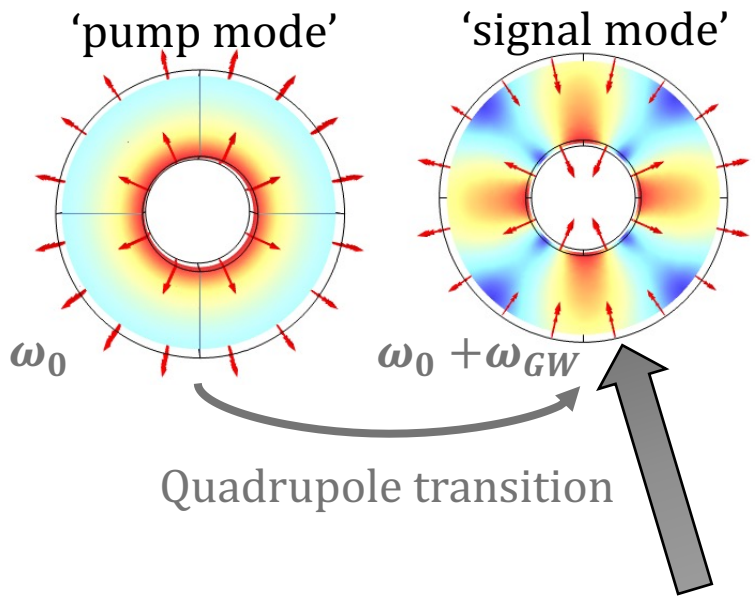
RF Cavities as ‘Weber Bars’

GW Tidal Force → **Shakes Cavity Walls** → **Changes EM Modes in Cavity**



GW Force has quadrupole symmetry



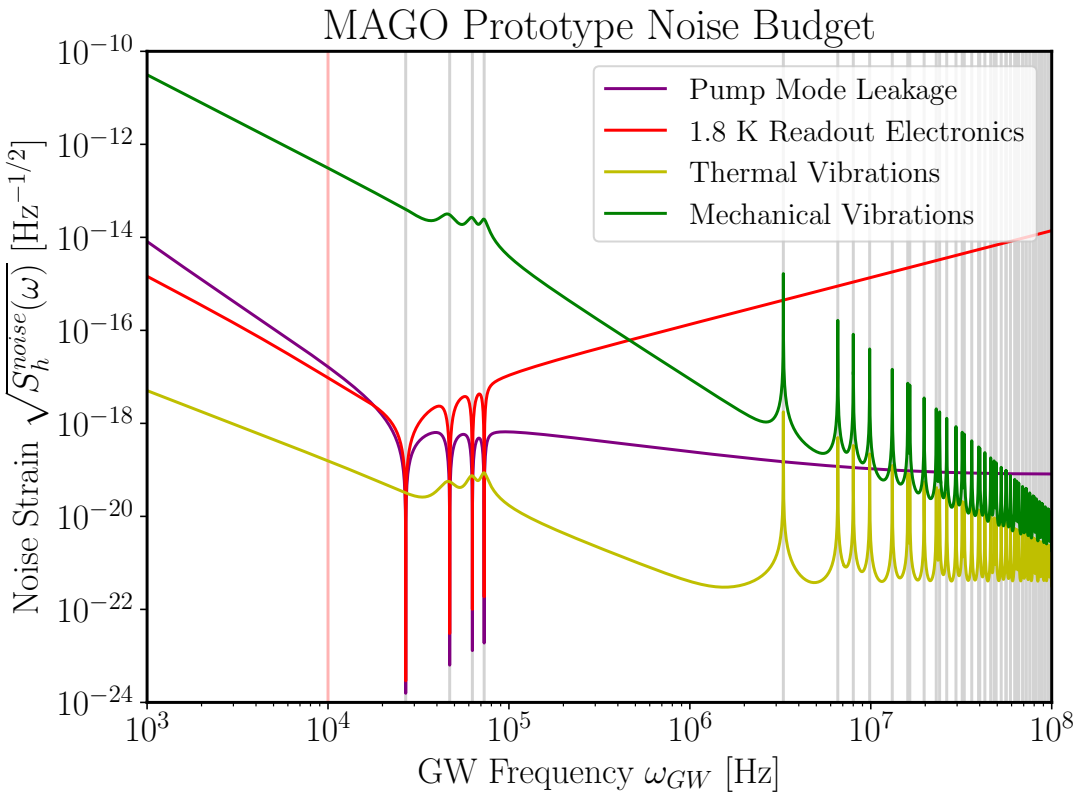


GW source

Graviton → Phonon → Photon

GW signal

How to Make the Experiment Work

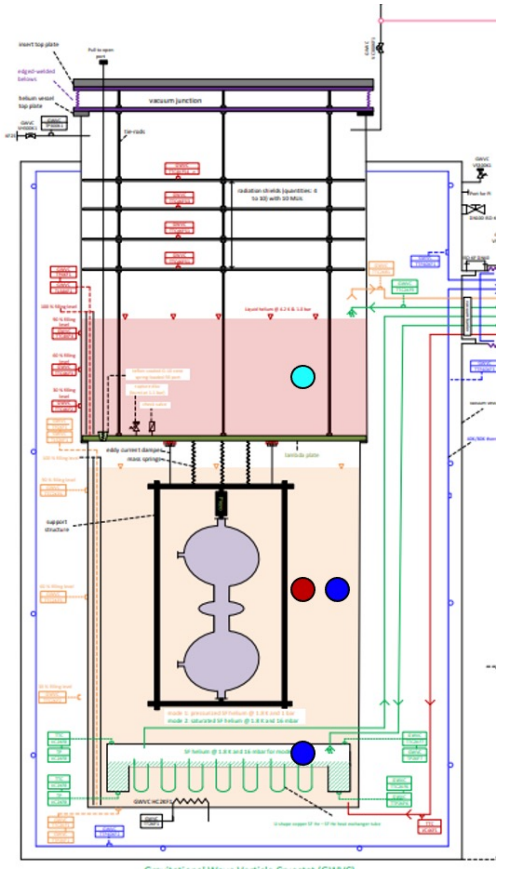


Signal Power
→ Cavity resonators with high Q

Thermal Noise
& **Thermal Vibrations**
→ Cryogenic Temperatures

Vibrations
→ Suspension System & Isolation

Pump Mode
→ Dedicated RF system



The MAGO Cavity

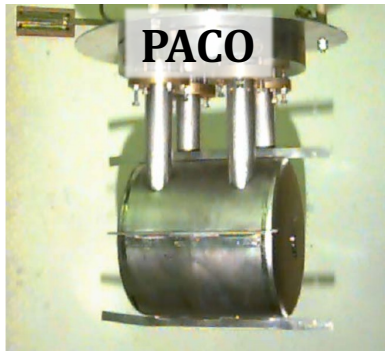
- Original idea developed & tested 'PACO'

→ Bernard et al. arXiv:0004031 (2000)

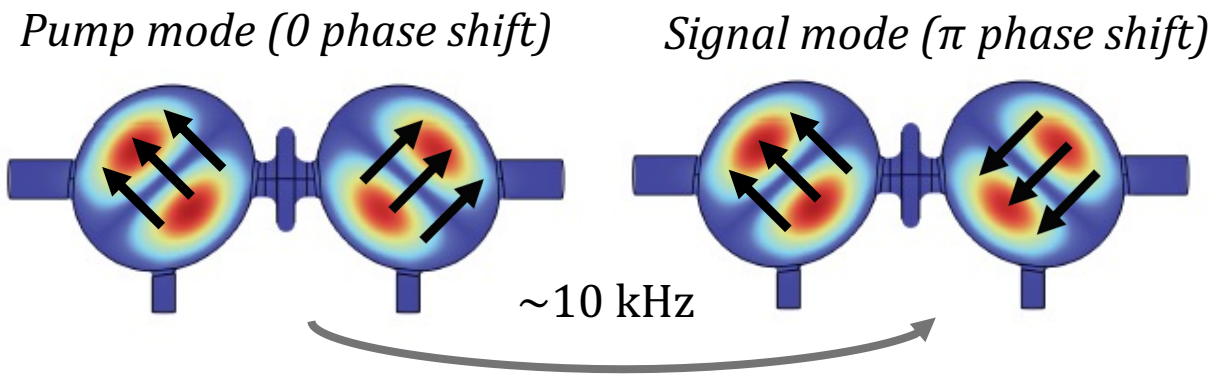
- Improved prototype 'MAGO' built in early 2000s

→ Ballantini et al. arXiv:0502054 (2005)

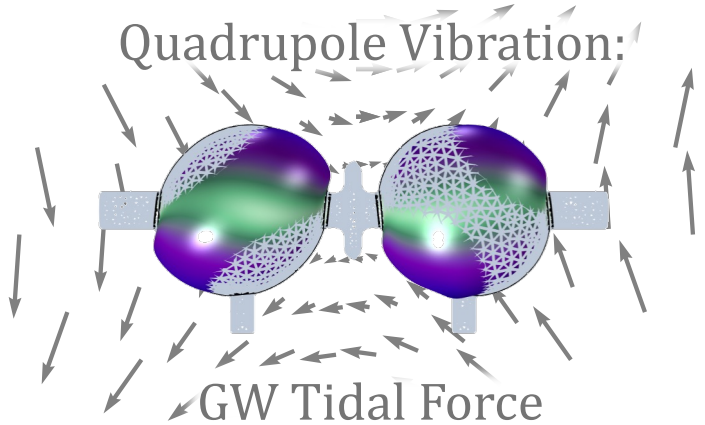
- Never treated and tested (until now)



EM Modes:



Quadrupole Vibration:



The MAGO Revival

- Renewed interest in MAGO cavity for *high* frequency GWs
  → Berlin et al. arXiv:2303.01518 (2023)
- Project now started in Hamburg & at Fermilab
- MAGO cavity has been tuned, treated and prepared for cold testing
- Design of RF system, cryostat & suspension system is under way
- Goal is to have a first ‘physics run’ with the MAGO prototype
- In the future: design our own cavity for improved sensitivity

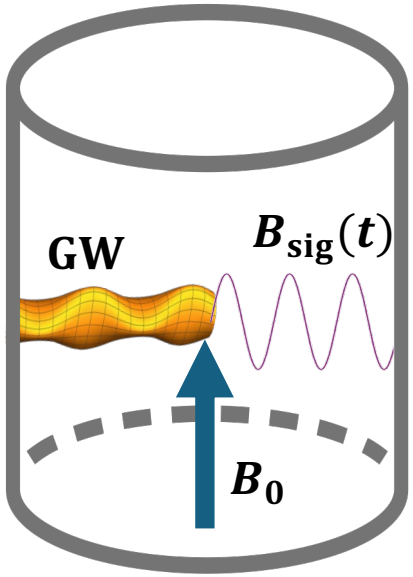
Takeaways

- High frequency GWs are messengers of new physics
- RF cavities are uniquely suited tools to detect them
- The MAGO prototype cavity will search for GWs with 10 – 100 kHz
- A future experimental design will hold even more potential

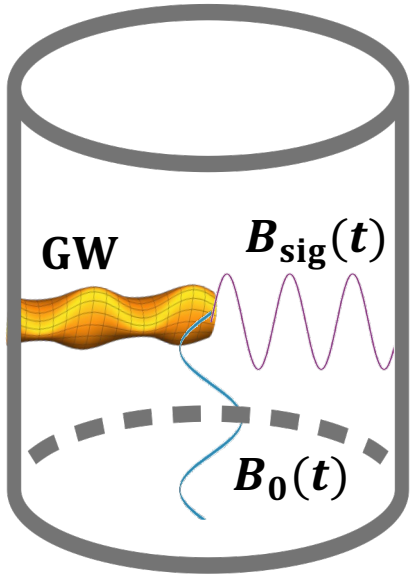
Backup

RF Cavities as Graviton-Photon Converters

Static B Field (c.f. ADMX, HAYSTAC)

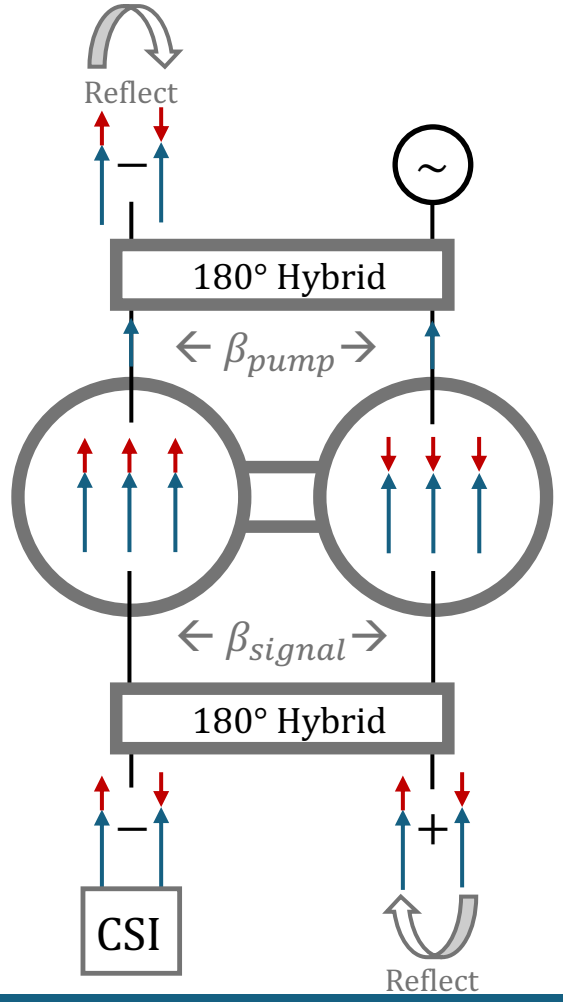


Up-Conversion of Pump Mode



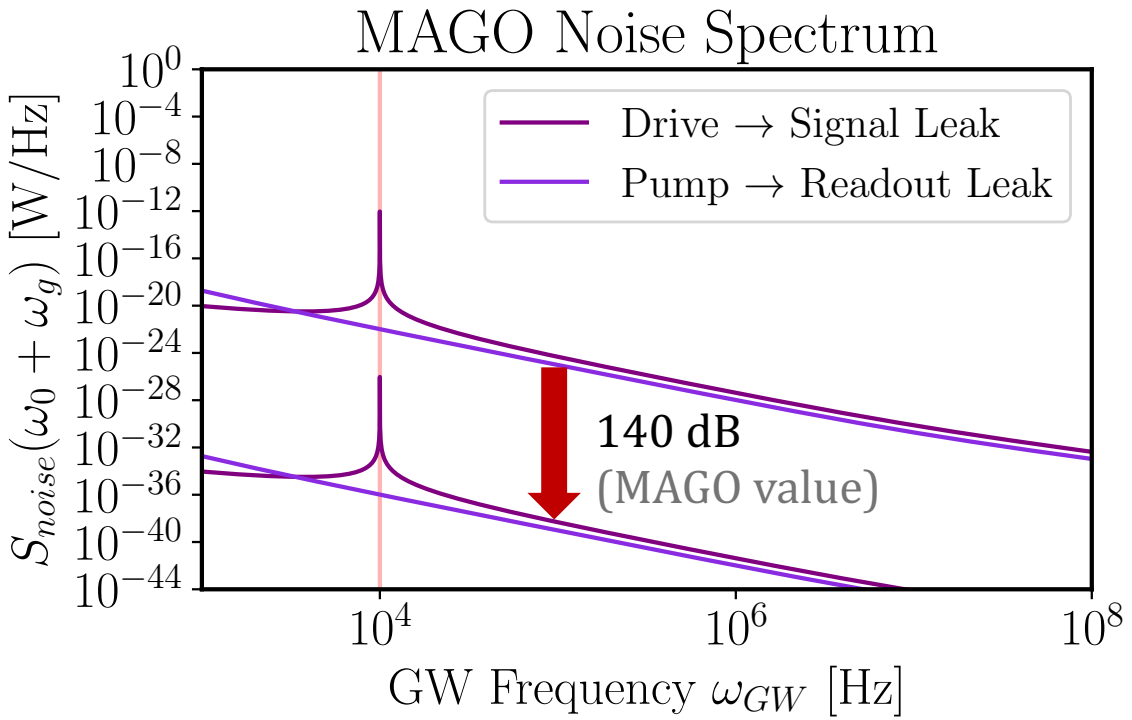
'inverse Gertsenshtein effect'

Noise From The Pump Mode Suppression
→ Exploit the mode symmetries



→ Suppresses driving the *signal mode*

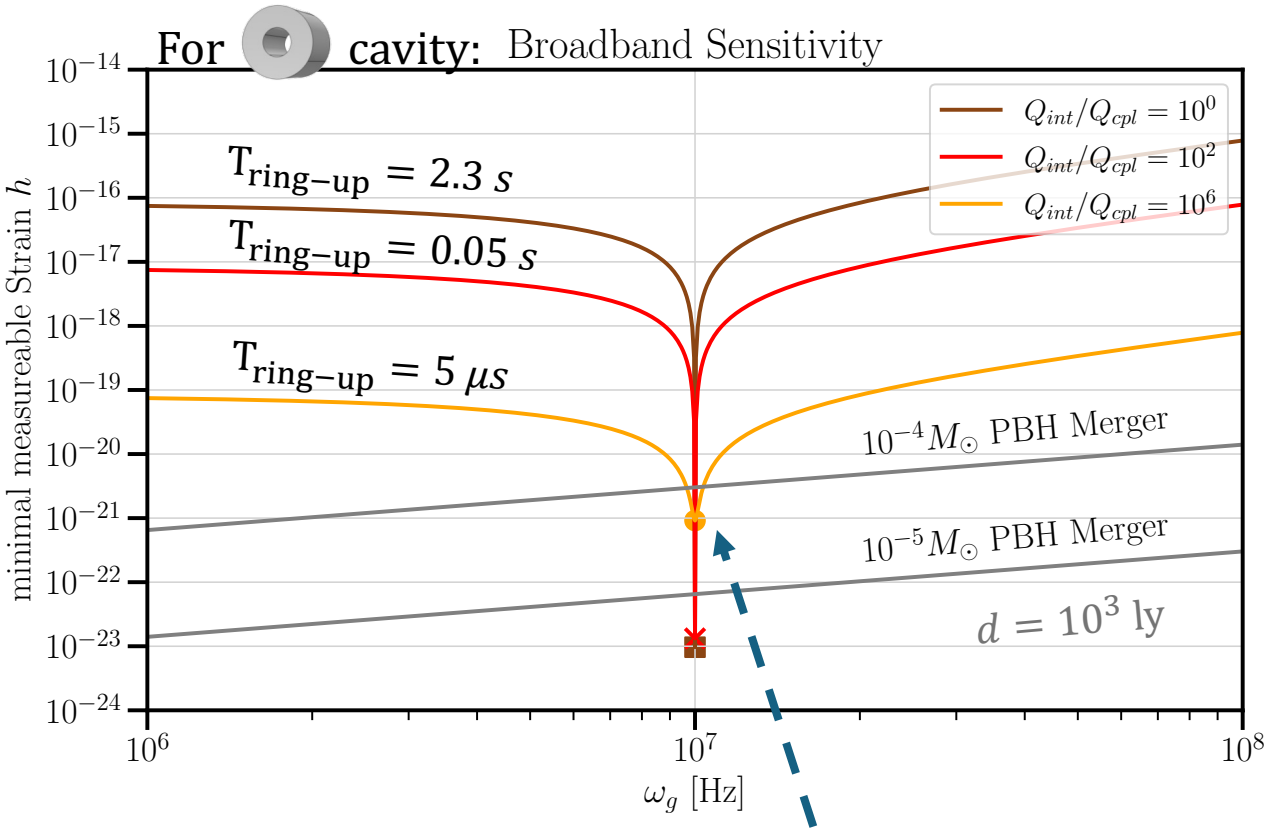
→ Suppresses reading out the *pump mode*



Extra benefit:
Can couple to pump & signal mode independently
→ β_{pump} and β_{signal} can be different

Future Sensitivity To Predicted Sources

PBH Mergers: Strongly Overcouple



Signal time in orange bandwidth: 13 μs

Superradiance: Critical Coupling