A Superconducting, Levitated Detector of Gravitational Waves

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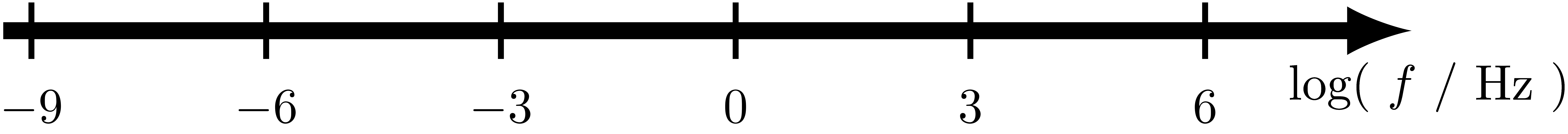
Gravitational waves

$$g_{\mu\nu}(t) = \eta_{\mu\nu} + h_{\mu\nu}(t)$$
$$h_{\mu\nu}(t) = h_{\mu\nu}\, e^{2\pi i f t}$$

$$\mathscr{L}_{\text{int}} = h_{\mu\nu} T^{\mu\nu}$$



sub-kHz GWs

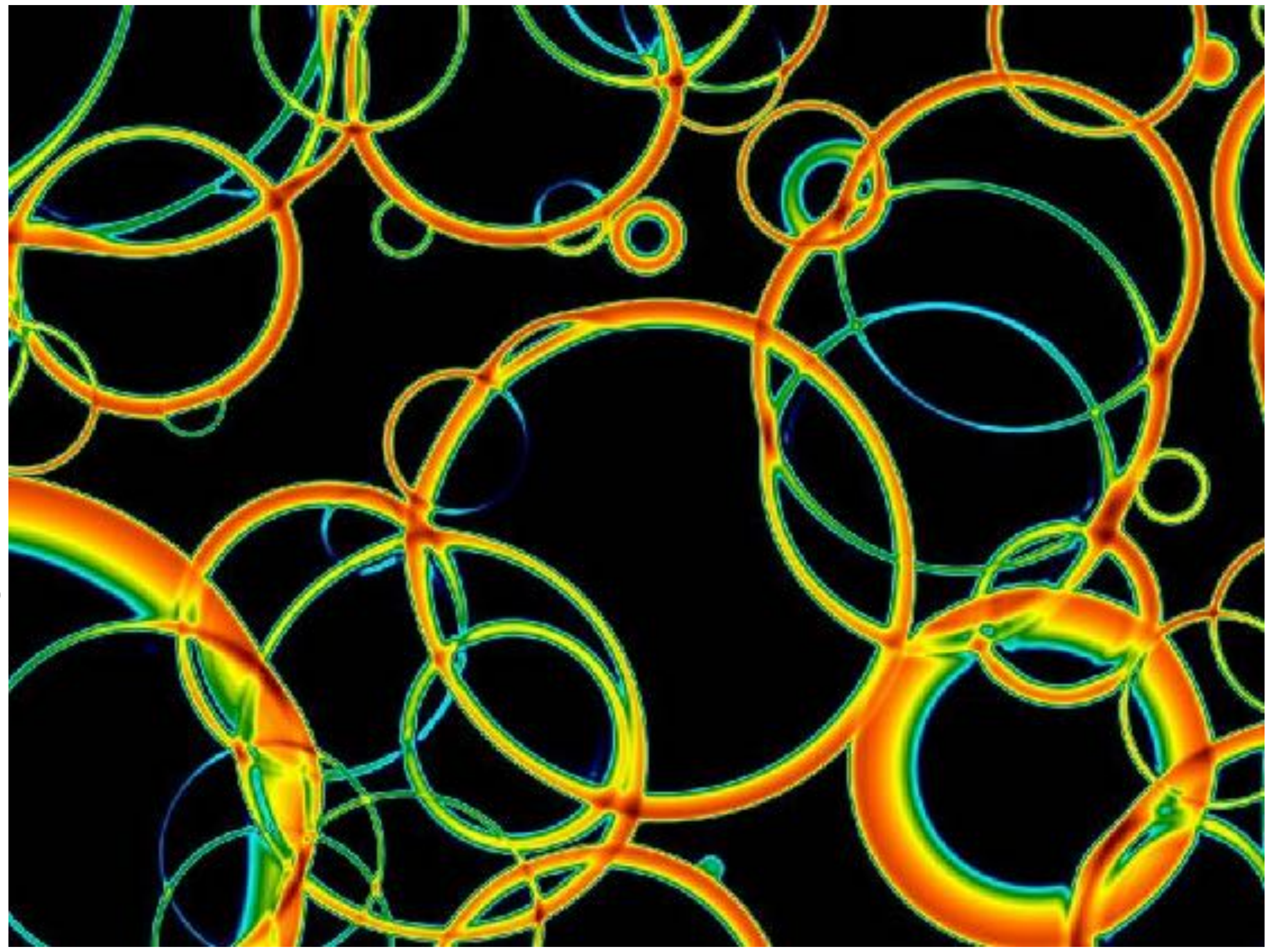


Image: D. Weir

Cosmological
phase transitions?

Core-collapse
supernova

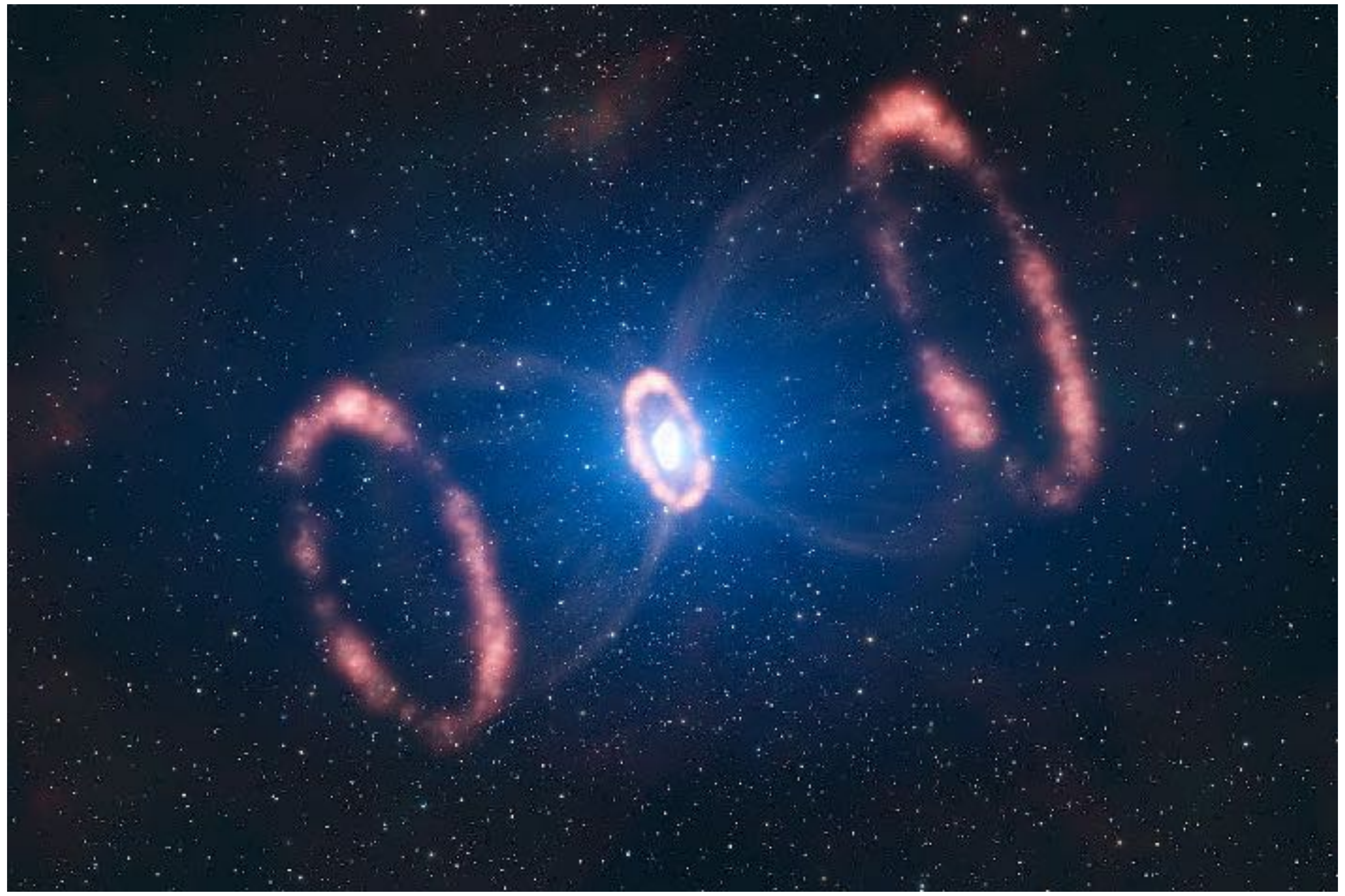


Image: ESO/L. Calçada

Solar mass BH
mergers

SMBH mergers

Inflation?

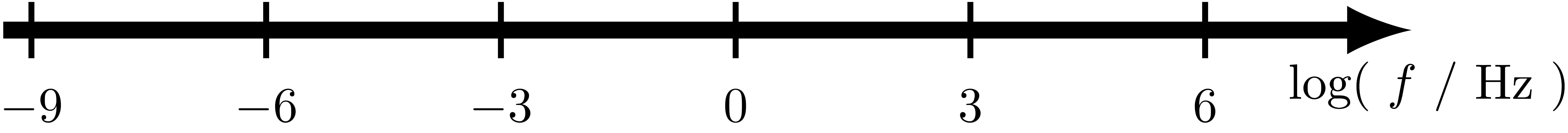
-9 -6 -3 0 3 6 $\log(\ f\ /\ \mathrm{Hz}\ )$

High frequency GWs

Superradiant axion clouds?

QCD phase transition
in NS mergers?

PBH mergers?



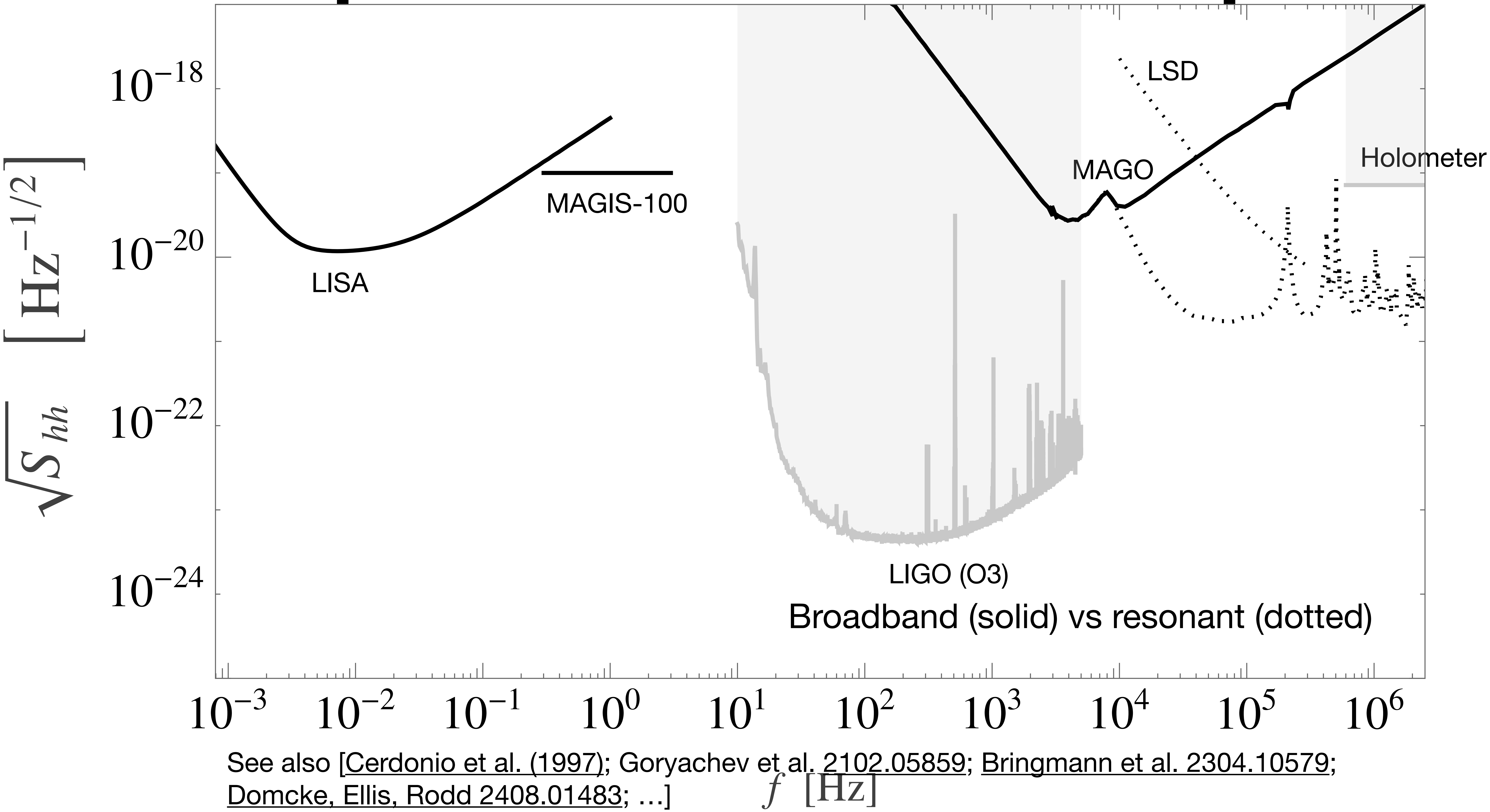
Axion superradiance

$$m_a \sim \frac{1}{R_{\rm BH}}$$

$$f \sim 2m_a \approx 30\,\text{kHz}\left(\frac{M_\odot}{M_{\rm BH}}\right) \qquad h \sim 10^{-22}\,\alpha^7 \frac{\epsilon}{10^{-3}} \frac{10\,\text{kpc}}{r} \frac{M_{\rm BH}}{M_\odot}$$

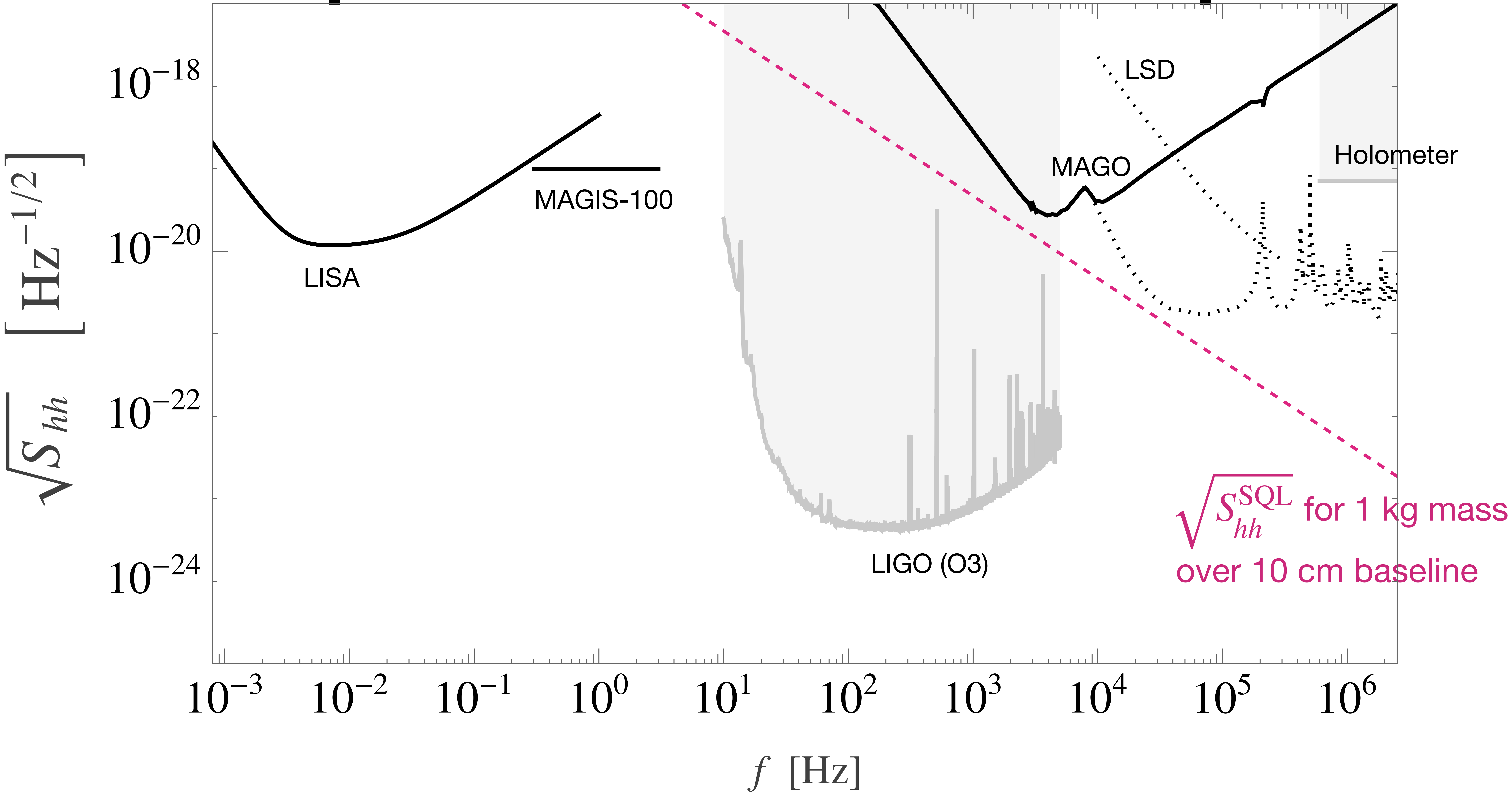
[Arvanitaki, Dubovsky 1004.3558; Baumann et al. 1908.10370; Sprague et al. 2409.03714;…]

Experimental landscape



See also [Cerdonio et al. (1997); Goryachev et al. 2102.05859; Bringmann et al. 2304.10579; Domcke, Ellis, Rodd 2408.01483; …]

Experimental landscape



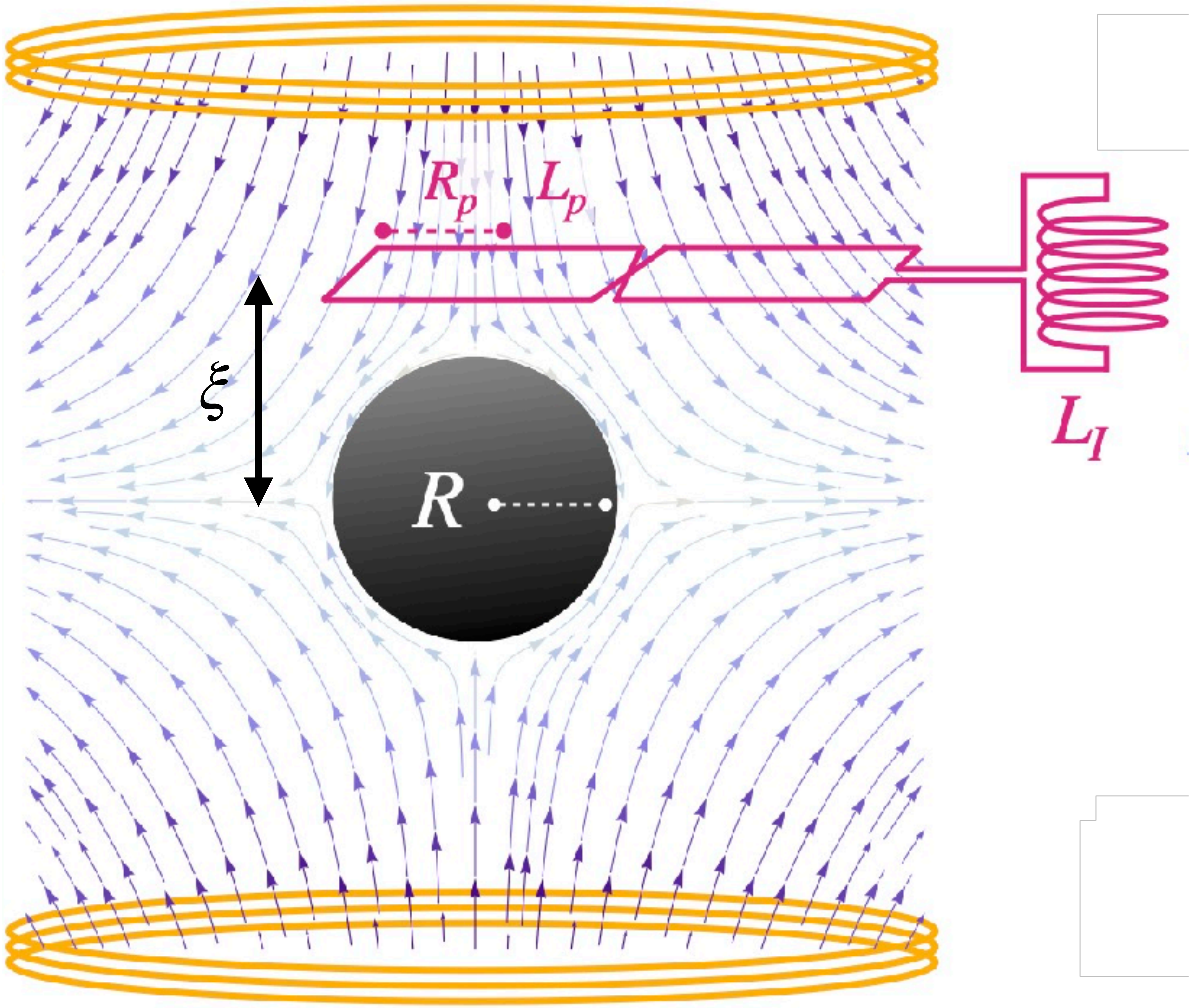
Levitated superconductors

- Levitate a superconducting sphere in a quadrupolar trap

$$H_0 = \frac{\omega_0^2}{4}\mathbf{z}_\perp^2 + \frac{\omega_0^2}{2}z^2, \qquad \omega_0 = \sqrt{\frac{3}{2\rho}b_z}$$

- Magnetic flux through pick-up loop sensitive to sphere-loop separation

$$\Phi_{\rm PUL} = \beta R^2 b_z \times \xi$$



$$\mathbf{B}_0 = b_z\left(\frac{x}{2}\hat{\mathbf{x}} + \frac{y}{2}\hat{\mathbf{y}} - z\hat{\mathbf{z}}\right)$$

[Goodkind Rev. Sci. Instrum. (1999); Griggs et al. PRApplied (2017); Higgins, Kalia, Liu 2310.18398] …

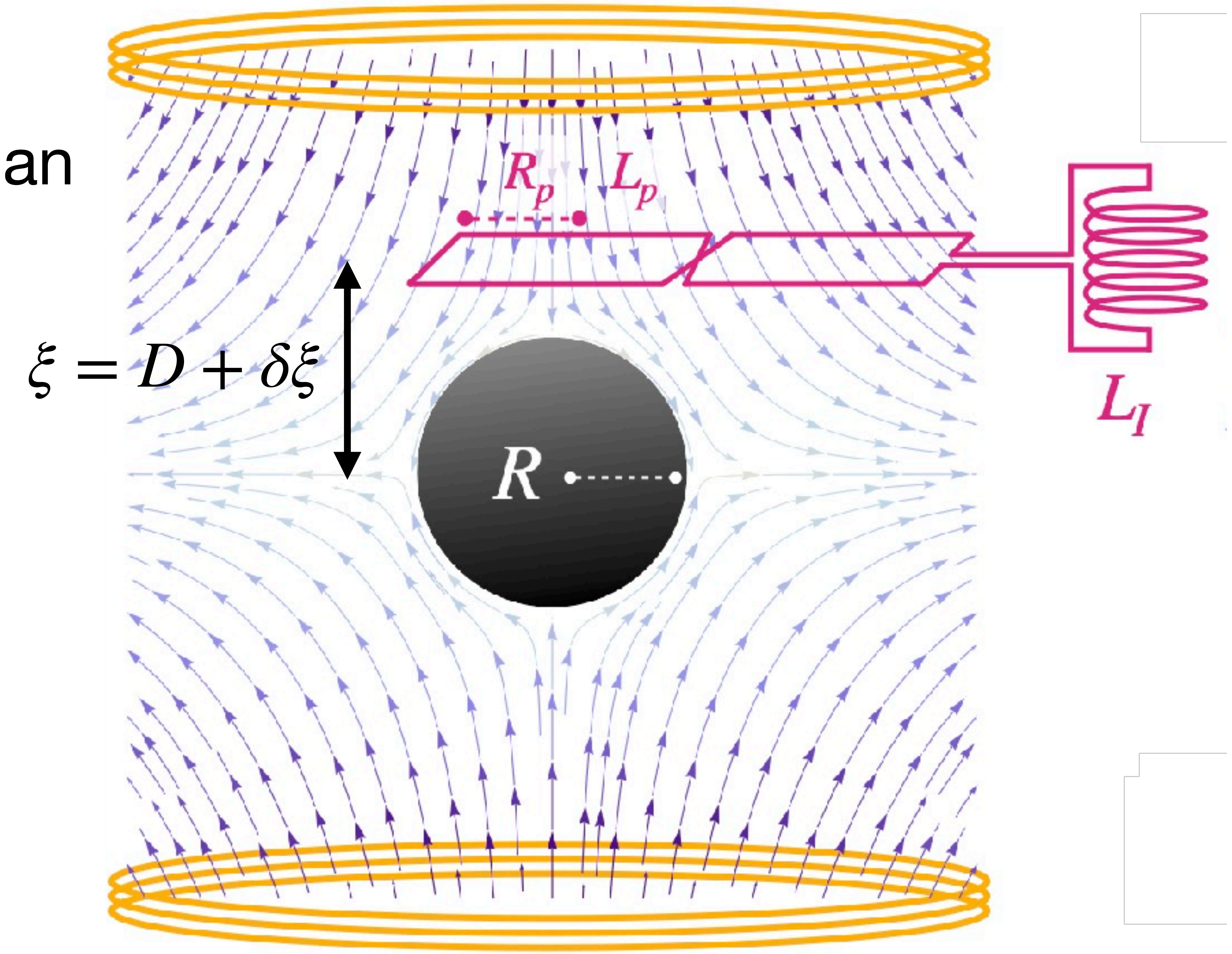
GW force

- In long-wavelength limit of proper detector frame, GW exerts a Newtonian force

$$F_i(\mathbf{x}, t) = \frac{m}{2} x^i \ddot{h}_{ij}(t)$$

- When $\omega_{\rm GW} \gg \omega_0$, an equatorial GW causes a relative acceleration:

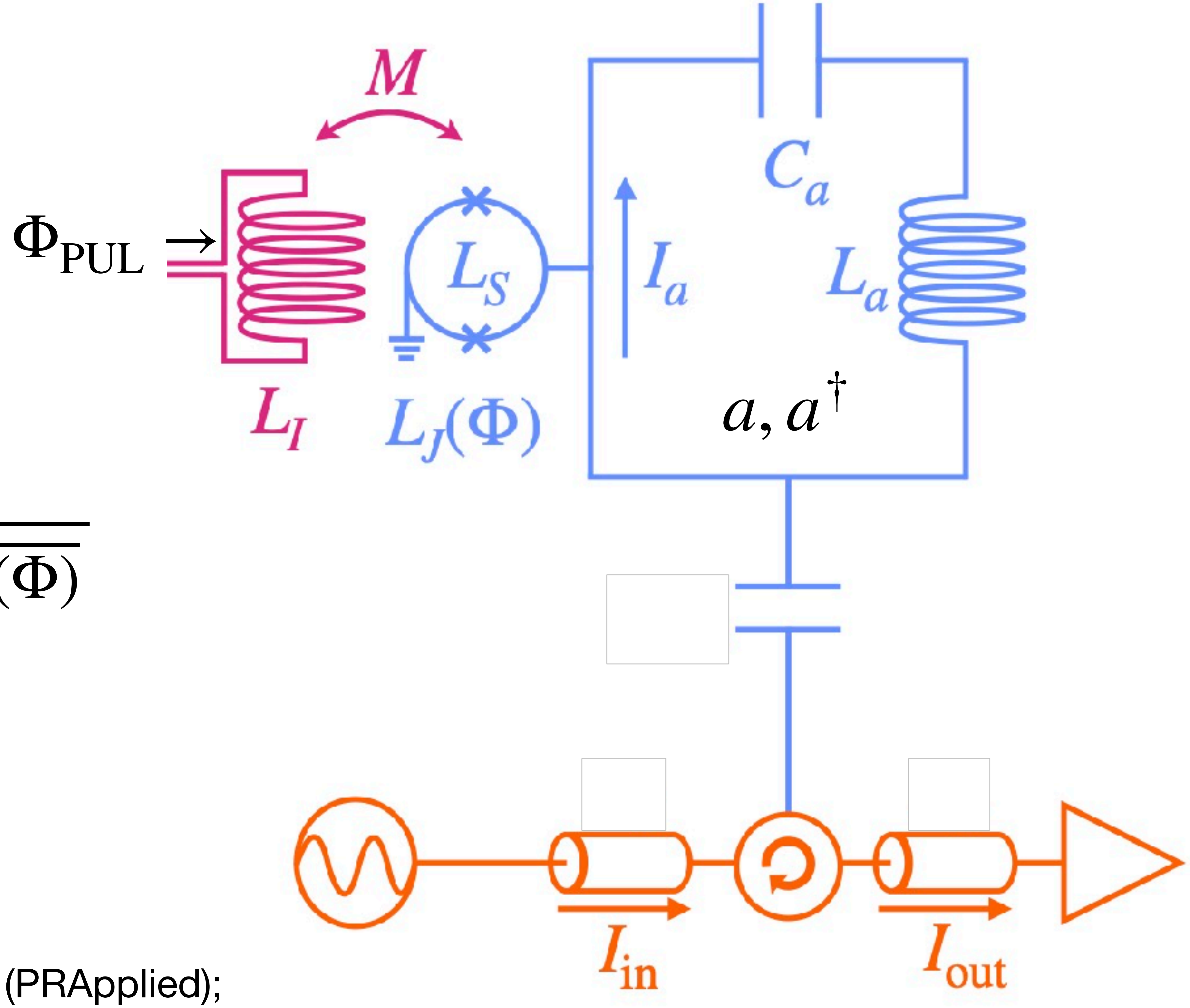
$$\ddot{\xi} \approx \frac{1}{2} \ddot{h}_{zz} D$$



Flux-tunable microwave resonators

- Inductively couple loop to SQUID
- SQUID inductance changes with flux, causing change in inductance of circuit $L(\Phi)$
- Resonant frequency $\omega_a(\Phi) = \dfrac{1}{\sqrt{C\,L(\Phi)}}$

$$H = \omega_a(\Phi)\, a^\dagger a$$
$$\approx \left(\omega_a(\Phi_0) + \frac{\partial \omega_a}{\partial \Phi}\delta\Phi\right) a^\dagger a$$



[Schmidt et al. 2401.08854 (PRApplied);
Rodrigues, Bothner, Steele (Nature Comms);
Kuenstner et al. 2210.05576;...]

Magnetic interferometer

- Pump resonator with microwave photons

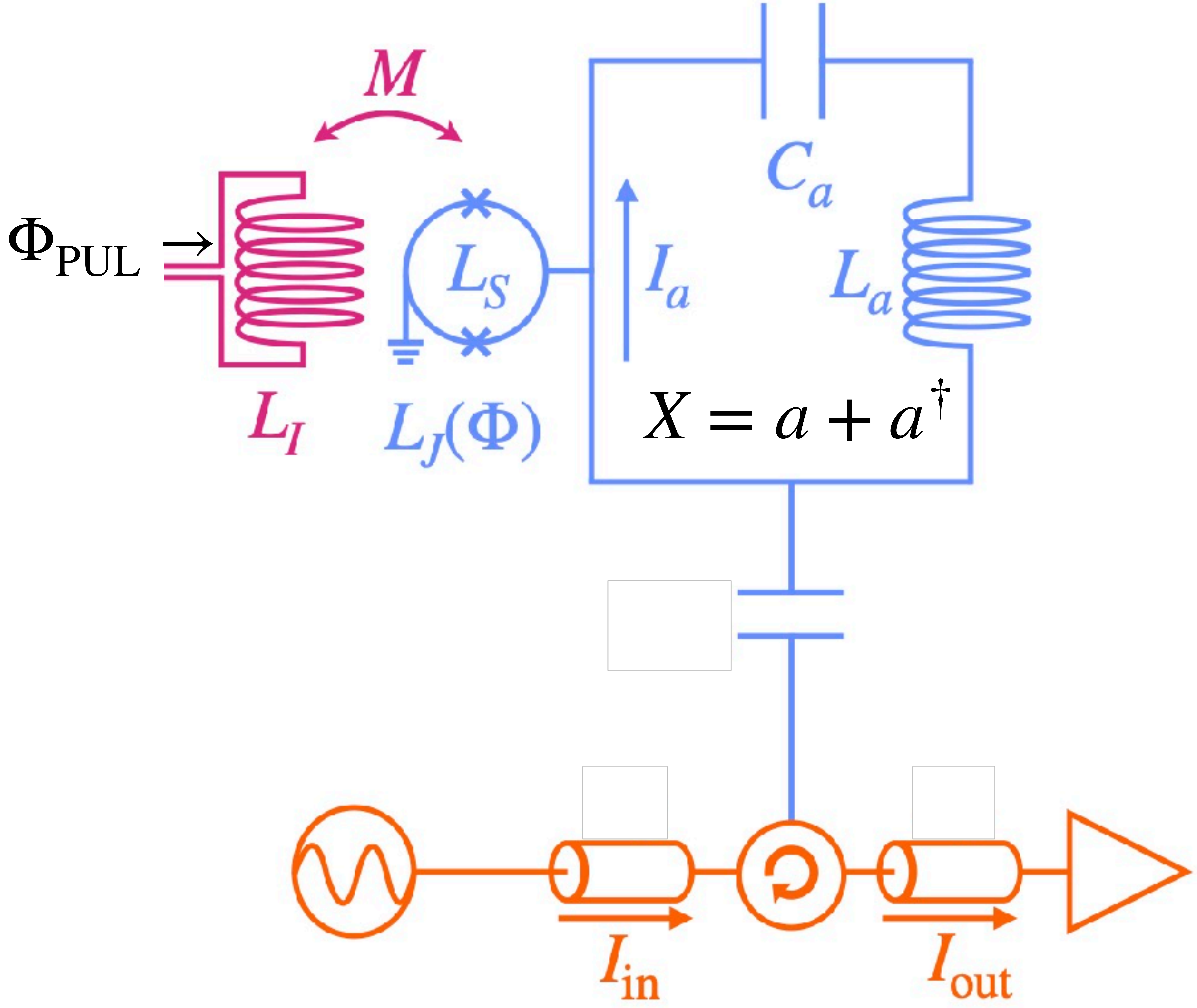
$$H_{\text{int}} = \frac{\partial \omega_a}{\partial \Phi} \delta\Phi \, a^\dagger a$$

$$\xrightarrow{a \to \alpha + a} g \, \xi \, X$$

- Effective coupling between loop-sphere distance ξ and resonator mode

$$g = \alpha \times \beta R^2 b_z \times \lambda_\Phi \times \frac{d\omega_a}{d\Phi}$$

- Read output current response (or Y_{out}) of resonator



System dynamics

- The system Hamiltonian is $H \approx \frac{1}{2}\omega_0^2 x^2 + \frac{p^2}{2m} + \frac{\omega_a}{2}(X^2 + Y^2) + gx\,X$

- Noise in the strain estimator is

$$S_{hh}(\nu) = \frac{4}{m^2 D^2 \nu^2} \Big(\; \chi_{YX}(\nu) \; + \; \chi_{YX}(\nu) \; ^{-1} \Big),$$

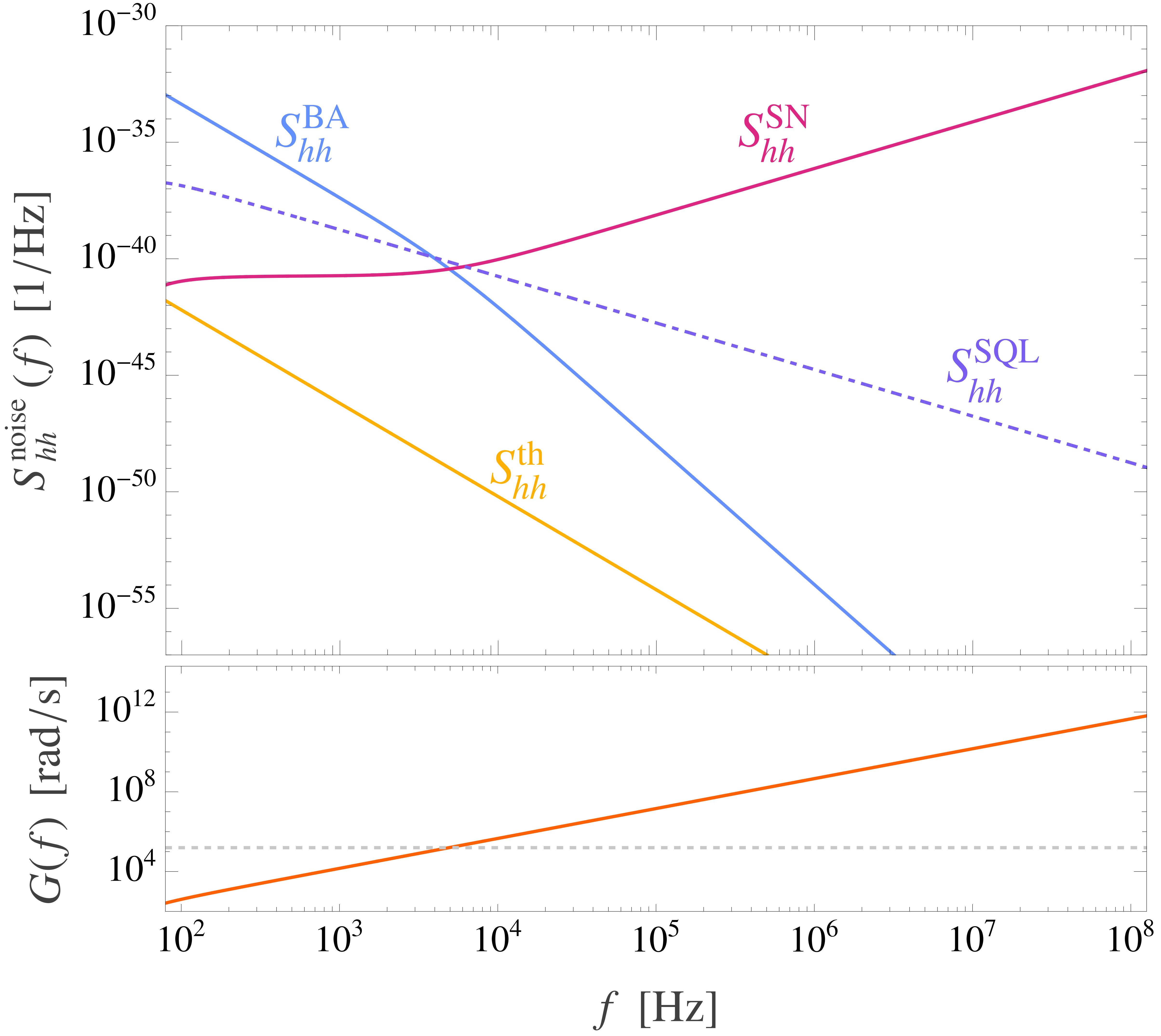
where

$$\chi_{YX}(\nu) = -\,2\kappa g^2 \chi_c^2(\nu)\chi_m(\nu)/x_0^2,$$

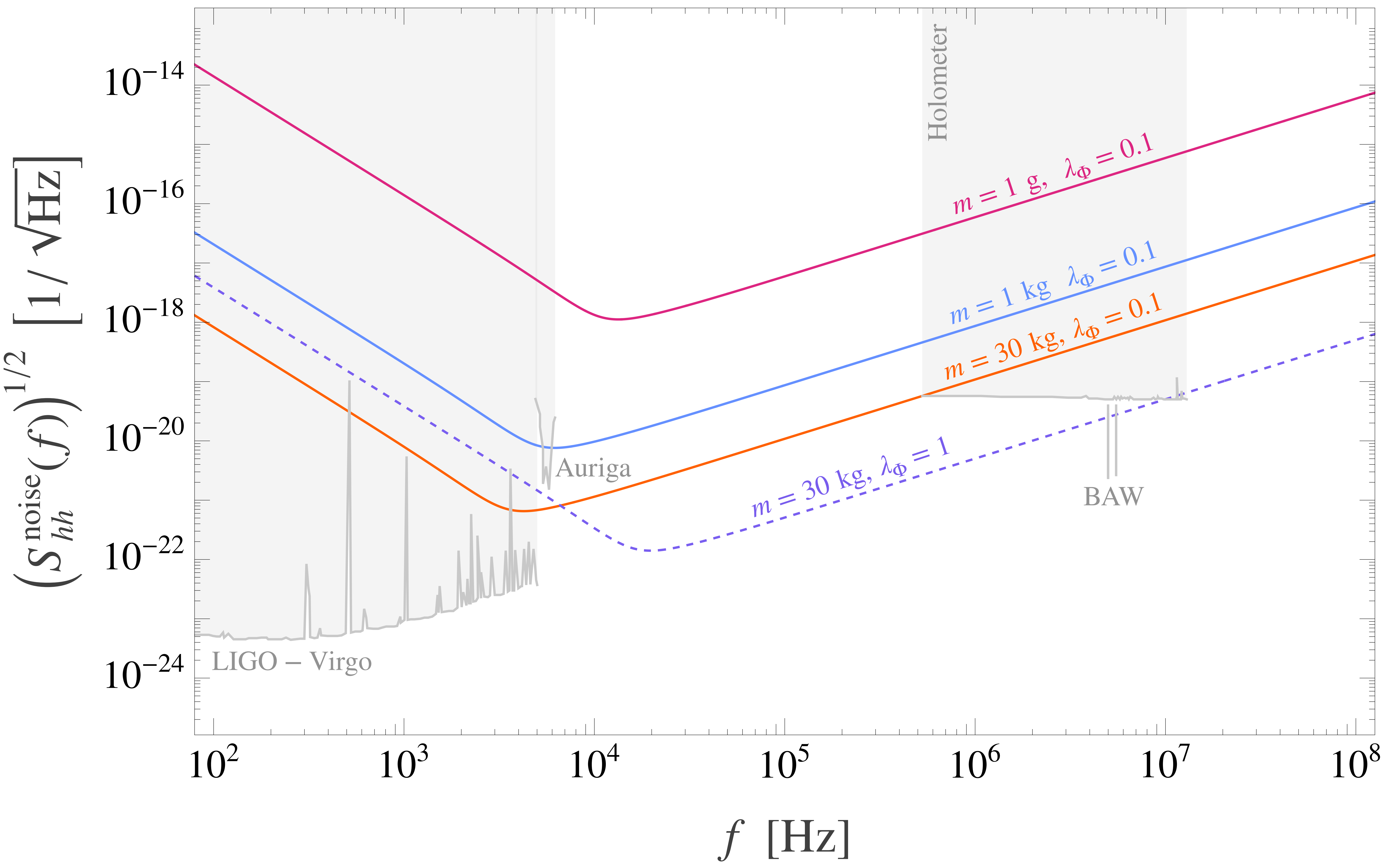
$$\chi_c(\nu) = (i\nu - \kappa/2)^{-1},$$

$$\chi_m(\nu) = -\,(m\nu^2)^{-1}\,.$$

Measurement noise



Mass m	1 kg
Density ρ	$11.3\ \mathrm{g/cm^3}$
Baseline D	2.8 cm
Temperature T	10 mK
Magnetic gradient b_z	30 T/m
Loop coupling β	1.6
SQUID coupling λ_Φ	0.1
Resonator frequency ω_c	$2\pi\times$ 10 GHz
Resonator loss κ	$2\pi\times$ 46 kHz
Pump power P	$2\ \times 10^{-16}$ W
Flux sensitivity $\frac{d\omega}{d\Phi}$	$2\pi\times$ 1 GHz



$m = 1$ g, $\lambda_\Phi = 0.1$
$m = 1$ kg $\lambda_\Phi = 0.1$
$m = 30$ kg, $\lambda_\Phi = 0.1$
$m = 30$ kg, $\lambda_\Phi = 1$
Holometer
Auriga
BAW
LIGO − Virgo
$\left(S_{hh}^{\text{noise}}(f)\right)^{1/2}\ [1/\sqrt{\text{Hz}}]$
f [Hz]
10^{-14}
10^{-16}
10^{-18}
10^{-20}
10^{-22}
10^{-24}
10^2
10^3
10^4
10^5
10^6
10^7
10^8

Conclusions

- SLedDoG concept can have sensitivity to kHz-MHz gravitational waves
- Large magnetic coupling lowers imprecision noise at higher frequencies, enabling SQL-limited measurement noise
- If technical noise can be brought below quantum noise, promising avenue for GW detection
- What do realistic GW signatures look like? Can we use quantum resources to optimize sensitivity to these signals?