and Ultralight Axion Dark Matter

Detecting High-Frequency Gravitational Waves with Superconducting Cavities

Asher Berlin (Fermilab)

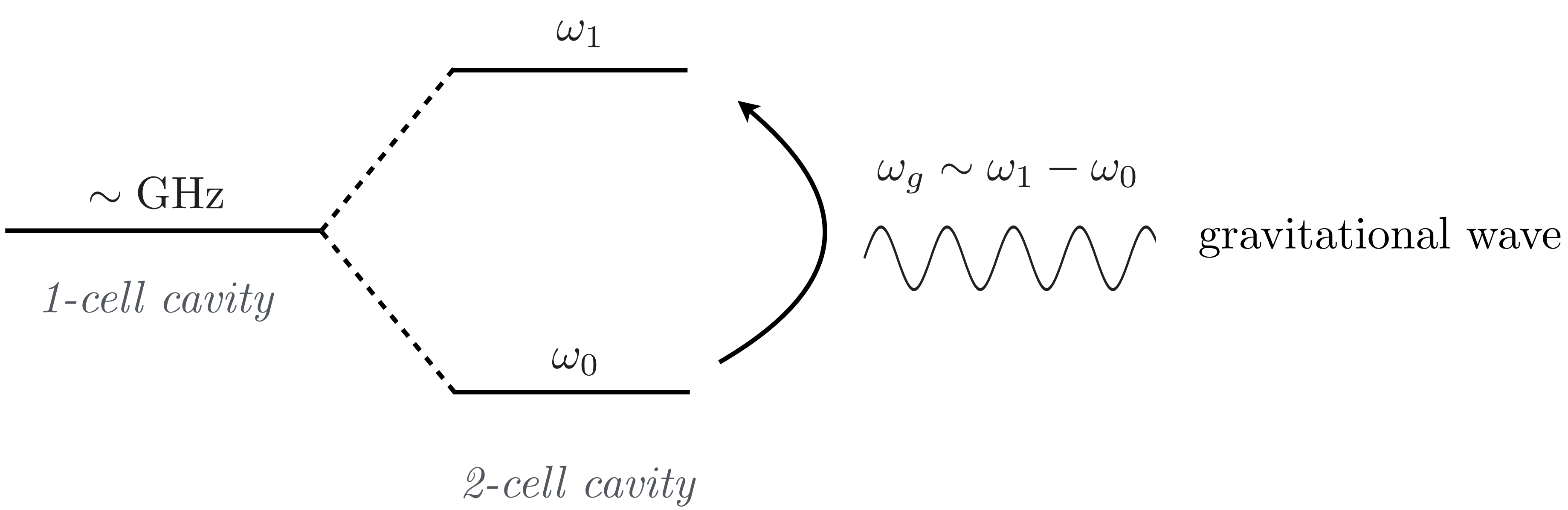
Quantum Technologies for Fundamental Physics,
Ettore Majorana Foundation, Erice, September 4th 2023

arXiv:2112.11465, arXiv:2303.01518

arXiv:1912.11048, arXiv:1912.11056, arXiv:2007.15656, arXiv:2207.11346

Concept

MAGO (**M**icrowave **A**pparatus for **G**ravitational wave **O**bservation)



High quality-factor SRF cavity amplifies resonant signal and suppresses EM noise

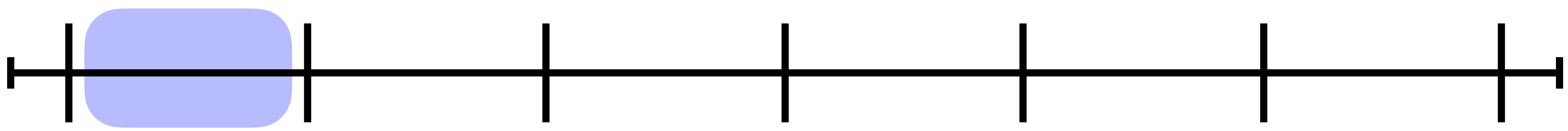
Timeline

MAGO (**M**icrowave **A**pparatus for **G**ravitational wave **O**bservation)

Timeline

MAGO (**M**icrowave **A**pparatus for **G**ravitational wave **O**bservation)

1970s



time

theory

Bernard, Pegoraro, Picasso, Radicati

On the operation of a tunable electromagnetic detector for gravitational waves

F Pegoraro†, E Picasso‡ and L A Radicati‡§
†Scuola Normale Superiore, Pisa, Italy
‡CERN, Geneva, Switzerland

Received 6 December 1977, in final form 20 April 1978

Abstract. The i
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ELECTROMAGNETIC DETECTOR FOR GRAVITATIONAL WAVES

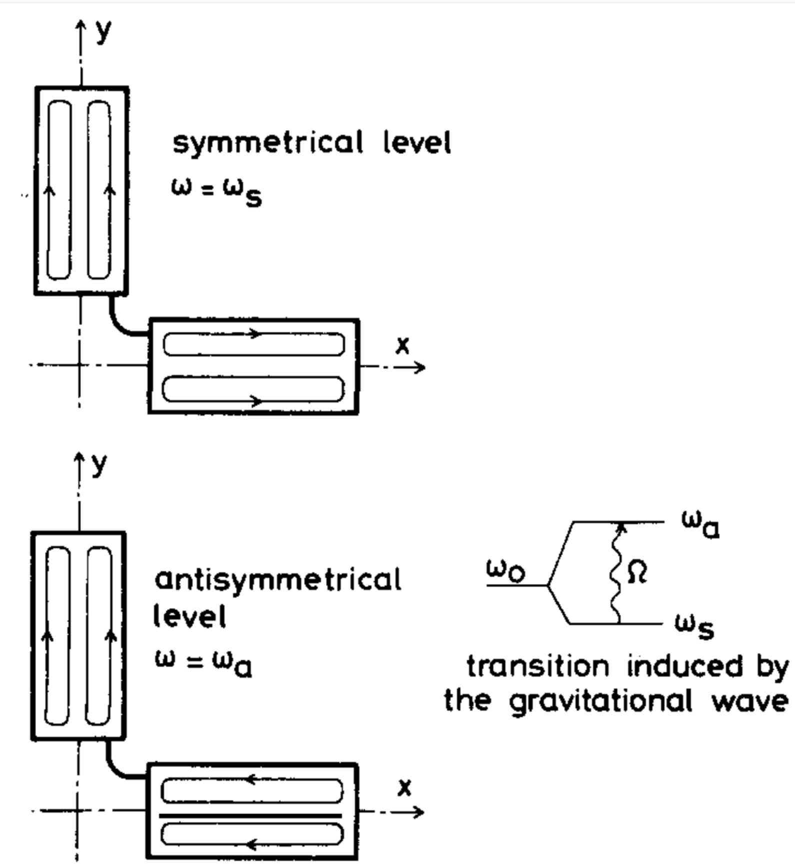
F. PEGORARO, L.A. RADICATI
Scuola Normale Superiore, Pisa, Italy

and

Ph. BERNARD and E. PICASSO
CERN, Geneva, Switzerland

Received 29 June 1978

We analyze the mode of operation of a two-level parametric electromagnetic detector for gravitational waves which is tunable and potentially more sensitive than the mechanical antennas currently considered.



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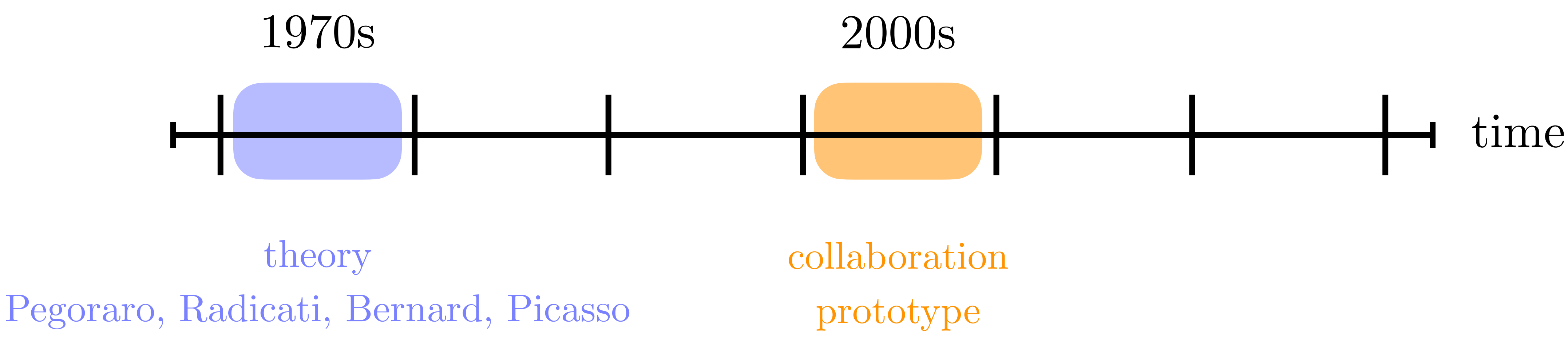

two superconducting spherical cells joined by a deformable (tunable) aperture

Timeline

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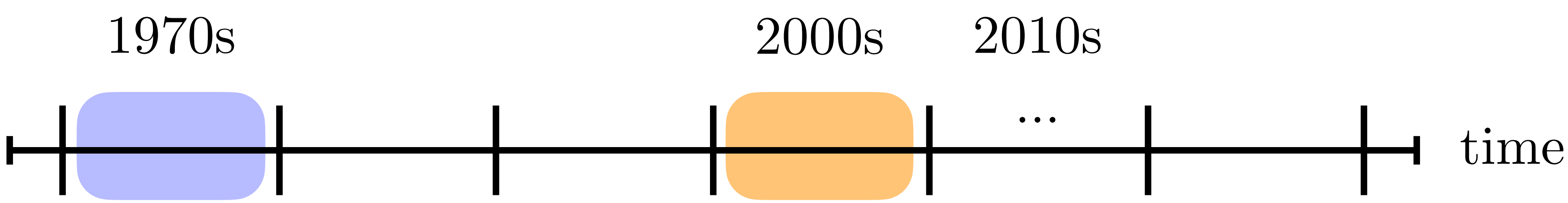

theory
Pegoraro, Radicati, Bernard, Picasso

collaboration
prototype

effort/funding pulled and moved to Virgo

in display at the University of Genoa

Timeline

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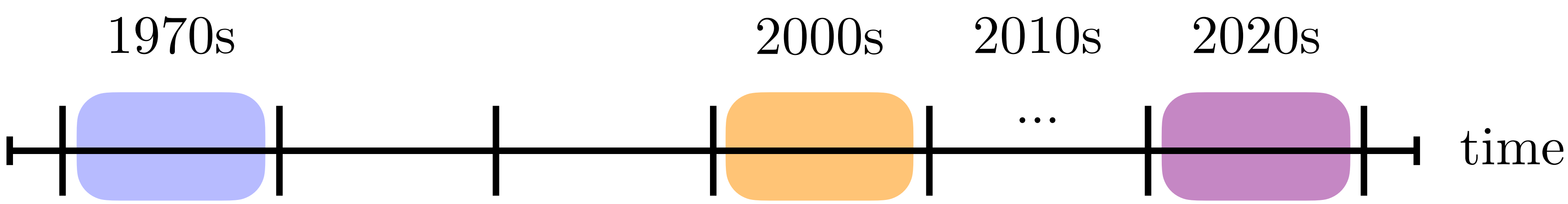

theory
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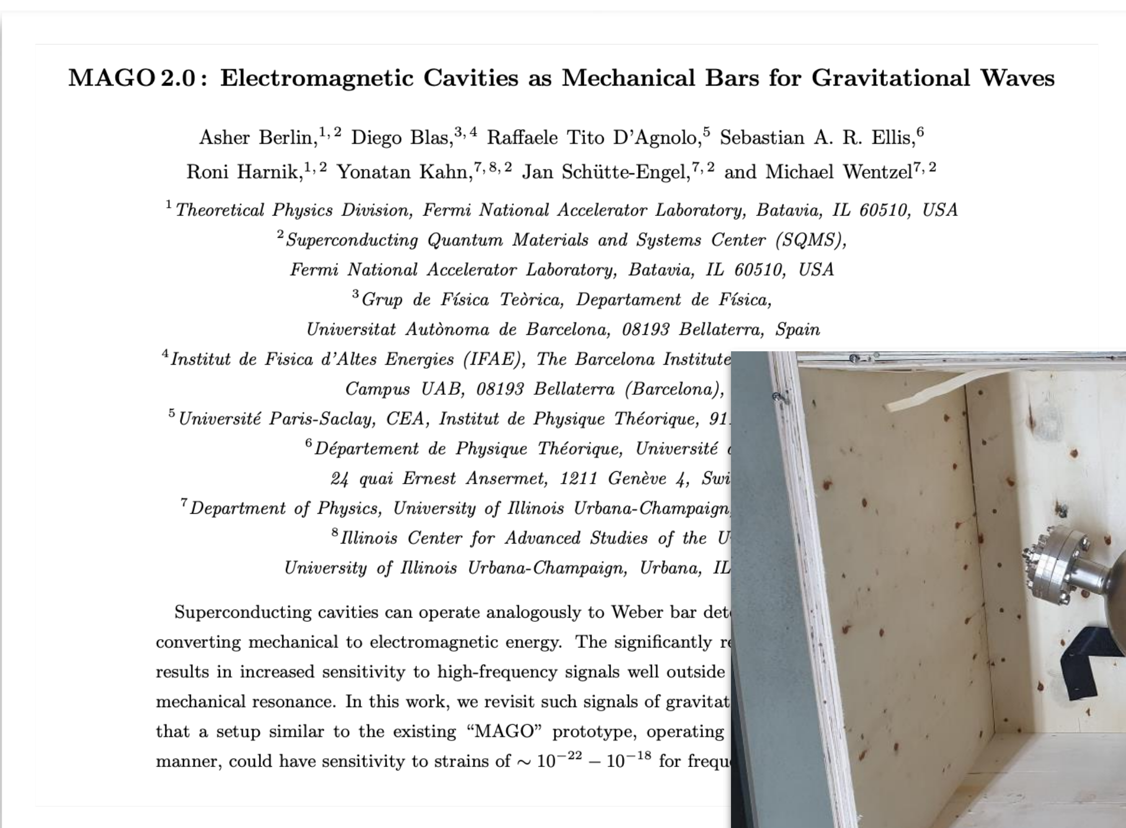
collaboration
prototype

renewed interest
DESY/FNAL

(Talks by Marc Wenskat, Bianca Giaccone)

new analysis,
improved sensitivity estimate

initial measurements ongoing at DESY
(will move to FNAL soon after)



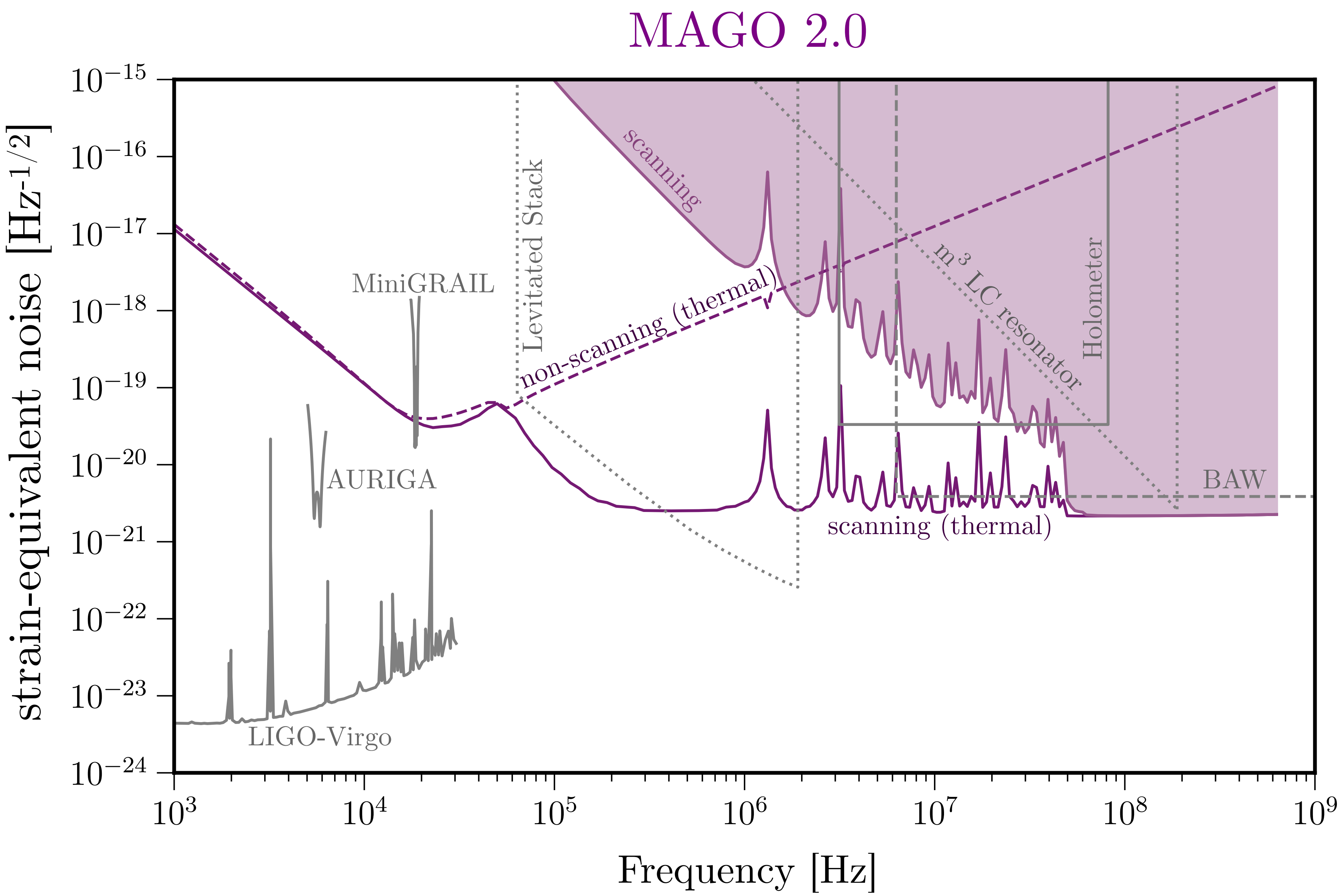
MAGO 2.0 : Electromagnetic Cavities as Mechanical Bars for Gravitational Waves

Asher Berlin,[1,2] Diego Blas,[3,4] Raffaele Tito D'Agnolo,[5] Sebastian A. R. Ellis,[6]
Roni Harnik,[1,2] Yonatan Kahn,[7,8,2] Jan Schütte-Engel,[7,2] and Michael Wentzel[7,2]

[1] *Theoretical Physics Division, Fermi National Accelerator Laboratory, Batavia, IL 60510, USA*
[2] *Superconducting Quantum Materials and Systems Center (SQMS), Fermi National Accelerator Laboratory, Batavia, IL 60510, USA*
[3] *Grup de Física Teòrica, Departament de Física, Universitat Autònoma de Barcelona, 08193 Bellaterra, Spain*
[4] *Institut de Fisica d'Altes Energies (IFAE), The Barcelona Institute ... Campus UAB, 08193 Bellaterra (Barcelona), ...*
[5] *Université Paris-Saclay, CEA, Institut de Physique Théorique, 91...*
[6] *Département de Physique Théorique, Université ... 24 quai Ernest Ansermet, 1211 Genève 4, Swi...*
[7] *Department of Physics, University of Illinois Urbana-Champaign...*
[8] *Illinois Center for Advanced Studies of the U... University of Illinois Urbana-Champaign, Urbana, IL...*

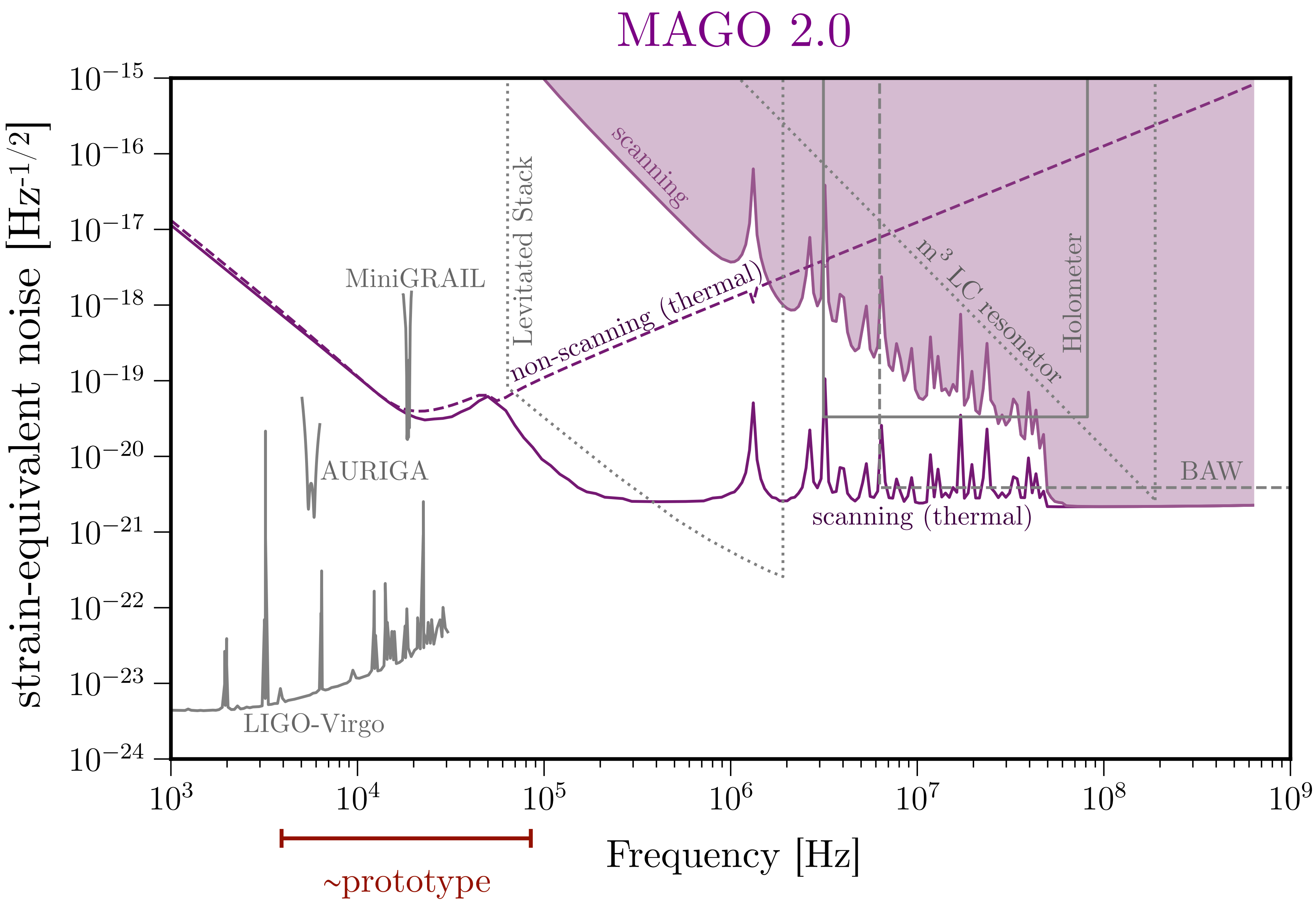
Superconducting cavities can operate analogously to Weber bar det... converting mechanical to electromagnetic energy. The significantly r... results in increased sensitivity to high-frequency signals well outside ... mechanical resonance. In this work, we revisit such signals of gravitat... that a setup similar to the existing "MAGO" prototype, operating ... manner, could have sensitivity to strains of $\sim 10^{-22} - 10^{-18}$ for frequ...

Goals



MAGO 2.0
strain-equivalent noise [Hz$^{-1/2}$]
Frequency [Hz]
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{3}
10^{4}
10^{5}
10^{6}
10^{7}
10^{8}
10^{9}
scanning
Levitated Stack
MiniGRAIL
non-scanning (thermal)
m^3 LC resonator
Holometer
AURIGA
BAW
scanning (thermal)
LIGO-Virgo

Goals


MAGO 2.0
strain-equivalent noise [Hz-1/2]
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~prototype
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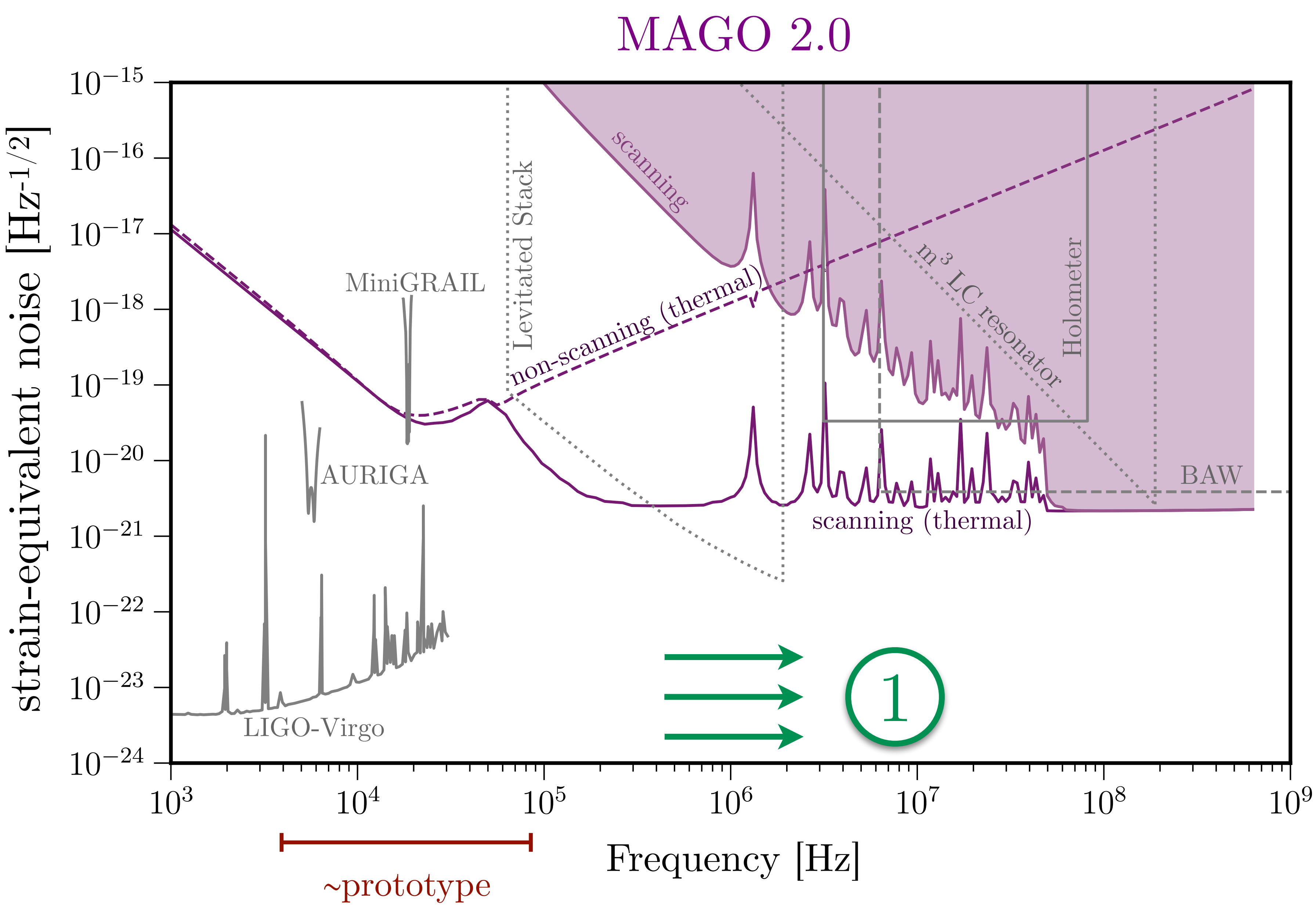
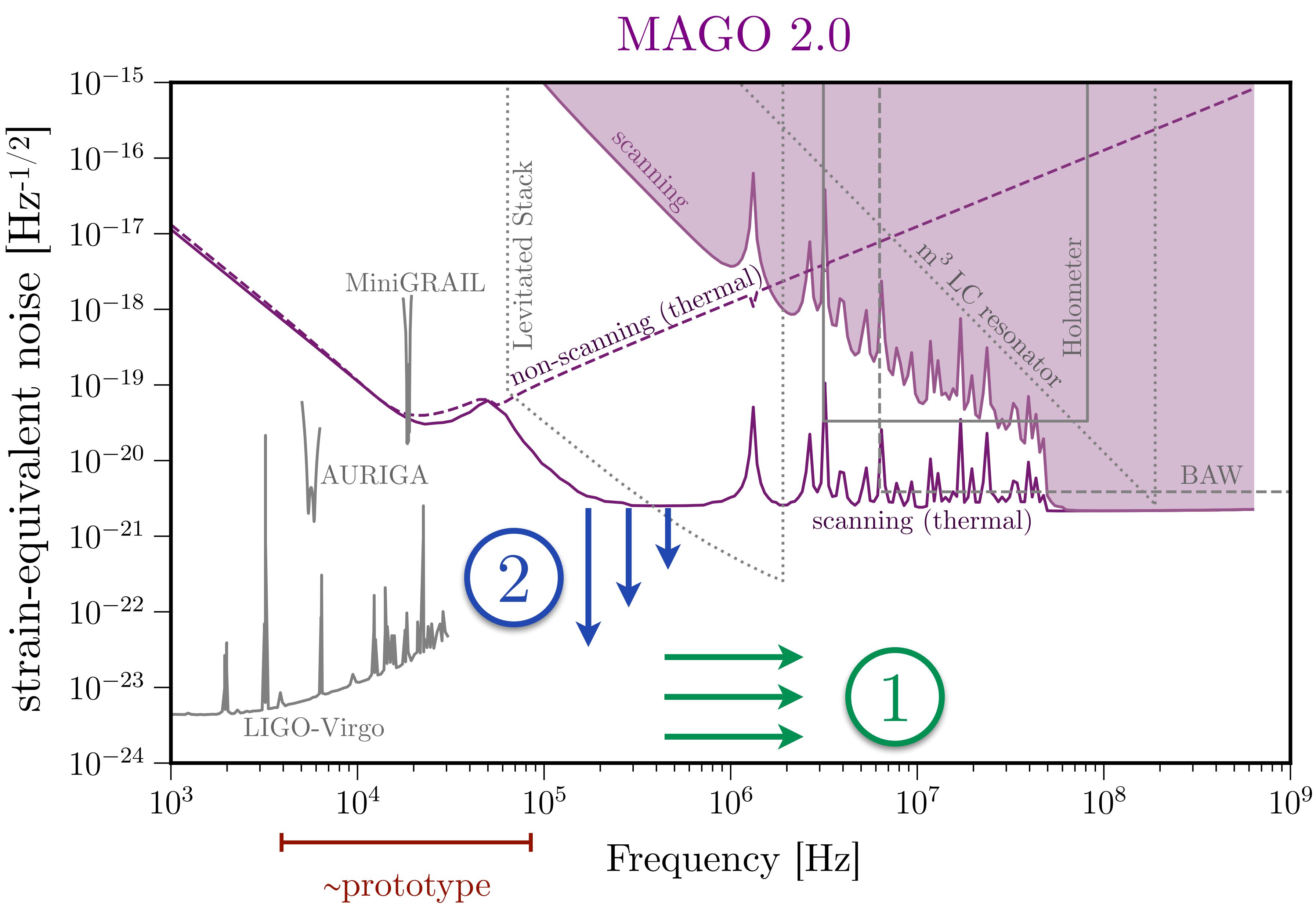


Goal 1:

≫ kHz

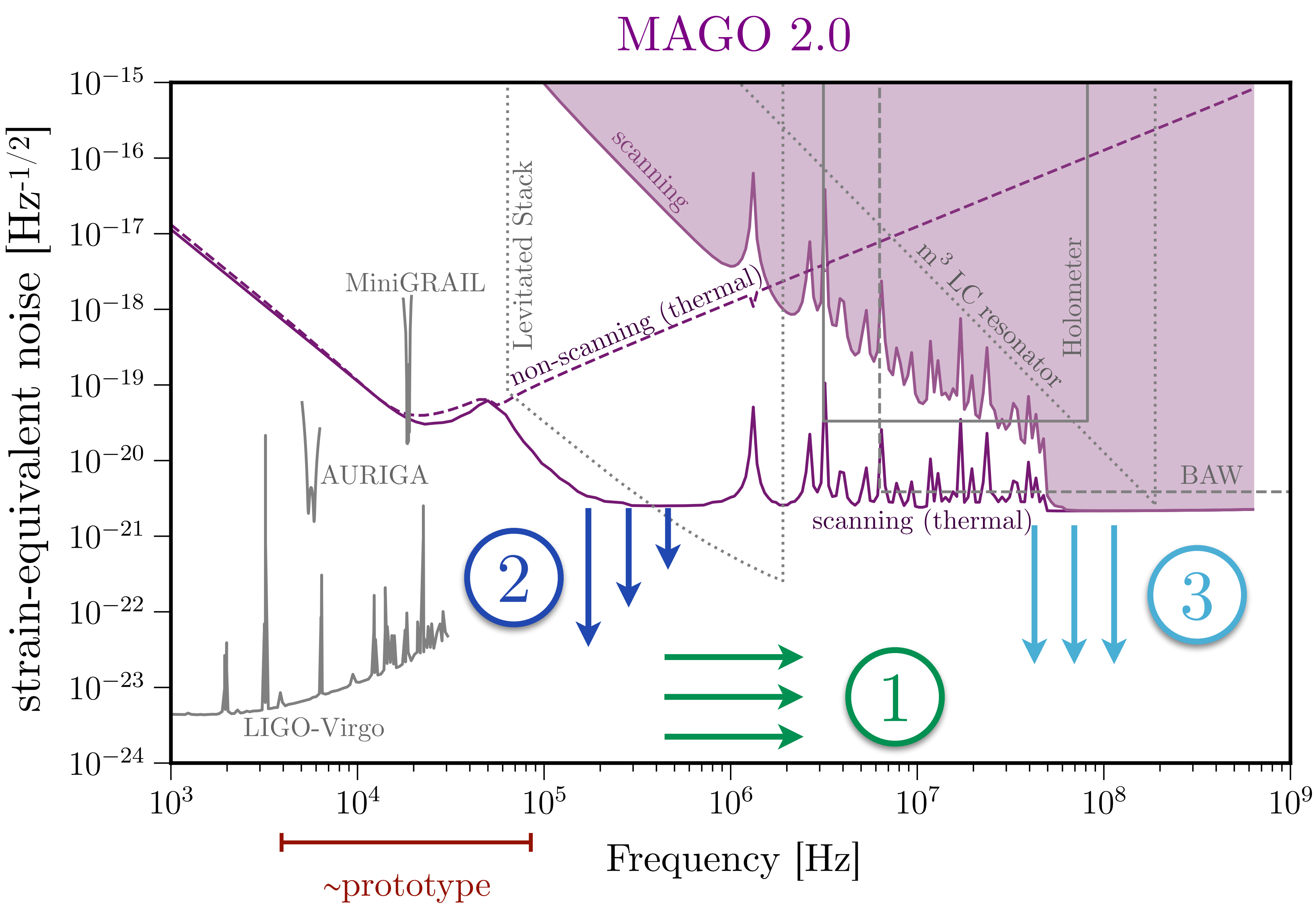
Goals



Goal 1:
≫ kHz

Goal 2:
optimal scaling

Goals



Goal 1:
≫ kHz

Goal 2:
optimal scaling

Goal 3:
smaller strain

Outline

I. MAGO: Conceptual Overview of Setup and Signal

II. MAGO: Noise and "Why SRF?"

III. Bonus: A Similar Setup for Axion Dark Matter

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I. MAGO: Conceptual Overview of Setup and Signal

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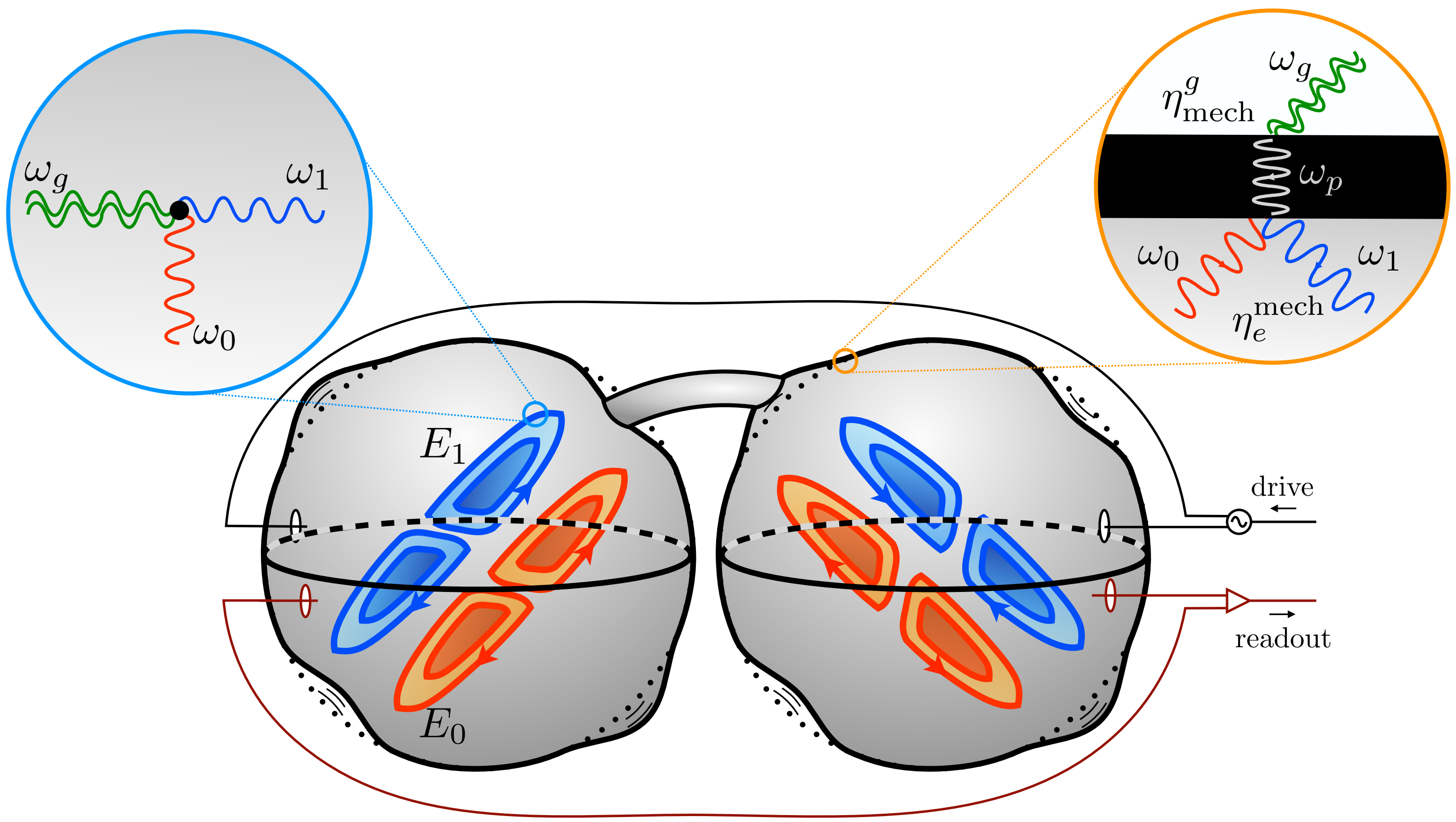
Signal Schematic

Direct: GW $\rightarrow$ EM

Indirect: GW $\rightarrow$ mechanical $\rightarrow$ EM



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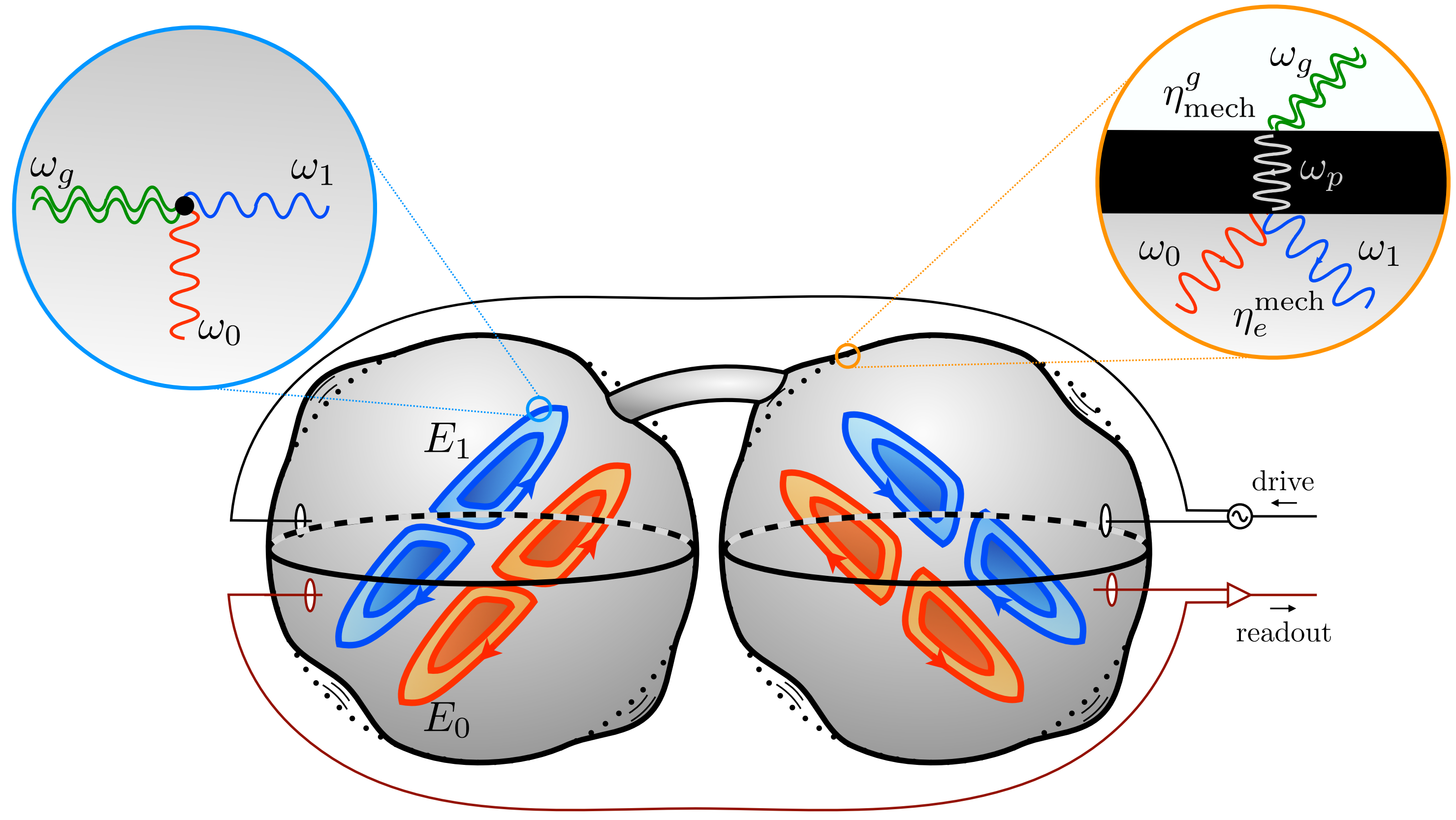
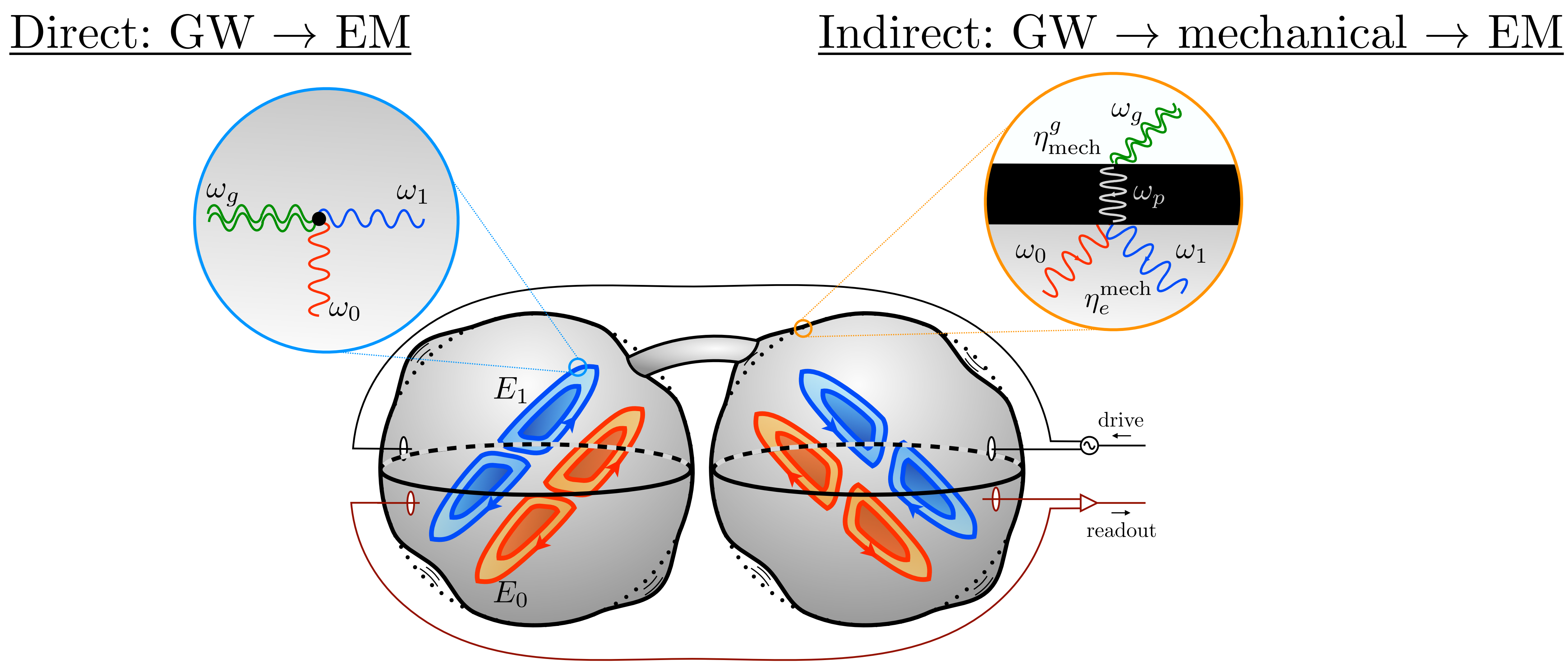


1. "Pump mode" E_0, B_0 driven at $\omega_0 \sim$ GHz

Signal Schematic



1. "Pump mode" E_0, B_0 driven at $\omega_0 \sim$ GHz
2. GW of frequency $\omega_g \ll$ GHz drives power at $\omega_0 + \omega_g$

Signal Schematic

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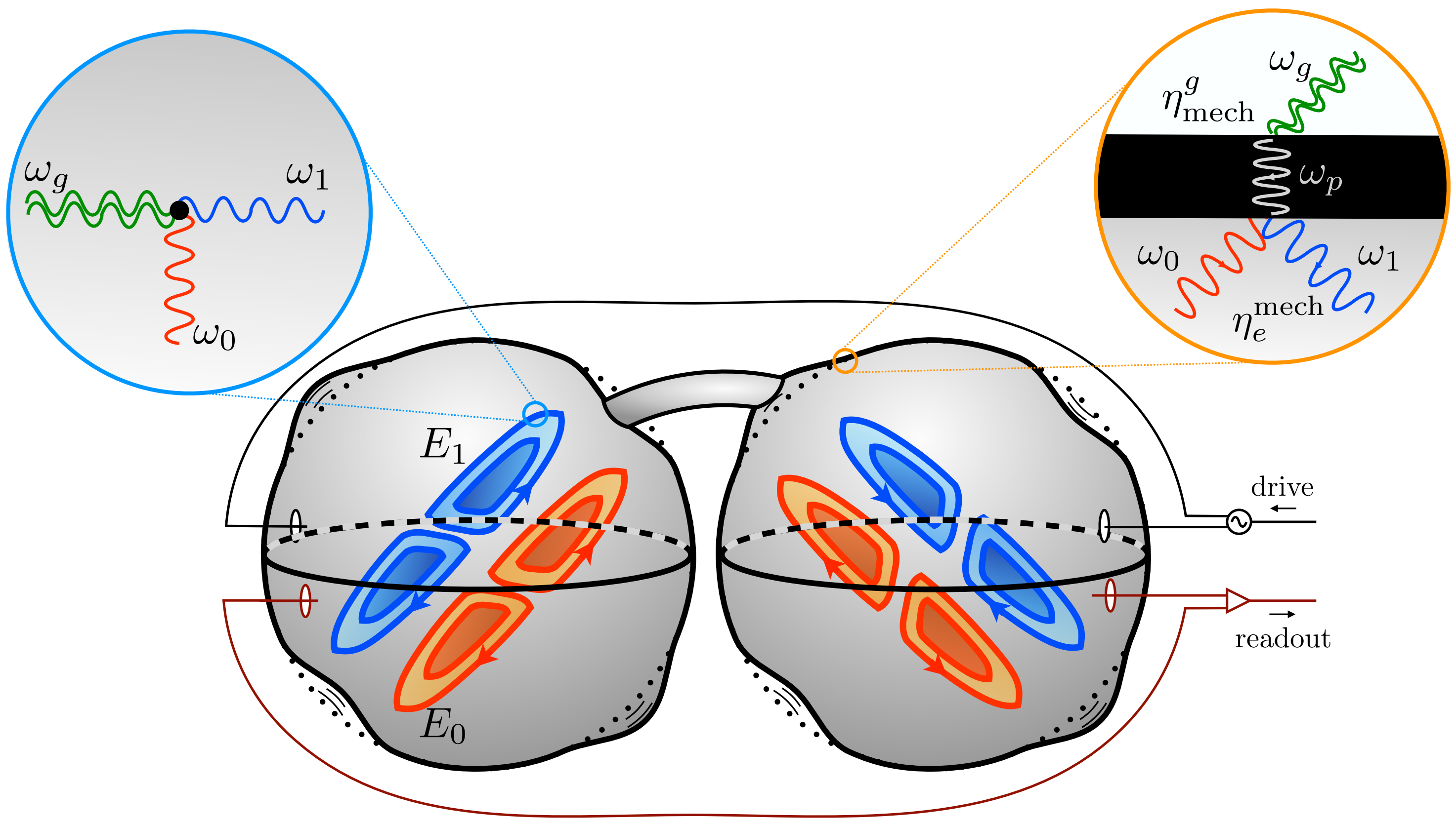
Indirect: GW $\to$ mechanical $\to$ EM



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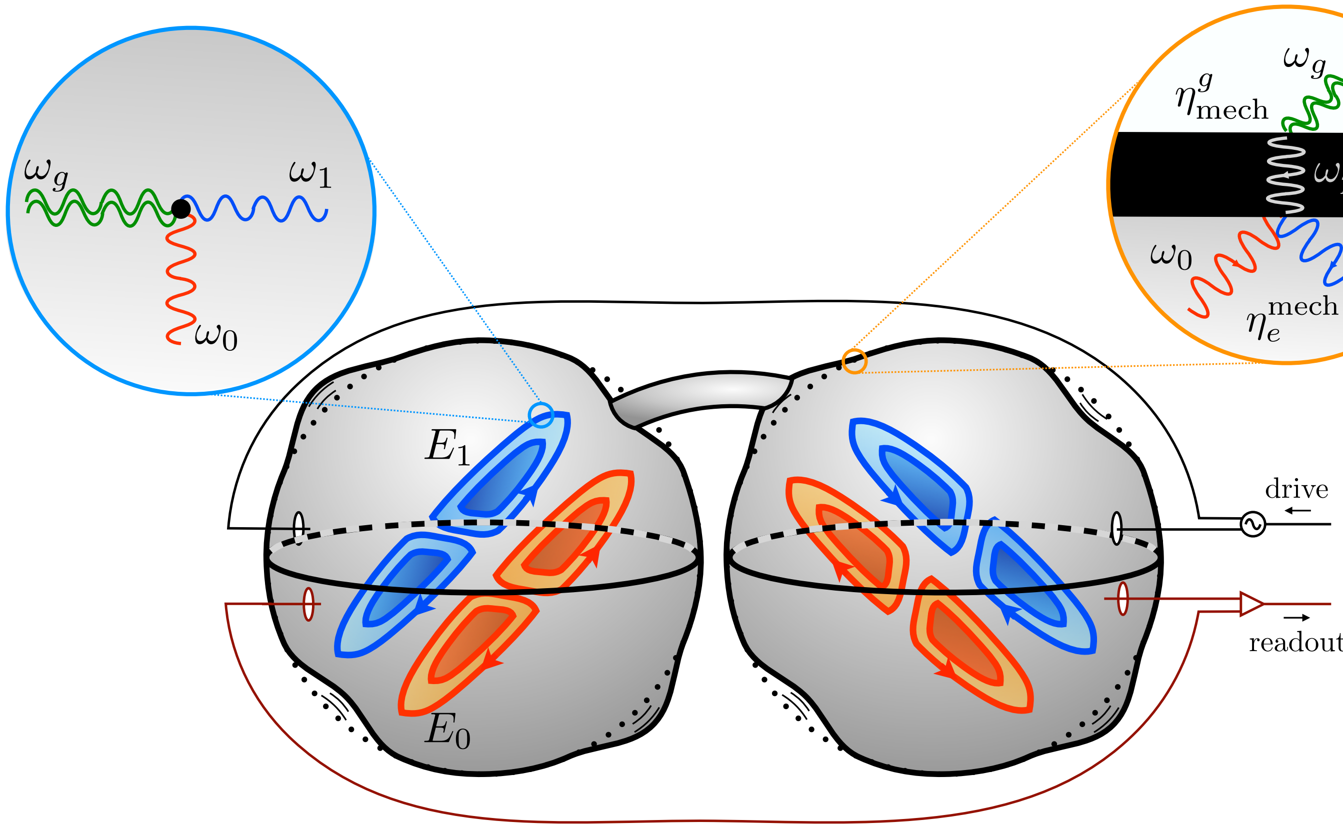
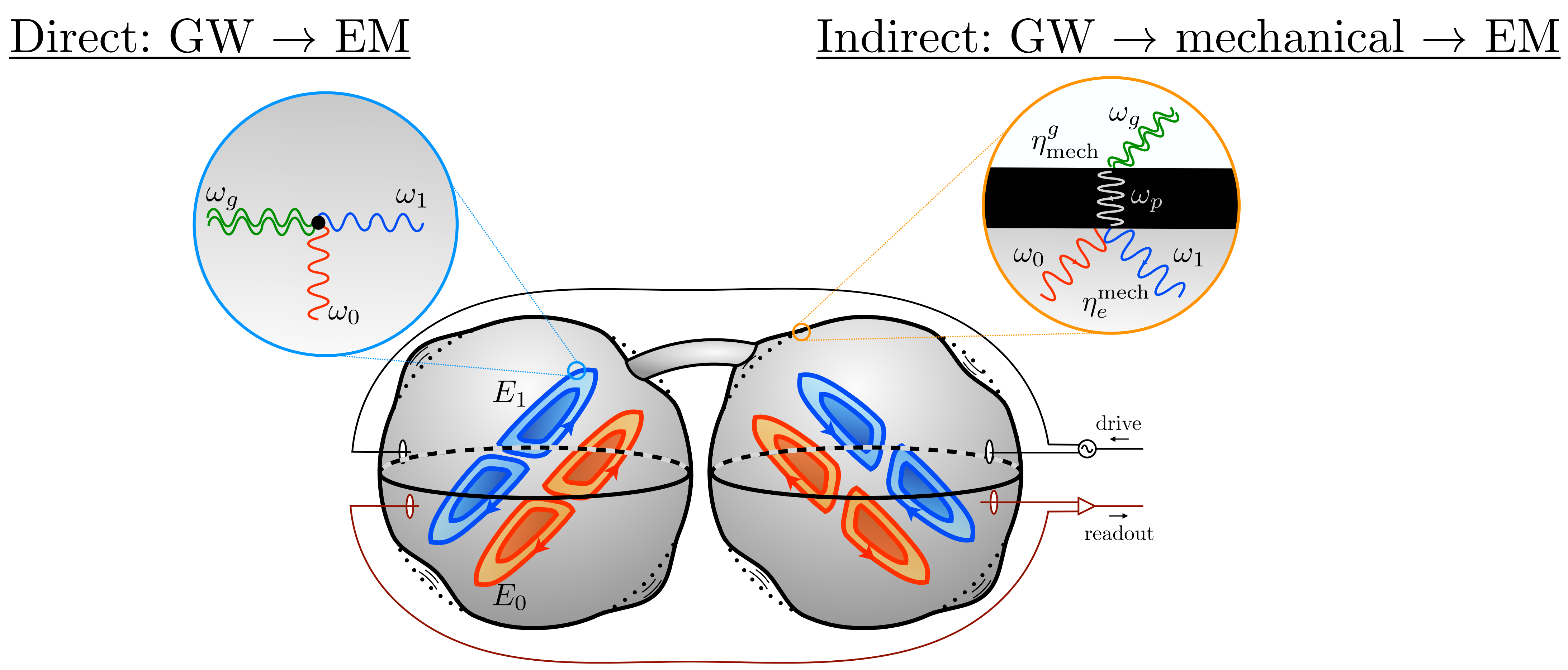


pump mode = symmetric EM configuration

signal mode = antisymmetric EM configuration

Signal Schematic



pump mode = symmetric EM configuration

signal mode = antisymmetric EM configuration

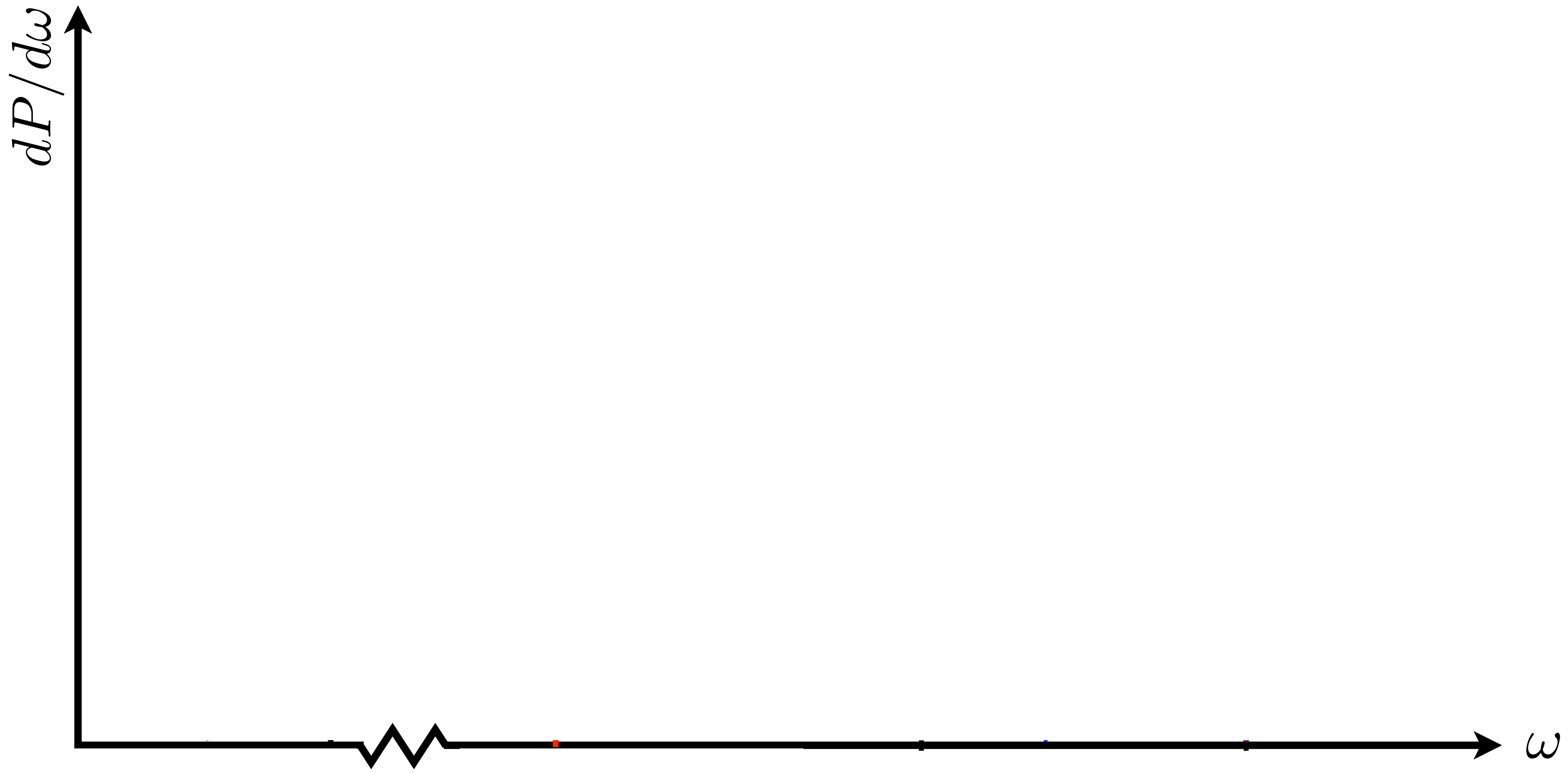
- MAGO prototype $\Longrightarrow$ geometric discrimination ~ 10^{-14} in power

MAGO prototype: few kHz - 50 kHz

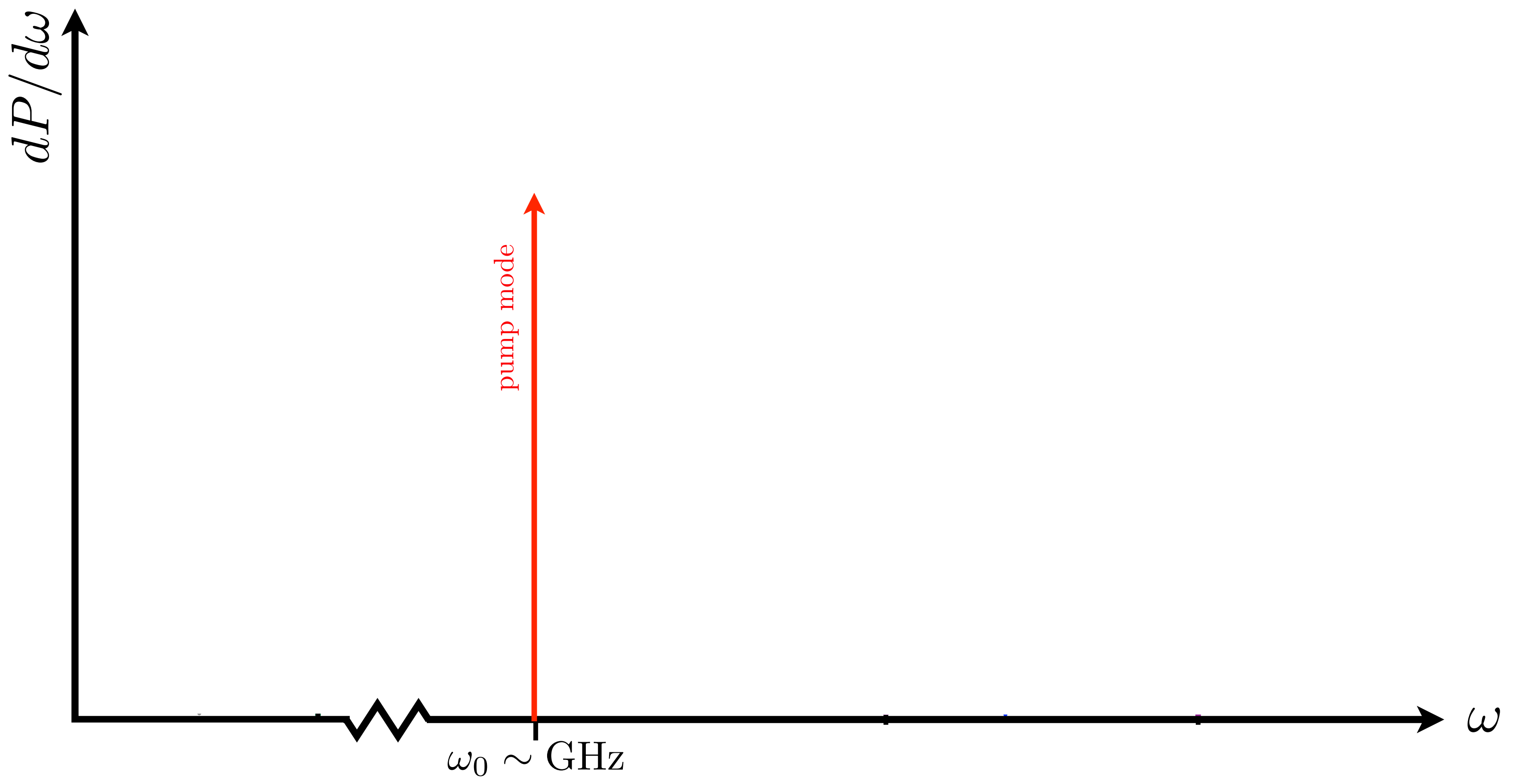
- $\omega_1 - \omega_0 \ll$ GHz tunable by mechanically deforming the connecting aperture

$$\omega_{\text{antisymm.}} - \omega_{\text{symm.}} \sim (R_{\text{aperture}}/R_{\text{sphere}})^3 \times \text{GHz}$$

Signal Schematic



Signal Schematic



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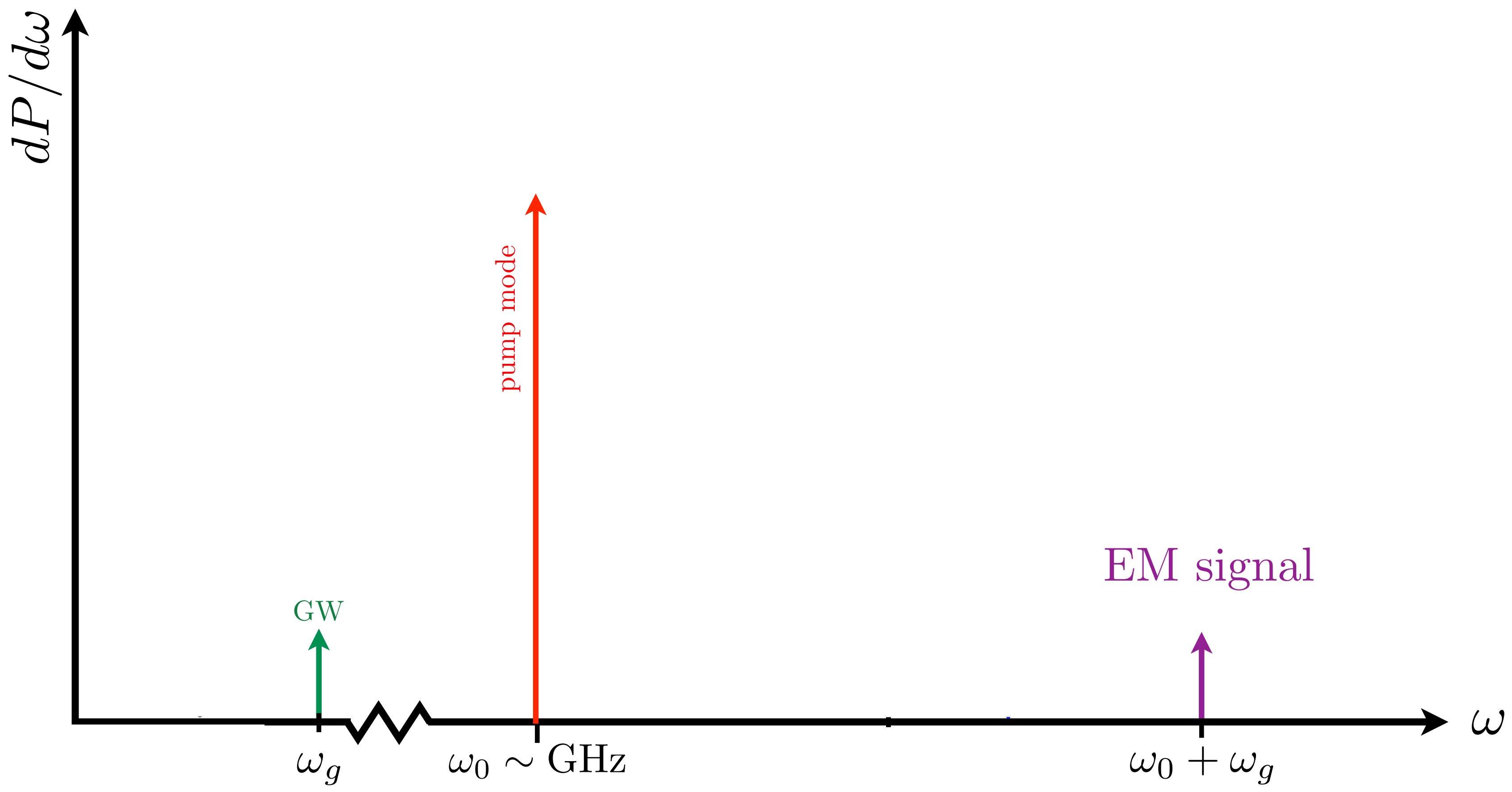
Signal Schematic



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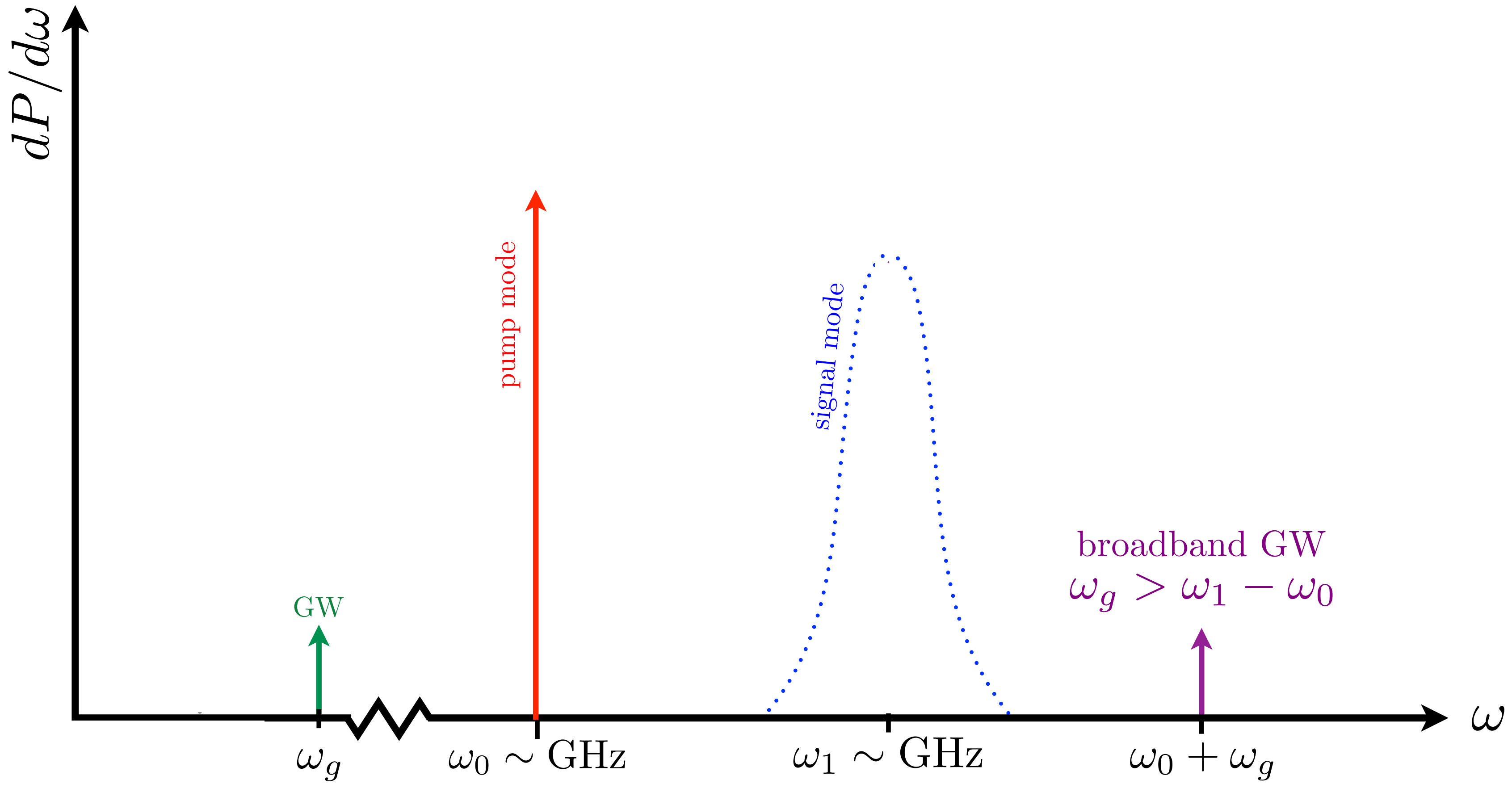
2. GW of frequency $\omega_g \ll$ GHz drives power at $\omega_0 + \omega_g$

Signal Schematic



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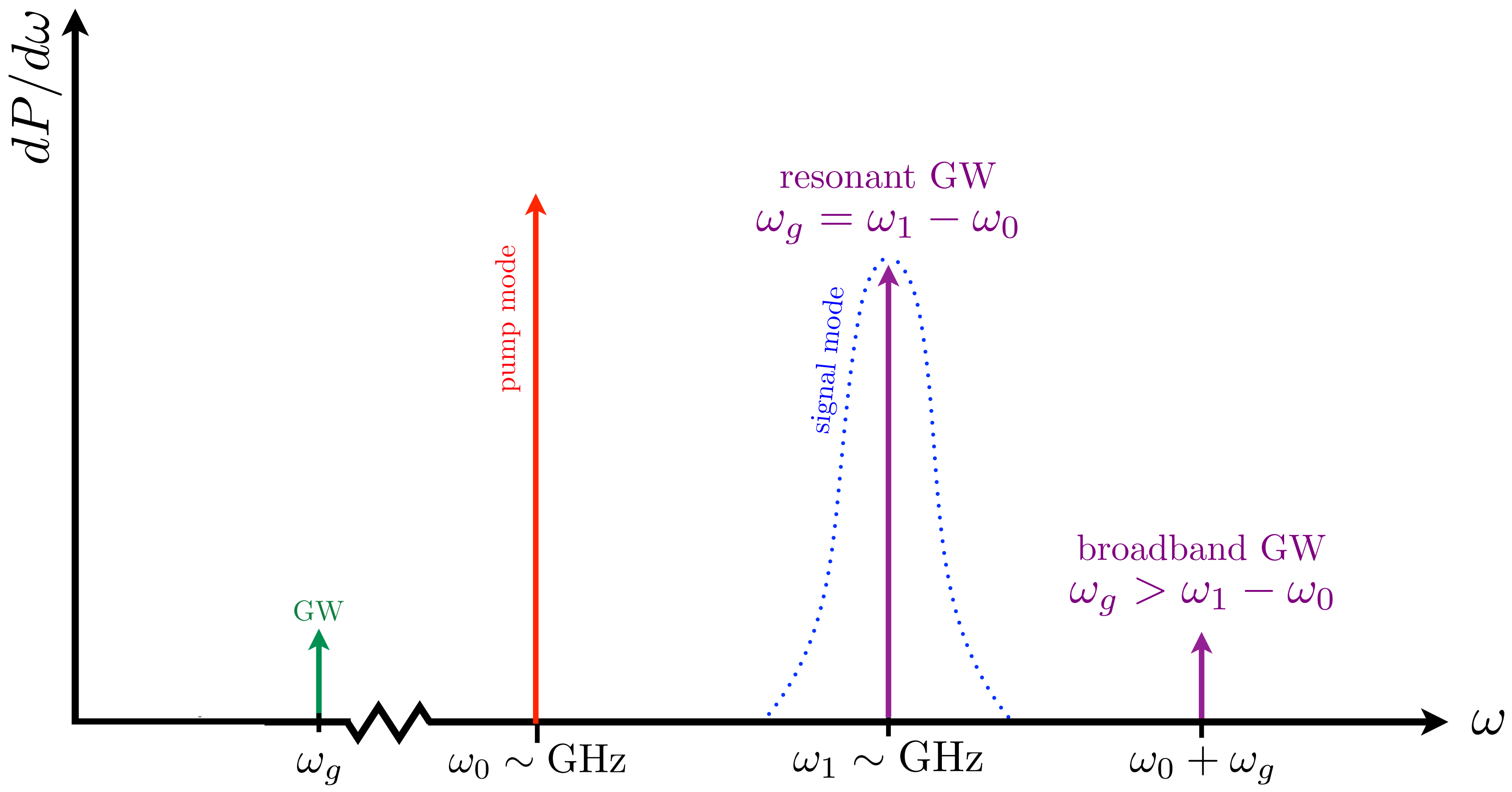

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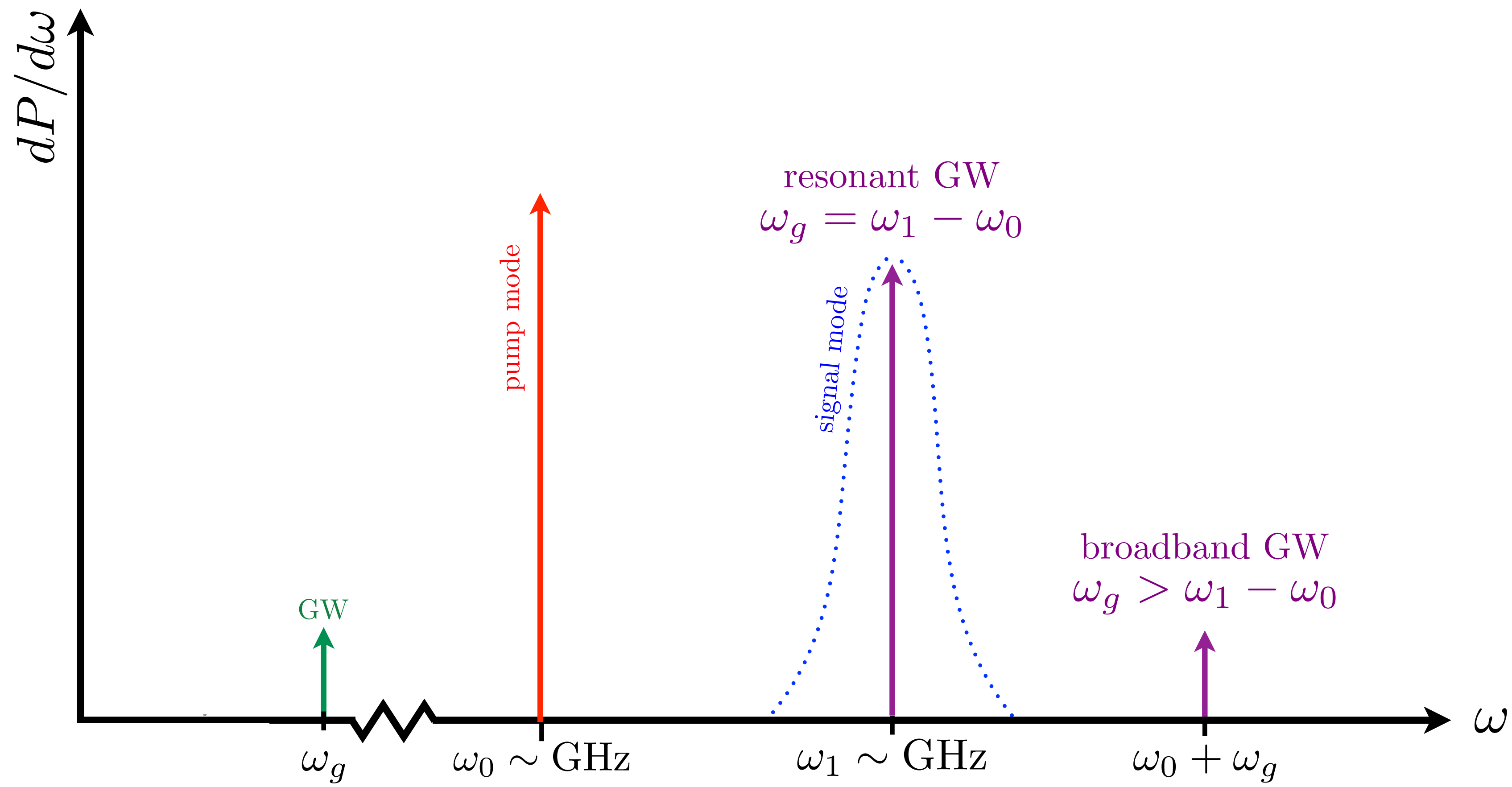
($\omega_1 - \omega_0 \ll$ GHz tunable by mechanically deforming the connecting aperture)

Signal Schematic



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($\omega_1 - \omega_0 \ll$ GHz tunable by mechanically deforming the connecting aperture)

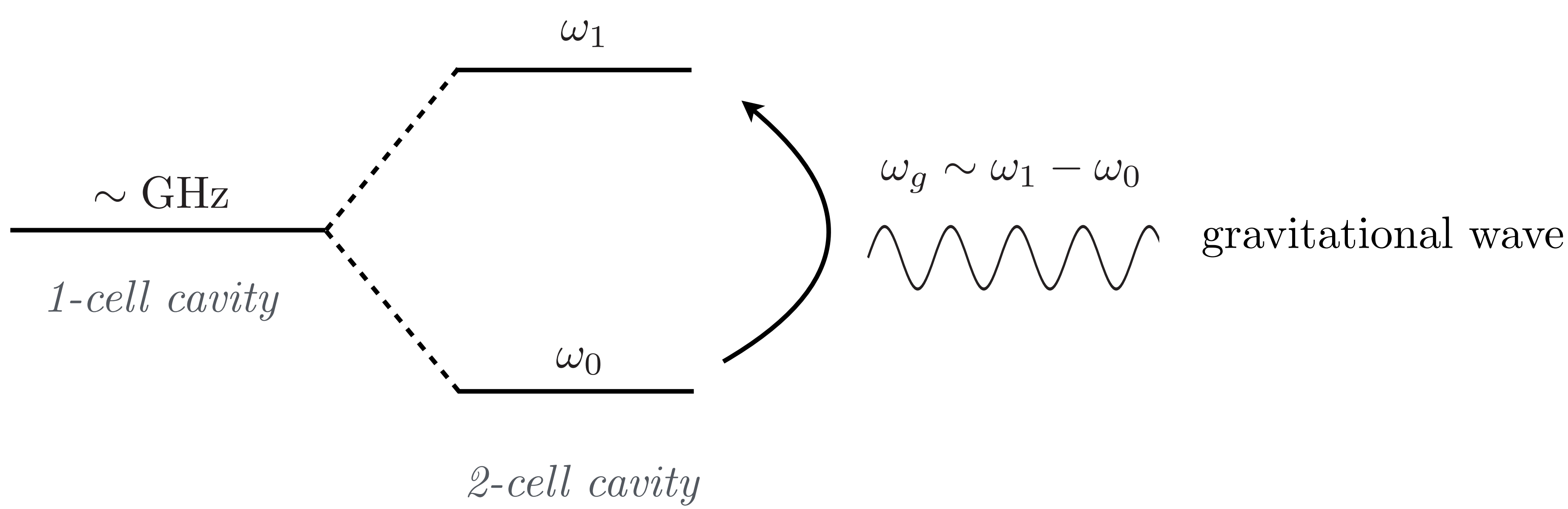
✓ Goal 1: $\gg$ kHz

Goal 2: optimal scaling

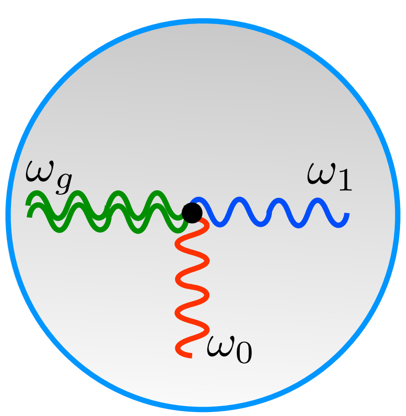
Goal 3: smaller strain

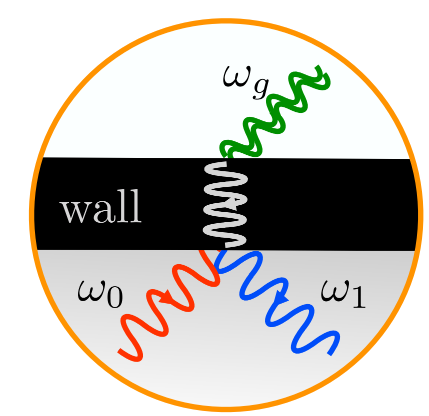
Signal Parametrics

How does this work?



direct photon-coupling or mechanical-coupling

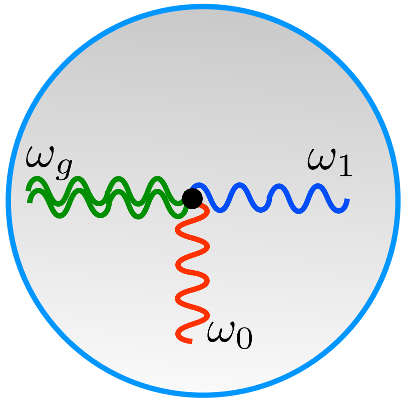




Signal Parametrics

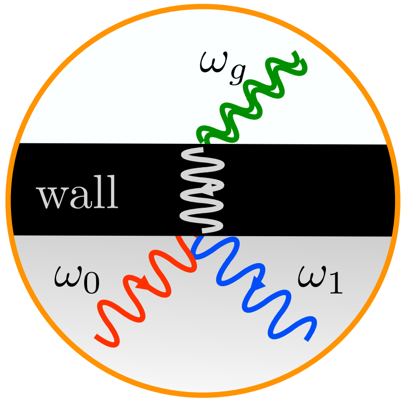
Direct: GW → EM

(Sebastian Ellis's talk)



"inverse-Gertsenshtein effect"

Indirect: GW → mechanical → EM



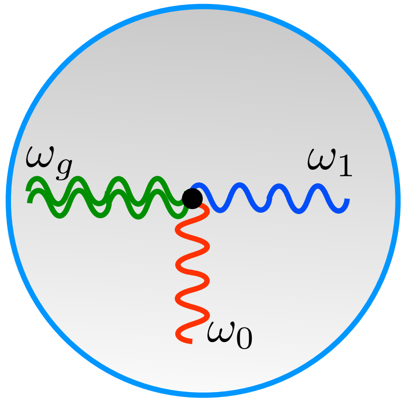
"Weber cavity"

This dominates since mechanical resonances are much less "stiff" than EM resonances (speed of sound << speed of light).

Signal Parametrics

Direct: GW → EM

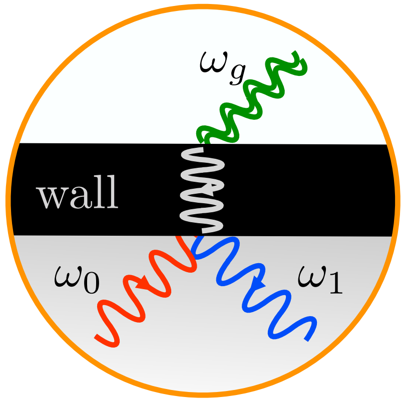
(Sebastian Ellis's talk)



photons excited by directly absorbing gravitons

$$E_{\mathrm{sig}} \sim Q\, h_{\mathrm{PD}}\, E_0$$

Indirect: GW → mechanical → EM



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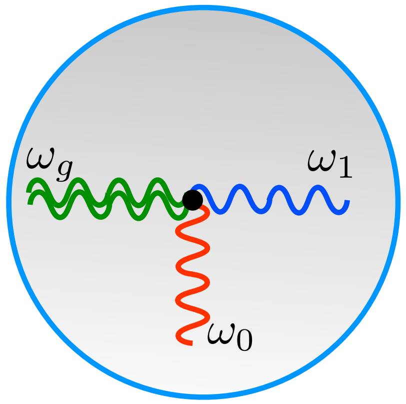

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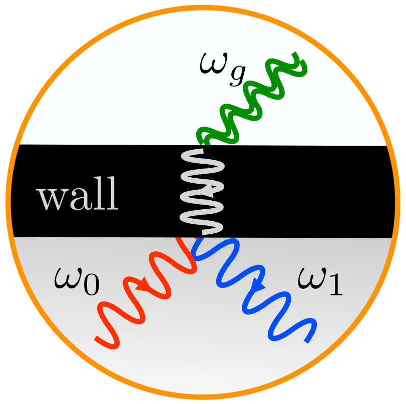


cavity shakes, which mixes EM modes

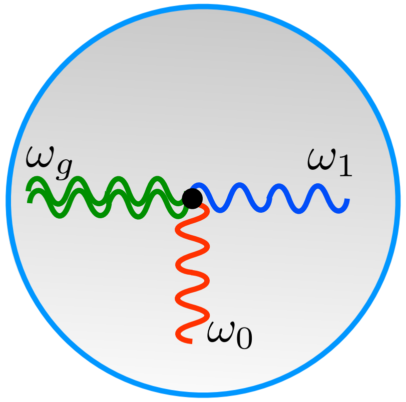
$$E_{\mathrm{sig}} \sim \frac{\Delta x_{\mathrm{cav}}}{L_{\mathrm{cav}}}\, Q\, E_0 \sim \frac{Q\, h_{\mathrm{PD}}\, E_0}{\max\left(\omega_g\, L_{\mathrm{cav}}\,,\; c_s\right)^2}$$

speed of sound $c_s \sim 10^{-6} \implies$ mechanical signal dominates for $\omega_g \ll \mathrm{GHz}$

Signal Parametrics

Direct: GW → EM

(Sebastian Ellis's talk)



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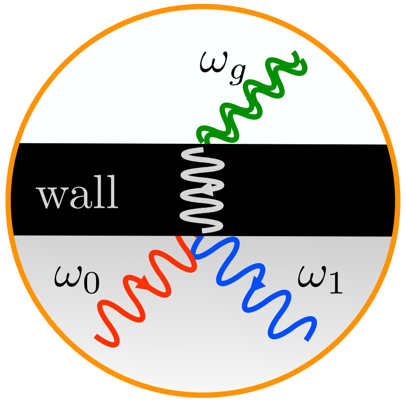

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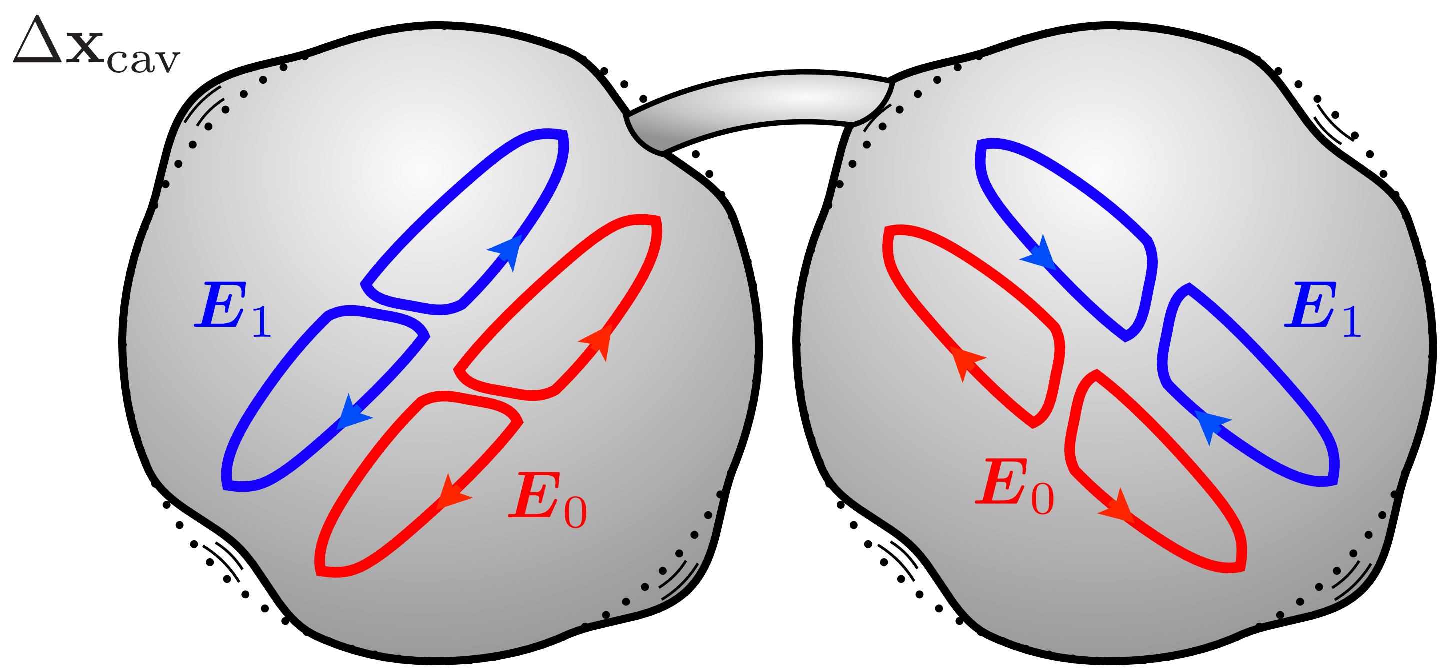
✓ Goal 1: $\gg$ kHz

✓ Goal 2: optimal scaling

Goal 3: smaller strain

Mechanical Signal



(TE_{112} mode)

mechanical → EM transduction

$$\int_{S_{\rm cav}} d\boldsymbol{A}\cdot\Delta\mathbf{x}_{\rm cav}\,\left(\boldsymbol{E}_0\cdot\boldsymbol{E}_1^* - \boldsymbol{B}_0\cdot\boldsymbol{B}_1^*\right)$$

$\Delta\mathbf{x}_{\rm cav} \propto \cos 2\phi$ *(quadrupole)*

$B \sim \cos\phi$ *(dipole in field, quadrupole in norm)*

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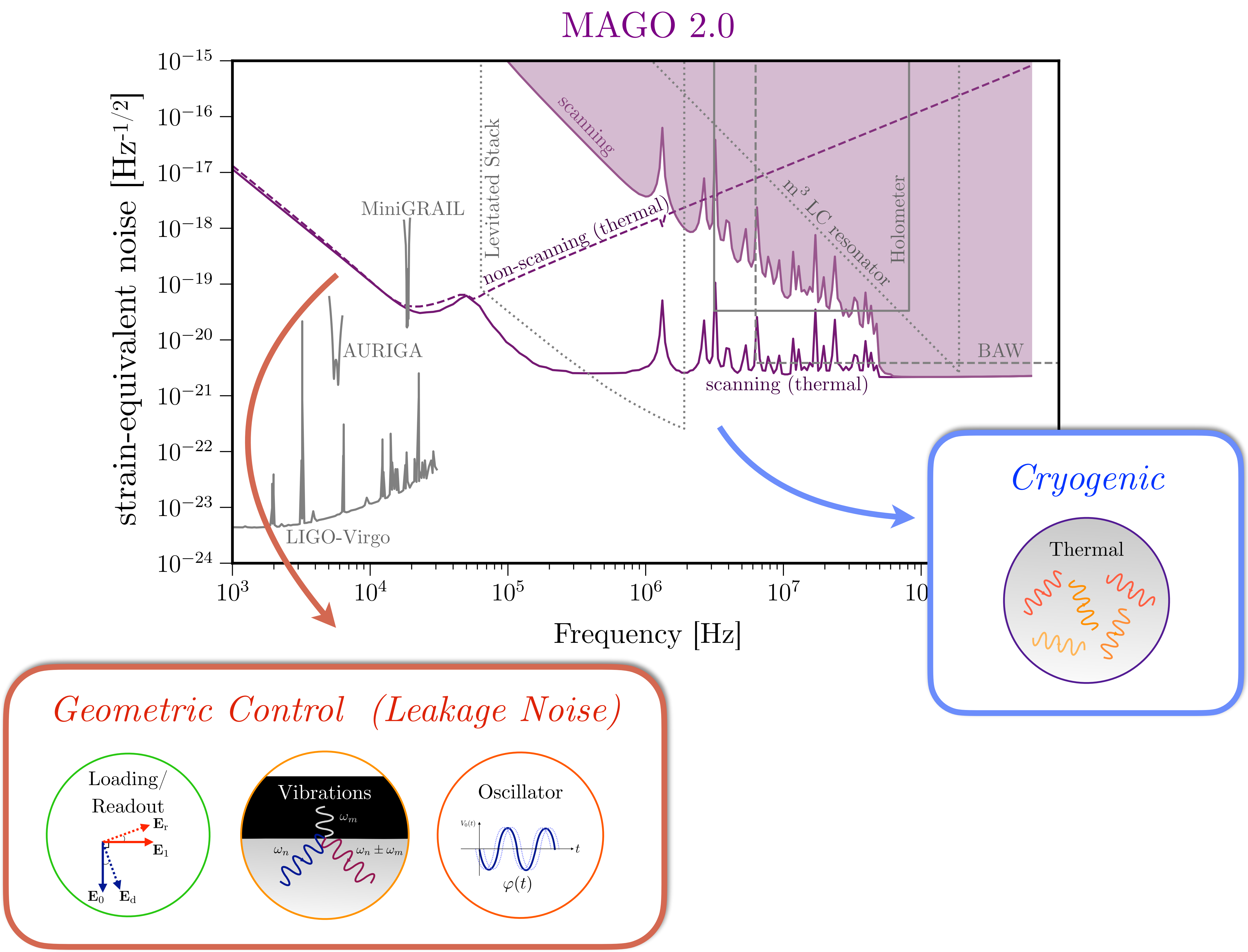
Noise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strain-equivalent noise [Hz-1/2]
Frequency [Hz]
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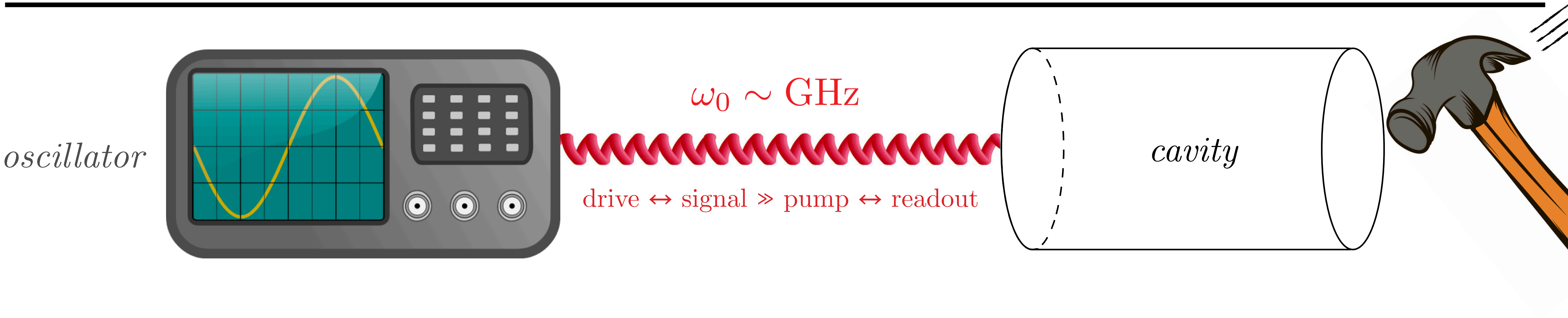
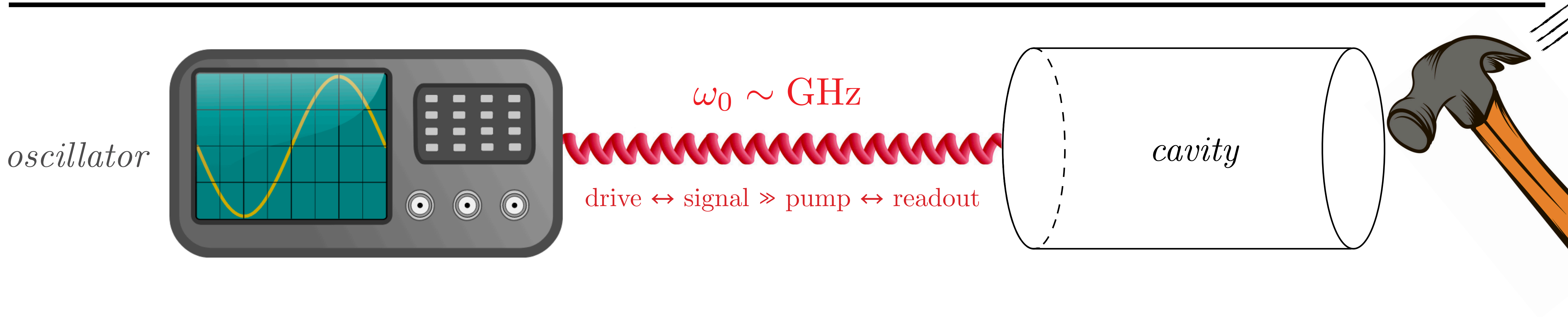
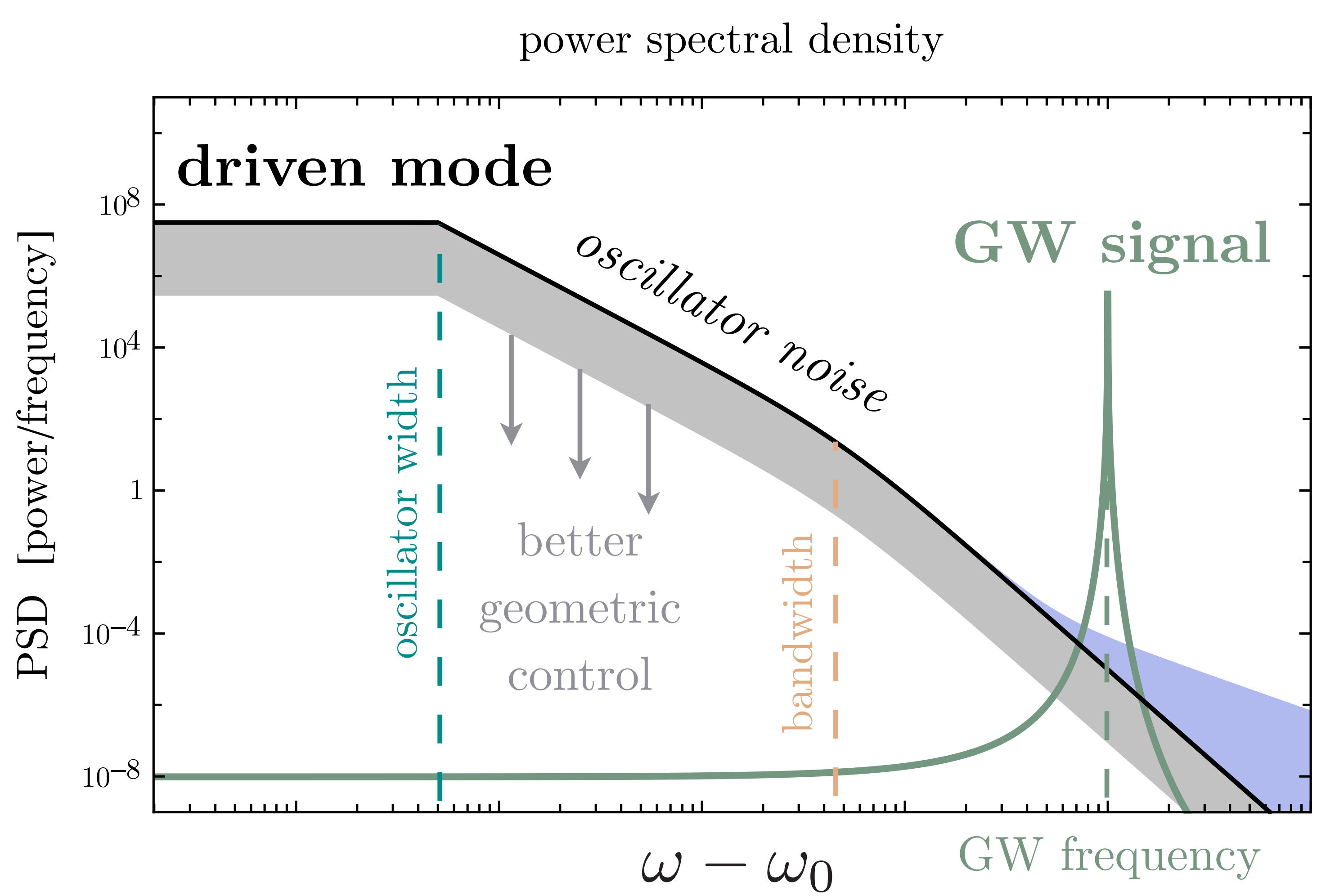
m³ LC resonator
Holometer
BAW
scanning (thermal)
Cryogenic
Thermal
Geometric Control (Leakage Noise)
Loading/
Readout
Vibrations
Oscillator

Leakage Noise: Mechanical Vibrations



Leakage Noise: Mechanical Vibrations

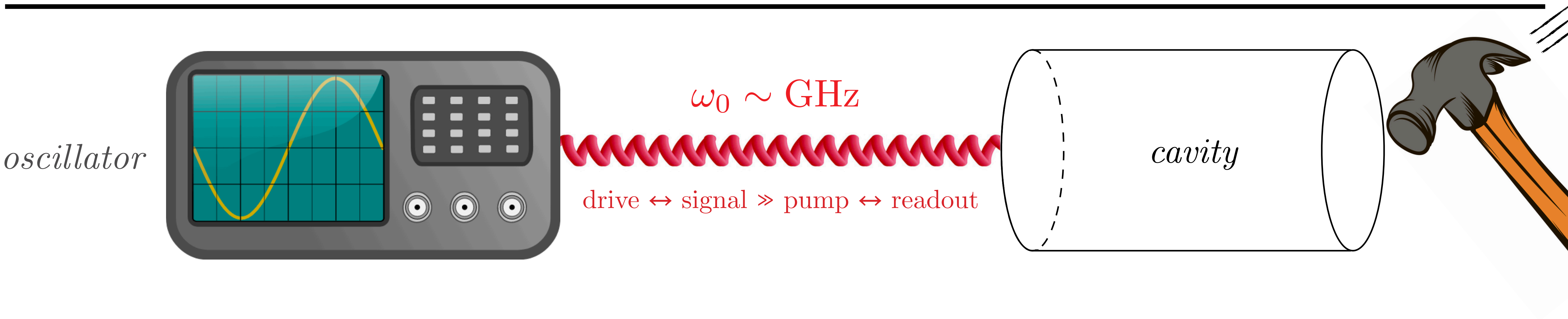




mechanical vibrations

Larger "leakage noise" for smaller GW frequencies

Leakage Noise: Mechanical Vibrations



Spectral Density of Mechanical Noise

$$S_{\text{mech}} \propto P_{\text{in}}\, S_{\text{force}}(\omega_g)/M_{\text{cav}}^2 \times (\text{EM response}) \times (\text{mech. response})$$

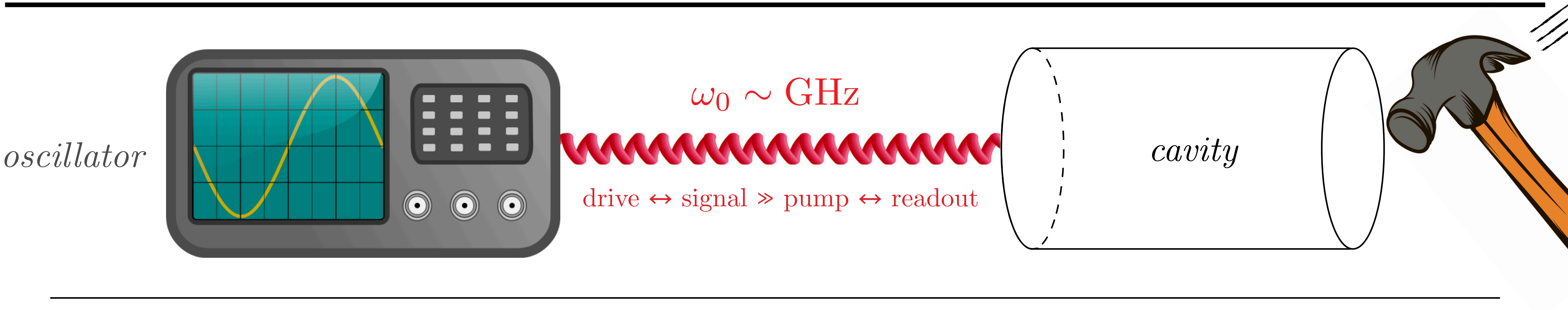
input power

vibrational force

cavity mass

How to estimate the noisy force that couples to cavity?

Leakage Noise: Mechanical Vibrations



Thermal Vibrations

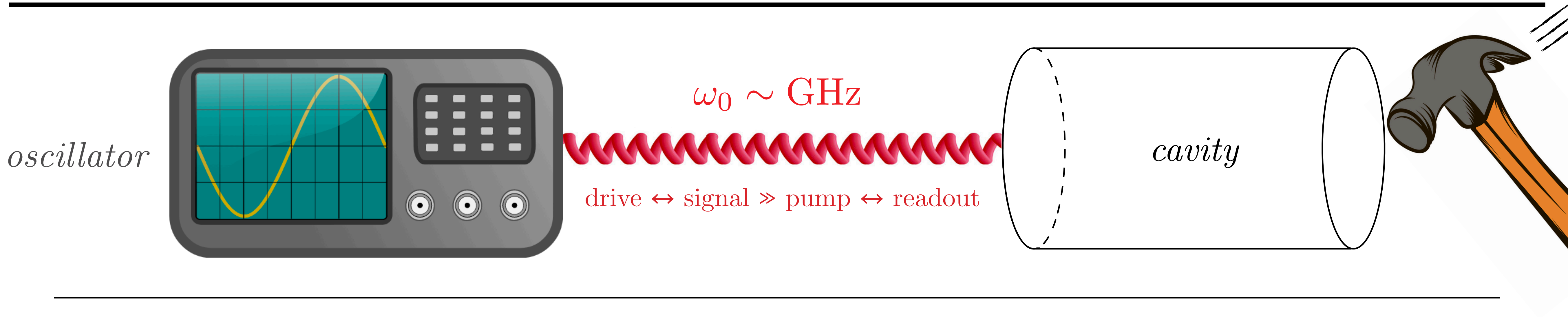
$$S_{\text{force}}^{(\text{thermal})} \sim 10^{-22}\ \mathrm{N}^2\ \mathrm{Hz}^{-1} \times \left(\frac{M_{\text{cav}}}{10\ \mathrm{kg}}\right)\left(\frac{\omega_{\text{mech}}}{10\ \mathrm{kHz}}\right)\left(\frac{T}{2\ \mathrm{K}}\right)\left(\frac{10^6}{Q_{\text{mech}}}\right)$$

Without any attenuation, we expect much stronger vibrations from the environment

$$S_{\text{force}}(\omega \gg \mathrm{kHz}) \sim 10^{-9}\ \mathrm{N}^2\ \mathrm{Hz}^{-1} \times \left(\frac{M_{\text{cav}}}{10\ \mathrm{kg}}\right)^2\left(\frac{\text{wobble}}{1\ \mathrm{nm}}\right)^2\left(\frac{10^6}{Q_{\text{mech}}}\right)\left(\frac{\mathrm{kHz}}{\omega}\right)^{1,2,\ldots}$$

normalized to match observed frequency shifts + conservative extrapolation at higher frequencies

Leakage Noise: Mechanical Vibrations



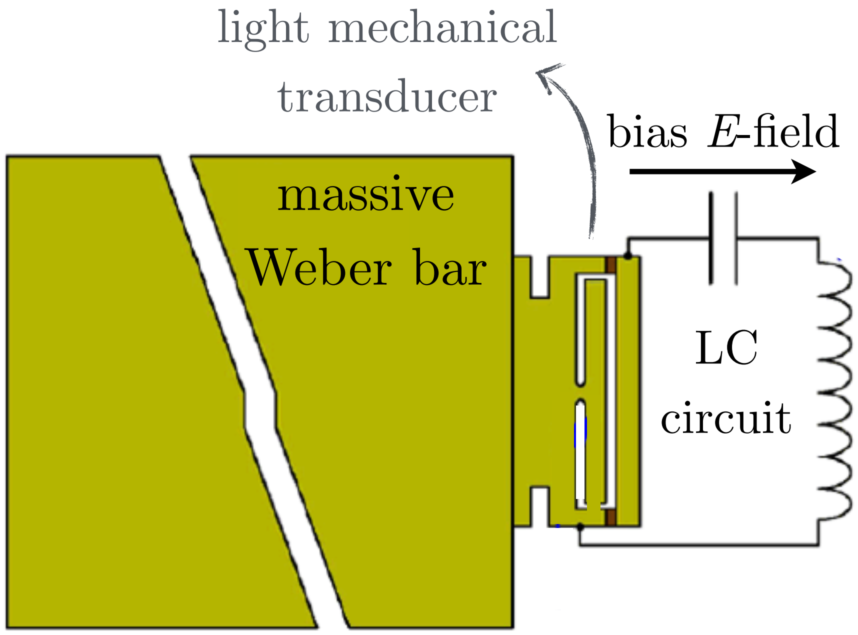
Power Spectral Density of Mechanical Noise

$$S_{\text{mech}} \propto P_{\text{in}}\, S_{\text{force}}(\omega_g)/M_{\text{cav}}^2 \times (\text{EM response}) \times (\text{mech. response})$$

Why superconducting cavities, as opposed to ton-scale bars?

High-Q

Why Superconducting Cavities?



$Q_{\mathrm{LC}} \sim 10^6 \ll Q_{\mathrm{cav}}$

Modern-day Weber bars are also efficient mechanical → EM transducers, but are limited by LC noise away from mechanical resonance.

High-Q

Why Superconducting Cavities?

Electromagnetic quality factor, $Q \sim 10^{10}$

$\downarrow$

- Amplifies resonant signals.
- Suppresses thermal photon noise.

High-Q

Why Superconducting Cavities?

Electromagnetic quality factor, $Q \sim 10^{10}$

$\downarrow$

- Amplifies resonant signals.
- Suppresses thermal photon noise.

✓ Goal 1:
$\gg$ kHz

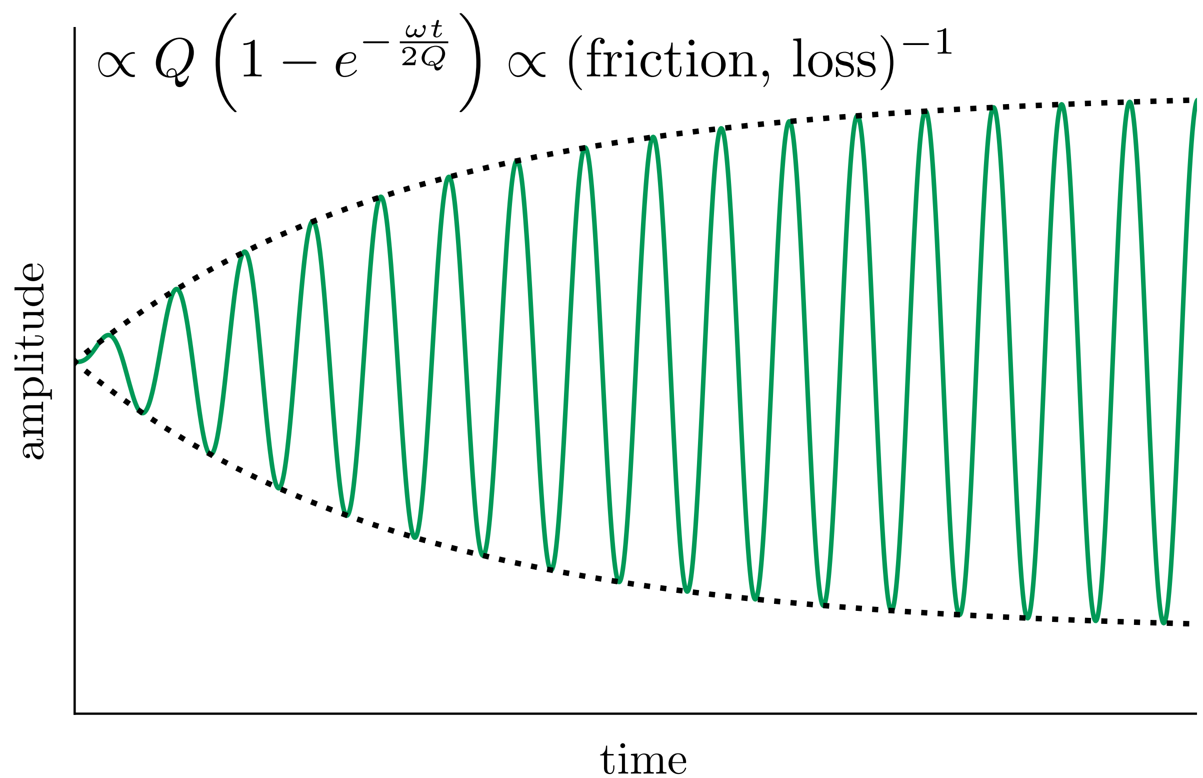
✓ Goal 2:
optimal scaling

✓ Goal 3:
smaller strain

High-Q: Signal

High-Q Enhances Resonance

driving term
on resonance



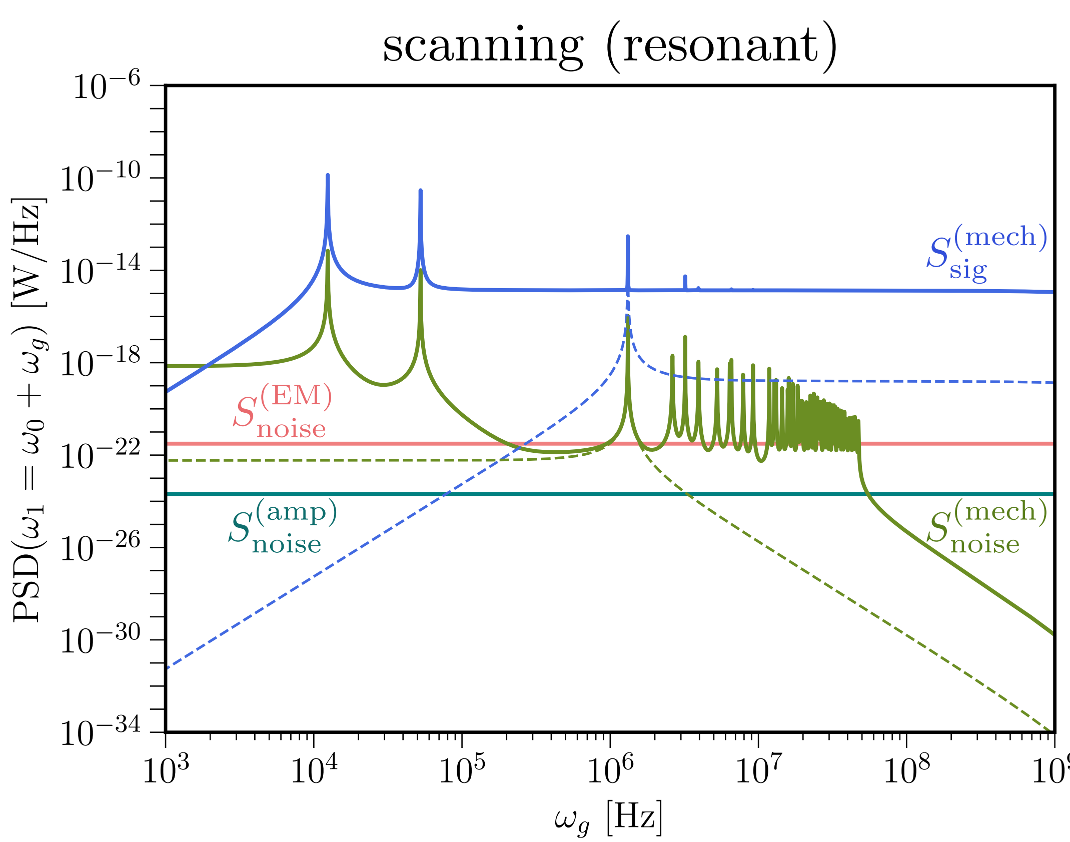
$Q \sim 10^{10}$ oscillations

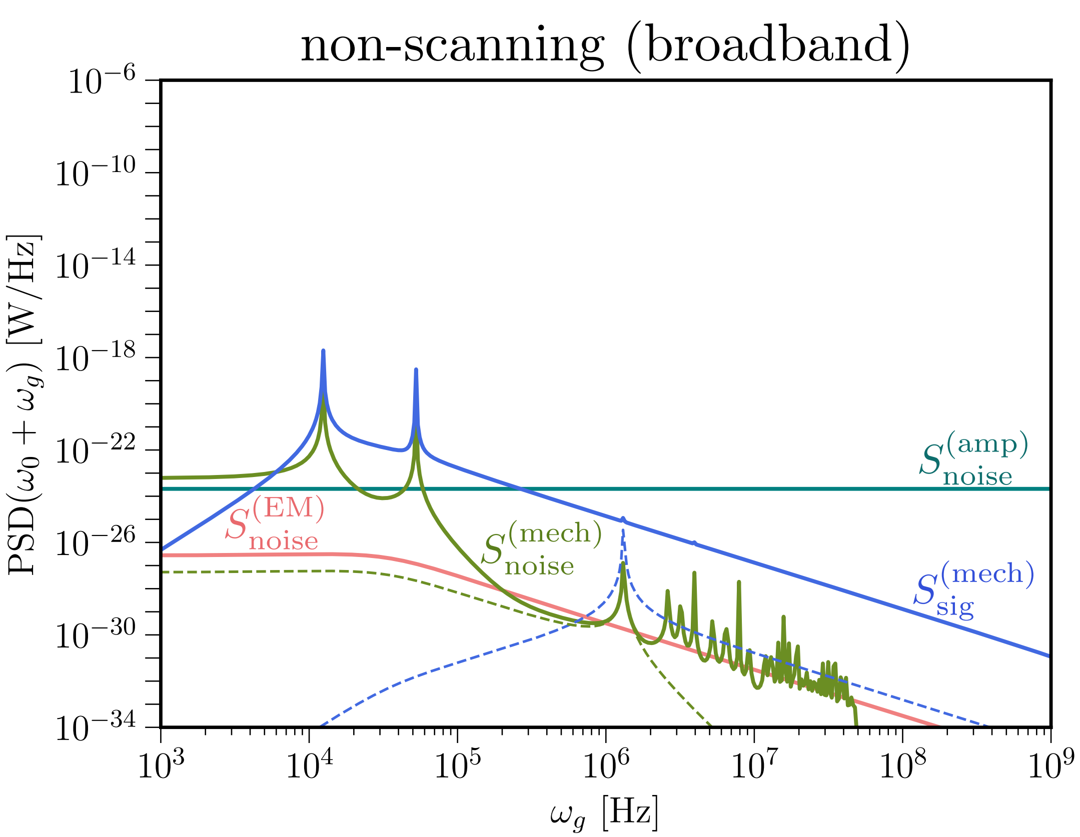
On resonance, larger Q means a longer time to drive power into a detector, thus amplifying an initially small signal.

High-Q: Noise

High-Q Suppresses Noise

- Mechanical noise typically only dominates for GW freq. ~ mechanical resonance.
- Thermal photon noise relevant elsewhere, which is suppressed by high-Q (low resistance).





< MHz: mechanical noise ~ $1/M_{\rm cav}^n$

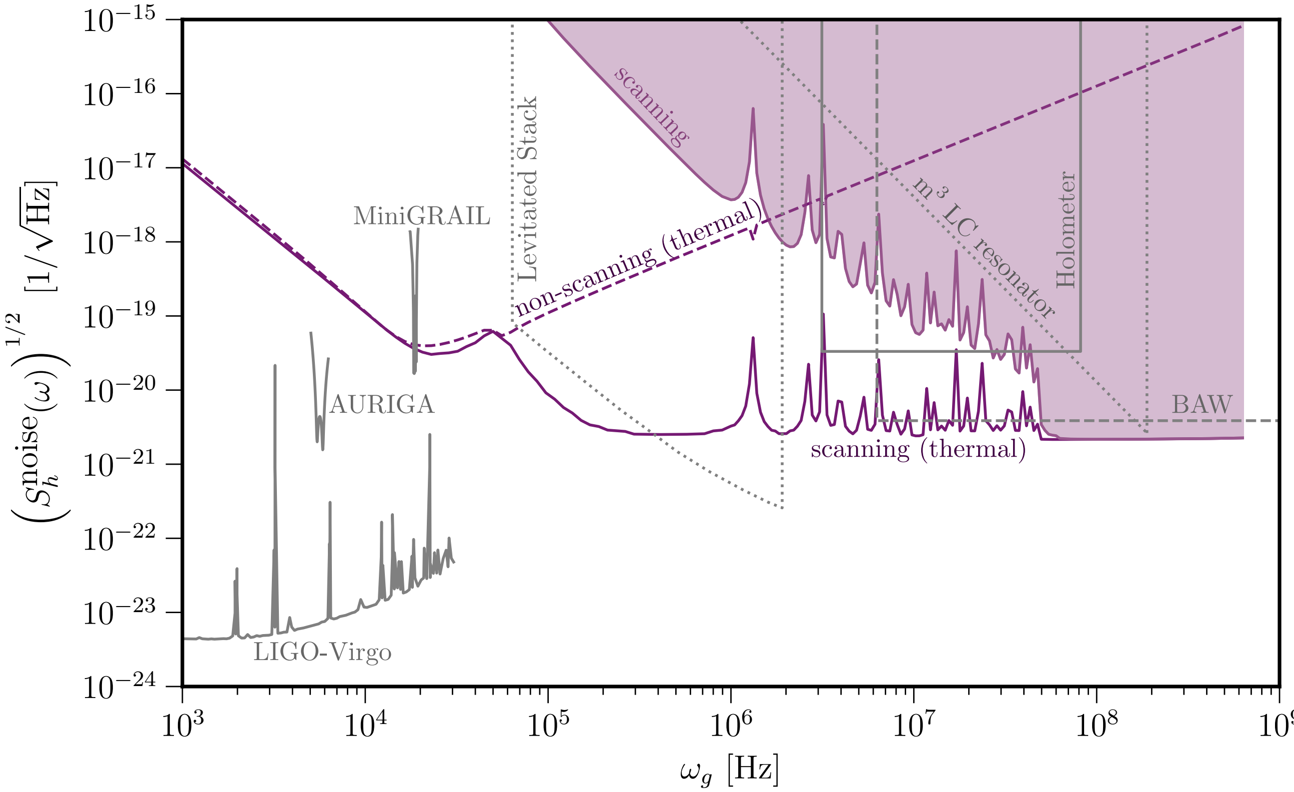
> MHz: EM noise ~ $T_{\rm cav}/Q$

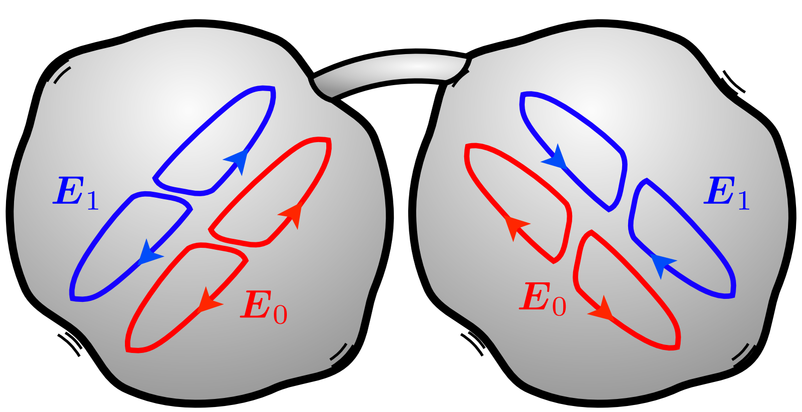
< MHz: mechanical noise ~ $1/M_{\rm cav}^n$

> MHz: amplifier noise ~ $\hbar \times$ GHz

MAGO Outlook

- MAGO is a more powerful than previously appreciated.
- Revitalization is in progress, $\frac{1}{\sqrt{2}}\Big(|\mathrm{FNAL}\rangle \pm |\mathrm{DESY}\rangle\Big)$.
- New high-frequency sources?
- Optimal design?



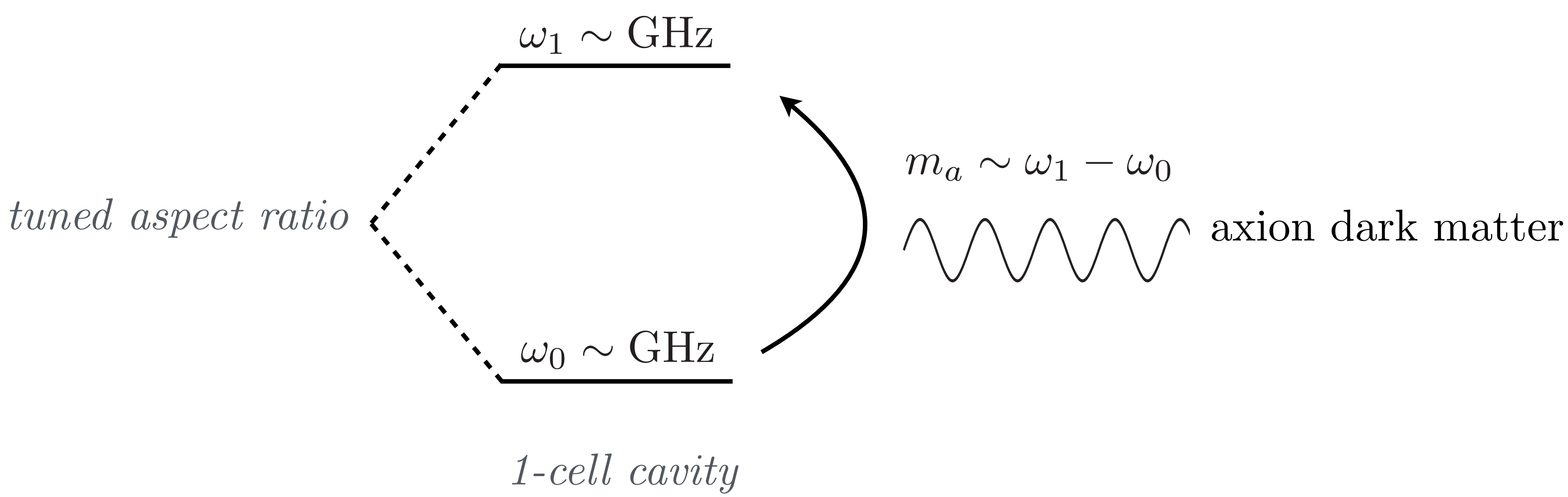


Outline

I. MAGO: Conceptual Overview of Setup and Signal

II. MAGO: Noise and "Why SRF?"

III. Bonus: A Similar Setup for Axion Dark Matter

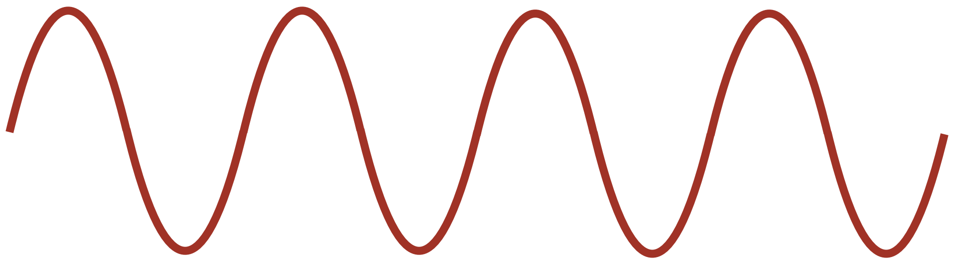


Axion Electrodynamics

prepared EM field

$\sim \cos\omega_0 t$

(frequency ~ your choice)



Axion Electrodynamics

prepared EM field

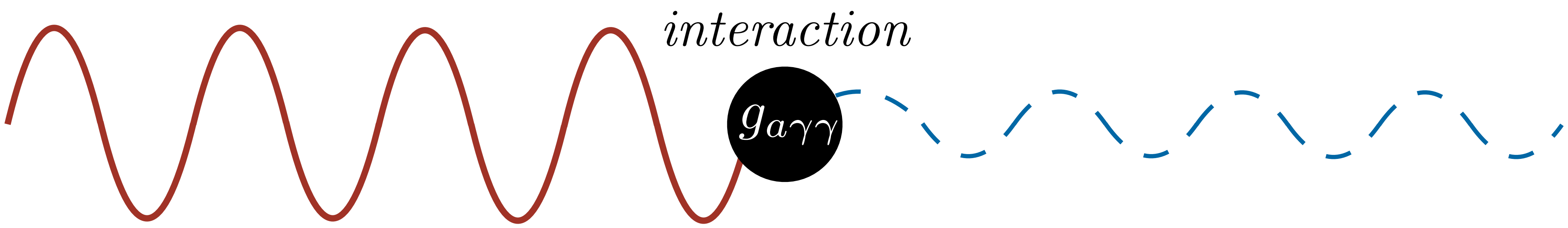
$\sim \cos \omega_0 t$

(frequency ~ your choice)

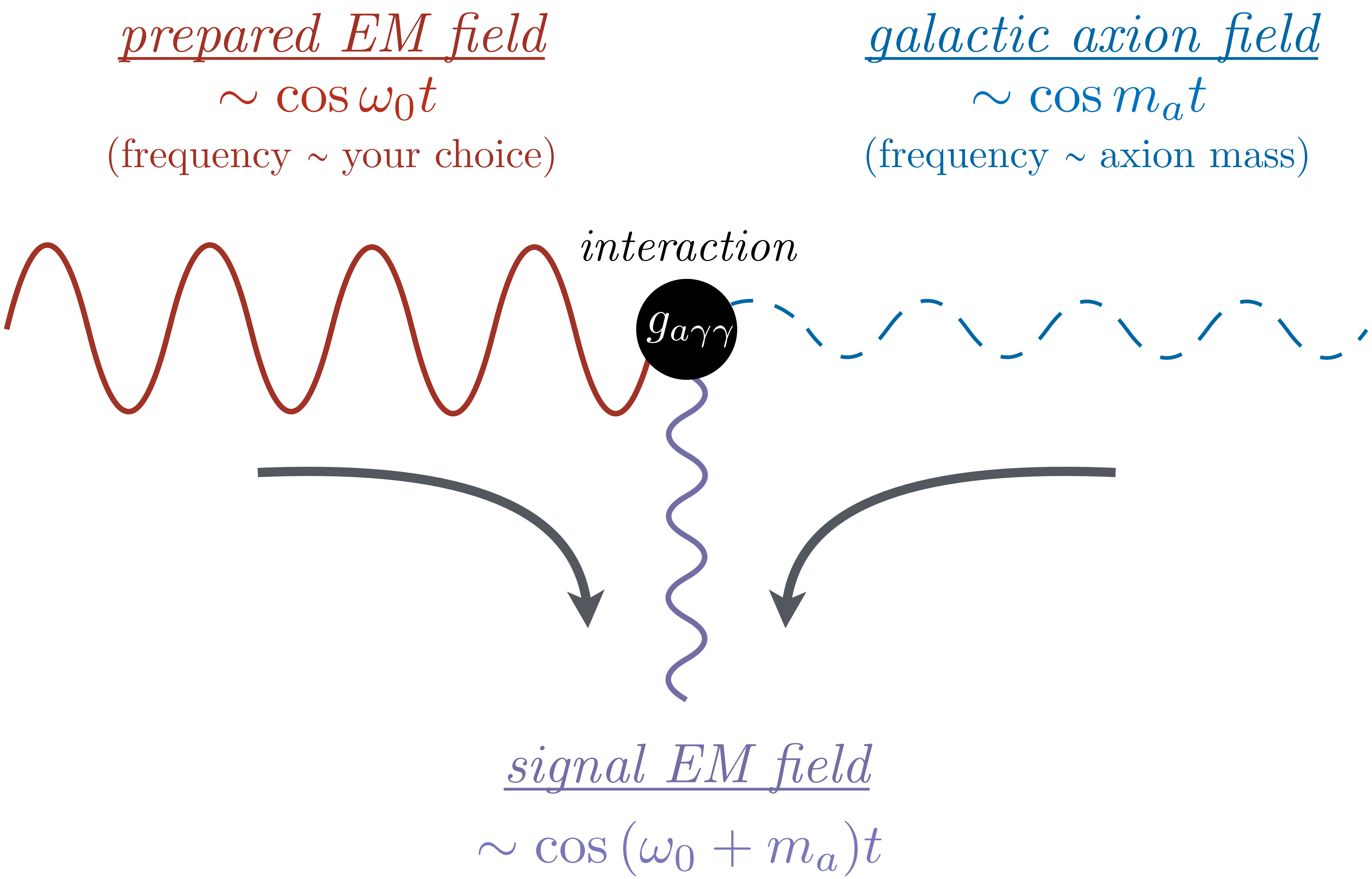
galactic axion field

$\sim \cos m_a t$

(frequency ~ axion mass)



Axion Electrodynamics



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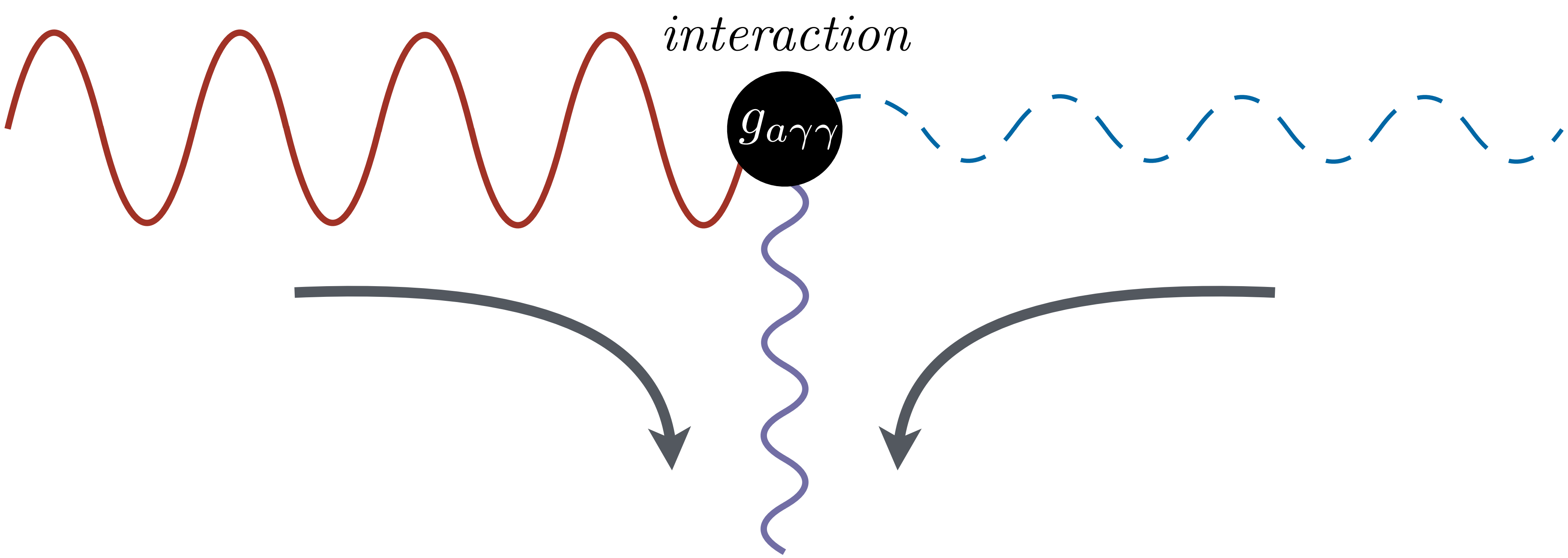


signal EM field

$\sim \cos(\omega_0 + m_a)t$

ideal detector is resonantly matched to signal frequency

signal power $\propto (\omega_0 + m_a)\ \cos(\omega_0 + m_a)t$

Static-Field vs. Oscillating-Field

prepared EM field

$\sim \cos \omega_0 t$

(frequency ~ your choice)

$\boxed{\text{signal power} \propto (\omega_0 + m_a)\ \cos(\omega_0 + m_a)t}$

galactic axion field

$\sim \cos m_a t$

(frequency ~ axion mass)

Static-Field vs. Oscillating-Field

prepared EM field

$\sim \cos \omega_0 t$

(frequency ~ your choice)

$\boxed{\text{signal power} \propto (\omega_0 + m_a)\, \cos(\omega_0 + m_a) t}$

galactic axion field

$\sim \cos m_a t$

(frequency ~ axion mass)

Static-Field Resonators

($\omega_0 = 0$, resonator frequency $= m_a$)

(most axion experiments)

Oscillating-Field/Heterodyne Resonators

($\omega_0 \neq 0$, resonator frequency $= \omega_0 + m_a$)

$(m_a \ll \omega_0)$

Static-Field vs. Oscillating-Field

prepared EM field

$\sim \cos \omega_0 t$

(frequency ~ your choice)

signal power $\propto (\omega_0 + m_a)\, \cos{(\omega_0 + m_a)t}$

galactic axion field

$\sim \cos m_a t$

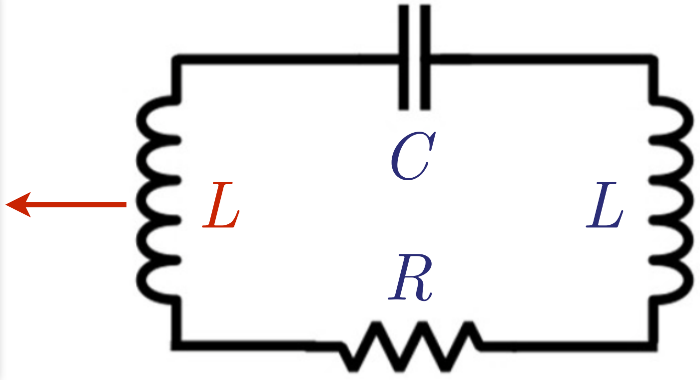
(frequency ~ axion mass)

Static-Field Resonators

($\omega_0 = 0$, resonator frequency $= m_a$)

LC circuit

(DM Radio @ SLAC, kHz-GHz)



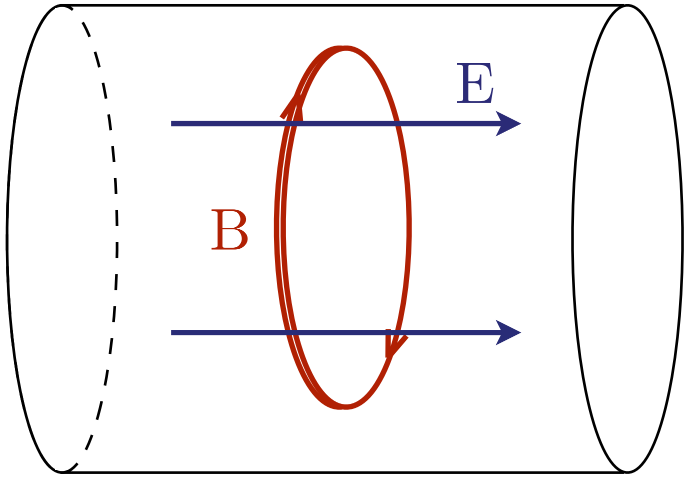
Oscillating-Field/Heterodyne Resonators

($\omega_0 \neq 0$, resonator frequency $= \omega_0 + m_a$)

($m_a \ll \omega_0$)

RF Cavity

($\omega_0 \sim$ GHz)



Static-Field vs. Oscillating-Field

prepared EM field

$\sim \cos \omega_0 t$

(frequency ~ your choice)

signal power $\propto (\omega_0 + m_a) \cos(\omega_0 + m_a)t$

galactic axion field

$\sim \cos m_a t$

(frequency ~ axion mass)

Static-Field Resonators

($\omega_0 = 0$, resonator frequency $= m_a$)

Oscillating-Field/Heterodyne Resonators

($\omega_0 \neq 0$, resonator frequency $= \omega_0 + m_a$)

($m_a \ll \omega_0$)

Static-Field vs. Oscillating-Field

prepared EM field

$\sim \cos \omega_0 t$

(frequency ~ your choice)

signal power $\propto (\omega_0 + m_a) \cos(\omega_0 + m_a)t$

galactic axion field

$\sim \cos m_a t$

(frequency ~ axion mass)

Static-Field Resonators

$(\omega_0 = 0\ ,\ \text{resonator frequency} = m_a)$

resonator frequency ~ axion mass

Very difficult to build resonators below ~ kHz

Oscillating-Field/Heterodyne Resonators

$(\omega_0 \neq 0\ ,\ \text{resonator frequency} = \omega_0 + m_a)$

$(m_a \ll \omega_0)$

Static-Field vs. Oscillating-Field

prepared EM field

$\sim \cos \omega_0 t$

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signal power $\propto (\omega_0 + m_a) \cos (\omega_0 + m_a) t$

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resonator frequency ~ axion mass

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Oscillating-Field/Heterodyne Resonators

($\omega_0 \neq 0$, resonator frequency $= \omega_0 + m_a$)

$(m_a \ll \omega_0)$

resonator frequency $\sim \omega_0 + m_a \sim \omega_0$

Can operate at preferred resonant frequency ~ GHz

Static-Field vs. Oscillating-Field

prepared EM field

$\sim \cos \omega_0 t$

(frequency ~ your choice)

signal power $\propto (\omega_0 + m_a) \cos (\omega_0 + m_a) t$

galactic axion field

$\sim \cos m_a t$

(frequency ~ axion mass)

Static-Field Resonators

($\omega_0 = 0$, resonator frequency $= m_a$)

resonator frequency ~ axion mass

Very difficult to build resonators below ~ kHz

Oscillating-Field/Heterodyne Resonators

($\omega_0 \neq 0$, resonator frequency $= \omega_0 + m_a$)

$(m_a \ll \omega_0)$

resonator frequency $\sim \omega_0 + m_a \sim \omega_0$

Can operate at preferred resonant frequency ~ GHz

SRF: smaller masses

Static-Field vs. Oscillating-Field

prepared EM field

$\sim \cos \omega_0 t$

(frequency ~ your choice)

signal power $\propto (\omega_0 + m_a) \cos(\omega_0 + m_a)t$

galactic axion field

$\sim \cos m_a t$

(frequency ~ axion mass)

Static-Field Resonators

$(\omega_0 = 0\ ,\ \text{resonator frequency} = m_a)$

resonator frequency ~ axion mass

Very difficult to build resonators below ~ kHz

Oscillating-Field/Heterodyne Resonators

$(\omega_0 \neq 0\ ,\ \text{resonator frequency} = \omega_0 + m_a)$

$(m_a \ll \omega_0)$

resonator frequency $\sim \omega_0 + m_a \sim \omega_0$

Can operate at preferred resonant frequency ~ GHz

SRF: smaller masses

Static-Field vs. Oscillating-Field

prepared EM field

$\sim \cos \omega_0 t$

(frequency ~ your choice)

signal power $\propto (\omega_0 + m_a) \cos(\omega_0 + m_a)t$

galactic axion field

$\sim \cos m_a t$

(frequency ~ axion mass)

Static-Field Resonators

$(\omega_0 = 0\ ,\ \text{resonator frequency} = m_a)$

resonator frequency ~ axion mass

Very difficult to build resonators below ~ kHz

small axion masses $\implies$ suppressed signal power

signal power $\propto m_a$

Oscillating-Field/Heterodyne Resonators

$(\omega_0 \neq 0\ ,\ \text{resonator frequency} = \omega_0 + m_a)$

$(m_a \ll \omega_0)$

resonator frequency $\sim \omega_0 + m_a \sim \omega_0$

Can operate at preferred resonant frequency ~ GHz

SRF: smaller masses

Static-Field vs. Oscillating-Field

<u>*prepared EM field*</u>

$\sim \cos \omega_0 t$

(frequency ~ your choice)

signal power $\propto (\omega_0 + m_a) \cos(\omega_0 + m_a)t$

<u>*galactic axion field*</u>

$\sim \cos m_a t$

(frequency ~ axion mass)

<u>Static-Field Resonators</u>

($\omega_0 = 0$, resonator frequency $= m_a$)

resonator frequency ~ axion mass

Very difficult to build resonators below ~ kHz

small axion masses $\Longrightarrow$ suppressed signal power

signal power $\propto m_a$

<u>Oscillating-Field/Heterodyne Resonators</u>

($\omega_0 \neq 0$, resonator frequency $= \omega_0 + m_a$)

$(m_a \ll \omega_0)$

resonator frequency $\sim \omega_0 + m_a \sim \omega_0$

Can operate at preferred resonant frequency ~ GHz

signal power independent of axion mass for $m_a \ll \omega_0$

signal power $\propto \omega_0$

SRF: smaller masses

Static-Field vs. Oscillating-Field

prepared EM field

$\sim \cos \omega_0 t$

(frequency ~ your choice)

signal power $\propto (\omega_0 + m_a) \cos{(\omega_0 + m_a)t}$

galactic axion field

$\sim \cos m_a t$

(frequency ~ axion mass)

Static-Field Resonators

$(\omega_0 = 0\ ,$ resonator frequency $= m_a)$

resonator frequency ~ axion mass

Very difficult to build resonators below ~ kHz

small axion masses $\implies$ suppressed signal power

signal power $\propto m_a$

Oscillating-Field/Heterodyne Resonators

$(\omega_0 \neq 0\ ,$ resonator frequency $= \omega_0 + m_a)$

$(m_a \ll \omega_0)$

resonator frequency $\sim \omega_0 + m_a \sim \omega_0$

Can operate at preferred resonant frequency ~ GHz

signal power independent of axion mass for $m_a \ll \omega_0$

signal power $\propto \omega_0$

enhancement of $\omega_0/m_a \sim 10^6$ for $\omega_0 \sim$ GHz and $m_a \sim$ kHz

SRF: smaller masses | better scaling

Static-Field vs. Oscillating-Field

prepared EM field

$\sim \cos \omega_0 t$

(frequency ~ your choice)

signal power $\propto (\omega_0 + m_a)\ \cos{(\omega_0 + m_a)t}$

galactic axion field

$\sim \cos m_a t$

(frequency ~ axion mass)

Static-Field Resonators

$(\omega_0 = 0\ ,\ \text{resonator frequency} = m_a)$

resonator frequency ~ axion mass

Very difficult to build resonators below ~ kHz

small axion masses $\Longrightarrow$ suppressed signal power

signal power $\propto m_a$

Oscillating-Field/Heterodyne Resonators

$(\omega_0 \neq 0\ ,\ \text{resonator frequency} = \omega_0 + m_a)$

$(m_a \ll \omega_0)$

resonator frequency $\sim \omega_0 + m_a \sim \omega_0$

Can operate at preferred resonant frequency ~ GHz

signal power independent of axion mass for $m_a \ll \omega_0$

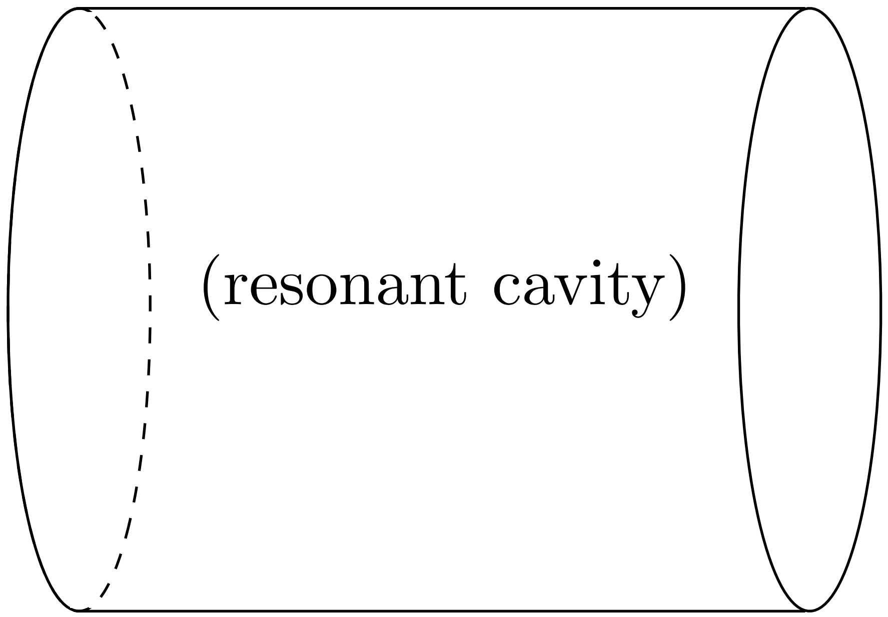
signal power $\propto \omega_0$

enhancement of $\omega_0/m_a \sim 10^6$ for $\omega_0 \sim$ GHz and $m_a \sim$ kHz

What is a concrete example of an oscillating-field/heterodyne resonator?

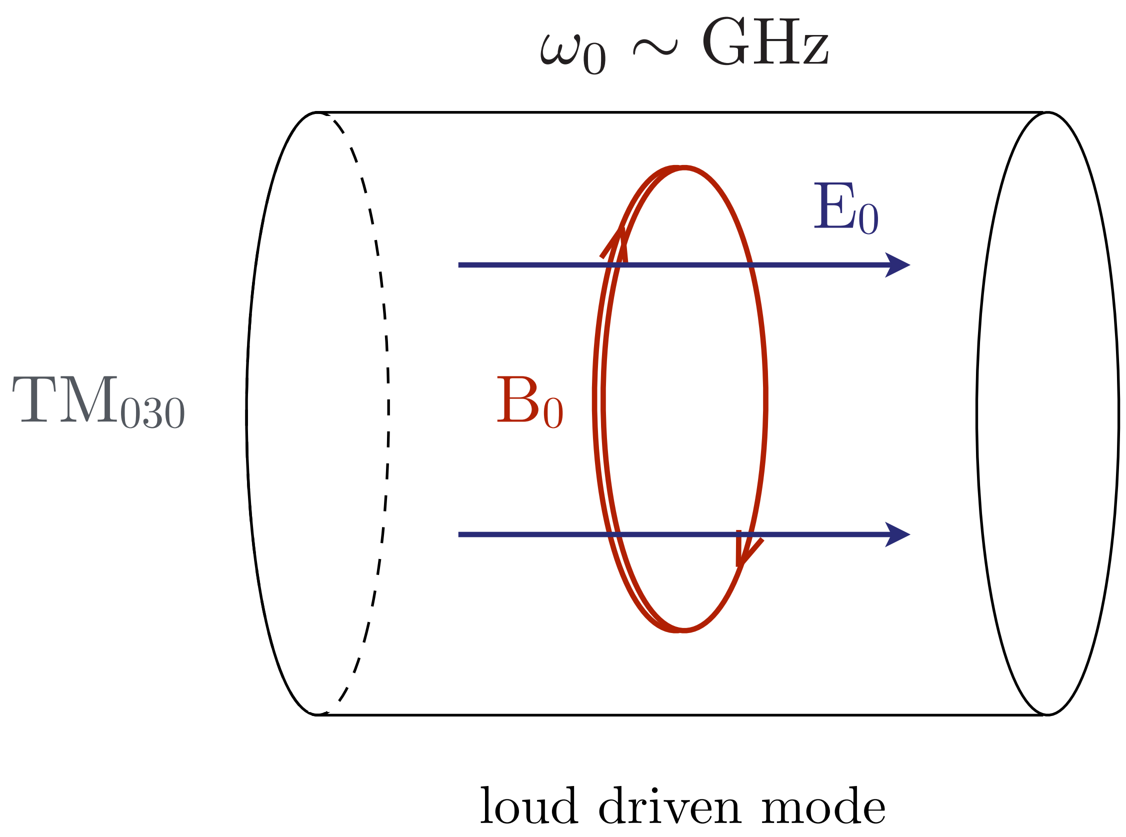
Heterodyne Detection of Axion Dark Matter

Heterodyne Detection of Axion Dark Matter



“Frequency Conversion” between two ~ GHz cavity modes

Heterodyne Detection of Axion Dark Matter



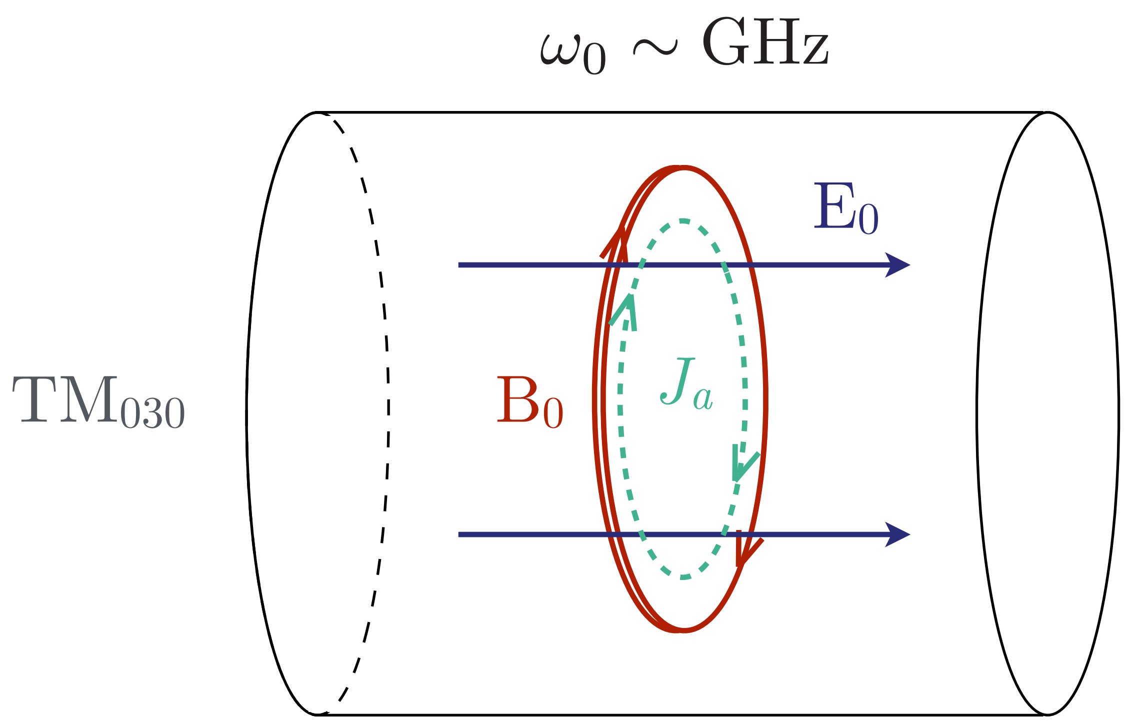
<u>"Frequency Conversion" between two ~ GHz cavity modes</u>

1. Prepare the cavity with a large amount of power at mode ω_0 .
2. Axion dark matter resonantly transfers a small amount of power to mode ω_1 .
3. Scan over frequency-splittings (axion masses) by slightly deforming the cavity.

Heterodyne Detection of Axion Dark Matter

axion background

$\cos m_a t$



loud driven mode

effective axion current

$$J_a \sim g_{a\gamma\gamma}\, B\, \partial_t a$$
$$\propto \cos\left(\omega_0 \pm m_a\right)t$$

“Frequency Conversion” between two ~ GHz cavity modes

1. Prepare the cavity with a large amount of power at mode ω_0 .
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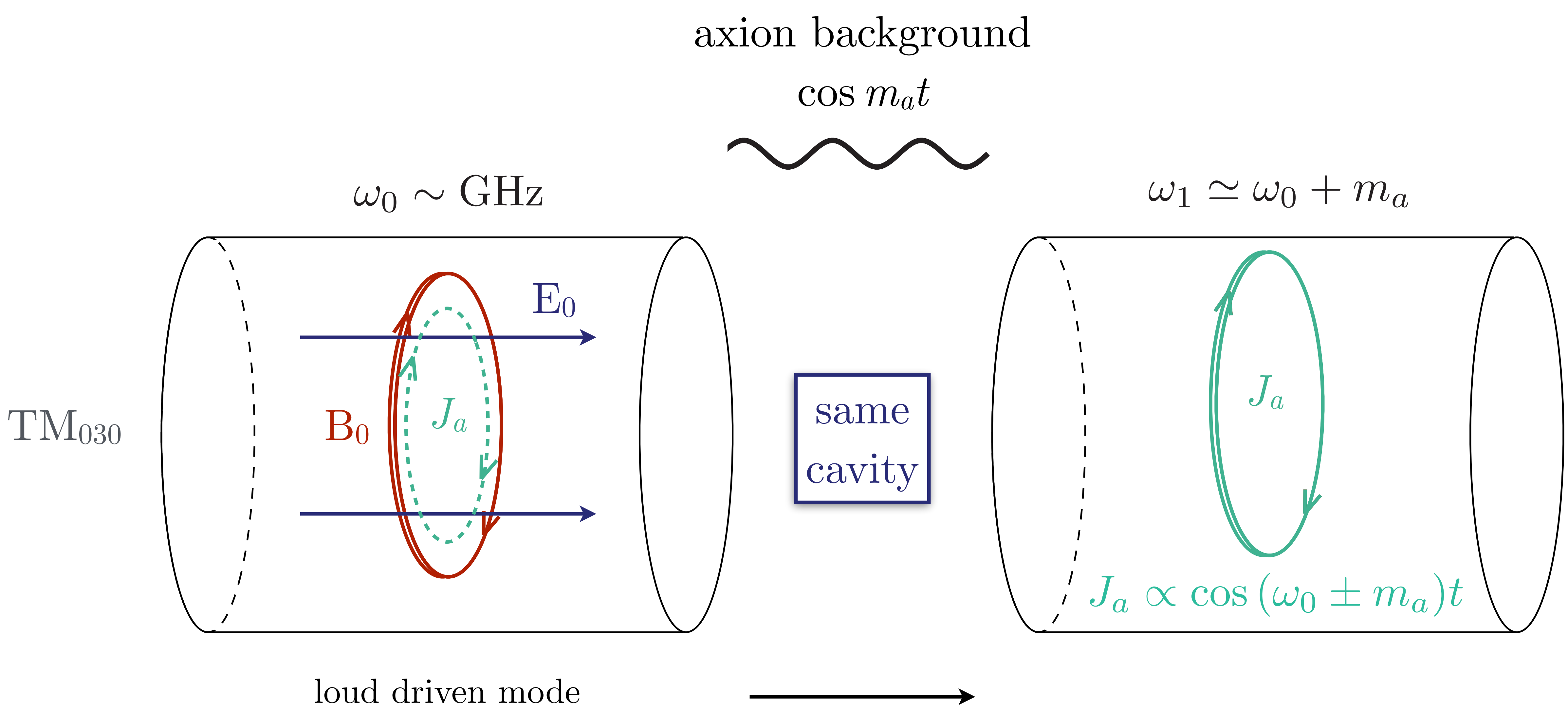
Heterodyne Detection of Axion Dark Matter



"Frequency Conversion" between two ~ GHz cavity modes

1. Prepare the cavity with a large amount of power at mode ω_0 .
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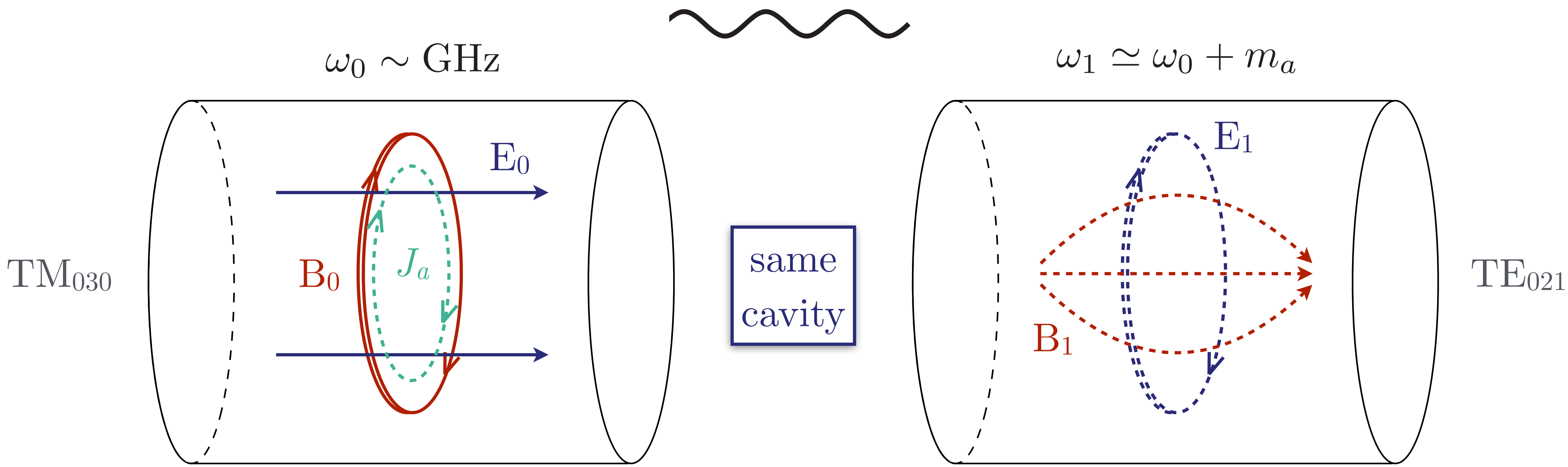
Heterodyne Detection of Axion Dark Matter

axion background

$\cos m_a t$



loud driven mode

quiet signal mode (different profile and frequency)

$$\int_{V_{\mathrm{cav}}} d^3\mathbf{x}\ \boldsymbol{B}_0 \cdot \boldsymbol{E}_1^*$$

"Frequency Conversion" between two ~ GHz cavity modes

1. Prepare the cavity with a large amount of power at mode ω_0 .
2. Axion dark matter resonantly transfers a small amount of power to mode ω_1 .
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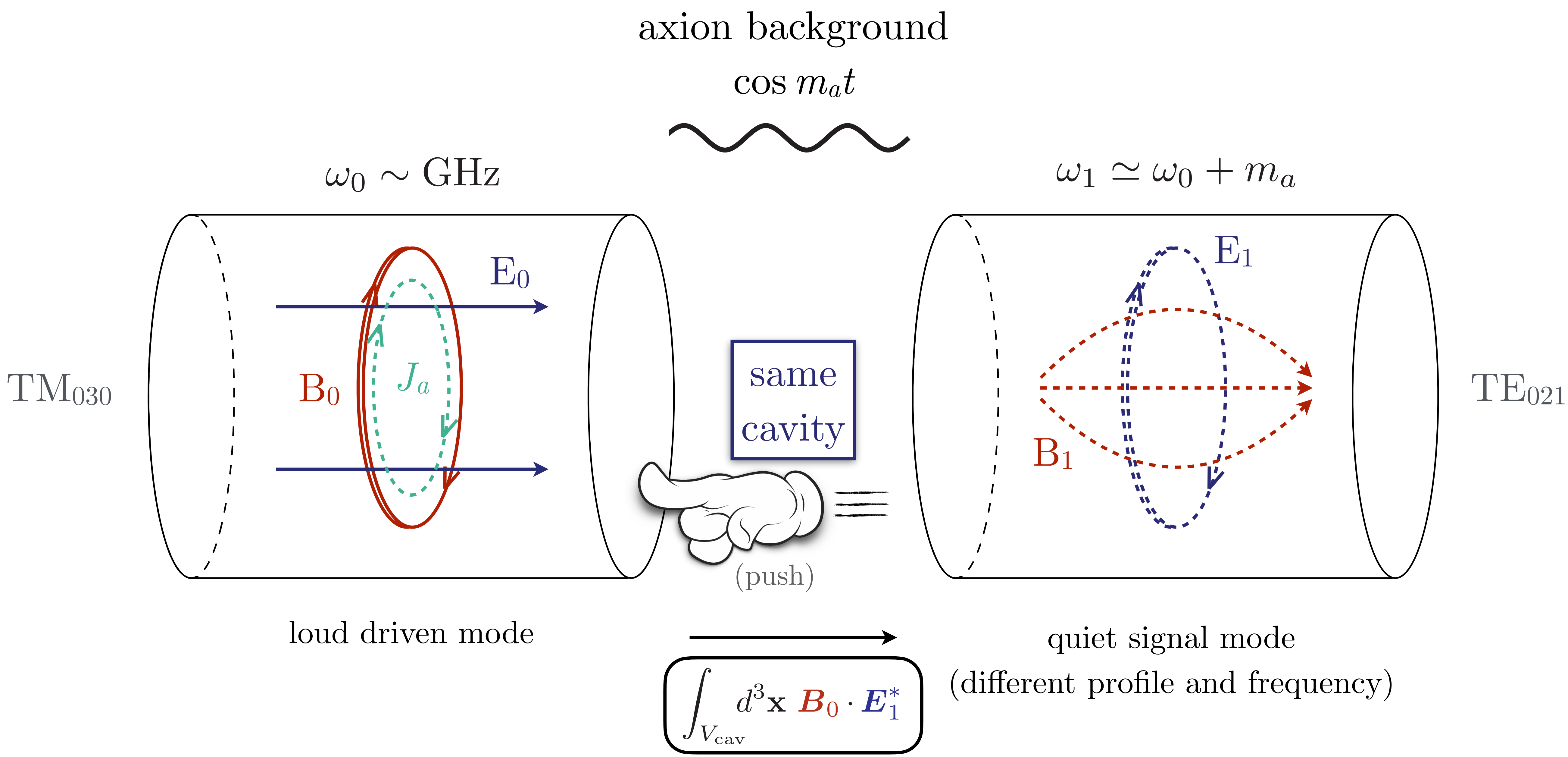
Heterodyne Detection of Axion Dark Matter



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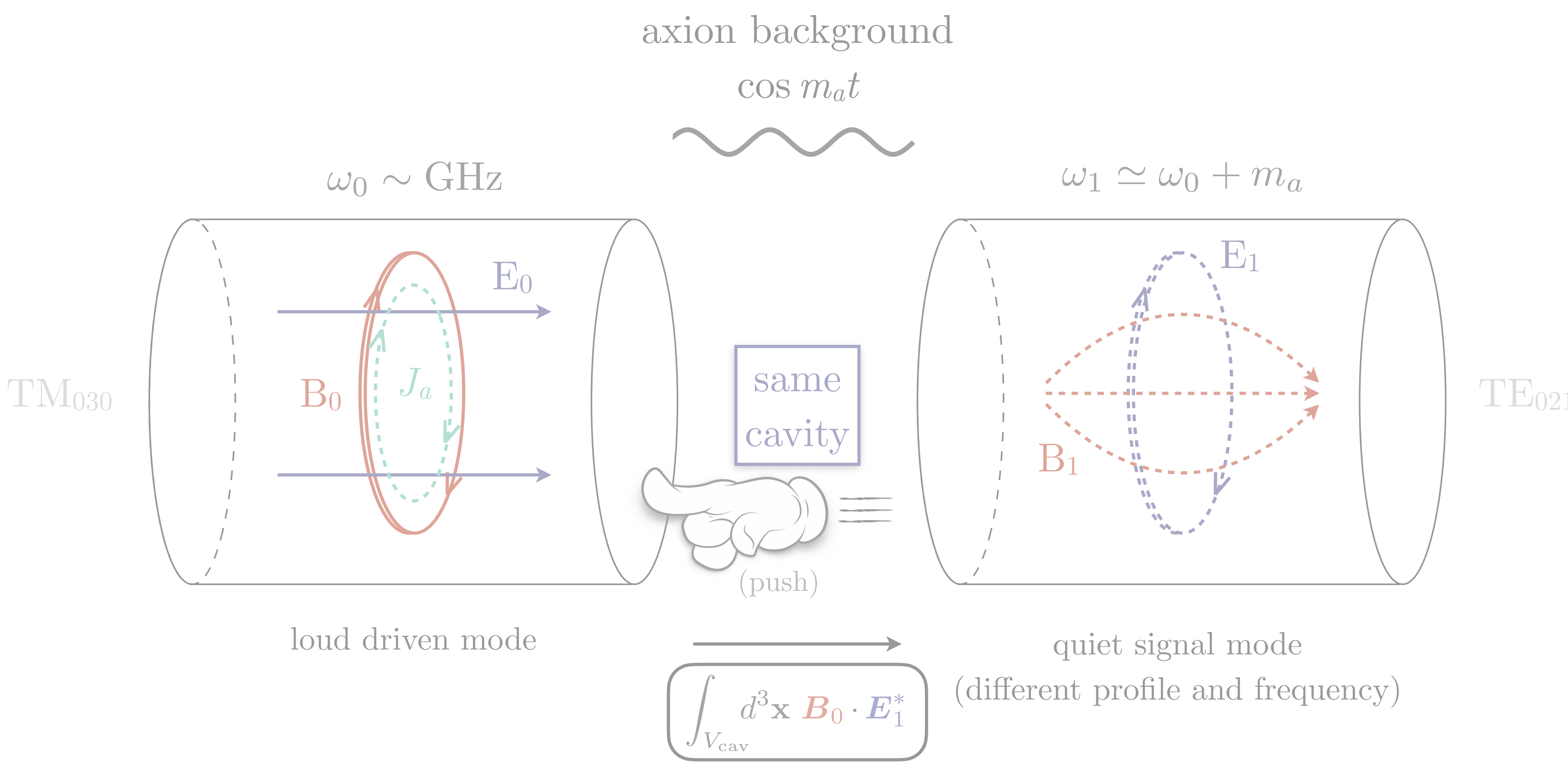
Heterodyne Detection of Axion Dark Matter



<u>signal is always read out at ~ GHz</u>

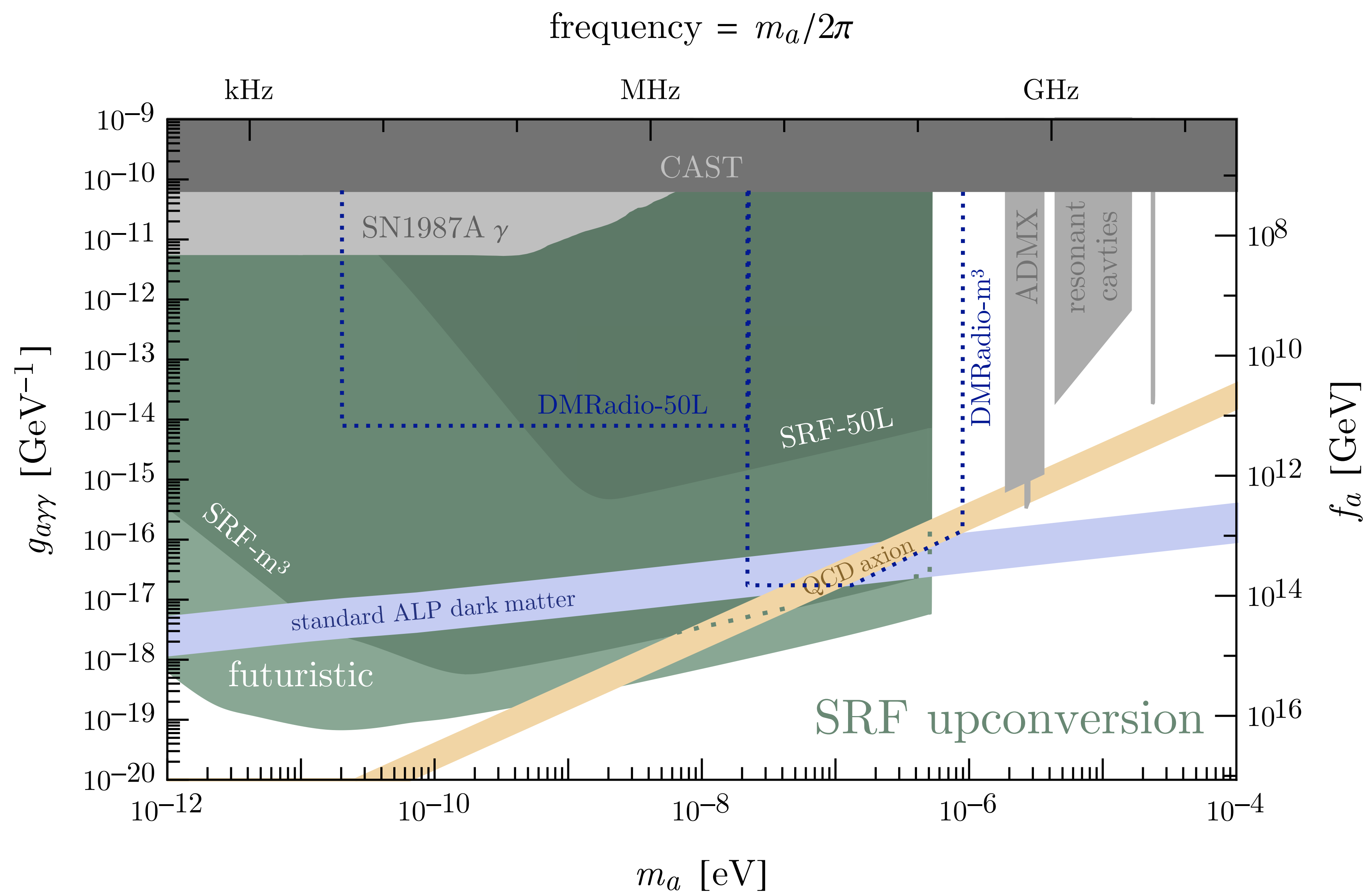
directly benefit from $Q \sim 10^{11}$

signal power enhanced by GHz$/m_a \gg 1$

<u>suppressed mechanical noise</u>

$\boldsymbol{E}_0 \cdot \boldsymbol{E}_1 = \boldsymbol{B}_0 \cdot \boldsymbol{B}_1 = 0$

Heterodyne Detection of Axion Dark Matter



(prototype arriving soon at Fermilab)

Outlook

Superconducting cavities

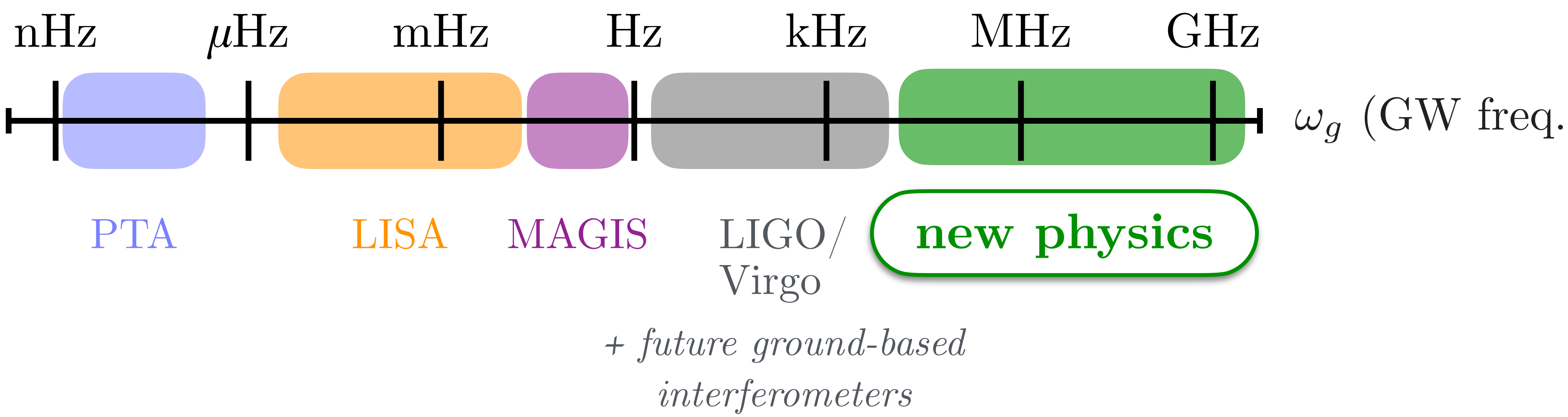
- Currently unexplored high-frequency gravitational waves.
- Axion dark matter with Compton wavelength many orders of magnitude larger than detector.
- meV dark photons, photon mass, millicharged dark matter, millicharged particles, ...

Now is an important time

- Now beginning to explore new physics at scales currently unaccessible with previous technology.
- How can technologies coming online be steered to make the biggest impact on fundamental physics?

Back Up Slides

Spectrum



Known Astrophysics

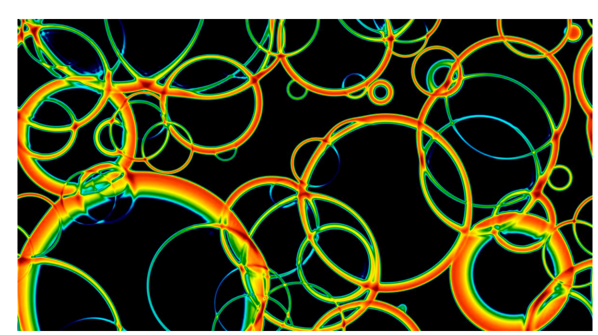
$$\omega_g \lesssim \frac{1}{10\,GM}$$

$$\sim 10 \text{ kHz} \times \frac{M_\odot}{M}$$

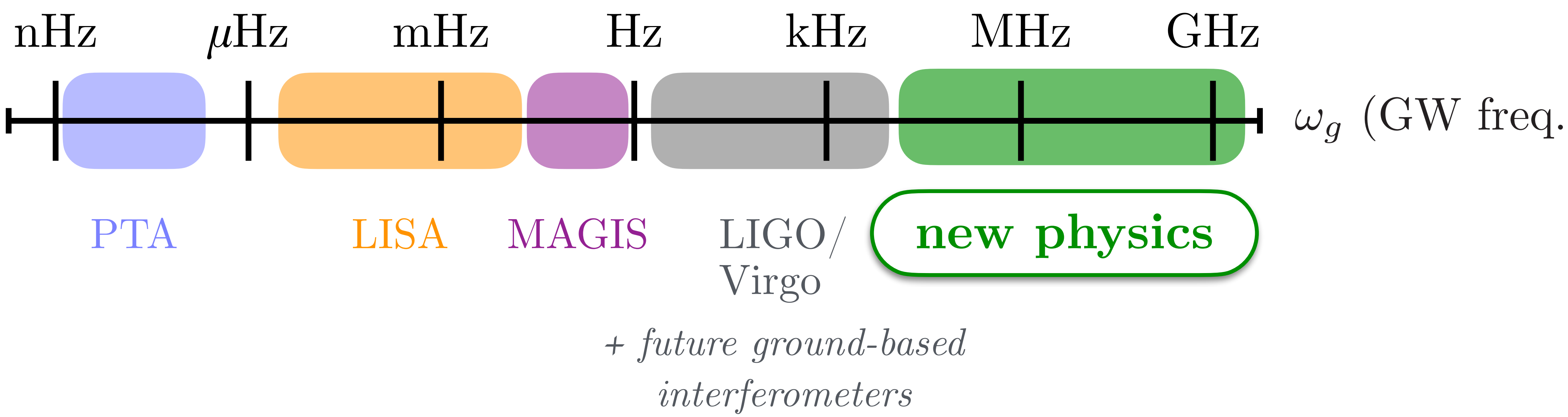
Early Universe

$$T_\gamma \Big|_{\text{event}} \gtrsim 10^{11} \text{ GeV}$$

$$\implies \omega_g \gtrsim 10 \text{ kHz}$$



Spectrum



Honest take on primordial signals

$$S_h \sim \frac{d\langle h^2 \rangle}{d\omega_g}$$

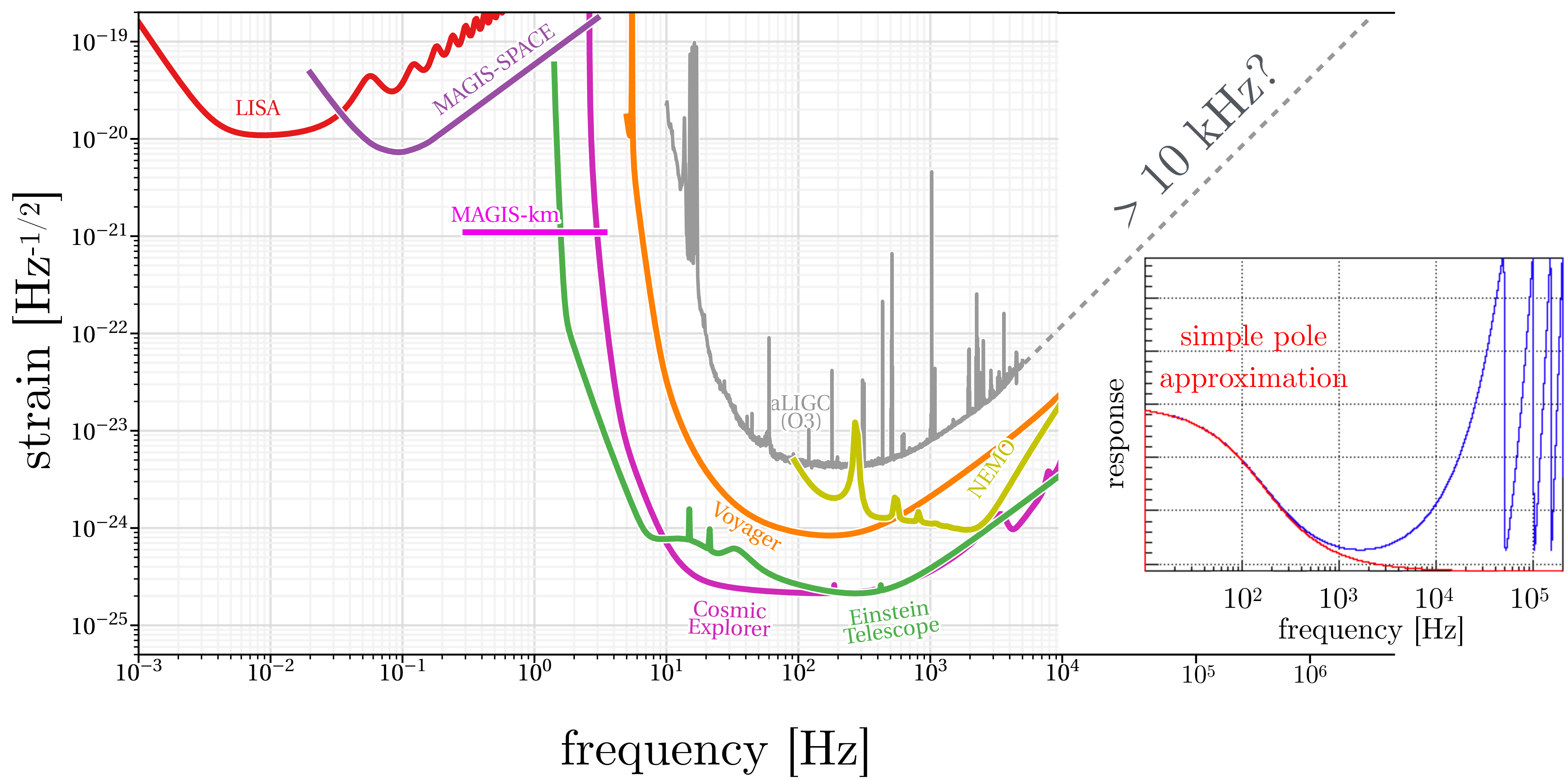
$$\rho_g \sim \omega_g^2 \, h^2 / G$$

$$\implies \Omega_g(\omega_g) \sim \frac{1}{\rho_{\rm cr}} \frac{d\rho_g}{d\log\omega_g} \sim \mathcal{O}(1) \times \left(\frac{\omega_g}{\rm kHz}\right)^3 \left(\frac{S_h^{1/2}}{10^{-22}\ {\rm Hz}^{-1/2}}\right)^2$$

*Cosmologically viable sources of primordial high-frequency GWs are not (*yet*) detectable*

High-Frequencies at LIGO/Virgo

Why not just extend LIGO/Virgo to higher frequencies?



Cutoff at 10 kHz is a human decision

Lack of feasible calibration of optical response (transfer function)

Signal Parametrics

Direct: GW → EM

(Sebastian Ellis's talk)

metric in the PD frame

$$h_{\rm PD} \sim (\omega_g \, L_{\rm cav})^2 \, h_{\rm TT}$$

GW induces effective current

$$j_{\rm eff} \sim (E_0/L_{\rm cav}) \, h_{\rm PD}$$

effective current sources signal EM field

$$E_{\rm sig} \sim Q \, h_{\rm PD} \, E_0$$

Indirect: GW → mechanical → EM

GW induces tidal force

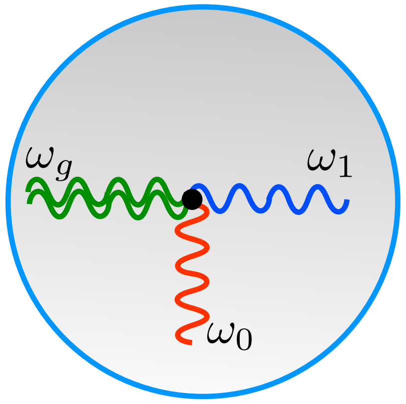
$$F \sim (M_{\rm cav}/L_{\rm cav}) \, h_{\rm PD}$$

tidal force deforms cavity

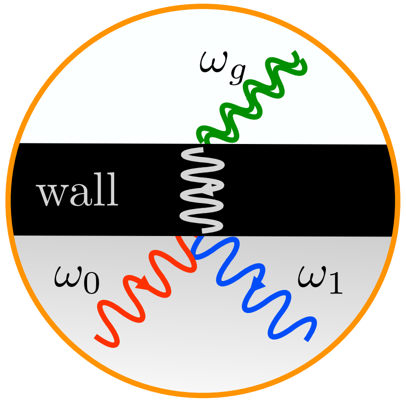
$$\Delta x_{\rm cav} \sim \frac{F/M_{\rm cav}}{\max\,(\omega_g \, , \, c_s/L_{\rm cav})^2}$$

deformation mixes EM modes

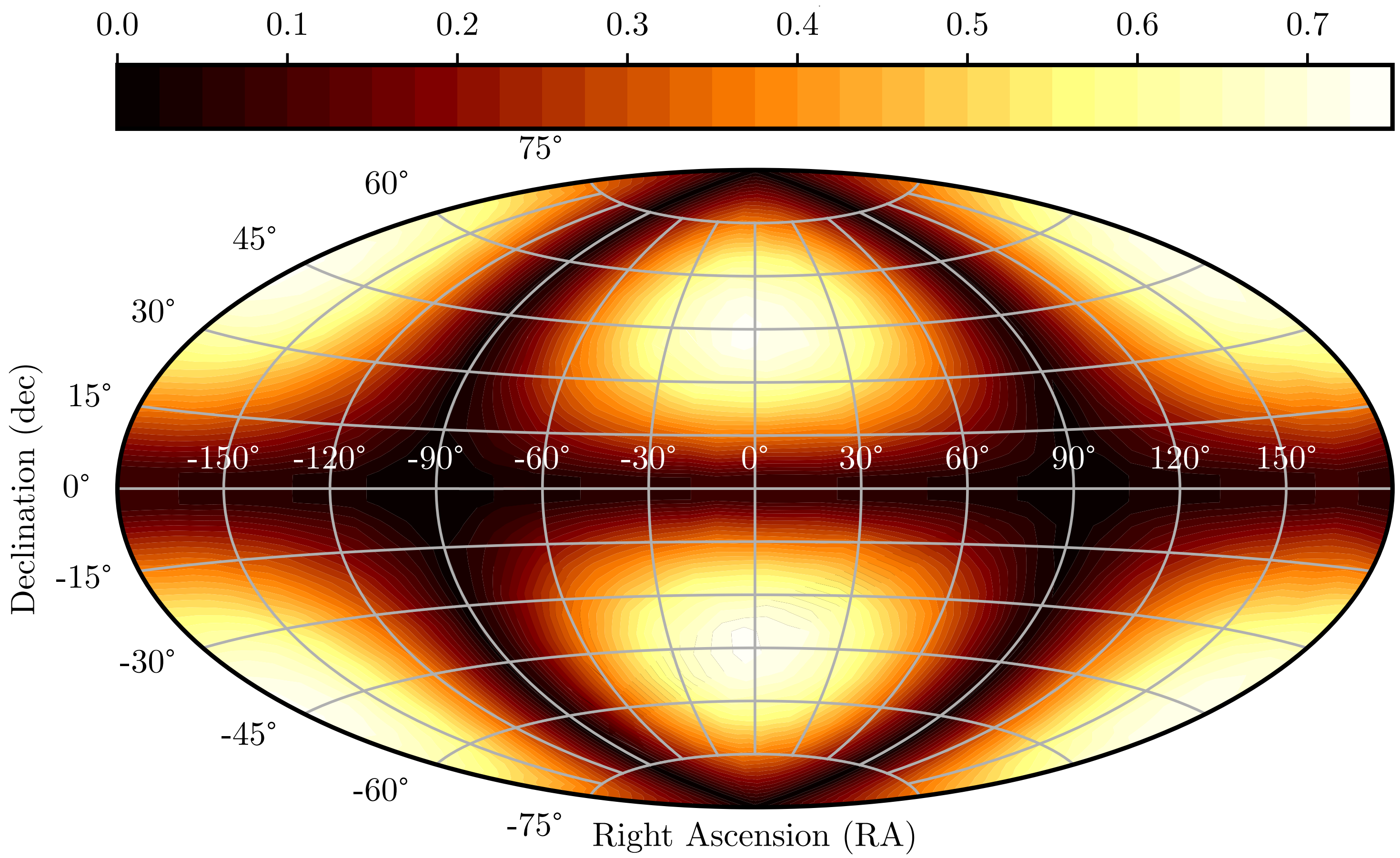
$$E_{\rm sig} \sim \frac{\Delta x_{\rm cav}}{L_{\rm cav}} \, Q \, E_0 \sim \frac{Q \, h_{\rm PD} \, E_0}{\max\,(\omega_g \, L_{\rm cav} \, , \, c_s)^2}$$



speed of sound $c_s \sim 10^{-6}$ $\Longrightarrow$ mechanical signal dominates for $\omega_g \ll$ GHz

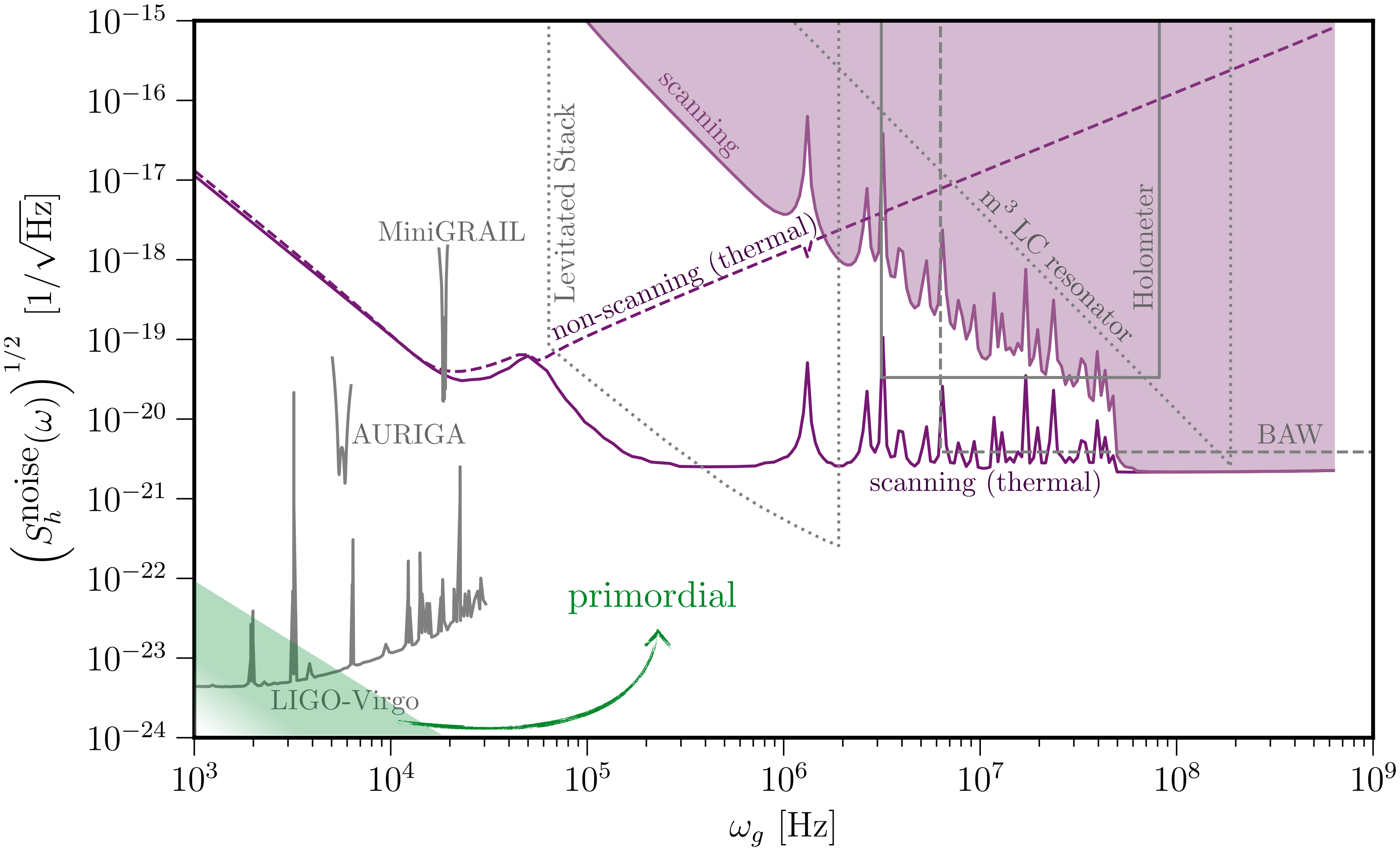


Mechanical Signal



sky map of mechanical-EM coupling

Strain-Equivalent Noise (incoherent GWs)

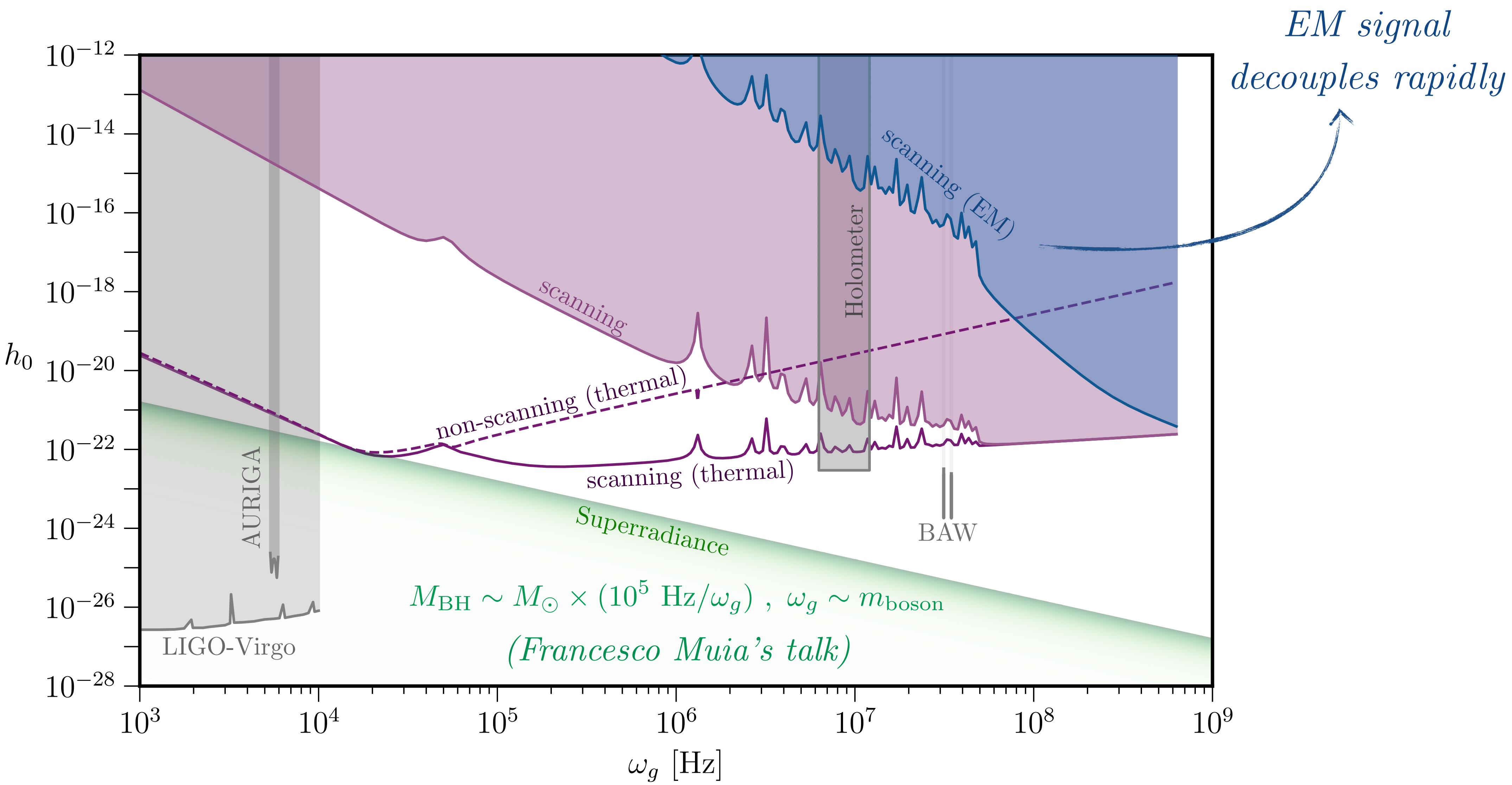


shaded = conservative estimate of vibrational noise

unshaded = irreducible vibrational noise

Non-scanning (broadband) search is ideal for transient sources

Coherent GWs



shaded = conservative estimate of vibrational noise

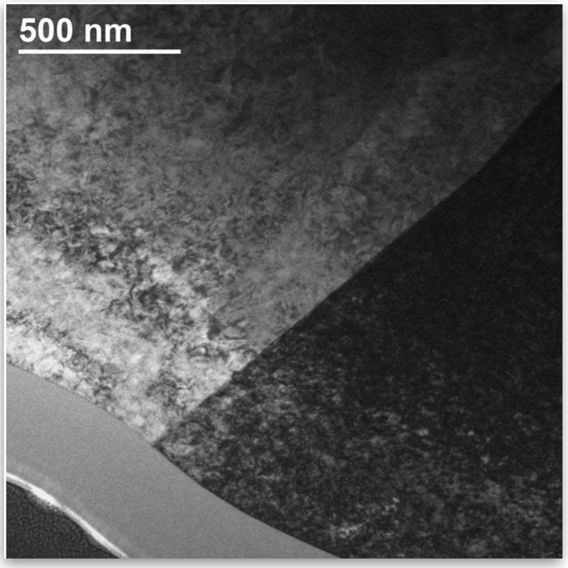
unshaded = irreducible vibrational noise

$$\rho_g \sim \rho_{\rm DM} \times \left(\frac{\omega_g}{10\ \text{MHz}}\right)^2 \left(\frac{h_0}{10^{-22}}\right)^2$$

SRF

Why superconducting cavities?

1. most efficient engineered oscillators
   (long coherence)
2. large oscillating fields
   (0.2 T, ~GHz)
3. precisely manufactured and operated
   (nm-precision)
4. already used for new physics searches
   (experimentalists)



Gravity + Electromagnetism

Einstein-Maxwell Action

$$\mathscr{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \longrightarrow S = -\frac{1}{4} \int d^4x \sqrt{-g}\, g^{\mu\nu} g^{\rho\sigma} F_{\mu\rho} F_{\nu\sigma}$$

$$g_{\mu\nu} = \underbrace{\eta_{\mu\nu}}_{\text{flat space}} + \underbrace{h_{\mu\nu}}_{\text{gravitational wave}}$$

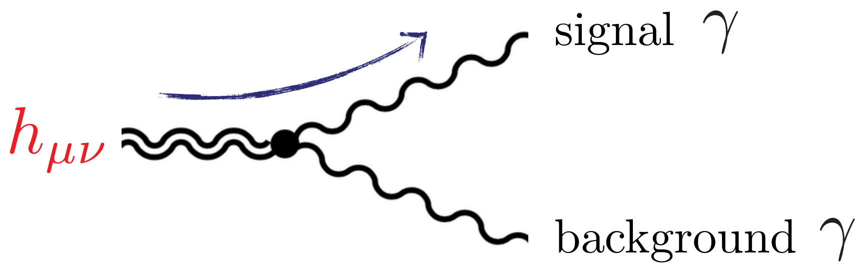
Expand in $h_{\mu\nu} \ll 1$

$$\boxed{S \supset -\frac{1}{2} \int d^4x\, j^\mu_{\text{eff}} A_\mu \qquad j^\mu_{\text{eff}} \equiv \partial_\nu \left(\frac{1}{2} h\, F^{\mu\nu} + h^\nu{}_\alpha\, F^{\alpha\mu} - h^\mu{}_\alpha\, F^{\alpha\nu} \right)}$$

Gravity + Electromagnetism

$$\boxed{\begin{gathered} S \supset -\frac{1}{2}\int d^4x\, j^\mu_{\text{eff}}\, A_\mu \\[1em] j^\mu_{\text{eff}} \equiv \partial_\nu \left(\frac{1}{2}\, h\, F^{\mu\nu} + h^\nu{}_\alpha\, F^{\alpha\mu} - h^\mu{}_\alpha\, F^{\alpha\nu} \right) \end{gathered}}$$

"Inverse-Gertsenshtein Effect" : j^μ_{eff} is an "**effective current**" that sources small oscillating EM fields in the presence of background EM fields.



(graviton-to-photon conversion)

Gauge/Frame Dependence : $h^{\mu\nu}$ and j^μ_{eff} do **not** transform covariantly like $\mathcal{O}(h)$ tensors such as Riemann, which transforms as $R_{\mu\nu\rho\sigma} \to R_{\mu\nu\rho\sigma} + \mathcal{O}(h^2)$.

Gauge/Frame Dependence

In linearized theory, a residual invariance remains.

$$x^\mu \to x'^\mu = x^\mu + \xi^\mu(x) \text{ where } \partial_\mu \xi_\nu \sim \mathcal{O}(h)$$

This "gauge freedom" corresponds to different choices of frames, which does not impact the physics.

Gauge/Frame Dependence

Transverse-Traceless (TT) Frame

simpler metric
more popular choice

Proper Detector (PD) Frame

less simple metric
conceptually more simple

Gauge/Frame Dependence

Transverse-Traceless (TT) Frame

- $$h^{\mathrm{TT}}_{\mu\nu} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & h_+ & h_\times & 0 \\ 0 & h_\times & -h_+ & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} e^{i\omega_g (t-z)}$$

  (simple form of the metric)

- Free test masses remain at rest during passage of GW.

  (therefore can be used to mark the coordinates)

- Effects are subtle.

  (e.g., "normally" rigid objects are deformed)

Proper Detector (PD) Frame

- $$\lim_{\omega_g x \ll 1} h^{\mathrm{PD}}_{\mu\nu} \sim (\omega_g\, x)^2\, h^{\mathrm{TT}}_{\mu\nu}$$

  (typically only employed in the long-wavelength limit)

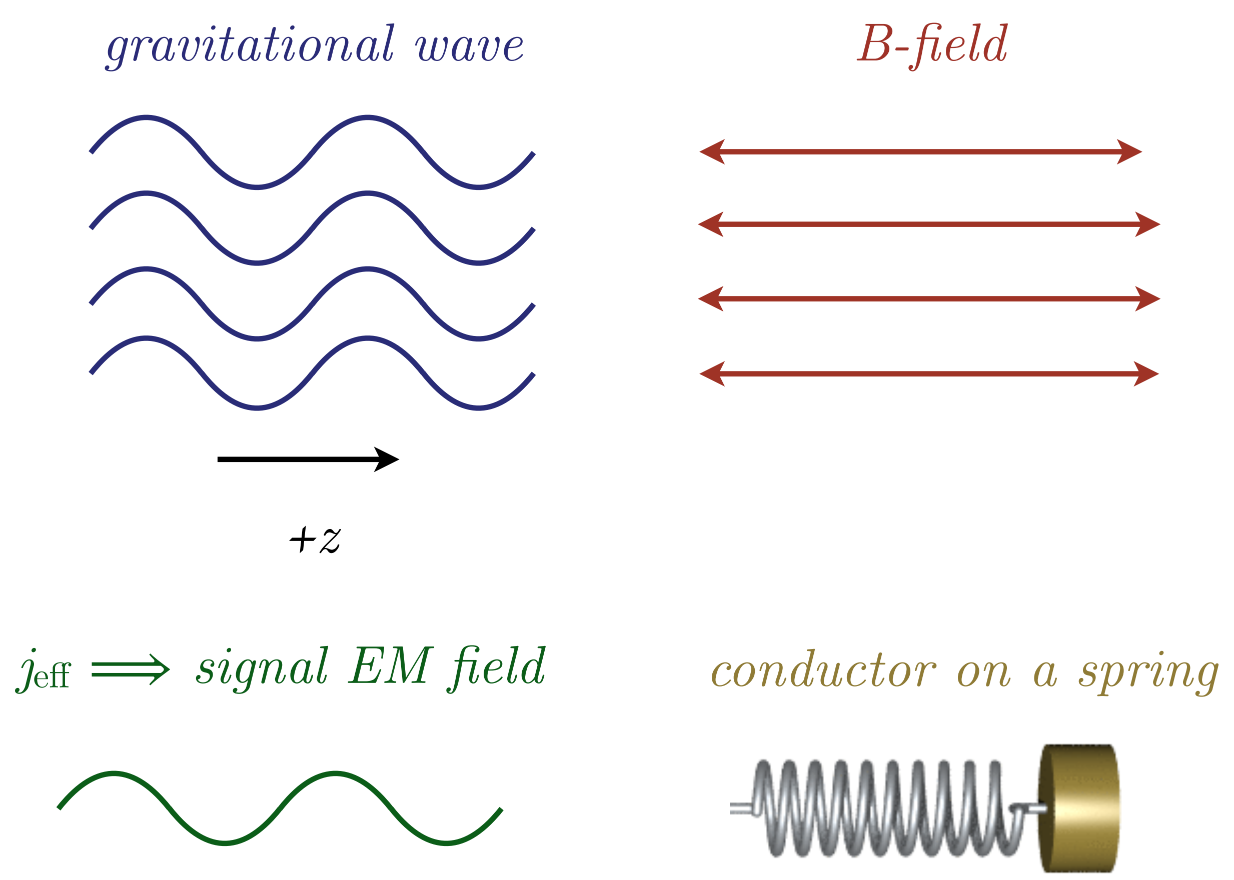
- Natural coordinates of the experimenter, marked by a rigid ruler.

  (Fermi normal coordinates)

- Effects are less subtle, since metric reduces to flat space in long-wavelength limit.

  (effects can be phrased in terms of Newtonian-like physics)

Toy Example

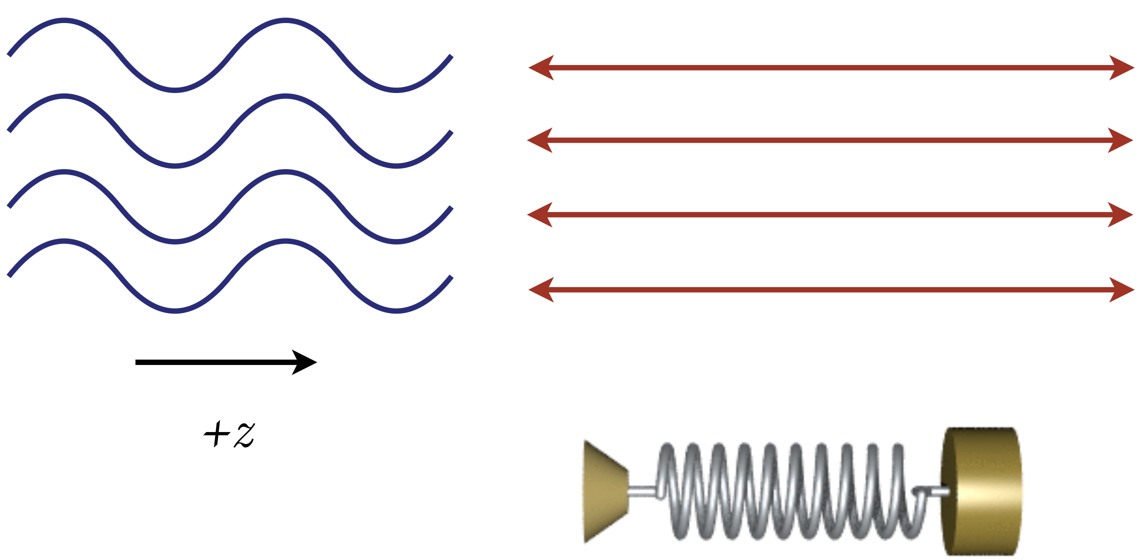


How large is the (gauge-invariant) current that is induced on the conductor?

Toy Example

Transverse-Traceless (TT) Frame

gravitational wave *homogenous and static B-field*



oscillating conductor on a spring

Lorentz force drives current!

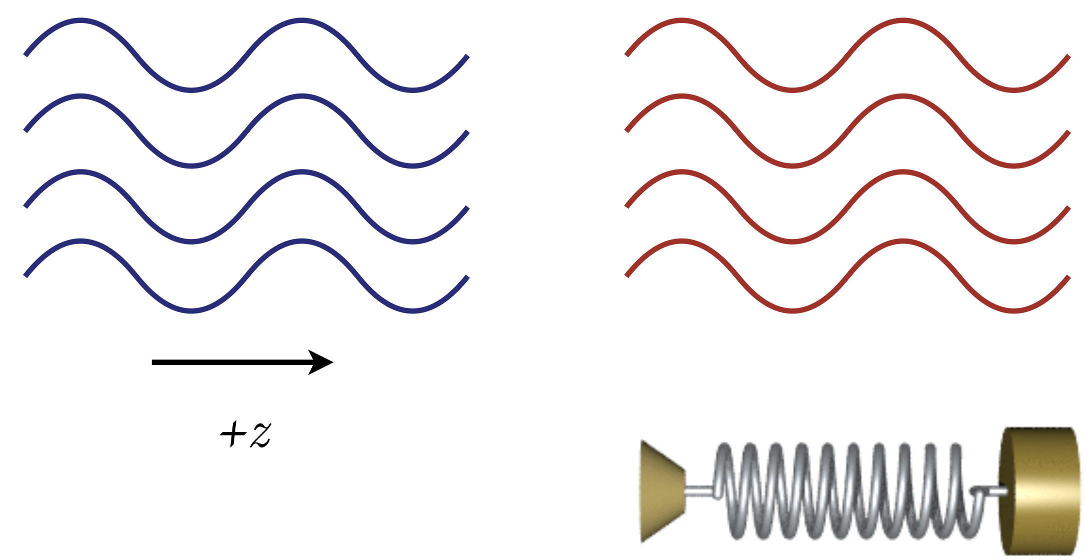
$$j^{\mu}_{\text{eff}} \equiv \partial_\nu \left(\frac{1}{2} \cancel{h F^{\mu\nu}} + \cancel{h^{\nu}{}_{\alpha}} F^{\alpha\mu} - h^{\mu}{}_{\alpha} F^{\alpha\nu} \right)$$

$$= -\partial_{\nu} h^{\mu}{}_{\alpha} F^{\alpha\nu} = 0$$ *No signal?*

$\nu = t$ or z

Proper Detector (PD) Frame

gravitational wave *dynamical B-field*

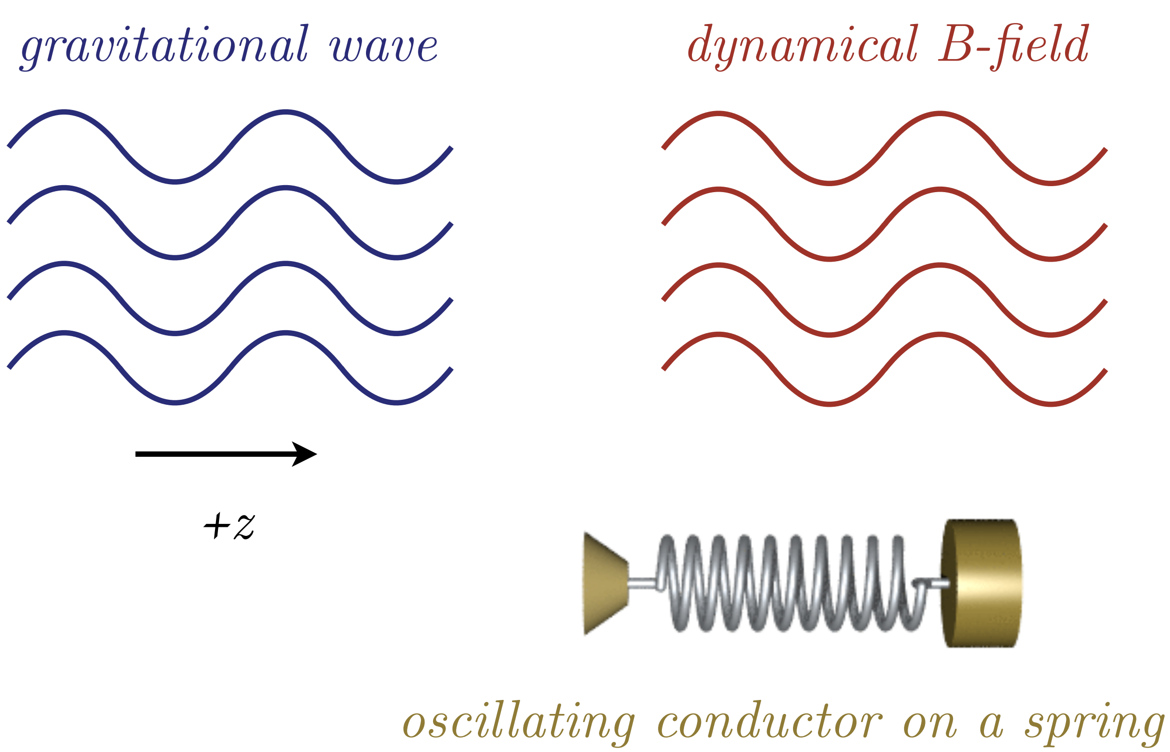


conductor on a stiff spring

$j_{\text{eff}} \neq 0$ *signal!*

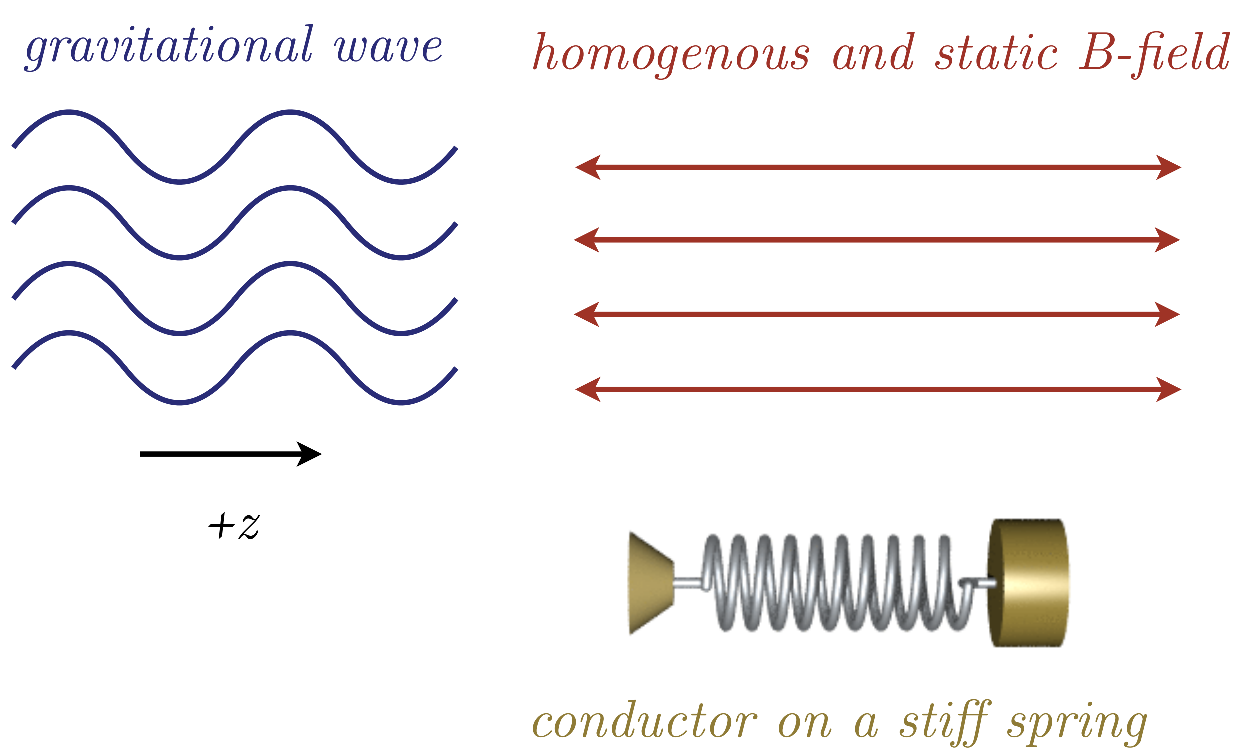
Toy Example

Transverse-Traceless (TT) Frame



$$j_{\text{eff}} = 0$$

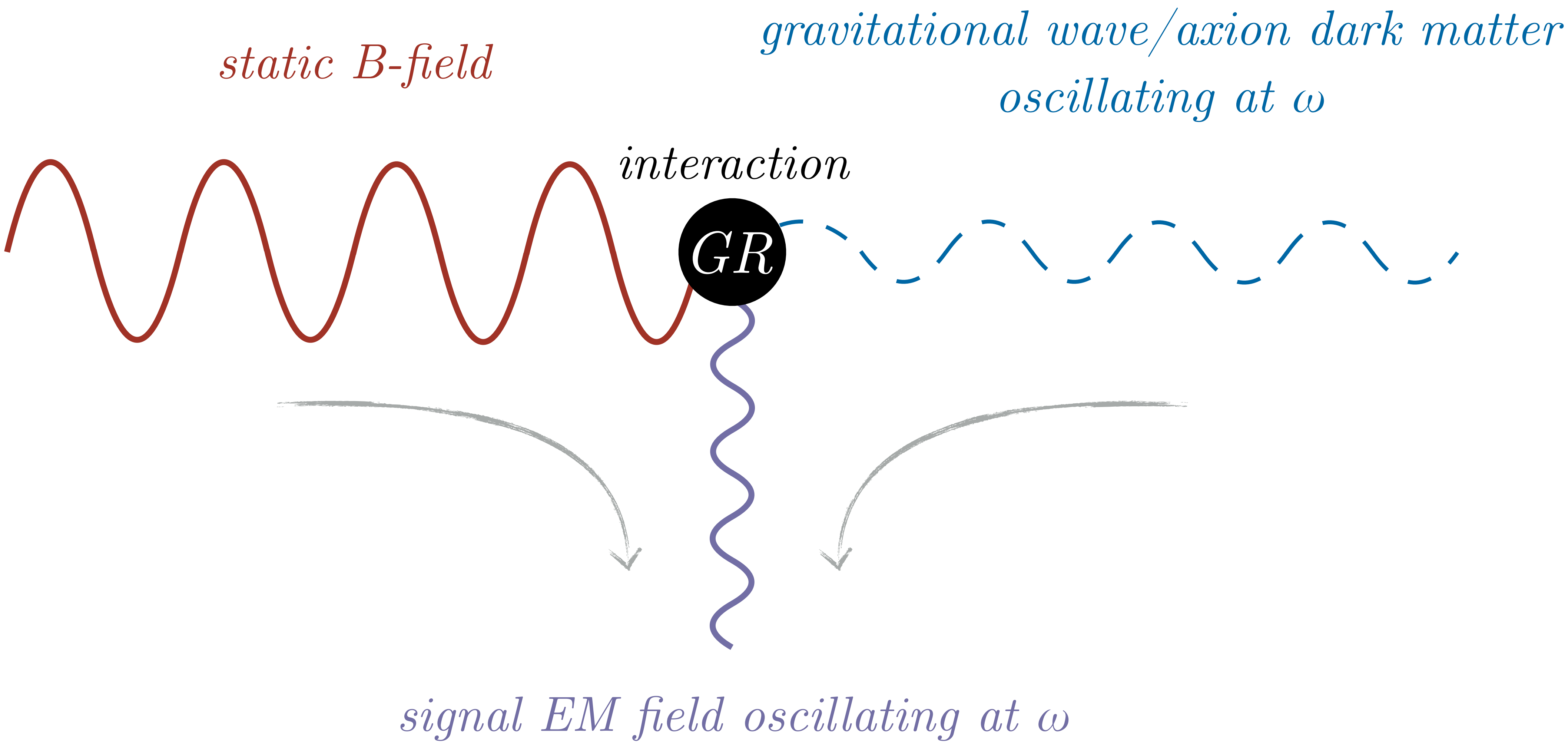
Proper Detector (PD) Frame



$$j_{\text{eff}} \neq 0$$ *signal!*

B-fields and detectors are most naturally defined in this frame.

Axion Analogy



$$\underline{\text{GW}}:\ j_{\text{eff}} \sim h\,\omega\,B_0$$

$$\underline{\text{axion DM}}:\ j_{\text{eff}} \sim g_{a\gamma\gamma}\,a\,\omega\,B_0$$

$$\boxed{h \sim g_{a\gamma\gamma}\,a \sim 10^{-22}}$$ (current sensitivity)

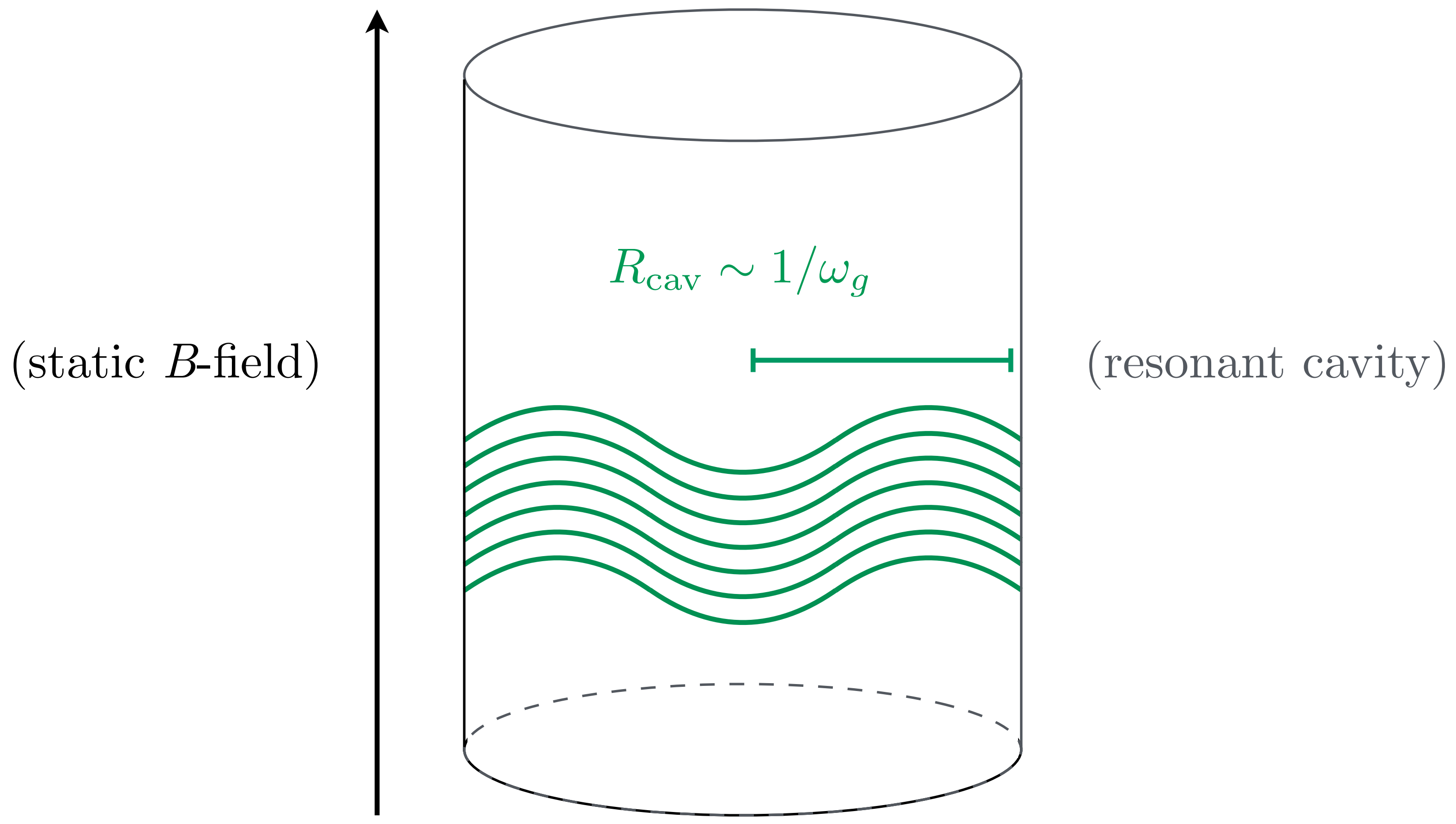
(not including important temporal and spatial differences)

Technical Aside

Proper Detector Frame

typically only used in the long-wavelength limit $\omega_g \, x \ll 1$

cavity resonance: $\omega_g \, R_{\text{cav}} \sim 1$



Technical Aside

Proper Detector Frame

typically only used in the long-wavelength limit $\omega_g \, x \ll 1$

cavity resonance: $\omega_g \, R_{\text{cav}} \sim 1$

In fact, full set of terms can be summed for a single Fourier-mode

$$\boxed{\begin{aligned} h_{00} &= -R_{0i0j} \, x^i \, x^j \times 2 \left[-\frac{i}{\omega_g z} + \frac{1 - e^{-i\omega_g z}}{(\omega_g z)^2} \right] \\ h_{ij} &= -\frac{1}{3} \, R_{ikjl} \, x^k \, x^l \times 6 \left[-\frac{1 + e^{-i\omega_g z}}{(\omega_g z)^2} - 2i \, \frac{1 - e^{-i\omega_g z}}{(\omega_g z)^3} \right] \\ h_{0i} &= -\frac{2}{3} \, R_{0jik} \, x^j \, x^k \times 3 \left[-\frac{i}{2 \, \omega_g z} - \frac{e^{-i\omega_g z}}{(\omega_g z)^2} - i \, \frac{1 - e^{-i\omega_g z}}{(\omega_g z)^3} \right] \end{aligned}}$$

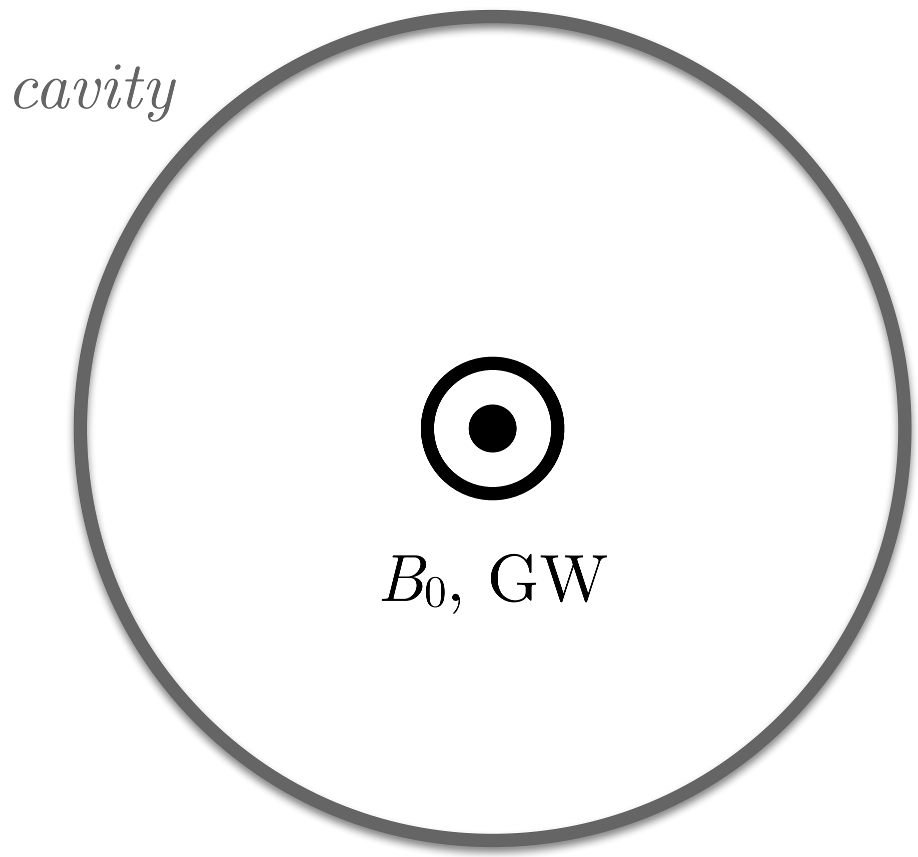
$$\lim_{\omega_g \to 0} \left[\cdots \right] \to 1$$

$$R_{\mu\nu\rho\sigma} \sim \omega_g^2 \, h^{\text{TT}}$$

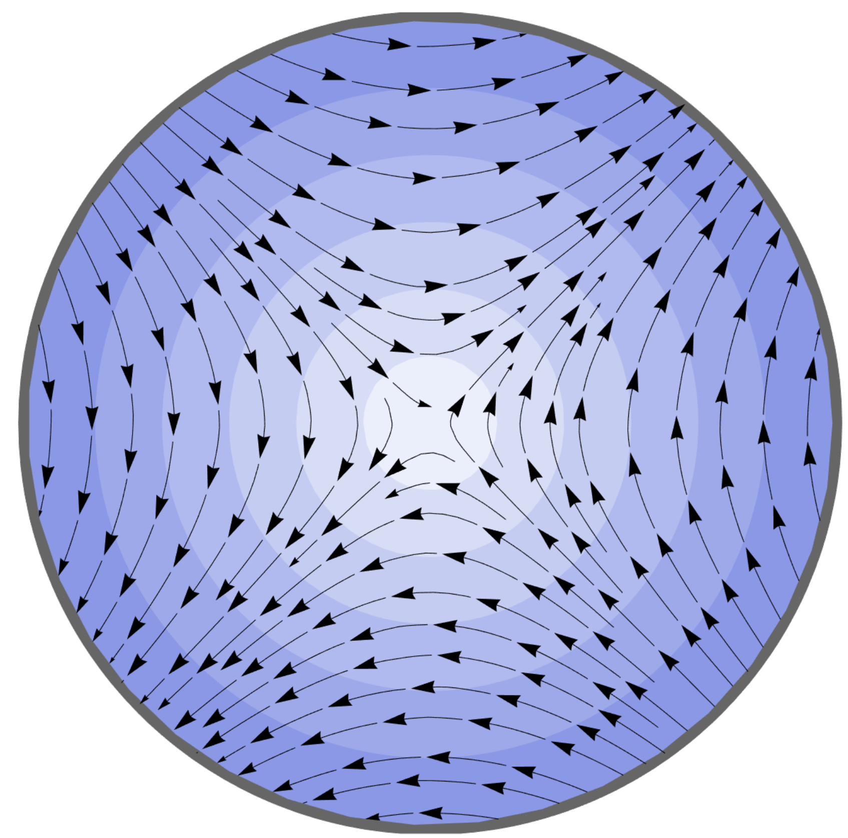
Mode-Structure

Proper Detector Frame

$$\omega_g \sim 1/R_{\mathrm{cav}}$$



B-field, GW



effective current

$$j_{\mathrm{eff}} \sim h\, B_0\, \omega_g^2\, r\, e^{2i\phi}$$

more important at higher frequencies

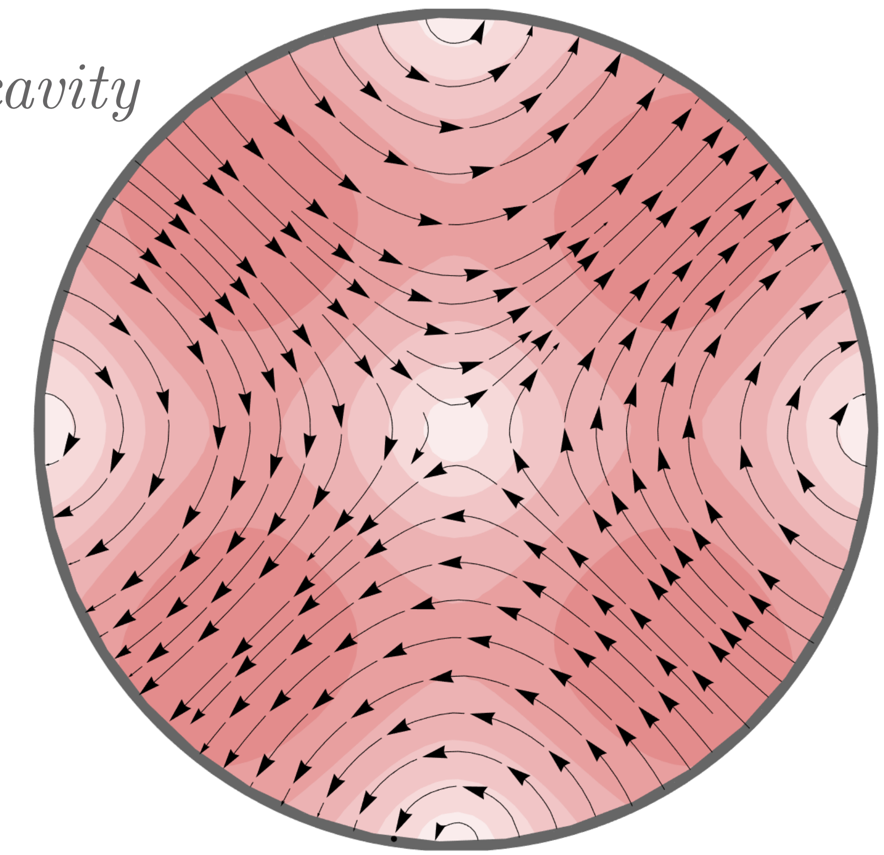
spin-2

Mode-Structure

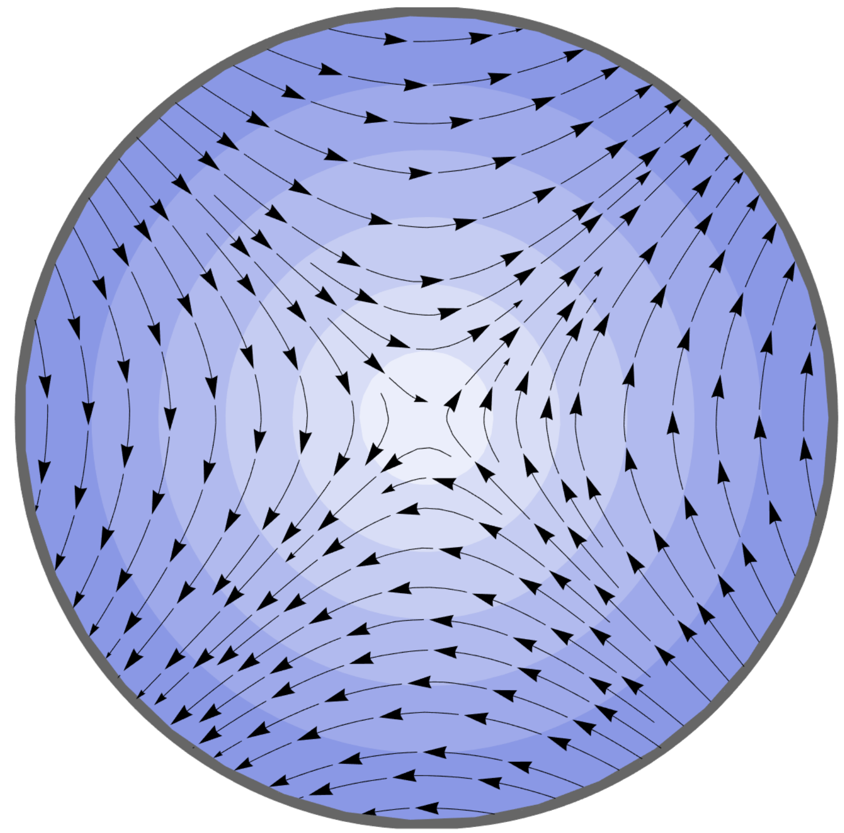
Proper Detector Frame

$$\omega_g \sim 1/R_{\mathrm{cav}}$$

cavity



large
overlap



E-field of TE_{212} mode

effective current

$$j_{\mathrm{eff}} \sim h\, B_0\, \omega_g^2\, r\, e^{2i\phi}$$

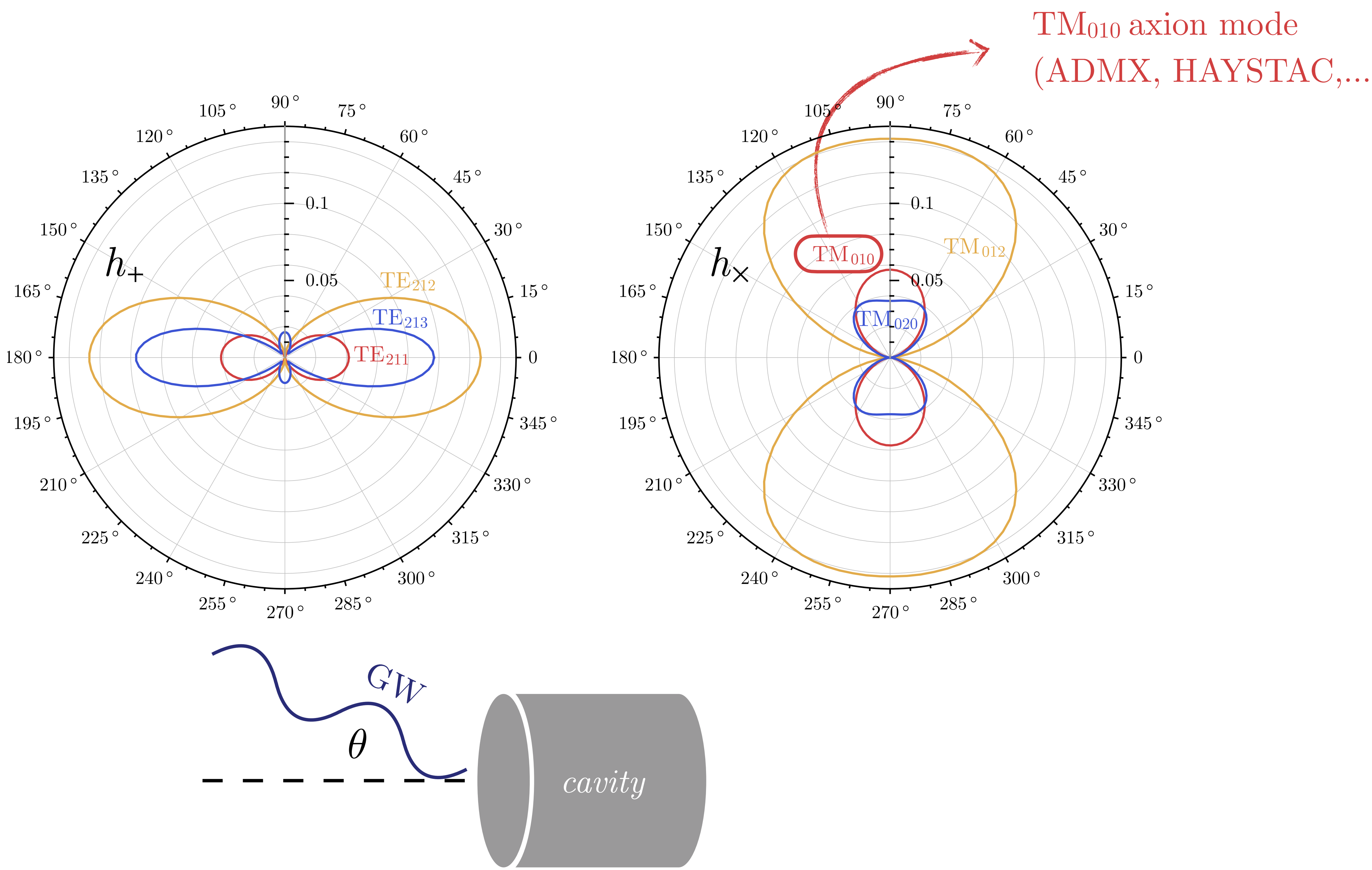
more important at higher frequencies

spin-2

Mode-Structure

The most optimal mode for GW detection
is **not** *the most optimal mode for axion detection.*

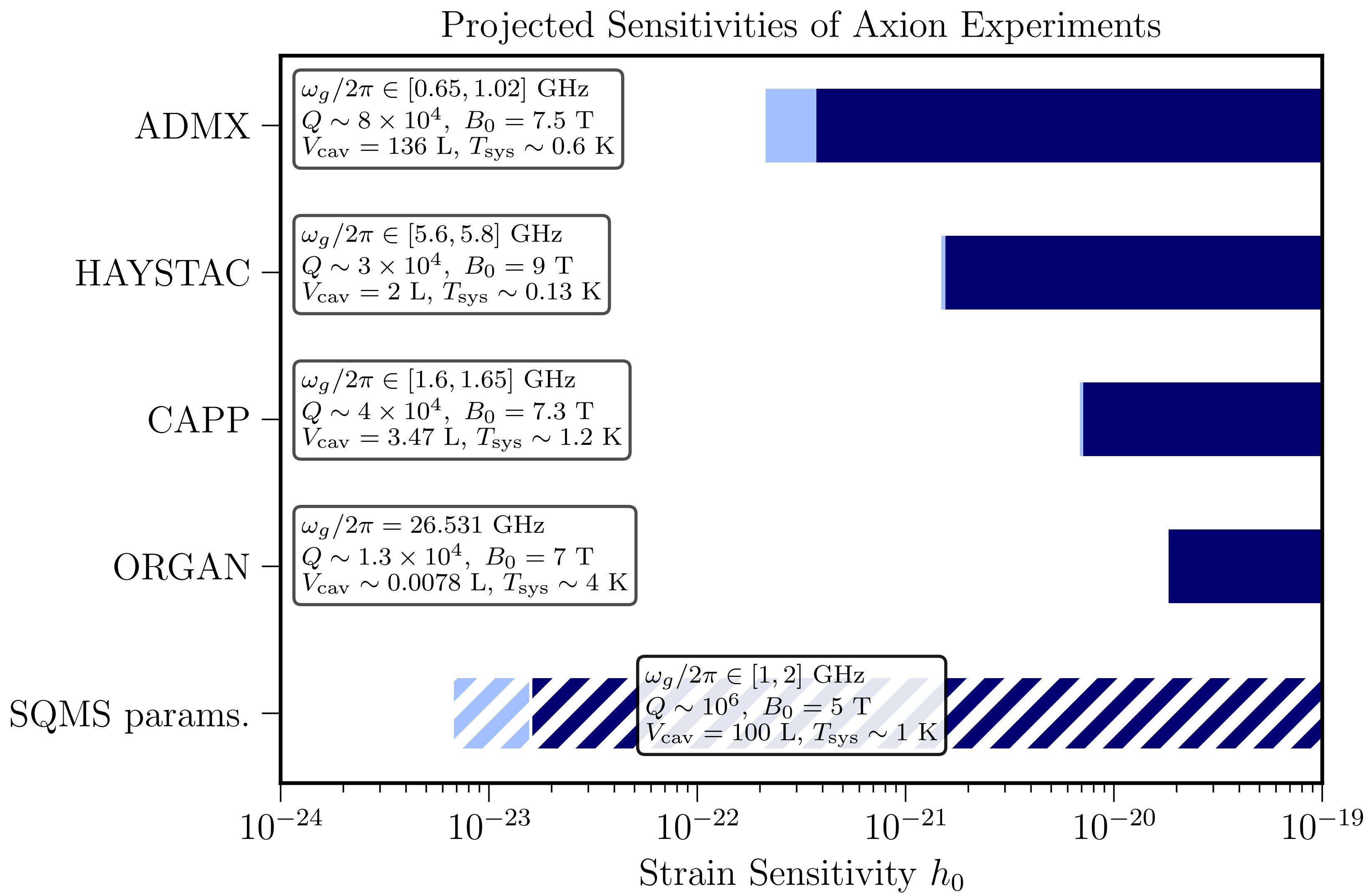
Angular Sensitivity



Lack of symmetry for an unaligned GW $\Longrightarrow$ GWs couple to most EM modes

Only a reanalysis of axion dark matter experimental data is needed.

Strain Sensitivity



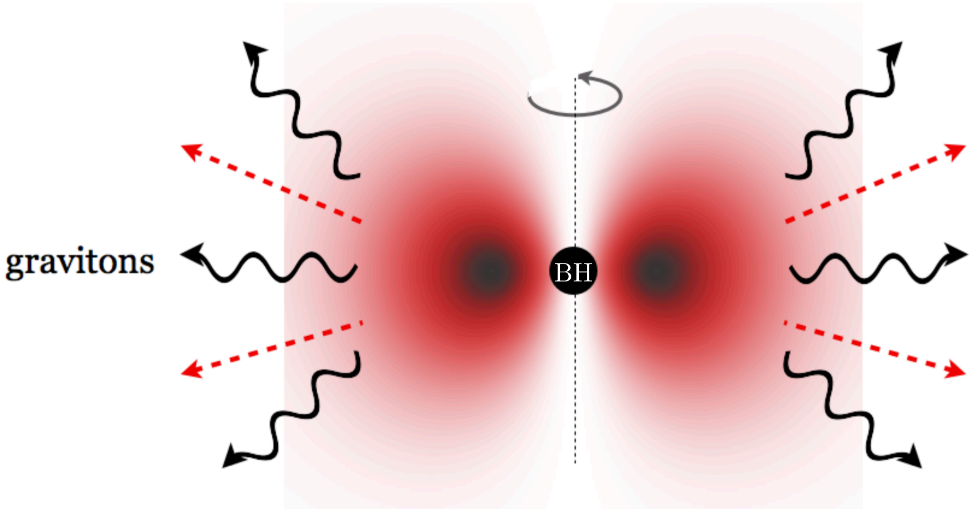
$$\boxed{\omega_g \sim \text{GHz}}$$

Only a reanalysis of axion dark matter experimental data is needed.

How to extend the frequency band?

Sources

higher frequency $\Longrightarrow$ smaller mass $\Longrightarrow$ smaller signals



Exotic Sub-Earth Mass Mergers

$$\omega_g \sim \text{few} \times \text{GHz} \times (M_\oplus / M_{\text{binary}}) \, (r_{\text{min}} / r_{\text{binary}})^{3/2}$$

To fully ring up a narrow resonant cavity, like ADMX

$$M_{\text{binary}} \lesssim 10^{-5} \, M_\oplus$$

$$\Downarrow$$

$$h \lesssim 10^{-29} \times (1 \text{ pc}/D)$$

Superradiance

$$M_{\text{BH}} \sim 100 \times M_\oplus \;\; , \;\; m_{\text{axion}} \sim 1 \; \mu\text{eV}$$

$$\Downarrow$$

$$h \sim 10^{-27} \times (10 \text{ kpc}/D)$$