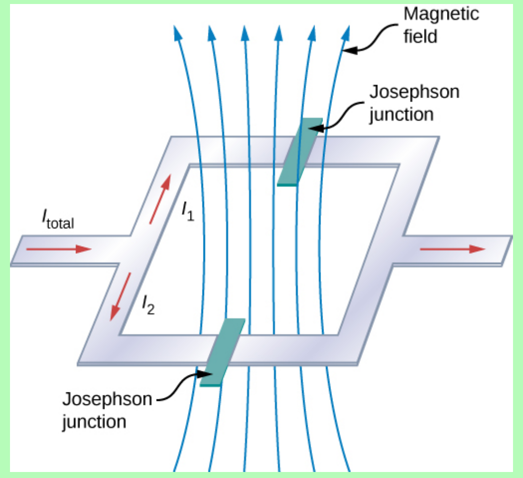
Quantum Sensors for Fundamental Physics

Sebastian A. R. Ellis

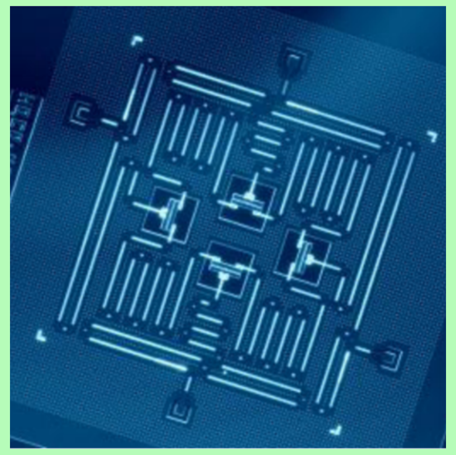
University of Geneva

What are Quantum Sensors?

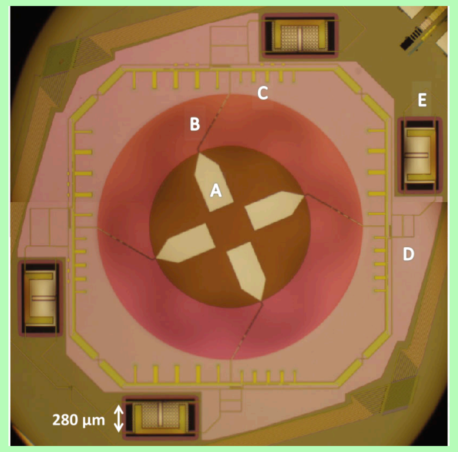
What are Quantum Sensors?



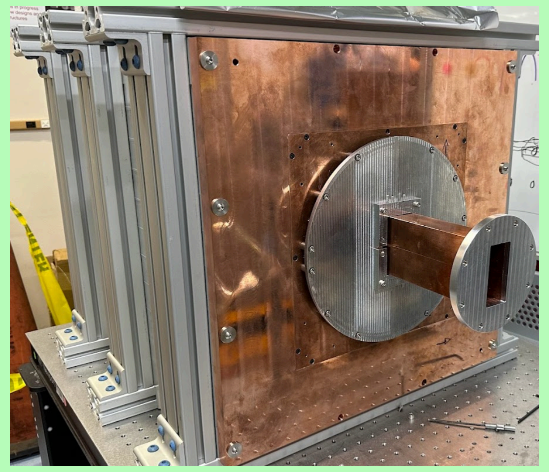
SQUID



Qubit



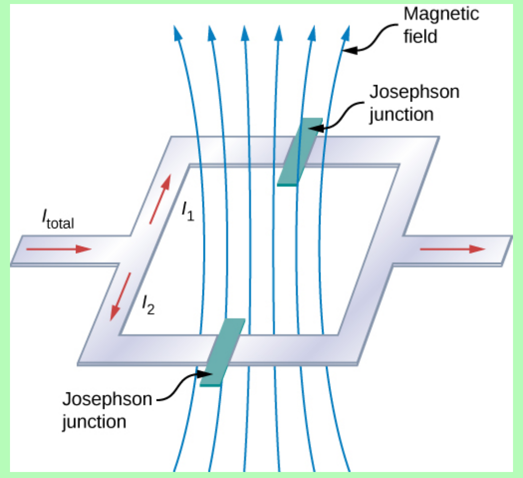
TES



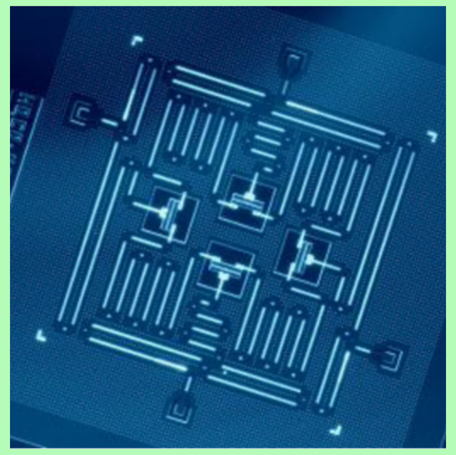
Cavity

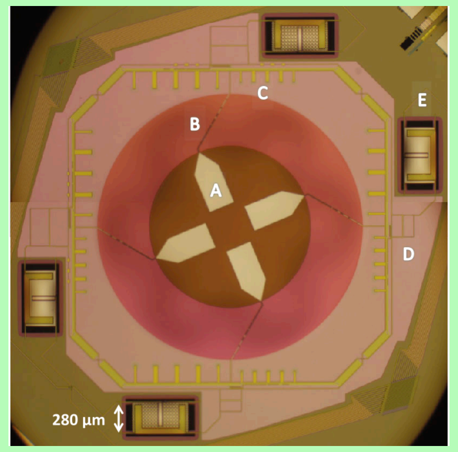
Superconductivity

What are Quantum Sensors?

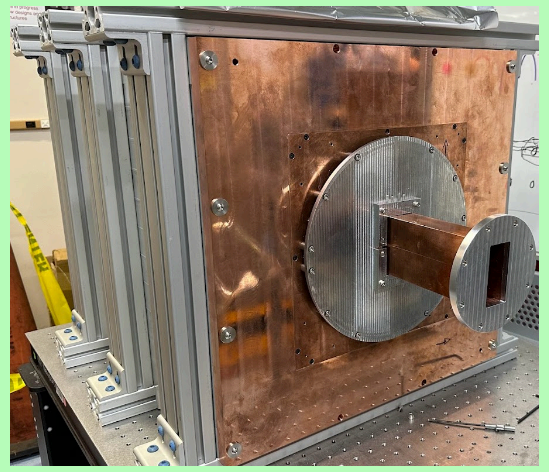


SQUID

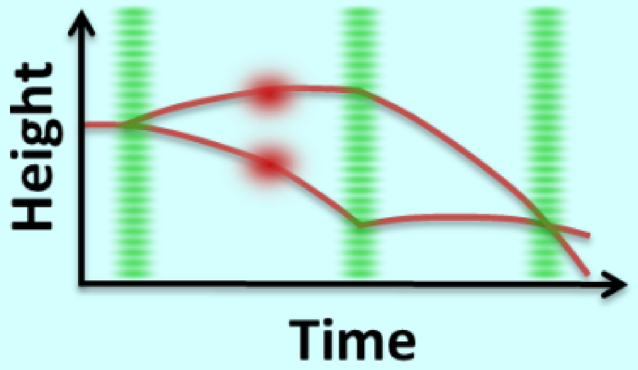

Qubit



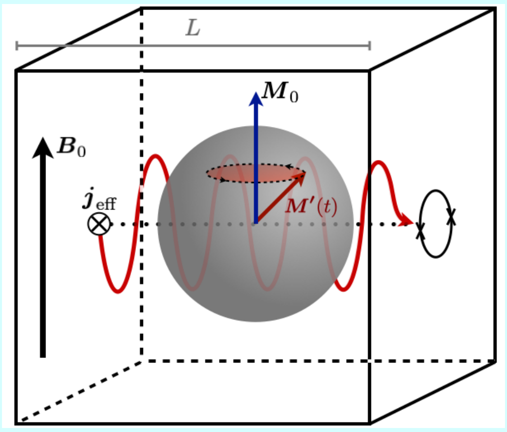
TES


Cavity

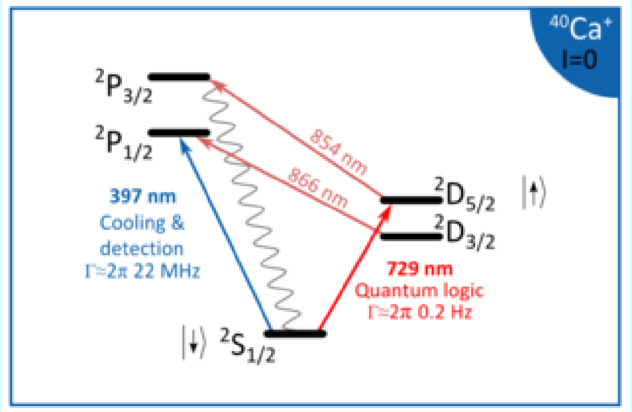
Superconductivity



Atom Interf.



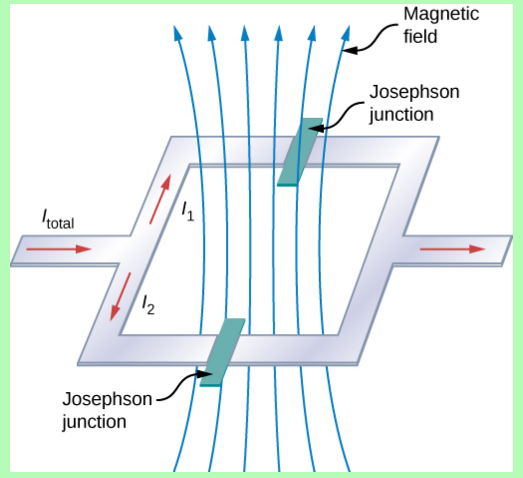
NMR



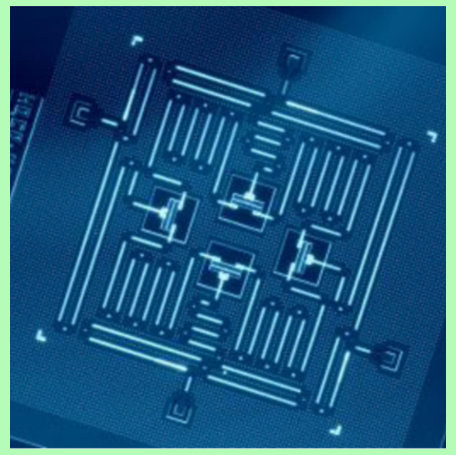
Atomic Clock

Quantum systems

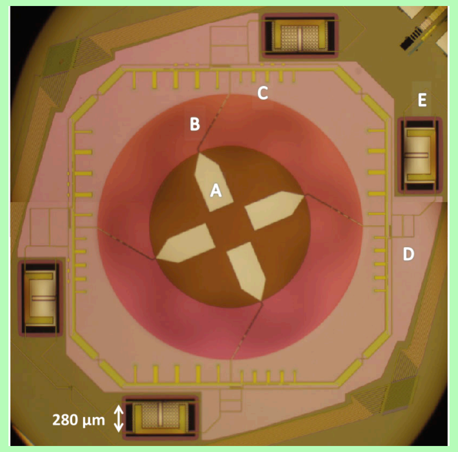
What are Quantum Sensors?



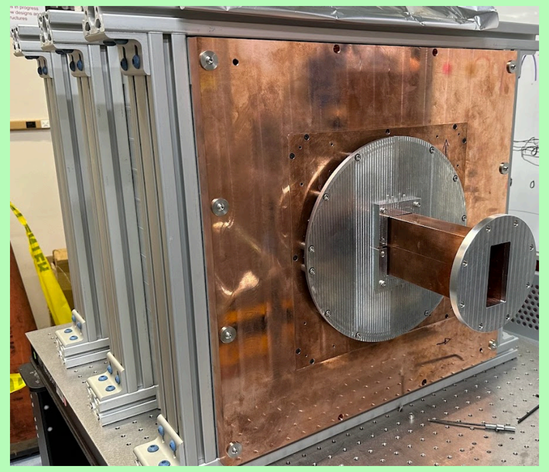
SQUID



Qubit

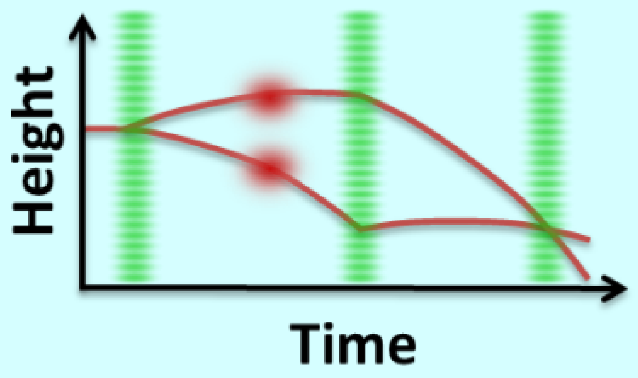


TES

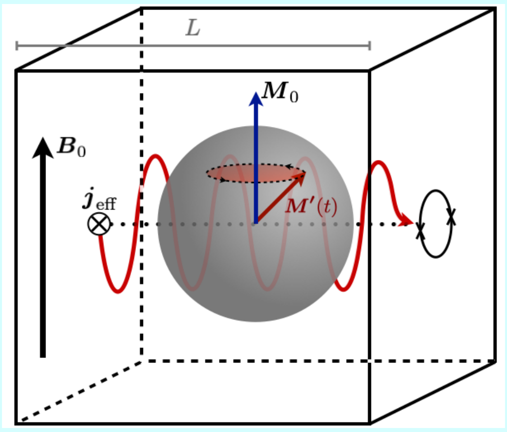


Cavity

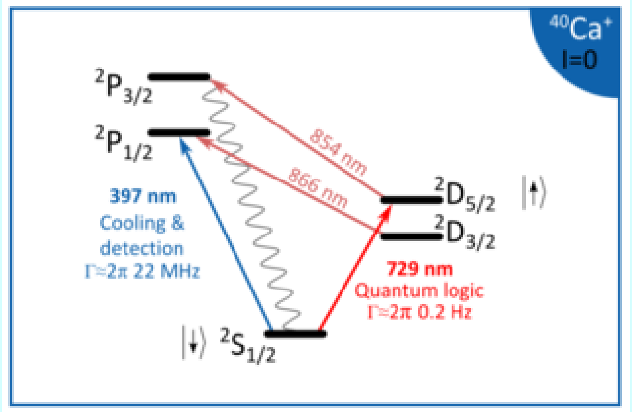
Superconductivity



Atom Interf.

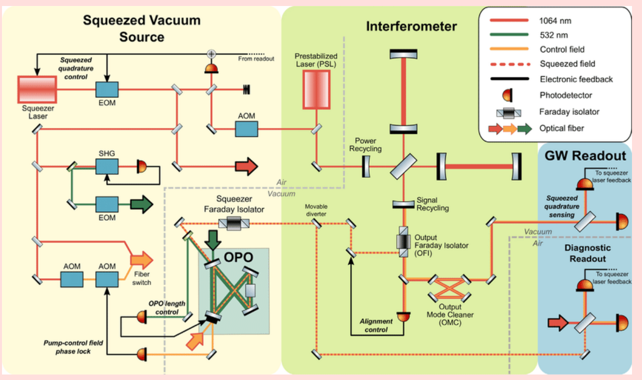


NMR

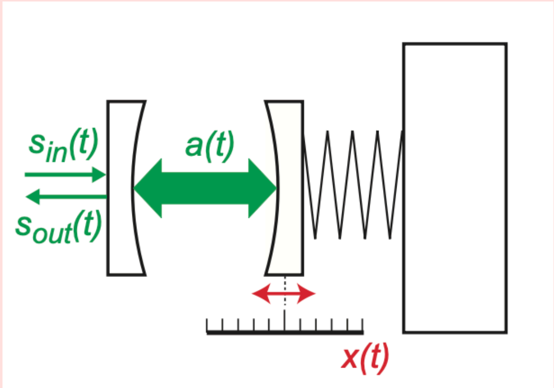


Atomic Clock

Quantum systems



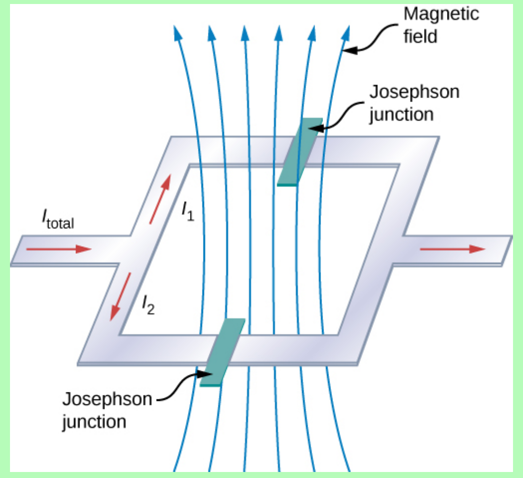
Laser Interf.



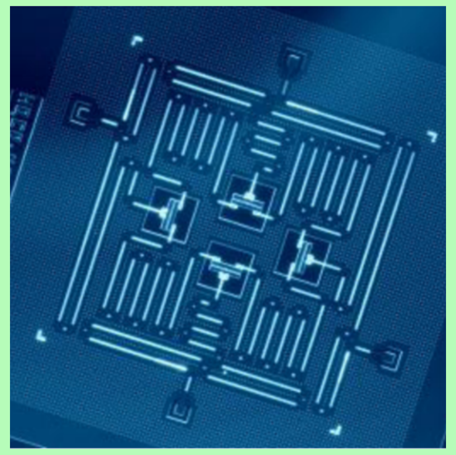
Optomechanical

Quantum techniques

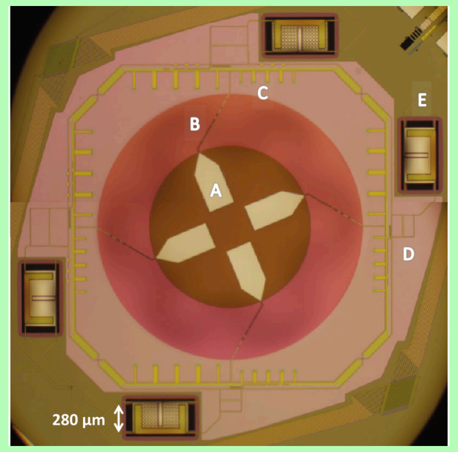
What are Quantum Sensors?



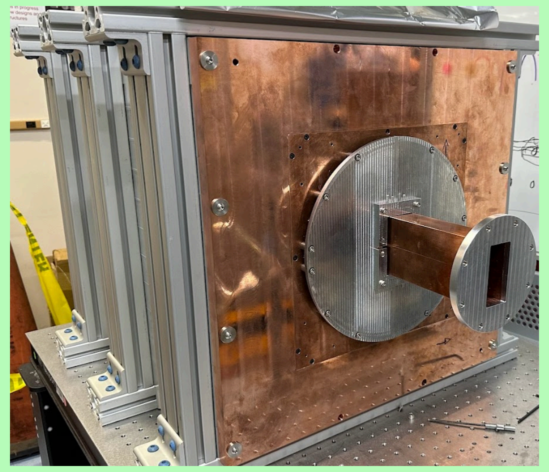
SQUID



Qubit

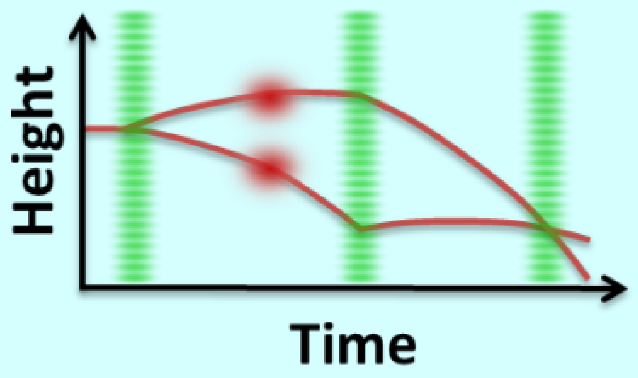


TES

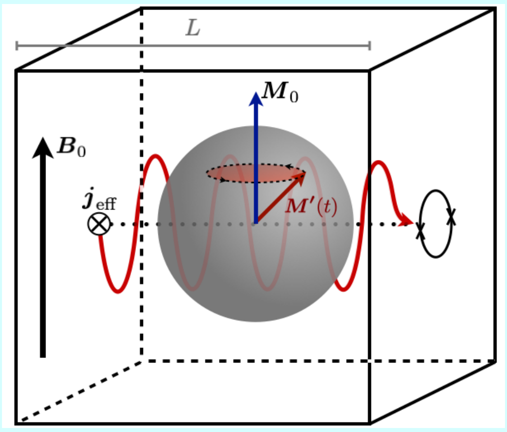


Cavity

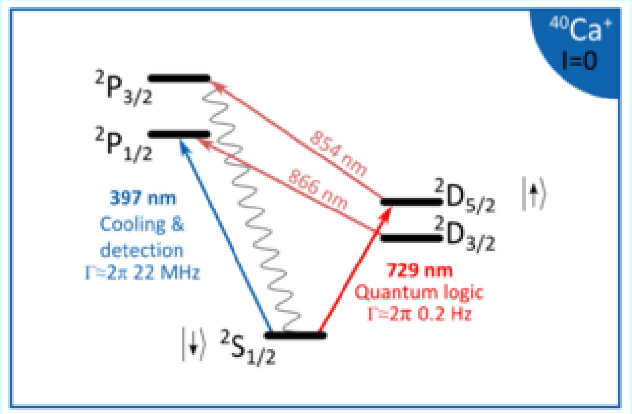
Superconductivity



Atom Interf.

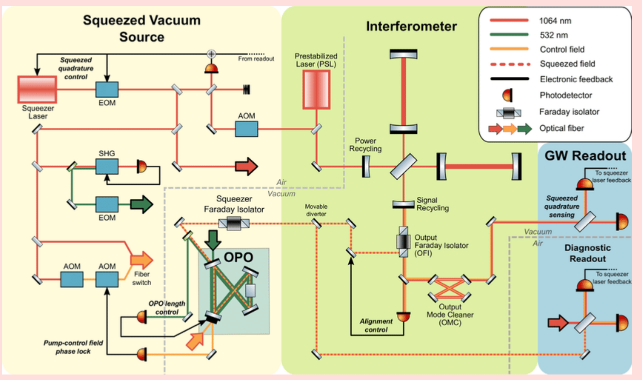


NMR

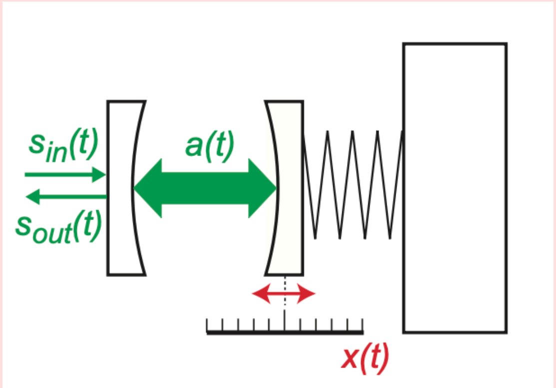


Atomic Clock

Quantum systems



Laser Interf.



Optomechanical

Quantum techniques

And more, w/ applications summarised in:

Quantum Sensing for Fundamental Physics

A. Chou et al, hep-ex/2311.01930

What is Quantum Sensing?

What is Quantum Sensing?

Quantum Noise:

What is Quantum Sensing?

Quantum Noise: $G_{xx}(\tau) = \langle x(\tau)x(0)\rangle$

What is Quantum Sensing?

Quantum Noise:

$$G_{xx}(\tau) = \langle x(\tau)x(0)\rangle$$

$$G^{\mathrm{C}}_{xx}(\tau) = \langle x(0)x(0)\rangle \cos \Omega\tau$$

What is Quantum Sensing?

Quantum Noise: $G_{xx}(\tau) = \langle x(\tau)x(0)\rangle$

$$G^{\mathrm{C}}_{xx}(\tau) = \langle x(0)x(0)\rangle \cos \Omega\tau$$

$$G^{\mathrm{Q}}_{xx}(\tau) = \langle x(0)x(0)\rangle \cos \Omega\tau + \frac{1}{M\Omega}\langle p(0)x(0)\rangle \sin \Omega\tau$$

What is Quantum Sensing?

Quantum Noise: $G_{xx}(\tau) = \langle x(\tau)x(0)\rangle$

$$G^{\mathrm{C}}_{xx}(\tau) = \langle x(0)x(0)\rangle \cos \Omega\tau$$

$$G^{\mathrm{Q}}_{xx}(\tau) = \langle x(0)x(0)\rangle \cos \Omega\tau + \frac{1}{M\Omega}\langle p(0)x(0)\rangle \sin \Omega\tau$$

Quantum Measurement:

$$\mathcal{O}^{\mathrm{C}} \supset \{P,\ \boldsymbol{A},\ \Phi, \ldots\}$$

$$\mathcal{O}^{\mathrm{Q}} \supset \{\hat{N}_\gamma,\ \hat{S}_i,\ \hat{a} \pm \hat{a}^\dagger, \ldots\}$$

+ techniques: e.g. squeezing, entanglement, non-demolition, ...

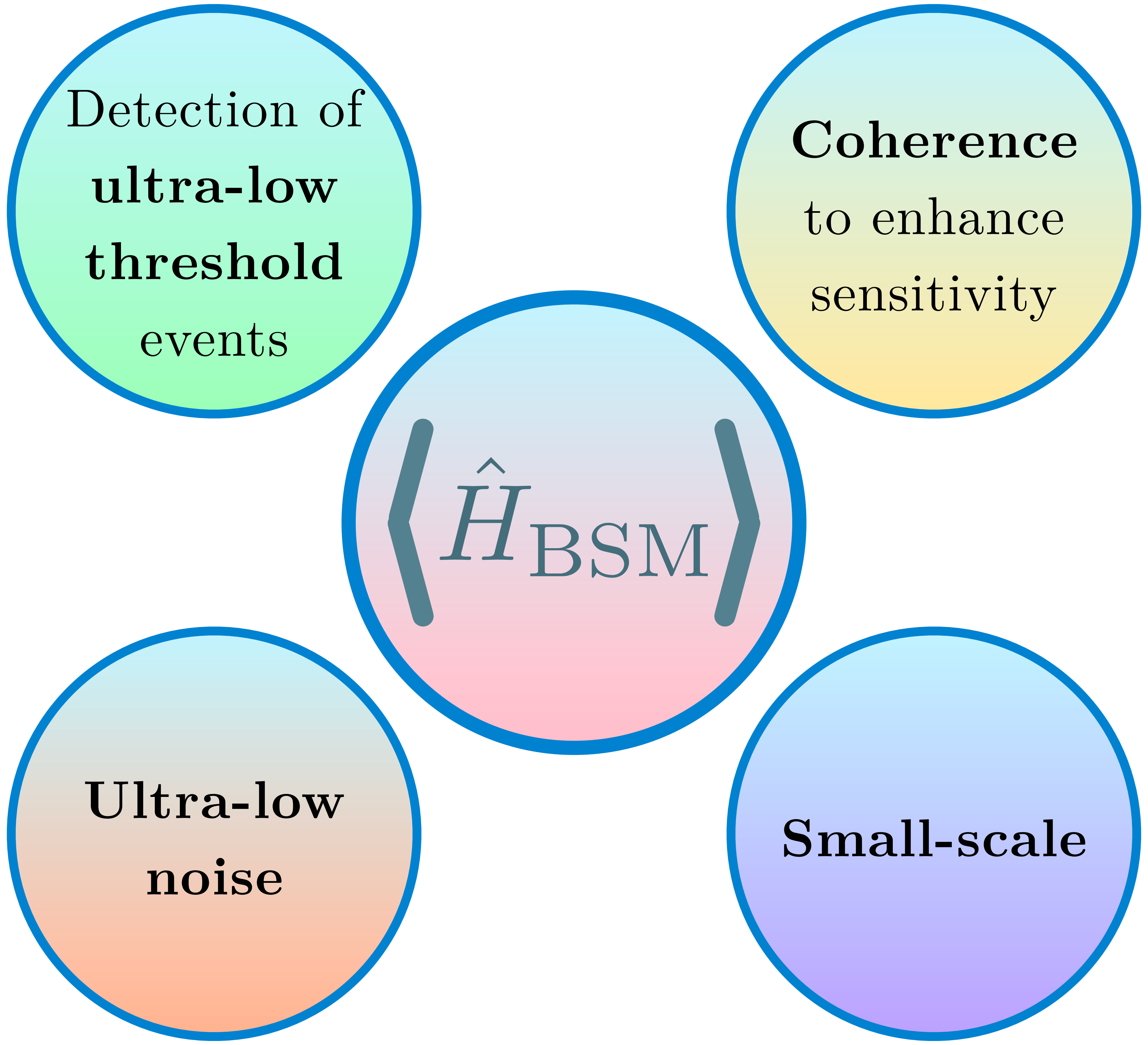
Accelerator Technology In the Quantum Age

Quantum Sensing Needs

Superconducting Cavities

Accelerator Technology In the Quantum Age

Quantum Sensing Needs



Superconducting Cavities

Accelerator Technology In the Quantum Age

Quantum Sensing Needs

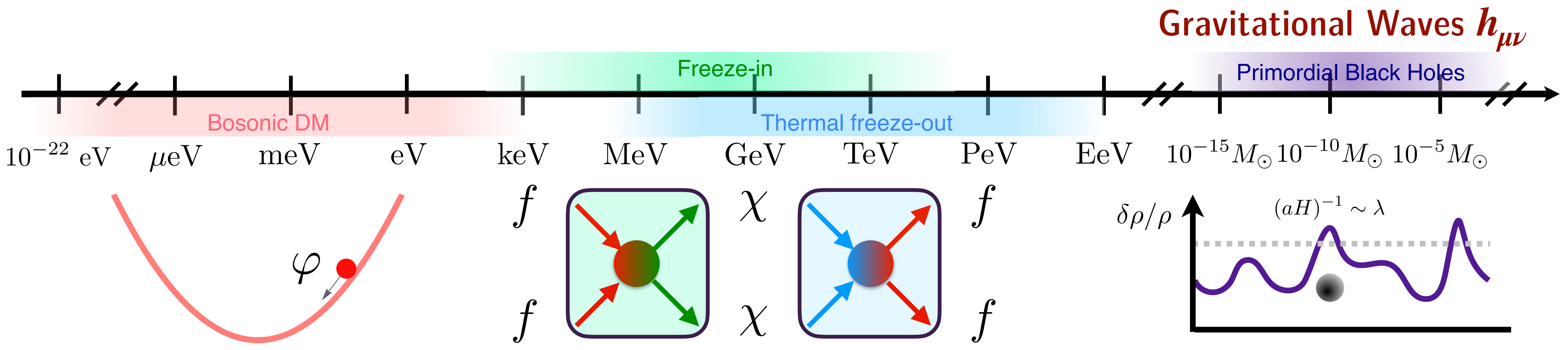
- Detection of **ultra-low threshold** events
- **Coherence** to enhance sensitivity
- $\left\langle \hat{H}_{\mathrm{BSM}} \right\rangle$
- **Ultra-low noise**
- **Small-scale**

Superconducting Cavities

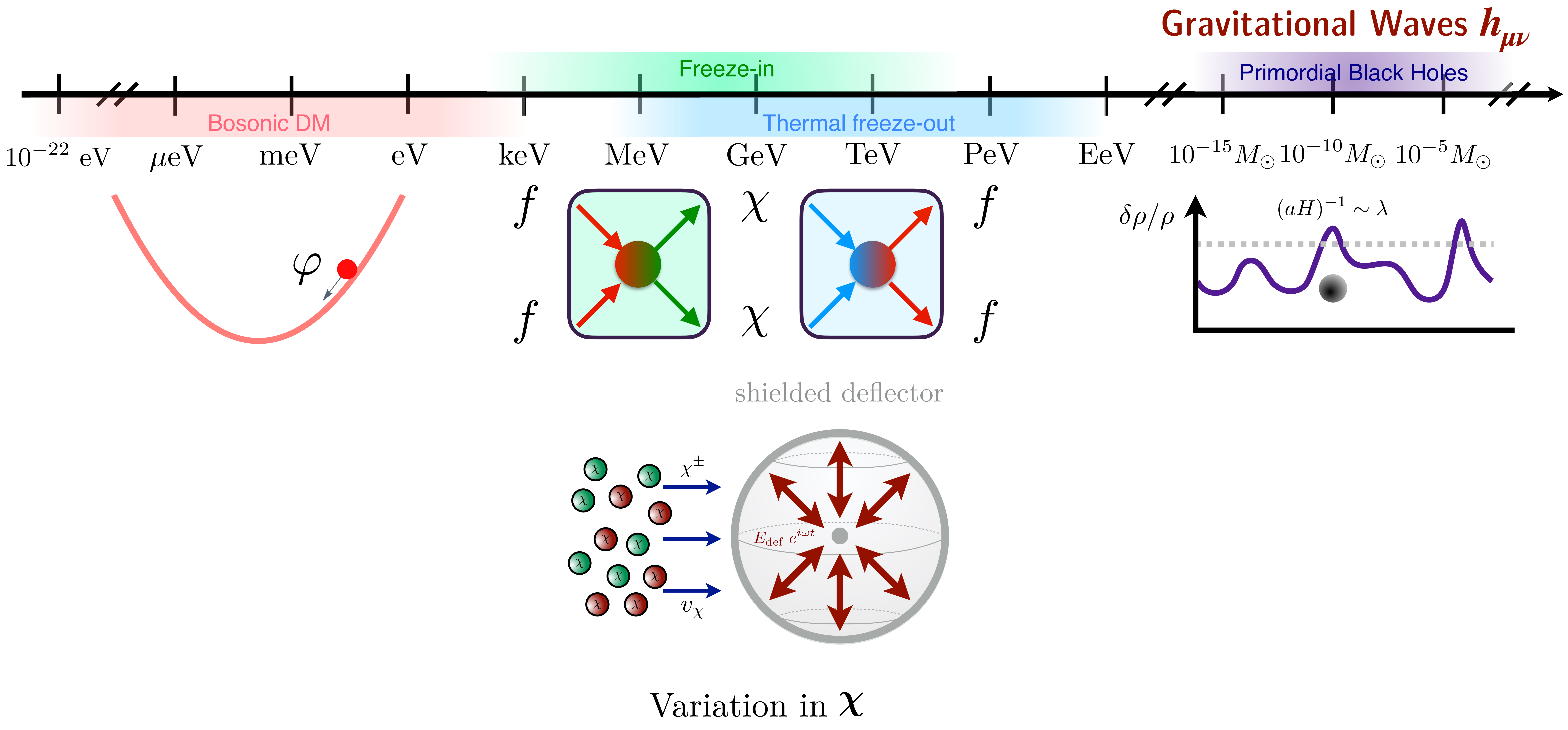
- **Large/ coherent** background EM fields
- Large $\boldsymbol{Q}$ means **long coherence**

- **Low noise**
- **Fits on a table***

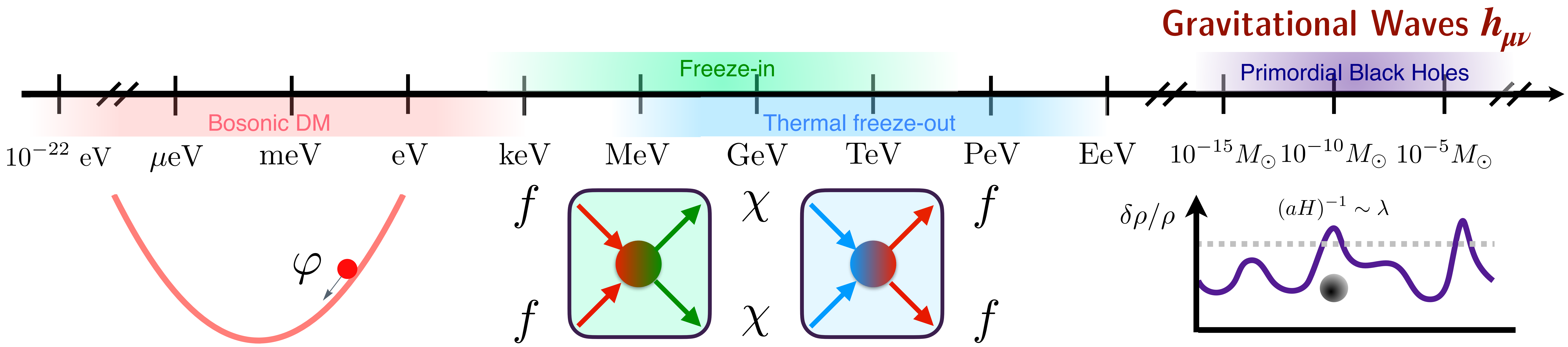
The Dark Matter Bestiary

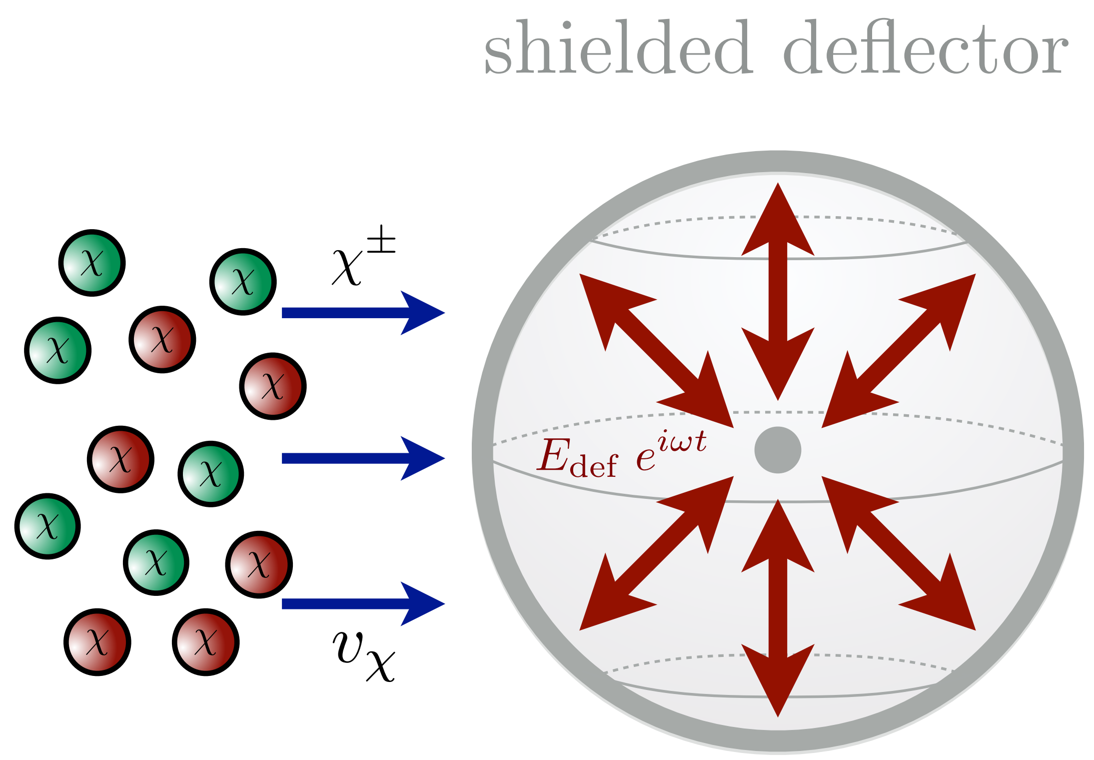


The Dark Matter Bestiary



The Dark Matter Bestiary

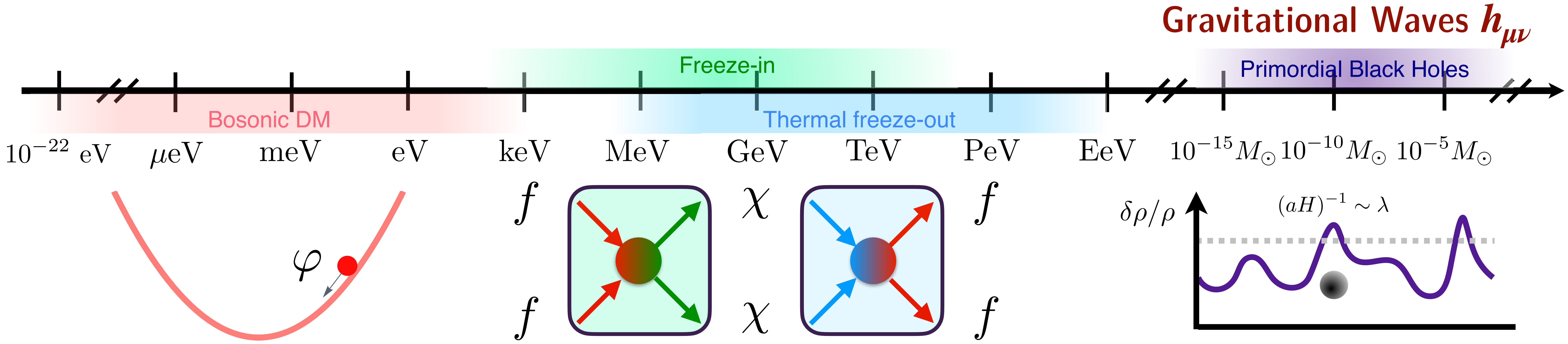


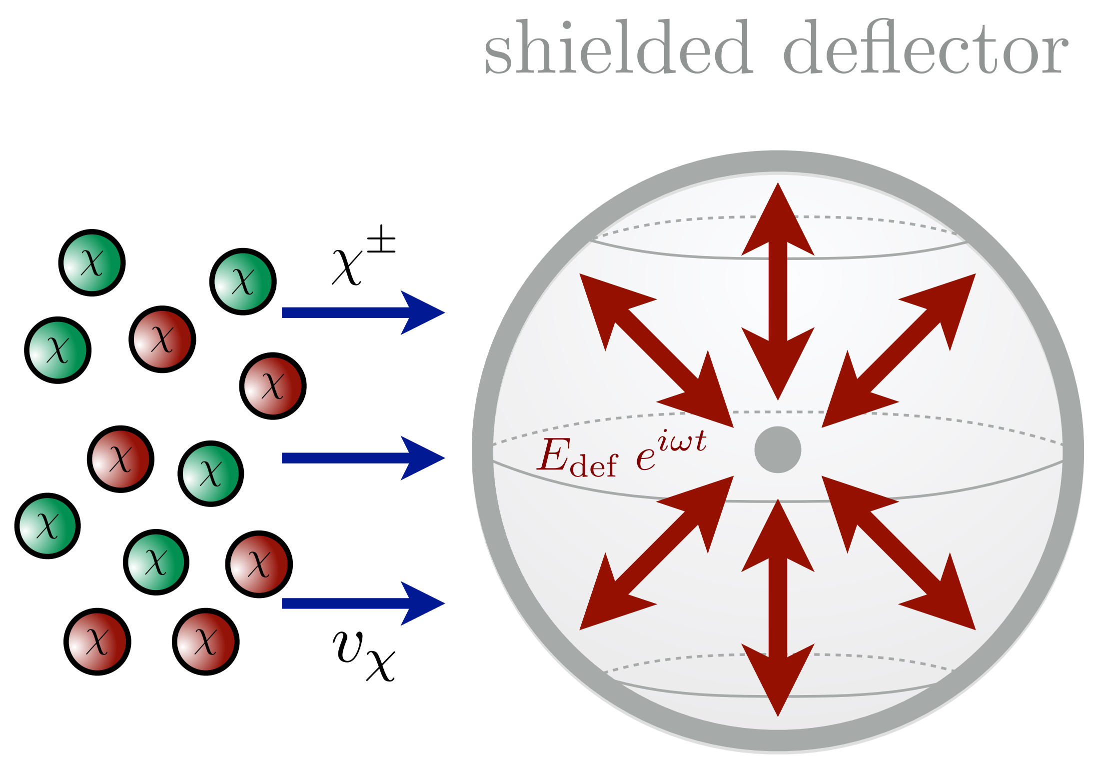


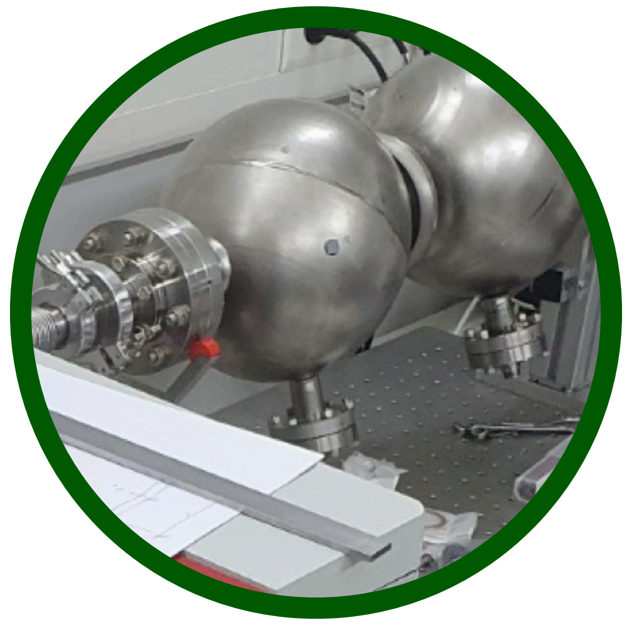
Variation in $\boldsymbol{a}$

Variation in $\boldsymbol{\chi}$

The Dark Matter Bestiary





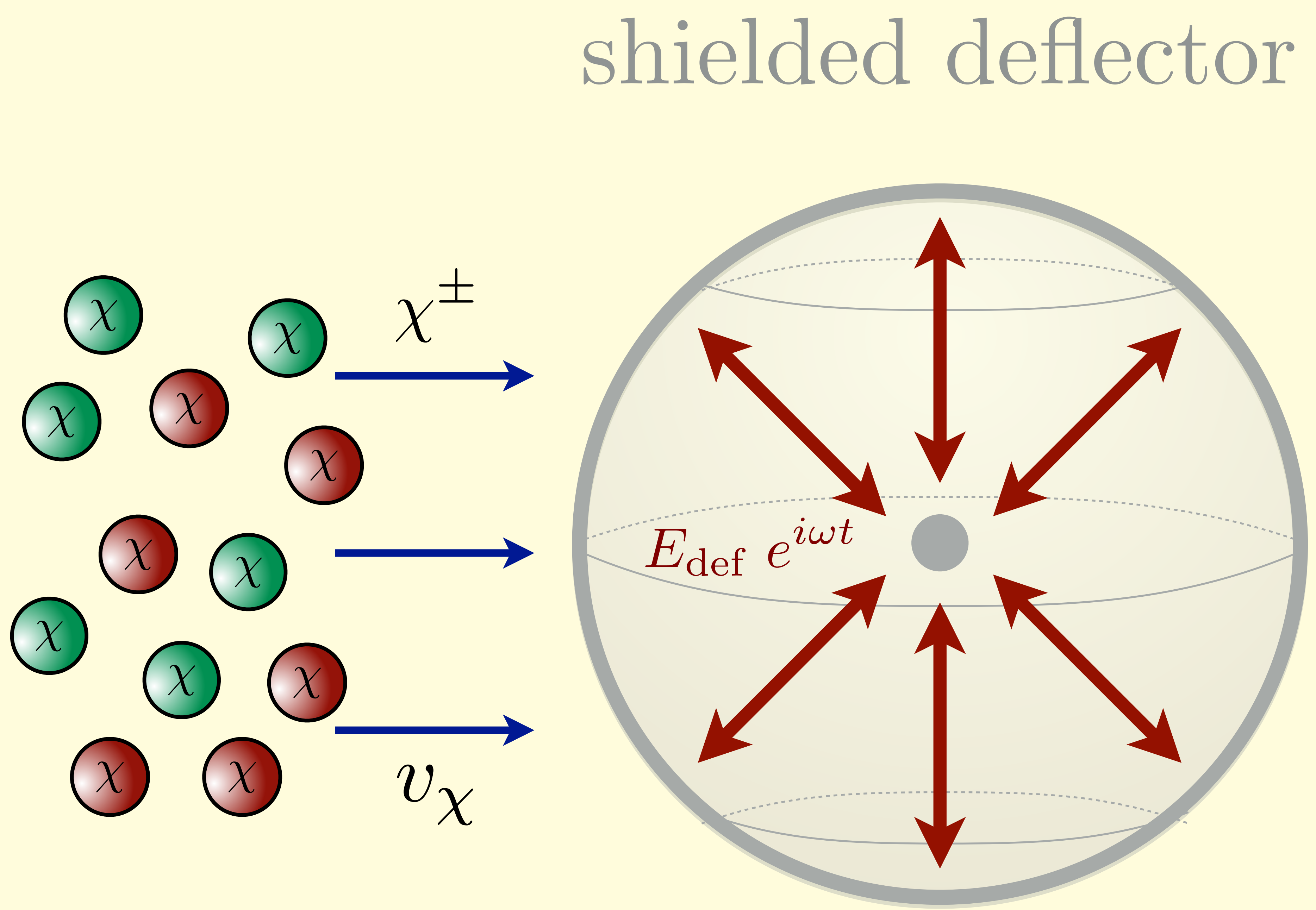


Variation in $\boldsymbol{a}$

Variation in $\boldsymbol{\chi}$

Variation in $\boldsymbol{h_{\mu\nu}}$

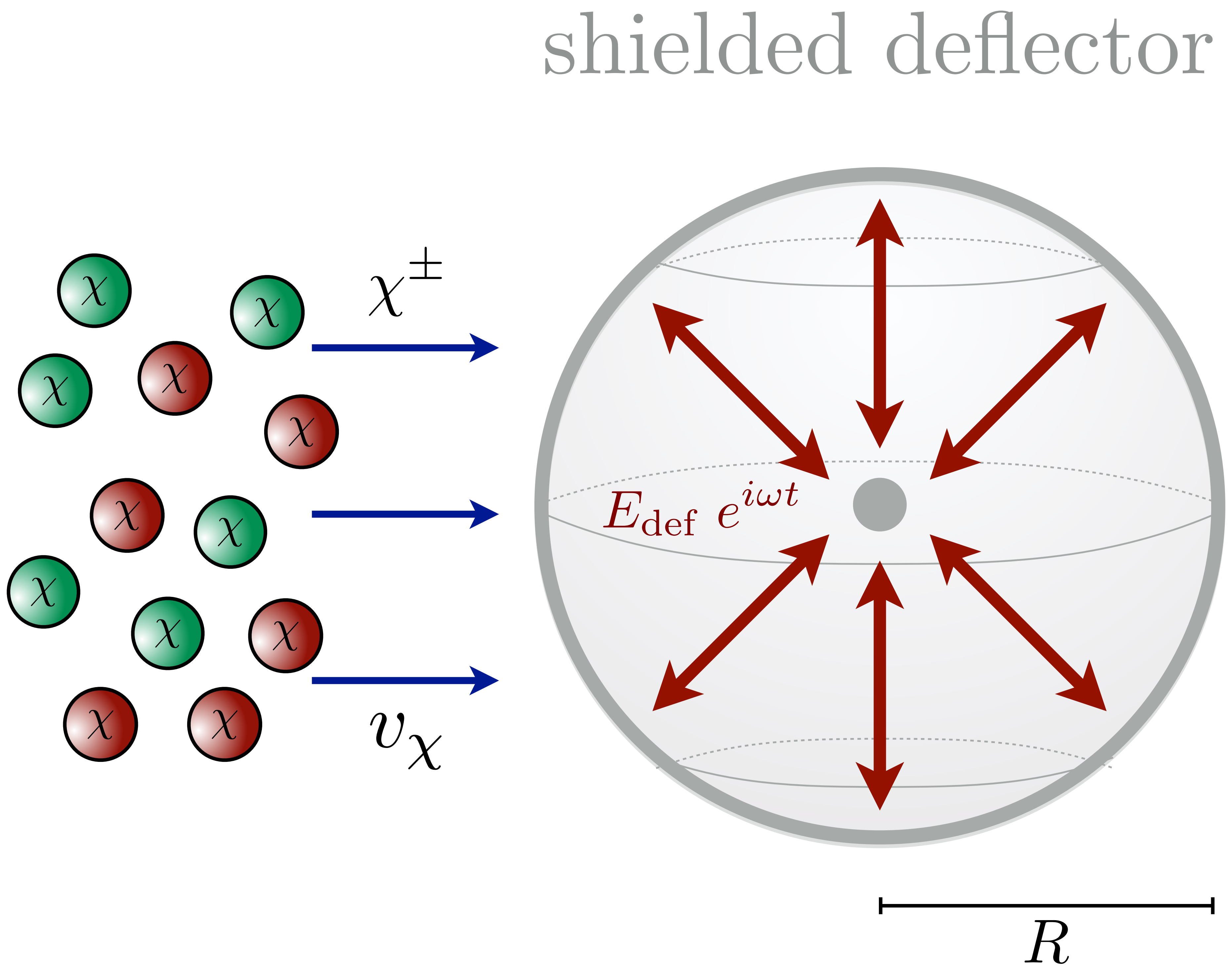
Variation in χ



Ultra-low β

A. Berlin, R. T. D'Agnolo, SARE, P. Schuster, N. Toro
PRL. 124 (2020) 1, 011801

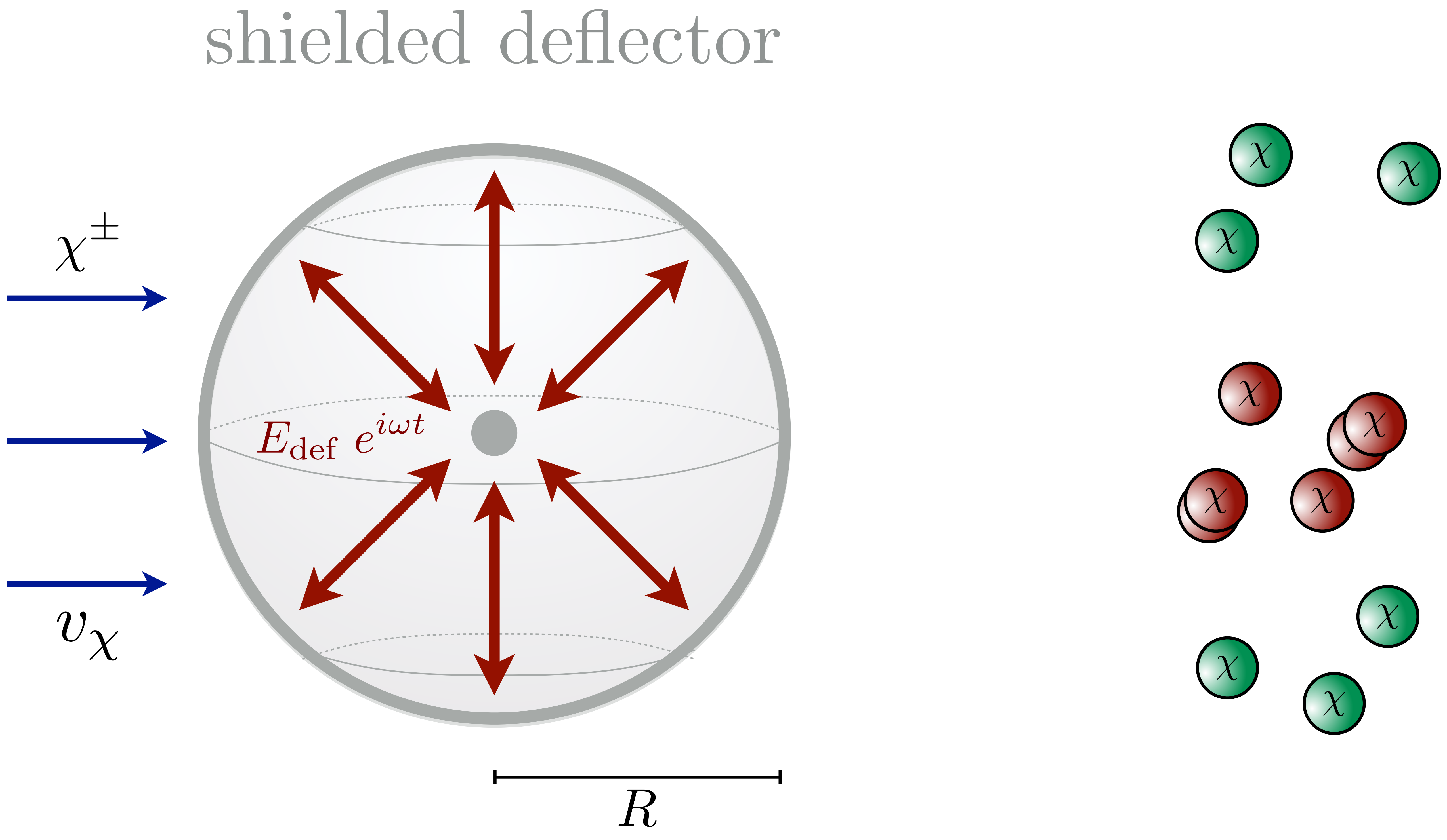
Accelerator for Millicharged DM: $\beta \sim 10^{-3}$



$$\omega \lesssim \pi\, v_\chi / R \sim \mathrm{MHz} \times (R/\mathrm{meter})^{-1}$$

quasi-static limit!

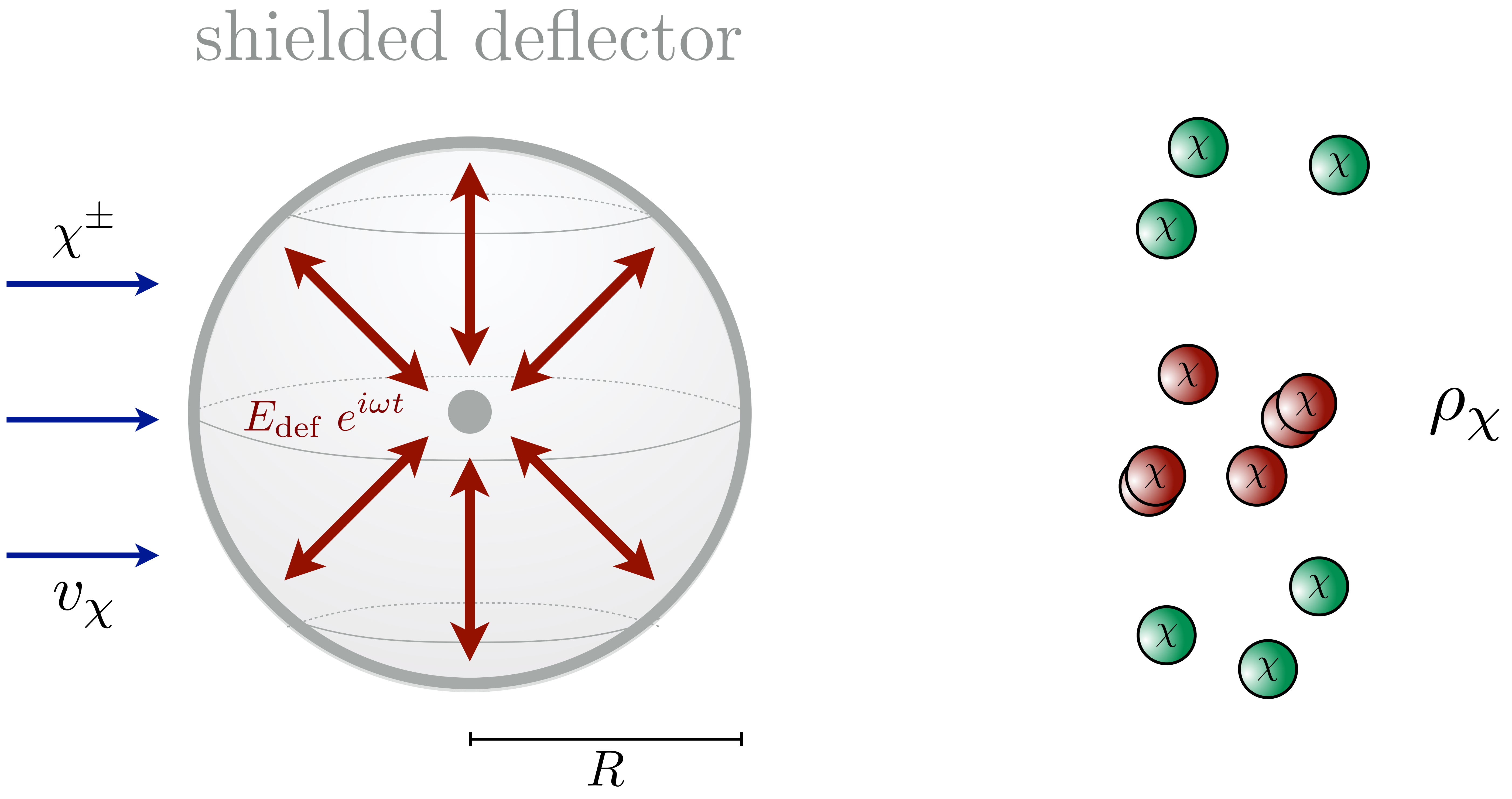
Accelerator for Millicharged DM: $\beta \sim 10^{-3}$



$$\omega \lesssim \pi\, v_\chi / R \sim \mathrm{MHz} \times (R/\mathrm{meter})^{-1}$$

quasi-static limit!

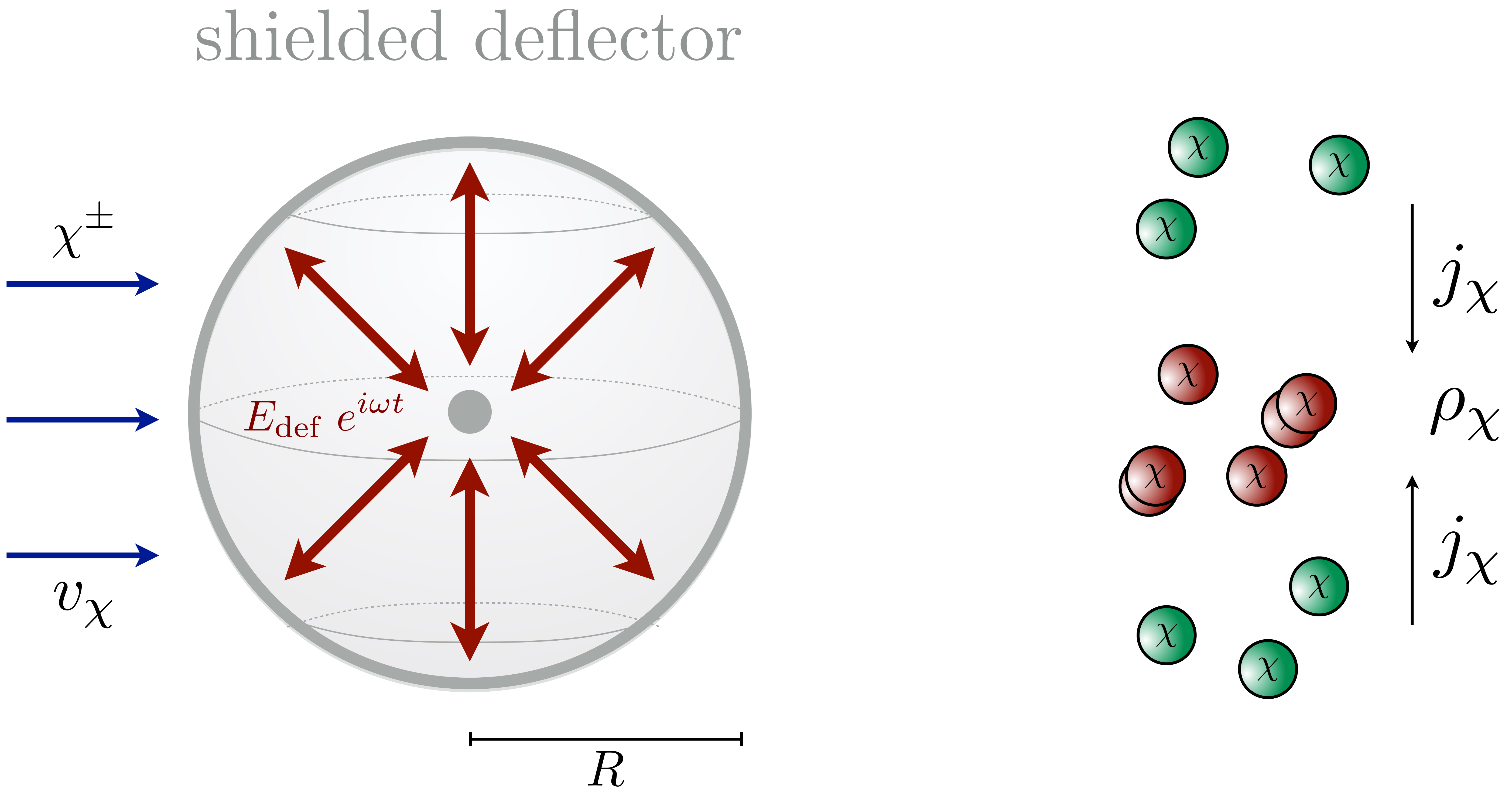
Accelerator for Millicharged DM: $\beta \sim 10^{-3}$



$$\omega \lesssim \pi\, v_\chi / R \sim \text{MHz} \times (R/\text{meter})^{-1}$$

quasi-static limit!

Accelerator for Millicharged DM: $\beta \sim 10^{-3}$

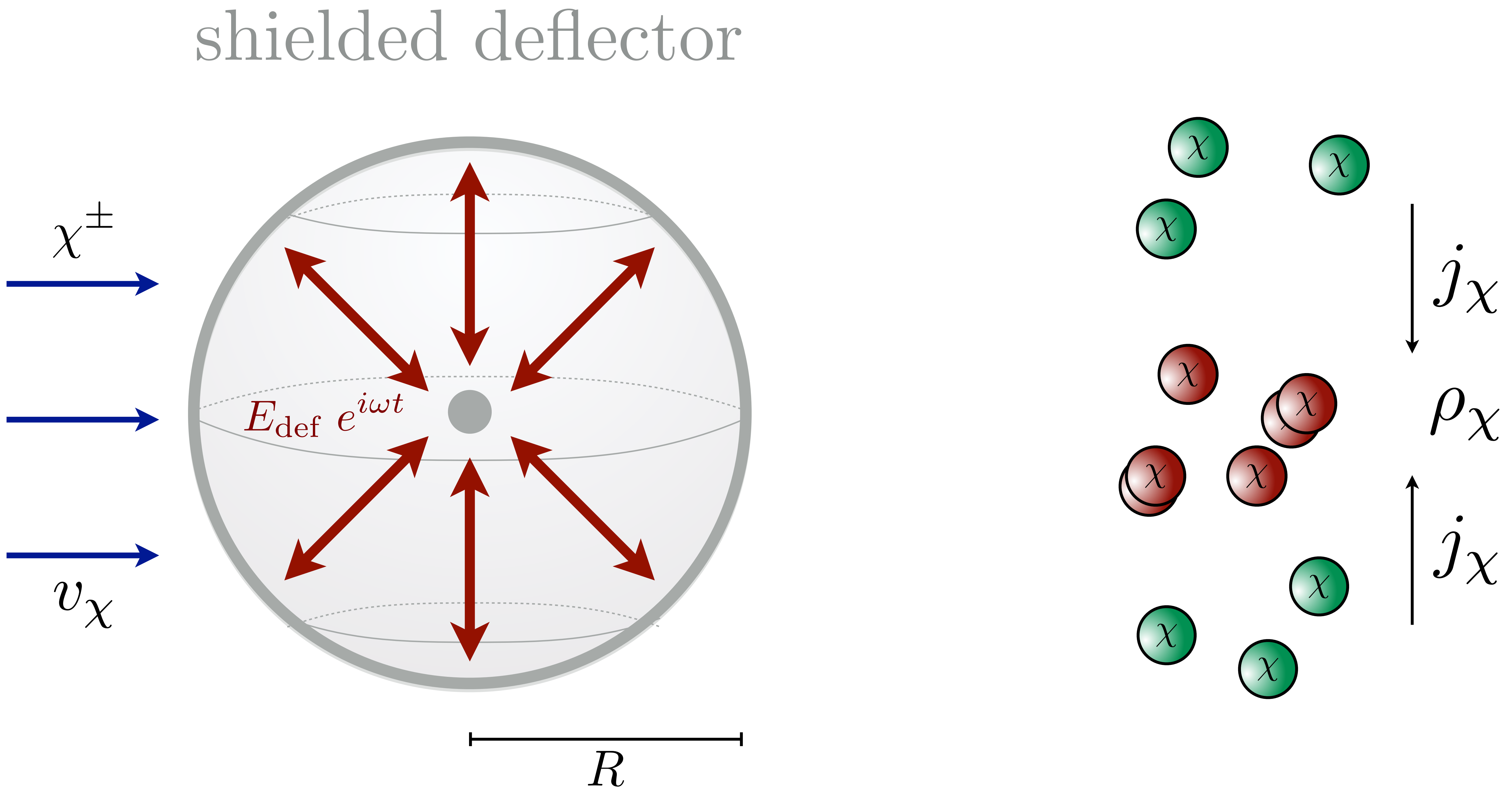


$$\omega \lesssim \pi\, v_\chi / R \sim \text{MHz} \times (R/\text{meter})^{-1}$$

quasi-static limit!

Accelerator for Millicharged DM: $\beta \sim 10^{-3}$

Think magnetic horn (only electric)



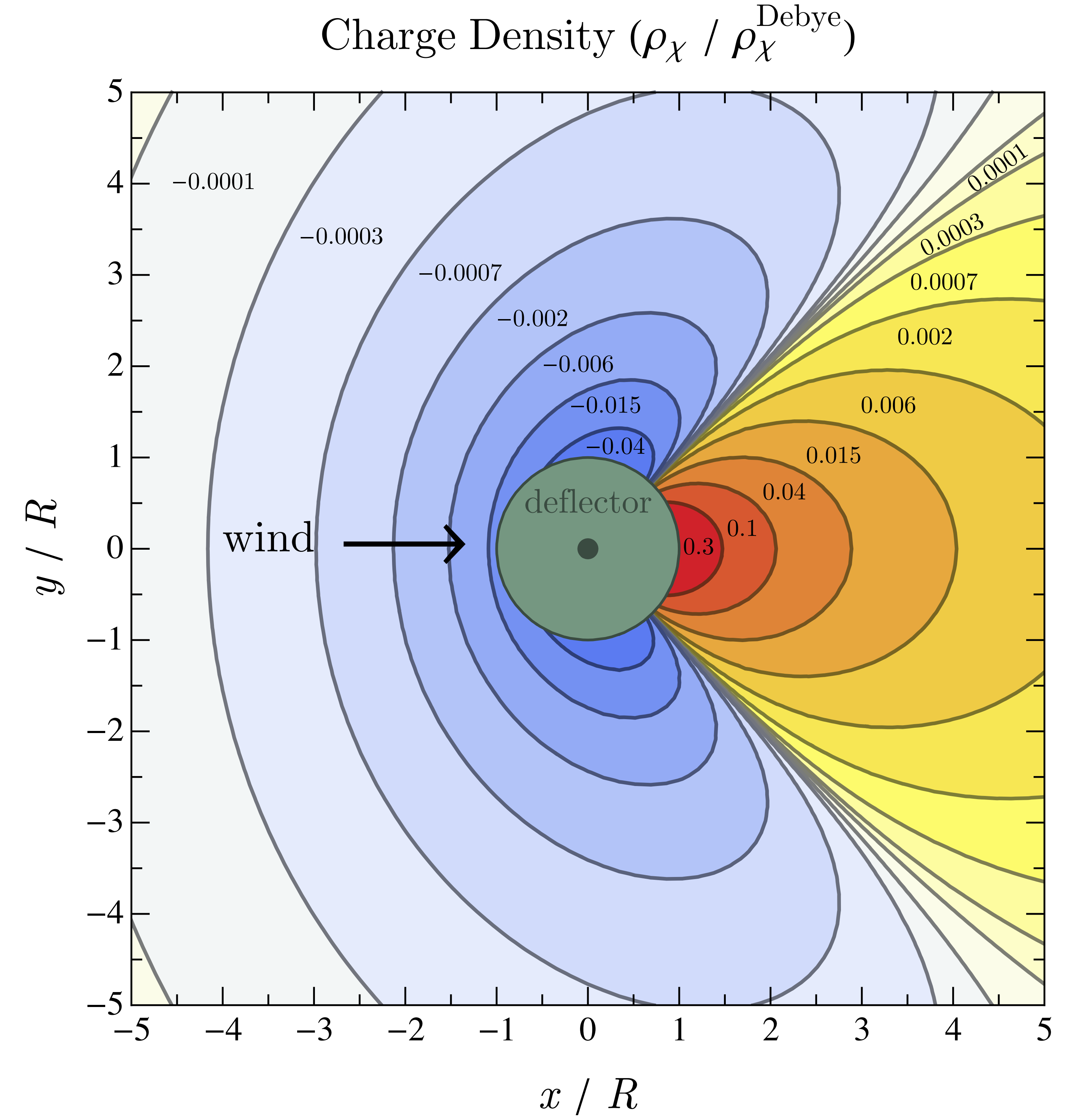
$$\omega \lesssim \pi\, v_\chi / R \sim \text{MHz} \times (R/\text{meter})^{-1}$$

quasi-static limit!

Millicharged DM Waves

Effect vanishes in limit where $v_{\text{wind}} \to 0$

$$\rho_\chi(\mathbf{x}) \sim \rho_\chi^{\text{Debye}}(R) \left(\frac{v_{\text{wind}}}{v_0}\right)^2 \left(\frac{R}{|\mathbf{x}|}\right)^3$$

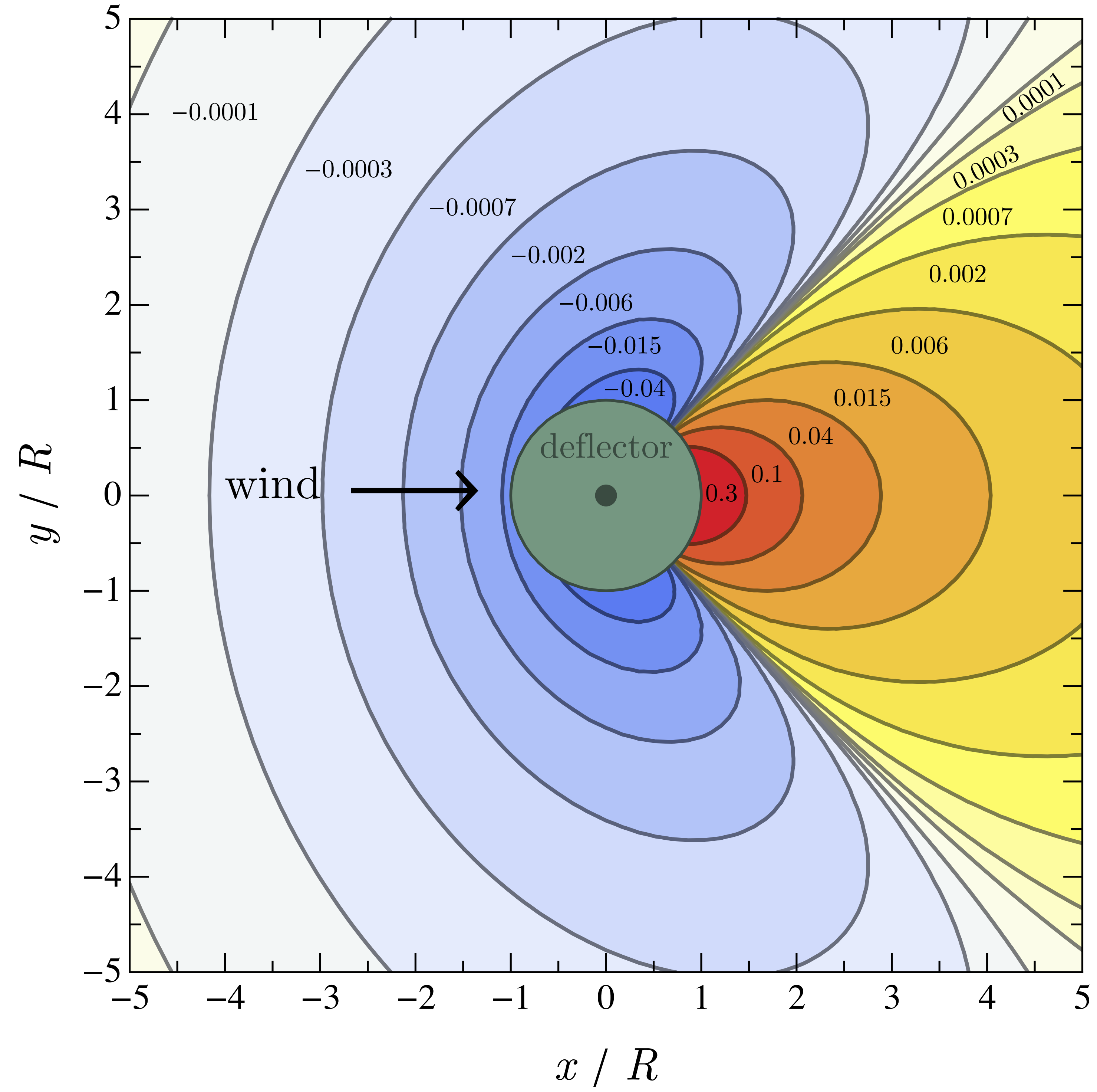


Millicharged DM Waves

Effect vanishes in limit where $v_{\rm wind} \to 0$

$$\rho_\chi(\mathbf{x}) \sim \rho_\chi^{\rm Debye}(R) \left(\frac{v_{\rm wind}}{v_0}\right)^2 \left(\frac{R}{|\mathbf{x}|}\right)^3$$

Charge Density (ρ_χ / $\rho_\chi^{\rm Debye}$)

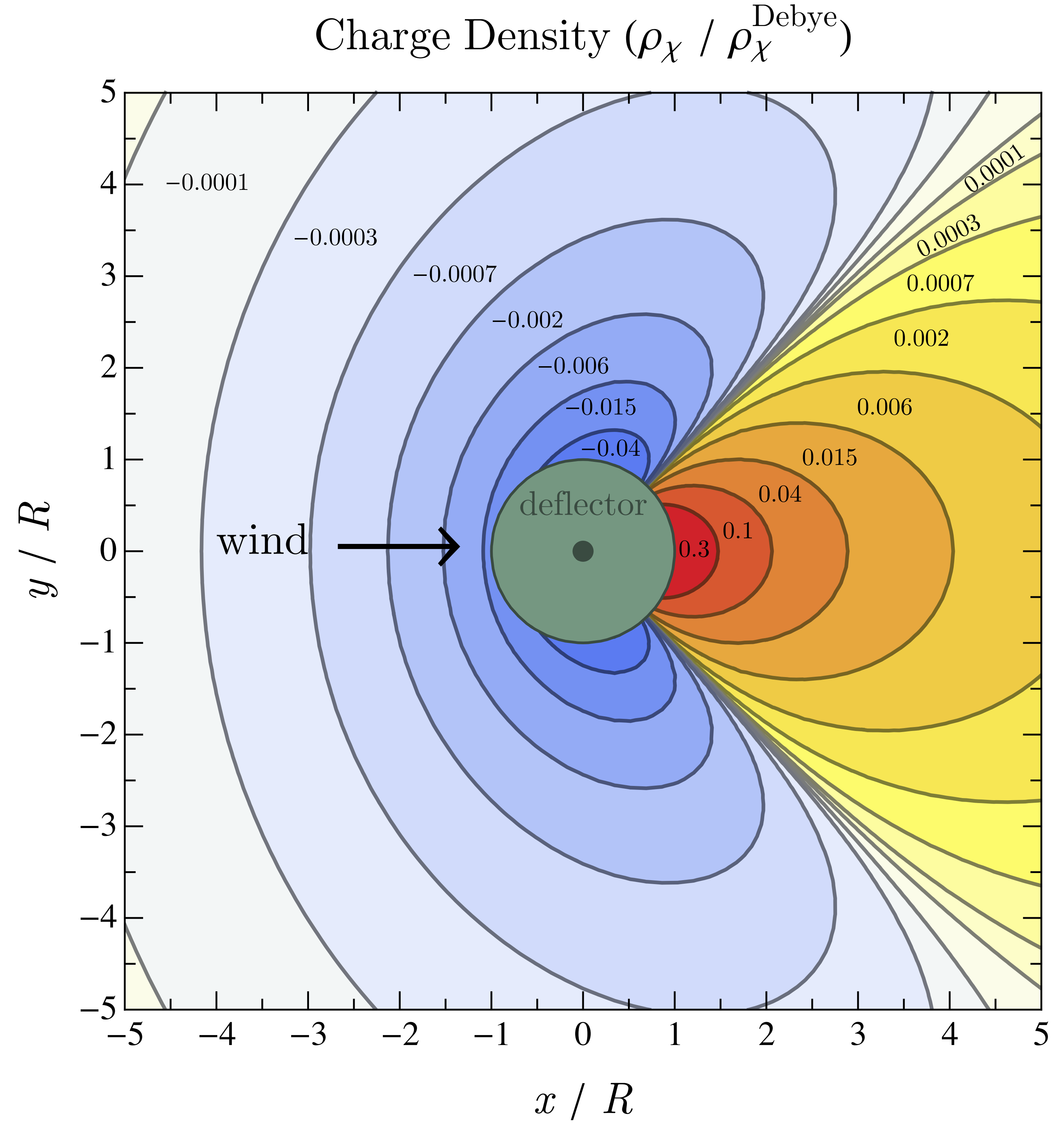


Detecting them?

Millicharged DM Waves

Effect vanishes in limit where $v_{\text{wind}} \to 0$

$$\rho_\chi(\mathbf{x}) \sim \rho_\chi^{\text{Debye}}(R) \left(\frac{v_{\text{wind}}}{v_0}\right)^2 \left(\frac{R}{|\mathbf{x}|}\right)^3$$



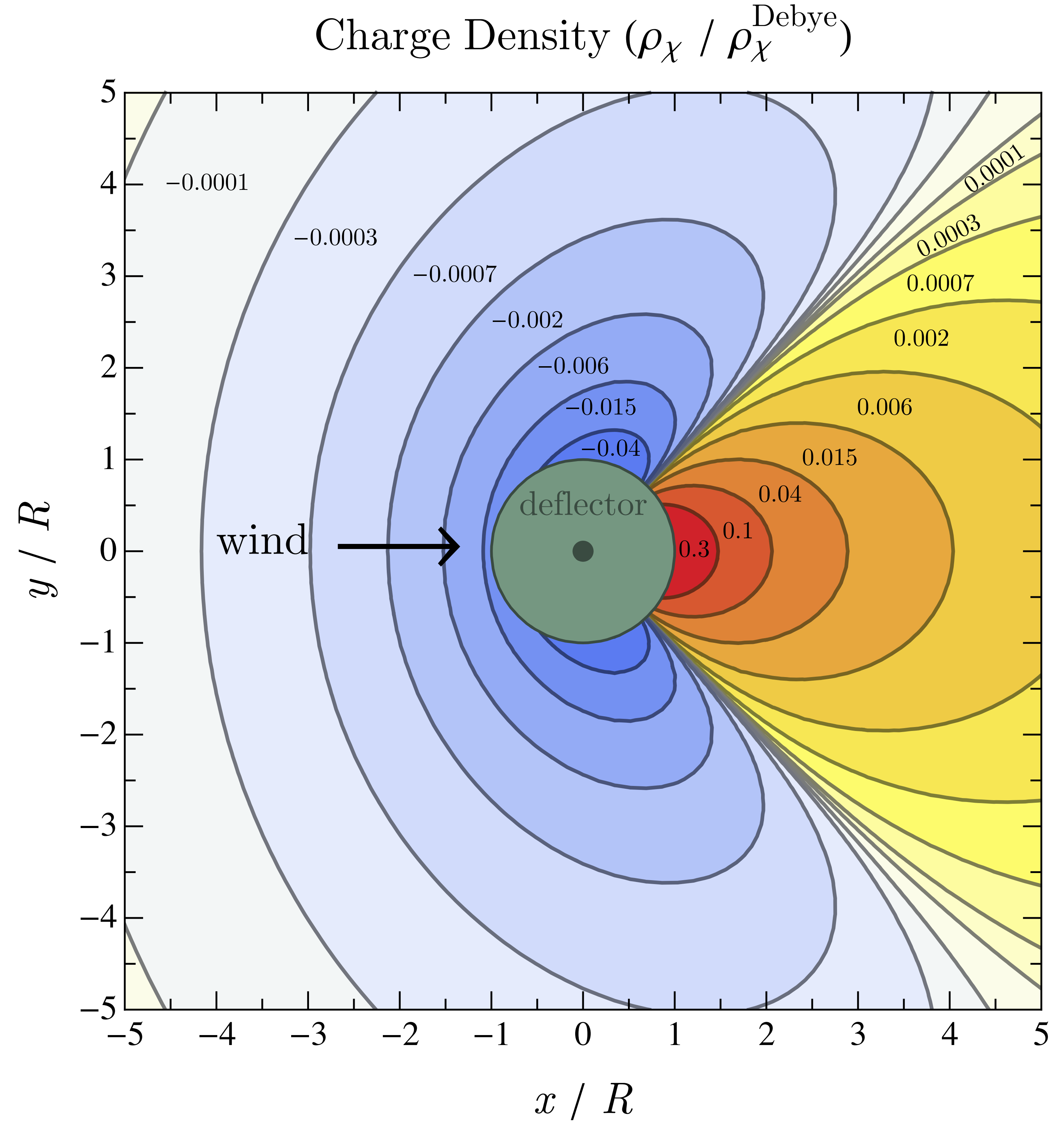
Detecting them?

Since E-field signal dominant, capacitative pickup optimal

Millicharged DM Waves

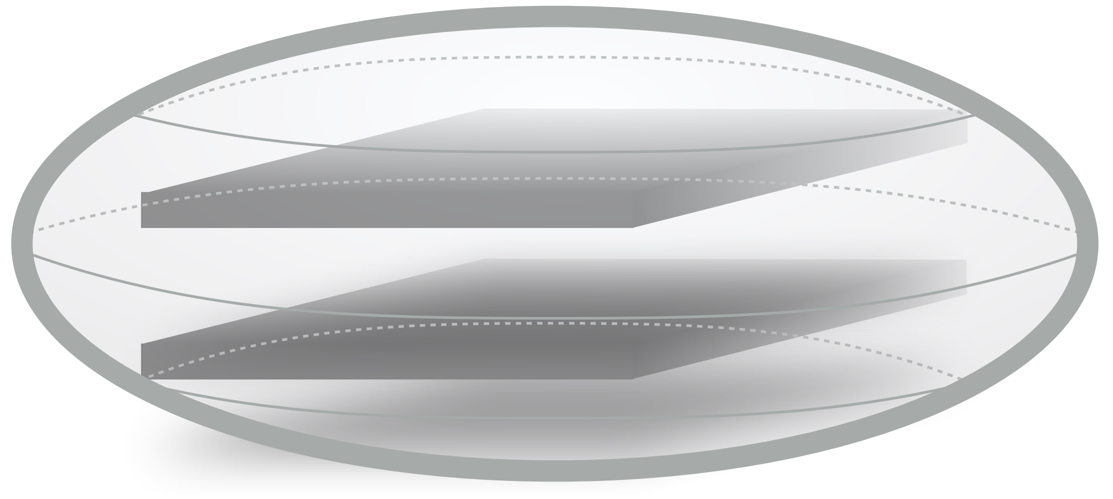
Effect vanishes in limit where $v_{\rm wind} \to 0$

$$\rho_\chi(\mathbf{x}) \sim \rho_\chi^{\rm Debye}(R)\left(\frac{v_{\rm wind}}{v_0}\right)^2\left(\frac{R}{|\mathbf{x}|}\right)^3$$



Detecting them?

Since E-field signal dominant, capacitative pickup optimal



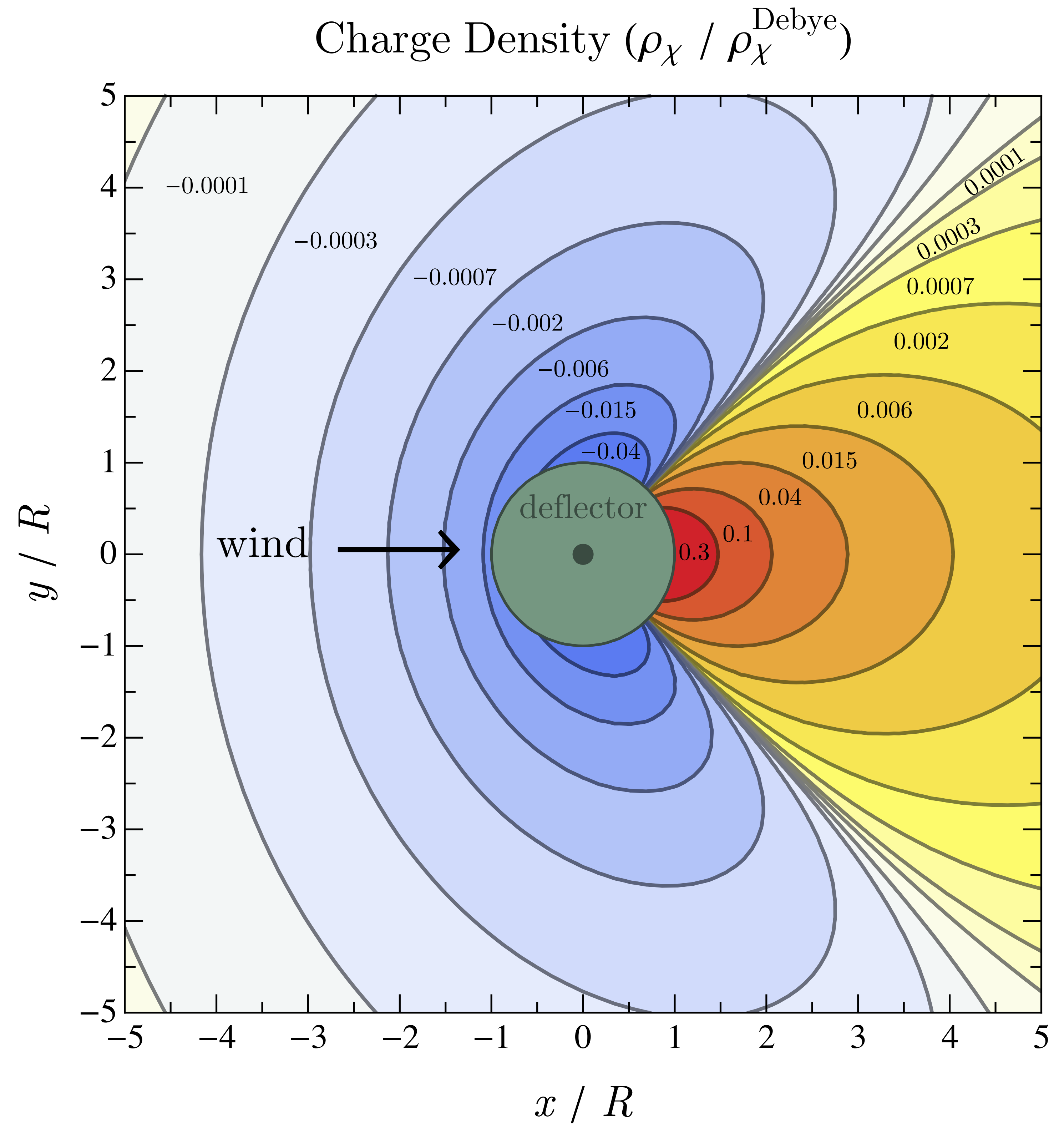
$$U_{\rm s} = \int_V \frac{1}{2}\epsilon \mathbf{E}^2$$

Effective volume of capacitor/antenna — bounded by shielded volume

Millicharged DM Waves

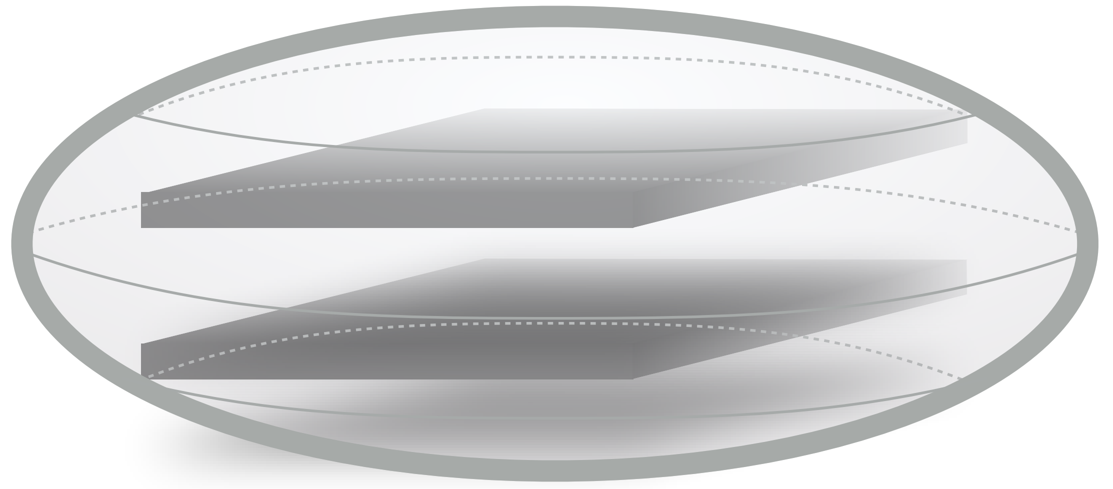
Effect vanishes in limit where $v_{\rm wind} \to 0$

$$\rho_\chi(\mathbf{x}) \sim \rho_\chi^{\rm Debye}(R) \left(\frac{v_{\rm wind}}{v_0}\right)^2 \left(\frac{R}{|\mathbf{x}|}\right)^3$$



Detecting them?

Since E-field signal dominant, capacitative pickup optimal

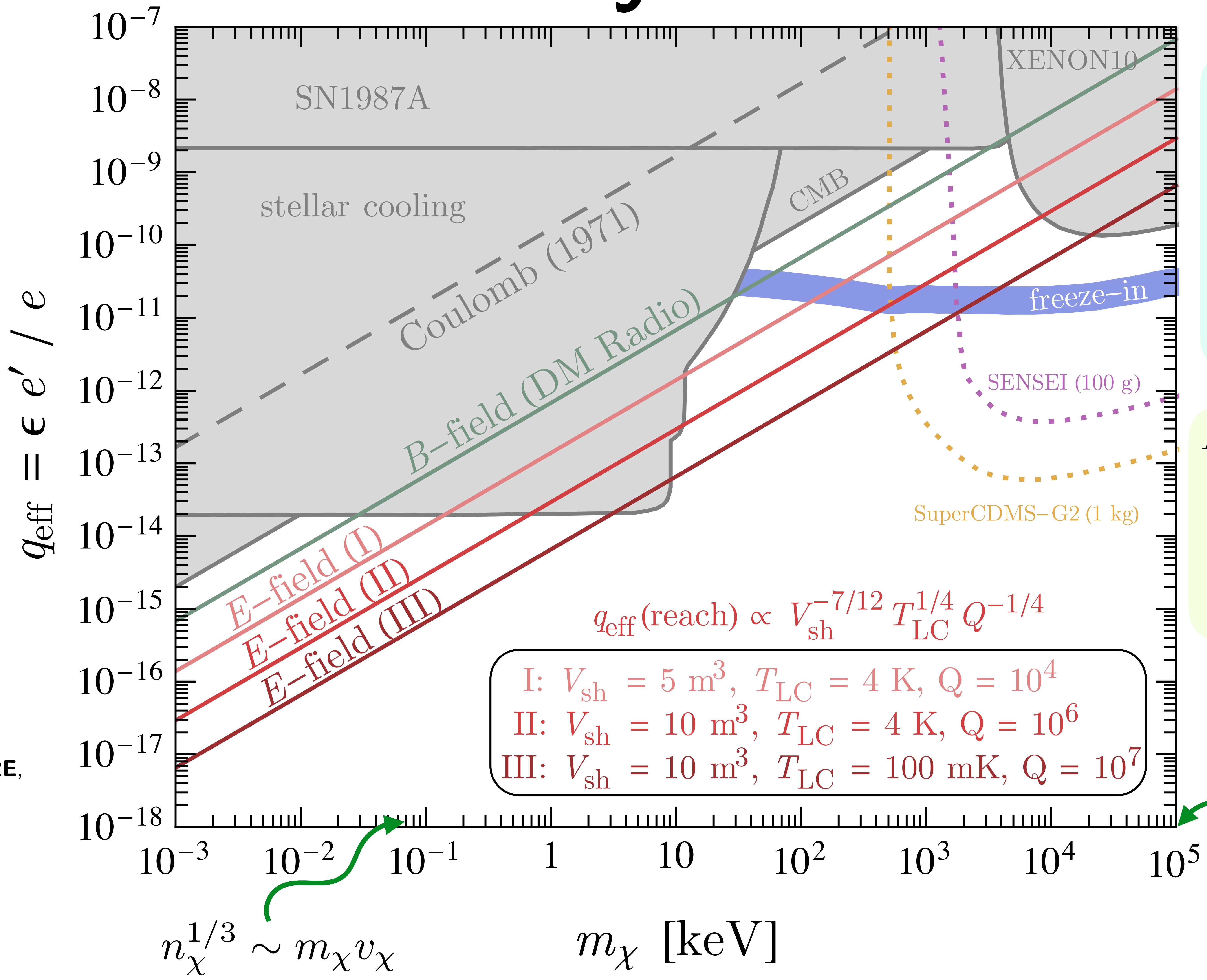


$$U_s = \int_V \frac{1}{2}\epsilon \mathbf{E}^2$$

Effective volume of capacitor/antenna — bounded by shielded volume

We want EM resonator, but could use e.g. *ion traps*

Experimental Sensitivity



$t_{\rm int} = 1$ yr

$\omega = 100$ kHz

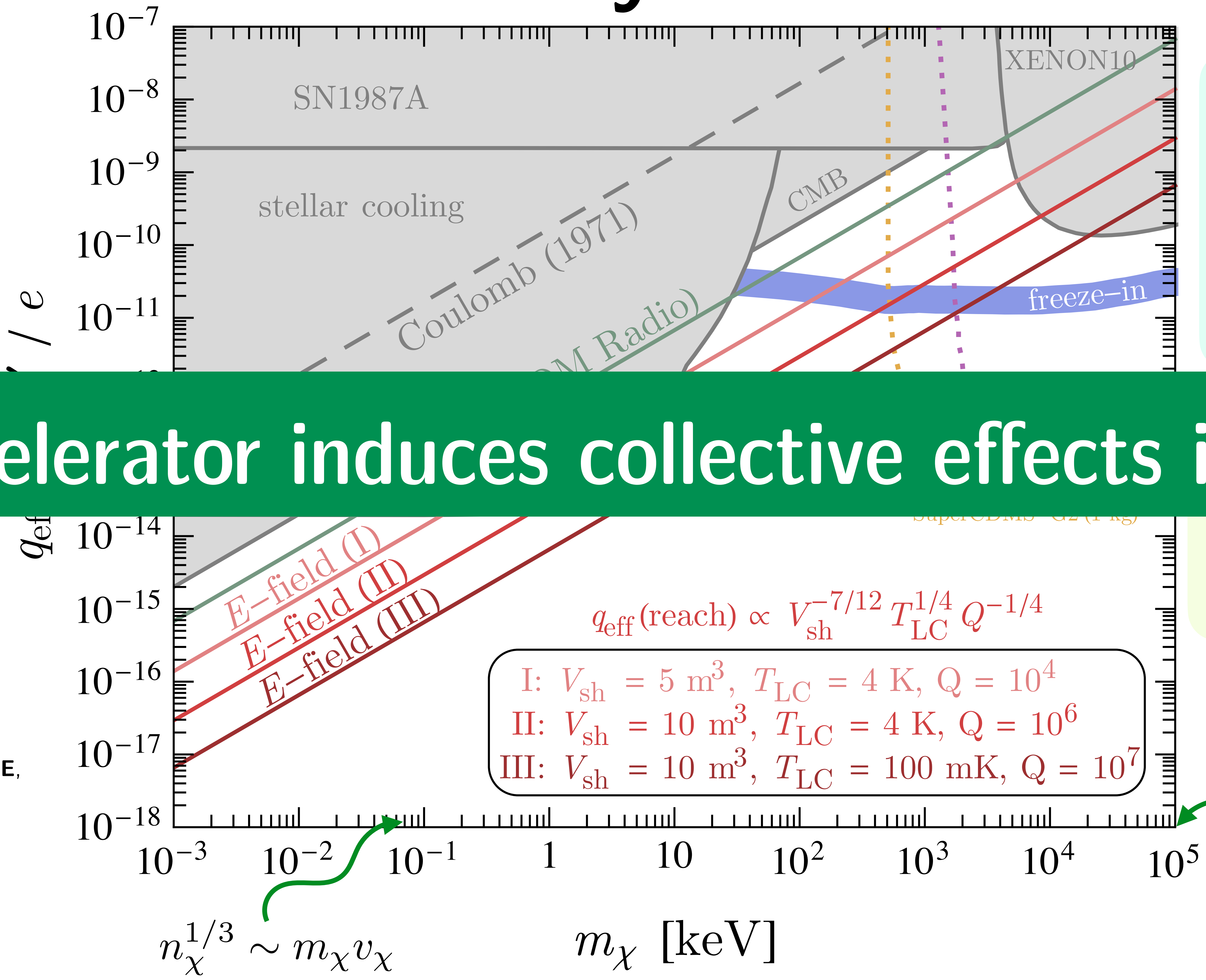
$\langle E_{\rm def} \rangle = 10$ kV/cm

$$E_\chi \sim 10^{-12}\,\text{kV/cm} \times \left(\frac{q_{\rm eff}}{10^{-10}}\right)^2 \times \left(\frac{m_\chi}{\text{keV}}\right)^{-2}$$

$n_\chi \sim 10^7$ m^{-3}

PRL 124 (2020) 1, 011801
hep-ph/1908.06982
A. Berlin, R. T. D'Agnolo, **SARE**, P. Schuster, N. Toro

Experimental Sensitivity



$t_{int} = 1$ yr

$\omega = 100$ kHz

$\langle E_{def} \rangle = 10$ kV/cm

$\times \left(\frac{\ }{10^{-10}}\right)$

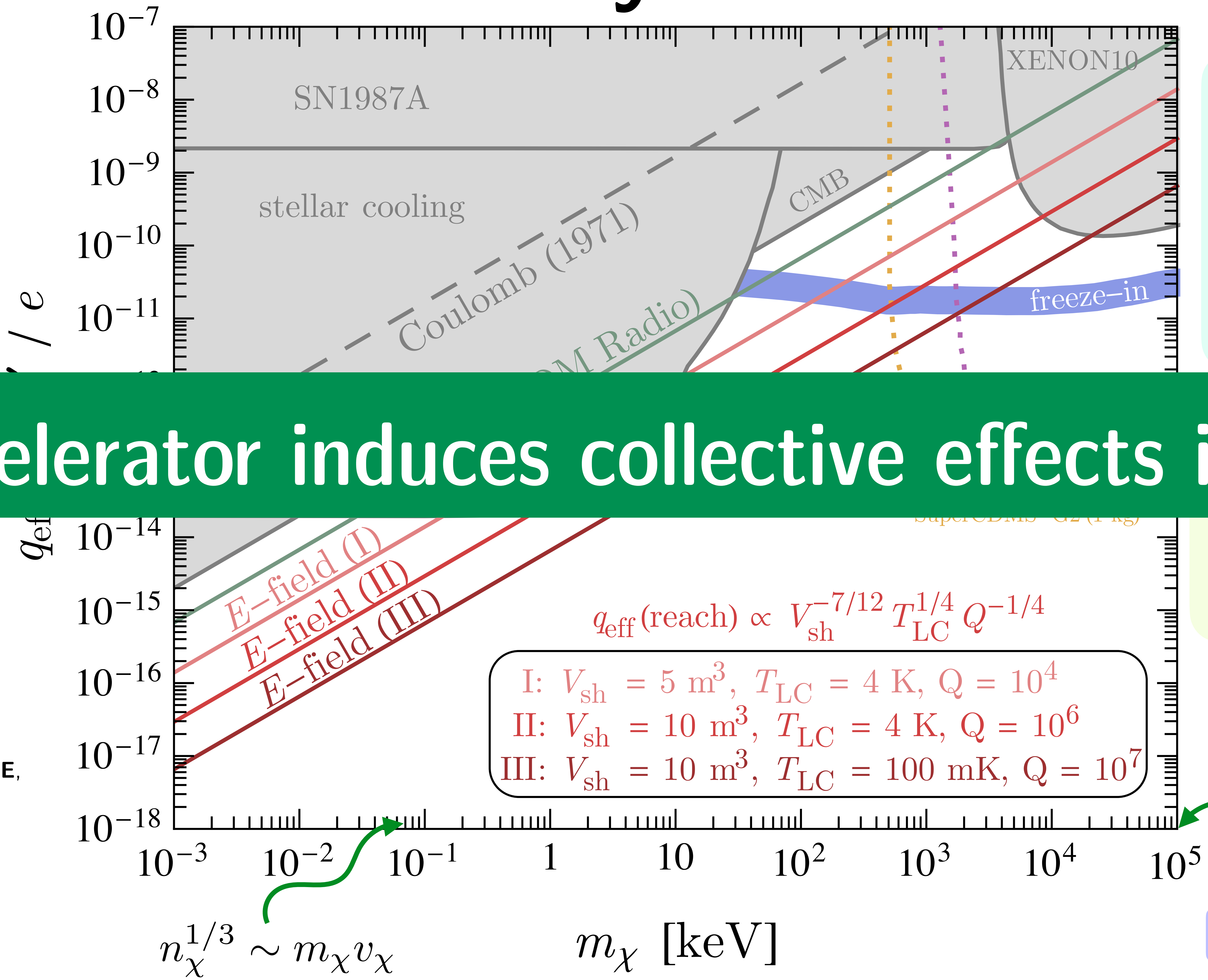
$\times \left(\frac{m_\chi}{\text{keV}}\right)^{-2}$

$n_\chi \sim 10^7\ m^{-3}$

Accelerator induces collective effects in DM!

PRL 124 (2020) 1, 011801
hep-ph/1908.06982
A. Berlin, R. T. D'Agnolo, **SARE**,
P. Schuster, N. Toro

Experimental Sensitivity



$t_{\rm int} = 1$ yr

$\omega = 100$ kHz

$\langle E_{\rm def}\rangle = 10$ kV/cm

$\times \left(\frac{m_\chi}{\rm keV}\right)^{-2}$

Accelerator induces collective effects in DM!

PRL 124 (2020) 1, 011801
hep-ph/1908.06982
A. Berlin, R. T. D'Agnolo, **SARE**, P. Schuster, N. Toro

See backup for a related concept

VARIATION IN a

A. Berlin, R. T. D'Agnolo, SARE, C. Nantista, J. Neilson, P. Schuster, S. Tantawi, N. Toro, K. Zhou
JHEP 07 (2020) 088

A. Berlin, R. T. D'Agnolo, SARE, K. Zhou
Phys.Rev.D 104 (2021) 11, L111701

$\beta \sim 1$

Signal In a Resonator

Signal In a Resonator

Axion-induced magnetic field induces an E.M.F.: $\mathcal{E}_a \sim V^{2/3}\,\partial_t B_a$

Signal In a Resonator

Axion-induced magnetic field induces an E.M.F.: $\mathcal{E}_a \sim V^{2/3}\,\partial_t B_a$

$$P_{\rm sig} \sim \omega_{\rm sig}^2 B_a^2 V \min\left(\frac{Q_r}{\omega_{\rm sig}}, \frac{Q_a}{m_a}\right)$$

$Q_a \sim 1/\langle v^2 \rangle$

Signal In a Resonator

Axion-induced magnetic field induces an E.M.F.: $\mathcal{E}_a \sim V^{2/3}\,\partial_t B_a$

$$P_{\rm sig} \sim \omega_{\rm sig}^2 B_a^2 V \min\left(\frac{Q_r}{\omega_{\rm sig}}, \frac{Q_a}{m_a}\right)$$

$Q_a \sim 1/\langle v^2 \rangle$

Maximise: $\omega_{\rm sig}$, B_a, V

Signal In a Resonator

Axion-induced magnetic field induces an E.M.F.: $\mathcal{E}_a \sim V^{2/3}\,\partial_t B_a$

$$P_{\rm sig} \sim \omega_{\rm sig}^2 B_a^2 V \min\left(\frac{Q_r}{\omega_{\rm sig}}, \frac{Q_a}{m_a}\right)$$

$Q_a \sim 1/\langle v^2 \rangle$

Maximise: $\omega_{\rm sig}$, B_a, V

Signal In a Resonator

Axion-induced magnetic field induces an E.M.F.: $\mathcal{E}_a \sim V^{2/3}\,\partial_t B_a$

$$P_{\rm sig} \sim \omega_{\rm sig}^2 B_a^2 V \min\left(\frac{Q_r}{\omega_{\rm sig}}, \frac{Q_a}{m_a}\right)$$

$Q_a \sim 1/\langle v^2\rangle$

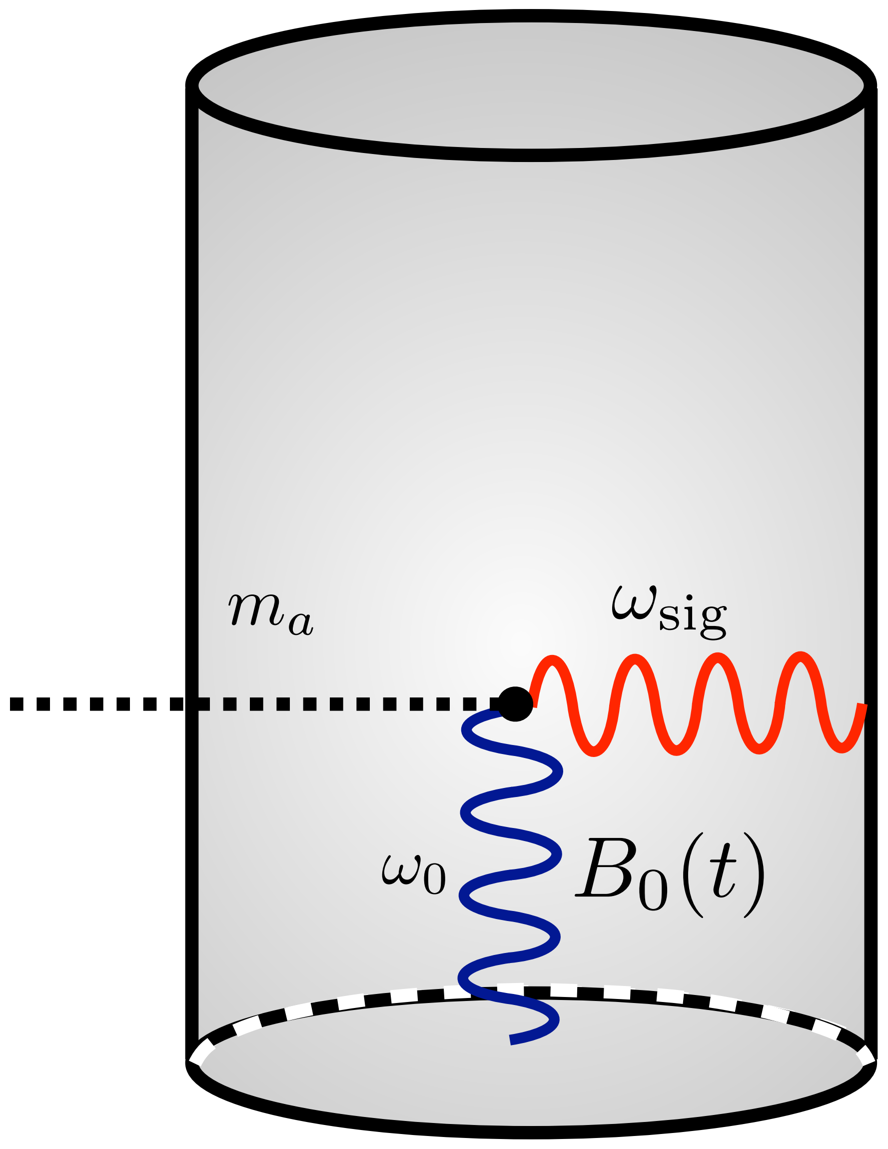
Maximise: $\omega_{\rm sig}$, B_a, V

WARNING

QUANTITIES OFTEN LINKED

Heterodyne Resonator:

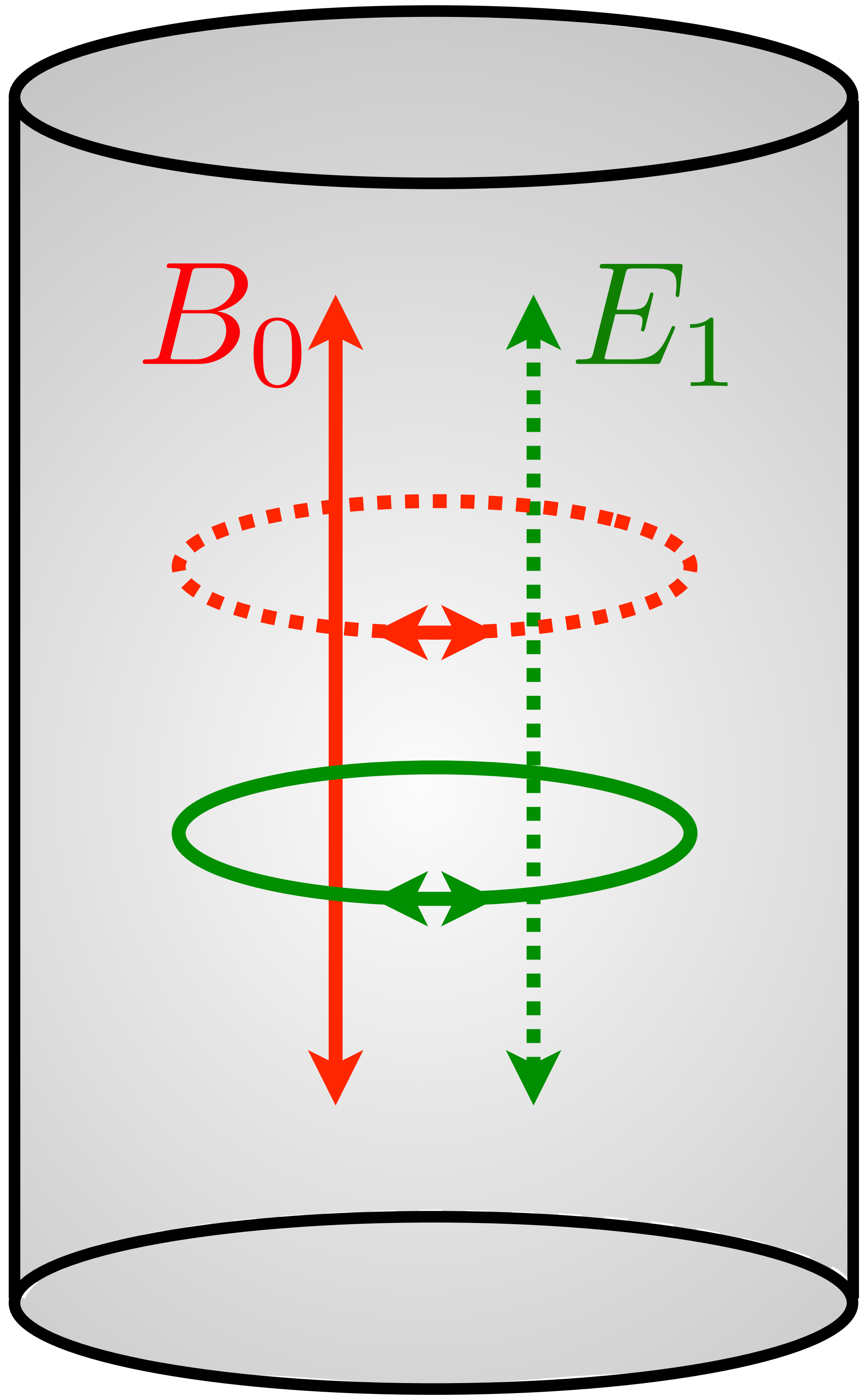
$$\omega_{\rm sig} \sim \omega_0 \pm m_a \sim V^{-1/3}$$



JHEP 07 (2020) 088, hep-ph/1912.11048
A. Berlin, R. T. D'Agnolo, SARE, P. Schuster, N. Toro, C. Nantista, J. Neilson, S. Tantawi, K. Zhou

Also: R. Lasenby *Phys.Rev.D* 102 (2020) 1, 015008 hep-ph/1912.11056

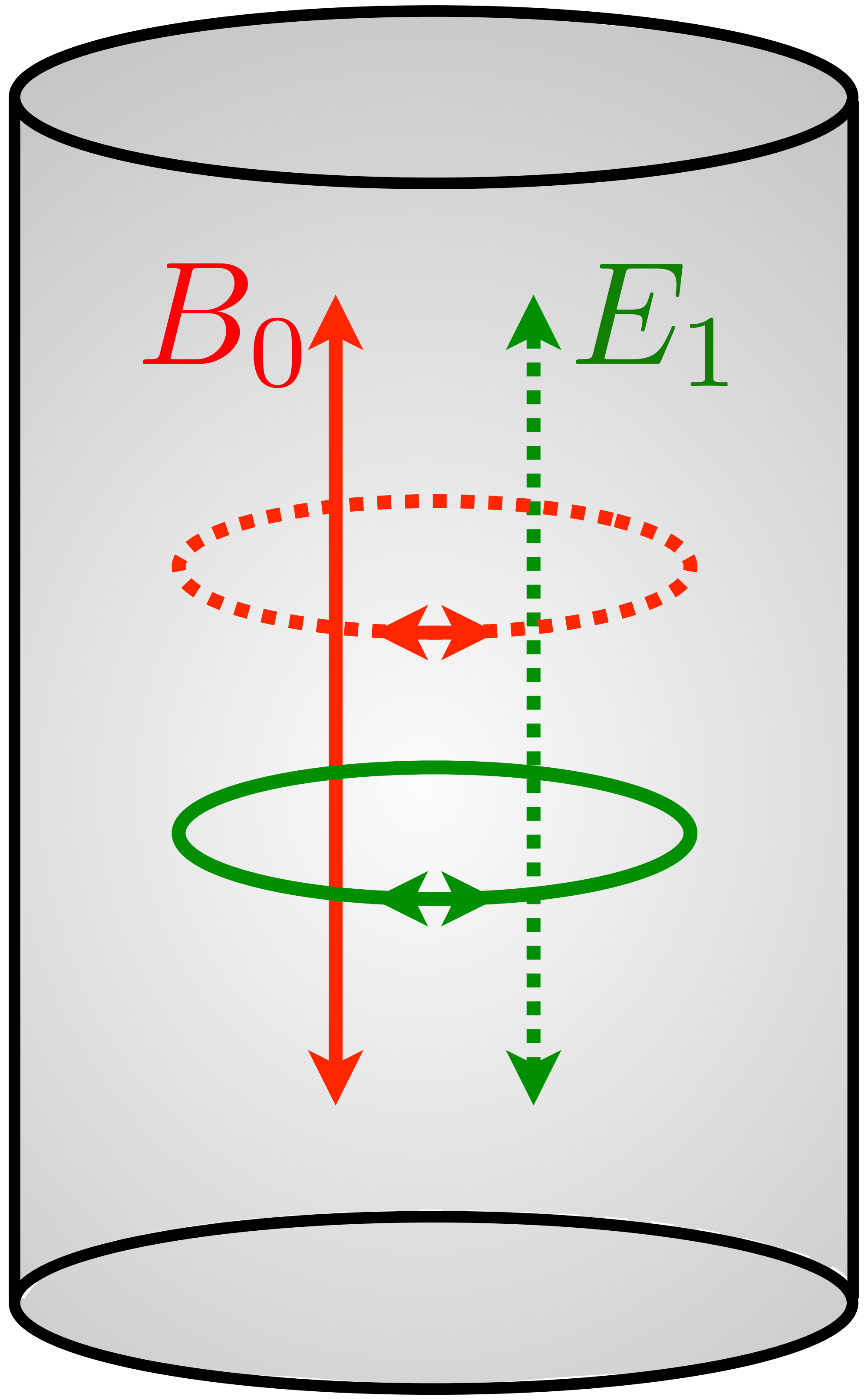
How Does it Work?

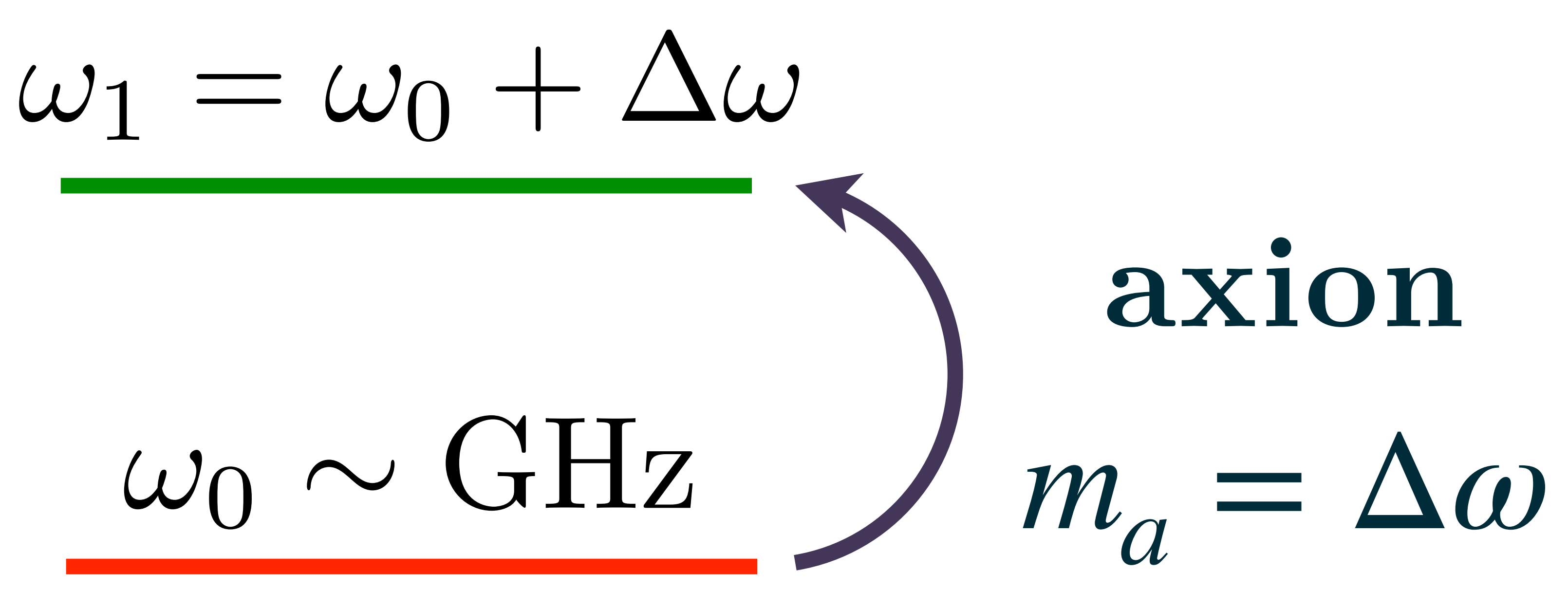


$$\omega_1 = \omega_0 + \Delta\omega$$

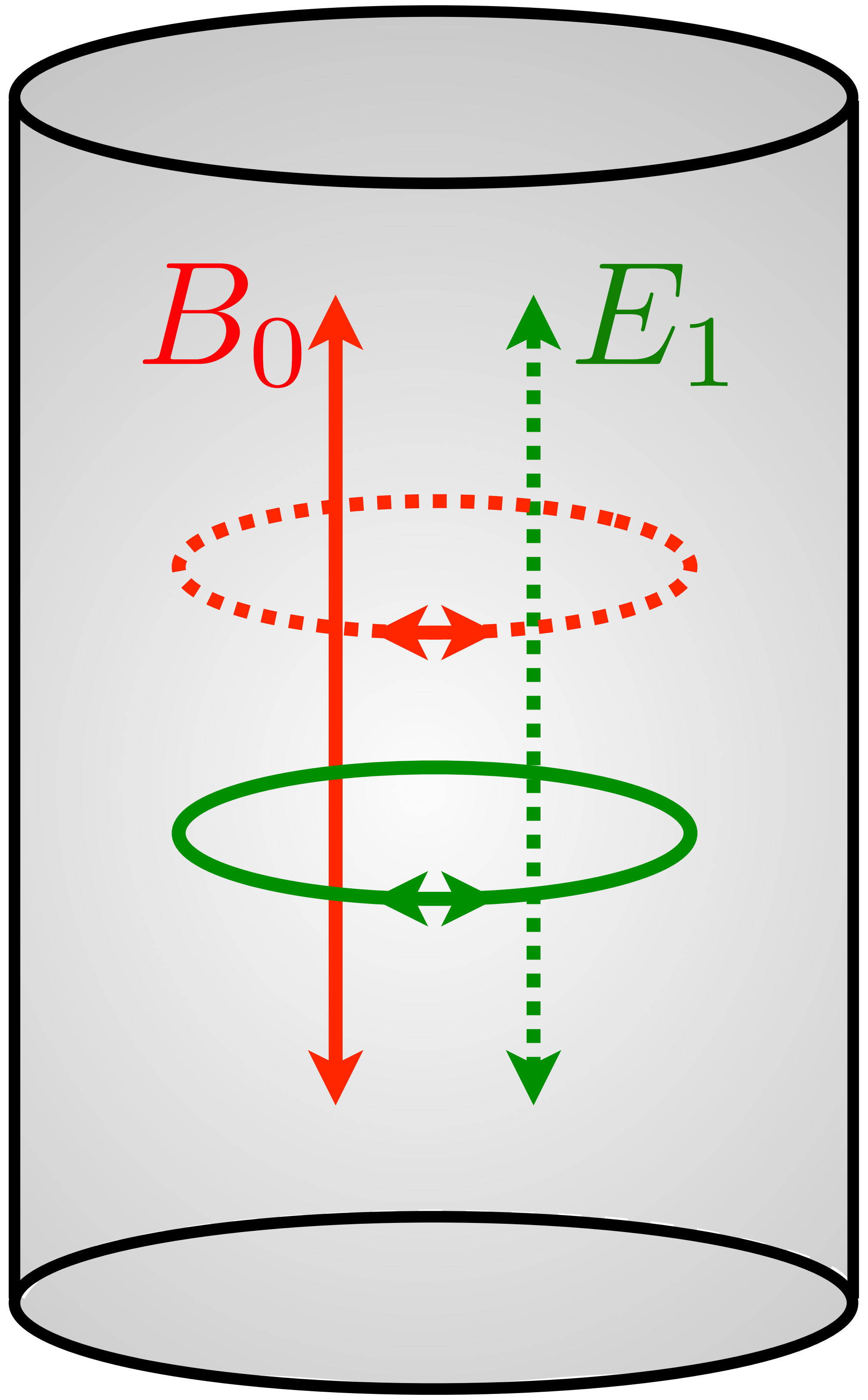
$$\omega_0 \sim \text{GHz}$$

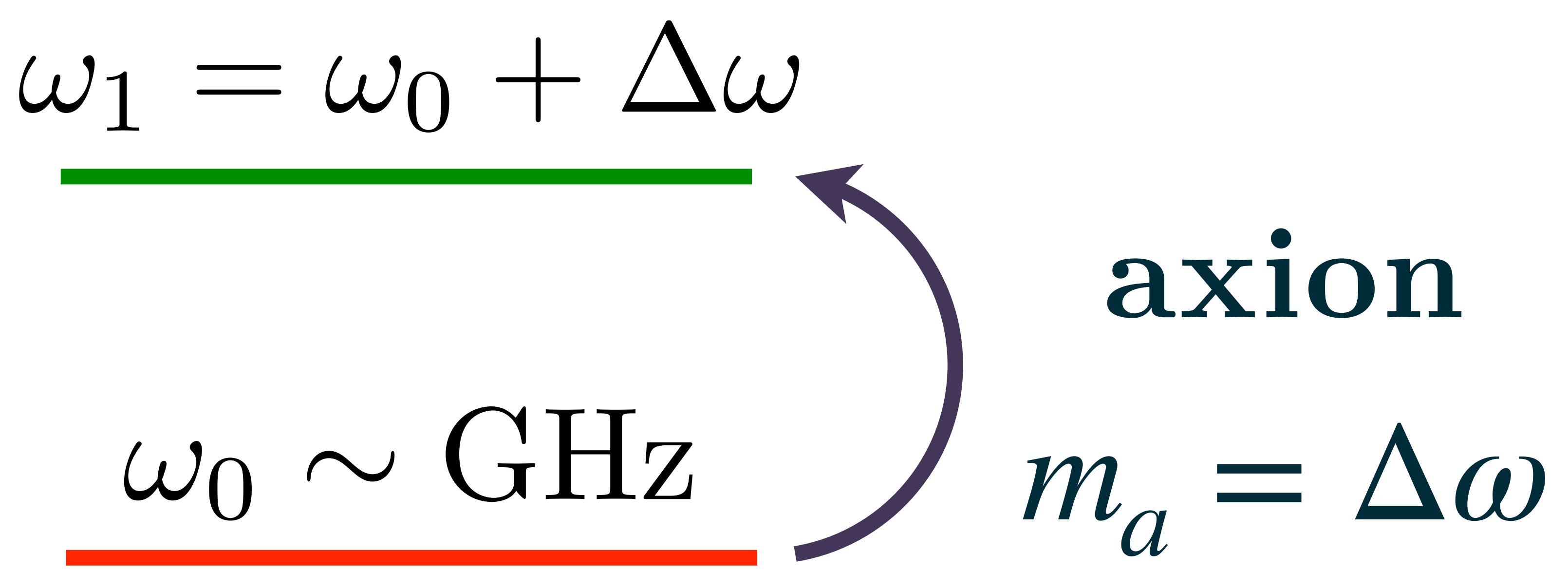
How Does it Work?





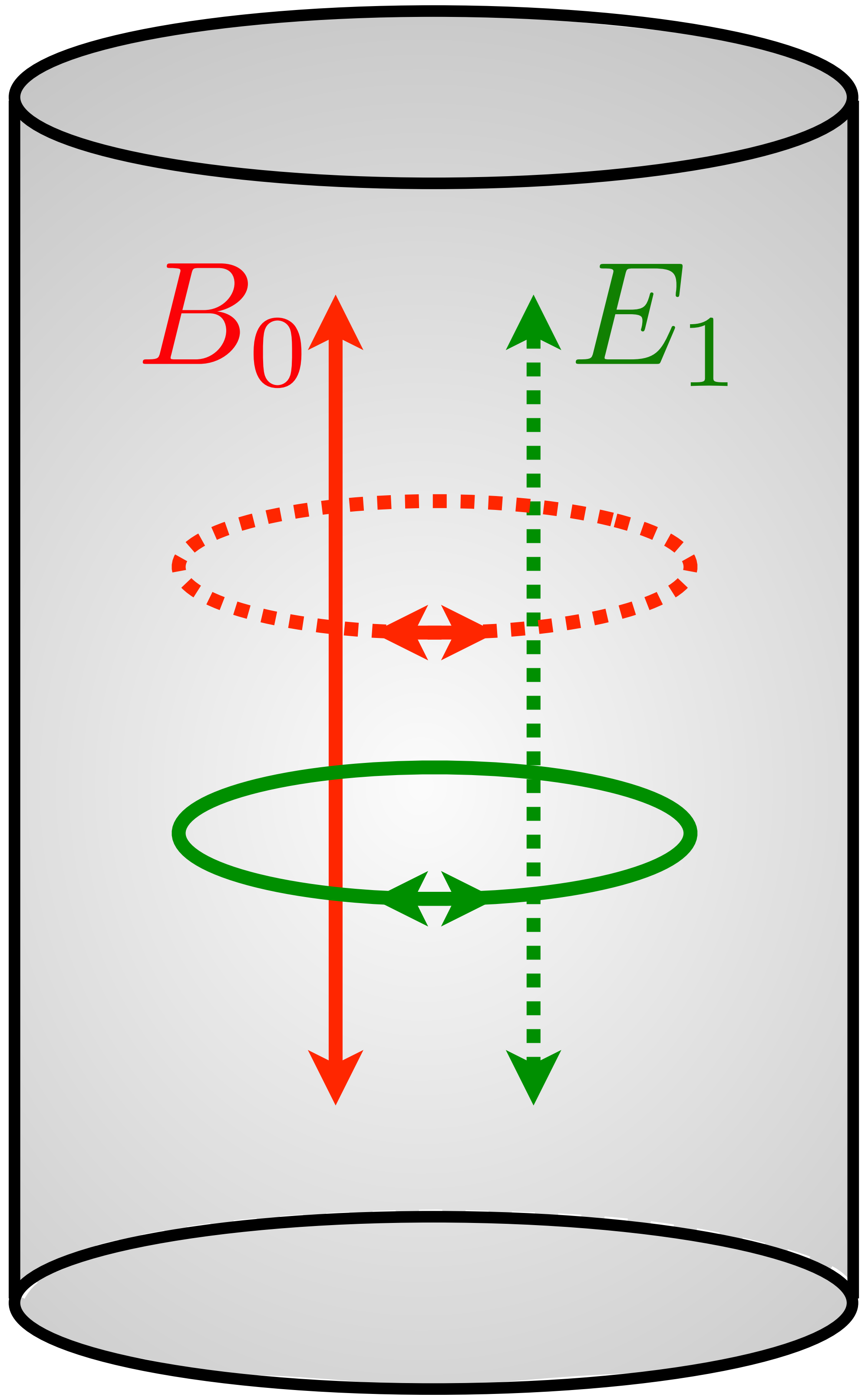
How Does it Work?





Probe many axion masses requires scanning $\Delta\omega$

How Does it Work?



$\omega_1 = \omega_0 + \Delta\omega$

$\omega_0 \sim \mathrm{GHz}$

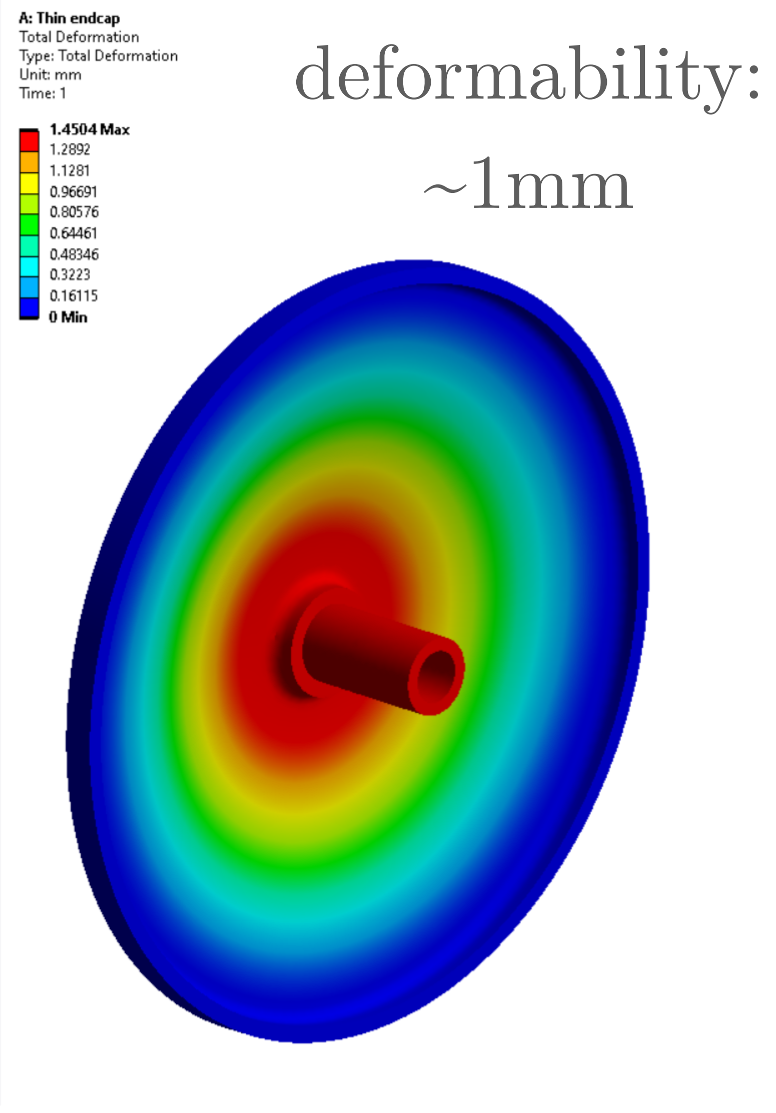
axion

$m_a = \Delta\omega$

Probe many axion masses requires scanning $\Delta\omega$

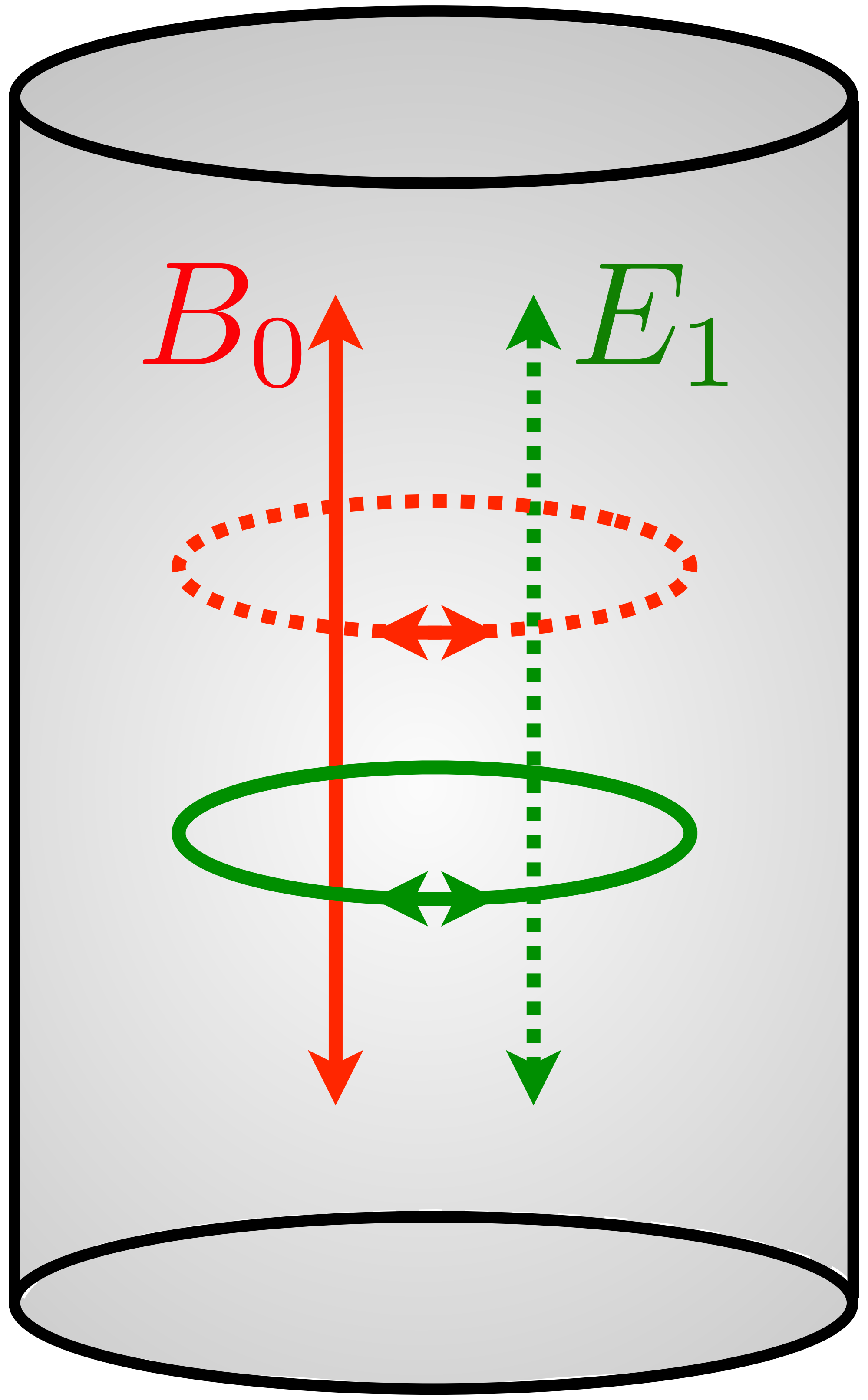
Tunability

$\Delta\omega \ll \mathrm{GHz}$



Courtesy: Marco Oriunno (SLAC)

How Does it Work?



$\omega_1 = \omega_0 + \Delta\omega$

$\omega_0 \sim \text{GHz}$

axion

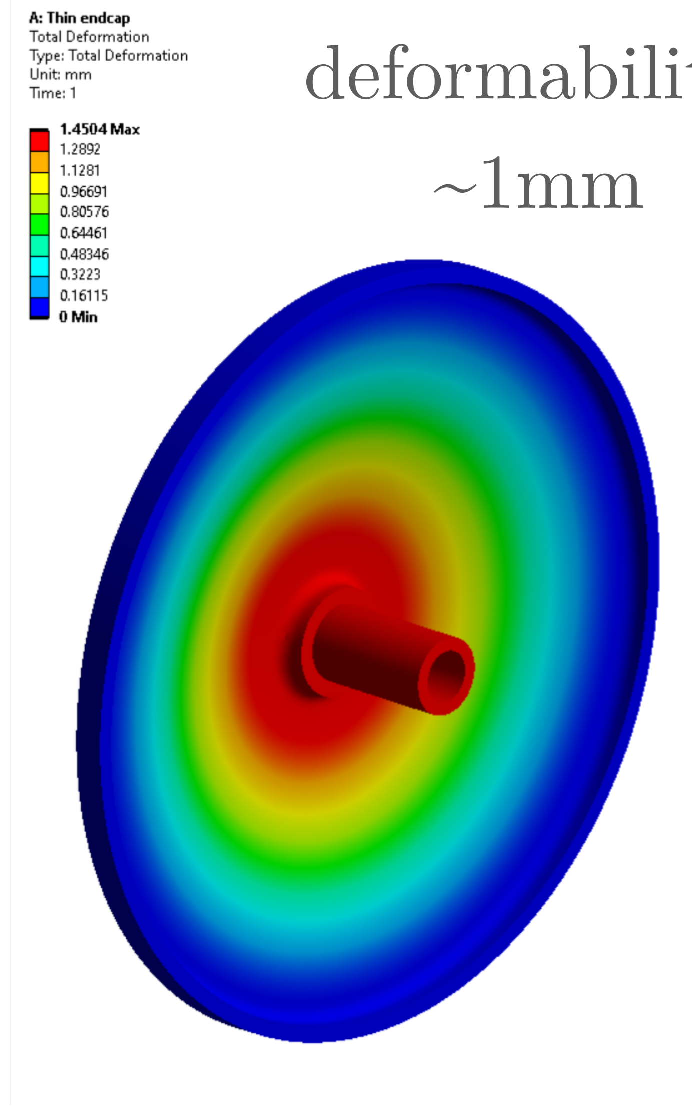
$m_a = \Delta\omega$

Probe many axion masses requires scanning $\Delta\omega$

Tunability

$\Delta\omega \ll \text{GHz}$

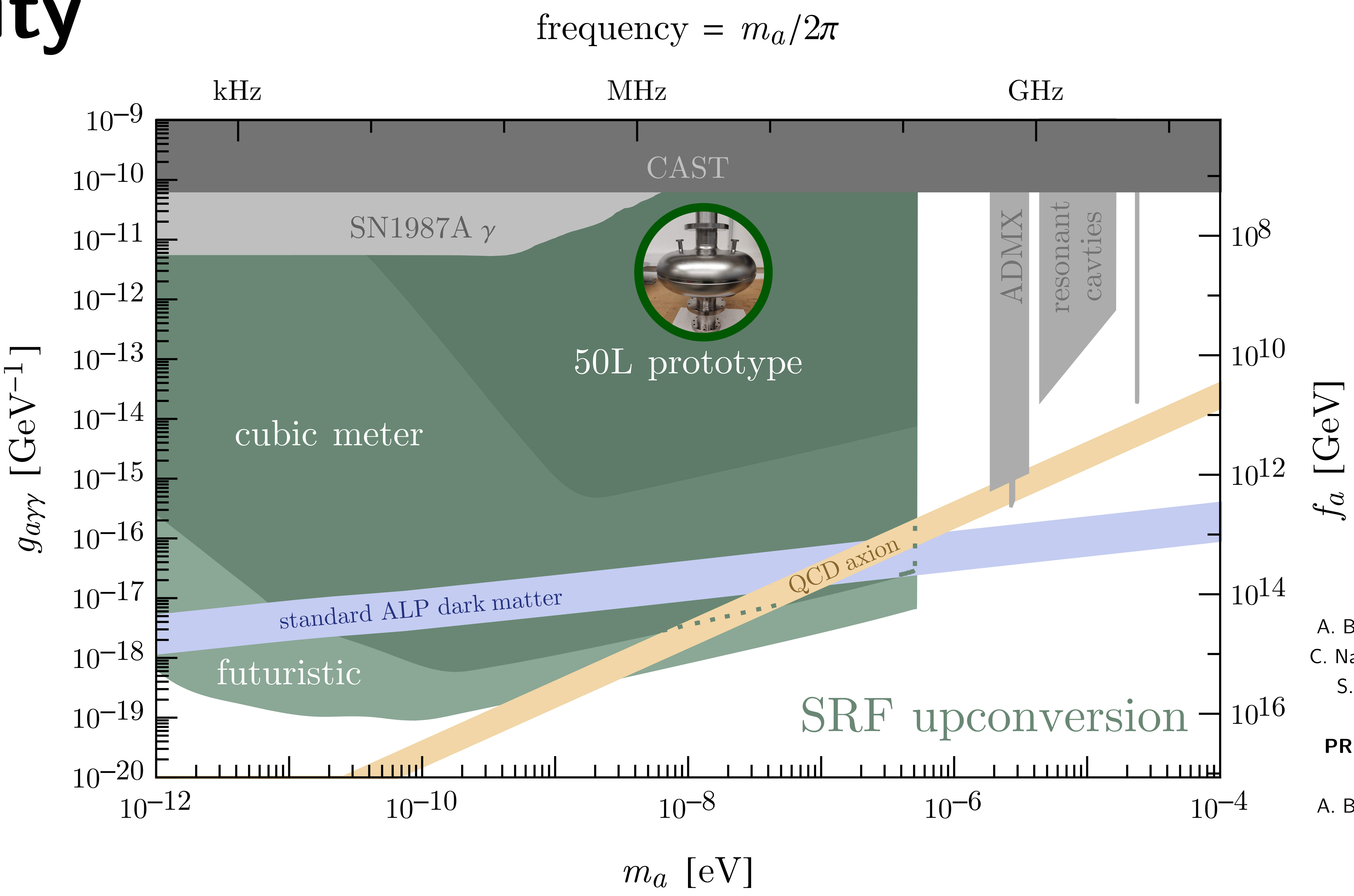
deformability: ~1mm



Courtesy: Marco Oriunno (SLAC)

Resonant with ***beat frequency*** of applied EM field and axion signal

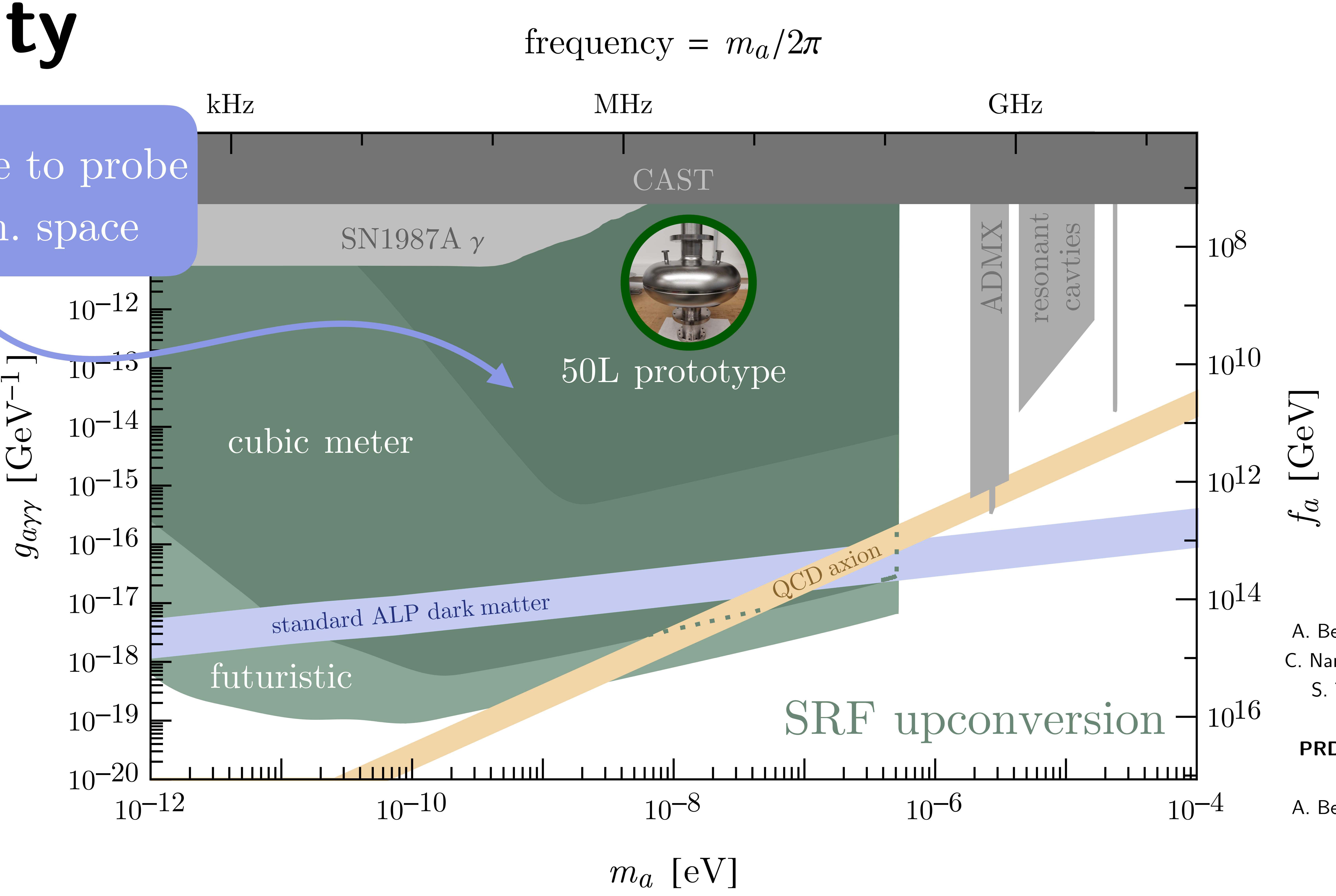
Sensitivity



JHEP 07 (2020) 088
hep-ph/1912.11048
A. Berlin, R. T. D'Agnolo, **SARE**, C. Nantista, J. Neilson, P. Schuster, S. Tantawi, N. Toro, K. Zhou

PRD 104 (2021) 11, L111701
hep-ph/2007.15656
A. Berlin, R. T. D'Agnolo, **SARE**, K. Zhou

Sensitivity



SC Prototype to probe new param. space

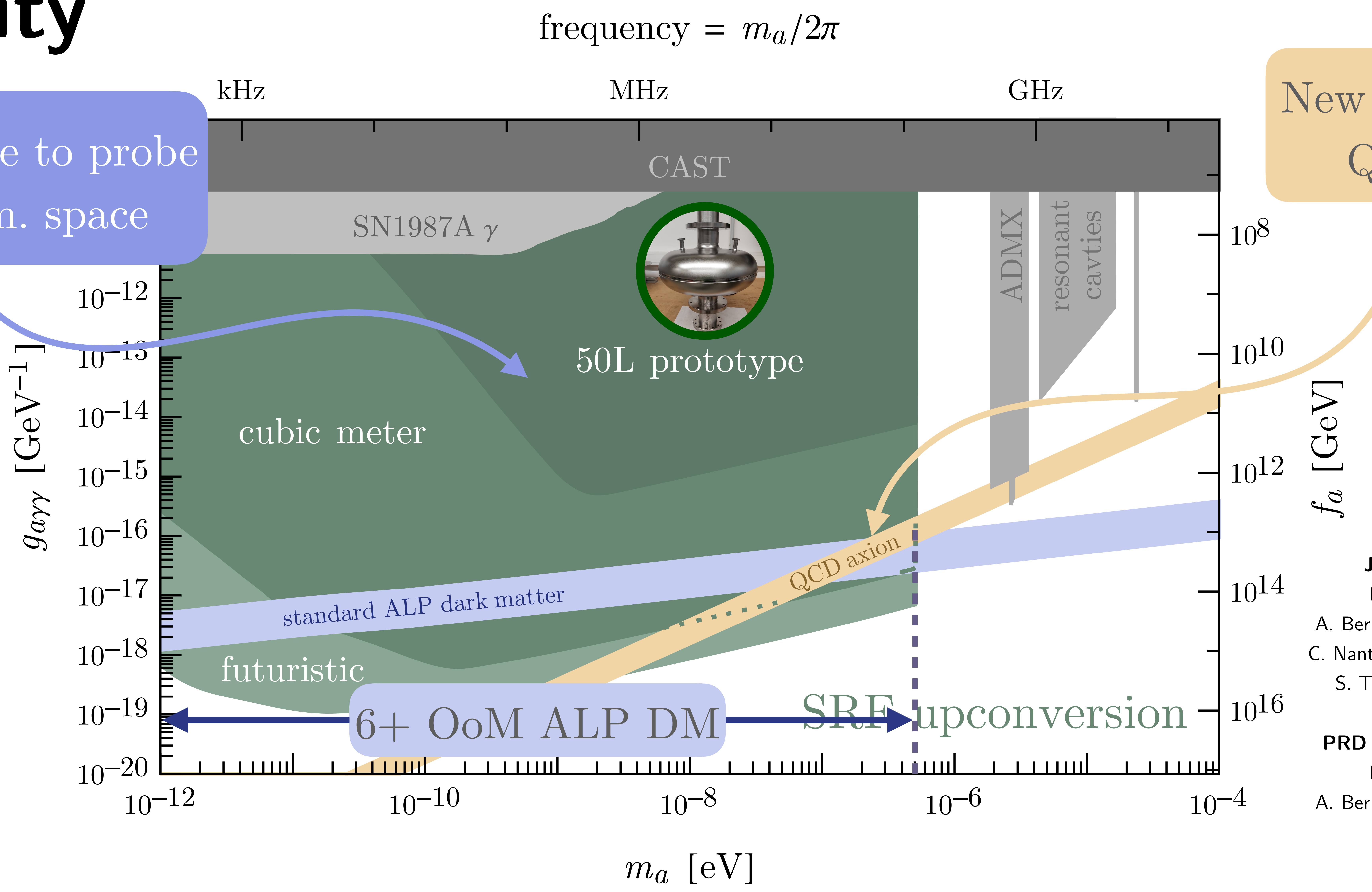
JHEP 07 (2020) 088
hep-ph/1912.11048
A. Berlin, R. T. D'Agnolo, **SARE**, C. Nantista, J. Neilson, P. Schuster, S. Tantawi, N. Toro, K. Zhou

PRD 104 (2021) 11, L111701
hep-ph/2007.15656
A. Berlin, R. T. D'Agnolo, **SARE**, K. Zhou

Sensitivity

SC Prototype to probe new param. space

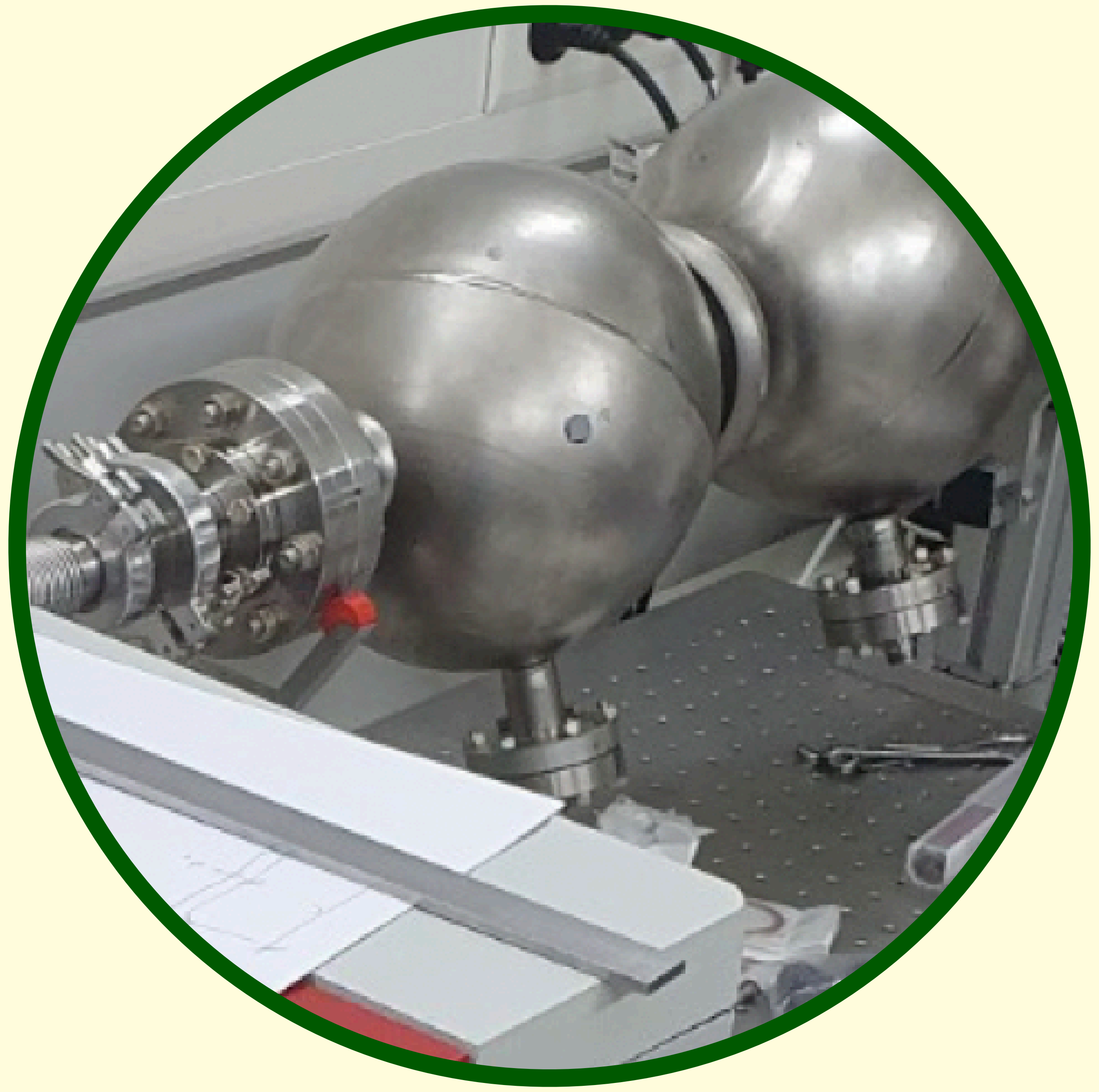
New sensitivity to QCD axion



JHEP 07 (2020) 088
hep-ph/1912.11048
A. Berlin, R. T. D'Agnolo, **SARE**, C. Nantista, J. Neilson, P. Schuster, S. Tantawi, N. Toro, K. Zhou

PRD 104 (2021) 11, L111701
hep-ph/2007.15656
A. Berlin, R. T. D'Agnolo, **SARE**, K. Zhou

VARIATION IN $h_{\mu\nu}$



A. Berlin, D. Blas, R. T. D'Agnolo, SARE, R. Harnik, Y. Kahn, J. Schütte-Engel
Phys.Rev.D 105 (2022) 11, 116011

A. Berlin, D. Blas, R. T. D'Agnolo, SARE, R. Harnik, Y. Kahn, J. Schütte-Engel, M. Wentzel
Phys.Rev.D 108 (2023) 8, 084058

$\beta \sim 1$

Gravitational Waves

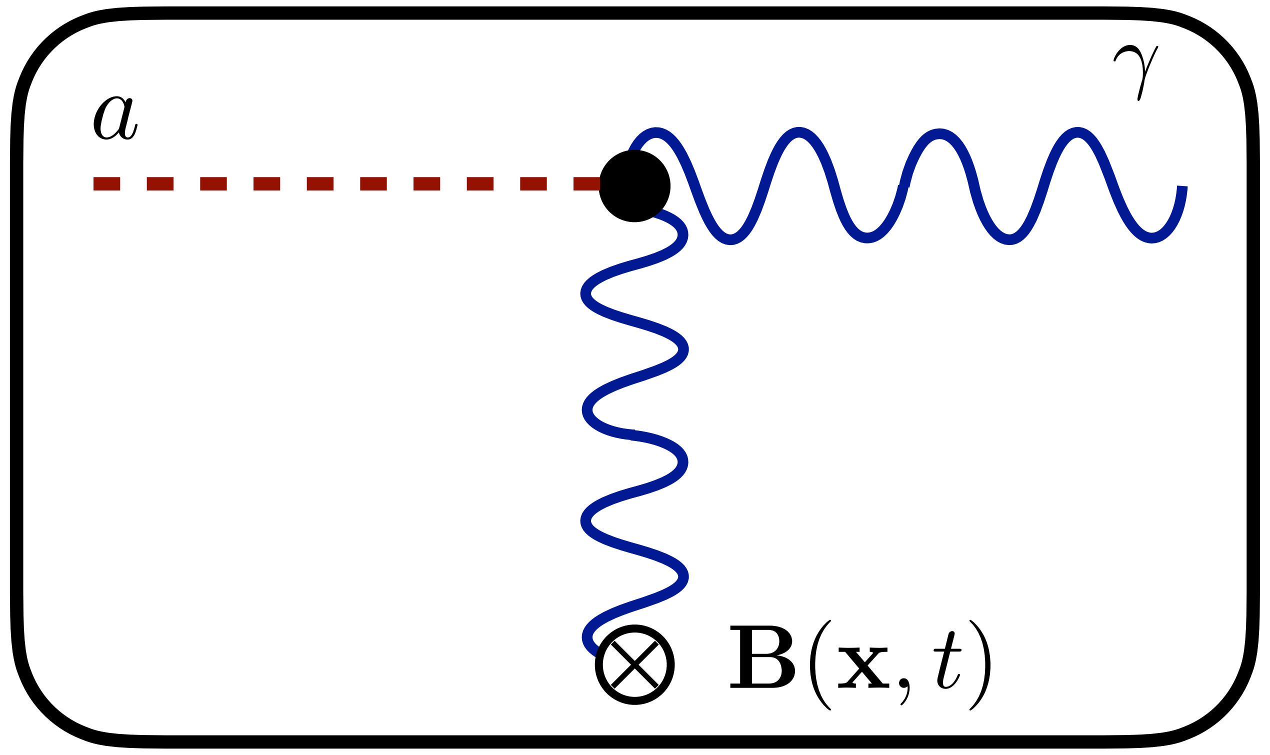
Angular momentum:

differs from axion by index structure

Gravitational Waves

Angular momentum:

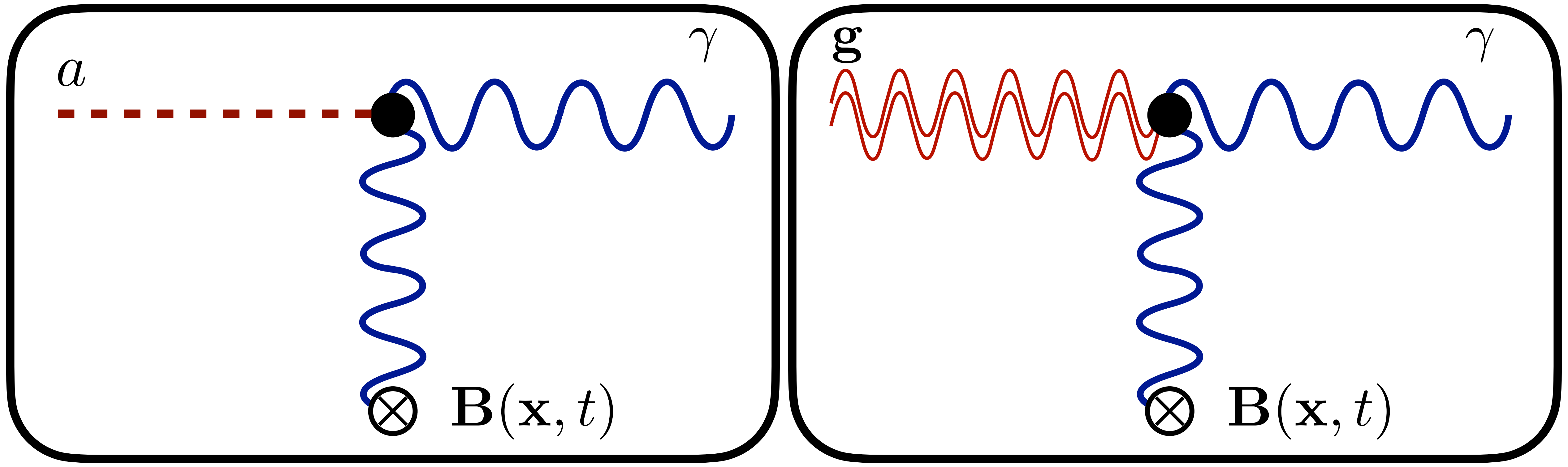
differs from axion by index structure



Gravitational Waves

Angular momentum:

differs from axion by index structure

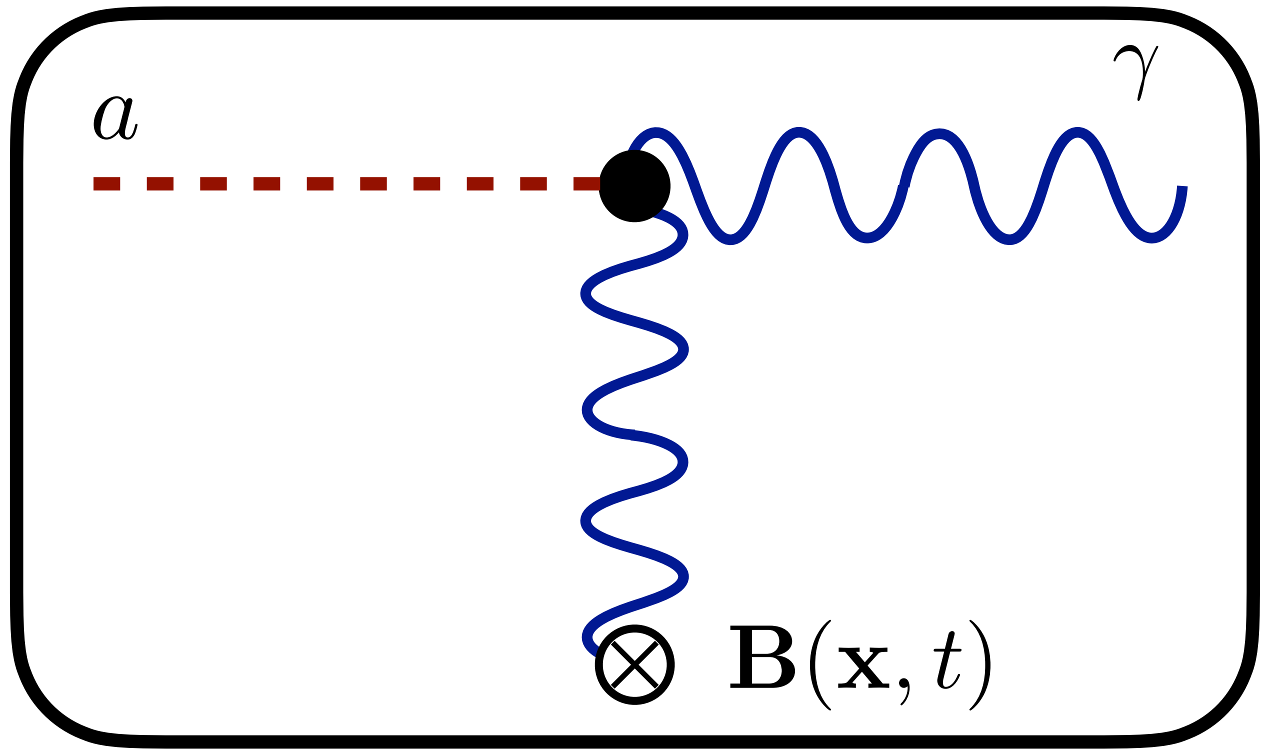


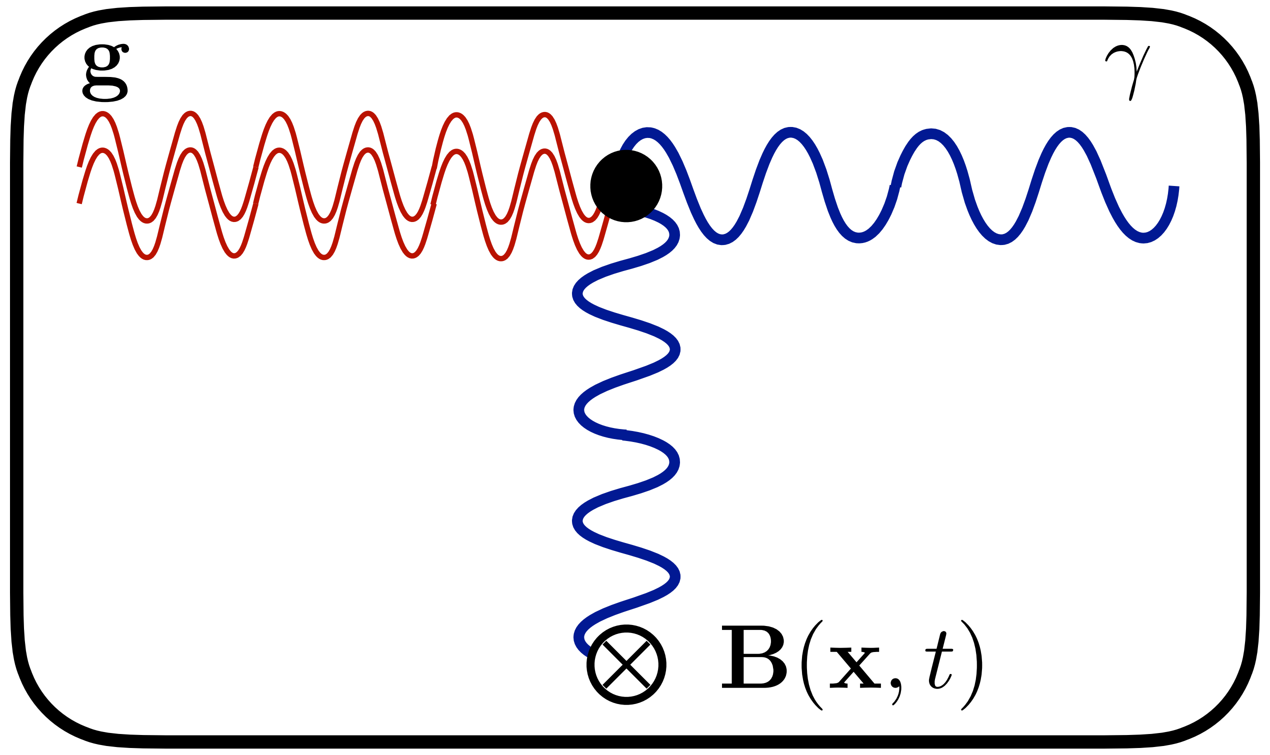
Gertsenshtein (1962)
Zeldovich (1973)
Raffelt & Stodolsky (1988)

Gravitational Waves

Angular momentum:

differs from axion by index structure





Gertsenshtein (1962)
Zeldovich (1973)
Raffelt & Stodolsky (1988)

Effective interaction:

$$\mathcal{L} \supset -\frac{1}{2} j^{\mu}_{\text{eff}} A_{\mu}$$

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

PRD 105 116011 hep-ph/2112.11465
A. Berlin, D. Blas, R. T. D'Agnolo, **SARE,** R. Harnik, Y. Kahn, J. Schütte-Engel

See also ***PRL 129 4, 041101 hep-ph/2202.00695***
V. Domcke, C. Garcia-Cely, N. L. Rodd

Axion Experiments x Gravitational Waves

Existing Axion Experiments:

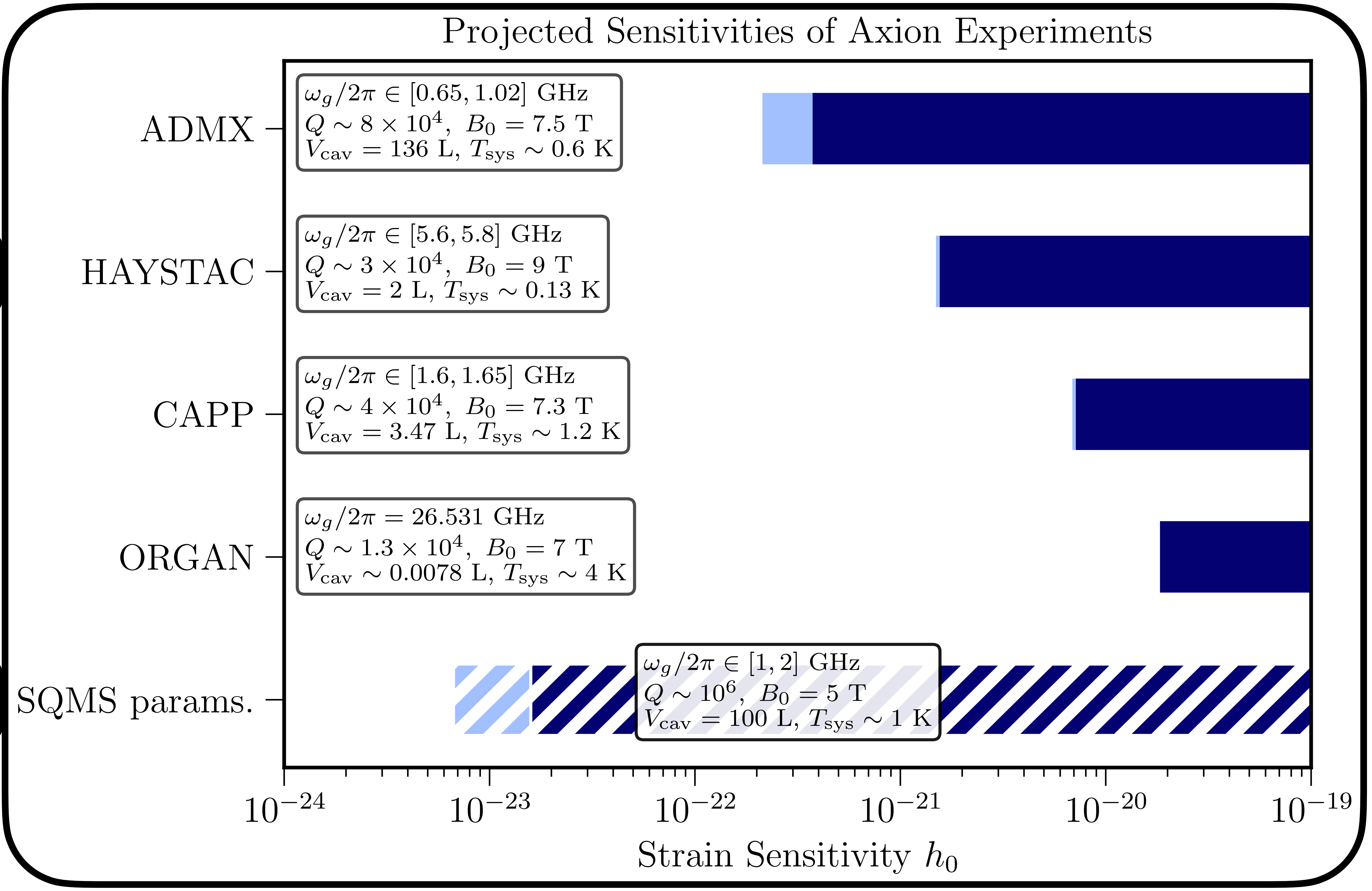
PRD 105 116011 hep-ph/2112.11465
A. Berlin, D. Blas, R. T. D'Agnolo, **SARE,** R. Harnik, Y. Kahn, J. Schütte-Engel

Axion Experiments x Gravitational Waves

Already using quantum techniques

Existing Axion Experiments:

Likely quantum tech.



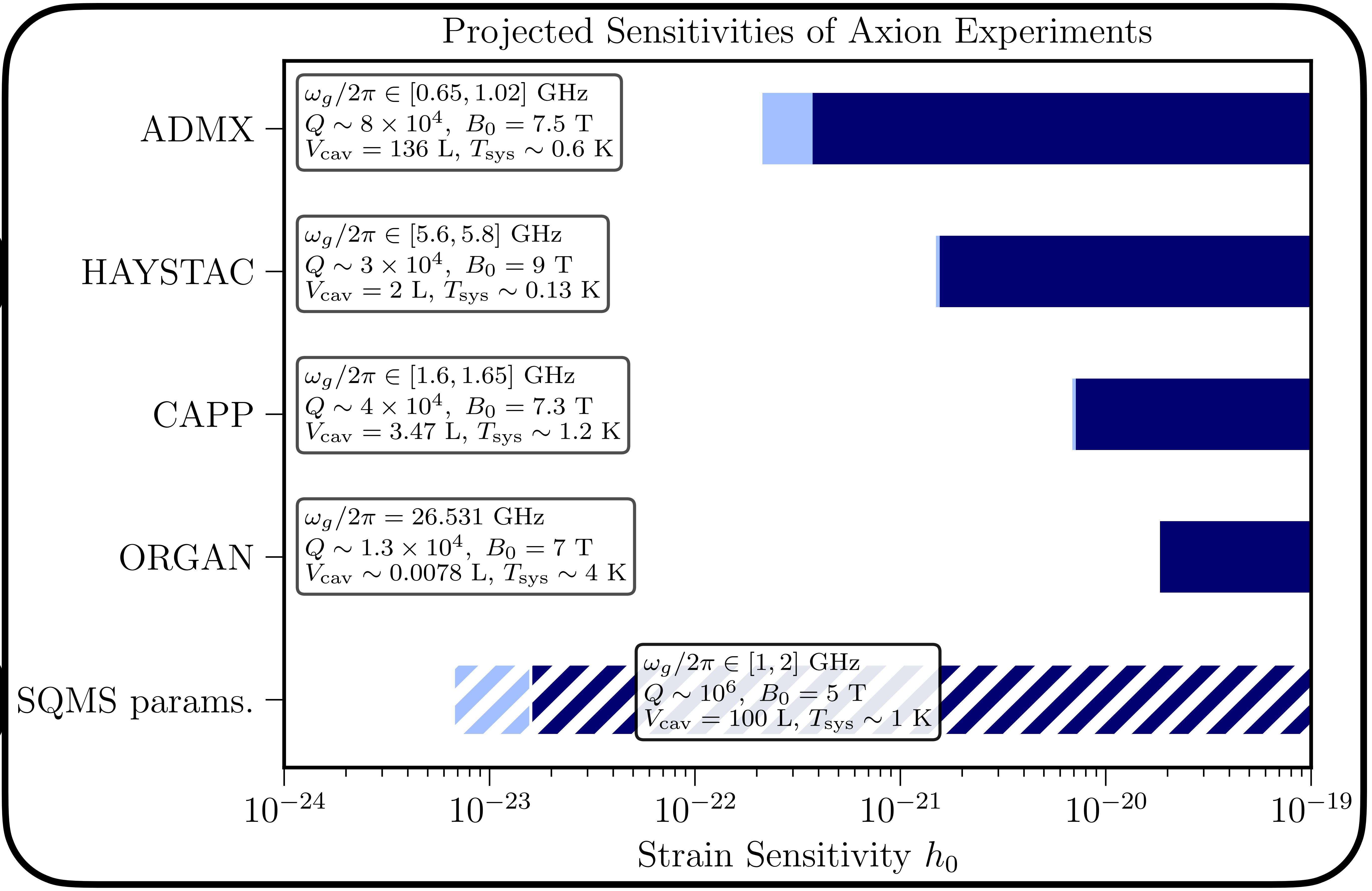
PRD 105 116011 hep-ph/2112.11465
A. Berlin, D. Blas, R. T. D'Agnolo, **SARE,** R. Harnik, Y. Kahn, J. Schütte-Engel

Axion Experiments x Gravitational Waves

Already using quantum techniques

Existing Axion Experiments:

Likely quantum tech.



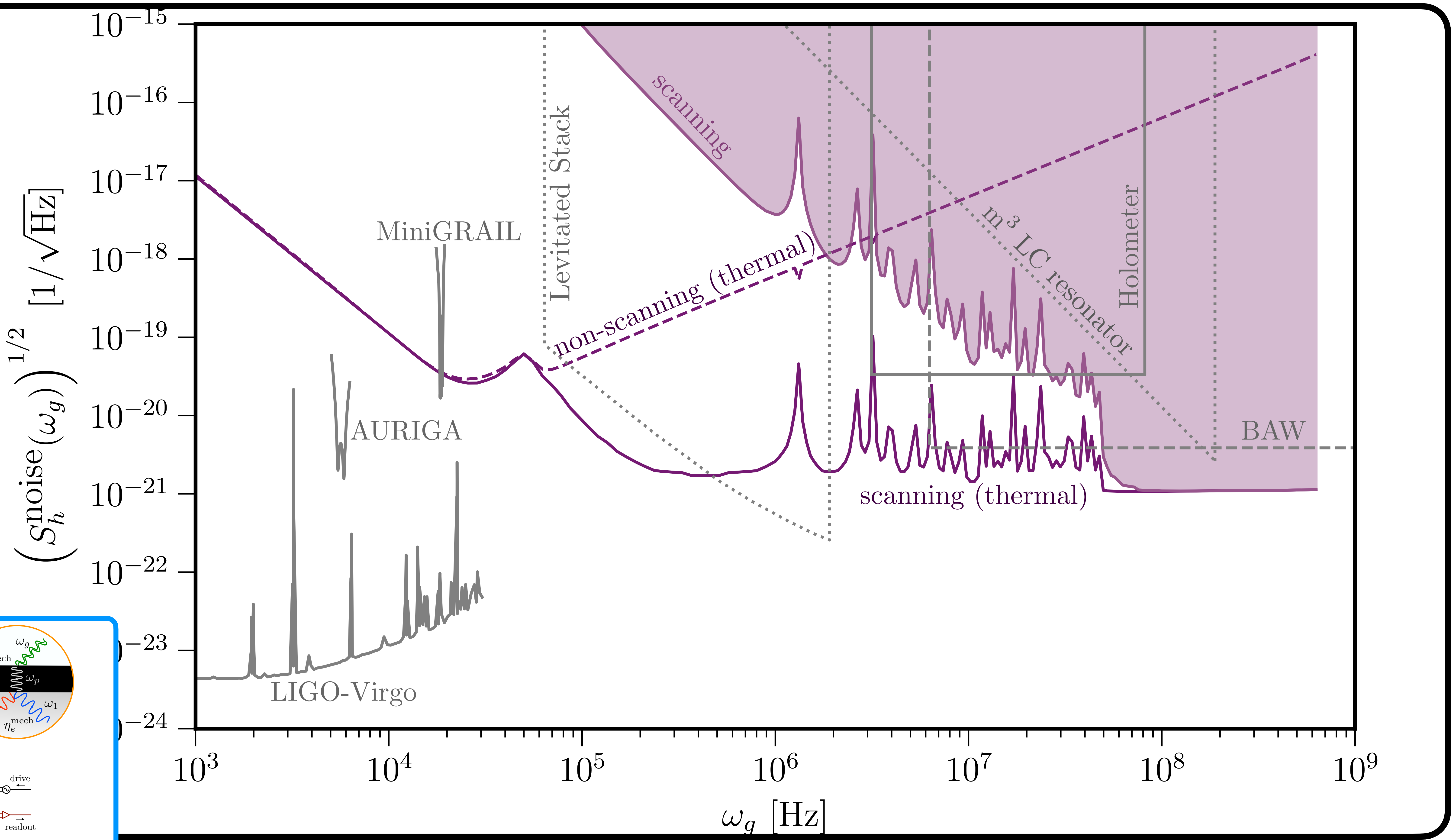
PRD 105 116011 hep-ph/2112.11465

A. Berlin, D. Blas, R. T. D'Agnolo, **SARE,** R. Harnik, Y. Kahn, J. Schütte-Engel

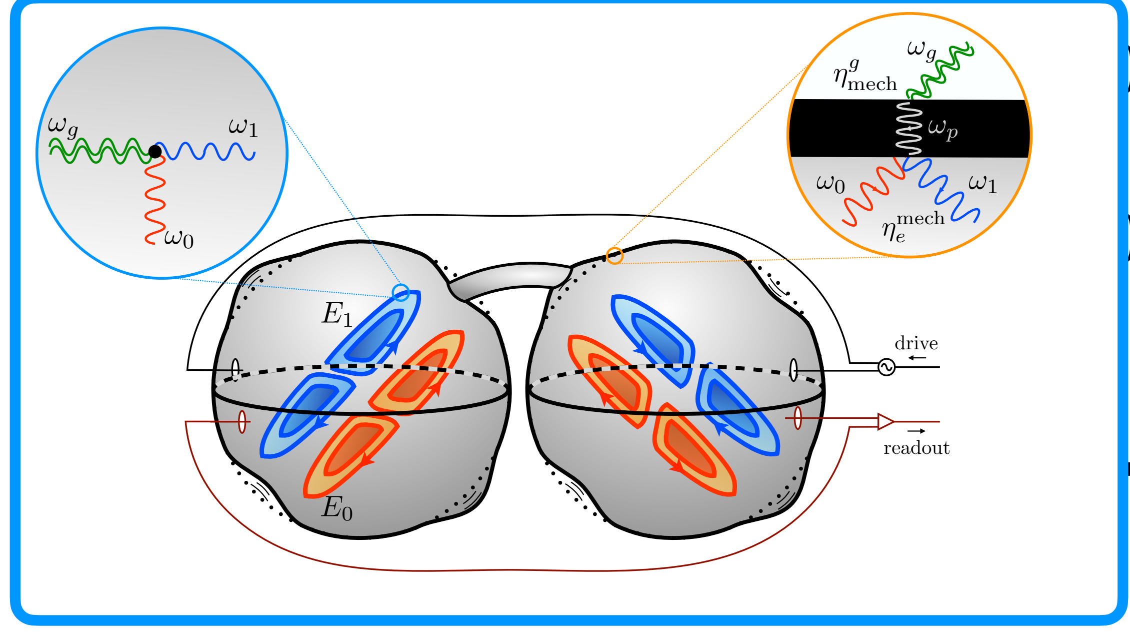
See also: GWs at MADMAX, V. Domcke, **SARE**, J. Kopp (**hep-ph/2409.06462**)

Leverage General Relativity

$h\,\hat{h}_{\mu\nu}T^{\mu\nu}$



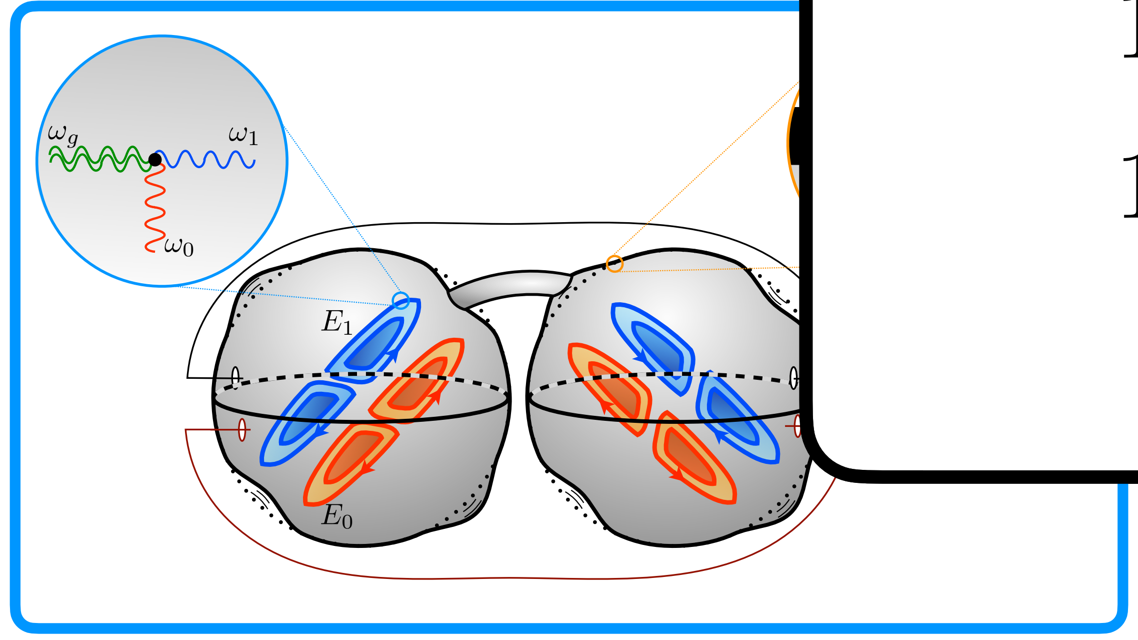
PRD 108 8, 084058
hep-ph/2303.01518
A. Berlin, D. Blas, R. T. D'Agnolo, **SARE,** R. Harnik, Y. Kahn, J. Schütte-Engel, M. Wentzel

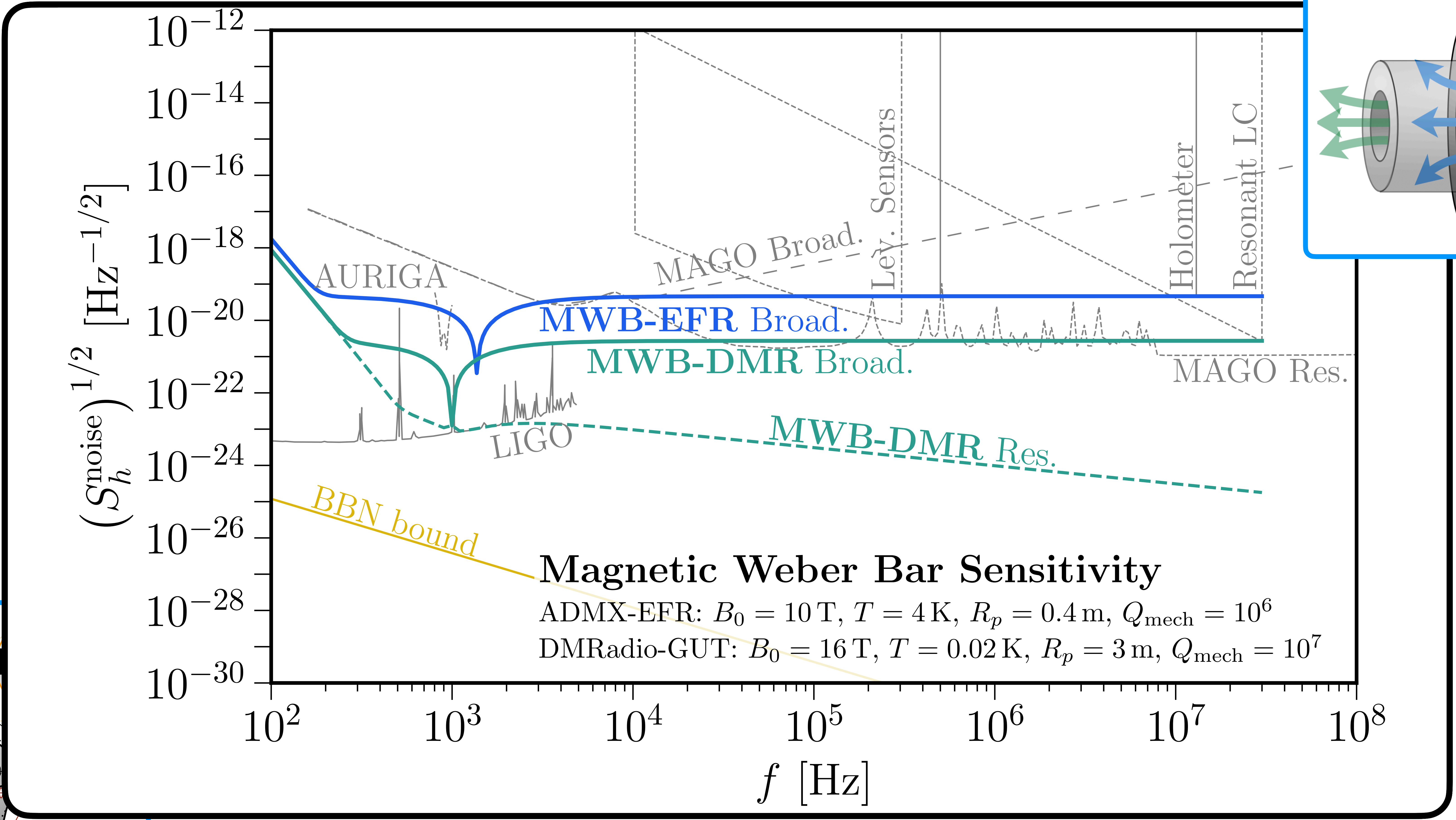


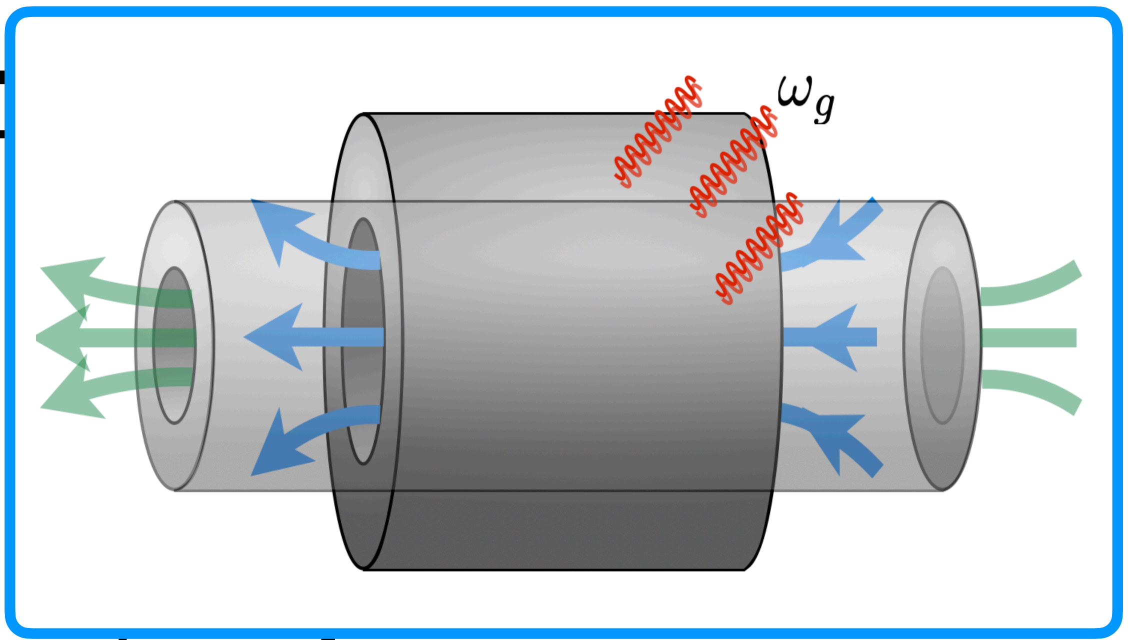
Leverage General Relativity

$h\,\hat{h}_{\mu\nu}T^{\mu\nu}$

PRD 108 8, 084058
hep-ph/2303.01518
A. Berlin, D. Blas, R. T. D'Agnolo, **SARE,** R. Harnik, Y. Kahn, J. Schütte-Engel, M. Wentzel

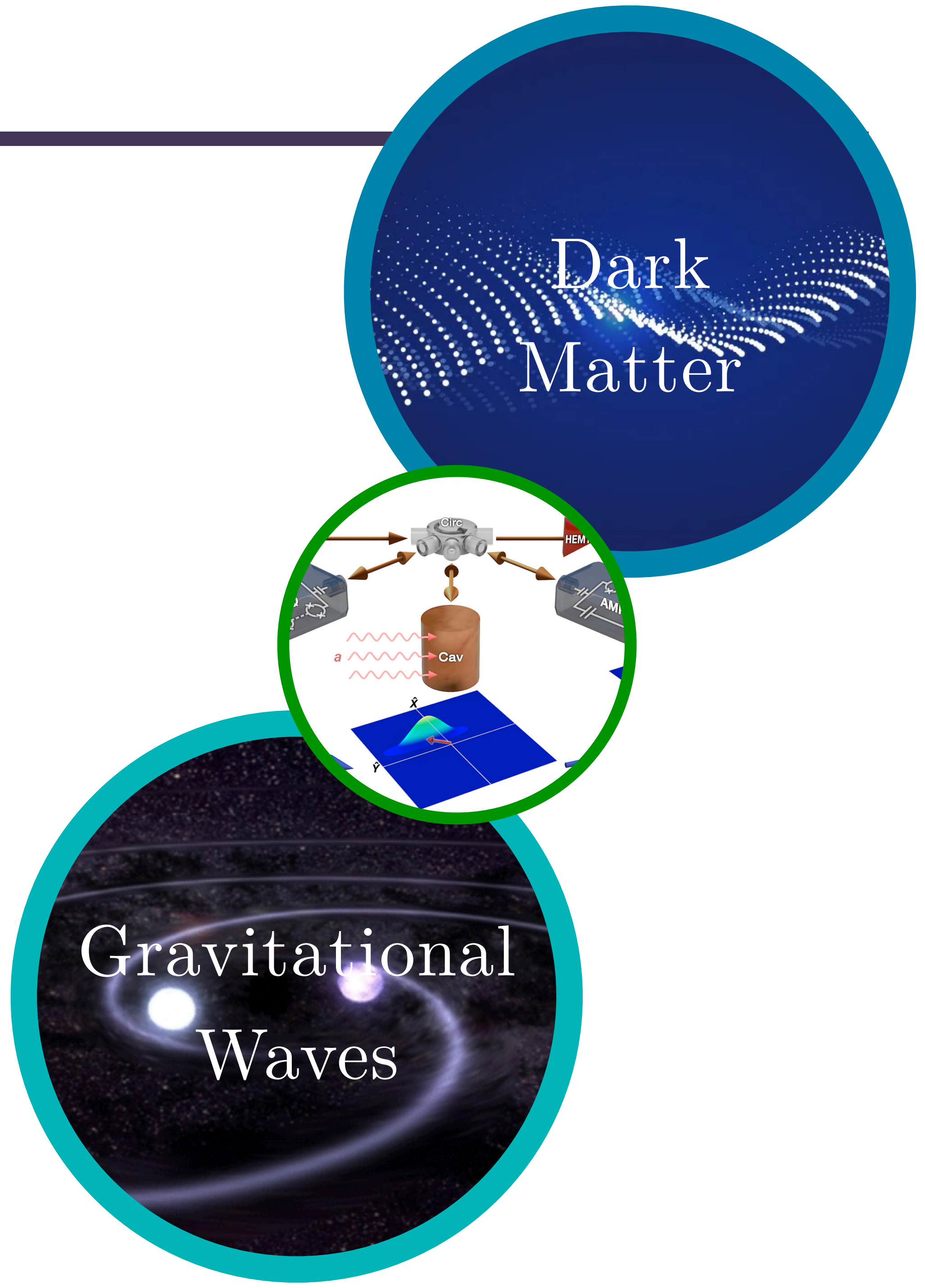






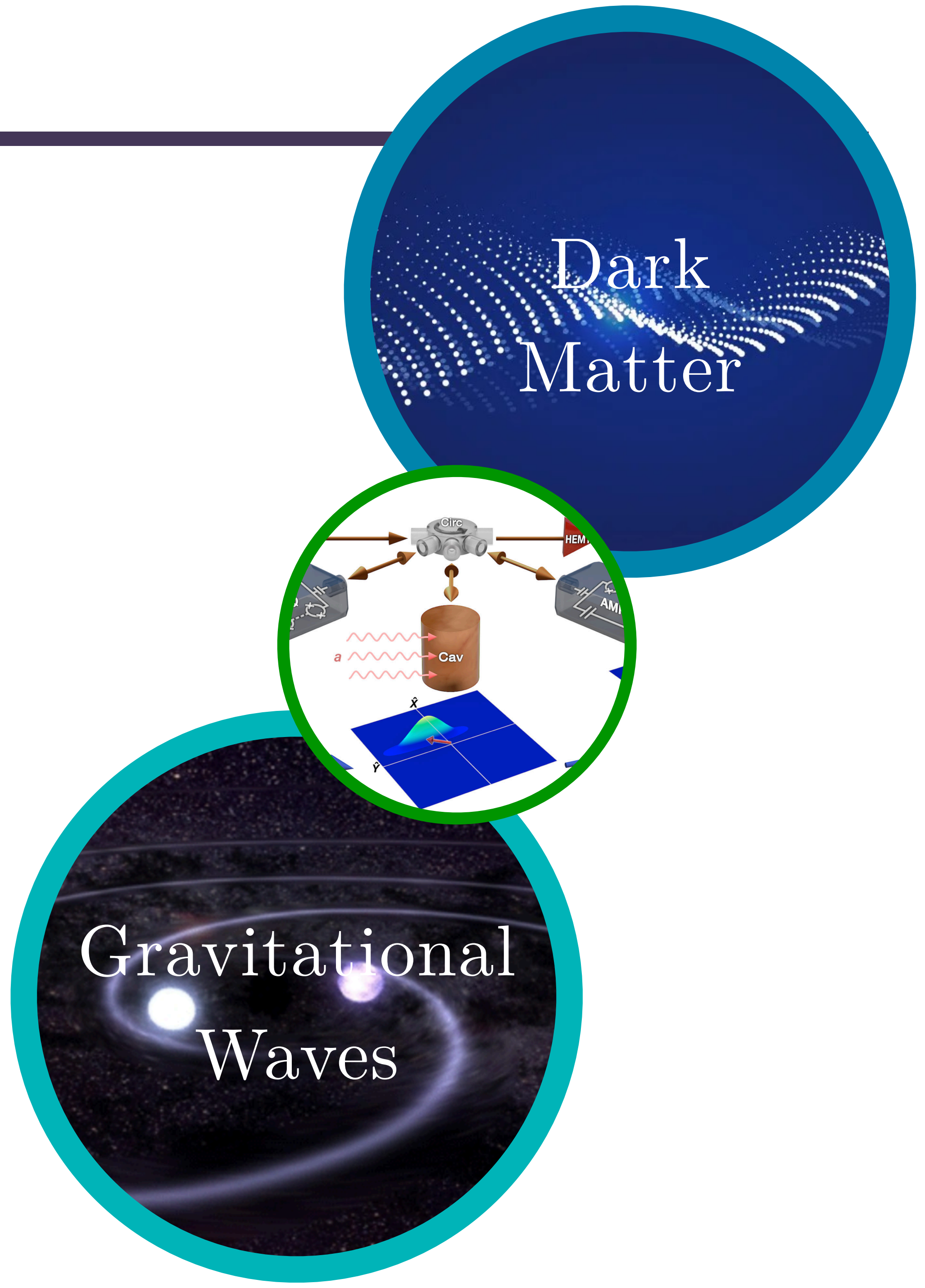
hep-ph/2408.01483
V. Domcke, **SARE,** N. L. Rodd

Summary

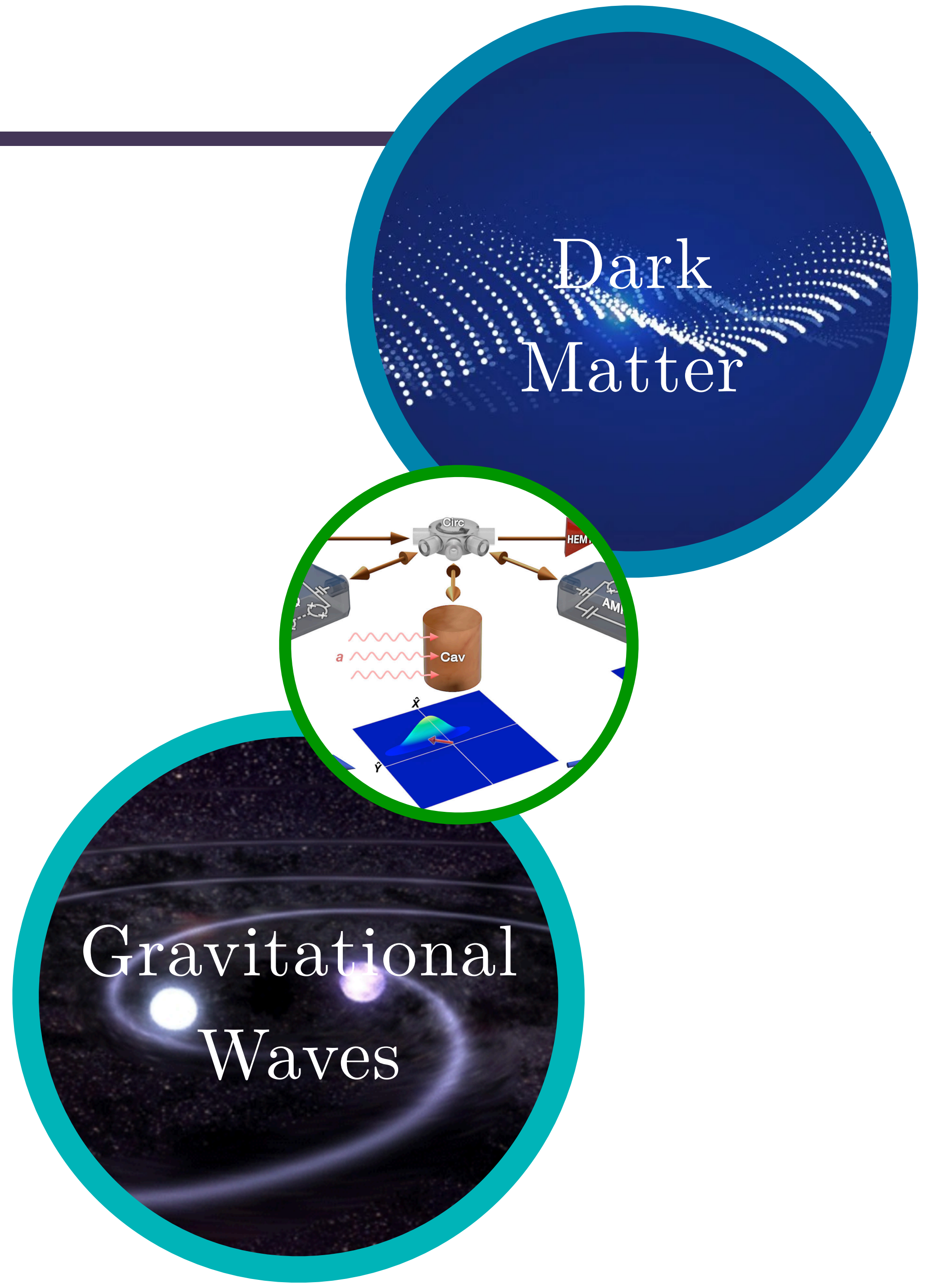


Summary

Age of Quantum for detecting weakly-coupled signals just beginning



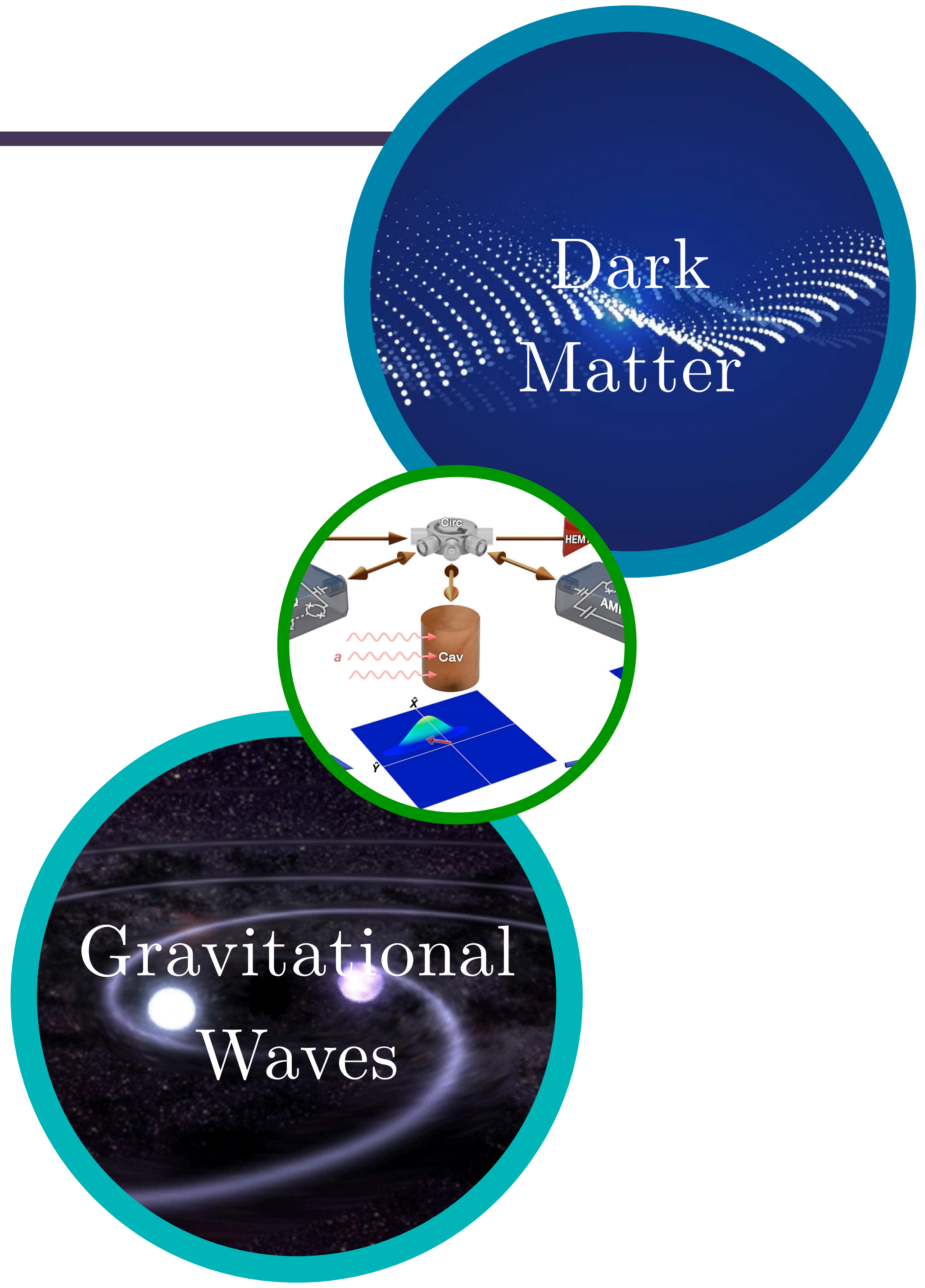
Summary



Age of Quantum for detecting weakly-coupled signals just beginning

Sensors classed as "quantum" in various ways

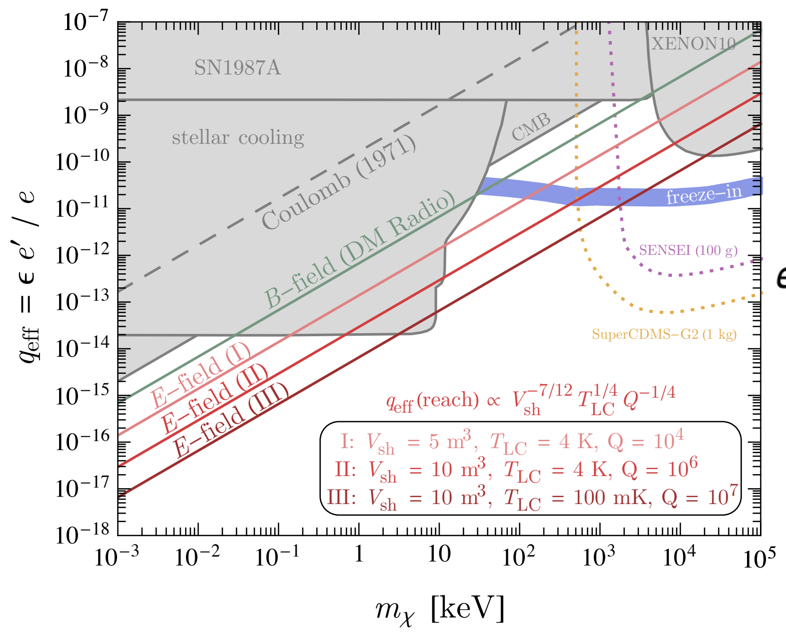
Summary

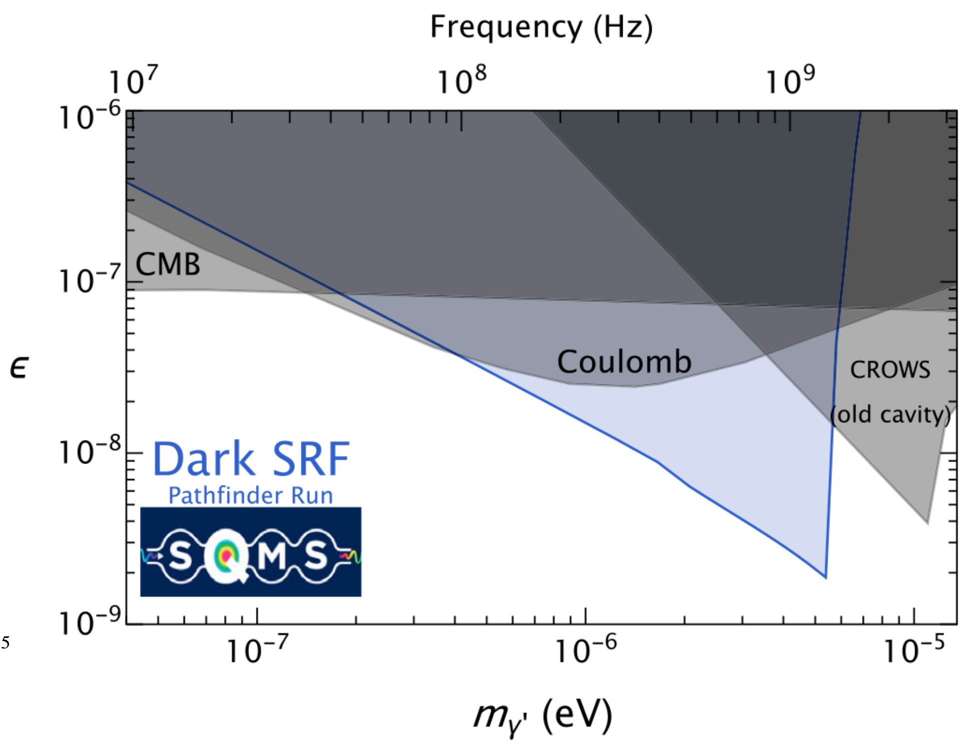


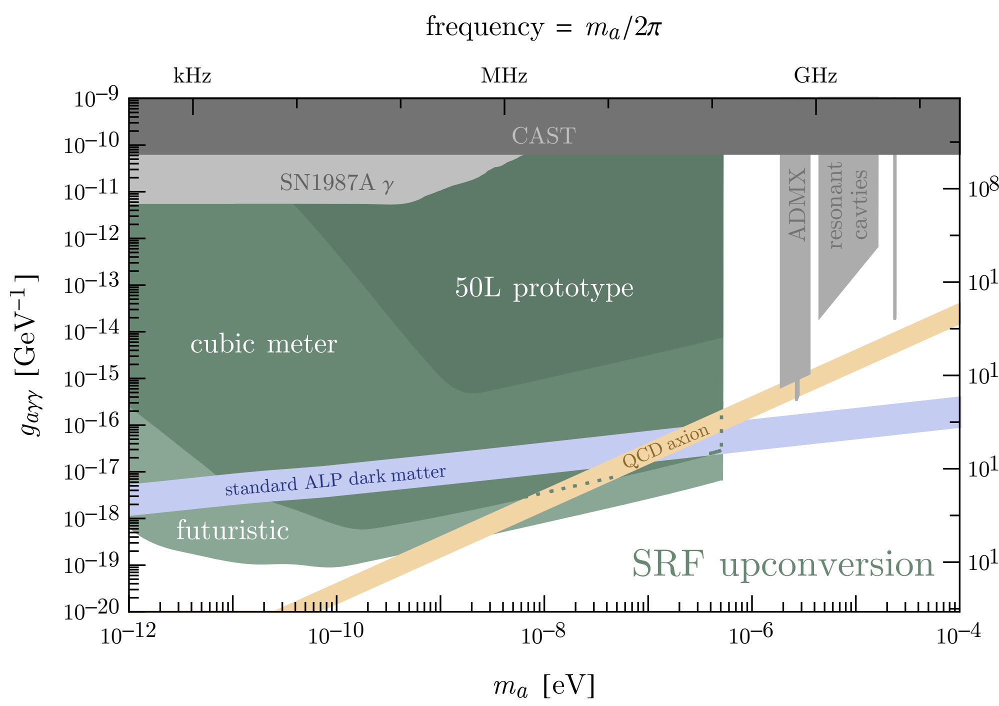
Age of Quantum for detecting weakly-coupled signals just beginning

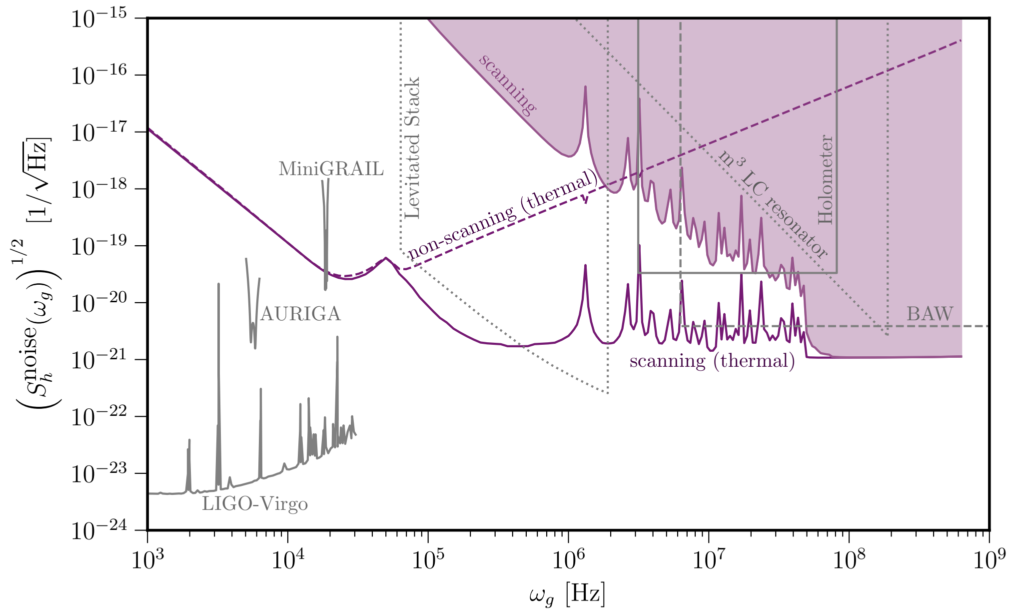
Sensors classed as “quantum” in various ways

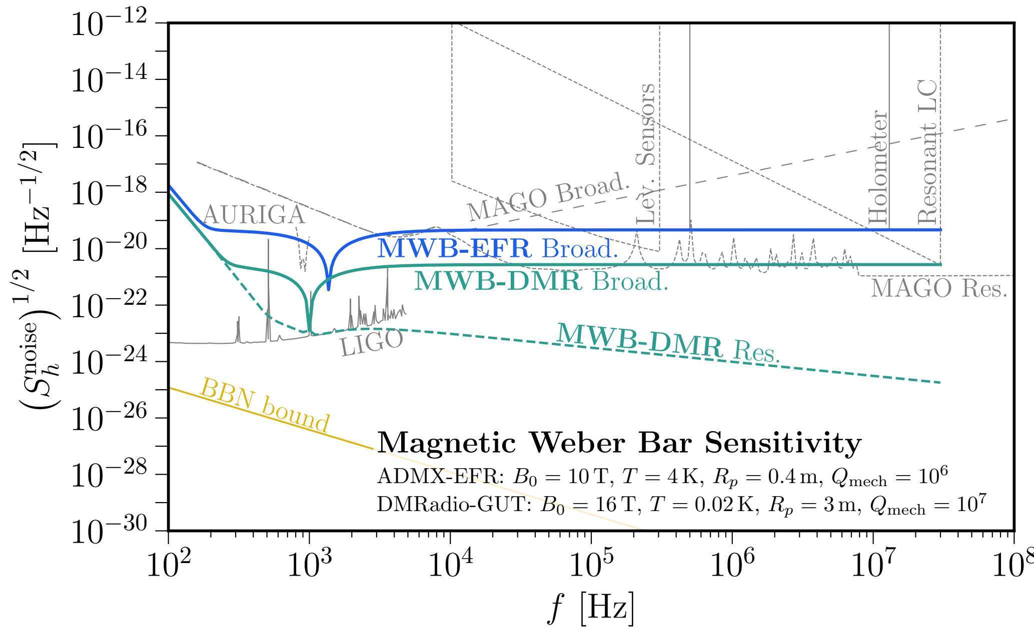
Accelerator tech can probe wide range of signals:







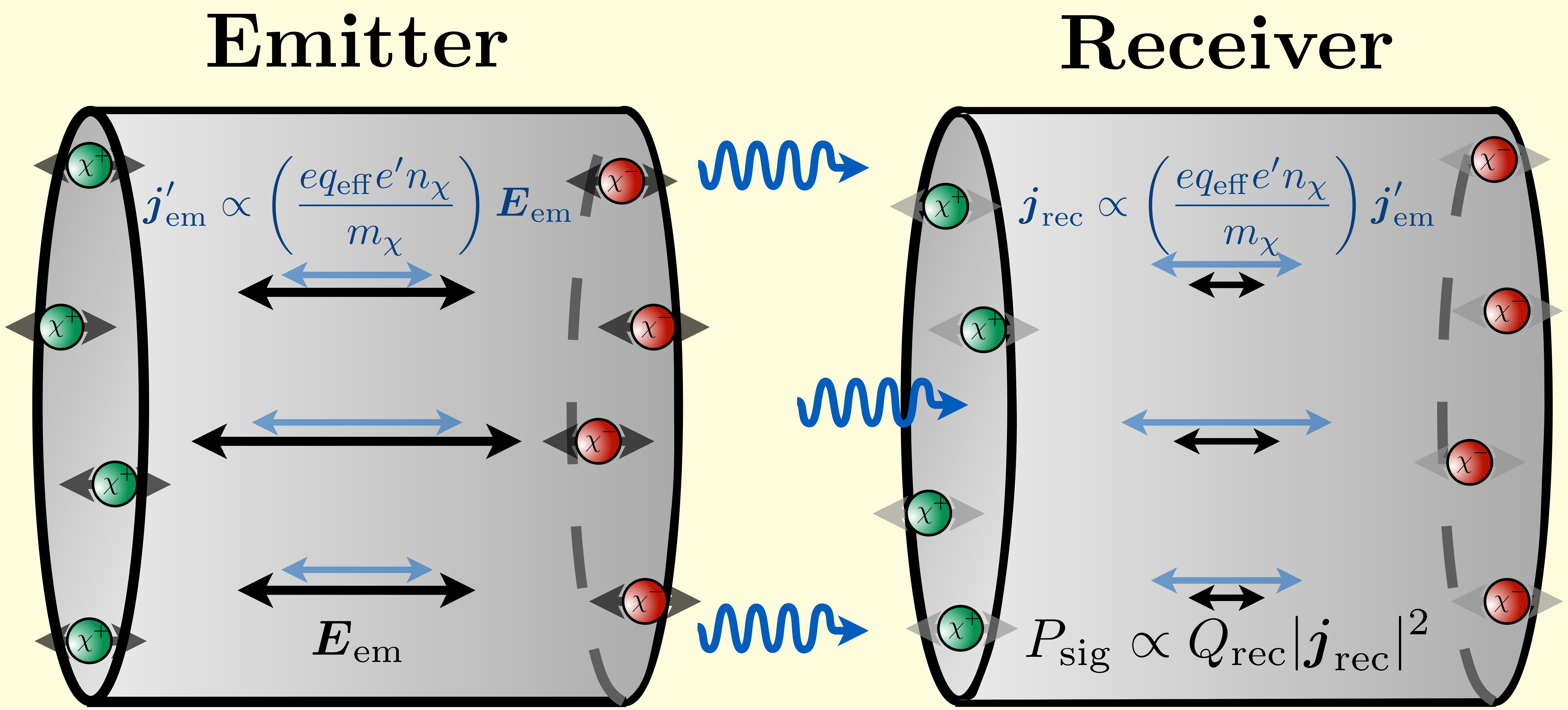




For those interested, quantum sensing for fundamental physics ⊃ classical, quantum, atomic physics, materials physics, fluid dynamics, statistics, GR, QFT…

Backup

Variation in A, χ



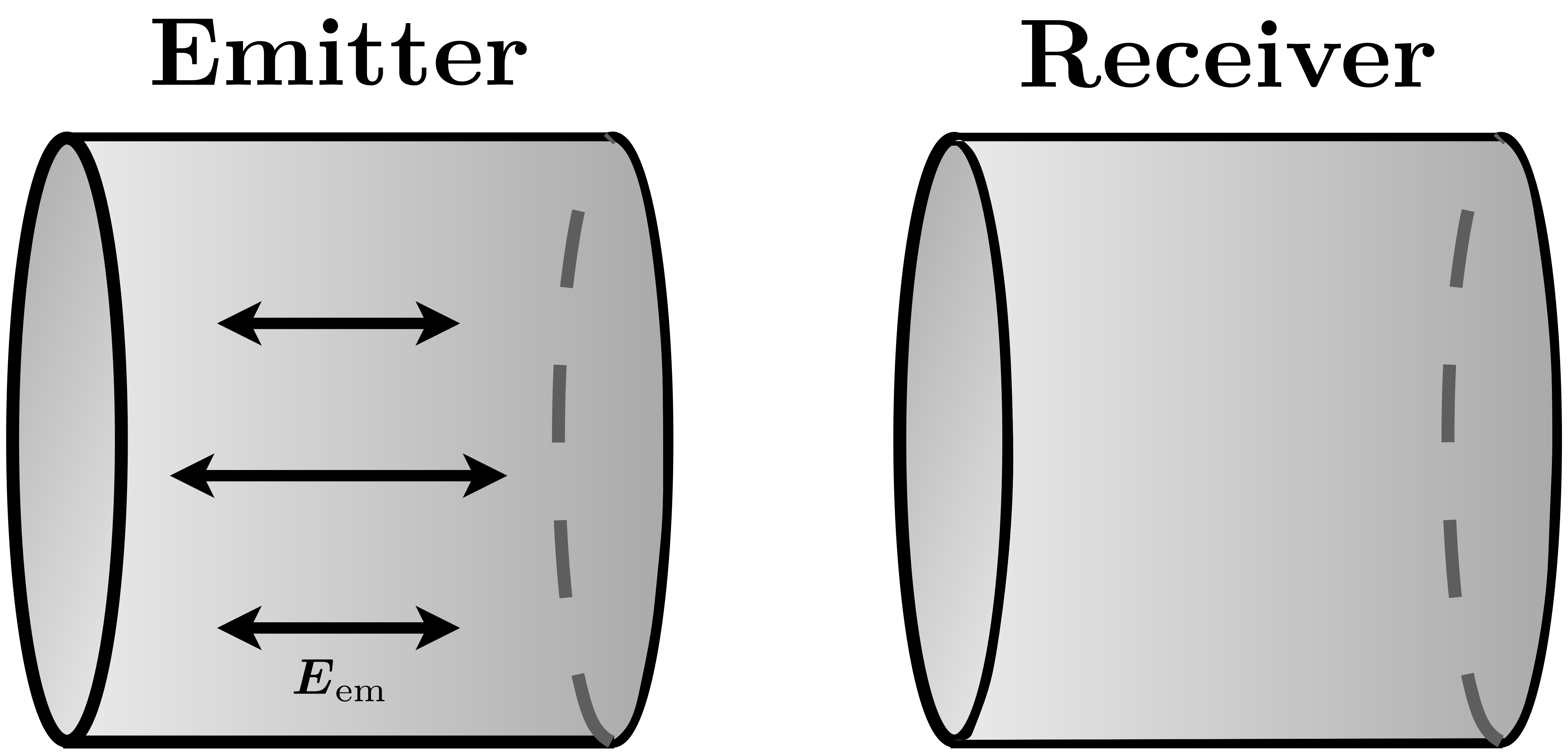
$\beta \sim 1$

A. Berlin, R. T. D'Agnolo, SARE, J. Radkovski
JHEP 08 (2023) 017

Light-Shining-Through-Walls

Search for Dark Photons (not DM)

J. Jaeckel, A. Ringwald (2008)

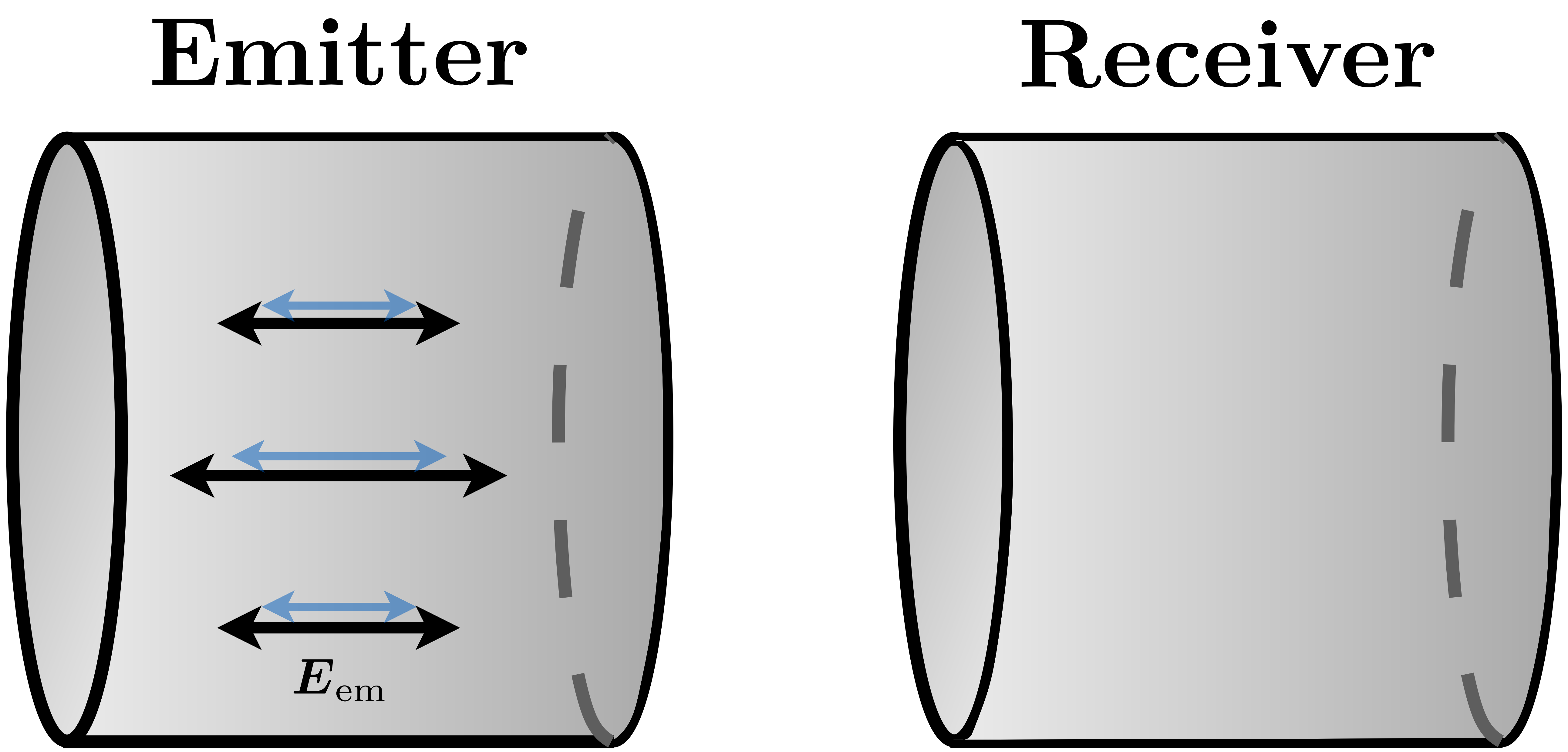


P. Graham, J. Mardon, S. Rajendran, Y. Zhao (2014)

Light-Shining-Through-Walls

Search for Dark Photons (not DM)

J. Jaeckel, A. Ringwald (2008)

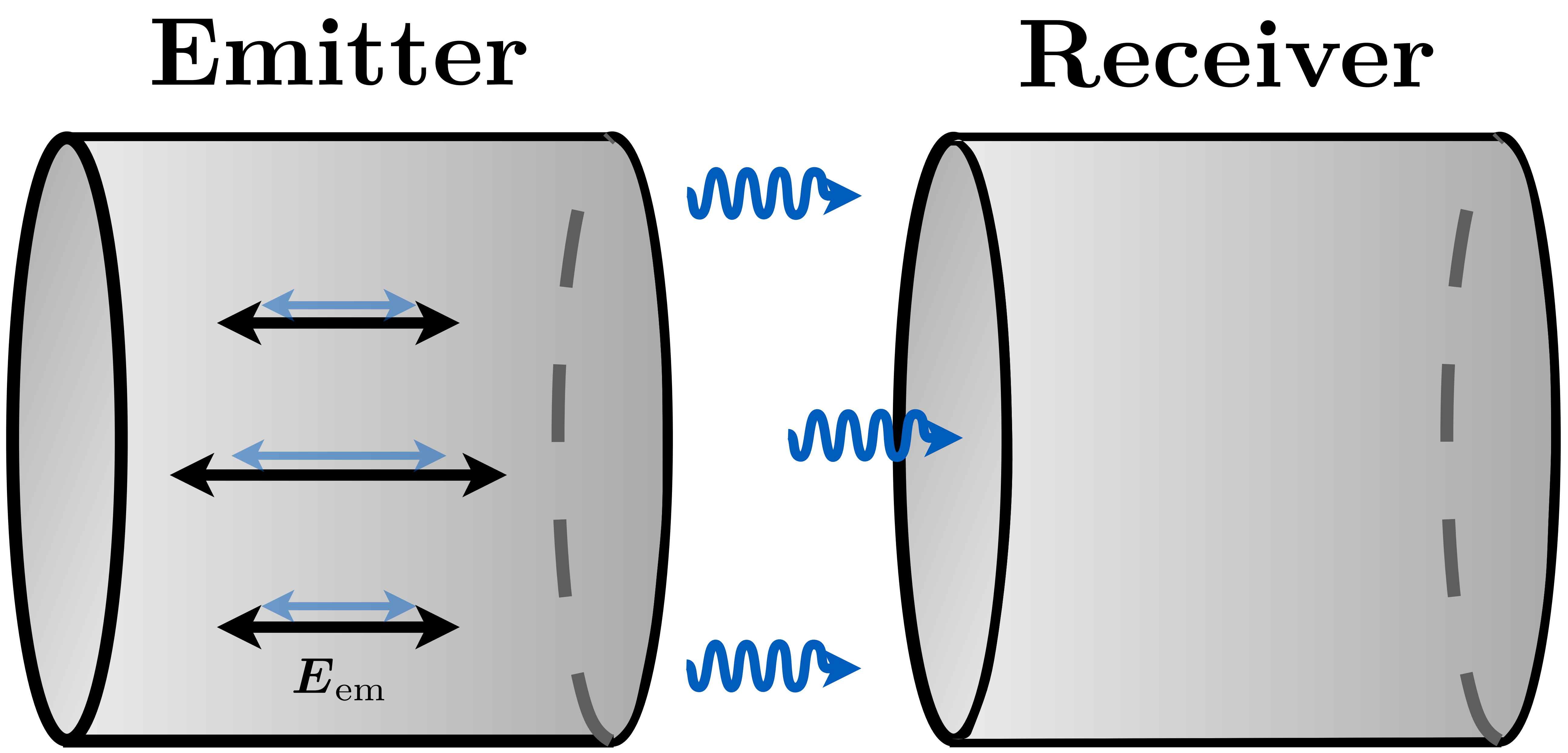


P. Graham, J. Mardon, S. Rajendran, Y. Zhao (2014)

Light-Shining-Through-Walls

Search for Dark Photons (not DM)

J. Jaeckel, A. Ringwald (2008)

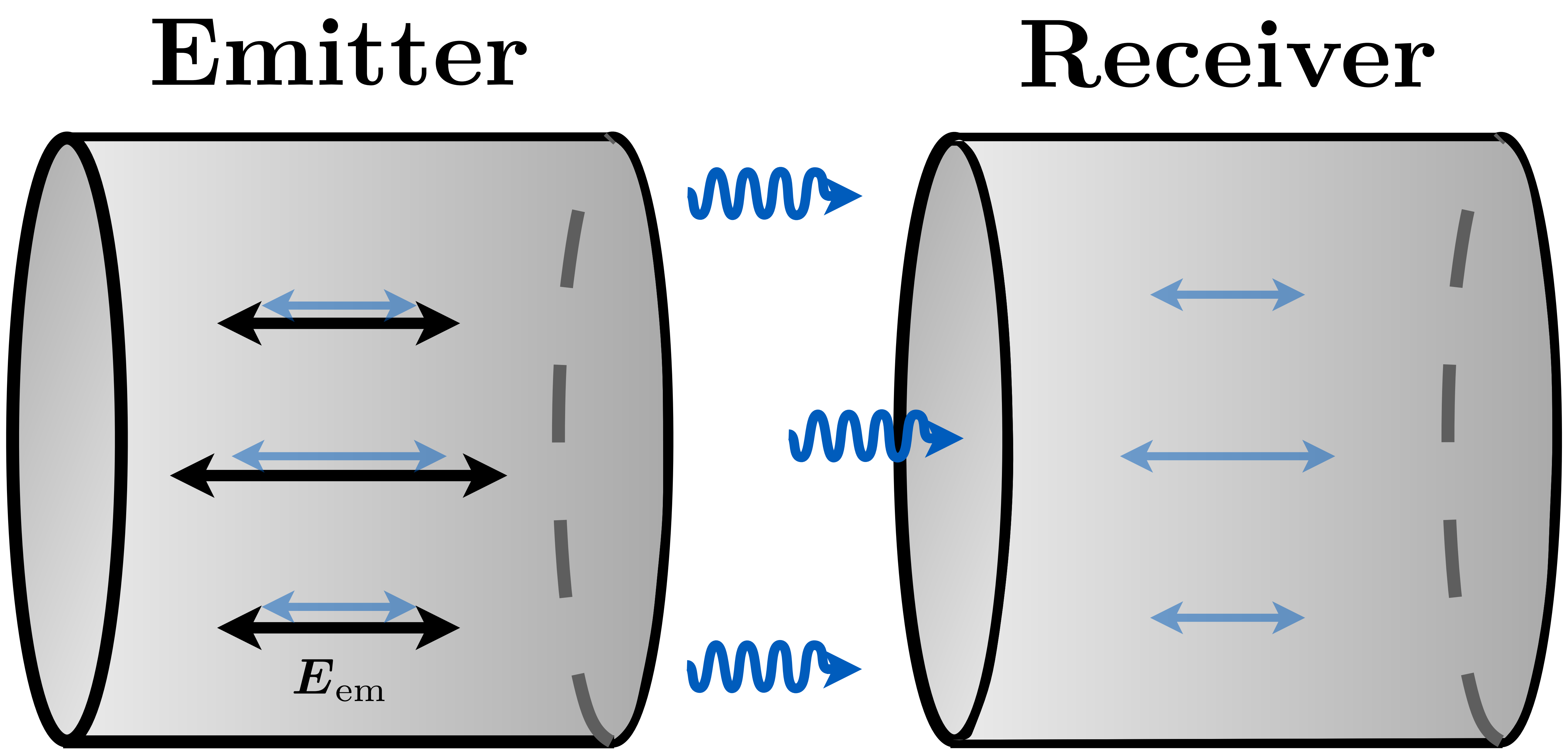


P. Graham, J. Mardon, S. Rajendran, Y. Zhao (2014)

Light-Shining-Through-Walls

Search for Dark Photons (not DM)

J. Jaeckel, A. Ringwald (2008)

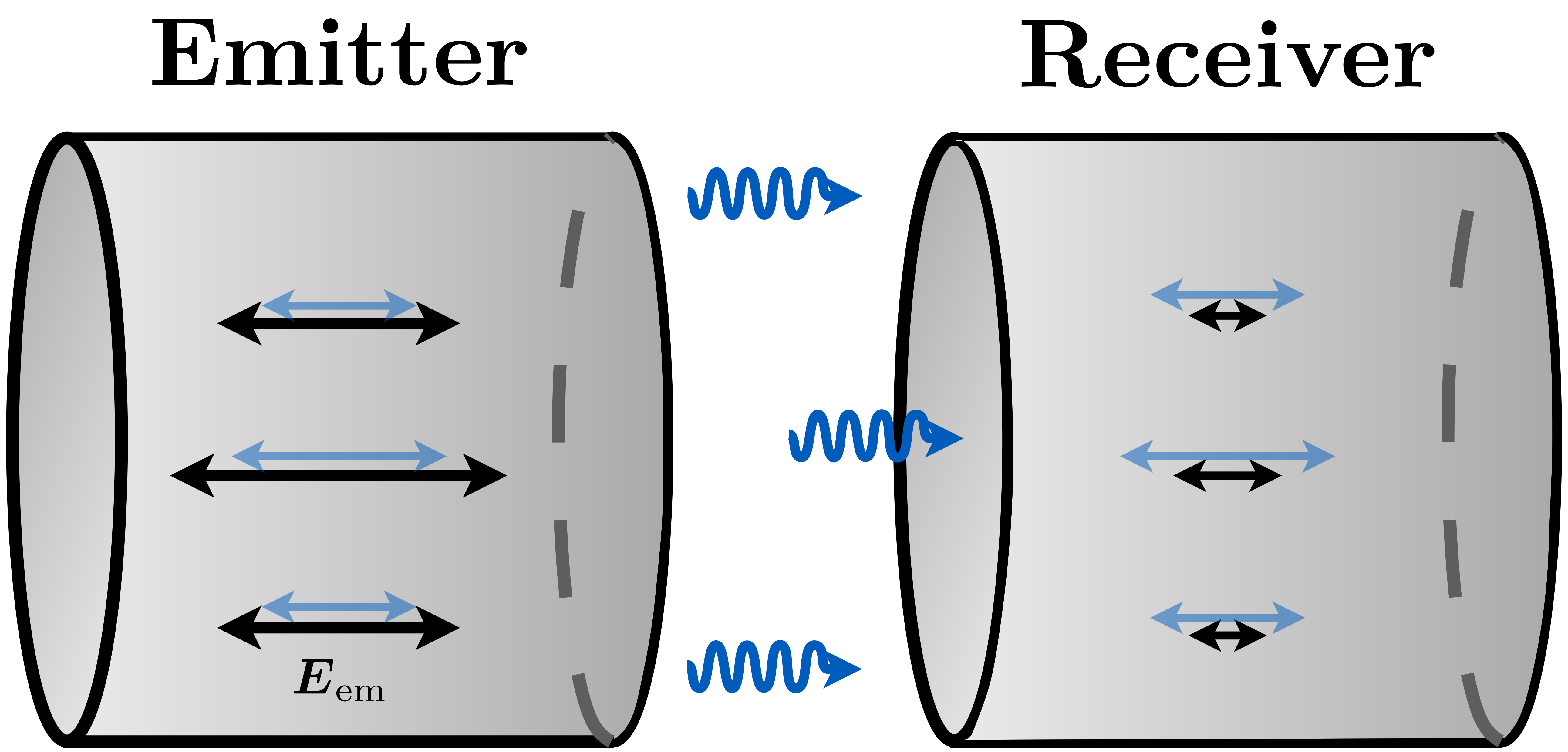


P. Graham, J. Mardon, S. Rajendran, Y. Zhao (2014)

Light-Shining-Through-Walls

Search for Dark Photons (not DM)

J. Jaeckel, A. Ringwald (2008)

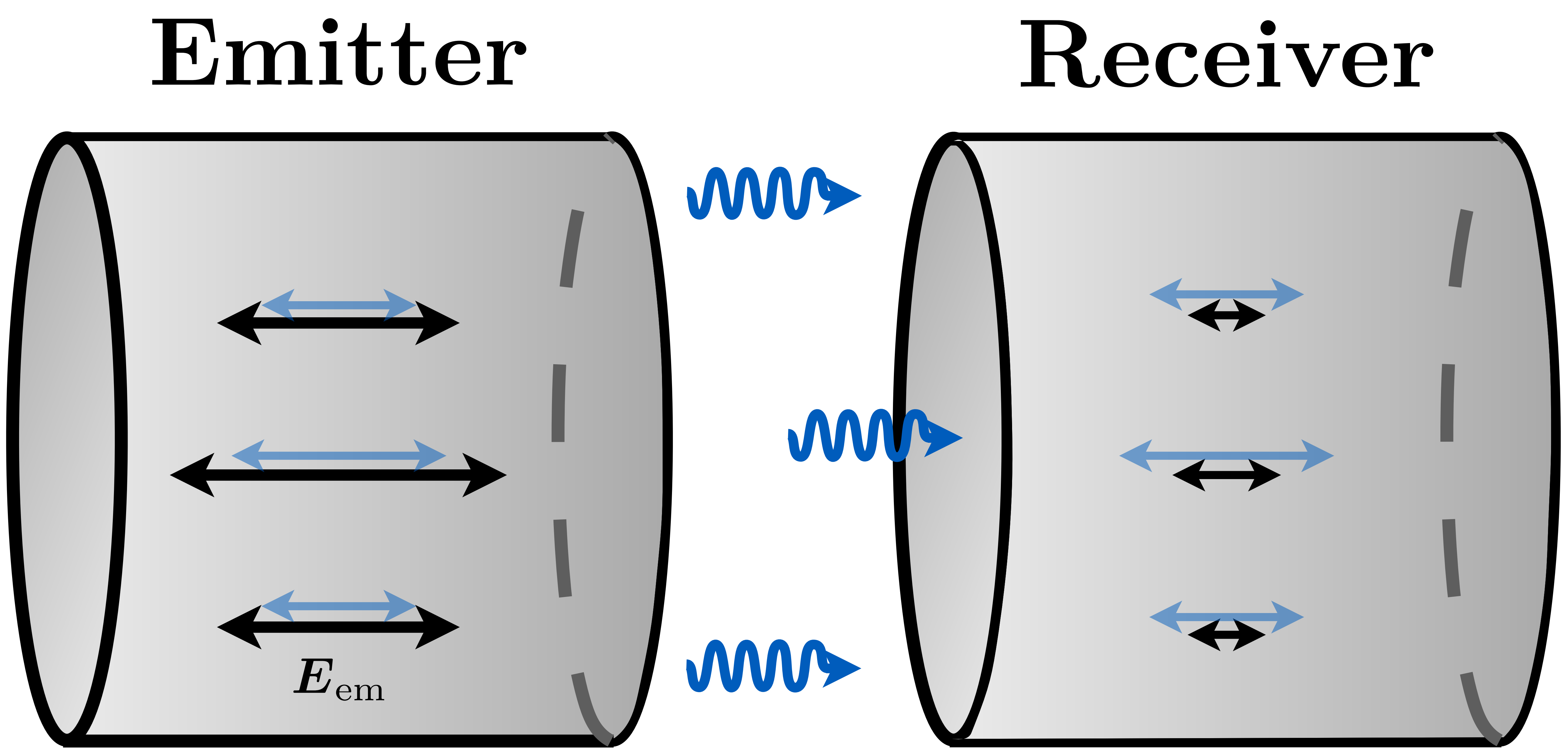


P. Graham, J. Mardon, S. Rajendran, Y. Zhao (2014)

Light-Shining-Through-Walls

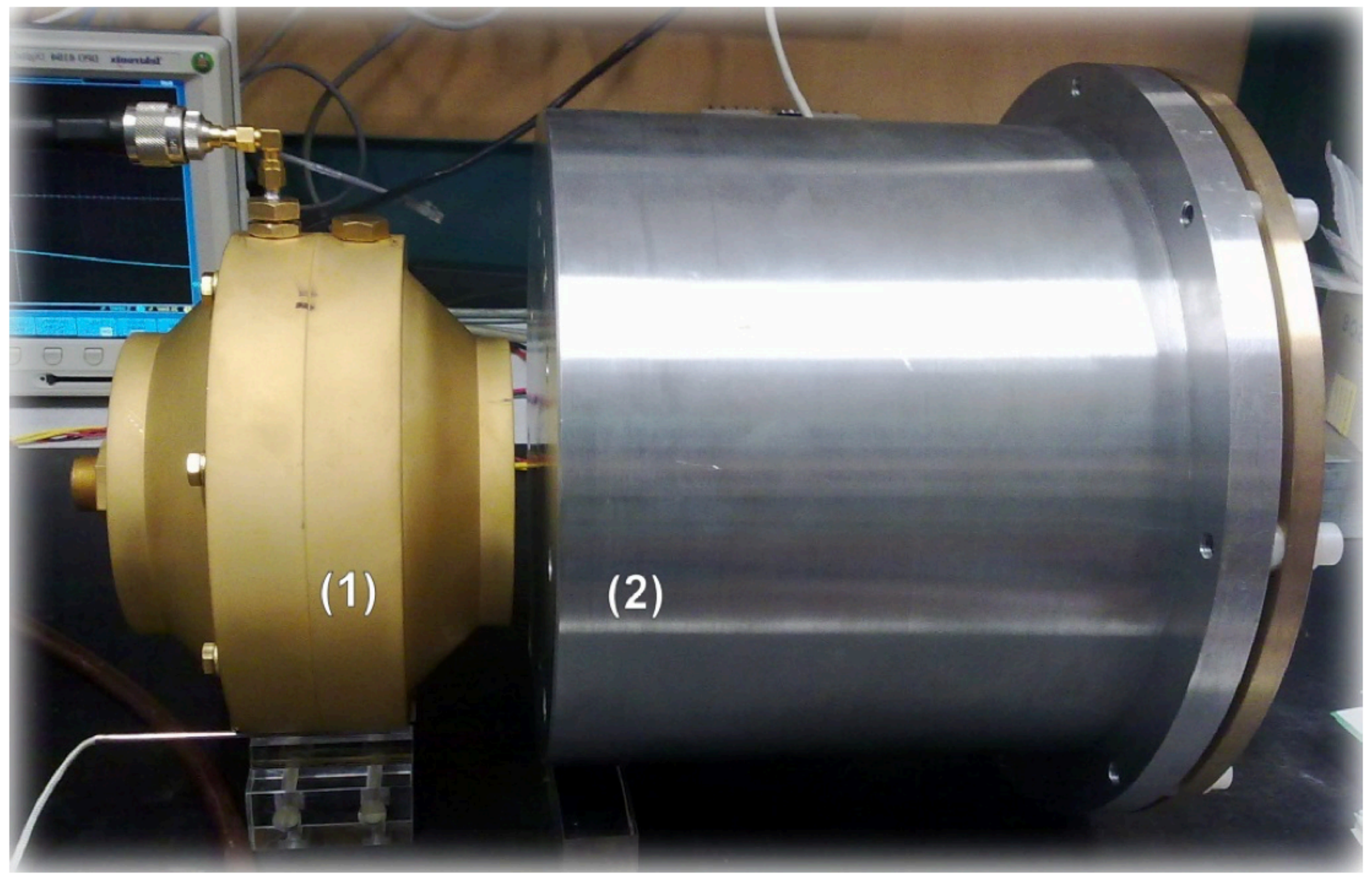
Search for Dark Photons (not DM)

J. Jaeckel, A. Ringwald (2008)



P. Graham, J. Mardon, S. Rajendran, Y. Zhao (2014)

First Experiment: CROWS
M. Betz, F. Caspers et al (2013)



Dark Photon Searches w/ Cavities

Ongoing experiment @ FNAL: *DarkSRF*

A. Romanenko et al (2023)

Dark Photon Searches w/ Cavities

Ongoing experiment @ FNAL: *DarkSRF*

Leverage high-Q SRF cavities developed at Superconducting Quantum Materials & Systems

A. Romanenko et al (2023)

Dark Photon Searches w/ Cavities

Ongoing experiment @ FNAL: *DarkSRF*

Leverage high-Q SRF cavities developed at Superconducting Quantum Materials & Systems

$Q_0 = 4.5 \times 10^{10}$

A. Romanenko et al (2023)

Dark Photon Searches w/ Cavities

Ongoing experiment @ FNAL: *DarkSRF*

Leverage high-Q SRF cavities developed at Superconducting Quantum Materials & Systems

$Q_0 = 4.5 \times 10^{10}$

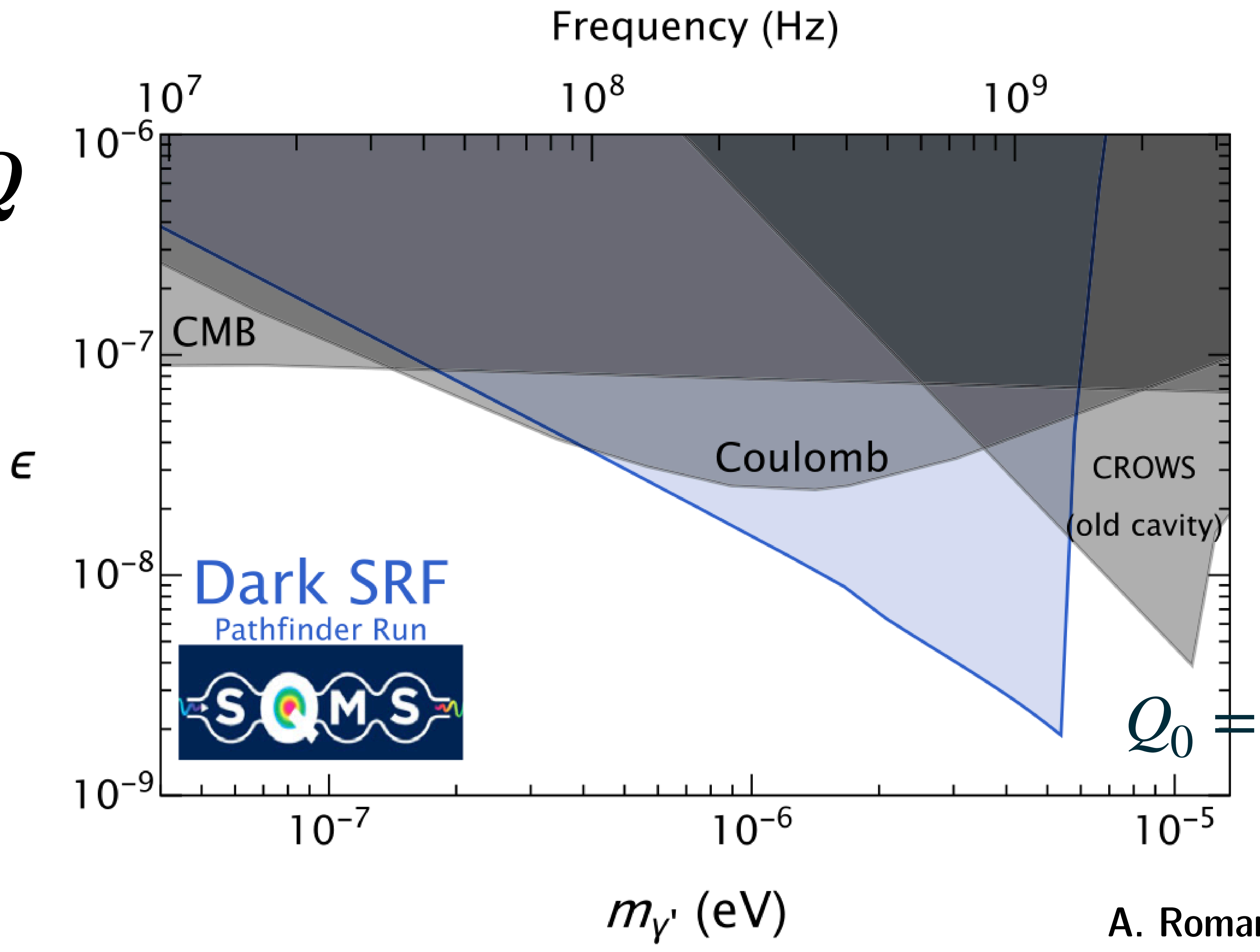
$Q_0 = 3.0 \times 10^{10}$

A. Romanenko et al (2023)

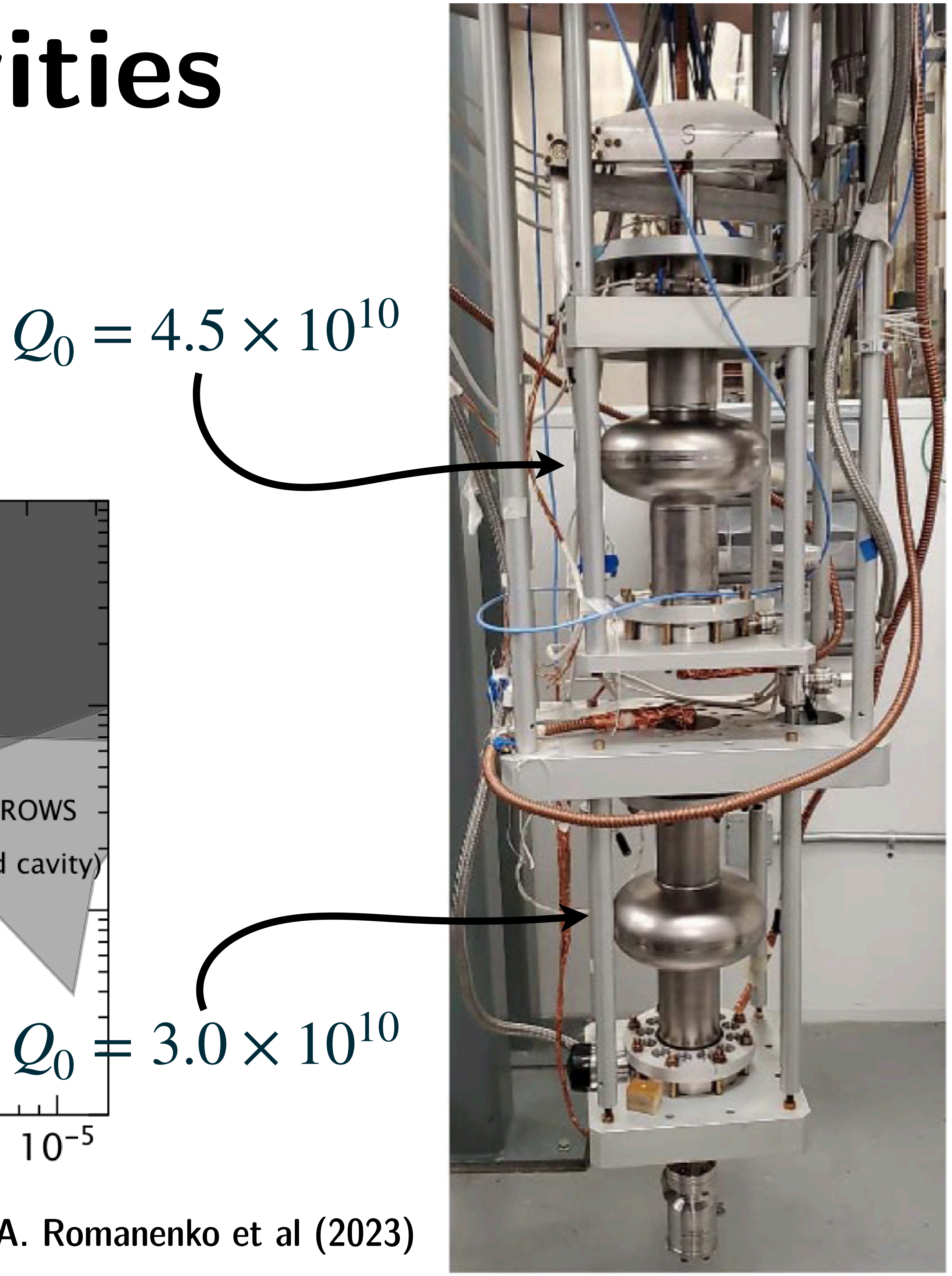
Dark Photon Searches w/ Cavities

Ongoing experiment @ FNAL: *DarkSRF*

Leverage high-Q SRF cavities developed at Superconducting Quantum Materials & Systems



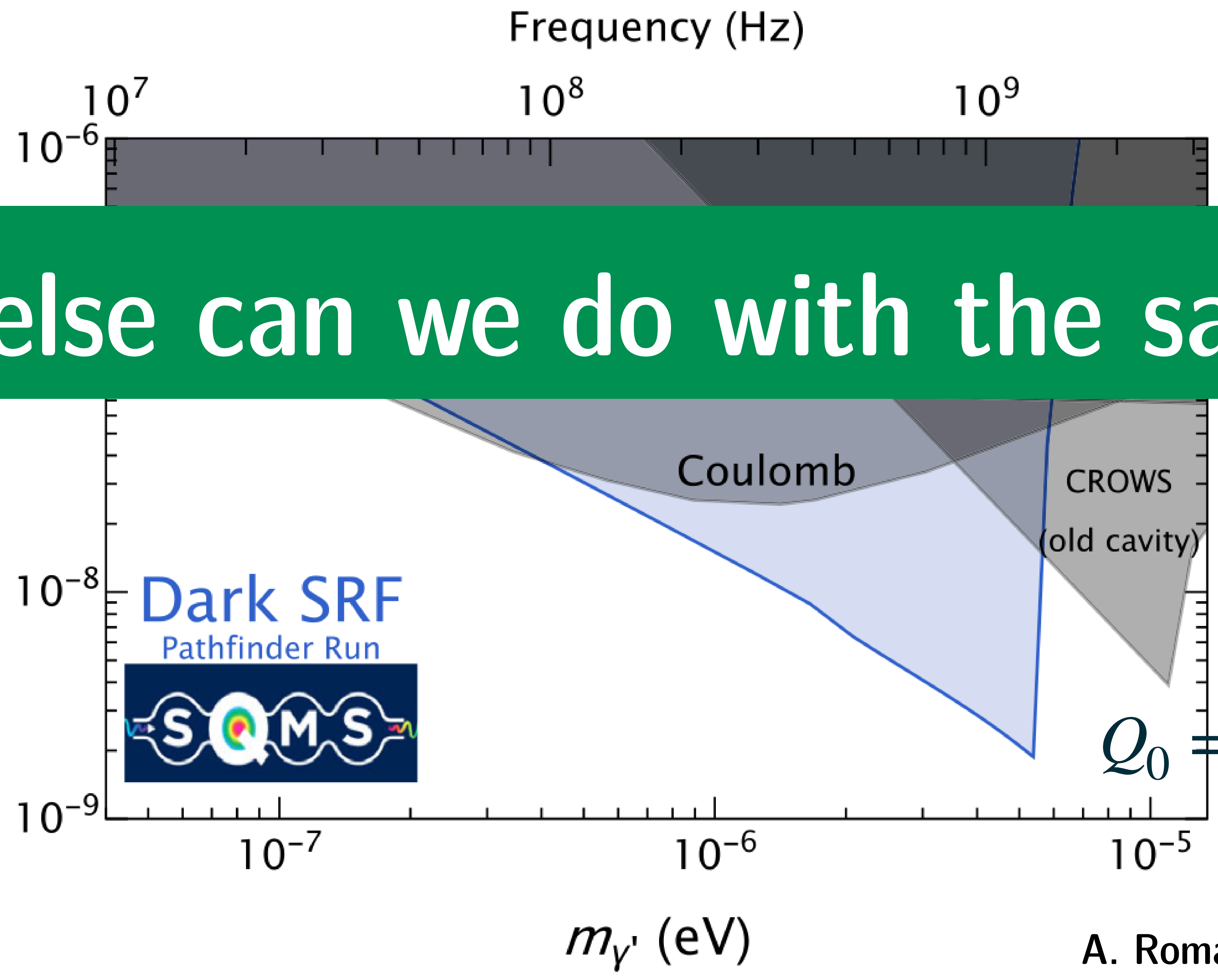
A. Romanenko et al (2023)



Dark Photon Searches w/ Cavities

Ongoing experiment @ FNAL: *DarkSRF*

Leverage high-Q
SRF c
developed at
Superconducting
Quantum **M**aterials &
Systems



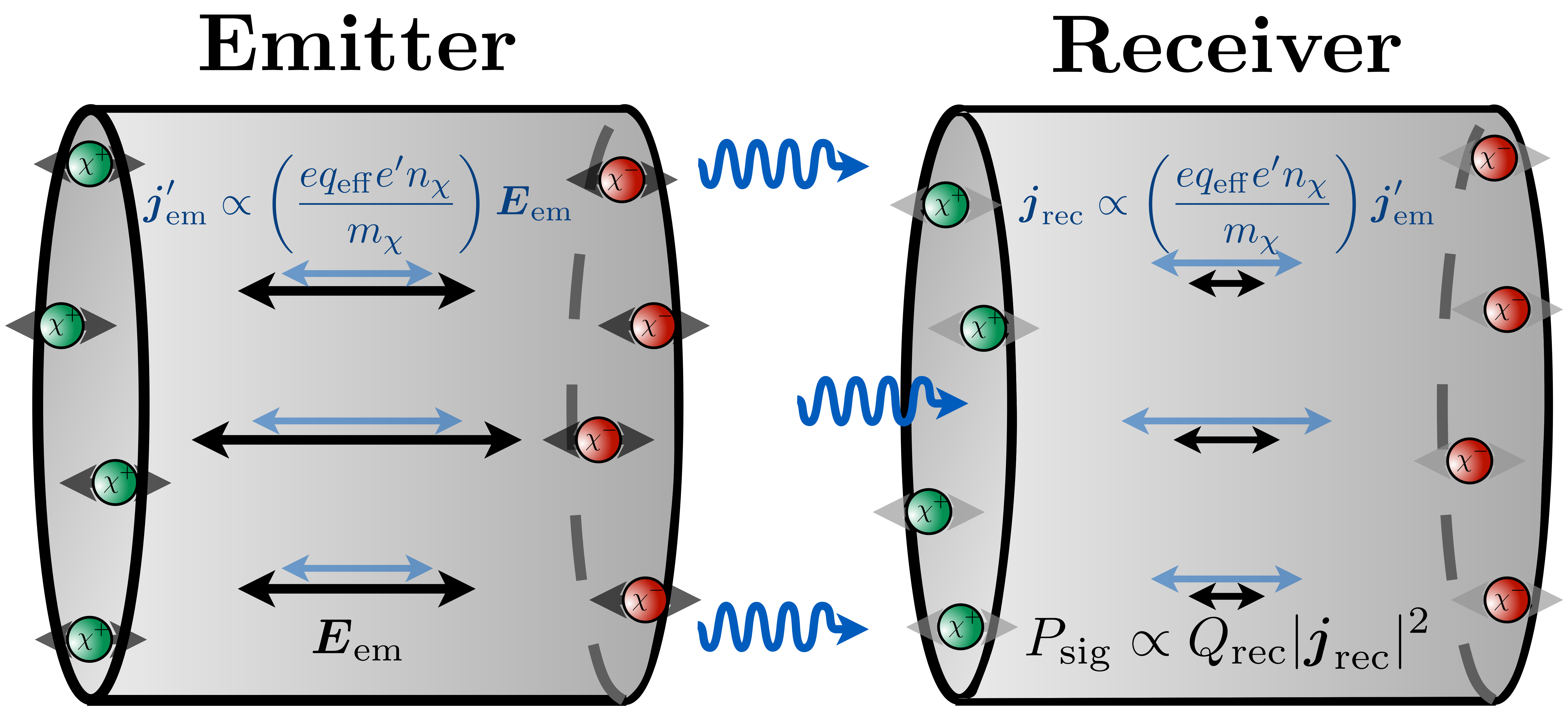
$Q_0 = 4.5 \times 10^{10}$

$Q_0 = 3.0 \times 10^{10}$

A. Romanenko et al (2023)

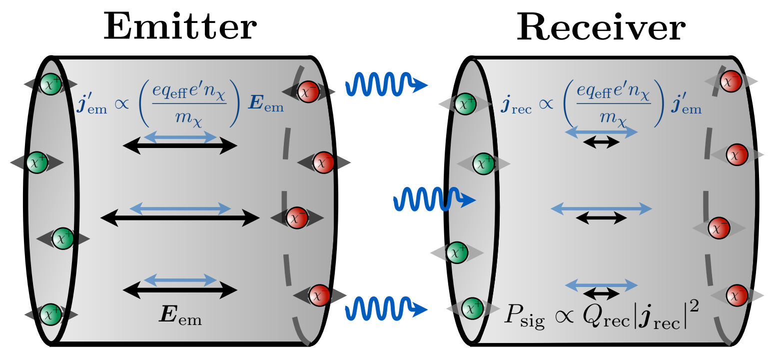
What else can we do with the same setup?

Millicharged DM at LSW Experiments



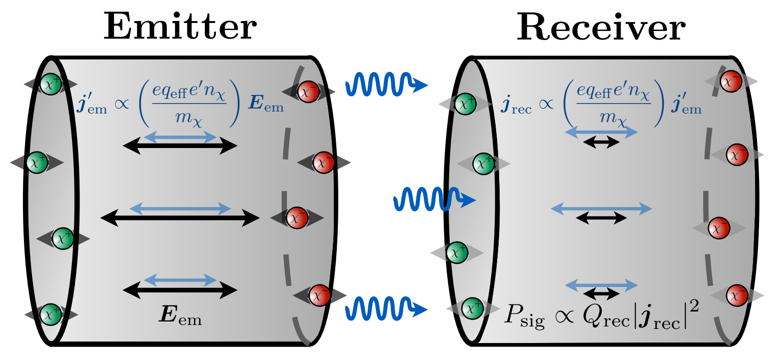
A. Berlin, R. T. D'Agnolo, SARE, J. Radkovski
JHEP 08 (2023) 017

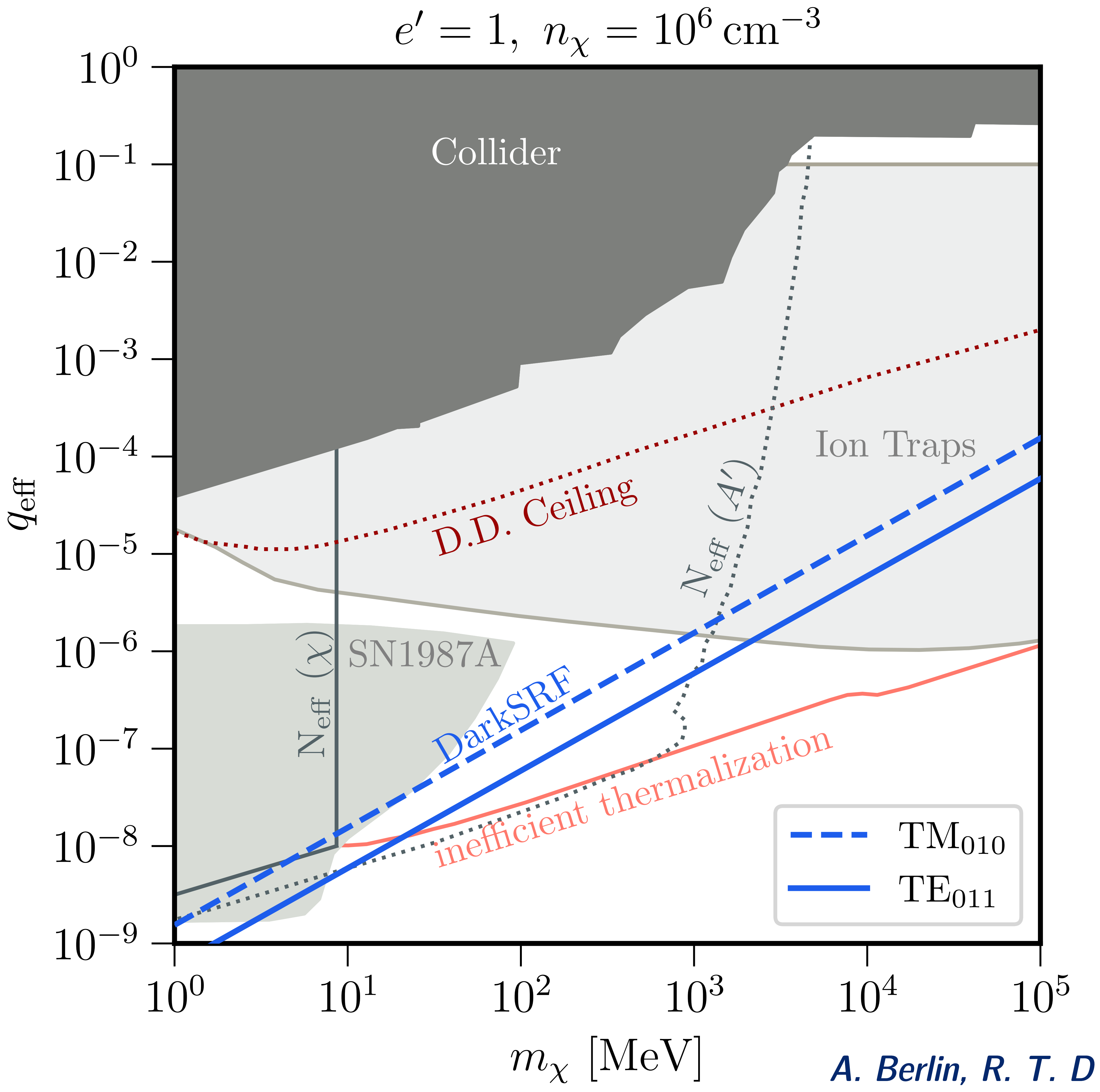
Millicharged DM at LSW Experiments

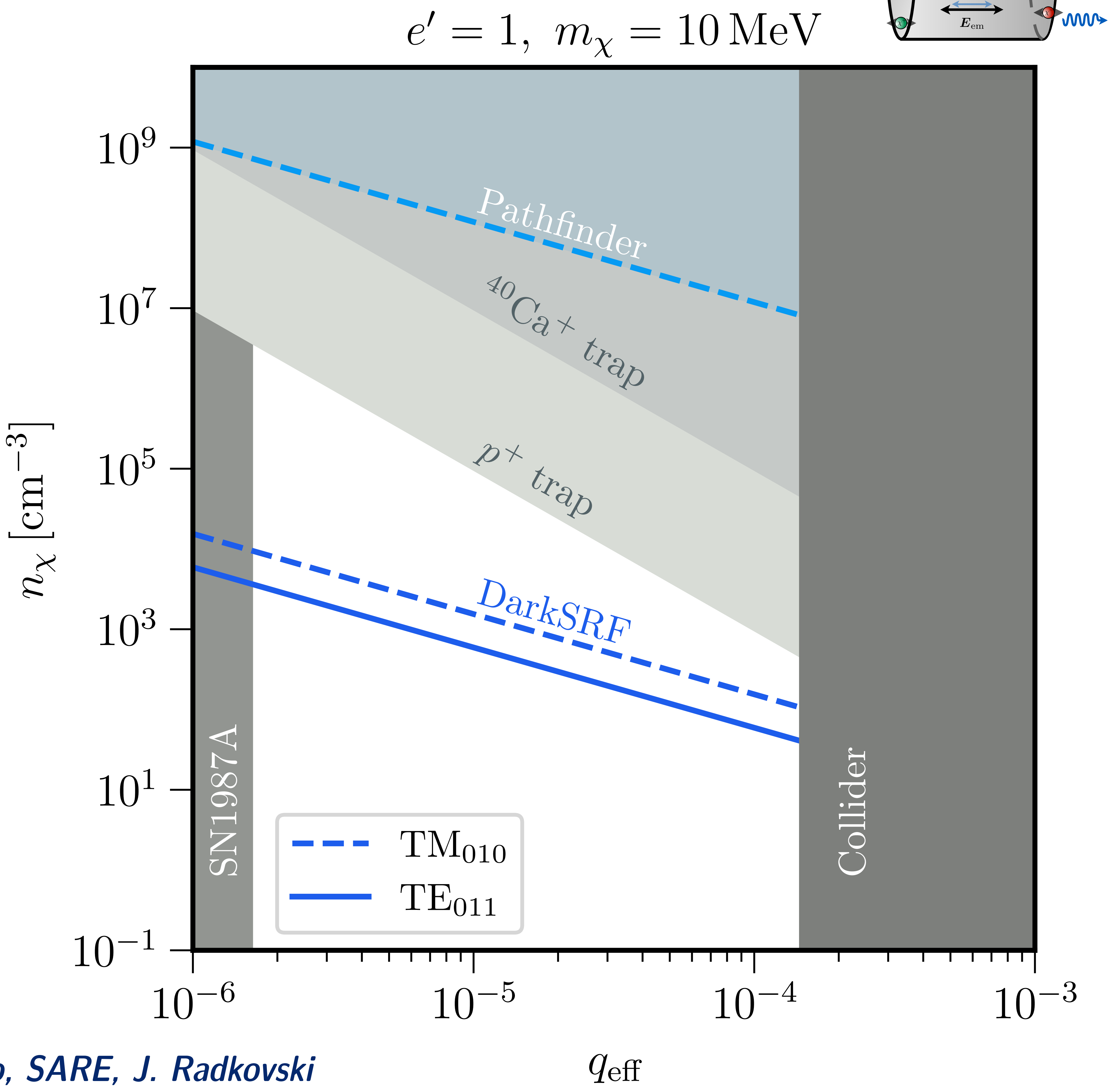


A. Berlin, R. T. D'Agnolo, SARE, J. Radkovski
JHEP 08 (2023) 017

Millicharged DM at LSW Experiments







A. Berlin, R. T. D'Agnolo, SARE, J. Radkovski
JHEP 08 (2023) 017

Variation in a

A. Berlin, R. T. D'Agnolo, SARE, C. Nantista, J. Neilson, P. Schuster, S. Tantawi, N. Toro, K. Zhou
JHEP 07 (2020) 088

A. Berlin, R. T. D'Agnolo, SARE, K. Zhou
Phys.Rev.D 104 (2021) 11, L111701

$\beta \sim 1$

Axion, ALPs and Axion Electrodynamics

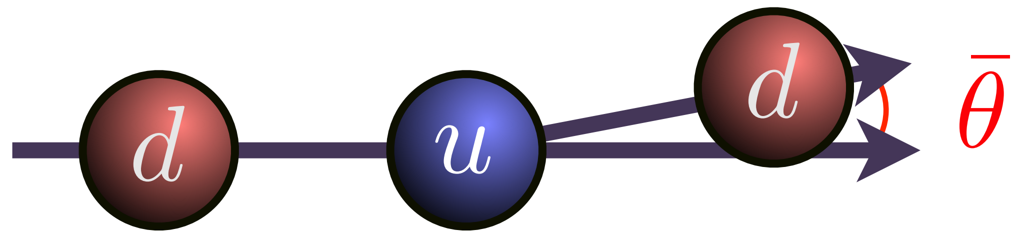
Axion introduced to solve strong CP problem

$$\mathcal{L} \supset \left(\frac{a}{f_a} + \bar{\theta}\right) \frac{g_s^2}{32\pi^2} G^a_{\mu\nu}\tilde{G}^{\mu\nu,a}$$

Peccei & Quinn (1977)
Weinberg (1978)
Wilczek (1978)

$$d_n \sim 10^{-16}\bar{\theta}\ e\ \mathrm{cm}$$

$$d_n^{\exp} \lesssim 10^{-26}\ e\ \mathrm{cm}$$



Mixing w/ pion or from full theory:

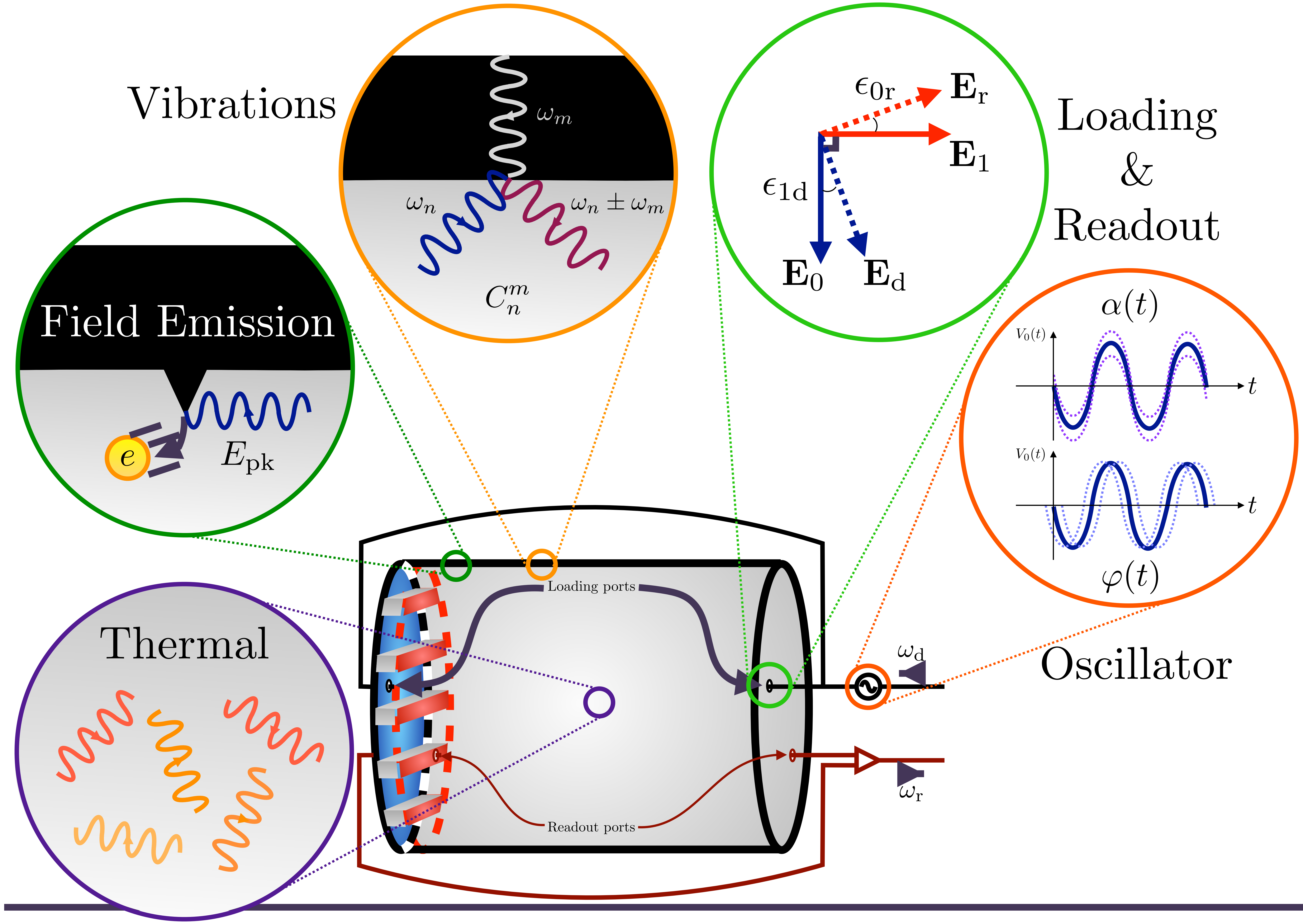
$$\mathcal{L} \supset -\frac{g_{a\gamma\gamma}}{4}\, a\, F\tilde{F} = -g_{a\gamma\gamma}\, a\, \mathbf{E}\cdot\mathbf{B}$$

$$\nabla\cdot\mathbf{E} = \rho - g_{a\gamma\gamma}\mathbf{B}\cdot\nabla a$$

$$\nabla\times\mathbf{B} = \partial_t\mathbf{E} + \mathbf{J} - g_{a\gamma\gamma}\left(\mathbf{E}\times\nabla a - \mathbf{B}\partial_t a\right)$$

Maxwell's new and improved Equations

All Noise Sources



- ***Thermal noise***: requires cryo
- ***Field Emission***: careful design & limits peak B-field
- ***Vibrations***: design to reduce microphonics, isolation, cryo
- ***Loading/Readout & Phase***: design to improve coupling to pump & signal modes. Low phase-noise pump & readout electronics

Signal to Noise

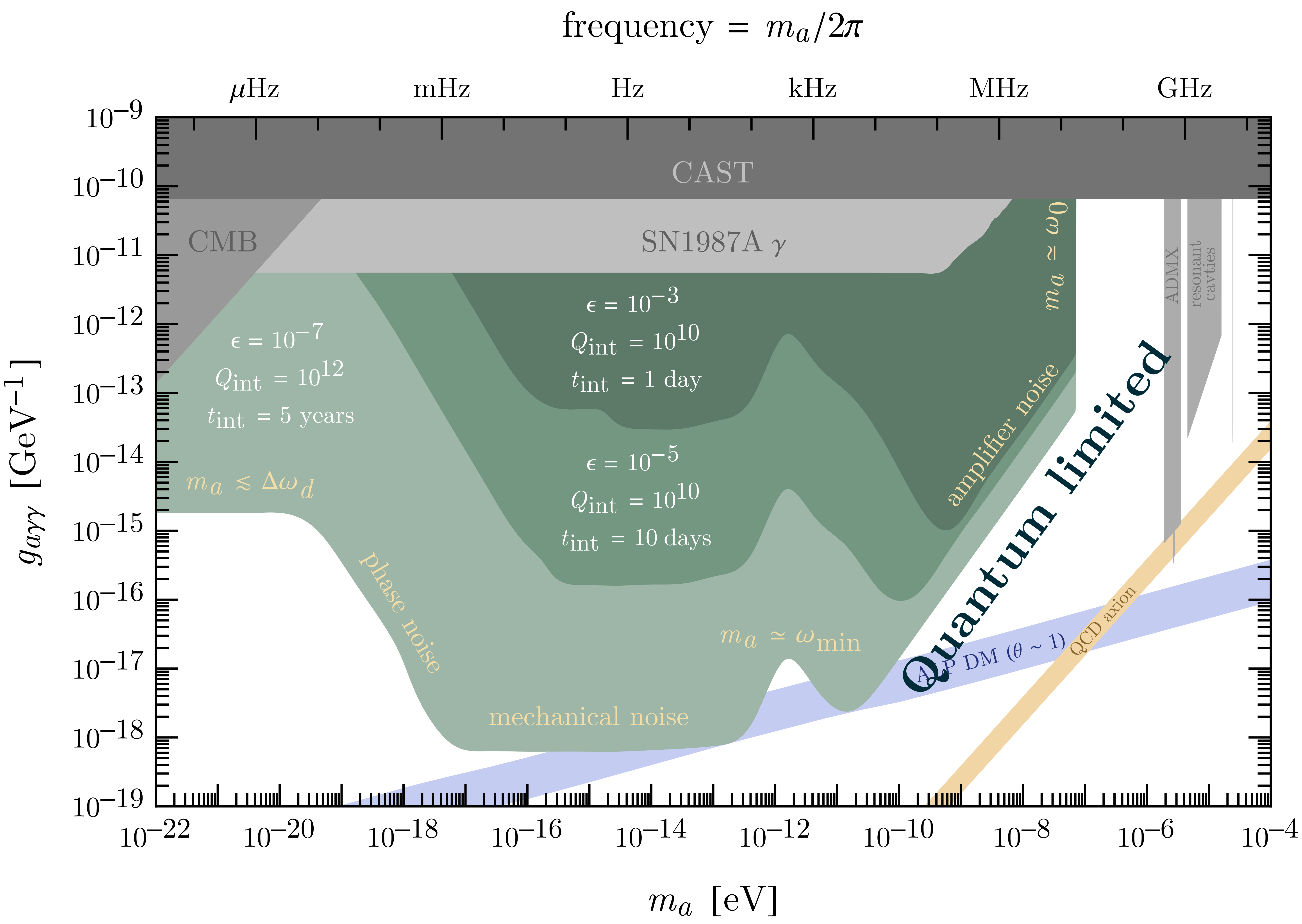
Thermal noise dominated:

$$\mathrm{SNR} \sim \frac{\rho_{\mathrm{DM}}\, V}{m_a\, \omega_1} \left(g_{a\gamma\gamma}\, \eta_{10}\, B_0\right)^2 \left(\frac{Q_a\, Q_{\mathrm{int}}\, t_e}{T}\right)^{1/2}$$

Comparison with LC resonator:

$$\frac{\mathrm{SNR}}{\mathrm{SNR}^{\mathrm{LC}}} \sim \frac{\omega_0 \pm m_a}{m_a} \left(\frac{Q_{\mathrm{int}}}{Q_{\mathrm{LC}}}\right)^{1/2} \left(\frac{T_{\mathrm{LC}}}{T}\right)^{1/2} \left(\frac{B_0}{B_{\mathrm{LC}}}\right)^2$$

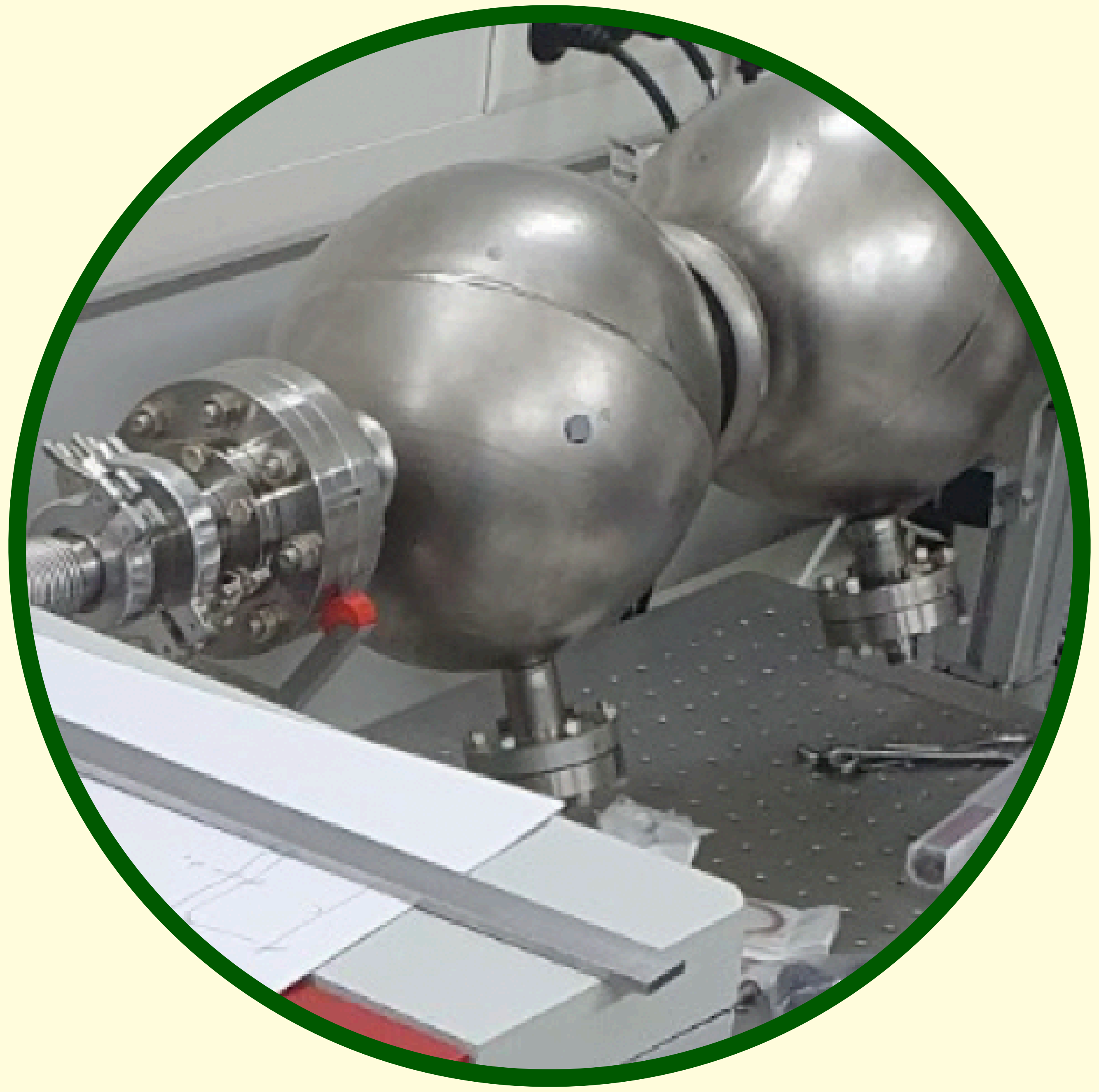
Broadband Axion Sensitivity



***JHEP* 07 (2020) 088, hep-ph/1912.11048**
A. Berlin, R. T. D'Agnolo, **SARE,** P. Schuster, N. Toro, C. Nantista, J. Neilson, S. Tantawi, K. Zhou

***PRD* 104 (2021) 11, L111701, hep-ph/2007.15656**
A. Berlin, R. T. D'Agnolo, **SARE,** K. Zhou

VARIATION IN $h_{\mu\nu}$

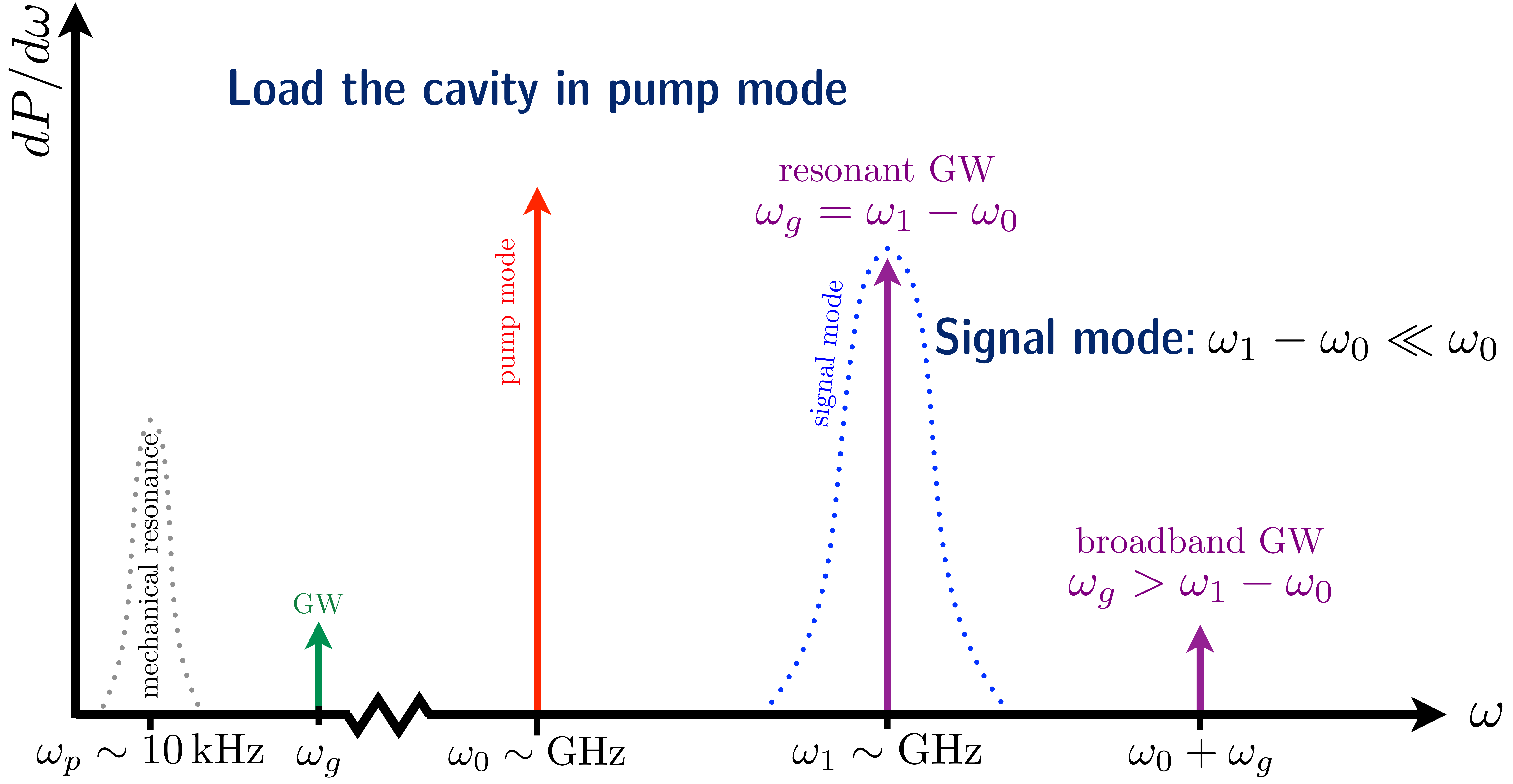


A. Berlin, D. Blas, R. T. D'Agnolo, SARE, R. Harnik, Y. Kahn, J. Schütte-Engel
Phys.Rev.D 105 (2022) 11, 116011

A. Berlin, D. Blas, R. T. D'Agnolo, SARE, R. Harnik, Y. Kahn, J. Schütte-Engel, M. Wentzel
Phys.Rev.D 108 (2023) 8, 084058

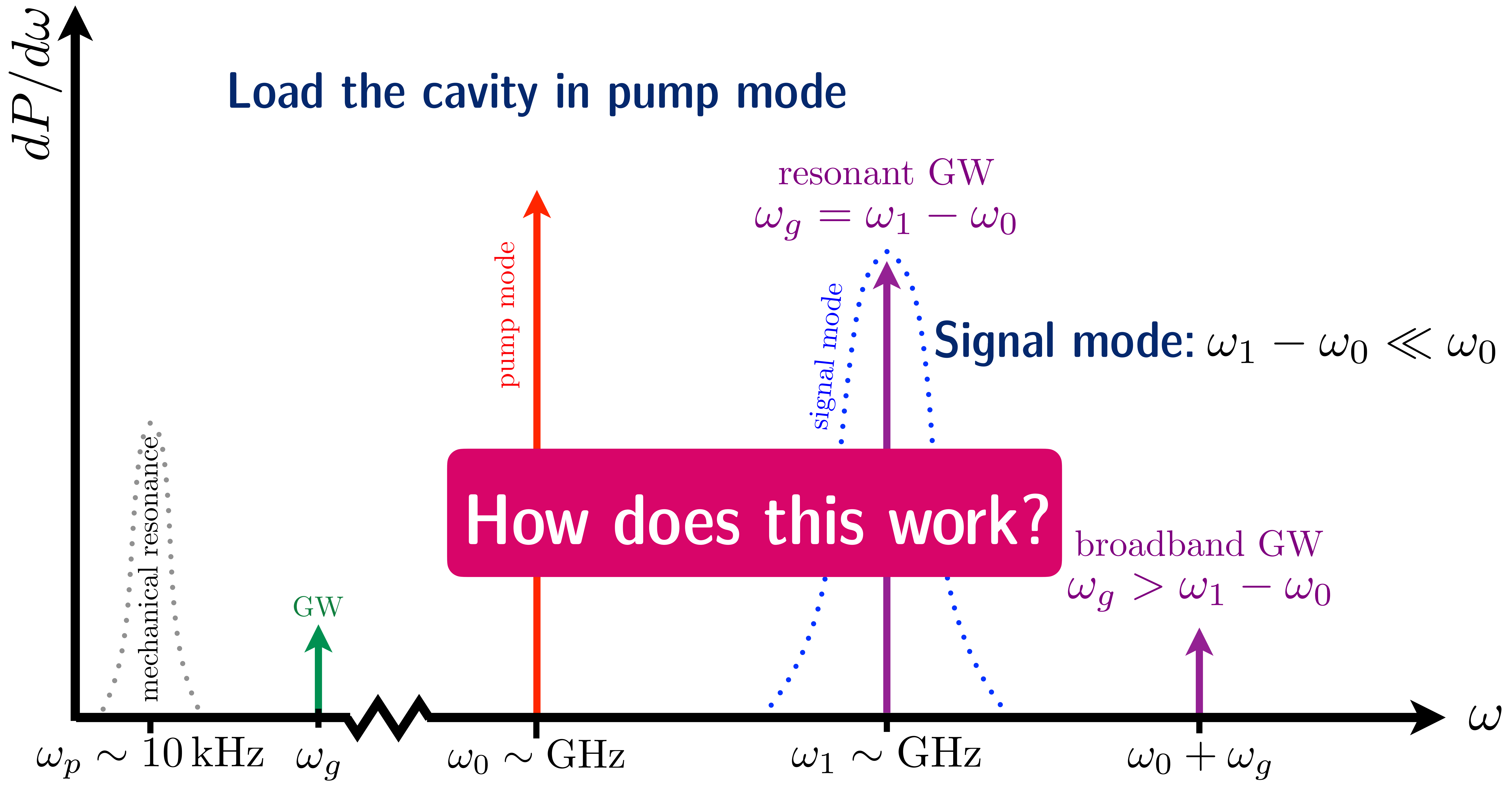
$\beta \sim 1$

MAGO 2.0



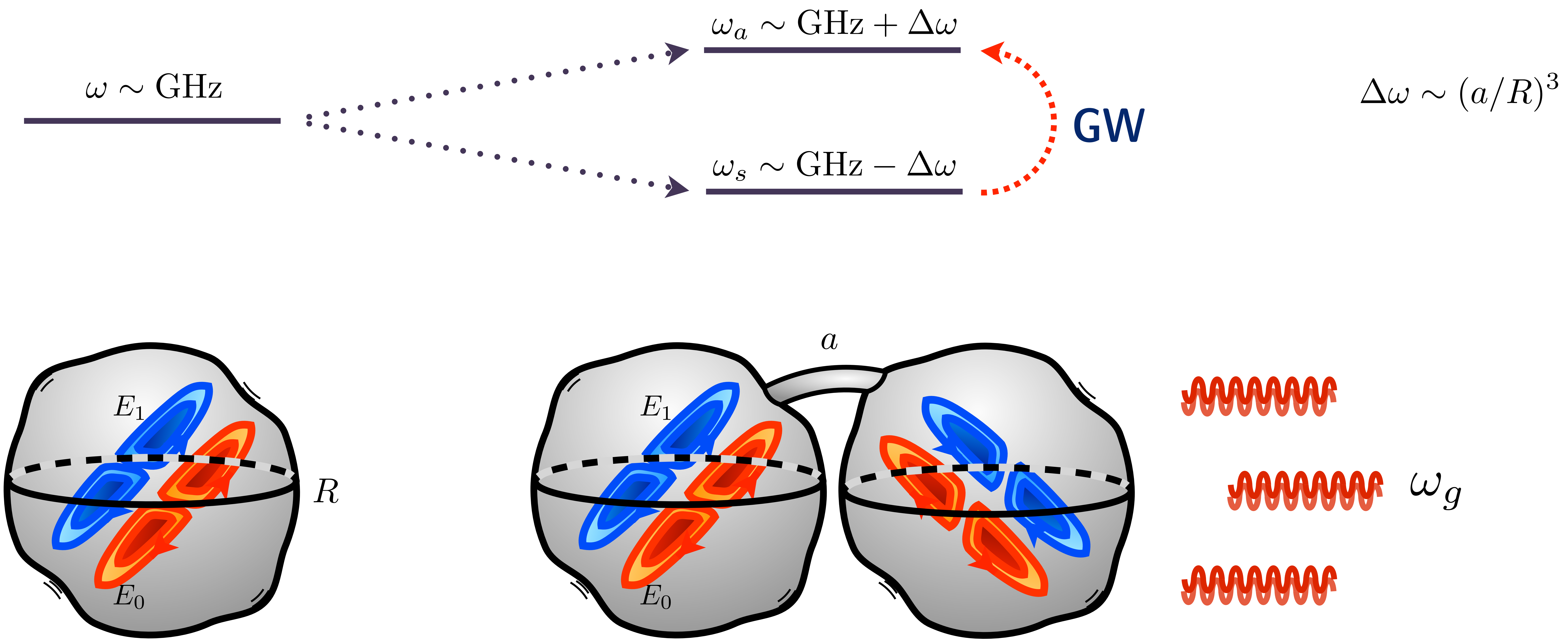
$dP/d\omega$
Load the cavity in pump mode
resonant GW
$\omega_g = \omega_1 - \omega_0$
pump mode
signal mode
Signal mode: $\omega_1 - \omega_0 \ll \omega_0$
mechanical resonance
GW
broadband GW
$\omega_g > \omega_1 - \omega_0$
ω
$\omega_p \sim 10\,\mathrm{kHz}$
ω_g
$\omega_0 \sim \mathrm{GHz}$
$\omega_1 \sim \mathrm{GHz}$
$\omega_0 + \omega_g$

MAGO 2.0



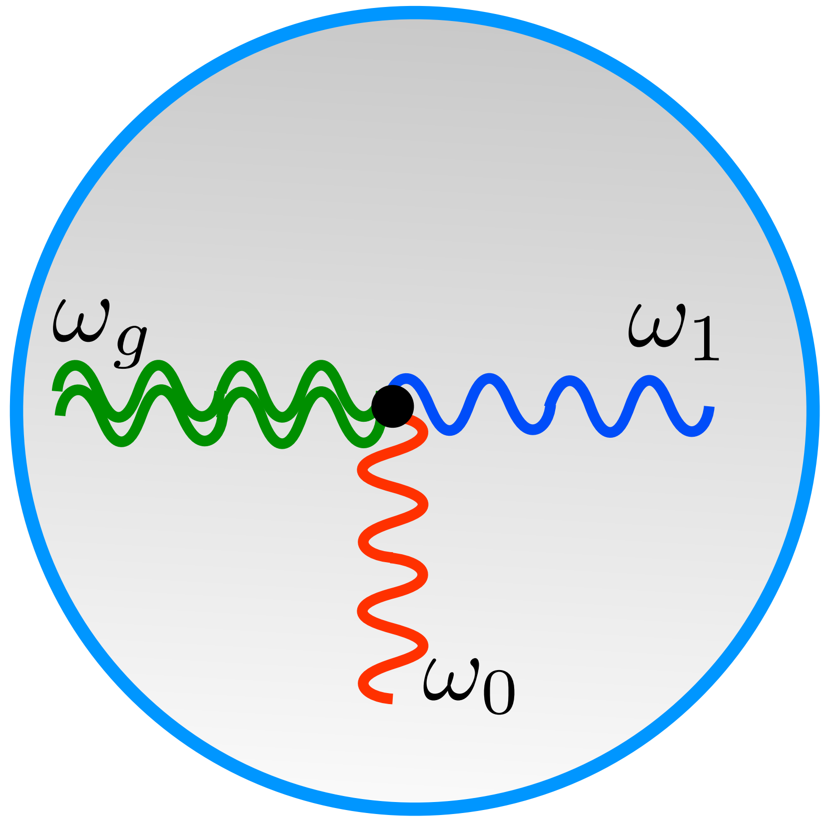
$dP/d\omega$
Load the cavity in pump mode
resonant GW
$\omega_g = \omega_1 - \omega_0$
pump mode
signal mode
Signal mode: $\omega_1 - \omega_0 \ll \omega_0$
mechanical resonance
How does this work?
broadband GW
$\omega_g > \omega_1 - \omega_0$
GW
ω
$\omega_p \sim 10\,\mathrm{kHz}$
ω_g
$\omega_0 \sim \mathrm{GHz}$
$\omega_1 \sim \mathrm{GHz}$
$\omega_0 + \omega_g$

MAGO 2.0


$\omega \sim \mathrm{GHz}$
$\omega_a \sim \mathrm{GHz} + \Delta\omega$
$\omega_s \sim \mathrm{GHz} - \Delta\omega$
GW
$\Delta\omega \sim (a/R)^3$
E_1
E_0
R
a
E_1
E_0
ω_g

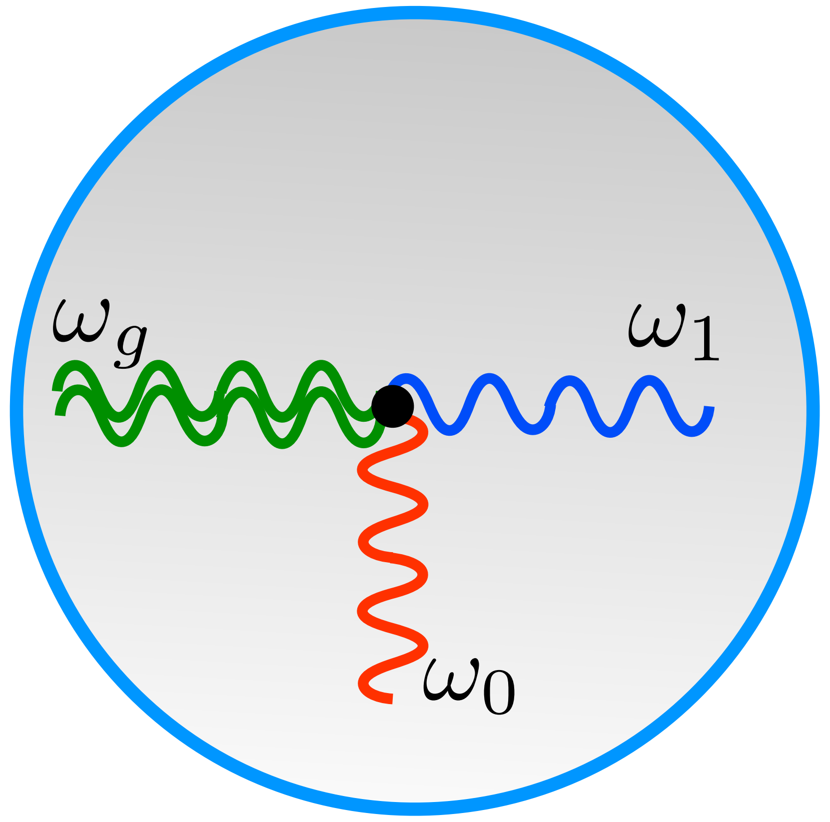
EM and Mechanical signals

EM and Mechanical signals



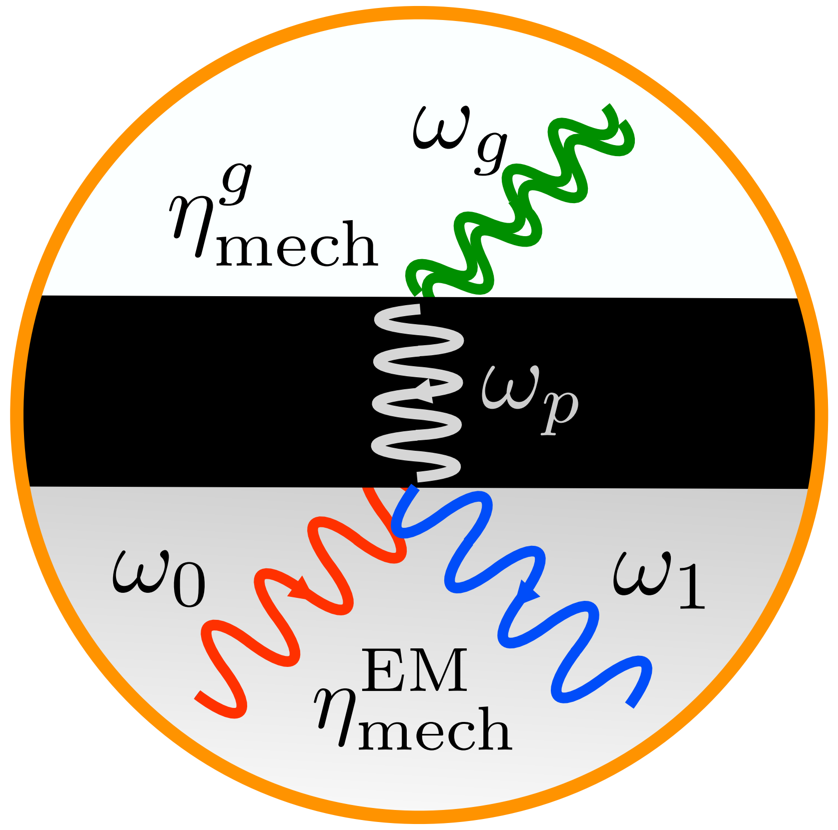
Parametrics of the EM signal: $E_{\rm sig}^{\rm (EM)} \sim Q_{\rm em}\,(\omega_g\,L_{\rm cav})^2\,h^{\rm TT}\,E_0$

EM and Mechanical signals

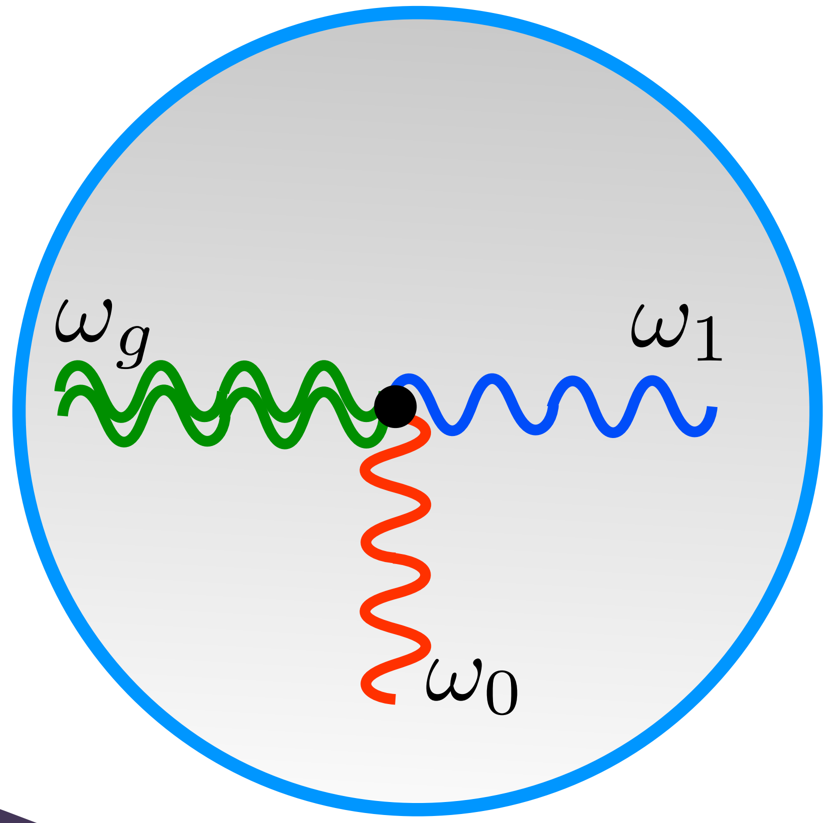


Parametrics of the EM signal: $E_{\rm sig}^{\rm (EM)} \sim Q_{\rm em}\,(\omega_g\,L_{\rm cav})^2\,h^{\rm TT}\,E_0$

Mechanical signal: $$E_{\rm sig}^{\rm (mech)} \sim Q_{\rm em}\,h^{\rm TT}\,E_0\;\min\left(1\,,\,\frac{\omega_g\,L_{\rm cav}}{c_s}\right)^2$$



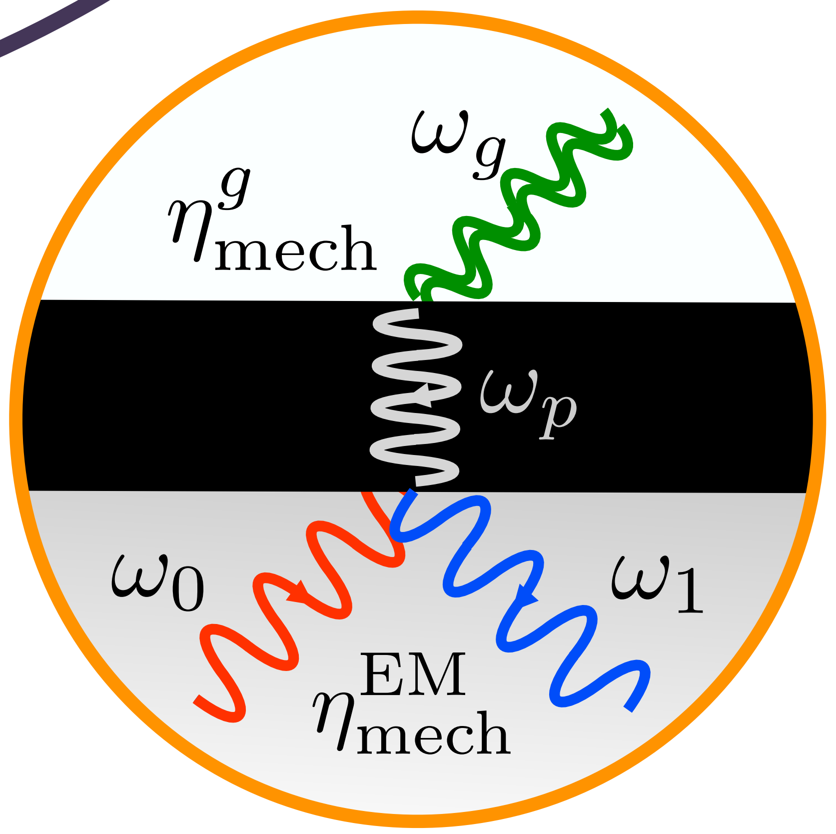
EM and Mechanical signals



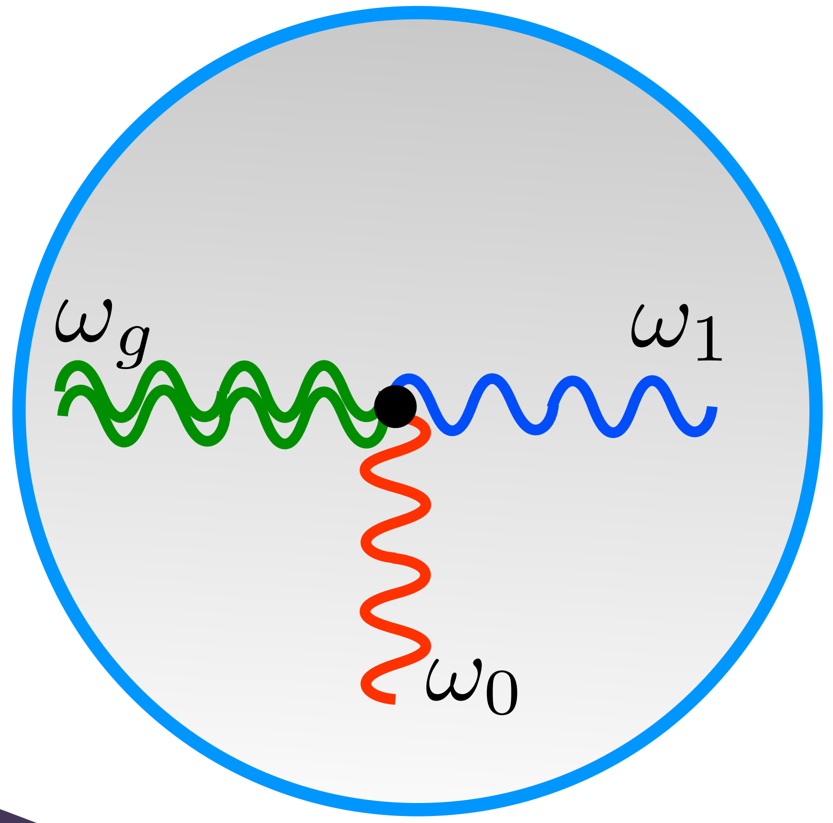
Parametrics of the EM signal: $E_{\rm sig}^{\rm (EM)} \sim Q_{\rm em}\,(\omega_g\,L_{\rm cav})^2\,h^{\rm TT}\,E_0$

Enhanced up to $1/c_s^2 \gg 1$ (!)

Mechanical signal: $E_{\rm sig}^{\rm (mech)} \sim Q_{\rm em}\,h^{\rm TT}\,E_0\,\min\left(1\,,\,\frac{\omega_g\,L_{\rm cav}}{c_s}\right)^2$



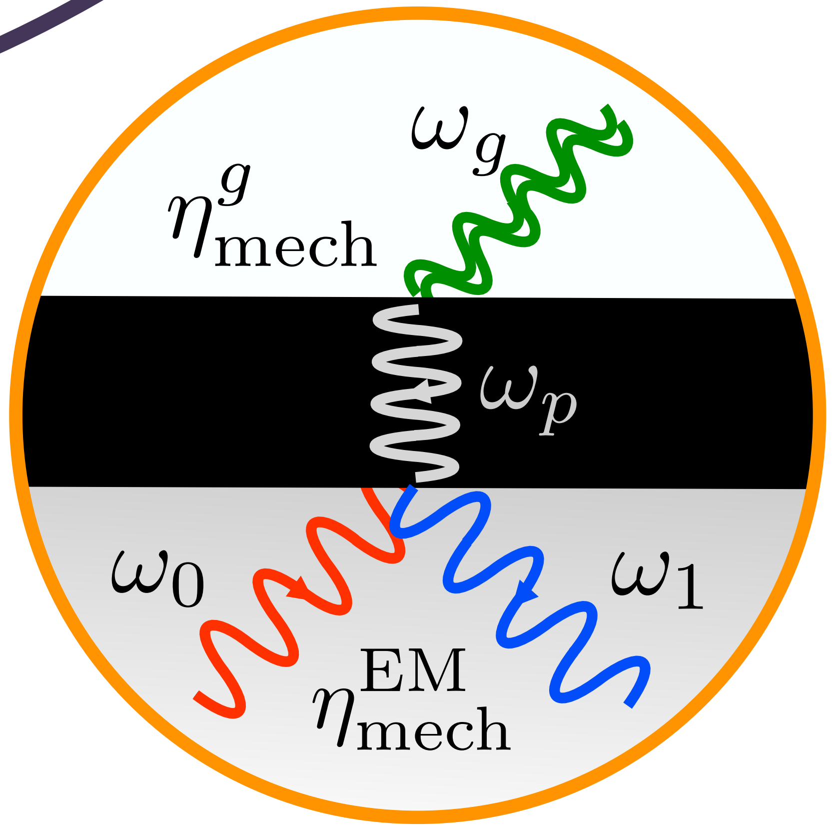
EM and Mechanical signals



Parametrics of the EM signal: $E_{\rm sig}^{\rm (EM)} \sim Q_{\rm em}\,(\omega_g\,L_{\rm cav})^2\,h^{\rm TT}\,E_0$

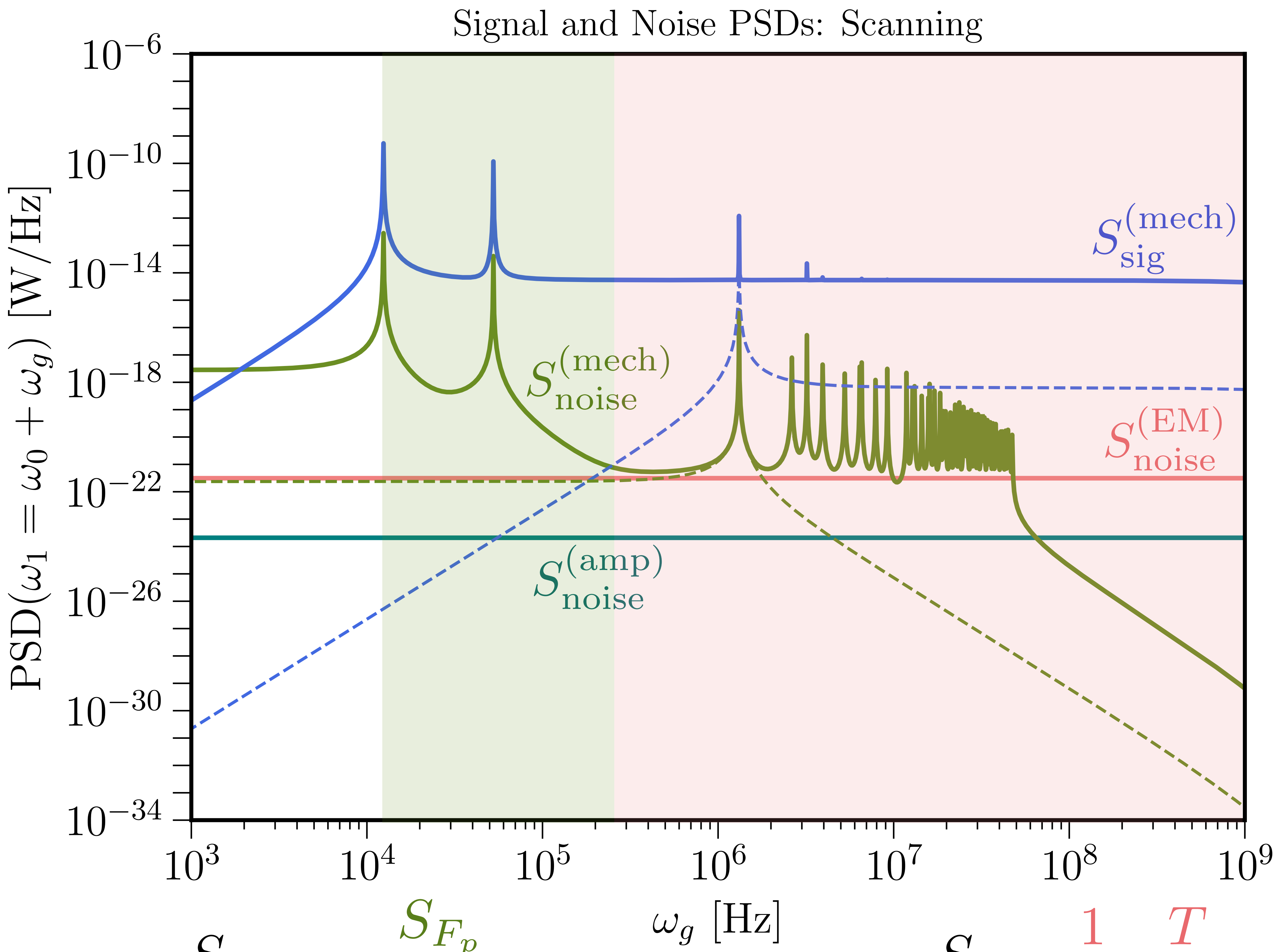
Enhanced up to $1/c_s^2 \gg 1$ *(!)*

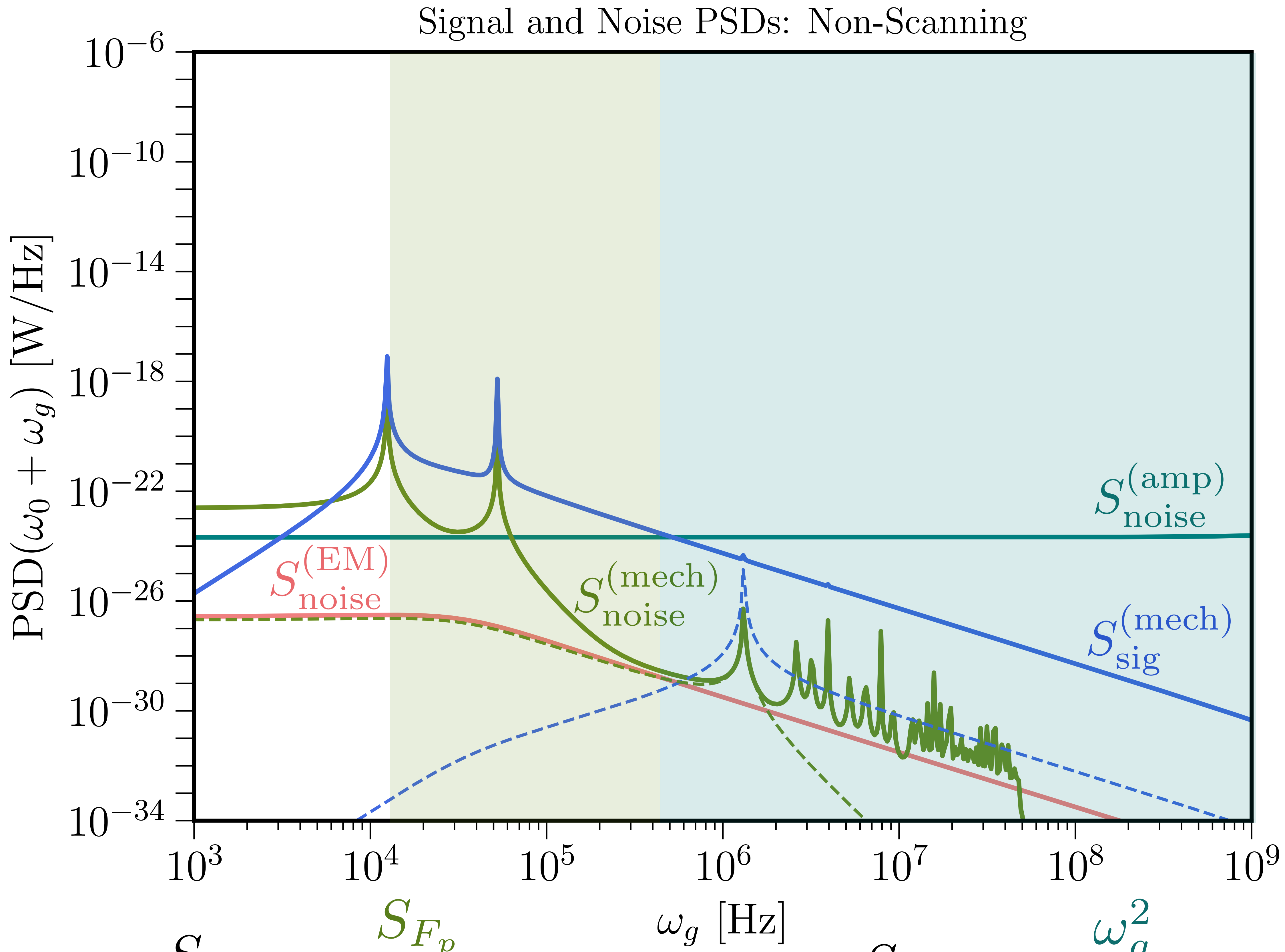
Mechanical signal: $E_{\rm sig}^{\rm (mech)} \sim Q_{\rm em}\,h^{\rm TT}\,E_0\,\min\left(1\,,\,\frac{\omega_g\,L_{\rm cav}}{c_s}\right)^2$



Mechanical modes less "rigid" than EM modes

Noise in MAGO 2.0





$$S_h \sim \frac{S_{F_p}}{\omega_g^4 (ML)^2}$$

Mech < MHz

$$S_h \sim \frac{1}{Q} \frac{T}{\omega_0 U_0}$$

EM Th. > MHz

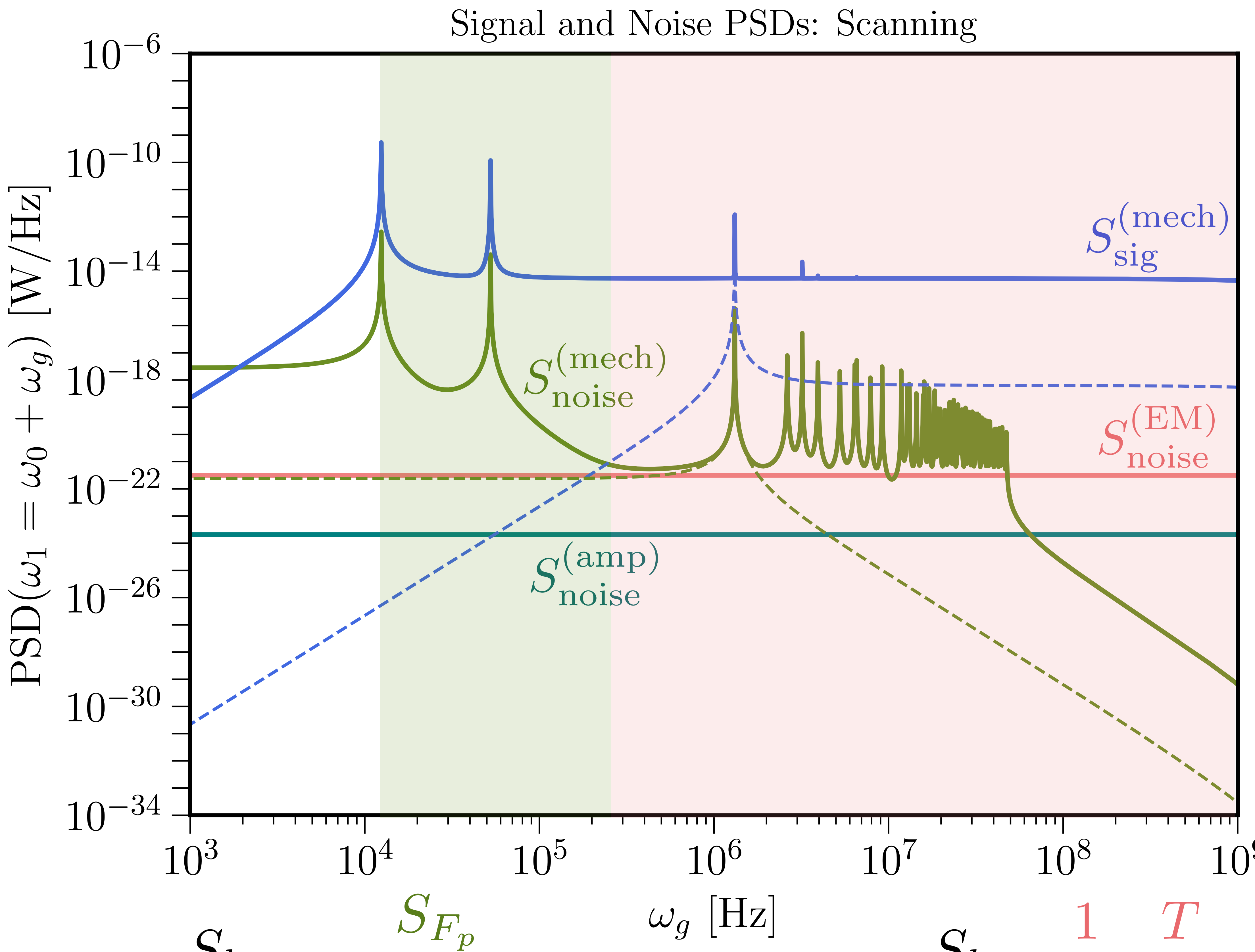
$$S_h \sim \frac{S_{F_p}}{\omega_g^4 (ML)^2}$$

Mech < MHz

$$S_h \sim \frac{\omega_g^2}{\hbar\omega_0(\omega_0 U_0)}$$

Amp > MHz

Noise in MAGO 2.0

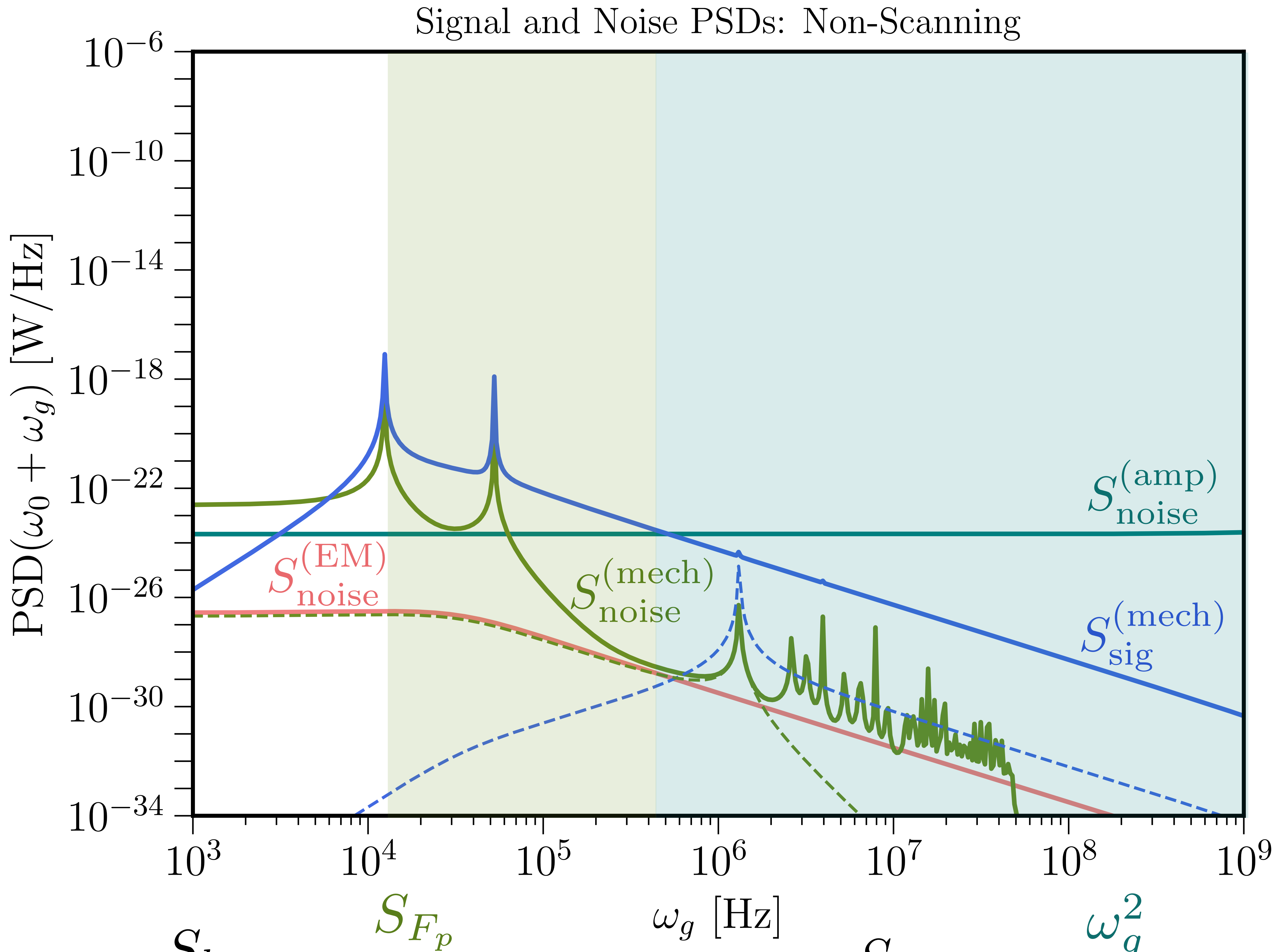


$$S_h \sim \frac{S_{F_p}}{\omega_g^4 (ML)^2}$$

Mech $<$ MHz

$$S_h \sim \frac{1}{Q} \frac{T}{\omega_0 U_0}$$

EM Th. $>$ MHz



$$S_h \sim \frac{S_{F_p}}{\omega_g^4 (ML)^2}$$

Mech $<$ MHz

$$S_h \sim \frac{\omega_g^2}{\hbar\omega_0(\omega_0 U_0)}$$

Amp $>$ MHz

NB: missing radiation damping effect studied in *Löwenberg, Moortgat-Pick: 2307.14379*

MAGO 2.0: Mechanical and EM Signals

MAGO 2.0: Mechanical and EM Signals

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

MAGO 2.0: Mechanical and EM Signals

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

Microwave Apparatus for Gravitational Waves Observation

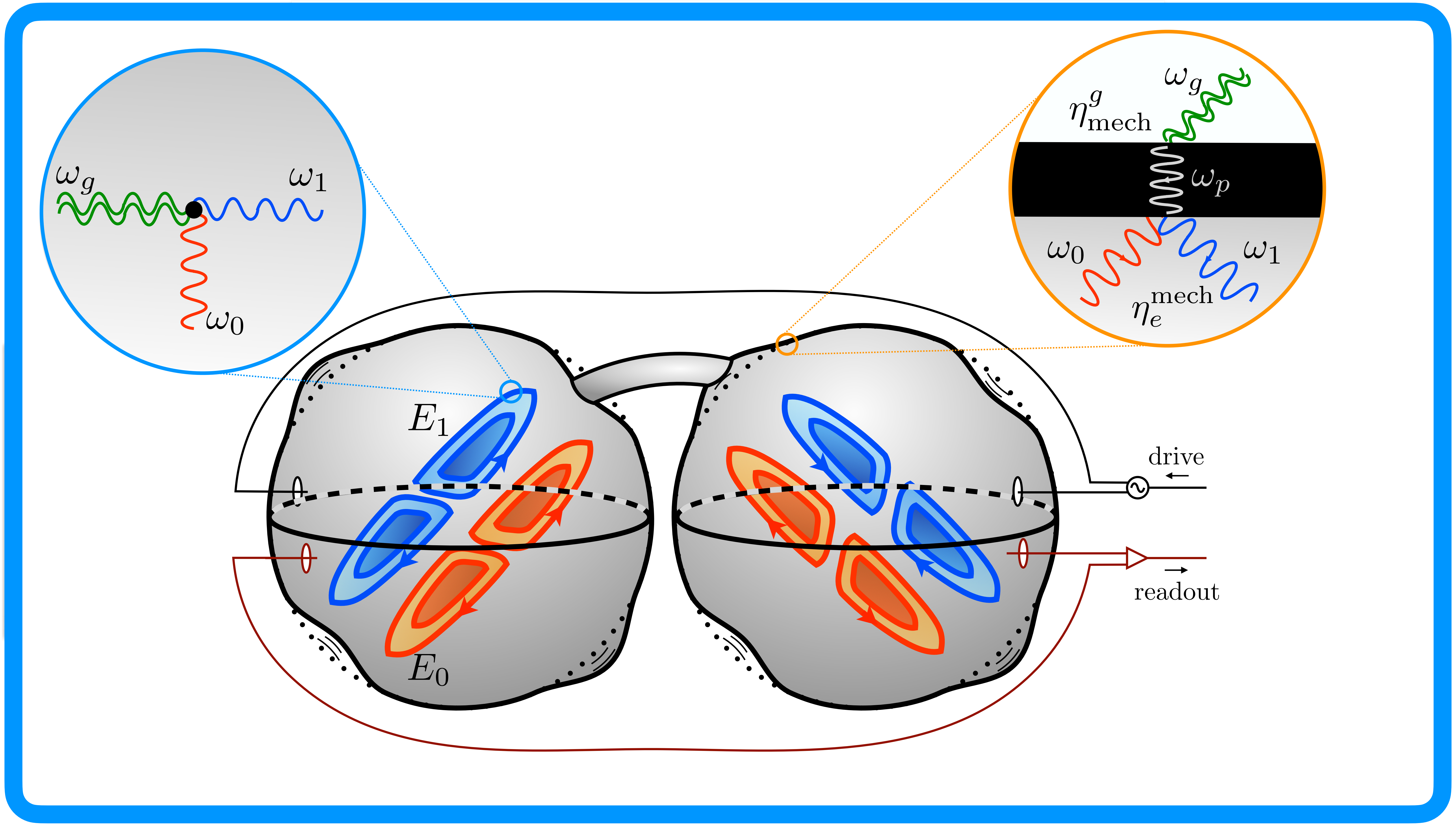
R. Ballantini, A. Chincarini, S. Cuneo, G. Gemme,* R. Parodi, A. Podestà, and R. Vaccarone
INFN and Università degli Studi di Genova, Genova, Italy

Ph. Bernard, S. Calatroni, E. Chiaveri, and R. Losito
CERN, Geneva, Switzerland

R.P. Croce, V. Galdi, V. Pierro, and I.M. Pinto
INFN, Napoli, and Università degli Studi del Sannio, Benevento, Italy

E. Picasso
INFN and Scuola Normale Superiore, Pisa, Italy and
CERN, Geneva, Switzerland

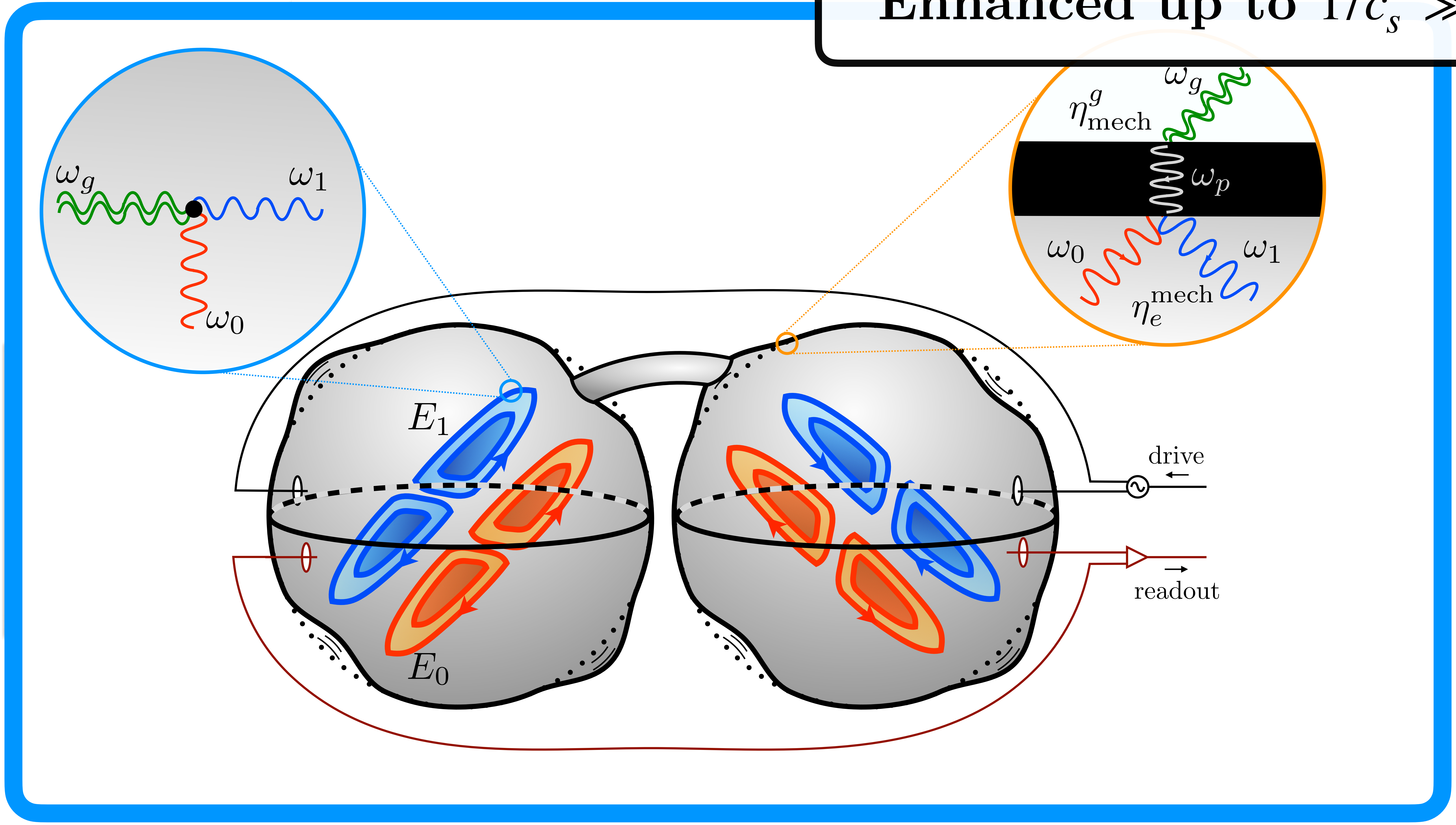
MAGO 2.0: Mechanical and EM Signals



PRD 108 8, 084058
hep-ph/2303.01518
A. Berlin, D. Blas, R. T. D'Agnolo, **SARE,** R. Harnik, Y. Kahn, J. Schütte-Engel, M. Wentzel

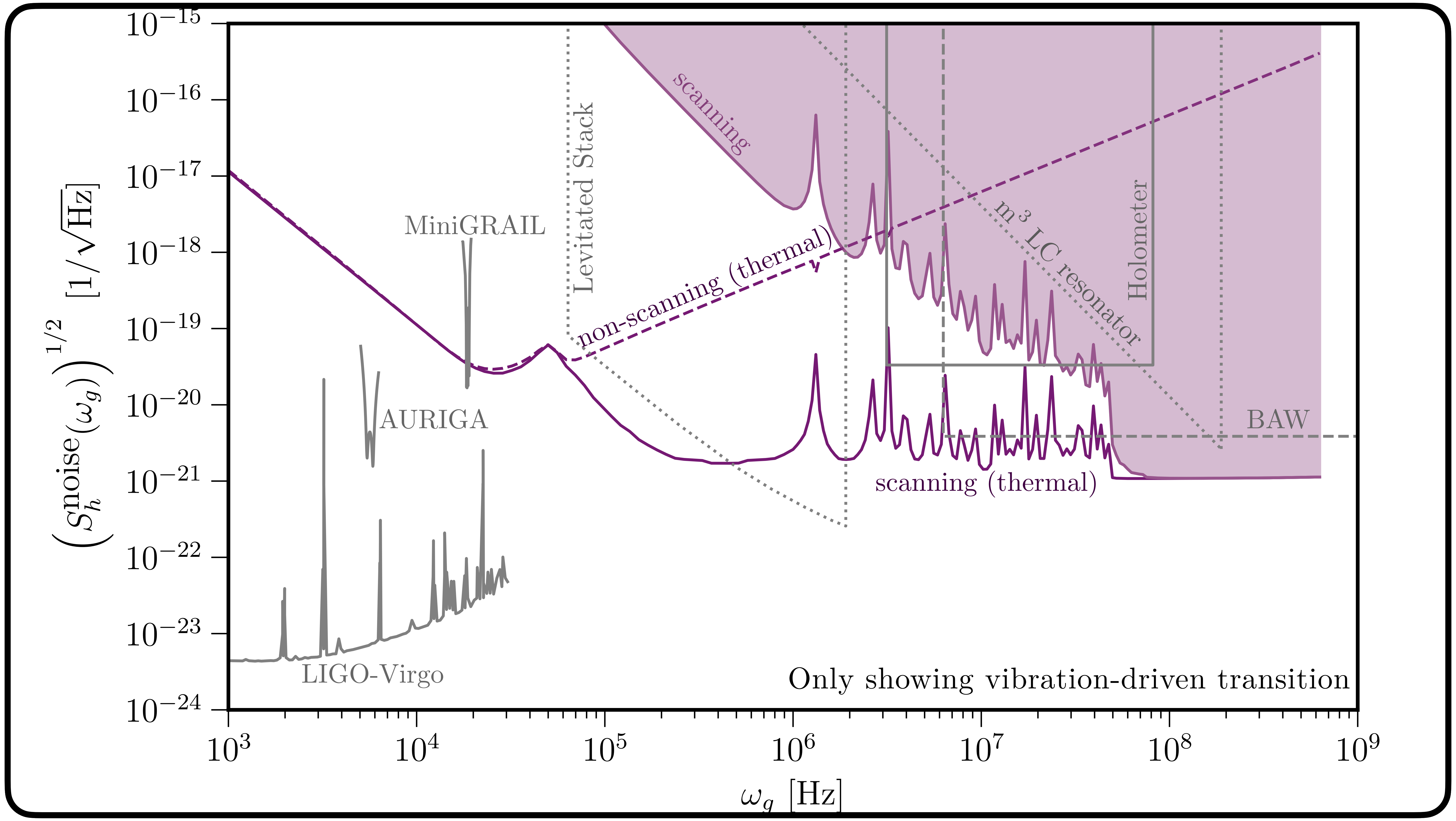
MAGO 2.0: Mechanical and EM Signals

Enhanced up to $1/c_s^2 \gg 1$



PRD 108 8, 084058
hep-ph/2303.01518
A. Berlin, D. Blas, R. T. D'Agnolo, **SARE,** R. Harnik, Y. Kahn, J. Schütte-Engel, M. Wentzel

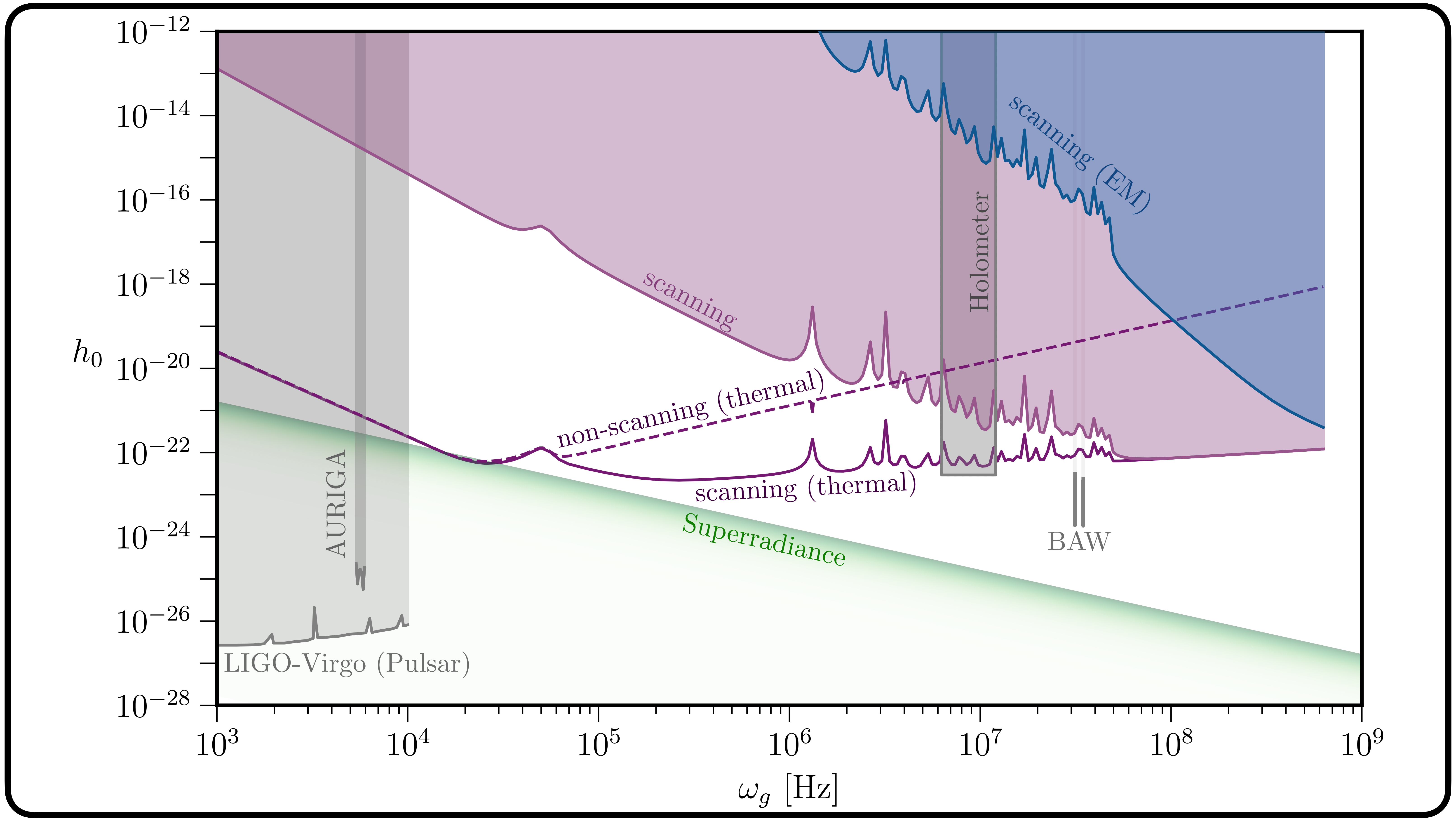
MAGO 2.0



PRD 108 8, 084058
hep-ph/2303.01518
A. Berlin, D. Blas, R. T. D'Agnolo, **SARE,** R. Harnik, Y. Kahn, J. Schütte-Engel, M. Wentzel

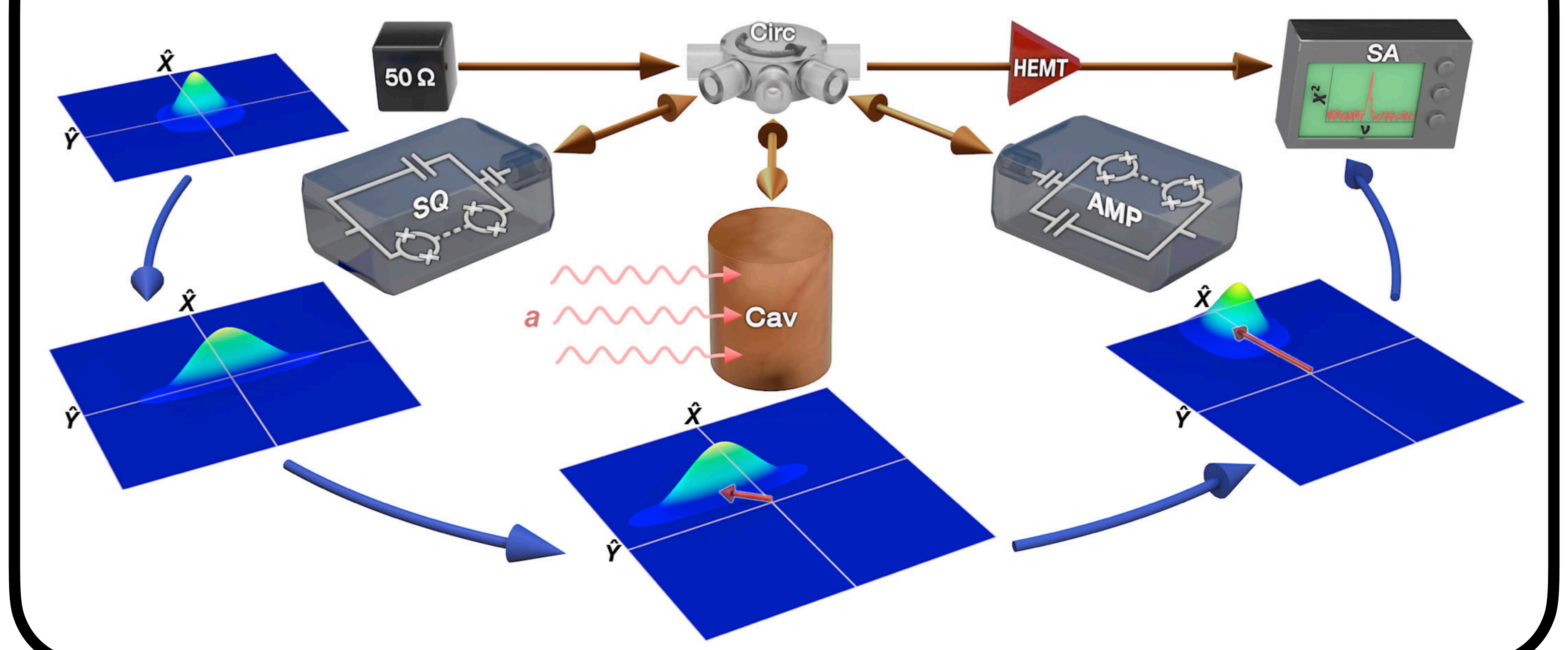
MAGO 2.0 — coherent GWs

$h\,\hat{h}_{\mu\nu}T^{\mu\nu}$



PRD 108 8, 084058
hep-ph/2303.01518
A. Berlin, D. Blas, R. T. D'Agnolo, **SARE,** R. Harnik, Y. Kahn, J. Schütte-Engel, M. Wentzel

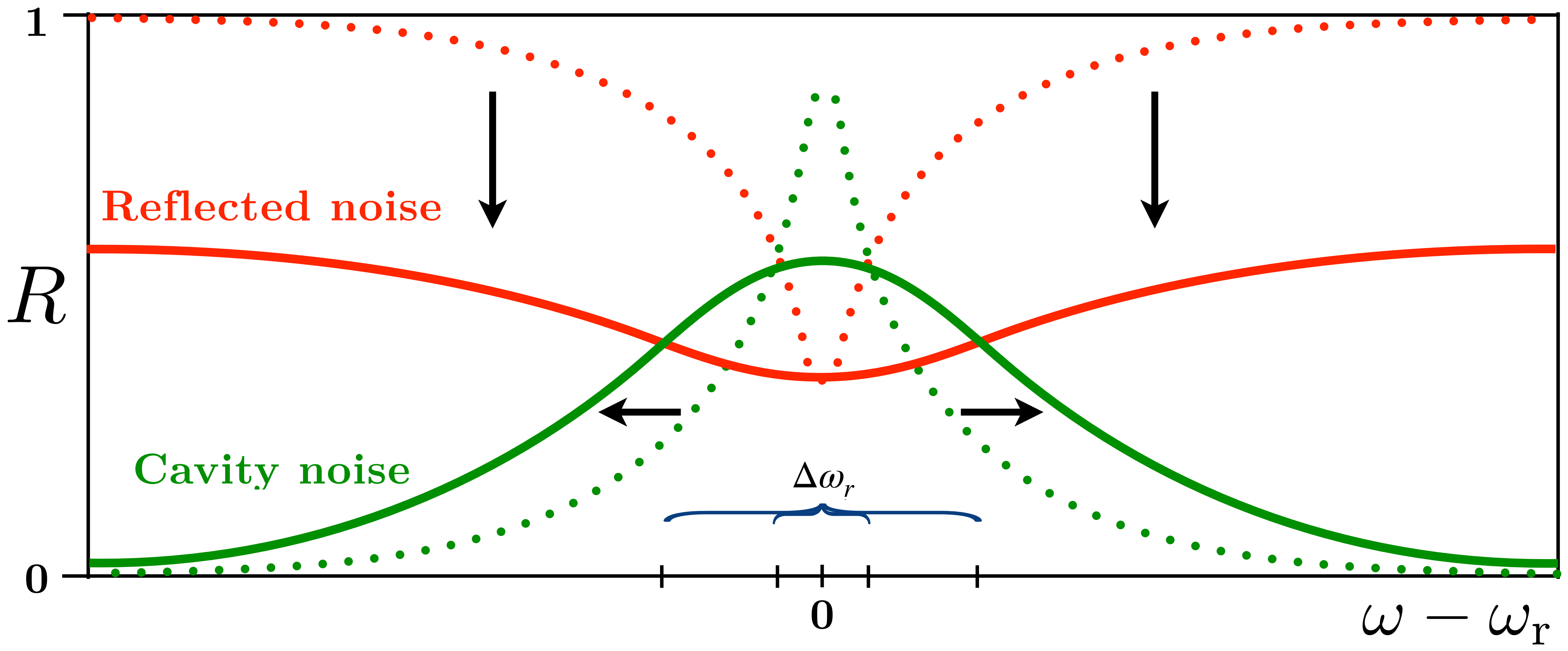
Quantum, Ubi Est?



HAYSTAC:
Nature ***590***, *238*
quant-ph/2008.01853

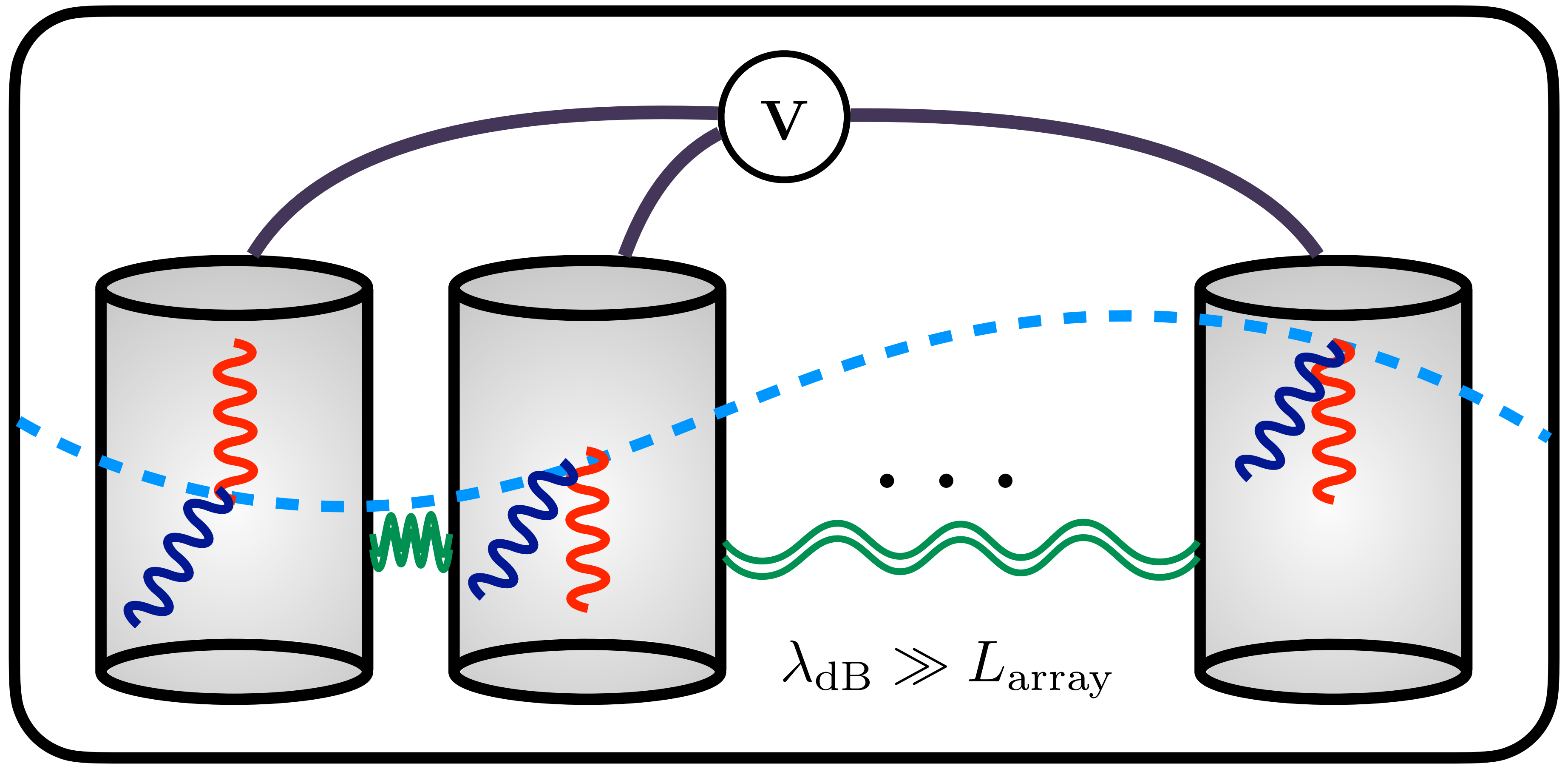
Technique already in use elsewhere, ***applicable to heterodyne approach***

"Squeeze the Vacuum"



Increases scan rate $\mathcal{R}$

Quantum, Ubi Est?



$$\lambda_{\rm dB} \sim R_\oplus \left(\frac{10^{-13}\,{\rm eV}}{m_a}\right)$$

Increases scan rate $\mathcal{R}$

See e.g. Brady et al
***PRX Quantum* 3*, 030333 (2022)*
quant-ph/2203.05375

Entangle the Sensors

Usual scaling with $N_{\rm det}$: $\quad {\rm SNR} \propto \sqrt{N_{\rm det}}$

$$g_{a\gamma\gamma} \propto 1/(N_{\rm det})^{1/4}$$

Entangled sensors w/ squeezed vacuum: $\quad {\rm SNR} \propto N_{\rm det}$

"Heisenberg Limit"

$$g_{a\gamma\gamma} \propto 1/\sqrt{N_{\rm det}}$$

Giovanetti, Lloyd & Maccone
*Science **306**, 1330 (2004)*