Accelerator Technology Meets Quantum Sensing

Sebastian A. R. Ellis

University of Geneva

What is Quantum Sensing?

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Quantum Sensors:

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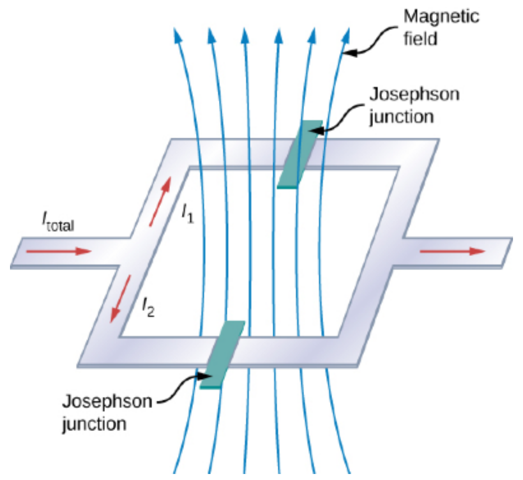
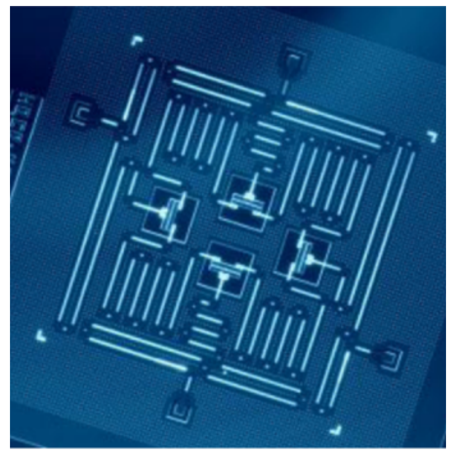
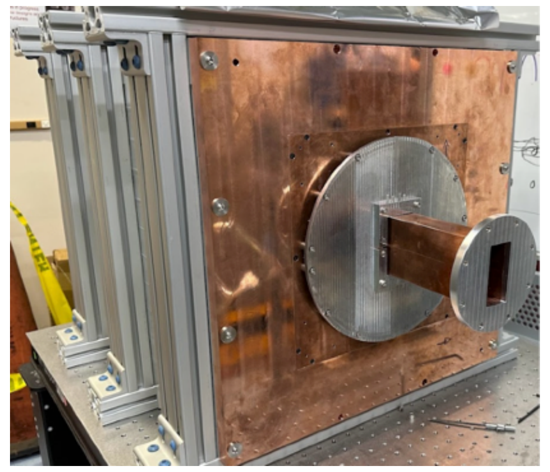


SQUID

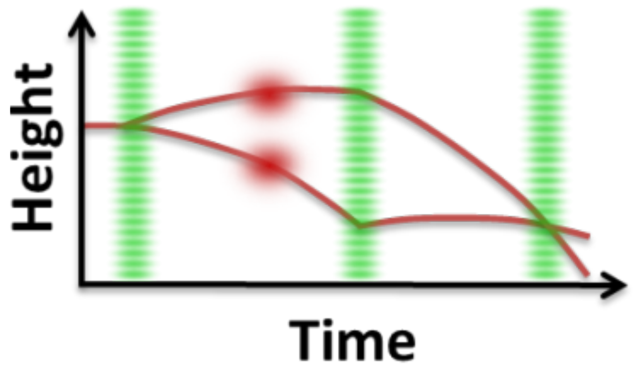


Qubit

Sichanugrist, Wednesday

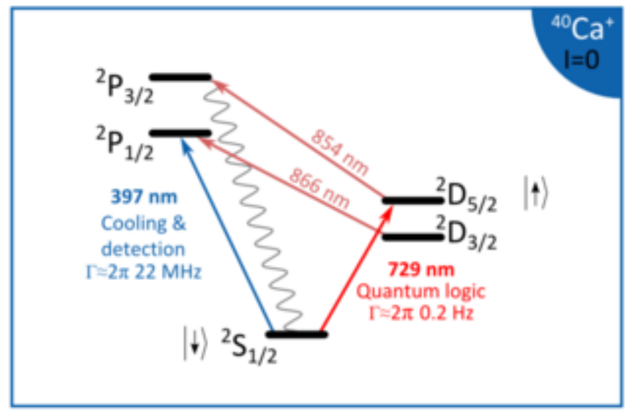


Cavity

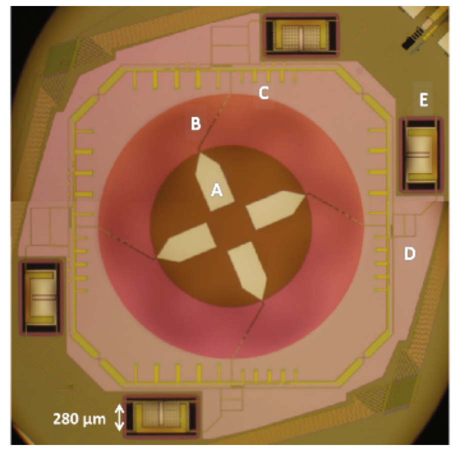


Atom Interf.

Elder, Tuesday

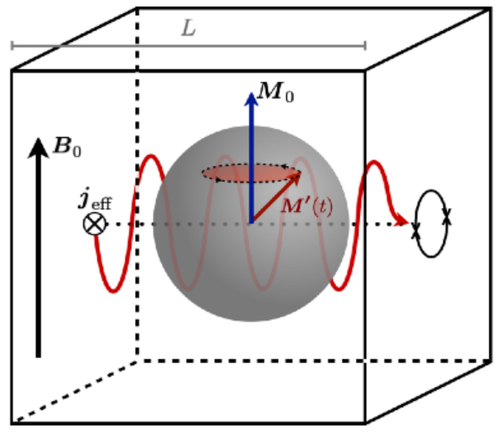


Atomic Clock



TES

Cosmo/Astro telescopes



NMR

What is Quantum Sensing?

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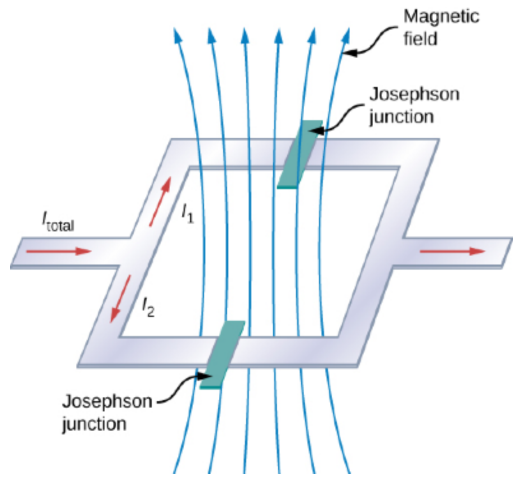

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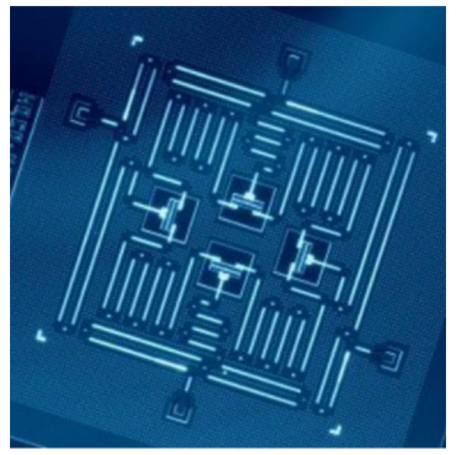

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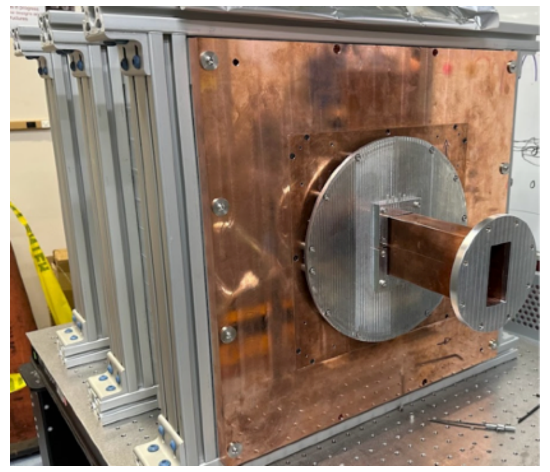

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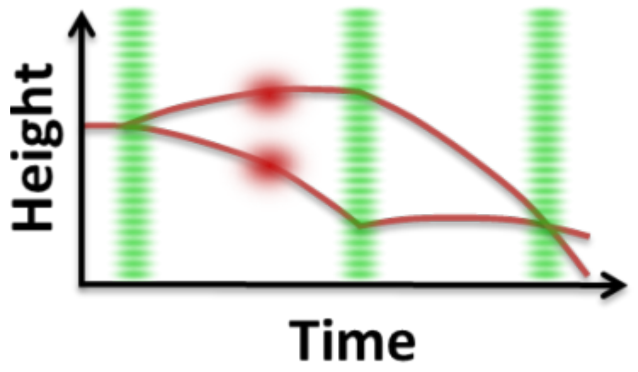

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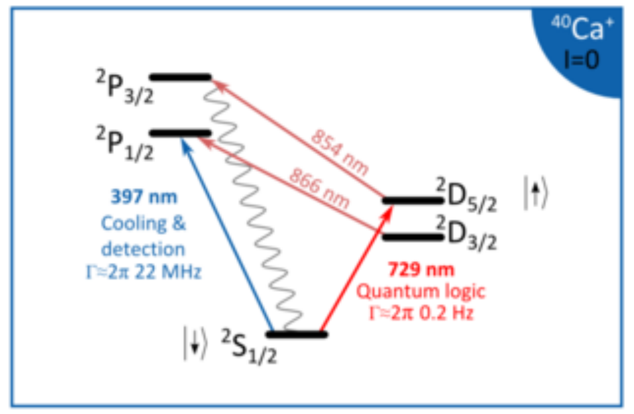

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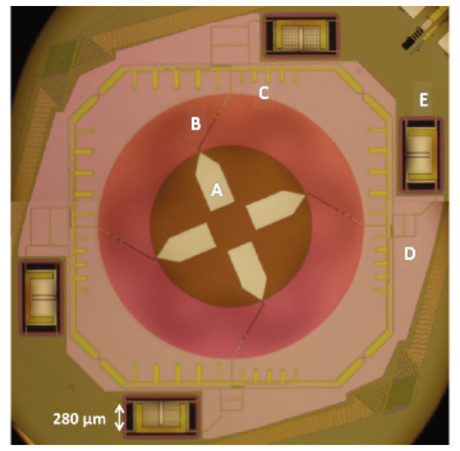

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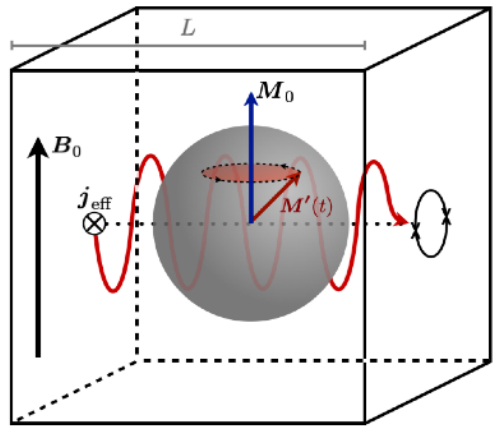

NMR

And more, w/ applications summarised in:

Quantum Sensing for Fundamental Physics

A. Chou et al, hep-ex/2311.01930

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

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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

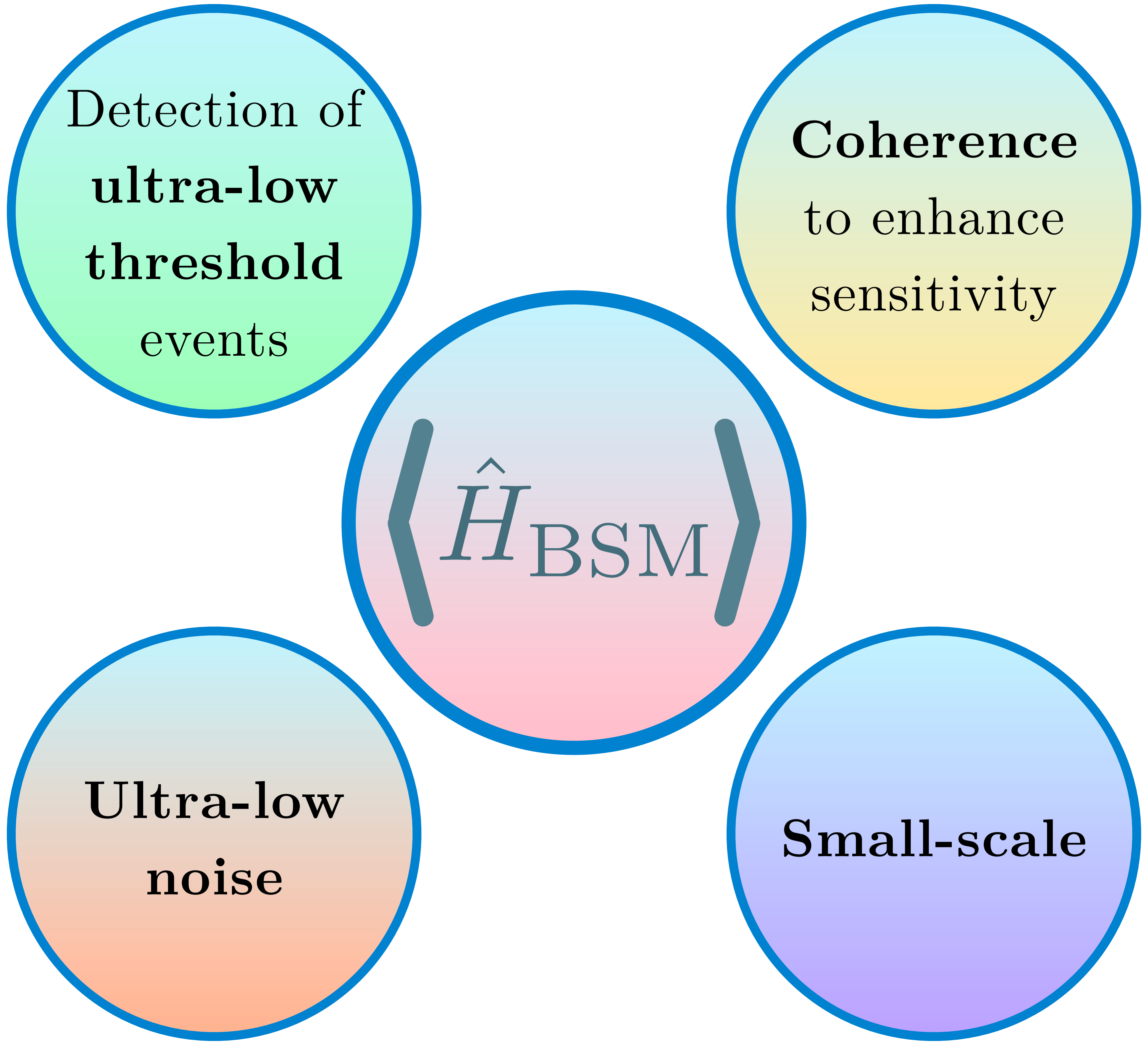
Quantum Sensing Needs

$$\left\langle \hat{H}_{\mathrm{BSM}} \right\rangle$$

Resonant cavities

Accelerator Technology In the Quantum Age

Quantum Sensing Needs



Resonant cavities

Accelerator Technology In the Quantum Age

Quantum Sensing Needs

Detection of **ultra-low threshold** events

Coherence to enhance sensitivity

$\langle \hat{H}_{\mathrm{BSM}} \rangle$

Ultra-low noise

Small-scale

Resonant cavities

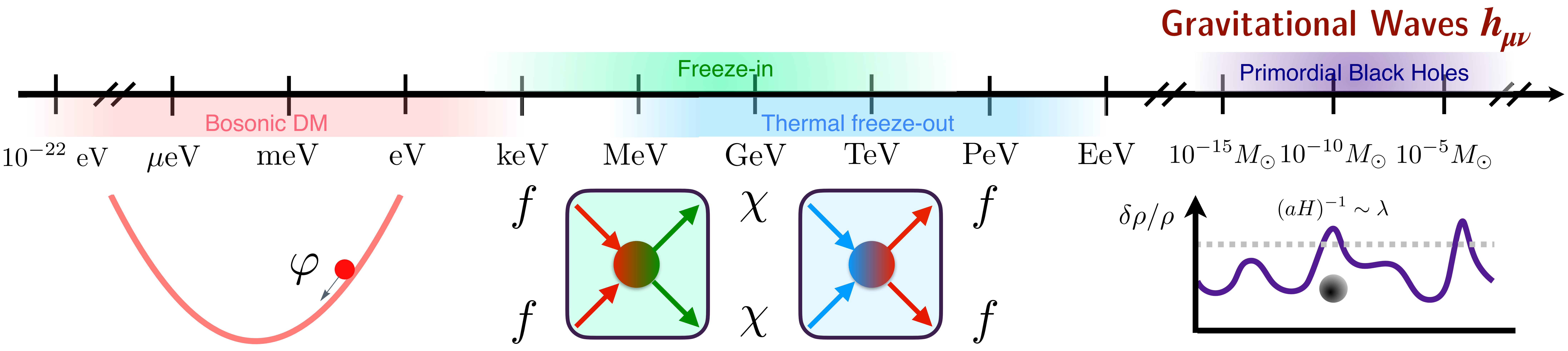
Large/ coherent background EM fields

Large $\boldsymbol{Q}$ means **long coherence**

Low noise

Fits on a table*

The Dark Matter Bestiary



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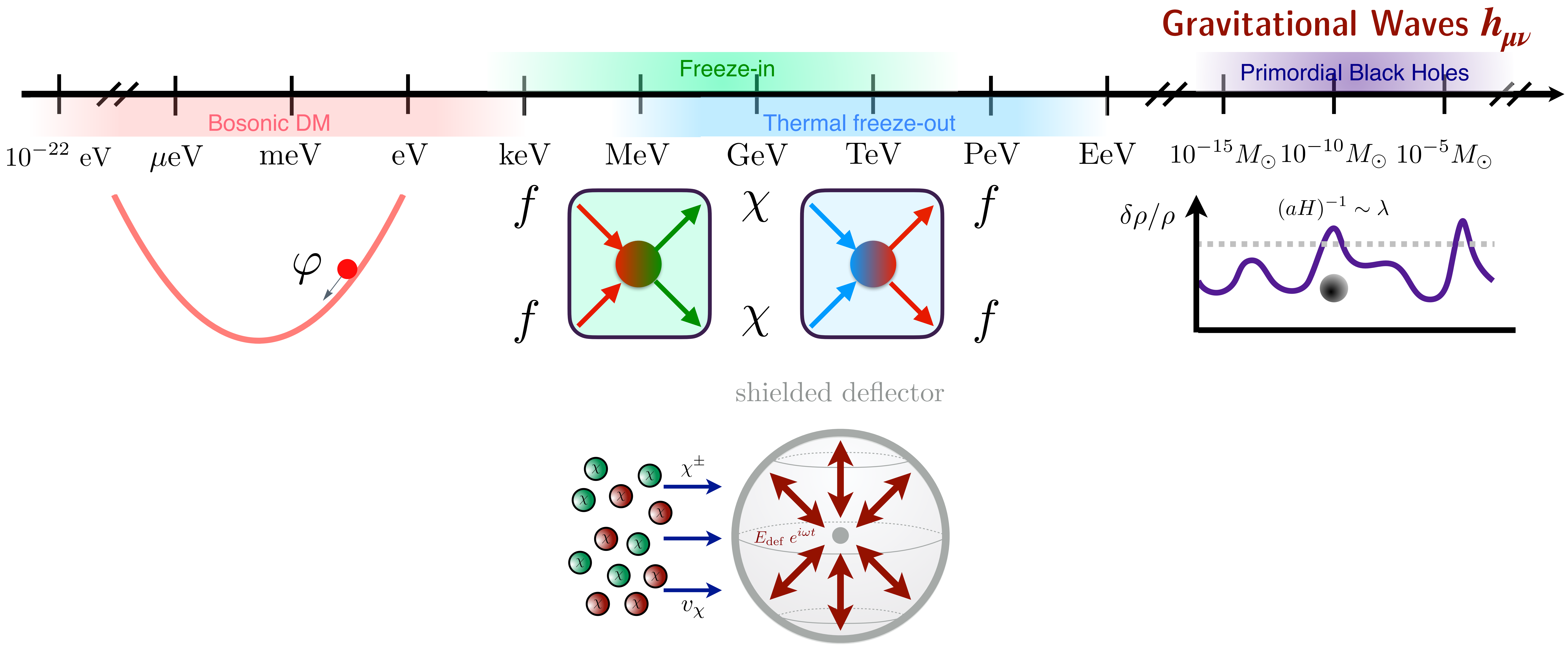
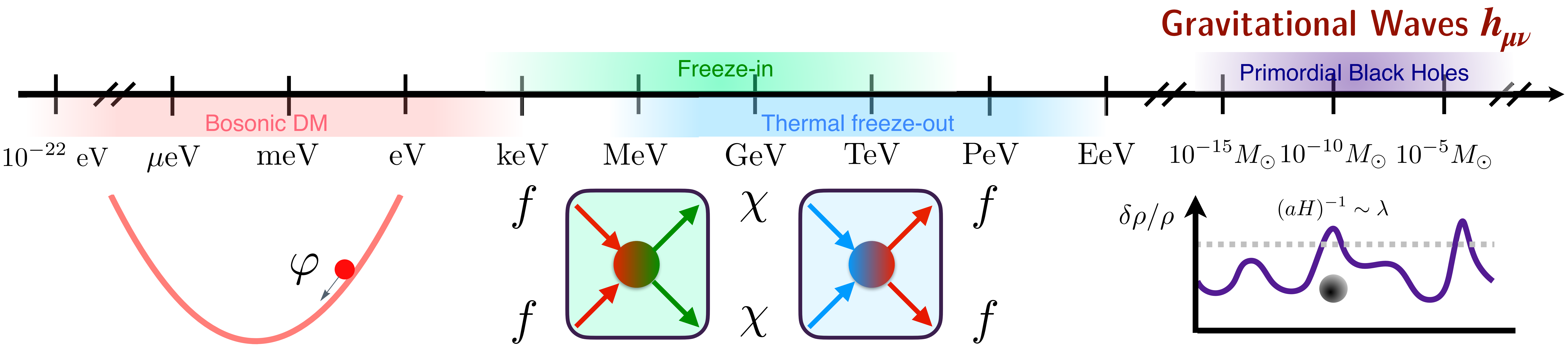
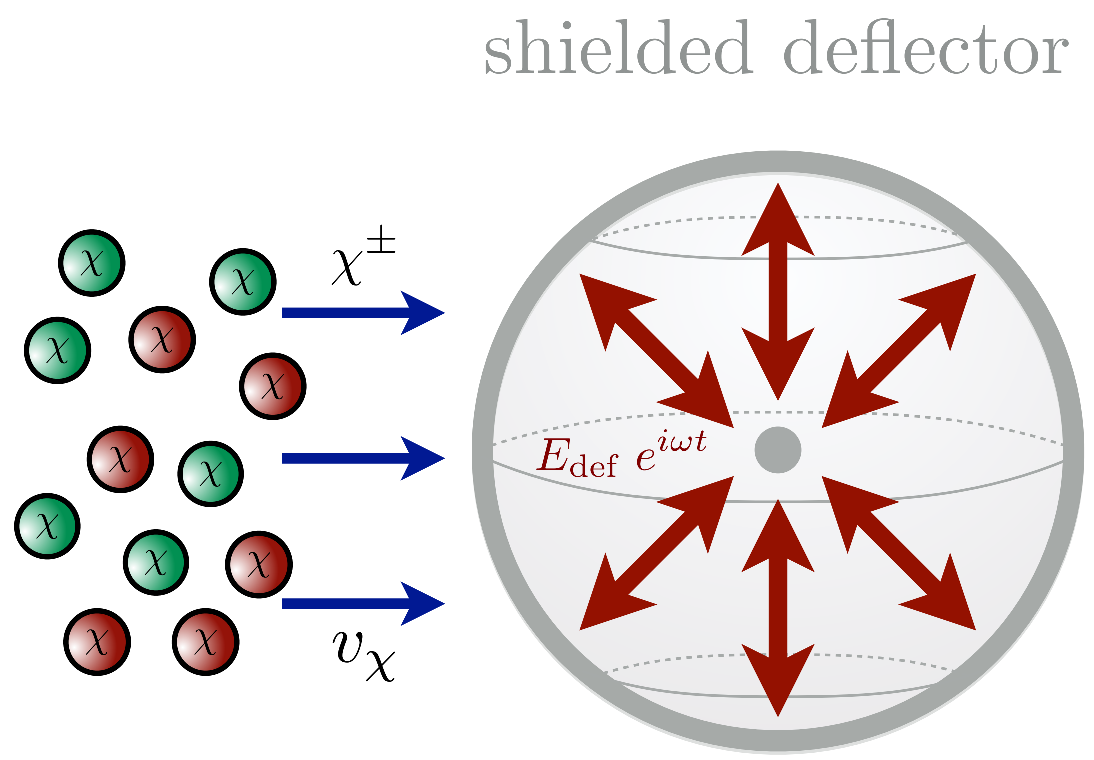


Variations in χ, χ minor

The Dark Matter Bestiary



Variation in $\boldsymbol{a}$



Variations in χ, χ minor

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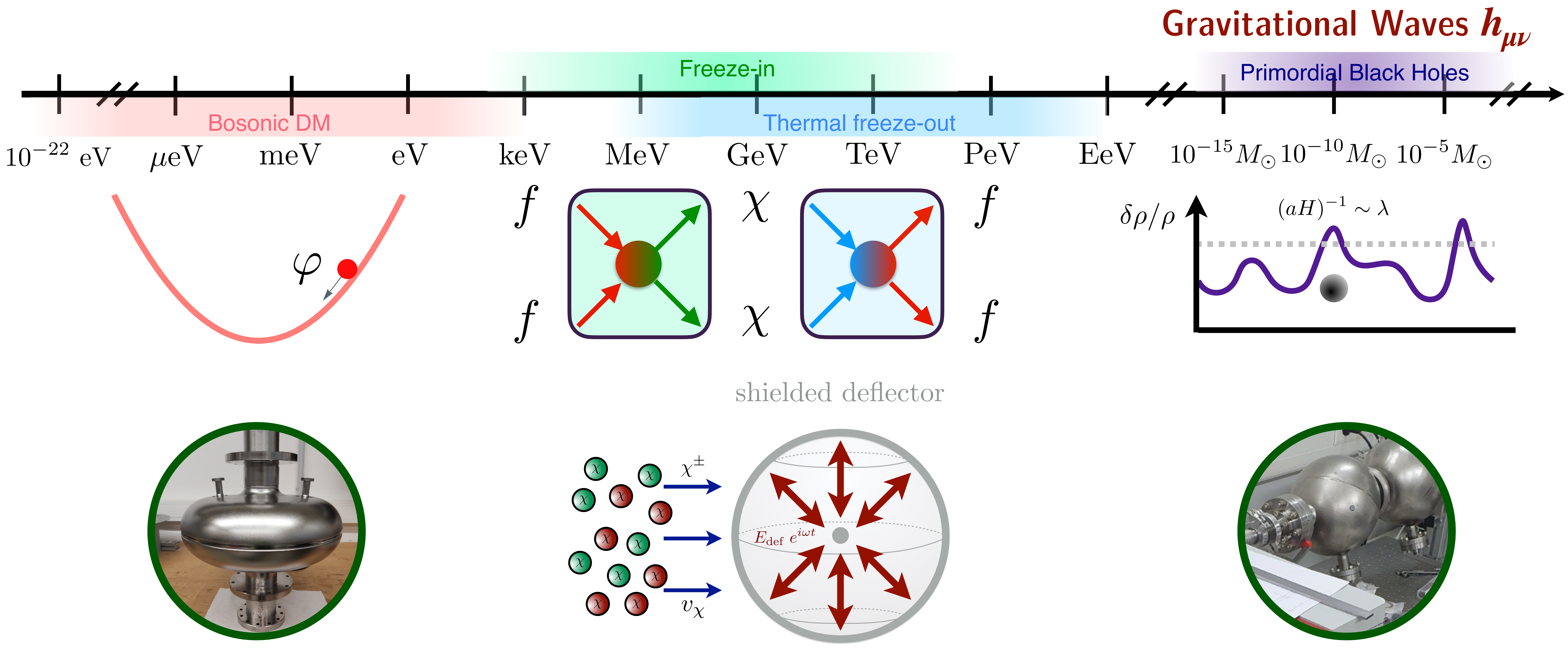
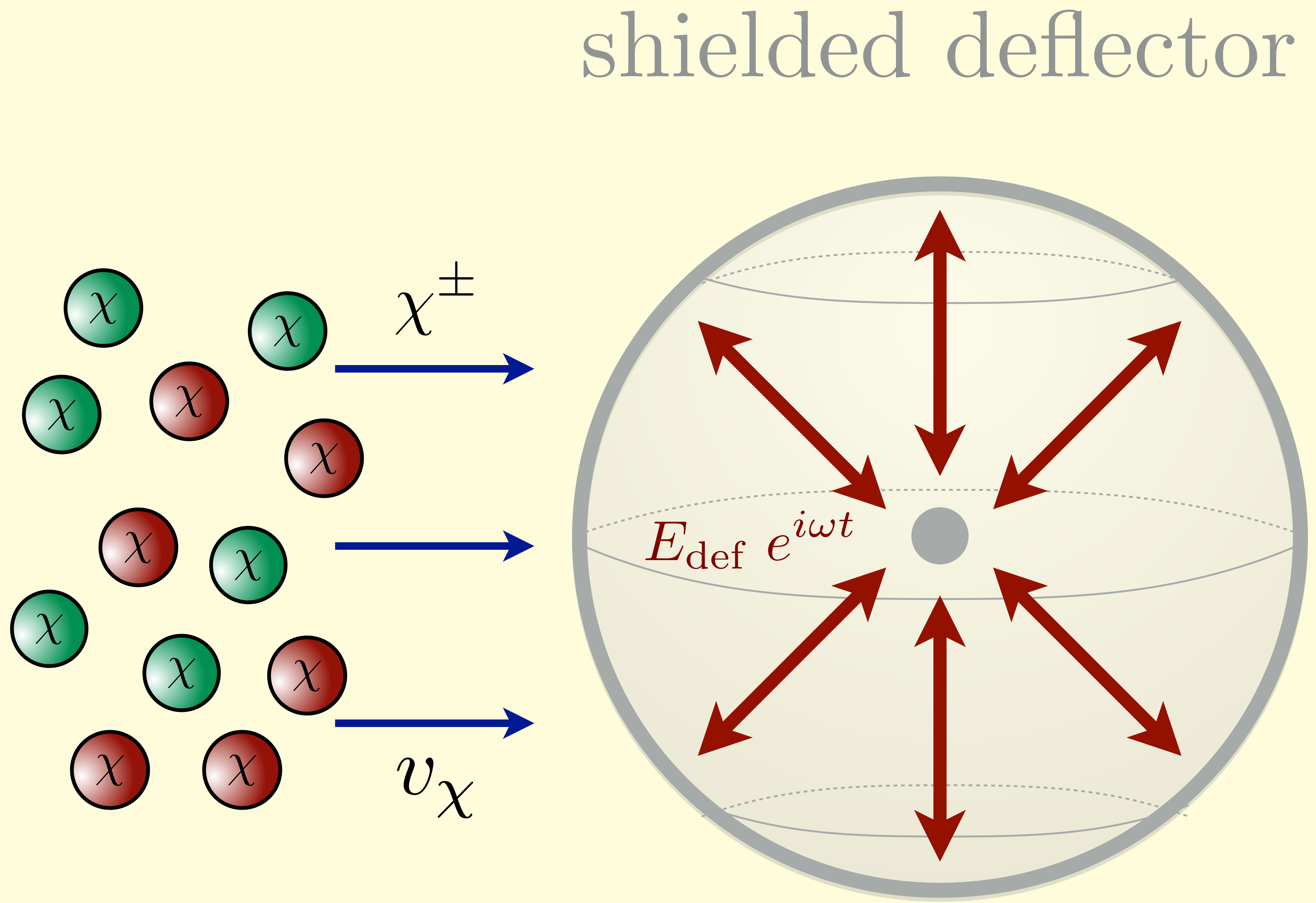


Variation in a

Variations in χ, χ minor

Variation in $h_{\mu\nu}$

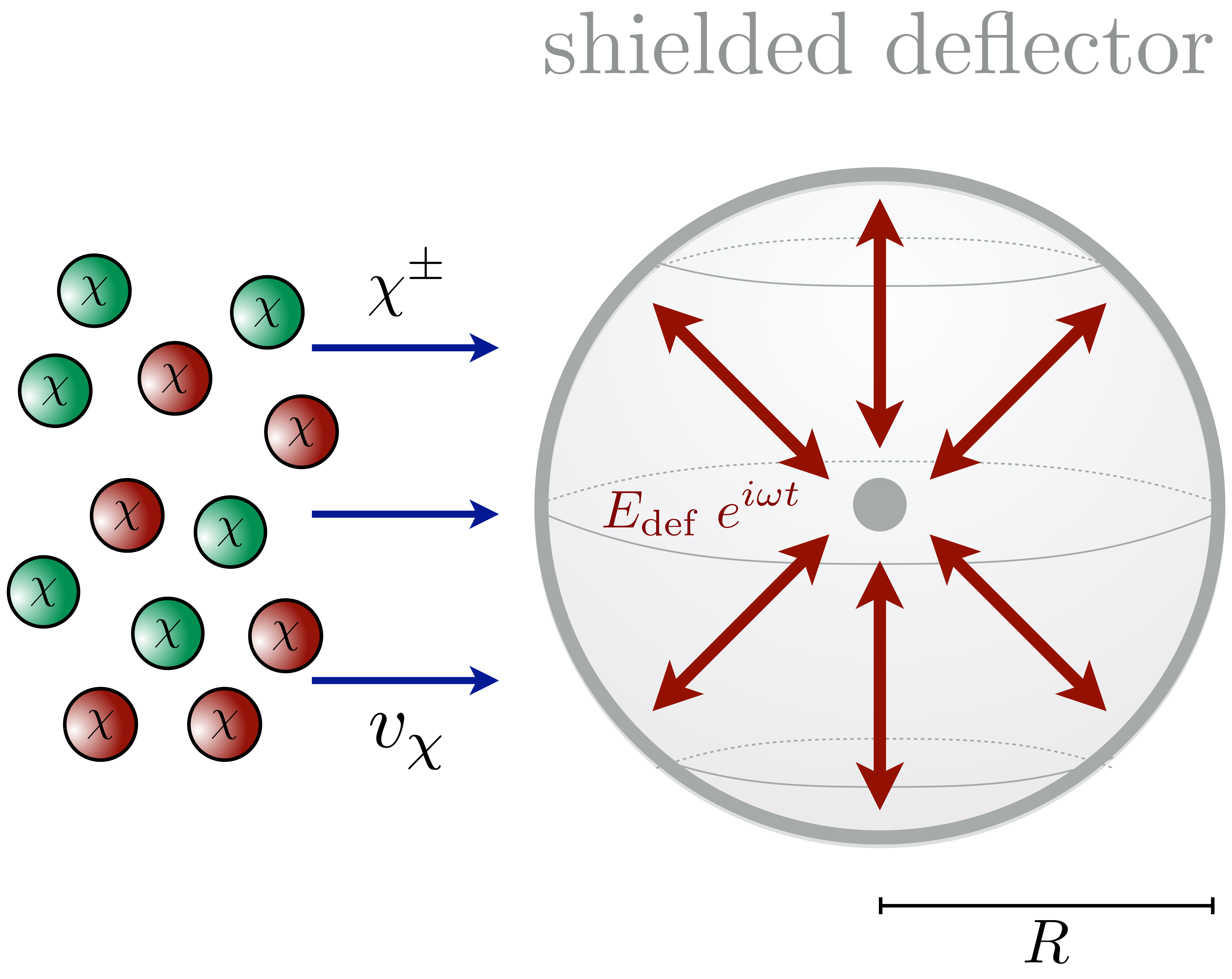
Variation in χ



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!

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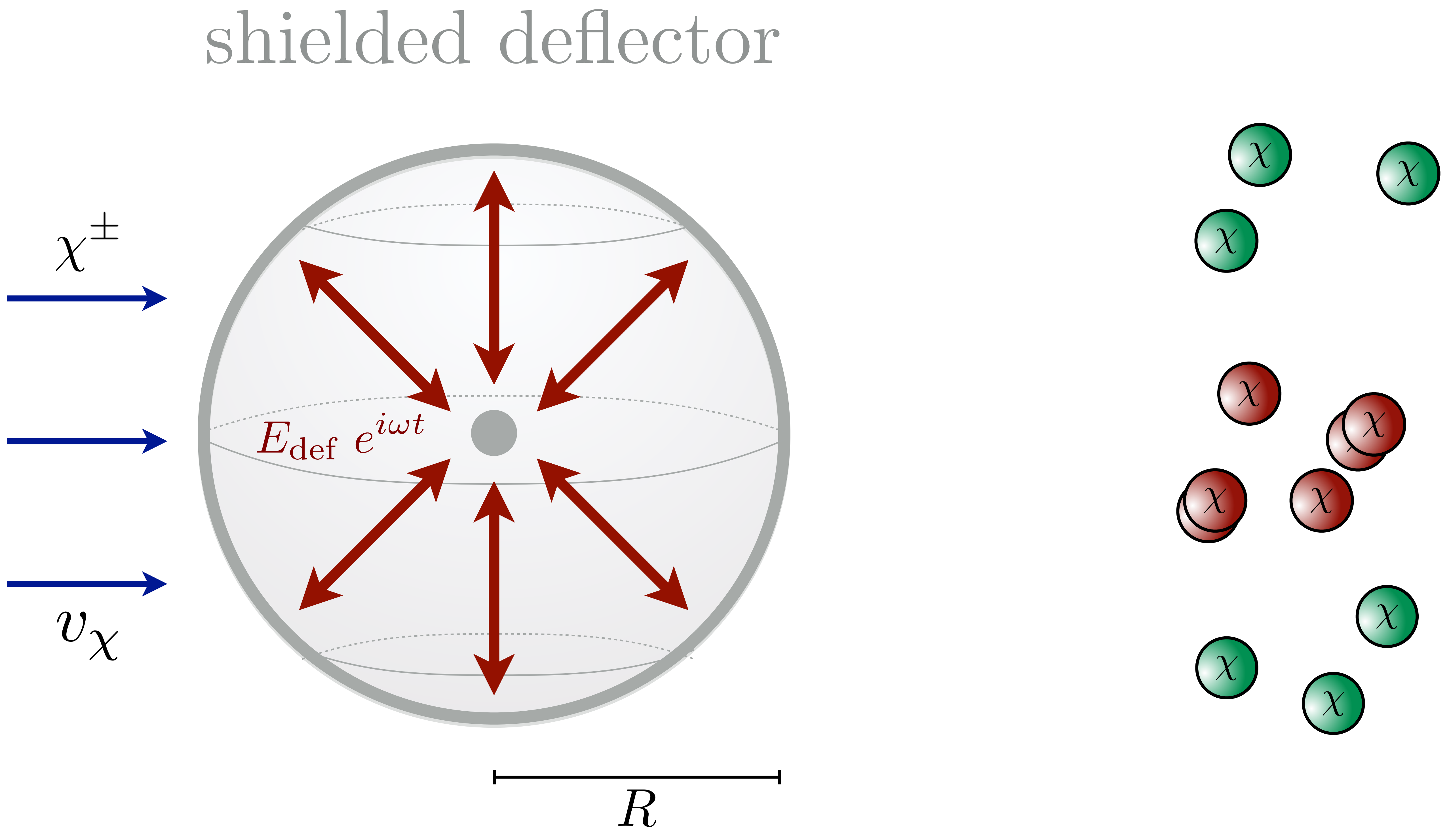

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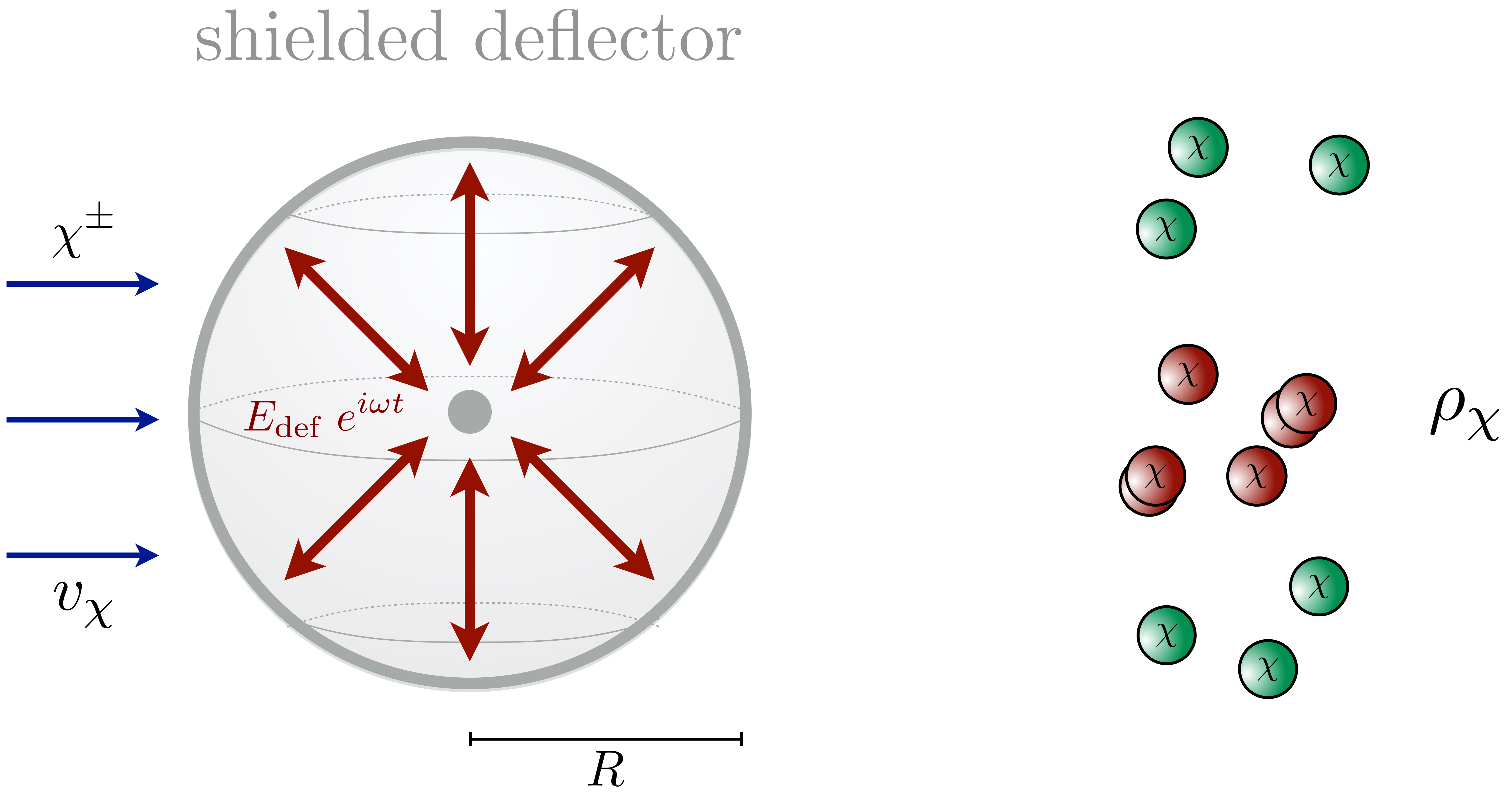

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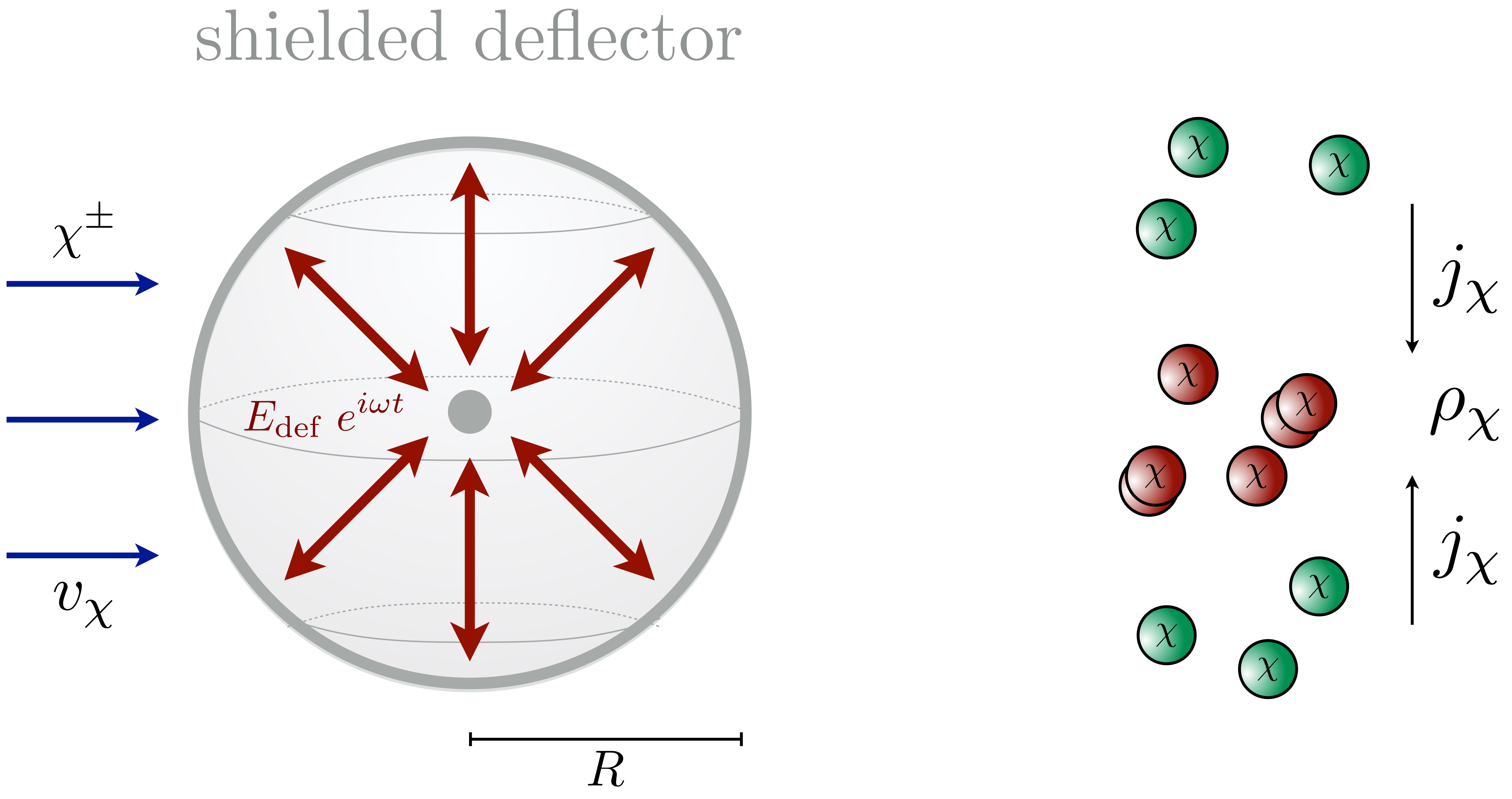

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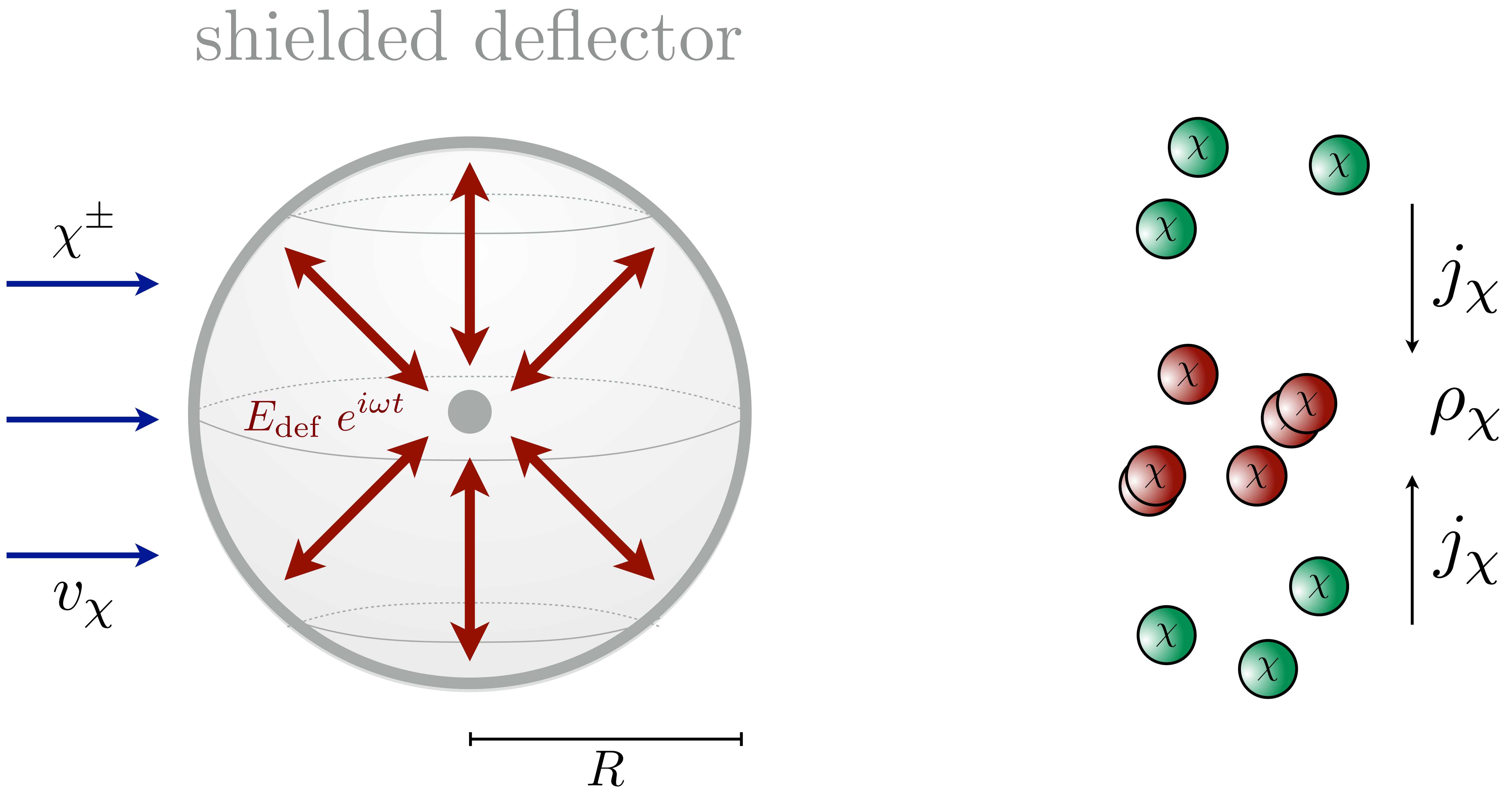
Accelerator for Millicharged DM: $\beta \sim 10^{-3}$

Think magnetic horn (only electric)



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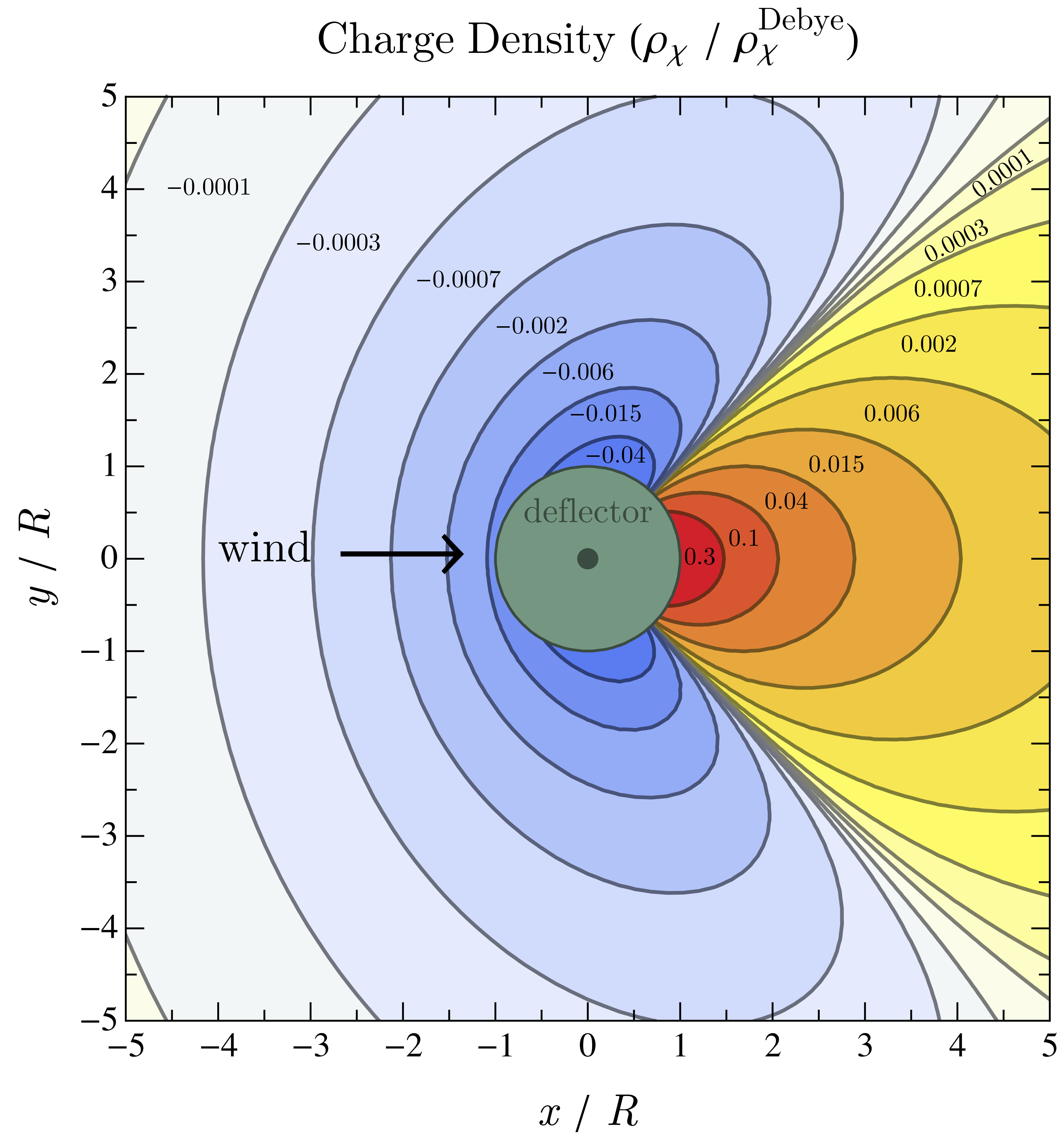
quasi-static limit!

Millicharged DM Waves

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

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



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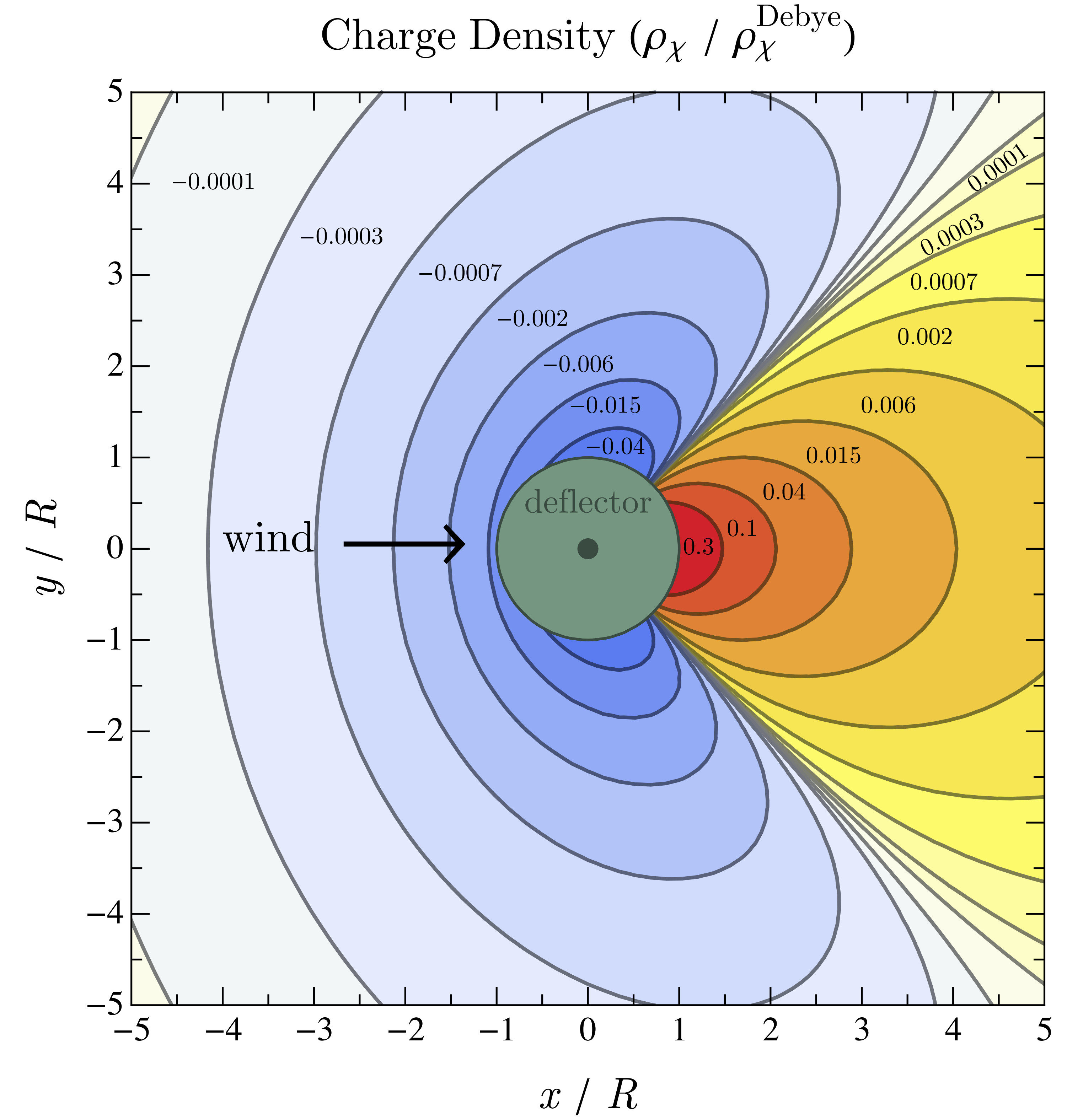

Detecting them?

Millicharged DM Waves

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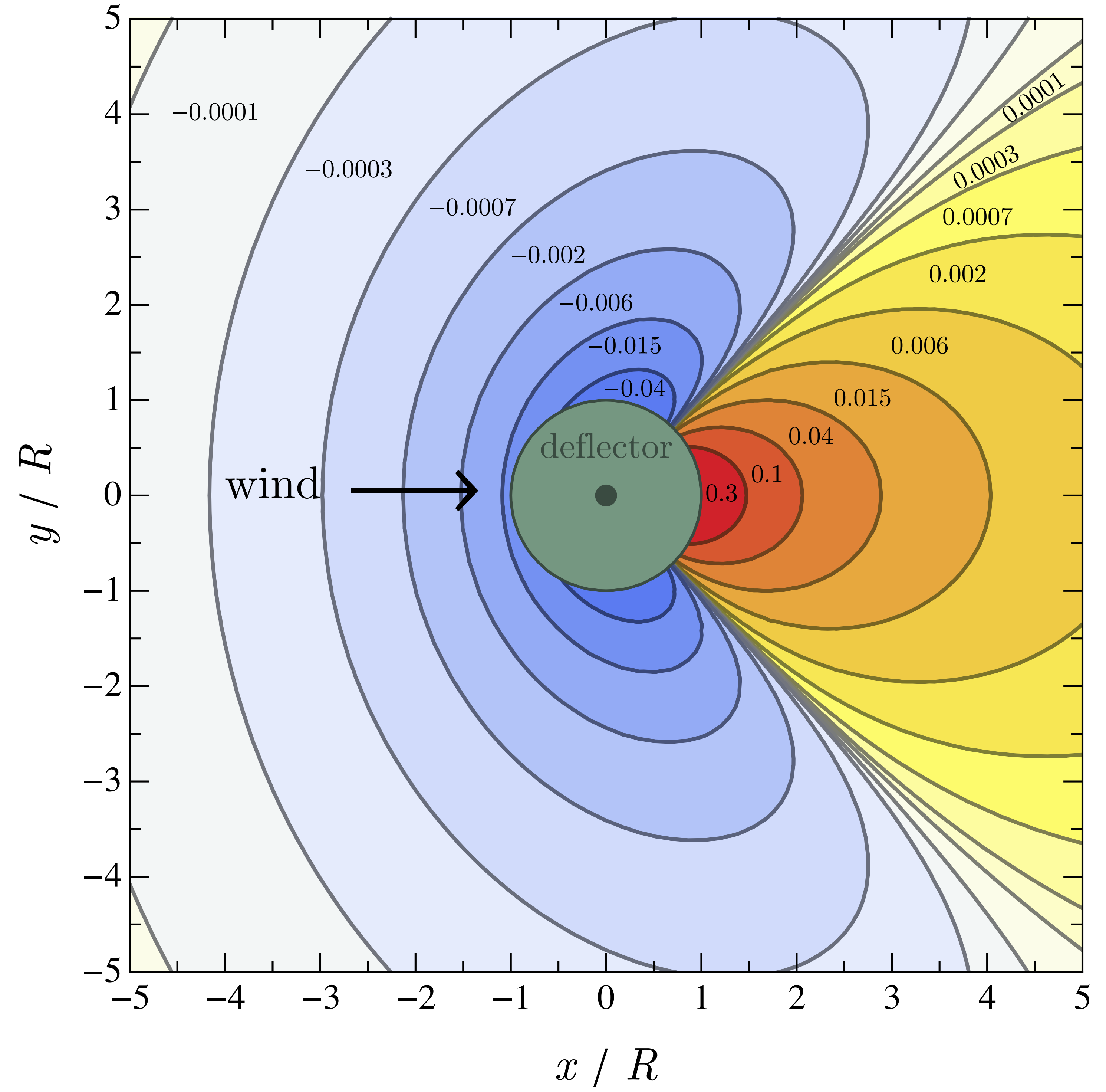
Charge Density (ρ_χ / ρ_χ^{Debye})



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Since E-field signal dominant, capacitative pickup optimal

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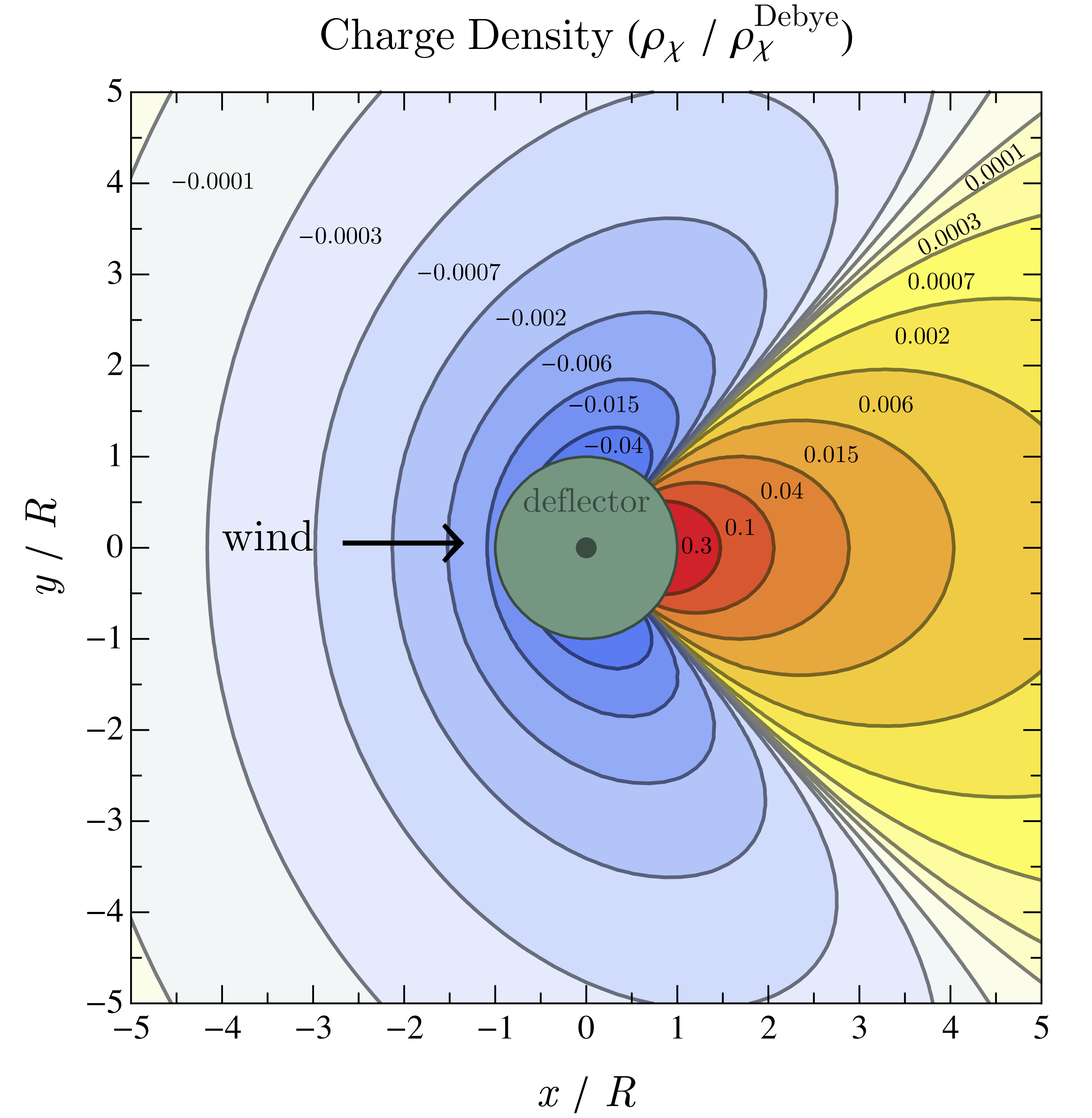

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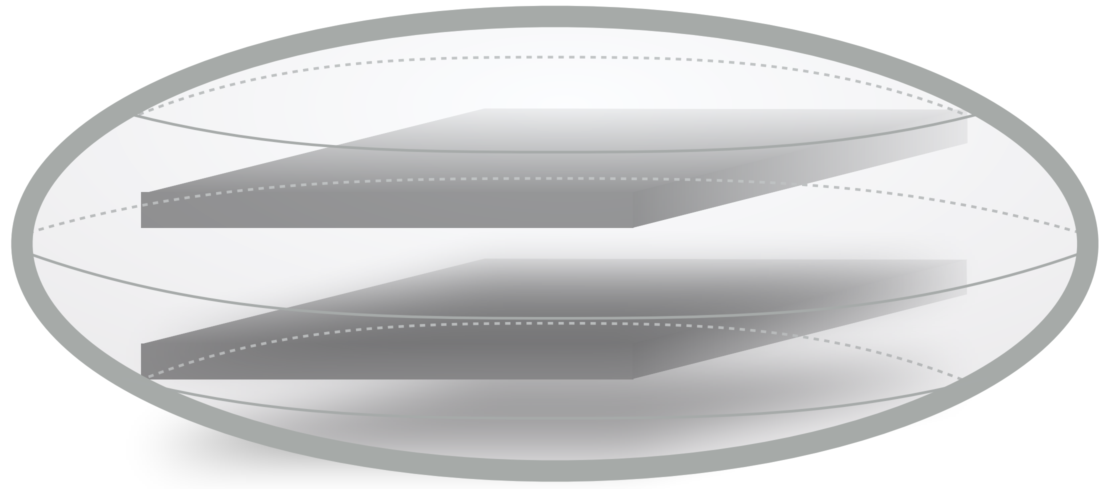

$$U_{\rm s} = \int_V \frac{1}{2} \epsilon \mathbf{E}^2$$

Effective volume of capacitor/antenna — bounded by shielded volume

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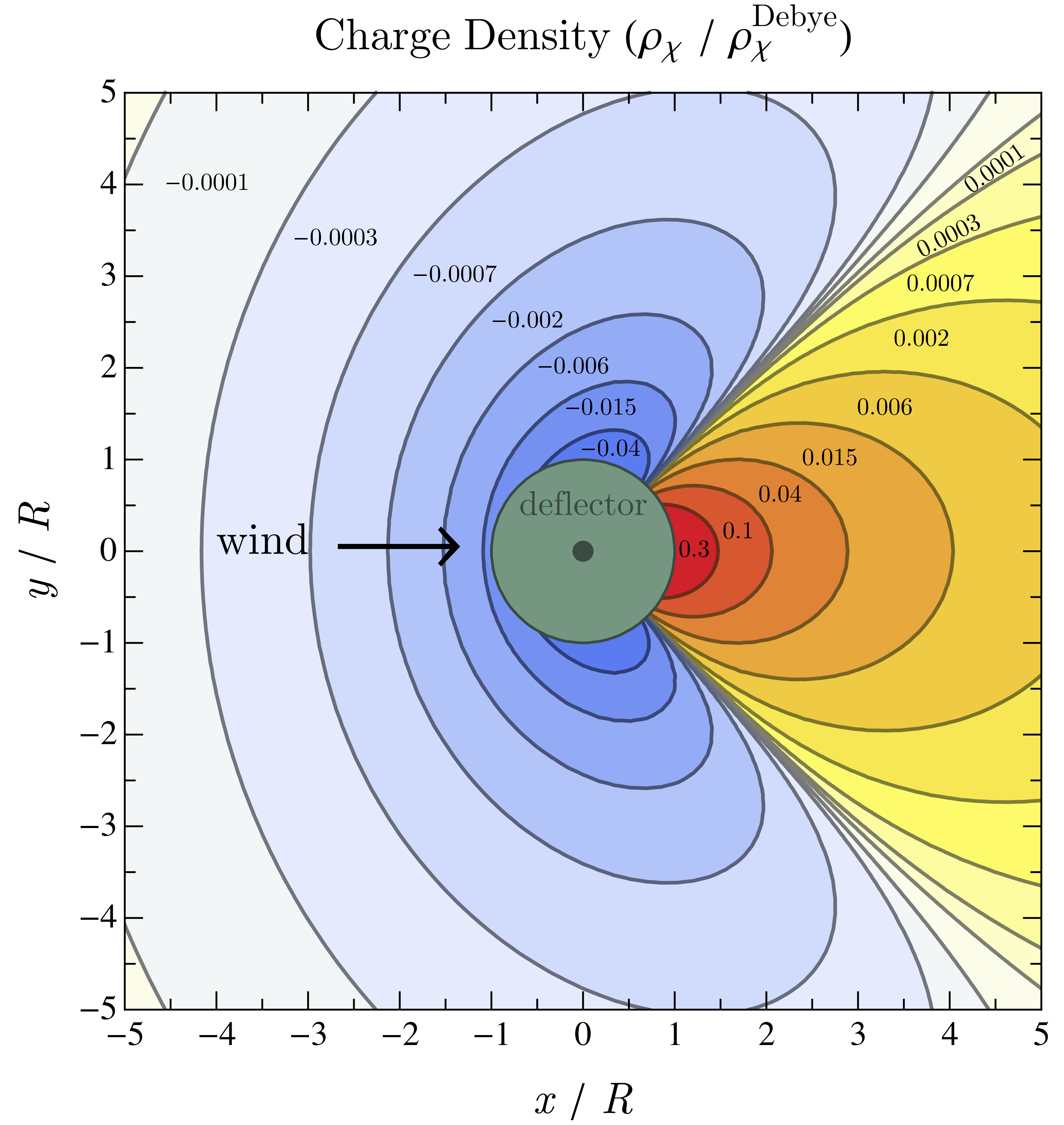

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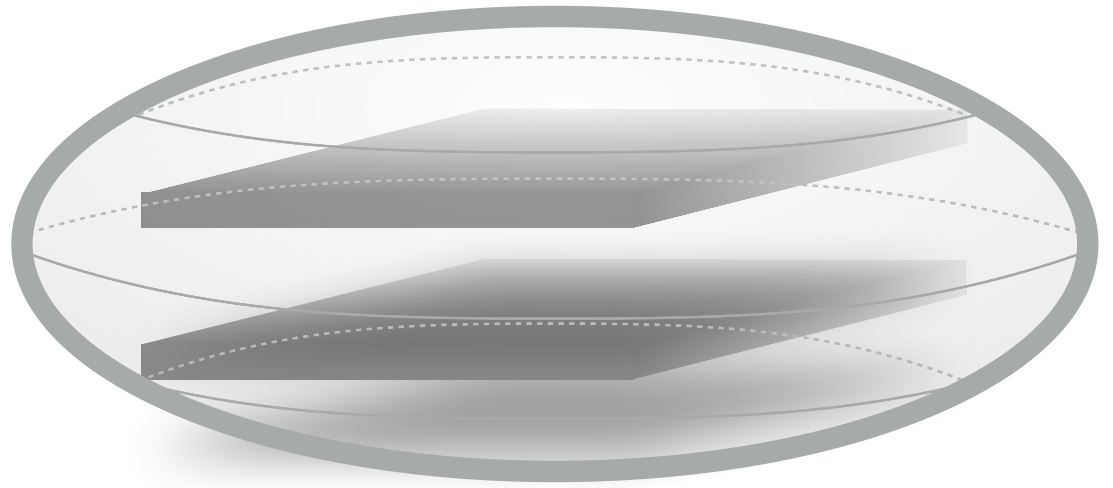
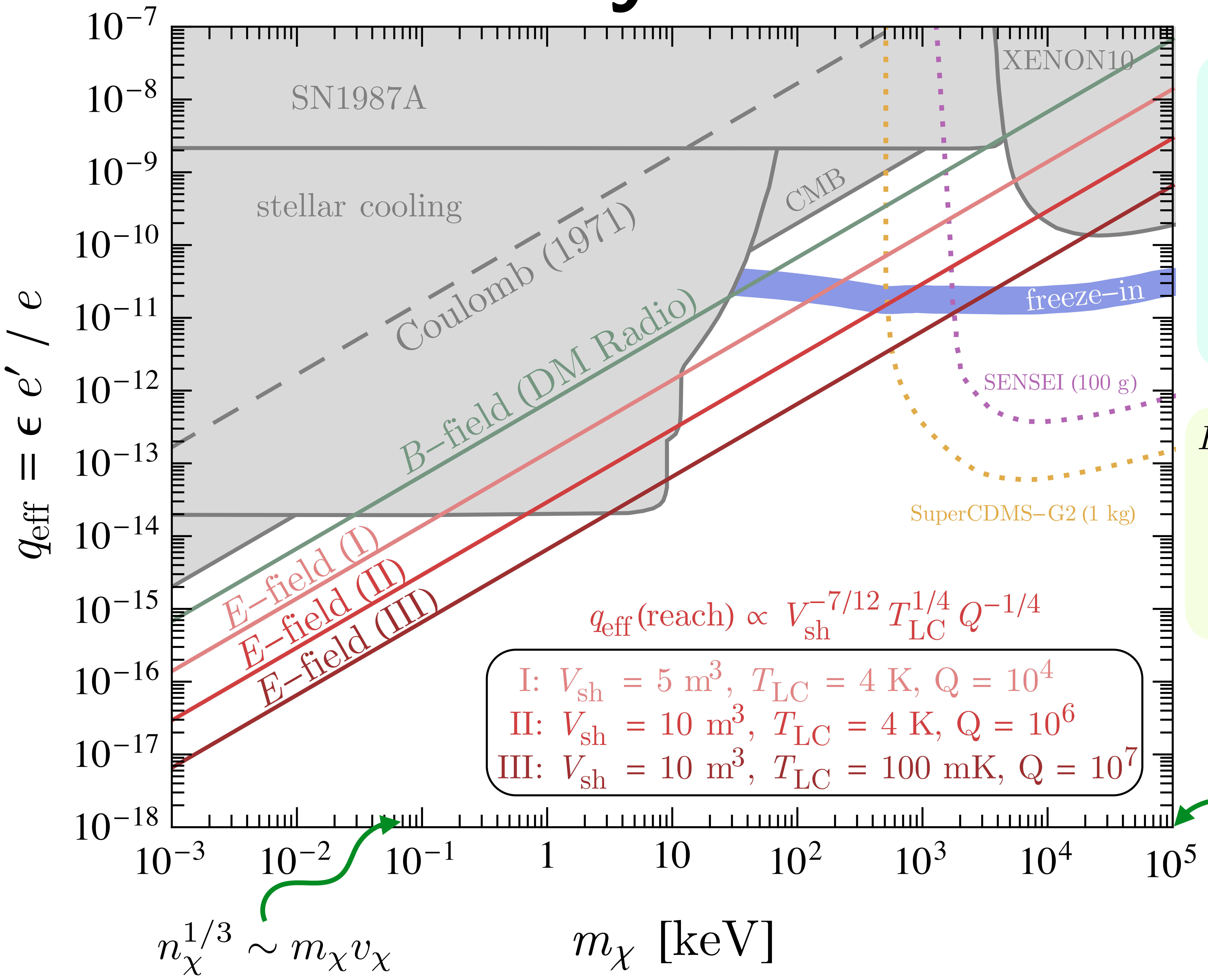


$$U_s = \int_V \frac{1}{2}\epsilon \mathbf{E}^2$$

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

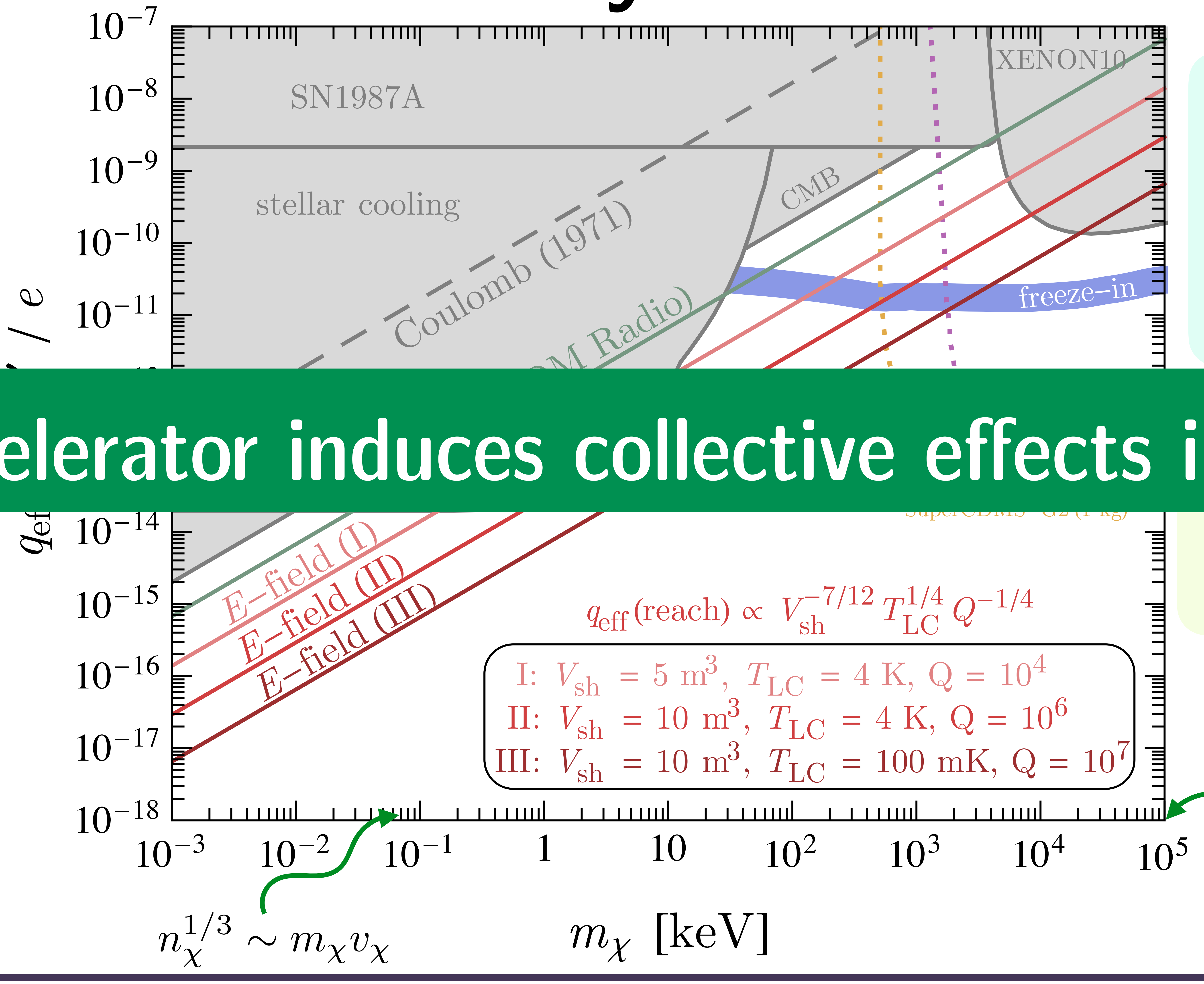
$\omega = 100$ kHz

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

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

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

Experimental Sensitivity



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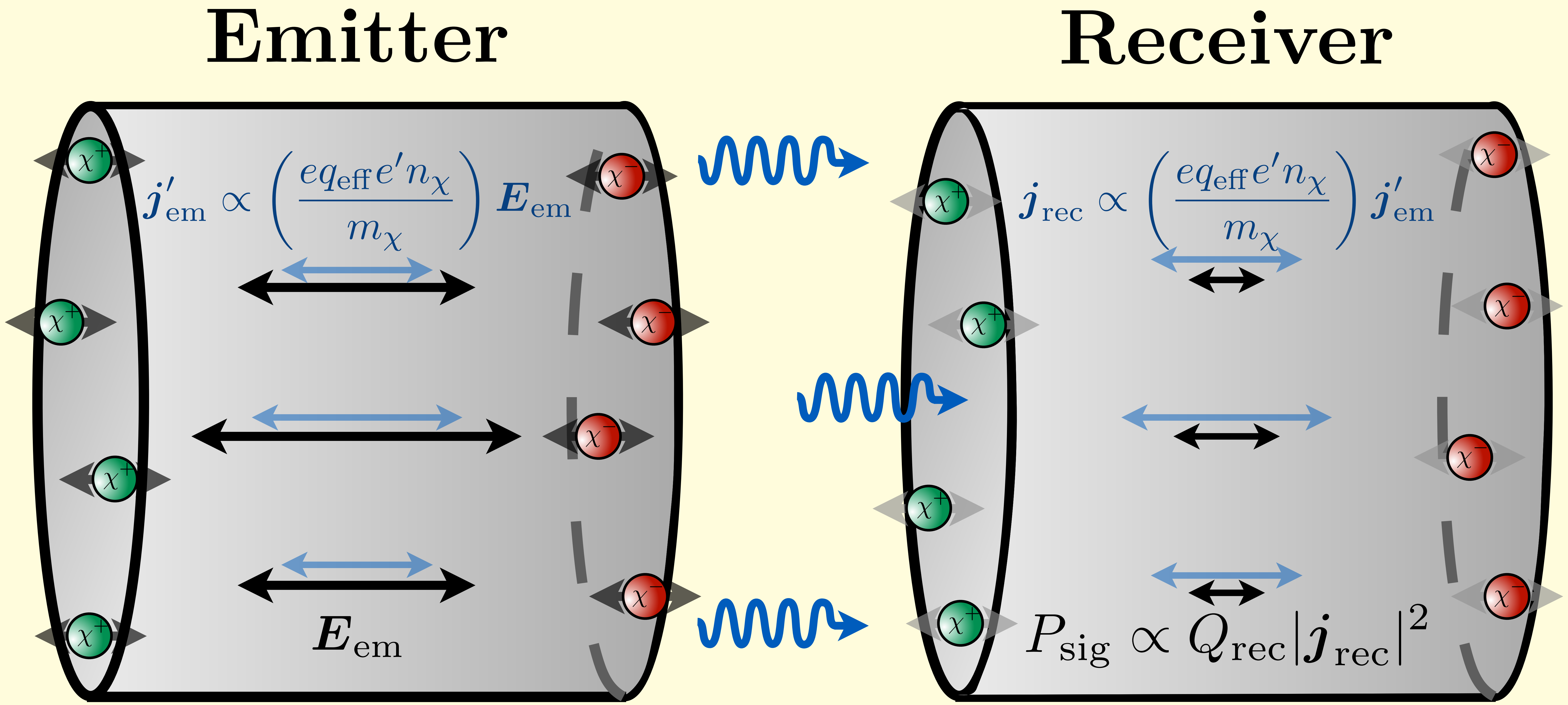
$\times \left(\frac{\ \ }{10^{-10}}\right)$

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

Accelerator induces collective effects in DM!

Variation in A, χ minor



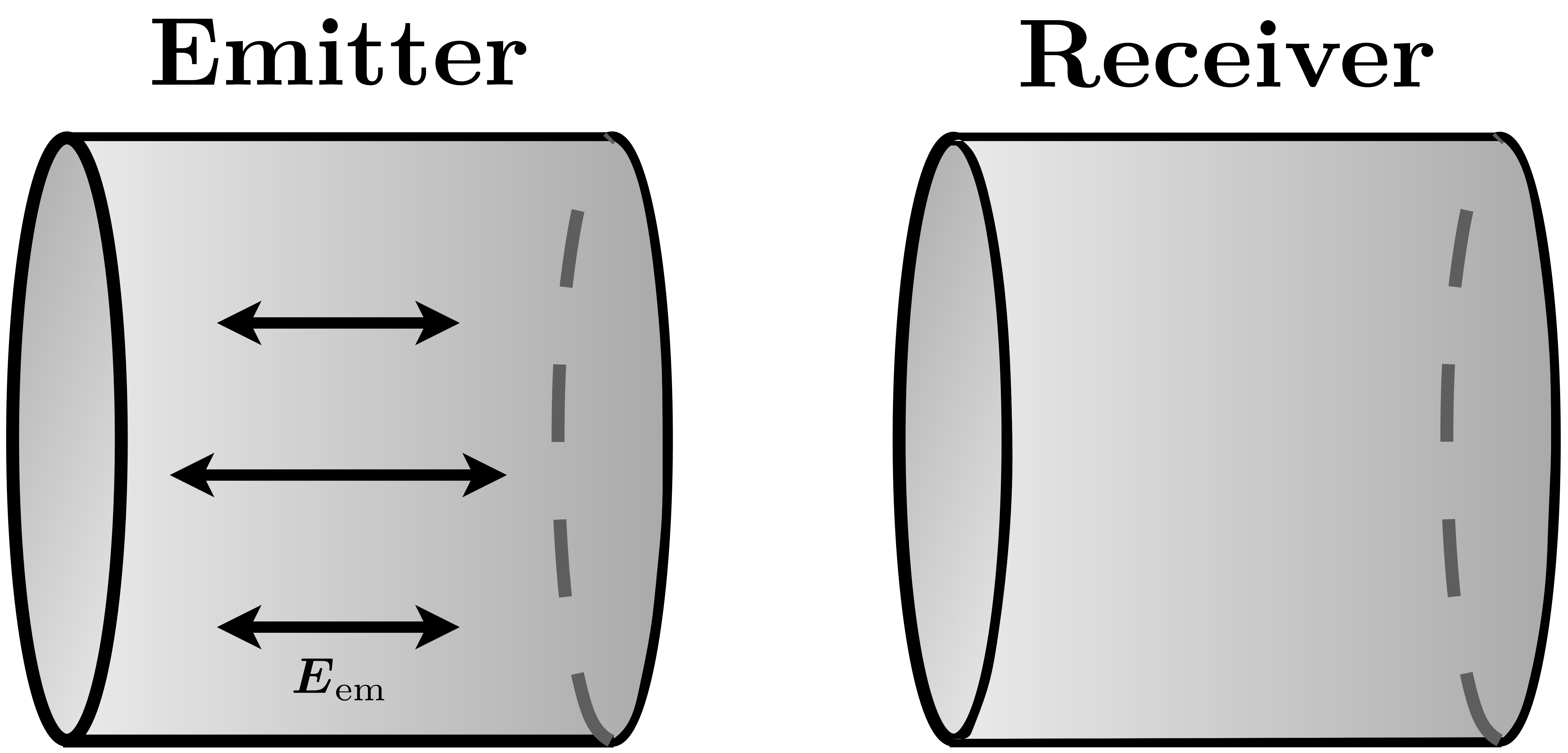
$\beta \sim 1$

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)



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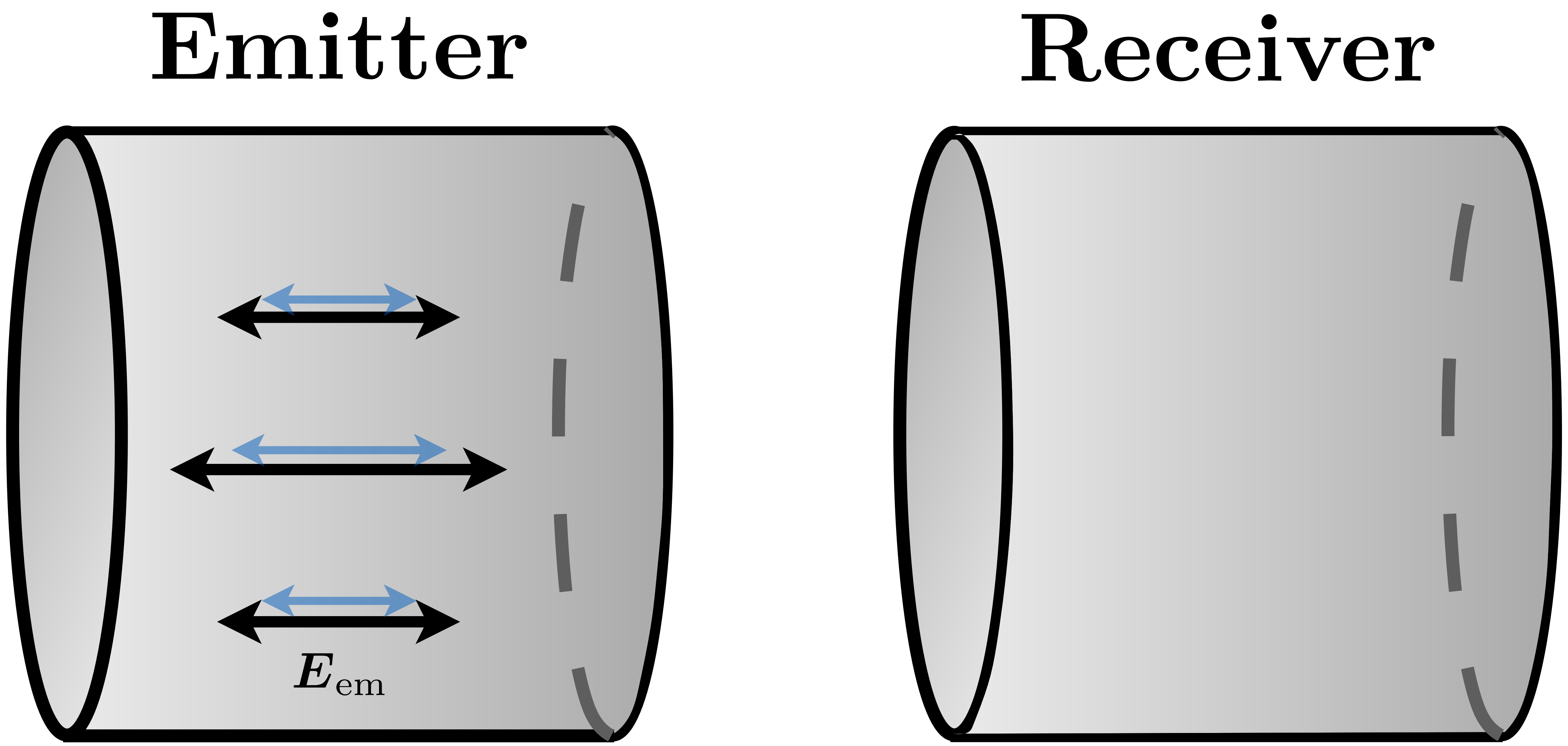

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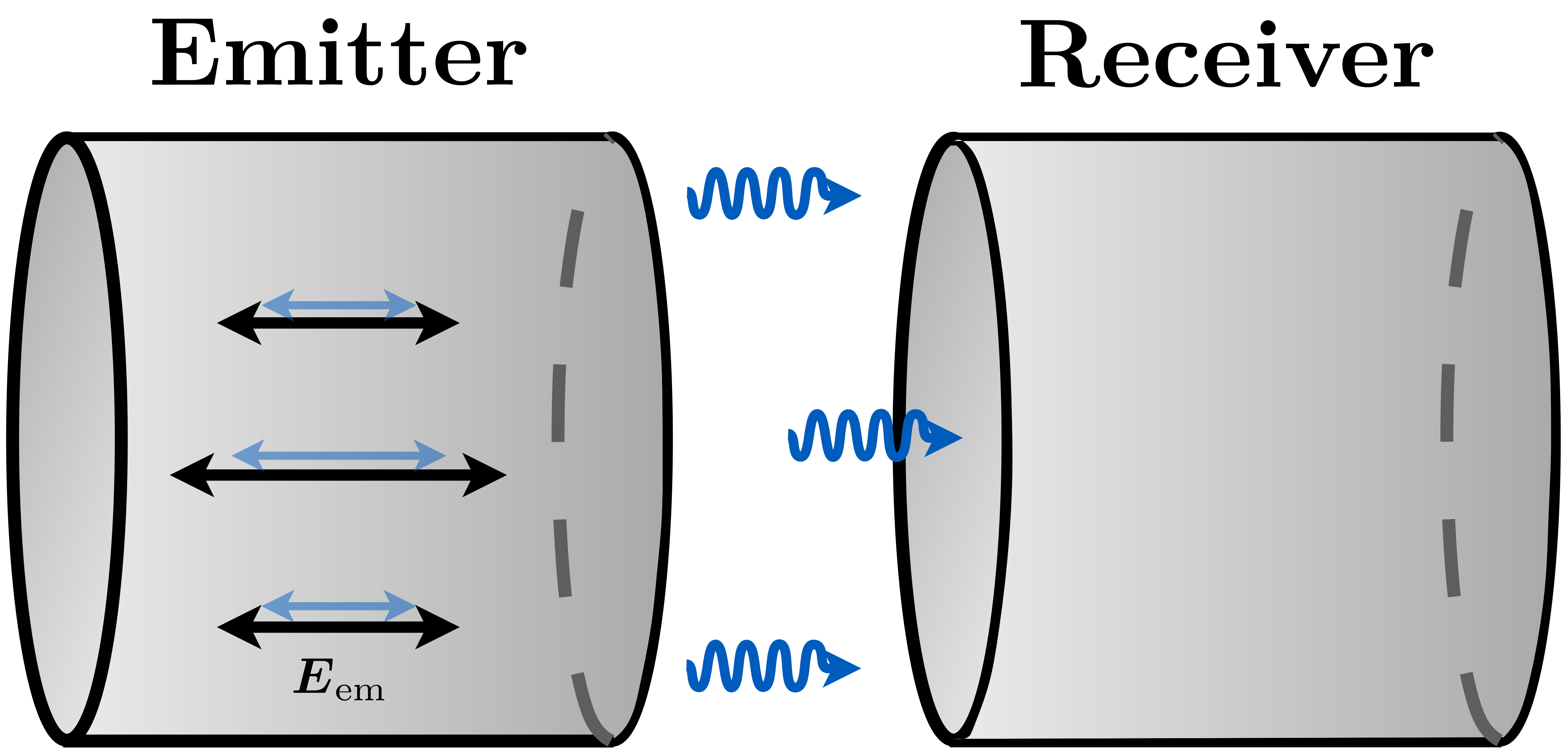

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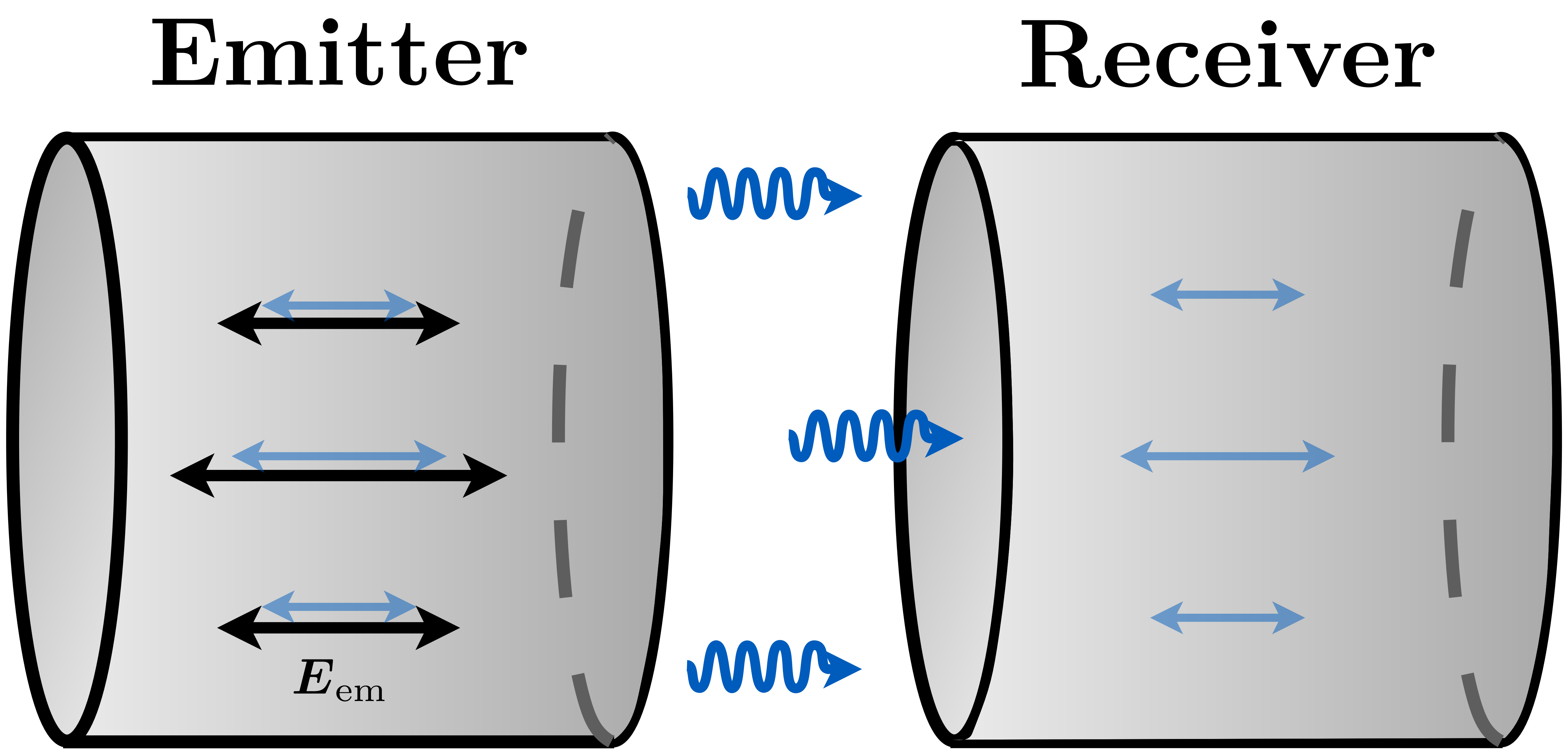

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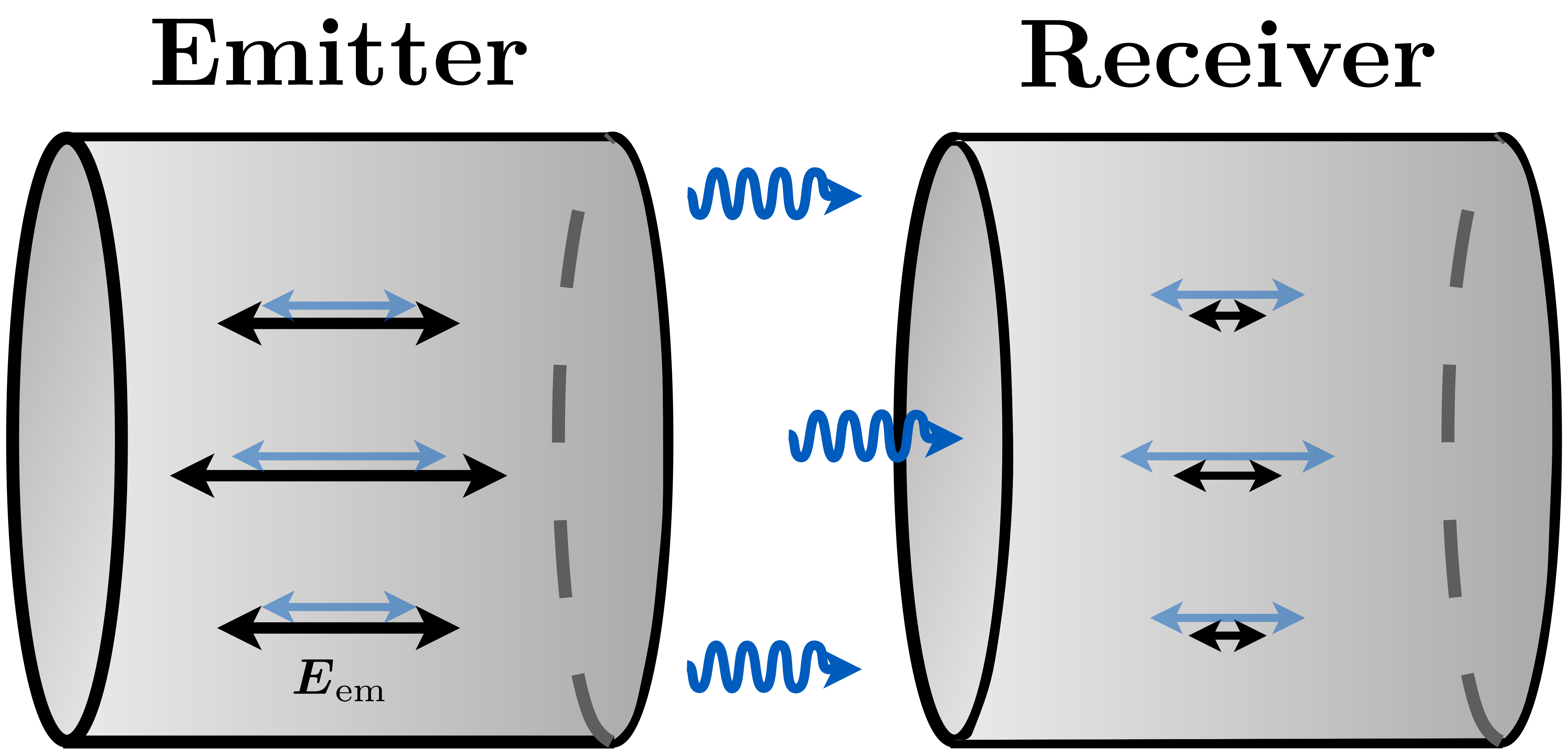

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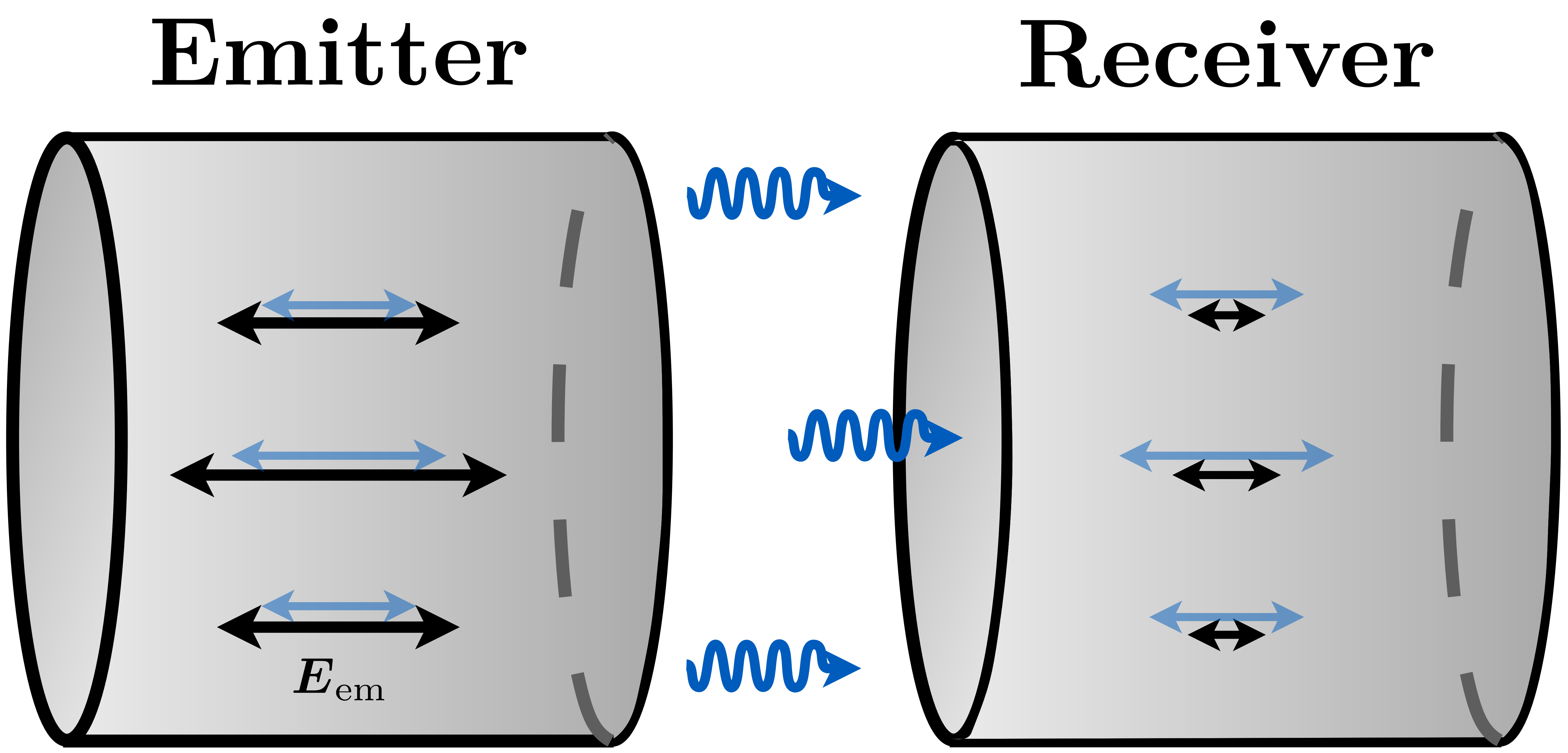
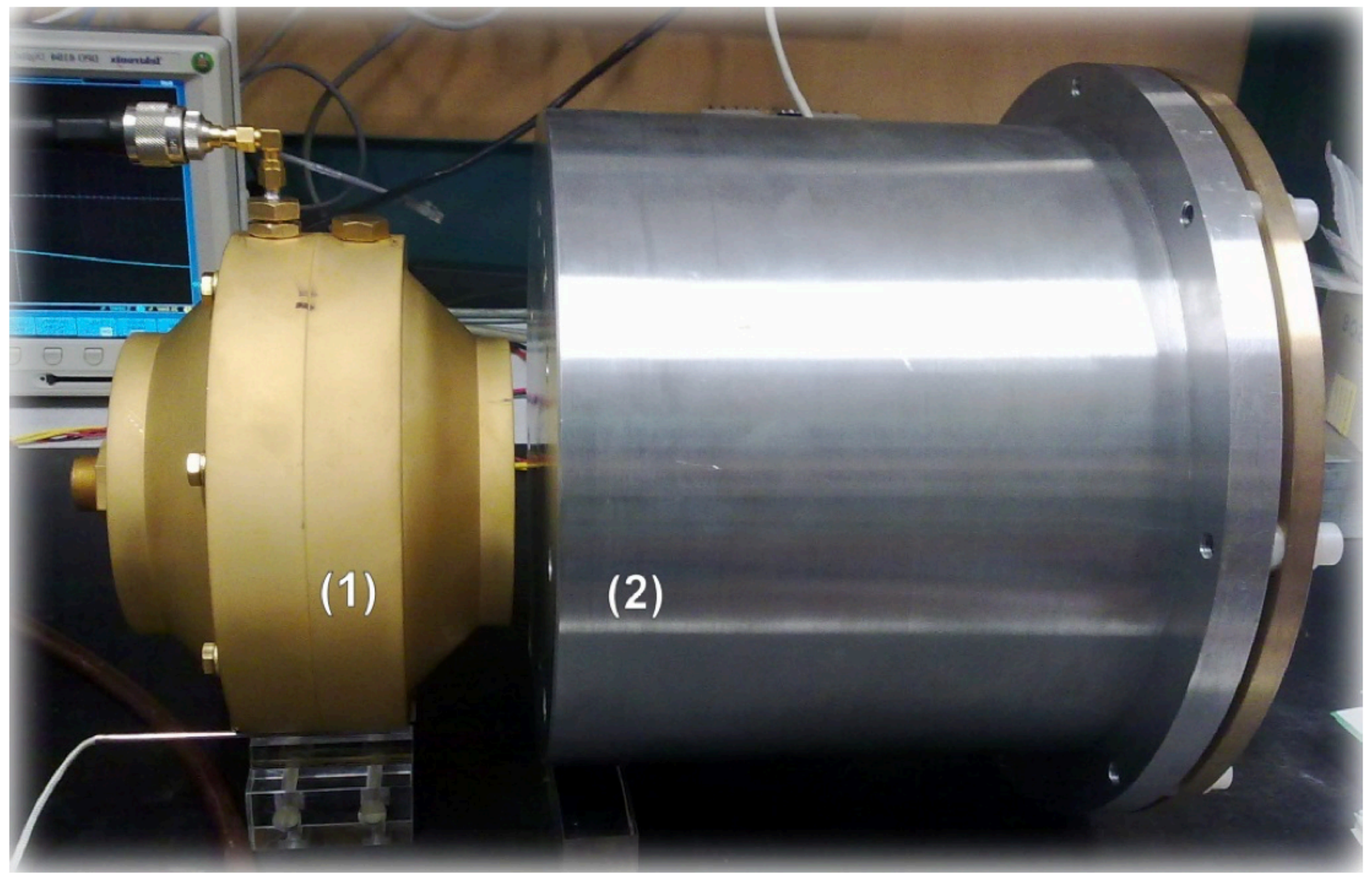


P. Graham, J. Mardon, S. Rajendran, Y. Zhao (2014)

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



Dark Photon Searches w/ Cavities

Ongoing experiment @ FNAL: *DarkSRF*

A. Romanenko et al (2023)

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

A. Romanenko et al (2023)

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

A. Romanenko et al (2023)

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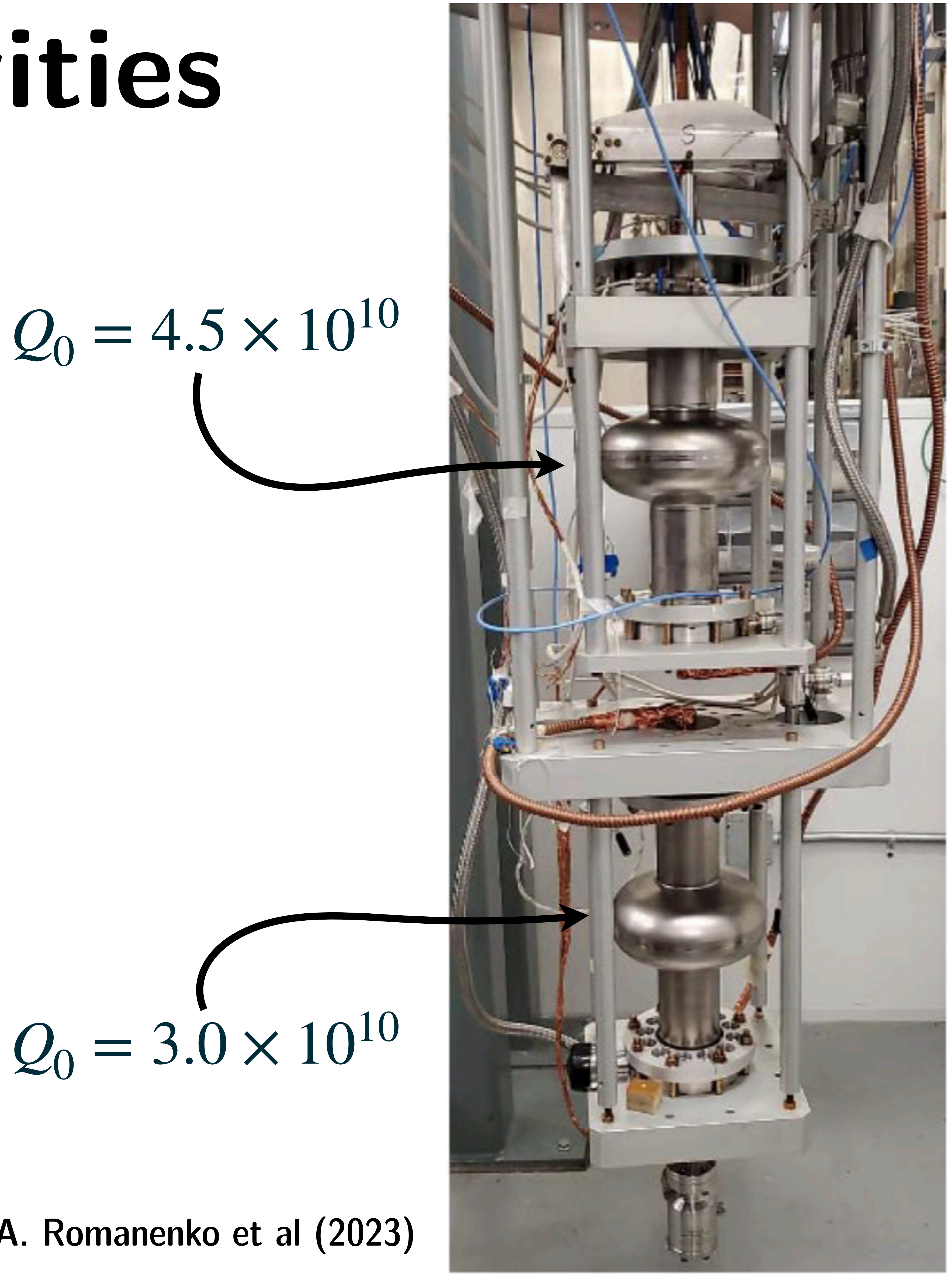

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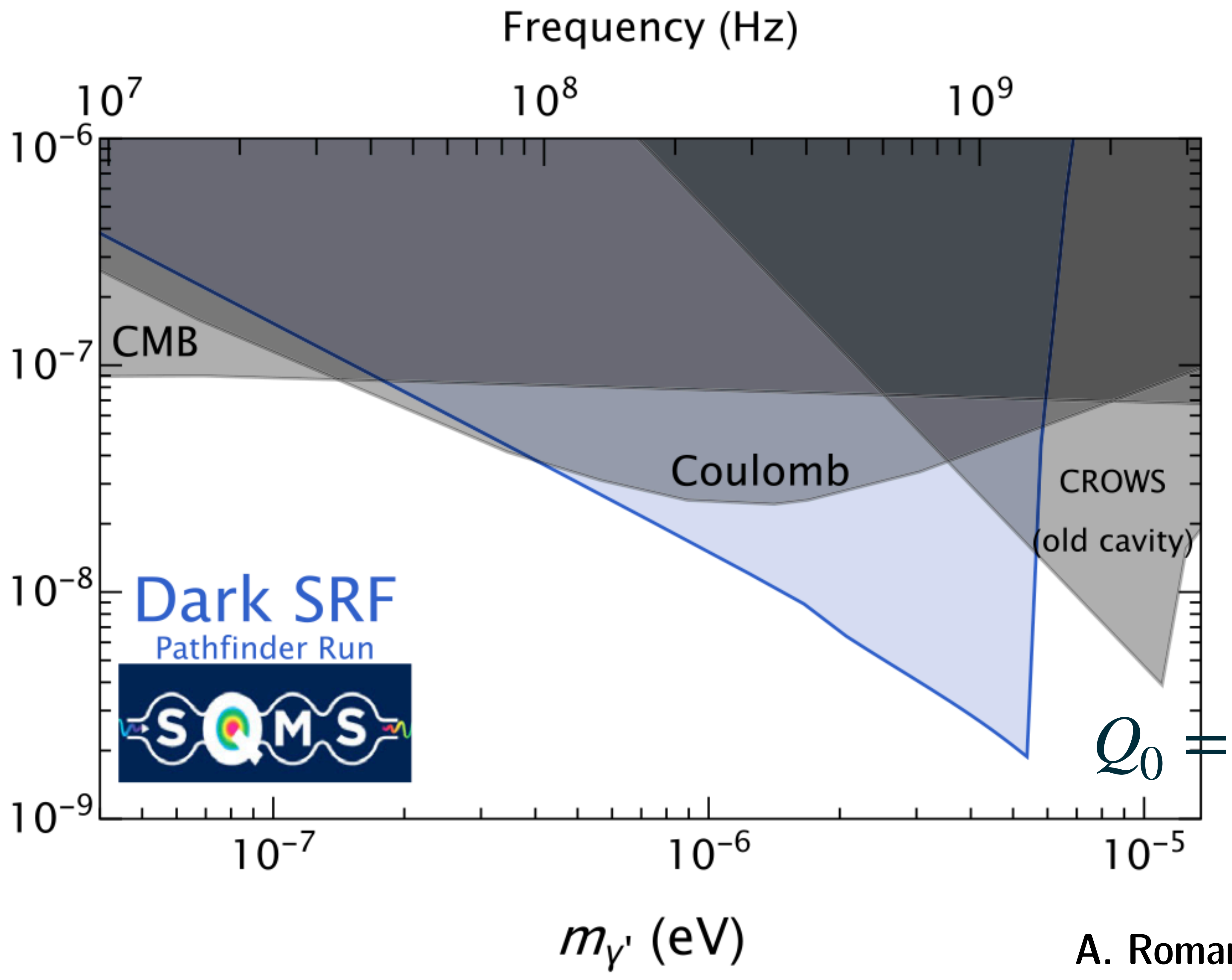

A. Romanenko et al (2023)

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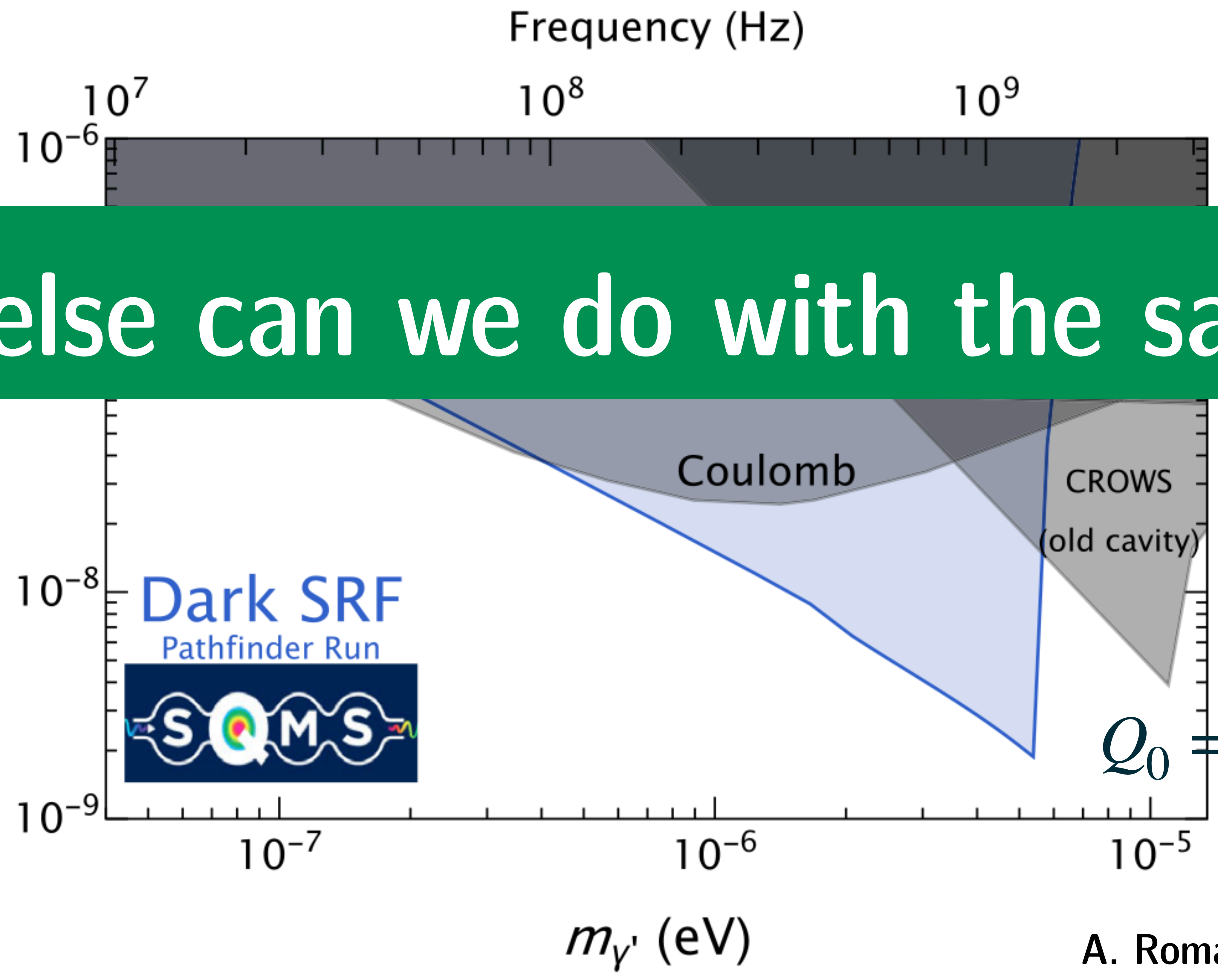


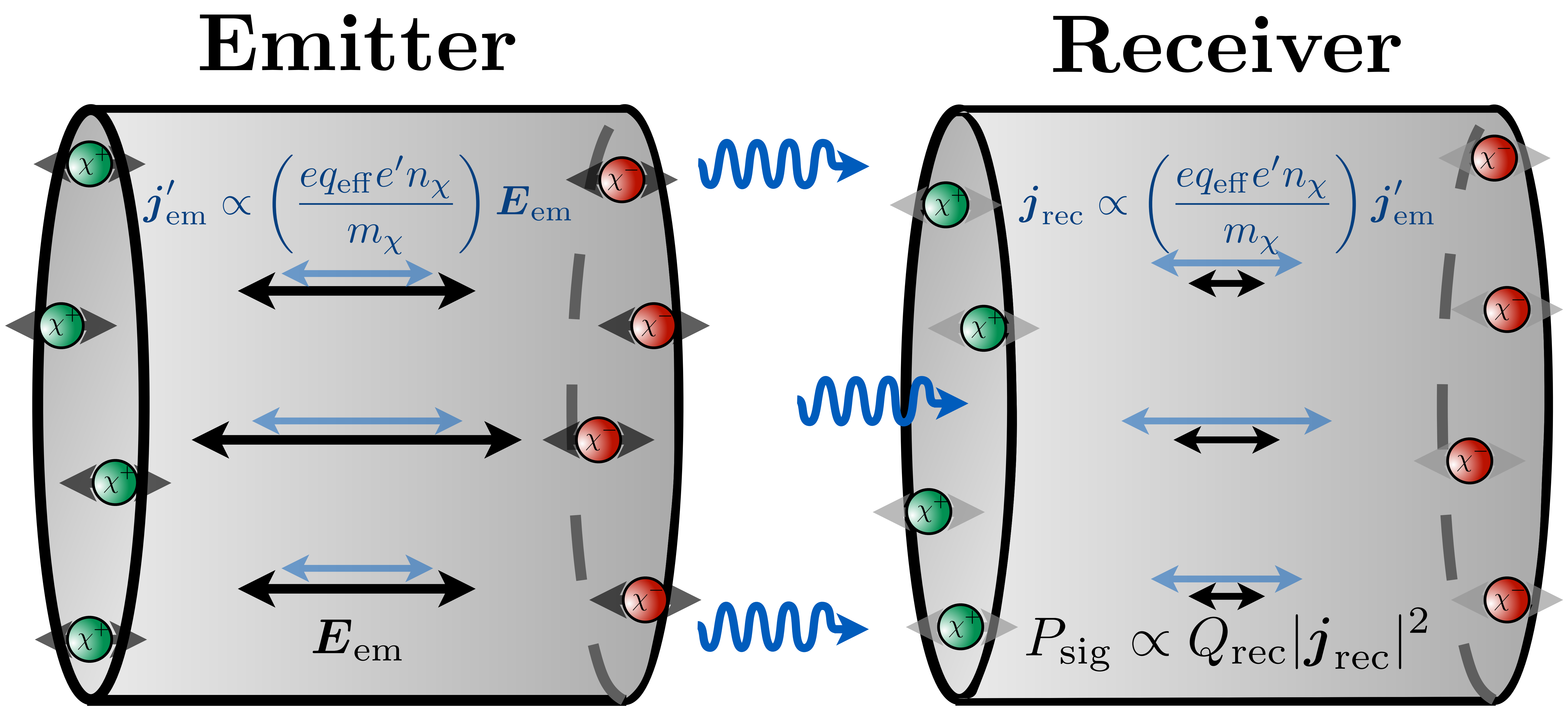
A. Romanenko et al (2023)

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

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

What else can we do with the same setup?

Millicharged DM at LSW Experiments



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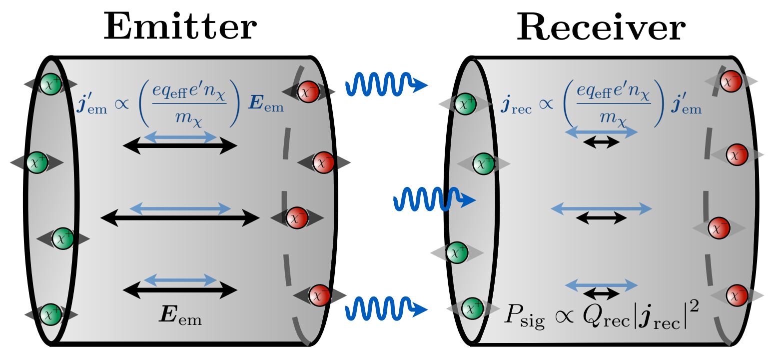

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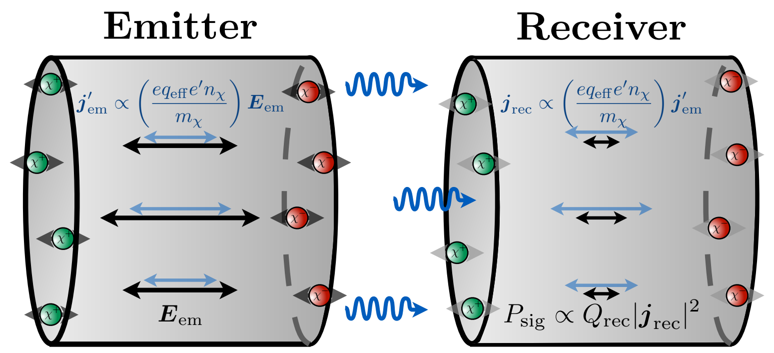
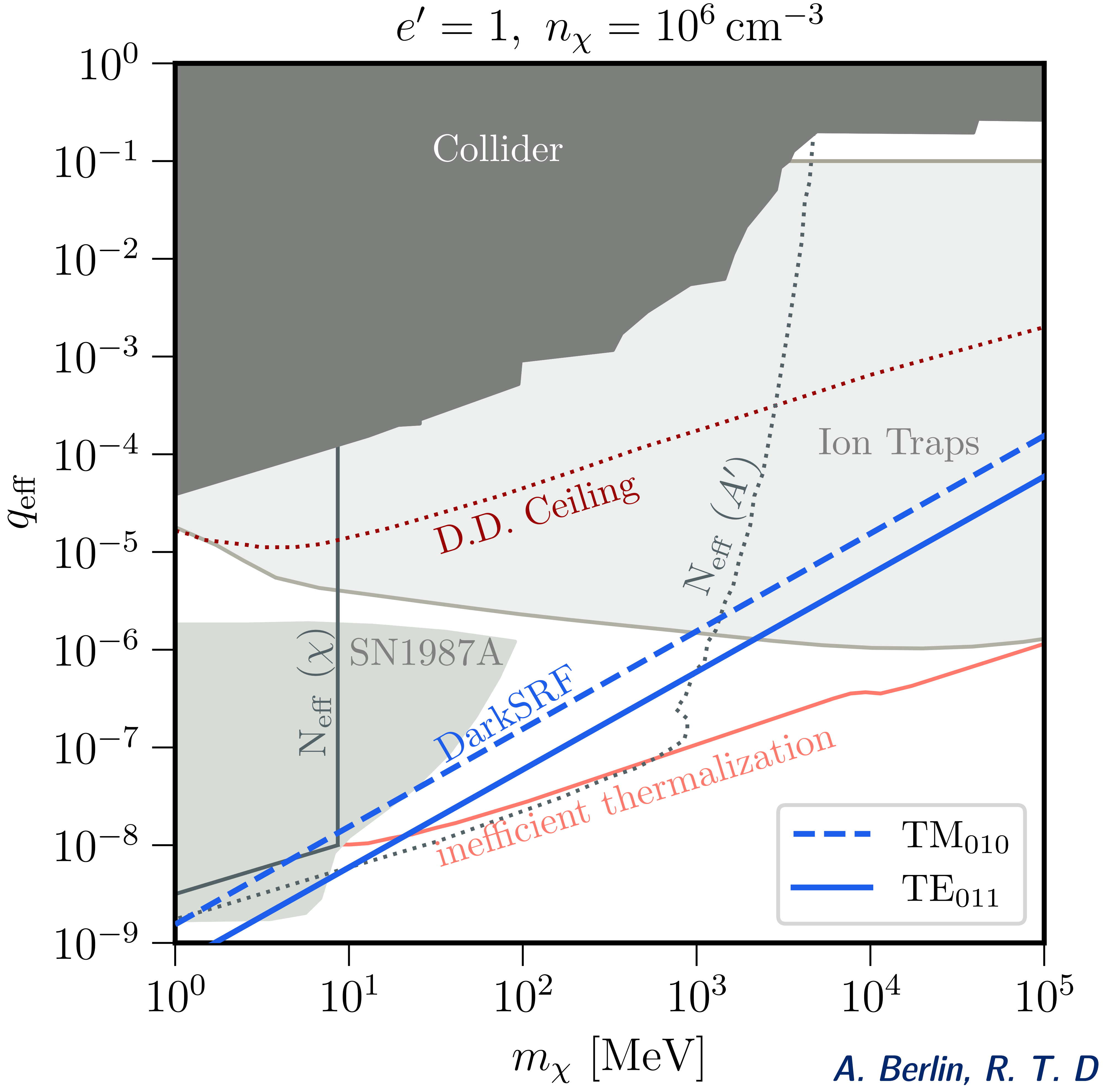
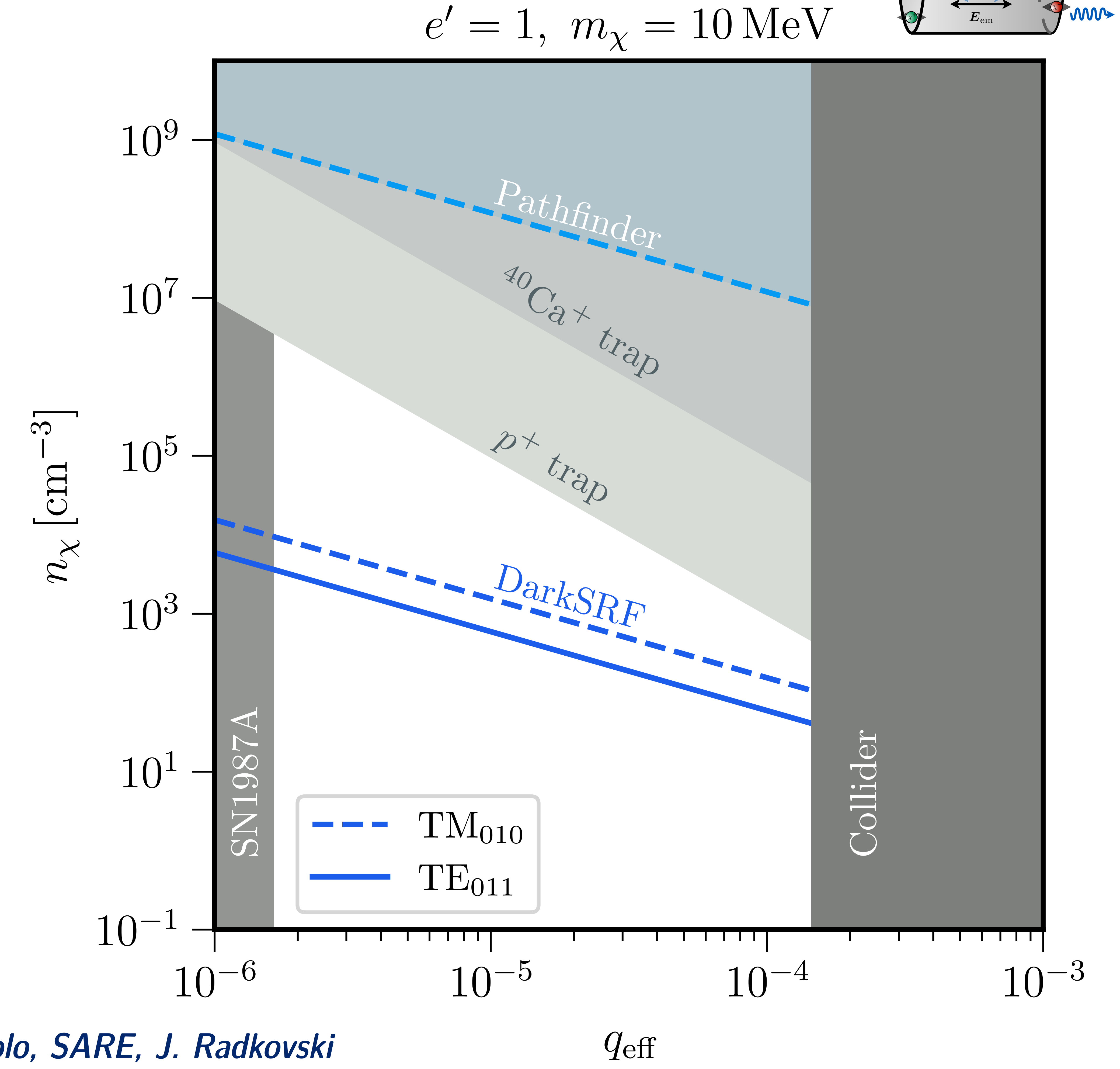
JHEP 08 (2023) 017

Millicharged DM at LSW Experiments







A. Berlin, R. T. D'Agnolo, SARE, J. Radkovski
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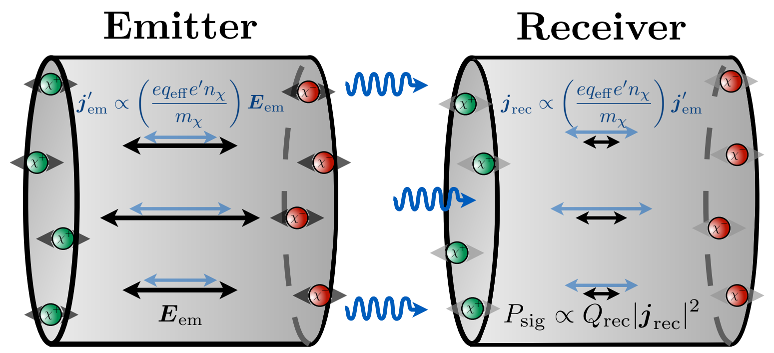

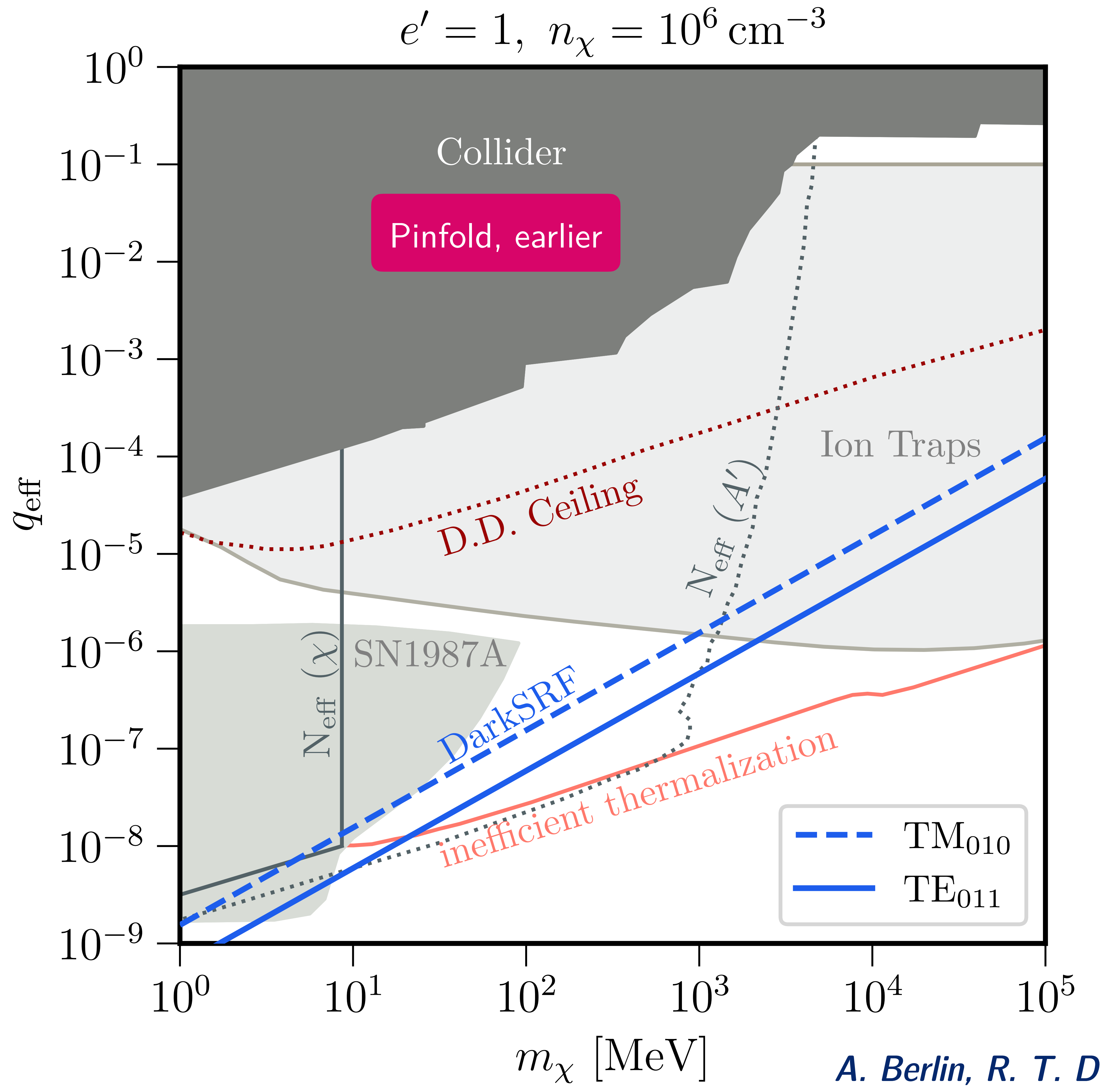

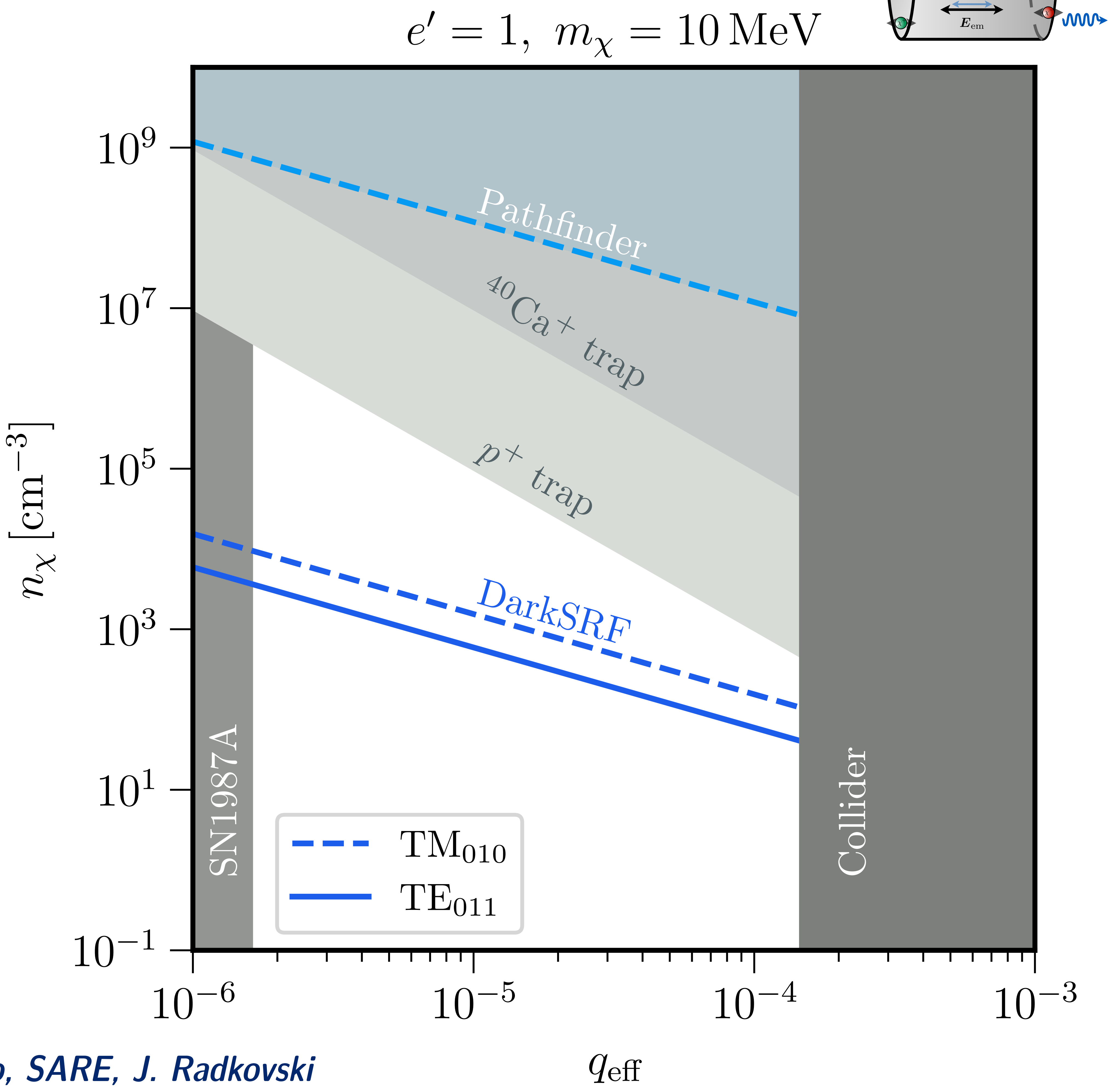

A. Berlin, R. T. D'Agnolo, SARE, J. Radkovski
JHEP 08 (2023) 017

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

$\beta \sim 1$

Signal In a Resonator

Signal In a Resonator

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

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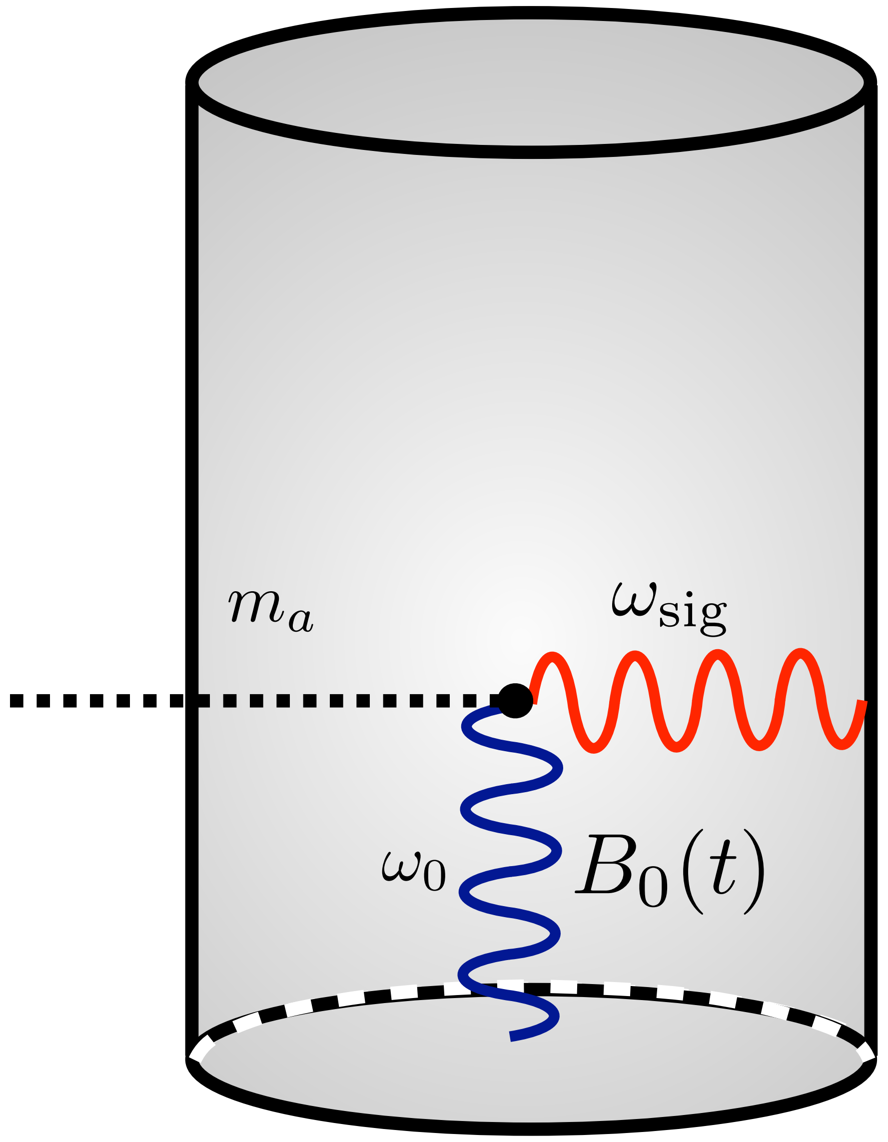
Maximise: $\omega_{\rm sig}$, B_a, V

Heterodyne Resonator:

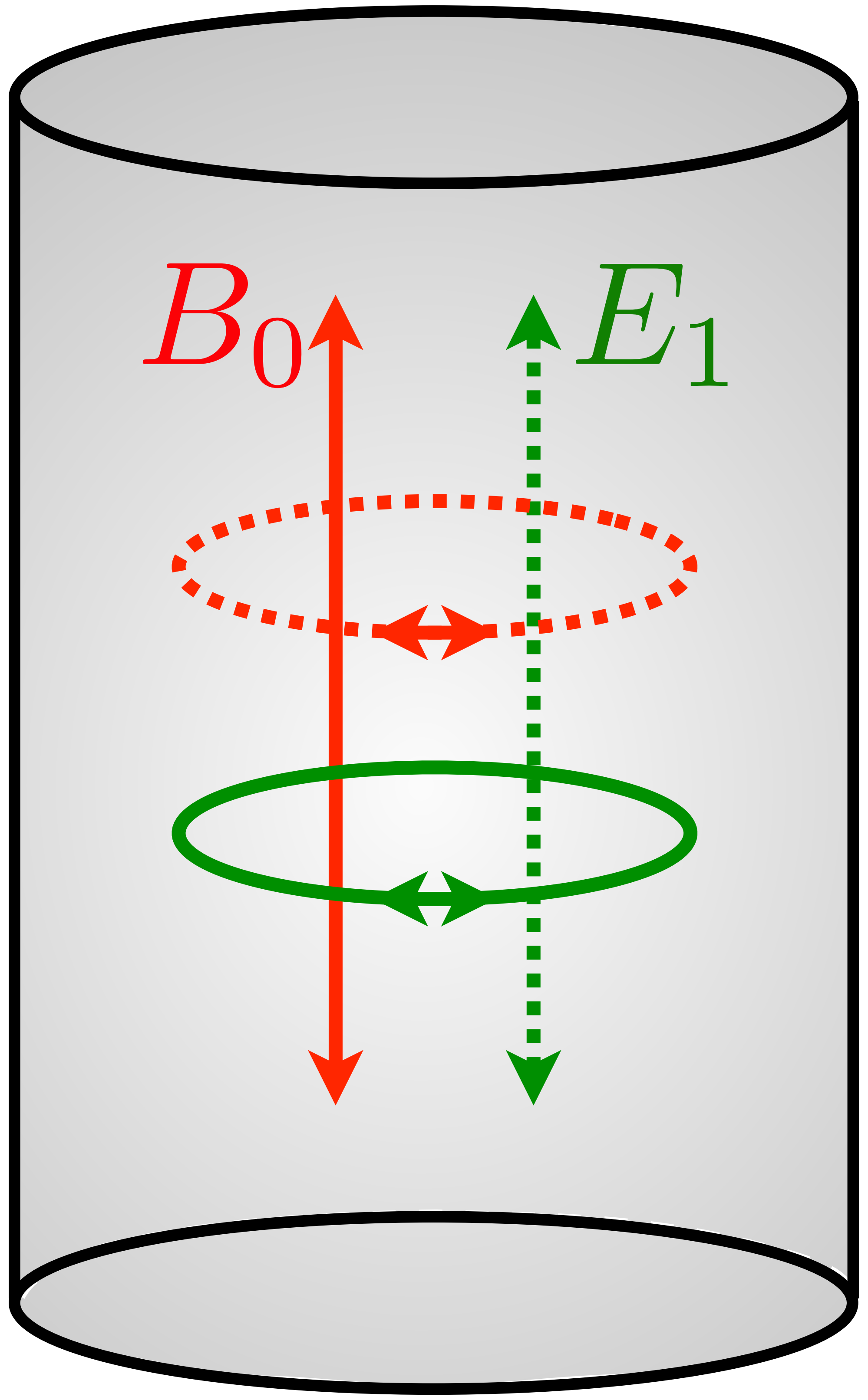
$$\omega_{\rm sig} \sim \omega_0 \pm m_a \sim V^{-1/3}$$



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?



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

$$\omega_0 \sim \mathrm{GHz}$$

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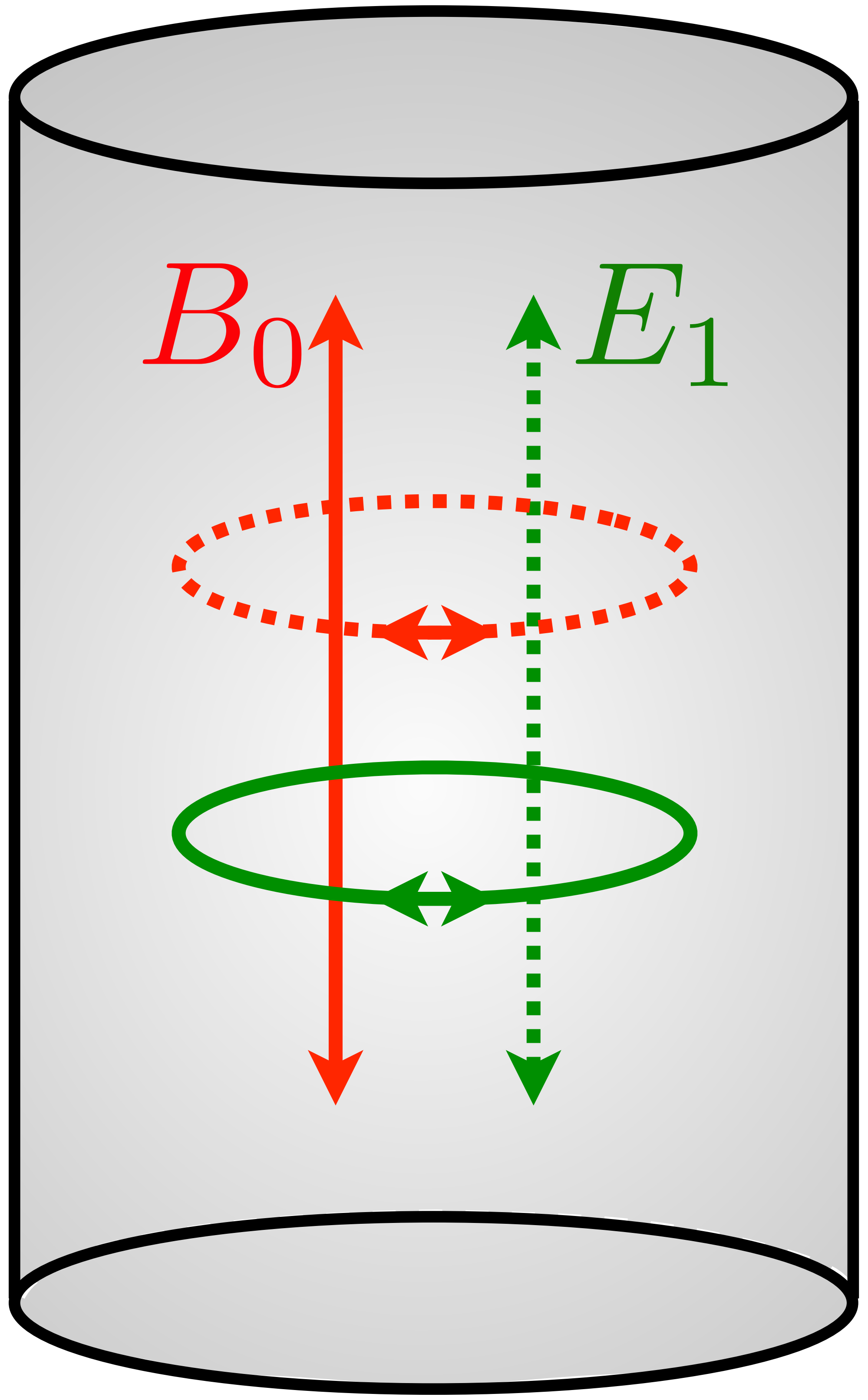

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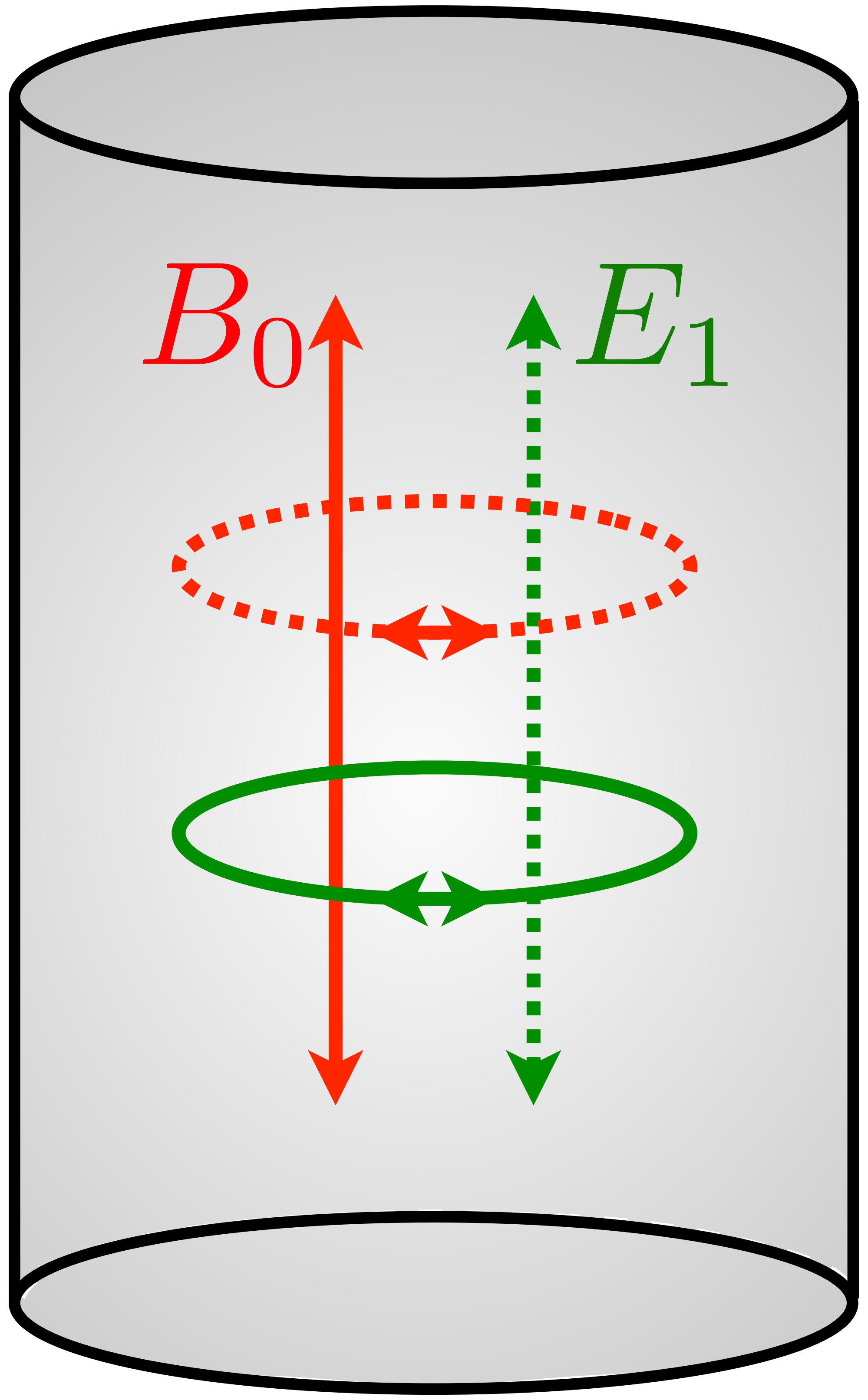

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$\omega_0 \sim \text{GHz}$

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

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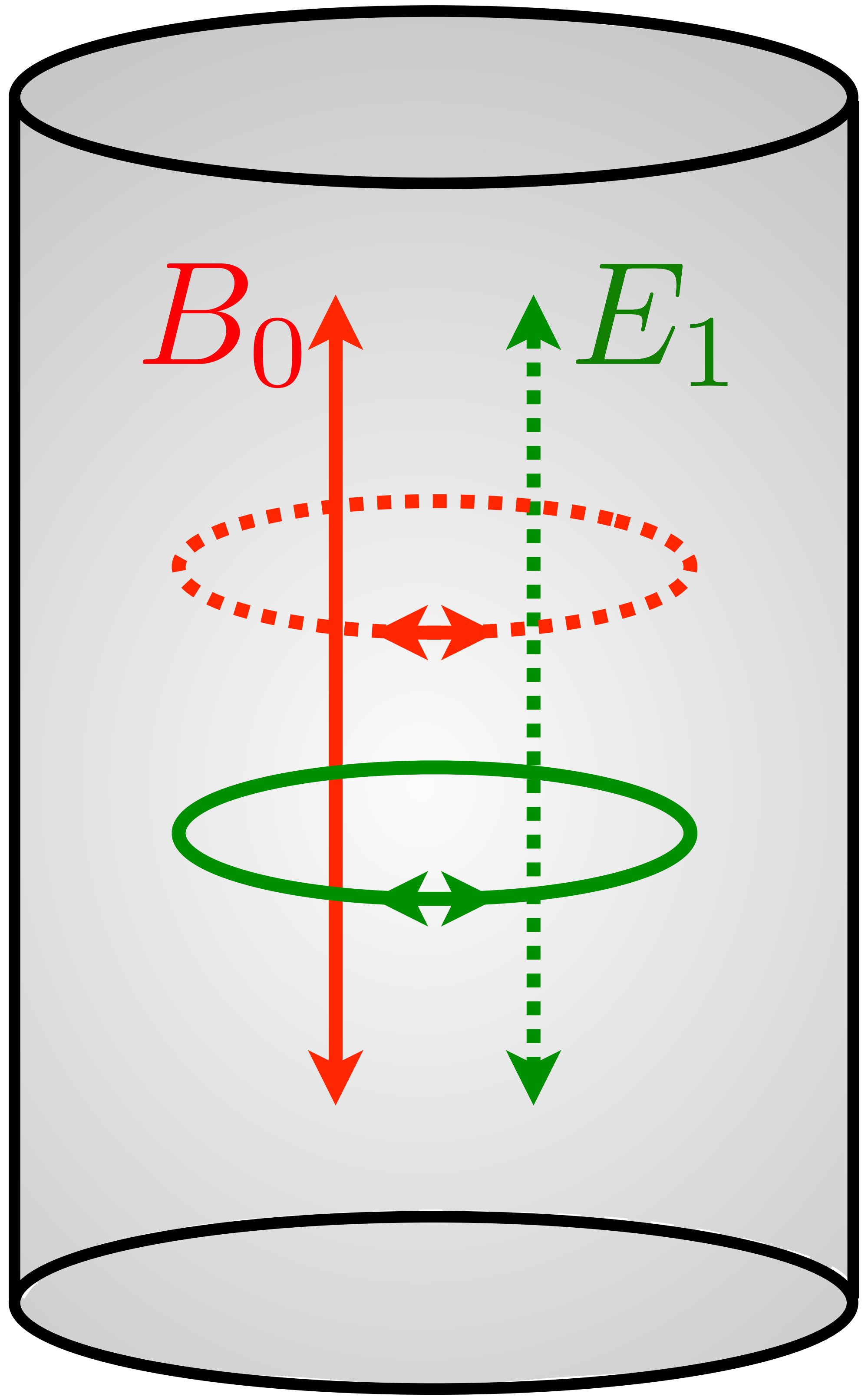

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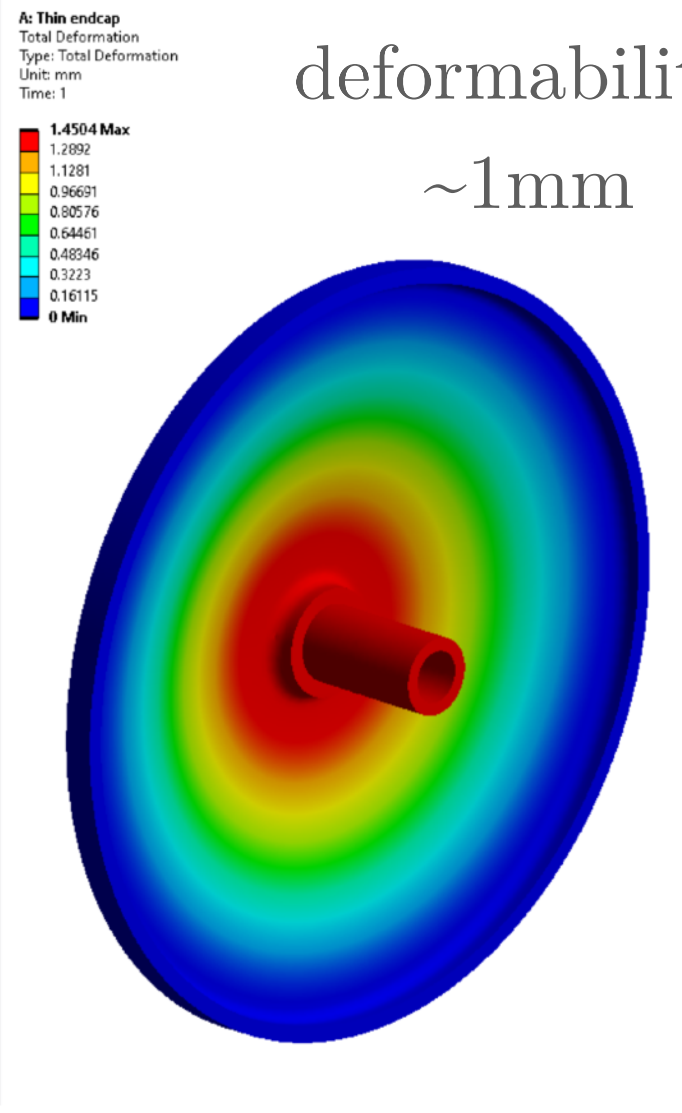
Tunability

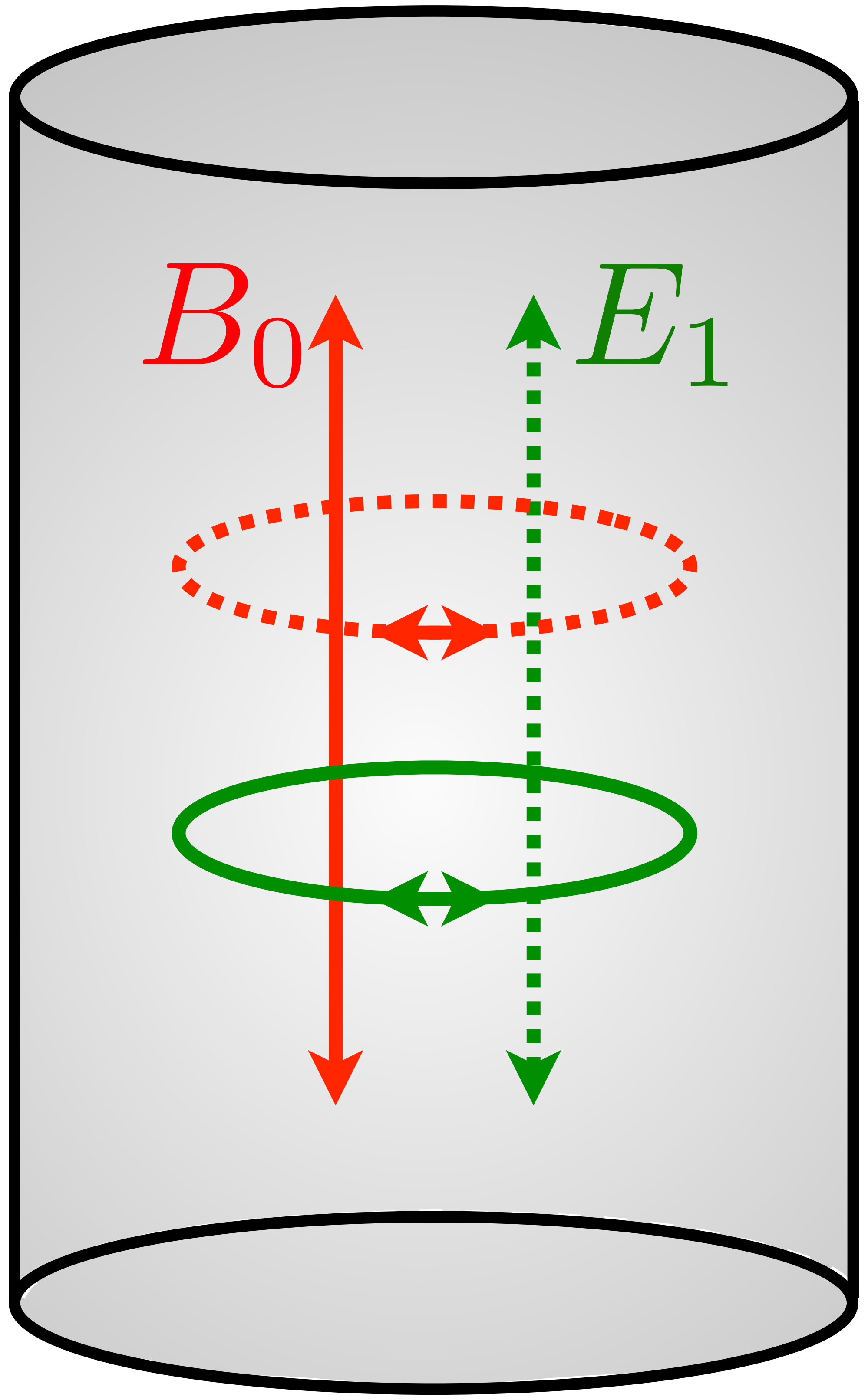
$\Delta\omega \ll \text{GHz}$

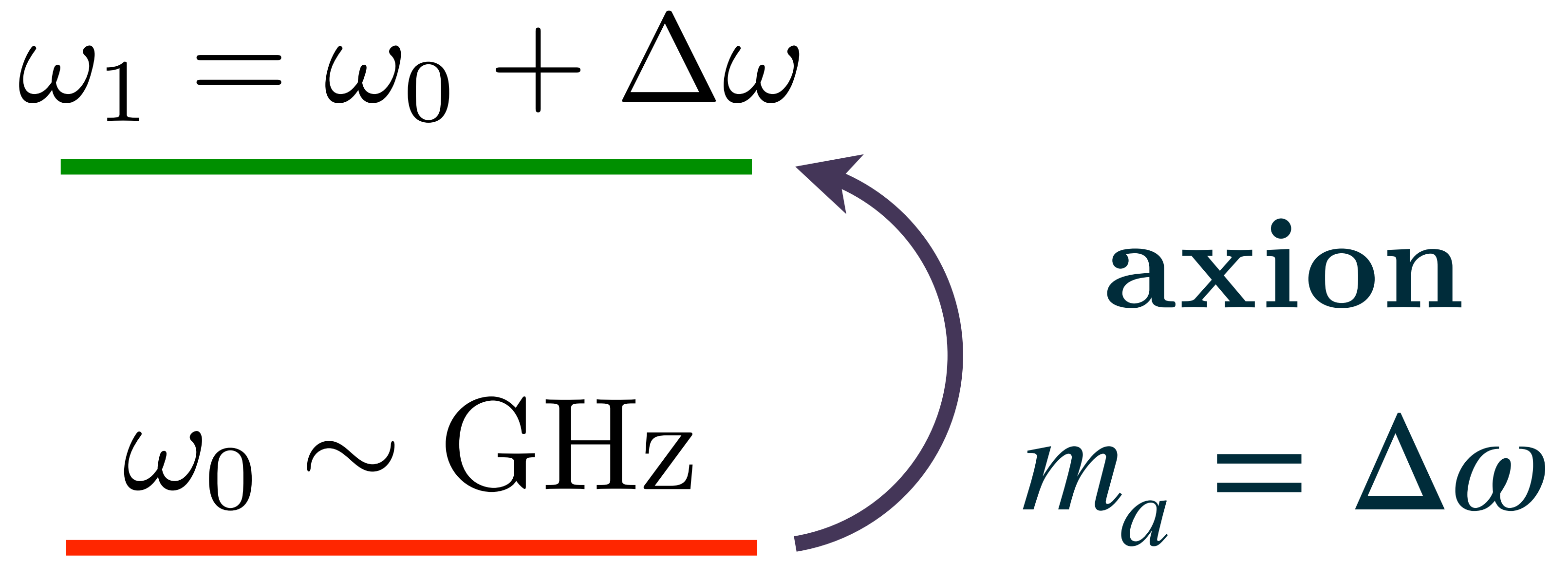
deformability: ~1mm



Courtesy: Marco Oriunno (SLAC)

How Does it Work?





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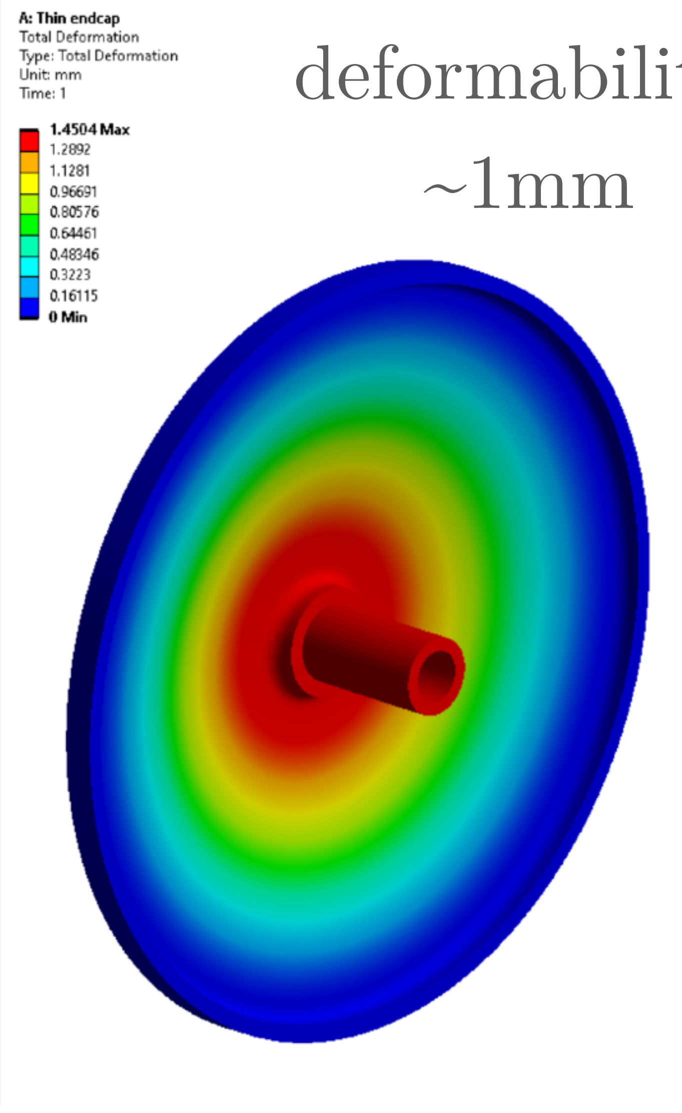
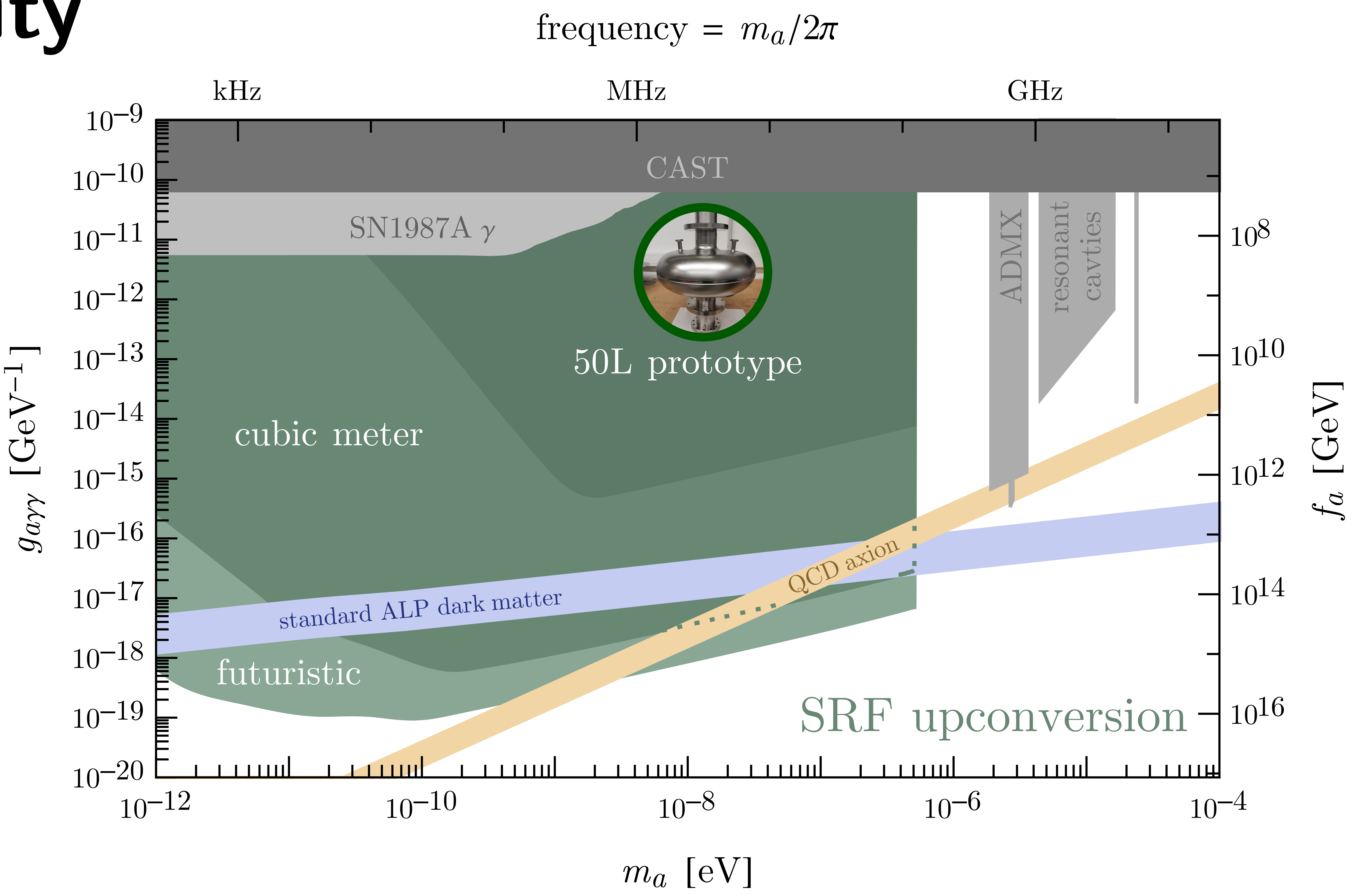


Courtesy: Marco Oriunno (SLAC)

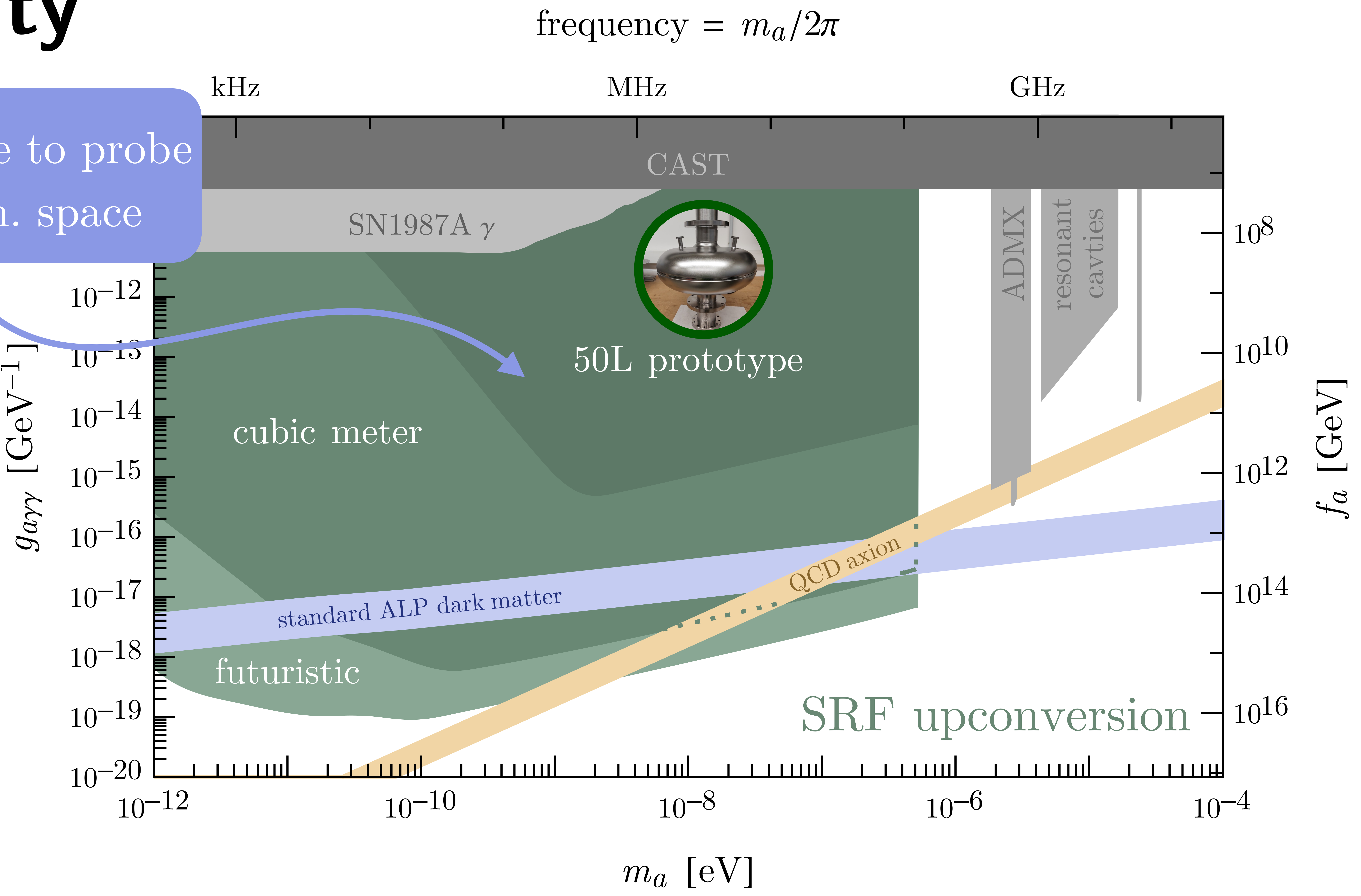
Resonant with ***beat frequency*** of applied EM field and axion signal

Sensitivity

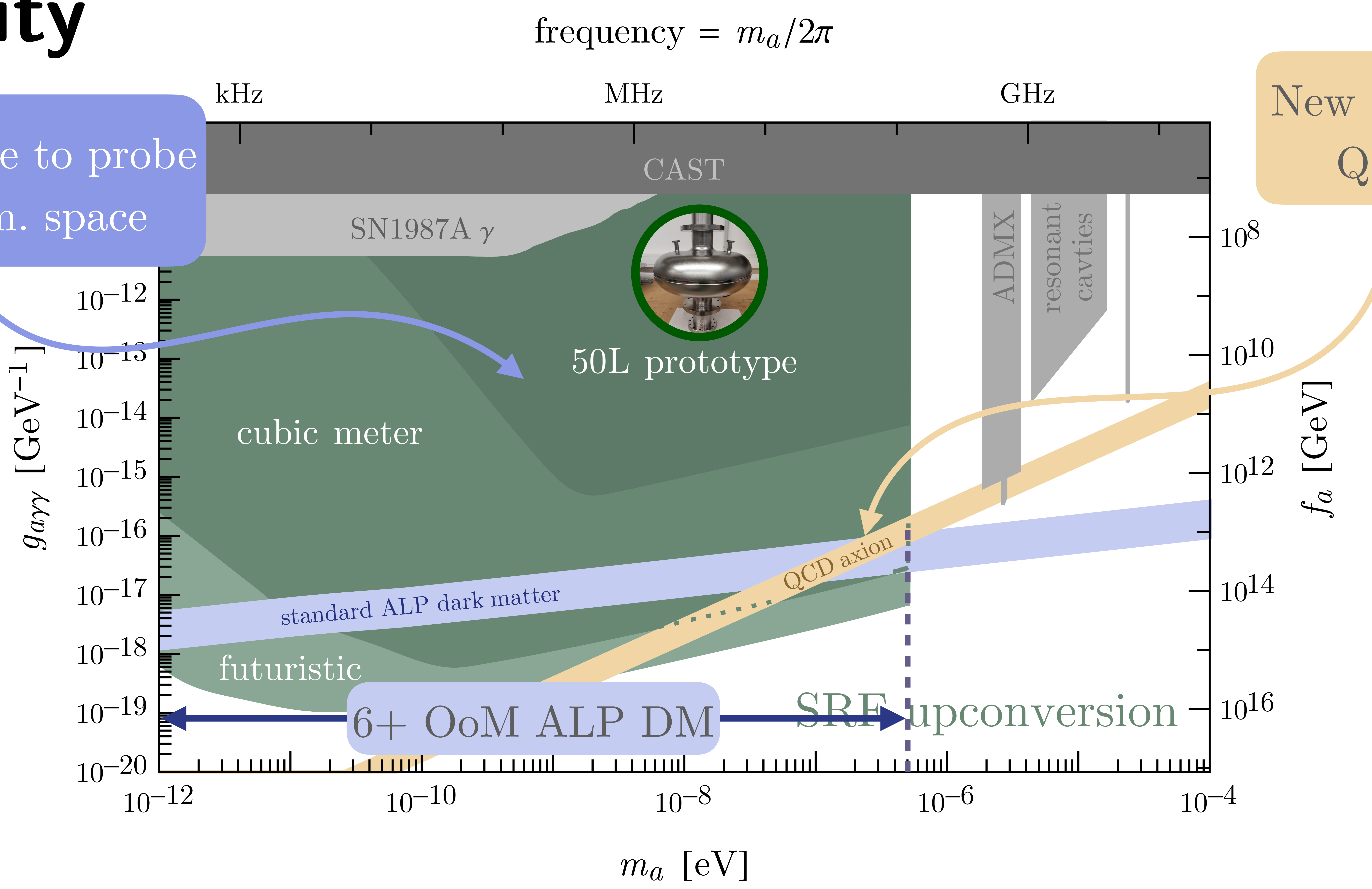


Sensitivity

SC Prototype to probe new param. space



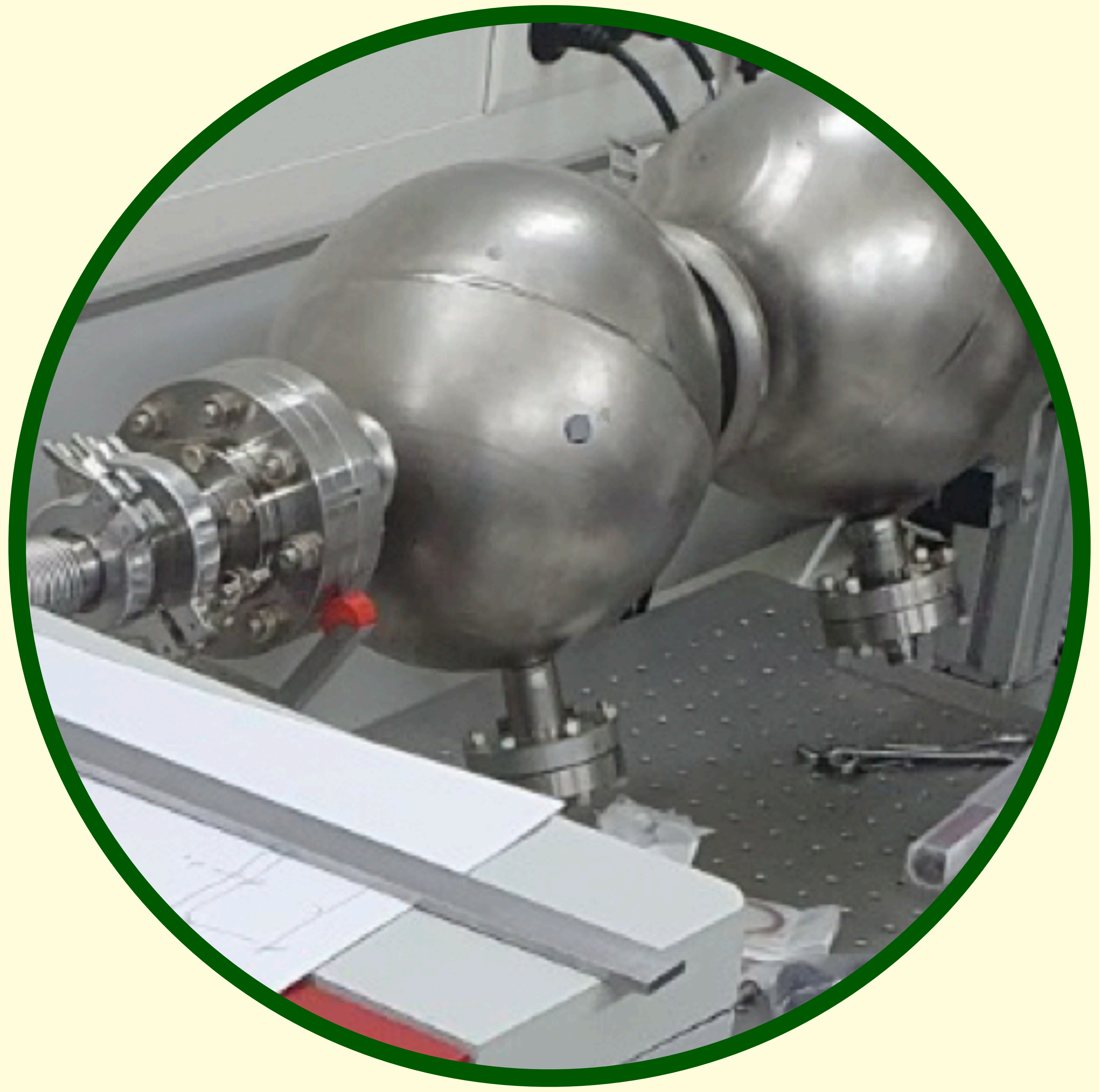
Sensitivity



SC Prototype to probe new param. space

New sensitivity to QCD axion

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

$\beta \sim 1$

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

Gravitational Waves

Angular momentum:

differs from axion by index structure

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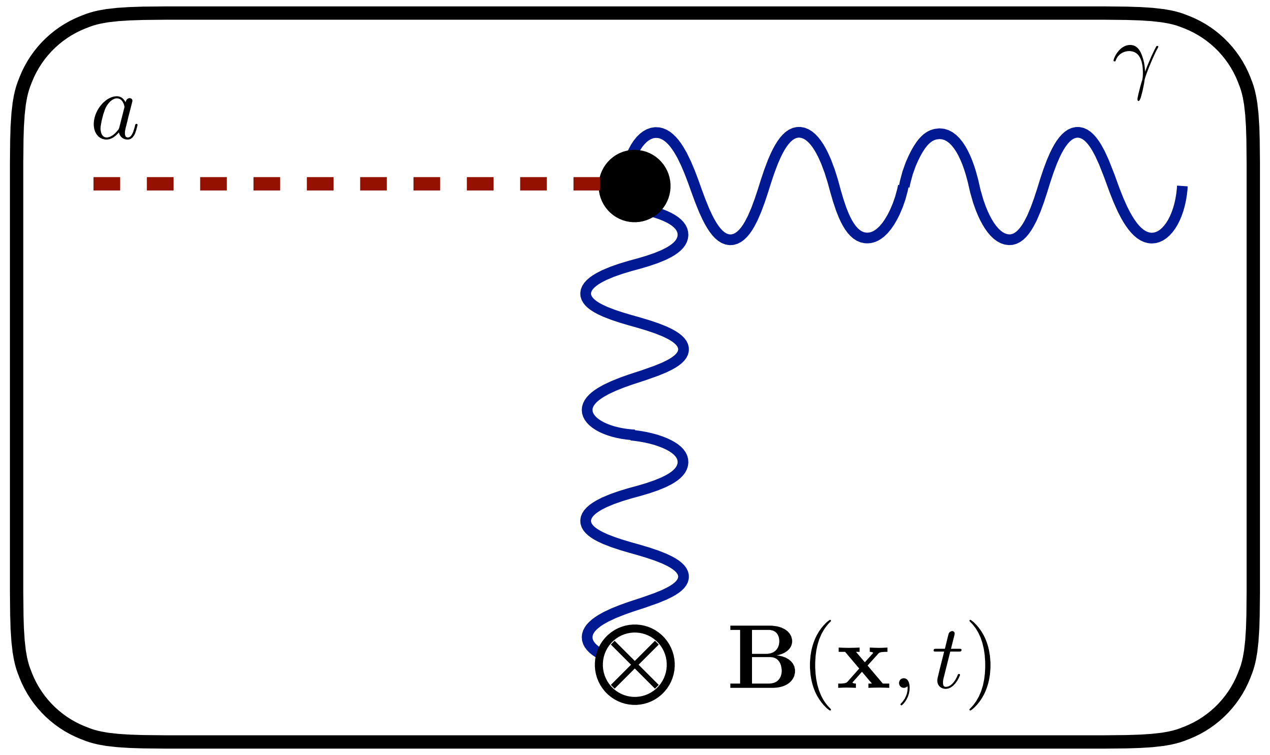
differs from axion by index structure



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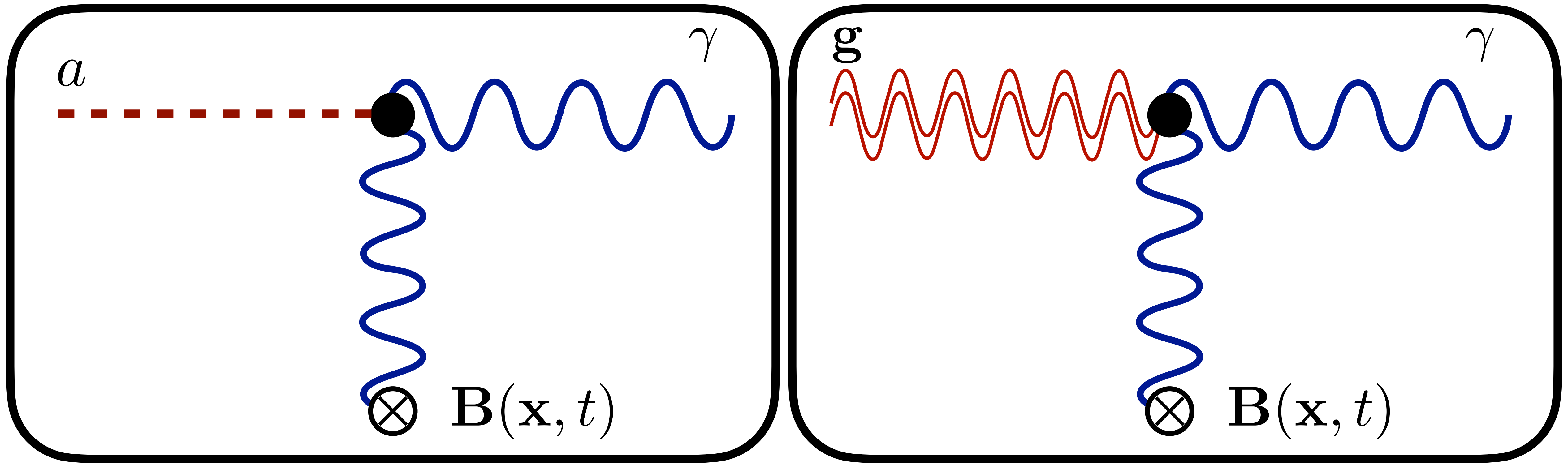

Gertsenshtein (1962)
Zeldovich (1973)
Raffelt & Stodolsky (1988)

Gravitational Waves

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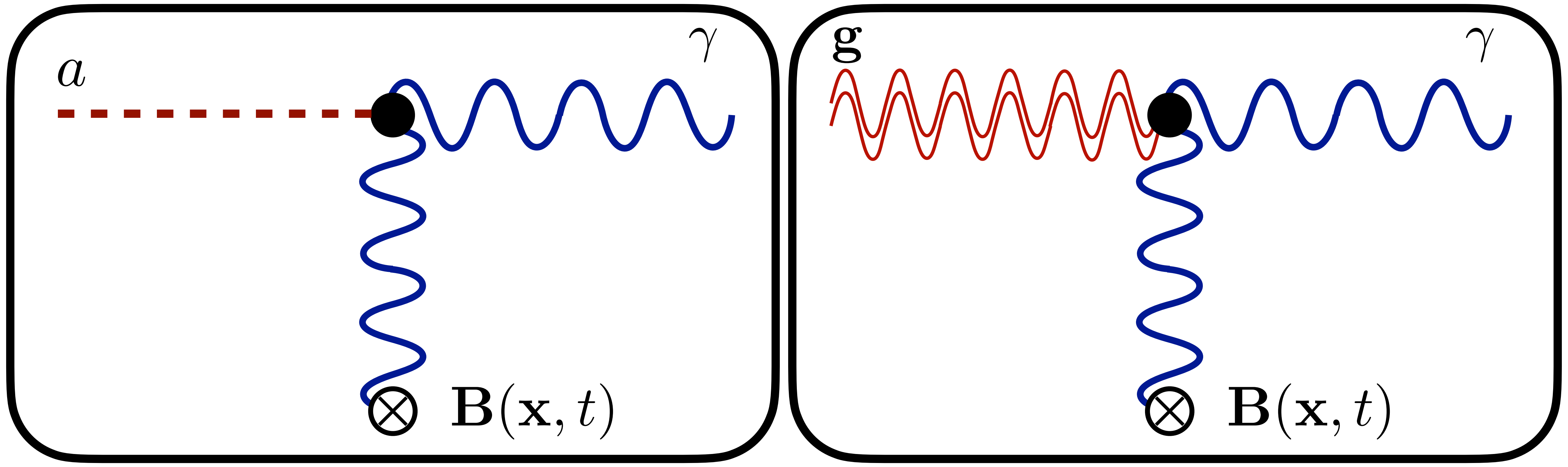


Gertsenshtein (1962)
Zeldovich (1973)
Raffelt & Stodolsky (1988)

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:

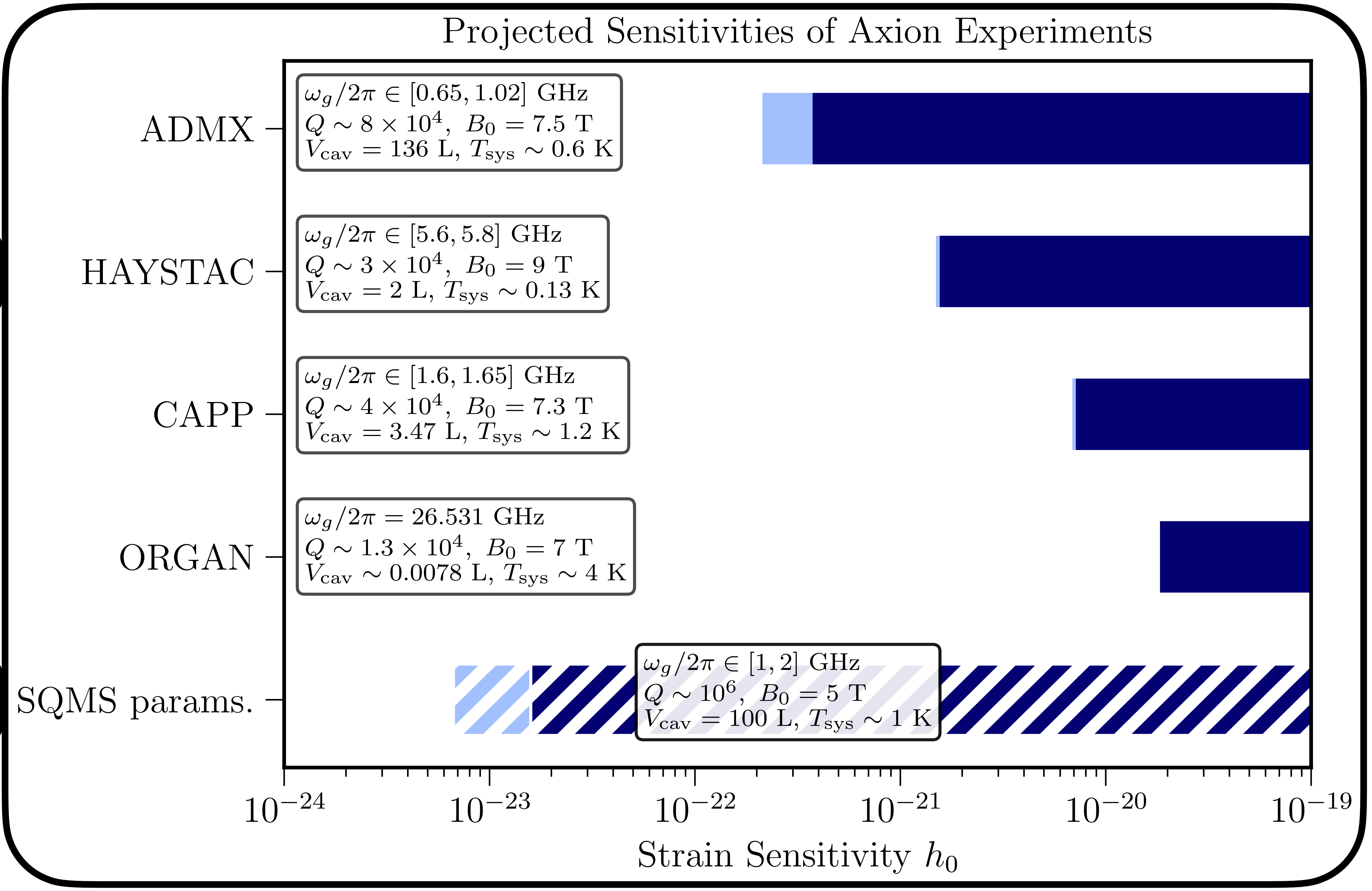
PRD 105 116011 hep-ph/2112.11465
A. Berlin, D. Blas, R. T. D'Agnolo, **SARE,** R. Harnik, Y. Kahn, J. Schütte-Engel

Axion Experiments x Gravitational Waves

Already using quantum techniques

Existing Axion Experiments:

Likely quantum tech.



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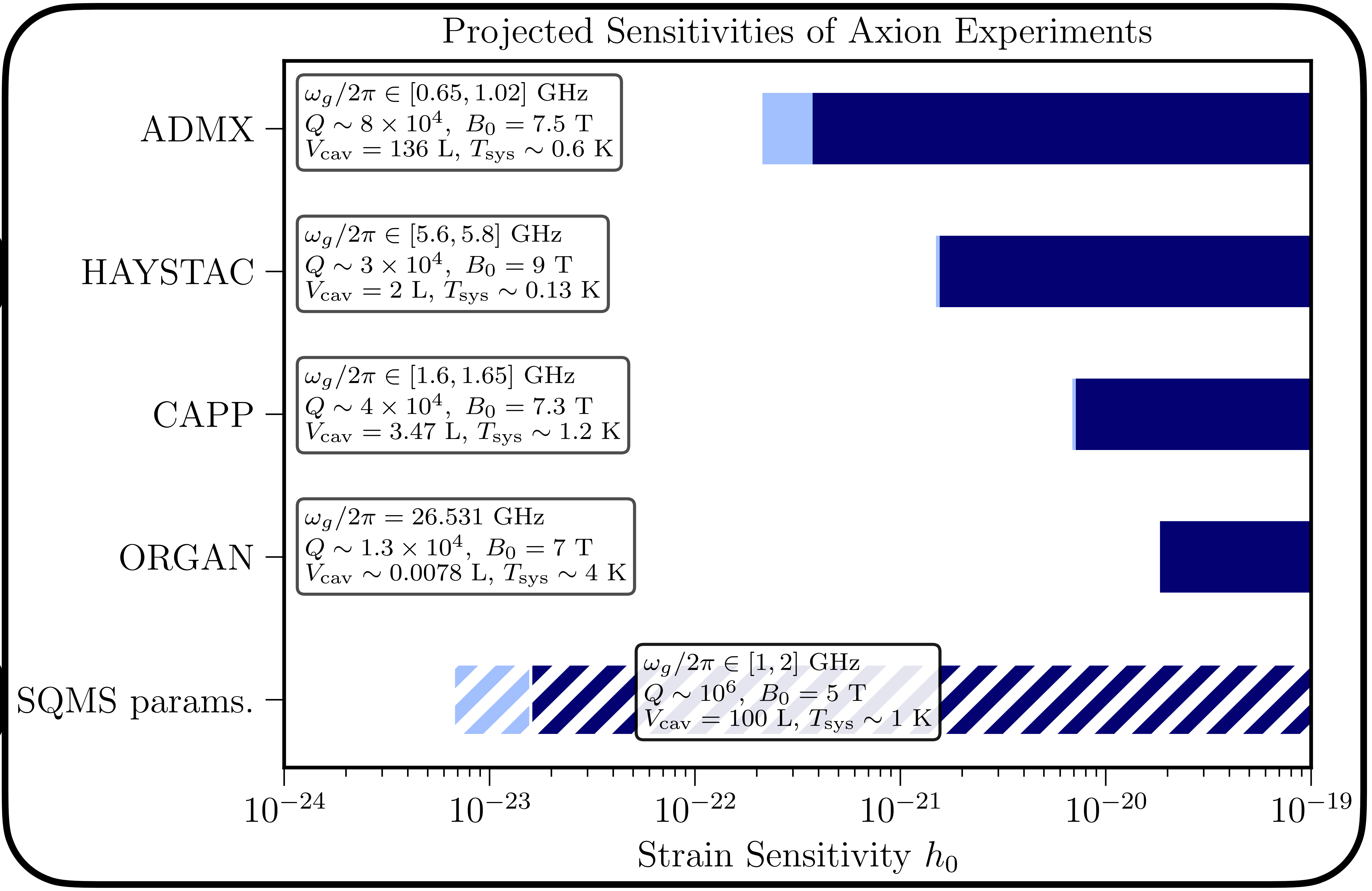

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More? *To appear w/ V. Domcke & J. Kopp*

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

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

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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

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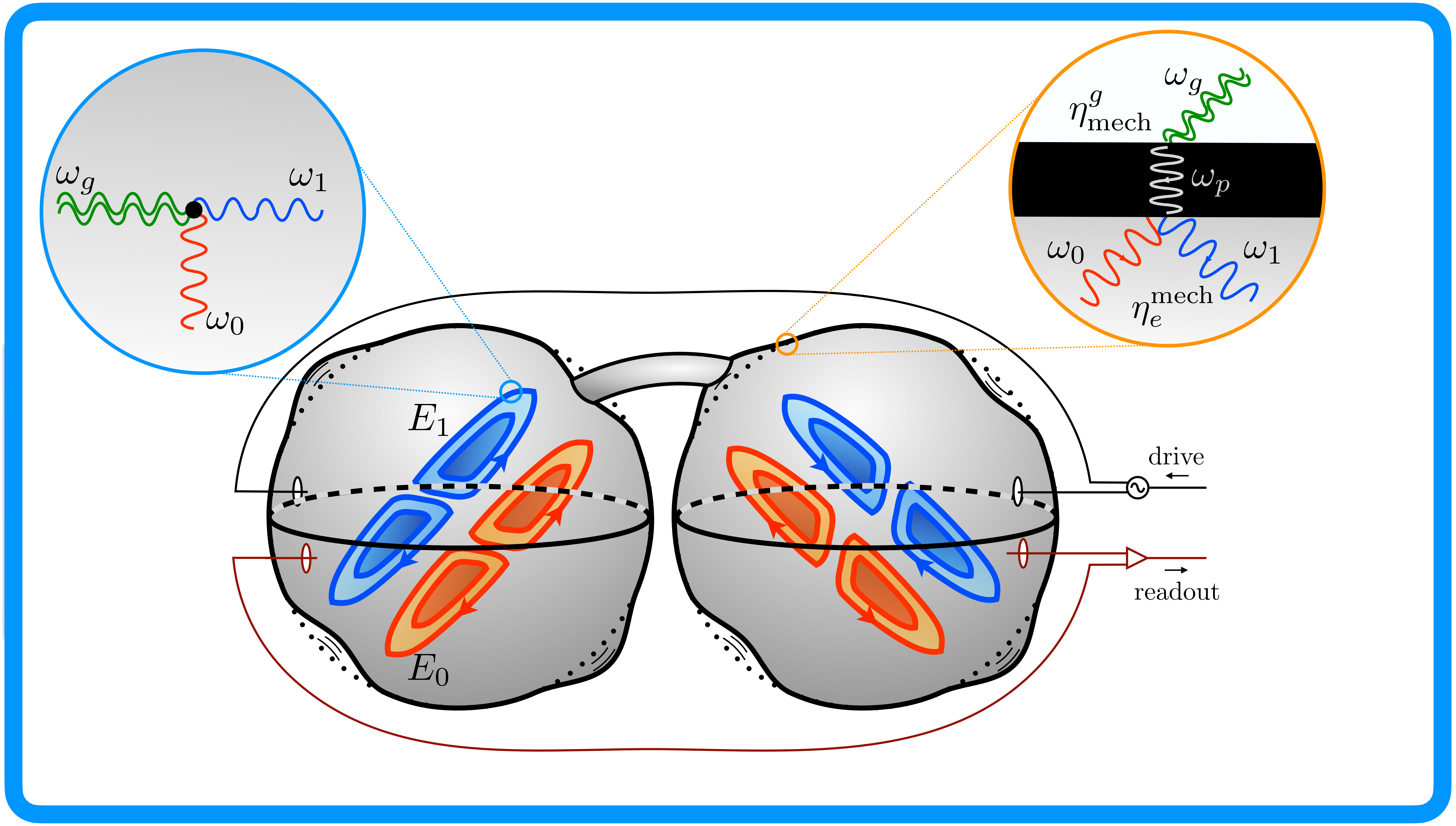

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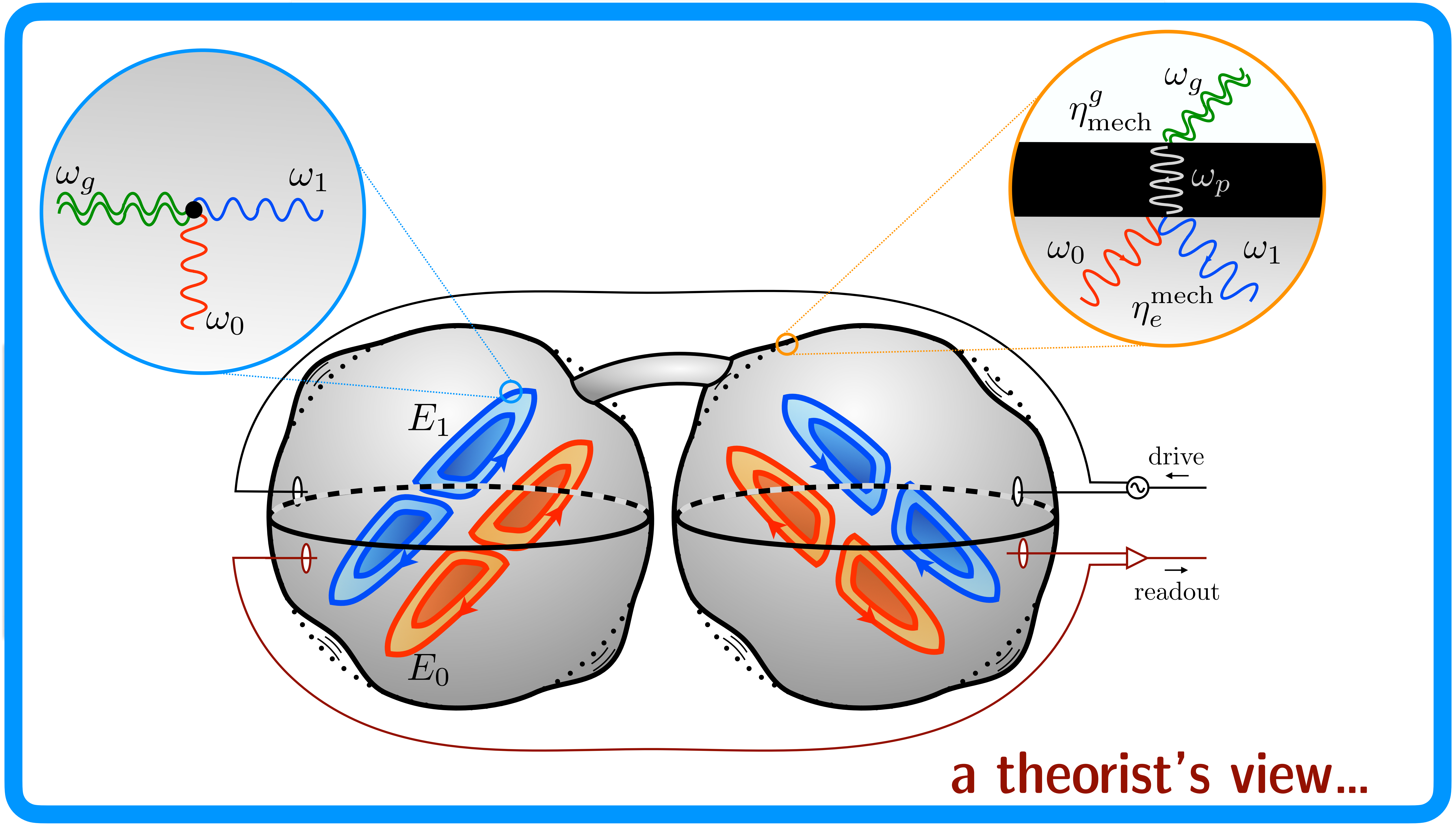

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EM and Mechanical signals

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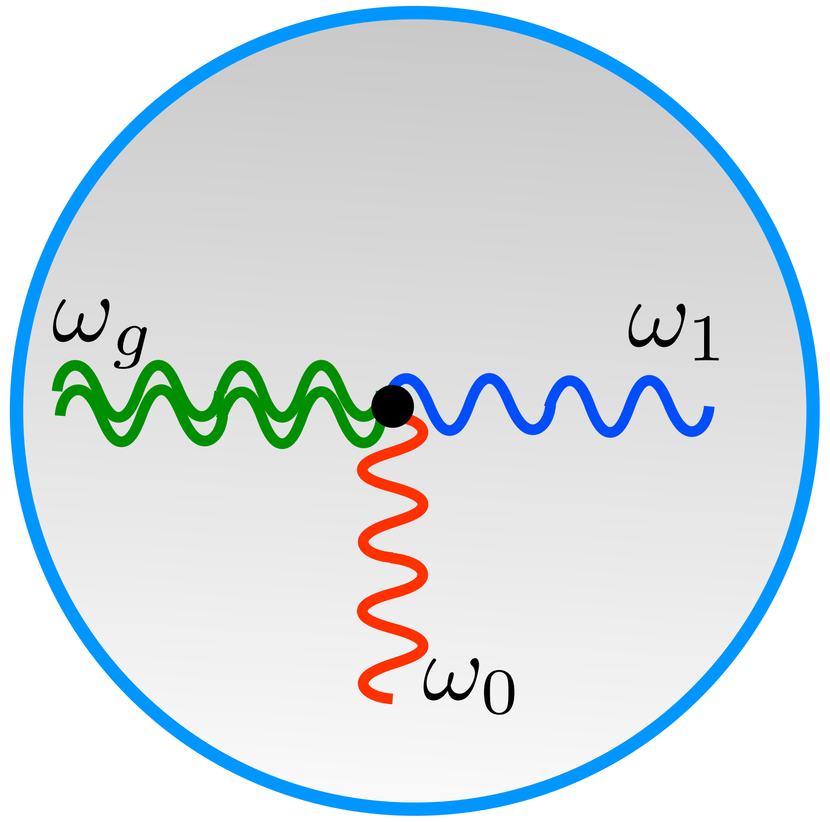
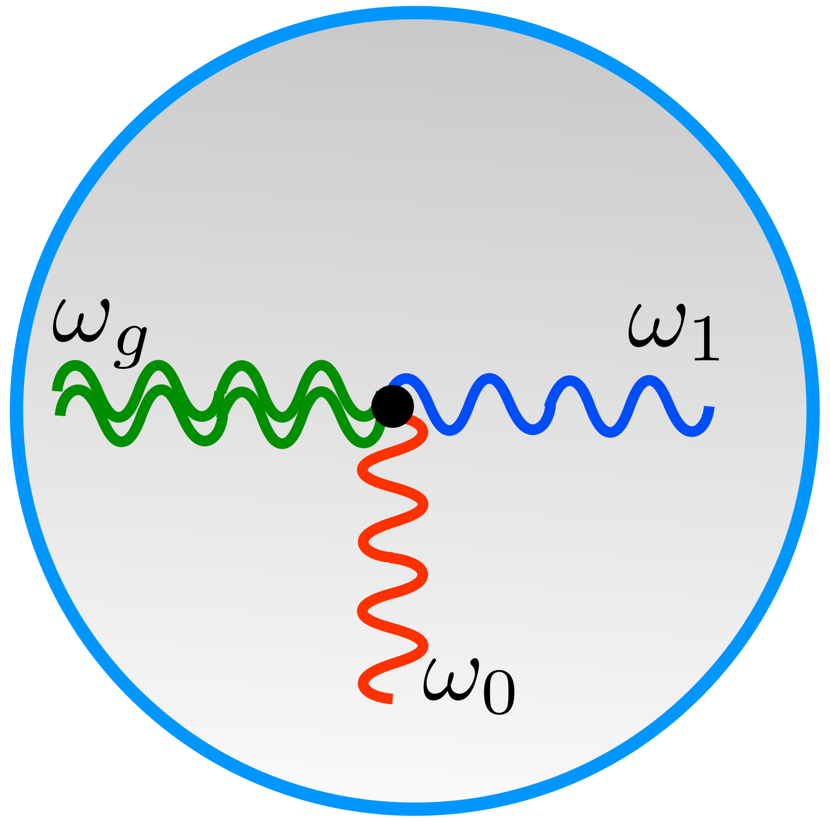


Parametrics of the EM signal: $E_{\rm sig}^{\rm (EM)} \sim Q_{\rm em}\,(\omega_g\,L_{\rm cav})^2\,h^{\rm TT}\,E_0$

EM and Mechanical signals



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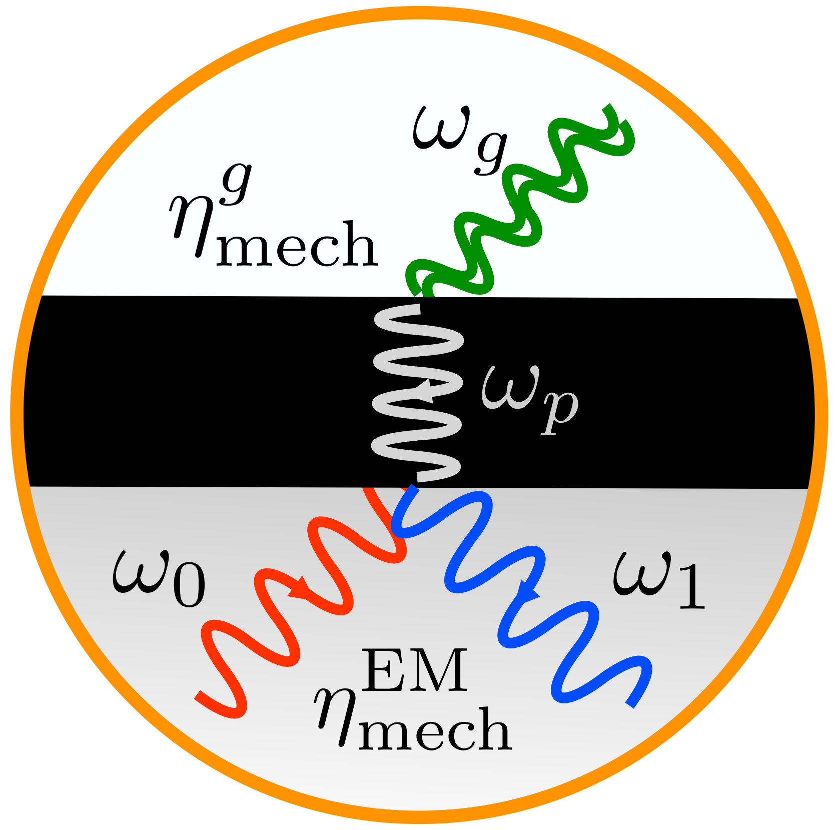
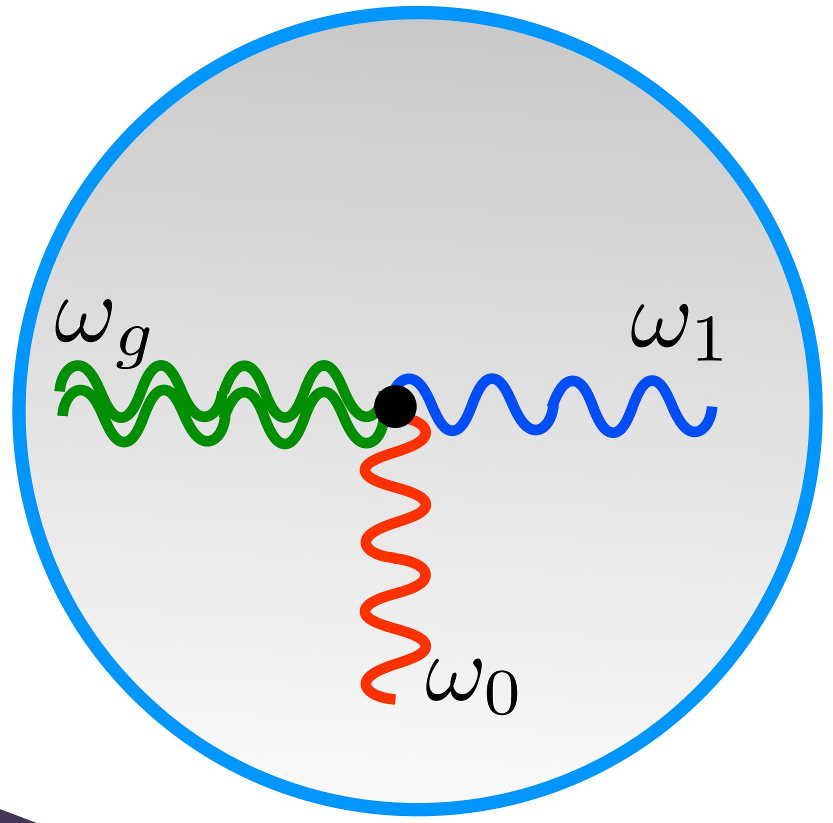
Mechanical signal: $E_{\rm sig}^{\rm (mech)} \sim Q_{\rm em}\,h^{\rm TT}\,E_0\,\min\left(1\,,\,\frac{\omega_g\,L_{\rm cav}}{c_s}\right)^2$



EM and Mechanical signals



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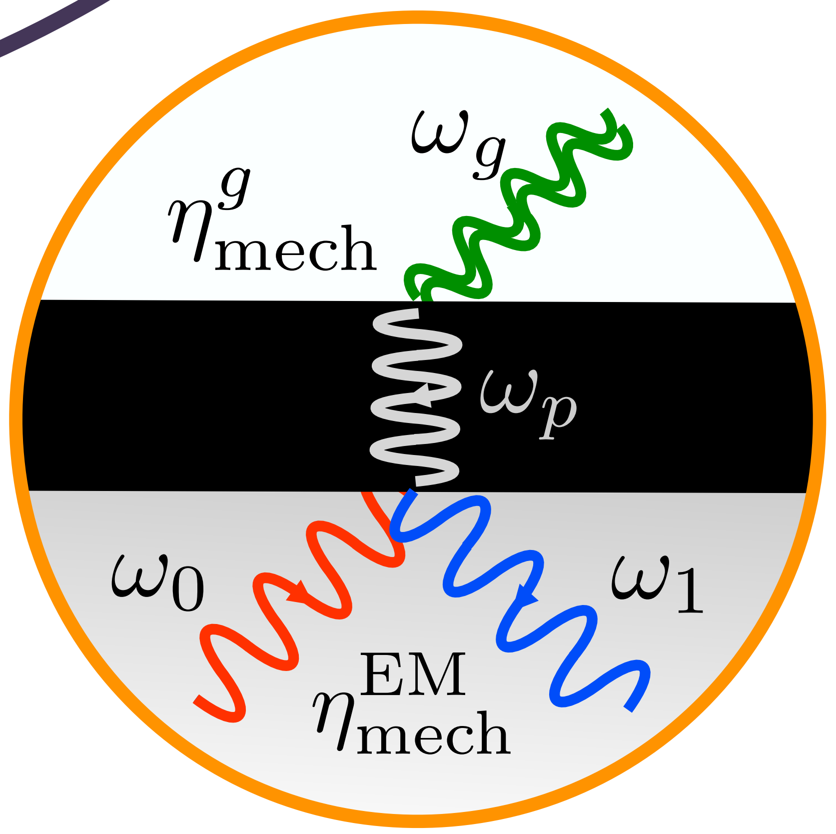
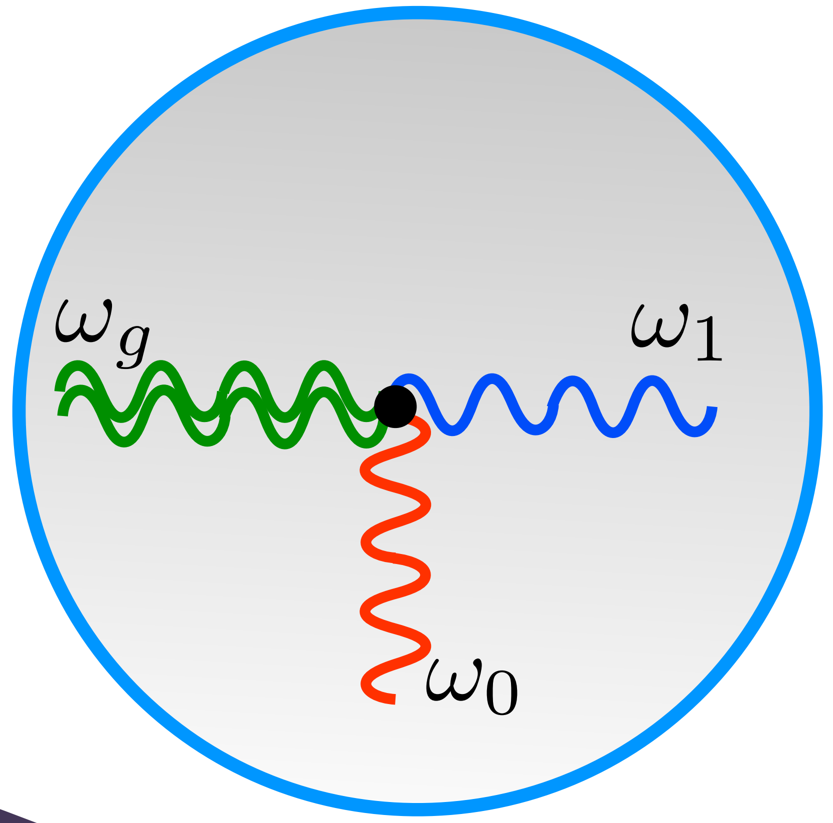
Enhanced up to $1/c_s^2 \gg 1$ *(!)*

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



EM and Mechanical signals



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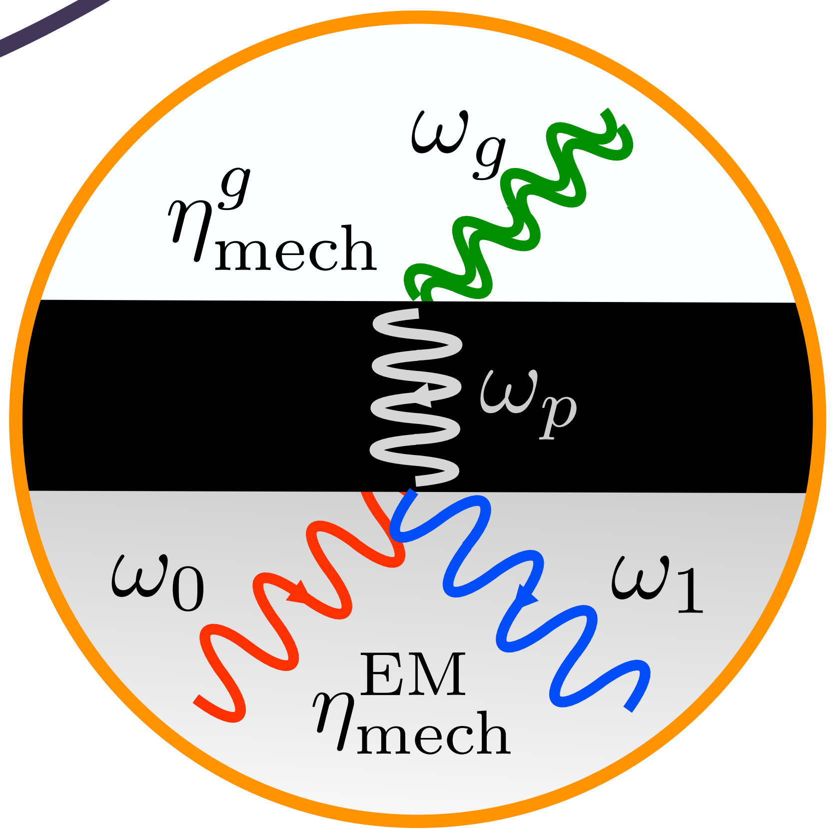
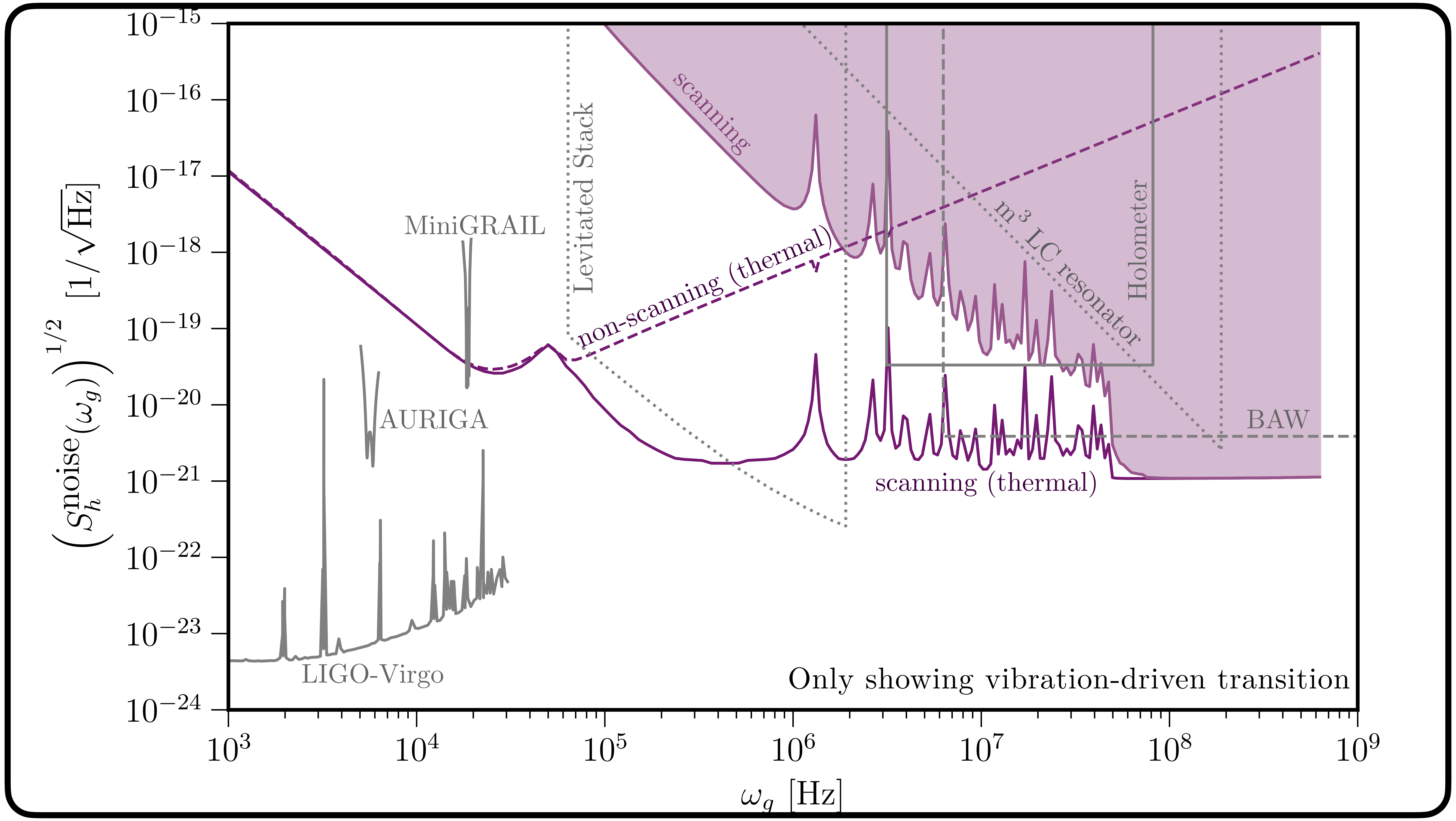


Mechanical modes less "rigid" than EM modes

MAGO 2.0



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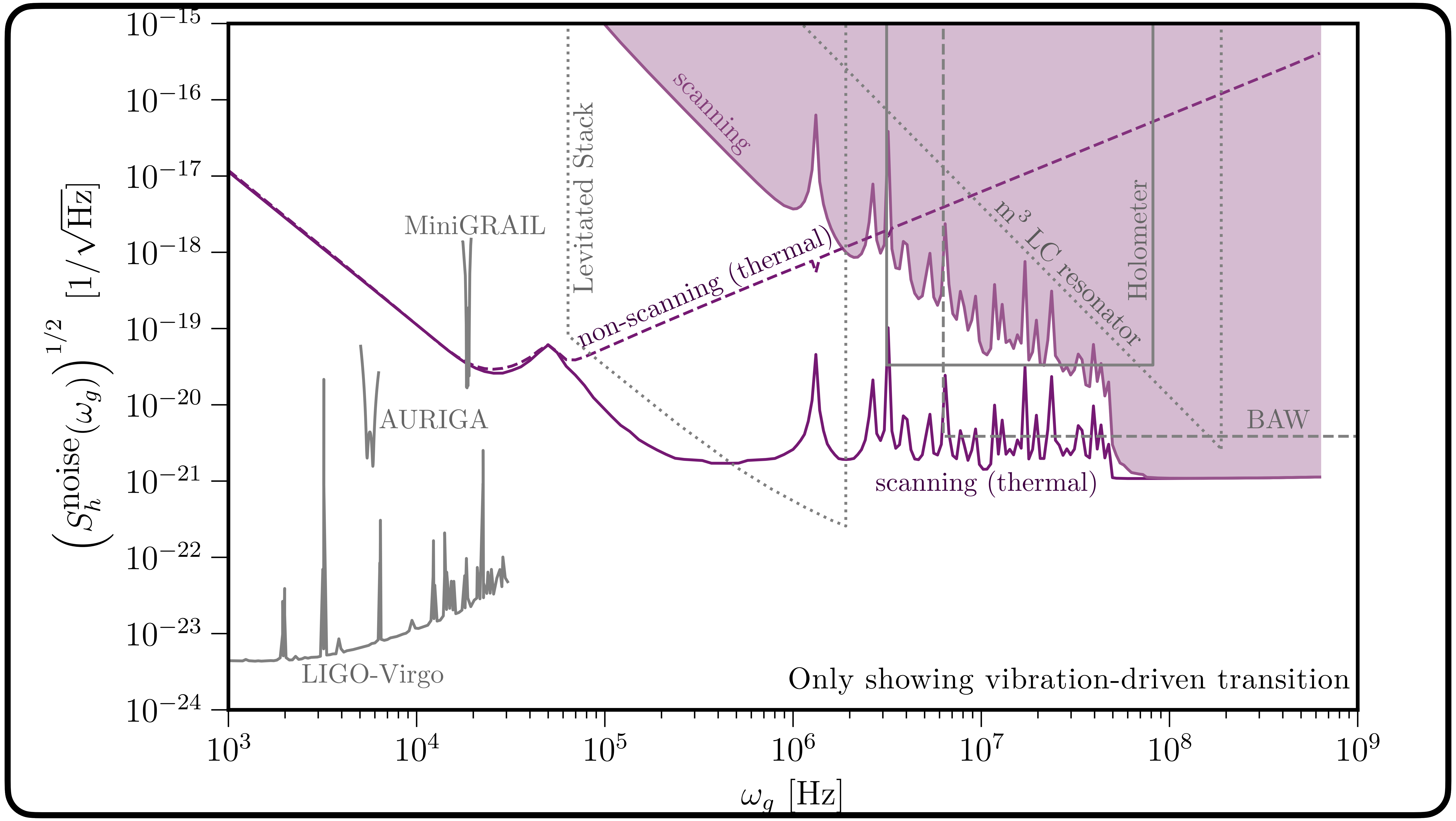

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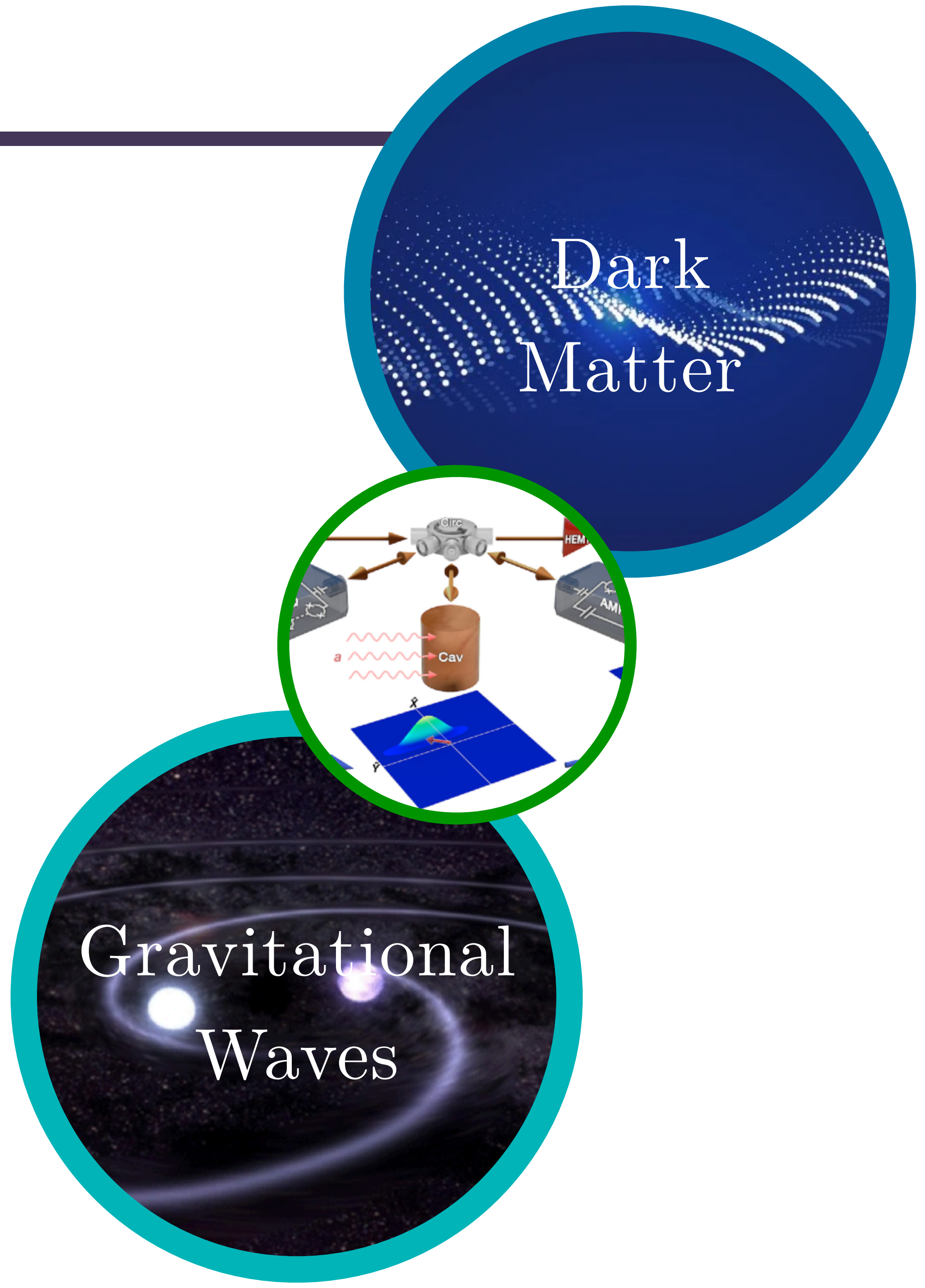
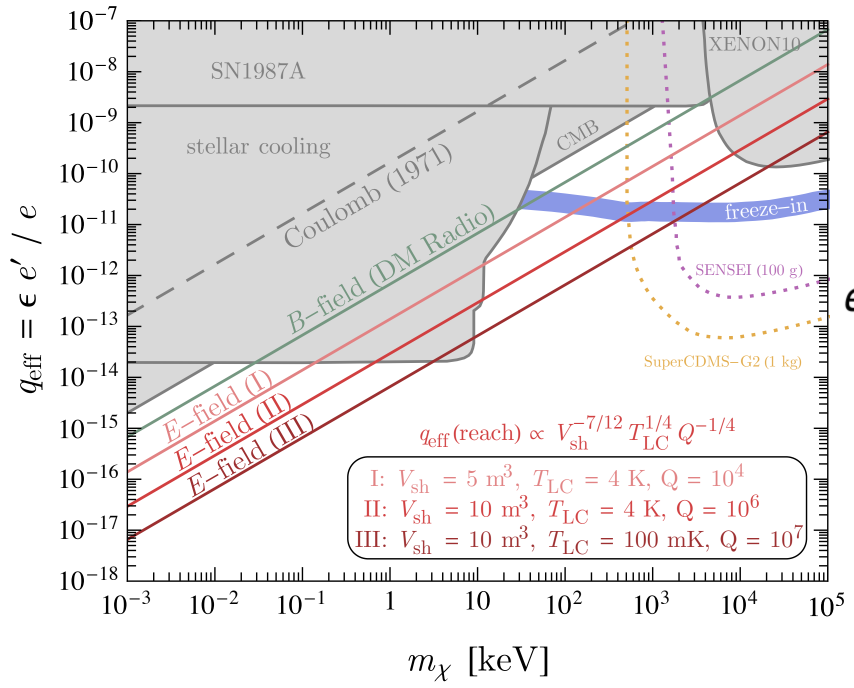
SQUIDs for quantum sensing of other unlikely Weber Bar? *To appear with V. Domcke & N. L. Rodd*

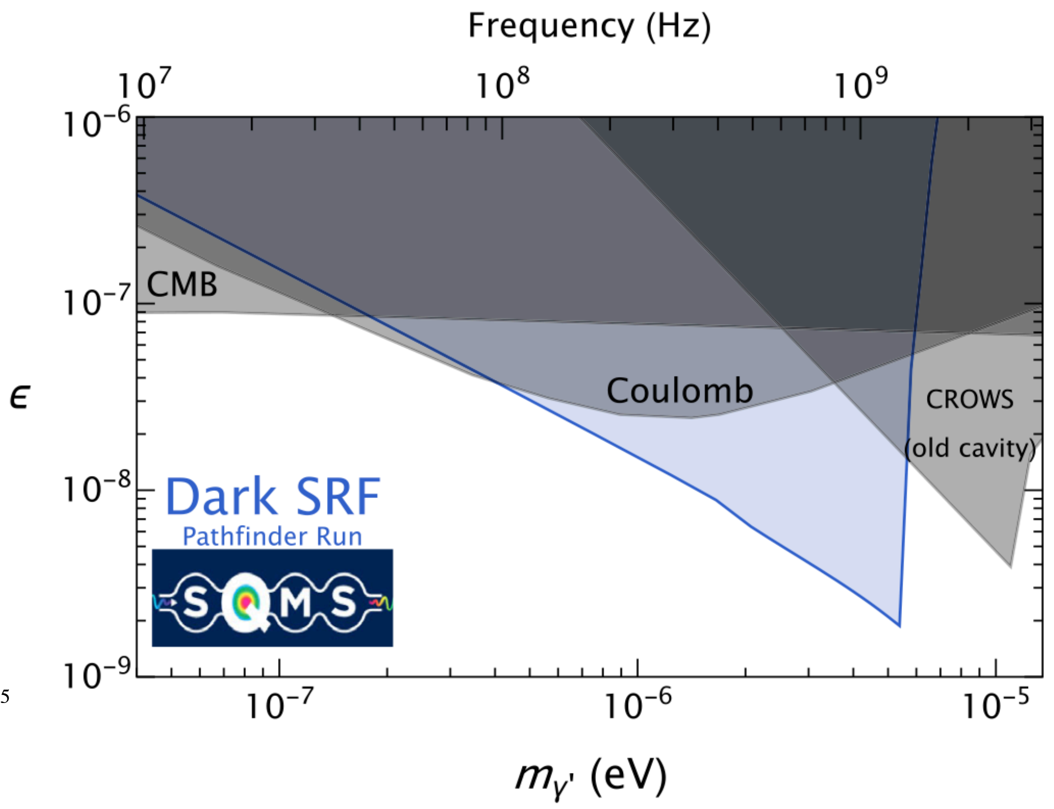
Summary



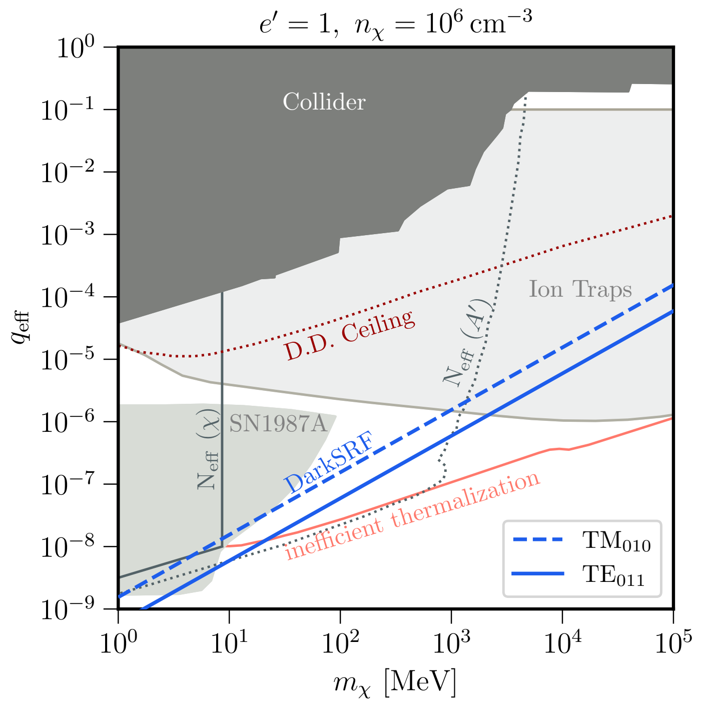
Dark Matter
Gravitational Waves



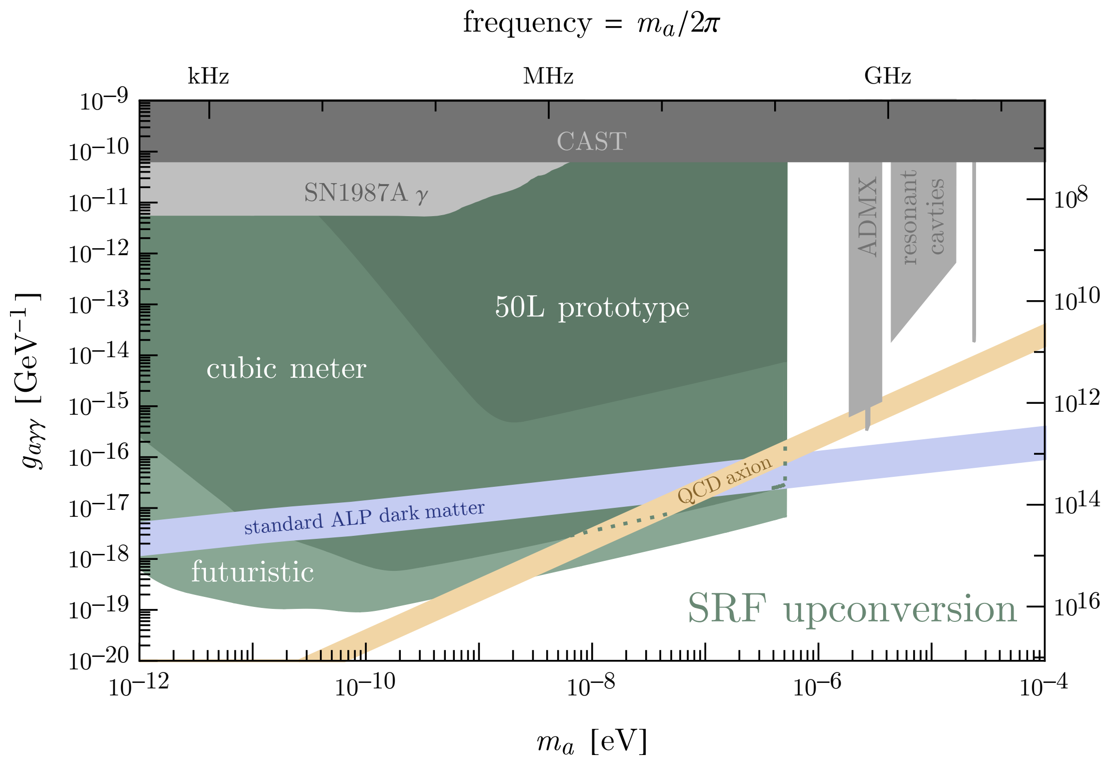
SN1987A
stellar cooling
XENON10
CMB
Coulomb (1971)
B-field (DM Radio)
freeze-in
E-field (I)
E-field (II)
E-field (III)
$q_{\rm eff} = \epsilon\, e' / e$
m_χ [keV]



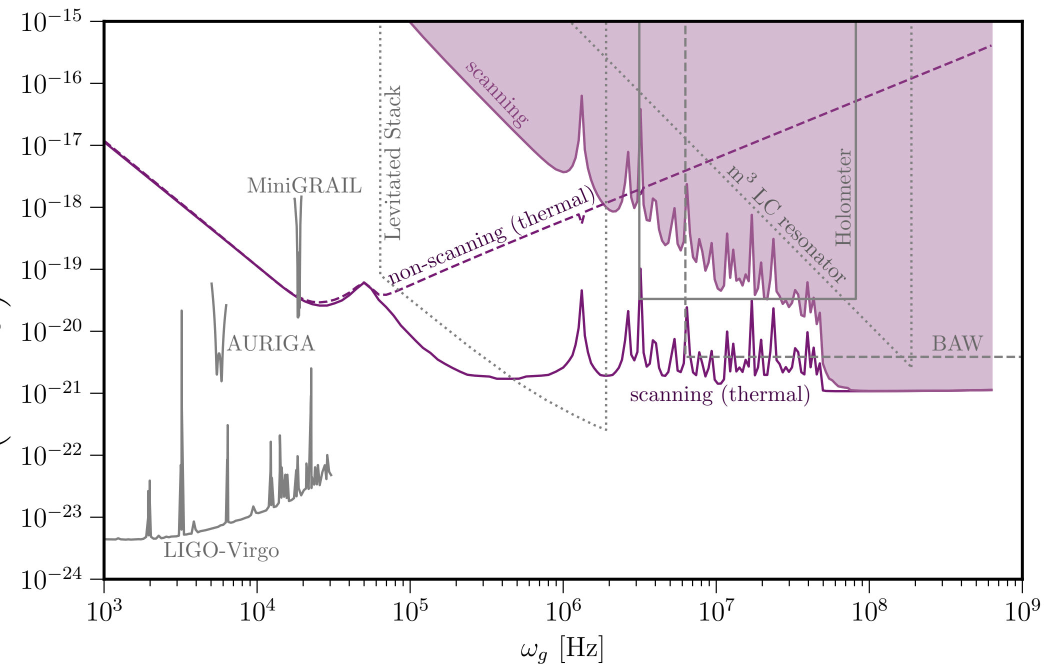
Frequency (Hz)
CMB
Coulomb
CROWS
(old cavity)
Dark SRF
Pathfinder Run
SQMS
ϵ
$m_{\gamma'}$ (eV)



$e' = 1,\ n_\chi = 10^6\,\mathrm{cm}^{-3}$
Collider
Ion Traps
D.D. Ceiling
SN1987A
DarkSRF
inefficient thermalization
TM010
TE011
$q_{\rm eff}$
m_χ [MeV]

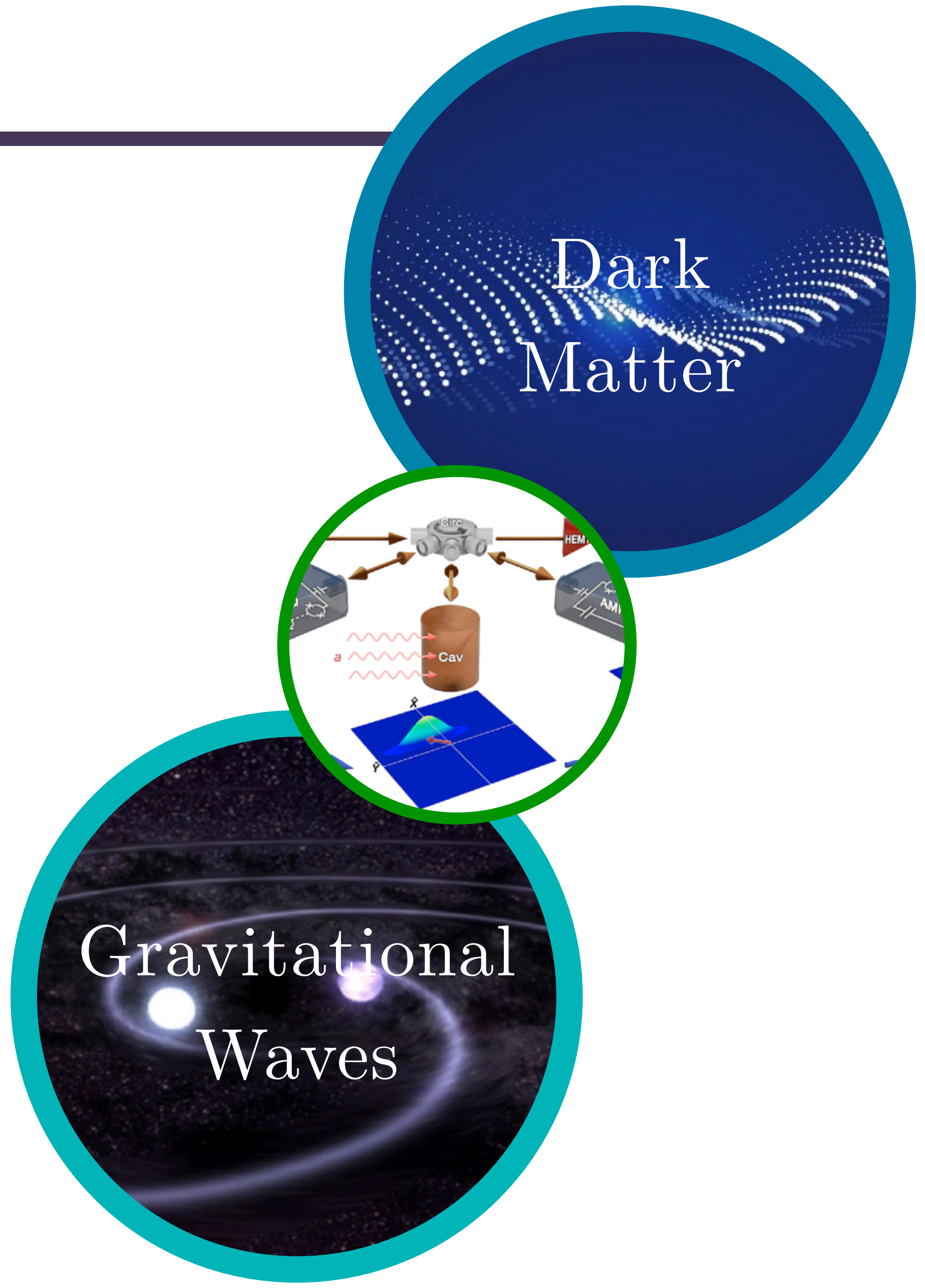


frequency = $m_a/2\pi$
kHz
MHz
GHz
CAST
SN1987A γ
50L prototype
cubic meter
ADMX
resonant cavities
standard ALP dark matter
QCD axion
futuristic
SRF upconversion
$g_{a\gamma\gamma}$ [GeV^{-1}]
m_a [eV]

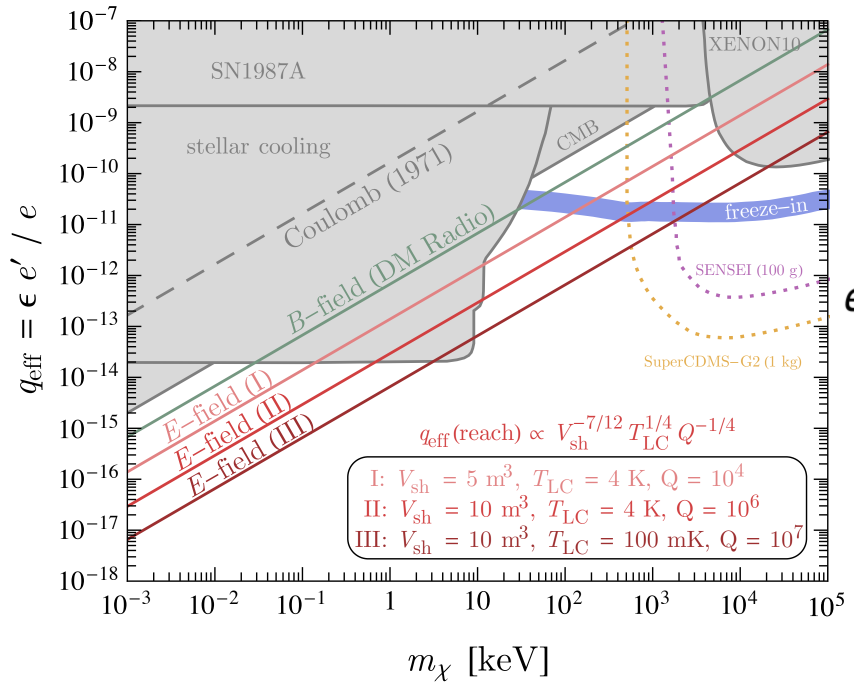


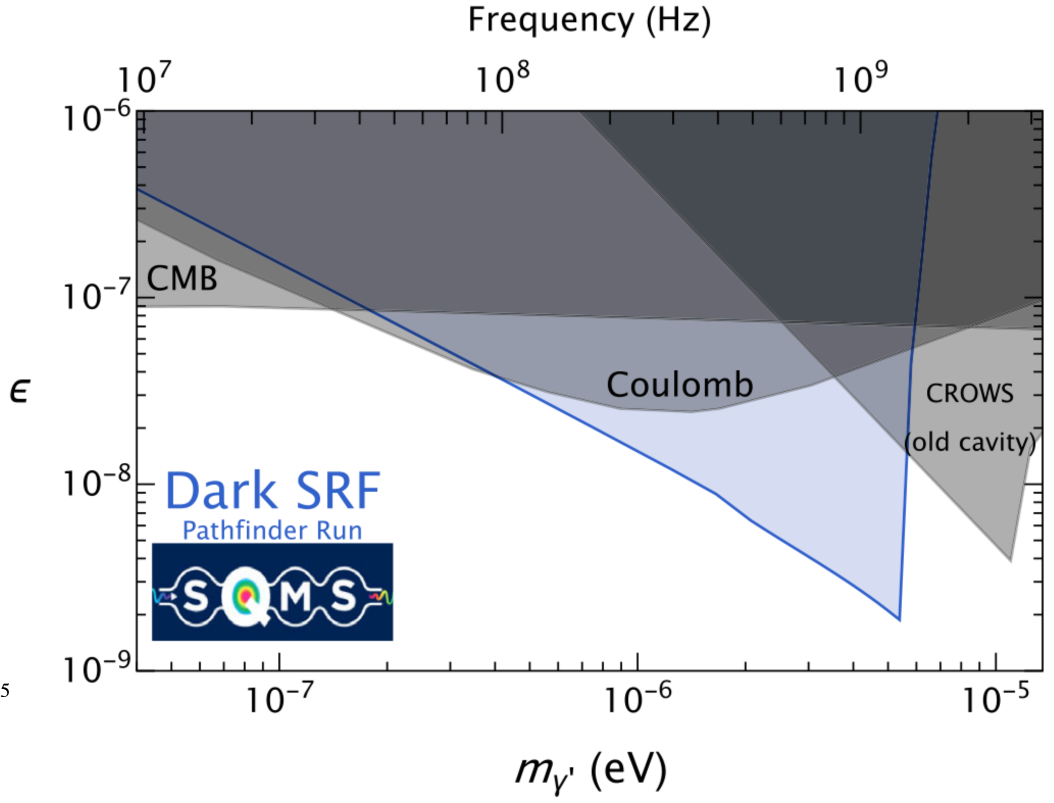
scanning
MiniGRAIL
Levitated Stack
non-scanning (thermal)
m^3 LC resonator
Holometer
AURIGA
BAW
scanning (thermal)
LIGO-Virgo
ω_g [Hz]

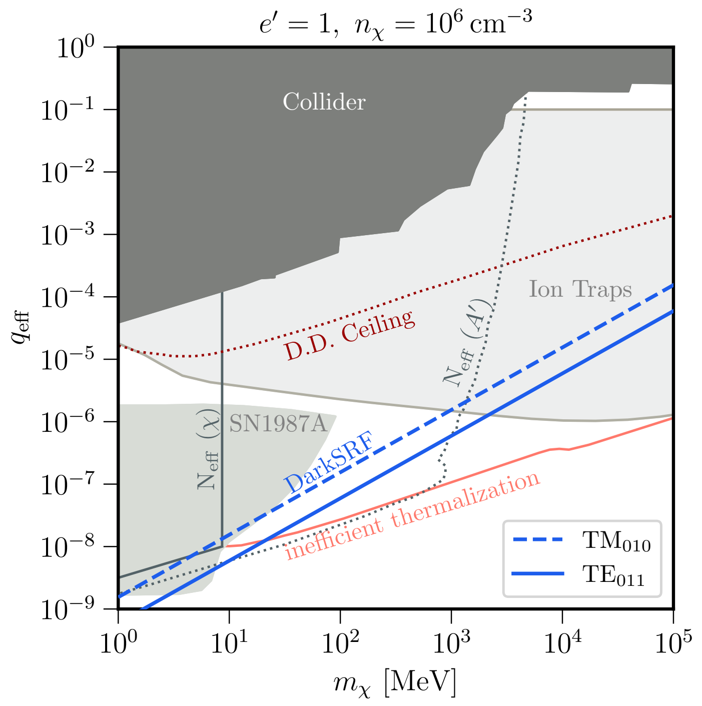
Summary

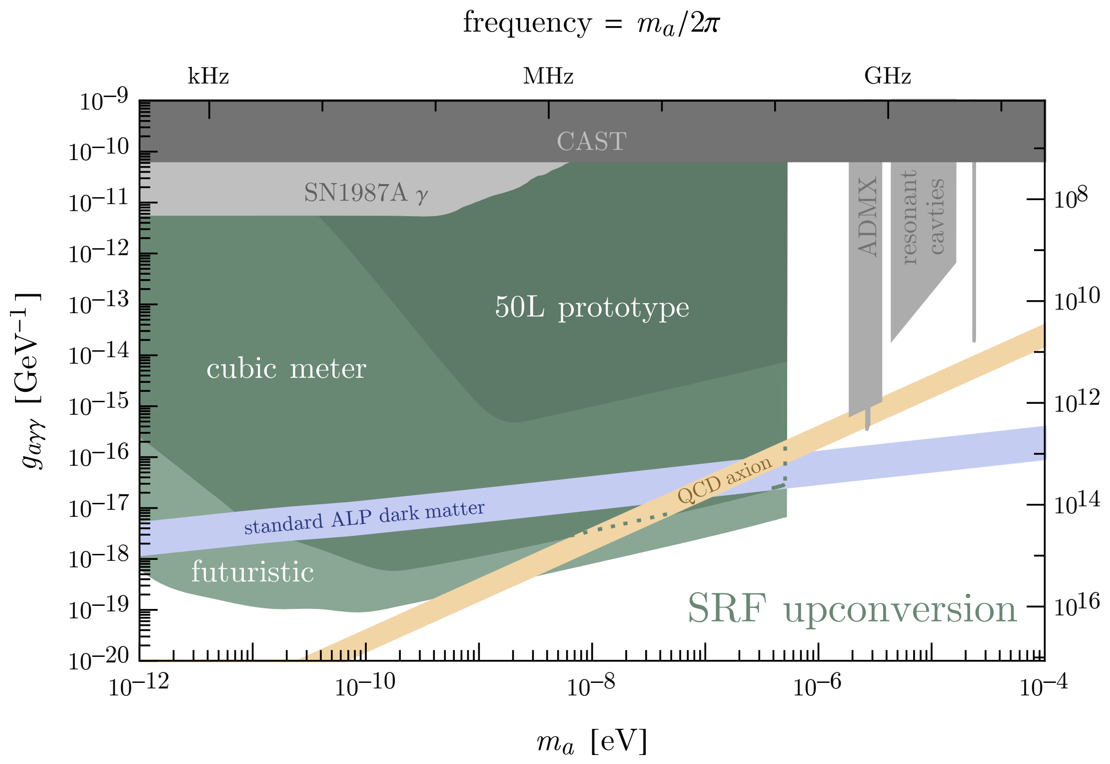


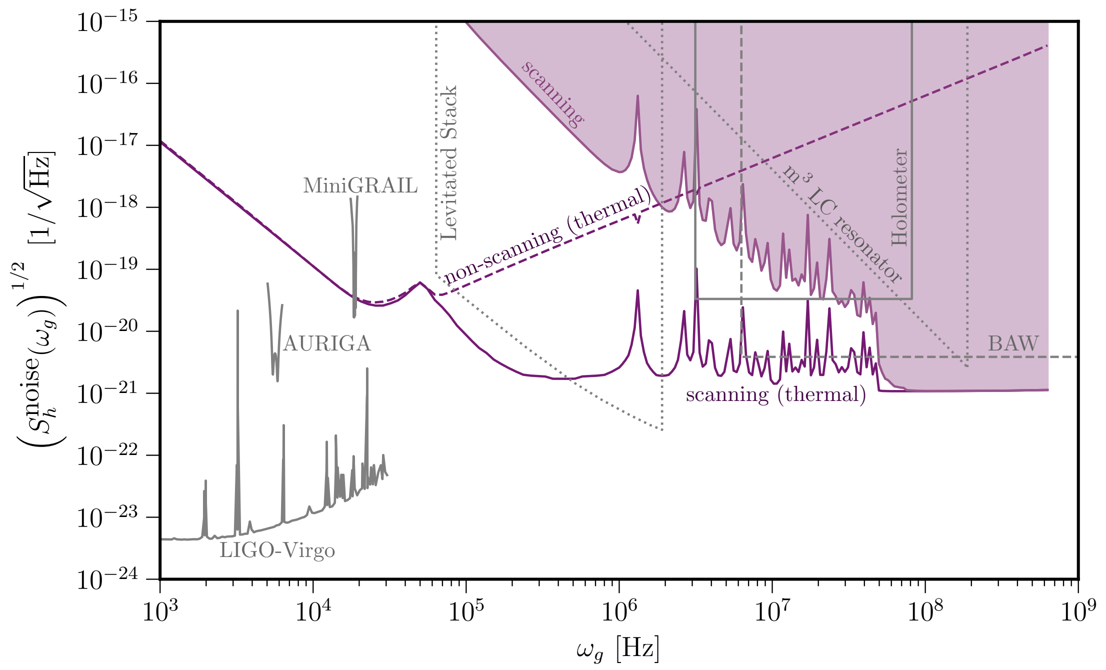
Age of Quantum for detecting weakly-coupled signals just beginning











Summary

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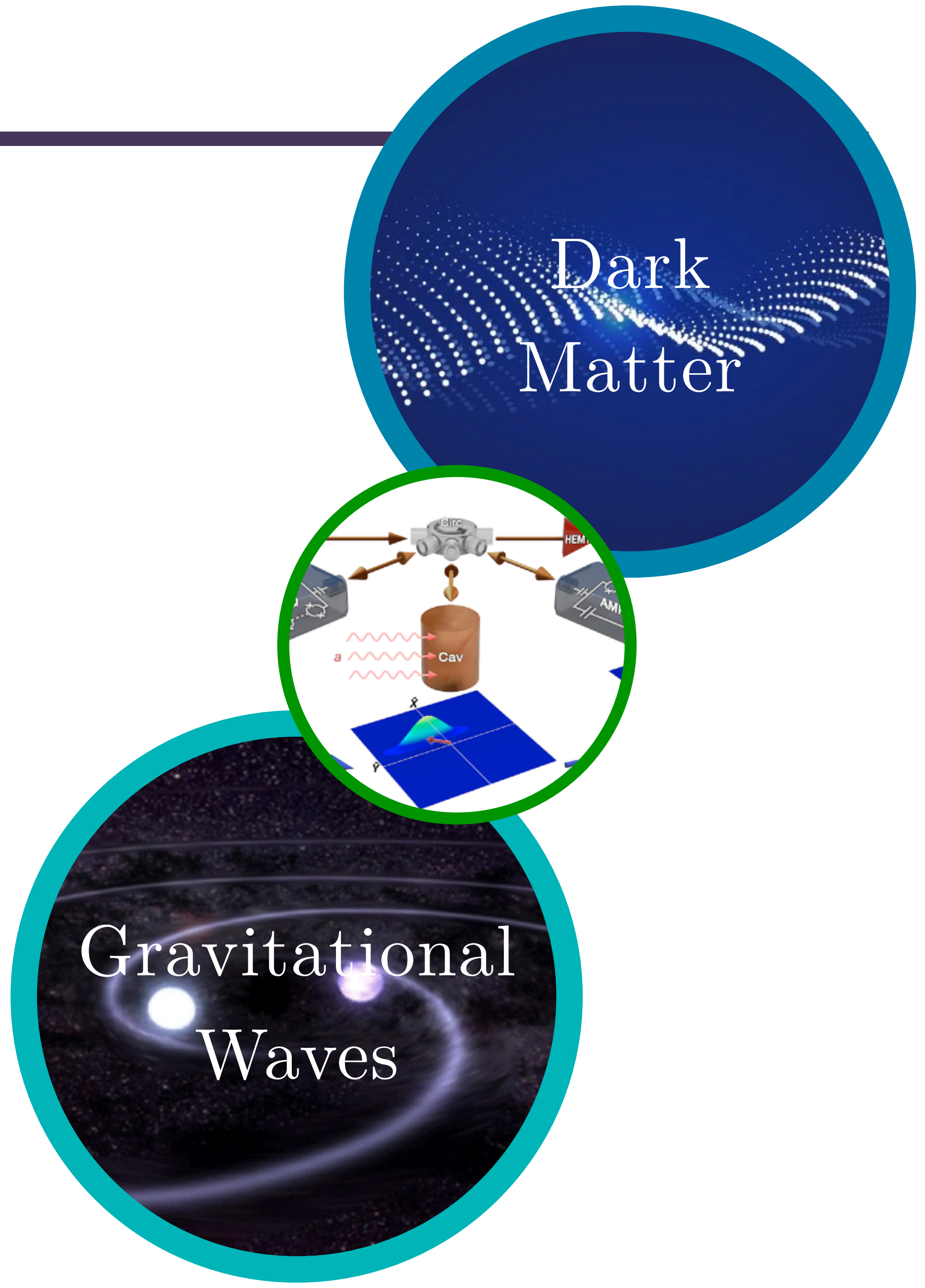
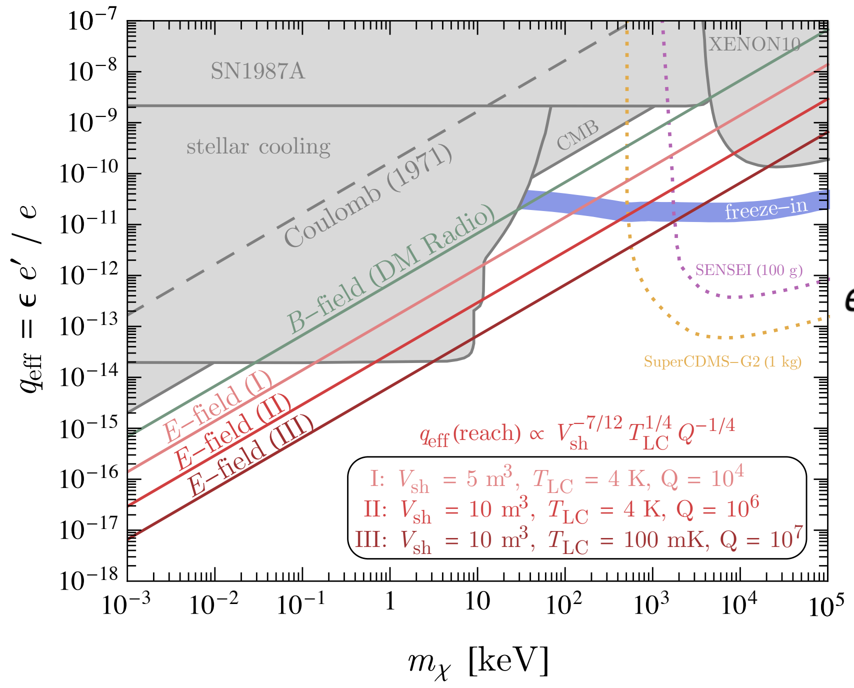
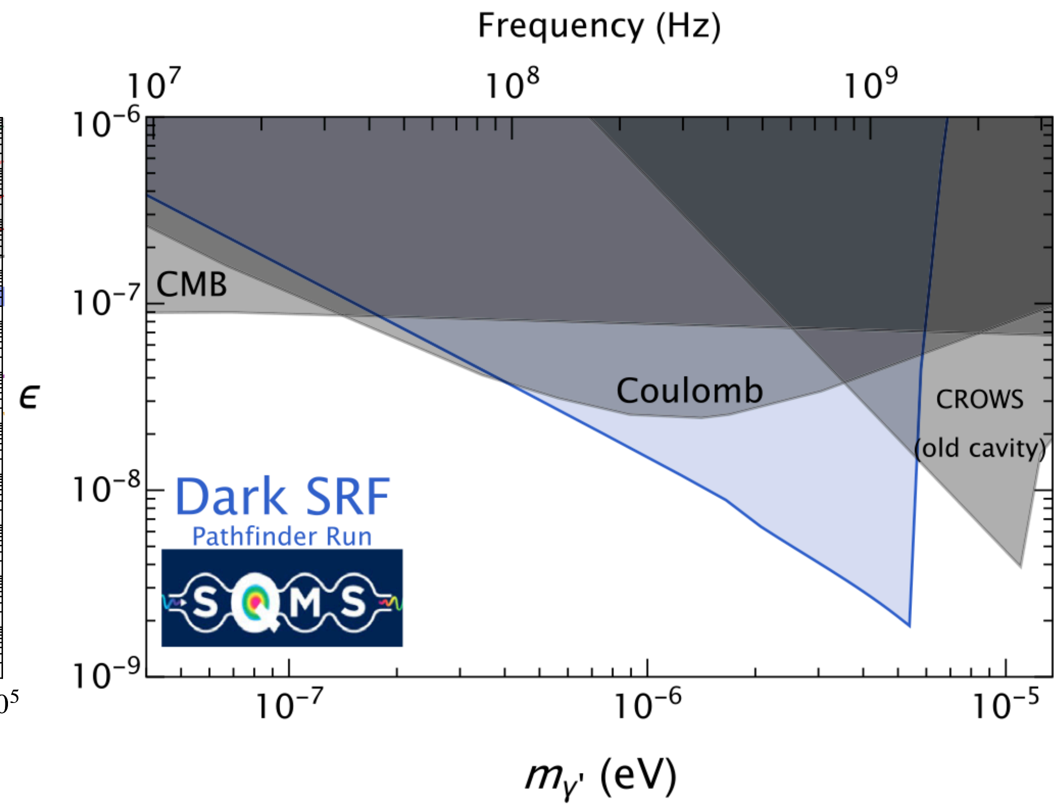
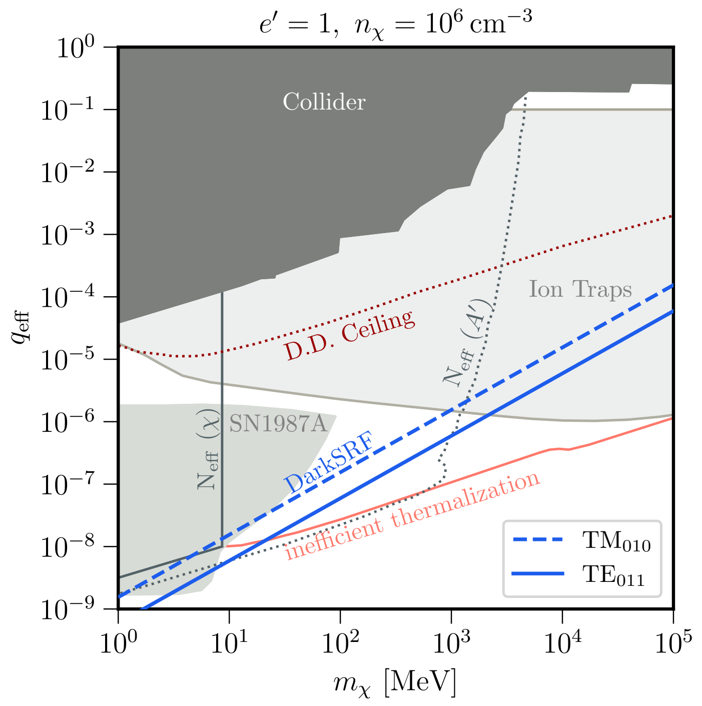
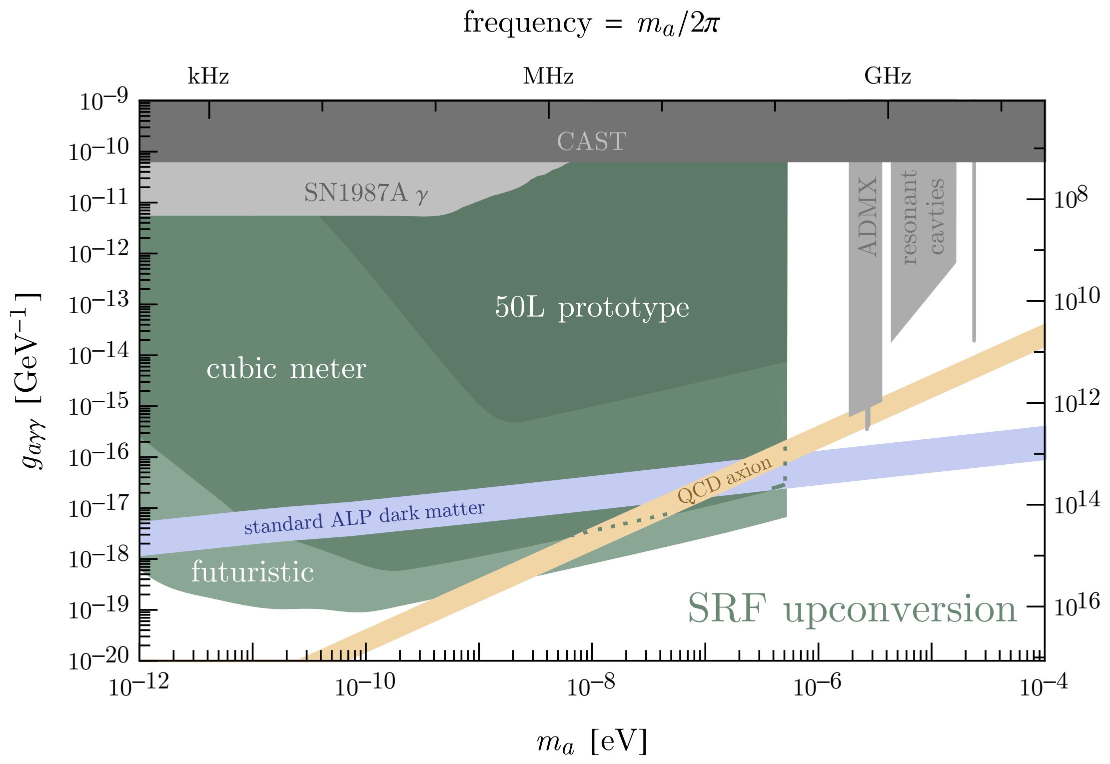
Sensors classed as "quantum" in various ways

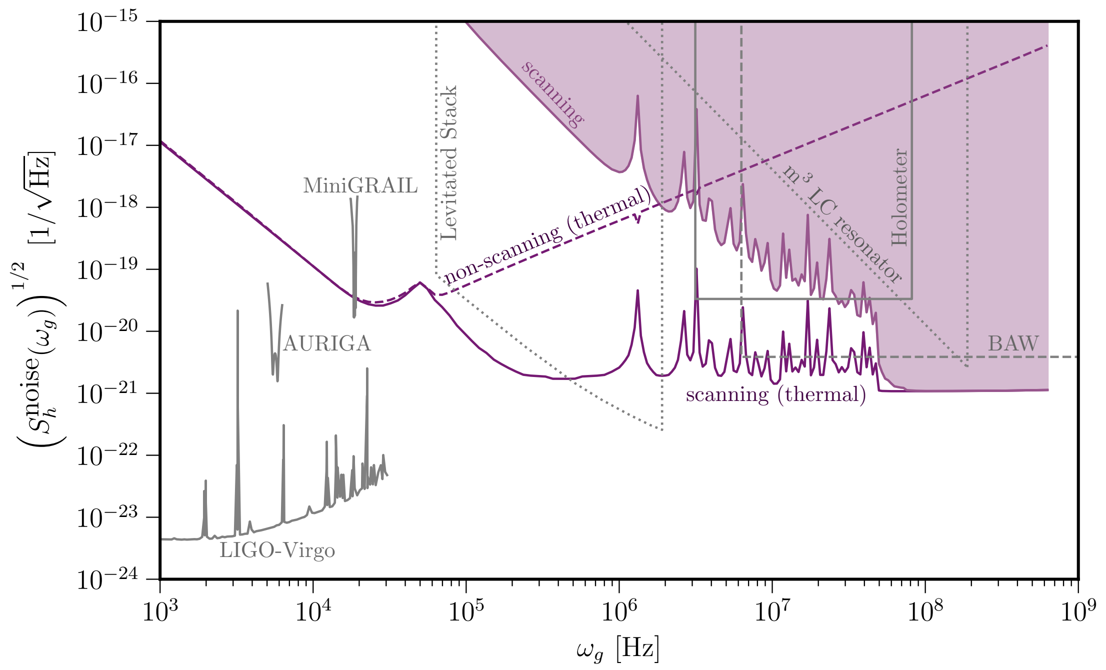




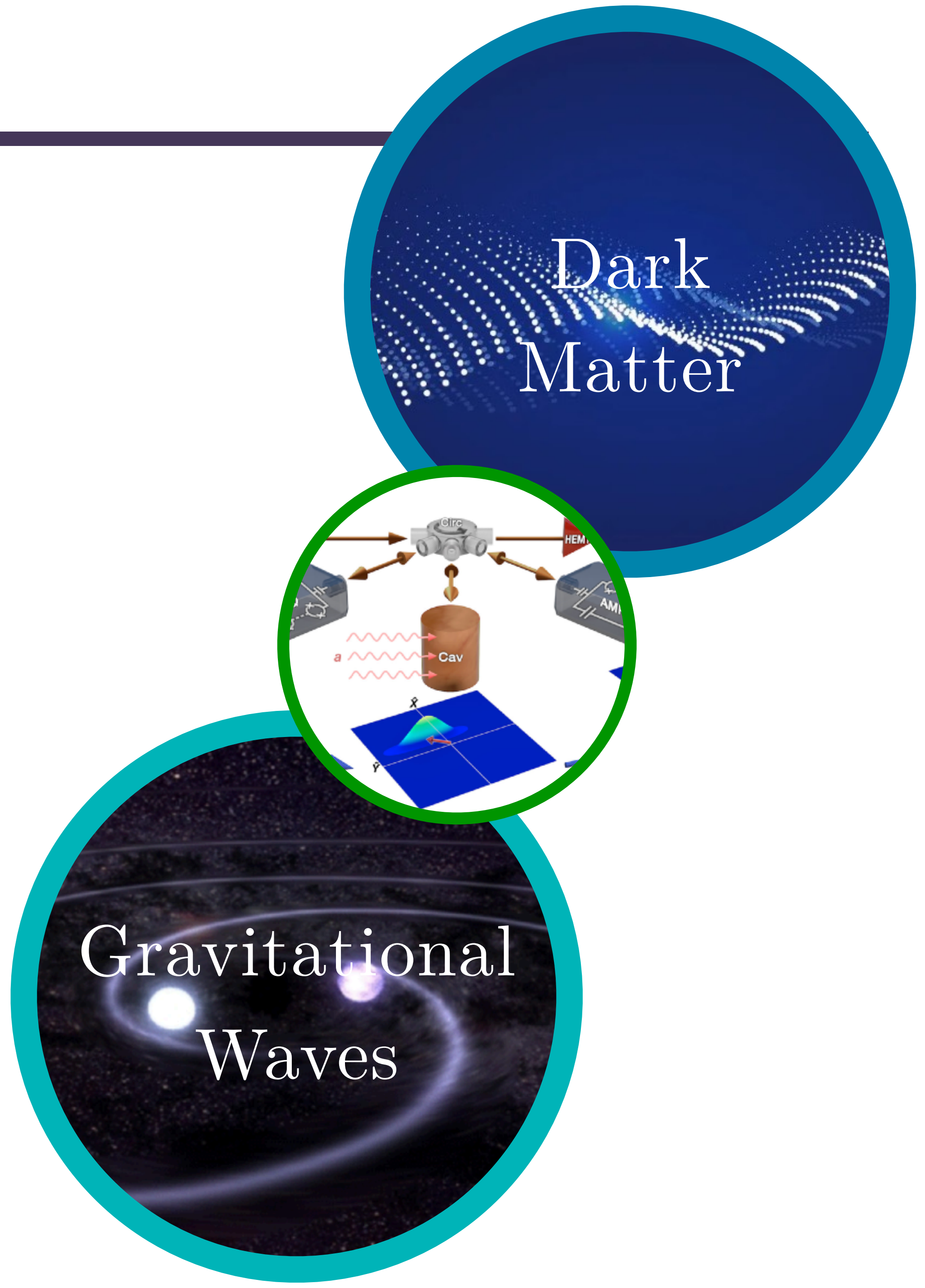








Summary



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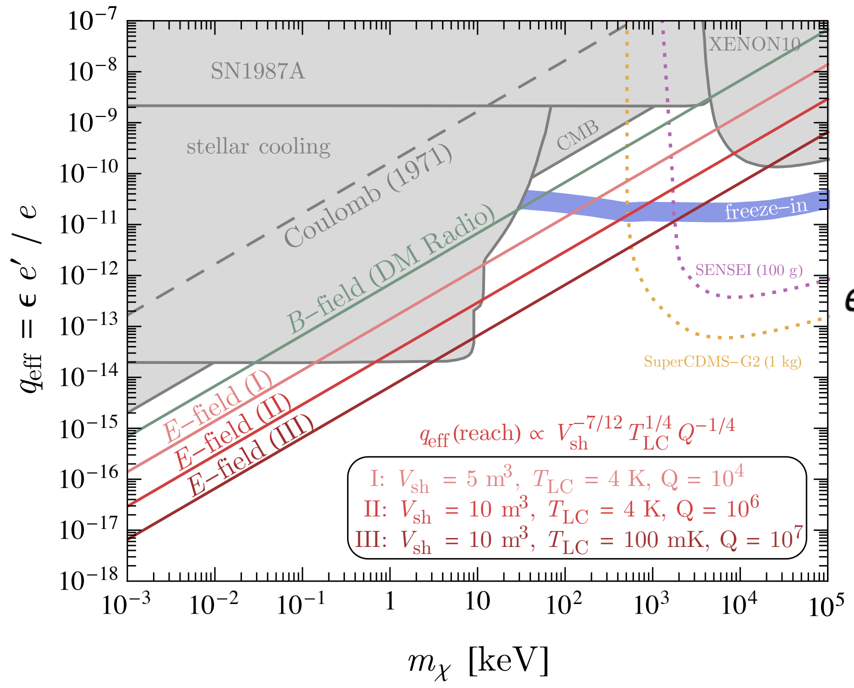
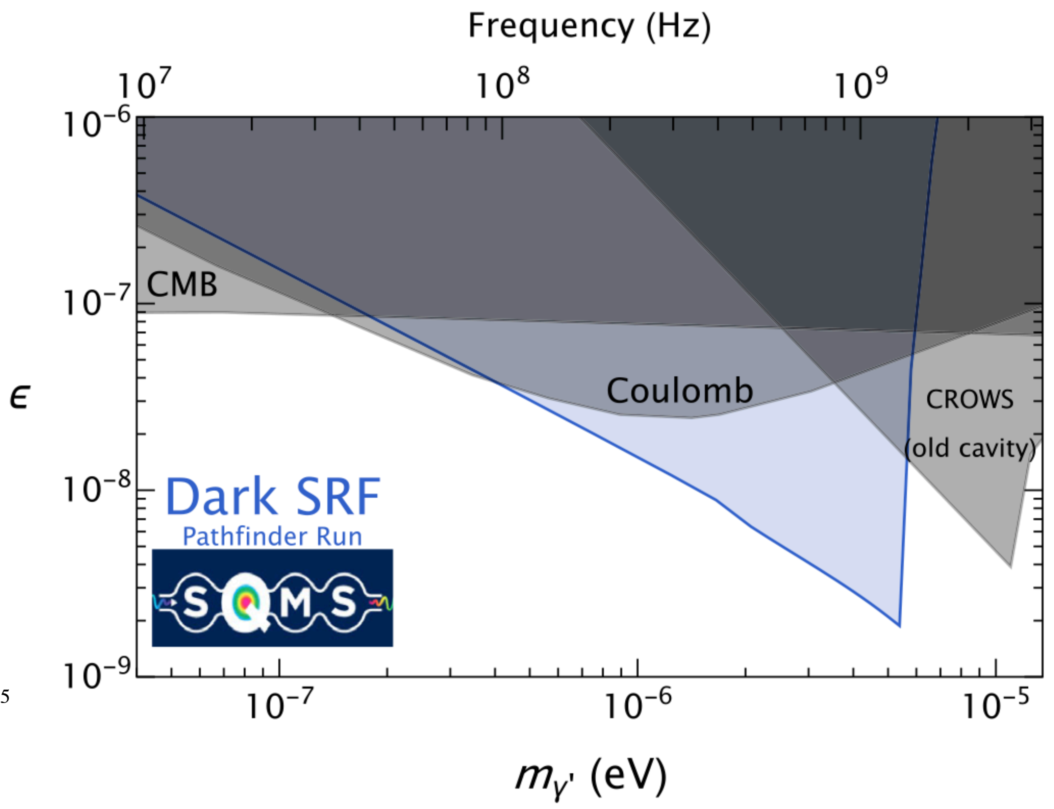
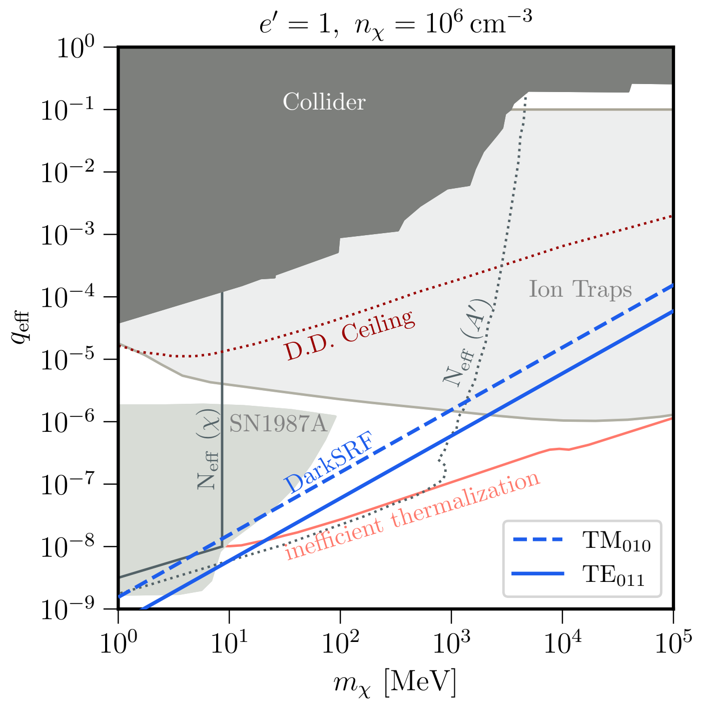
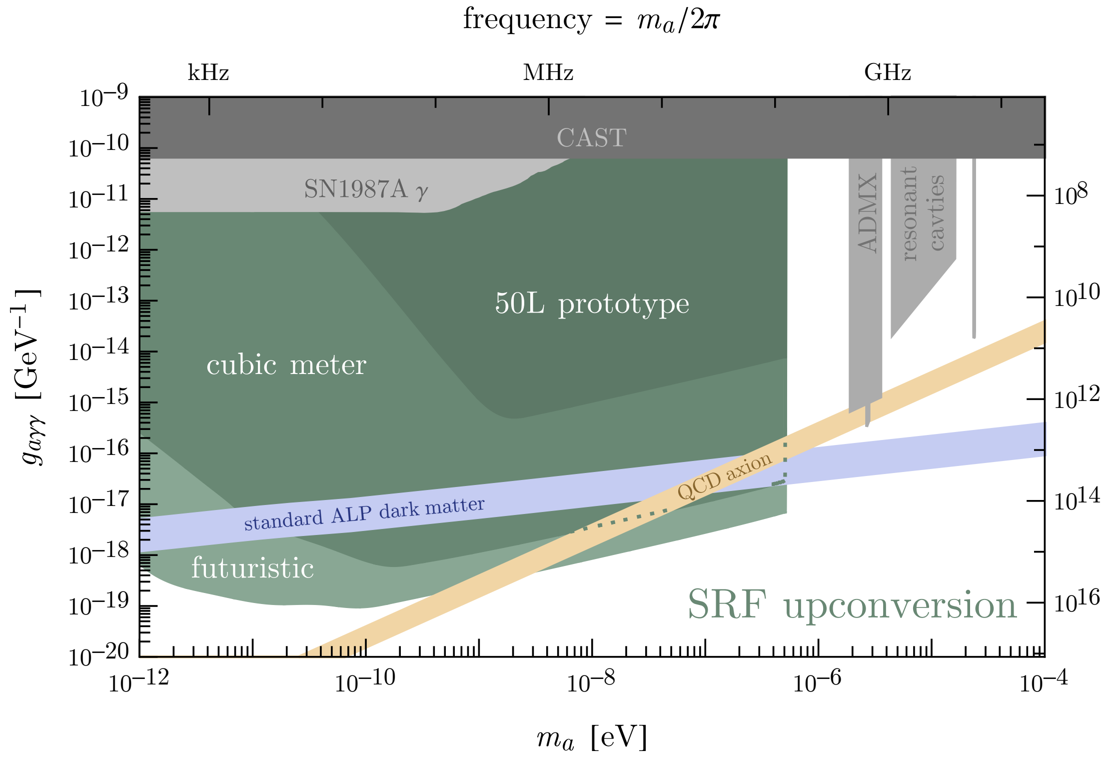
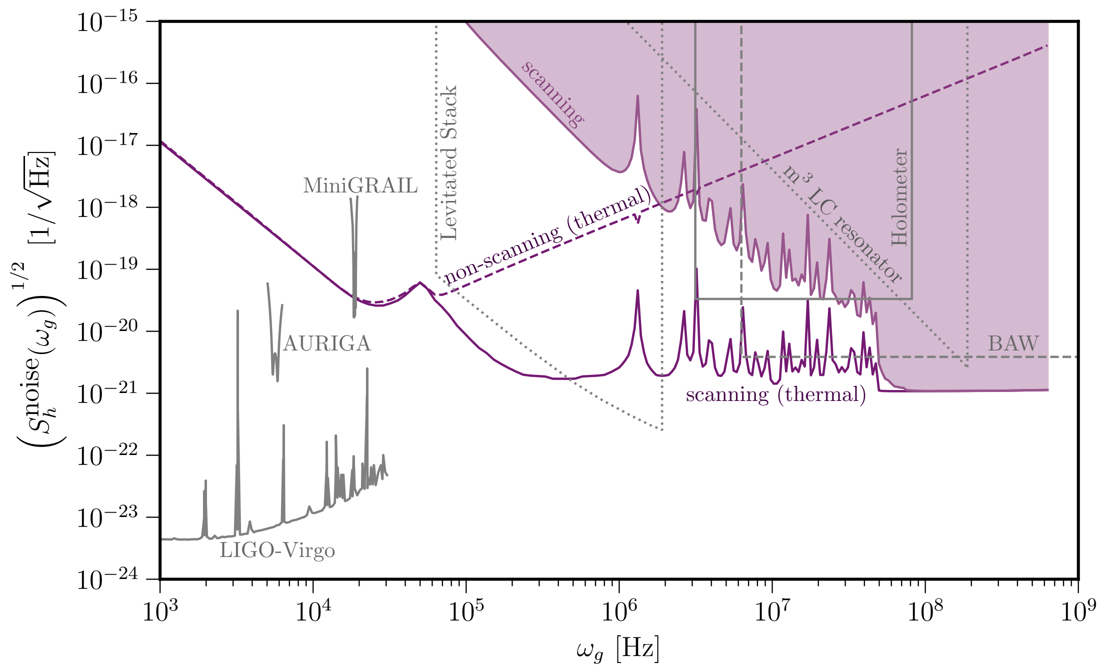
Accelerator tech can probe wide range of signals:











For those interested, quantum sensing is a fascinating intersection of classical, quantum, atomic physics, materials physics, fluid dynamics, statistics, GR, QFT…