Searching for Ultra-Light Hidden Photons

with:

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and experimental collaborators:

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Surjeet Rajendran, UC Berkeley

OUTLINE

1. Ultra-light hidden photons: theory

2. Searching for ultra-light hidden photons

3. The importance of the longitudinal mode

4. Searching for hidden photon dark matter

ULTRA-LIGHT HIDDEN PHOTONS

"ULTRA-LIGHT HIDDEN PHOTONS"

Hidden Photons:

Kinetically-mixed, massive, $U(1)'$ gauge boson A':

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{A'} + \mathcal{L}_{kin.\ mix}$$

$\mathcal{L}_{A'}$: $\left(-\,{}^{1}\!/_{4}\, F'^{\,2} + {}^{1}\!/_{2}\, m_{\gamma'}^{2}\, A'^{2}_{\mu}\right)$

$\mathcal{L}_{kin.\ mix}$: $-\,2\varepsilon F_{\mu\nu} F'^{\mu\nu}$

Kinetic mixing $\varepsilon \ll 1$

Ultra-light:

Macroscopic Compton wavelength

$$\lambda_{Compton} = 1\ \mathrm{m} \times (10^{-6}\ \mathrm{eV}/m_{\gamma'})$$

A THOUGHT ON TINY MASSES

$$\lambda_{Compton} = \mathbf{1\ m \times (10^{-6}\ eV}/m_{\gamma'}\mathbf{)}$$

How to generate $m_{\gamma'} \lesssim 10^{-6}\,\mathrm{eV}$?

Stuckelberg mass vs. **Higgs mechanism**

— $m_{\gamma'}$ generated at string scale

— $m_{\gamma'}$ generated dynamically
— Constraints on light Higgs states
— Higgs decouples as $g_D \rightarrow 0$
— Assume light states decoupled

What does this new field do?

Macroscopic, mixes with photon

⬇

Modification of EM

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{A'} + \mathcal{L}_{kin.\,mix}$$

$$\mathcal{L}_{A'} = \left(-\tfrac{1}{4} F'^2 + \tfrac{1}{2} m_{\gamma'}^2 A'^2_\mu\right)$$

$$\mathcal{L}_{kin.\,mix} = -2\varepsilon F_{\mu\nu} F'^{\mu\nu}$$

Diagonalize

Mass basis

— *massless* photon
with coupling $e A_\mu J^\mu$

— *massive* hidden photon
with coupling $\underline{\varepsilon e} A'_\mu J^\mu$

Interaction basis

— *interacting* photon
non-interacting hidden photon

— mass mixing $\begin{pmatrix} 0 & \varepsilon \\ \varepsilon & 1 \end{pmatrix} m_{\gamma'}^2$

2 Important Points

<u>Important point 1</u>

all effects decouple when $m_{\gamma'}^2 \rightarrow 0$

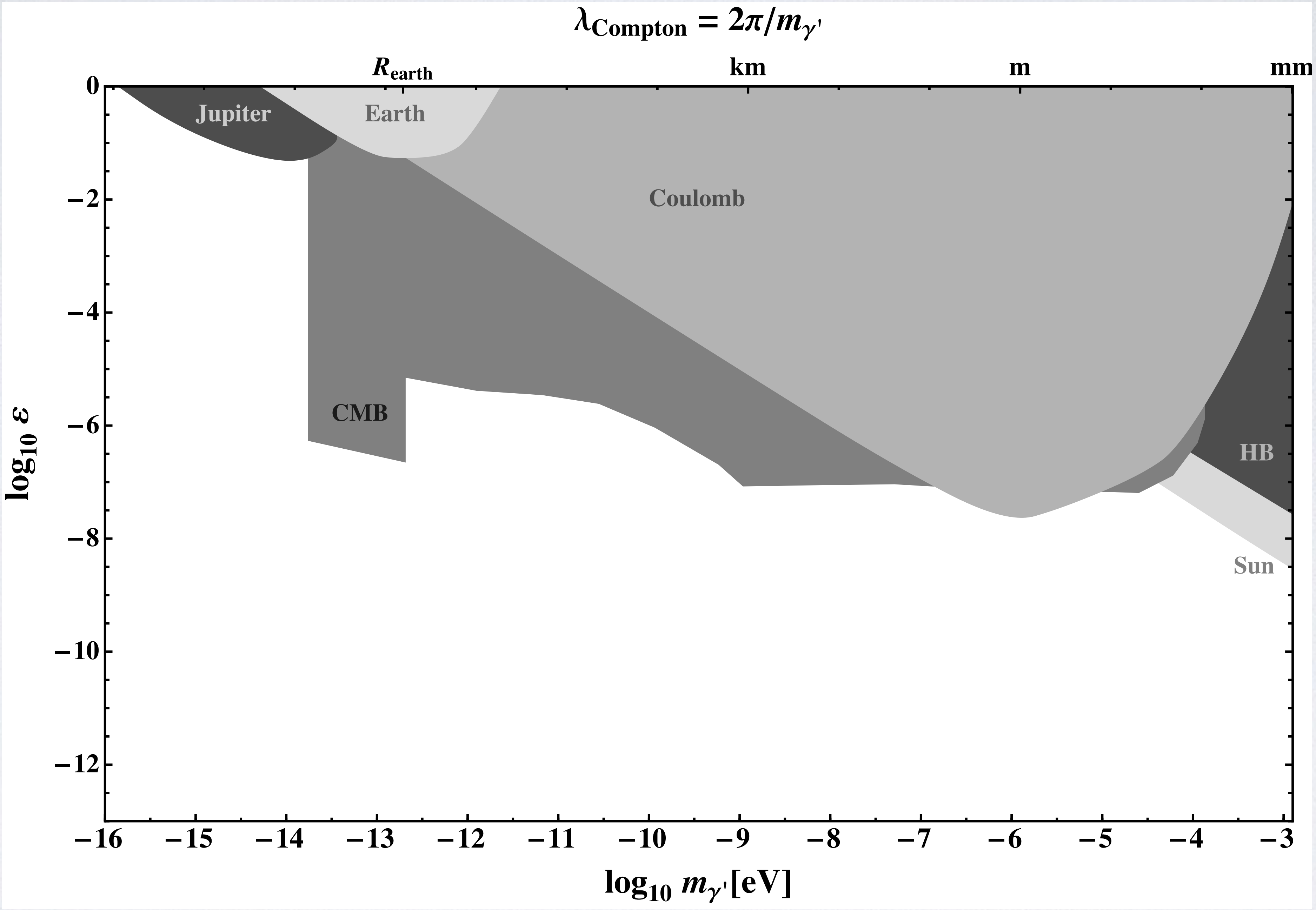
a massive hidden ... 1 longitudinal

<u>Interaction basis</u>

— *interacting* photon
non-interacting hidden photon

— ~~mass mixing $\begin{pmatrix} 0 & \varepsilon \\ \varepsilon & 1 \end{pmatrix} m_{\gamma'}^2$~~

ULTRA-LIGHT HIDDEN-PHOTON CONSTRAINTS

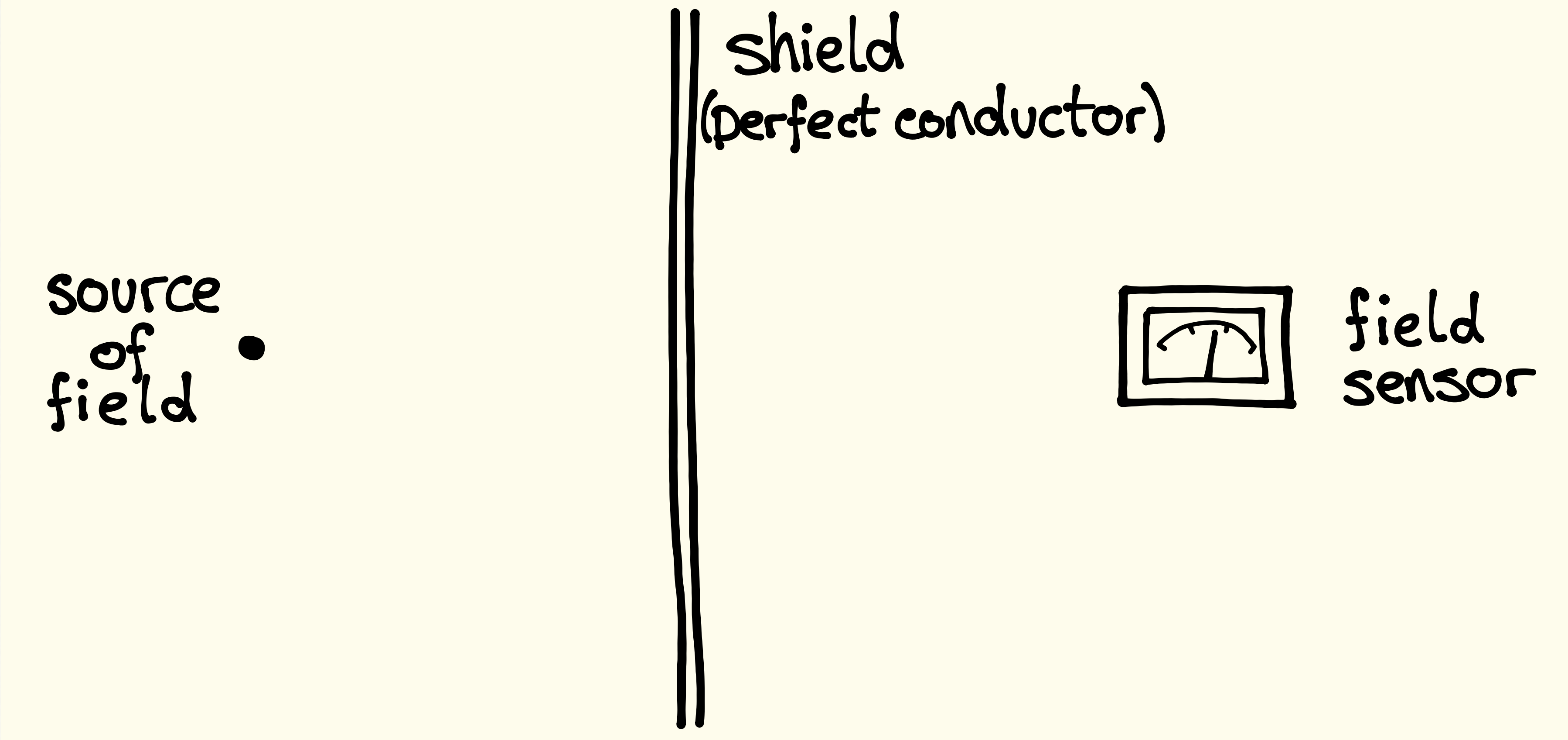


from 1002.0329, 1302.3884

DETECTING ULTRA-LIGHT HIDDEN PHOTONS

Detecting the hidden photon

our motto: Fields leak through shields



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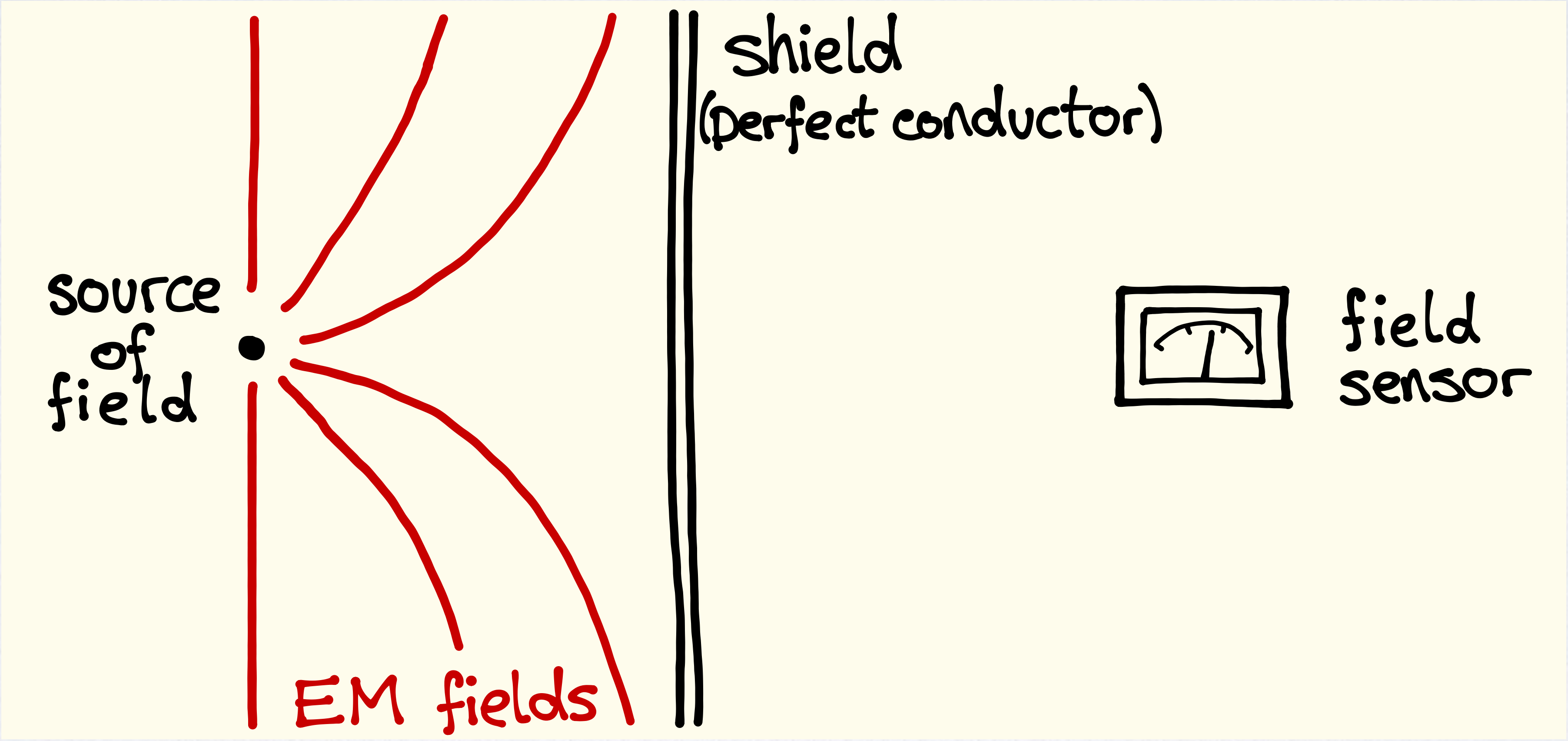
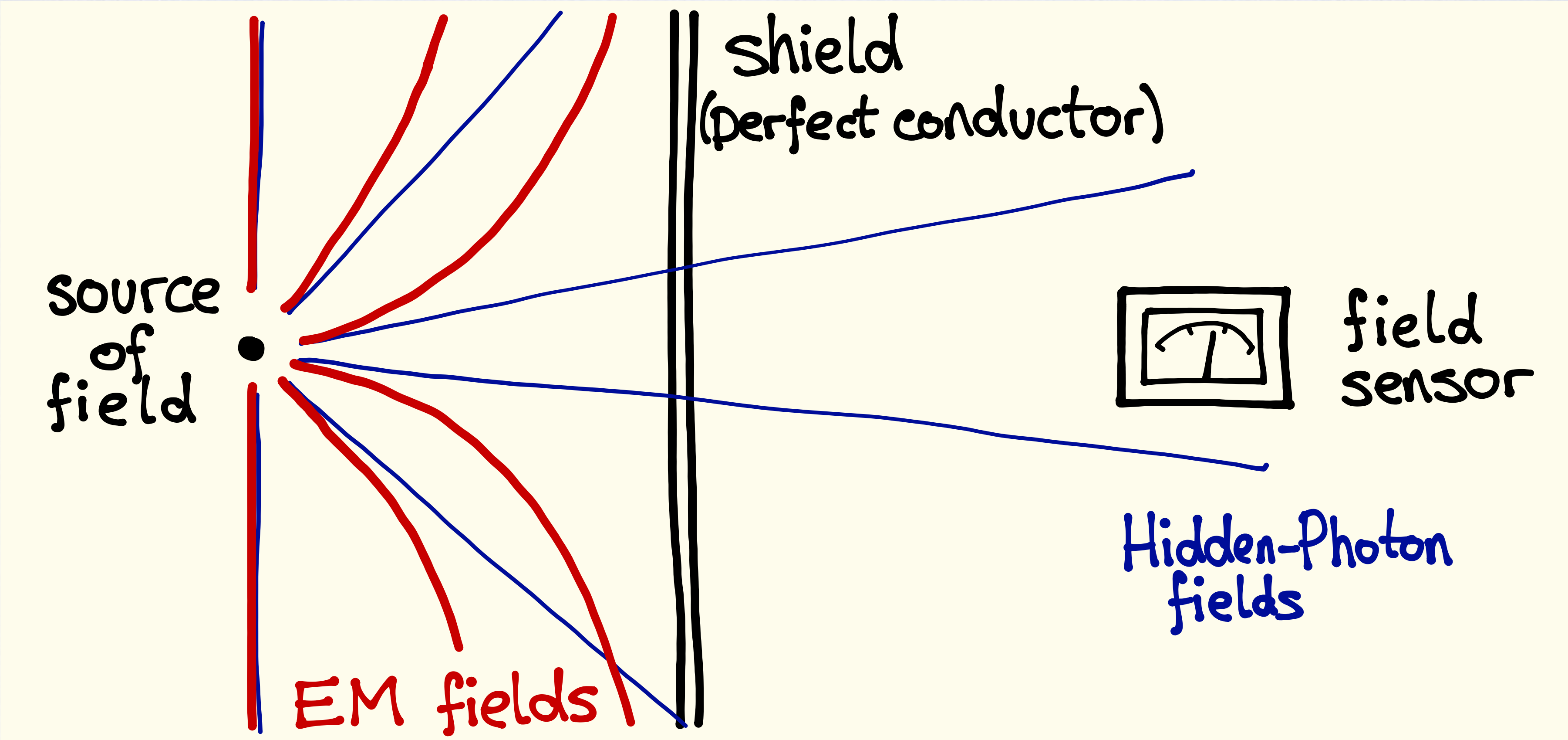


DETECTING THE HIDDEN PHOTON

our motto: **Fields leak through shields**



Detecting the hidden photon

Signal size: first estimate

— Source fields $(E, B)_{\mathrm{source}}$
— ε to produce hidden photon
— ε for hidden photon to backreact on sensor

$$\rightarrow \quad (E, B)_{\mathrm{detected}} \sim \varepsilon^2 (E, B)_{\mathrm{source}} \quad ?$$

DETECTING THE HIDDEN PHOTON

Signal size: first estimate

— Source fields $(E, B)_{source}$
— ε to produce hidden photon
— ε for hidden photon to backreact on sensor

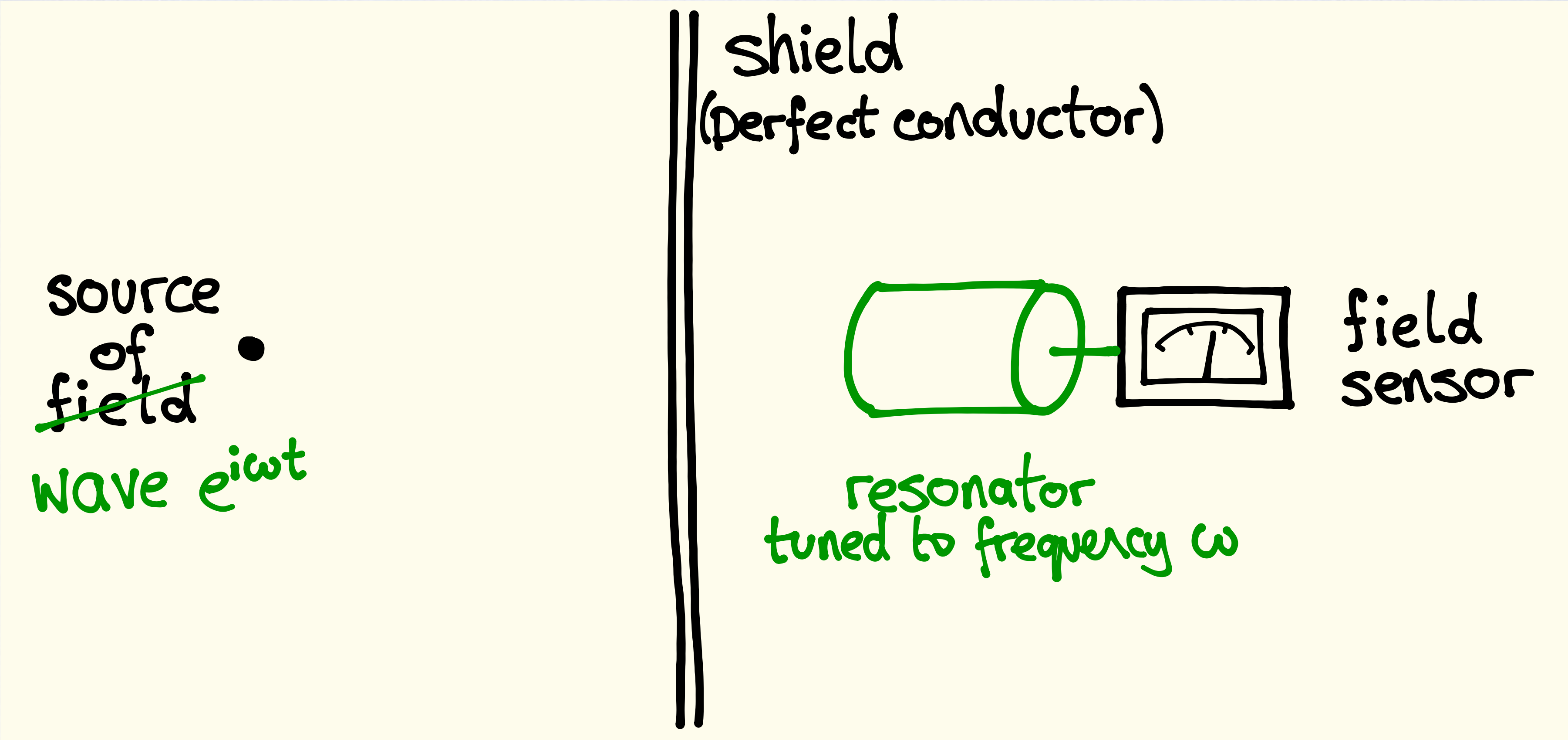
~~→ $(E, B)_{detected} \sim \varepsilon^2 (E, B)_{source}$?~~

→ $(E, B)_{detected} \sim (\ldots)\, \varepsilon^2 (E, B)_{source}$

missing factor to give decoupling as $m_{\gamma'} \to 0$

DETECTING THE HIDDEN PHOTON

Improve with resonance



DETECTING THE HIDDEN PHOTON

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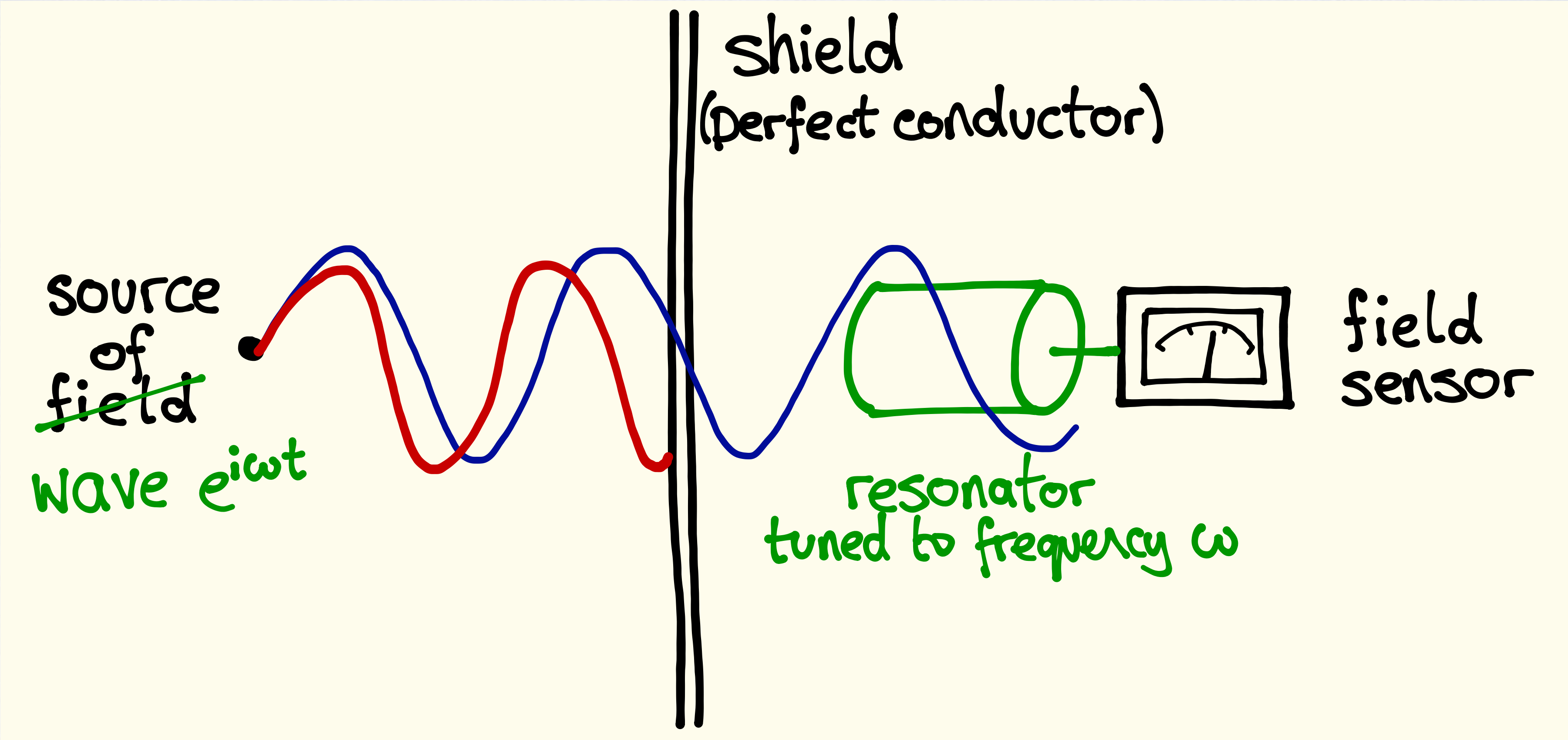


DETECTING THE HIDDEN PHOTON

Signal size: first estimate

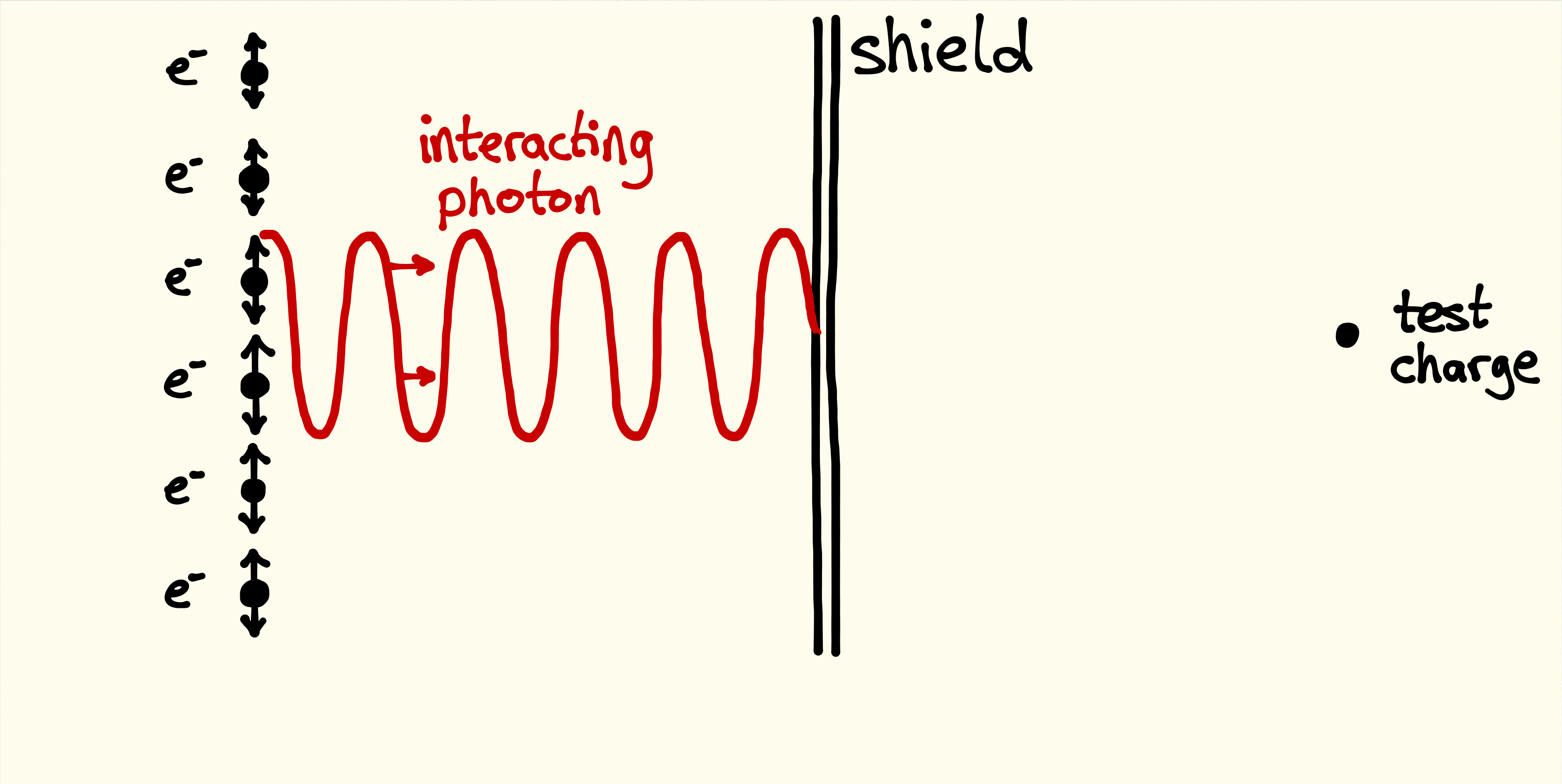
— Source fields $(E, B)_{\text{source}}$
— ε to produce hidden photon
— ε for hidden photon to backreact on sensor
— $Q \gg 1$ resonant enhancement

~~$\rightarrow \quad (E, B)_{\text{detected}} \sim \varepsilon^2 (E, B)_{\text{source}}$~~ ?

$$\rightarrow \quad (E, B)_{\text{detected}} \sim (\ldots)\, Q\, \varepsilon^2 (E, B)_{\text{source}}$$

missing factor to give
decoupling as $m_{\gamma'} \rightarrow 0$

Signal size take 2



Interaction basis

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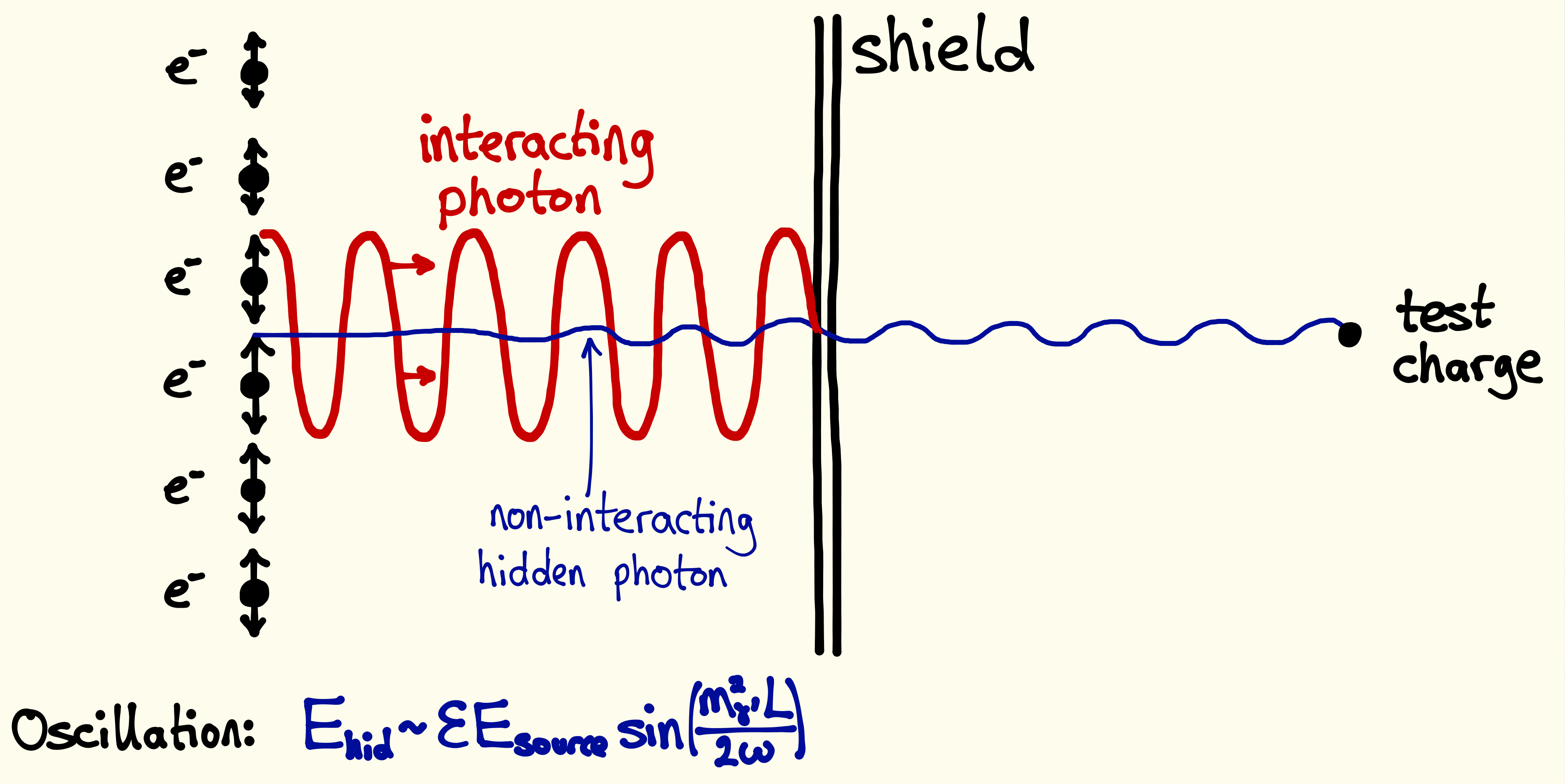
non-interacting hidden photon

— mass mixing $\begin{pmatrix} 0 & \varepsilon \\ \varepsilon & 1 \end{pmatrix} m_{\gamma'}^2$

Signal size take 2



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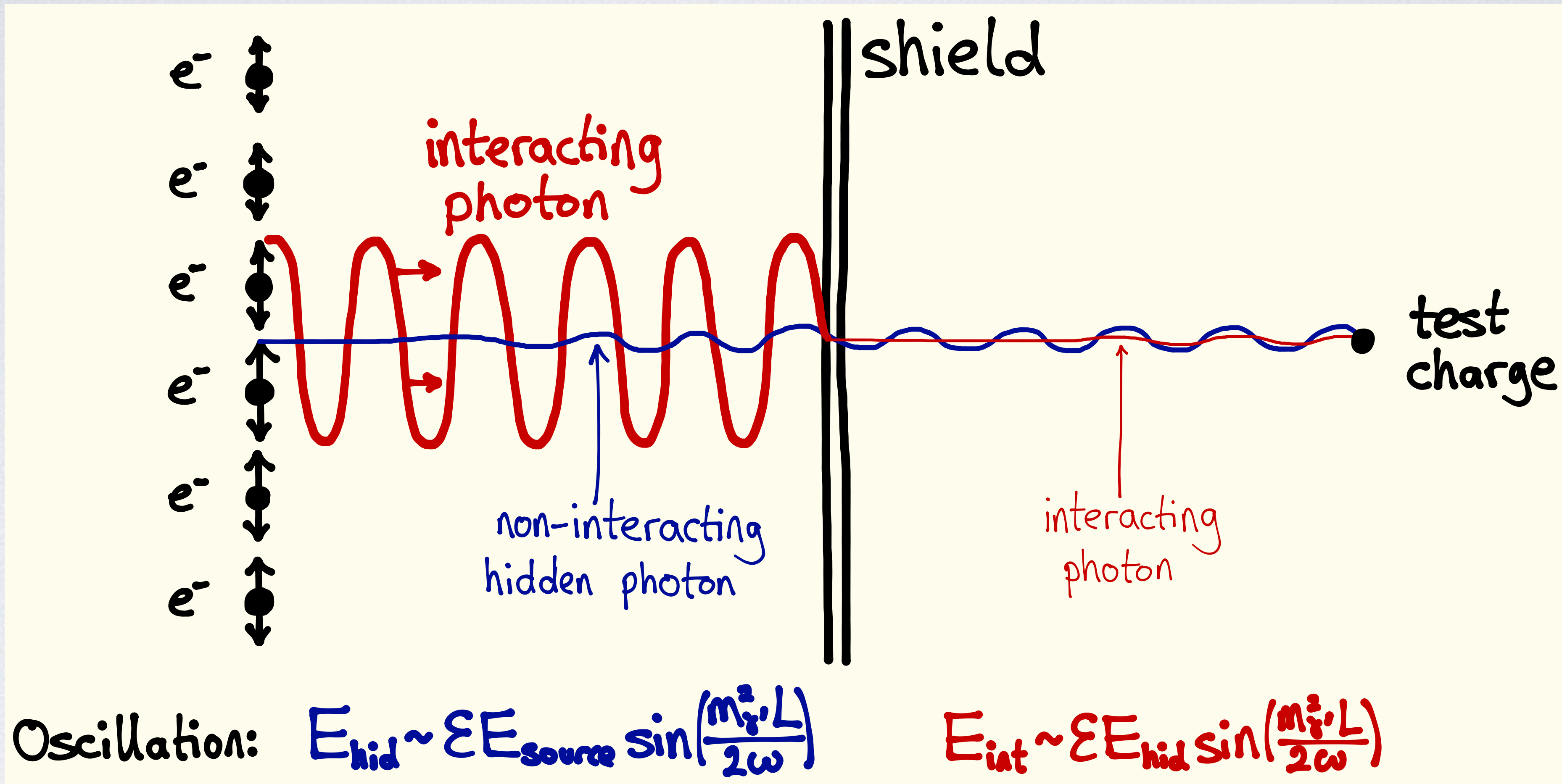

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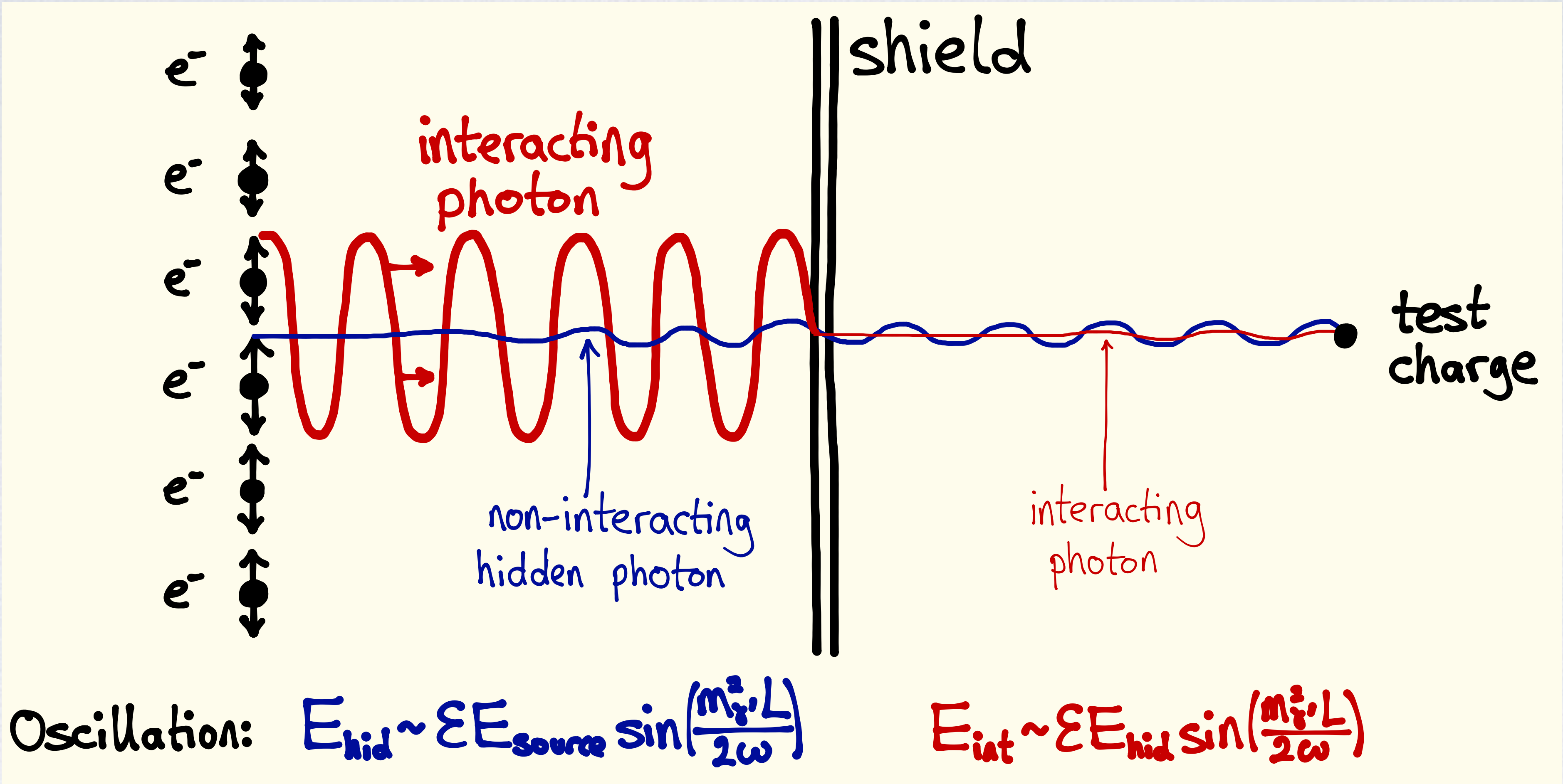


$\rightarrow \quad (E, B)_{detected} \sim (m_\gamma{}^4 L^2/\omega^2)\, Q\, \varepsilon^2\, (E, B)_{source}$

"Light Shining through Walls" experiments

— The *ALPs* axion search uses this setup (+ static *B*-field)

— Can immediately repurpose for hidden photons Ahlers et al 0706.2836

— Laser cavities: probes μm wavelengths

Microwave cavities

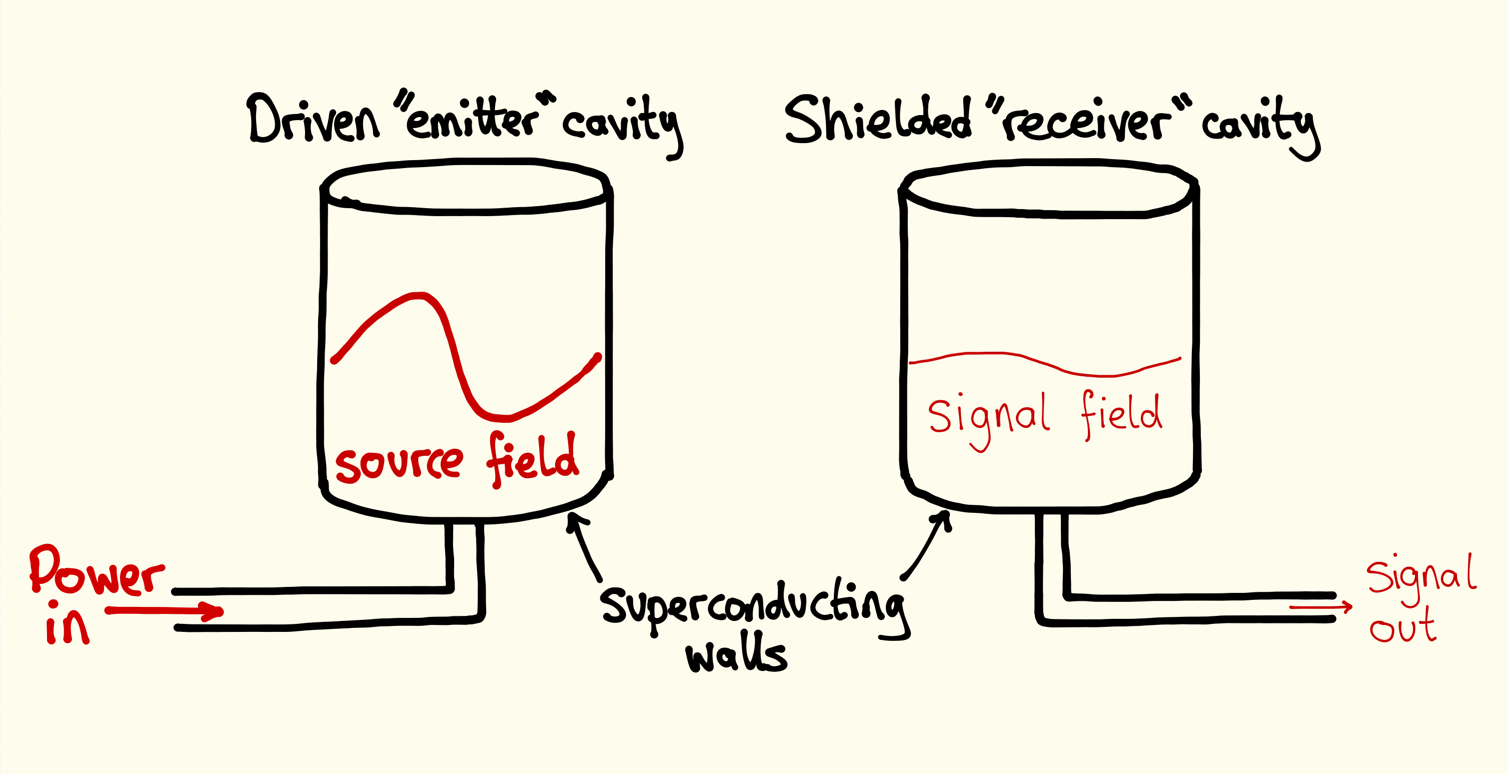
Microwave cavities are ideal

Jaekel & Ringwald 0707.2063

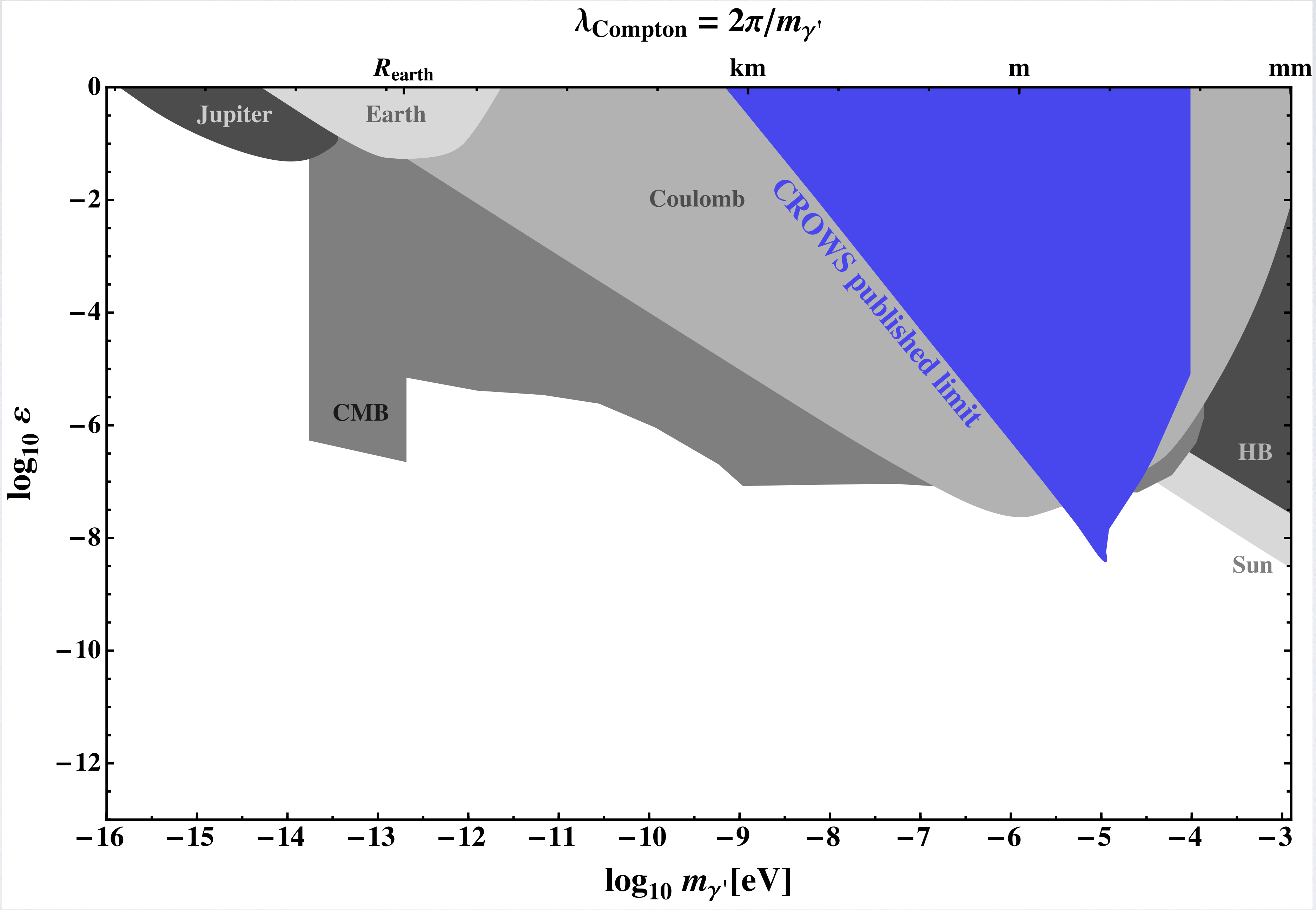
— amazing resonators: $Q \sim 10^{10}$
— 2 cavities can be tuned to same frequency
— **cm-m** wavelengths
— ~~same signal scaling as above~~

Early-stage experiments

— Povey et al 1003.0964
— ADMX 1007.3766
— CROWS 1310.8098



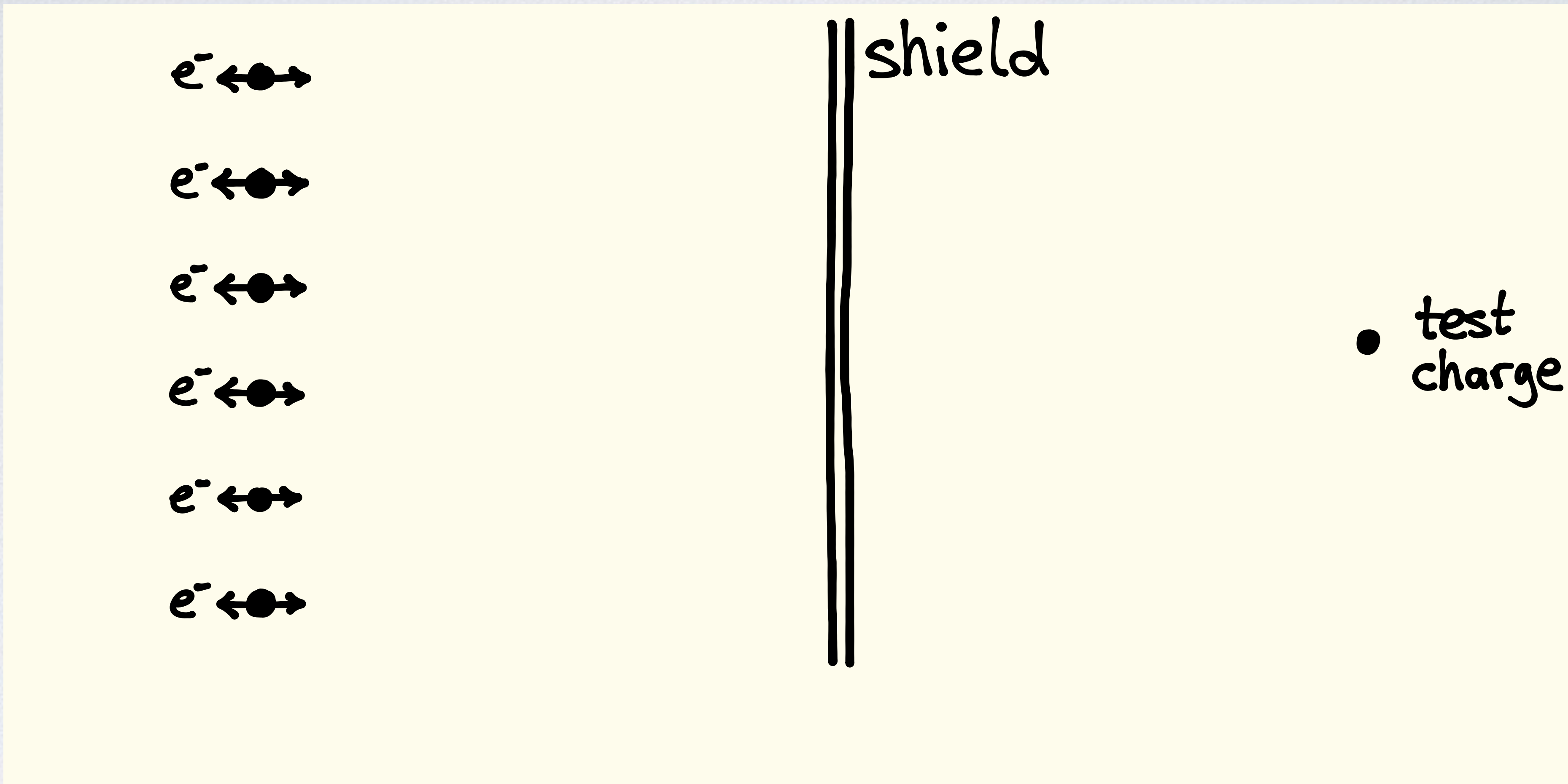
CERN Resonant Weakly-Interacting sub-eV Particle Search (CROWS)



1310.8098

THE IMPORTANCE OF THE LONGITUDINAL MODE

Signal size take 3: longitudinal waves



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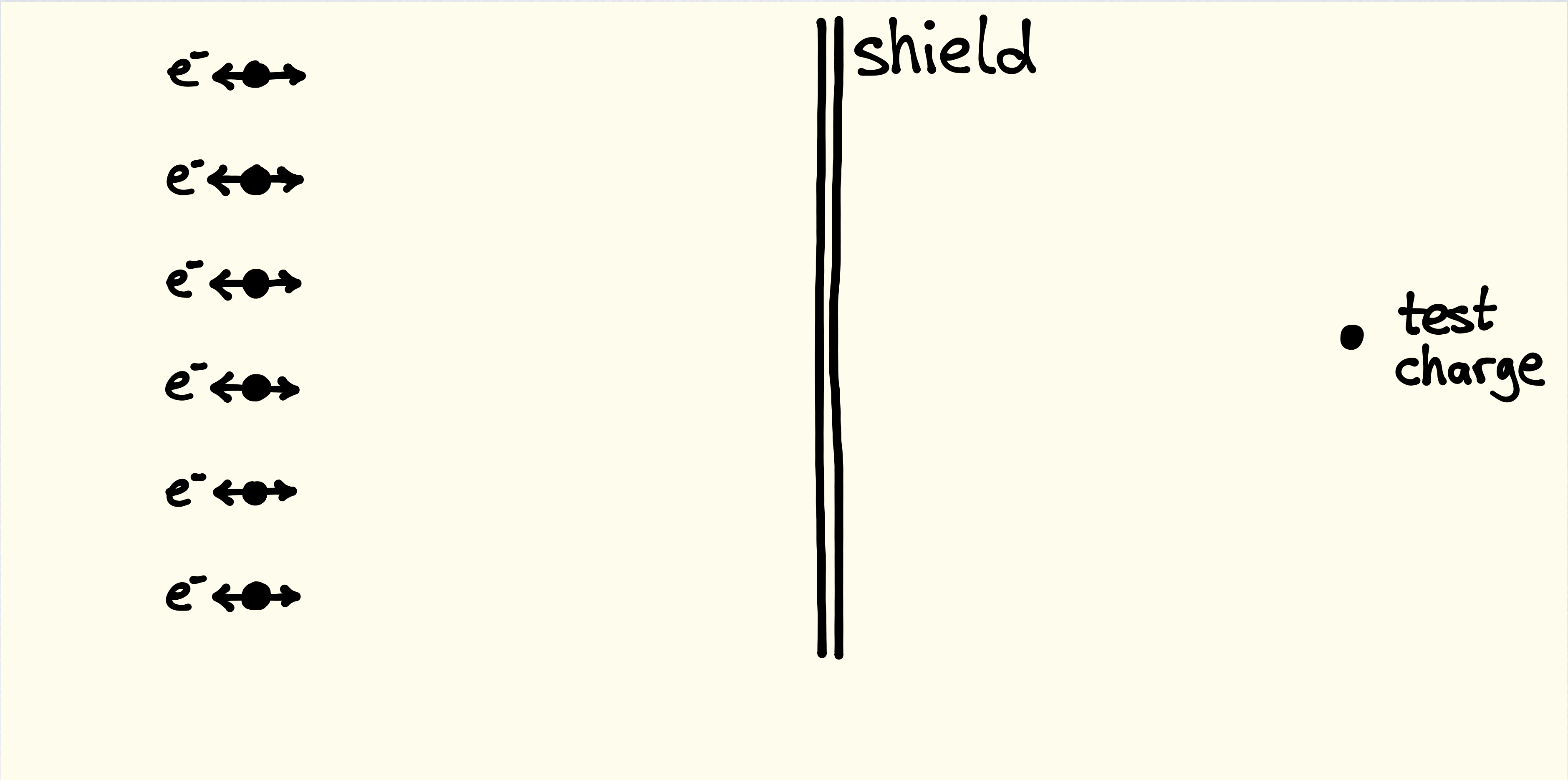
SIGNAL SIZE TAKE 3: LONGITUDINAL WAVES



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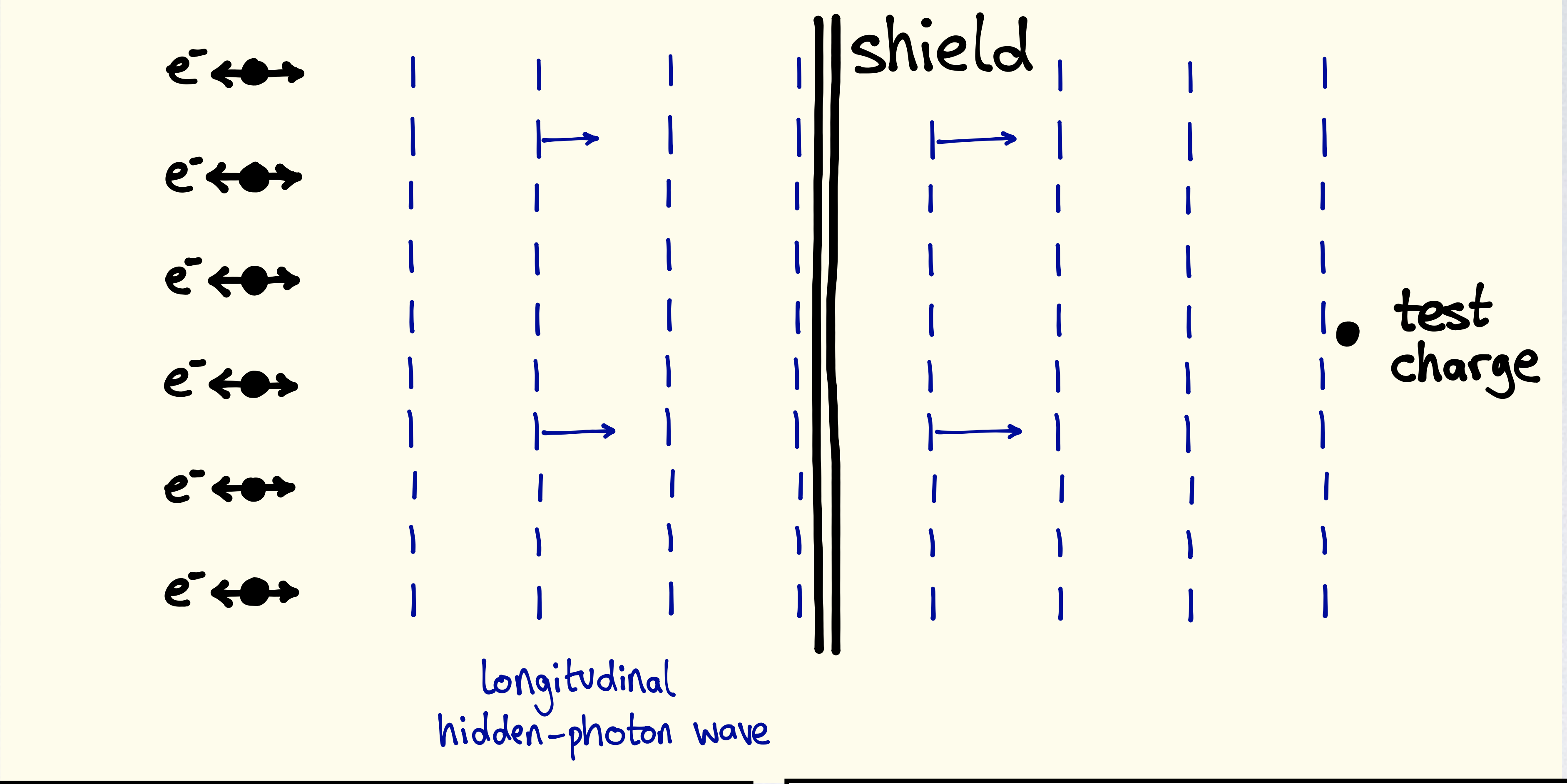
with coupling $\underline{\varepsilon e} A'_\mu J^\mu$

longitudinal mode A'_L
with
coupling εe **to electric charge**

Signal size take 3: longitudinal waves



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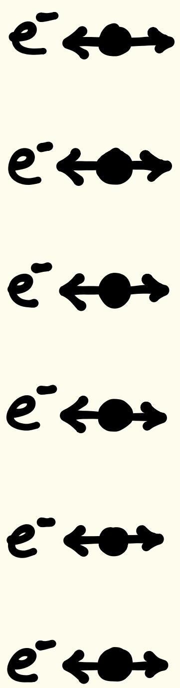
→

longitudinal mode A'_L
with
coupling εe to electric charge

SIGNAL SIZE TAKE 3: LONGITUDINAL WAVES

$A'_z \propto \varepsilon J_z$



$E'_z = -\partial_z A'_0 - \partial_0 A'_z$

$\partial_t A'_0 = -\partial_z A'_z$ (from of EoM for A')

⬇

$E'_z = (-i/\omega)(\omega^2 - k^2) A'_z \propto m_{\gamma'}^2/\omega\, A'_z$

⬇

$\varepsilon E'_z \propto (\varepsilon^2 m_{\gamma'}^2/\omega)\, J_z$

Mass basis

— *massless* photon with coupling $eA_\mu J^\mu$

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➡

longitudinal mode A'_L

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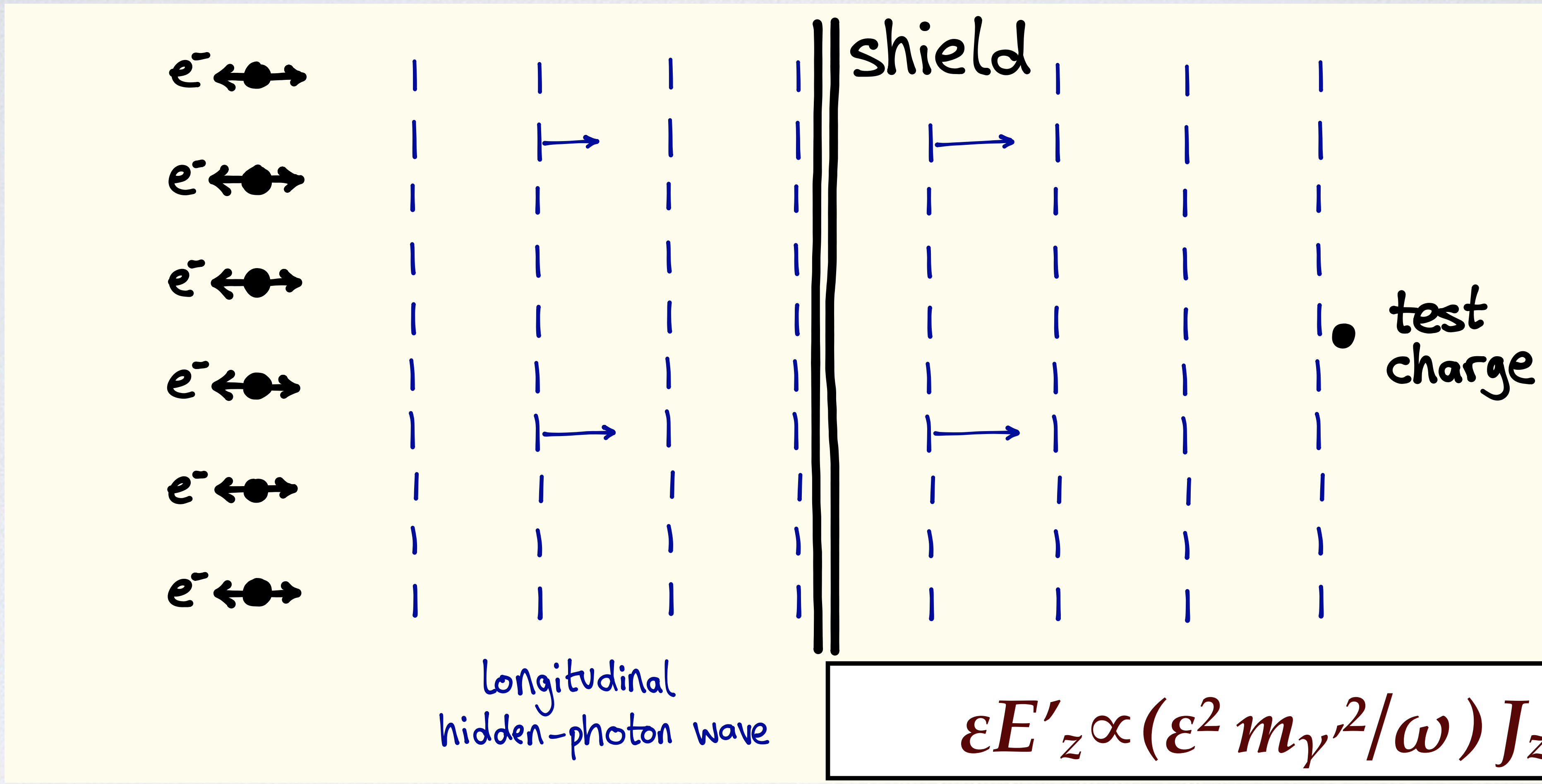
Signal size take 3: longitudinal waves



$$\varepsilon E'_z \propto (\varepsilon^2 m_{\gamma'}^2/\omega)\, J_z$$

~~$\rightarrow \quad (E, B)_{\text{detected}} \sim (m_{\gamma'}^4 L^2/\omega^2)\, Q\, \varepsilon^2\, (E, B)_{\text{source}}$~~

$\rightarrow \quad (E, B)_{\text{detected}} \sim (m_{\gamma'}^2/\omega^2)\, Q\, \varepsilon^2\, (E, B)_{\text{source}}$

Microwave cavities

Microwave cavities are ideal

Jaekel & Ringwald 0707.2063

- amazing resonators: $Q{\sim}10^{10}$
- 2 cavities can be tuned to same frequency
- self-shielding
- cm-m wavelengths
- ~~same signal scaling as above~~

improved from	$(m_{\gamma'}^4/\omega^4)\,\varepsilon^2$
to	$(m_{\gamma'}^2/\omega^2)\,\varepsilon^2$

Early-stage experiments

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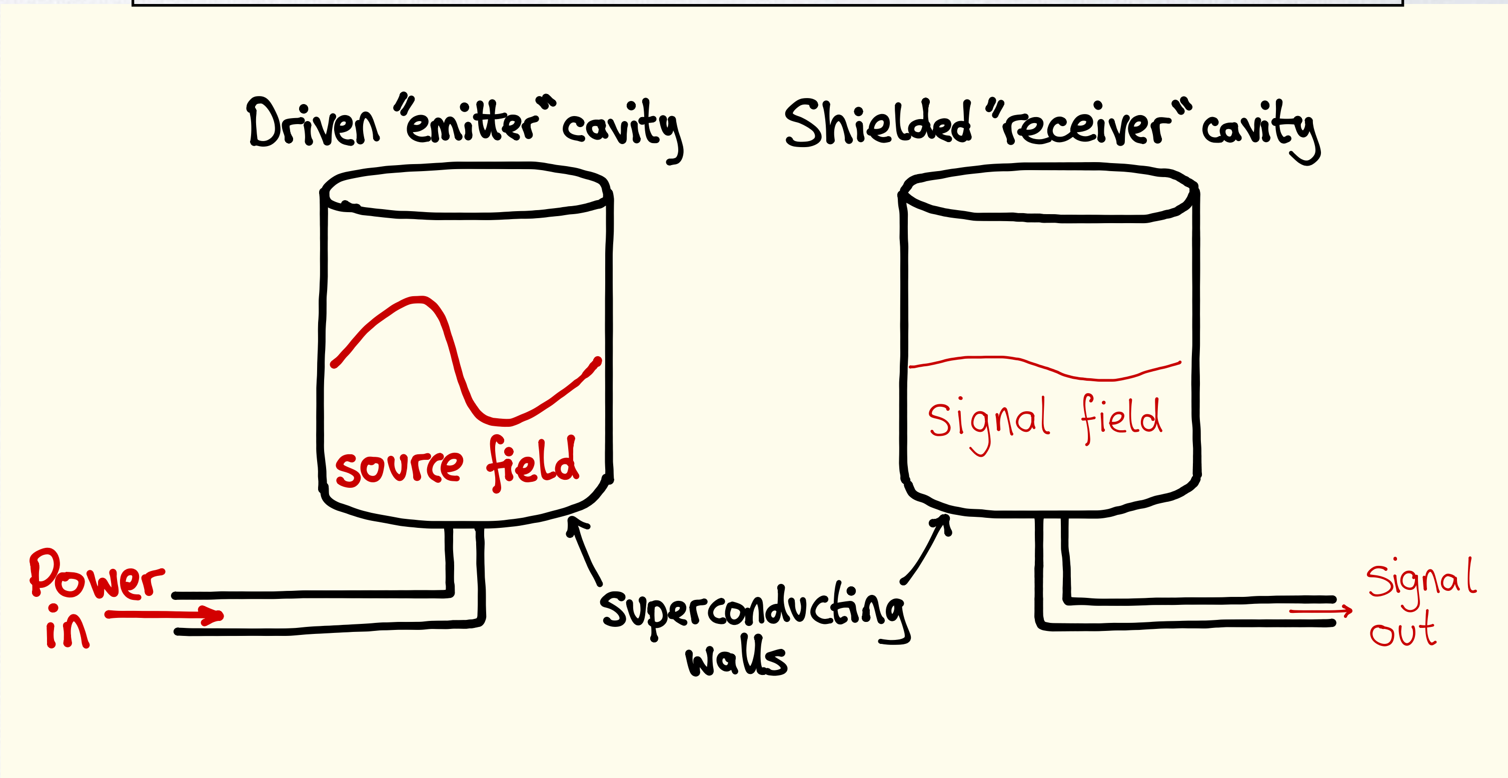

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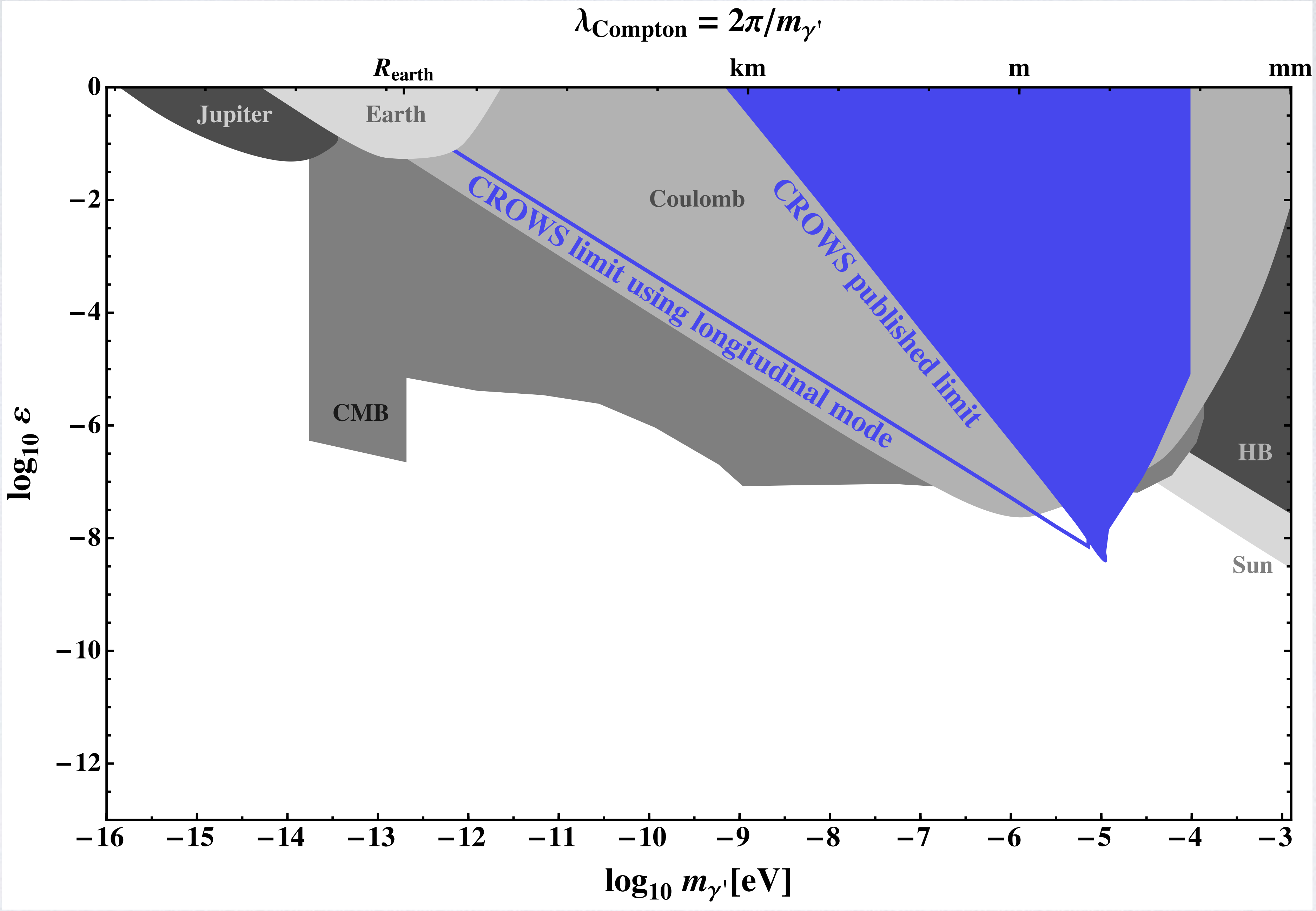
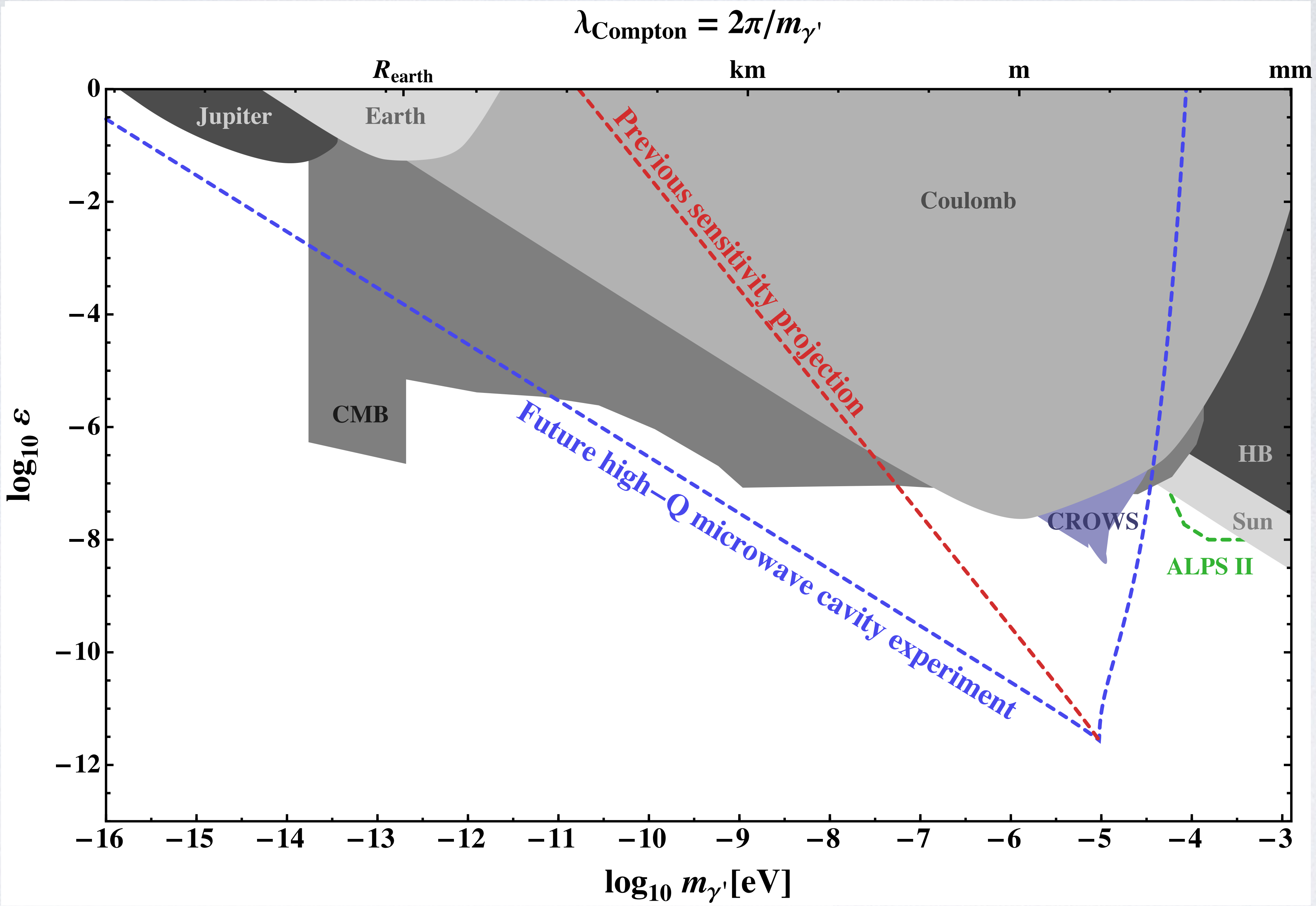


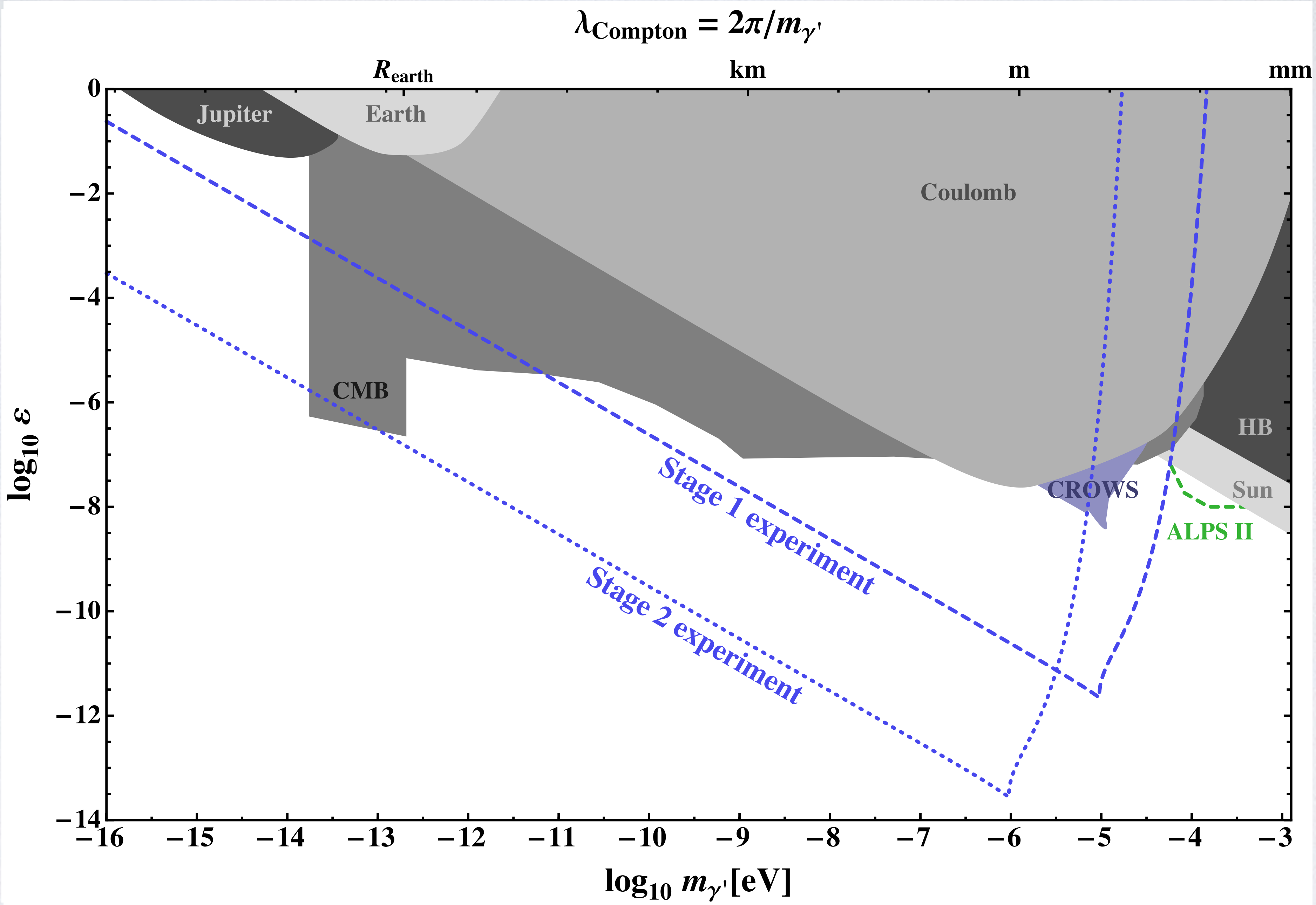
P.Graham, J.Mardon, S. R. & Y. Zhao 1407.4806

FUTURE EXPERIMENTS



FUTURE EXPERIMENTS

Stage 1: B_{em}=1 T, size ~10 cm, $Q=10^{10}$, T= 4K, 1 month



Stage 2: B_{em}=1 T, size ~1 m, $Q=10^{12}$, T= 0.1K, 1 year

DM DETECTION WITH A RADIO INSIDE A FARADAY CAGE

Hidden-photon dark matter

Boson with $m \gtrsim 10^{-20}\,\mathrm{eV}$ can be good DM (e.g. axion)

— must be *very* cold
— must have very high occupation number
— Hidden photon could work

Nelson & Scholtz 1105.2812

Hidden-Photon DM is an oscillating E' field with

— $\rho_{DM} \approx E'^2$
— Random direction (Lorentz breaking, but hard to tell)
— Frequency $\omega = m_{\gamma'}$
— Coherence time $t \sim 1/(v^2\omega) \sim 10^6/\omega$

Cosmology

— Energy density dilutes as $1/a(t)^2$ when $H > m_{\gamma'}$
— Avoid this with non-minimal coupling $\mathcal{L} \supset (1/12)\mathcal{R}\, A'^2_\mu$
⟶ Large mass from graviton loops?
⟶ Overproduced by inflationary perturbations if $R=0.2$
— Is there a safe way to produce it? (I can't answer that yet)

Arias et al 1201.5902

Hidden-photons as dark matter

Like an electric field that penetrates conducting shields

— $E' \approx \sqrt{\rho_{DM}} \approx 2000$ V/m

Has fixed frequency

— $\omega = m_{\gamma'}$, $\delta\omega/\omega = 10^{-6}$

Can excite an electromagnetic resonator

<u>electromagnetic cavities</u>

— ADMX is automatically sensitive!

Arias et al 1201.5902

— restricted to $m_{\gamma'} \sim 10^{-4}$-10^{-6} eV (set by cavity size)

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Arias et al 1201.5902

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LC circuits

— resonators

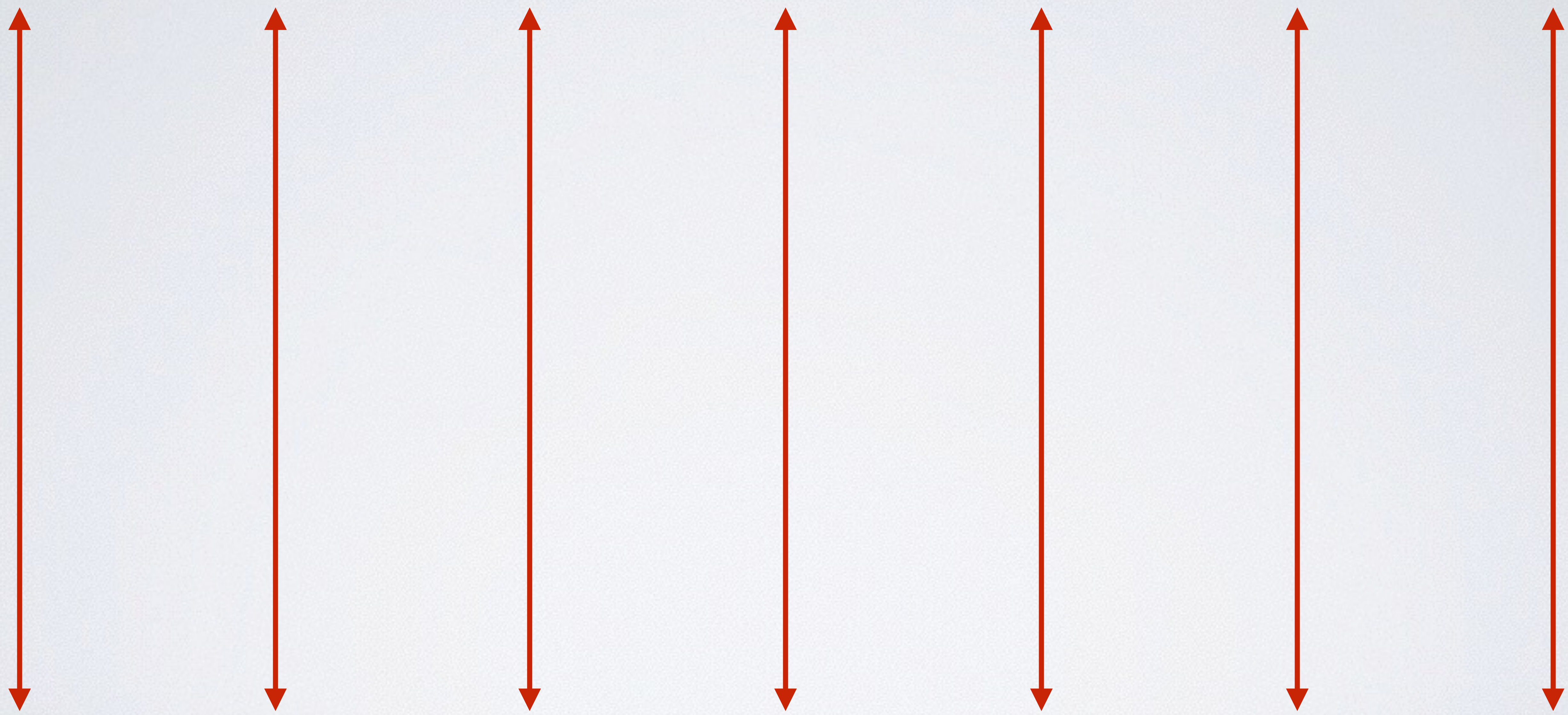
— much wider and lower frequency range than cavities

⟶ can probe much lower masses

S. Chaudhuri et. al. 1411.7382

EXPERIMENTAL SETUP

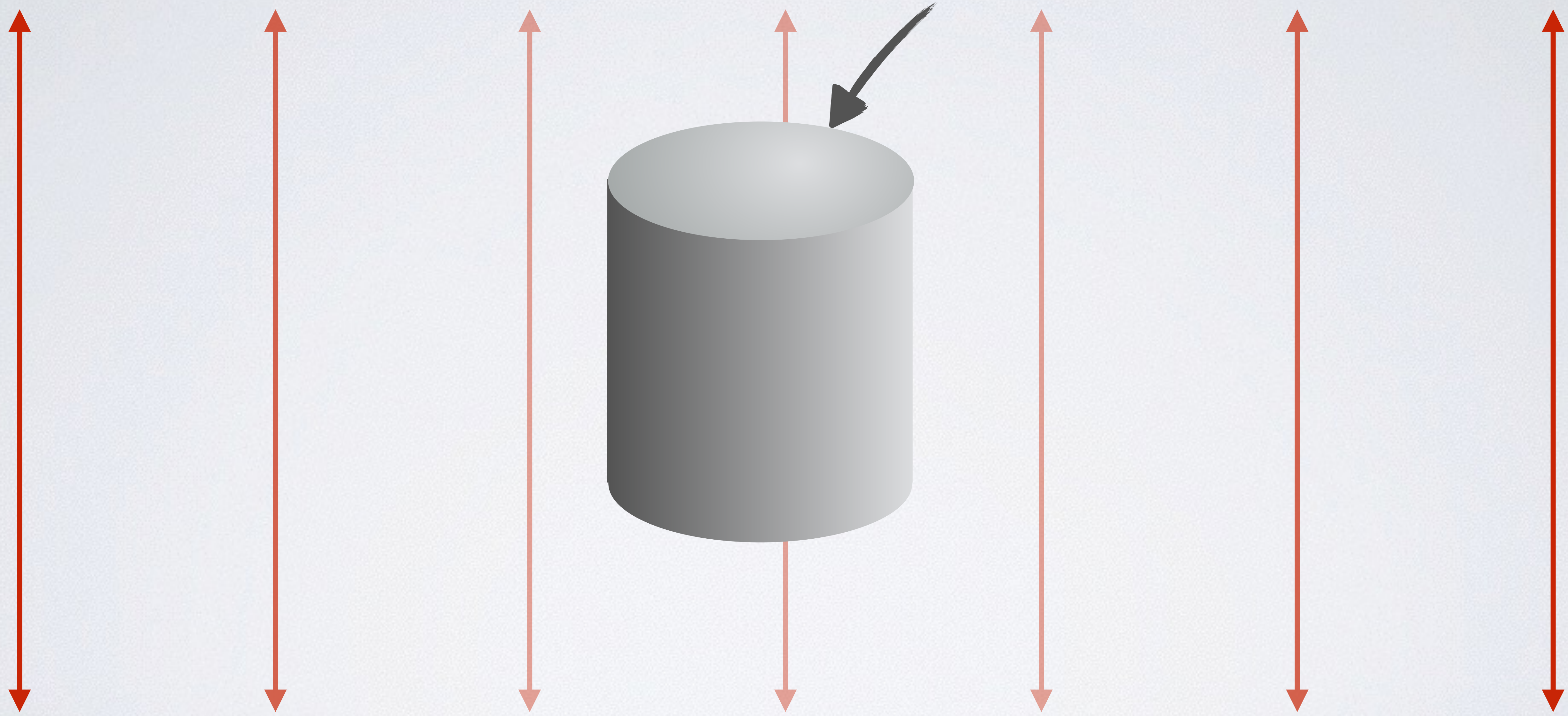
oscillating E' field
(dark matter)



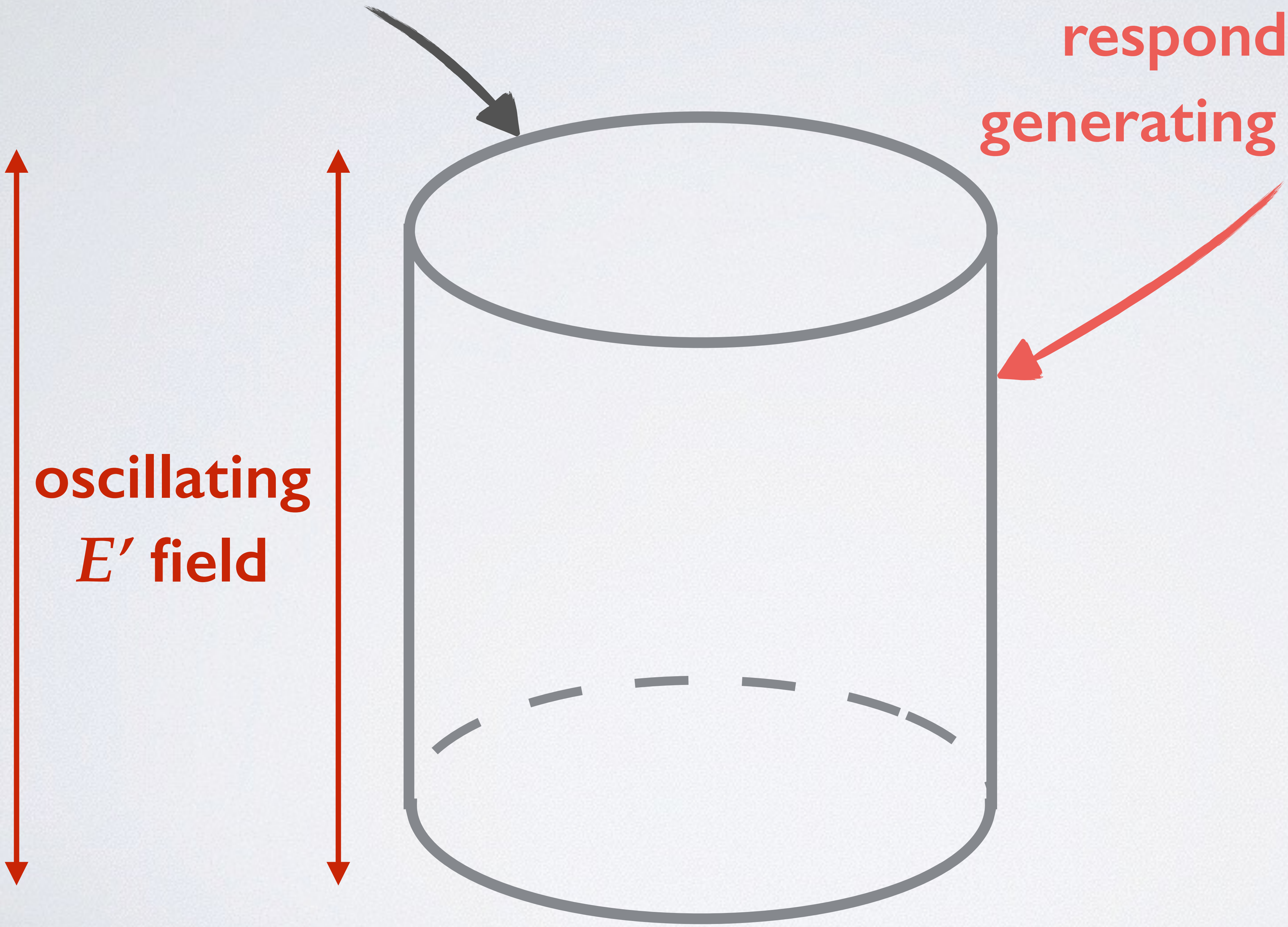
EXPERIMENTAL SETUP

oscillating E' field (dark matter)

Metal box to shield backgrounds (Faraday cage)



THE SIGNAL INSIDE THE BOX



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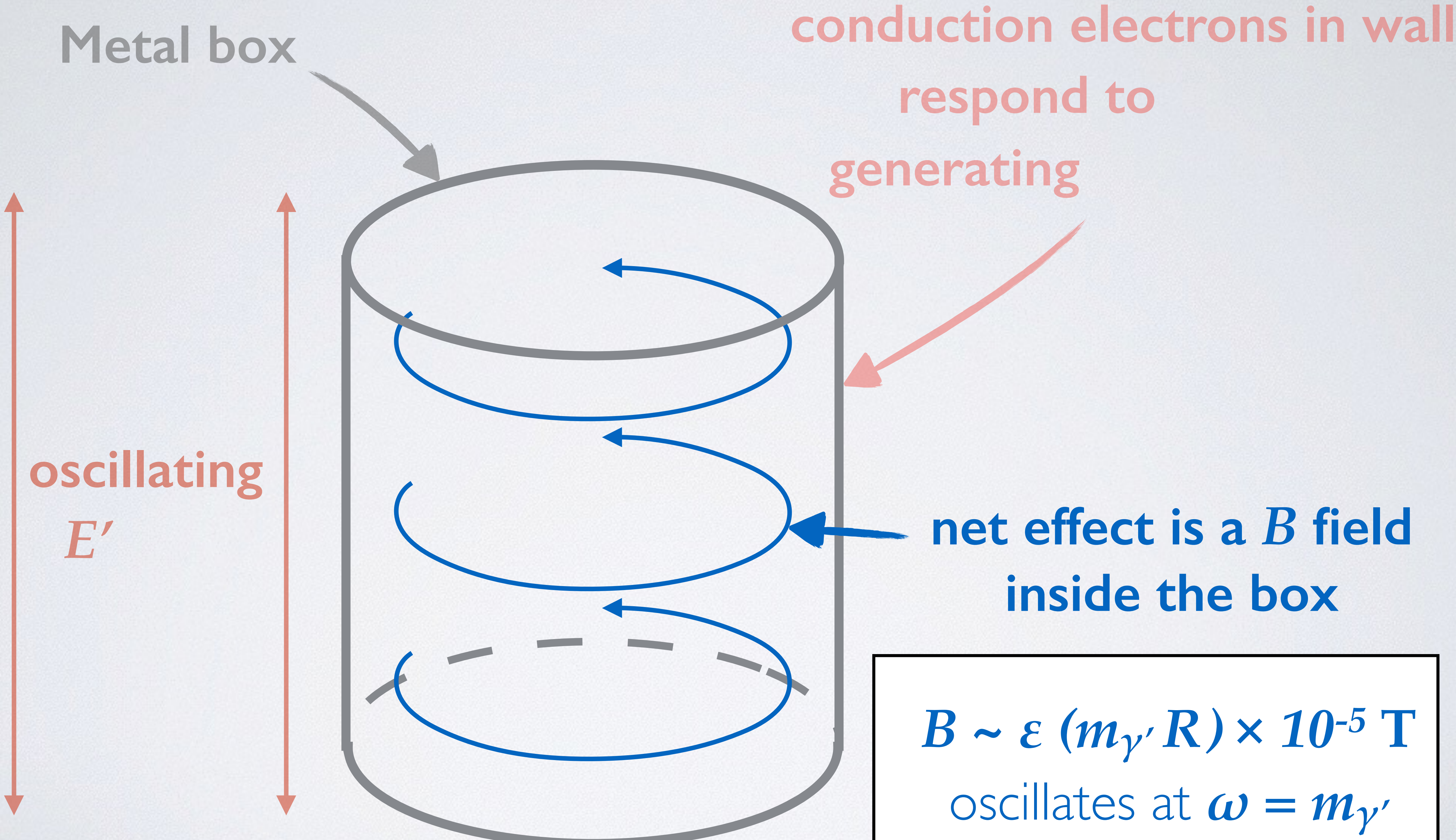


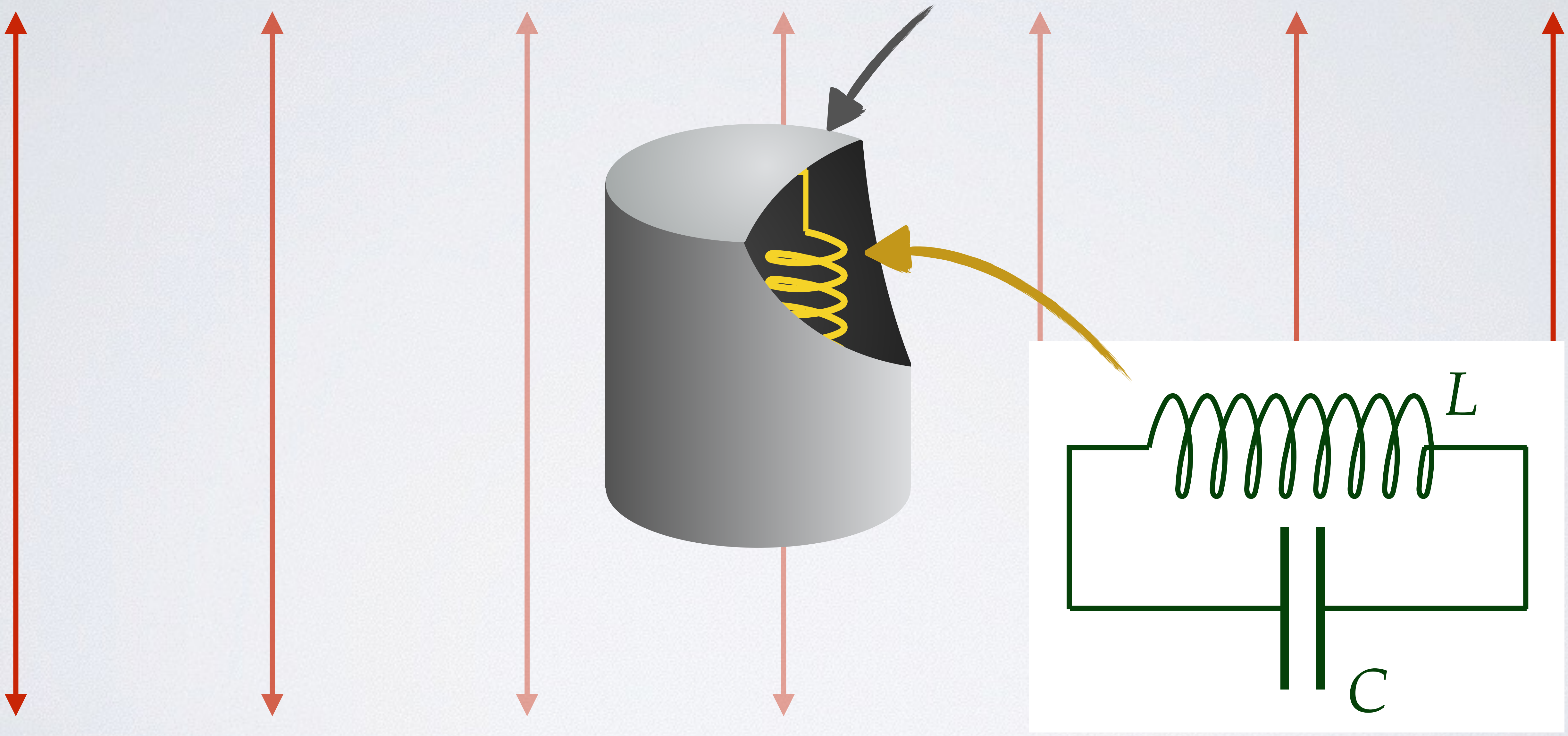
$B \sim \varepsilon\,(m_{\gamma'} R) \times 10^{-5}\ \mathrm{T}$

oscillates at $\omega = m_{\gamma'}$

Experimental setup

oscillating E' field
(dark matter)

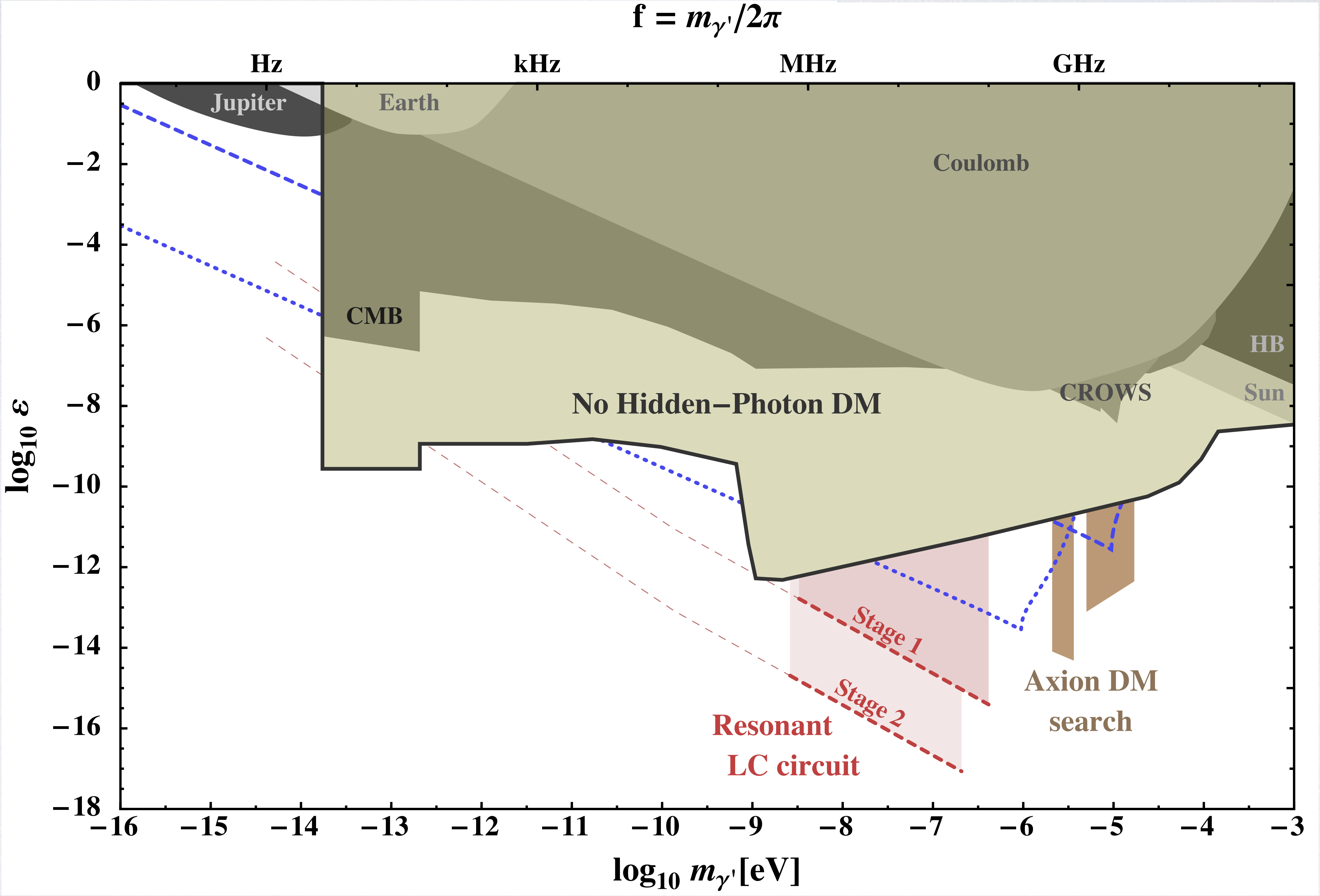
Metal box to shield backgrounds
(Faraday cage)



Tunable resonant LC circuit
(a radio)

EXPECTED REACH

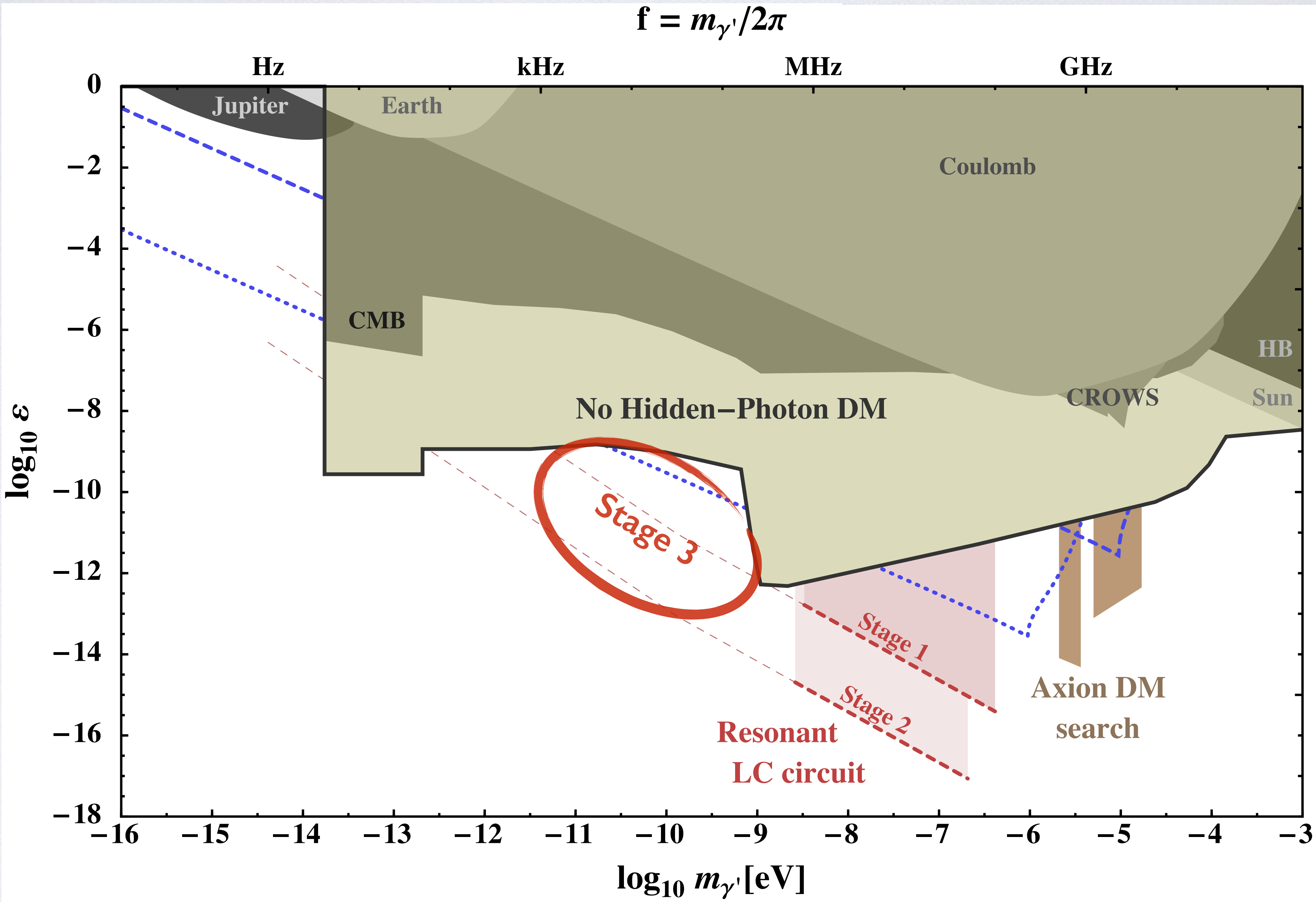
Stage 1: size ~50 cm, T= 4K, Q=10^6, 1 year scan



Stage 2: size ~1 m, T= 10mK, Q=10^6, 1 year scan

EXPECTED REACH

Stage 1: size ~50 cm, T= 4K, Q=10⁶, 1 year scan



Stage 2: size ~1 m, T= 10mK, Q=10⁶, 1 year scan

THANK YOU