SEARCHING FOR ULTRA-LIGHT HIDDEN PHOTONS

with:

Peter Graham, Jeremy Mardon & Yue Zhao

and experimental collaborators:

Kent Irwin, Saptarshi Chaudhuri, Sami Tantawi, Vinod Bharadwaj

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
5. Cosmological Solution to the Hierarchy Problem

ULTRA-LIGHT HIDDEN PHOTONS

"ULTRA-LIGHT HIDDEN PHOTONS"

Hidden Photons:

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

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

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

$\mathcal{L}_{A'}$: $(-\ {}^1/_4 F'^2 + {}^1/_2\, m_{\gamma'}^2 A'^2_\mu)$

Kinetic mixing $\varepsilon \ll 1$

Ultra-light:

Macroscopic Compton wavelength

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

What does this new field do?

Macroscopic, mixes with photon

⬇

Modification of EM

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Modification of EM

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

$\mathcal{L}_{A'}$: $(-\,{}^1/_4\, F'^{\,2} + {}^1/_2\, m_{\gamma'}^2\, A'^2_\mu)$

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

Diagonalize

Mass basis

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

— *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

Important point 1

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

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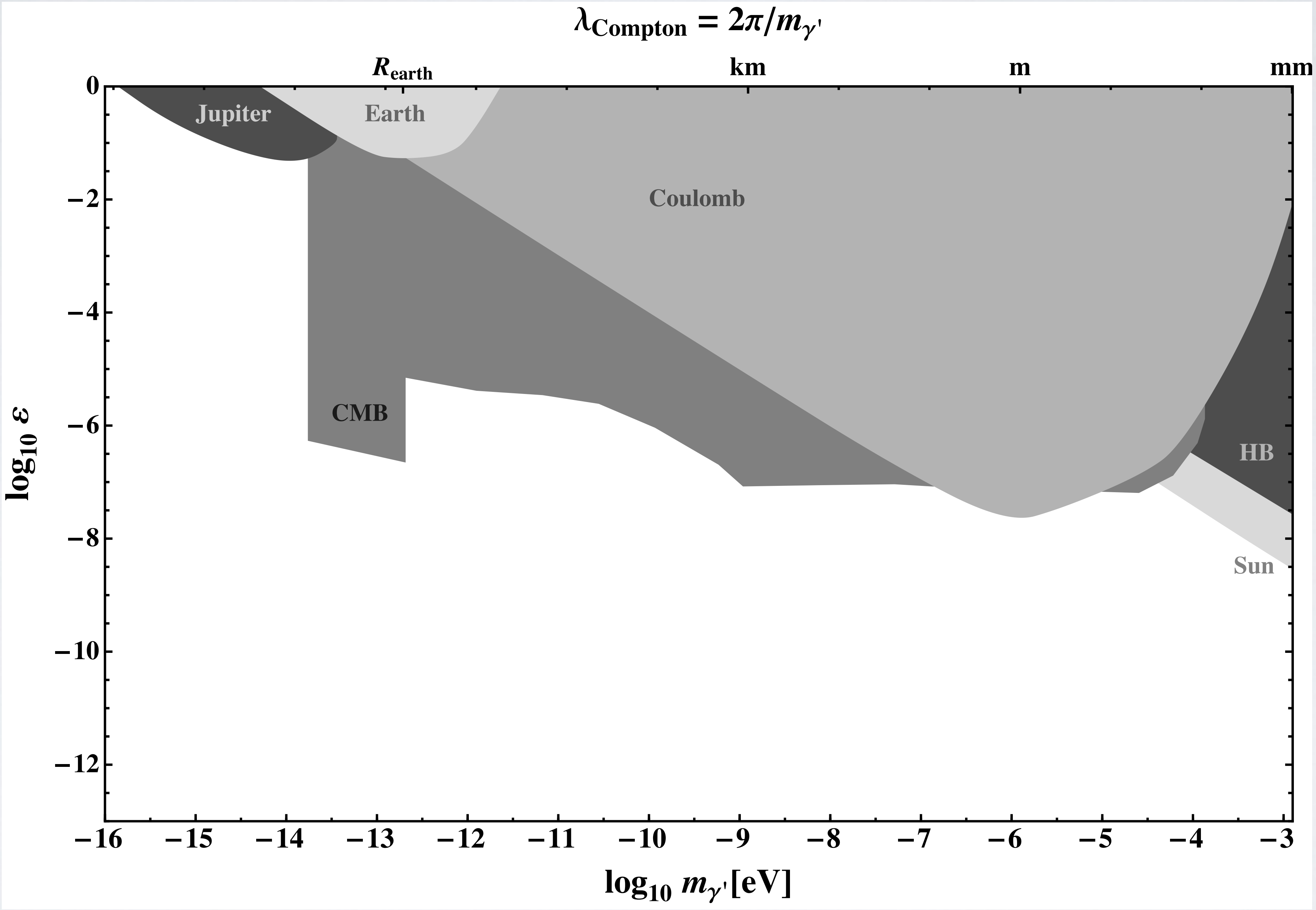
all effects decouple when $m_{\gamma'}^2 \rightarrow 0$

Important point 2

a massive hidden photon has **2 transverse** modes + **1 longitudinal**

ULTRA-LIGHT HIDDEN-PHOTON CONSTRAINTS

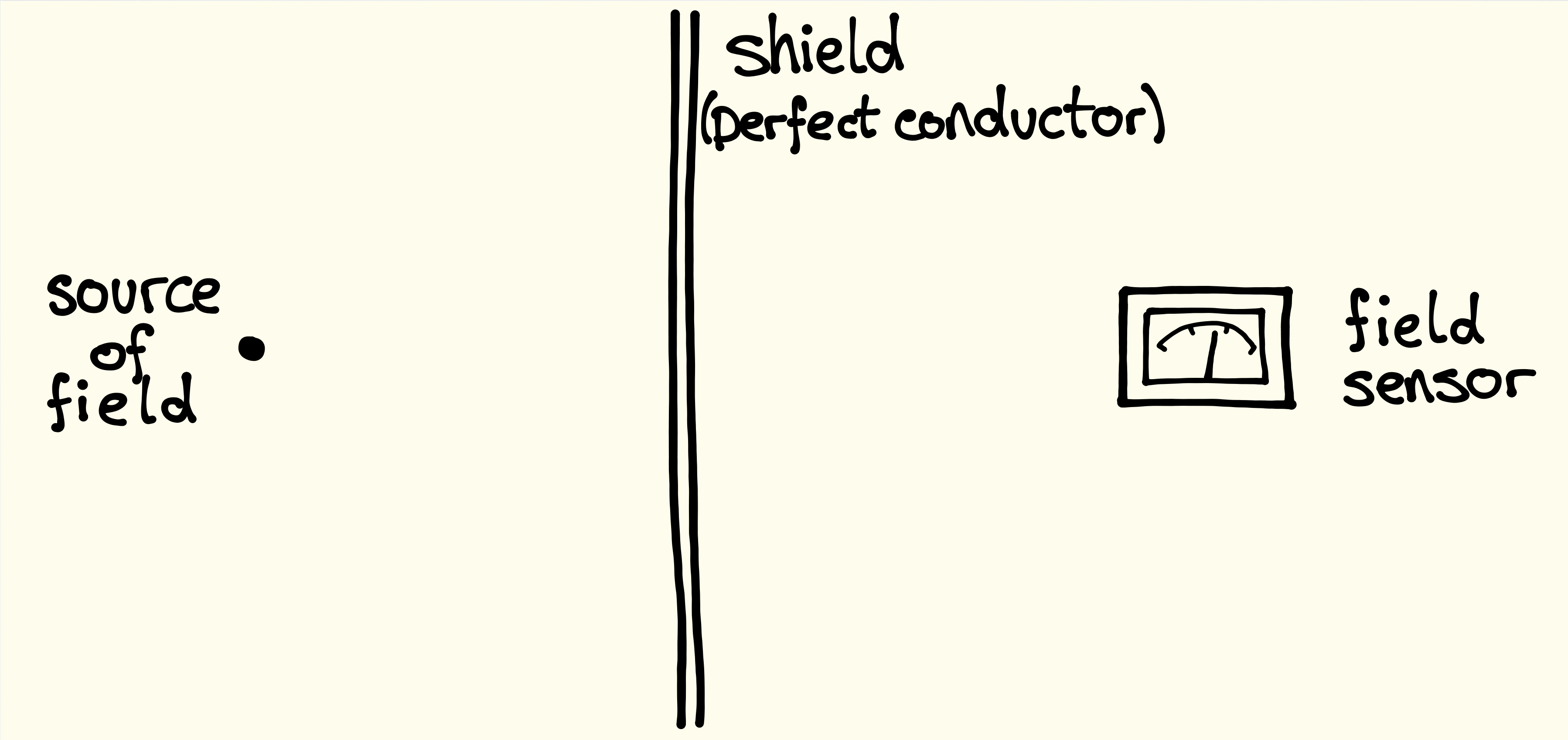


from 1002.0329, 1302.3884

DETECTING ULTRA-LIGHT HIDDEN PHOTONS

DETECTING THE HIDDEN PHOTON

our motto: **Fields leak through shields**



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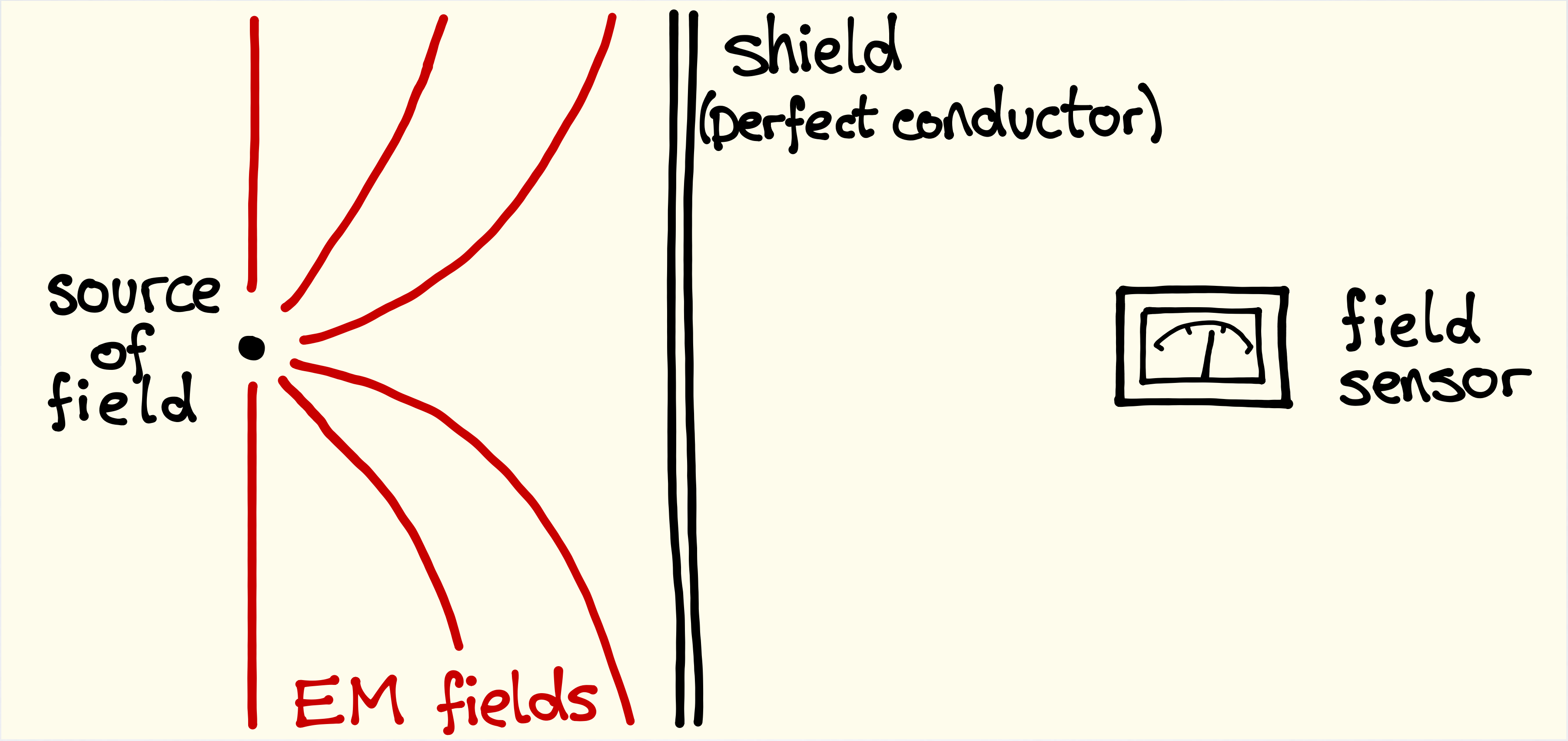

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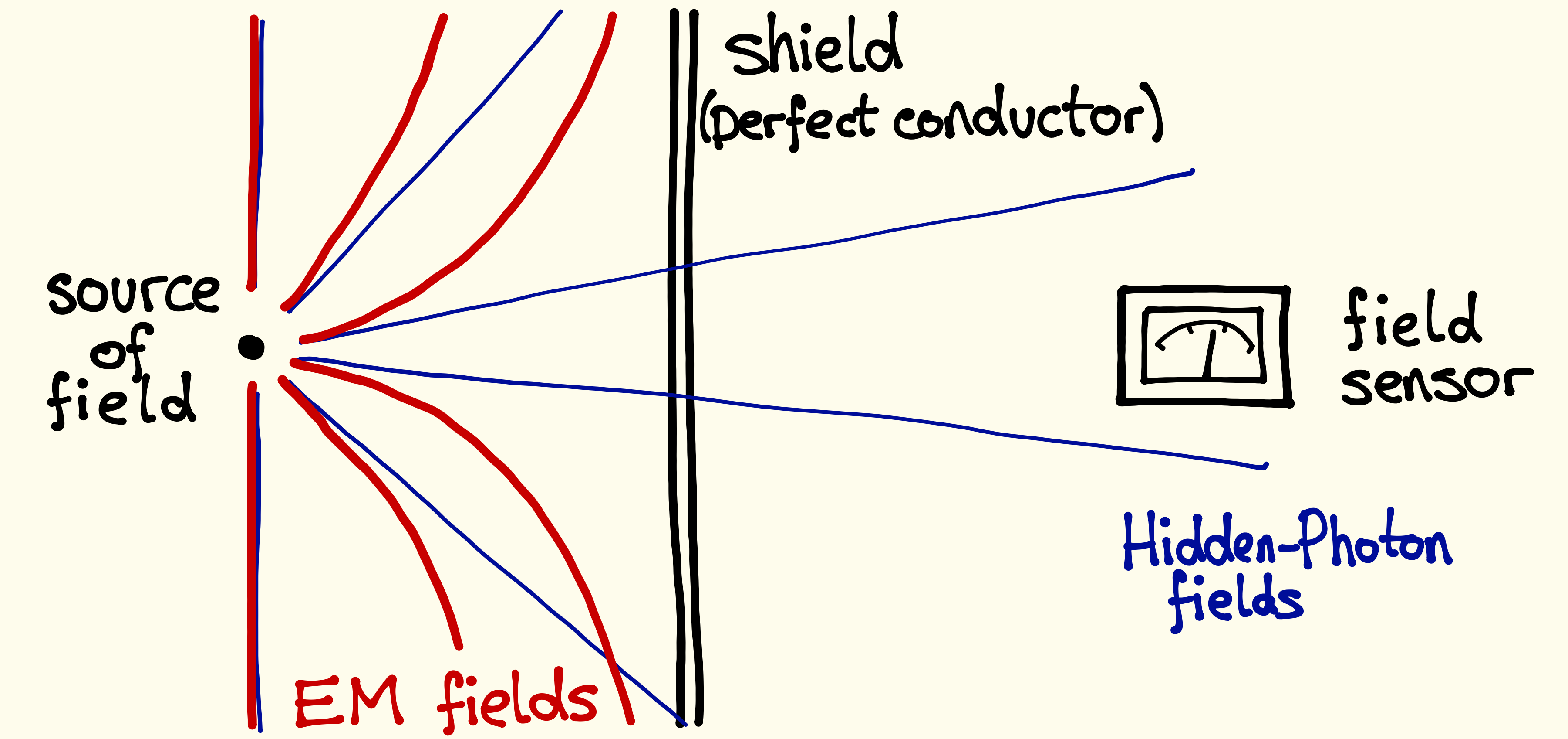

Detecting the hidden photon

Signal size: first estimate

— Source fields $(E, B)_{source}$

— ε to produce hidden photon

— ε for hidden photon to backreact on sensor

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

DETECTING THE HIDDEN PHOTON

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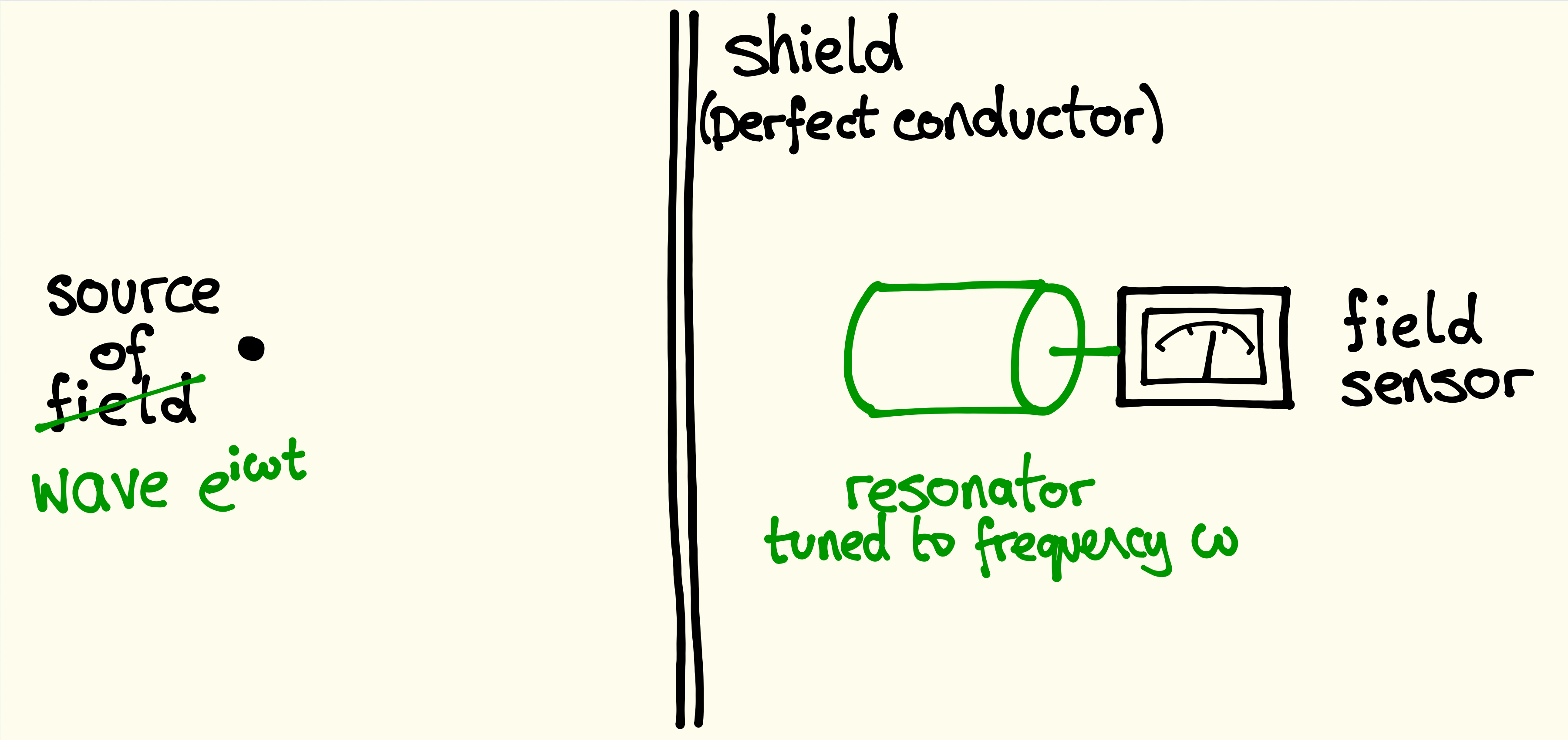
~~$\rightarrow$ $(E, B)_{detected} \sim \varepsilon^2 (E, B)_{source}$~~ ?

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

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

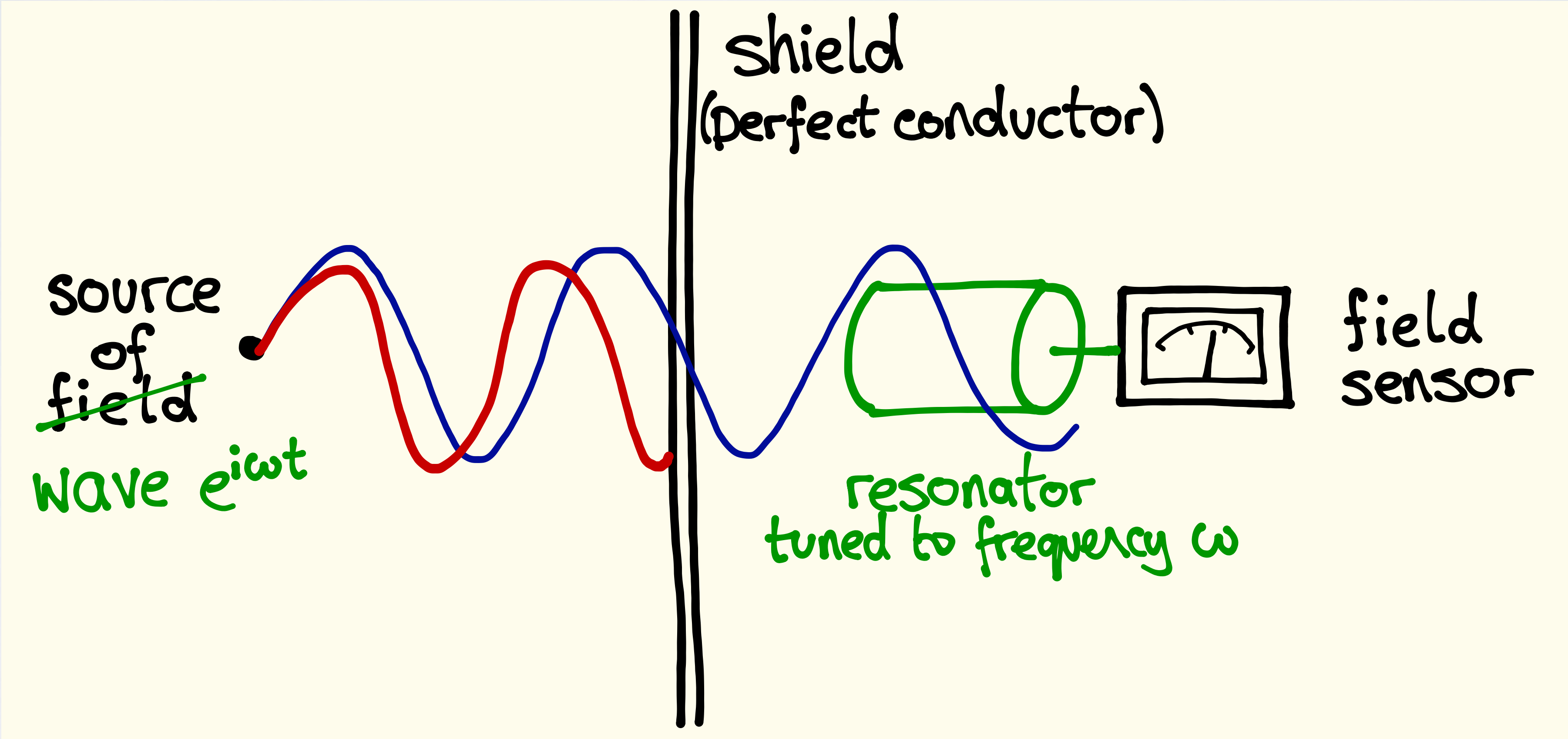
Detecting the hidden photon

Improve with resonance



Detecting the hidden photon

Improve with resonance



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

— $Q \gg 1$ resonant enhancement

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

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

missing factor to give
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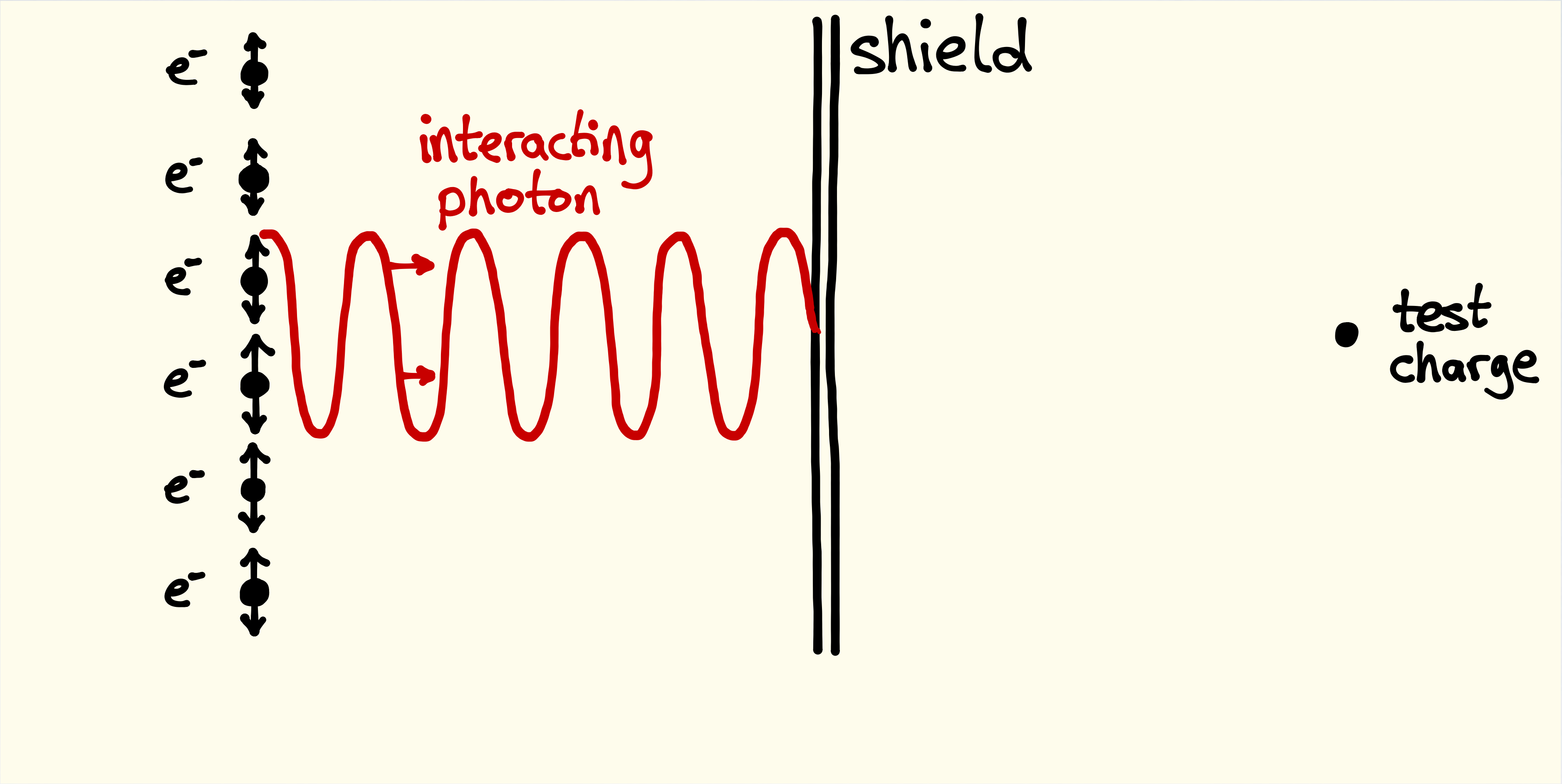
Signal size take 2



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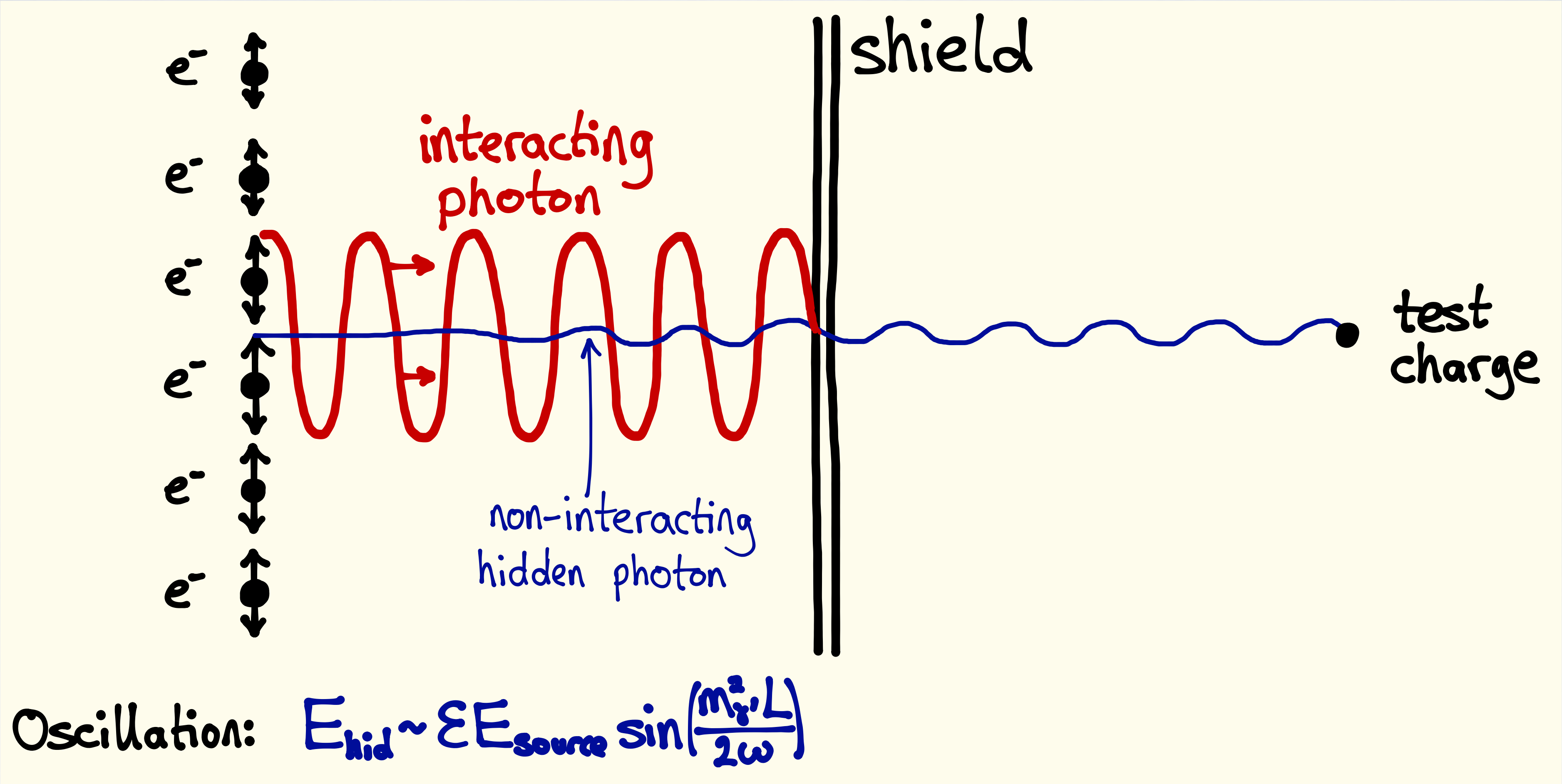

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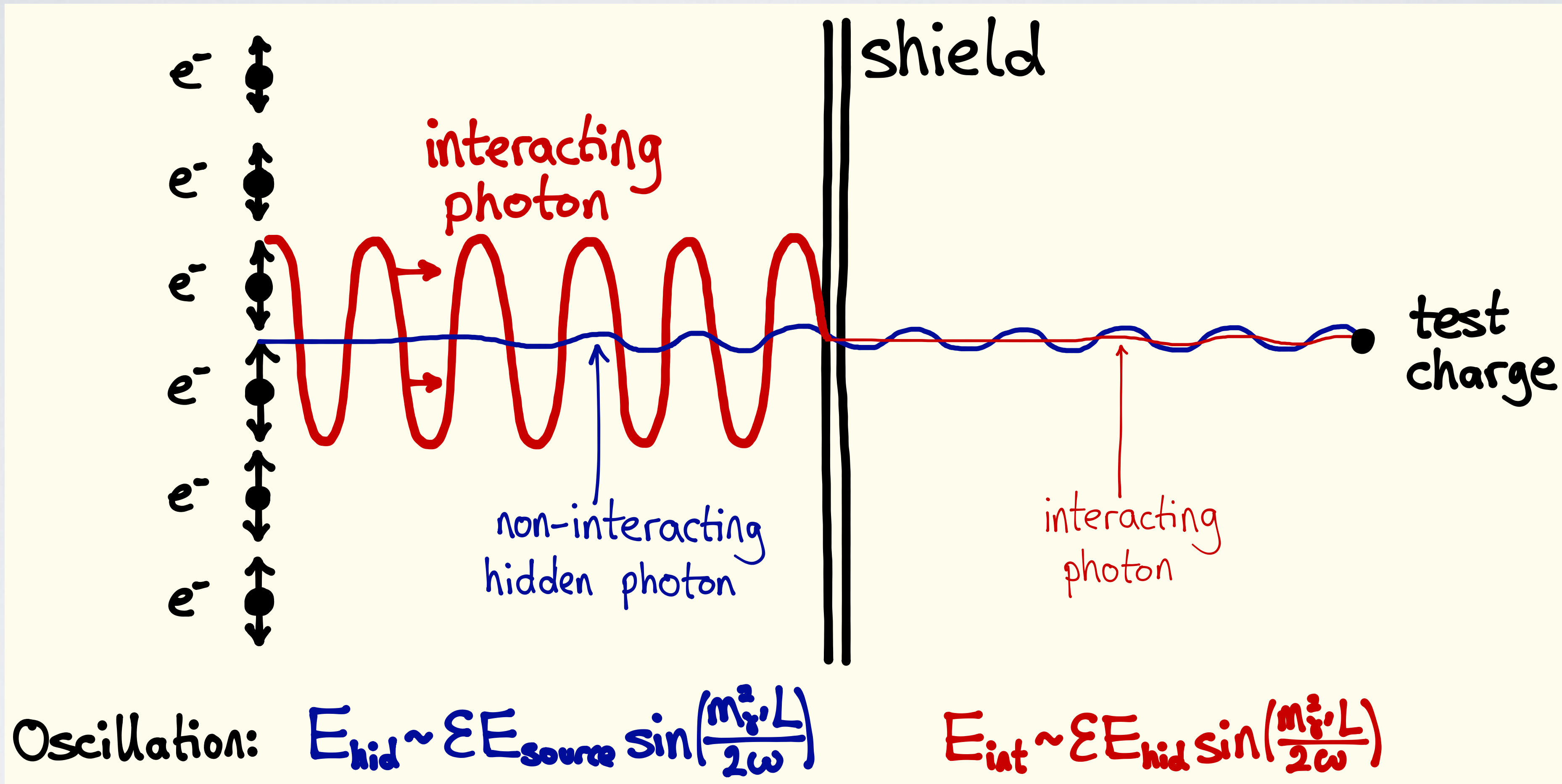

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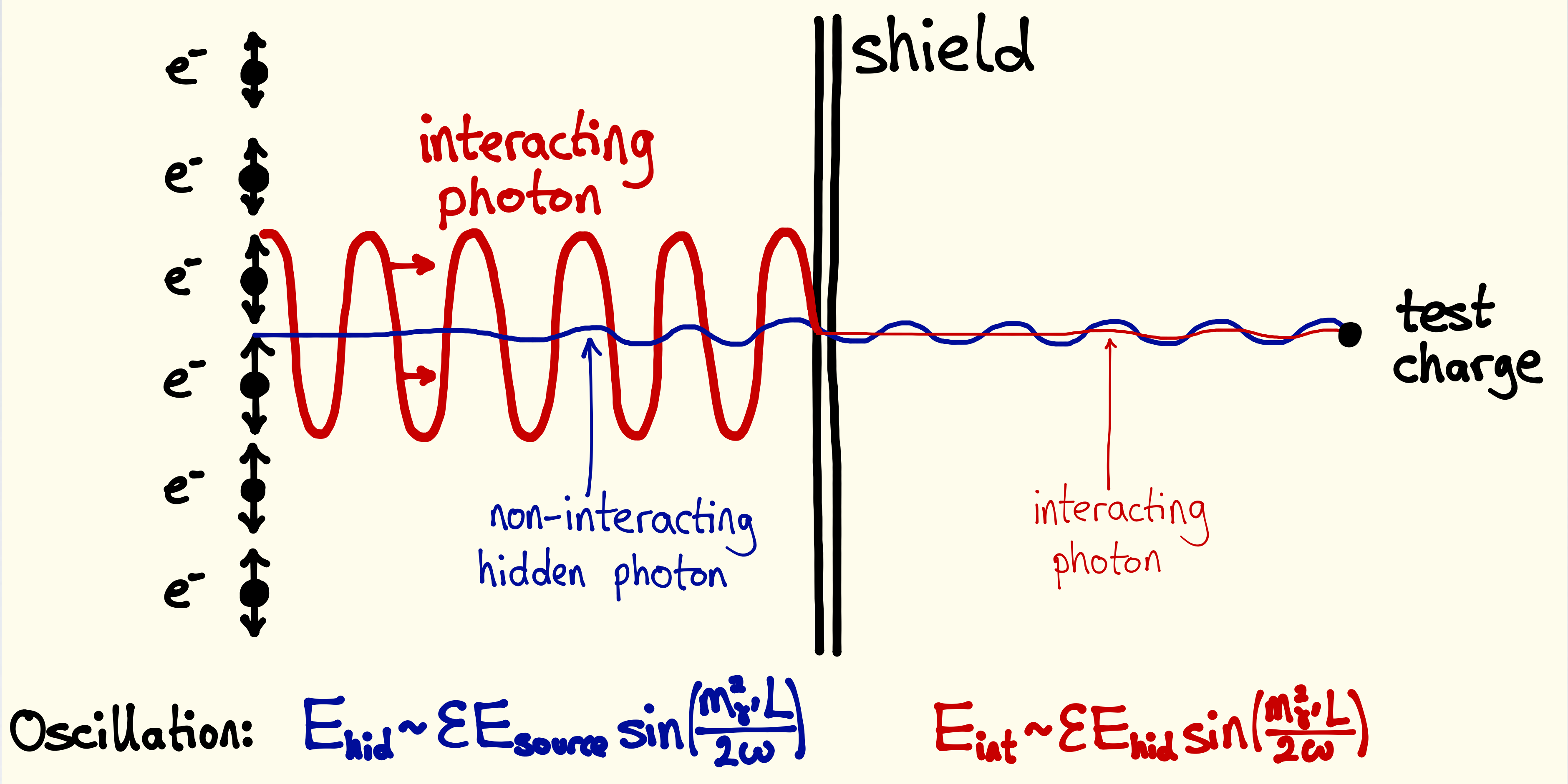


$\rightarrow$ $(E, B)_{\text{detected}} \sim (m_\gamma{}^4 L^2/\omega^2)\ Q\ \varepsilon^2\ (E, B)_{\text{source}}$

"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

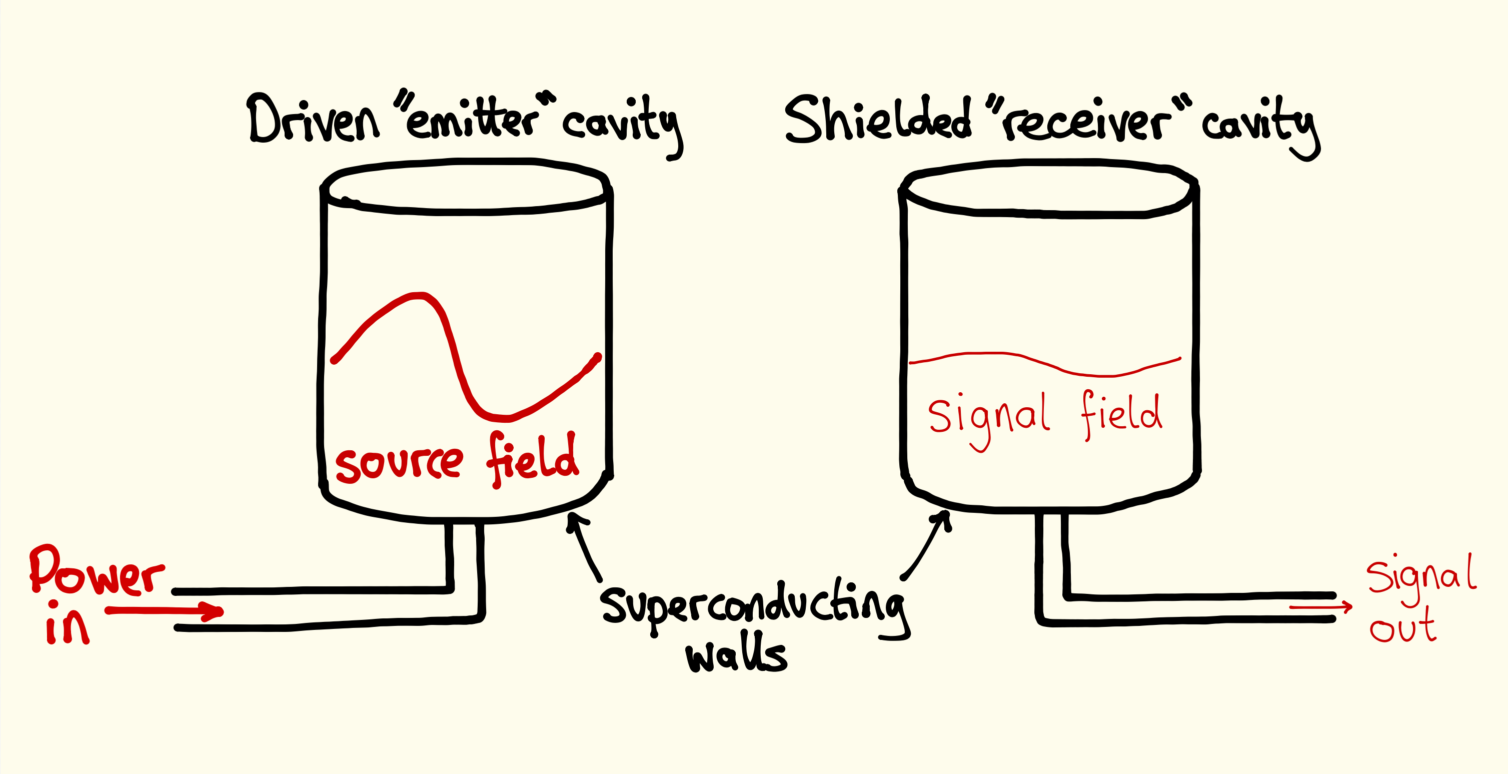
Microwave cavities are ideal

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



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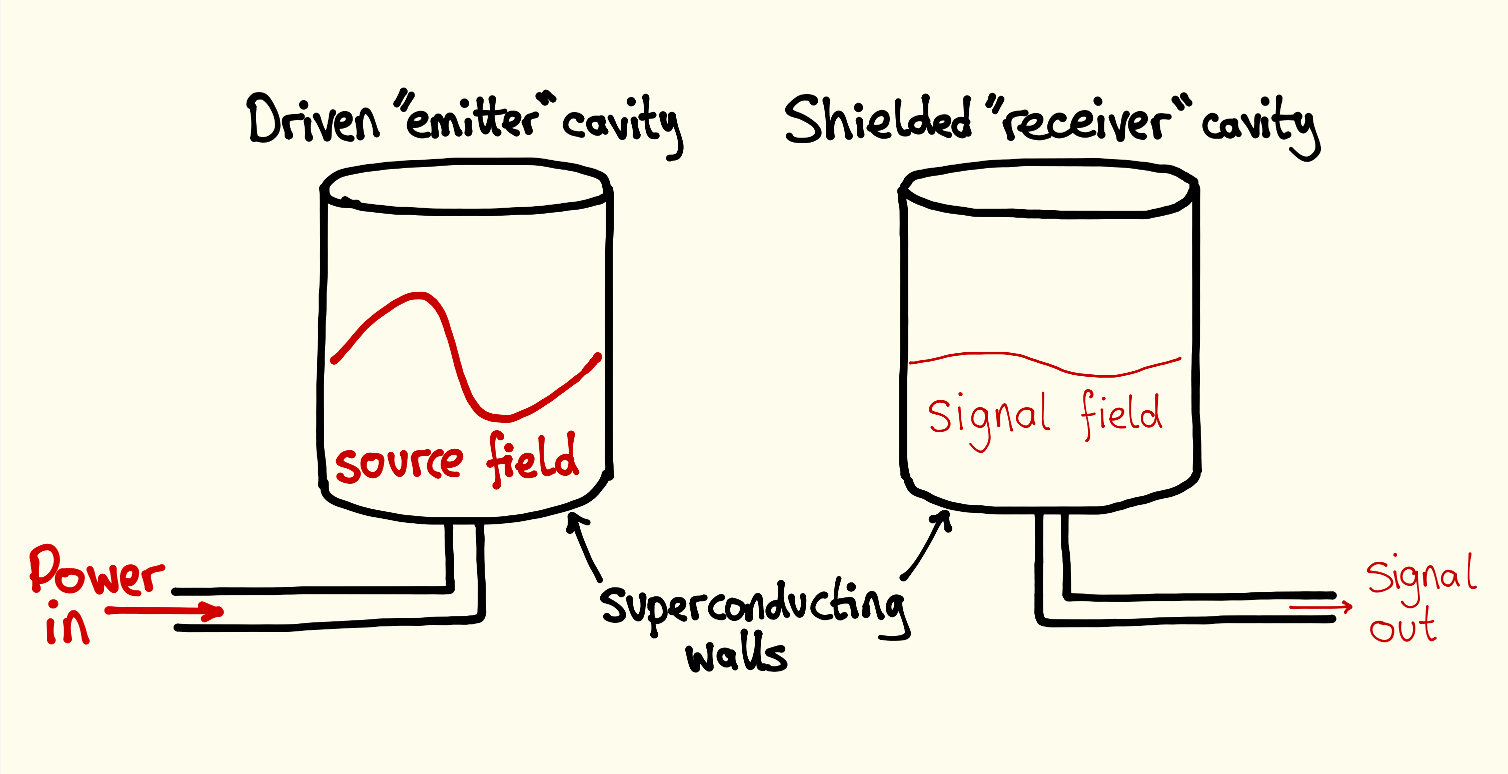
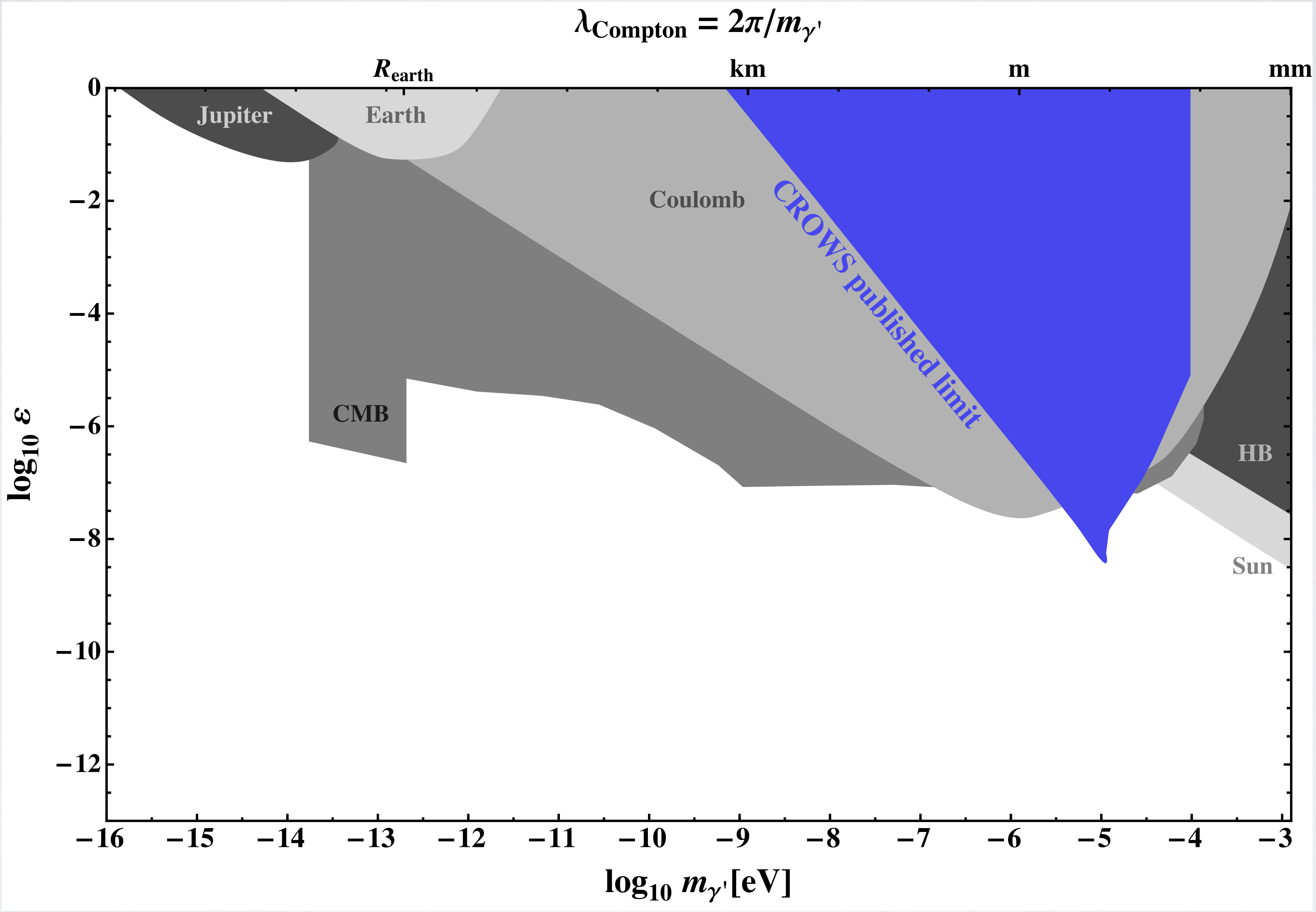


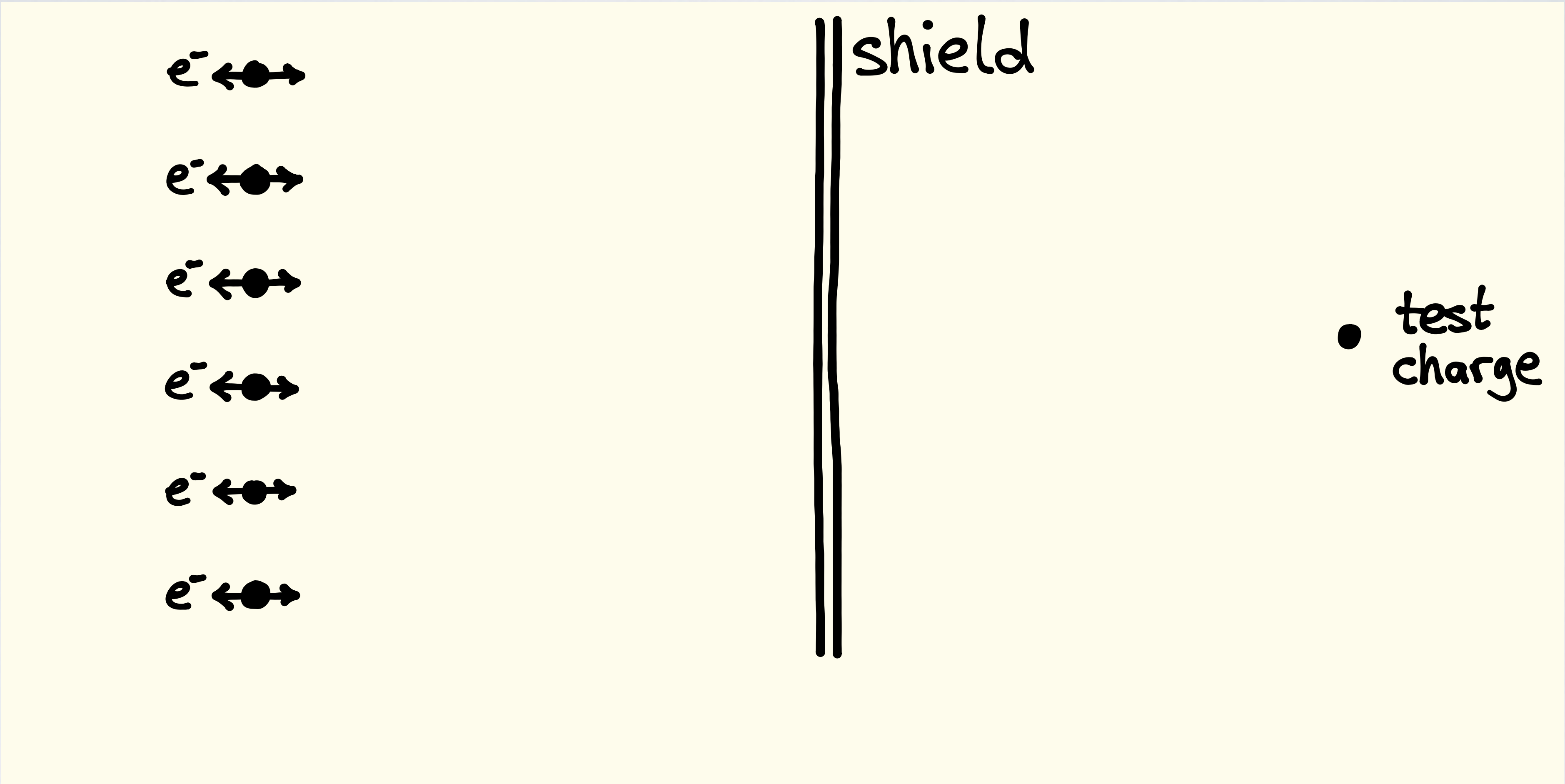
CERN Resonant Weakly-Interacting sub-eV Particle Search (CROWS)



1310.8098

THE IMPORTANCE OF THE LONGITUDINAL MODE

Signal size take 3: longitudinal waves



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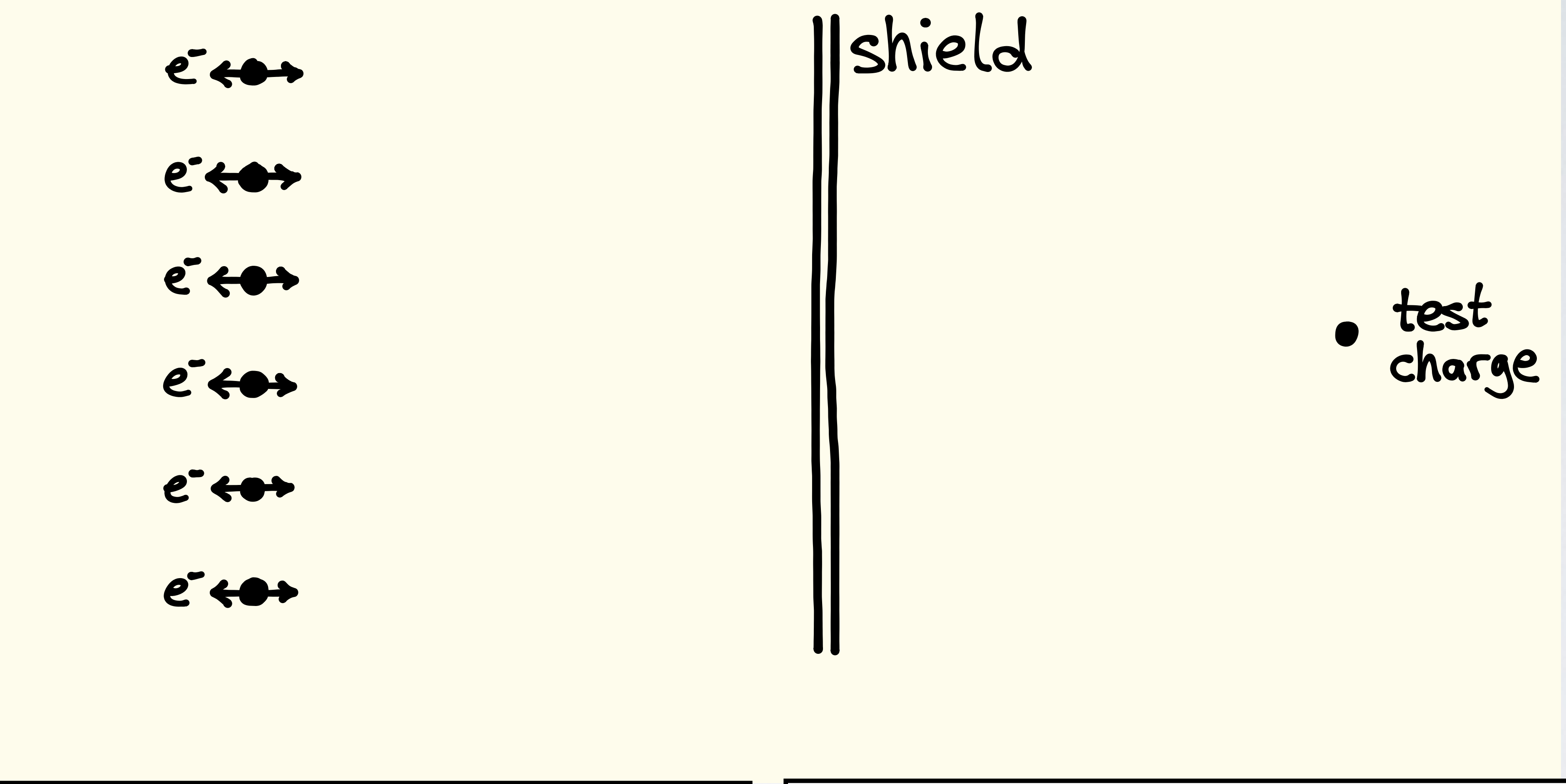

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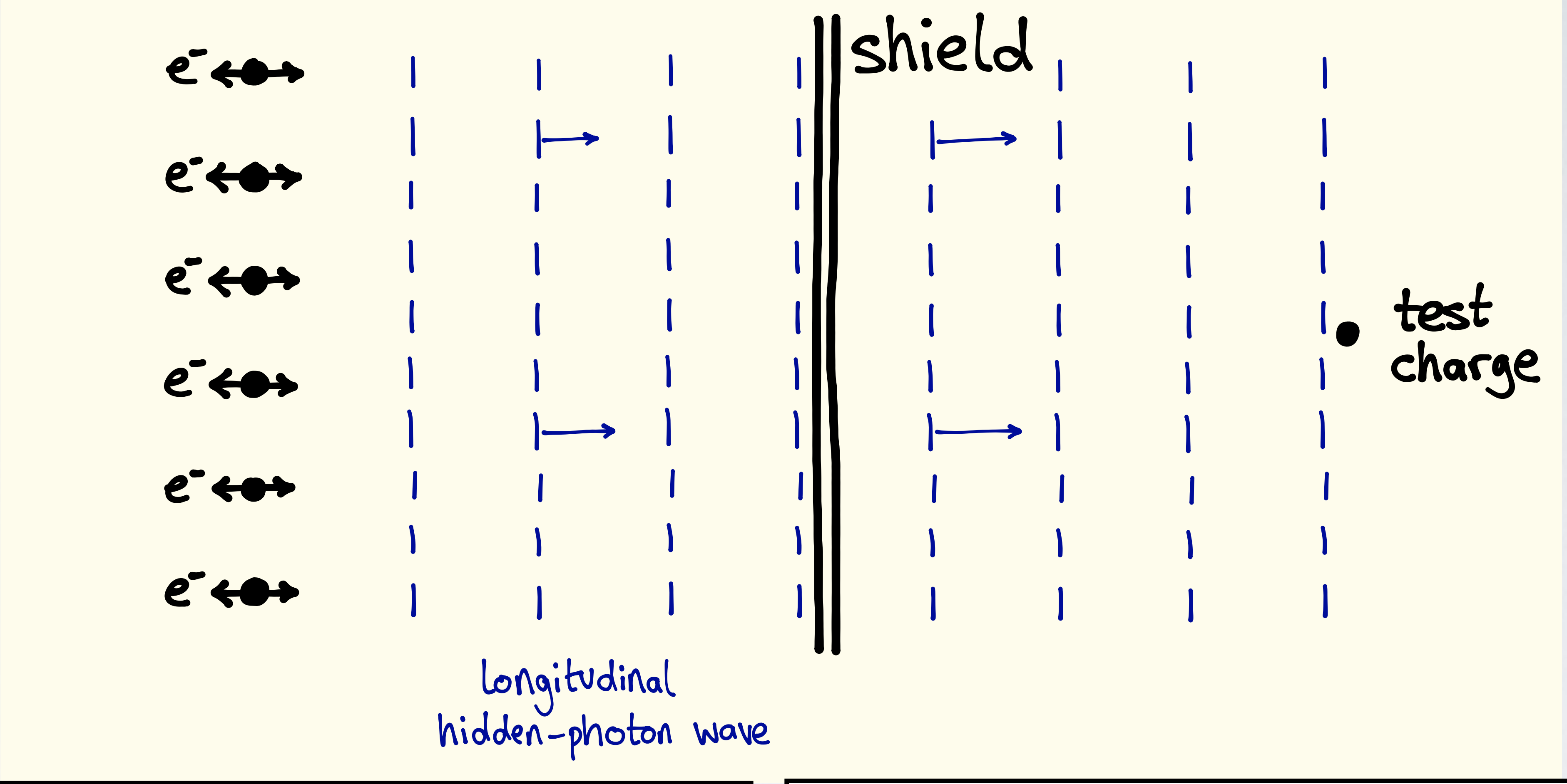
longitudinal mode A'_L

with

coupling εe to electric charge

Signal size take 3: longitudinal waves



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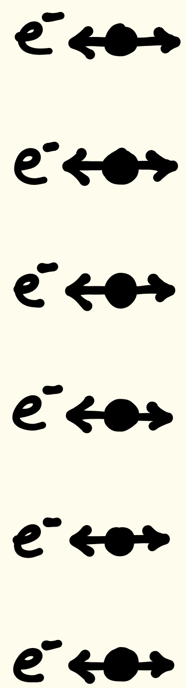
Signal size take 3: longitudinal waves

$A'_z \propto \varepsilon J_z$



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

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

⬇

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

⬇

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

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➡

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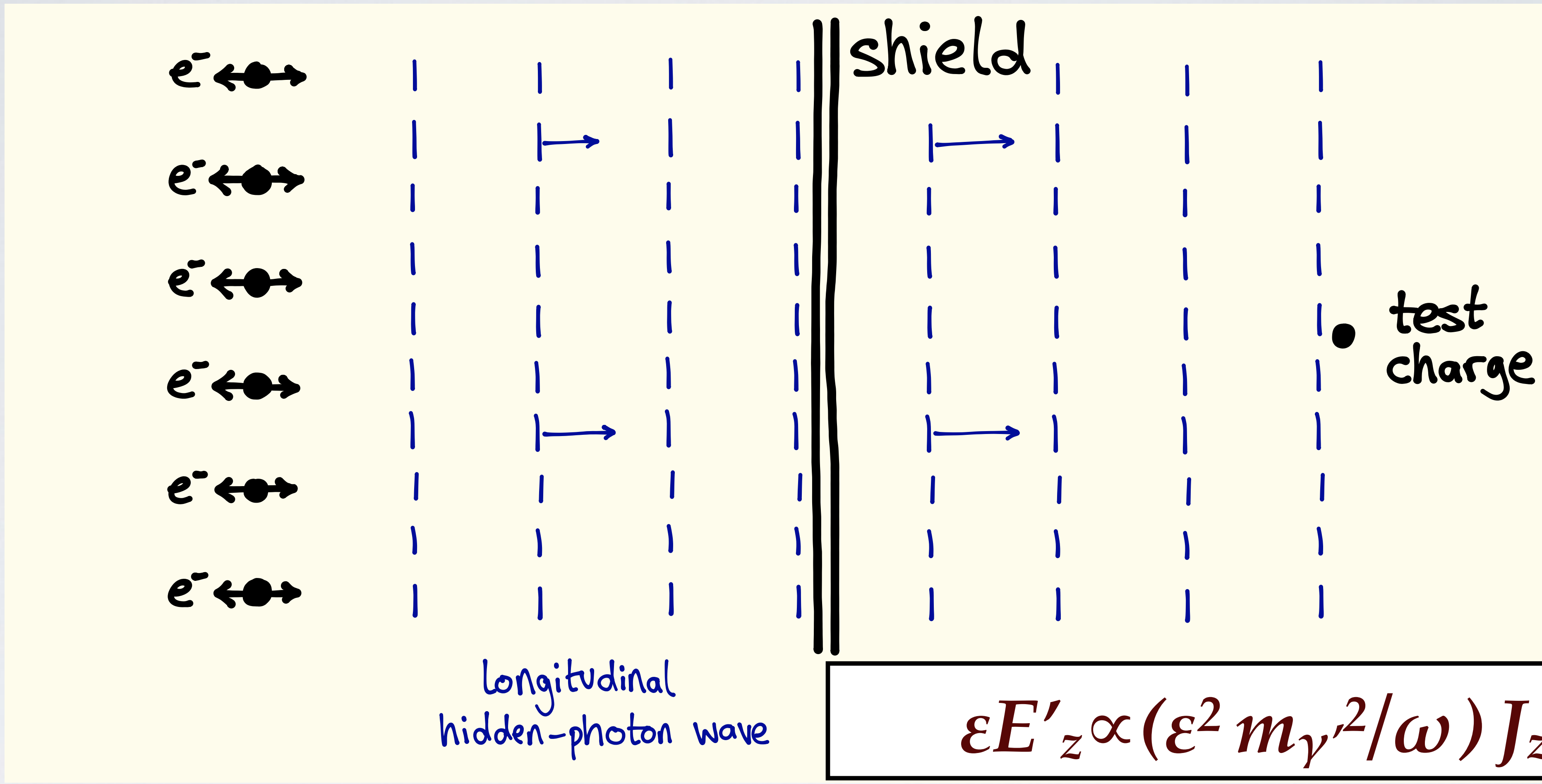
SIGNAL SIZE TAKE 3: LONGITUDINAL WAVES



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

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

MICROWAVE CAVITIES

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- — 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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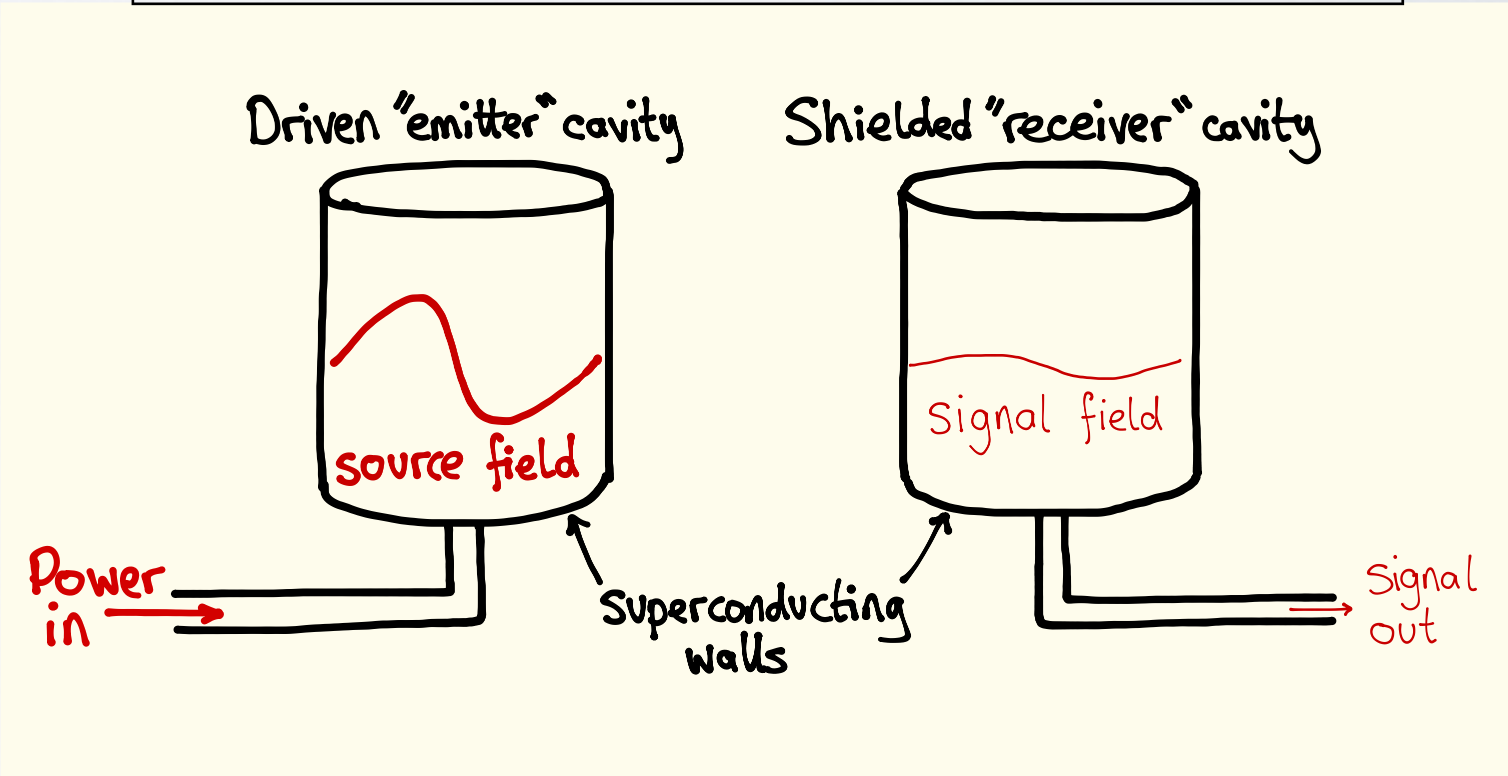
- — CROWS 1310.8098



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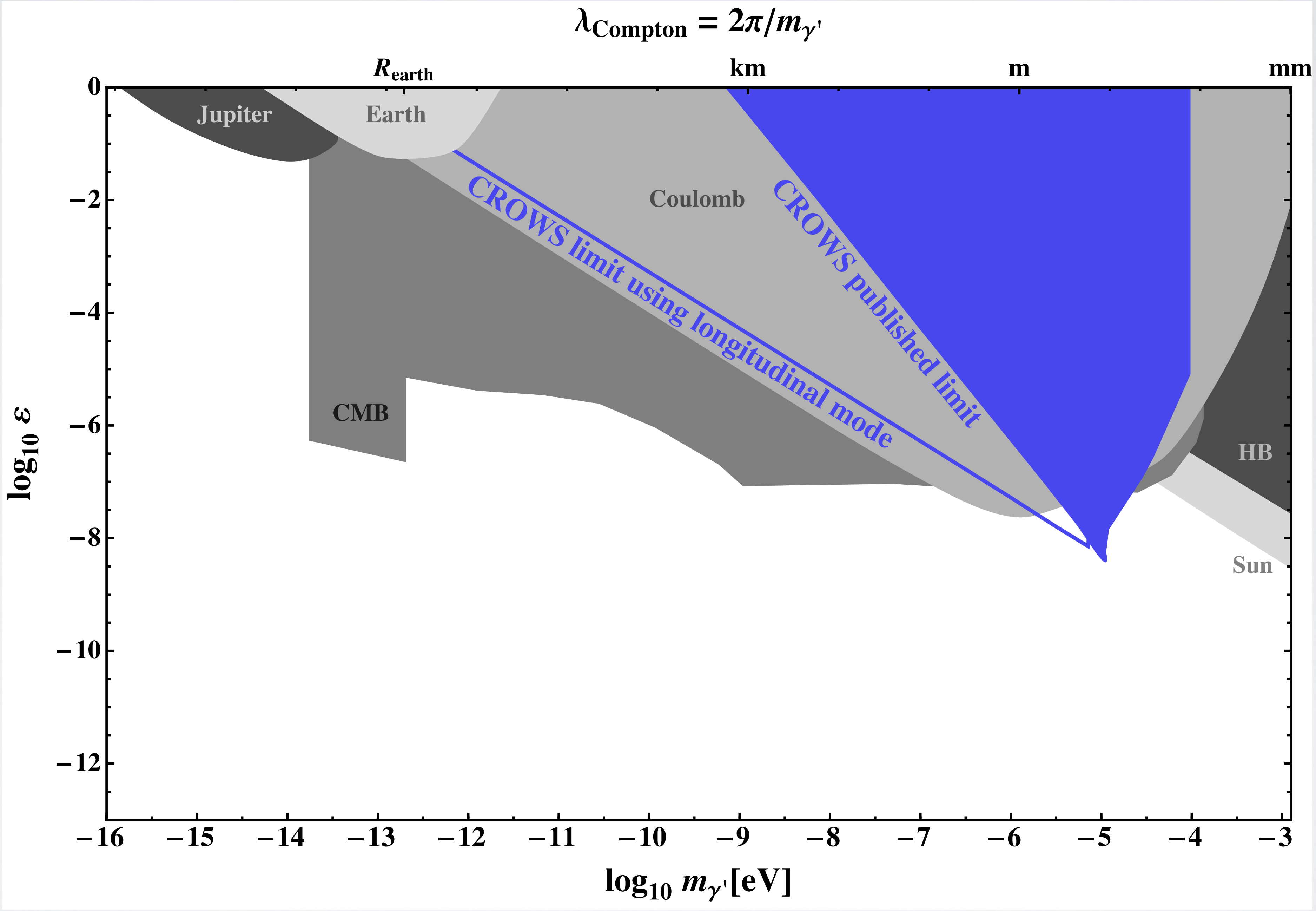
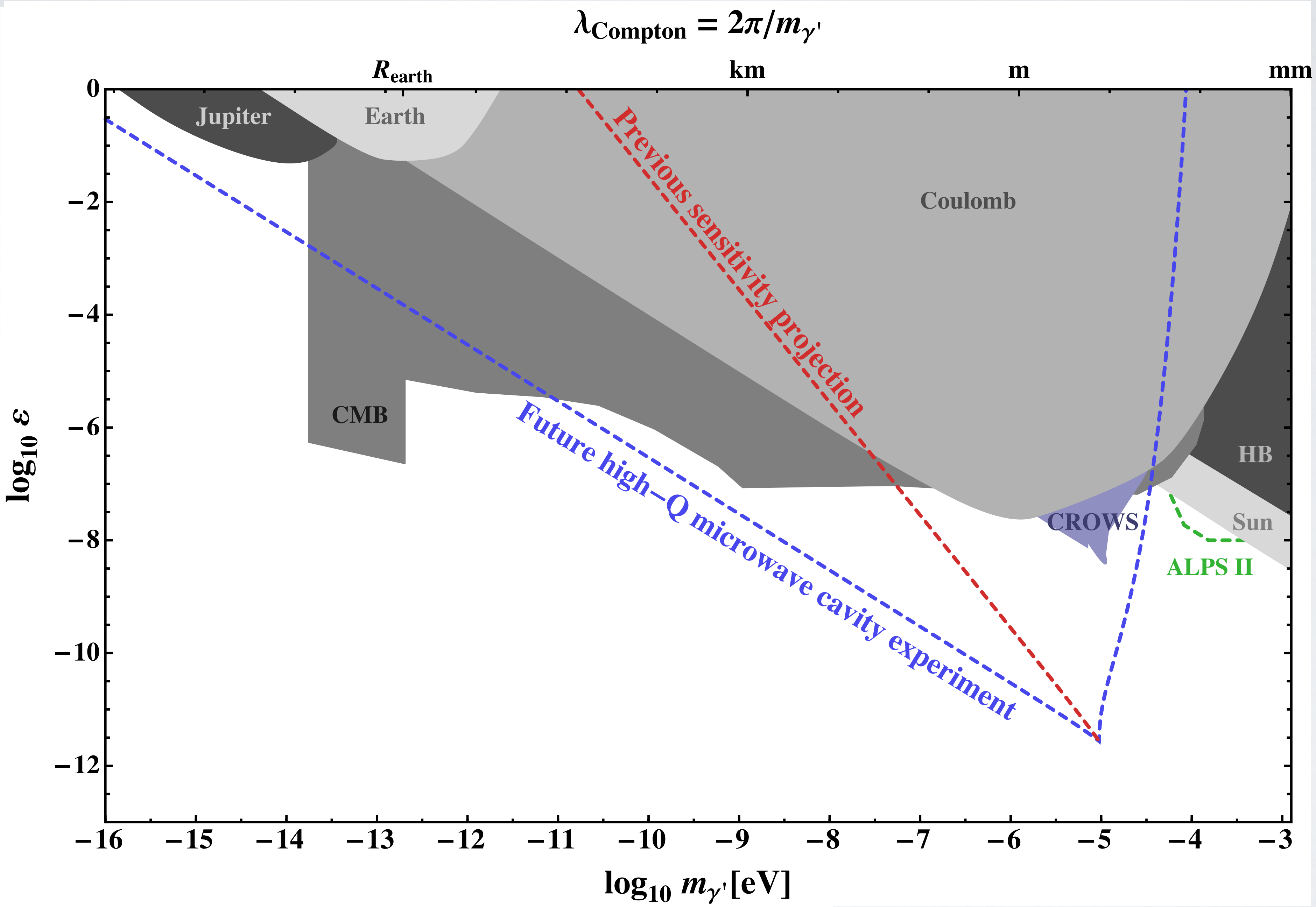


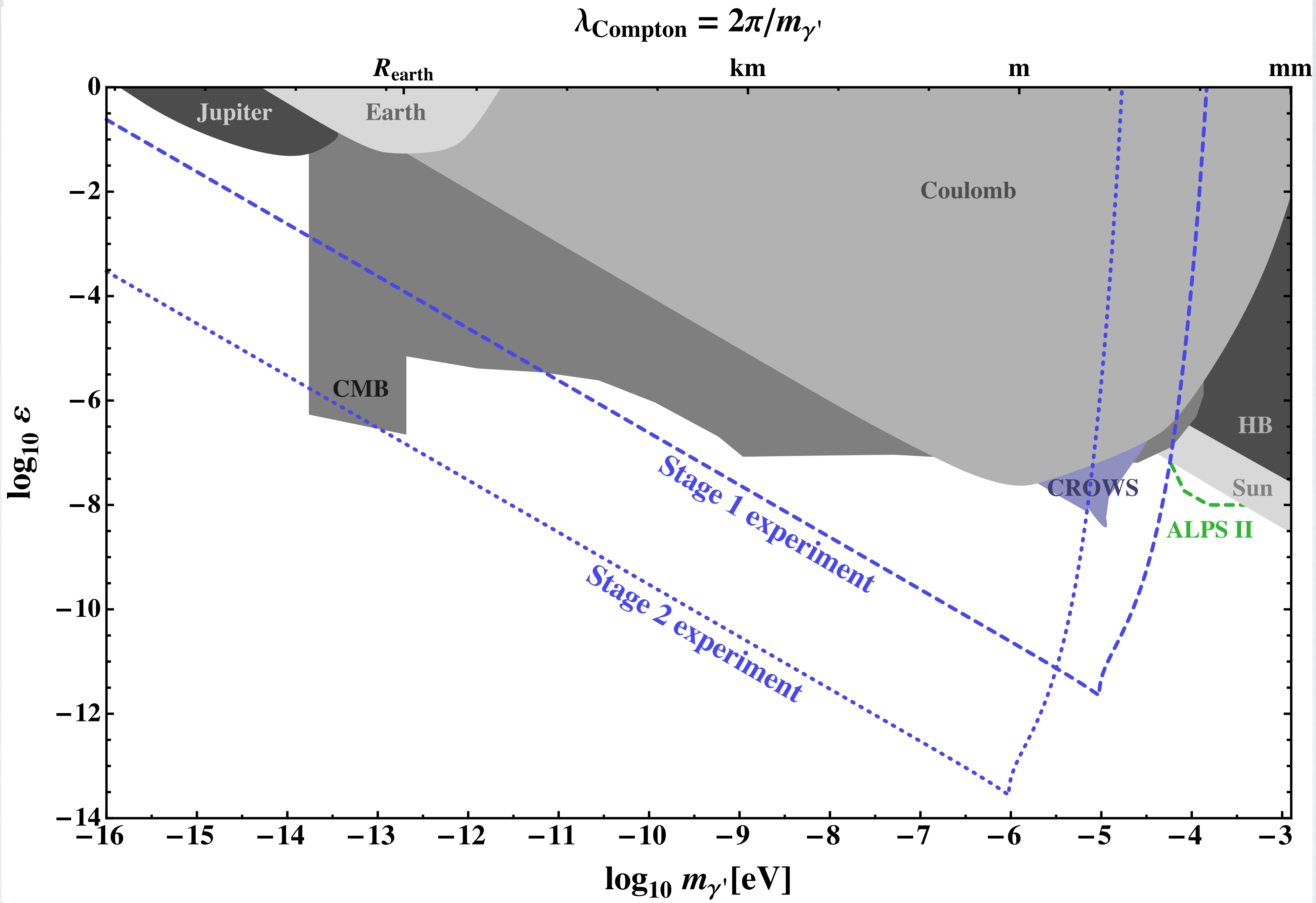
P.Graham, J.Mardon, S. R. & Y. Zhao 1407.4806

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 $m \gtrsim 10^{-20}$ 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 $\mathcal{L} \supset (1/12)\mathcal{R}\, A'_\mu{}^2$
⟶ Large mass from graviton loops?
⟶ Overproduced by inflationary perturbations if $R=0.2$
— Is there a safe way to produce it? (yes, through inflation)

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

electromagnetic cavities

— 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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(set by cavity size)

LC circuits

— resonators

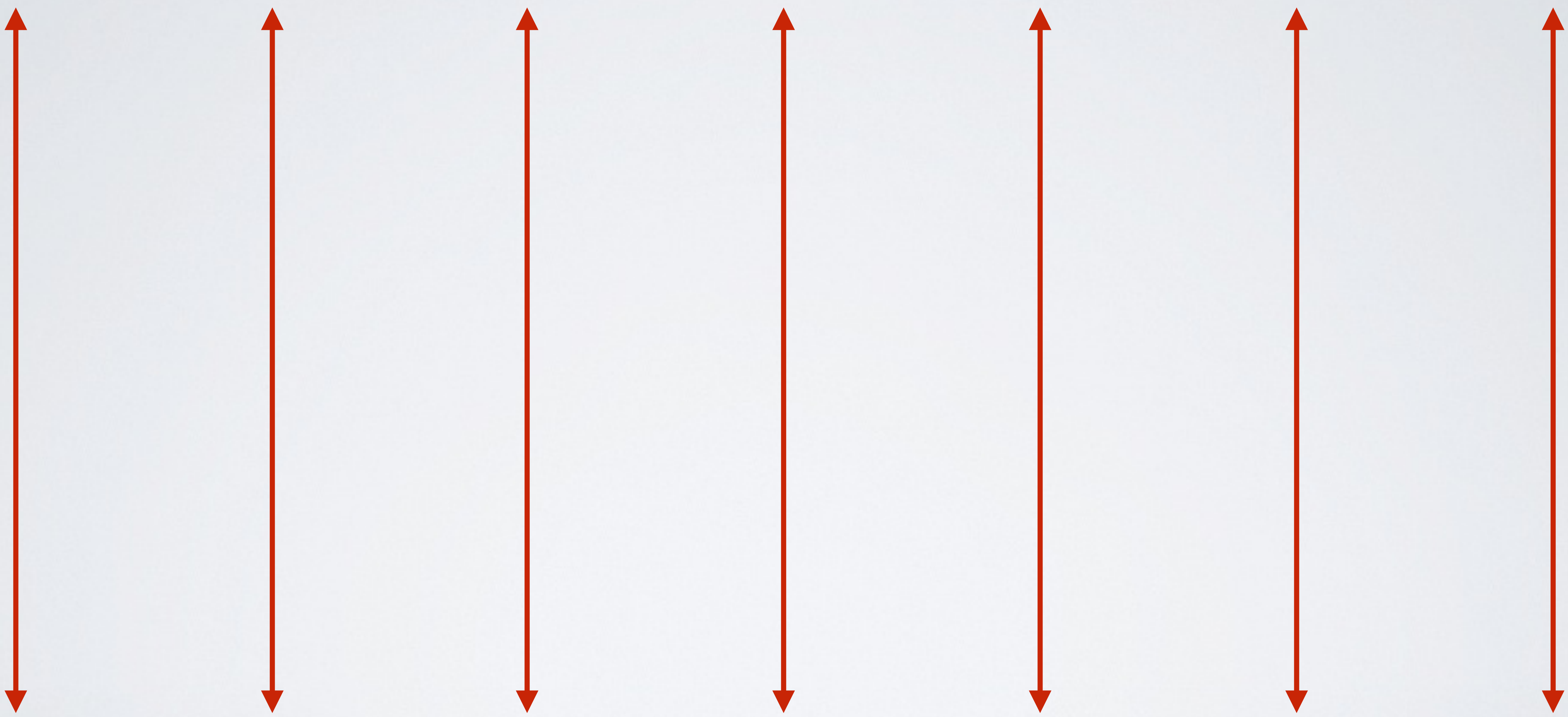
— much wider and lower frequency range than cavities

⟶ can probe much lower masses

S. Chaudhuri et. al. 1411.7382

EXPERIMENTAL SETUP

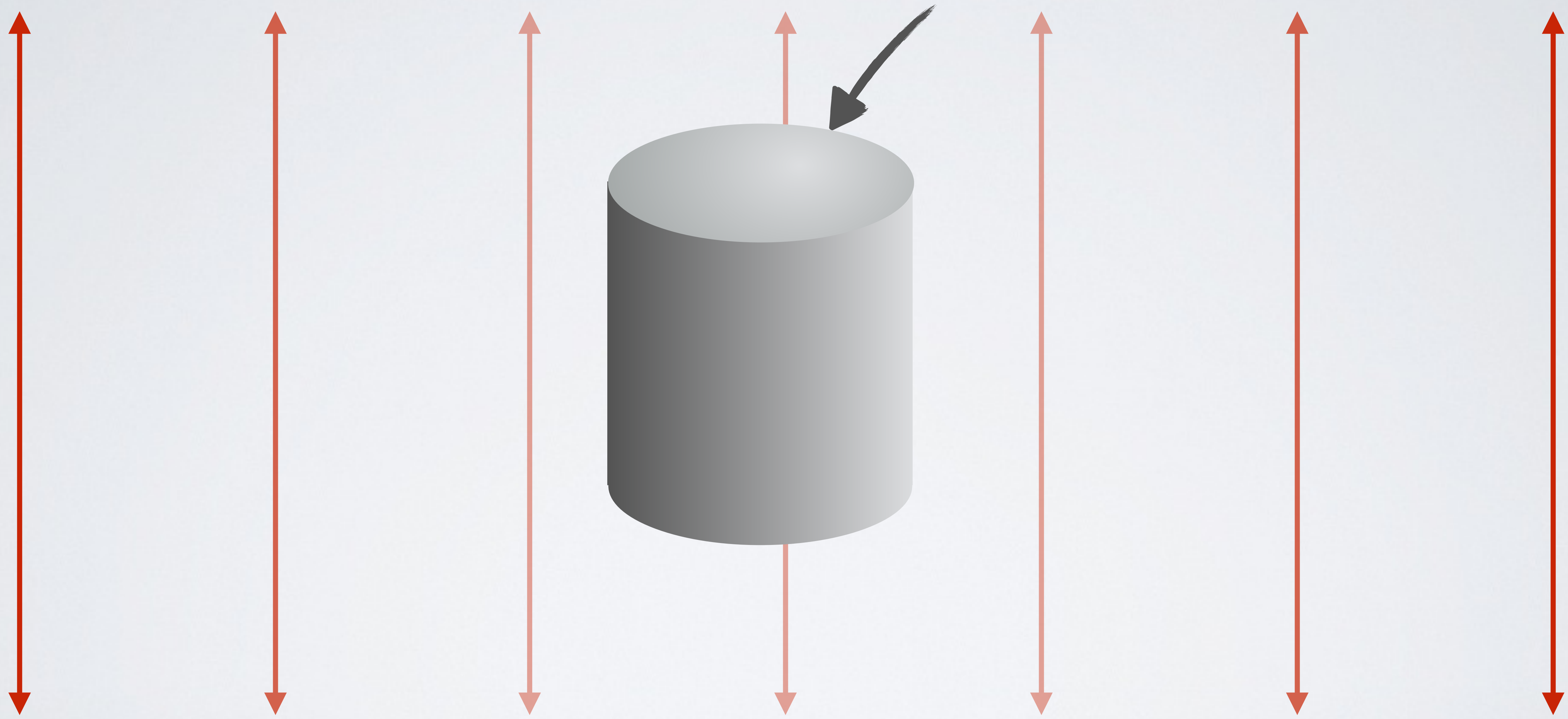
oscillating E' field (dark matter)



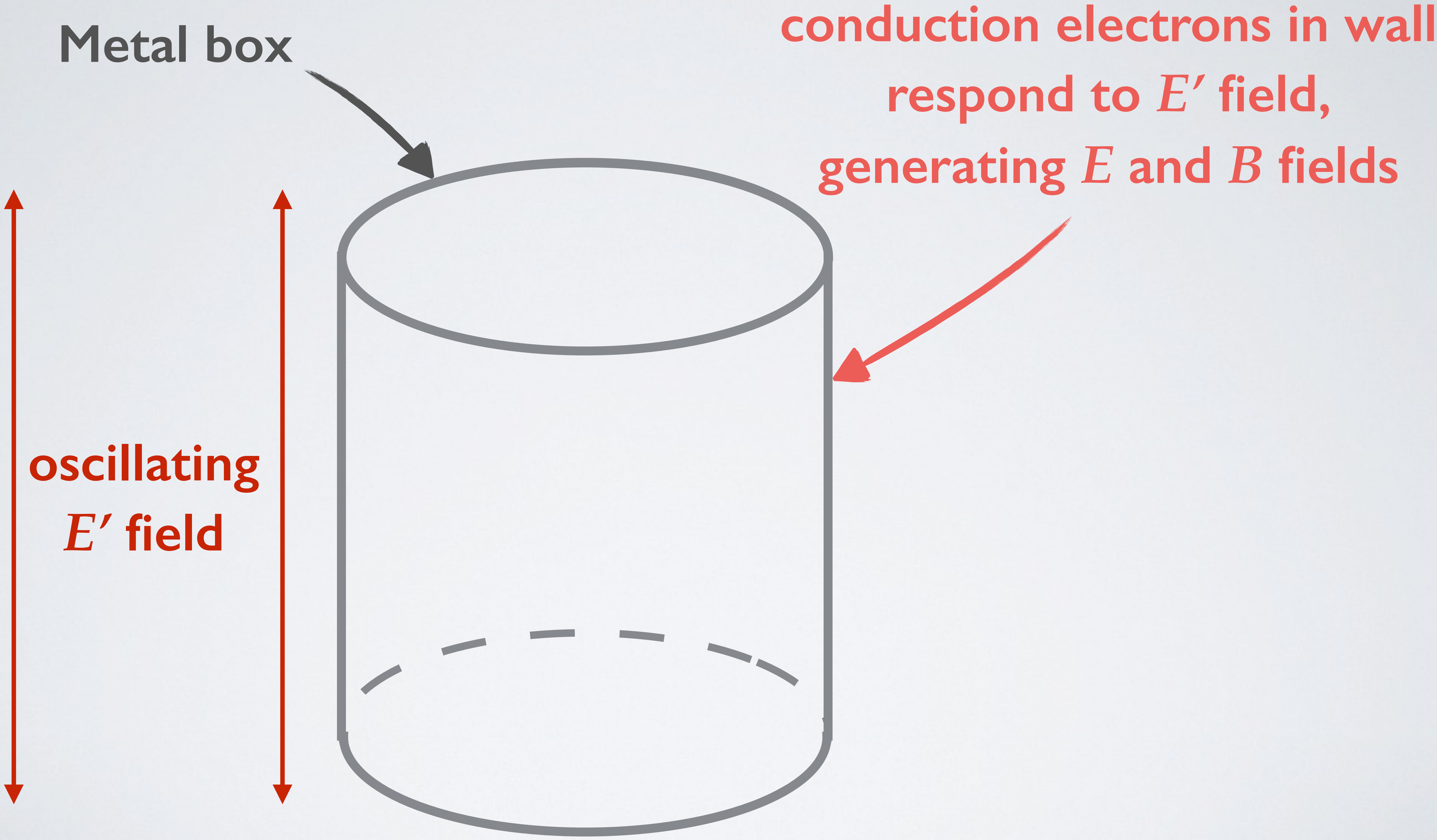
EXPERIMENTAL SETUP

oscillating E' field (dark matter)

Metal box to shield backgrounds (Faraday cage)



The signal inside the box



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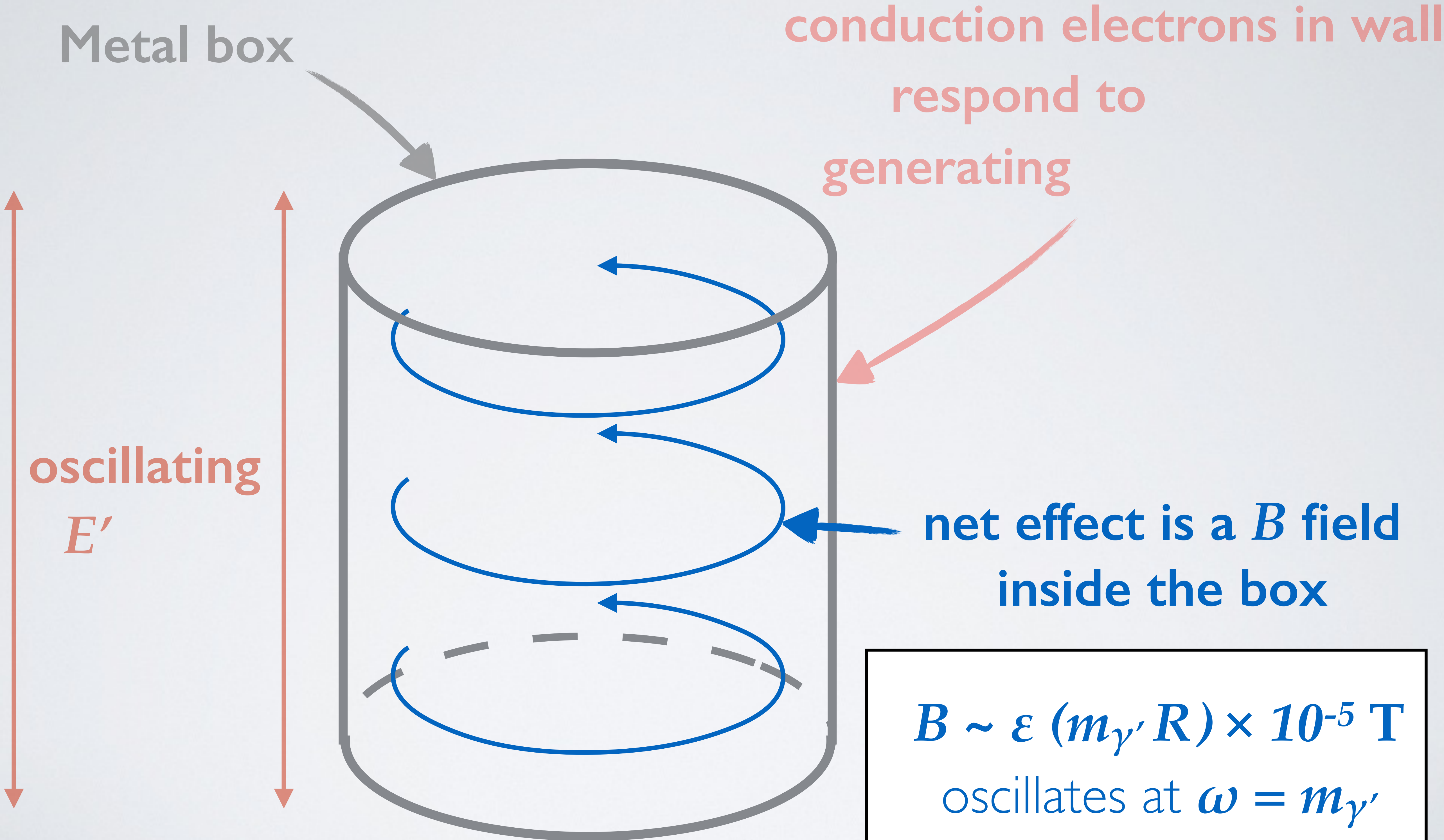

$B \sim \varepsilon\,(m_{\gamma'} R) \times 10^{-5}$ T

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

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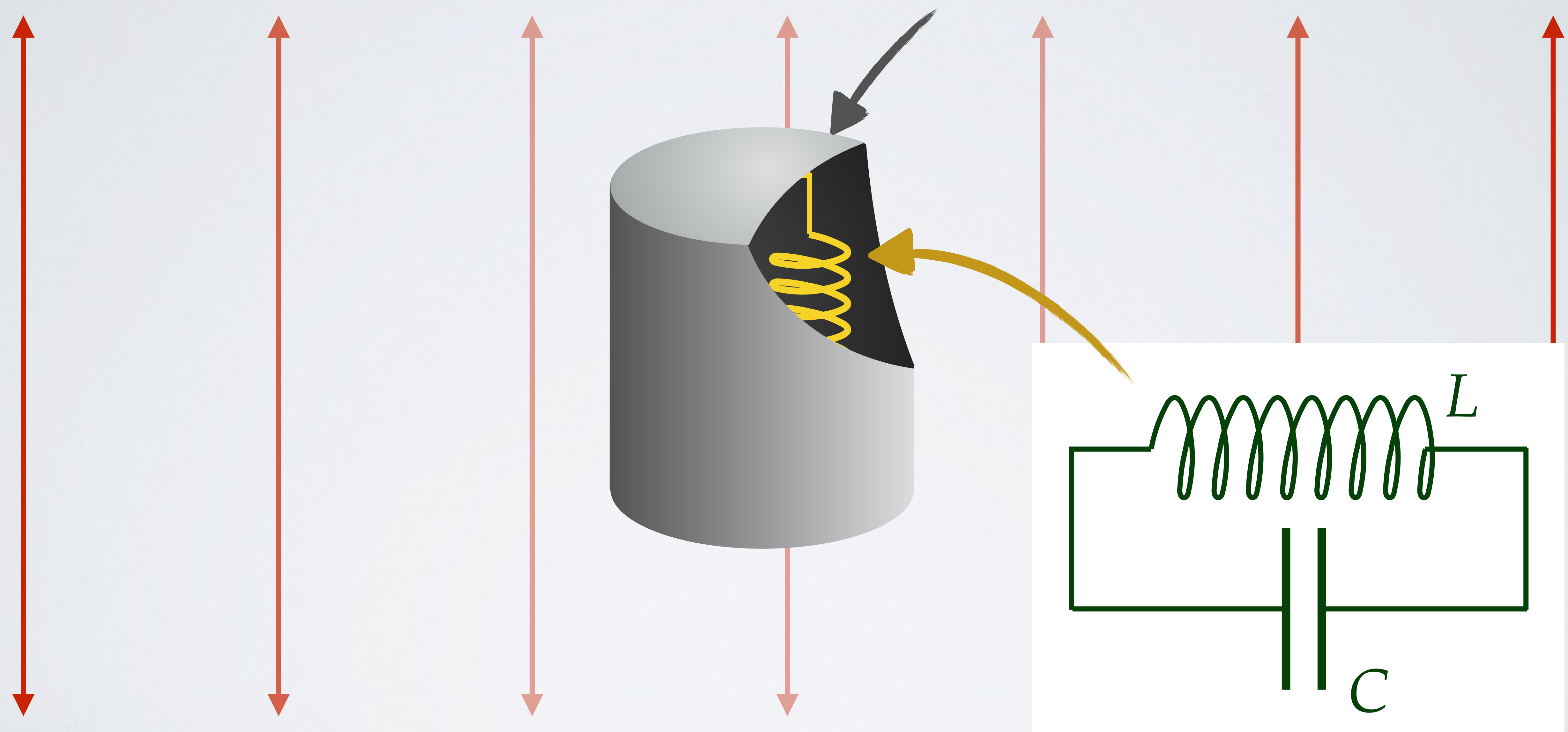


Tunable resonant LC circuit (a radio)

REACH

STAGE I

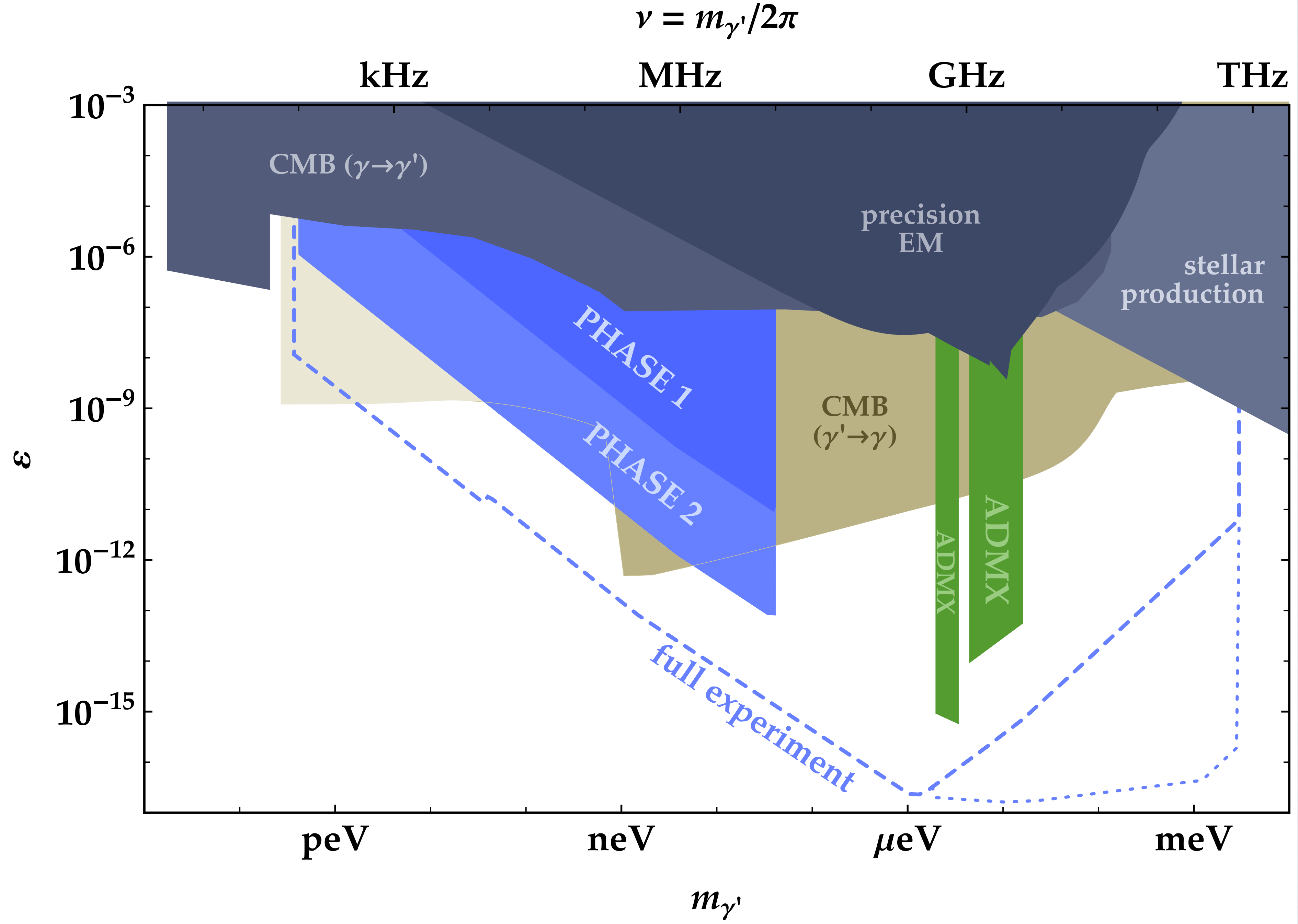
size ~ 350ml — 1m   Q~10^6

T~4K, thermal noise limited

FULL DESIGN

size ~ 1m   Q~10^6

T~0.1K, thermal noise limited



Cosmological Solution to The Hierarchy Problem

Surjeet Rajendran, UC Berkeley

Relaxion: Cosmological Solution to the Hierarchy Problem

QCD axion + Long Period of inflation solves Hierarchy Problem

$$\mathcal{L} \supset (-M^2 + g\phi)|h|^2 + gM^2\phi + g^2\phi^2 + \cdots + \Lambda^4 \cos\frac{\phi}{f}$$

M cuts off SM
loops.

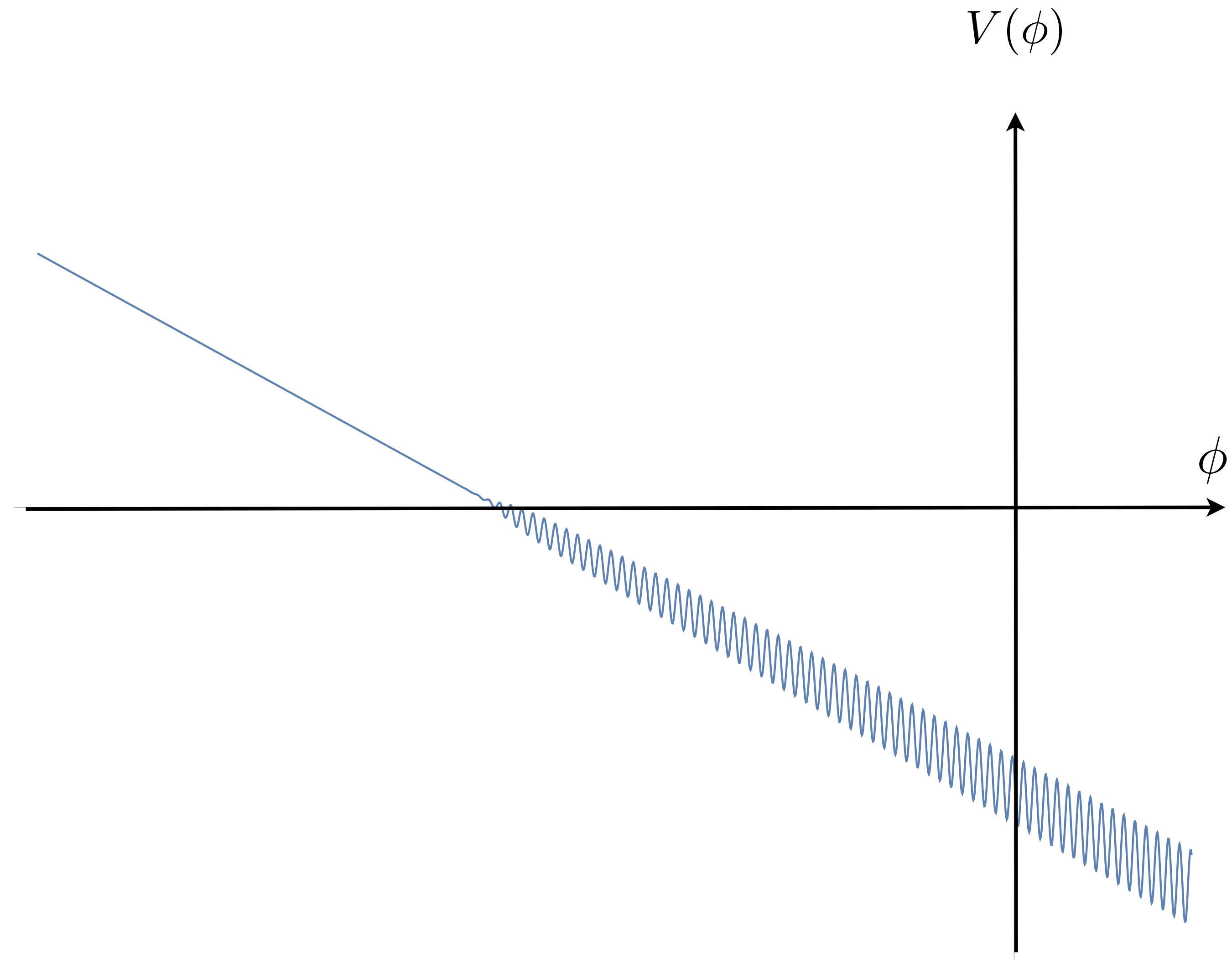
Continuous shift symmetry
broken completely by g.

The axion here is non-compact.

Relaxion: Cosmological Solution to the Hierarchy Problem

$$\mathcal{L} \supset (-M^2 + g\phi)|h|^2 + gM^2\phi + g^2\phi^2 + \cdots + \Lambda^4 \cos\frac{\phi}{f}$$

- Take initial ϕ value such that $m_h^2 > 0$
- During inflation, ϕ slow-rolls, scanning physical Higgs mass.
- ϕ hits value where ~ m_h^2 crosses zero.
- Barriers grow until rolling has stopped.



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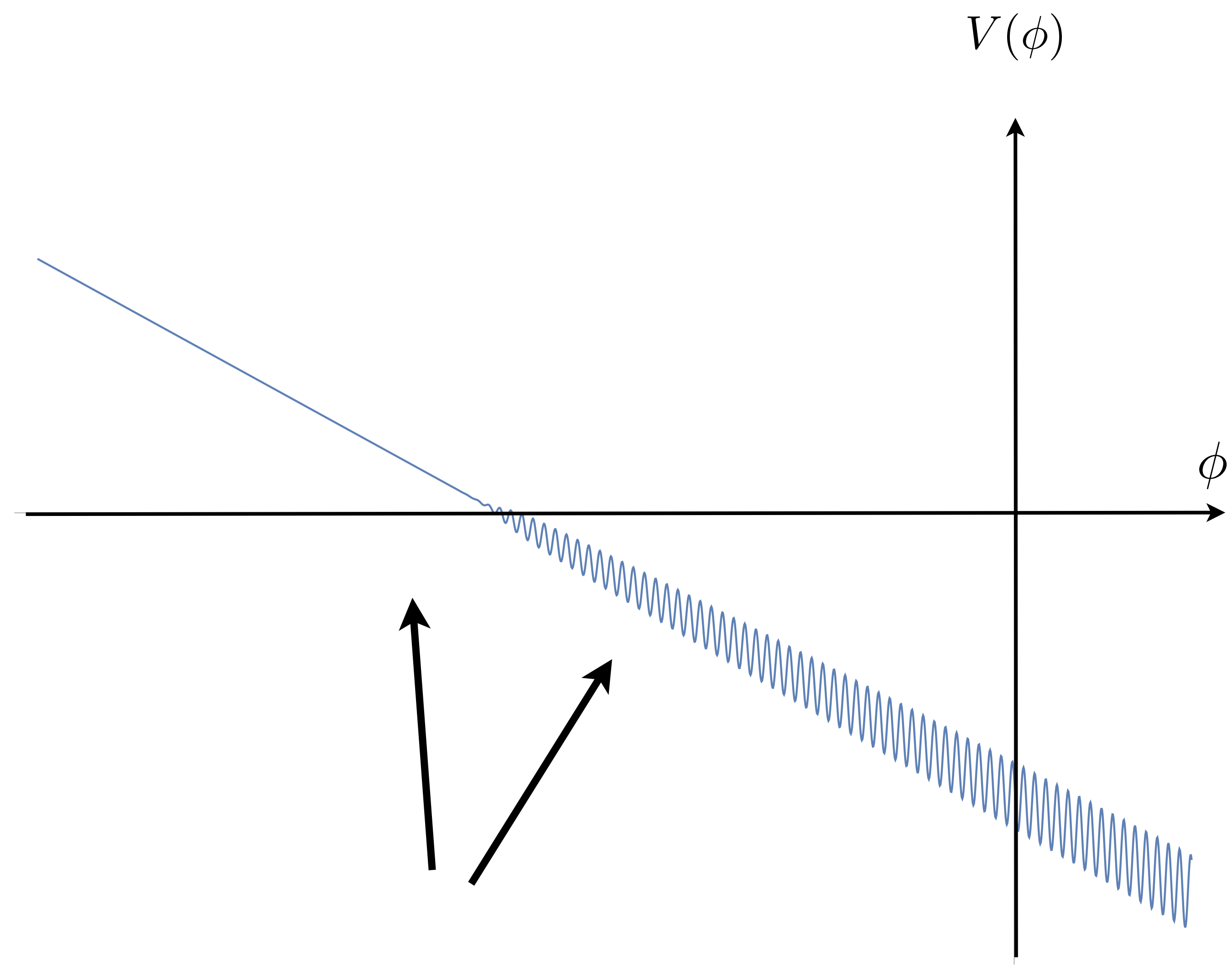

Key: Barriers grow because they depend on the Higgs vev.

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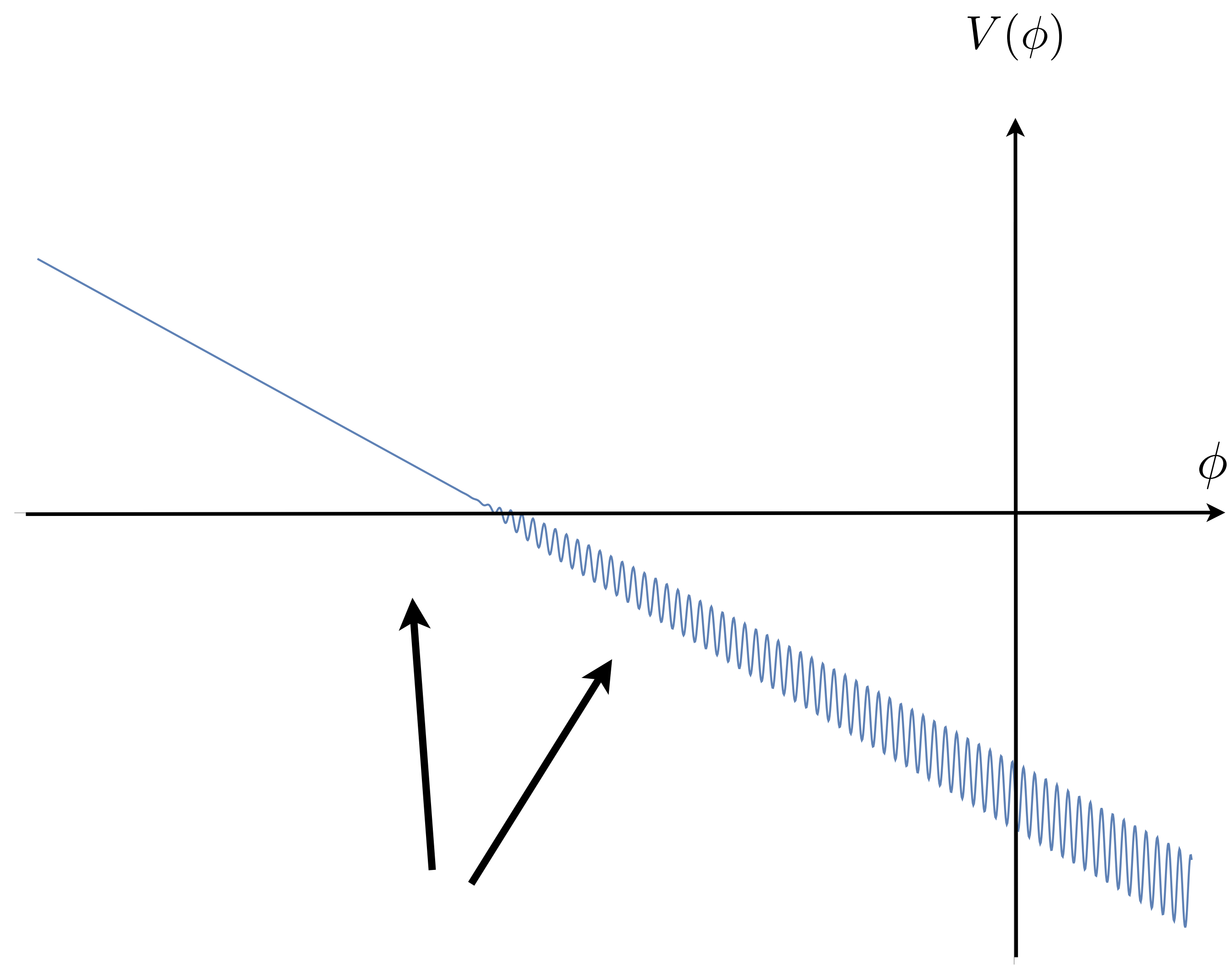


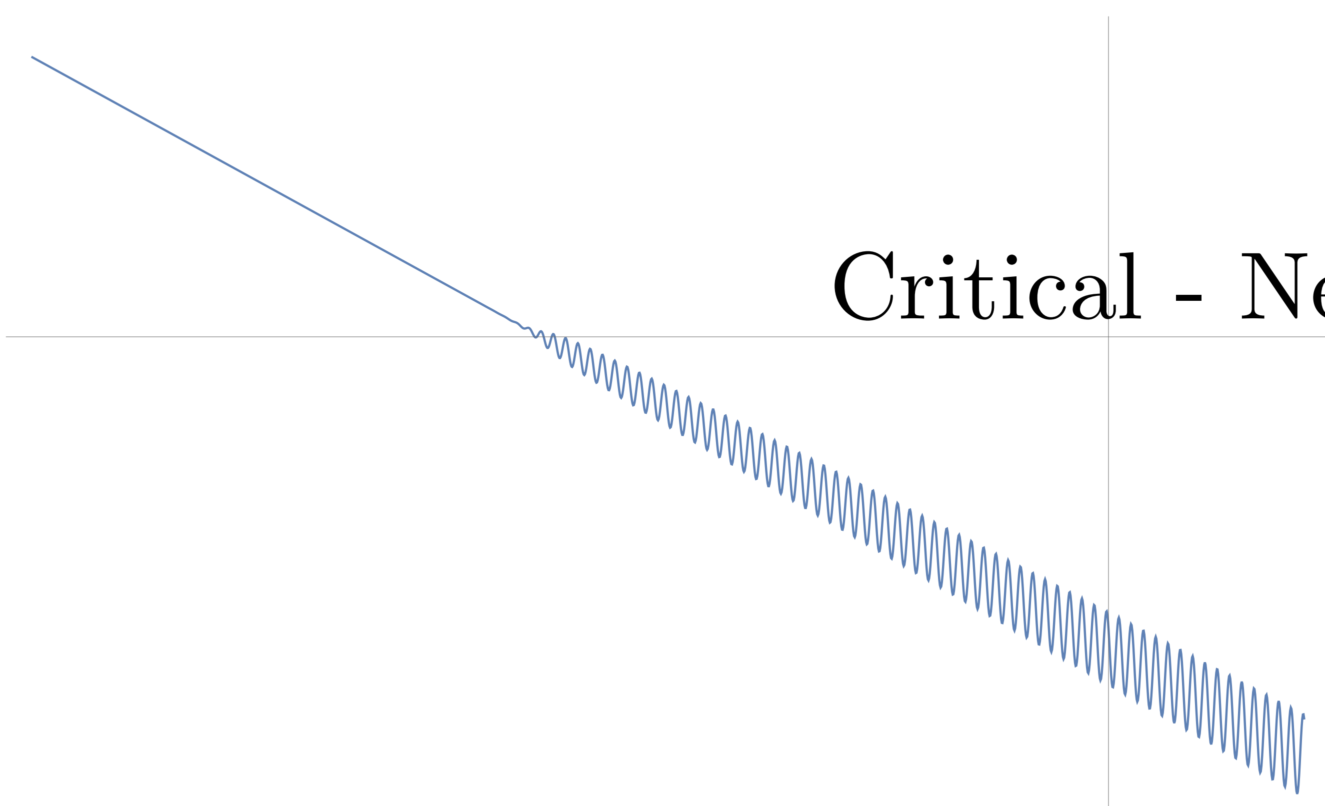
Can push cut-off to M ~ 1000 TeV

Key: Barriers grow because they depend on the Higgs vev.

Relaxion Conditions

Self-organized criticality?

- Dissipation - Dynamical evolution of Higgs mass (field) must stop. **Hubble friction**.
- Higgs back-reaction - EWSB must stop the evolution at the appropriate value. **Yukawa couplings**.
- Long time period - There must be a sufficiently long time period during the early universe for scanning. **Inflation**.
- Self-similarity - Cutoff-dependent quantum corrections will choose an arbitrary point where the Higgs mass is cancelled. **Periodic axion**.



$$\text{Critical - Need } \frac{\partial V}{\partial h} = 0, \frac{\partial^2 V}{\partial h^2} \approx 0$$

THANK YOU

Hidden photon dark matter from inflation

“Vector Dark Matter from Inflationary Fluctuations”

Peter Graham, Jeremy Mardon & Surjeet Rajendran

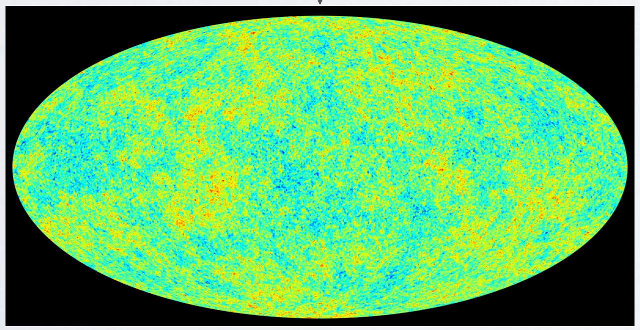
arXiv:1504.02102

Inflation
$\Rightarrow$ coherent particle production

scalar

inflaton fluctuations

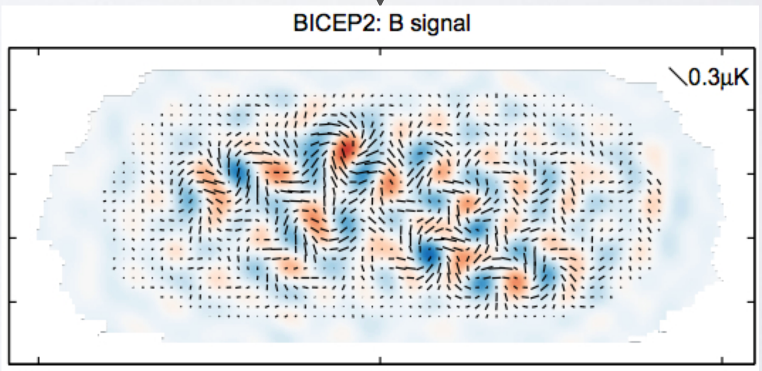
adiabatic density perturbations

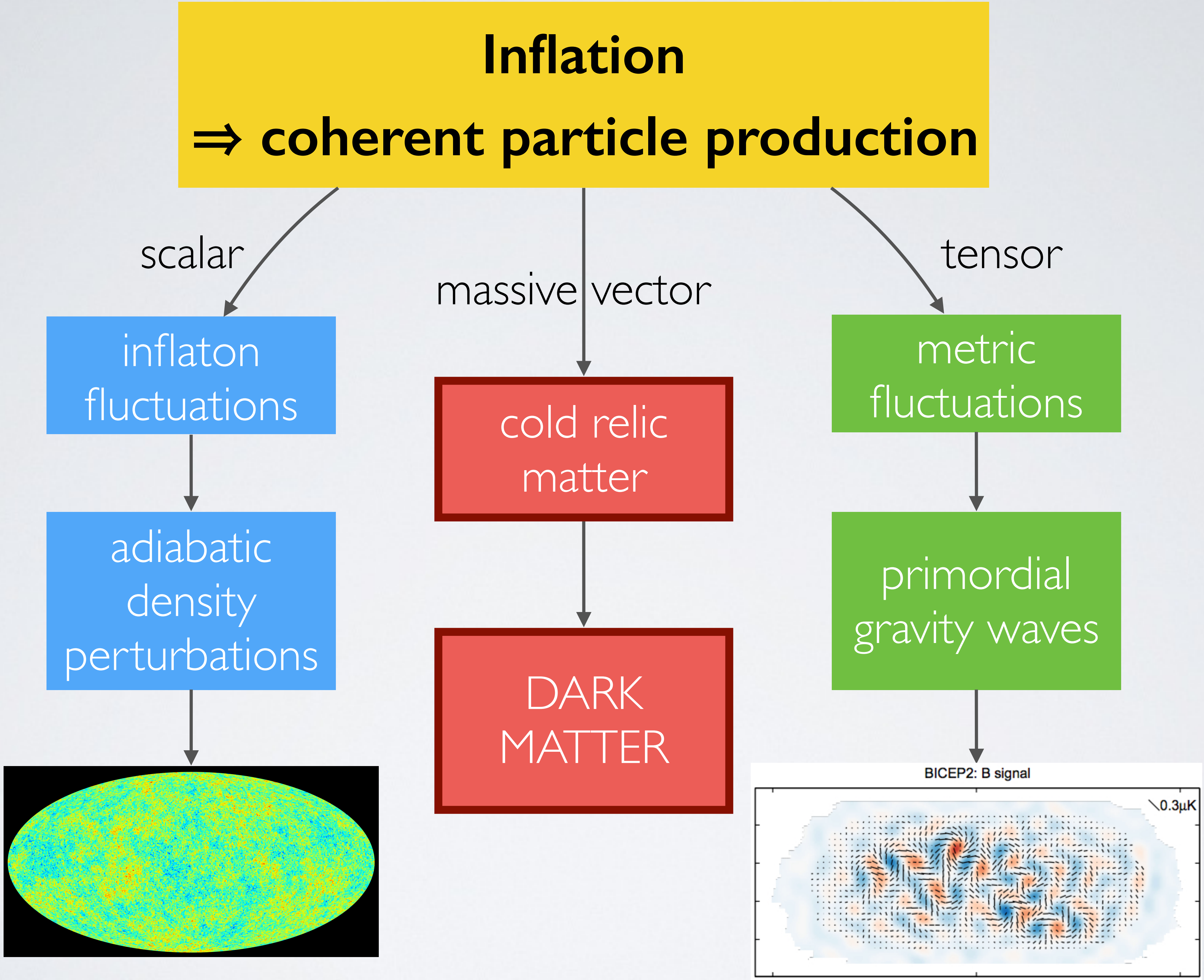


tensor

metric fluctuations

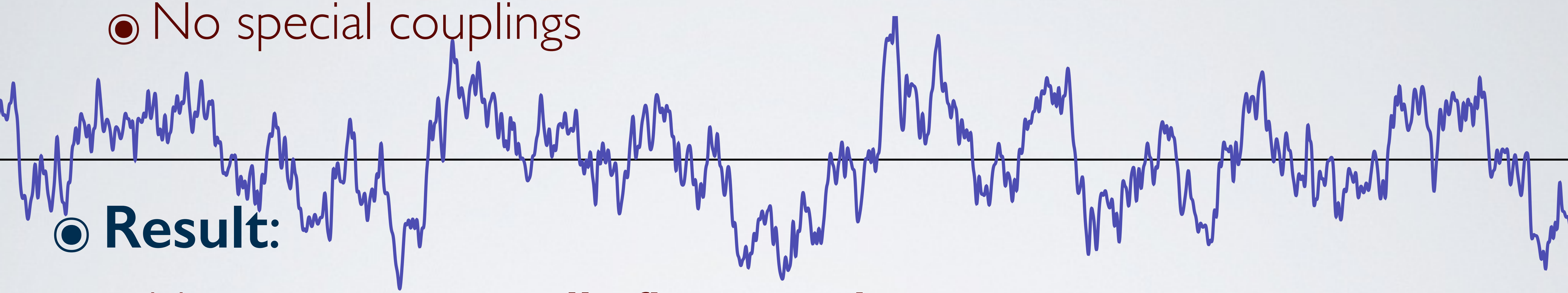
primordial gravity waves




Inflation
⇒ coherent particle production
scalar
massive vector
tensor
inflaton fluctuations
cold relic matter
metric fluctuations
adiabatic density perturbations
DARK MATTER
primordial gravity waves
BICEP2: B signal
0.3μK

INFLATIONARY VECTOR PRODUCTION

- **Requirements:**
  - **Stueckelberg mass** or Higgs scale above H_I
  - No special couplings



- **Result:**
  - Vector **automatically fluctuated into existence**
  - Ends up as **cold matter**

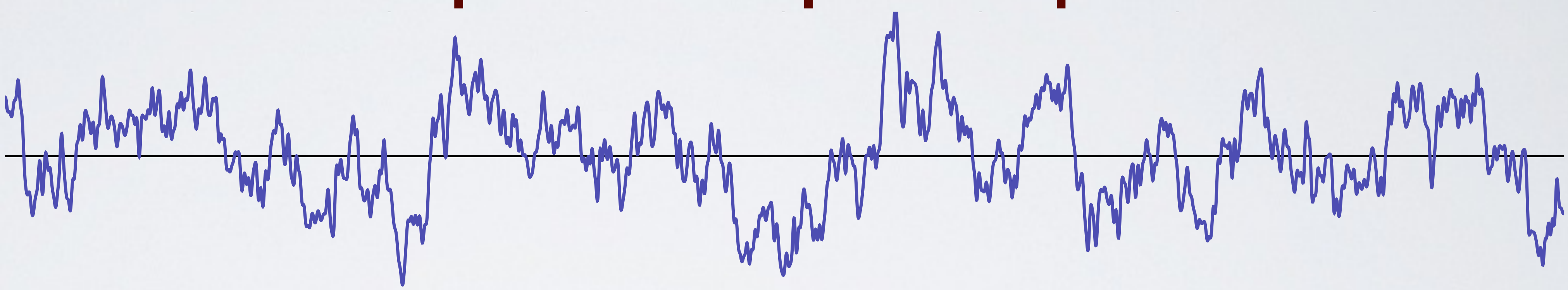
$$\frac{\Omega_A}{\Omega_{\rm cdm}} \approx \sqrt{\frac{m}{6\times 10^{-6}\,\mathrm{eV}}}\left(\frac{H_I}{10^{14}\,\mathrm{GeV}}\right)^2$$

  - Spectrum peaked at intermediate wavelengths
    $\longrightarrow$ dangerous **large-scale isocurvature is absent**

New Probe of Inflation

- **Map out direction and amplitude as experiment sweeps through space**

— Could we **infer the primordial power spectrum?**

— This: 

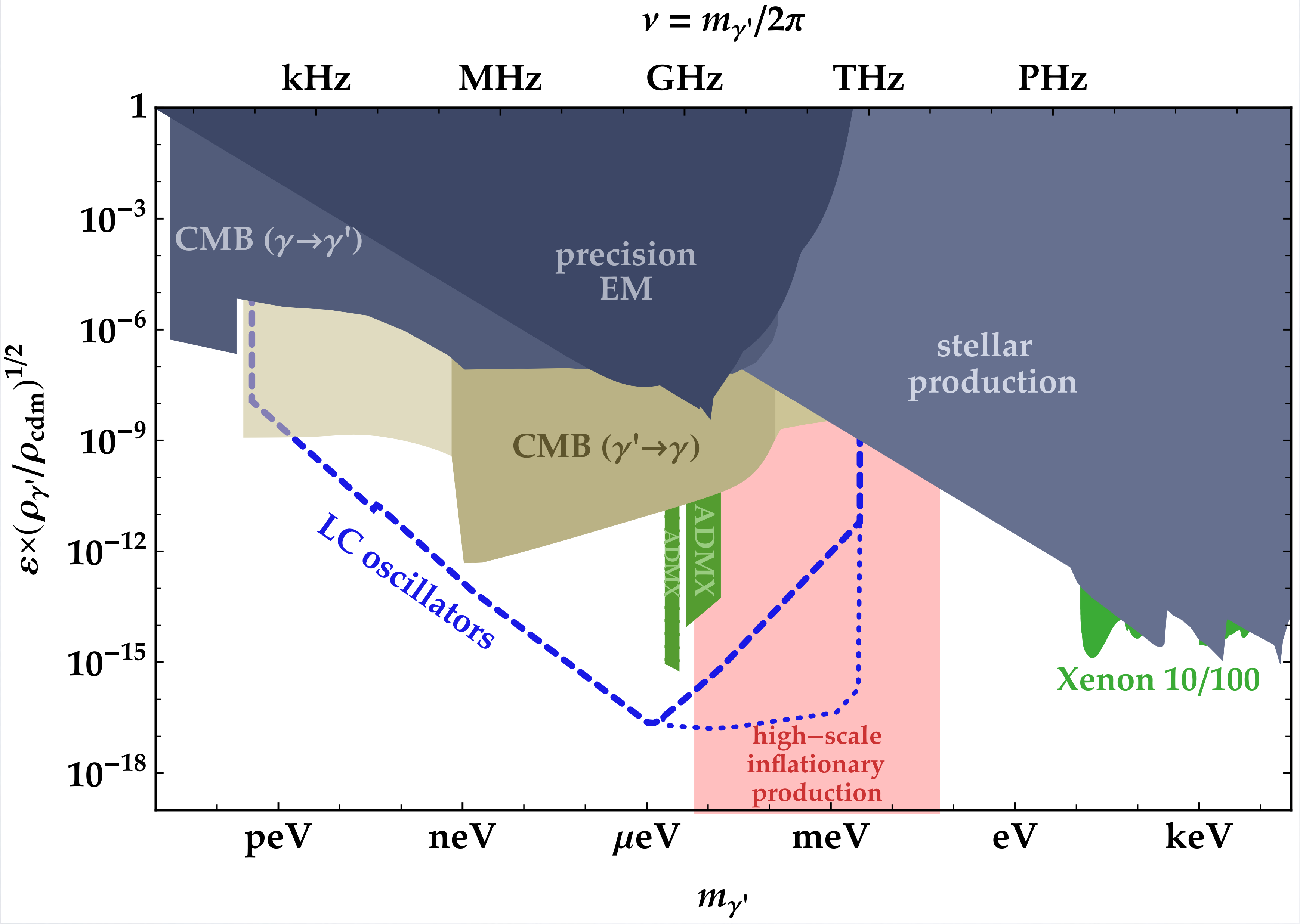
goes through non-linear structure formation (very complicated)

— *If* primordial spectrum reconstructed, would give a **new probe of inflation** itself

PRODUCTION SUMMARY

Inflation produced full DM abundance

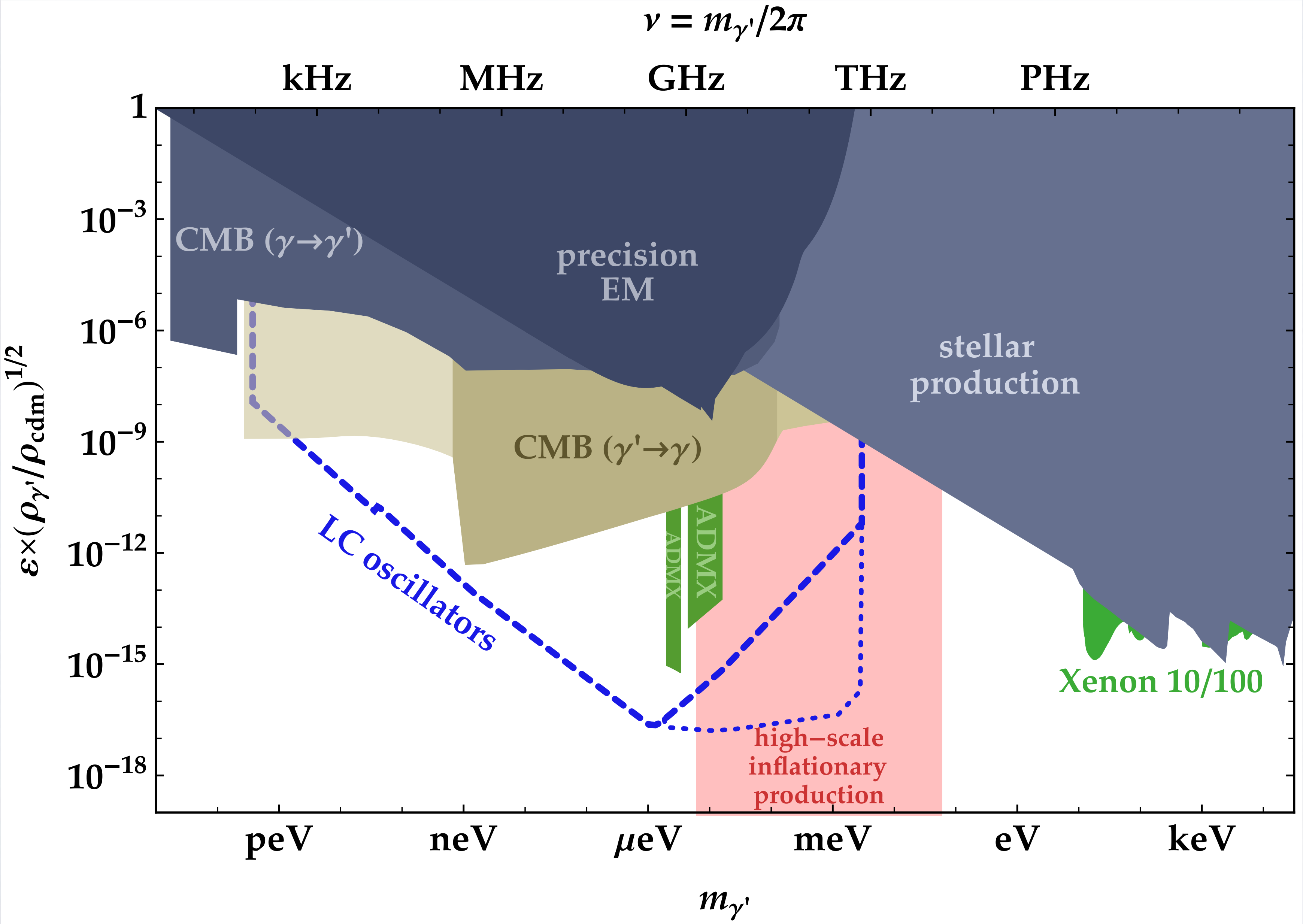
Inflation produced DM subcomponent



PRODUCTION SUMMARY

Inflation produced full DM abundance →

← **Inflation produced DM subcomponent**



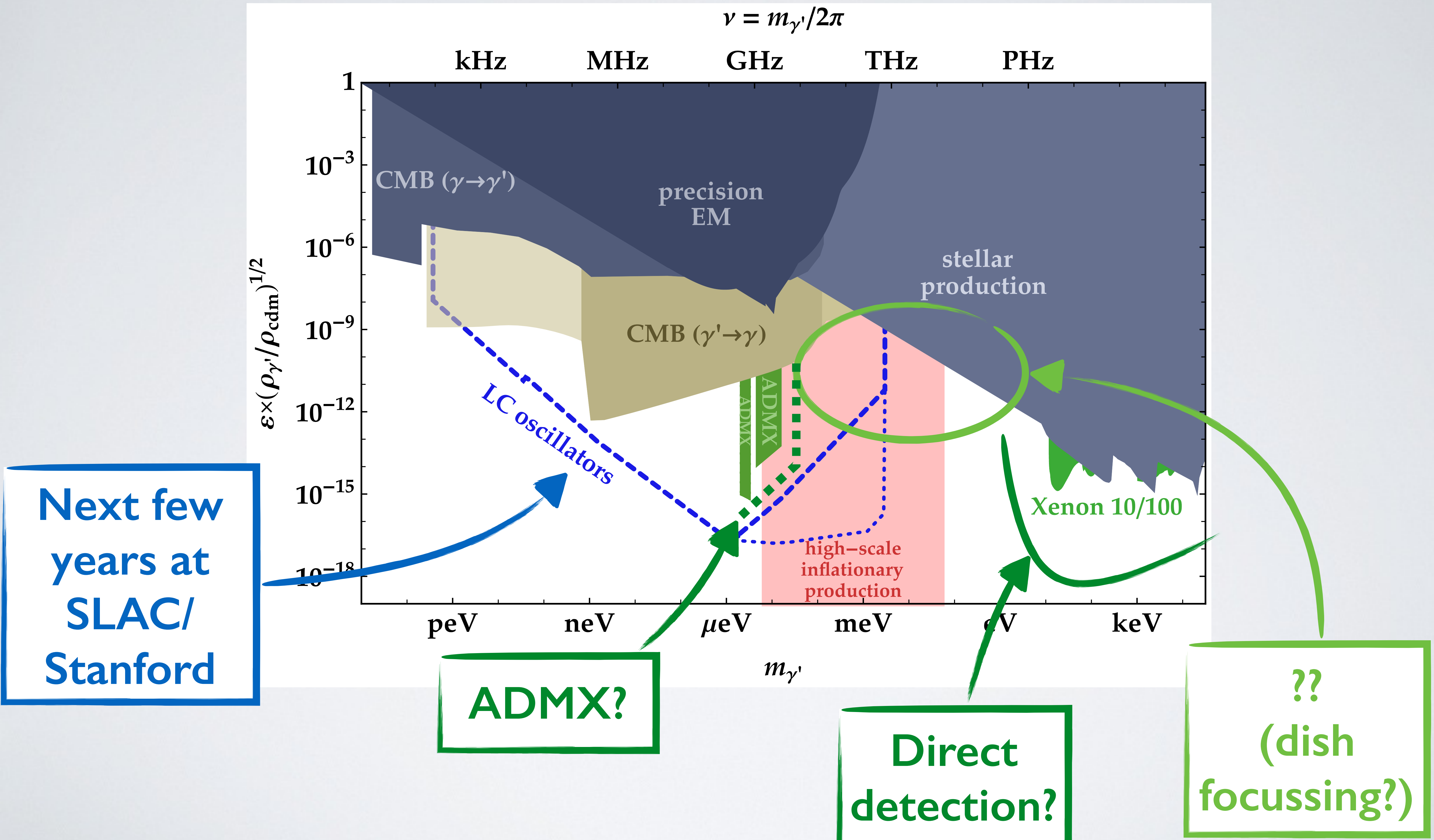
ALSO:

— **Misalignment production possible** (with special $A_\mu A^\mu \mathcal{R}$ coupling)

Arias et al 1201.5902

— **Production not fully explored** (work in progress)

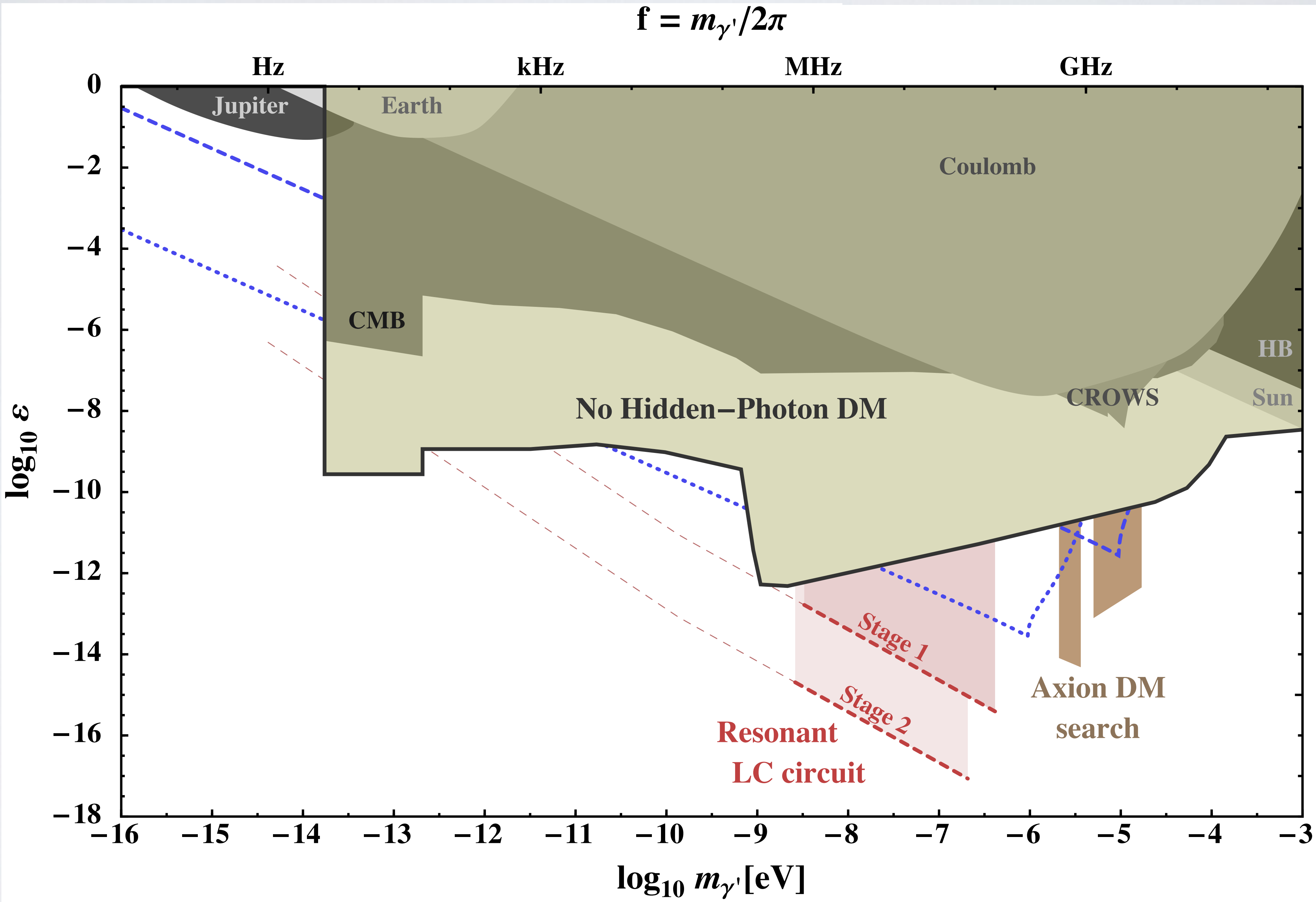
DETECTION SUMMARY



THANK YOU

EXPECTED REACH

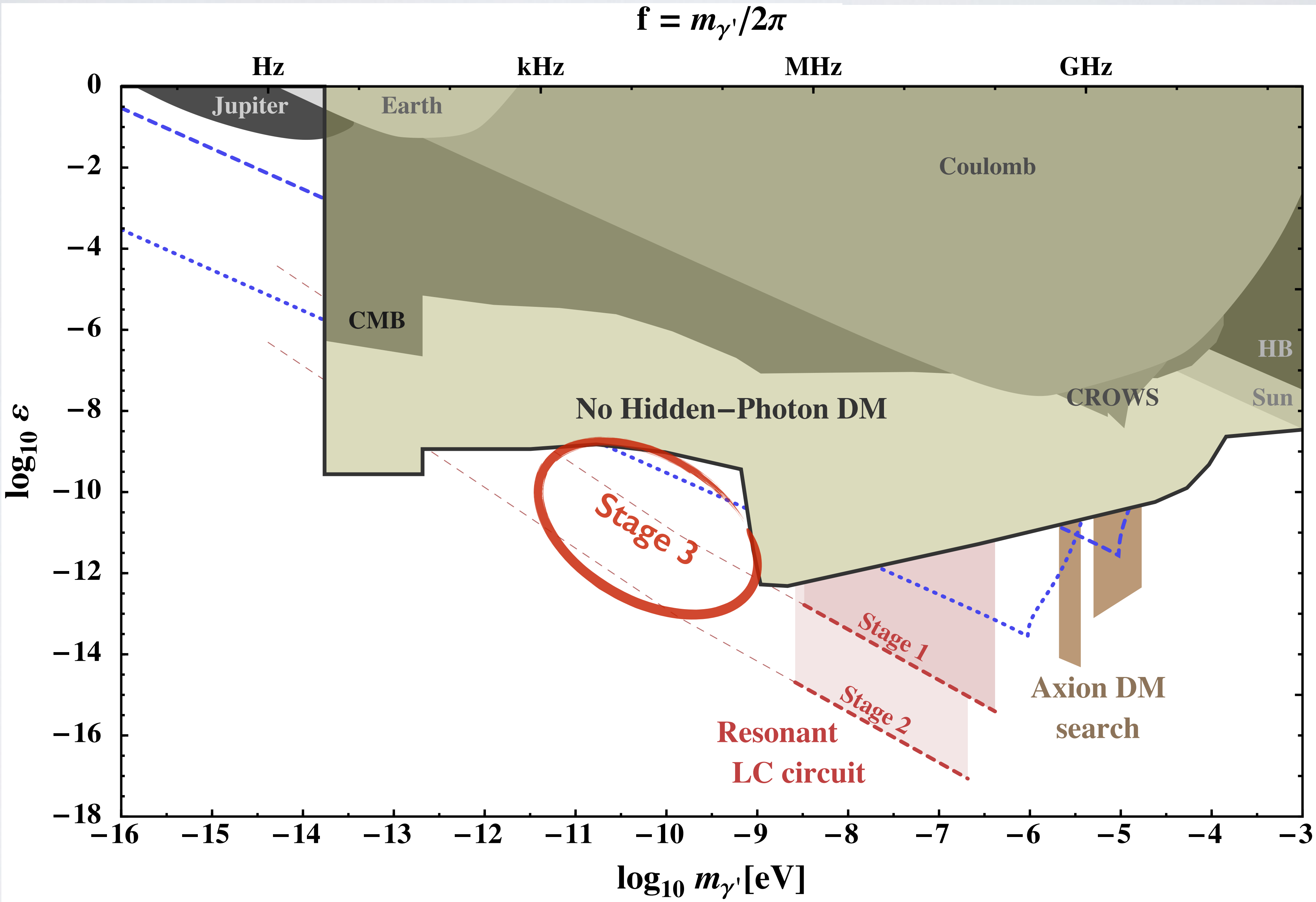
Stage 1: size ~50 cm, T= 4K, Q=10^6, 1 year scan



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

EXPECTED REACH

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



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