The Future of Dark Sector Searches

Jeremy Mardon
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Future of Dark Sector Searches: Part I

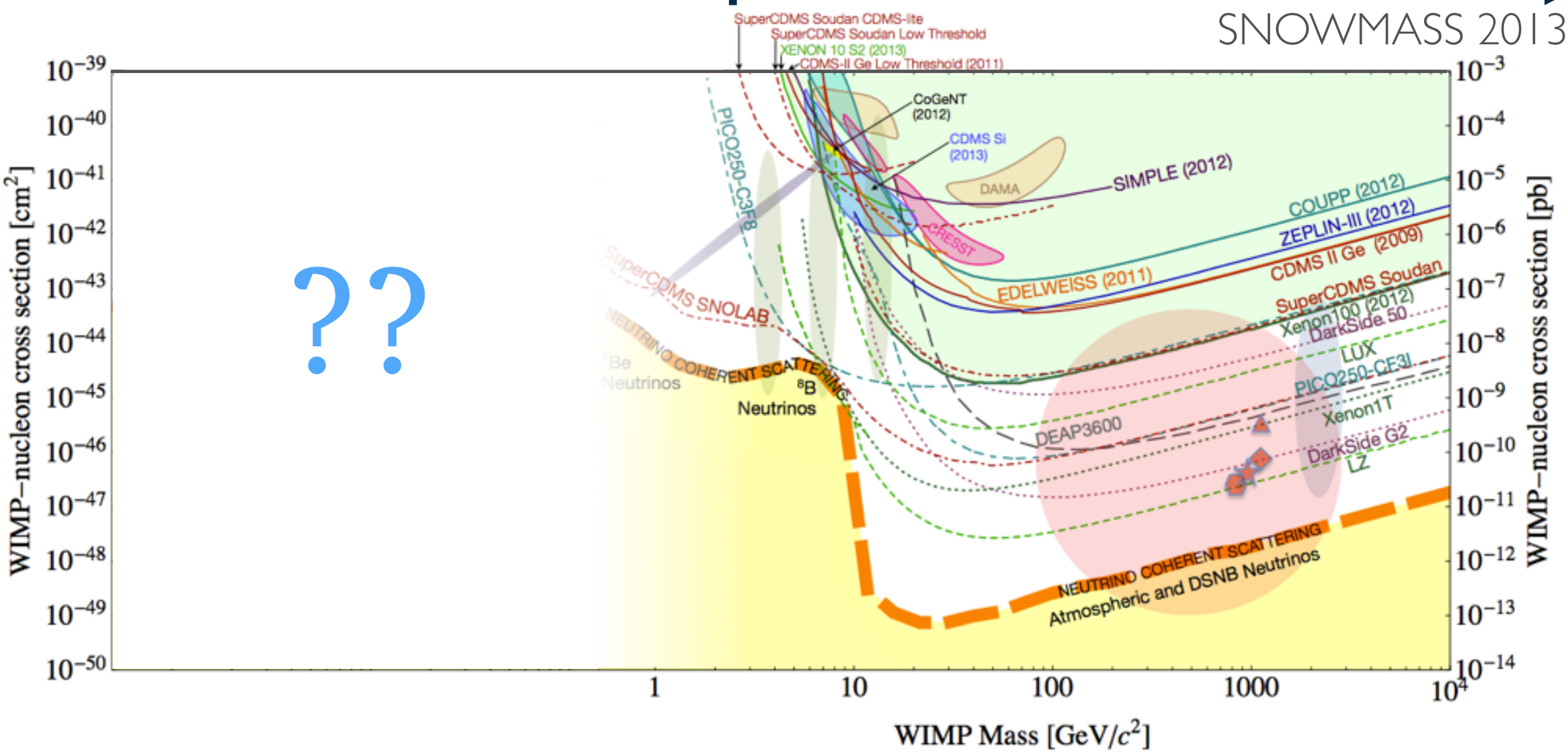
Direct Detection of sub-GeV Dark Matter

Jeremy Mardon, SITP, Stanford

THE DIRECT DETECTION PROGRAM

Weak scale being thoroughly probed

SNOWMASS 2013



??

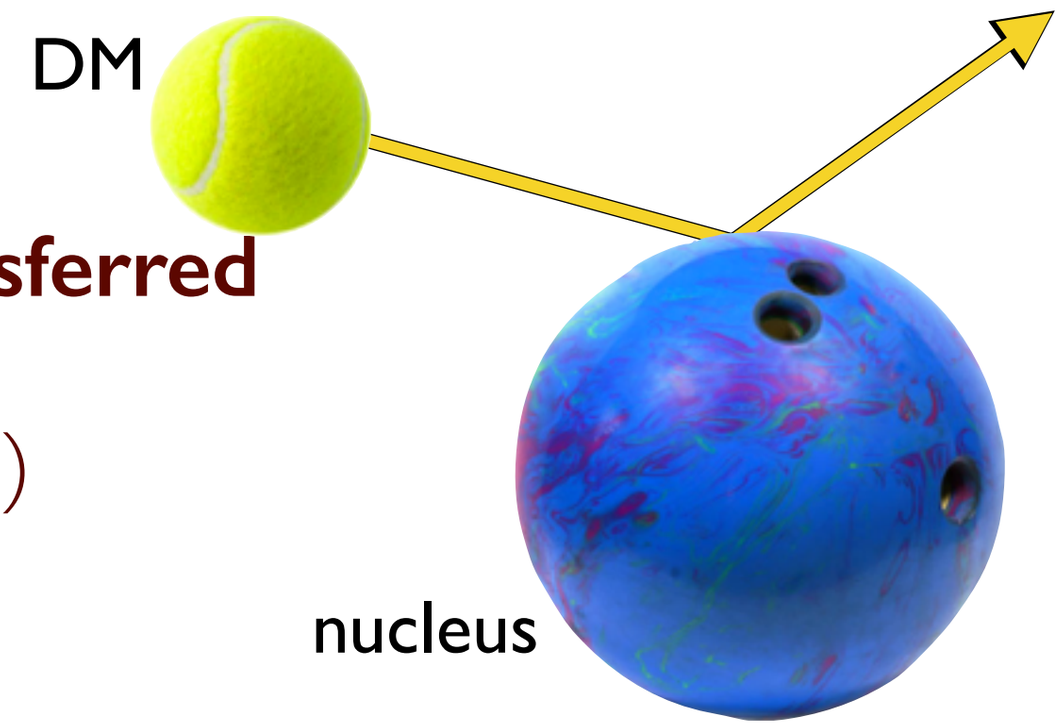
how to test sub-GeV masses?

Recoils from sub-GeV DM

Nuclear recoils

— only **fraction of DM energy transferred**

— produces heat/phonons
(harder to detect than ionization)

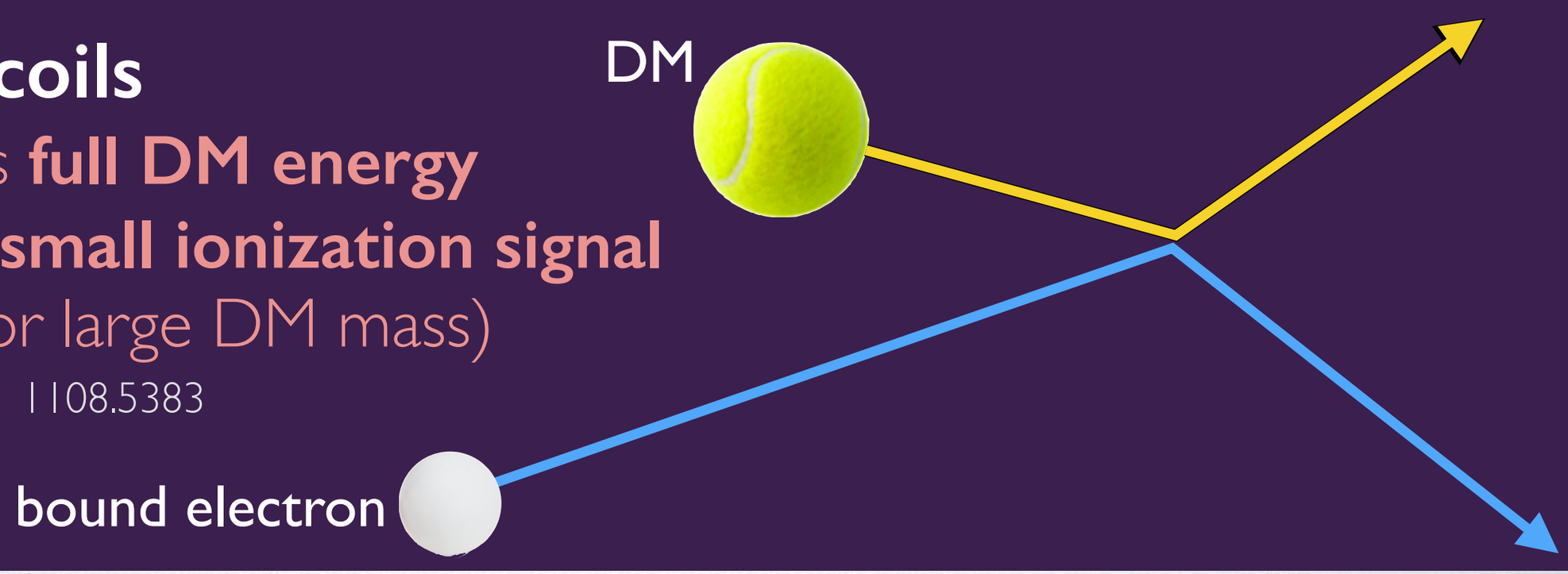


Electron recoils

— can access **full DM energy**

— produces **small ionization signal**
(even for large DM mass)

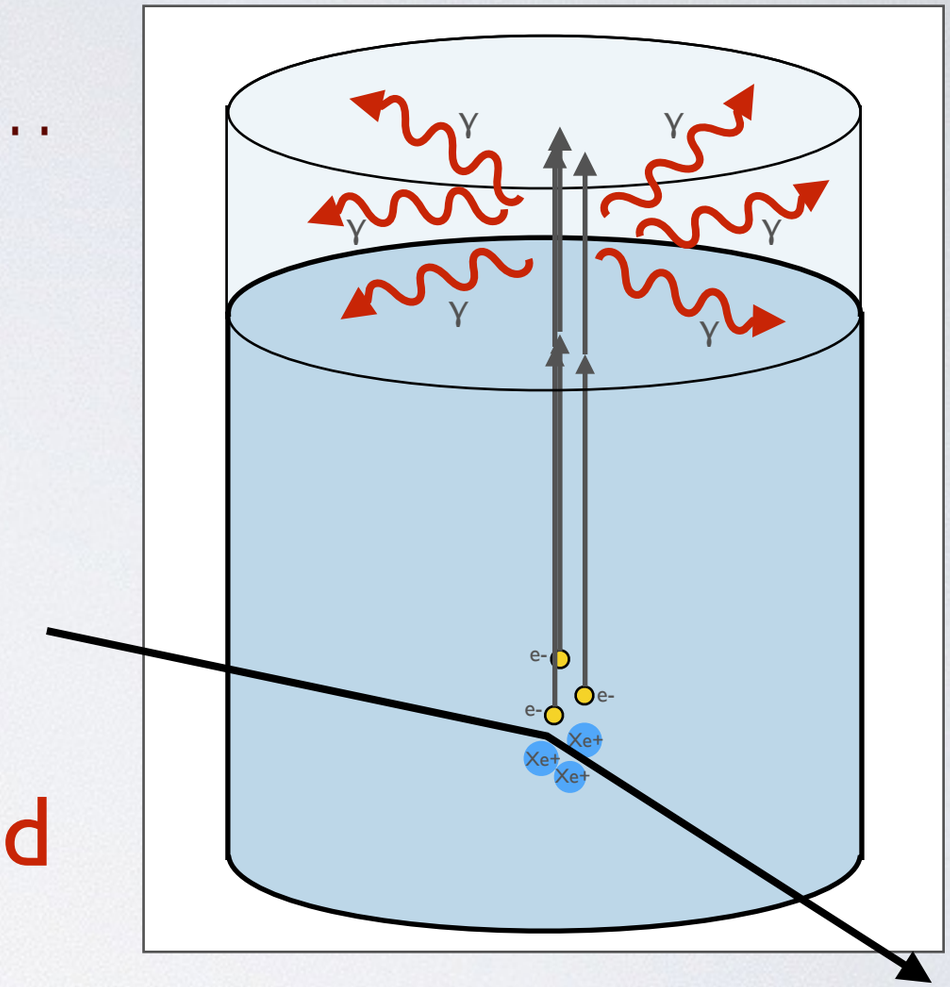
1108.5383



Technology 1: Dual-phase Nobles

Xenon100/Xenon1T, LUX/LZ, DarkSide, …

Amplification by scintillation in gas (S2 signal)



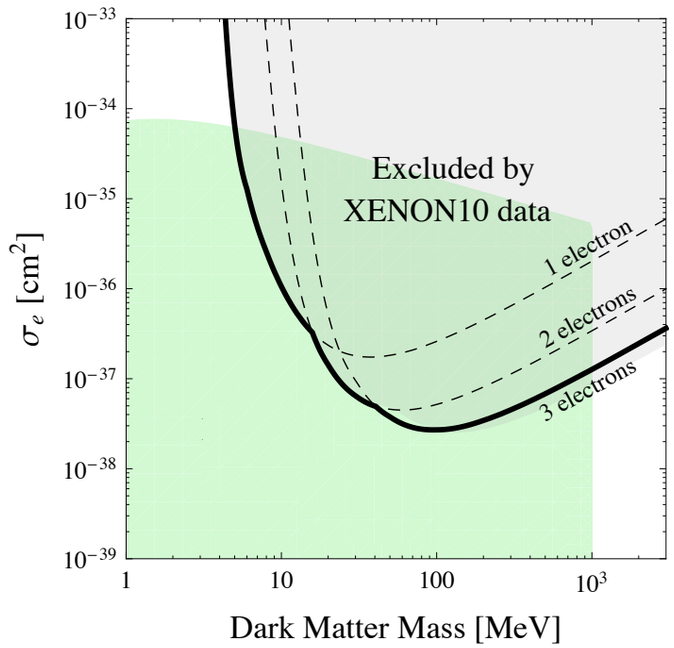
Single-electron sensitivity established

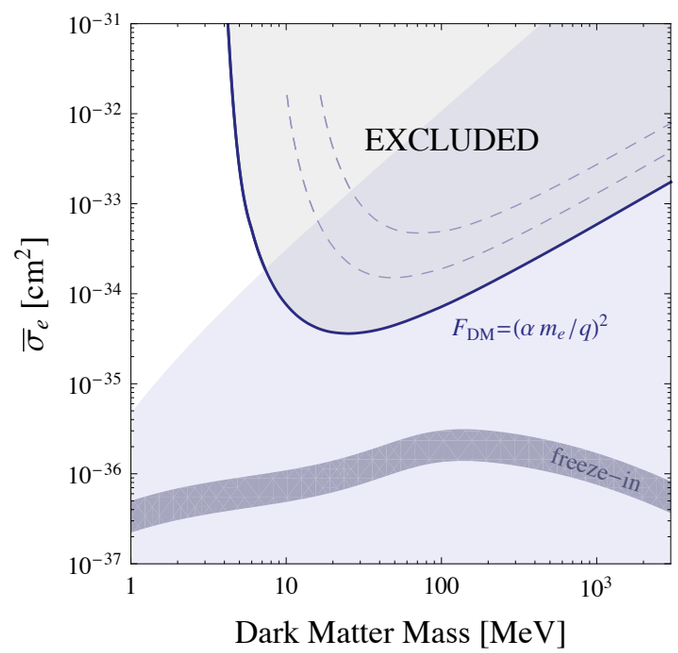
~10 eV ionization threshold

⟶ ~10 MeV DM mass reach

Technology 1: Dual-phase Nobles

First sub-GeV mass limits were set using Xenon10 data





R. Essig, A. Manalaysay, JM, P. Sorensen & T. Volansky
arXiv:1206.2644

Upcoming analyses from LUX & Xenon100

Limited by real **single-electron backgrounds**:

— **impurities:** trap electrons & release them later?

— **insufficient E-field** at liquid surface: ditto?

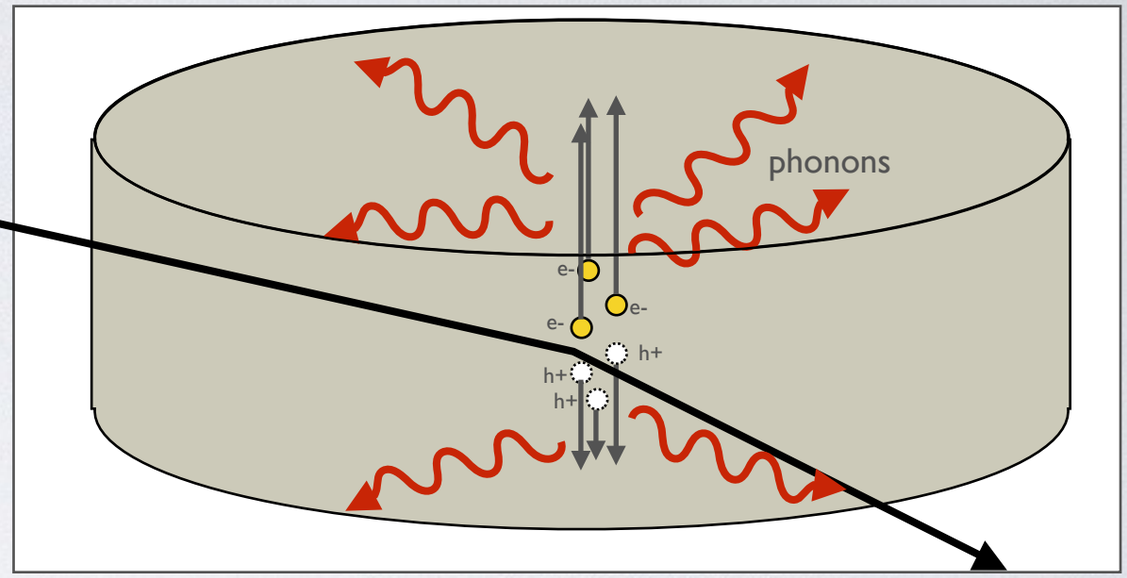
— **spontaneous emission** from cathode?

— Great improvements to be made with a little R&D

see Peter Sorensen's talk at 6:15

TECHNOLOGY 2: CDMS GE/SI

Amplification by Luke-Neganov phonon emission



~eV ionization threshold

⟶sub-MeV DM mass reach

Status:

Single/few electron sensitivity being developed.

5 year time scale?

Backgrounds might be much smaller than in xenon.

Matt Pyle
Tali Figueroa-Feliciano
& others

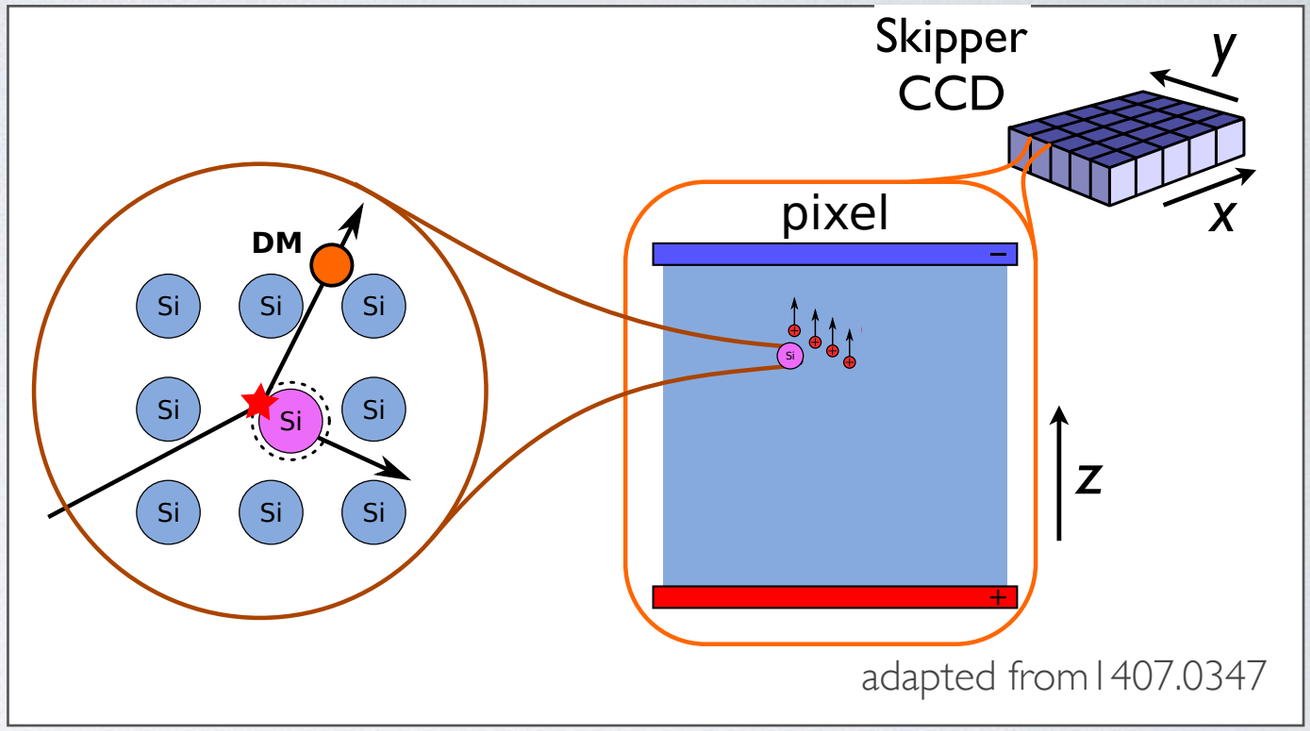
TECHNOLOGY 3: DAMIC SI CCDS

DAMIC uses thick CCDs as target (Juan Estrada's group)

"Skipper" CCDs

repeated measurement of single charge see 1106.1839

will allow single-electron sensitivity



Status:

small target (10-100g)

single-electron sensitivity is close

2+ year time scale?

EVENT RATES: THEORY

Requires detailed modeling for each material

— sensitive to tails of electron wavefunctions

— Noble liquids ✔

— tractable if approximated as gas rather than liquid

1108.5383, 1206.2644

— Semiconductors ✔

— semi-analytic treatment gets close

see 1203.25 31, 1508.07361

— new results from detailed numerical computation using solid state codes

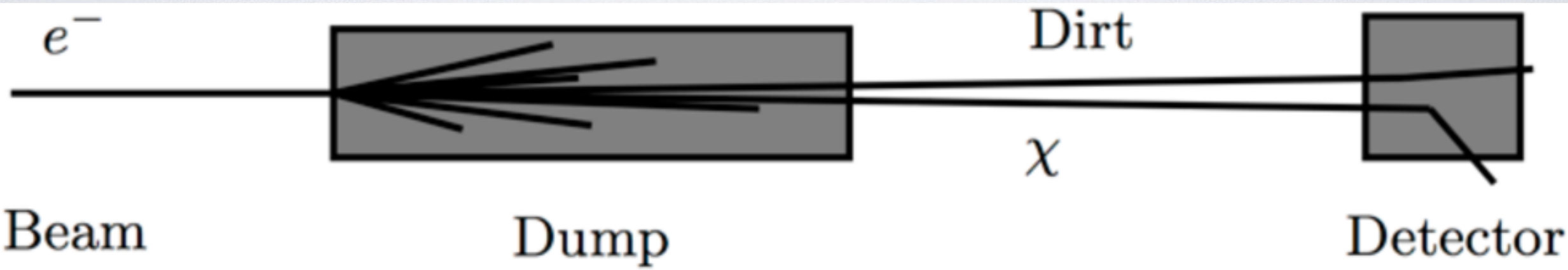
R. Essig, M. Fernandez-Serra, JM, Adrian Soto, T. Volansky & T.T. Yu 1509.01598

What kind of DM models does this probe?

ALTERNATIVE: BEAM DUMP SEARCHES

Produce light DM
in beam dump

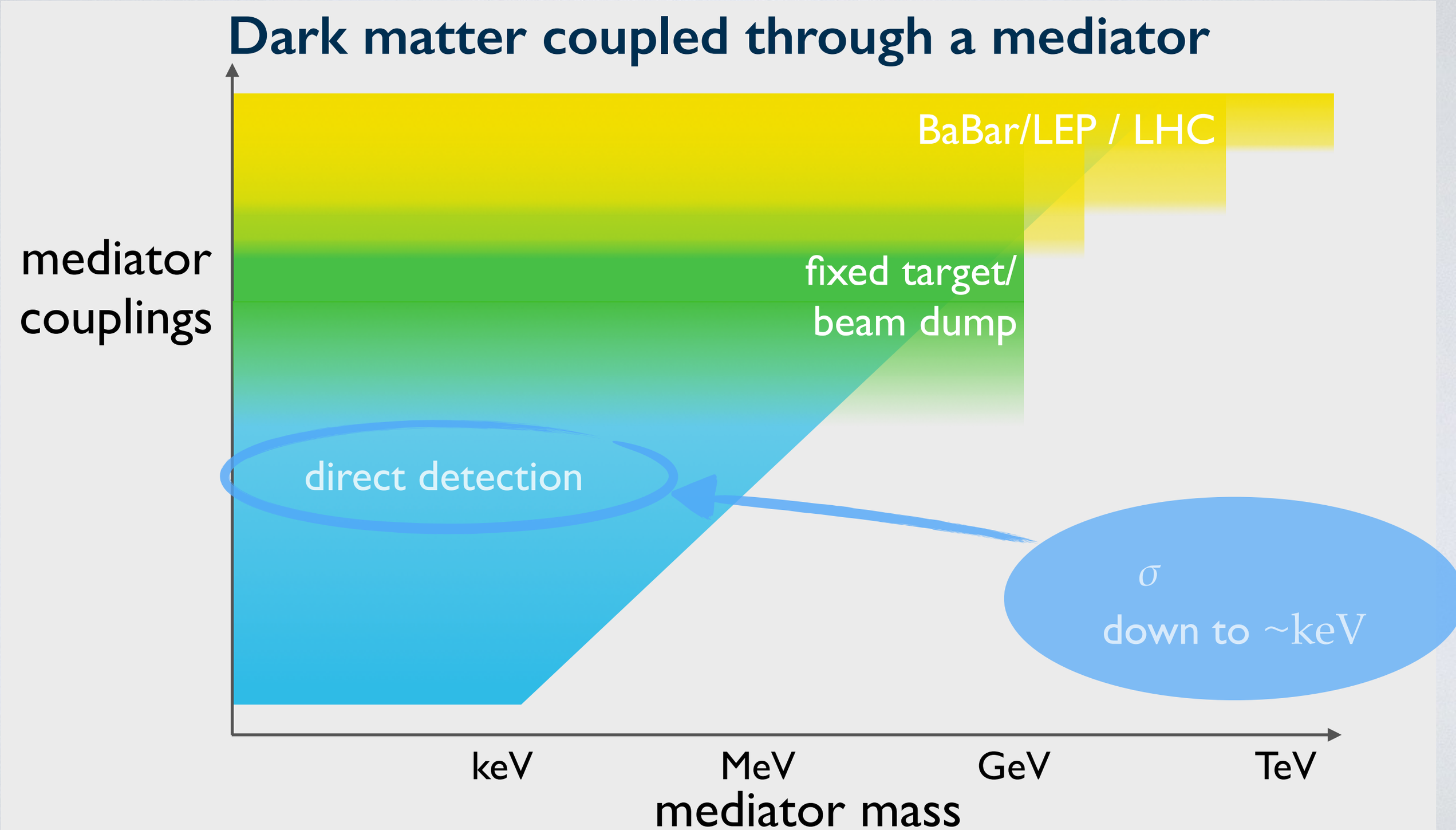
Detect DM scattering
in far detector



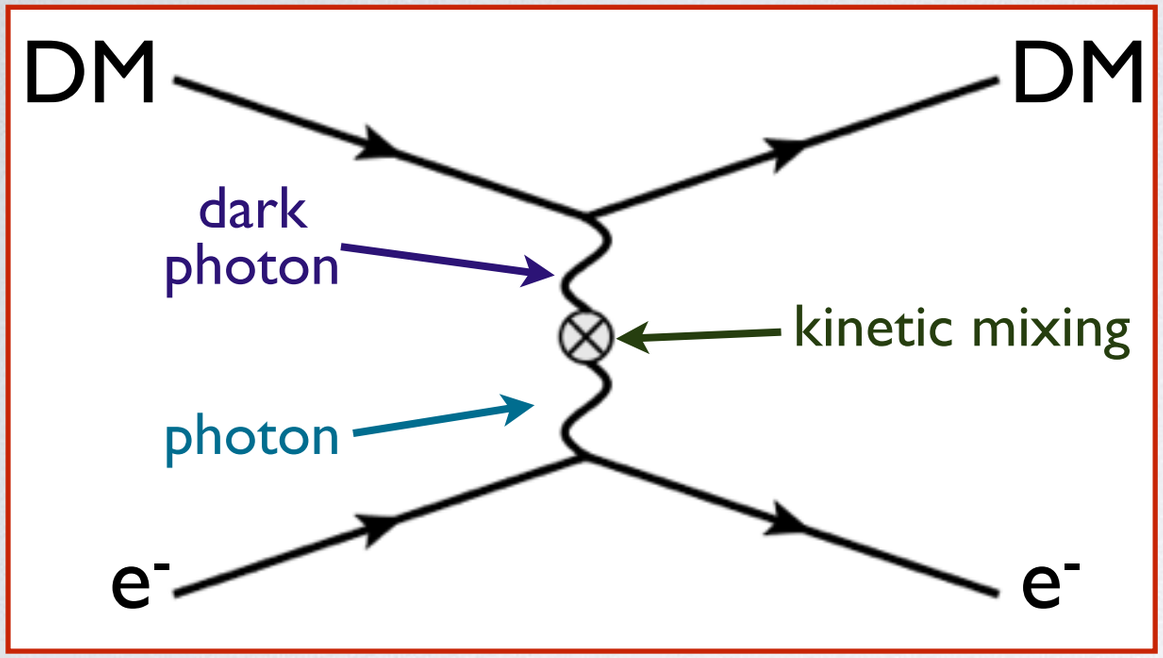
for review see e.g. talk by G Krnjaic at
https://indico.classe.cornell.edu/event/38/session/0/contribution/29/material/slides/0.pdf

Comparison w. Direct Detection

(SCHEMATIC)



BENCHMARK MODELS: LIGHT MEDIATORS

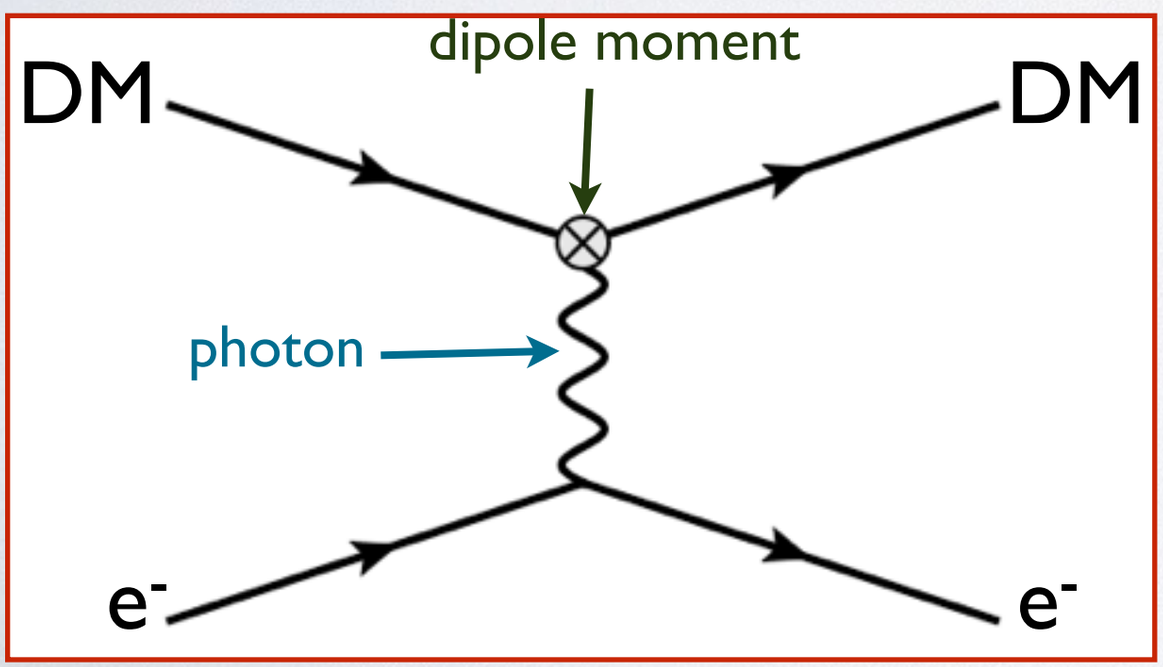


hidden photon mediator:

— light (~10 MeV)

— massless (or << keV)

e.g. Essig et al 1108.5383, Lin et al 1111.0293, Chu et al 1112.0493
Hall et al 0911.1120



dipole moment:

— MDM

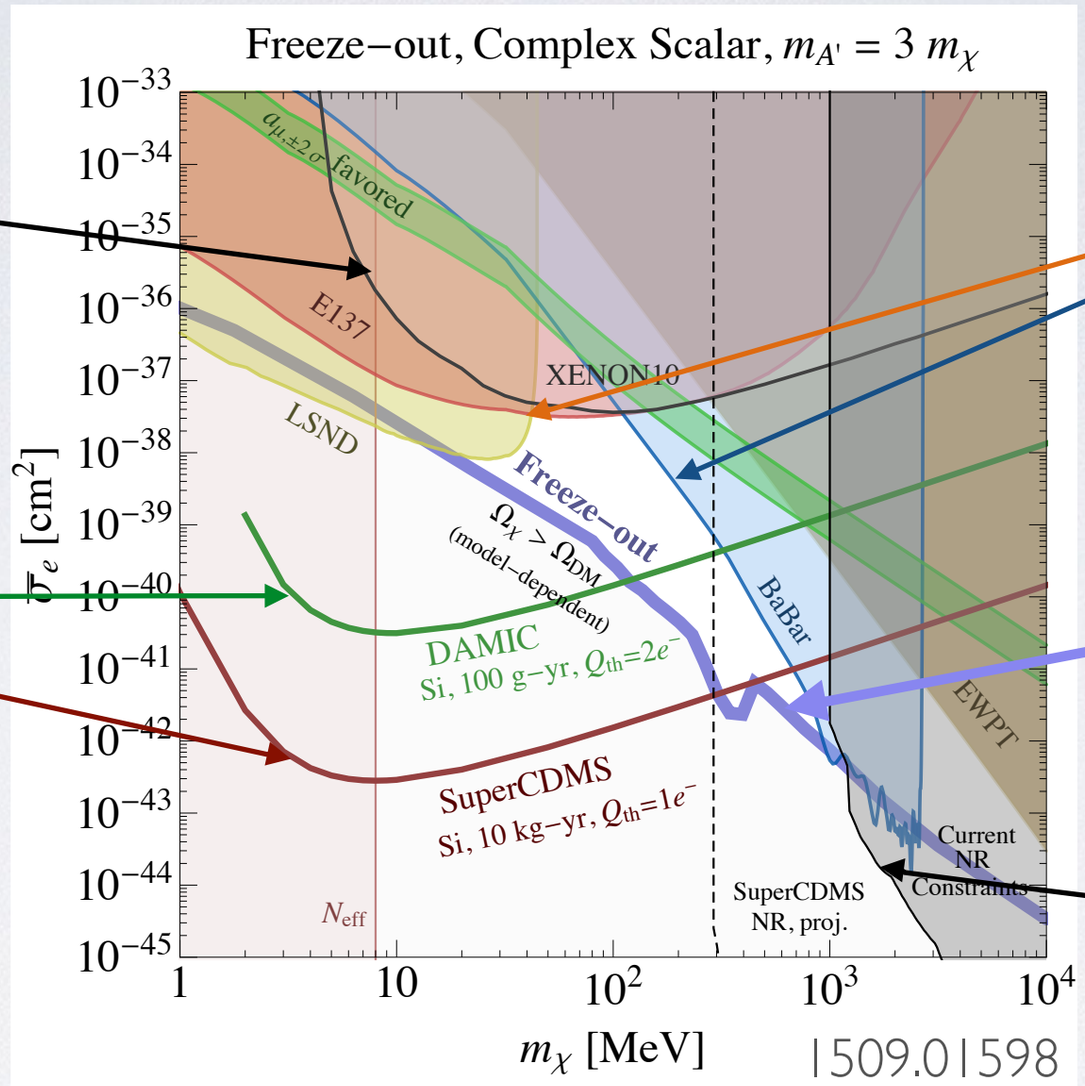
— EDM

Sigurdson et al Phys.Rev. D70 (2004) 083501 + Erratum-ibid.
Graham et al 1203.2531

MeV-GeV HIDDEN-PHOTON MEDIATOR

Xenon10
e⁻ recoil

CDMS/DAMIC
e⁻ recoil
projection



collider/
beam-dump
constraints

Freeze-out
abundance

conventional
direct detection

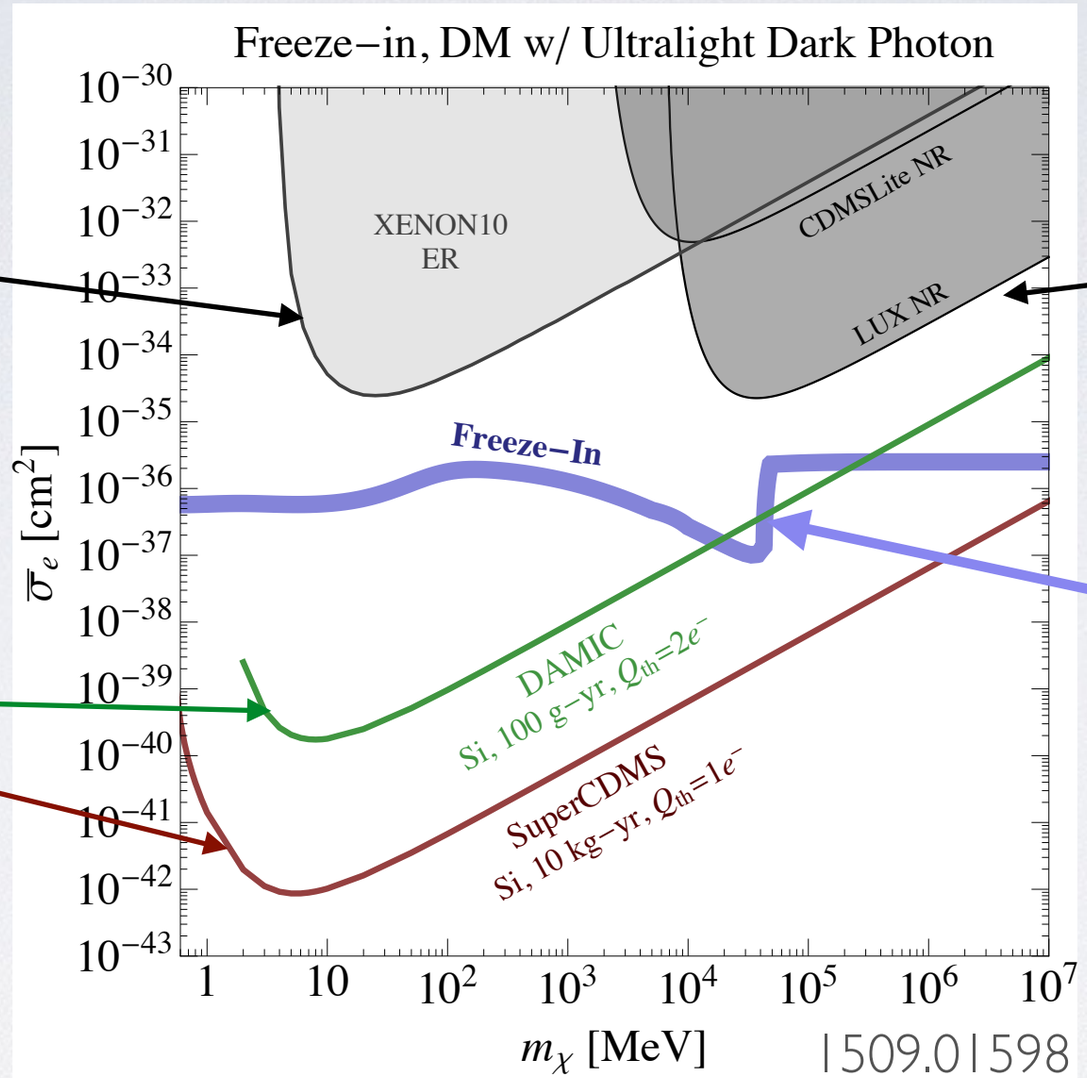
— Probes **well-motivated parameter space**

— **Competitive with beam-dump and collider searches**

SUB-KeV HIDDEN-PHOTON MEDIATOR

Xenon10
e⁻ recoil

CDMS/DAMIC
e⁻ recoil
projection



conventional
direct detection

Freeze-in
abundance

— Probes **well-motivated parameter space**

— Beam-dump and collider searches not sensitive here

— **May be better than conventional DD at high masses!**

Discovery with modulation

No event-by-event background discrimination

Large annual modulation fraction

1509.01598

around 3-10%

Directional modulation

due to alignment of semiconductor crystal with DM wind

(work in progress)

SUMMARY

Program

— Search for **DM-electron scattering**

— Signal: **single/few ionized electrons**

Challenges

— low thresholds — new backgrounds — checking modulation

Reach

Noble liquid target	Semiconductor target
$E_{\mathrm{thresh}} \sim 10$ eV	$E_{\mathrm{thresh}} \sim 1$ eV
$m_{\mathrm{DM,min}} \sim 10$ MeV	$m_{\mathrm{DM,min}} \sim 1$ MeV

well-motivated models to be probed

complimentary to beam-dump searches

Future of Dark Sector Searches: Part II

Searching for Ultra-light Hidden-Photons

Jeremy Mardon, SITP, Stanford

Hidden Photons

"Hidden Photons" (a.k.a. dark photons, paraphotons)

5th force: a **copy of Electromagnetism**, but with

— **small hidden-photon mass** (= finite range)

— **small coupling ε** (the "kinetic mixing" parameter)

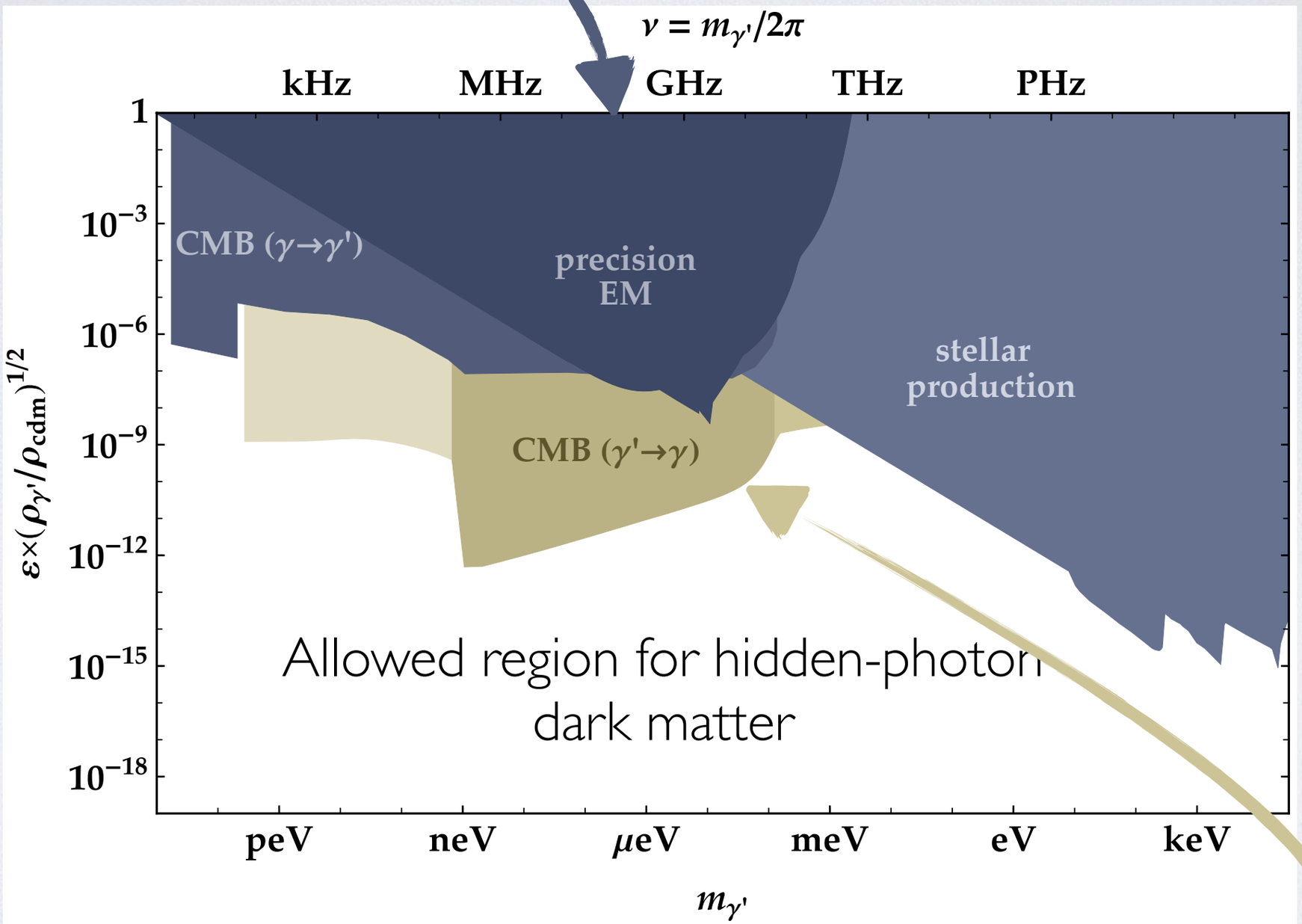
Long-range
Couples to charged particles
⬇
Modification of EM

New light particle
⬇
Cosmo/astro effects

New massive particle
⬇
Dark matter
(compare to axion)

Hidden Photon Constraints

EXCLUDED
(independent of contribution to dark matter)



EXCLUDED AS DARK MATTER

Arias et al 1201.5902

Searching for Hidden Photon Dark Matter

Jeremy Mardon, SITP, Stanford

HIDDEN PHOTONS AS DARK MATTER

Light boson as dark matter

— **classical field**
— oscillation frequency $\omega = m_{A'}$
— coherence time $\sim 10^6/\omega$

pseudoscalar

vector

axion

— coherent scalar field
— no direction
— misalignment production?

hidden photon

— vector field
— points in **random direction**
— inflationary production?

Graham, JM & Rajendran 1504.02102
Pospelov Ritz & Voloshin 0807.3279
Nelson & Scholtz 1105.2812

HIDDEN PHOTON DM: RESONANT SEARCHES

A "**hidden electric field**" that penetrates shielding

— $E' \approx \sqrt{\rho_{\rm DM}} \approx 2000$ **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**

Redondo et al 1201.5902

Hidden Photon DM: resonant searches

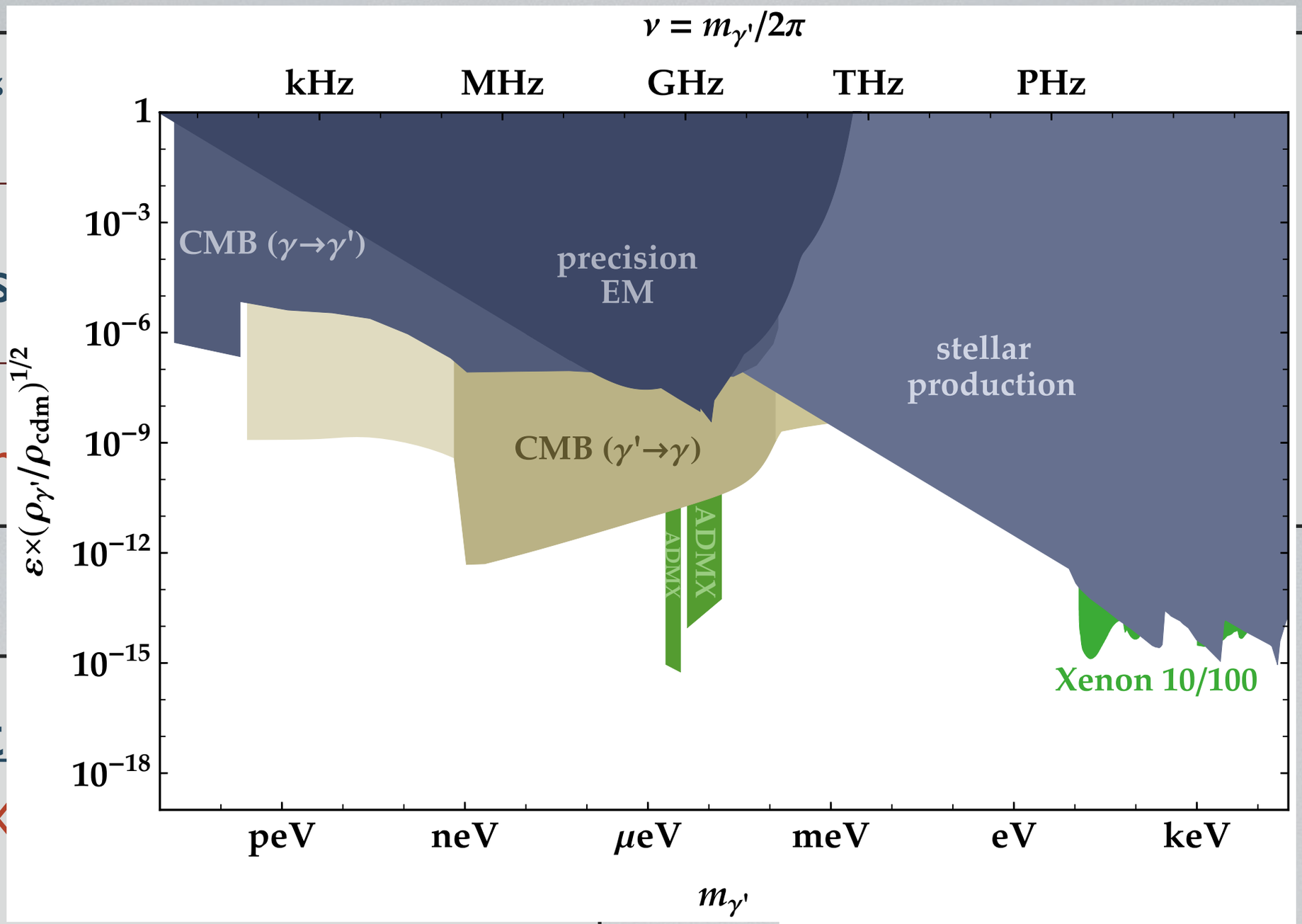
A "

Has

Car

elect

— ADMX



An et al 1412.8378
Redondo et al 1201.5902

HIDDEN PHOTON DM: RESONANT SEARCHES

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<u>electromagnetic cavities</u>

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Redondo et al 1201.5902

<u>**LC circuits**</u>

— **much wider and lower frequency range** than cavities

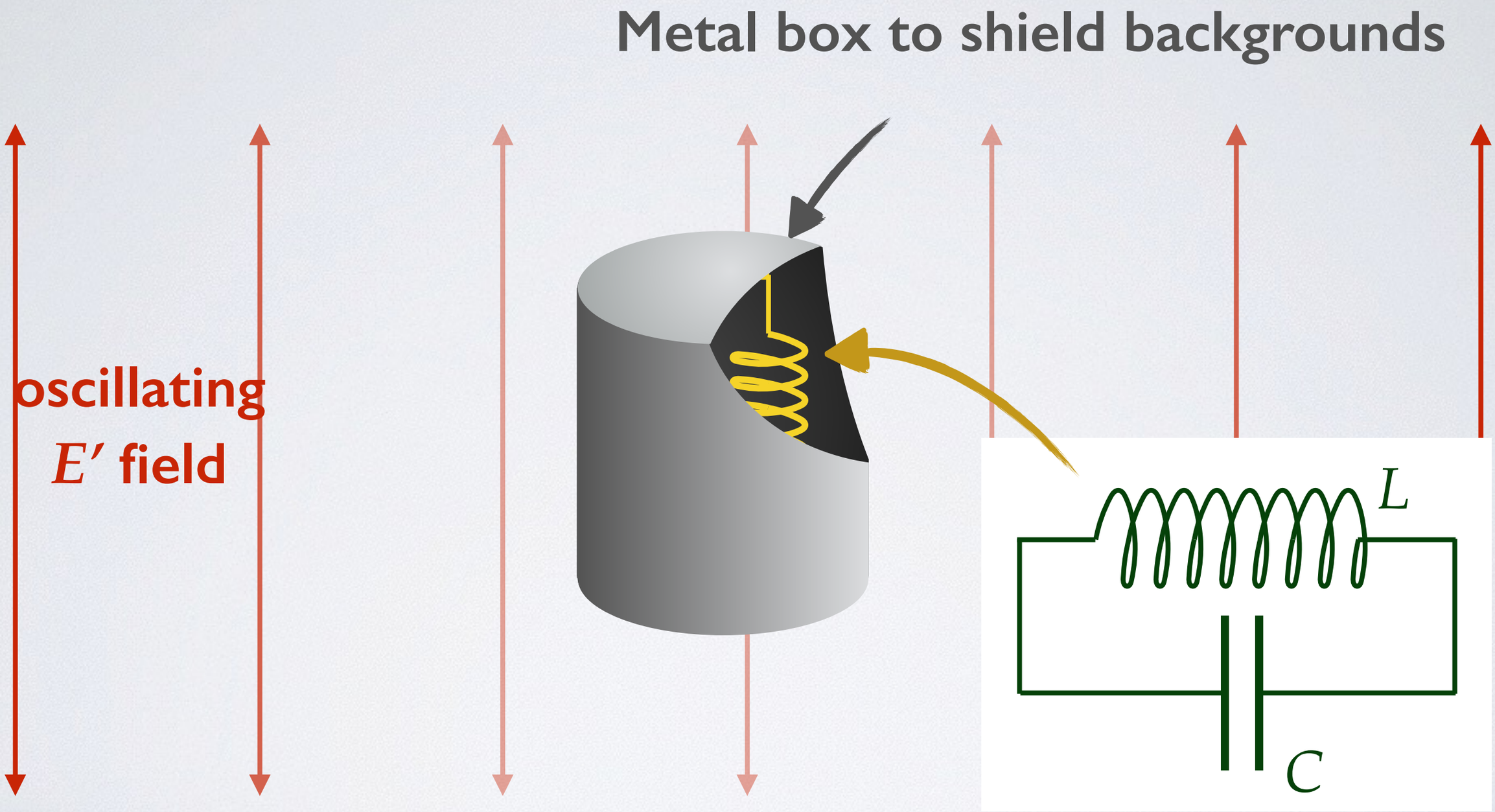
DM Radio:
A tunable LC-circuit for hidden-photon dark matter

"A Radio for Hidden-Photon Dark Matter Detection"

Saptarshi Chaudhuri, Peter Graham, Kent Irwin, J. M., Surjeet Rajendran & Yue Zhao

arXiv:1411.7382

EXPERIMENTAL SETUP

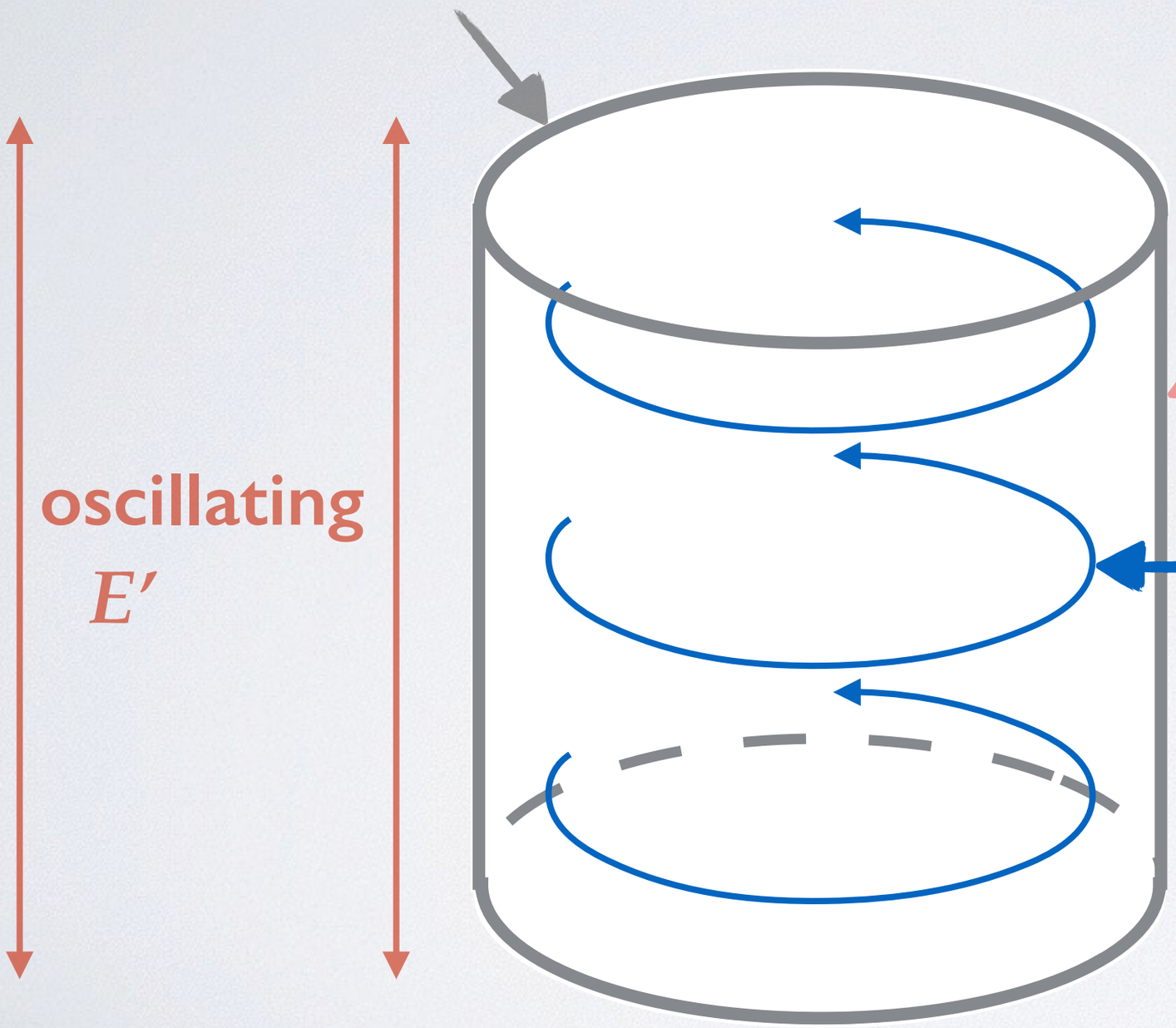


Tunable resonant LC circuit
Read out with SQUID

THE SIGNAL INSIDE A SHIELD

Metal box to shield backgrounds

conduction electrons in wall respond to cancelling observable combination $E+\varepsilon E'$



…but generating real B field inside the shield

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

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

THE **DM RADIO** COLLABORATION

Experiment

Kent Irwin (PI)

Saptarshi Chaudhuri (see talk tomorrow)

Dale Li

Christopher Williams

Betty Young

Max Silva-Feaver

Sarah Stokes Kernasovkiy

Theory

Peter Graham

Jeremy Mardon

Surjeet Rajendran

Yue Zhao

SLAC

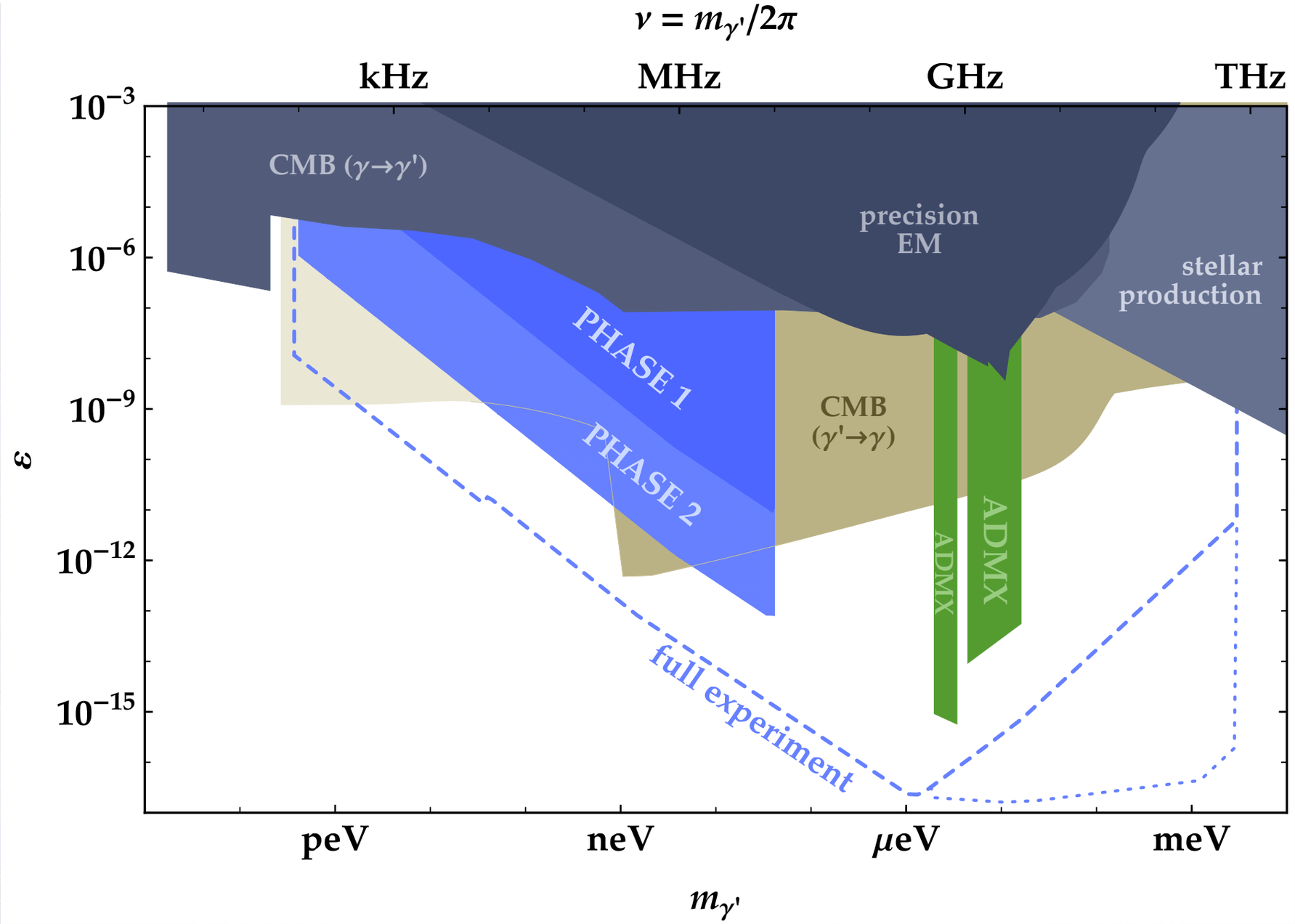
KIPAC

Stanford University

REACH

PHASES 1&2
(funded & under construction)
size ~ 350ml — 1m Q~10^6 T~4K

FULL DESIGN
size ~ 1m
Q~10^6 T~0.1



Key Points

Hidden Photons are

a possible **5th-force carrier**

and **dark-matter candidate**

Experiments **extremely similar to axion searches**

…but **easier** because:

i) **No static B-field** needed

ii) stellar cooling constraints are weaker

Hidden-photon DM search with **LC resonator**

has **huge reach** (upcoming at SLAC/Stanford)

key refs: 1201.5902, 1407.4806, 1411.7382

Extras

Confirming a signal

Excellent **cross-checks** are possible:

— always at same **fixed frequency**

— **orientation dependence** is characteristic of vector

— phase and directional **coherence over ~1000 wavelengths**

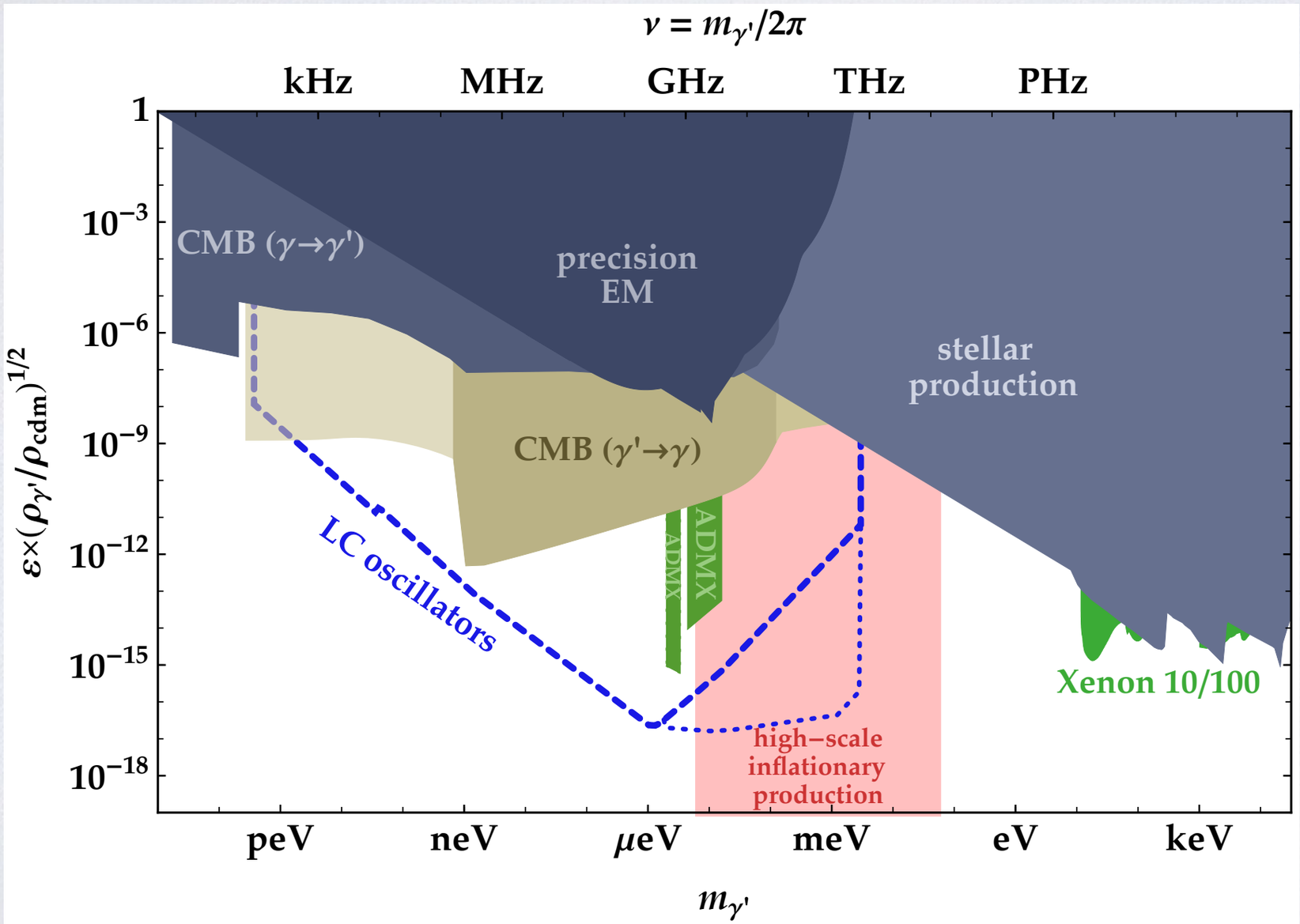
— could **map out phase and direction** over time

PRODUCTION SUMMARY

Inflation produces full DM abundance →

Graham, JM & Rajendran 1504.02102

← **Inflation produces DM subcomponent**



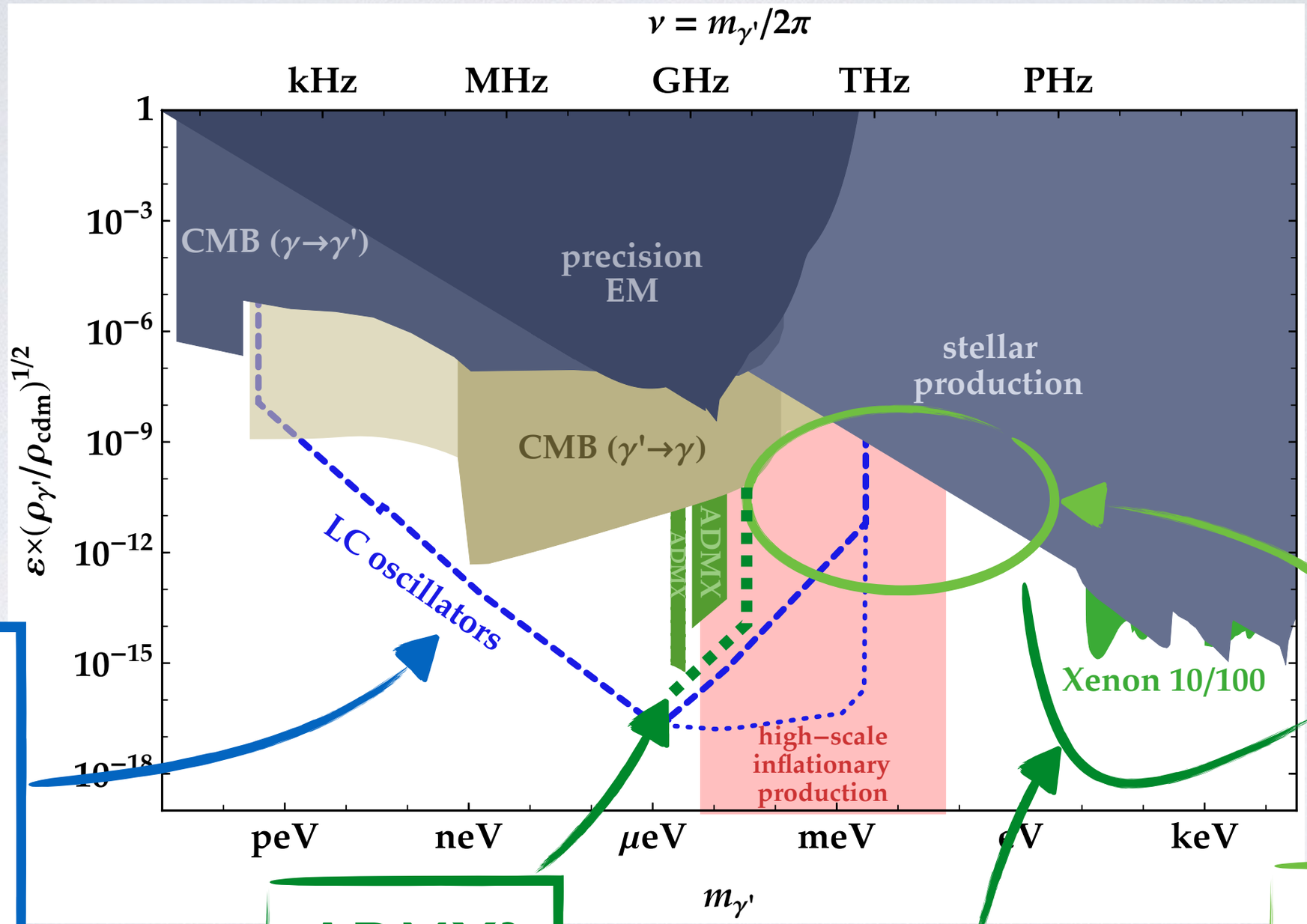
ALSO:

— 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



Next few years at SLAC/ Stanford

1411.7382

ADMX?

1201.5902

Direct detection?

1412.8378

?? (dish focussing?)

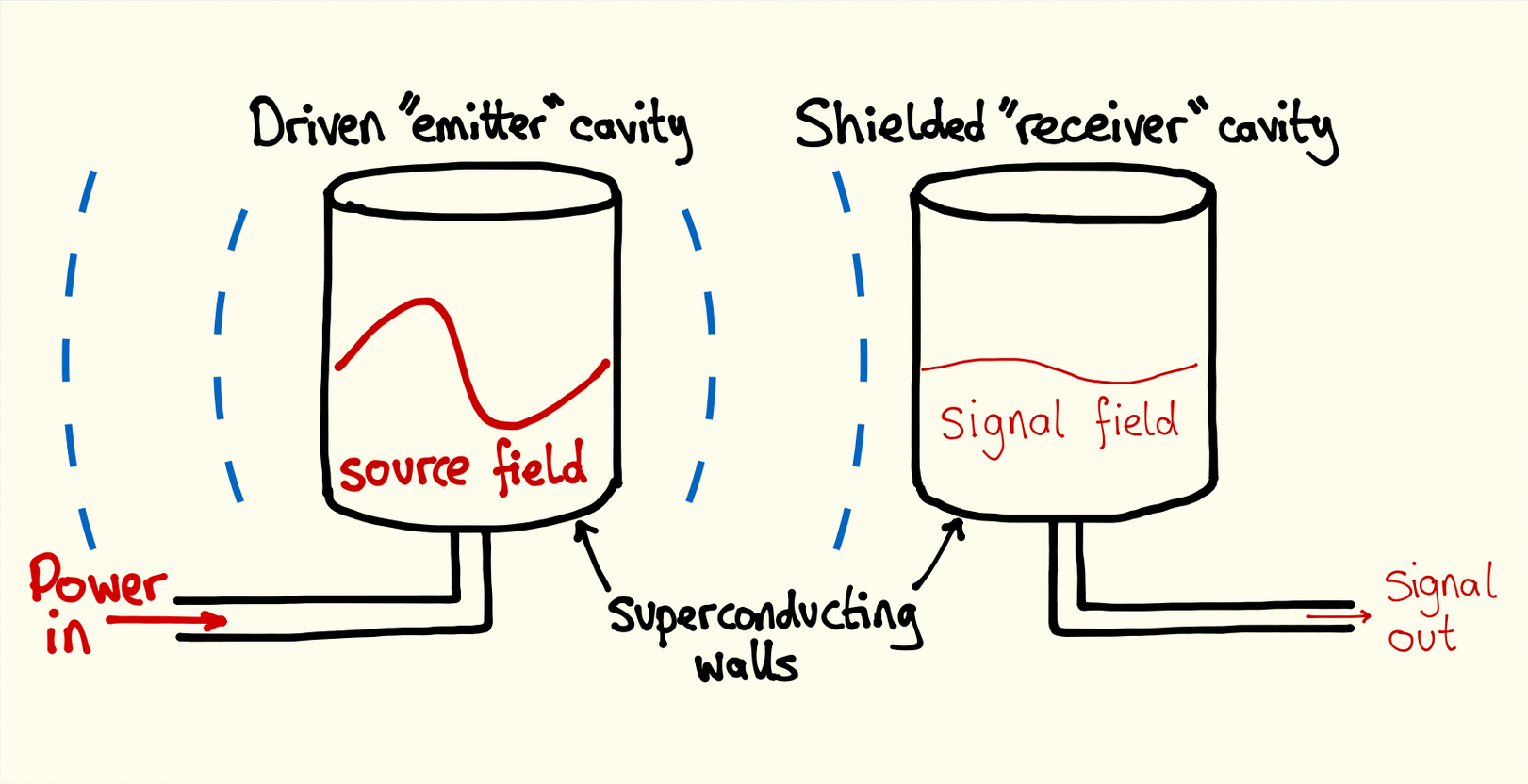
1212.2970

Light-Through-Walls Searches for Hidden Photons

Jeremy Mardon, SITP, Stanford

LIGHT-THROUGH-WALLS CAVITY SEARCH

The hidden photon is an **unshieldable** addition to Electromagnetism



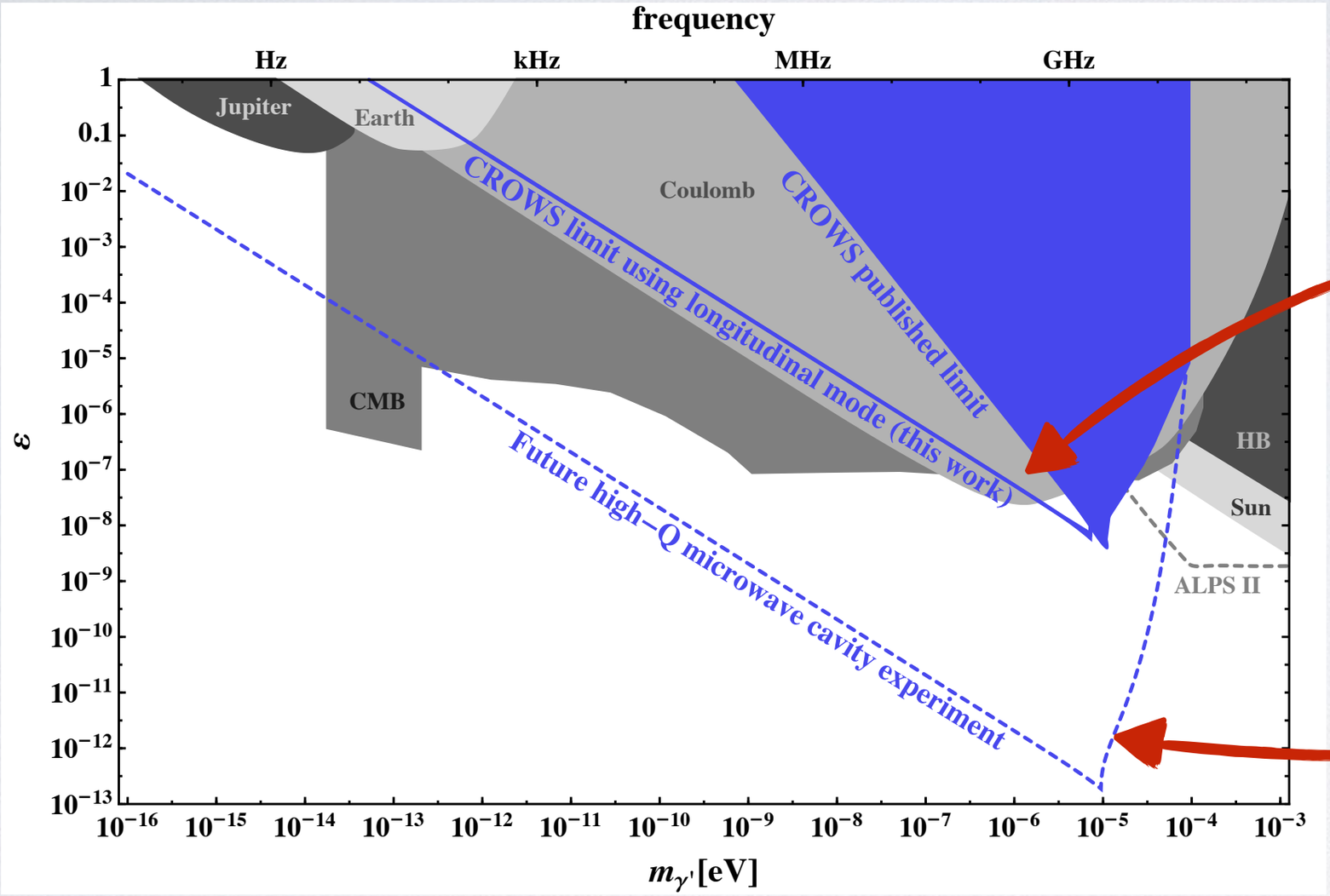
Jaeckel & Ringwald 0707.2063

— tune 2 cavities to same frequency

— drive one cavity, pick up signal in well-shielded 2nd cavity

— resonant enhancement

REACH



early-stage bound
CROWS collaboration
1310.8098
see Graham, J. M., Rajendran & Zhao
1407.4806

Potential reach
proposal with Sami Tantawi & Vinod Bharadwaj

— **large potential reach**

— corresponding **axion search is weak** ($g_{a\gamma\gamma} \sim 10^{-7}$GeV) 1310.8098