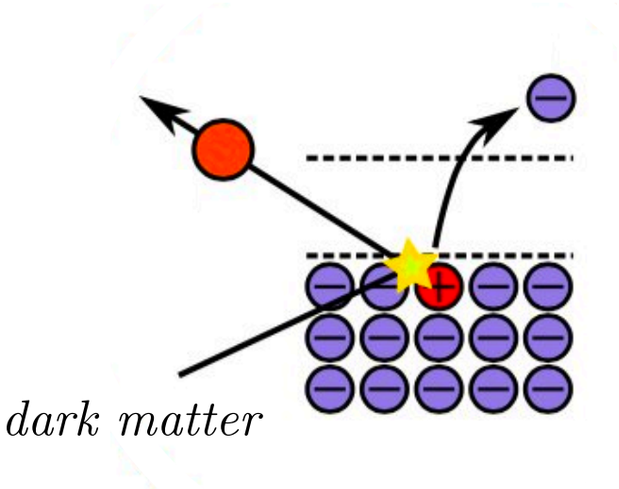
Direct Detection of Light Dark Matter



Asher Berlin - Fermilab

Seattle Snowmass Summer Meeting
July 23, 2022

See also:
arXiv:2203.10089, arXiv:2203.14923
arXiv:2203.14915, arXiv:2203.07250
arXiv:2203.08297, arXiv:2203.09488
arXiv:2203.12714, arXiv:2203.07492,...

What Do We Know?

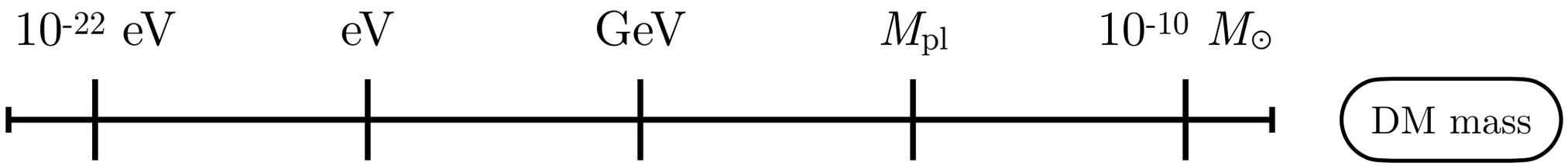
dark matter resides in galaxies (including our own)

velocity: $v_{\rm DM} \sim 100$ km/s $\sim 10^{-3}\ c$

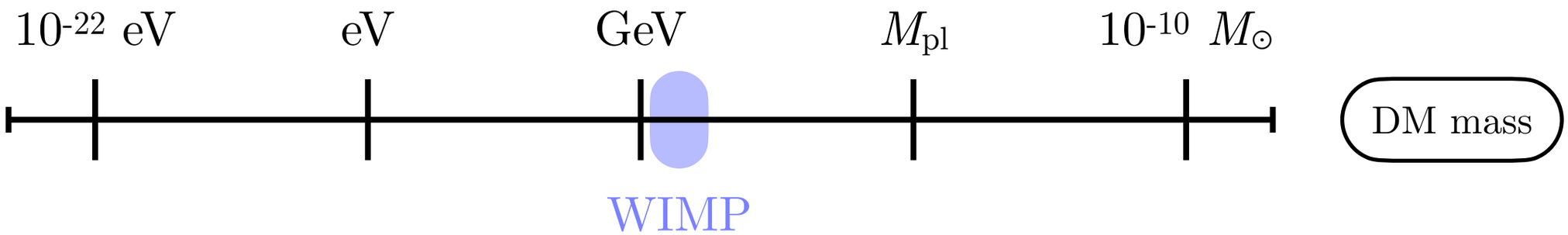
mass density: $m_{\rm DM}\, n_{\rm DM} \sim {\rm GeV/cm}^3$

Few heavy particles or many light particles?
What is the dark matter mass?

What Do We Know?

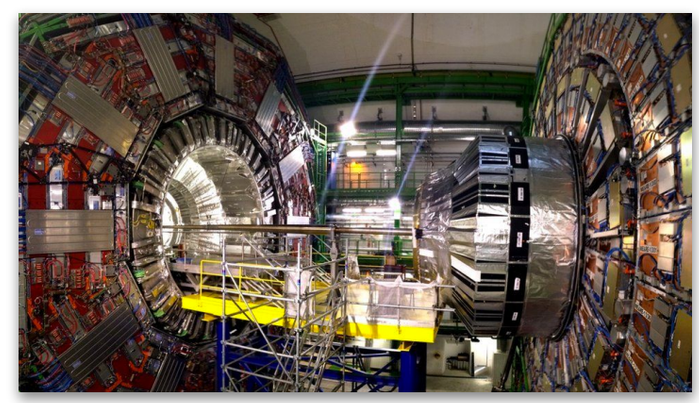


What Do We Know?

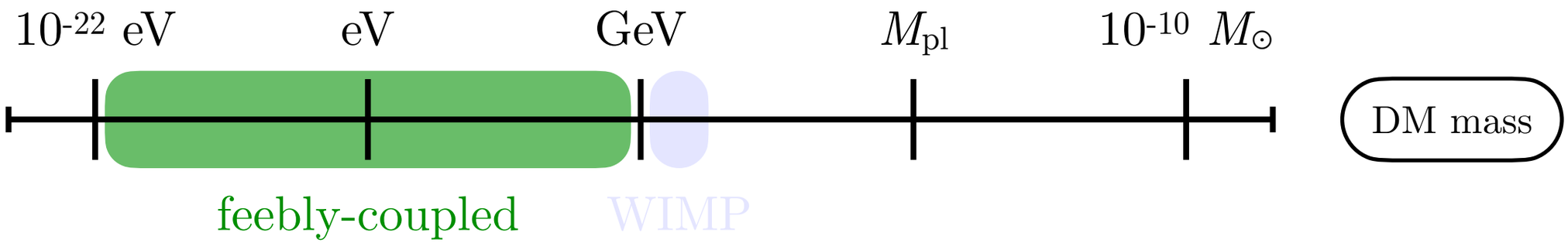


The search for WIMPs has been an incredible success.

What now?



Going Further



The search for WIMPs has been an incredible success.

What now?

Maybe the dark matter and hierarchy problem are not solved together.

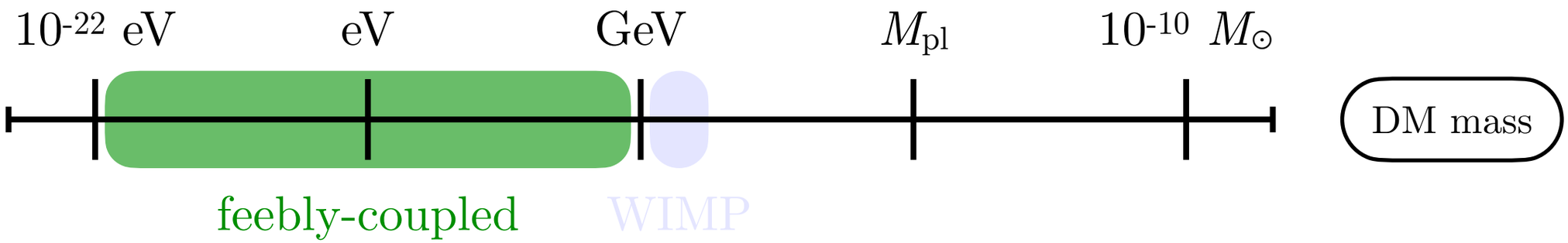
↓

If so, the space of motivated signals is dramatically enlarged.

↓

This motivates a strong diversification of the experimental program.

Going Further



New Theoretical Targets

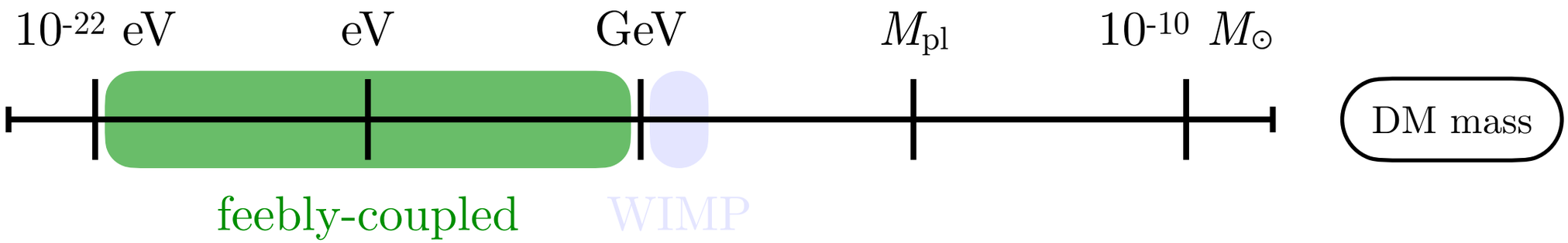
What are cosmologically-motivated and viable models?

What is new technology sensitive to?

Where are the biggest gaps in coverage?

When do we stop and reevaluate?

Going Further



New Technology

Opportunity to explore new physics at previously inaccessible scales.

How can these developments be steered to make the biggest impact on dark matter physics?

Role of theory/theorists

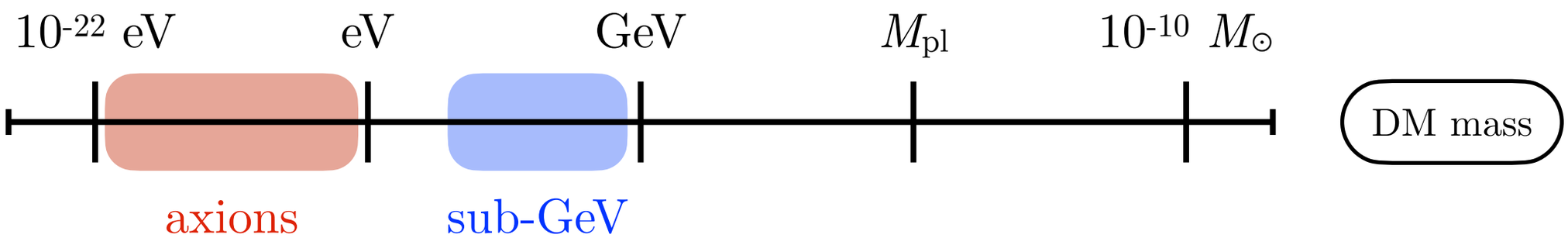
Creative repurposing of existing detectors.

Motivating/conceiving/designing new small-scale experiments.

This is especially crucial in emerging fields.

Theorists played a major role in most experiments/proposals that will be highlighted here.

Outline



Ultralight Axion Dark Matter

I.

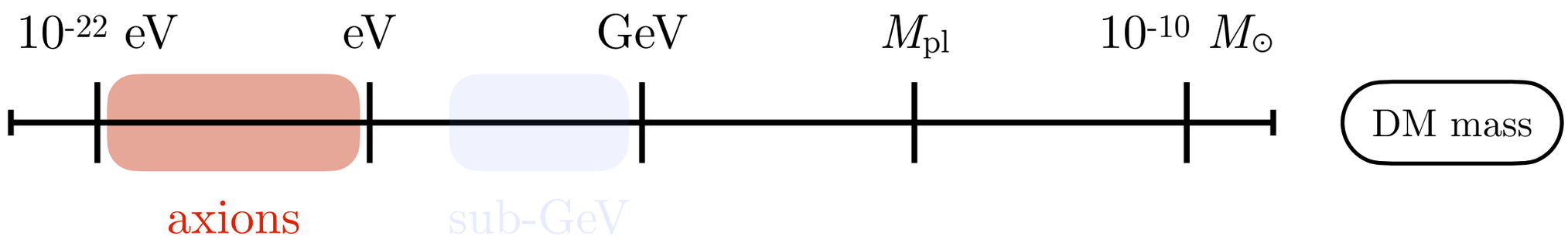
Resonant cavities
LC circuits
Dielectric haloscopes
< SQL
QCD-coupling, ...

Light Particle Dark Matter

II.

skipper CCDs
supercond. nanowires
low-gap materials, ...

Outline



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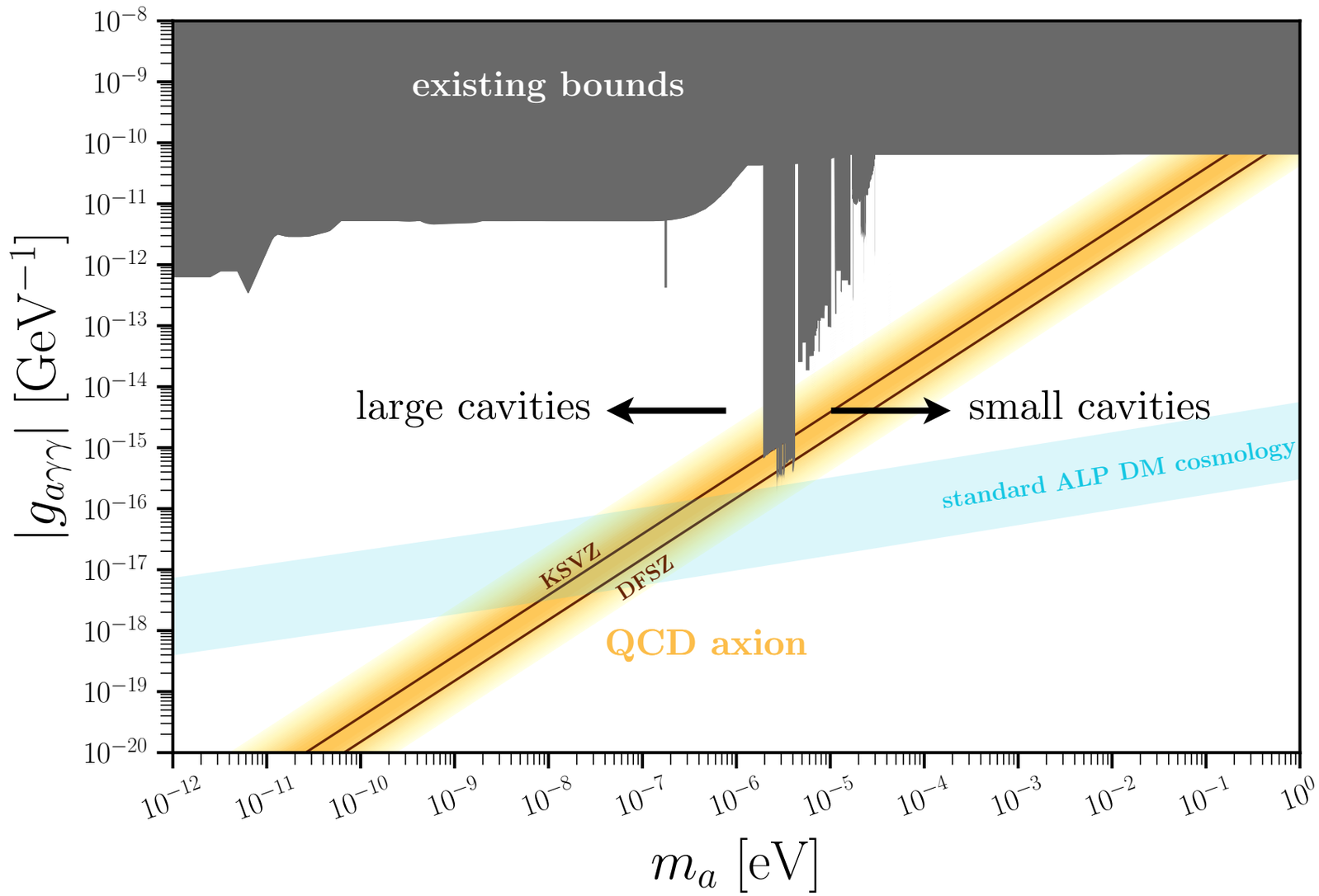
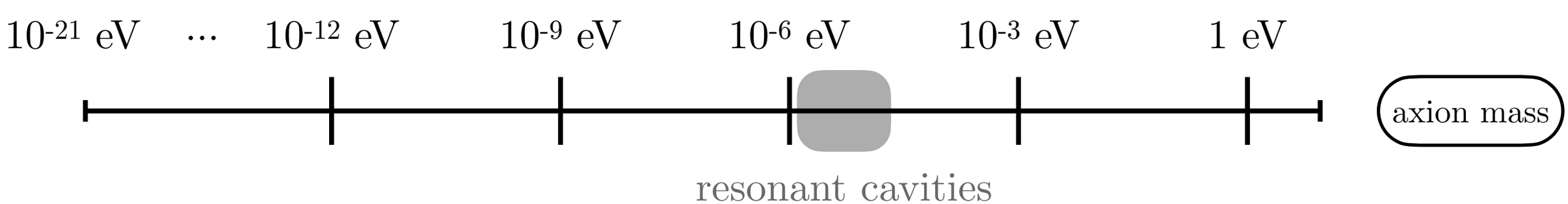
I. Ultralight Axion Dark Matter

Axion Parameter Space

electromagnetically-coupled axions, $\mathscr{L} \sim g_{a\gamma\gamma}\, a\, F\tilde{F}$

(axion + $B \to$ photon)





Axion Parameter Space

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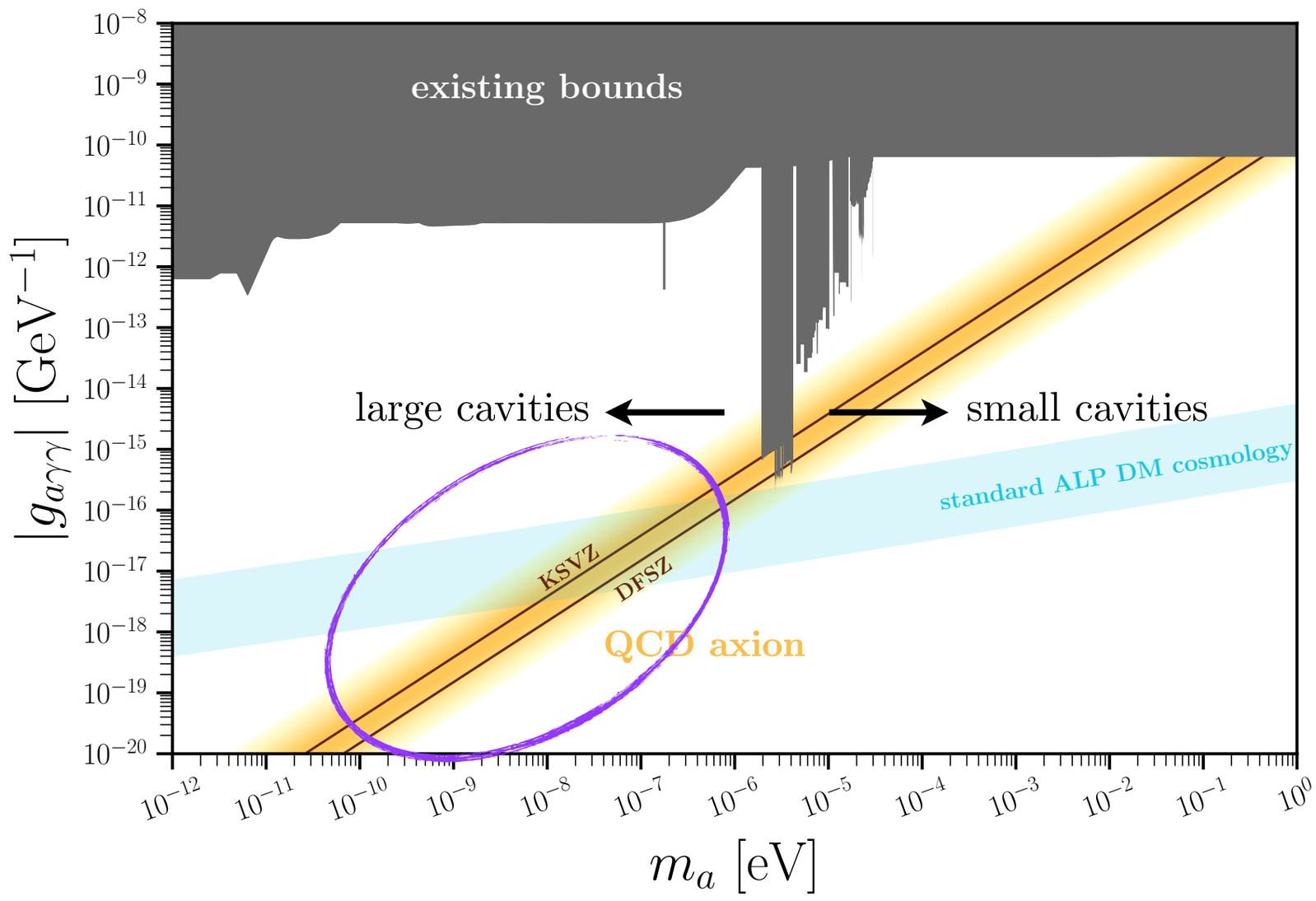
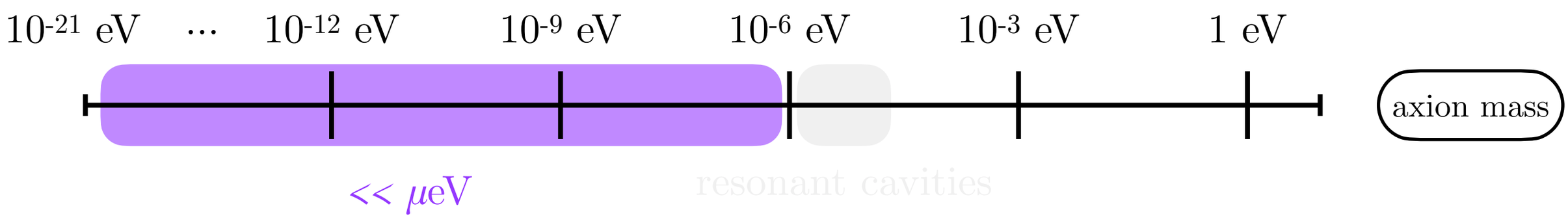
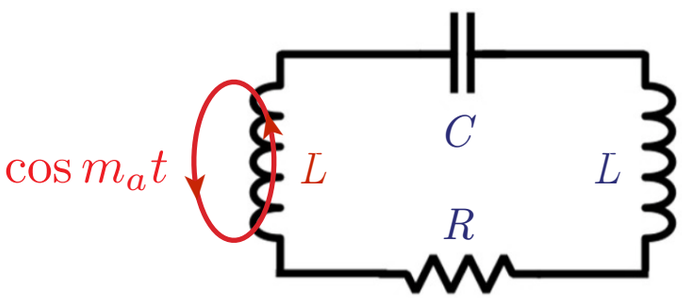


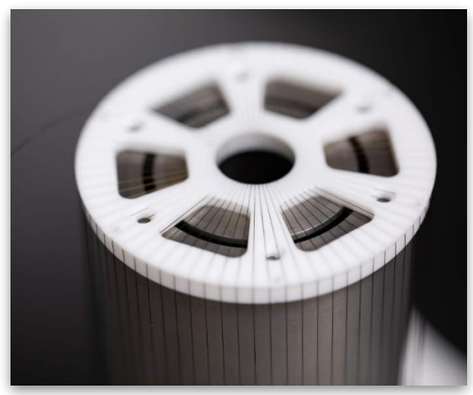


Below ~Micro-eV

LC circuits (DMRadio)

arXiv:2204.13781, arXiv:2203.11246



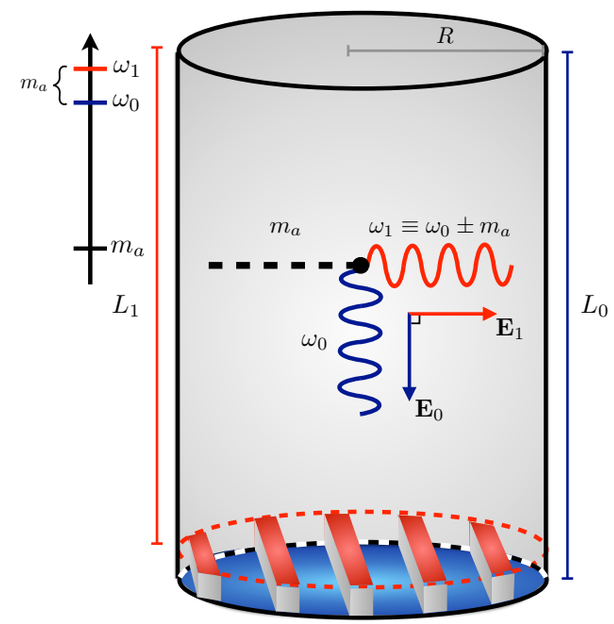


$$\omega_{\rm LC} \sim \frac{1}{\sqrt{LC}} \sim m_a \ll \frac{1}{\text{length}}$$

$$B \sim \text{few} \times \ \text{T}$$

Heterodyne/Upconversion (SRF cavities)

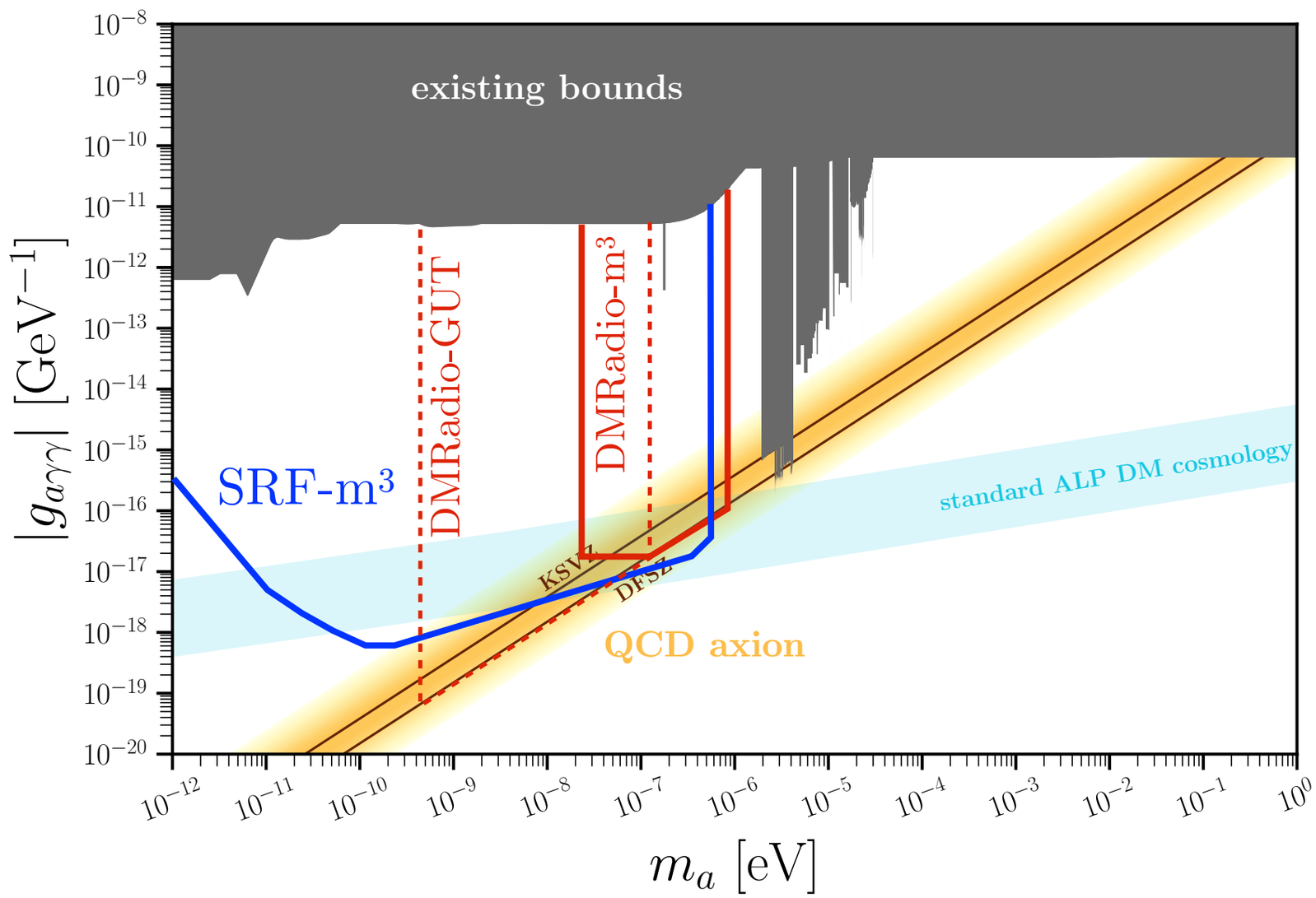
arXiv:1912.11048, arXiv:1912.11056, arXiv:2007.15656

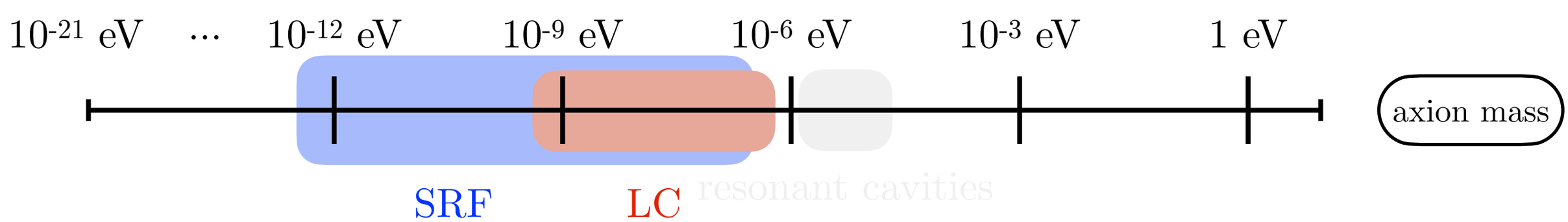


$$\Delta\omega \sim m_a \ll \omega \sim \text{GHz}$$

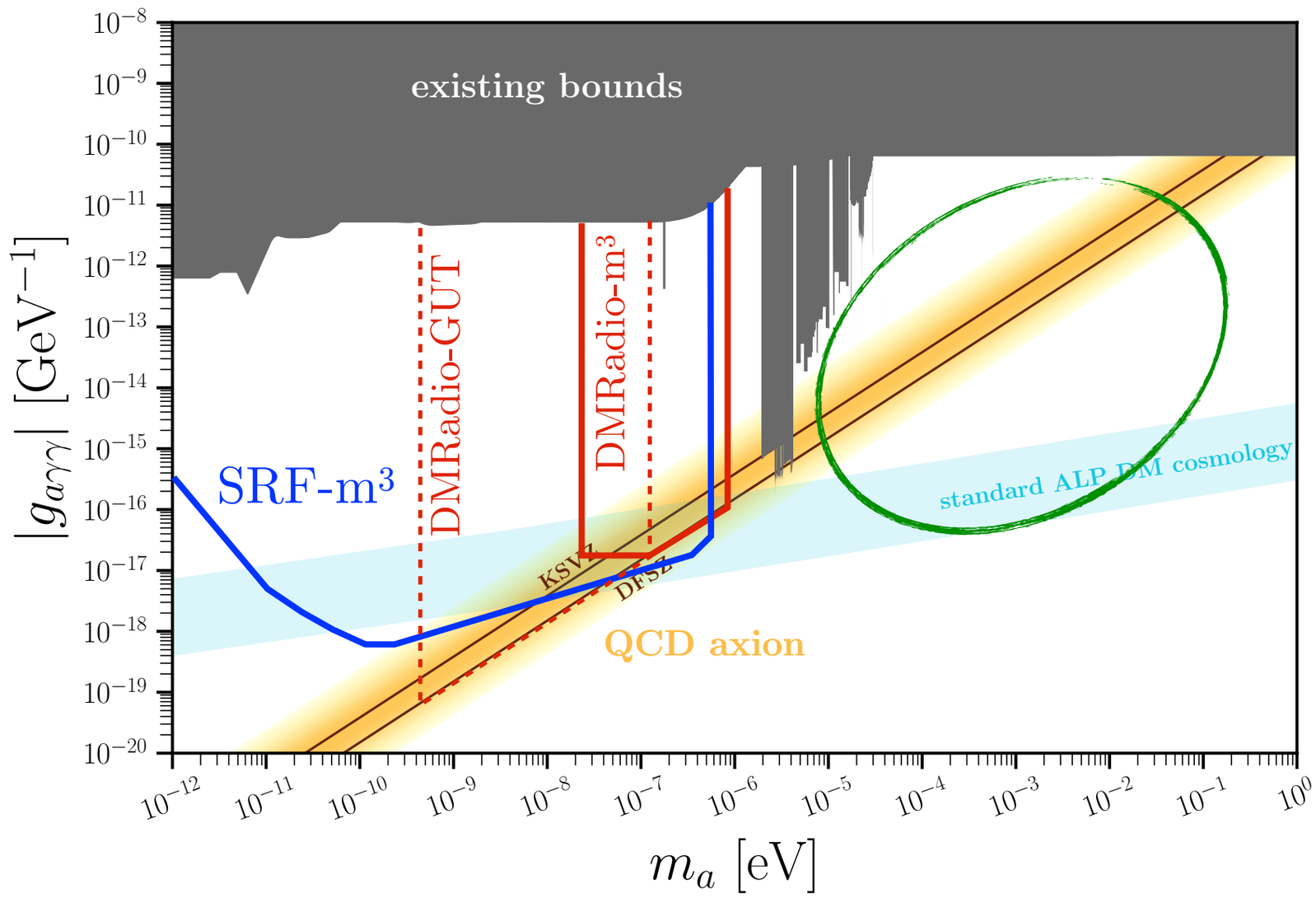
$$Q \sim \text{few} \times 10^{11}$$

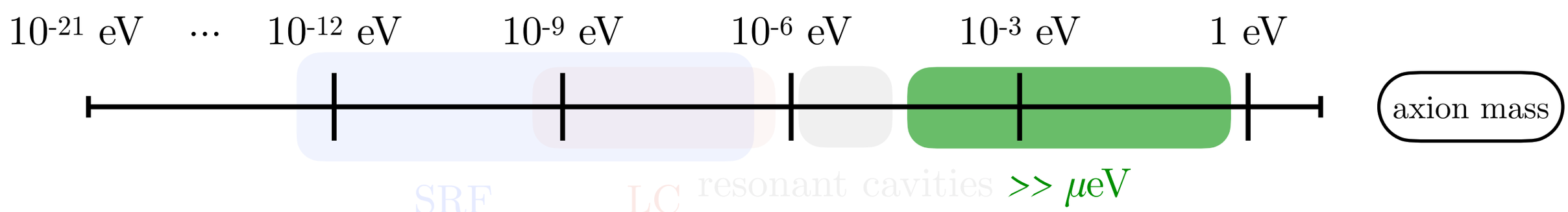
Below ~Micro-eV





Above ~Micro-eV

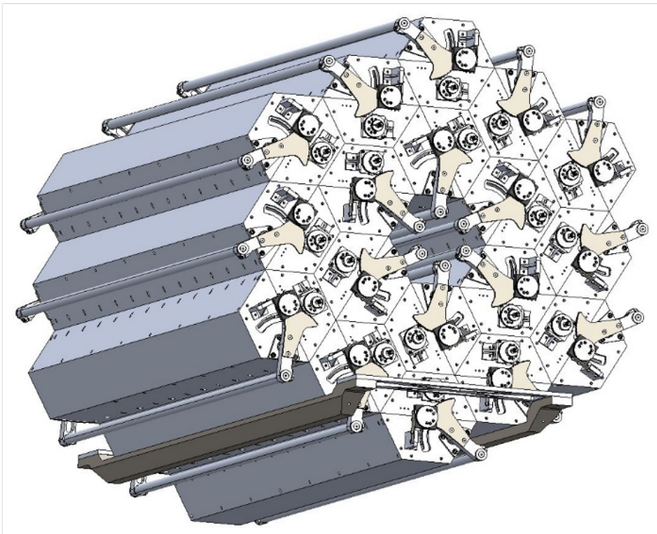




Above ~Micro-eV

Resonant Cavity (ADMX-EFR)

arXiv:2203.14923

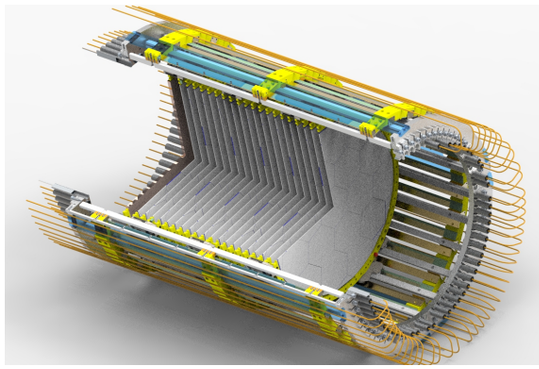


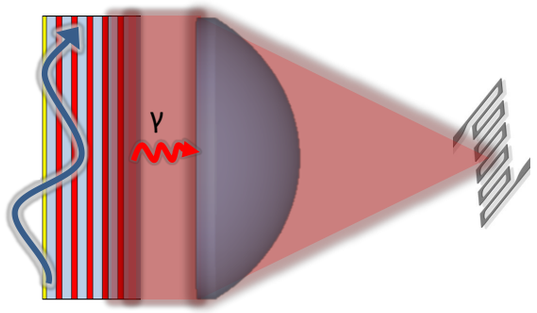
combine signal from 18 smaller cavities

2-4 GHz ~ 8-16 μeV

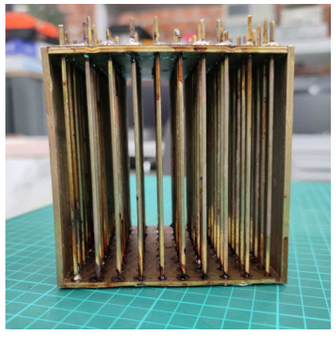
Dielectric/Plasma (MADMAX, LAMPOST, ALPHA)

arXiv:1901.07401, arXiv:2110.01582, arXiv:1904.11872





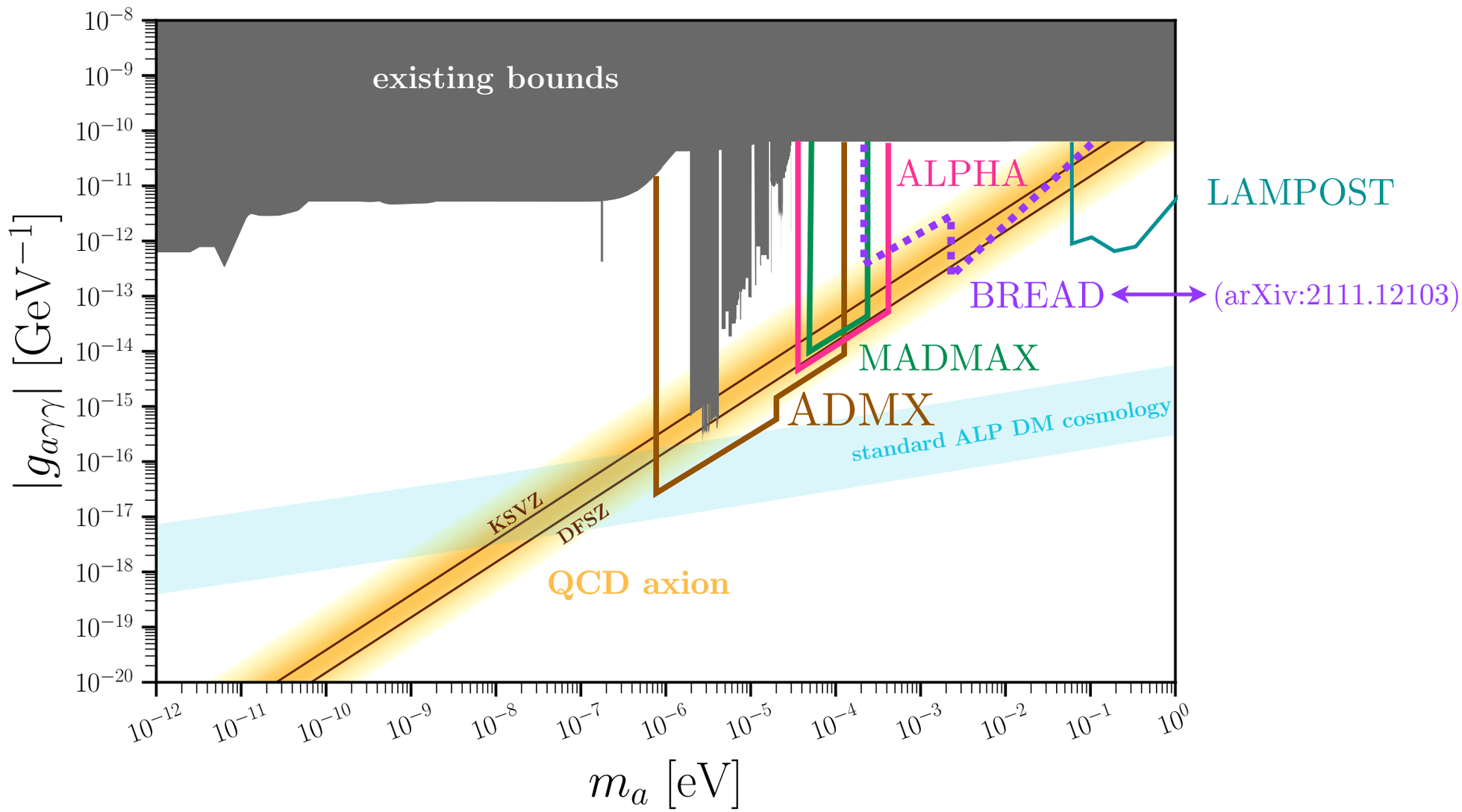
MADMAX/LAMPPOST: dielectric stacks

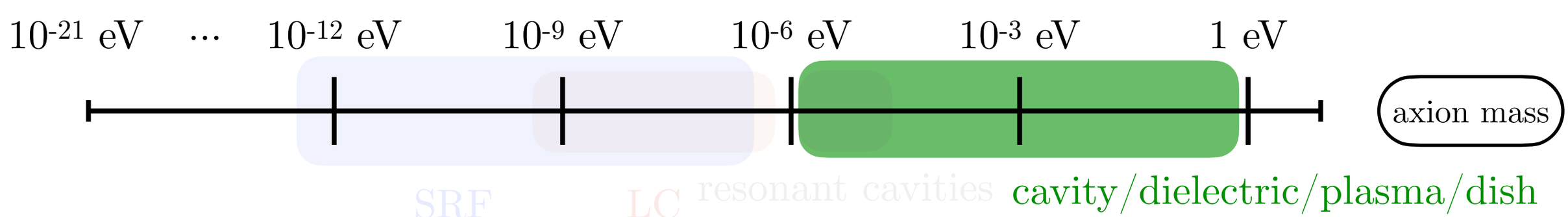


ALPHA: wire metamaterial

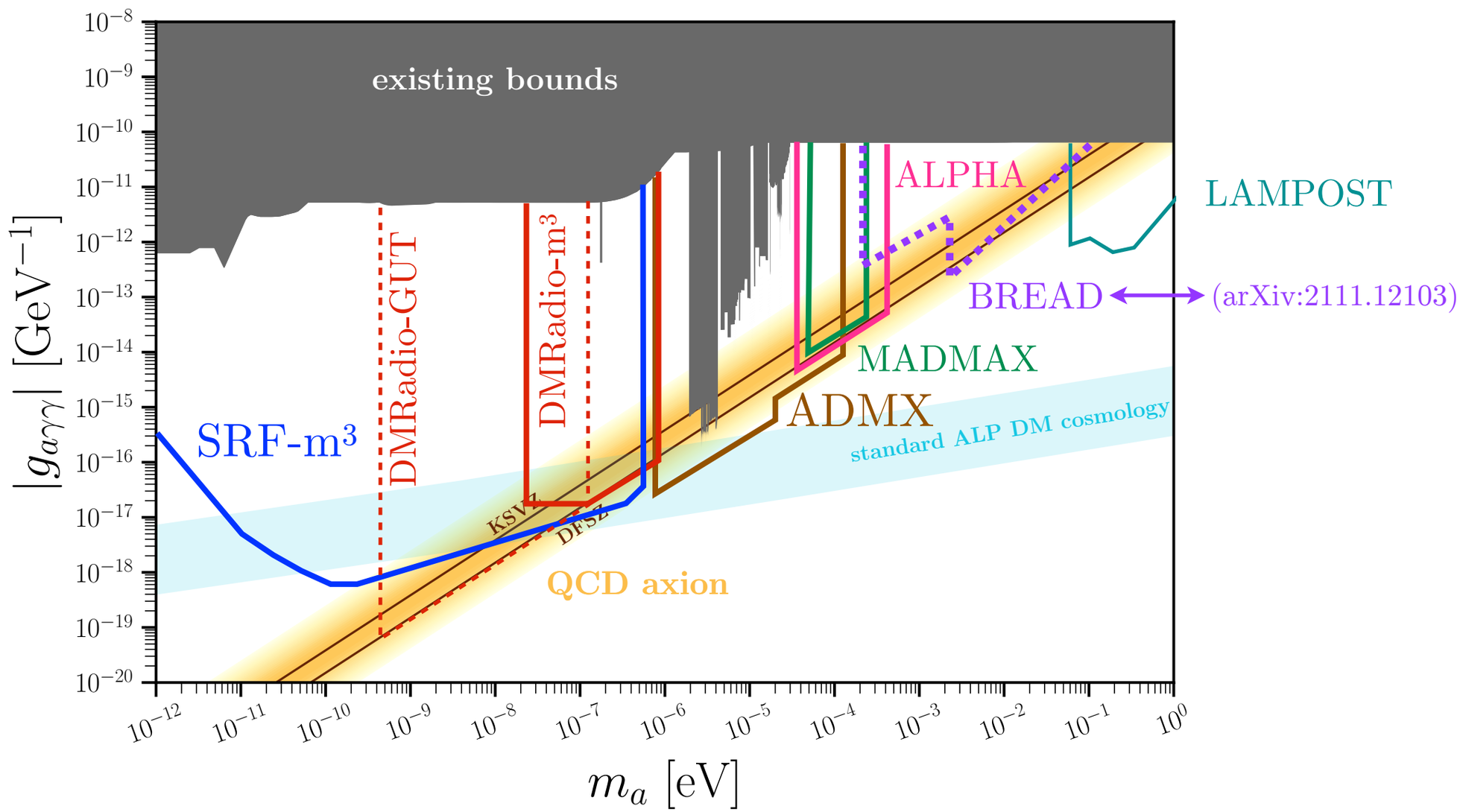
modify photon's dispersion relation

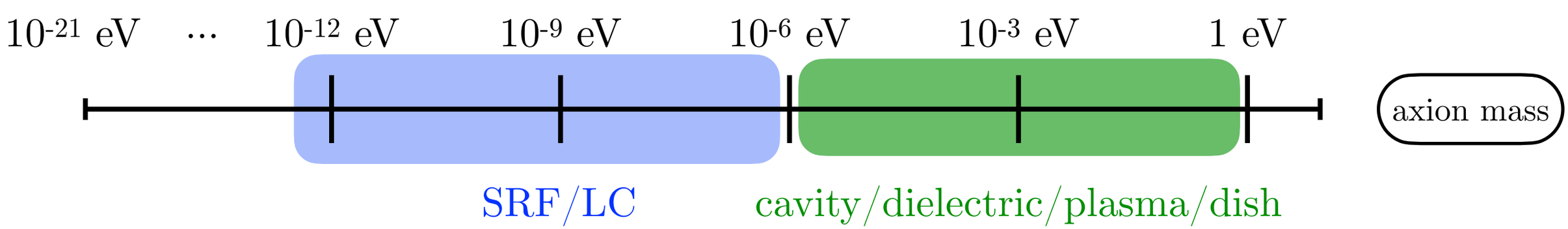
Above ~Micro-eV





Summary of Projections



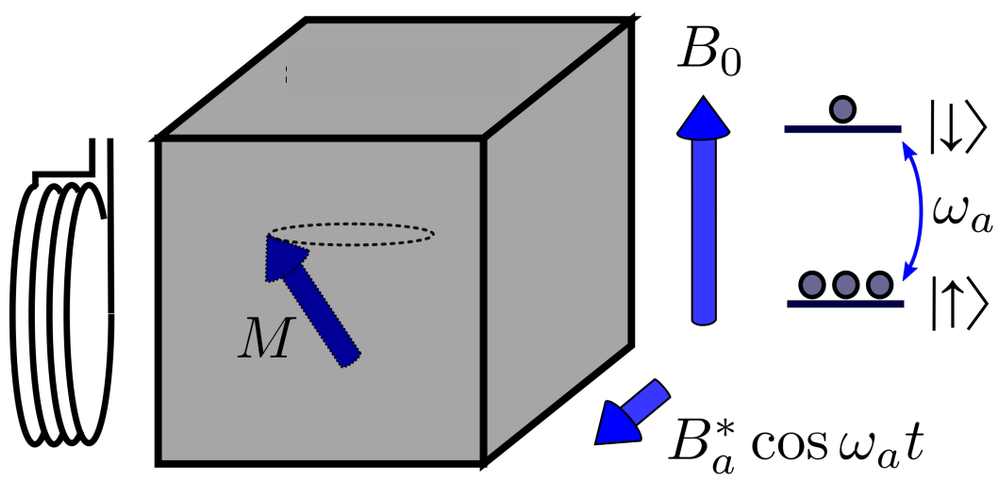


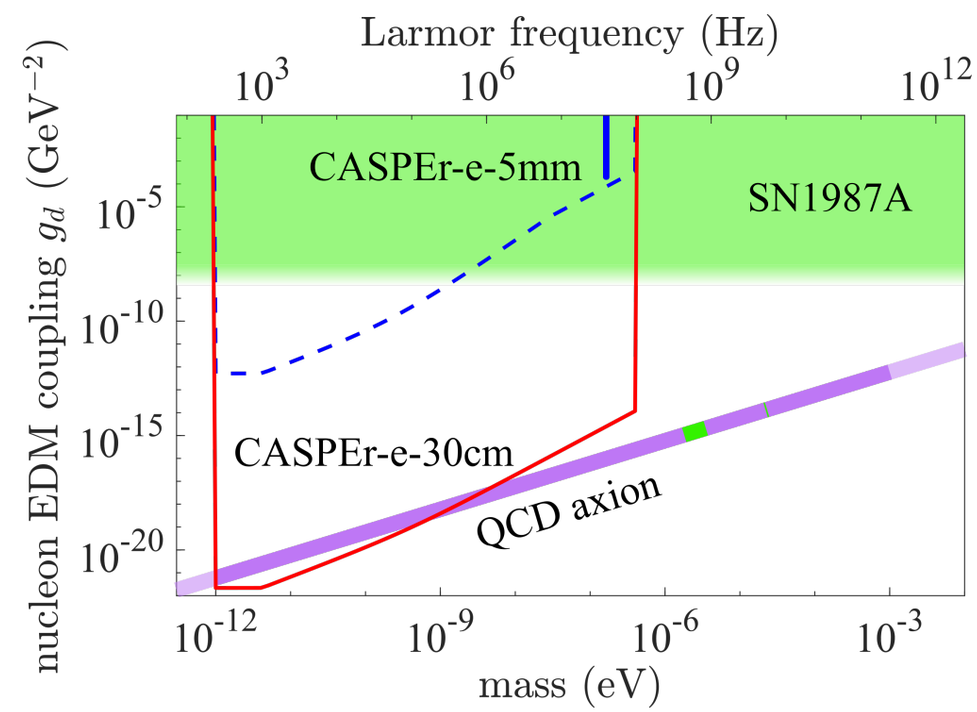
QCD Coupling

QCD-coupled axions, $\mathscr{L} \sim g_{agg}\, a\, G\tilde{G}$

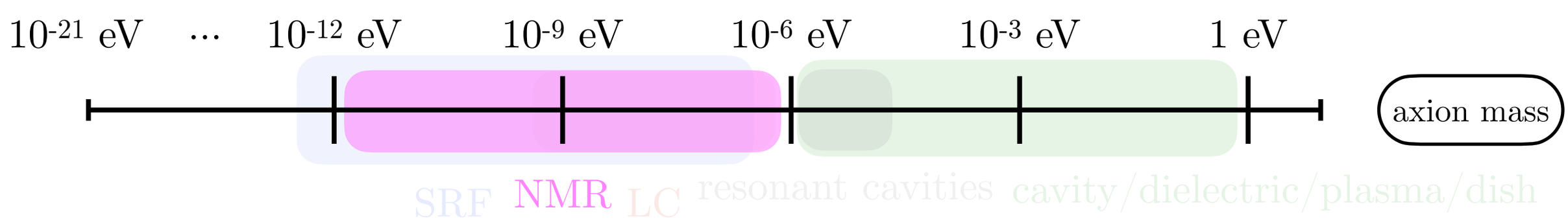
NMR-like Signal in Ferroelectrics (CASPEr-electric)

arXiv:1306.6089



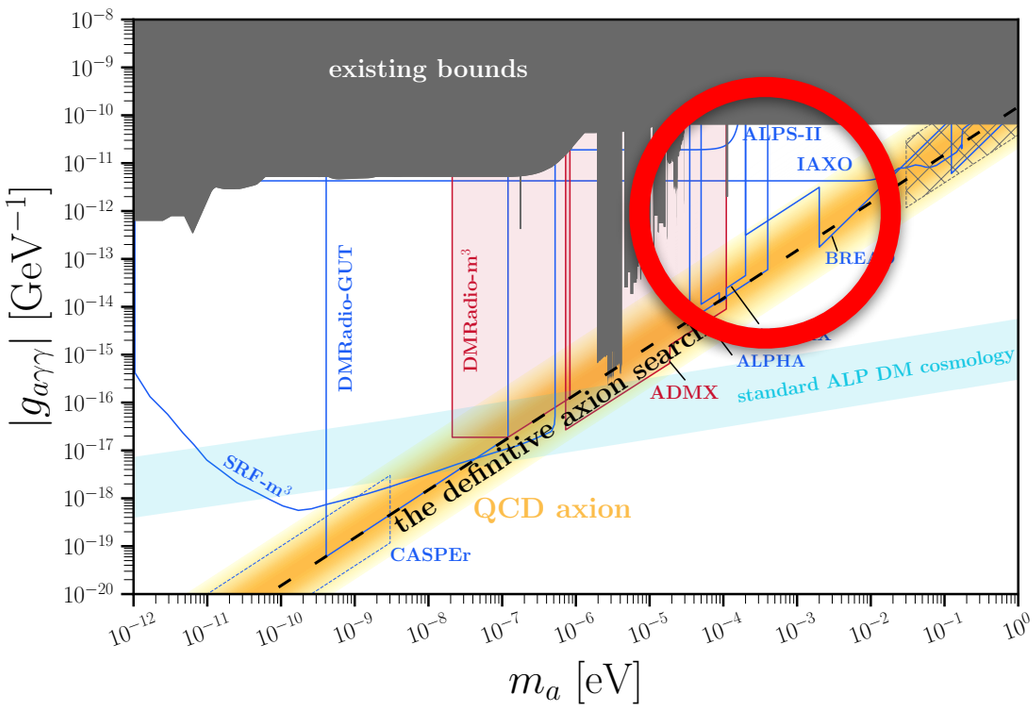


Oscillating neutron EDM → Rabi flopping/Tilted magnetization

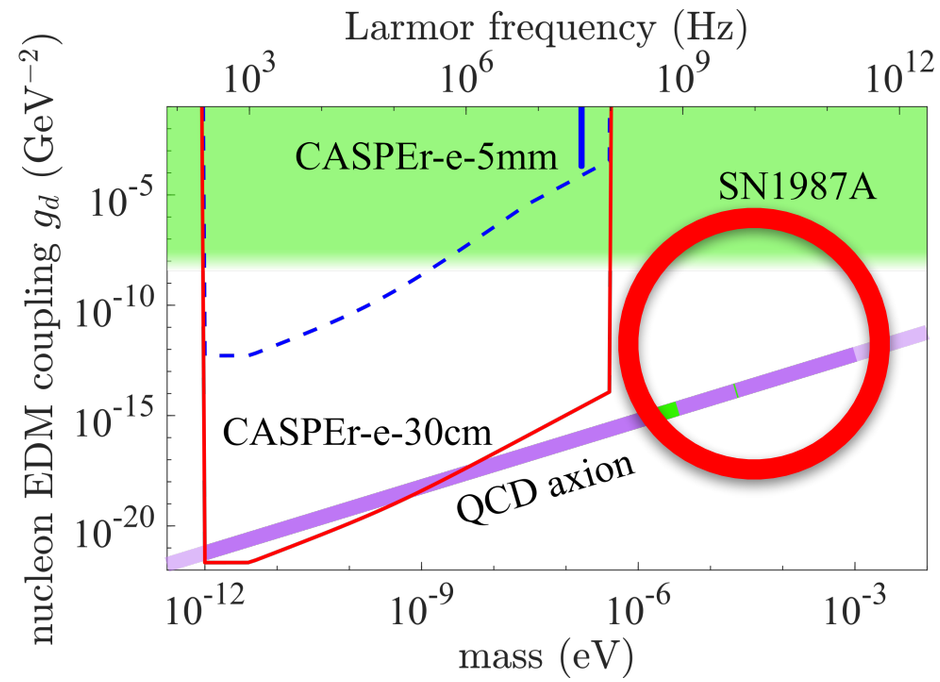


Opportunities in Axion Detection

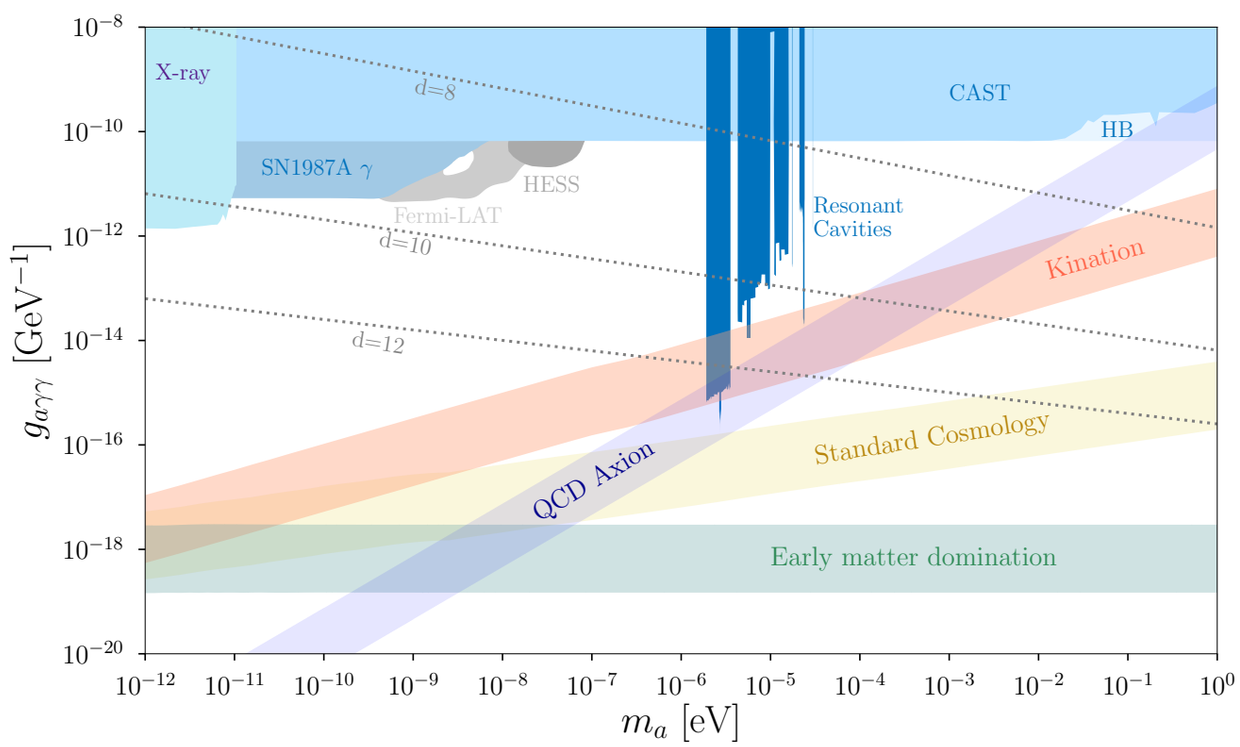
EM-coupled DM at ~meV~THz



QCD-coupled DM at > μeV~GHz

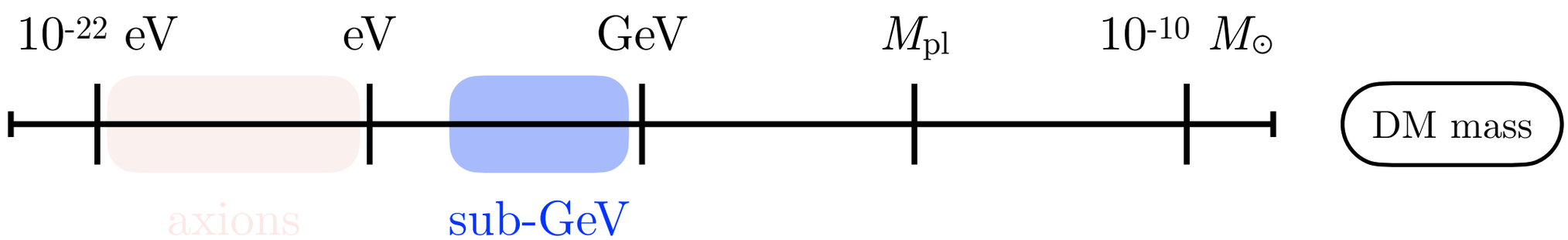


New Theory Targets



arXiv:1905.06952

Outline



Ultralight Axion Dark Matter

I.

Resonant cavities
LC circuits
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Light Particle Dark Matter

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skipper CCDs
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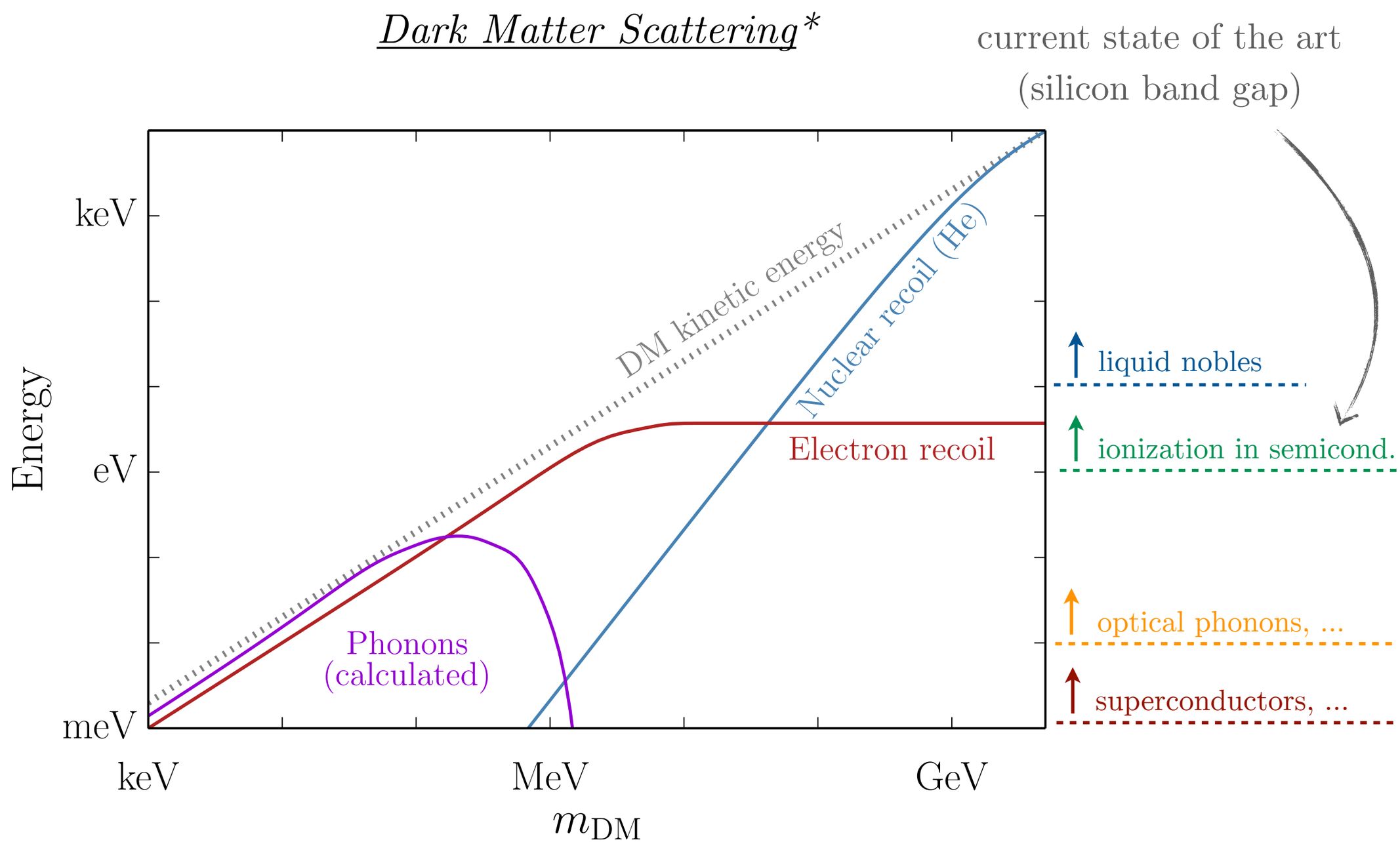
low-gap materials, ...

II. Light Particle Dark Matter

Kinematic Matching



inelastic scatters → better kinematic matching at small masses

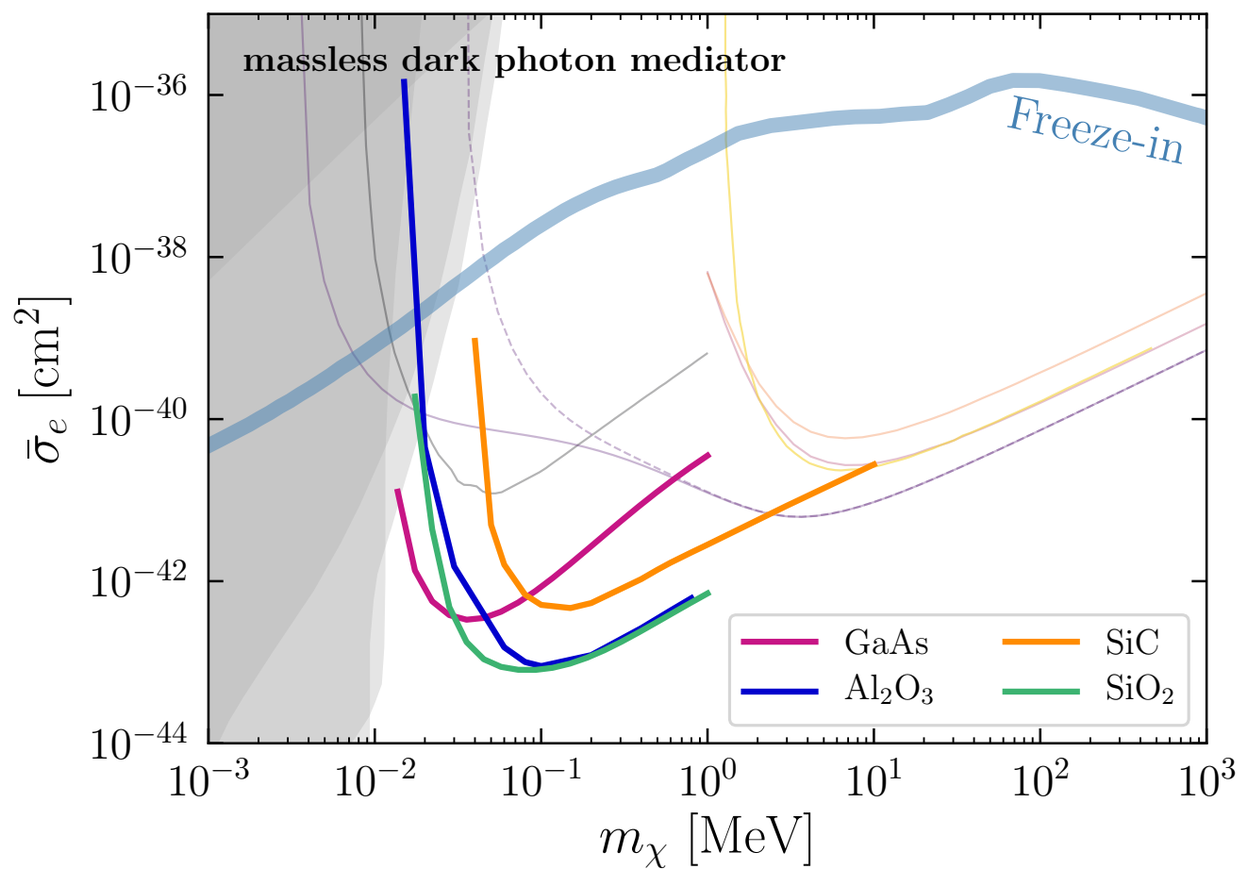
(*ignoring absorption for sake of time)

arXiv:2203.08297
arXiv:1904.07915

Multitude of Proposed Materials

From minimal mention in Snowmass-2013 to now...
(multiple target materials spanning many couplings within theory space)

- Solid-state charge detectors
  (CCDs, semiconductor crystals + dopants)
- Exotic narrow gap semiconductors,
  Dirac Materials
  ($La_3Cd_2As_6$, $Eu_5In_2Sb_6$, $ZrTe_5$)
- Polar Materials
  (GaAs, SiC, Al_2O_3, SiO_2)
- Molecules/vibrational modes
  (CO, HF)
- Superfluids/superconductors
  (He, Al)
- Organic Scintillators +...

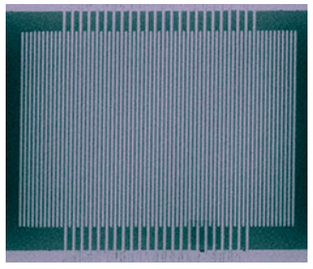


only small target exposures required to explore new parameter space

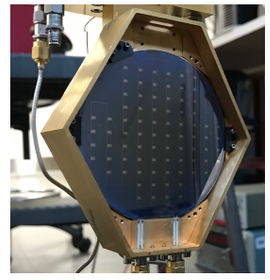
arXiv:2108.03239

Multitude of Proposed Sensors

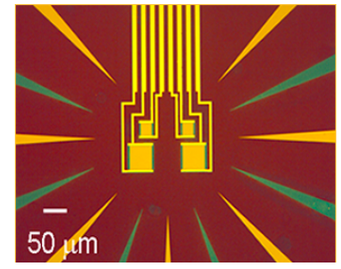
SNSPDs



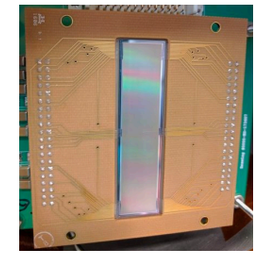
KIDs



TESs



skipper CCDs



+...

lowering thresholds and backgrounds

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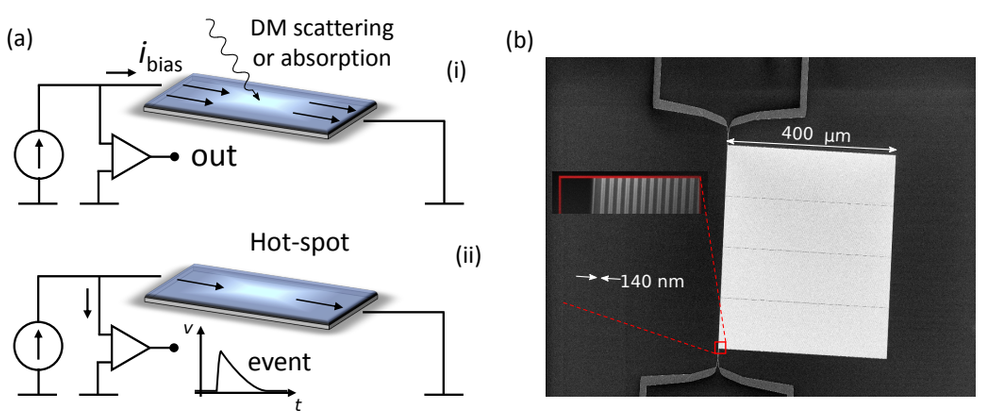
superconducting nanowires

arXiv:1903.05101

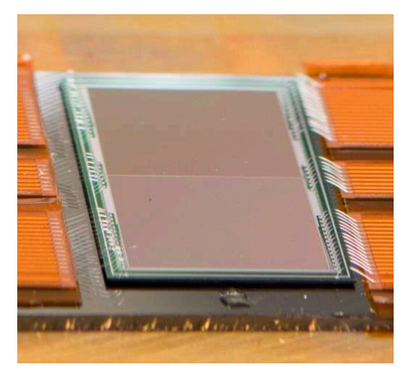


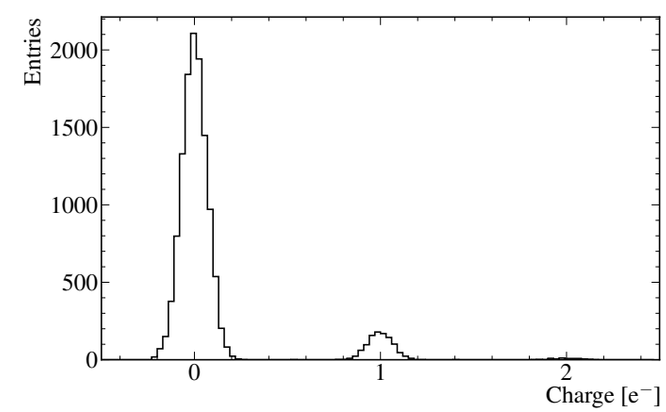
infrared/optical photon counting

dark count ~1 per day

skipper CCDs, SENSEI

arXiv:1706.00028





non-destructive repeated charge counting

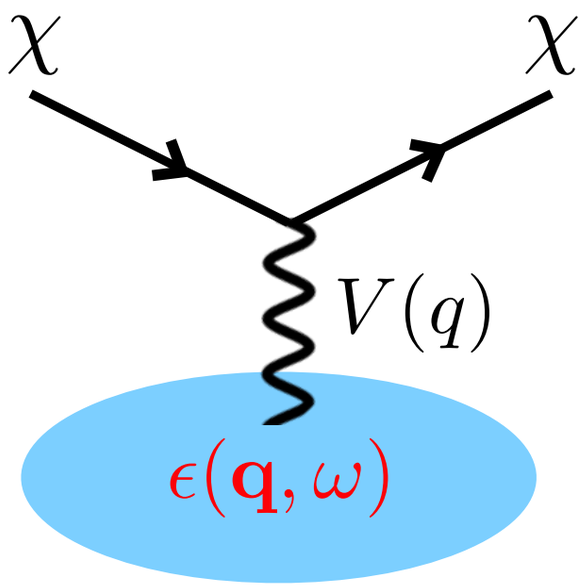
dark count < 10^{-3} e/pix/day

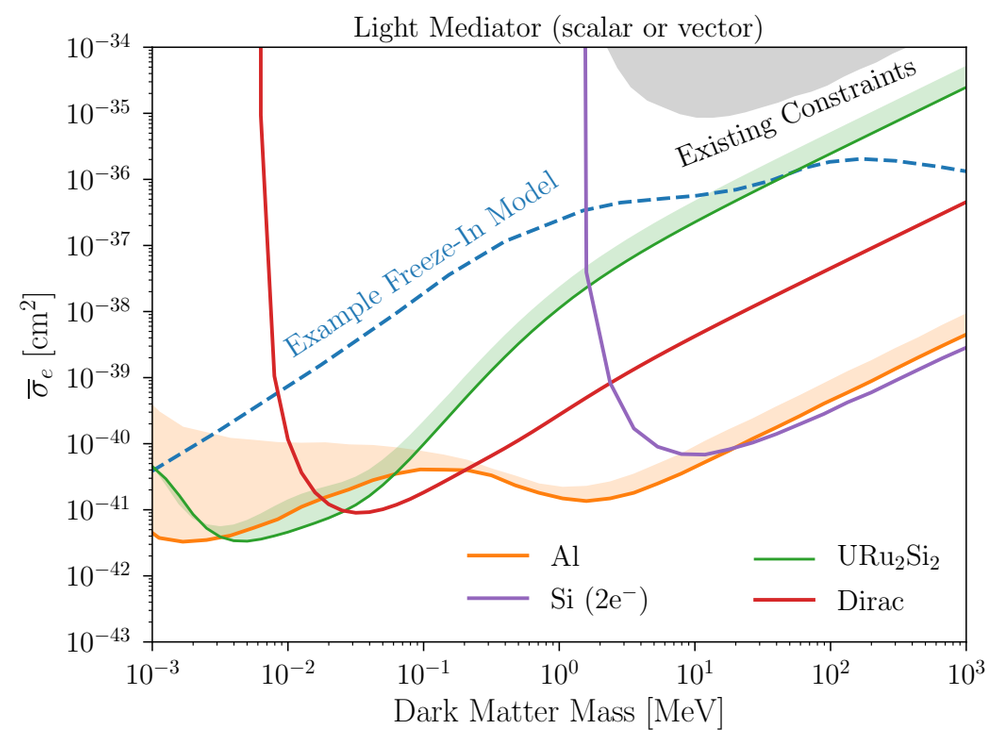
dopants to lower threshold from eV to 10 meV?

A Better Understanding of the Material Response

For any DM coupling to electron density,
scattering is determined by dielectric function

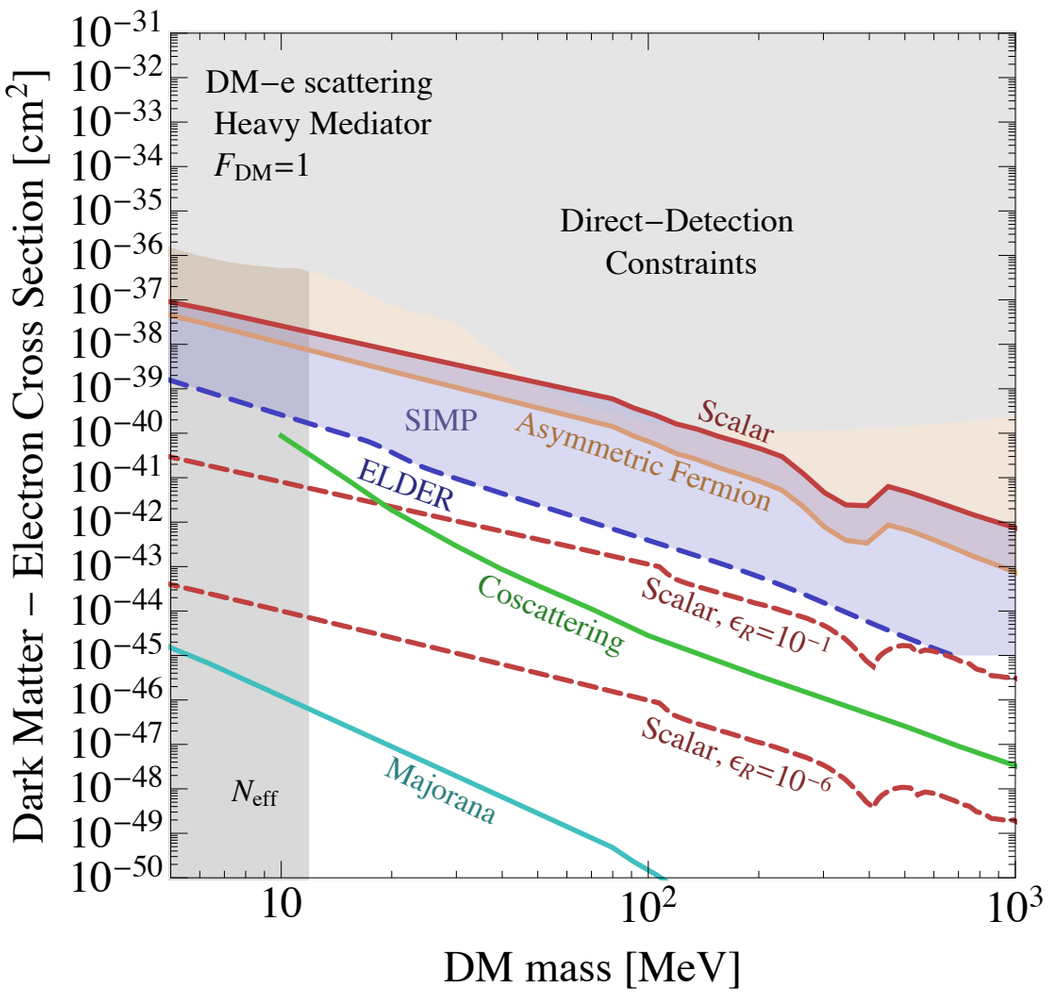
$$\Gamma(\mathbf{v}_\chi) = \int \frac{\mathrm{d}^3\mathbf{q}}{(2\pi)^3} |V(\mathbf{q})|^2 \left[2\frac{q^2}{e^2} \, \mathrm{Im}\left(-\frac{1}{\epsilon(\mathbf{q}, \omega_\mathbf{q})} \right) \right]$$

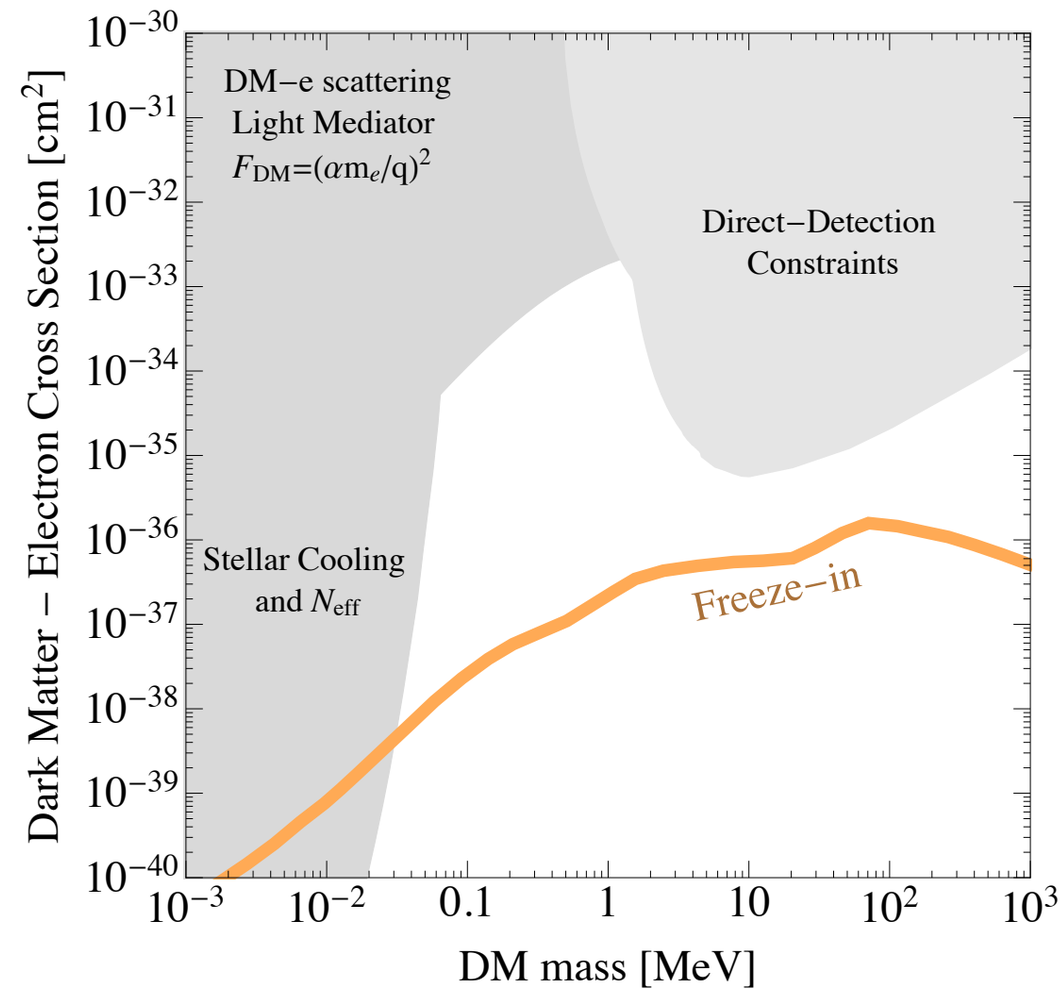




arXiv:2101.08263
arXiv:2101.08275

Identifying Theory Targets





What other cosmologically-motivated, predictive, viable, and detectable models exist below an MeV?

arXiv:2203.08297

Collective Excitations of Dark Matter

Direct *Deflection* of Dark Matter

arXiv:1908.06982, arXiv:2111.01796

Inducing and detecting collective "ripples" in the dark matter "fluid"

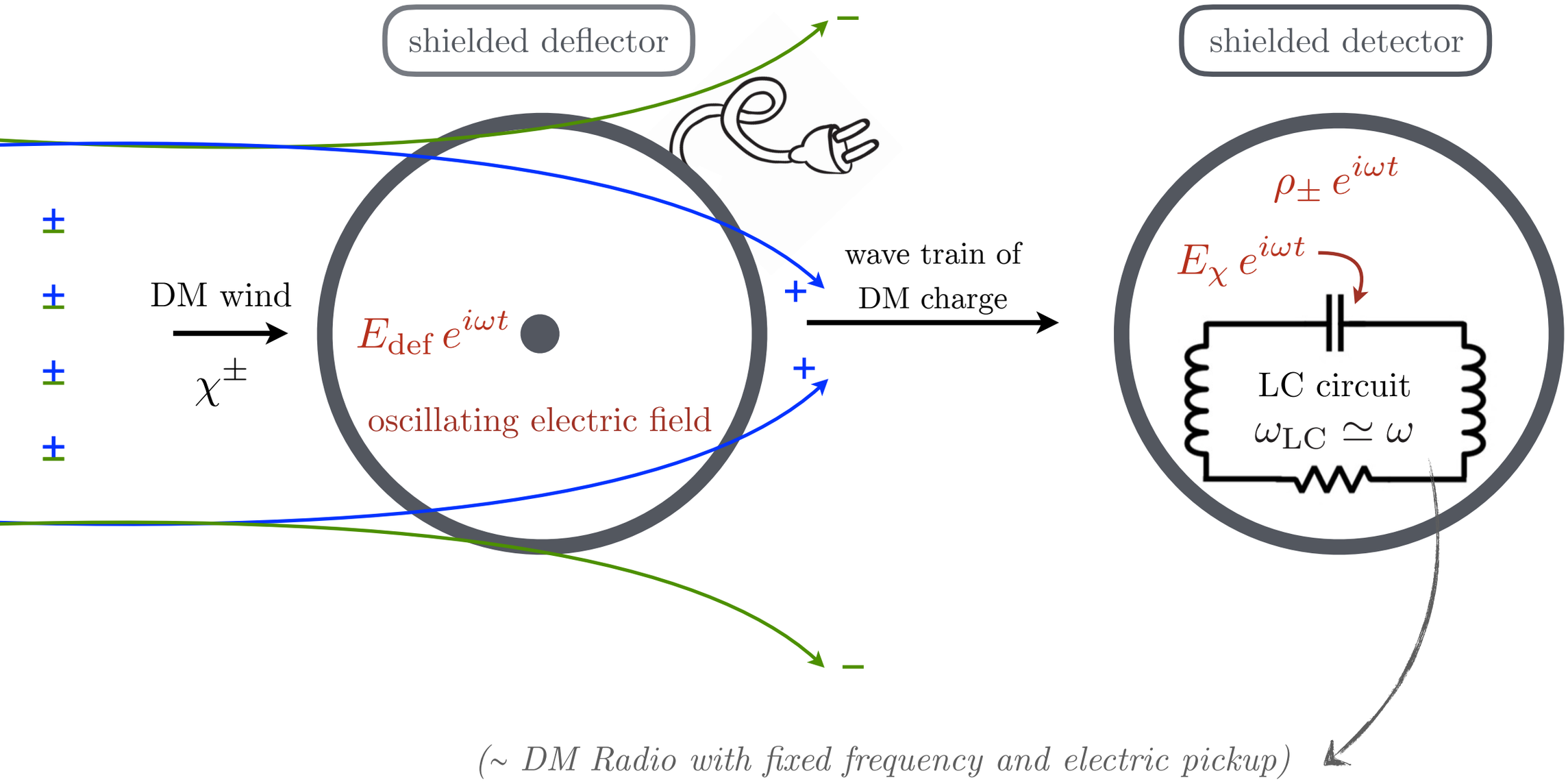
Direct *Deflection*

A large number density implies more than just large flux, it enables inducing **enhanced** collective effects into the classical DM fluid. This is easier to do for smaller masses.

Collective Excitations of Dark Matter

Direct *Deflection* of Dark Matter

arXiv:1908.06982, arXiv:2111.01796



(~ DM Radio with fixed frequency and electric pickup)

no kinematic barrier,
small momentum enhancement

Collective Excitations of Dark Matter

Direct *Deflection* of Dark Matter

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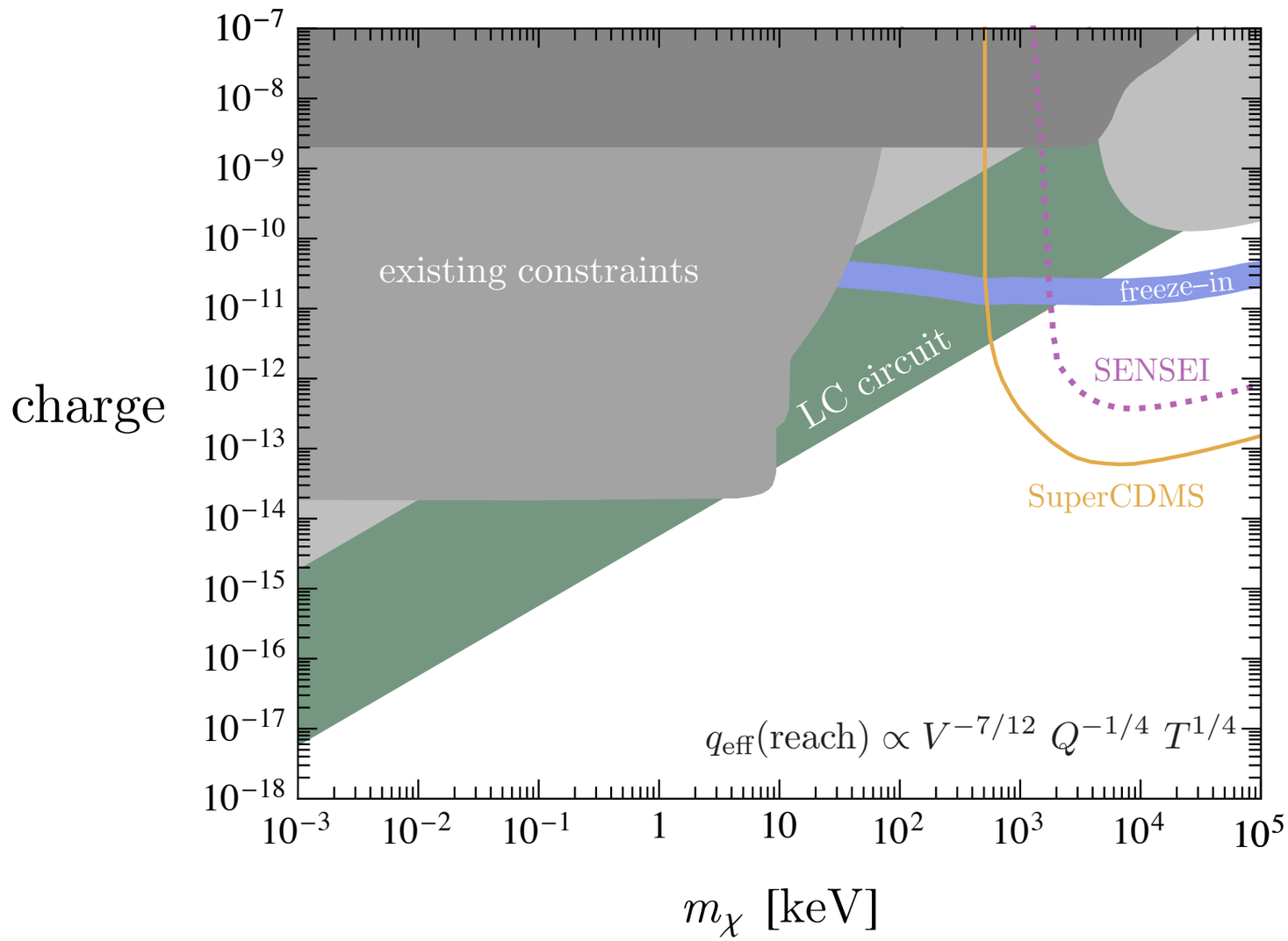


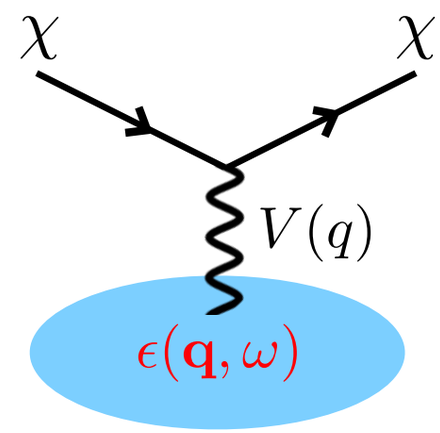
New parameter space within reach (ultimate sensitivity) for 0.1 (10) m³ volumes, 10^3 (10^7) Q-factors, and 4 K (100 mK) temperatures.

Opportunities in Low-Threshold Direct Detection

New Material Targets

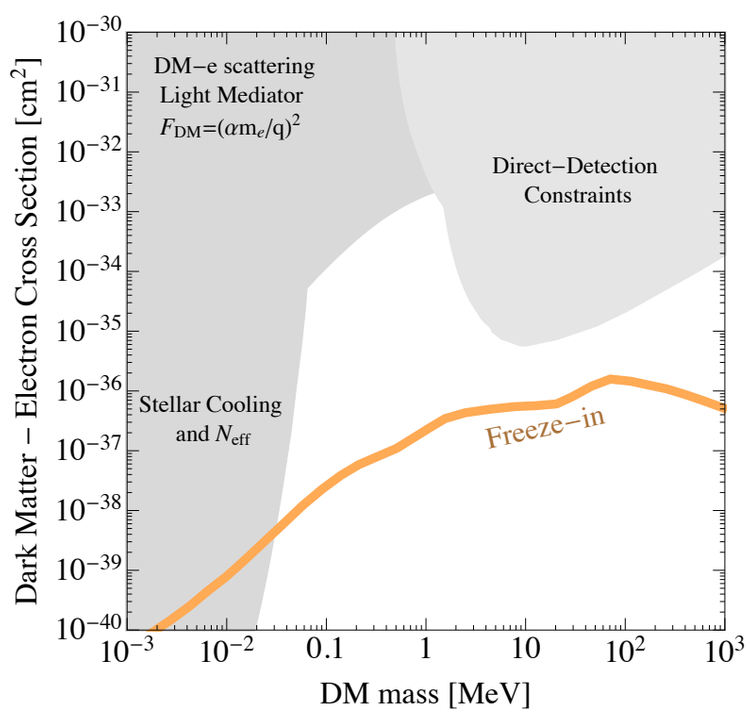
- Solid-state charge detectors
- Exotic narrow gap semiconductors
- Polar Materials
- Molecules/vibrational modes
- Superfluids/superconductors
- Dirac Materials
- Organic Scintillators
- +...?

Signal Calculation



precise understanding of material response

keV-MeV Theory Targets



Experimental Developments

What are novel backgrounds?

How to detect single phonons/magnons, ...?

Outlook

Now is an important time

We are now beginning to explore physics beyond the Standard Model
at scales currently inaccessible with previous technology.

How can technologies coming online be steered to make the
biggest impact on fundamental physics?

A shift in our priors has motivated a larger set of signals.
Many bang-for-buck experiments > single catch-all experiment.

Theory and experiment are evolving together in this effort.
The role of theorists is crucial in emerging fields.

see "Snowmass2021 Theory Frontier: Theory Meets the Lab"
arXiv:2203.10089