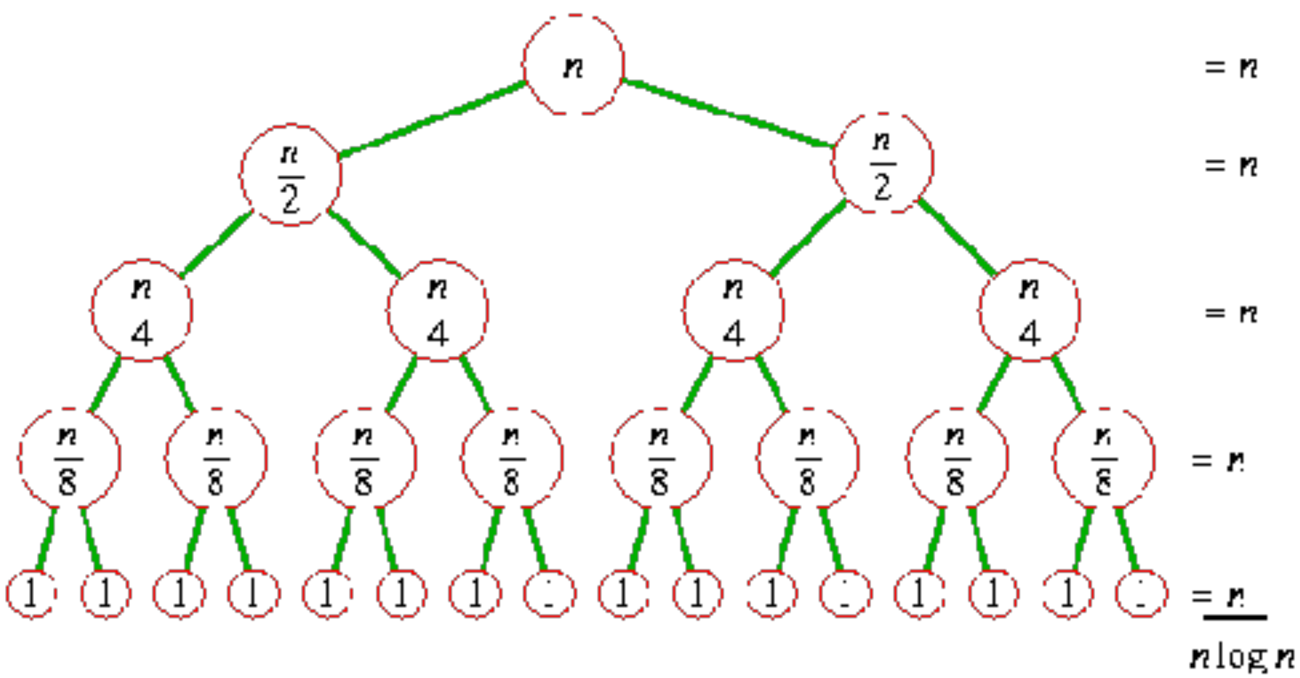
NEW IDEAS IN DARK MATTER DIRECT DETECTION

Kathryn M. Zurek

OUTLOOK

- What is the challenge for the next decade in searching for dark matter?



The universe is dominated by invisibles!

WIMP or (axion)

How to be ready for anything? Hidden Sectors

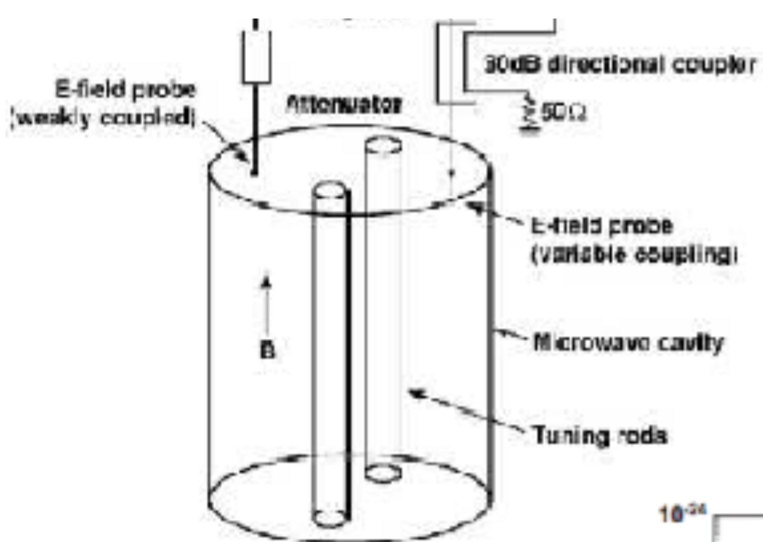
How do I search for these things?

- Paradigm shift. Developing new search strategies to search for new candidates

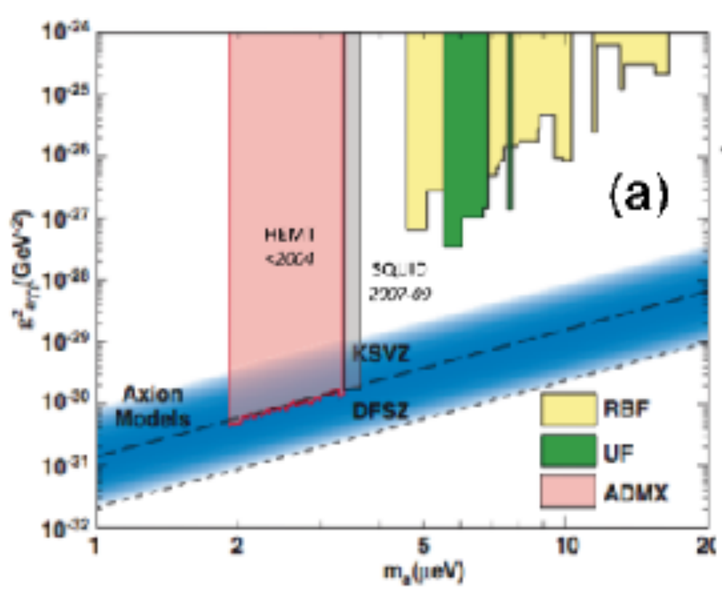
THEORY AND EXPERIMENT INTERPLAY

- When Searching for Dark Matter it helps to know what you’re looking for

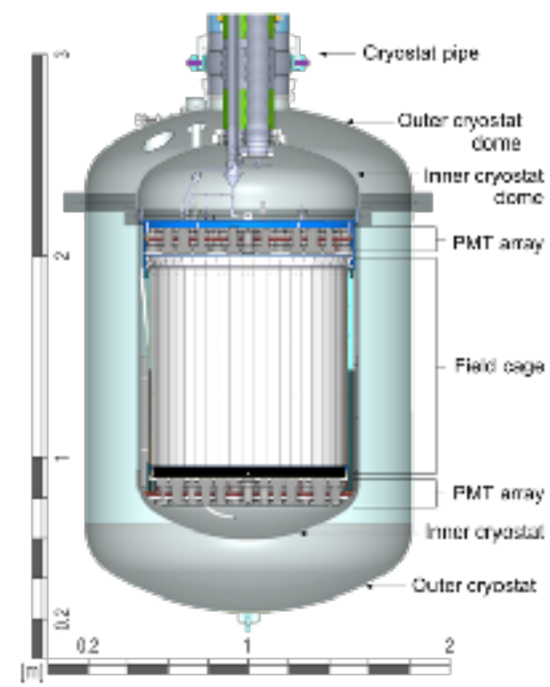
axions



ADMX

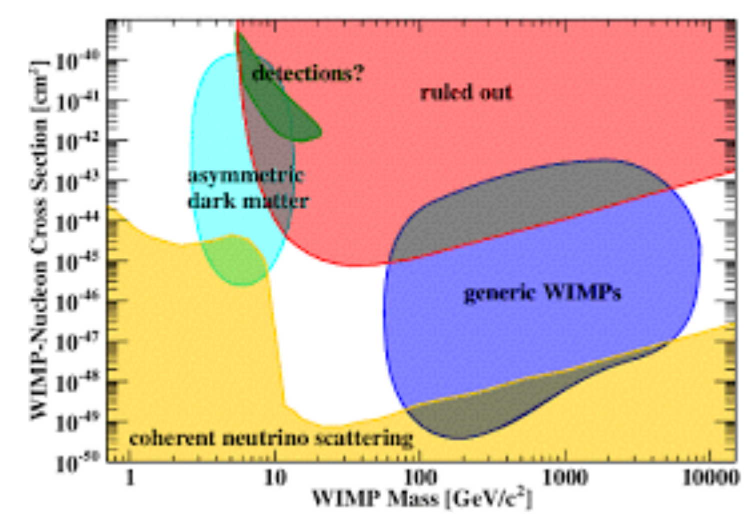


WIMPs



XENON

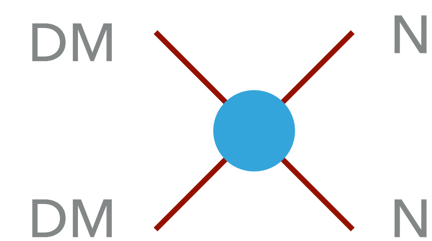
APS Physics Today



Both scenarios are fairly predictive in both mass and interaction probability with SM

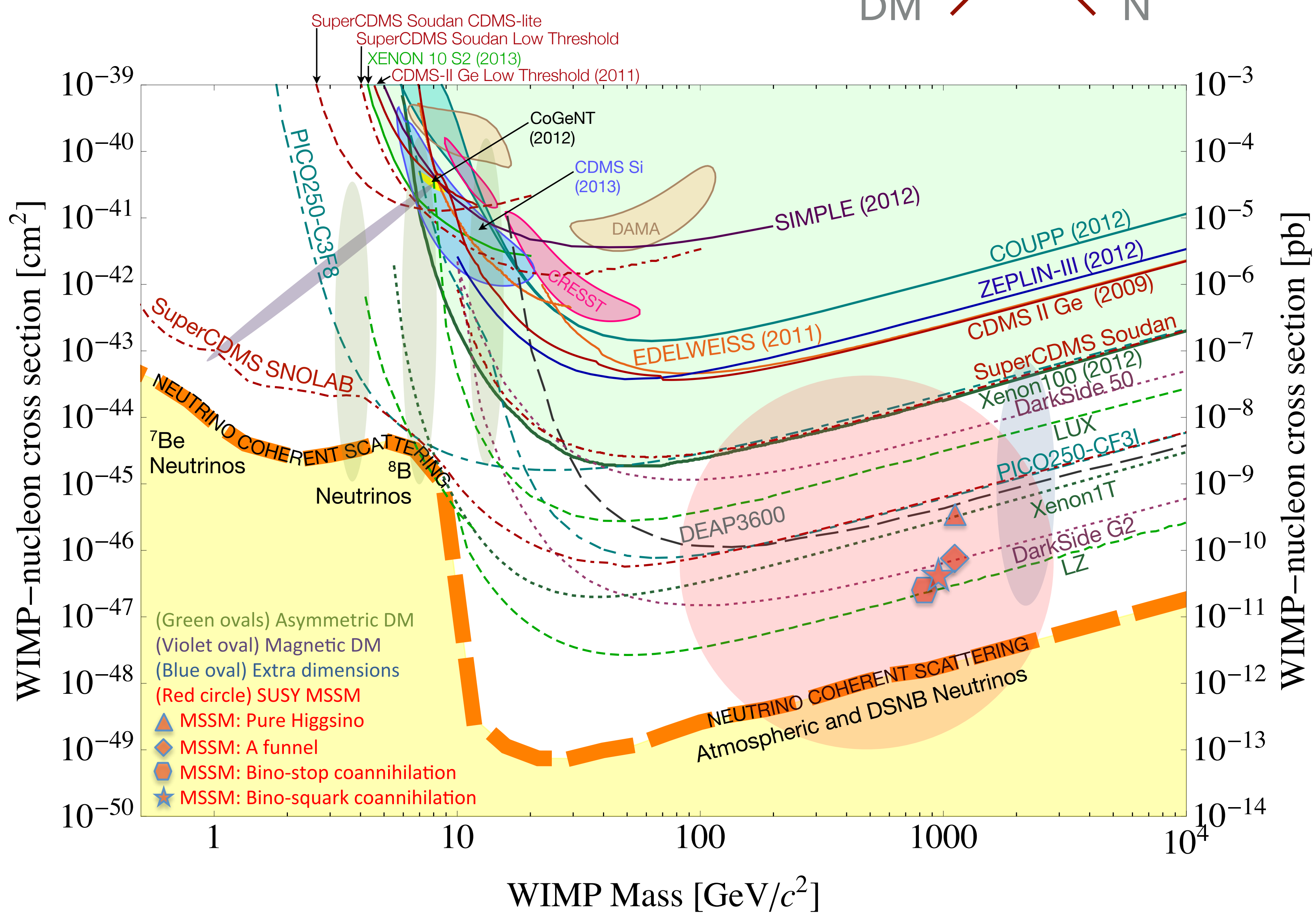
THEORY AND EXPERIMENT INTERPLAY

- Except when that means that we stop looking …. elsewhere



Z-boson interacting dark matter: ruled out

Higgs interacting dark matter: active target



THEORY AND EXPERIMENT INTERPLAY

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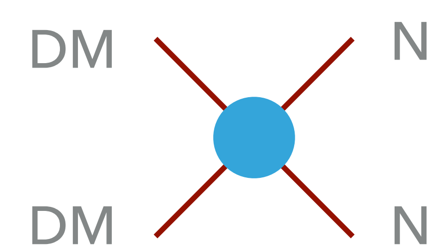

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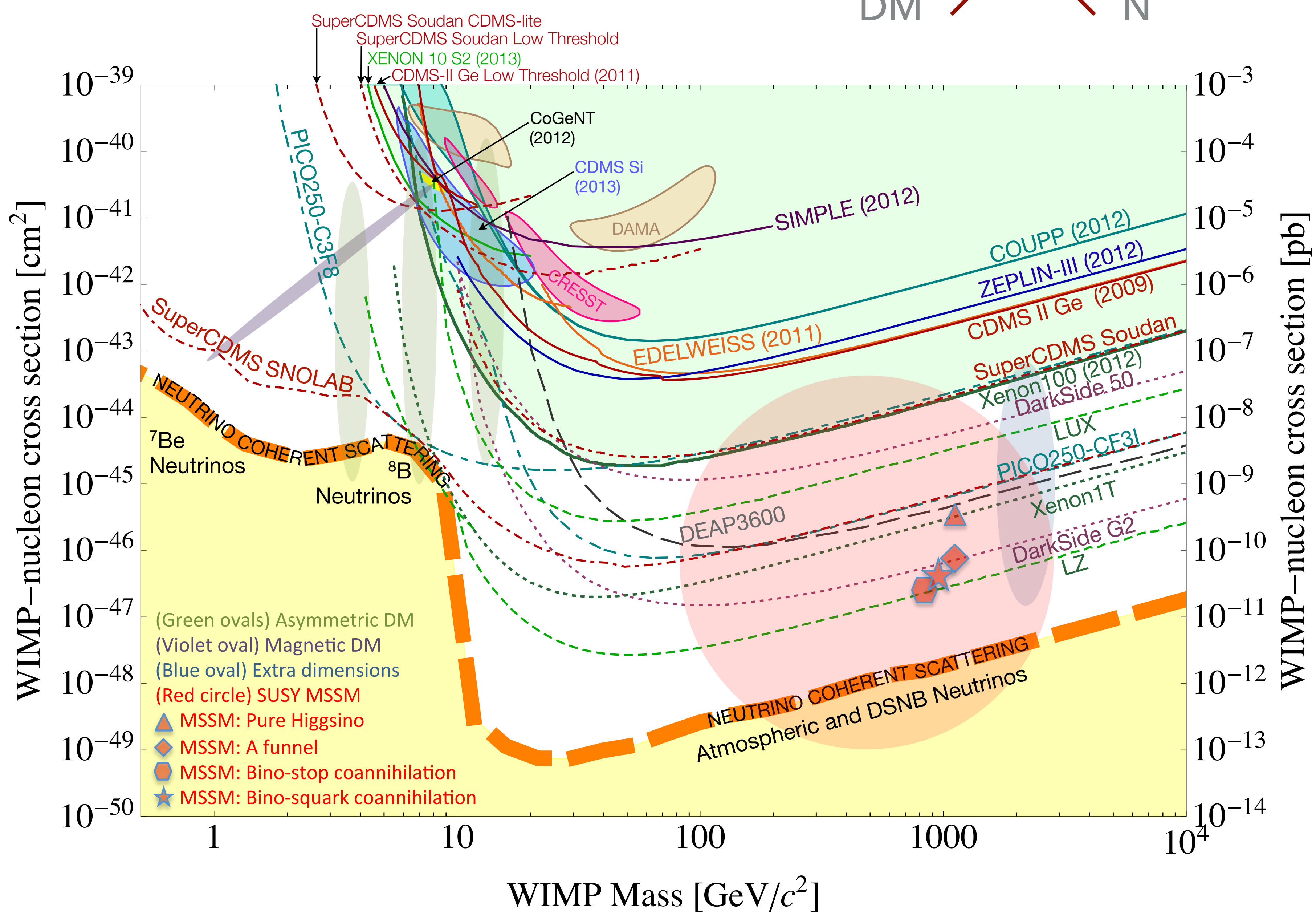
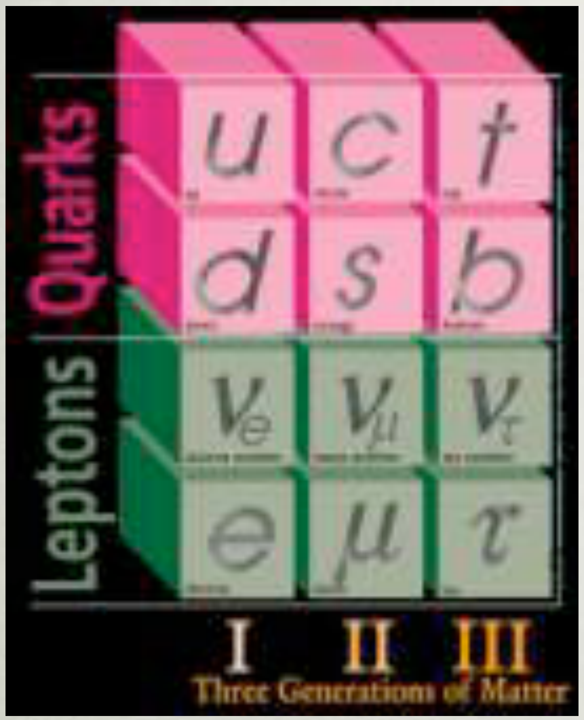


Paradigm Shift

Our thinking has shifted

Energy



From a single, stable very weakly interacting particle .....
(WIMP, axion)

Models: Light DM sectors,
Secluded WIMPs, Dark Forces, Asymmetric DM .....
Production: freeze-in, freeze-out and decay,
asymmetric abundance, non-thermal mechanisms .....

...to a hidden world or "hidden valley" with multiple states, new interactions

$M_p \sim 1$ GeV

Standard Model

Inaccessibility

PANDORA'S BOX?

- You might worry that without a theoretical lock (WIMP/ axion tyranny) we have no guidance
- Universe + terrestrial experiments provide substantial guidance

Halo Shapes
Weakly Self-interacting

Direct Probes
Weakly Interacting with Us

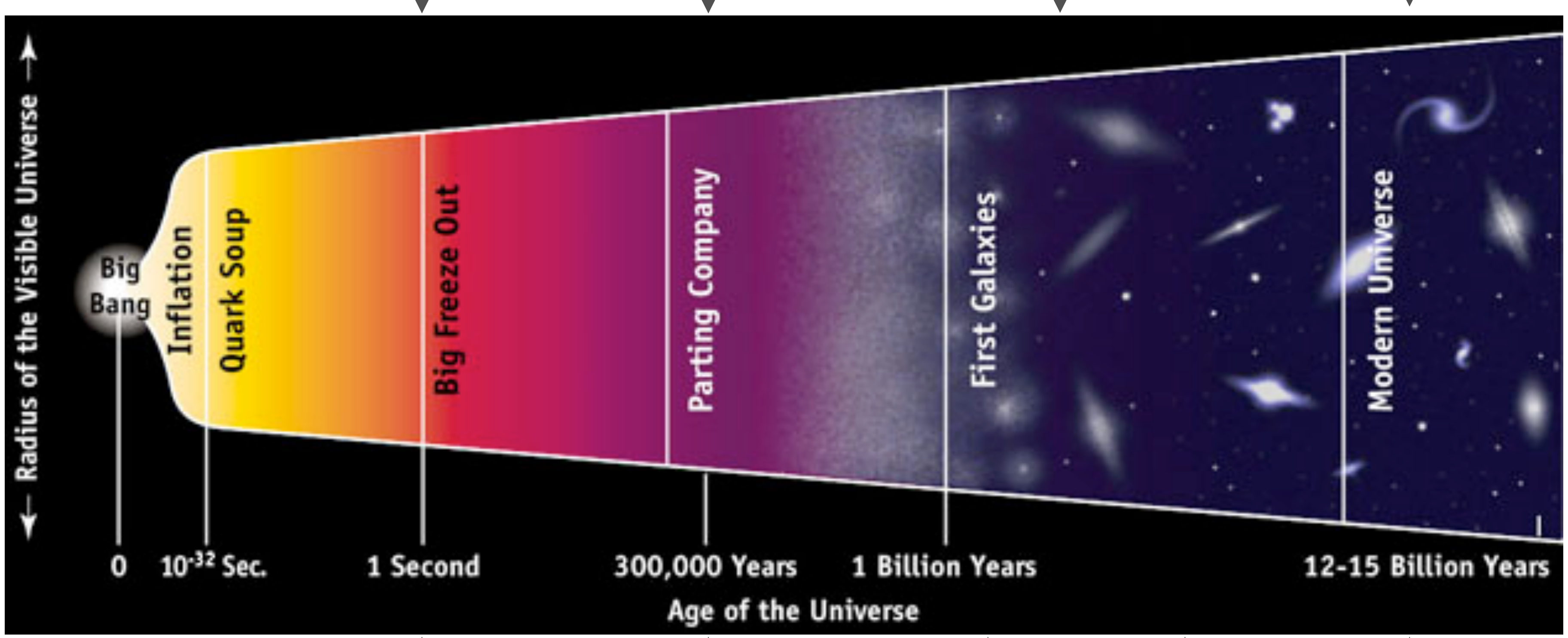
BBN
Not Free Baryons

CMB

LSS

MACHO searches + Lya
Not Bound Baryons

LSS+Bullet Cluster
Not Modified Gravity



BBN
(baryons)

CMB
(curvature)

Supernovae
(DE)

LSS
(matter)

Galaxy curves
(matter)

PANDORA'S BOX?

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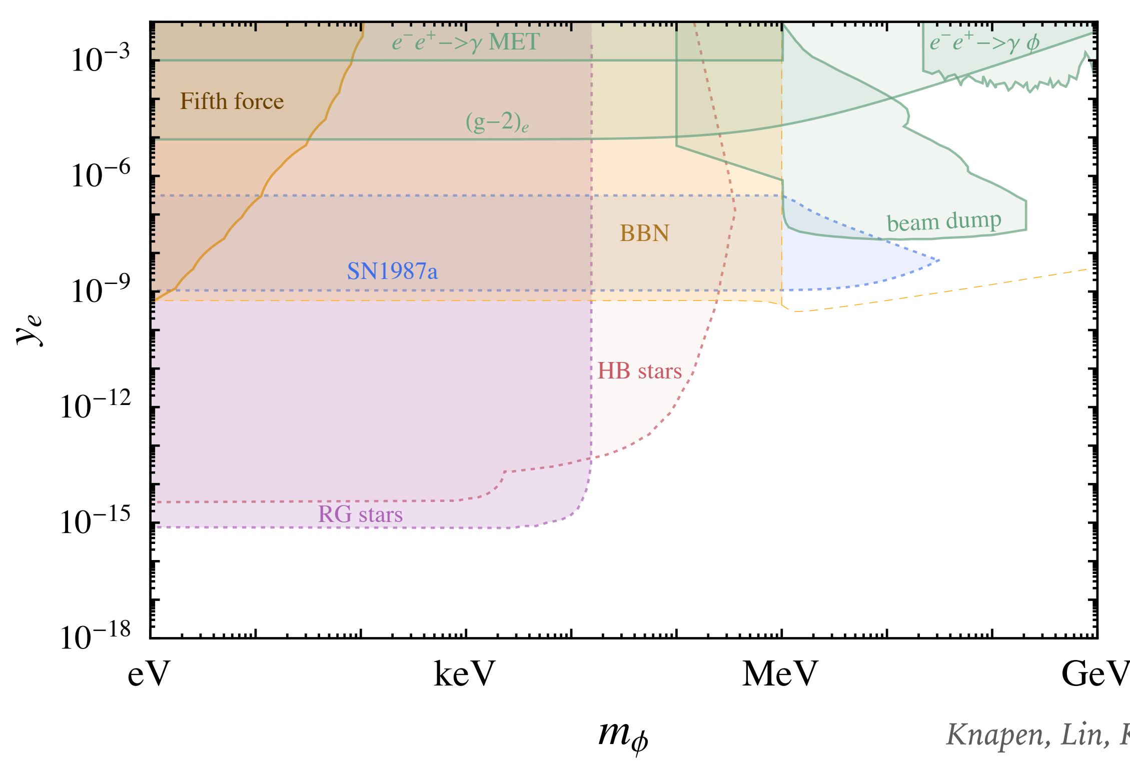
- Universe + terrestrial experiments provide substantial guidance



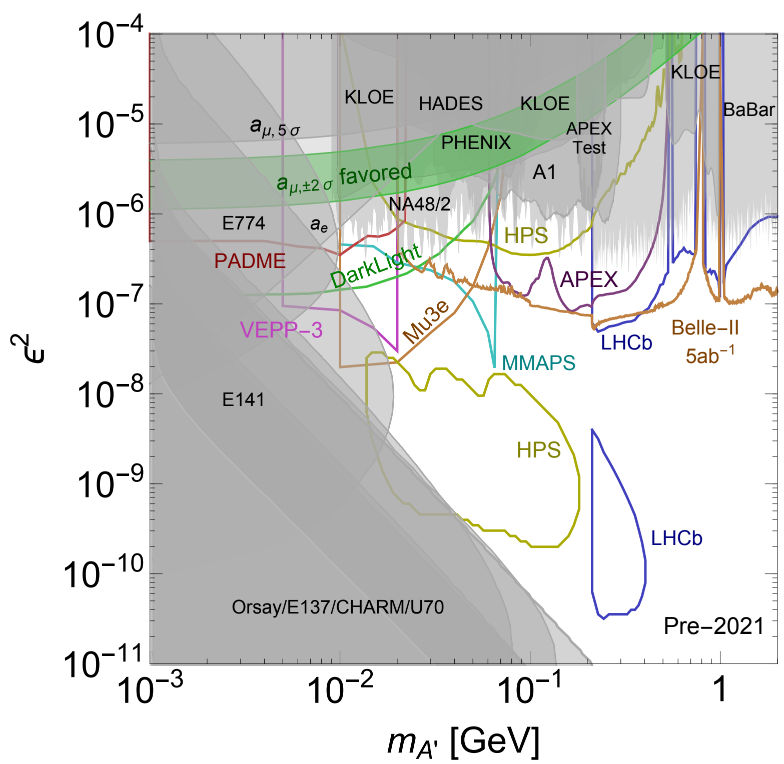
Knapen, Lin, KZ 1709.07882

TERRESTRIAL EXPERIMENTS

- Scale of connector sector fixes terrestrial experiment

Standard Model → Connector → Dark Matter

Energy



Dark Sectors community report 1608.08632

Supersymmetric

GUT

Baryogenesis

Weak

Non-Abelian

High Energy Collider

Hidden Charged

Light

Intensity Experiment

Dark Disk

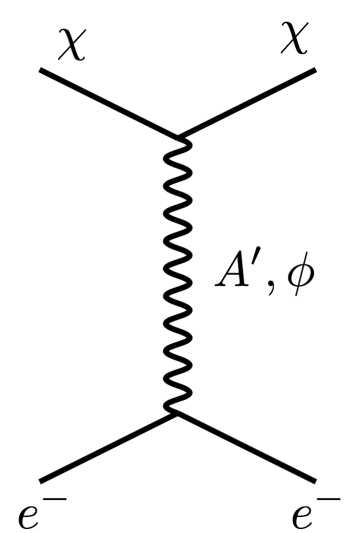
Direct Detection

Atomic

Inaccessibility

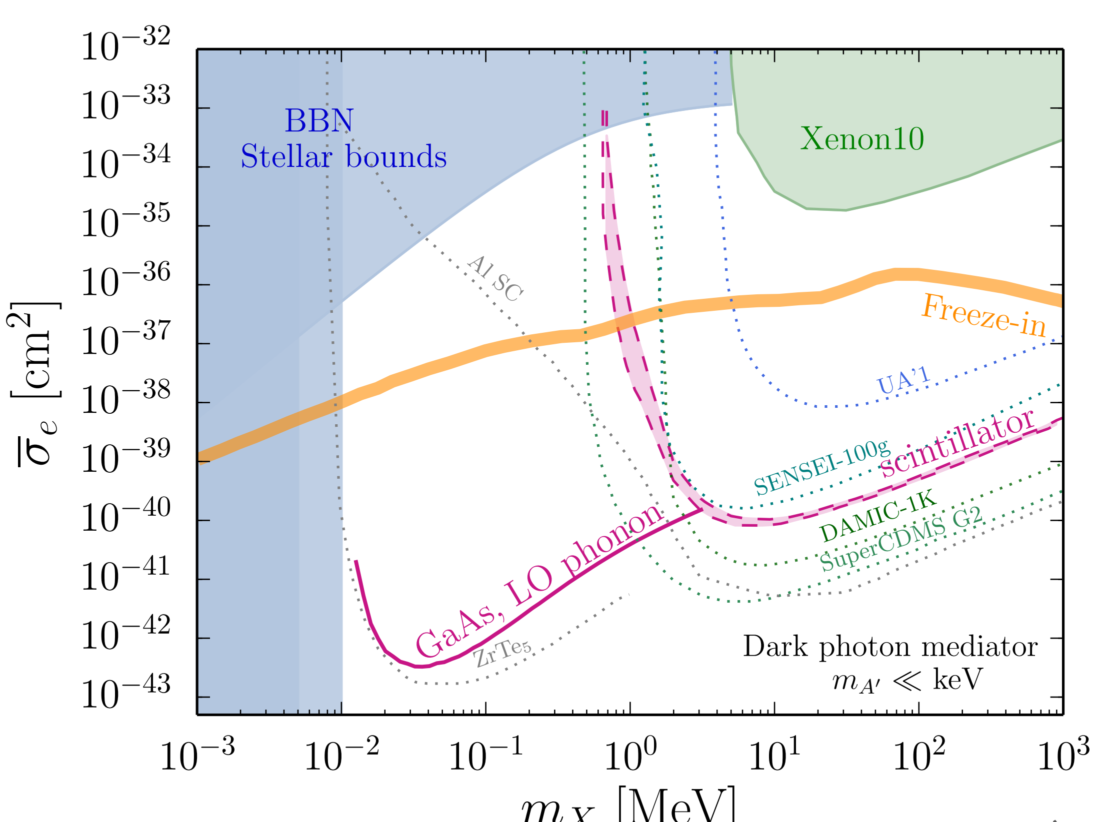
DM ABUNDANCE AS A GUIDE

- If DM abundance is related to its coupling to the SM in any way, can lead to a predictive framework

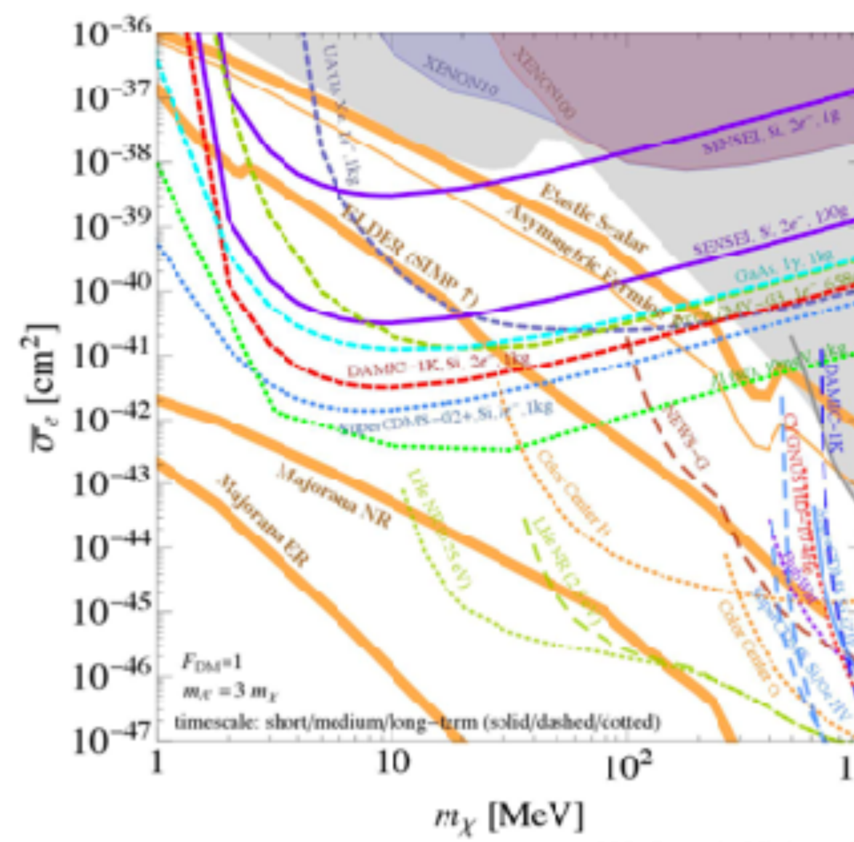


Freeze-in

Asymmetric Dark Matter



Knapen, Lin, Pyle KZ 1712.06598



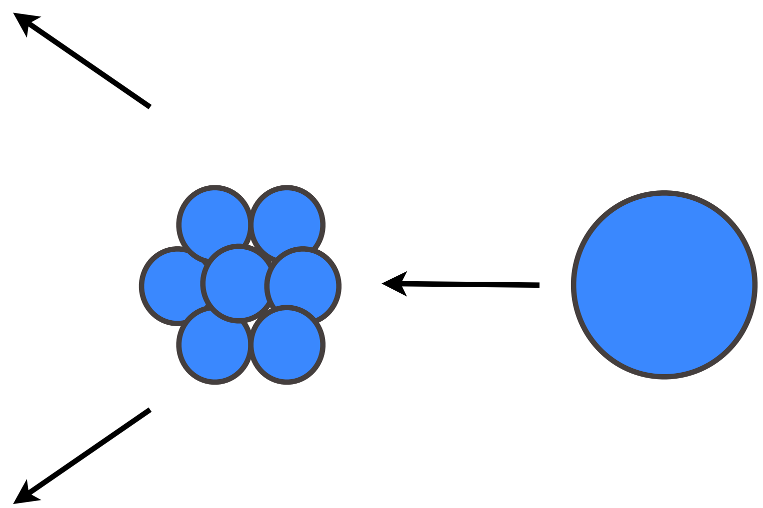
Lin, Yu, KZ 1111.0293

US Cosmic Visions 1707.04591

LIGHTER TARGETS FOR LIGHTER DARK MATTER

- Nuclear recoil experiments; basis of enormous progress in direct detection

$q, \; E_D$



$v \sim 10^{-3} c$

$$v \sim 300 \text{ km/s} \sim 10^{-3} c \quad \Longrightarrow \quad E_D \sim 100 \text{ keV}$$

$$E_D = \frac{q^2}{2m_N} \qquad\qquad q_{\rm max} = 2 m_X v$$

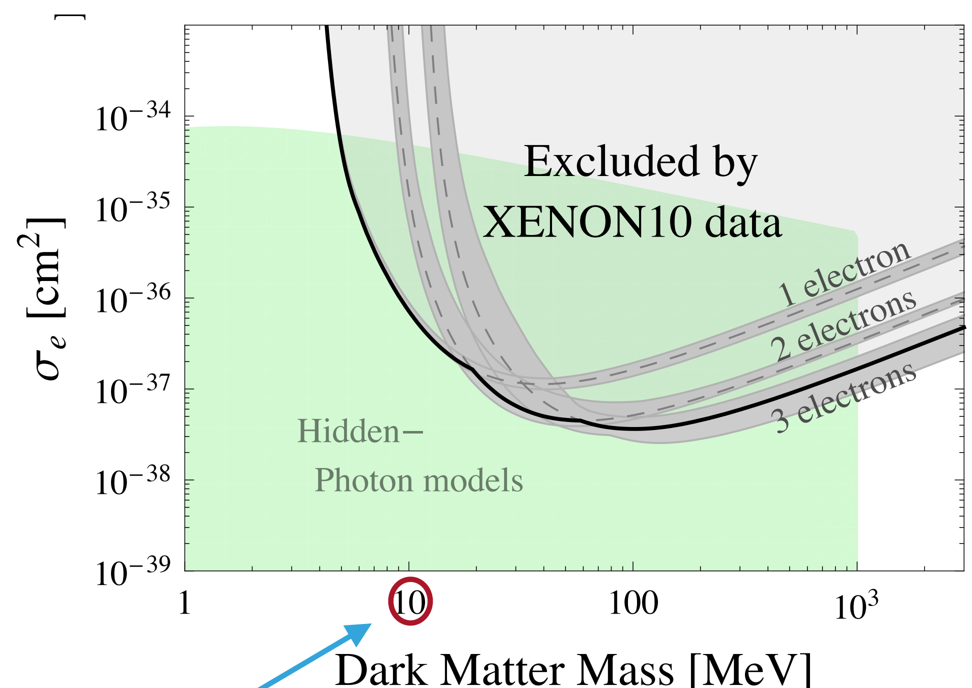
LIGHTER TARGETS FOR LIGHTER DARK MATTER

$$E_D = \frac{q^2}{2m_e} \qquad q_{\max} = 2m_X v$$

- In insulators, like xenon

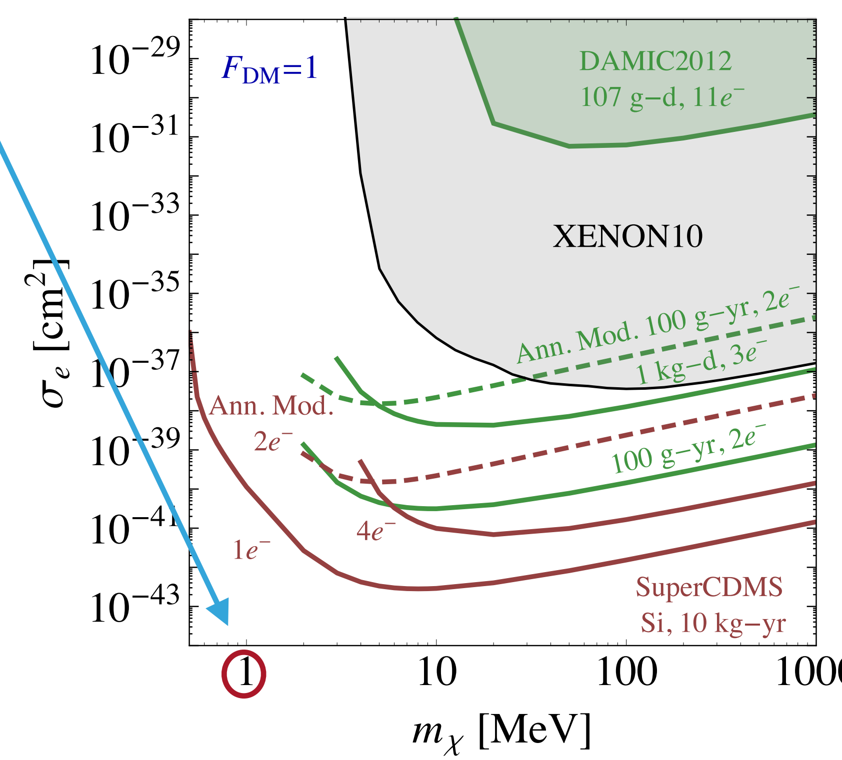
Tightly bound; ionize for signal

P. Sorensen et al 1206.2644



Gap = DM Kinetic Energy

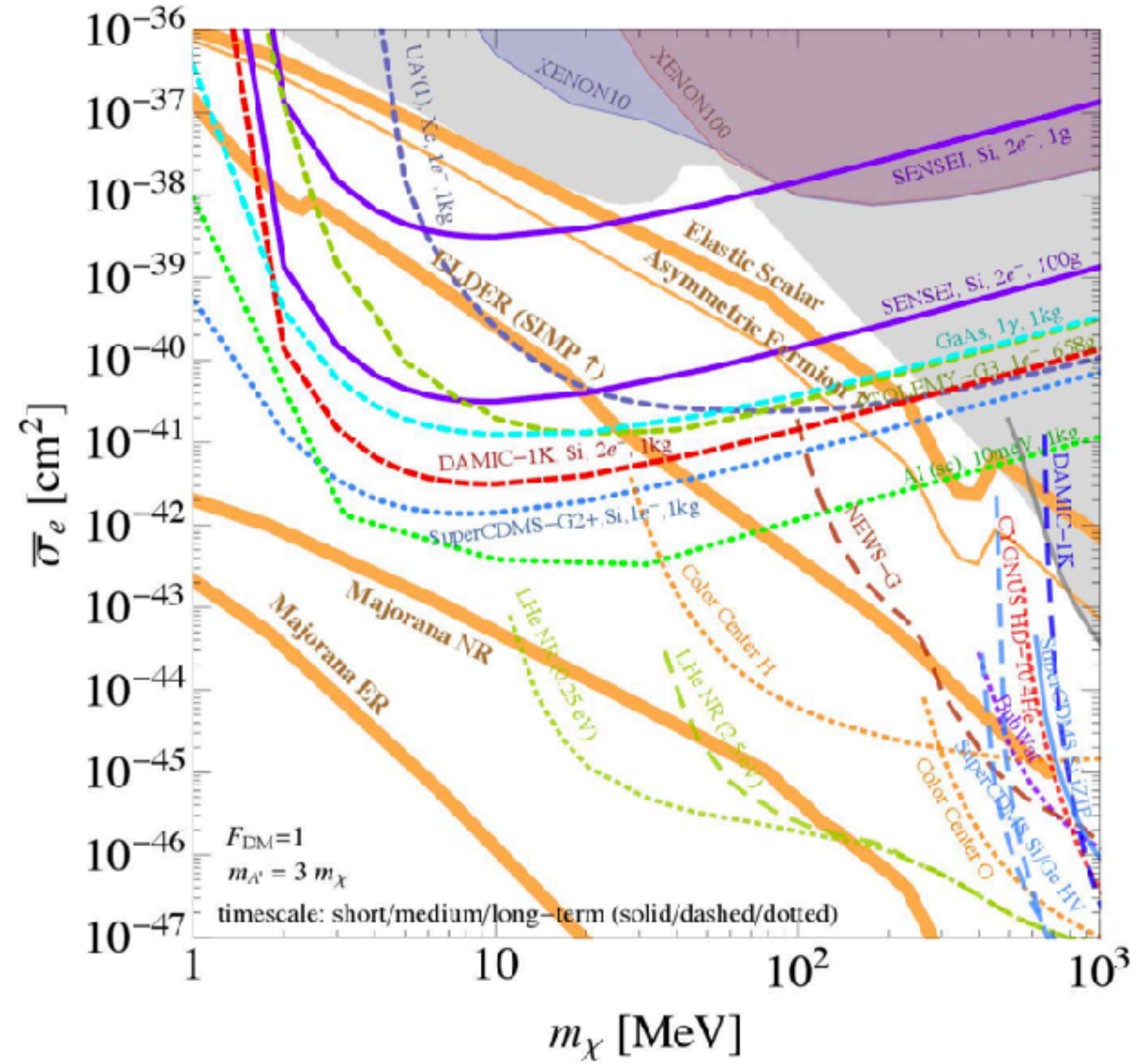
Essig et al 1509.01598



- In semi-conductors, like Ge, Si

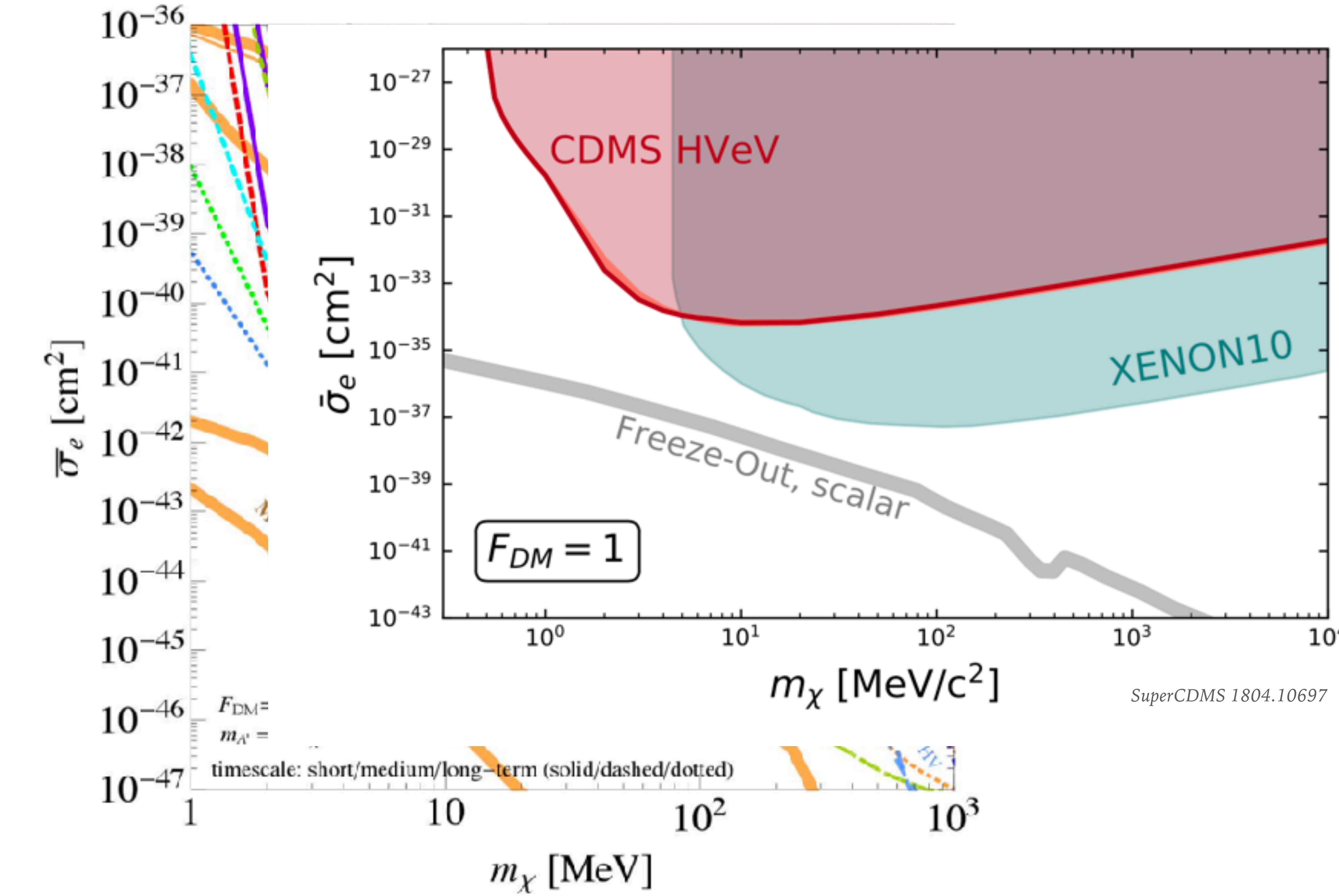
Excite electron to conduction band

CURRENT STATUS: MEV AND HEAVIER



US Cosmic Visions 1707.04591

CURRENT STATUS: MEV AND HEAVIER

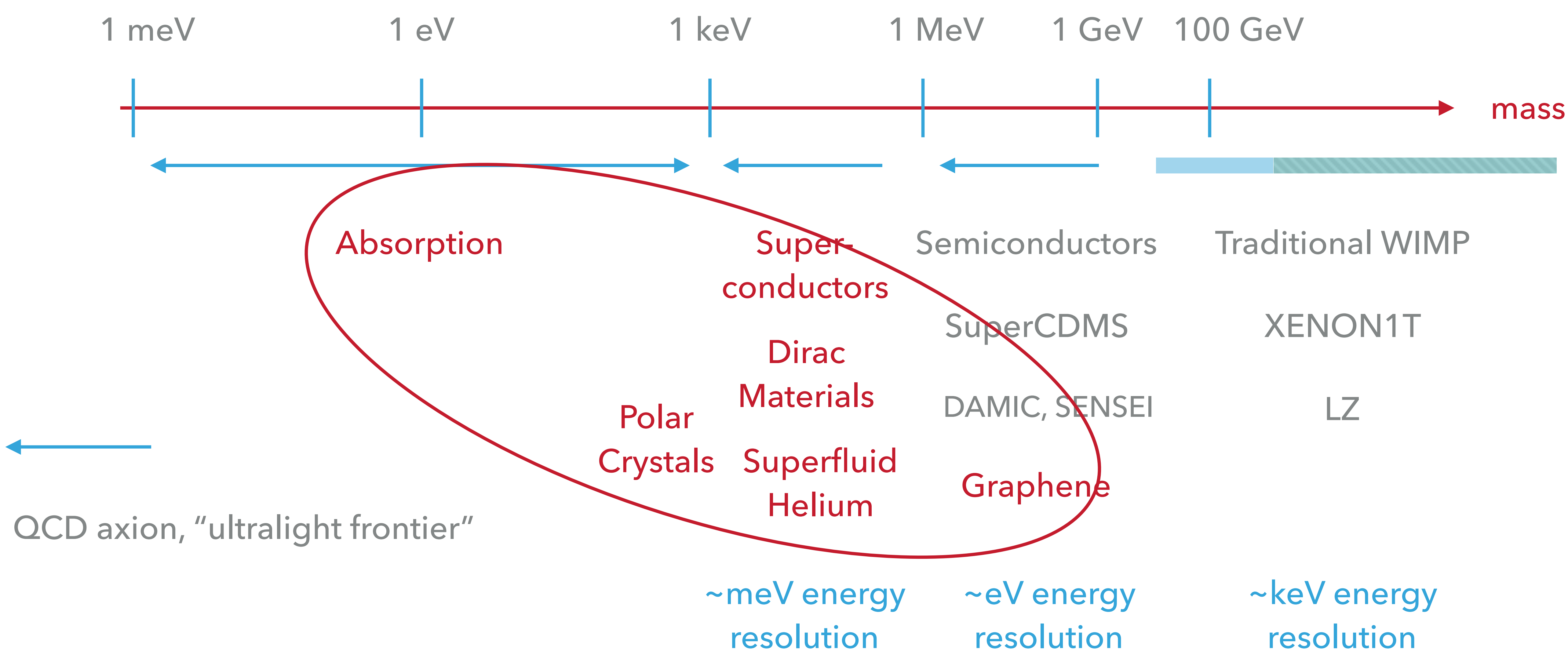


SuperCDMS 1804.10697

US Cosmic Visions 1707.04591

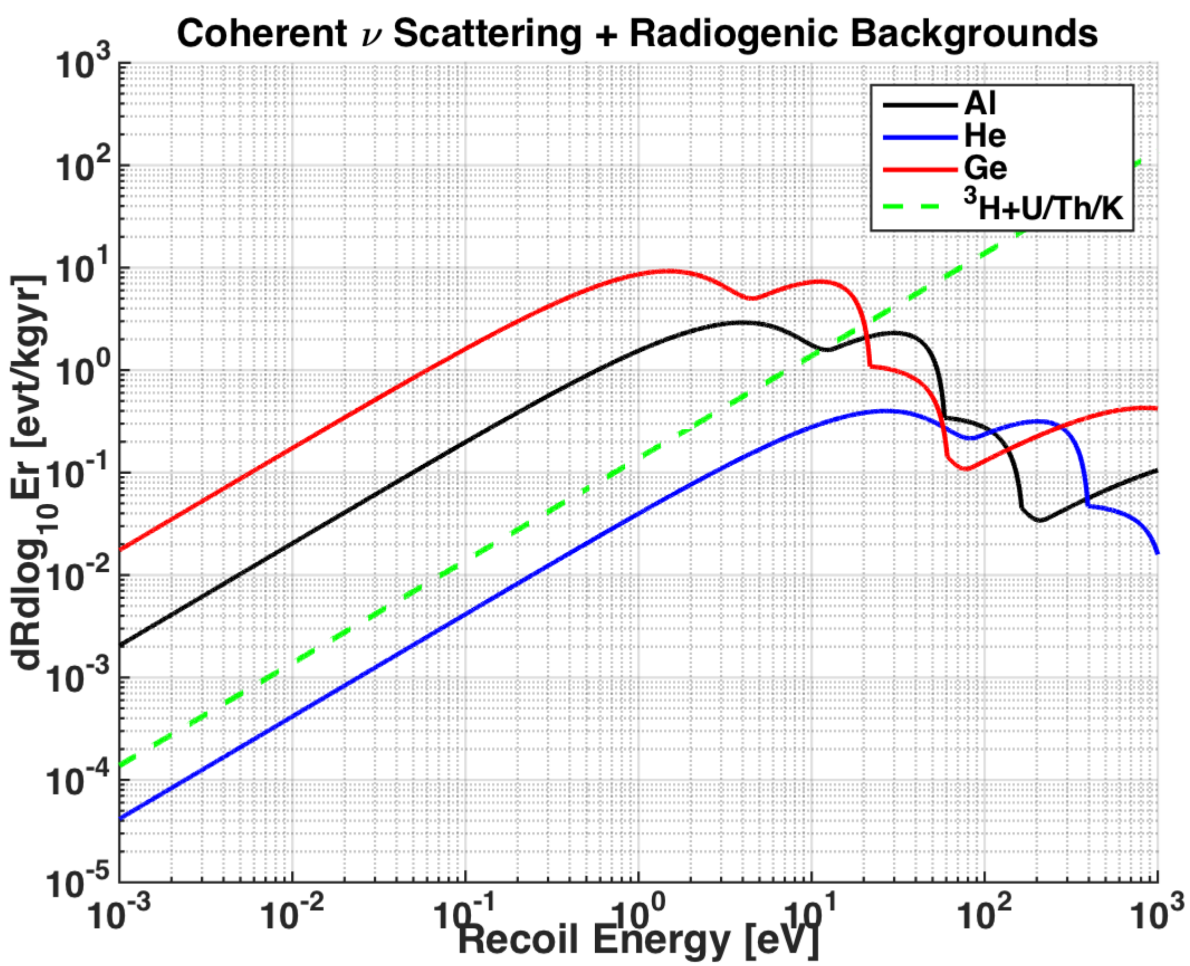
LOOKING BEYOND BILLIARD BALLS

- Experimental Panorama

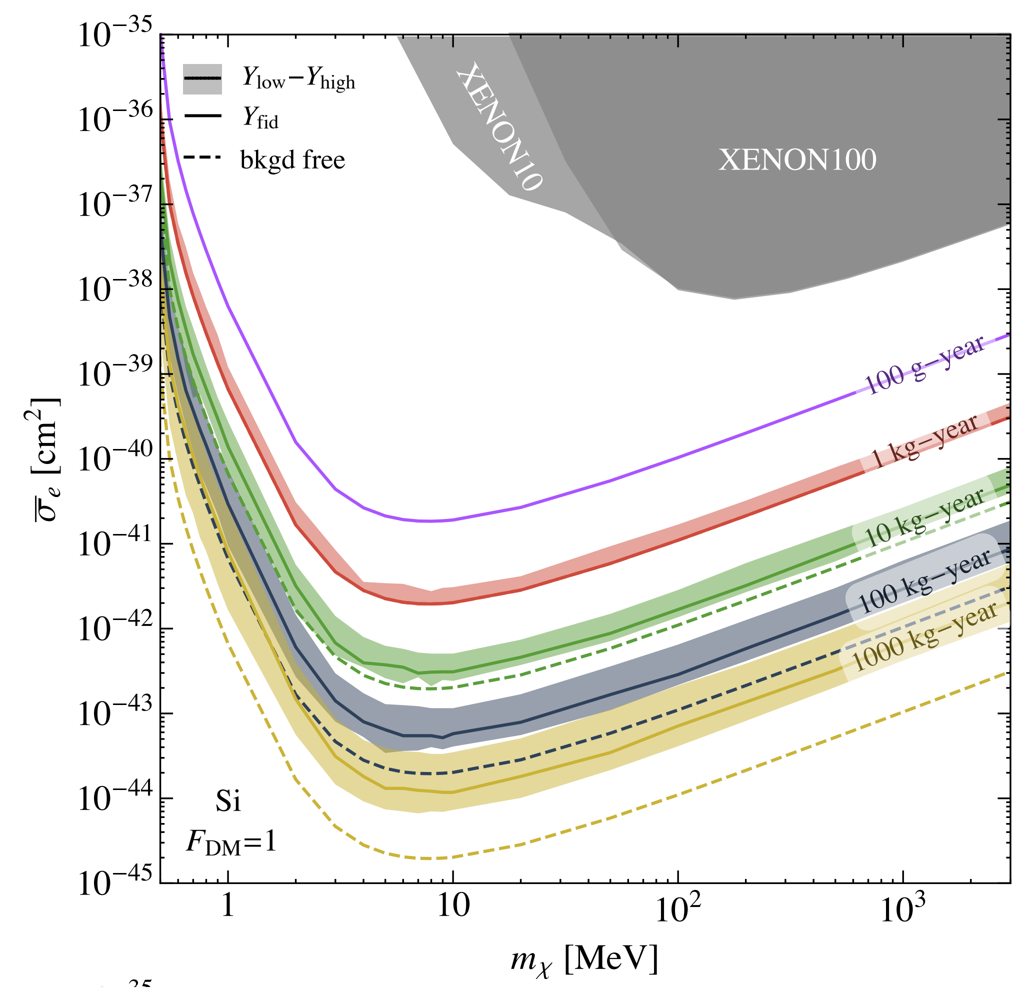


NEUTRINO DETECTION

- Good energy resolution detectors also make good solar neutrino detectors



Hochberg, Pyle, Zhao, KZ 1512.04533



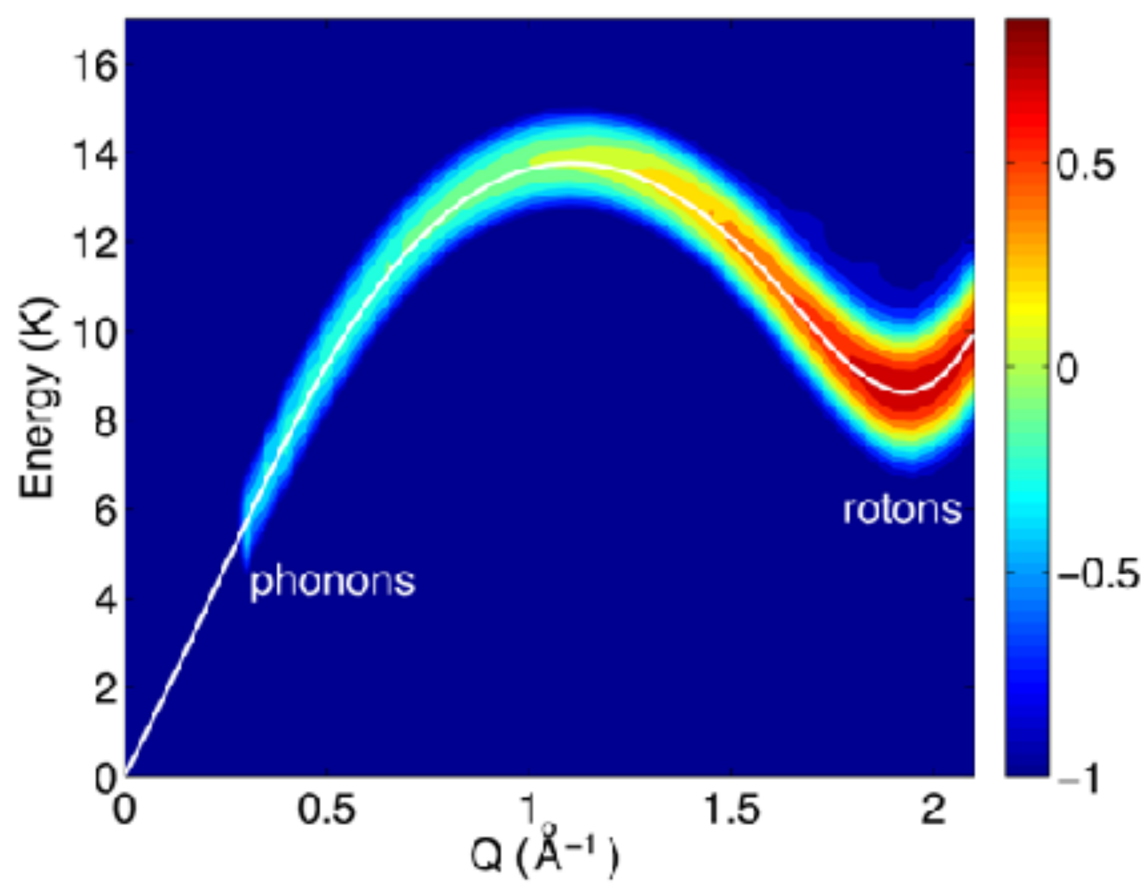
Essig, Sholapurkar, Yu 1801.10159

COUPLING TO COHERENT MODES

- Once DM drops below an MeV, its deBroglie wavelength is longer than the inter particle spacing in typical materials
- Therefore, coupling to coherent excitations in materials makes sense!
- Coherent excitations = phonon modes
- Applied to superfluid helium, semiconductors, superconductors, polar materials
- Details depend on nature of coherent modes in target material

PHONONS IN MATERIALS

- Properties of materials are characterized by
  - a) their dispersion
  - b) “Dynamic structure factor” — the amplitude of the response at a given momentum transfer and energy deposition



HELIUM

Schutz, KZ 1604.08206, Knapen, Lin, KZ 1611.06228

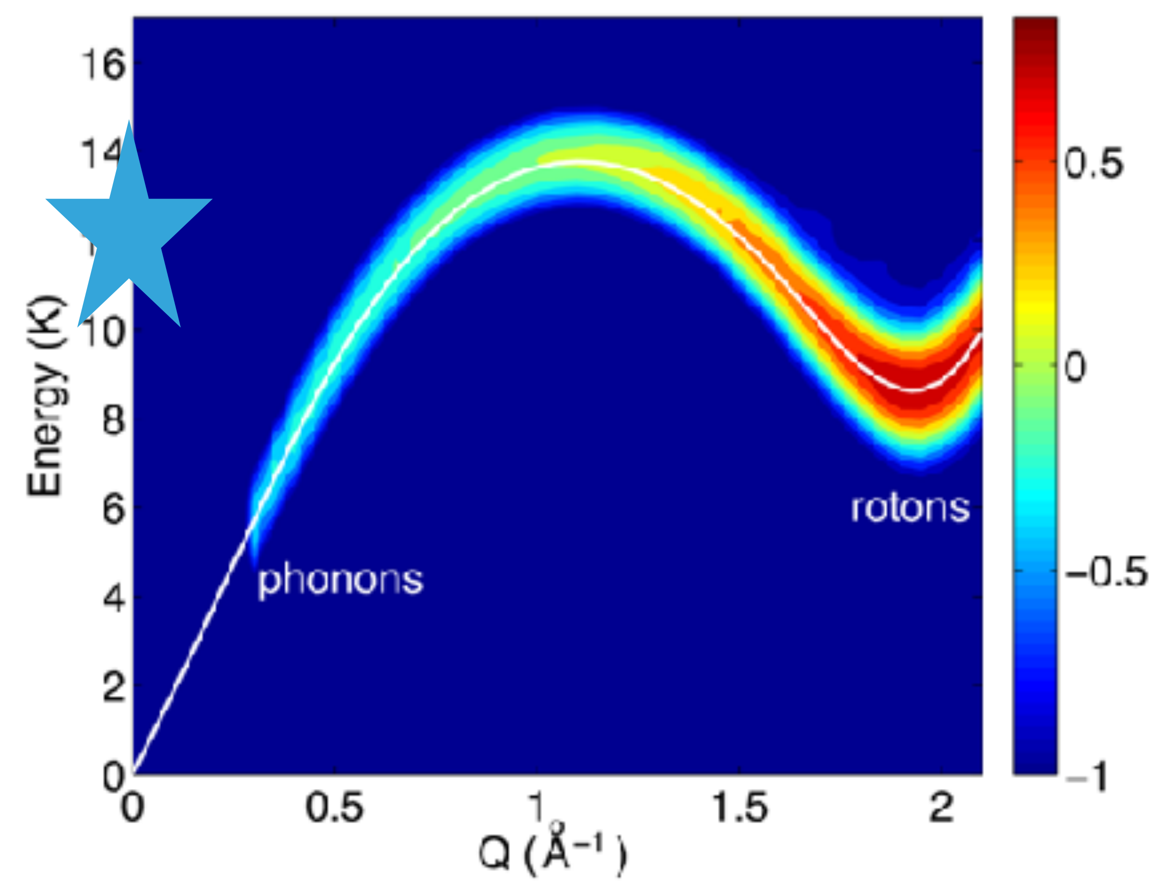
- Superfluid helium is an optically weak material already considered for nuclear recoils. McKinsey group, UC Berkeley.
- To detect lighter DM, couple to phonon modes.
- Viable? At first glance — no

$$E_D \sim v_X q$$

vs

$$c_s \ll v_X$$

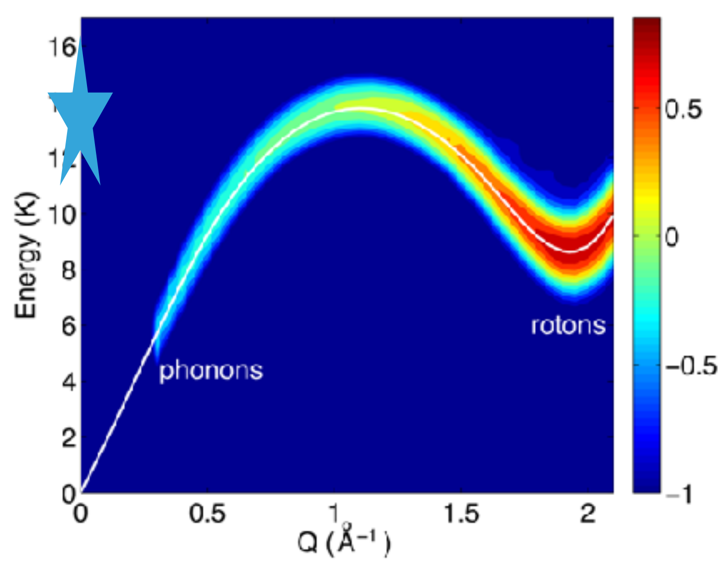
$$E_D \sim c_s q$$

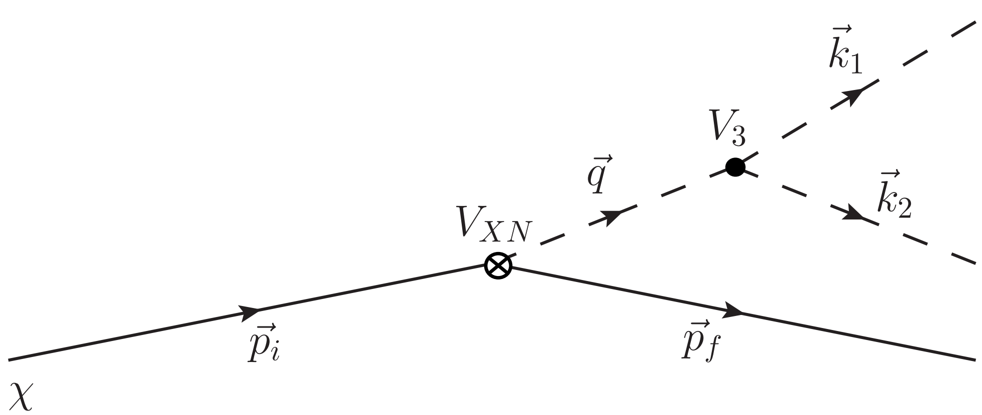


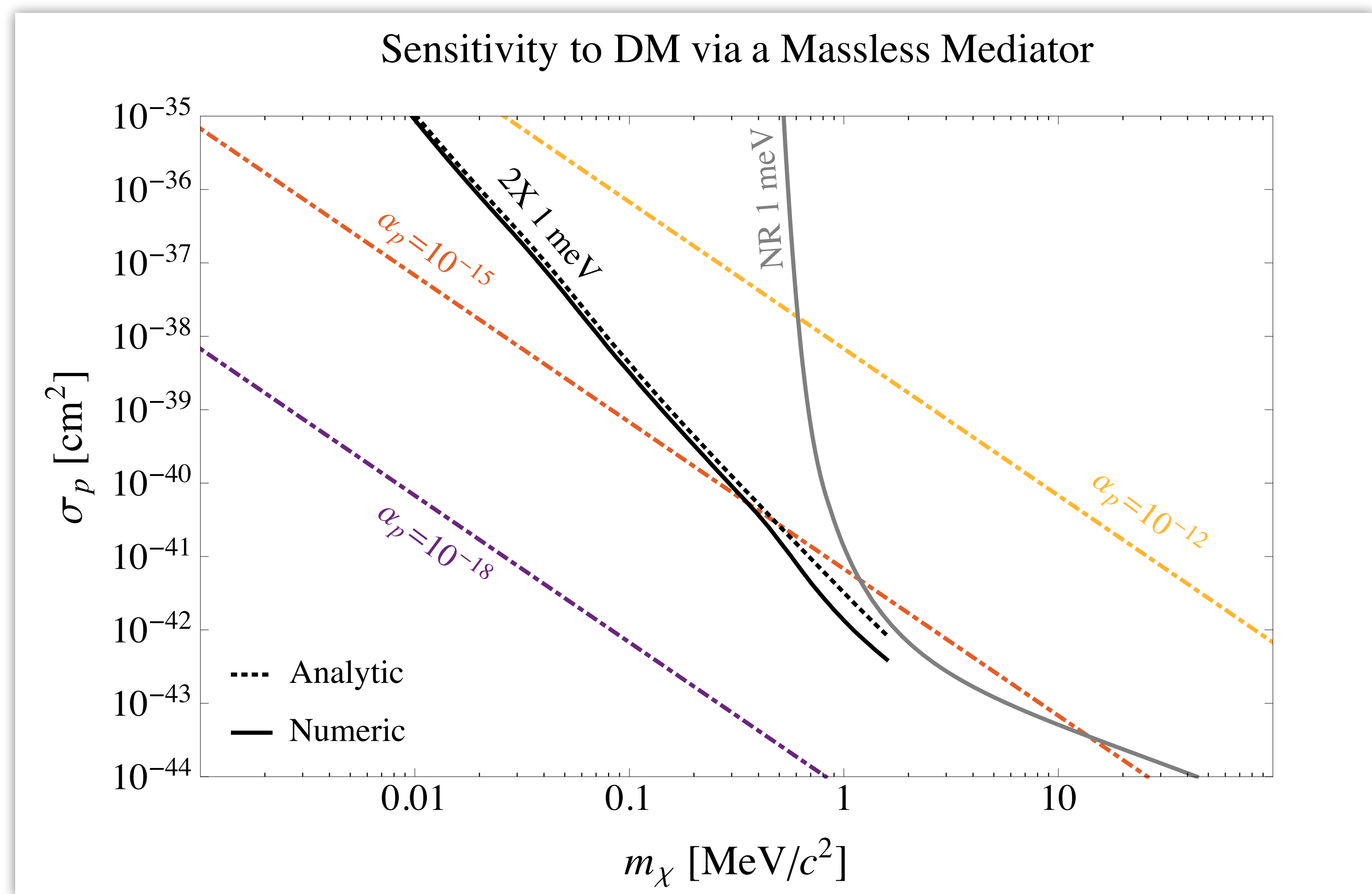
- Next glance -- yes!

SUPERFLUID HELIUM

Schutz, KZ 1604.08206, Knapen, Lin, KZ 1611.06228







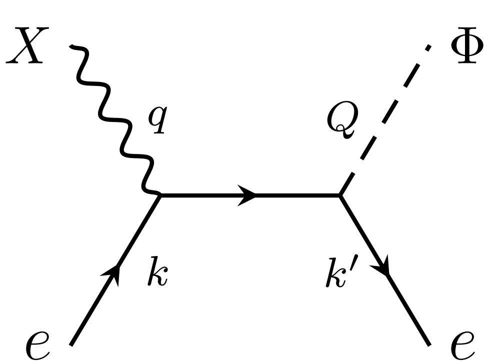
Multiple Acoustic Phonon

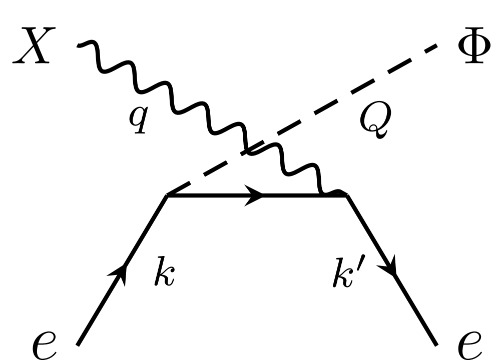
SEMI- AND SUPER-CONDUCTORS

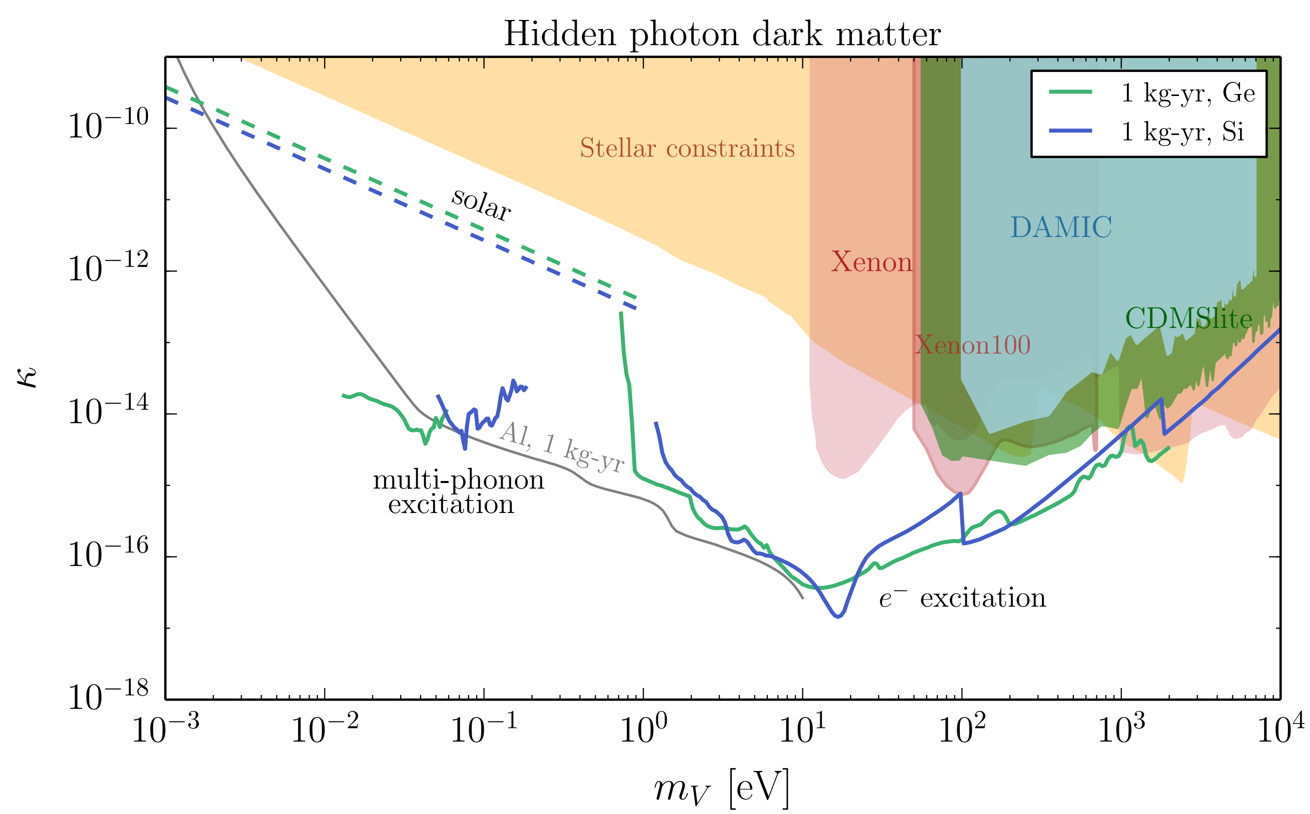
Hochberg, Lin, KZ 1604.06800, 1608.01994

- Absorption of axions and dark photons

$$\langle n_e \sigma_{\rm abs} v_{\rm rel} \rangle_\gamma = -\frac{\mathrm{Im}\,\Pi(\omega)}{\omega}$$







SEMI- AND SUPER-CONDUCTORS

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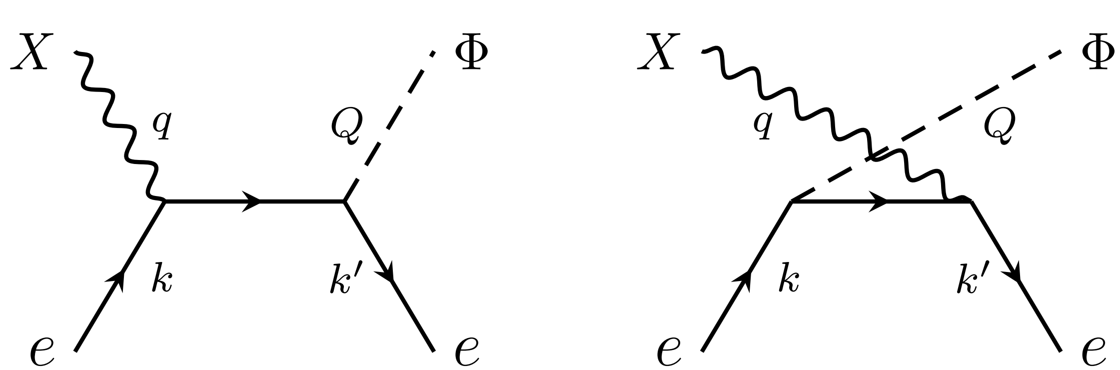
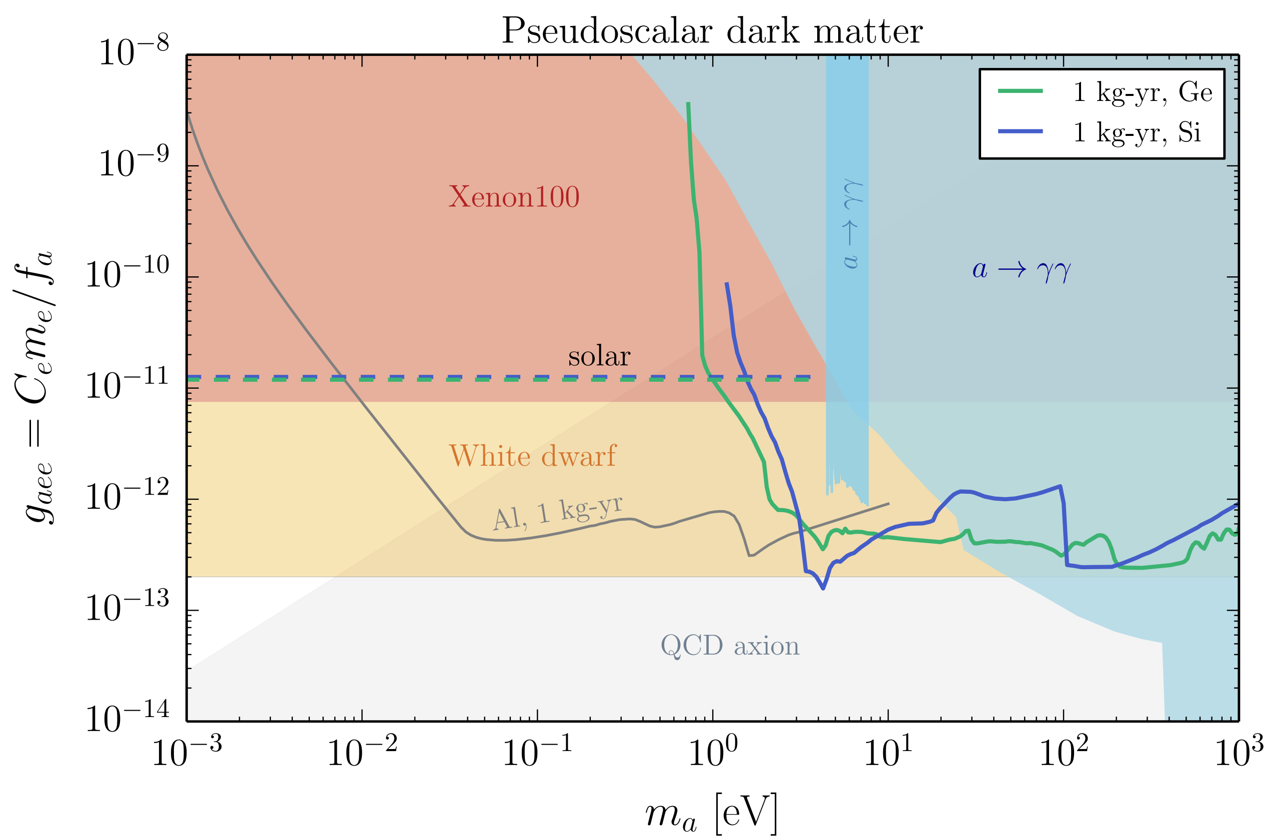
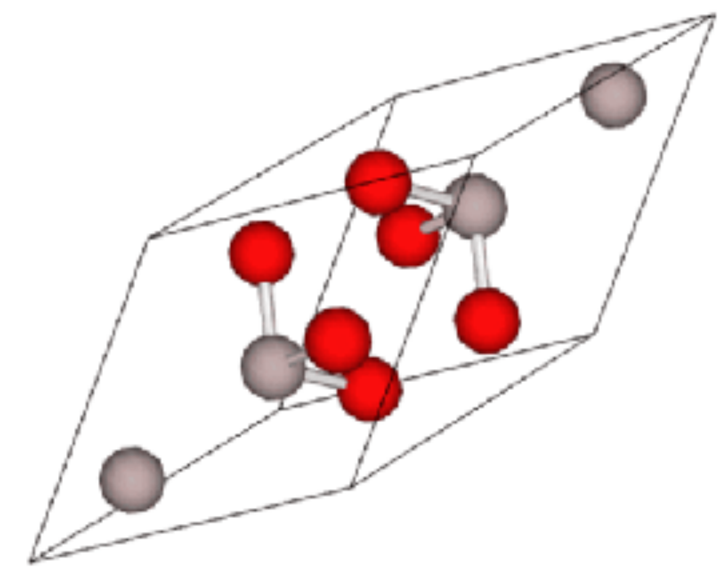


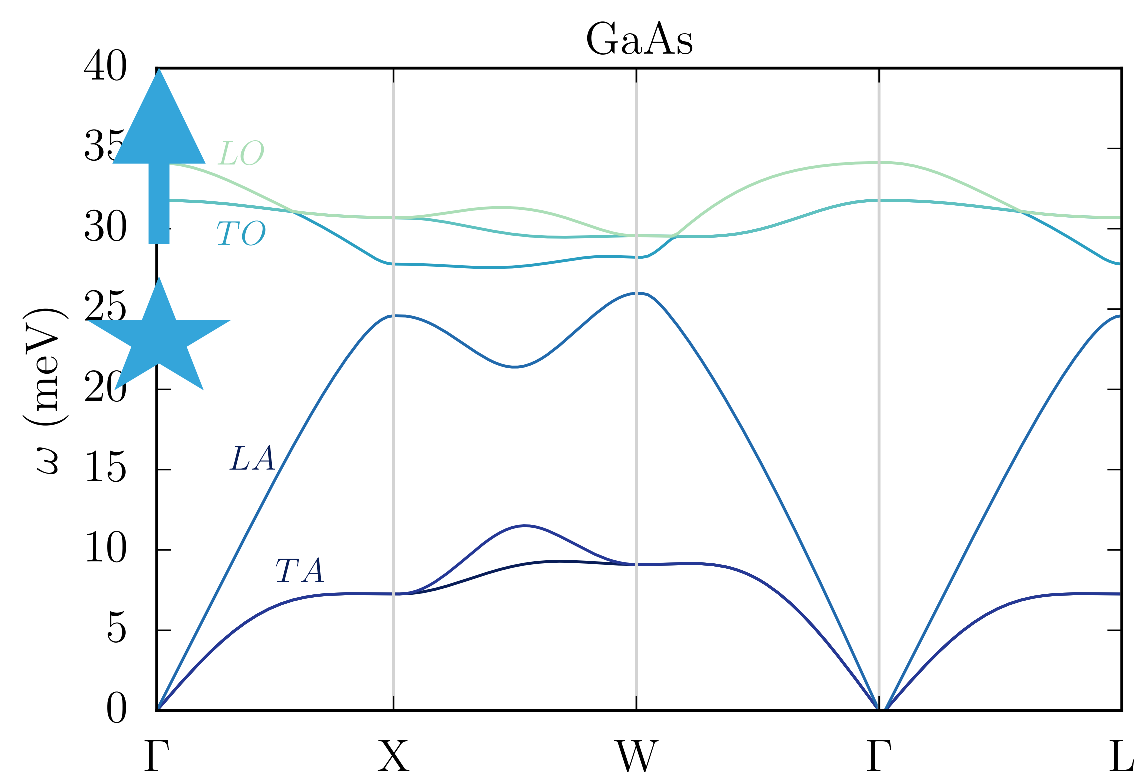


POLAR MATERIALS

Knapen, Lin, Pyle, KZ, 1712.06598 Griffin, Knapen, Lin, Pyle, KZ, 1807.10291

- Optical phonons — what are they?
- Optical phonons arise in materials with more than one type of atom
- Atoms oscillate in anti-phase
- Out of phase oscillations give rise to an oscillating dipole moment; dipole moment couples strongly to photon

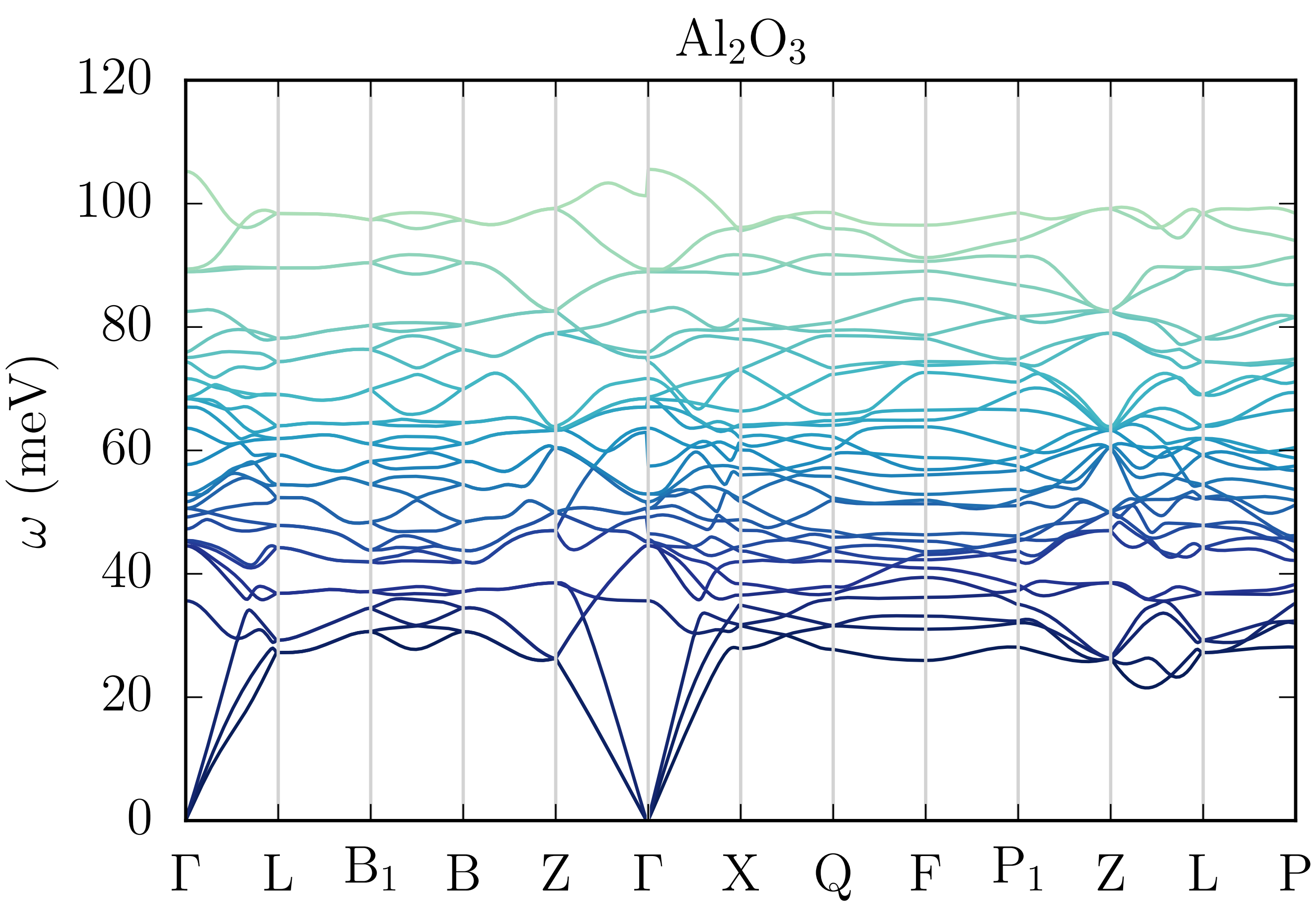


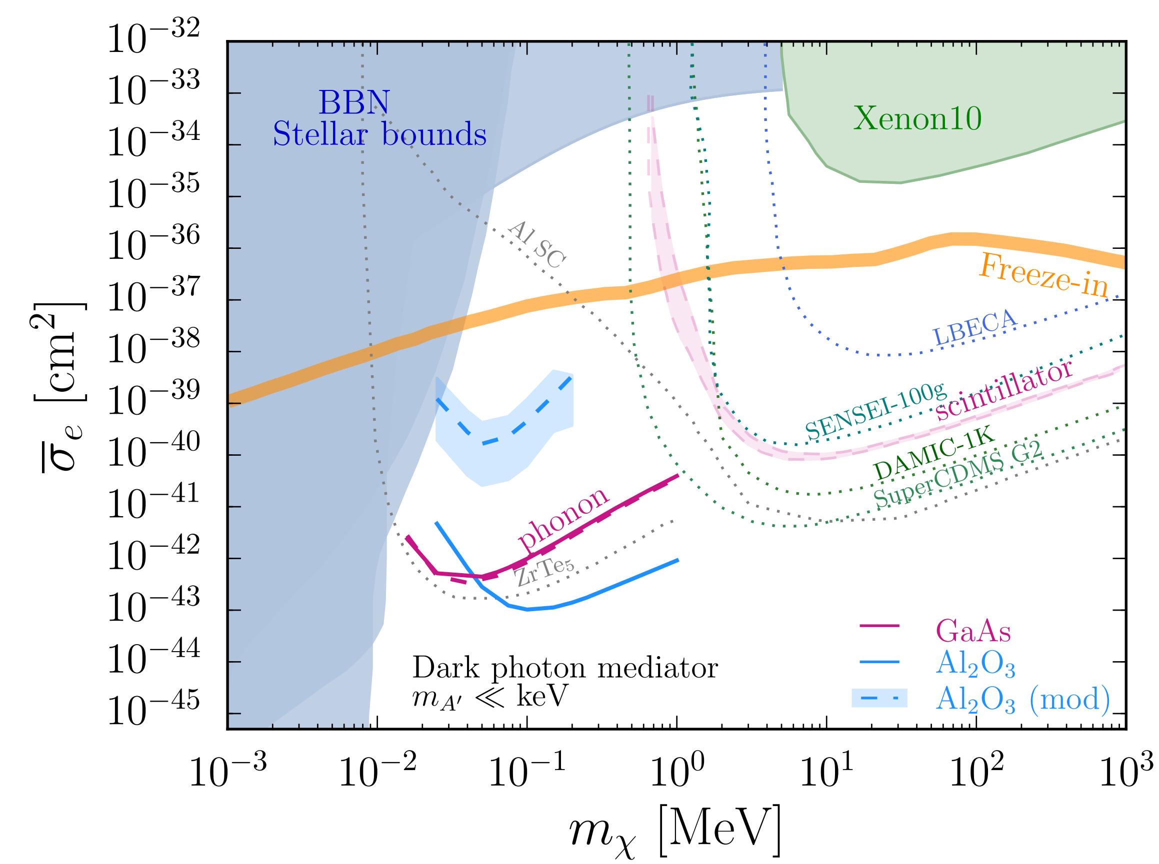


POLAR MATERIALS

Knapen, Lin, Pyle, KZ, 1712.06598 Griffin, Knapen, Lin, Pyle, KZ, 1807.10291

Single Optical Phonon, Single Acoustic Phonon

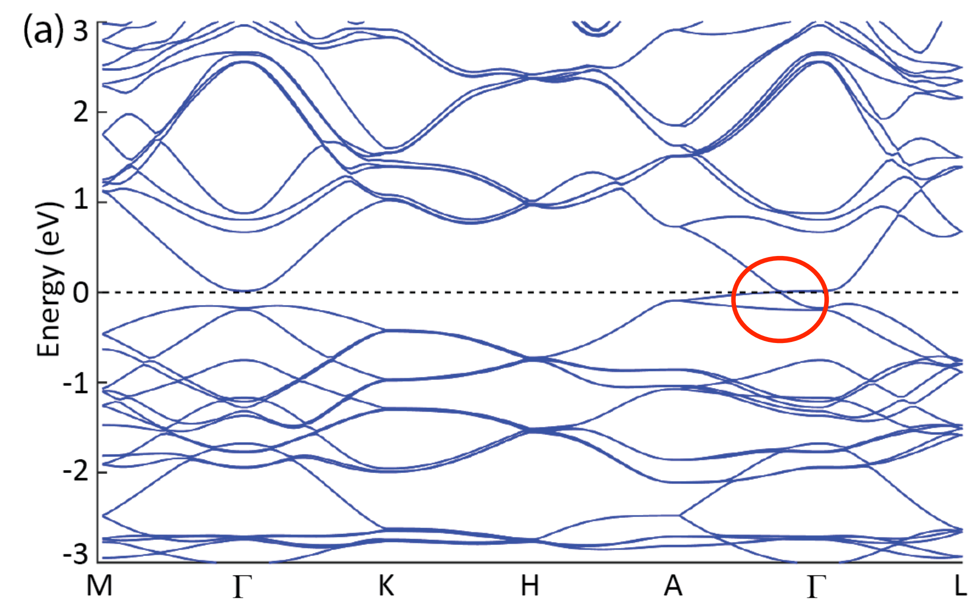




DIRAC MATERIALS

1708.08929

- Exotic electronic structure allows one to do other cool things
- Materials can be "quantum engineered"
- Correlation between electrons gives rise to a unique band structure
- Hamiltoanian looks like free QED near Dirac point



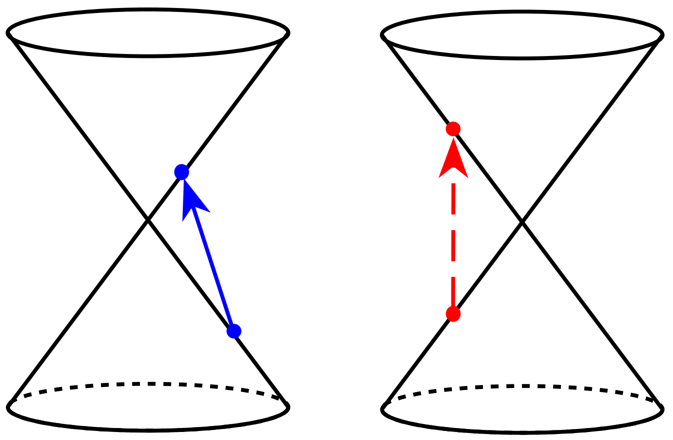
Yonit Hochberg,[1,2,*] Yonatan Kahn,[3,†] Mariangela Lisanti,[3,‡] Kathryn M. Zurek,[4,5,§] Adolfo Grushin,[6,7,¶] Roni Ilan,[8,**] Zhenfei Liu,[9] Sinead Griffin,[9] Sophie Weber,[9] and Jeffrey Neaton[9]

DIRAC MATERIALS

1708.08929

- In QED, gauge invariance protects photon from obtaining a mass

$$H_{\boldsymbol{\ell}} = \begin{pmatrix} 0 & v_F \boldsymbol{\ell}\cdot\boldsymbol{\sigma} - i\Delta \\ v_F \boldsymbol{\ell}\cdot\boldsymbol{\sigma} + i\Delta & 0 \end{pmatrix}, \qquad E^{\pm}_{\boldsymbol{\ell}} = \pm\sqrt{v_F^2 \boldsymbol{\ell}^2 + \Delta^2}.$$



- Optical response behaves exactly as charge renormalization in QED

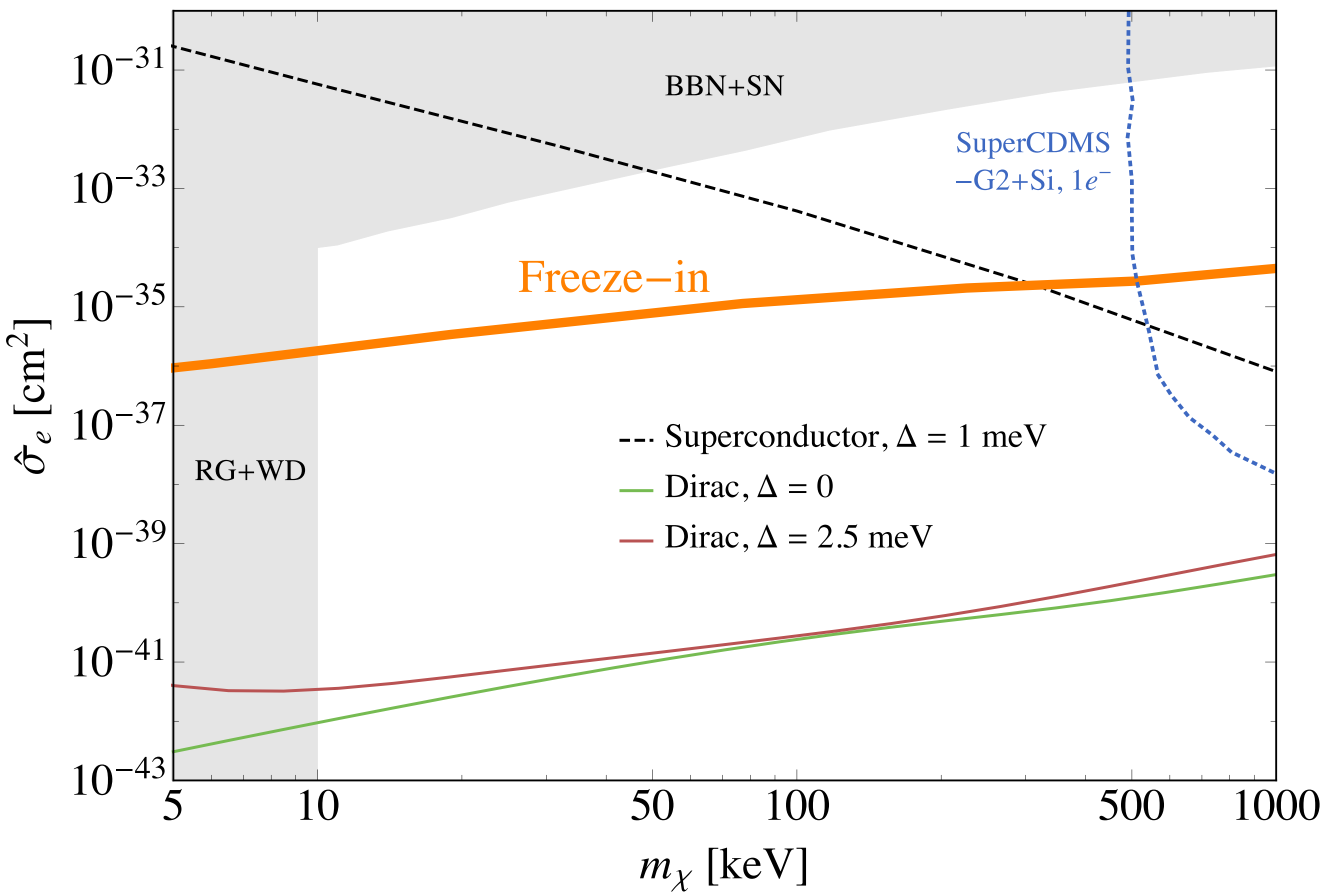
$$(\epsilon_r)_{\text{semimetal}} = 1 - \frac{e^2 g}{24\pi^2 \kappa v_F} \frac{1}{\mathbf{q}^2} \left\{ -\mathbf{q}^2 \ln \left| \frac{4\Lambda^2}{\omega^2/v_F^2 - \mathbf{q}^2} \right| - i\pi \mathbf{q}^2 \Theta(\omega - v_F |\mathbf{q}|) \right\}$$

DIRAC MATERIALS

1708.08929

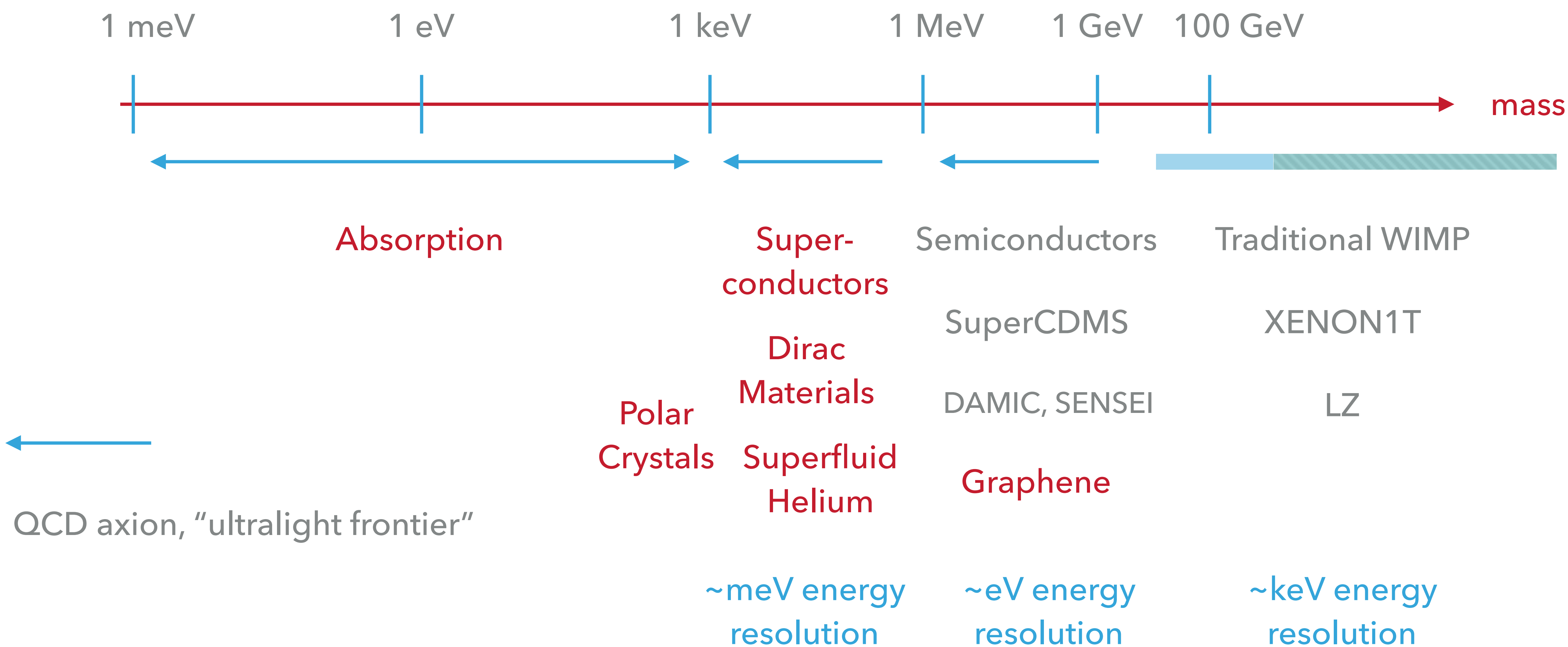
- Coupling of dark photon to electrons depends on the size of the optical response
- Meaning: weaker optical response is stronger sensitivity to dark photon

$$\mathcal{L} \supset \varepsilon e \frac{q^2}{q^2 - \Pi_{T,L}} \tilde{A}'^{T,L}_{\mu} J^{\mu}_{\mathrm{EM}}$$



LOOKING BEYOND BILLIARD BALLS

- Experimental Panorama



EXPERIMENTAL PROGRESS

- These experiments are becoming funded (and new call from DoE for small projects expected early next year)

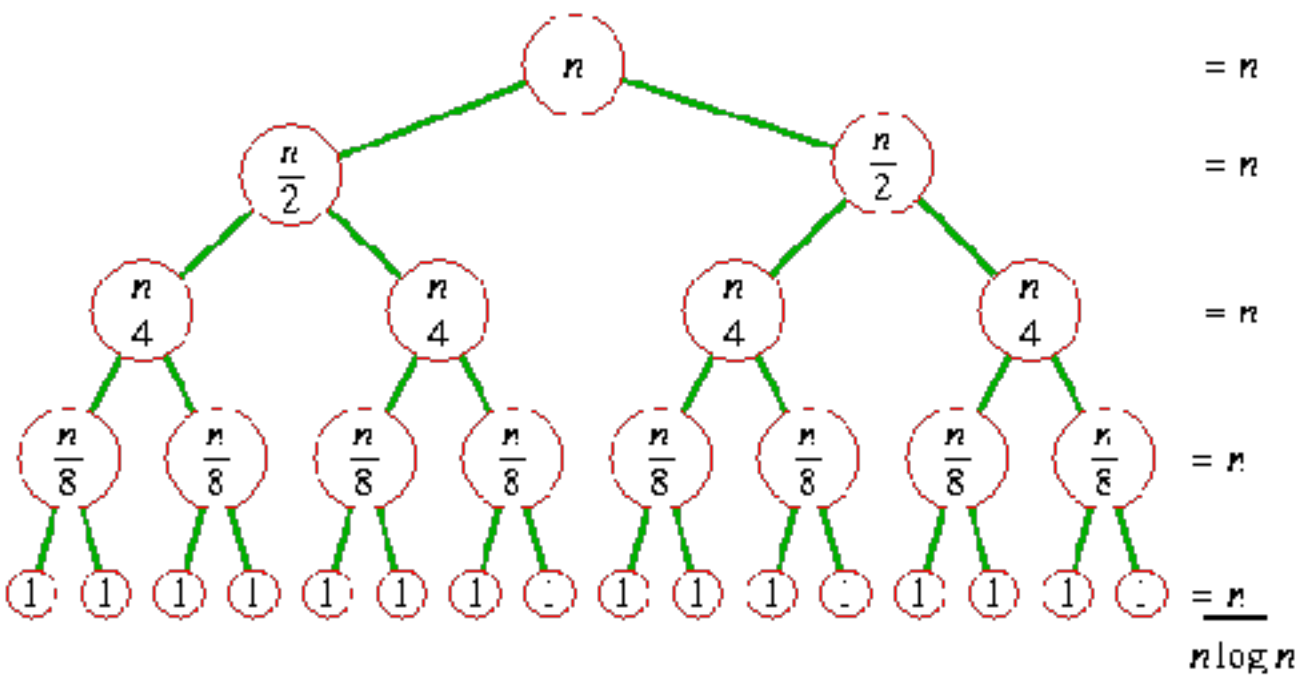
Main Science Goal	Experiment	Target	Readout	Estimated Timeline
Sub-GeV Dark Matter (Electron Interactions)	SENSEI	Si	charge	ready to start project (2 yr to deploy 100g)
	DAMIC-1K	Si	charge	ongoing R&D 2018 ready to start project (2 yr to deploy 1 kg)
	UA′(1) liquid Xe TPC	Xe	charge	ready to start project (2 yr to deploy 10kg)
	Scintillator w/ TES readout	GaAs(Si,B)	light	2 yr R&D 2020 in sCDMS cryostat
	NICE; NaI/CsI cooled crystals	NaI CsI	light	3 yr R&D 2020 ready to start project
	Ge Detector w/ Avalanche Ionization Amplification	Ge	charge	3 yr R&D 1 yr 10kg detector 1 yr 100kg detector
	PTOLEMY-G3, 2d graphene	graphene	charge directionality	1 yr fab prototype 1 yr data
	supercond. Al cube	Al	heat	10+ yr program
Sub-GeV Dark Matter (Nucleon Interactions)	Superfluid helium with TES readout	He	heat, light	1 yr R&D; 2018 ready to start project; 2022 run
	Evaporation & detection of He-atoms by field ionization	superfluid helium, crystals with long phonon mean free path (e.g. Si, Ge)	heat	3 yr R&D; 2020 ready to start project R&D
	color centers	crystals (CaF)	light	R&D effort ongoing
	Magnetic bubble chamber	Single molecule magnet crystals	Spin-avalanche (Magnetic flux)	R&D effort ongoing

THE CHALLENGE

- Now is not the time for narrowing our search for dark matter; the playing field is still wide open
- Moving beyond nuclear recoils into phases of matter crucial to access broader areas of DM parameter space
- Target diversity essential. graphene, superconductors, semiconductors, helium, polar crystals, Dirac or Weyl materials ….
- Leverage progress in materials and condensed matter physics
- Realizing program 5-10+ years into the future

THE OUTLOOK

- We are not without tools!



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WIMP or (axion)

How to be ready for anything? Hidden Sectors

How do I search for these things?