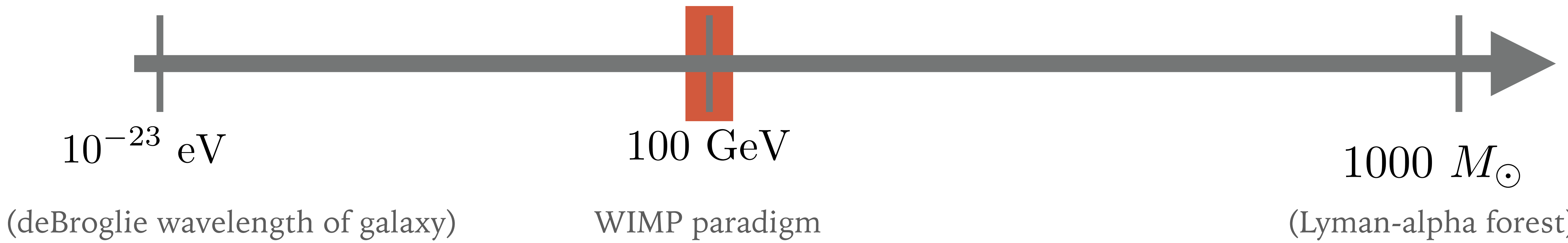
NEW IDEAS IN DARK MATTER DETECTION

Kathryn M. Zurek

DARK MATTER DETECTION: A FULL COURT PRESS



$$1\ M_\odot \sim 10^{57}\ \text{GeV}$$

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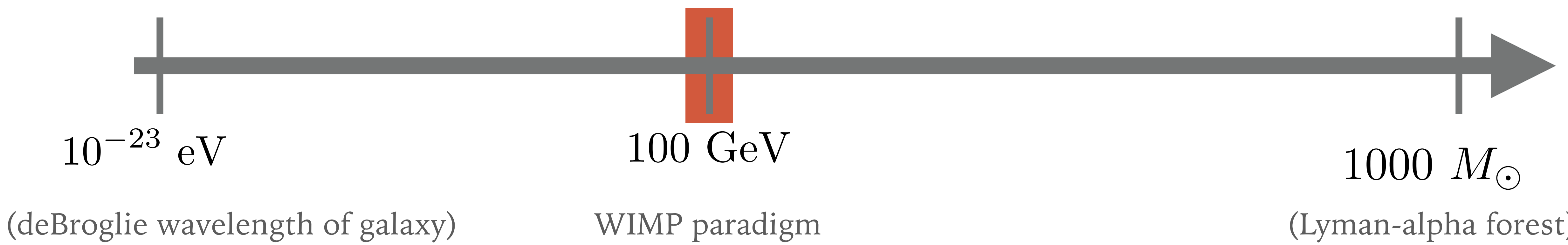

- WIMP paradigm: a good place to start looking
- Reason: weak forces have the right scale, for detection, abundance, and cosmology

$$\sigma_{wk} \simeq \frac{g_{wk}^4 \mu_{XT}^2}{4\pi m_Z^4} \simeq 10^{-34}\ \mathrm{cm}^2 \left(\frac{100\ \mathrm{GeV}}{M}\right)^2$$

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$$\sigma_{wk} v_{fo} \simeq \frac{g_{wk}^4 \mu_{XT}^2}{4\pi m_Z^4} \frac{c}{3} \simeq 10^{-24} \frac{\mathrm{cm}^3}{\mathrm{s}} \left(\frac{100\ \mathrm{GeV}}{M} \right)^2$$

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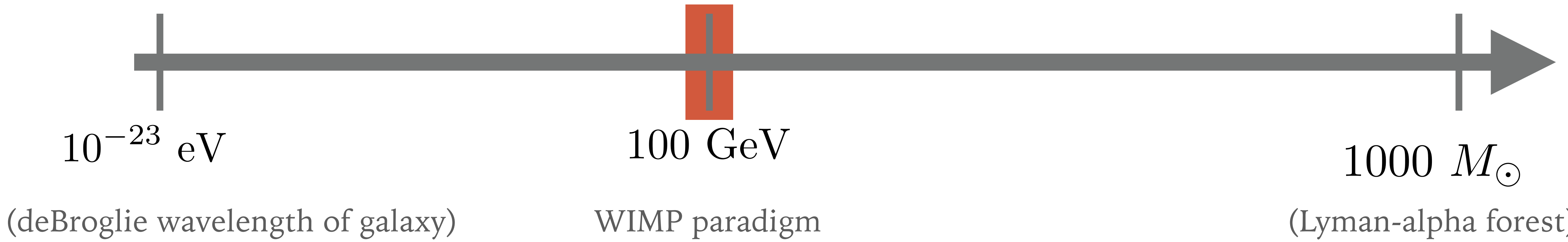
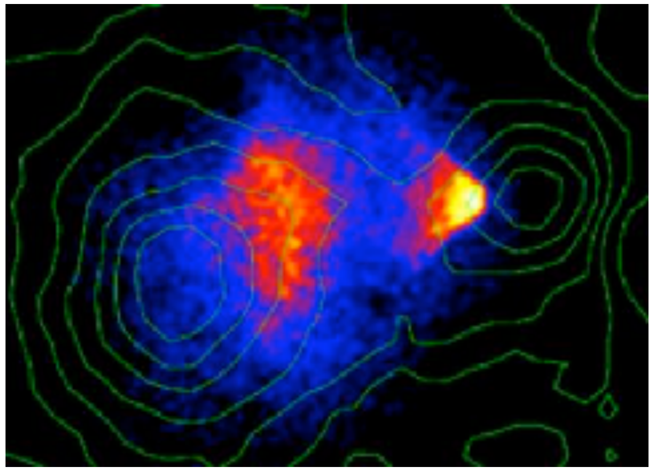


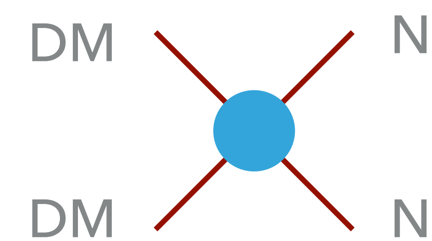
- WIMP paradigm: a good place to start looking
- Cross-sections are too small to have relevant impacts on structure formation

$$\sigma_{SIDM} \lesssim 10^{-24}\ \mathrm{cm}^2/\mathrm{GeV}$$



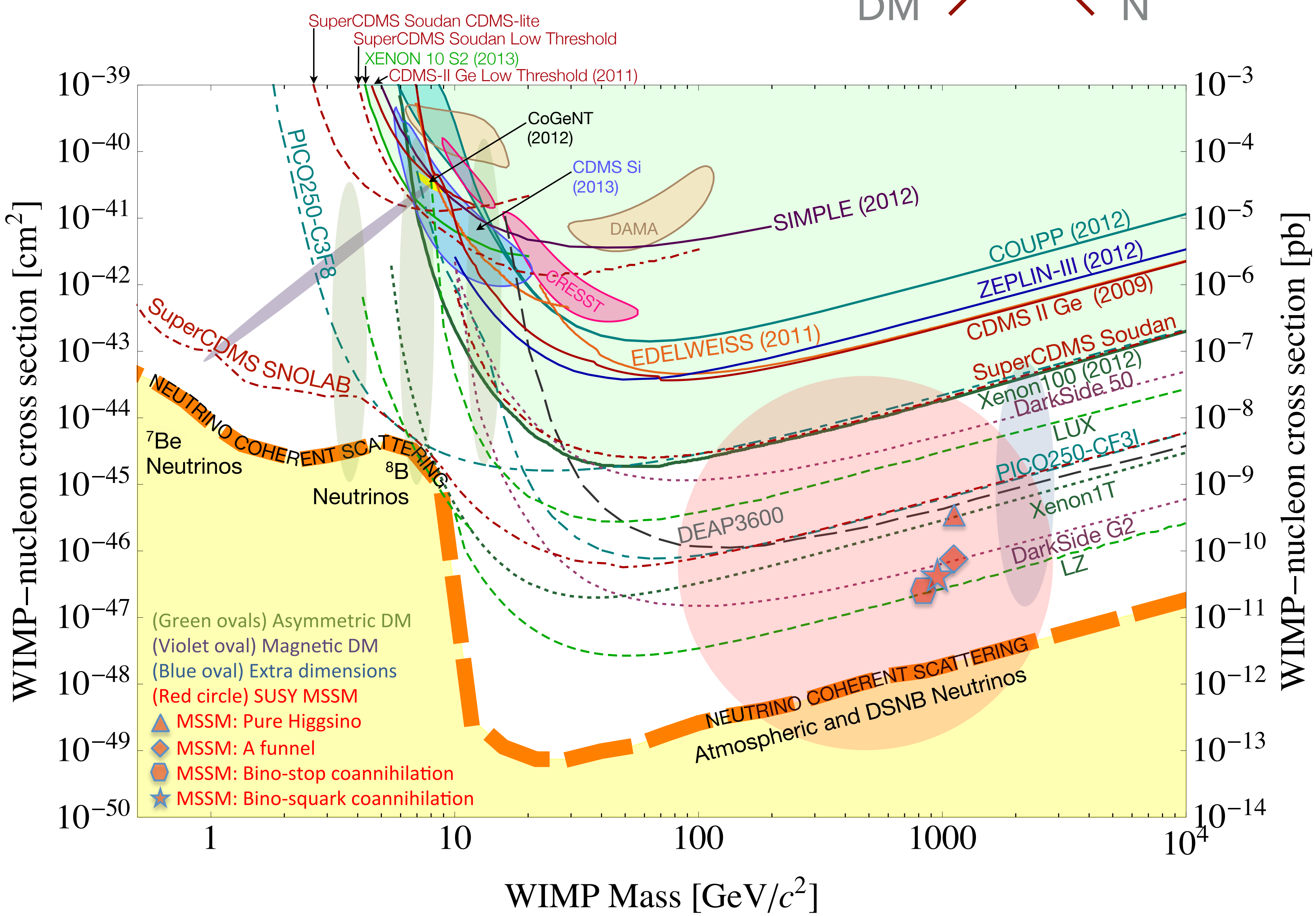
DETECTABLE INTERACTION RATES

- WIMP: not dead but continually pressured



Z-boson interacting dark matter: ruled out

Higgs interacting dark matter: active target



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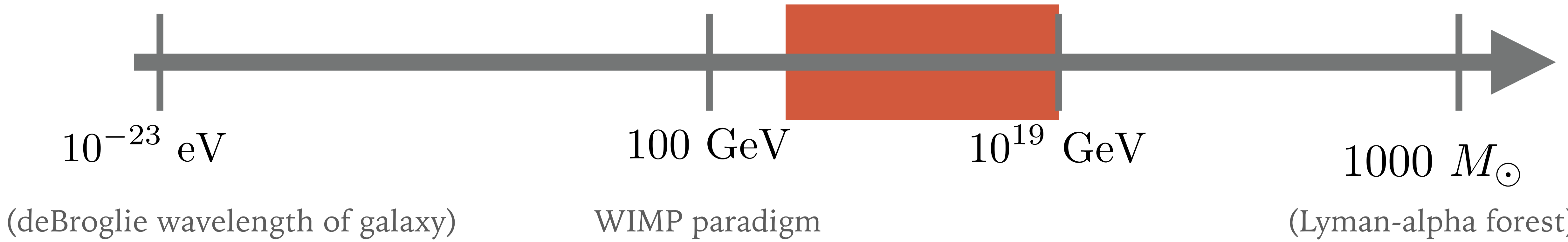
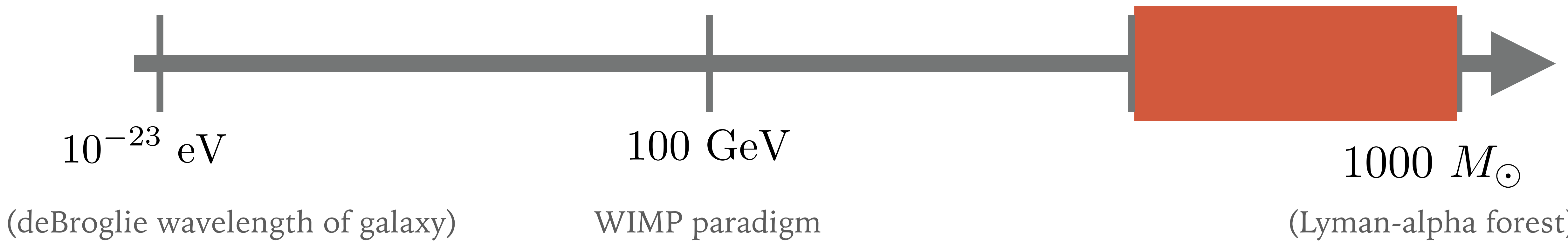


$$\sigma_{wk} v_{fo} \simeq \frac{g_{wk}^4 \mu_{XT}^2}{4\pi m_Z^4}\frac{c}{3} \simeq 10^{-24}\frac{\mathrm{cm}^3}{\mathrm{s}}\left(\frac{100\ \mathrm{GeV}}{M}\right)^2$$

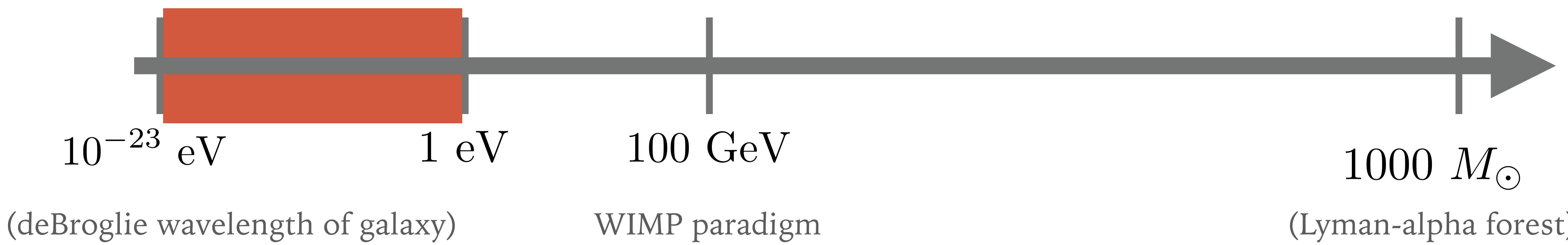
- Heavier dark matter: setting relic abundance through interactions with Standard Model is challenging (NB: exceptions)
- At heavier masses, detection through Standard Model interactions is (generally) not motivated by abundance

DARK MATTER DETECTION: A FULL COURT PRESS



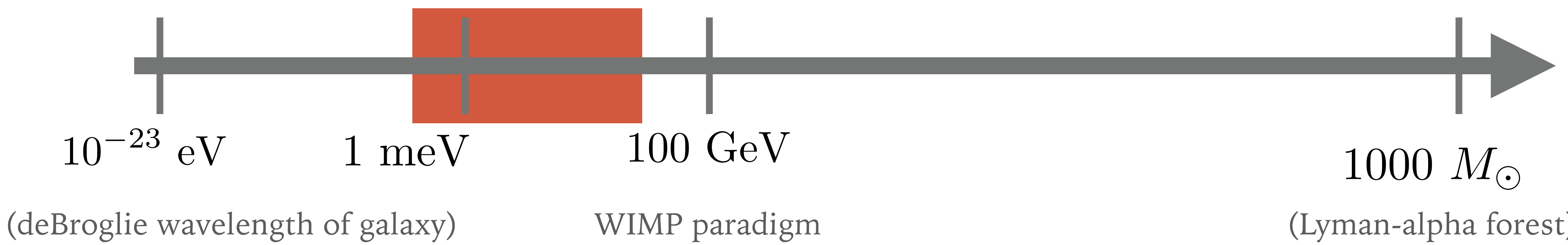
- Look for gravitational means to detect structure
- Above $10^{-13}\ M_\odot$ Pulsar timing, interferometers can be effective
- Project of the (far) future to use laboratory clocks to detect small gravitational redshift effects

DARK MATTER DETECTION: A FULL COURT PRESS



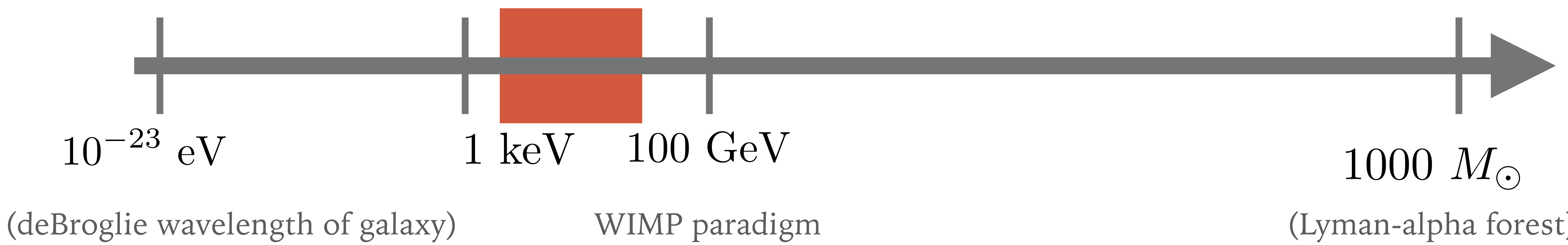
- Ultralight dark matter: dark matter behaves like a wave rather than an individual particle, e.g. axion
- Detection techniques focus on utilizing this coherence
- Cavities, AMO techniques

DARK MATTER DETECTION: A FULL COURT PRESS



- Focus on an intermediate range where observation via particle interactions with SM is still highly motivated *though not detectable with traditional WIMP experiments*
- *Arise generically in top-down constructions*

DARK MATTER DETECTION: A FULL COURT PRESS



- Dark sector dynamics are complex and astrophysically relevant.

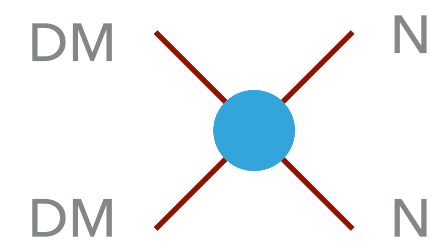
$$\sigma_{str} \simeq \frac{4\pi\alpha_s^2}{M^2} \simeq 10^{-24}\ \mathrm{cm}^2 \left(\frac{1\ \mathrm{GeV}}{M}\right)^2$$

- Abundance may still be set by (thermal) population from SM sector

$$\sigma_{wk} v_{fo} \simeq \frac{g_{wk}^4 \mu_{XT}^2}{4\pi m_Z^4}\frac{c}{3} \simeq 10^{-24}\frac{\mathrm{cm}^3}{\mathrm{s}}\left(\frac{100\ \mathrm{GeV}}{M}\right)^2$$

TOWARDS HIDDEN SECTOR DARK MATTER

- Developments in condensed matter make this possible



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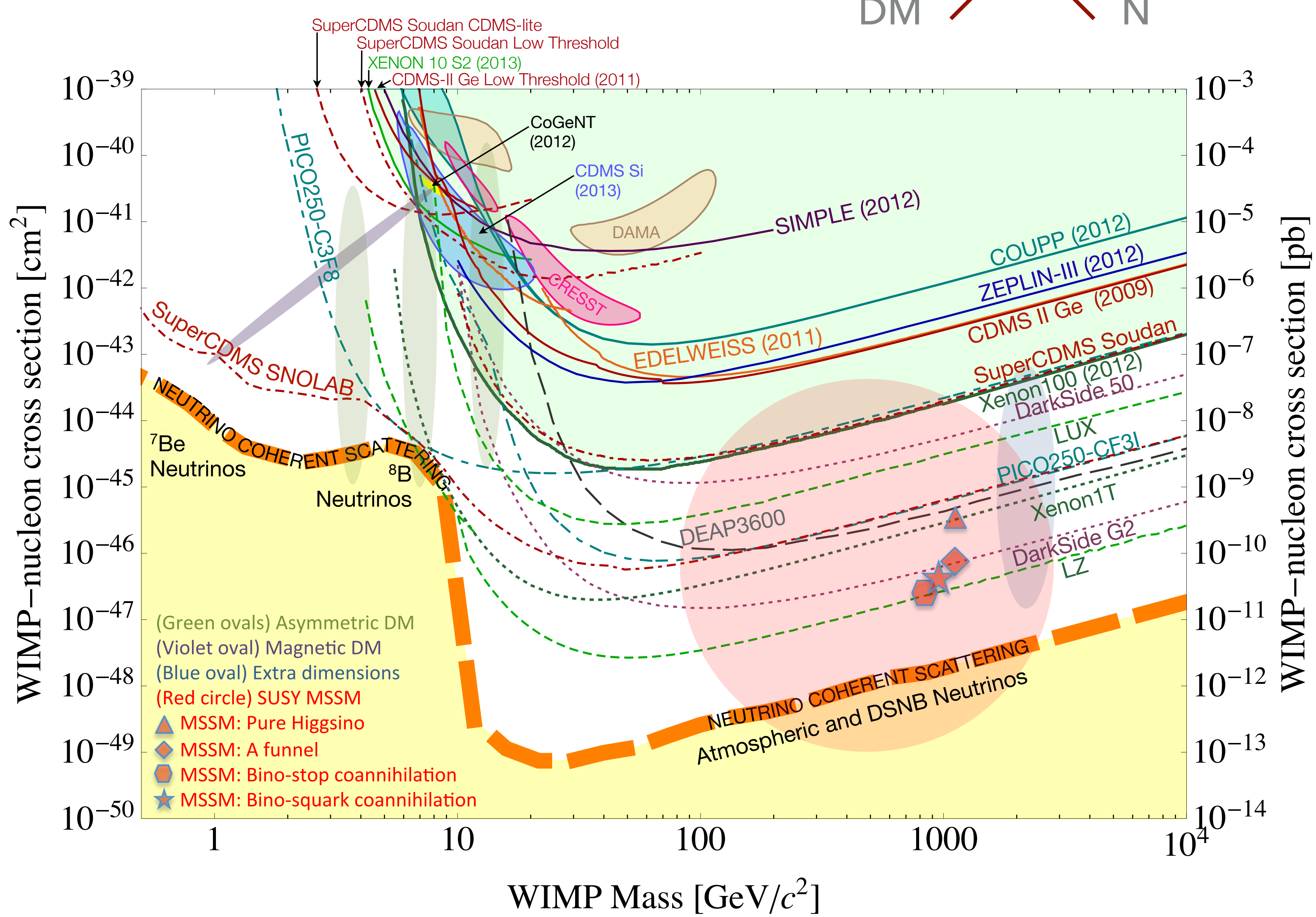
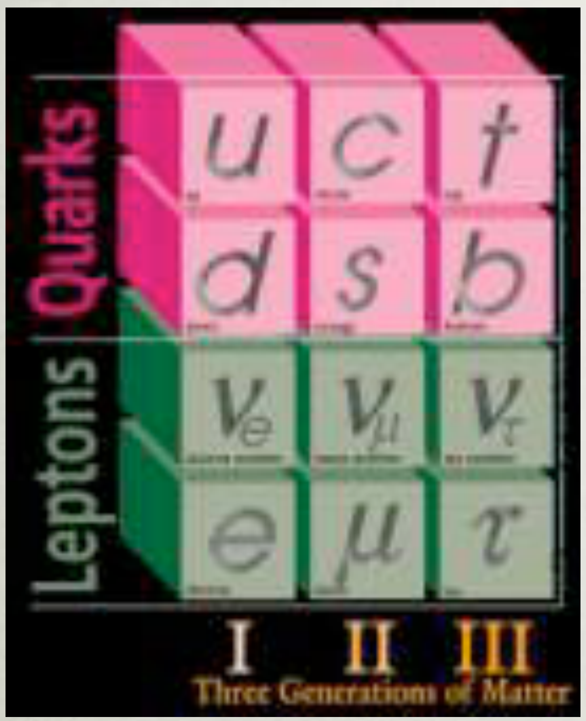


Paradigm Shift

Our thinking has shifted



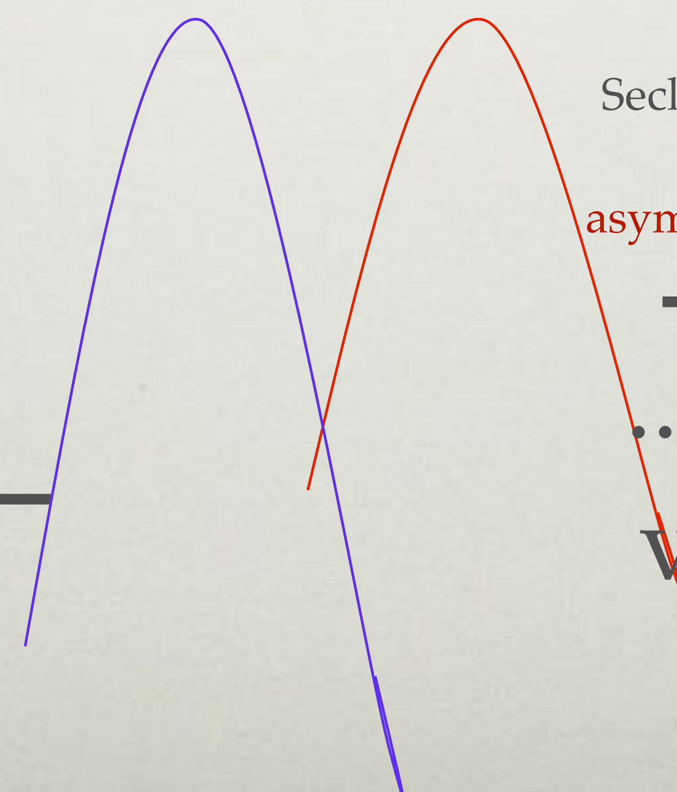
Energy

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 .....

$M_p \sim 1$ GeV

Standard Model

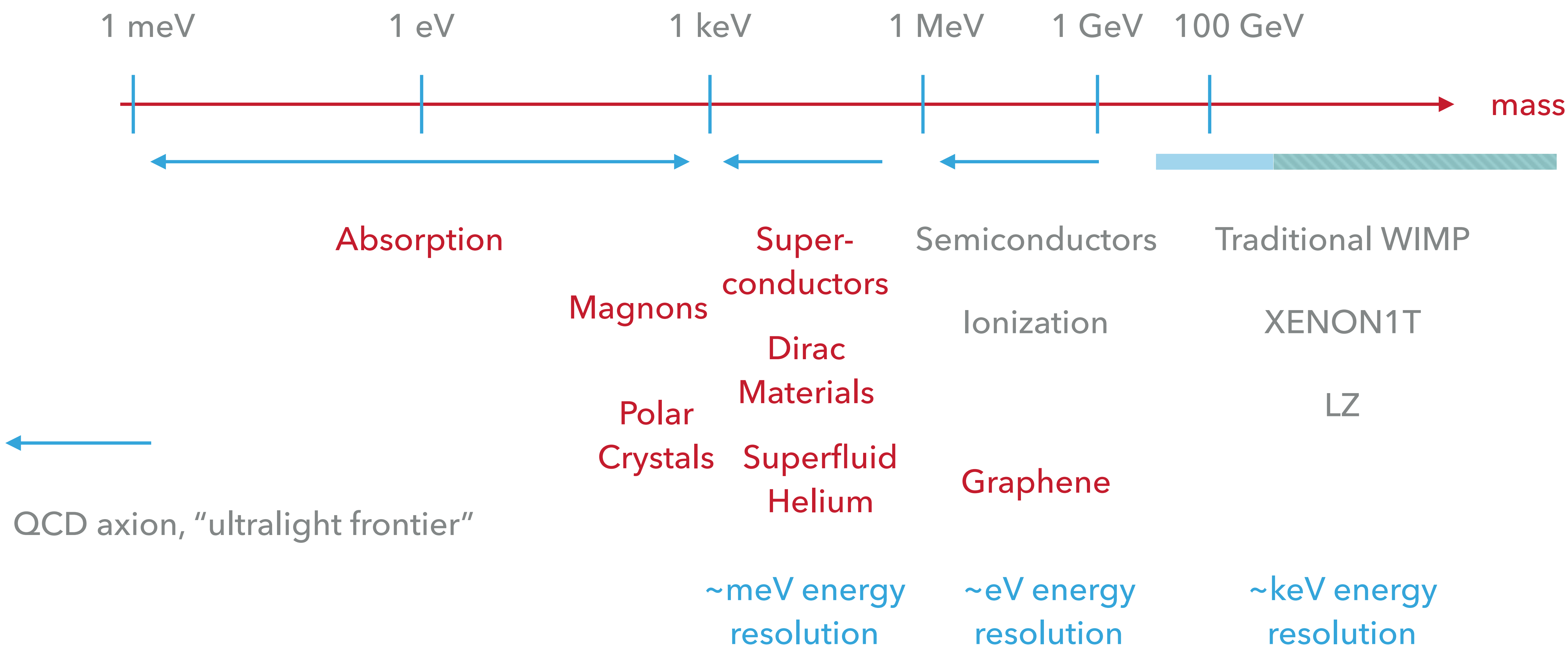


...to a hidden sector/ valley with multiple states, new interactions

Inaccessibility

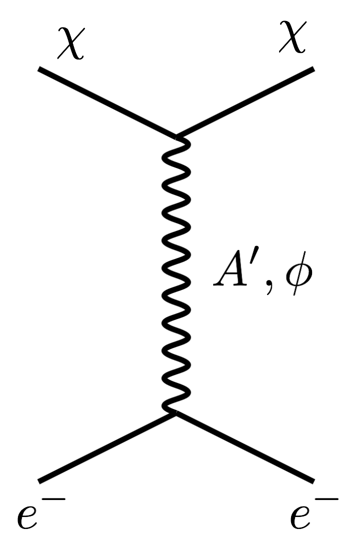
TOWARDS HIDDEN SECTOR DARK MATTER

- Experimental Panorama



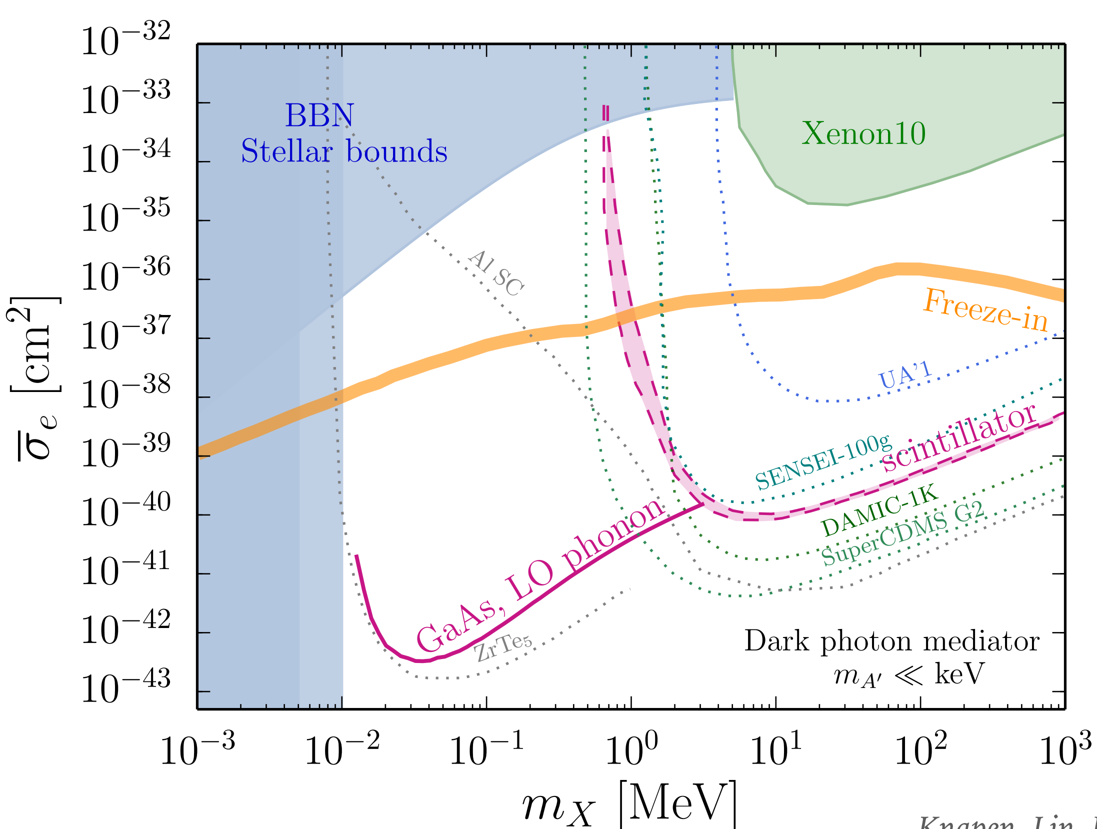
DM ABUNDANCE AS A GUIDE

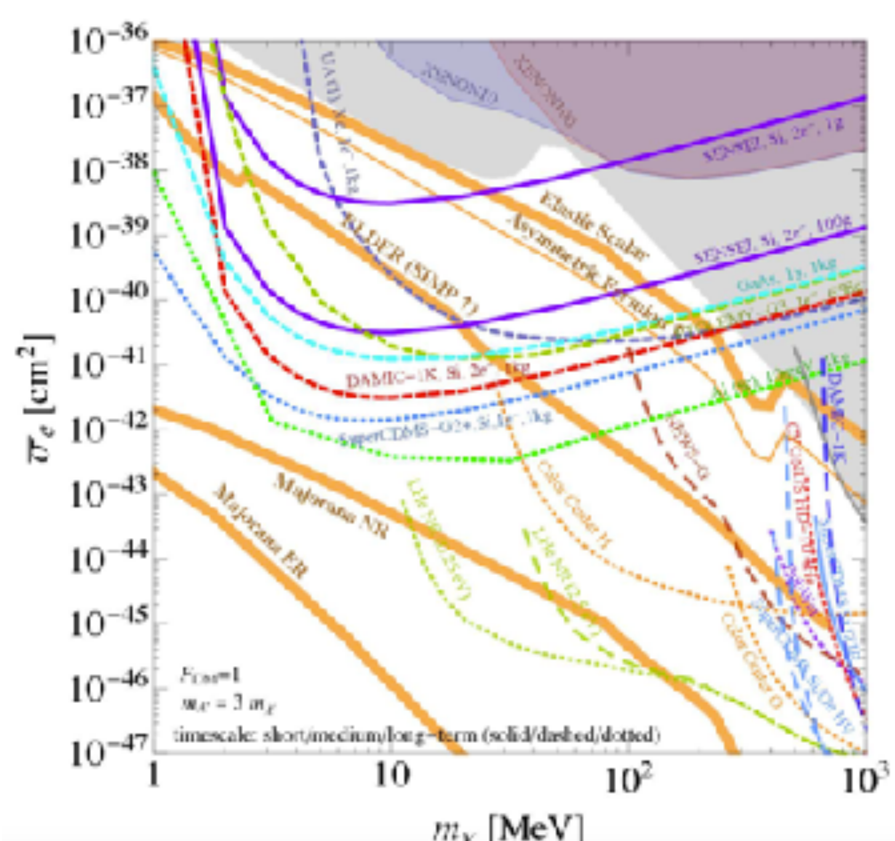
- If DM abundance is related to its coupling to the SM in any way, that provides a guide where to look



Freeze-in

Asymmetric Dark Matter





Knapen, Lin, Pyle KZ 1712.06598

US Cosmic Visions 1707.04591

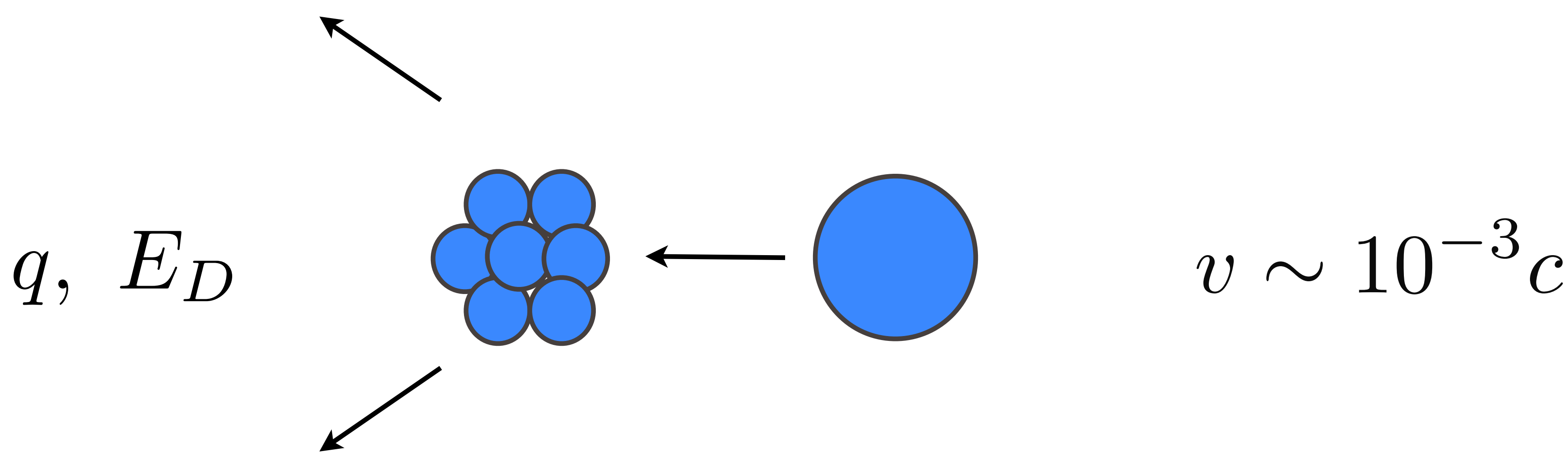
COMPLEMENTARITY TO ACCELERATOR SEARCHES

- High energy accelerators probe particles with mass at high energy scale of the collider with *large* couplings to SM

- Direct detection experiments are “intensity” experiments — they probe light mediators with *small* couplings to SM

LOOKING BEYOND BILLIARD BALLS

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



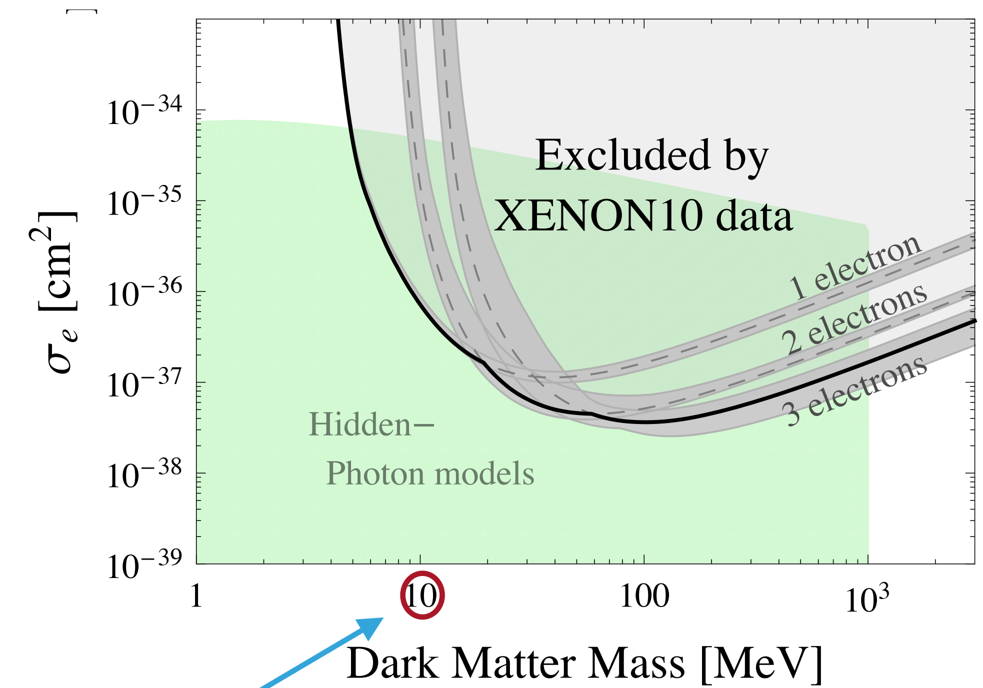
$$v \sim 300\ \mathrm{km/s} \sim 10^{-3} c \quad \Longrightarrow \quad E_D \sim 100\ \mathrm{keV}$$

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

LIGHTER TARGETS FOR LIGHTER DARK MATTER

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

P. Sorensen et al 1206.2644

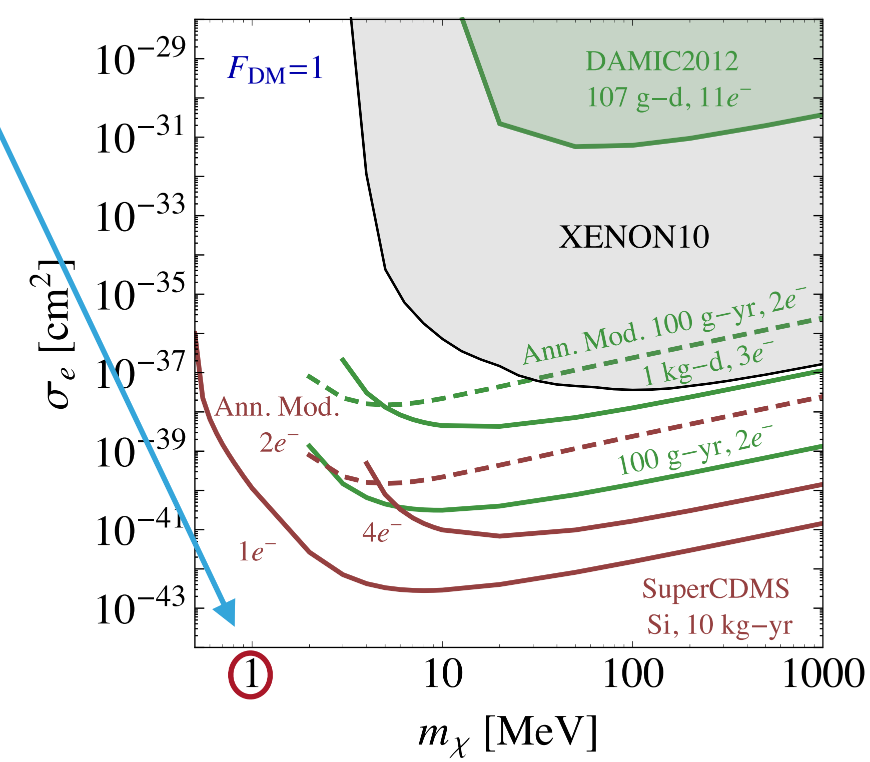


- In insulators, like xenon

  Tightly bound; ionize for signal

Gap = DM Kinetic Energy

Essig et al 1509.01598



- In semi-conductors, like Ge, Si

  Excite electron to conduction band

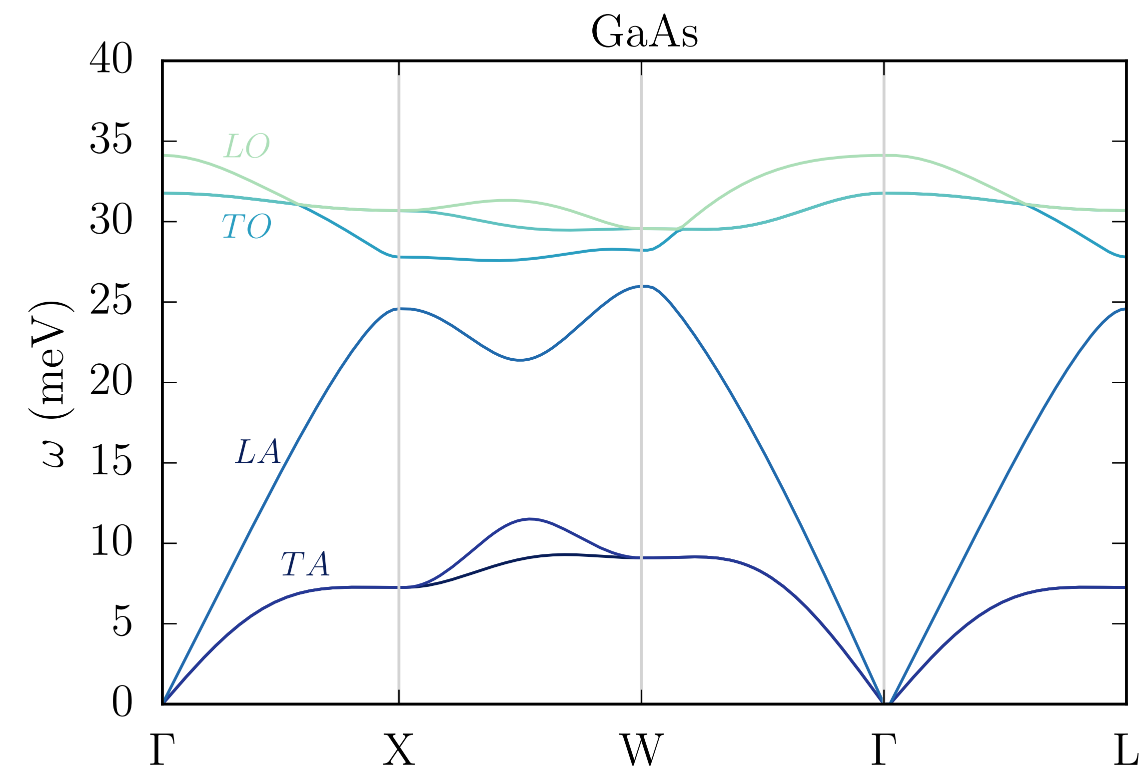
EXCITING COLLECTIVE MODES

Schutz, KZ 1604.08206, Knapen, Lin, KZ 1611.06228, Knapen, Lin, Pyle, KZ 1712.06598 Griffin, Knapen, Lin, KZ 1807.10291

- Once DM drops below an MeV, its deBroglie wavelength is longer than the inter particle spacing in typical materials
- Therefore, coupling to collective excitations in materials makes sense!
- Collective excitations = phonon modes
- Can be applied to just about any material
- (partial) calculations exist for superfluid helium, semiconductors, superconductors, polar materials
- Details depend on
  - 1) *nature of collective modes in target material*
  - 2) *nature of DM couplings to target*

NATURE OF COLLECTIVE OSCILLATIONS OF IONS — PHONONS

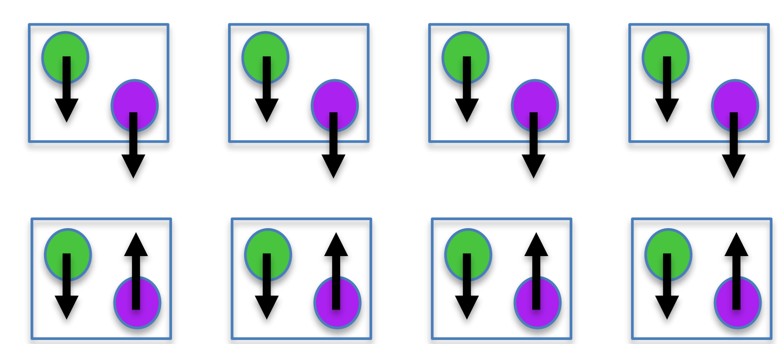
- Number of collective modes: 3 x number of ions in unit cell
- 3 of those modes describe in phase oscillation — acoustic phonons — and have a translation symmetry implying gapless dispersion
- The remaining modes are gapped



Momentum transfer

Acoustic

Optical

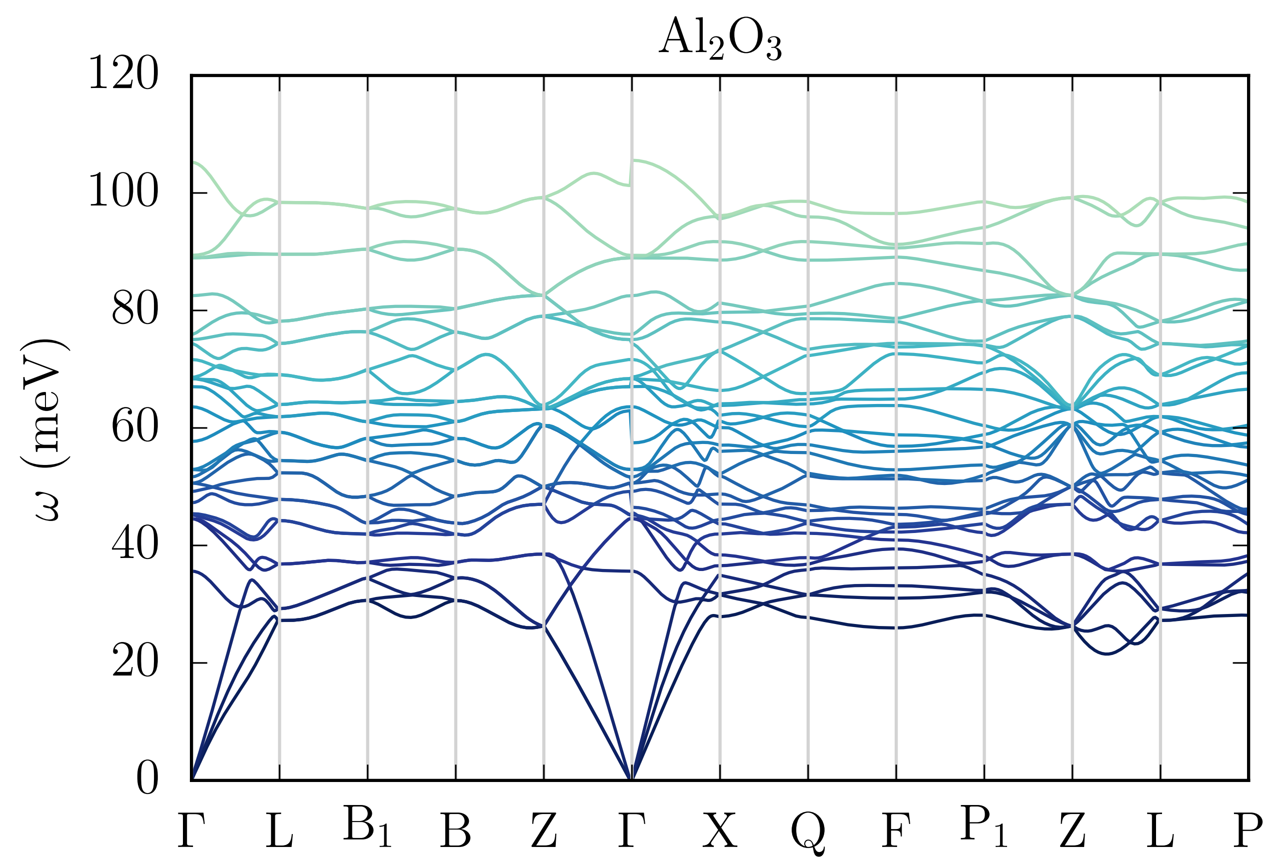


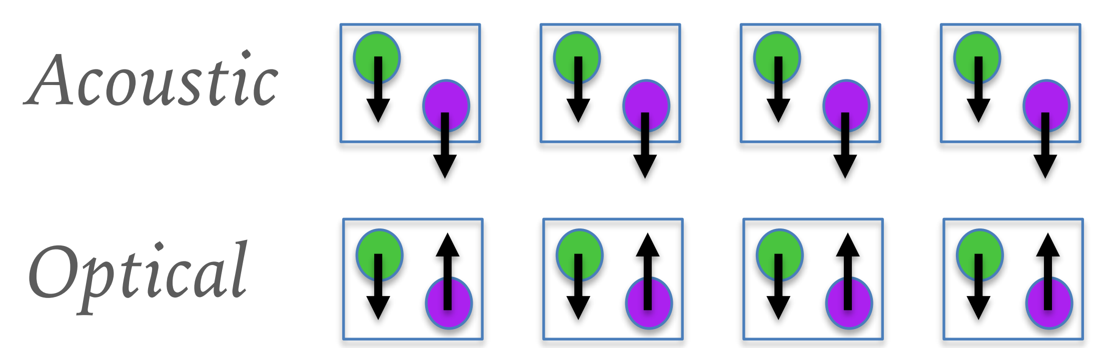
Knapen, Lin, Pyle, KZ 1712.06598 Griffin, Knapen, Lin, KZ 1807.10291

NATURE OF COLLECTIVE MODES

- Some materials have an abundance of these modes
- When these gapped modes result from oscillations of more than one type of ion, it sets up an oscillating dipole
- *Polar Materials*

Sapphire





KINEMATICS OF COLLECTIVE MODES

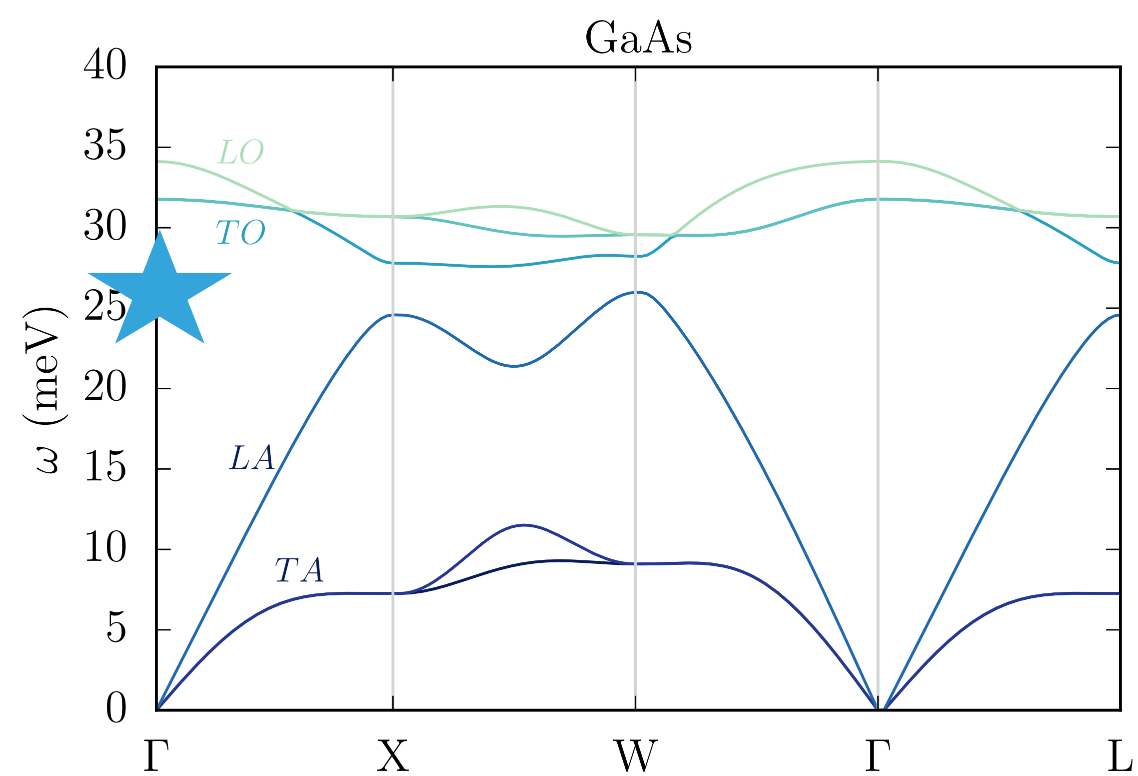
- First element to enter is the kinematics

$$E_D \sim v_X q$$

vs

$$E_D \sim c_s q$$

$$c_s \ll v_X$$

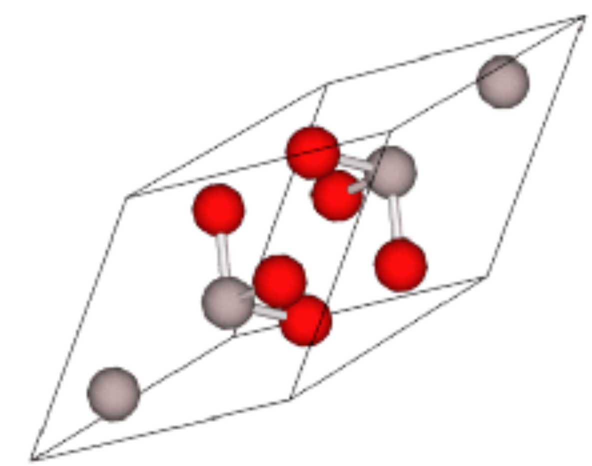


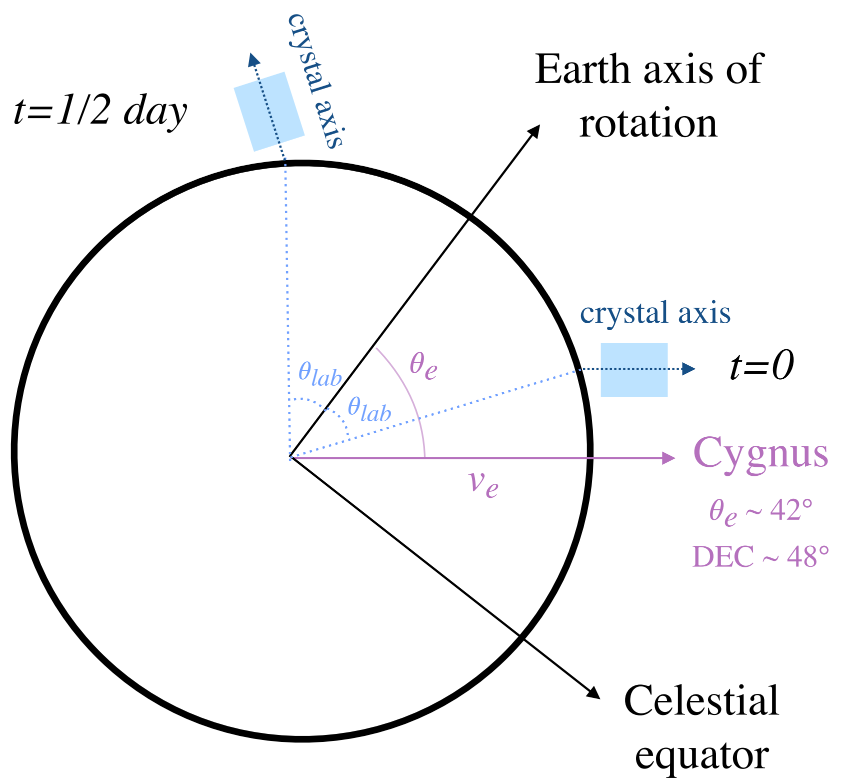
- Better coupling to gapped modes

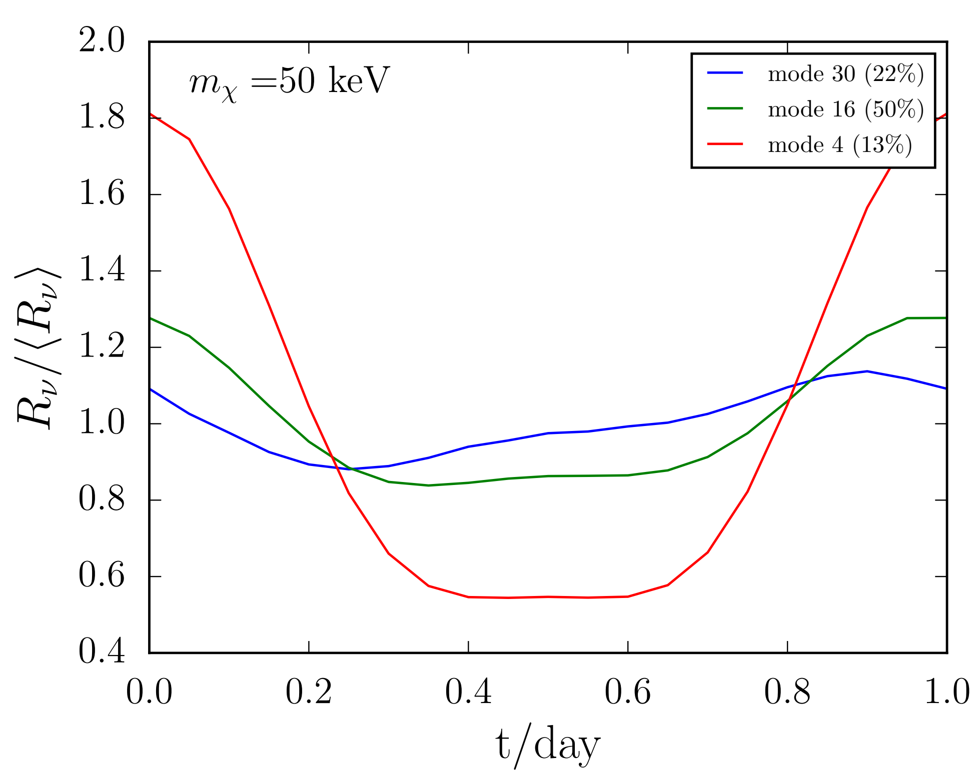
DIRECTIONALITY IN ANISOTROPIC MATERIALS!

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

- Crystal Lattice is not Isotropic
- Especially pronounced in sapphire

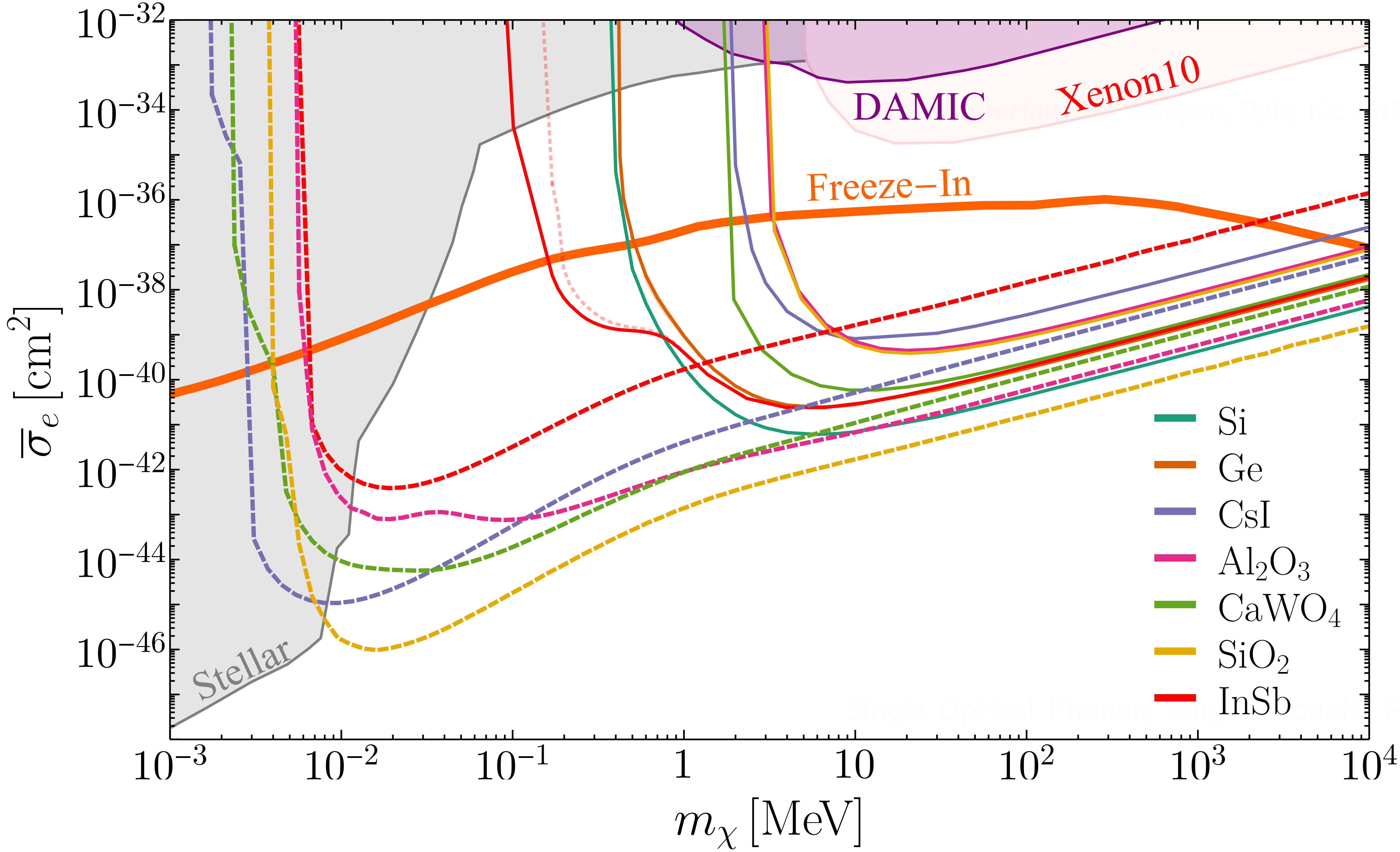






OPTICAL PHONONS IN POLAR MATERIALS

Griffing, Inzani, Trickle, Zhang, KZ, 1910.10716



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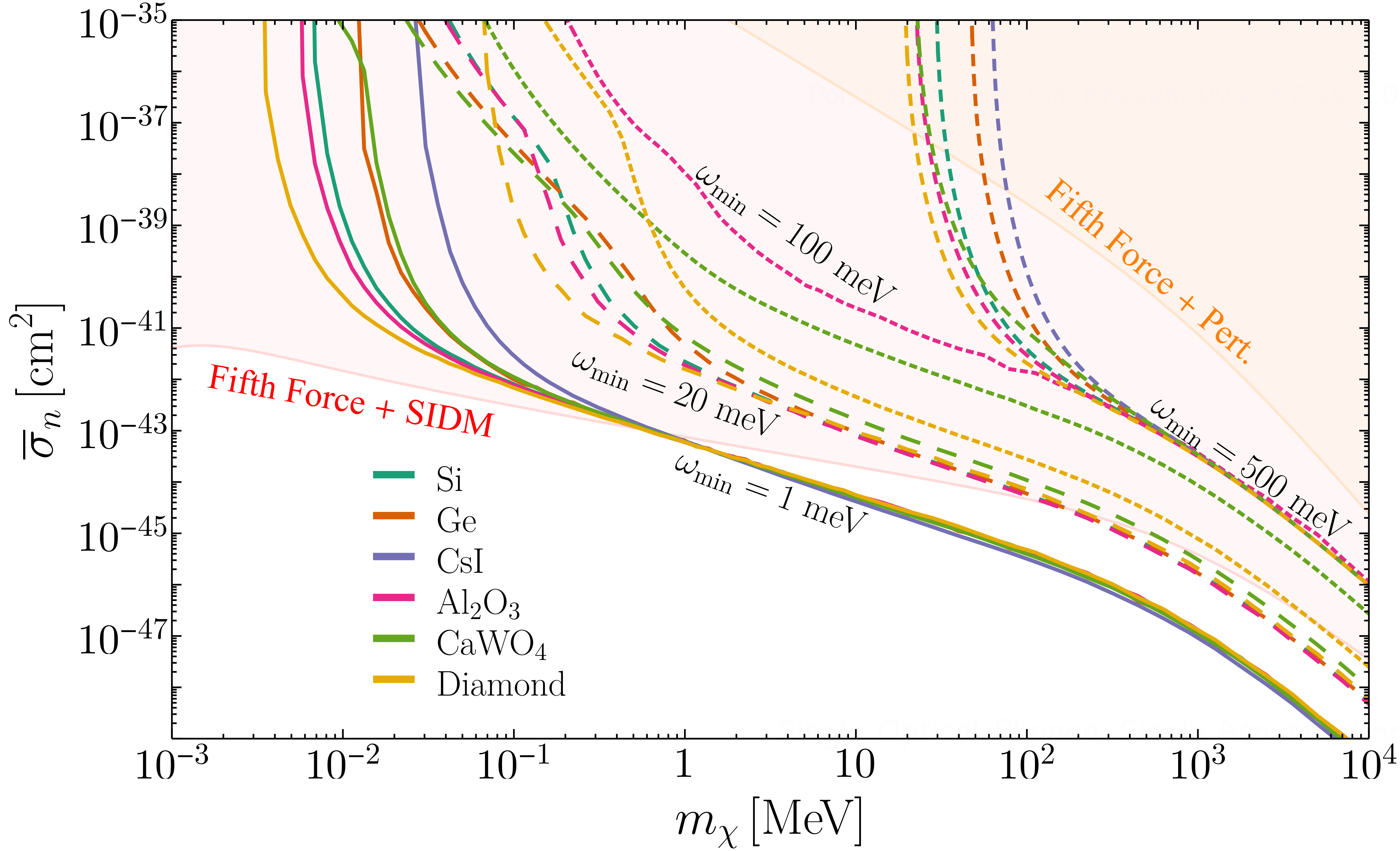
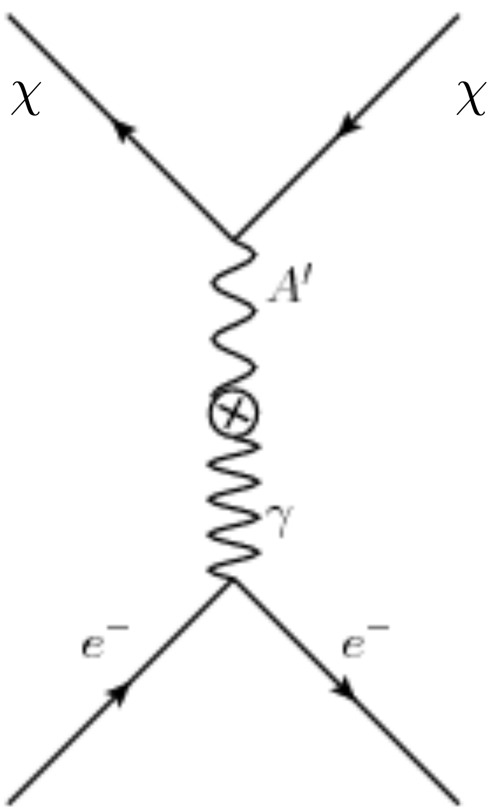


COUPLING TO TARGET, AND IMPORTANCE OF TARGET DIVERSITY

- Why? Dark matter interaction is sensitive to material type
- Dirac materials versus ordinary metals
- Consider dark photon mediated dark matter:



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

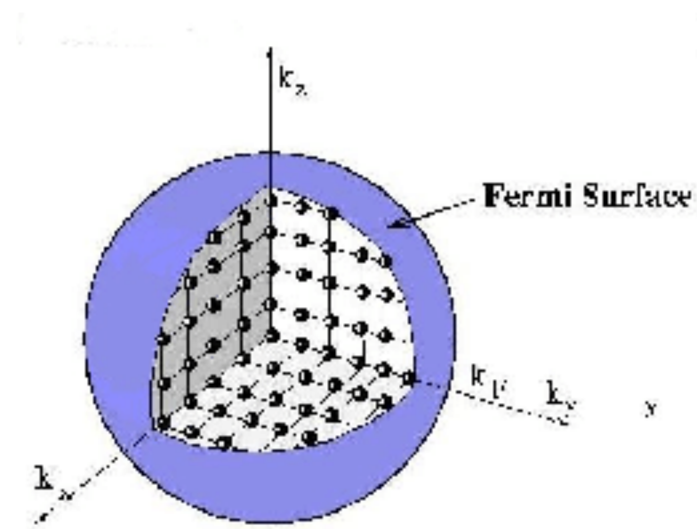
Polarization tensor characterizes in-medium optical response

- Metals have very strong optical response, and hence weak coupling to dark photons

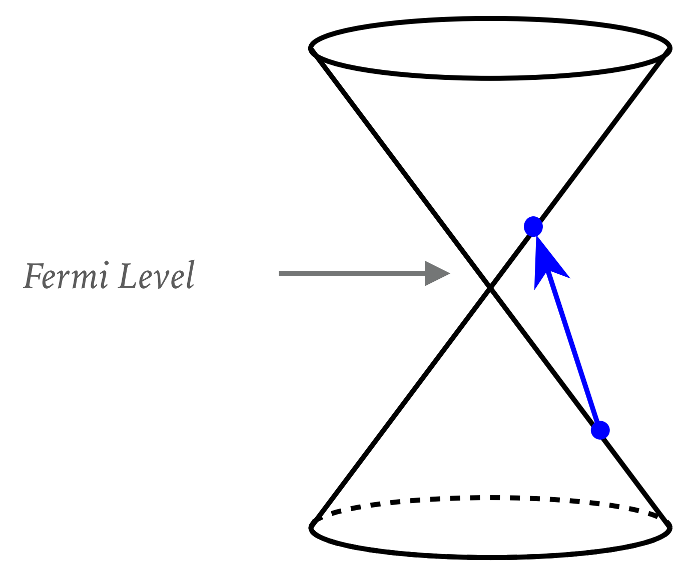
OPTICAL RESPONSE OF “SEMI-METALS

- Band structure can be “quantum engineered”
- Instead of a spherical Fermi surface as in a metal, the electrons have a cone structure
- Linear dispersion implies a Dirac equation, like QED
- In QED, gauge invariance protects photon from obtaining a mass

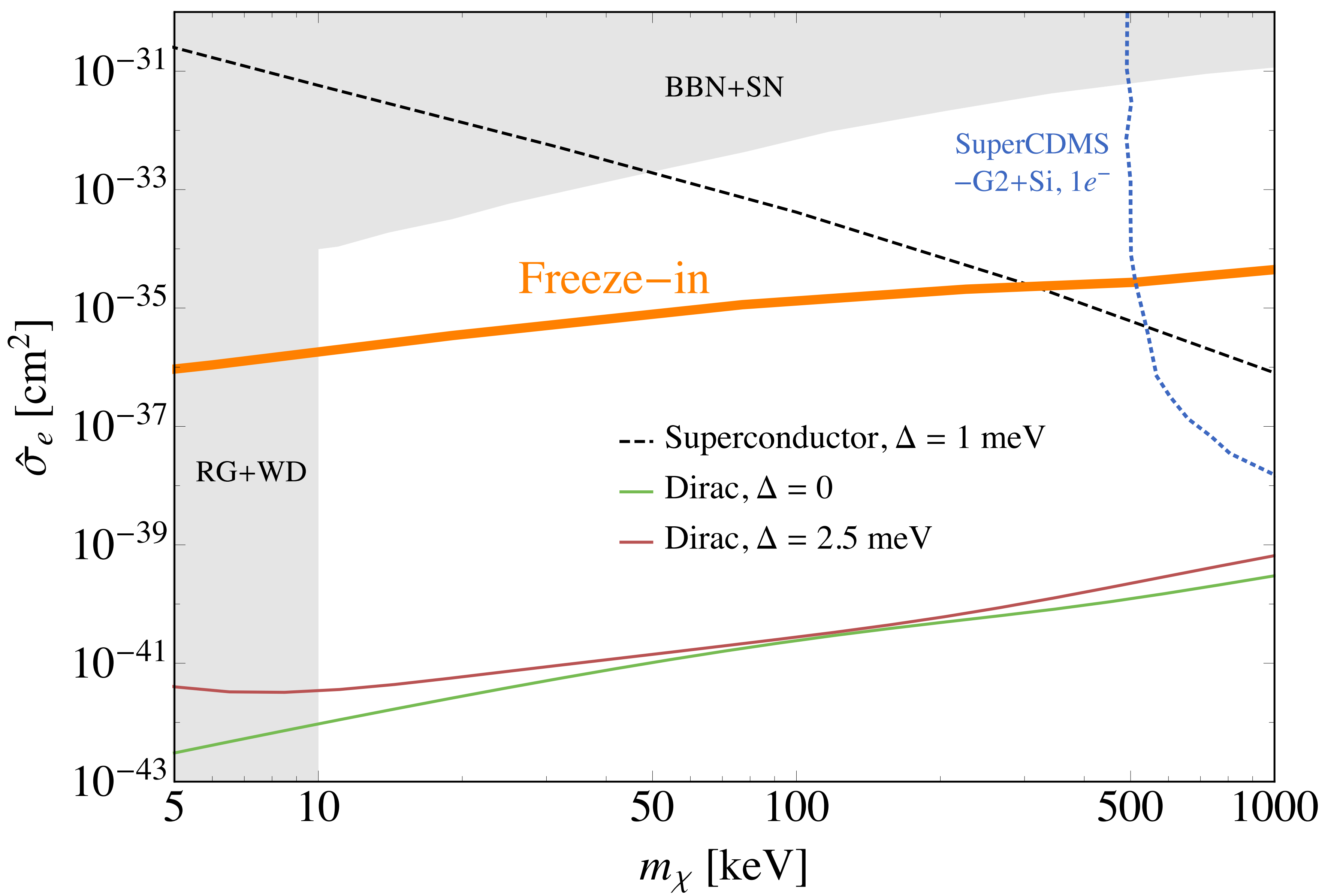
Metal



Semi-Metal



COMPARISON OF METAL AND SEMI-METAL



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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]

1708.08929

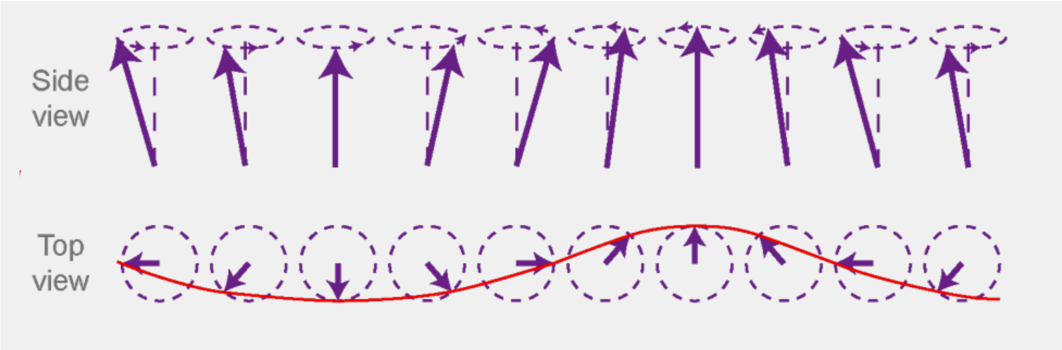
SPIN-DEPENDENT INTERACTIONS

Trickle, Zhang, KZ 1905.13744

- Some types of particle interactions have dominant interactions with spin

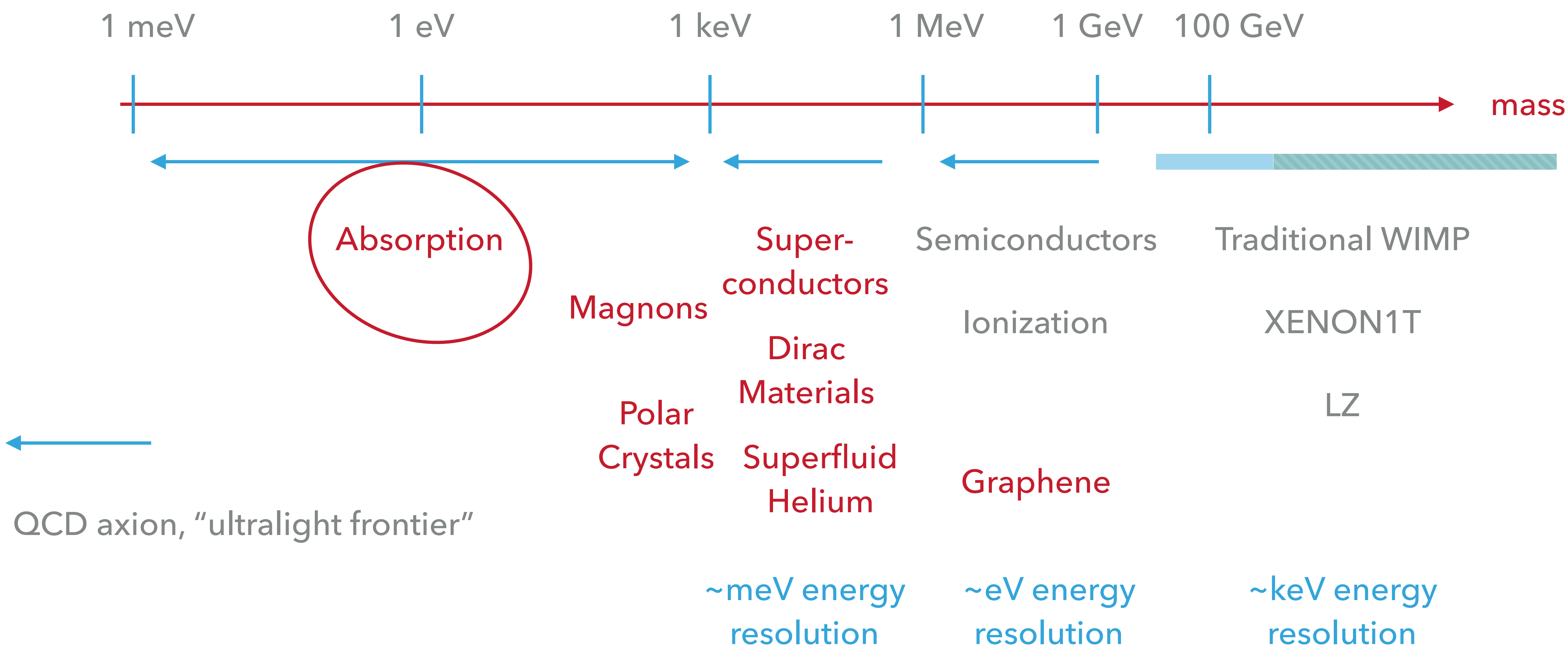
Magnetic dipole DM	$\mathcal{L} = \frac{g_\chi}{\Lambda_\chi}\bar{\chi}\sigma^{\mu\nu}\chi\, V_{\mu\nu} + g_e\bar{e}\gamma^\mu e\, V_\mu$
Anapole DM	$\mathcal{L} = \frac{g_\chi}{\Lambda_\chi^2}\bar{\chi}\gamma^\mu\gamma^5\chi\, \partial^\nu V_{\mu\nu} + g_e\bar{e}\gamma^\mu e\, V_\mu$

- Collective (electron) spin-waves = magnons
- Magnetically ordered materials (ferro- or ferri-magnets)



TOWARDS HIDDEN SECTOR DARK MATTER

- Experimental Panorama

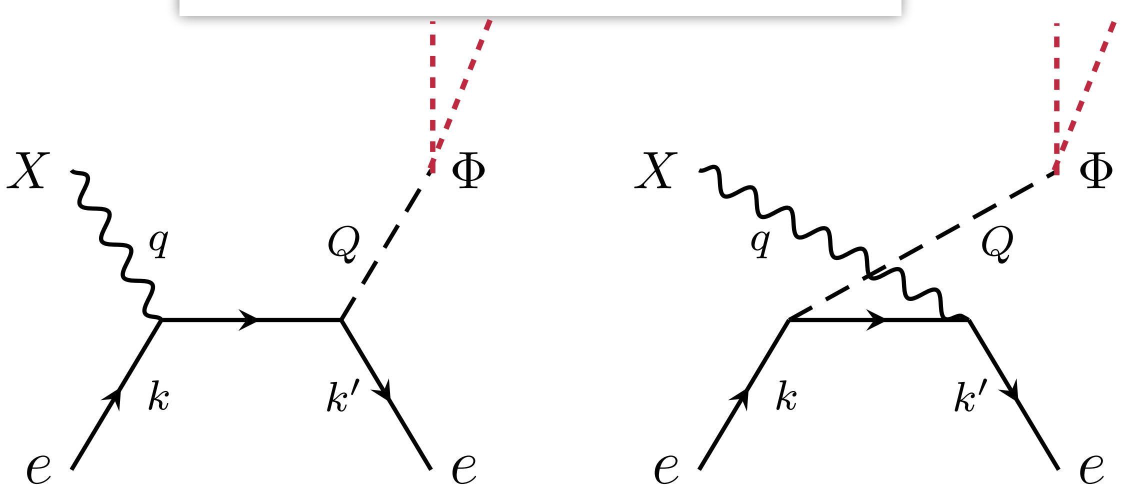


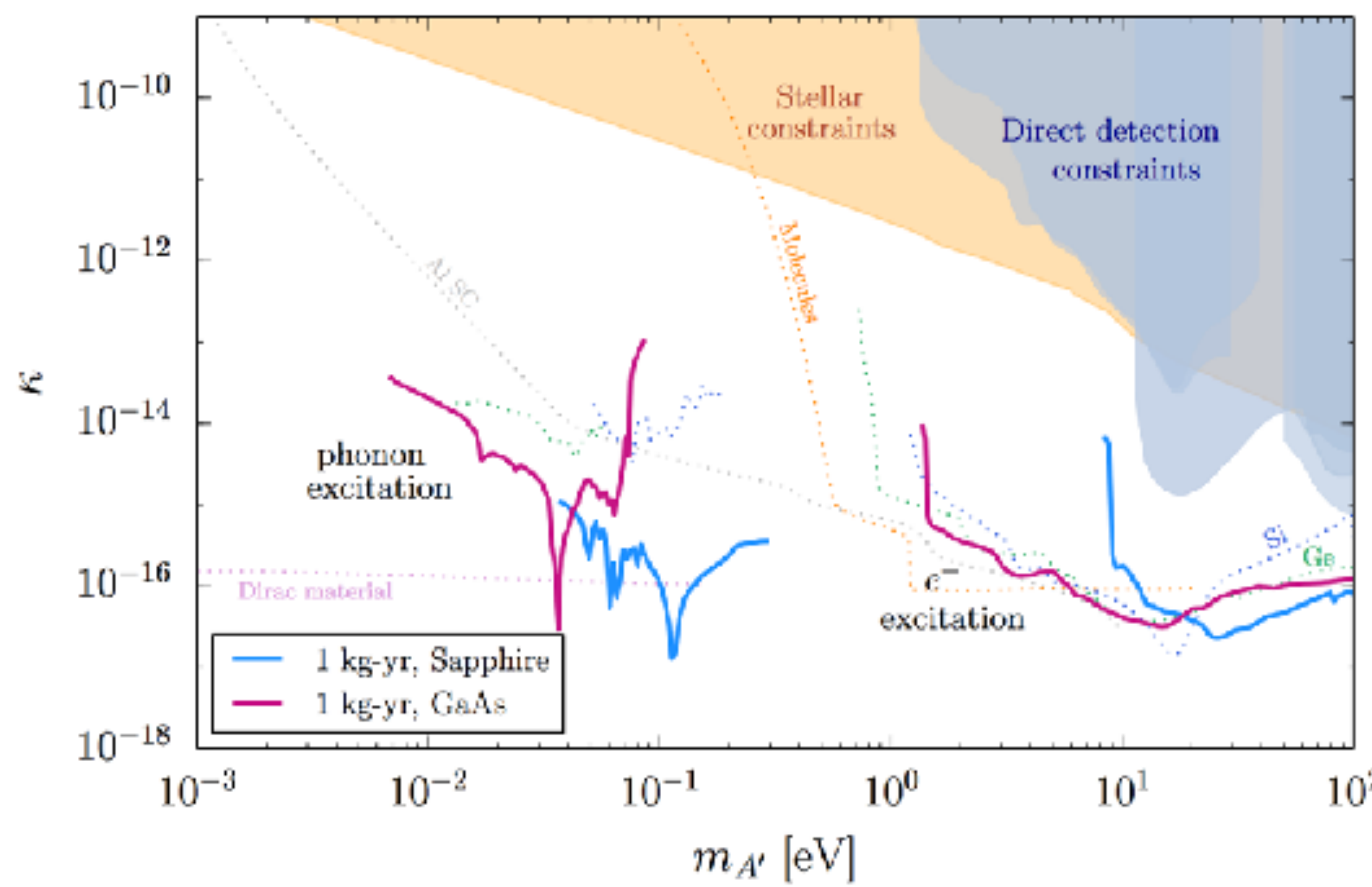
SEARCHING FOR AXIONS AND OTHER ULTRALIGHT PARTICLES

- Rather than depositing kinetic energy, entire mass energy can be deposited
- Typically requires inelastic processes on the lattice to absorb momentum

Griffin, Knapen, Lin, KZ 1807.10291

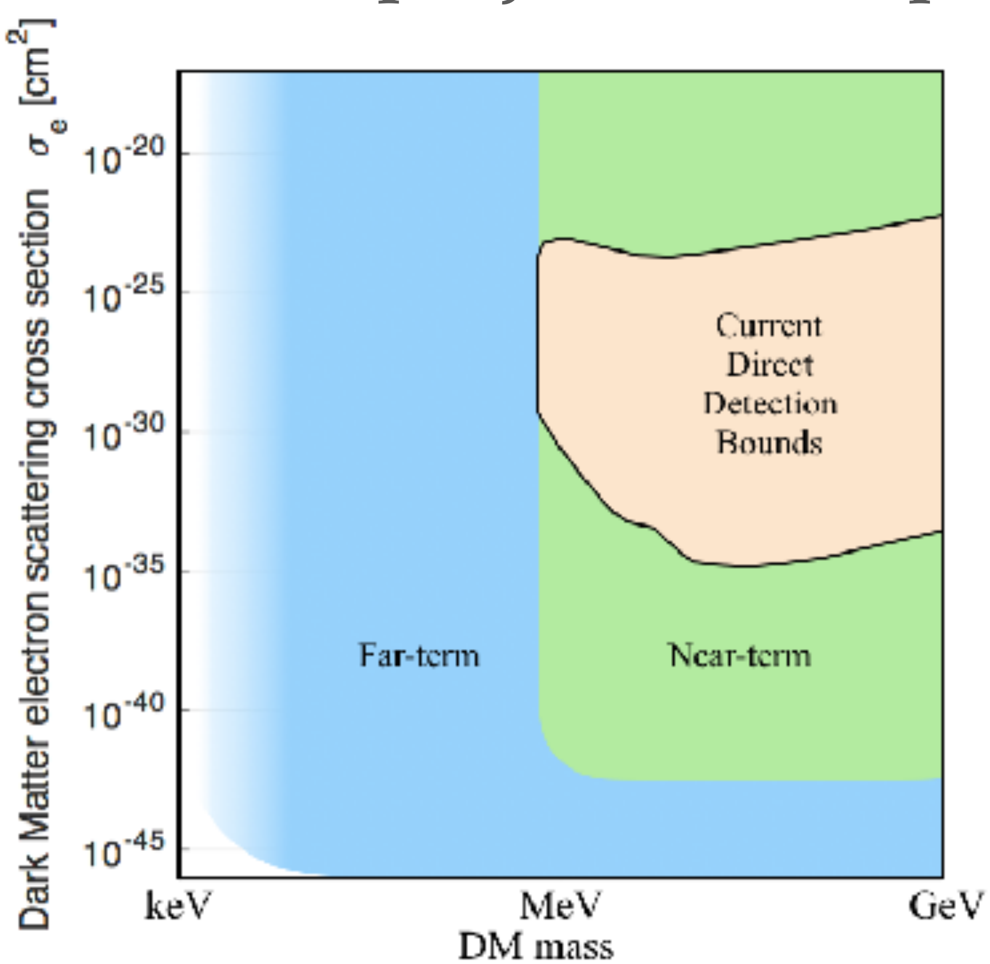
$$\langle n_e \sigma_{\rm abs} v_{\rm rel} \rangle_\gamma = -\frac{\mathrm{Im}\,\Pi(\omega)}{\omega}$$

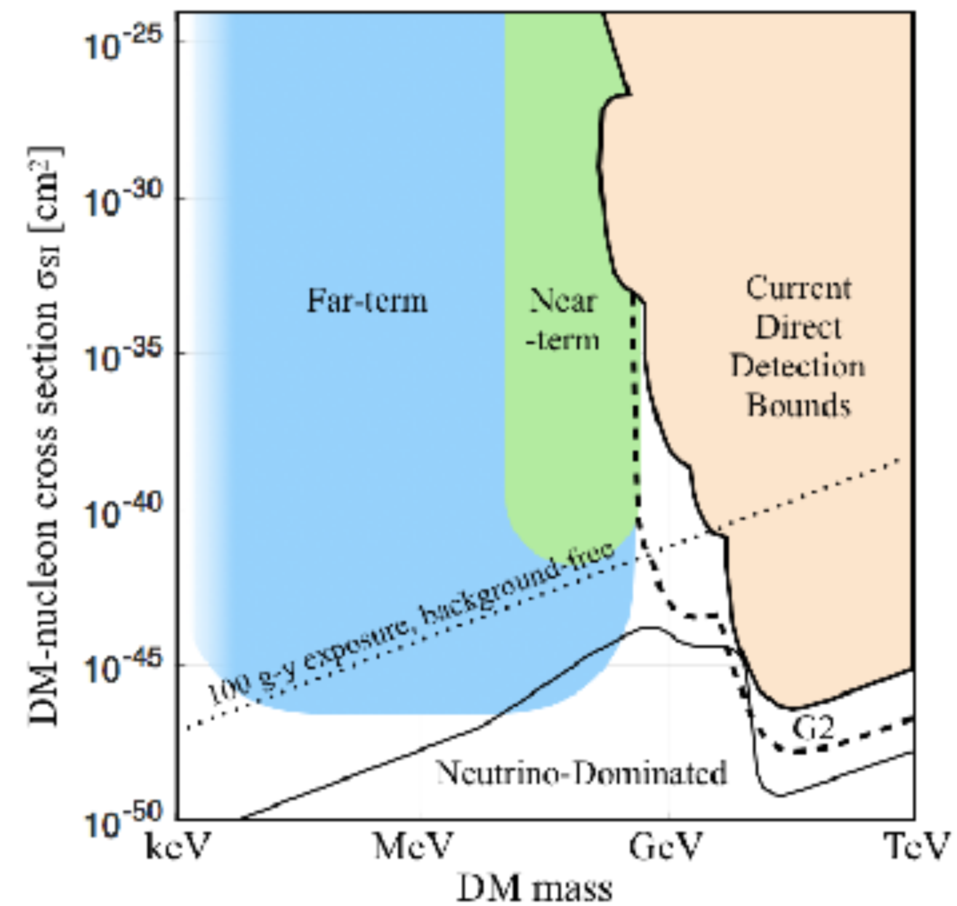




DARK MATTER NEW INITIATIVES

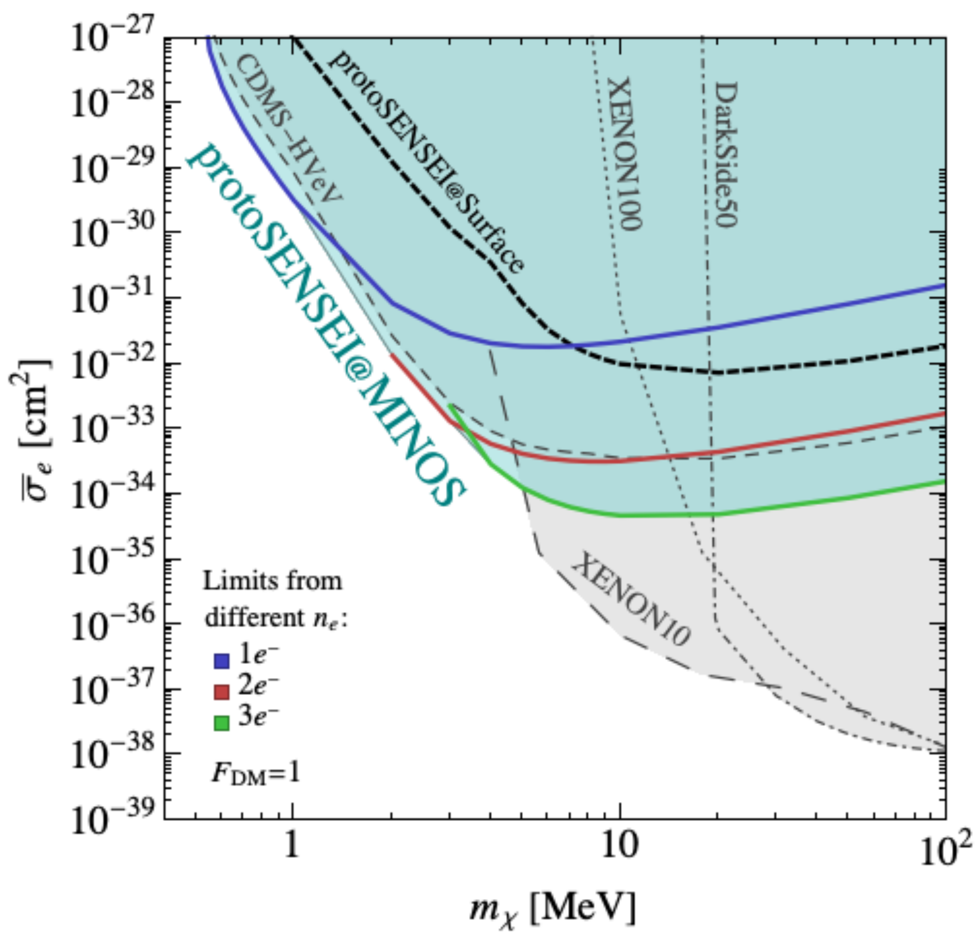
- A number of experimental proposals available both for small project development and R&D



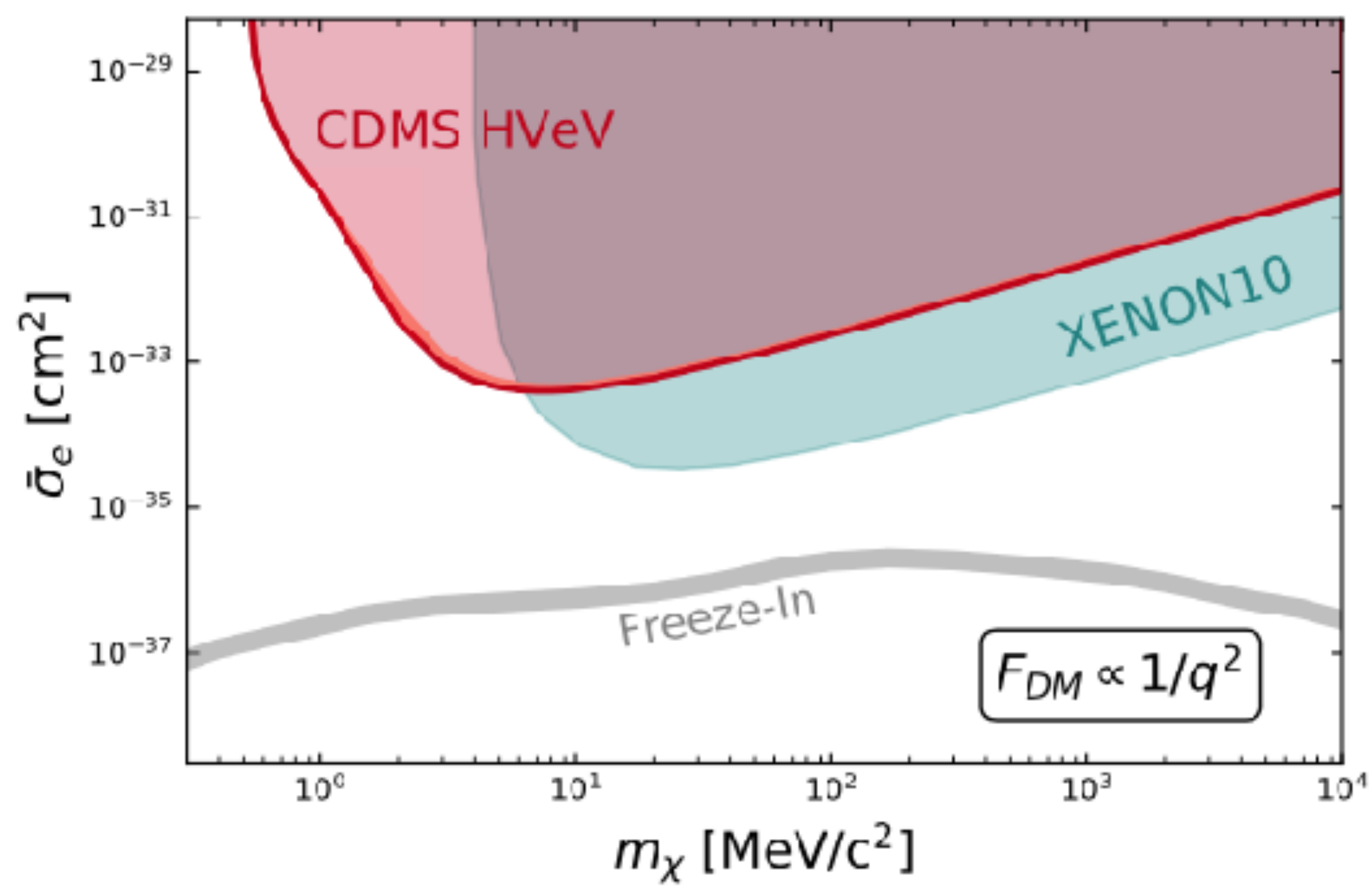


EXPERIMENTAL PROGRESS

- Results with small detectors already published



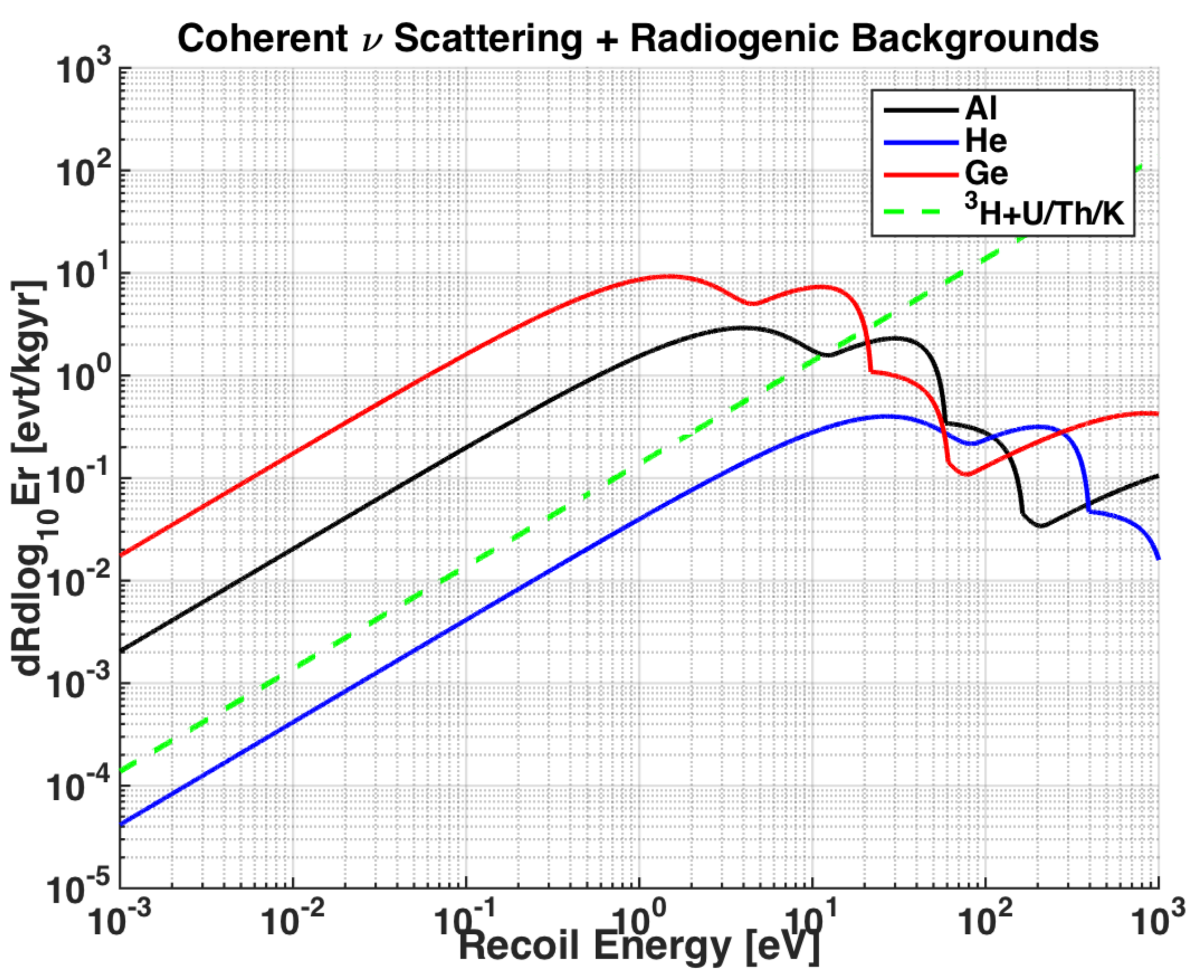
SENSEI Collaboration, 1901.10478



SuperCDMS 1804.10697

BACKGROUNDS AND A SOLAR NEUTRINO DETECTOR

- Radiogenic backgrounds improve with better energy resolution detectors — not a problem
- p+p solar neutrinos become important with kg-year exp



Recoil Energy Range [eV]	Integrated Scattering Rate [recoils $(\mathrm{kg{\cdot}yr})^{-1}$]		
	Ge	Si	He
<0.01	72	16	1.0
0.01–0.1	34	13	0.5
0.1–1	16	5	0.013
1–10	0.8	0.9	1.6×10^{-4}
>10	0.10	0.012	0.012

Coherent Photon Scattering

Need good photon veto

Hochberg, Pyle, Zhao, KZ 1512.04533

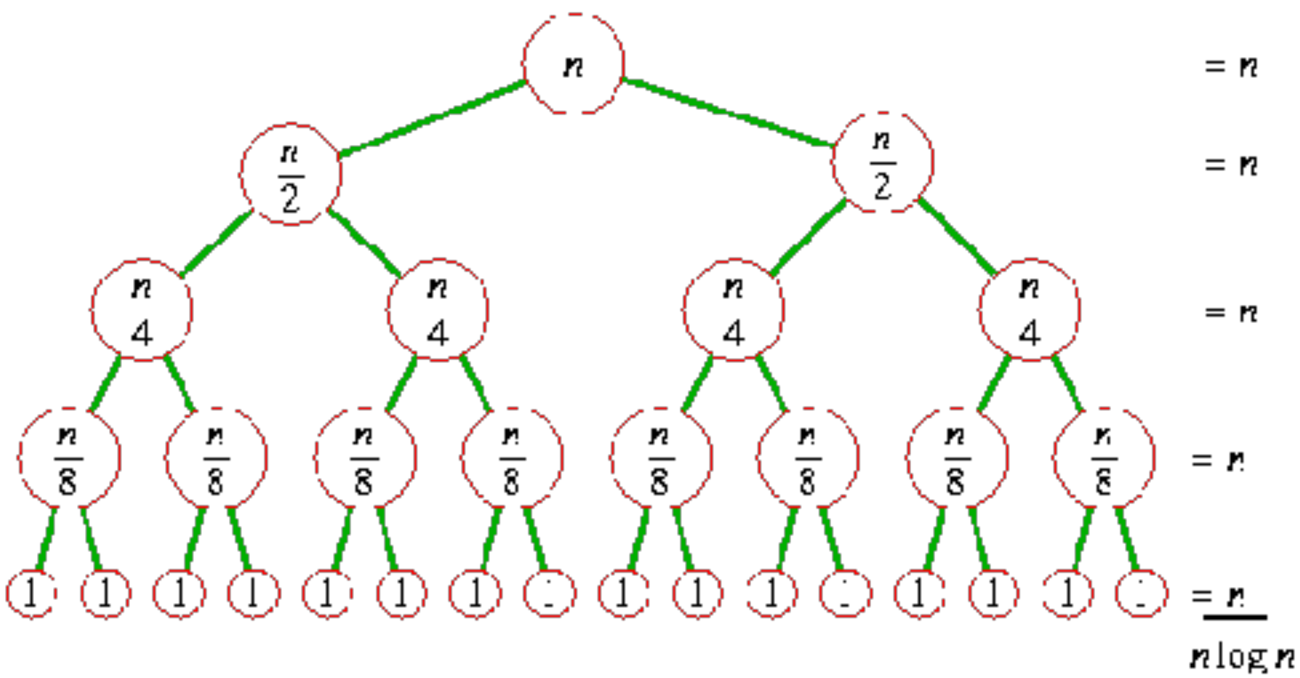
Robinson 2016

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!



The universe is dominated by invisibles!

WIMP or (axion)

How to be ready for anything? Hidden Sectors

How do I search for these things?