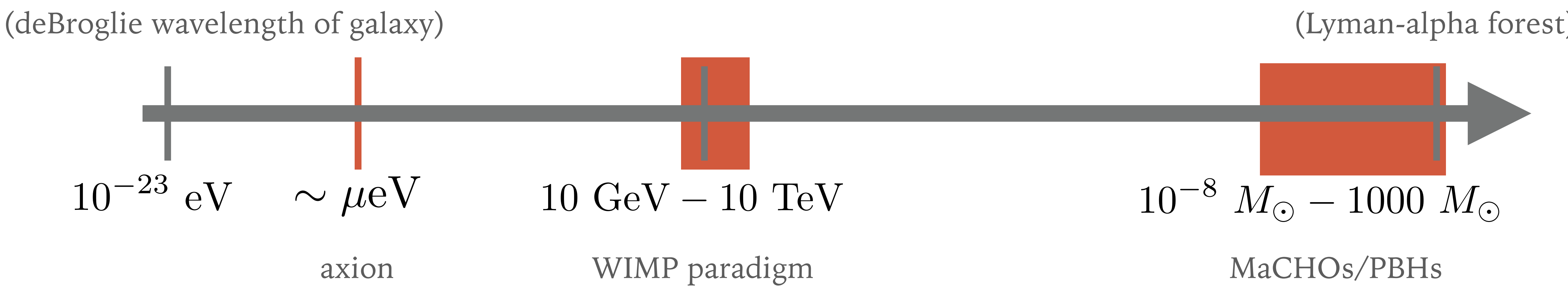
NEW IDEAS IN DARK MATTER DETECTION

Kathryn M. Zurek

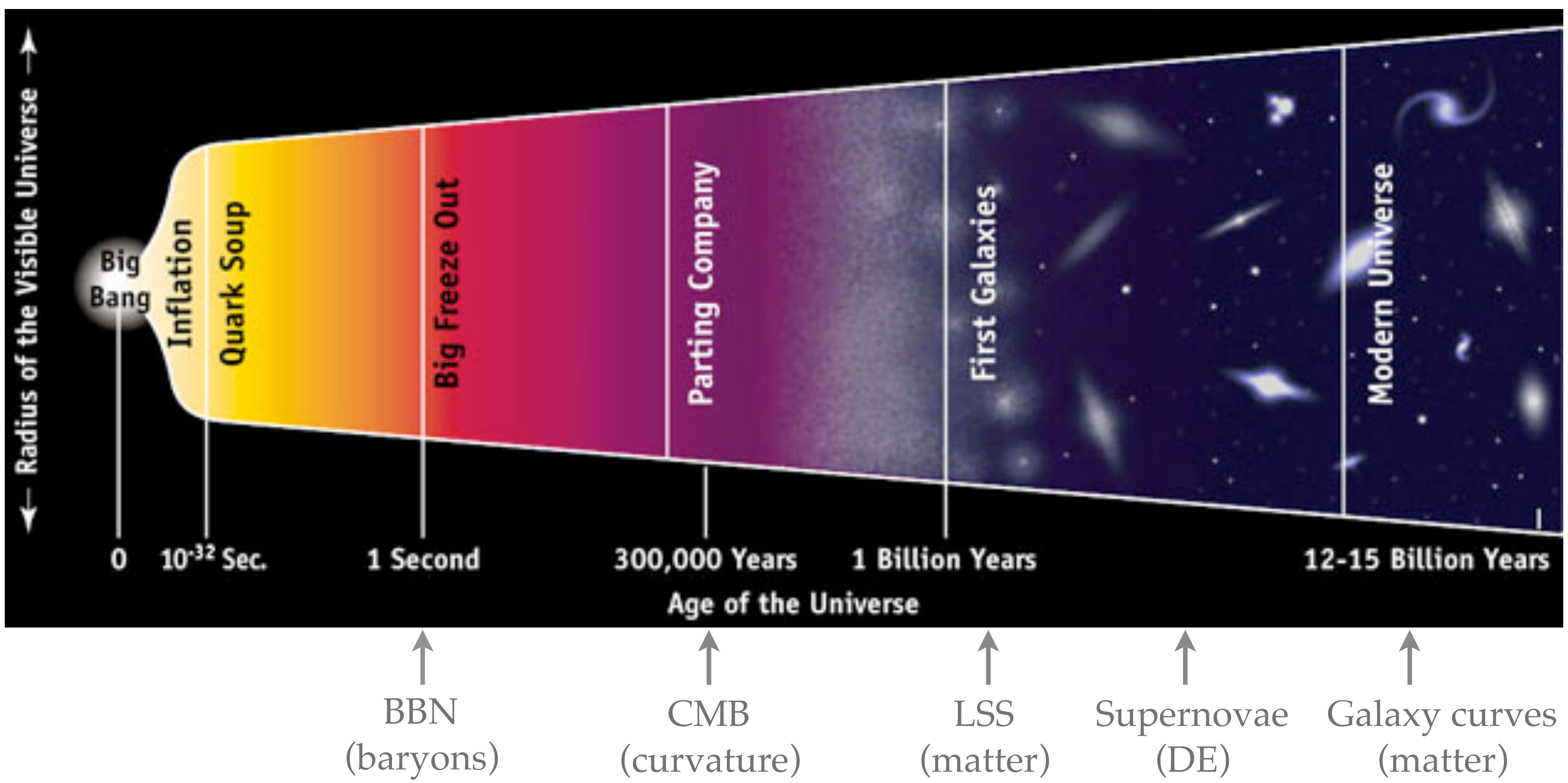
DARK MATTER DETECTION: A FULL COURT PRESS



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

DARK MATTER DETECTION: COSMOLOGICAL CONSISTENCY

- Any particle dark matter candidate must satisfy the entire range of observations. This alone gives us a lamplight.



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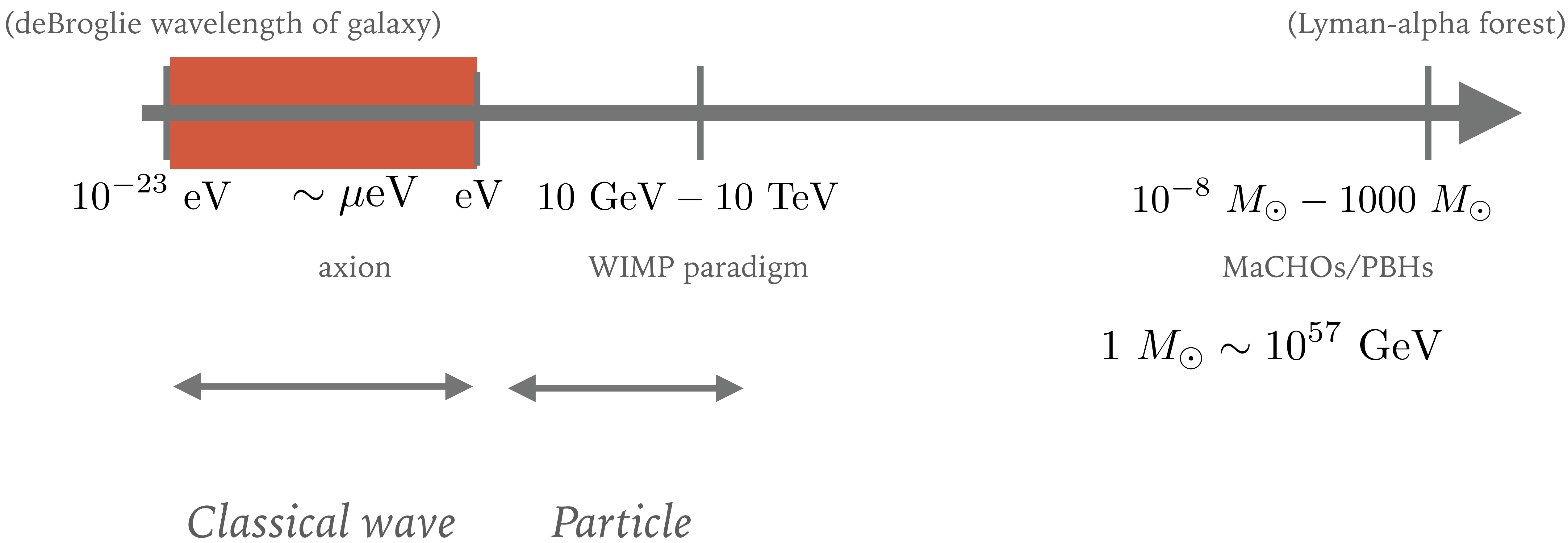

- Ultralight dark matter: dark matter behaves like a wave rather than an individual particle, e.g. axion
- Detection techniques focus on utilizing this coherence
- Cavities, AMO techniques *Talks of Baryakhtar, Irwin, Kahn, Winslow*

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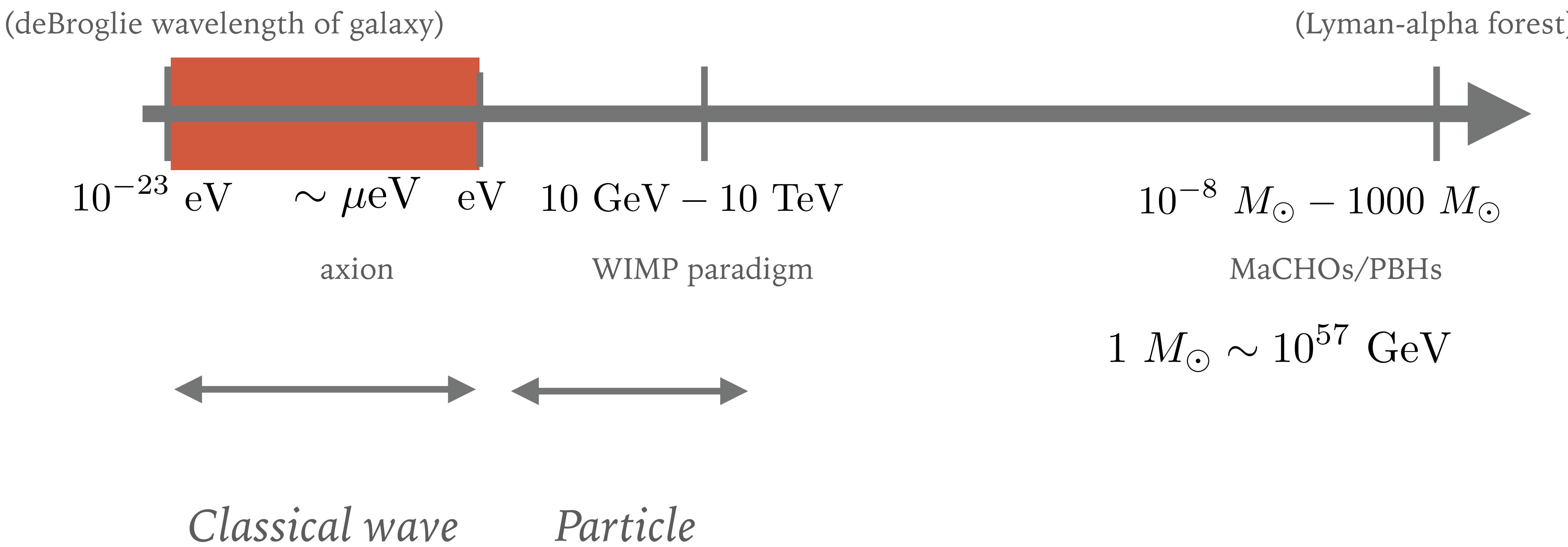
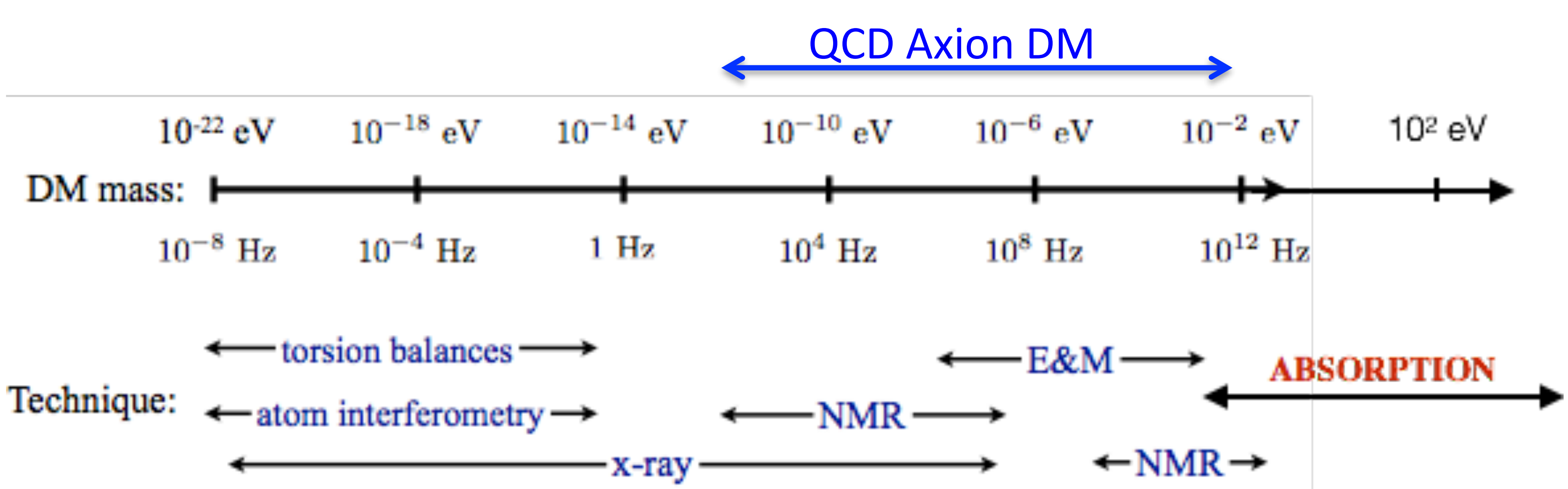
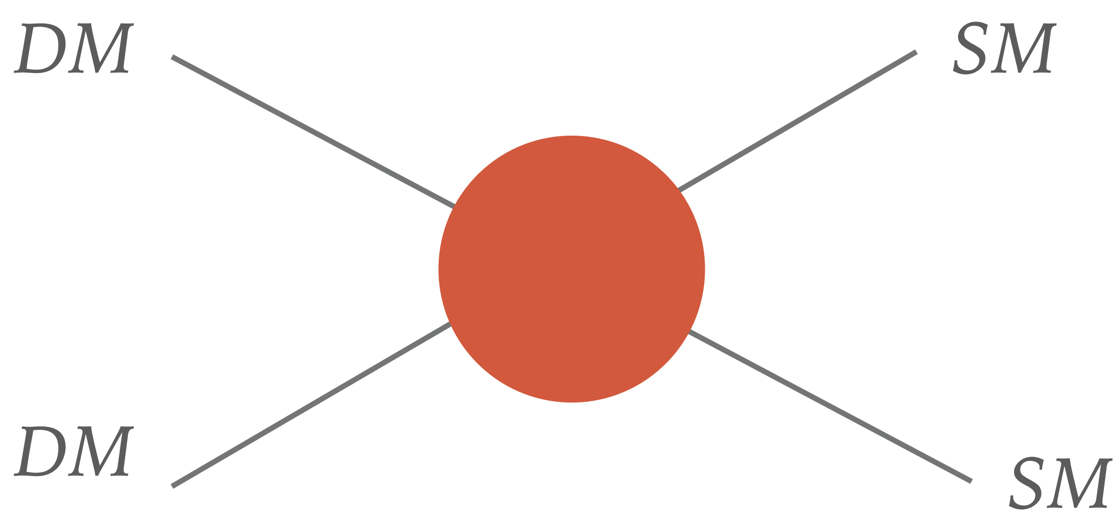




SETTING ABUNDANCE THROUGH INTERACTIONS WITH SM

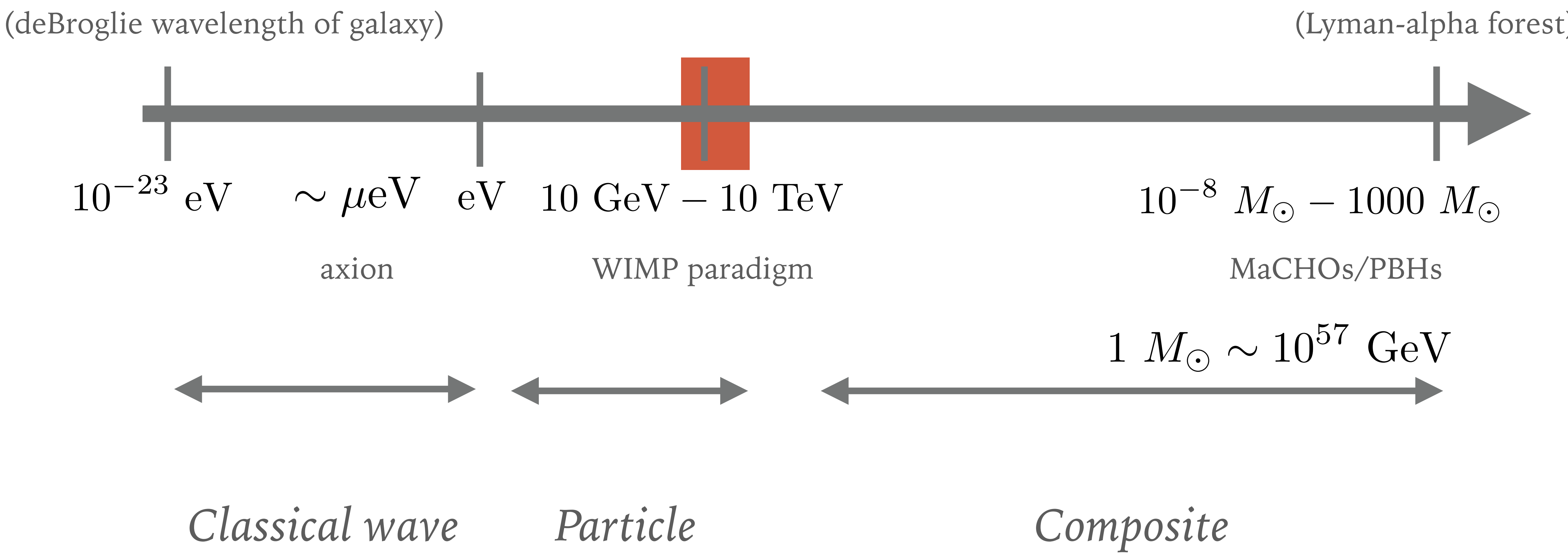
- Freeze-out paradigm



$$\rho_{DM} = \rho_{obs}$$

$$\langle \sigma v \rangle \simeq 3 \times 10^{-26}\ \mathrm{cm}^3/\mathrm{s}$$

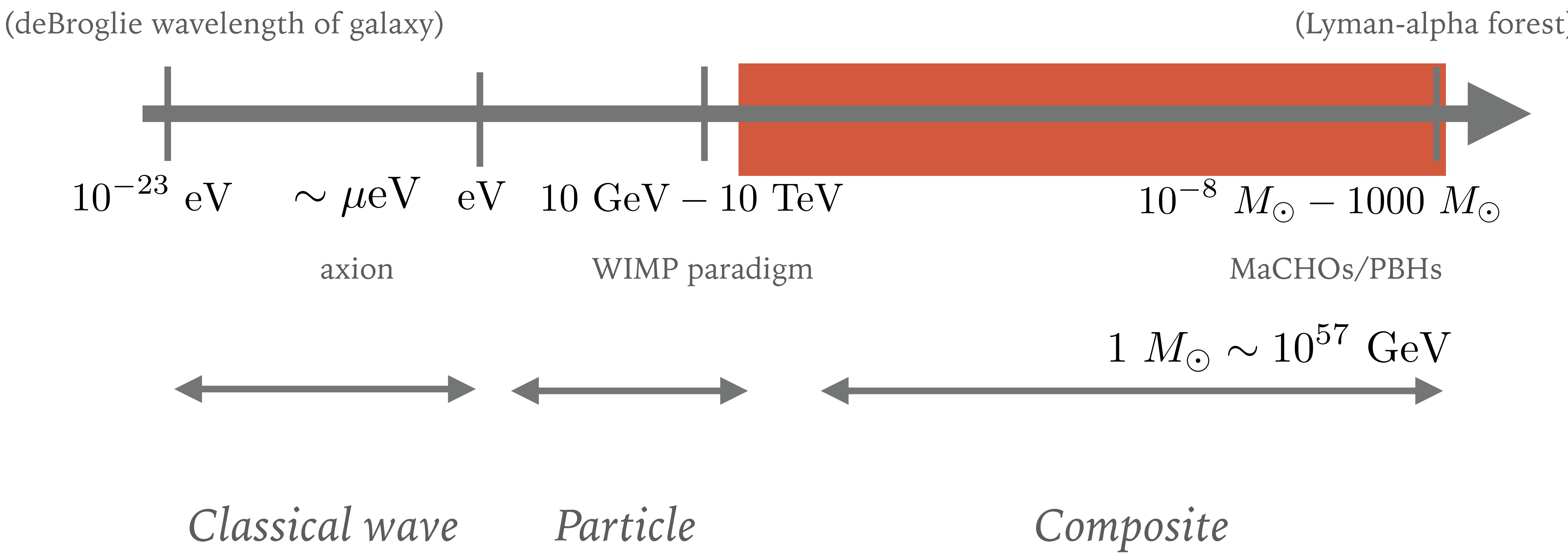
DARK MATTER DETECTION: A FULL COURT PRESS



- Weak forces have the right scale for abundance and cosmology

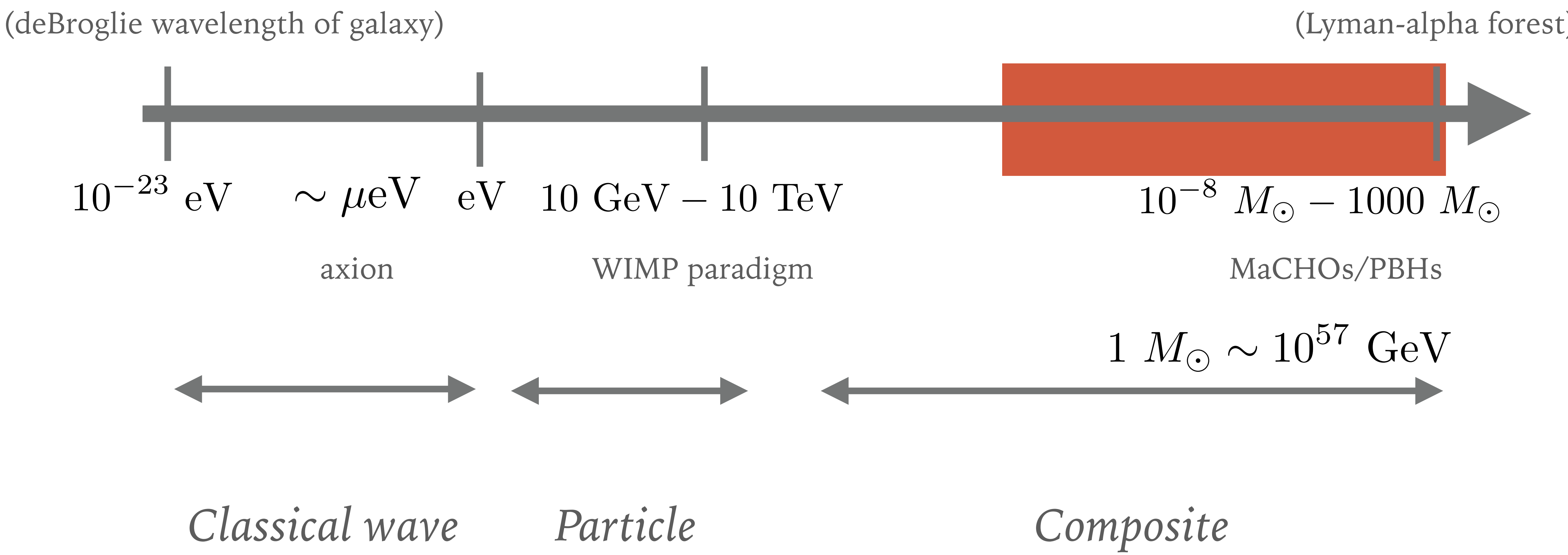
$$\sigma_{wk} v_{fo} \simeq \frac{g_{wk}^4 \mu_{XT}^2}{4\pi m_Z^4}\frac{c}{3} \simeq 10^{-24}\,\frac{\mathrm{cm}^3}{\mathrm{s}}\left(\frac{100\ \mathrm{GeV}}{M}\right)^2$$

DARK MATTER DETECTION: A FULL COURT PRESS



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

DARK MATTER DETECTION: A FULL COURT PRESS

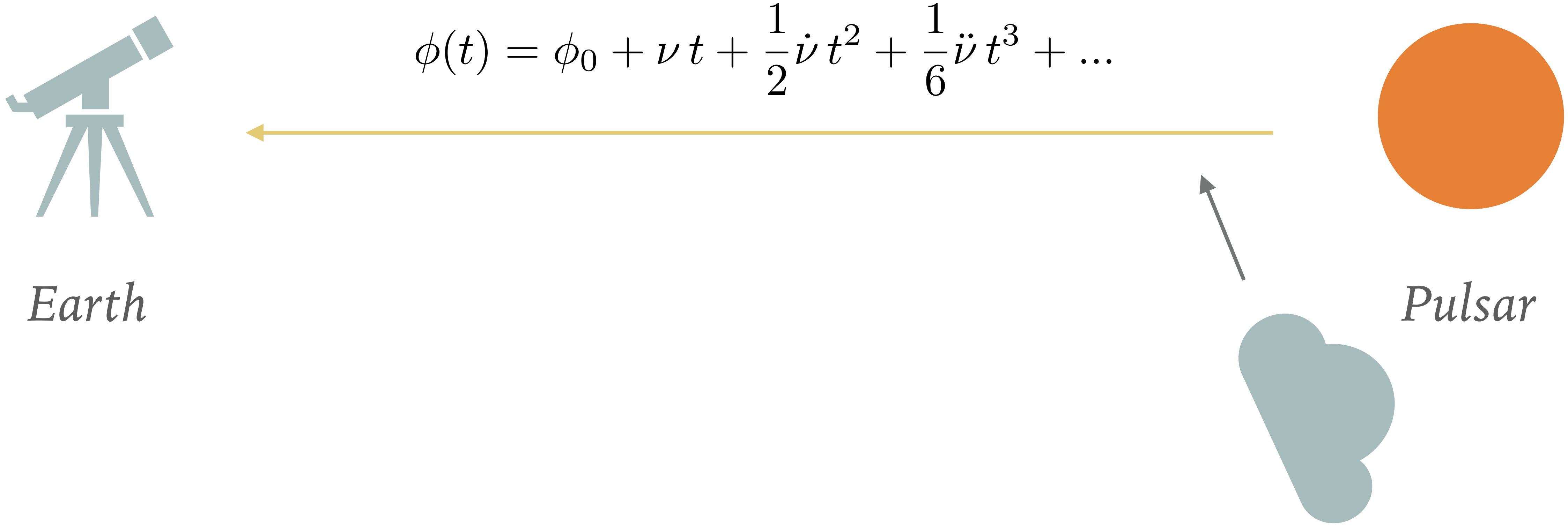


- Look for gravitational means to detect structure
- Above $10^{-13}\ M_\odot$ Pulsar timing can be effective
- Project of the (far) future to use laboratory clocks to detect small gravitational redshift effects

GRAVITATIONAL EFFECTS OF DARK MATTER SUBSTRUCTURE

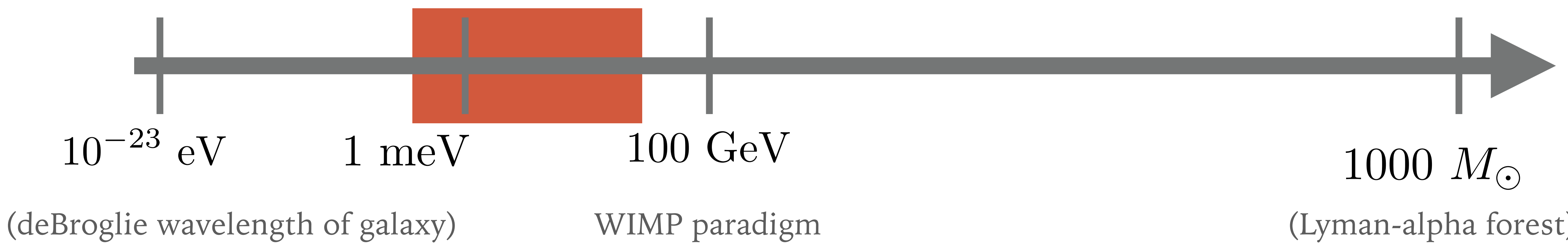
- Accurate clocks and transiting objects — the time-of-arrival of a pulse is very stable. Deviations can signal transiting object.

$$\phi(t) = \phi_0 + \nu\, t + \frac{1}{2}\dot{\nu}\, t^2 + \frac{1}{6}\ddot{\nu}\, t^3 + \ldots$$



- Principle can be applied to many systems with accurate clocks   *Talk of Carney*

DARK MATTER DETECTION: A FULL COURT PRESS

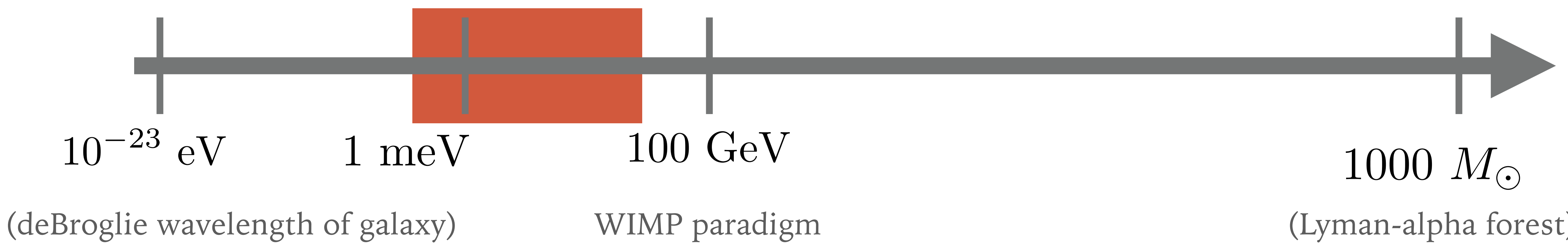


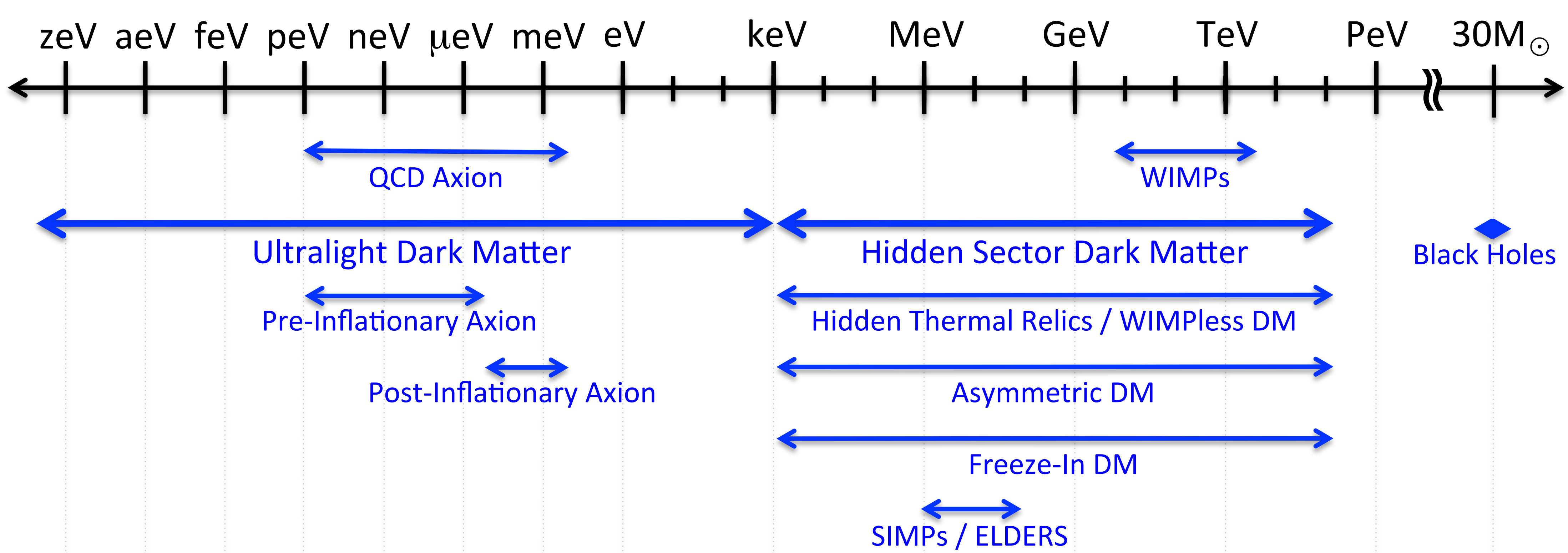
- Intermediate range where observation via particle interactions with SM is still highly motivated though not detectable with traditional WIMP experiments

Talk of Pyle, Zhang

- Arise generically in top-down constructions — hidden sector/valley paradigm

DARK MATTER DETECTION: A FULL COURT PRESS





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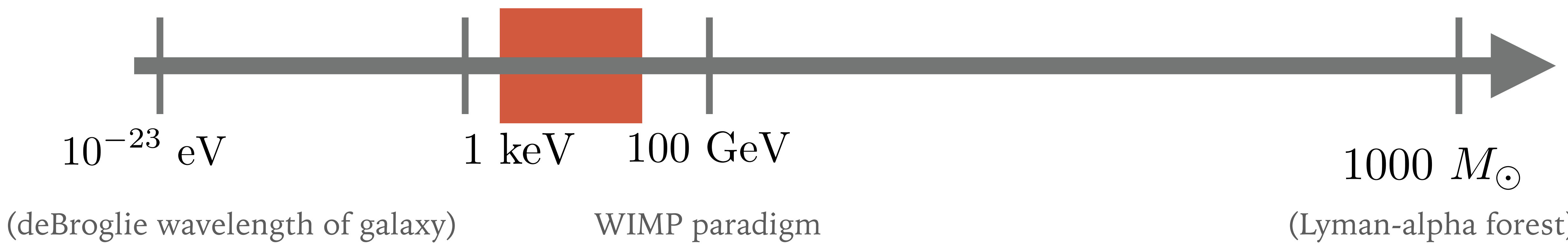


- Dark sector dynamics are complex and astrophysically relevant.

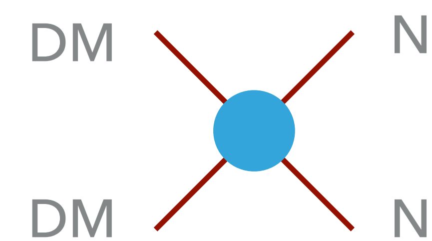
$$\sigma_{str} \simeq \frac{4\pi\alpha_s^2}{M^2} \simeq 10^{-24}\ \mathrm{cm}^2 \left(\frac{1\ \mathrm{GeV}}{M}\right)^2$$

- 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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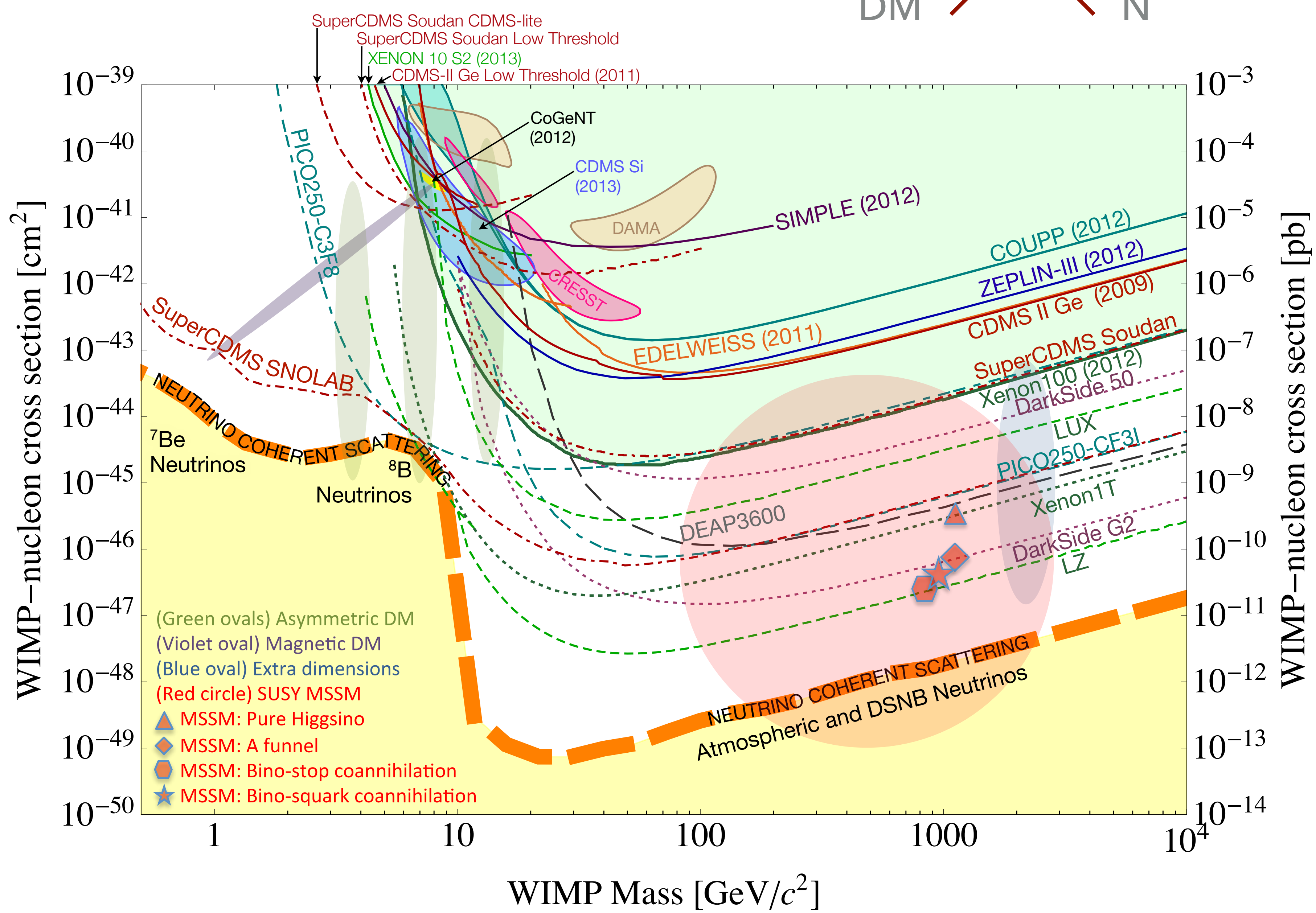
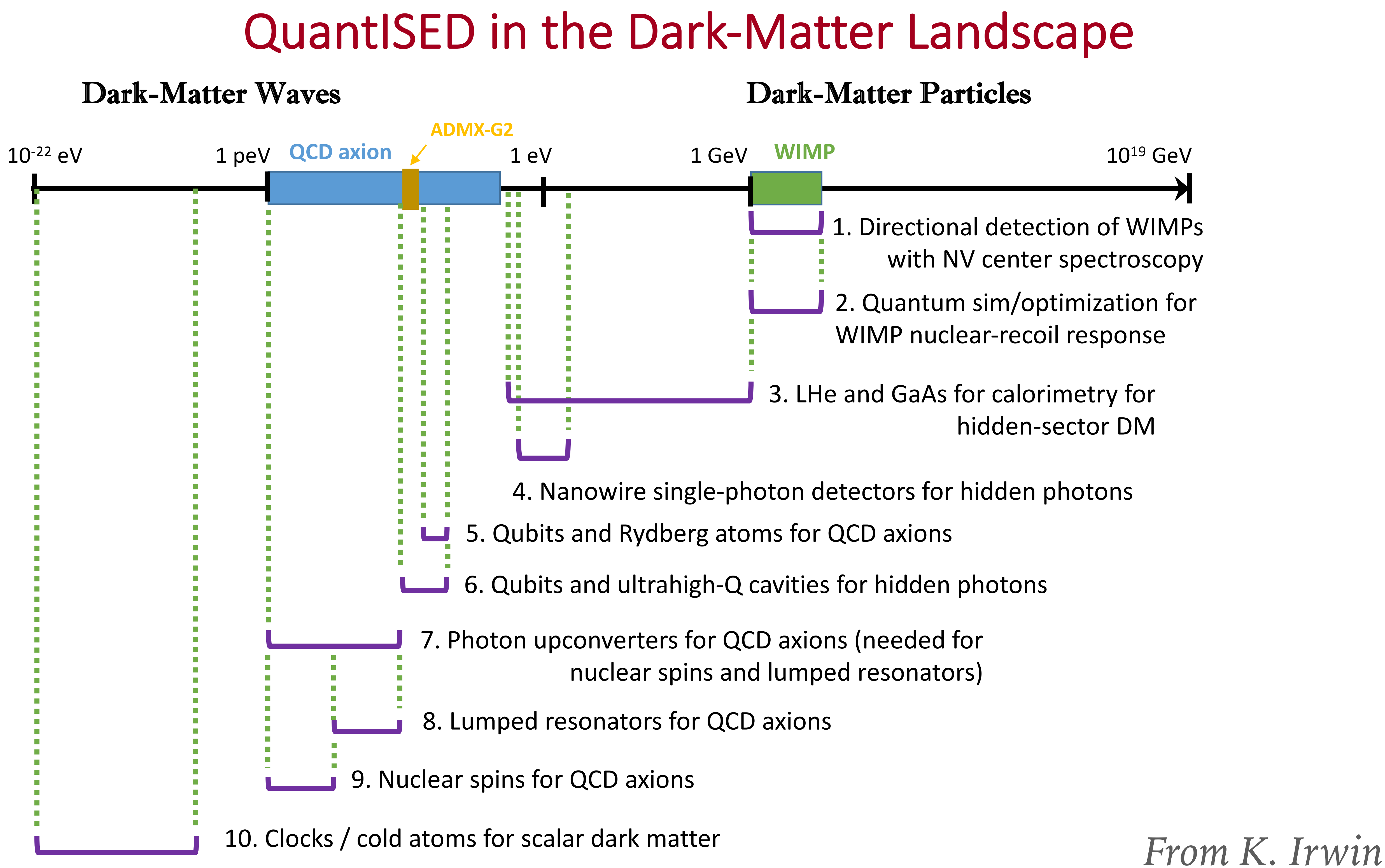


WHY QIS?

- Technology for detecting weak fields and single quanta is directly connected to technologies for QIS
  - Quantum sensing
  - For wave DM, that implies utilizing e.g. entanglement and squeezing
  - For particle DM, that implies sensing single photons, electrons and phonons *Talk of Noroozian, Nam*
- SQUIDs (weak magnetic fields), SNSPDs (single photons), TES and MKIDs (single electrons, phonons) — superconducting sensors

WHY QIS?


QuantISED in the Dark-Matter Landscape
Dark-Matter Waves
Dark-Matter Particles
ADMX-G2
10^{-22} eV
1 peV
QCD axion
1 eV
1 GeV
WIMP
10^{19} GeV
1. Directional detection of WIMPs with NV center spectroscopy
2. Quantum sim/optimization for WIMP nuclear-recoil response
3. LHe and GaAs for calorimetry for hidden-sector DM
4. Nanowire single-photon detectors for hidden photons
5. Qubits and Rydberg atoms for QCD axions
6. Qubits and ultrahigh-Q cavities for hidden photons
7. Photon upconverters for QCD axions (needed for nuclear spins and lumped resonators)
8. Lumped resonators for QCD axions
9. Nuclear spins for QCD axions
10. Clocks / cold atoms for scalar dark matter
From K. Irwin

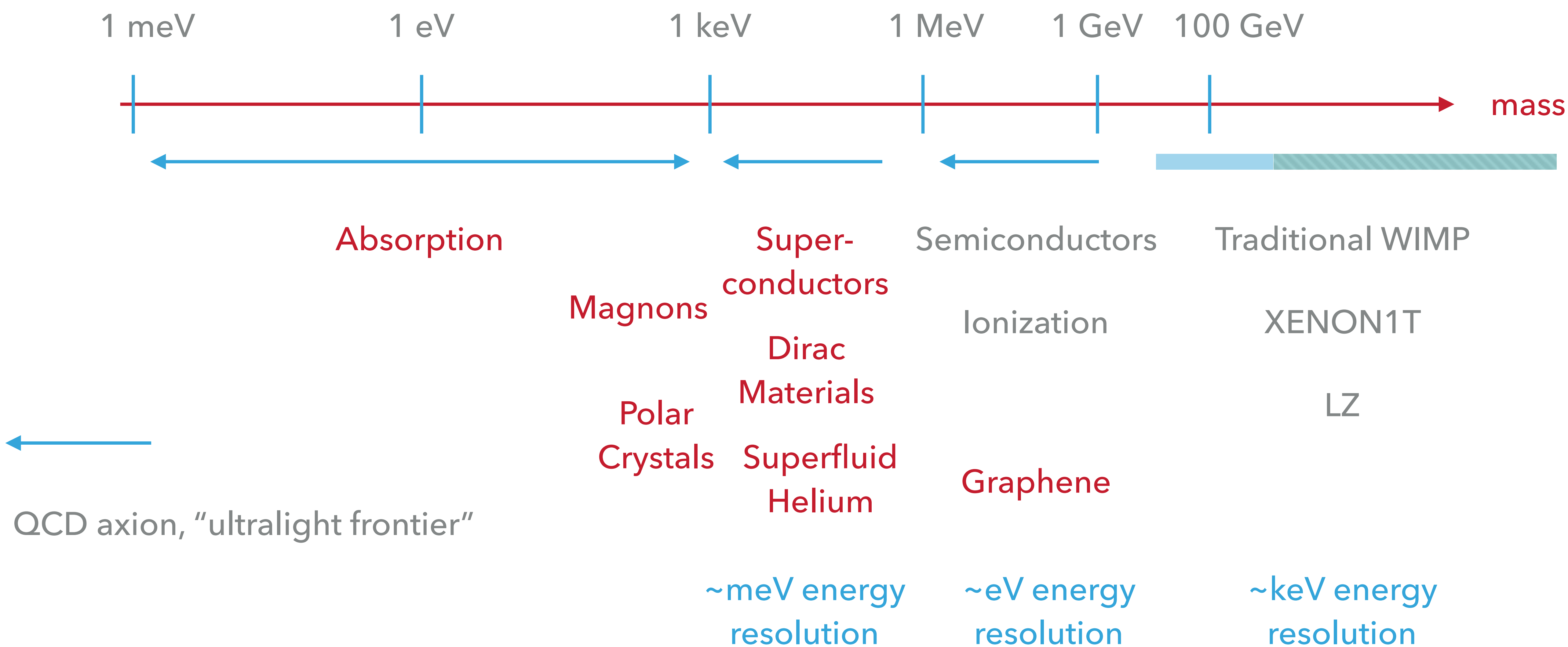
WHY QIS?

- Highlight three:

1. single electron excitation in silicon by DM and detection with CCDs
2. single optical phonon excitation by DM in polar materials and detection with superconducting sensors (TESs)
3. quantum material design

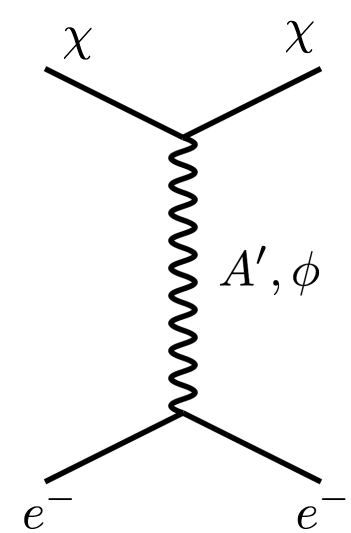
NEW IDEAS IN DARK MATTER DETECTION

- Experimental Panorama



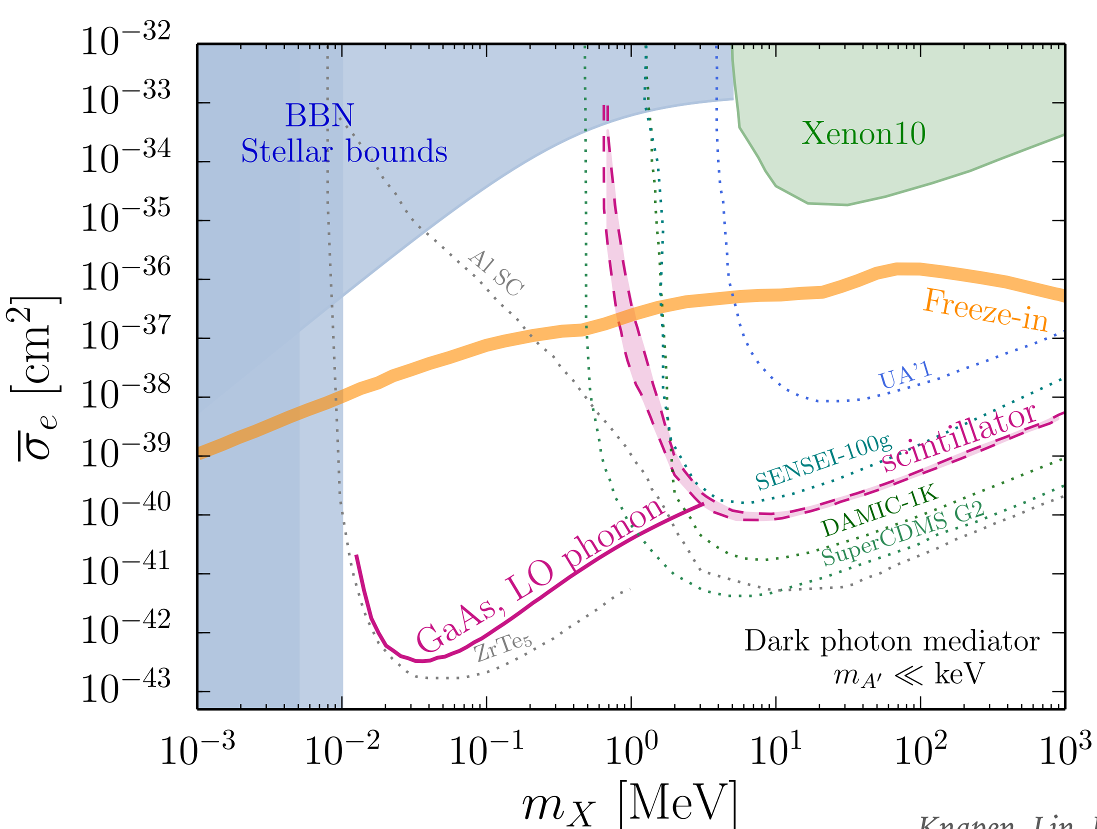
DM ABUNDANCE AS A GUIDE

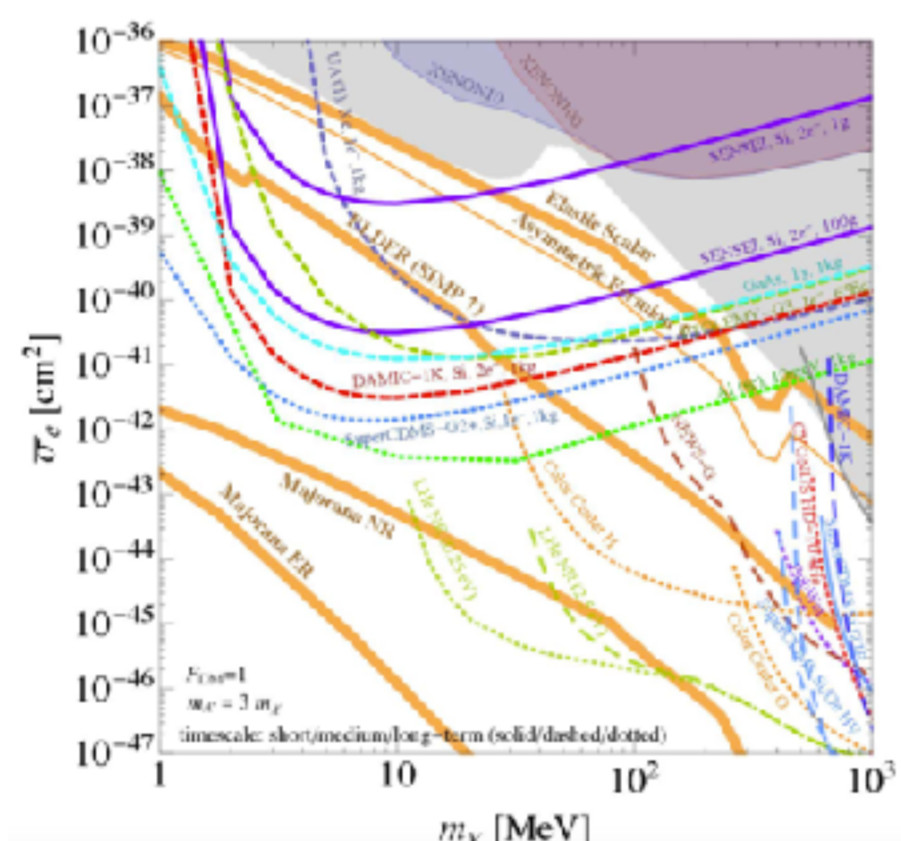
- If DM abundance is related to its coupling to the SM in any way, that provides a guide where to look



Freeze-in

Asymmetric Dark Matter





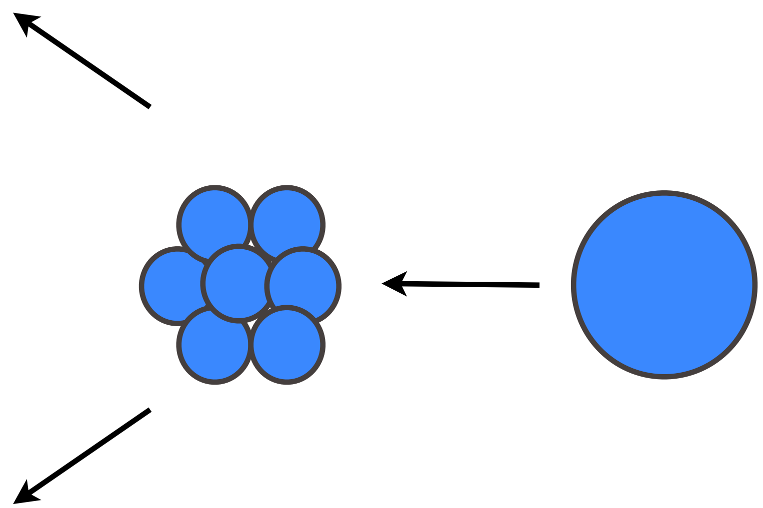
Knapen, Lin, Pyle KZ 1712.06598

US Cosmic Visions 1707.04591

LIGHTER TARGETS FOR LIGHTER DARK MATTER

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

$q, \; E_D$



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

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

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

LIGHTER TARGETS FOR LIGHTER DARK MATTER (1)

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

- In insulators, like xenon

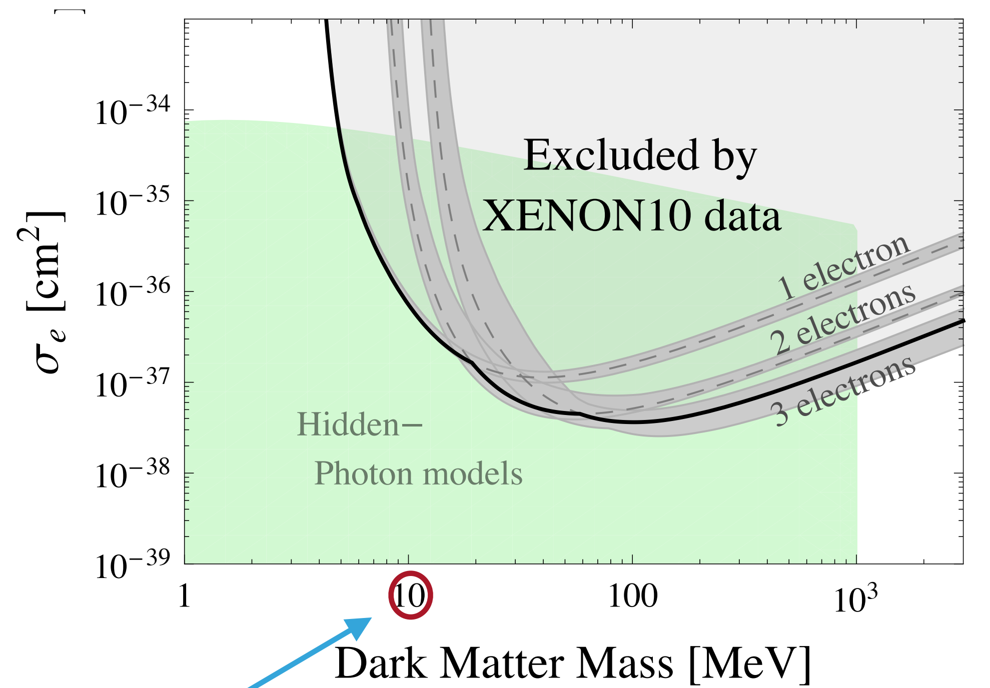
  Tightly bound; ionize for signal

- In semi-conductors, like Ge, Si

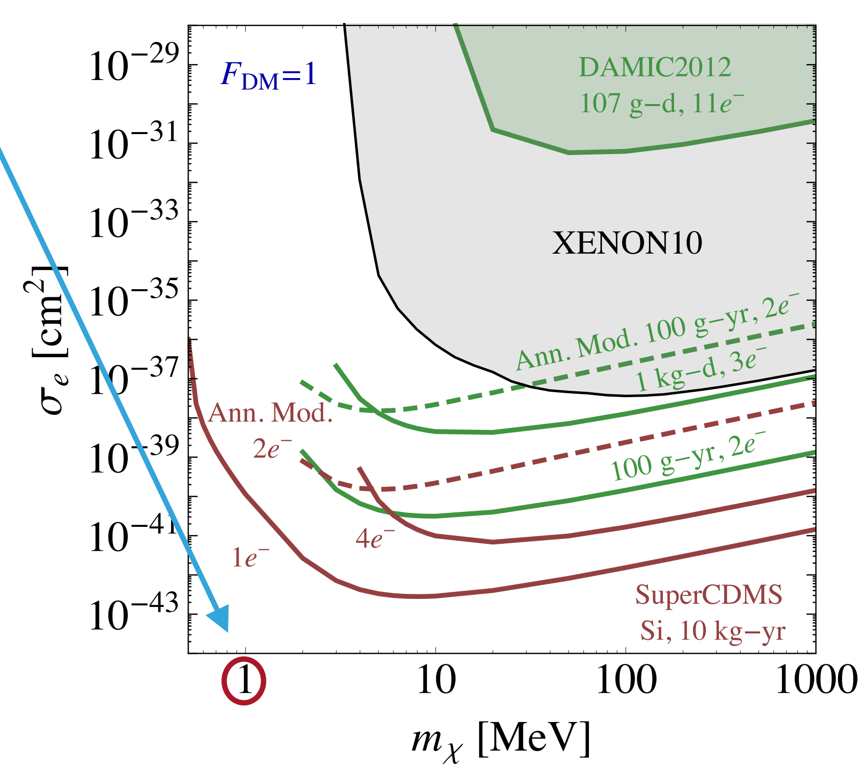
  Excite electron to conduction band

Gap = DM Kinetic Energy

P. Sorensen et al 1206.2644

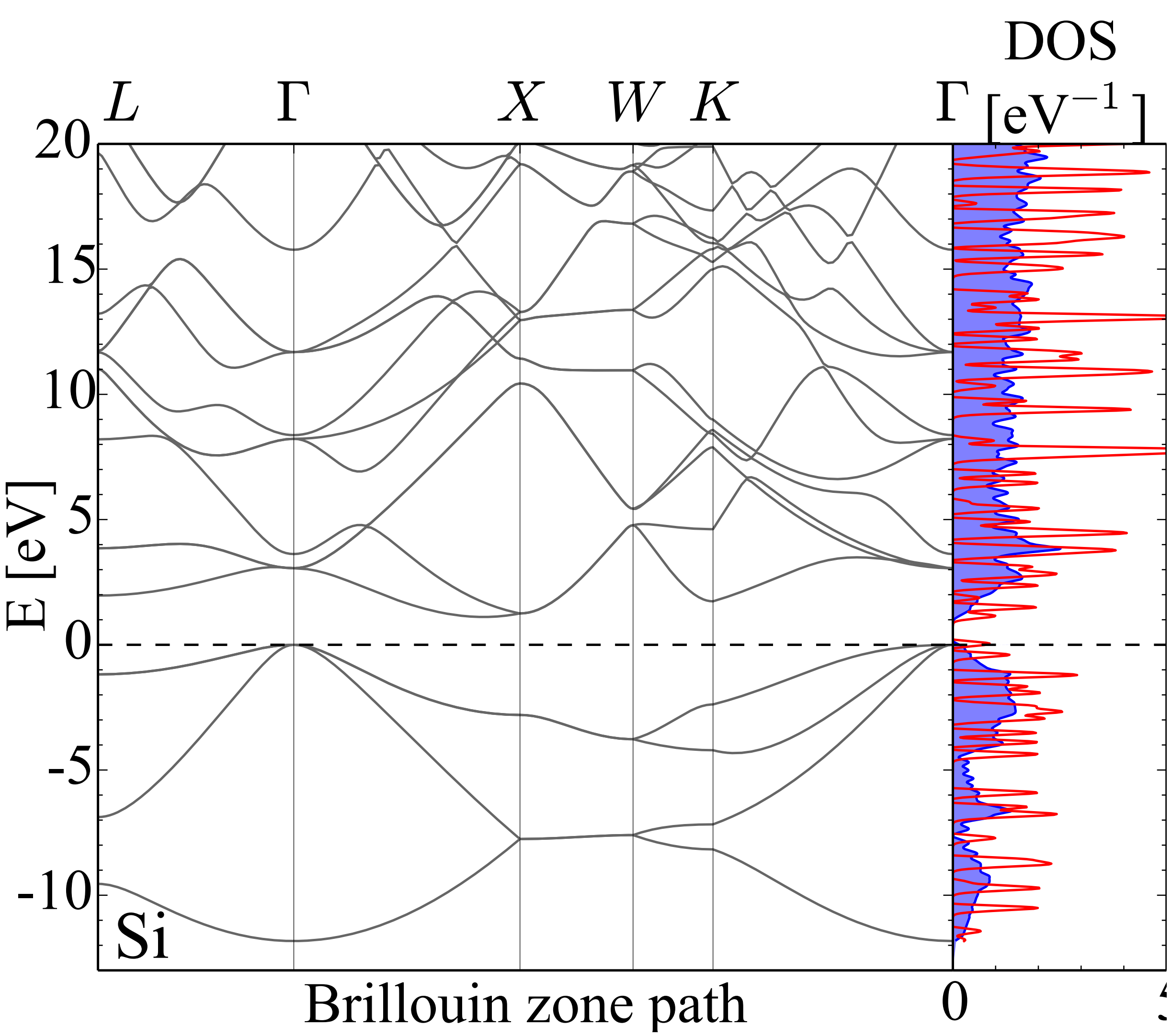


Essig et al 1509.01598



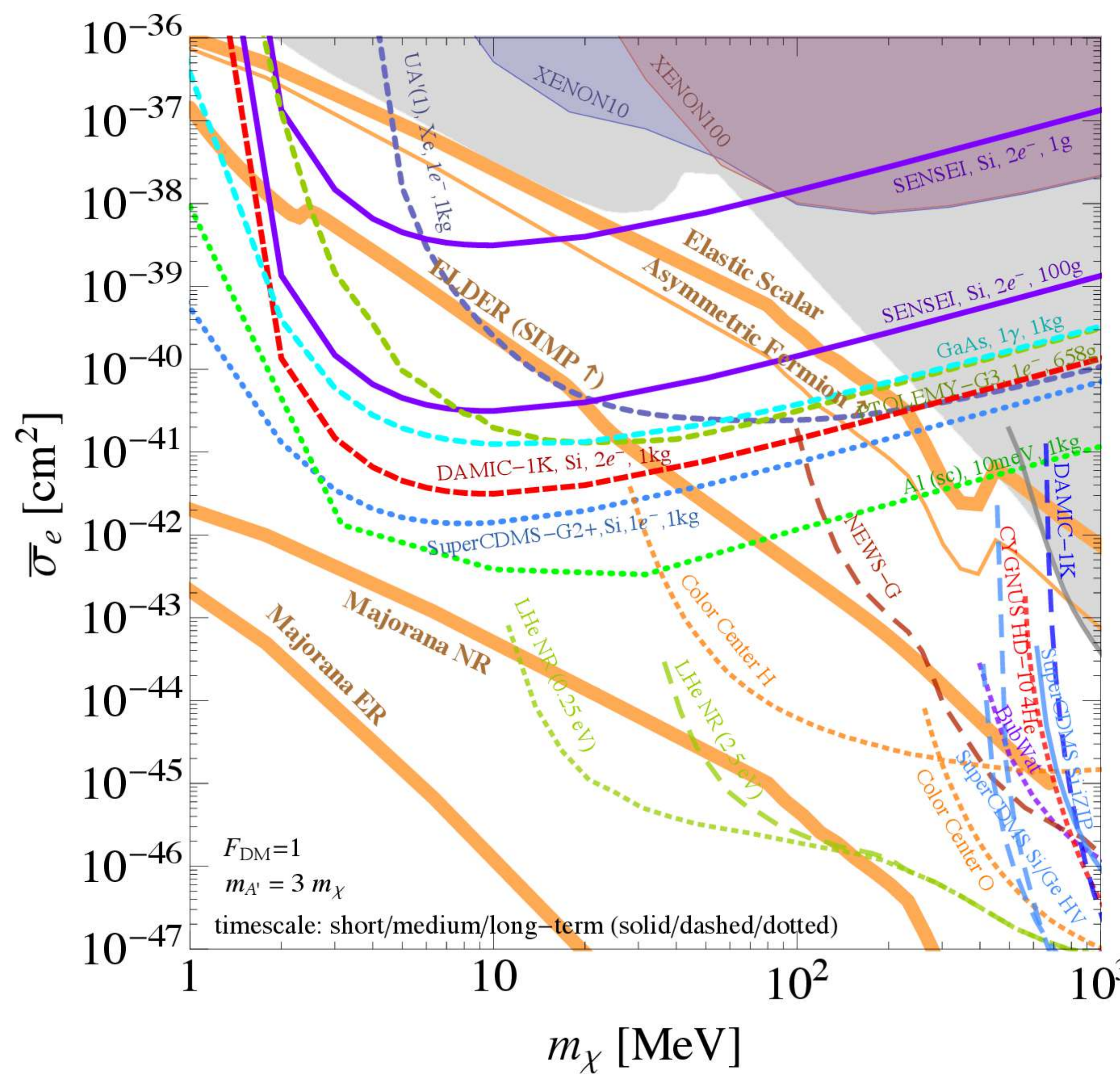
ELECTRON EXCITATION IN SEMICONDUCTORS (1)

- Silicon semiconductors lend themselves well to light dark matter detection above an MeV



Essig et al 1509.01598

U.S. Cosmic Visions 2017



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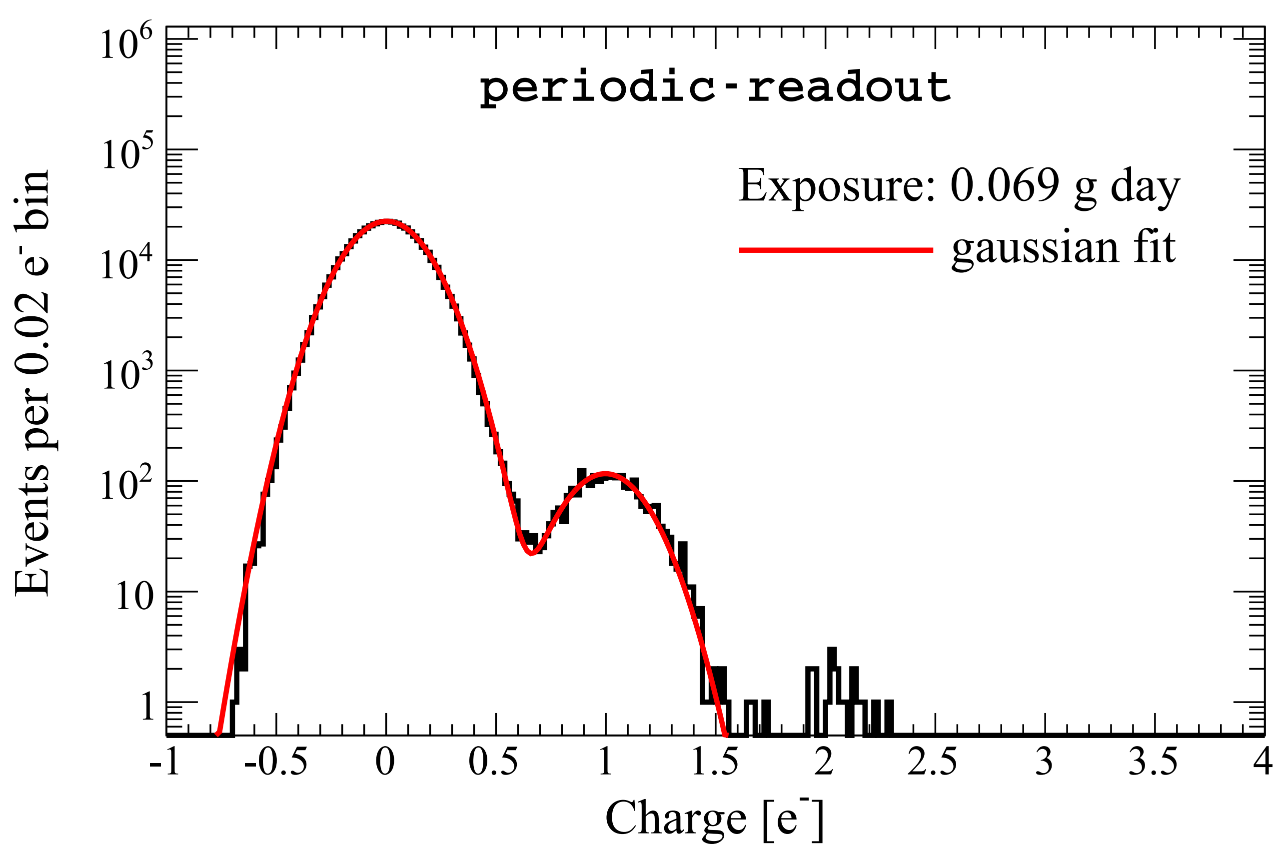
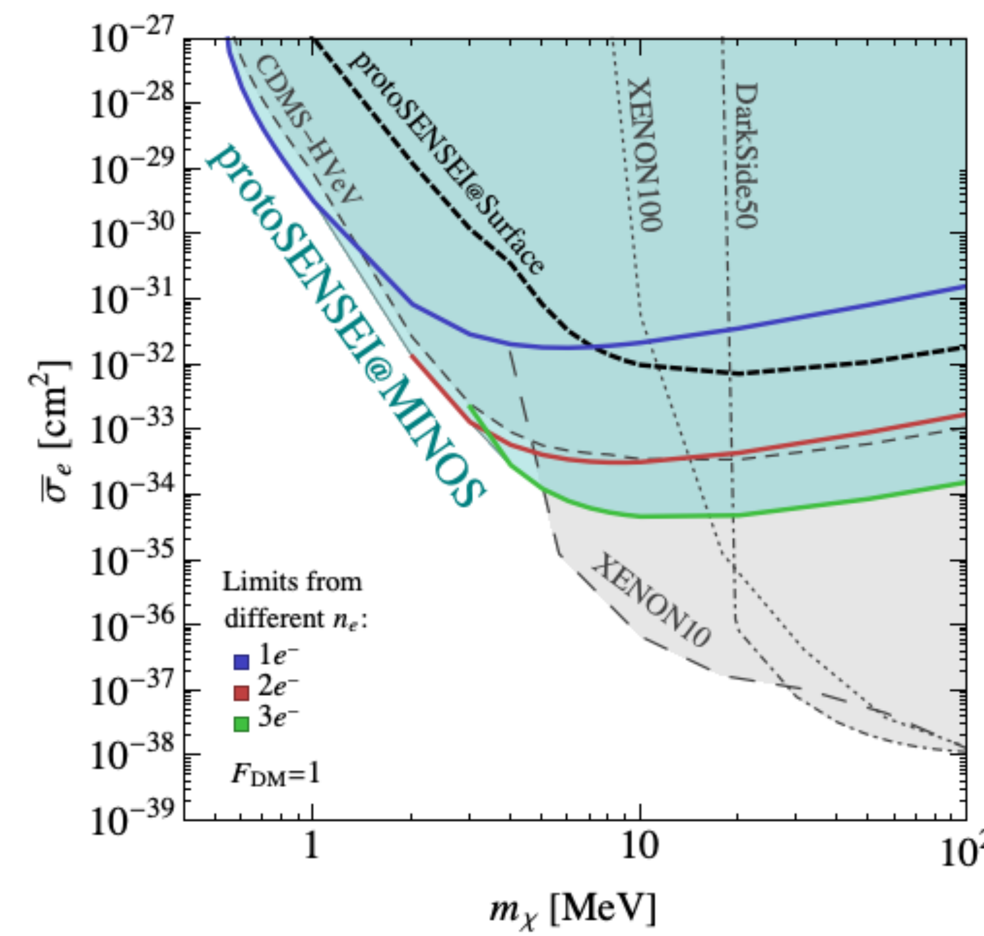




SENSEI Collaboration, 1901.10478

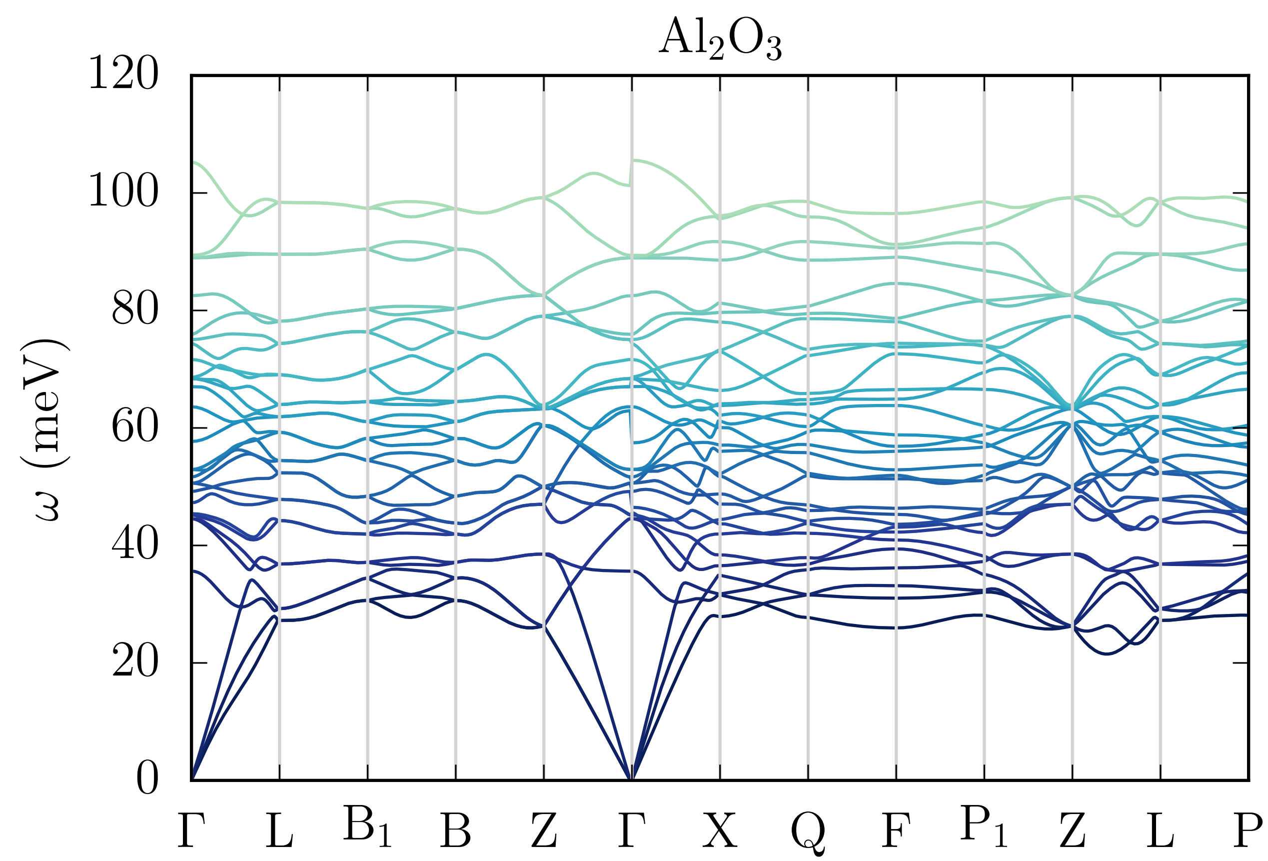
EXCITING COLLECTIVE MODES (2)

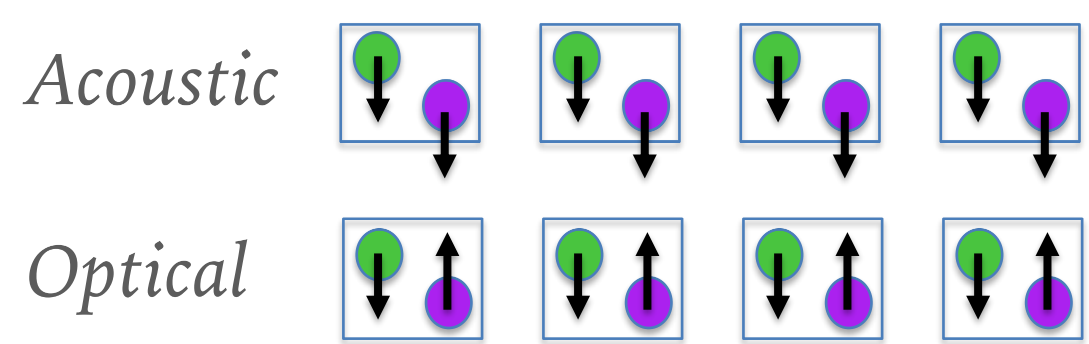
- Once DM drops below an MeV, its deBroglie wavelength is longer than the inter particle spacing in typical materials
- Therefore, coupling to collective excitations in materials makes sense!
- Collective excitations = phonon modes, spin waves (magnons)
- Can be applied to just about any material
- (partial) 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 MODES (2)

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

Sapphire





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

KINEMATICS OF COLLECTIVE MODES (2)

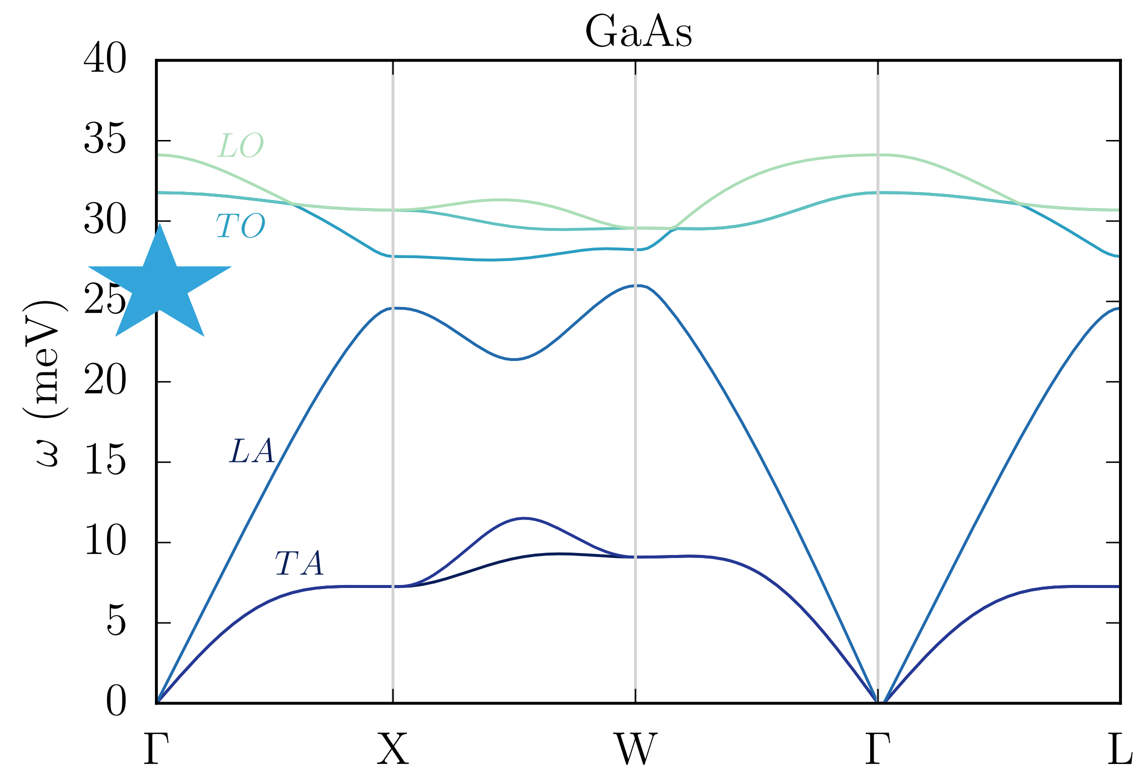
- First element to enter is the kinematics

$$E_D \sim v_X q$$

vs

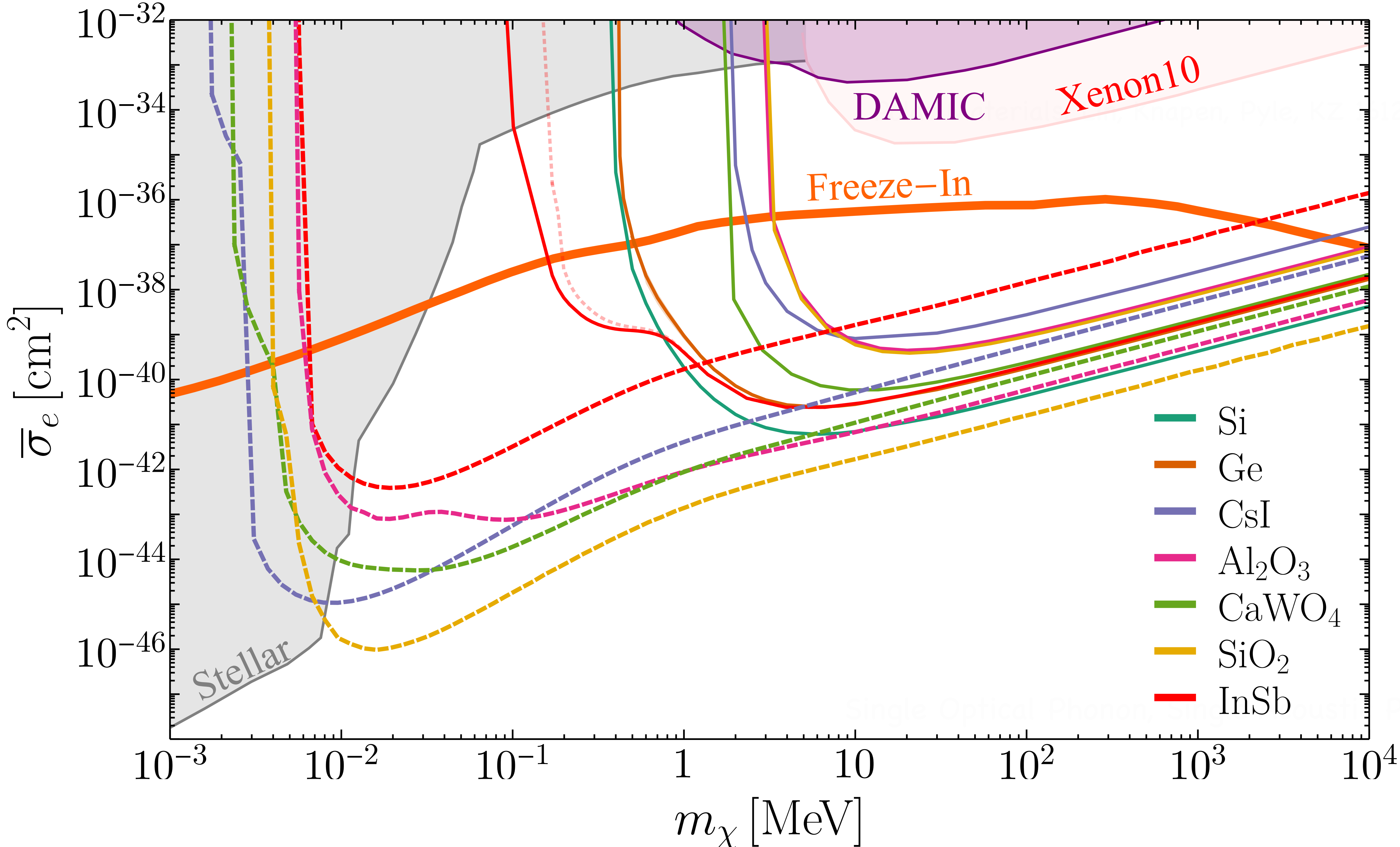
$$E_D \sim c_s q$$

$$c_s \ll v_X$$



- Better coupling to gapped modes

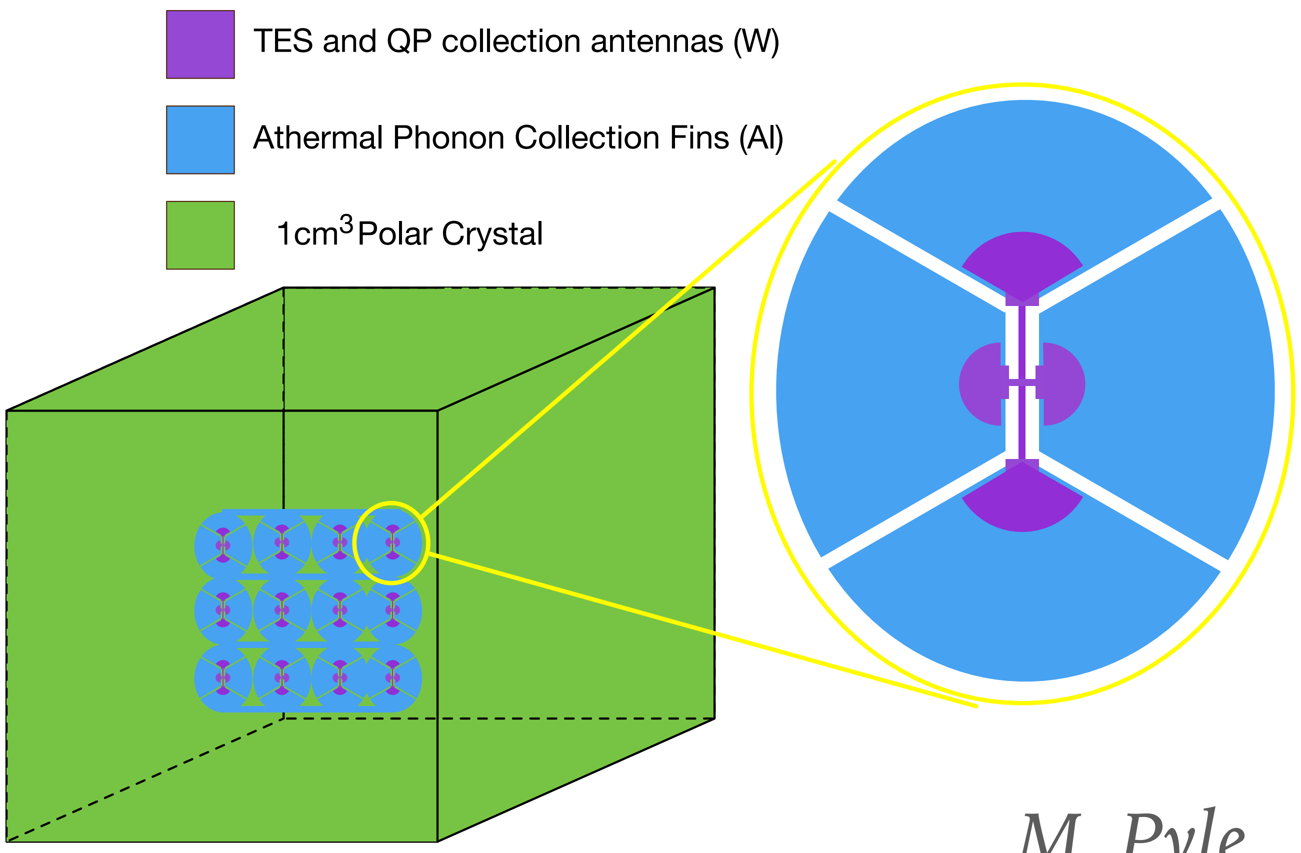
OPTICAL PHONONS IN POLAR MATERIALS (2)



Griffin, Inzani, Trickle, Zhang, KZ, 1910.10716

COMMON R&D PATH

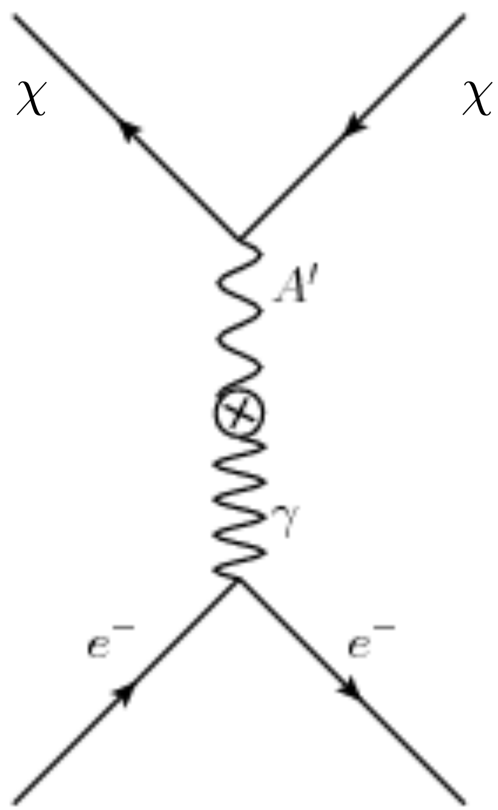
- Sensor can be coupled to multiple targets
- Zero-field read-out of phonons
- For a polar crystal target — Sub-eV Polar Interactions Cryogenic Experiment (SPICE)



M. Pyle

QUANTUM MATERIALS AND DM DETECTION (3)

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



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

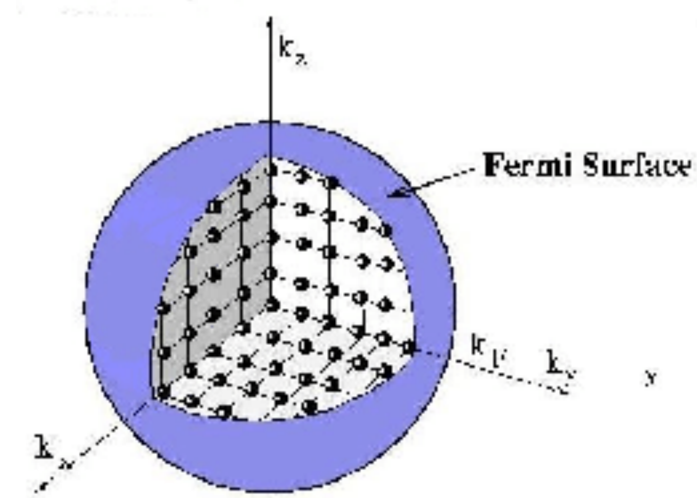
Polarization tensor characterizes in-medium optical response

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

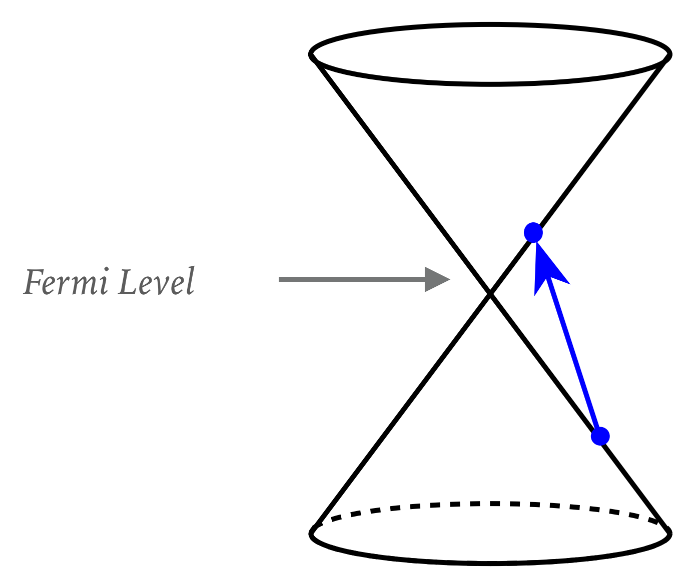
OPTICAL RESPONSE OF “SEMI-METALS (3)

- 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

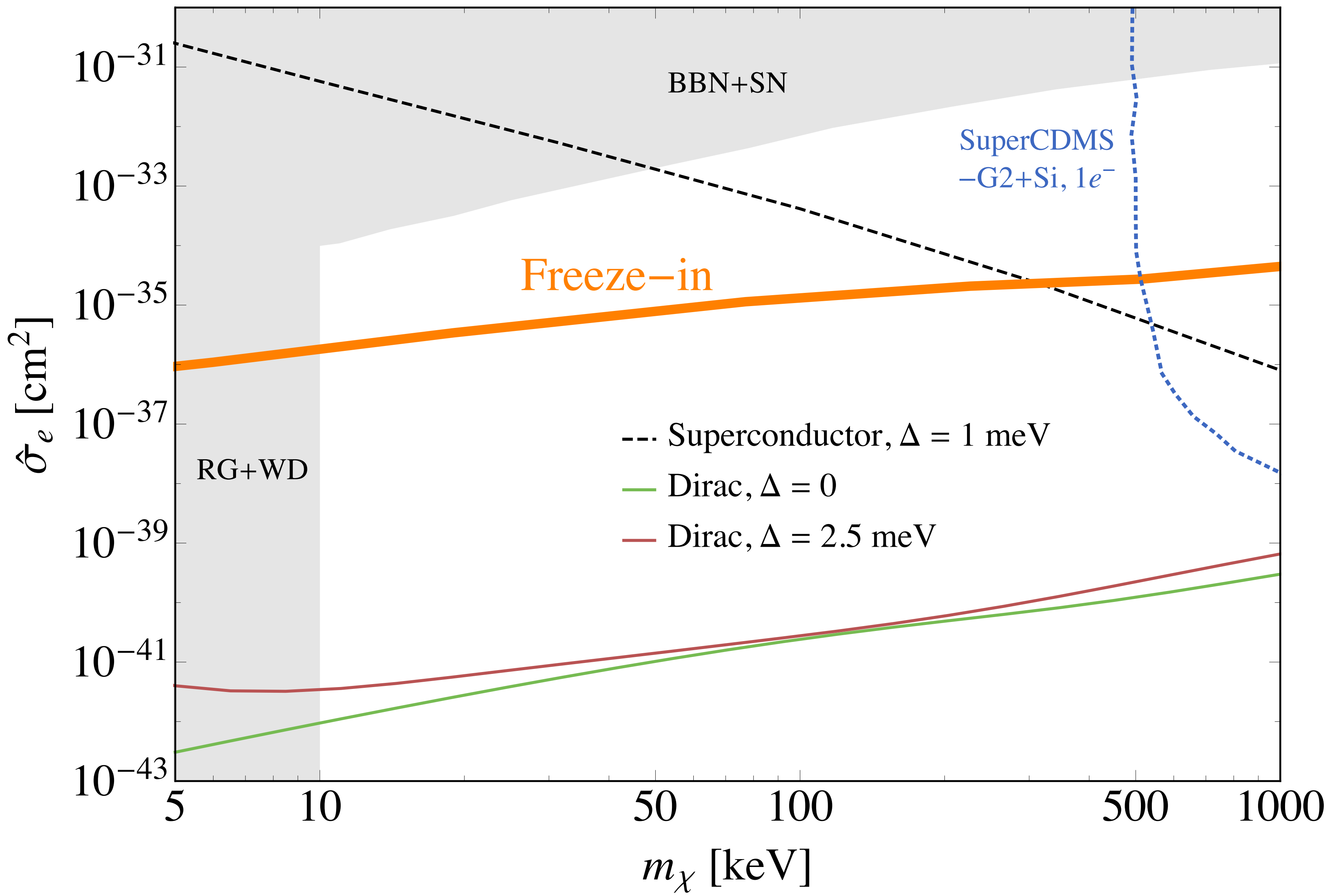
Metal



Semi-Metal



COMPARISON OF METAL AND SEMI-METAL (3)



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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]

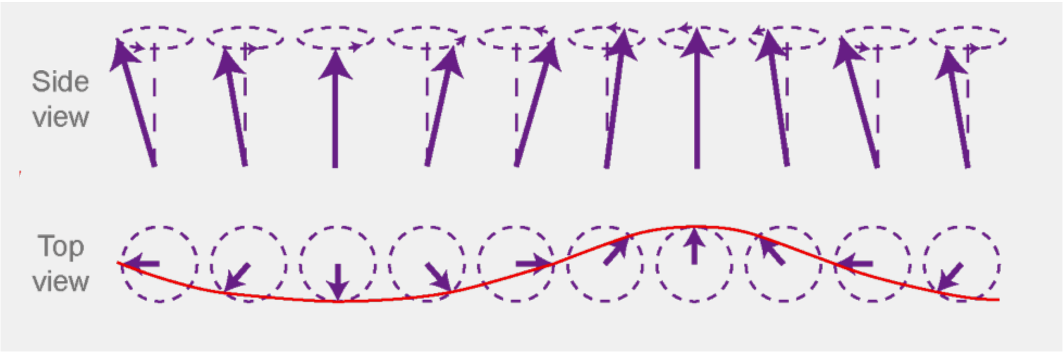
1708.08929

MAGNONS AND SPIN EXCITATIONS

- 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)

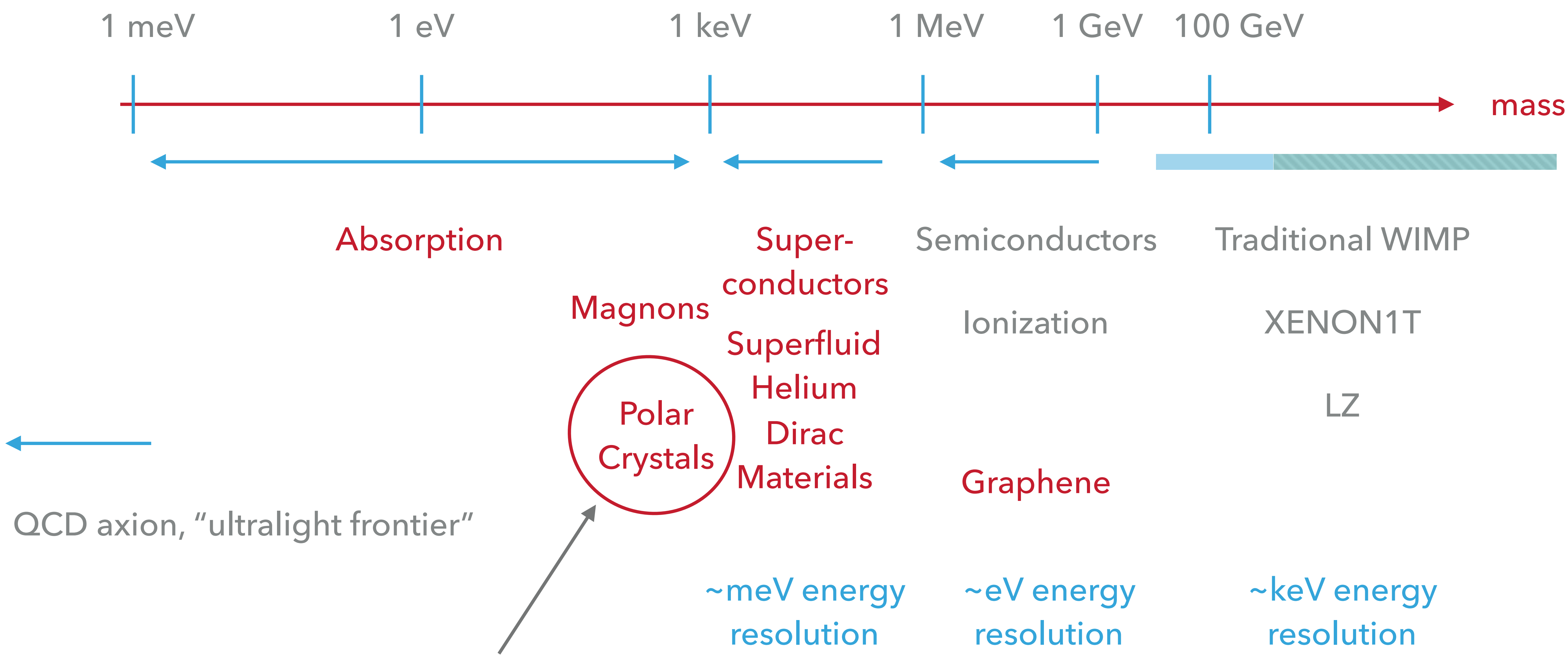


- Strong coupling to axions because gradient of axion behaves like magnetic field

Mitridate, Trickle, Zhang, KZ

LOOKING BEYOND BILLIARD BALLS

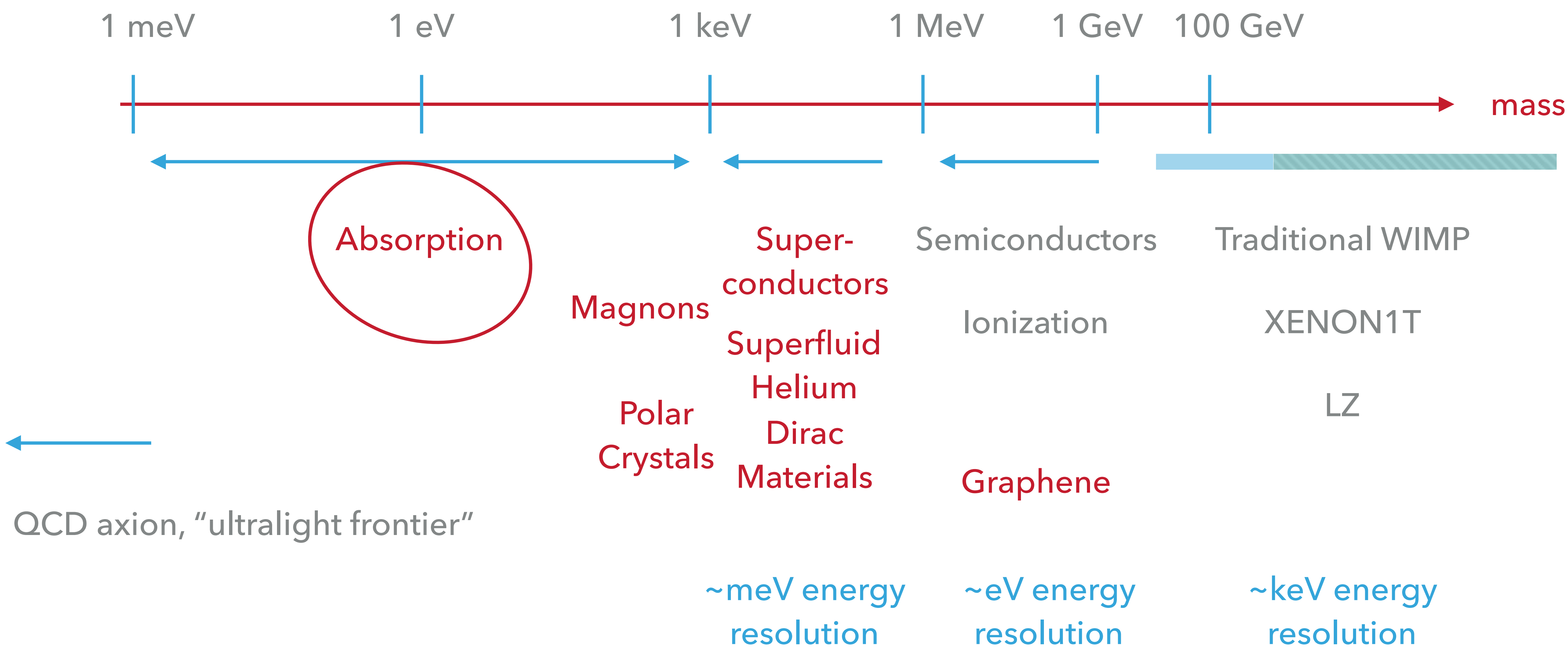
- Experimental Panorama



Strongest sensitivity to light DM for both coupling to nucleons and charge

LOOKING BEYOND BILLIARD BALLS

- Experimental Panorama

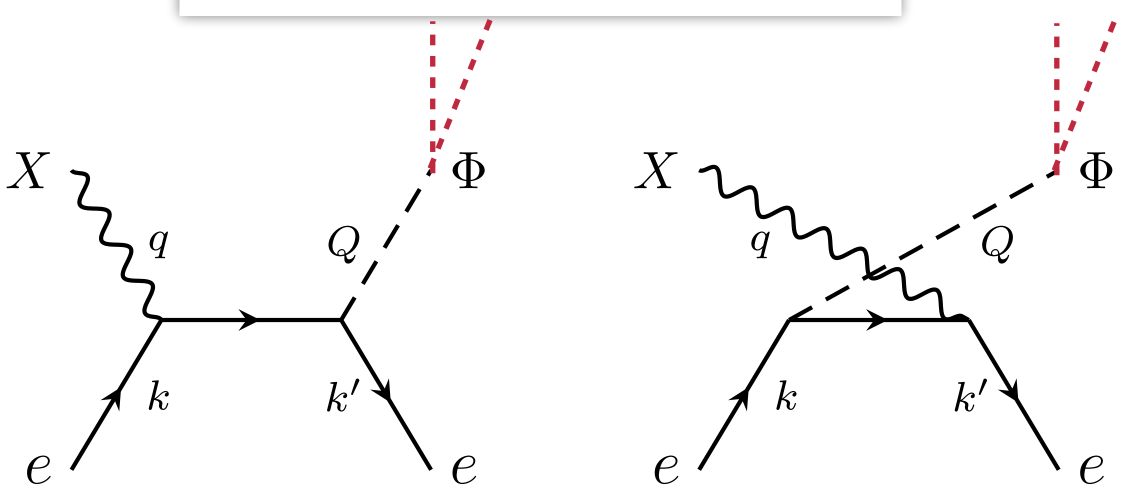


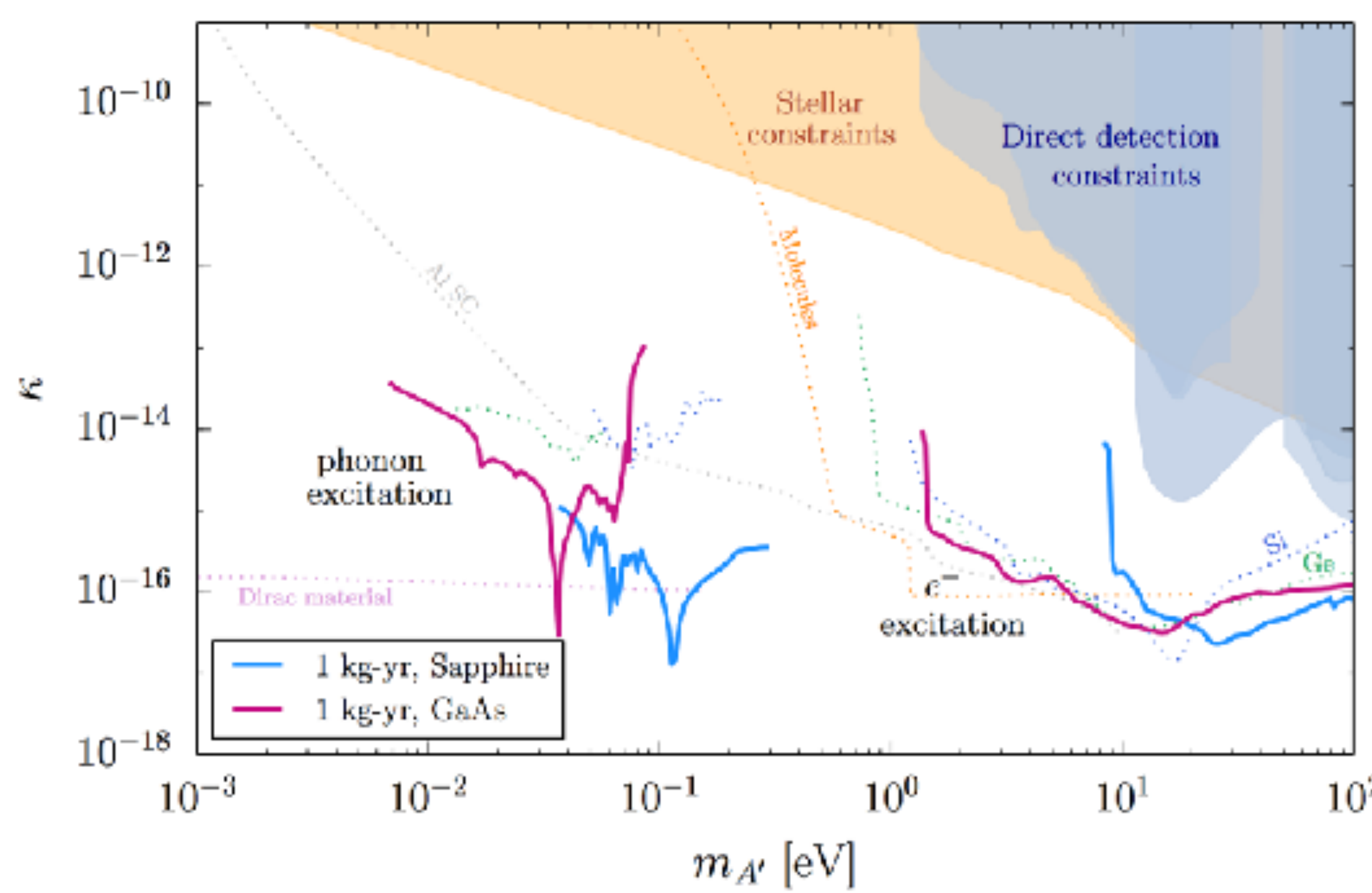
SEARCHING FOR AXIONS AND OTHER ULTRALIGHT PARTICLES

- 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

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



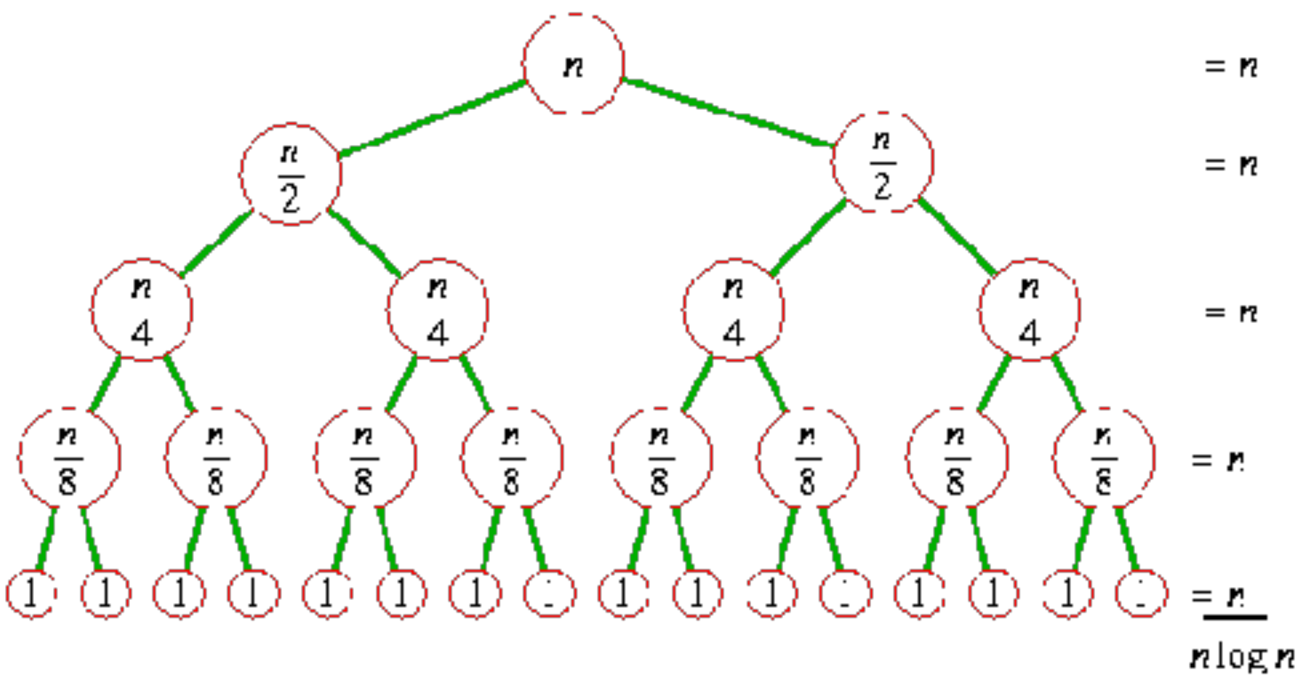


THE CHALLENGE

- Now is not the time for narrowing our search for Invisibles; the playing field is still wide open
- Leverage progress in quantum sensing, materials, condensed matter, AMO
- Moving beyond nuclear recoils into phases of matter crucial to access broader areas of DM parameter space
- 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?