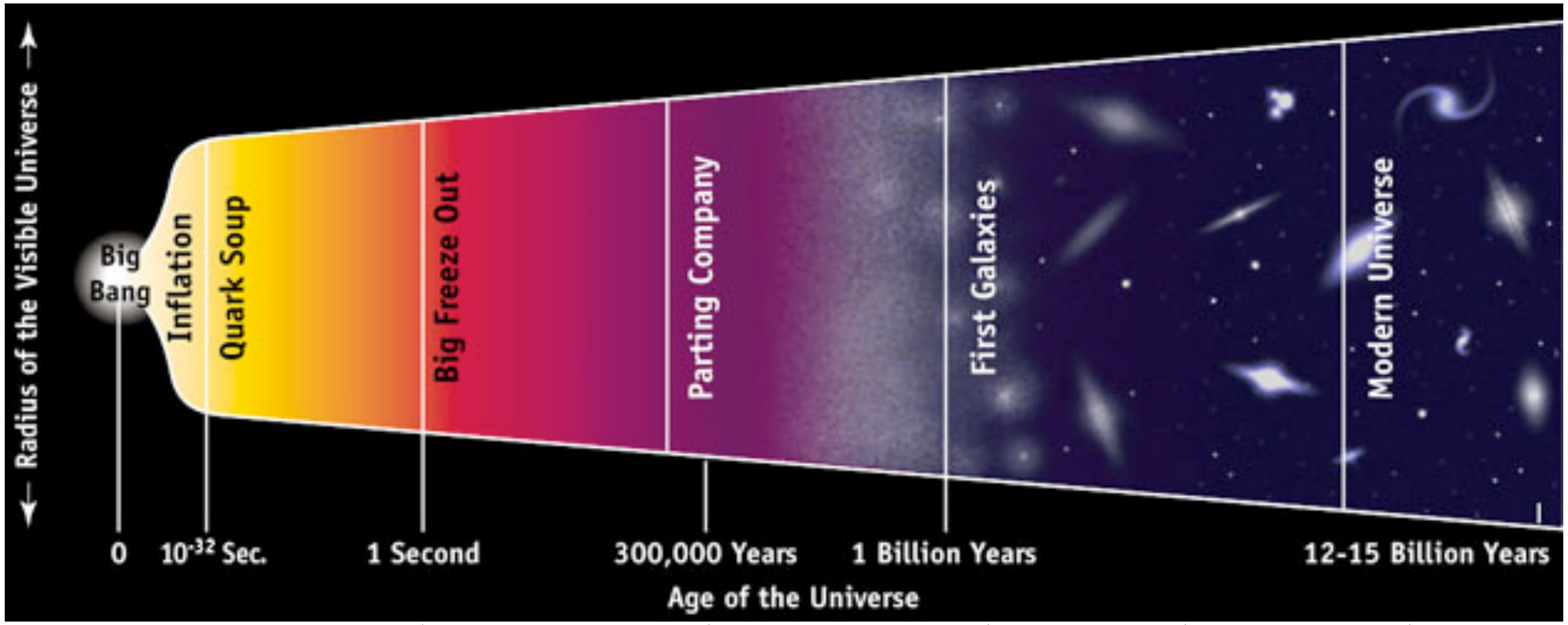
IDENTIFICATION OF DARK MATTER PANORAMA: CHALLENGES AND PROMISE

Kathryn Zurek

WHY DARK MATTER? (WHY NEW PARTICLE PHYSICS?)

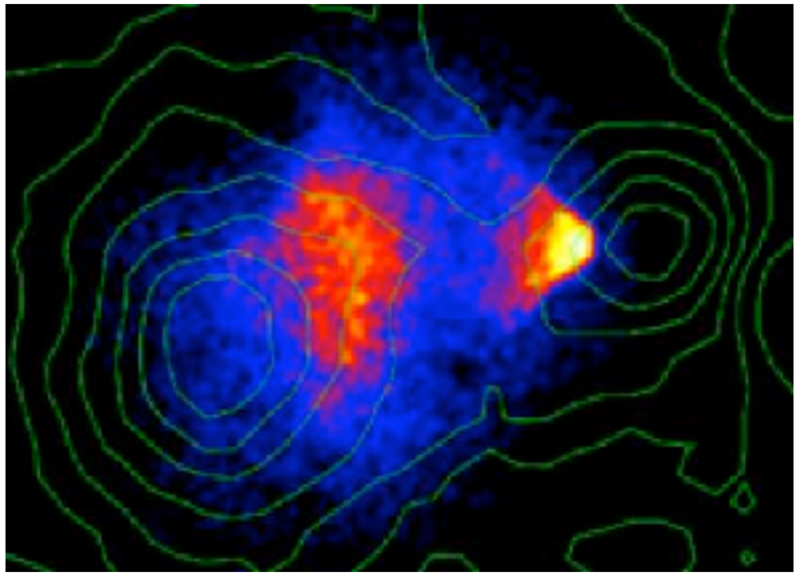
- The dark matter paradigm is the only successful framework for understanding the entire range of observations from the time the Universe is 1 sec old.



BBN (baryons) | CMB (curvature) | LSS (matter) | Supernovae (DE) | Galaxy curves (matter)

SUPER-WEAKLY INTERACTING

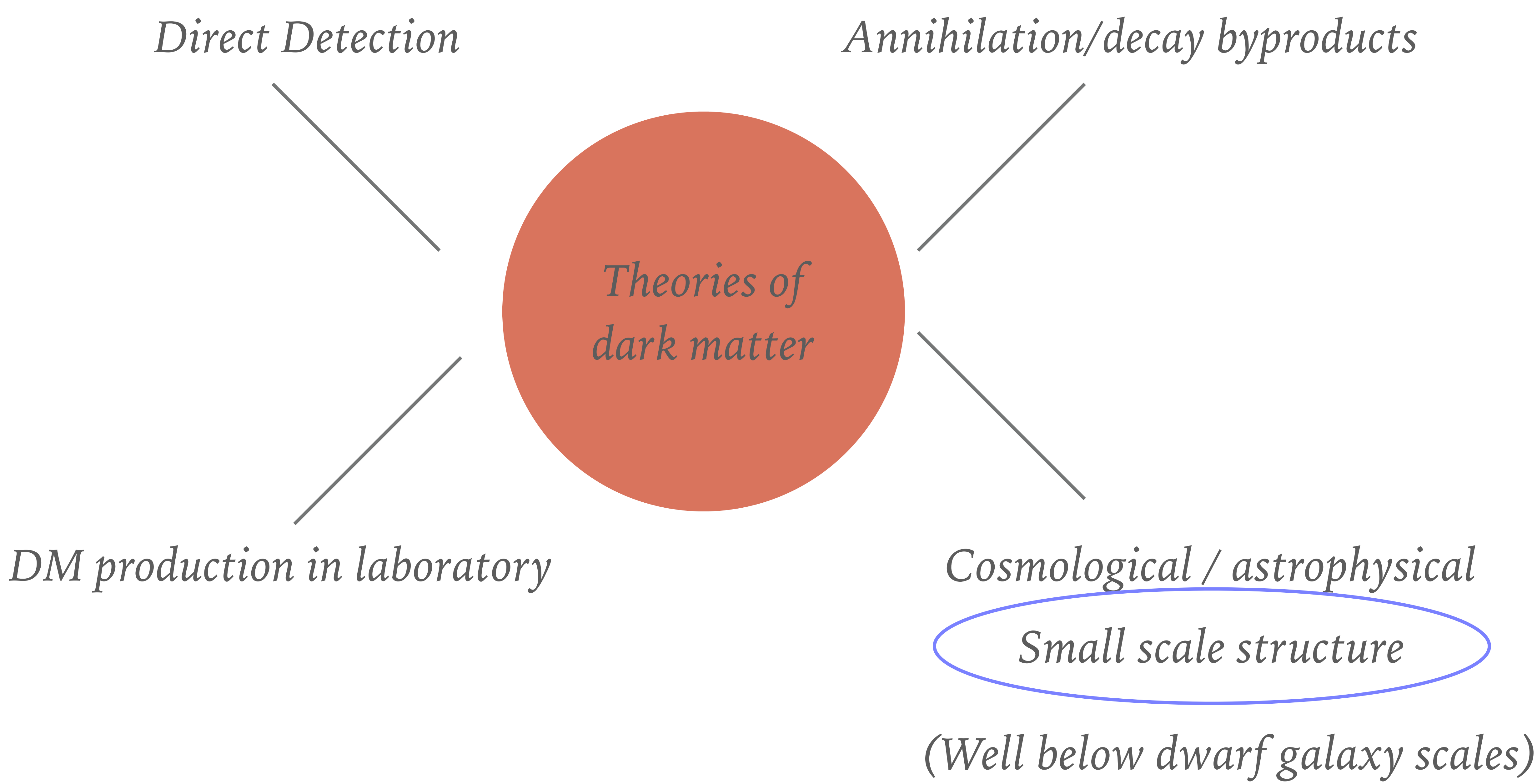
- Gravitational Coherence ....



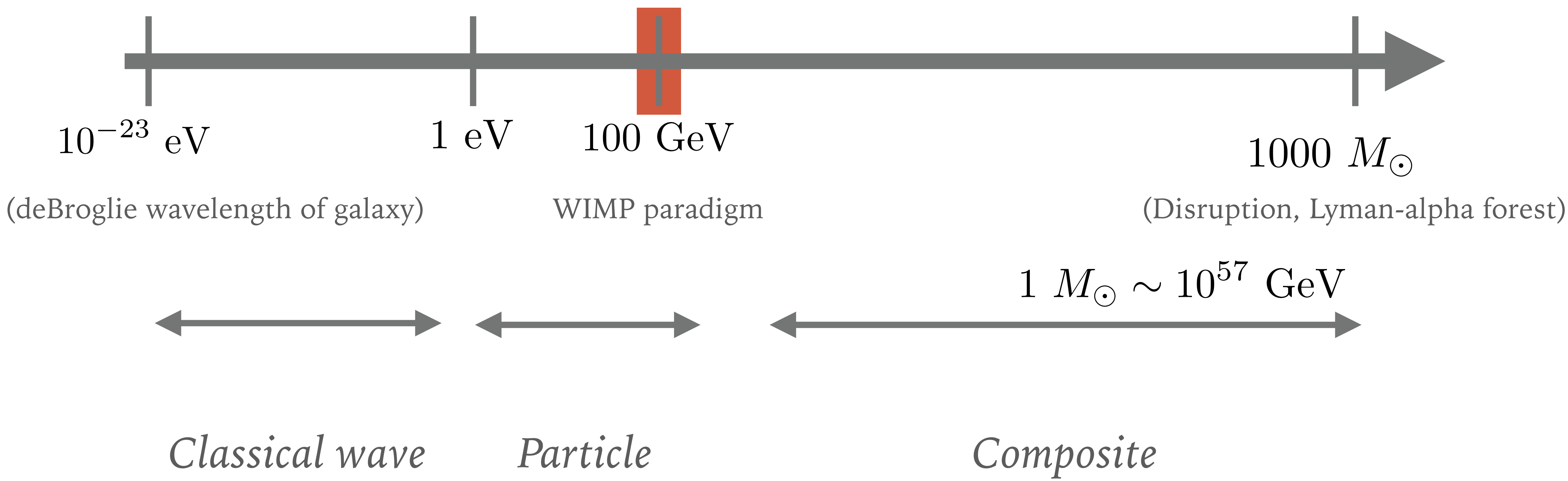
... on cosmological scales!

  - Helps us learn about aggregate properties of dark matter
- Particle properties much harder
- Fundamental premise: DM has interactions other than gravitational

MANY FACES OF DARK MATTER



DARK MATTER DETECTION: A FULL COURT PRESS



IDENTIFICATION OF DARK MATTER: CHALLENGES AND PROMISE

- Challenge: WIMP paradigm is not dead, but it's under enormous pressure. Promise: Still opportunities for discovery in coming years
- Challenge: Vast majority of QCD axion parameter space still un-probed. Promise: ADMX has made enormous progress and there are many new ideas being developed
- Challenge: Hidden sector dark matter represents a vast and mostly unconstrained frontier. Promise: There are a suite of experiments that can probe well-motivated models in the coming 5-10 years
- Challenge: Dark matter may interact only gravitationally. Promise: Probes of dark matter substructure may still tell us about underlying theory

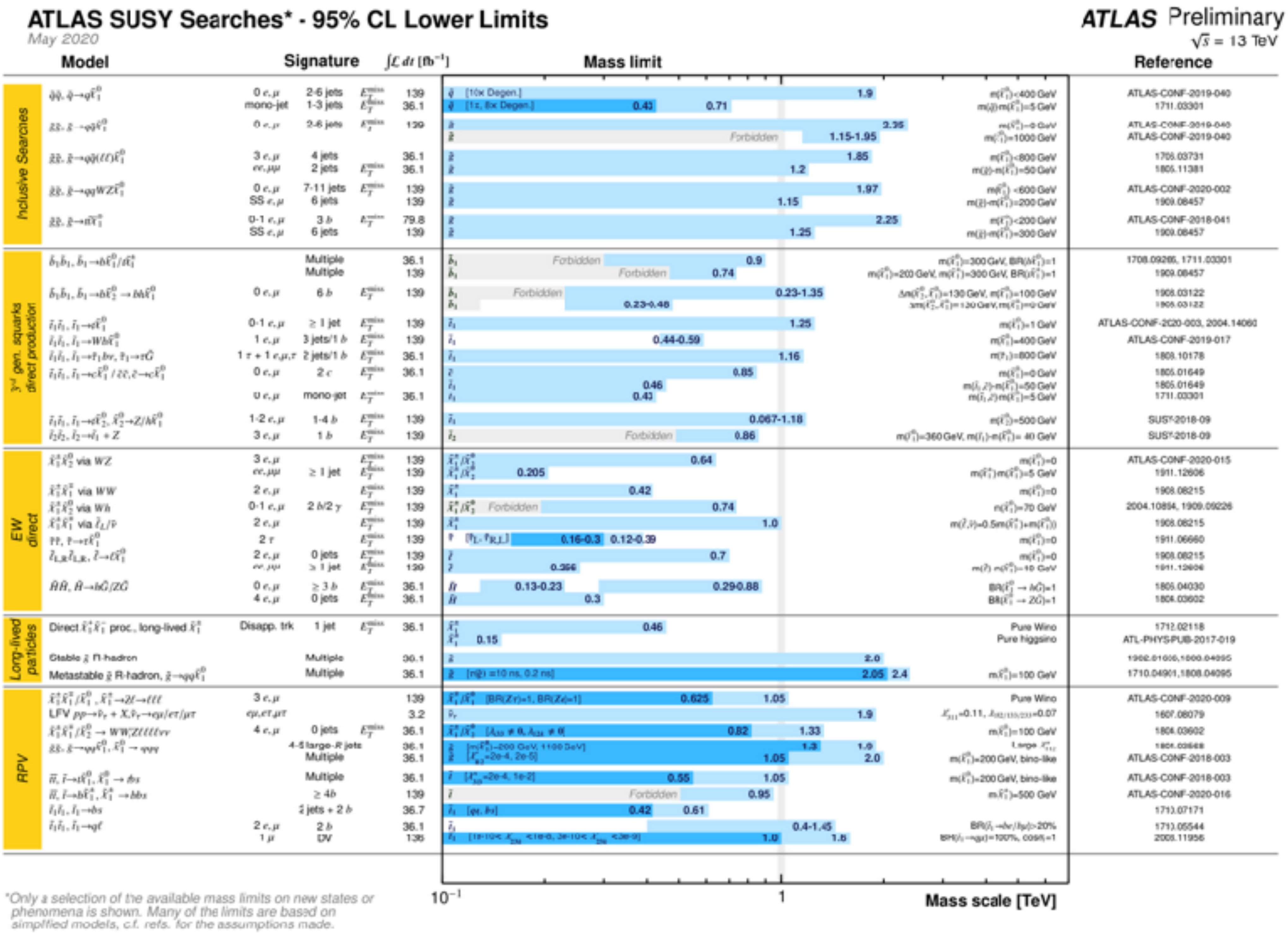
CHALLENGES: THE WIMP PARADIGM

- Decades of searching for the WIMP, with no evidence of new physics at the weak scale
- Production at accelerators strongly constrains colored states, not thermal electroweakinos

$$3 \times 10^{-26}\ \mathrm{cm}^3/\mathrm{s} \sim \frac{g_{wk}^4}{4\pi(2\ \mathrm{TeV})^2}$$

- Most promising avenue currently seems to be “mini-split” scenario, with colored super-partners well above TeV scale

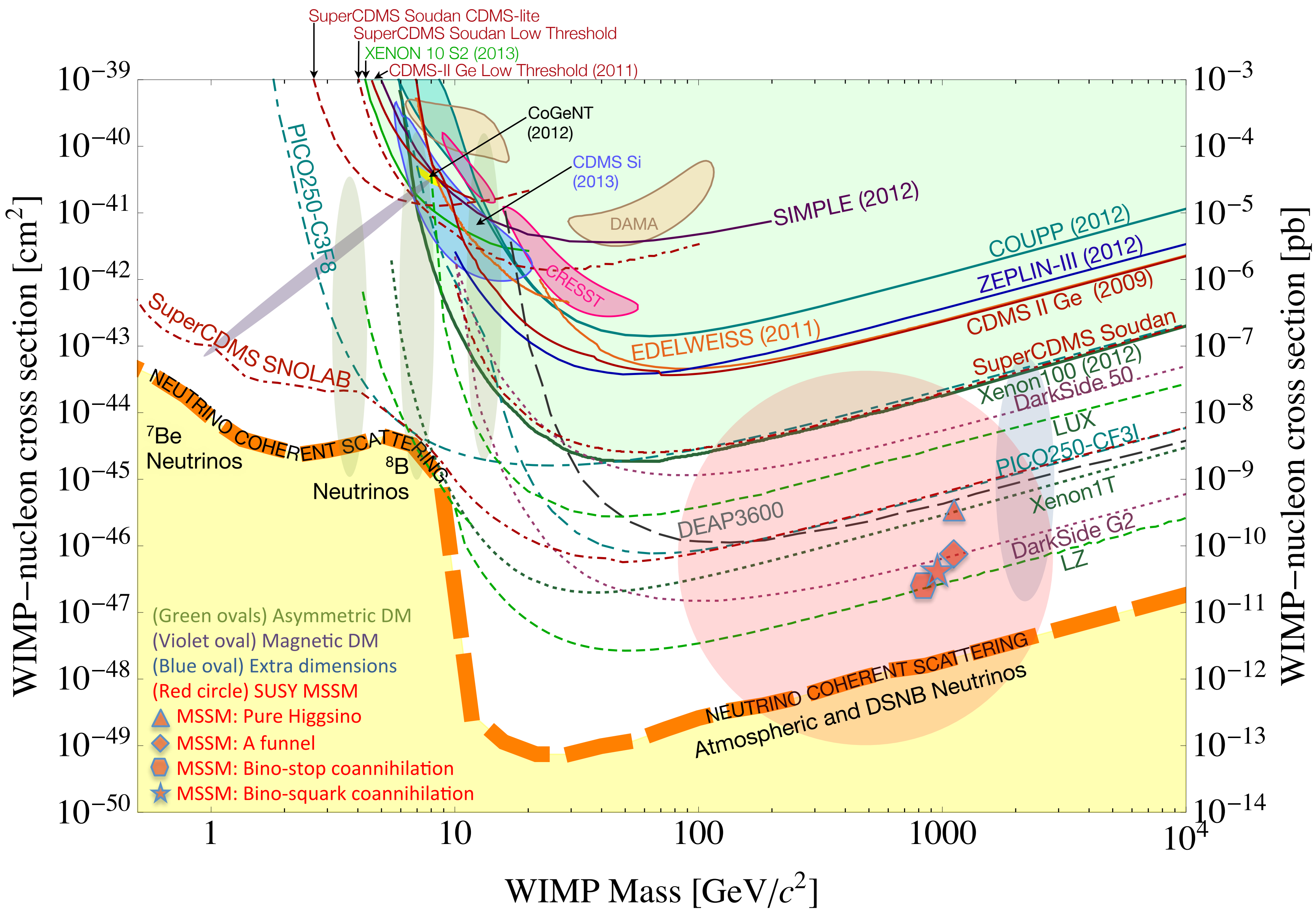
CHALLENGES: THE WIMP PARADIGM



PROMISE: DETECTING HIGGS INTERACTING DARK MATTER

Z-boson interacting dark matter: ruled out

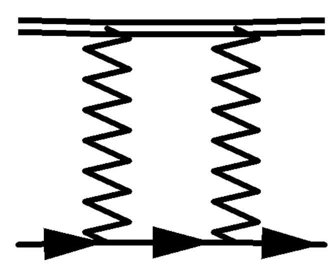
Higgs interacting dark matter: active target

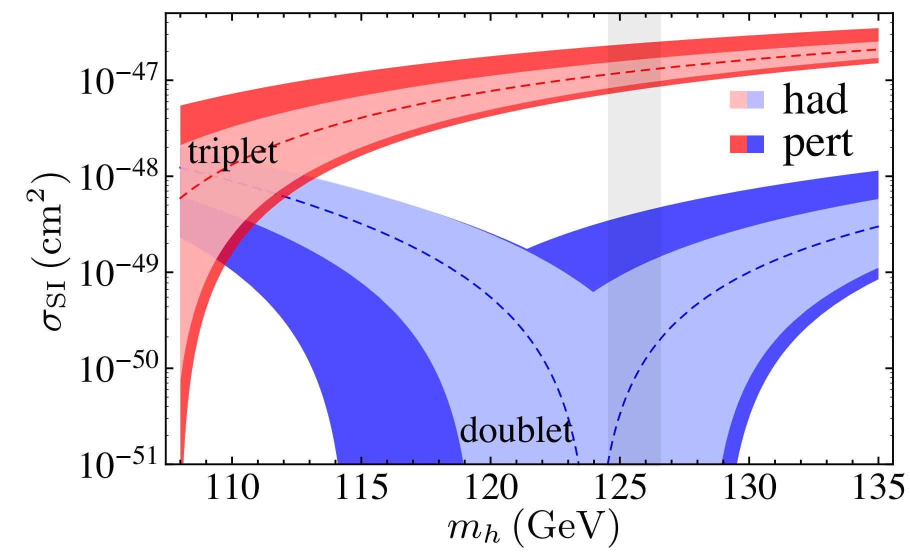


PROMISE: ELECKTROWEAKINOS VIA 1-LOOP PROCESSES

- Challenge: even LZ will struggle to reach the wino

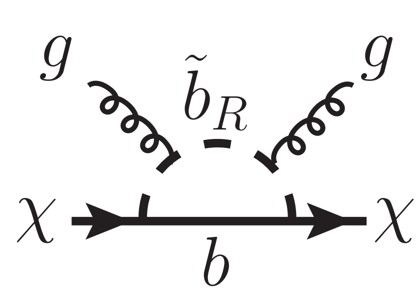
Wino and Higgsino

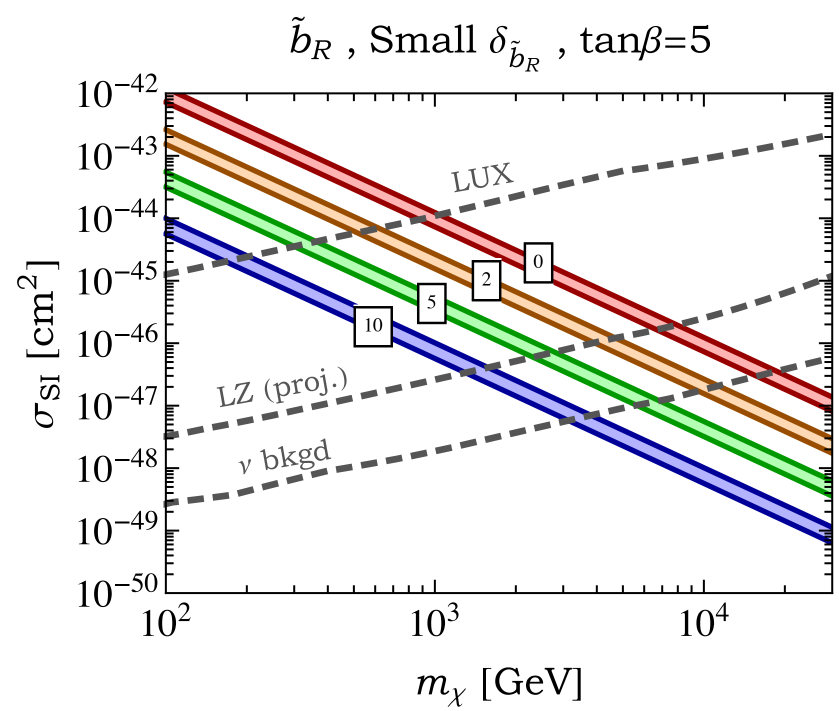




Hill and Solon

Bino

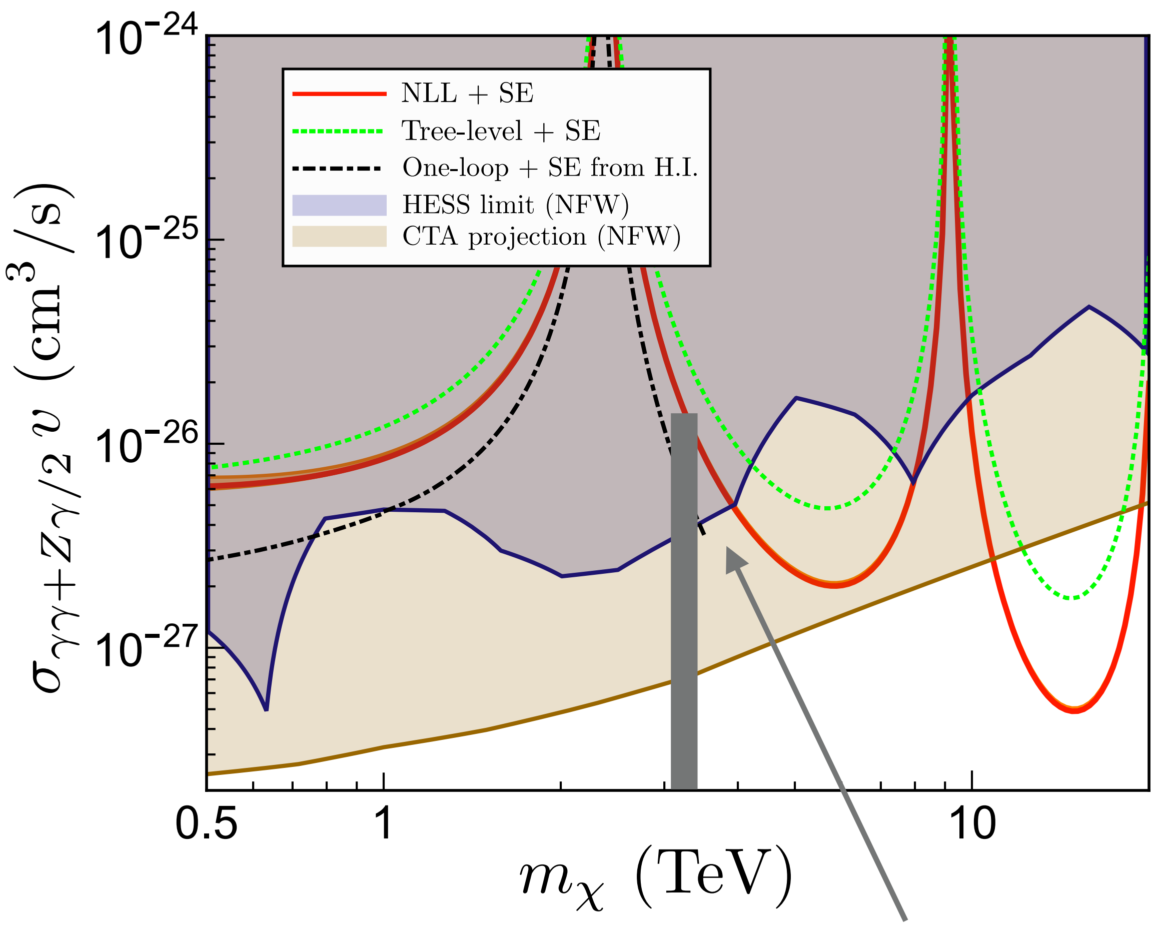


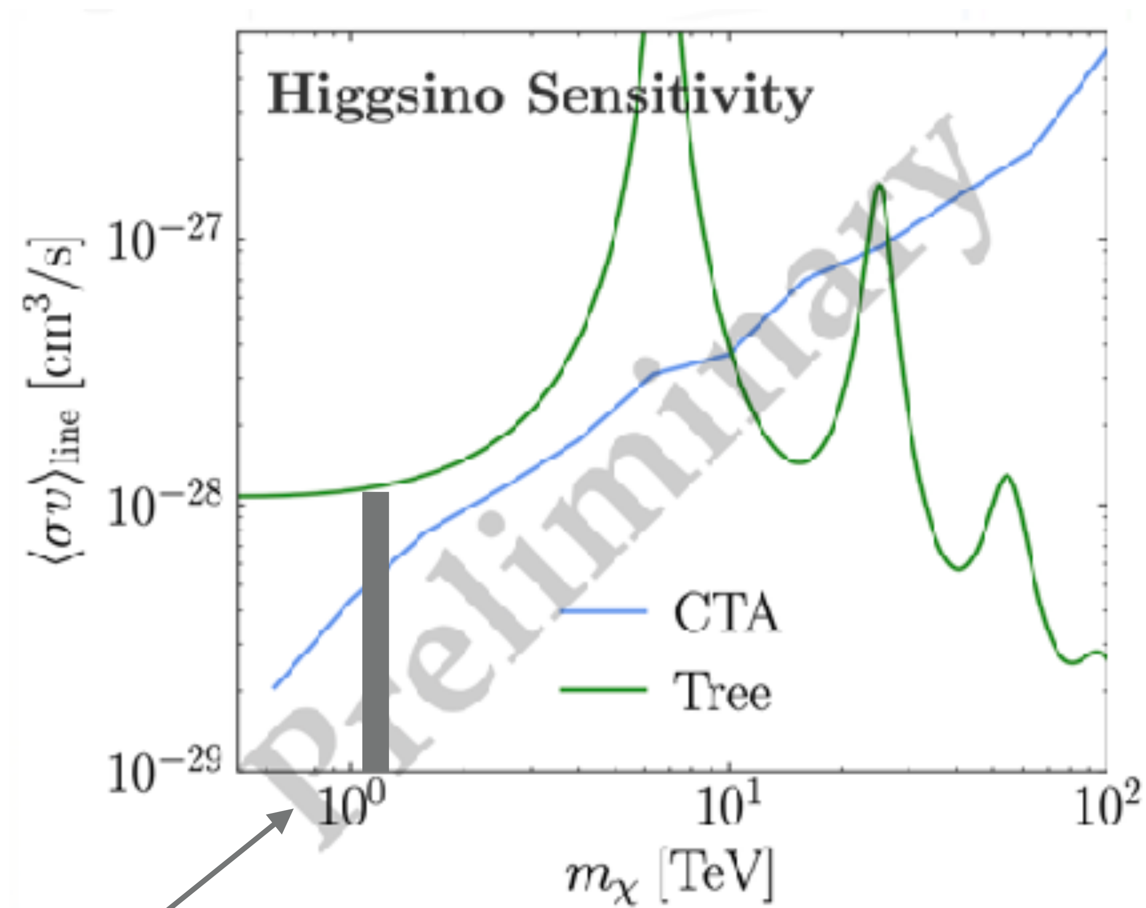


Berlin, Robertson, Solon, KZ

PROMISE: INDIRECT DETECTION STILL HAS REACH ON THERMAL ELECTROWEAKINOS

- Currently some sensitivity to winos and possible future sensitivity with CTA to Higgsinos





Thermal wino *Thermal Higgsino*

Ovanesyan, Slatyer, Stewart

courtesy N. Rodd

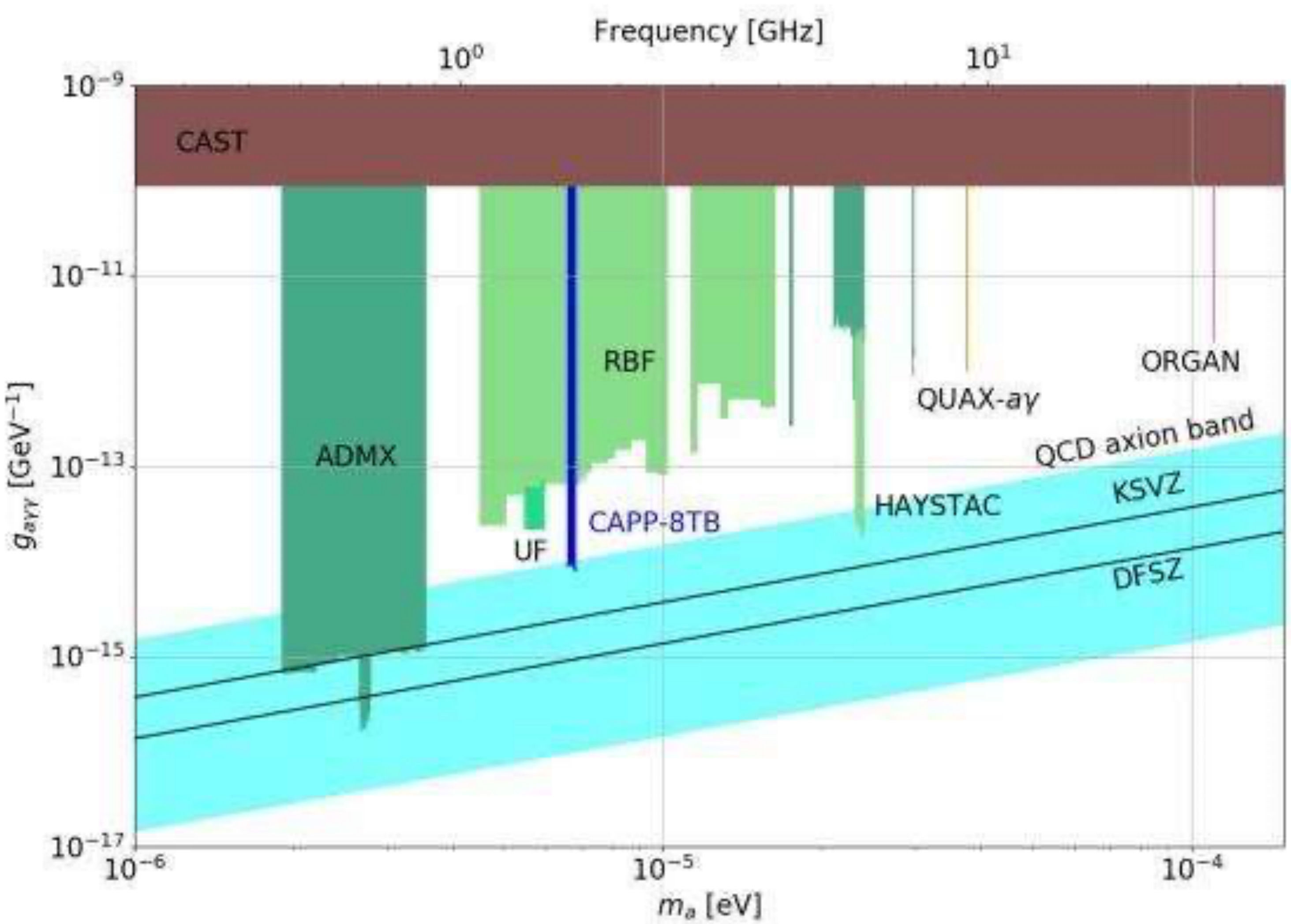
PROMISE: AXION DETECTION HAS SENSITIVITY TO THE QCD AXION!

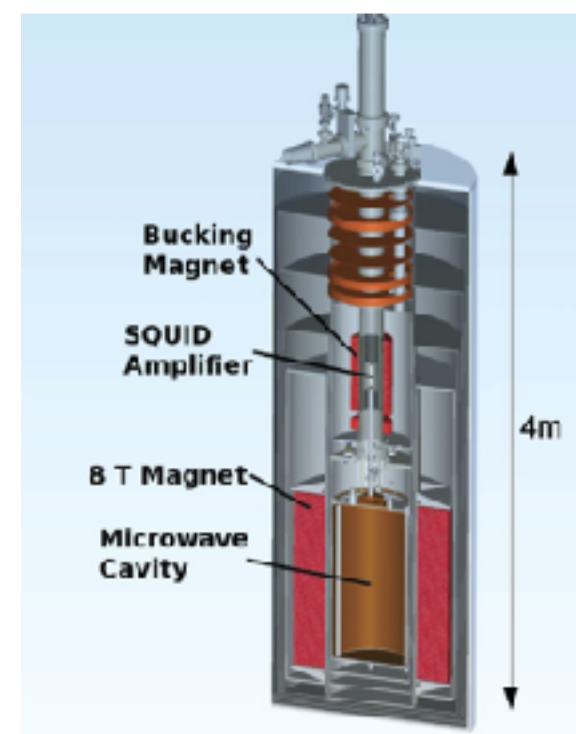
(deBroglie wavelength of galaxy) (Lyman-alpha forest)

10^{-23} eV | $\sim \mu$eV | 10 GeV – 10 TeV | $10^{-8}\ M_\odot - 1000\ M_\odot$

axion | WIMP paradigm | MaCHOs/PBHs

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

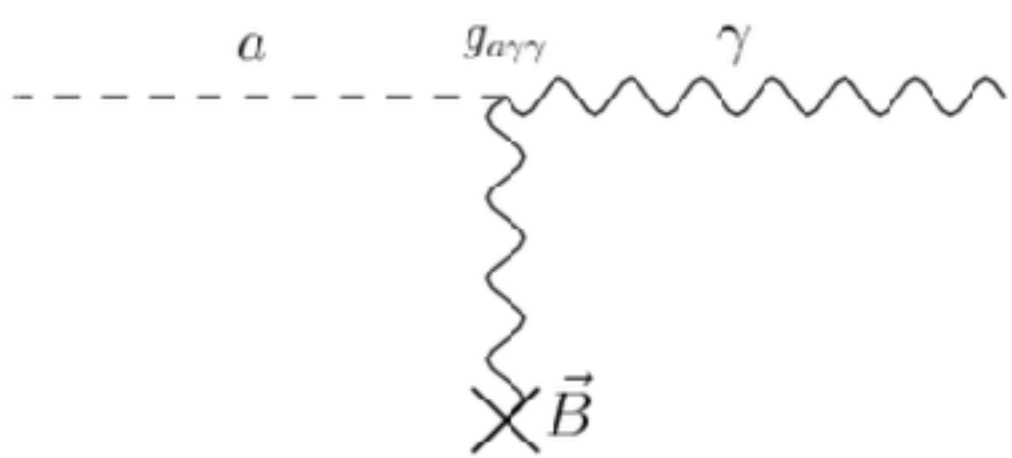




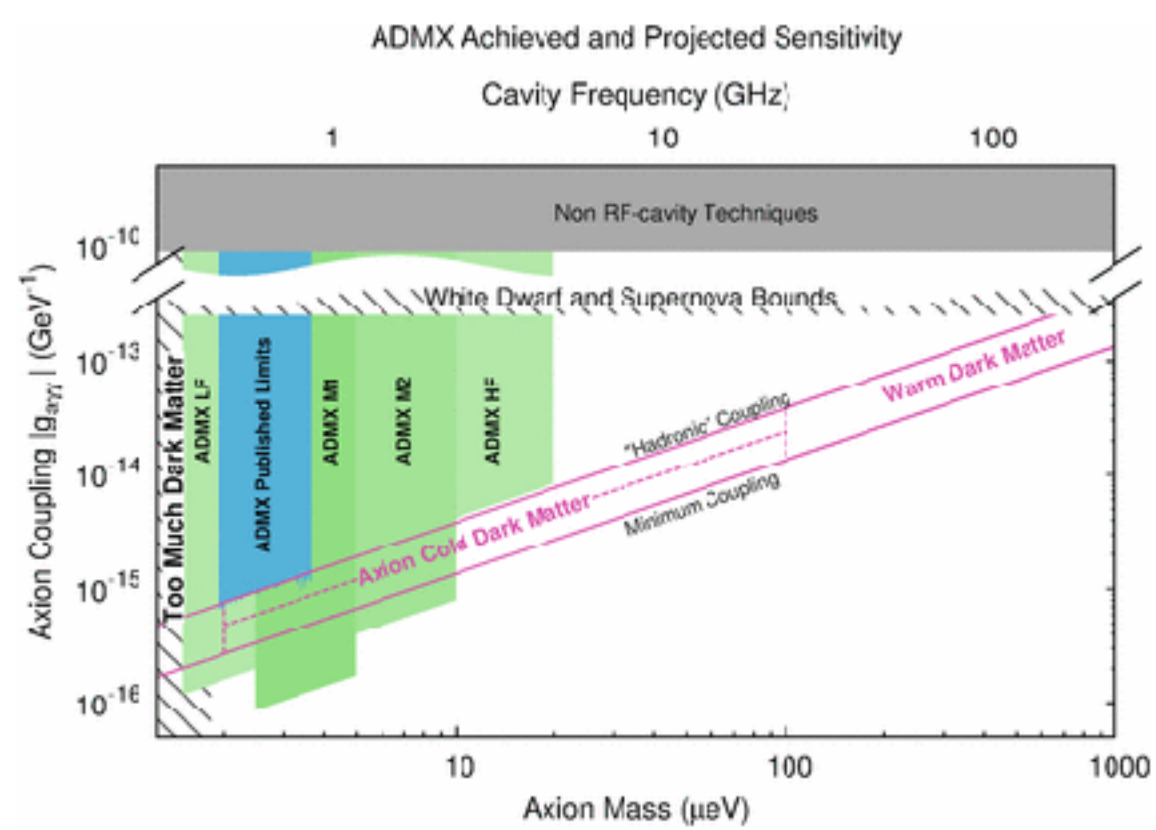
By Institute for Basic Science for phys.org

CHALLENGE: VERY LIMITED FREQUENCY RANGE IN MASS

- The classic, decades-old Sikivie proposal is now achieving sensitivity to the QCD axion
- Challenge: scaling to higher frequency and covering the whole range originally motivated by misalignment will be very challenging because of matching axion mass to cavity size



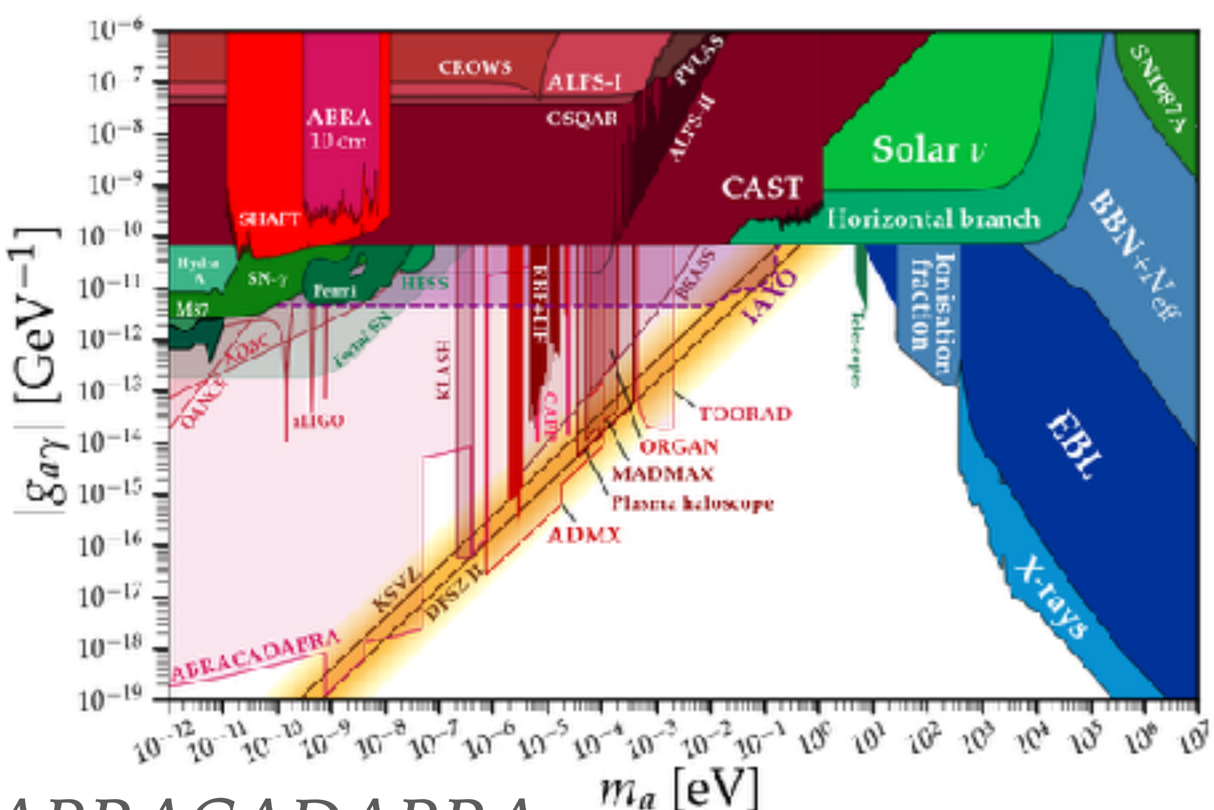
$$V \sim f^{-2} - f^{-3} \qquad \frac{d\nu}{dt} \propto B^4 V^2$$



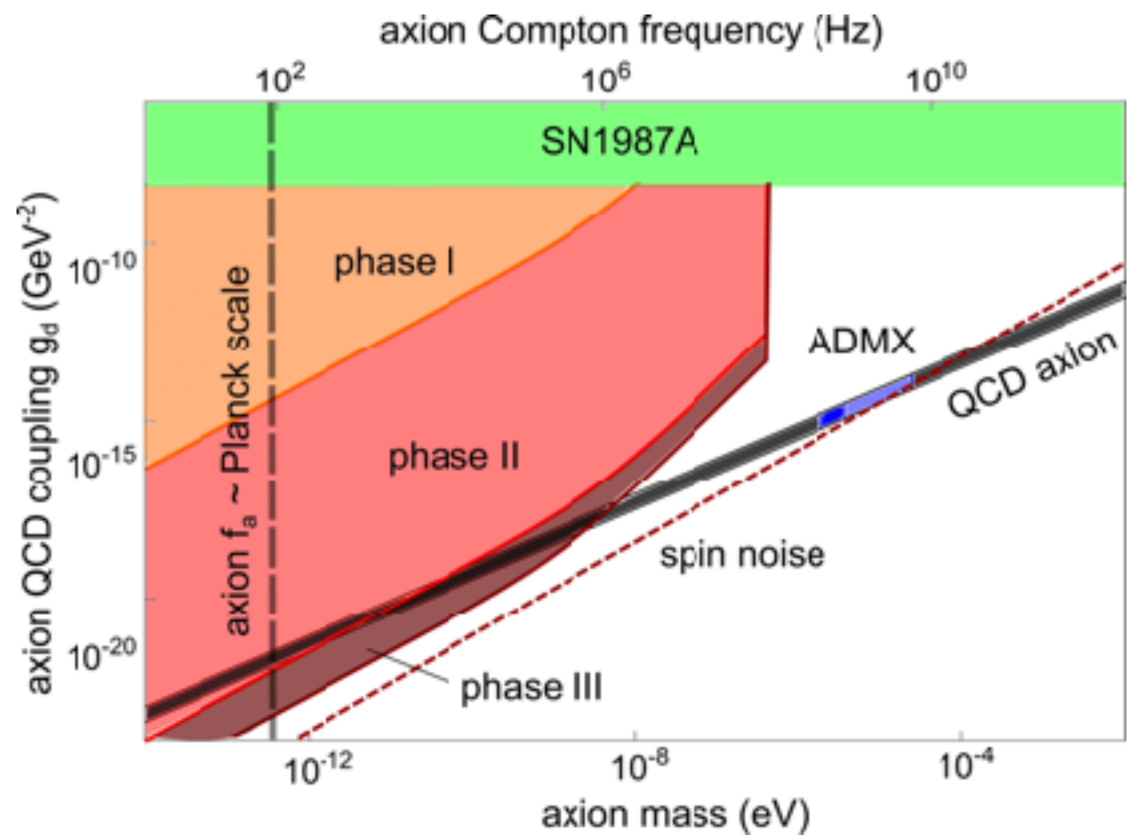
L. Rosenberg in PNAS

PROMISE: IDEAS FOR AXION DETECTION HAS UNDERGONE A RENAISSANCE

- Much broader range of experiments to probe the entire mass range



ABRACADABRA

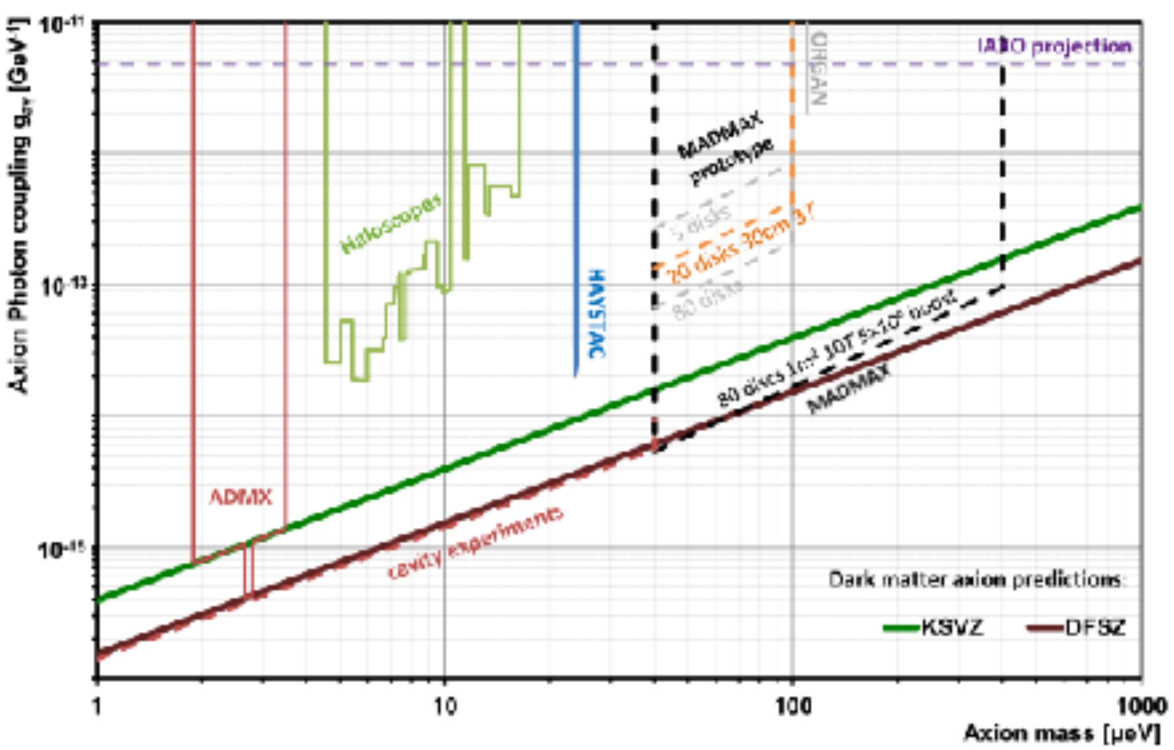


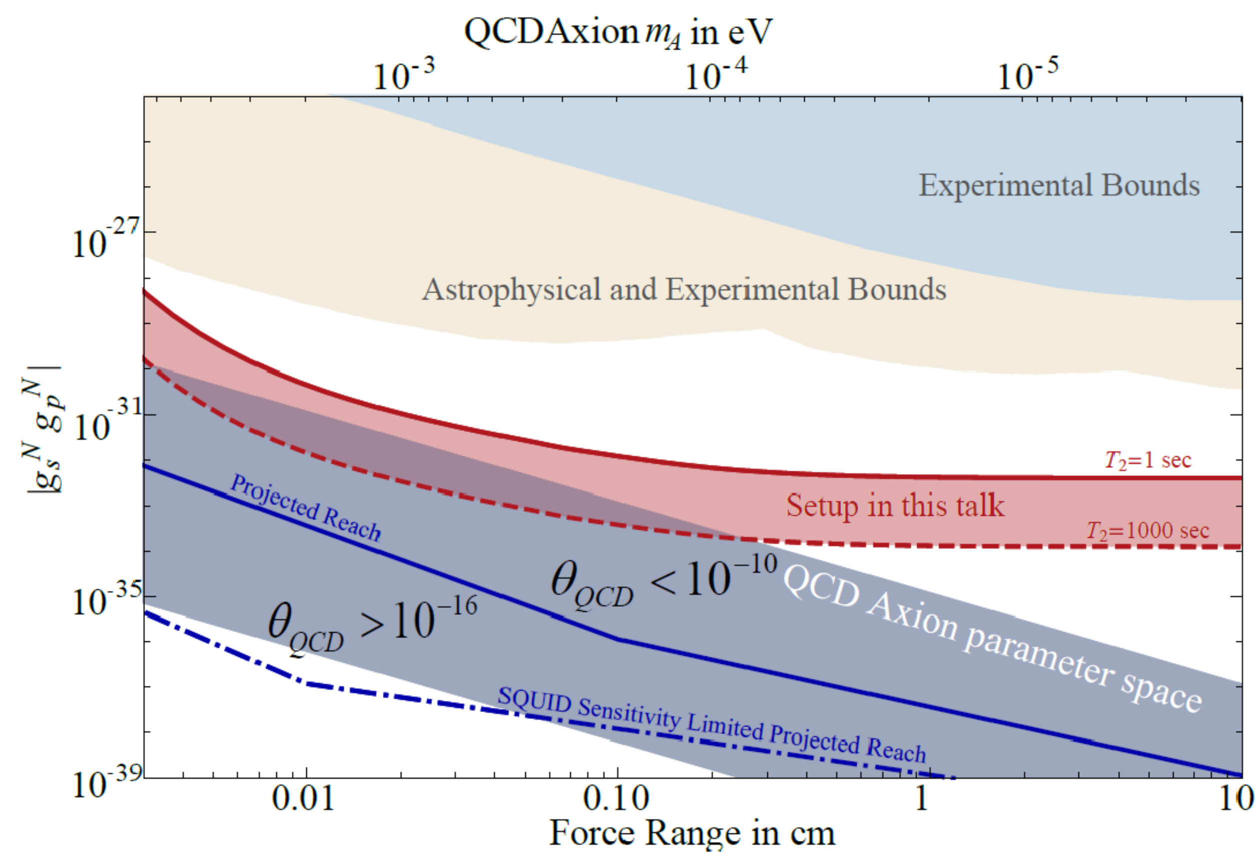
CASPEr

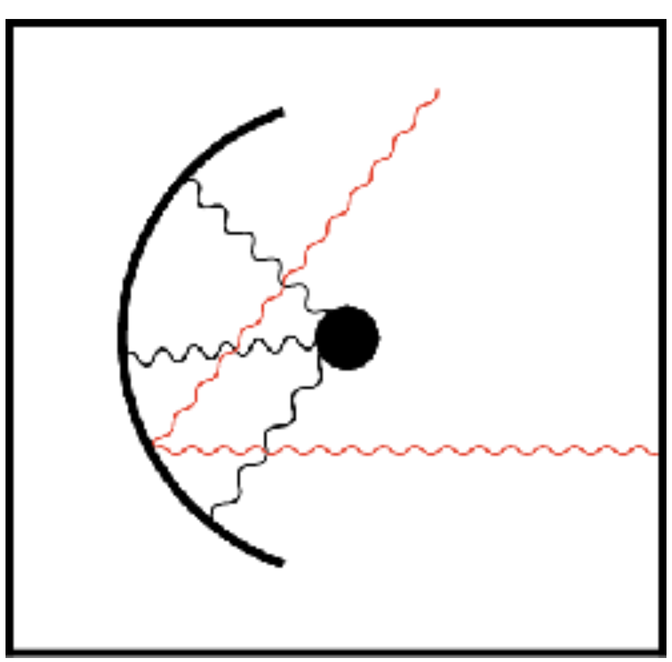
- Challenge: remains to be seen how real constraints evolve

PROMISE: IDEAS FOR AXION DETECTION HAS UNDERGONE A RENAISSANCE

- For example, dish antenna or spin-dependent force

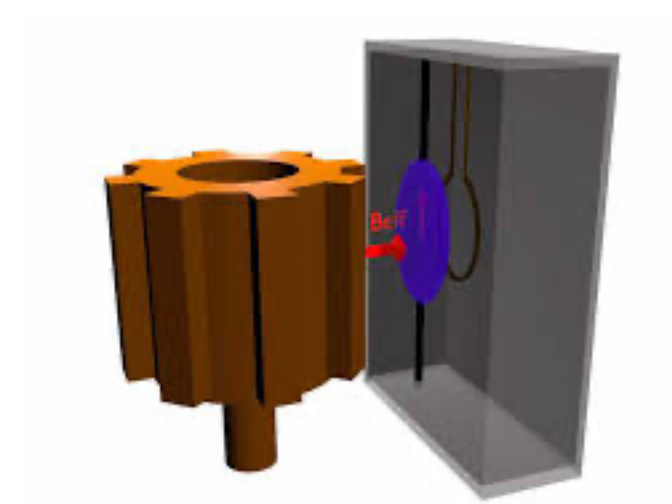




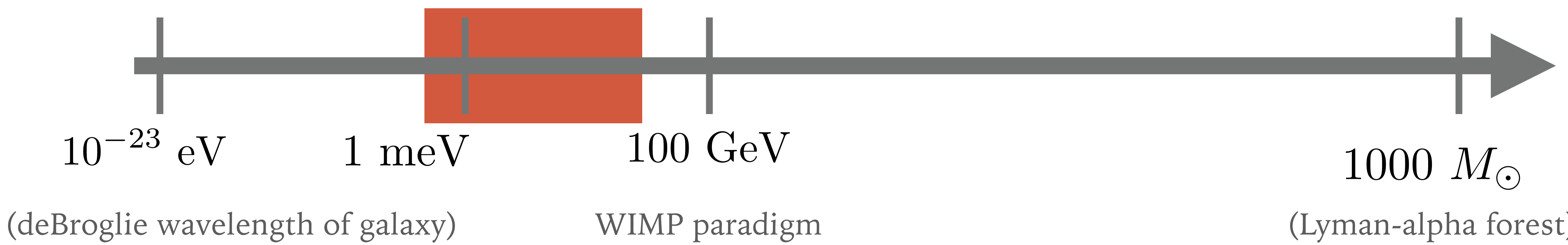


MADMAX

ARIADNE



DARK MATTER DETECTION: A FULL COURT PRESS



- Between 1 meV and 1 eV, dark matter behaves like a classical wave, but cavity techniques will be challenging. Detection may be possible via excitation of "collective modes" = phonons
- Intermediate mass range above an eV where observation via particle interactions with SM is still highly motivated though not detectable with traditional WIMP experiments
- Arise generically in top-down constructions — hidden sector/valley paradigm

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

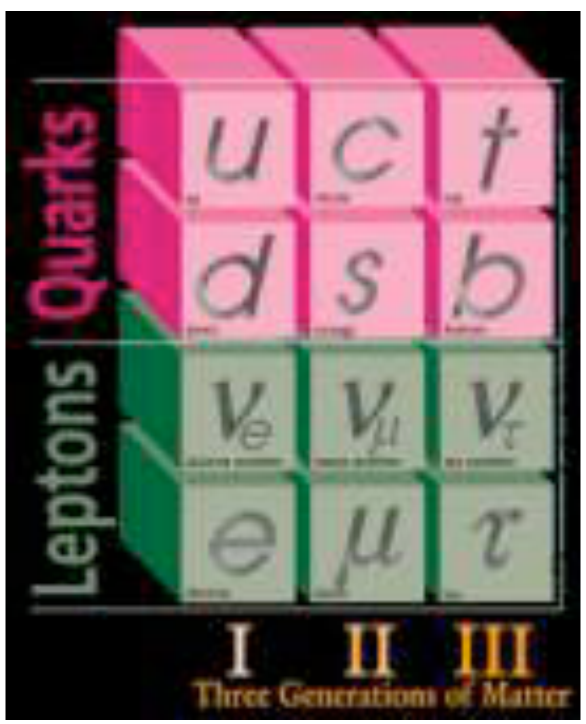
$$\sigma_{wk} v_{fo} \simeq \frac{g_{wk}^4 \mu_{XT}^2}{4\pi m_Z^4}\frac{c}{3} \simeq 10^{-24}\frac{\mathrm{cm}^3}{\mathrm{s}}\left(\frac{100\ \mathrm{GeV}}{M}\right)^2$$

HIDDEN SECTOR DARK MATTER

- Scale of connector sector fixes terrestrial experiment

Standard Model → Connector → Dark Matter

Energy



GUT

Weak

High Energy Collider

Light

Intensity Experiment

Direct Detection

Supersymmetric

Baryogenesis

$$\pi_v^+ \pi_v^- \to \pi_v^0 \pi_v^0$$

Non-Abelian

Hidden Charged

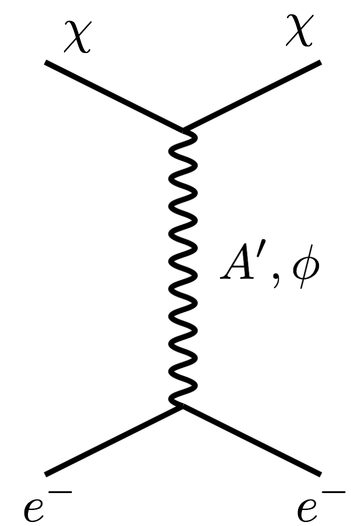
Dark Disk

Atomic

Inaccessibility

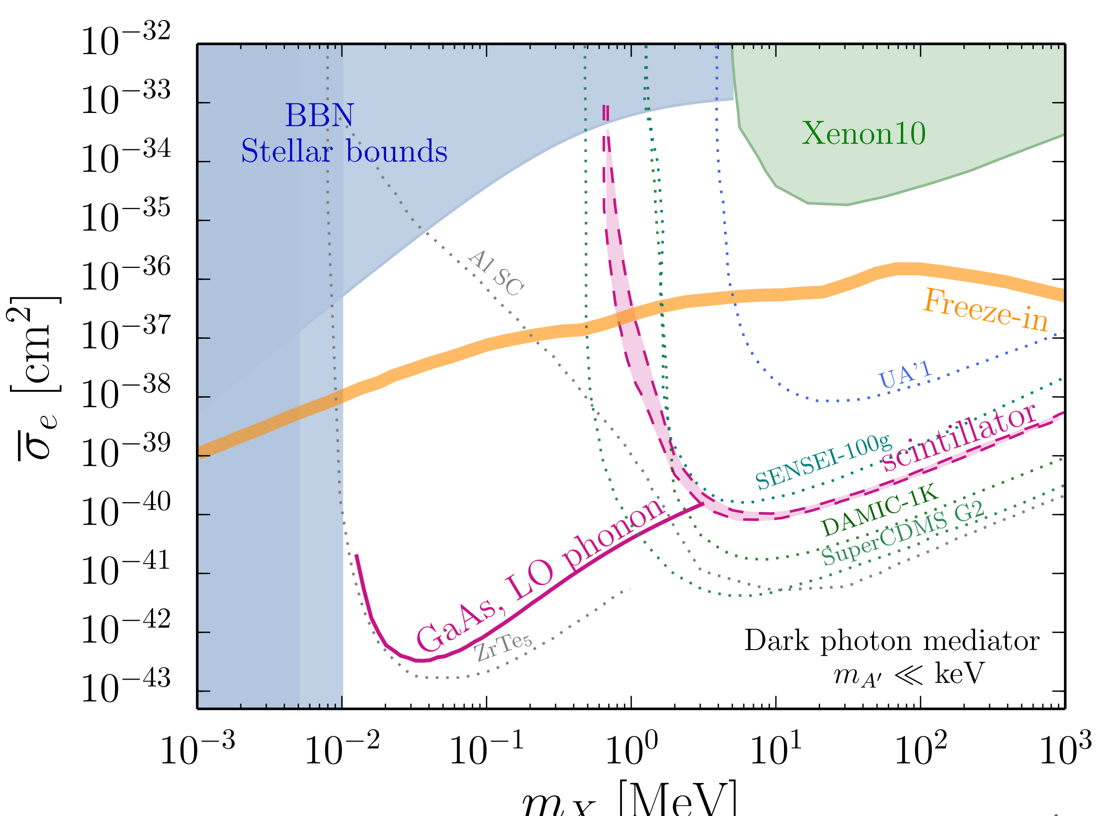
HIDDEN DM ABUNDANCE AS A GUIDE

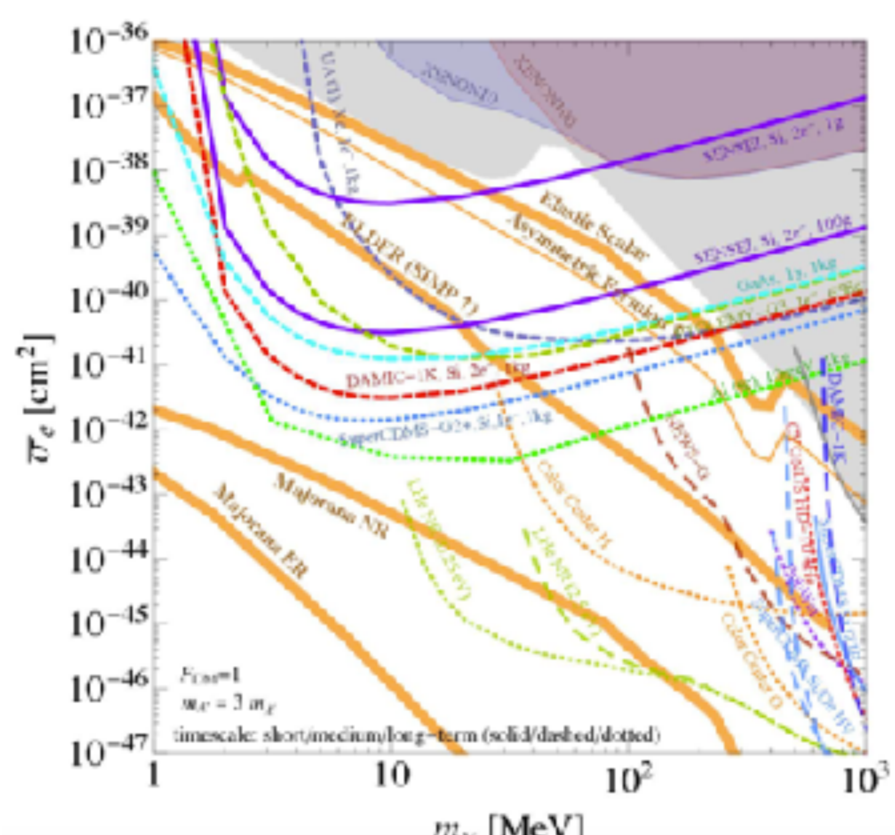
- If DM abundance is related to its coupling to the SM in any way, that provides a guide where to look



Freeze-in

Asymmetric Dark Matter



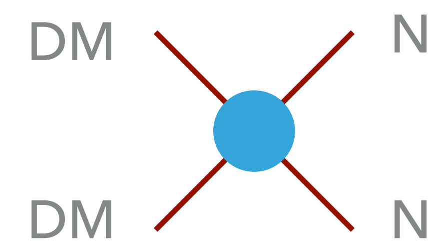


Knapen, Lin, Pyle KZ 1712.06598

US Cosmic Visions 1707.04591

TOWARDS HIDDEN SECTOR DARK MATTER

- Developments in condensed matter make this possible



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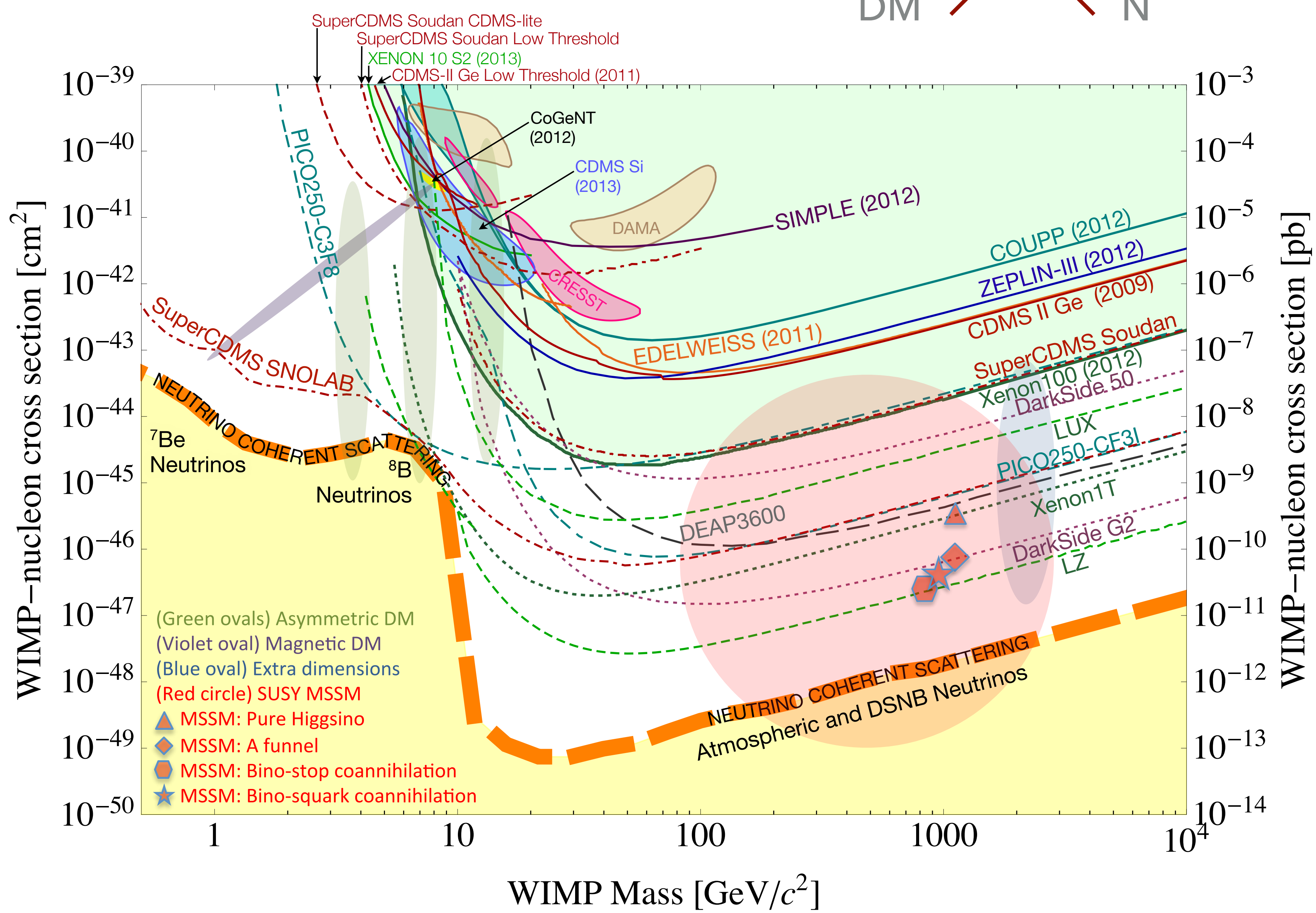
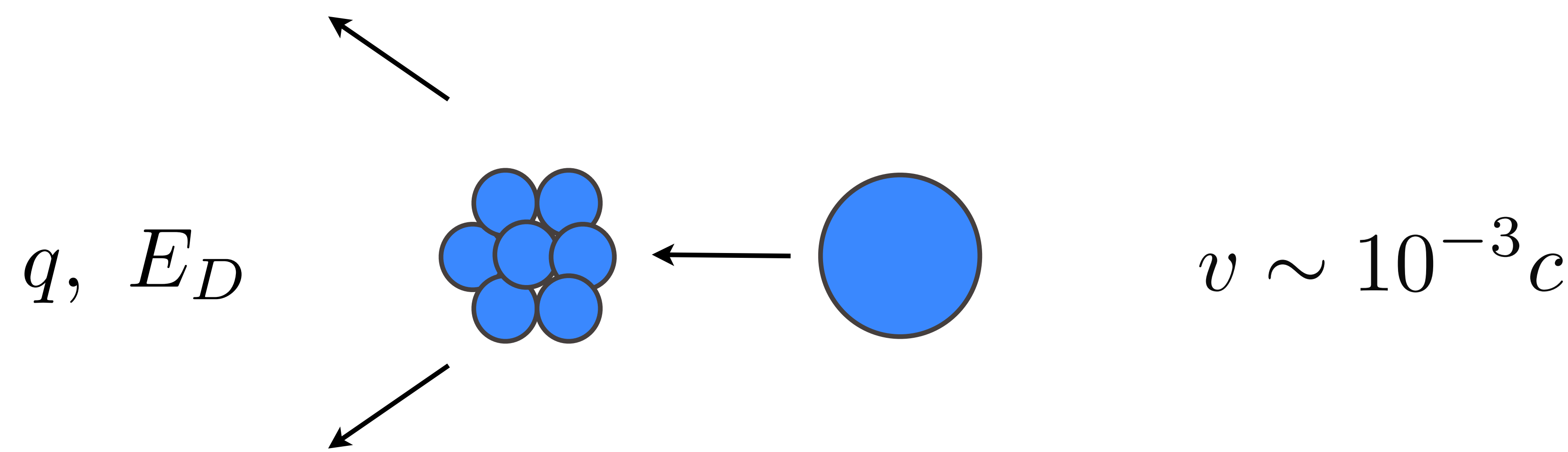


LIGHTER TARGETS FOR LIGHTER DARK MATTER

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

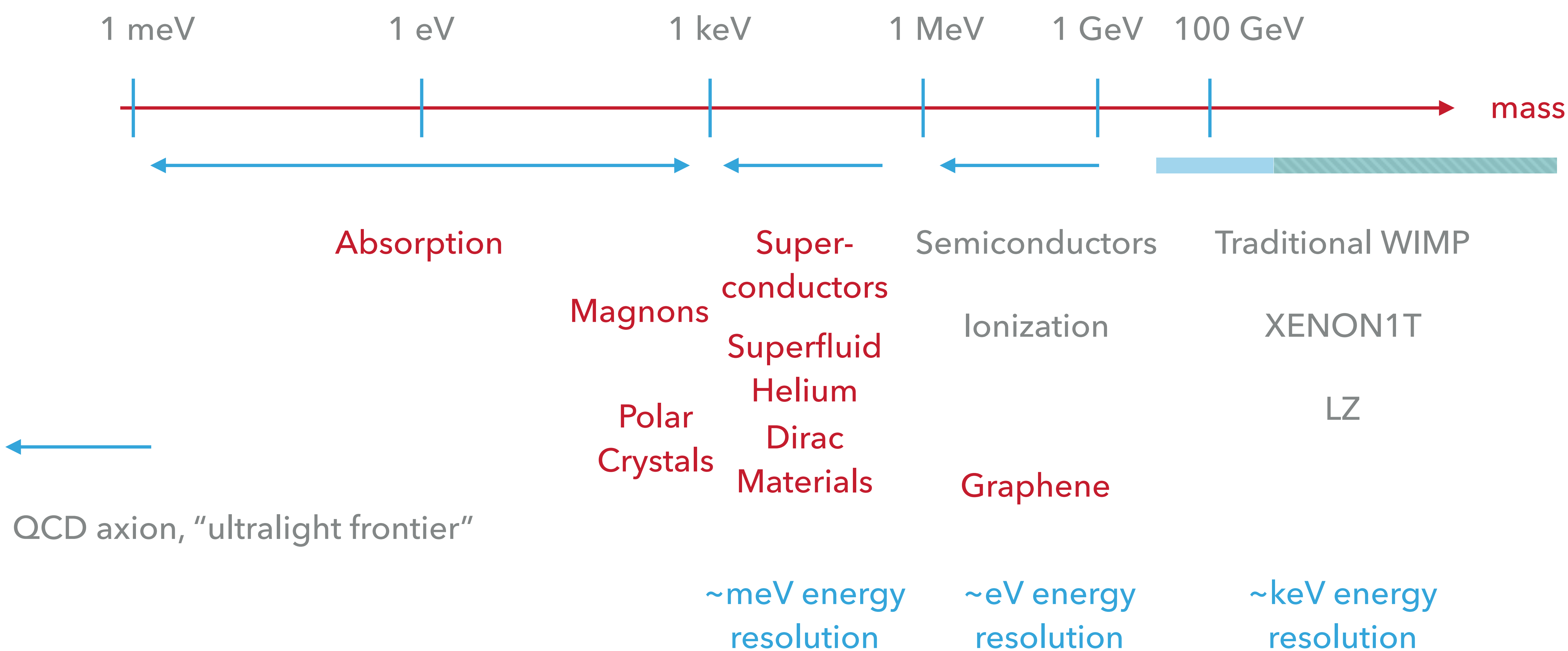


$$v \sim 300 \text{ km/s} \sim 10^{-3} c \quad \Longrightarrow \quad E_D \sim 100 \text{ keV}$$

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

PROMISE: NEW DETECTION PARADIGMS FOR LIGHT DARK MATTER

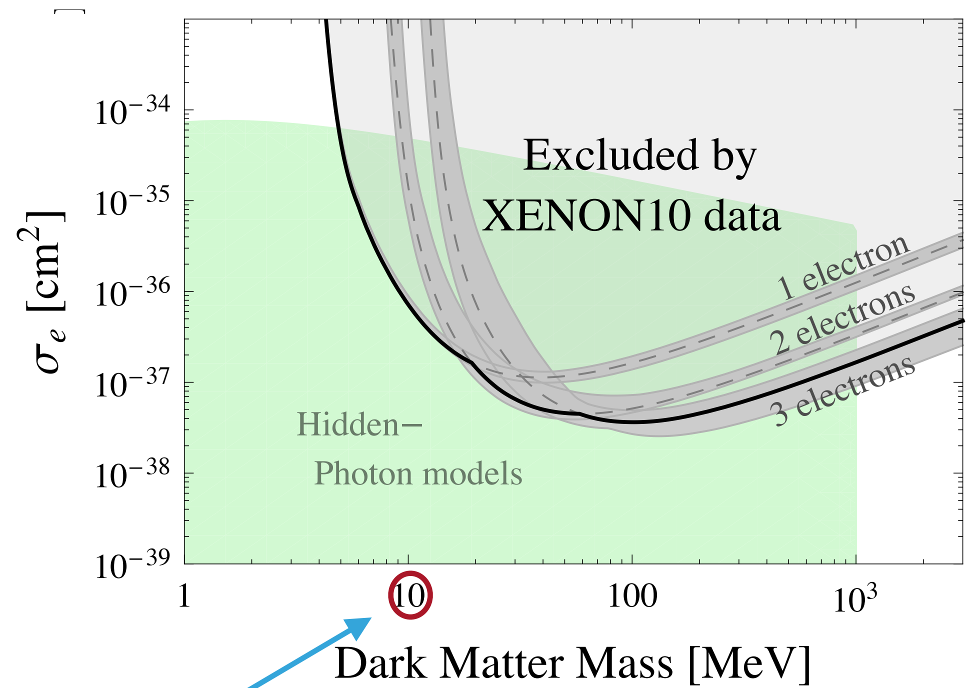
- Experimental Panorama



LIGHTER TARGETS FOR LIGHTER DARK MATTER

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

P. Sorensen et al 1206.2644

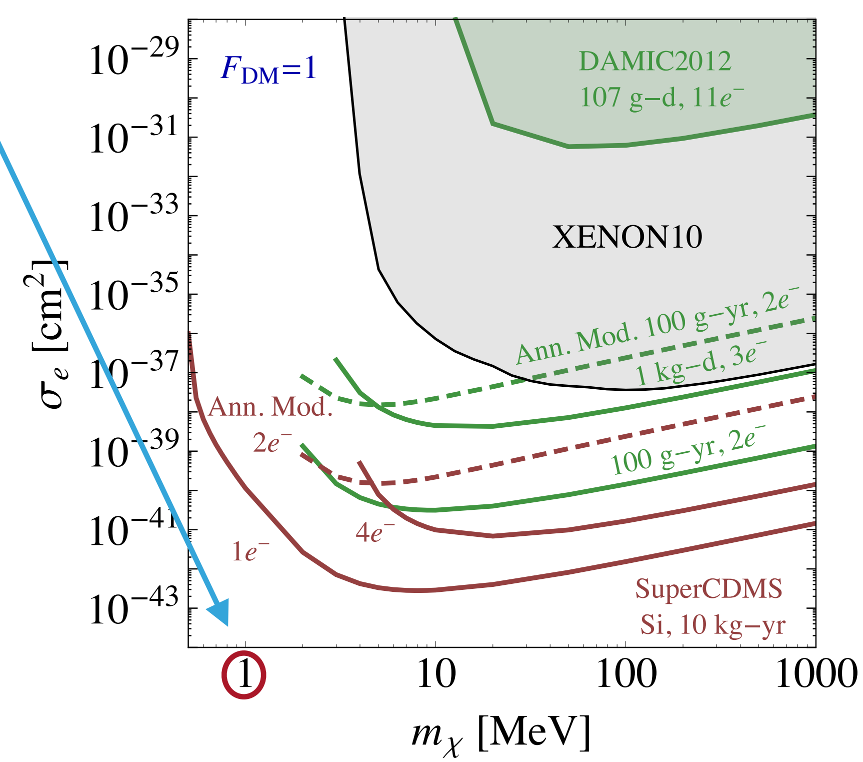


- In insulators, like xenon

Tightly bound; ionize for signal

Gap = DM Kinetic Energy

Essig et al 1509.01598

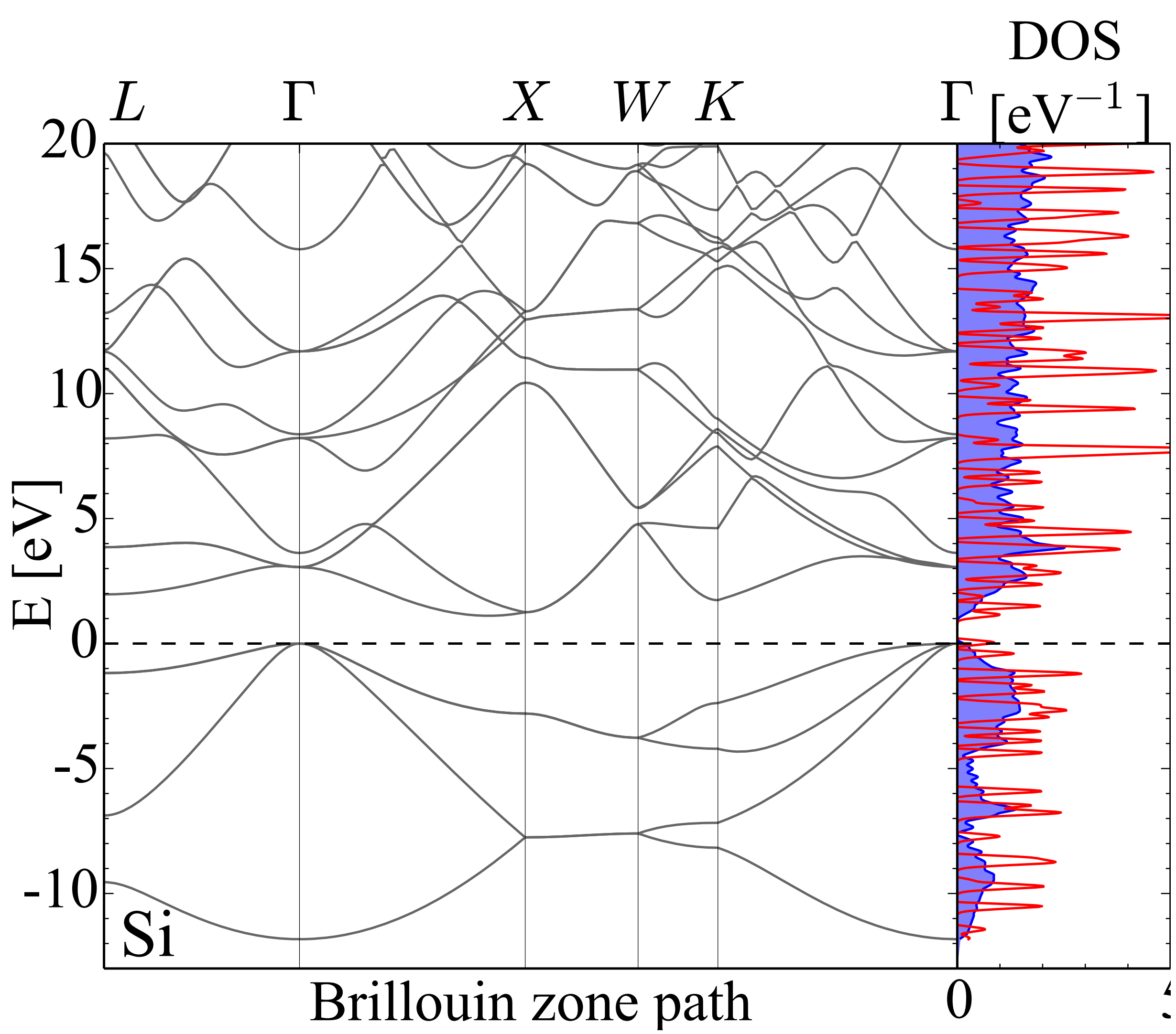


- In semi-conductors, like Ge, Si

Excite electron to conduction band

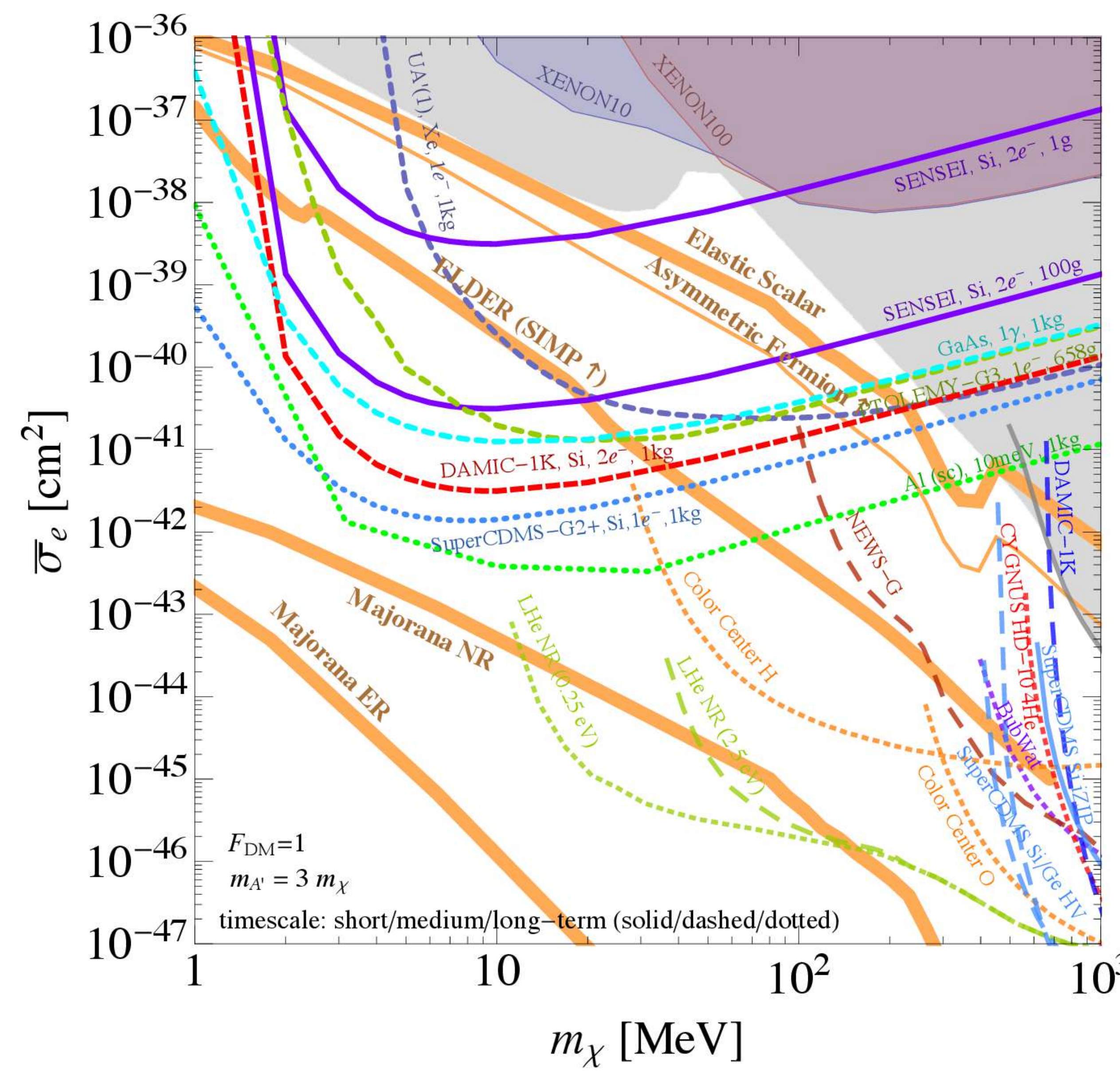
ELECTRON EXCITATION IN SEMICONDUCTORS AND NOBLE LIQUIDS

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



Essig et al 1509.01598

U.S. Cosmic Visions 2017



ELECTRON EXCITATION IN SEMICONDUCTORS AND NOBLE LIQUIDS

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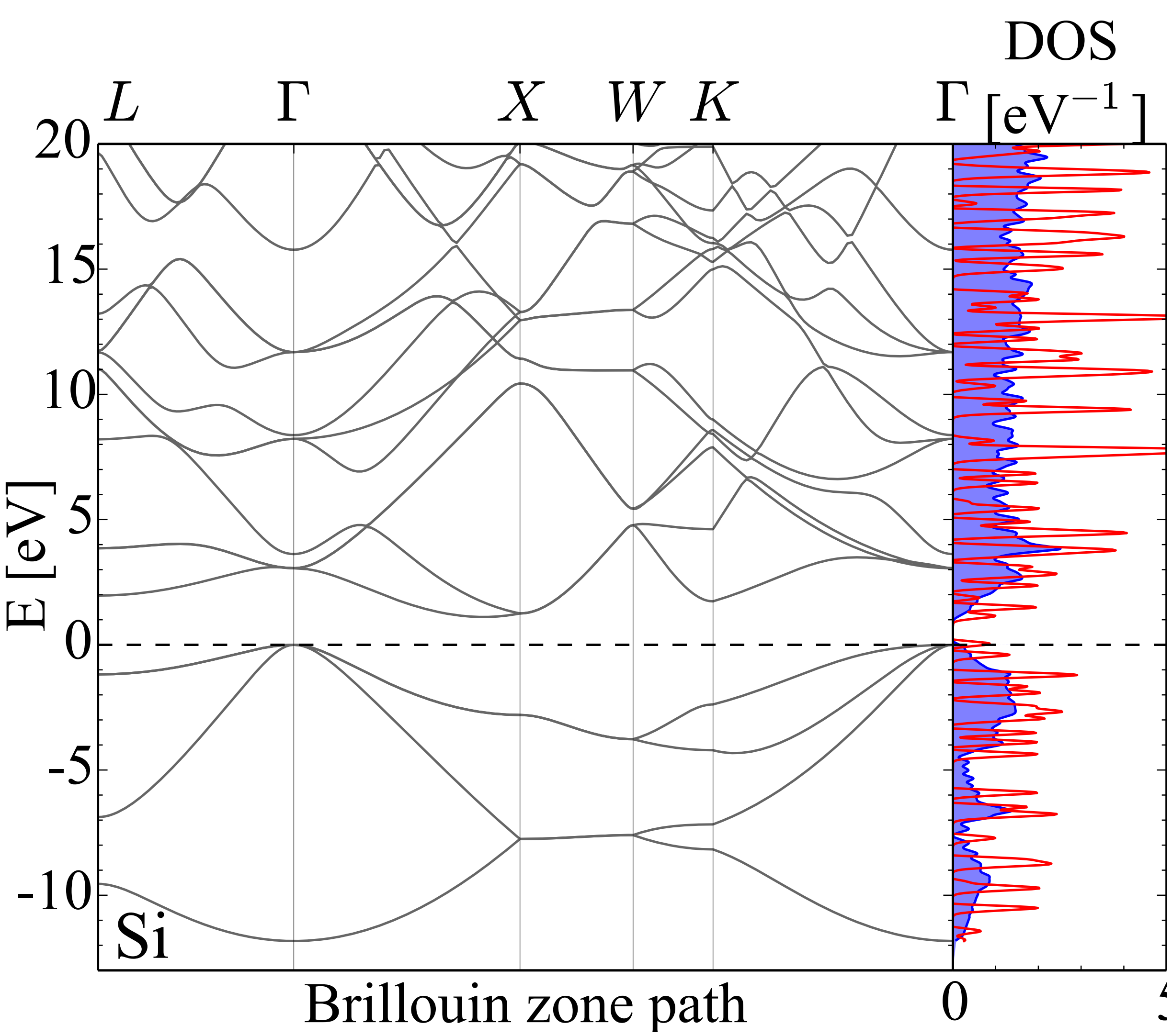
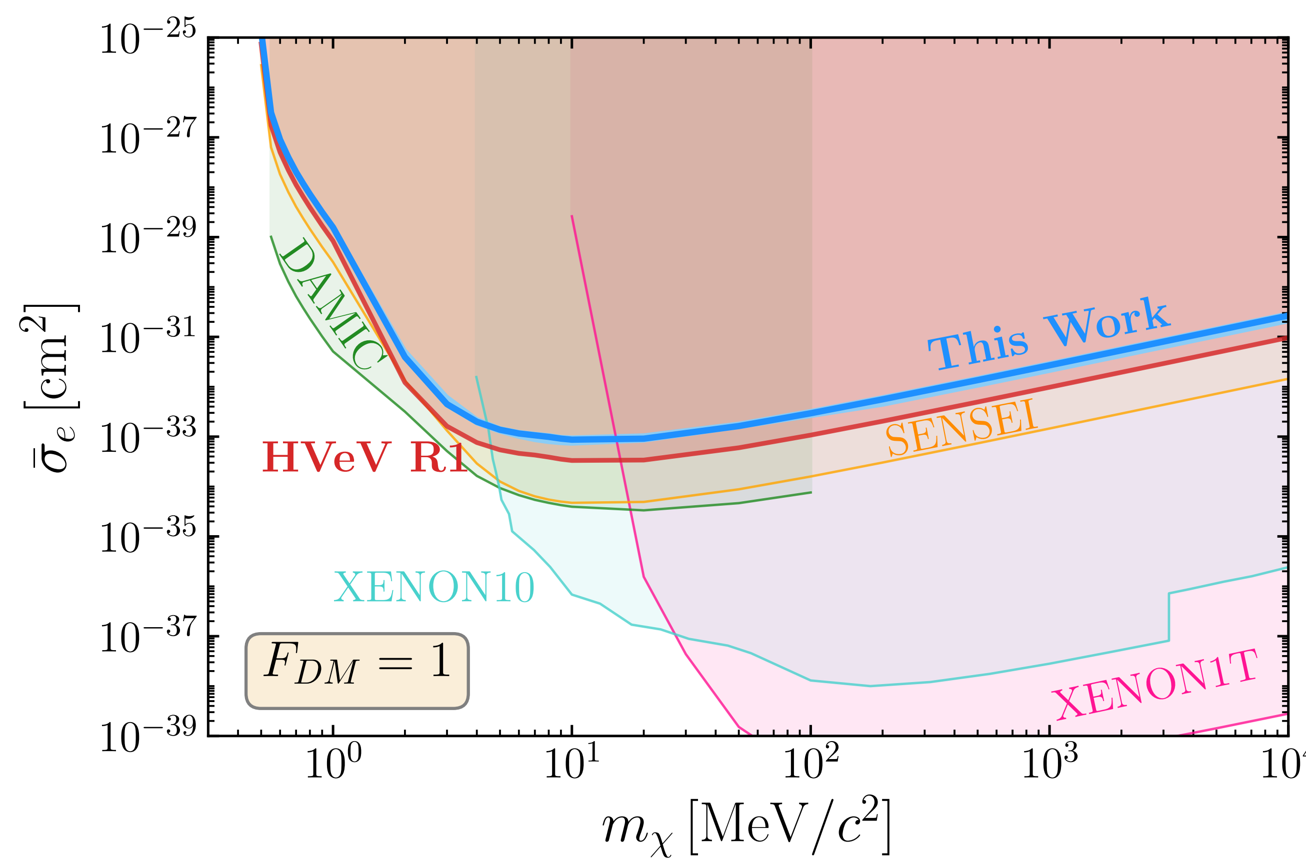


Essig et al 1509.01598

SuperCDMS Collaboration 2005.10256



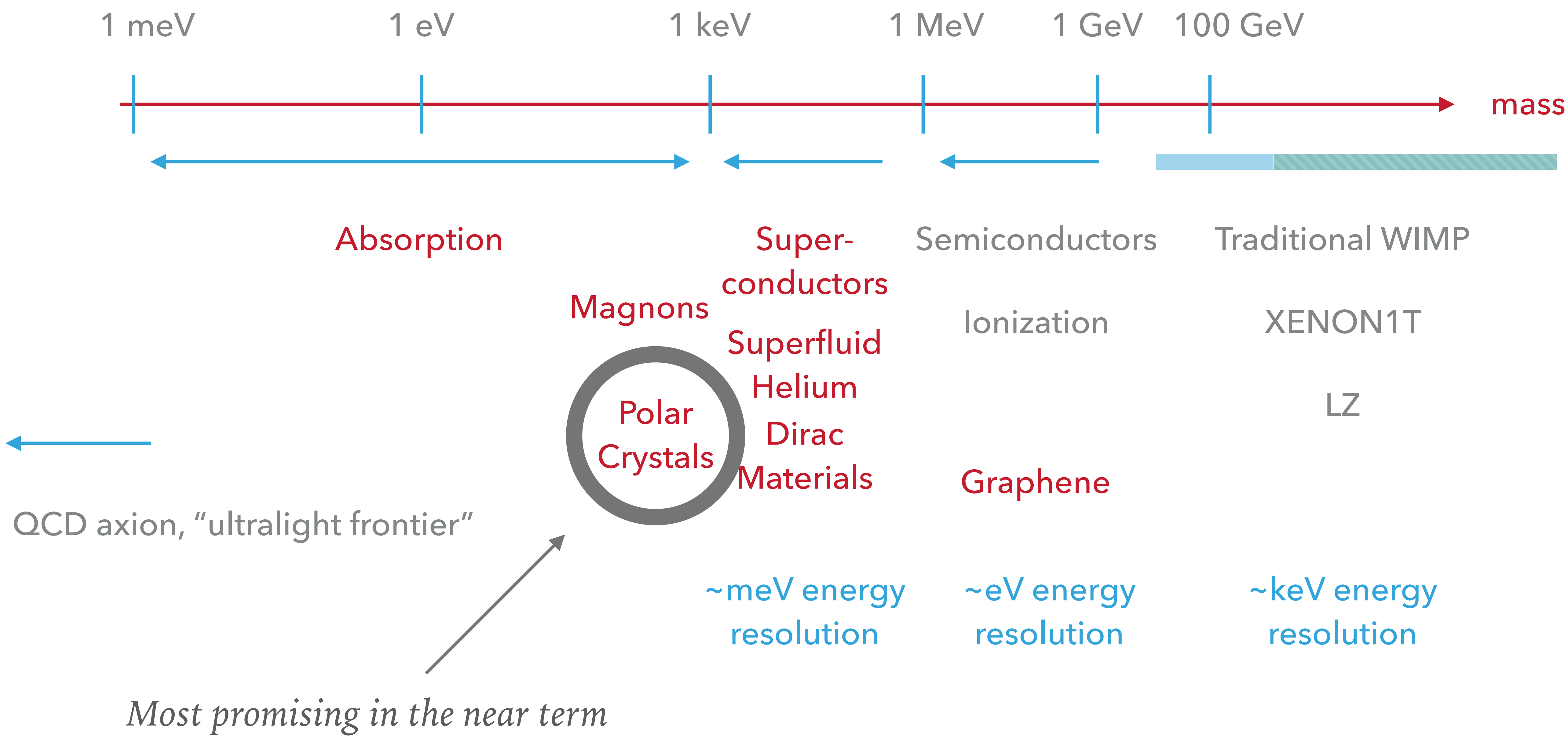
EXCITING COLLECTIVE MODES

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, 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*

PROMISE: NEW DETECTION PARADIGMS FOR LIGHT DARK MATTER

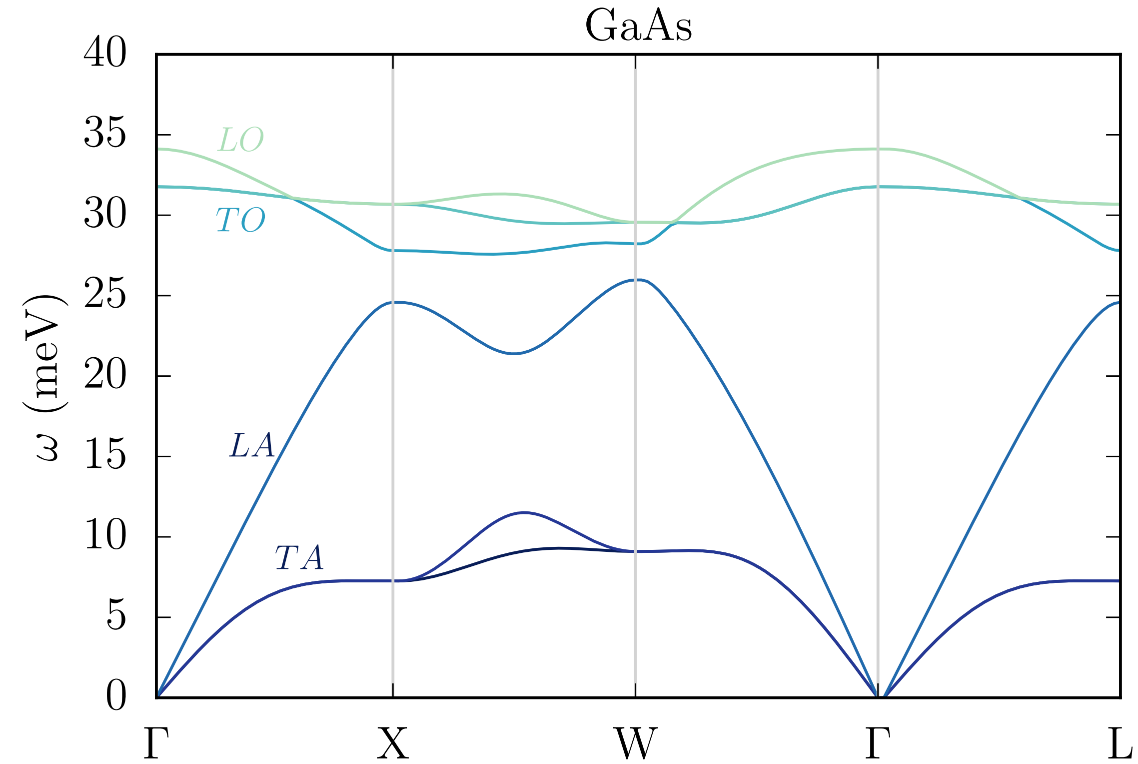
- Experimental Panorama

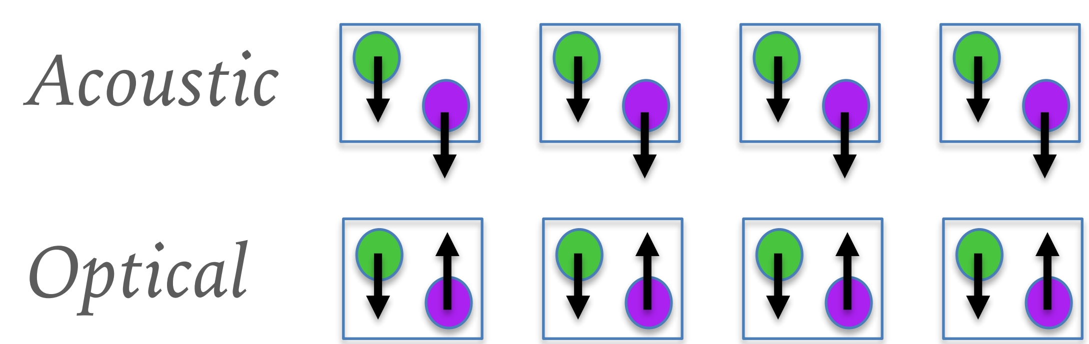


NATURE OF COLLECTIVE MODES

- 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*

GaAs



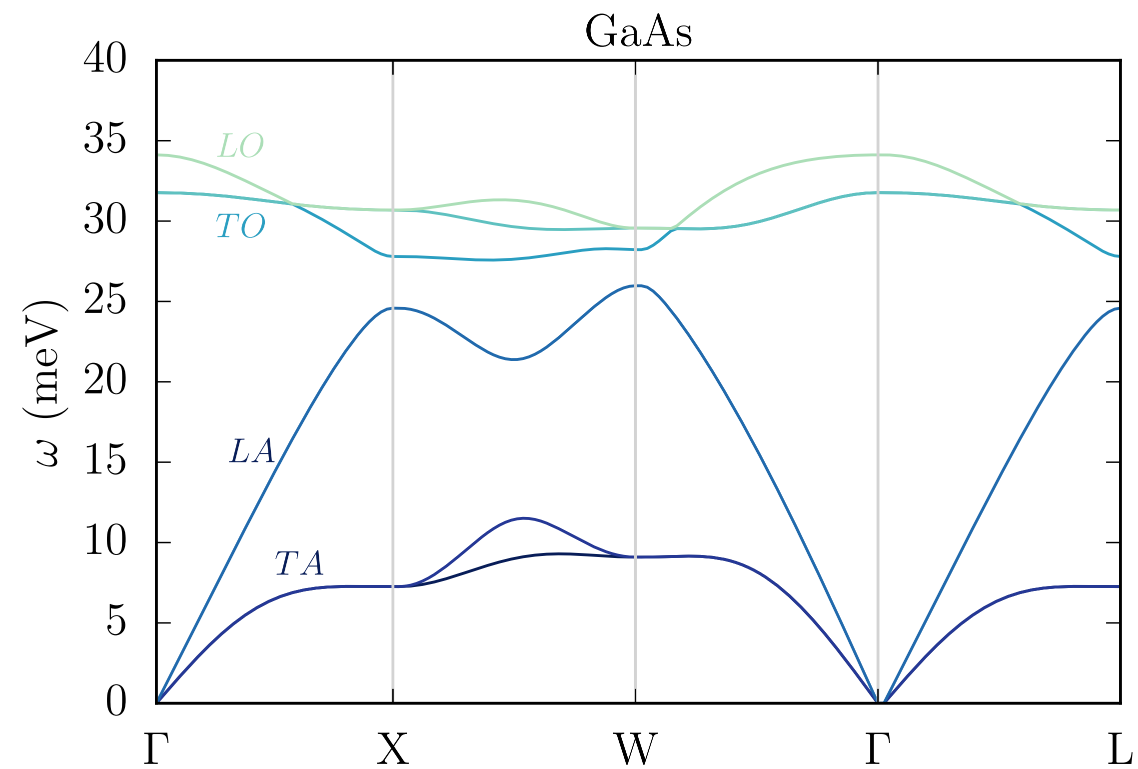


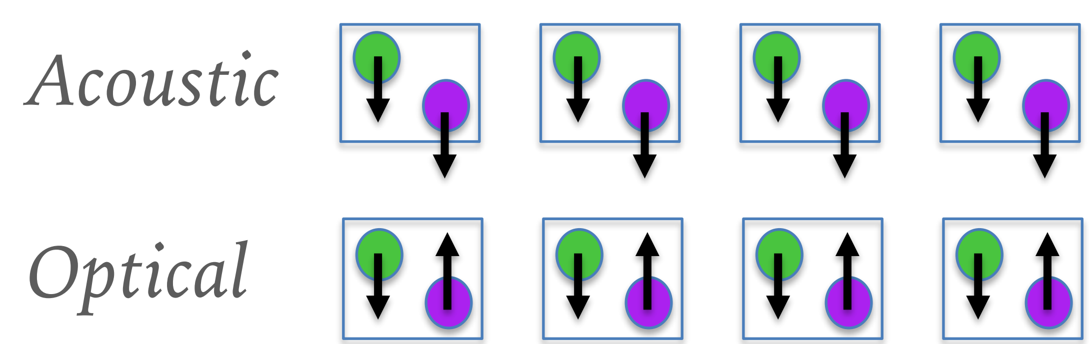
Knapen, Lin, Pyle, KZ 1712.06598 Griffin, Knapen, Lin, KZ 1807.10291

SCATTERING ON COLLECTIVE MODES IN POLAR MATERIALS

- Gapped optical modes are also ideal for sub-MeV dark matter scattering
  - i) energy spectrum of modes matches dark matter kinetic energy
  - ii) When these gapped modes result from oscillations of more than one type of ion, we have an oscillating dipole

GaAs

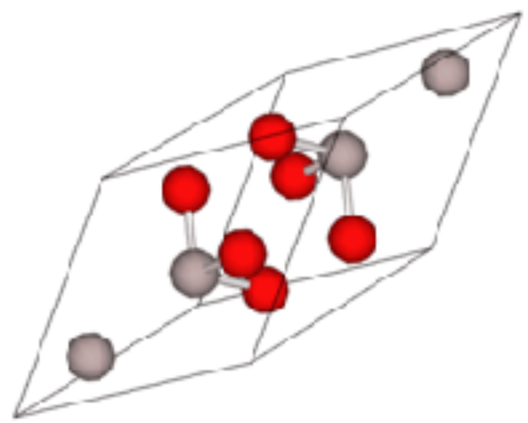




Knapen, Lin, Pyle, KZ 1712.06598 Griffin, Knapen, Lin, KZ 1807.10291

KINEMATICS OF COLLECTIVE MODES (2)

- First element to enter is the kinematics

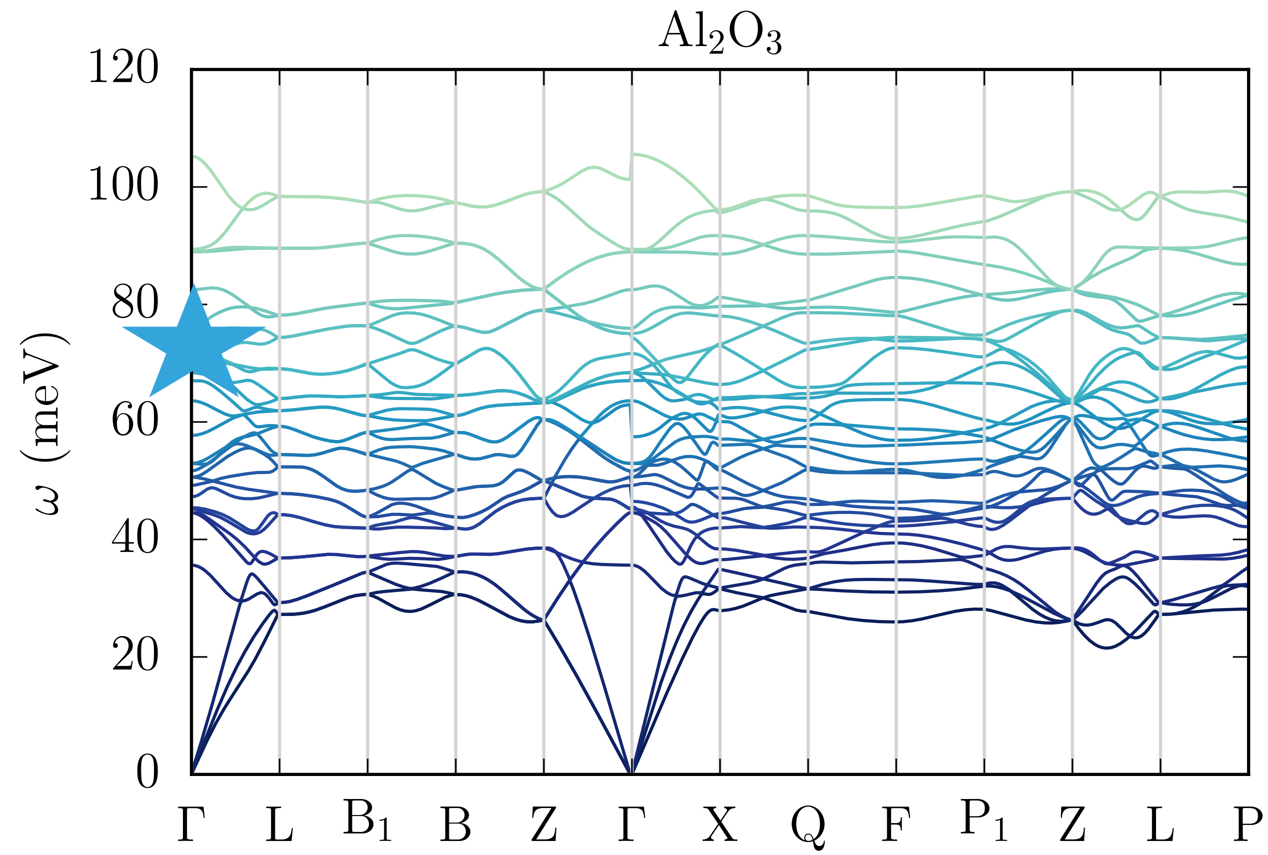


$$E_D \sim v_X q$$

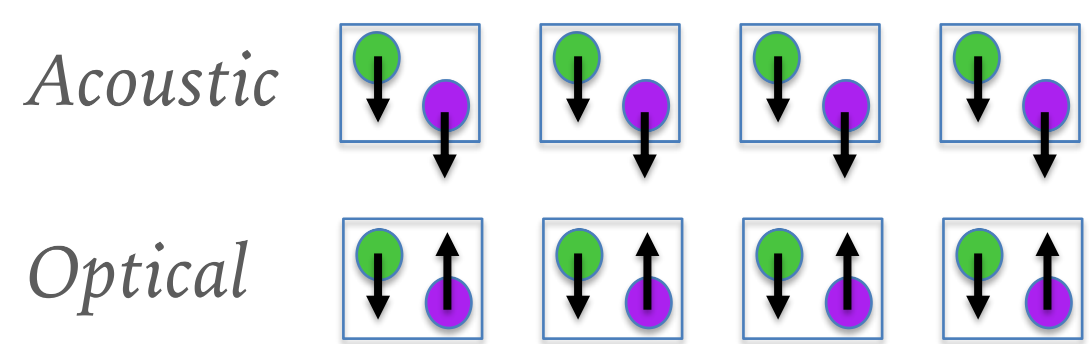
vs

$$c_s \ll v_X$$

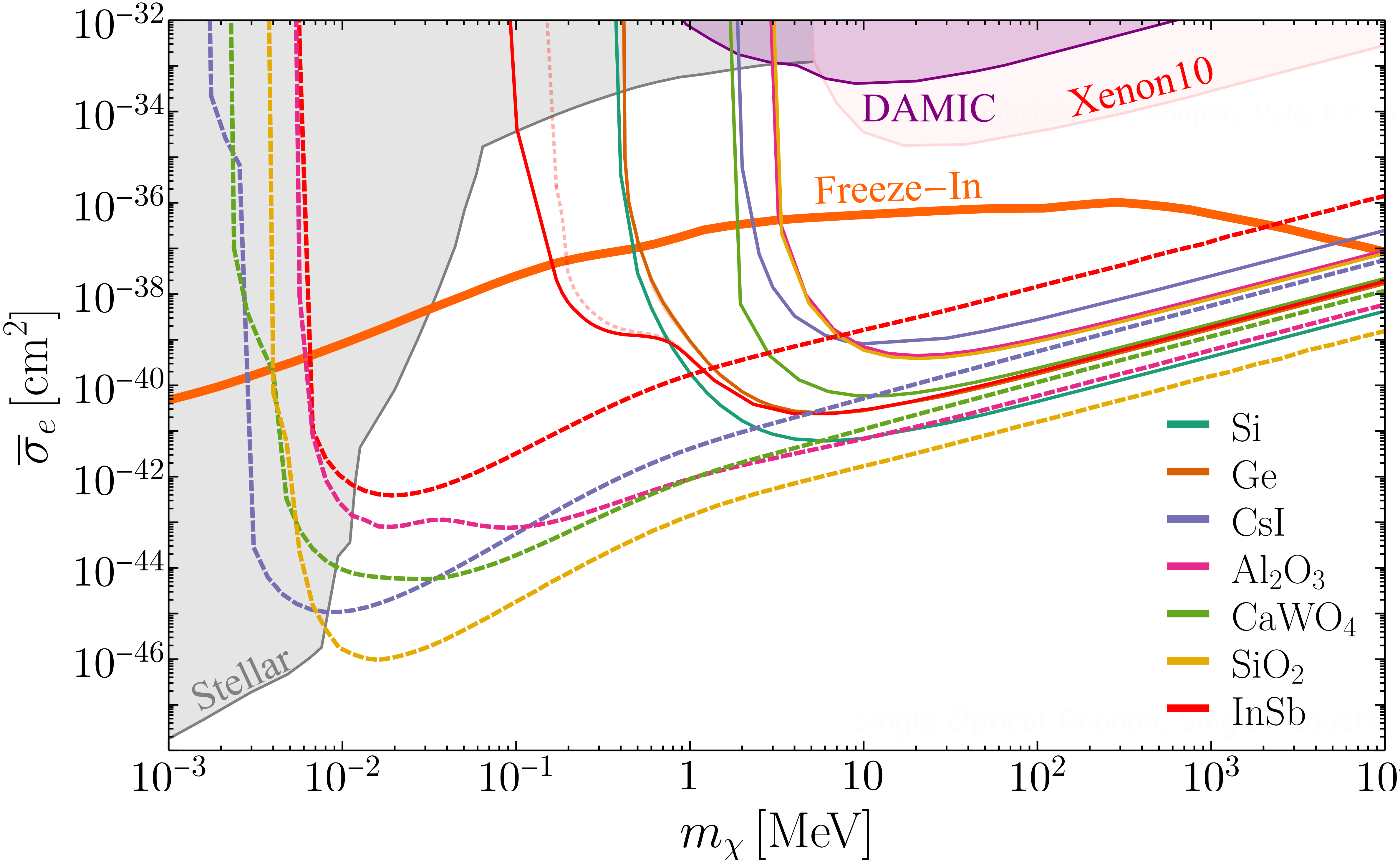
$$E_D \sim c_s q$$



- Coupling to gapped modes



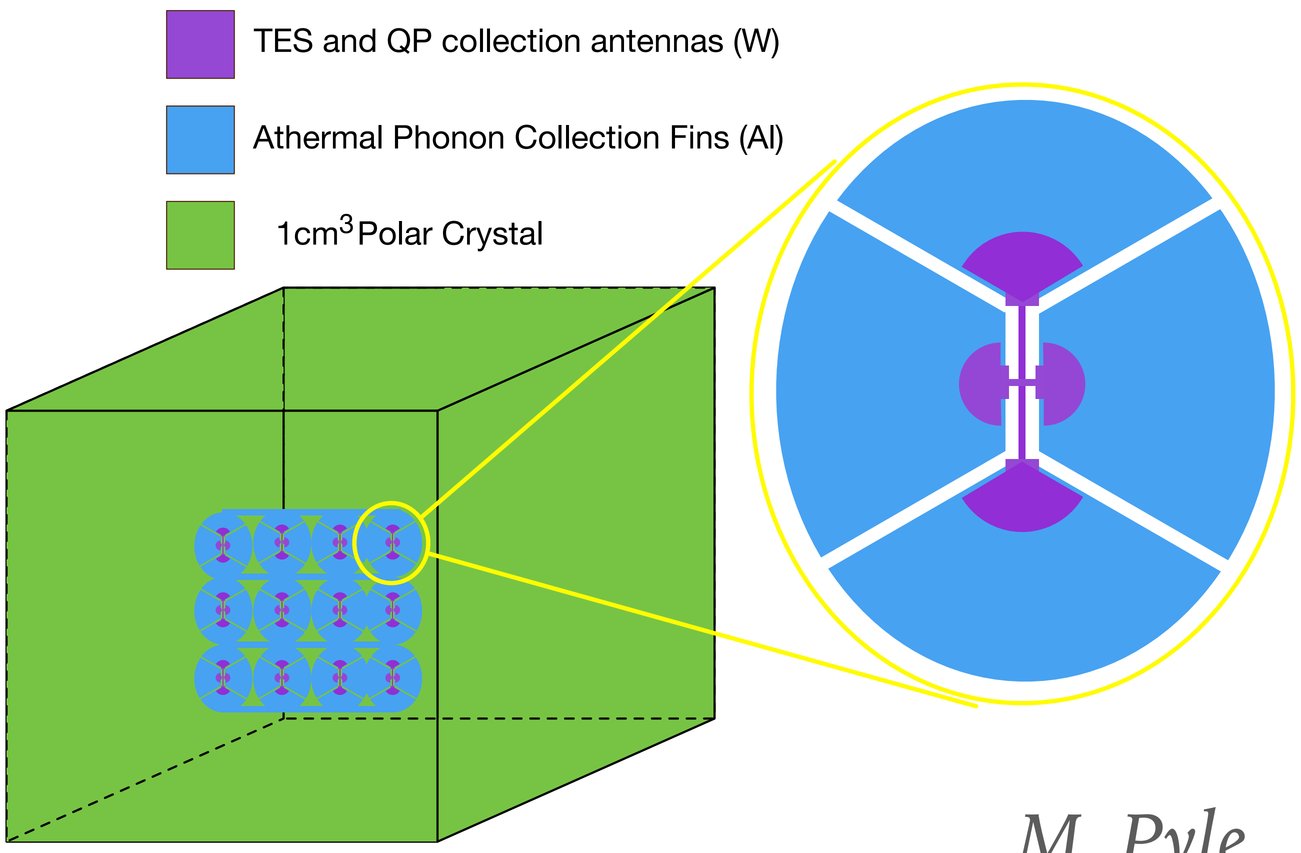
OPTICAL PHONONS IN POLAR MATERIALS (2)



Griffin, Inzani, Trickle, Zhang, KZ, 1910.10716

COMMON R&D PATH

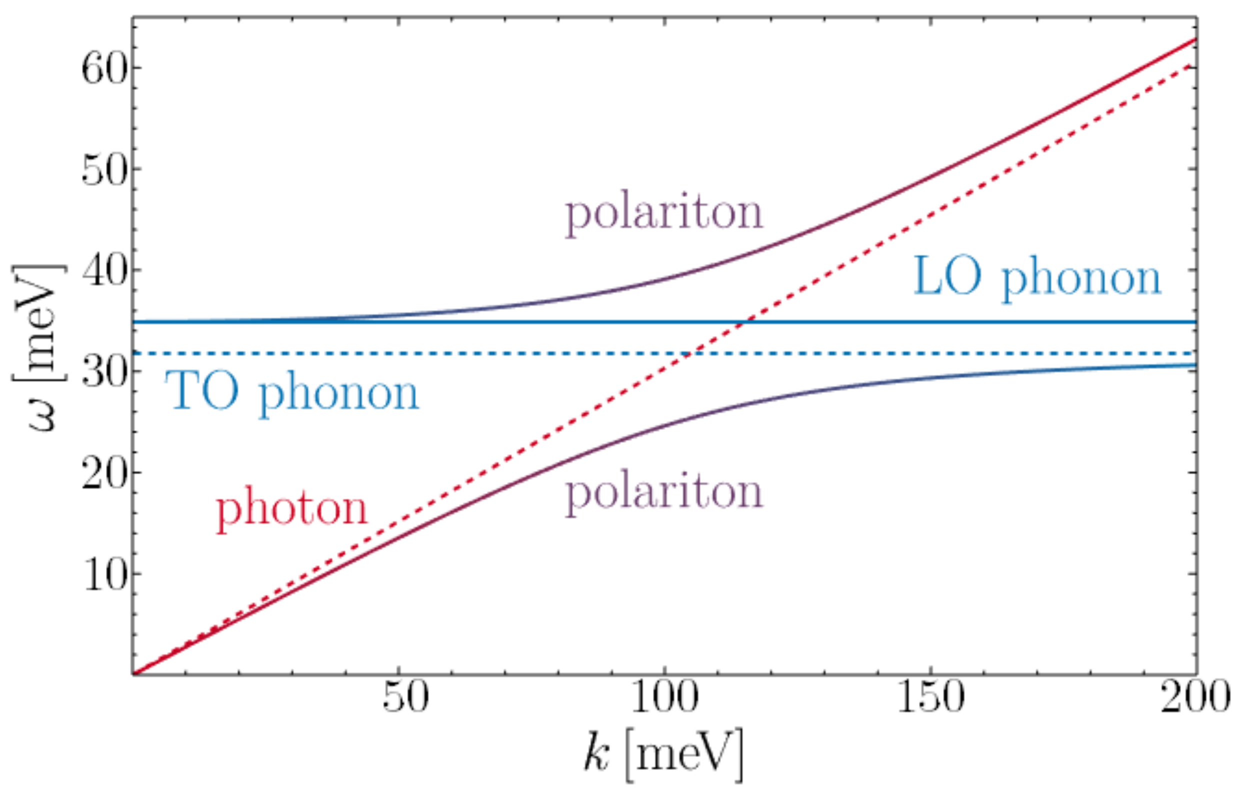
- Sensor can be coupled to multiple targets
- Zero-field read-out of phonons
- Funded for R&D by DoE Dark Matter New Initiatives
- For a polar crystal target — Sub-eV Polar Interactions Cryogenic Experiment (SPICE)

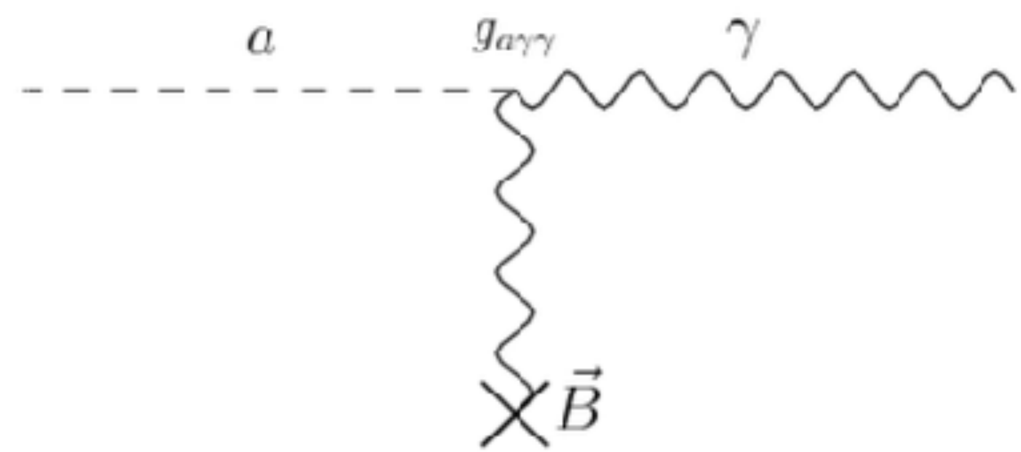


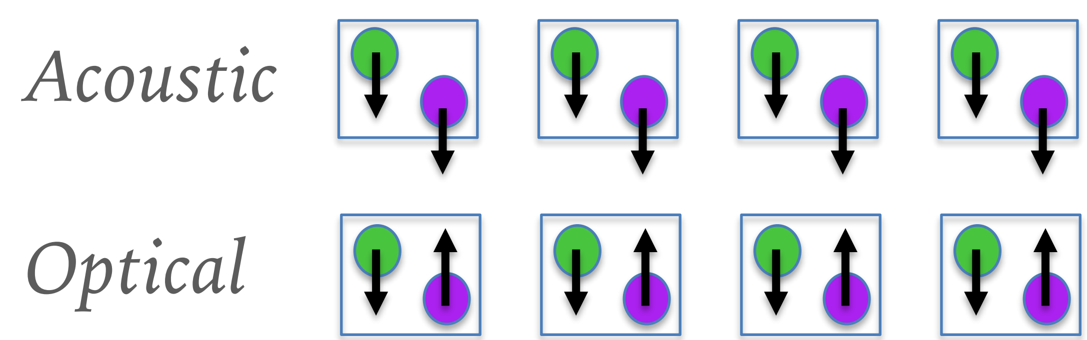
M. Pyle

AXION EXCITATION OF PHONON-POLARITONS

- The photon mixes with these collective modes at very low momentum transfer







Mitridate, Trickle, Zhang, KZ 2005.10256

AXION EXCITATION OF PHONON-POLARITONS

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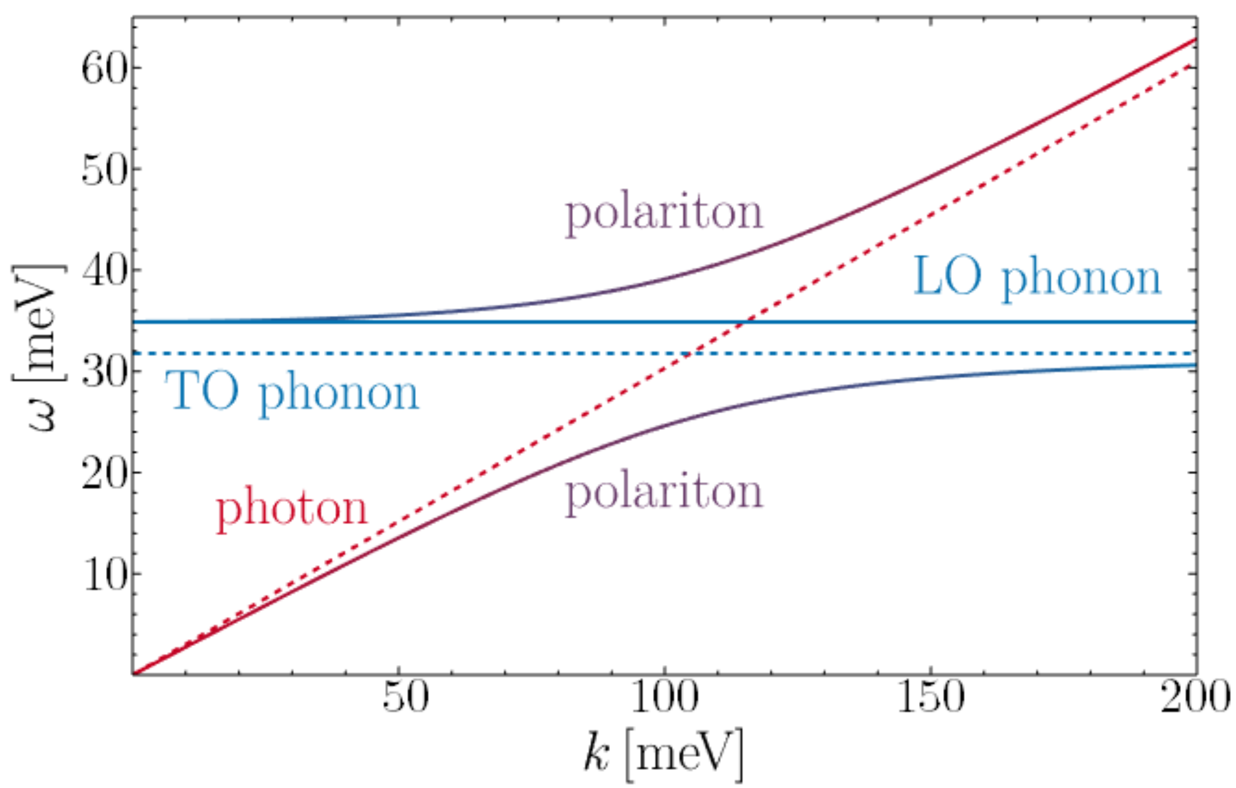
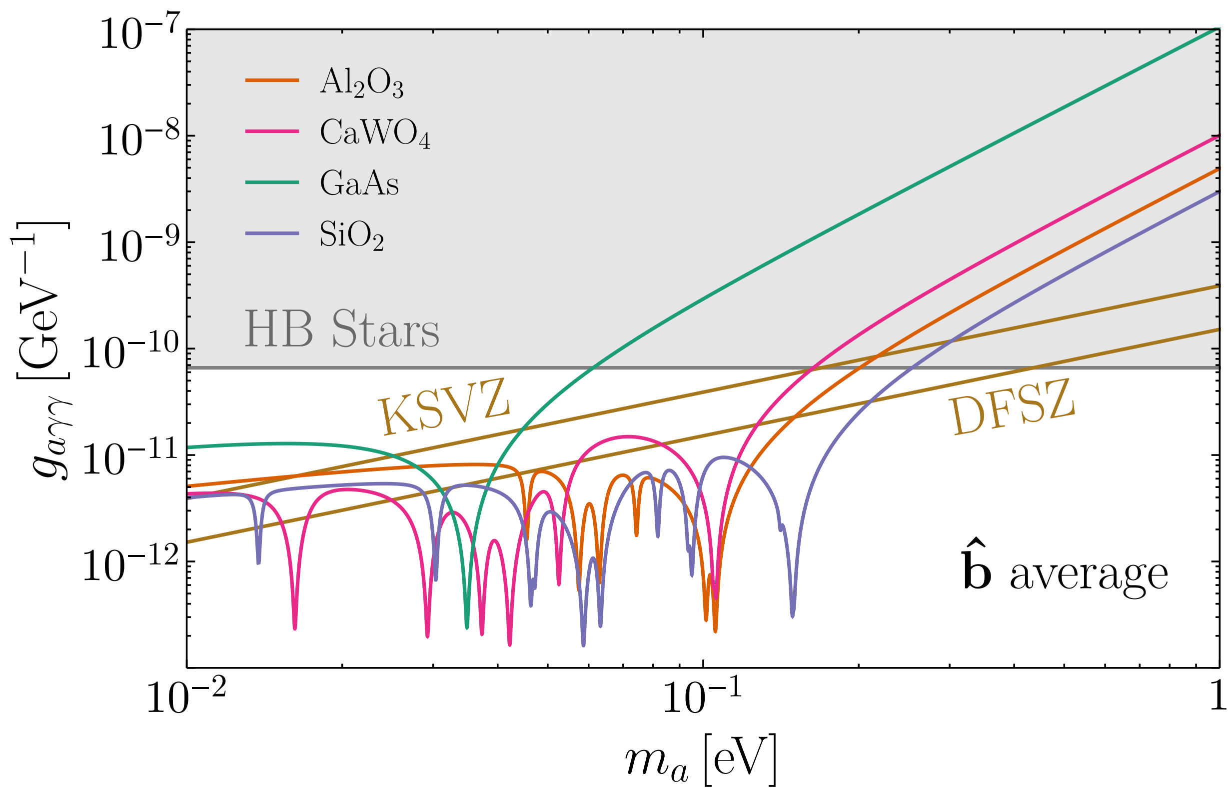
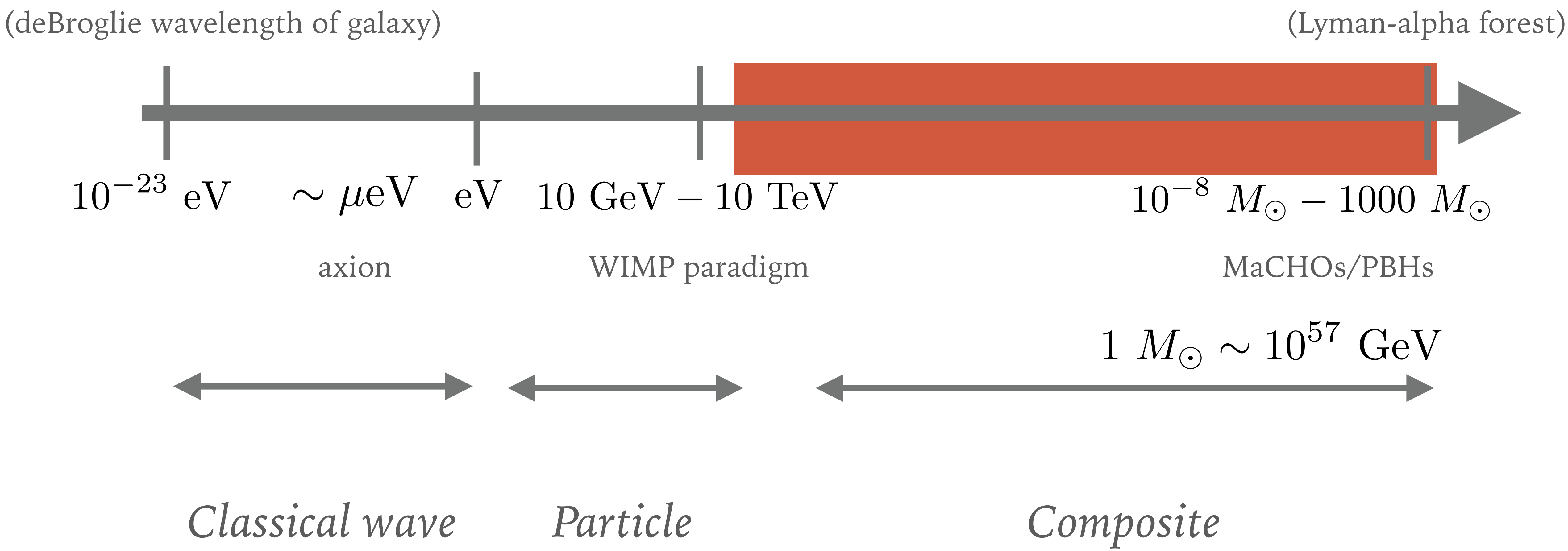




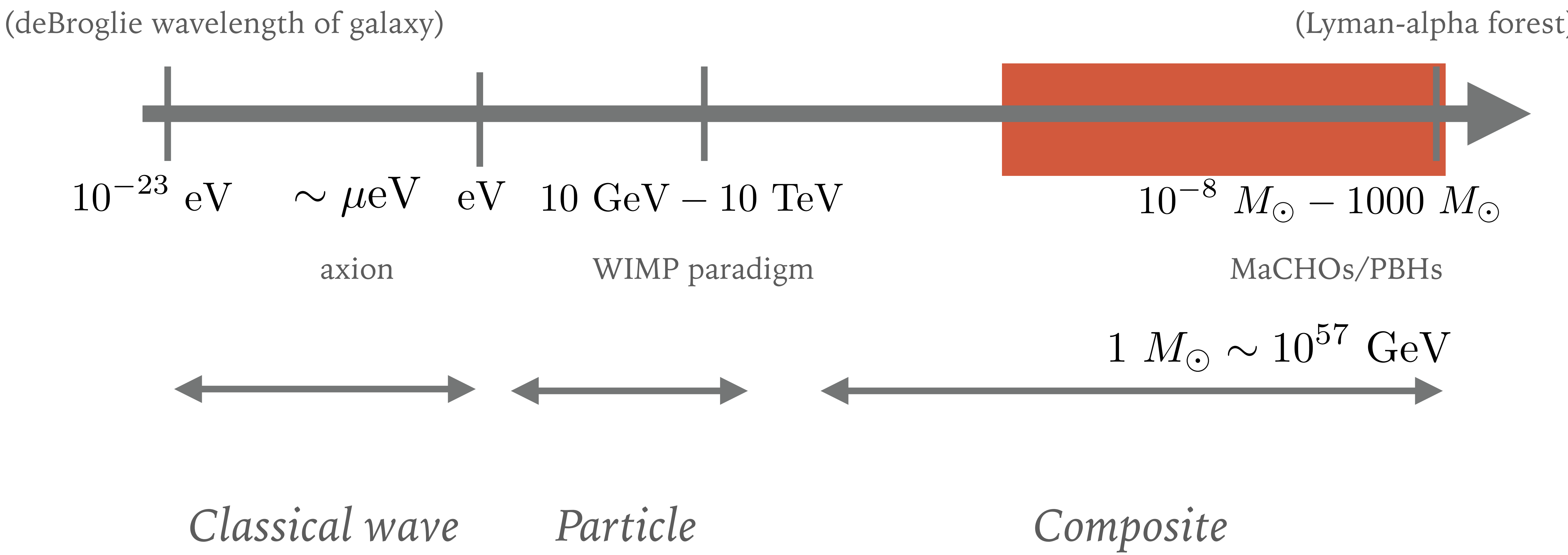
Mitridate, Trickle, Zhang, KZ 2005.10256

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

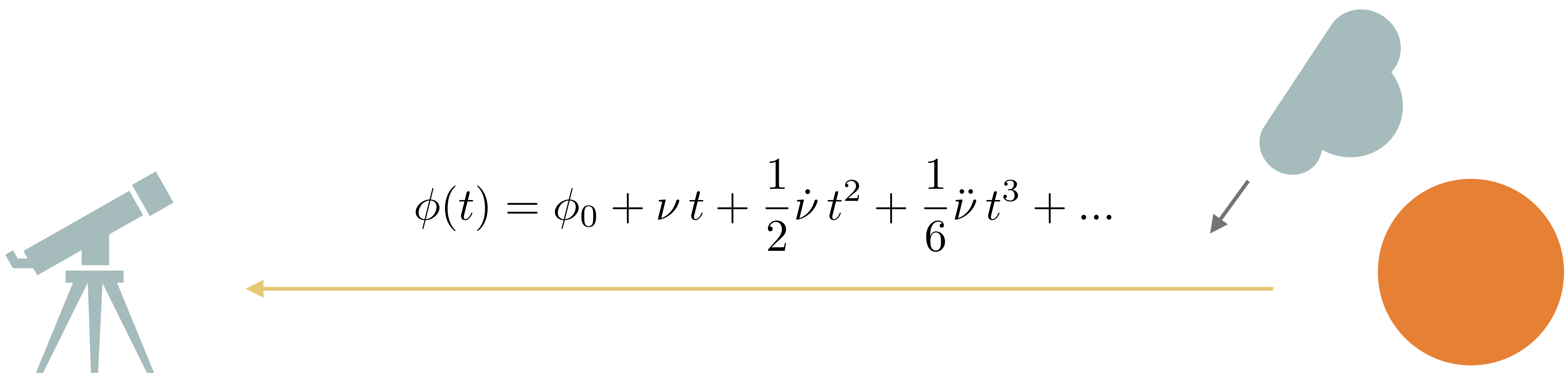
DARK MATTER DETECTION: A FULL COURT PRESS



- Look for gravitational means to detect structure
- Above $10^{-13}\ M_\odot$ e.g. pulsar timing may 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 stable. Deviations can signal transiting object.



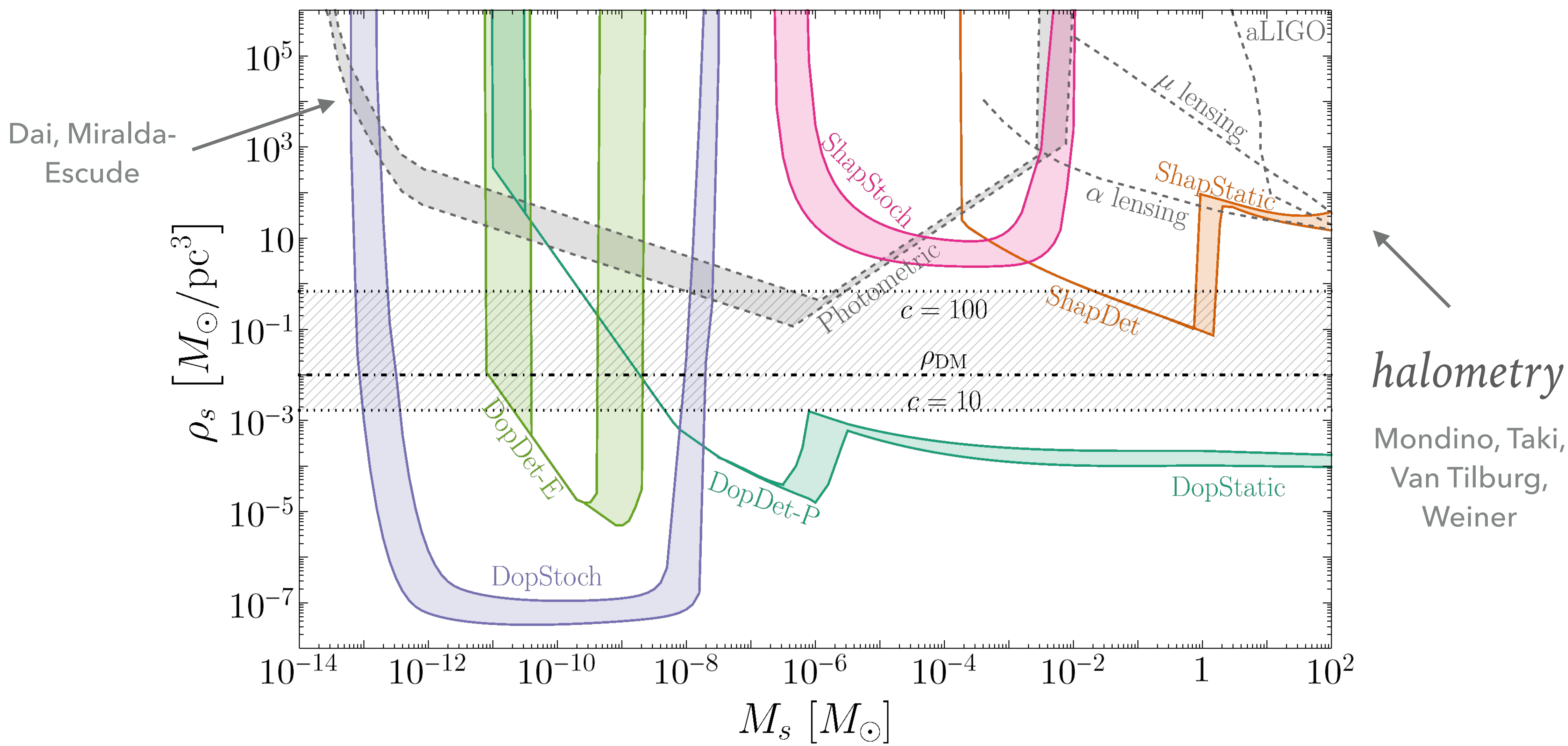
$$\phi(t) = \phi_0 + \nu\, t + \frac{1}{2}\dot{\nu}\, t^2 + \frac{1}{6}\ddot{\nu}\, t^3 + \ldots$$

Earth *Pulsar*

- Principle can be applied to many systems with accurate clocks
- Transiting clump can accelerate earth or pulsar (Doppler) or change the potential along line of sight (Shapiro)

GRAVITATIONAL EFFECTS OF DARK MATTER SUBSTRUCTURE

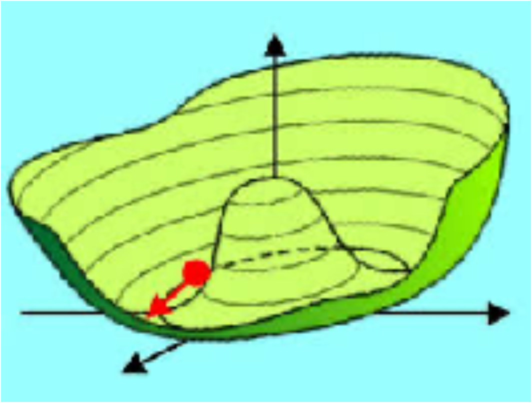
Ramani, Trickle, KZ 2005.03030



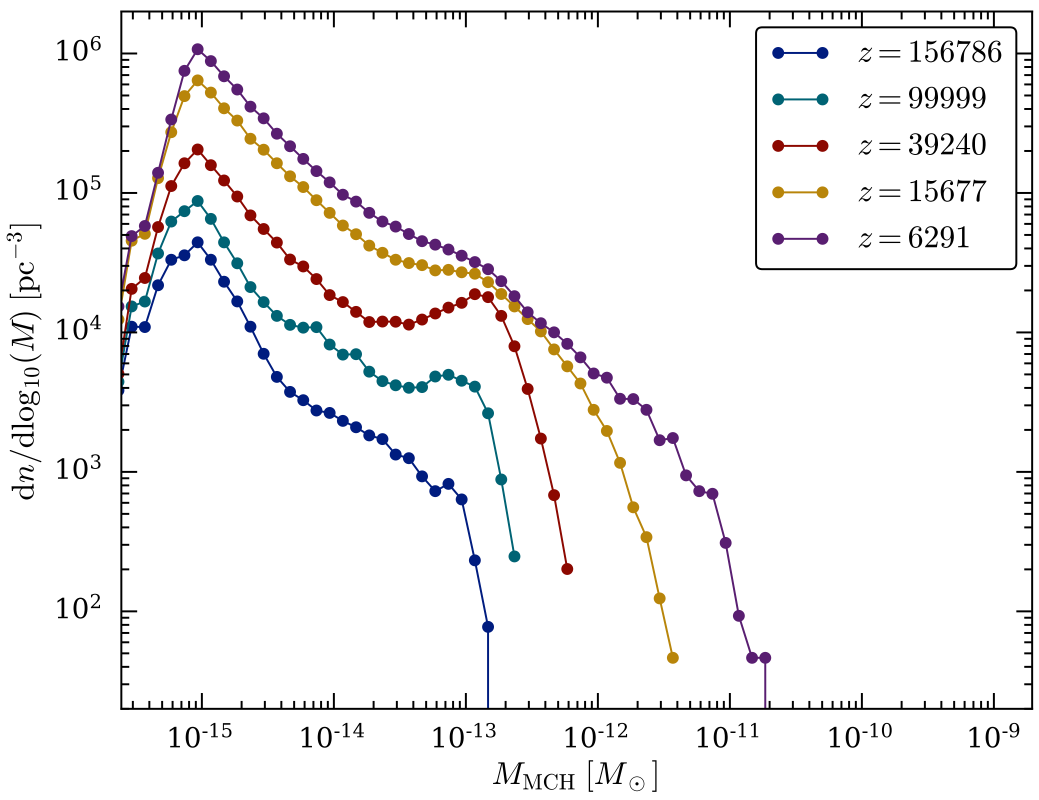
- Working with Nanograv-developed (PTA collaboration) machinery to forecast more realistic prospects for detection

MODELS WITH ENHANCED SMALL SCALE POWER

- Axion models, where PQ symmetry breaks after inflation

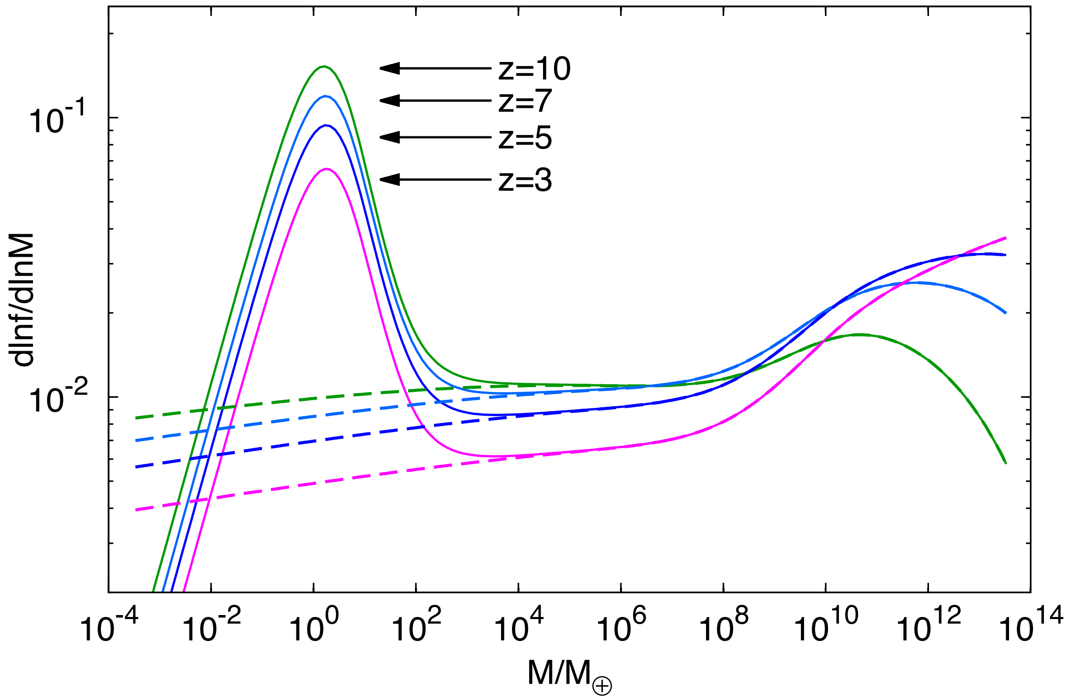


Eggemeier, Redondo et al 1911.09417



- Periods of early matter domination can lead to growth of structure on small scales

Erickcek, Sigurdson 1106.0536

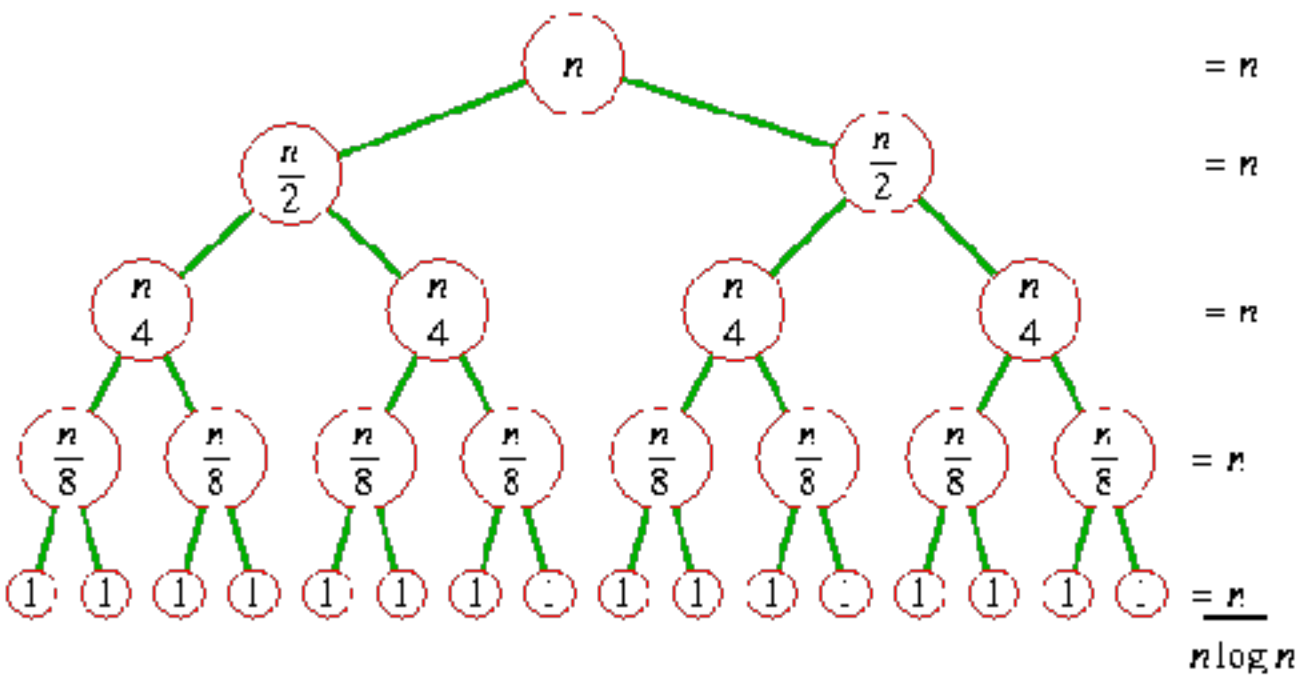


THE CHALLENGE

- Now is not the time for narrowing our search for Invisibles; the playing field is still wide open
- Fortunately the Identification of Dark Matter has spurred ideas for many new experimental and observational efforts, on all avenues
- Lack of evidence for WIMP has given rise to renewed interest in axion, including more robust theoretical predictions and new ideas for probes
- New ideas for hidden sector/valley dark matter and probes for such light dark matter states
- New opportunities to search for dark matter substructure over the next decade

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 new candidates?