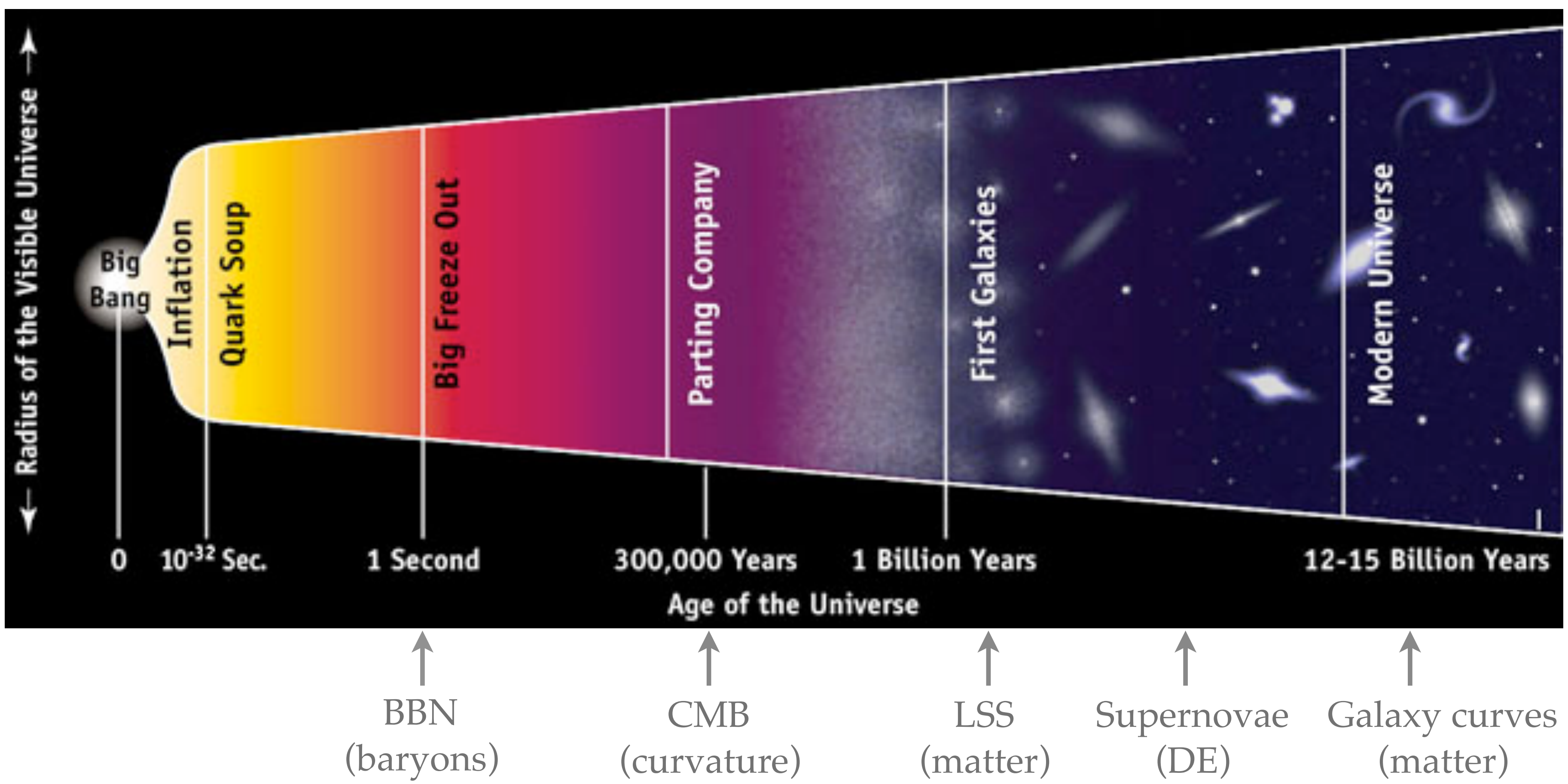
NEW IDEAS IN SEARCHING FOR INVISIBLES

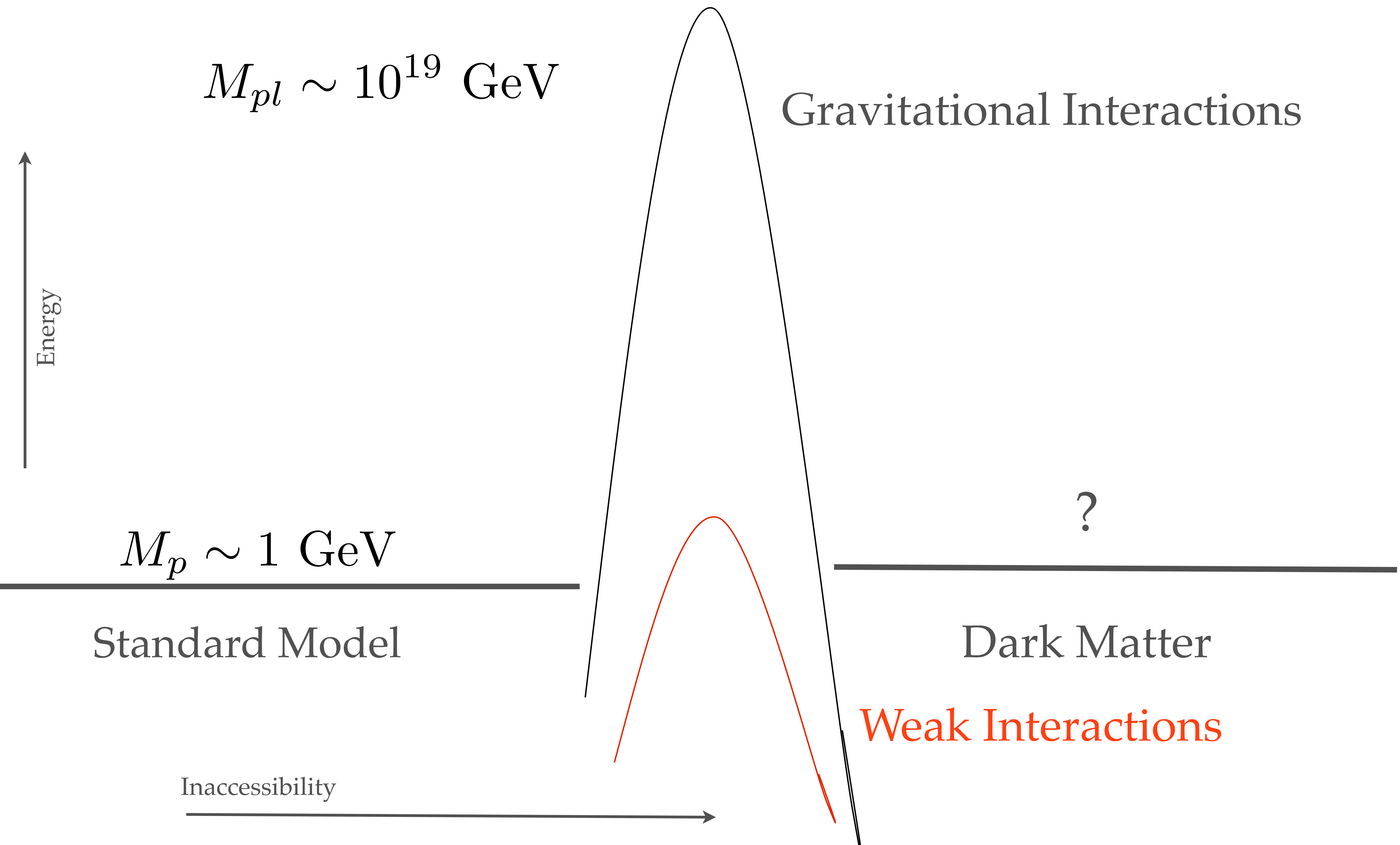
Kathryn M. Zurek

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.

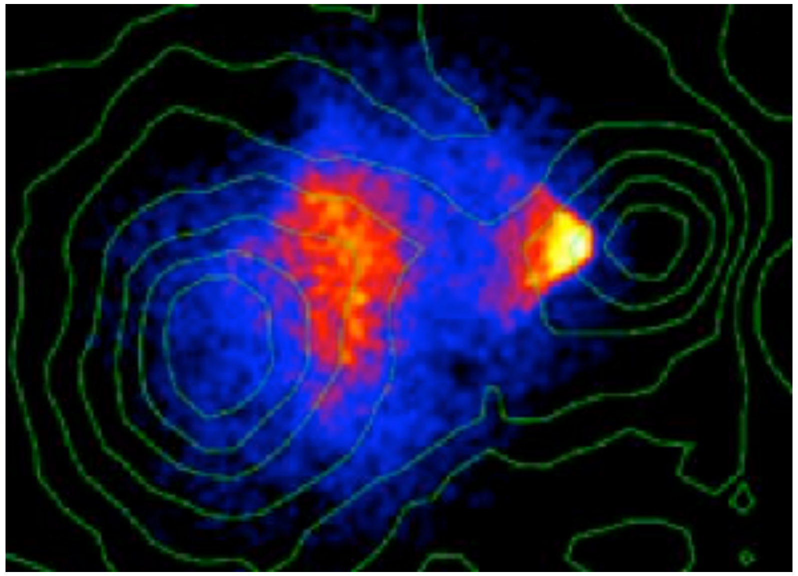


EVERYTHING WE KNOW ABOUT DM COMES FROM GRAVITY



SUPER-WEAKLY INTERACTING

- Gravitational Coherence ....



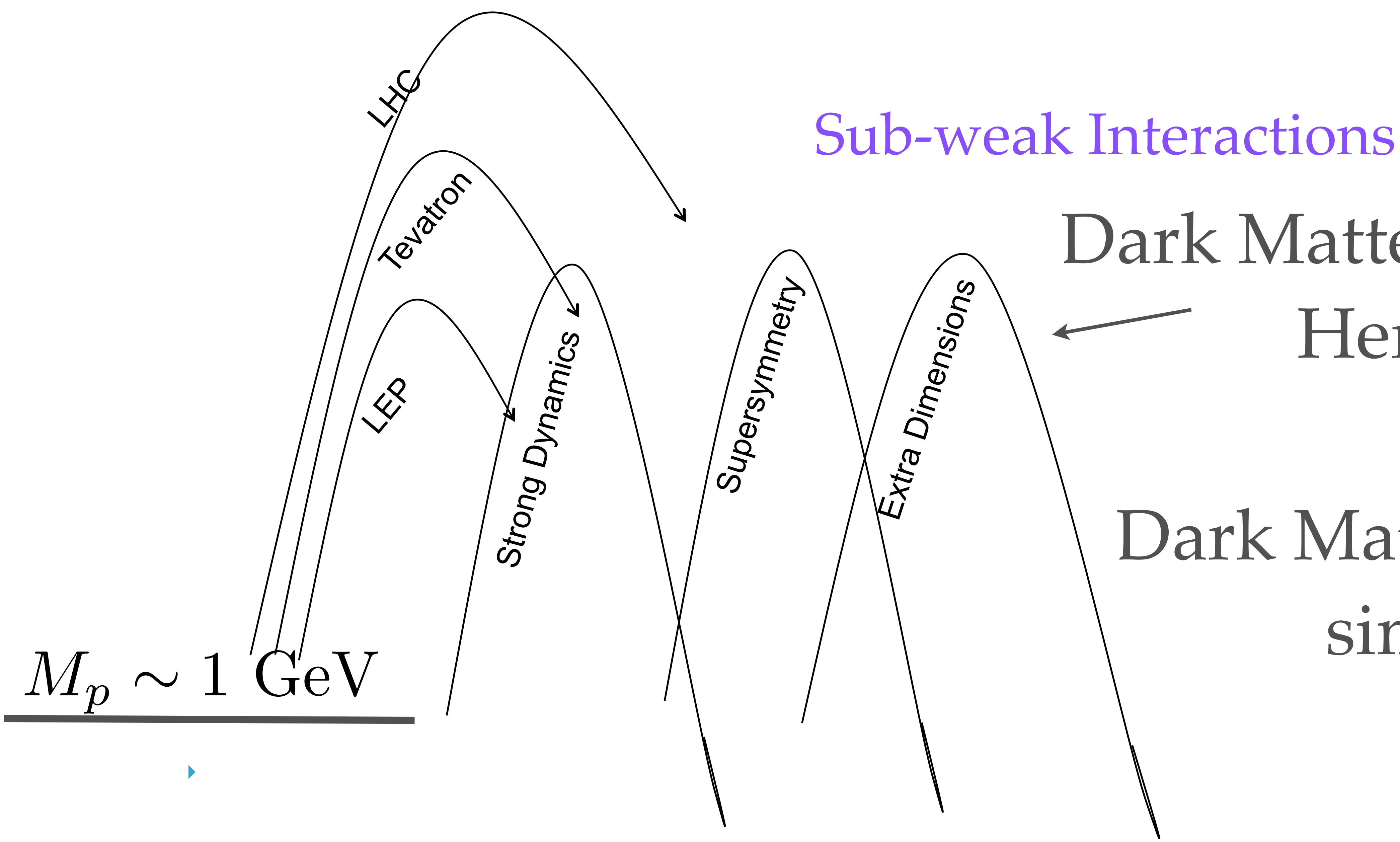
... on cosmological scales!

  - Helps us learn about aggregate properties of dark matter

- Particle properties much harder
- Fundamental premise: DM has interactions other than gravitational

PARTICLE PHYSICS PROVIDES SOME IDEAS

- Dark Matter is part of solution to "deeper" problems



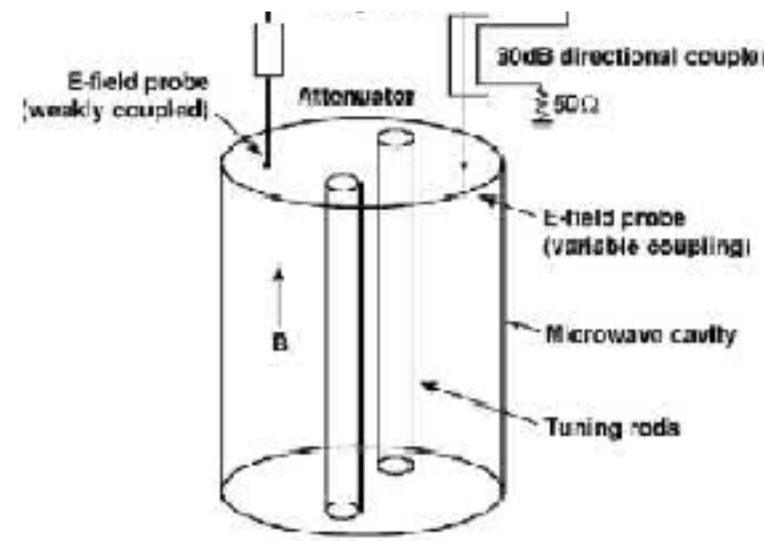
Dark Matter Resides Here!

Dark Matter itself is simple

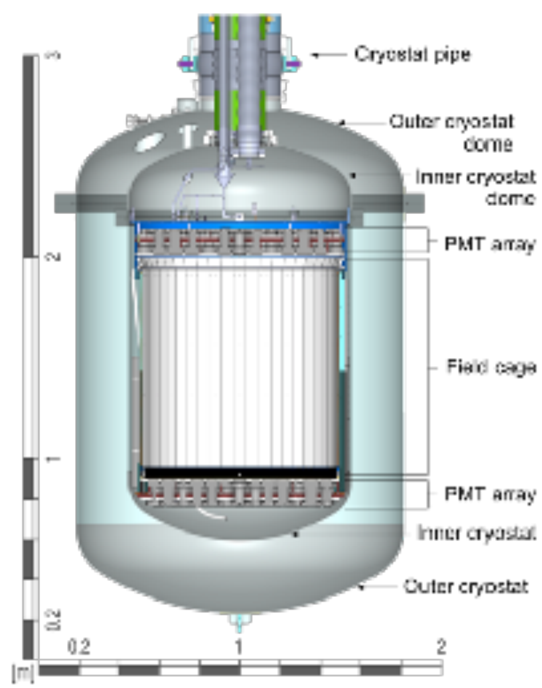
THEORY AND EXPERIMENT INTERPLAY

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

axions

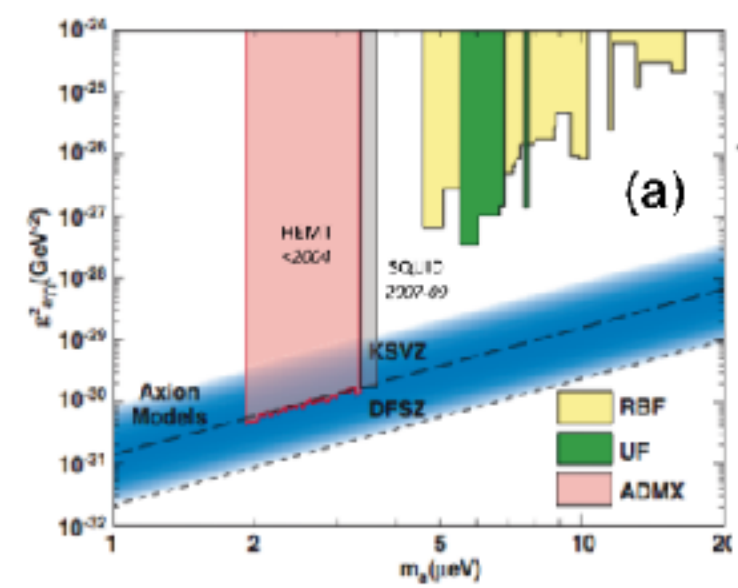


WIMPs

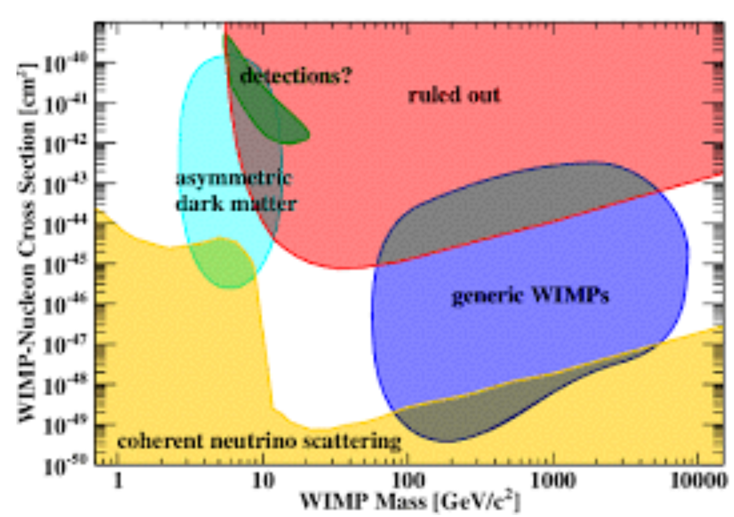


XENON

ADMX



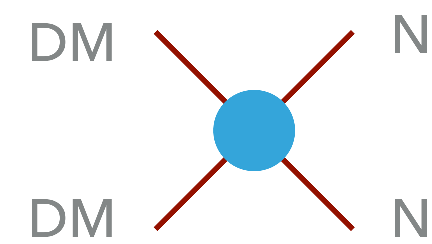
APS Physics Today



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

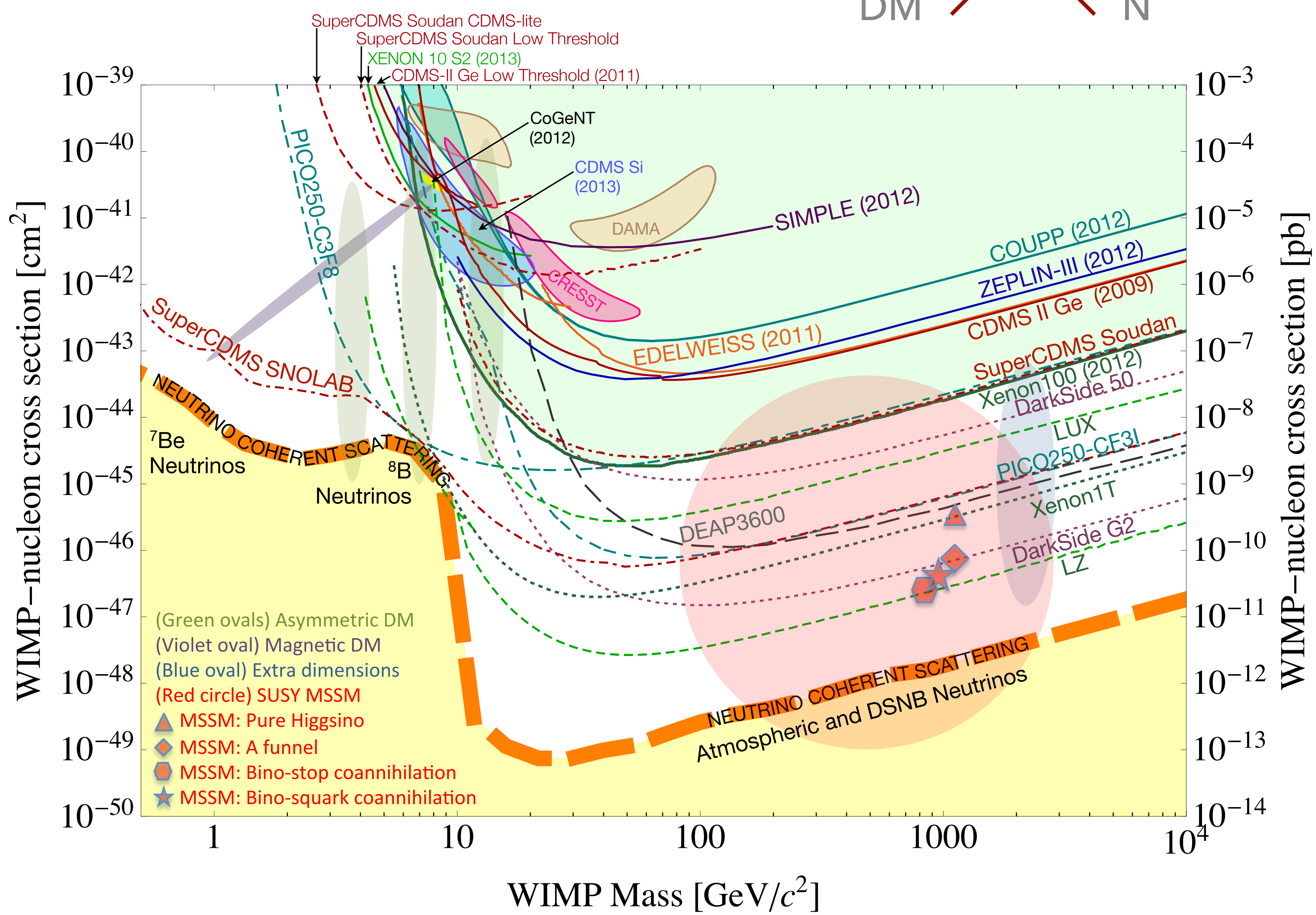
THEORY AND EXPERIMENT INTERPLAY

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



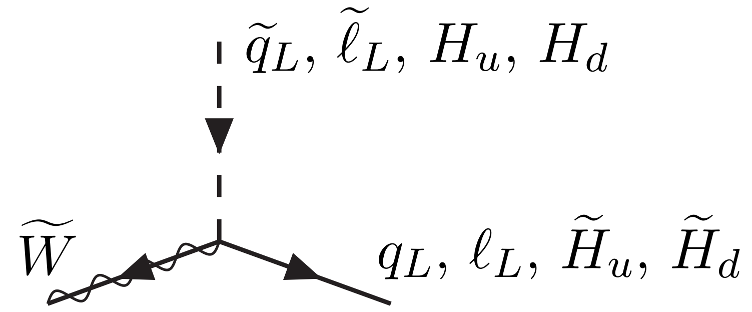
Z-boson interacting dark matter: ruled out

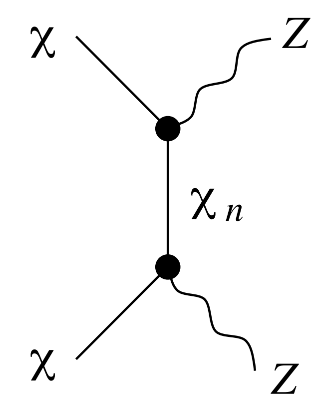
Higgs interacting dark matter: active target



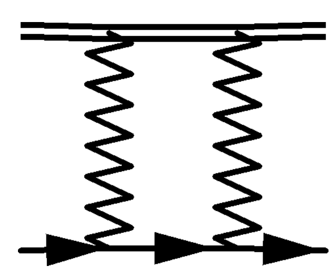
CLOSURE OF SUSY TARGET SPACE DECEPTIVE

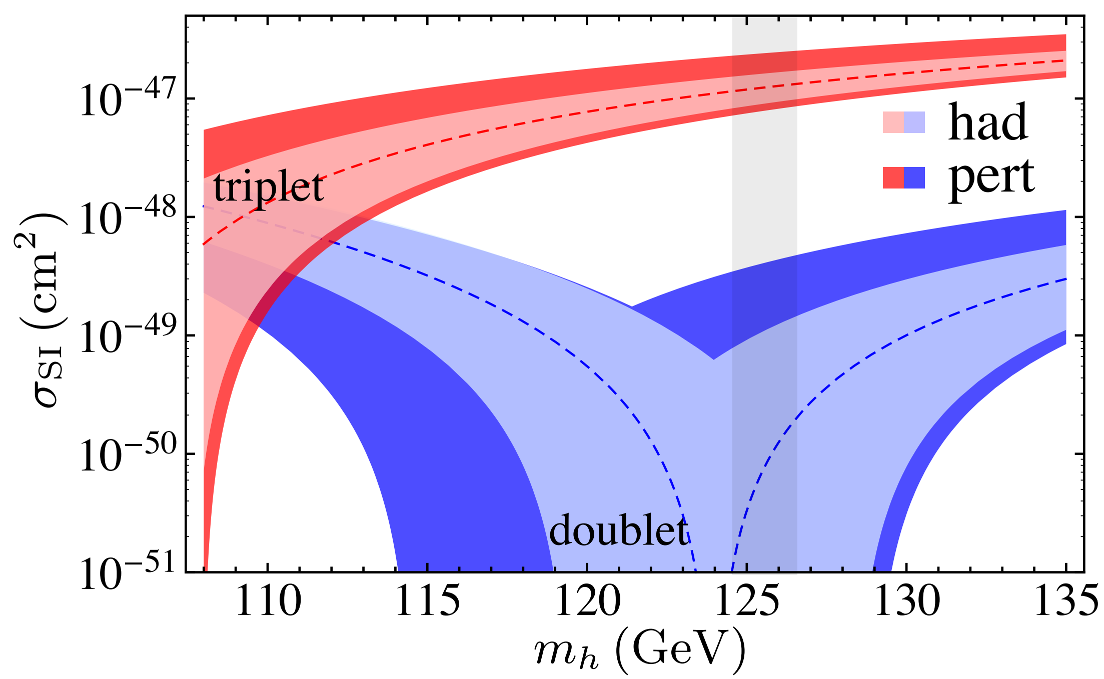
- "Pure" neutralino does not couple to Higgs at tree level
- e.g. pure Wino or Higgsino or Bino
- But, Wino has detectable indirect detection signature through coupling to gauge bosons





Wino and Higgsino

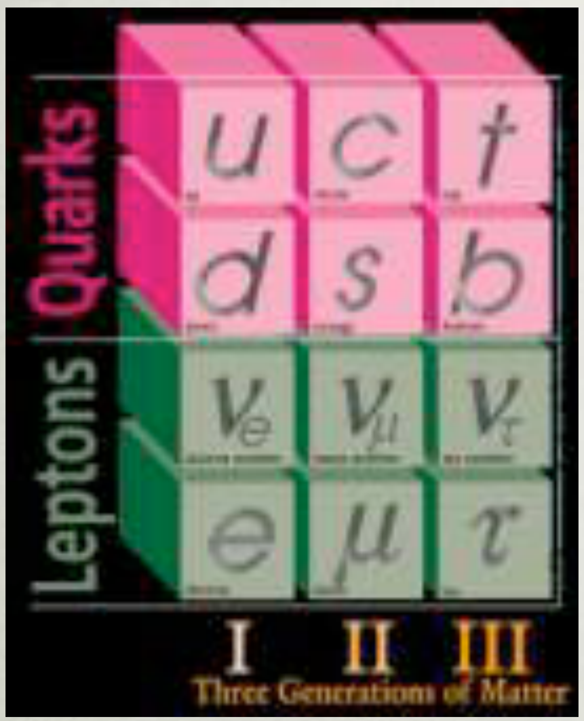




Hill and Solon

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

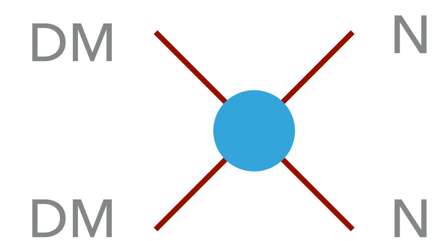
Standard Model

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

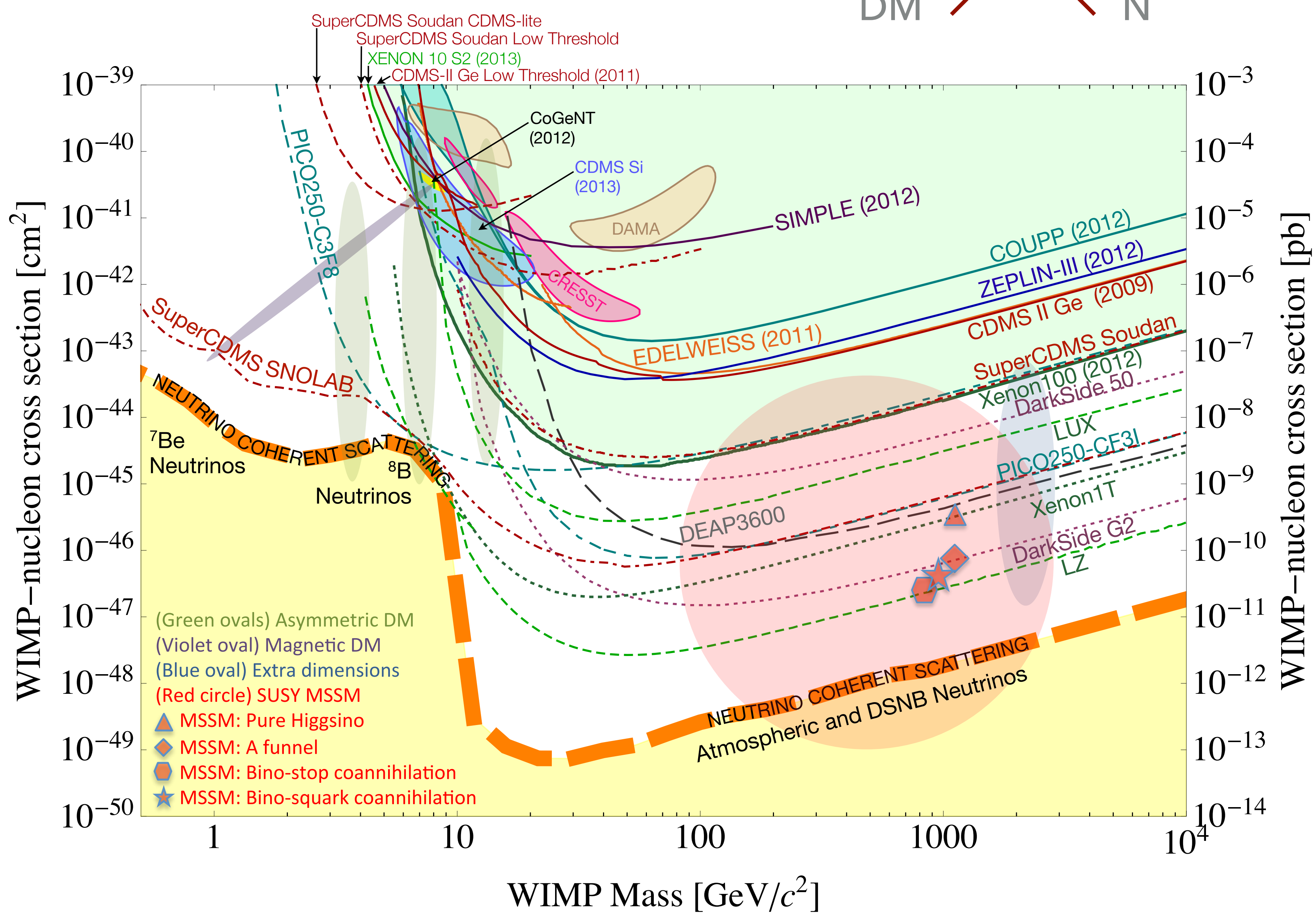
Inaccessibility

THEORY AND EXPERIMENT INTERPLAY

- Push towards light dark matter



???



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

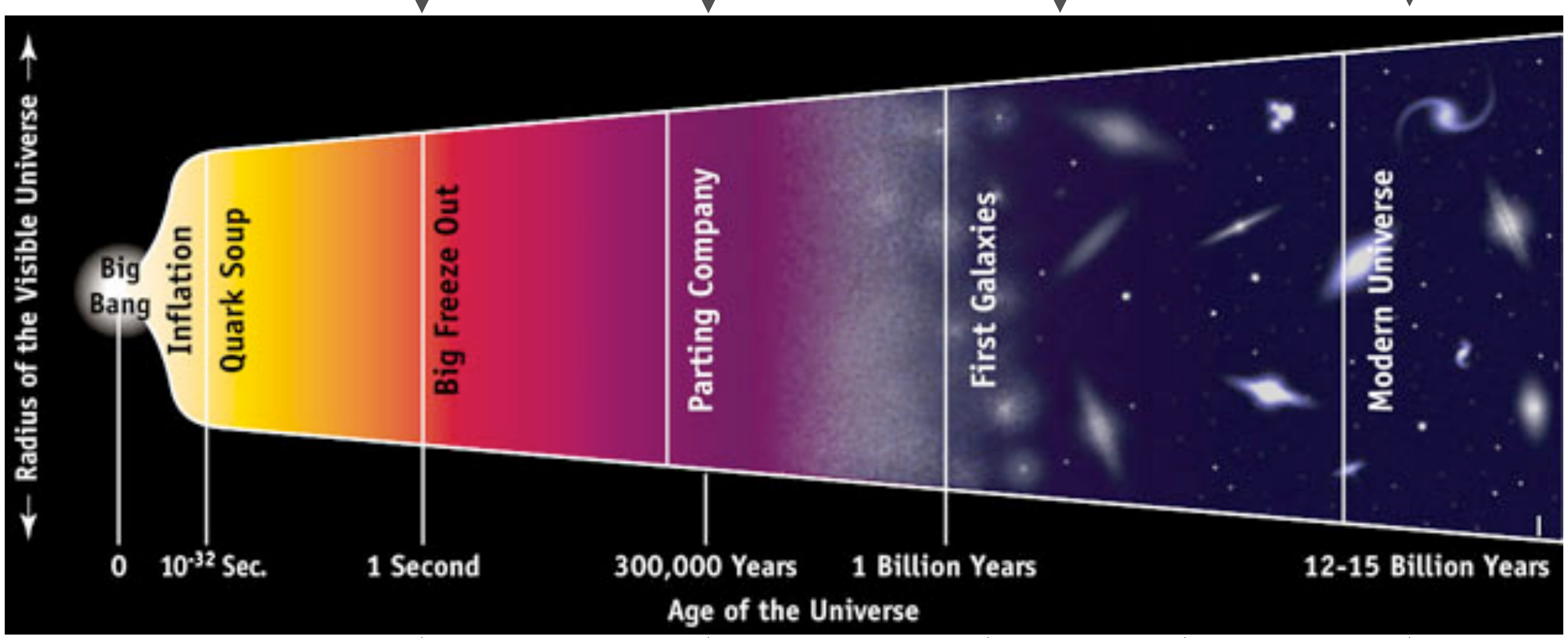
Direct Probes
Weakly Interacting with Us

BBN CMB
Not Free Baryons

LSS

MACHO searches + Lya
Not Bound Baryons

LSS+Bullet Cluster
Not Modified Gravity



BBN
(baryons)

CMB
(curvature)

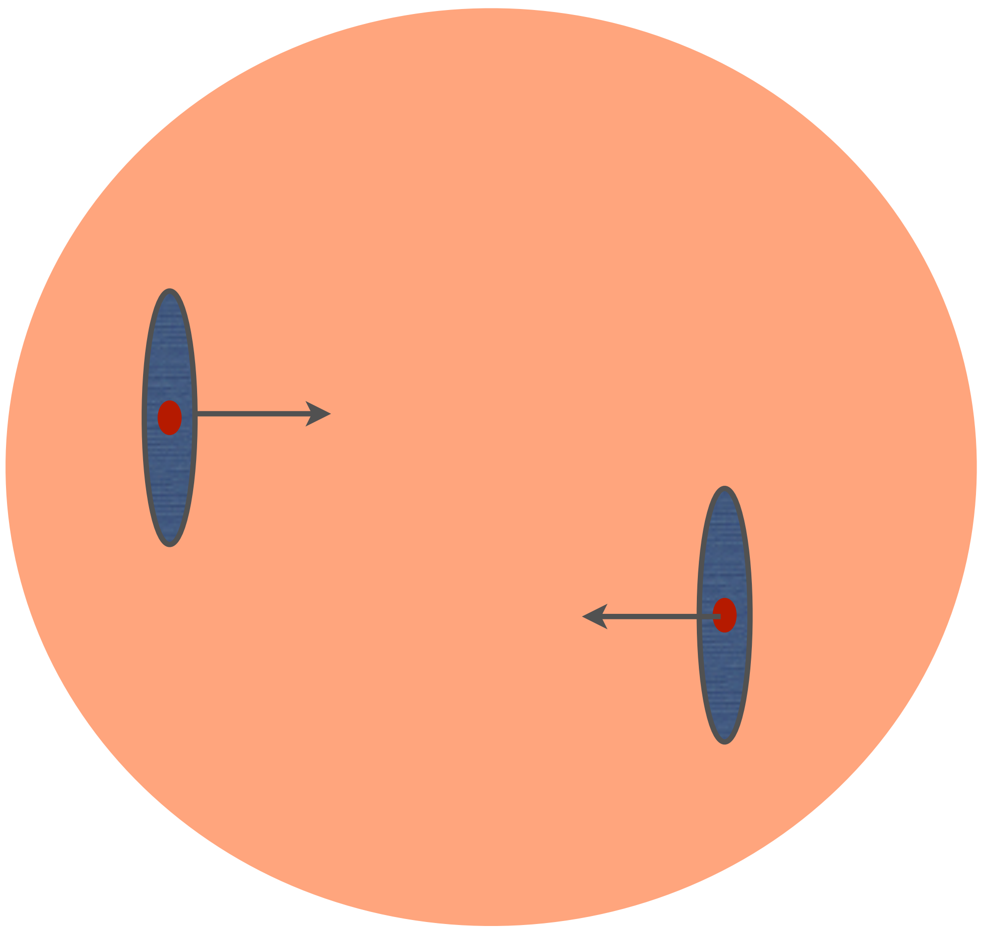
Supernovae
(DE)

LSS
(matter)

Galaxy curves
(matter)

WHY THE (SUB-)WEAK SCALE IS COMPELLING

- Abundance of new stable states set by interaction rates



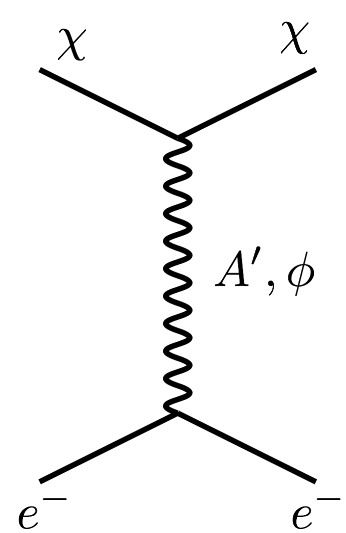
Freeze-out

Measured by CMB + LSS

$$\Gamma = n\sigma v = H \qquad \Longrightarrow \sigma \sim \frac{1}{(20\ \text{TeV})^2}$$

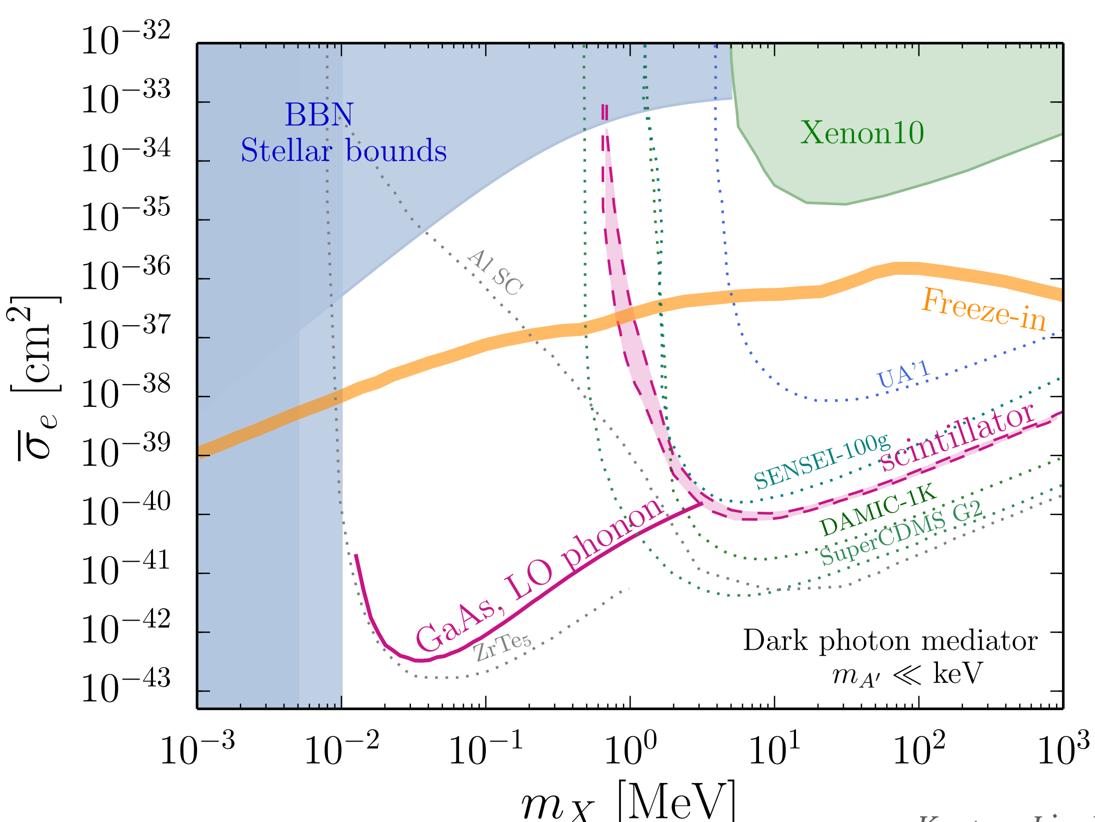
DM ABUNDANCE AS A GUIDE

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

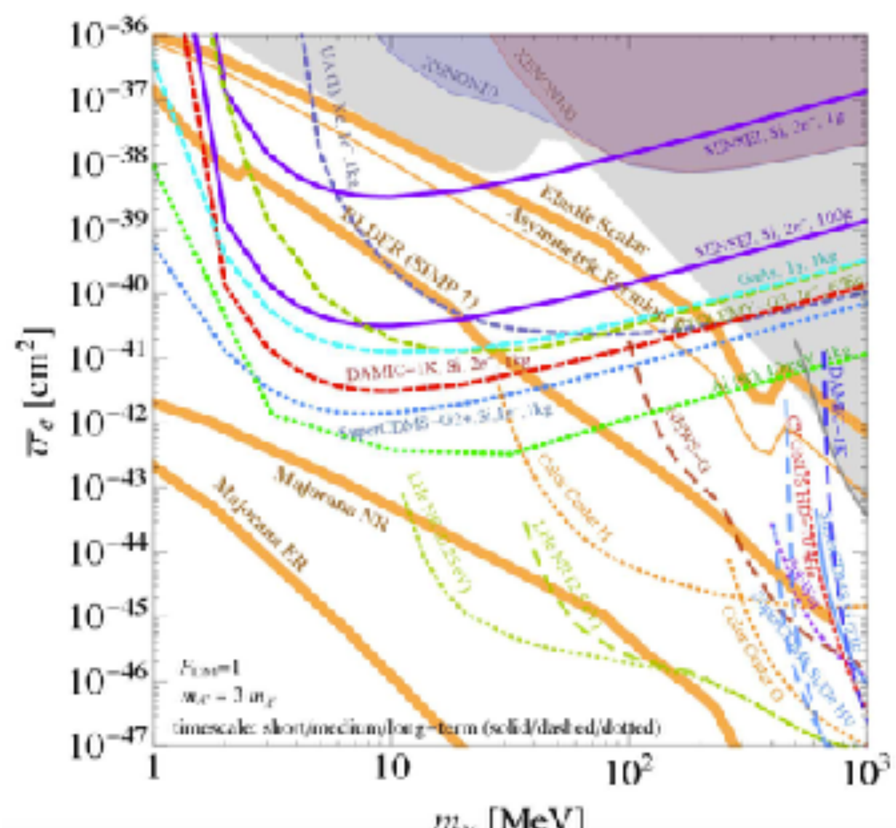


Freeze-in

Asymmetric Dark Matter



Knapen, Lin, Pyle KZ 1712.06598

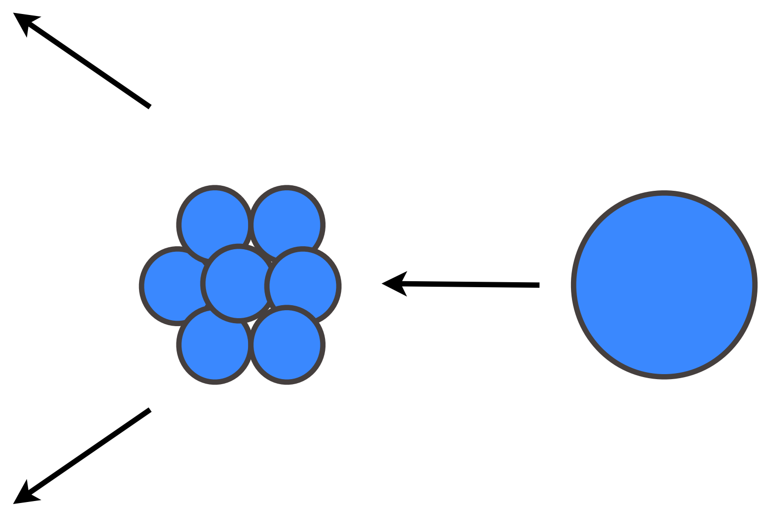


US Cosmic Visions 1707.04591

LIGHTER TARGETS FOR LIGHTER DARK MATTER

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

$q, \; E_D$



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

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

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

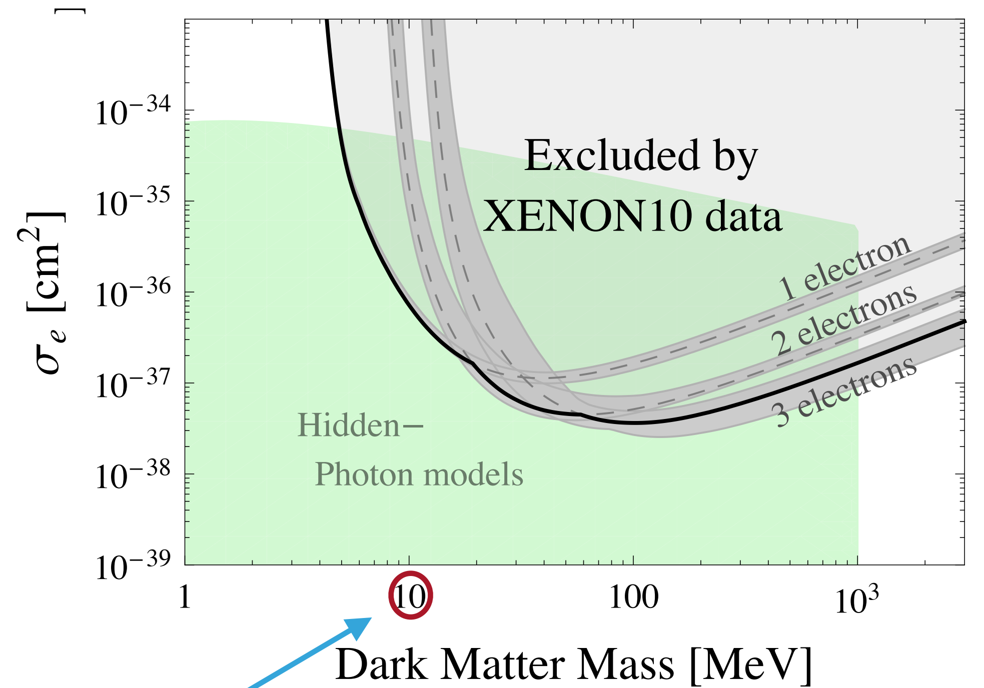
LIGHTER TARGETS FOR LIGHTER DARK MATTER

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

- In insulators, like xenon

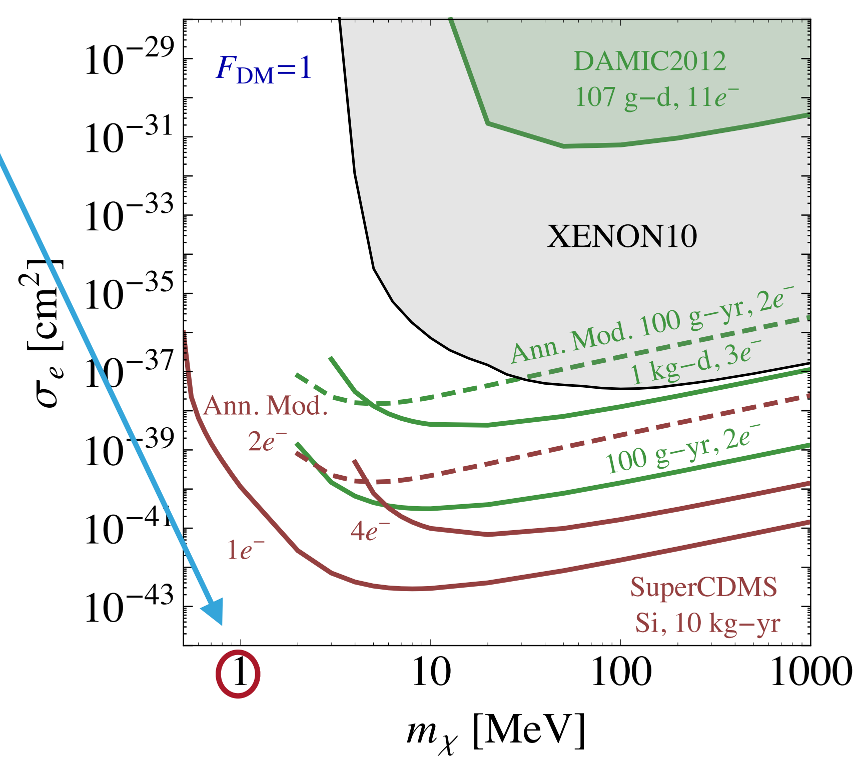
  Tightly bound; ionize for signal

P. Sorensen et al 1206.2644



Gap = DM Kinetic Energy

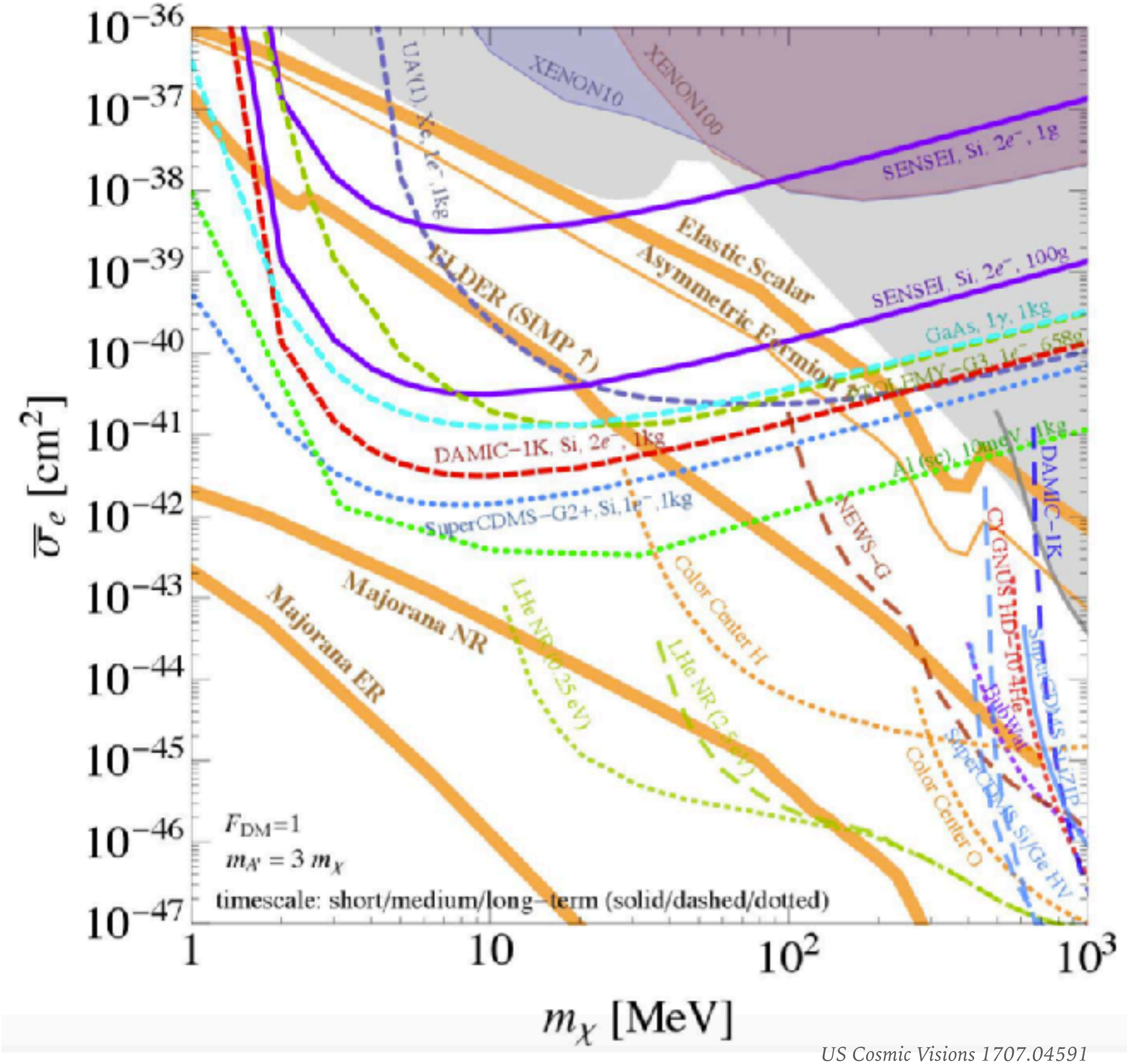
Essig et al 1509.01598



- In semi-conductors, like Ge, Si

  Excite electron to conduction band

CURRENT STATUS: MEV AND HEAVIER



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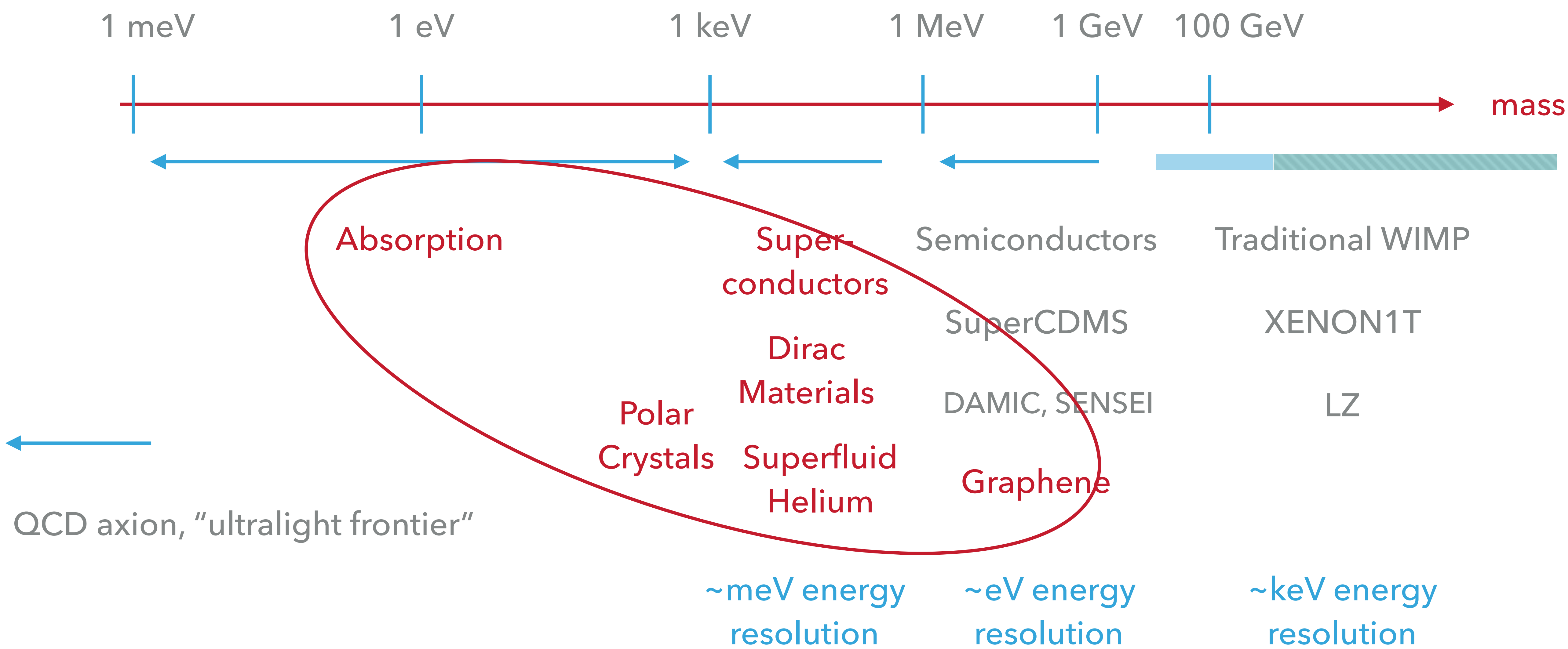
LOOKING BEYOND BILLIARD BALLS

- Experimental Panorama



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

SUPERFLUID HELIUM

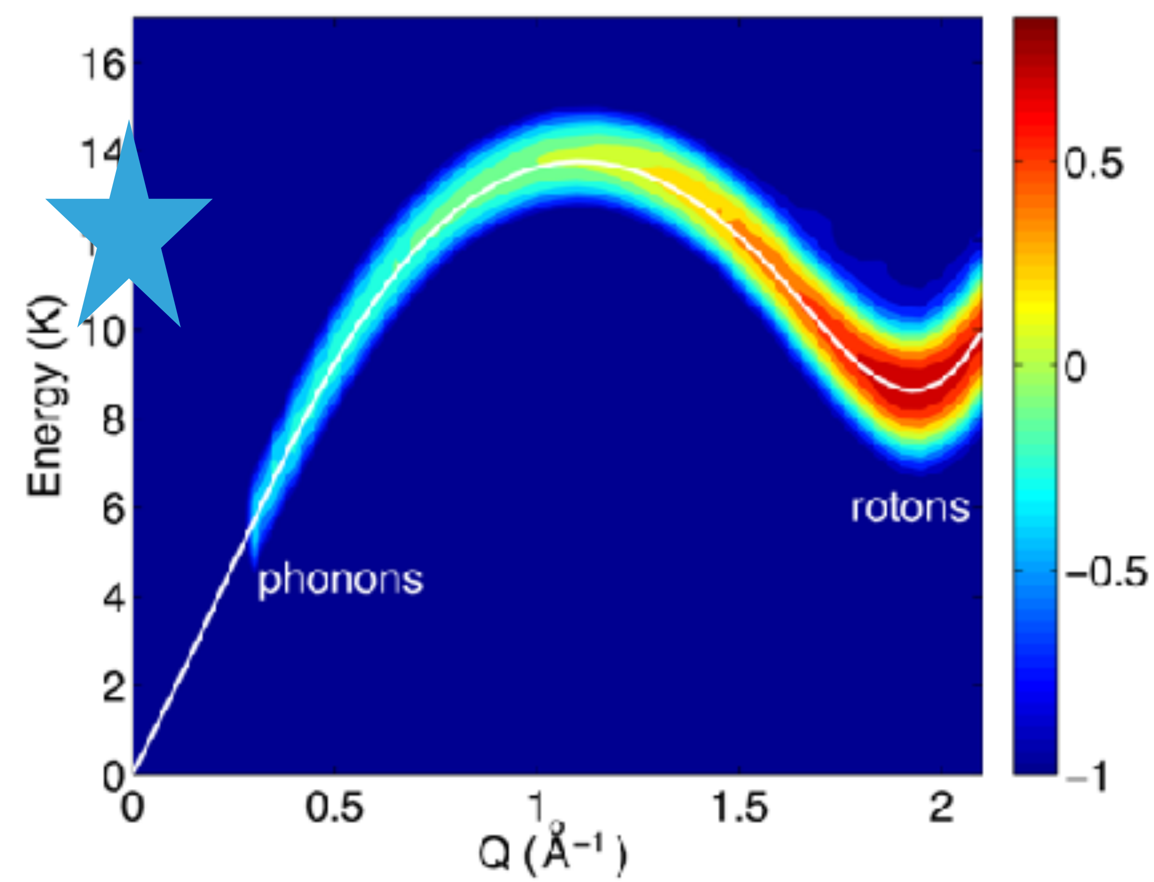
Schutz, KZ 1604.08206, Knapen, Lin, KZ 1611.06228

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

$$E_D \sim v_X q$$

vs $\qquad c_s \ll v_X$

$$E_D \sim c_s q$$



- Next glance -- yes!

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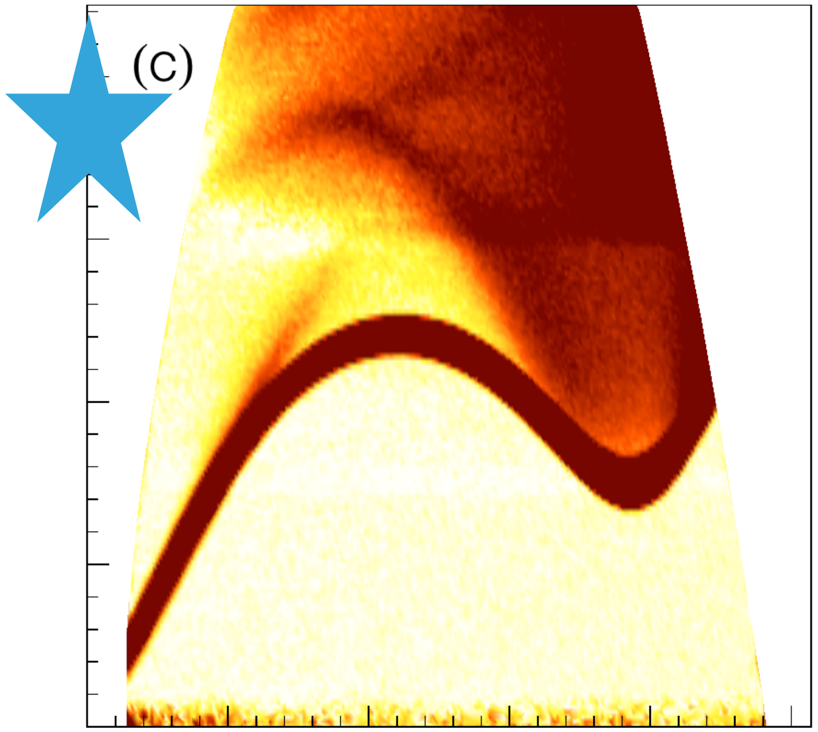


Beauvois et al 1605.02638

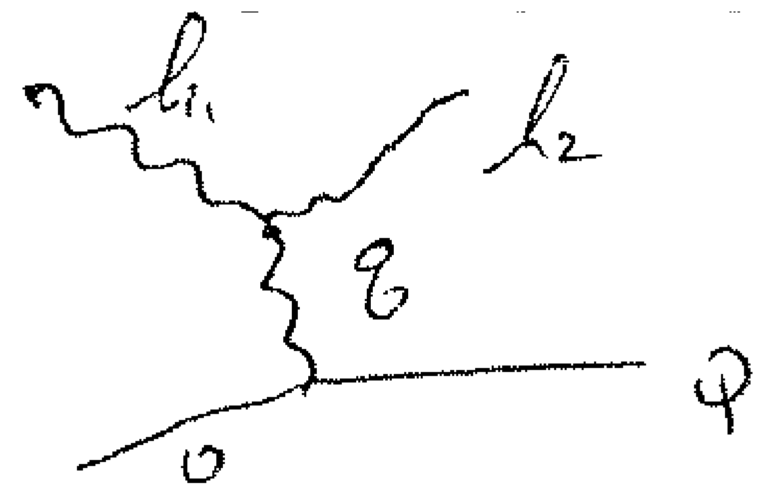
SUPERFLUID HELIUM

Schutz, KZ 1604.08206, Knapen, Lin, KZ 1611.06228

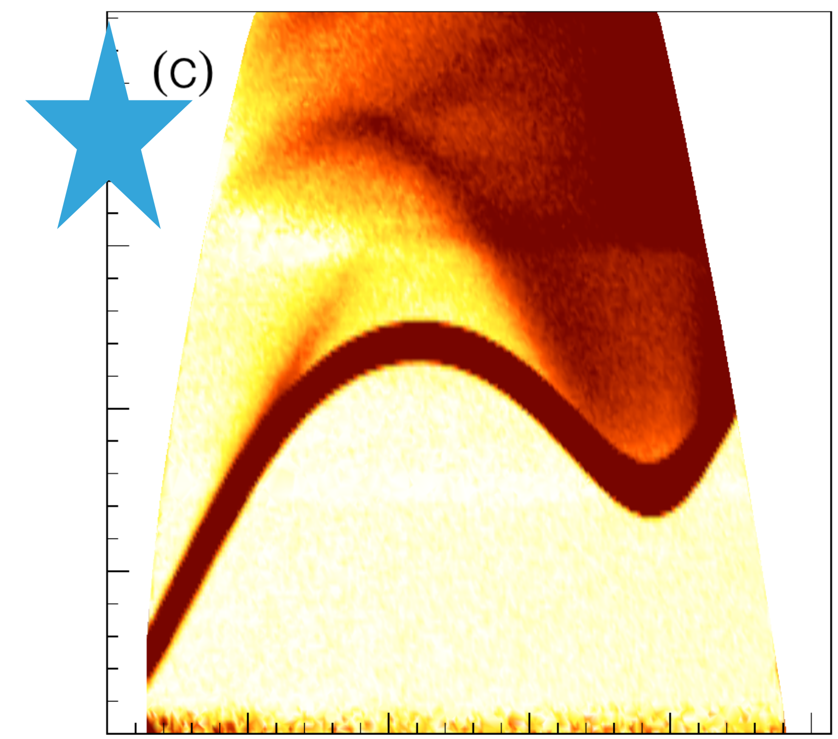
- Calculated and observed for cold neutrons

Internal note, R. Golub, 1977

$$V_3 = \int d^3r \left[\frac{\vec{v} \cdot \rho' \vec{v}}{2} \frac{1}{3!} \frac{d}{d\rho}\left(\frac{c^2}{\rho}\right)(\rho')^3 \right]$$



- However, this is in a very different kinematic regime
- No existing calculations in regime of interest



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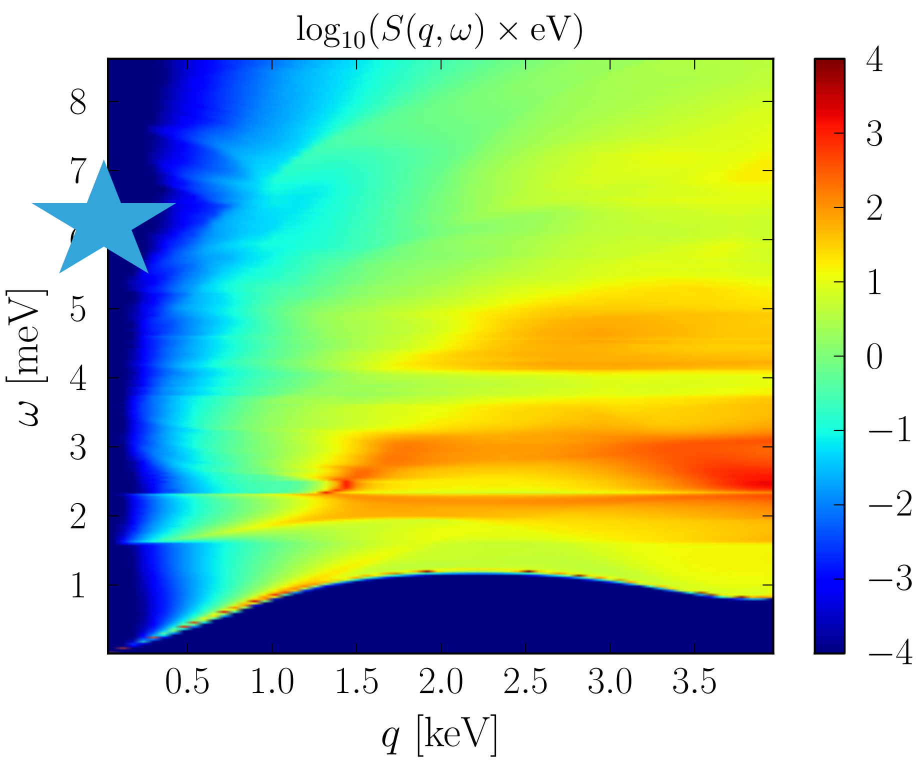
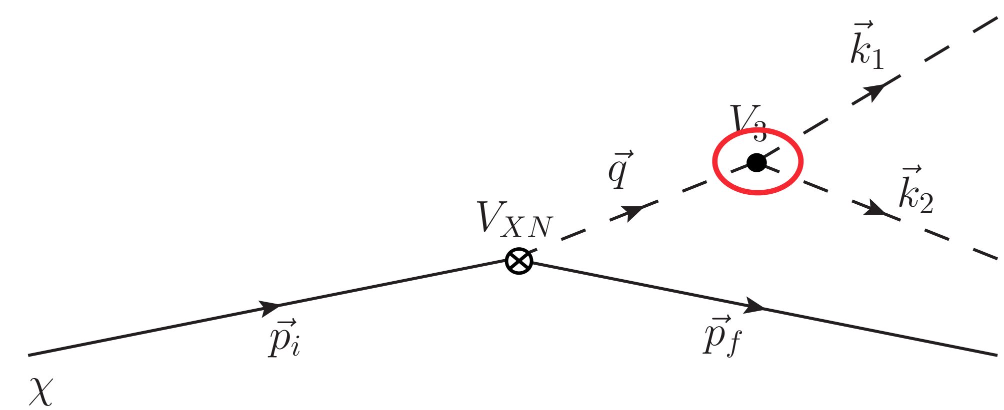
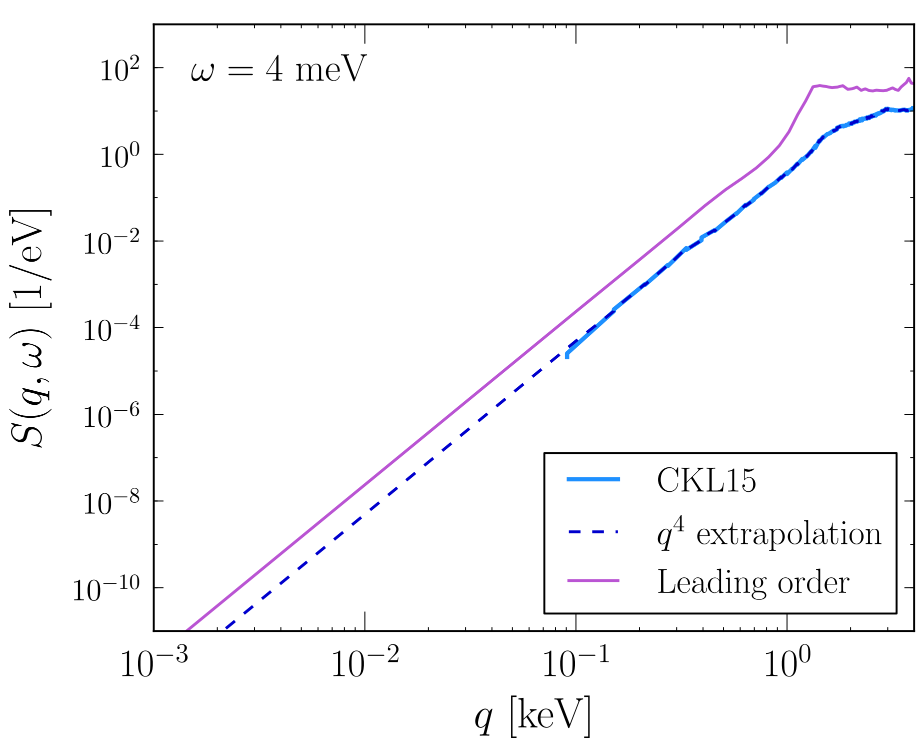




$$\langle \mathbf{q}-\mathbf{k},\mathbf{k}|\delta H|\mathbf{q}\rangle = \frac{\mathbf{q}\cdot(\mathbf{q}-\mathbf{k})S(\mathbf{k}) + \mathbf{q}\cdot\mathbf{k}\,S(\mathbf{q}-\mathbf{k}) - q^2 S(\mathbf{k})S(\mathbf{q}-\mathbf{k})}{2m_{\mathrm{He}}\sqrt{N}\sqrt{S(\mathbf{q}-\mathbf{k})S(\mathbf{k})S(\mathbf{q})}}$$



$$\Sigma(\mathbf{q},\omega) = \epsilon_0(\mathbf{q}) + \frac{1}{2}\int \frac{d^3\mathbf{k}}{(2\pi)^3}\frac{V|\langle \mathbf{q}-\mathbf{k},\mathbf{k}|\delta H|\mathbf{q}\rangle|^2}{\omega - \Sigma(\mathbf{q}-\mathbf{k},\omega-\epsilon_0(\mathbf{k})) - \Sigma(\mathbf{k},\omega-\epsilon_0(\mathbf{q}-\mathbf{k}))}$$

$$S(\mathbf{q},\omega) = -\frac{1}{\pi}\frac{S(k)\,\mathrm{Im}\,\Sigma(\mathbf{q},\omega)}{(\omega-\epsilon_0(\mathbf{q}))^2 + (\mathrm{Im}\,\Sigma(\mathbf{q},\omega))^2}$$

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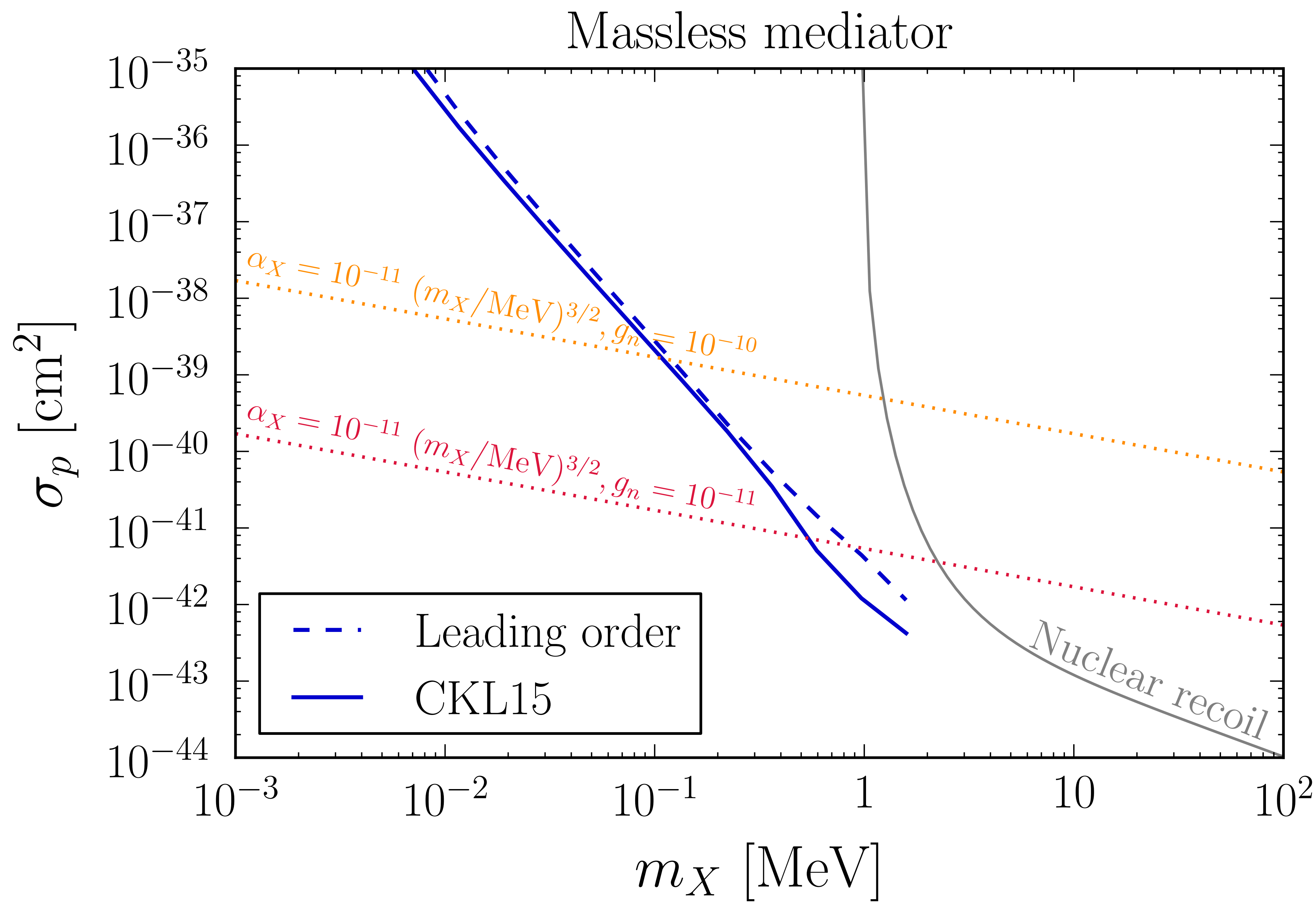
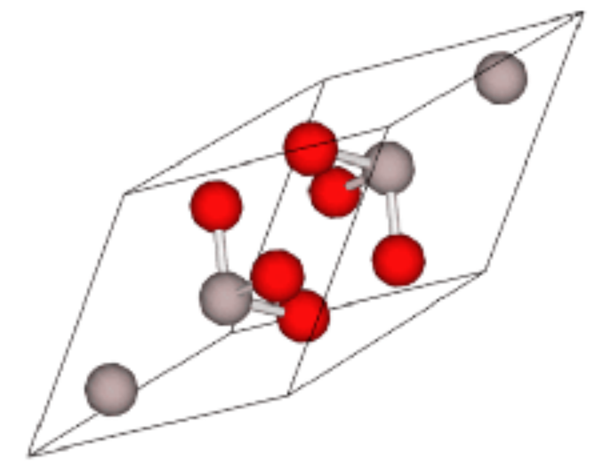
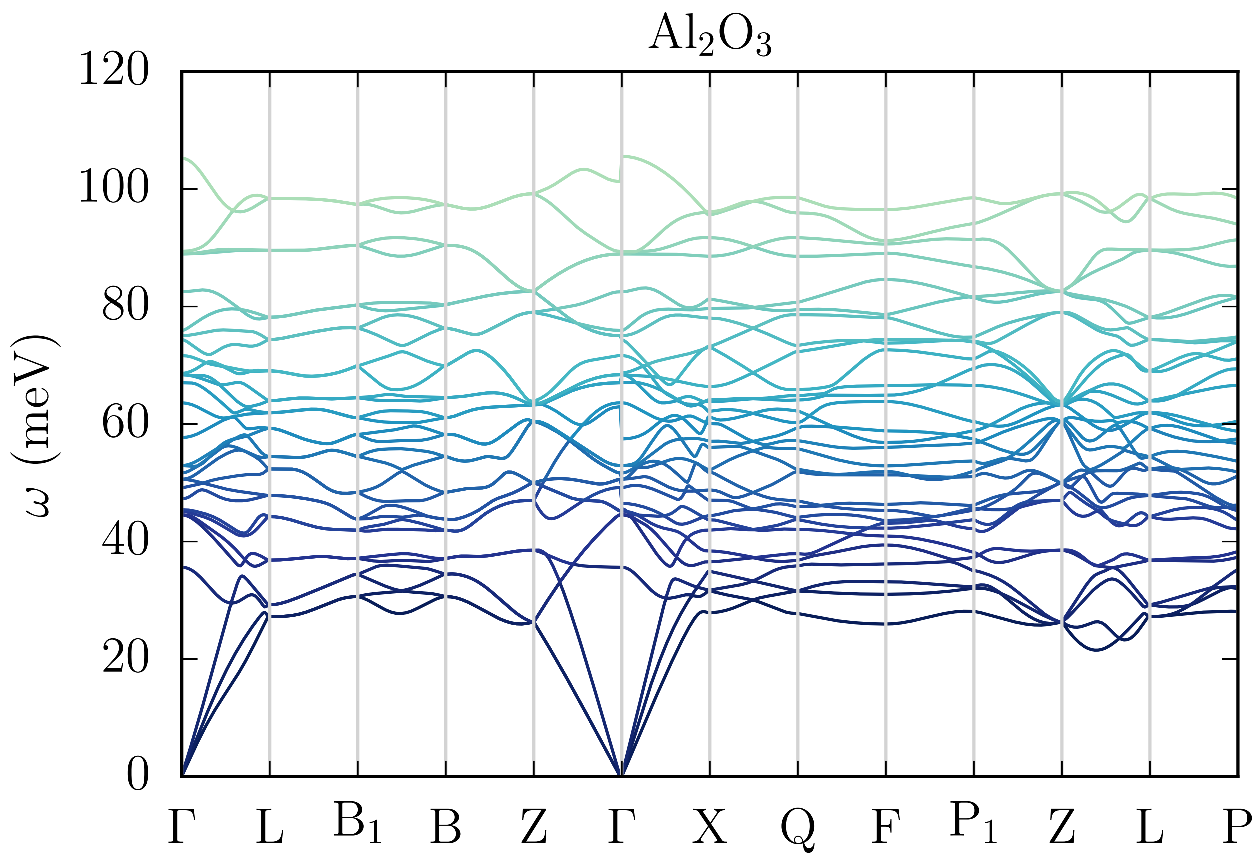


OPTICAL PHONONS

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

- Gapped excitations (optical phonons) in materials with more than one type of
- Quite generic in semiconductors with more than one type of ion in the Brioullin Zone
- Al2O3 (sapphire), InSb, CsI, NaI
- Even crystals with only one type of ion can have "optical" phonons
  - diamond

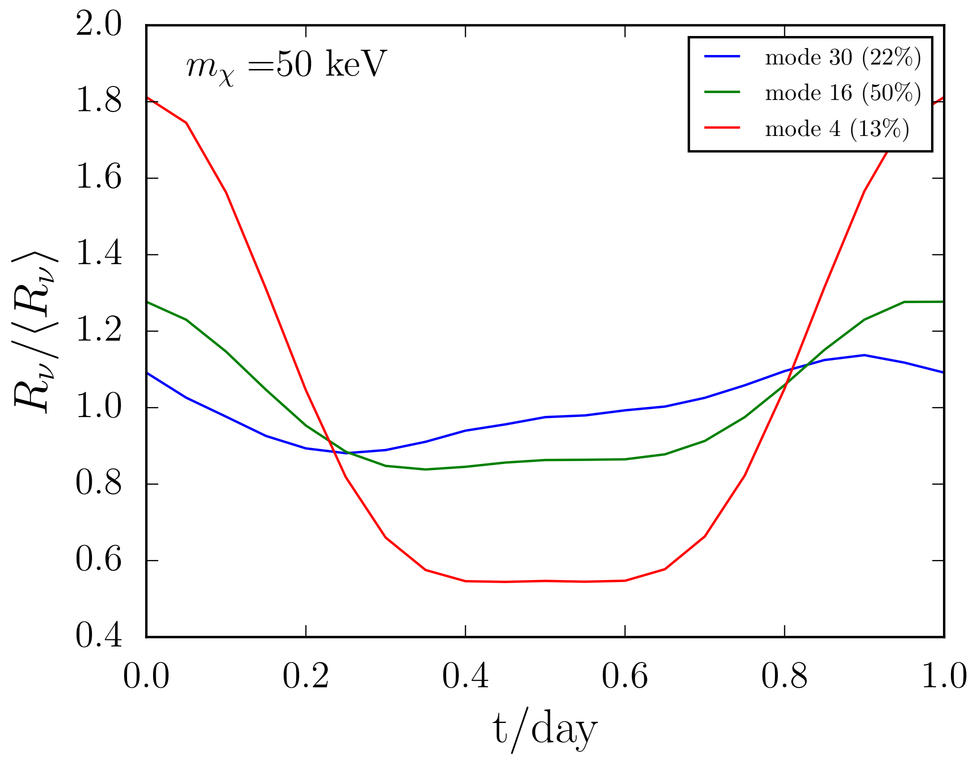


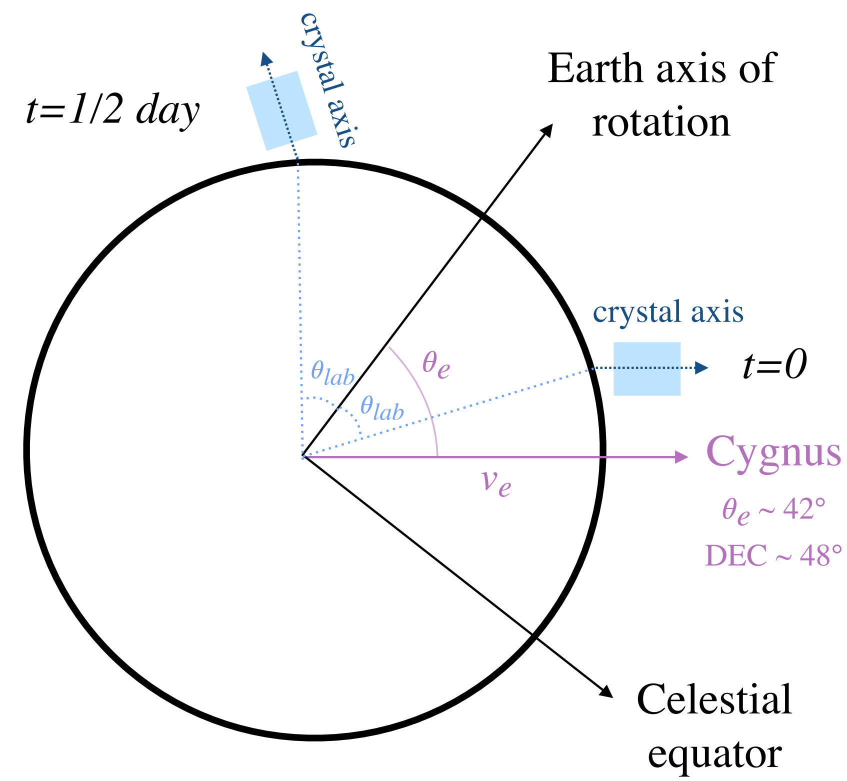


DIRECTIONALITY IN ANISOTROPIC MATERIALS!

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

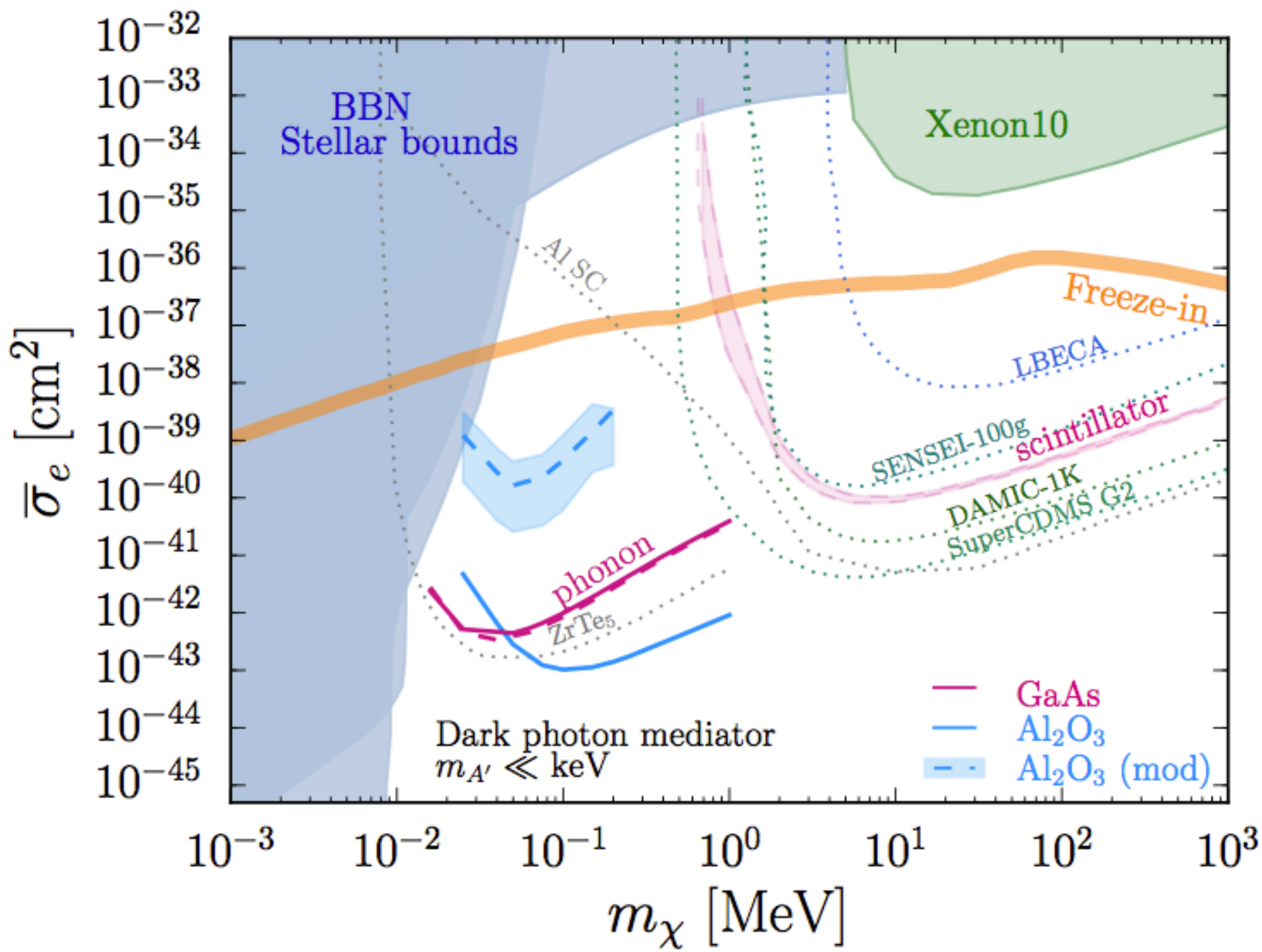
- Crystal Lattice is not Isotropic
- Especially pronounced in sapphire





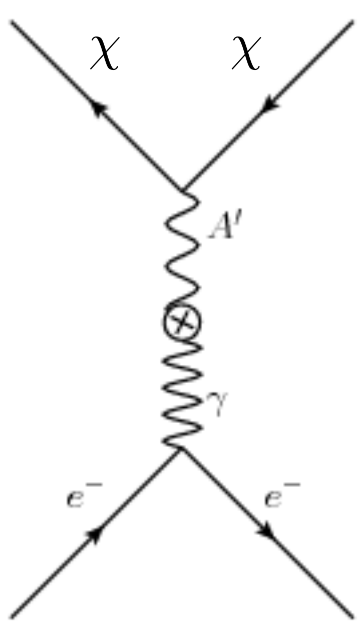
OPTICAL PHONONS IN POLAR MATERIALS

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



TARGET DIVERSITY

- Why? Strength of dark matter portal is sensitive to material type
- Fun theoretical playground: Dirac materials versus ordinary metals (e.g. aluminum superconductor)
- Consider dark photon mediated dark matter:

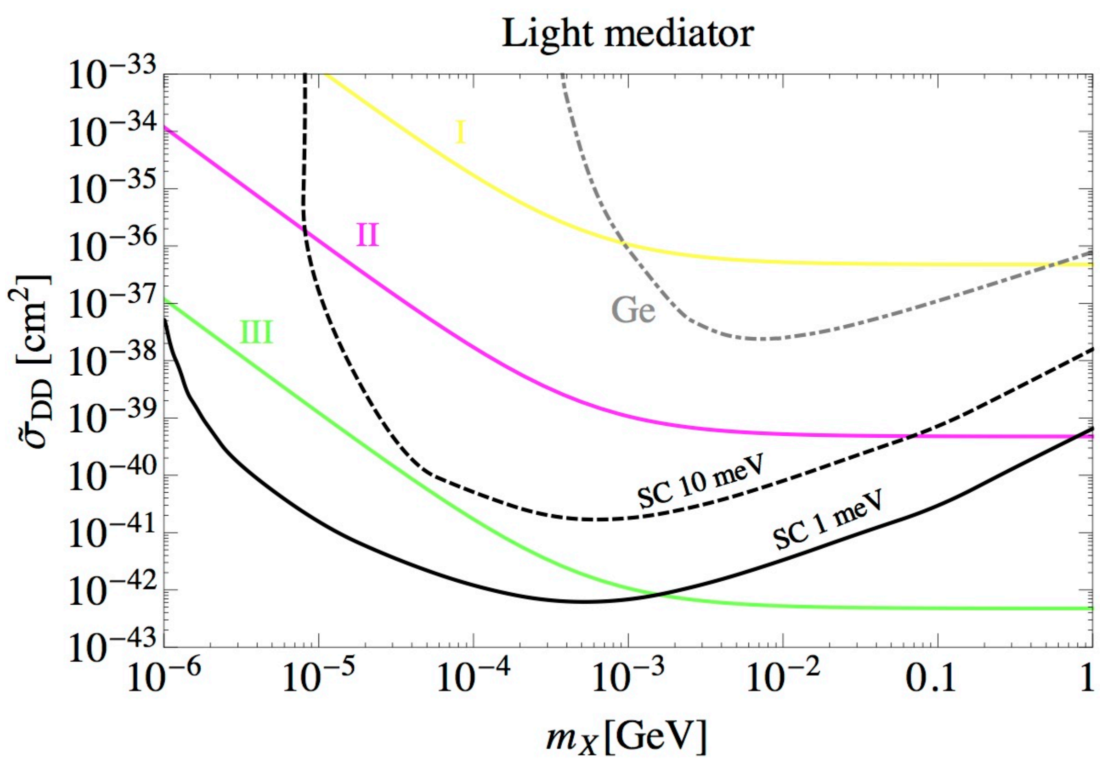


$$\mathcal{L} \supset \varepsilon e \frac{q^2}{q^2 - \Pi_{T,L}} \tilde{A}'^{T,L}_{\mu} J^{\mu}_{\mathrm{EM}}$$

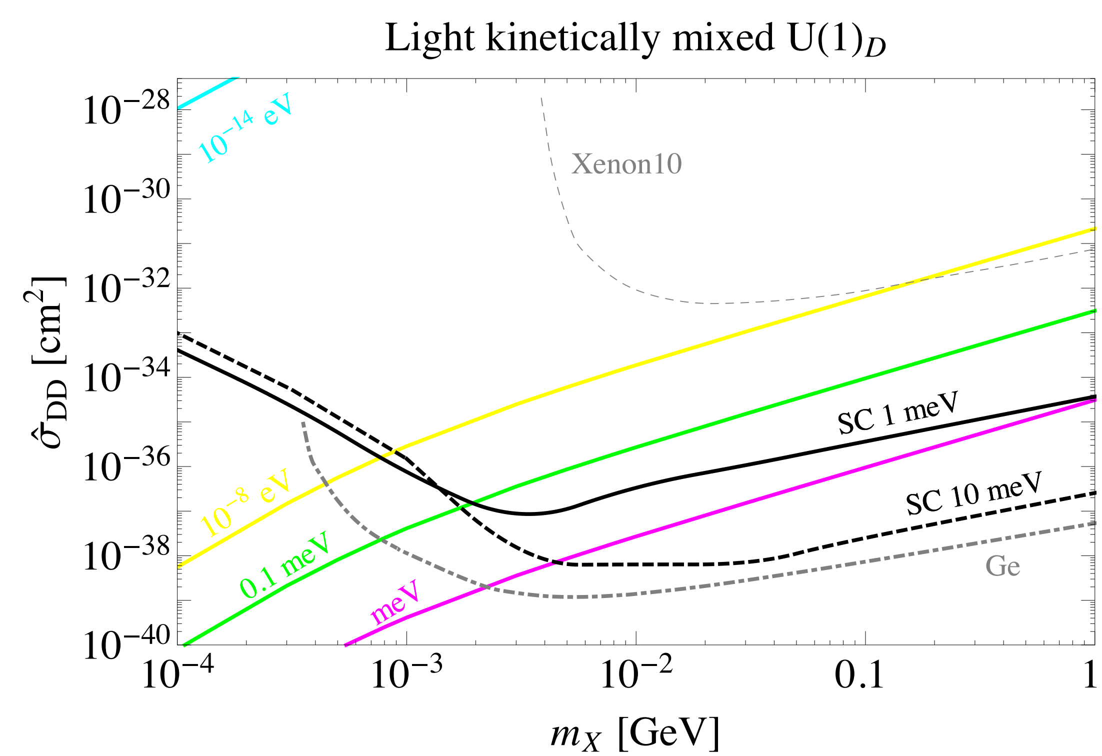
TARGET DIVERSITY

Hochberg, Pyle, Zhao, KZ 1512.04533

- Metals have large Fermi surface ⟷ large optical response
- Large polarization tensor ⟷ Weak sensitivity to dark photon



No optical response



Dark photon response

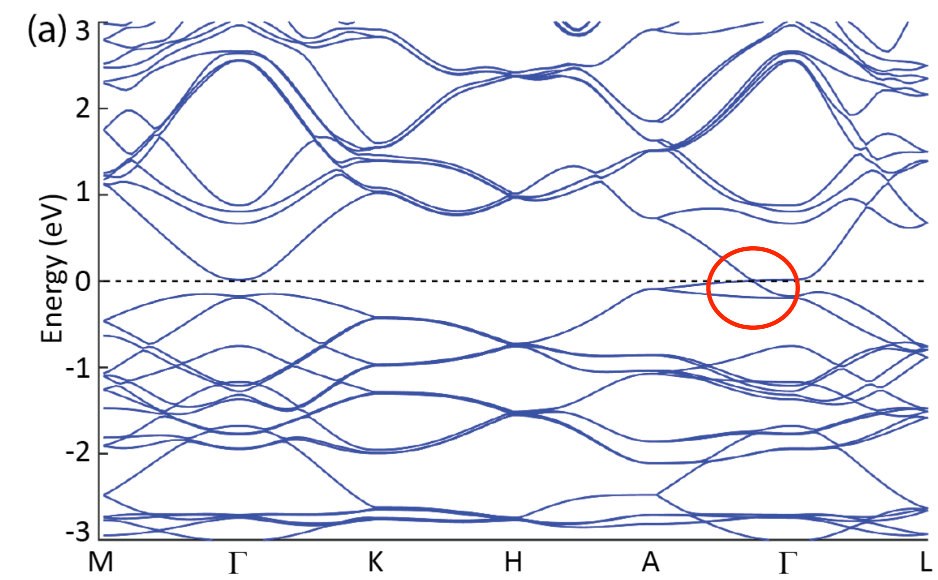
OPTICAL RESPONSE

- Superconductors have a large optical response because of their giant Fermi surface
- But that also means large density of target electrons, implying large rate
- Small density of target electrons, small optical response, but small rate
- Are we in a bind?
- Ward identity saves the day!

1708.08929

WEYL OR DIRAC SEMI-METALS ~ 3D GRAPHENE

- Materials can be “quantum engineered”
- Correlation between electrons gives rise to a unique band structure
- Hamiltonian looks like free QED near Dirac point
- In QED, gauge invariance protects photon from obtaining a mass



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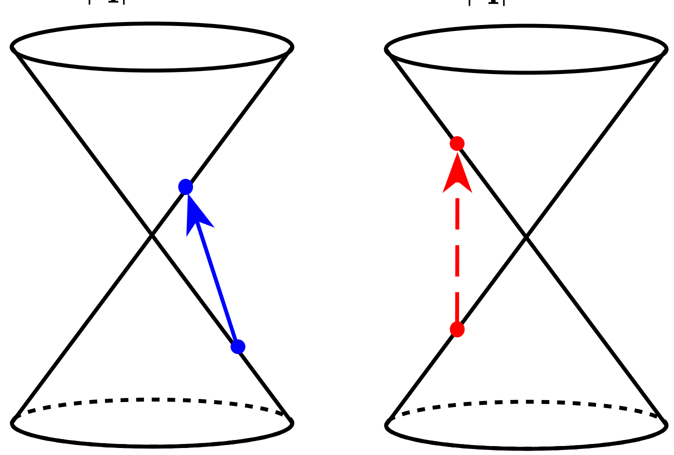
Kathryn M. Zurek,[4,5,§] Adolfo Grushin,[6,7,¶] Roni Ilan,[8,**]
Zhenfei Liu,[9] Sinead Griffin,[9] Sophie Weber,[9] and Jeffrey Neaton[9]

RELATIVISTIC FERMIONS, OBEY DIRAC EQUATION

- Optical response behaves exactly as electric charge renormalization in QED
- Weaker Optical Response
- Stronger Sensitivity to Dark Photon
- Relativistic Fermions, Obey Dirac Equation

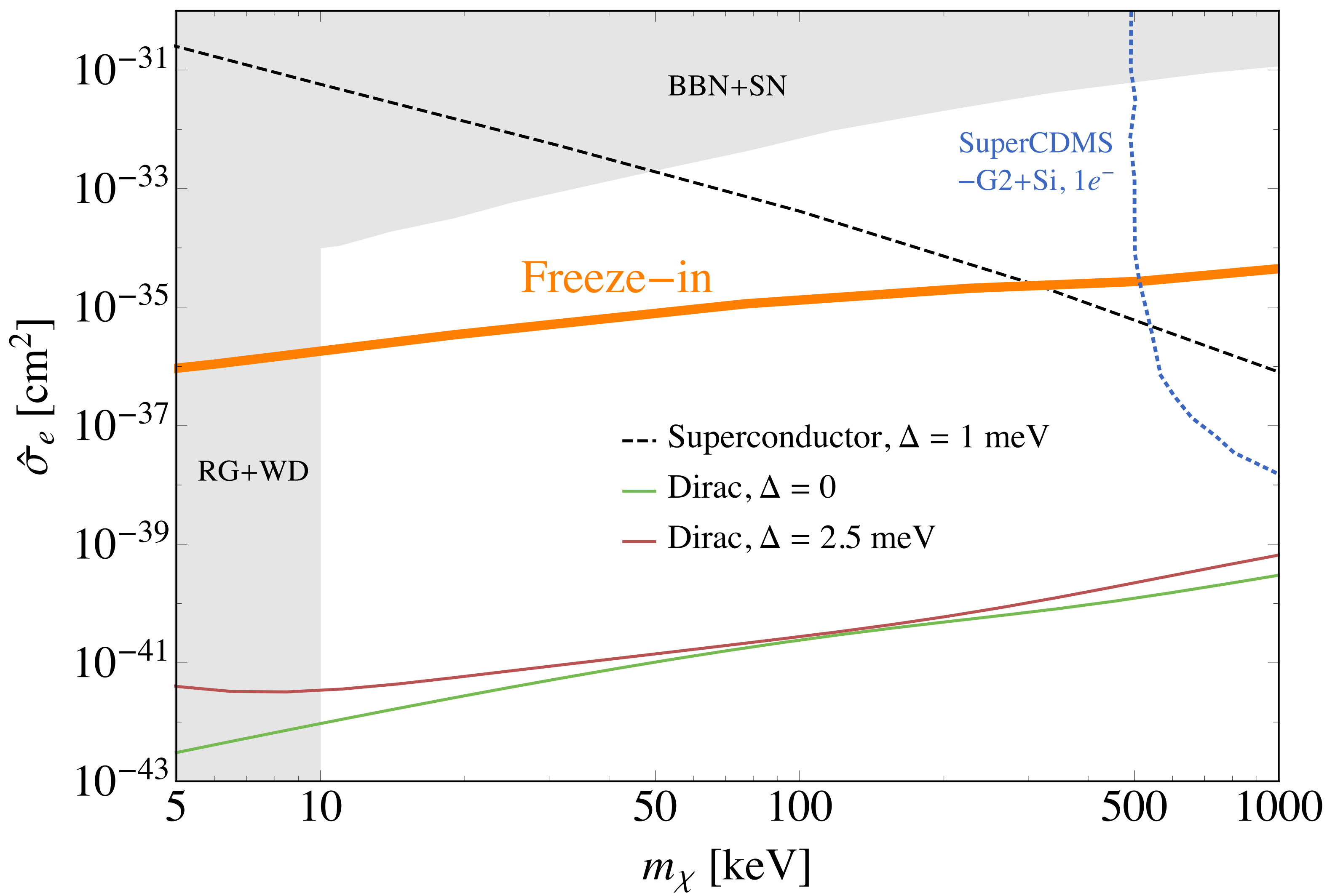
$$\mathcal{L} \supset \varepsilon e \frac{q^2}{q^2 - \Pi_{T,L}} \tilde{A'}^{T,L}_{\mu} J^{\mu}_{\rm EM}$$



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

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

SEMI-ANALYTIC RATES



Particle Physics

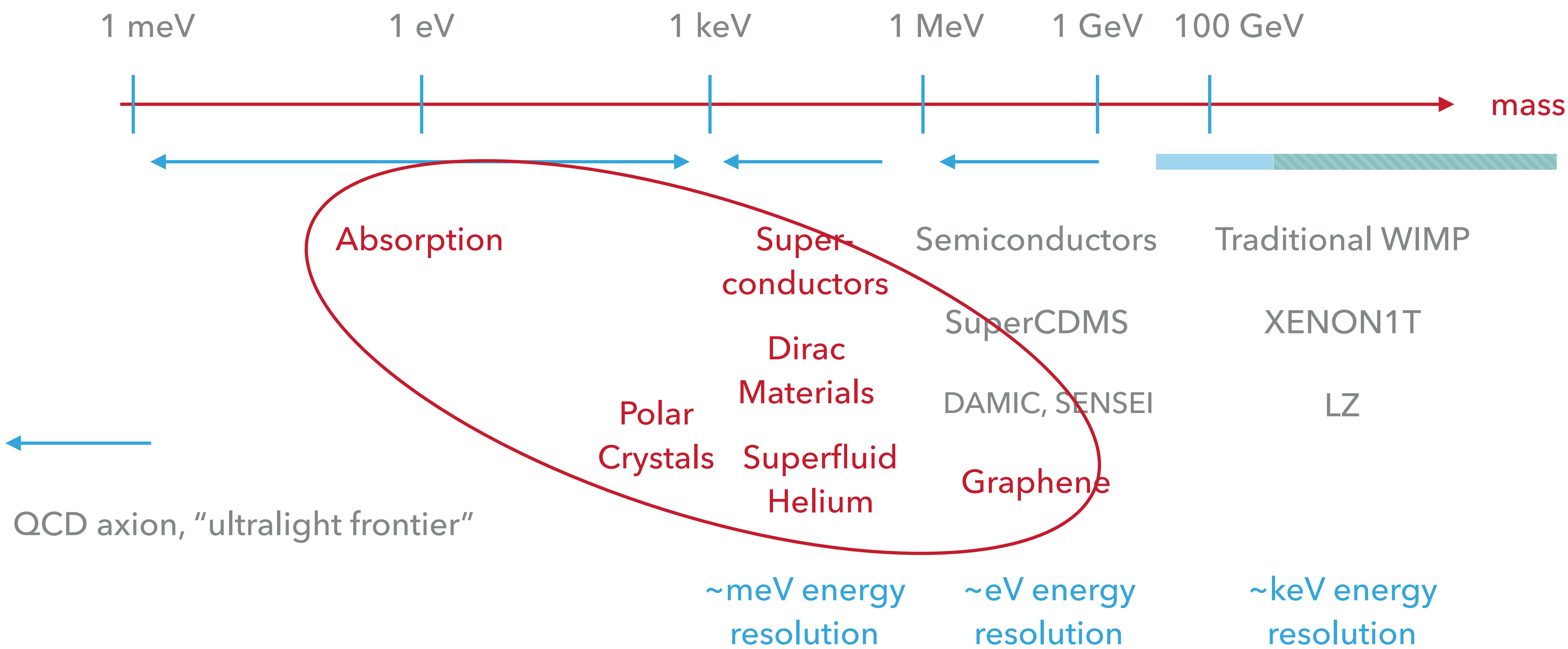
$$\langle|\mathcal{M}|^2\rangle \simeq \frac{16 m_e^2 m_\chi^2 g_D^2 e^2 \varepsilon^2}{\left(q^2 - m_{A'}^2\right)^2 |1 - \Pi_L(q)/q^2|^2} = \frac{16 m_e^2 m_\chi^2 g_D^2 e^2 \varepsilon^2}{\left(q^2 - m_{A'}^2\right)^2} \frac{1}{|\epsilon_r(q)|^2}$$

Condensed Matter Physics

$$|f_{-,\mathbf{k}\to+,\mathbf{k}'}(\mathbf{q})|^2 = \frac{1}{2}\frac{(2\pi)^3}{V}\left(1 - \frac{\boldsymbol{\ell}\cdot\boldsymbol{\ell}'}{|\boldsymbol{\ell}||\boldsymbol{\ell}'|}\right)\delta(\mathbf{q} - (\boldsymbol{\ell}' - \boldsymbol{\ell}))$$

LOOKING BEYOND BILLIARD BALLS

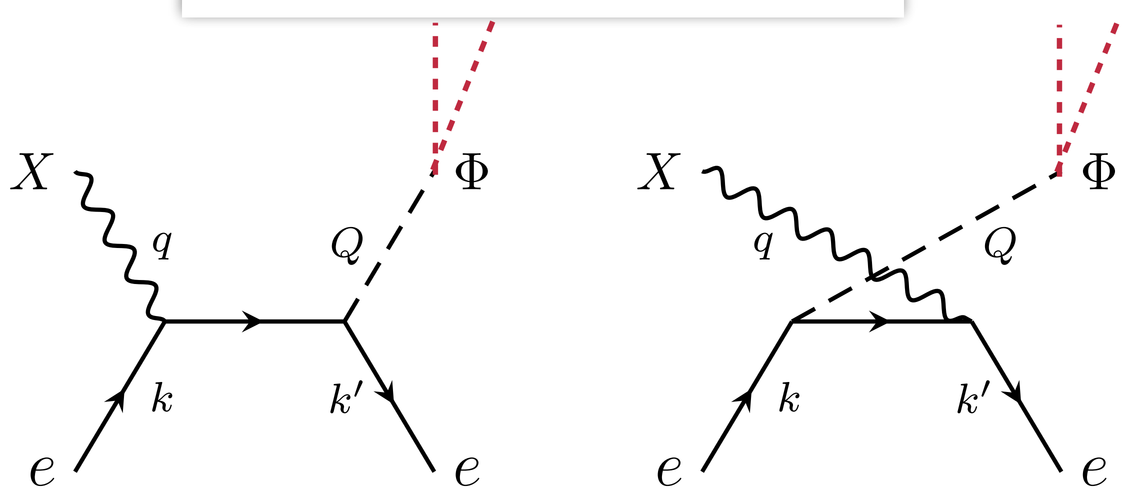
- Experimental Panorama

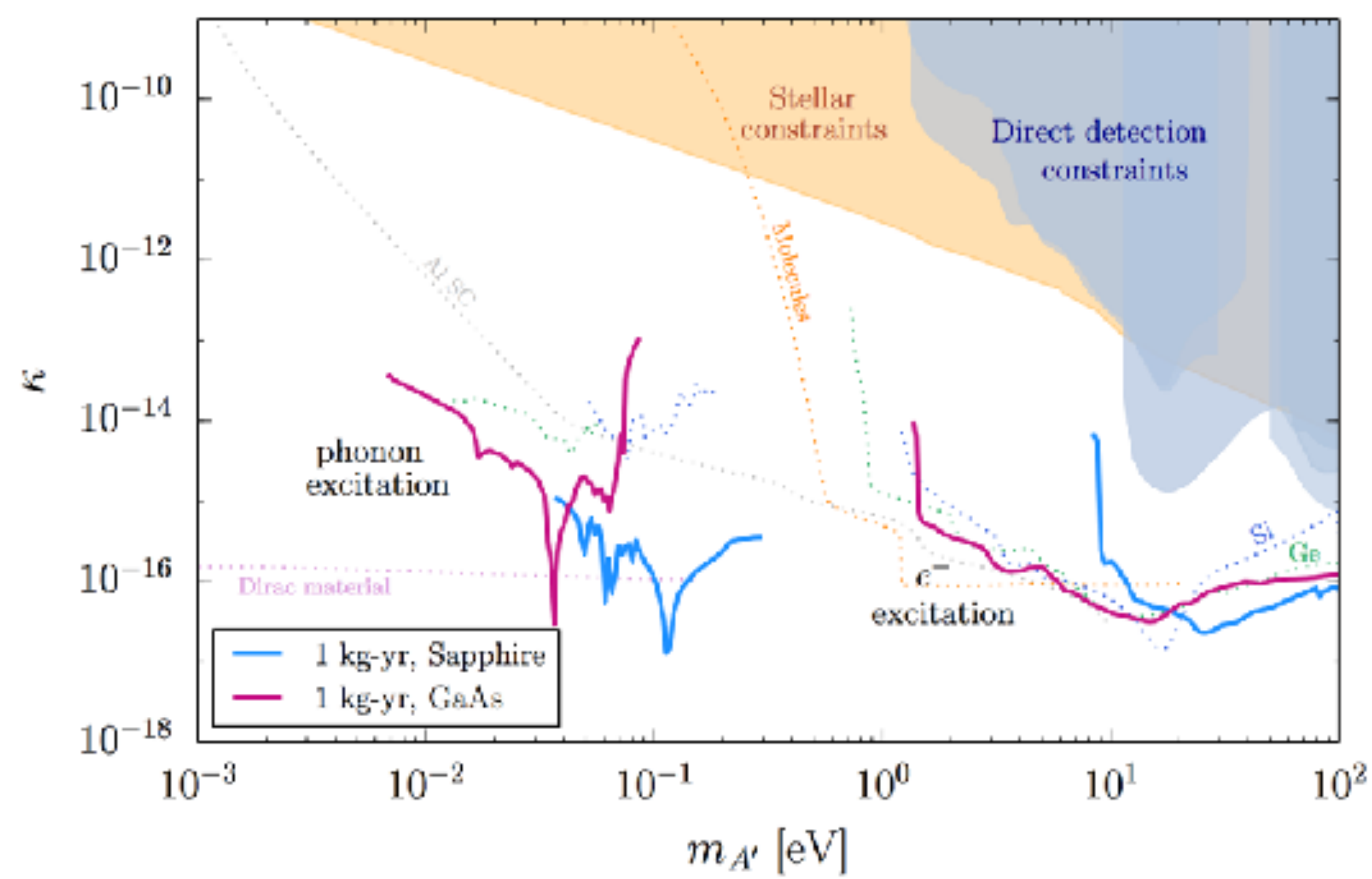


SEARCHING FOR AXIONS AND OTHER ULTRALIGHT PARTICLES

Griffin, Knapen, Lin, KZ 1807.10291

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





EXPERIMENTAL PROGRESS

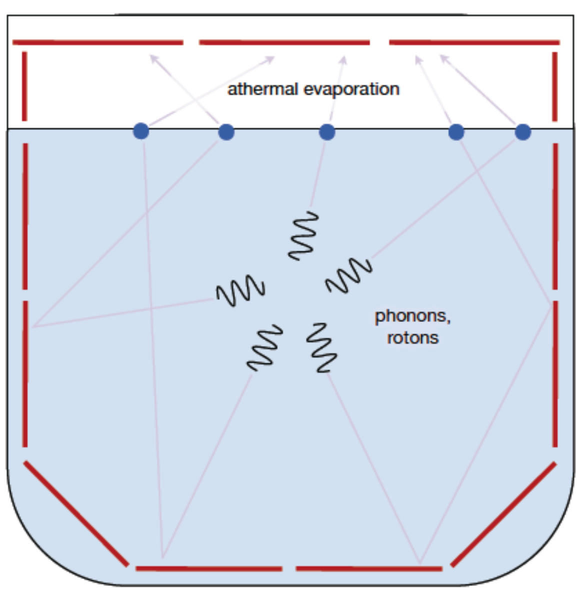
- A number of experimental proposals available both for small project development and R&D

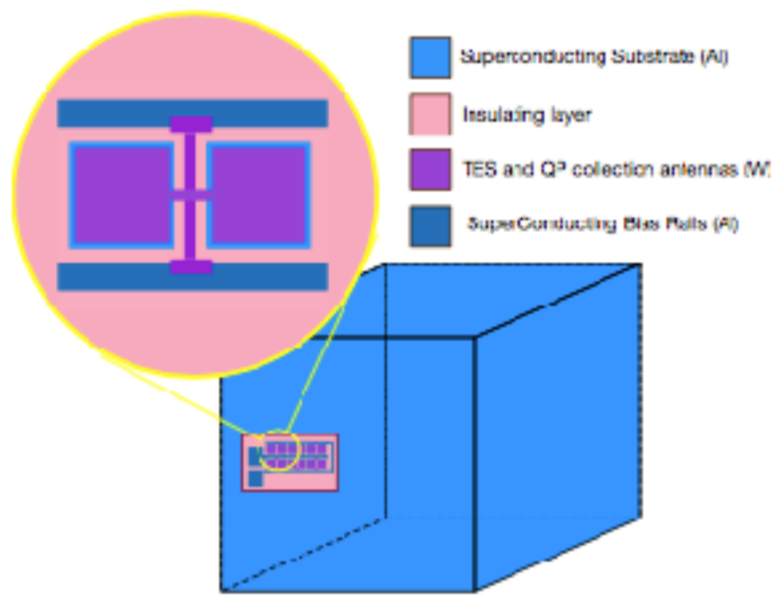
Main Science Goal	Experiment	Target	Readout	Estimated Timeline
Sub-GeV Dark Matter (Electron Interactions)	SENSEI	Si	charge	ready to start project (2 yr to deploy 100g)
	DAMIC-1K	Si	charge	ongoing R&D 2018 ready to start project (2 yr to deploy 1 kg)
	UA′(1) liquid Xe TPC	Xe	charge	ready to start project (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

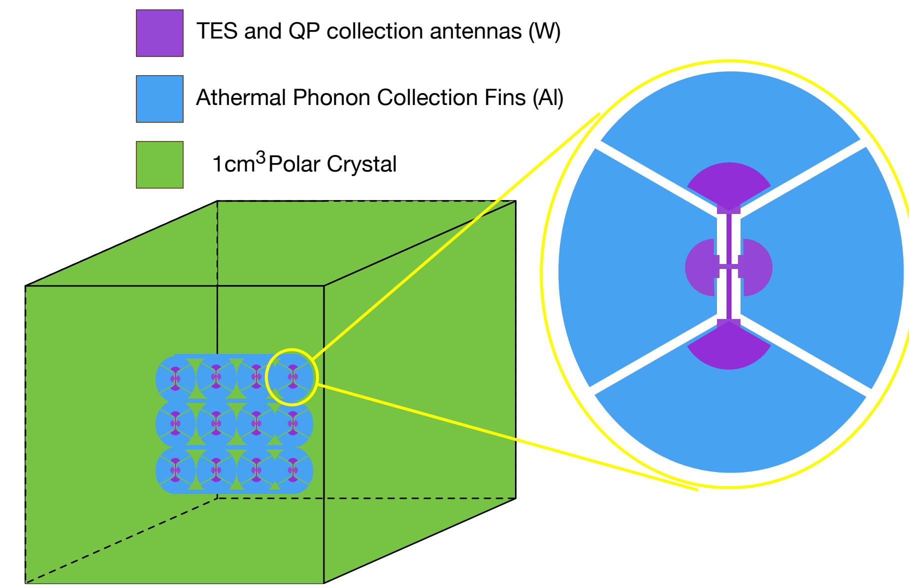
Cosmic Visions Whitepaper, 1707.04591

COMMON R&D PATH

- Sensor can be coupled to multiple targets — target diversity



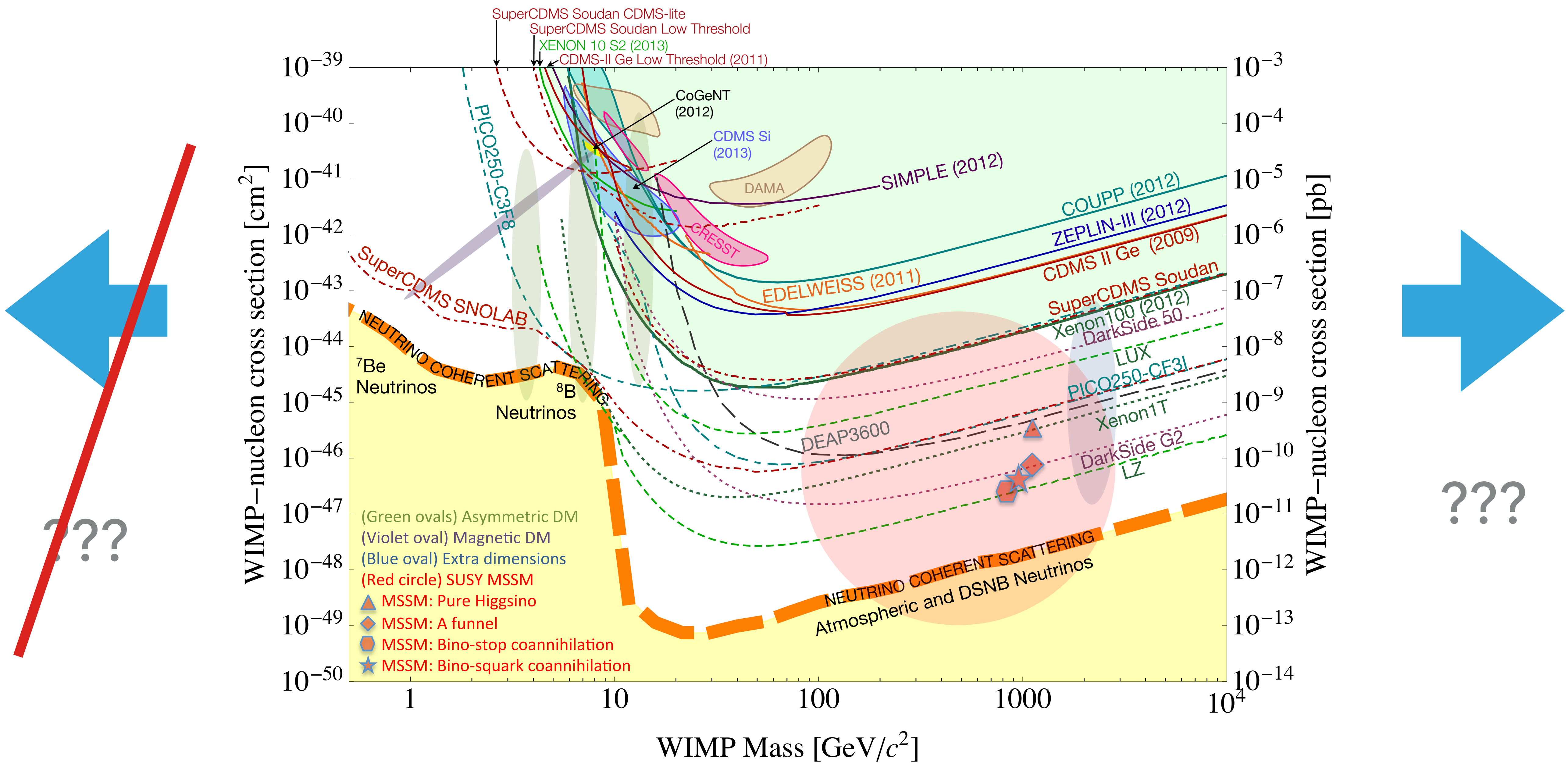




- Sensor development and material exploration funded as part of QIS collaboration based in Berkeley / LBL

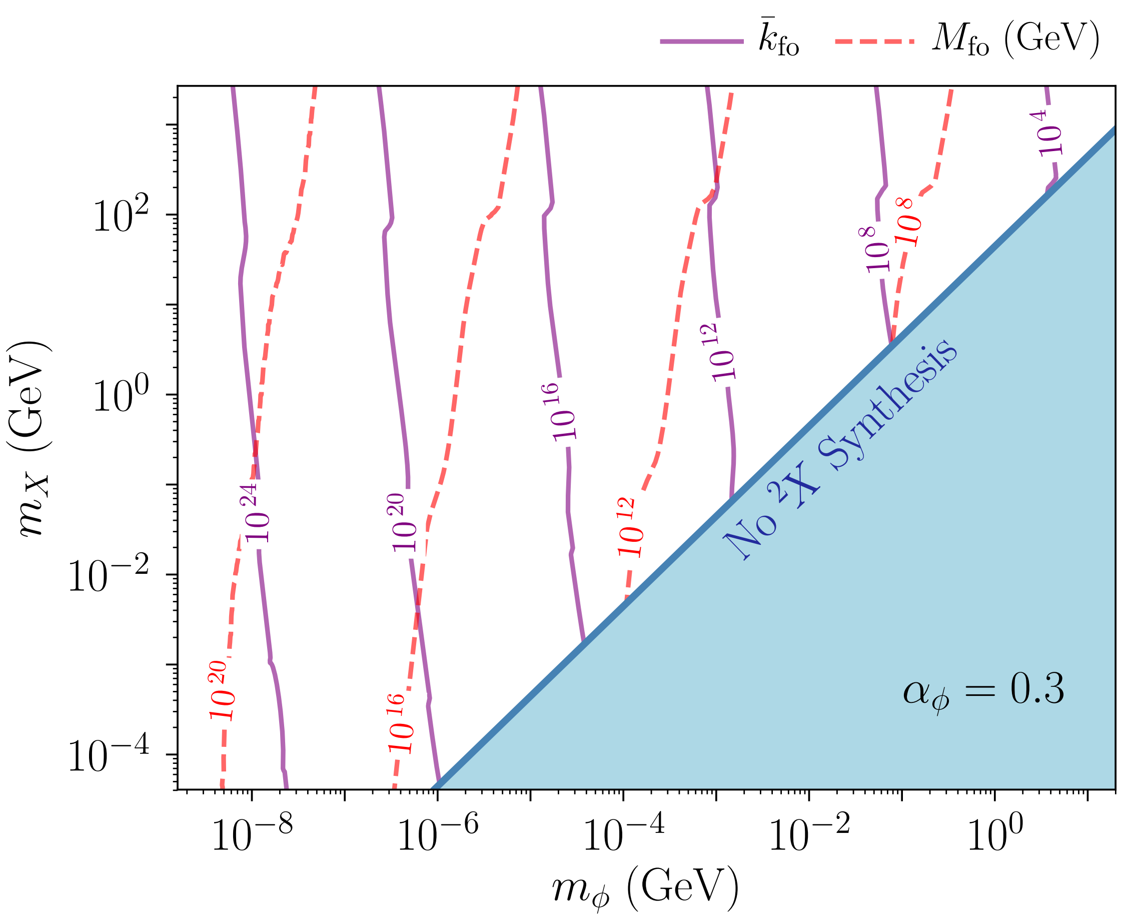
SUPER-HEAVY DARK MATTER

- Keeping the eyes open….



REMOVE ELECTROMAGNETISM FROM STANDARD MODEL

- Take BBN temp at 0.1 MeV (due to deuterium bottleneck)
- Solve Boltzmann equation $$\frac{dN}{dt} = k n_k \sigma_{kN} v_k$$
  - With Coulomb barrier $N \sim 9.5$
  - Without Coulomb barrier $N \sim 10^9$

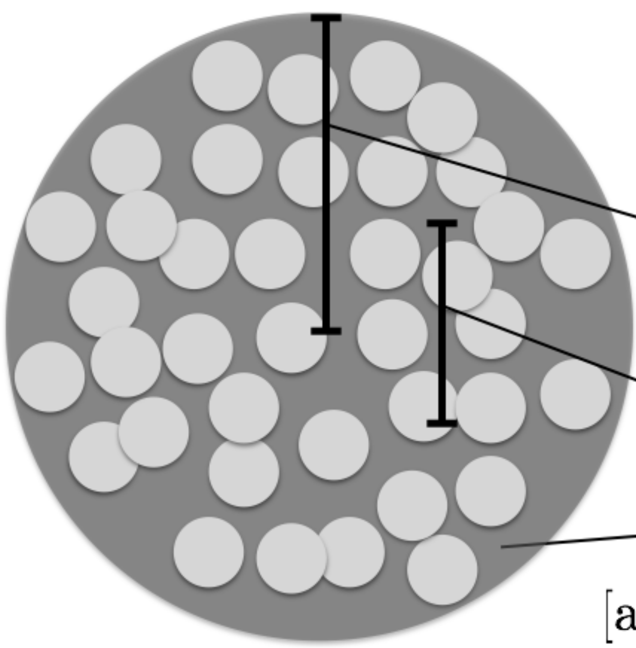


Gresham, Lou, KZ 1707.02316

WHY ARE LOW THRESHOLD DETECTORS GOOD FOR SUCH BIG COMPOSITE STATES?

- Answer: form factor and coherent enhancement

saturated nugget
$(N > N_{\rm sat})$



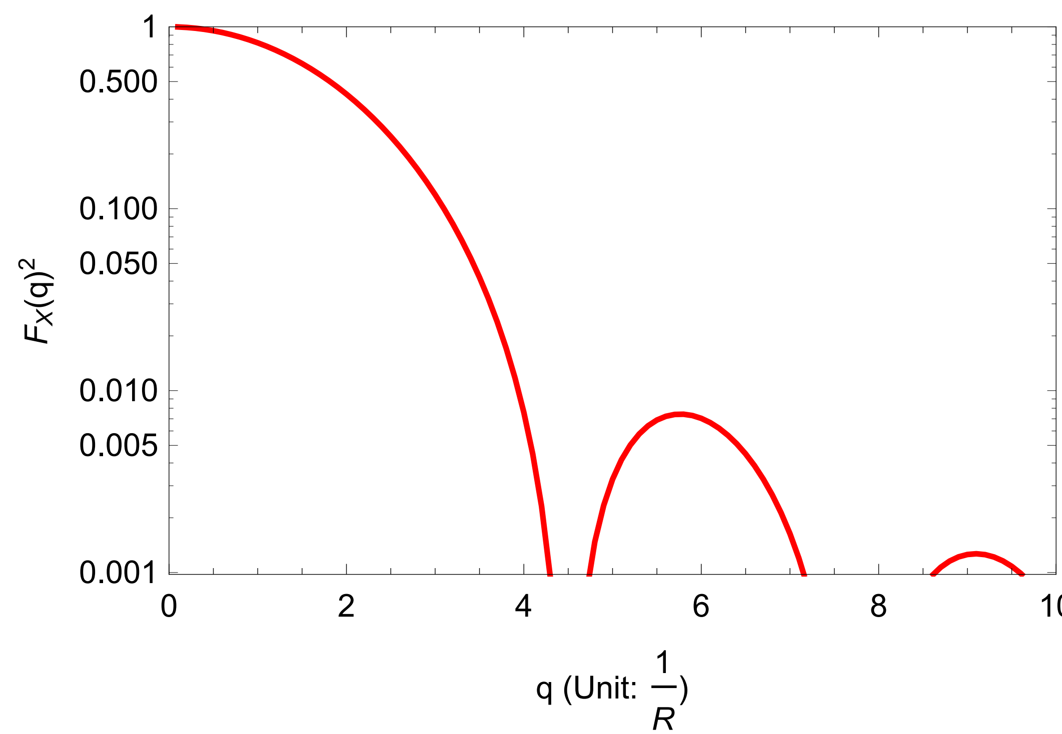
$$N_{\rm sat} \equiv \frac{4\pi}{3}\frac{n_{\rm sat}}{m_{\rm eff}^3}$$

$$M_N = N\bar{m}_X + \epsilon_{\rm surf}N^{2/3}$$

$$R_N = \left(\frac{4\pi}{3}\frac{N}{n_{\rm sat}}\right)^{1/3}$$

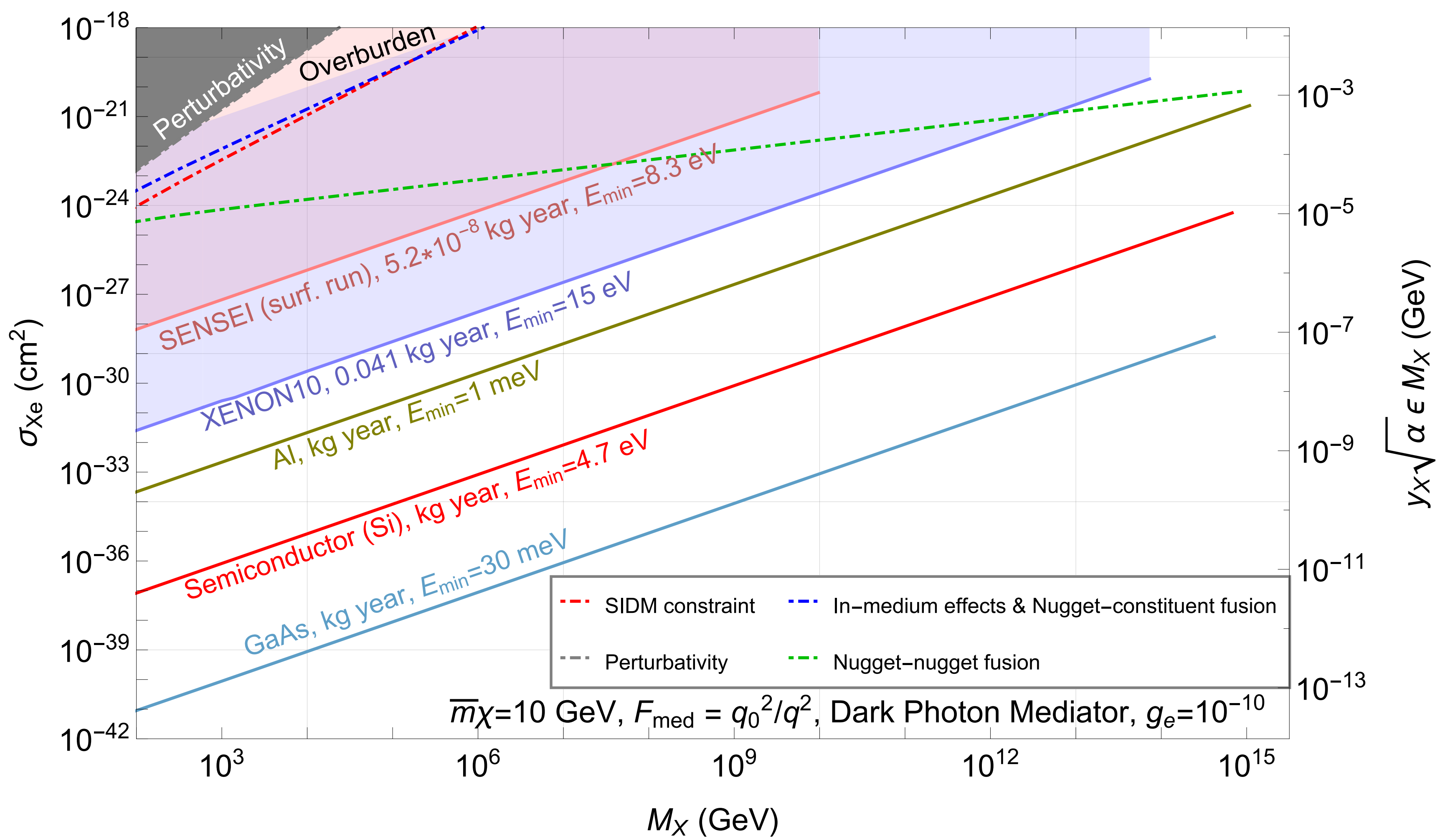
$m_{\rm eff}^{-1}$ = effective force range

$\langle\phi\rangle \neq 0$
[also $\langle V^0\rangle \neq 0$ if vector V^μ present]



NUGGET REACH

- Small-low threshold detectors win by several orders of magnitude in cross-section



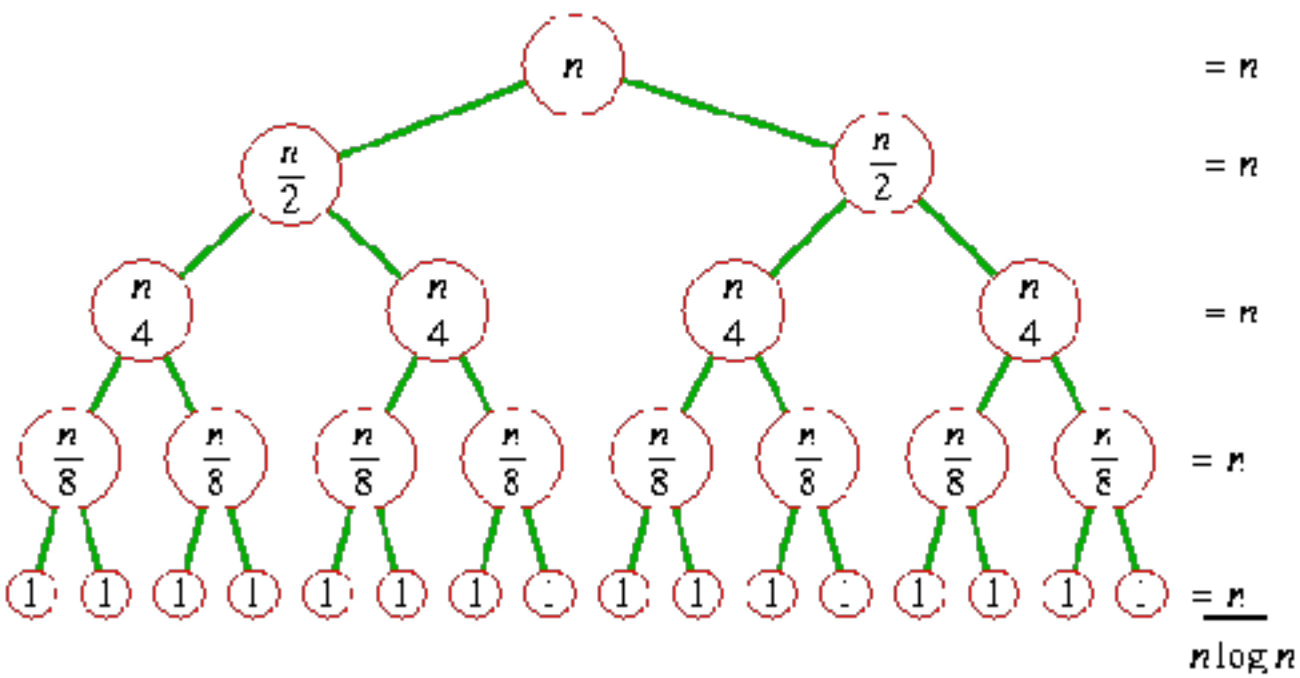
Coskuner, Grabowska, Knapen, KZ 1812.xxxxx

THE CHALLENGE

- Now is not the time for narrowing our search for Invisibles; 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?