

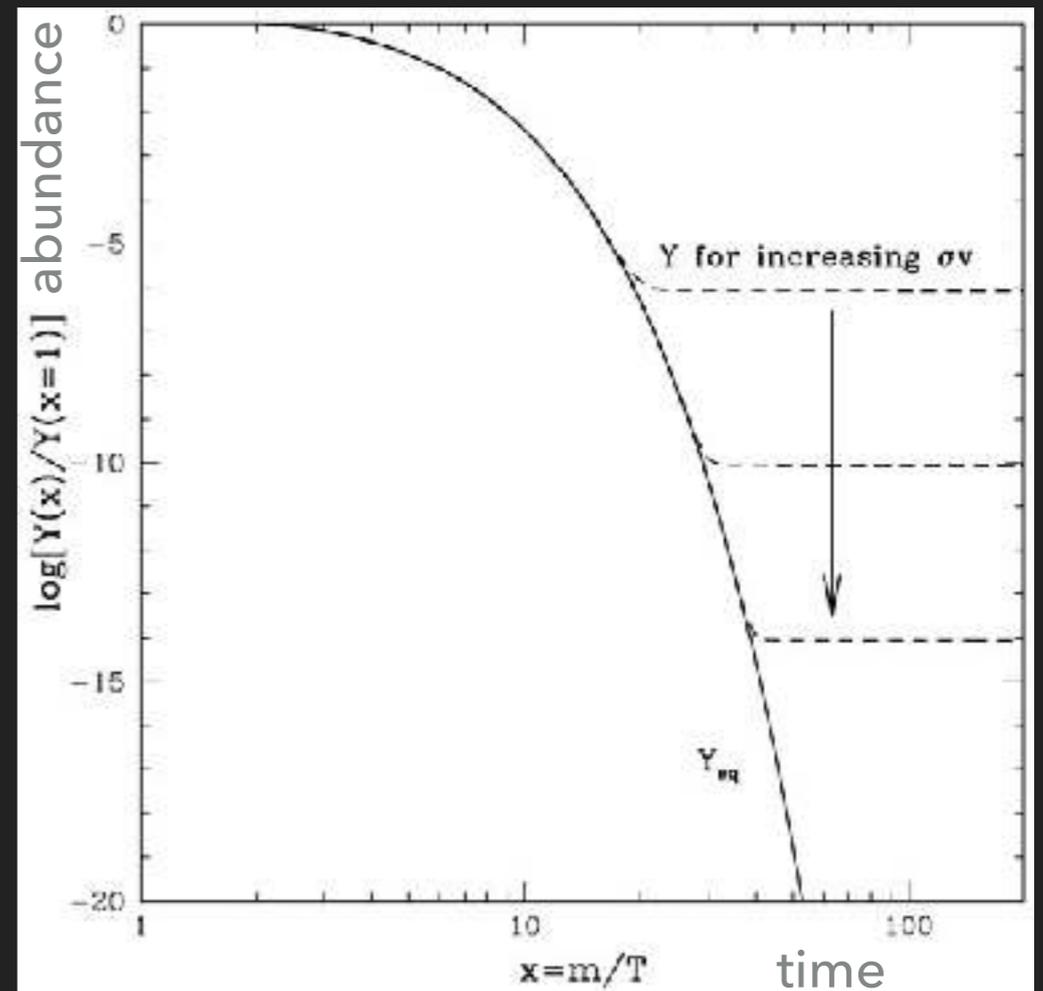
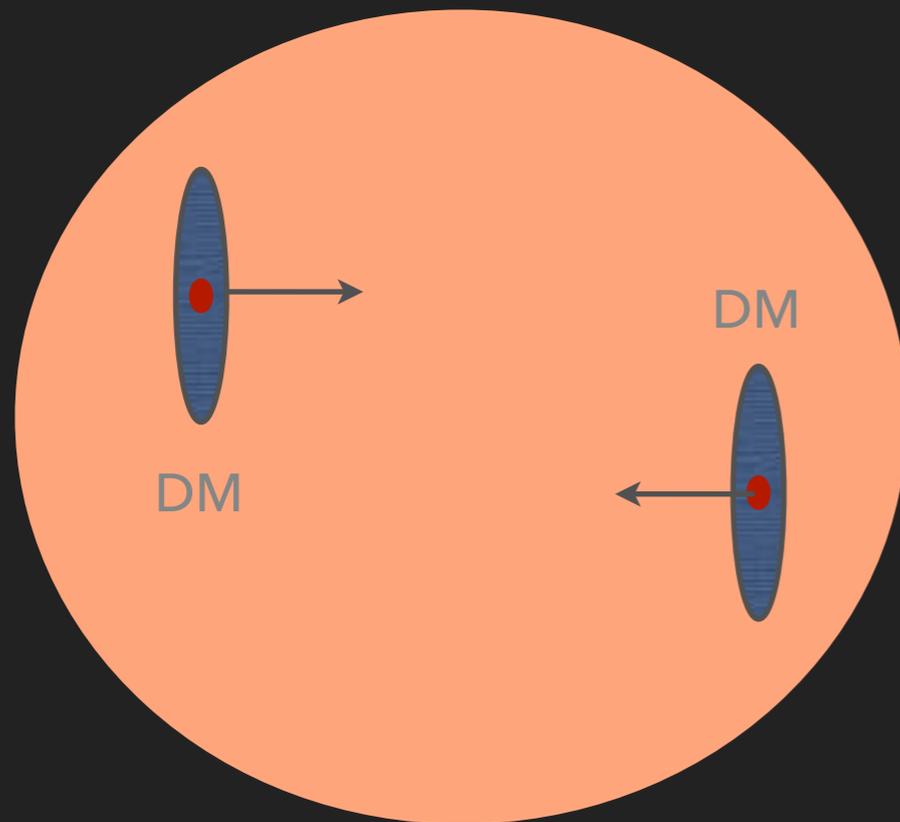
K. ZUREK

Berkeley Lab & CERN

DM WITHOUT PREJUDICE

NEW IDEAS IN DARK MATTER THEORY

- ▶ Old paradigm: weak scale dark matter (with relic density fixed by freeze-out)

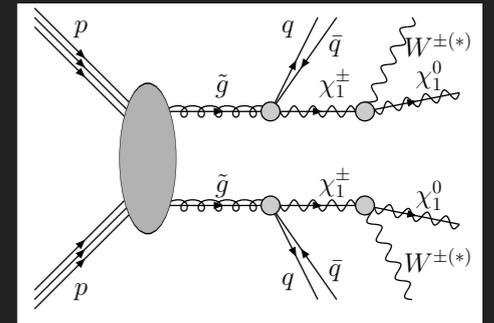


$$n\langle\sigma v\rangle = H(T_{fo})$$

$$\implies \langle\sigma v\rangle \simeq \frac{1}{(20 \text{ TeV})^2} \simeq \frac{g_{wk}^4}{4\pi(2 \text{ TeV})^2}$$

Kolb and Turner

WEAK SCALE PARADIGM: UNDER ASSAULT



ATLAS SUSY Searches* - 95% CL Lower Limits
December 2017

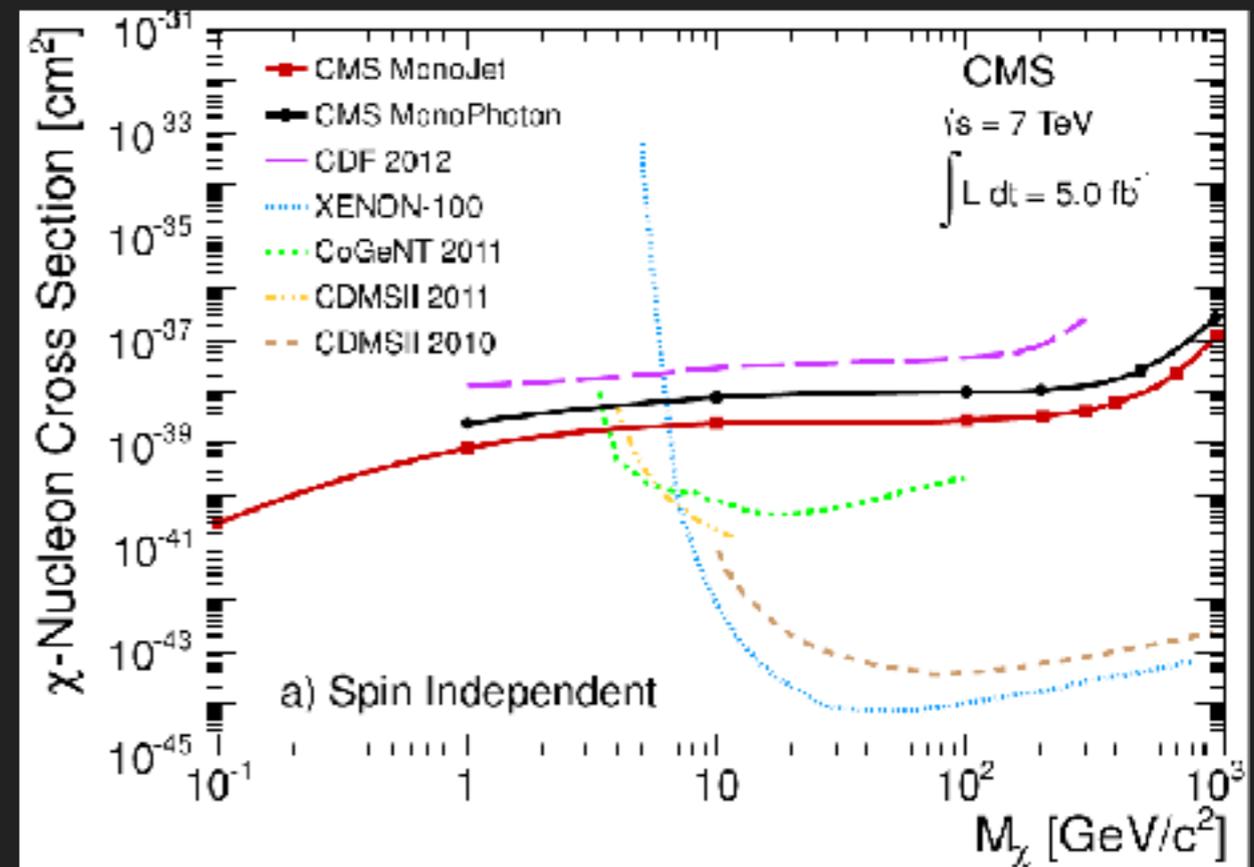
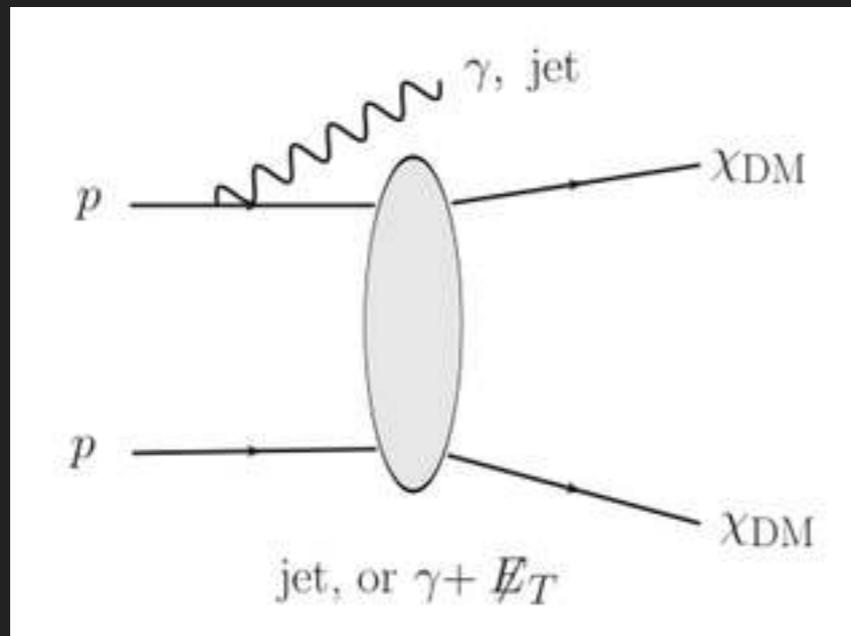
ATLAS Preliminary
 $\sqrt{s} = 7, 8, 13$ TeV

Model	$\mu_0, M_{1/2}, A_0$	Jets	E_{T}^{miss}	$\int L dt [fb^{-1}]$	Mass limit	$\sqrt{s} = 7, 8$ TeV	$\sqrt{s} = 13$ TeV	Reference	
Inclusive Searches	$\tilde{g}\tilde{g} \rightarrow g\tilde{\chi}_1^0\tilde{\chi}_1^0$	1	2-3 jets	Yes	56.1	0	1.87 TeV	$m(\tilde{g}) = 2000$ GeV, $m(\tilde{q}) = 1000$ GeV, $m(\tilde{\chi}_1^0) = 100$ GeV	1712.0559
	$\tilde{g}\tilde{g} \rightarrow g\tilde{\chi}_1^0\tilde{\chi}_1^0$ (compressed)	micro-jet	1-3 jets	Yes	56.1	0	790 GeV	$m(\tilde{g}) = 2000$ GeV, $m(\tilde{q}) = 1000$ GeV, $m(\tilde{\chi}_1^0) = 100$ GeV	1711.0557
	$\tilde{g}\tilde{g} \rightarrow g\tilde{\chi}_1^0\tilde{\chi}_1^0$	1	2-3 jets	Yes	56.1	0	2.83 TeV	$m(\tilde{g}) = 2000$ GeV, $m(\tilde{q}) = 1000$ GeV, $m(\tilde{\chi}_1^0) = 100$ GeV	1712.0559
	$\tilde{g}\tilde{g} \rightarrow g\tilde{\chi}_1^0\tilde{\chi}_1^0$	1	2-3 jets	Yes	56.1	0	2.01 TeV	$m(\tilde{g}) = 2000$ GeV, $m(\tilde{q}) = 1000$ GeV, $m(\tilde{\chi}_1^0) = 100$ GeV	1712.0559
	$\tilde{g}\tilde{g} \rightarrow g\tilde{\chi}_1^0\tilde{\chi}_1^0$	0-1 jets	2 jets	Yes	14.7	0	1.7 TeV	$m(\tilde{g}) = 2000$ GeV, $m(\tilde{q}) = 1000$ GeV, $m(\tilde{\chi}_1^0) = 100$ GeV	1611.0561
	$\tilde{g}\tilde{g} \rightarrow g\tilde{\chi}_1^0\tilde{\chi}_1^0$	0-1 jets	4 jets	-	26.1	0	1.81 TeV	$m(\tilde{g}) = 2000$ GeV, $m(\tilde{q}) = 1000$ GeV, $m(\tilde{\chi}_1^0) = 100$ GeV	1708.0571
	$\tilde{g}\tilde{g} \rightarrow g\tilde{\chi}_1^0\tilde{\chi}_1^0$	1	2-11 jets	Yes	26.1	0	1.8 TeV	$m(\tilde{g}) = 2000$ GeV, $m(\tilde{q}) = 1000$ GeV, $m(\tilde{\chi}_1^0) = 100$ GeV	1708.0571
	GMSB (if NLSP)	1-2 jets + 1 jet	0-2 jets	Yes	32.1	0	2.0 TeV	$m(\tilde{g}) = 2000$ GeV, $m(\tilde{q}) = 1000$ GeV, $m(\tilde{\chi}_1^0) = 100$ GeV	1607.0569
	GGM (no NLSP)	2 jets	-	Yes	26.1	0	2.78 TeV	$m(\tilde{g}) = 2000$ GeV, $m(\tilde{q}) = 1000$ GeV, $m(\tilde{\chi}_1^0) = 100$ GeV	ATLAS COM-2017-080
	GGM (bino NLSP)	1	2 jets	Yes	26.1	0	2.06 TeV	$m(\tilde{g}) = 2000$ GeV, $m(\tilde{q}) = 1000$ GeV, $m(\tilde{\chi}_1^0) = 100$ GeV	ATLAS COM-2017-080
Constrained GGM	1	micro-jet	Yes	20.0	0	825 GeV	$m(\tilde{g}) = 2000$ GeV, $m(\tilde{q}) = 1000$ GeV, $m(\tilde{\chi}_1^0) = 100$ GeV	1502.0128	
Direct	$\tilde{g}\tilde{g} \rightarrow g\tilde{\chi}_1^0\tilde{\chi}_1^0$	1	2 jets	Yes	26.1	0	1.26 TeV	$m(\tilde{g}) = 2000$ GeV, $m(\tilde{q}) = 1000$ GeV, $m(\tilde{\chi}_1^0) = 100$ GeV	1711.0191
	$\tilde{g}\tilde{g} \rightarrow g\tilde{\chi}_1^0\tilde{\chi}_1^0$	0-1 jets	2 jets	Yes	26.1	0	1.87 TeV	$m(\tilde{g}) = 2000$ GeV, $m(\tilde{q}) = 1000$ GeV, $m(\tilde{\chi}_1^0) = 100$ GeV	1711.0191
Via squark production	$\tilde{q}\tilde{q} \rightarrow q\tilde{\chi}_1^0\tilde{\chi}_1^0$	0	2 jets	Yes	26.1	0	891 GeV	$m(\tilde{q}) = 2000$ GeV, $m(\tilde{g}) = 1000$ GeV, $m(\tilde{\chi}_1^0) = 100$ GeV	1708.0571
	$\tilde{q}\tilde{q} \rightarrow q\tilde{\chi}_1^0\tilde{\chi}_1^0$	2 jets (150)	1 jet	Yes	26.1	0	205-790 GeV	$m(\tilde{q}) = 2000$ GeV, $m(\tilde{g}) = 1000$ GeV, $m(\tilde{\chi}_1^0) = 100$ GeV	1708.0571
	$\tilde{q}\tilde{q} \rightarrow q\tilde{\chi}_1^0\tilde{\chi}_1^0$	0-2 jets	1-2 jets	Yes	1712.0	0	117-170 GeV	$m(\tilde{q}) = 2000$ GeV, $m(\tilde{g}) = 1000$ GeV, $m(\tilde{\chi}_1^0) = 100$ GeV	1305.2102, ATLAS-COM-2017-077
	$\tilde{q}\tilde{q} \rightarrow q\tilde{\chi}_1^0\tilde{\chi}_1^0$	0-2 jets	0-2 jets	Yes	207.026	0	99-156 GeV	$m(\tilde{q}) = 2000$ GeV, $m(\tilde{g}) = 1000$ GeV, $m(\tilde{\chi}_1^0) = 100$ GeV	1504.0884, 1709.0410, 1711.11528
	$\tilde{q}\tilde{q} \rightarrow q\tilde{\chi}_1^0\tilde{\chi}_1^0$	0	micro-jet	Yes	26.1	0	93-130 GeV	$m(\tilde{q}) = 2000$ GeV, $m(\tilde{g}) = 1000$ GeV, $m(\tilde{\chi}_1^0) = 100$ GeV	1711.0551
	$\tilde{q}\tilde{q} \rightarrow q\tilde{\chi}_1^0\tilde{\chi}_1^0$	2 jets (150)	1 jet	Yes	20.0	0	160-520 GeV	$m(\tilde{q}) = 2000$ GeV, $m(\tilde{g}) = 1000$ GeV, $m(\tilde{\chi}_1^0) = 100$ GeV	1433.6328
	$\tilde{q}\tilde{q} \rightarrow q\tilde{\chi}_1^0\tilde{\chi}_1^0$	2 jets (150)	1 jet	Yes	26.1	0	200-750 GeV	$m(\tilde{q}) = 2000$ GeV, $m(\tilde{g}) = 1000$ GeV, $m(\tilde{\chi}_1^0) = 100$ GeV	1706.0568
LSP direct	$\tilde{g}\tilde{g} \rightarrow g\tilde{\chi}_1^0\tilde{\chi}_1^0$	2 jets	0	Yes	26.1	0	10-593 GeV	$m(\tilde{g}) = 2000$ GeV, $m(\tilde{q}) = 1000$ GeV, $m(\tilde{\chi}_1^0) = 100$ GeV	ATLAS COM-2017-039
	$\tilde{g}\tilde{g} \rightarrow g\tilde{\chi}_1^0\tilde{\chi}_1^0$	2 jets	0	Yes	26.1	0	790 GeV	$m(\tilde{g}) = 2000$ GeV, $m(\tilde{q}) = 1000$ GeV, $m(\tilde{\chi}_1^0) = 100$ GeV	ATLAS COM-2017-039
	$\tilde{g}\tilde{g} \rightarrow g\tilde{\chi}_1^0\tilde{\chi}_1^0$	2 jets	0	Yes	26.1	0	790 GeV	$m(\tilde{g}) = 2000$ GeV, $m(\tilde{q}) = 1000$ GeV, $m(\tilde{\chi}_1^0) = 100$ GeV	1708.0571
	$\tilde{g}\tilde{g} \rightarrow g\tilde{\chi}_1^0\tilde{\chi}_1^0$	2 jets	0	Yes	26.1	0	1.18 TeV	$m(\tilde{g}) = 2000$ GeV, $m(\tilde{q}) = 1000$ GeV, $m(\tilde{\chi}_1^0) = 100$ GeV	ATLAS COM-2017-039
	$\tilde{g}\tilde{g} \rightarrow g\tilde{\chi}_1^0\tilde{\chi}_1^0$	2 jets	0-2 jets	Yes	26.1	0	500 GeV	$m(\tilde{g}) = 2000$ GeV, $m(\tilde{q}) = 1000$ GeV, $m(\tilde{\chi}_1^0) = 100$ GeV	ATLAS COM-2017-039
	$\tilde{g}\tilde{g} \rightarrow g\tilde{\chi}_1^0\tilde{\chi}_1^0$	0-1 jets	3 jets	Yes	20.0	0	278 GeV	$m(\tilde{g}) = 2000$ GeV, $m(\tilde{q}) = 1000$ GeV, $m(\tilde{\chi}_1^0) = 100$ GeV	1501.0119
	$\tilde{g}\tilde{g} \rightarrow g\tilde{\chi}_1^0\tilde{\chi}_1^0$	4 jets	0	Yes	20.0	0	435 GeV	$m(\tilde{g}) = 2000$ GeV, $m(\tilde{q}) = 1000$ GeV, $m(\tilde{\chi}_1^0) = 100$ GeV	1435.5306
Low μ_0 / high $M_{1/2}$	GGM (no NLSP) weak prod. $\tilde{g}\tilde{g} \rightarrow g\tilde{\chi}_1^0\tilde{\chi}_1^0$	1 jet + 1 jet	-	Yes	20.0	0	115-370 GeV	$m(\tilde{g}) = 2000$ GeV, $m(\tilde{q}) = 1000$ GeV, $m(\tilde{\chi}_1^0) = 100$ GeV	1507.0543
	GGM (no NLSP) weak prod. $\tilde{g}\tilde{g} \rightarrow g\tilde{\chi}_1^0\tilde{\chi}_1^0$	2 jets	-	Yes	26.1	0	1.06 TeV	$m(\tilde{g}) = 2000$ GeV, $m(\tilde{q}) = 1000$ GeV, $m(\tilde{\chi}_1^0) = 100$ GeV	ATLAS COM-2017-080
	Direct $\tilde{g}\tilde{g} \rightarrow g\tilde{\chi}_1^0\tilde{\chi}_1^0$ proc. long-lived \tilde{L}	0-1 jets	1 jet	Yes	26.1	0	90 GeV	$m(\tilde{g}) = 2000$ GeV, $m(\tilde{q}) = 1000$ GeV, $m(\tilde{\chi}_1^0) = 100$ GeV	1712.0519
	Direct $\tilde{g}\tilde{g} \rightarrow g\tilde{\chi}_1^0\tilde{\chi}_1^0$ proc. long-lived \tilde{L}	0-1 jets	1 jet	Yes	10.4	0	455 GeV	$m(\tilde{g}) = 2000$ GeV, $m(\tilde{q}) = 1000$ GeV, $m(\tilde{\chi}_1^0) = 100$ GeV	1500.0502
	Stable stopped \tilde{R} hadron	1	1-5 jets	Yes	27.0	0	158 GeV	$m(\tilde{g}) = 2000$ GeV, $m(\tilde{q}) = 1000$ GeV, $m(\tilde{\chi}_1^0) = 100$ GeV	1361.6504
	Stable \tilde{R} hadron	1 jet	-	-	0.9	0	1.56 TeV	$m(\tilde{g}) = 2000$ GeV, $m(\tilde{q}) = 1000$ GeV, $m(\tilde{\chi}_1^0) = 100$ GeV	1666.0518
	Metastable \tilde{R} hadron	0-1 jets	-	-	0.9	0	1.57 TeV	$m(\tilde{g}) = 2000$ GeV, $m(\tilde{q}) = 1000$ GeV, $m(\tilde{\chi}_1^0) = 100$ GeV	1666.0518
RPV	Metastable \tilde{R} hadron $\tilde{g}\tilde{g} \rightarrow g\tilde{\chi}_1^0\tilde{\chi}_1^0$	0-1 jets	-	Yes	22.8	0	2.37 TeV	$m(\tilde{g}) = 2000$ GeV, $m(\tilde{q}) = 1000$ GeV, $m(\tilde{\chi}_1^0) = 100$ GeV	1710.0491
	GMSB, stable \tilde{R} hadron $\tilde{g}\tilde{g} \rightarrow g\tilde{\chi}_1^0\tilde{\chi}_1^0$	1-2 jets	-	-	19.1	0	637 GeV	$m(\tilde{g}) = 2000$ GeV, $m(\tilde{q}) = 1000$ GeV, $m(\tilde{\chi}_1^0) = 100$ GeV	1601.0745
	GMSB, stable \tilde{R} hadron $\tilde{g}\tilde{g} \rightarrow g\tilde{\chi}_1^0\tilde{\chi}_1^0$	2 jets	-	Yes	20.0	0	440 GeV	$m(\tilde{g}) = 2000$ GeV, $m(\tilde{q}) = 1000$ GeV, $m(\tilde{\chi}_1^0) = 100$ GeV	1434.5307
	$\tilde{g}\tilde{g} \rightarrow g\tilde{\chi}_1^0\tilde{\chi}_1^0$	0-1 jets	-	-	20.0	0	1.2 TeV	$m(\tilde{g}) = 2000$ GeV, $m(\tilde{q}) = 1000$ GeV, $m(\tilde{\chi}_1^0) = 100$ GeV	1504.0516
	$\tilde{g}\tilde{g} \rightarrow g\tilde{\chi}_1^0\tilde{\chi}_1^0$	0-1 jets	-	-	0.2	0	1.8 TeV	$m(\tilde{g}) = 2000$ GeV, $m(\tilde{q}) = 1000$ GeV, $m(\tilde{\chi}_1^0) = 100$ GeV	1607.0569
	Bilinear RPV GMSB	0-1 jets	0-3 jets	Yes	20.0	0	1.41 TeV	$m(\tilde{g}) = 2000$ GeV, $m(\tilde{q}) = 1000$ GeV, $m(\tilde{\chi}_1^0) = 100$ GeV	1434.5306
	$\tilde{g}\tilde{g} \rightarrow g\tilde{\chi}_1^0\tilde{\chi}_1^0$	0-1 jets	-	Yes	15.0	0	1.14 TeV	$m(\tilde{g}) = 2000$ GeV, $m(\tilde{q}) = 1000$ GeV, $m(\tilde{\chi}_1^0) = 100$ GeV	ATLAS COM-2017-078
Other	$\tilde{g}\tilde{g} \rightarrow g\tilde{\chi}_1^0\tilde{\chi}_1^0$	0-1 jets	-	Yes	20.0	0	450 GeV	$m(\tilde{g}) = 2000$ GeV, $m(\tilde{q}) = 1000$ GeV, $m(\tilde{\chi}_1^0) = 100$ GeV	1434.5306
	$\tilde{g}\tilde{g} \rightarrow g\tilde{\chi}_1^0\tilde{\chi}_1^0$	0	4-7 large-R jets	-	26.1	0	1.315 TeV	$m(\tilde{g}) = 2000$ GeV, $m(\tilde{q}) = 1000$ GeV, $m(\tilde{\chi}_1^0) = 100$ GeV	1504.0516
	$\tilde{g}\tilde{g} \rightarrow g\tilde{\chi}_1^0\tilde{\chi}_1^0$	0-1 jets	0-3 jets	-	26.1	0	2.1 TeV	$m(\tilde{g}) = 2000$ GeV, $m(\tilde{q}) = 1000$ GeV, $m(\tilde{\chi}_1^0) = 100$ GeV	1704.0573
	$\tilde{g}\tilde{g} \rightarrow g\tilde{\chi}_1^0\tilde{\chi}_1^0$	0-1 jets	0-3 jets	-	26.1	0	1.89 TeV	$m(\tilde{g}) = 2000$ GeV, $m(\tilde{q}) = 1000$ GeV, $m(\tilde{\chi}_1^0) = 100$ GeV	1704.0573
	$\tilde{g}\tilde{g} \rightarrow g\tilde{\chi}_1^0\tilde{\chi}_1^0$	0	2-10 jets	-	26.1	0	109-472 GeV	$m(\tilde{g}) = 2000$ GeV, $m(\tilde{q}) = 1000$ GeV, $m(\tilde{\chi}_1^0) = 100$ GeV	1710.0171
	$\tilde{g}\tilde{g} \rightarrow g\tilde{\chi}_1^0\tilde{\chi}_1^0$	0-1 jets	2 jets	-	26.1	0	1.83 TeV	$m(\tilde{g}) = 2000$ GeV, $m(\tilde{q}) = 1000$ GeV, $m(\tilde{\chi}_1^0) = 100$ GeV	1710.0244
	Other	0	2 jets	Yes	20.0	0	510 GeV	$m(\tilde{g}) = 2000$ GeV, $m(\tilde{q}) = 1000$ GeV, $m(\tilde{\chi}_1^0) = 100$ GeV	1501.0125

*Only a selection of the available mass limits on new states or parameters is shown. Many of the limits are based on simplified models, e.g. rule for the assumptions made.

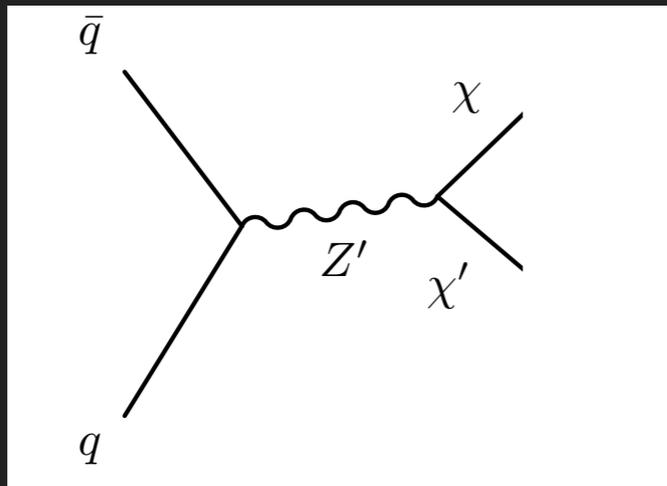
MONO-X AS GENERAL DM SEARCH?

- ▶ Mono-photon, -Z, -jet, -Higgs, -b, -t

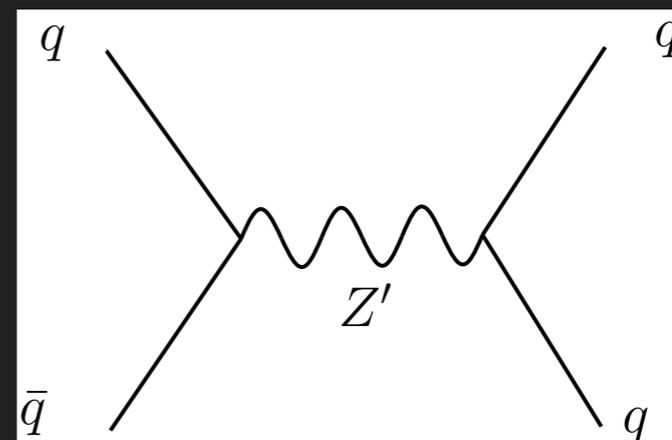


MONO-X IS NOT A DISCOVERY CHANNEL*

- ▶ LHC is a mediator machine, not a DM machine
- ▶ *Except in special circumstances, the mediator will be discovered first in visible channel



Mono-X

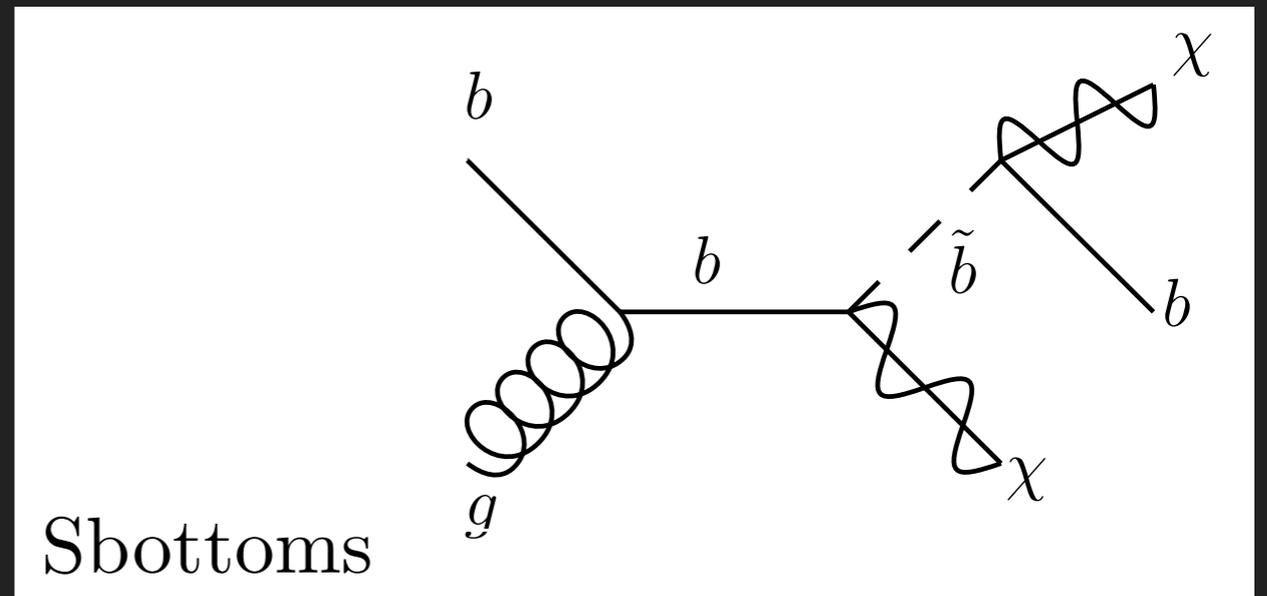
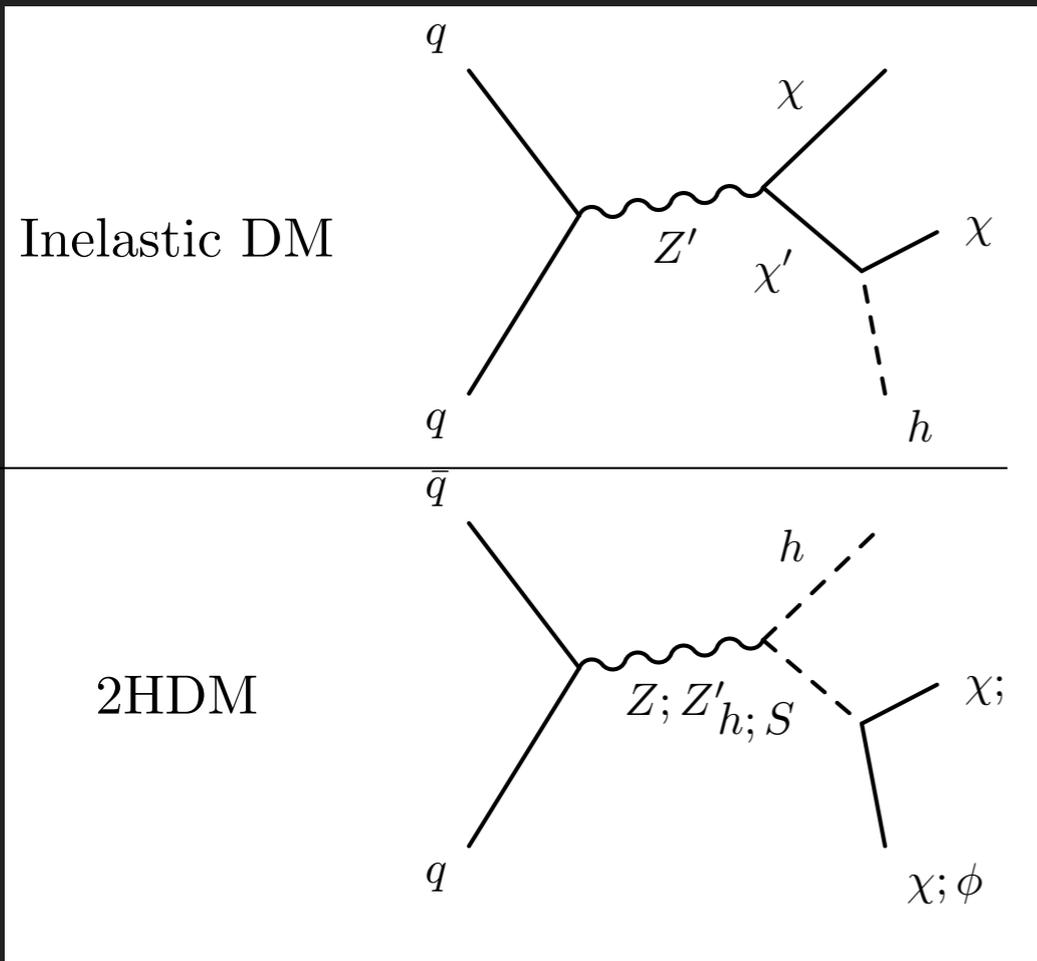


Direct Search

MONO-X IS NOT A DISCOVERY CHANNEL*

► *Special circumstances

Search	Model where it matters
mono- h	Inelastic DM, 2HDM
mono- z	Inelastic DM, 2HDM
mono-jet	Squark mediated production, compressed spectrum
mono- b	Sbottom mediated production, compressed spectrum



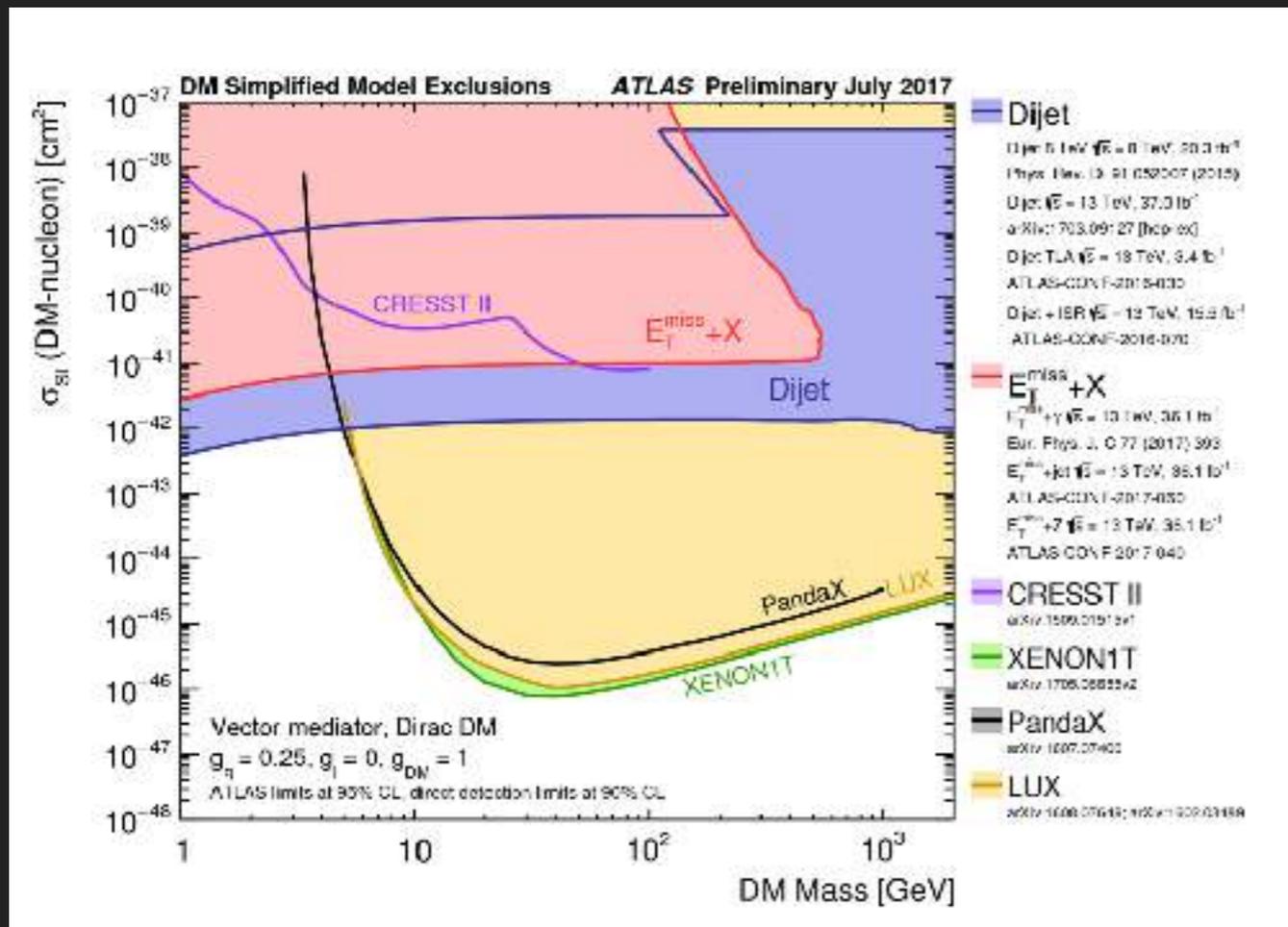
PROJECTING LHC CONSTRAINTS ON DD PLANE IS DECEIVING

▶ A simple example:

$$m_X = 1 \text{ GeV}, \quad m_\phi \simeq 5 \text{ MeV}$$

$$g_X = 10^{-3}, \quad g_q = 10^{-3}$$

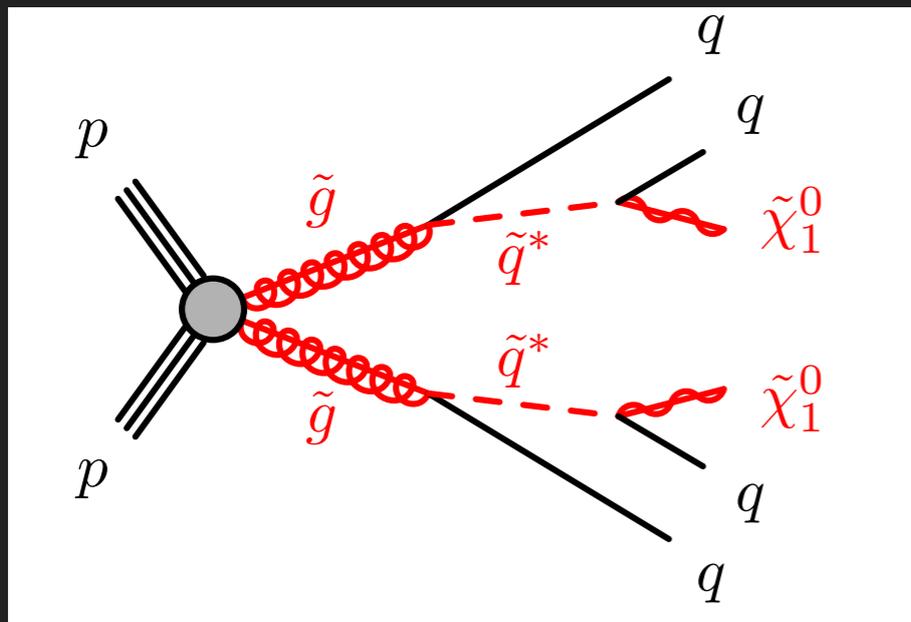
$$\sigma_n \simeq 10^{-39} \text{ cm}^2$$



LHC is a Heavy Mediator Machine, not a Dark Matter Machine!

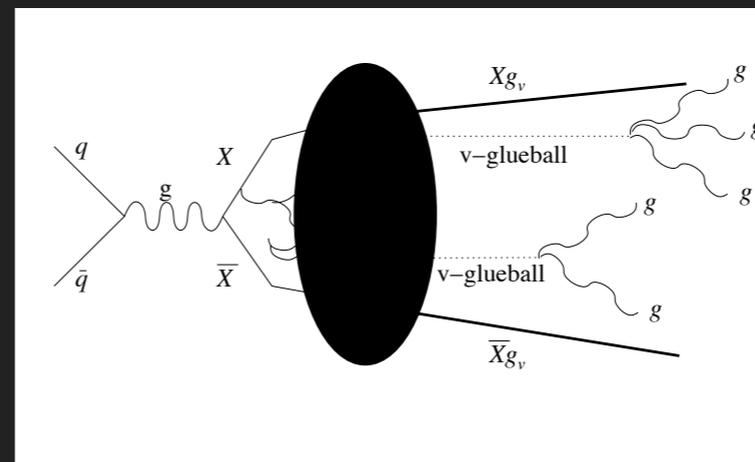
SEARCHES FOR DARK MATTER IN EXOTIC FINAL STATES

- ▶ Production of mediators with exotic decays to hidden sector, including with displaced vertices



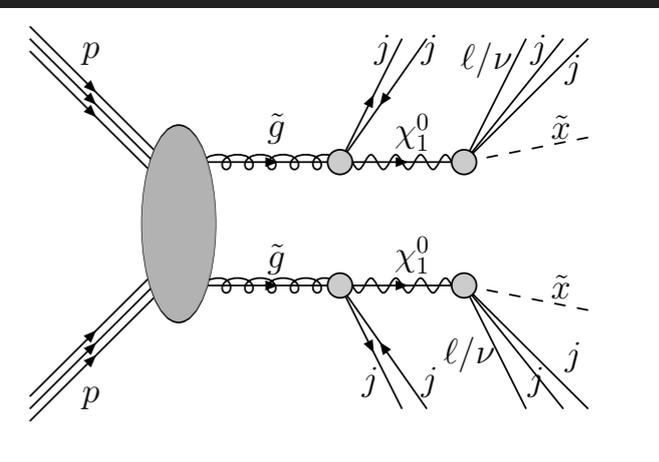
On the radar, some limited searches in SUSY scenarios with prejudice, e.g. ATLAS displaced gluino analysis 1710.04901 on Split SUSY

Classic Hidden Valley



hep-ph/0604261

Asymmetric DM



1310.2617

Still space for searches for DM with multi-jet/leptons and displaced vertices, small invariant mass and limited MET; some constraints can be placed by recasting existing searches

TOWARDS LIGHT DARK MATTER

Dark Matter May Reside in a Hidden Sector

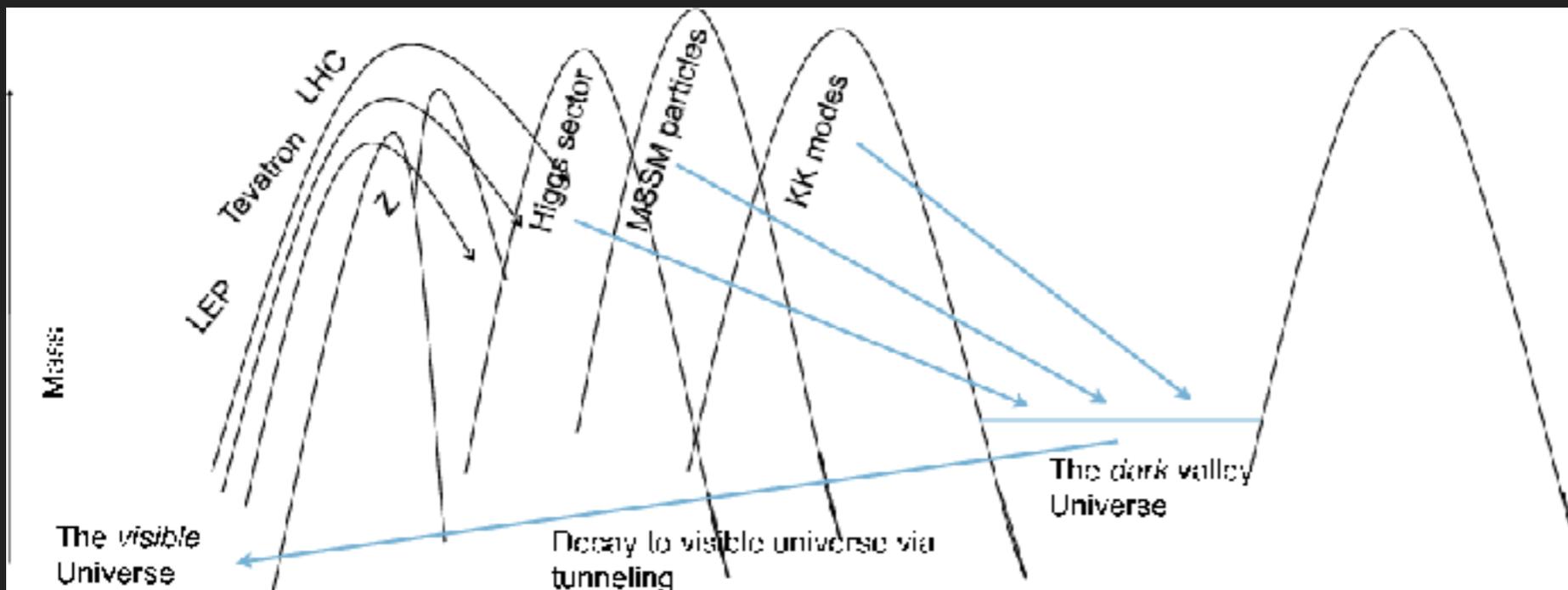


e.g. a stable dark pion

no weak force

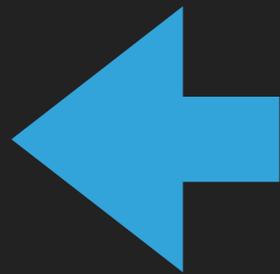
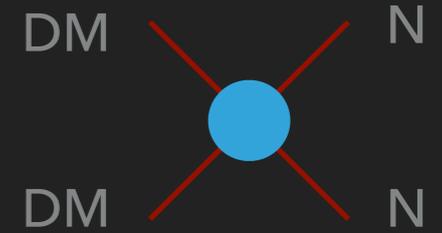
$$\pi_v^+ \pi_v^- \rightarrow \pi_v^0 \pi_v^0$$

$$\pi_v^0 \rightarrow b\bar{b}, \gamma\gamma$$

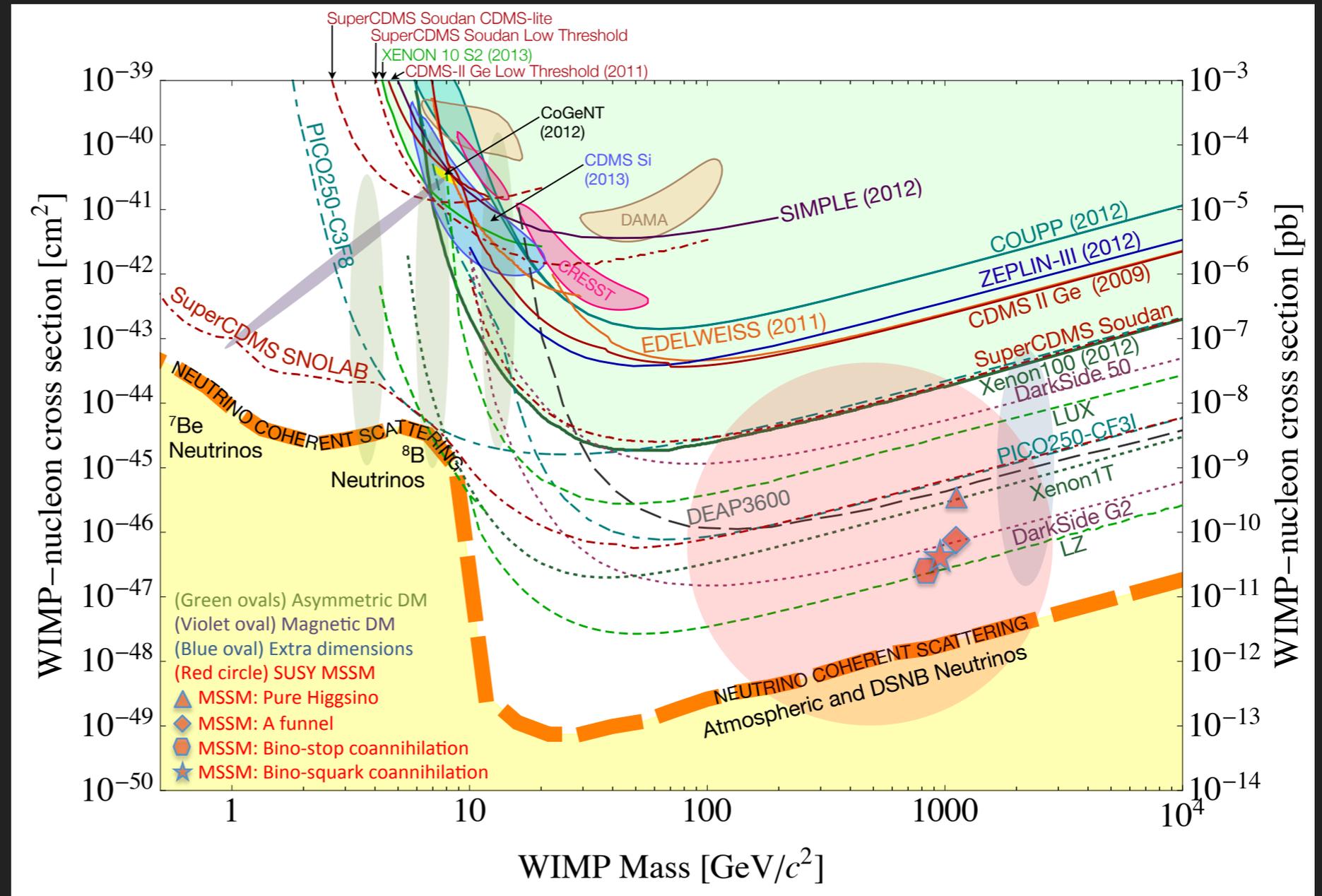


Hidden Valley Paradigm

WEAK SCALE PARADIGM: UNDER ASSAULT



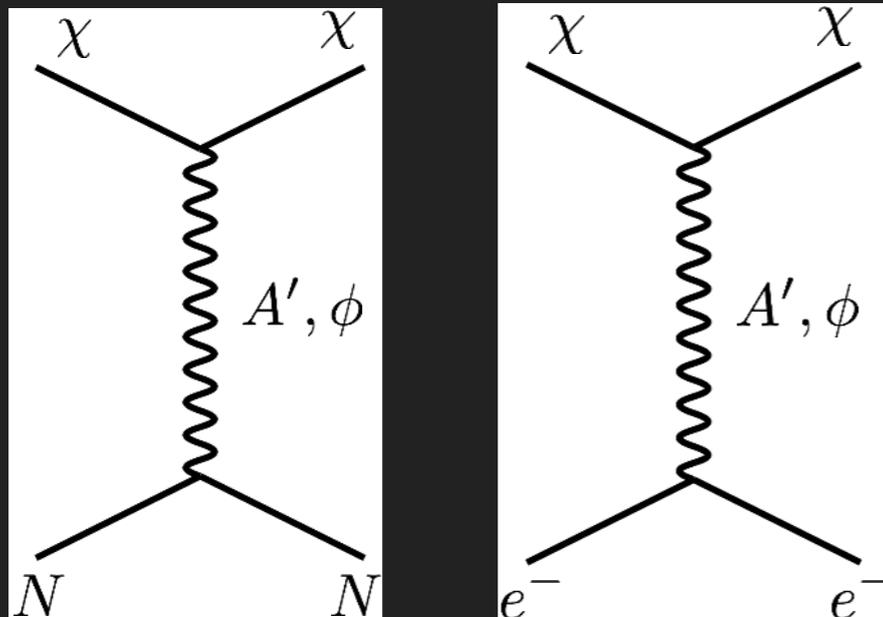
???



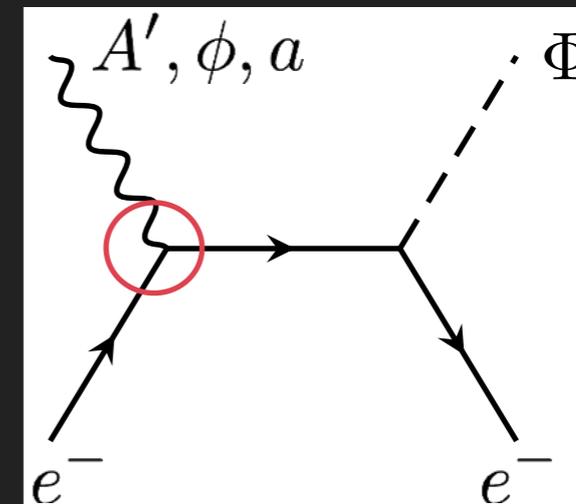
“MODELS” FOR LOW-MASS DIRECT DETECTION EXPERIMENTS

► Dark Photon Mediator and Dark Matter

Scattering



Absorption



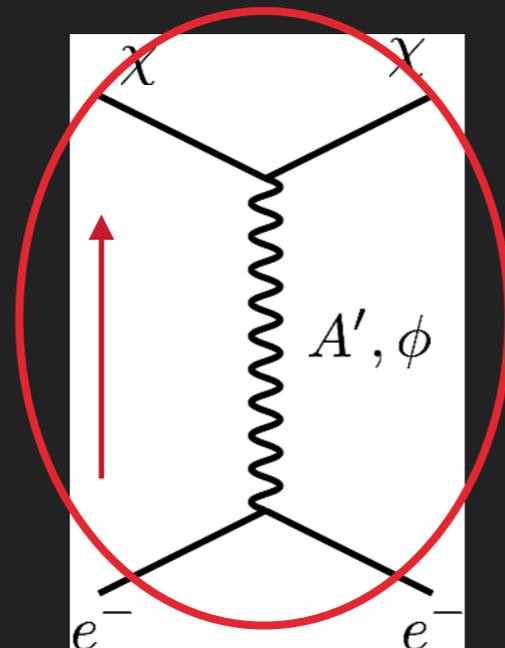
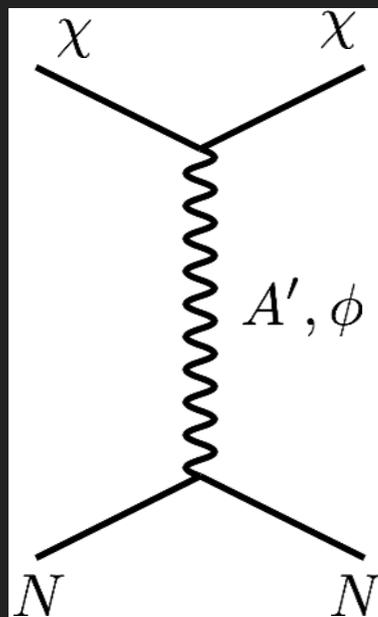
$$\sigma_{\text{DD}}^{\text{massless}} \simeq 1 \times 10^{-39} \text{ cm}^2 \left(\frac{\alpha_T \alpha_\chi}{10^{-30}} \right) \left(\frac{\mu_{T\chi}}{m_e} \right)^2 \left(\frac{\text{keV}}{q} \right)^4$$

$$g_e \simeq \epsilon e$$

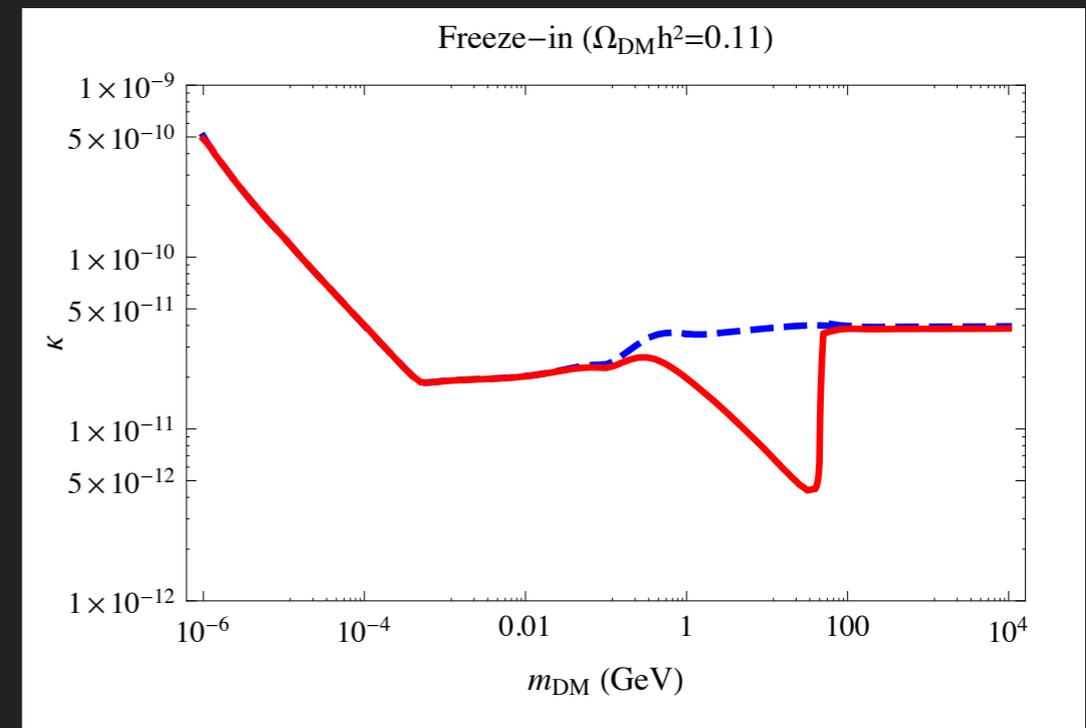
“MODELS” FOR LOW-MASS DIRECT DETECTION EXPERIMENTS

► Dark Photon Mediator and Dark Matter

Scattering



Freeze-in

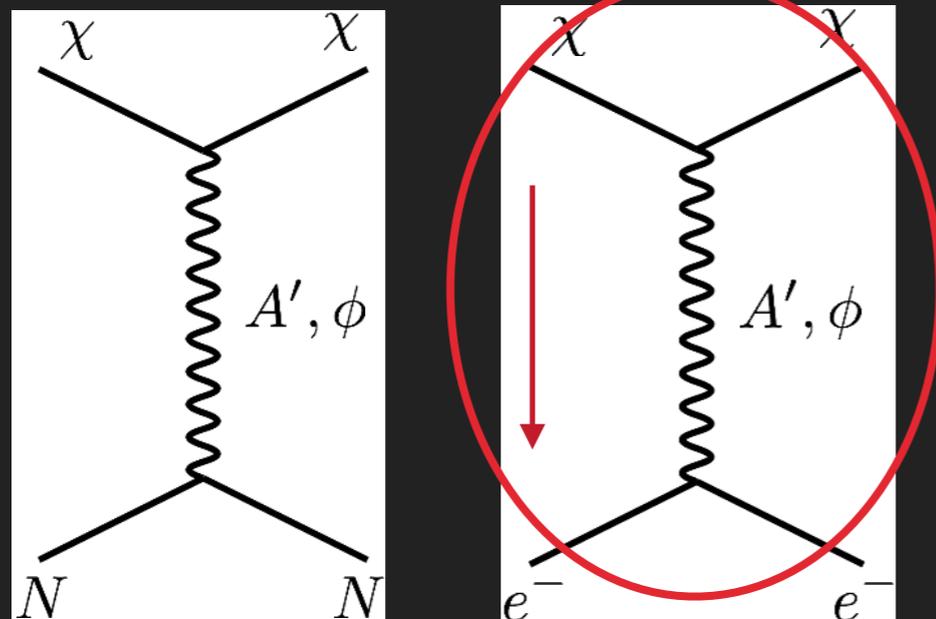


Chu, Hambye, Tytgat 1112.0493

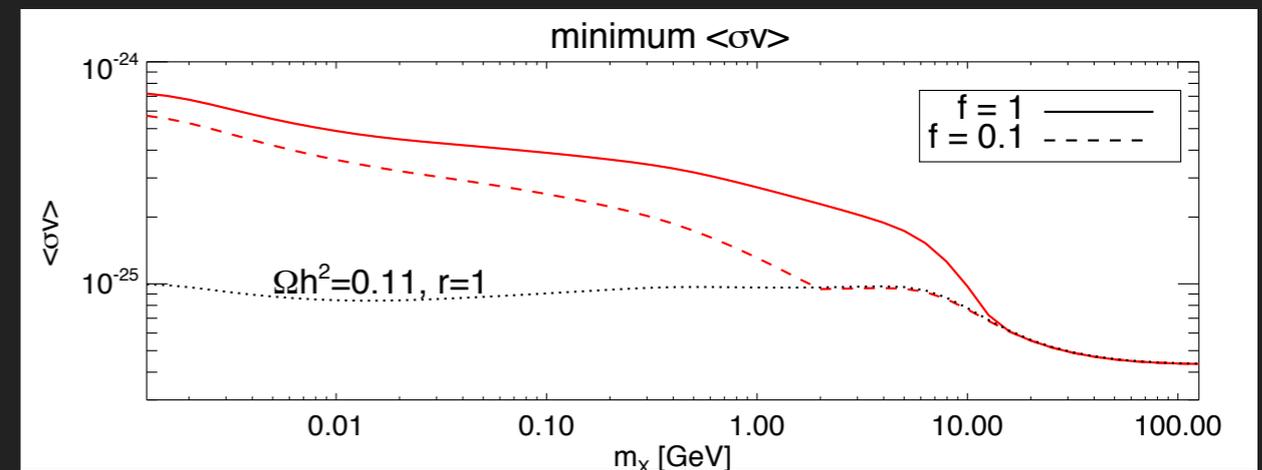
“MODELS” FOR LOW-MASS DIRECT DETECTION EXPERIMENTS

► Dark Photon Mediator and Dark Matter

Scattering

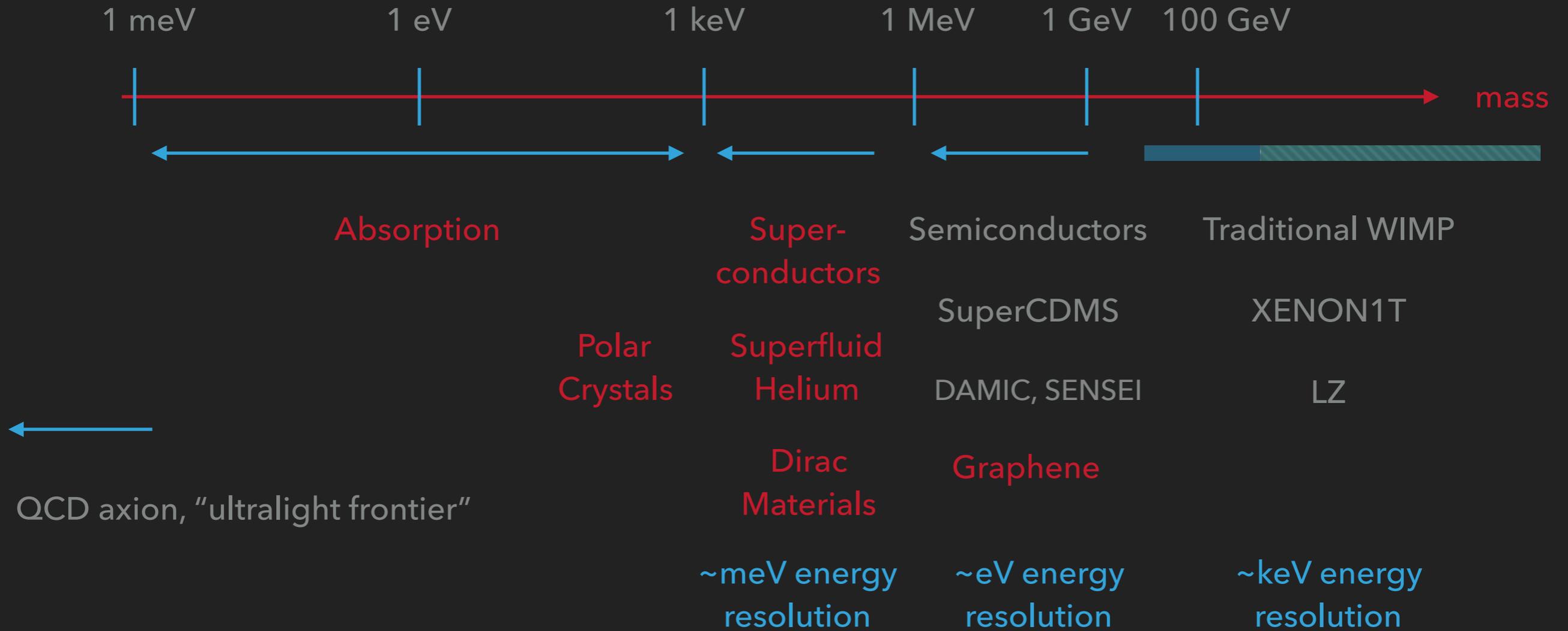


Asymmetric Dark Matter



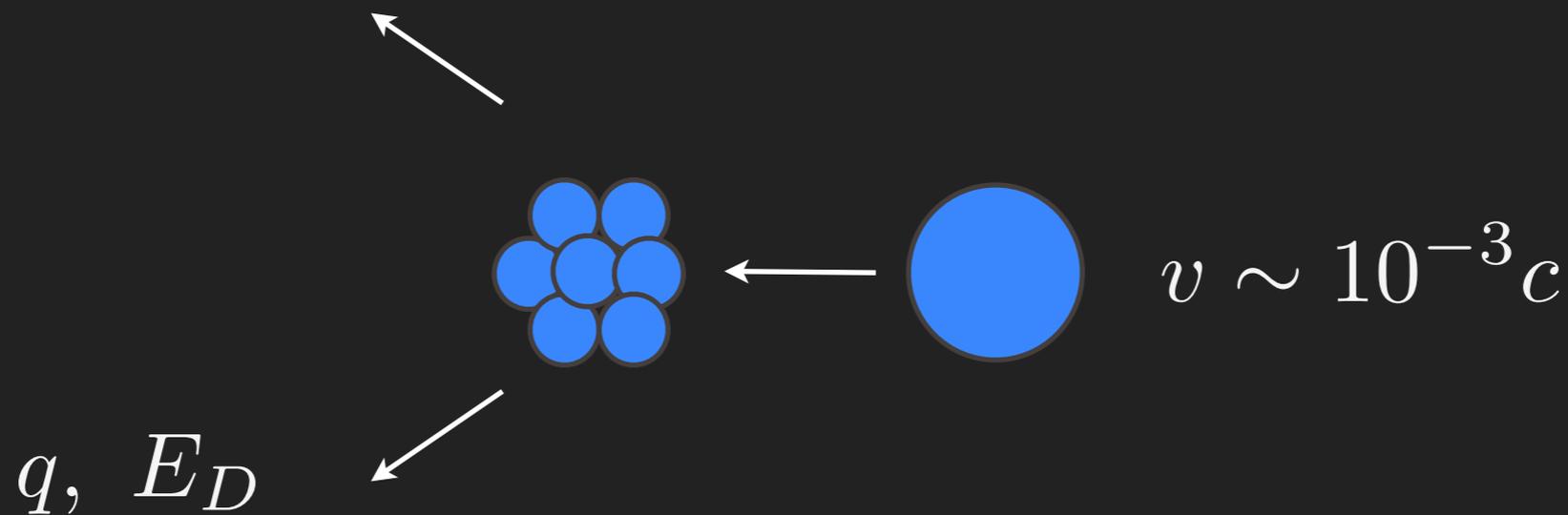
Lin, Yu, KZ 1111.0293

DARK MATTER LANDSCAPE



DIRECT DETECTION GOLD STANDARD

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



$$v \sim 300 \text{ km/s} \sim 10^{-3}c \implies E_D \sim 100 \text{ keV} \quad \text{for 50 GeV target}$$

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

MORE BANG FOR THE BUCK WITH ELECTRONS

$$E_D = \frac{q^2}{2m_e} \quad q_{\max} = 2m_\chi v$$

▶ In insulators, like xenon

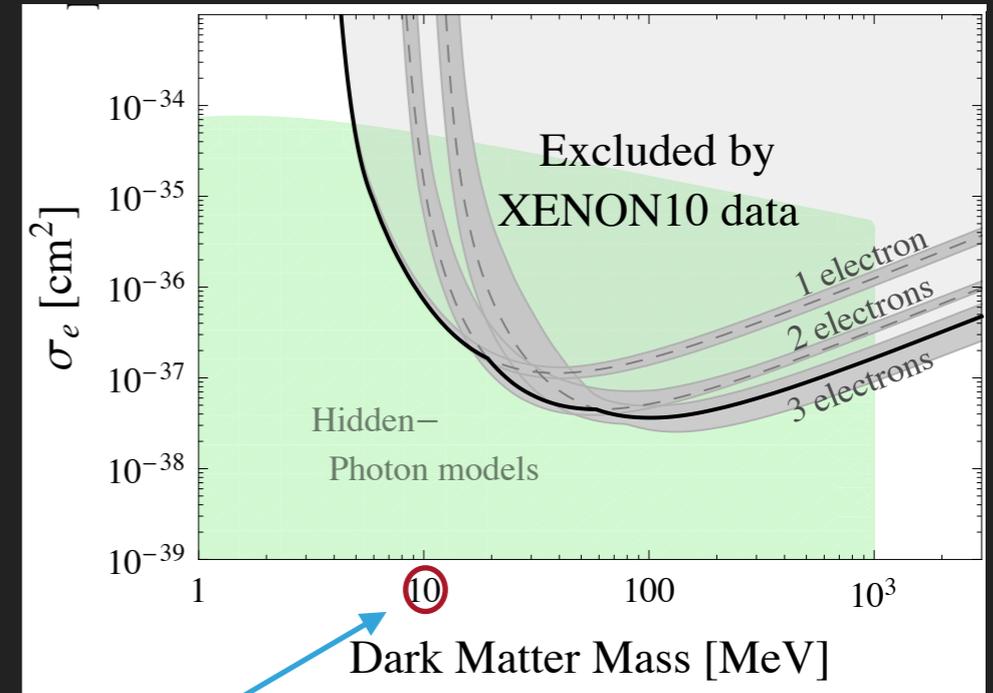
Tightly bound; ionize for signal

Gap = DM Kinetic Energy

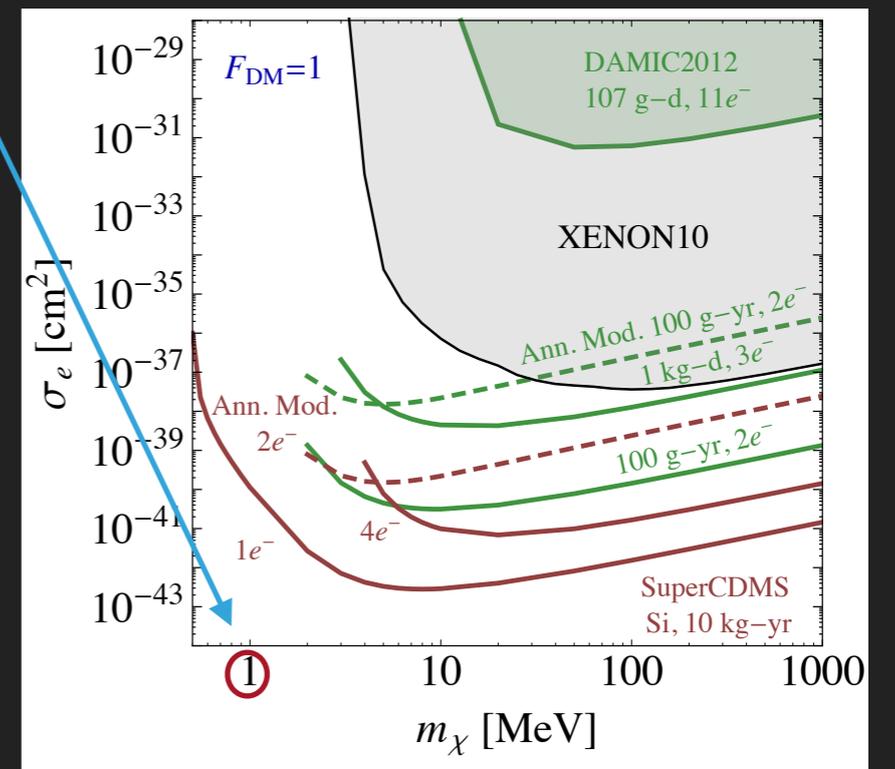
▶ In semi-conductors, like Ge, Si

Excite electron to conduction band

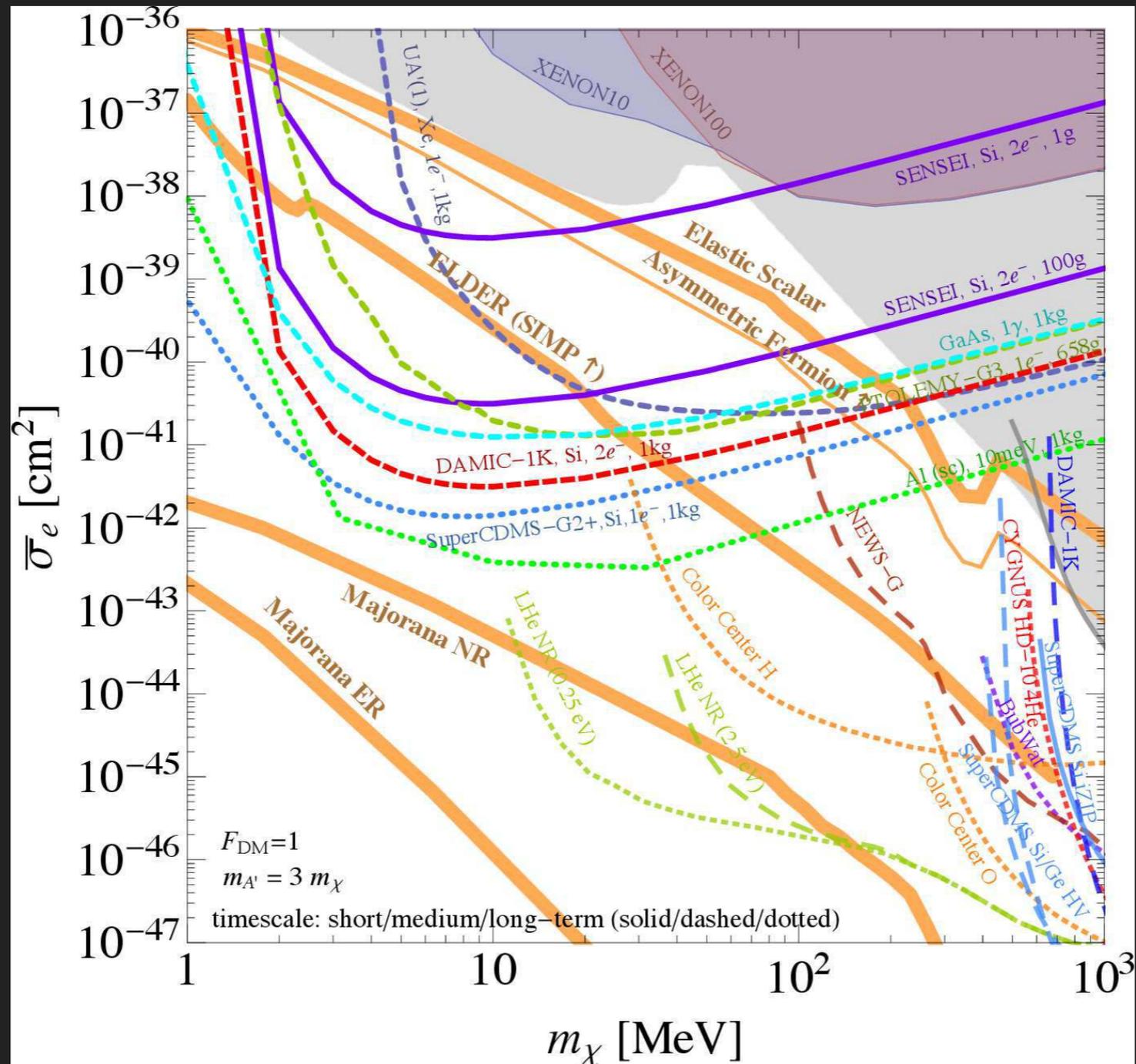
P. Sorensen et al 1206.2644



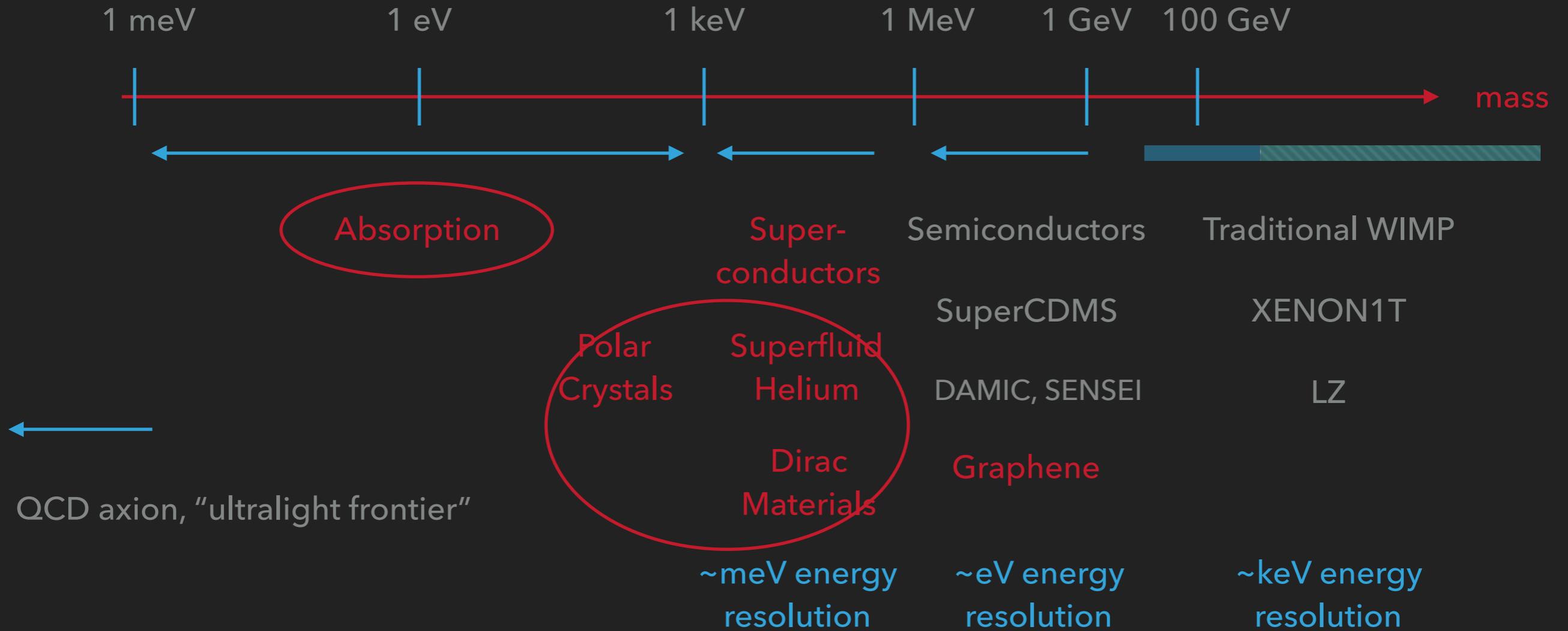
Essig et al 1509.01598



DEVELOPMENT OF NEW TECHNOLOGIES

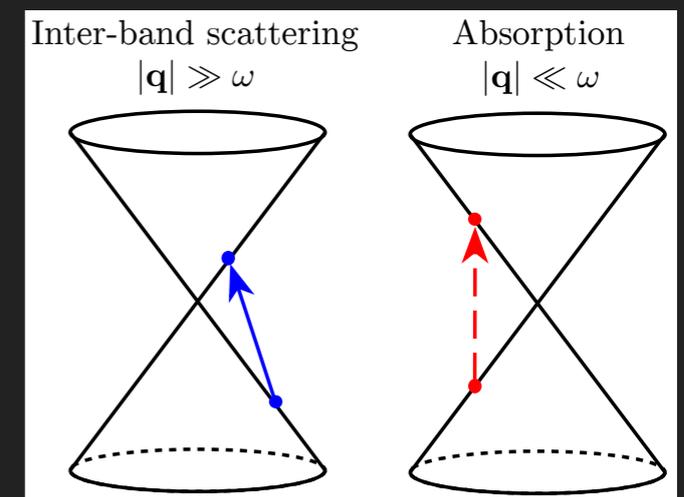
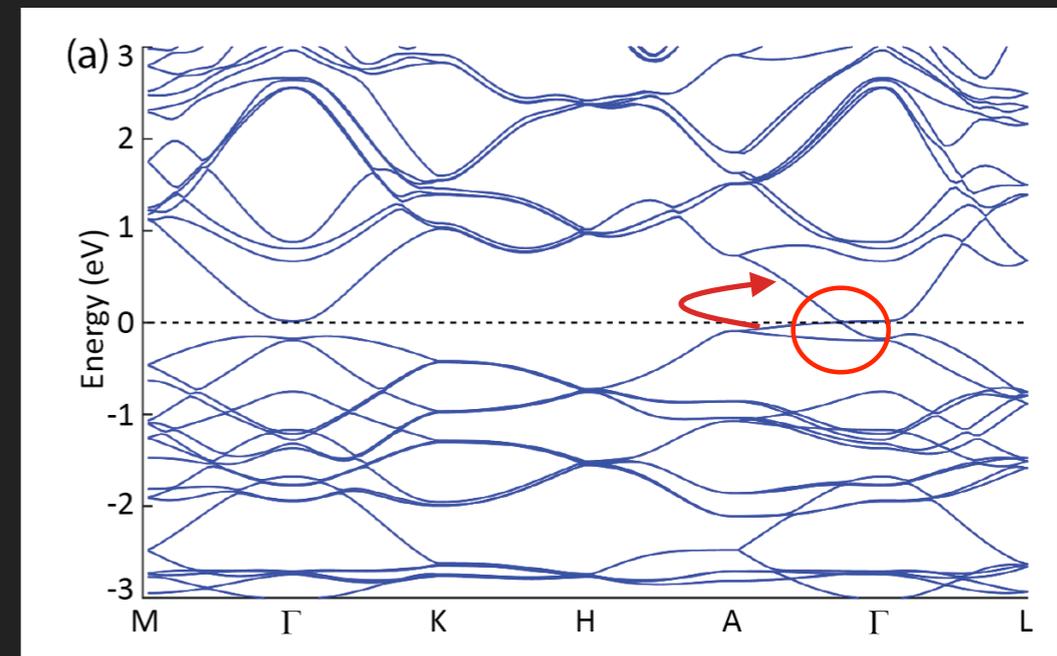


DARK MATTER LANDSCAPE



WEYL OR DIRAC SEMI-METALS ~ 3D GRAPHENE

- ▶ Materials can be “quantum engineered”
- ▶ Correlation between electrons gives rise to a unique band structure
- ▶ Small gap, small density of states near Fermi surface
- ▶ Hamiltonian looks like free QED near Dirac point
- ▶ In QED, gauge invariance protects photon from obtaining a mass

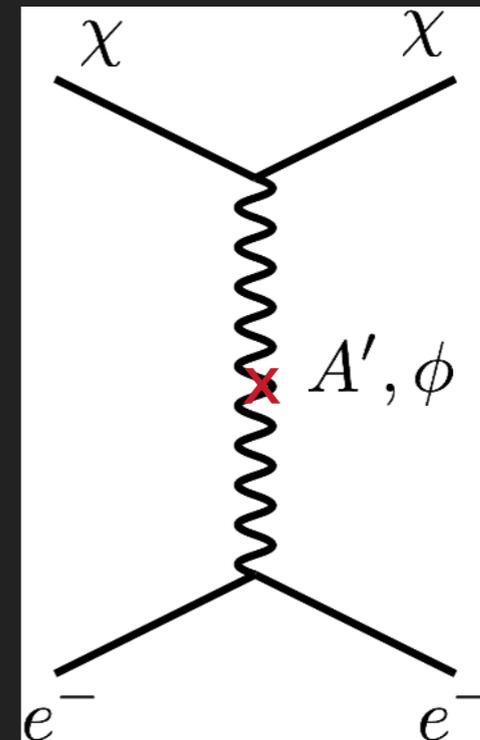


WEYL OR DIRAC SEMI-METALS ~ 3D GRAPHENE

- ▶ Optical response behaves exactly as electric charge renormalization in QED

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

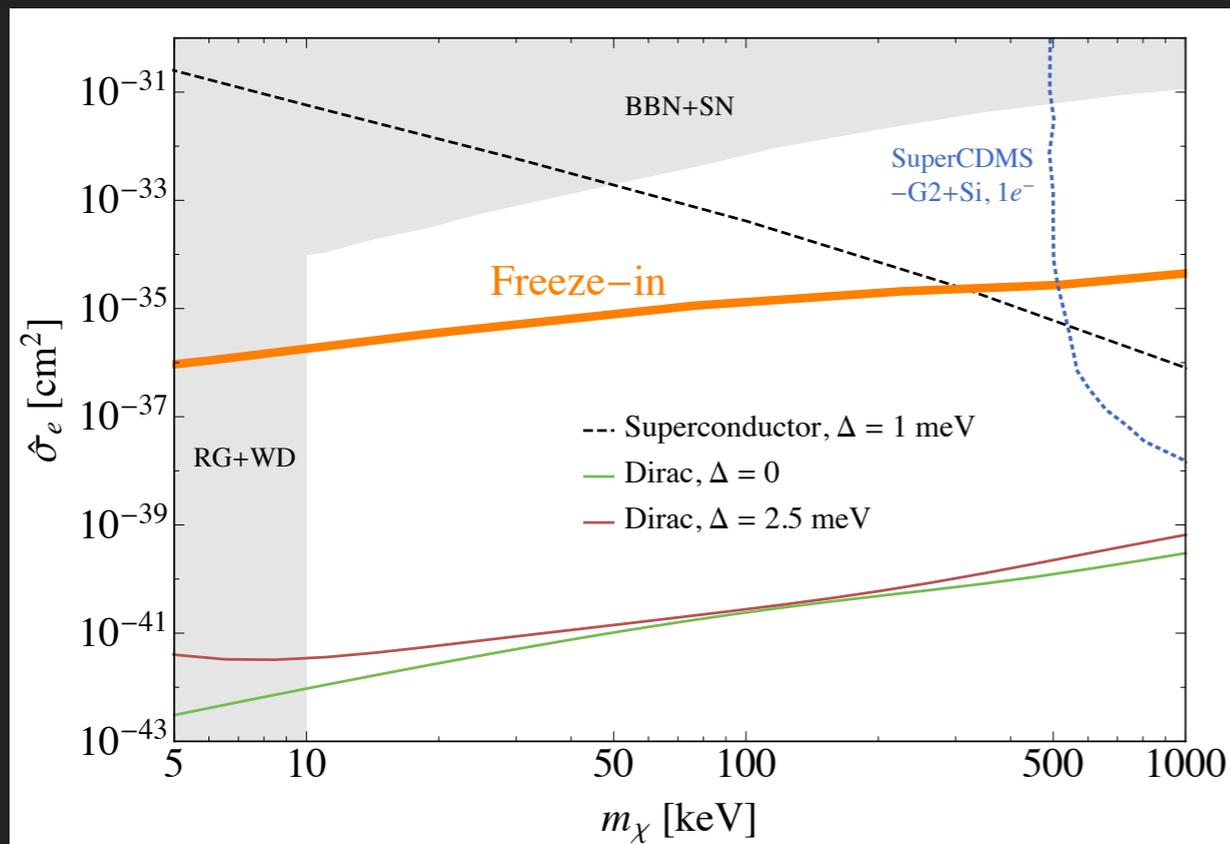
- ▶ Weak Optical Response
- ▶ Strong Sensitivity to Dark Photon



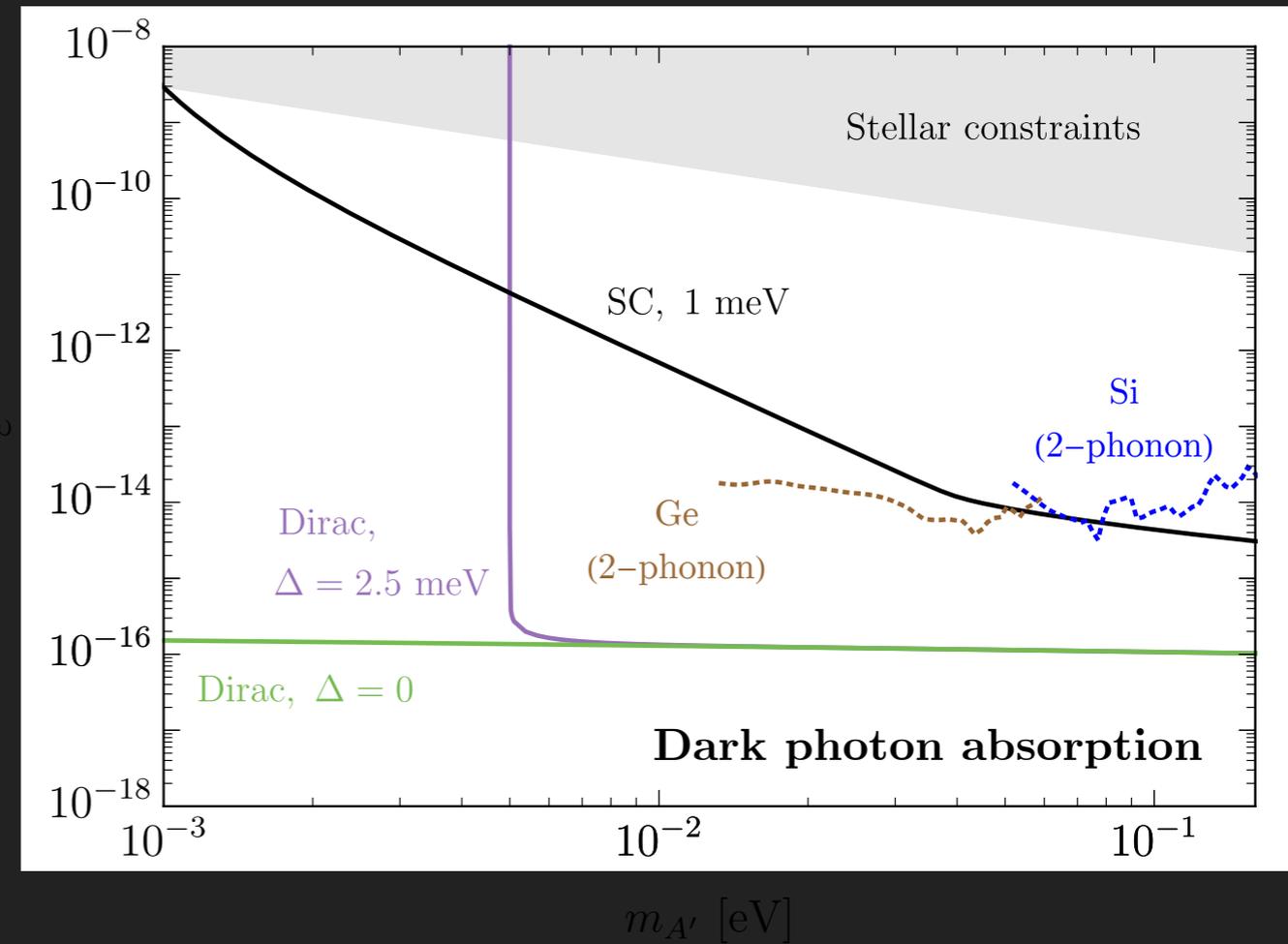
Yonit Hochberg,^{1,2,*} Yonatan Kahn,^{3,†} Mariangela Lisanti,^{3,‡}
 Kathryn M. Zurek,^{4,5,§} Adolfo Grushin,^{6,7,¶} Roni Ilan,^{8,**}
 Zhenfei Liu,⁹ Sinead Griffin,⁹ Sophie Weber,⁹ and Jeffrey Neaton⁹

WEYL OR DIRAC SEMI-METALS ~ 3D GRAPHENE

Scattering



Absorption



DARK MATTER COUPLING TO NUCLEONS — HELIUM

- ▶ Superfluids are naturally insensitive to noise. A good light DM detector? In the context of ordinary nuclear recoils, yes, see e.g. 1605.00694
- ▶ To detect lighter DM, couple to phonon modes.
- ▶ Viable? At first glance – no

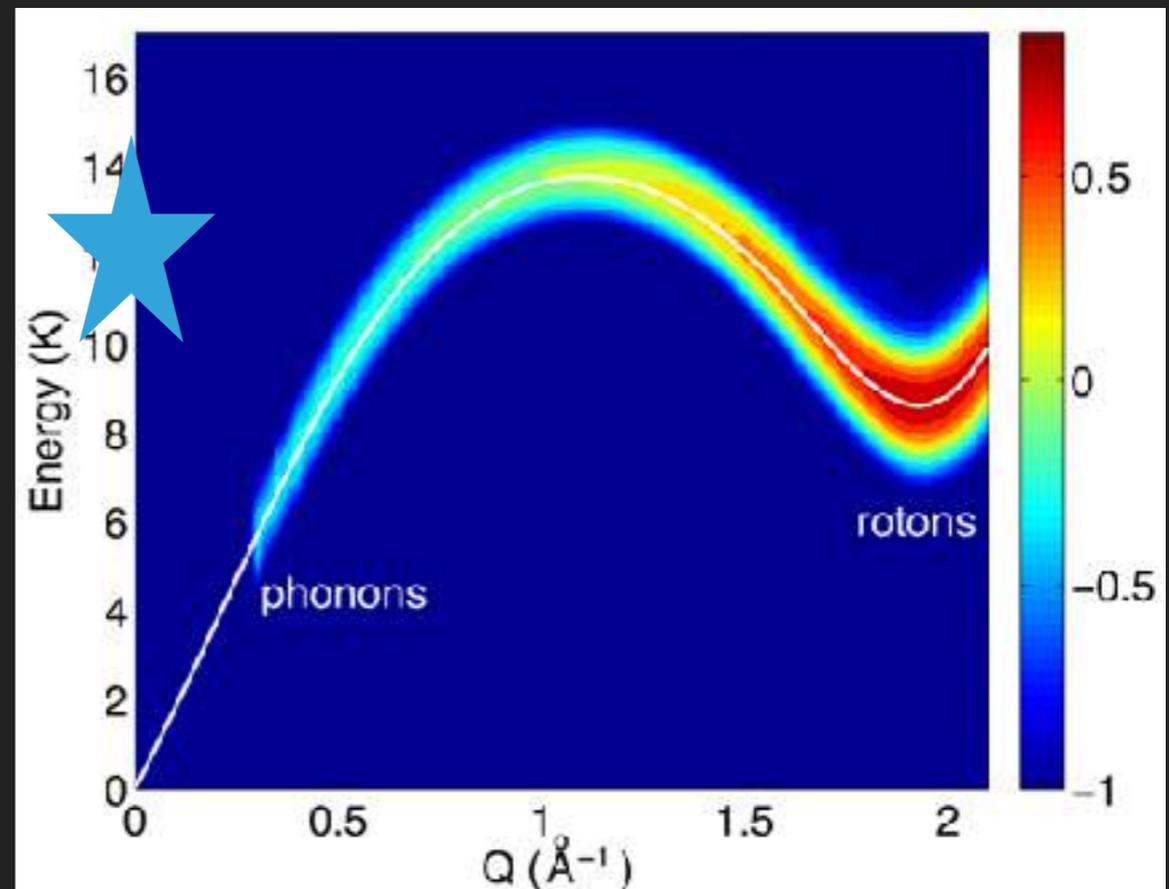
$$E_D \sim v_X q$$

vs

$$c_s \ll v_X$$

$$E_D \sim c_s q$$

- ▶ Next glance -- yes!



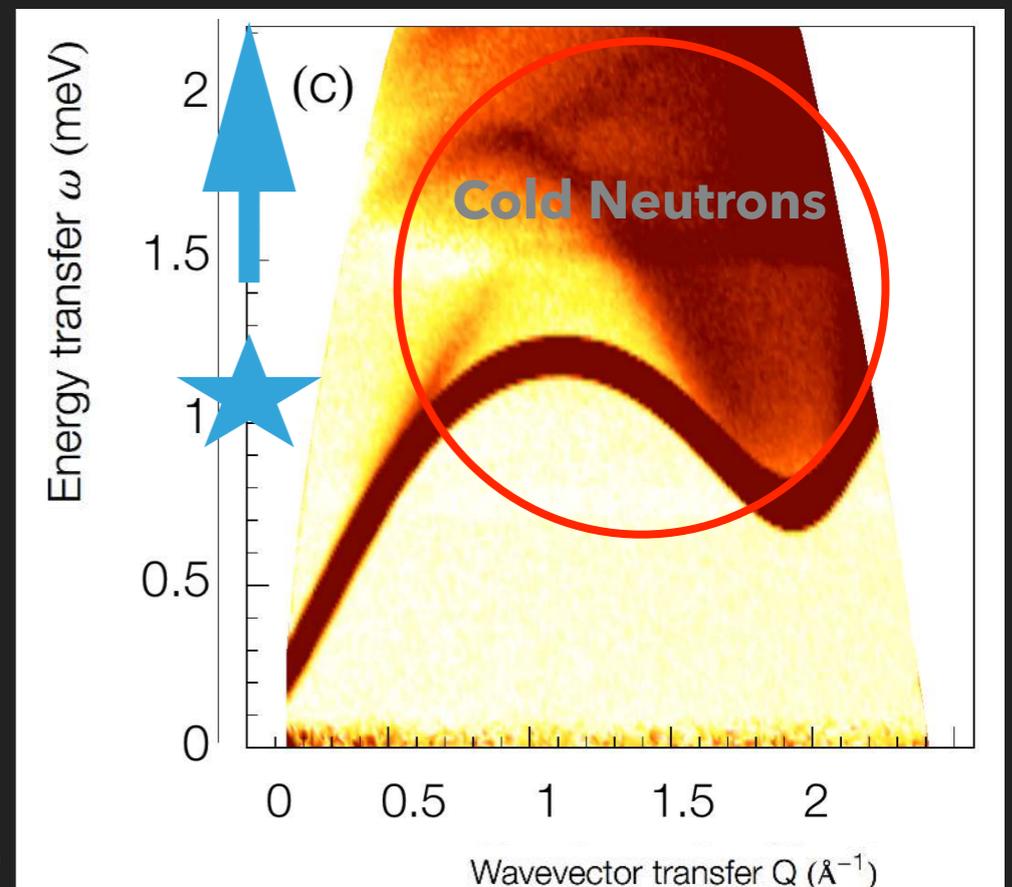
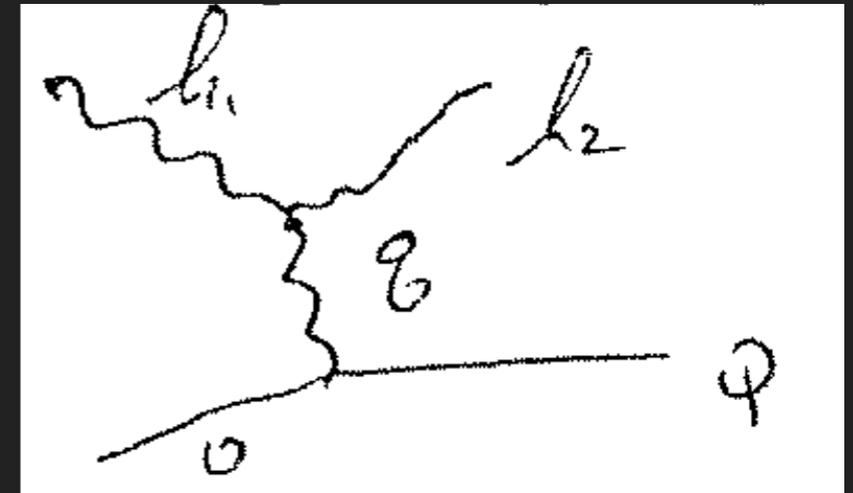
MULTI-EXCITATIONS

- ▶ Calculated and observed for cold neutrons

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

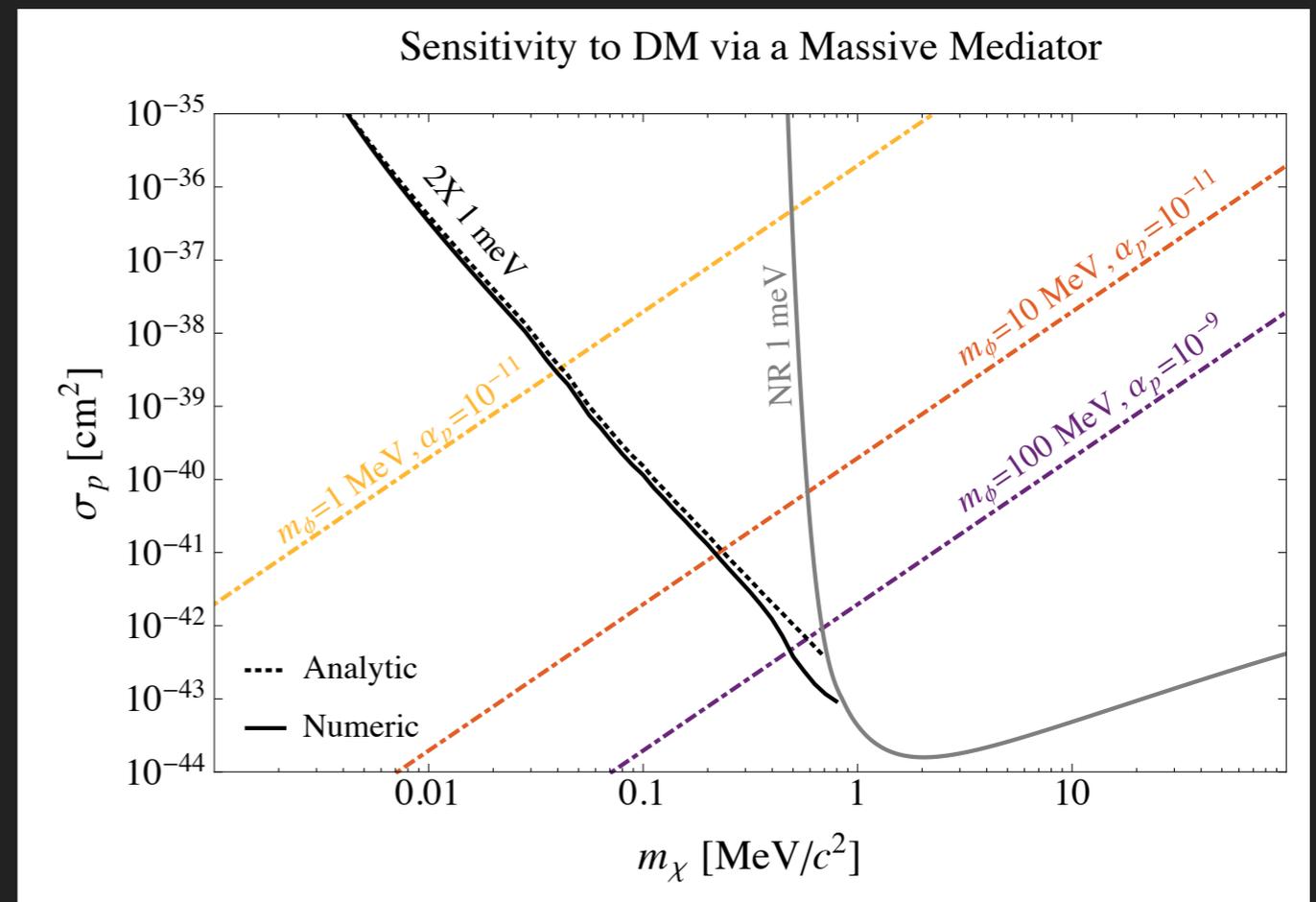
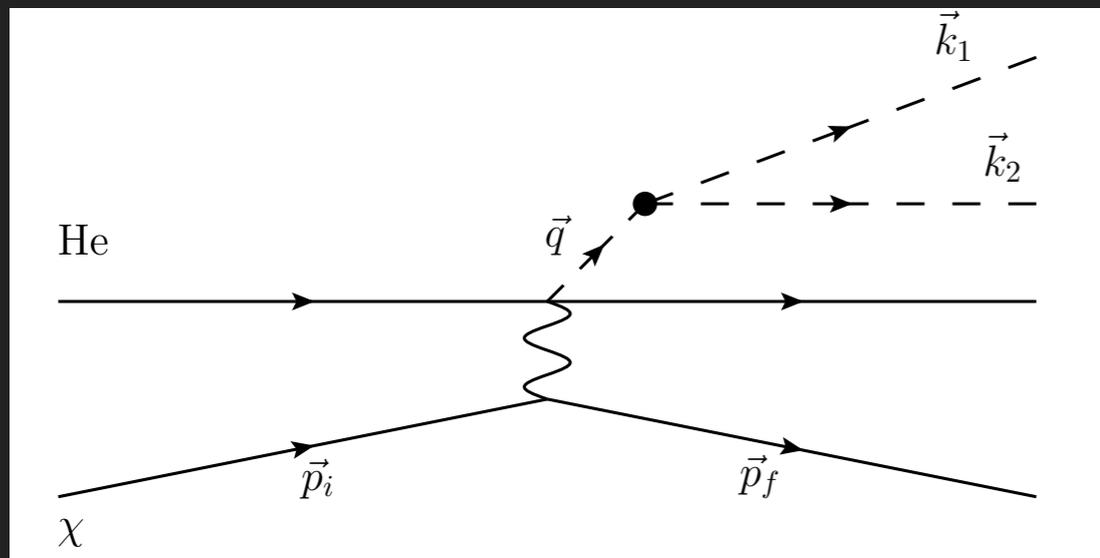
- ▶ However, this is in a very different kinematic regime
- ▶ No existing calculations in regime of interest

Internal note, R. Golub, 1977



MULTI-EXCITATIONS

- ▶ emit back-to-back excitations to bleed off energy while conserving momentum

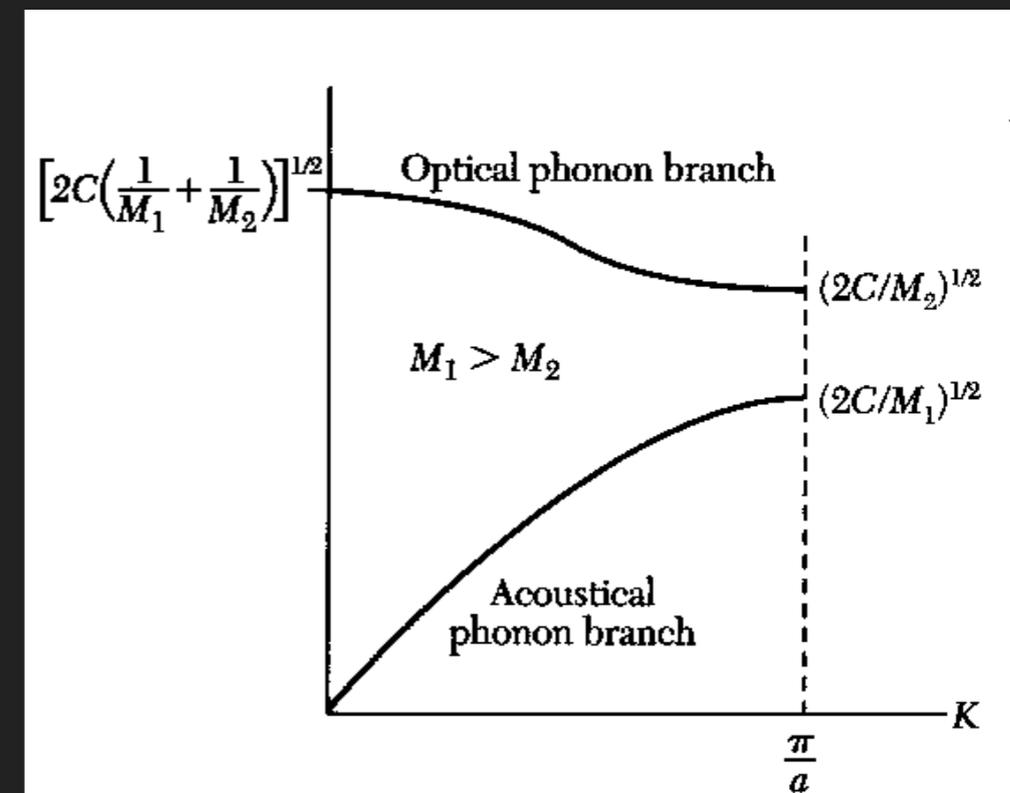
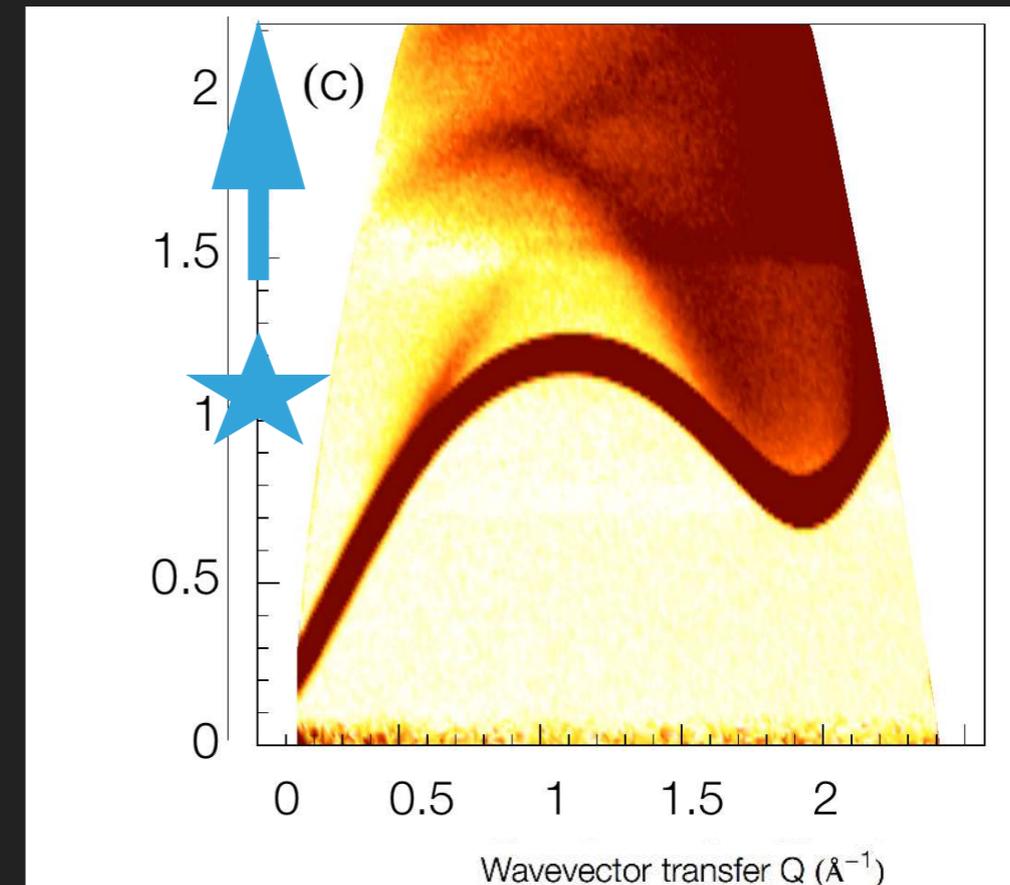


Great potential!

IN CRYSTALS

- ▶ Highly Polarizable Material
- ▶ Like Sapphire (Al_2O_3) and GaAs
- ▶ Gapped Phonons = Better Kinematic Matching

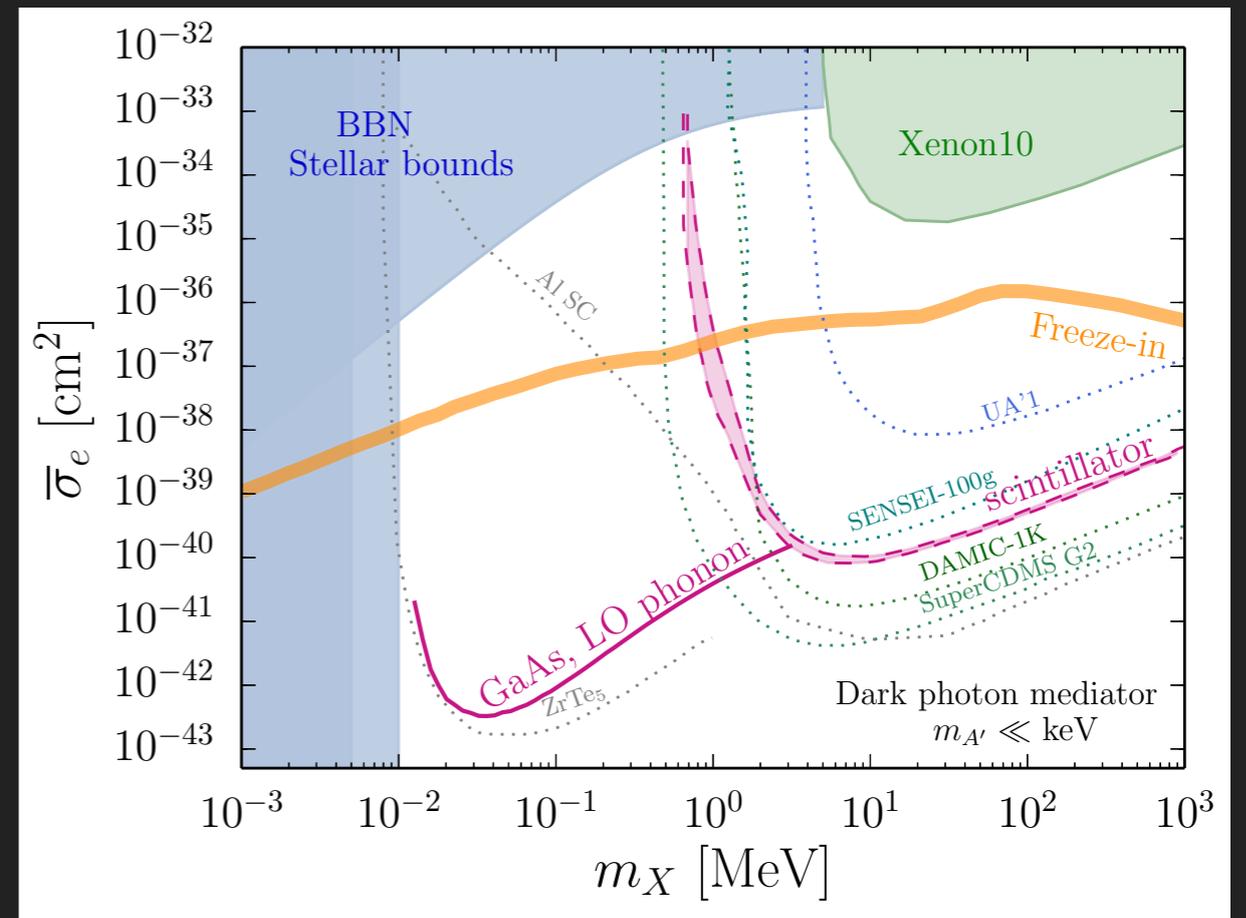
Helium



Polar Crystal

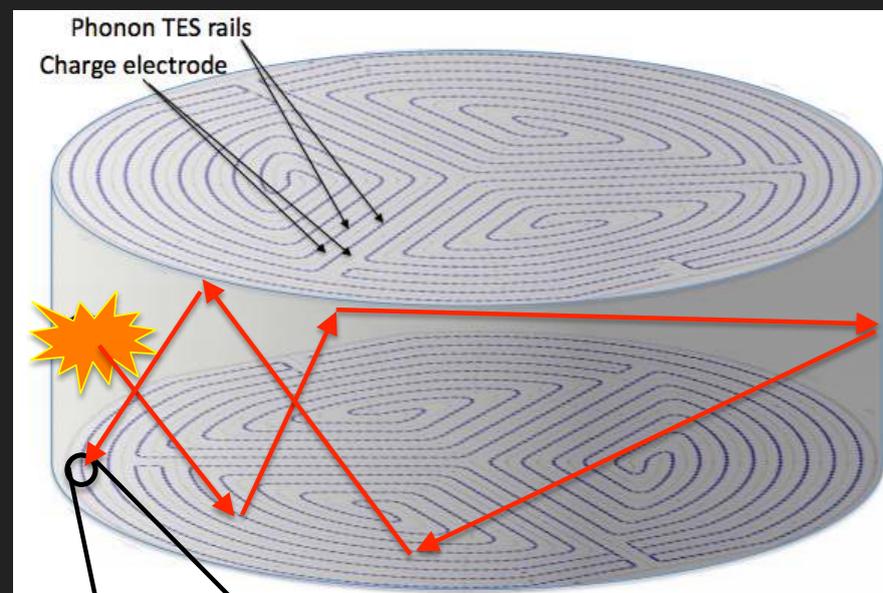
IN CRYSTALS

- ▶ Highly Polarizable Material
- ▶ Like Sapphire (Al_2O_3) and GaAs
- ▶ Gapped Phonons = Better Kinematic Matching



ROAD FORWARD

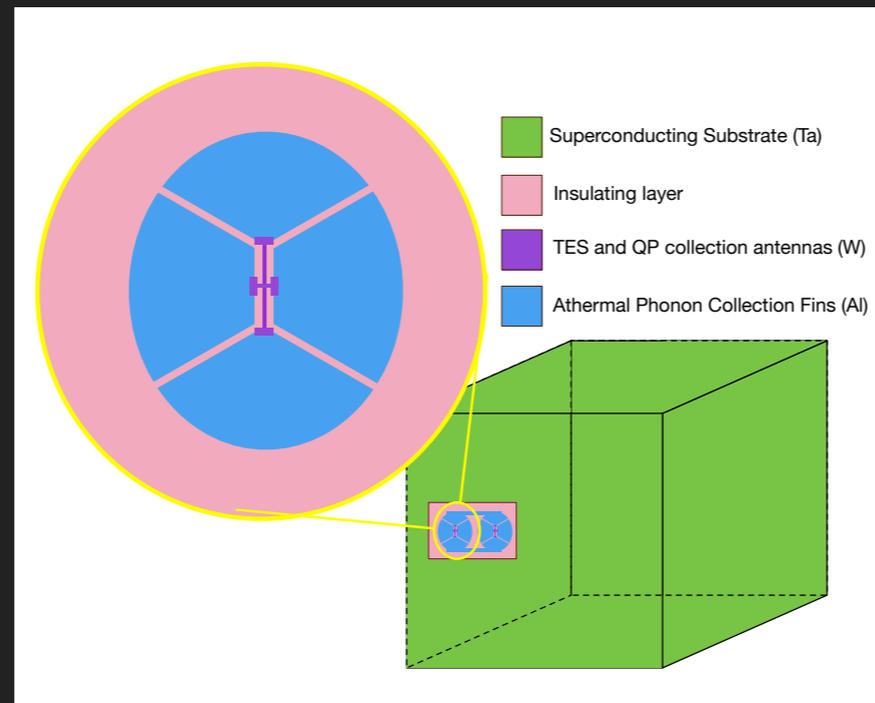
- ▶ Large part depends on better energy resolution sensors (TESs or KIDs); TESs or KIDs are portable to multiple targets



Semiconductors SuperCDMS

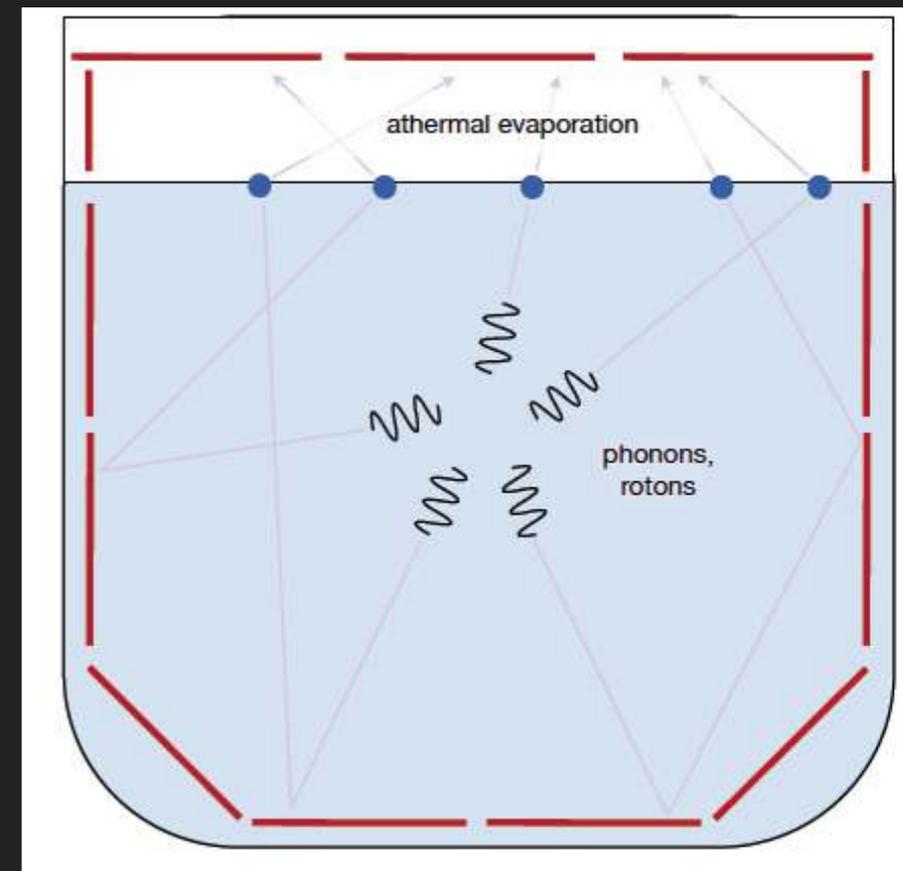
Current energy resolution: ~300 eV

Goal: ~1 eV



Superconductors

Goal: ~1 meV



Superfluid Helium

Goal: ~1 meV

ROAD FORWARD

- ▶ New ideas for dark matter detection!
- ▶ 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

SUMMARY

ROAD FORWARD

