The Direct Detection of Dark Matter

overview of the field, fall 2016

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DBD16

Disclaimer: summarizing this field in 45m is impossible

Attempting only a tour of (some) strategies, not players.

Outline:

- Big-picture thoughts
  - Recoil kinematics and threshold
- m_{DM}>1GeV
  - Noble liquids
  - ‘Other’ cross section terms
- m_{DM}<1GeV
  - Nuclear recoils
  - Electron recoils

What do we know?

- Dark matter forms structures at galaxy (and larger) scales
  -> cold enough to not escape a potential well

- In our position in our potential well, ρ_{DM} ~ 0.3 GeV/cm^3

- We have tested *some* types of DM interactions for *some* m_{DM}

What do we know?

- Dark matter forms structures at galaxy (and larger) scales
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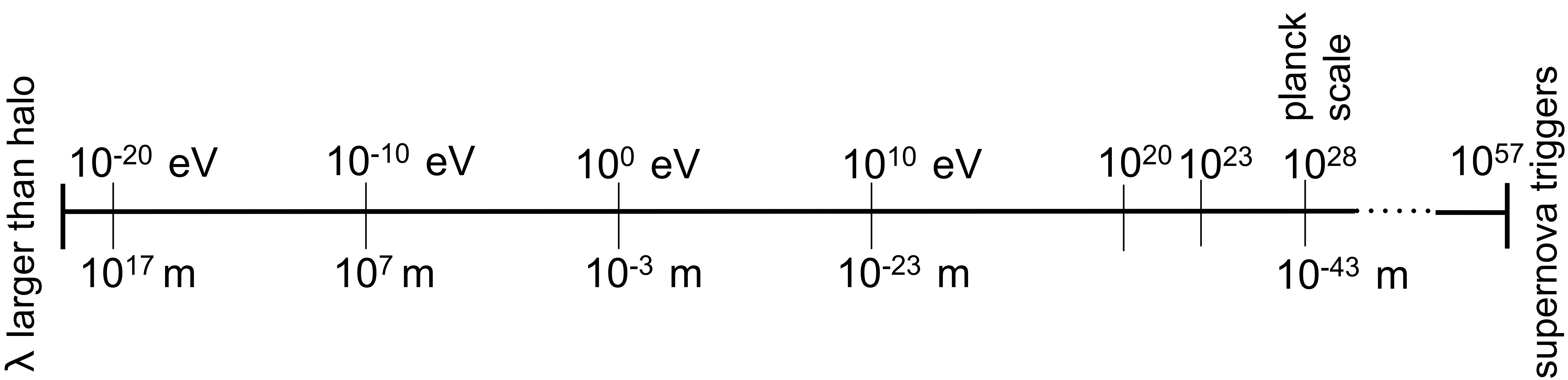
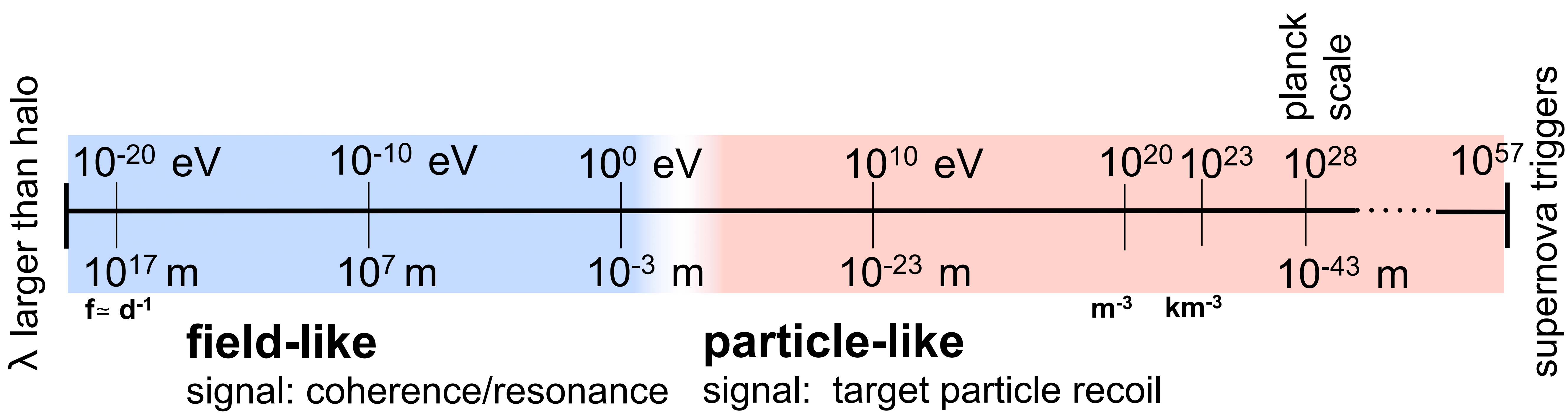
- We have tested *some* types of DM interactions for *some* m_{DM}

We *can* quote an allowed mass range... but it's a depressing exercise.



We have to start the search somewhere...



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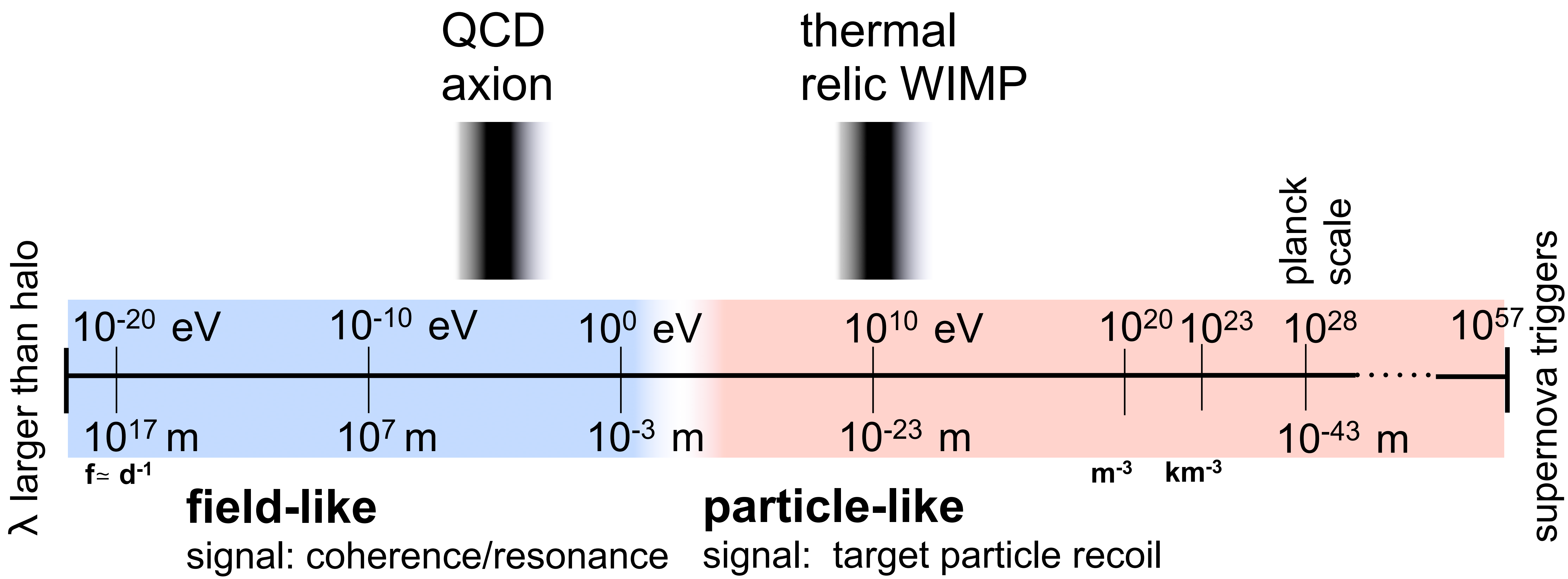
Well-established programs probing two distinct and well-motivated hypotheses.

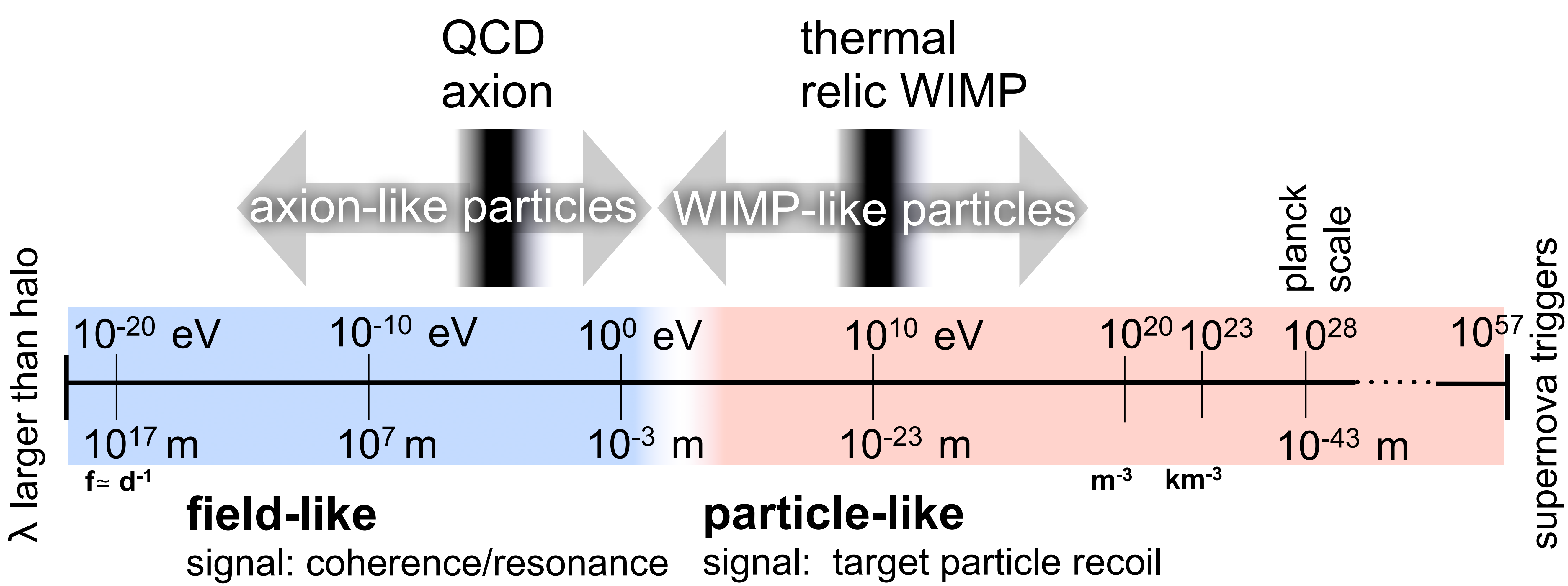


We have to start the search somewhere...

Well-established programs probing two distinct and well-motivated hypotheses.

Possibly only the starting points for a broader search
(a search perhaps guided by less specific theory motivations...)

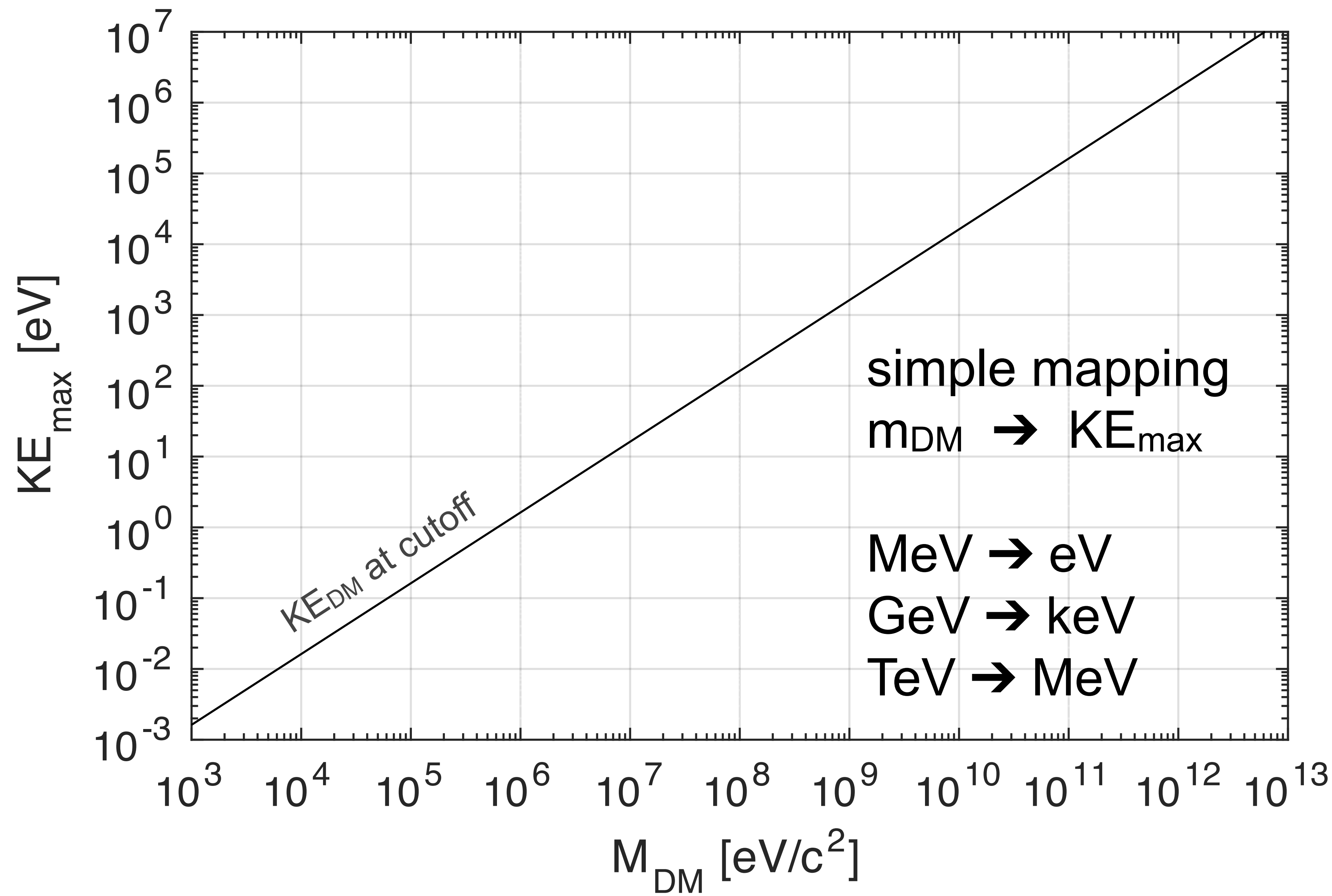
I will focus on the particle-like case. (thanks Gray for your excellent axion talk)



particle-like DM step one: What is the maximum KE_{DM}?

DM particle velocities cut off by (local) escape velocity: $v_{max} \simeq 540$ km/s

$KE_{max} \simeq 1/2\ m_{DM}\ v_{max}^2$



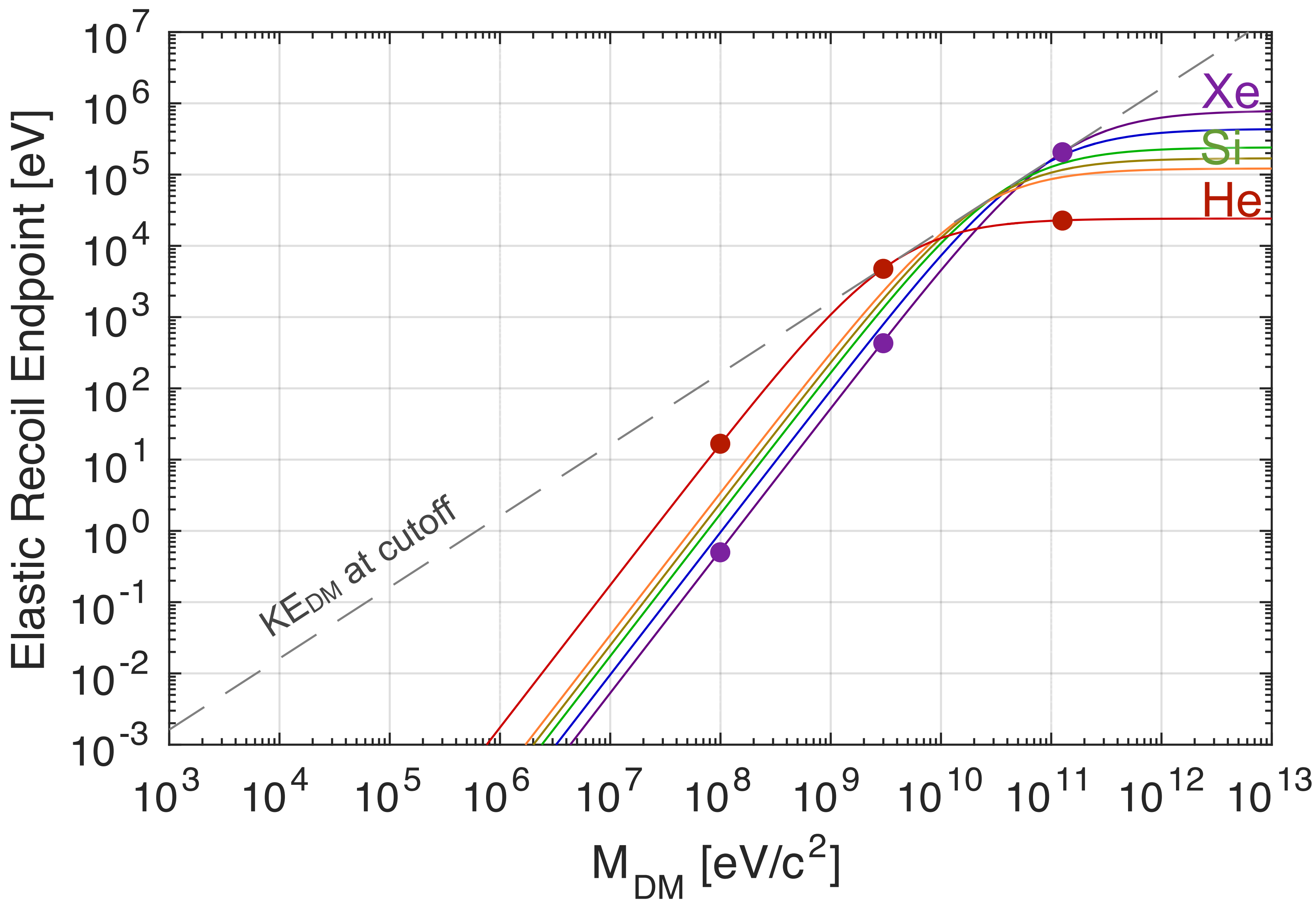
Nuclear recoils : (nearly-)classical elastic kinematics

when $m_{DM} \simeq m_{target}$, efficient coupling of KE_{DM} into target

in the GeV mass range, recoil endpoint energies are in the keV range

Good NR threshold: ~100 eV (➔ mass of hundreds of MeV)

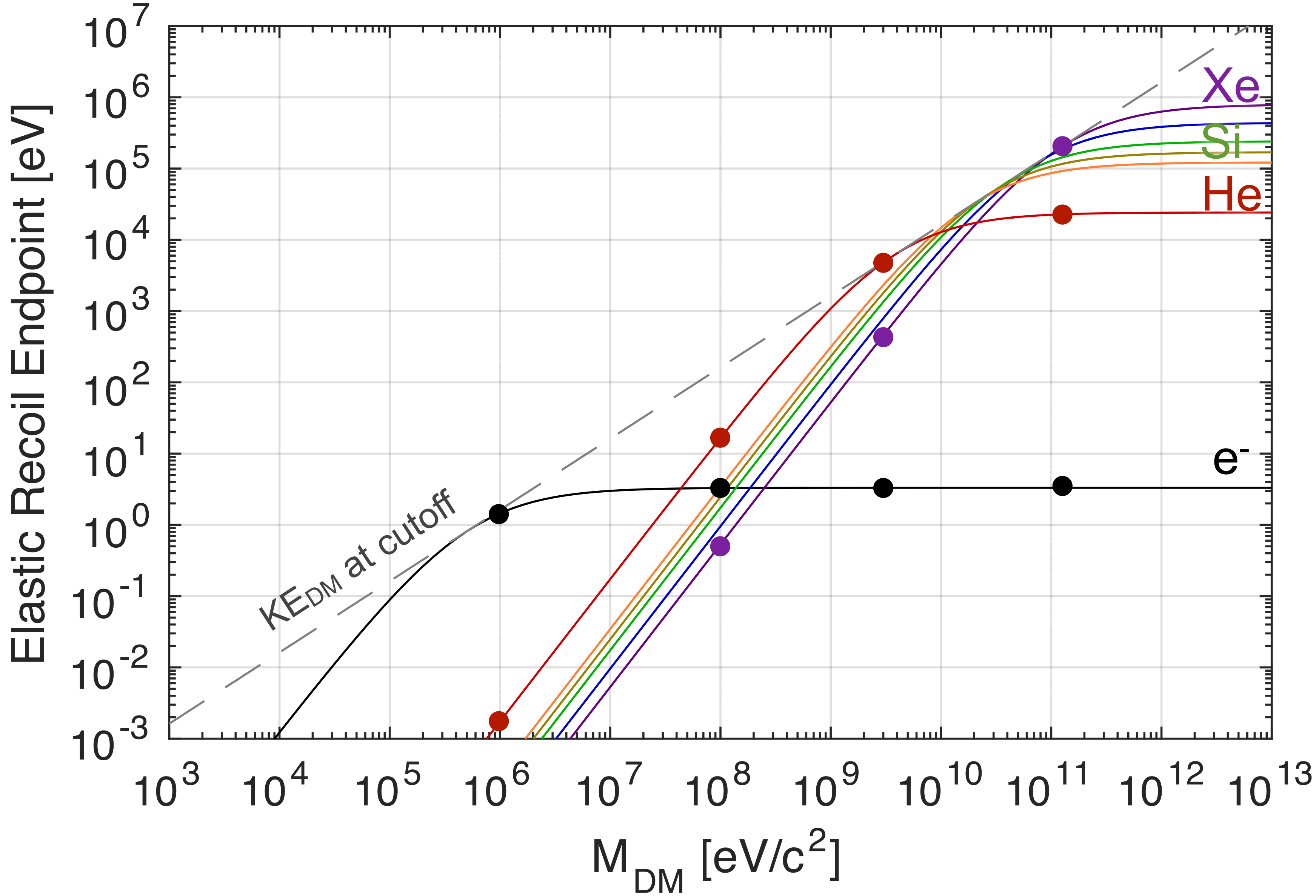
	Xe (120GeV)	He (4GeV)
m_{DM} = 120 GeV	~200 keV	~22 keV
m_{DM} = 4 GeV	~0.8 keV	~6 keV
m_{DM} = 0.1 GeV	~0.5 eV	~17 eV



Electron recoils: $m_{target} \simeq 0.5$ keV

comes with the obvious advantages, as if a super-light nucleus

10^3 energy boost at m_{DM} = MeV

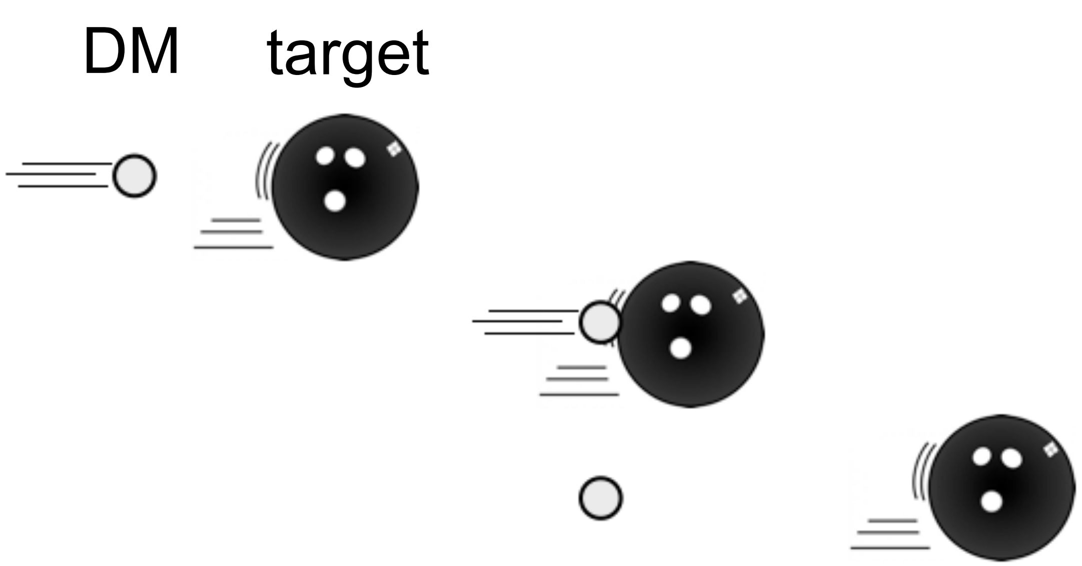


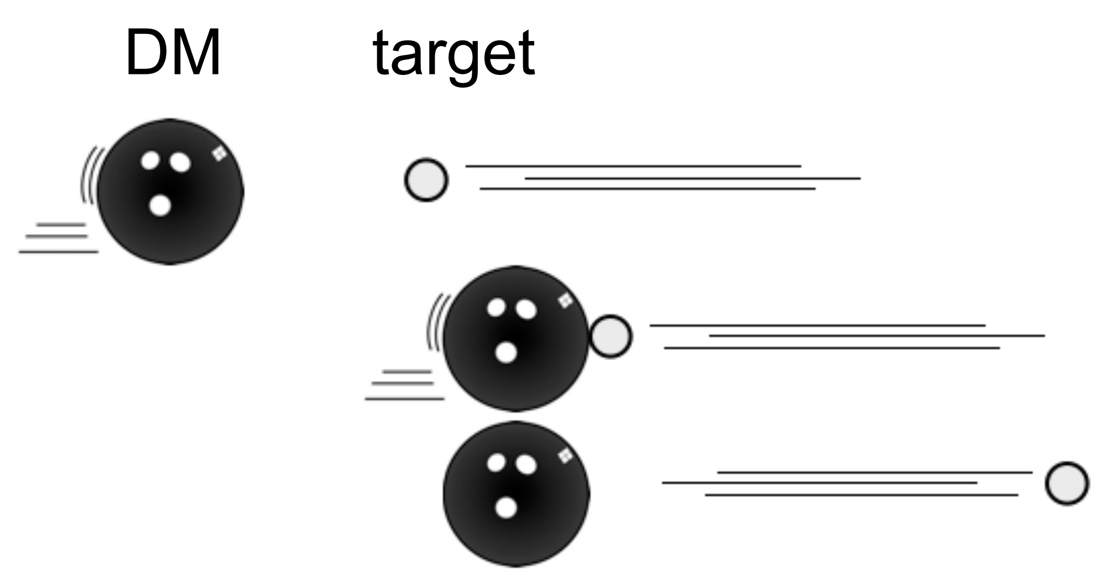
Electron recoils: $m_{target} \simeq$ 0.5 keV

and target itself has significant momentum

‘efficient coupling’ think: ‘goal is to leave the DM at rest’

strategy: DM hits moving target





Electron recoils: $m_{target} \simeq 0.5$ keV

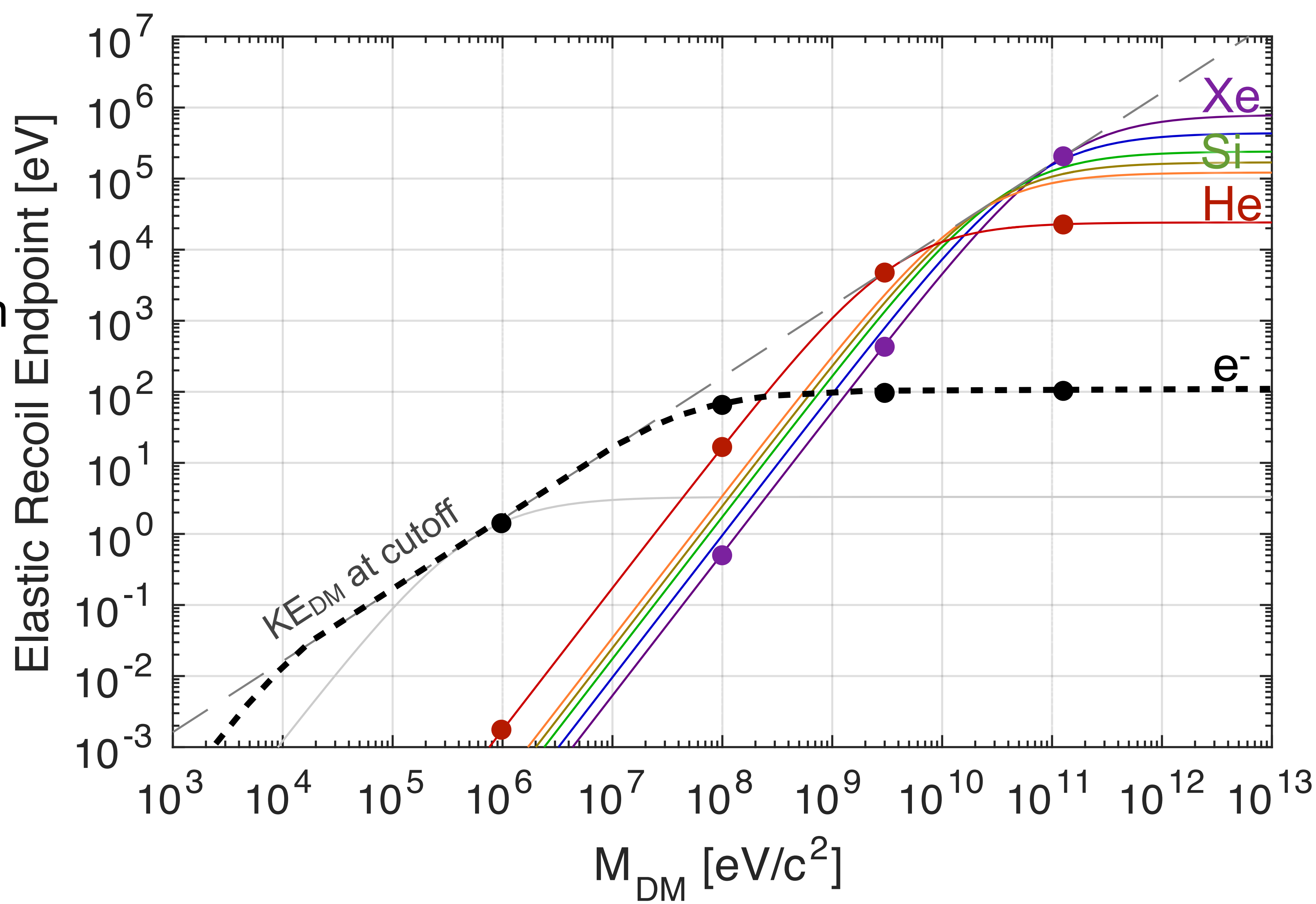
and target itself has significant momentum

punchline:

bound e^- efficiently couple to a wide range of m_{DM}

price: phasespace suppression

opens up MeV-scale DM to eV-scale detector thresholds

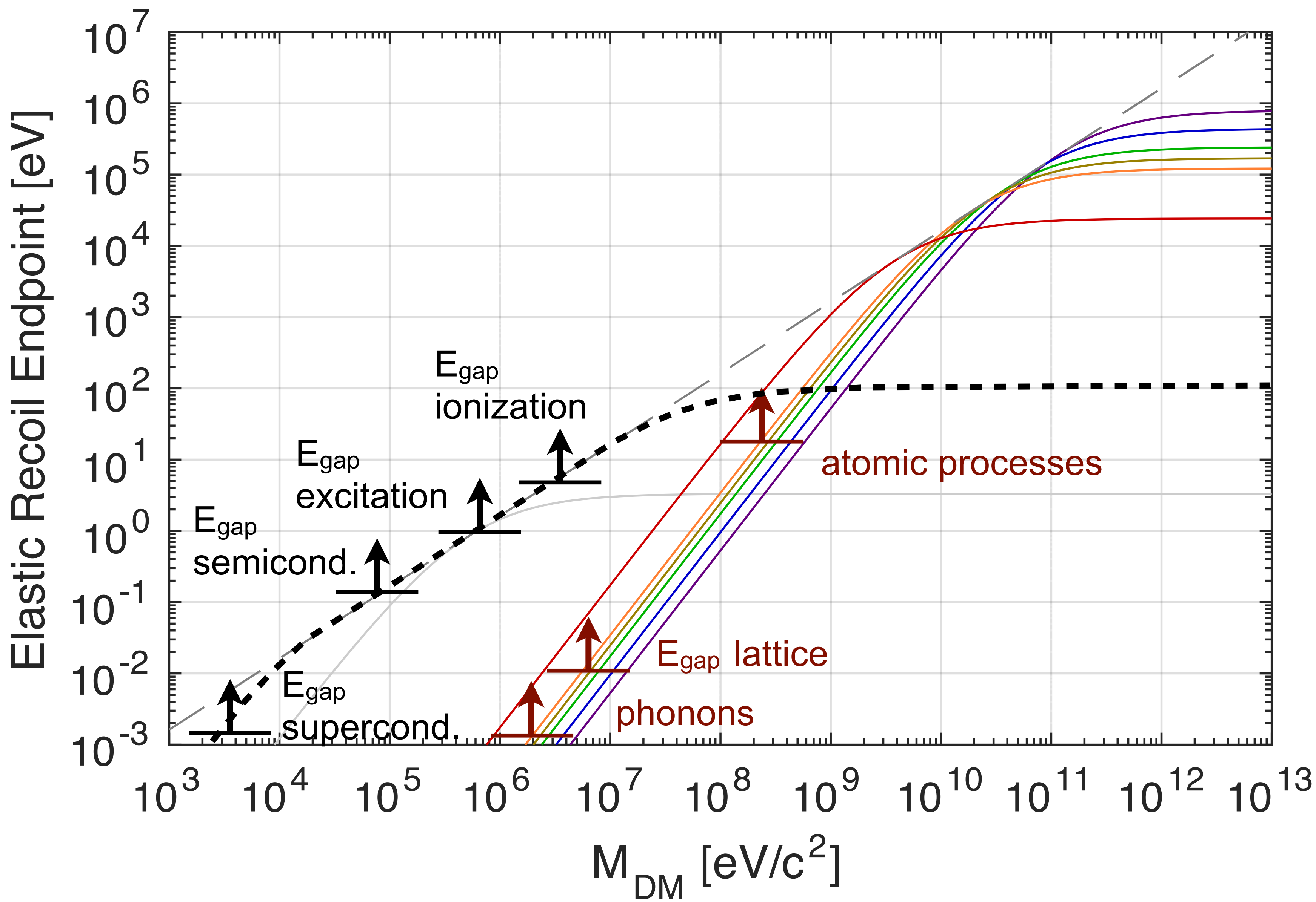


[End of kinetic lesson.]

Next question: Does the recoil excite something observable?

recoiling target particle must produce excitations to be observable

different excitations, different excitation production thresholds.

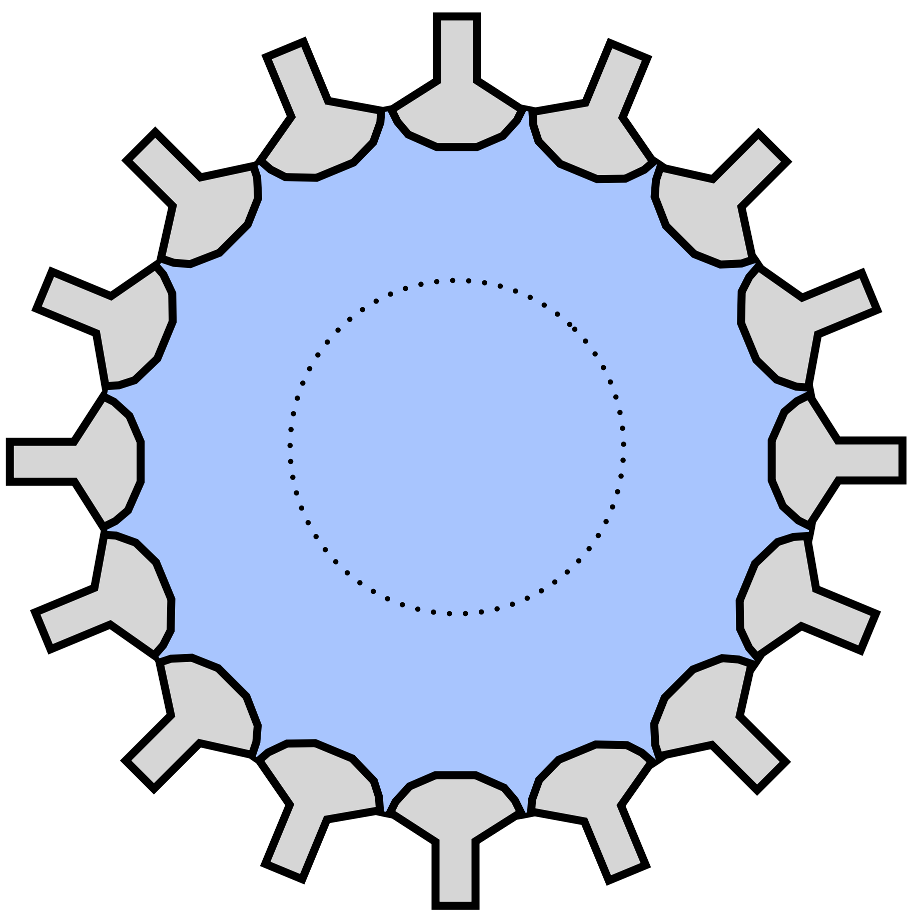


Nuclear Recoils in Liquid Ar and Xe

Two ER/NR discrimination options:

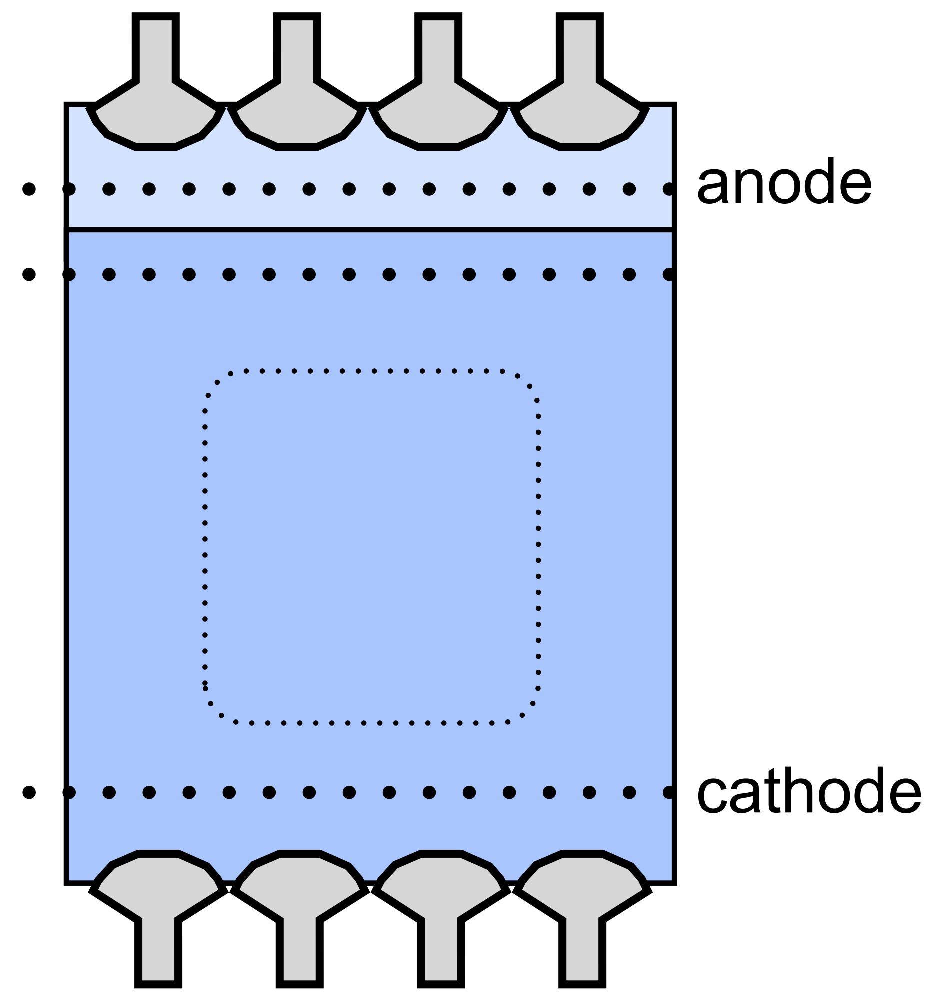
singlet vs triplet atomic excitation
(aka 'scintillation pulse shape')
Ar: 7:1500 ns Xe: 3:24 ns (+few ns propagation time)

threshold: enough photons to measure shape
design goal: maximize light collection



atomic excitation vs ionization
(aka 'charge yield' or 'S2/S1')

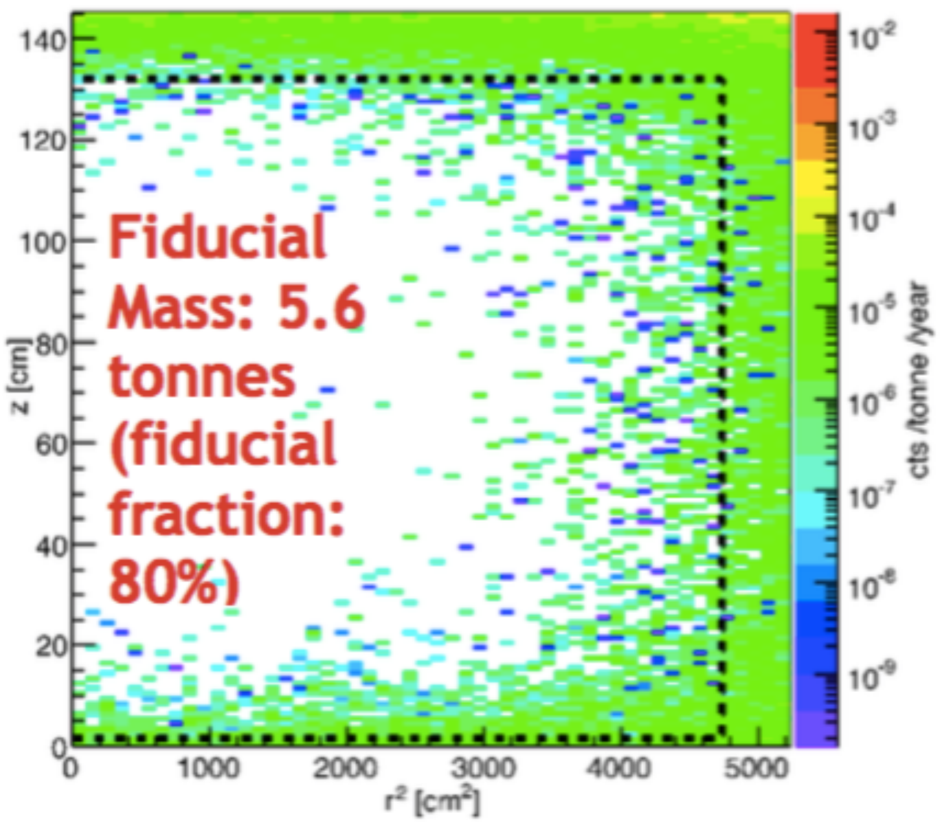
threshold: few photons, few electrons
design goal: *both* channels high-eff.



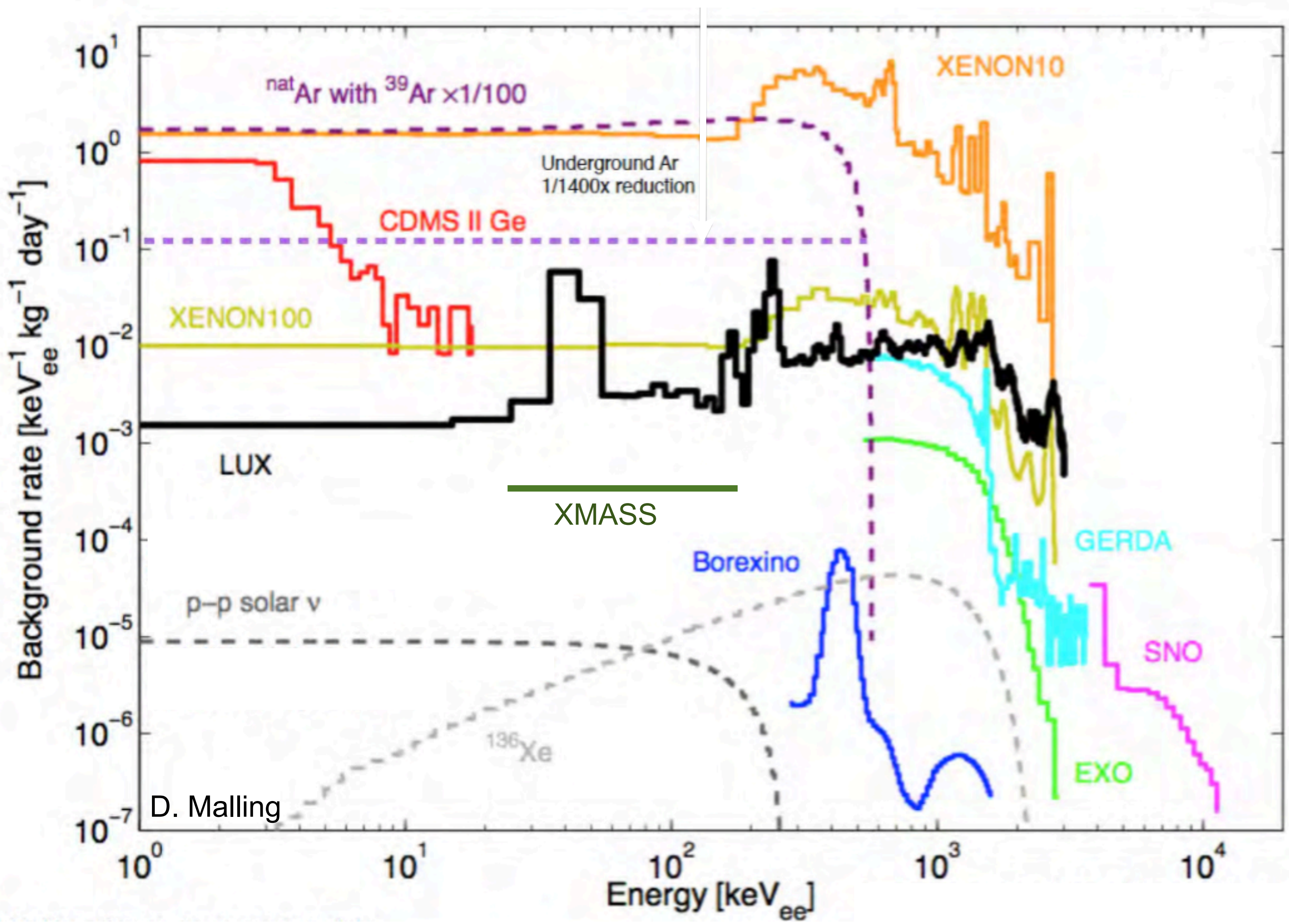
Nuclear Recoils in Liquid Ar and Xe

extreme reduction of backgrounds through self-shielding and fiducialization

LZ expectation
(after LS and LXe skin vetoes)



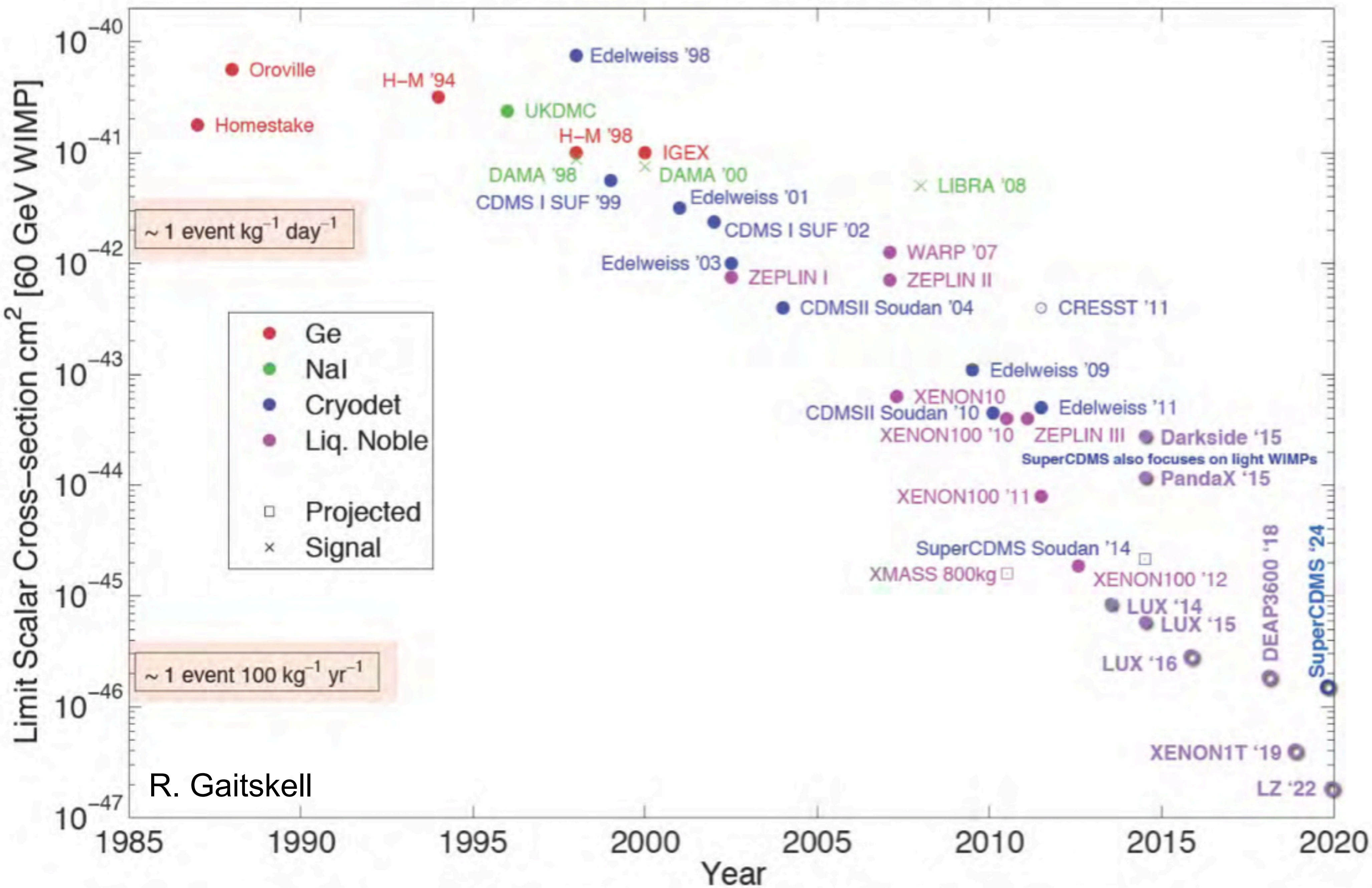
achieved ER backgrounds in the field



Nuclear Recoils in Liquid Xe and Ar

dominant technology for $m_{DM} \gtrsim$ few GeV

fast and steady progress (here plotting $m_{DM} = 60$ GeV)



Nuclear Recoils in Liquid Xe and Ar

	single-phase	**two-phase**
Xe	XMASS 1, 1.5T	ZEPLIN I, II, III XENON 10,100,1T,NT LUX, LZ Panda-X I, II
Ar	DEAP-3600 CLEAN	ArDM DarkSide-50, -20k
Ne	CLEAN	

note: of course, two-phase can still measure singlet:triplet ratio.

(main discriminator in DarkSide, charge signal mainly for fiducialization.)

Nuclear Recoils in Liquid Xe and Ar

	single-phase	two-phase
Xe	**XMASS 1, 1.5T**	ZEPLIN I, II, III **XENON** 10,100,**1T**,NT **LUX, LZ** Panda-X I, II
Ar	**DEAP-3600** CLEAN	ArDM DarkSide-50, -20k
Ne	CLEAN	

good representation here today!

next four talks:

XENON1T (Alessandro Manfredini)
LUX & LZ (Harry Nelson)
XMASS (K. Sato)
DEAP-3600 (Kevin Graham)

Nuclear Recoils in Liquid Xe and Ar

challenges of this and future generations:

1) **photon detection efficiency**
   fundamental importance in both single- and dual-phase

2) **internal backgrounds**
   Rn (material outgassing)
   Ar39, Ar37, Kr85, ...

3) **neutrino backgrounds are just around the corner...**

A word about neutrino backgrounds

neutrino coherent nuclear scattering

unshieldable

identical nuclear recoil

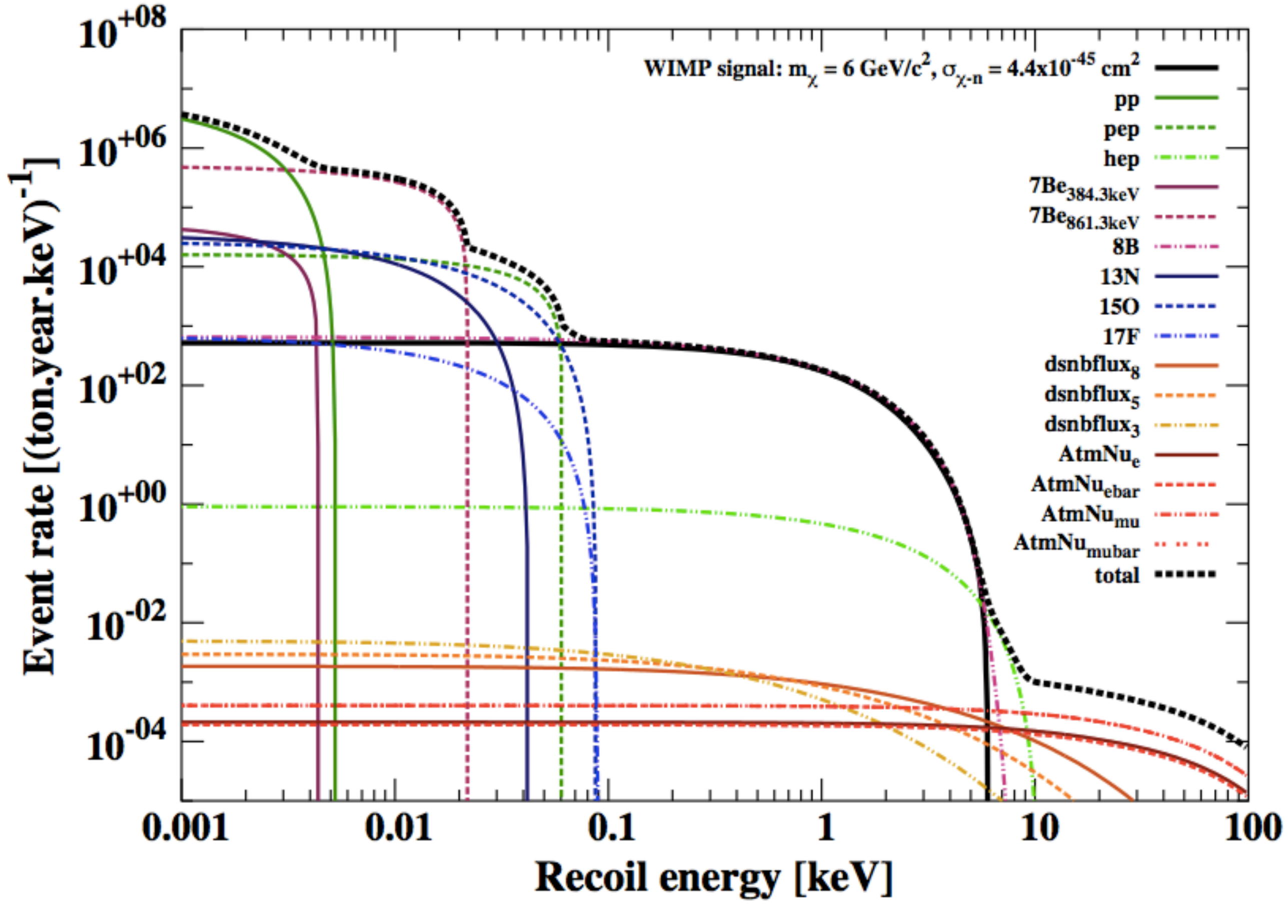
spectra nearly identical
(to specific m_{DM} spectra)

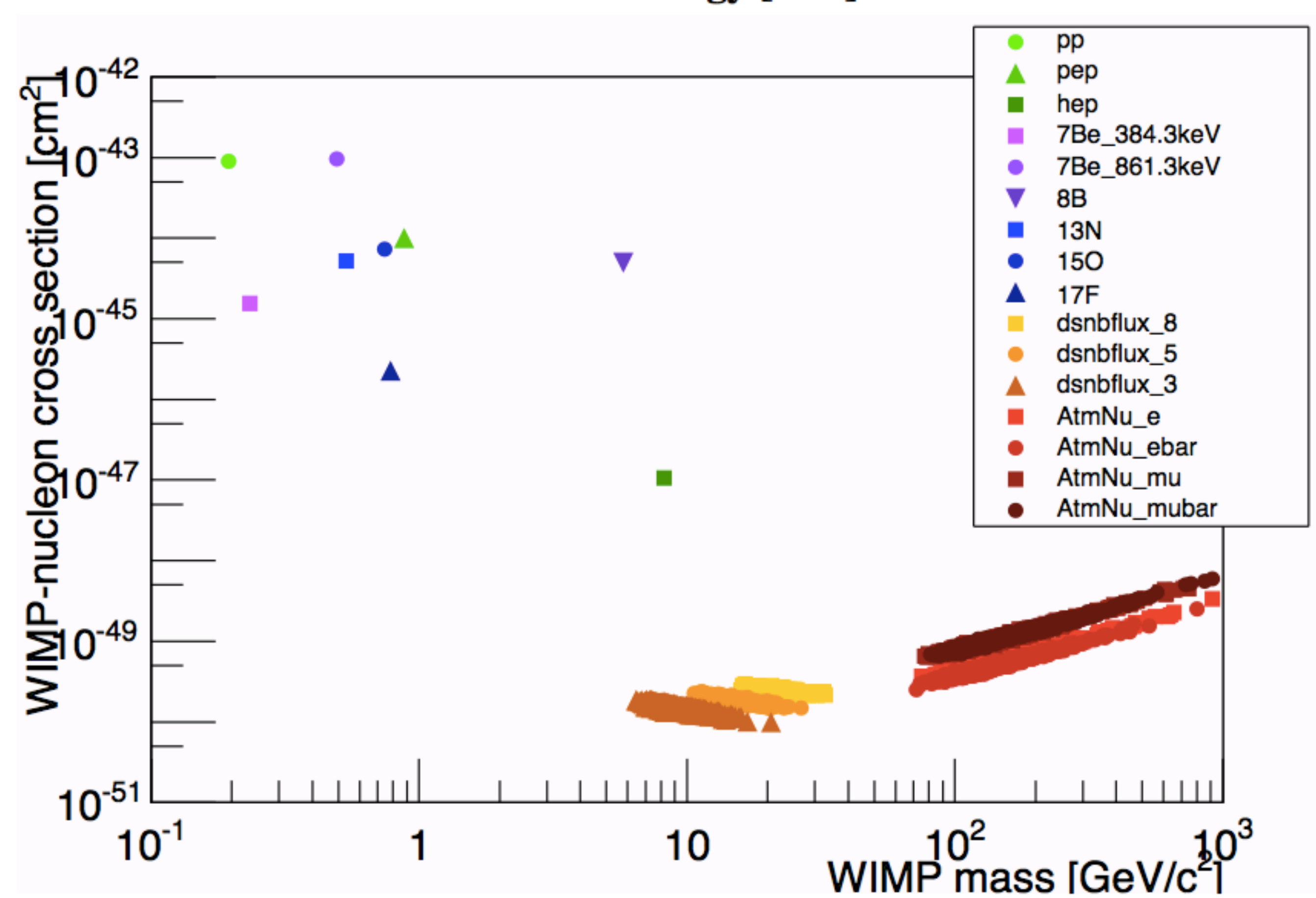
statistical discrimination?

1) slight DM-ν spectral differences
(multiple target masses help)
2) modulation (annual is ~2%)
3) directionality (NEWS: ~100kg and ~20keV)

punchline

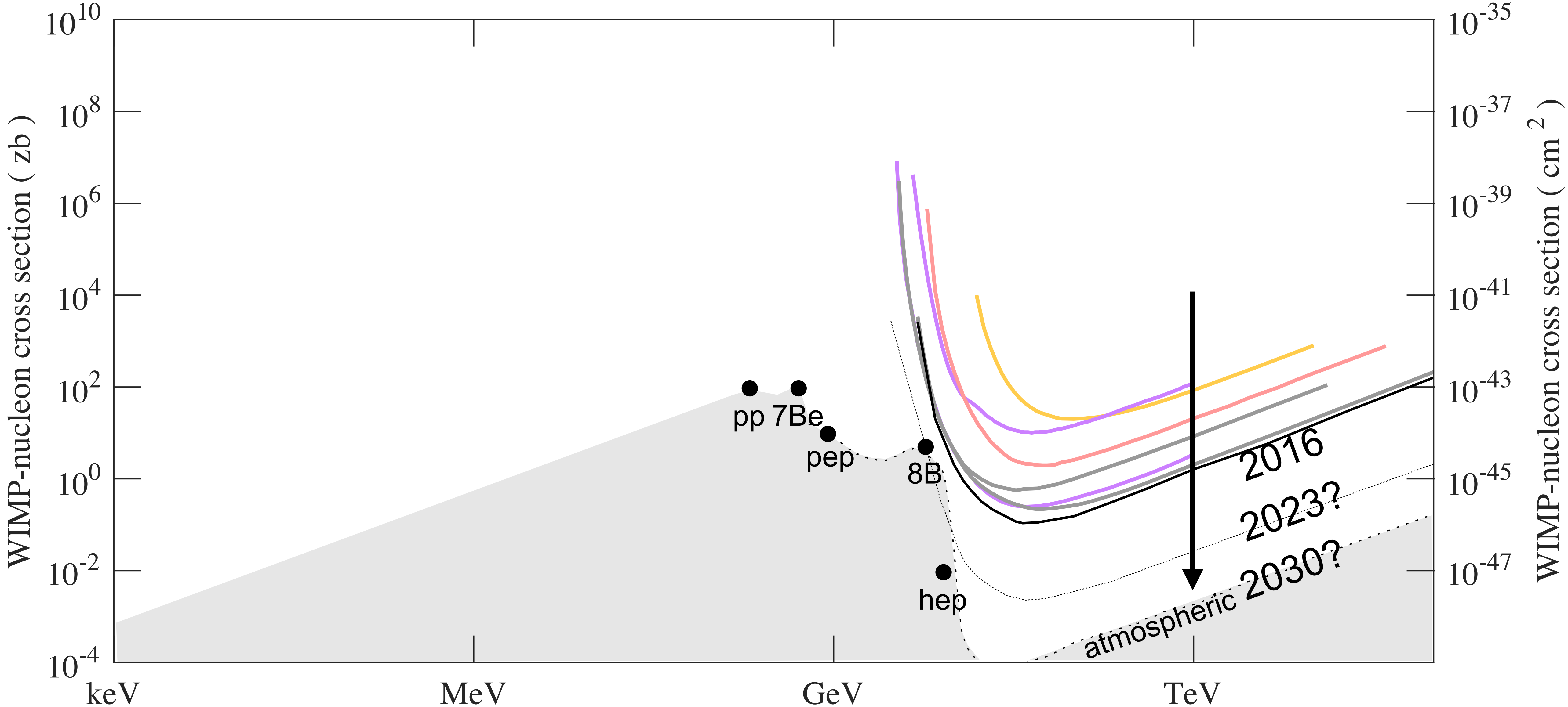
the golden era of ~t scaling is ending
entering background-dominated era of $\sim t^{1/2}$
(things are going to get very hard...)





Nuclear Recoils in Liquid Xe and Ar

Looks very much like we know what we're doing...



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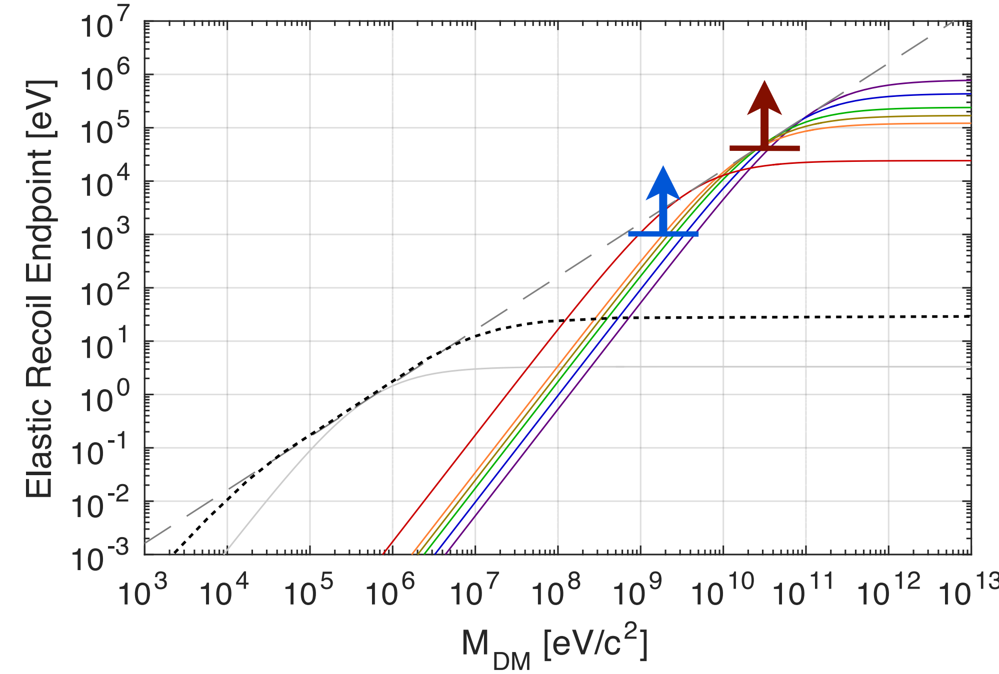
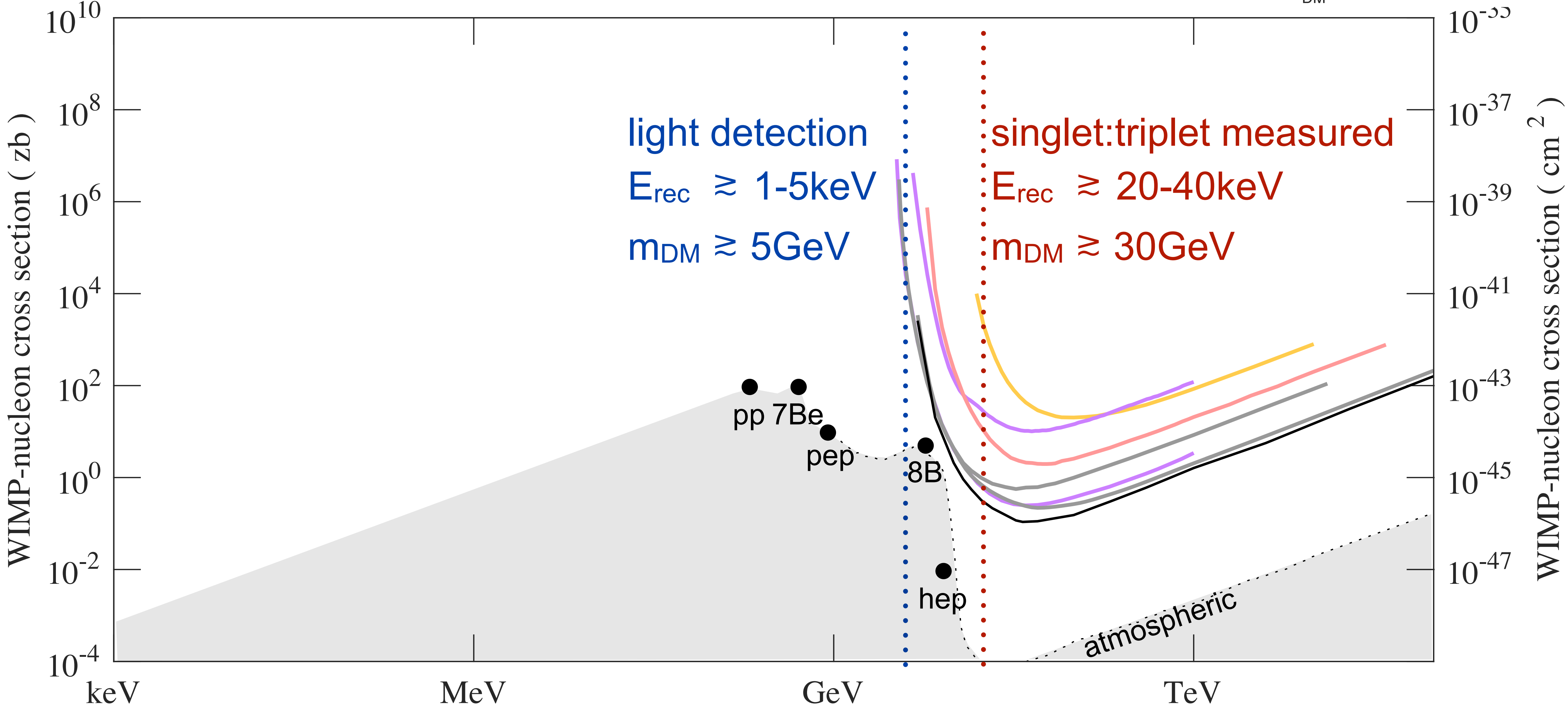


Probing the ‘standard WIMP’ mass very well.

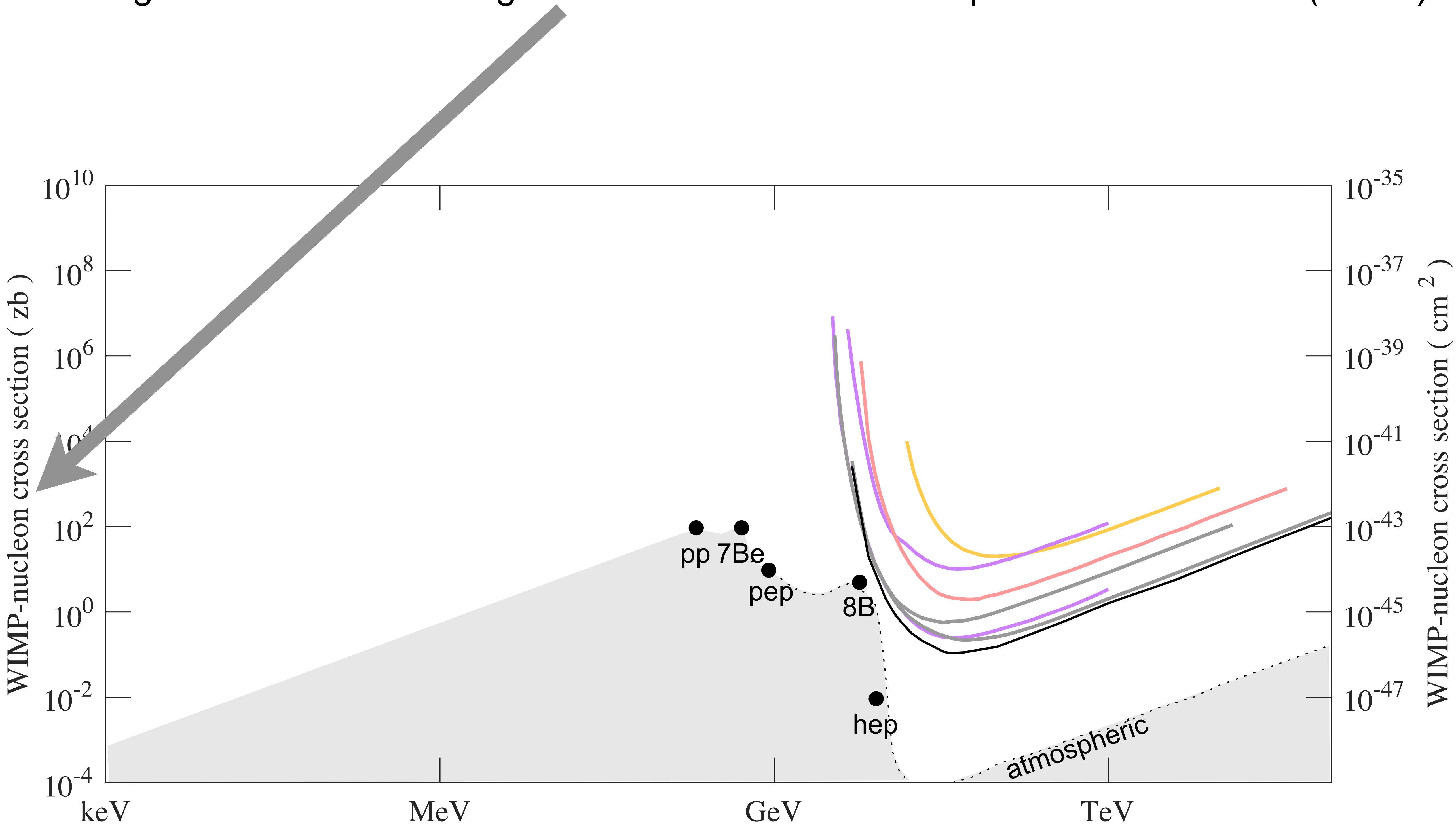
Thresholds set by photon *production*
and photon *detection*.



Nuclear Recoils in Liquid Xe and Ar

Looks very much like we know what we're doing...

... but glossed over something here. We have assumed a particular interaction (scalar).



‘Other’ Nuclear Recoils: list of effective field theories

What other cross section terms are possible?
Can write down a complete list.

Recent surveys of the effective field theory landscape.

Fitzpatrick et al. arXiv:1203.3542
Fitzpatrick et al. arxiv:1211.2818
Anand et al. arXiv:1308.6288
Anand et al. arXiv: 1405.6690
N.Larsen, IDM2016 presentation (right)
K. Schneck, SuperCDMS 2015 arXiv:1503.03379

SI Interaction: $\mathcal{O}_1 = 1$

Cannot obtain at lowest order: $\mathcal{O}_2 = (v^\perp)^2$

$\mathcal{O}_3 = i\vec{S}_N \cdot (\vec{q} \times \vec{v}^\perp)$

SD Interaction: $\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N$

$\mathcal{O}_5 = i\vec{S}_\chi \cdot (\vec{q} \times \vec{v}^\perp)$

$\mathcal{O}_6 = (\vec{S}_\chi \cdot \vec{q})(\vec{S}_N \cdot \vec{q})$

$\mathcal{O}_7 = \vec{S}_N \cdot \vec{v}^\perp$

$\mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}^\perp$

$\mathcal{O}_9 = i\vec{S}_\chi \cdot (\vec{S}_N \times \vec{q})$

$\mathcal{O}_{10} = i\vec{S}_N \cdot \vec{q}$

$\mathcal{O}_{11} = i\vec{S}_\chi \cdot \vec{q}$

$\mathcal{O}_{12} = \vec{S}_\chi \cdot (\vec{S}_N \times \vec{v}^\perp)$

$\mathcal{O}_{13} = i(\vec{S}_\chi \cdot \vec{v}^\perp)(\vec{S}_N \cdot \vec{q})$

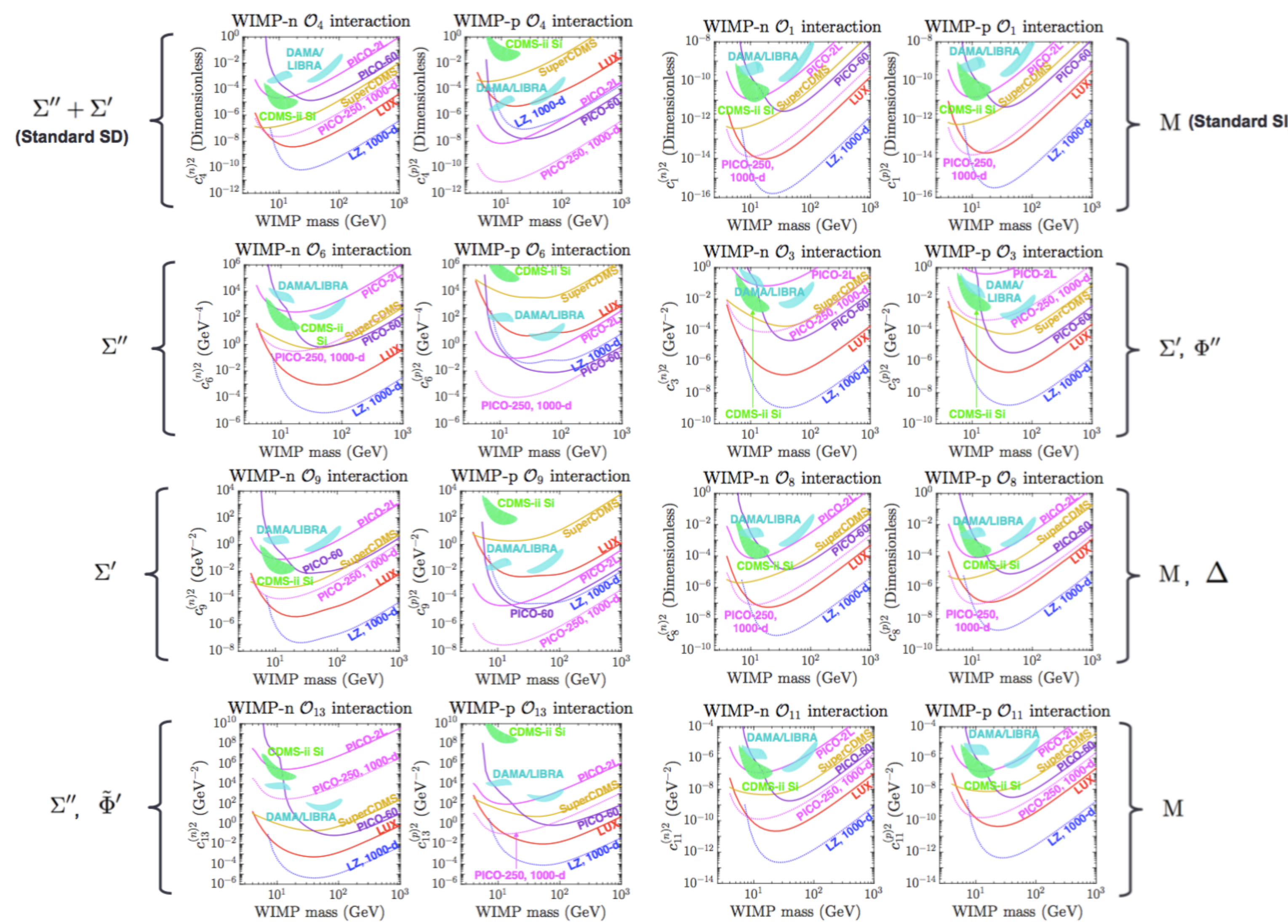
$\mathcal{O}_{14} = i(\vec{S}_\chi \cdot \vec{q})(\vec{S}_N \cdot \vec{v}^\perp)$

$\mathcal{O}_{15} = -(\vec{S}_\chi \cdot \vec{q})((\vec{S}_N \times \vec{v}^\perp) \cdot \vec{q})$

$\mathcal{O}_{16} = -((\vec{S}_\chi \times \vec{v}^\perp) \cdot \vec{q})(\vec{S}_N \cdot \vec{q})$

$\mathcal{O}_{12}$–$\mathcal{O}_{15}$: Exotic; do not arise from exchange of a spin-0 or spin-1 mediator

$\mathcal{O}_{16}$: Linear combo. of O_{12} and O_{15}



Operator combinations can interfere constructively or destructively
(but significant interference requires significant fine-tuning).

Simplistic take-away:
Existing experiments/plans do an ok job covering all the bases.

Biggest hole:
odd-proton nuclei
(eg, F as in PICO)

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	$\mathcal{O}_5 = i\vec{S}_\chi \cdot (\vec{q} \times \vec{v}^\perp)$	$\mathcal{O}_{13} = i(\vec{S}_\chi \cdot \vec{v}^\perp)(\vec{S}_N \cdot \vec{q})$	
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	$\mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}^\perp$	$\mathcal{O}_{16} = -((\vec{S}_\chi \times \vec{v}^\perp) \cdot \vec{q})(\vec{S}_N \cdot \vec{q})$	Linear combo. of O_{12} and O_{15}

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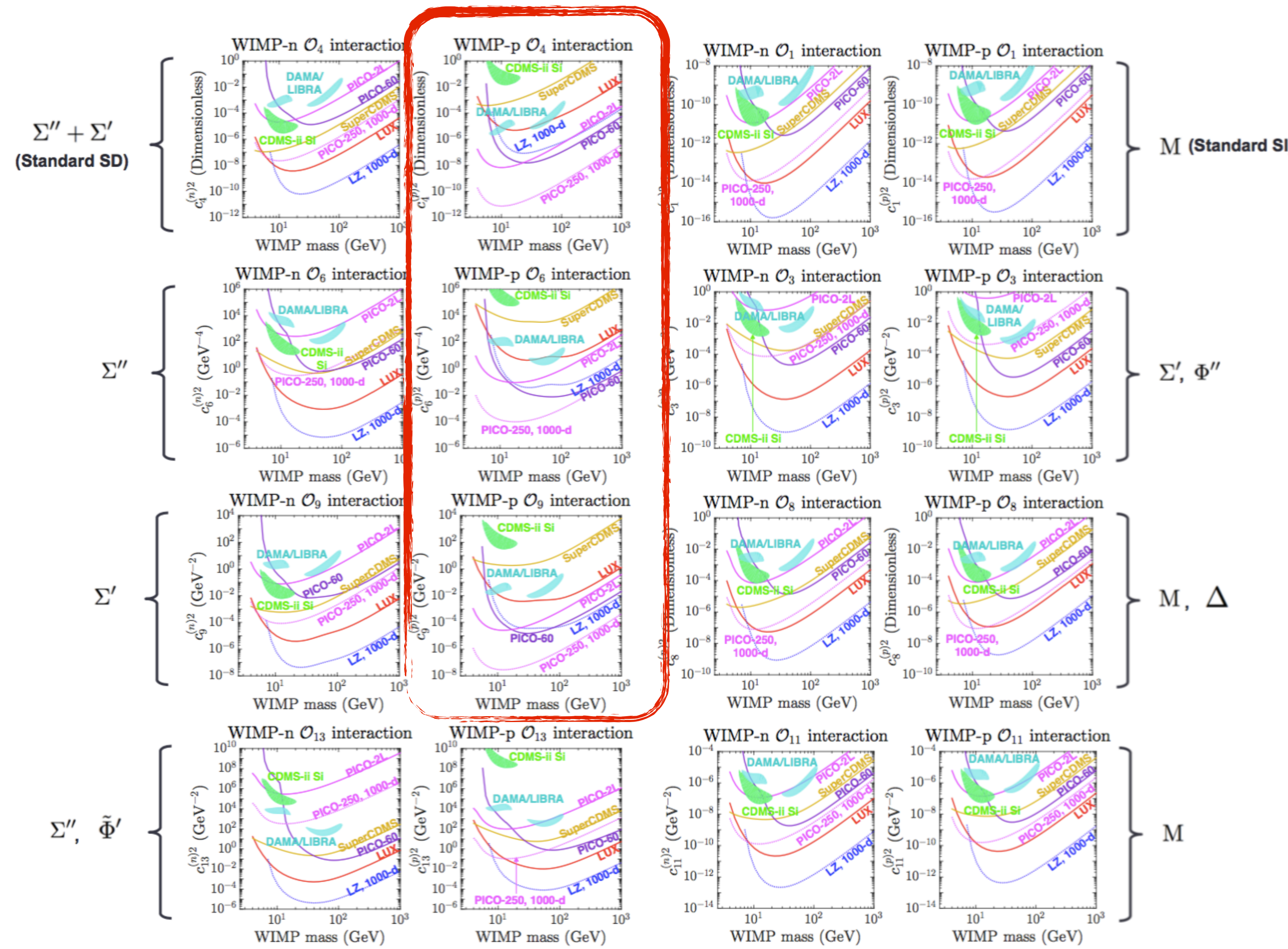

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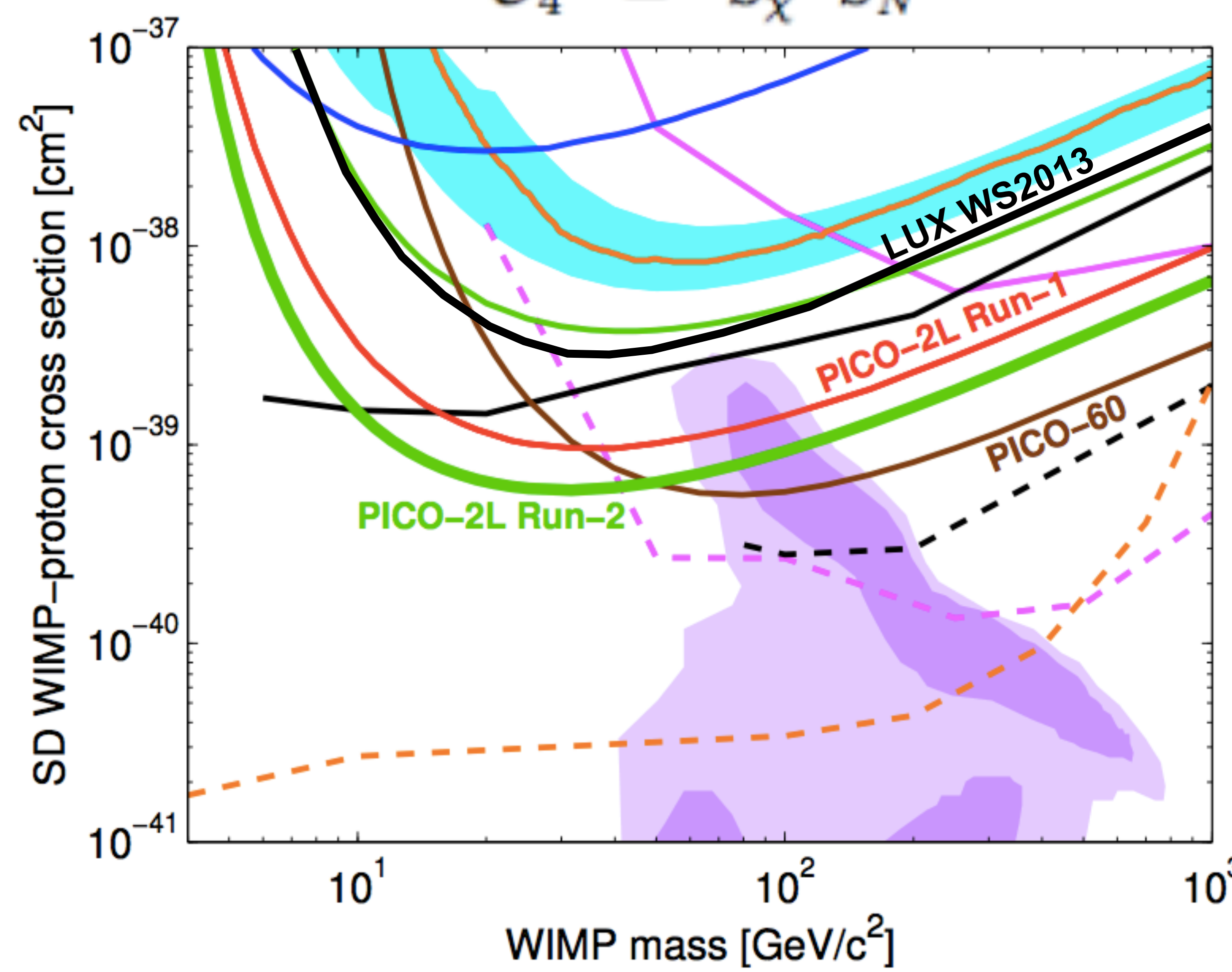

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Biggest hole:
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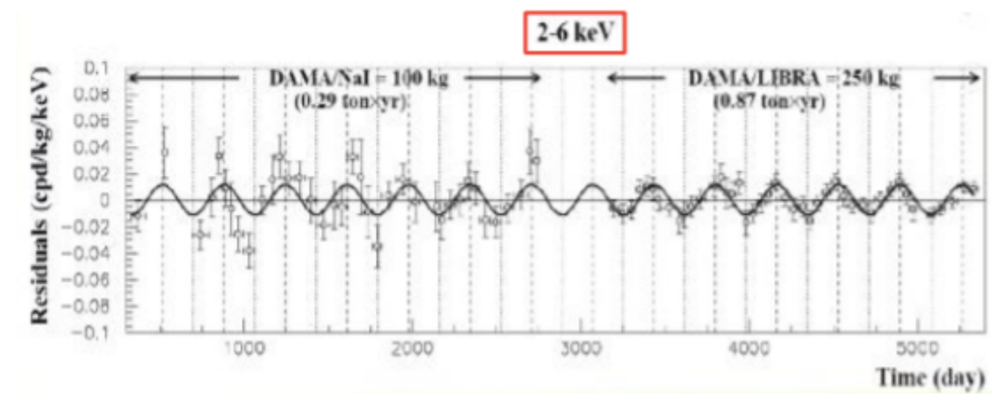
(eg, F as in PICO) upcoming talk from Ken Clark

‘Other’ Nuclear Recoils: DAMA/LIBRA

Inconsistent with non-Na searches...

...must resort to “Na is special in some way.”

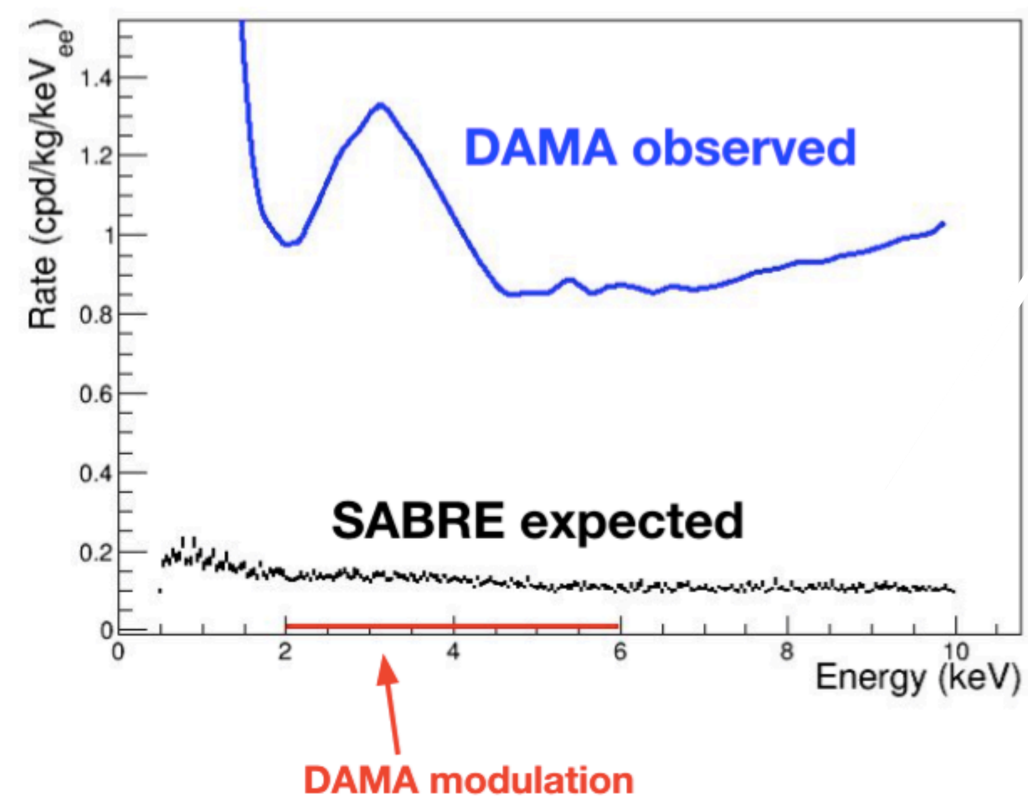
0.0112 cpd/kg/keV modulation
on top of ~**1** cpd/kg/keV



Multiple NaI(Tl)-specific efforts.

We’ll hear about them today!
COSINE-100 (Jay Hyun Jo)
PICO-LON (Ken-Ichi Fushimi)

Great progress in high-purity crystal growth
(I’ll let the experts discuss)

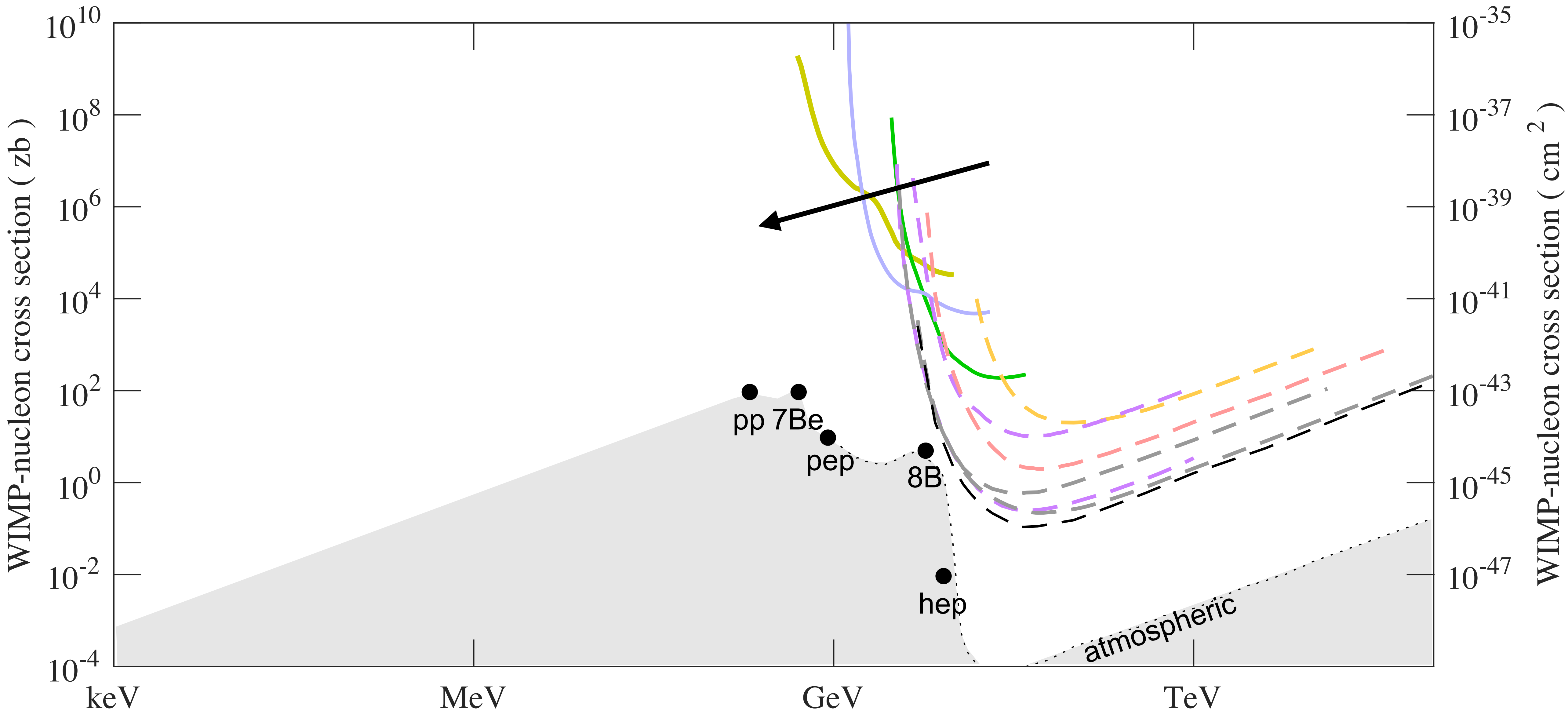


The pivot: sub-GeV nuclear recoils

Lower masses still wide open and untested.

Growing interest (including active detector R&D) for three reasons:

1) several ‘thresholdino’ observations hinted at few-GeV scale, since ruled out
2) theory options have broadened, de-emphasizing the standard WIMP
3) neutrino floor looming... what else can we do?

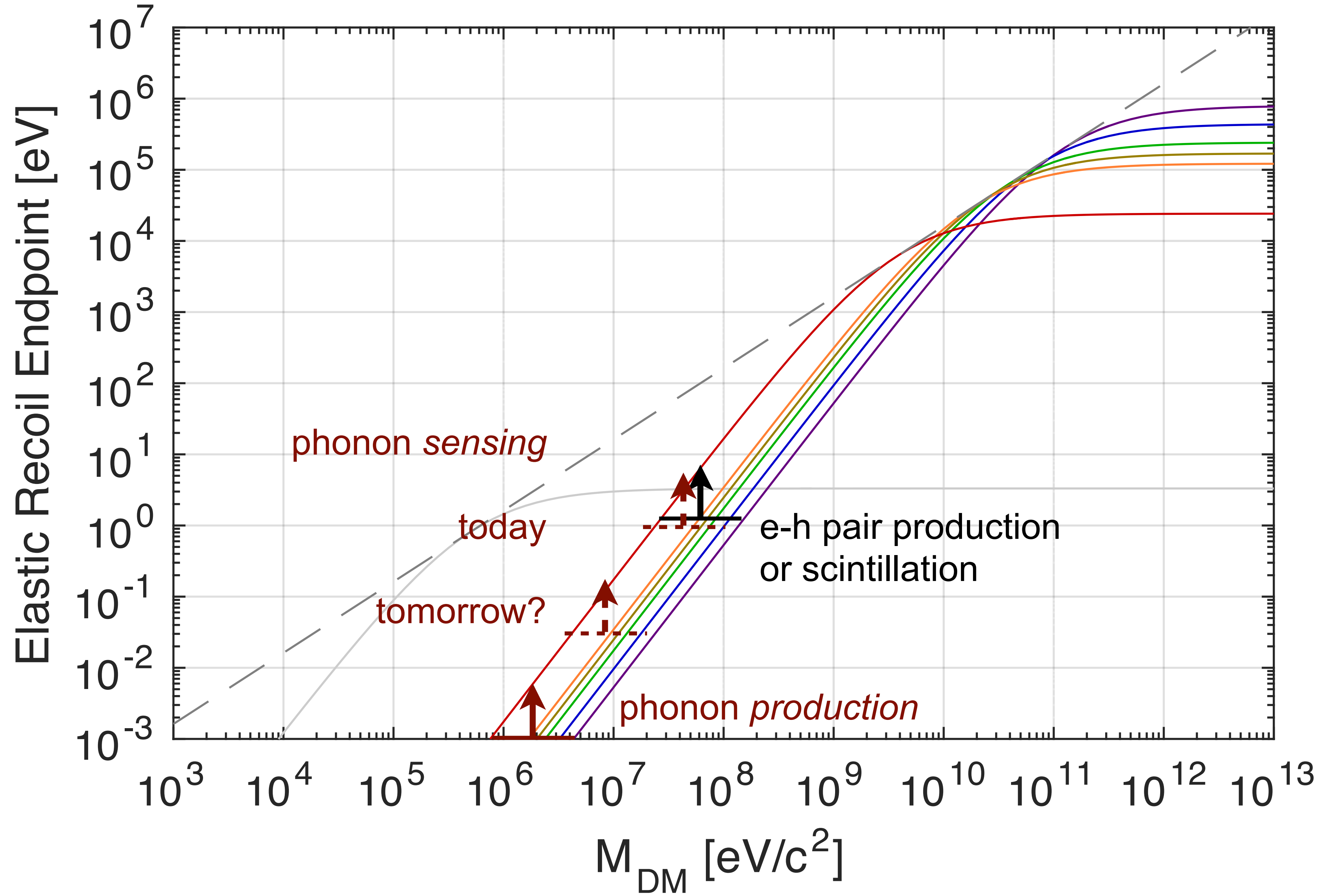


Low NR threshold strategy 1: phonons and heat

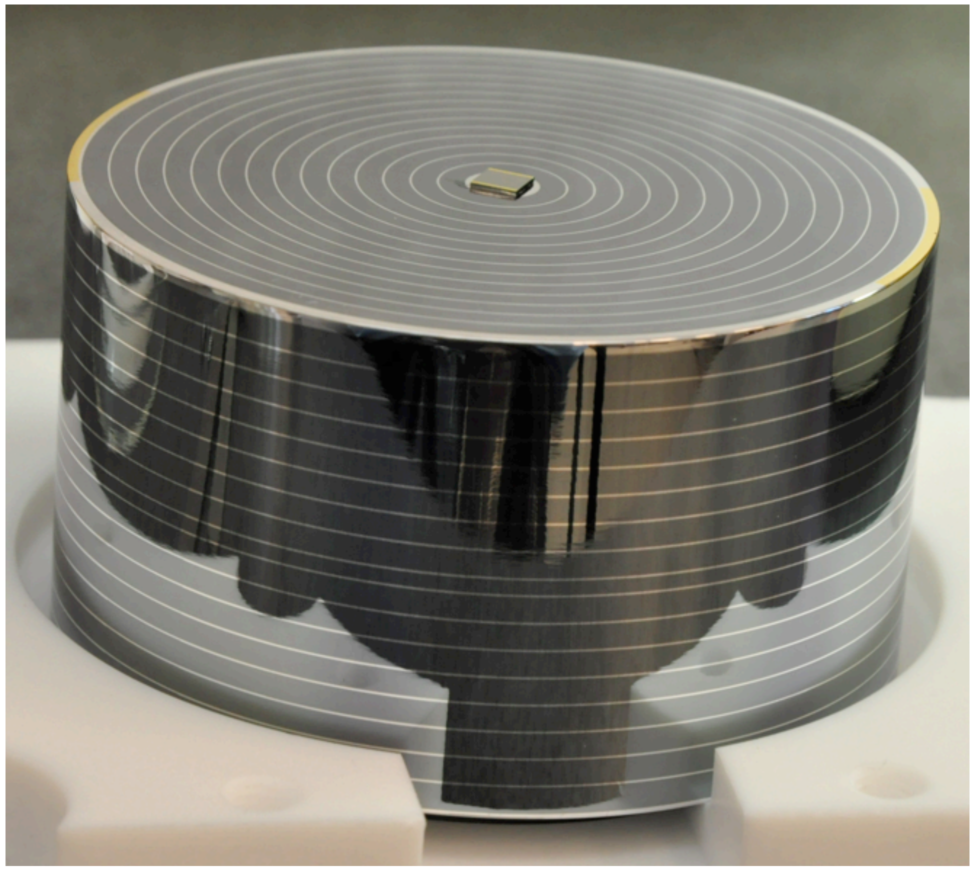
Upside 1: Threshold not excitation-energy-limited
(instead limited only by sensor noise, still plenty of room for improvement)

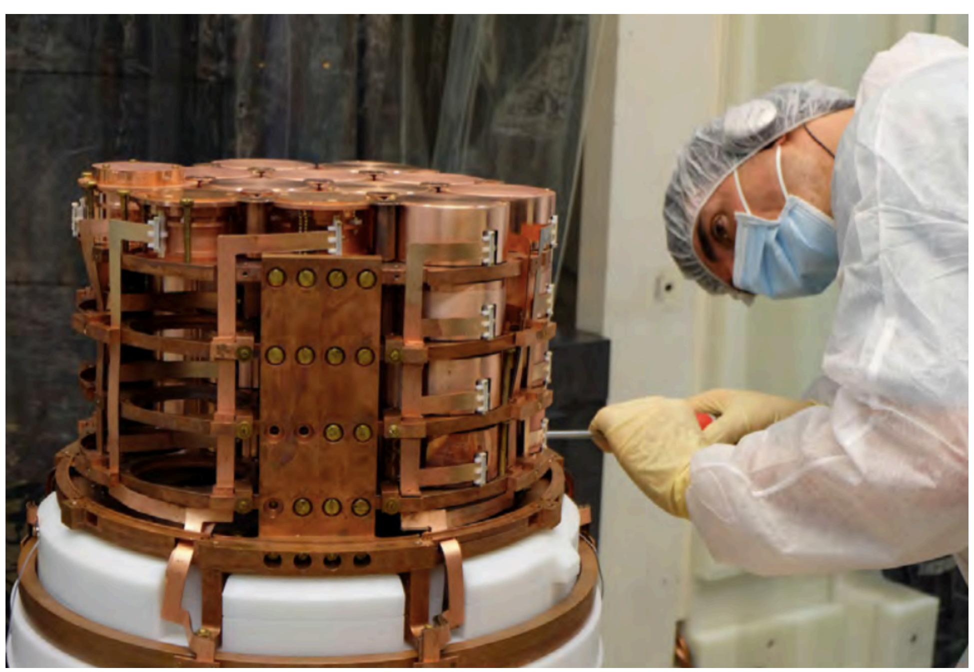
Upside 2: Most NR energy goes into phonons (~100% below other E_{gap} values)

Downside: mK temperatures (never easy)



Edelweiss III : heat + charge



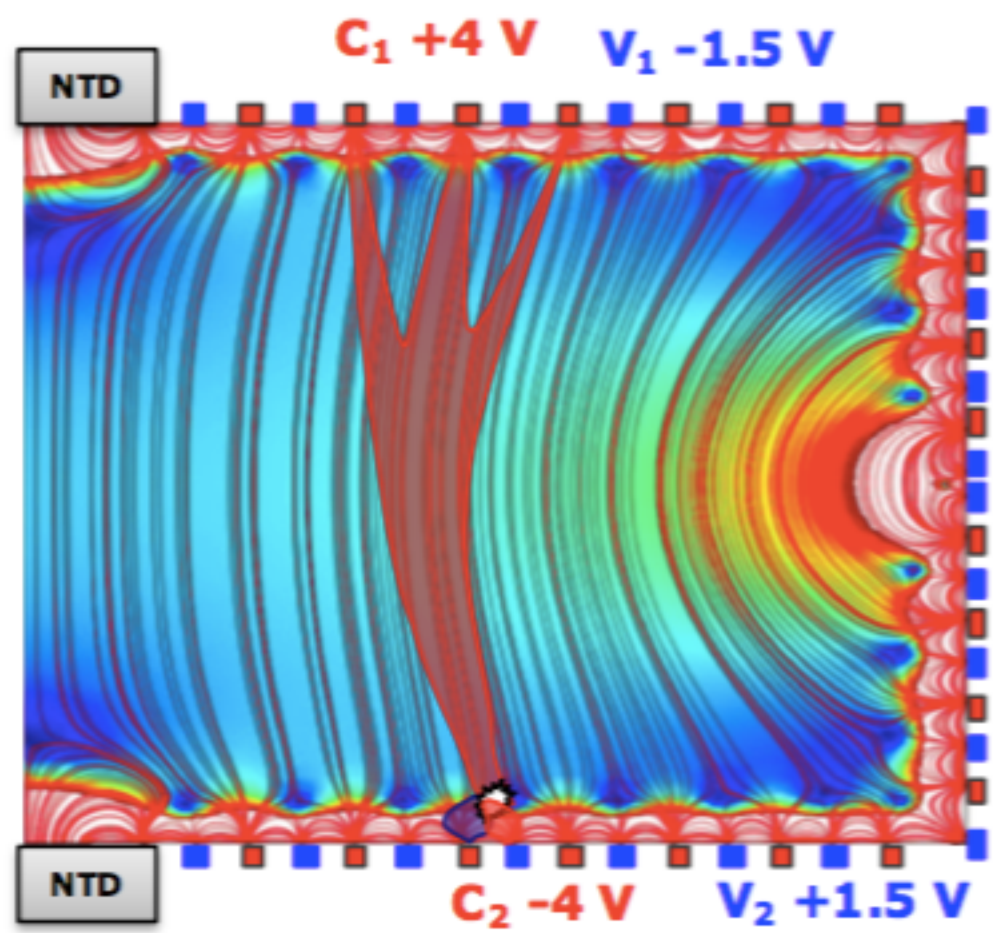


Ge targets, 800g mass each

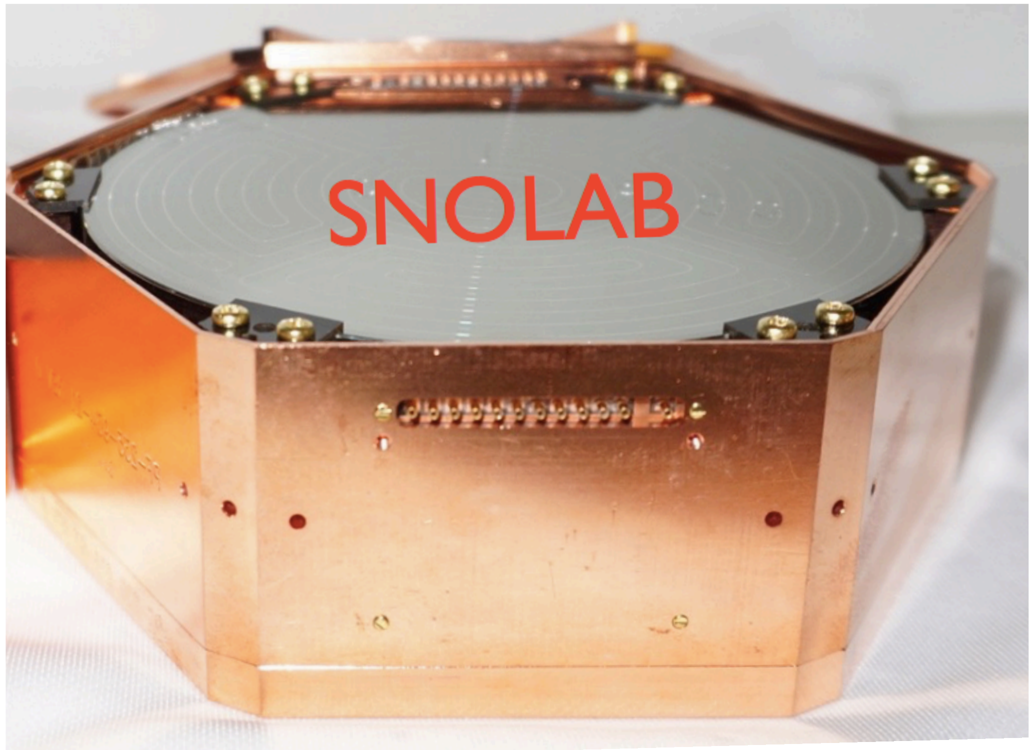
charge readout : 200 eV resolution
heat channel : NTD readout, similar resolution

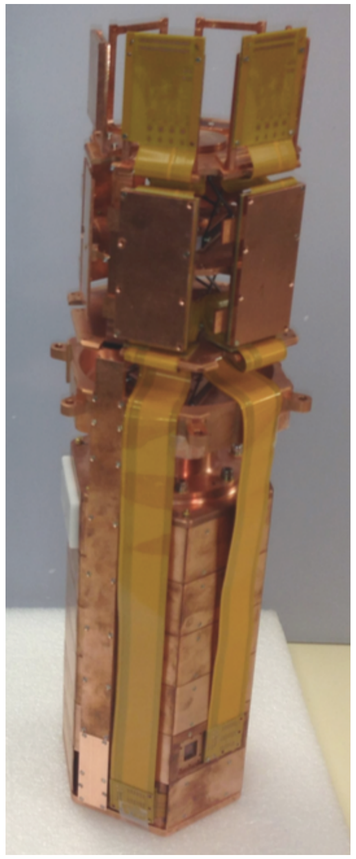
recent analysis down to E_{rec} = 2.4 keV

powerful vetoing of surface events by E-field



SuperCDMS SNOLAB : phonons + charge





Si + Ge targets   100mm diam.

not a heat detector, an athermal phonon detector
much more information (position, pulse shape)

12 phonon channels, ~50 eV resolution expected
4 charge channels, 100 eVee resolution exp. (HEMTs)

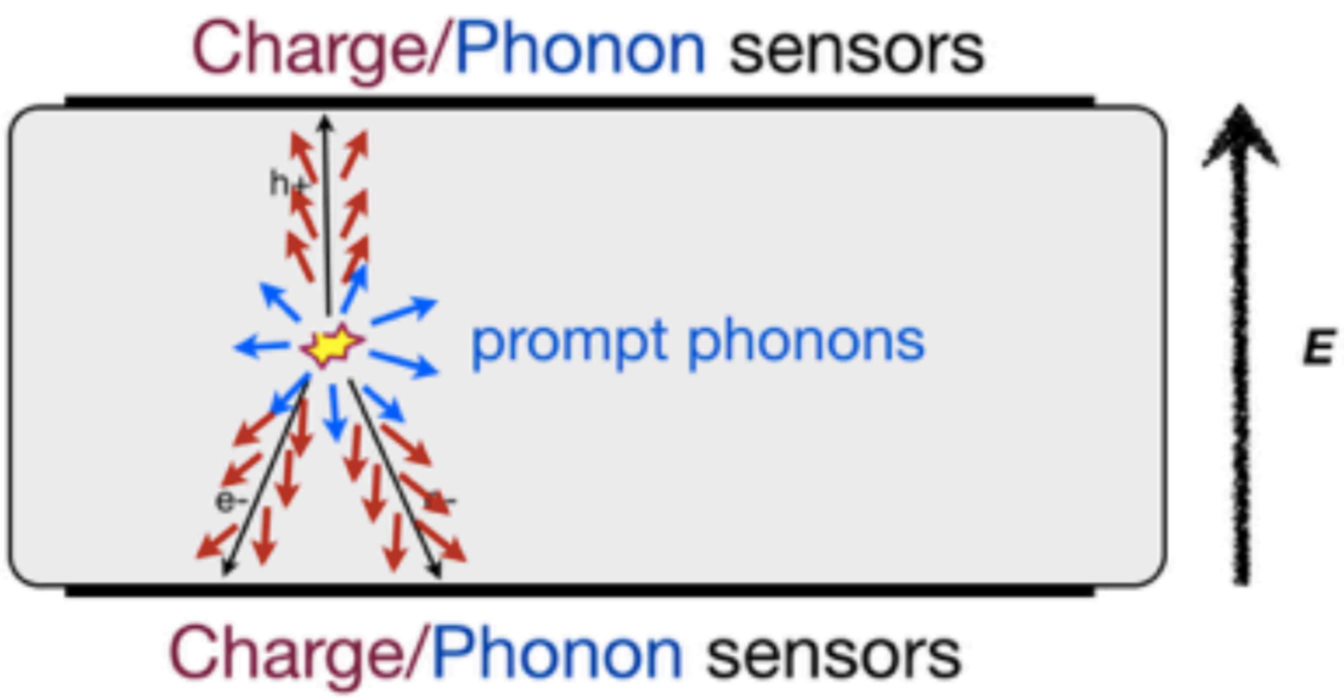
all channels on top and bottom surfaces
(TES readout, difficult to deposit W with desired T_c)

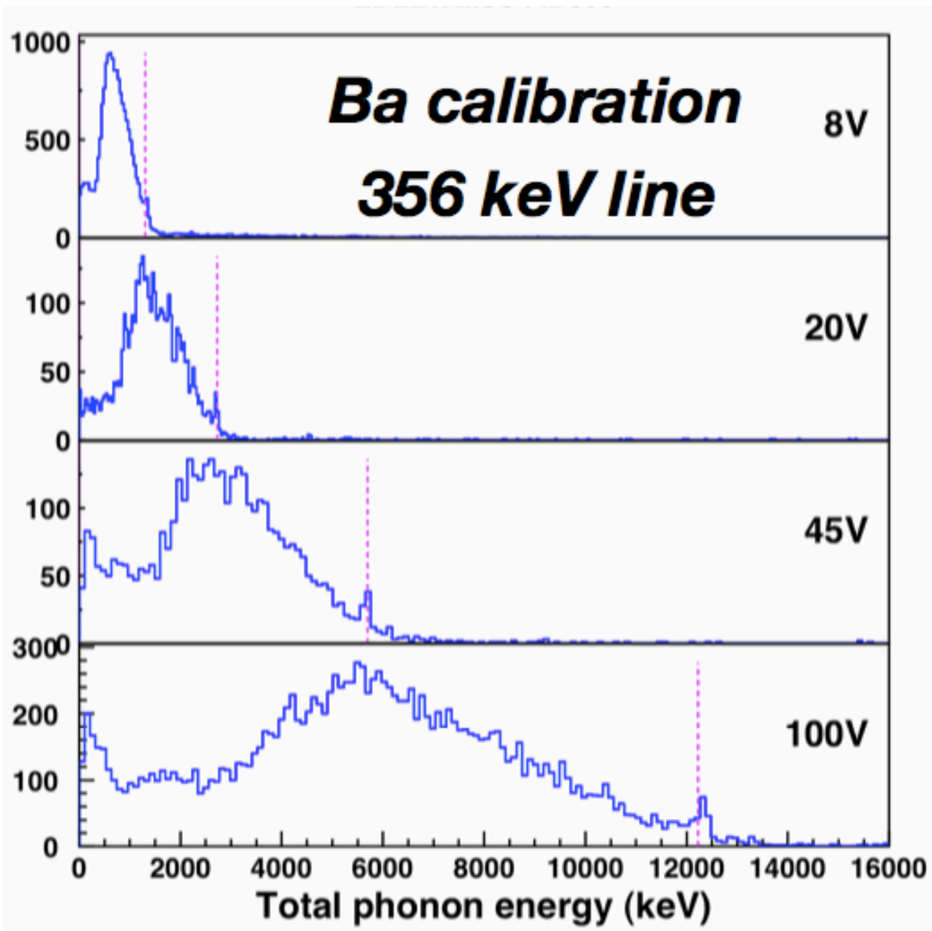
SNOLAB payload:
- 50 kg Ge with surface veto field (3 towers)
- 4 kg Si with surface veto field (1 tower)
- 5.6 kg Ge and 1.4 kg Si in HV mode (1 tower)

Recent SNOLAB sensitivity projections on arXiv.

Luke gain: turning a small e-h pair energy into a large phonon energy

charges `dragged' at critical velocity through lattice produce phonons at each lattice recoil.
(think of it as "phonon electroluminescence")



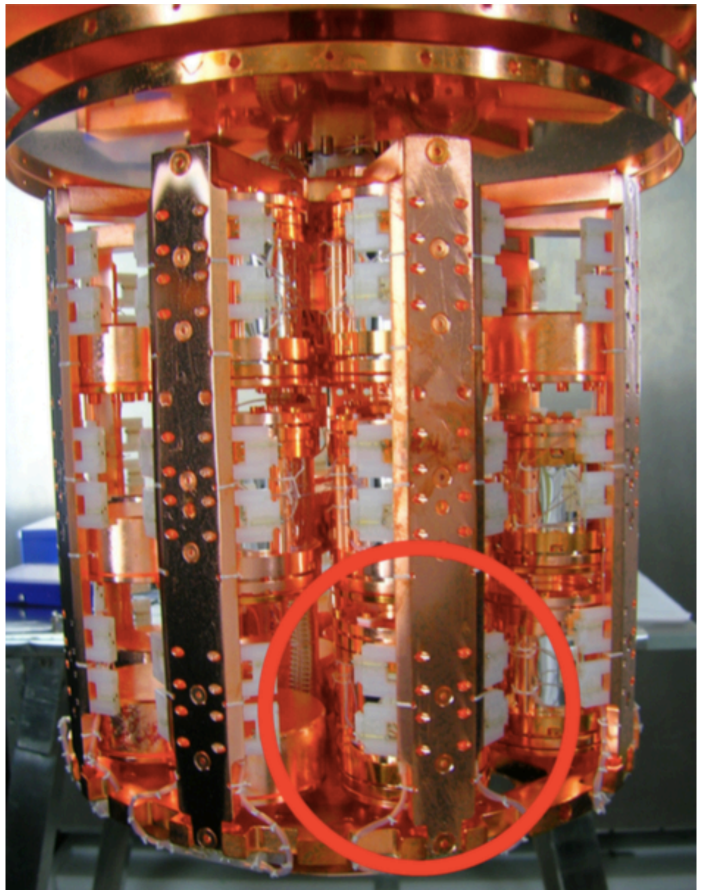


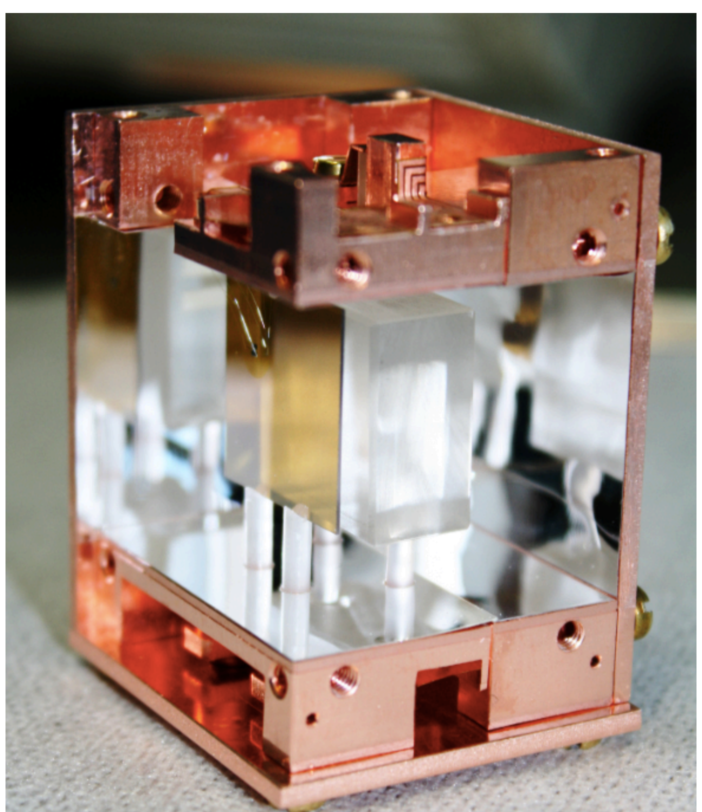
upside: dramatically lower threshold possible (both CDMS & Edelweiss: 60eVee achieved)

downside: discrimination no longer event-by-event (until extreme phonon resolution achieved)
voltage produces e-h dark count (can likely be solved, working on it)

Both SuperCDMS and EDELWEISS have operated in this mode already.
SuperCDMS has designed detectors specific to 100V operation.

CRESST : heat + scintillation





$CaWO_4$ target

TES readout of both heat and scintillation

Much progress on flagging surface backgrounds
(all surfaces scintillating)

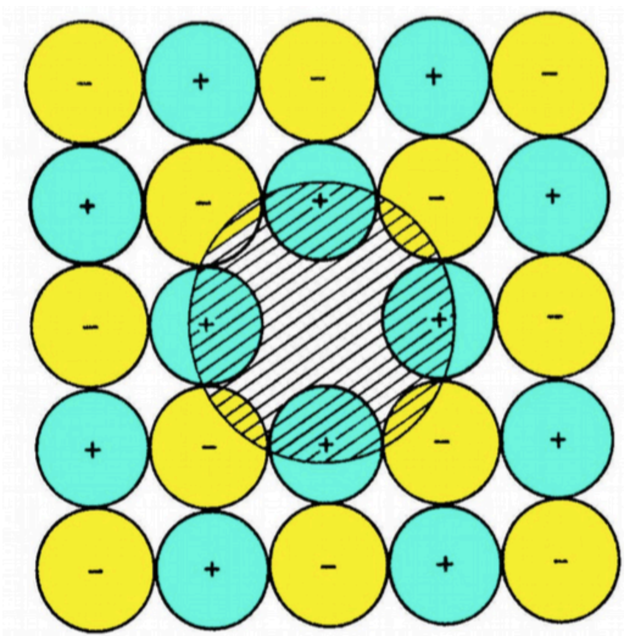
CRESST-II

250g target crystals
recent analysis of single best detector: 52 kg-d
threshold : **307eV** (12% eff.)
limit reported down to m_{DM} = 500 MeV (!)

CRESST-III

main strategies: smaller heat capacity (24g)
continued optimizing of TES coupling
tests suggest a **50eV** threshold likely achieved

Low NR threshold strategy 2: dislodging atoms from lattice



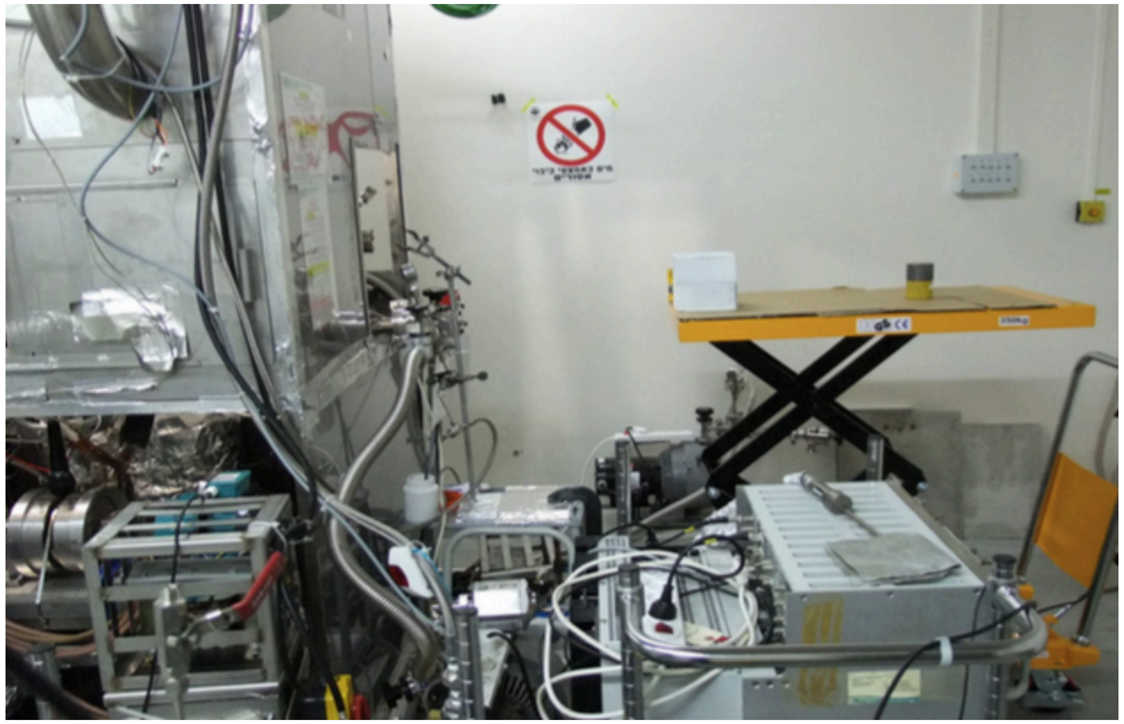
signal is lattice defects, observed through fluorescence

E_{gap} few-eV (still surveying the options)

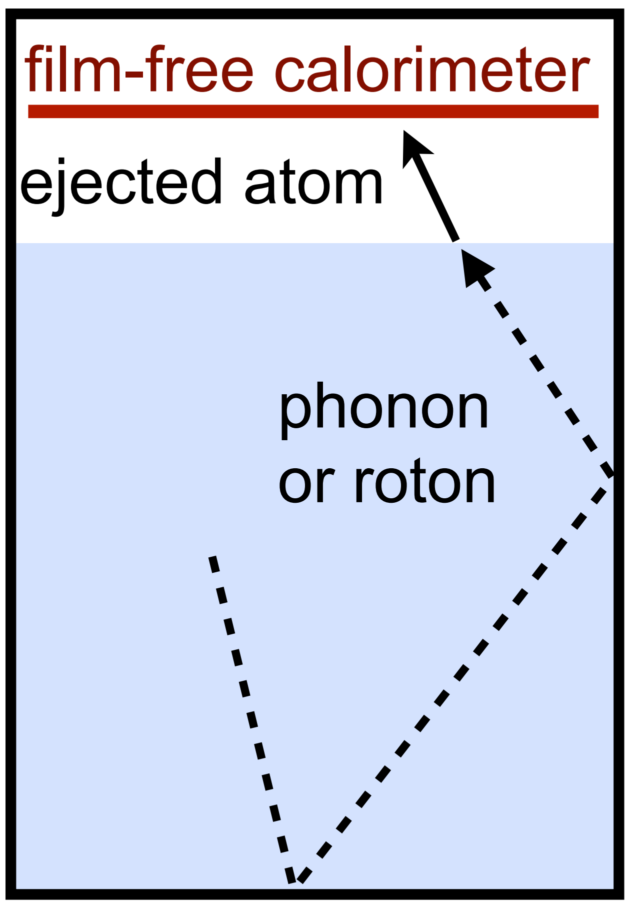
possibly re-settable through annealing

many unknowns... many backgrounds...

first neutron calibrations have begun (SARAF, Israel)



Low NR threshold strategy 3: amplification via van der Waals



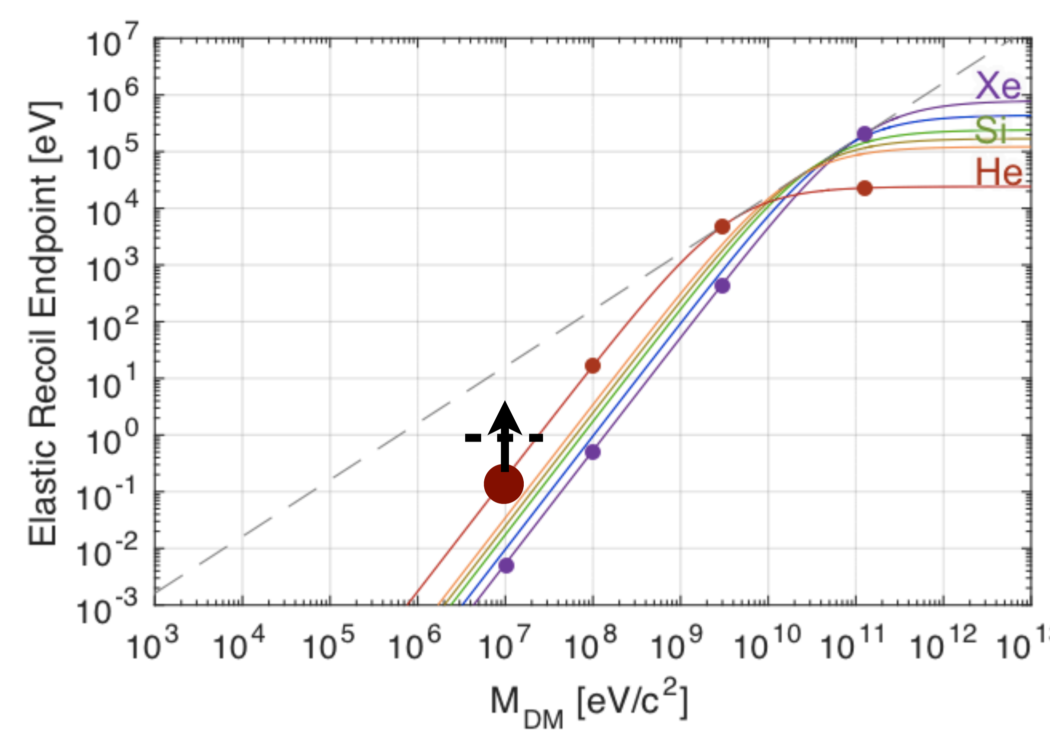
signal is atoms hitting a few-mK calorimeter array

~1meV/phonon signal boosted by ~10x boost
(~10meV/atom binding energy on typical material)

threshold is set by calorimeter noise
active area of research for many experiments
CRESST has achieved a 5eV photon det. threshold

~1 eV cal. threshold with ~10x van der Waals gain
-> ~100meV recoil threshold
-> ~10 MeV m_{DM}

possible to enter the meV range!



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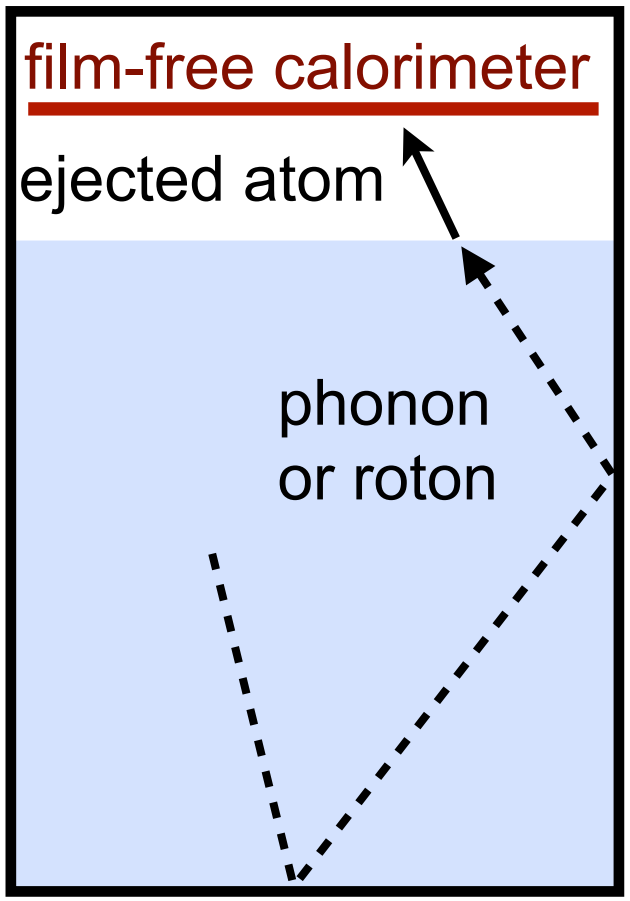

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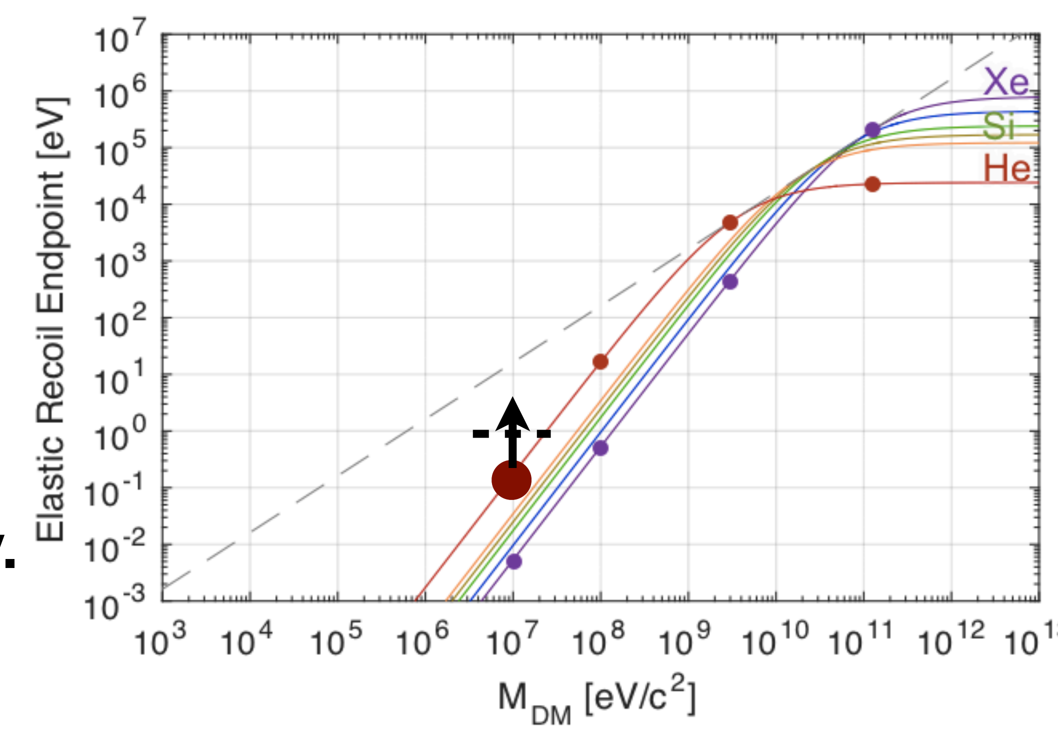


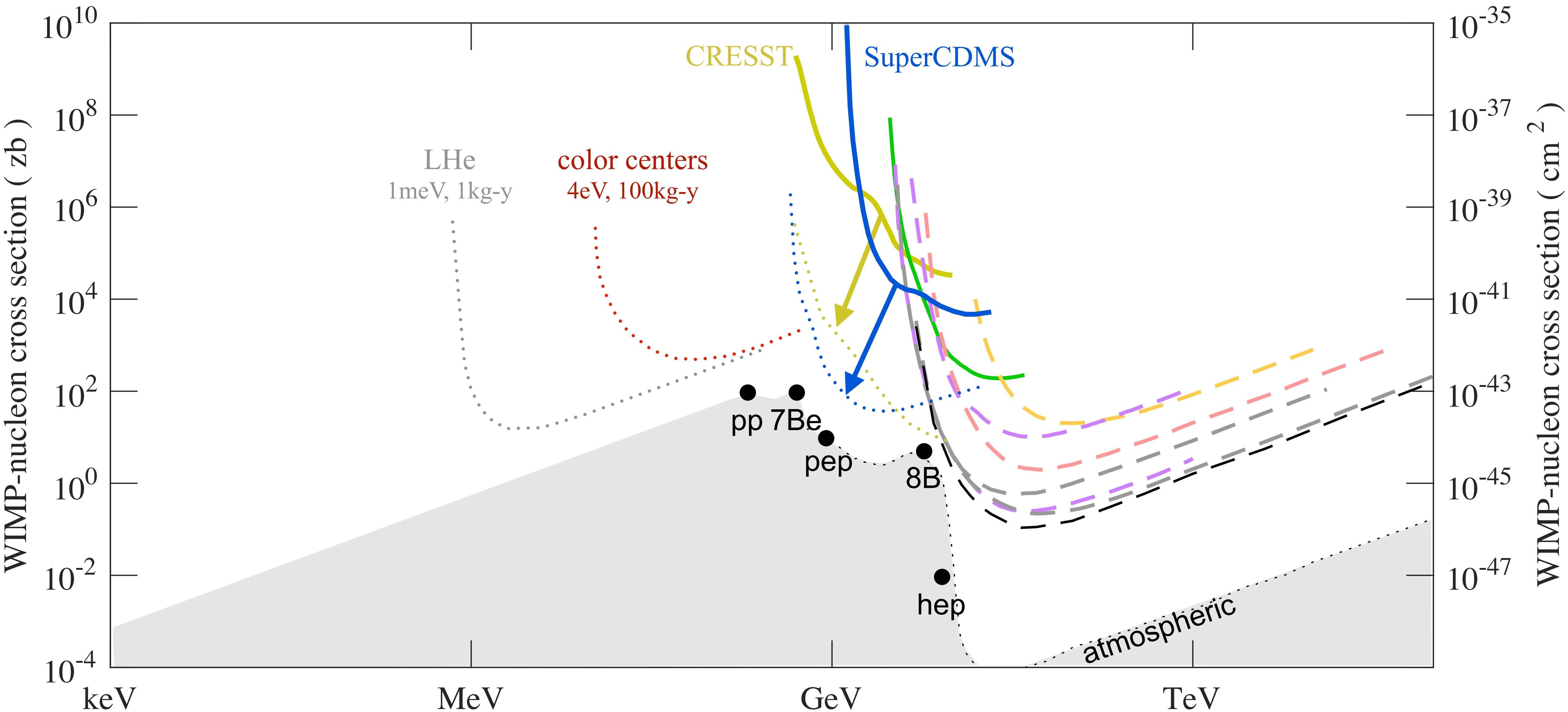
possible to enter the meV range!

main punchline of slide:
sounds like a really excellent postdoc opportunity.

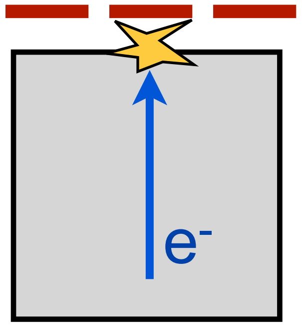
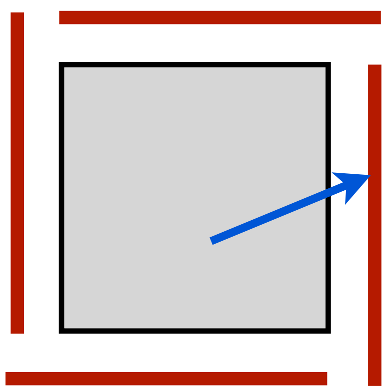
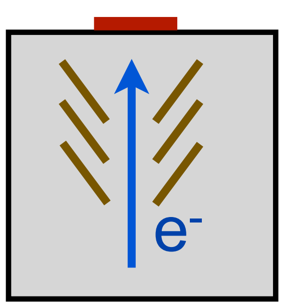
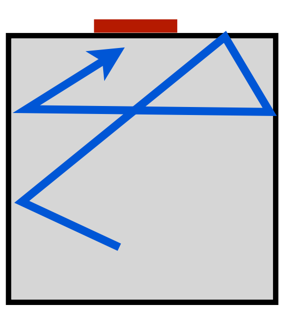
Prospects for sub-GeV dark matter using nuclear recoils

Existing plans may get us down to few-hundred MeV masses.

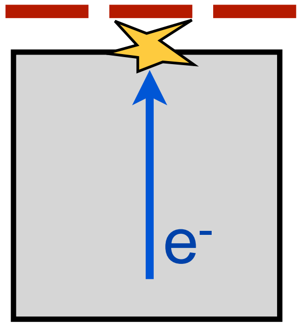
Over the next *n* years... continue to steadily improve existing technologies,
while still brainstorming for more revolutionary ideas.



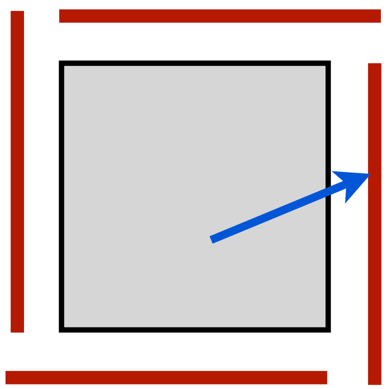
Sub-GeV dark matter using electron recoils : Options

		E_{rec} -> m_{DM}	amplification	dark count
	**LXe** sensing of e-	~10eV -> 10 MeV	electrolum.	field-induced
	**scintillator** sensing of photons with mK calorimetry	~10eV -> 10 MeV	none	?
	**semiconductor** sensing of e-h pairs	~1eV -> 1 MeV	Luke phonon production	field-induced
	**superconductor** sensing of broken quasiparticles	~1 meV -> 1 keV	none	?

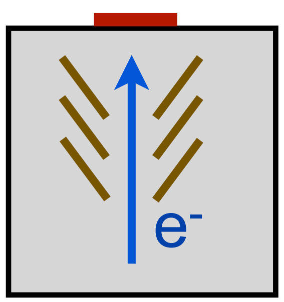
Sub-GeV dark matter using electron recoils : Options



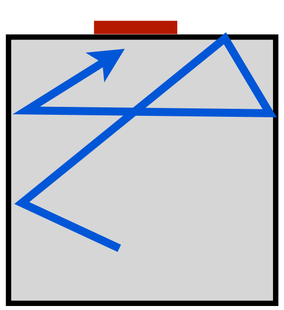
LXe
sensing of e^-



scintillator
sensing of photons with mK calorimetry

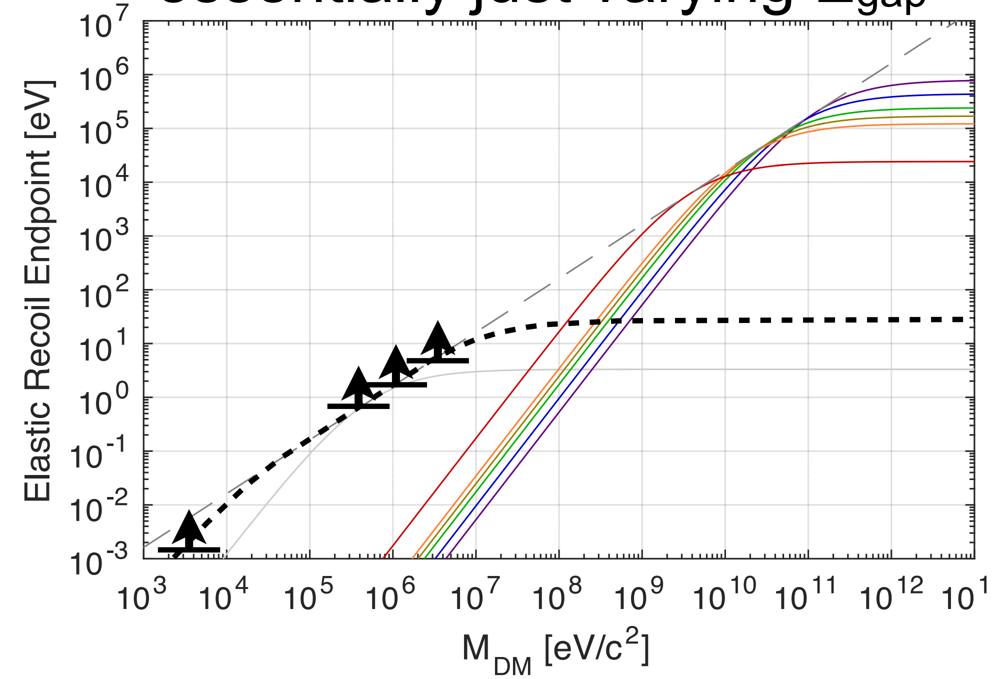


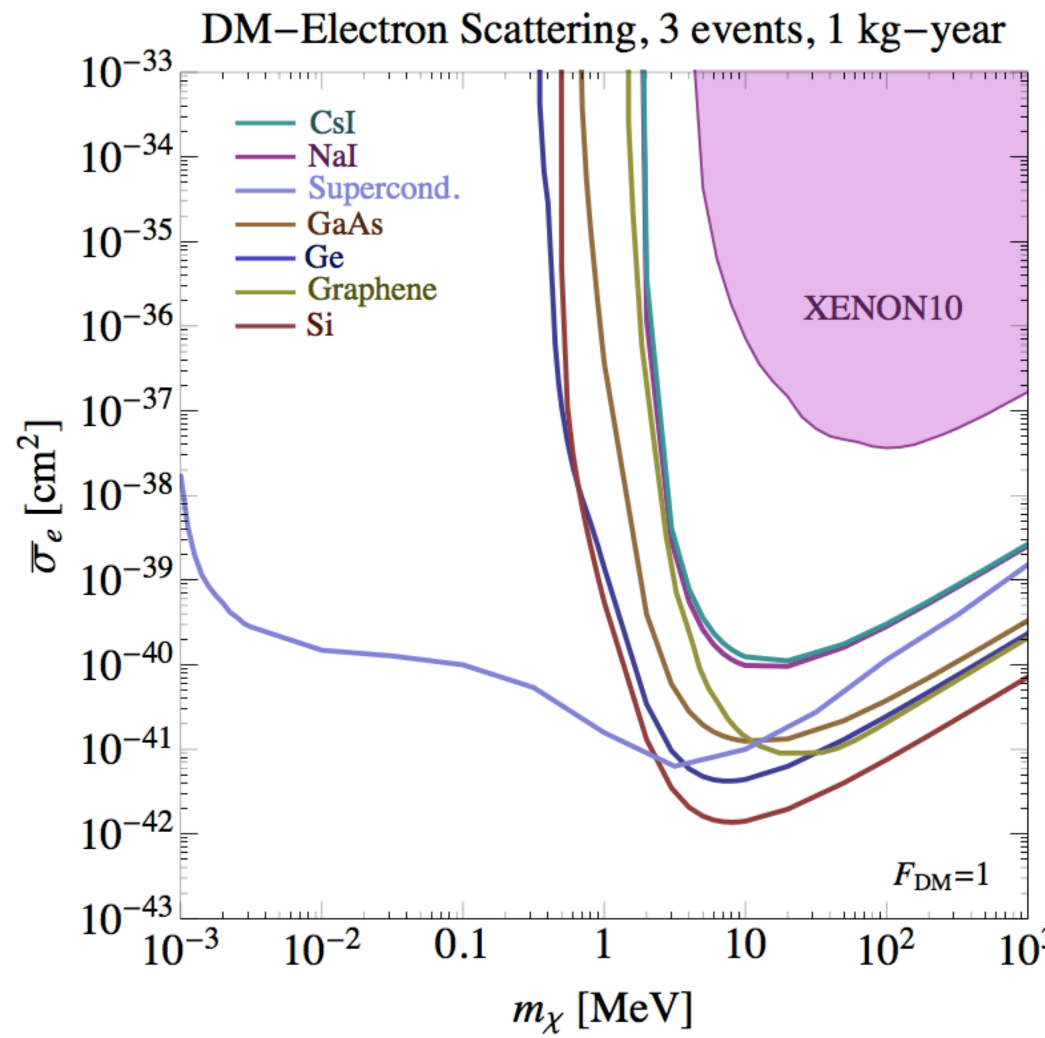
semiconductor
sensing of e-h pairs



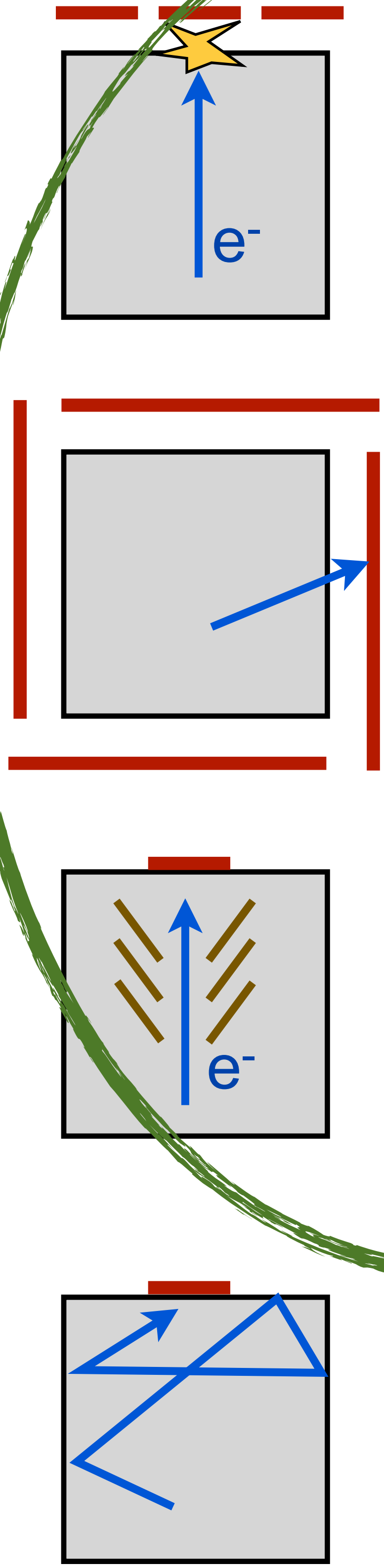
superconductor
sensing of broken quasiparticles

essentially just varying E_{gap}





Sub-GeV dark matter using electron recoils : Options



LXe
sensing of e-

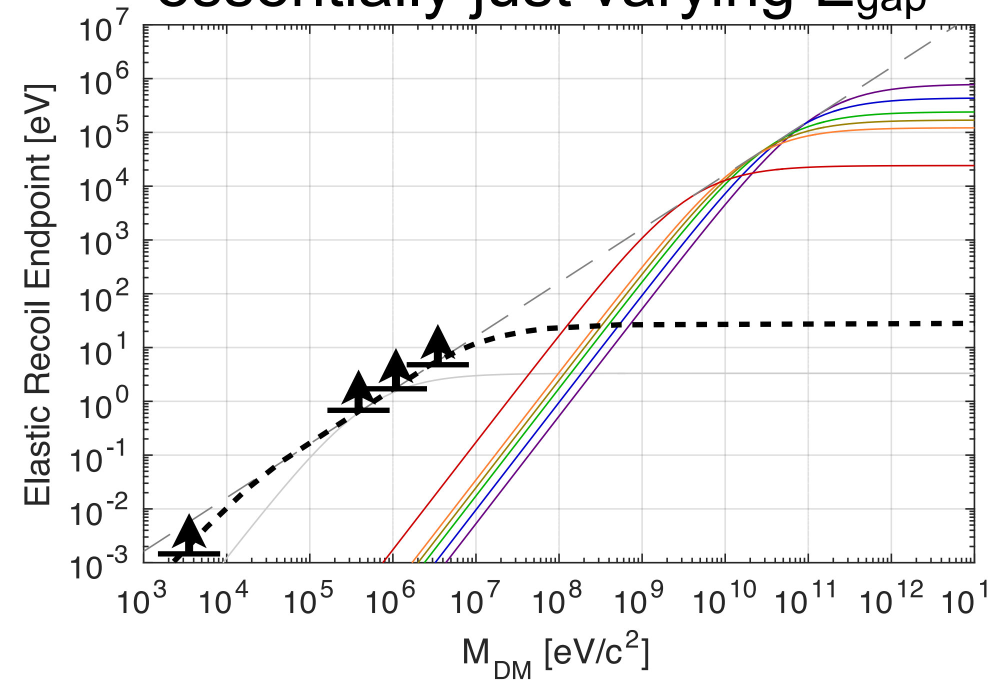
scintillator
sensing of photons
with mK calorimetry

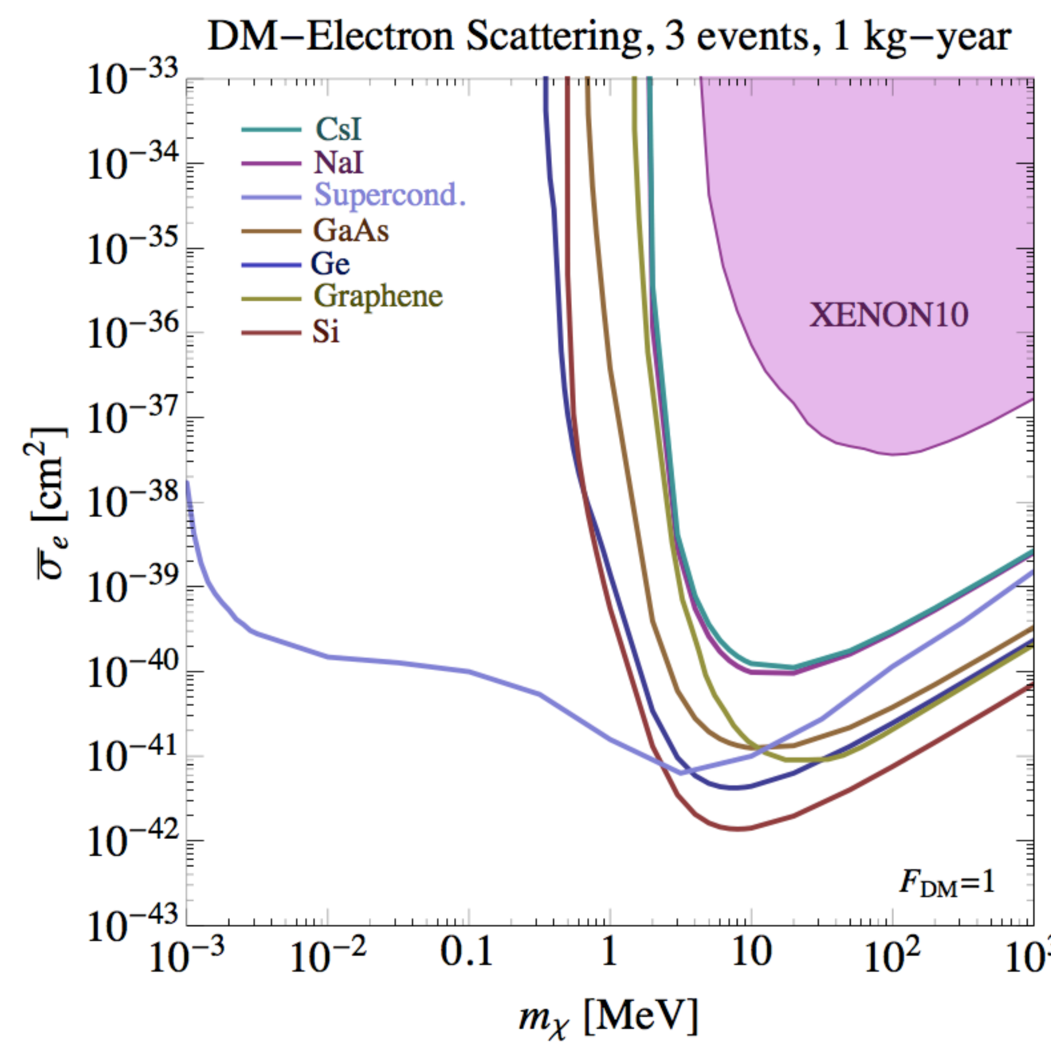
semiconductor
sensing of e-h pairs

superconductor
sensing of broken
quasiparticles

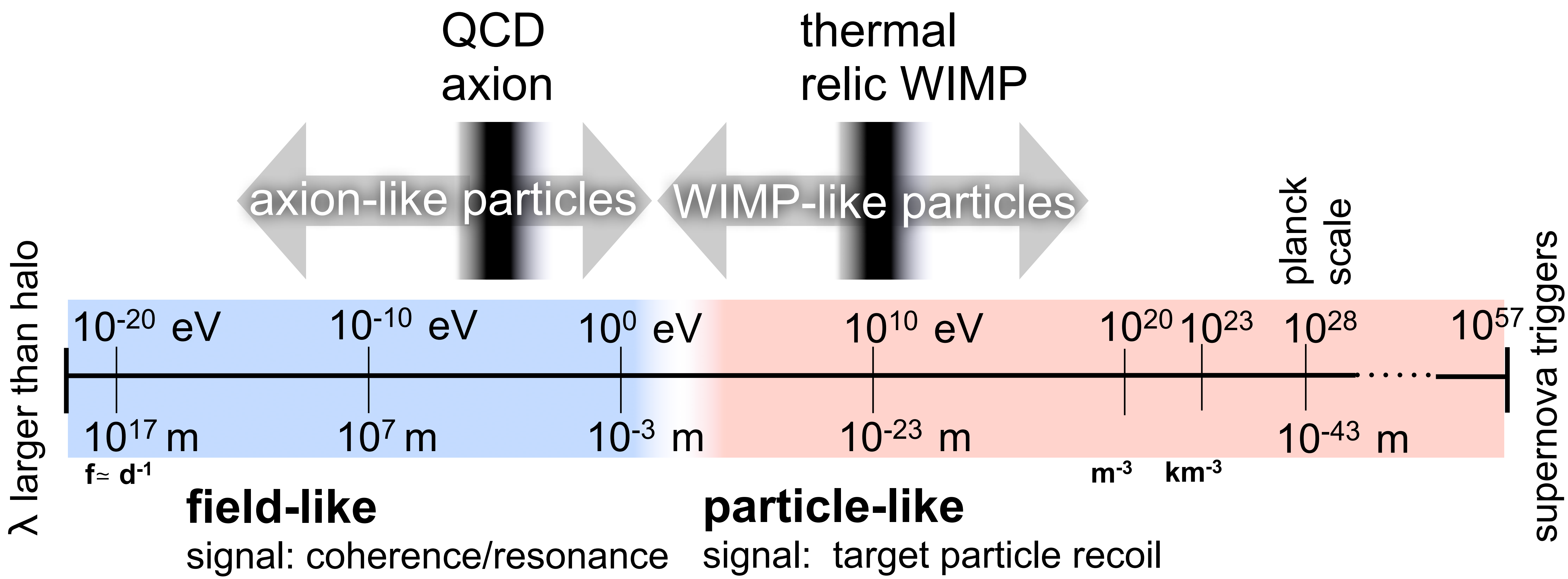
"for free"
in planned
NR programs

essentially just varying E_{gap}





Even lighter: observing an ambient field



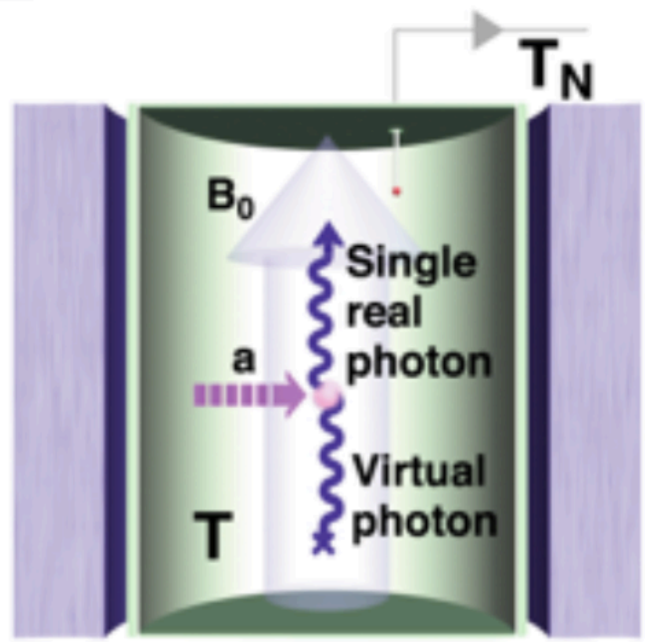
Even lighter: observing an ambient field

only a short comment:

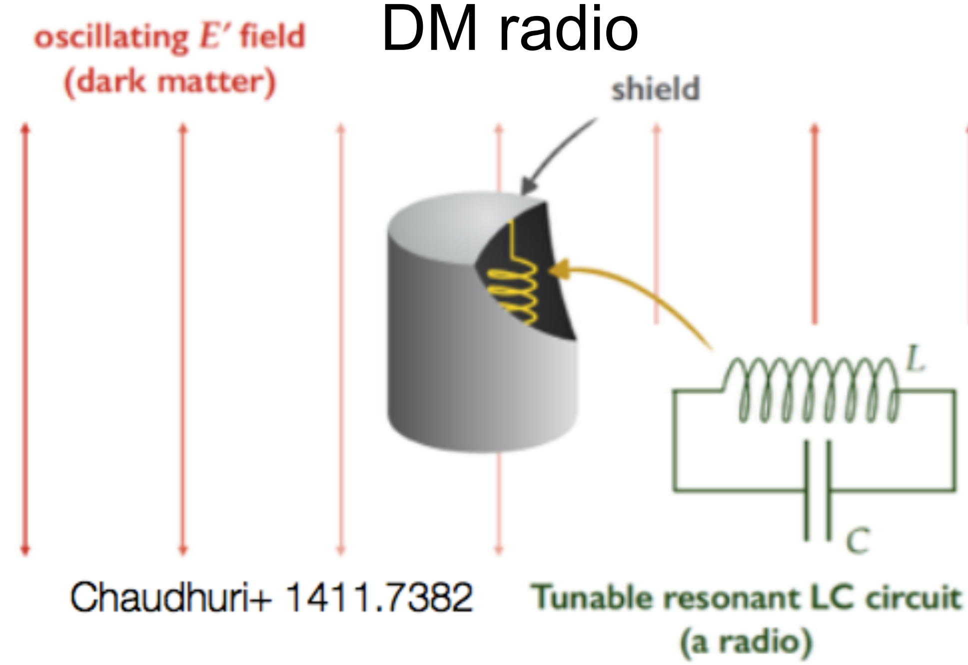
Growing experimental interest

Growing list of efforts and methods

ADMX & ADMX HF



DM radio

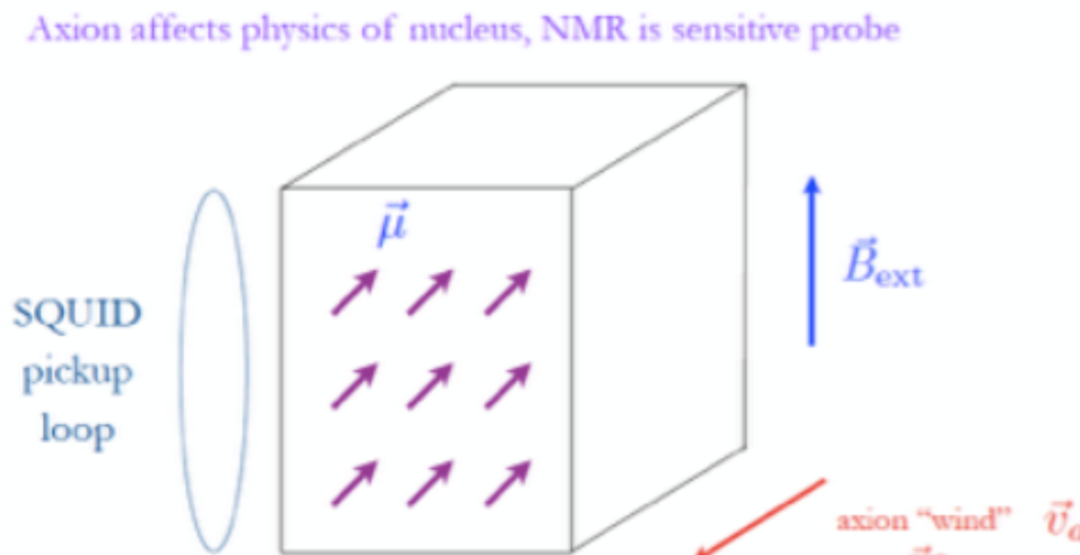


Chaudhuri+ 1411.7382

Search for Hidden Photons with a large Spherical Mirror

Döbrich+ 1510.05869

CASPEr

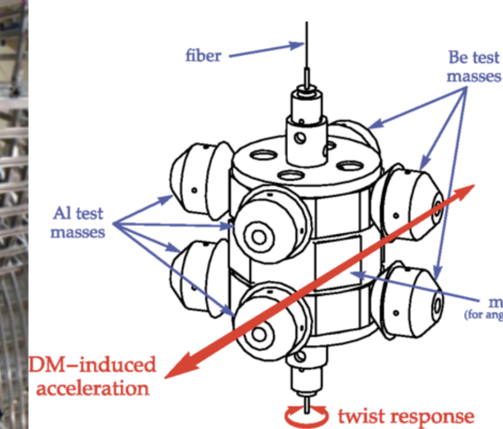


Budker+ 1306.6089

accelerometers

atomic

torsion pendulum



Summary:

- Big-picture thoughts
  - Goal is to absorb KE_{DM} , targets tuned accordingly

- m_{DM}>1GeV
  - Fast progress in nobles
    - m_{DM}~5GeV, backgrounds order 1e-3 /keVee/kg/d
  - Spin-dep. proton cross section motivates distinct technology
  - DAMA/LIBRA will be proved or disproved soon, Na-specific
  - Neutrino recoils a daunting prospect

- m_{DM}<1GeV
  - Choose either mK temperatures or e- recoils (or both)
  - Currently reaching m_{DM}~500MeV, limited by sensor noise
  - New efforts pushing to reduce these calorimetry thresholds to <100eV