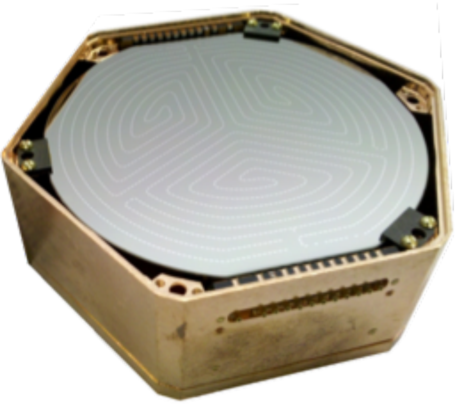
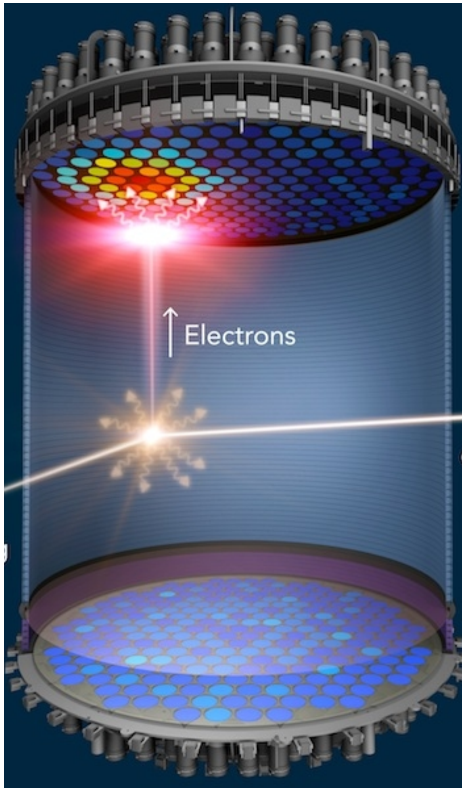
Design Drivers for Dark Matter Searches





Matt Pyle

UC Berkeley

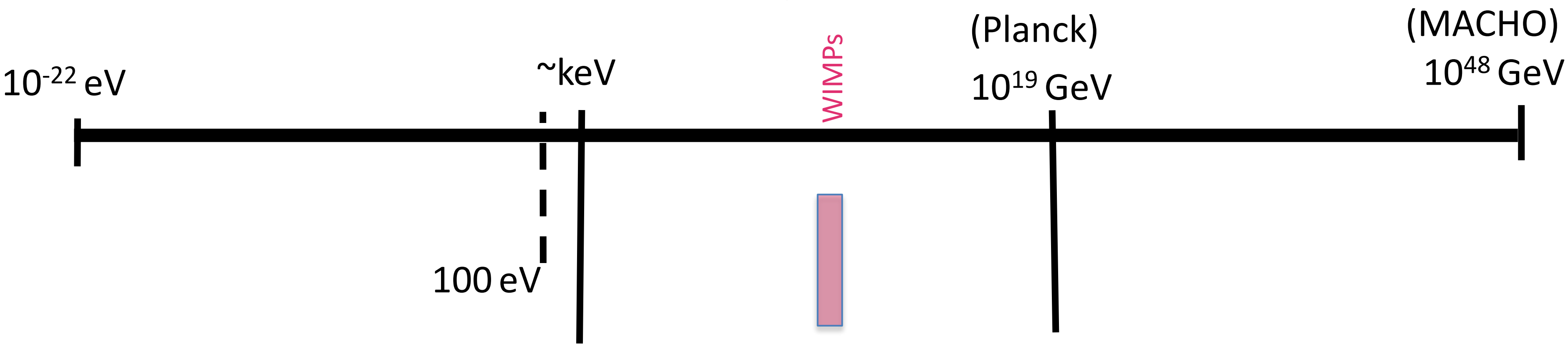
AIT DM School

18/02/18

Plan

- Briefest Theoretical Overview Ever!
- Interaction Processes and Experimental Design Drivers for Direct Detection
  - WIMPs: 10 GeV < M_{DM} < ~10 TeV
  - 100 MeV < M_{DM} < 6 GeV DM
  - 1 MeV < M_{DM} < 100 MeV DM
  - 10 meV < M_{DM} < 1 MeV DM
  - Ultralight DM: M_{DM} < 10 meV

10 Years Ago: WIMPs



10^{-22} eV

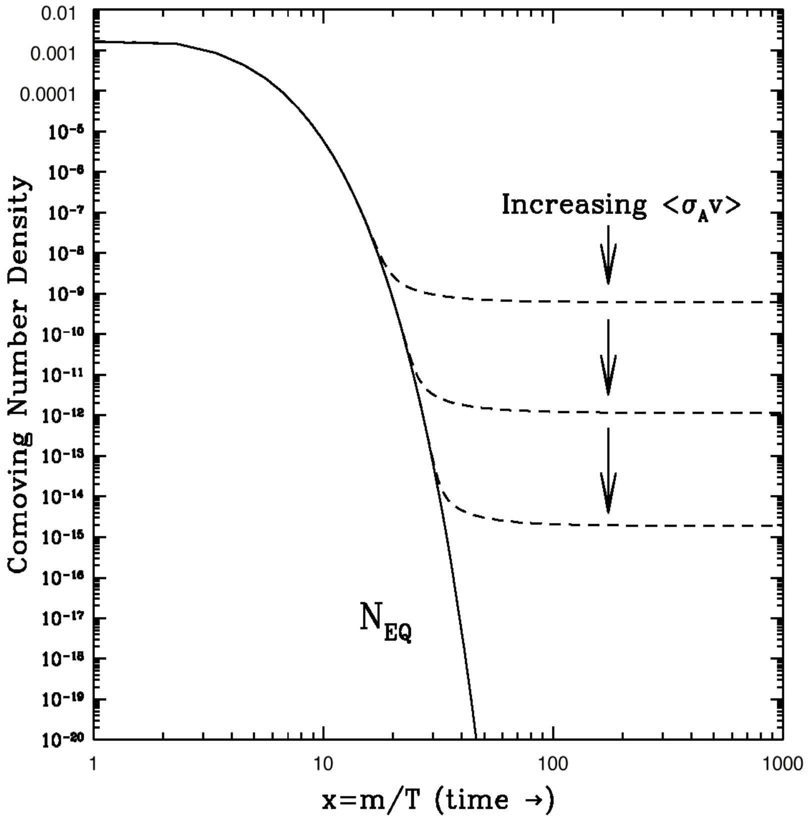
~keV

100 eV

WIMPs

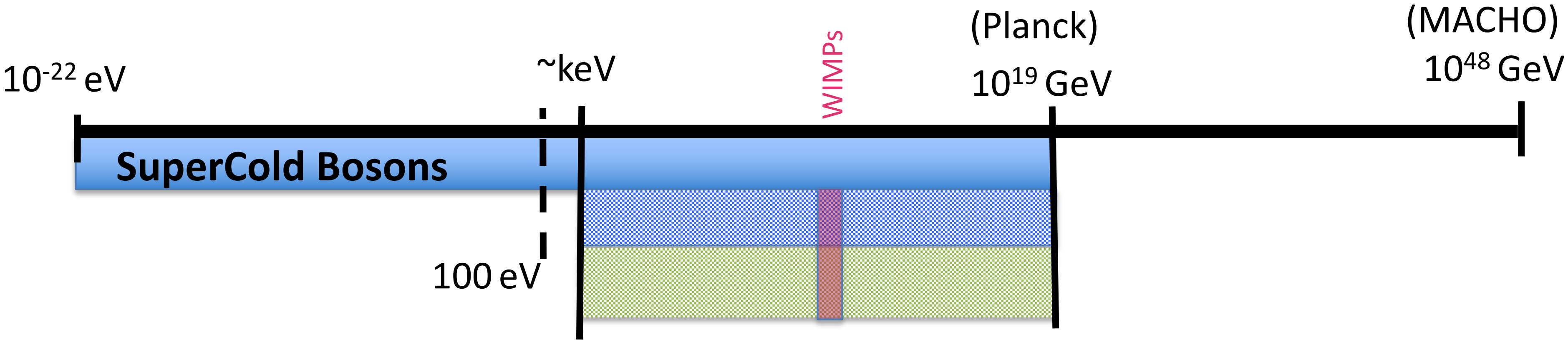
(Planck)
10^{19} GeV

(MACHO)
10^{48} GeV



- Relic DM density suggest weak scale cross sections
- New physics (and particles) at the weak scale could solve the hierarchy problem

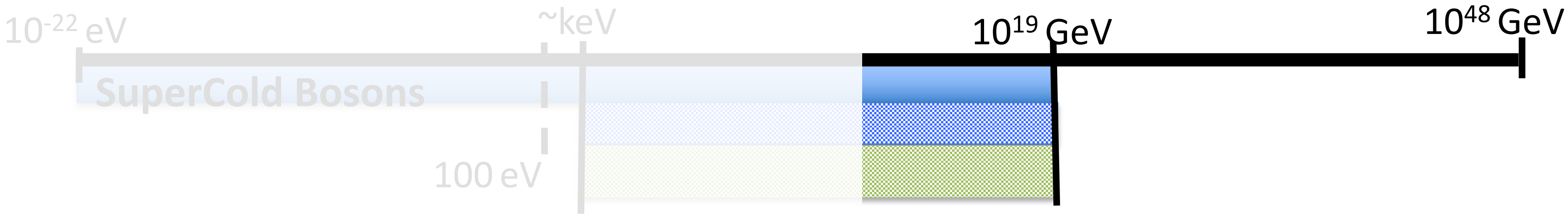
Today: Dark Matter Mass Parameter Space



- Assymetric Dark Matter Kaplan, Zurek et al: 0901.4117
- Freeze In Hall, et al: 0911.1120
- ELDER (Elatically Decoupling Relic) Kuflik et al 1512.04545
- Velocity dependent annihilation rates
- Excited State dependent annhiliation rates

US Cosmic Visions: New Ideas in Dark Matter: 1707.04591

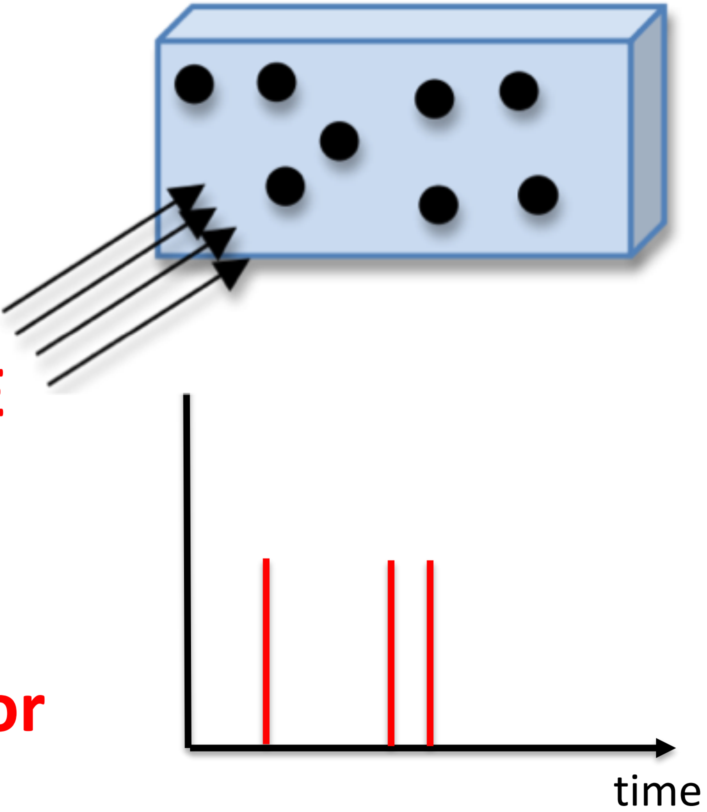
Experimental Design Drivers for Direct Detection



Design Drivers for M_{DM} >10 GeV

M_{DM} > 10 GeV: Tiny, Tiny Rates

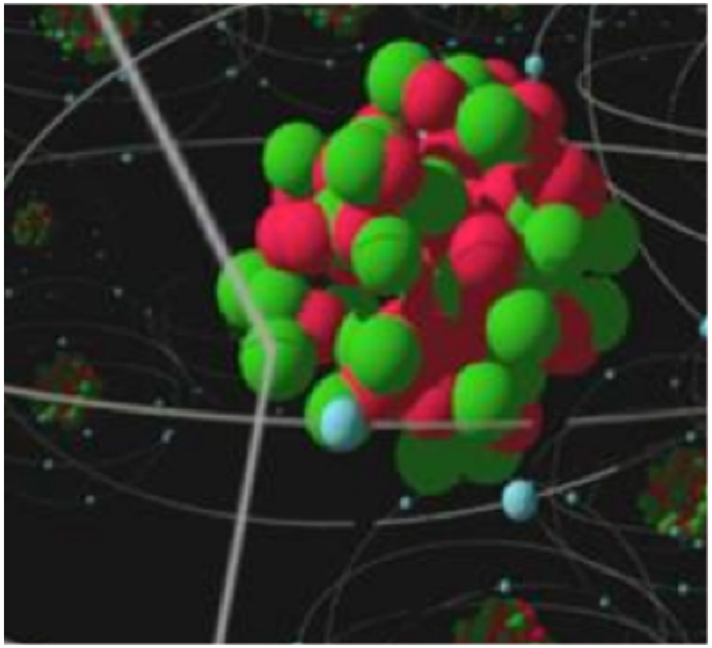
- $n_{DM} = \rho_{DM}/M_{DM}$:
  As M_{DM} gets bigger, n_{DM} gets smaller
- Interaction Rate, $\underset{\text{Really Small}}{R} = \underset{\text{Small}}{\sigma}\,\underset{\text{Small}}{n_{DM}}\,\underset{\textbf{HUGE}}{N_{exp}}$



Design Driver #1: Big Exposure

You need a really big particle detector

M_{DM} > 10 GeV: Coherent Elastic Scattering

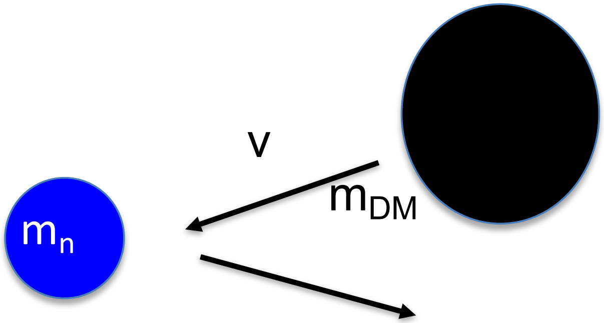


Scatter coherently off all the nucleons in a nucleus: $R \propto A^2$

Design Driver #2: Heavy Nuclei

Big Idea: For both very heavy and very light mass dark matter, we're going to take advantage of coherence

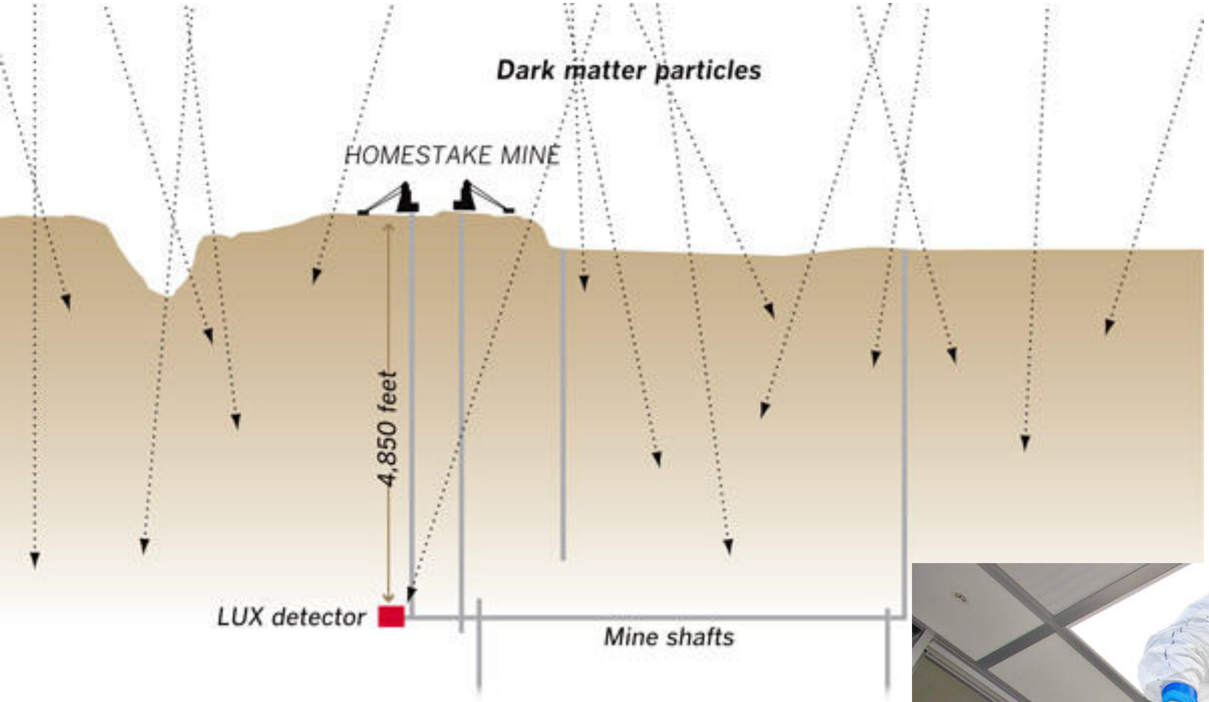
$M_{DM} > 10$GeV: Backgrounds



- Characteristic Recoil Energy: O(10keV)
- Same recoil energy as radiogenic backgrounds

Design Driver #3:
Minimal Radiogenic
Backgrounds

Get rid of the Hay

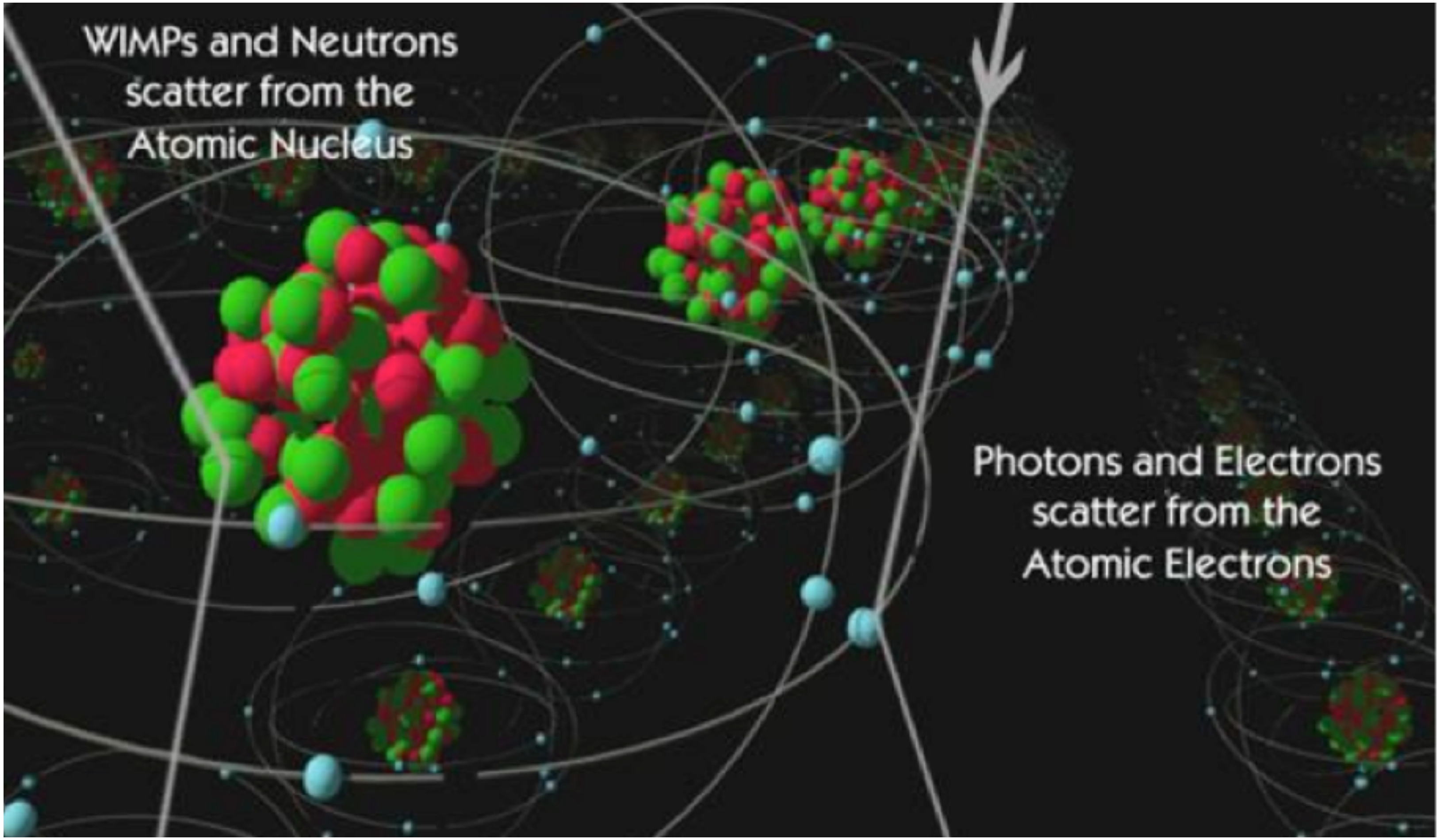


Go underground to shield detector from cosmic rays and their decay products

Use only radiopure materials and fabrication techniques

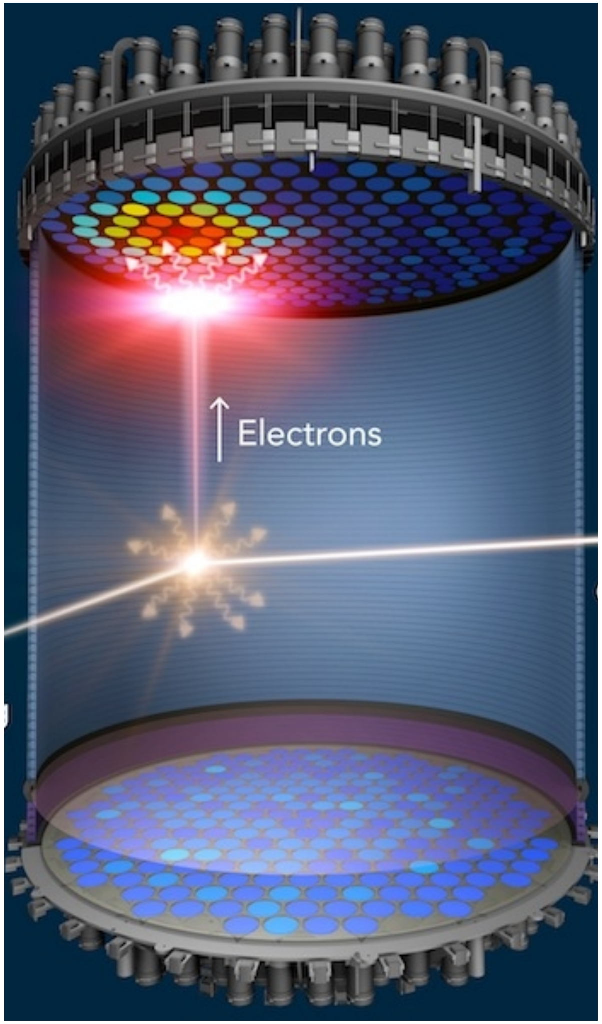
DEMO: Cloud Chamber

M_{DM} >10 GeV: Electronic Recoil / Nuclear Recoil Discrimination



Measure both scintillation light and ionization to distinguish nuclear recoils from electron recoils

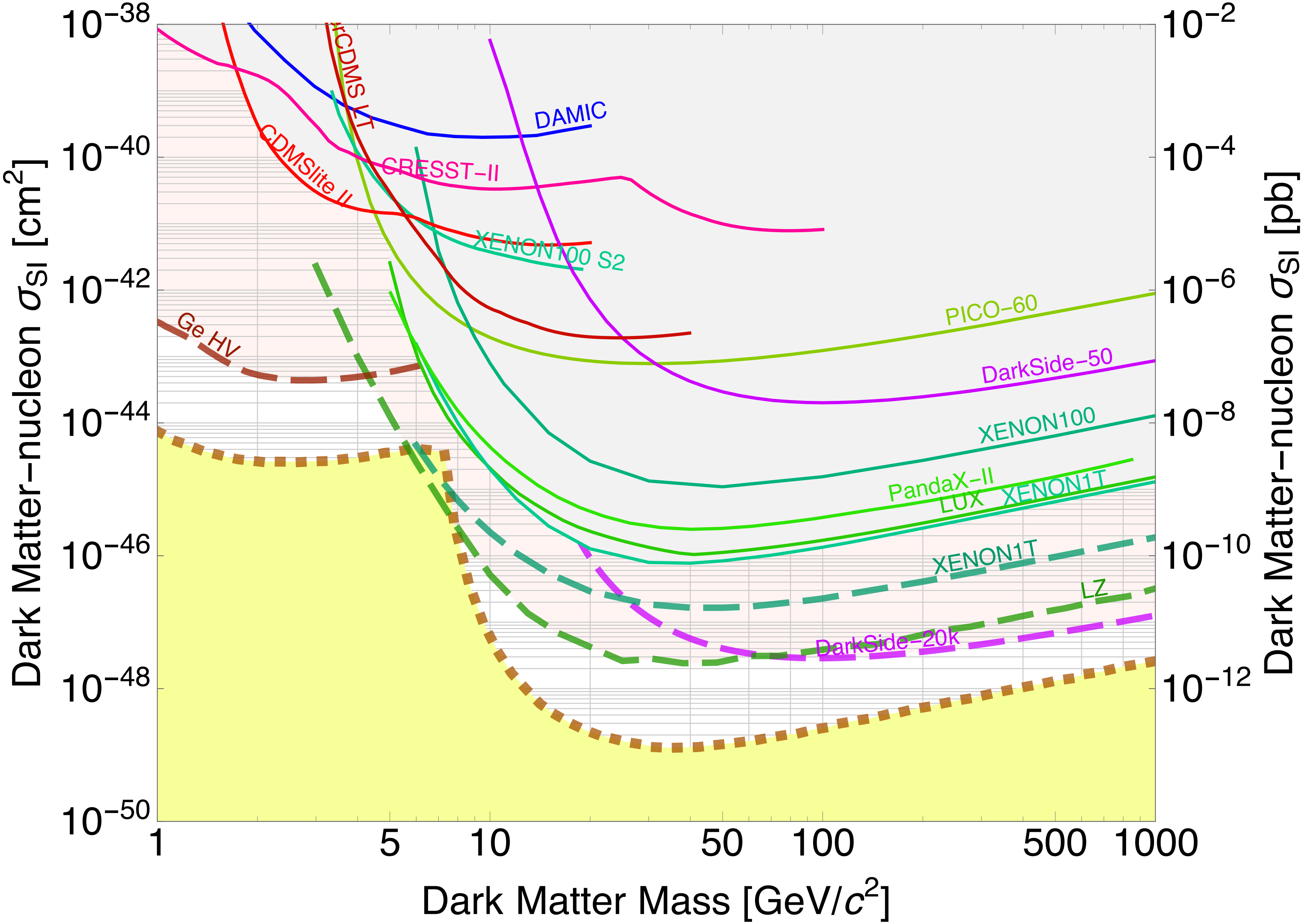
M_{DM} >~ 10 GeV: Liquid Noble TPCs

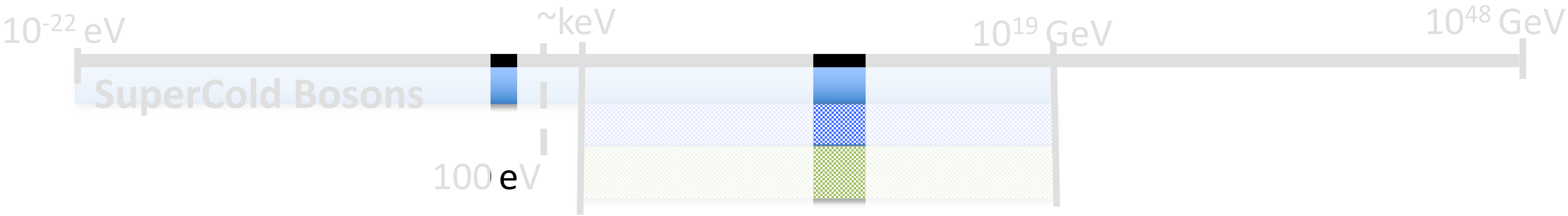


LZ (XENON 1T,PandaX)

- Exposure: (7 tons)
- High A: Xe
- Underground:
- Radioclean: self shielding
- Electronic/Nuclear Recoil Discrimination

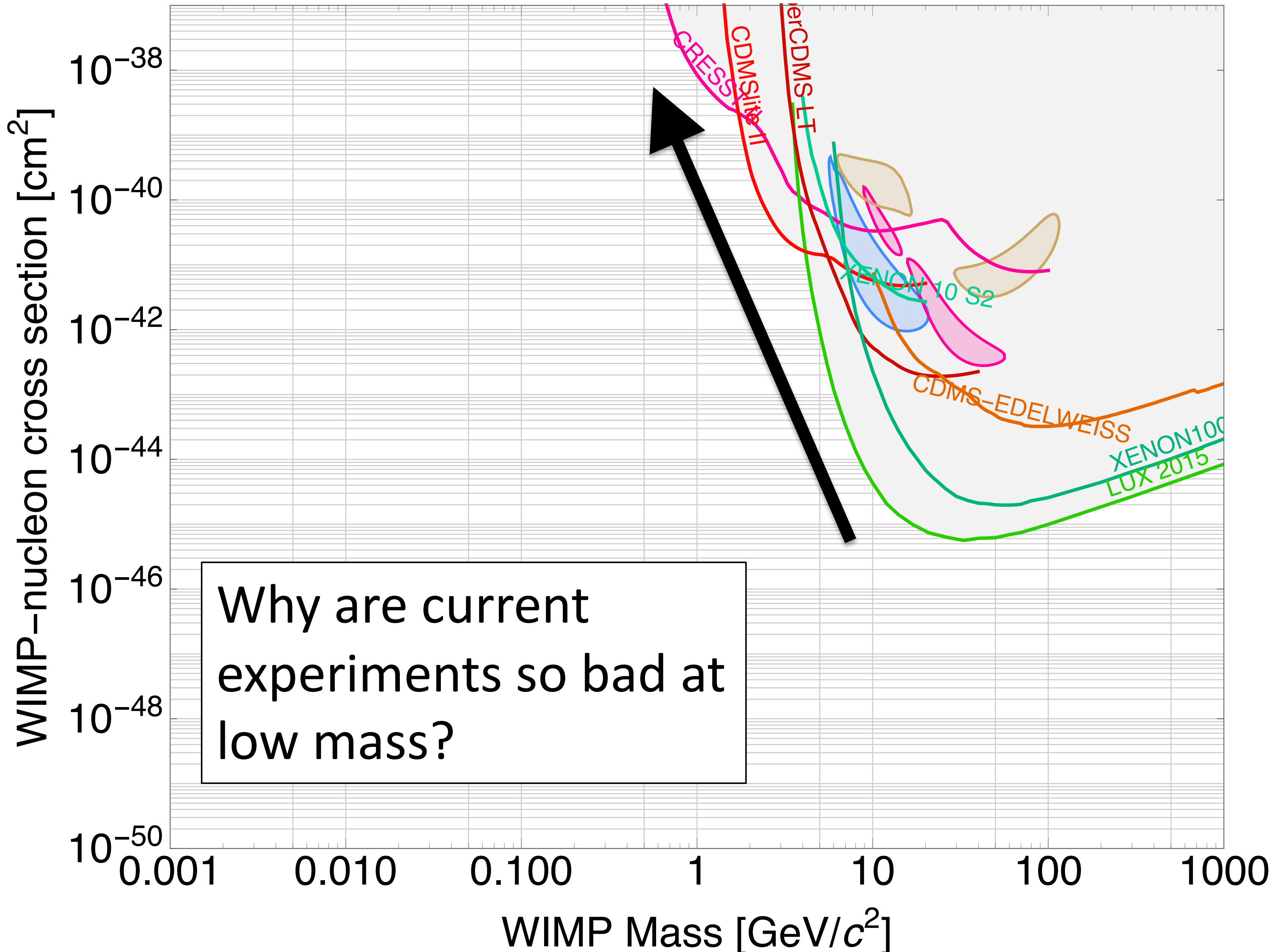
G2 High Mass Sensitivity Estimates





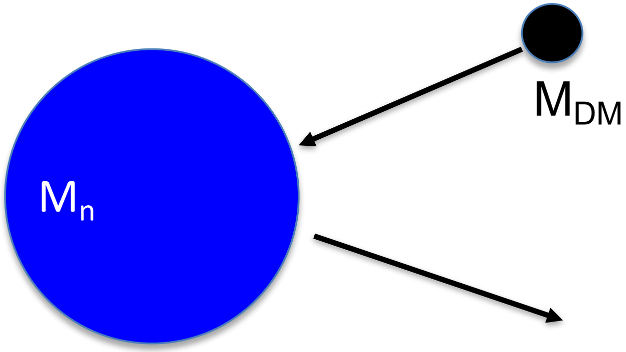
Design Drivers for
100 MeV < M_{DM} < 10 GeV Thermal Relics
and
1-10 eV ultra-cold bosons

Current Status: Elastic Nuclear Recoil Direct Detection



Why are current experiments so bad at low mass?

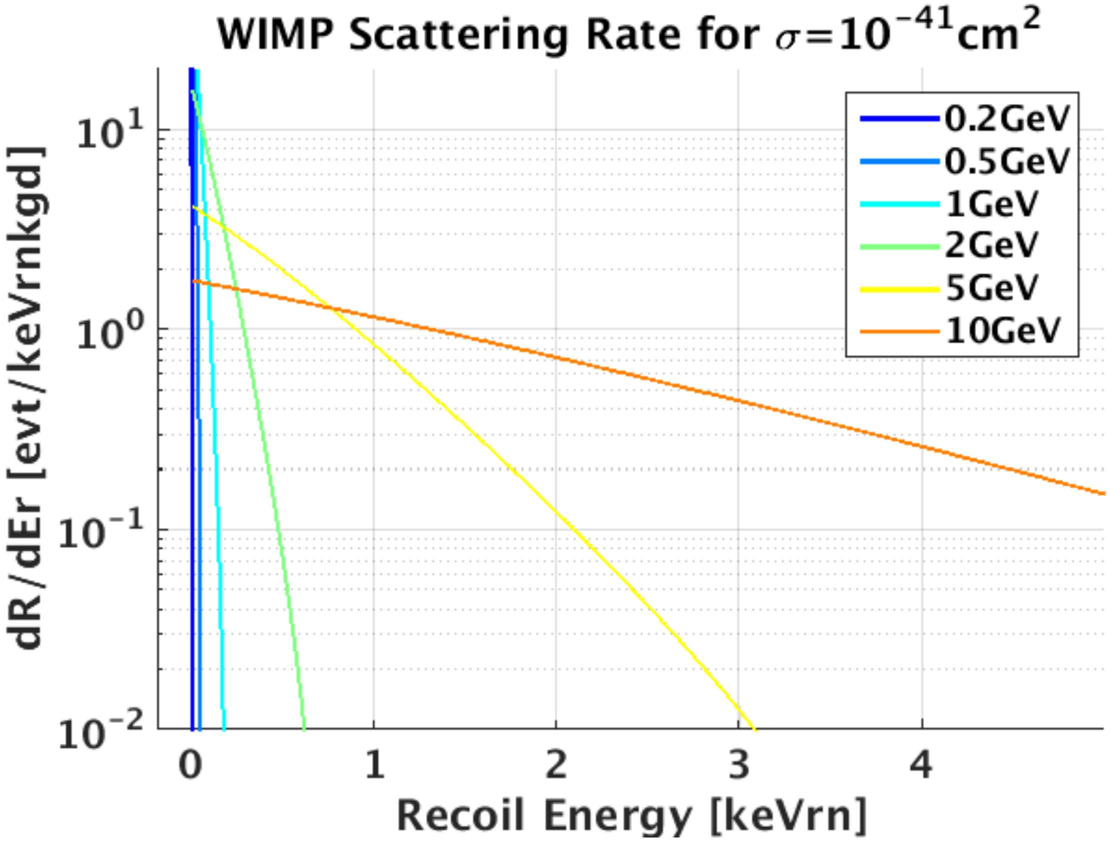
Tiny Recoil Energies



$$\Delta E = \frac{\Delta P^2}{2M_n} \lesssim \frac{2M_{DM}^2 v_{DM}^2}{M_n}$$

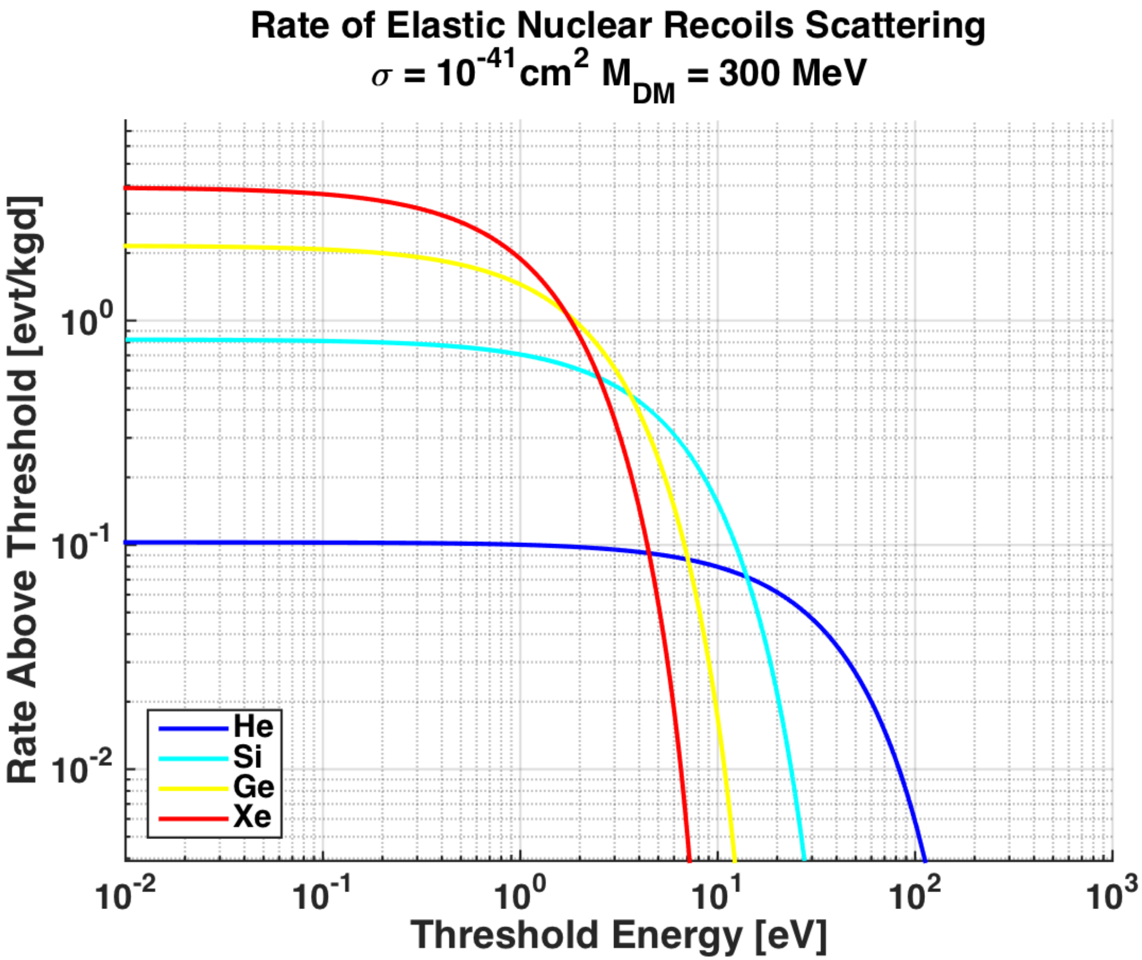
$$\lesssim \frac{4M_{DM}}{M_n} E_{DM}$$

- Large nuclei have large coherent rate enhancement
- Transfer of DM kinetic energy inefficient when $M_n >> M_{DM}$ for elastic scatters



#1 Dominant Design Driver: Energy Threshold

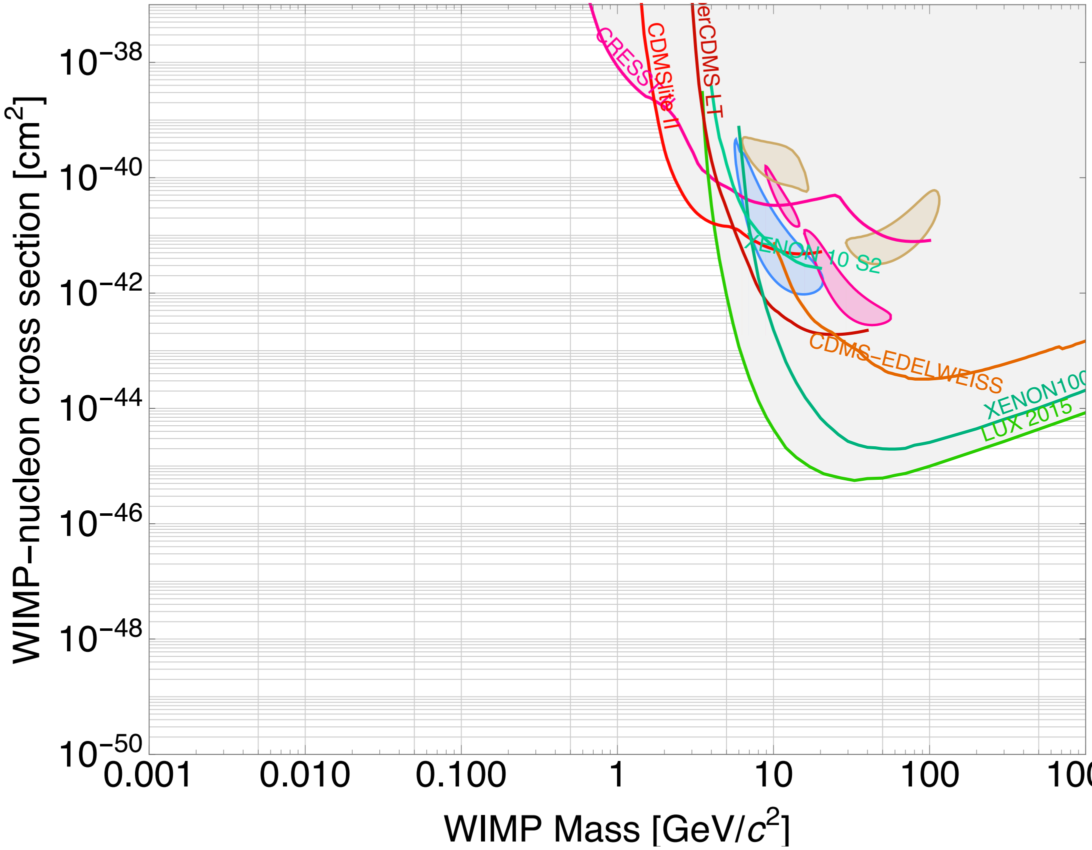
- Ge: larger rates with really small threshold requirements
- He: smaller rates with small threshold requirements



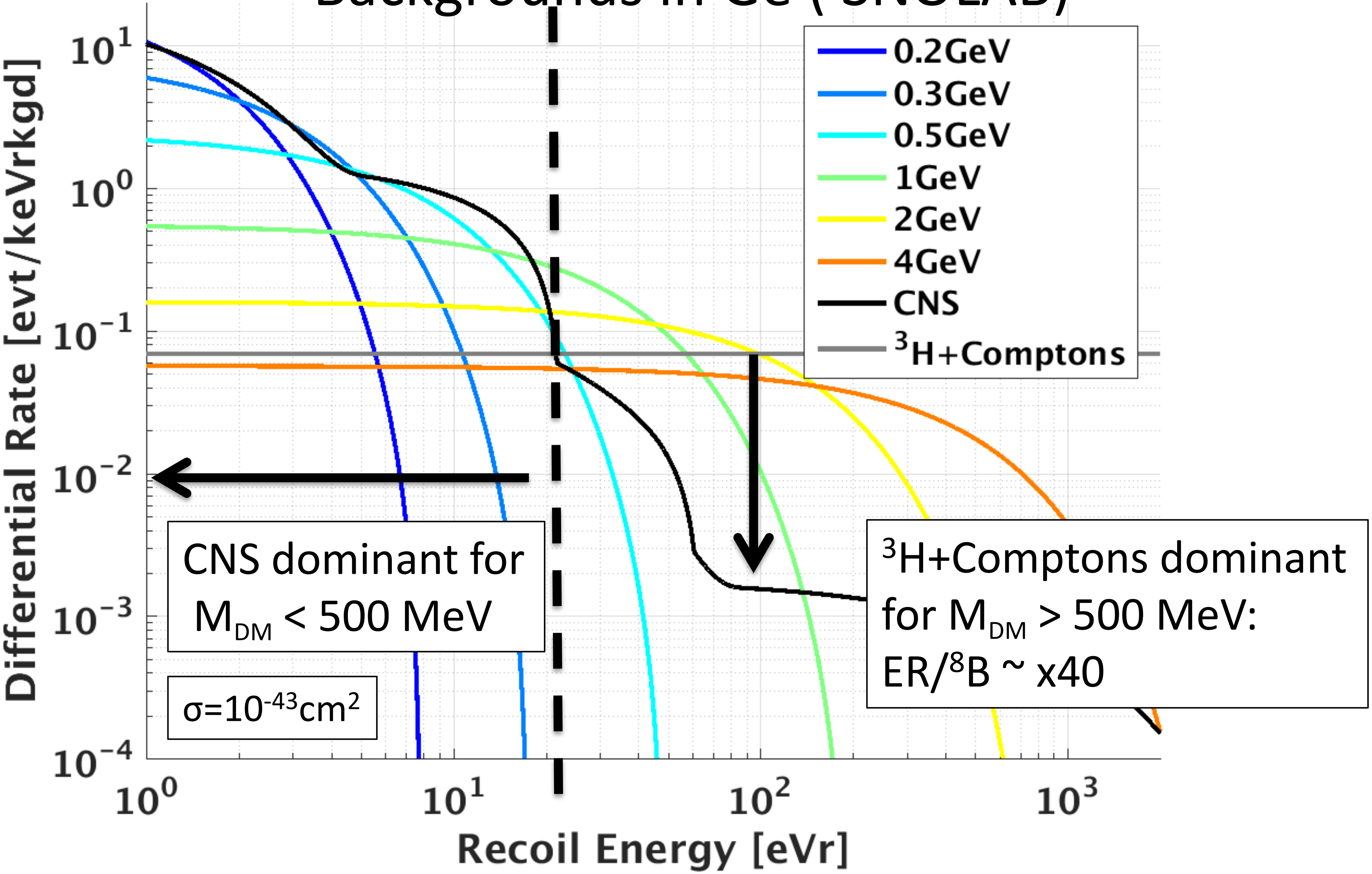
Everything Else Is Easier: Exposure

$$R = \sigma n_{DM} N_{exp}$$
$$= \sigma \frac{\rho_{DM}}{M_{DM}} N_{exp}$$

Interaction Rate
scales with $1/M_{DM}$



Everything Else Easier: Estimated Radiogenic Backgrounds in Ge (SNOLAB)

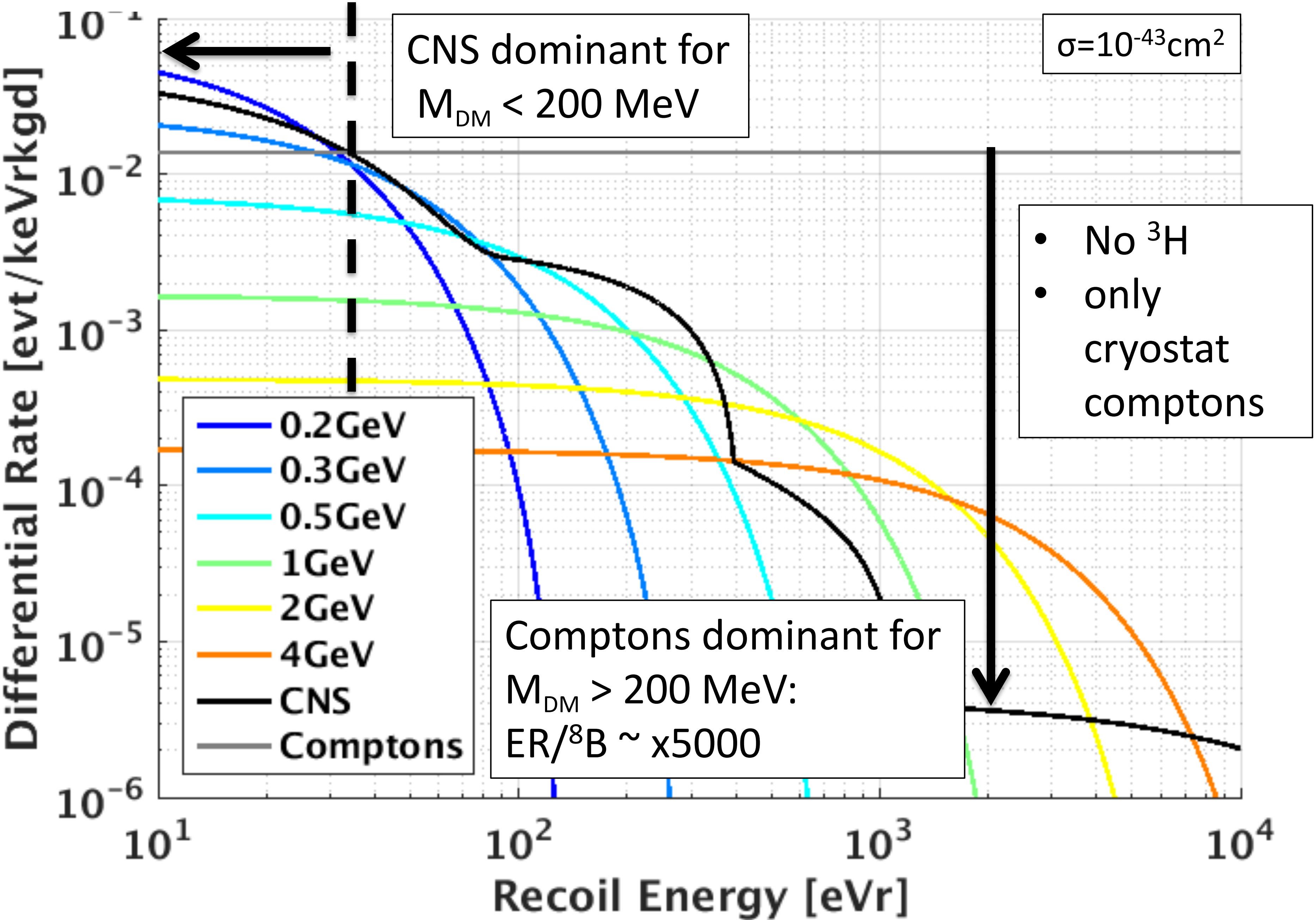


CNS dominant for M_{DM} < 500 MeV

$\sigma=10^{-43}\mathrm{cm}^2$

^{3}H+Comptons dominant for M_{DM} > 500 MeV: ER/^{8}B ~ x40

Estimated Radiogenic Backgrounds in He (~ SNOLAB)



CNS dominant for
M_{DM} < 200 MeV

$\sigma=10^{-43}\text{cm}^2$

- No ^3H
- only cryostat comptons

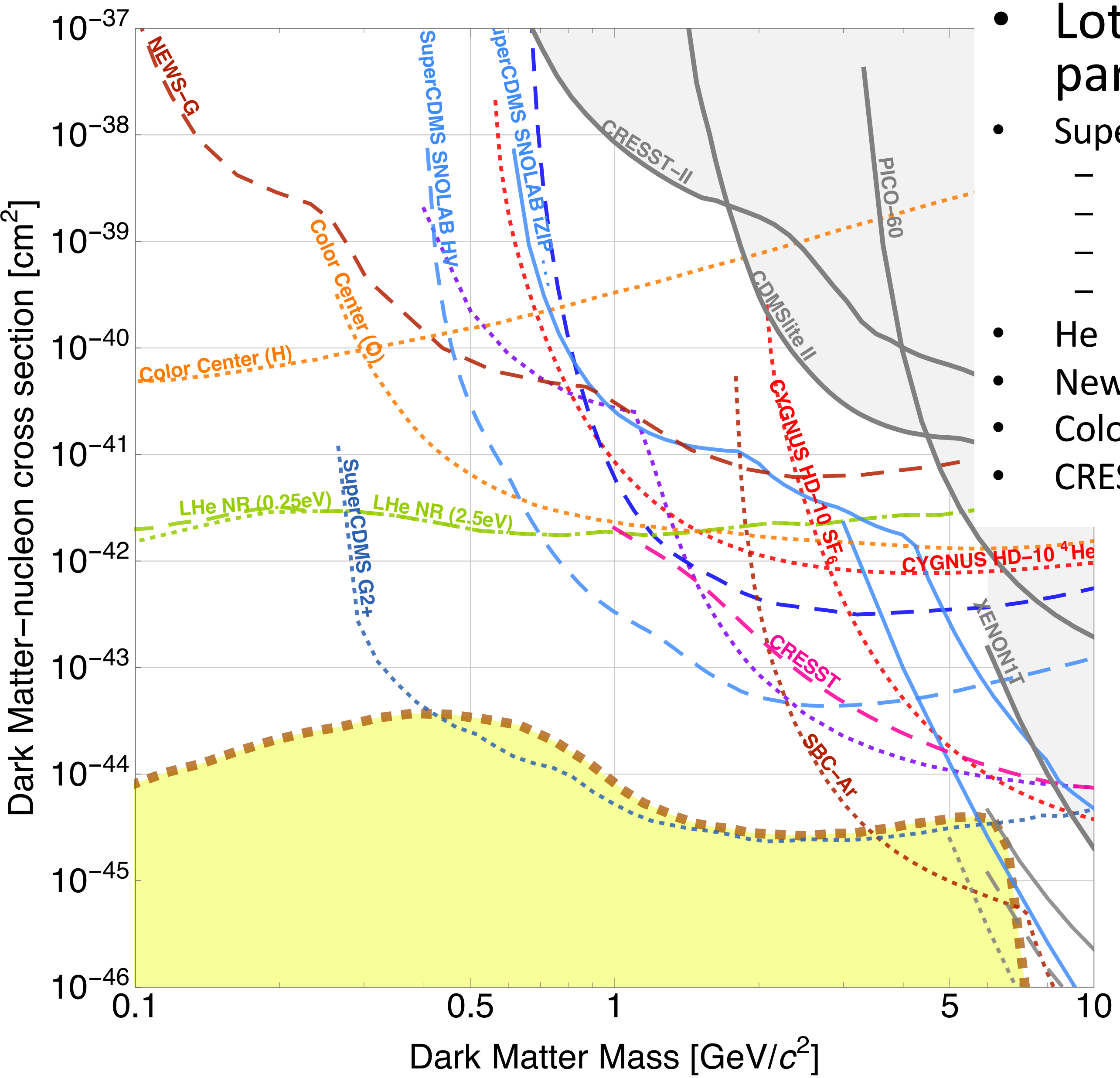
Comptons dominant for
M_{DM} > 200 MeV:
ER/^{8}B ~ x5000

Design Drivers for the Ultimate : 100 MeV < M_{DM} <6 GeV Experiment

	Ge	He
NR Energy Threshold	~ 10 eV	~ 100 eV
ER/NR Discrimination	~ x40	~ x5000

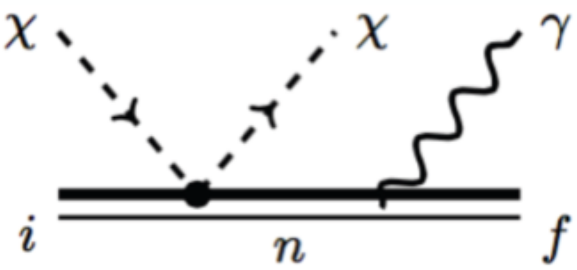
These numbers a bit handwavy
- LN Gain -> Different dR/dEr -> dR/d? stretching
- Depends upon radiopurity …

Sensitivity Estimates

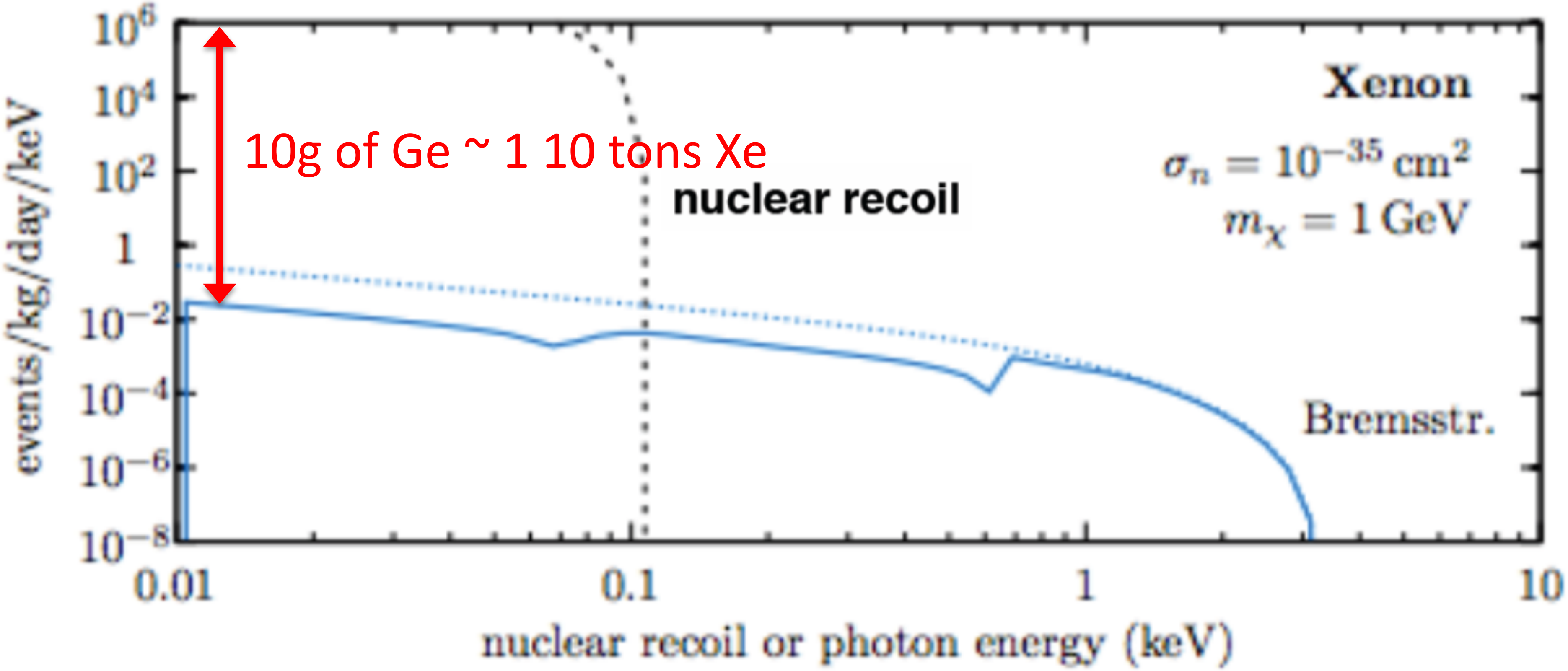


- Lots of unexplored parameter space
- SuperCDMS HV
  - 10 eVt (Ge)
  - 8 Ge x 1.4kg x 5yr x 80%
  - 1610.00006
  - Ideas to regain ER/NR
- He
- News G: Ne SPC
- Color Center
- CRESST

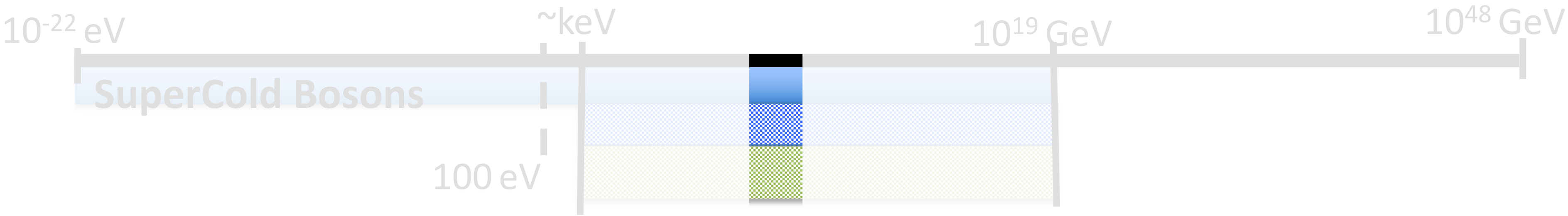
No Energy Sensitivity? Go Offshell?



- Kouvaris,Pradler [1607.01789]
- Significant rate penalty
  - Way more exposure
  - Backgrounds?
- DON’T DO IT UNLESS YOU MUST!

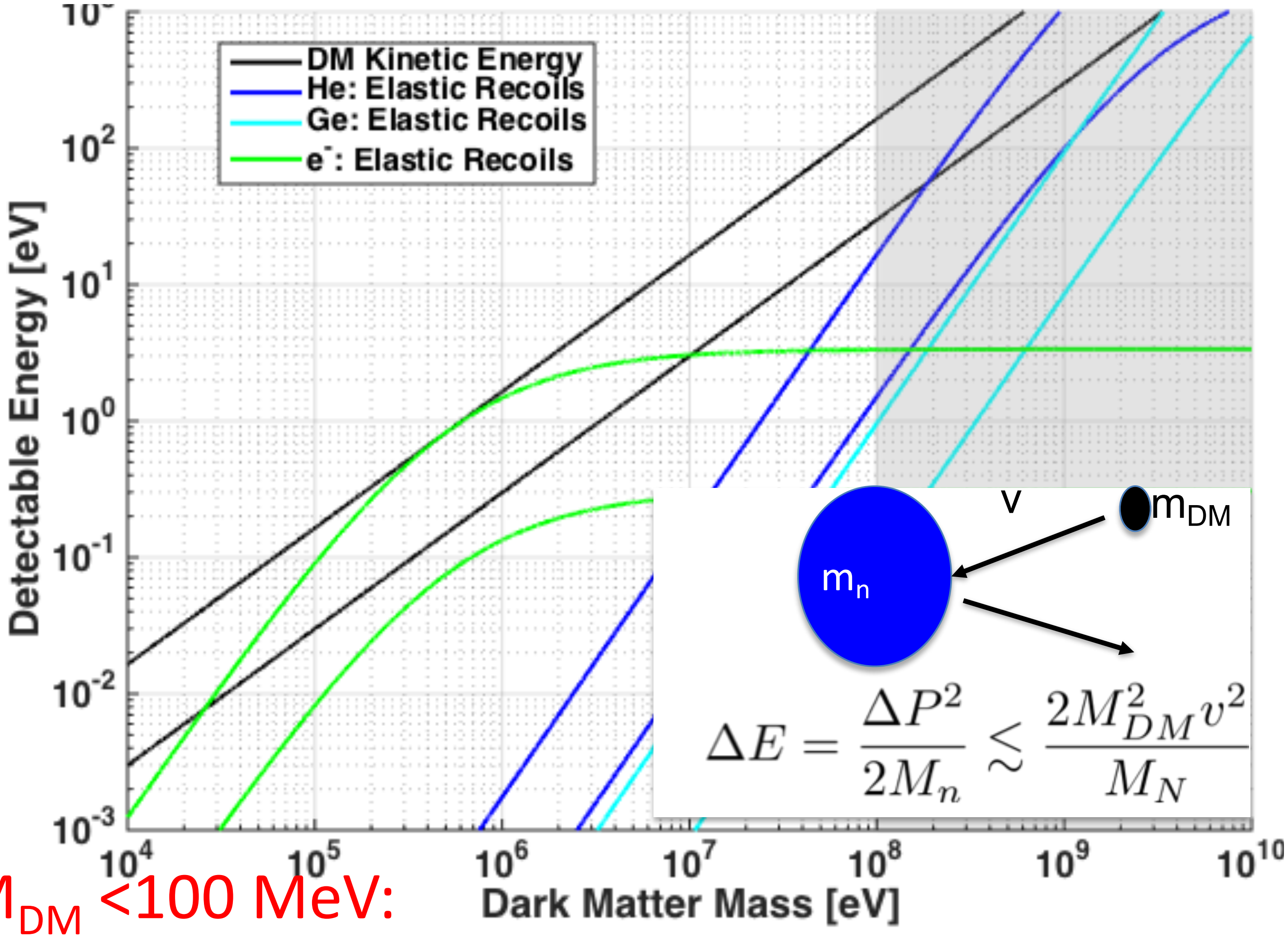


10g of Ge ~ 1 10 tons Xe



Design Drivers for
$1\ \text{MeV} < M_{DM} < 100\ \text{MeV}$

Nuclear Elastic Scattering Ionization Thresholds

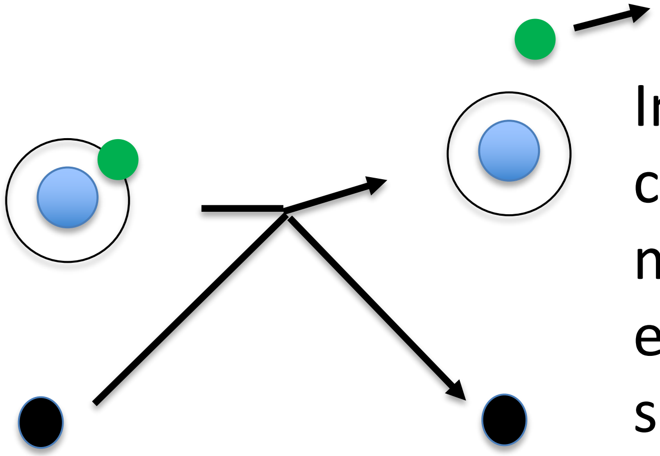


$$\Delta E = \frac{\Delta P^2}{2M_n} \lesssim \frac{2M_{DM}^2 v^2}{M_N}$$

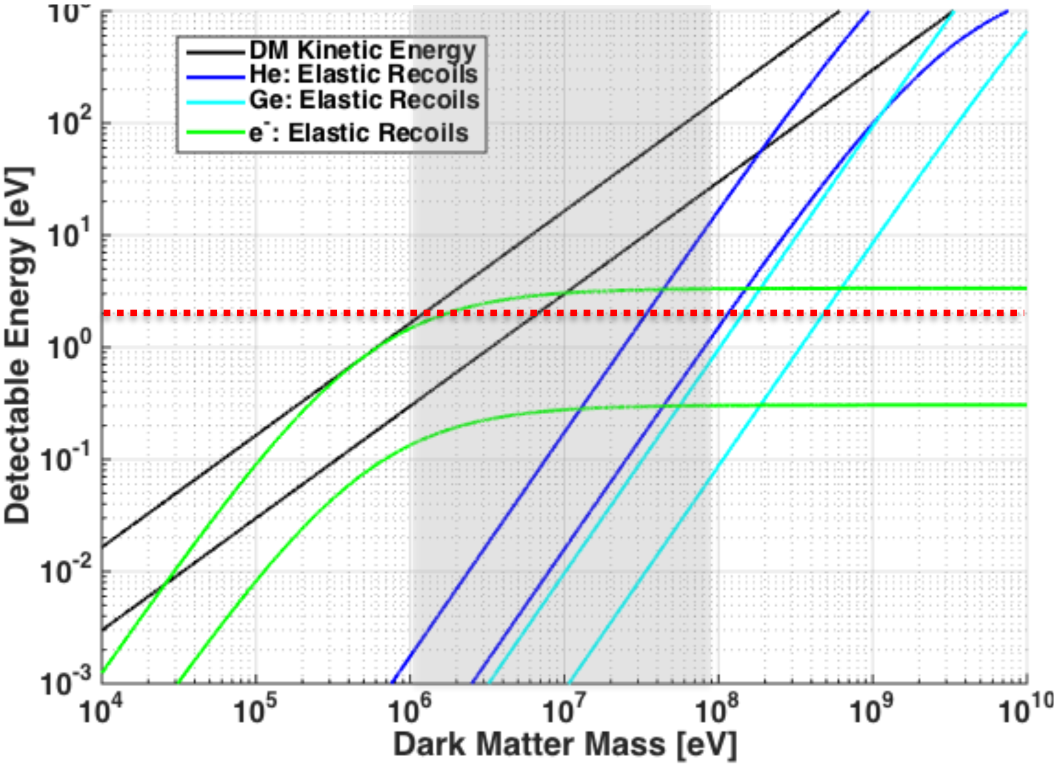
For M_{DM} <100 MeV:

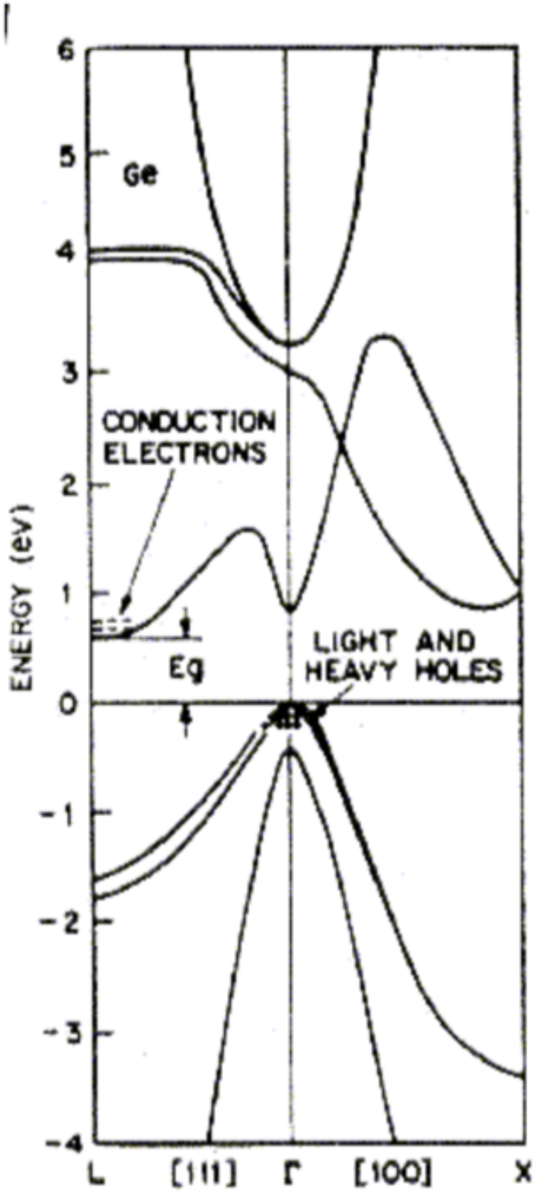
- Elastic He Nuclear Recoils won’t produce ionization
- Elastic Ge Nuclear Recoils won’t produce 1eV of phonons
- Look for e^- scatters instead!

Inelastic Electronic Scattering



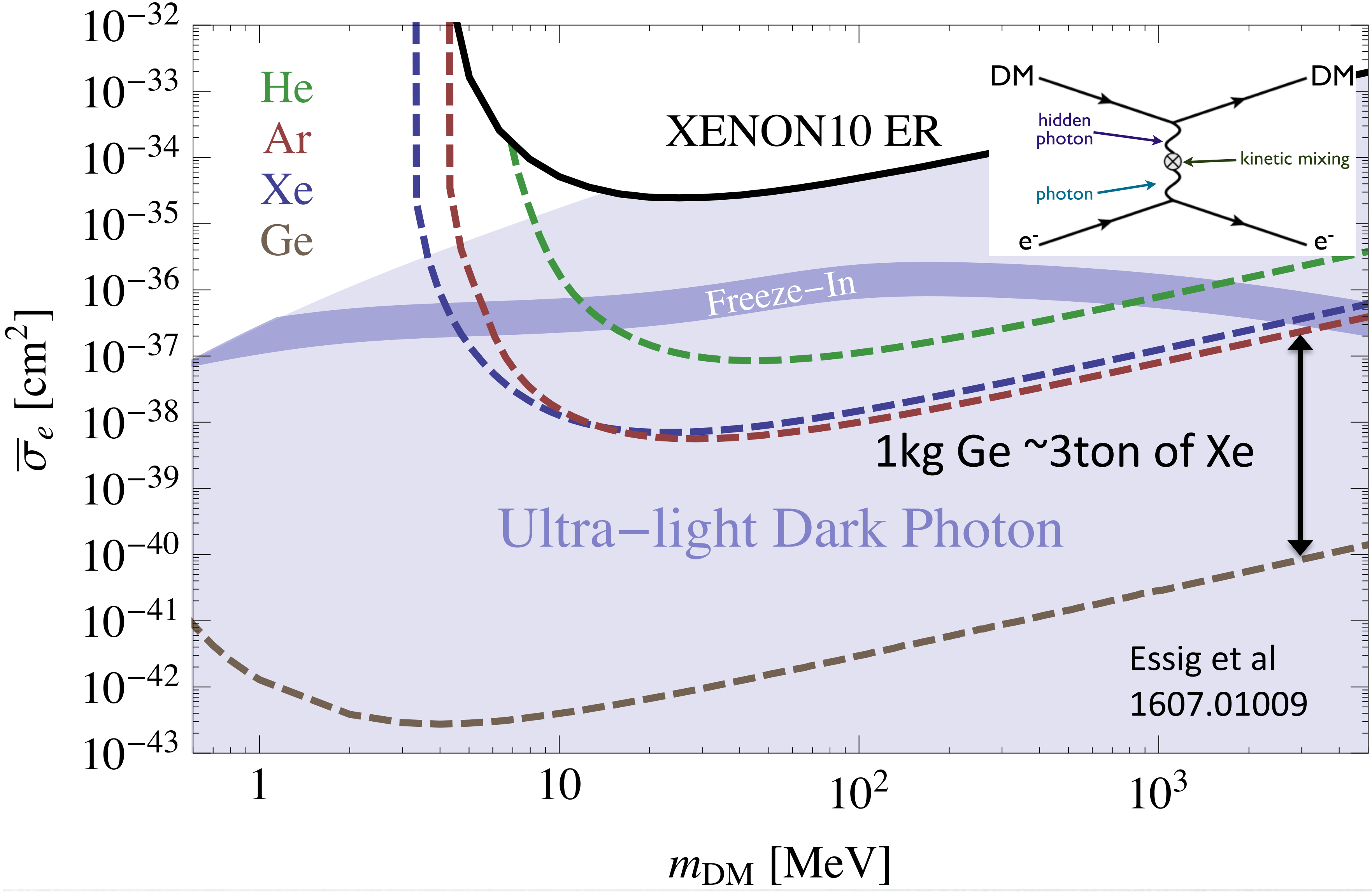
Inelastic e$^-$ recoils you can always conserve momentum and energy. Mass threshold set by bandgap





Smaller Bandgaps are Better

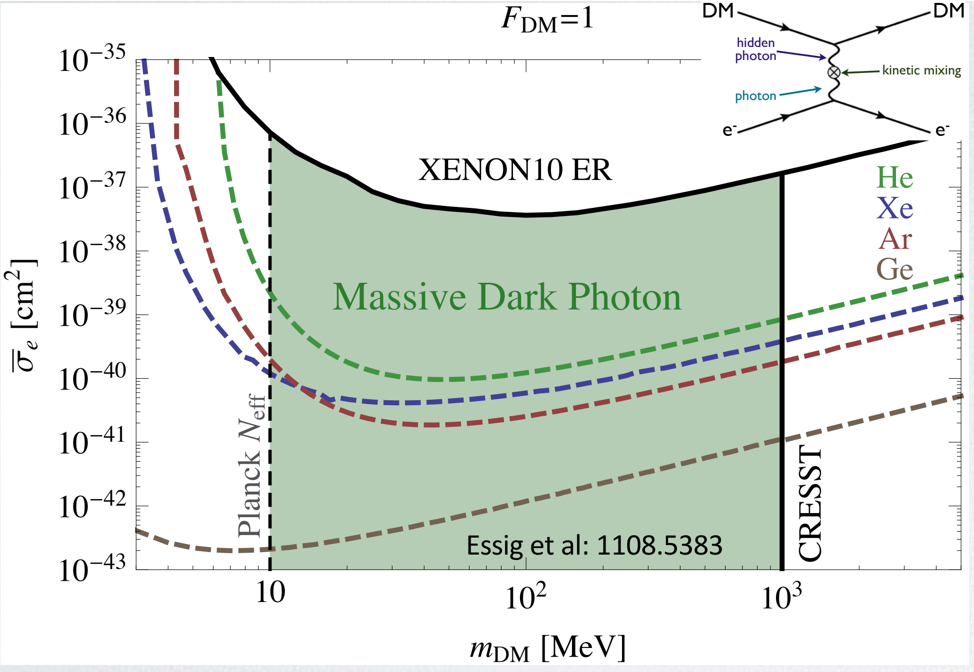
$F_{\mathrm{DM}} \propto 1/q^2$ (Ultra-light Mediator)



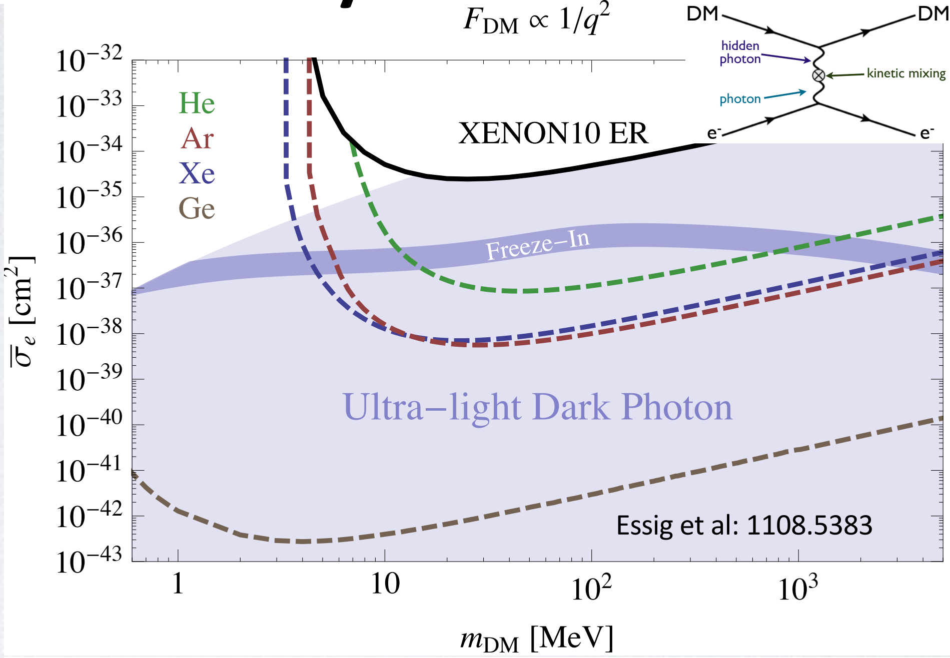
1kg Ge ~3ton of Xe

Essig et al
1607.01009

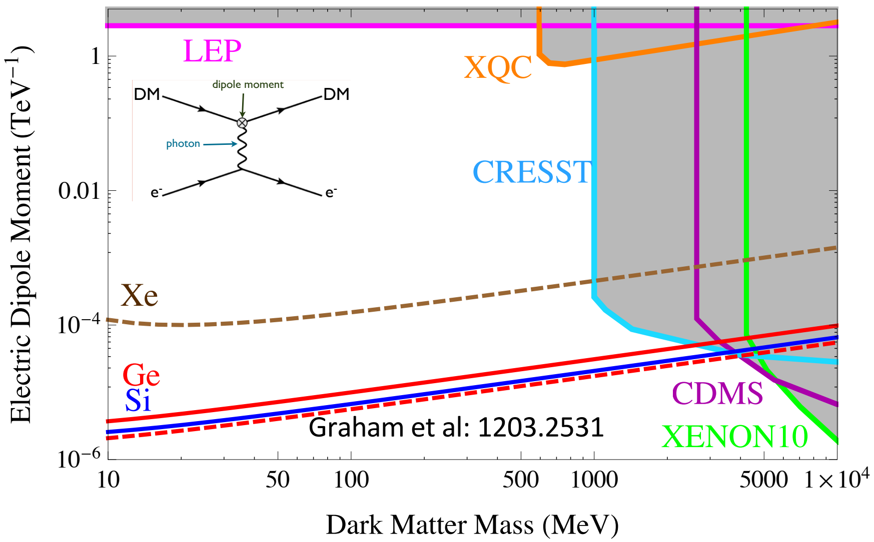
Potential ER Sensitivity Limits



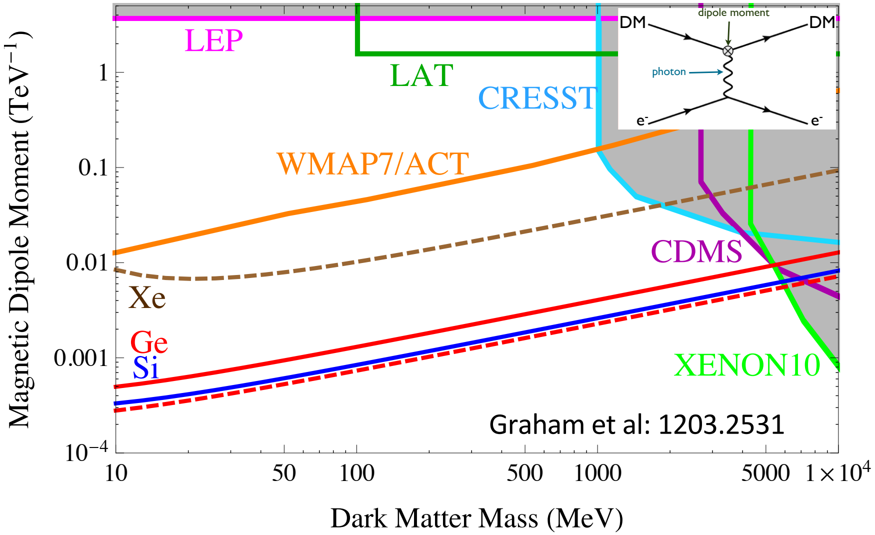
Essig et al: 1108.5383



Essig et al: 1108.5383

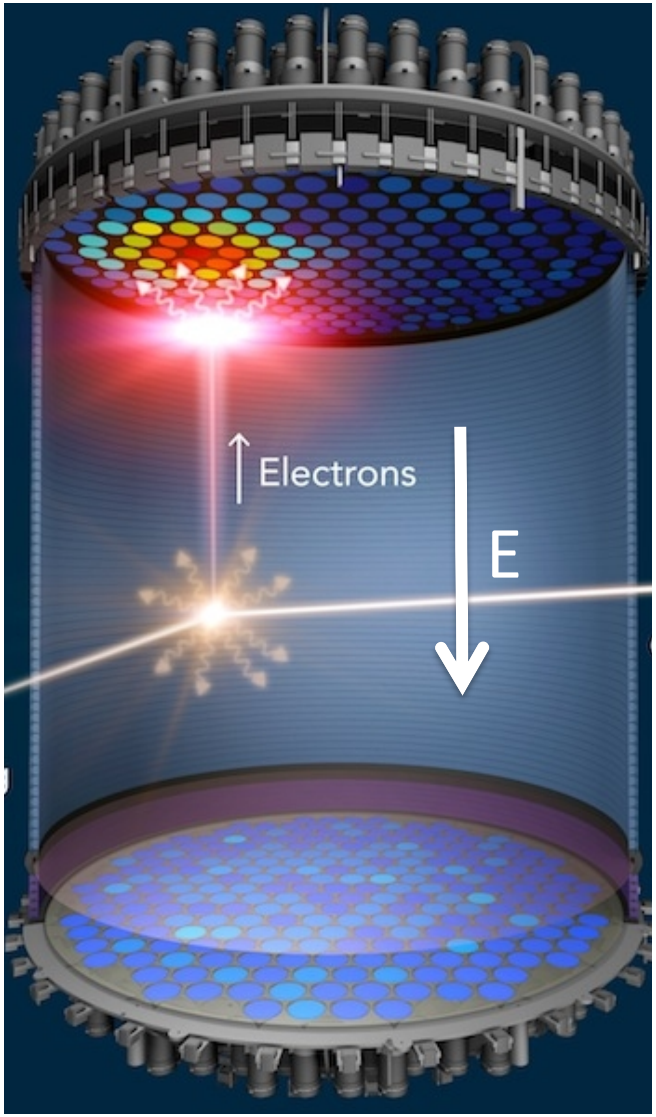


Graham et al: 1203.2531

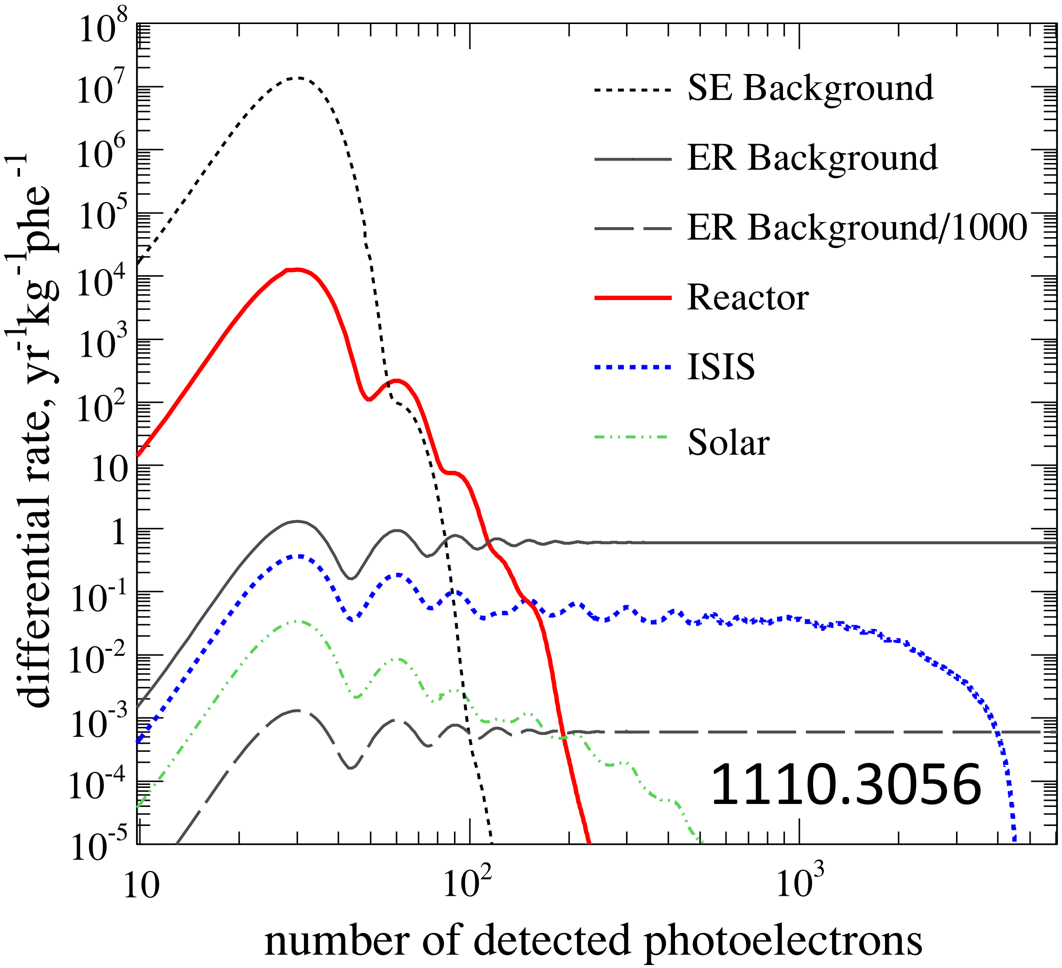


Graham et al: 1203.2531

Problem: Detector Backgrounds in TPCs



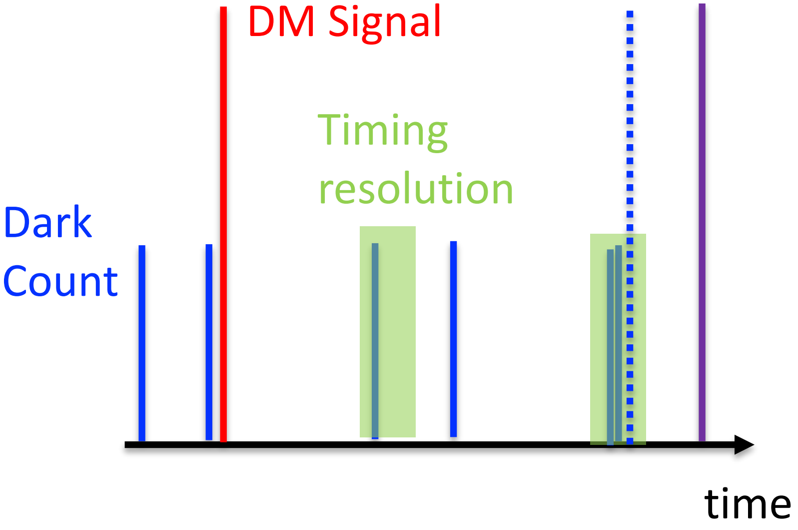
e$^-$ (S2) Background Rate in Zeplin III



R_{1e-} = 5.7 Hz -> YIKES!

Leakage is Non-Poissonian

Dark Leakage Needs to be Poissonian



N e^- background

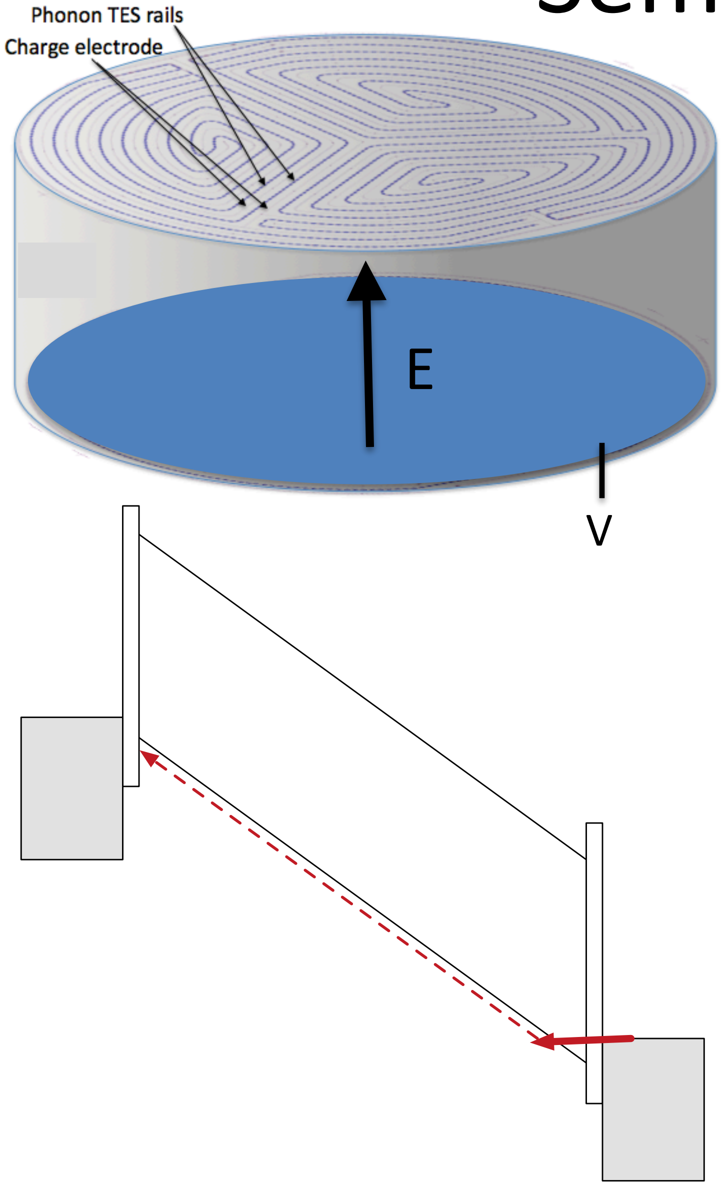
- N $1e^-$ events occur within detector timing resolution (Poissonian Leakage)
- N e^- leakage event (Non-Poissonian Leakage)

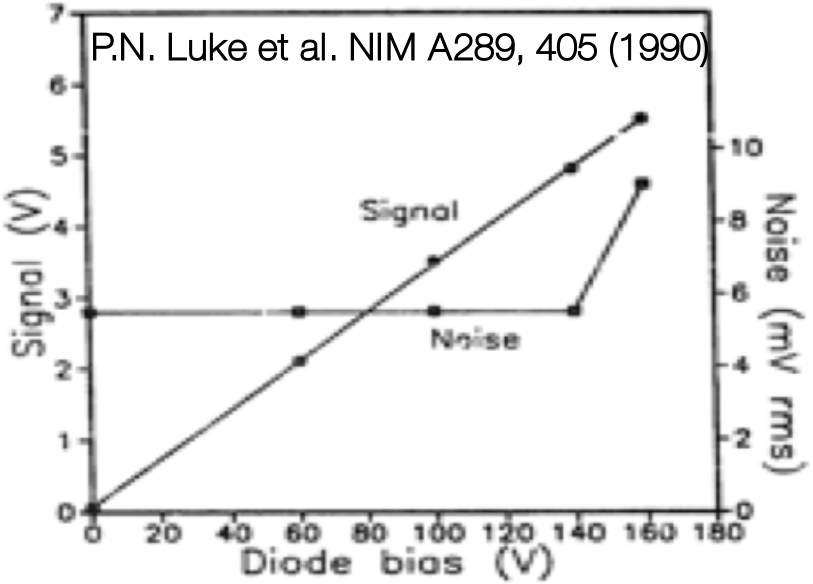
Xenon TPCs:

- R_{1e-} =10Hz
- Δt =100ns
- R_{2e-}(Poissonian) =10^{-5}Hz

Due to fast timing Xe TPCs can handle a relatively high $1e^-$ rate and still have $2e^-$ bin free. Unfortunately, leakage is non-poissonian (R&D needed)

Dark Leakage Rate in Biased Semiconductors

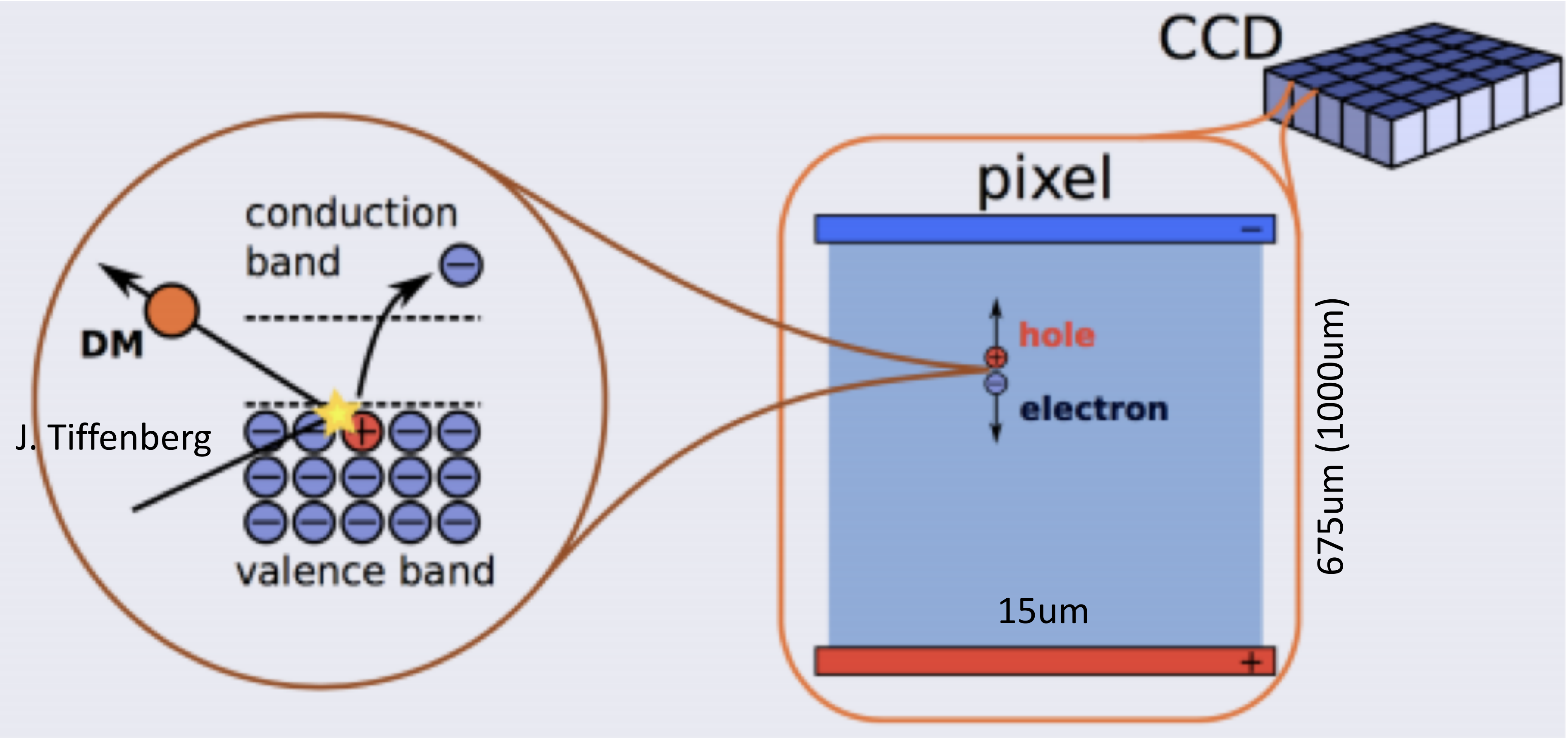



P.N. Luke et al. NIM A289, 405 (1990)

Man vs Nature

- Precision engineering required to have large E-fields and no leakage
- Often nature wins ☹

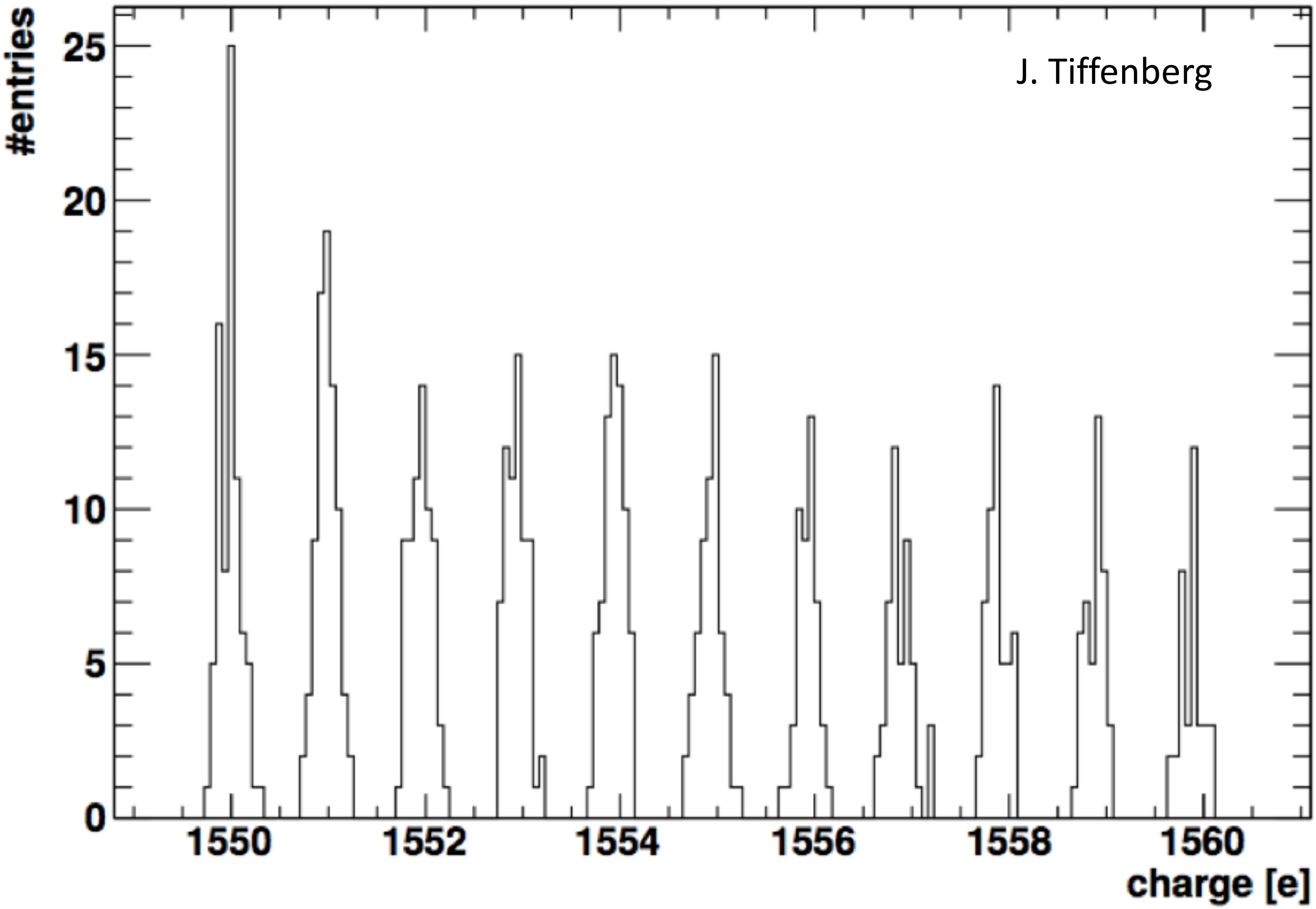
Si CCDs: Really Good Engineering



J. Tiffenberg

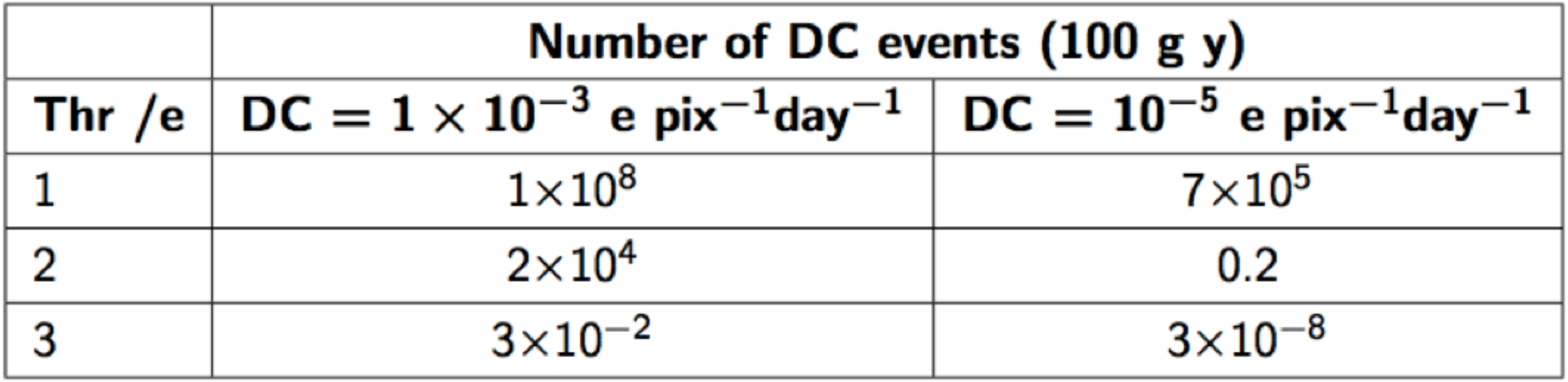
DAMIC &SINSEI:

SINSEI (DAMIC): Meets Single e^-/h^+ Sensitivity



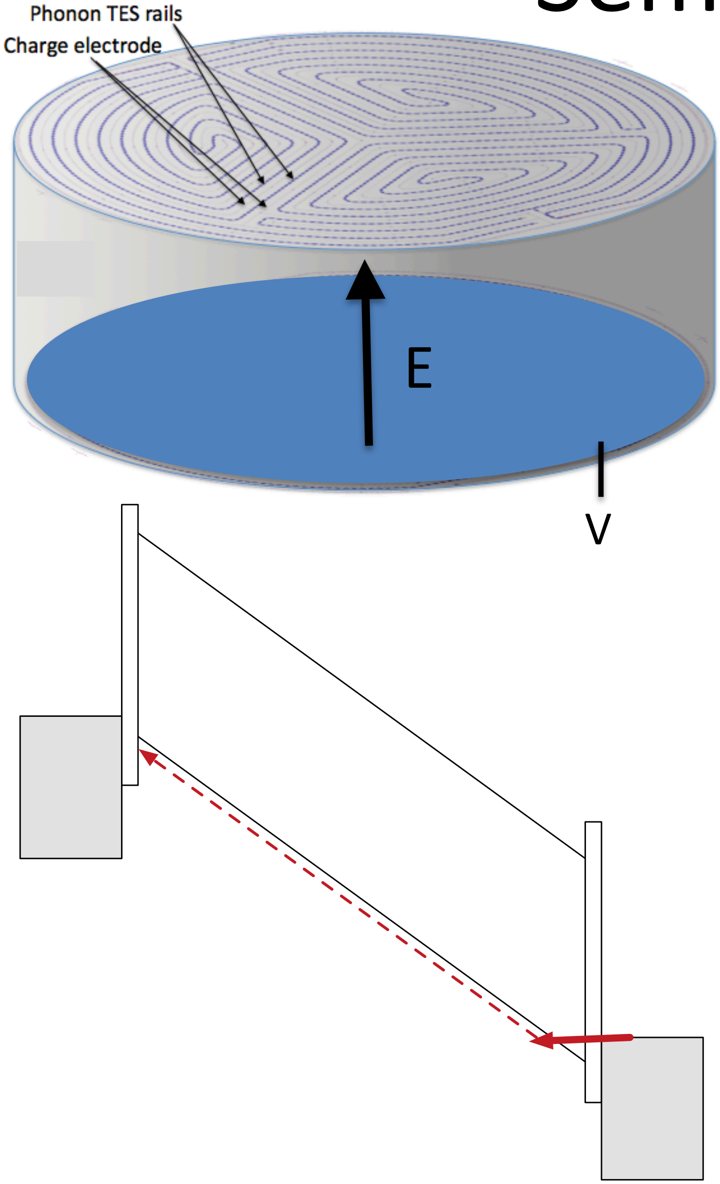
SINSEI/DAMIC: Dark Current

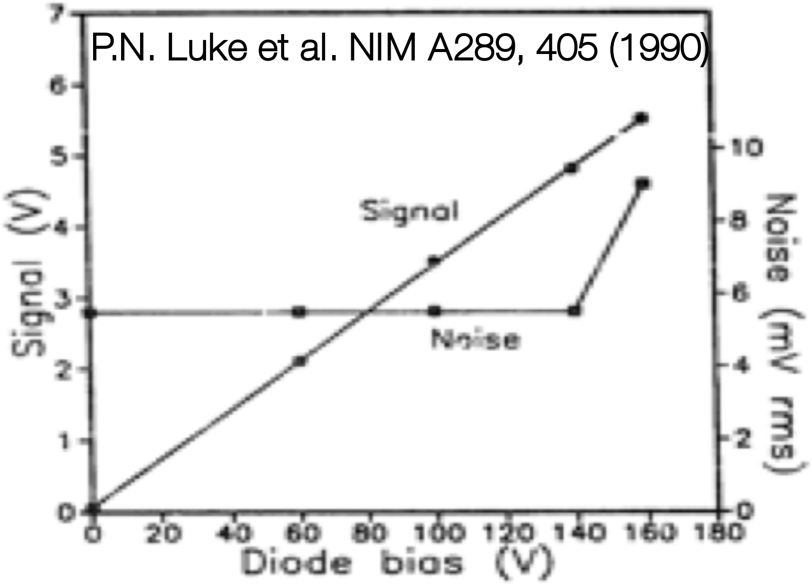
Dark Current: < 10-3 e/d/pixel
(arXiv:1611.03066)



	Number of DC events (100 g y)	
Thr /e	**DC = 1×10^{-3} e pix^{-1}day^{-1}**	**DC = 10^{-5} e pix^{-1}day^{-1}**
1	1×10^{8}	7×10^{5}
2	2×10^{4}	0.2
3	3×10^{-2}	3×10^{-8}

Problem: Dark Leakage Rate in Biased Semiconductors




P.N. Luke et al. NIM A289, 405 (1990)

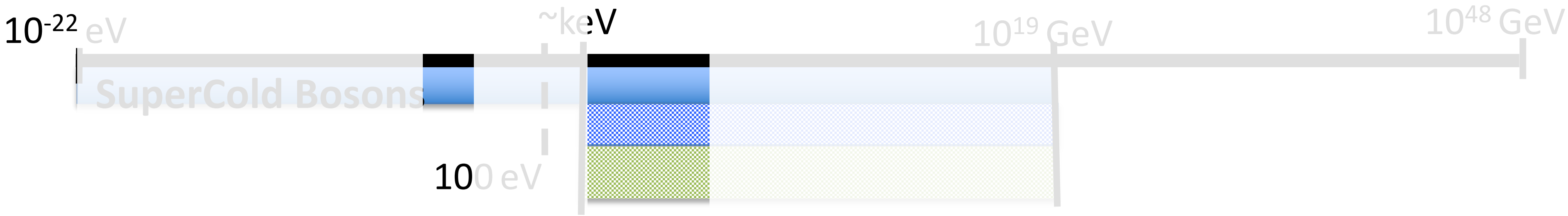
Man vs Nature

- Precision engineering required to have large E-fields and no leakage
- Often nature wins ☹

1MeV < M_{DM} <100 MeV Design Drivers

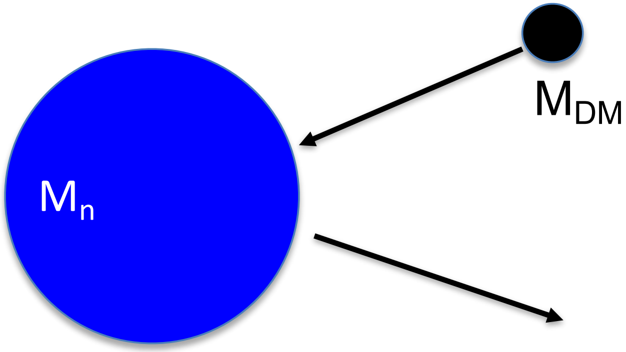
- Electron recoil detector
  - Sensitivity to few e^- excitation
    - Xe TPC, Si CCDs, SuperCDMS
  - Very small dark count rate that’s Poissonian
  - small bandgap
    - Si CCDs, SuperCDMS
- really sensitive nuclear recoil detector
- ~~Exposure:~~ 1 kgyr
- ~~Radioactive~~: dru

Or a really sensitive nuclear recoil detector



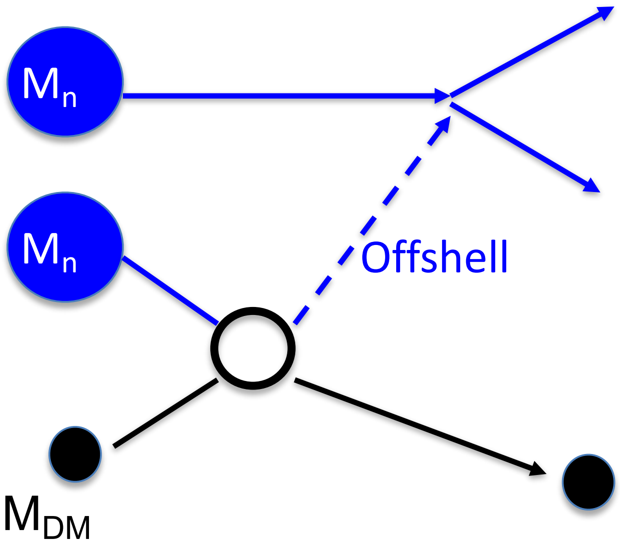
Design Drivers for 3keV < M_{DM} <1MeV Thermal Relics and 10 meV < M_{DM} < 1 eV Ultra-Cold Bosons

1) Off Shell Nuclear Processes



$$\Delta E = \frac{\Delta P^2}{2M_n} \lesssim \frac{2M_{DM}^2 v_{DM}^2}{M_n}$$
$$\lesssim \frac{4M_{DM}}{M_n} E_{DM}$$

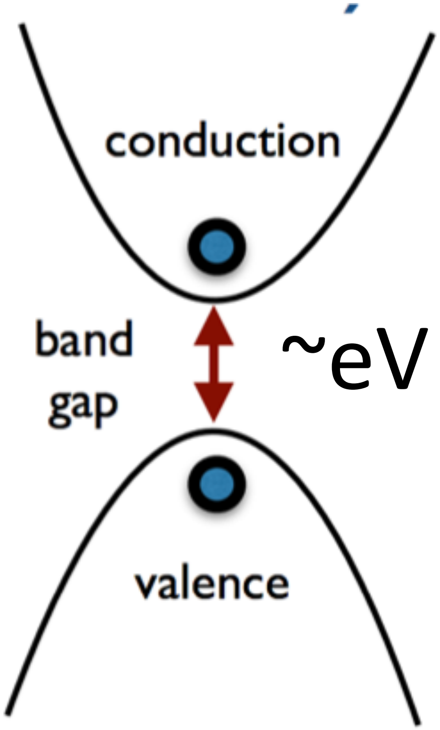
- Simple elastic NR scattering just doesn't give you a measureable recoil
- Use off-shell processes that produce 2 back to back offshell phonons
- 1604.08206 (Schutz and Zurek)



Design Driver: Energy Sensitivity

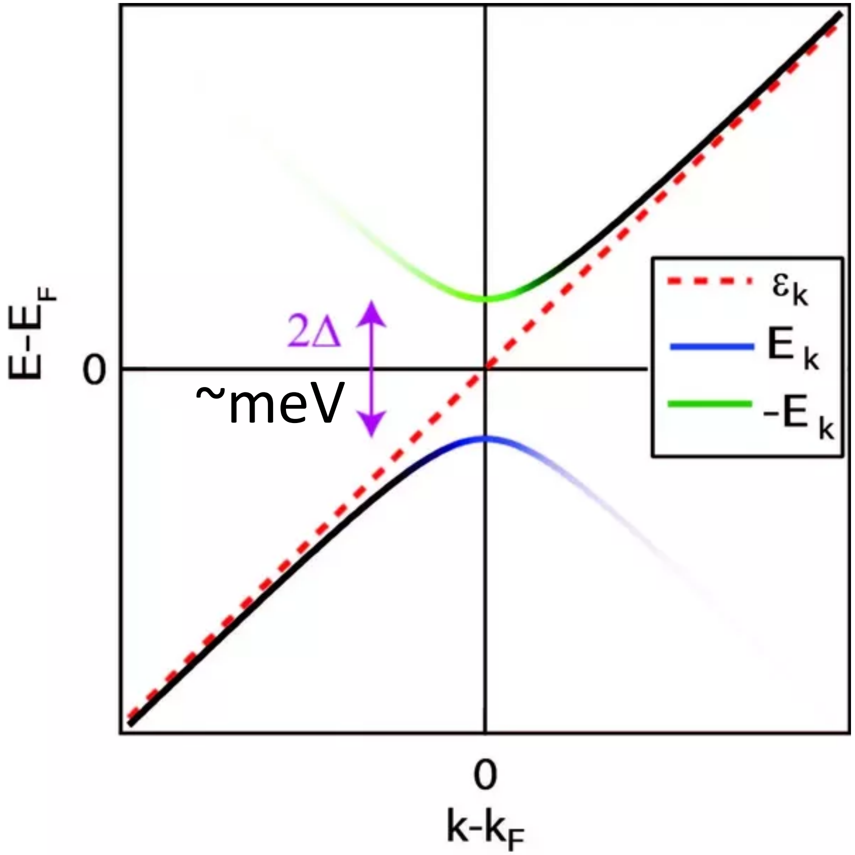
2) Inelastic e^- recoils with Superconducting Bandgaps

Semiconductors



MP et al: 1512.04533

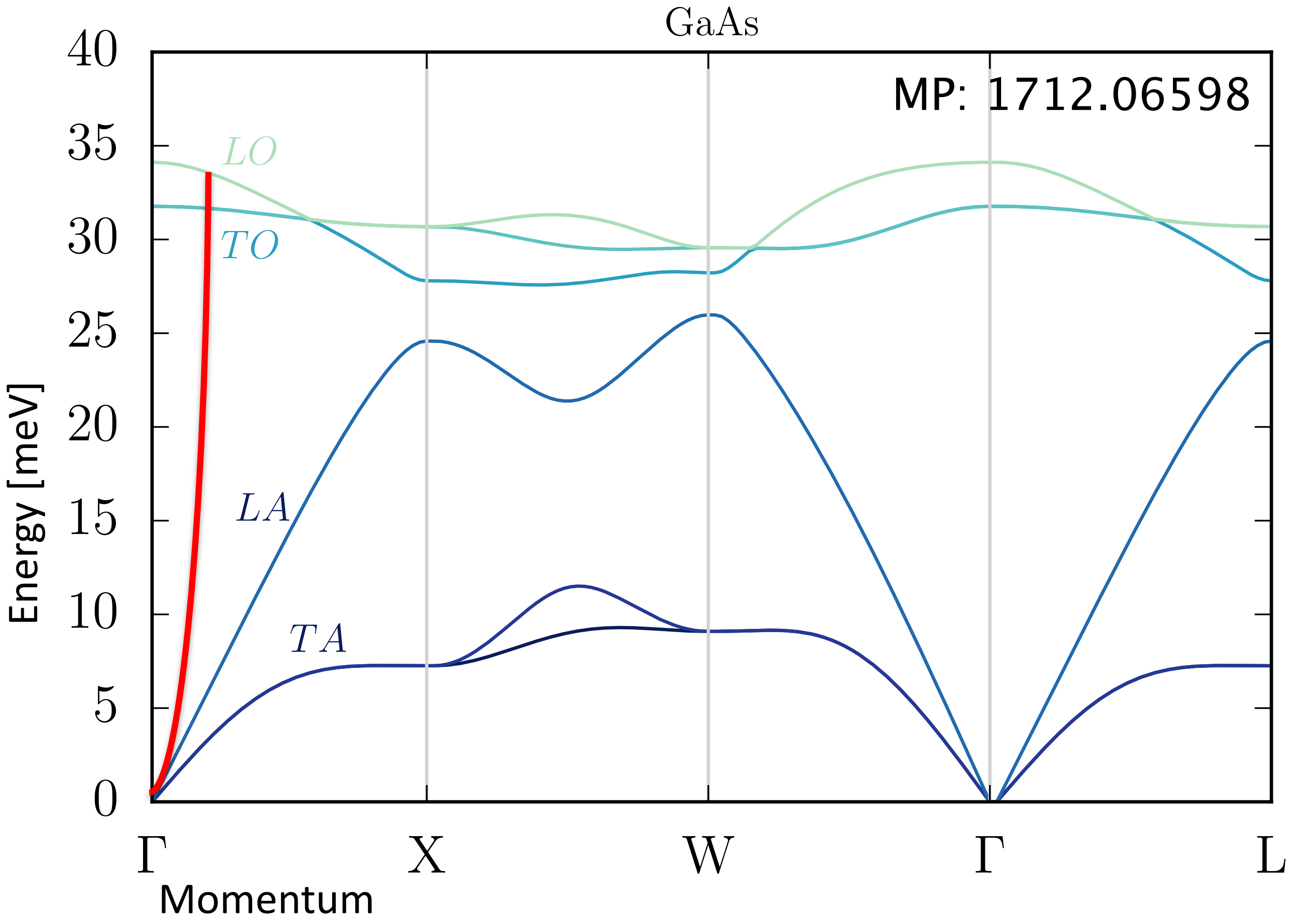
Superconductors



Design Driver: Energy Sensitivity

3) Inelastic Nuclear Recoils with Optical phonons

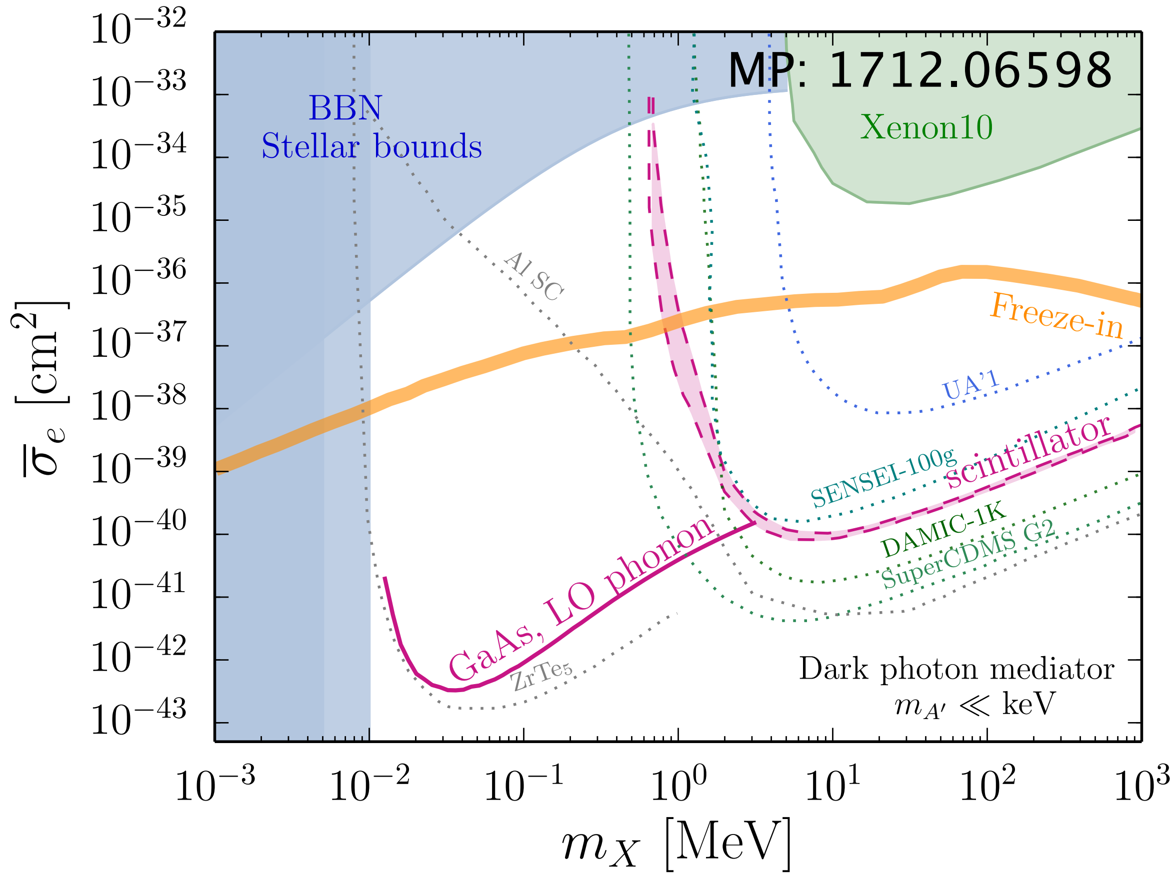
$$E_{DM} = \frac{P_{DM}^2}{2M_{DM}}$$



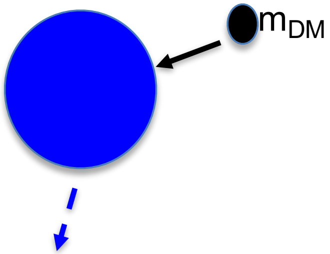
Design Driver: Single Optical Phonon Sensitivity

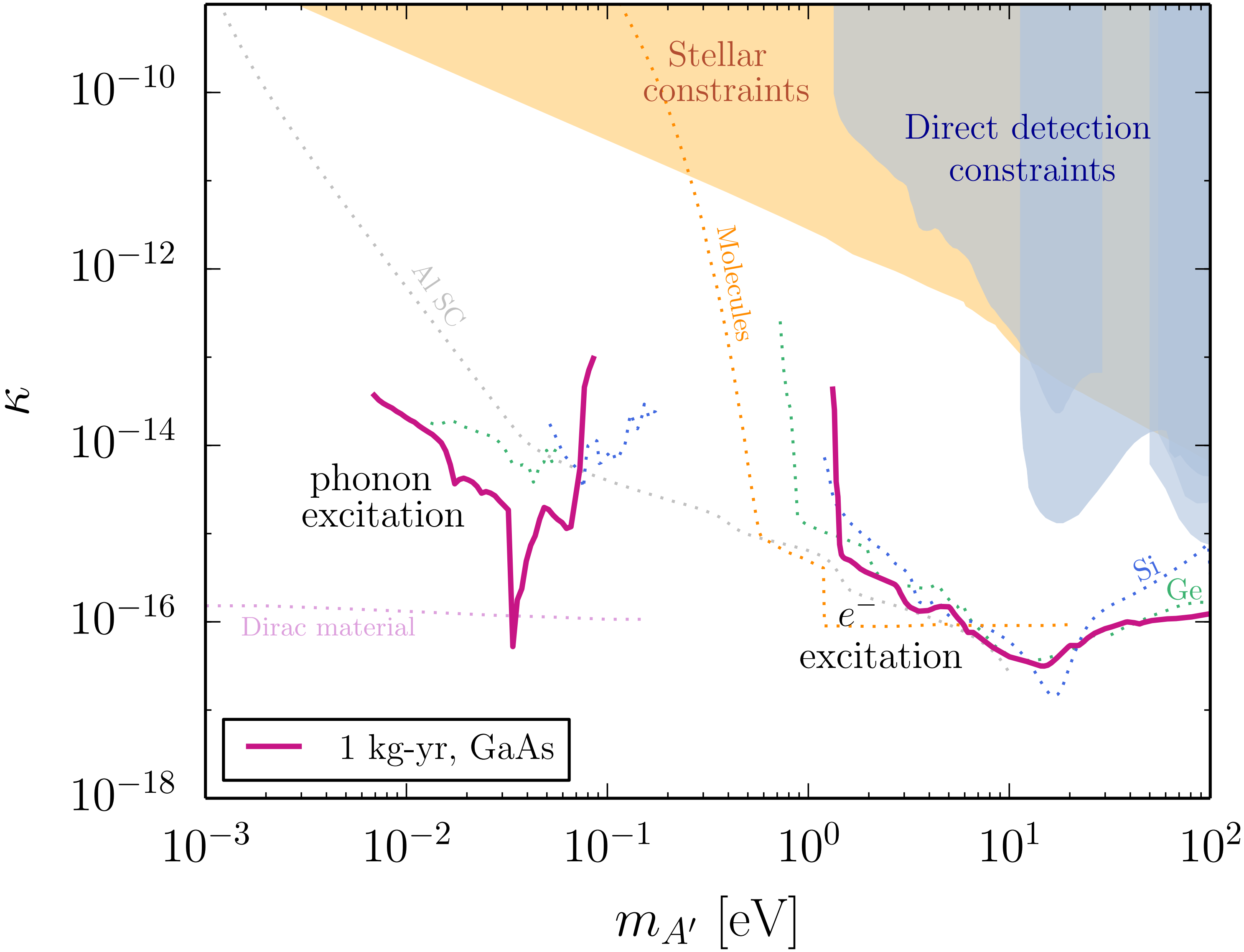
Dark Photon Couplings: Polar Crystals

- In ionic crystals, optical phonons are oscillating electric dipoles!
- Very large coupling to photons (black in the IR)
- Very large coupling to the dark photons


MP: 1712.06598

Ultra-cold Boson Absorption

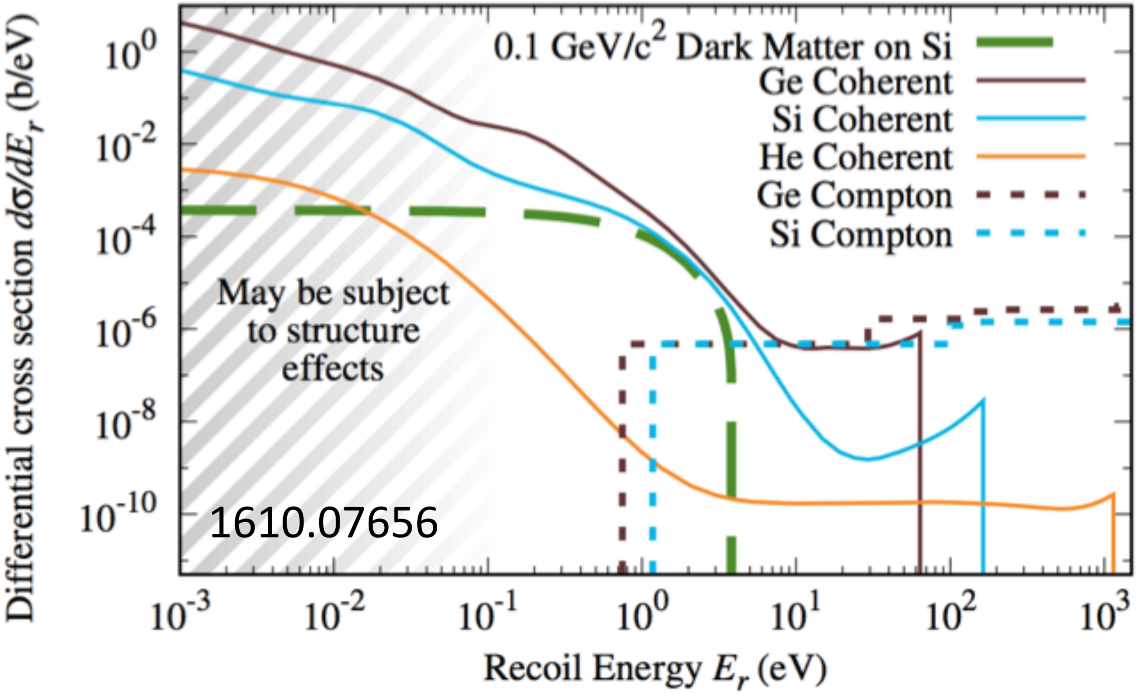


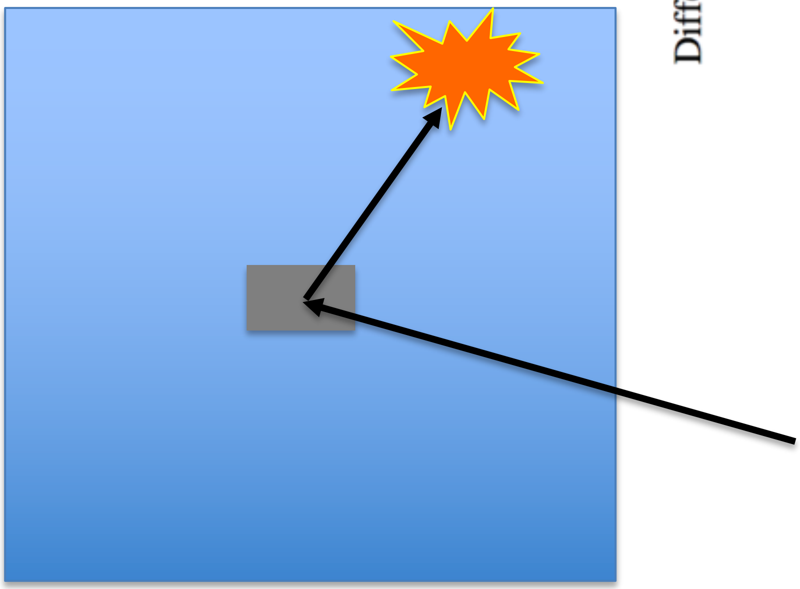


Coherent Photon Scattering

- High Energy Photons can coherently elastically scatter off nuclei
- Robinson: 1610.07656

1461keV Photon from ^{40}K





Build a Active Photon Veto

Design Drivers 10meV<M_{DM}<1MeV

- Sensitivity to single optical phonon (40meV)
- Radioactivity
  - 4π Active photon veto to remove coherent photon scattering
- ~~Exposure~~ (kgyr)

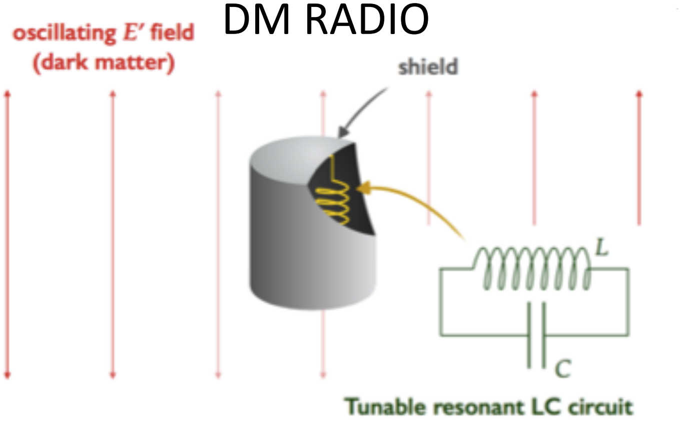
Design Drivers for M_{DM} <10 meV

Ultralight Dark Matter: M_{DM} <~ 10meV

For very small M_{DM}

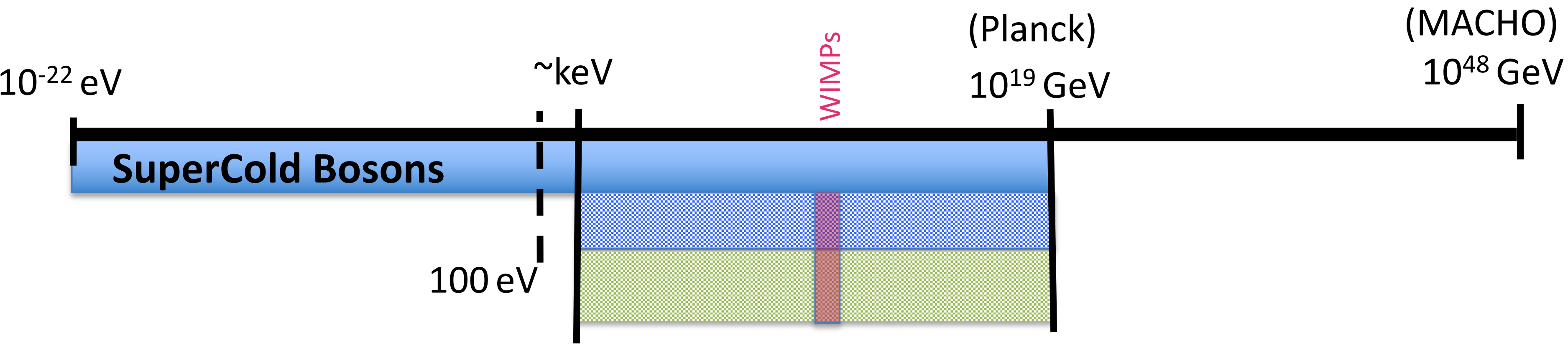
- A single particle carries negligible kinetic and rest mass energy
- $n_{DM} = \rho_{DM}/M_{DM}$, so n_{DM} is enormous: <n> >>1
- Classical Field: All of these particles interact coherently
- Build a radio

DM RADIO



ADMX

Conclusions



- Direct Detection design drivers different for different mass ranges -> Experiments will look very different
- M_{DM} >10 GeV: Noble TPCs
- M_{DM} < 10meV: Radio
- 10meV<M_{DM}<10GeV: Single excitation / ultra sensitive detectors