Superconducting Detectors for Coherent Neutrino Scattering, Low Mass Dark Matter

Enectalí Figueroa-Feliciano

Northwestern

Outline

- Some design considerations for low-mass dark matter and Coherent Elastic Neutrino-Nucleus Scattering
- Athermal Detectors
  - SuperCDMS iZIPs
  - SuperCDMS HV
- Measuring the Ionization Yield
- Thermal Detectors

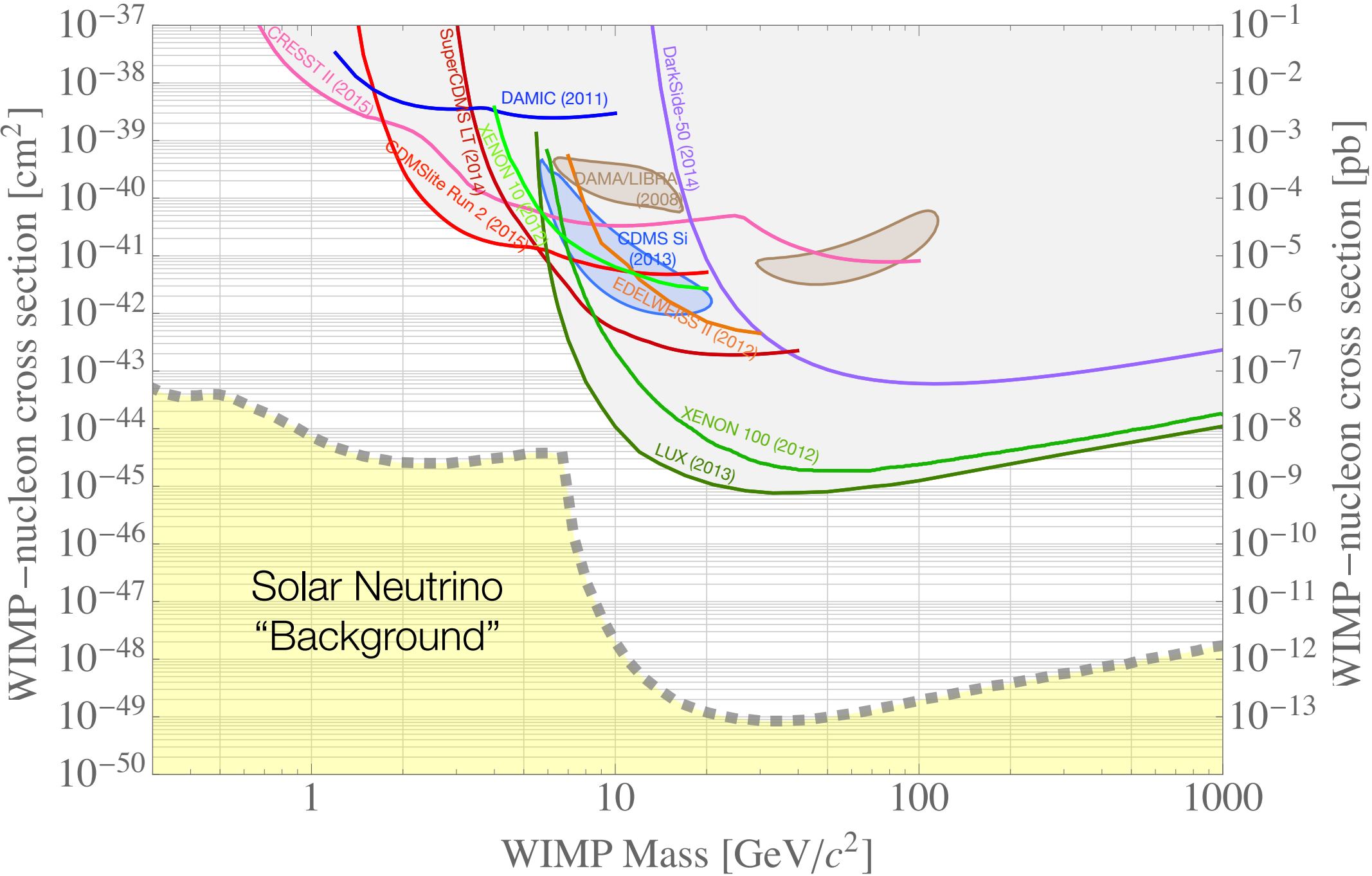
The SuperCDMS Collaboration

http://cdms.berkeley.edu

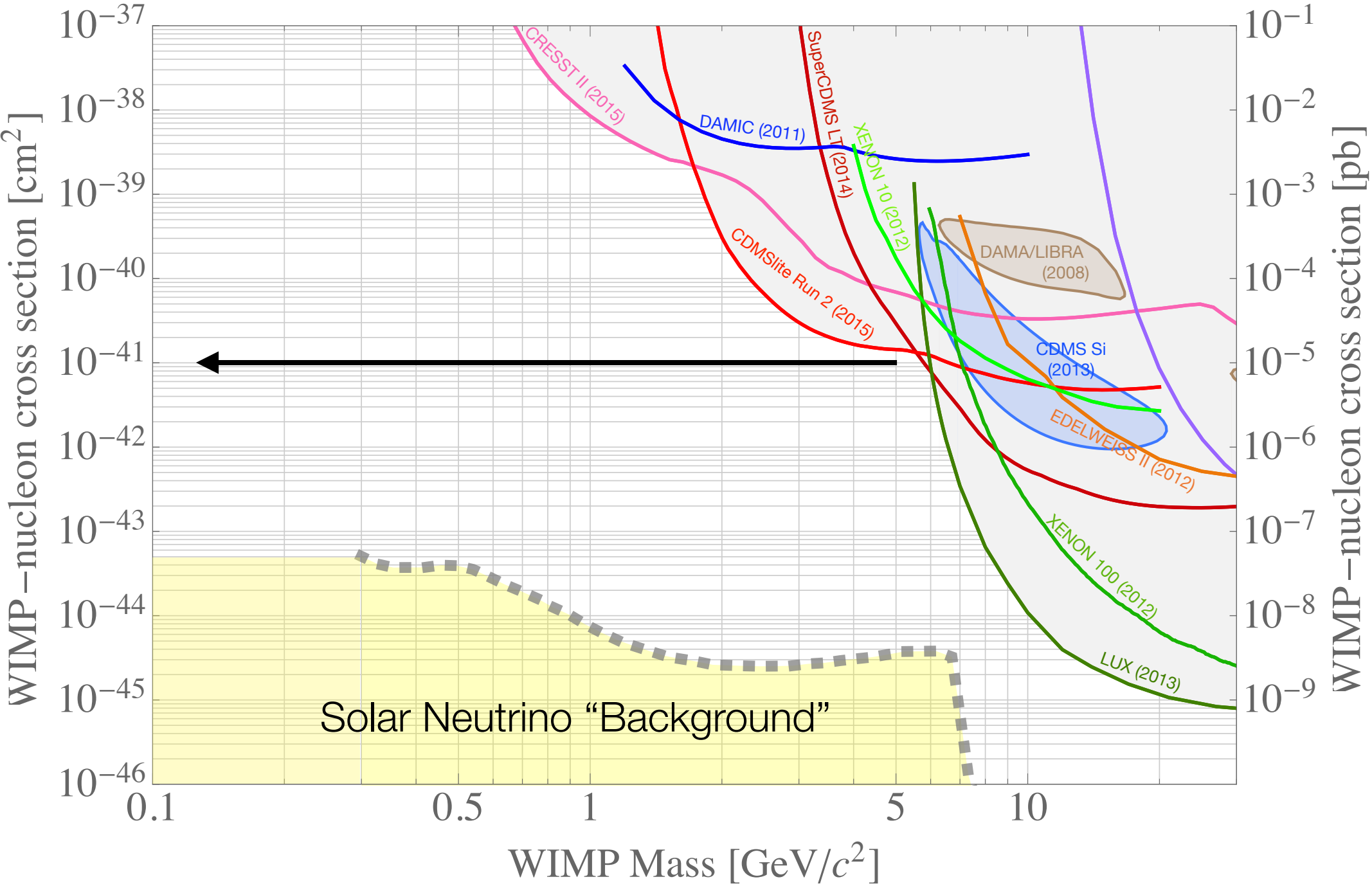
California Inst. of Tech.
CNRS-LPN*
Durham University
FNAL
NIST*
Northwestern
PNNL
Queen's University
SLAC
Southern Methodist U.
Santa Clara University
South Dakota SM&T
Stanford University
Texas A&M University
U. British Columbia
U. California, Berkeley
U. Colorado Denver
U. Evansville
U. Florida
U. Minnesota
U. South Dakota

* Associate members

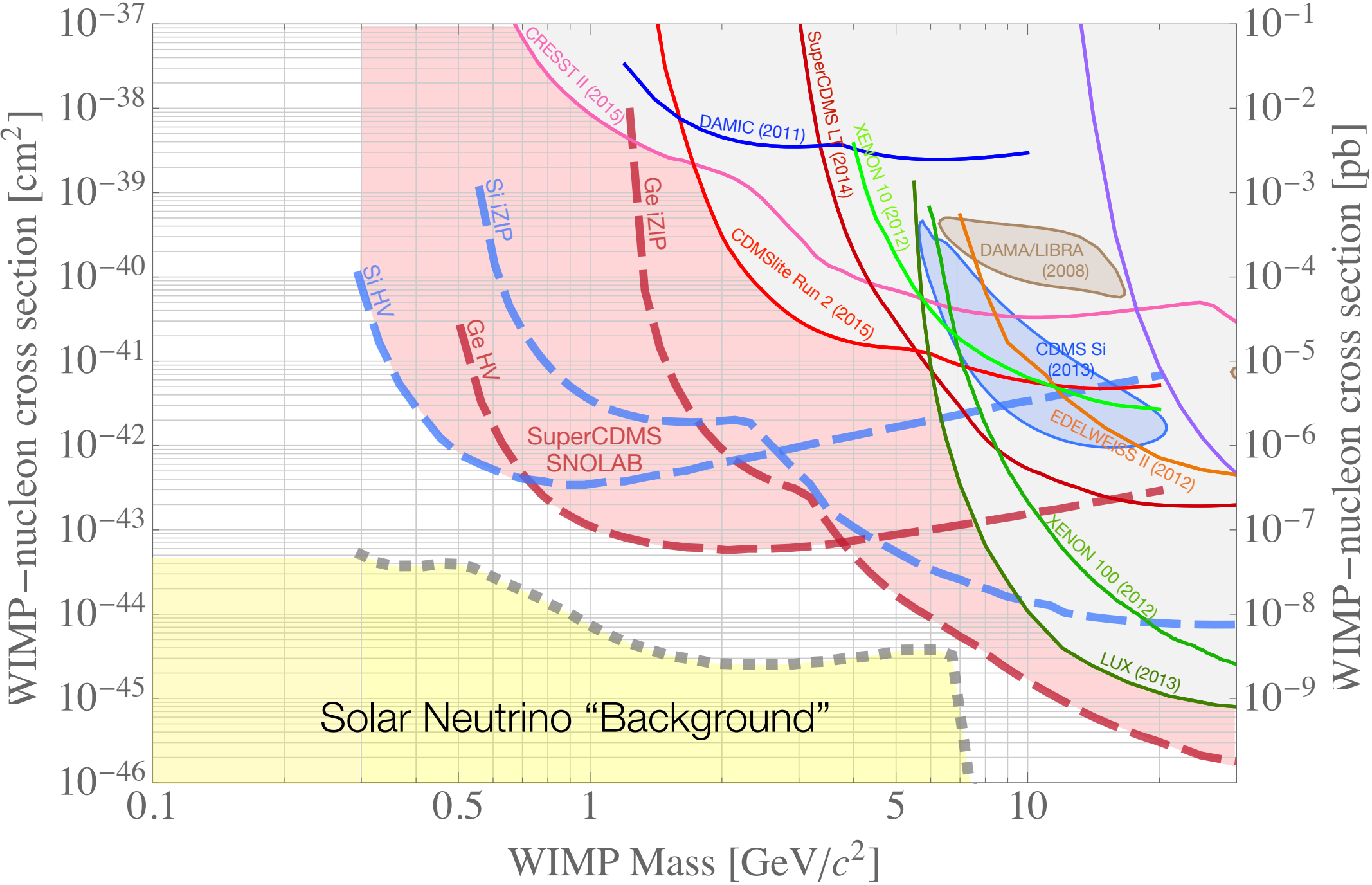
The WIMP Direct Detection Landscape



The low-mass WIMP Direct Detection Challenge



The low-mass WIMP Direct Detection Challenge



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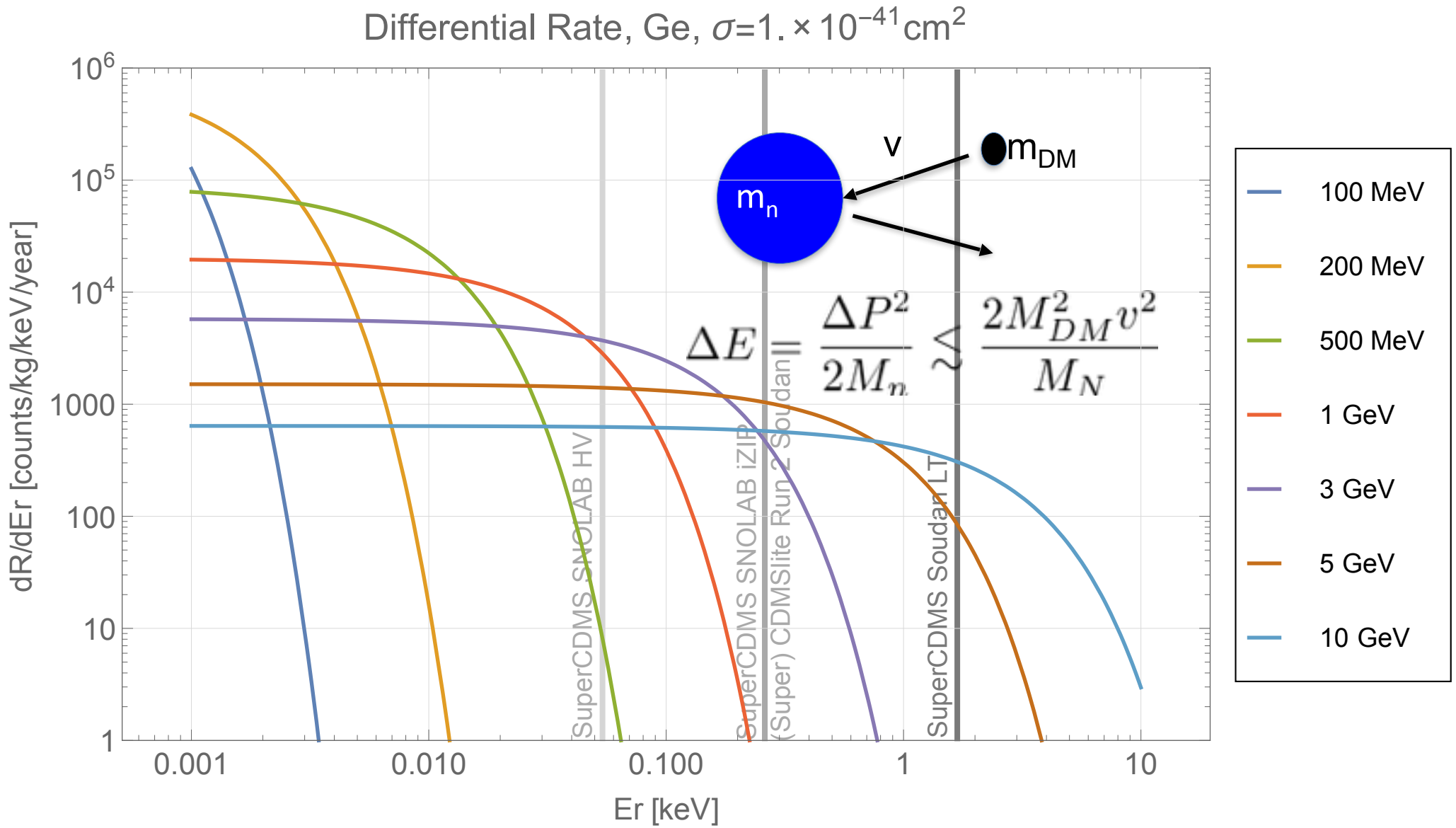
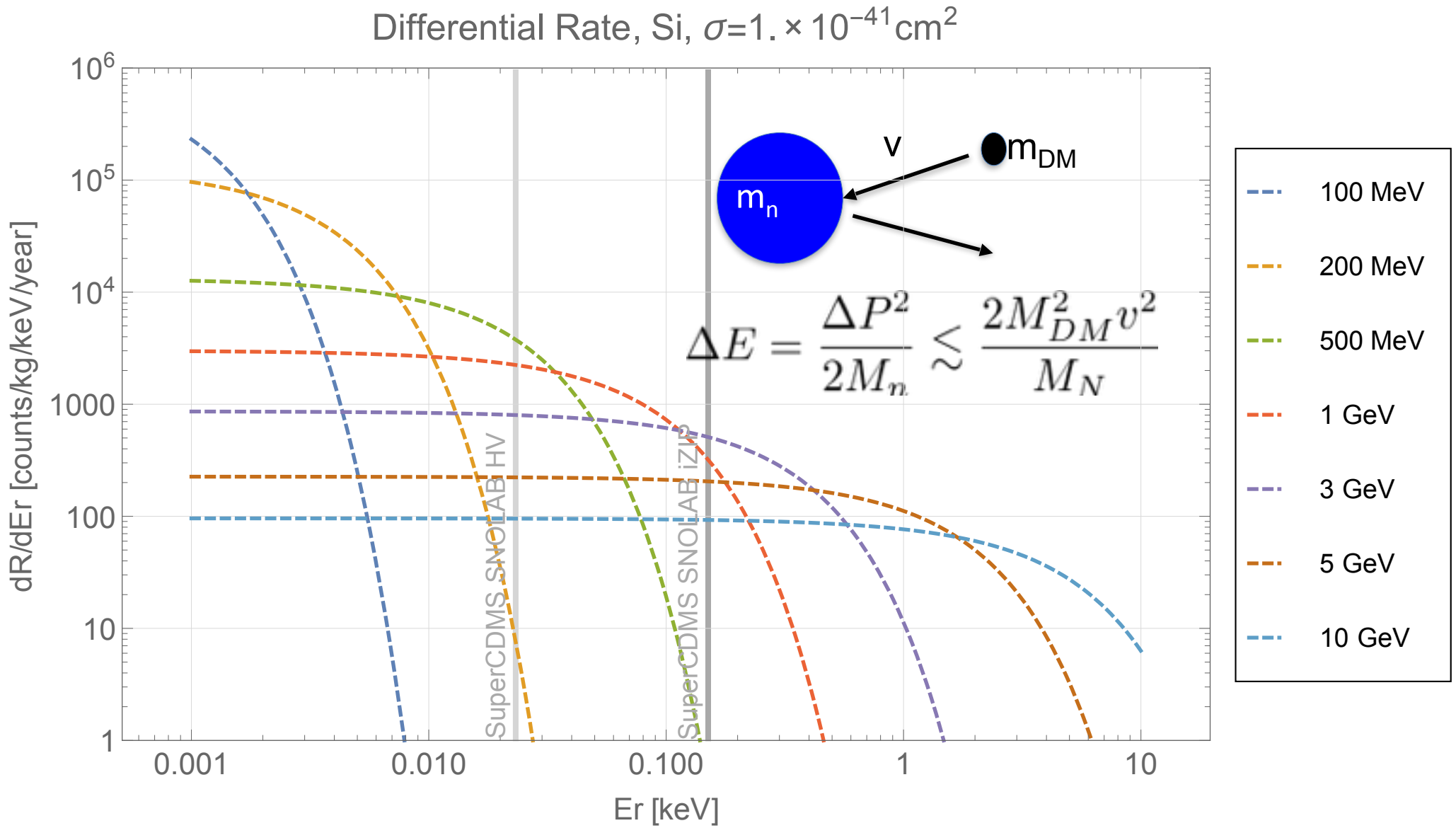


Detector Requirement: Extremely low thresholds!

The low-mass WIMP Direct Detection Challenge



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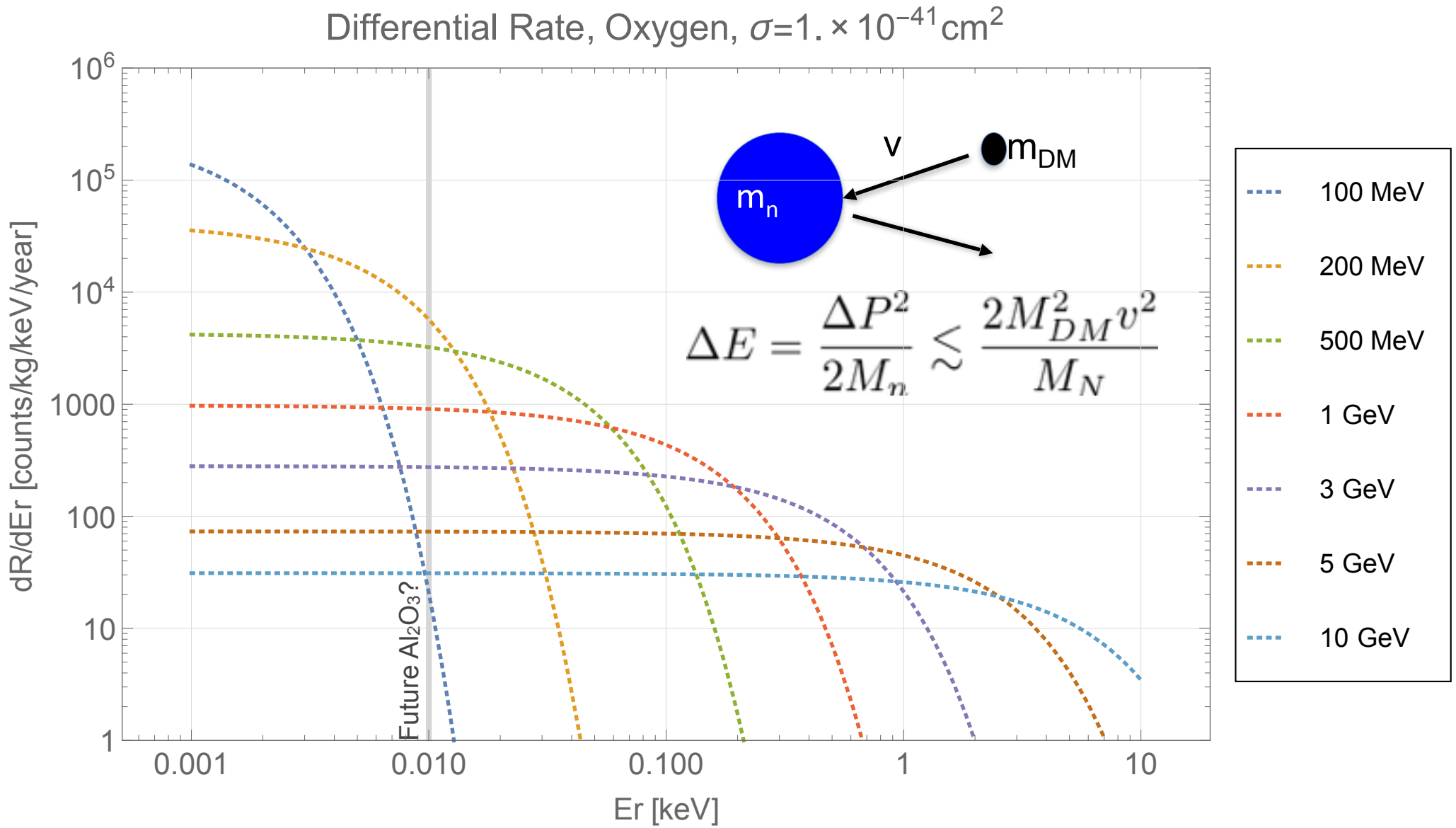

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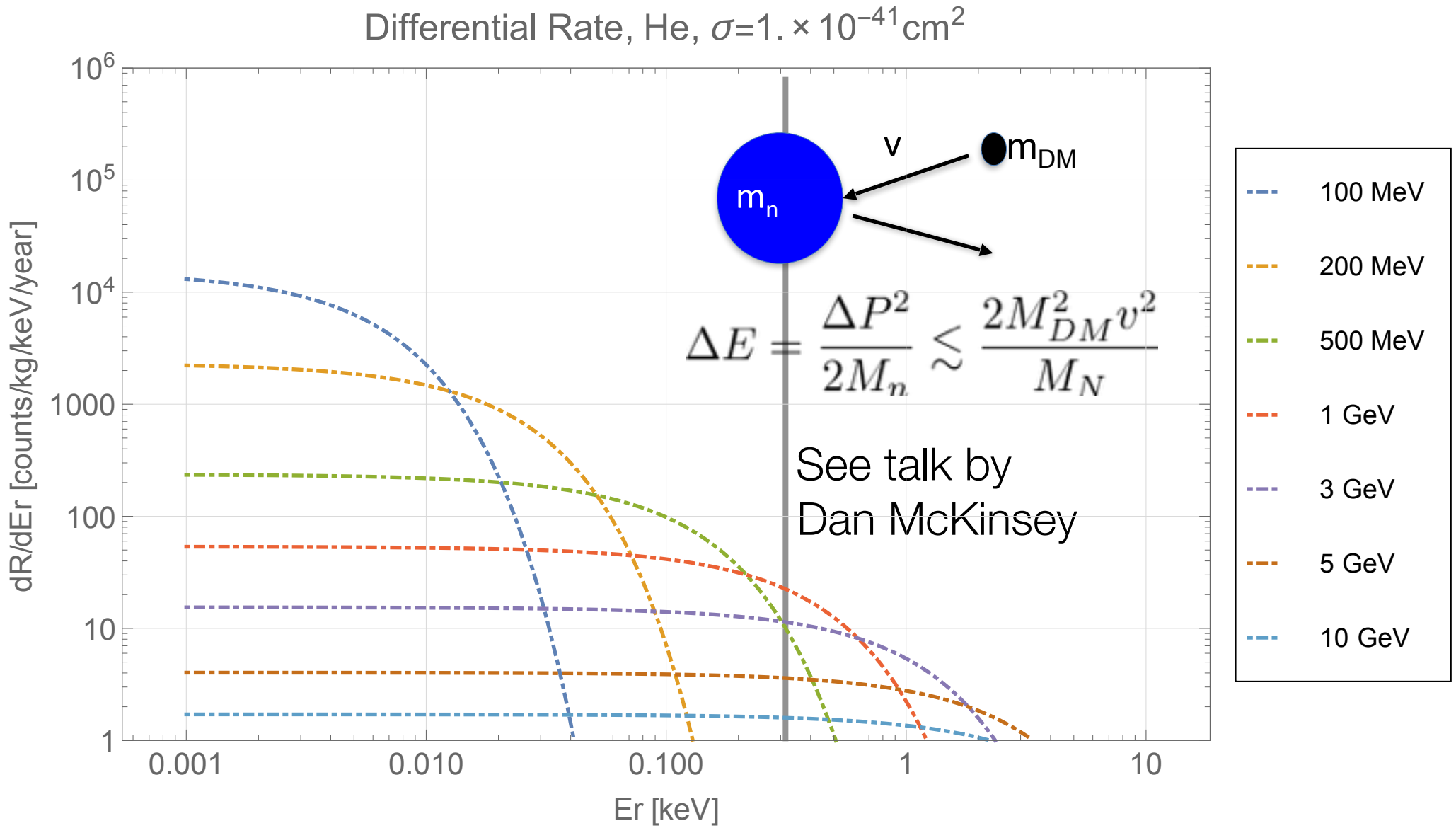
The low-mass WIMP Direct Detection Challenge

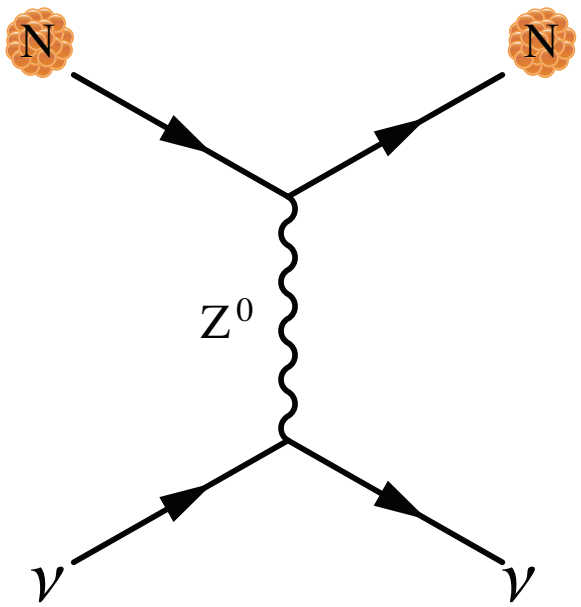


Detector Requirement: Extremely low thresholds!

Coherent Elastic ν-Nucleus Scattering

$$\frac{d\sigma}{dT} = \frac{G_F^2}{4\pi} Q_W^2 M_A \left(1 - \frac{M_A T}{2E_\nu^2}\right) F(q^2)^2$$

- σ: Cross Section
- T: Recoil Energy
- E_ν: Neutrino Energy
- G_F: Fermi Constant
- Q_W: Weak Charge
- M_A: Atomic Mass
- F: Form Factor



No flavor-specific terms!!!
Same rate for ν_e, ν_μ, and ν_τ

Why should we measure CE**ν**NS?

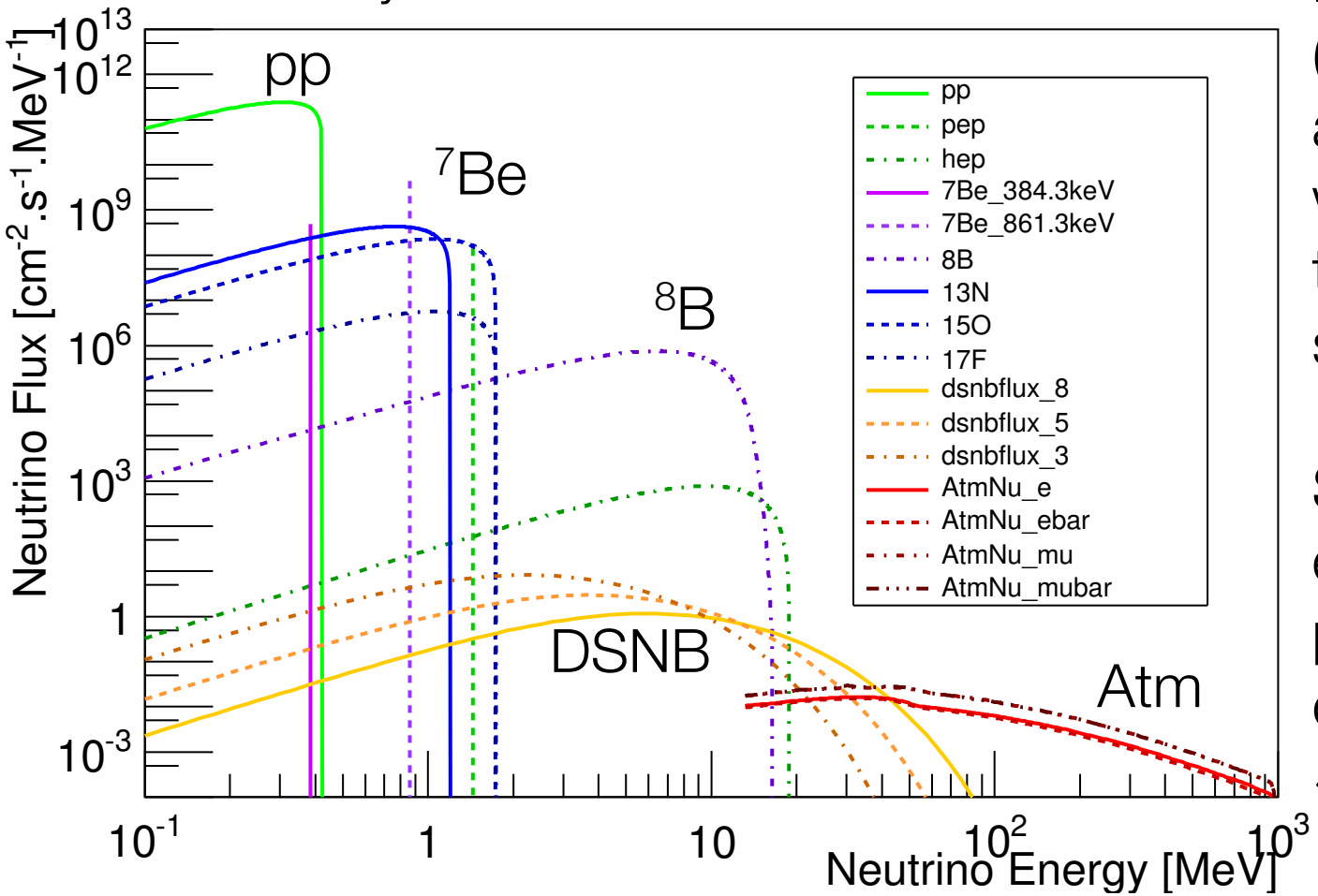
- Precisely predicted standard model interaction (~5% theoretical uncertainty)… but has never been observed!
- Probe of beyond-Standard-Model physics:
  - Non-standard neutrino interactions (NSI)
  - $\sin^2\theta_W$
  - Sterile Neutrinos (Smoking Gun Measurement!!!)
- Dominant interaction cross section (x10-100) for $E_\nu < 50$ MeV
- Neutrino-flavor-blind process
- Relevant in Supernova Dynamics
- Applications in:
  - Supernova neutrino detection
  - Solar neutrino physics
  - Nuclear physics
  - Geo-neutrino detection?

Neutrino Sources

4 sources to consider:

- The Sun + other cosmic sources
- Electron-capture sources
- Reactors
- Decay-at-rest sources

arXiv:1402.7137
1408.3581
1409.0050



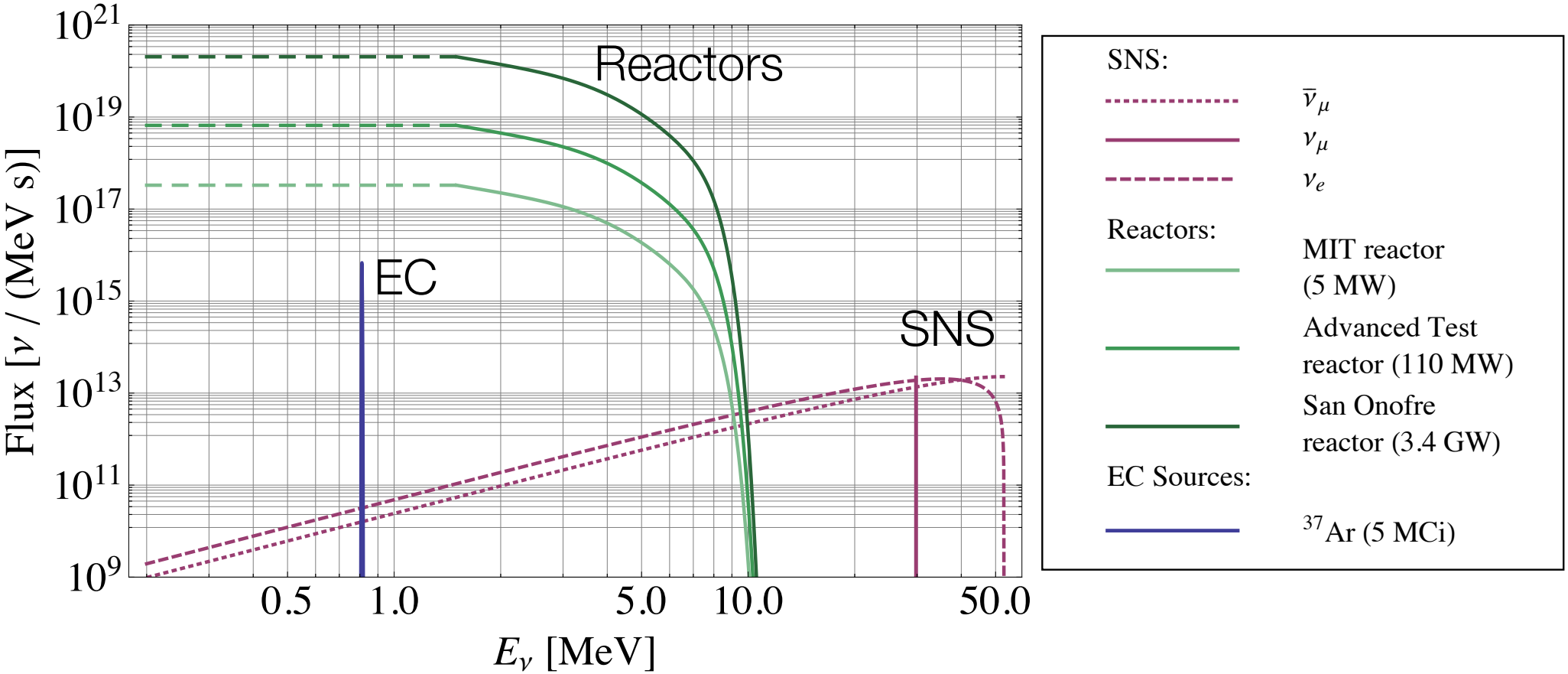
G2 Dark Matter Experiments (SuperCDMS SNOLAB and possibly LZ) will be able to detect the Solar ^{8}B CE**ν**NS signal!

Small number of events, but expect a positive CE**ν**NS detection in the next ~5 years…

Neutrino Sources

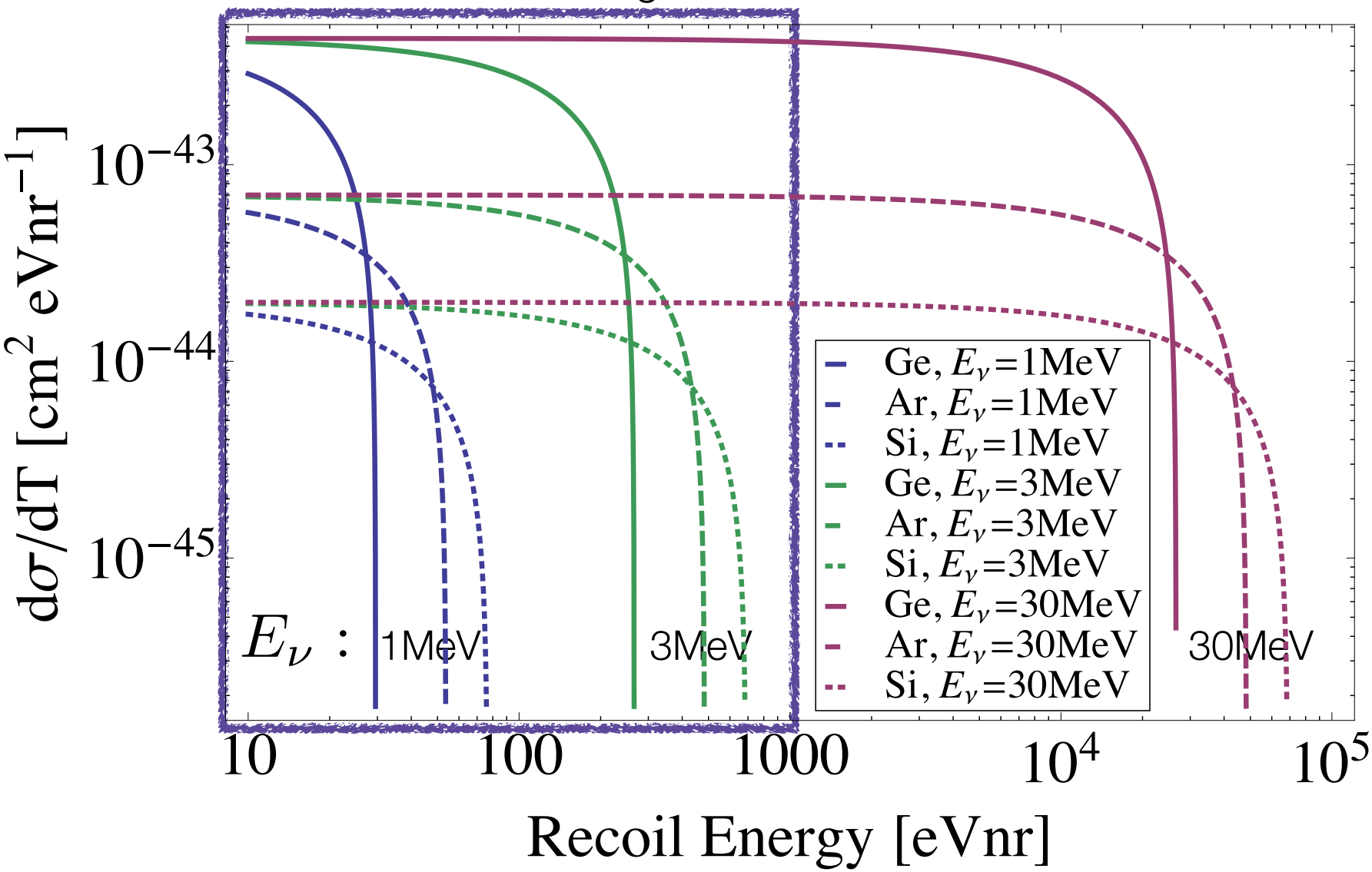
4 sources to consider:

- The Sun + other cosmic sources
- Electron-capture sources
- Reactors
- Decay-at-rest sources



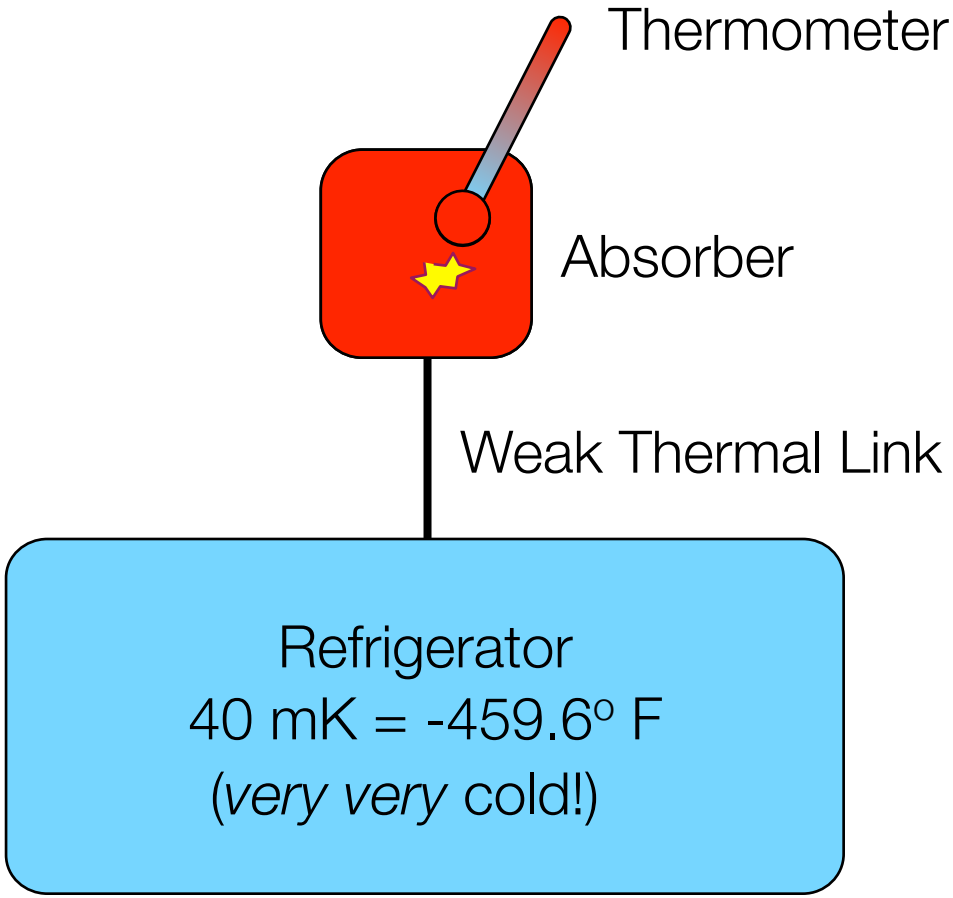
CE**ν**NS Cross Sections

Phonon Sensors particularly useful in this range

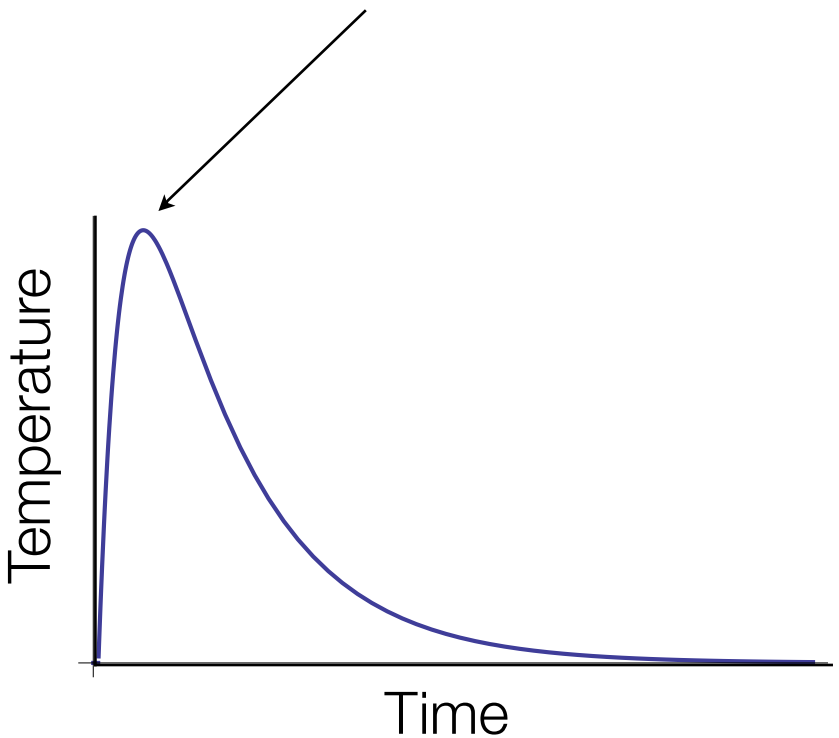


Detector Requirement: Extremely low thresholds!

Microcalorimeters 101

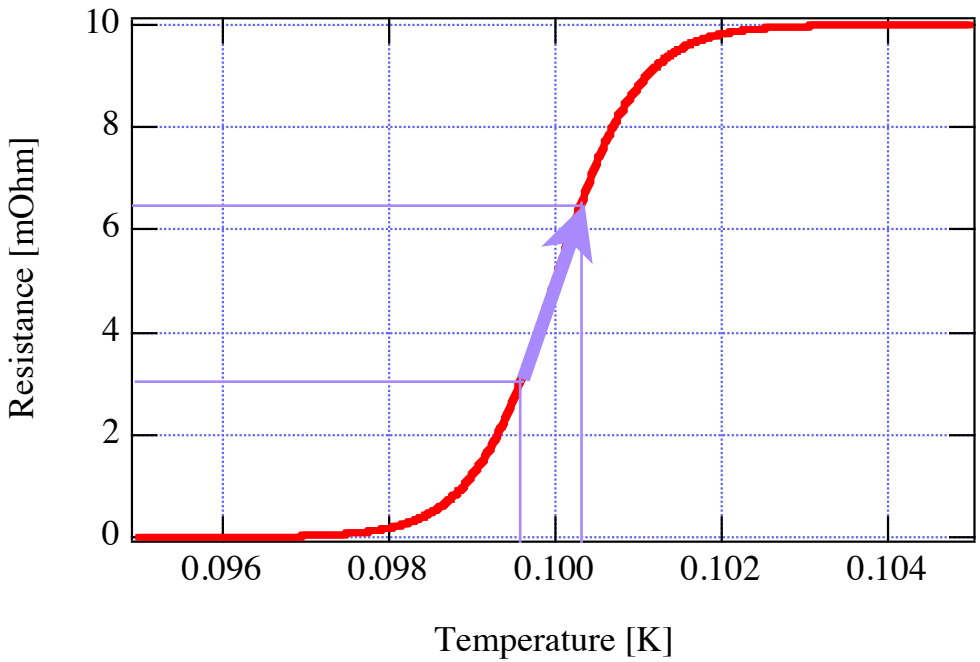


The height of the pulse is proportional to the energy deposited!



Microcalorimeters 102: Transition-Edge Sensros

- Refrigerator temperature has to be close to absolute zero
- Thermometer is a Superconducting Transition-Edge Sensor (TES)
- Readout is done with Superconducting Quantum Interference Devices (SQUIDs)

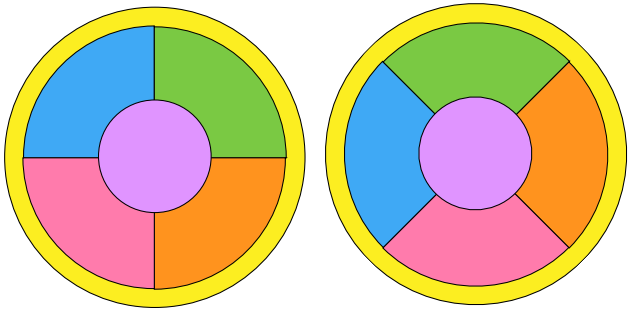


Athermal Detectors

SuperCDMS Detectors: iZIPs

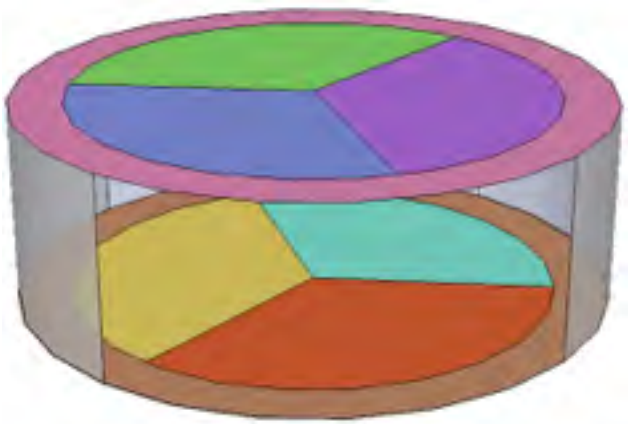
Ge (1.4 kg per detector)
Si (0.6 kg per detector)
4” Diameter
3.3 cm Thick

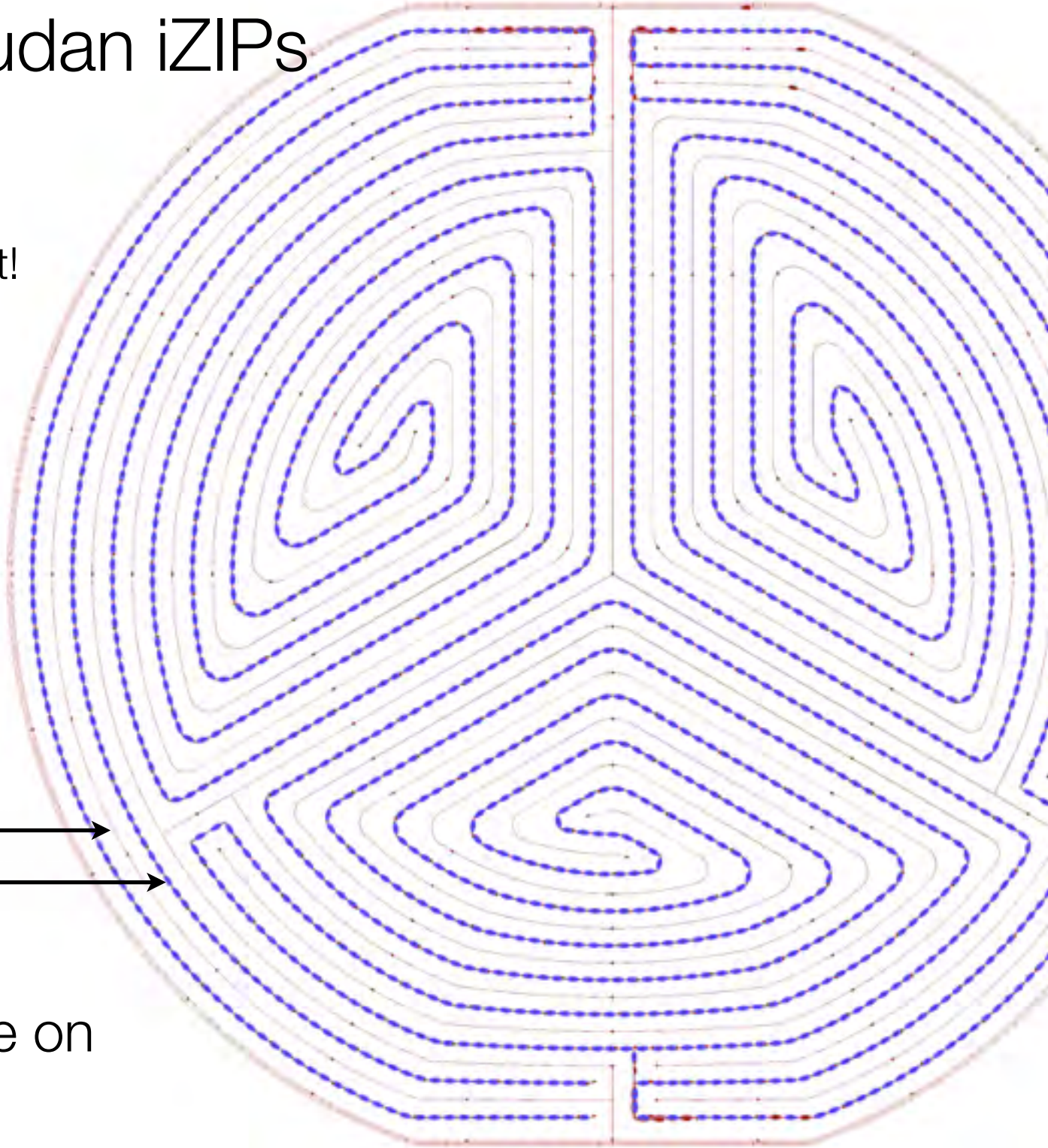
2 charge + 2 charge
6 phonon + 6 phonon



SuperCDMS Soudan iZIPs

8 phonon channels +
4 charge sensors =
Lots of information per event!

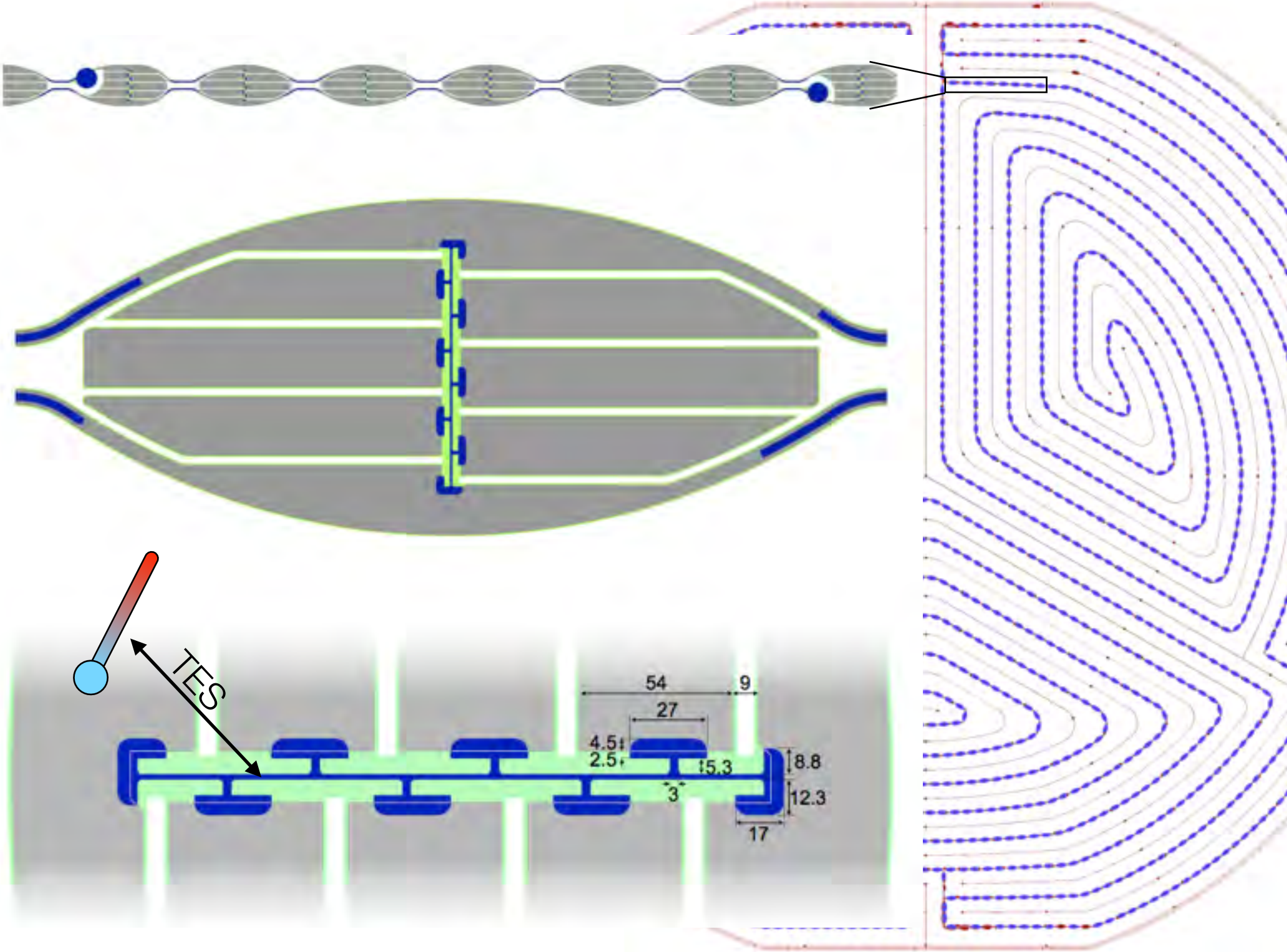




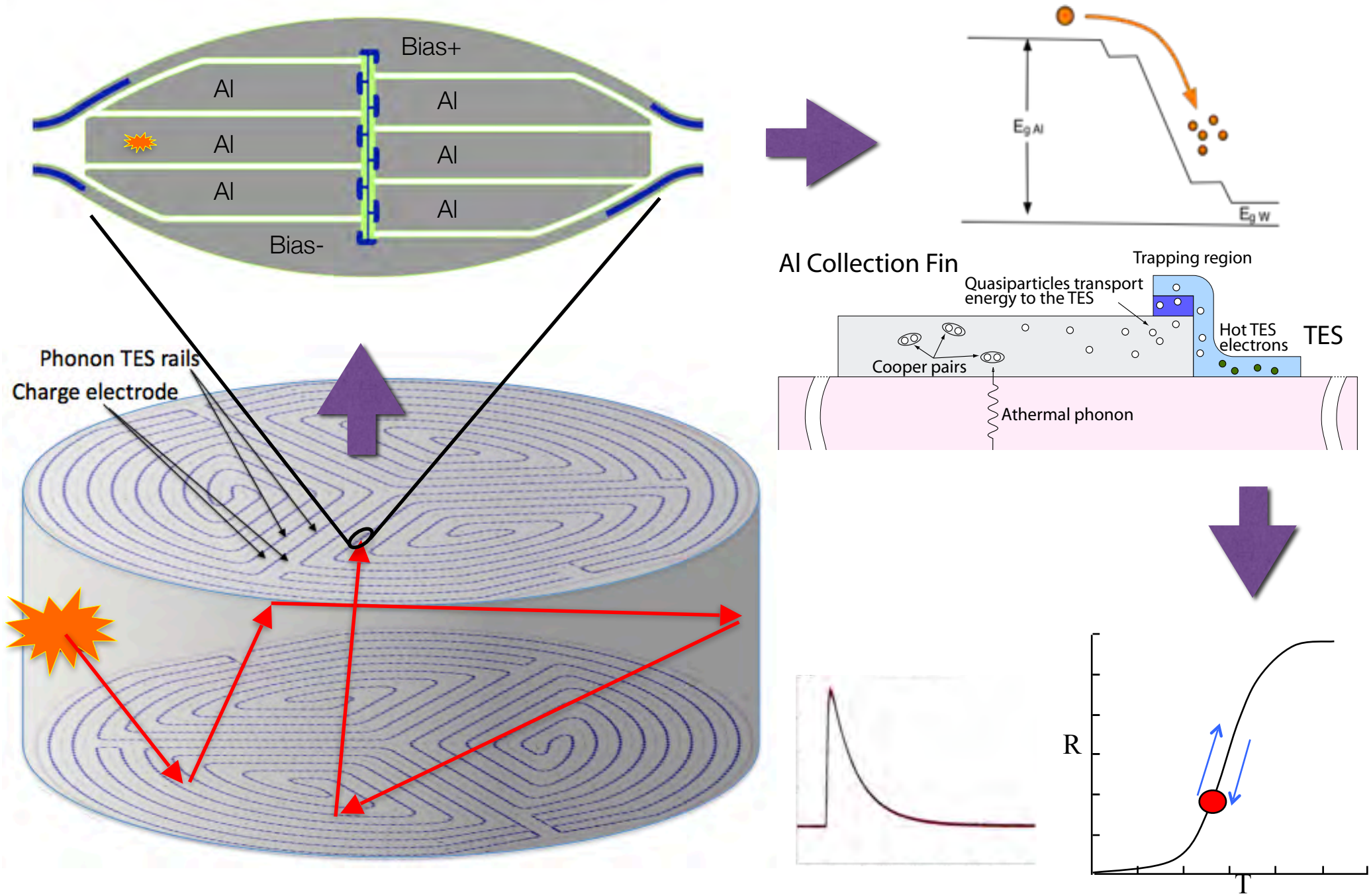
charge sensor (biased)

phonon sensor (grounded)

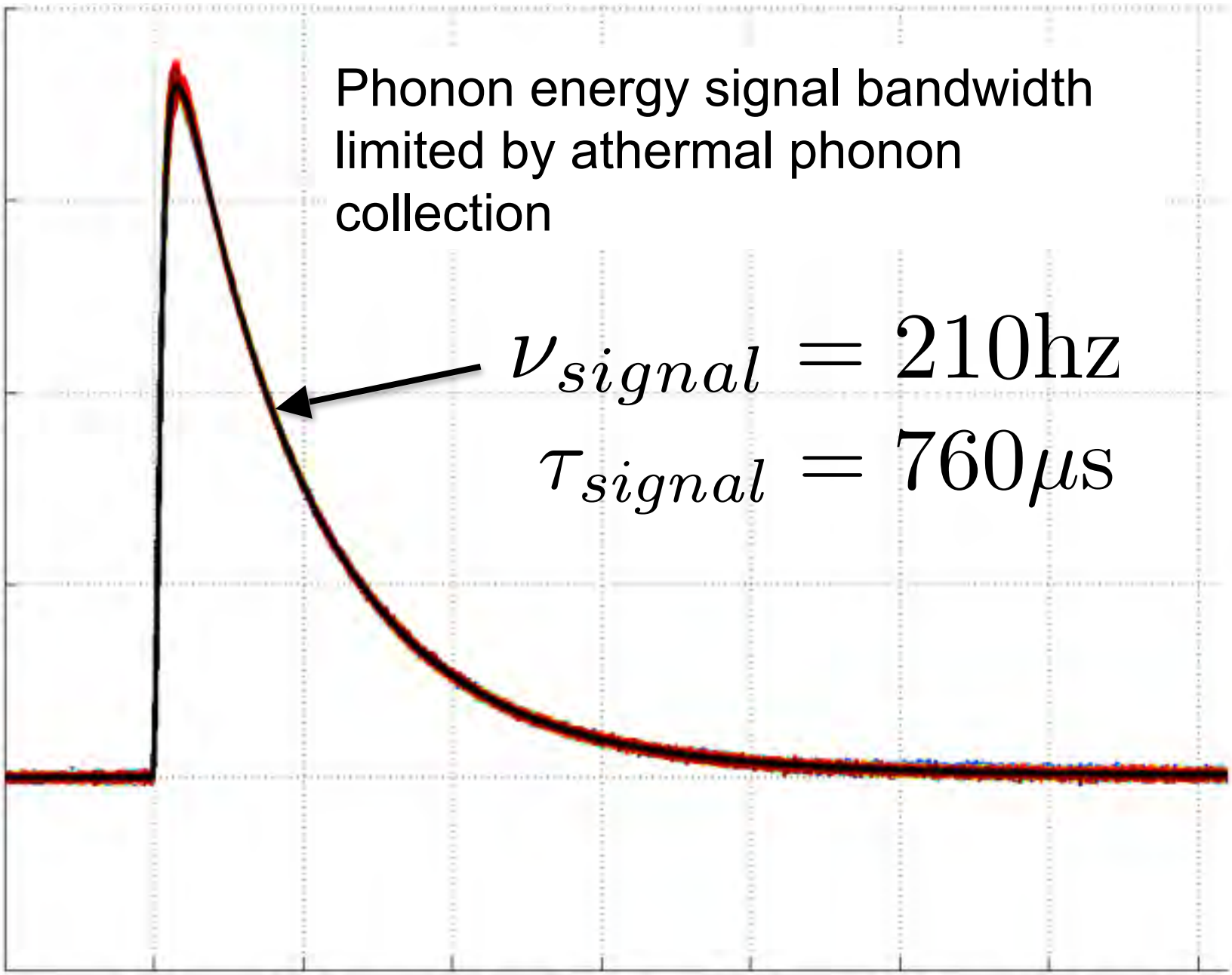
"interwoven" phonon *and* charge on each side!


TES
54
9
27
4.5
2.5
5.3
3
8.8
12.3
17

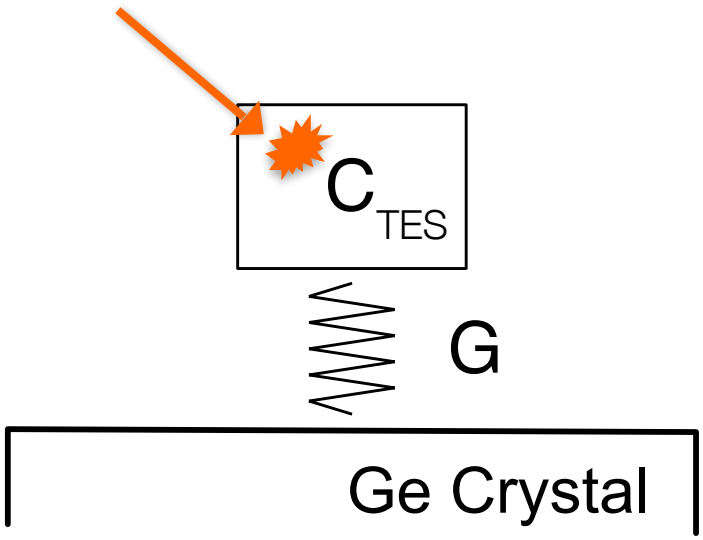
Getting Energy to the Athermal Phonon Sensors

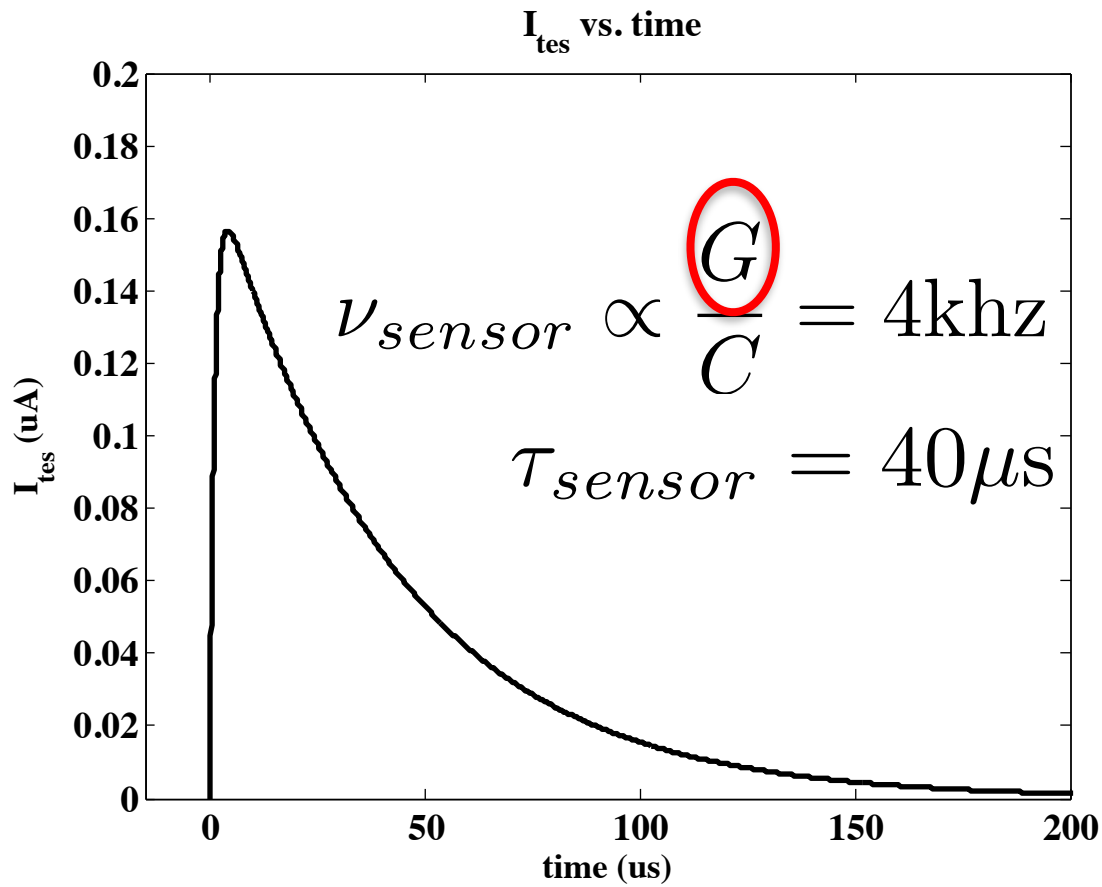


Phonon Signal Bandwidth



Transition Edge Sensor Bandwidth





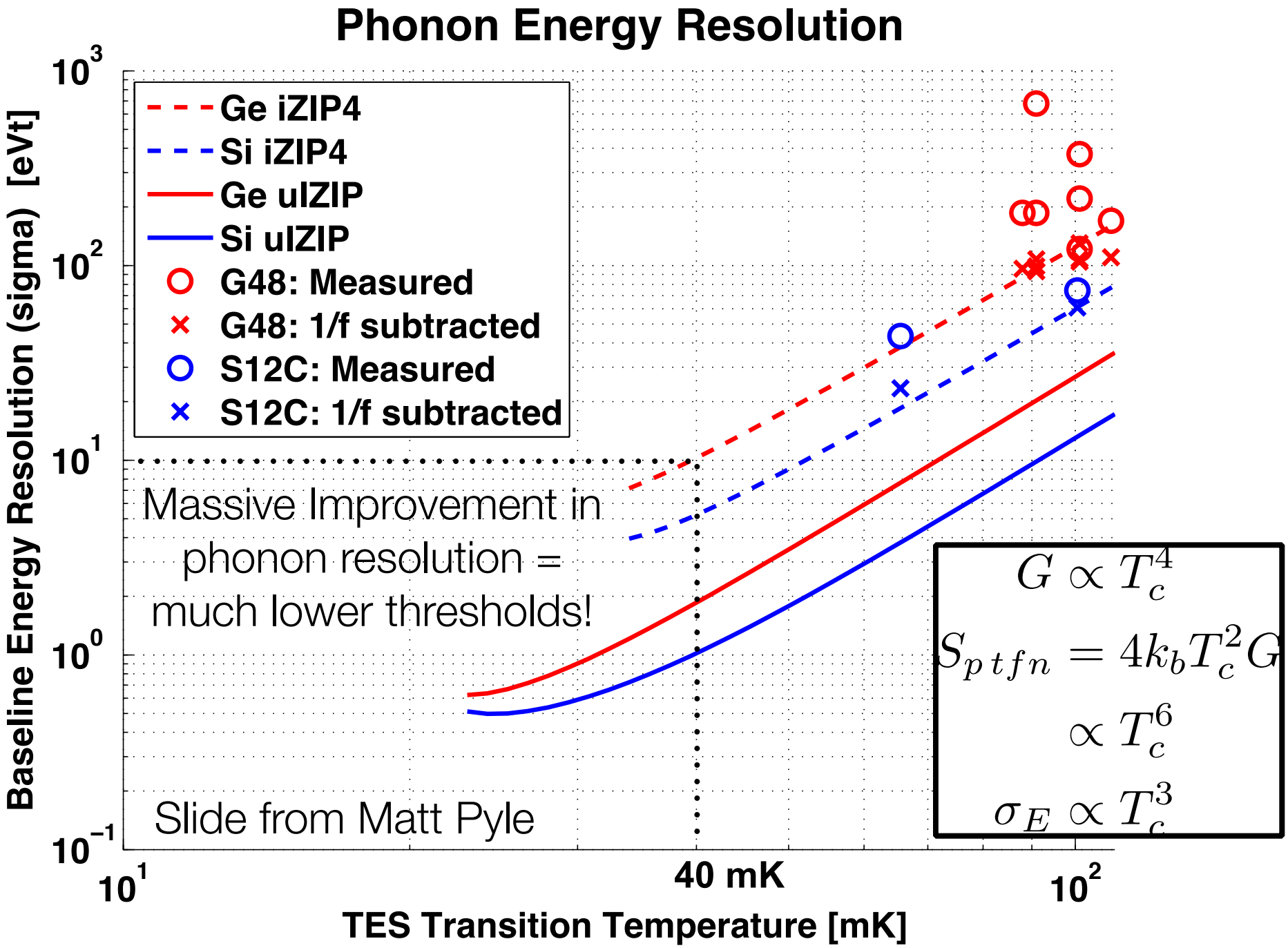
Need to slow down the TES

$$\tau_{signal} \gg \tau_{sensor}$$

$$\nu_{signal} \ll \nu_{sensor}$$

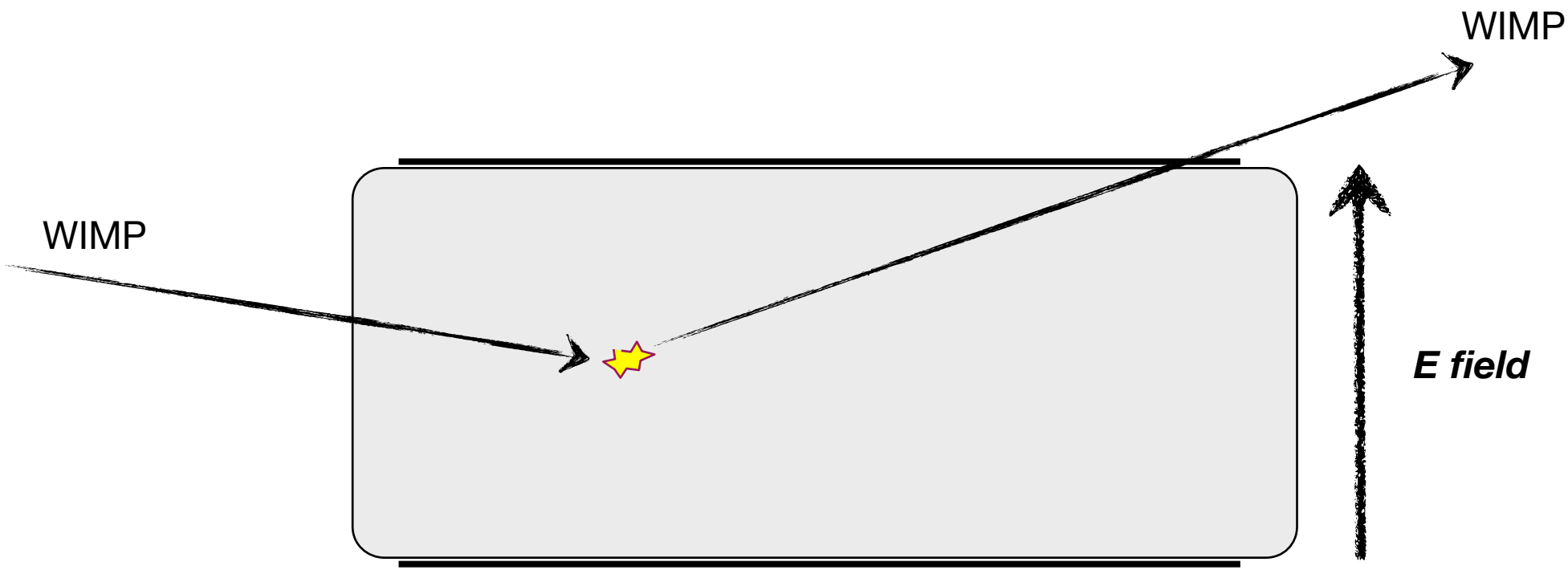
The TES's G in massive detectors determined by electron-phonon coupling of the TES

Better Phonon Sensitivity with Lower T_c!



SuperCDMS High-Voltage Operation

CDMSlite: CDMS low ionization threshold experiment

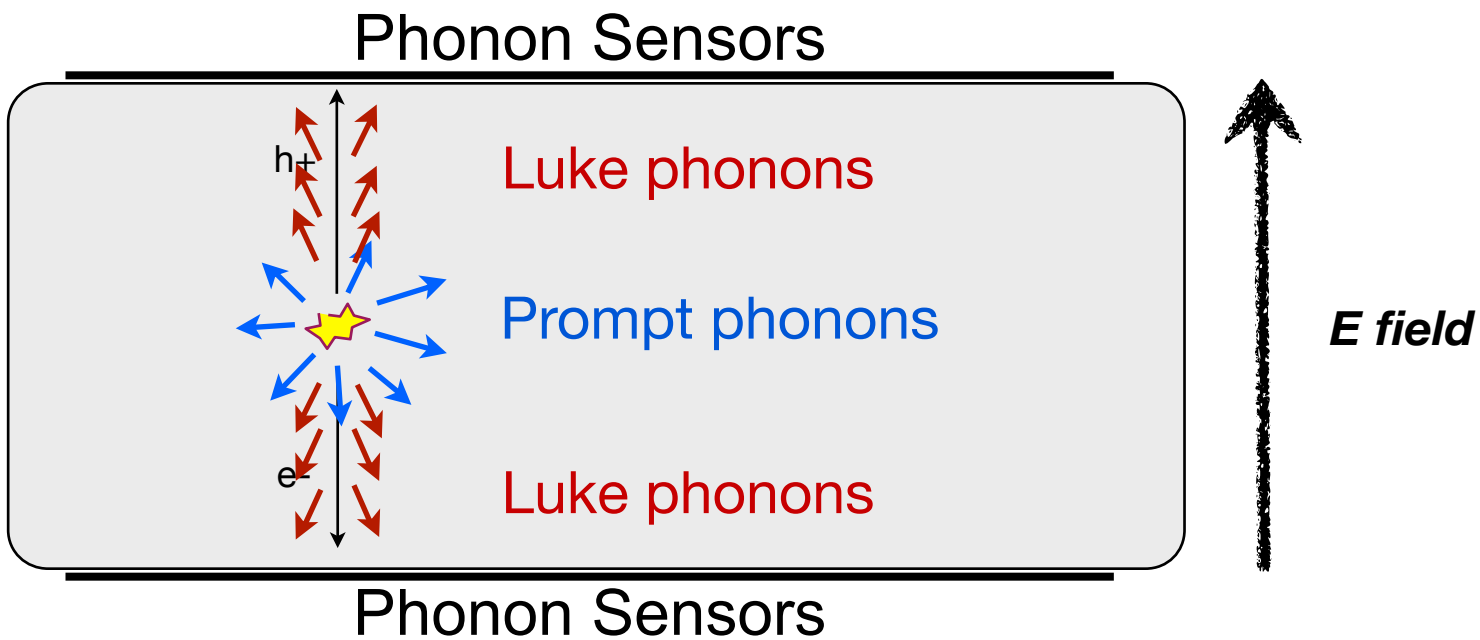


SuperCDMS High-Voltage Operation

SuperCDMS High-Voltage Operation

Phonon sensors measure amount of charge produced:
Phonon-based charge amplification!

See next talk by N. Mirabolfathi on HV detector studies



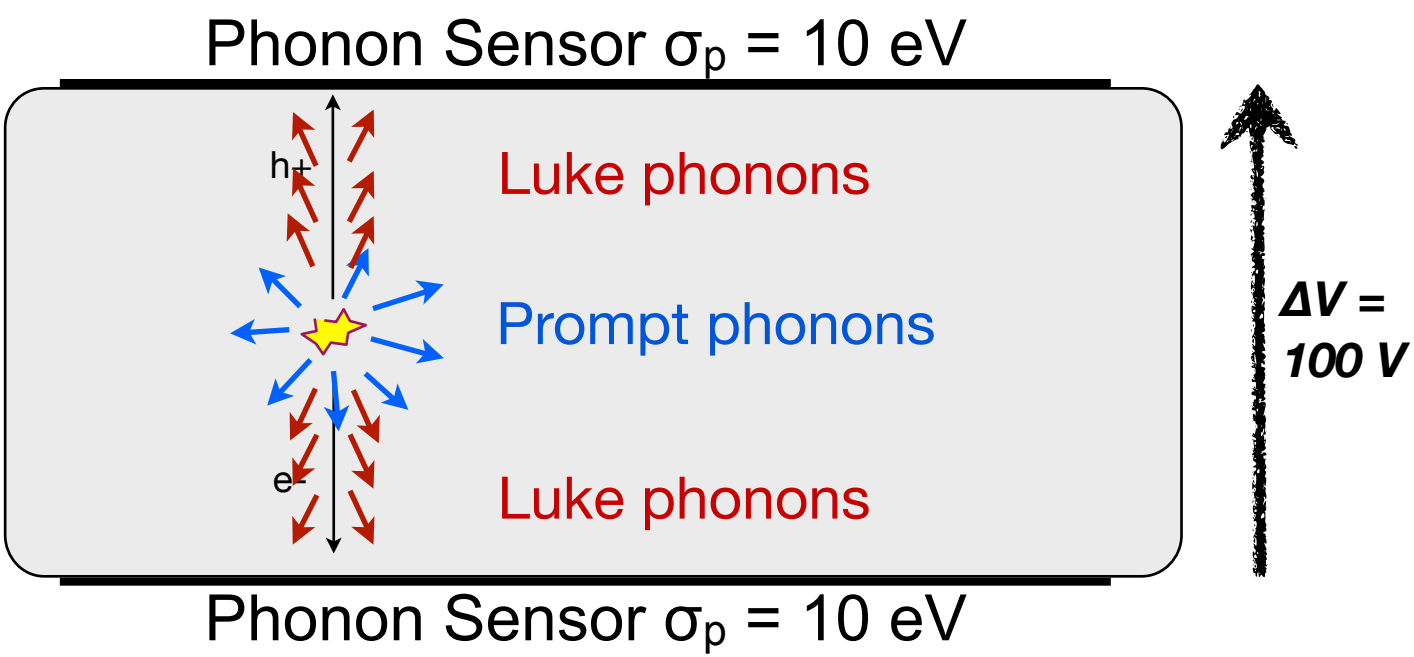
$$\text{Phonon energy} = E_{recoil} + E_{Luke}$$
$$= E_{recoil} + n_{eh}\, e^{-}\, \Delta V$$

What if you had both great phonon resolution AND a HV detector?

Single electron-hole pair resolution?

$$\text{Phonon energy} = E_{recoil} + E_{Luke}$$
$$= E_{recoil} + n_{eh}\, e^{-}\, \Delta V$$

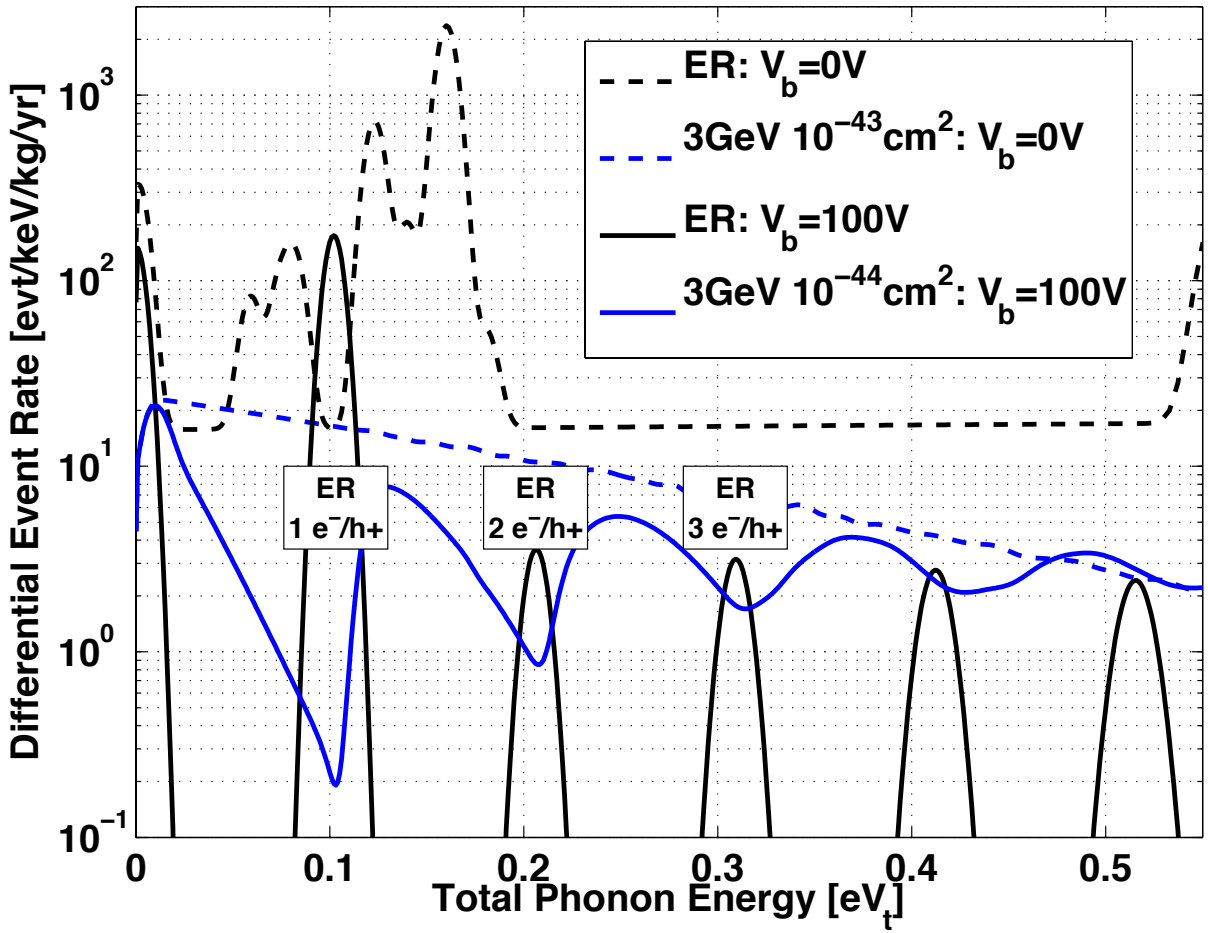
- If phonon resolution can be optimized to σ_p = 10 eV
- Make ΔV large (~100V)
- A single eh pair makes 100eV of signal, compared to the σ_p = 10 eV of the phonon sensor
- You can measure individual electron hole pairs!



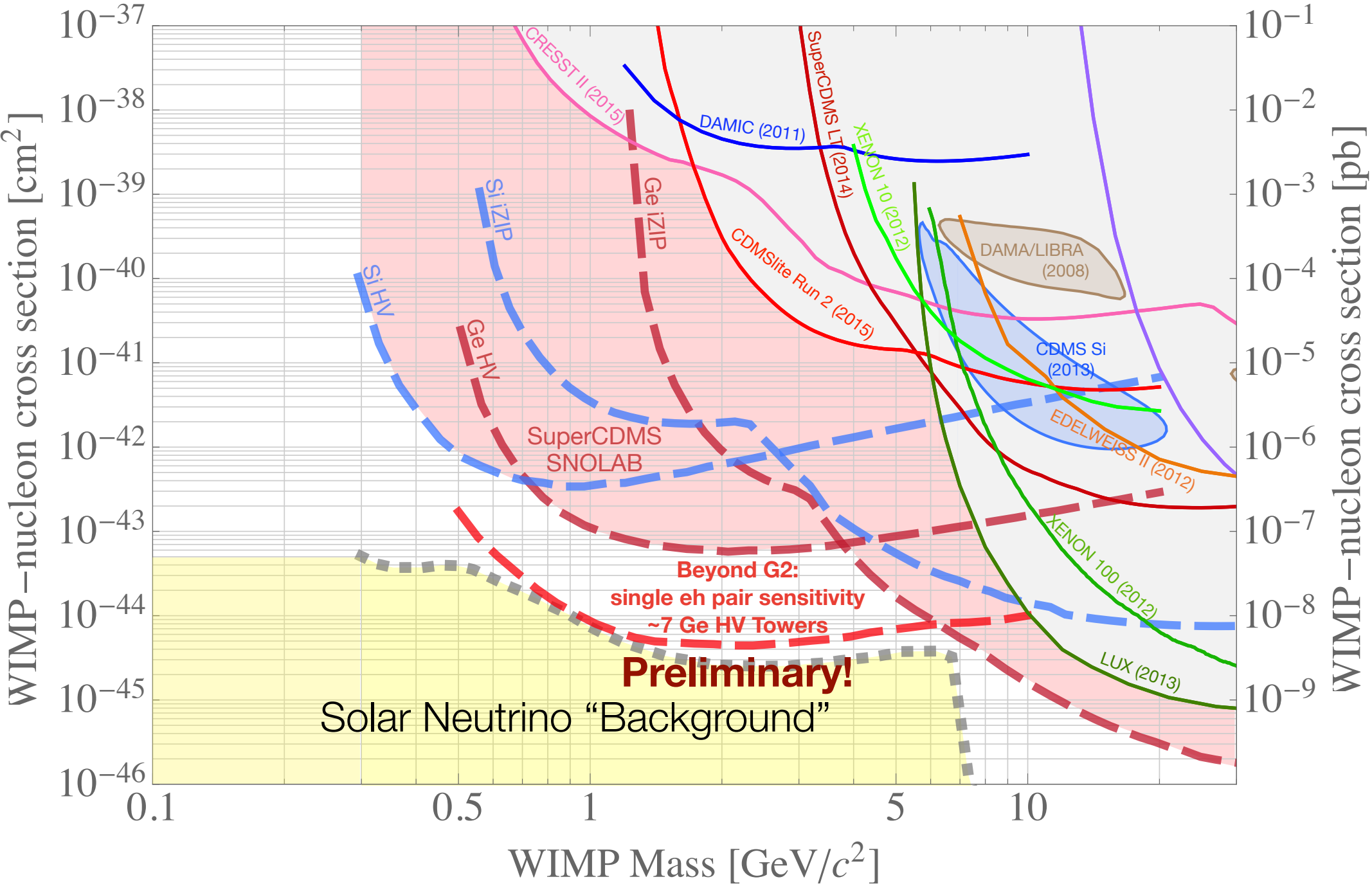
Regain Electron / Nuclear Recoil Discrimination!

$$\text{Phonon energy} = E_{recoil} + E_{Luke}$$
$$= E_{recoil} + n_{eh}\, e^{-}\, \Delta V$$

- For photons, all energy goes into making eh pairs. Assume it takes about 3 eV to make an eh pair.
- 4 eV photon makes 1 eh pair + 4 eV recoil = 104 eV
- 8 eV photon makes 2 eh pairs + 8 eV recoil = 208 eV
- For nuclear recoils, the ionization yield is about 10%
- 30 eVnr makes 1 eh pair + 30 eV recoil = 130 eV
- 60 eVnr makes 2 eh pairs + 60 eV recoil = 260 eV



To the Neutrino Background… and Beyond!



Measuring the Ionization Yield in Si and Ge

HV Detector Results Depend on Ionization Fraction (Yield)

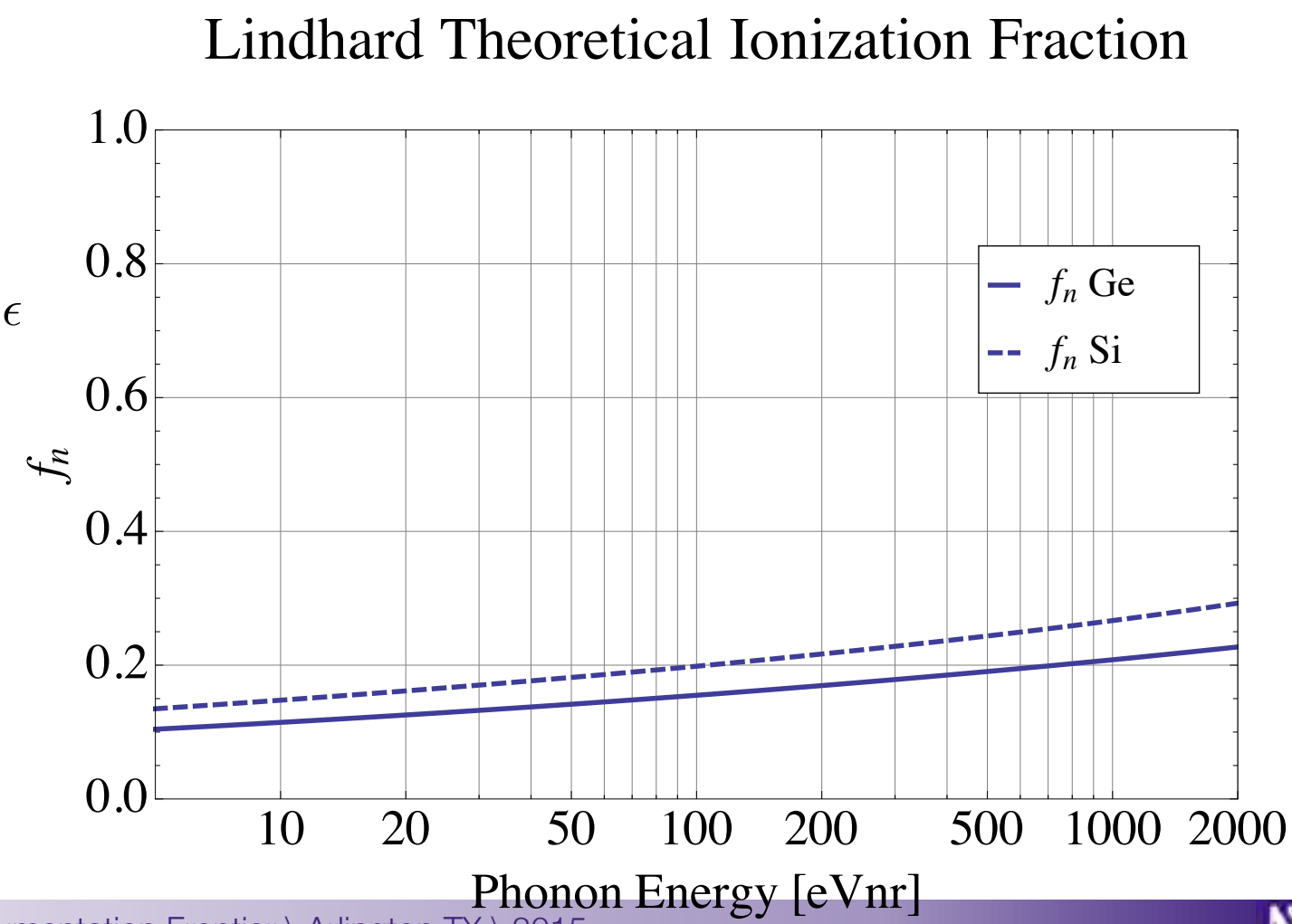
$$f_n = \frac{kg(\epsilon)}{1 + kg(\epsilon)}$$

Fraction of recoil energy deposited in target converted to ionization signal

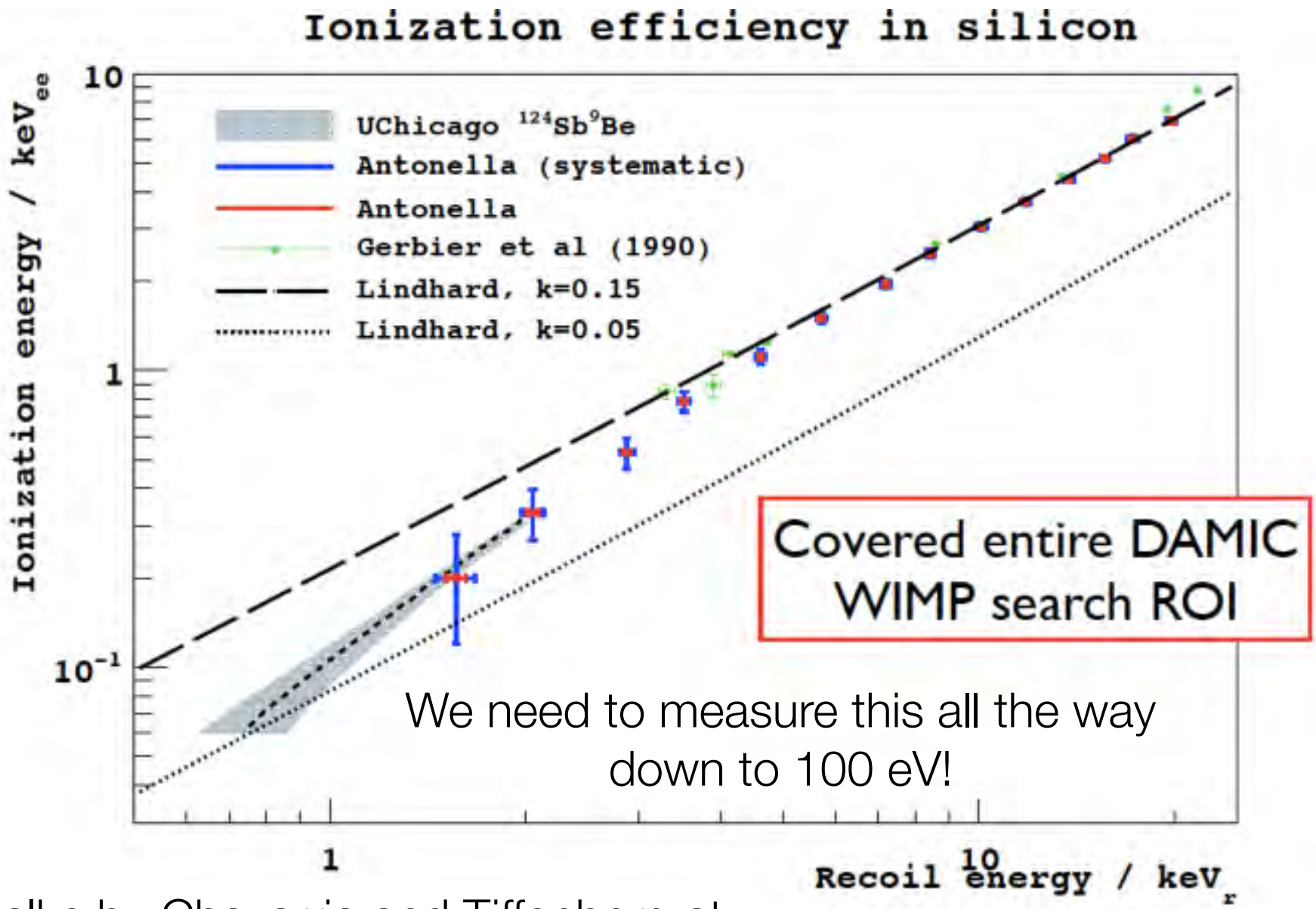
$$k = 0.2$$

$$g(\epsilon) = 3\epsilon^{0.15} + 0.7\epsilon^{0.6} + \epsilon$$

$$\epsilon = 11.5\,T\,Z^{-7/3}$$



Recent Measurements of Ionization Yield in Si



See talks by Chavarria and Tiffenberg at:
https://kicp-workshops.uchicago.edu/2015-lowecal/presentations.php

Ways to measure *yield* and σ_y using a HV detector

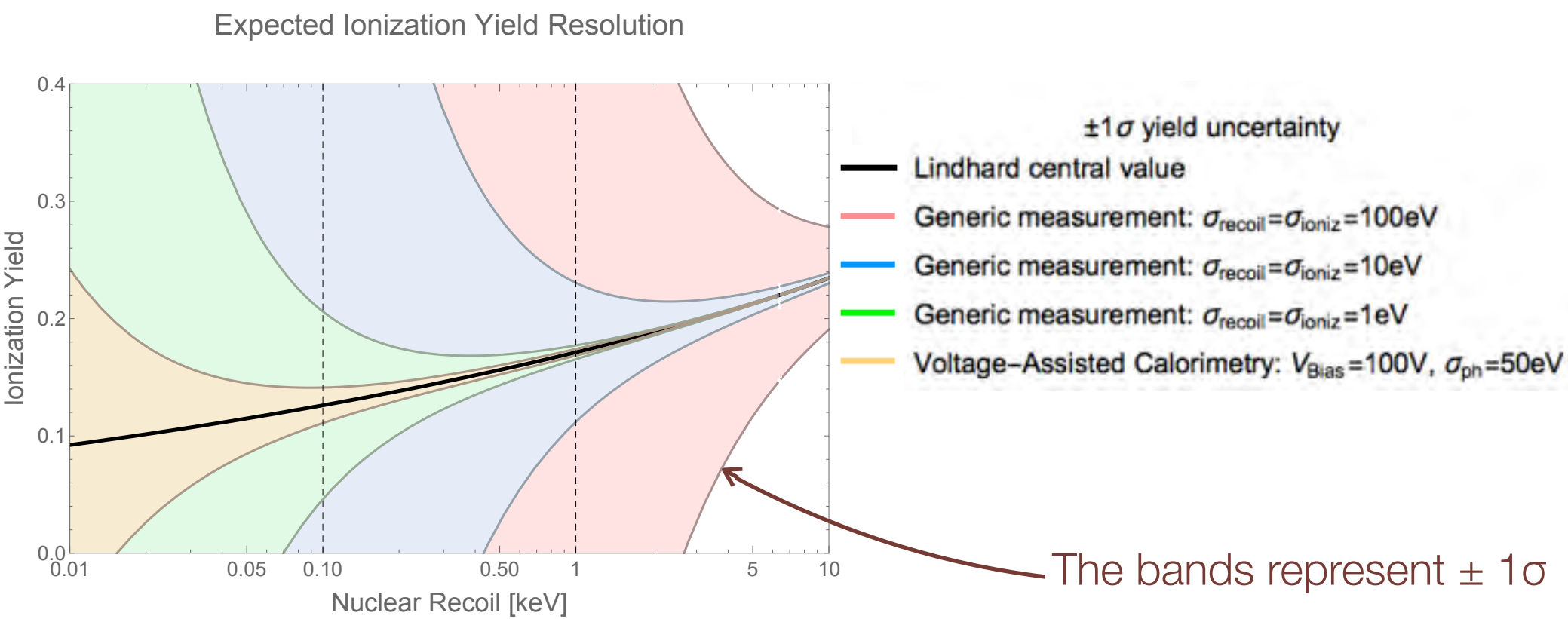
- With a HV detector we measure $E_{phon.}$, which effectively gives us $E_{ioniz.}$ with a very good resolution.
- By measuring the recoiling particle's scattering angle we can determine kinematically the recoil energy E_{recoil} with a very good resolution.
- Idea: take ionization yield measurements with a HV detector at a neutron scattering facility

$$y = \frac{\mathcal{E}_{eh}}{eV}\left(\frac{E_{phon.}}{E_{recoil}} - 1\right) \longrightarrow \sigma_y = \frac{\sqrt{E_{rec}^2\sigma_{ph}^2 + E_{ph}^2\sigma_{rec}^2}}{\frac{eV}{\mathcal{E}_{eh}}E_{rec}^2}$$

Look at that nice big number
in the denominator

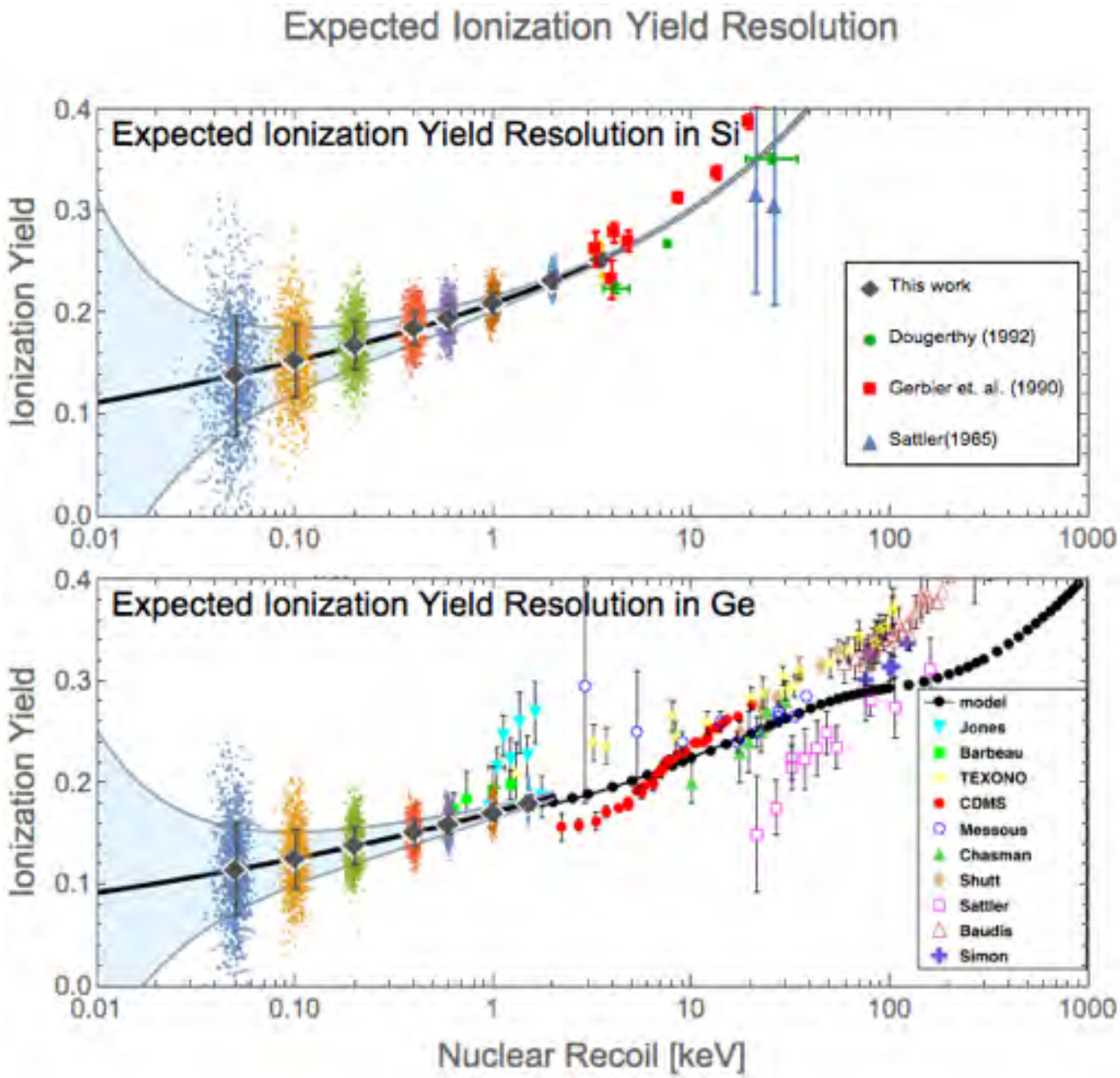
HV Detectors tame the low energy divergence

- Comparing the ±1σ yield uncertainty bands for a “generic" yield measurement with $\sigma_{recoil} = \sigma_{ioniz}$ vs a Voltage-Assisted Calorimetric measurement (HV detector)
  - Assuming: σ_{phon} = 50 eV, $\sigma_{recoil} \equiv \delta\phi$=1°, V=100V.



Simulations of Yield Measurement with HV detector

Assumes 100 eV phonon resolution

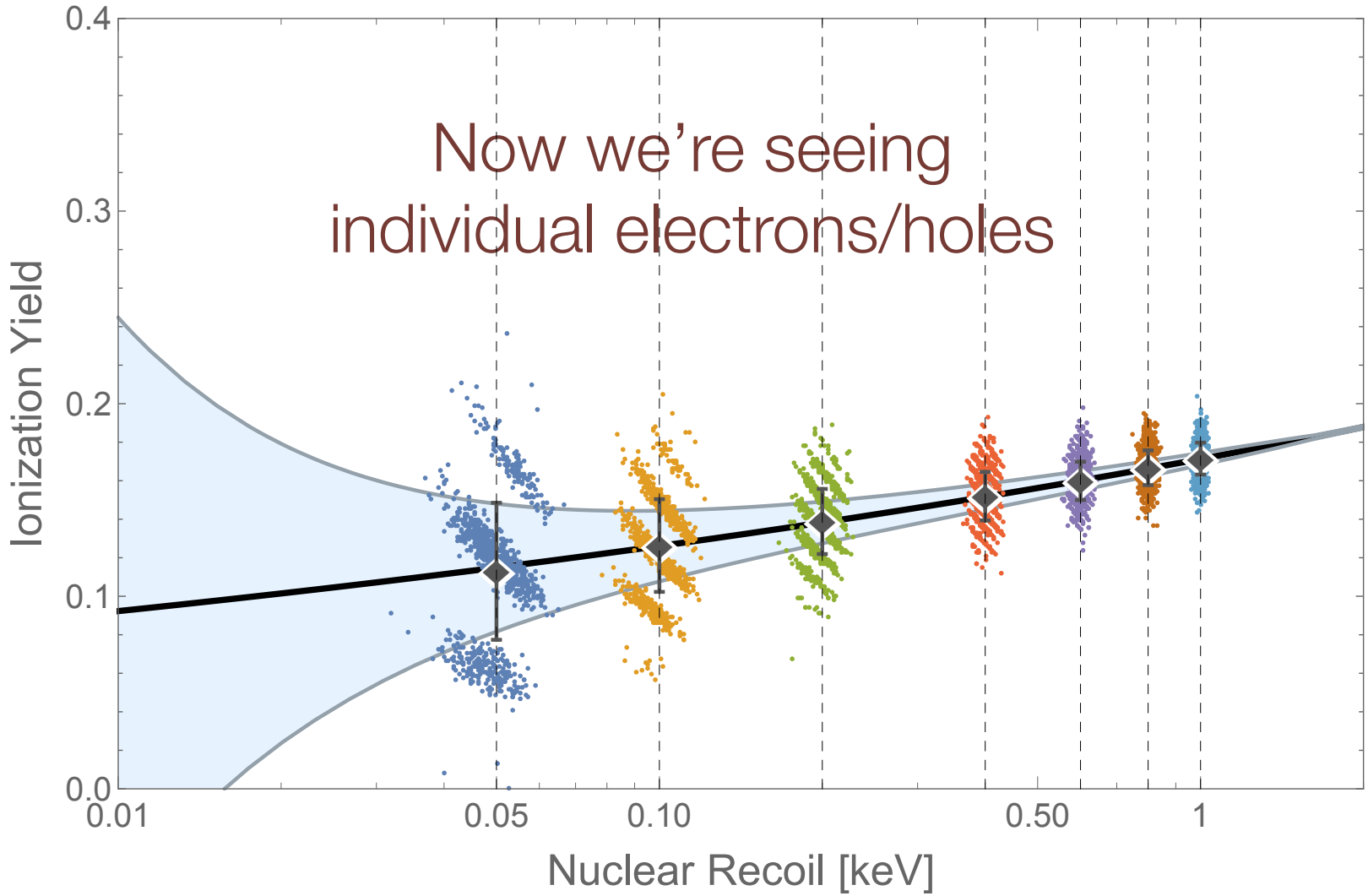


Simulations of Yield Measurement with HV detector

- Parameters:
  - $E_k(n)$=30 keV, σ_{phon}=10 eV, σ_{recoil}≡± 1°, V=100V, F=0.13

Expected Ionization Yield Resolution

Assumes 10 eV phonon resolution



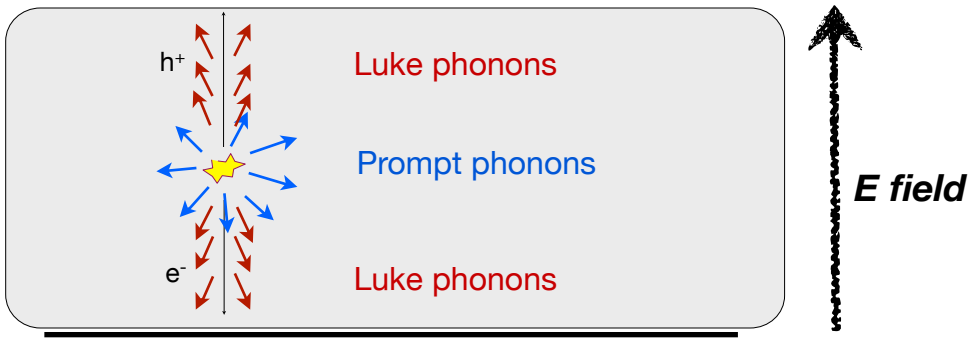
Applying SuperCDMS Technology to CE**ν**NS

RICOCHET
A Coherent Neutrino Scattering Program

Phonon energy = E_{recoil} + E_{Luke}

$$E_{\mathrm{Luke}} = n_{\mathrm{eh}}\, e\, \Delta V$$

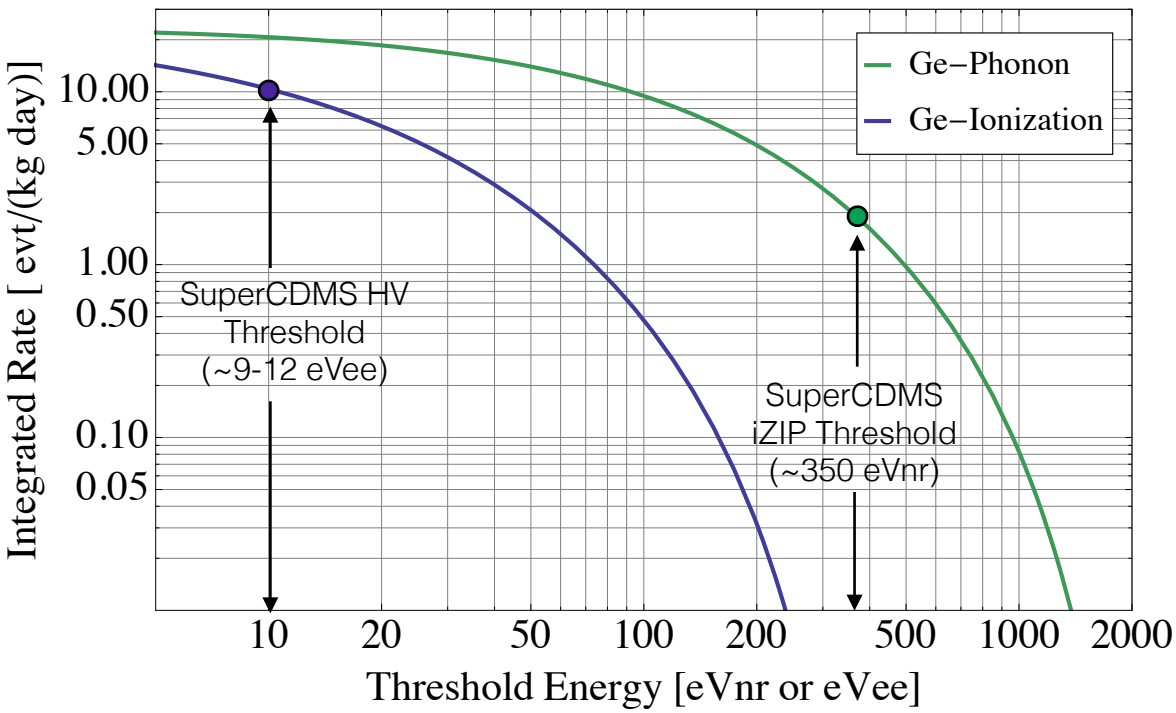
Big voltage = big phonon signal



- Luke phonons come from the work done to move the charge through the crystal
- New optimized phonon sensors will have an energy resolution of ~50 eV
- With 100 V bias, 4 electron-hole pairs generate 400 eV of phonon energy, 8σ above the phonon noise.
- Recent lab devices showed stable operation with voltages of up to 400 V — single electron sensitivity may be possible!

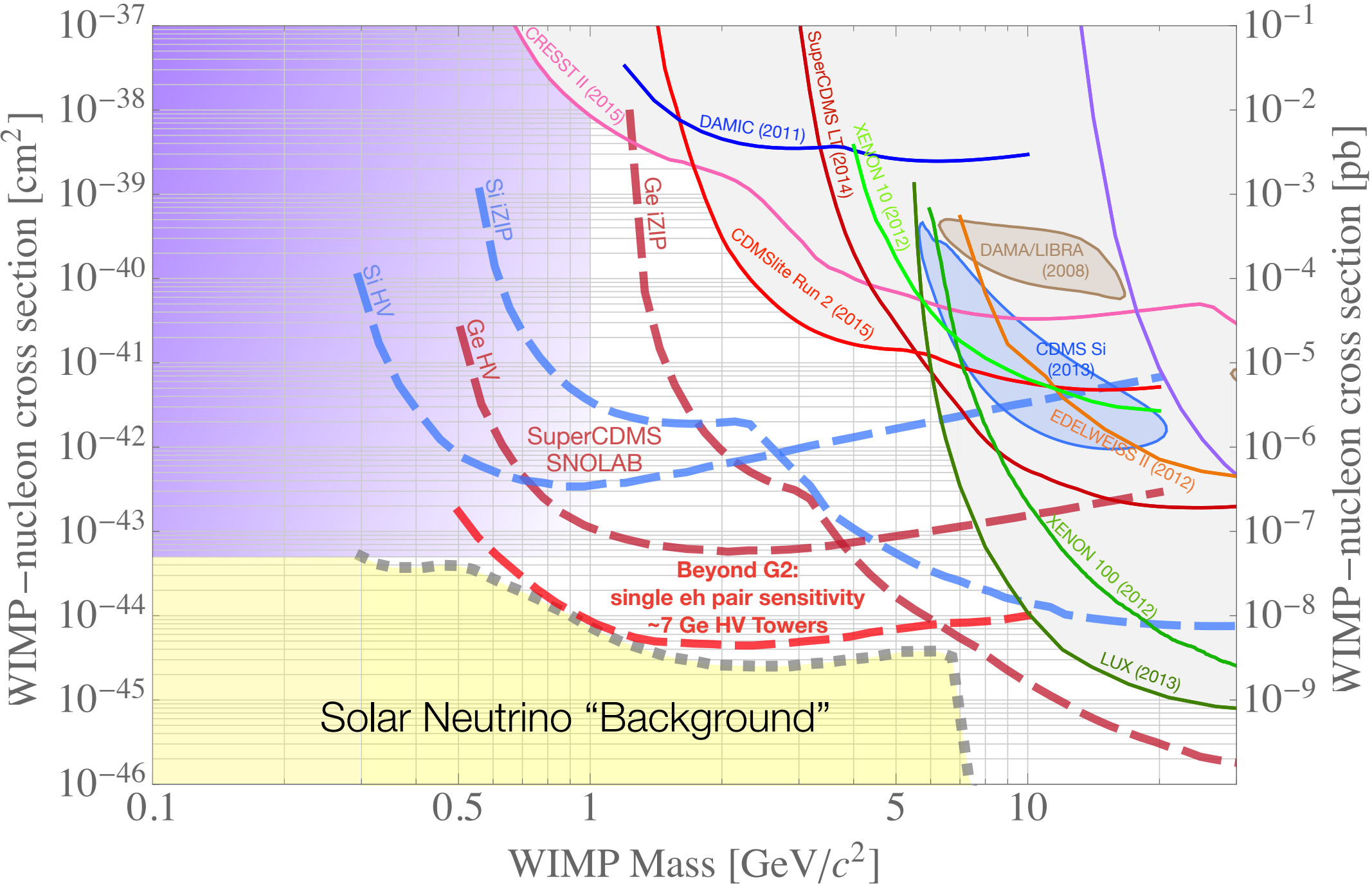
Rate at the Advanced Test Reactor

(110 MW reactor, 11 m from core)



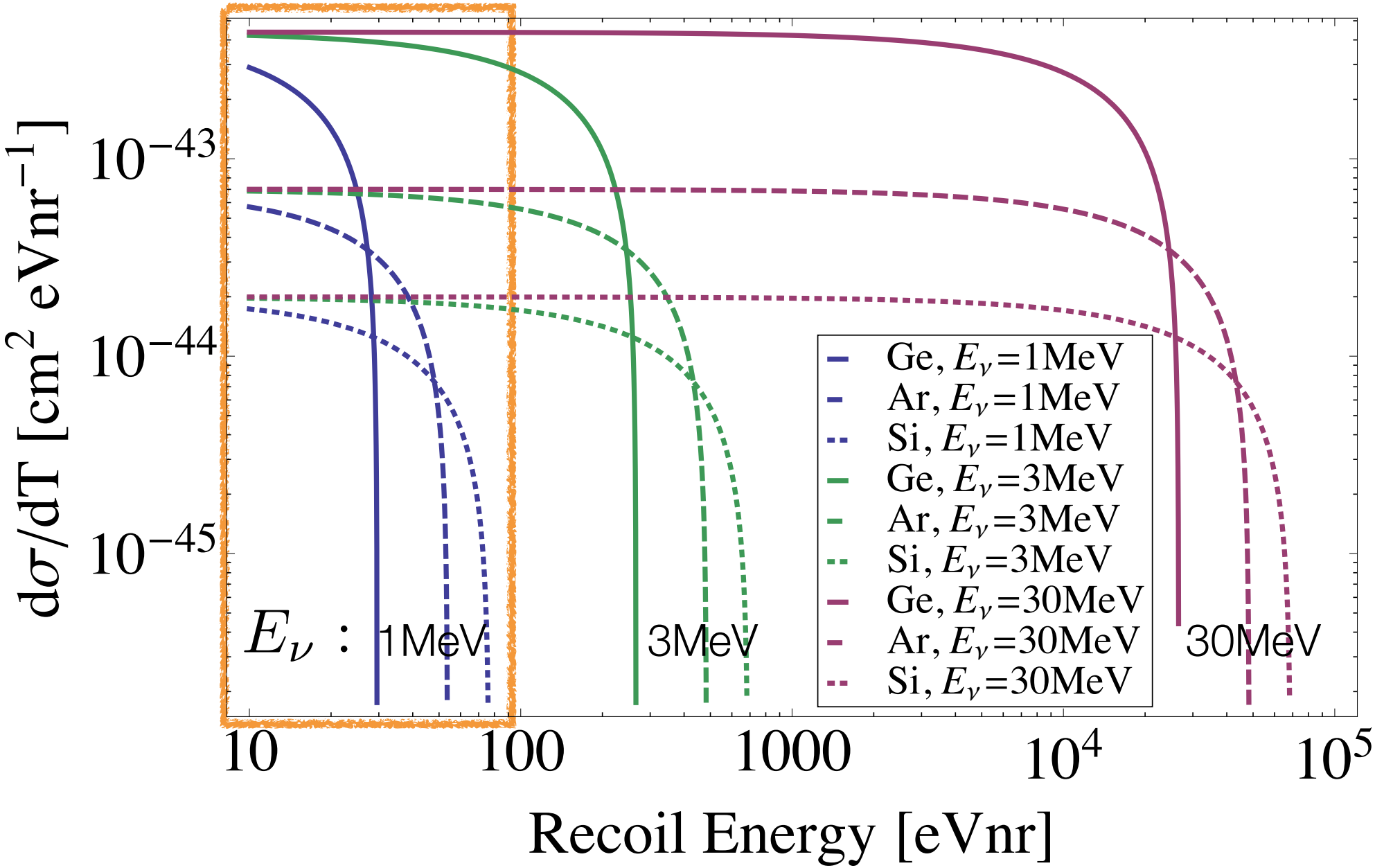
Thermal Detectors

Thermal Detectors Could Play a Role At the Lightest Masses



Ricochet Phase 2: CE**ν**NS with ~1 MeV neutrinos

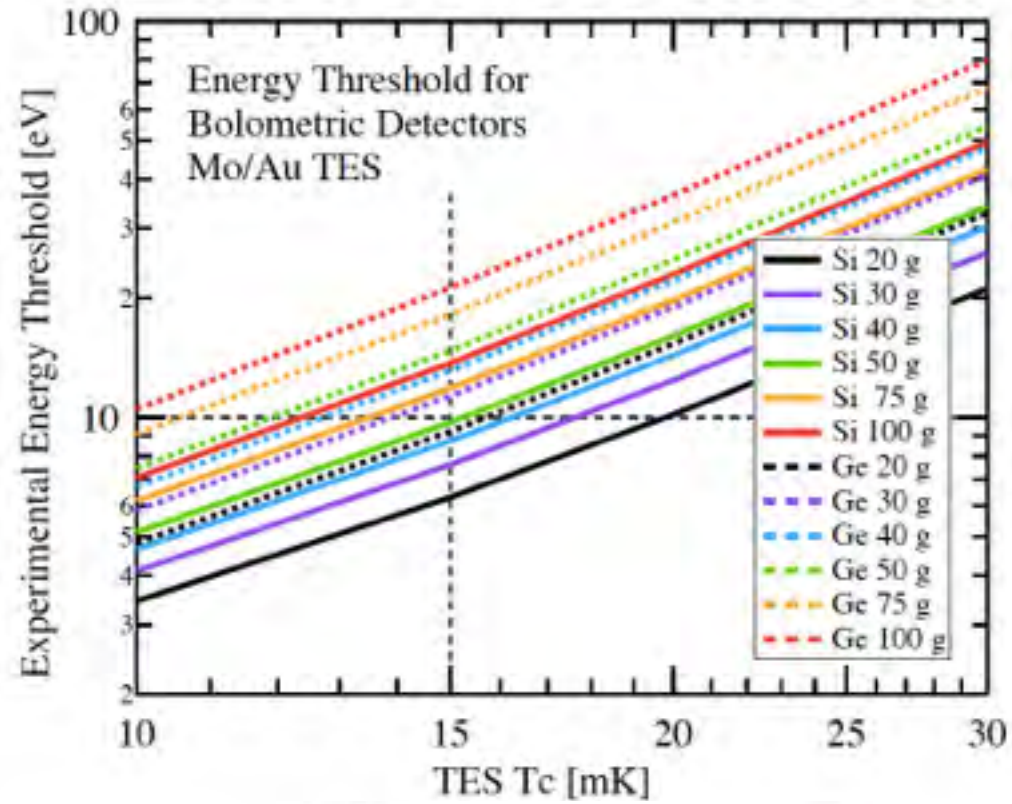
Need Thresholds of 10's of eV!

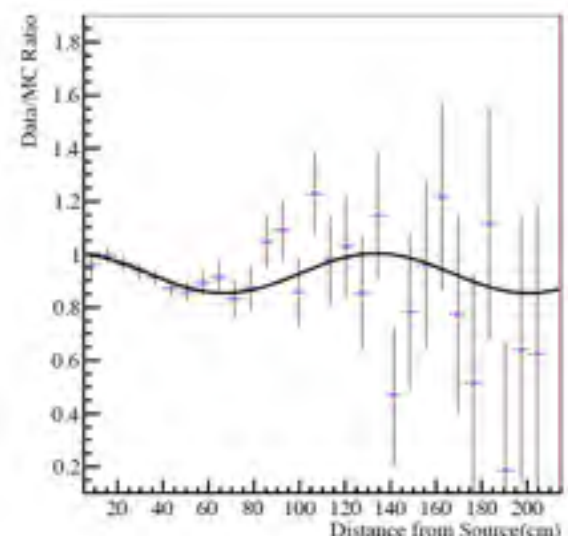


Ricochet Phase 2: CE**ν**NS with ~1 MeV neutrinos

arXiv:1107.3512

- Array of 10,000 elements with ^{37}Ar or ^{51}Cr source just outside shield (10 cm closest distance).
- Measuring time of 300 days (for ^{37}Ar, equivalent of 50 days signal, 250 days background).
- Background rate of 1 event/kg/day in energy region of interest
- R&D needed, would be a “smoking gun” experiment done if charged current experiments saw a signal.

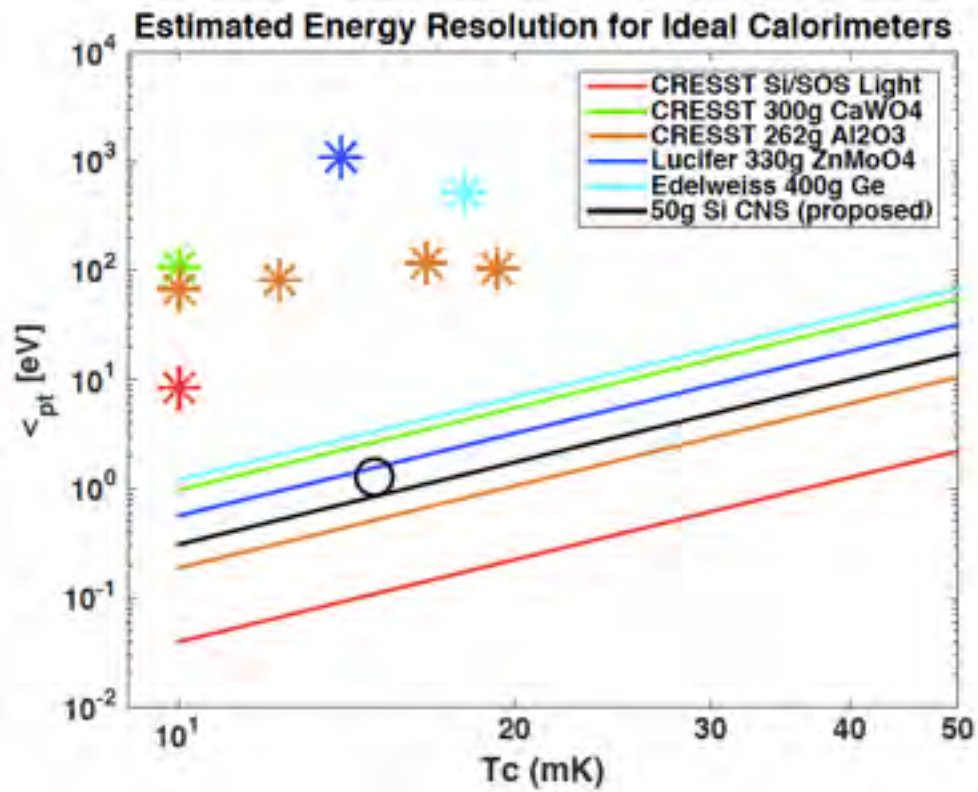


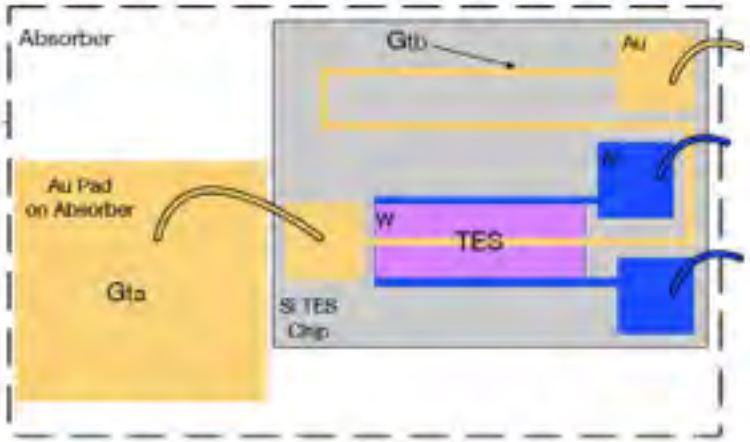


Detectors for 0νββ Decay

arXiv:1503.1200
Pyle, EFF, Sadoulet

- Optimizing the thermal and athermal time constants of the system to match the TES and signal bandwidths can greatly improve future massive 0νββ detectors, with resolutions below 10 eV.
- Wafer-sized Single-photon detectors with sub-eV resolution are possible!
- This technology had broad applications beyond dark matter and neutrino physics.
- R&D into active veto design will be important for many applications!





Conclusions

- Superconducting Detectors will make major contributions to the search for dark matter and neutrino physics
- R&D directions for Athermal detectors:
  - Optimization of resolution to reach single electron-hole discrimination
  - Electron / nuclear recoil discrimination strategies for sub keV recoils (more than one way to skin this cat)
  - Measurement of ionization yield down to 100 eV and below
- R&D directions for “Thermal” detectors:
  - Small pixel optimizations for 100 MeV dark matter and below and sterile neutrino searches with electron capture sources
  - TES thermometers for neutrino-less double beta decay and other massive calorimeters.
  - Single-photon detectors using CDMS-style athermal detectors (these have multiple uses!)
- R&D into active veto designs will be important to control backgrounds!