Probing Light WIMPs with SuperCDMS

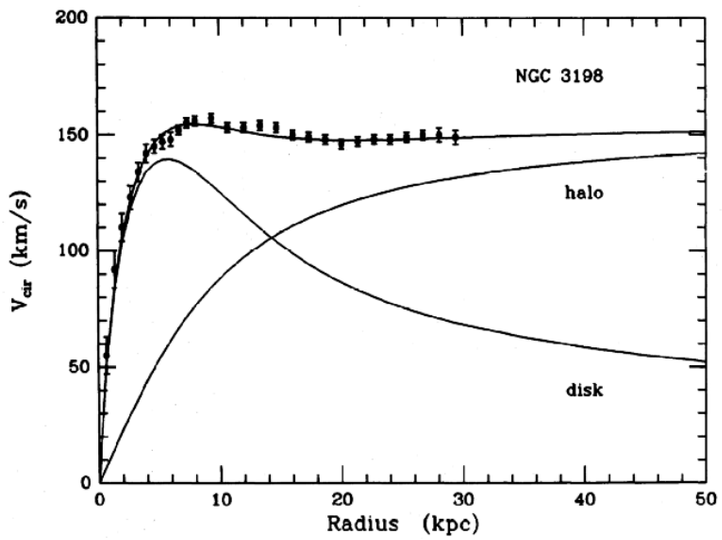
Adam Anderson

BNL Particle Physics Seminar
1 May 2014

Massachusetts Institute of Technology

Dark Matter on All Scales

galactic rotational velocities



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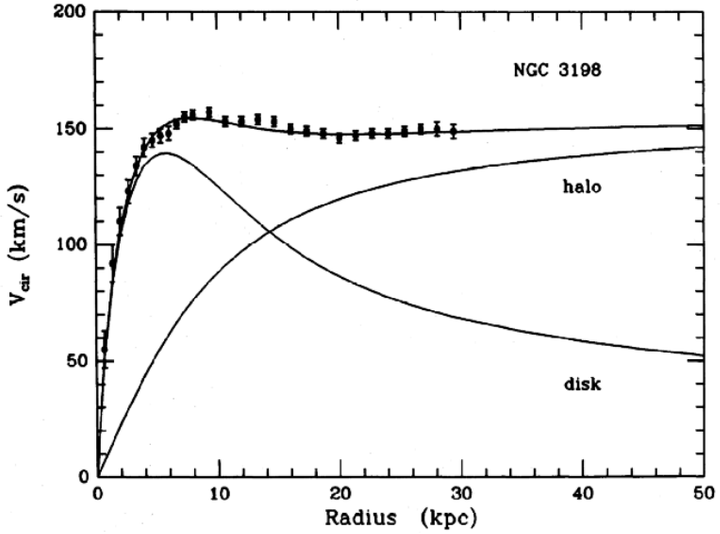
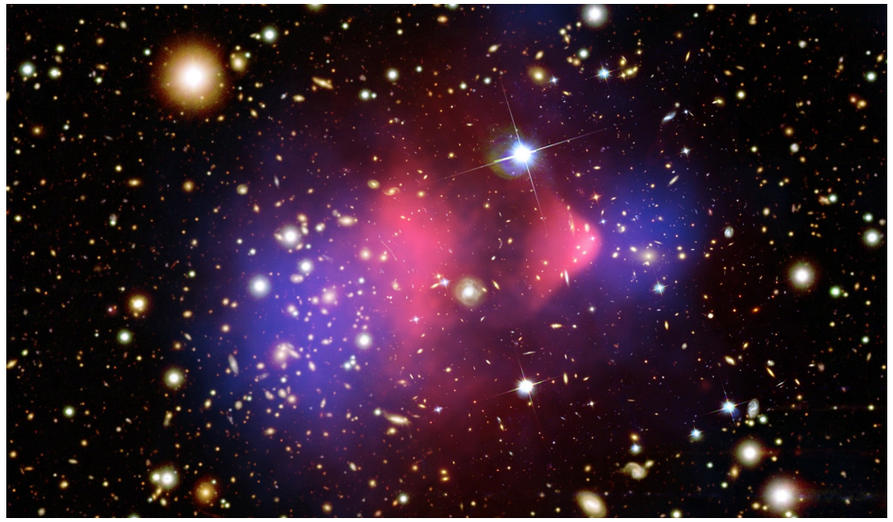


gravitational lensing of galaxy clusters



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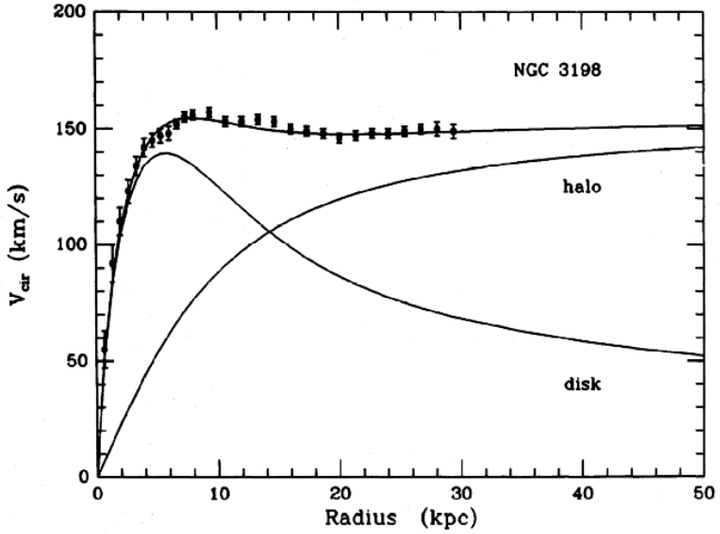

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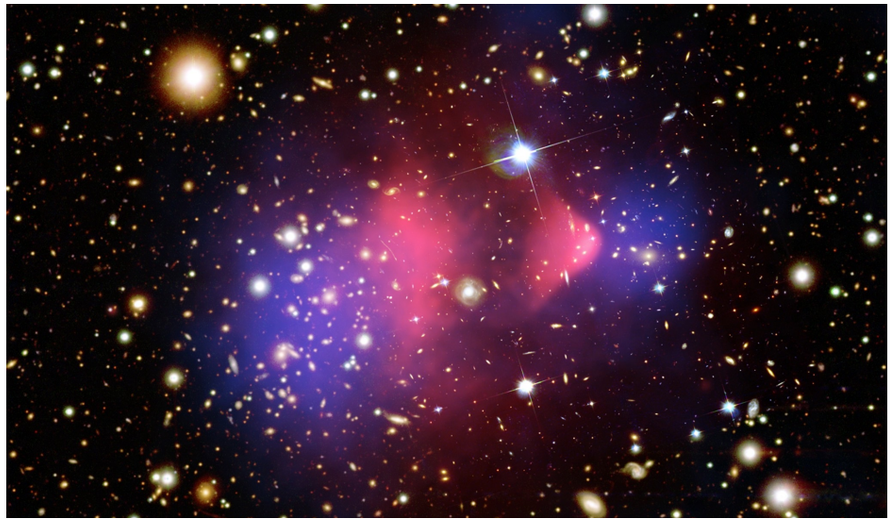
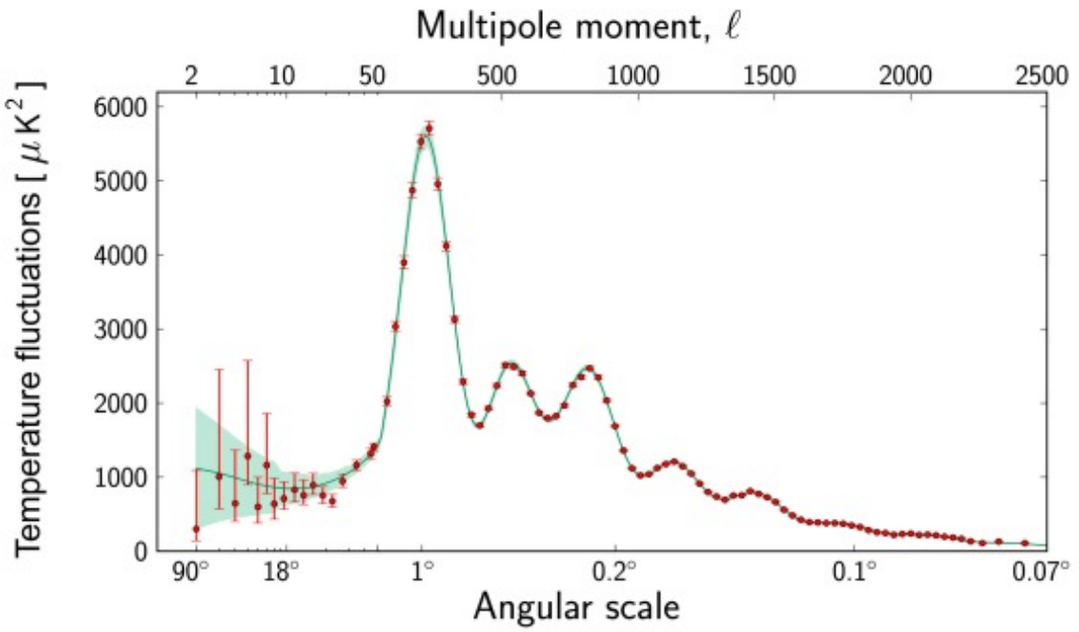
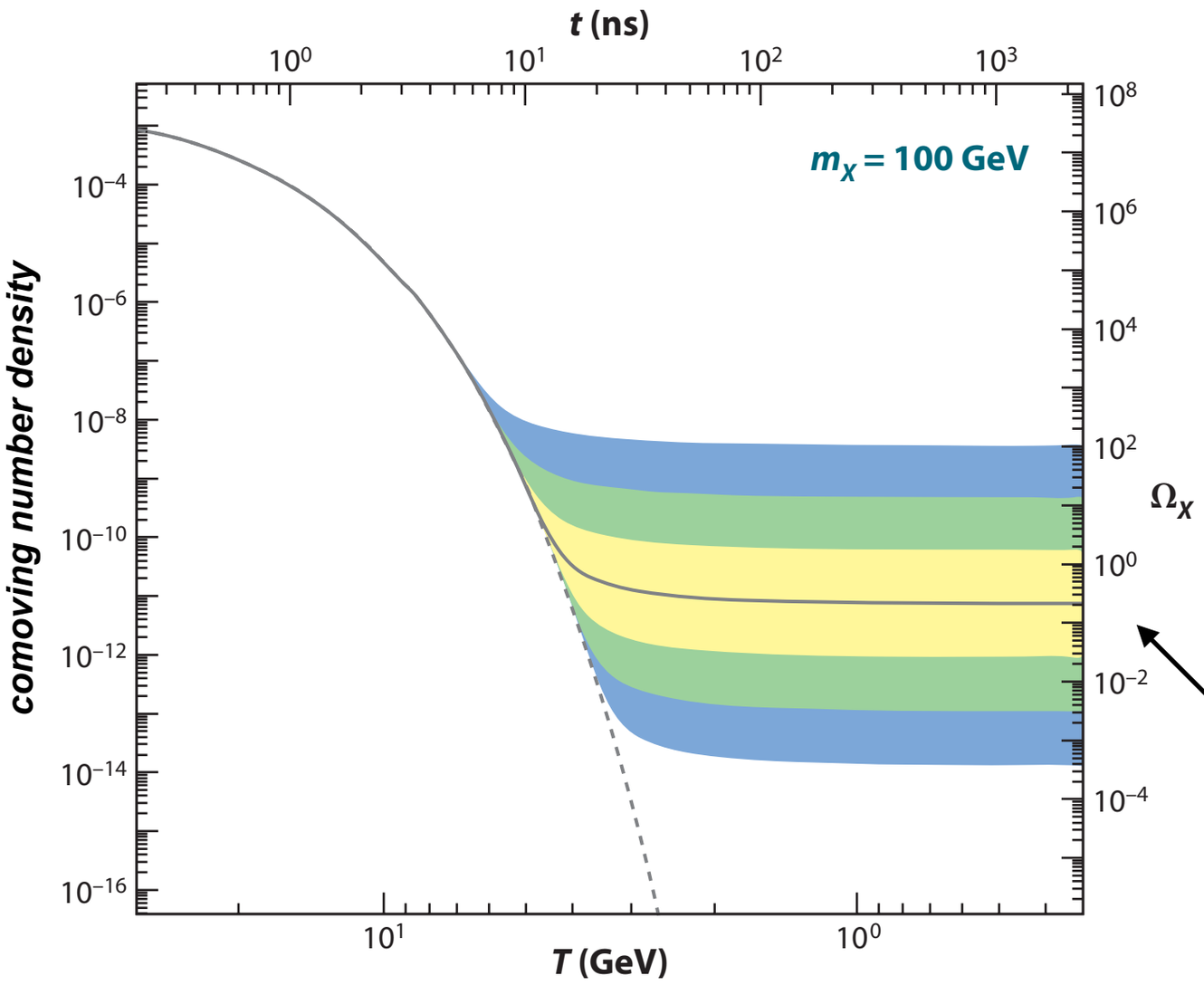


cosmic microwave background



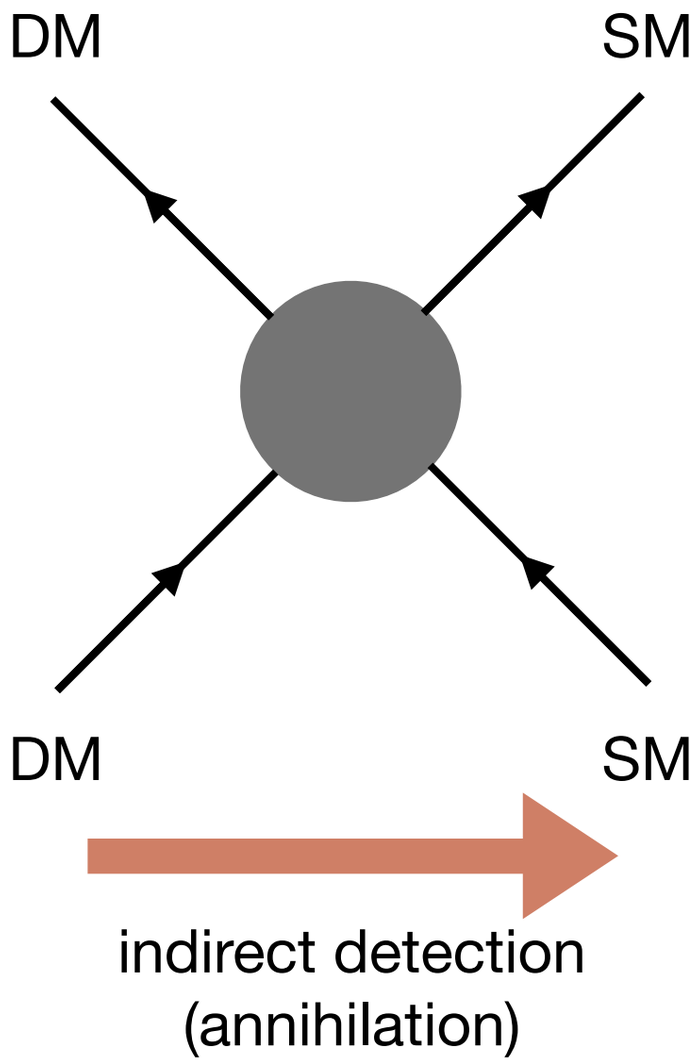
WIMP Paradigm



- New particle that is:
  - stable
  - electrically neutral
  - weakly and gravitationally interacting
- Produced thermally in the early universe
- "WIMP miracle"

weak-scale annihilation cross section produces correct relic density

WIMP Detection



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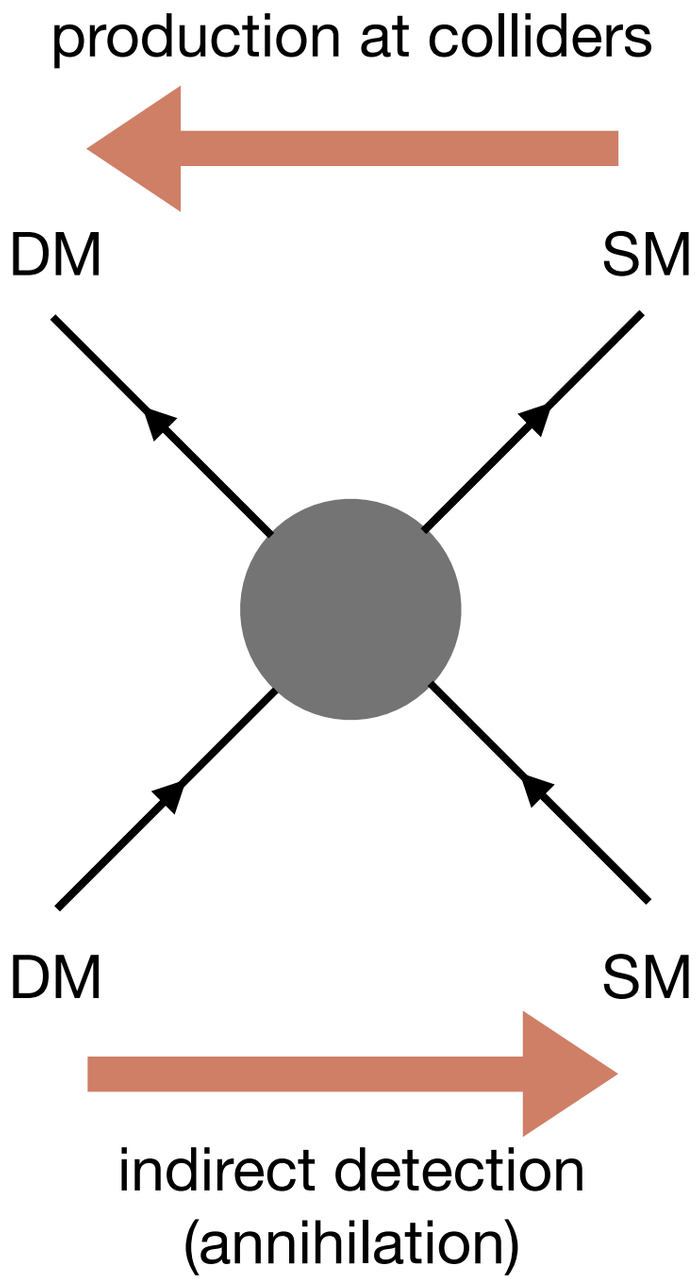

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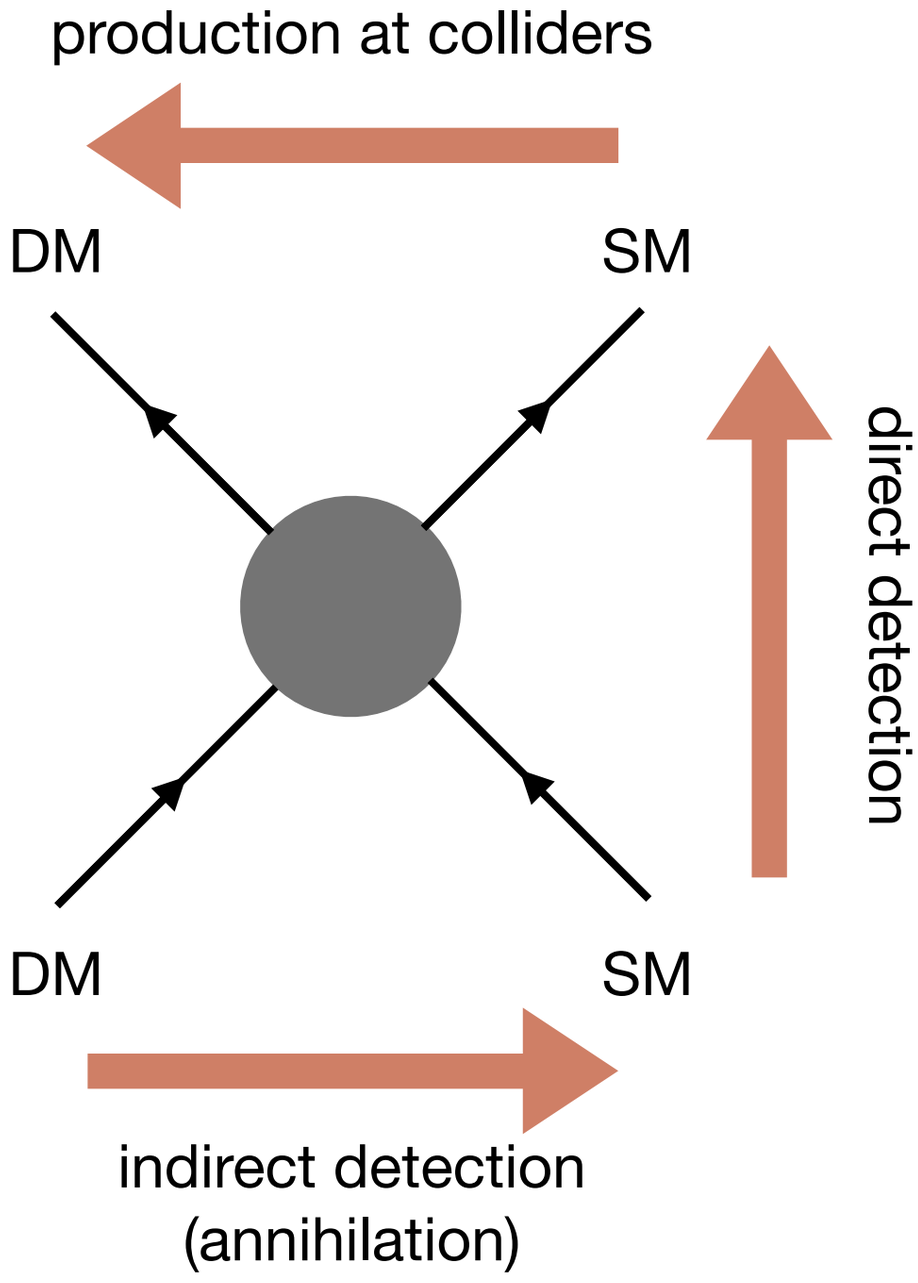

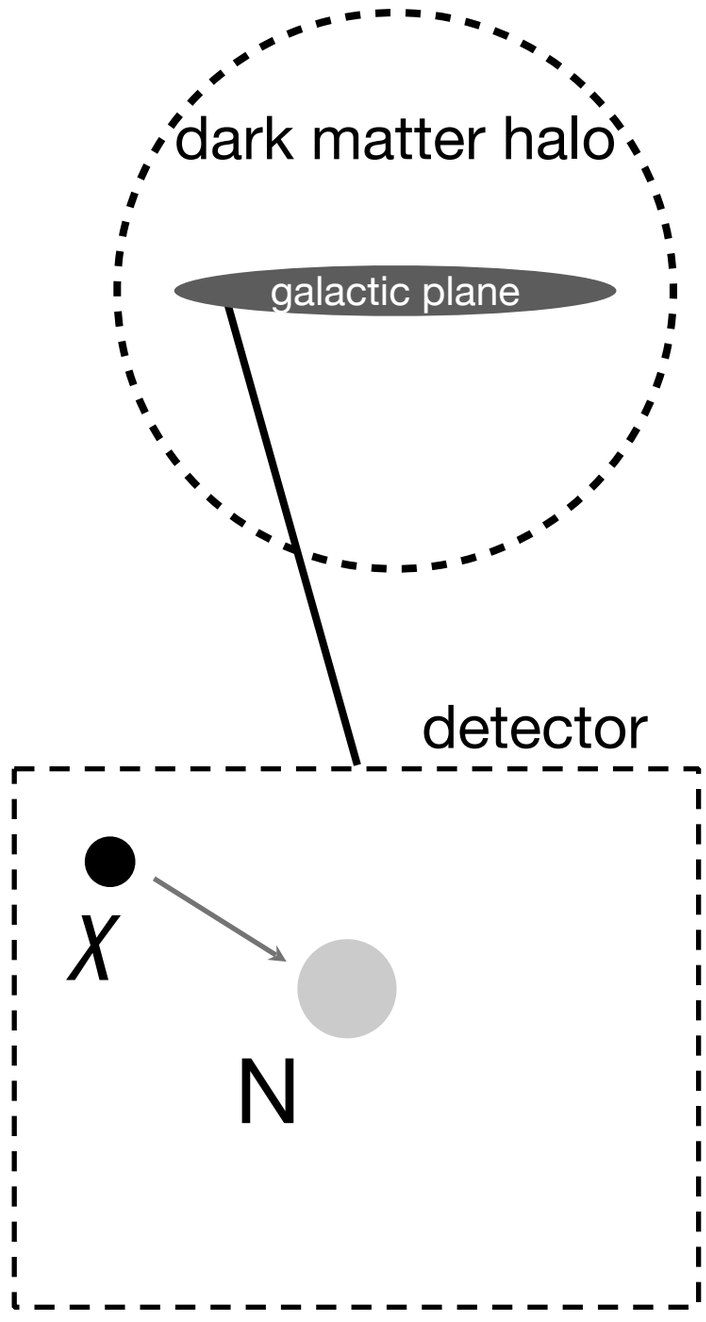

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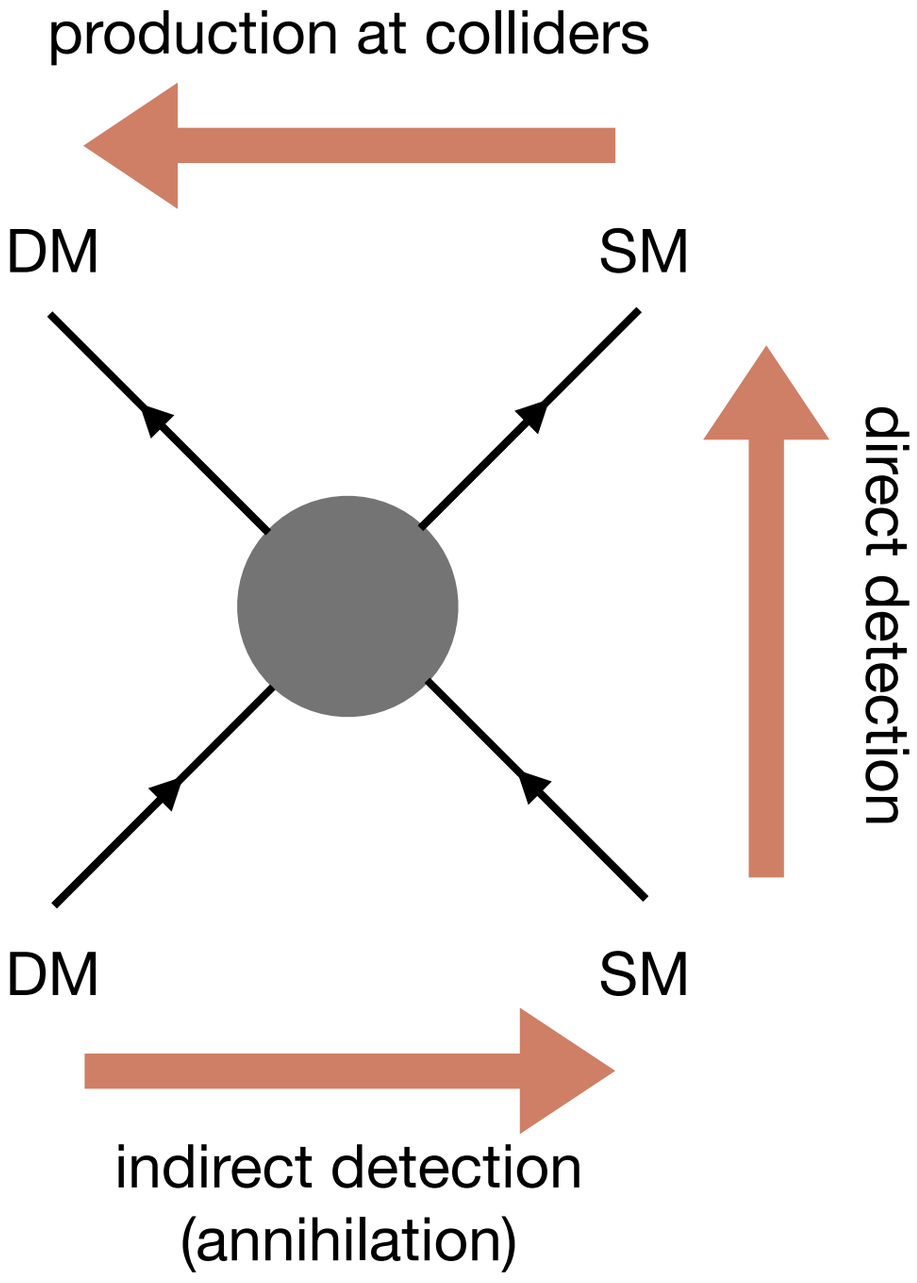
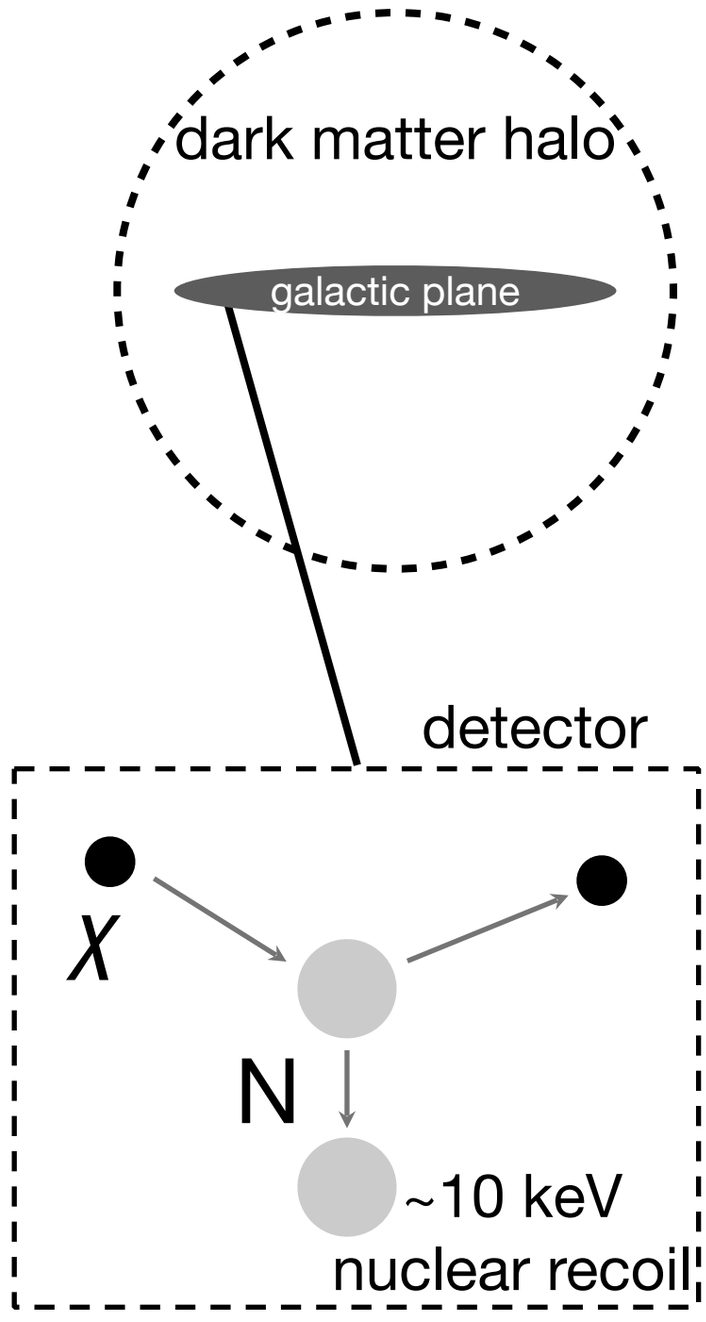


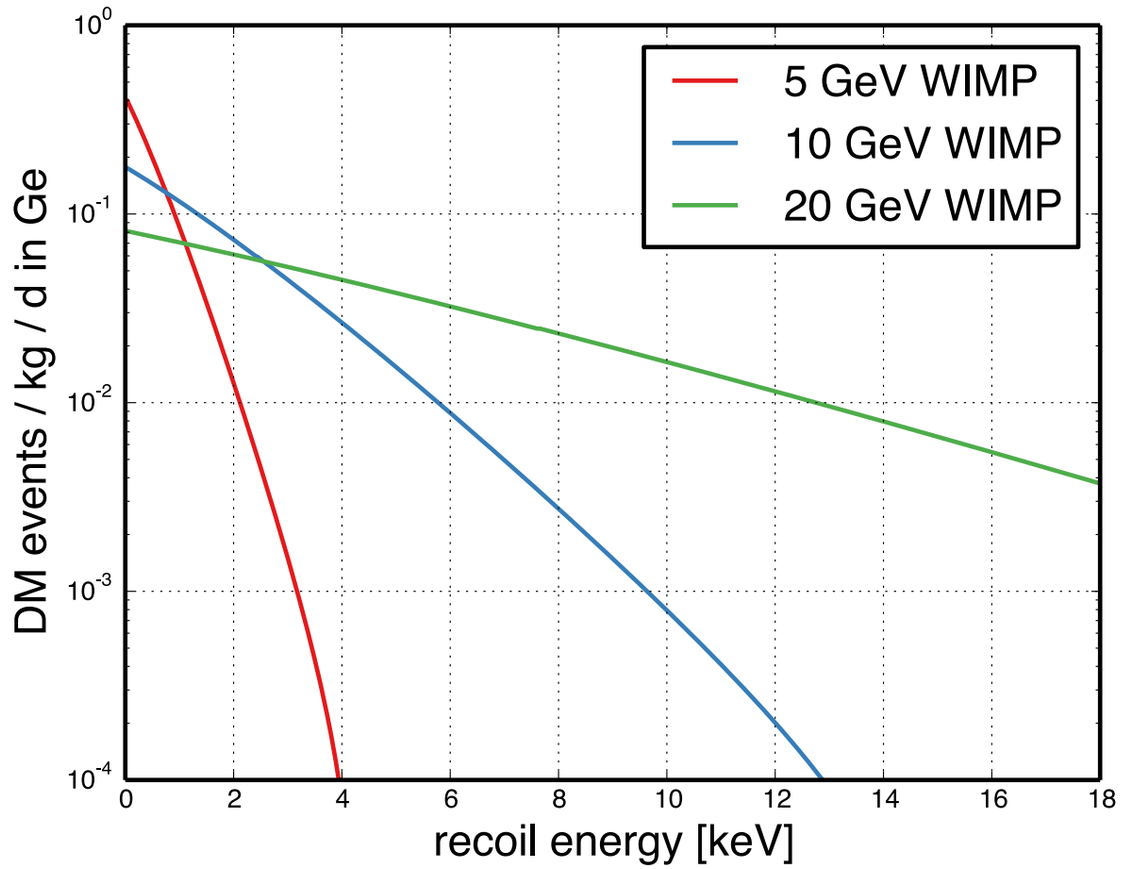


Direct Detection Signals

$$\left.\frac{dR}{dQ}\right|_Q = \frac{\rho_0 \sigma_0}{2\mu^2 m_{\rm dm}} A^2 \left|F(Q)\right|^2 \int_{v_{\rm min}(Q)} d^3v \, \frac{f(\mathbf{v}+\mathbf{v_e})}{v}$$

= measurement
= particle physics
= nuclear physics
= WIMP velocity distribution function

- Featureless exponential signal at low recoil energy
- Annual modulation in recoil rate due to earth's rotation



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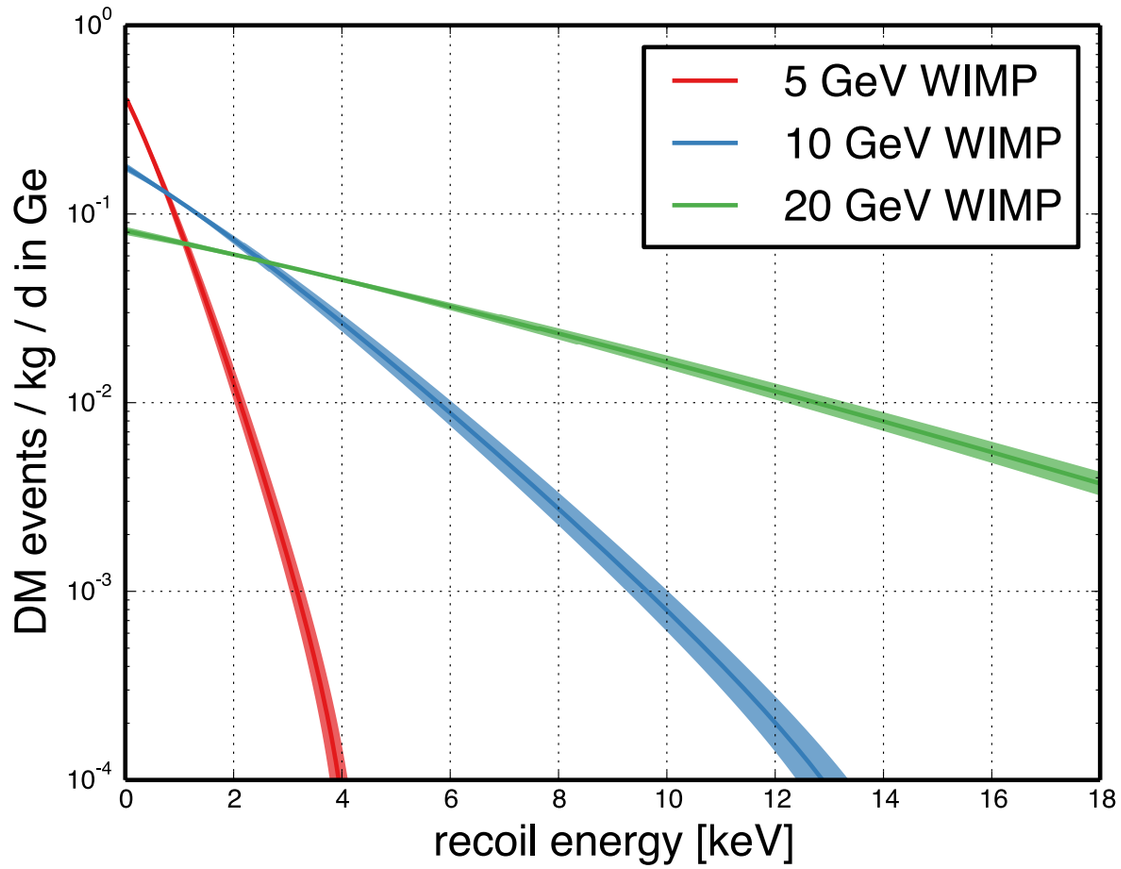
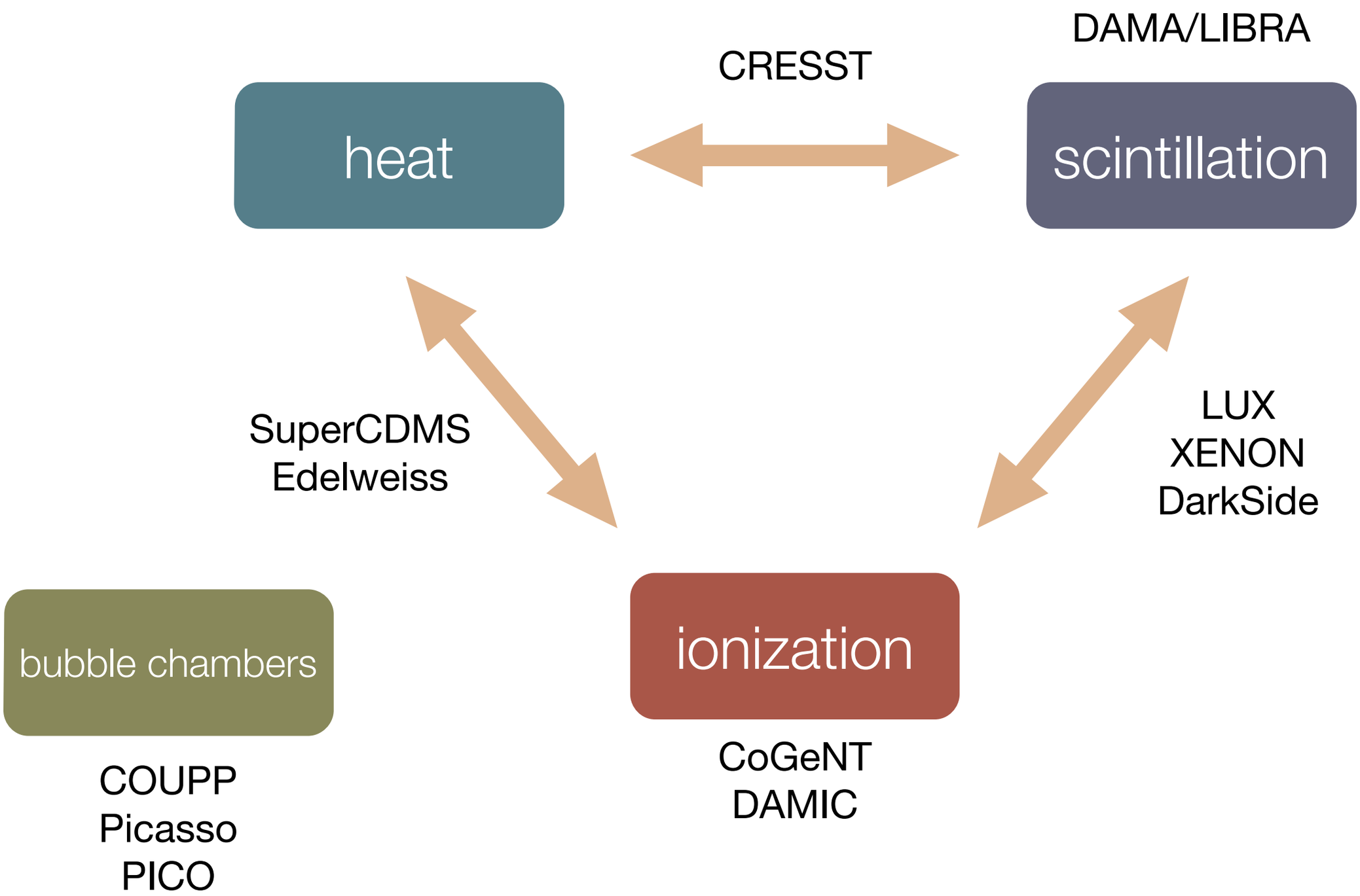
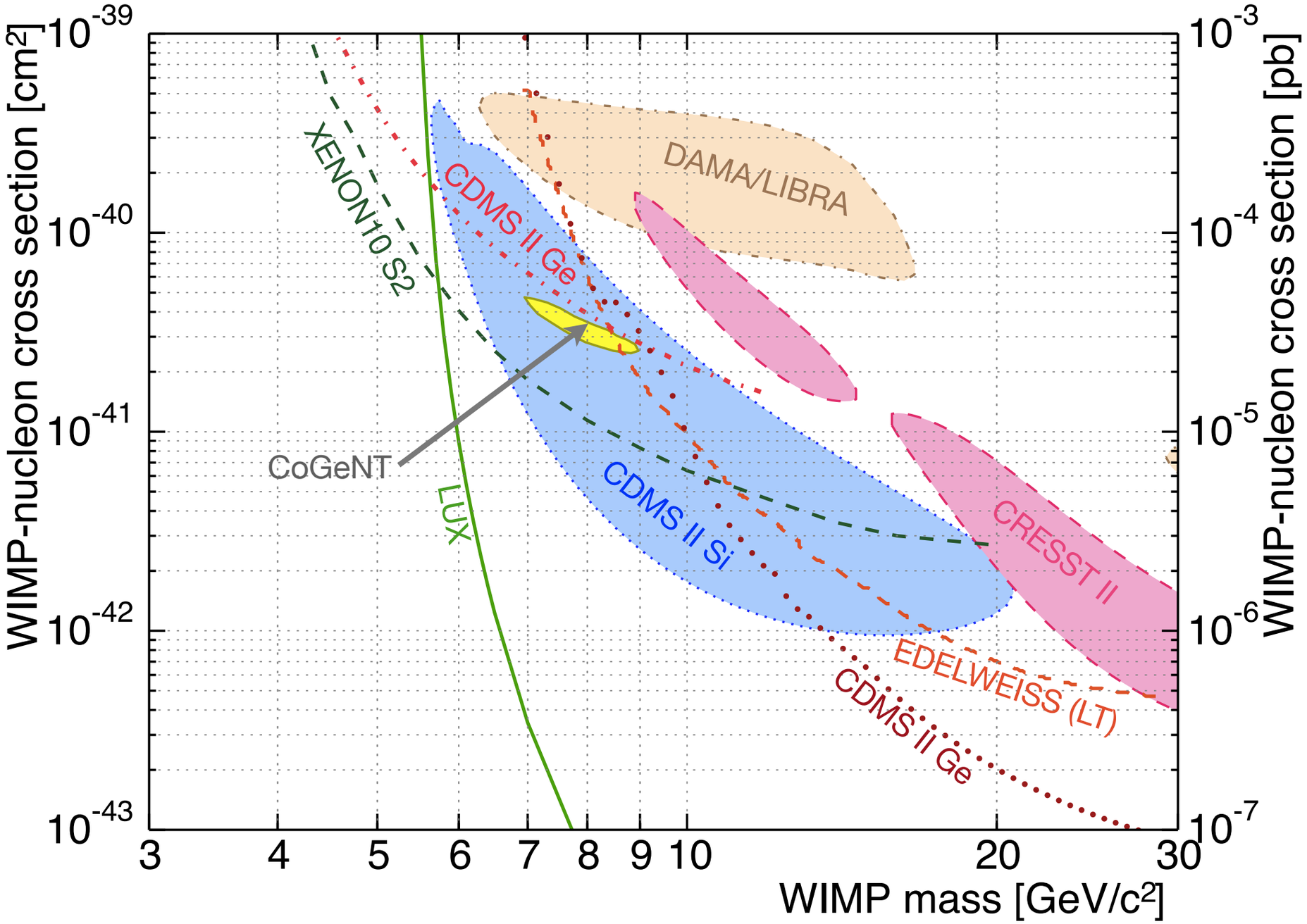


Direct Detection Approaches



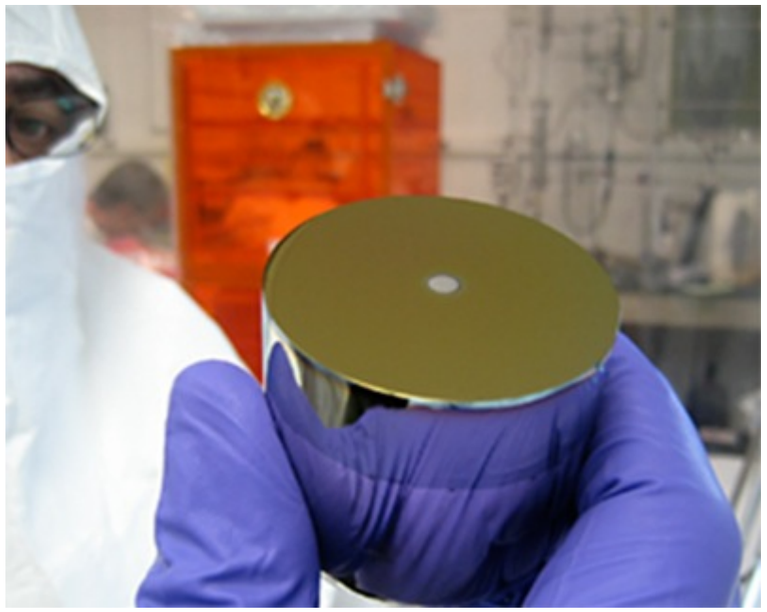
Low-mass Region before SuperCDMS

What can we say about low-mass dark matter “hints”?

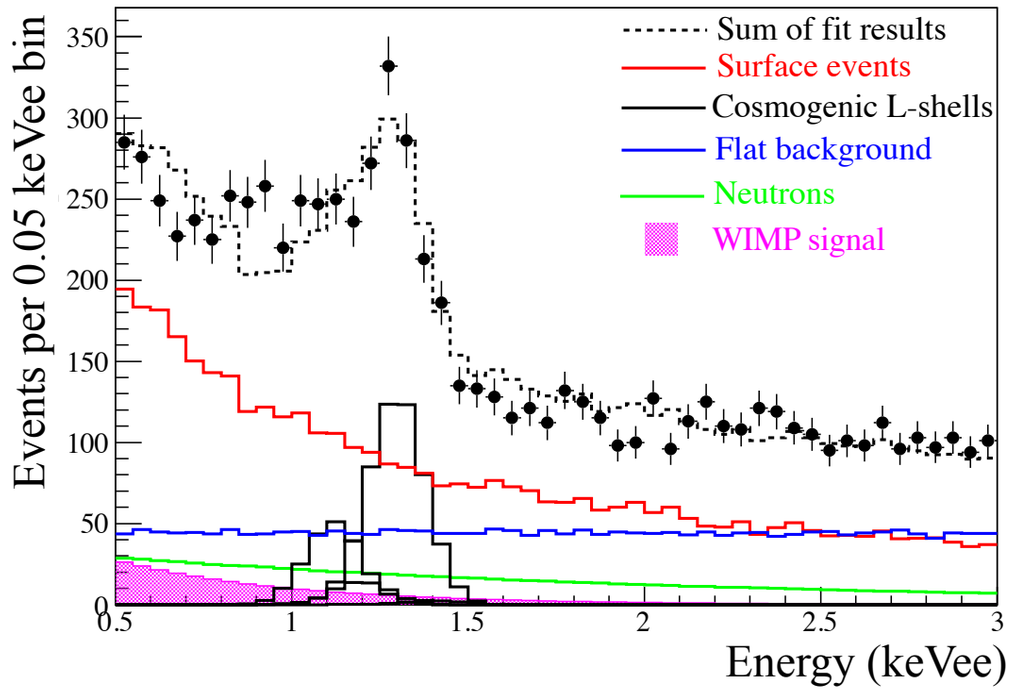


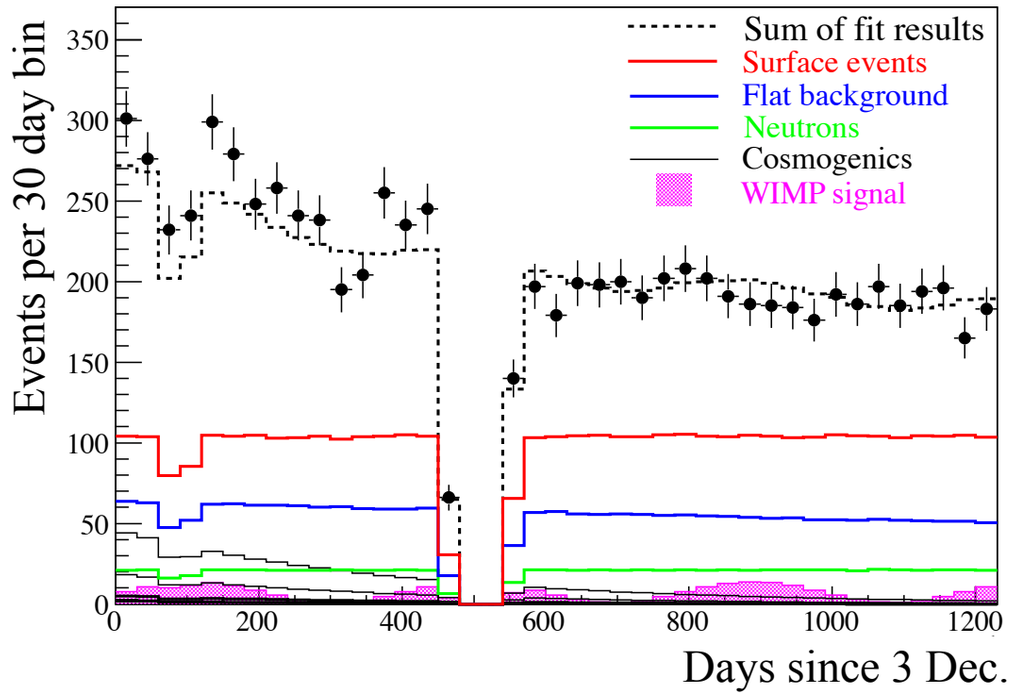
Hints from CoGeNT

- High-purity Ge detector
- Excellent energy resolution due to low detector capacitance
- Limited background discrimination (surface events)
- Several analyses have indicated 2-3σ excess in annual modulation and recoil



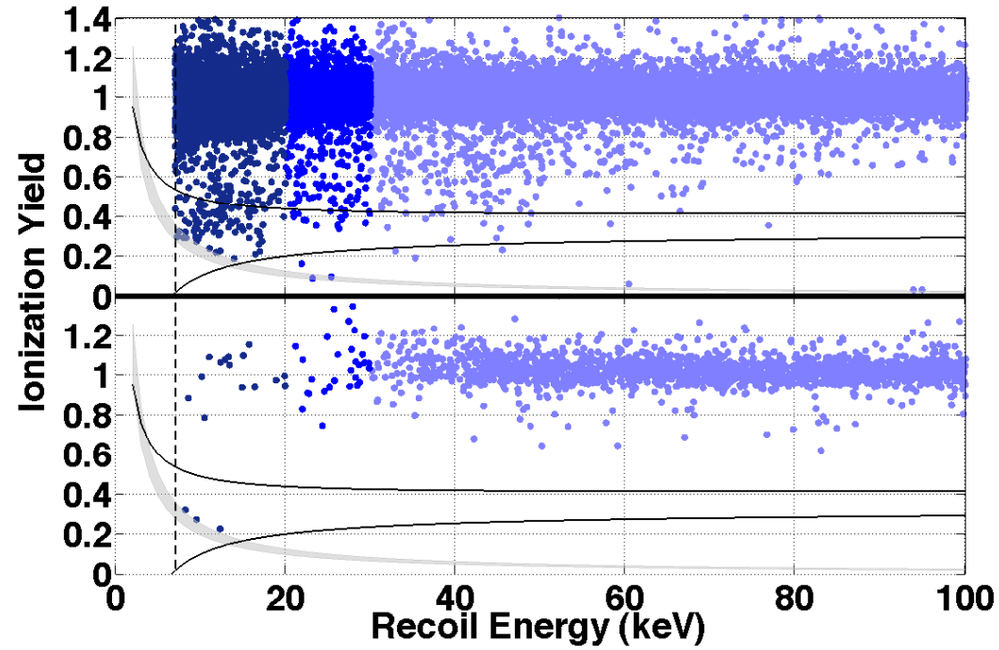
arXiv:1401.6234

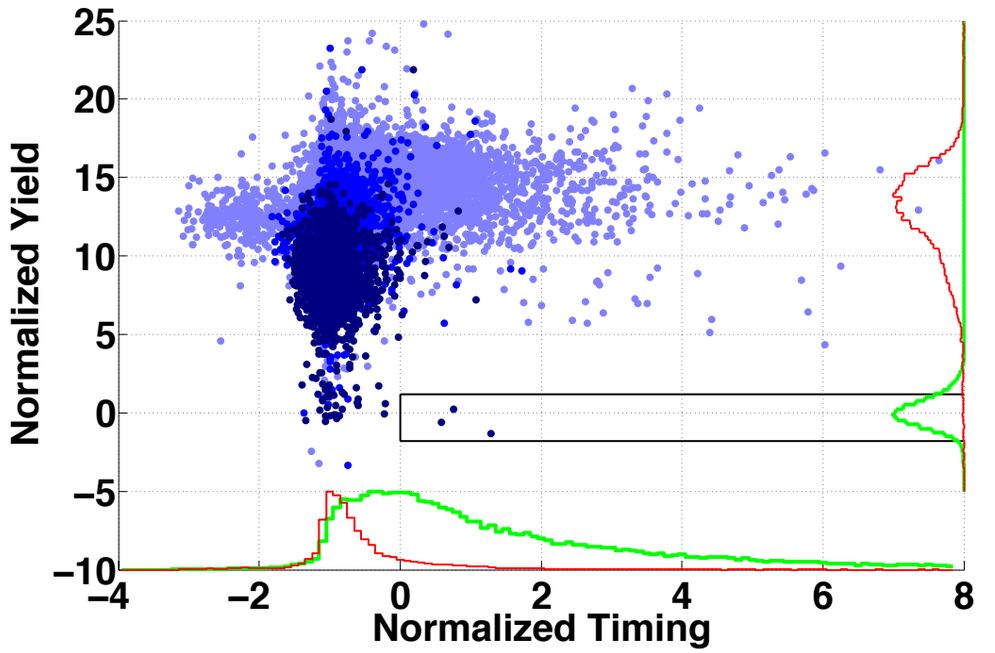




Hints from CDMS II Silicon

- Powerful background rejection using ionization yield and phonon risetime information
- 7 keVnr threshold, but efficiency rapidly dropping below 20 keVnr
- 3 events observed, 0.41 expected
- WIMP+background hypothesis favored over background-only with *p*-value of 0.19%



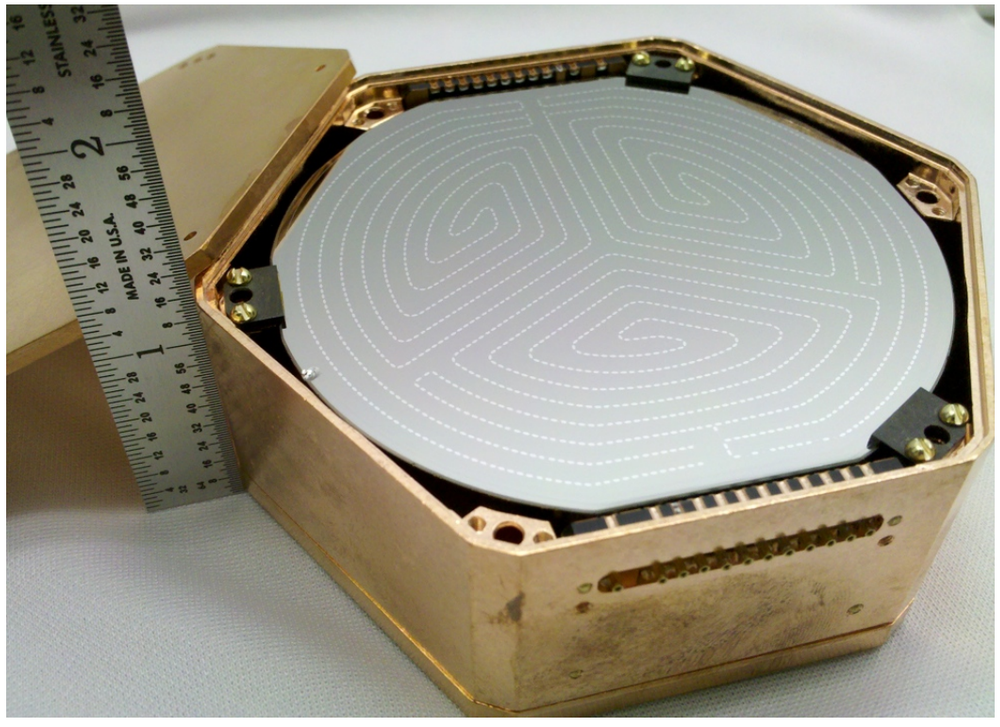


SuperCDMS

SuperCDMS Overview

- Upgrade to CDMS II experiment
- Cryogenic Ge detectors measure both ionization and phonons

0.6 kg Ge crystals



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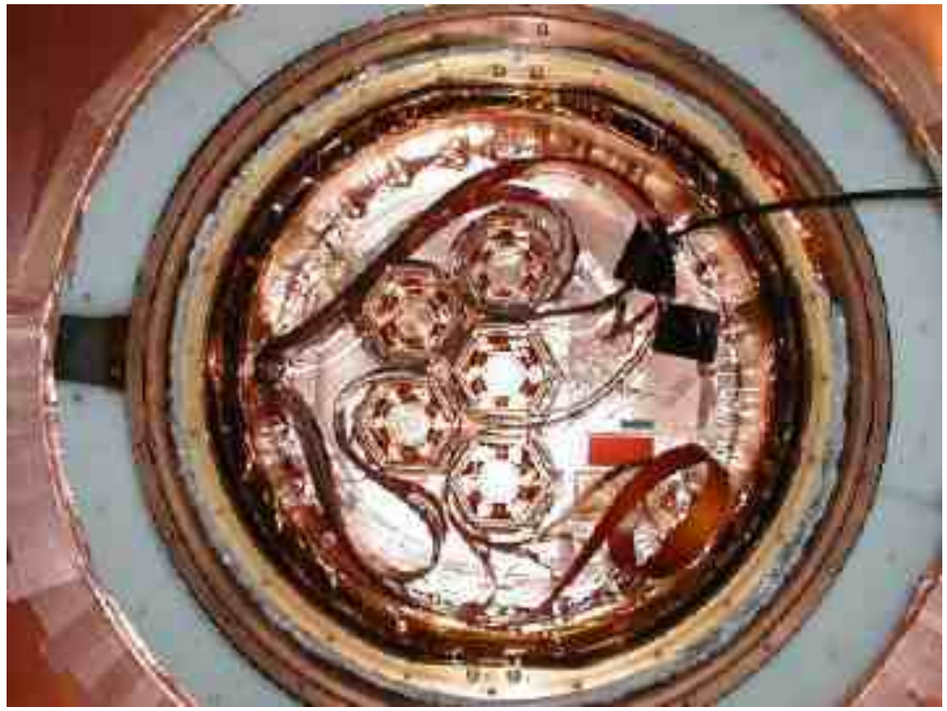
- Detectors operate at 50 mK in ^{3}He/^{4}He dilution fridge
- Continuous operation since spring 2012 (cold for over 2 years!)

icebox



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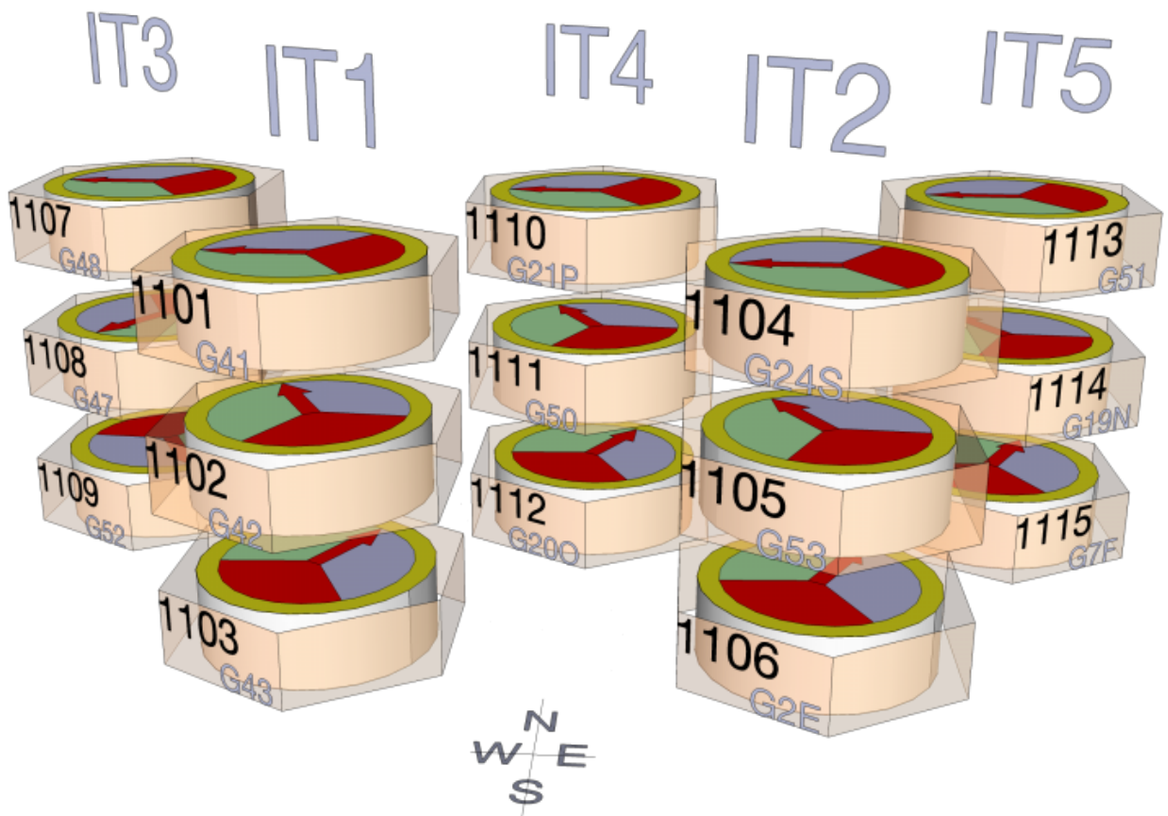

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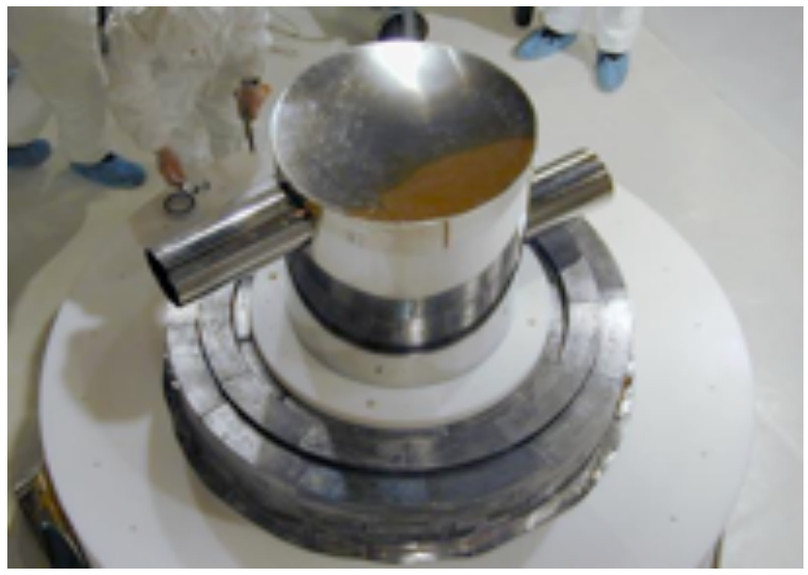
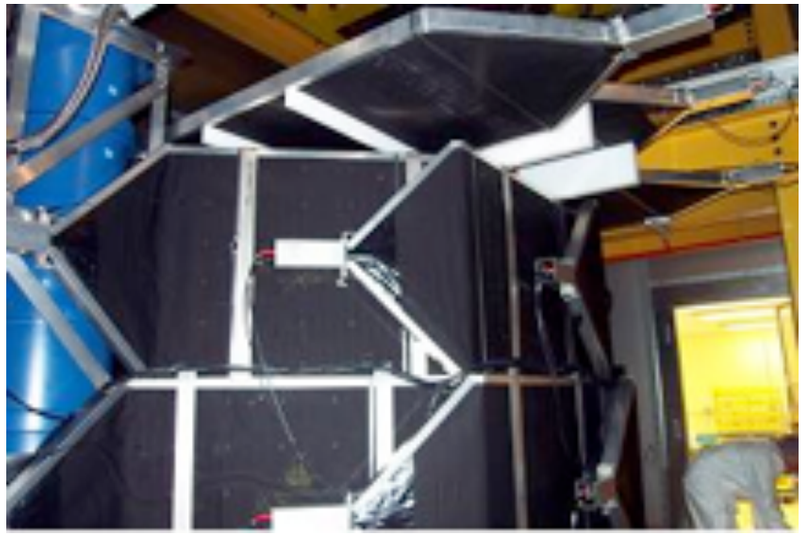
- 15 detectors x 0.6 kg = 9 kg target mass
- Active and passive shielding surround detectors

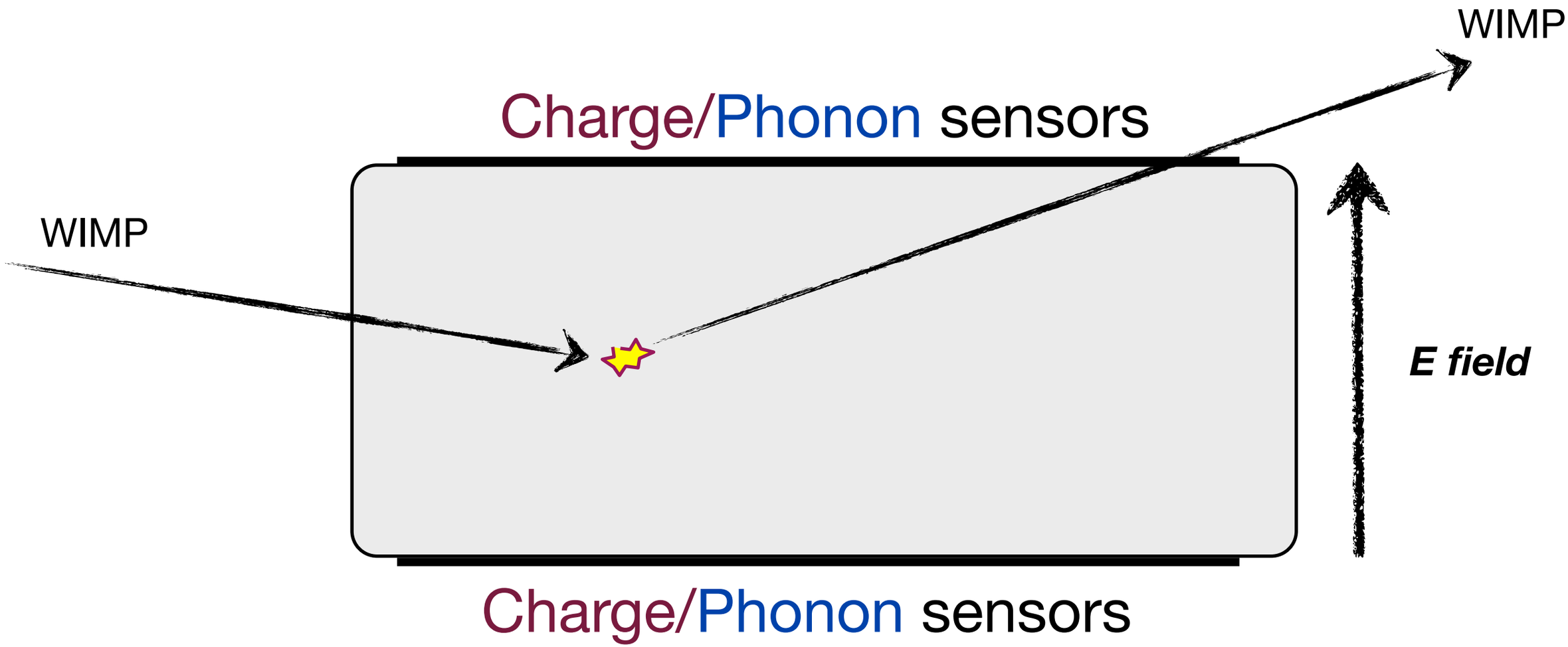
poly and lead shielding



muon veto



iZIP Detectors



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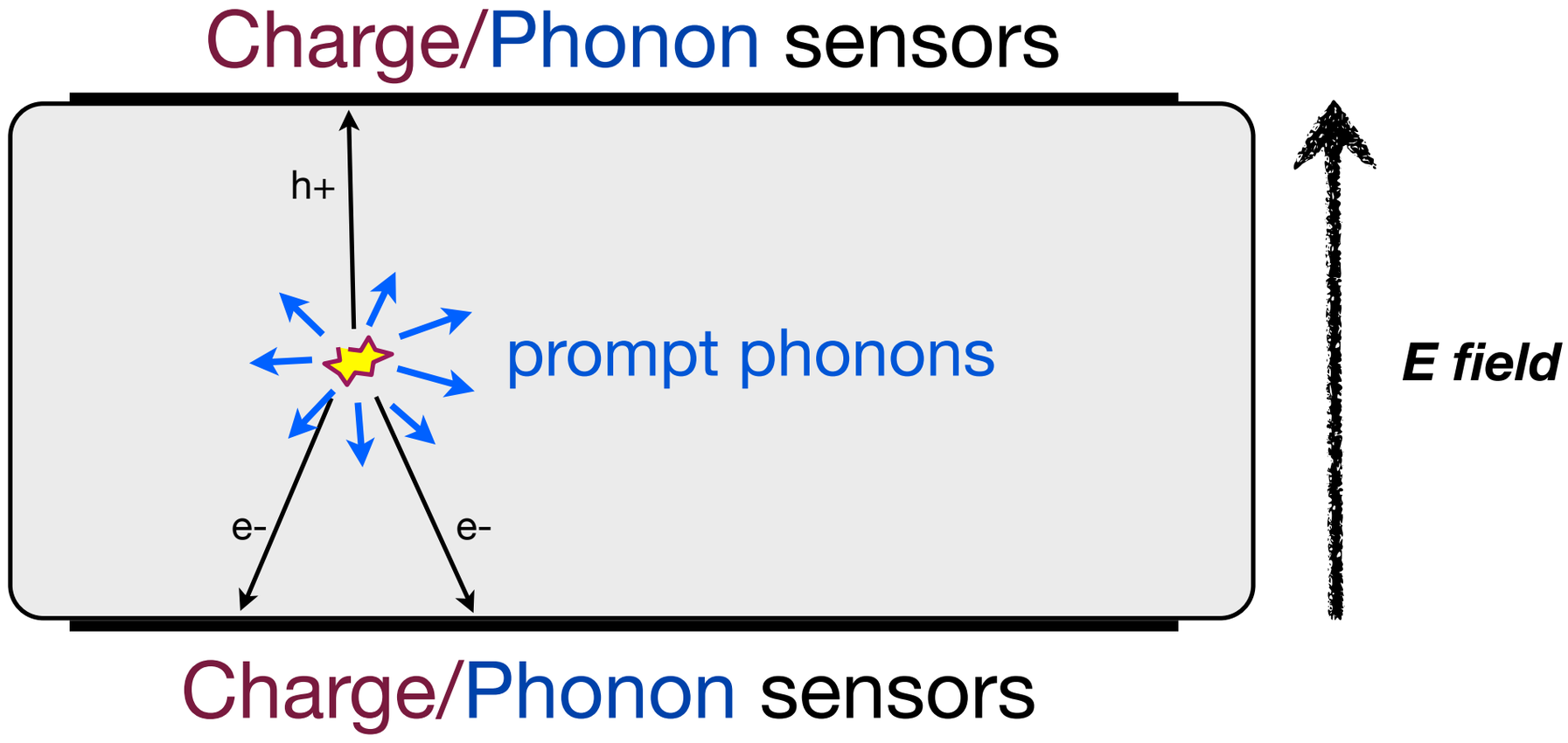

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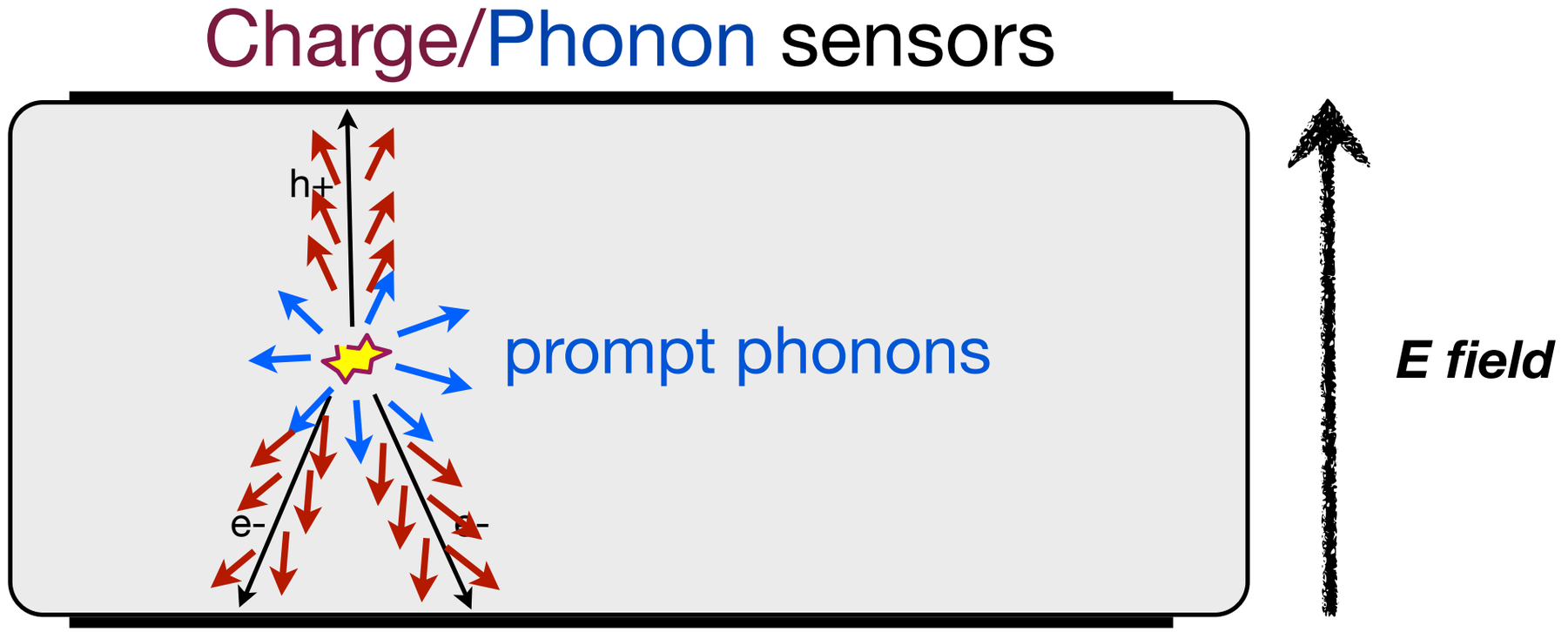
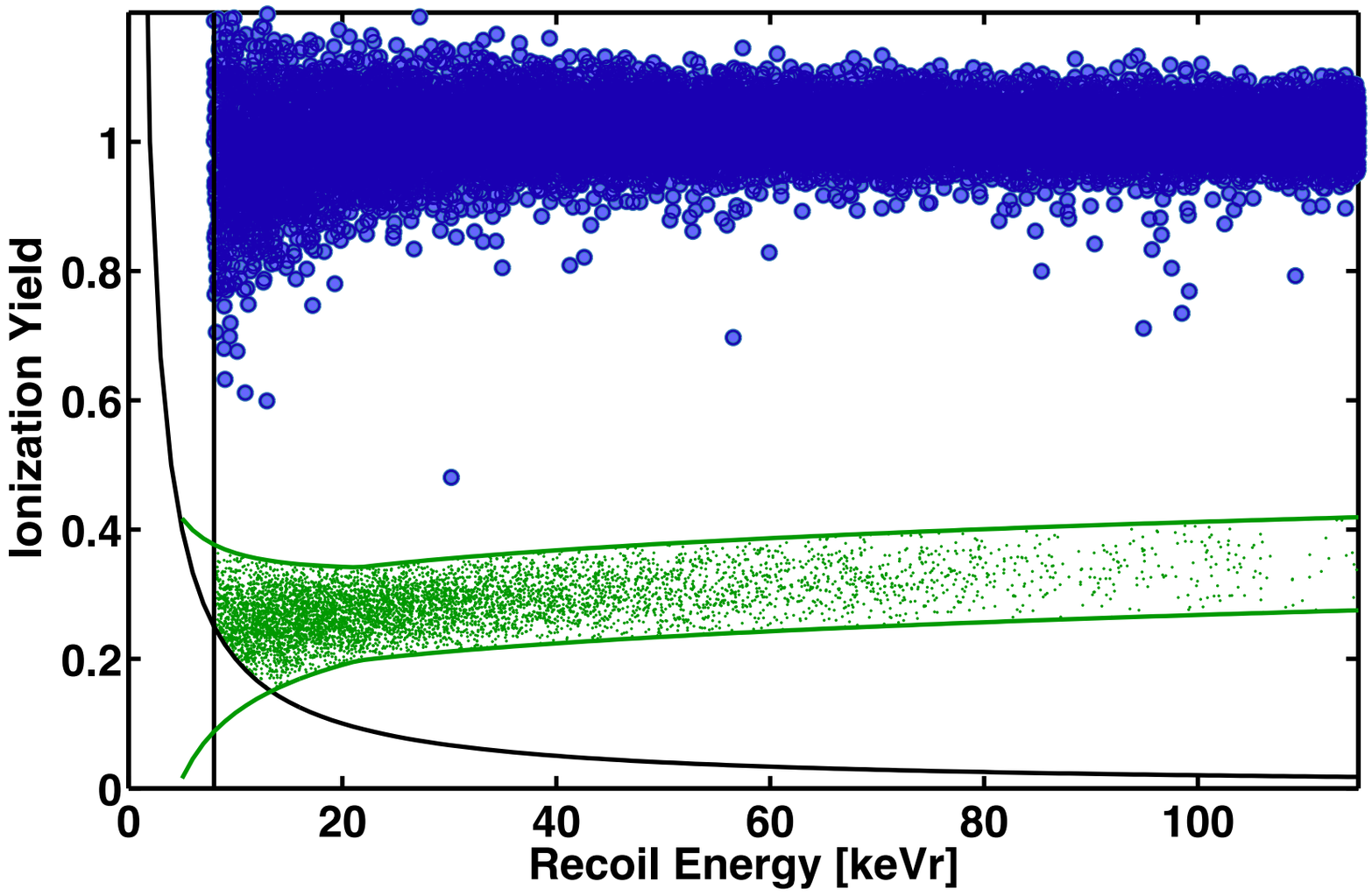


Phonon energy = E_{recoil} + E_{Luke}

iZIP Detectors: Electron Recoil Discrimination

Electron recoil / nuclear recoil discrimination possible with simultaneous measurement of ionization and phonons



^{133}Ba calibration *γ*

^{252}Cf calibration *n*

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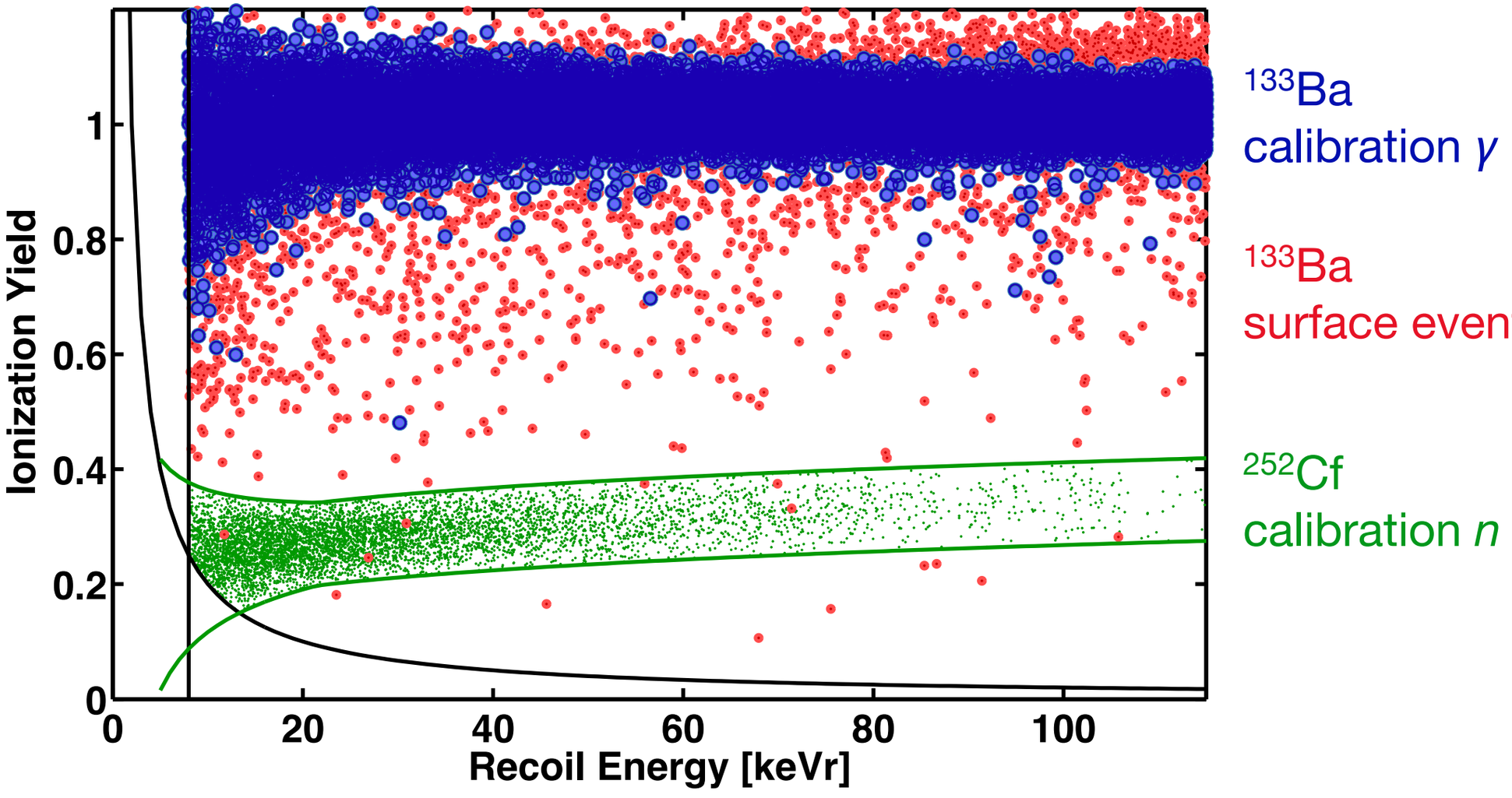
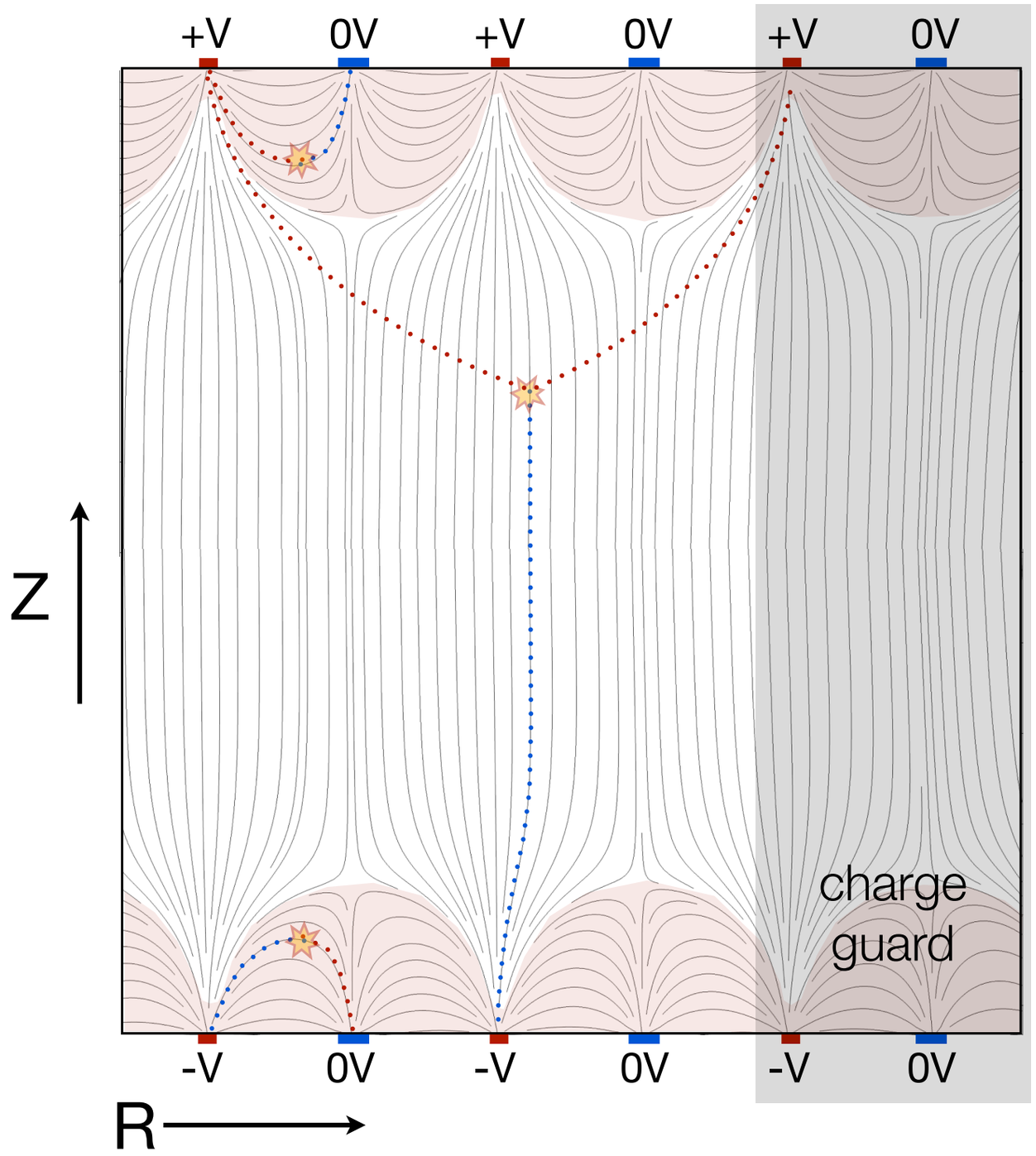
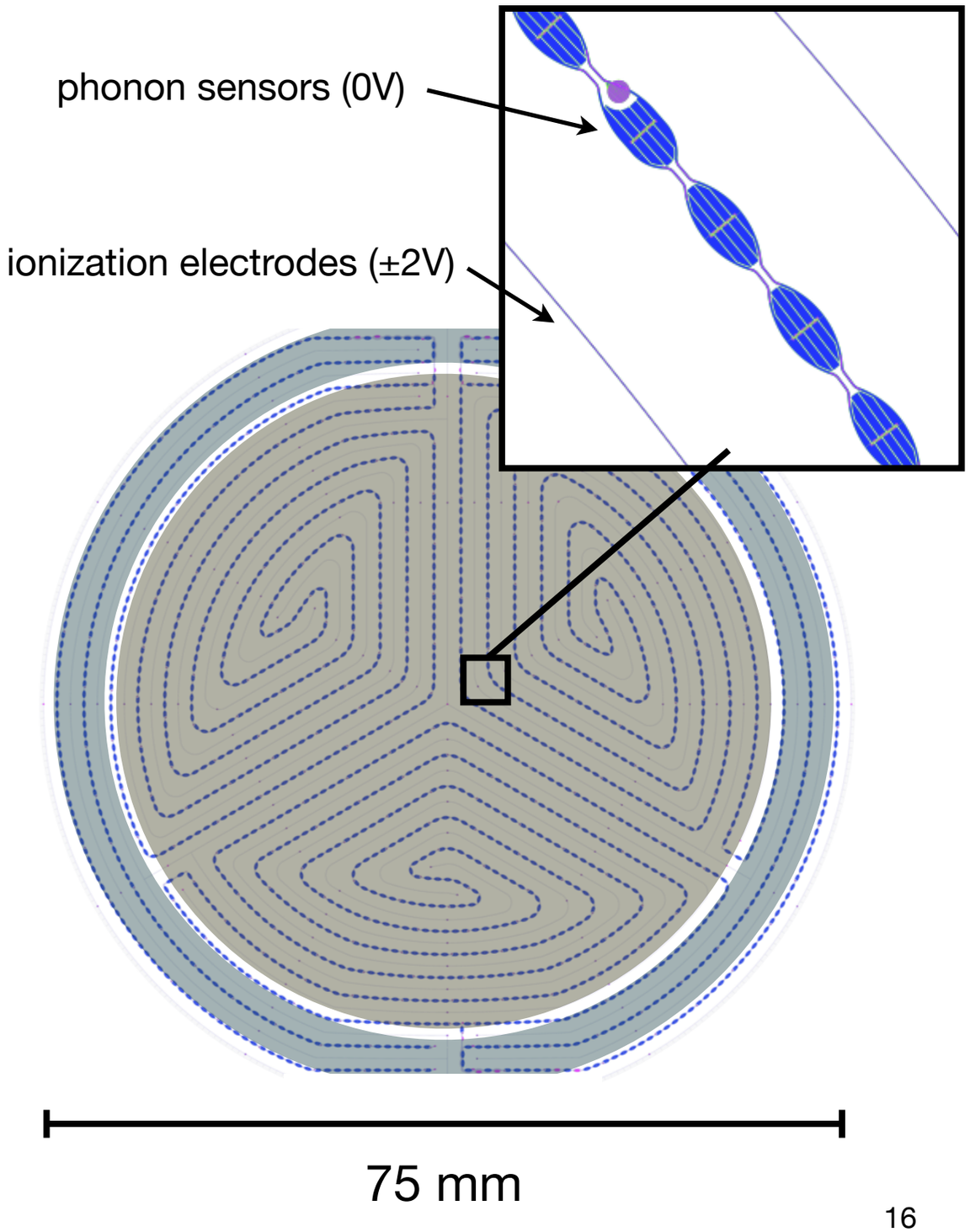


iZIP Detectors: Ionization Fiducialization





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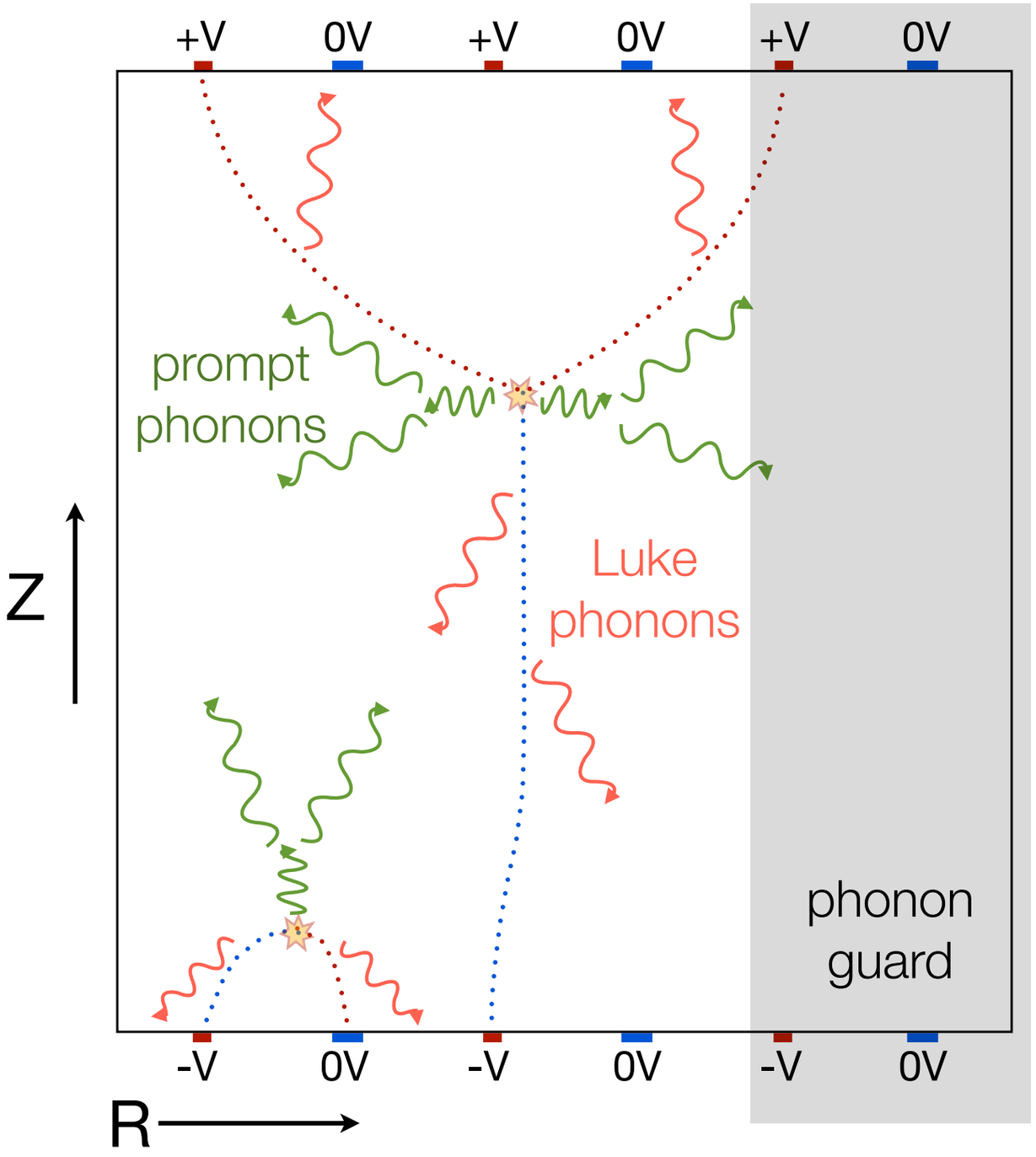
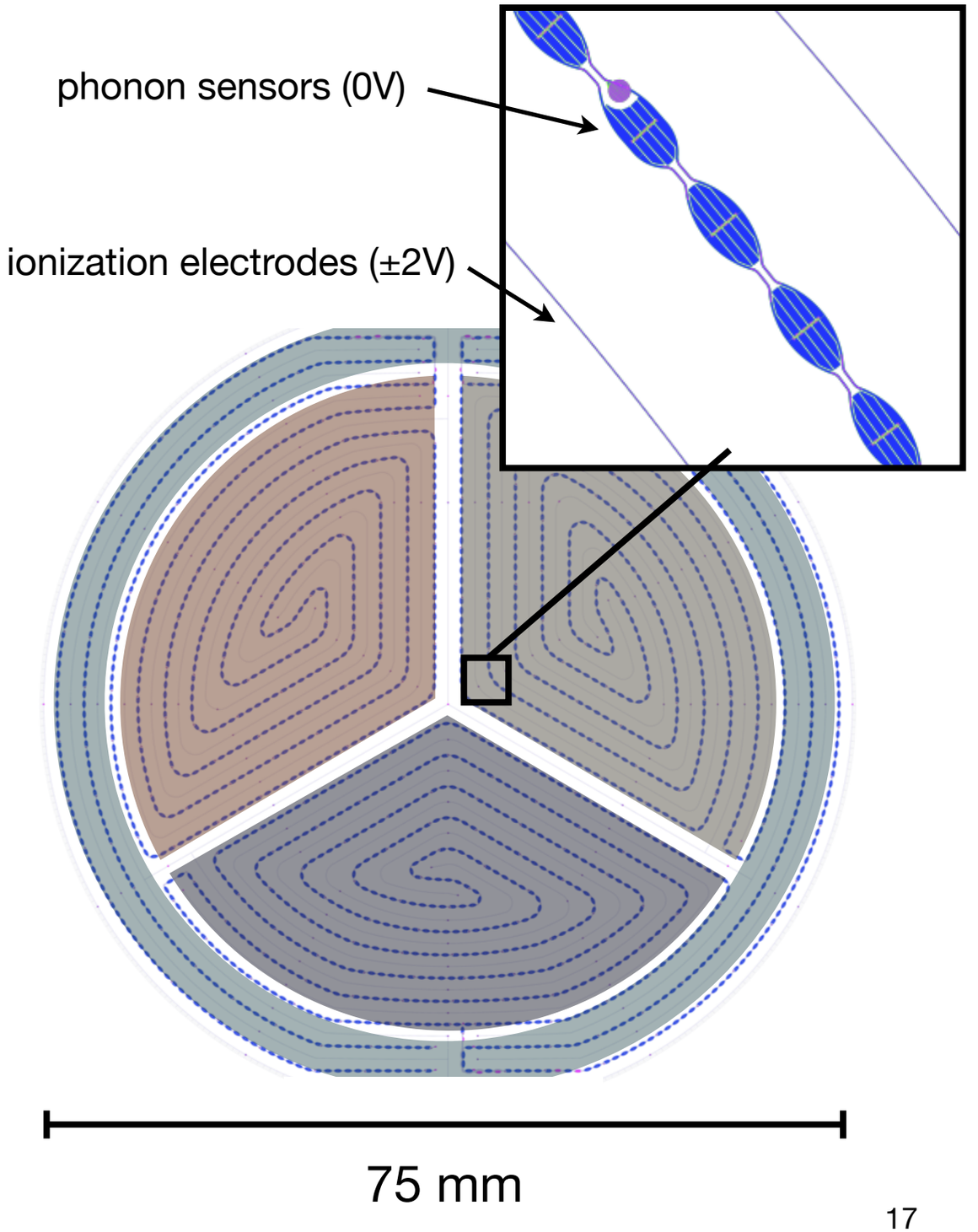
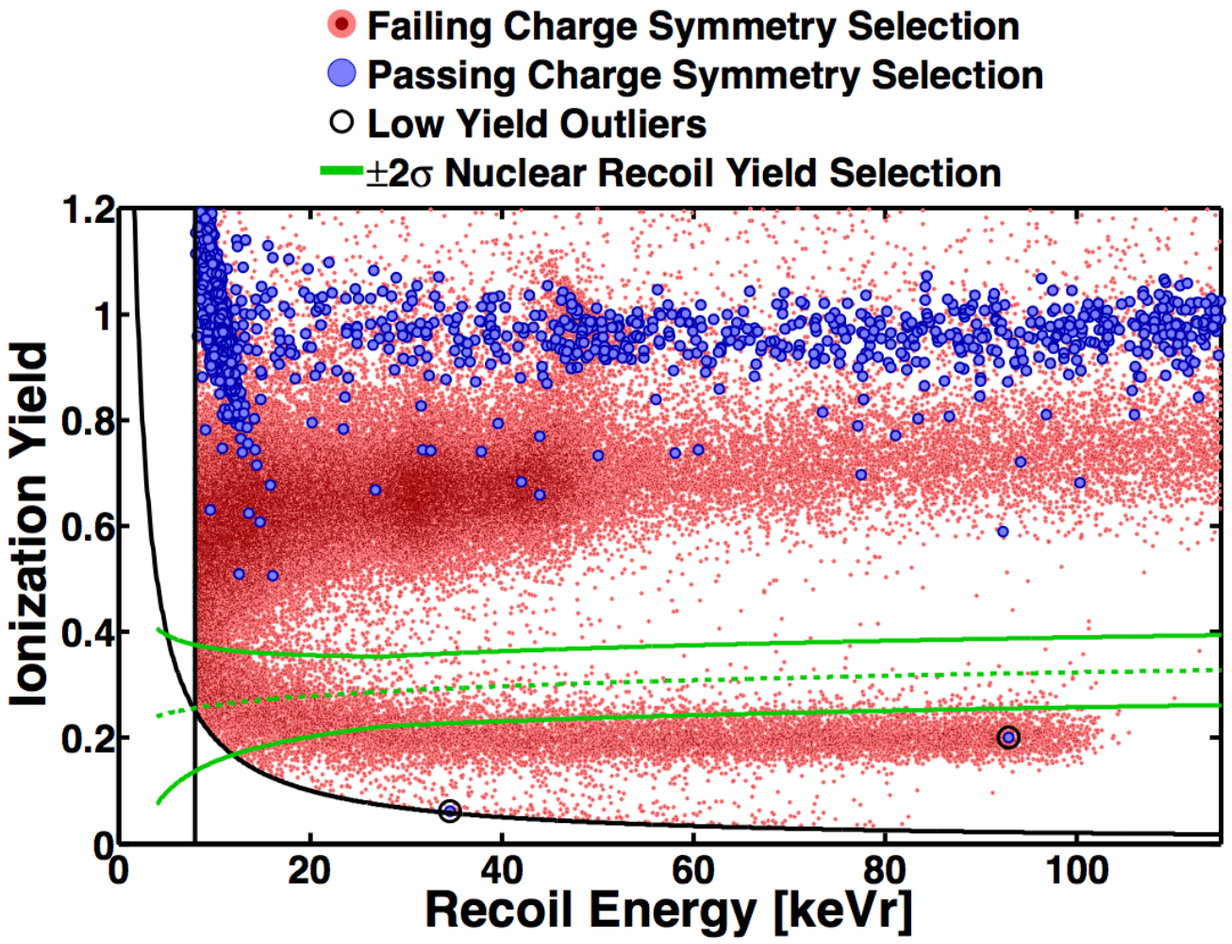
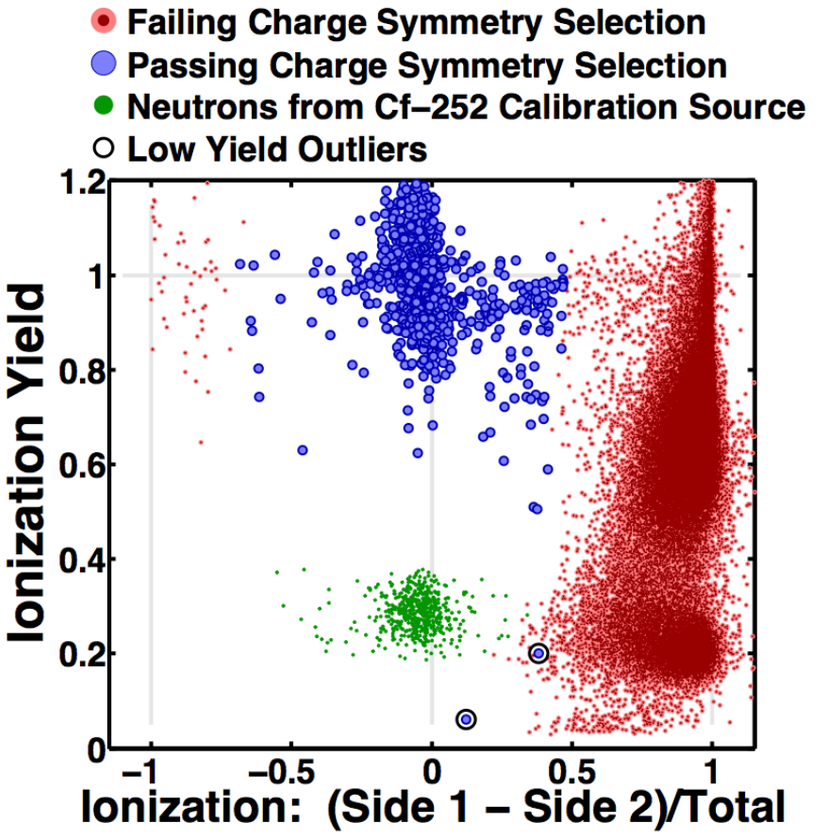


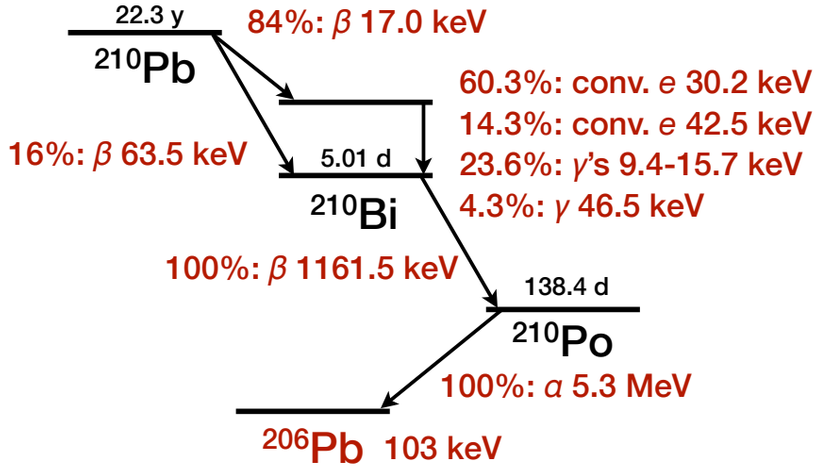


Surface Event Rejection



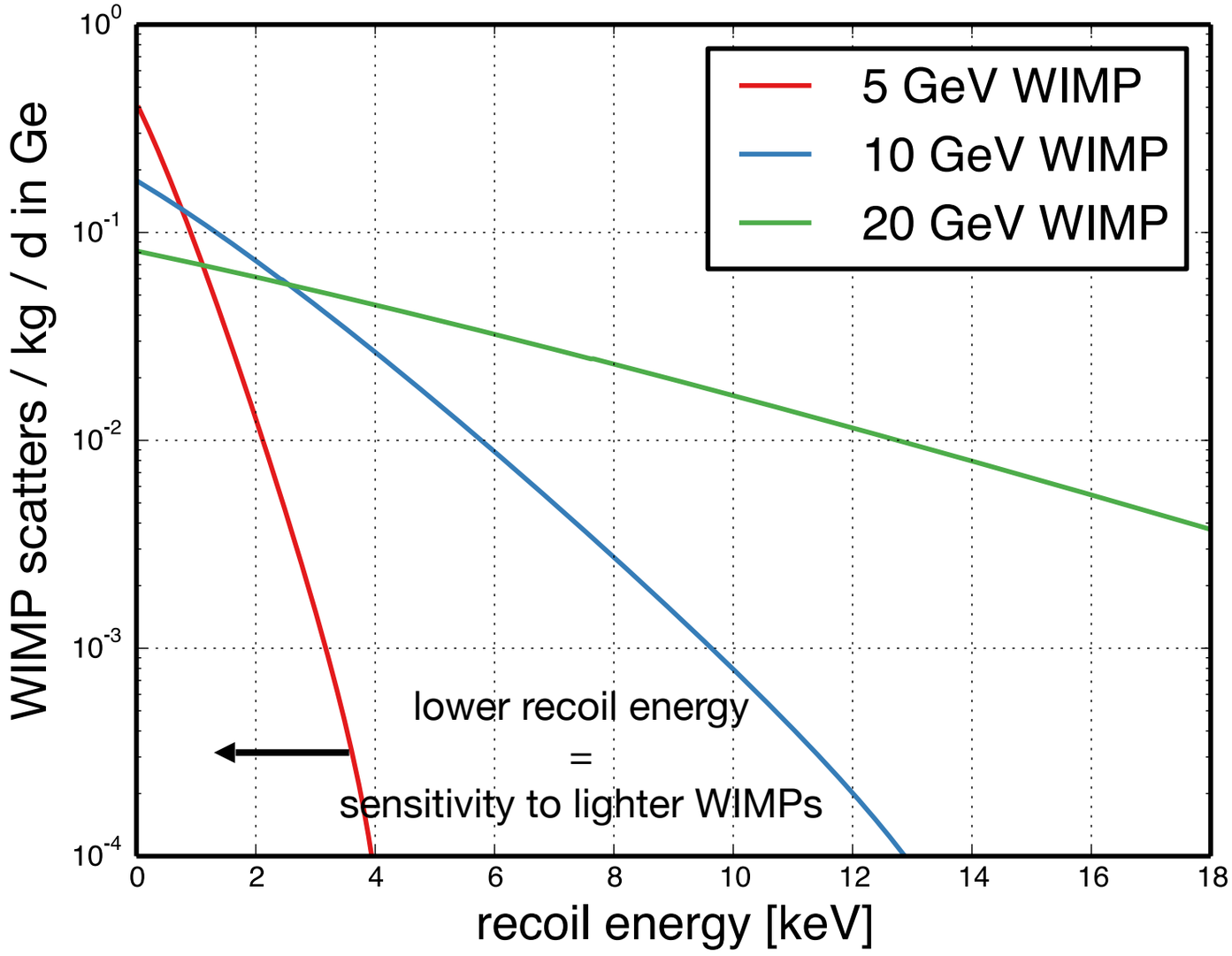


- Measured surface event rejection with ^{210}Pb source on detector in Soudan
- Background fraction < 2.9×10^{-5} (90% C.L.) at 60% NR acceptance in 8-115 keVr



Appl. Phys. Lett. **103**, 164105 (2013)

How can we do better?



How can we do better?

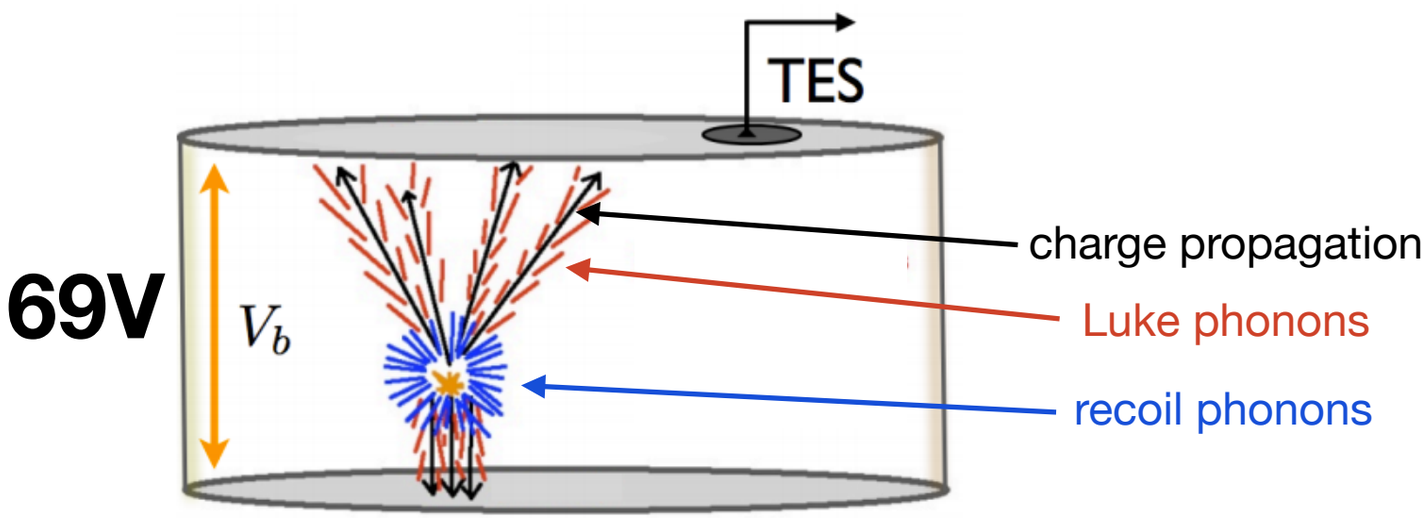
1.) Lower energy threshold: **CDMSlite**

CDMSlite: “low ionization threshold experiment”

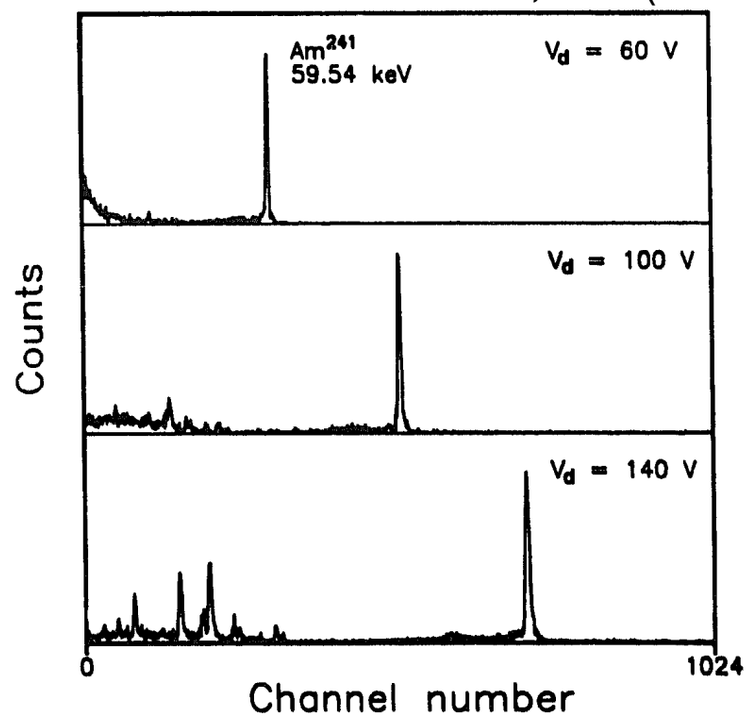
$$E_{total} = E_{recoil} + E_{luke}$$
$$= E_{recoil} + \frac{1}{3\,eV} E_Q \Delta V$$

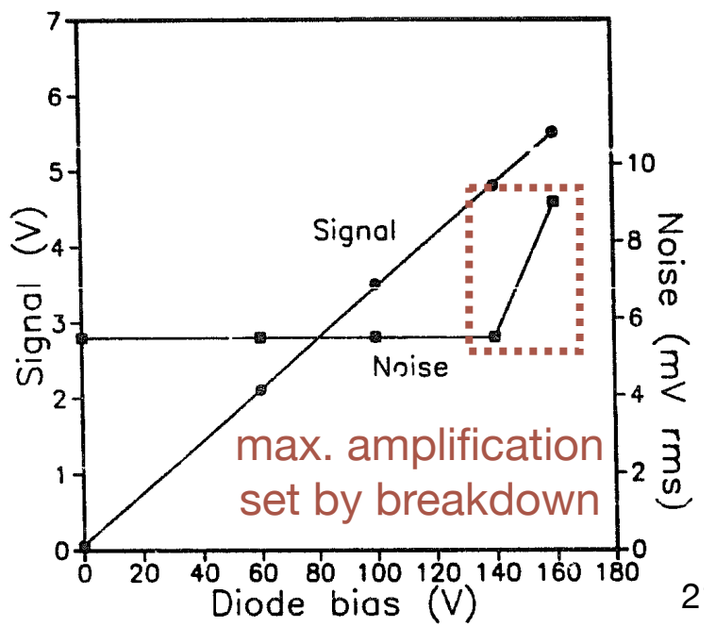
- Measure charge with phonons, and increase voltage to amplify signal

- Lose background discrimination, but achieve lower ionization energy threshold



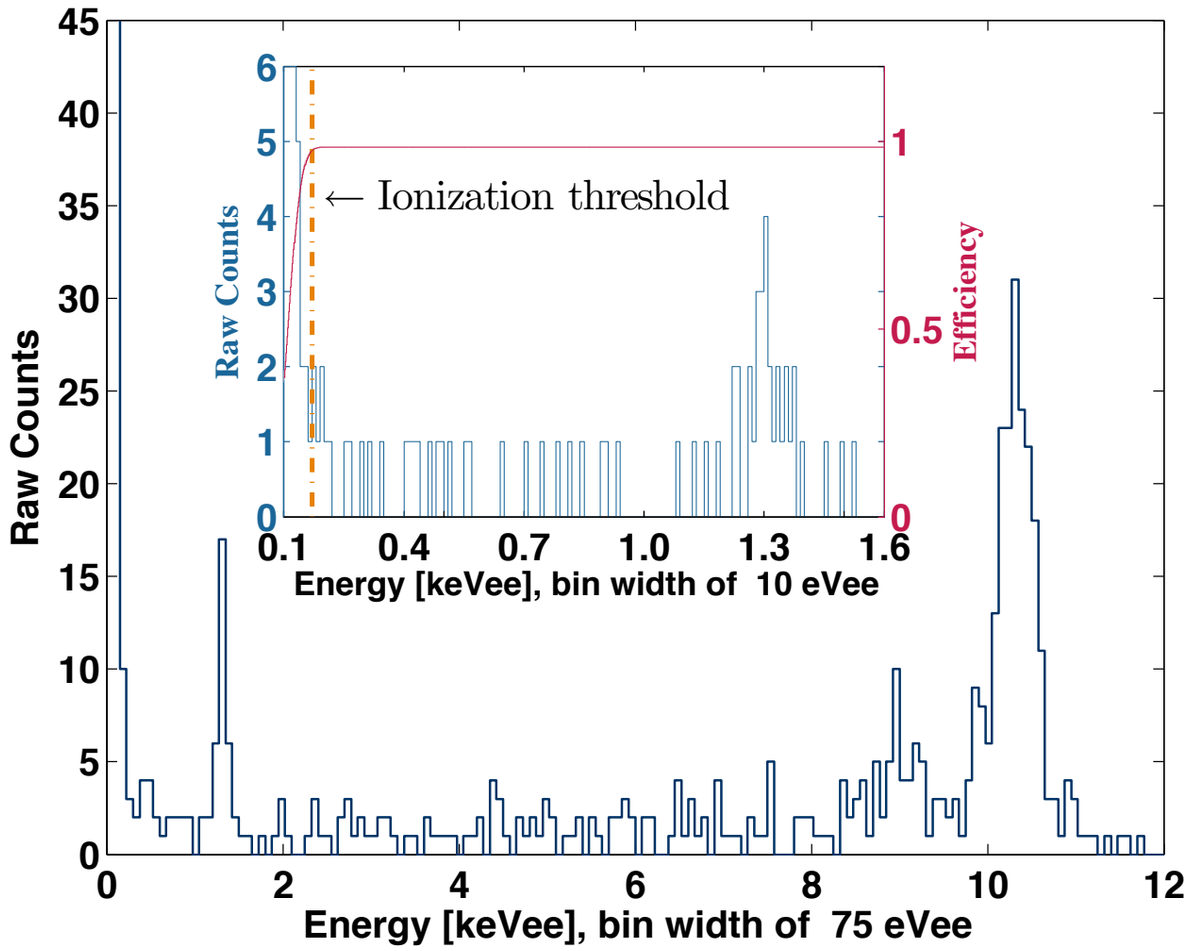
P.N. Luke et al. NIM A289, 405 (1990)



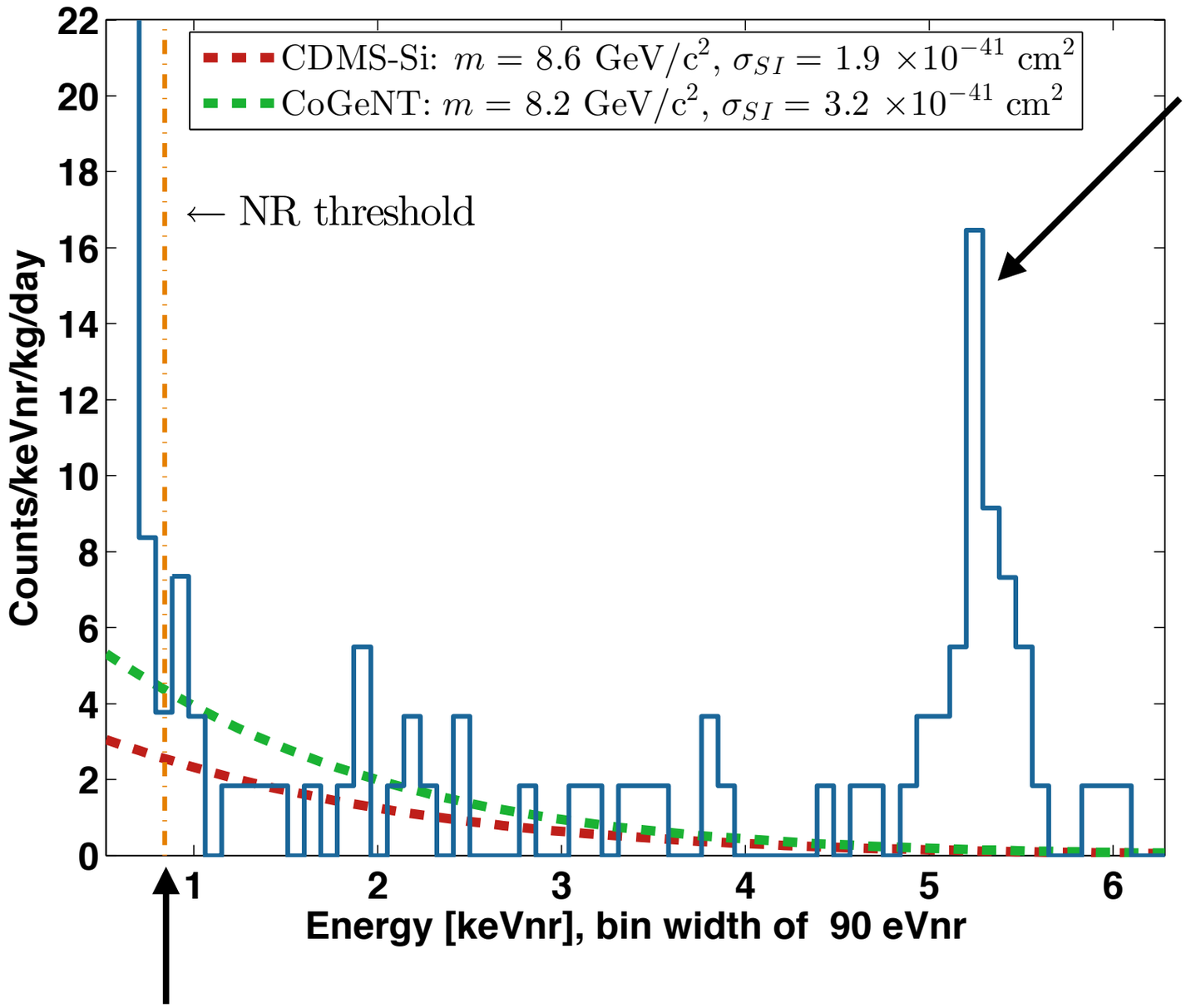


CDMSlite

- Tested several detectors in CDMSlite mode
- Acquired 6 kg-d of exposure on detector with best combination of breakdown voltage and threshold
- Ionization energy calibration with EC lines at 1.3 keVee and 10.4 keVee
- Operated stably at 69V or **24x** amplification (only 12x due to electronics limitations)
- 860 eVee => 170 eVee threshold



CDMSlite

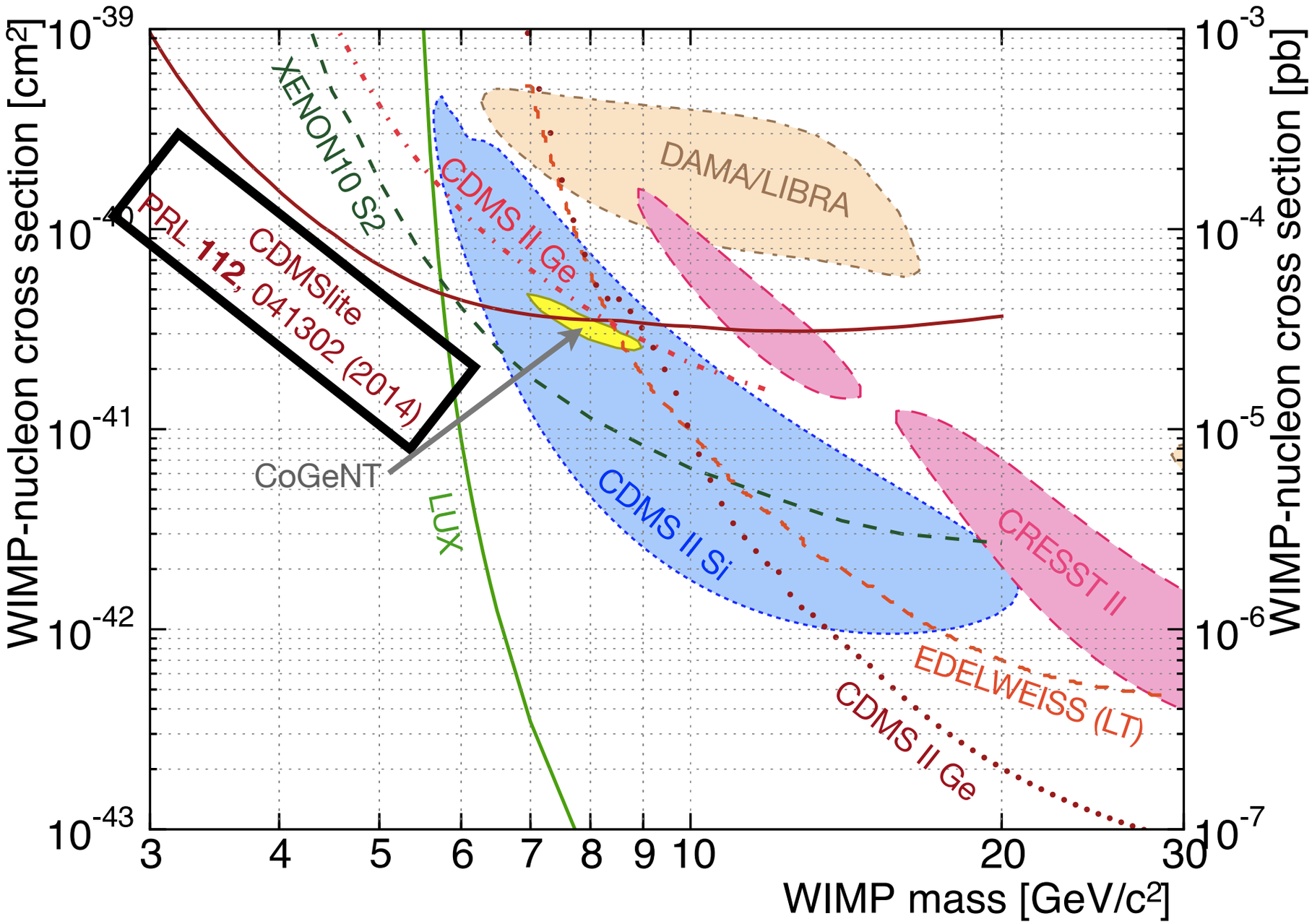


1.3 keVee EC line from ^{71}Ge, ^{68}Ge

800 eVnr threshold

(because of quenching, 15-20% of energy measured in ionization)

CDMSlite Constraints



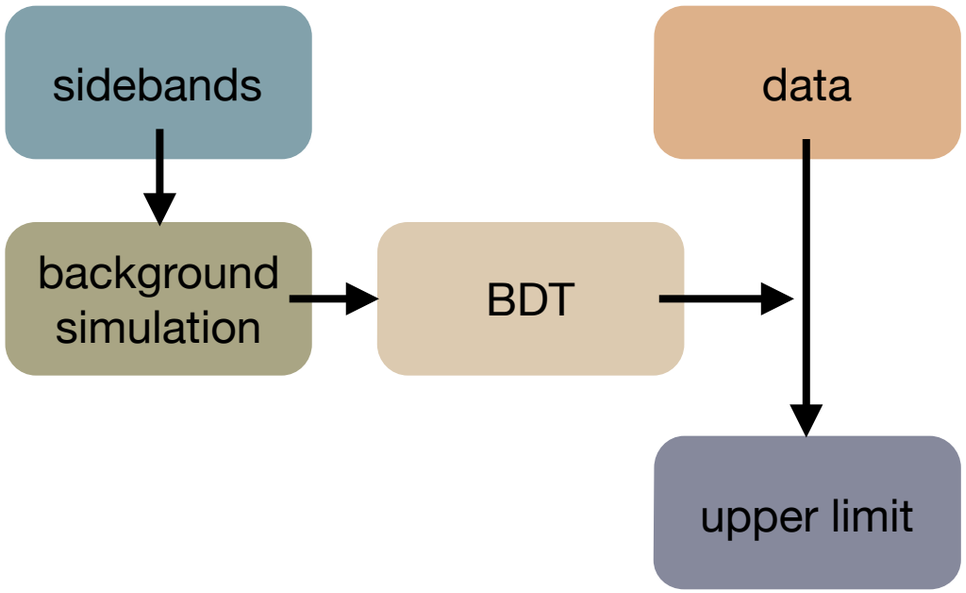
How can we do better?

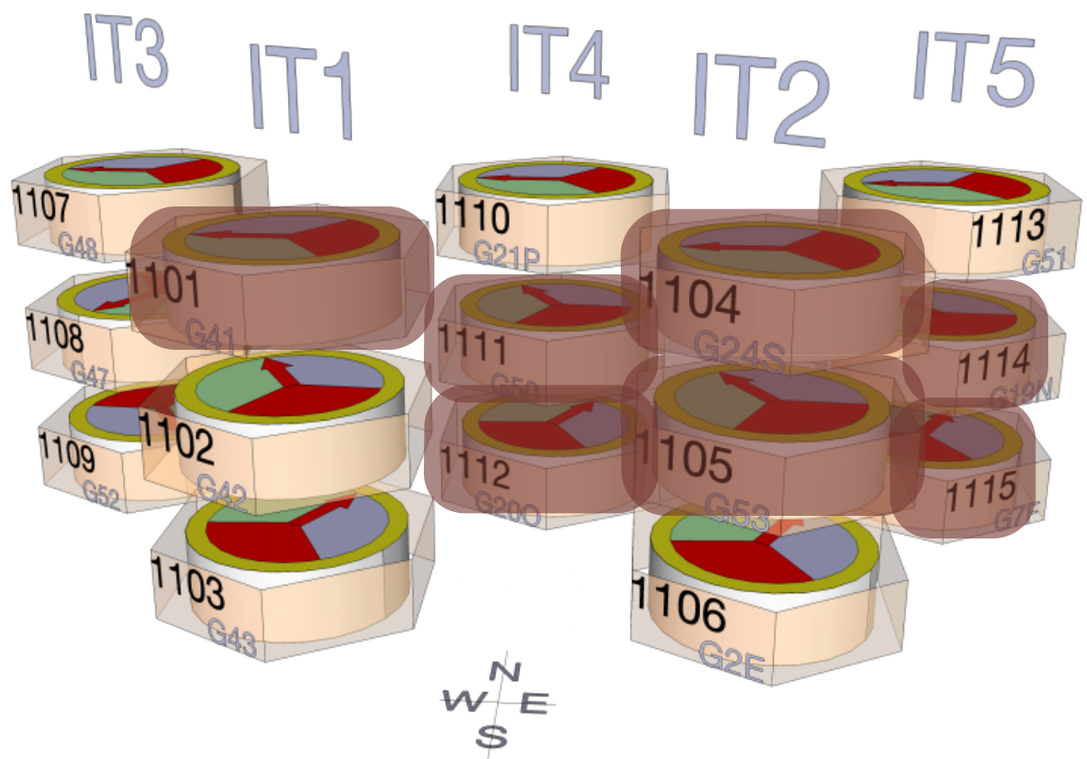
1.) Lower energy threshold: **CDMSlite**

2.) Improve exposure and background ID:
Low-energy analysis of SuperCDMS data

Low-energy Analysis

- Use 7 detectors with lowest trigger thresholds (~1.6 keV - 5 keV)
- 577 kg-d of exposure (Oct. 2012 - July 2013)
- **Background discrimination still possible near threshold!!**
- **Blind** analysis optimized for exclusion



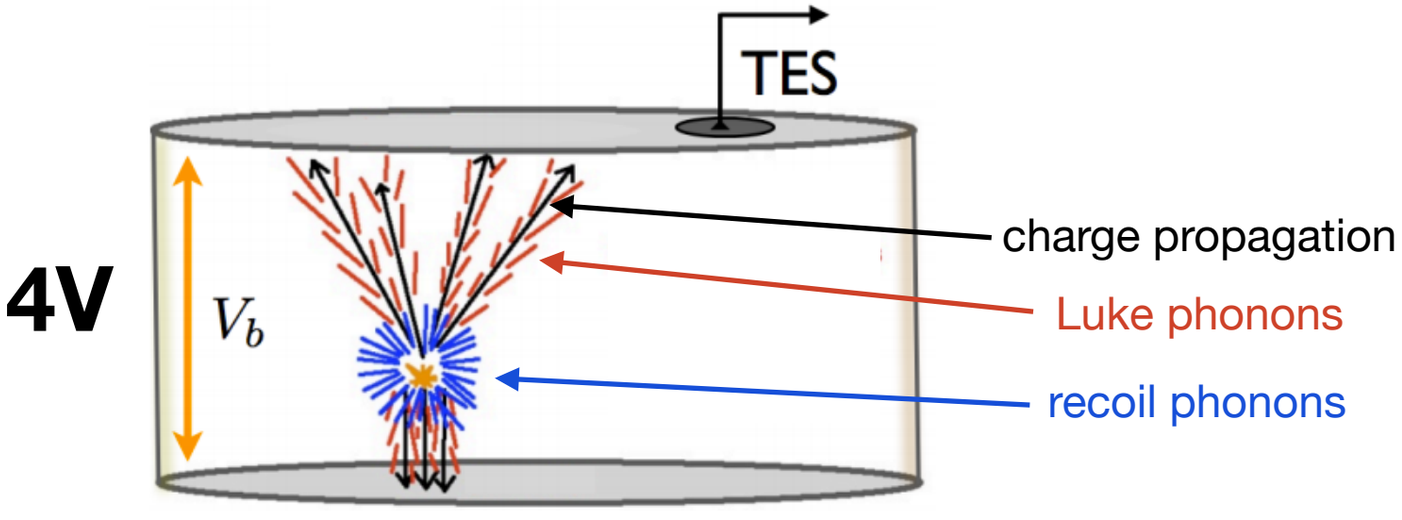


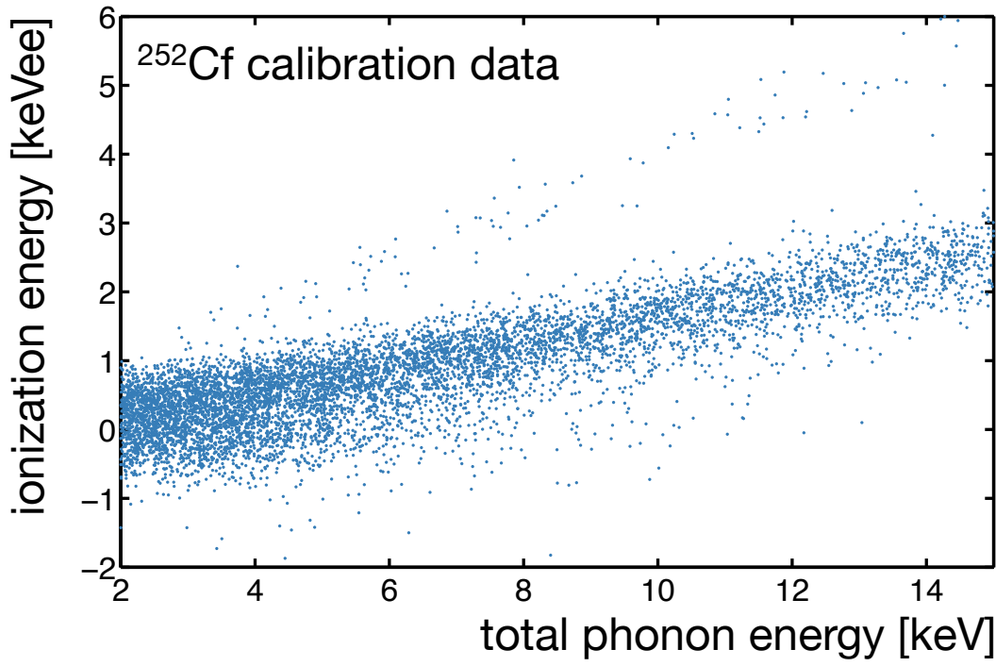
Calibration and Energy Scale

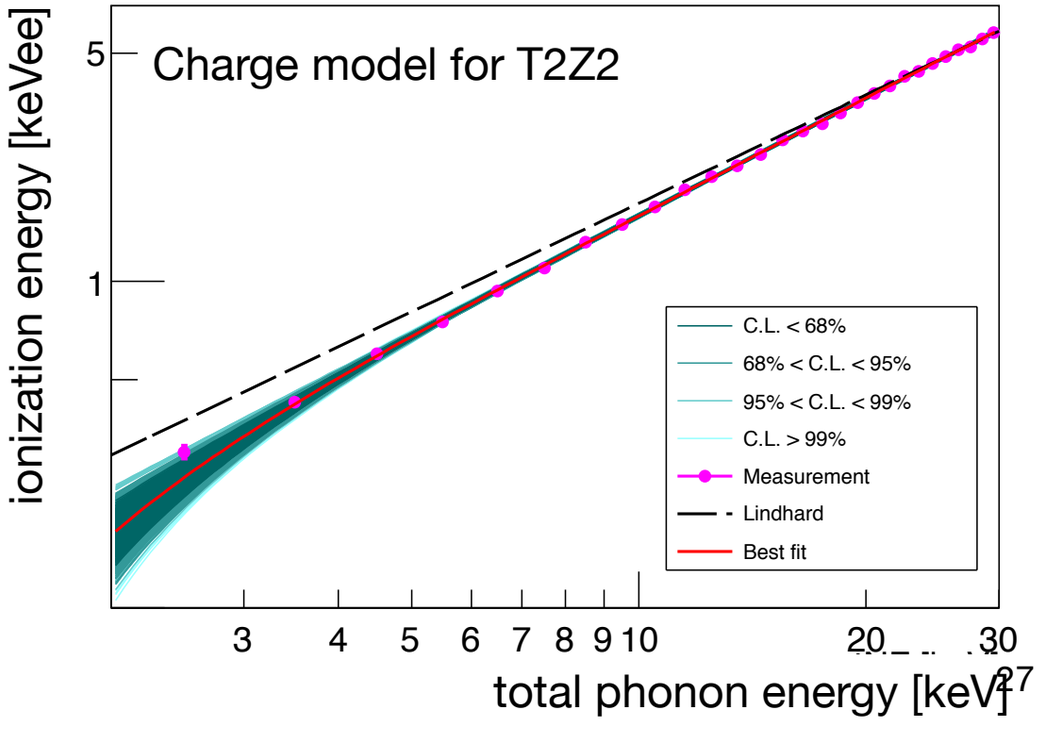
$$E_t = E_r + E_L$$

$$E_r = E_t - \frac{1}{3\,eV} E_Q(E_t)\Delta V$$

- Since signal-to-noise is poor, fit mean ionization energy for nuclear recoils
- Systematic uncertainties propagated into final limit
- Most detectors consistent with or slightly below Lindhard

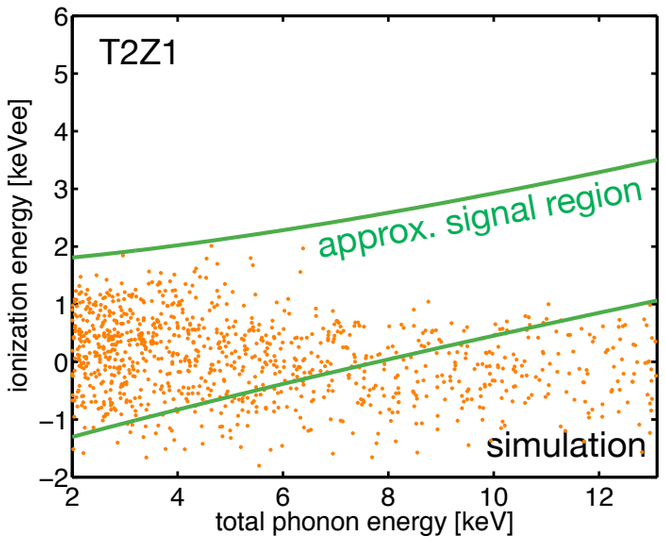




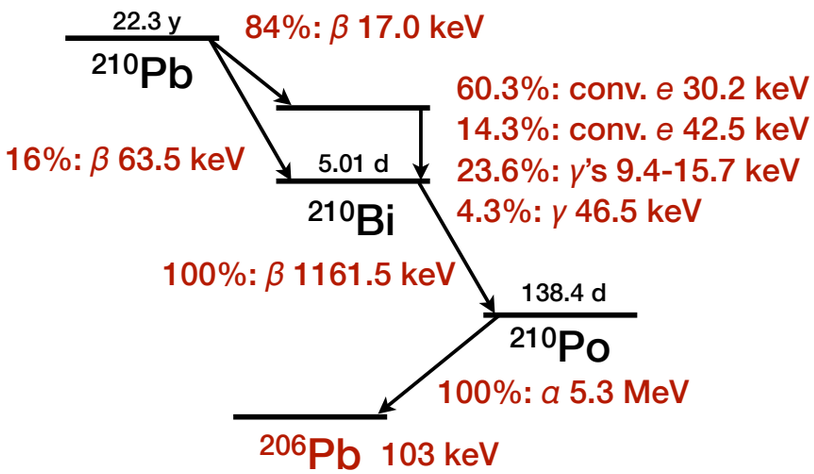


Dominant Backgrounds at Low Energy

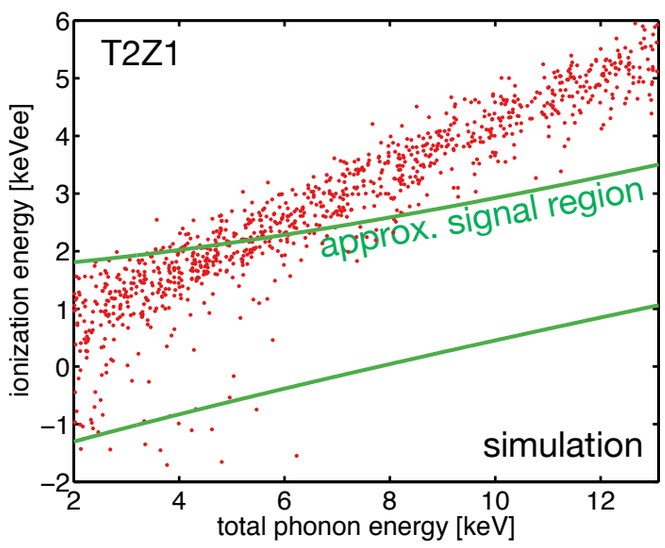
^{210}Pb “surface events”



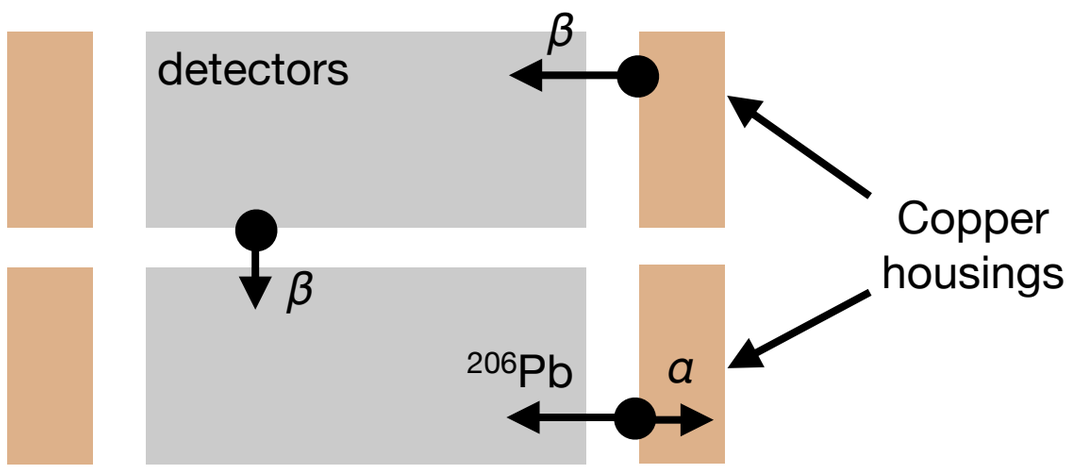
- betas and ^{206}Pb nuclei from ^{210}Pb decay chain
- events are located on detector face and sidewall ***surfaces*** from ^{222}Rn contamination



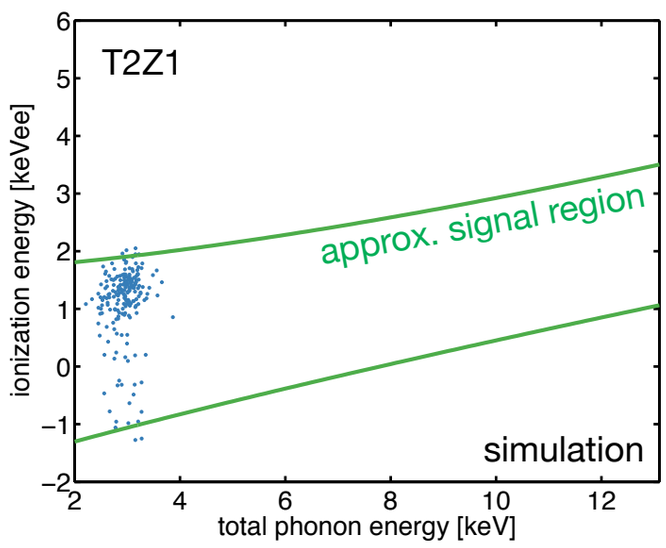
External gammas



- from radioactivity in shielding and cryostat



Internal activation lines



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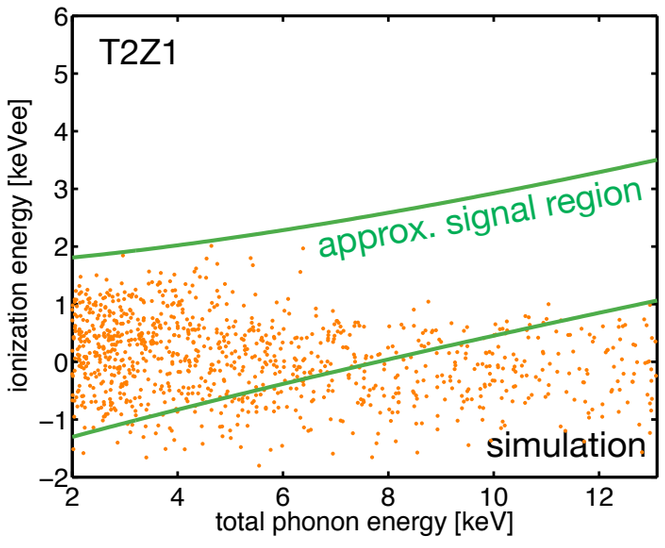

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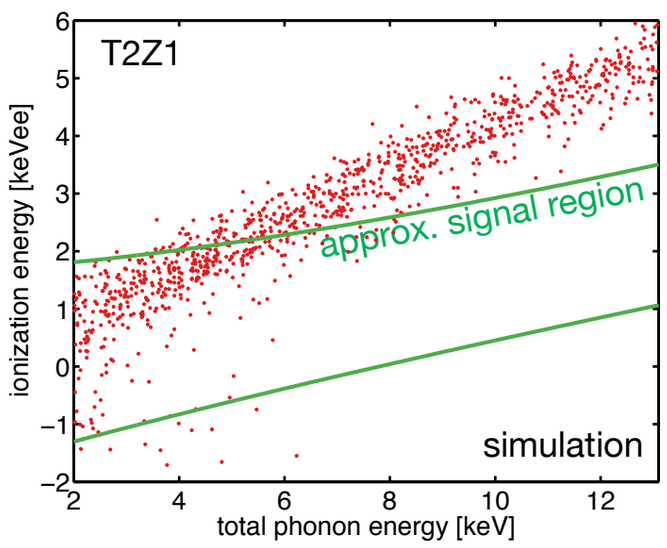

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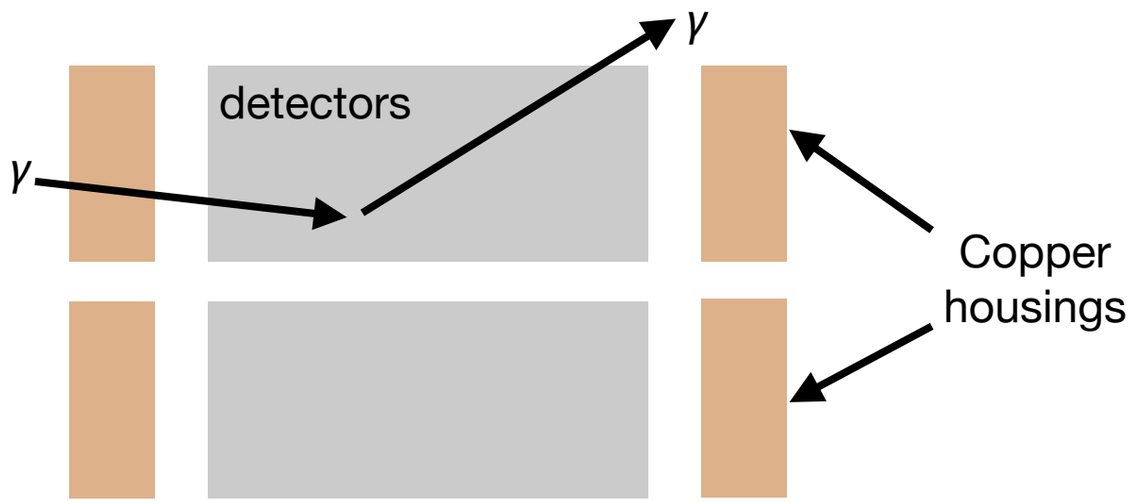
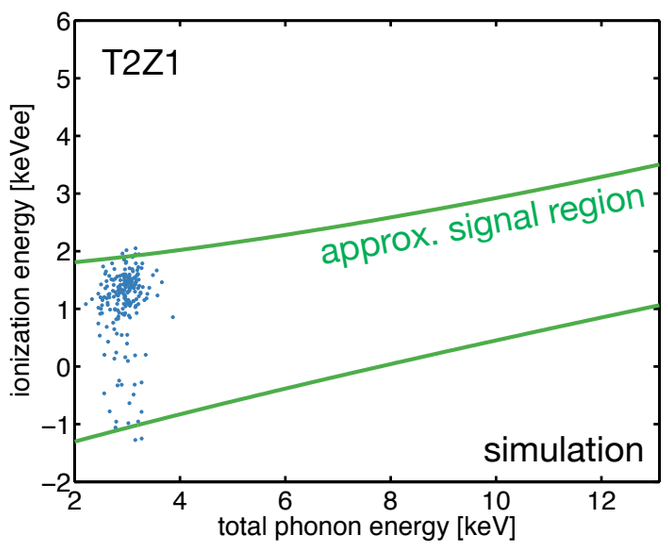


Internal activation lines



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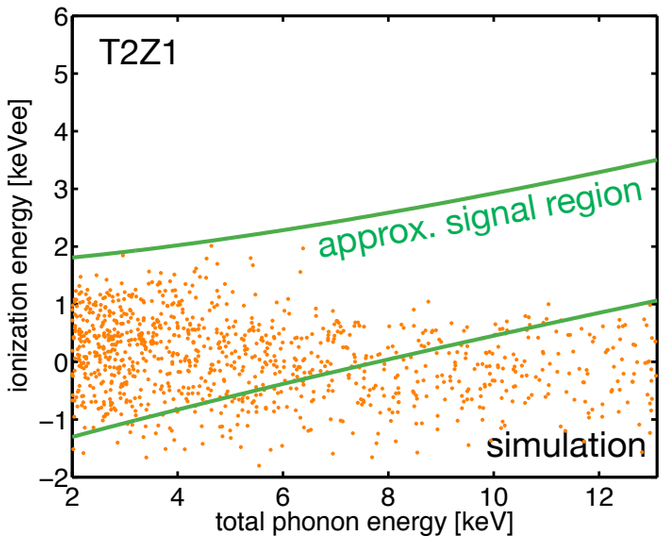

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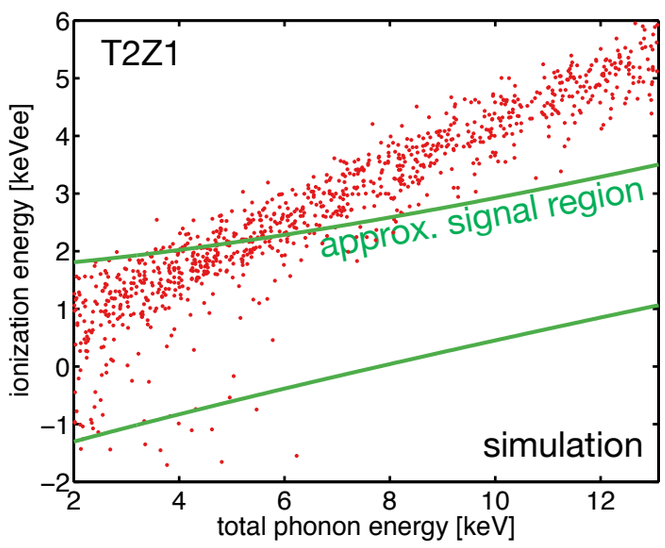

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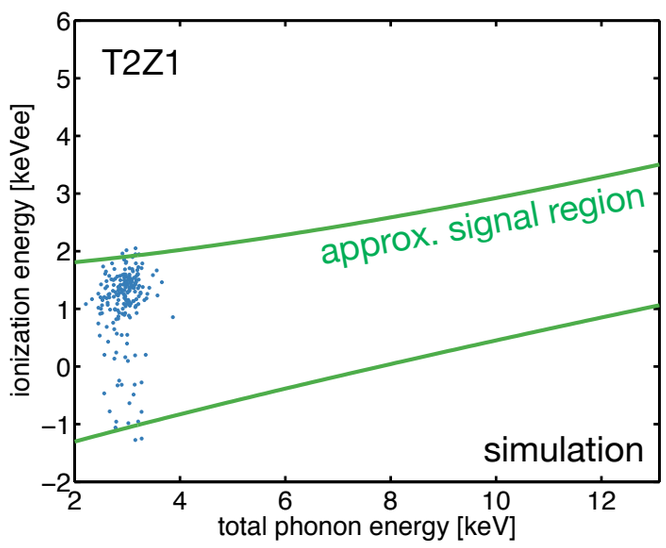

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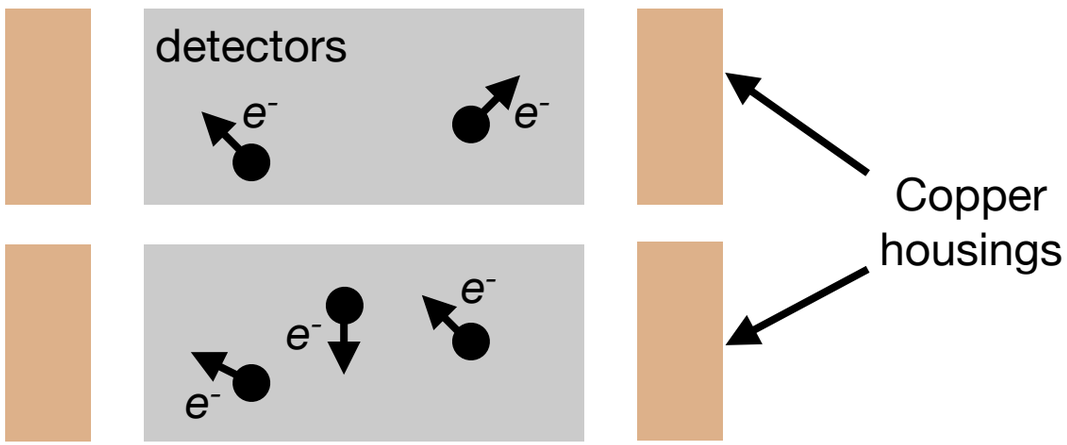
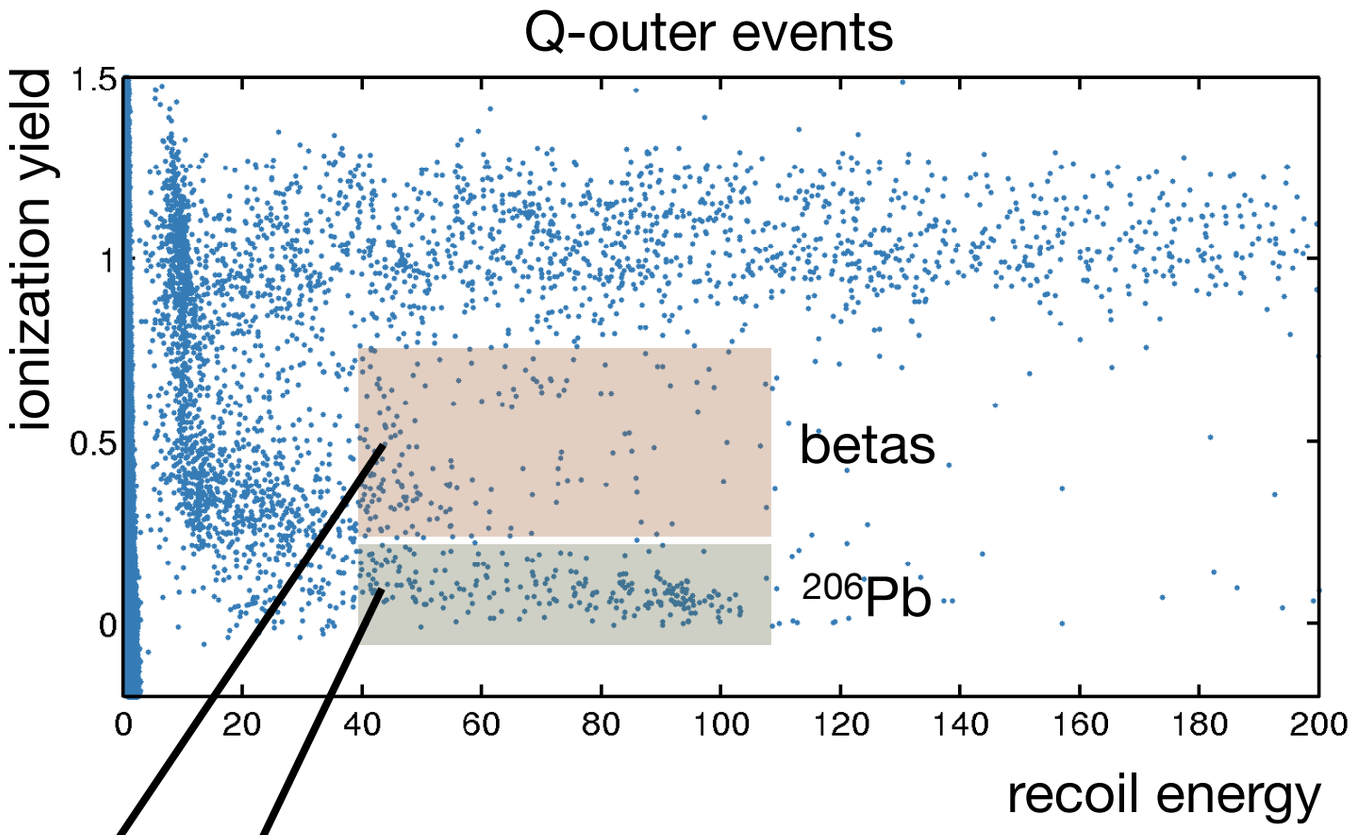
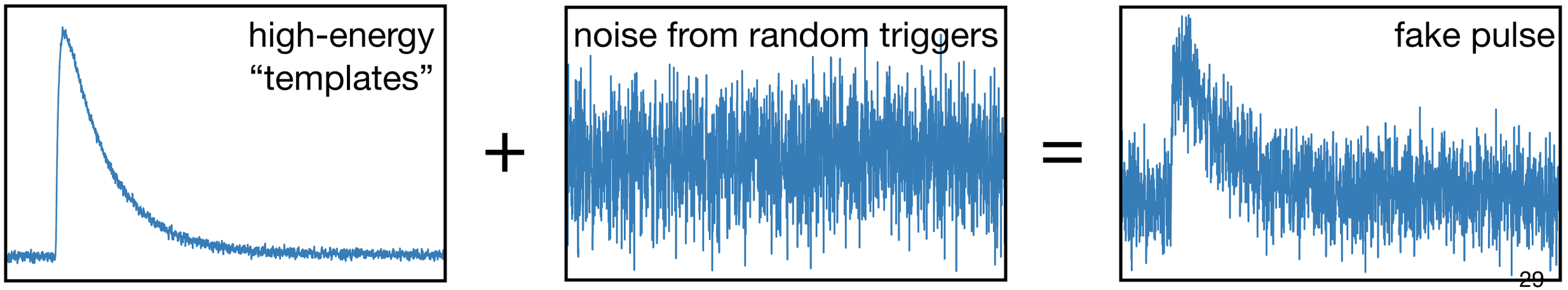


Detector Pulse Simulation



background type	*template source*
210	WIMP-search data (~40-100 keV)
External gammas	133 (~100 keV)
L-shell lines (~1 keVee)	K-shell decays (~10 keVee)

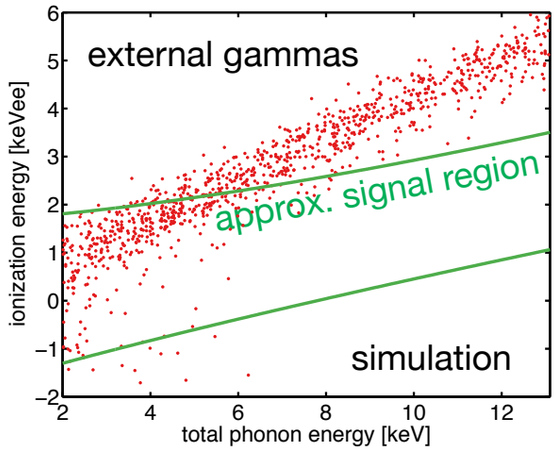
High-E events as templates for low-E events: **preserves pulse shape info**



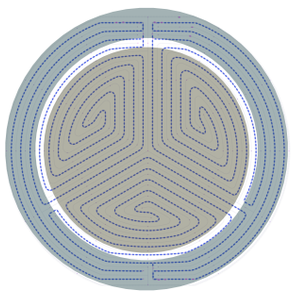
Discriminators

ionization yield
+
total phonon energy

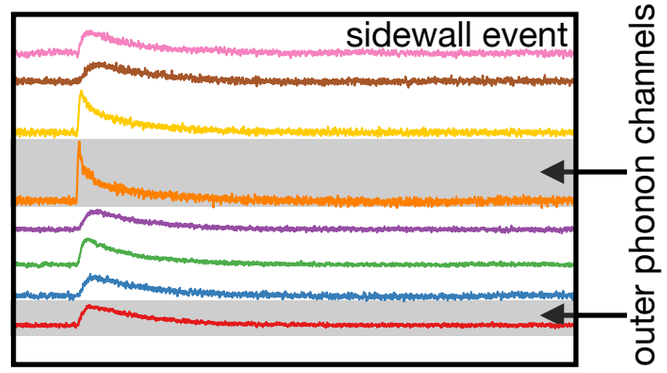
Bulk electron recoils



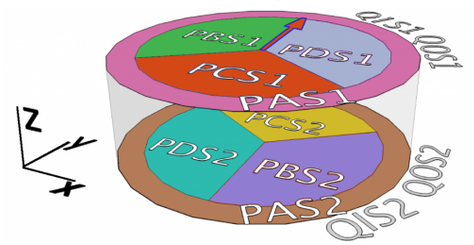
phonon “*r*-partition”



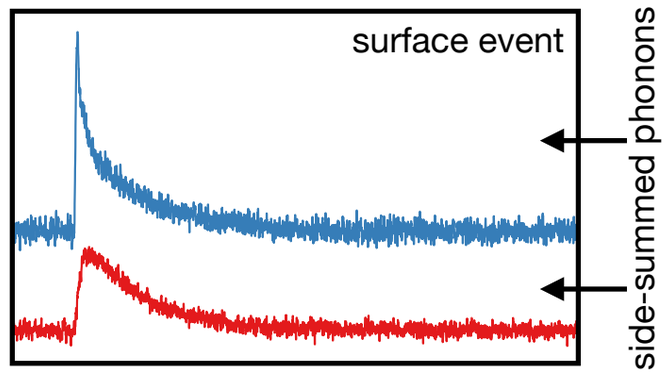
Low energy
sidewall events



phonon “*z*-partition”

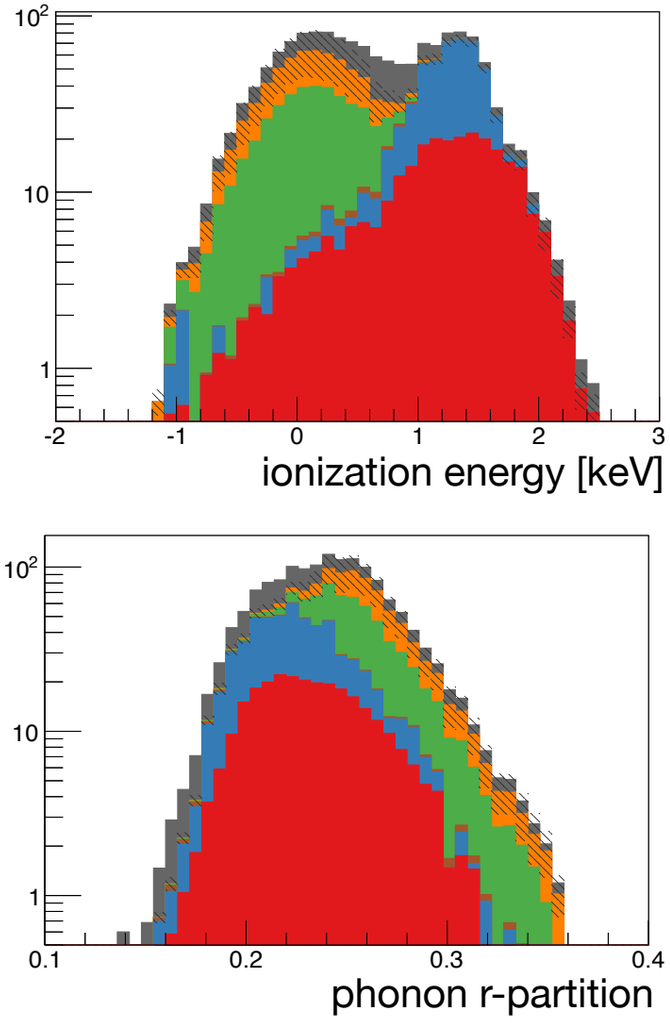


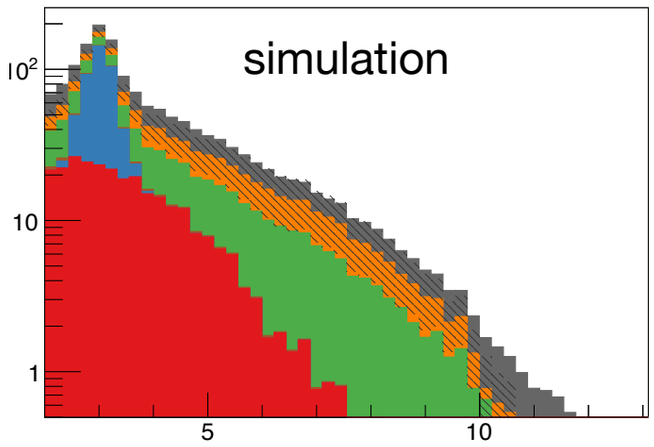
Low energy
surface events

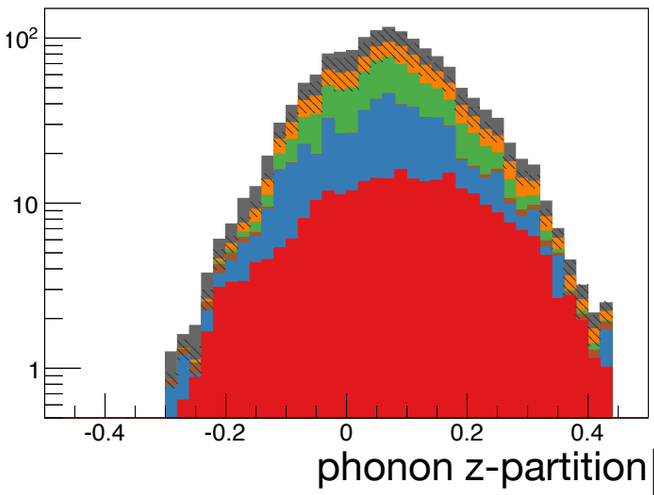


Boosted Decision Tree

BDT inputs

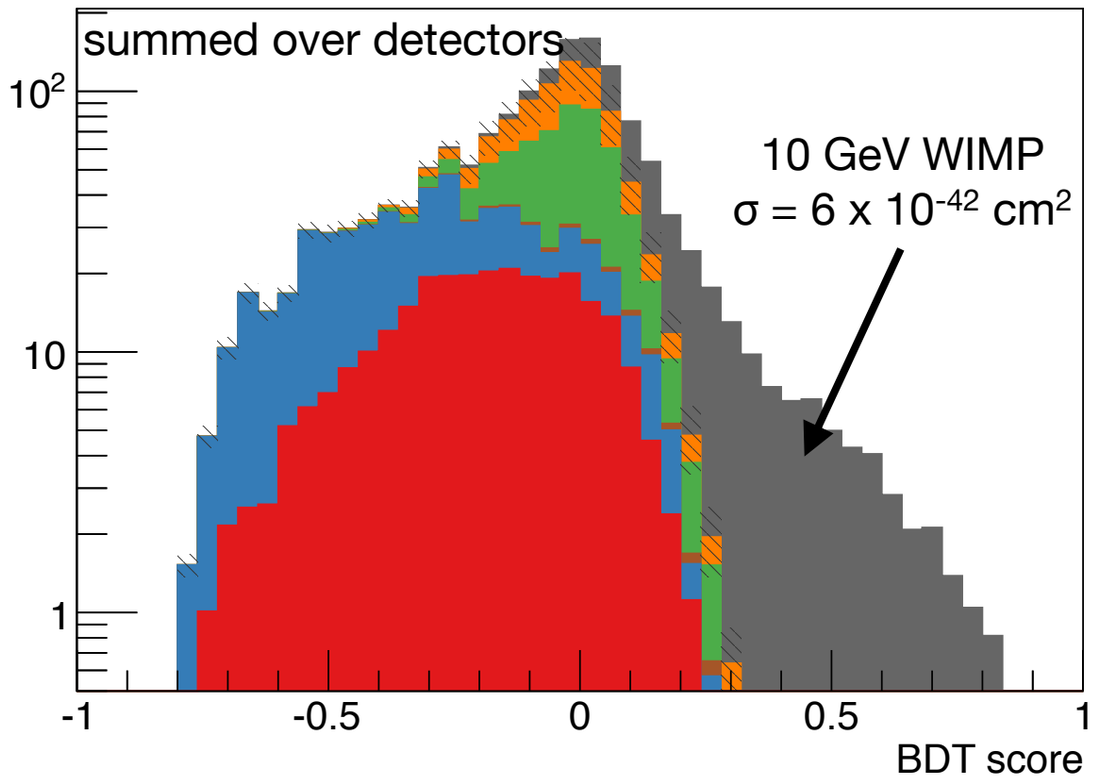


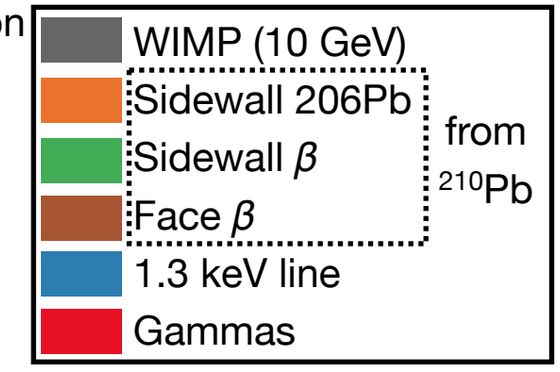




Background model: pulse simulation
Signal model: ^{252}Cf NR events reweighted to match 5, 7, 10, and 15 GeV WIMP

BDT output

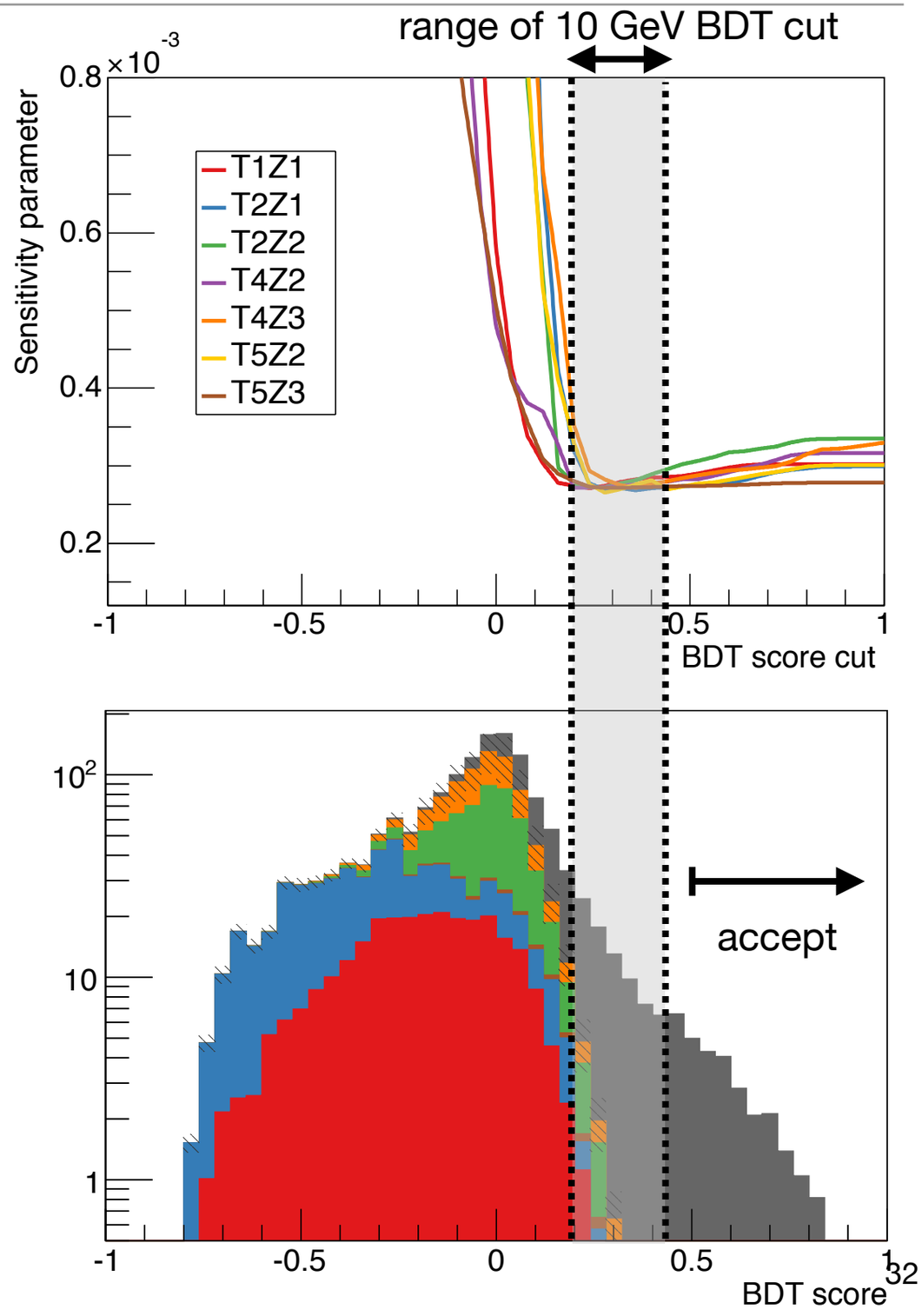




Construction: 1 BDT per detector
Optimization: set cuts simultaneously to minimize expected 90% CL upper limit on WIMP-nucleon cross section

Cut Optimization

- 1 BDT classifier per detector
- Each detector has a BDT cut that has to be optimized
- Set detector BDT cuts simultaneously to minimize expected 90% CL upper limit on WIMP nucleon cross section
- Final cut is the logical OR of all the BDT cuts optimized for WIMPs of 5, 7, 10, and 15 GeV



Selection Criteria and Efficiencies

Quality

- Remove periods of poor detector performance
- Remove misreconstructed and noisy pulses
- Measure efficiency with pulse Monte Carlo

Thresholds

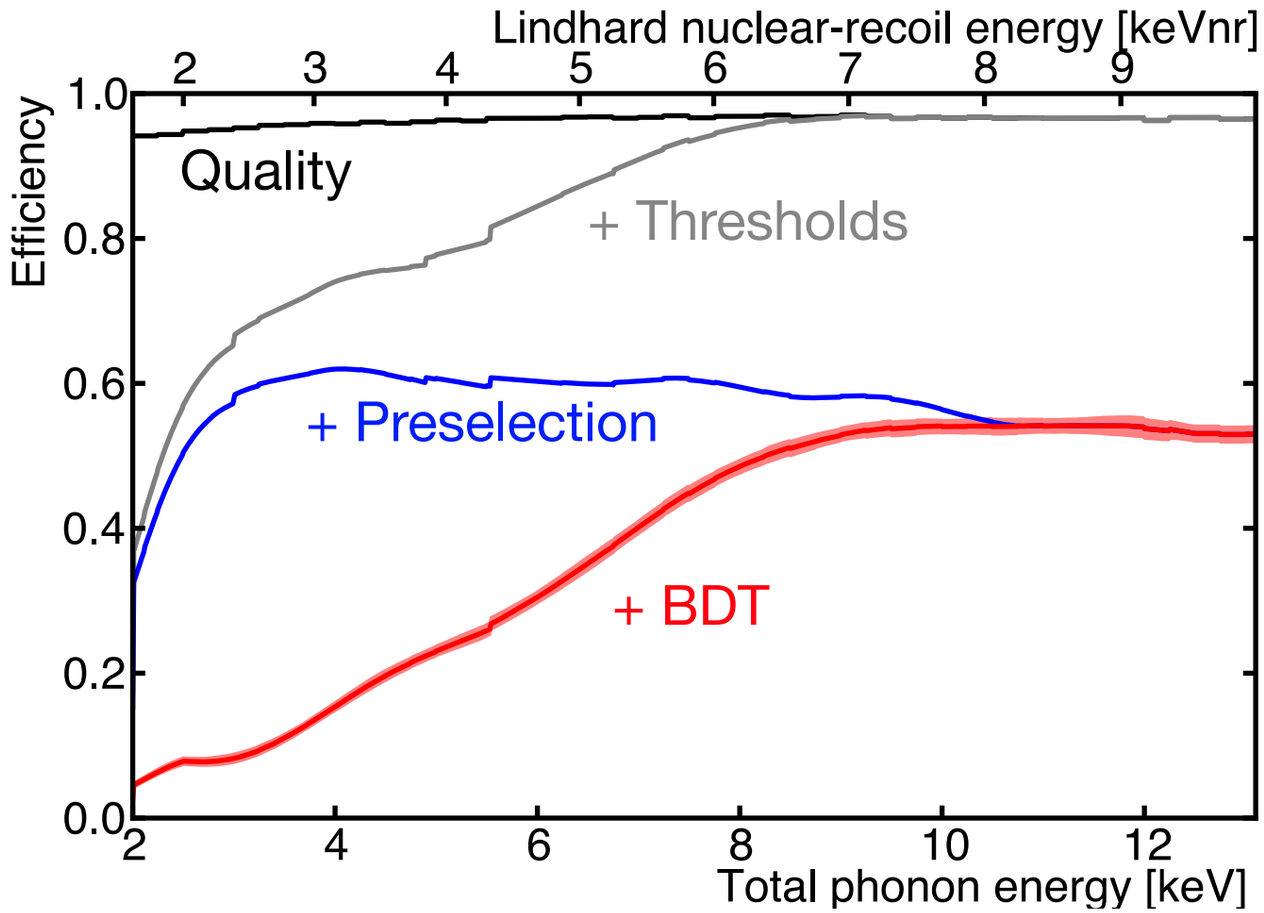
- Trigger and analysis thresholds 1.6-5 keVnr
- Measure efficiency using ^{133}Ba calibration data

Preselection

- Ionization consistent with nuclear recoils
- Ionization-based fiducialization
- Remove multiple-detector hits
- Remove events coincident with muon veto

BDT

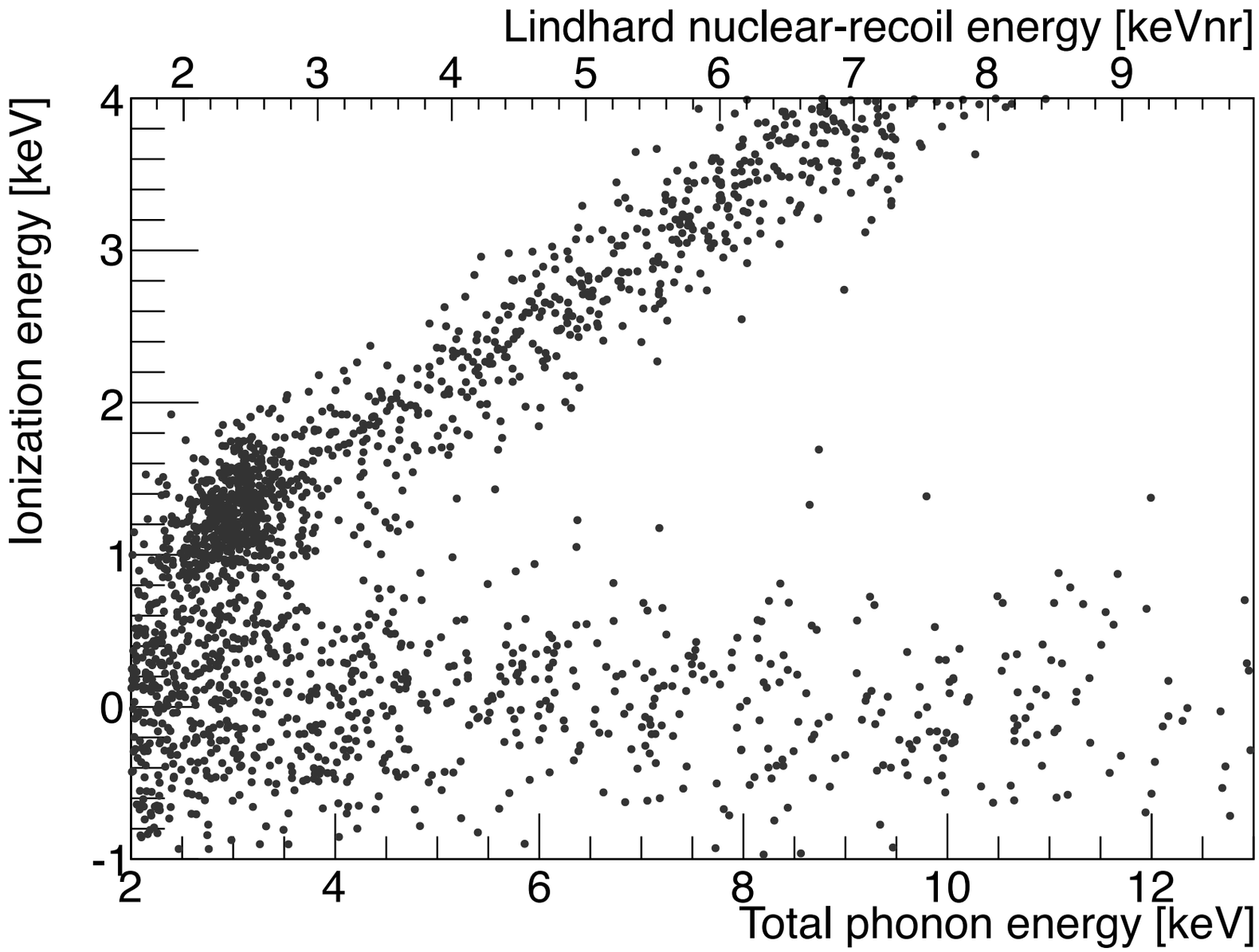
- Optimized cut on energy and phonon position estimators
- Estimate BDT+preselection efficiency using fraction of 252Cf passing



Includes ~20% correction, from Geant4 simulation, for multiple scattering in single detector

Unblinding: Before BDT

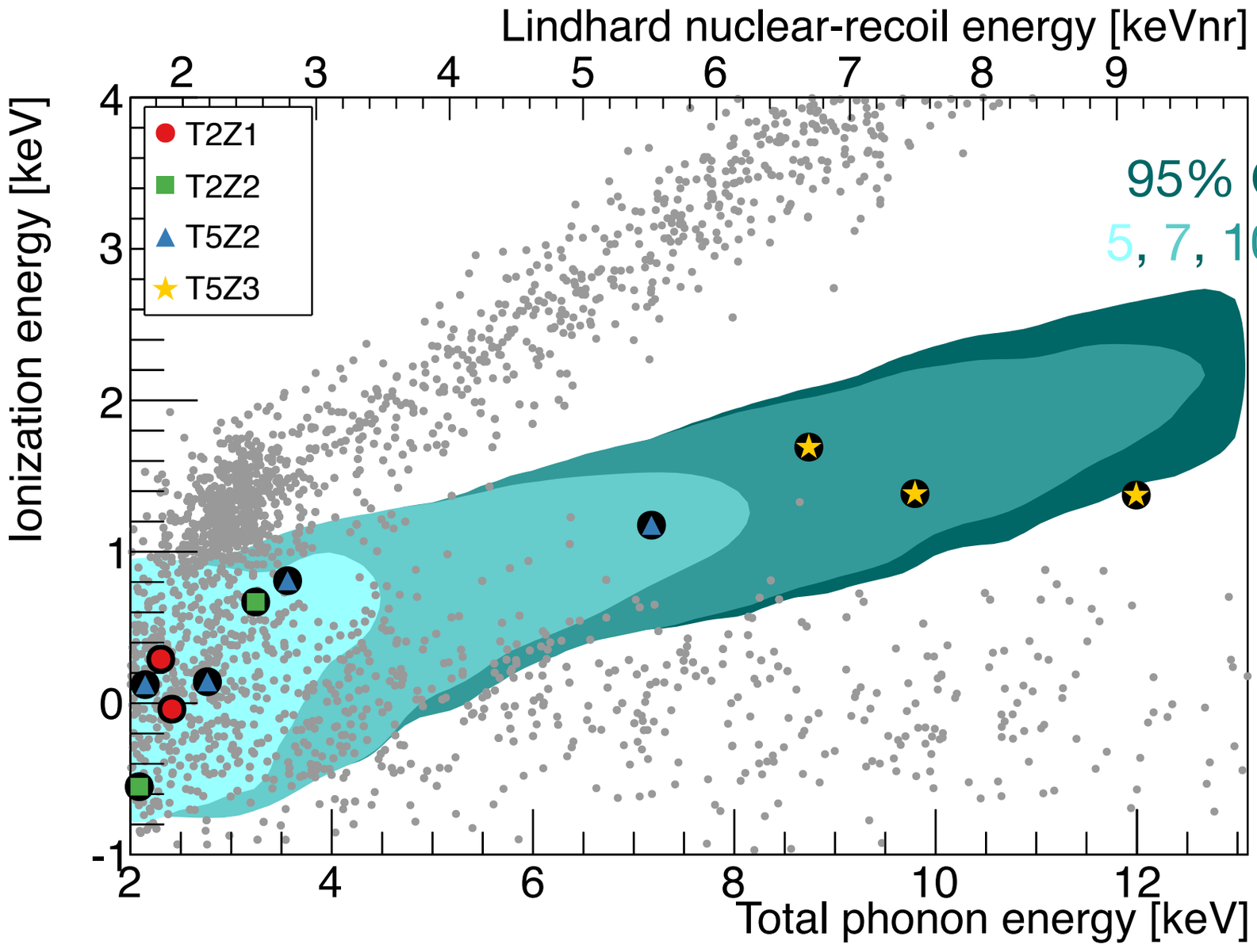
Expected background after BDT: **$6.1^{+1.1}_{-0.8}$ + (0.10 ± 0.02 neutrons)**



Passing data quality &
ionization fiducialization cuts

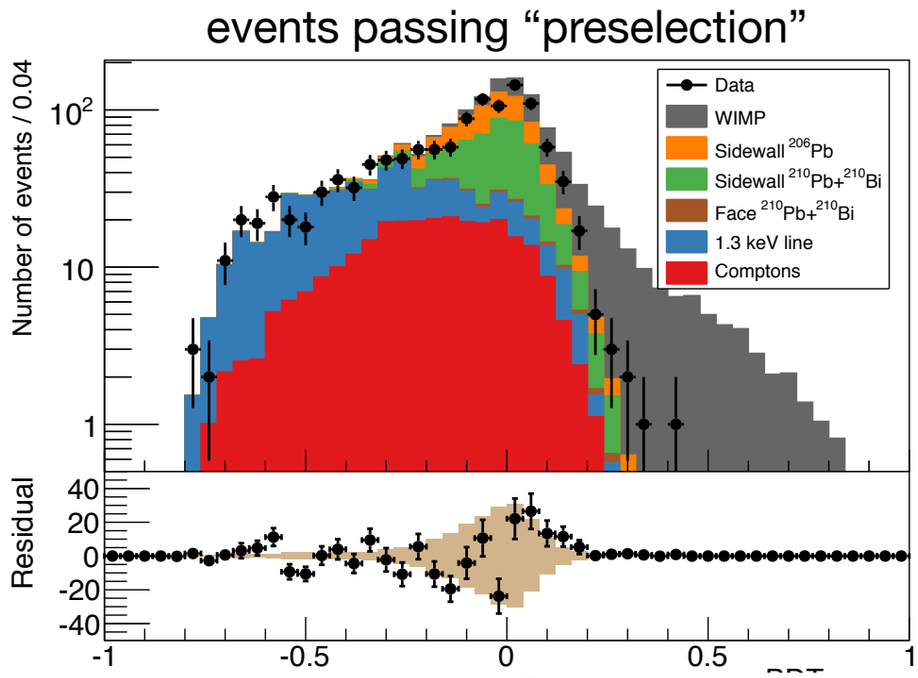
Unblinding: After BDT

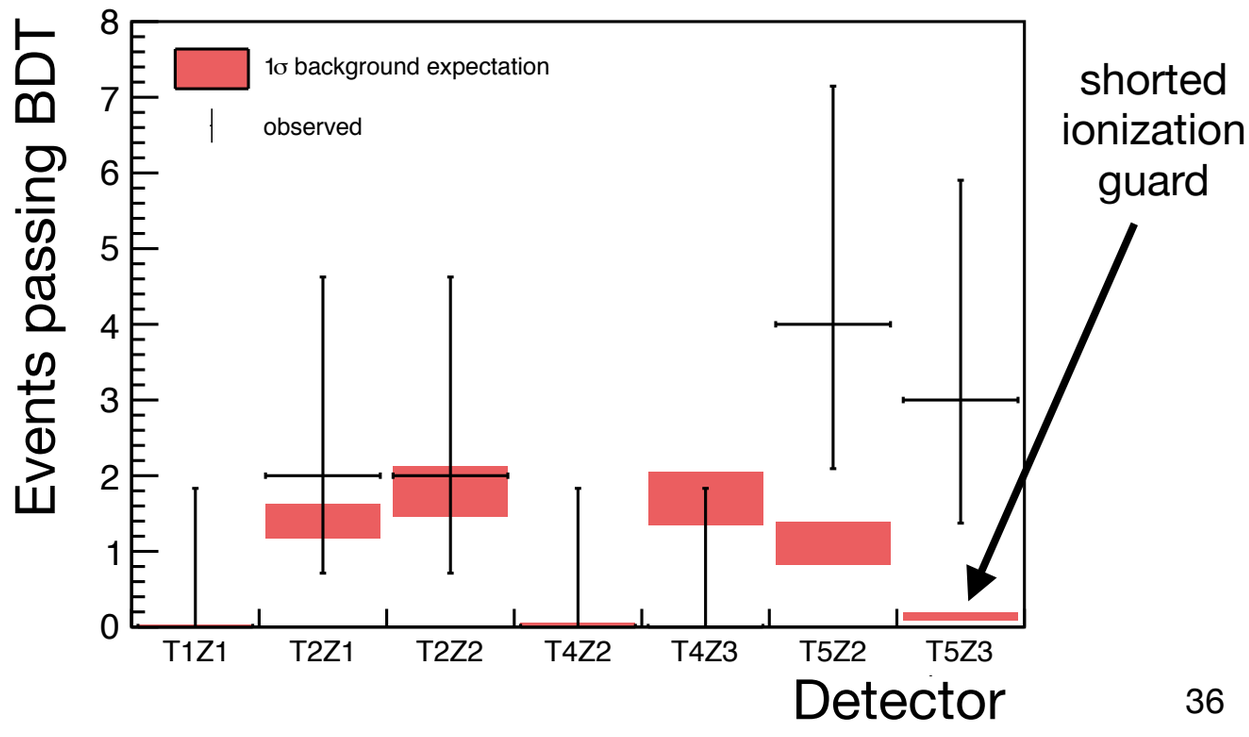
11 events observed passing BDT (expected $6.2^{+1.1}_{-0.8}$)



Post-Unblinding Comparison

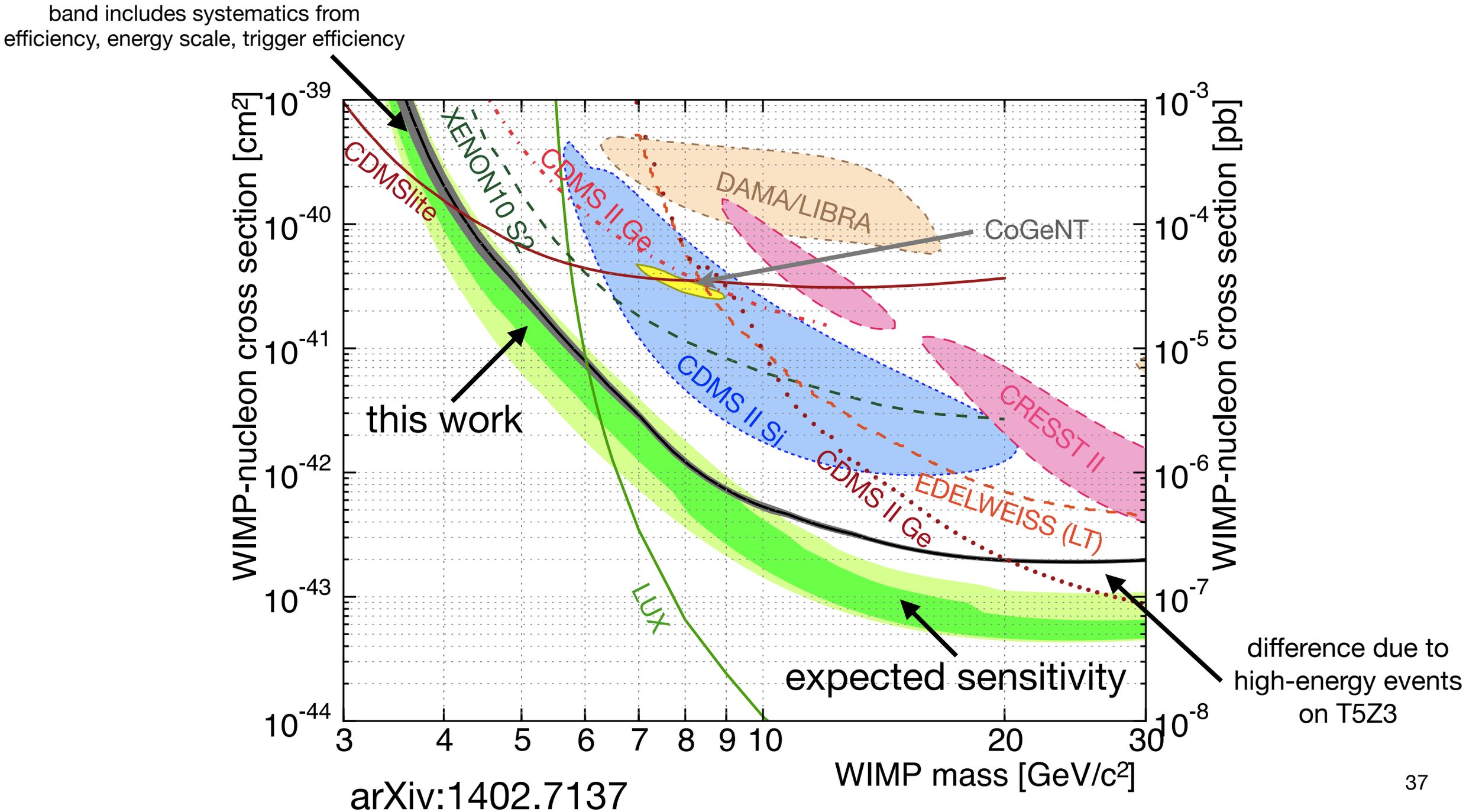
- Background model **accurate in full preselection region**
- Background consistent with expectations overall and on most individual detectors
- Shorted ionization guard on T5Z3 may have affected background model performance—*further study ongoing*
- Poisson p-value for T5Z3 is 0.04%, and even lower considering only high event energies





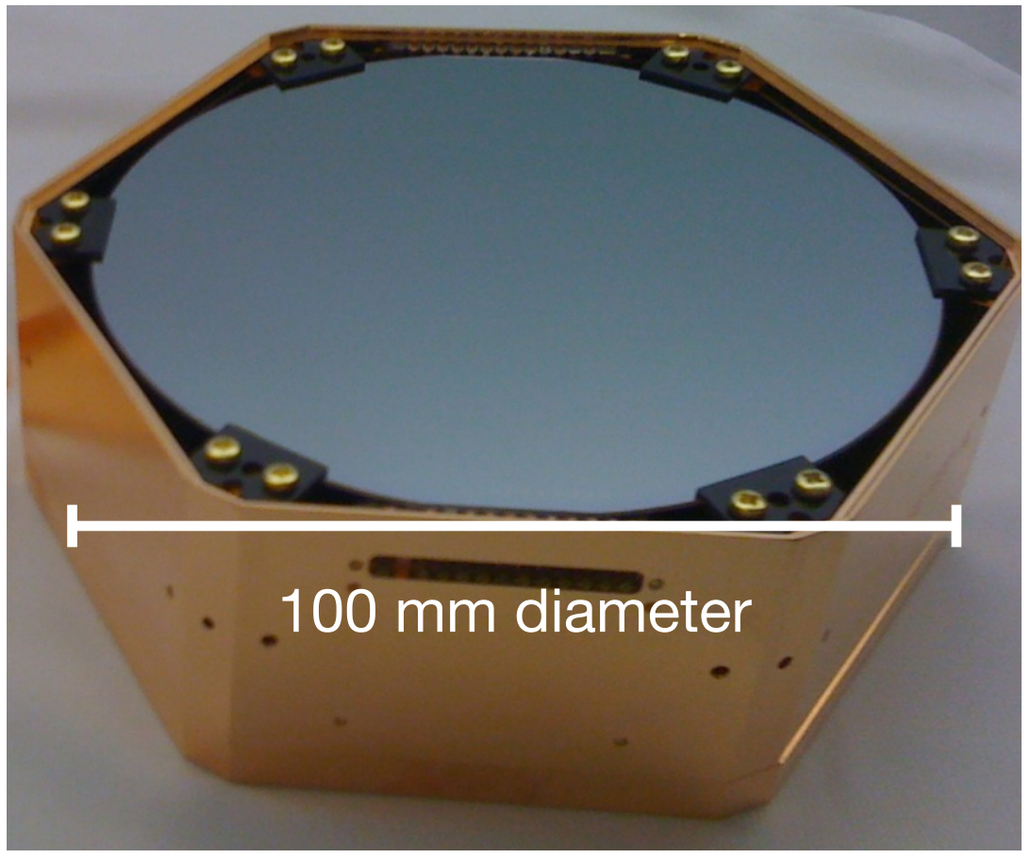
Limit

set 90% CL upper limit with optimal interval method (no background subtraction)



Future Perspectives: SuperCDMS @ SNOLAB

- **Larger** detectors: 1.4 kg 100 mm diameter crystals
- **More** detectors: 110 kg array (92+6 kg Ge + 11+1 kg Si)
- **Deeper** location: move to SNOLAB
- **Cleaner:** intensive materials screening program and active neutron veto
- **Lower** threshold: lower T_c of transition-edge sensors improves baseline noise
- **Smarter** analysis: exploit lessons learned Soudan analyses



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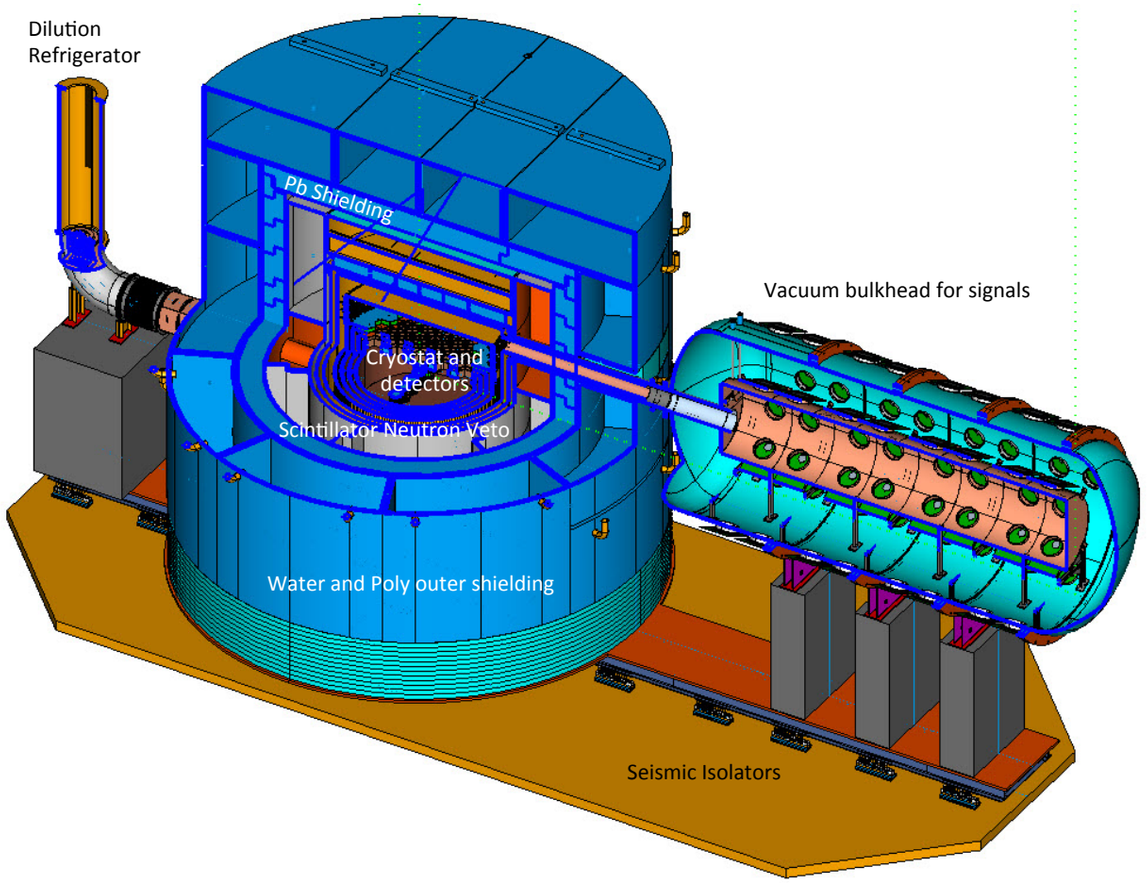

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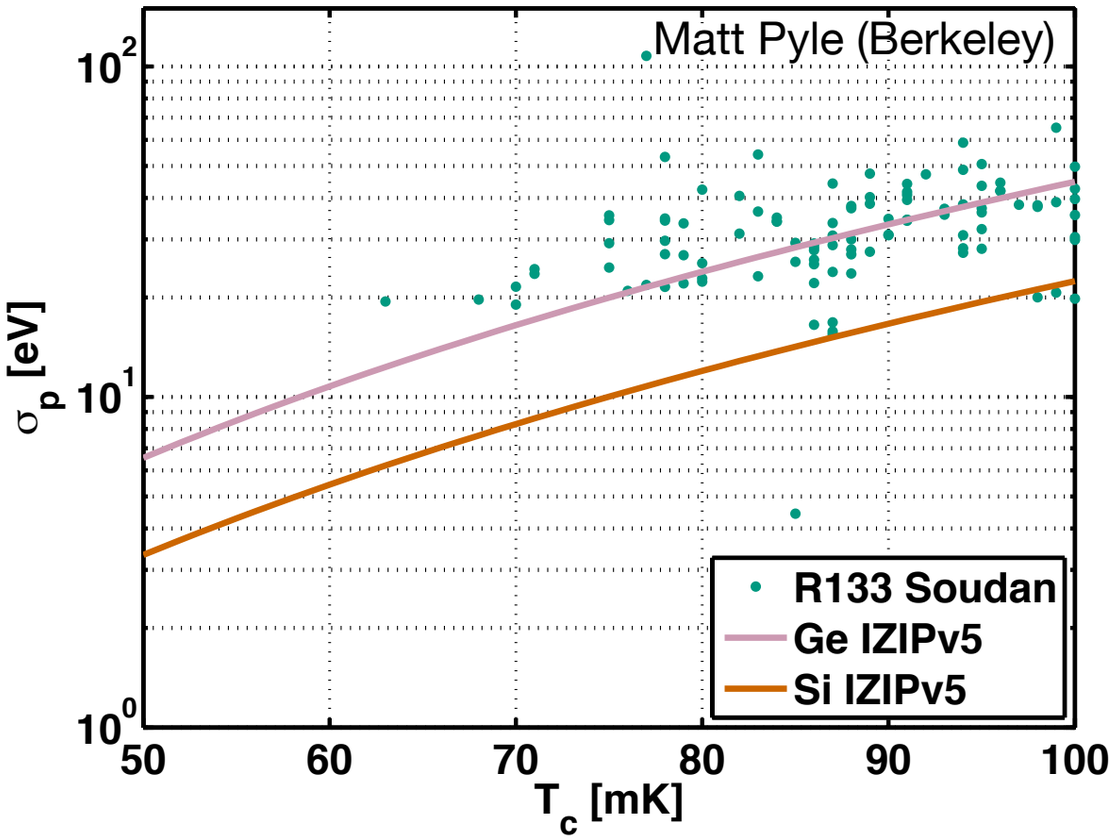

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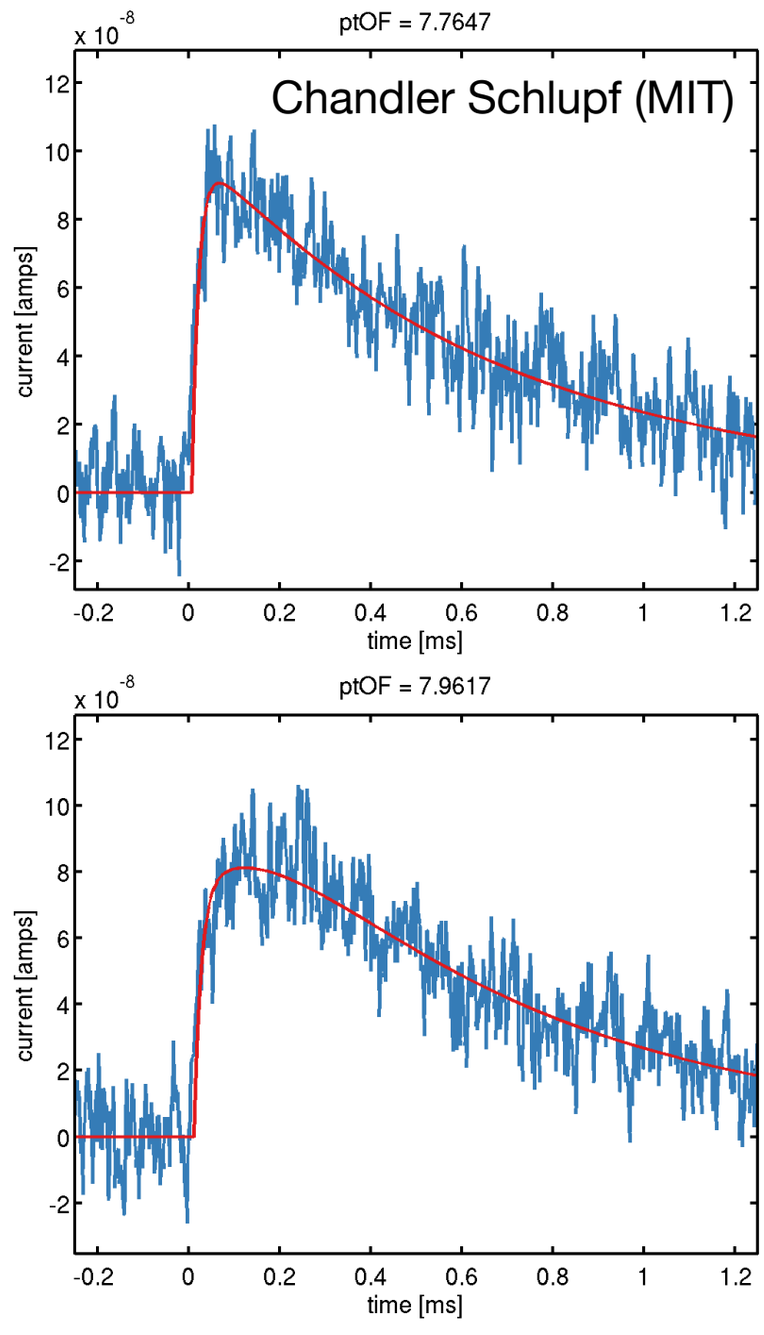
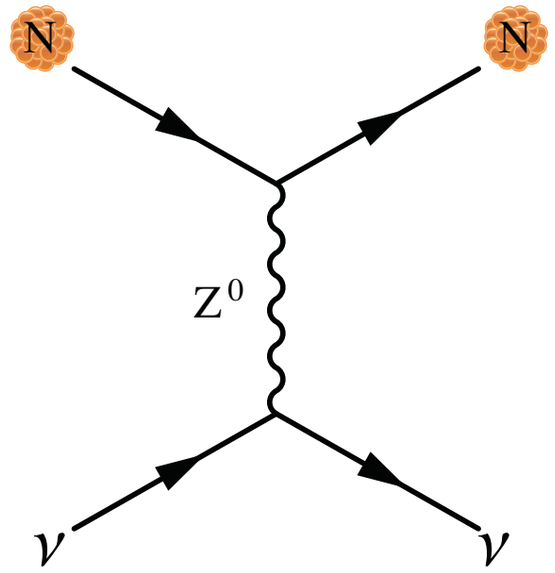
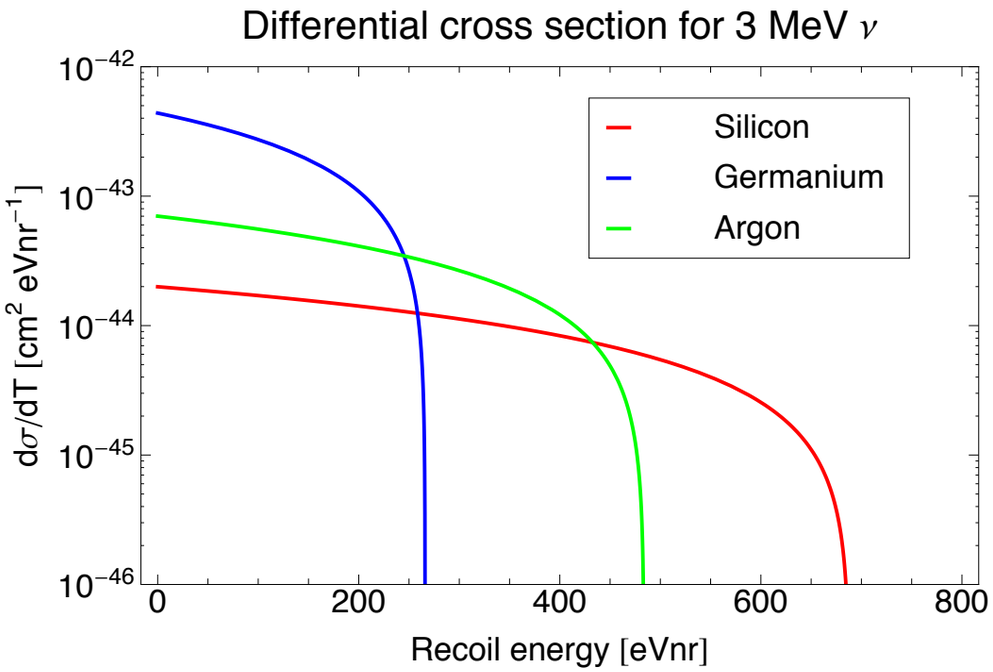
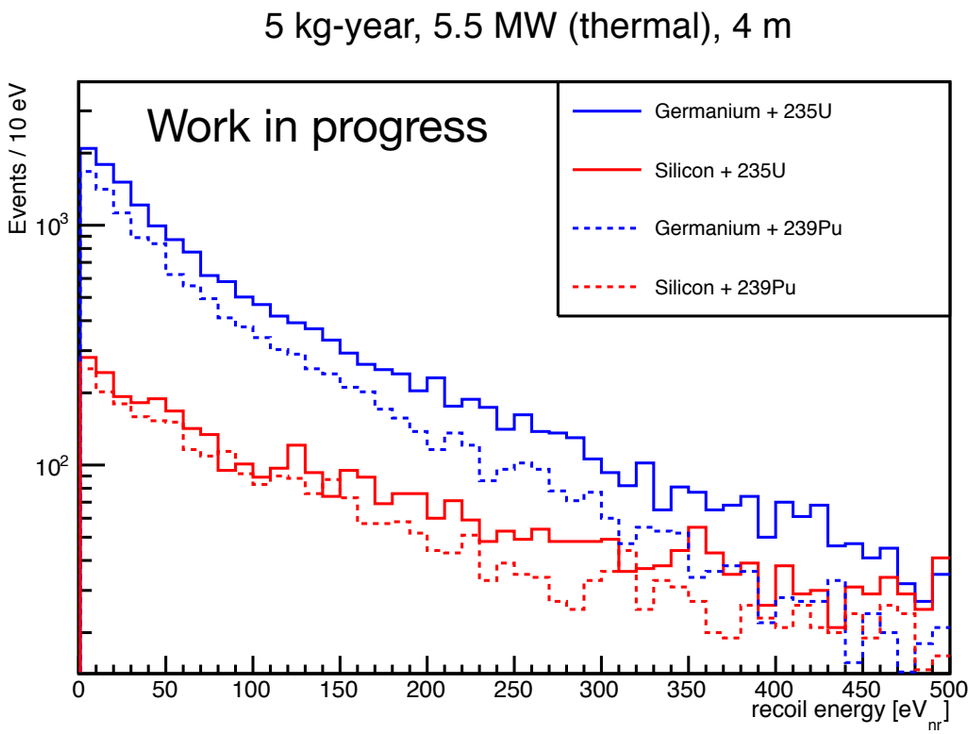


Future Perspectives: Applications to Neutrinos

- Unique sensitivity to coherent neutrino scattering: very **low** thresholds, **no** quenching
- Discovery possible at reactor, with strong constraints on nonstandard neutrino interactions
- Larger experiments with intense neutrino sources can probe sterile neutrino oscillations







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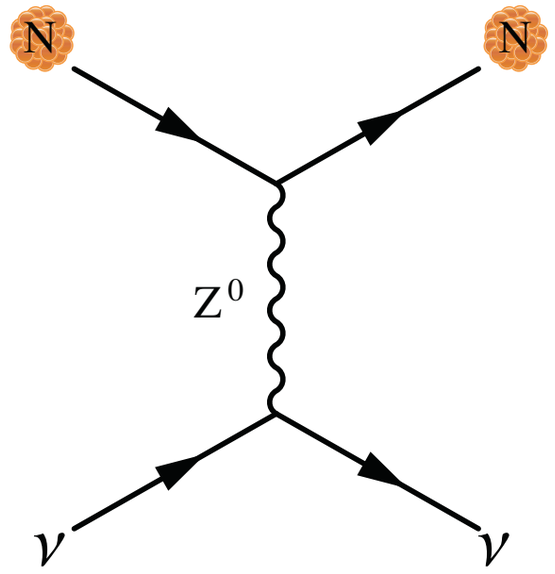
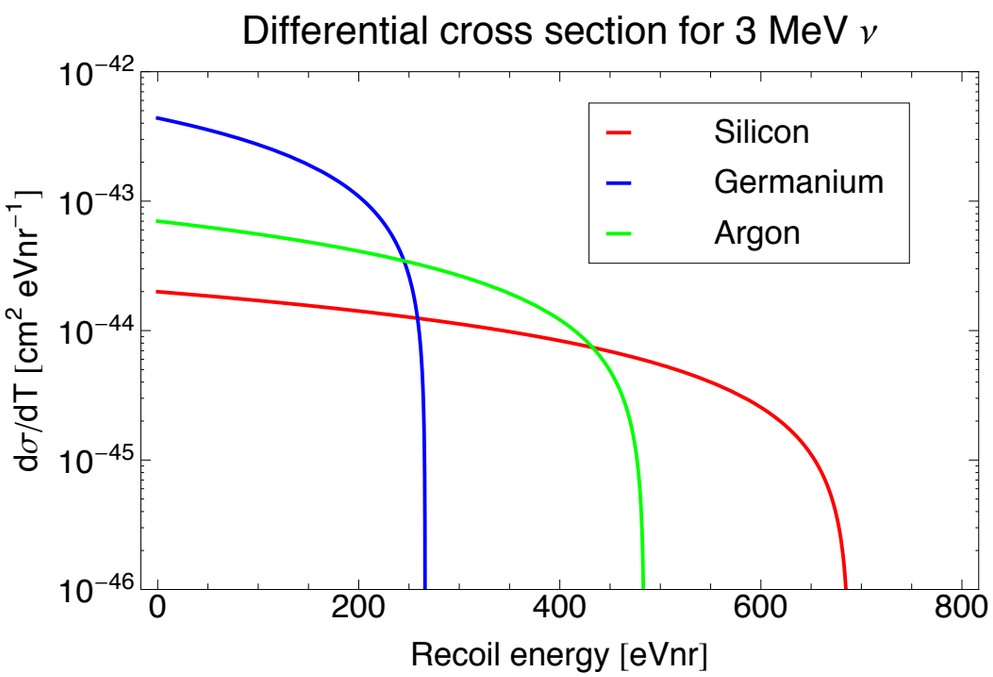
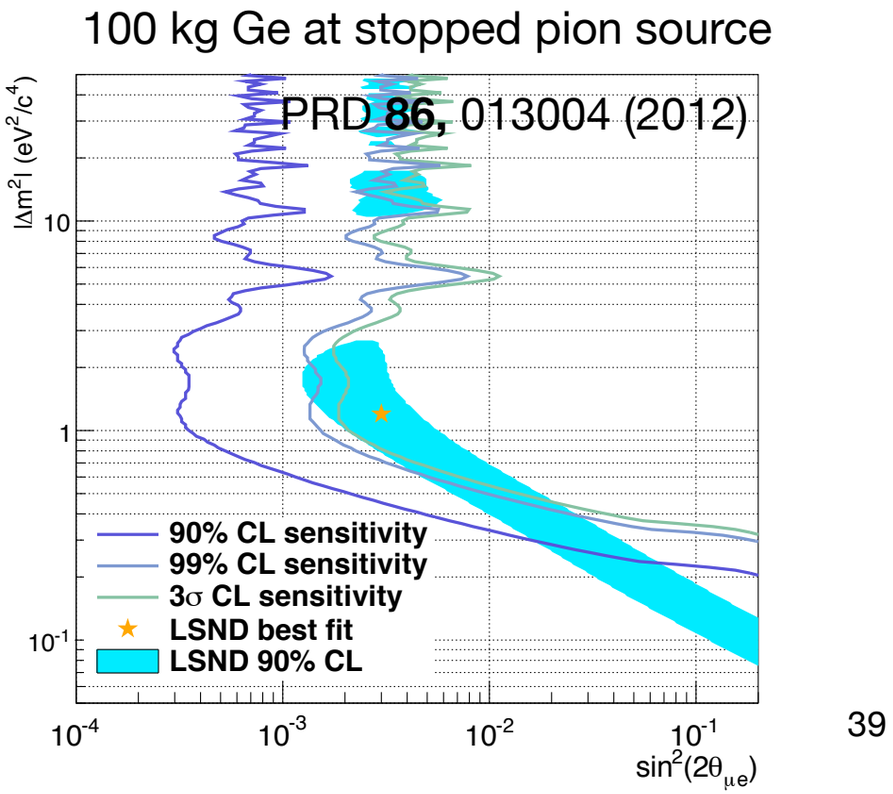
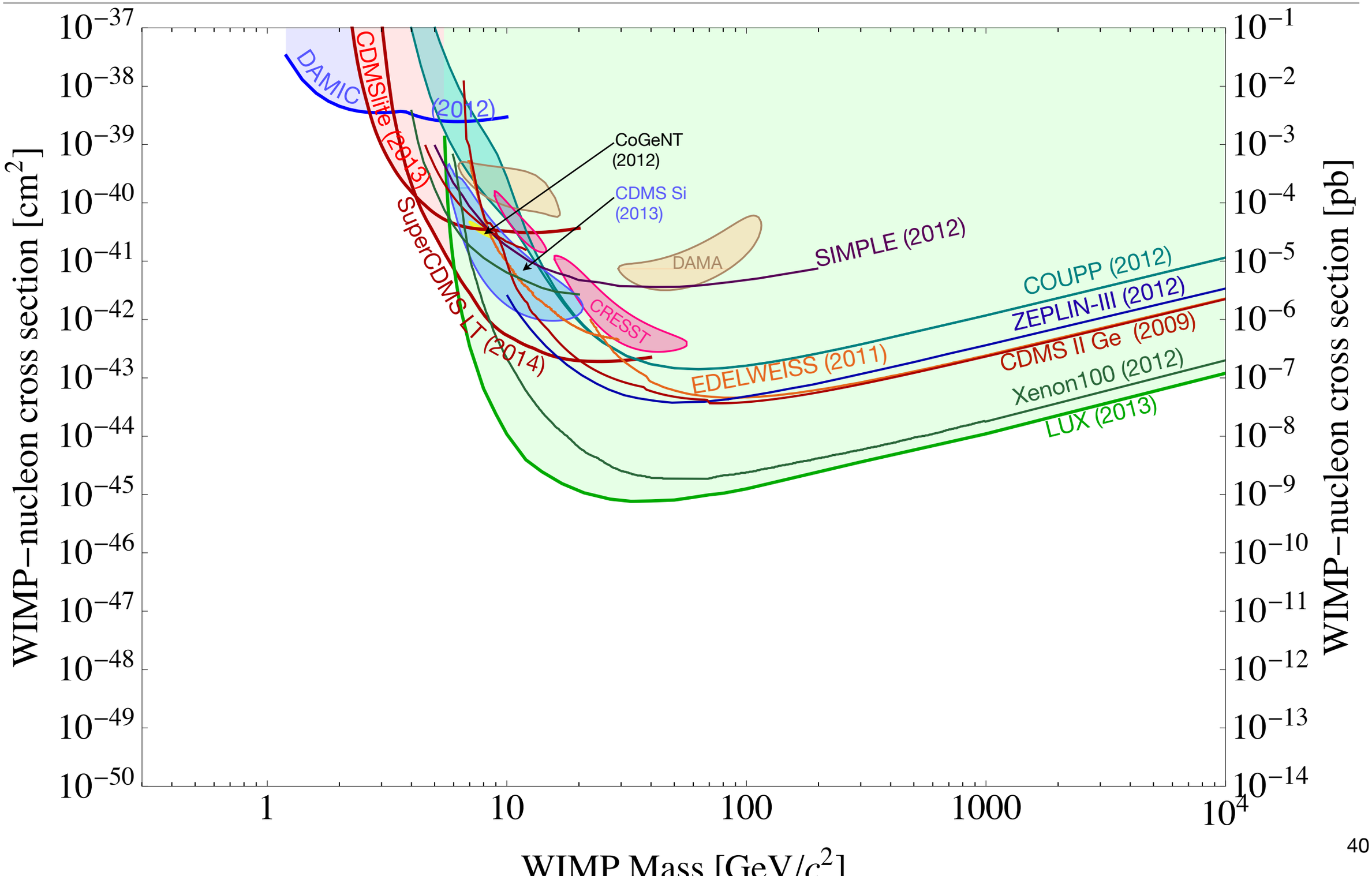


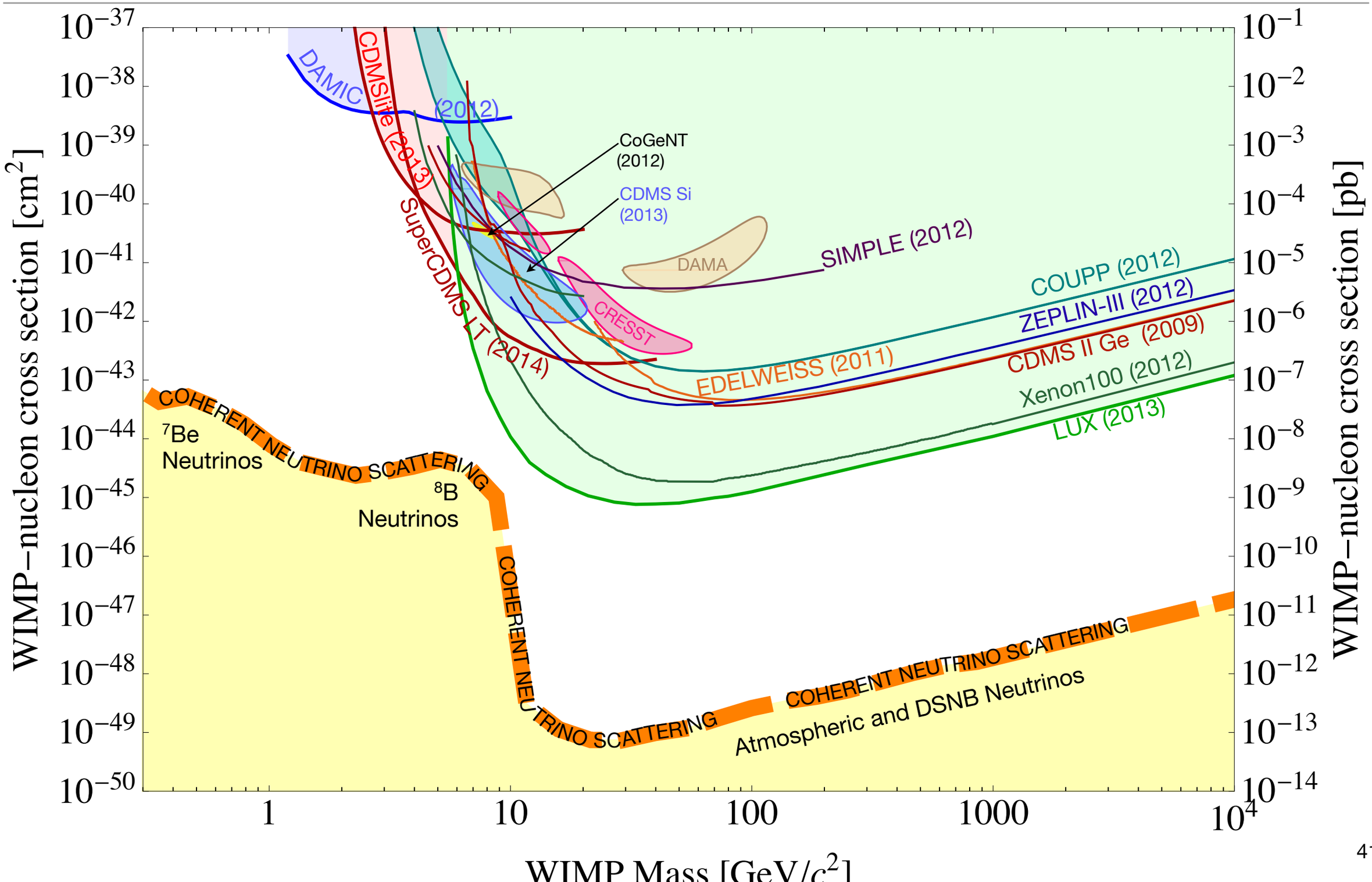




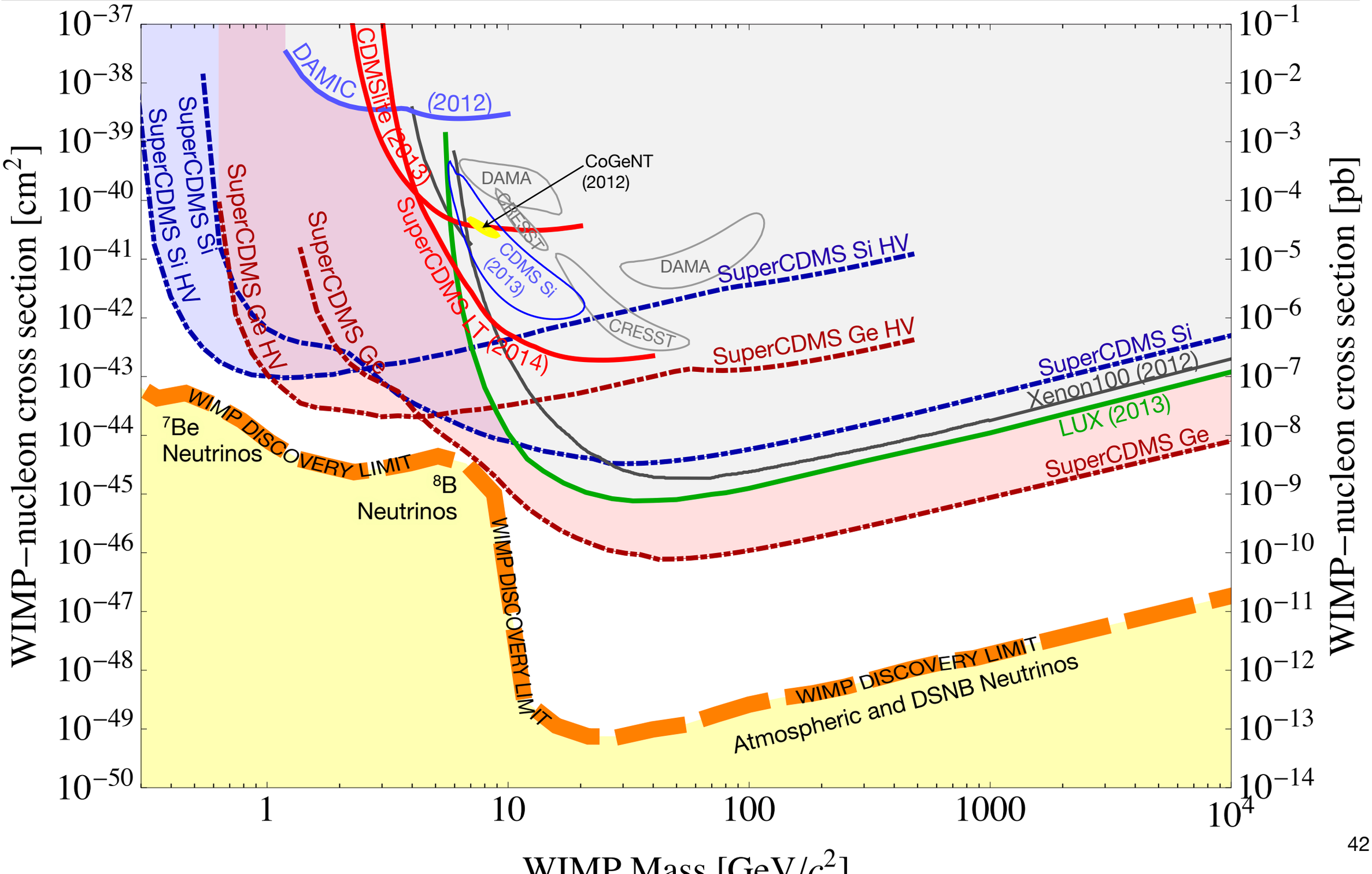
The Current Landscape



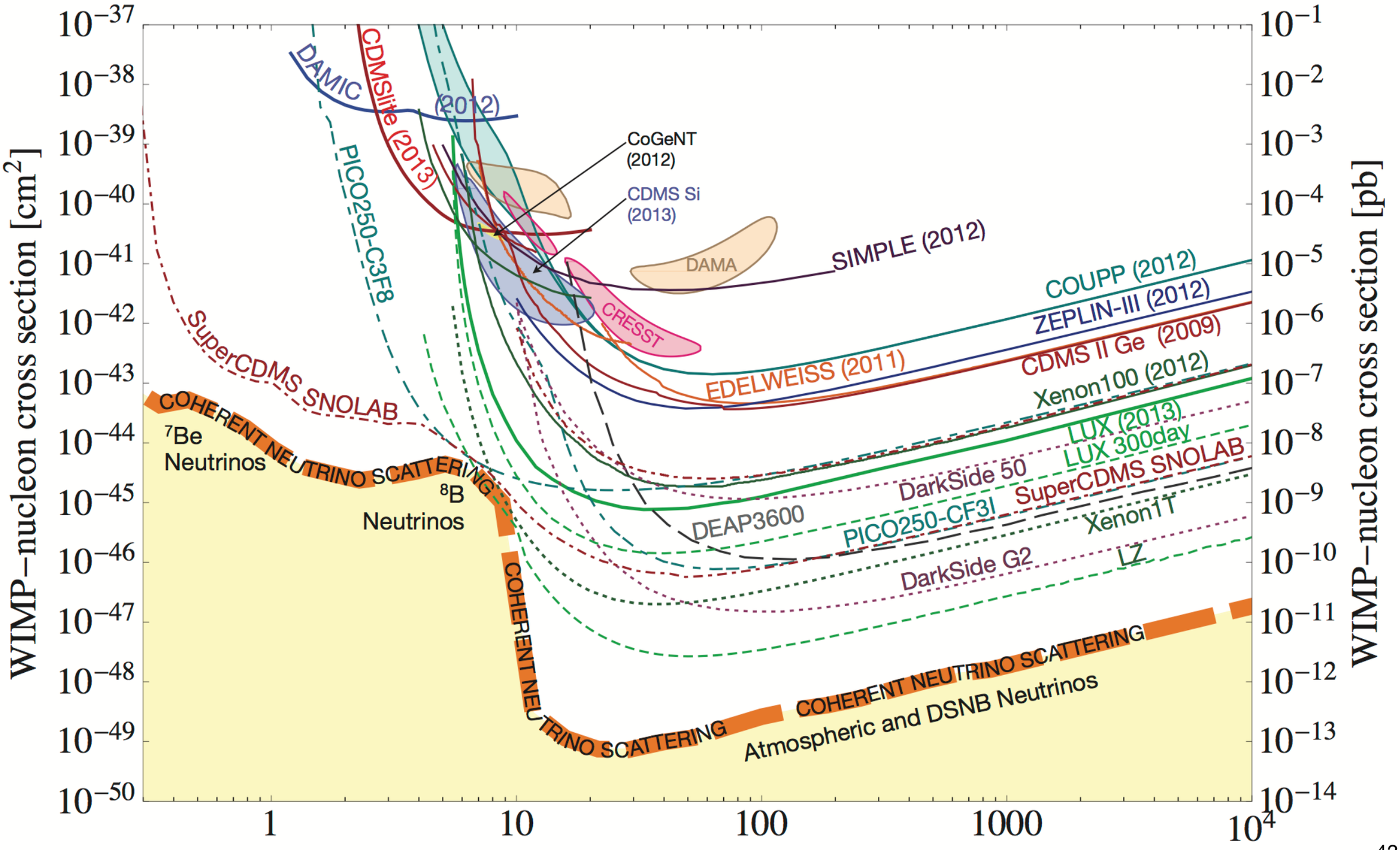
Coherent Neutrino Scattering “Floor”



The Future of SuperCDMS

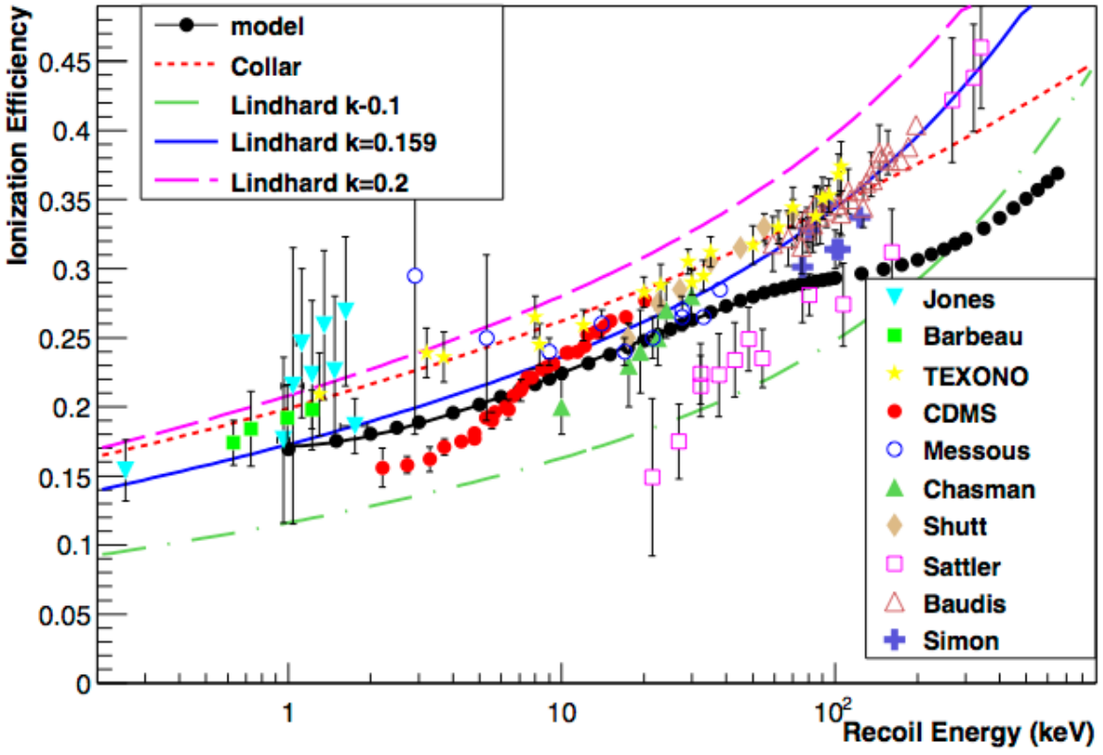


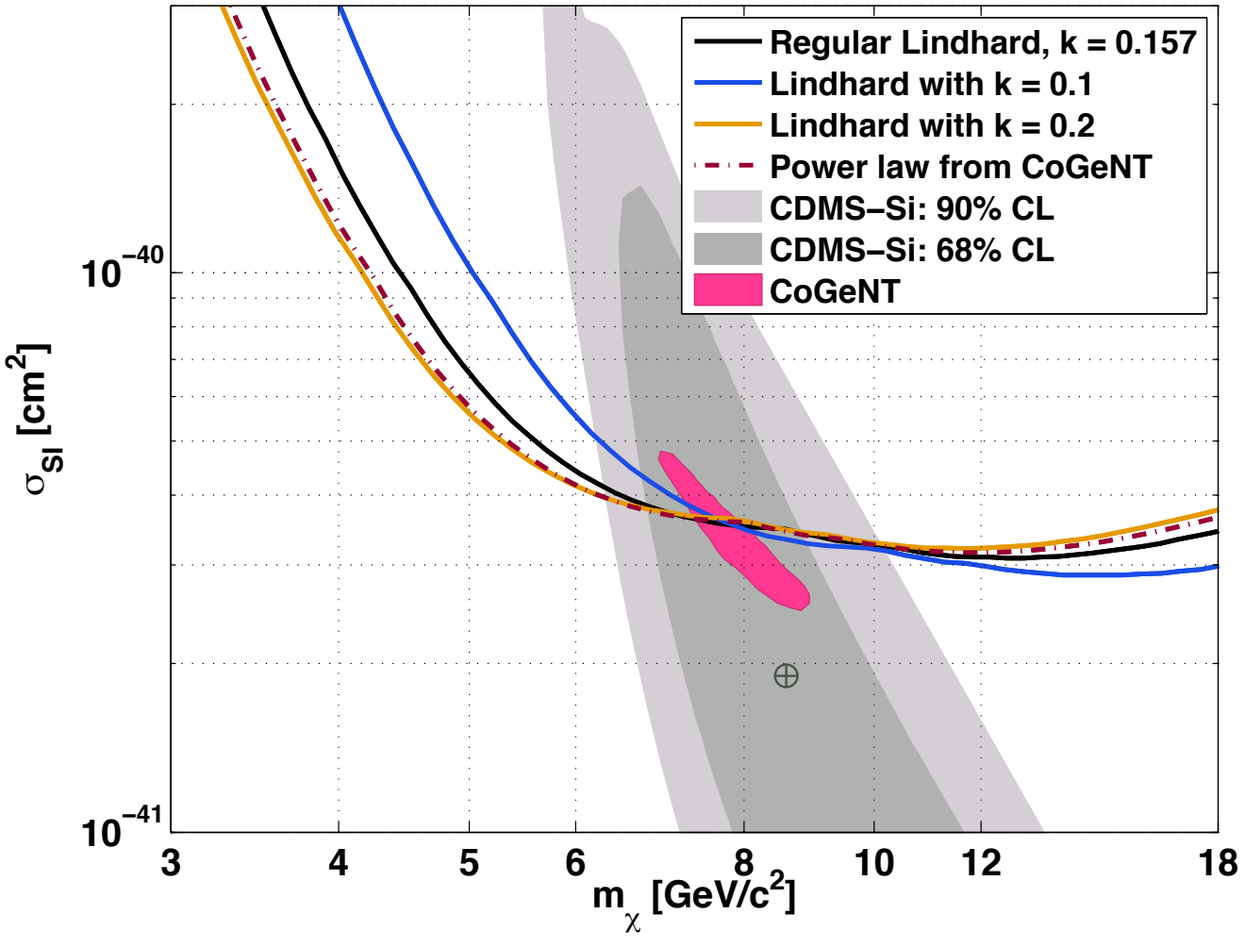
The Future Landscape



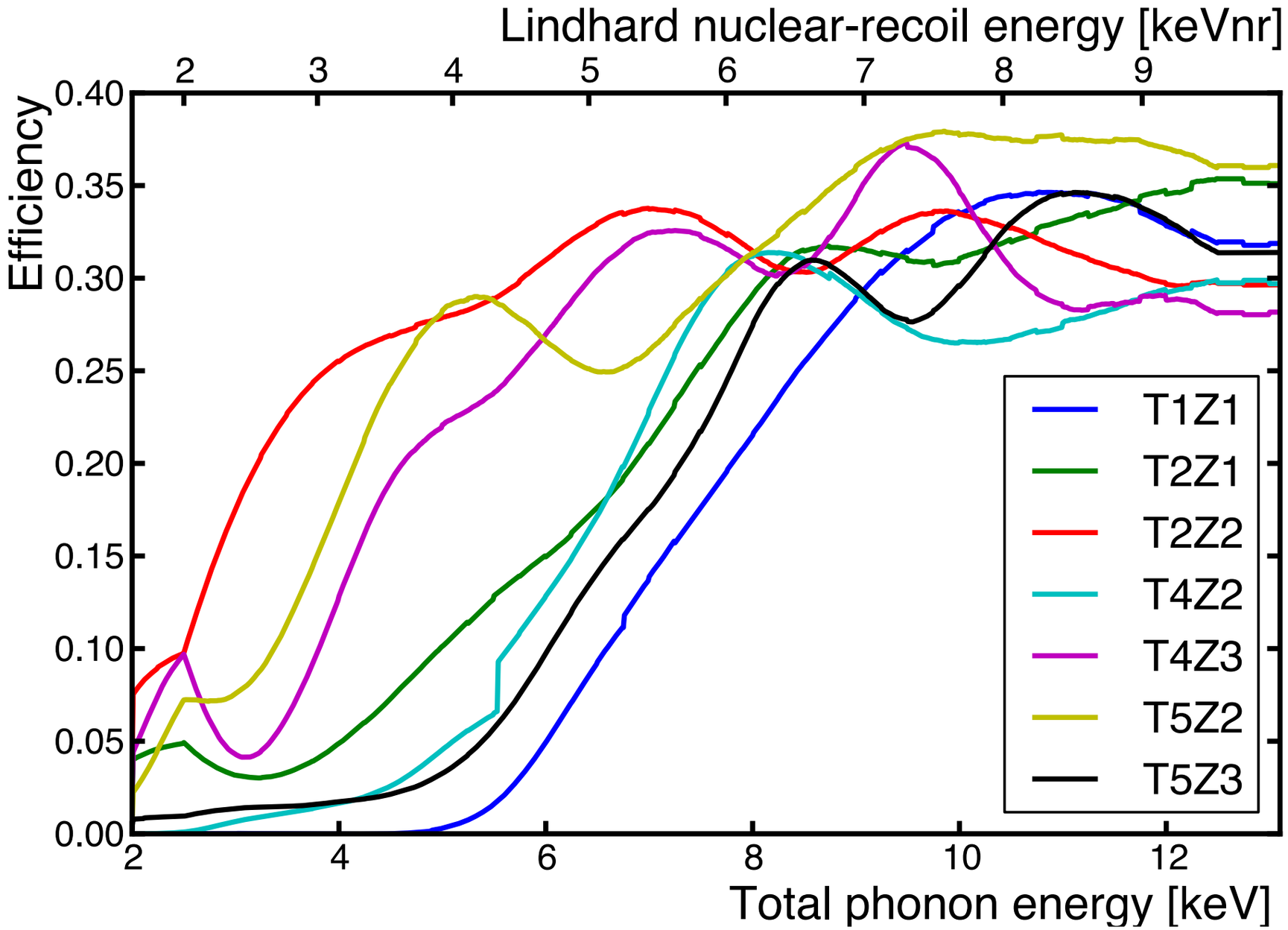
Backup

CDMSlite: Effect of Nuclear Recoil Energy Scale

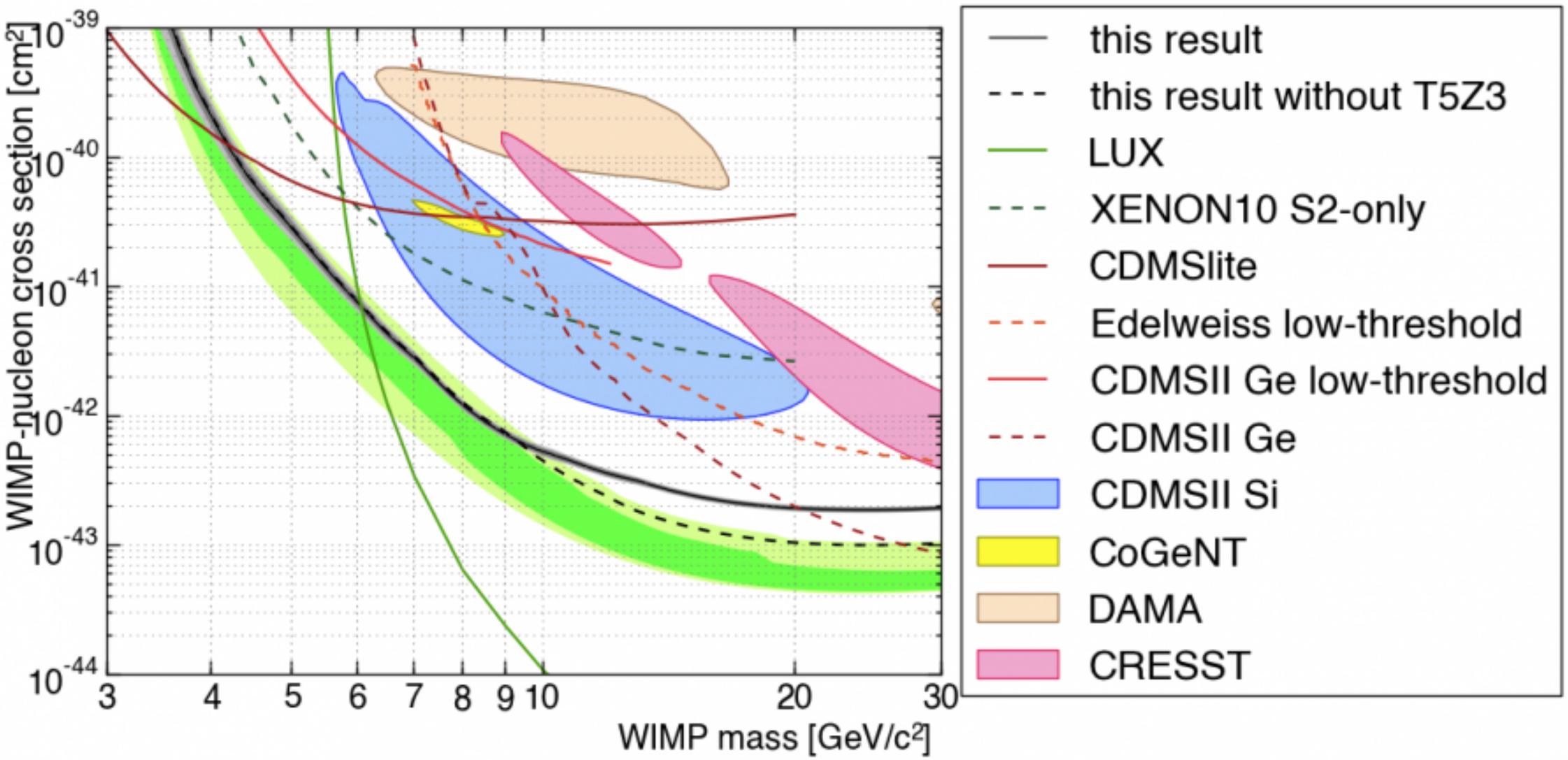




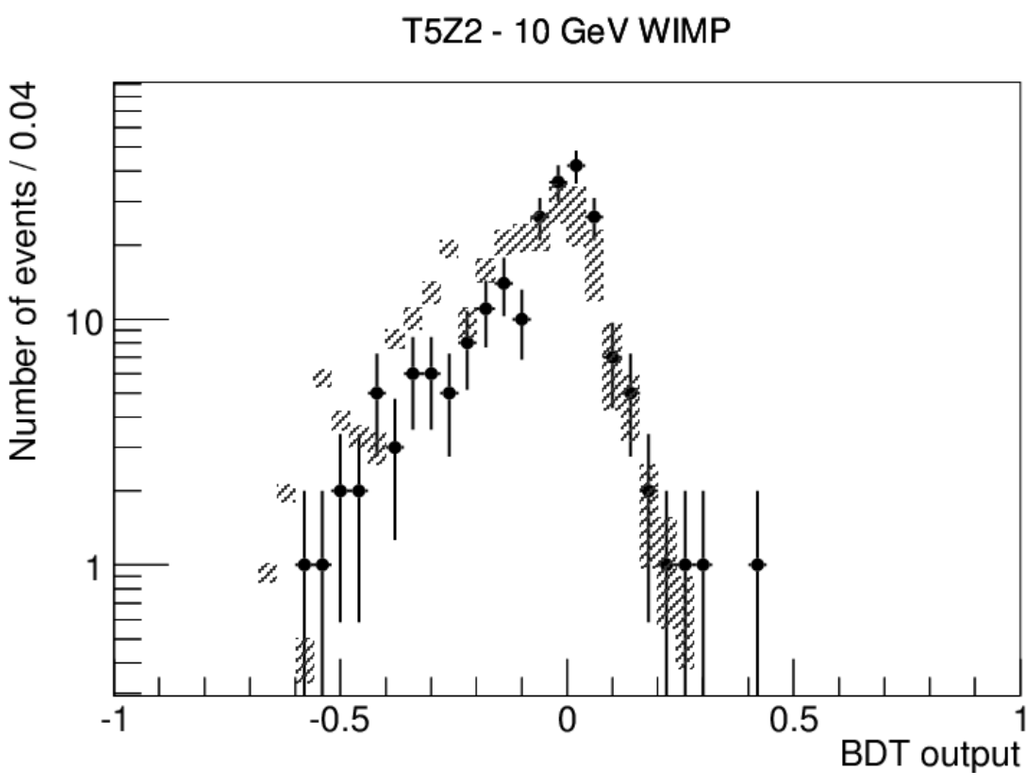
Efficiencies by Detector

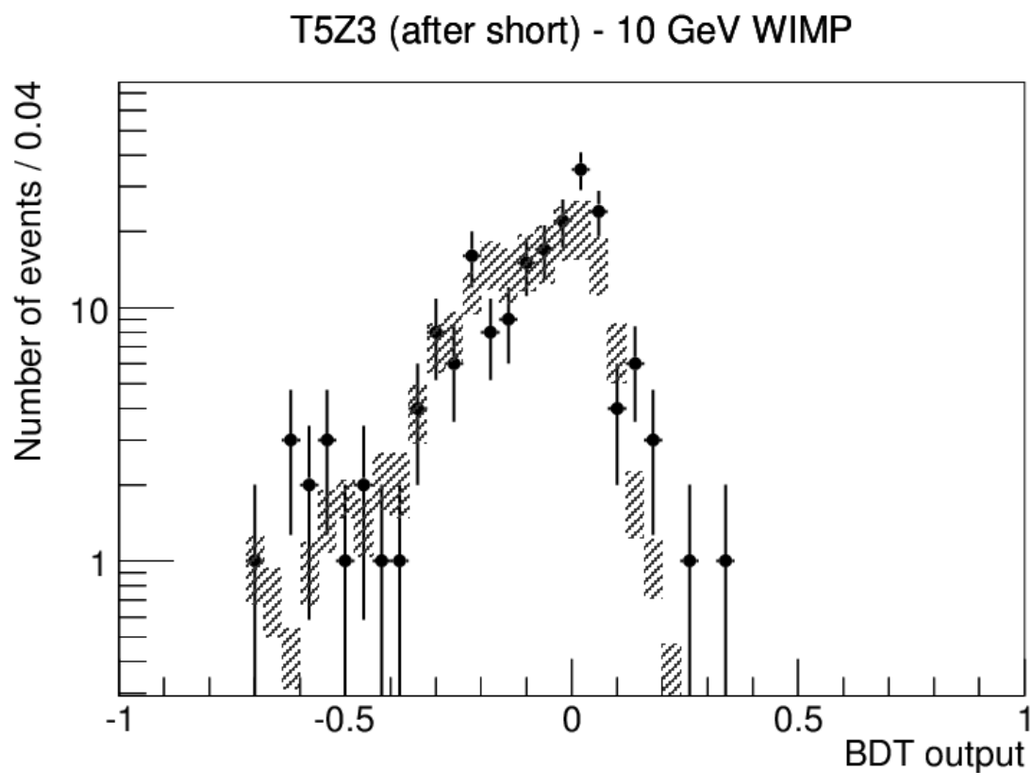


Limit without T5Z3

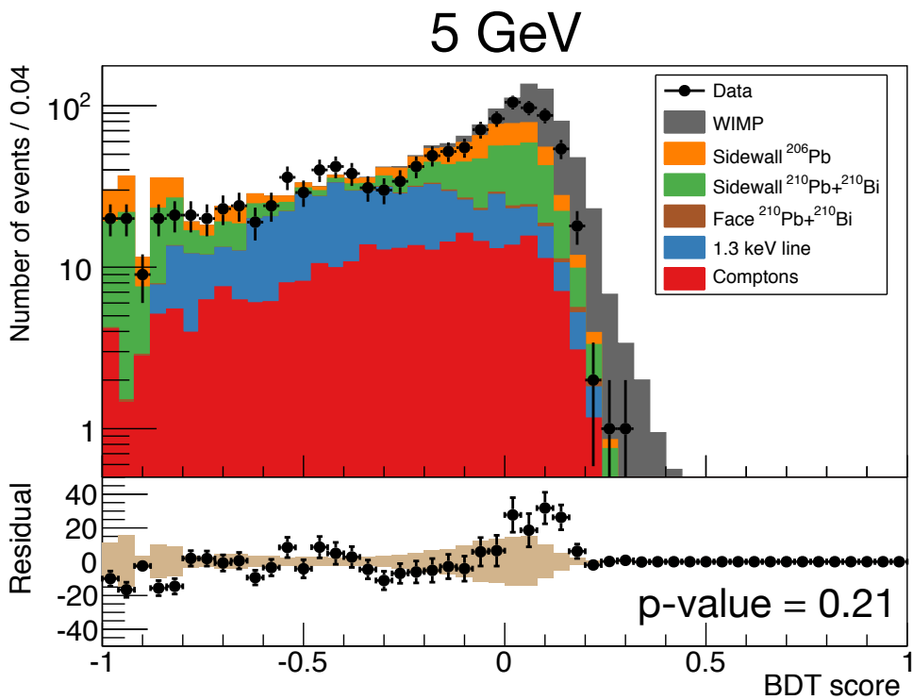


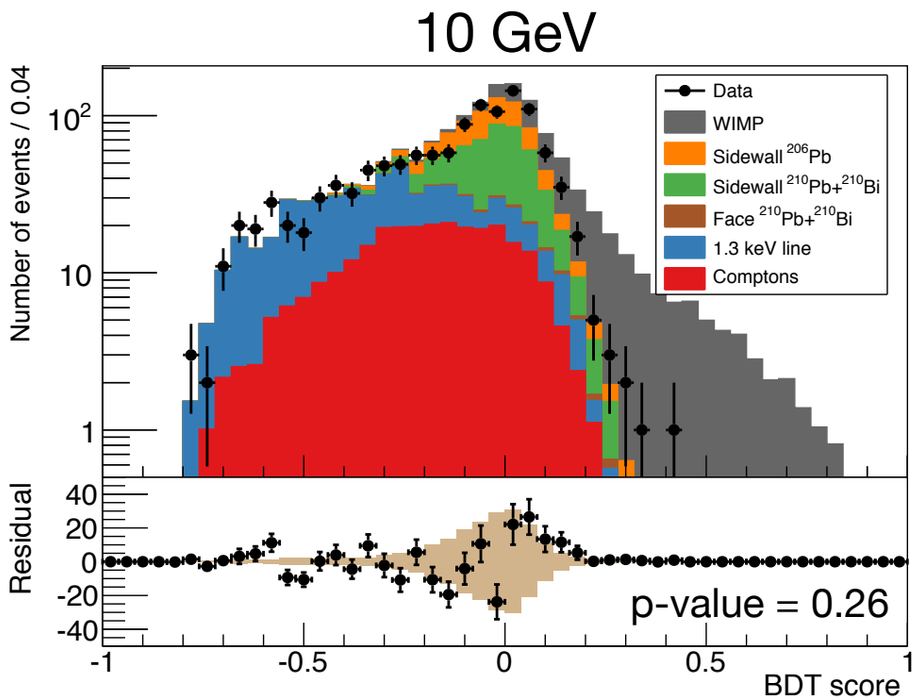
Tower 5 Data

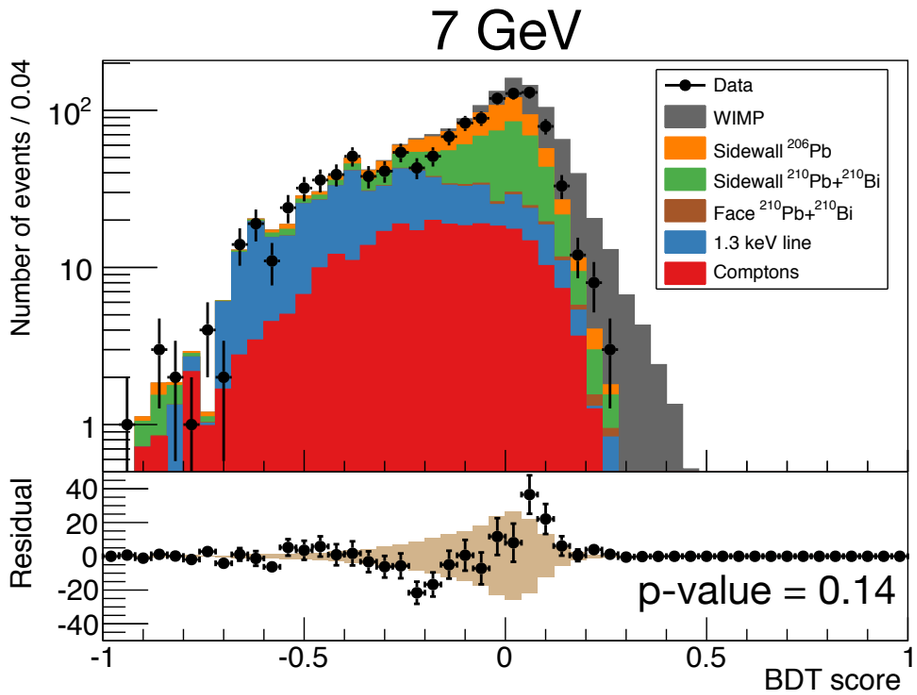

T5Z2 - 10 GeV WIMP
Number of events / 0.04
10
1
-1
-0.5
0
0.5
1
BDT output

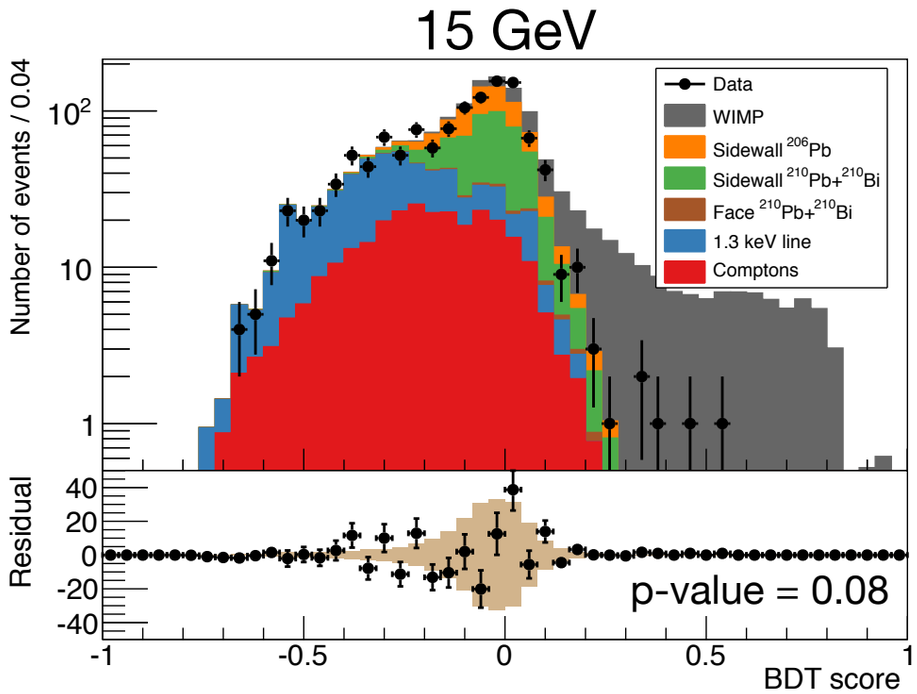

T5Z3 (after short) - 10 GeV WIMP
Number of events / 0.04
10
1
-1
-0.5
0
0.5
1
BDT output

BDT Distributions









BDT Input Distributions