Searching for low mass WIMPs with SuperCDMS and the neutrino background

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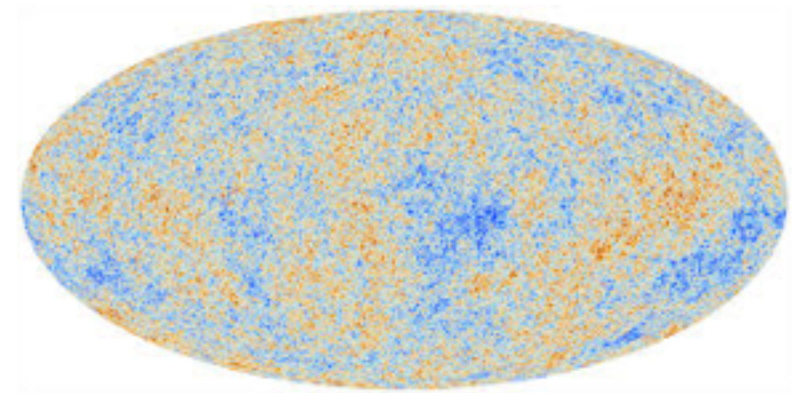
Outline

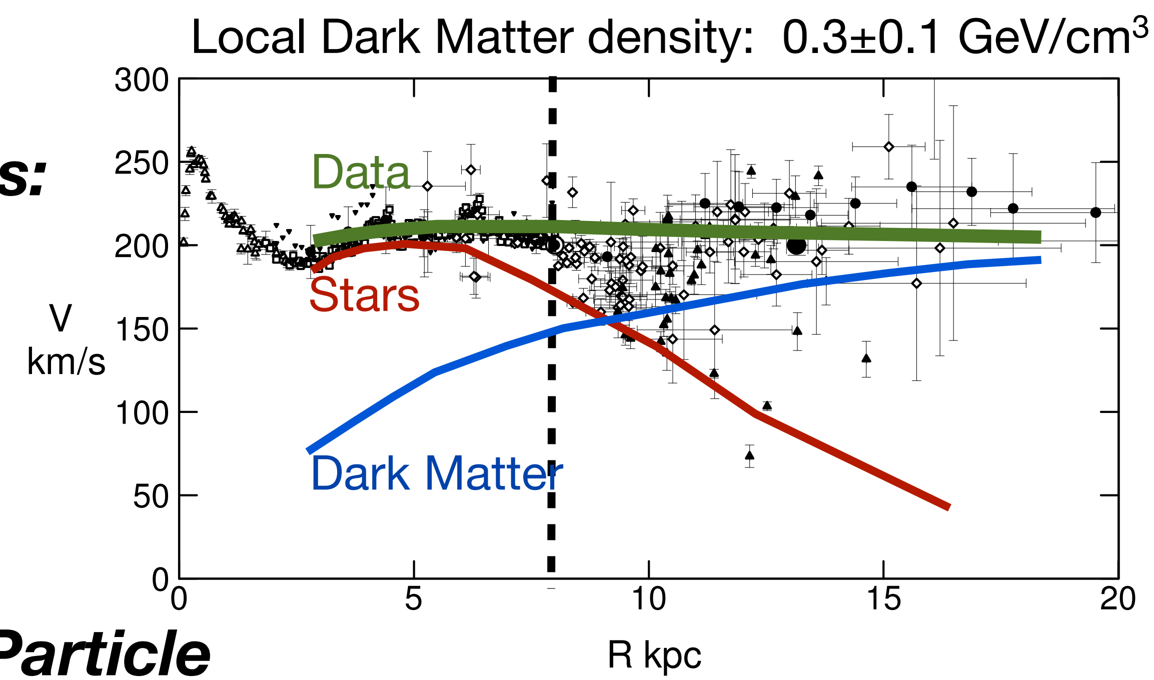
1. Direct Dark Matter detection
2. The SuperCDMS Experiment
3. CDMSLite
4. Low Threshold analysis
5. Neutrino background

Direct detection of Dark Matter



From precision cosmology (CMB, BAO, ...):

~26% of the matter/energy content of the universe if made of non baryonic Dark Matter



From rotation velocity measurement of galaxies:

Spiral galaxies are embedded in Dark Matter halo that outweights the luminous part by a factor ~10

Candidate WIMP: Weakly Interacting Massive Particle

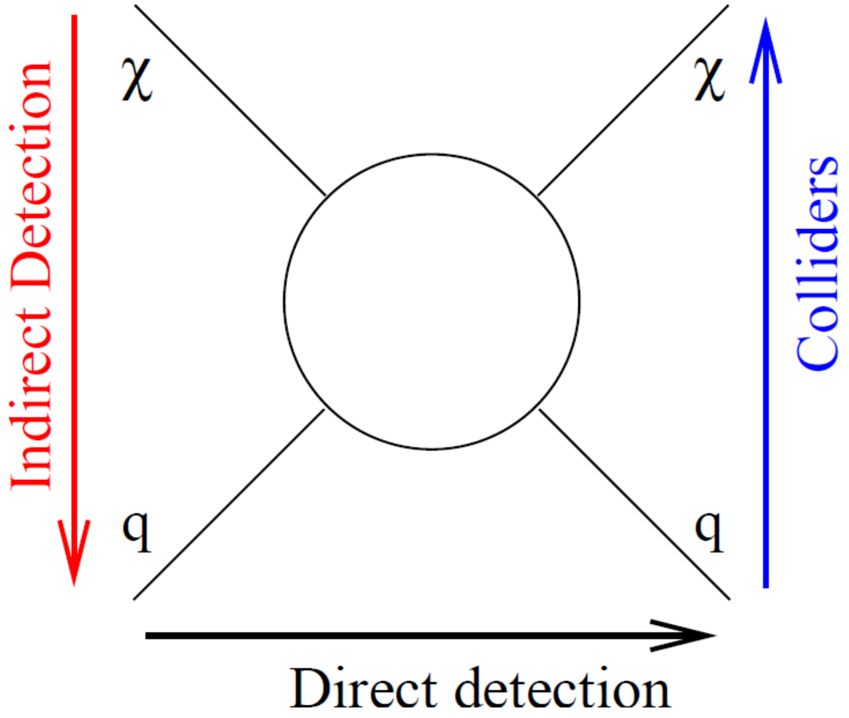
- Stable
- Neutral from charge and color
- Massive GeV - TeV
- Weak interaction

$$\Omega_{WIMP} = \mathcal{O}(1)$$

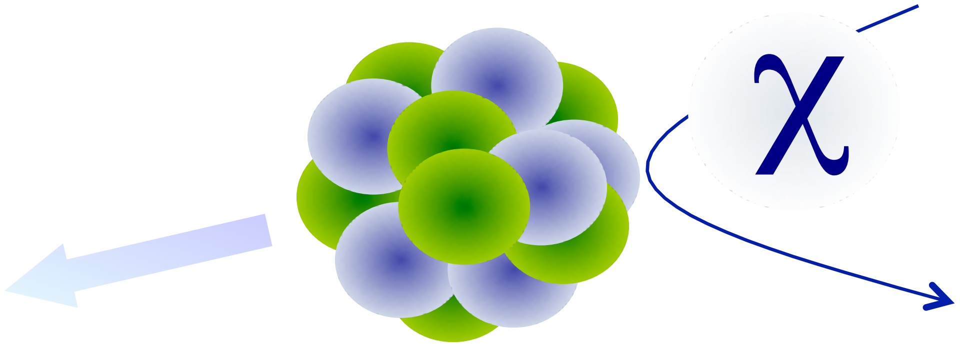
The WIMP miracle

Direct detection of Dark Matter

Dark Matter annihilation

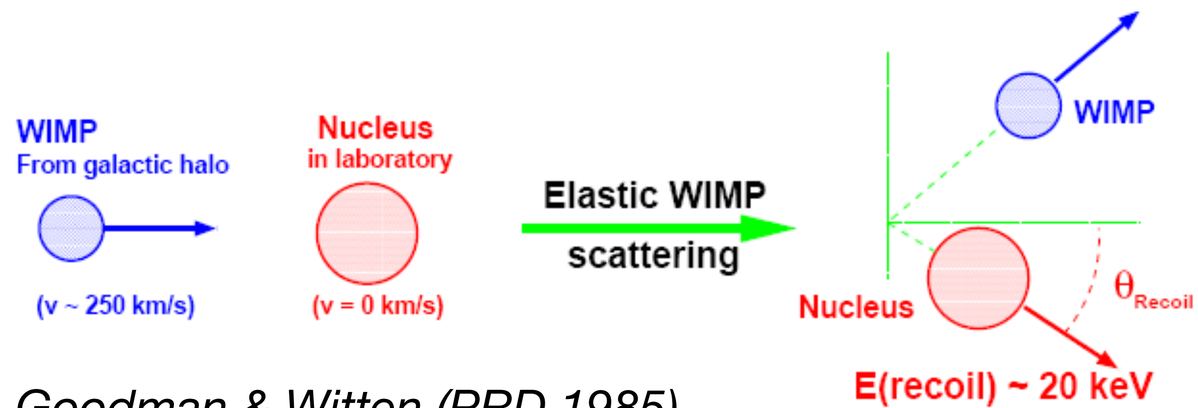


Dark Matter production



WIMP-nucleus elastic scattering

Direct detection of Dark Matter

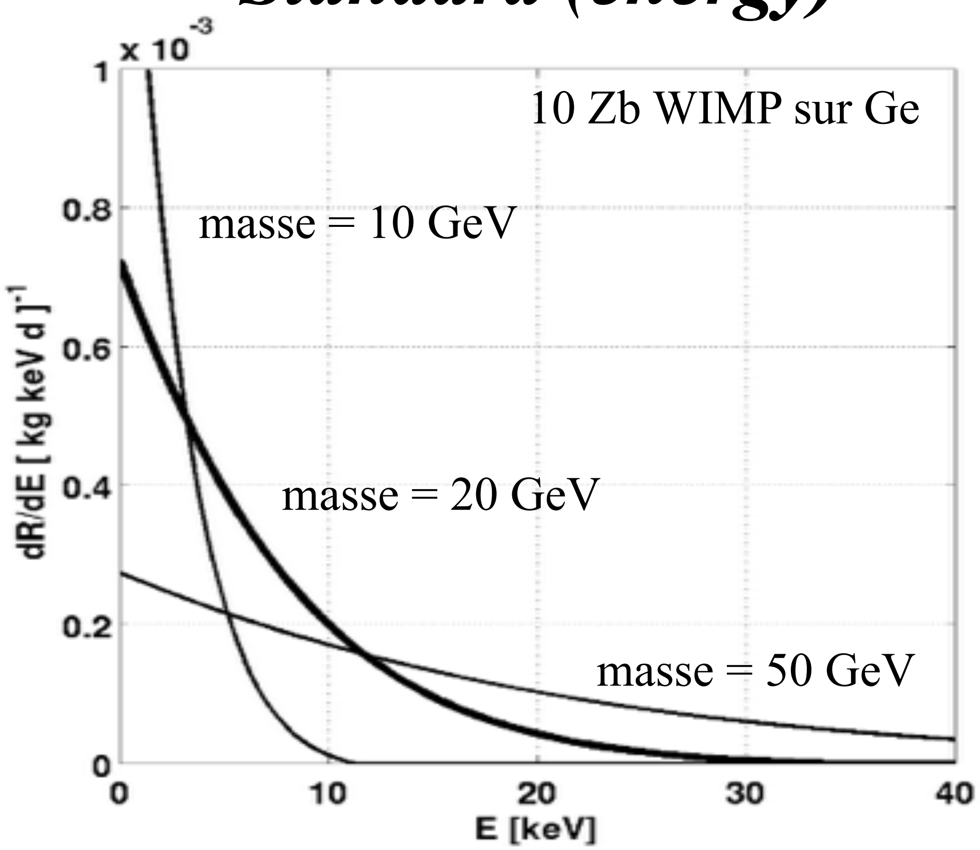


Goodman & Witten (PRD 1985)

Direct detection challenges:

- Low event rate: *R < O(10) evts/kg/year*
- Background reduction: *active + passive*
- Mean recoil energy: ~ *O(10) keV*

Standard (energy)

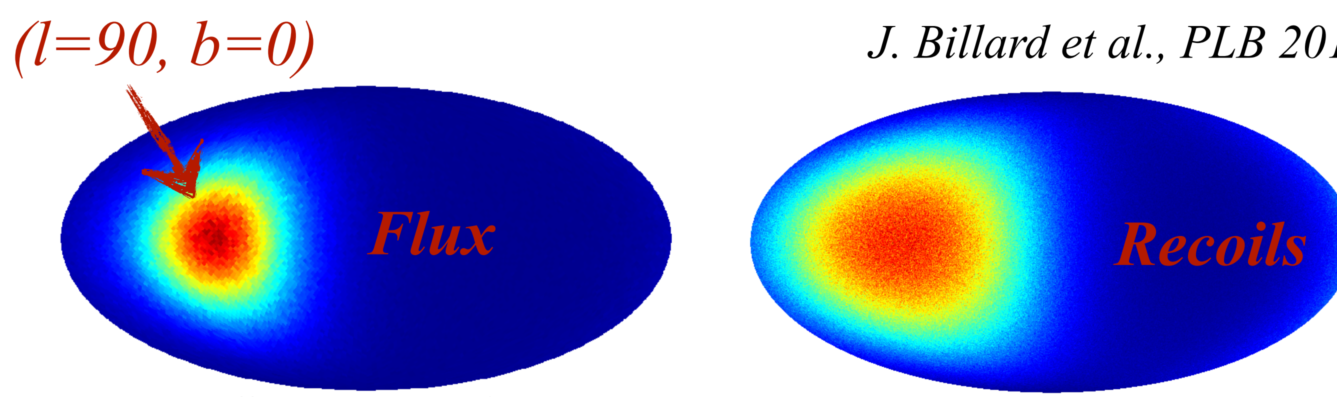


A simple and featureless exponential…

Directional (energy + direction)

Solar System rotation around the Galactic center

J. Billard et al., PLB 2010



Anisotropic WIMP flux inducing an anisotropic recoil distribution in Galactic coordinates

Direction of the nuclear recoils as the ultimate proof of a Dark Matter detection

The SuperCDMS experiment

California Inst. of Tech. | CNRS-LPN | FNAL | Mass. Inst. of Tech. | NIST Inst. of Tech.

PNNL | Queen's University | SLAC | Southern Methodist U. | Santa Clara University

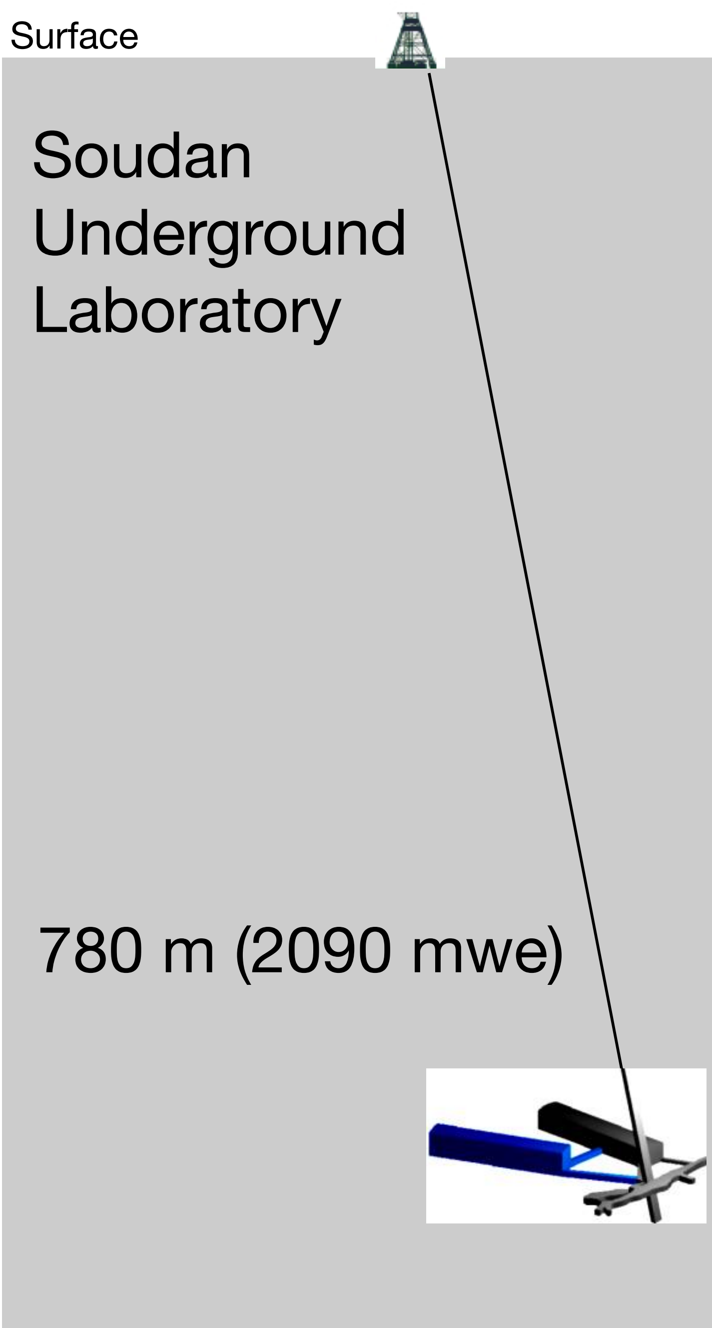
South Dakota SM&T | Stanford University | Texas A&M University | U. Autónoma de Madrid | U. British Columbia

U. California, Berkeley | U. Colorado Denver | U. Evansville | U. Florida | U. Minnesota | U. South Dakota

21 institutions

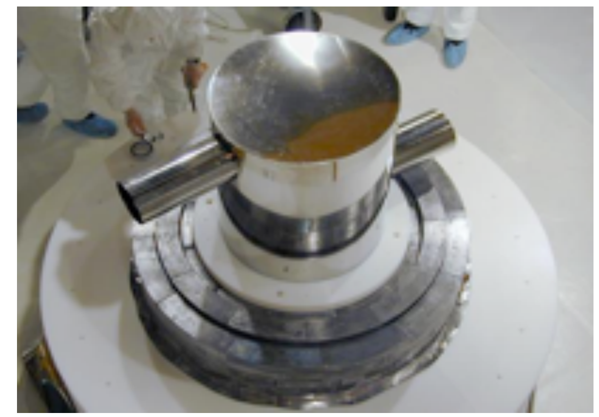
http://cdms.berkeley.edu

The SuperCDMS experiment

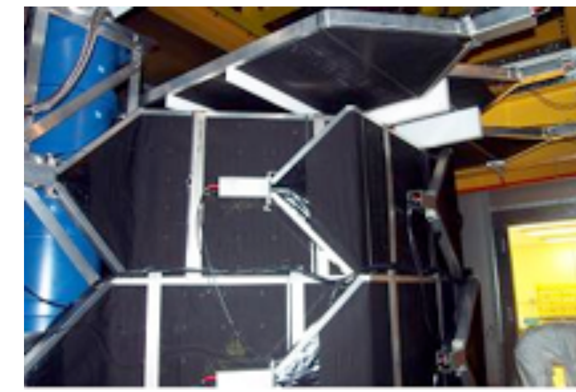


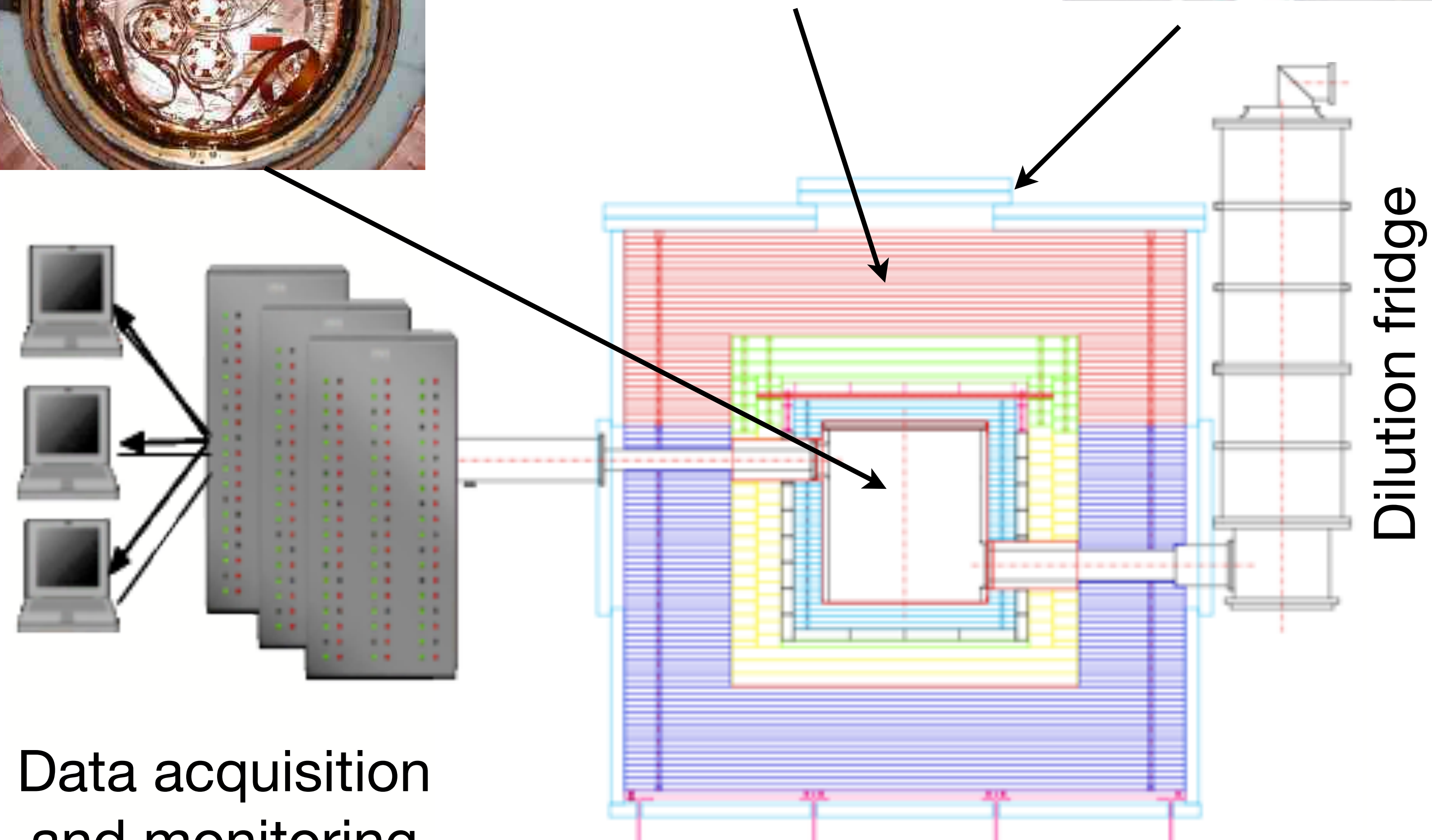
«The Icebox»
base temp. ~ 50 mK

Poly and lead shielding



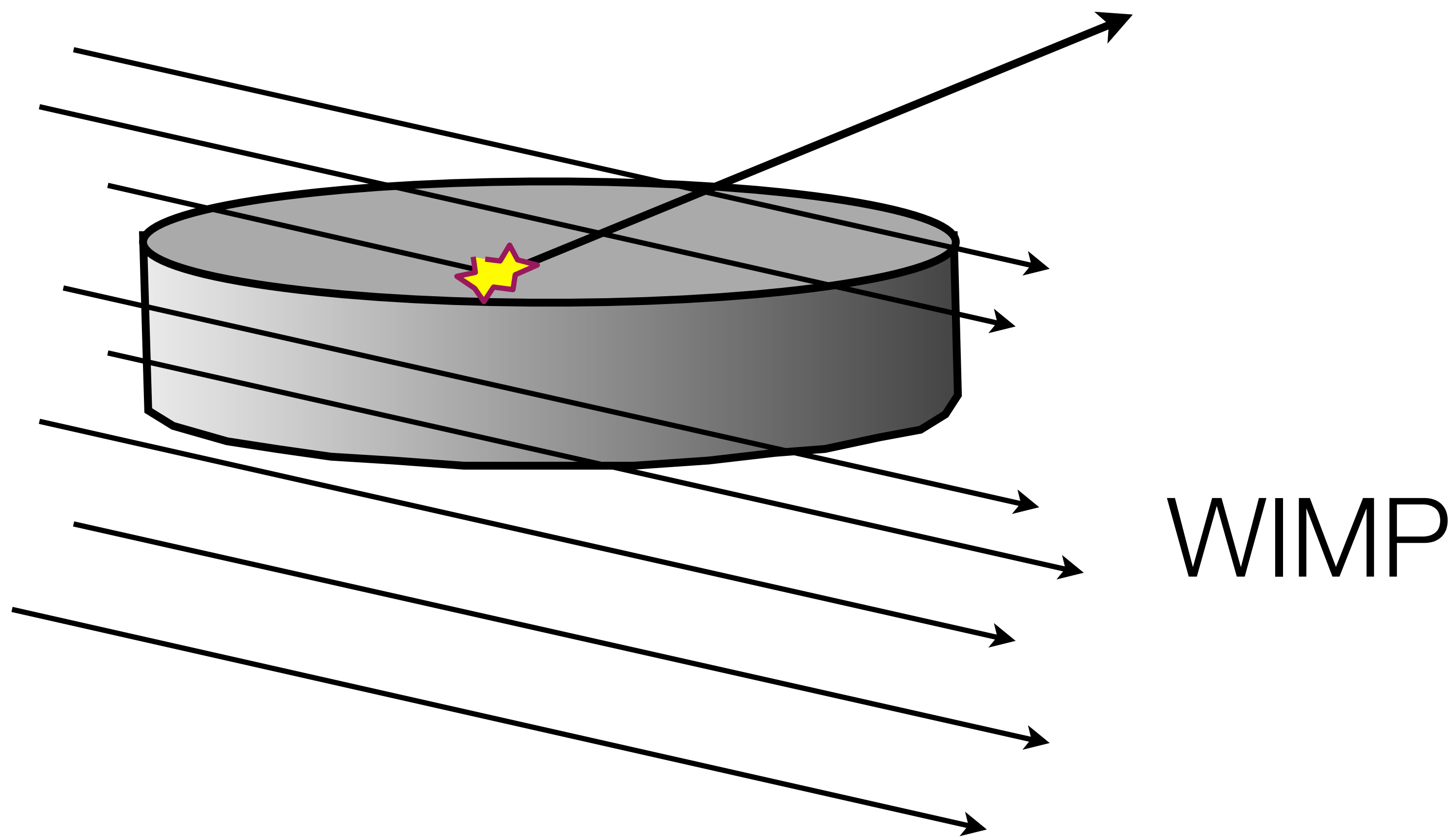
Muon veto





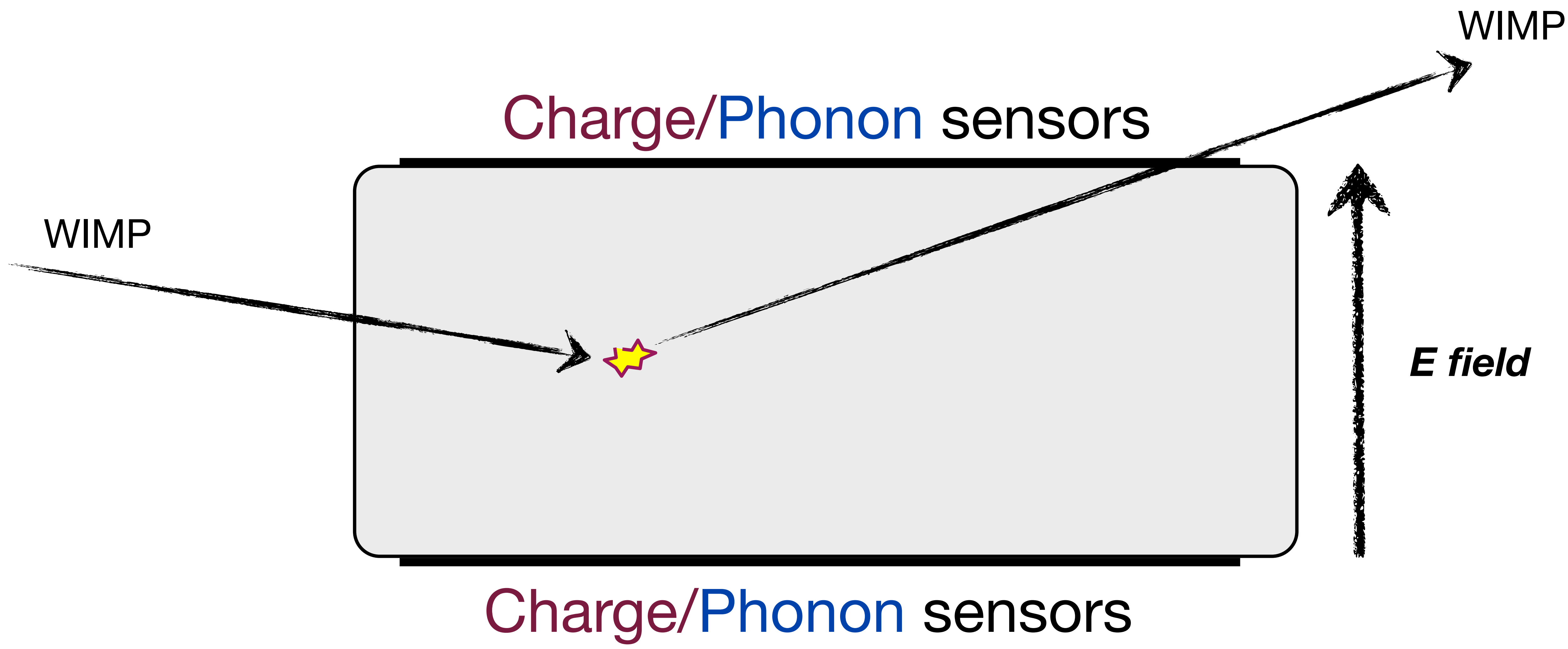
Data acquisition
and monitoring

The SuperCDMS experiment

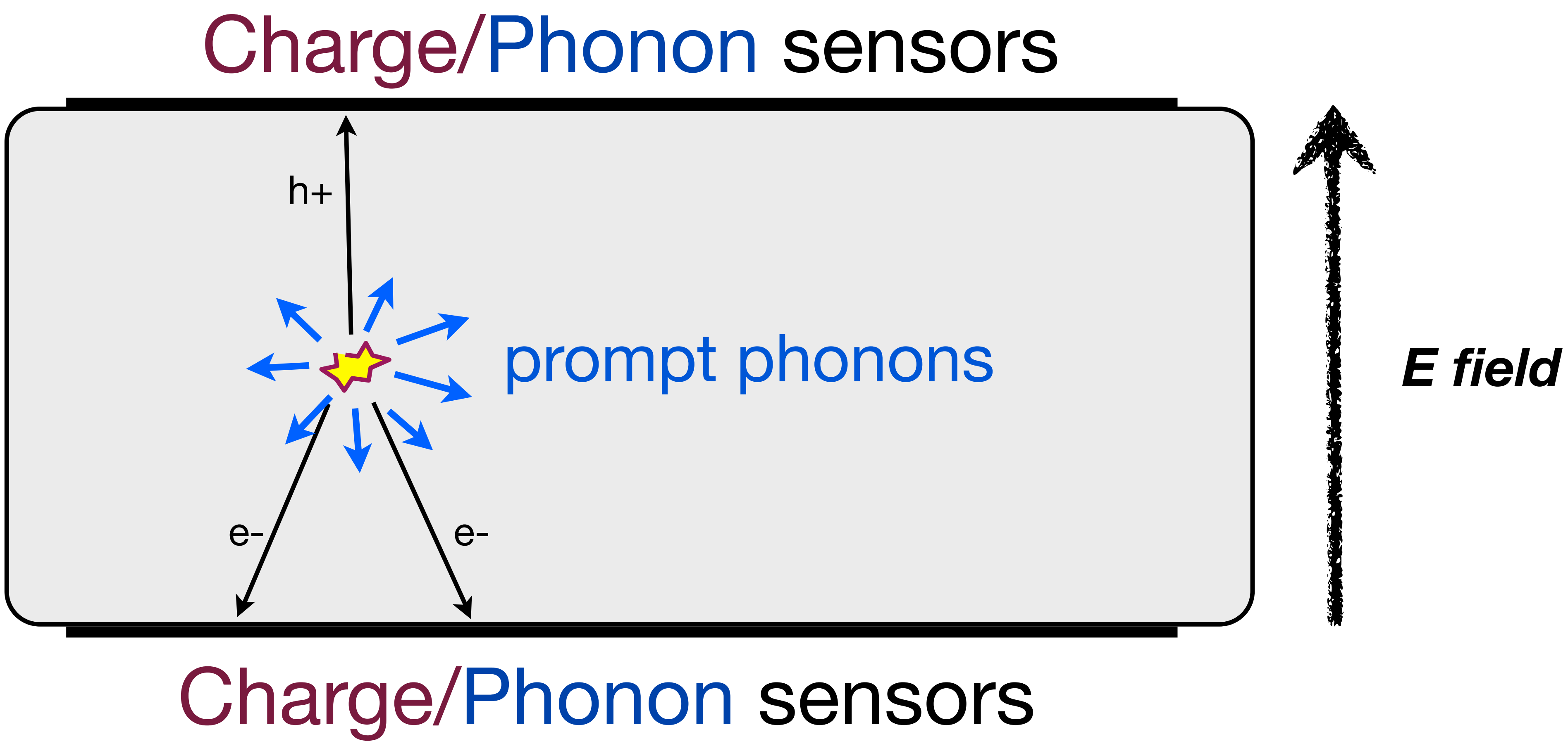


Cryogenic semiconductor detectors looking for WIMPs

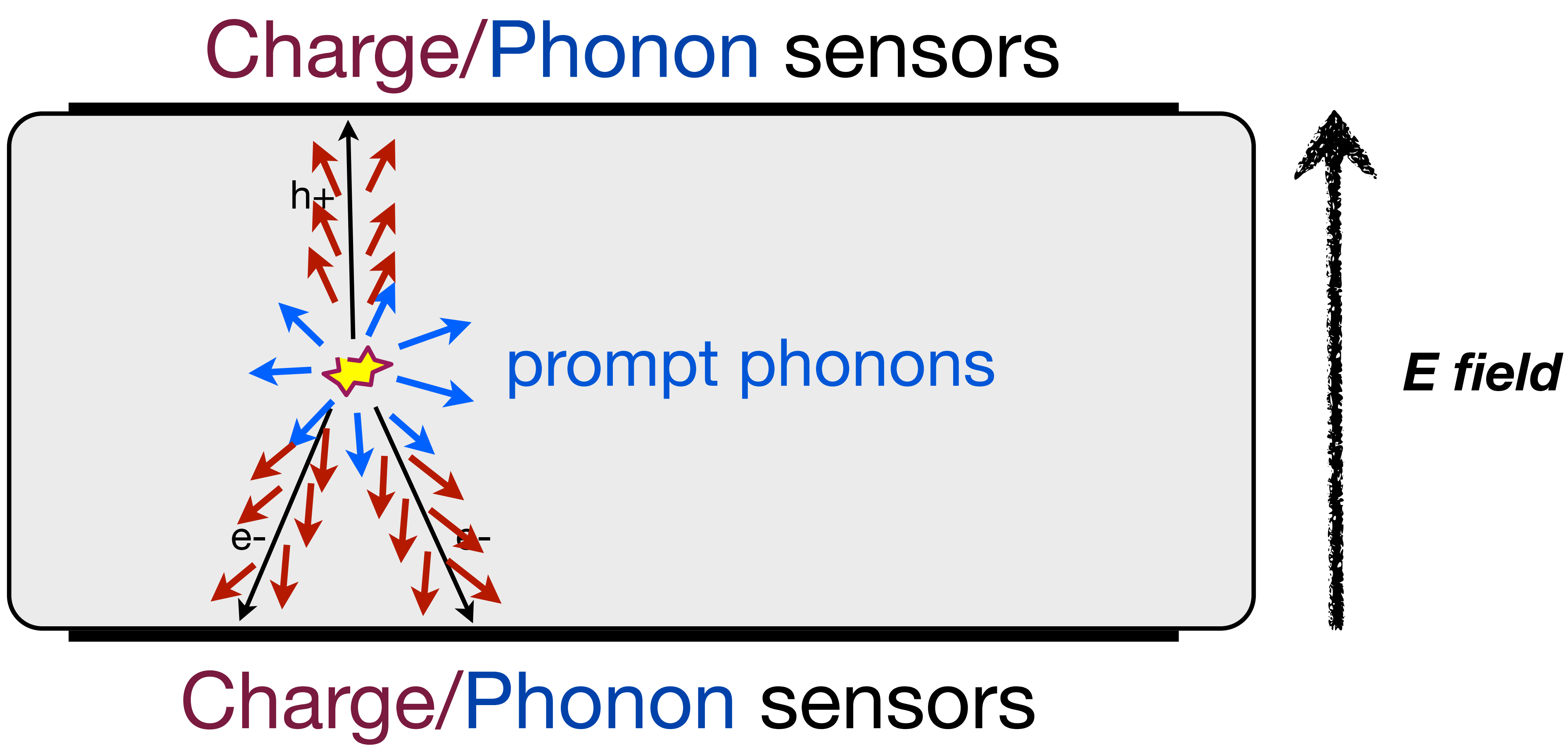
The SuperCDMS experiment



The SuperCDMS experiment



The SuperCDMS experiment



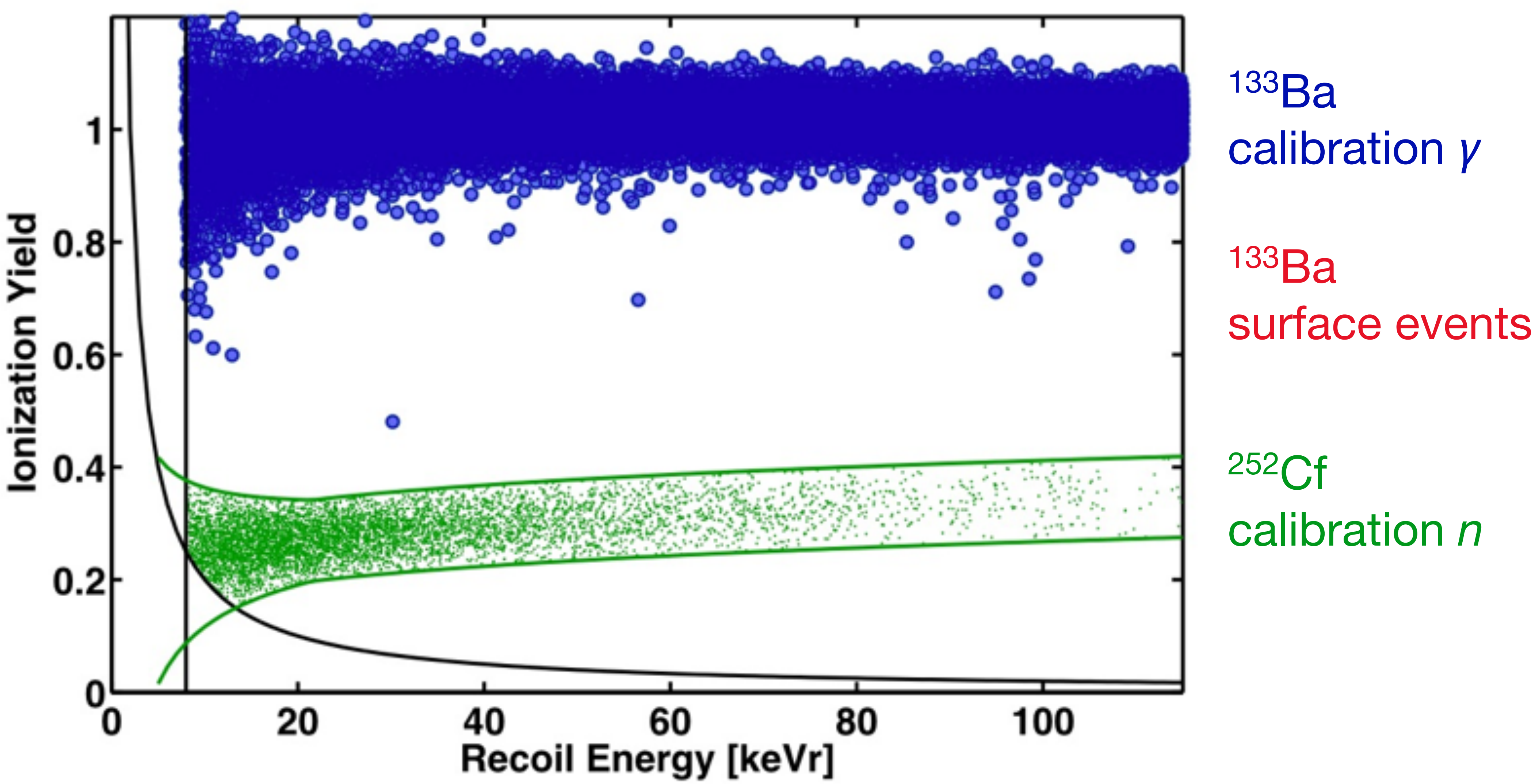
$$E_{total} = E_{recoil} + E_{luke}$$
$$= E_{recoil} + \frac{1}{3\,eV} E_Q \Delta V$$

The SuperCDMS experiment

Electron recoils have a **higher ionization yield** than nuclear recoils

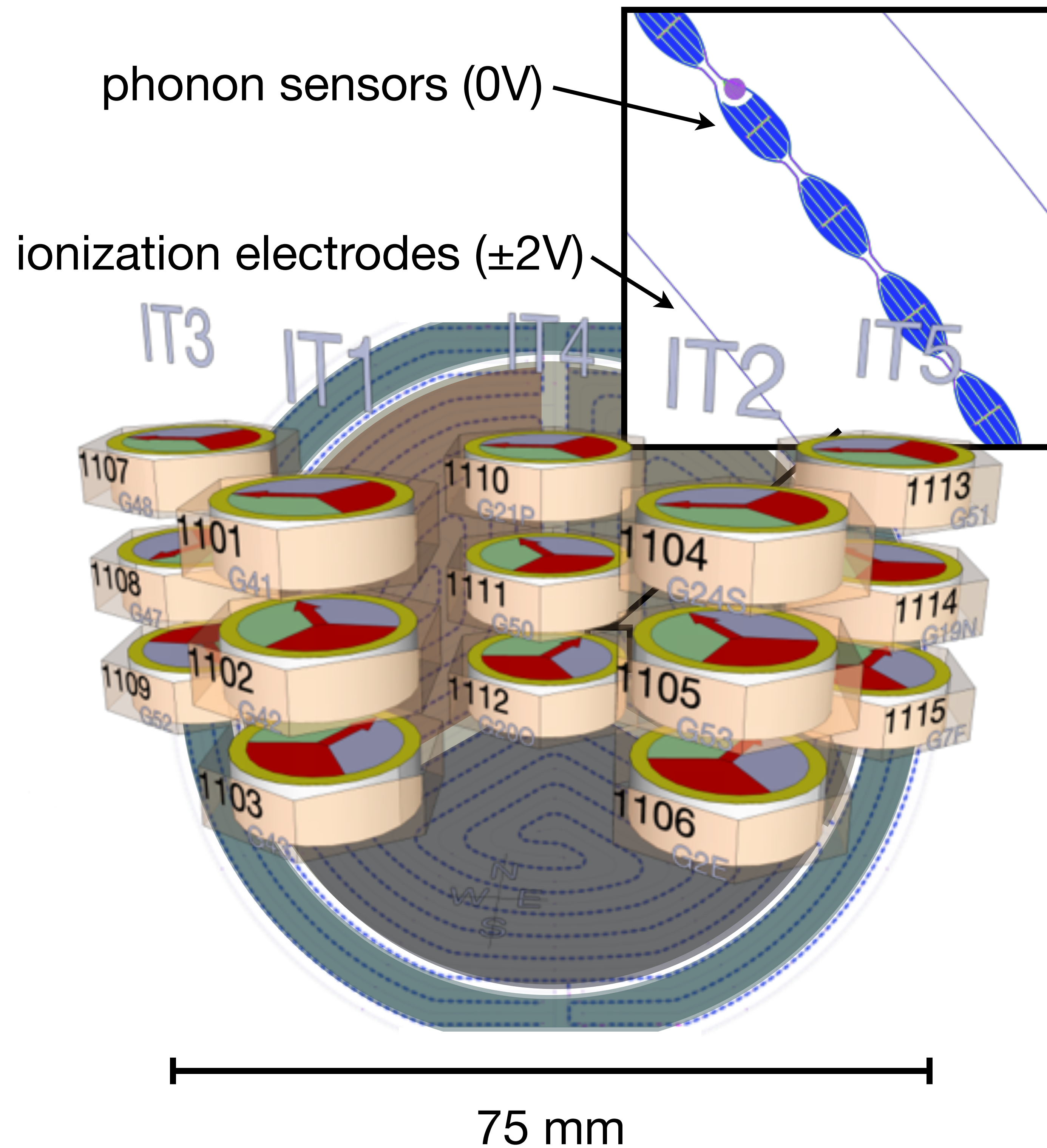
Surface events have a **reduced ionization yield** and can mimic nuclear recoils

$$Y = E_q / E_r$$



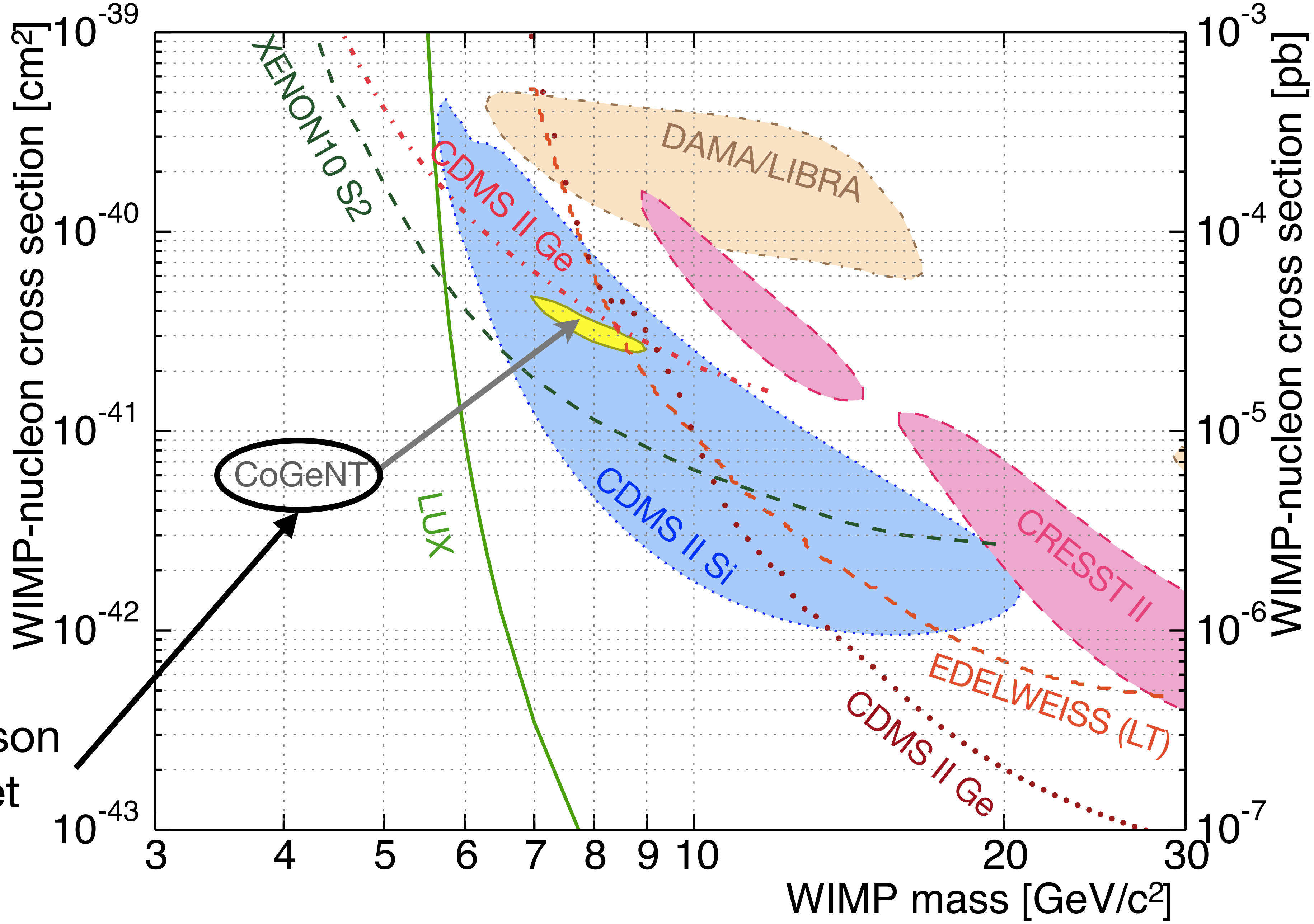
The SuperCDMS experiment

- Upgrade from CDMS II, in continuous operation since spring 2012 at Soudan Underground Laboratory
- 600g Germanium detectors measure ionization and non-equilibrium phonons
- interleaved sensors reject surface events
- ionization guard rejects sidewall events
- phonon channels reject sidewall events, provide 3D position estimators
- 15 detectors = 9 kg target mass



Low-mass Region (without SuperCDMS)

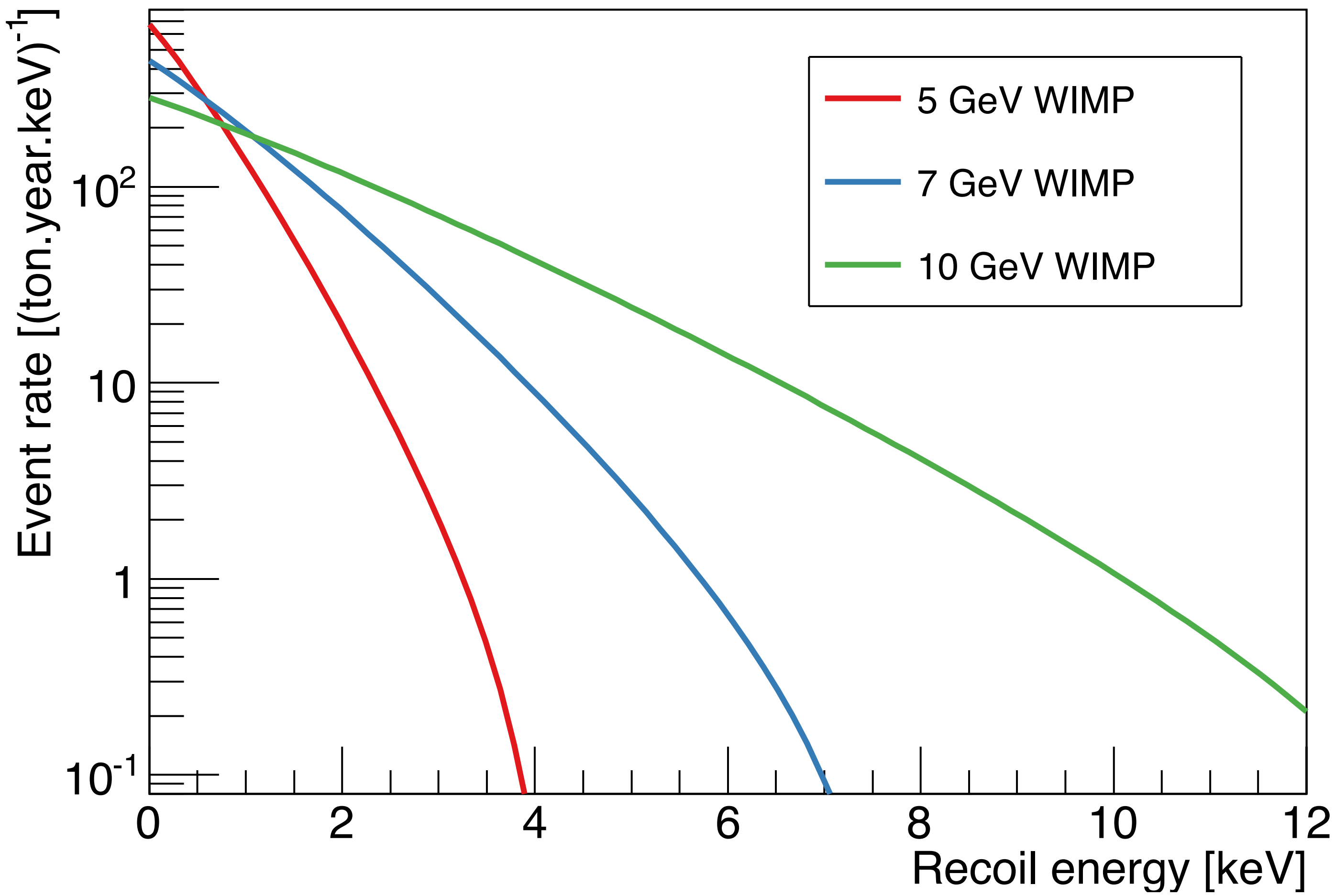
What can we say about low-mass dark matter “hints”?



direct comparison with Ge target

Strategies for Light WIMP Searches

Lowering the energy threshold is the key for light WIMP searches



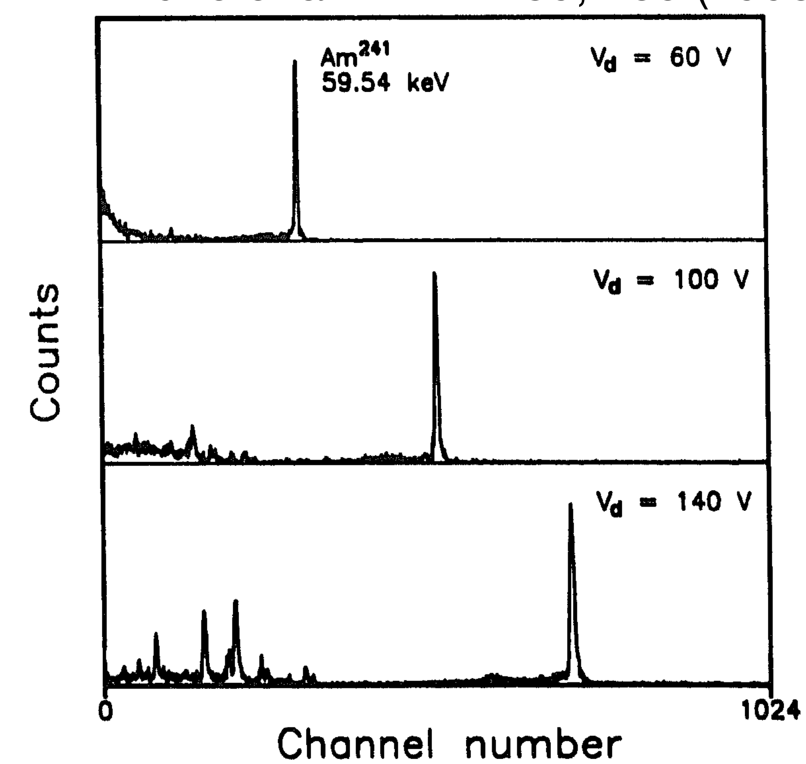
1. CDMSLite: Amplification of the signal to reduce the effective threshold

CDMSlite: “low ionization threshold experiment”

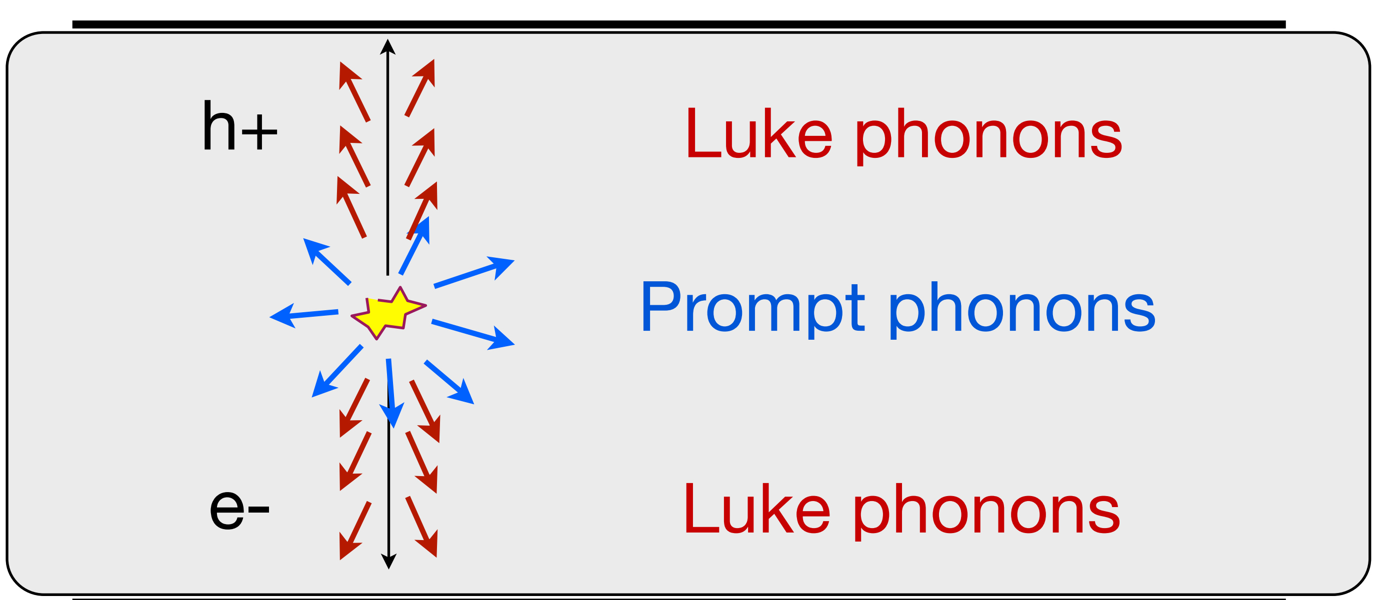
$$E_{total} = E_{recoil} + E_{luke}$$
$$= E_{recoil} + \frac{1}{3\,eV} E_Q \Delta V$$

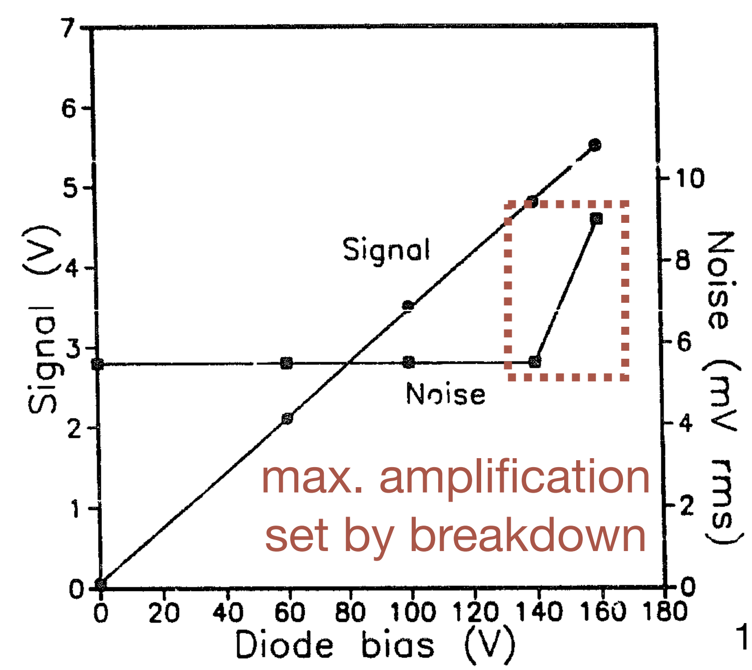
- Measure charge with phonons, and increase voltage to amplify signal
- Lose background discrimination, but achieve lower ionization energy threshold

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



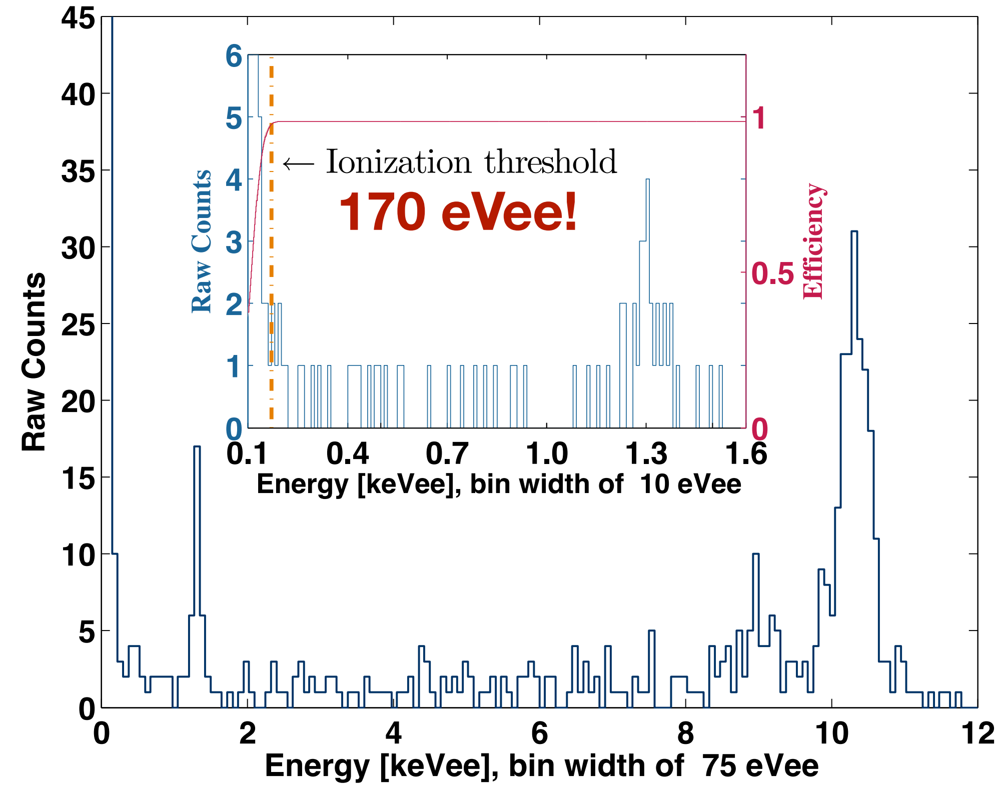
69V



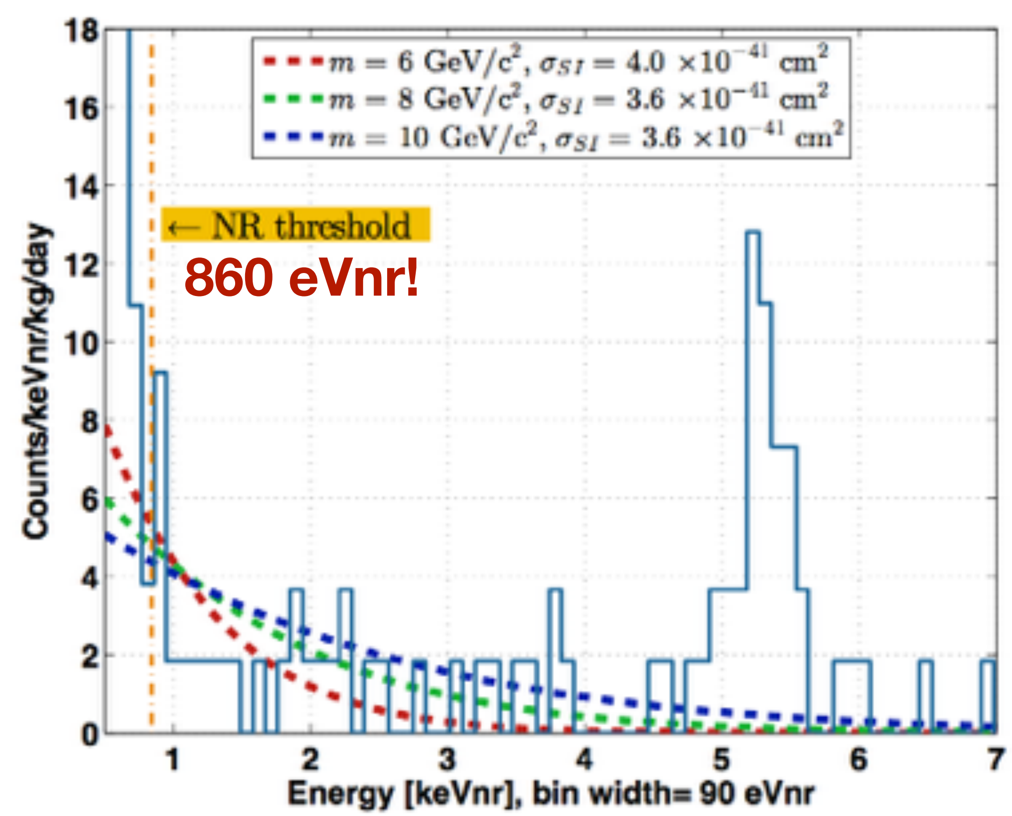


CDMSlite: Run 1

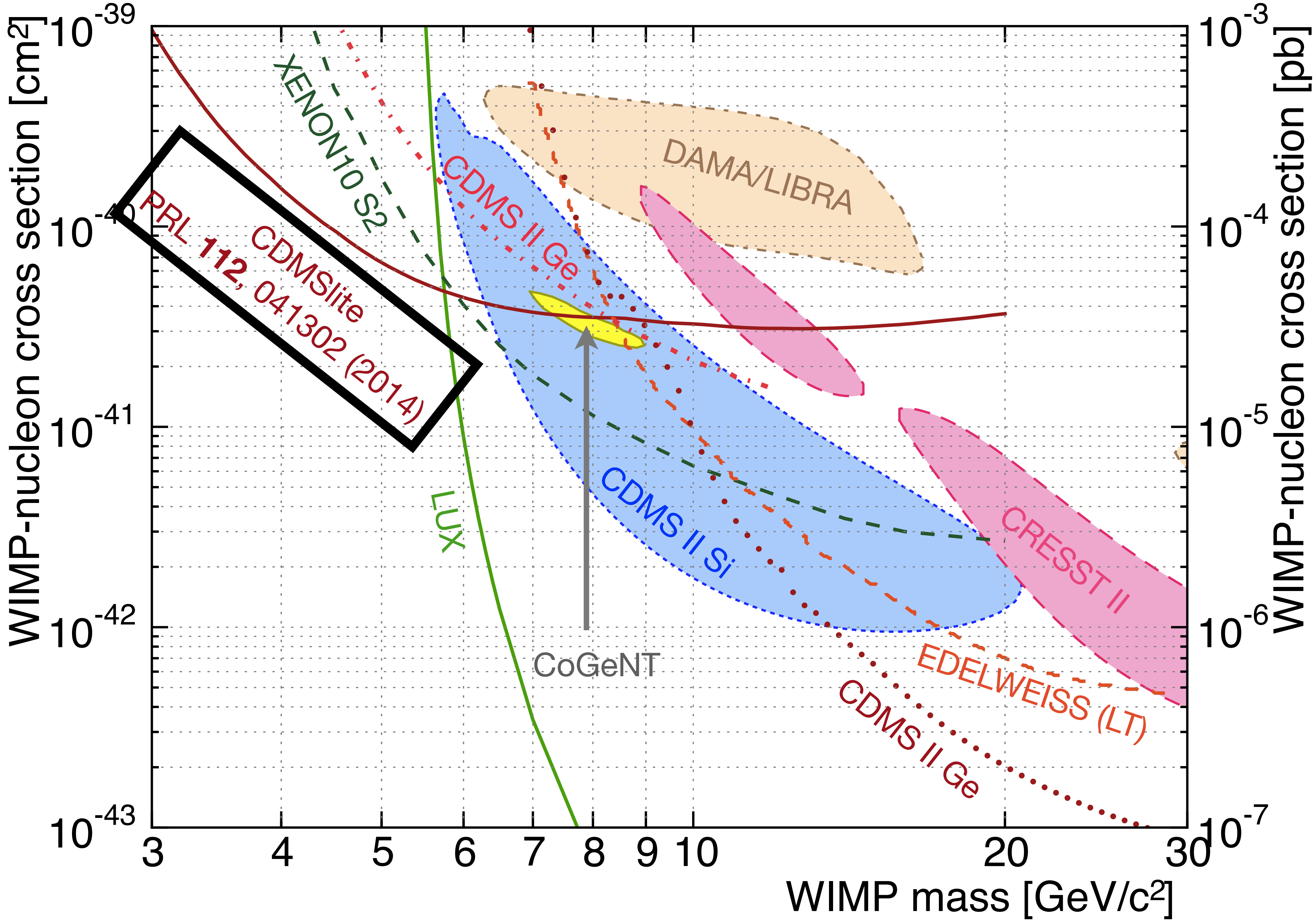
- Operated stably at 69V or **24x** amplification (only 12x due to electronics limitations) for 2 weeks
- Acquired 6 kg-days
- Ionization energy calibration with EC lines at 1.3 keVee and 10.4 keVee



- Must assume NR energy scale
- 170 eVee threshold => 860 eVnr
- **Great sensitivity to 6 GeV WIMP!**



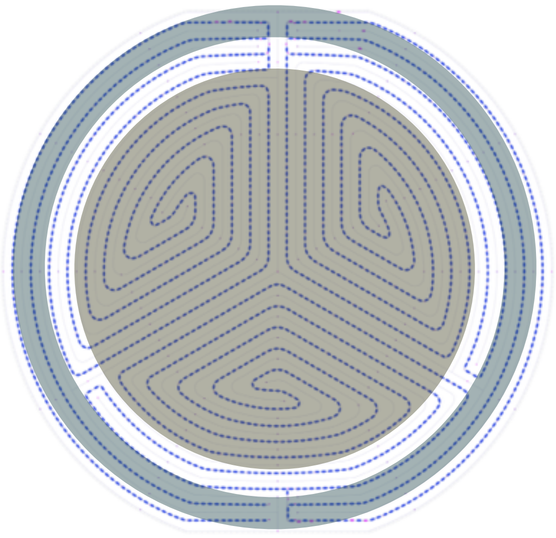
CDMSlite: Run 1 Results



CDMSLite: what's next?

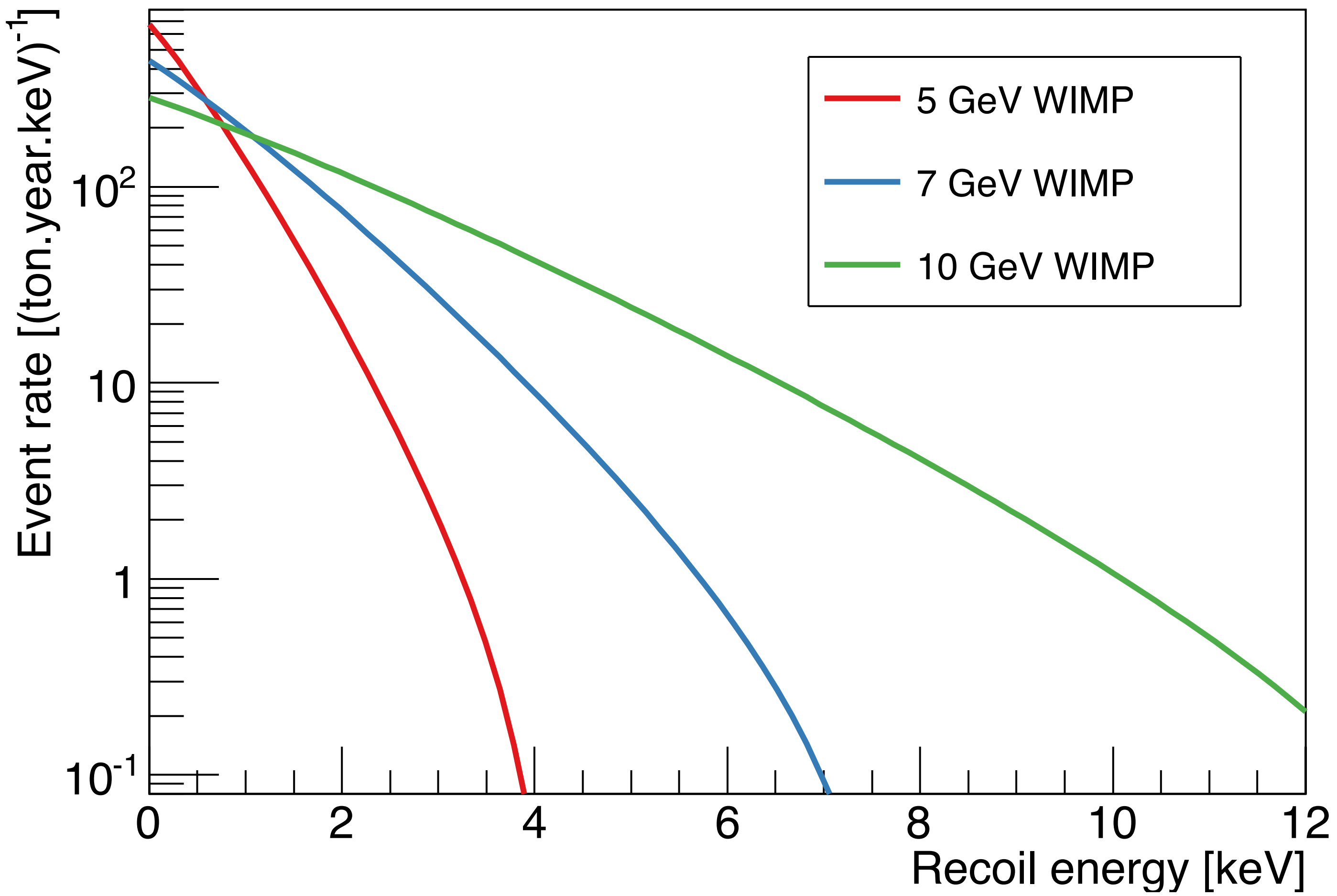
	Run 2	**Run 1**
raw exposure	4 months	15 days
baseline noise	8.3 eVee	13.3 eVee
resolution @ 1.3 eVee	30 eVee	50 eVee
threshold	80 eVee (preliminary)	170 eVee
background discrimination	reject sidewall surface events	none

CDMSlite can also use radial phonon info to reject backgrounds!



Strategies for Light WIMP Searches

Lowering the energy threshold is the key for light WIMP searches



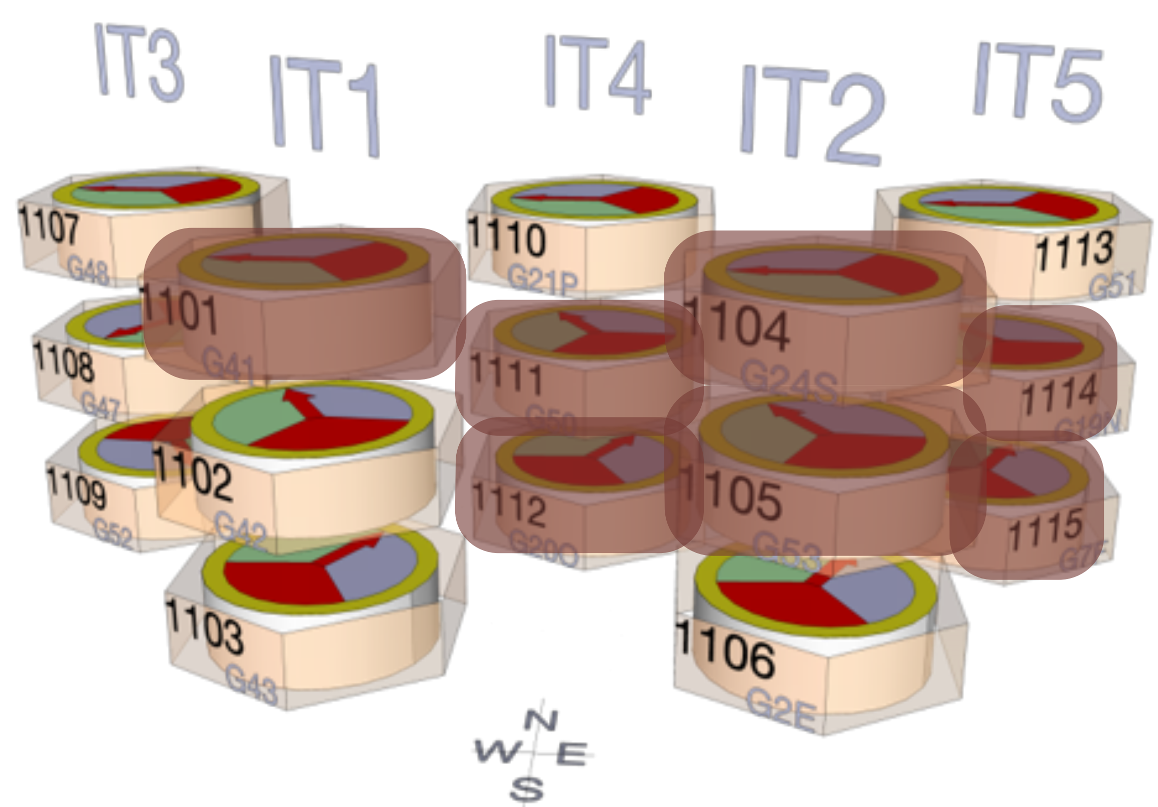
1. CDMSLite: Amplification of the signal to reduce the effective threshold

2. Low Threshold analysis: Improve exposure and extend background ID to low energy

Low Threshold analysis

Lowering the analysis thresholds down to the experiment's trigger thresholds

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

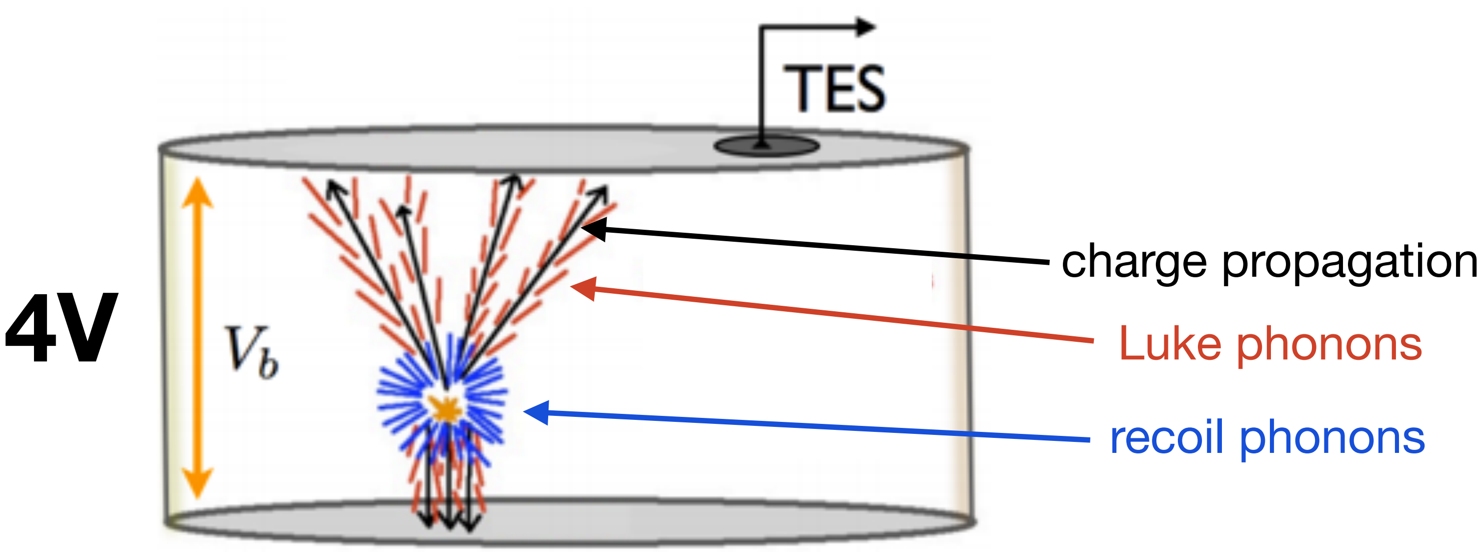


Calibration and Energy Scale

$$E_t = E_r + E_L$$

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

- Fit mean ionization energy as a function of total phonon energy for nuclear recoils
- Systematic uncertainties propagated into final limit using a MCMC approach
- Most detectors consistent with or slightly below Lindhard



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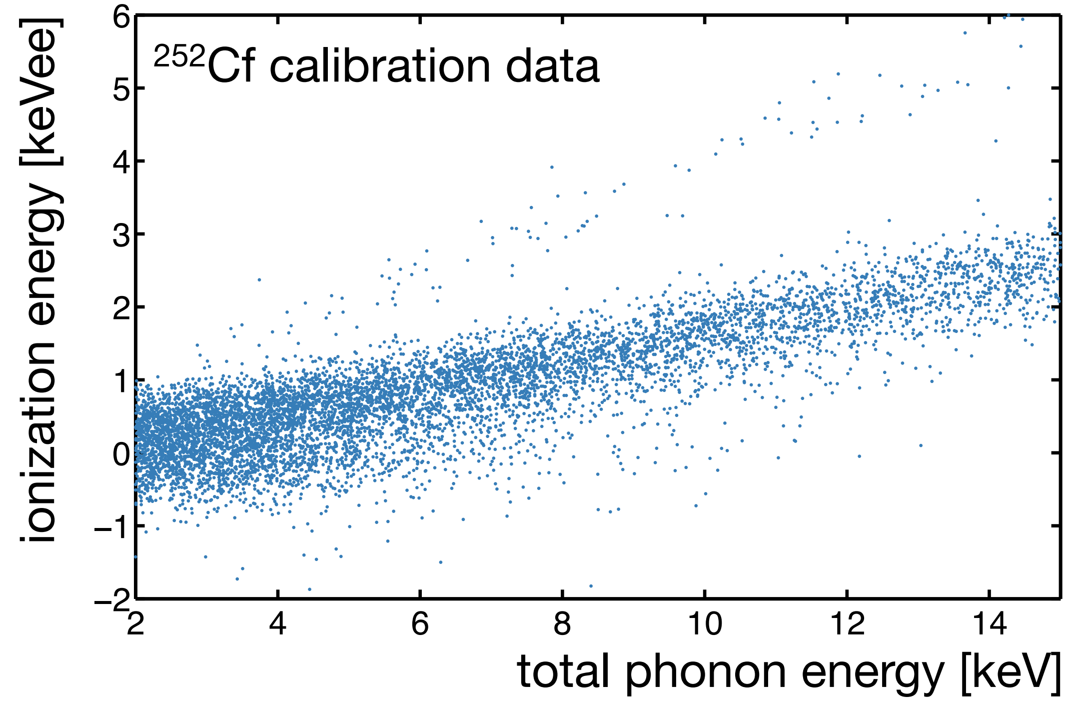
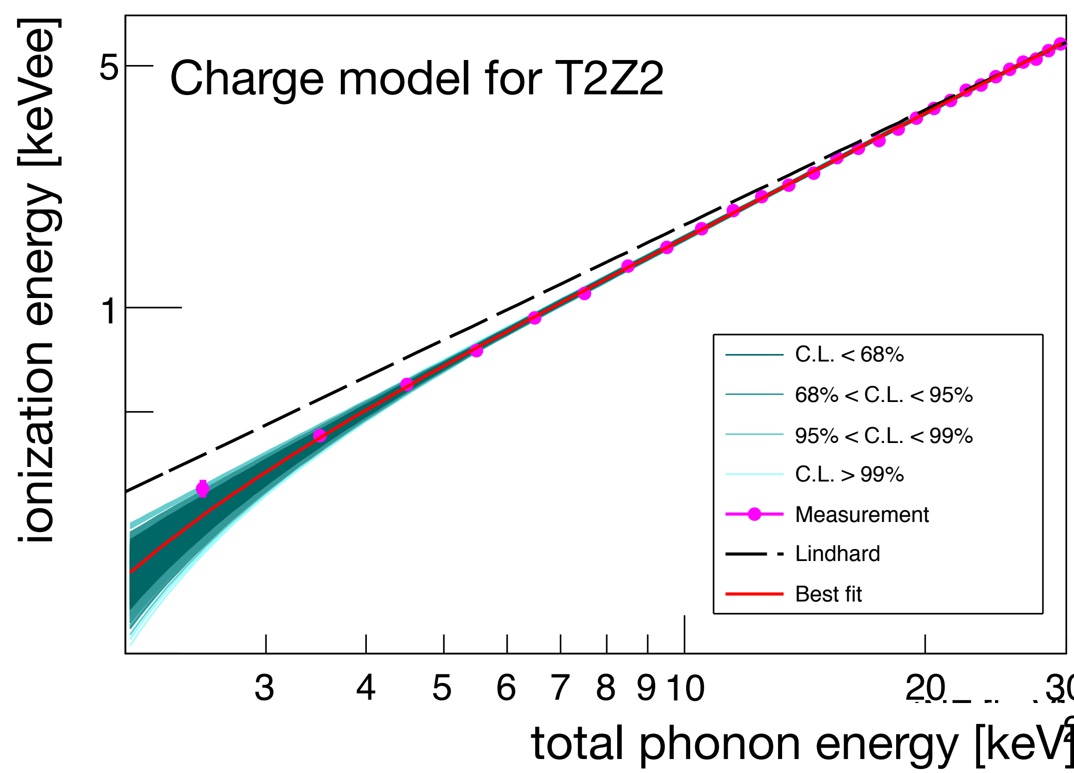
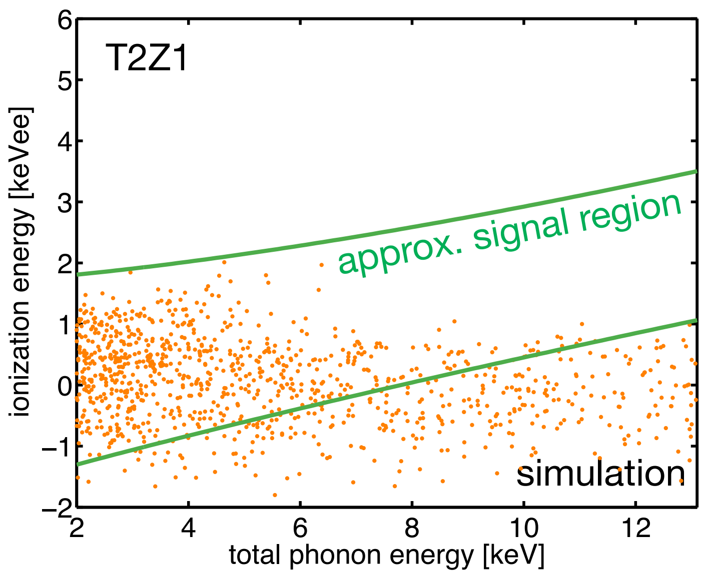


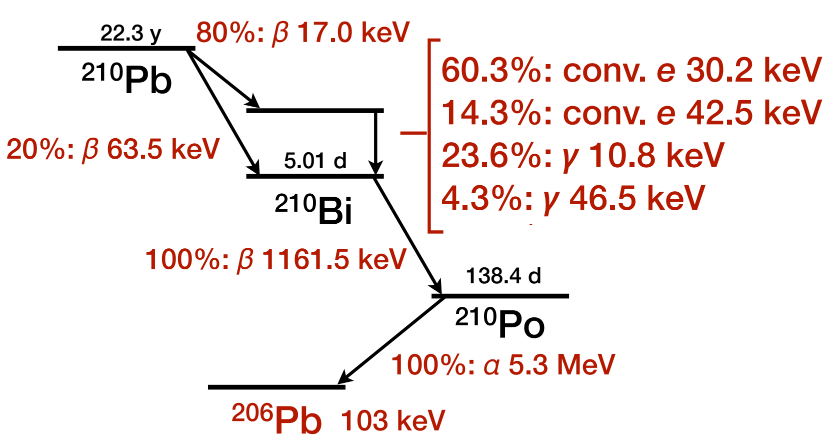


Low Threshold analysis

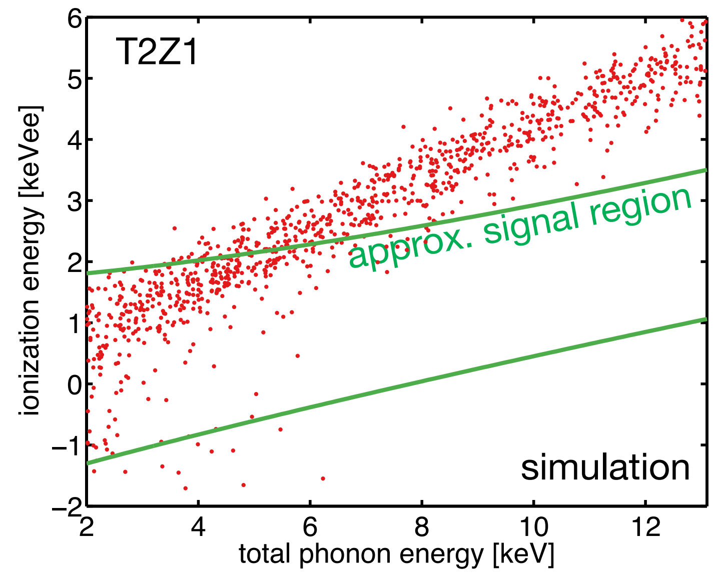
^{210}Pb "surface events"



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

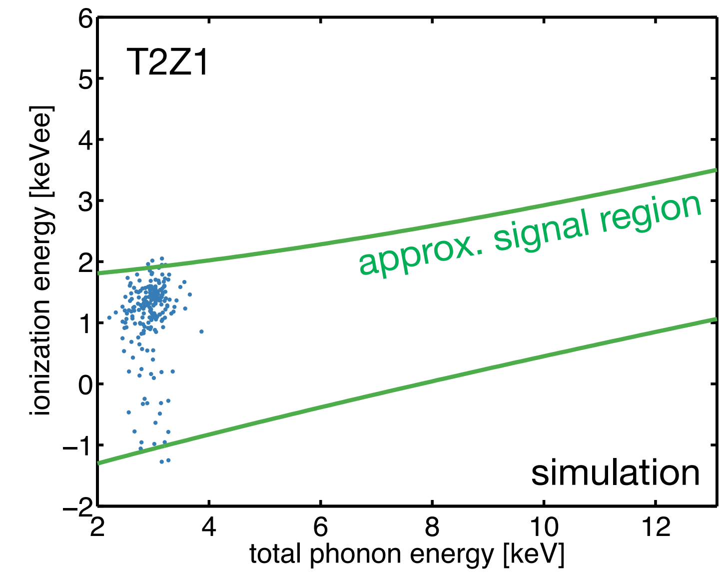


External gammas

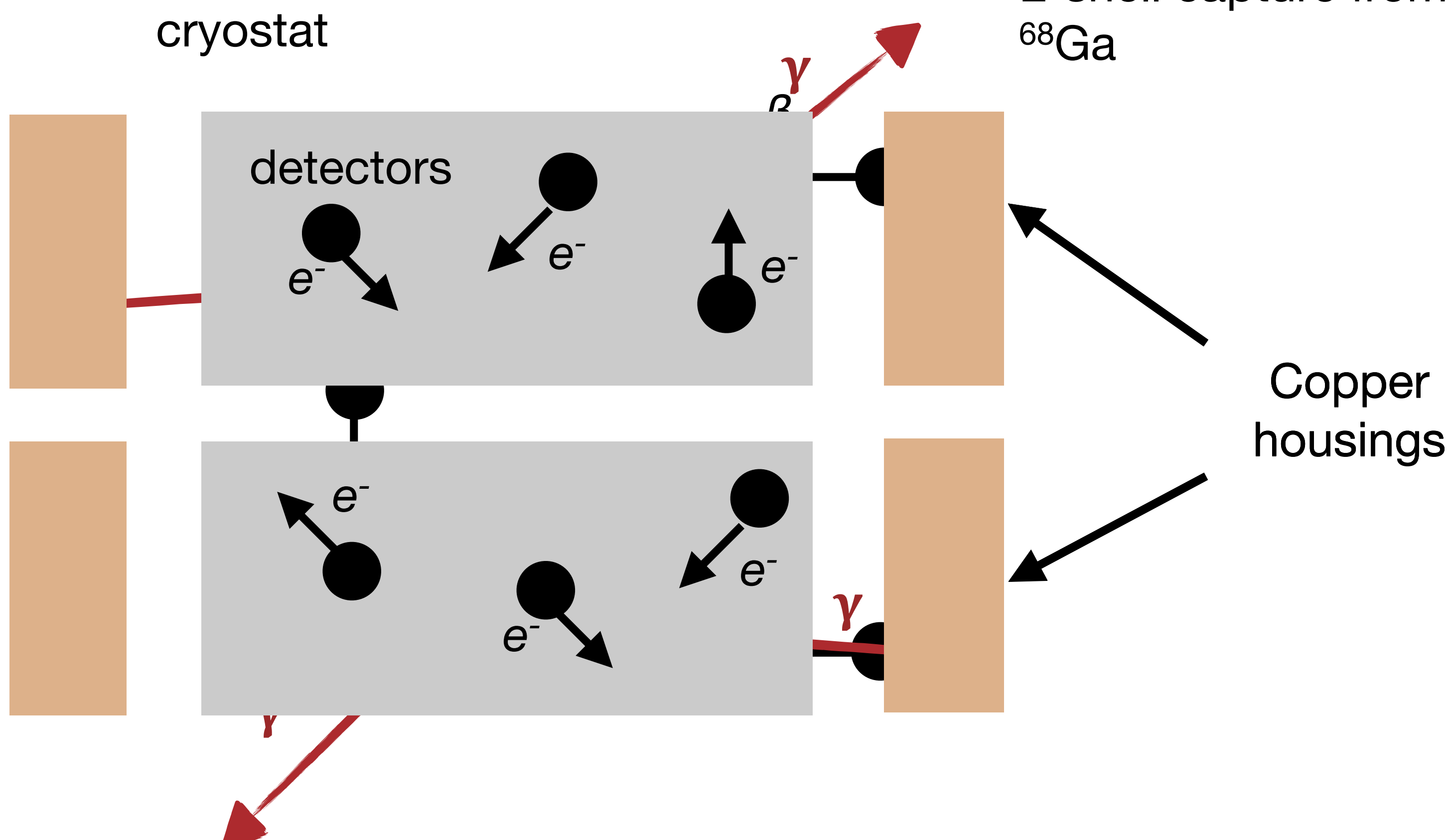


- from radioactivity in shielding and cryostat

Internal activation lines

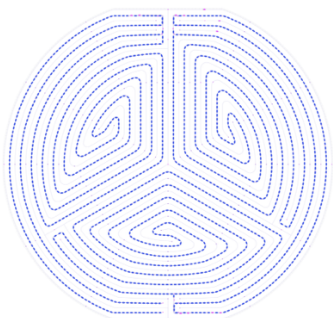


- L-shell capture from ^{68,71}Ge, ^{65}Zn, ^{68}Ga

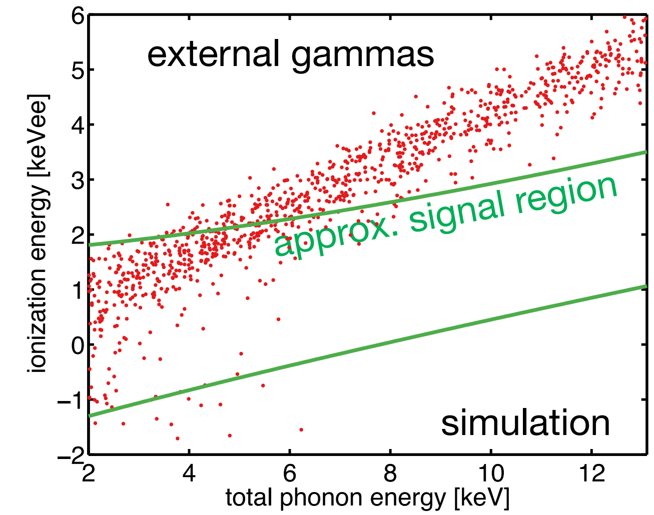


Low Threshold analysis

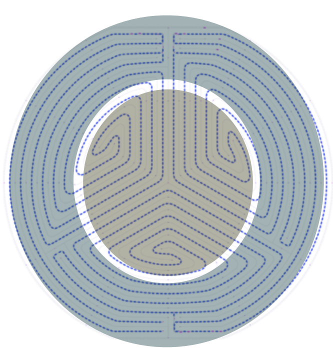
- Total phonon energy
- Ionization energy



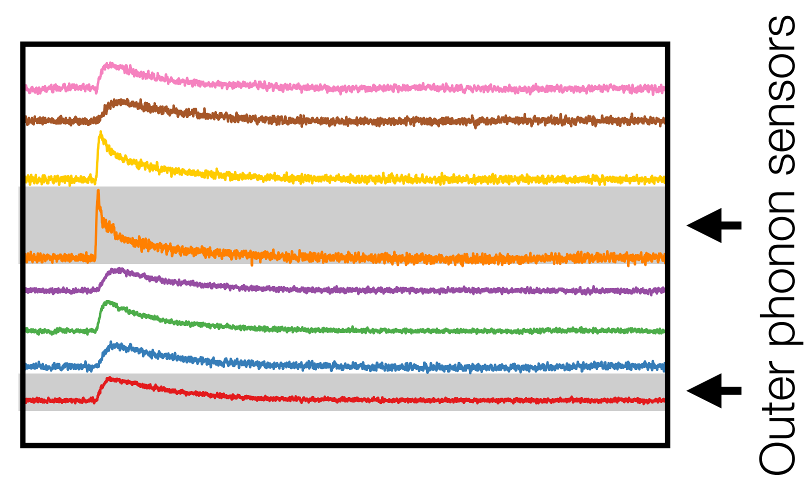
Bulk electron recoils



- Phonon « r-partition »

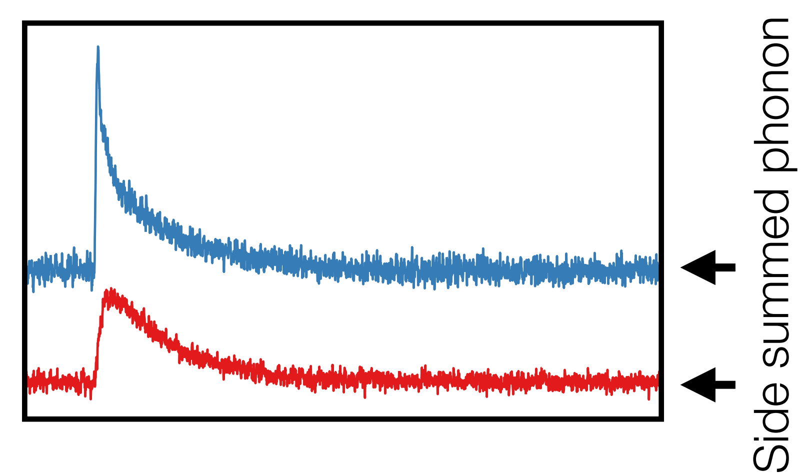


Low energy sidewall events



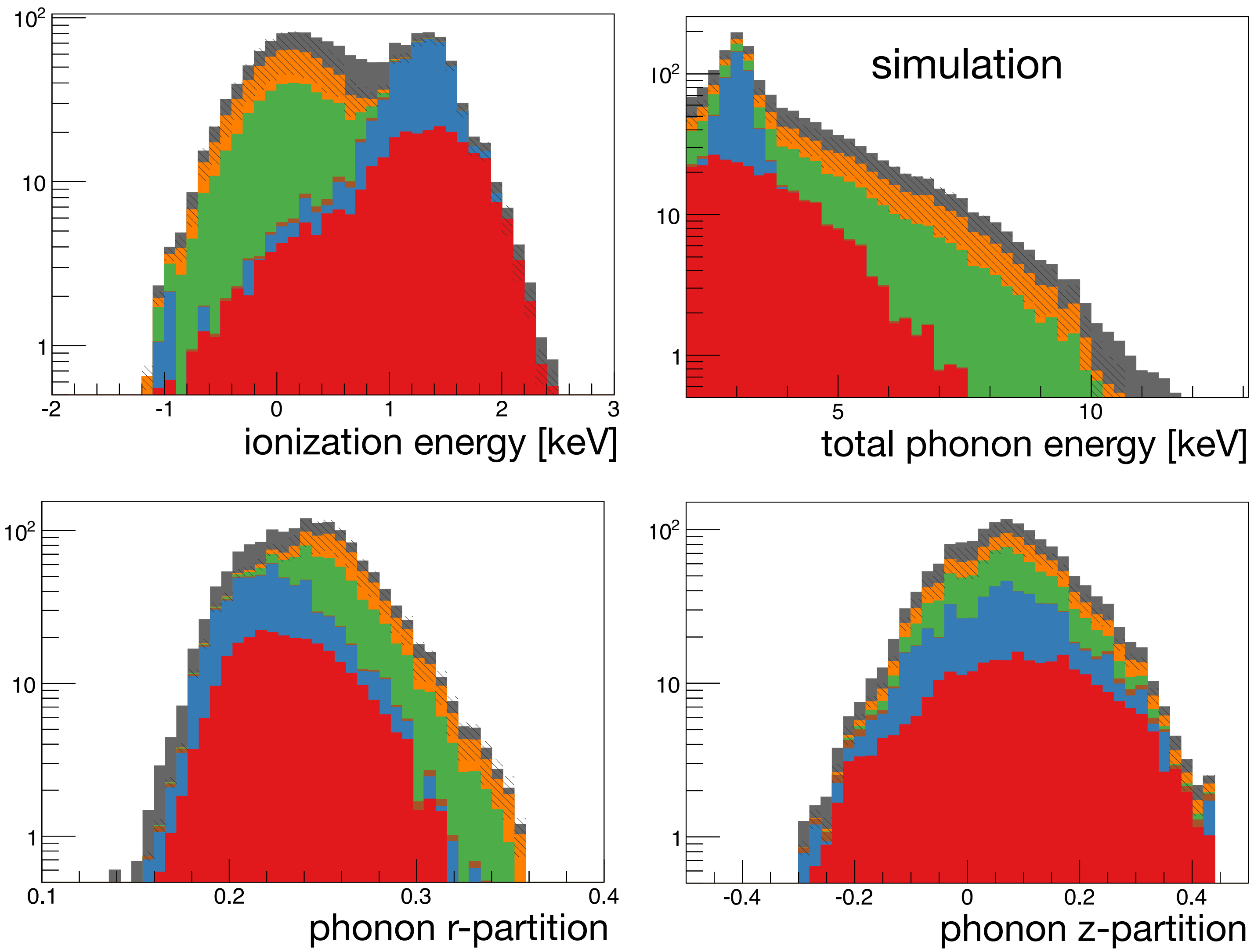
- Phonon « z-partition »

Low energy surface events

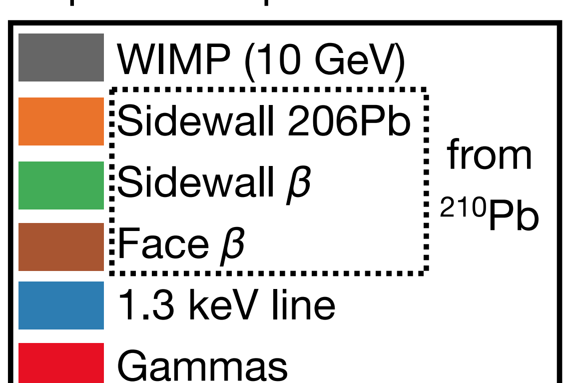


Low Threshold analysis

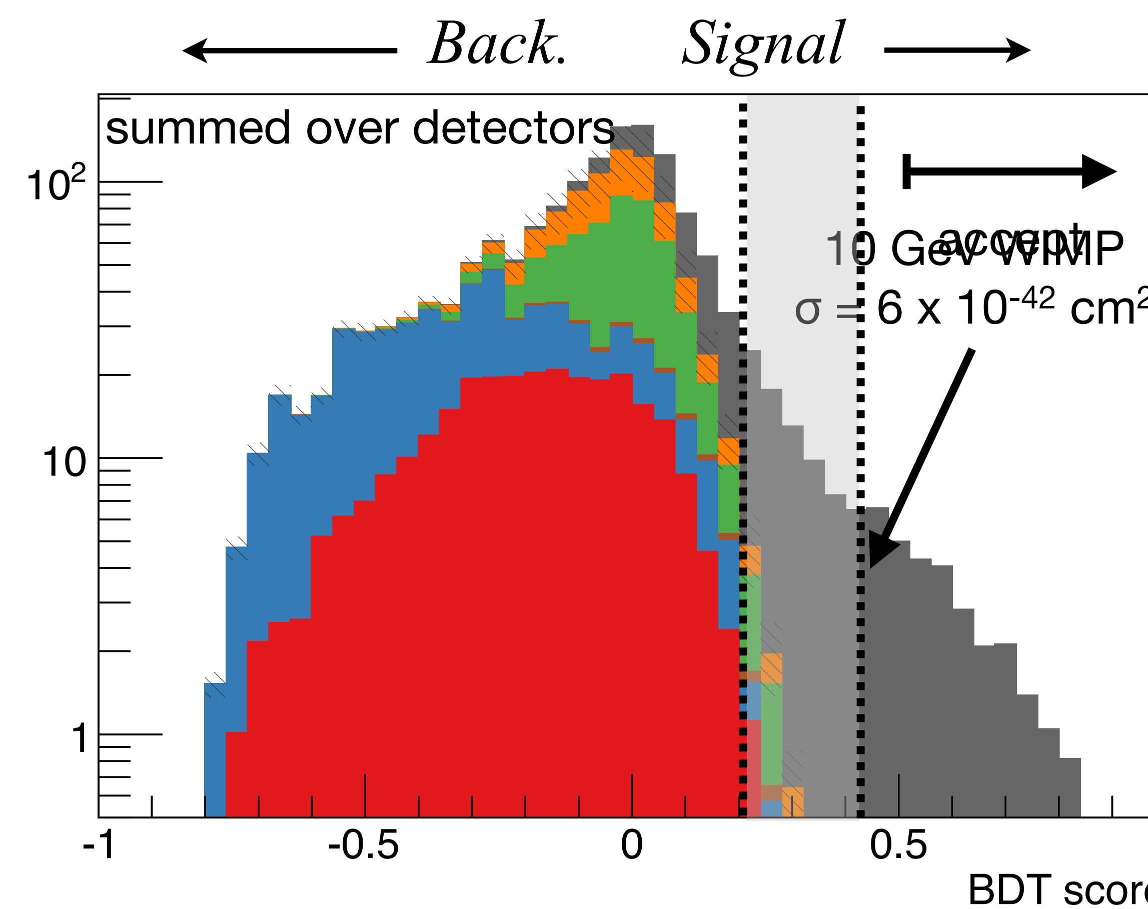
BDT inputs



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

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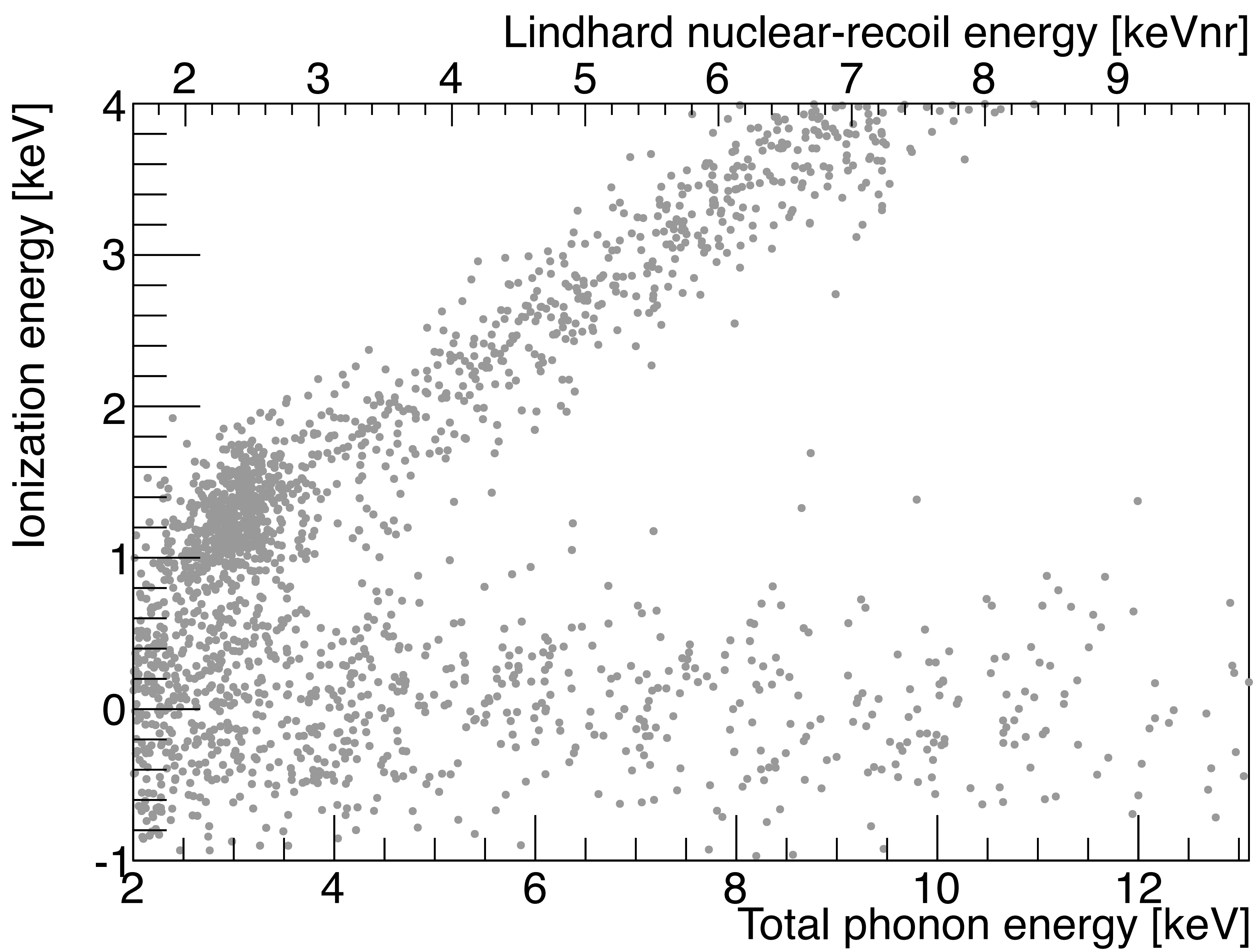
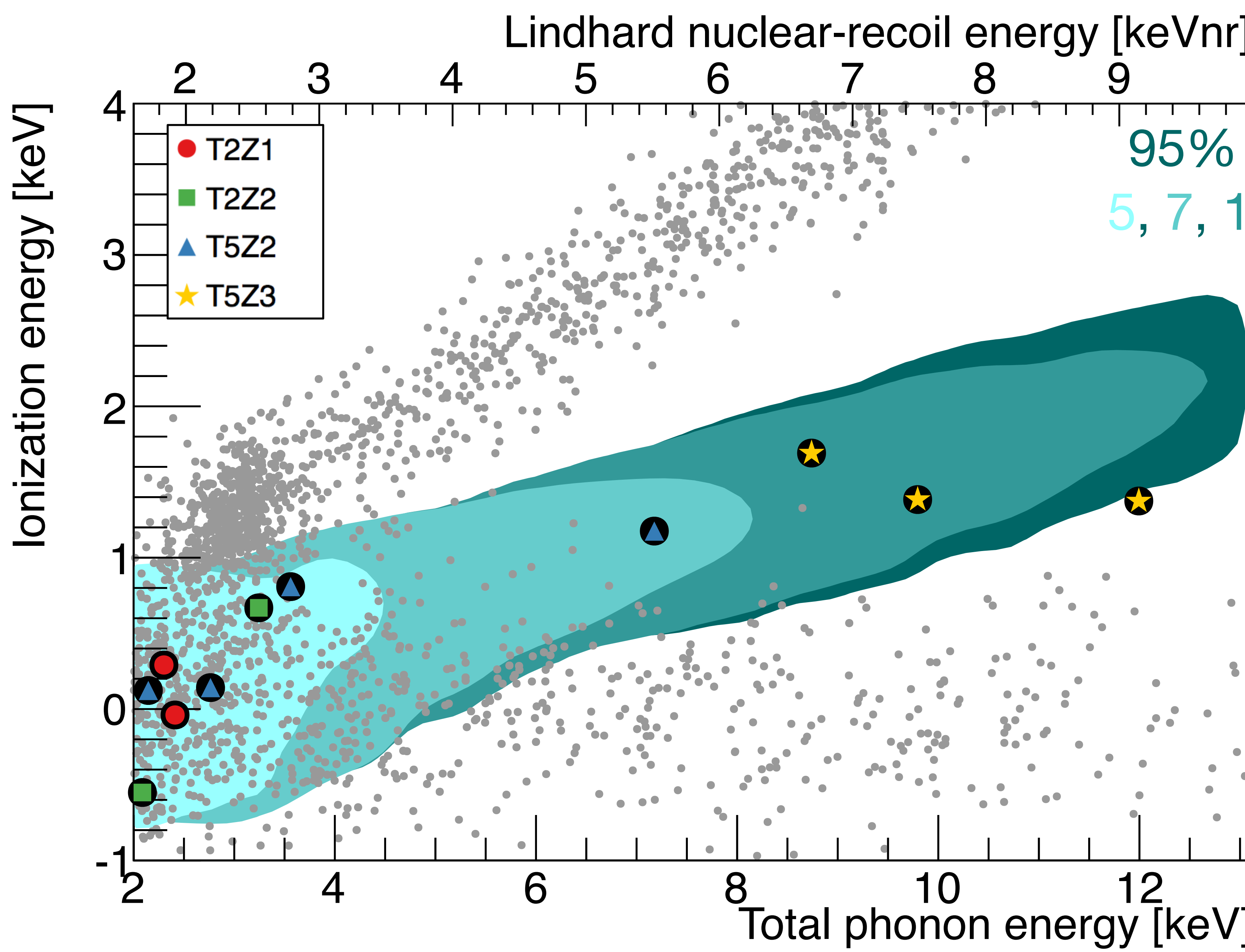
Low Threshold analysis

Passing data quality & ionization fiducialization cuts



Low Threshold analysis

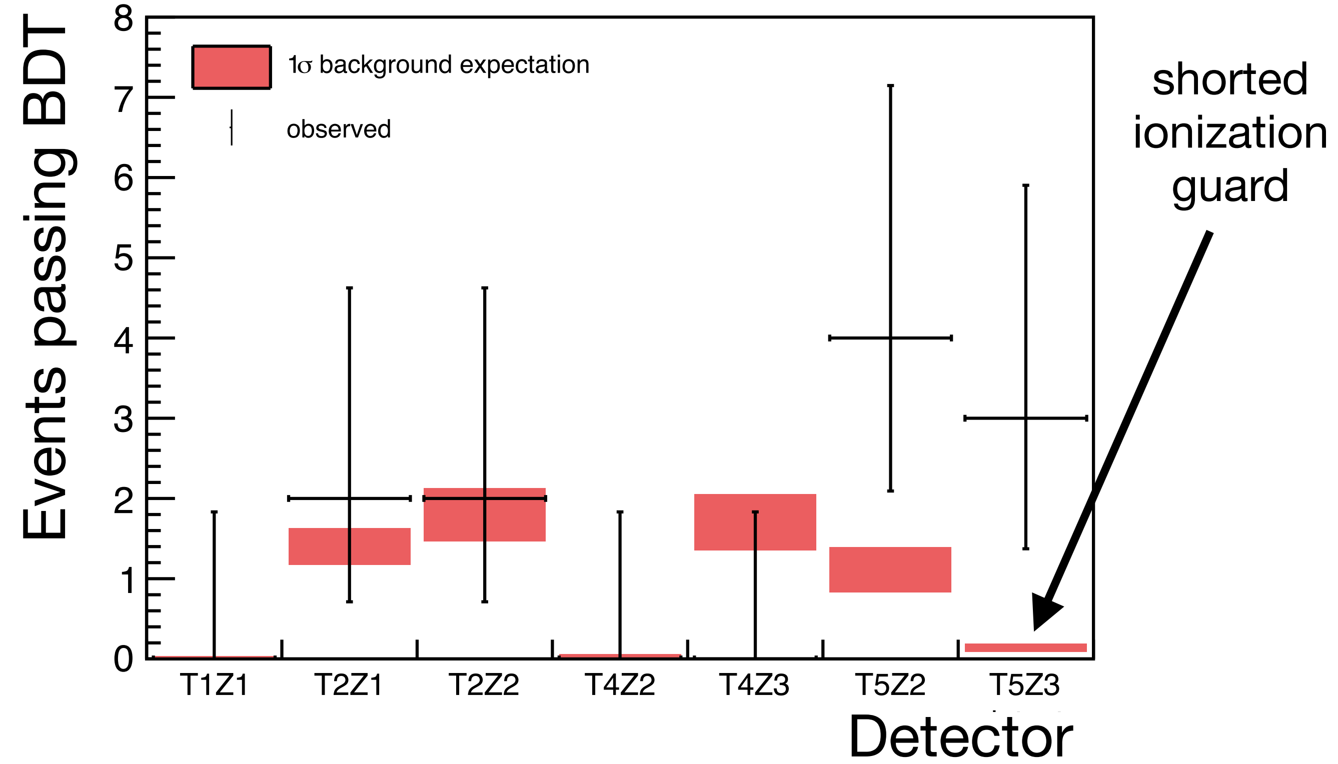
11 events observed passing BDT (expected $6.2^{+1.1}_{-0.8}$)

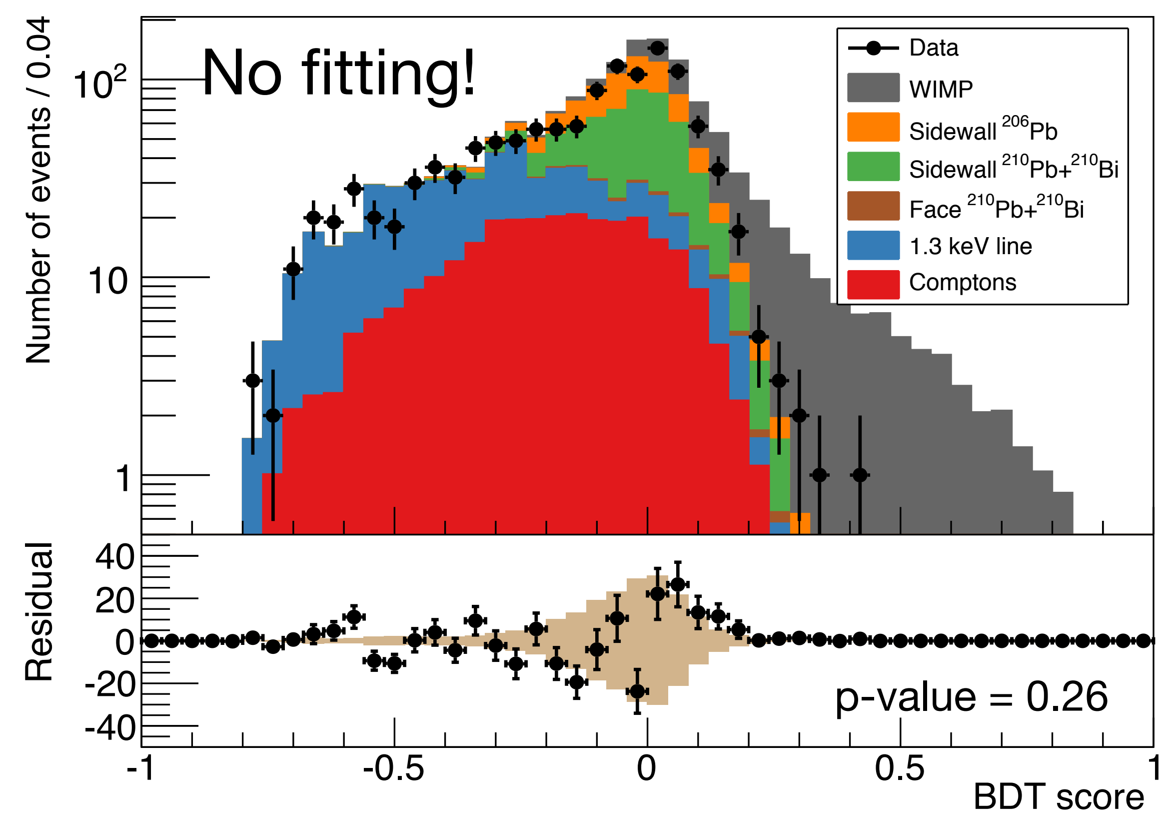


95% CL contours for
5, 7, 10, 15 GeV WIMP

Low Threshold analysis

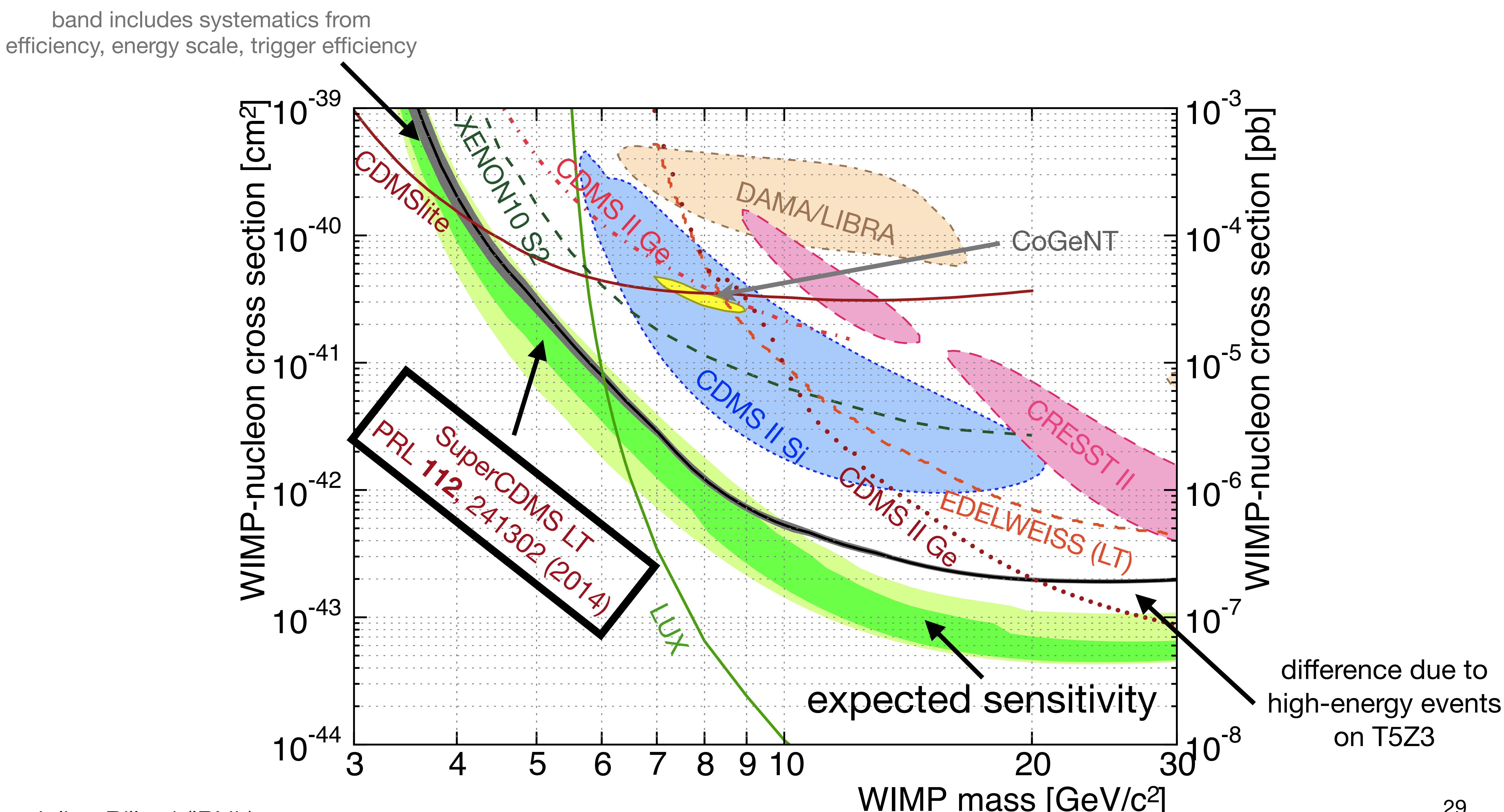
- Background consistent with expectations overall and on most individual detectors
- Shorted ionization guard on T5Z3 may have affected background model performance—*further study ongoing*
- Background model **accurate in full preselection region**
- Future 210-Pb calibration data to reduce systematics and enhance the sensitivity of the experiment



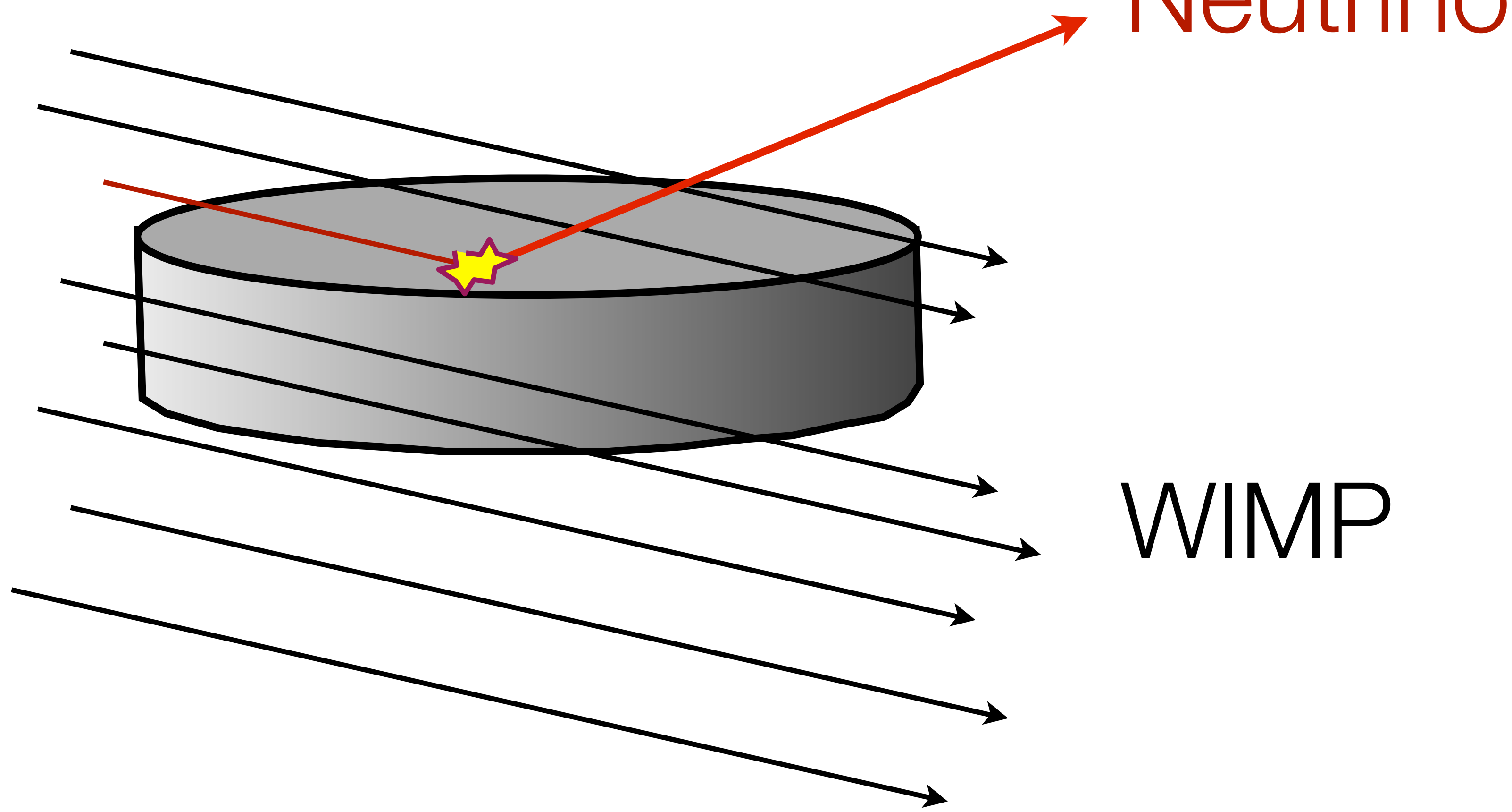


Low Threshold analysis

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



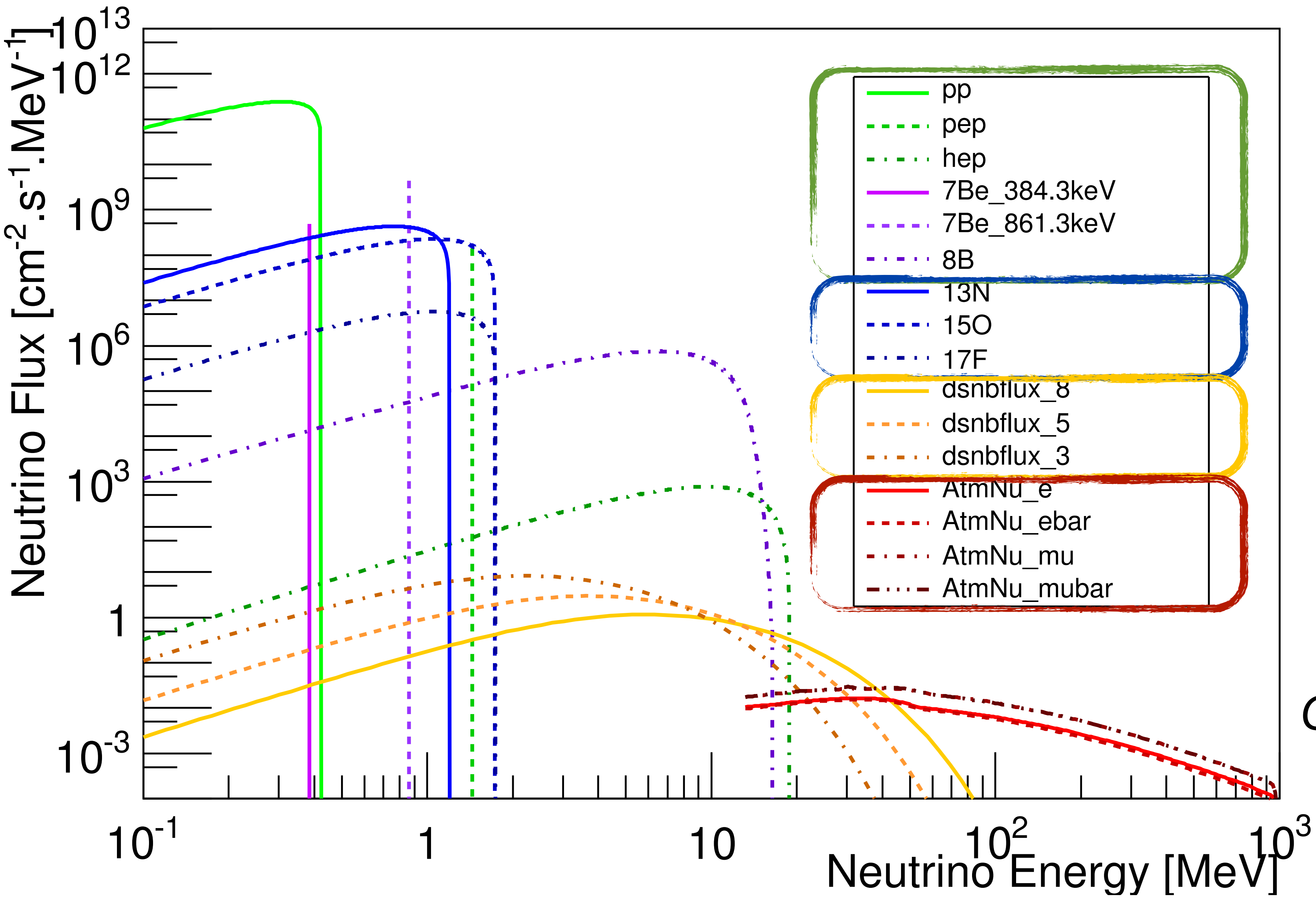
Neutrino background



Based on: - J. Billard, L. Strigari and E. Figueroa-Feliciano, PRD 89 (2014)
- F. Ruppin, J. Billard, L. Strigari and E. Figueroa-Feliciano, PRD 90 (2014)

Neutrino background

The neutrino flux at an Earth based detector:



Geo neutrinos are negligible

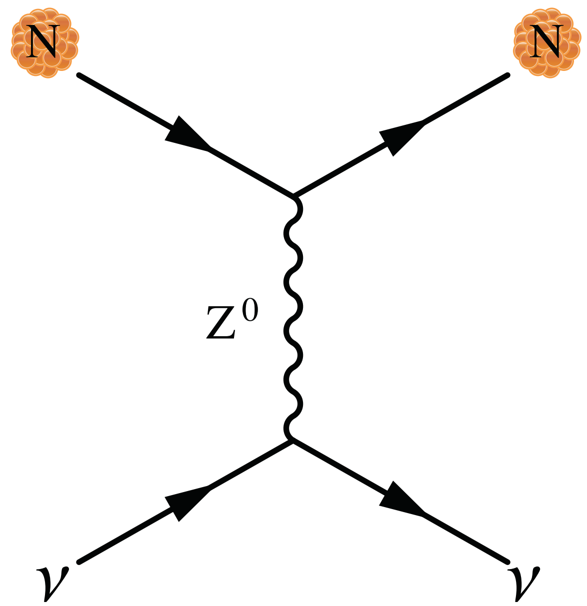
Neutrino background

Neutrino interactions with Dark Matter experiment target material

- Coherent neutrino scattering (CNS):

$$\frac{d\sigma(E_\nu, E_r)}{dE_r} = \frac{G_f^2}{4\pi} Q_w^2 m_N \left(1 - \frac{m_N E_r}{2E_\nu^2}\right) F^2(E_r)$$

- σ: Cross Section
- E_r: Recoil Energy
- E_ν: Neutrino Energy
- G_f: Fermi Constant
- Q_W: Weak Charge ~ **A**
- m_N: Atomic Mass



Neutral current

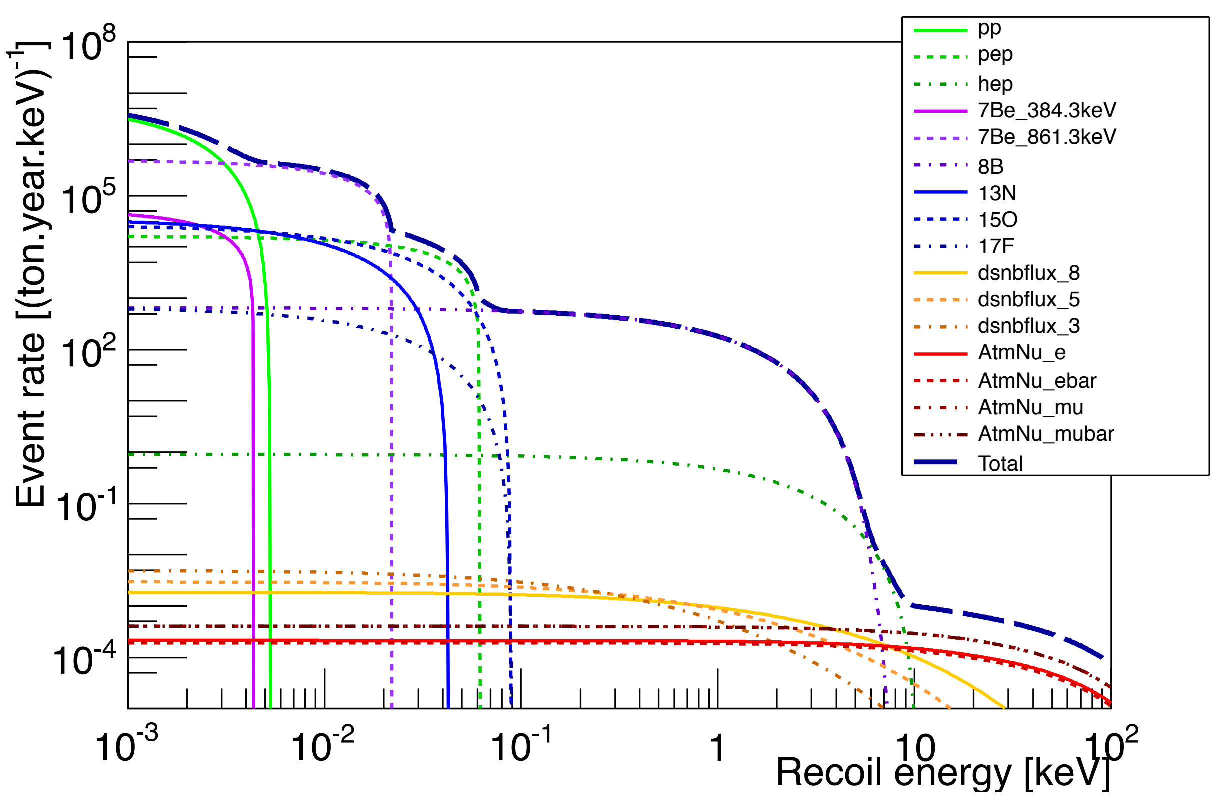
No flavor-specific terms!!!
Same rate for ν_e, ν_μ, and ν_τ

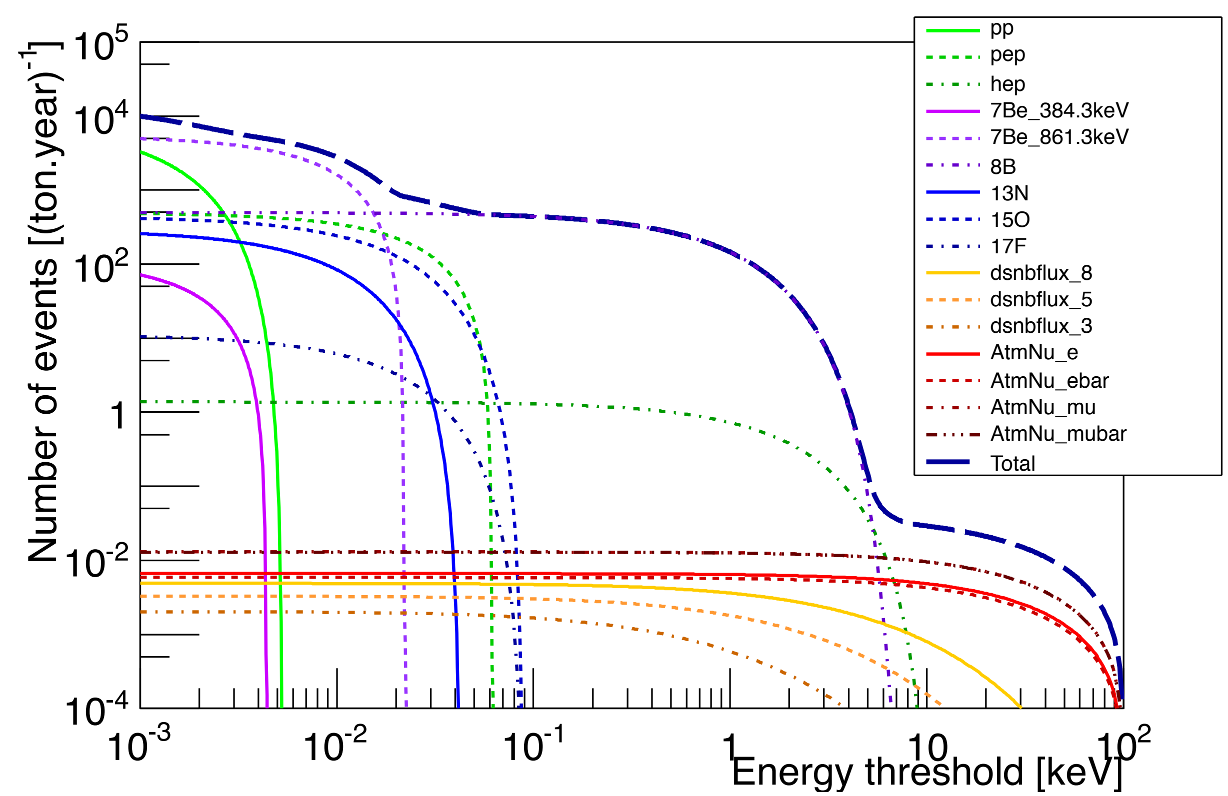
Ultimate background to direct detection

Neutrino background

Neutrino interactions with Dark Matter experiment target material

- Coherent neutrino scattering (CNS):



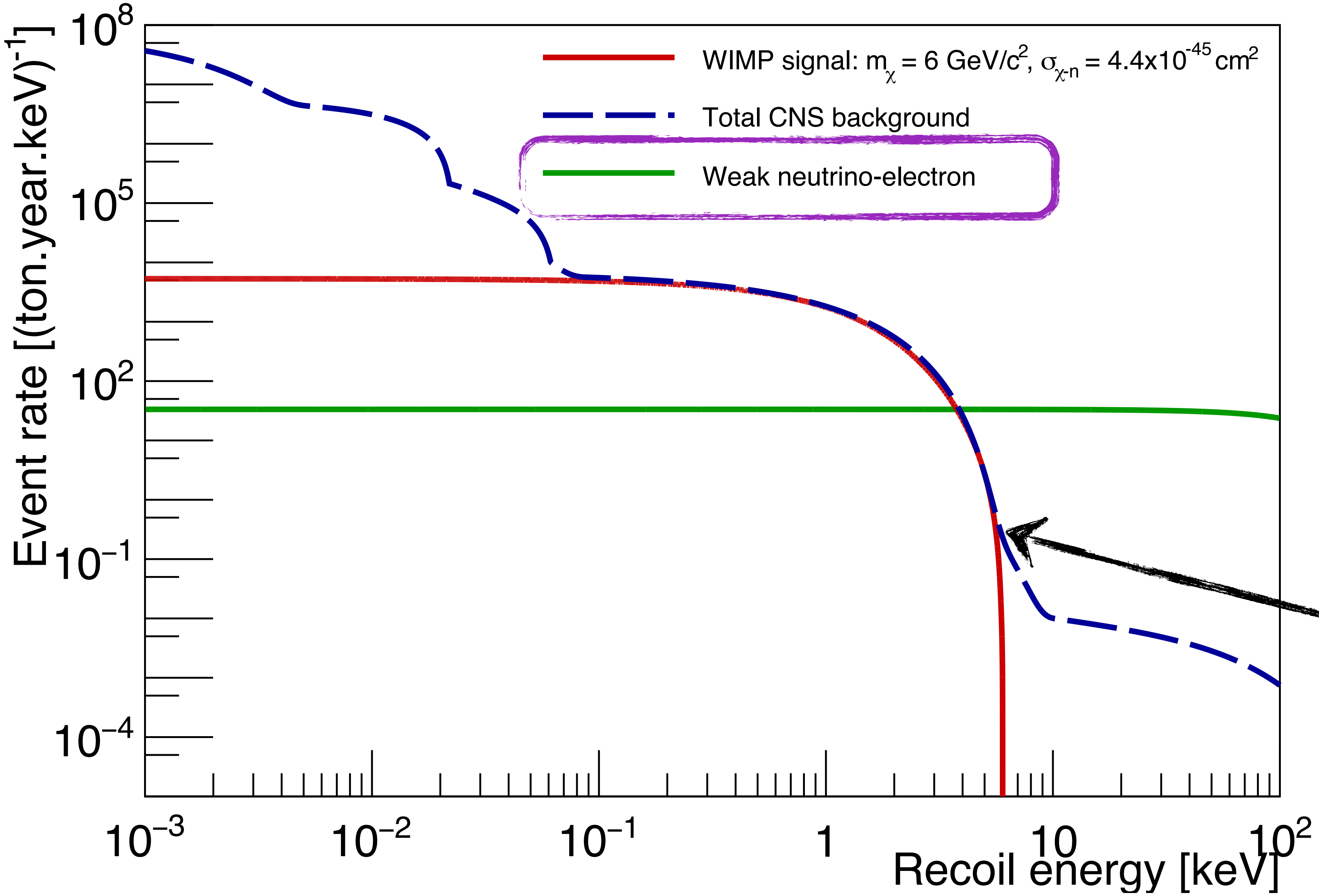


Depending on the Energy threshold, the CNS background can be very high!

- 1 keV threshold -> 100 evt/ton/year on Ge detector

Introduction to the neutrino background

Neutrino interactions with Dark Matter experiment target material



Neutrino-electron background

negligible for Ge cryogenic detectors
BUT
problematic for Xe based detectors

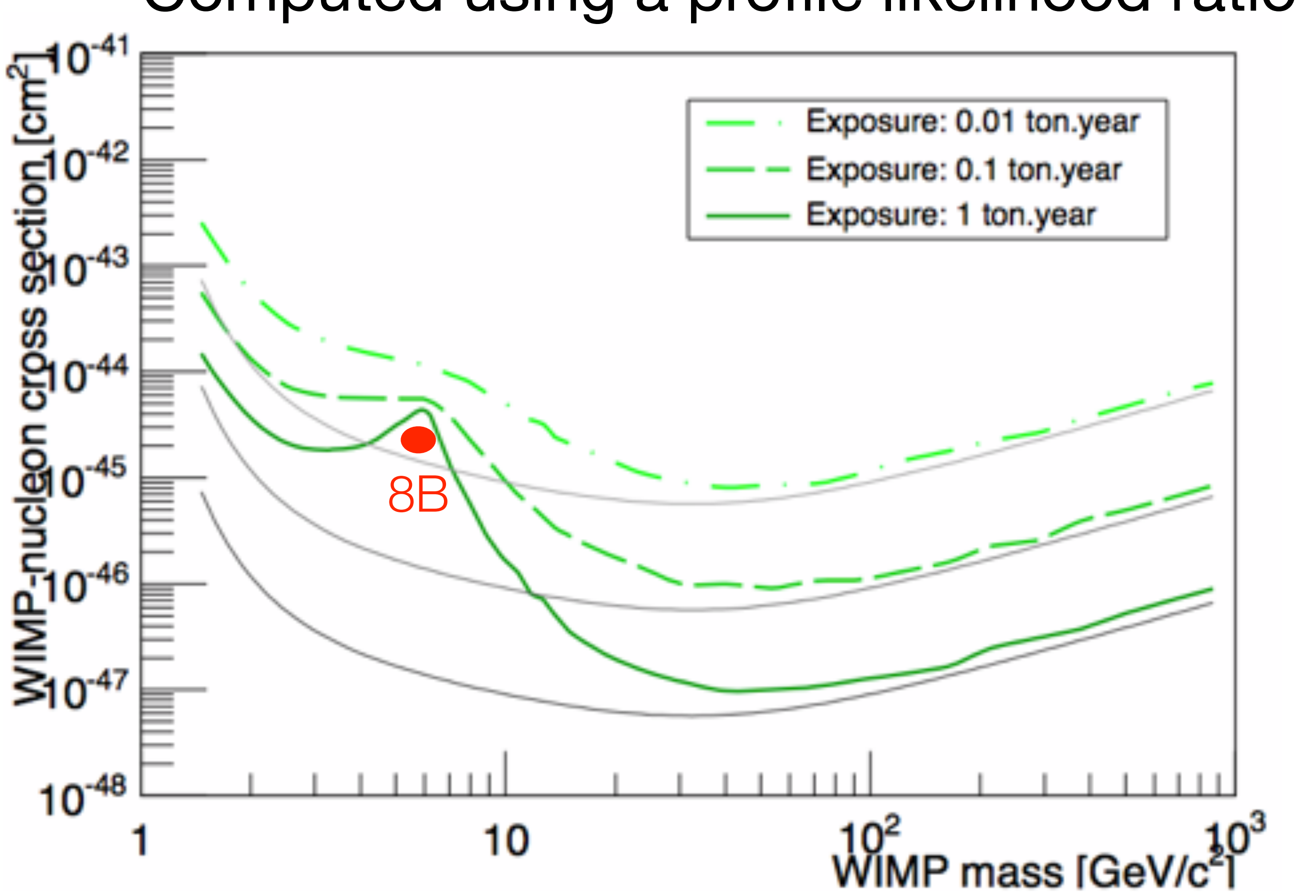
WIMP or neutrino??

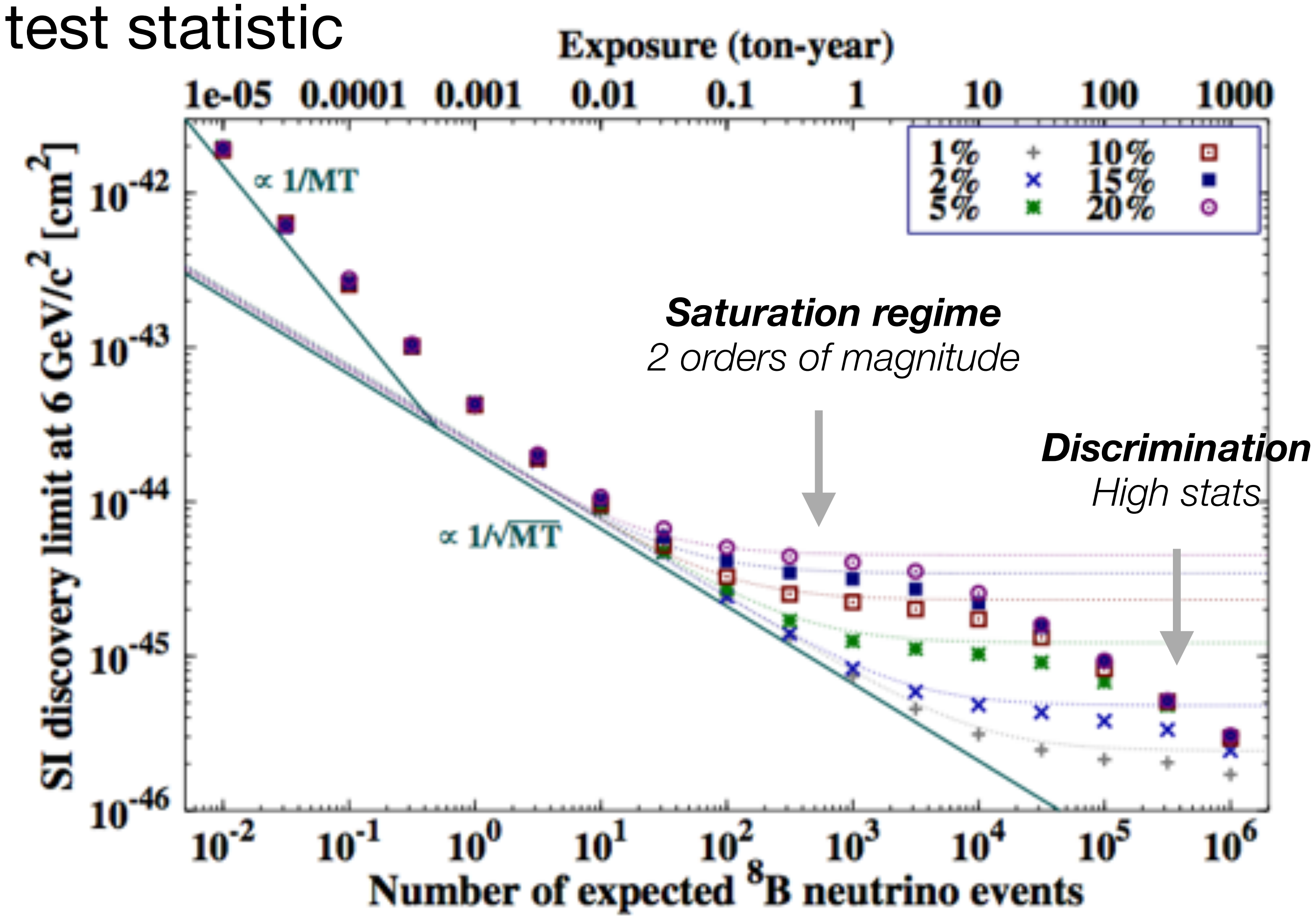
Impact on direct detection sensitivity

WIMP discovery potential:

(J. Billard, F. Mayet and D. Santos PRD 2012)

- 90% probability to get a 3 sigma or more WIMP discovery significance
- Computed using a profile likelihood ratio test statistic

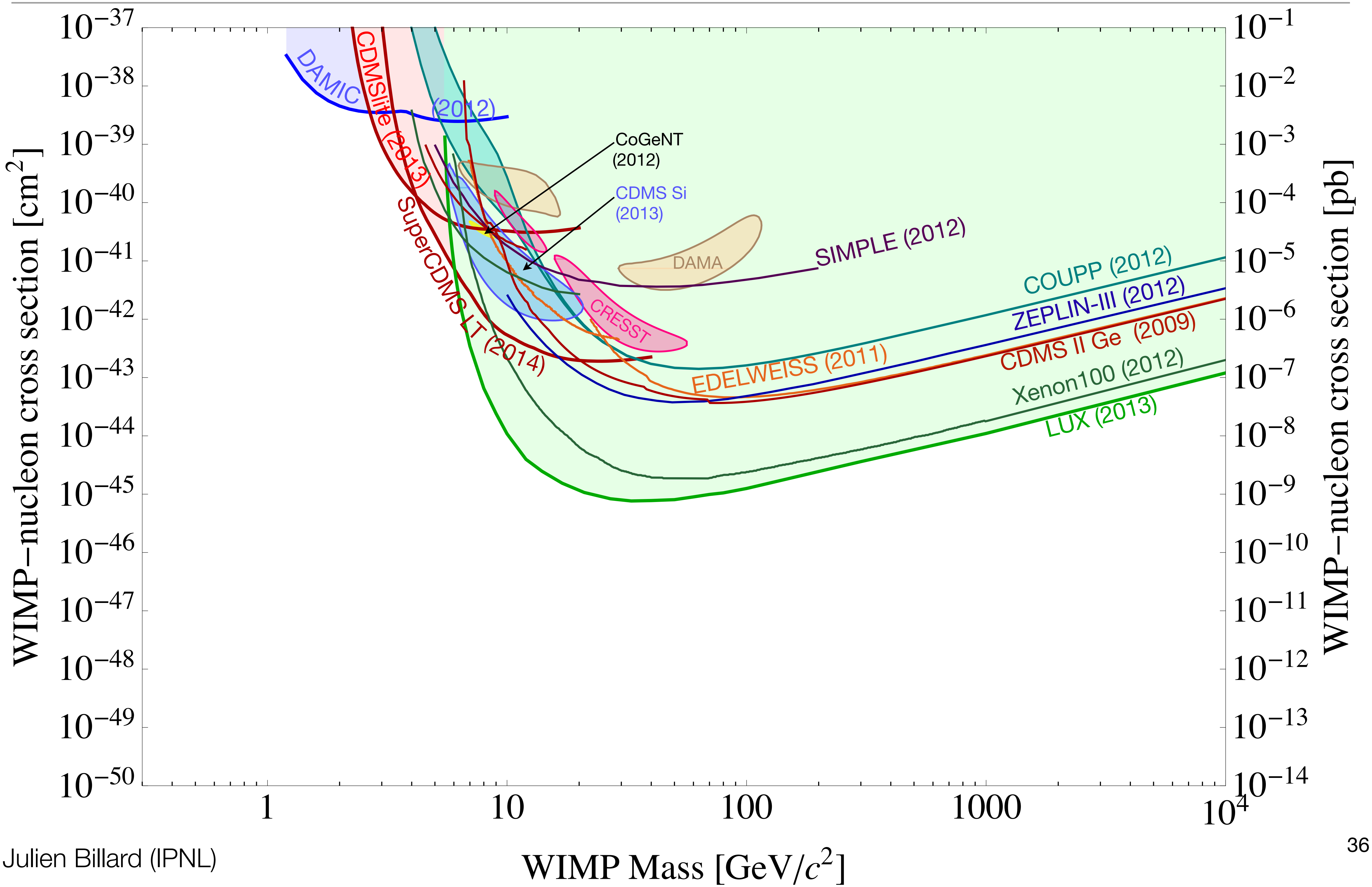




In the case of a **perfect spectral matching**, we expect the sensitivity to scale as:

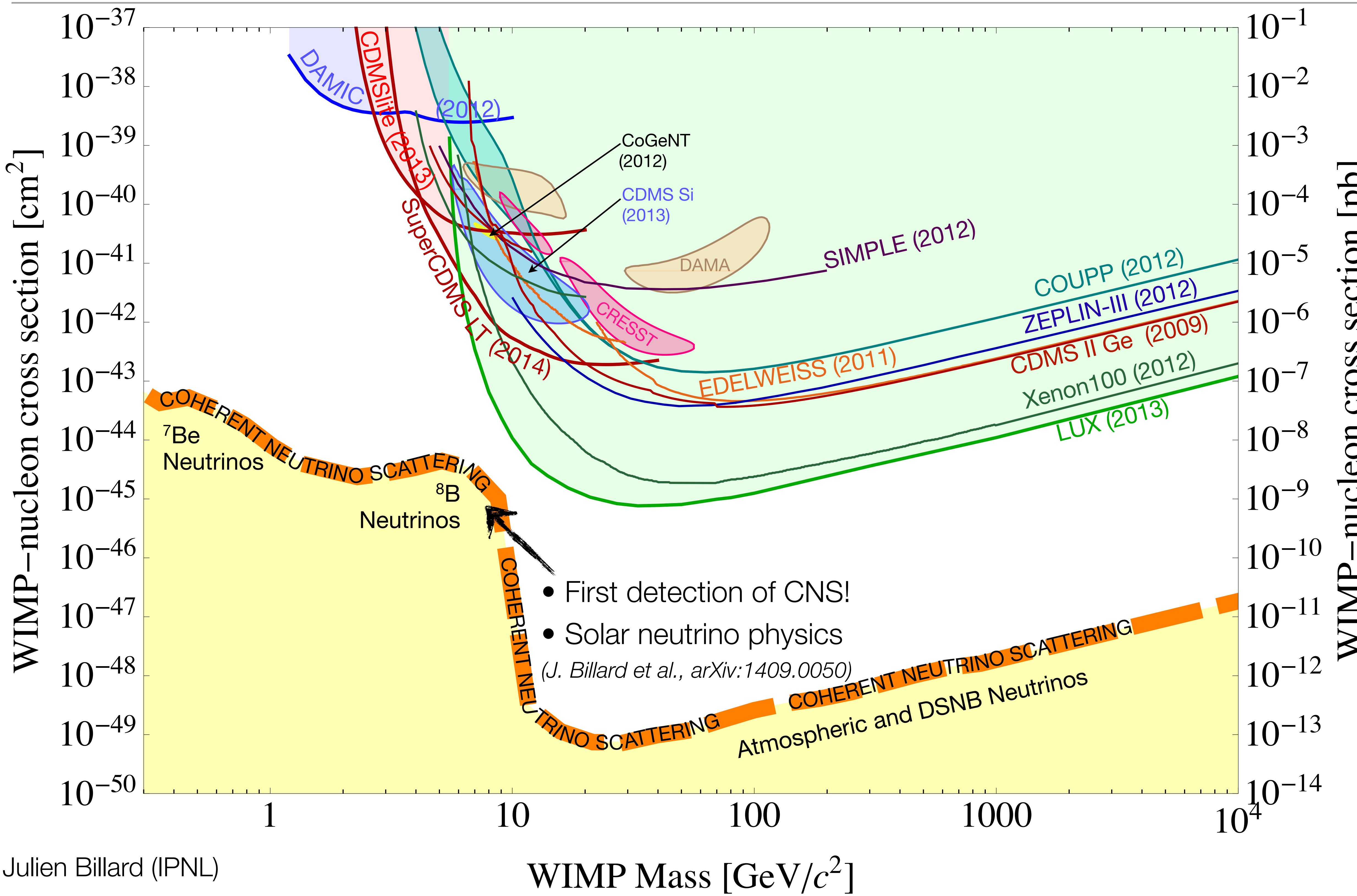
$$\sigma_{90\%} \propto \frac{\sqrt{N_\nu + \xi^2 (N_\nu)^2}}{N_\nu} = \sqrt{\frac{1+\xi^2 N_\nu}{N_\nu}},$$

Neutrino background



Julien Billard (IPNL)

Neutrino background



Julien Billard (IPNL)

Neutrino background

How to bypass this neutrino-induced saturation of the sensitivity?

1. Diminution of the systematic errors will lower the saturation regime

2. Add directional information! Solar neutrinos and WIMPs have 2 very different angular distributions *(P. Grothaus et al, PRD 90 (2014))*, 2D and 1D directionality *(J. Billard, PRD 91 (2015))*

3. Annual modulation? seems possible! *(J. H. Davis arXiv:1412.1475)*

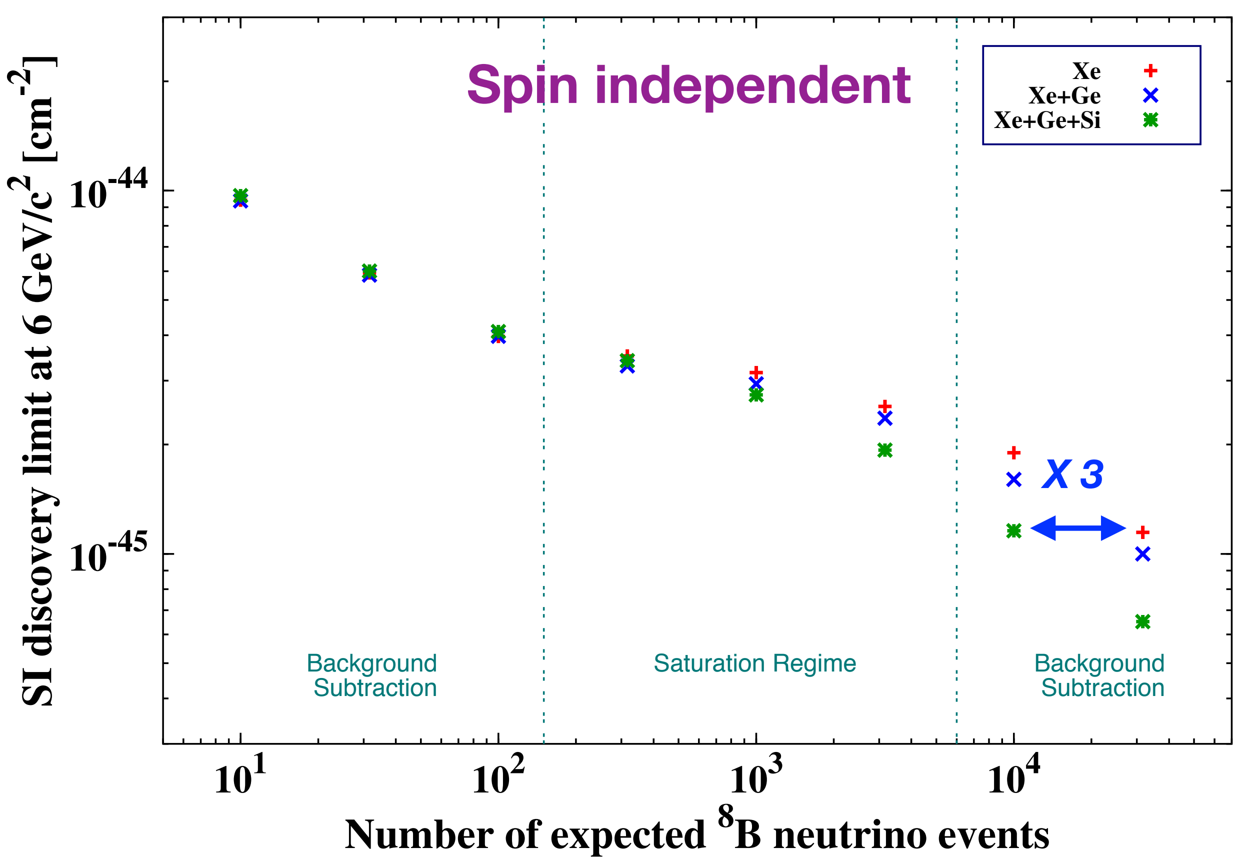
4. Target complementarity: combining data from several experiments.

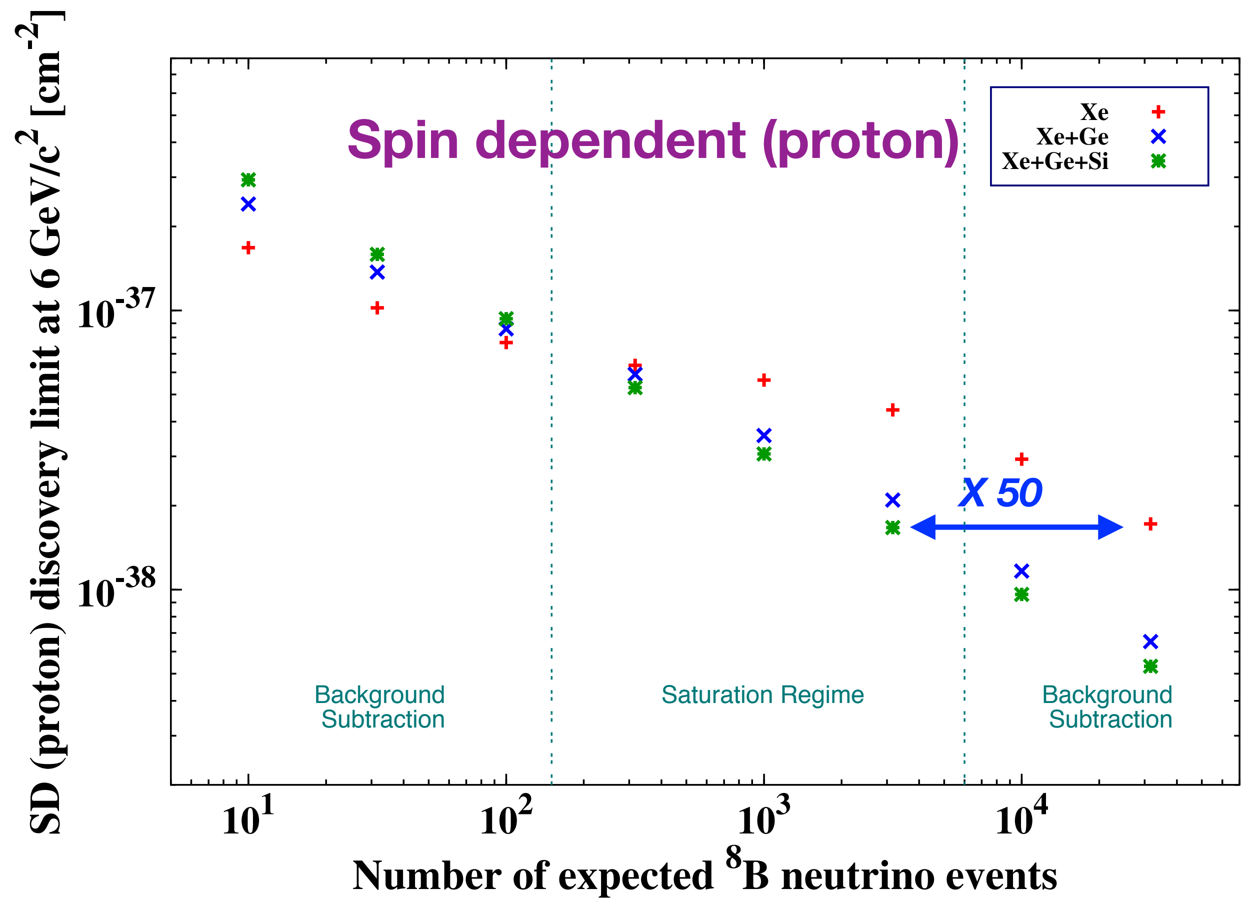
Neutrino background

Results from target complementarity

Considering a 6 GeV WIMP mass and a fixed systematic of 16% for 8B neutrinos

Total number of neutrinos equally distributed amongst each target nuclei

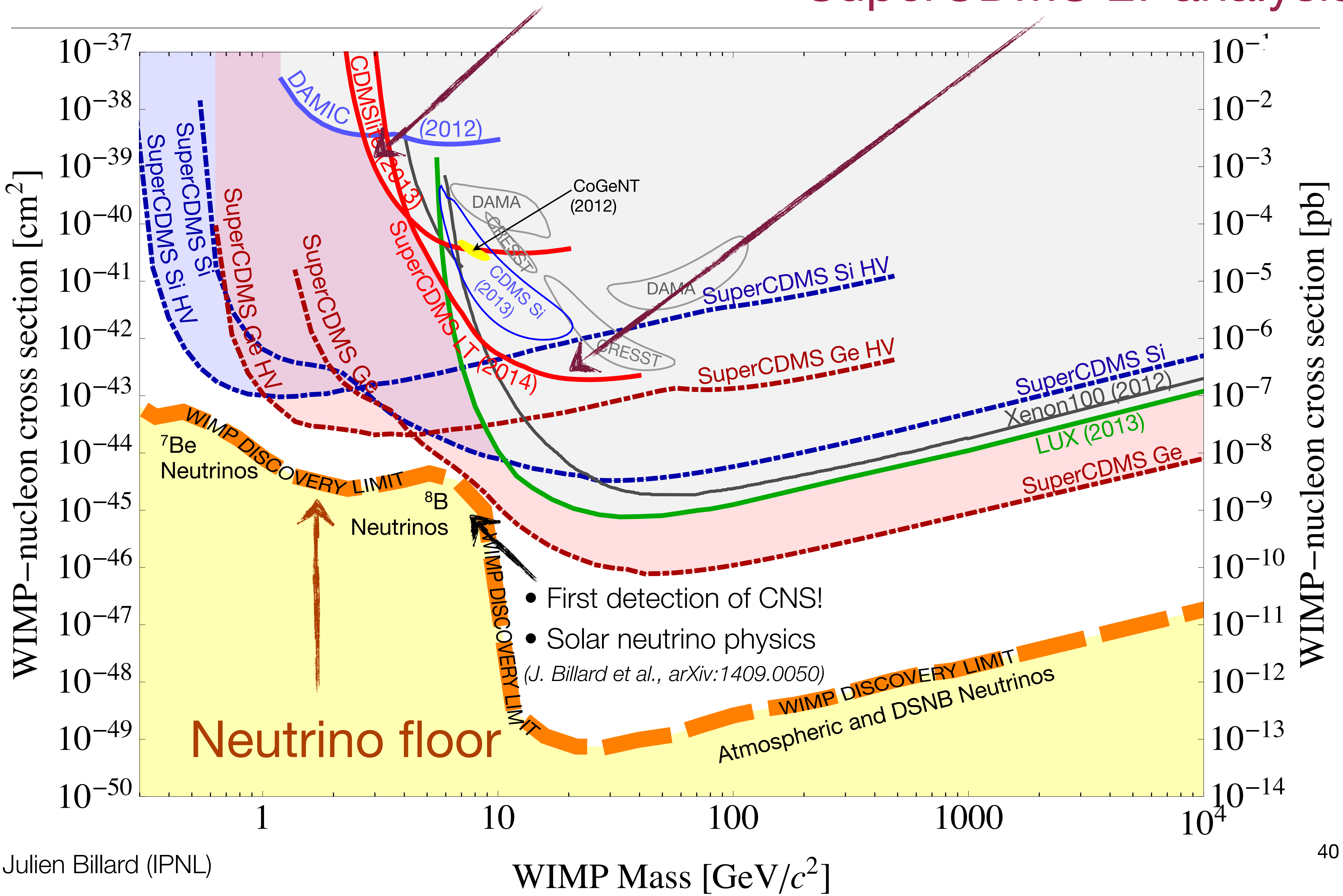




No more saturation regime in the SD-p case with Xe+Ge+Si -> ***no waste in exposure!***

Experiments should combine their data!

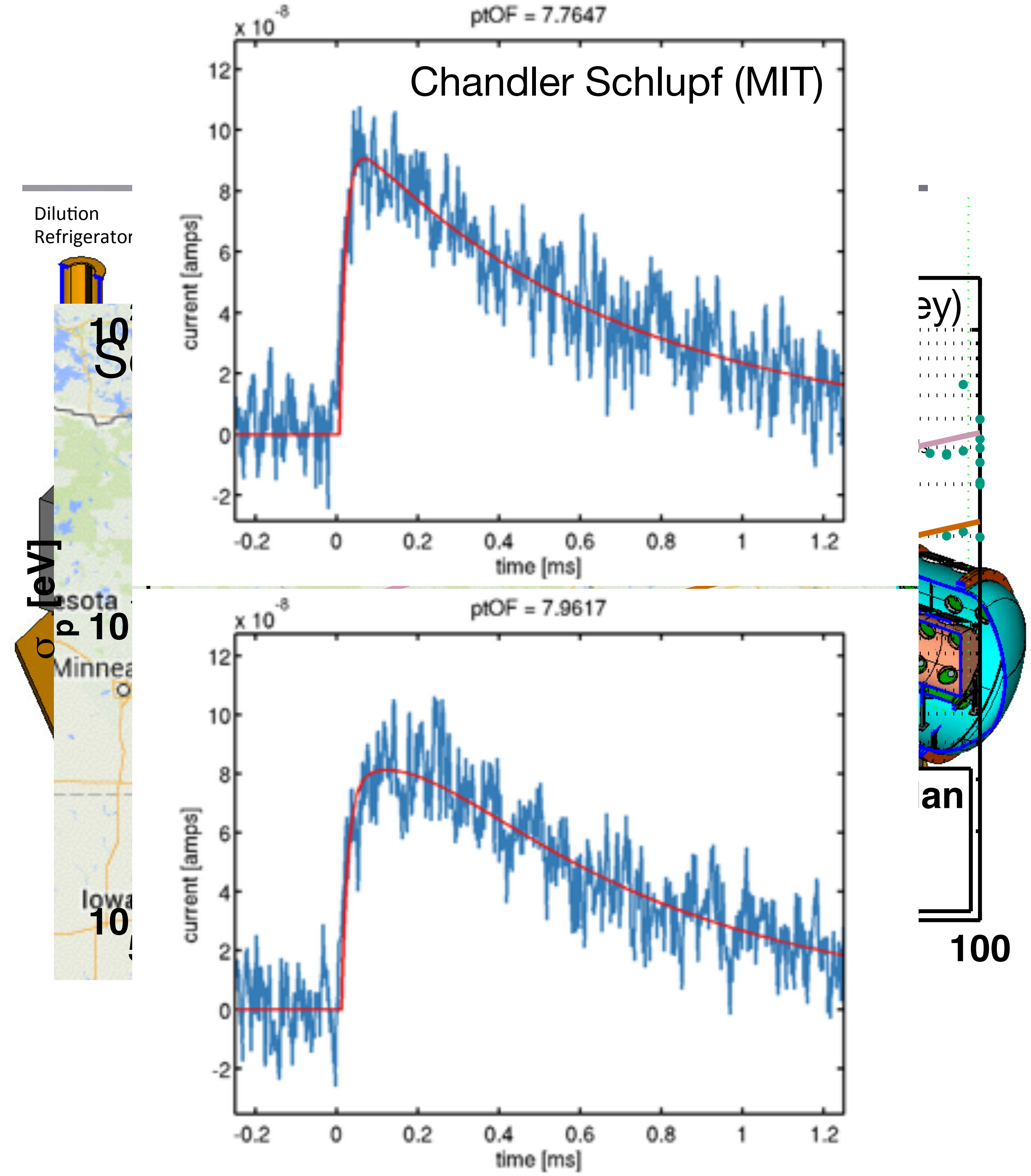
Conclusions



End

Future Perspectives: SuperCDMS @ SNOLAB

- **Larger** detectors: 1 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



Low Threshold analysis

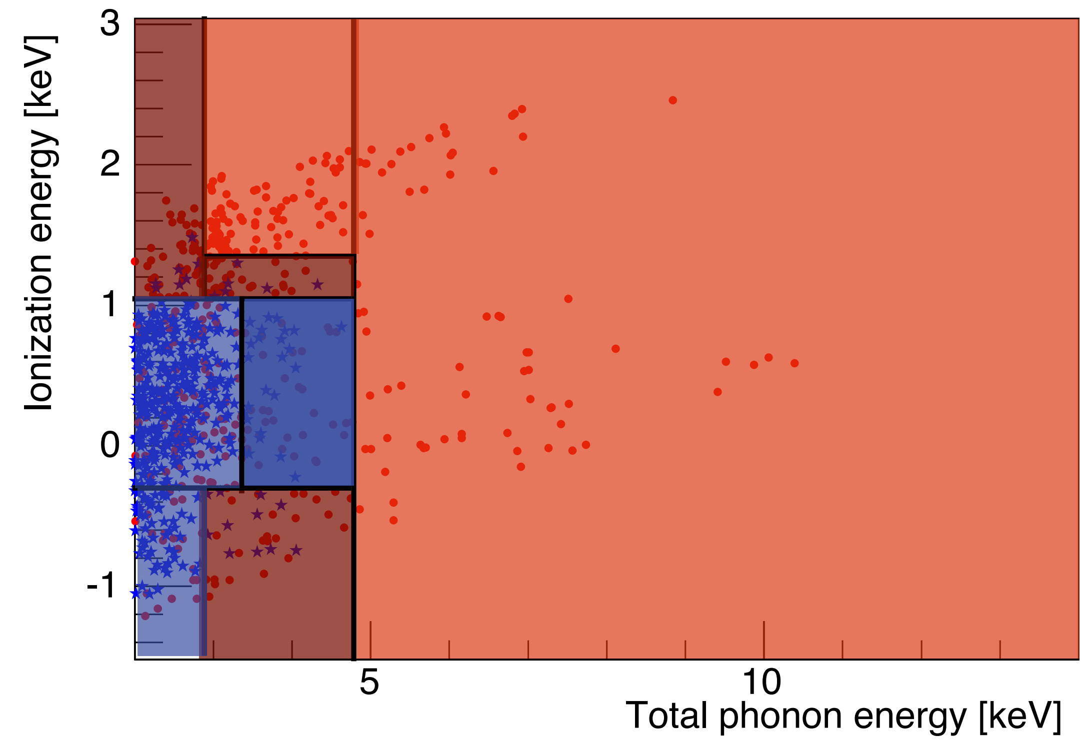
Improvement of the candidate event selection using Boosted Decision Trees

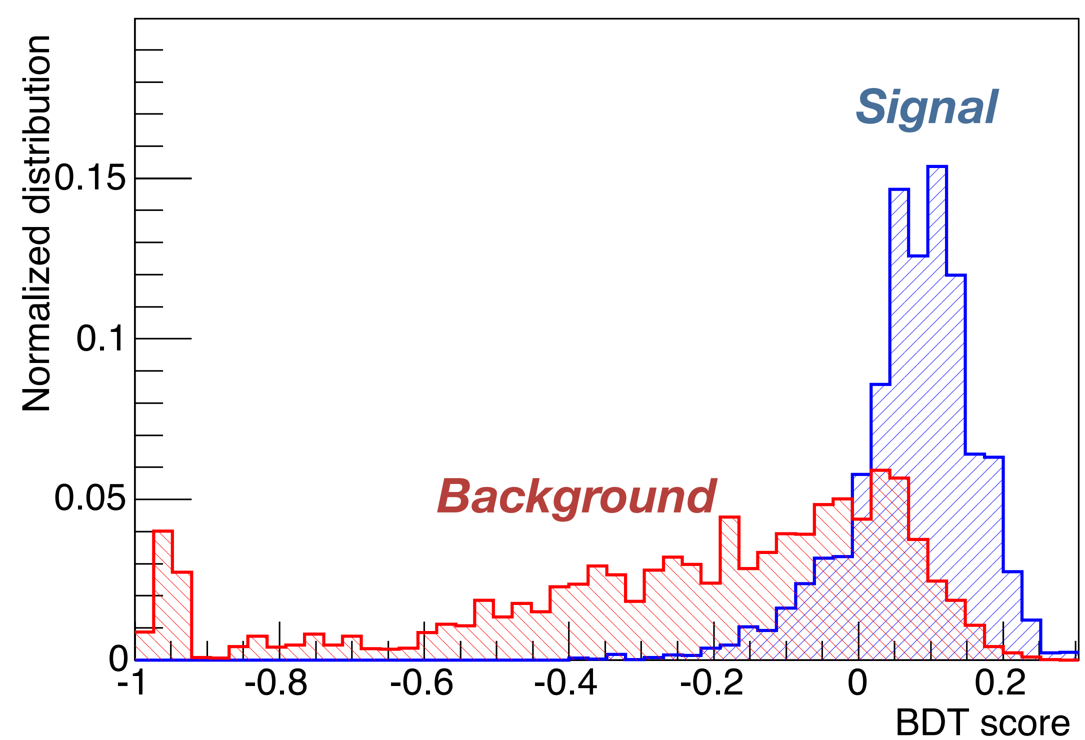
- Decision trees are a set of linear cuts in multidimensional space to optimize **signal**/**background** discrimination

- Construction of a « forest » of trees where misclassified events are given a higher weight for the following decision tree (*boosting*)

- Reduces the dimensionality of the parameter space to a single variable «BDT score »

- We used between 3 to 5 nodes and between 400 to 1000 trees (*no overtraining*)





Low Threshold analysis

Quality

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

Thresholds

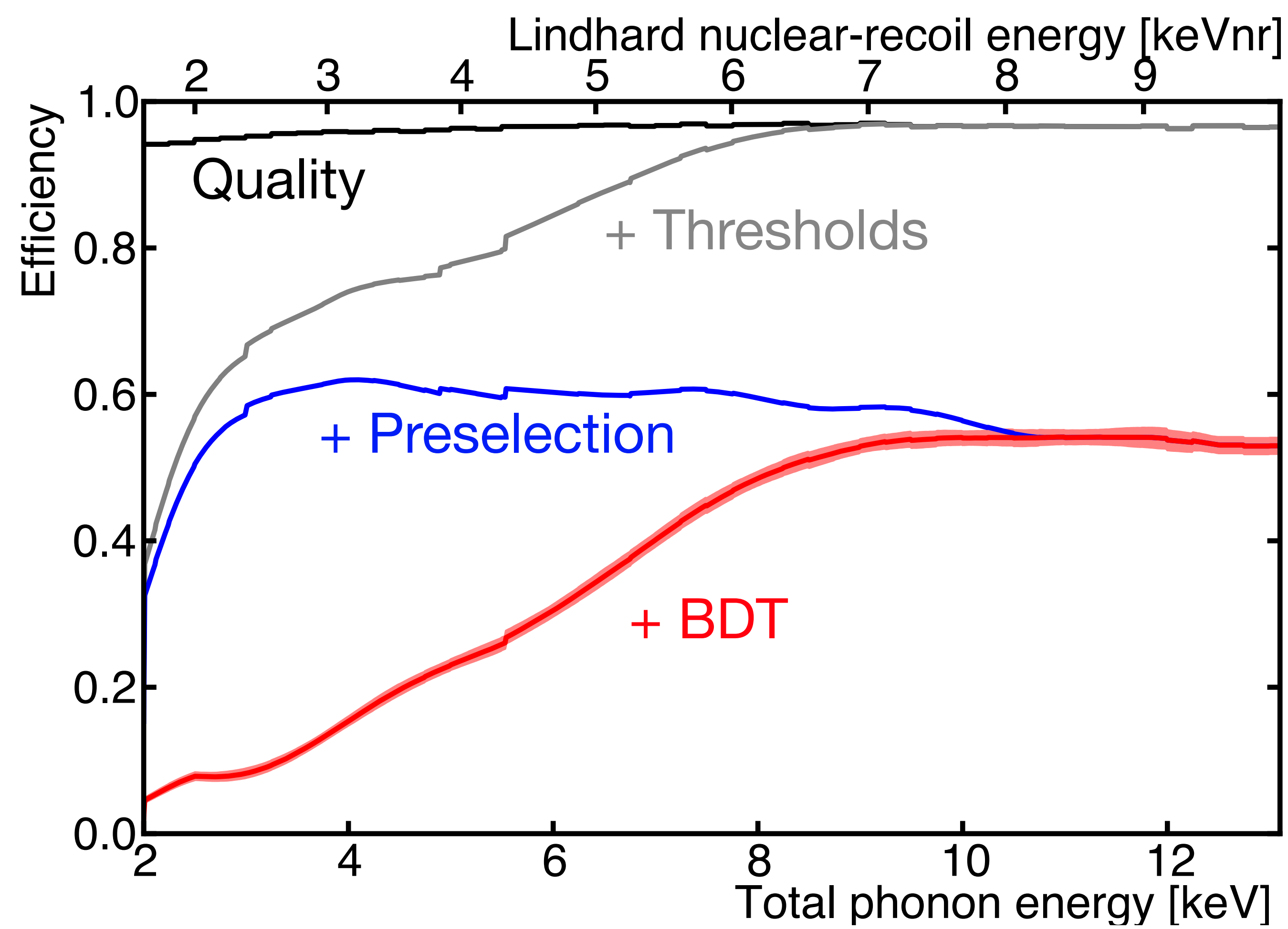
- Trigger and analysis thresholds 1.6-5 keVnr
- Measure efficiency using ^{133}Ba calibration data

Preselection

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

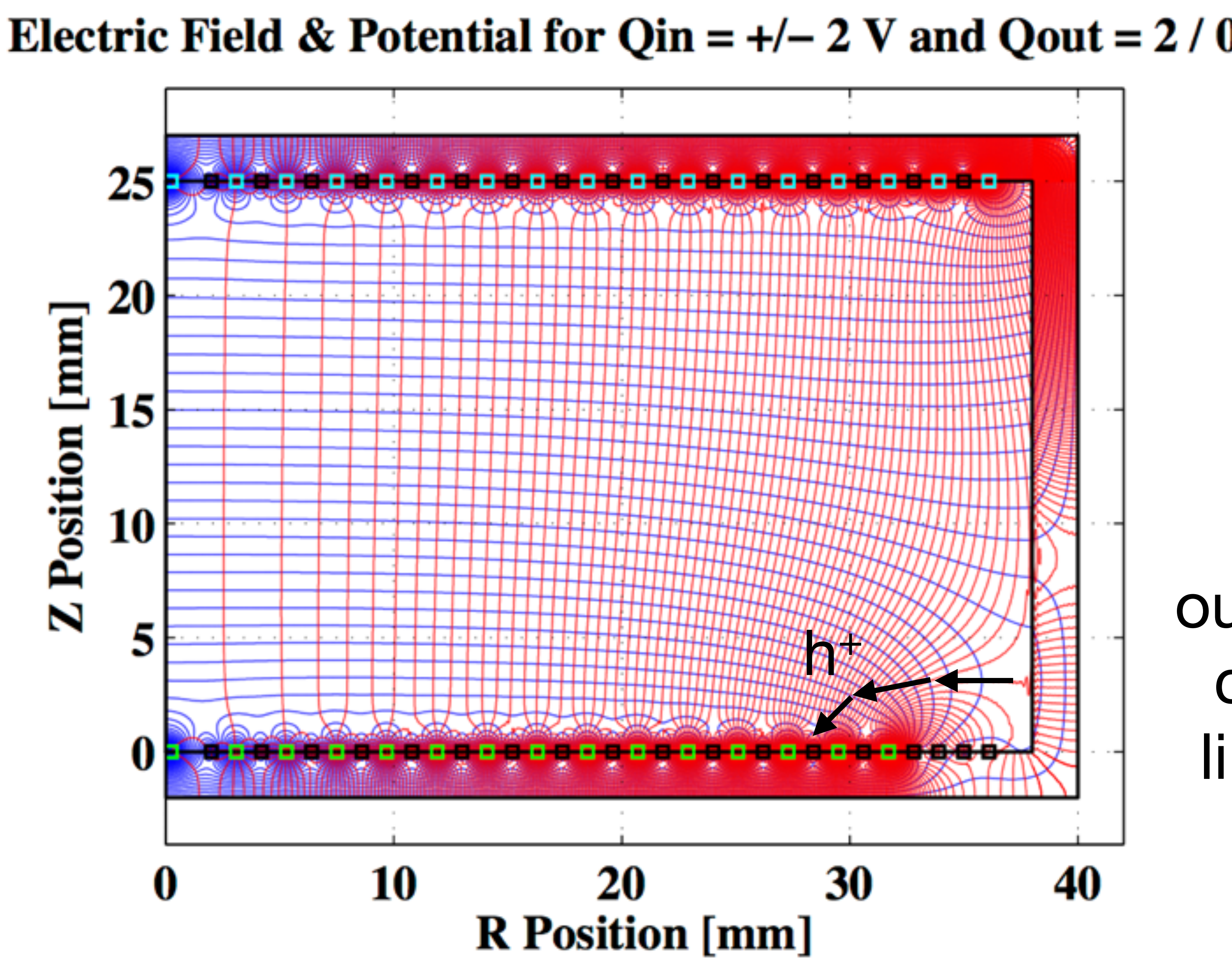
BDT

- 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

Electric Field in T5Z3

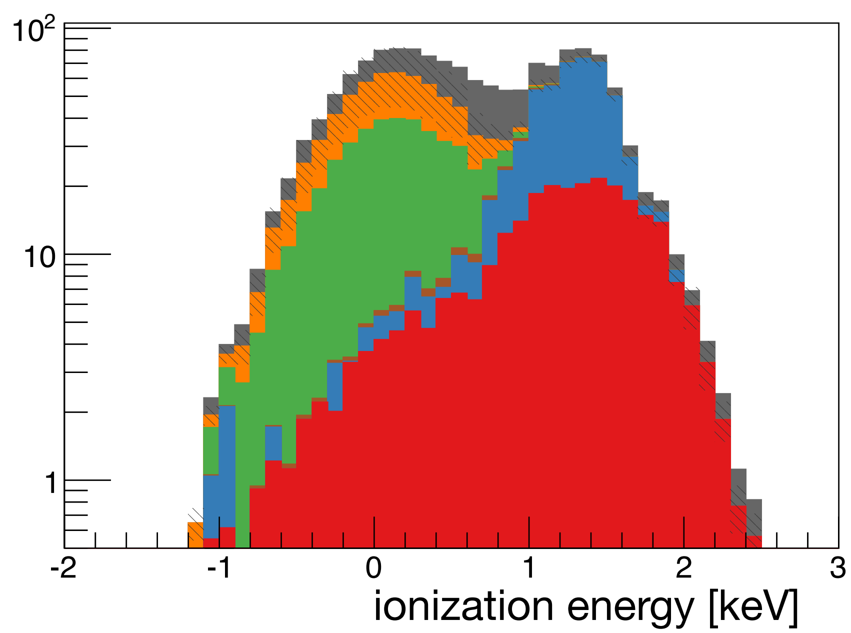


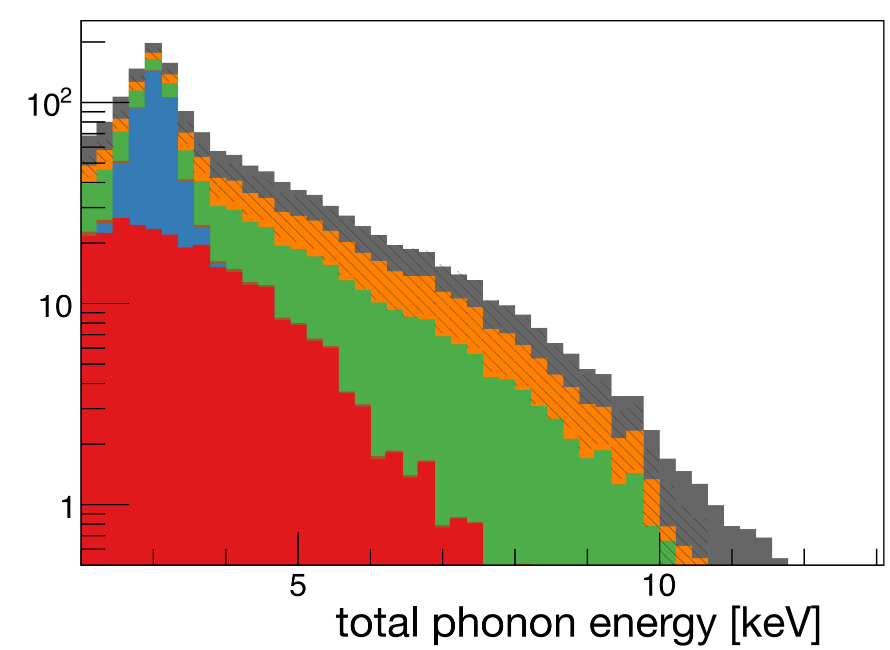
outer event can look like inner!

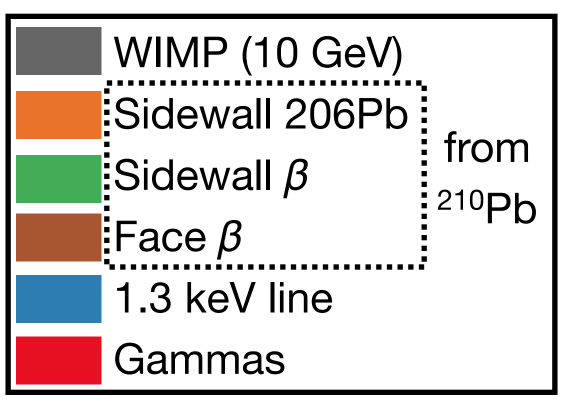
Low Threshold analysis

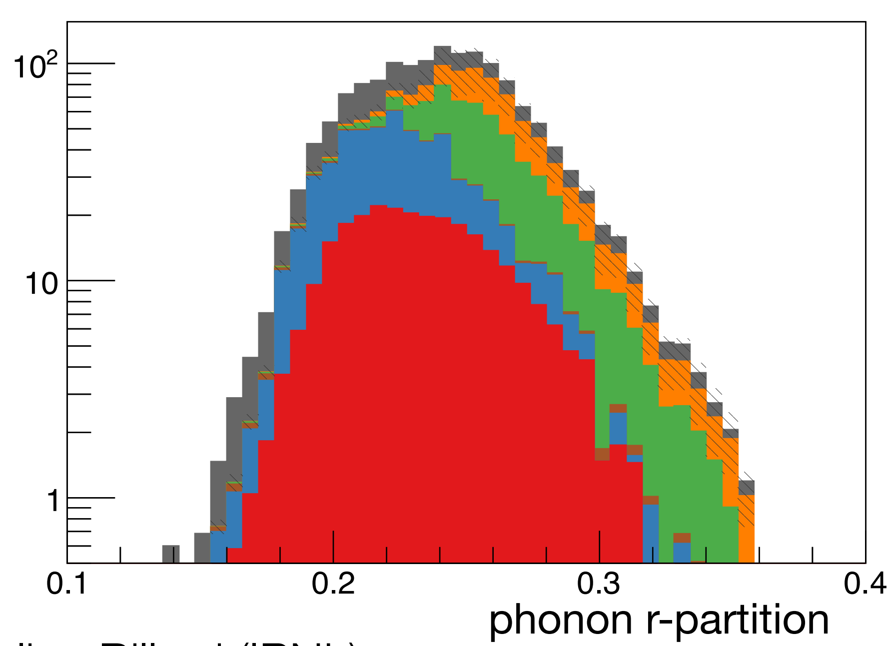
Background model: pulse simulation

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



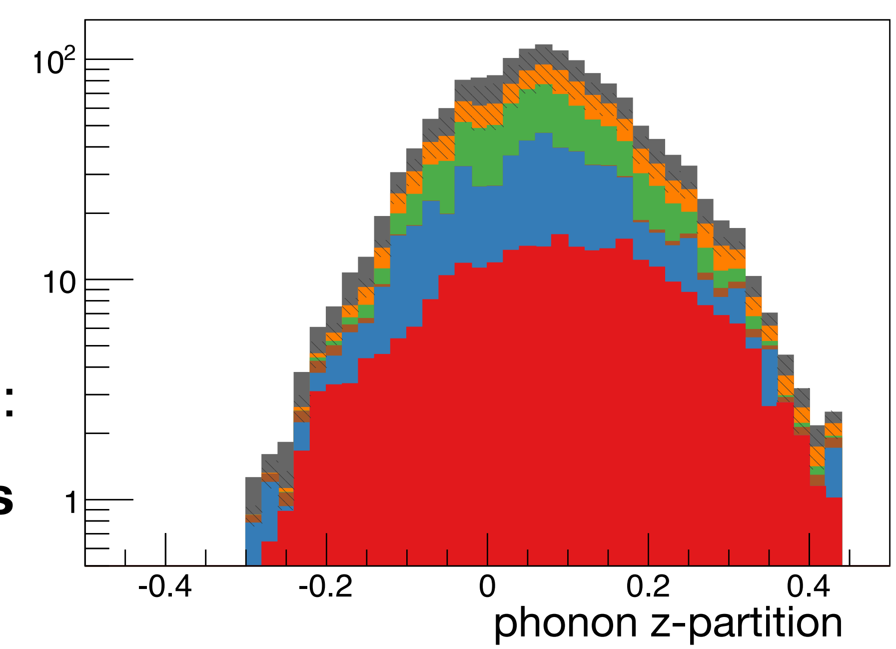






Optimized discrimination:

Boosted Decision Trees



Low Threshold analysis

- 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