Searching for low mass WIMPs with SuperCDMS and the neutrino background

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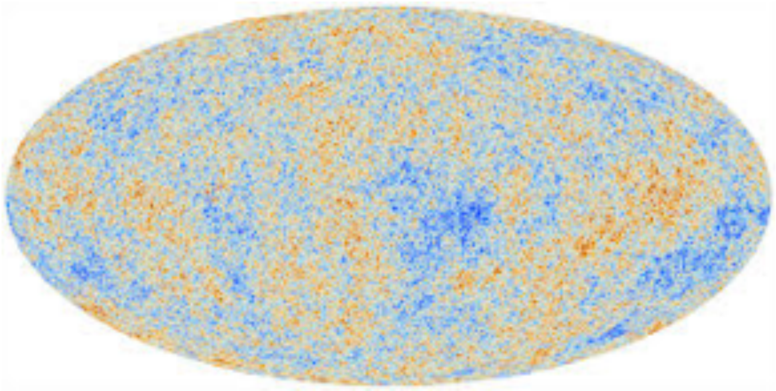
Outline

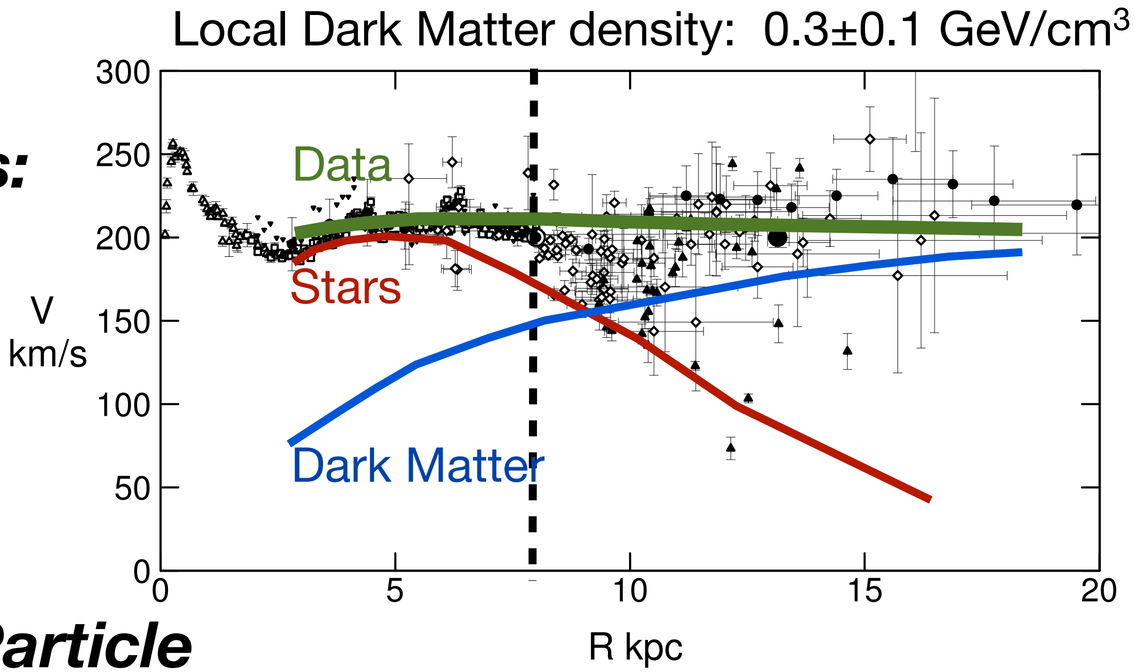
1. Direct Dark Matter detection
2. The SuperCDMS Experiment
3. CDMSLite
4. Low Threshold analysis
5. Neutrino background

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

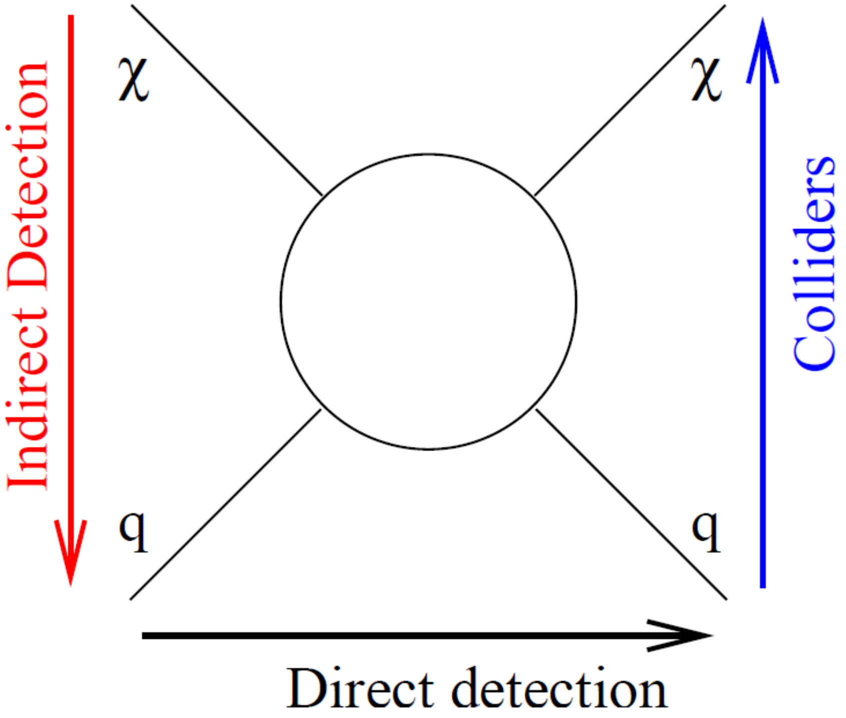
- Stable
- Neutral from charge and color
- Massive GeV - TeV
- Weak interaction

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

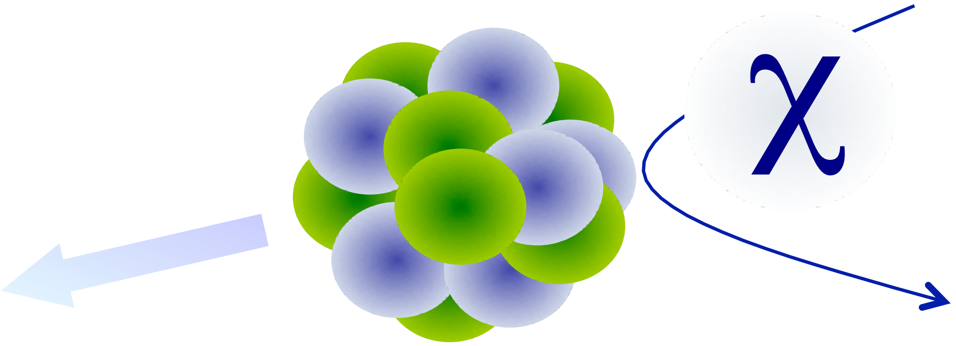
The WIMP miracle

Direct detection of Dark Matter

Dark Matter annihilation

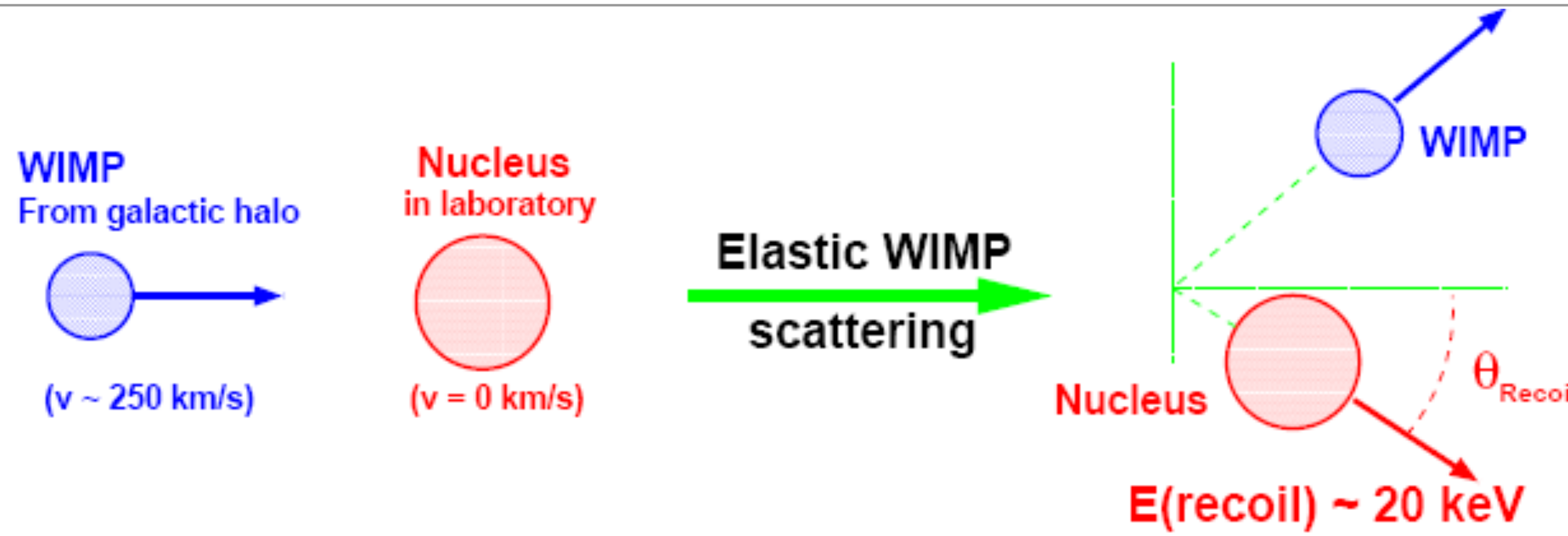


Dark Matter production



WIMP-nucleus elastic scattering

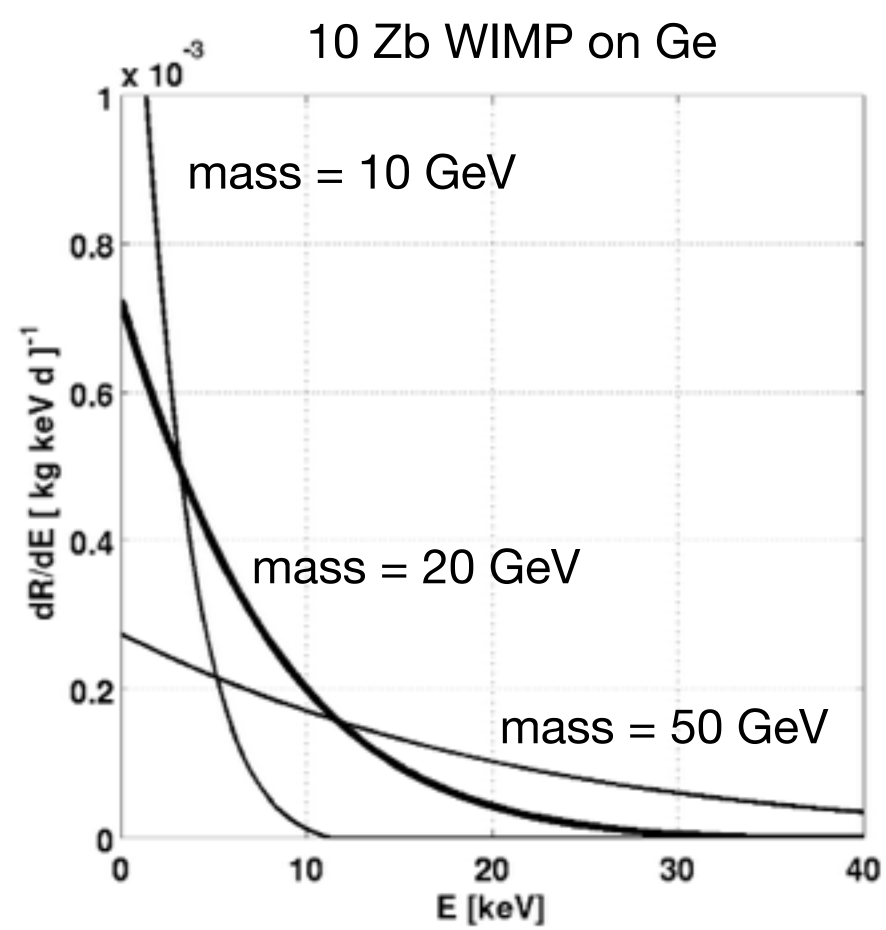
Direct detection of Dark Matter



Suggested in 1985 by M. W. Goodman and E. Witten (PRD 1985)

Differential event rate:

$$\frac{dR}{dE_r} = \frac{\sigma_0 \rho_0}{2 m_r^2 m_\chi} F^2(E_r) \int \frac{f(\vec{v})}{v} d^3 v$$



Direct detection challenge:

- Low event rate: *R < O(10) evts/kg/year*
- Mean recoil energy: ~ *O(10) keV*
- Very low background contamination
- Signal is featureless: a simple exponential

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

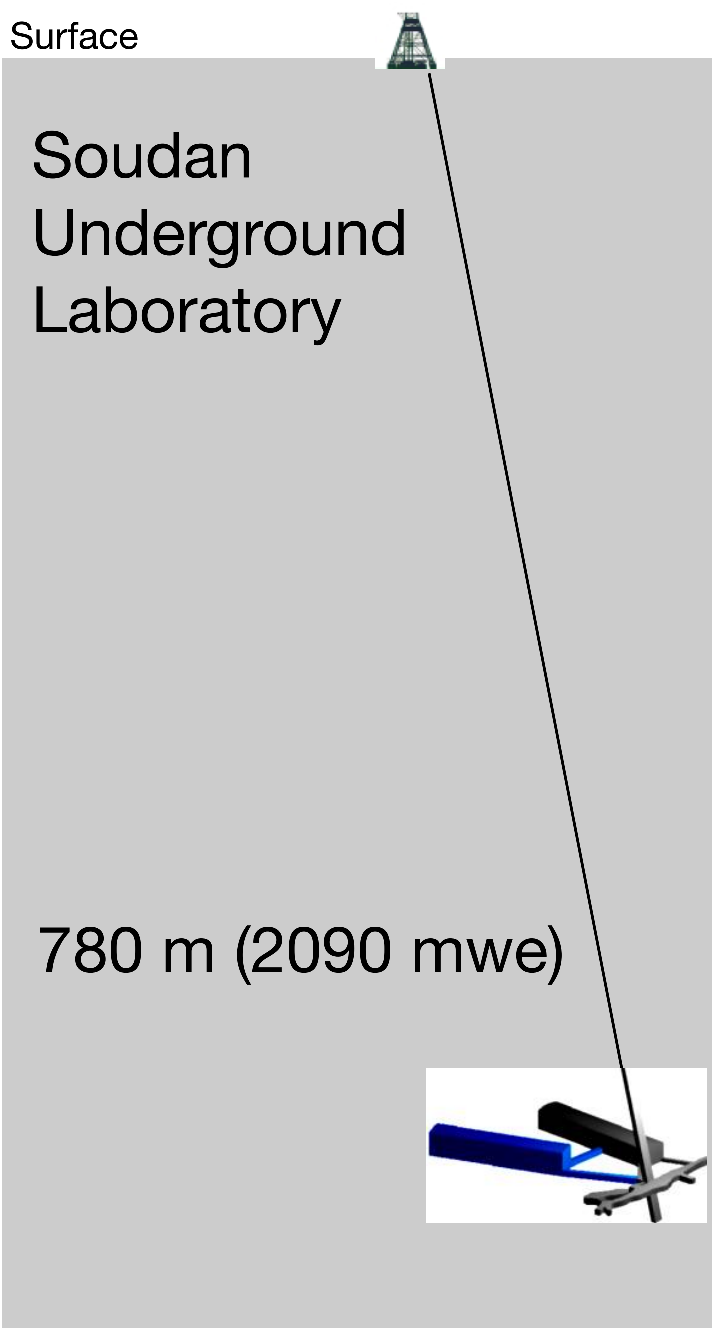
South Dakota SM&T | Stanford University | Texas A&M University | U. Autónoma de Madrid | U. British Columbia

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

21 institutions

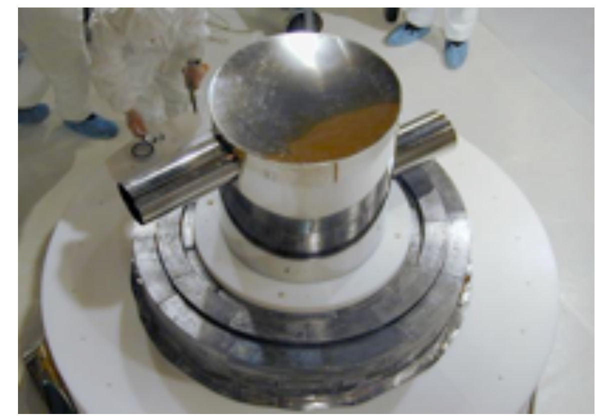
http://cdms.berkeley.edu

The SuperCDMS experiment

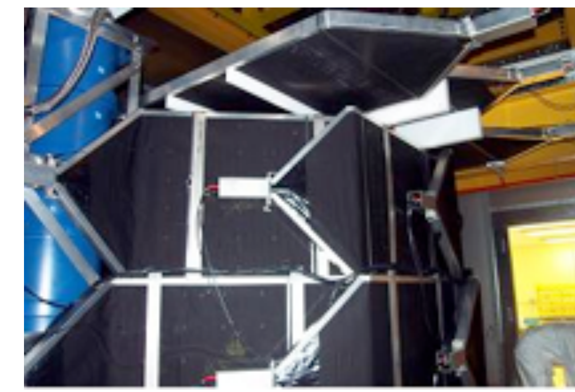


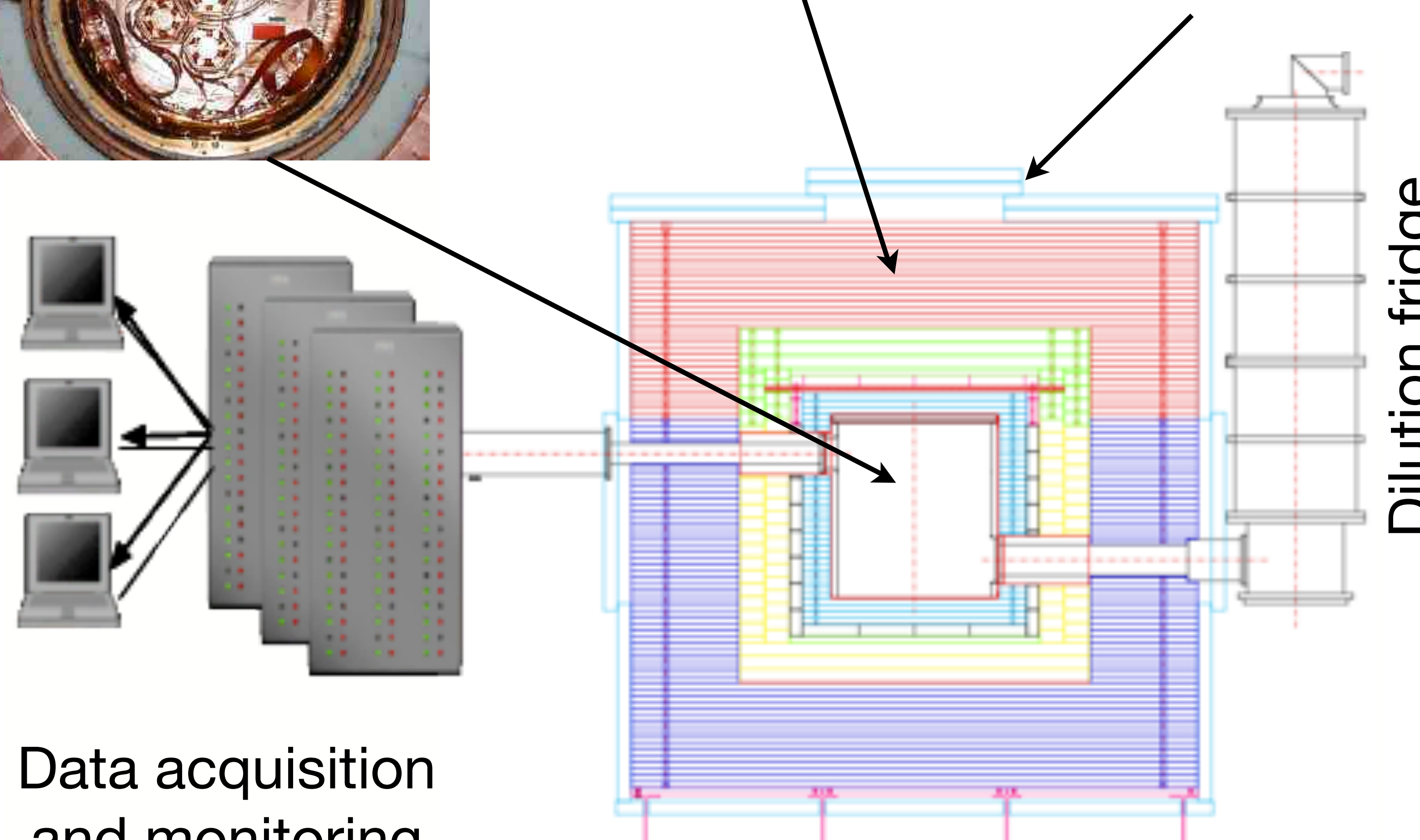
«The Icebox»
base temp. ~ 50 mK

Poly and lead shielding



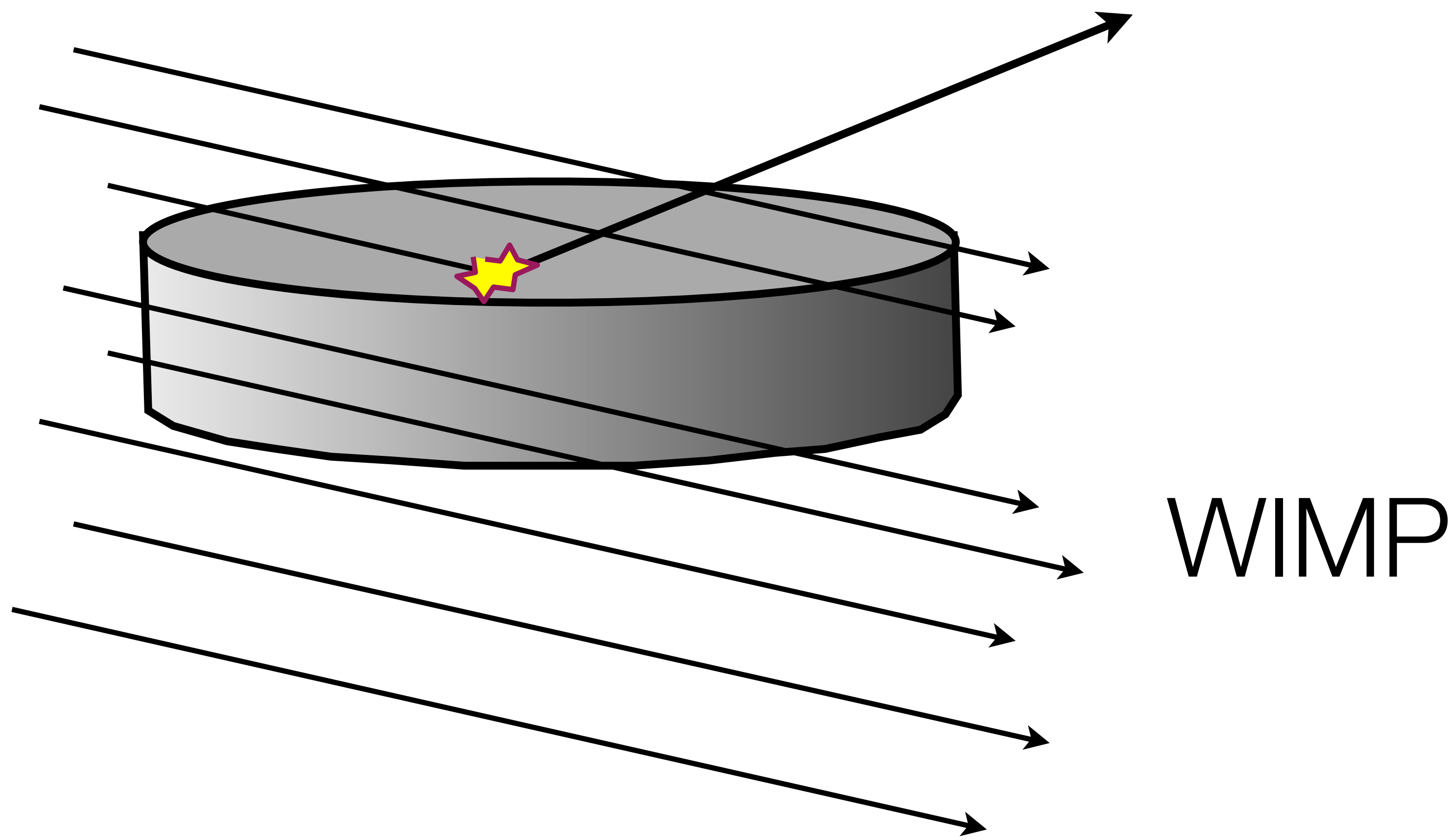
Muon veto





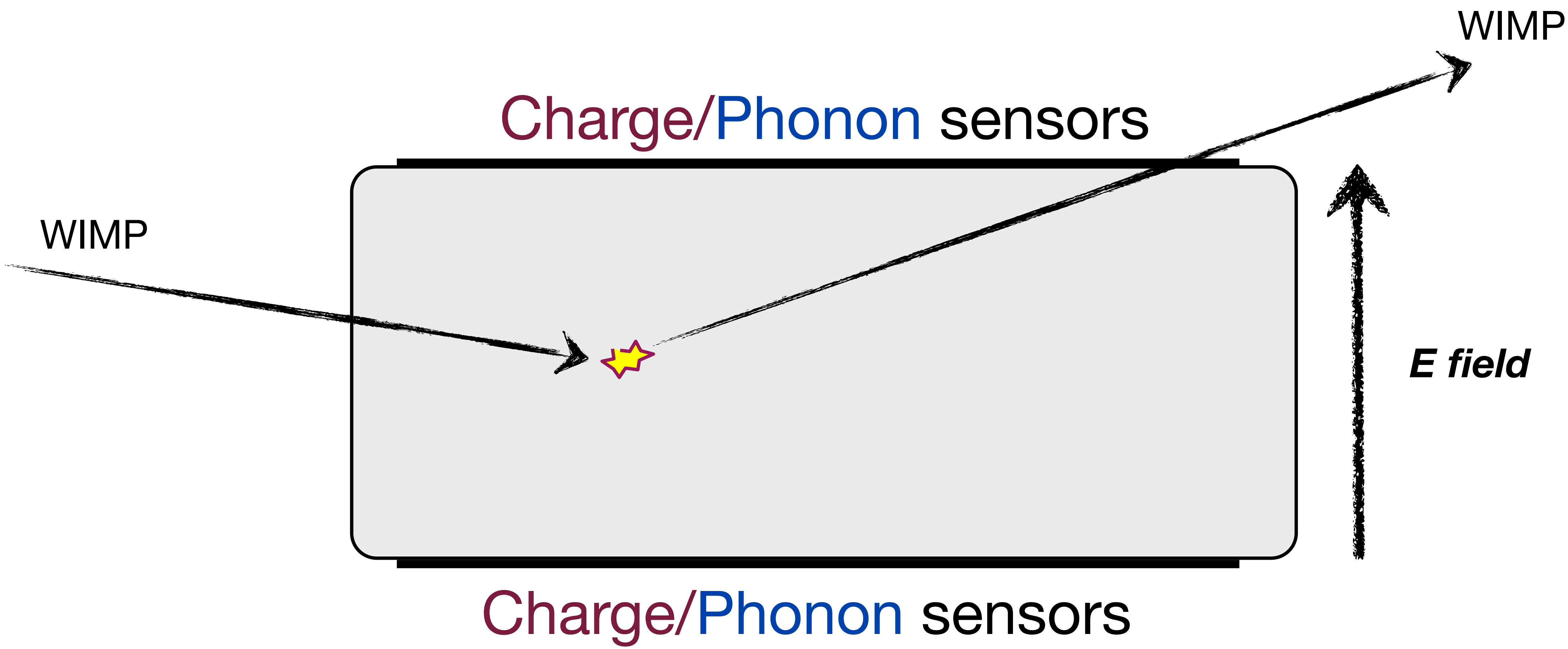
Data acquisition and monitoring

The SuperCDMS experiment

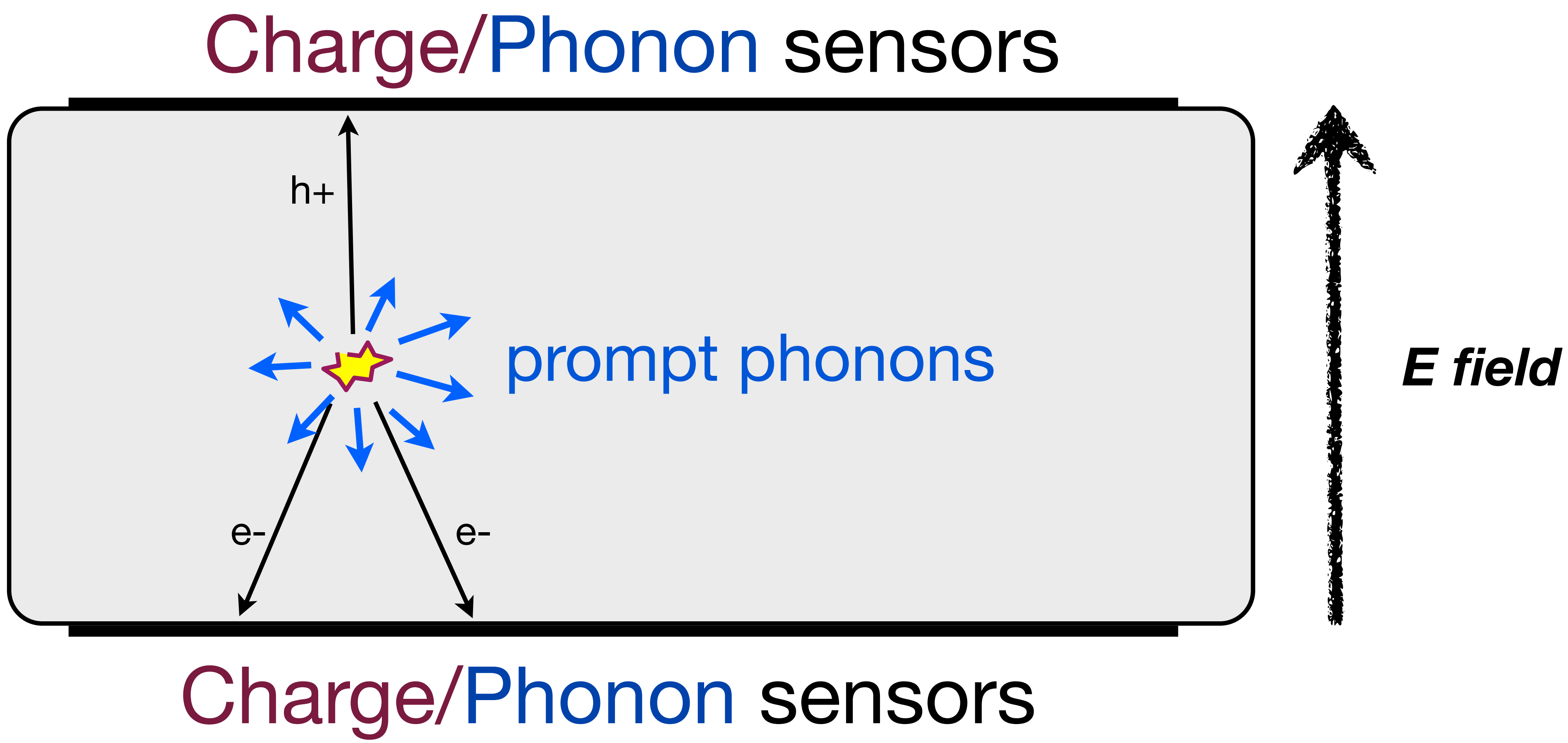


Cryogenic semiconductor detectors looking for WIMPs

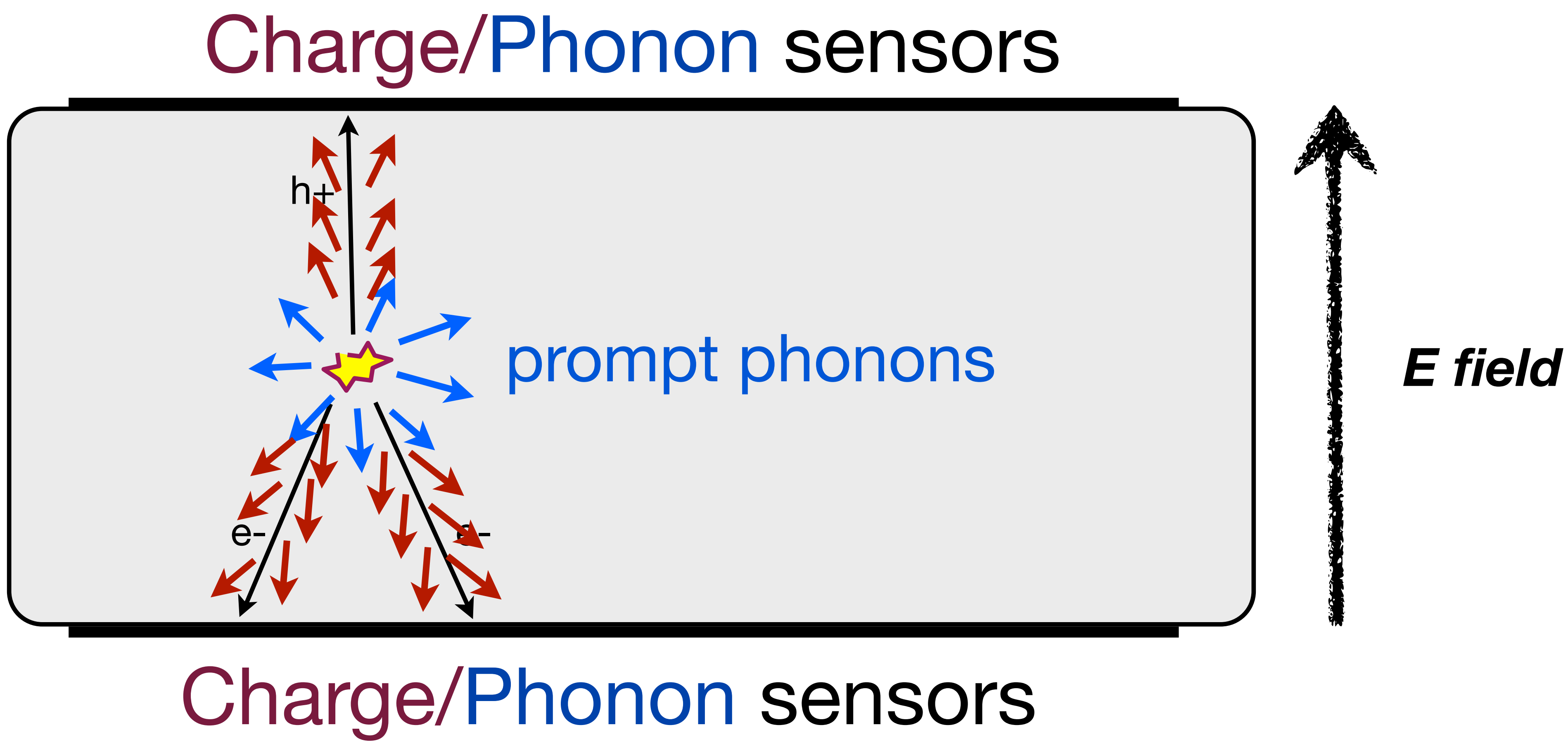
The SuperCDMS experiment



The SuperCDMS experiment



The SuperCDMS experiment



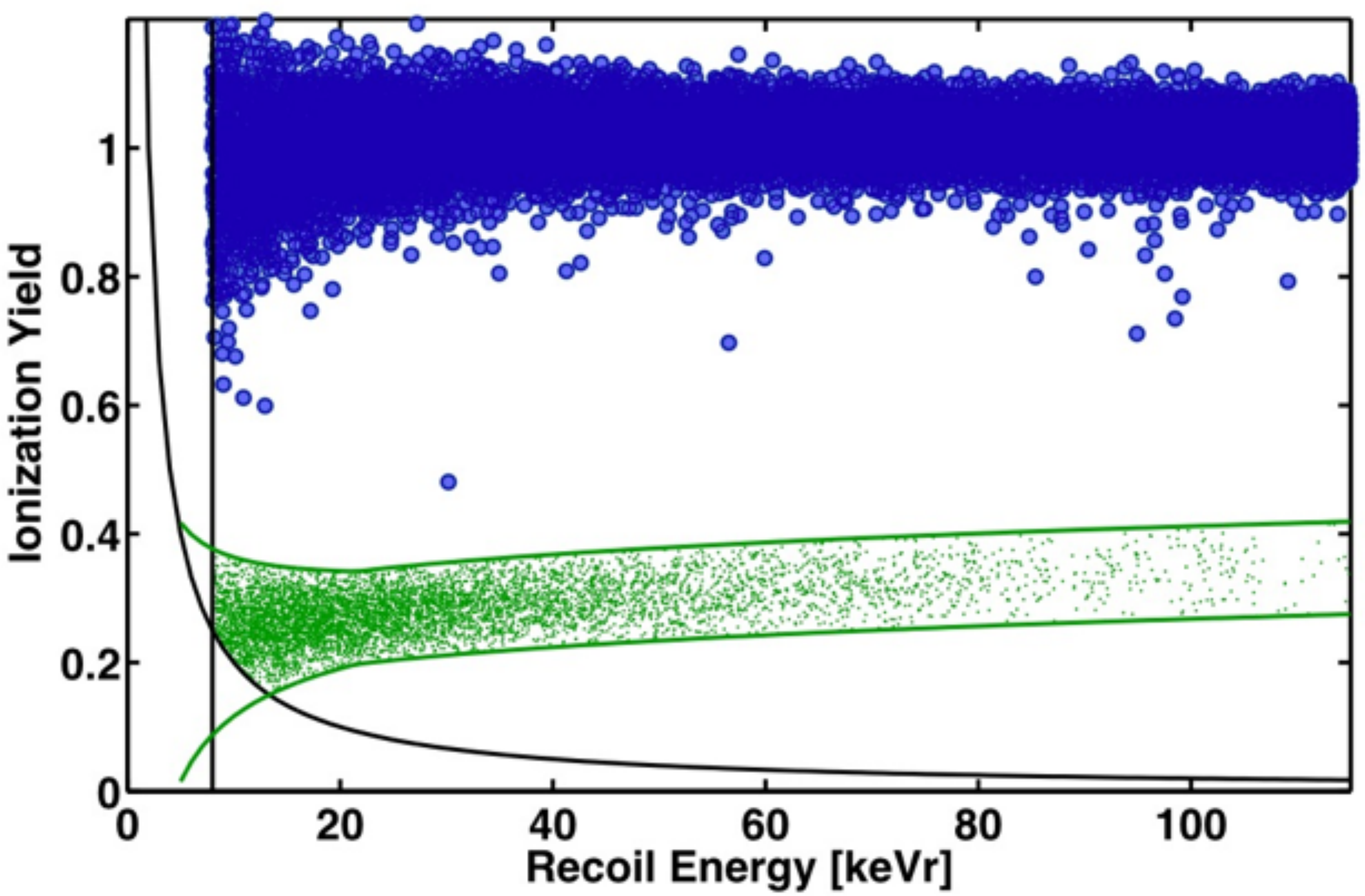
$$E_{total} = E_{recoil} + E_{luke}$$
$$= E_{recoil} + \frac{1}{3\ eV} E_Q \Delta V$$

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

$Y = E_q/E_r$



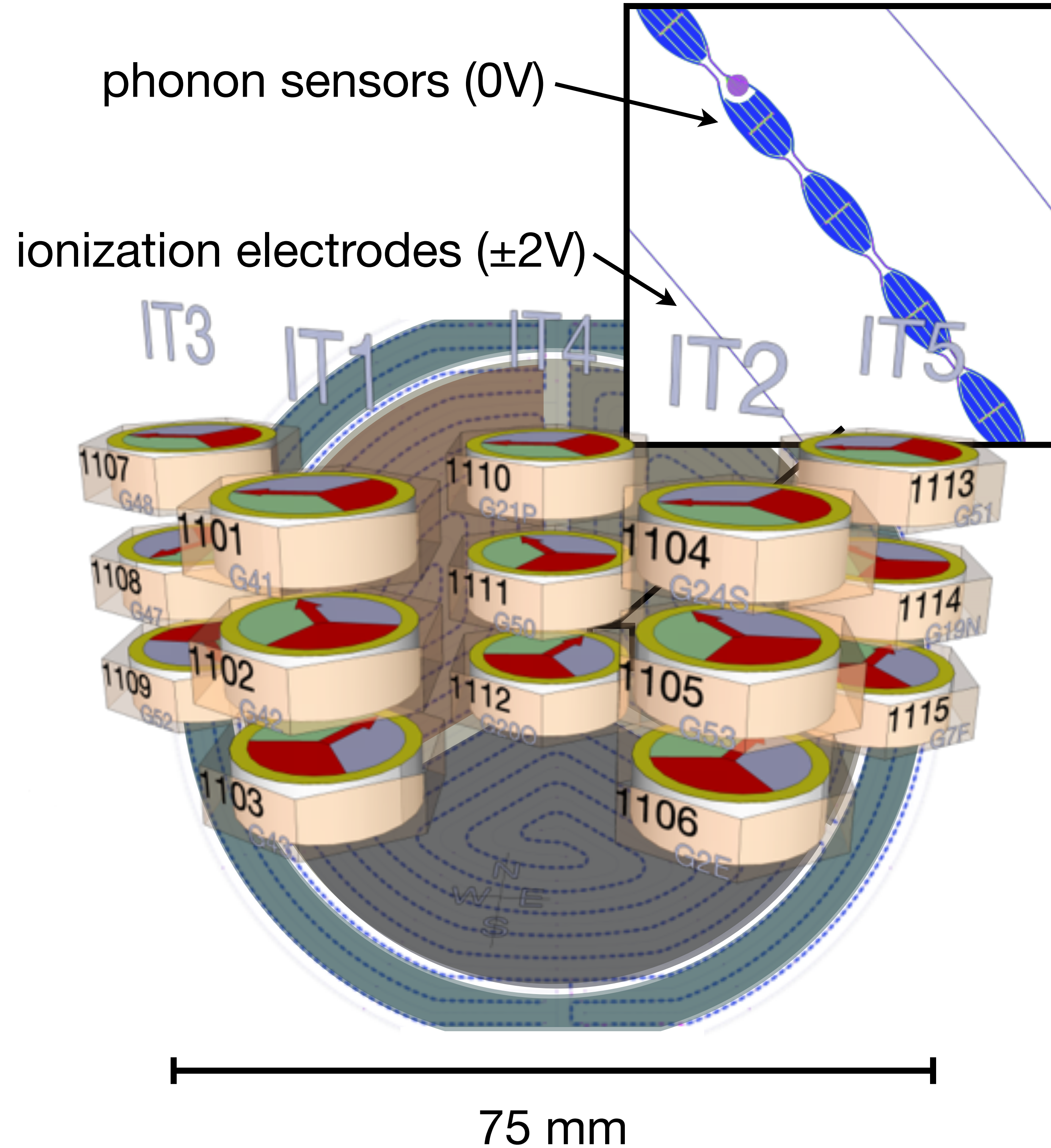
^{133}Ba calibration γ

^{133}Ba surface events

^{252}Cf calibration *n*

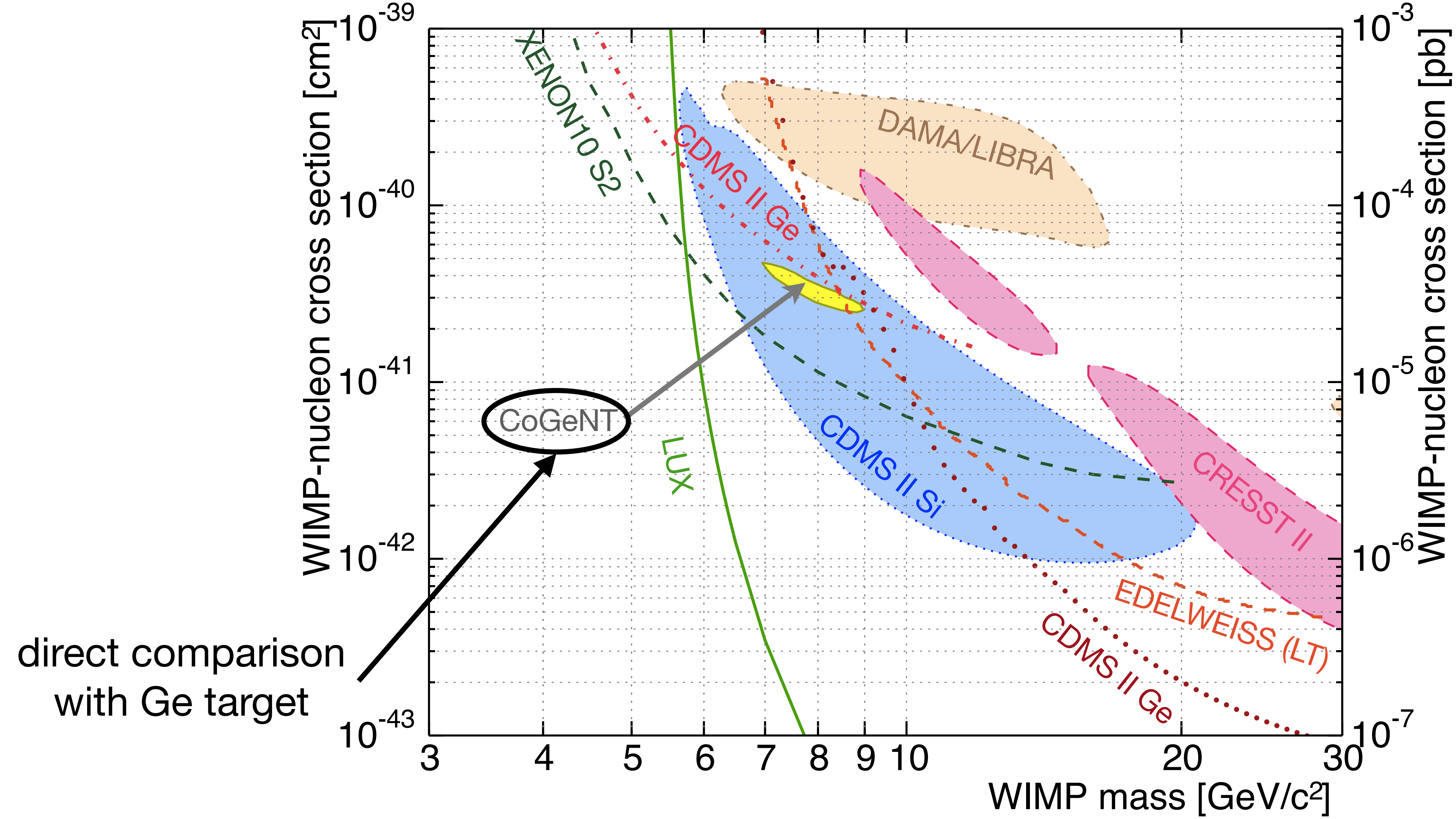
The SuperCDMS experiment

- 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”?



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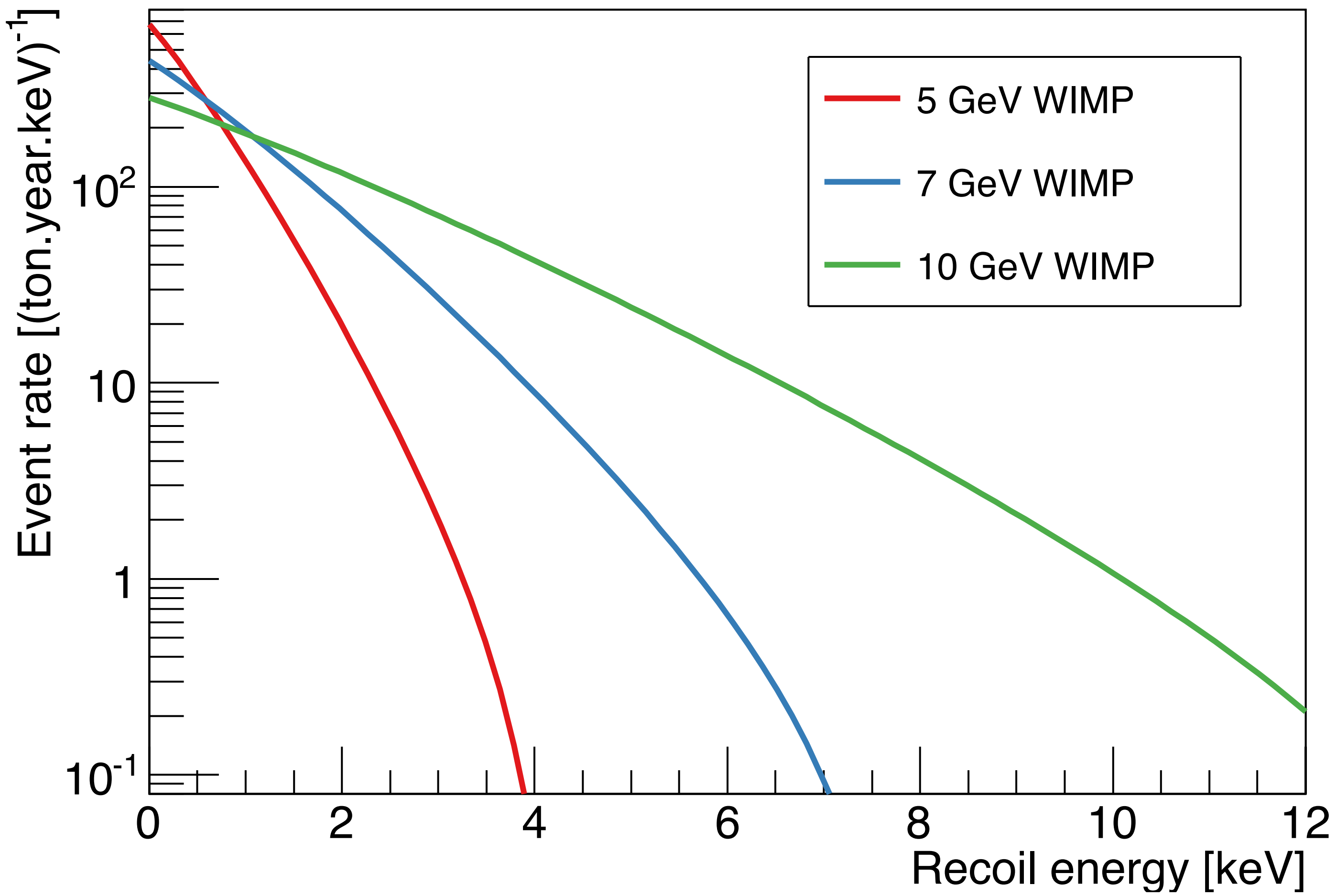
Strategies for Light WIMP Searches

Lowering the energy threshold is the key for light WIMP searches



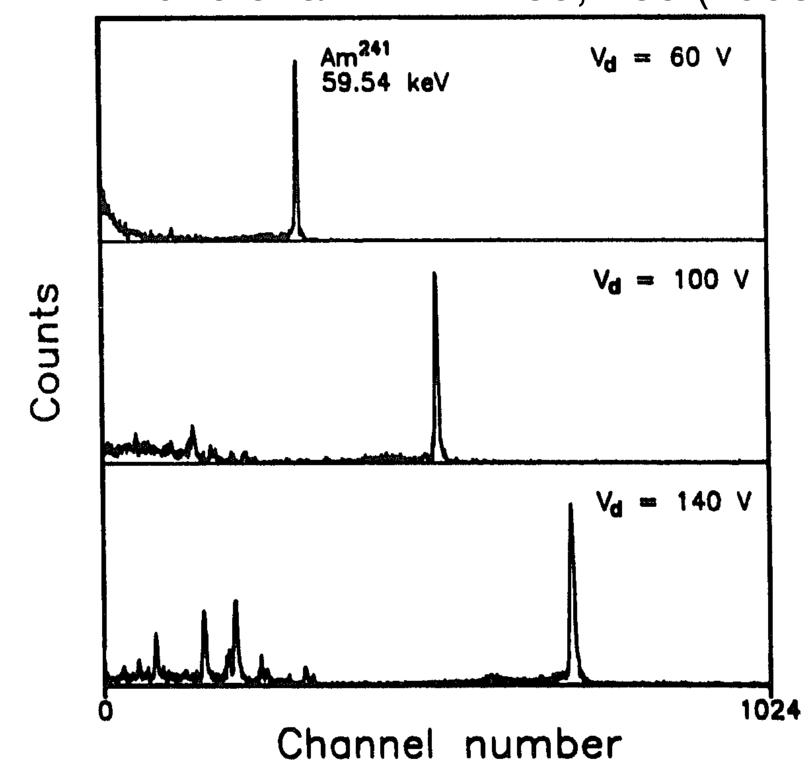
1. CDMSLite: Amplification of the signal to reduce the effective threshold

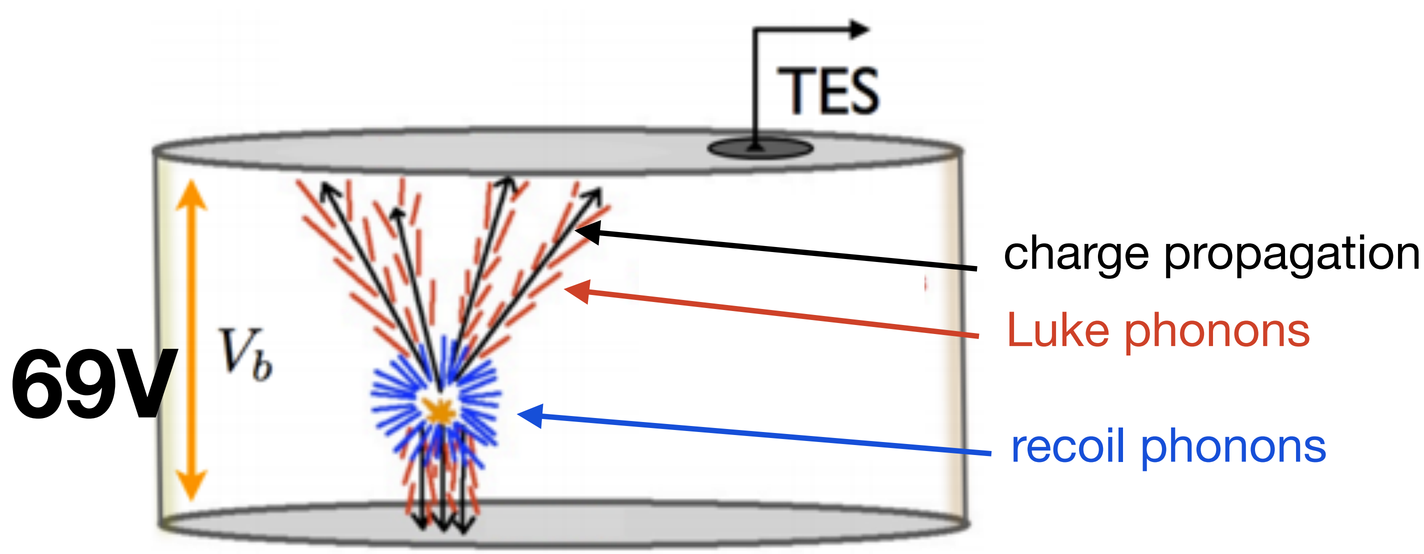
CDMSLite: first result!

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

- Measure charge with phonons, and increase voltage to amplify signal
- Achieve lower ionization energy threshold but « lose background identification »

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

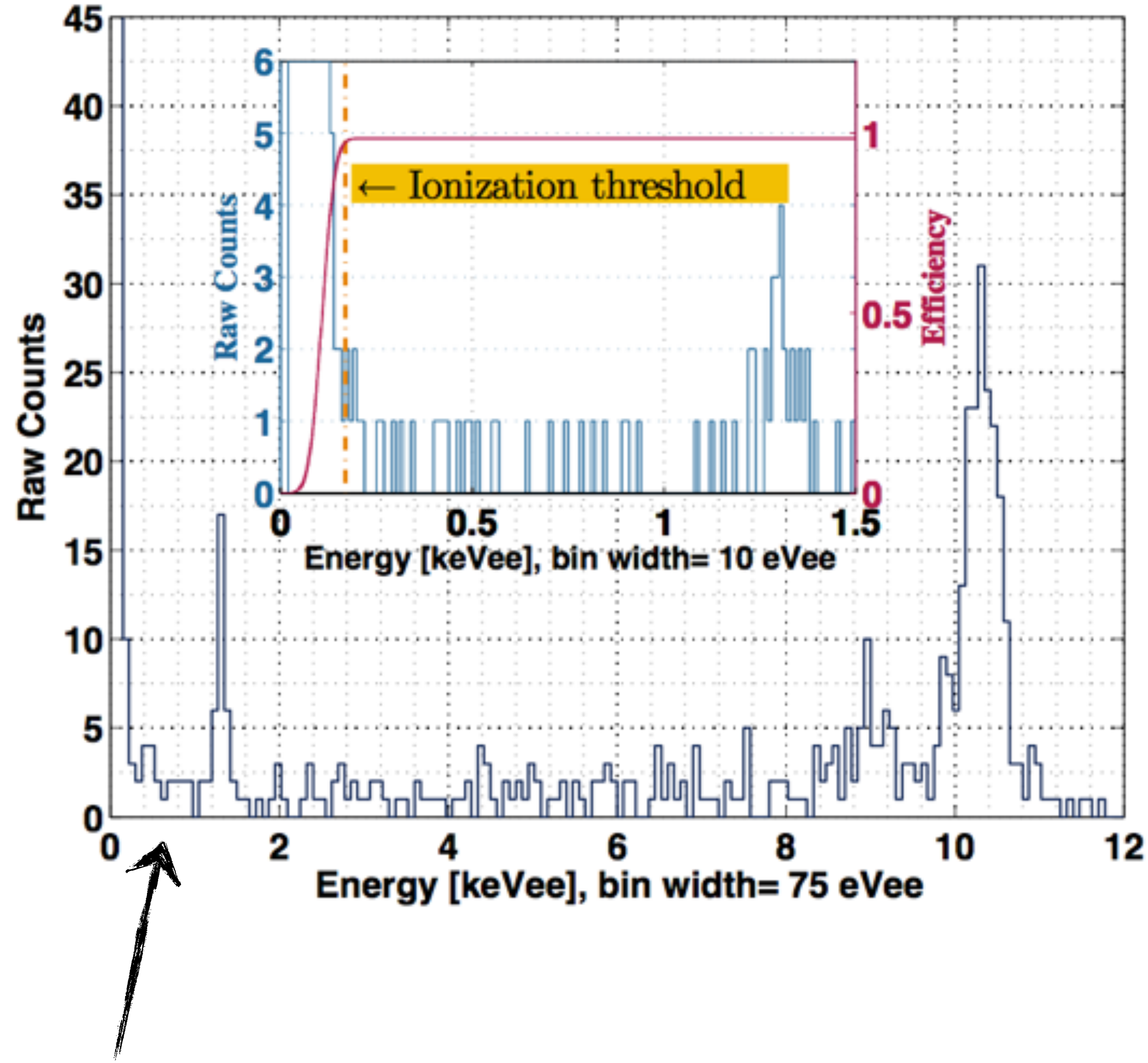




- Optimization of the bias voltage using the signal-to-noise ratio of the phonon signal
- Operated stably at 69V leading to **24x** amplification (**12x** effective)

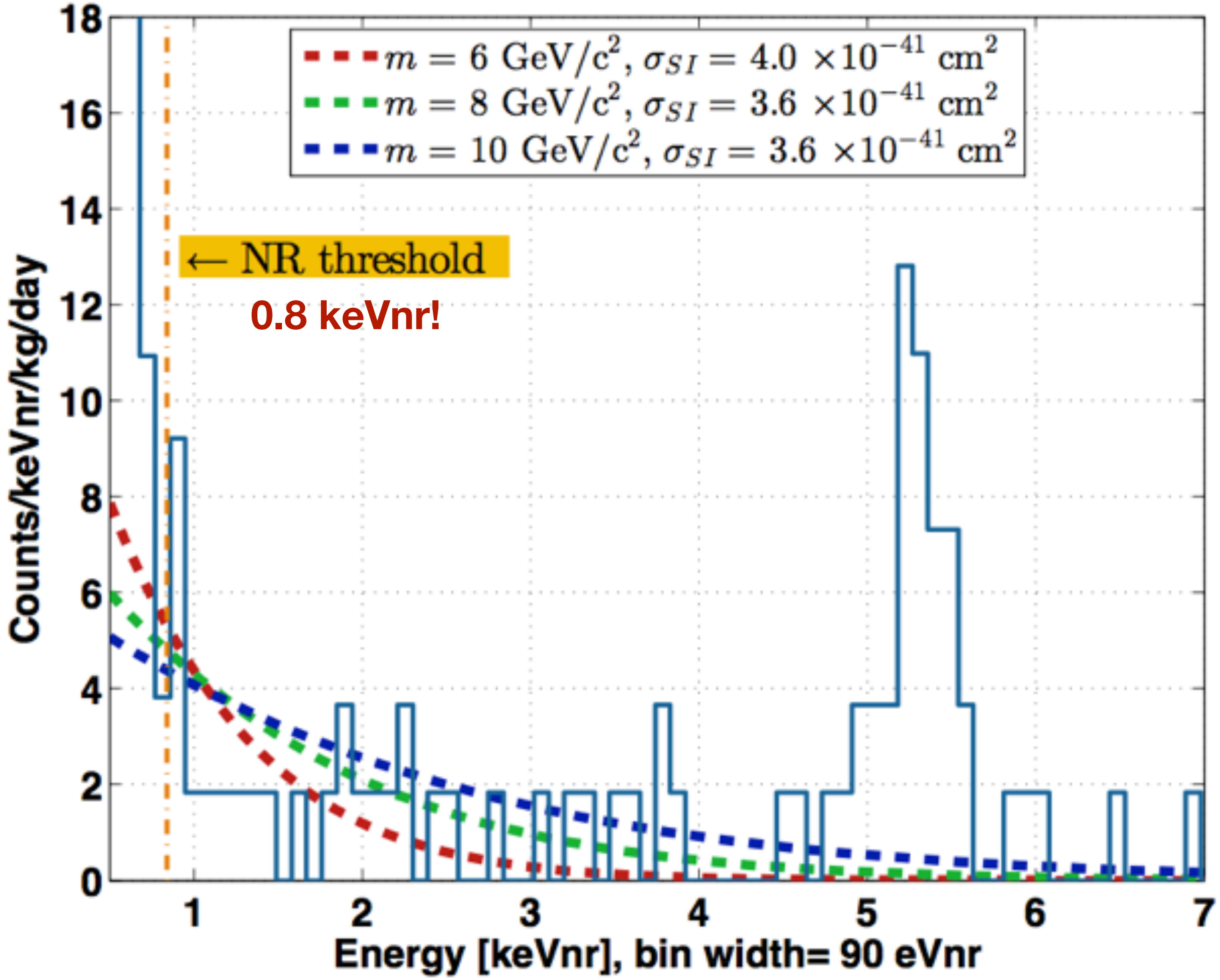
CDMSLite: first result!

- Calibration done using the Ge activation line at 10.36 keVee
- Energy threshold of 170 eVee!!
- Total efficiency about 98.5% above threshold
- Total exposure after data quality cut applied about 5.9 kg-days



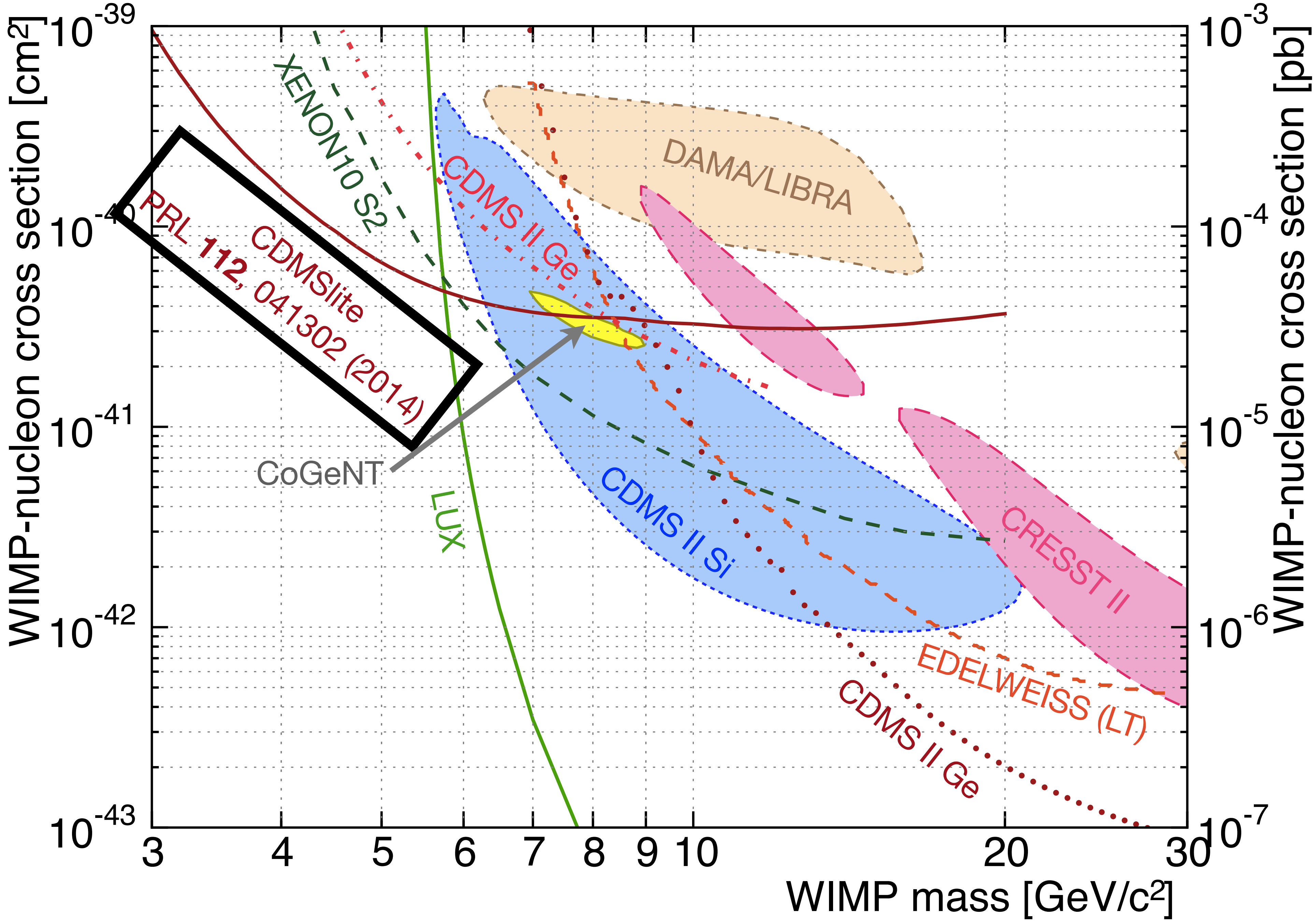
Energy range of interest for low WIMP mass

CDMSLite: first result!



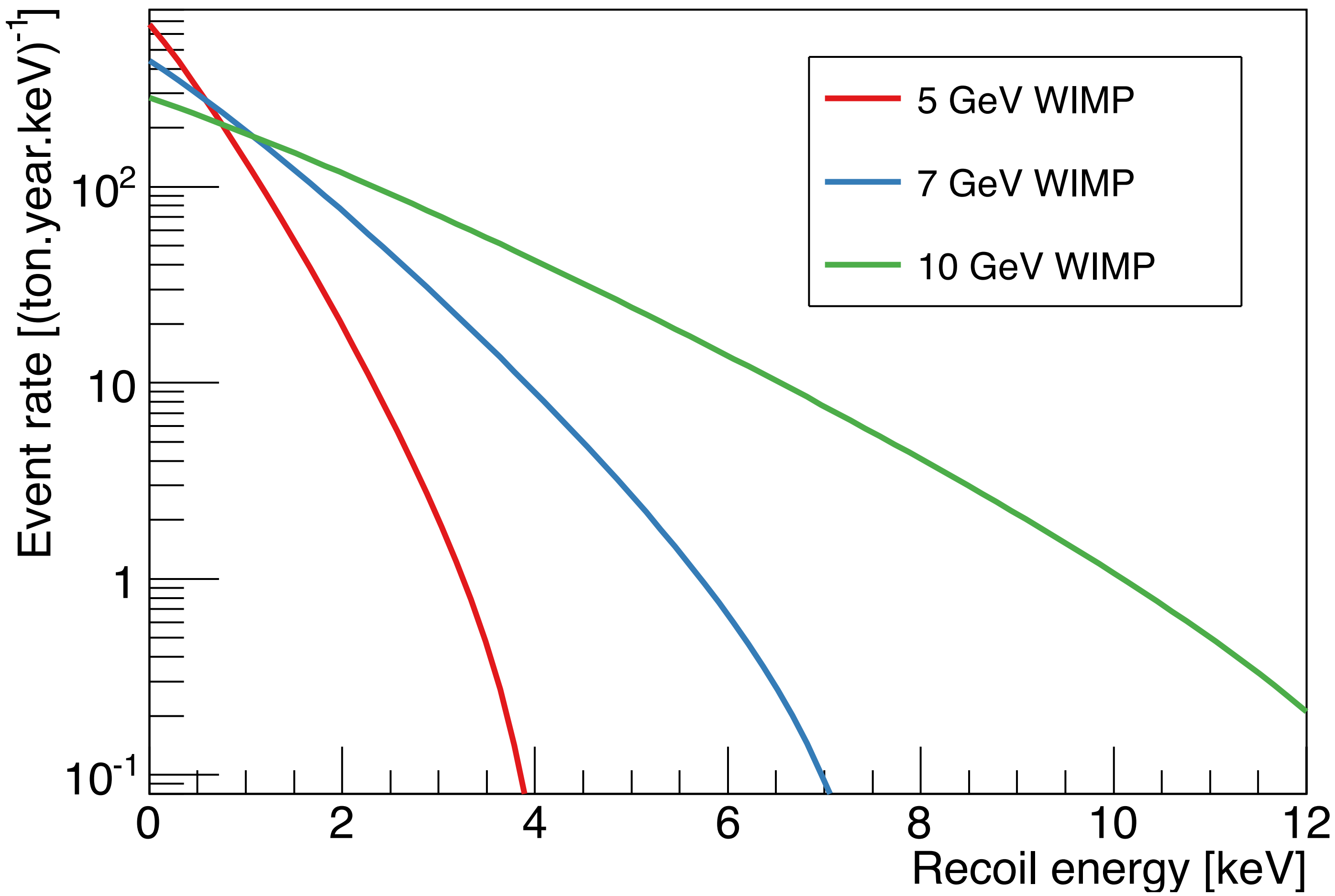
Conversion from eVee to eVnr following Lindhard's prediction

CDMSLite: first result!



Strategies for Light WIMP Searches

Lowering the energy threshold is the key for light WIMP searches



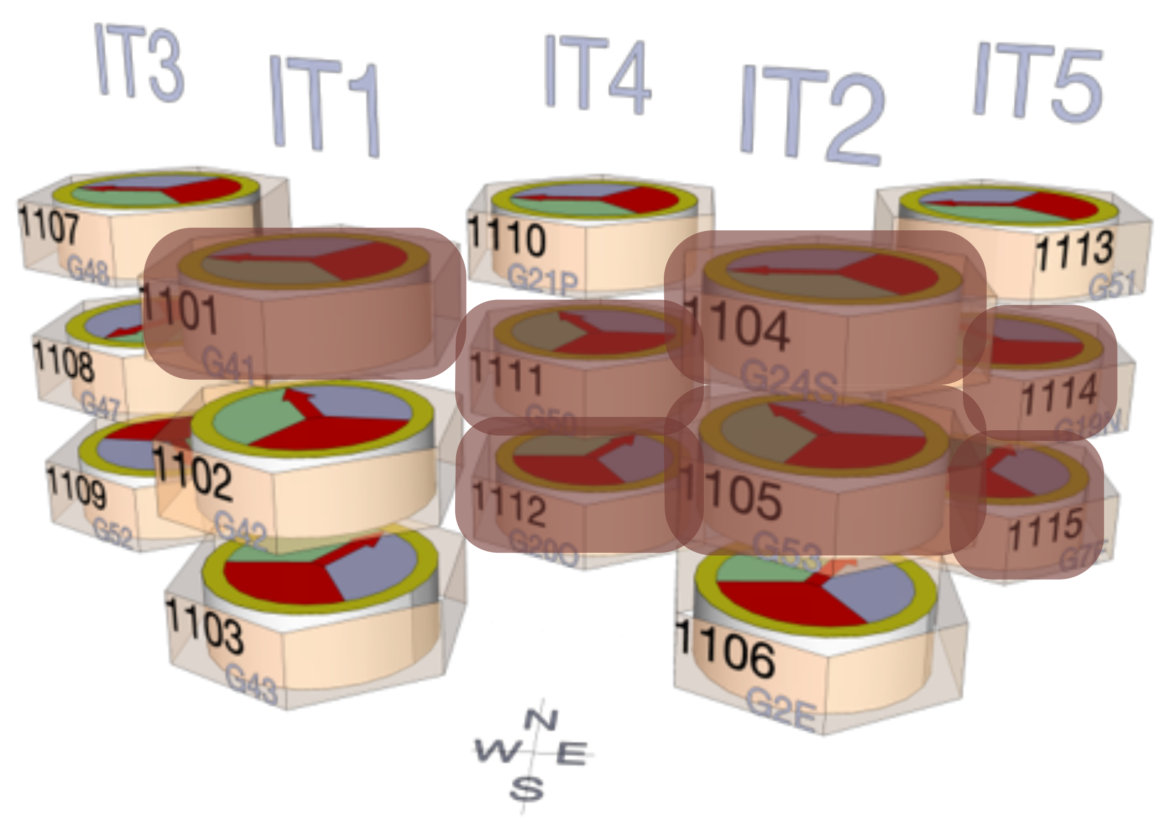
1. CDMSLite: Amplification of the signal to reduce the effective threshold

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**

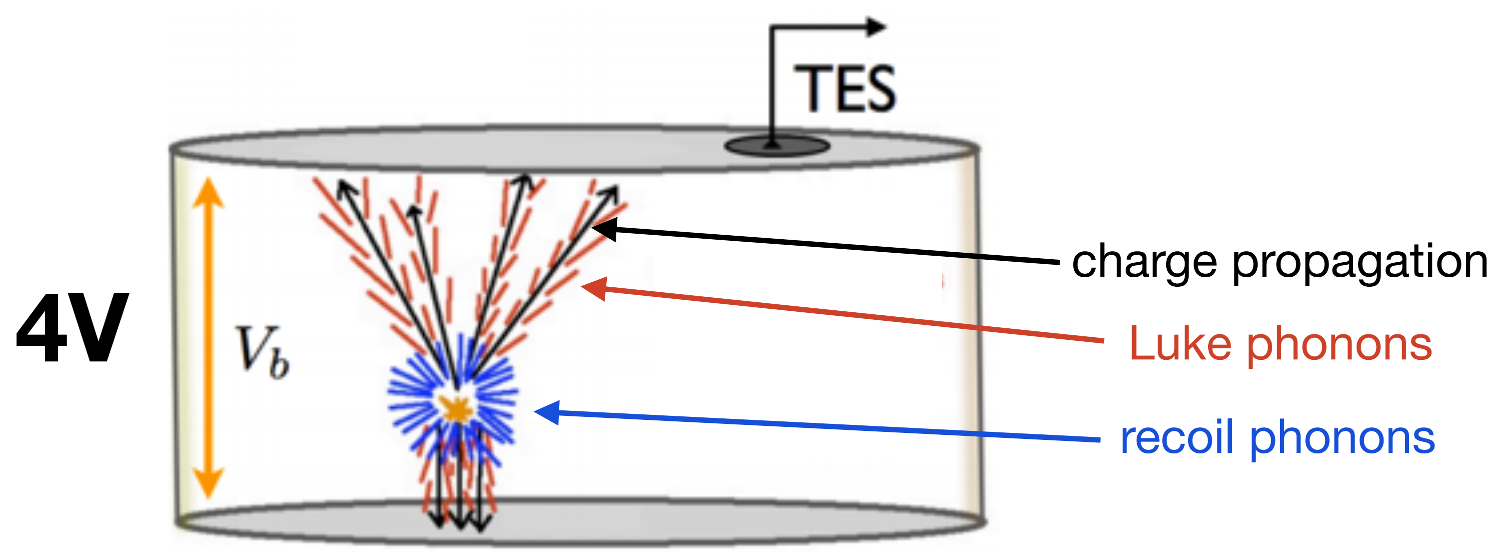


Calibration and Energy Scale

$$E_t = E_r + E_L$$

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

- Since signal-to-noise is poor, fit mean ionization 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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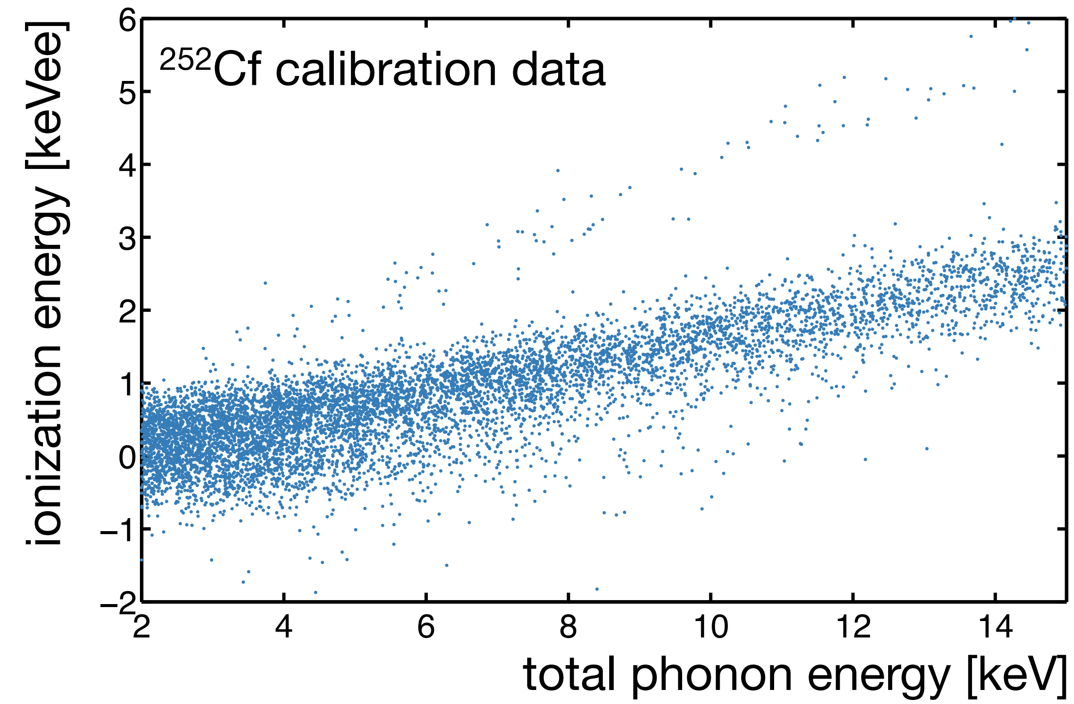
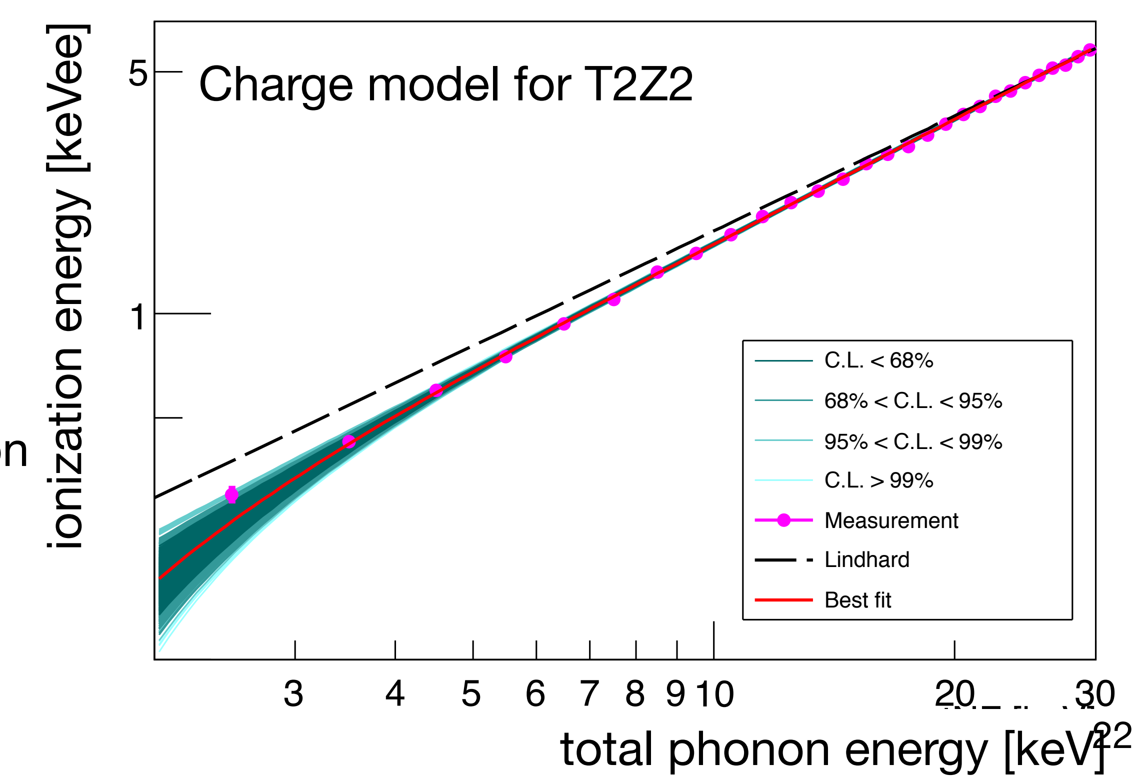
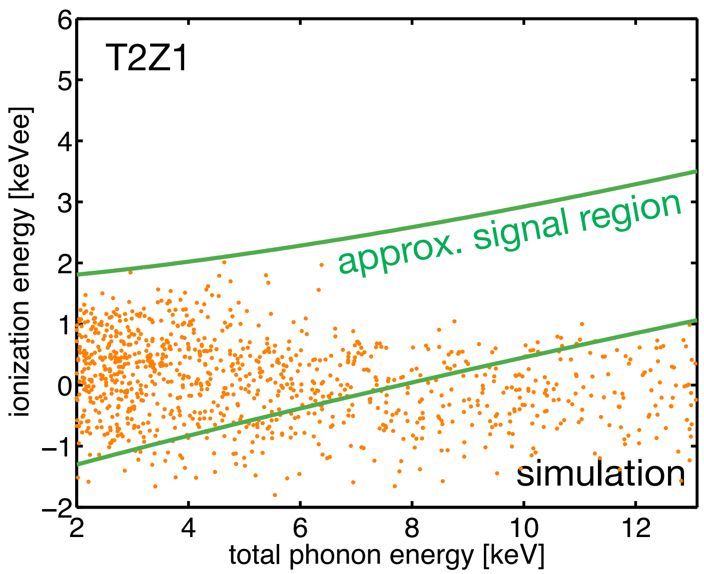


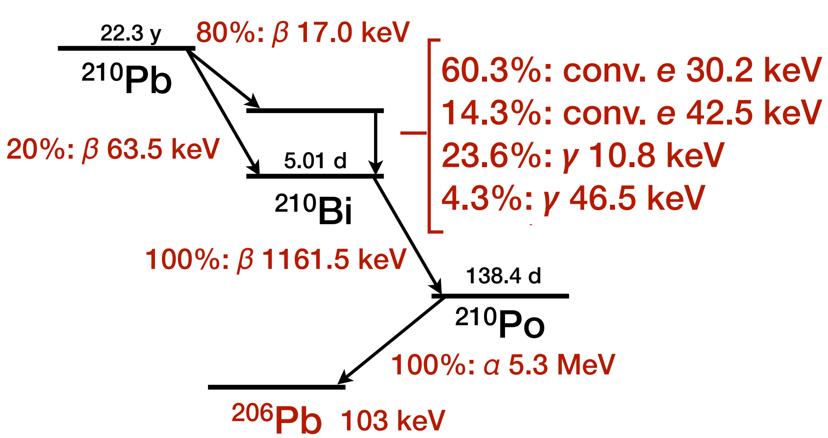


Low Threshold analysis

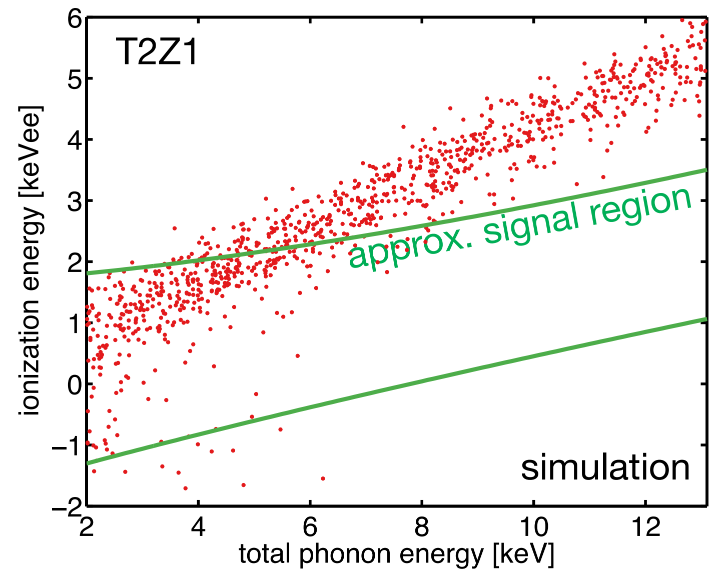
^{210}Pb "surface events"



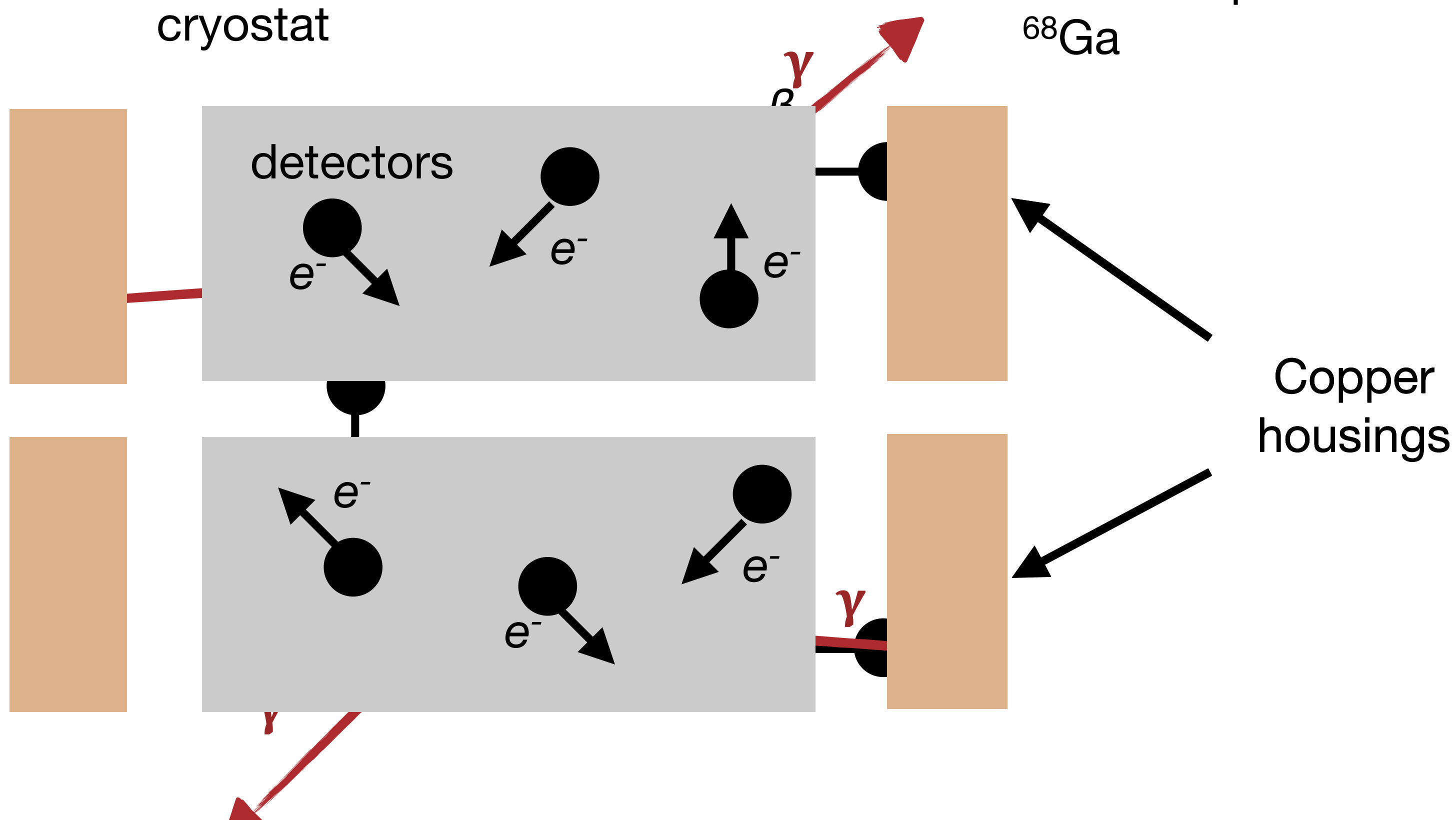
- betas and ^{206}Pb nuclei from ^{210}Pb decay chain
- events are located on detector face and sidewall ***surfaces*** from ^{222}Rn contamination



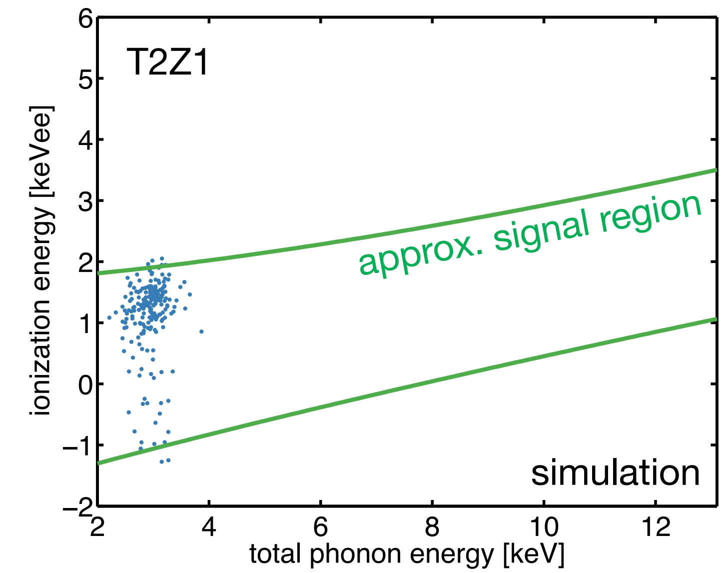
External gammas



- from radioactivity in shielding and cryostat



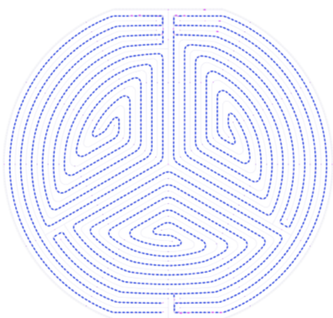
Internal activation lines



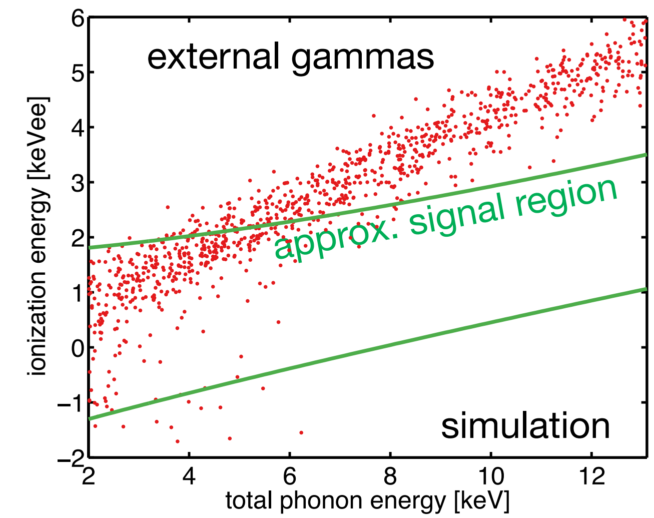
- L-shell capture from ^{68,71}Ge, ^{65}Zn, ^{68}Ga

Low Threshold analysis

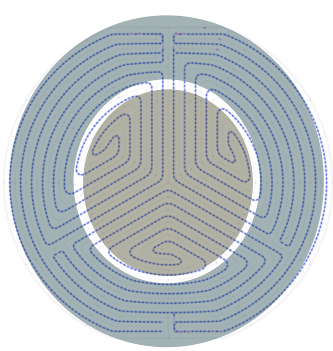
- Total phonon energy
- Ionization energy



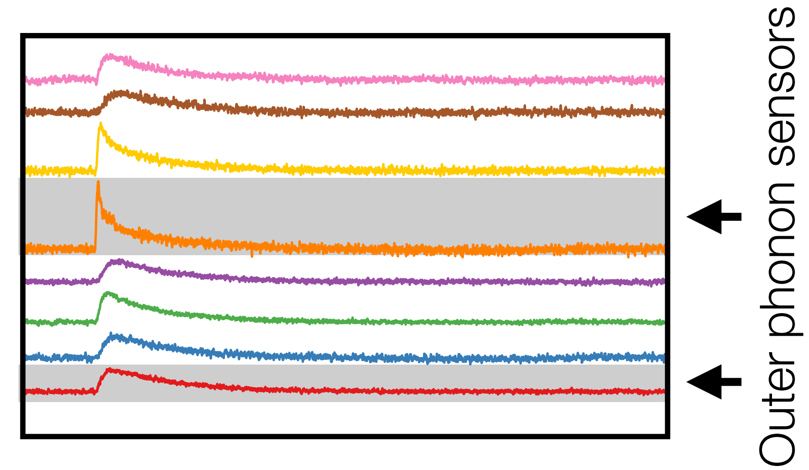
Bulk electron recoils



- Phonon « r-partition »

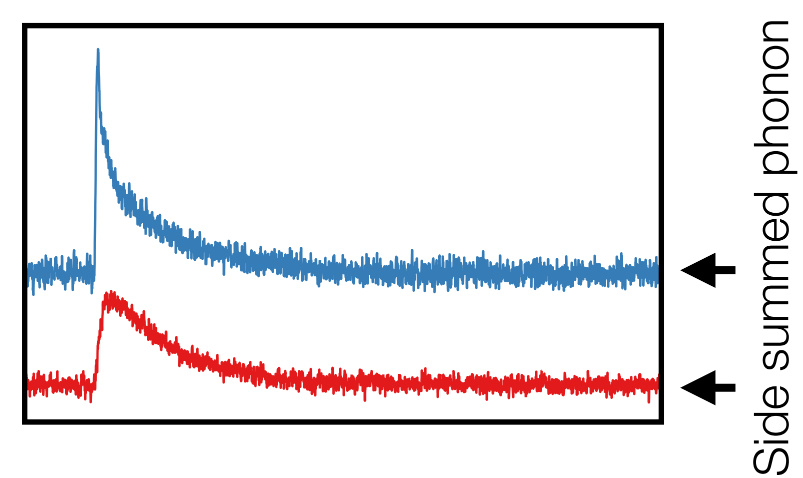


Low energy sidewall events



- Phonon « z-partition »

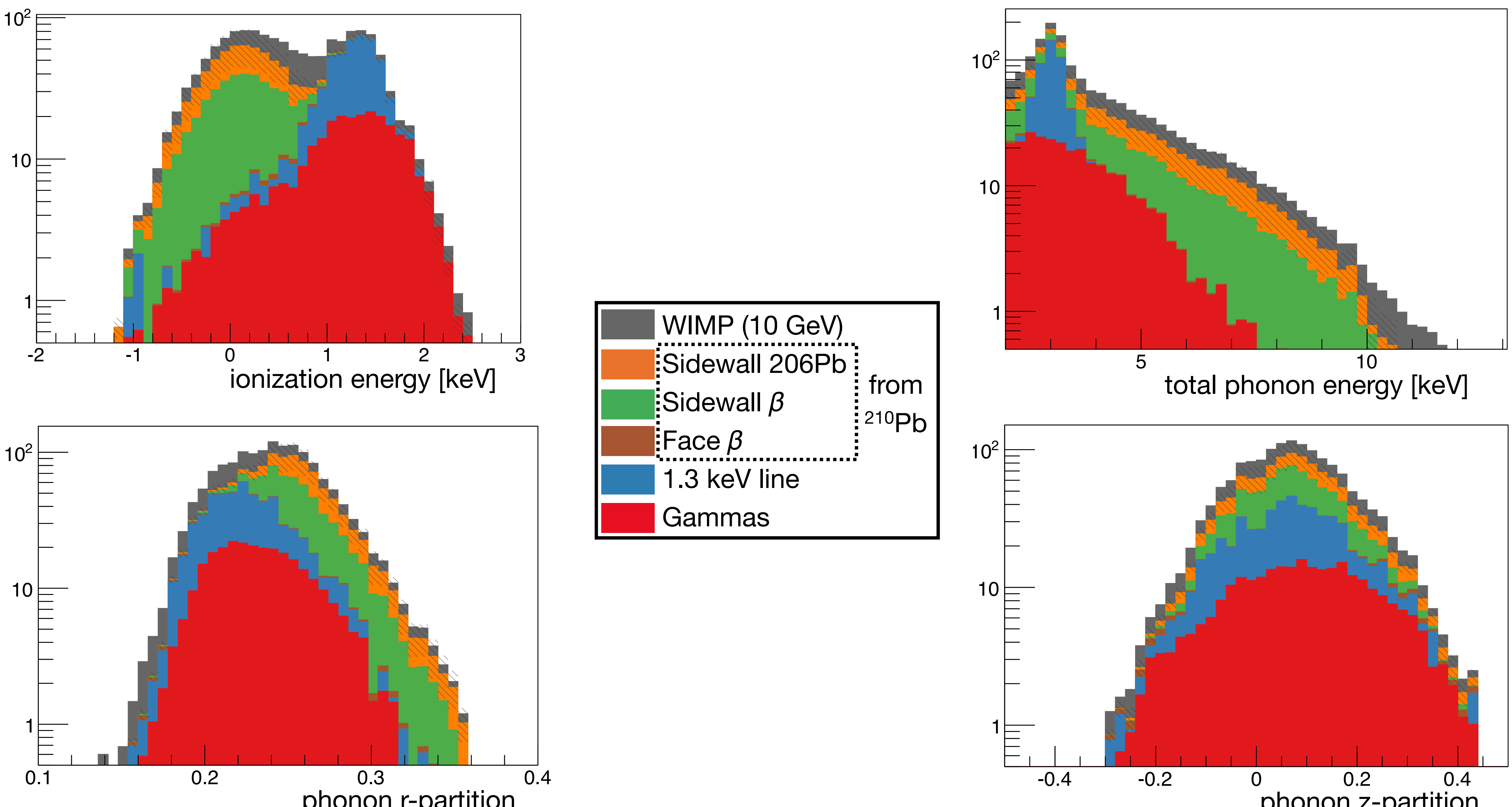
Low energy surface events



Low Threshold analysis

Background model: pulse simulation

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



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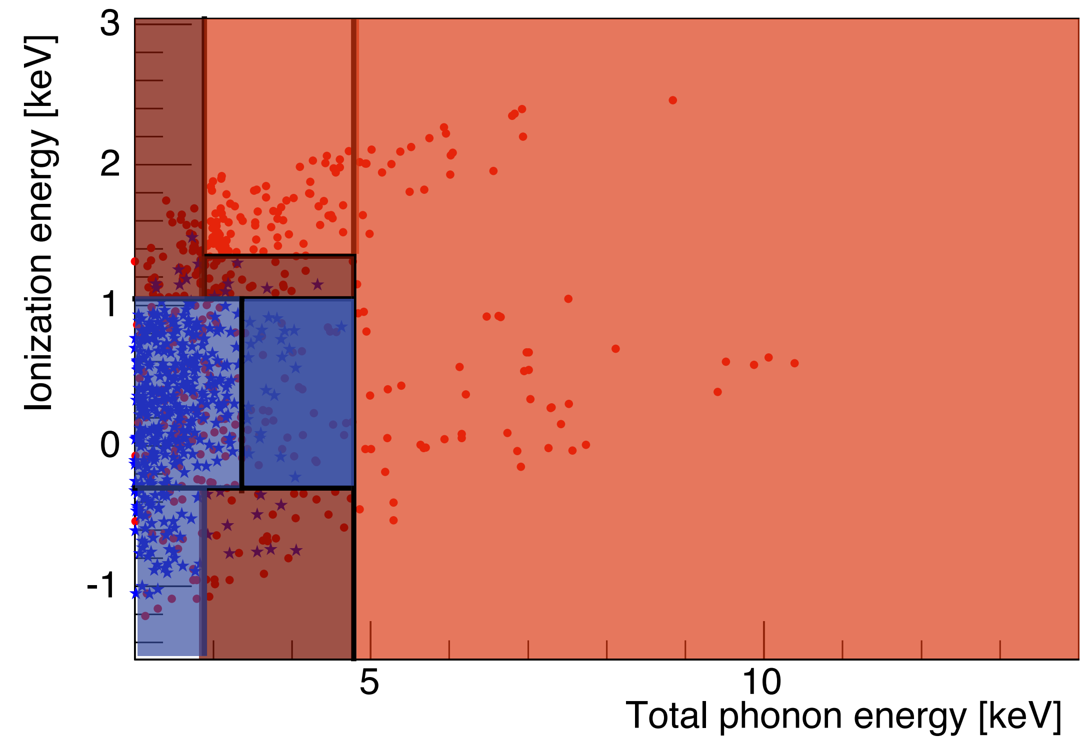
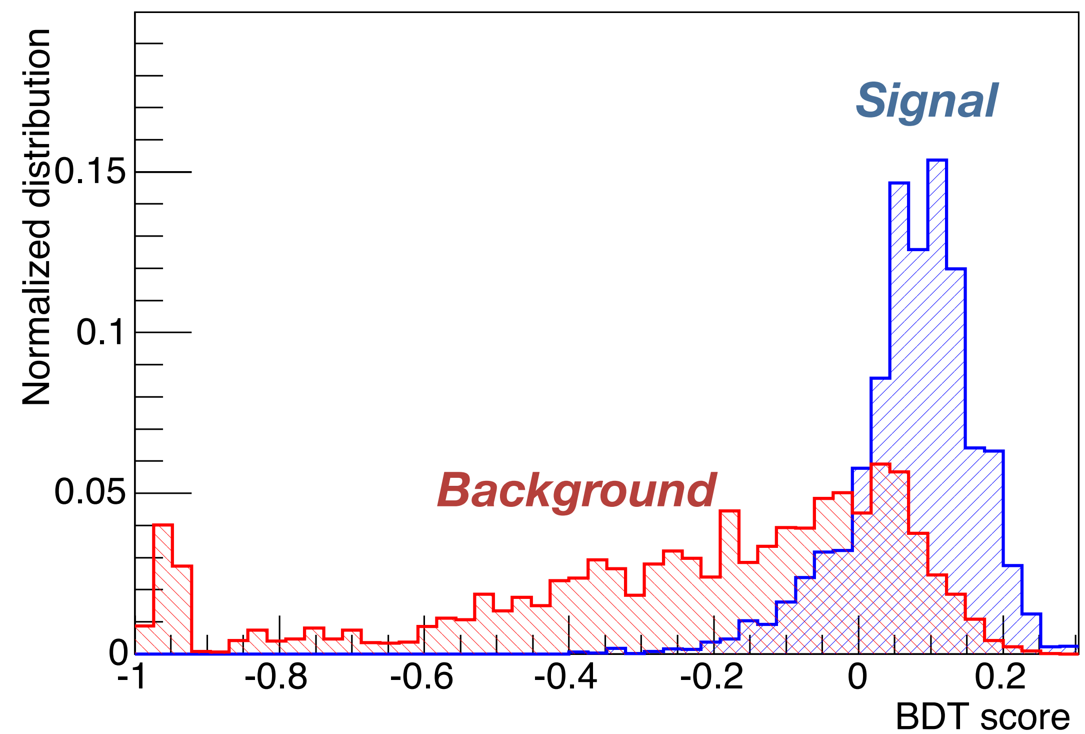
Low Threshold analysis

Improvement of the candidate event selection using Boosted Decision Trees

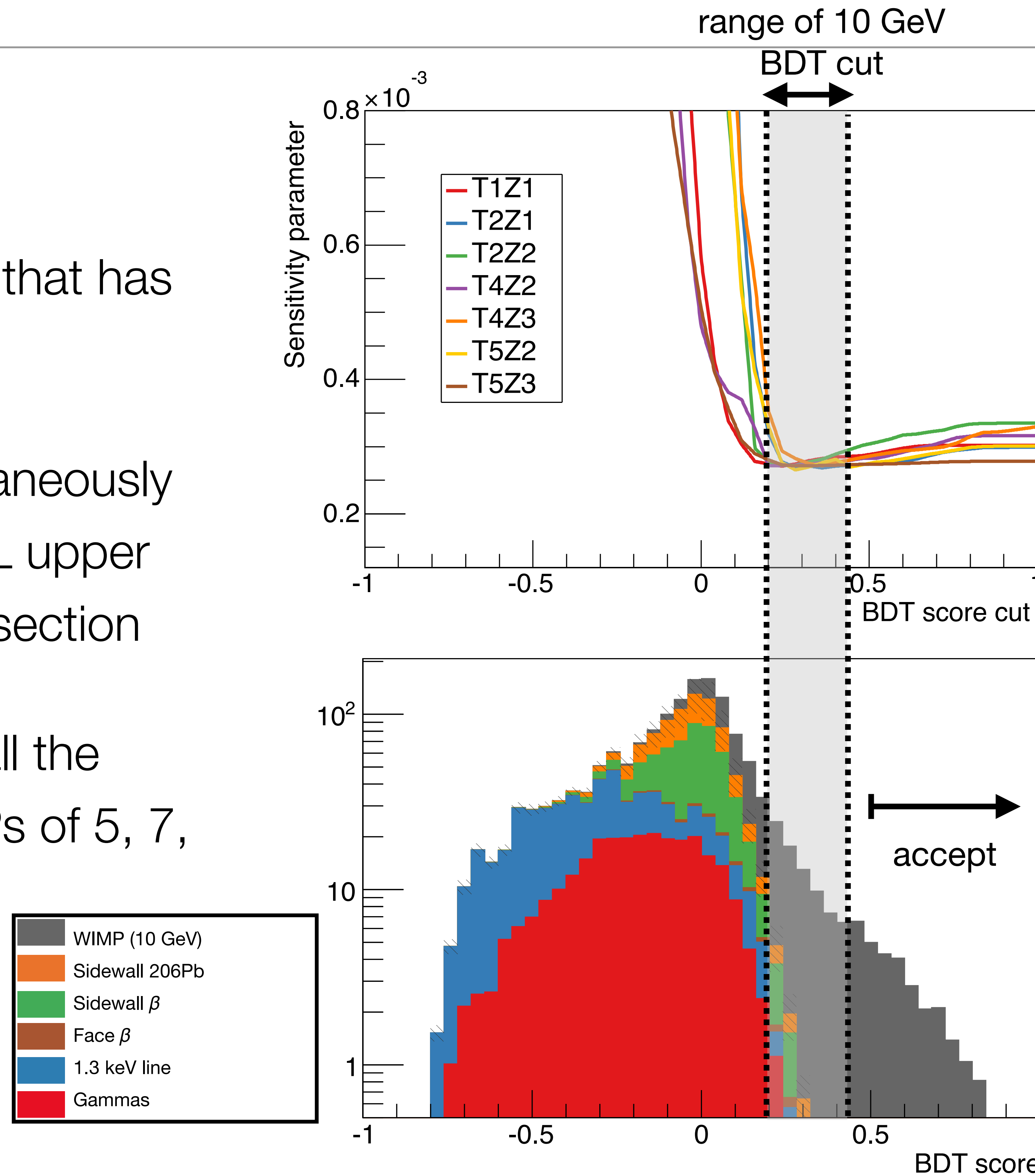
- Decision trees are a set of linear cuts in multidimensional space to optimize **signal**/ **background** discrimination
- Construction of a « forest » of trees where misclassified events are given a higher weight for the following decision tree (*boosting*)
- Reduces the dimensionality of the parameter 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

- 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



Low Threshold analysis

Quality

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

Thresholds

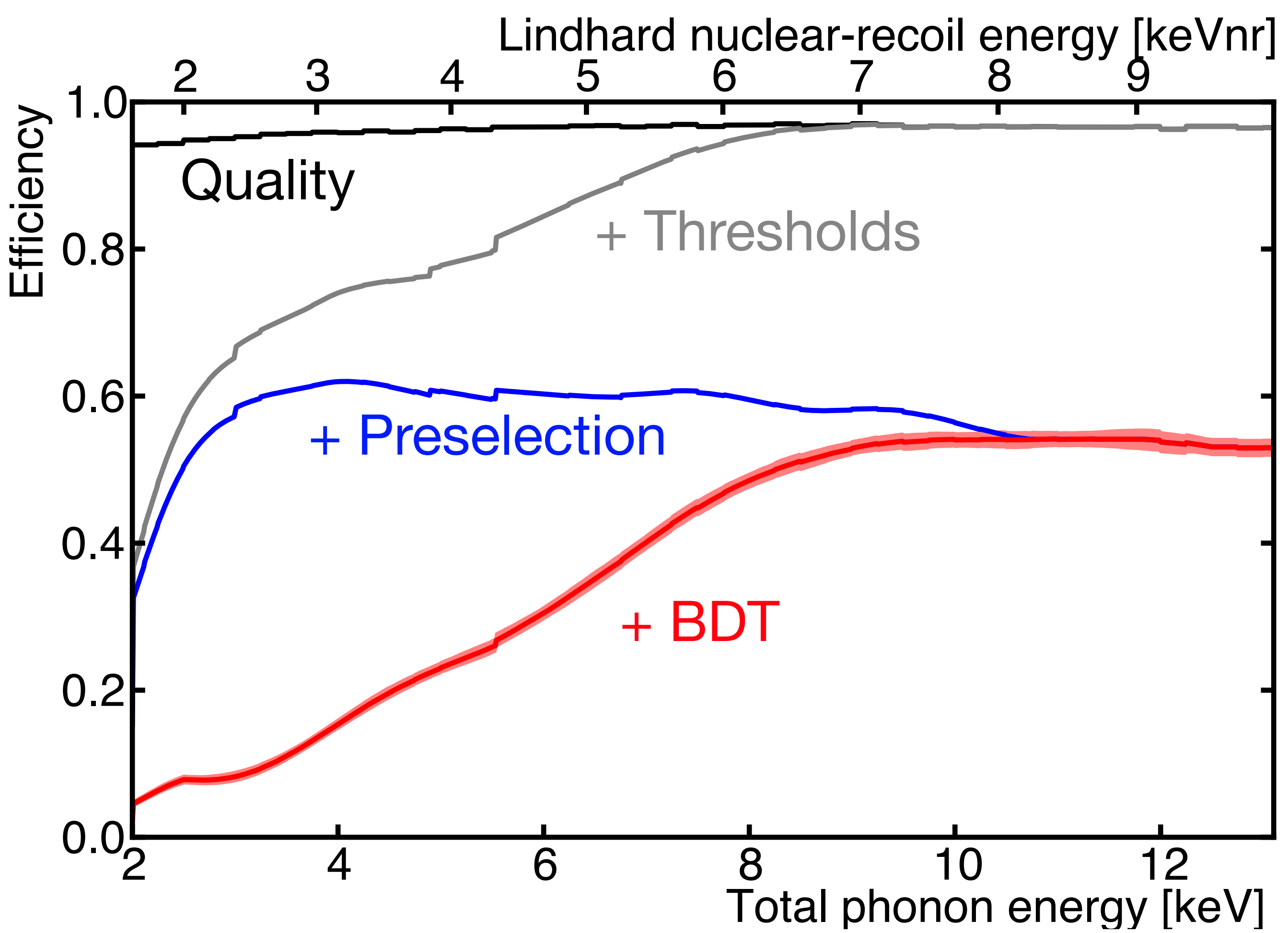
- Trigger and analysis thresholds 1.6-5 keVnr
- Measure efficiency using ^{133}Ba calibration data

Preselection

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

BDT

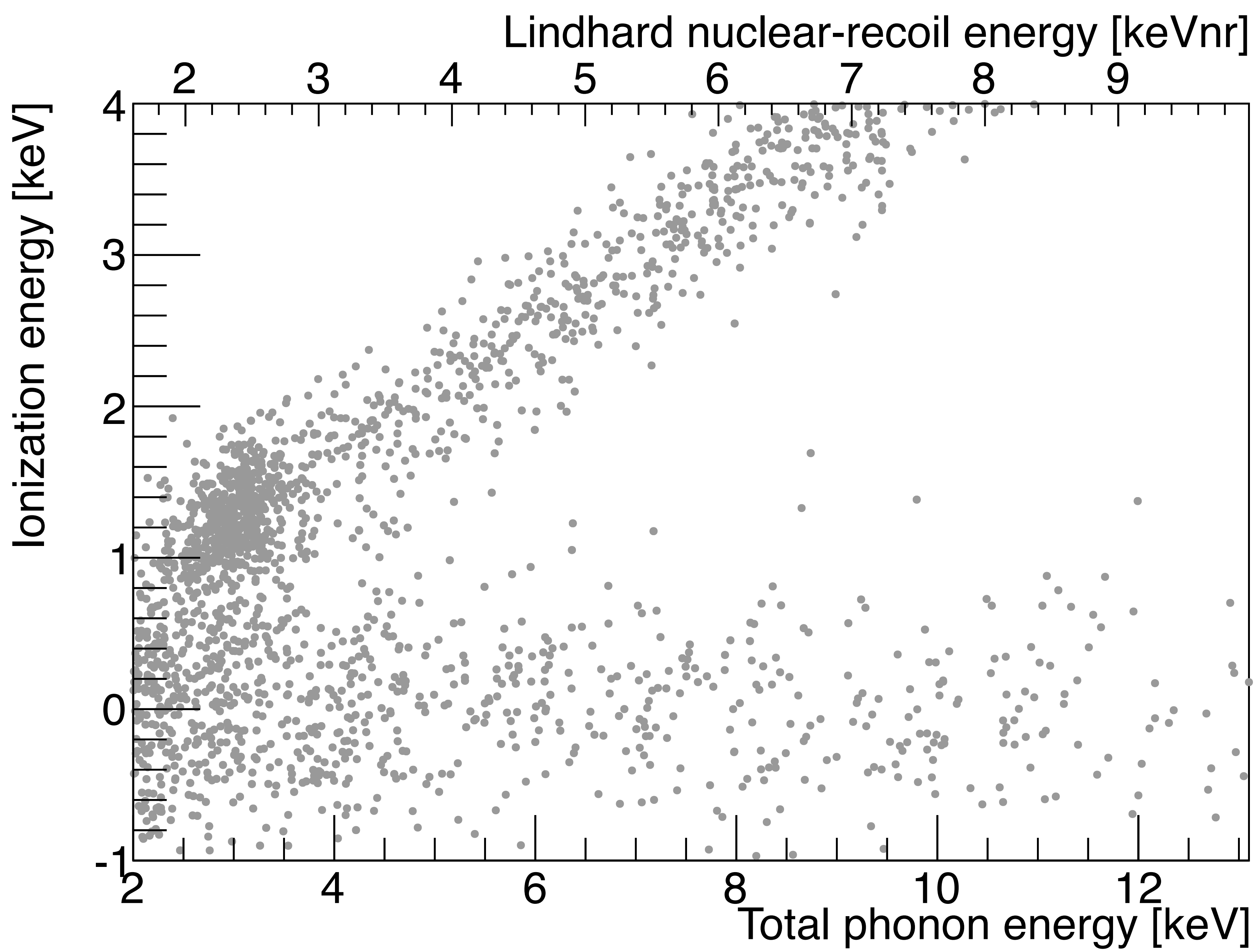
- Optimized cut on energy and phonon position estimators
- Estimate BDT+preselection efficiency using fraction of 252Cf passing



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

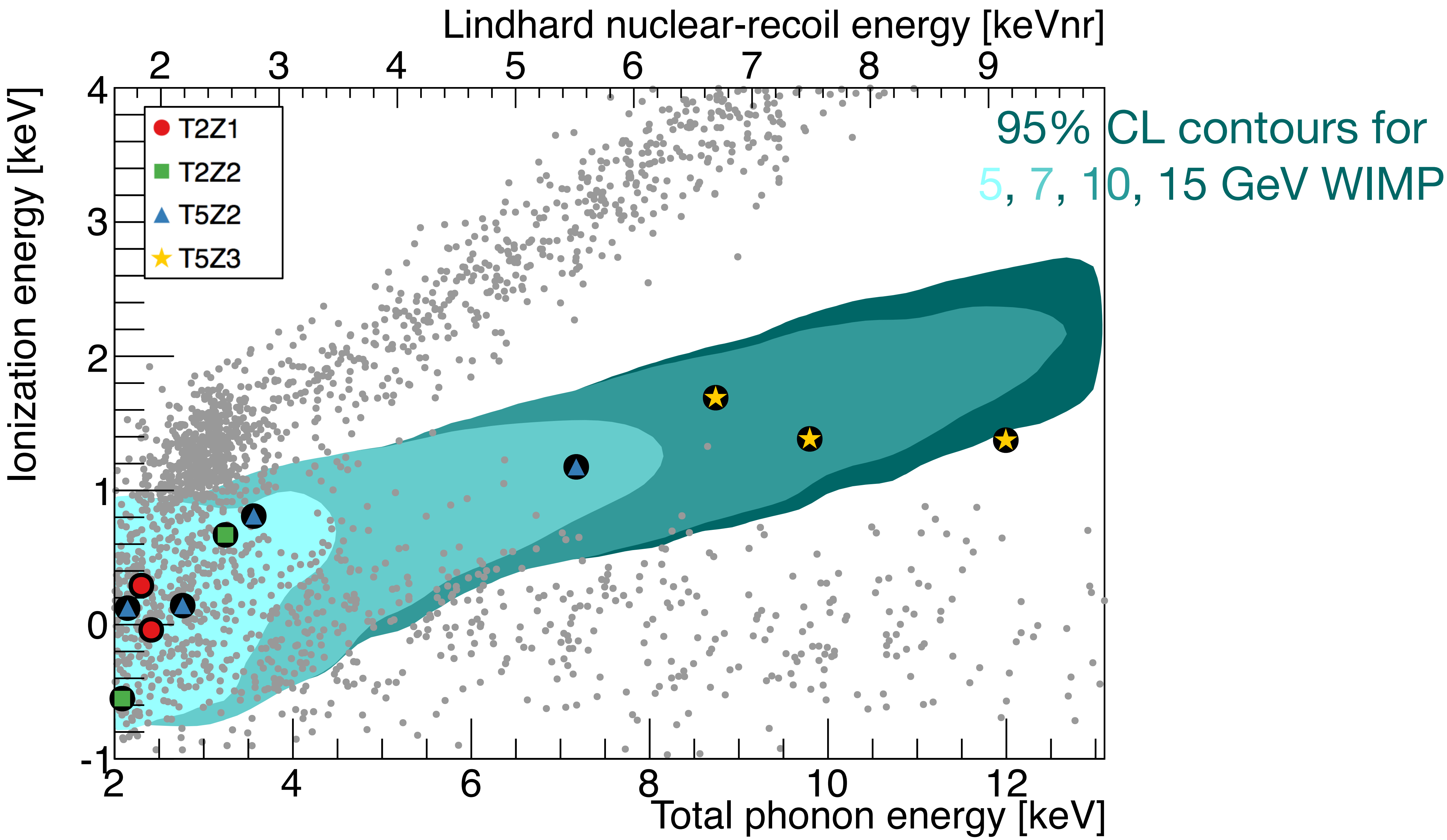
Low Threshold analysis

Passing data quality & ionization fiducialization cuts



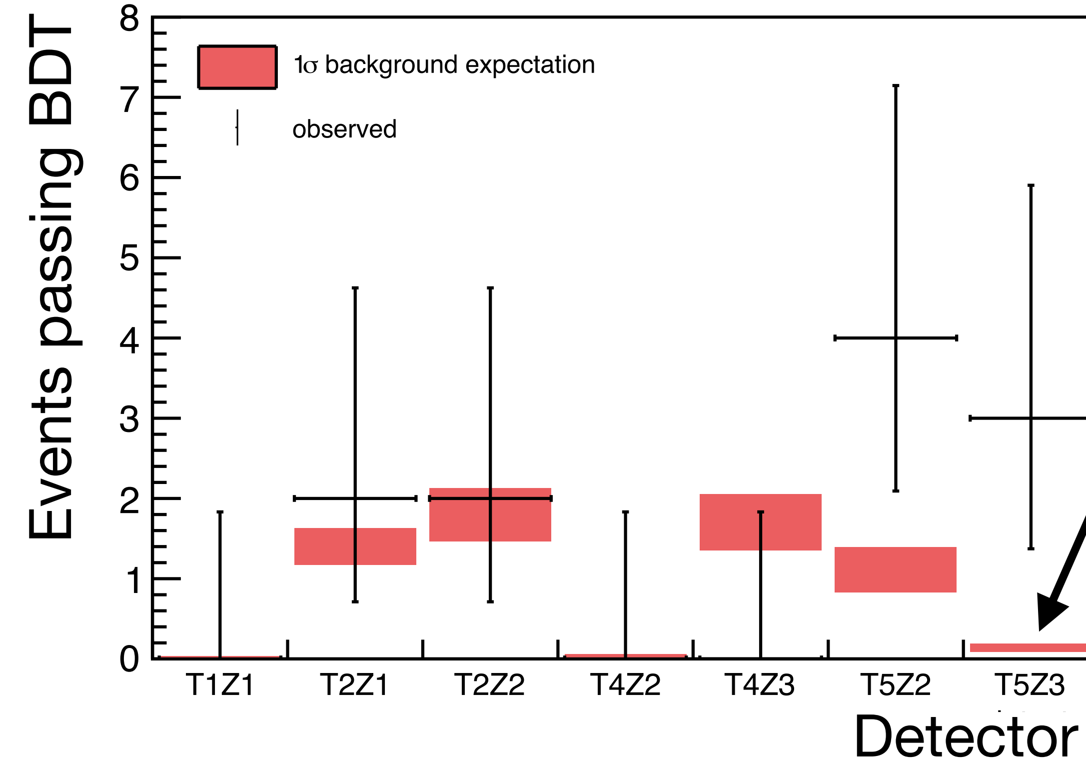
Low Threshold analysis

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

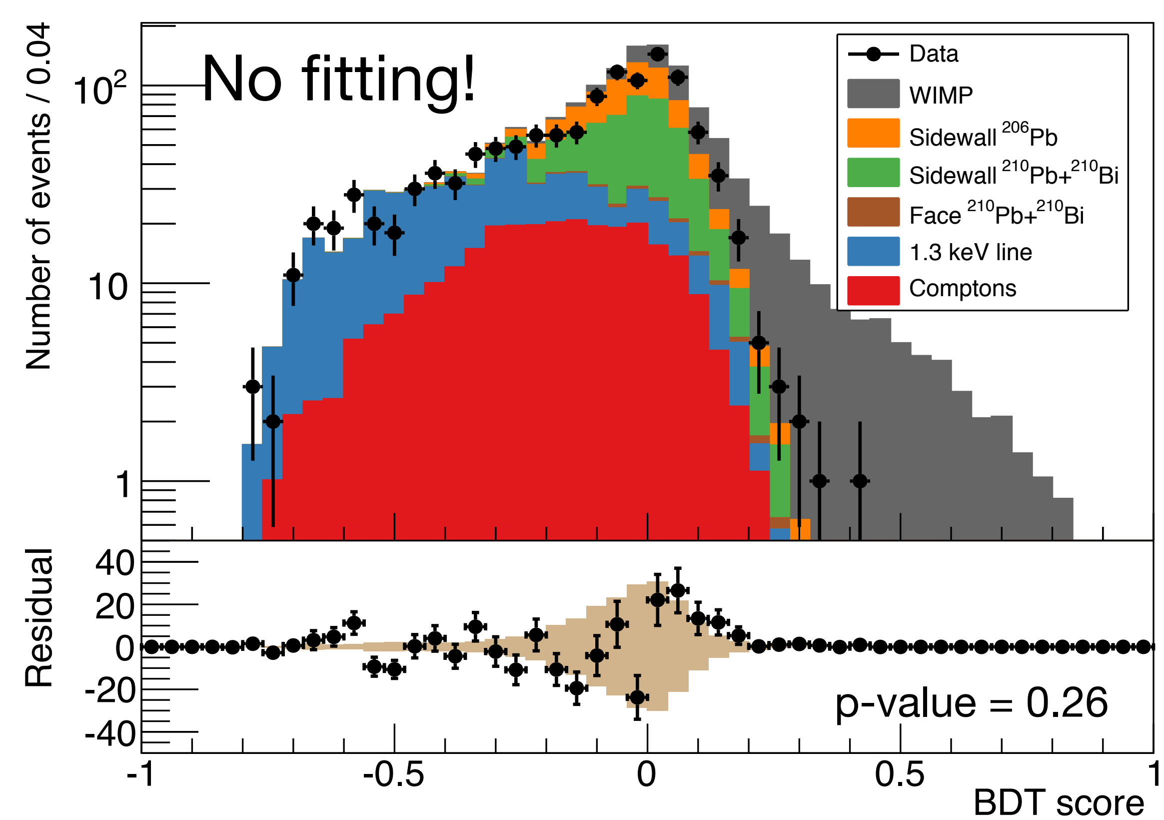


Low Threshold analysis

- 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



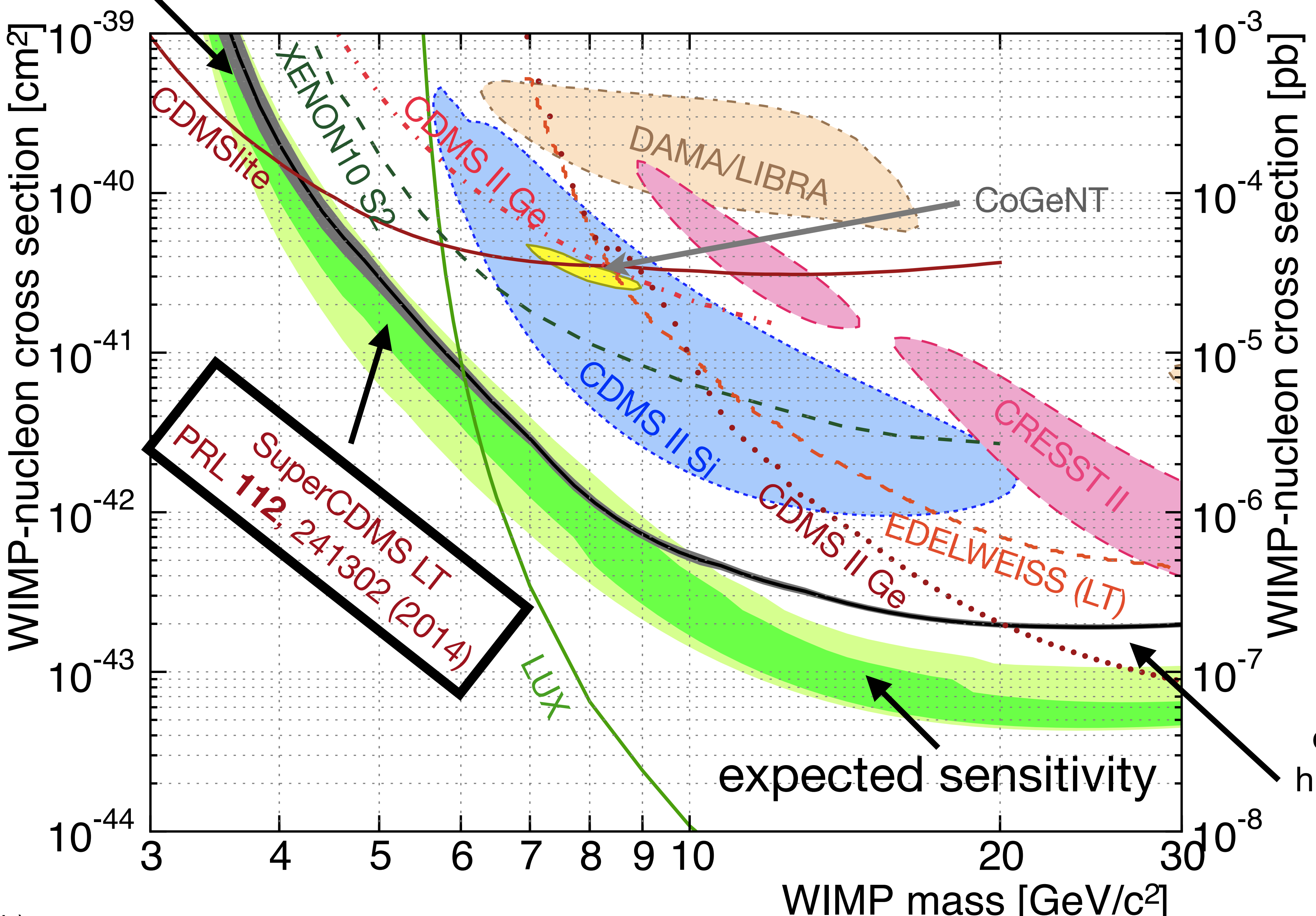
shorted ionization guard



Low Threshold analysis

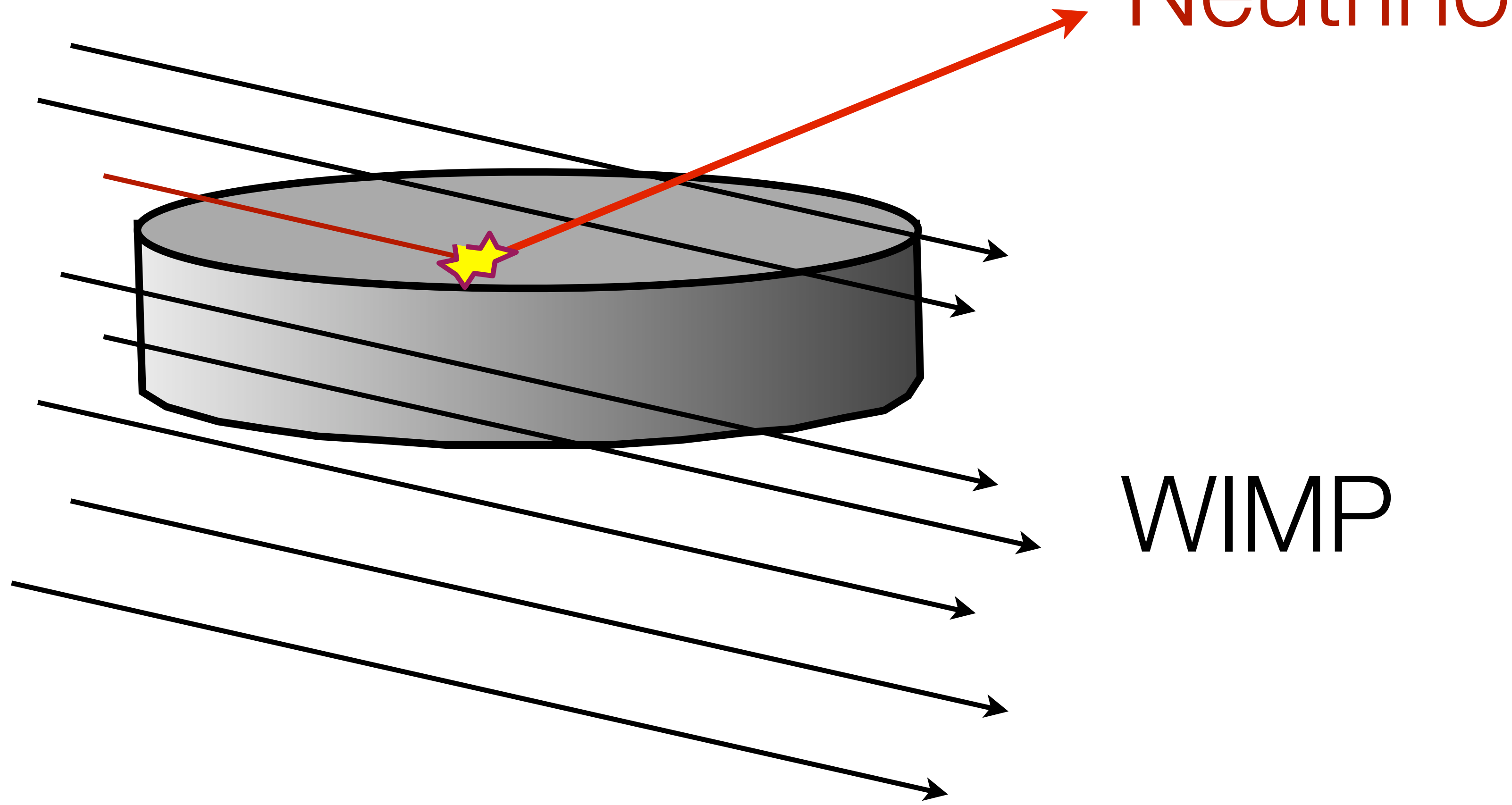
set 90% CL upper limit with optimal interval method (no background subtraction)

band includes systematics from
efficiency, energy scale, trigger efficiency



difference due to
high-energy events
on T5Z3

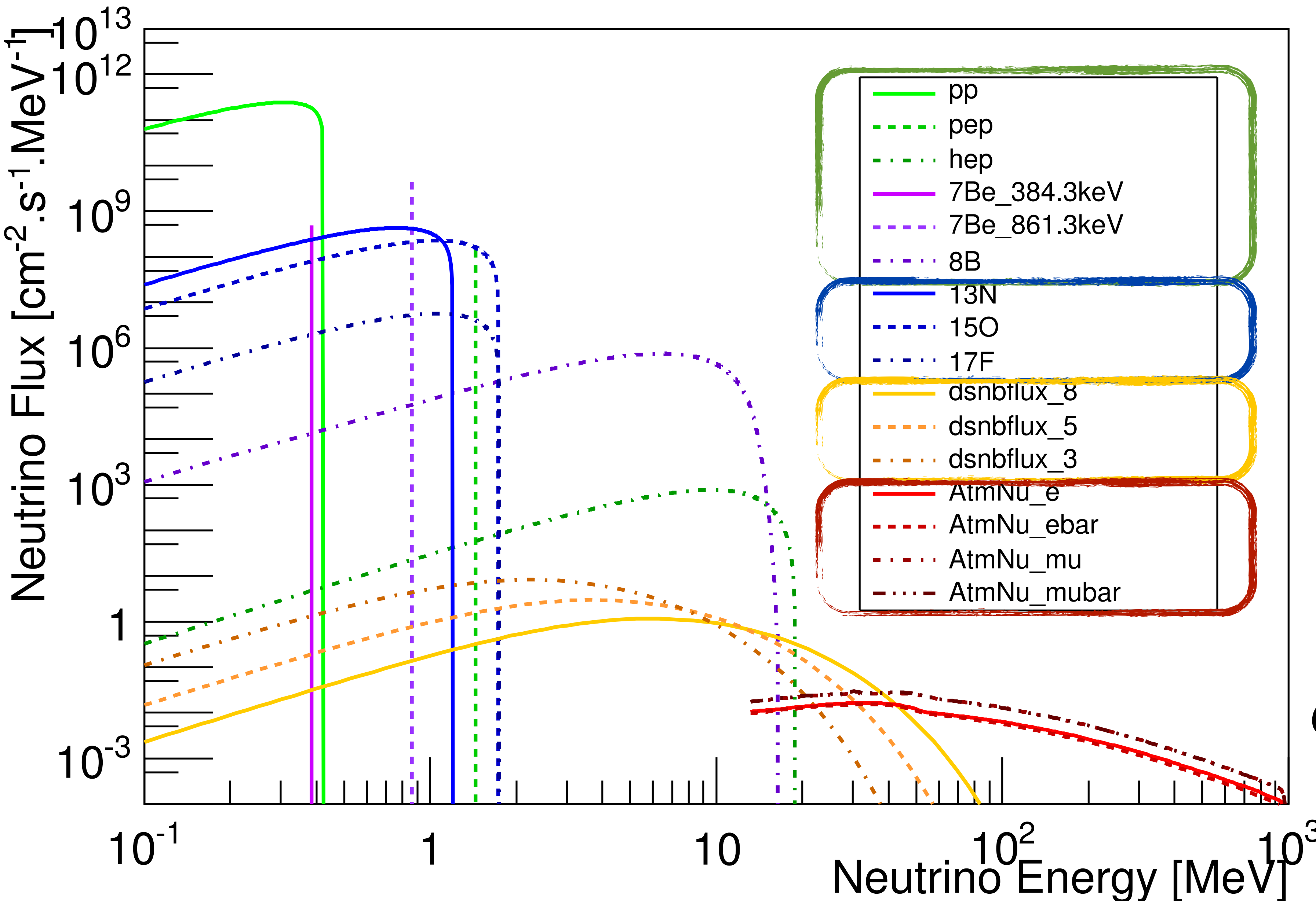
Neutrino background



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:



Solar neutrinos

CNO neutrinos

DSNB neutrinos

Atm. neutrinos

Geo neutrinos are negligible

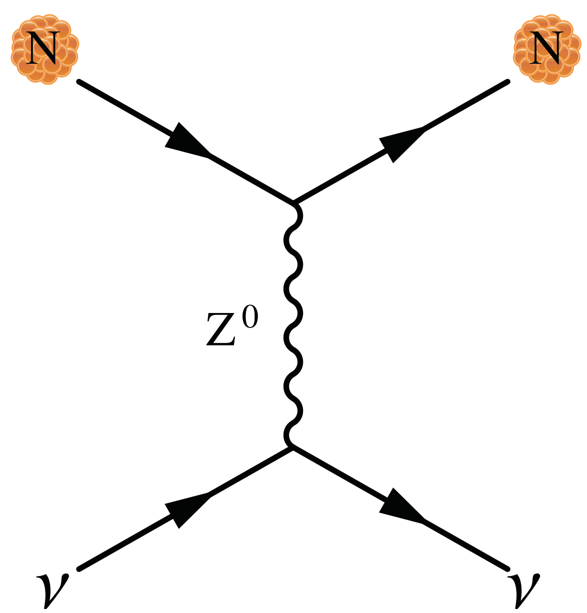
Neutrino background

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

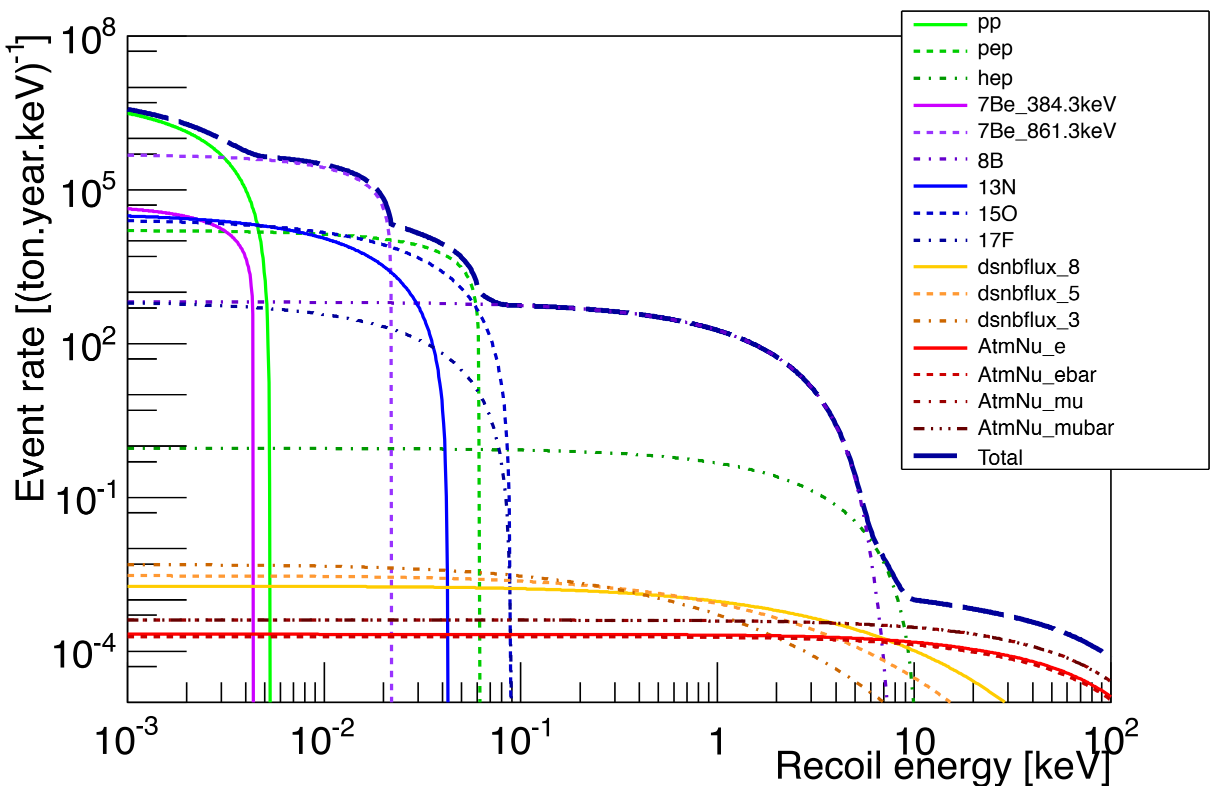
No flavor-specific terms!!!
Same rate for ν_e, ν_μ, and ν_τ

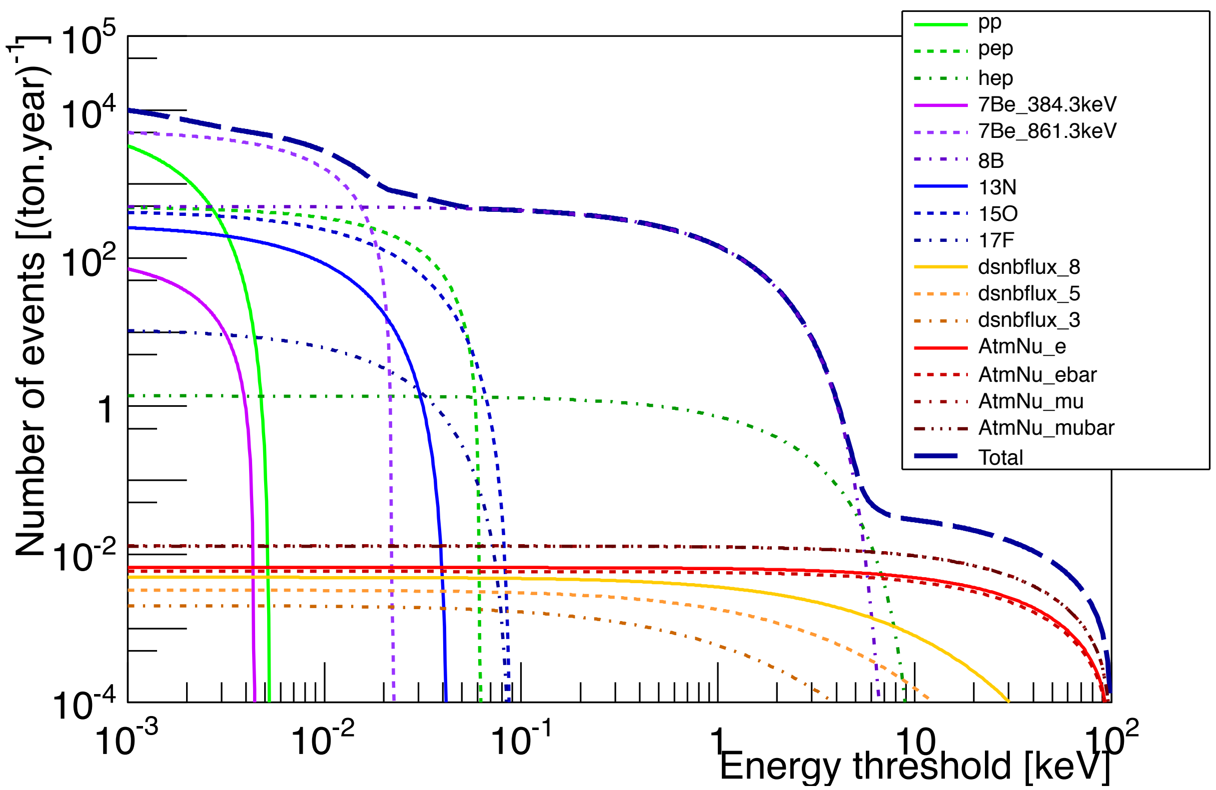
Ultimate background to direct detection

Neutrino background

Neutrino interactions with Dark Matter experiment target material

- Coherent neutrino scattering (CNS):



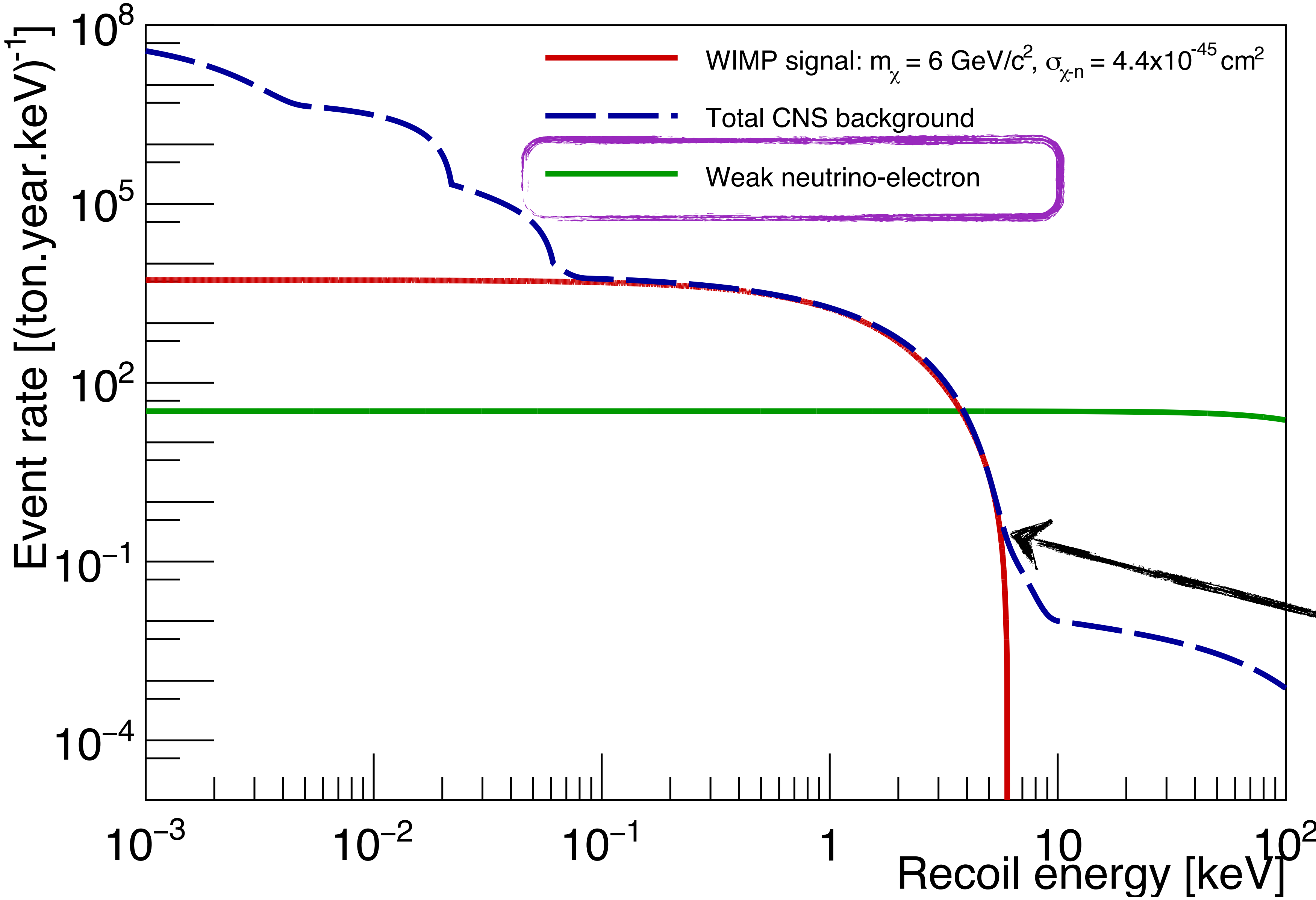


Depending on the Energy threshold, the CNS background can be very high!

- 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

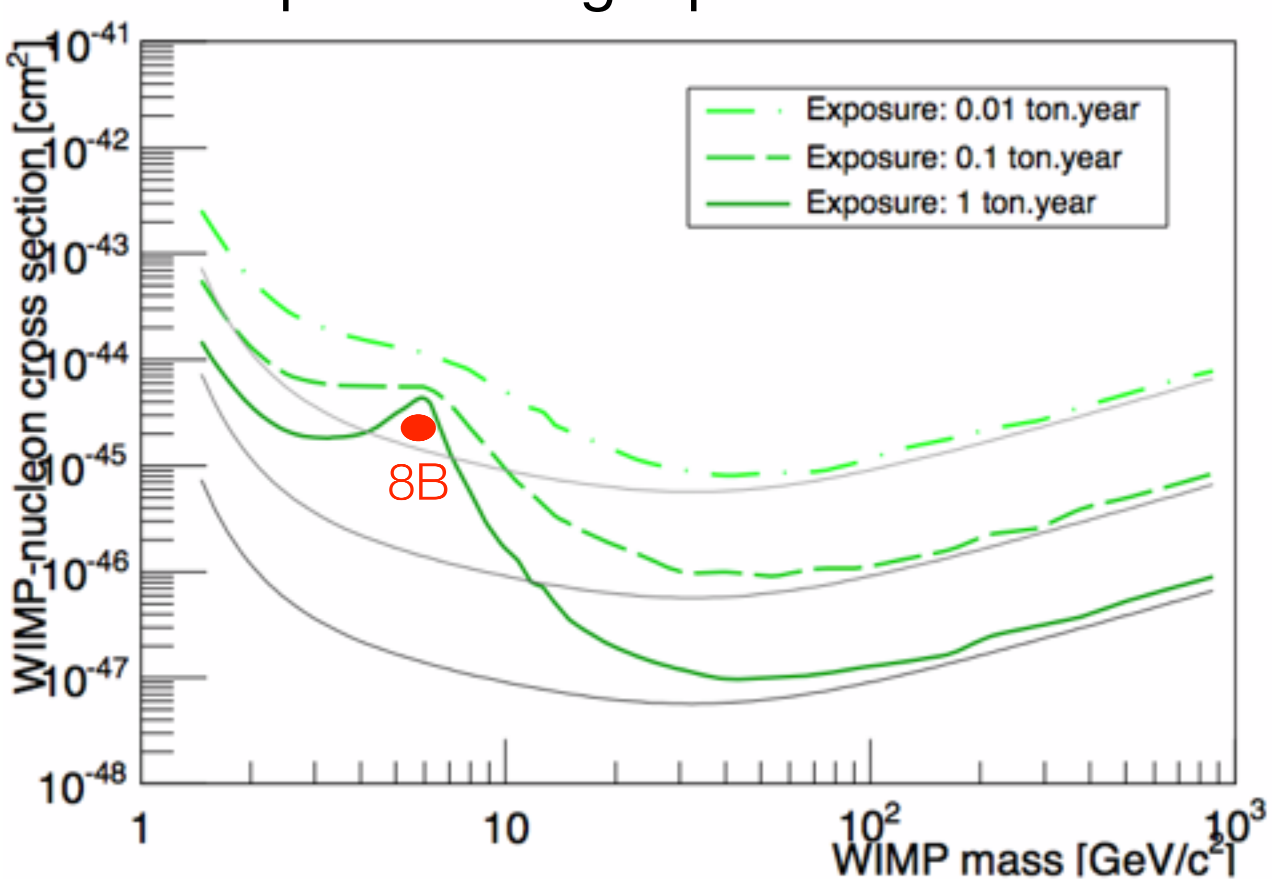
WIMP or neutrino??

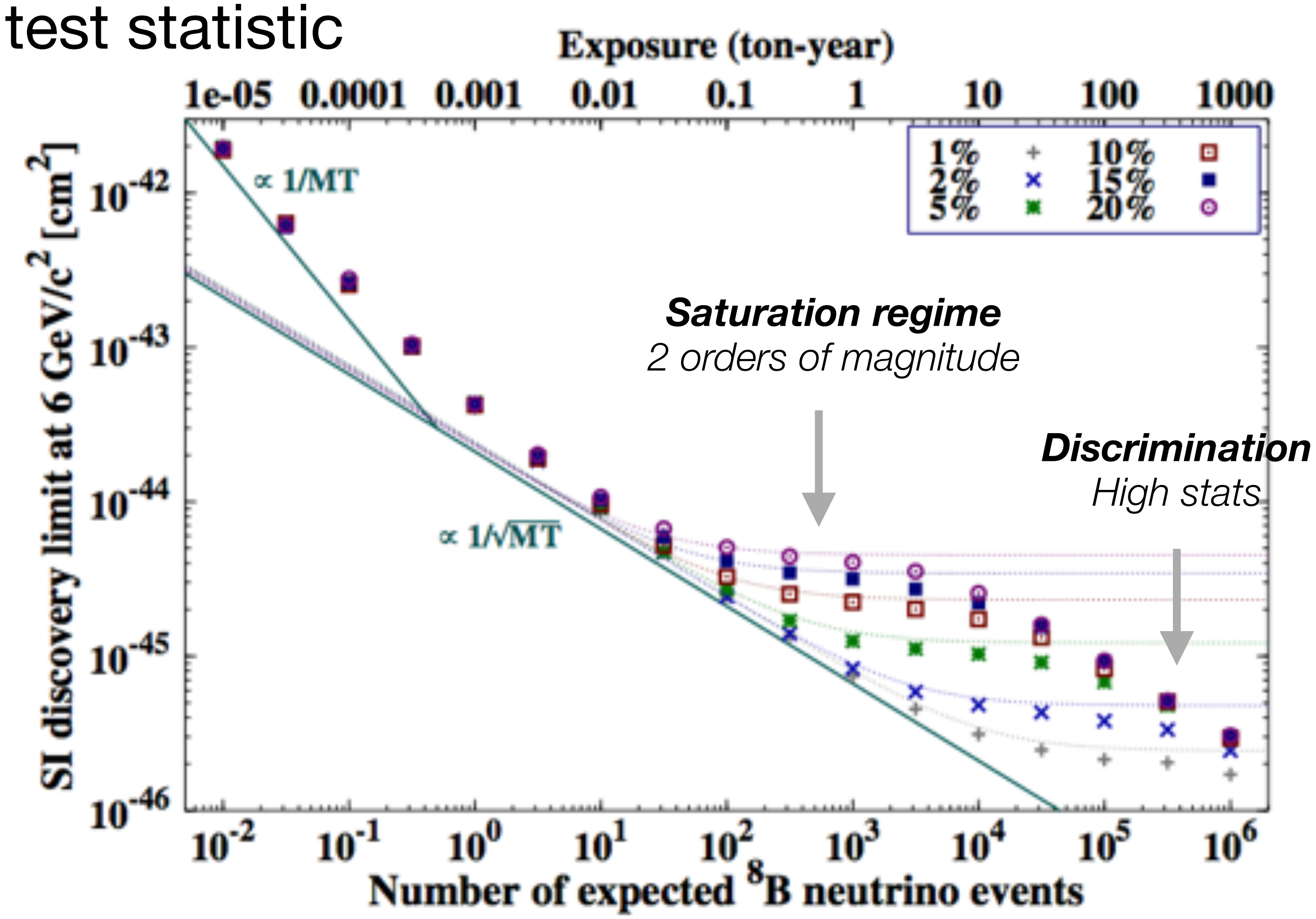
Impact on direct detection sensitivity

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

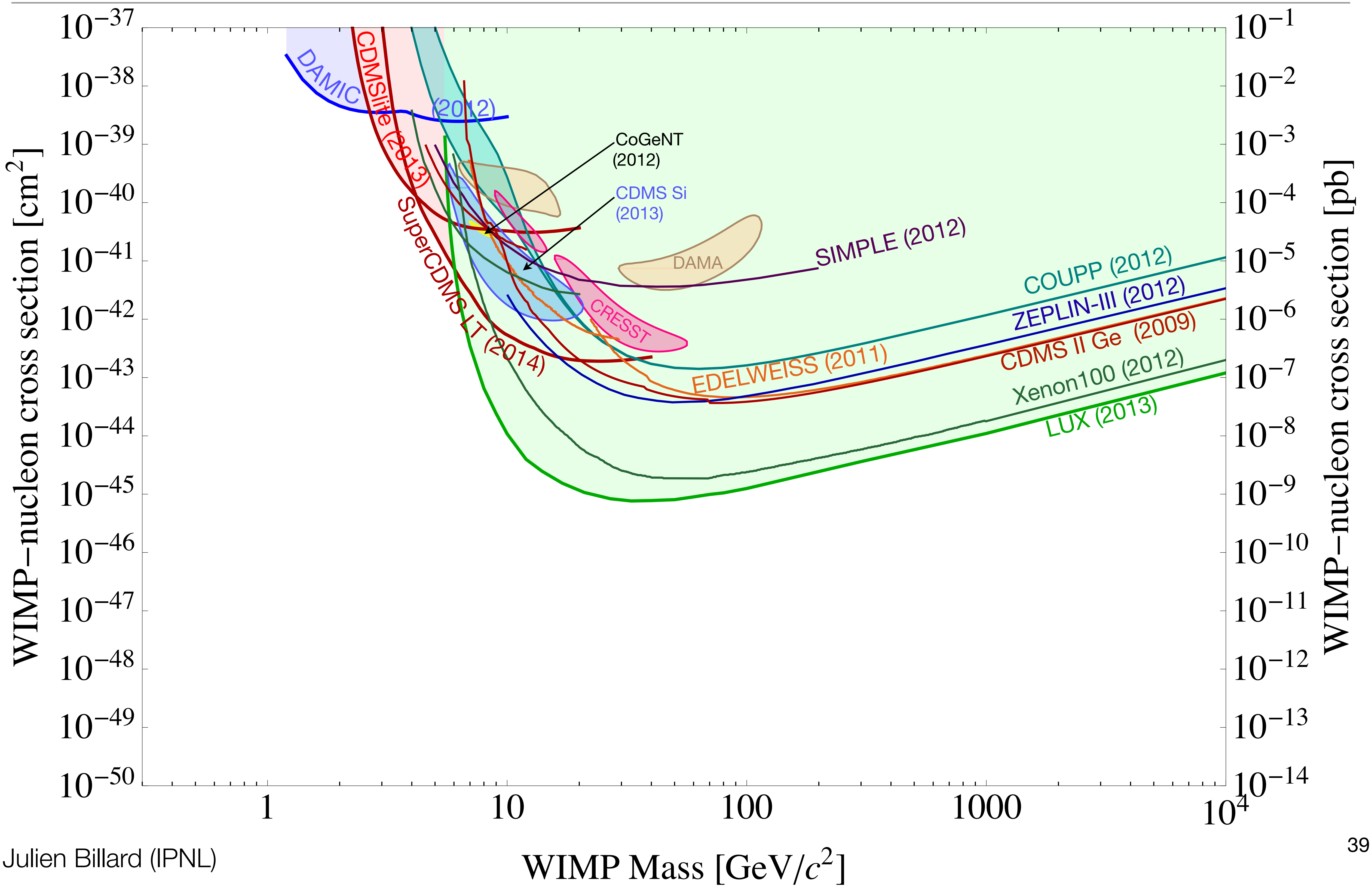




In the case of a **perfect spectral matching**, we expect the sensitivity to scale as:

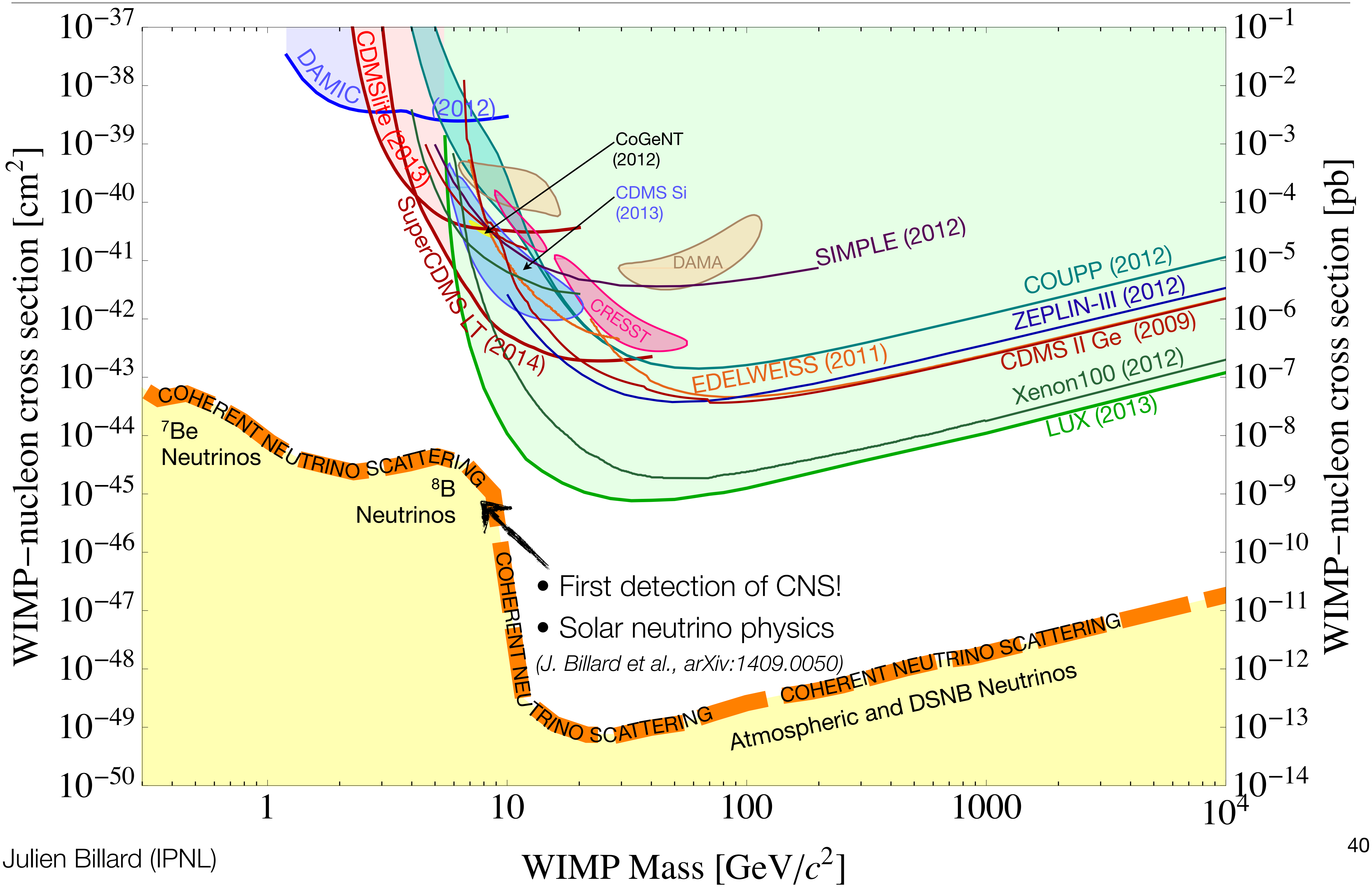
$$\sigma_{90\%} \propto \frac{\sqrt{N_\nu + \xi^2 (N_\nu)^2}}{N_\nu} = \sqrt{\frac{1+\xi^2 N_\nu}{N_\nu}},$$

Neutrino background



Julien Billard (IPNL)

Neutrino background



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Target complementarity

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, arXiv:1411.5946)*

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

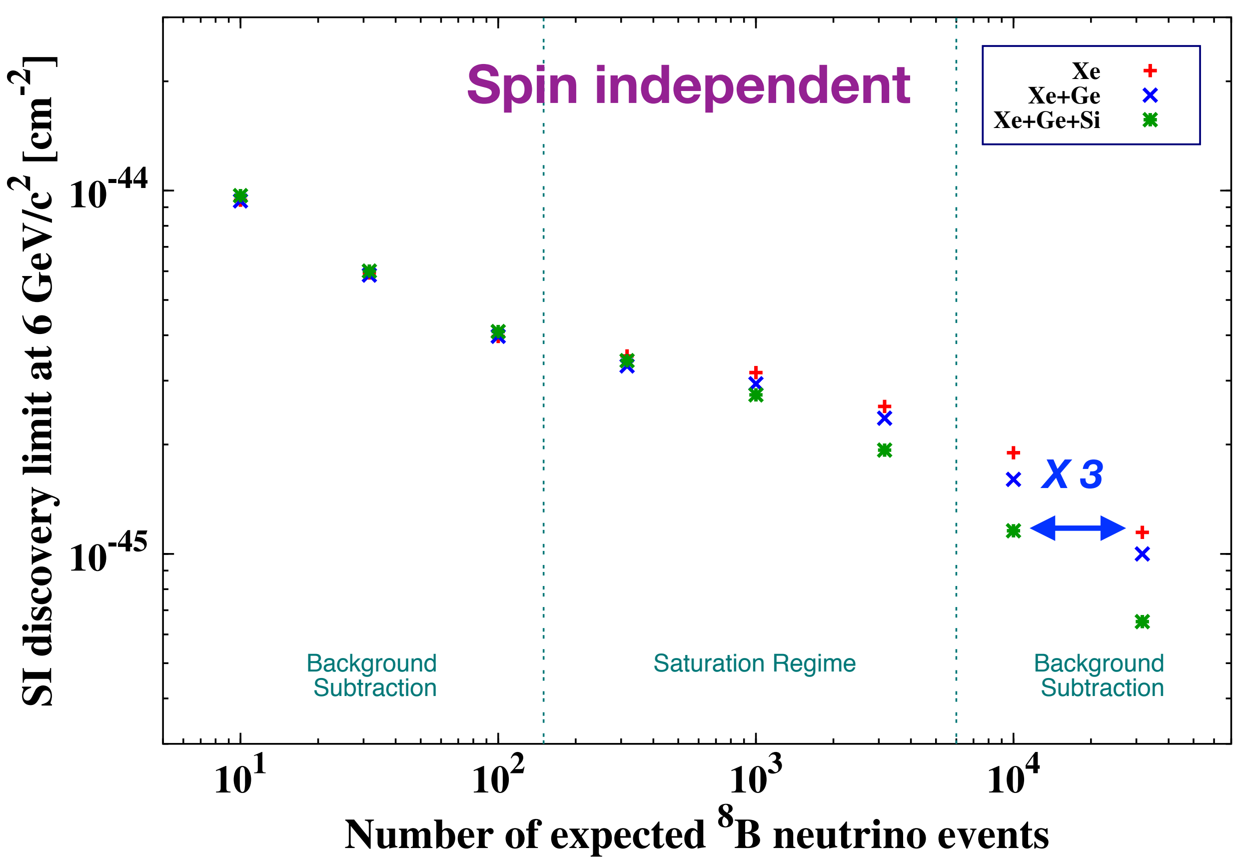
4. Target complementarity: combining data from several experiments.

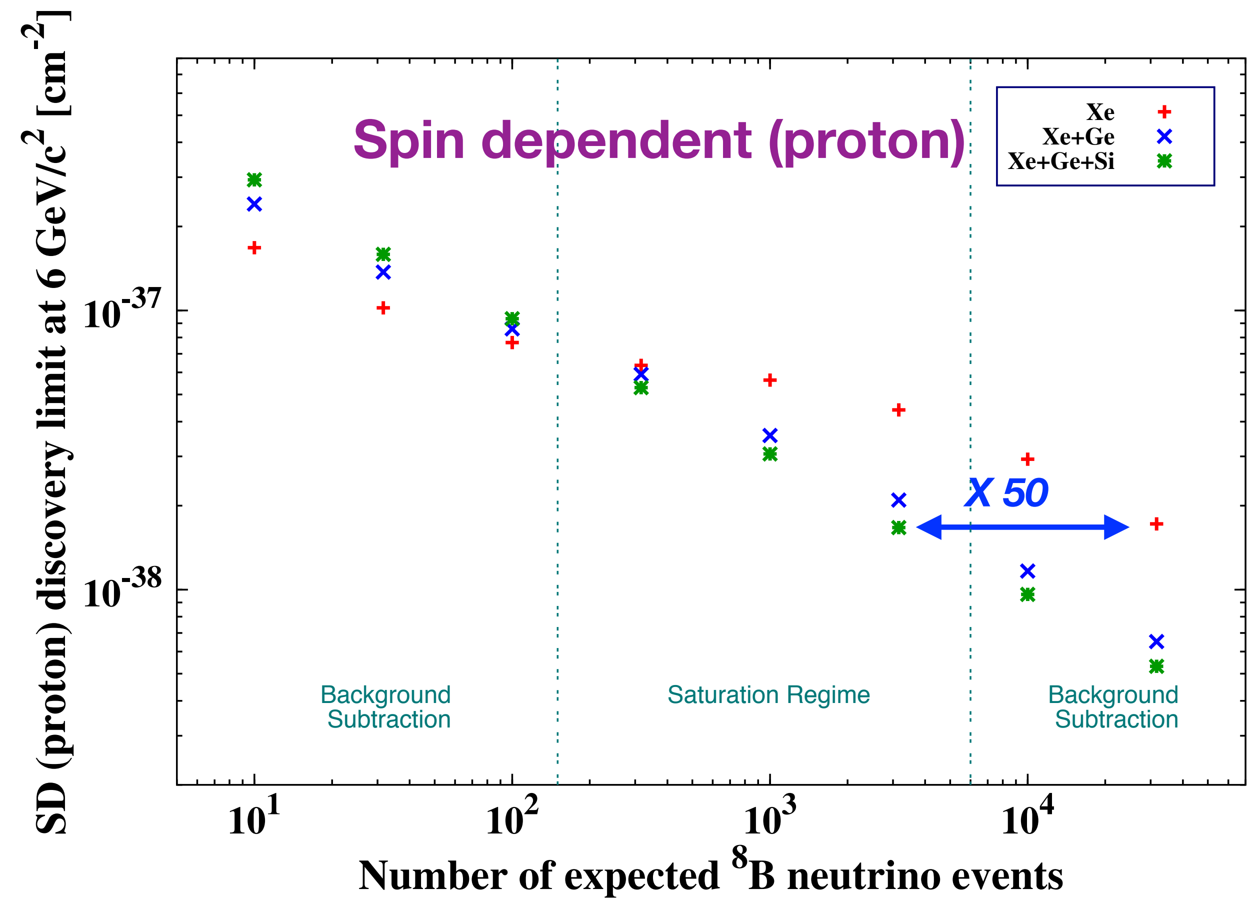
Target complementarity

Results from target complementarity

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

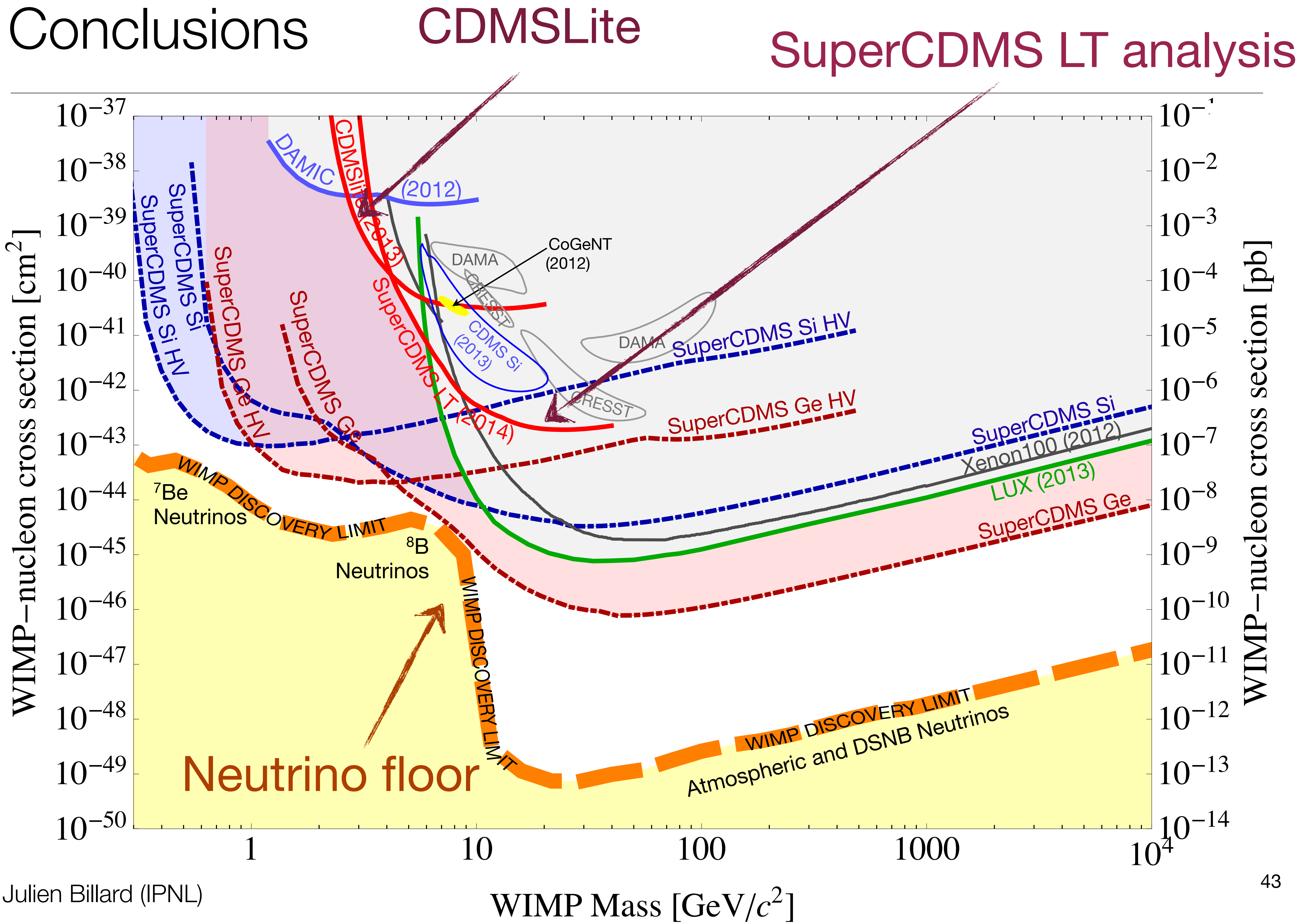
Total number of neutrinos equally distributed amongst each target nuclei





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

Conclusions



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