Search for Inelastic Dark Matter with the CDMS Experiment

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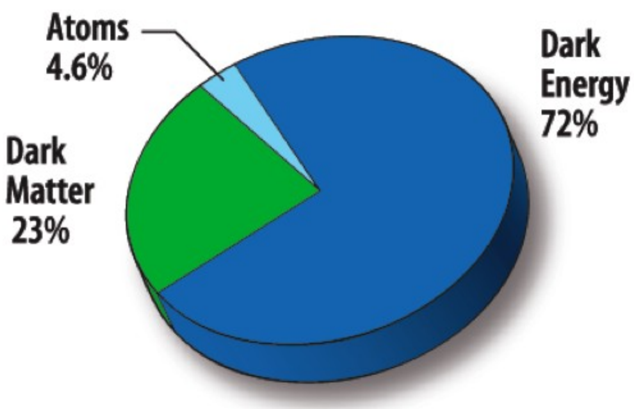
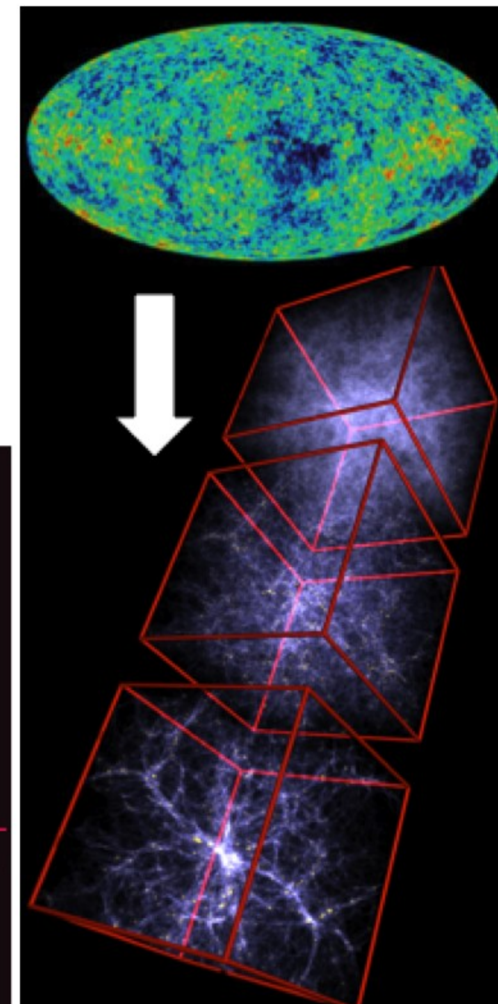
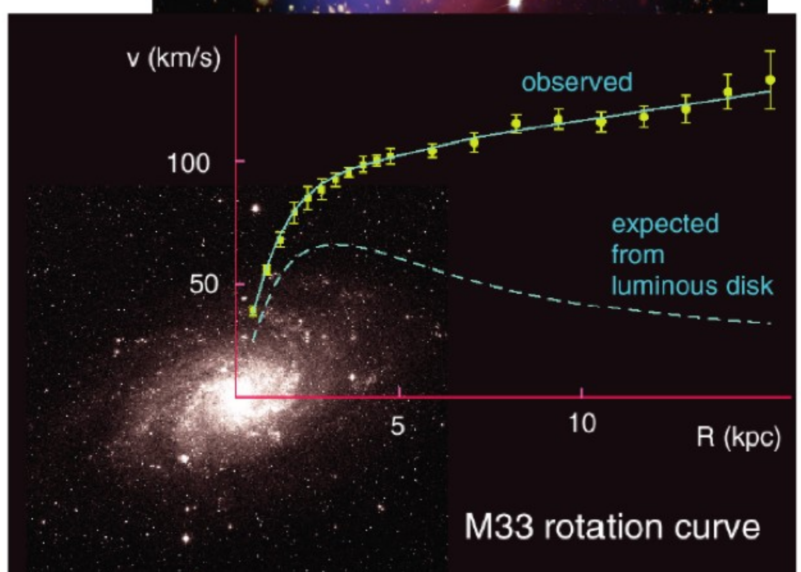
Cosmological observations



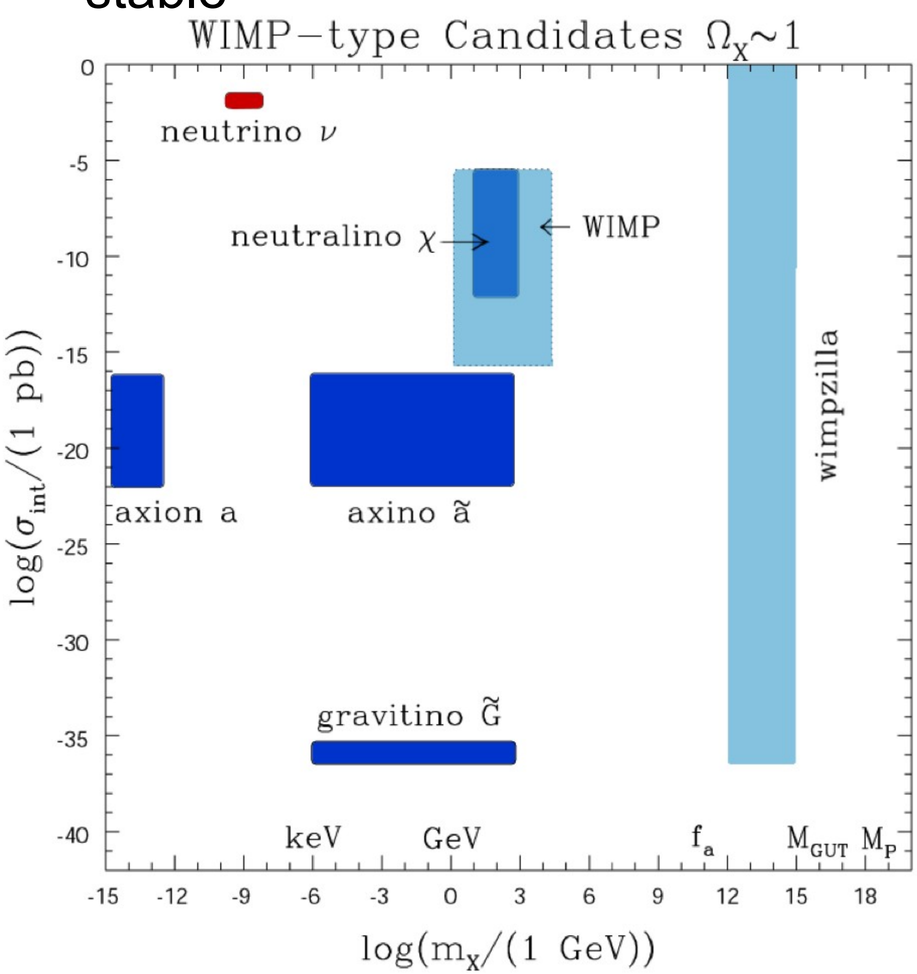
Evidence for dark matter on various scales:
- galaxies
- galaxy clusters
- large scale





Dark Matter and WIMPs

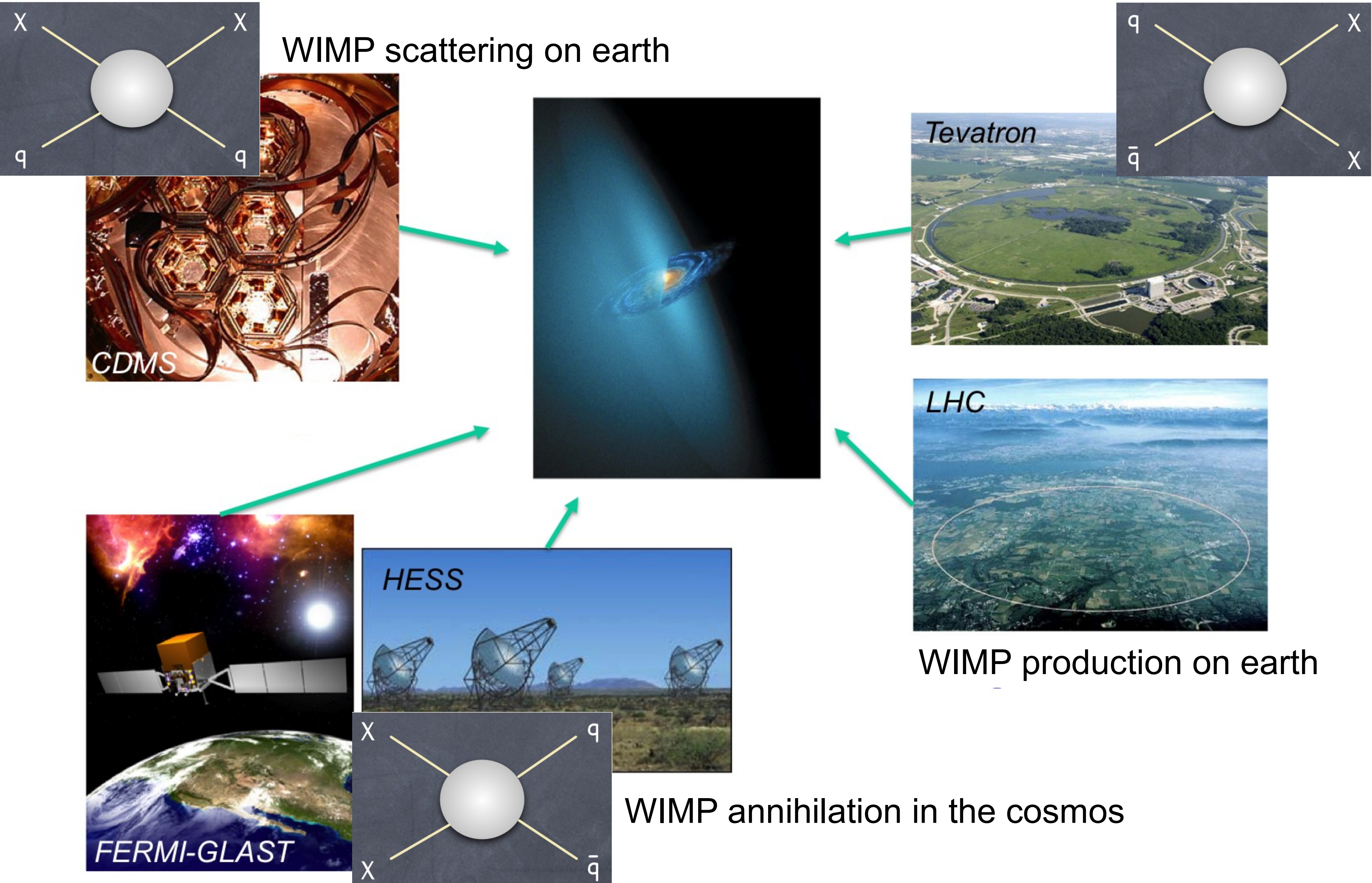
We “know“ that dark matter is
- non-baryonic
- cold (structure formation)
- does not emit or absorb light
- not strongly interacting
- stable



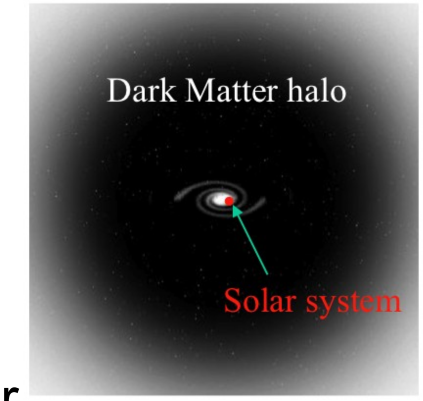
We do not know the
- mass
- cross section (interaction with matter, self-annihilation)

Weakly Interacting Massive Particle (WIMP) is a prominent dark matter candidate
- stable, massive particle produced thermally in the early universe
- produced with the correct thermal relic density
- weak-scale interaction cross sections
- arises naturally in various well-motivated extensions of the Standard Model (SUSY, UED, …)

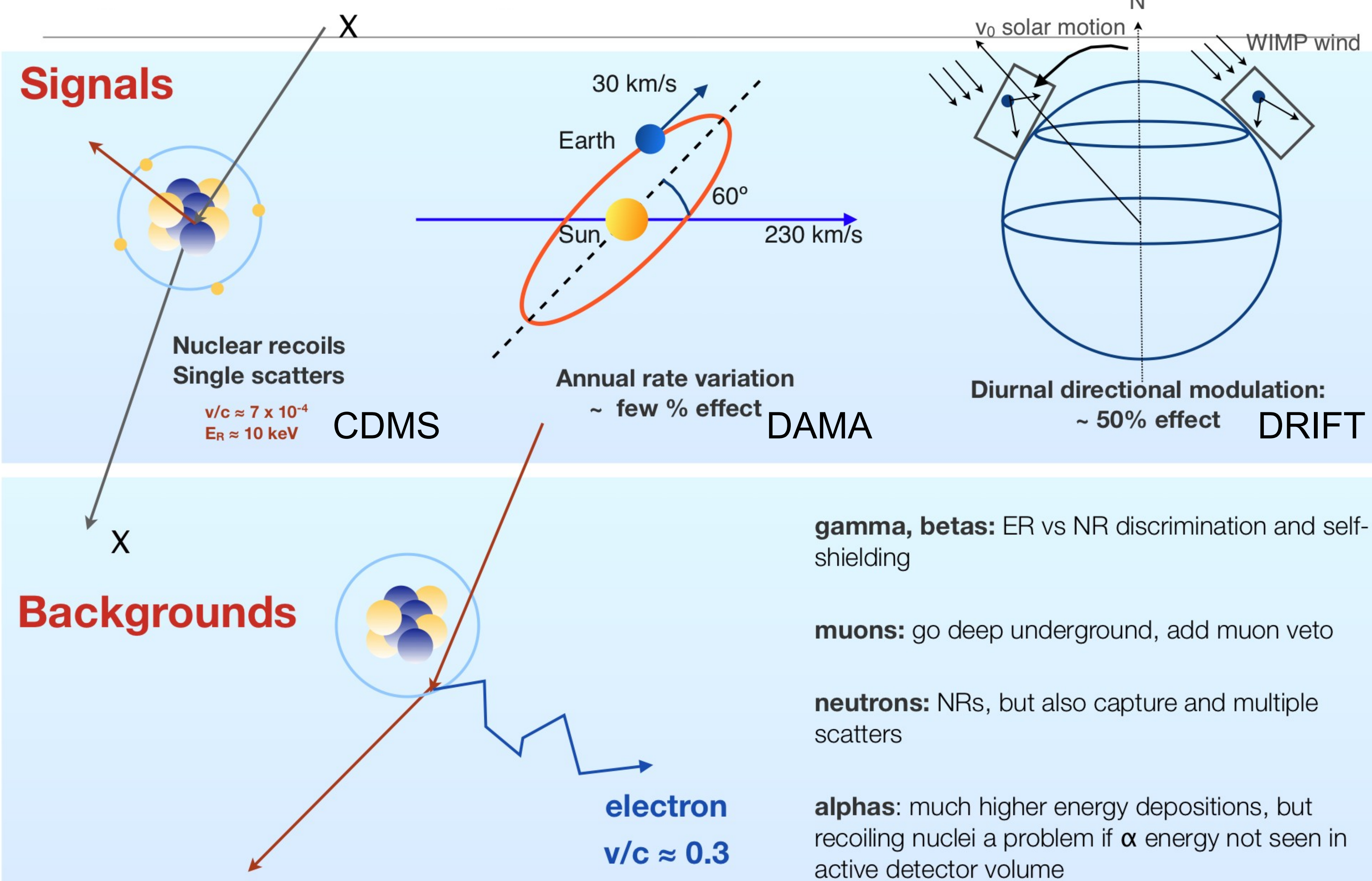
How can WIMPs be detected?



Signals and background



Main challenges:
- signal is very small (~keV)
- rare events (1 per ton per year?)
- background is usually millions of times higher

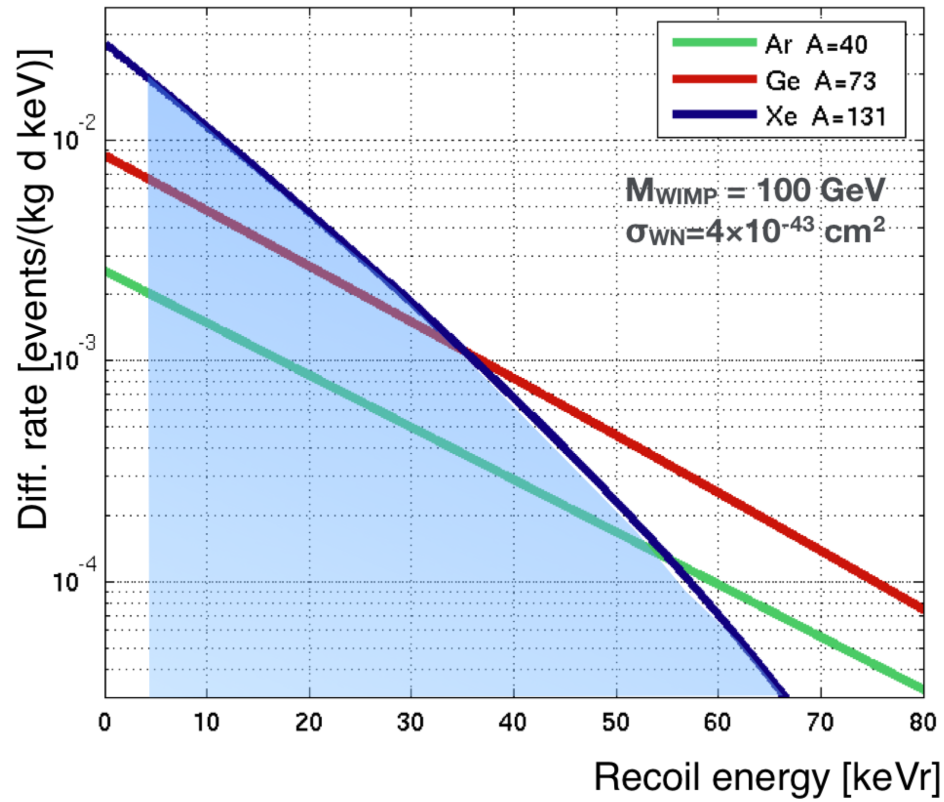


Direct detection of WIMPs

- elastic collisions with atomic nuclei
- differential rate depends on WIMP-velocity distribution, local WIMP density, target nuclei, threshold, atomic form factor, WIMP mass, WIMP-nucleon cross section

$$\frac{dR}{dE_R} = \frac{\sigma_0 \rho_0}{2 m_\chi \mu^2} F^2(E_R) \int_{\mathrm{v}_{\min}}^{\mathrm{v}_{\max}} \frac{f(\mathrm{v})}{\mathrm{v}} d\mathrm{v}$$

- assuming Maxwellian-velocity distribution → featureless nearly exponential spectrum



- WIMP scattering can be classified as:
  - spin-independent (scalar) interaction (WIMP couples to nuclear mass m_n)

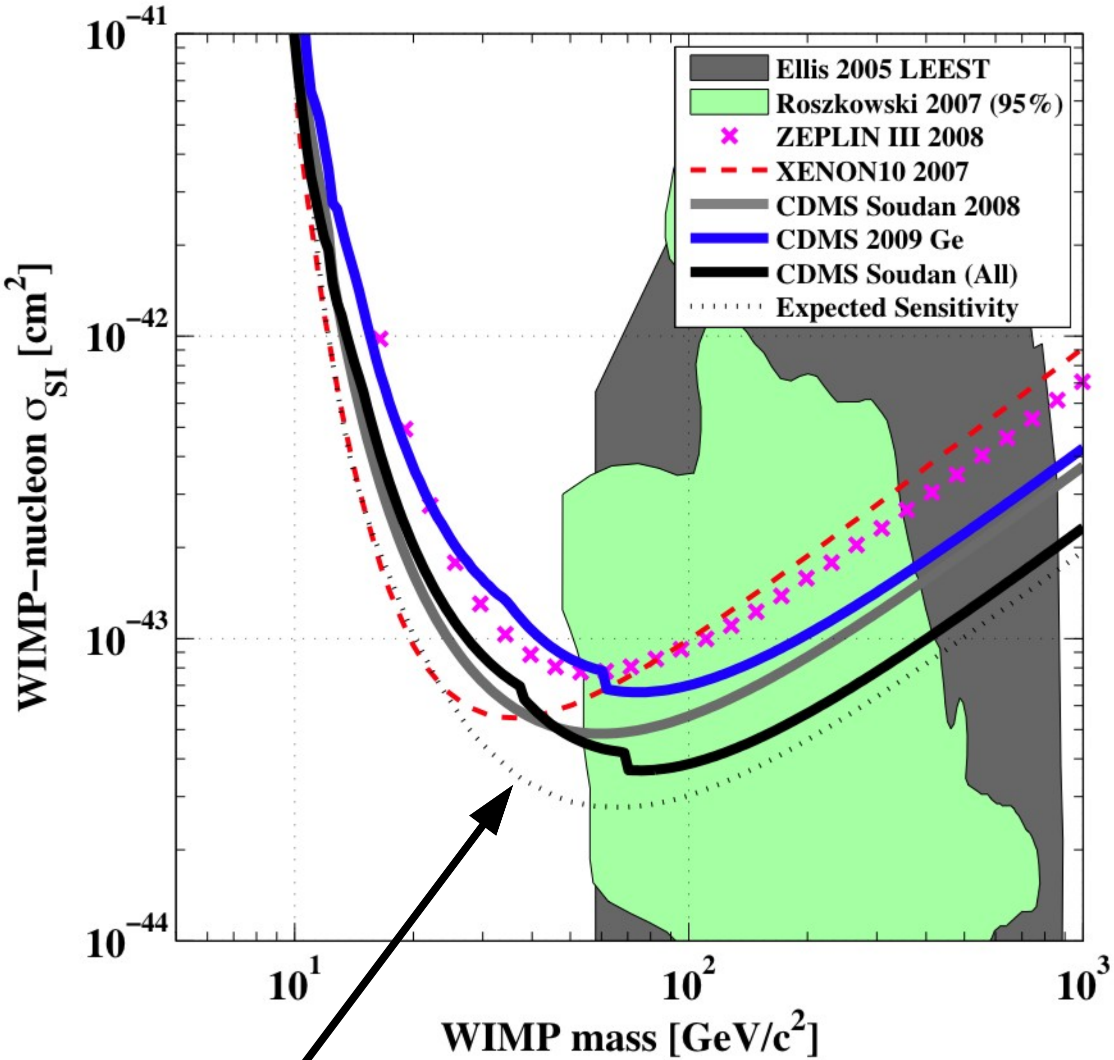
$$\sigma_{SI} = \frac{m_N^2}{4\pi (m_\chi + m_N)^2} \left[Z f_p + (A - Z) f_n \right]^2$$

  - spin-dependent interaction (WIMP couples to nuclear spin J_n)

$$\sigma_{SD} = \frac{32}{\pi} G_F^2 \frac{m_\chi^2 m_N^2}{(m_\chi + m_N)^2} \frac{J_N + 1}{J_N} \left(a_p \langle S_p \rangle + a_n \langle S_n \rangle \right)^2$$

f_p, f_n, a_p, a_n are effective couplings to protons and neutrons

CDMS results from the standard analysis



sensitivity based on total background estimate (surface events & neutron background)

- analysis range: 10 – 100 keV
- two candidate events at 12.3 keV and 15.5 keV
- background of 0.9±0.2 events (predominantly surface events)
- probability for two or more background events is 23%
- compute limit assuming spin-independent interactions using optimum interval method (without background subtraction)
- upper limit on the WIMP-nucleon cross section @ 70 GeV: $\sigma = 3.8 \cdot 10^{-44}$ cm² (combined with previous data taken in Soudan)

World leading 90% C.L. upper limit on scalar interaction cross sections for WIMP masses above ~70 GeV!

The DAMA/LIBRA results

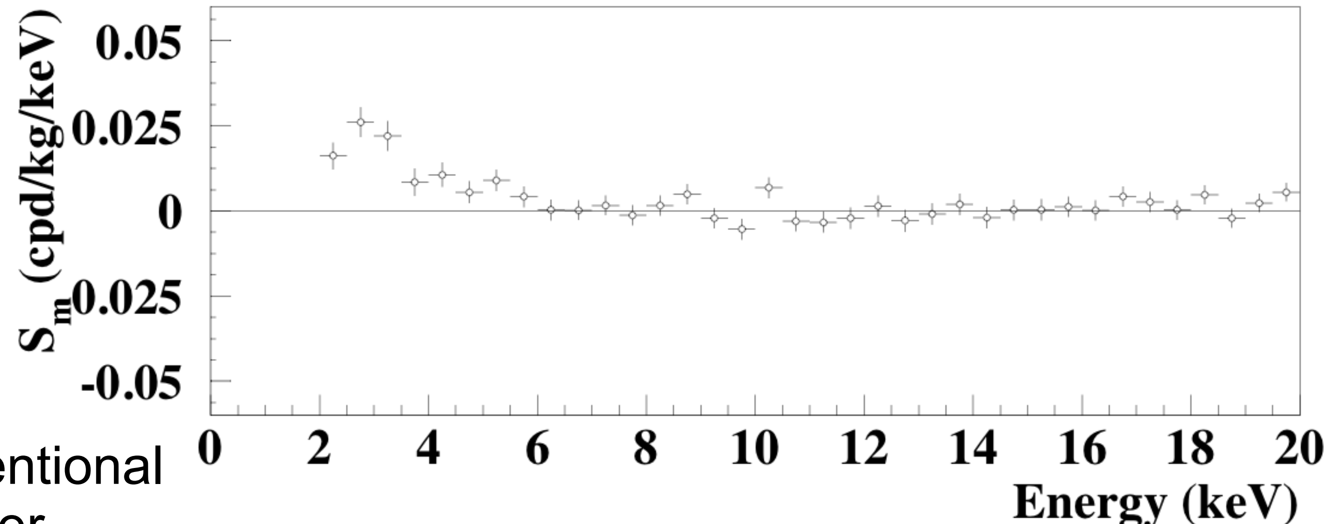
- observation of annual modulation at low recoil Energies (2 – 4 keV)

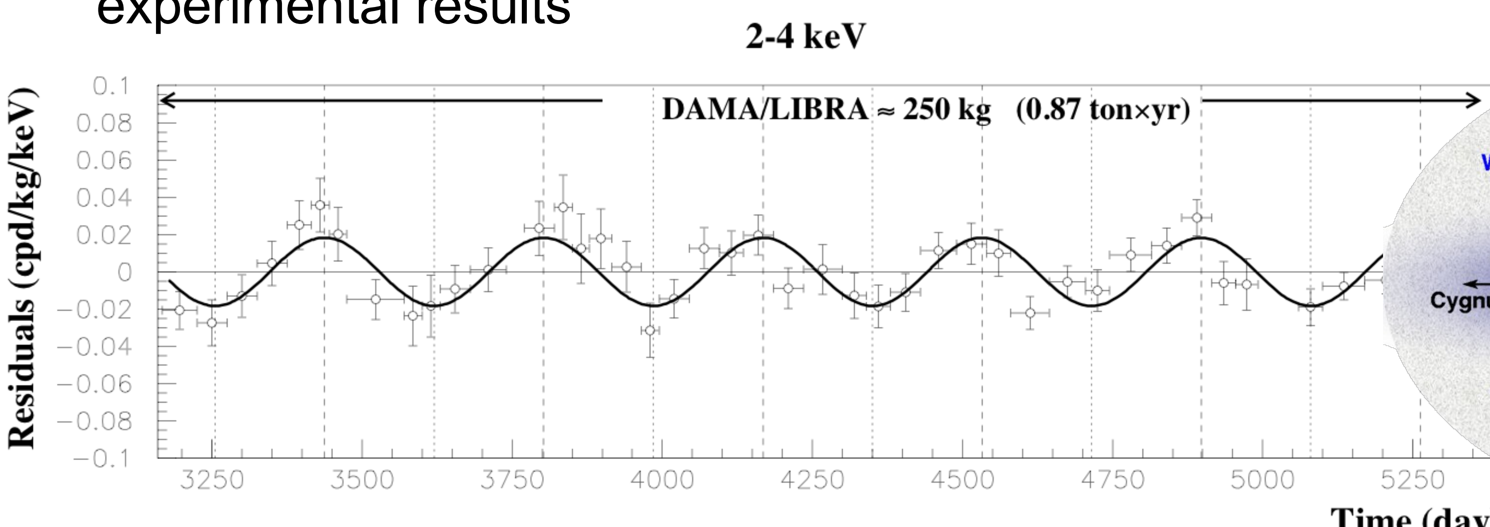
- evidence @ 8.9σ C.L.

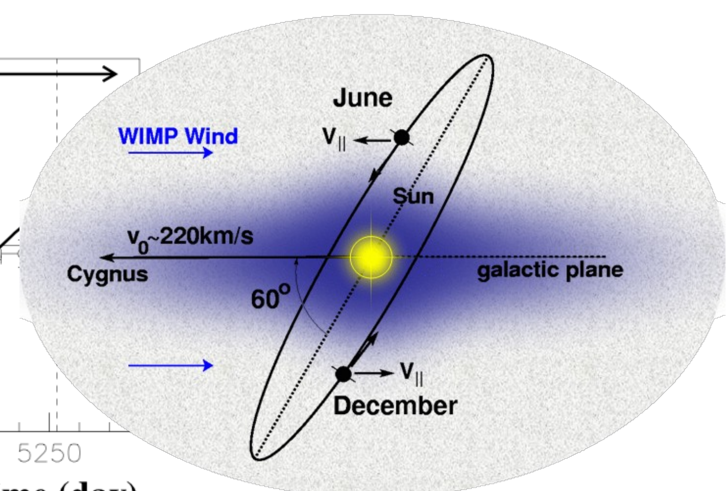
- measured over 13 annual cycles with exposure of 1.17 ton-years

- difficulties to explain this observation with the conventional WIMP model in light of other experimental results

$$\frac{\mathrm{dR}}{\mathrm{dE}}(\mathrm{E},t) = S_0(\mathrm{E}) + S_m(\mathrm{E}) \cdot \cos\left(\omega(t - t_0)\right)$$







Inelastic Dark Matter (IDM)

- 2 dark matter states with mass splitting δ ~100 keV

- WIMP-nucleus scattering through transition of WIMP into excited state WIMP*

- elastic scattering forbidden or highly supressed

- minimum velocity is increased

$$v_{\min} = \frac{1}{\sqrt{2 m_T E_{\text{rec}}}} \left(\frac{m_T E_{\text{rec}}}{\mu} + \delta \right)$$

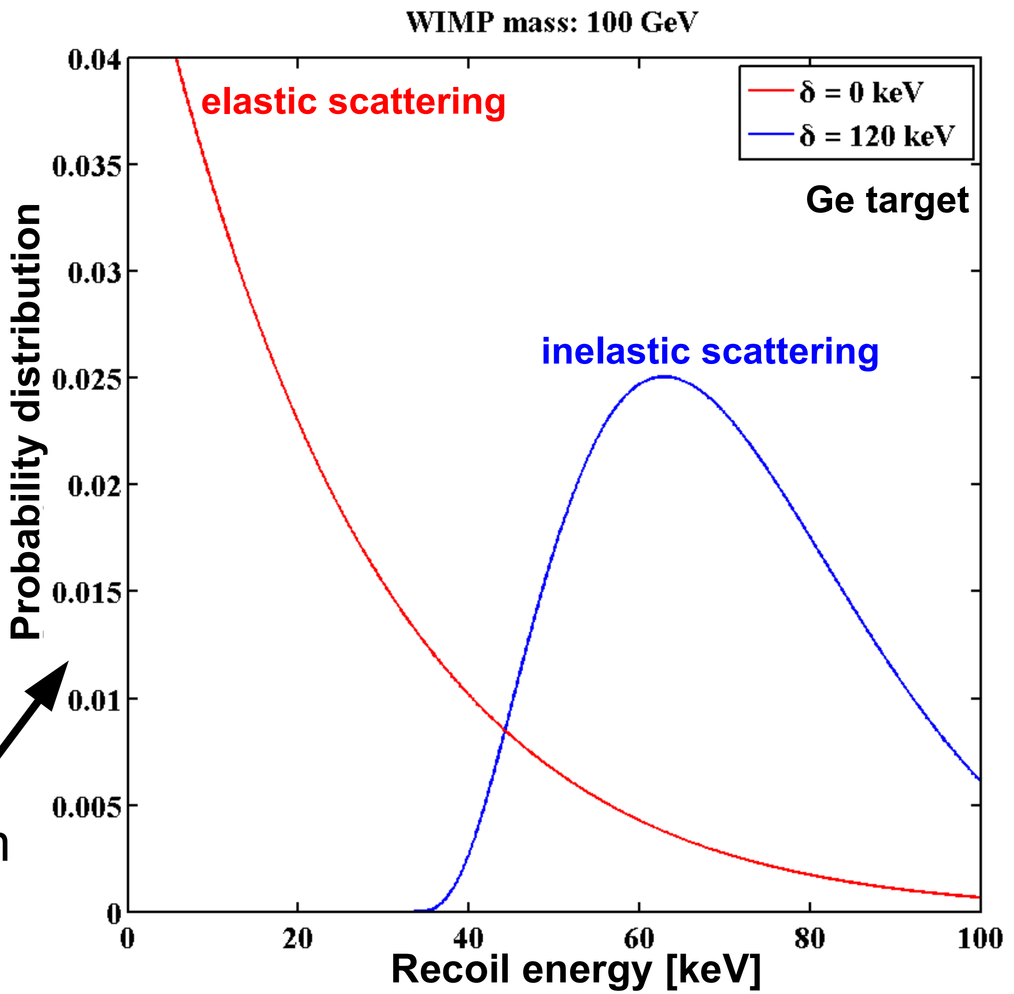
- experiments probe “higher“ part of velocity distribution

- high sensitivity to escape-velocity cutoff

- heavy targets are favoured

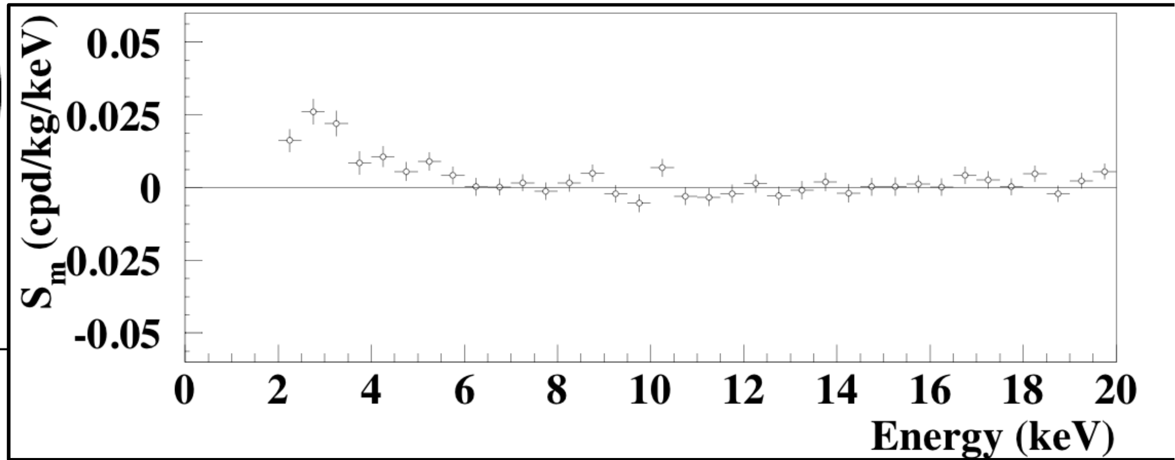
- significant change of the energy spectrum

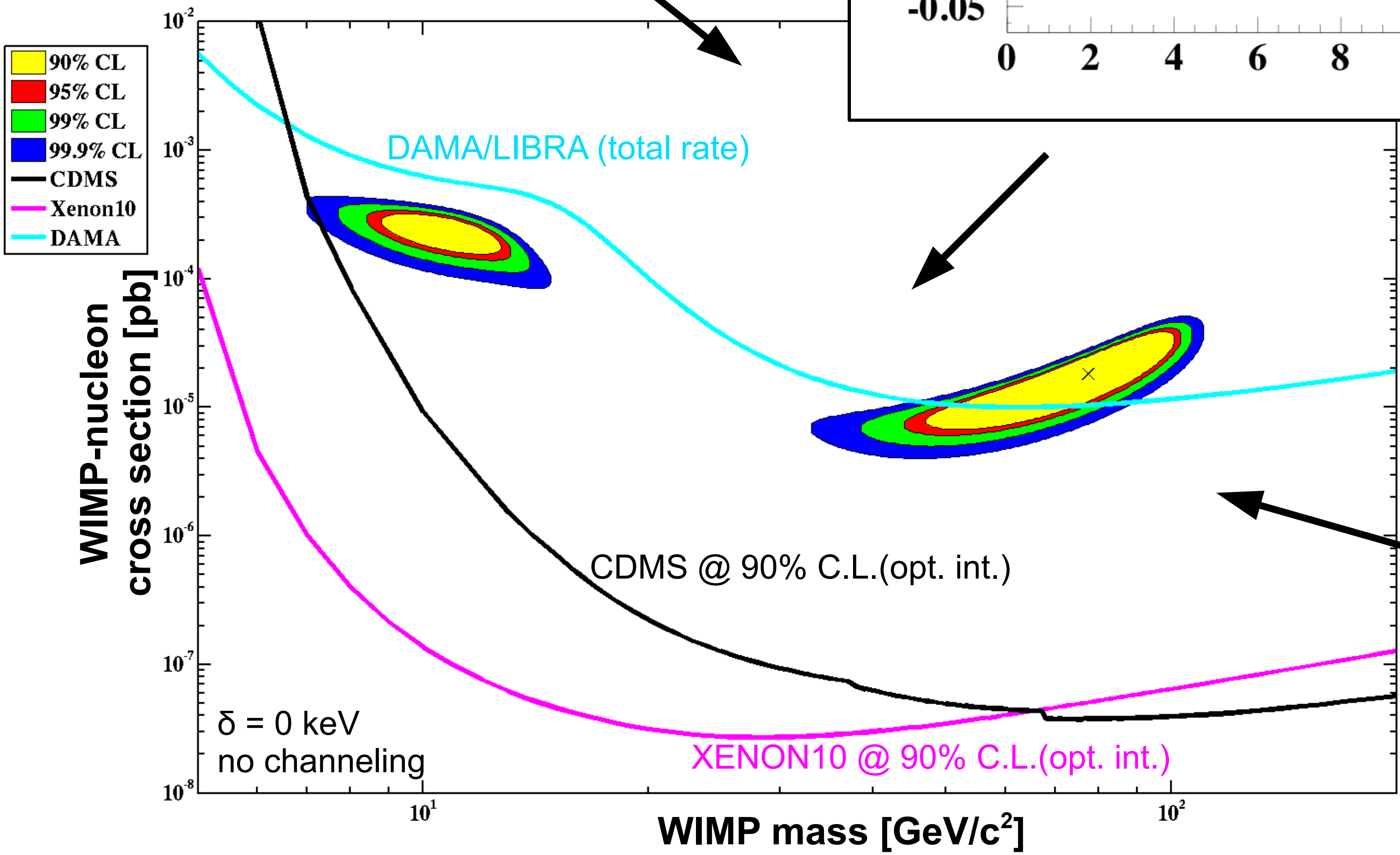
- enhancement of annual modulation



The DAMA/LIBRA allowed region

$$S_m(\mathrm{E}) = \frac{1}{2}\left(\frac{\mathrm{dR}}{\mathrm{dE}}(\mathrm{E}, 2^{\mathrm{nd}}\mathrm{June}) - \frac{\mathrm{dR}}{\mathrm{dE}}(\mathrm{E}, 2^{\mathrm{nd}}\mathrm{Dec})\right)$$





χ^2-goodness-of-fit-test with 17 degrees of freedom (10 – 20 keV combined into one bin)

constrain absolute value of χ^2 **not** $\Delta\chi^2$ with respect to the minimum

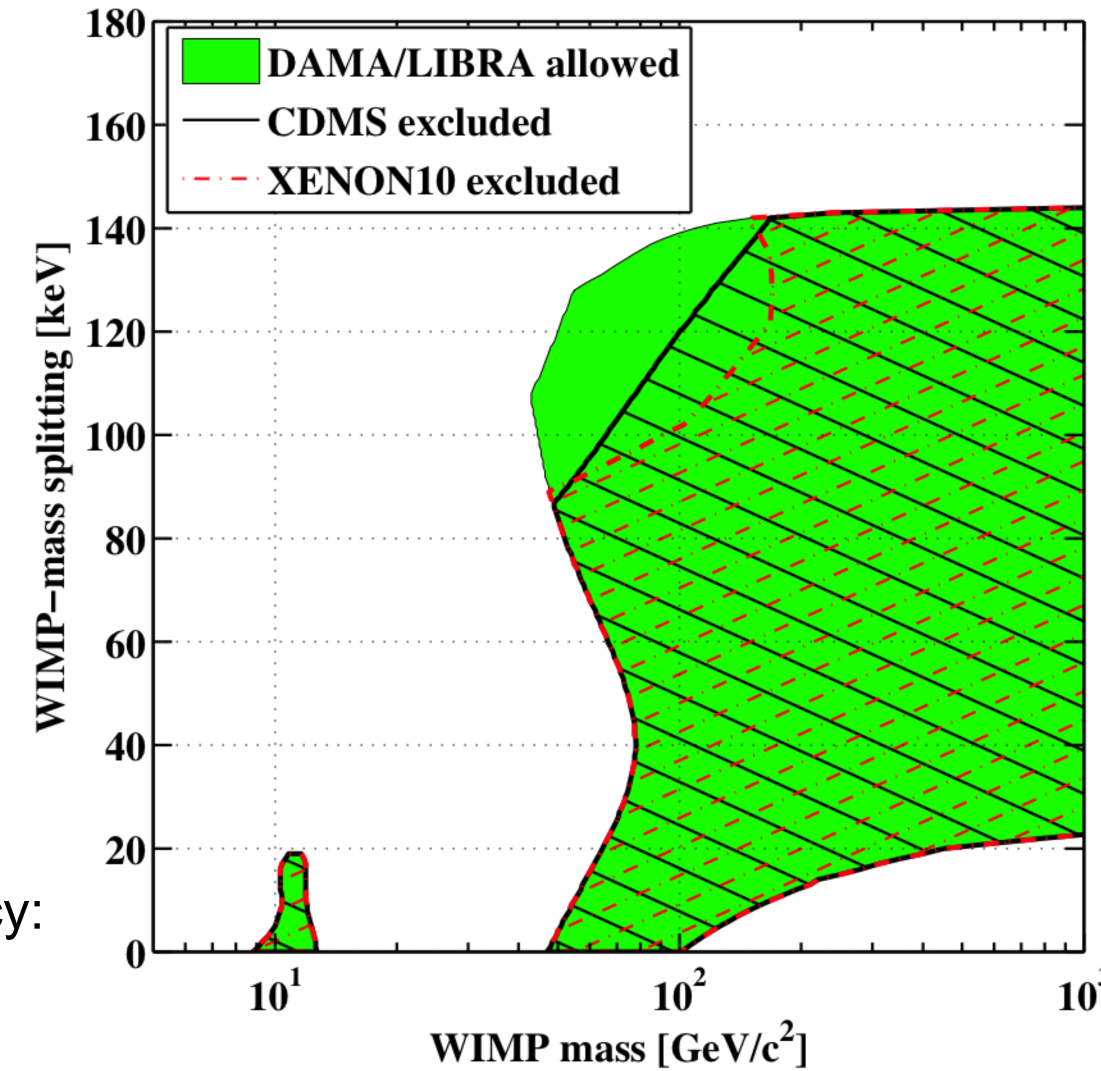
First constraints on IDM from CDMS

- Excluded regions are defined by demanding the upper limit on the cross section to completely rule out the DAMA/LIBRA allowed cross section intervals at a given WIMP mass and mass splitting.

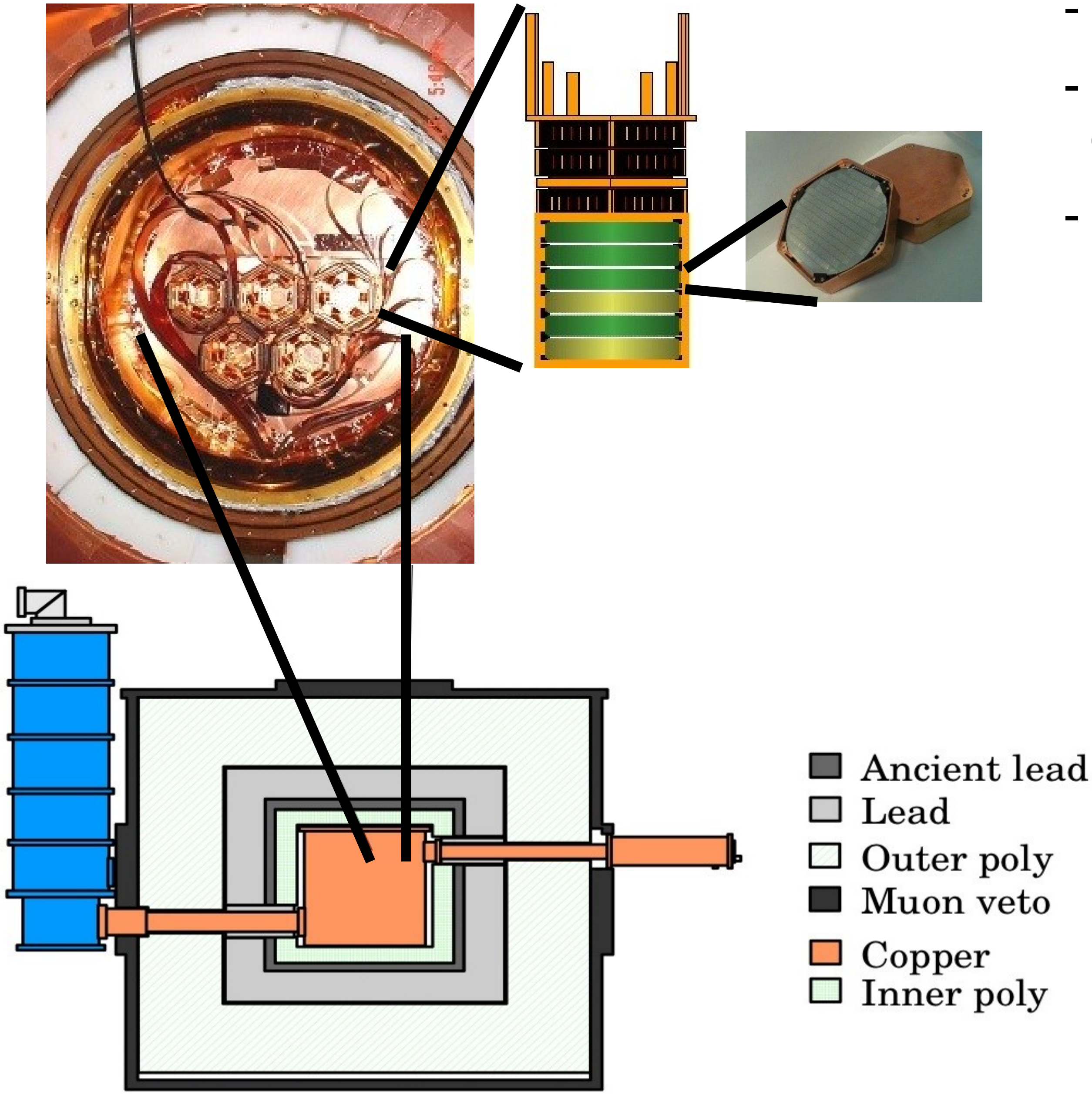
- all limits/allowed regions are @ 90% C.L.

- optimum interval method is used for CDMS and XENON10

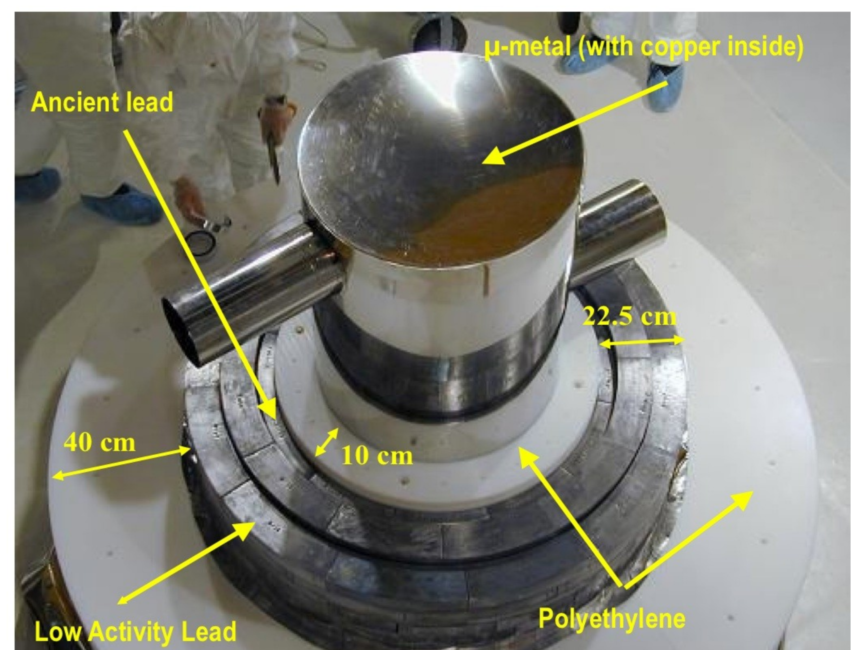
- used parameters are important:
  - escape velocity:
    - v_{esc} = 544 km/s
  - DAMA quenching factors:
    - q_I = 0.09
    - q_{Na} = 0.30
  - XENON10 scintillation efficiency:
    - L_{eff} = 0.19



The CDMS setup & shielding

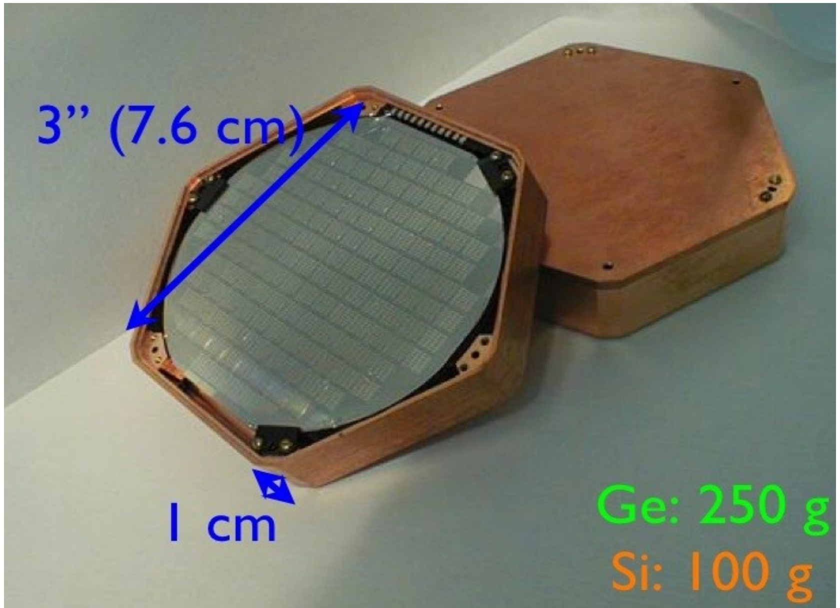


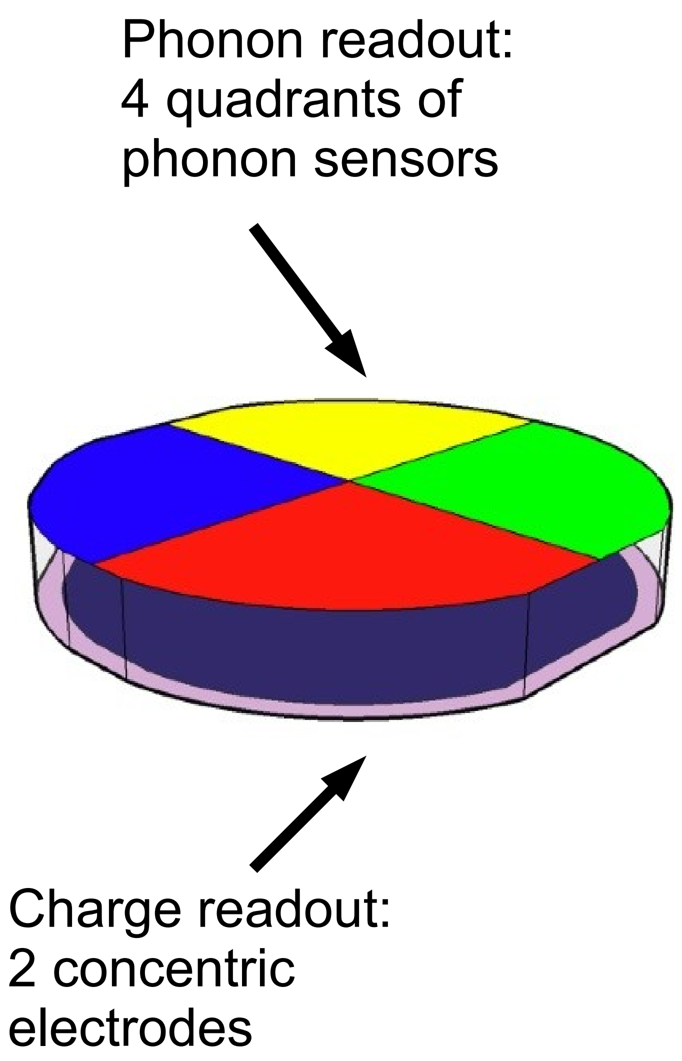
- 5 towers with 6 detectors each
- active veto against high energetic muons
- passive shielding:
  - lead against gammas from radioactive impurities
  - polyethylene to moderate neutrons from fission decays and from (α,n) interactions resulting from U/Th decays



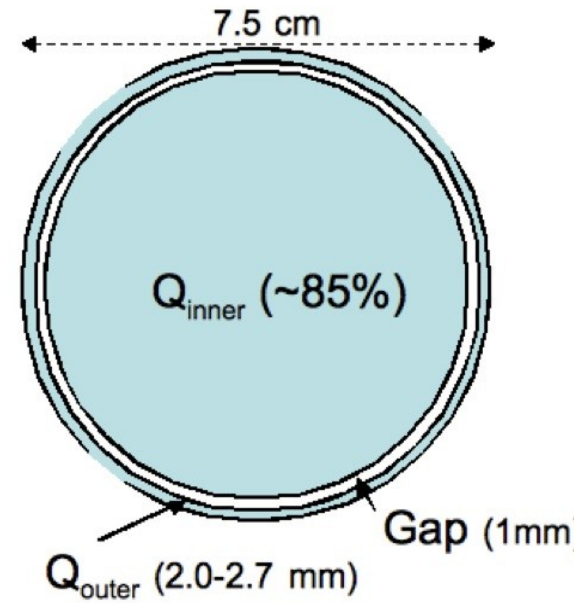
The CDMS ZIP detectors

- 19 Ge and 11 Si semiconductor detectors
- operated at cryogenic temperatures (~40 mK)
- 2 signals from interaction (ionization and phonon) → event by event discrimination between electron recoils and nuclear recoils
- z-sensitive readout
- xy-position imaging





The ionization readout



- interaction creates electron-hole pairs

→ seperate using applied electric field

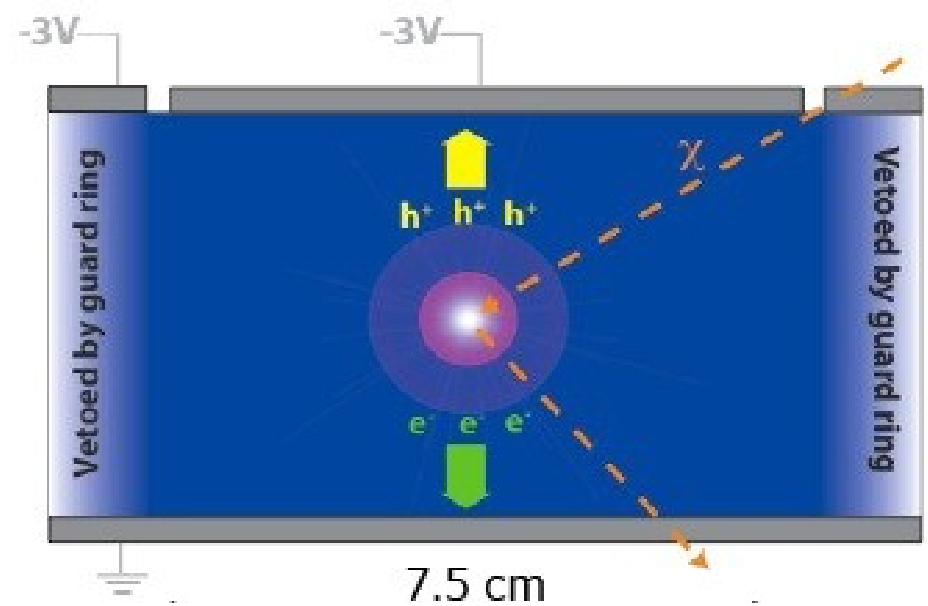
→ collect charges on electrodes on surface

- drift field of 3 V/cm (4V/cm) on Ge (Si) detectors
- interaction at crystal edges can have incomplete charge collection

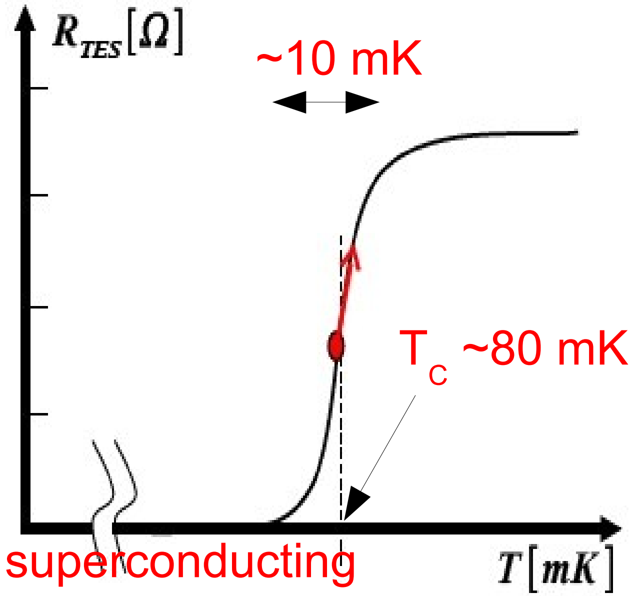
→ use outer electrode as guard ring

→ omit qouter events

- low-energy resolution: 3-4%



The phonon readout

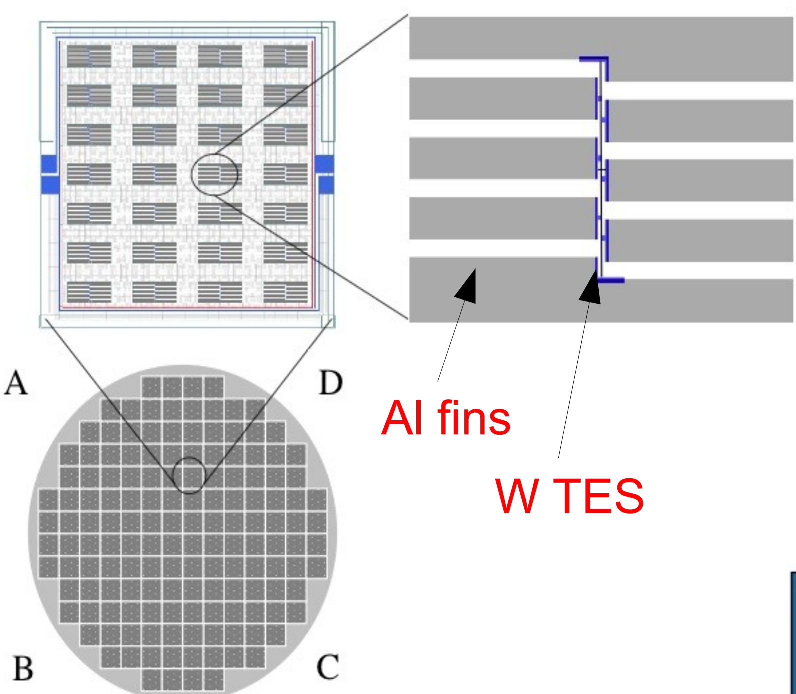


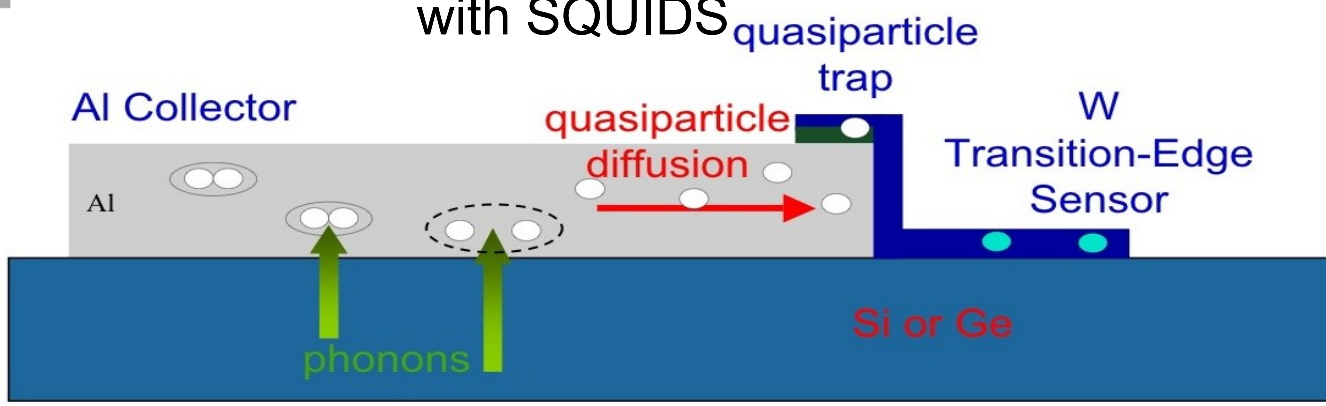
- segmented phonon readout (4 quadrants)
- each quadrant consists of 1036 tungsten TES (Transition Edge Sensors)
- fast response time ~5 μs
- low energy resolution: ~5%
- tungsten strips set just below the edge of superconductivity using bias voltage

→ energy deposition raises temperature

→ conductivity changes to normal

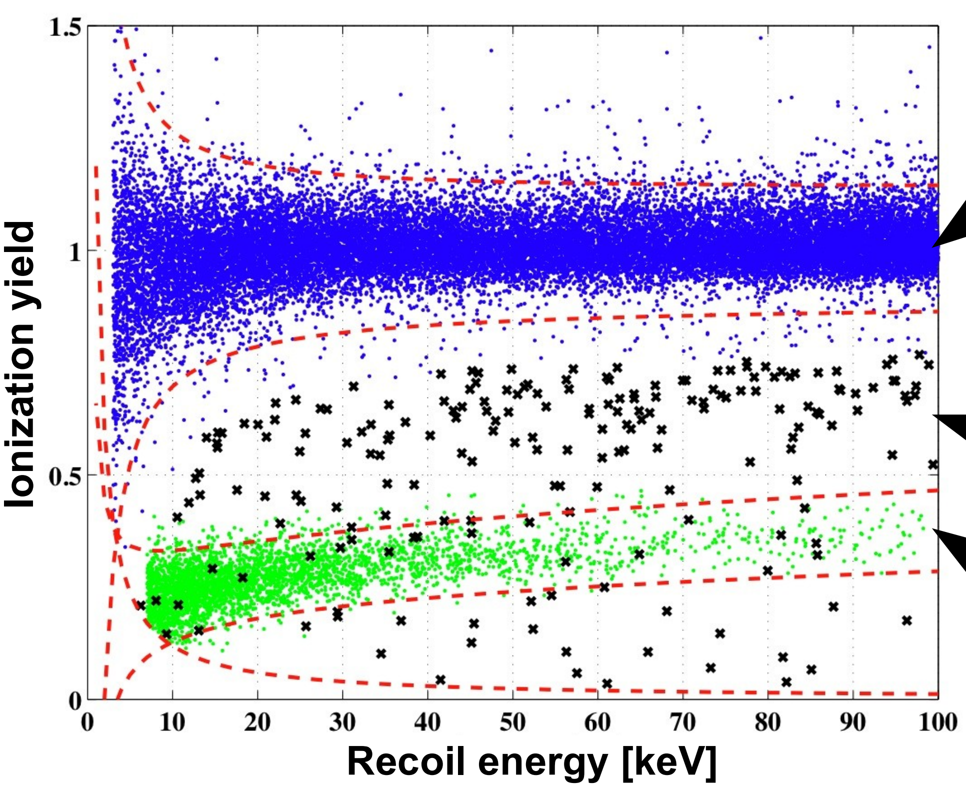
→ dramatic lowering of current read out with SQUIDS





Primary background rejection

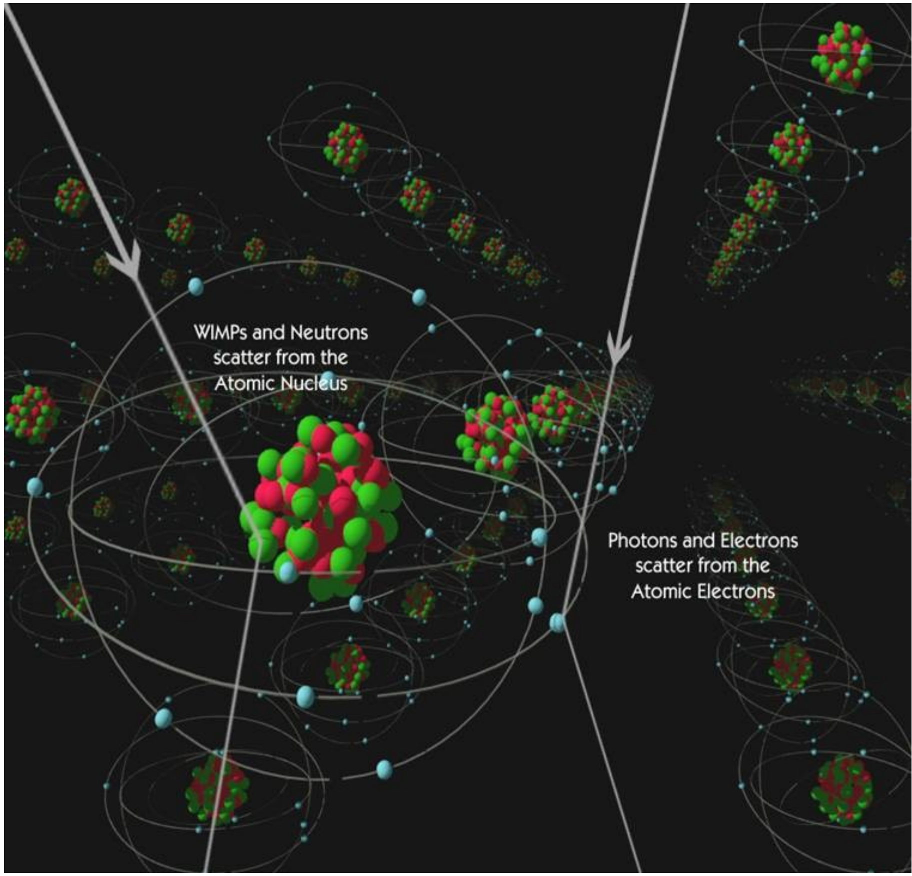
- most backgrounds (e, γ) produce electron recoils
- neutrons and WIMPs produce nuclear recoils which have a suppressed ionization signal
- define ionization yield as $y = \frac{E_{charge}}{E_{recoil}}$



electron recoils (^{133}Ba)

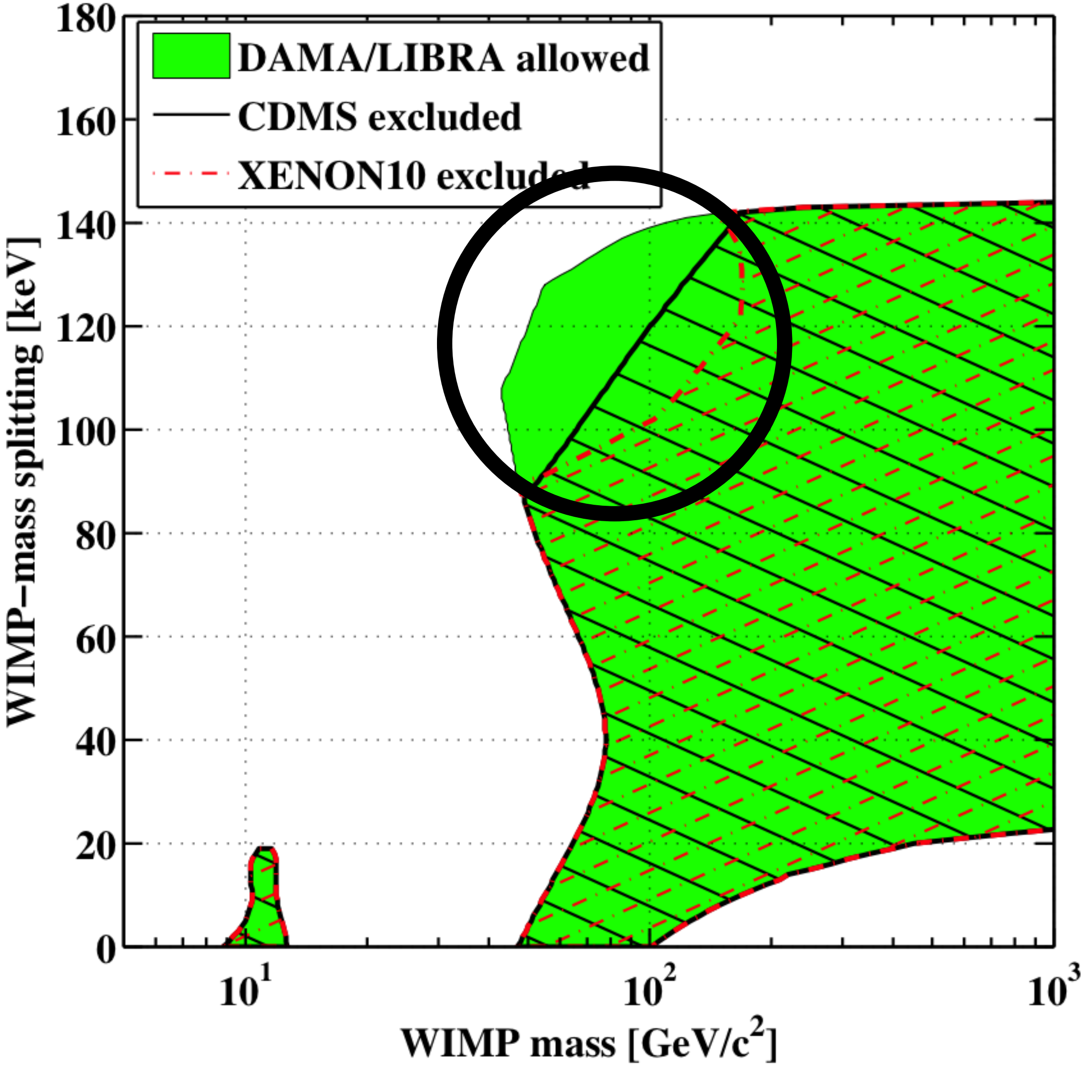
surface events

nuclear recoils (^{252}Cf) →signal region



- better than 1:10000 rejection of electron recoils based on ionization yield alone
- dominant remaining background: low-yield surface events

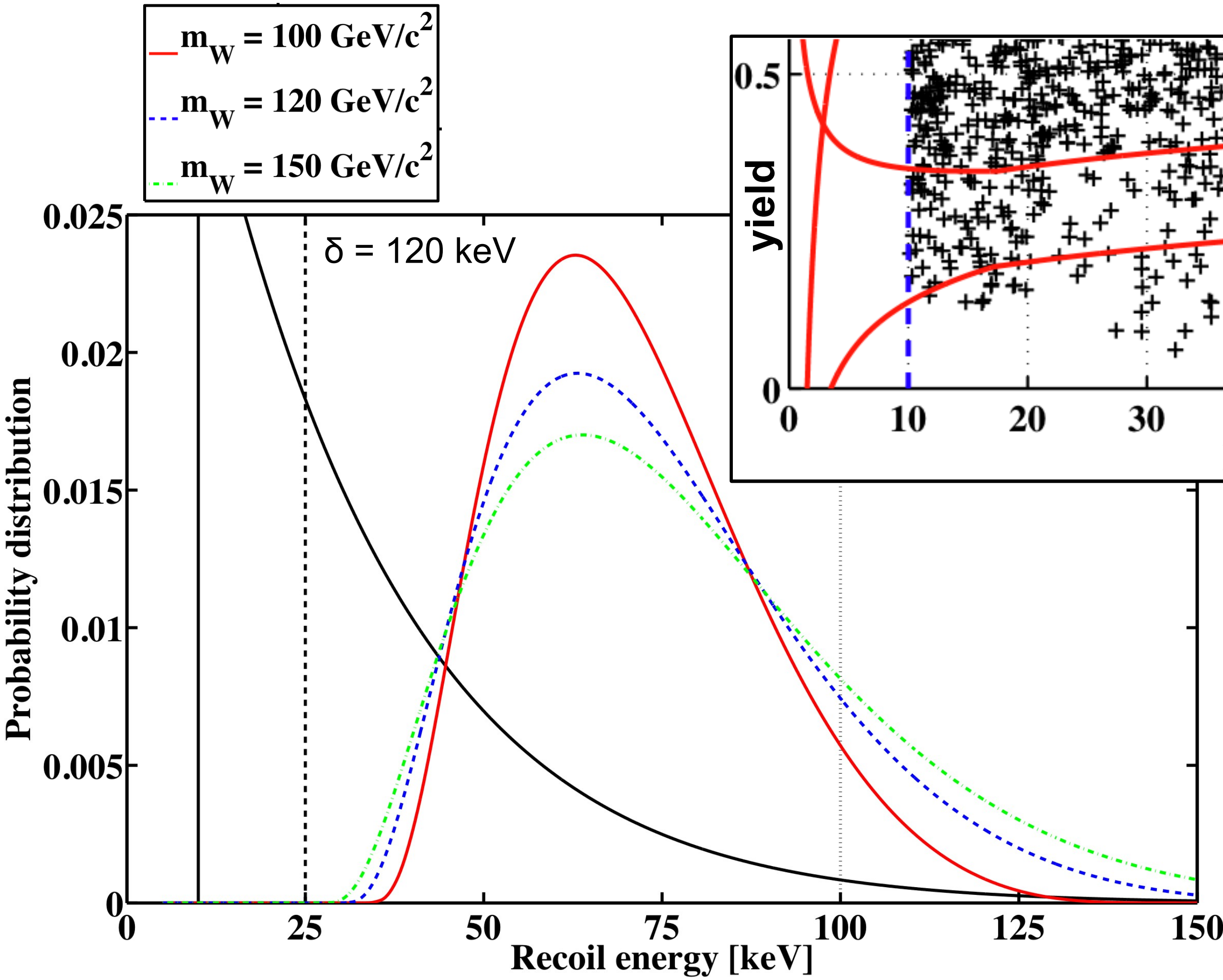
Remember...

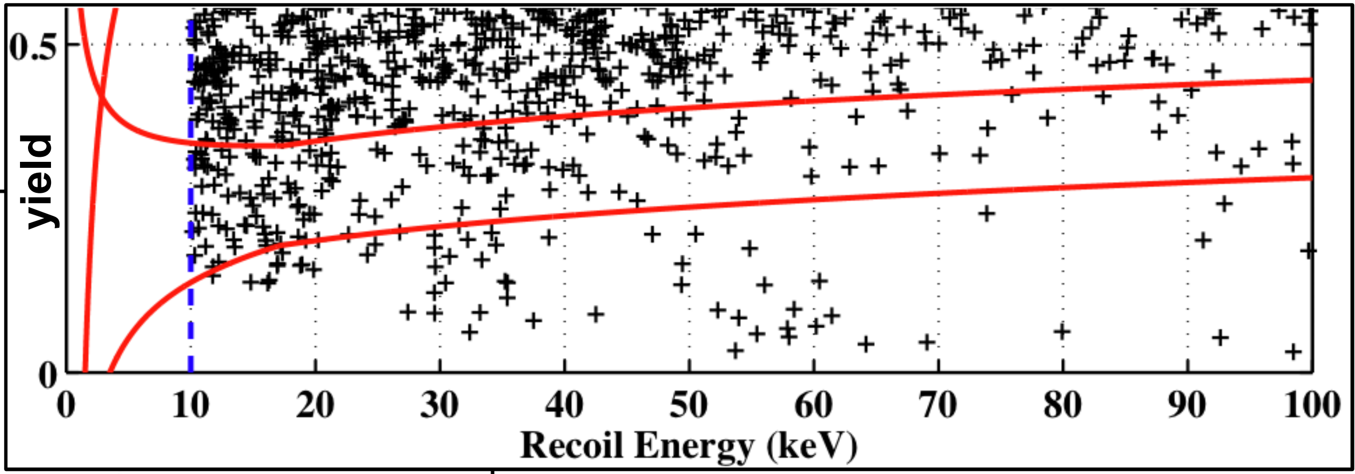


- energy range of standard analysis: 10 – 100 keV
- dominant background: surface events
- paramater space region of interest:
  WIMP-mass splitting δ: 80 – 140 keV
  WIMP mass m_W: 50 – 200 GeV/c^2

benchmark point: δ = 120 keV
m_W = 100 GeV/c^2

How can we improve the sensitivity?





WIMP search events failing the surface-event rejection cut.

Dominant surface event background at low energies where the rate is highly suppressed.

Differential rates in allowed parameter space extend to energies above upper analysis limit (100 keV).

Simply extend analysis range to 150 keV!

Improve surface event rejection cut!
Use all 6 five tower runs!
Energy range: 25 – 150 keV

Extending the analysis range

- in principle very simple task

- main problem is low statistics in the californium calibration data at energies above ~100 keV

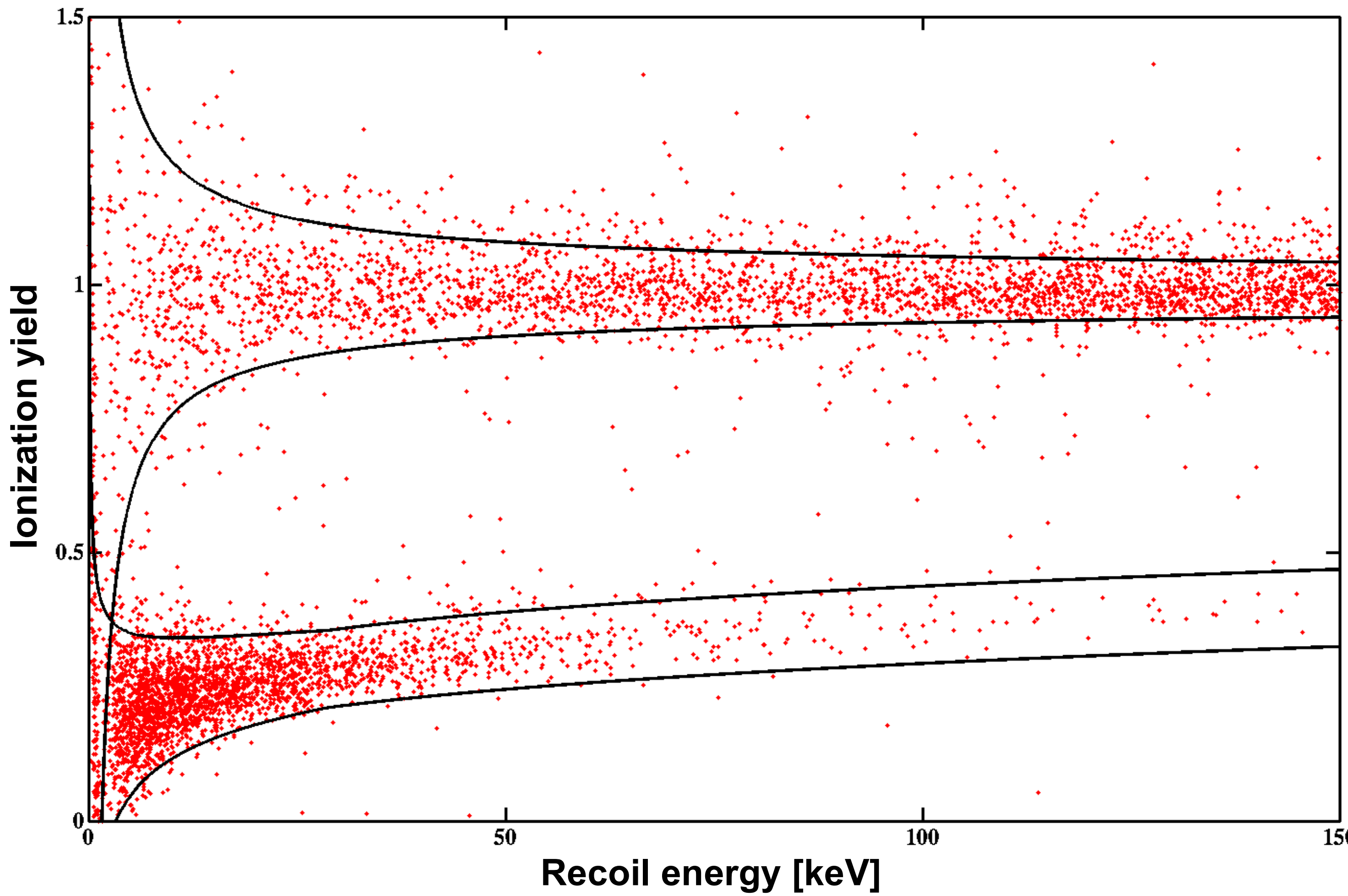
- always check results (cuts/efficiencies) at high energies combining all 6 runs

- compare results from combined data sets with extrapolations from low energies

- be conservative

- No cuts (except surface event rejection) have to be changed.

- Possible WIMP candidates above ~100 keV have to be checked with special care!



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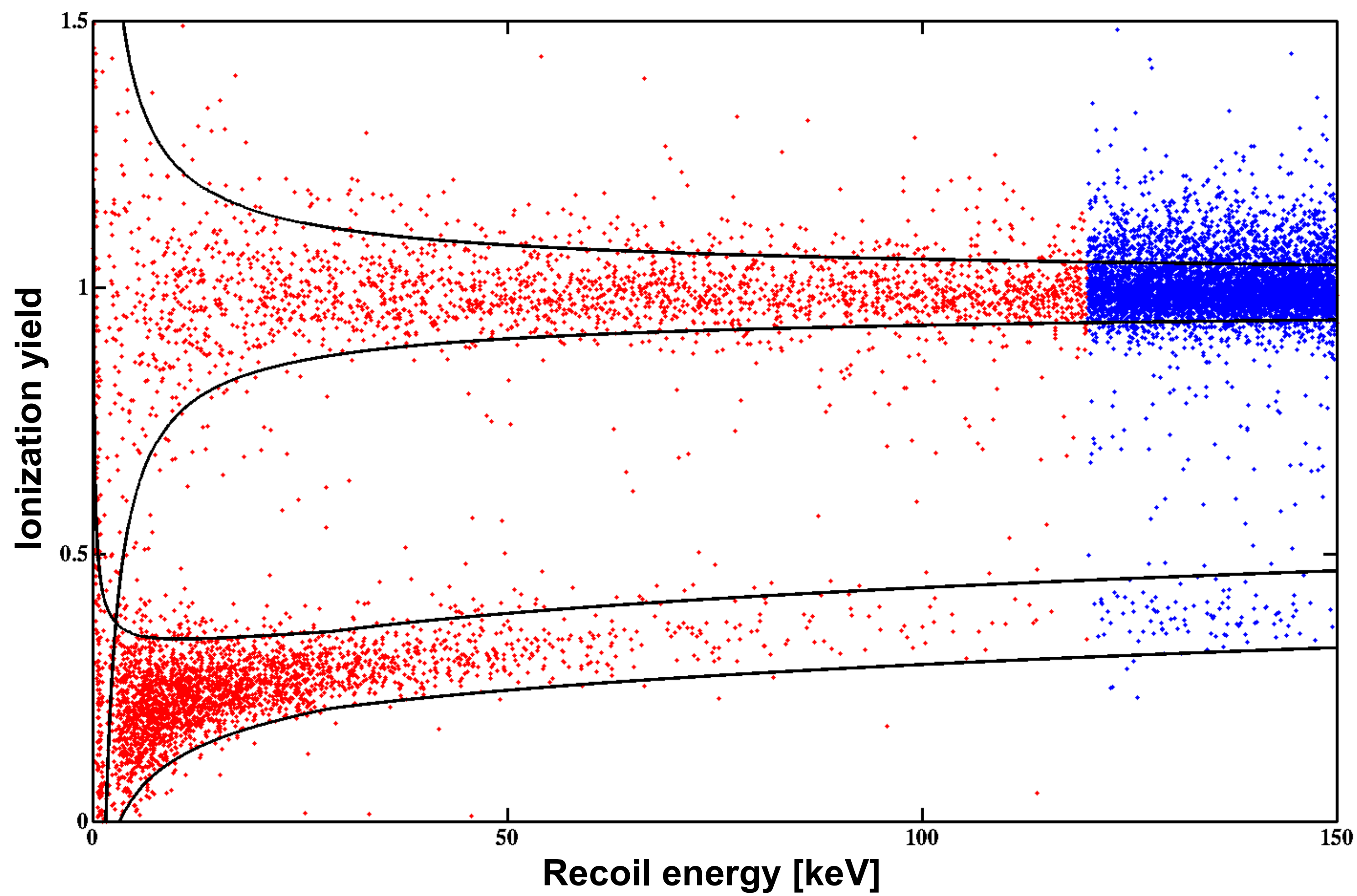
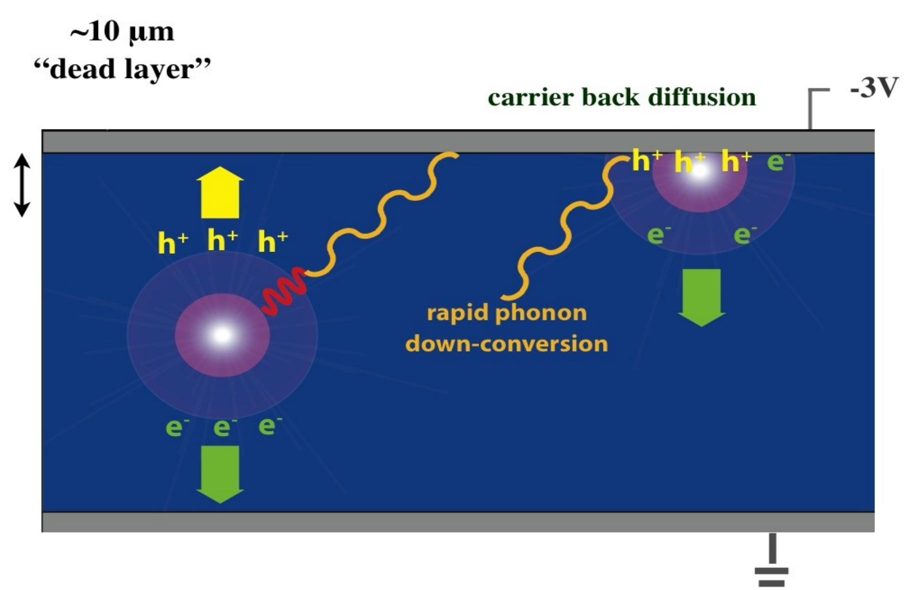


Surface events and contamination

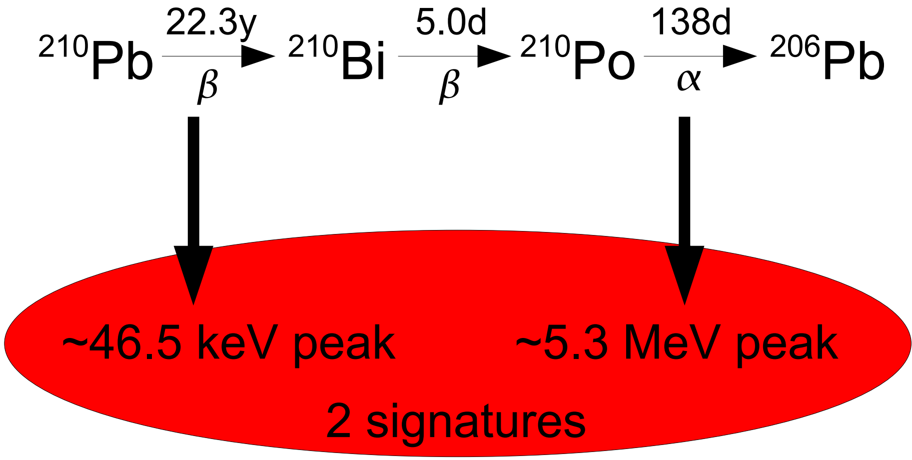
- reduced charge yield due to back-diffusion of charge carriers at the detector surface
- surface event background can be fully accounted for by two sources:
  1. low-energy electrons induced by the ambient photon flux from radioactive impurities in the experimental setup
  2. ^{210}Pb contamination of the detector surfaces



^{210}Pb contamination?

- detetctors are exposed to environmental Radon during fabrication, testing, ...
- ^{210}Pb is a decay product of ^{222}Rn and can be deposited on the detector surfaces

- decay chain:

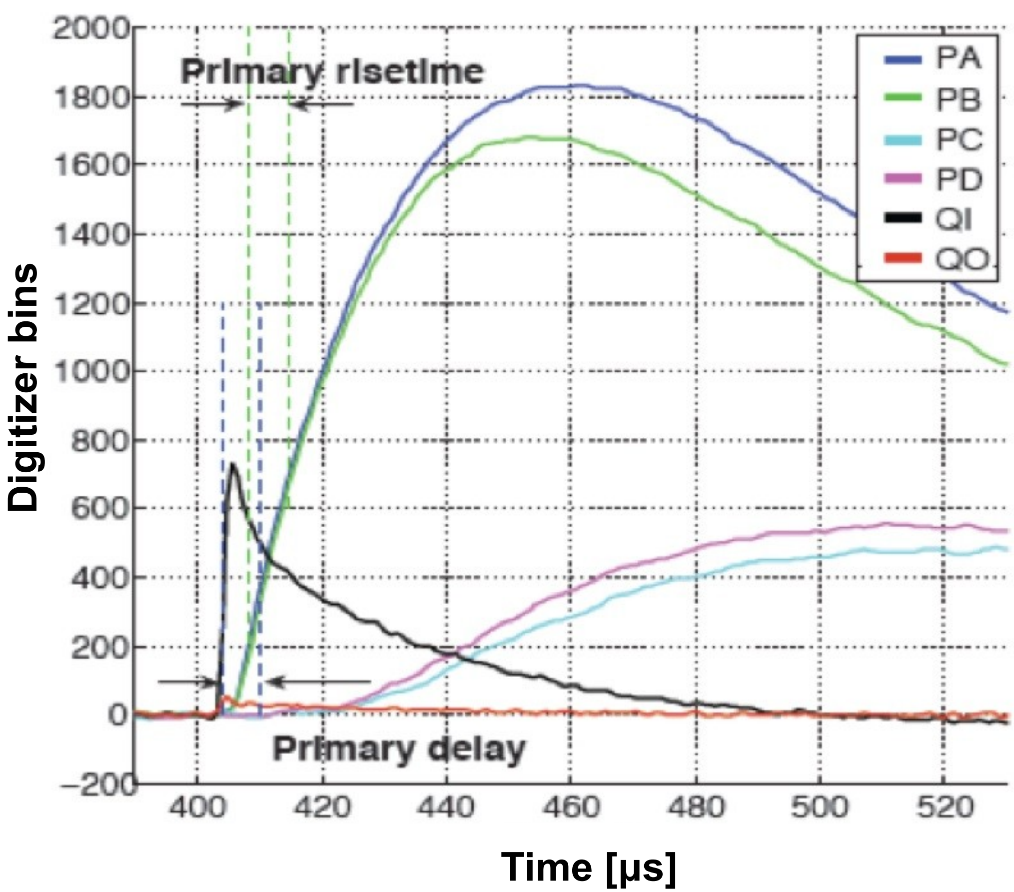


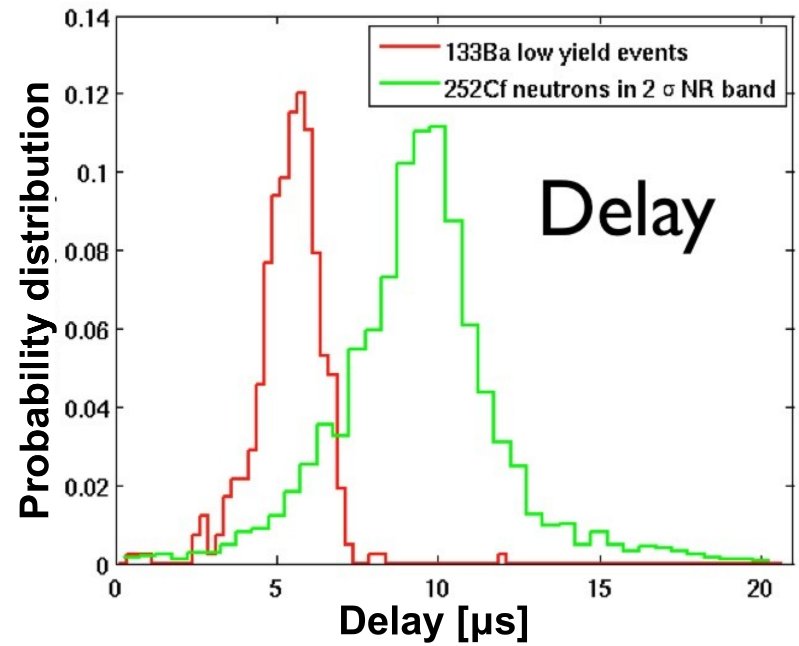
- significant reduction of this contribution for new towers (T3-T5)

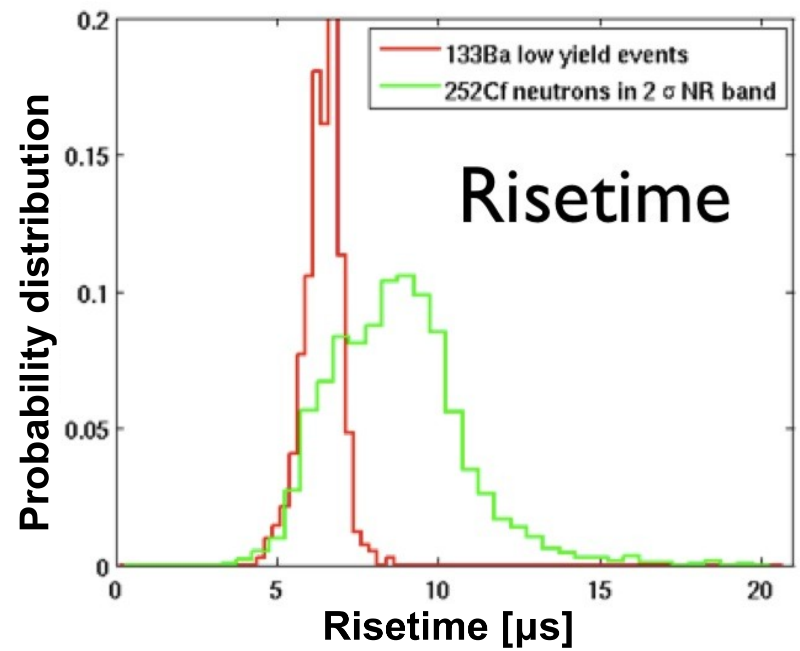
Phonon timing

Surface events are faster in timing than bulk nuclear recoils.

Use timing as discriminator to get rid of surface events.



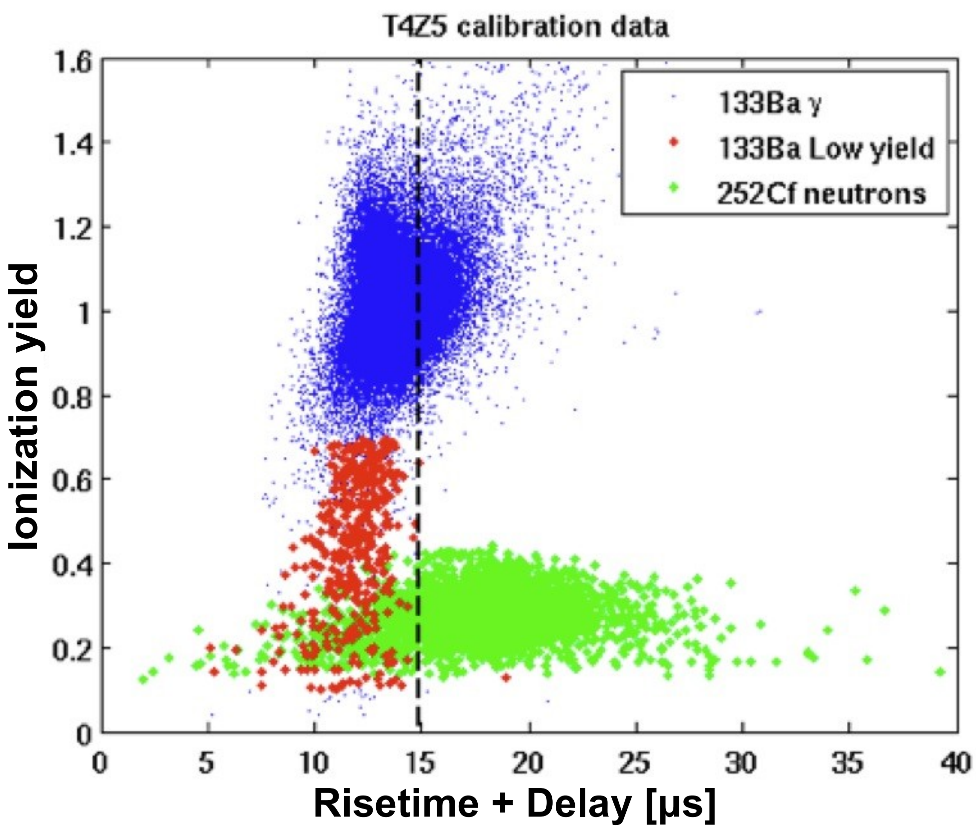


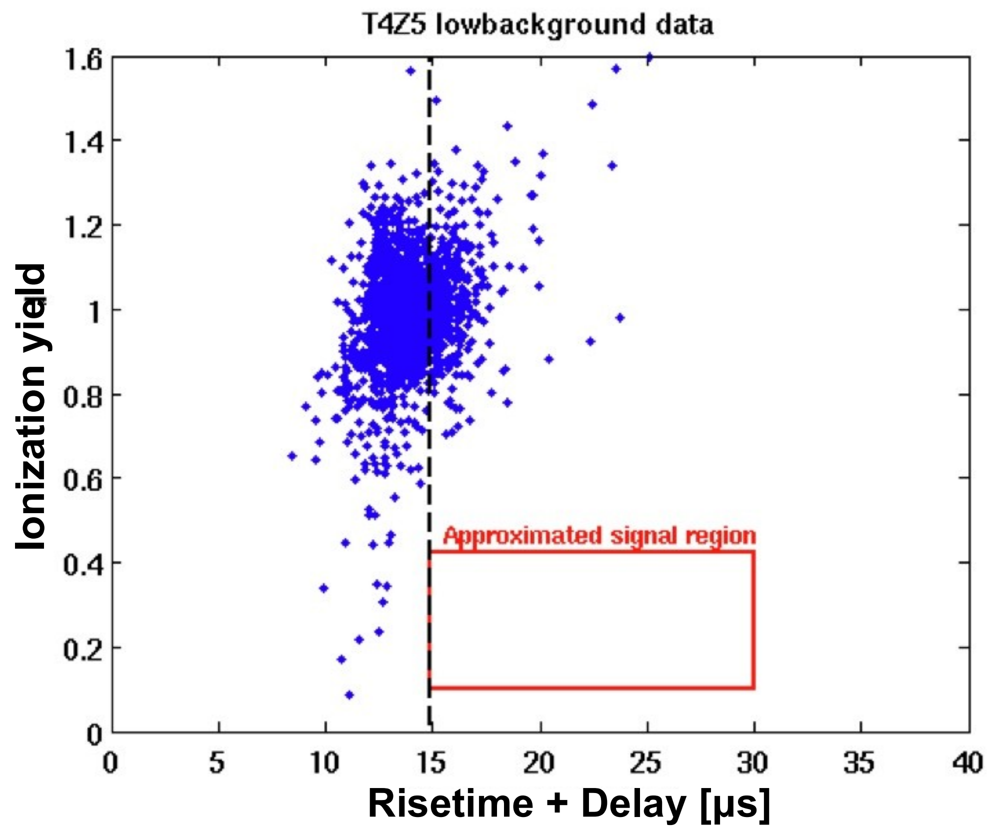


Surface-event rejection - principle

- use risetime+delay to define timing cut on calibration data
- allow less than one event total leakage within WIMP search data

- apply cut to lowbackground data
- surface event rejection ~200:1





A new surface-event rejection cut

need to use combined 5 tower data from all 6 runs (969.4 kg-days, germanium detectors only)

tighter timing cut for given leakage

lower efficiency

set new timing cut in the energy range of 25-150 keV to evade most of the leakage

looser timing cut for given leakage

higher efficiency

Which effect will be stronger?

New Timing Cut

optimize timing cut for WIMP mass of 100 GeV/c^2 and mass splitting of 120 keV

Analysis is **not** blind! But use only timing information from calibration data for setting the cut, **not** from WIMP search data.

Setting the timing cut

- estimate distribution of nuclear recoils from californium calibration data in each detector z→ nuclear-recoil efficiency ϵ

- compute differential rate for WIMP mass of 100 GeV/c^2 and mass splitting of 120 keV

spectrum averaged exposure $SAE_z(t_z)$

$$SAE = mT\frac{\int dE\frac{dR}{dE}\epsilon(E)}{\int dE\frac{dR}{dE}}$$

- estimate distribution of surface events from barium calibration data in each detector z→ leakage fraction l

- apply correction factors s for difference between barium and WIMP-search data

- include estimated number of nuclear recoil single scatter N_{NRSS}

expected leakage $n_z(t_z)$

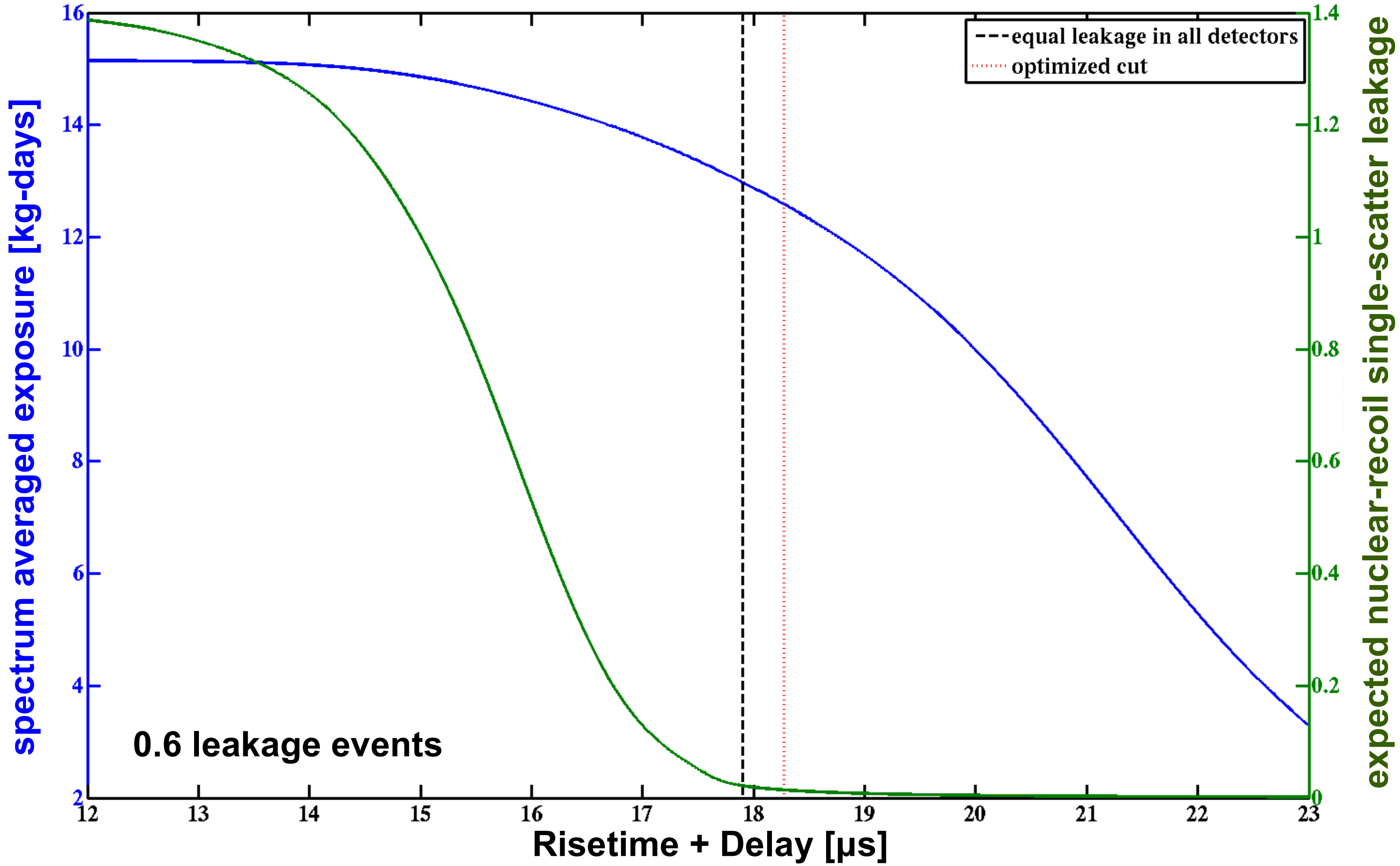
$$n_z = N_{\mathrm{NRSS}} \cdot \left(\sum_b s_z^b \cdot l_z^b \right)$$

Minimize $$f(t) = \left(1 - \frac{\sum_z SAE_z(t_z)}{(\sum_z SAE_z)_{max}}\right)^2 + \left(1 - \frac{\sum_z n_z(t_z)}{(\sum_z n_z)_{target}}\right)^2$$

predefined leakage (try different values)

Setting the timing cut - example

- optimize trade-off between background and exposure
- take different timing performance of different detectors into account
- cut set in the tail of the barium distribution → Main difficulty!
- gain ~20 kg-days exposure (SAE) with optimization



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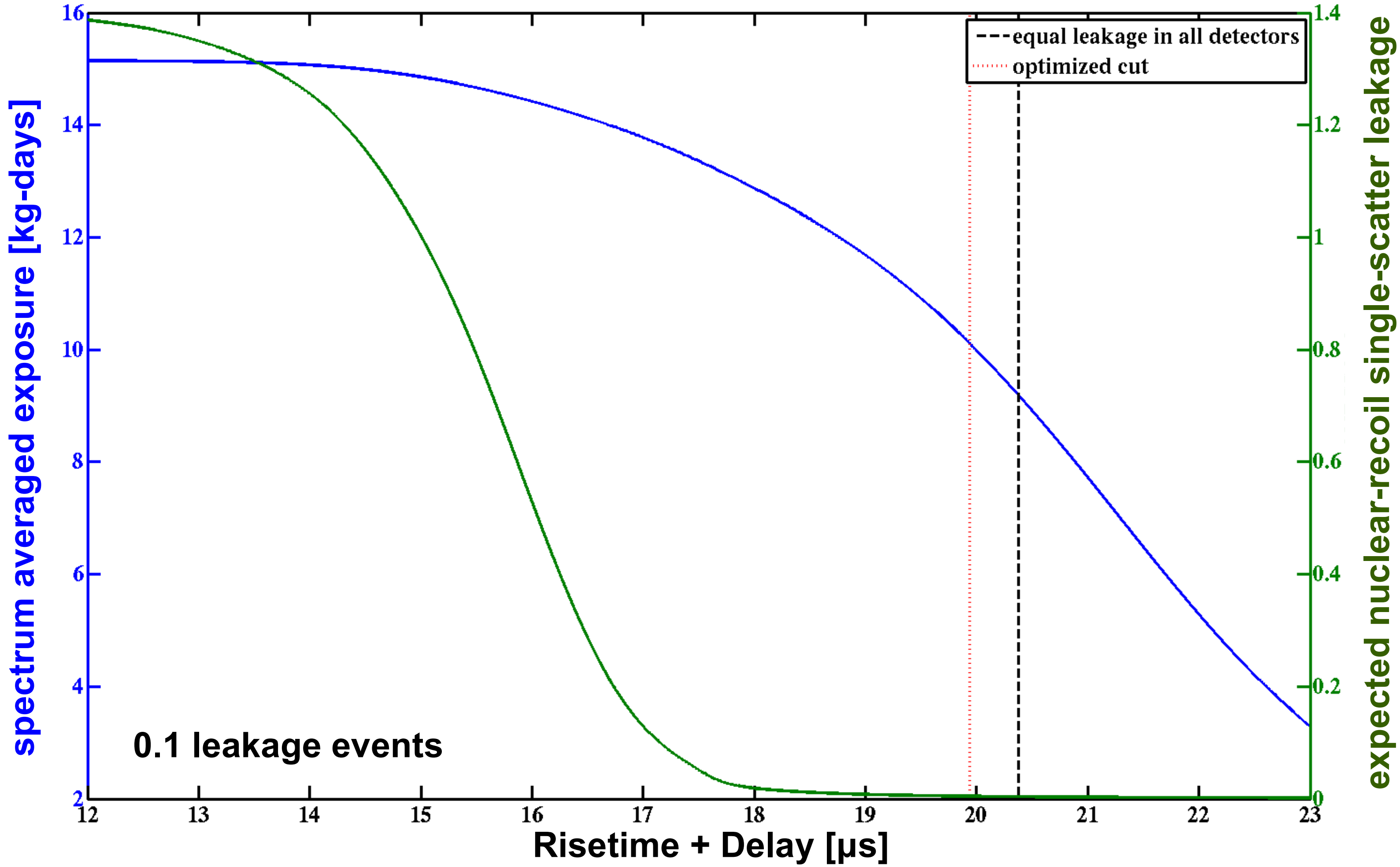


Which timing cut should we use?

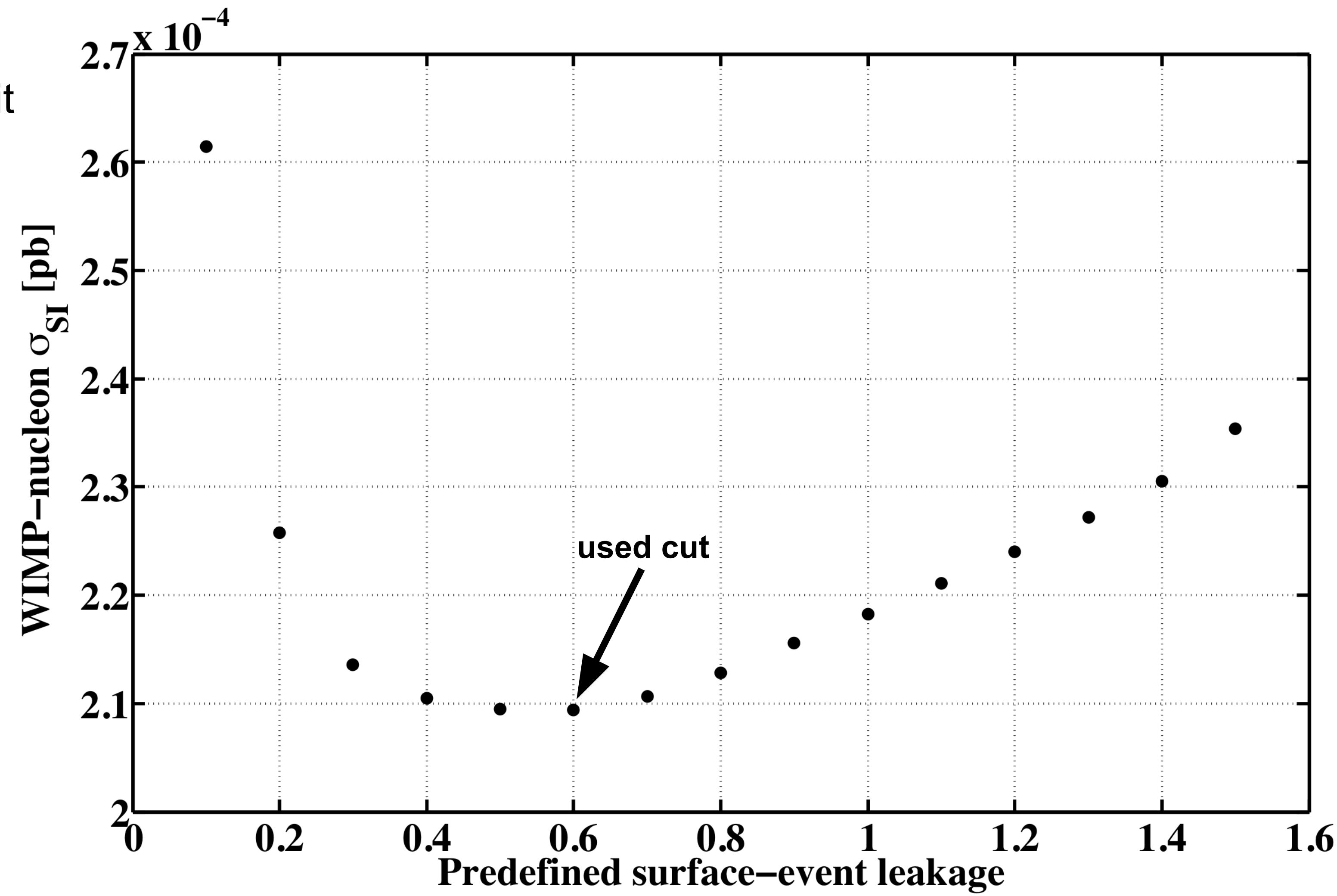
- estimate surface-event spectrum from energy spectrum of WIMP-search multiple scatters in the nuclear-recoil band and pass/fail ratios from barium calibration data

- use MC to generate 10^6 possible experimental outcomes for each cut

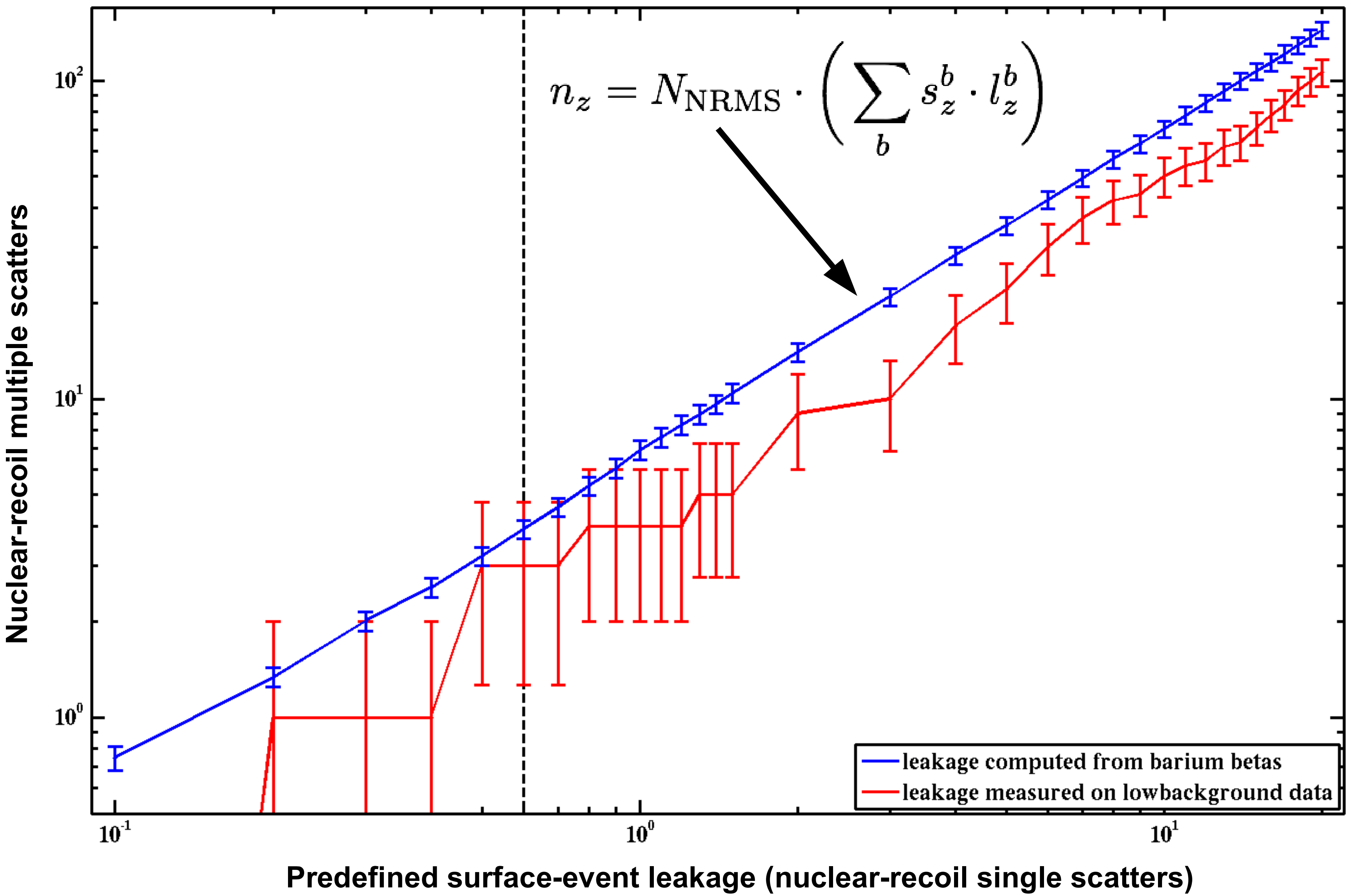
- compute mean cross section limit for benchmark values with optimum interval method

Use cut set to 0.6 leakage events on barium calibration data!

But check on WIMP-search data!



Test cut on WIMP-search multiples



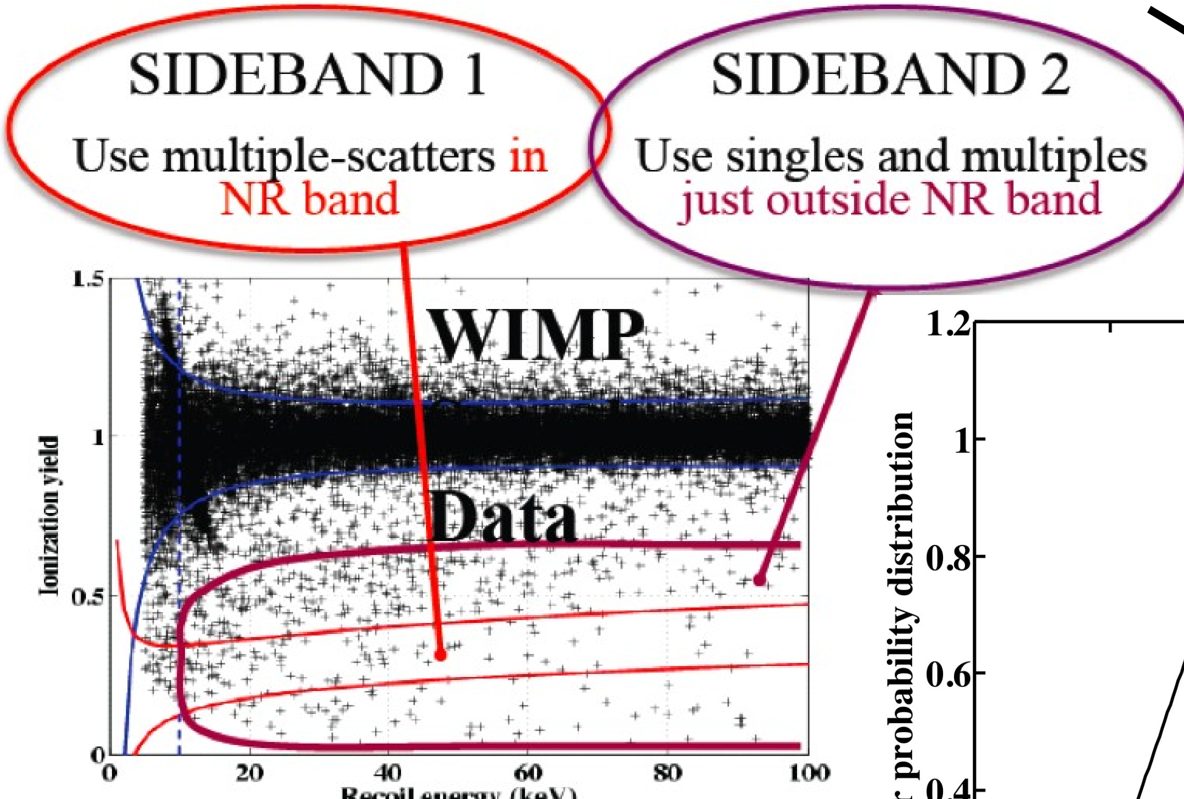
Surface-event leakage estimate

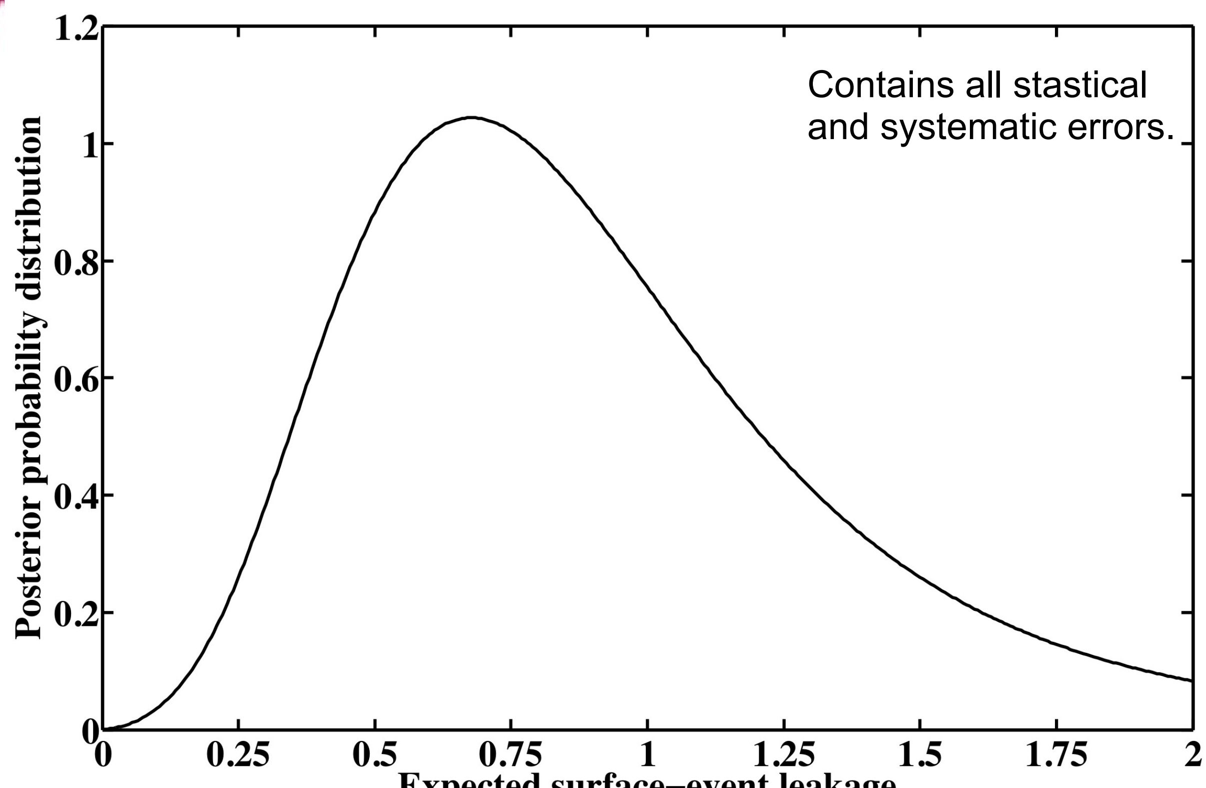
- expected surface-event leakage: $\mu = \langle N^{fail}_{sing.} \rangle \cdot \frac{\langle N^{pass}_{mult.} \rangle}{\langle N^{fail}_{mult.} \rangle}$

- use two independent event populations for estimating pass/fail-ratios

$0.8^{+0.5}_{-0.3}(\mathrm{stat.})^{+0.3}_{-0.2}(\mathrm{syst.})$

(in 25 -150 keV range,
all 6 five-tower runs)



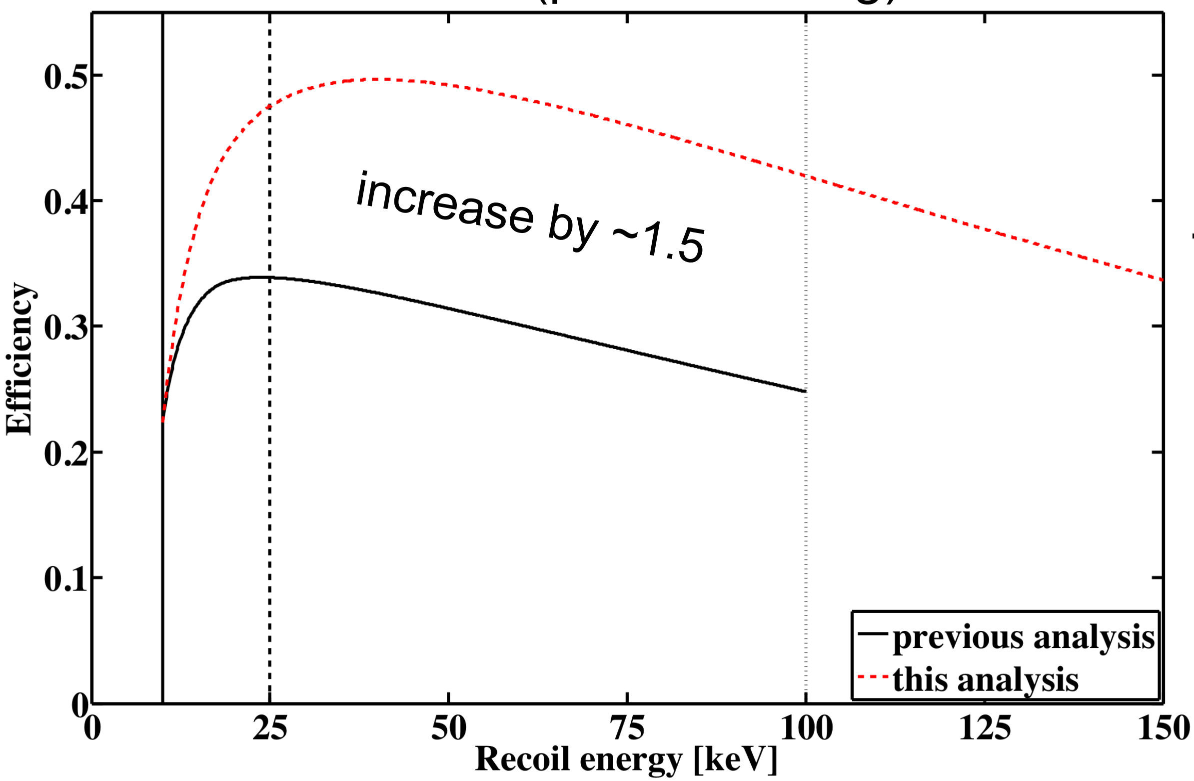


Bayesian approach → treat
background as random variable

Analysis summary

969.4 kg-days raw exposure

Cut criteria for WIMP candidates:
- energy range: 10 - 150 keV
- data quality
- veto-anticoincidence
- single-scatters
- inside fiducial volume (qinner cut)
- inside 2σ nuclear-recoil band
- no surface event (phonon timing)

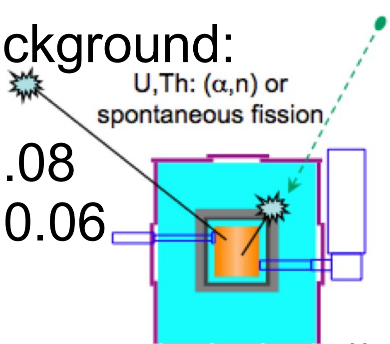


“Blind“ Analysis
Set all cuts and calculate efficiencies **before** looking at the signal region of the WIMP-search data.

Background summary
- expected number of surface leakage events:
  10 – 25 keV: $5.7^{+2.1}_{-1.5}(\mathrm{stat.})^{+1.0}_{-0.9}(\mathrm{syst.})$

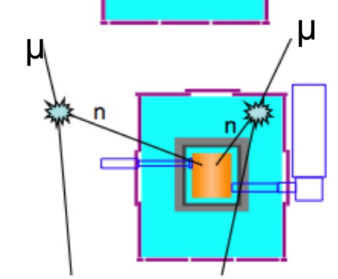
  25 – 150 keV: $0.8^{+0.5}_{-0.3}(\mathrm{stat.})^{+0.3}_{-0.2}(\mathrm{syst.})$

- estimated neutron background:
  (α,n) & fission:
  10 – 25 keV: 0.04 – 0.08
  25 – 150 keV: 0.03 – 0.06



  cosmogenic:
  10 – 25 keV: $0.06^{+0.07}_{-0.04}$

  25 – 150 keV: $0.04^{+0.05}_{-0.03}$

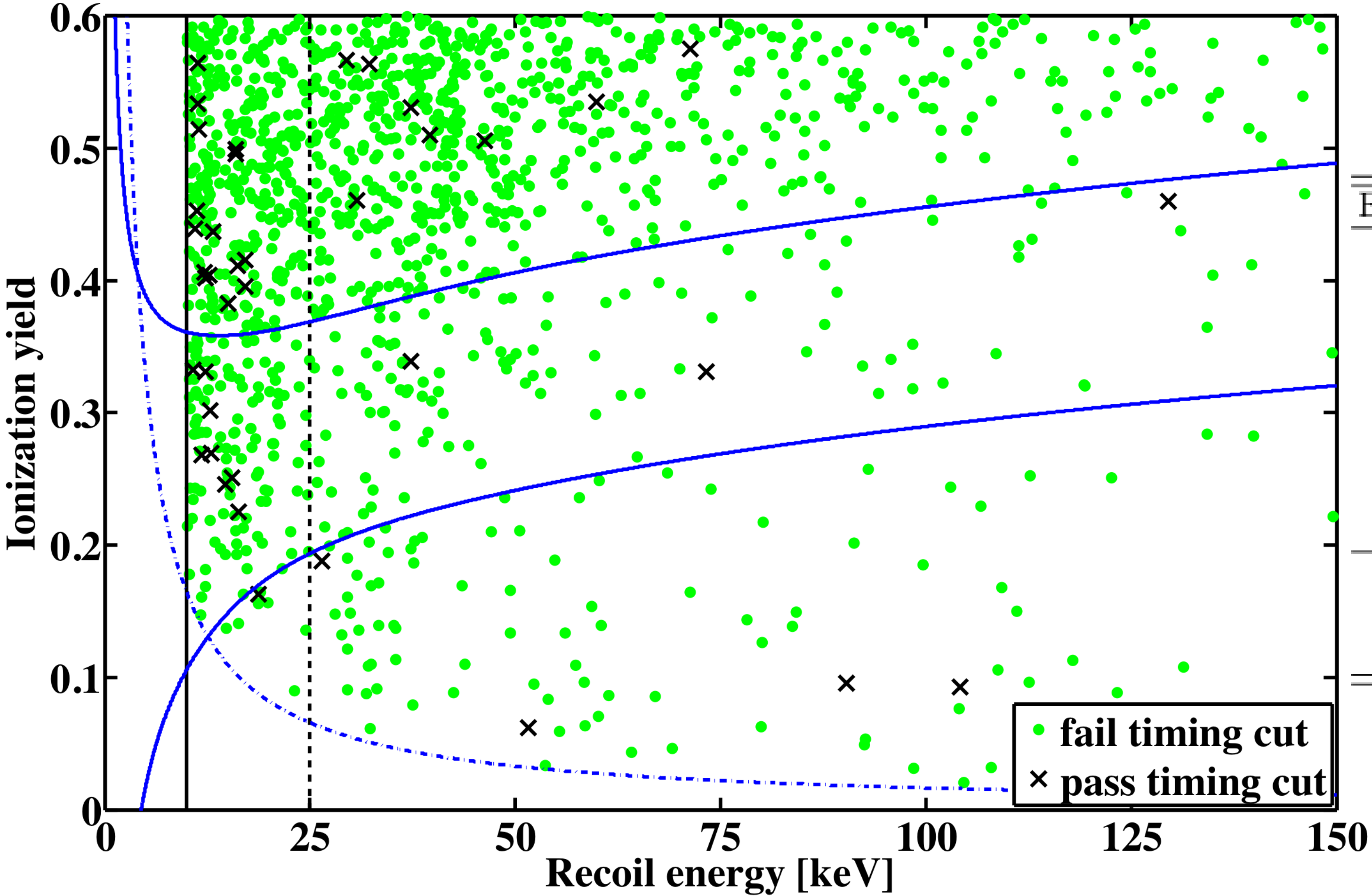


“Unblinding“

10 – 25 keV: 8 events (29% probability for 8 or more background events)

25 – 150 keV: 3 events (11% probability for 3 or more background events)

$$p(\geq N_{\mathrm{obs}}\ \mathrm{events}) = \int_0^\infty \mathrm{d}\mu\ P(\mu) \cdot \sum_{k=N_{\mathrm{obs}}}^{\infty} \frac{\mu^k e^{-\mu}}{k!}$$

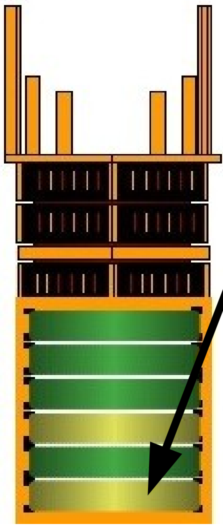


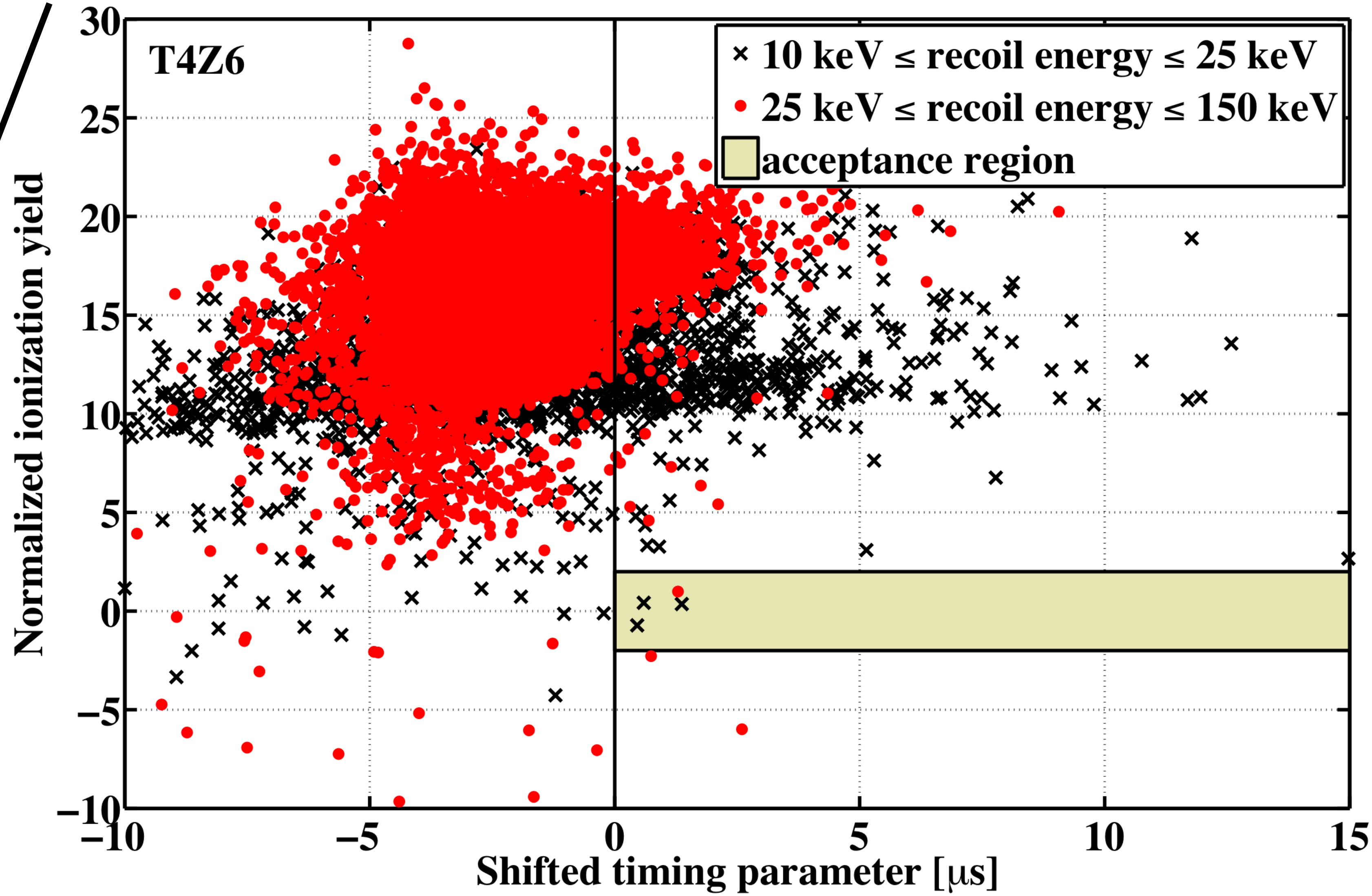
Energy (keV)	Detector	Run	Date
10.8	T2Z3	127	31.05.2008
11.8	T4Z6	124	31.05.2007
12.3*	T1Z5	125	27.10.2007
12.8	T3Z6	127	01.06.2008
13.0	T4Z6	125	05.10.2007
14.7	T3Z6	123	10.12.2006
15.5*	T3Z4	125	05.08.2007
16.4	T4Z6	123	30.10.2006
37.3	T4Z6	126	02.02.2008
73.3	T4Z2	126	04.02.2008
129.5	T1Z2	123	24.12.2006

“High-energy“ event 1

T4Z6 @ 37.3 keV Feb. 2, 2008

Endcap detector!

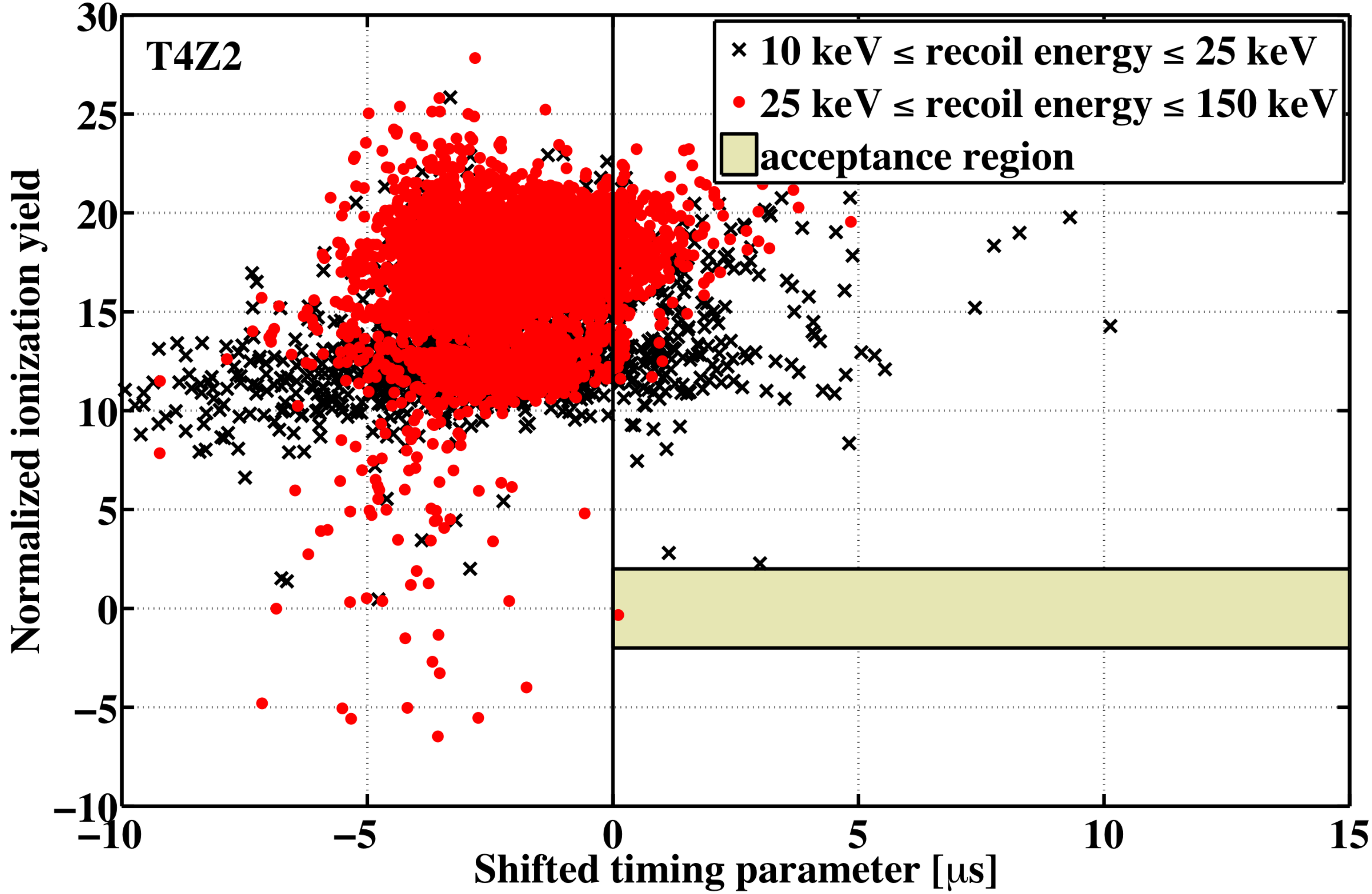




“High-energy“ event 2

T4Z2 @ 73.3 keV Feb. 4, 2008

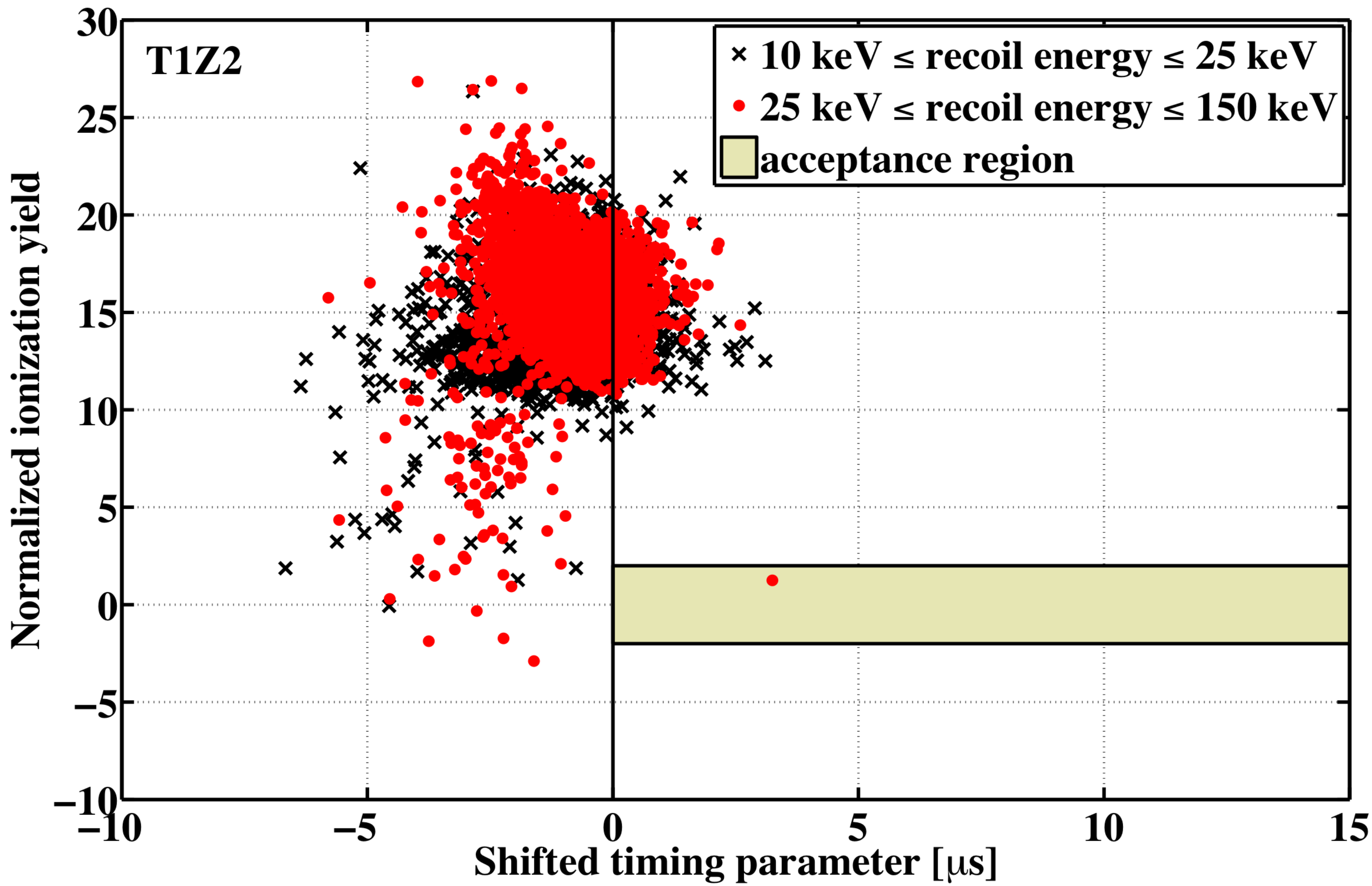
Extremely close to timing cut boundary!



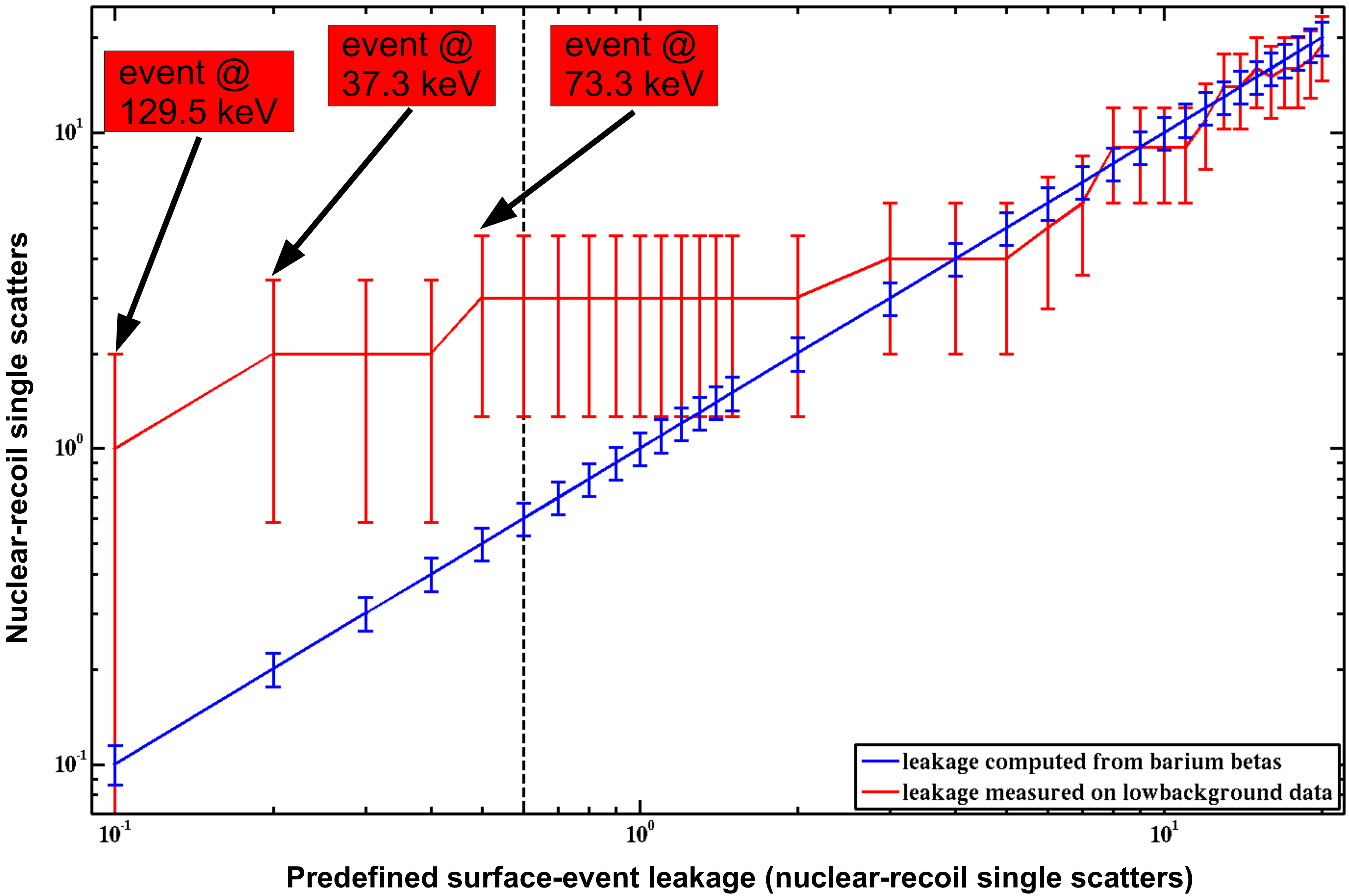
“High-energy“ event 3

T1Z2 @ 129.5 keV Christmas Eve, 2006

Not even cut by timing cut set to 0.1 leakage events / cut from previous analysis!

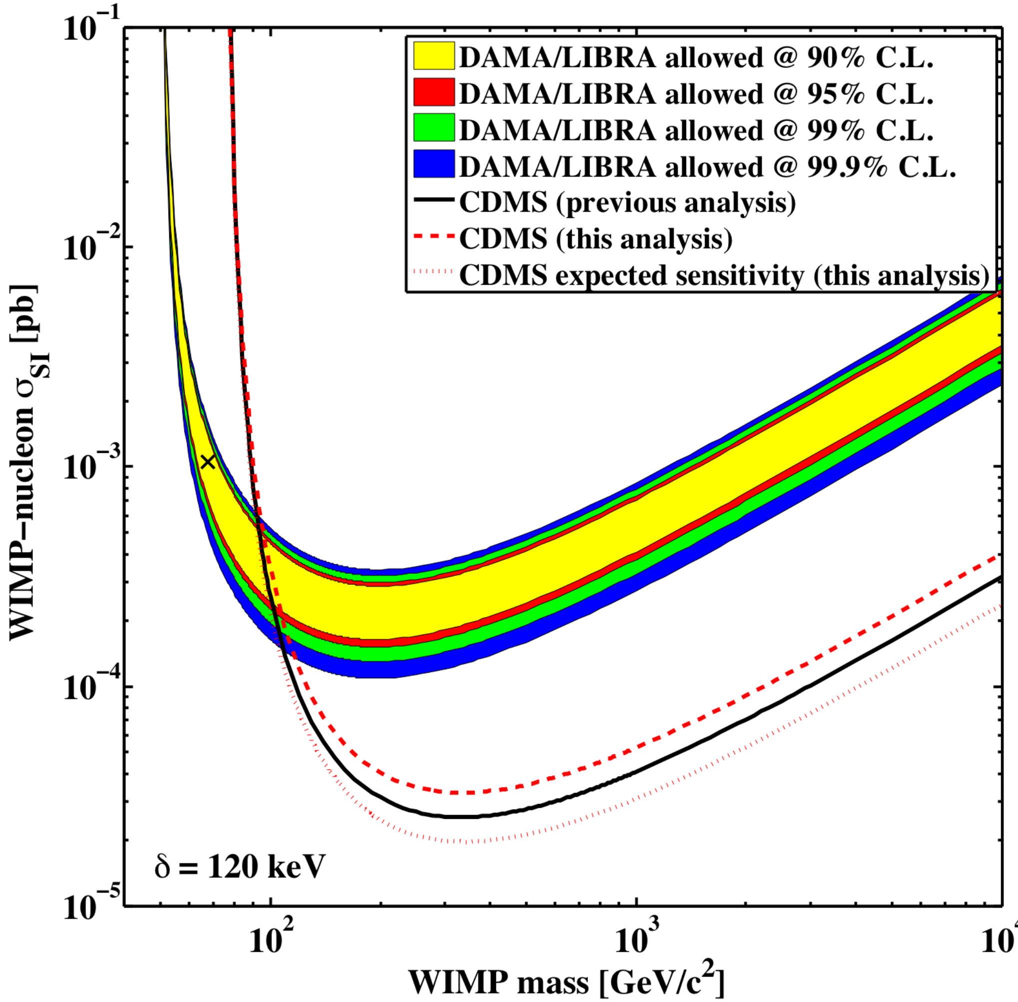


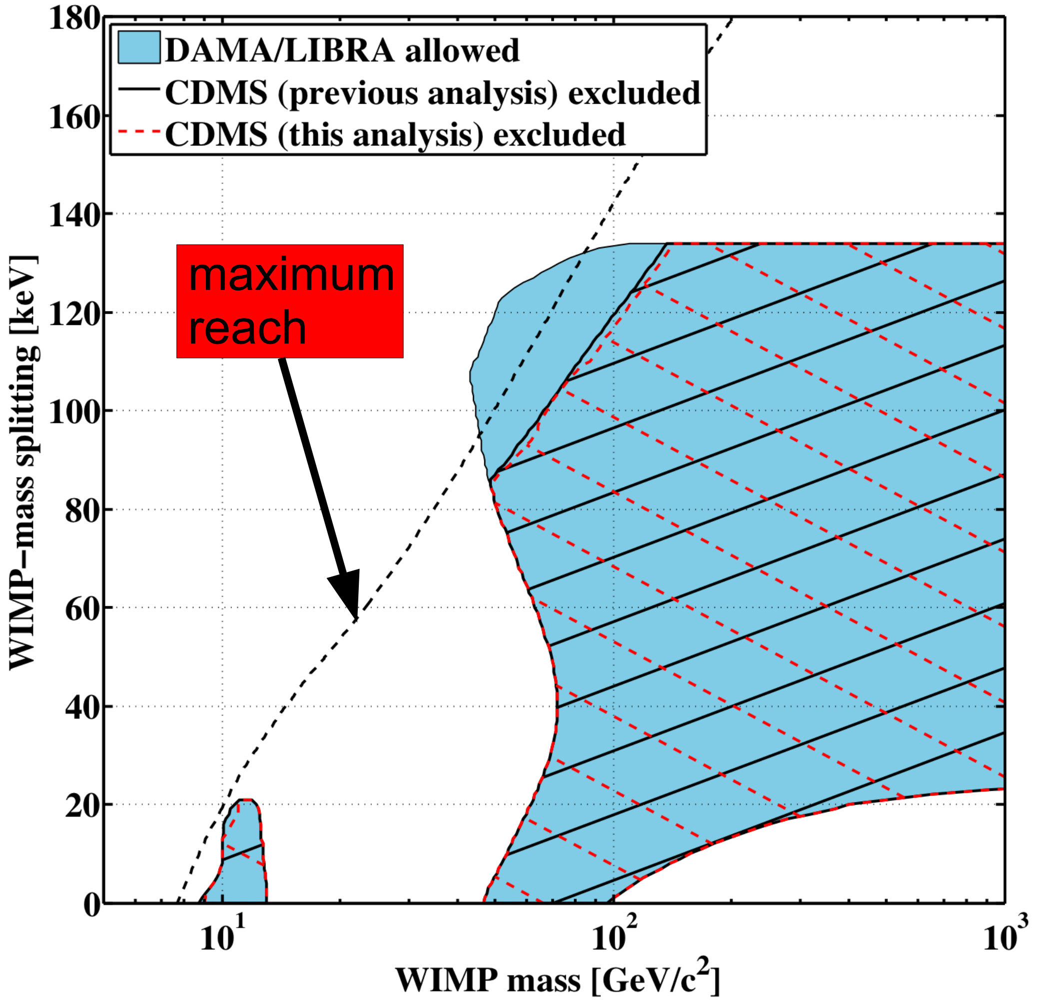
Varying the timing cut



Constraining the IDM model

- due to the occurance of the three “high-energy“ events the limit is weaker
- important parameters: escape velocity: v_{esc} = 544 km/s
  velocity dispersion: v_0 = 220 km/s
  DAMA quenching factors: q_I = 0.09 / q_{Na} = 0.30





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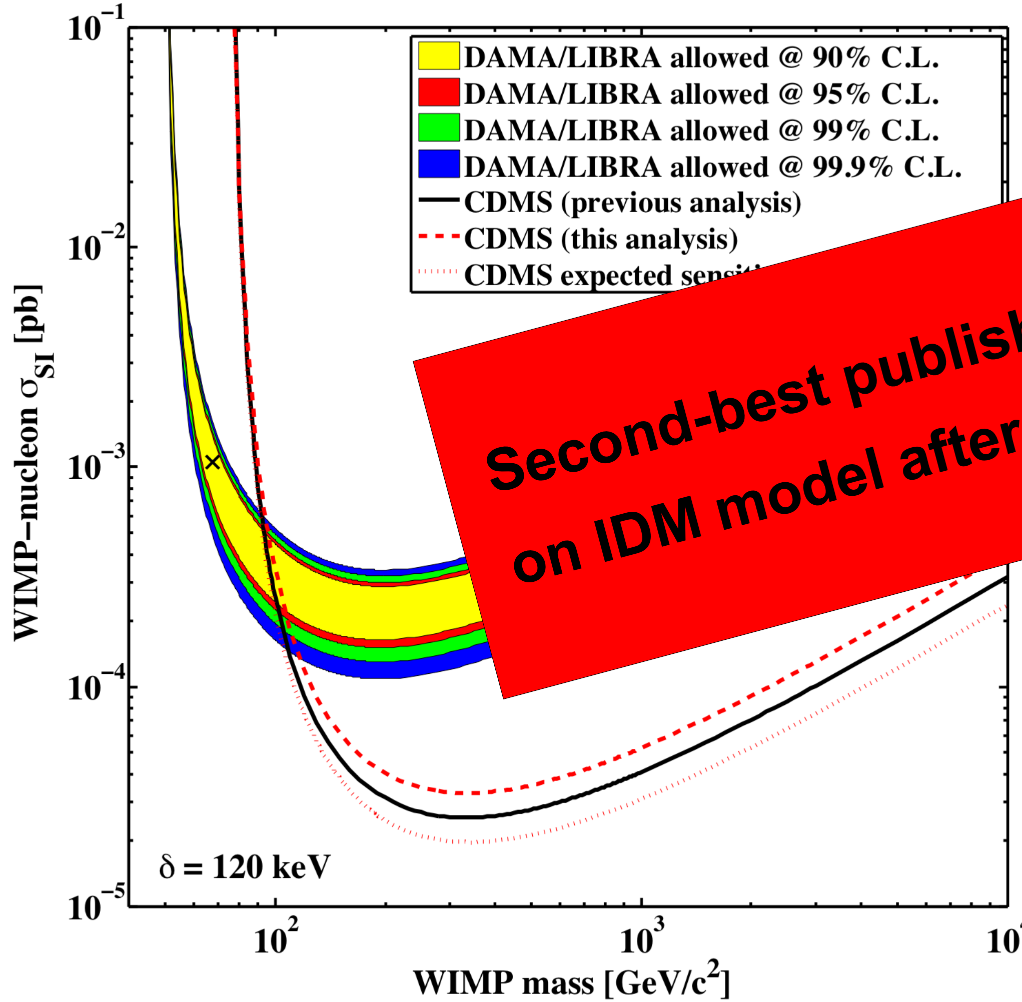
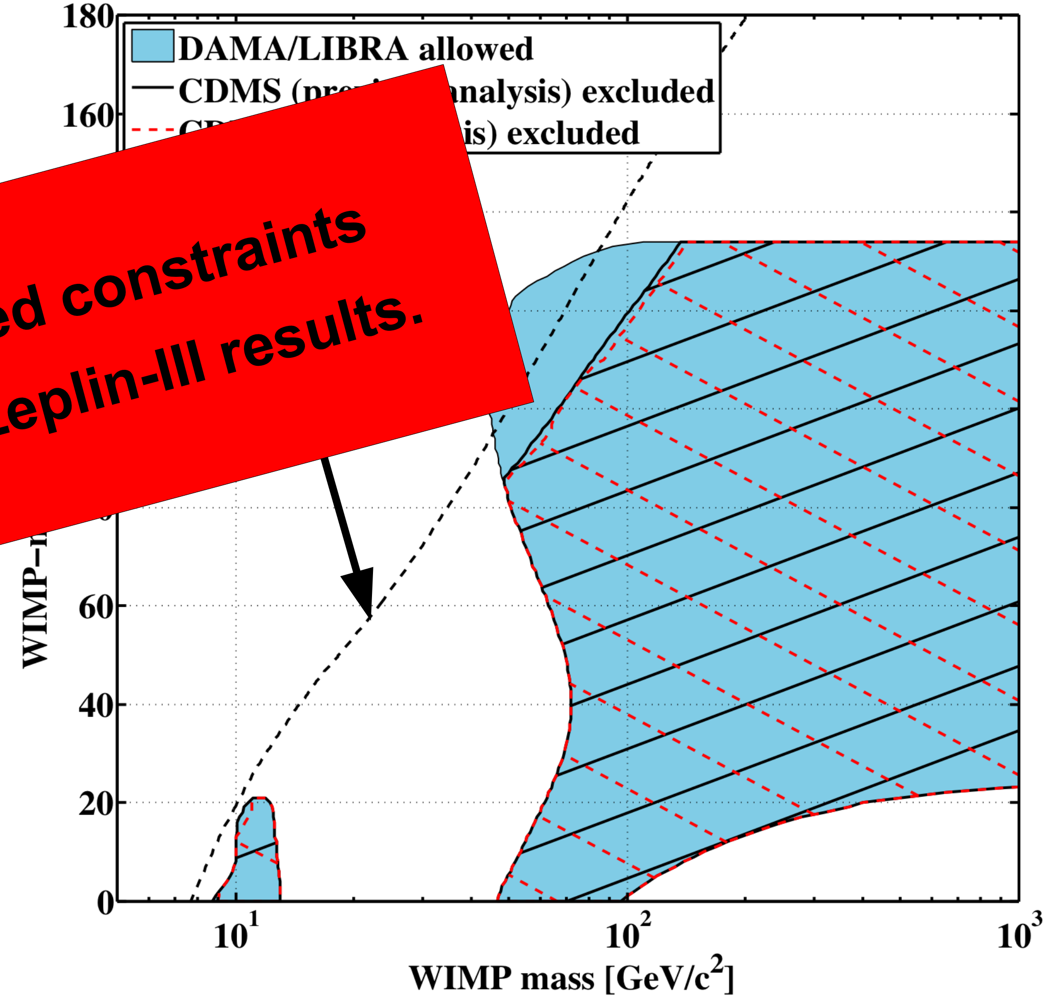
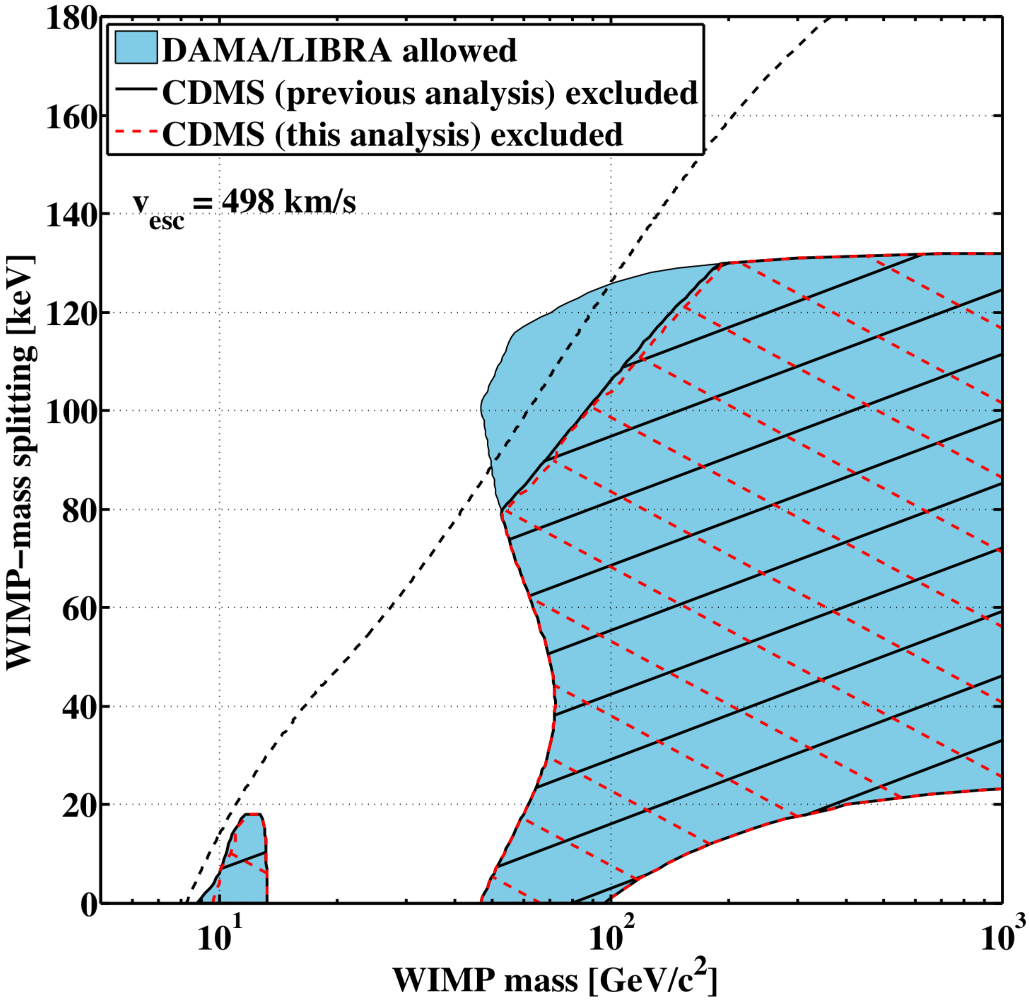


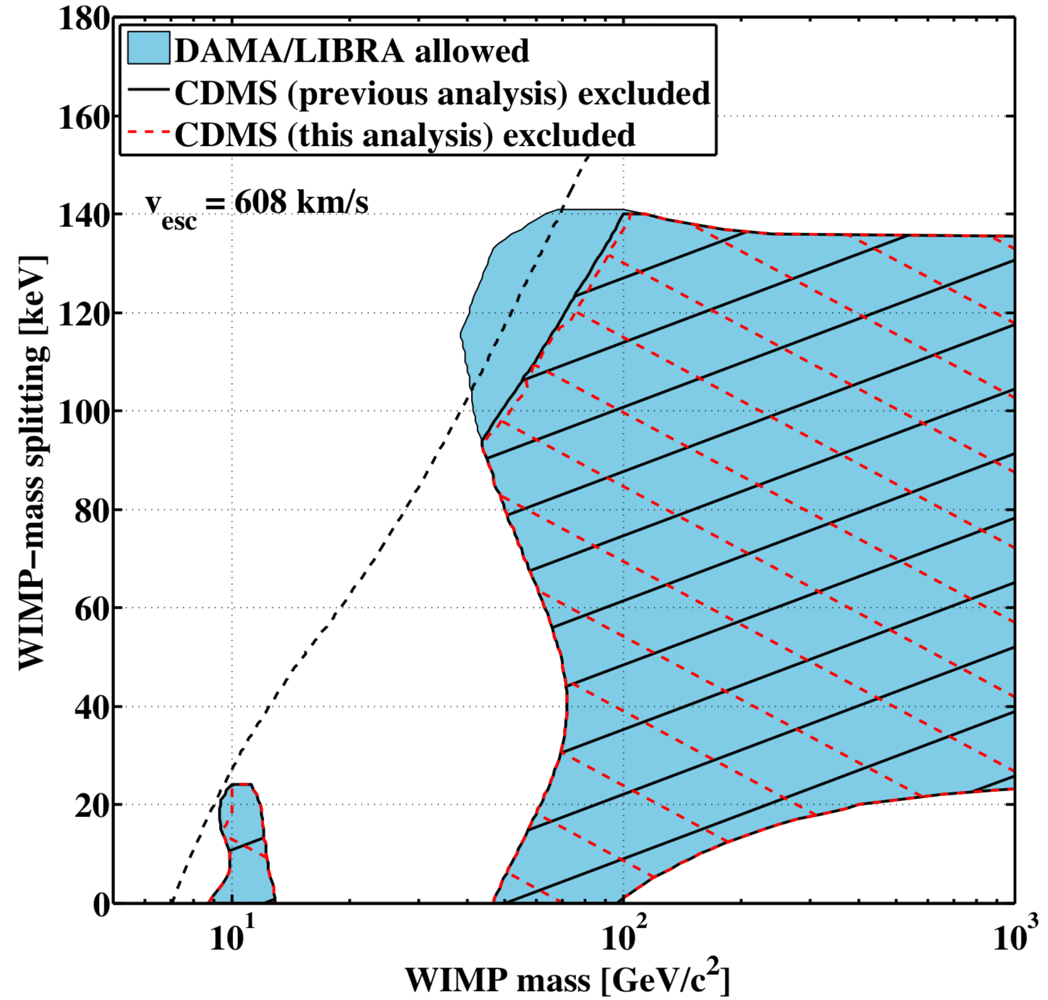


Second-best published constraints on IDM model after Zeplin-III results.

Varying the velocity-distribution parameters: v_{esc}

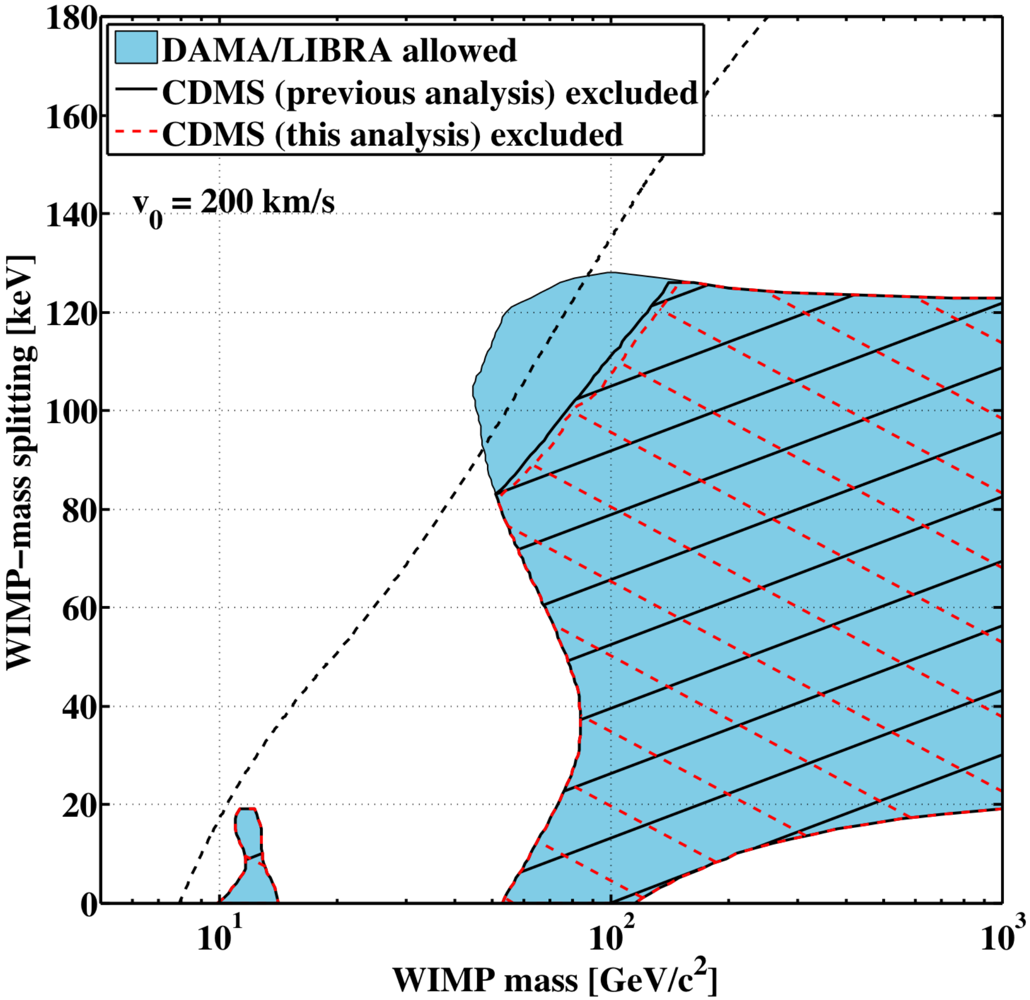
The capability of CDMS to constrain an IDM interpretation of the DAMA/LIBRA results is relatively independent of the actual value of the escape velocity.

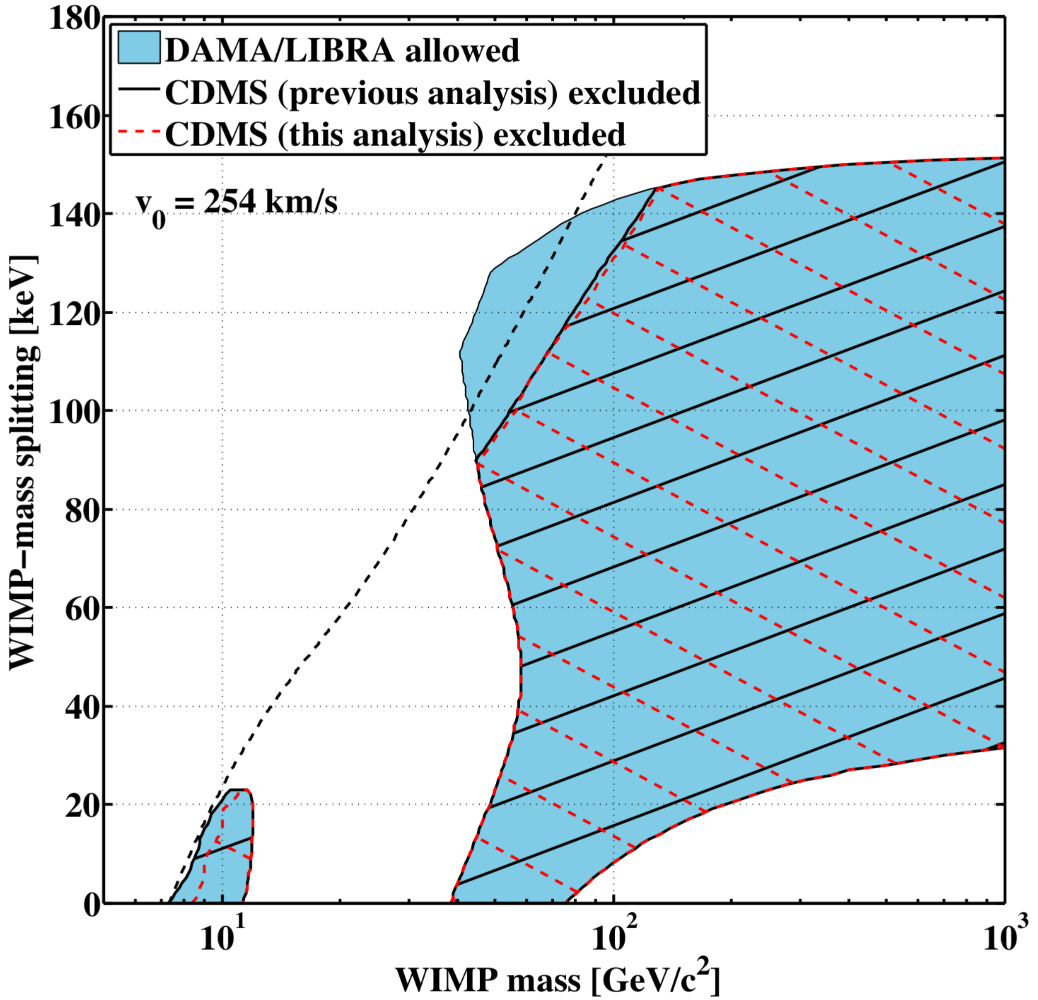




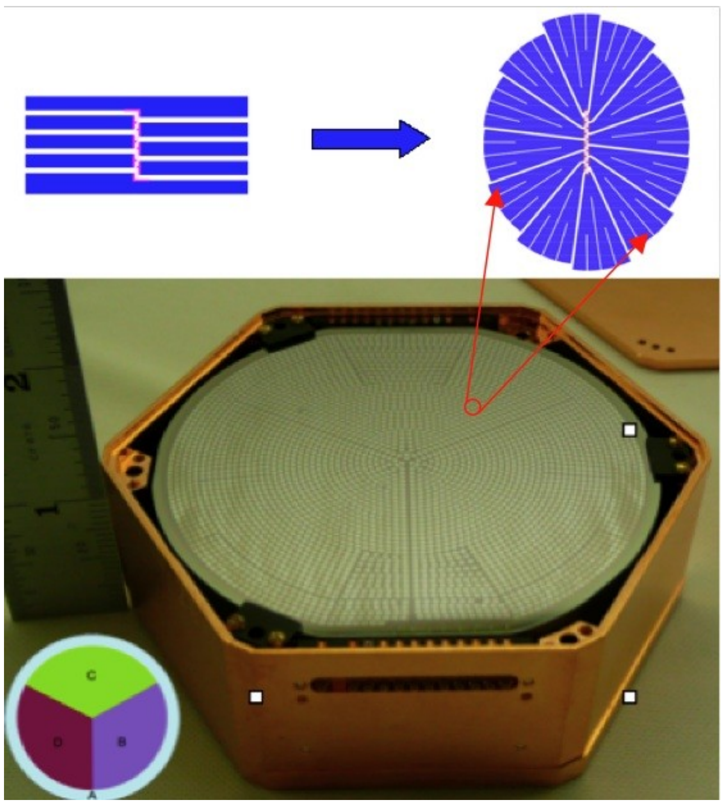
Varying the velocity-distribution parameters: v_0

The capability of CDMS to constrain an IDM interpretation of the DAMA/LIBRA results is relatively independent of the actual value of the velocity dispersion.

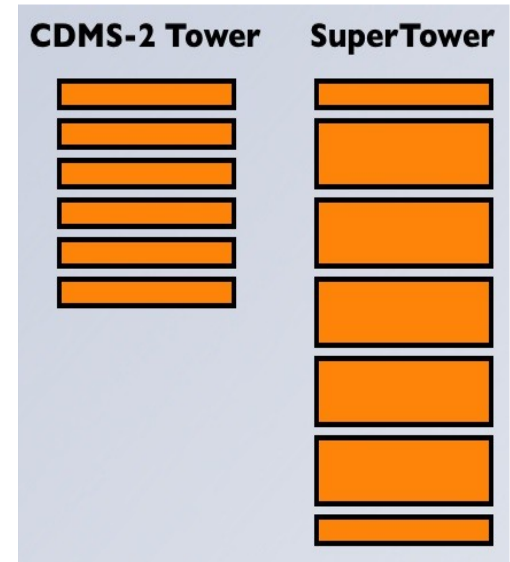


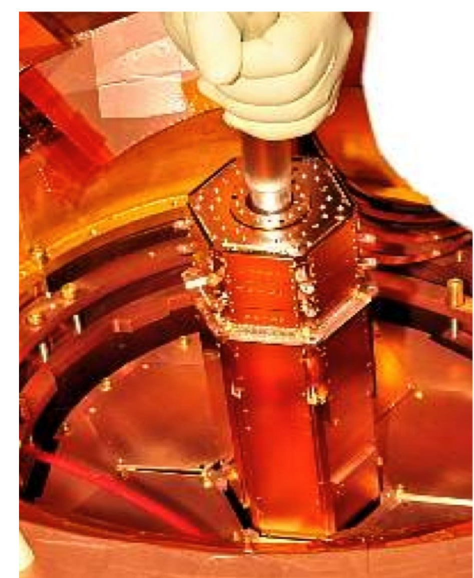


SuperCDMS



- 2.5 times more massive Ge detectors (1-inch thick)
- reduced surface/volume ratio to decrease background
- endcap Ge veto detectors in each tower
- improved Al-fin layout for better phonon collection
- modified phonon-sensor layout with outter phonon guard ring similar to outter charge electrode
- first SuperTower data is currently analyzed to evaluate surface-event discrimination and detector contamination





Summary

- inelastic dark matter analysis including energies up to 150 keV

- all five-tower runs combined

- improved surface-event rejection cut

- efficiency increased by ~1.5 compared to standard analysis

- three candidate events observed in 25 – 150 keV energy range:
    - one event in endcap detector
    - one event very close to the timing-cut boundary
    - one event far above the timing-cut boundary

- 11% probability to observe three or more background events between 25 keV and 150 keV (including neutron background)

- weaker constraints on IDM parameter space due to occurance of three “high-energy“ events

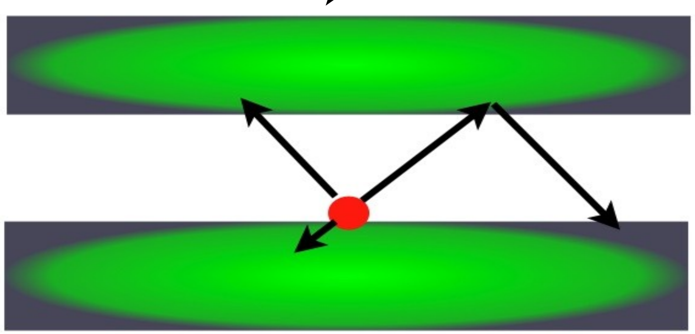
- second-best published limit on IDM parameter space

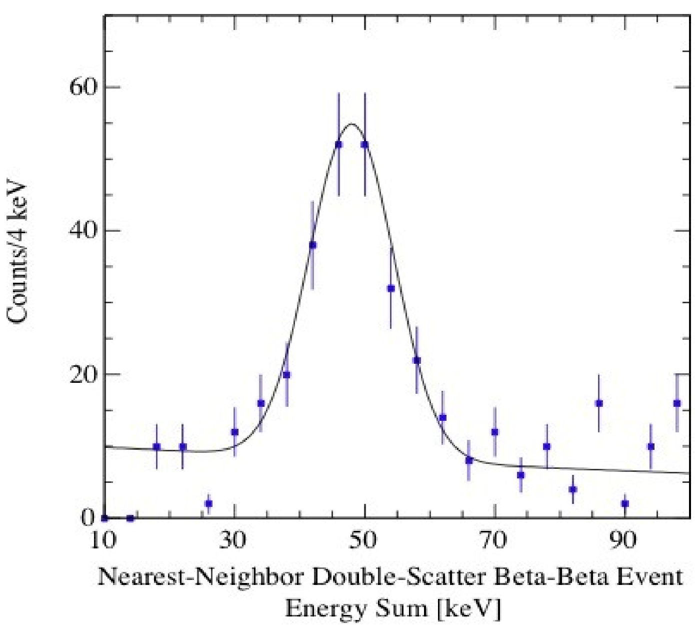
- publication sent to PRD (arXiv:1012.5078)

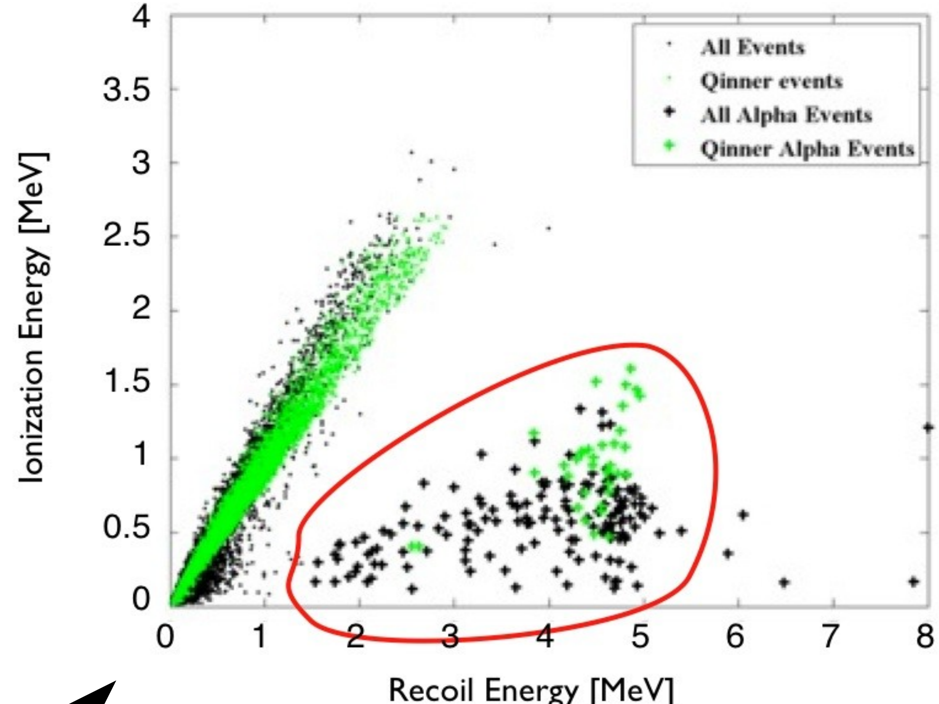
Backup Slides

Evidence for ^{210}Pb contamination

Sum over adjacent detectors (NND) to search for 46.5 keV peak!

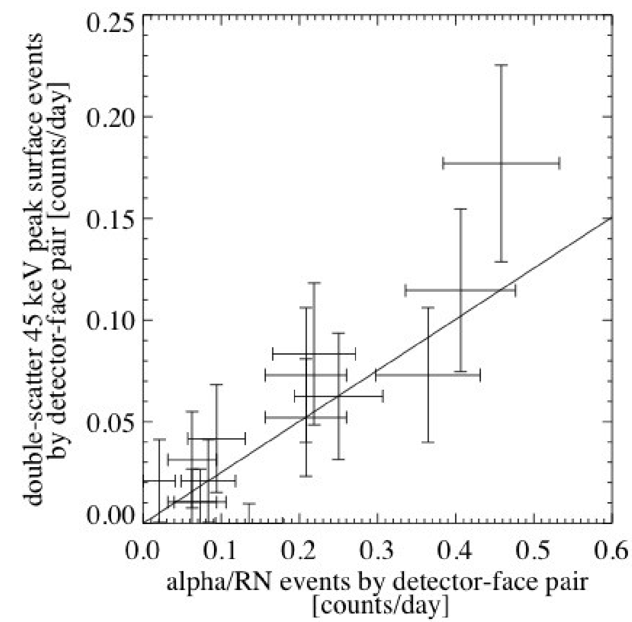




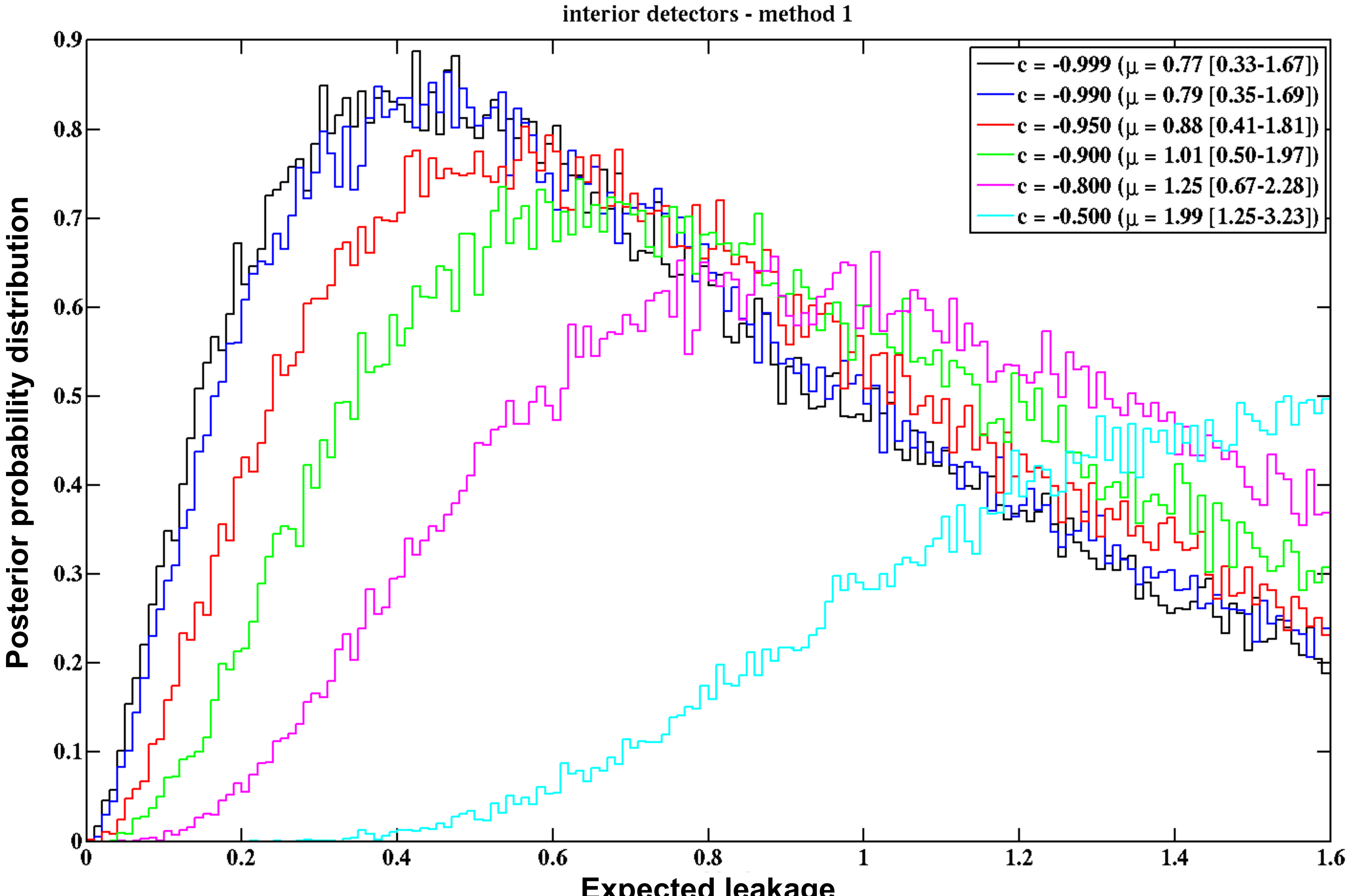


Check for low yield α's!

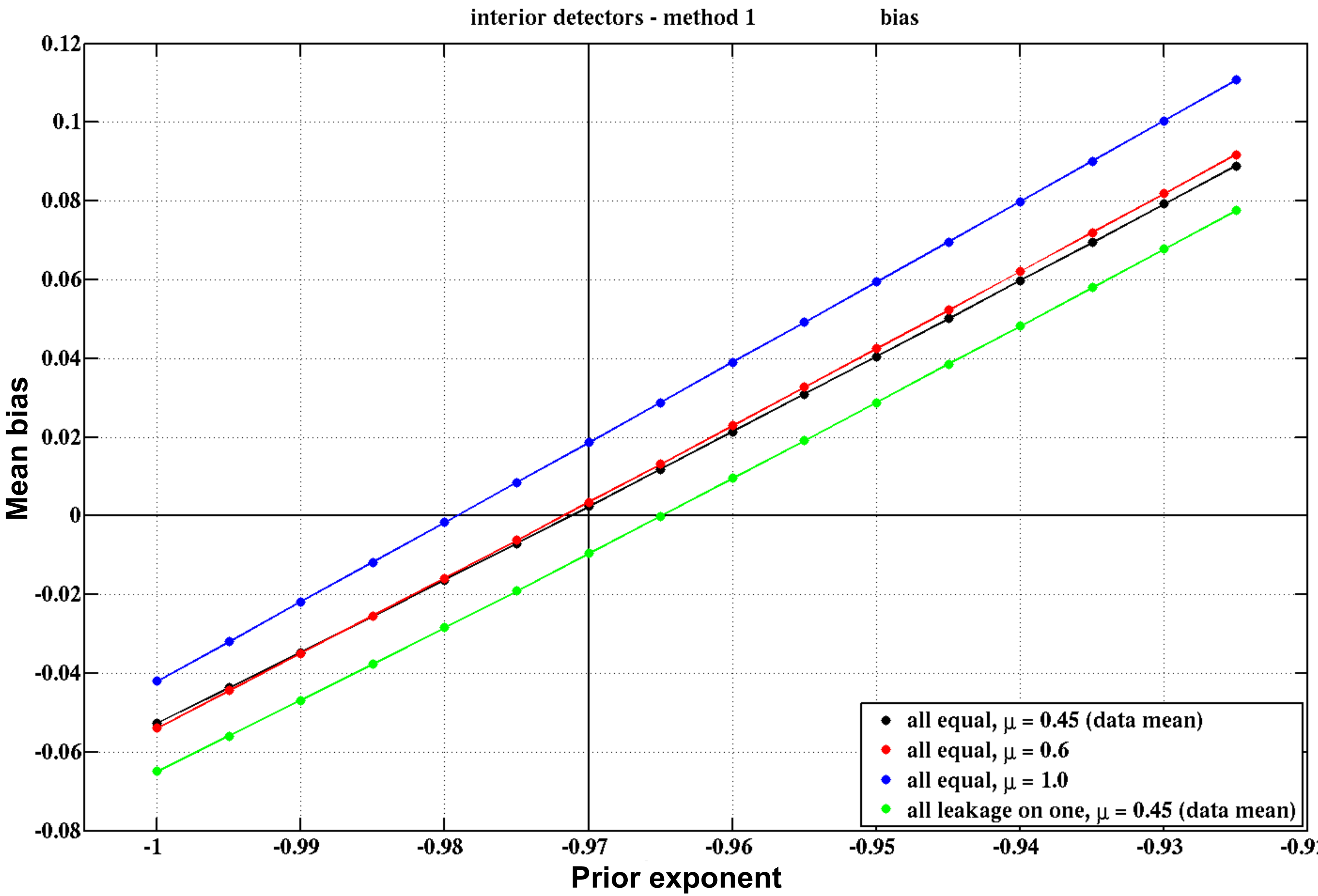
We see a strong correlation between both signatures.



Bayesian Leakage estimate



Bayesian Leakage estimate - bias



Bayesian Leakage estimate - coverage