Search for Inelastic Dark Matter with the CDMS Experiment

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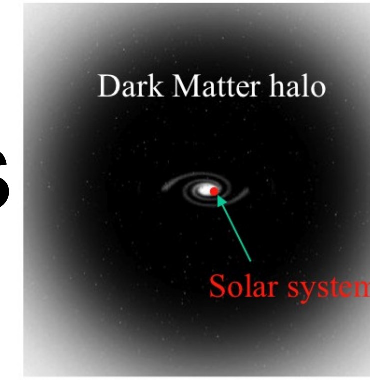
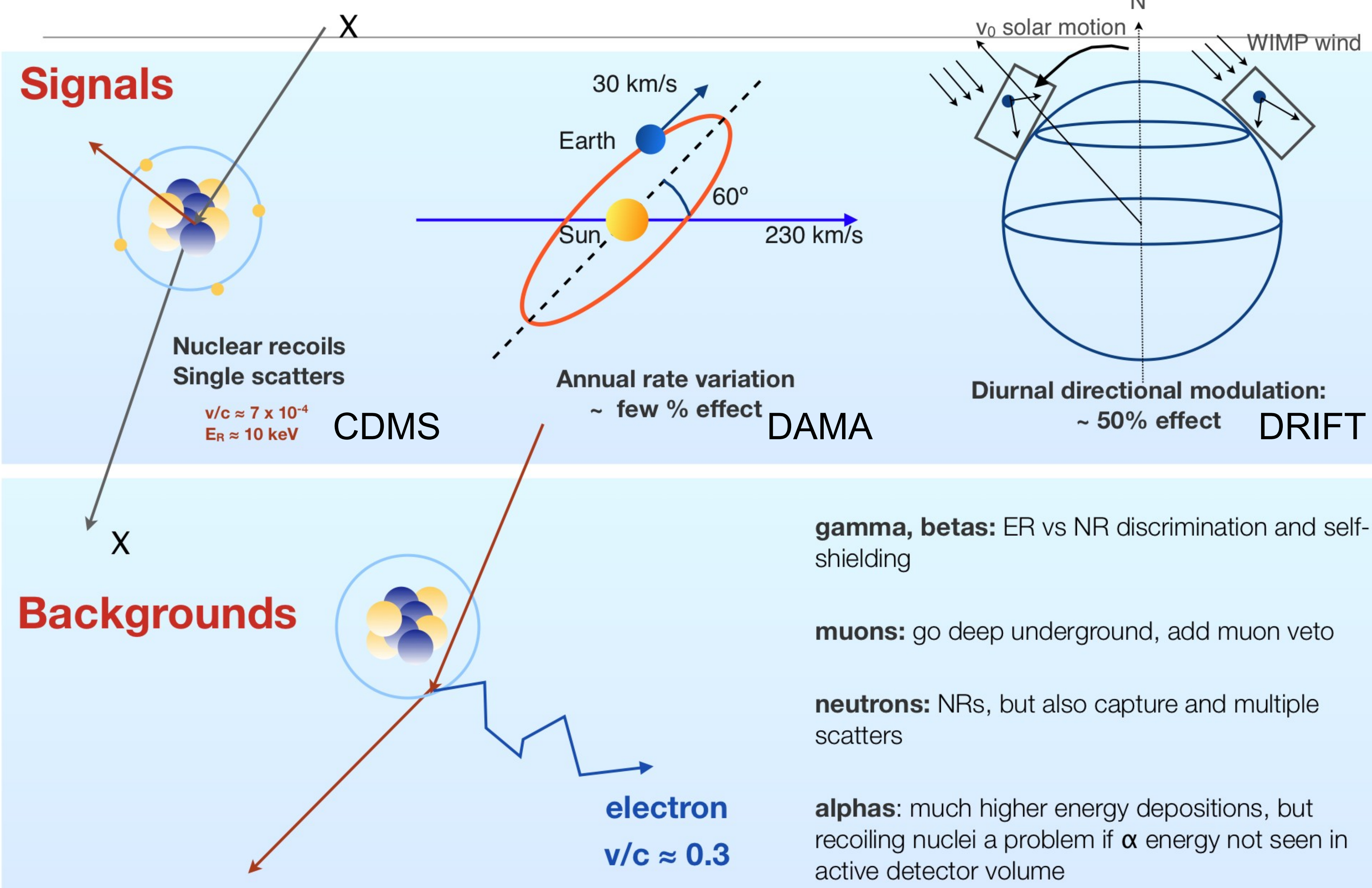
University of Zürich
Lausanne, June 16th, 2011
Joint Annual Meeting of the Swiss & Austrian Physical Society

Direct Detection of WIMPs



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



The DAMA/LIBRA results

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

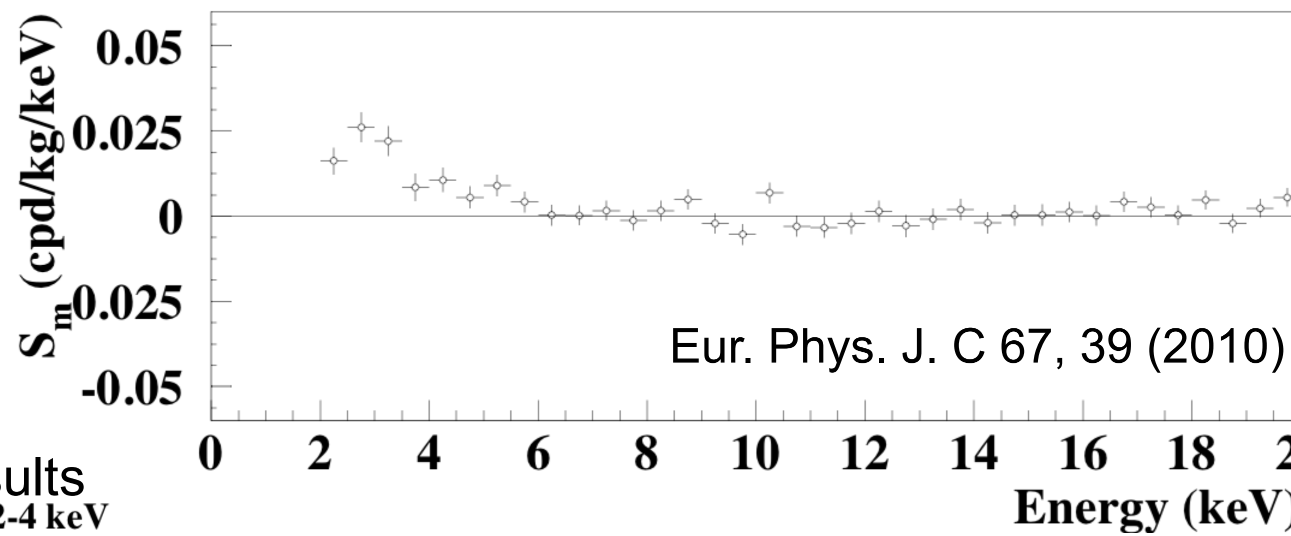
- evidence @ 8.9σ C.L.

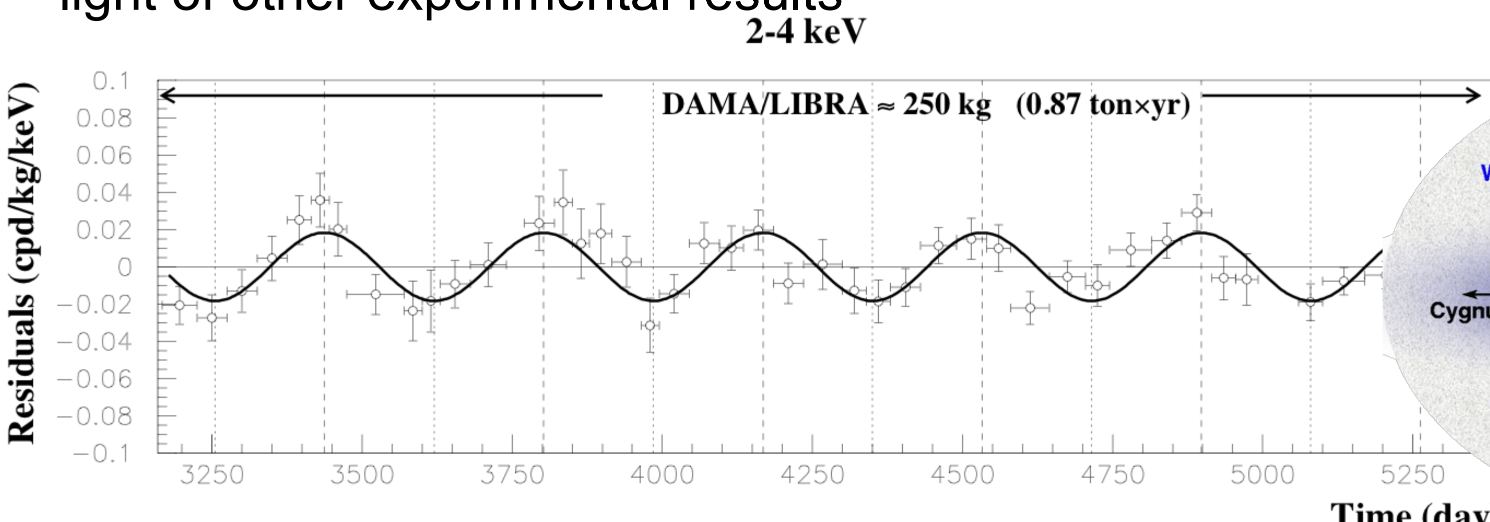
- measured over 13 annual cycles with exposure of 1.17 ton-years

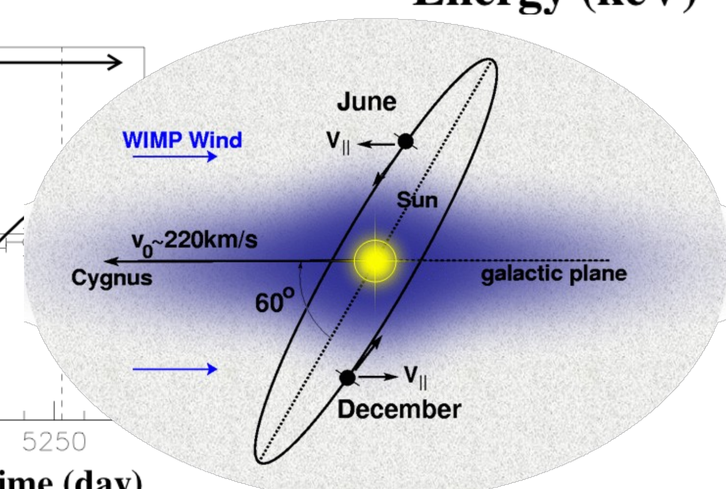
- difficulties to explain this observation with the conventional WIMP model in light of other experimental results

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

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







Inelastic Dark Matter (IDM)

Phys. Rev. D 64, 043502 (2001)

- 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

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

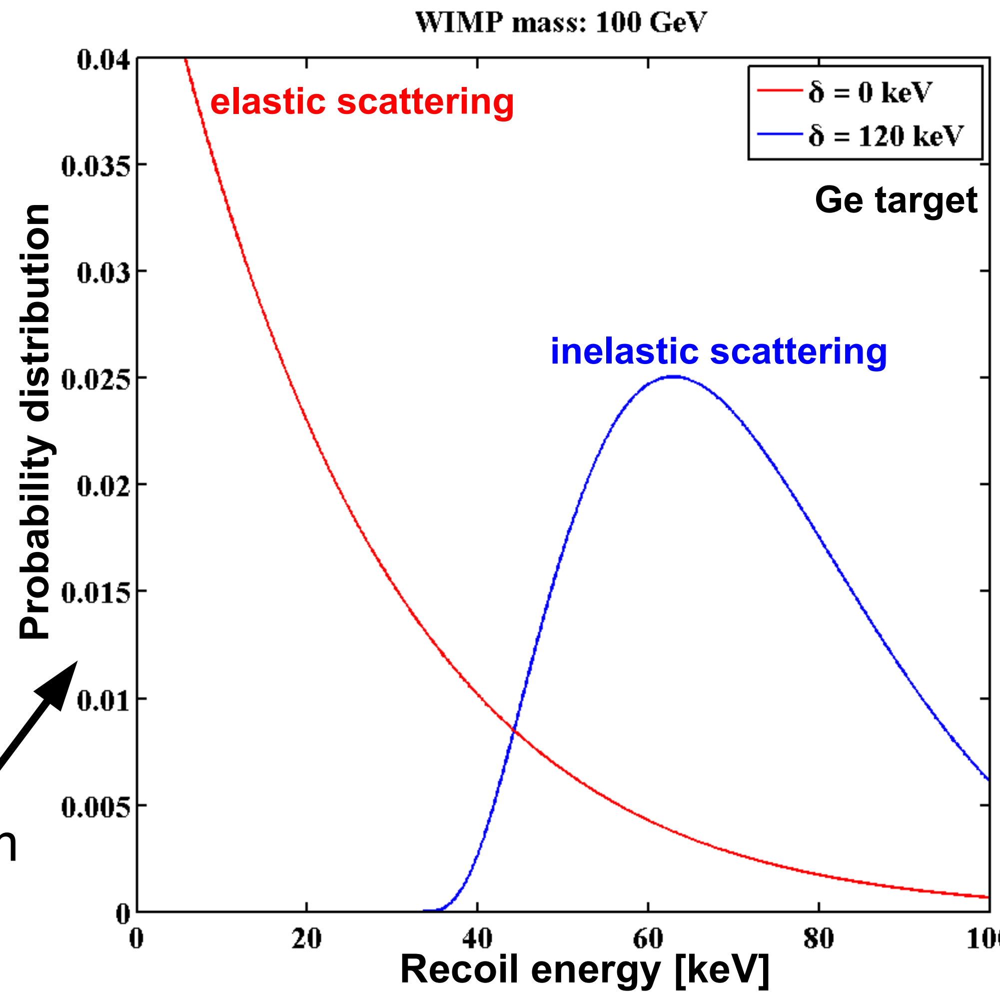
- experiments probe “higher“ part of velocity distribution

- high sensitivity to escape-velocity cutoff

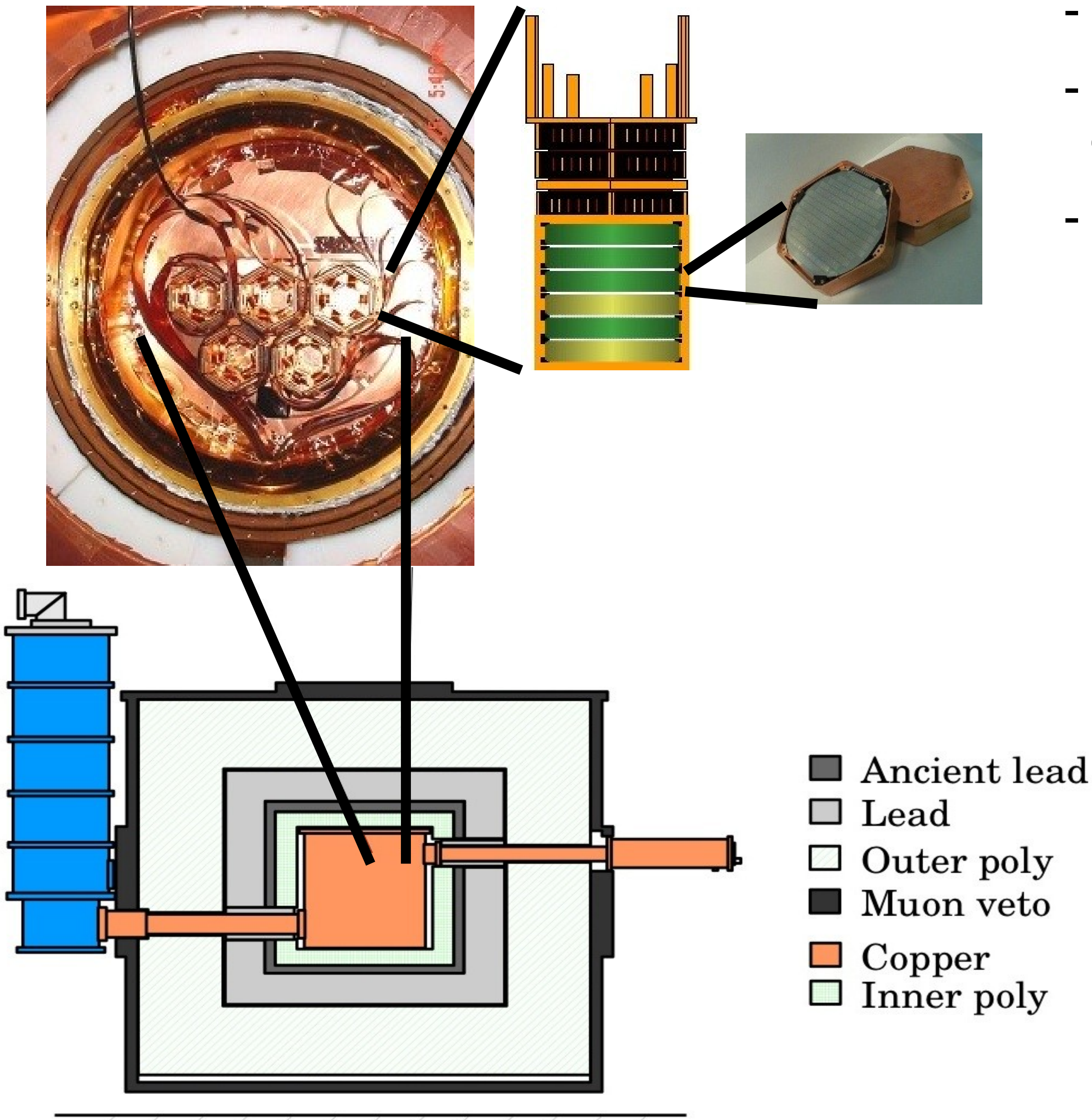
- heavy targets are favoured

- significant change of the energy spectrum

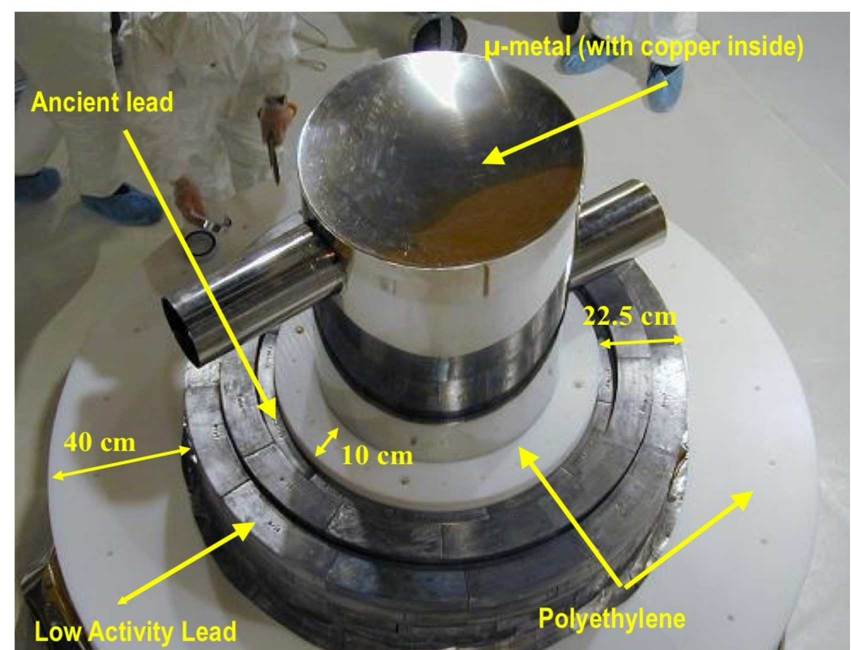
- enhancement of annual modulation



The CDMS setup & shielding

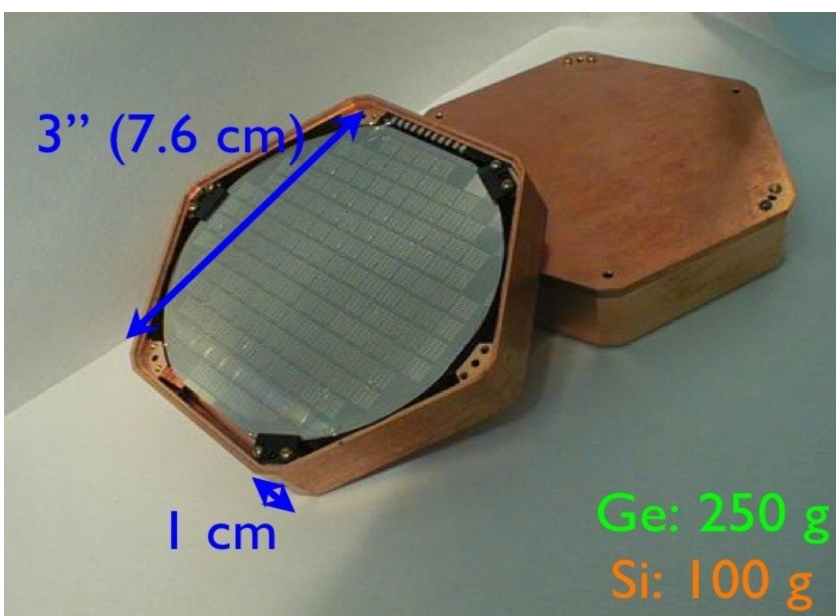


- 5 towers with 6 detectors each
- active veto against high energetic muons
- passive shielding:
  - lead against gammas from radioactive impurities
  - polyethylene to moderate neutrons from fission decays and from (α,n) interactions resulting from U/Th decays

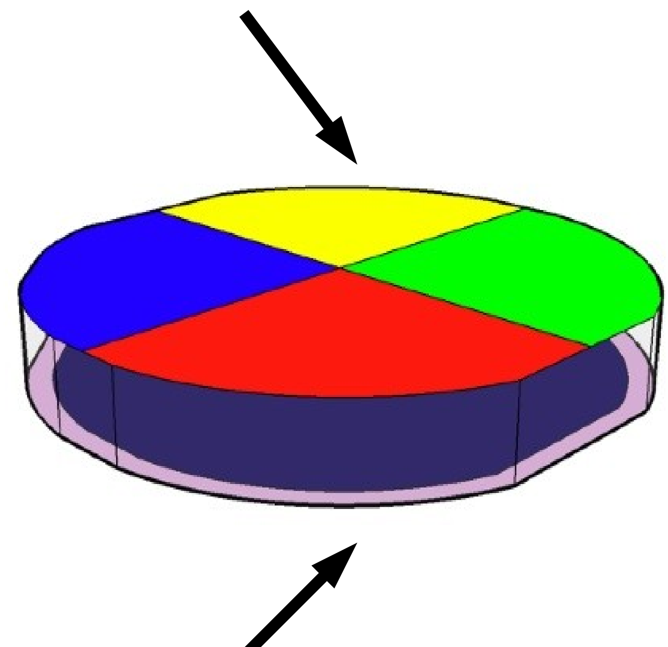


The CDMS ZIP detectors

- 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



Phonon readout:
4 quadrants of
phonon sensors



Charge readout:
2 concentric
electrodes

The ionization readout

- interaction creates electron-hole pairs

  → seperate using applied electric field

  → collect charges on electrodes on surface

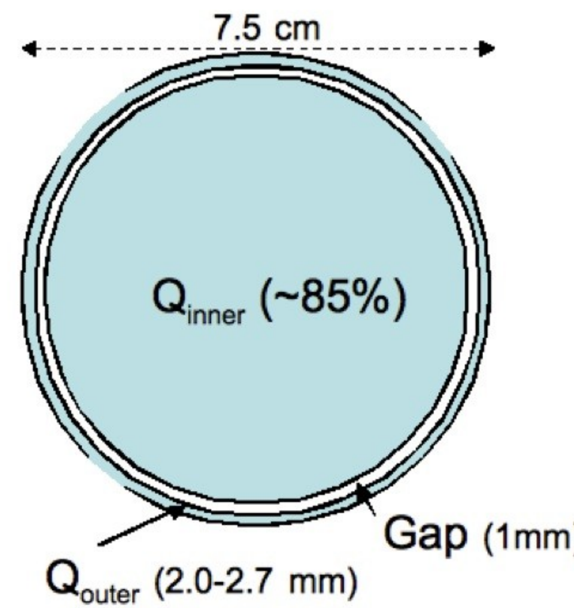
- drift field of 3 V/cm (4V/cm) on Ge (Si) detectors

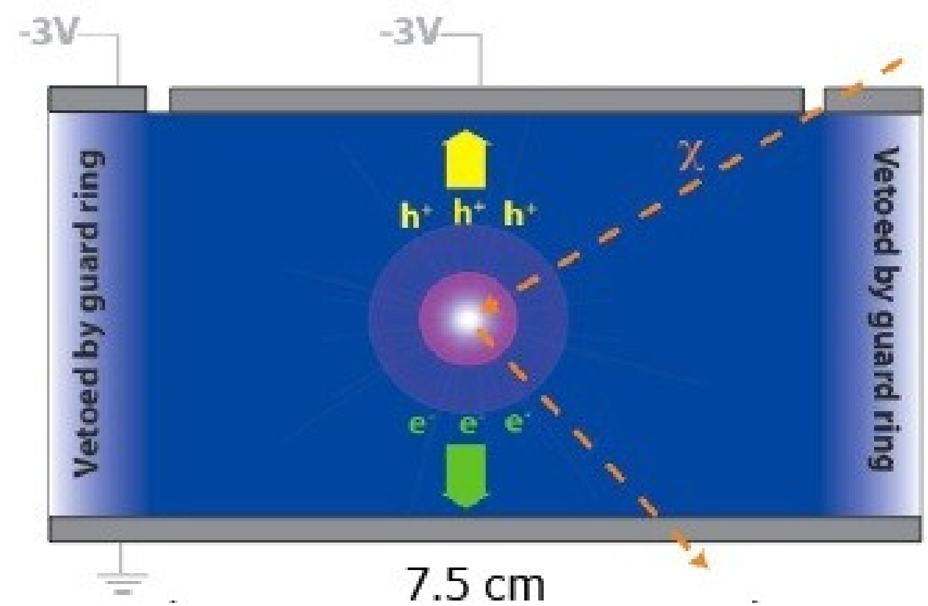
- interaction at crystal edges can have incomplete charge collection

  → use outer electrode as guard ring

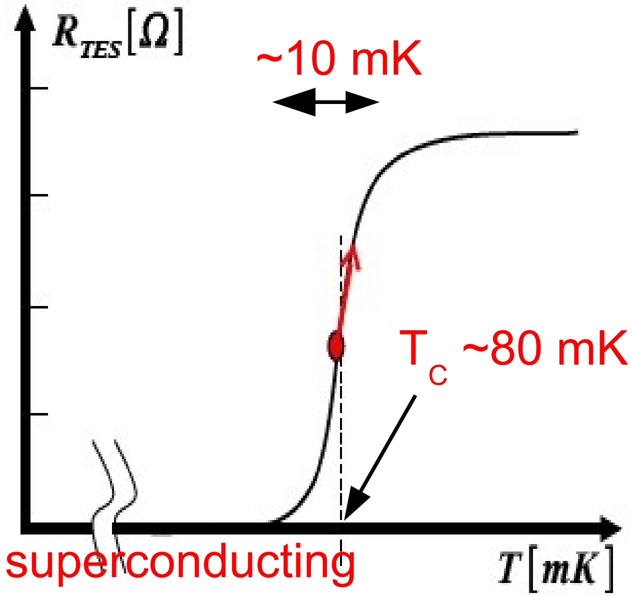
  → omit Q_{outer} events

- low-energy resolution: 3-4%





The phonon readout

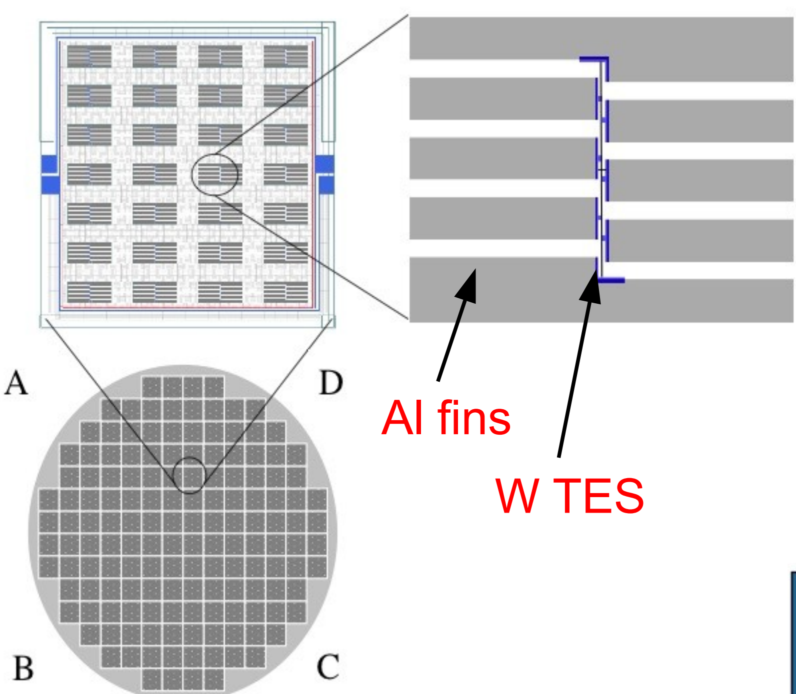


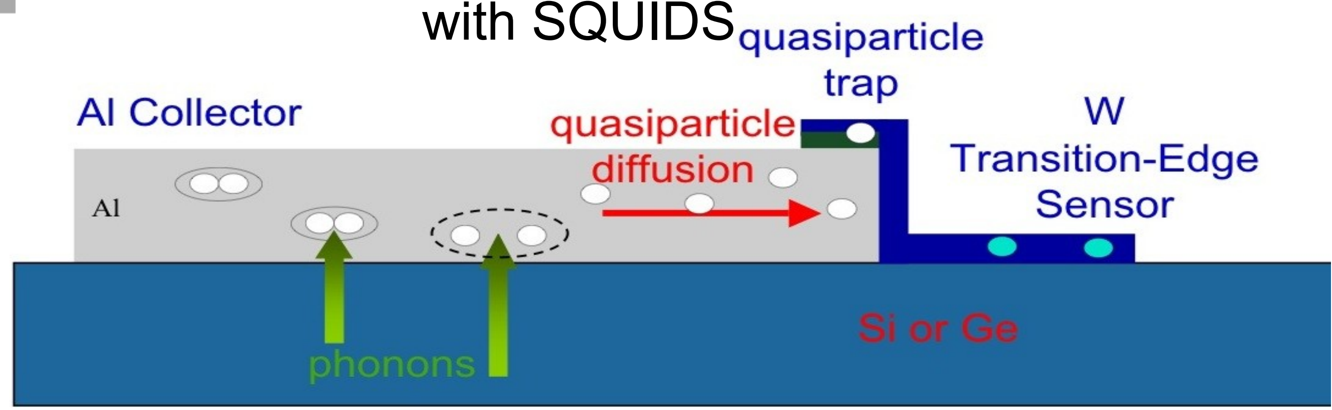
- segmented phonon readout (4 quadrants)
- each quadrant consists of 1036 tungsten TES (Transition Edge Sensors)
- fast response time ~5 μs
- low energy resolution: ~5%
- tungsten strips set just below the edge of superconductivity using bias voltage

→ energy deposition raises temperature

→ conductivity changes to normal

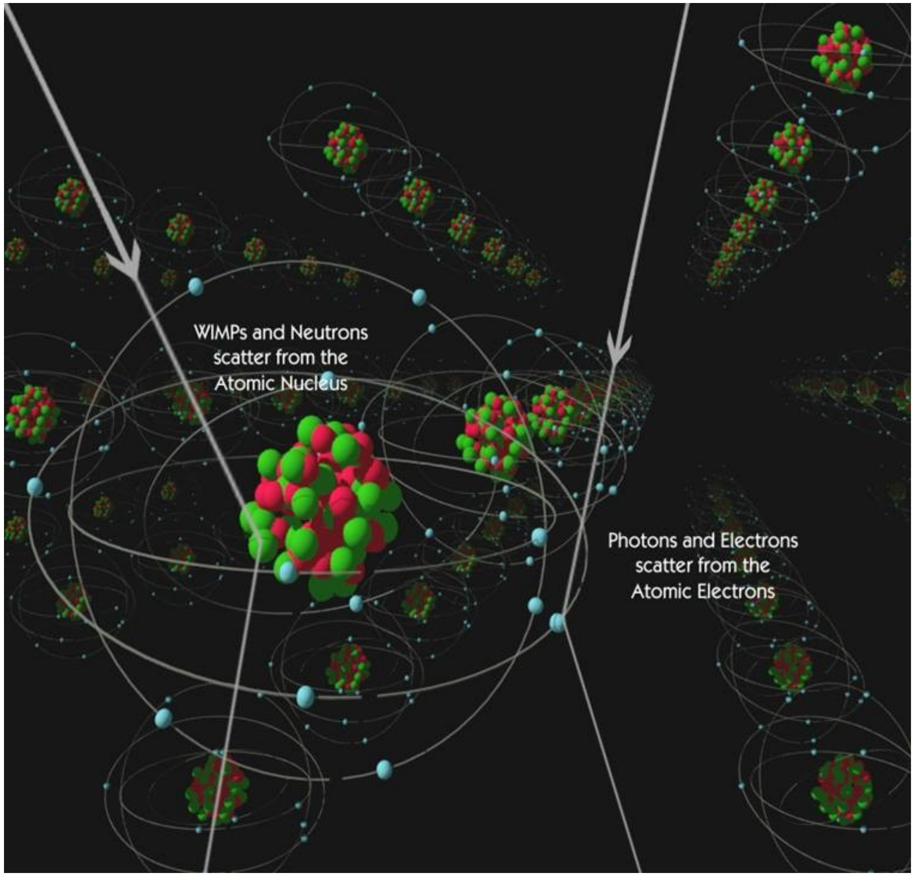
→ dramatic lowering of current read out with SQUIDS

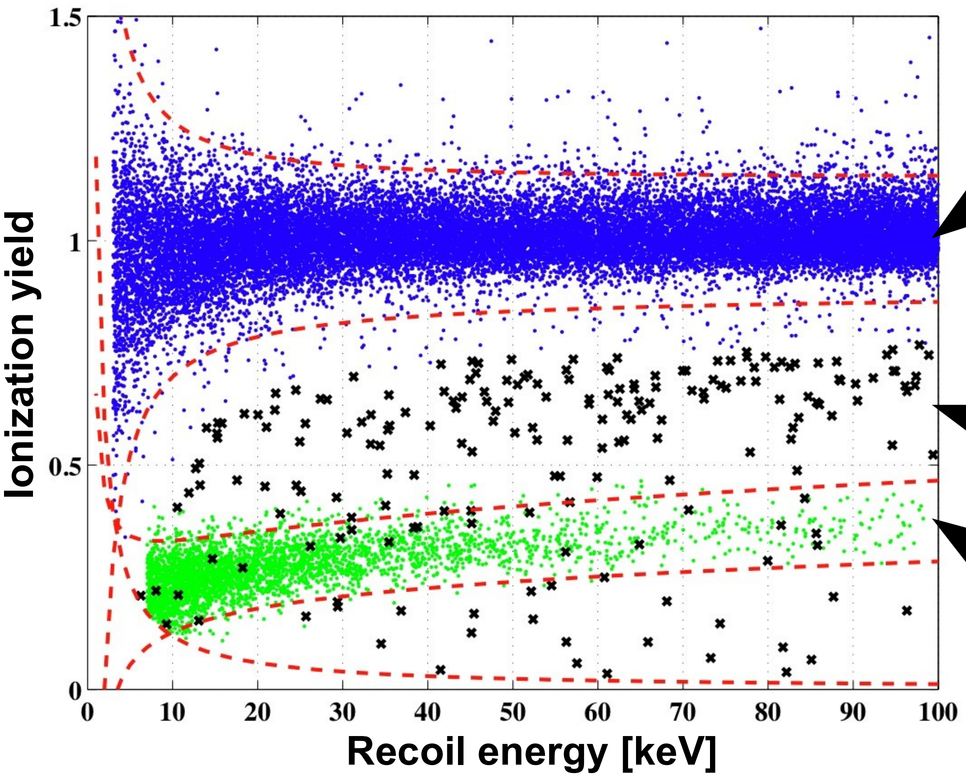




Primary background rejection

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

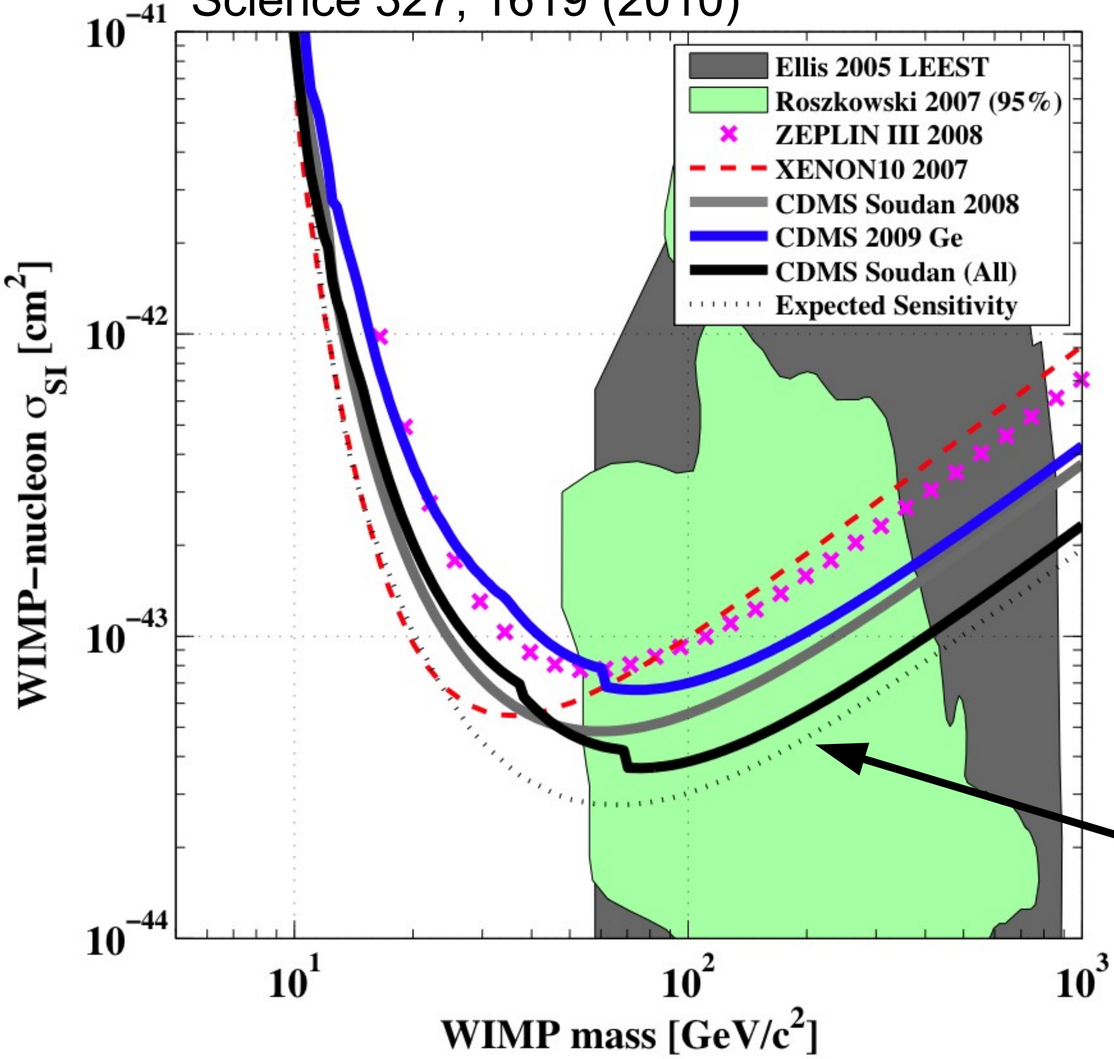




- better than 1:10000 rejection of electron recoils based on ionization yield alone
- dominant remaining background: low-yield surface events

CDMS results from the standard analysis

Science 327, 1619 (2010)



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

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

First constraints on IDM from CDMS

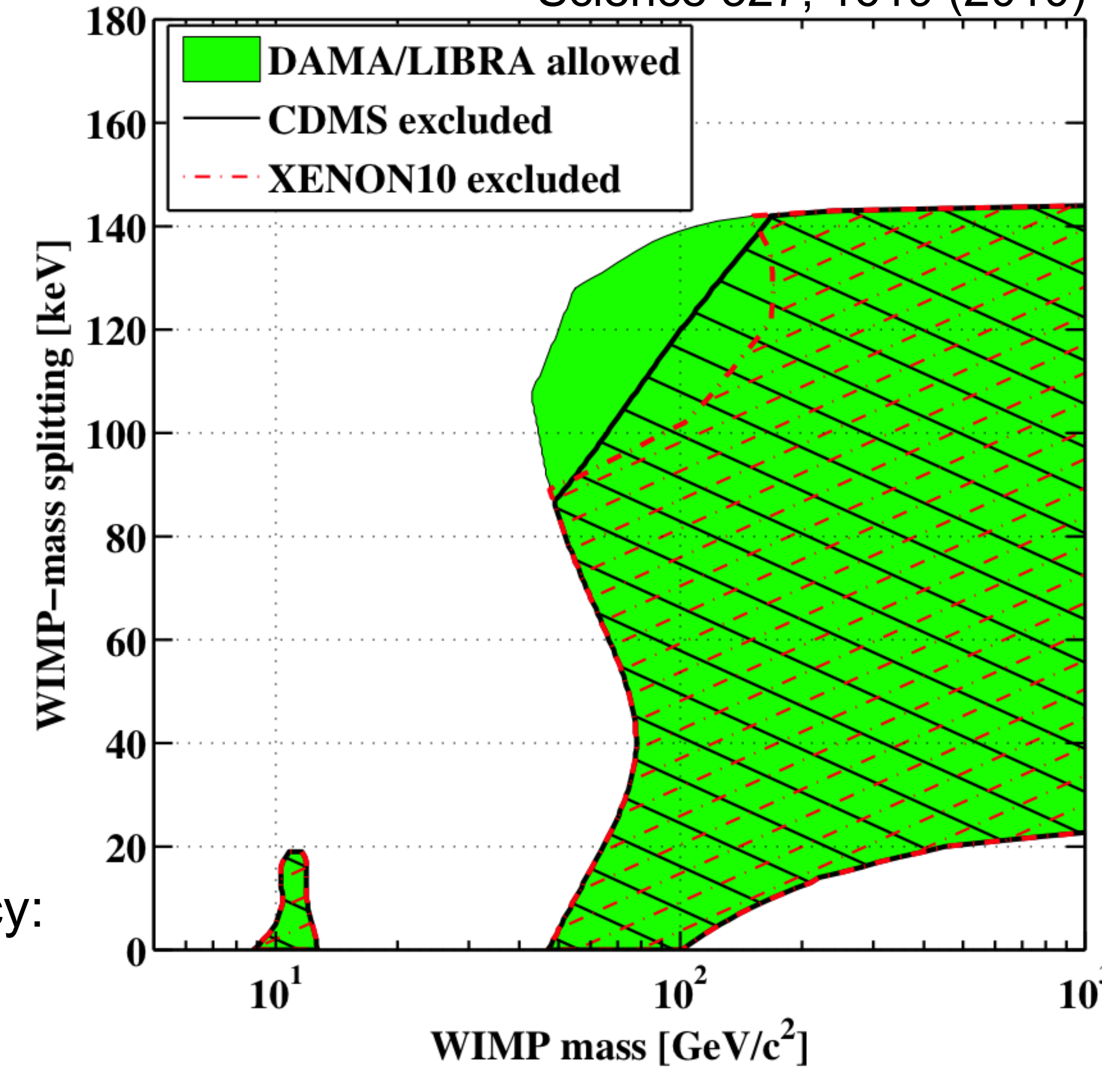
- Excluded regions are defined by demanding the upper limit on the cross section to completely rule out the DAMA/LIBRA allowed cross section intervals at a given WIMP mass and mass splitting.

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

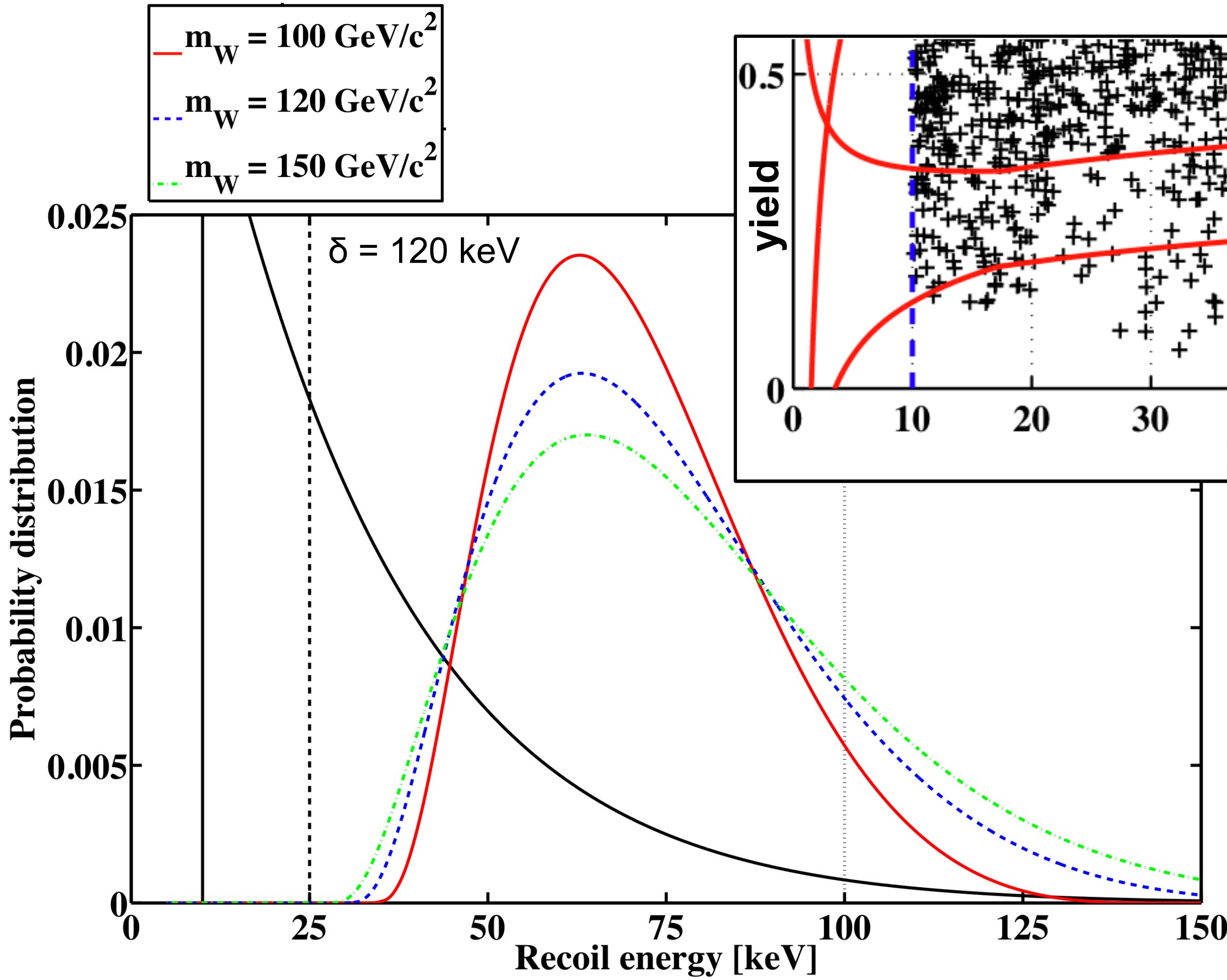
- optimum interval method is used for CDMS and XENON10

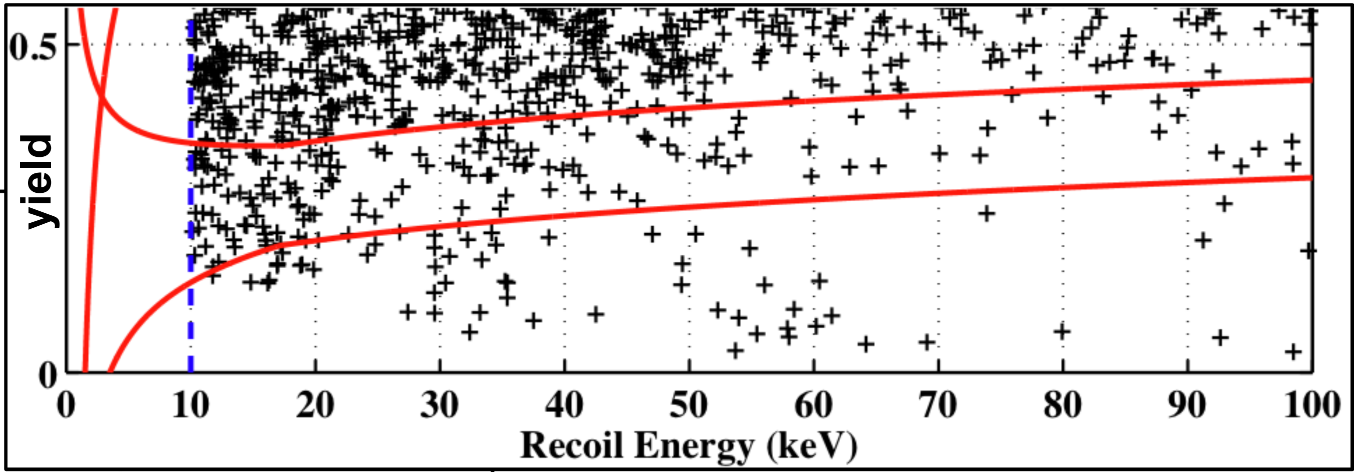
- used parameters are important:
  - escape velocity:
    - v_{esc} = 544 km/s
  - DAMA quenching factors:
    - q_I = 0.09
    - q_{Na} = 0.30
  - XENON10 scintillation efficiency:
    - L_{eff} = 0.19

Science 327, 1619 (2010)



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

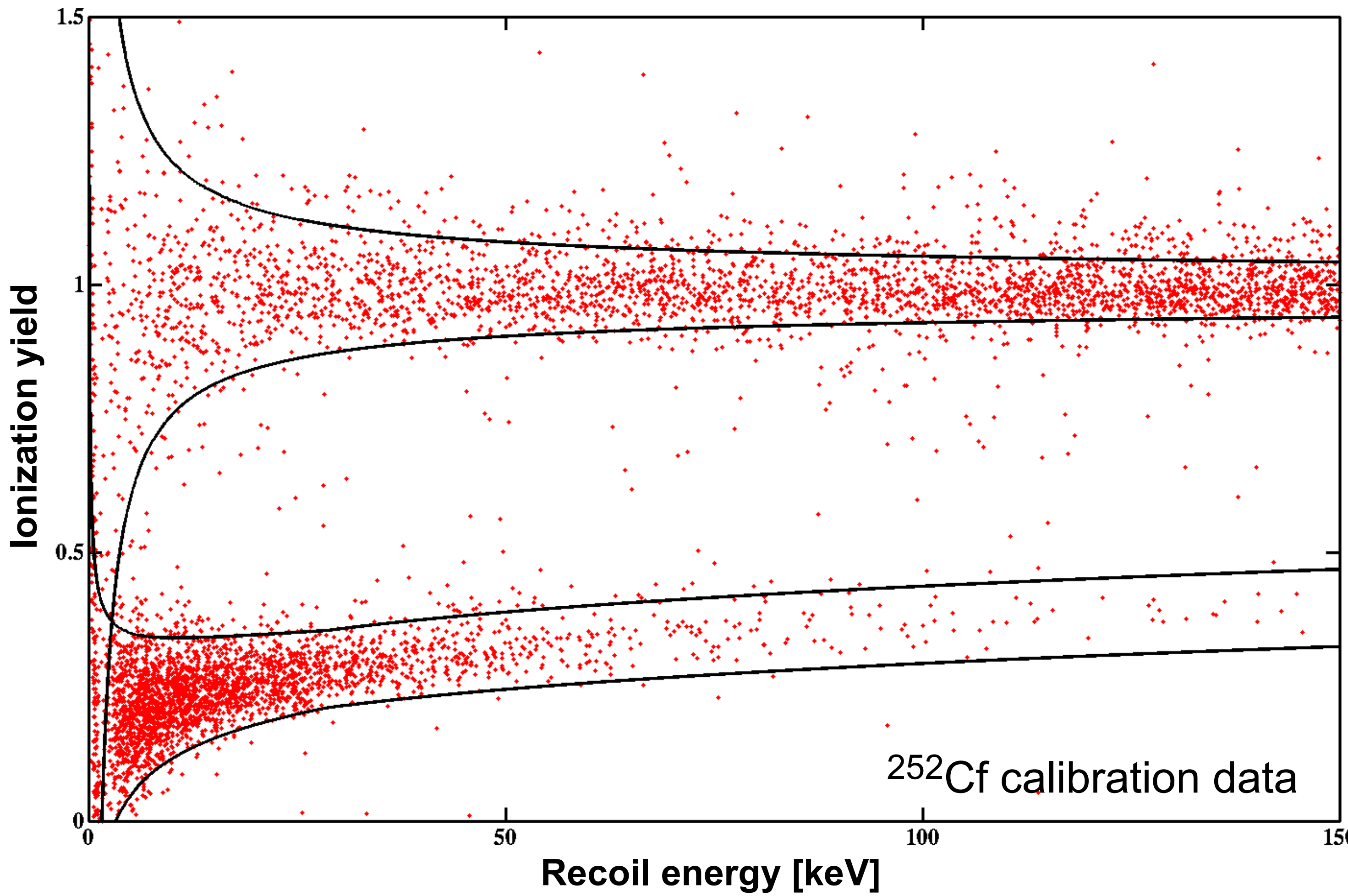
- always check results (cuts/efficiencies) at high energies combining all 6 runs

- 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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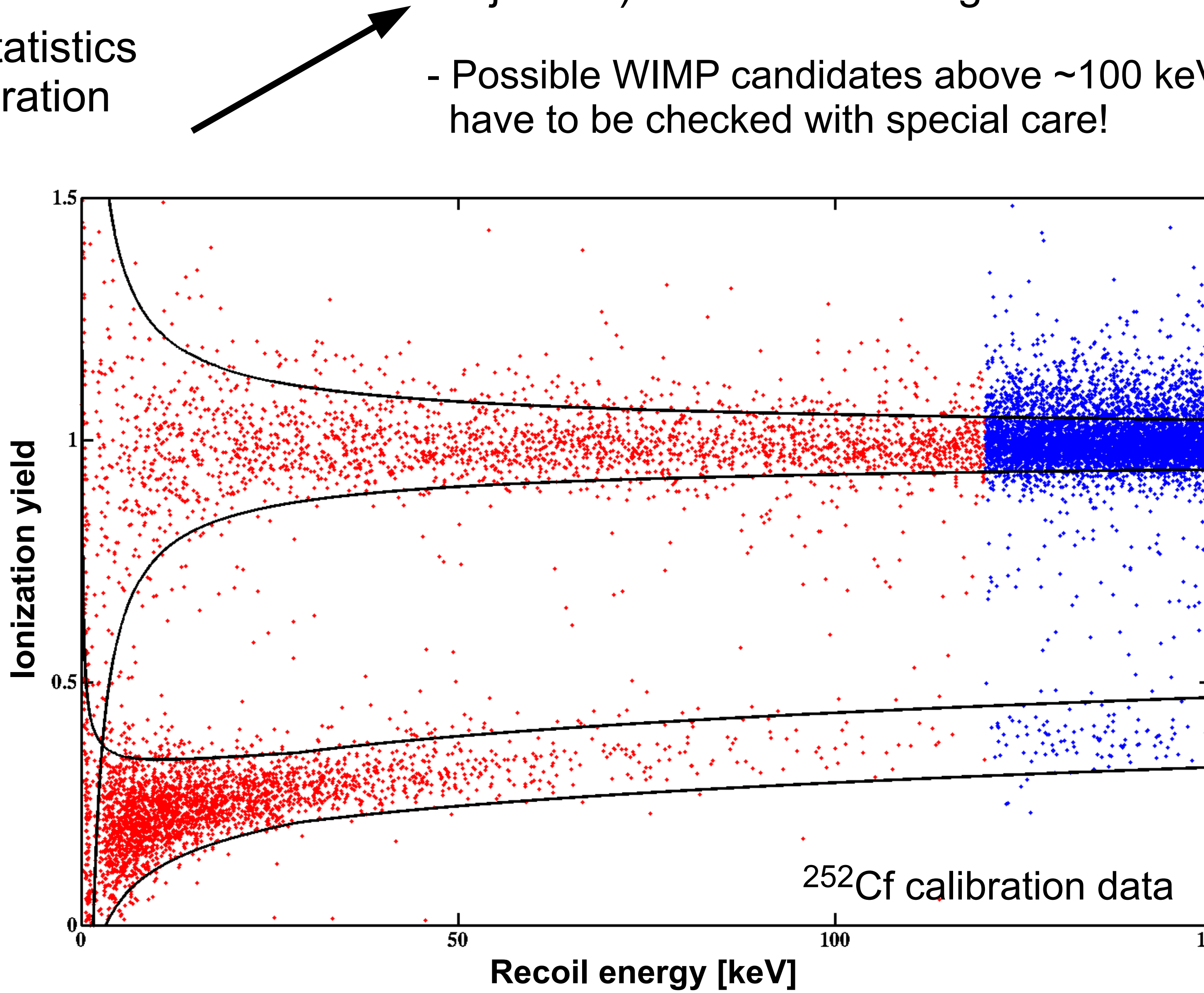
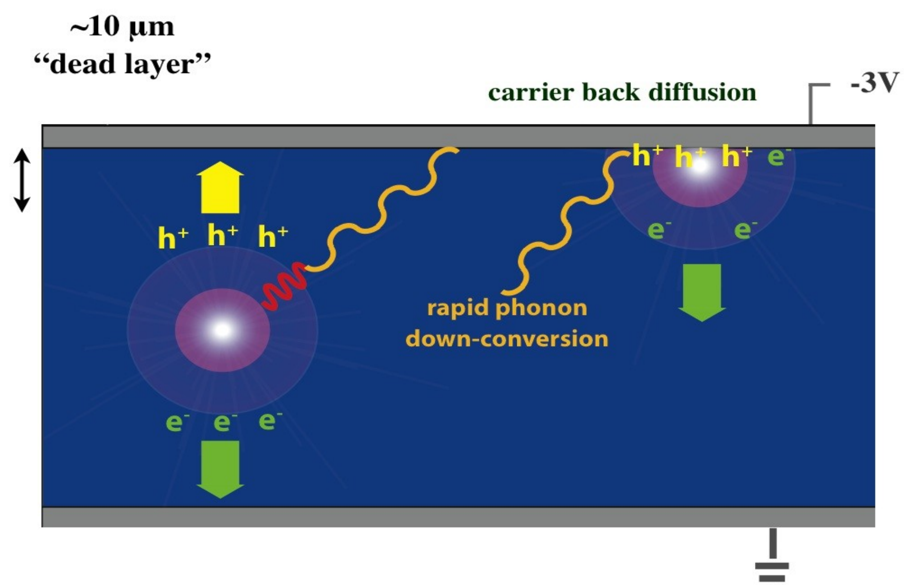


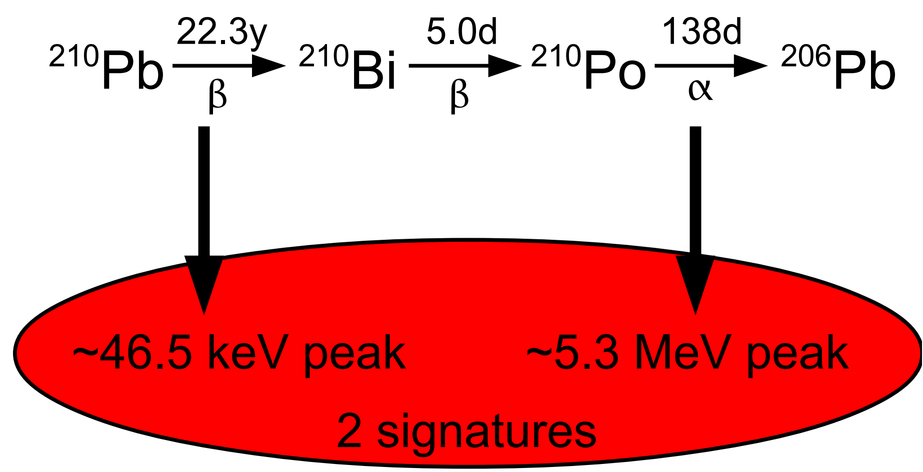
Surface events and contamination

- 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:



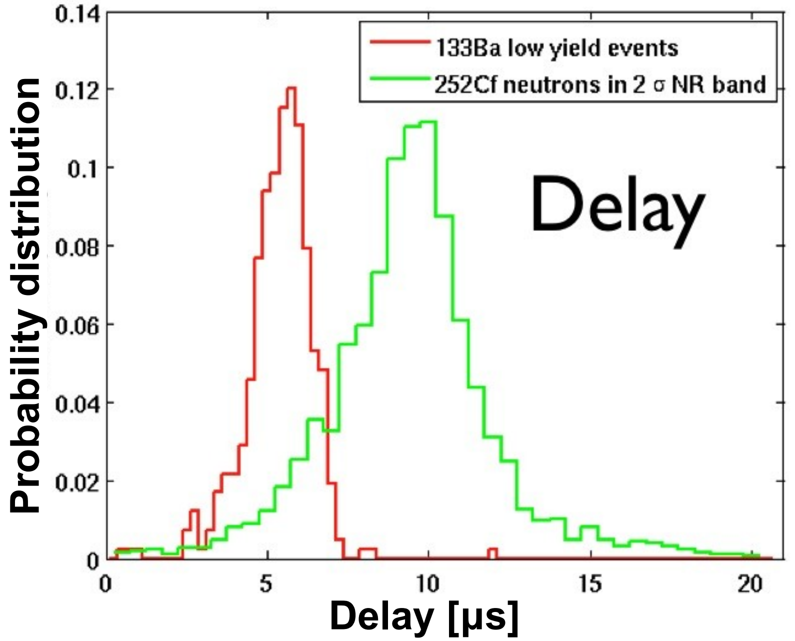
- significant reduction of this contribution for new towers (T3-T5)

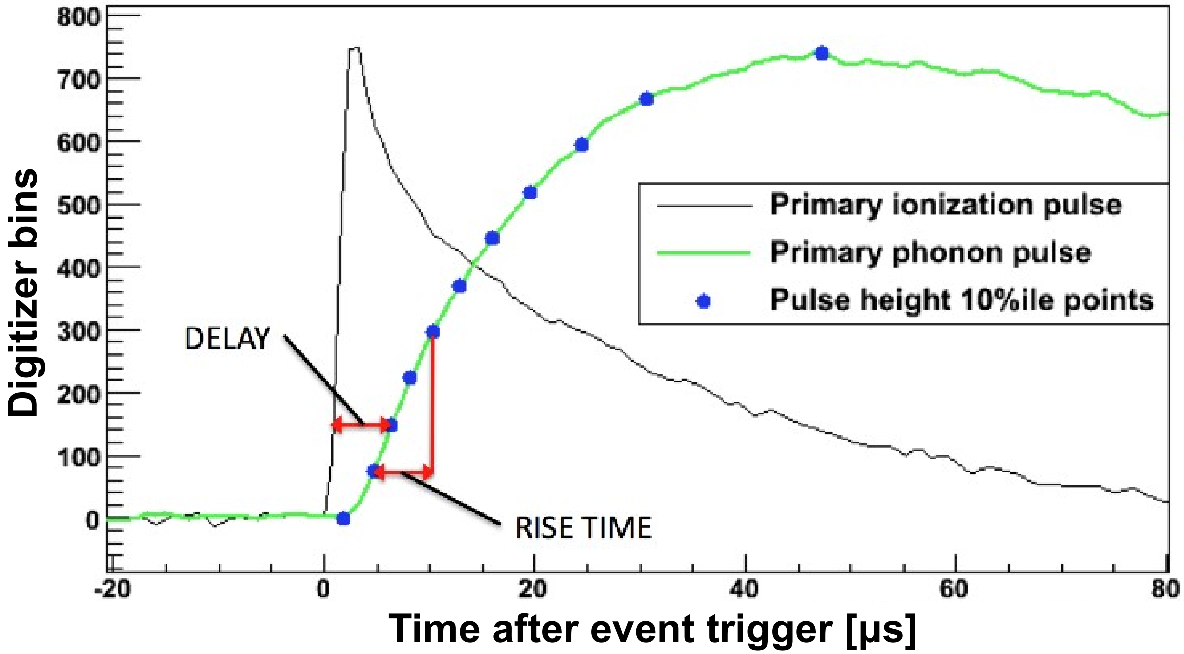
Phonon timing

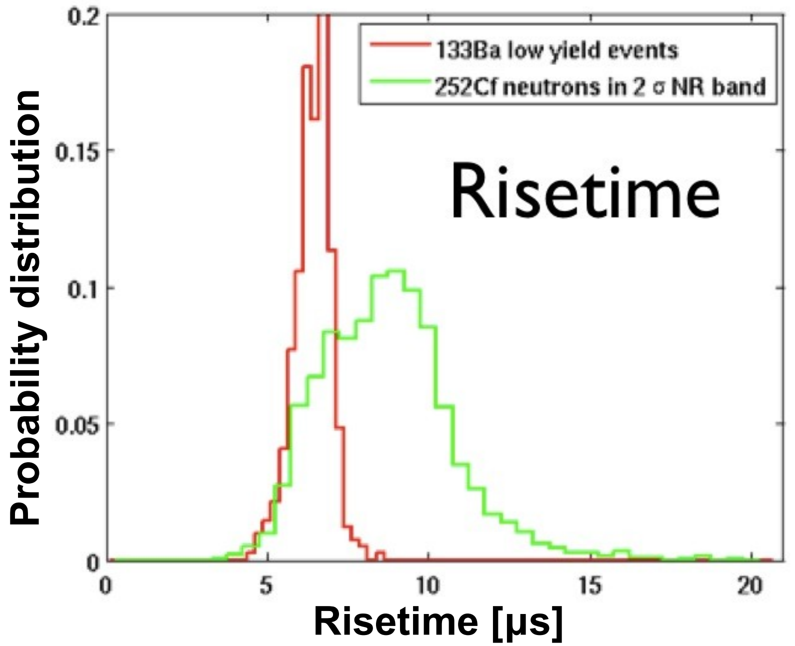
- Surface events are faster in timing than bulk nuclear recoils.

- Use delay+risetime as discriminator to define cut on calibration data.

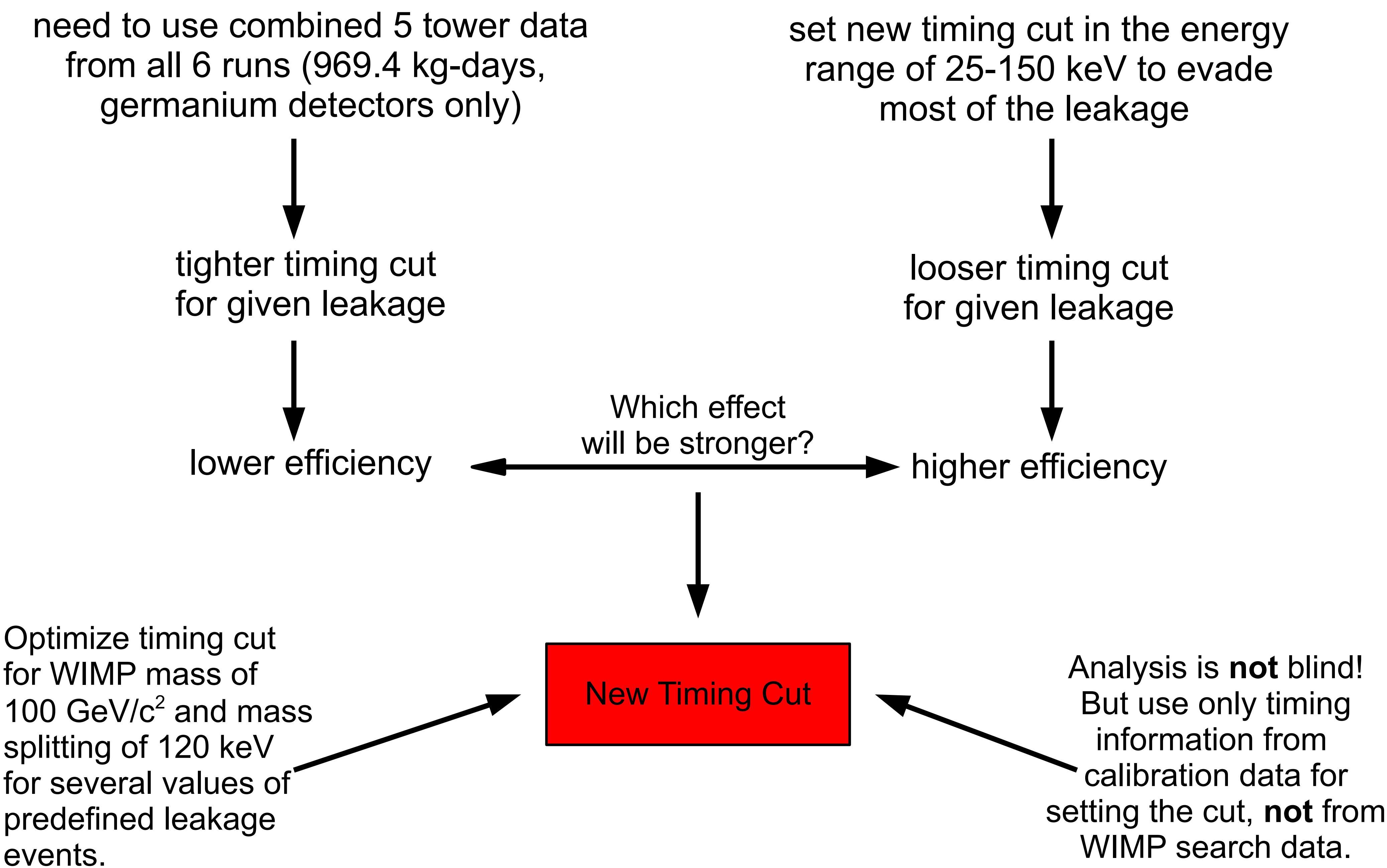
- Allow less then one total leakage event in WIMP-search data.



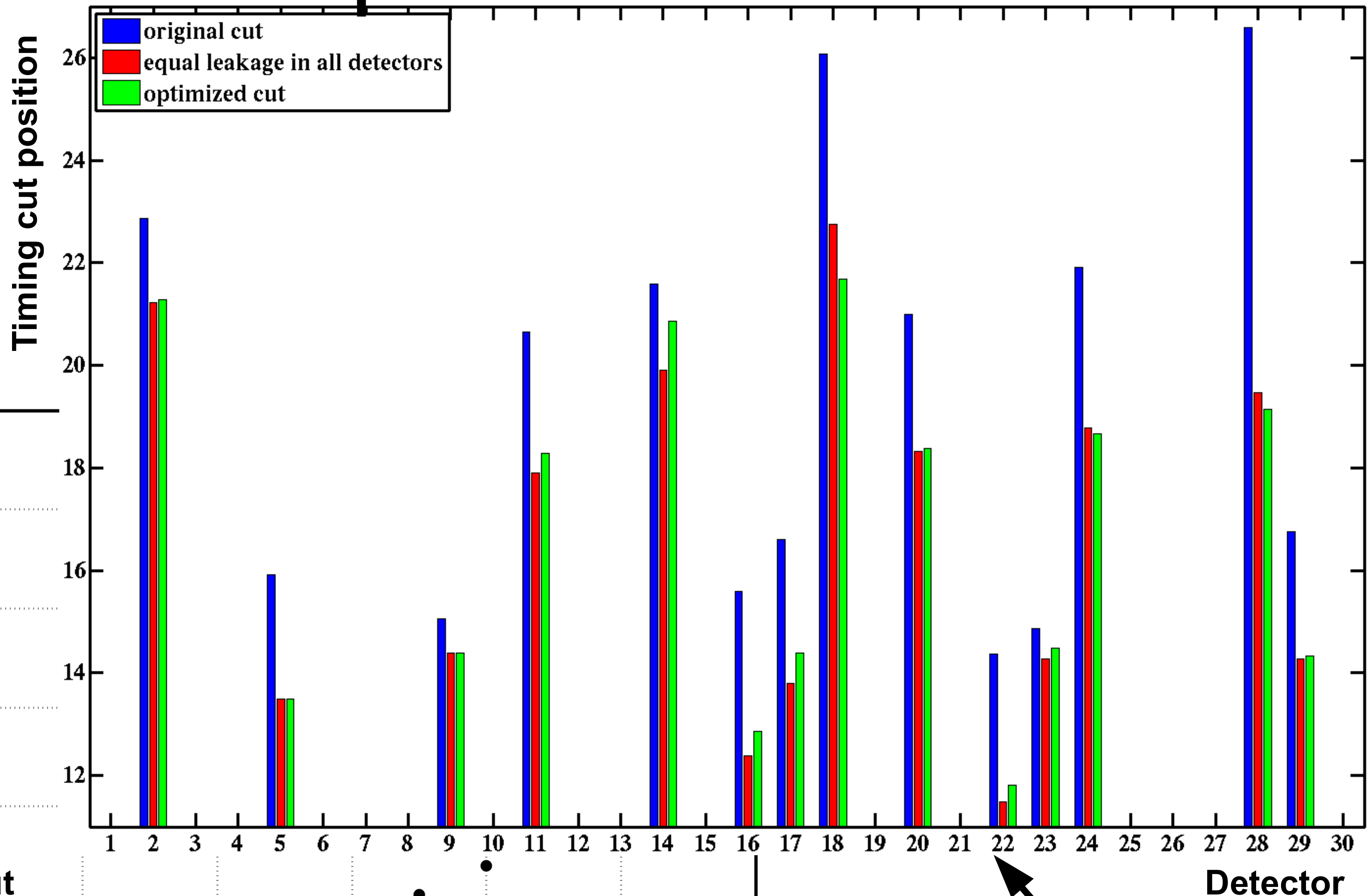




A new surface-event rejection cut

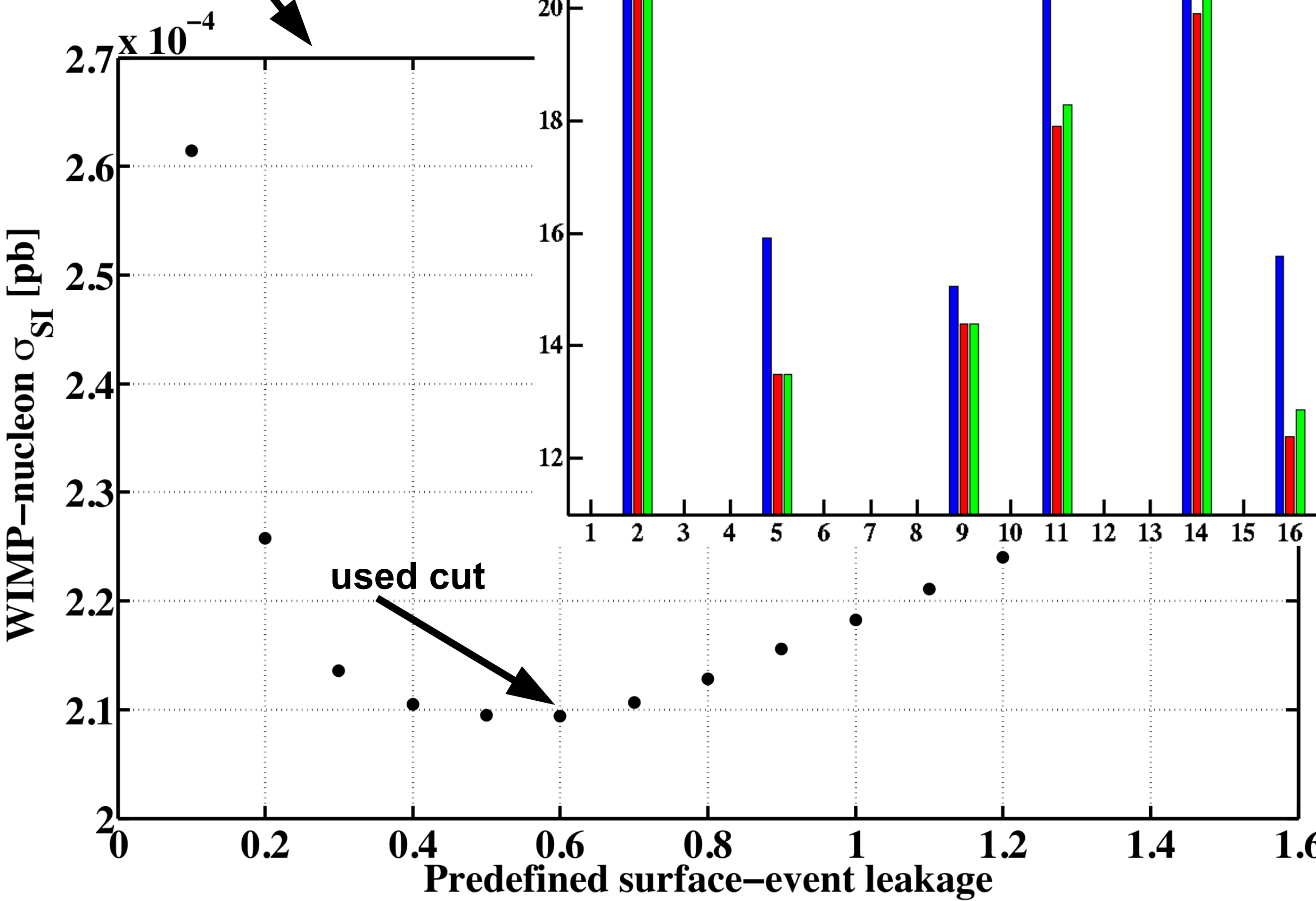


Cut optimization



timing cut positions
for 0.6 leakage events

sensitivity for
cut optimization



Gain ~20 kg-days
with optimization!

Surface-event leakage estimate

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

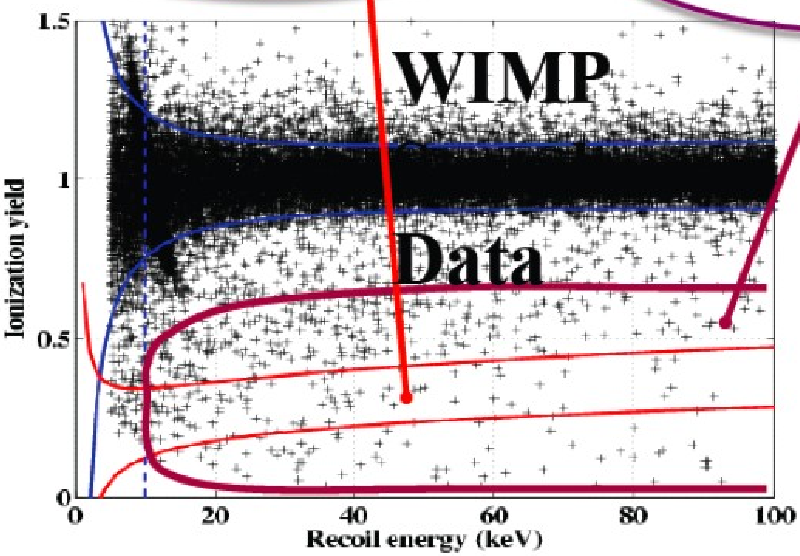
- use two independent event populations for estimating pass/fail-ratios

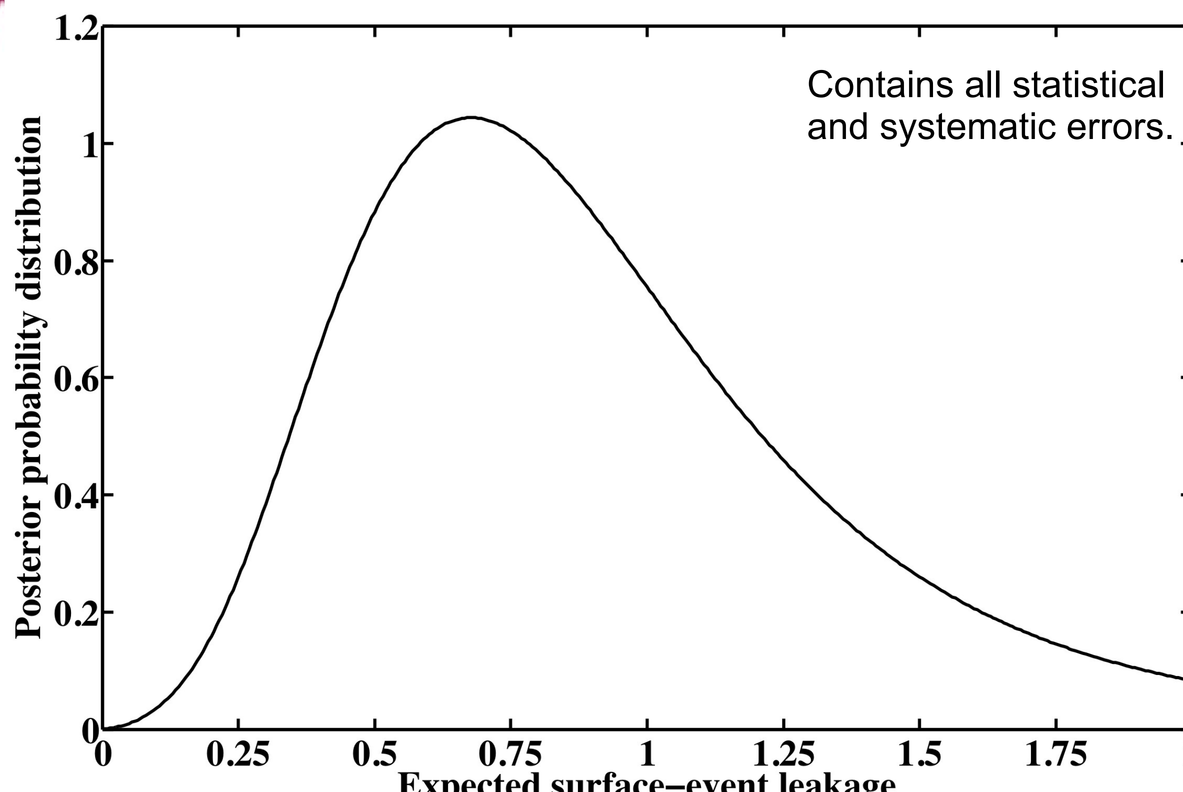
SIDEBAND 1
Use multiple-scatters in NR band

SIDEBAND 2
Use singles and multiples just outside NR band

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

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



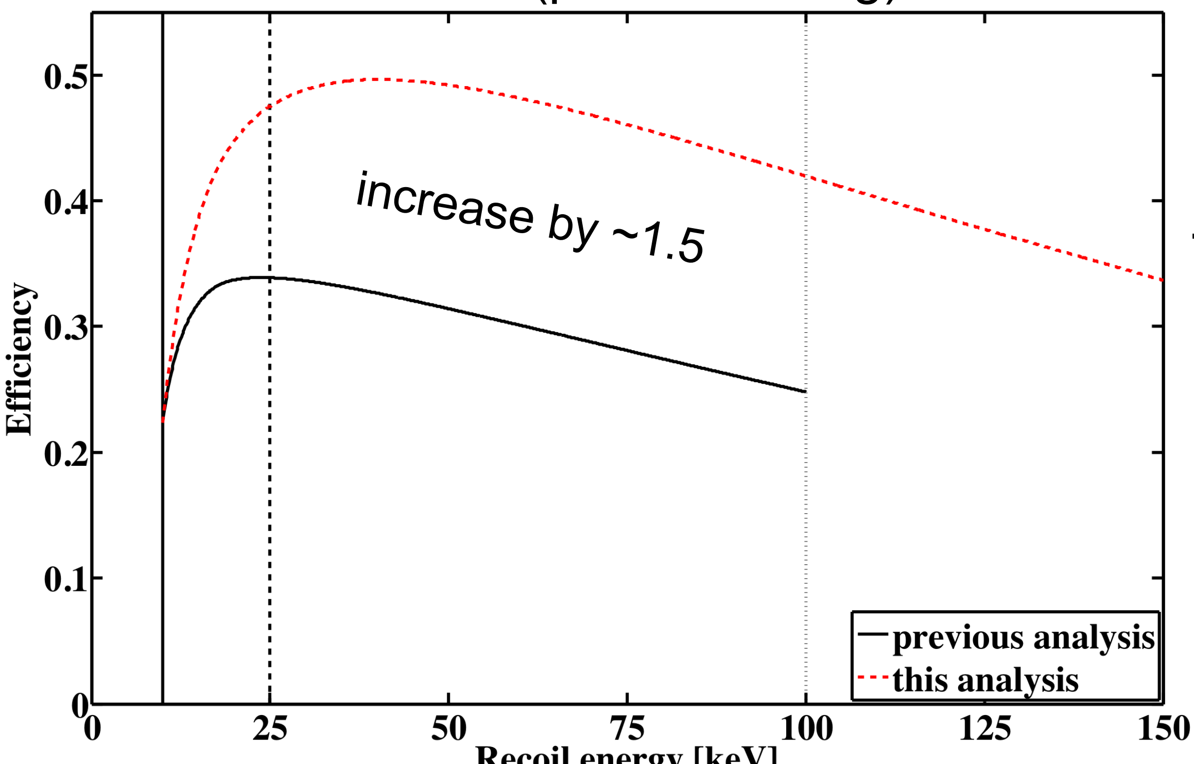


Bayesian approach → treat
background as random variable

Analysis summary

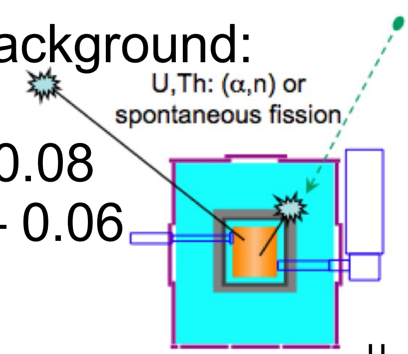
969.4 kg-days raw exposure

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)

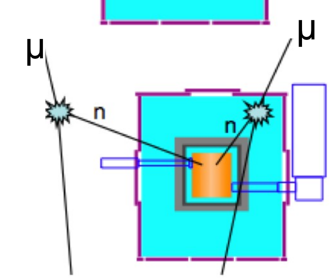


"Blind" Analysis
Set all cuts and calculate efficiencies **before** looking at the signal region of the WIMP-search data.

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: $0.04^{+0.05}_{-0.03}$

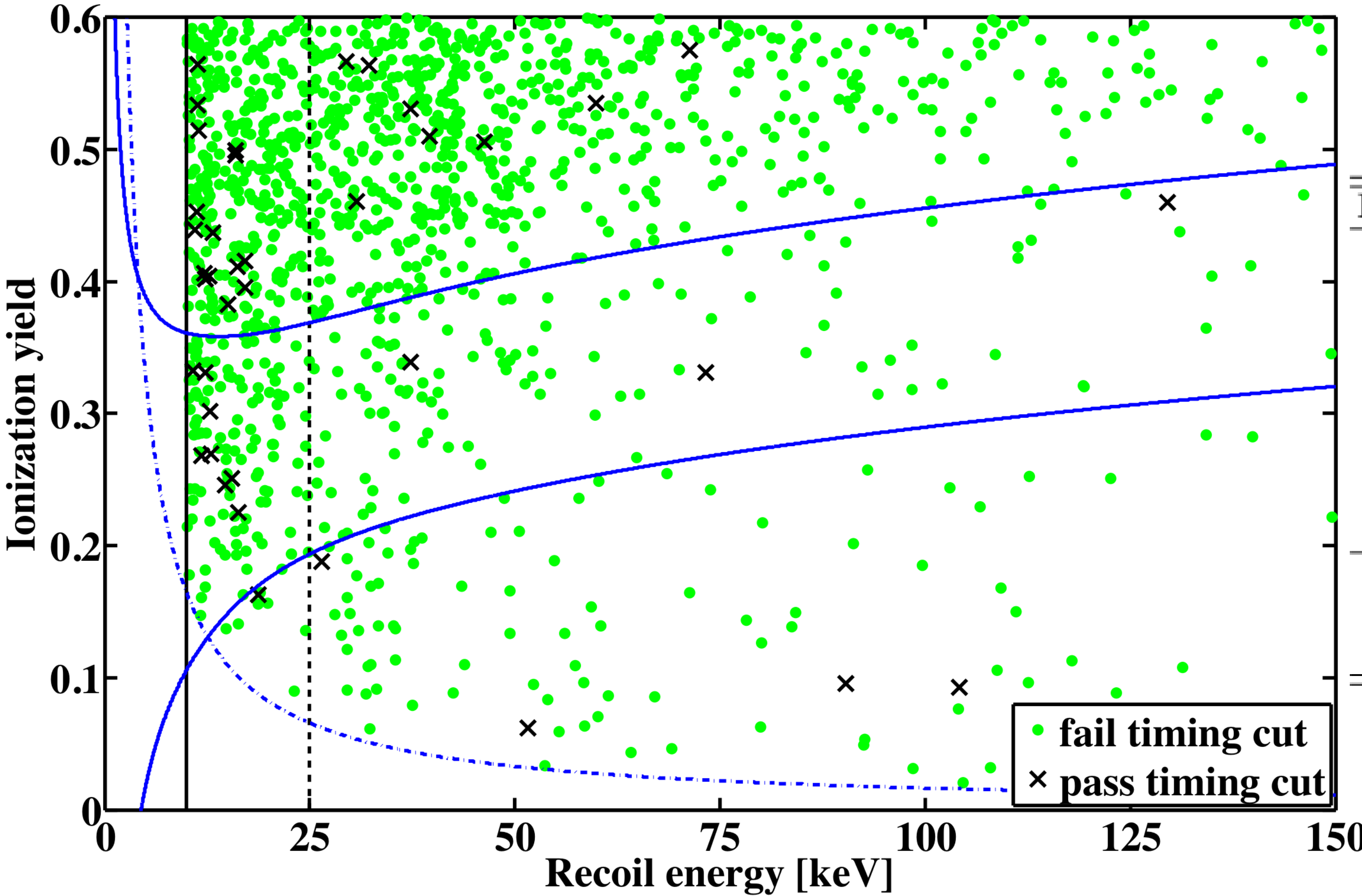


“Unblinding“

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)

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

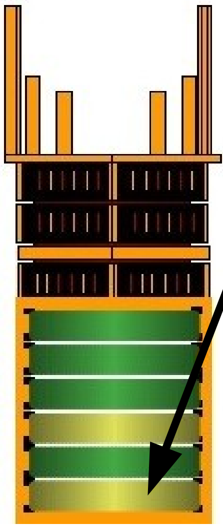


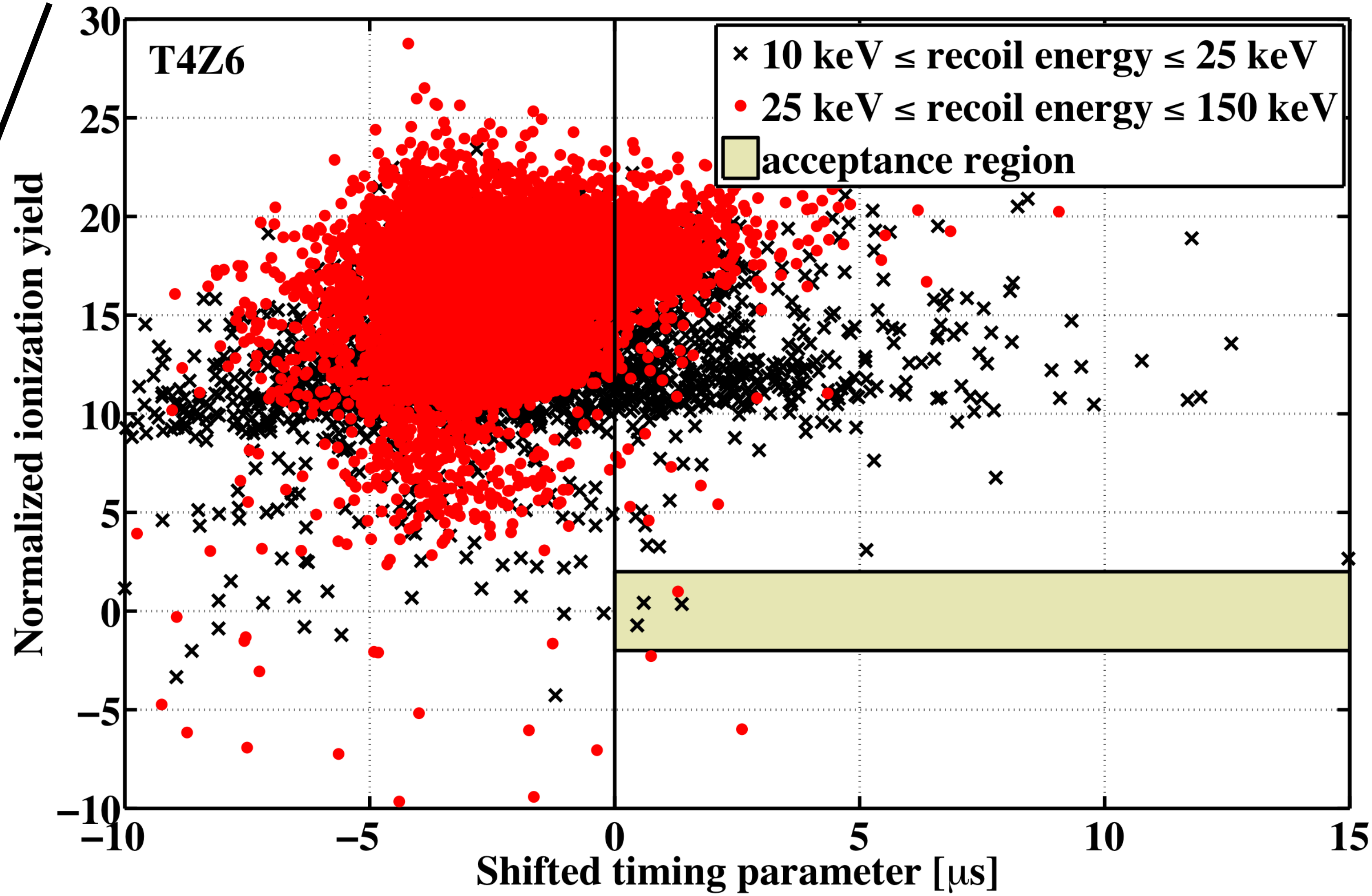
Energy (keV)	Detector	Run	Date
10.8	T2Z3	127	31.05.2008
11.8	T4Z6	124	31.05.2007
12.3*	T1Z5	125	27.10.2007
12.8	T3Z6	127	01.06.2008
13.0	T4Z6	125	05.10.2007
14.7	T3Z6	123	10.12.2006
15.5*	T3Z4	125	05.08.2007
16.4	T4Z6	123	30.10.2006
37.3	T4Z6	126	02.02.2008
73.3	T4Z2	126	04.02.2008
129.5	T1Z2	123	24.12.2006

“High-energy“ event 1

T4Z6 @ 37.3 keV Feb. 2, 2008

Endcap detector!

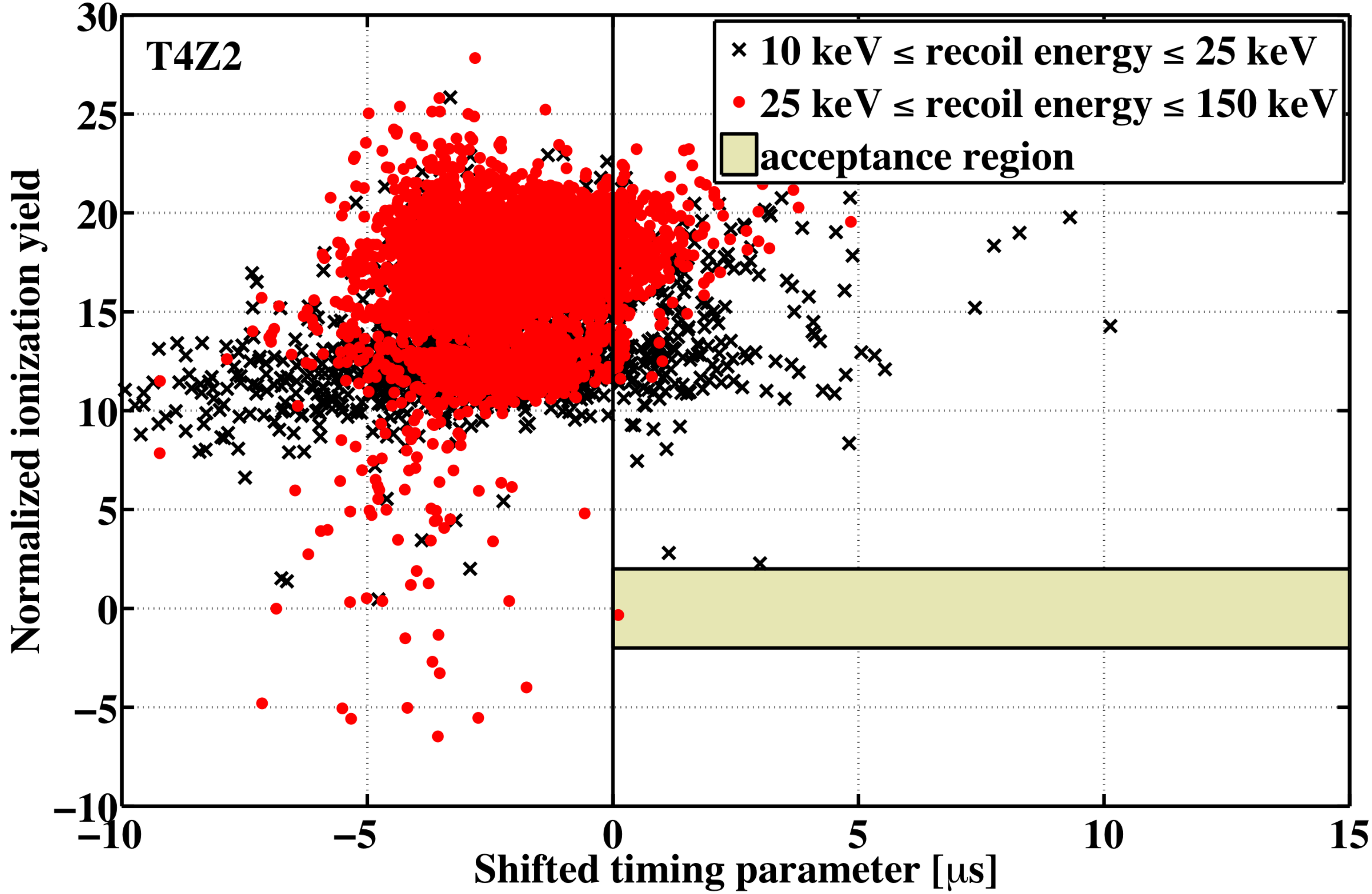




“High-energy“ event 2

T4Z2 @ 73.3 keV Feb. 4, 2008

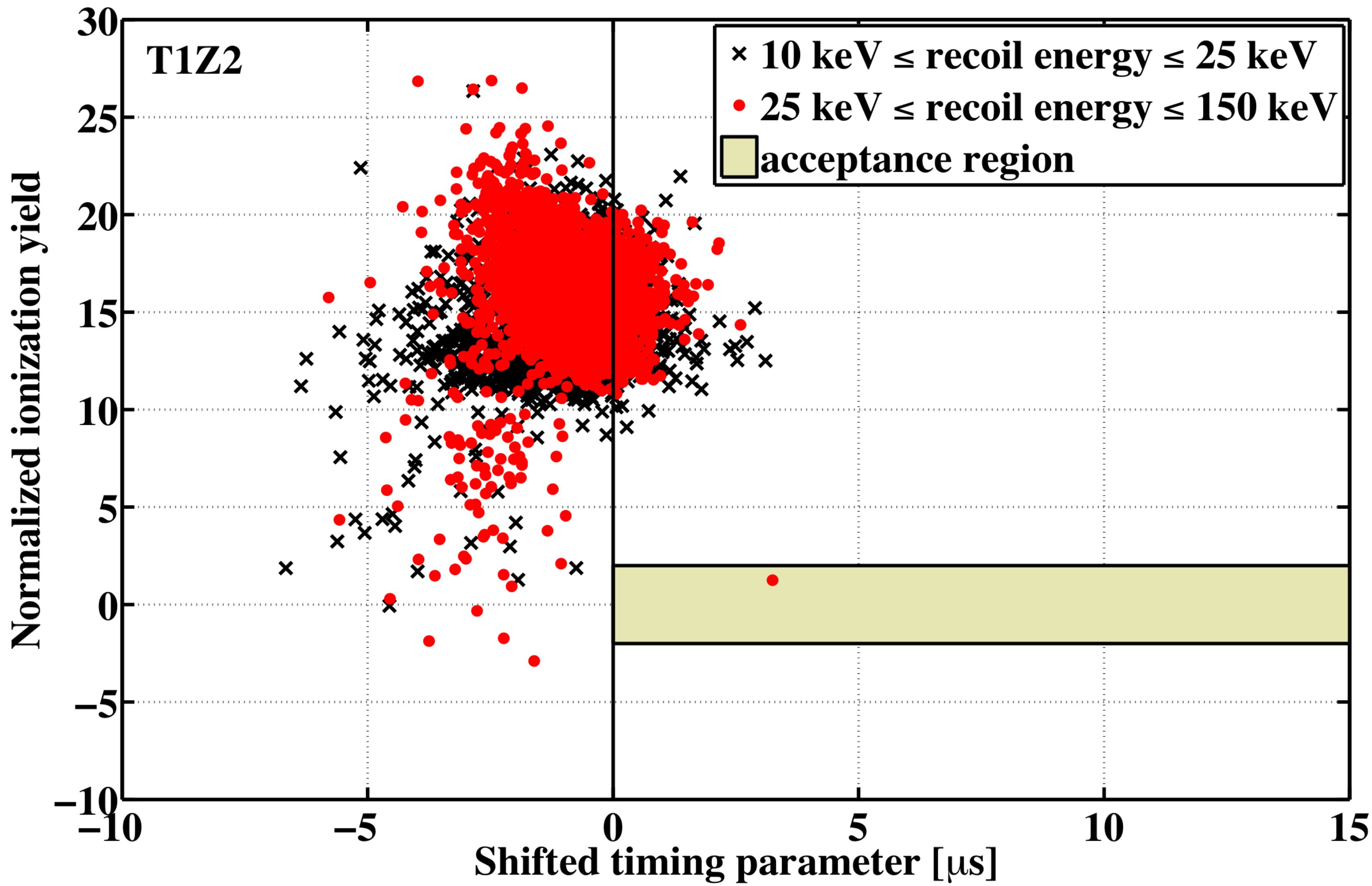
Extremely close to timing cut boundary!



“High-energy“ event 3

T1Z2 @ 129.5 keV Christmas Eve, 2006

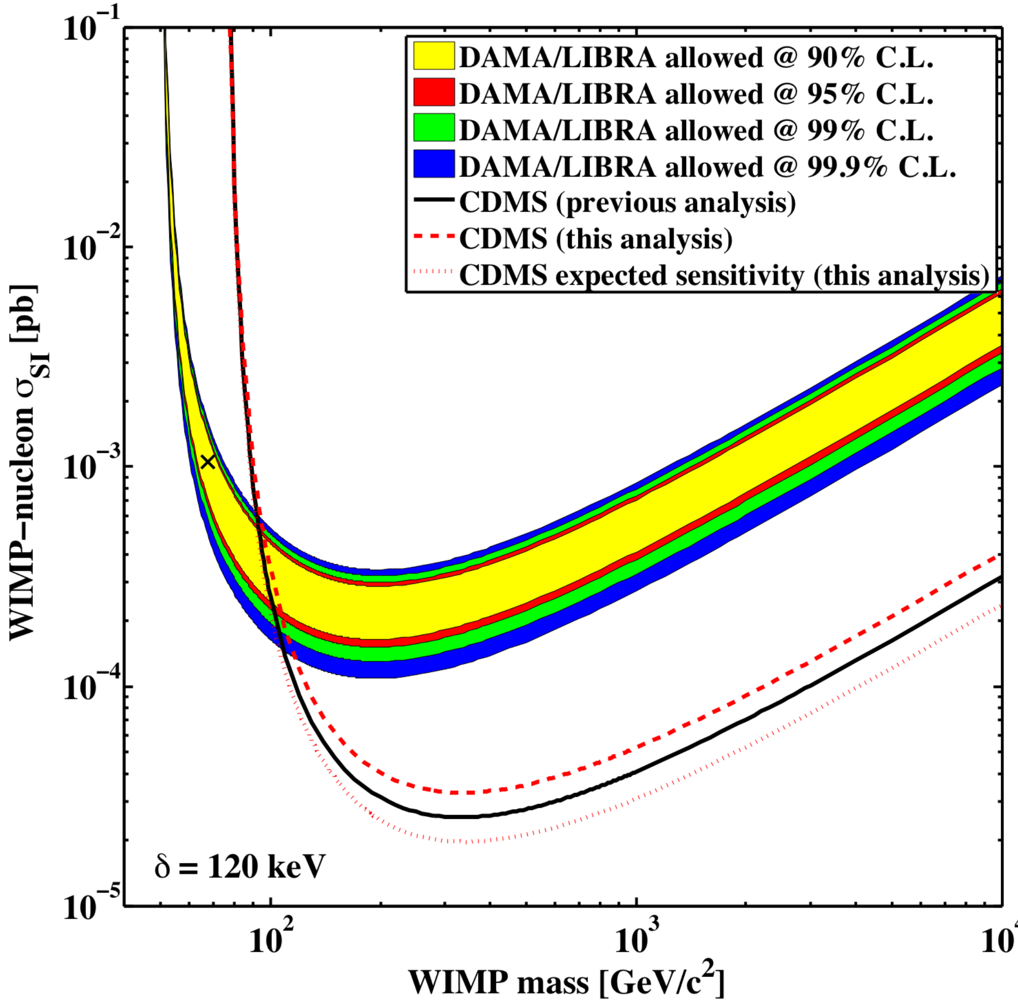
Not even cut by timing cut set to 0.1 leakage events / cut from previous analysis!

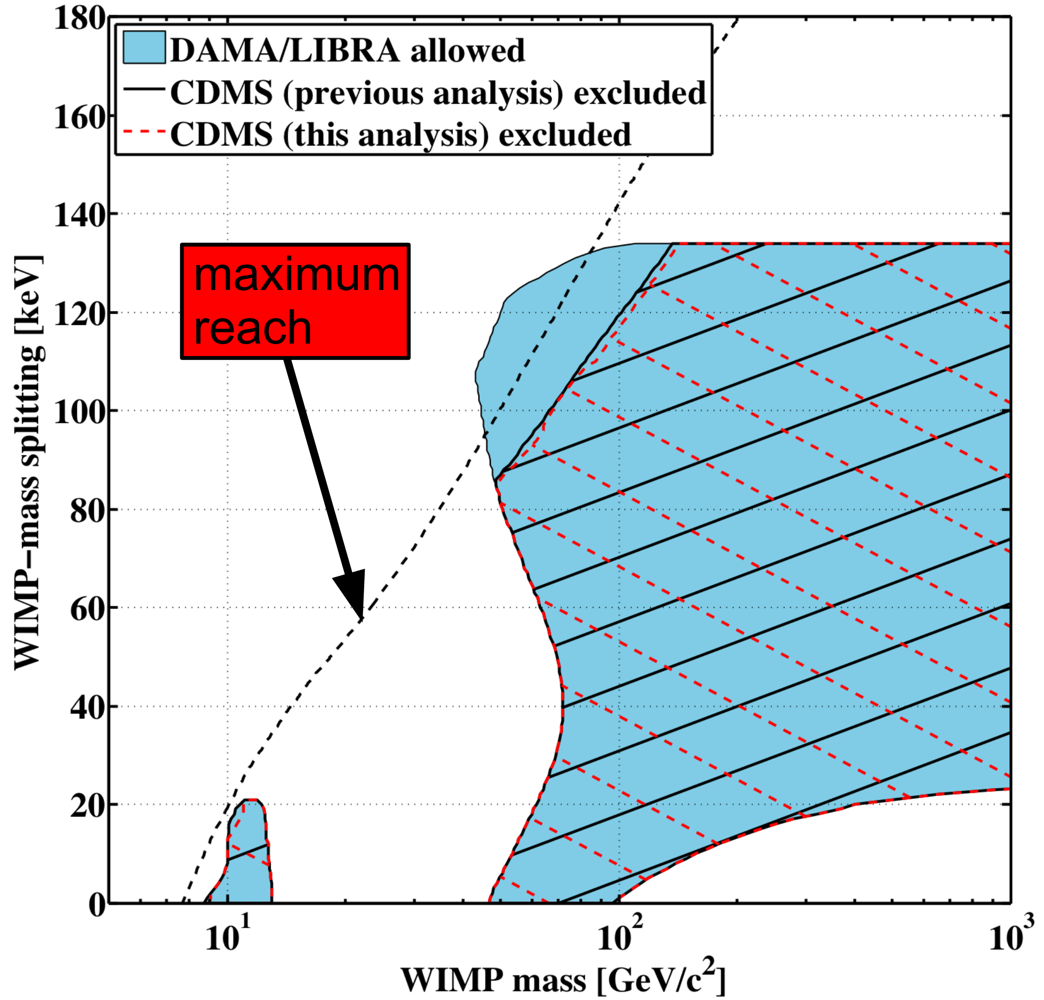


Phys. Rev. D 83, 112002 (2011)

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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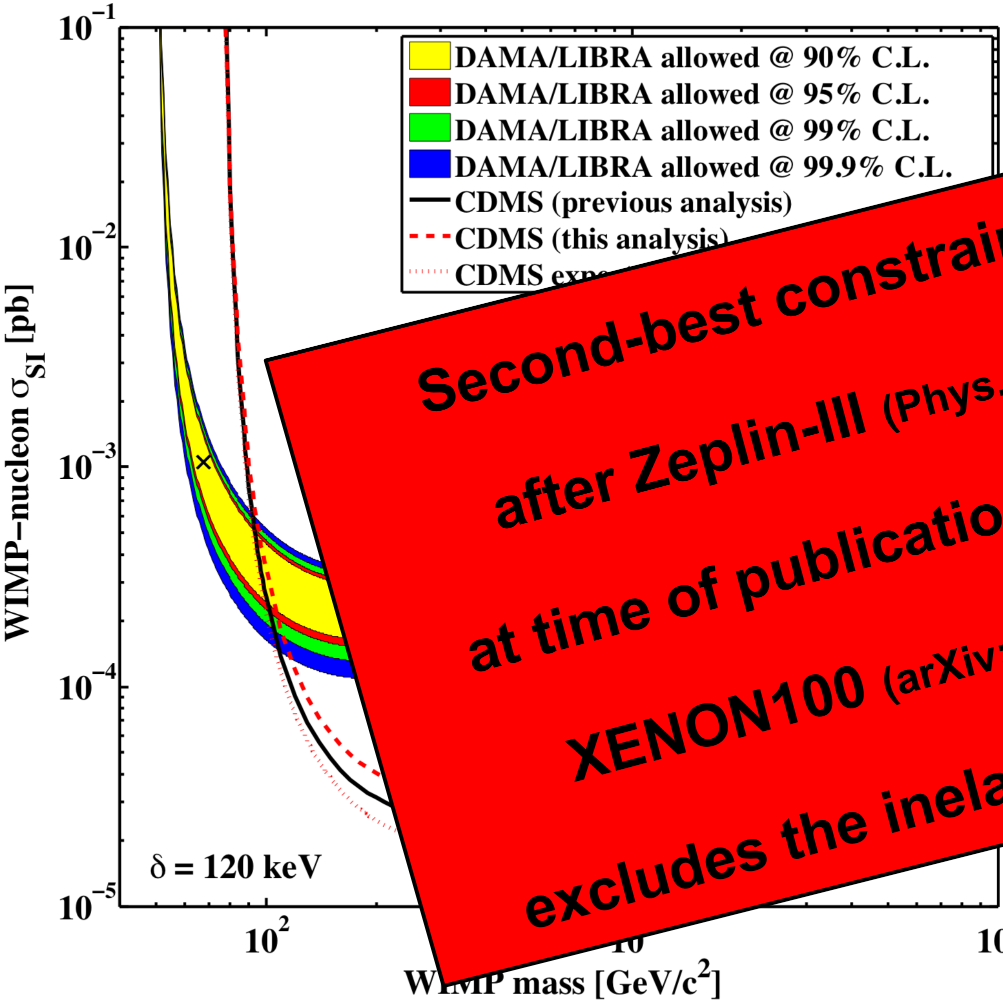

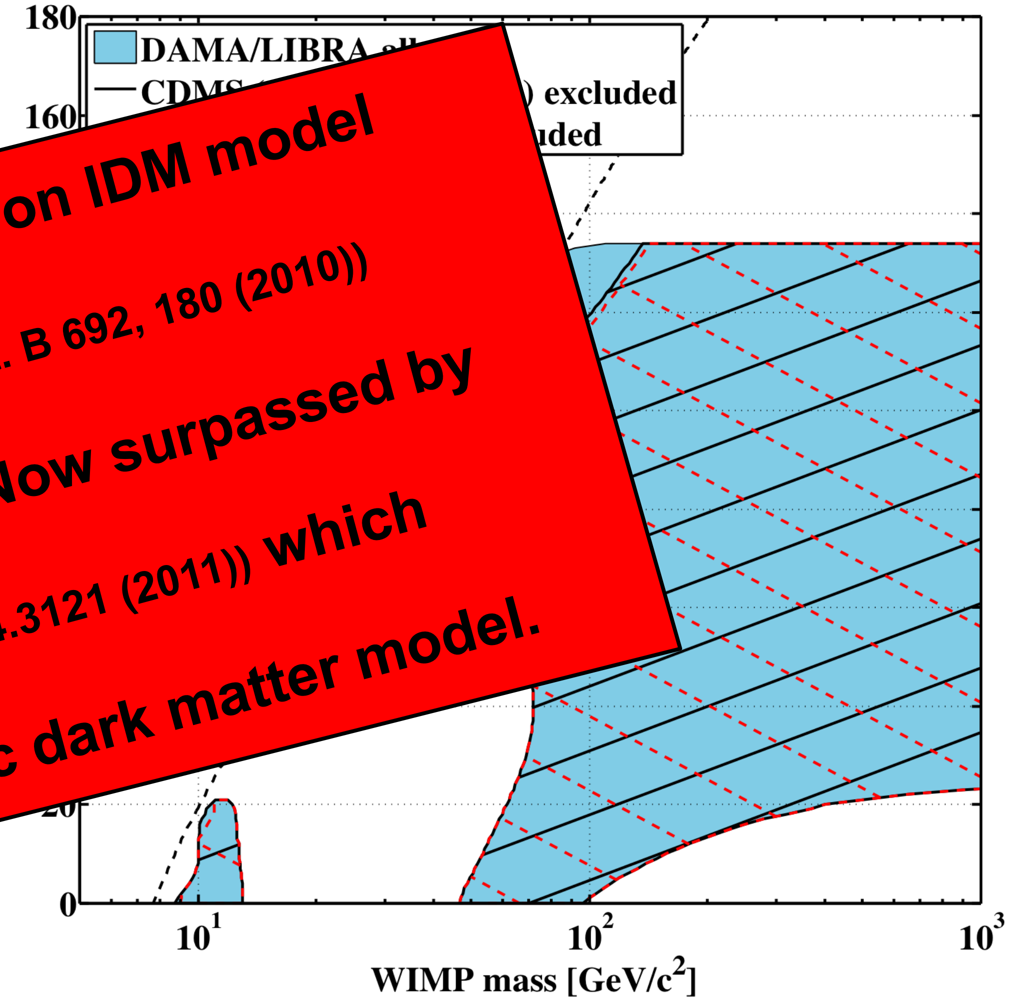

Second-best constraints on IDM model after Zeplin-III (Phys. Lett. B 692, 180 (2010)) **at time of publication. Now surpassed by XENON100** (arXiv:1104.3121 (2011)) **which excludes the inelastic dark matter model.**

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

- published in Phys. Rev. D 83, 112002 (2011)

- inelastic dark matter scenario now ruled out by XENON100 results

Backup Slides

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.