Direct Detection of Dark Matter with Cryogenic Experiments

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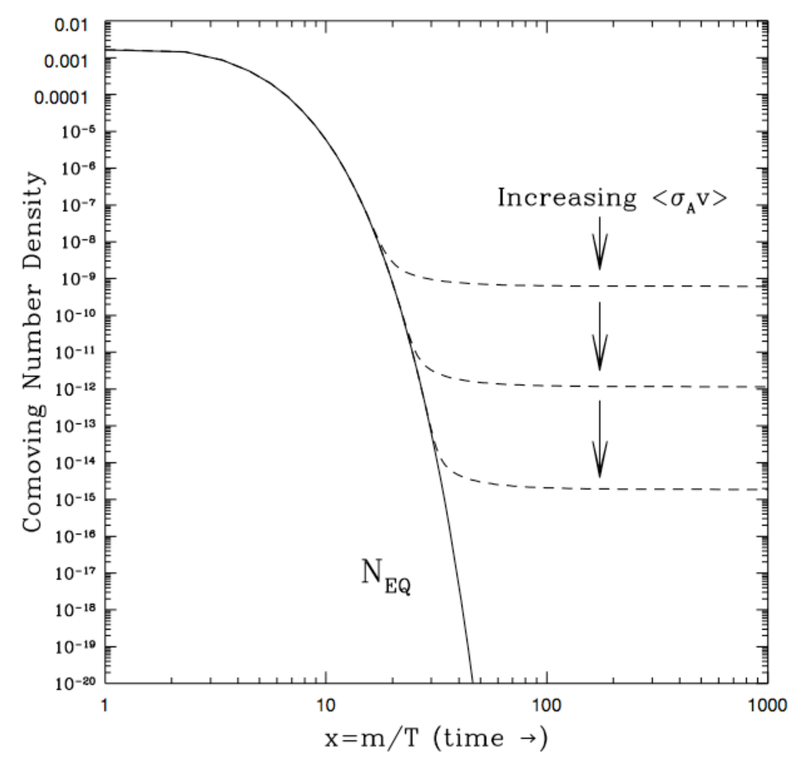
TeV Particle Astrophysics, Paris

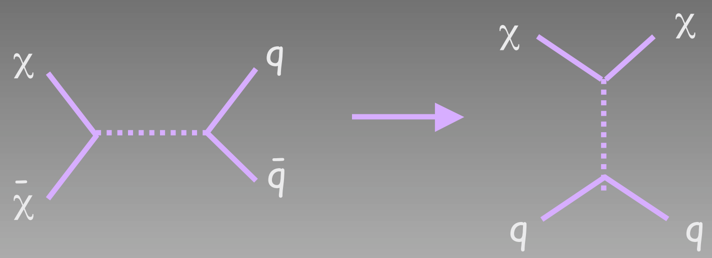
July 19, 2010

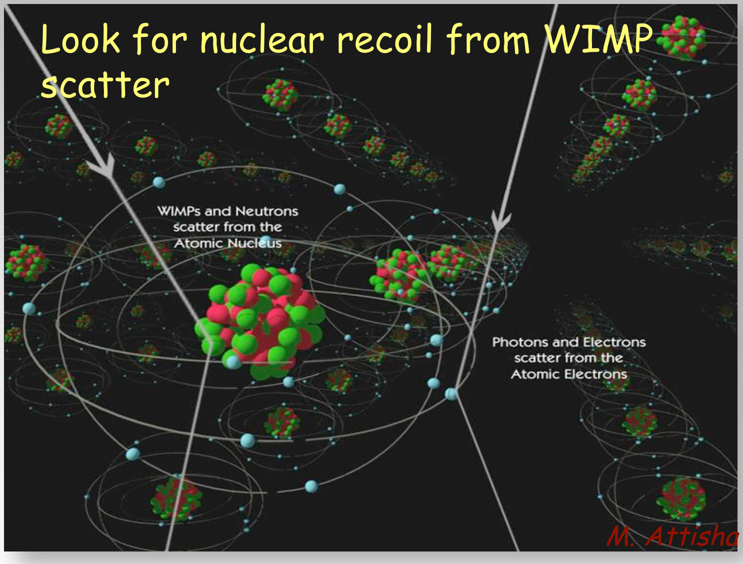
Is Dark Matter a WIMP?

particles with mass and annihilation cross section at the weak scale naturally yield correct relic density of CDM



Kolb & Turner, "The Early Universse"





Look for nuclear recoil from WIMP scatter

M. Attisha

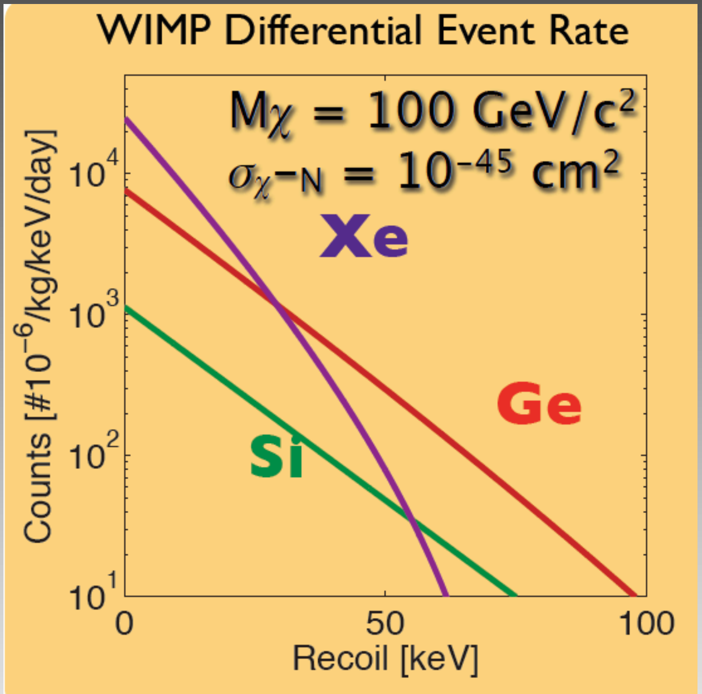
Direct Detection of Dark Matter

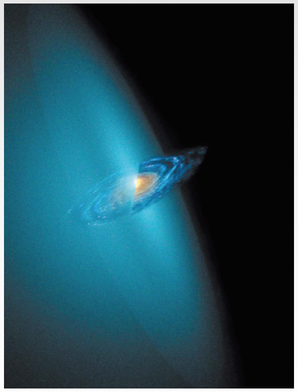
Expected signal:

- nuclear recoil
- featureless exponential ~ few 10's of keV
- rates <0.1 events /kg/day

Challenges:

- low energy thresholds (~10 keV)
- mitigation of natural radioactive background (1 banana ~1M decays/day)
- long exposures, underground operation

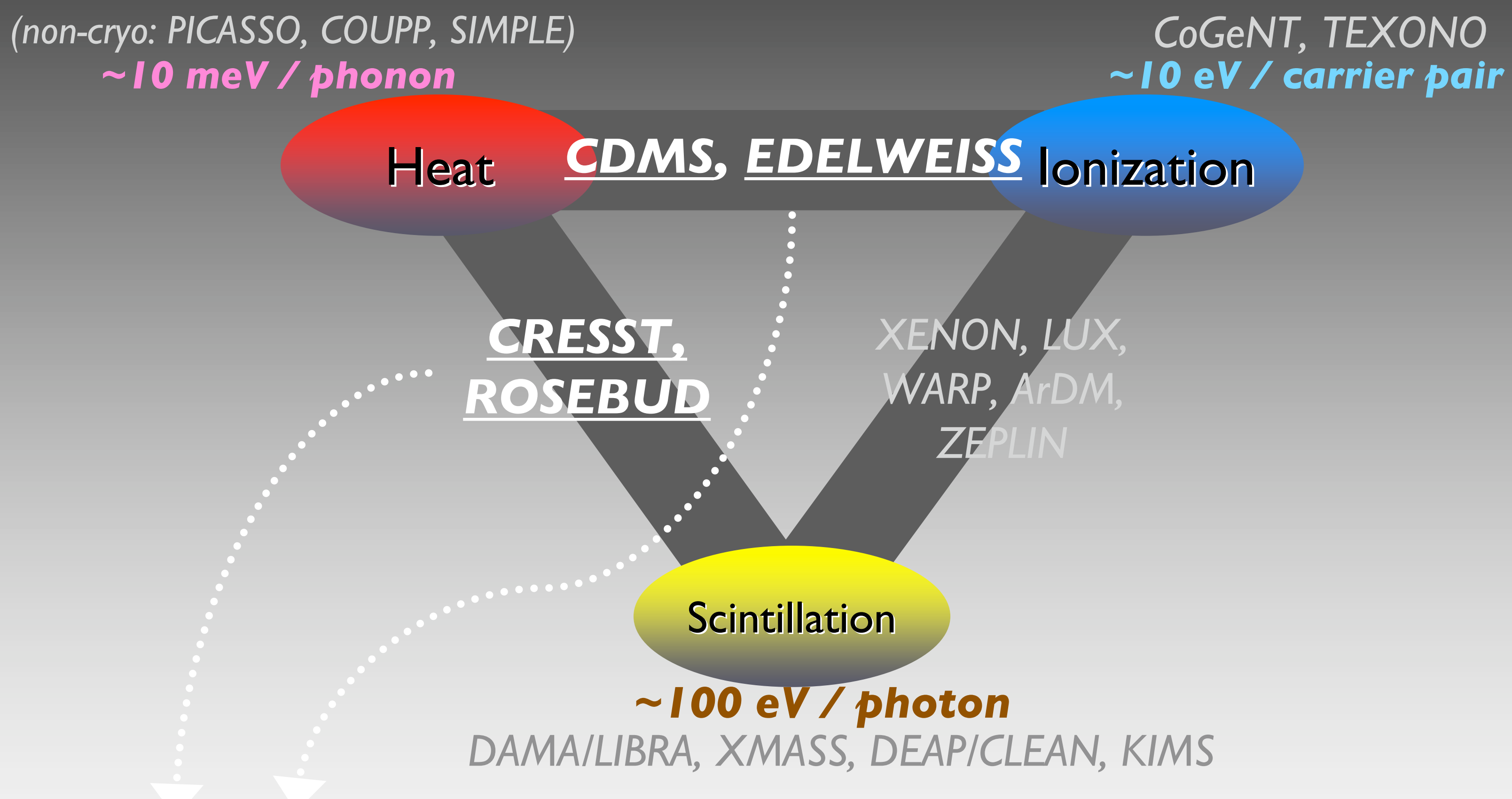




How are WIMPs Distributed?

- spherical Navarro-Frenk-White halo profile
- local density ~0.3 GeV/cm^3

Detection Strategies



(non-cryo: PICASSO, COUPP, SIMPLE)

~10 meV / phonon

CoGeNT, TEXONO

~10 eV / carrier pair

Heat

CDMS, EDELWEISS

Ionization

CRESST, ROSEBUD

XENON, LUX, WARP, ArDM, ZEPLIN

Scintillation

~100 eV / photon

DAMA/LIBRA, XMASS, DEAP/CLEAN, KIMS

Cryogenic Strategy:

reduced ionization or scintillation relative to heat signal

Major Backgrounds:

- *Gammas /betas (electron recoils)*
- *Neutrons (nuclear recoils)*
- *Alphas (for some, not all)*

Cryogenic Experiments

common features:

operating temperatures from 10-50 mK - detect small rises in temperature from electron or nuclear recoil

most sensitive to spin-independent cross-sections

modular - dozens of individual detectors, allows for rejection of neutron multiple scatters

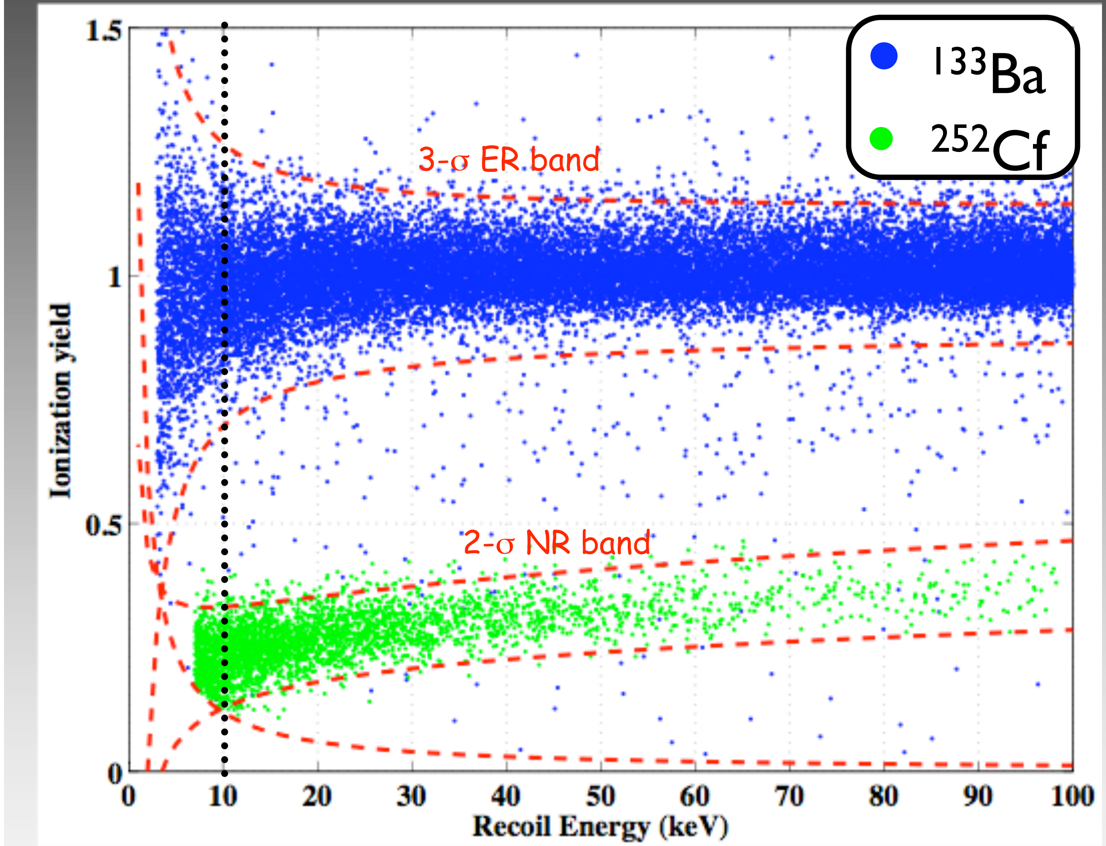
multiple target nuclei may be implemented

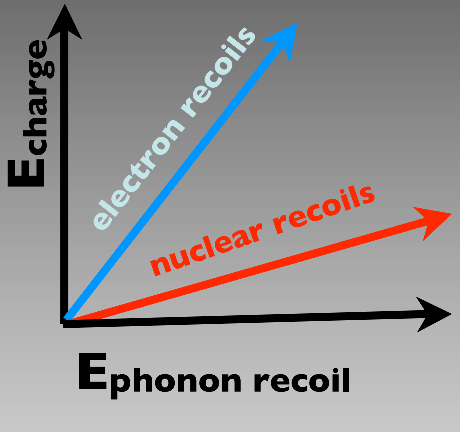
substrates intrinsically very pure and radiogenically clean

low noise = low energy thresholds

very high background rejection capabilities $>10^6$

Gamma Rejection (CDMS Example)





$$\text{Ionization Yield} = \frac{E_{charge}}{E_{phonon\ recoil}}$$

BETTER THAN 1:10^4 rejection of gammas based on ionization yield alone

Controlling Neutrons (CDMS Example)

1. Go Deep:

Soudan Mine: 2090 mwe
(muon rate reduced by >10^4)

2. Use Active Shielding:

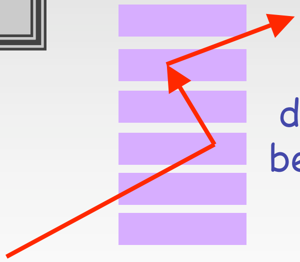
muon veto ~98% efficient

<< 1 unvetoed
single scatter
neutron / kg /year

3. Use Passive Shielding:

2 layers polyethylene -
shields from cosmogenic and
radiogenic neutrons

4. Use Event Topology



Neutrons may
double scatter or
be accompanied by
EM shower

5. Run Extensive Simulations:

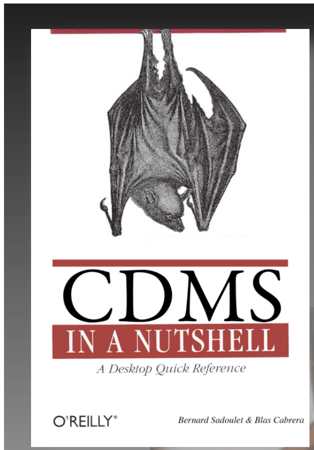
GEANT4

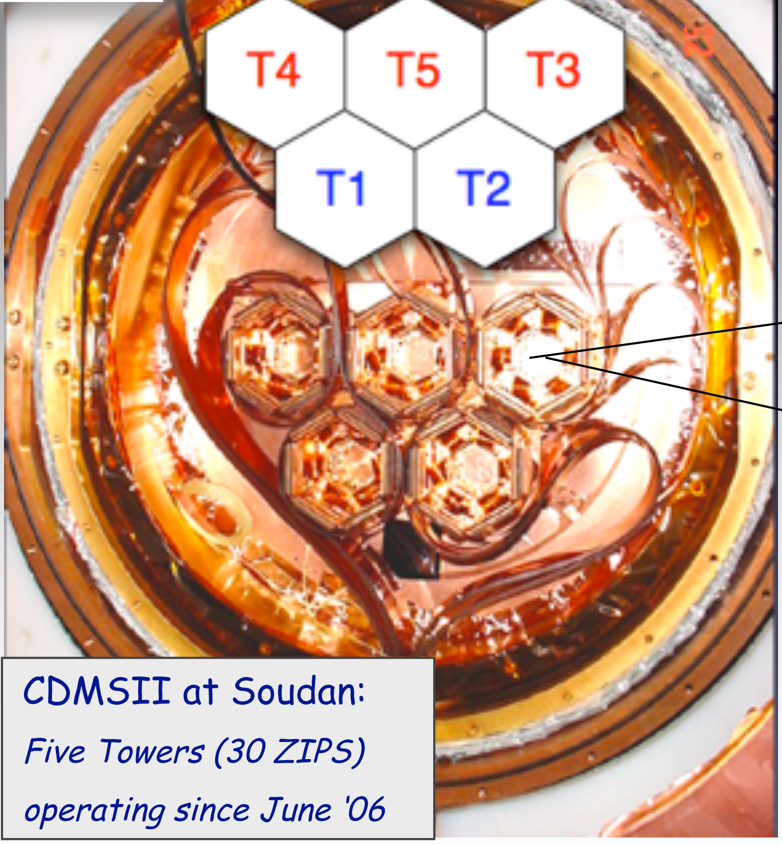
FLUKA+MCNPX

MUSIC

Recent Results

CDMS II Experiment

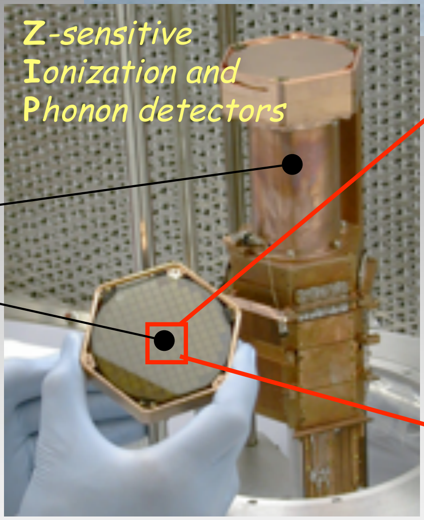

CDMS
IN A NUTSHELL
A Desktop Quick Reference
O'REILLY
Bernard Sadoulet & Blas Cabrera

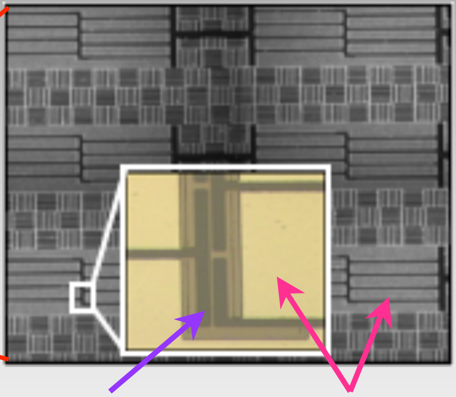


CDMSII at Soudan:

Five Towers (30 ZIPS)

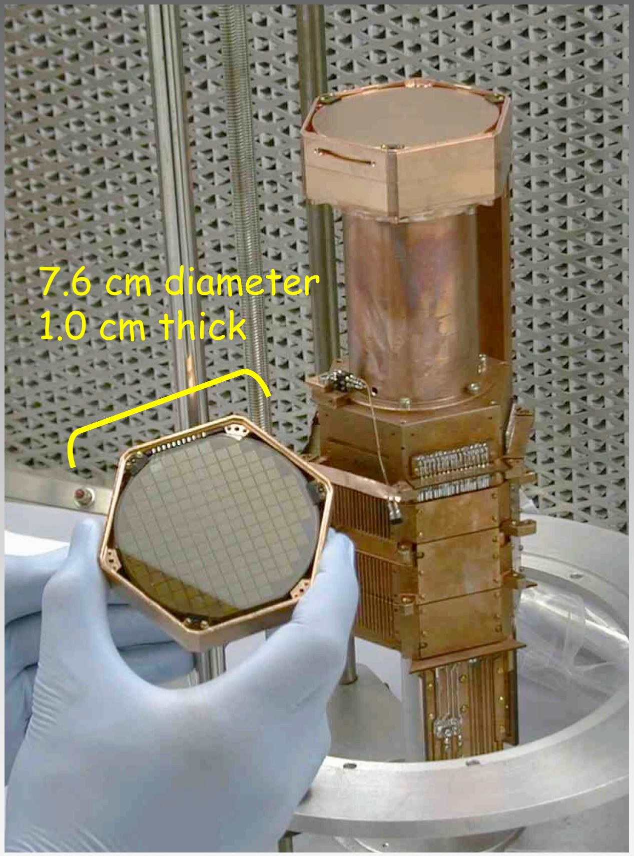
operating since June '06

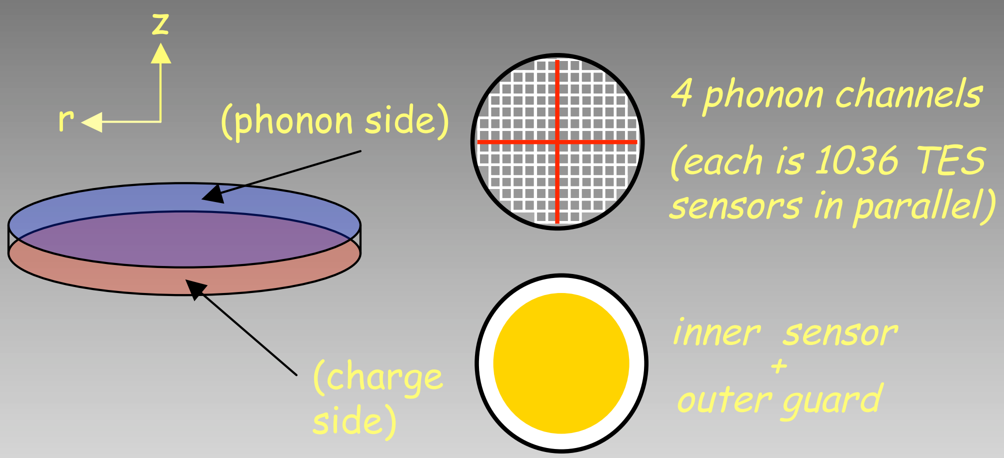




Most sensitive to spin-independent scattering: $\sigma \propto A^2$
4.75 kg Ge(A=73), 1.1 kg Si(A=28)

ZIP: Z-sensitive Ionization and Phonon Detectors





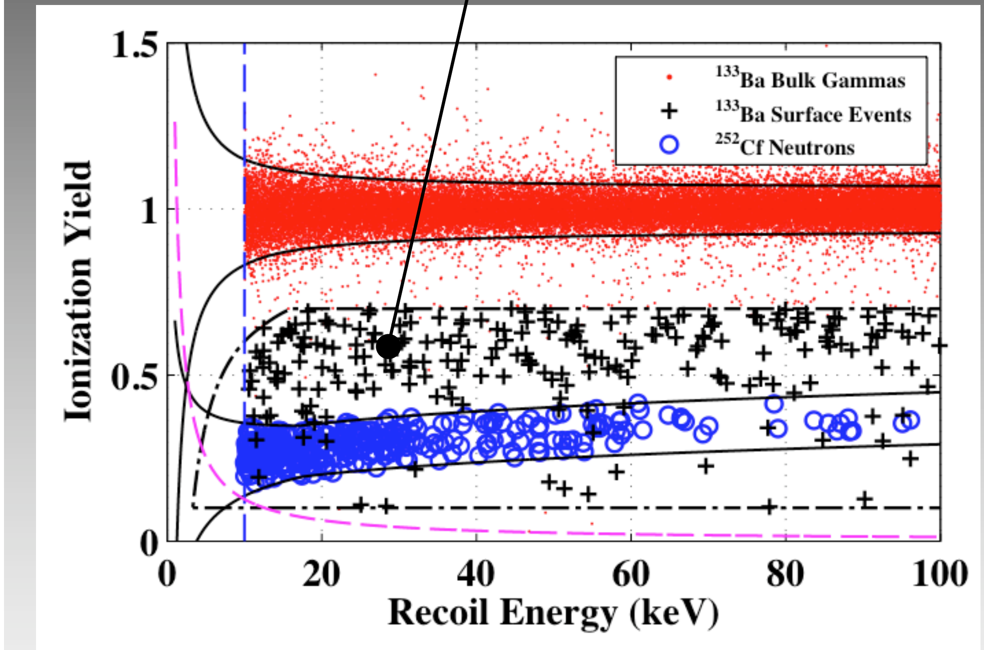
30 zip arranged in 5 towers

19 Ge (~240g each), 11 Si (~110g each)

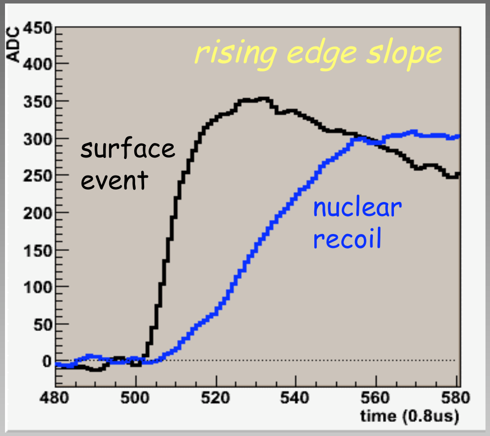
6 ZIPS stacked together per tower

Surface Event Rejection

10 μm “dead layer” results in reduced ionization collection

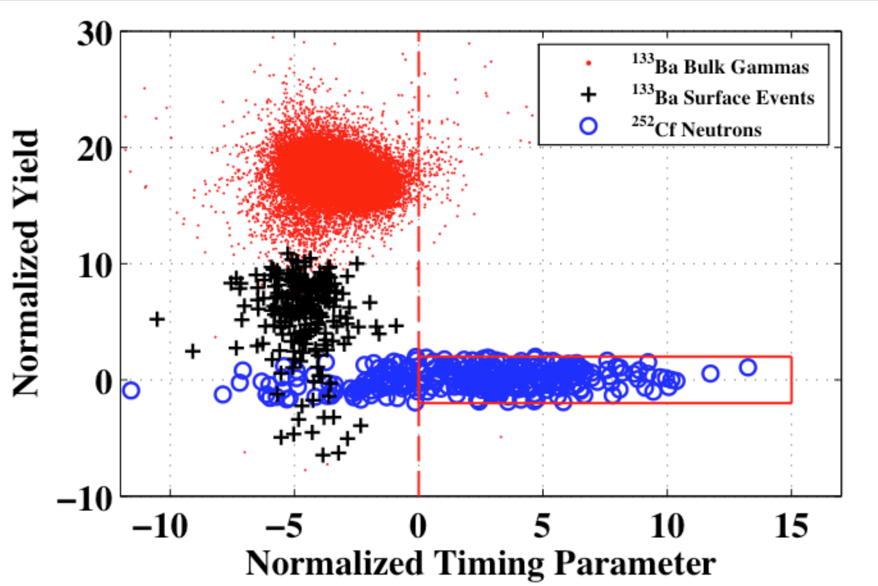


Phonon pulse shape (timing) distinguishes surface events



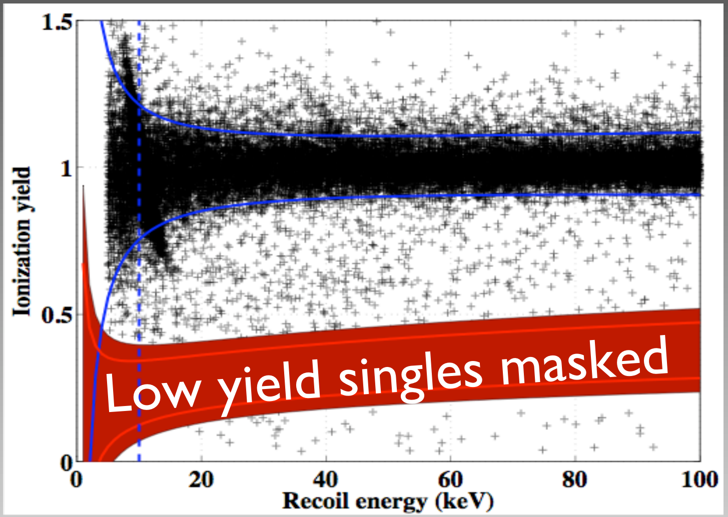
yield and “timing” achieves > 10^6 rejection of election recoils

timing parameter =
risetime + offset from ionization pulse



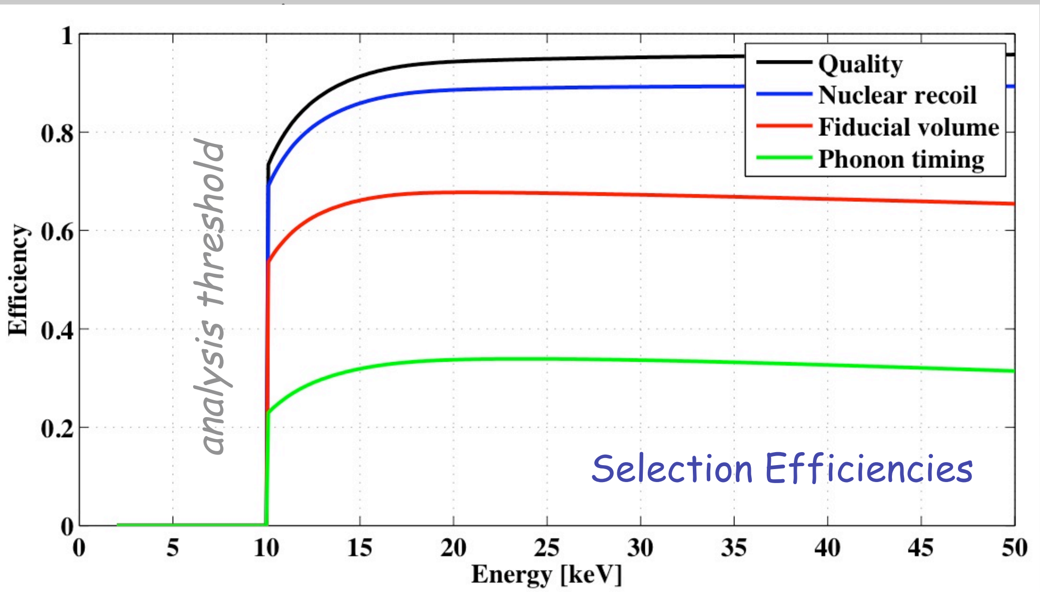
Results: Final Year of CDMS II Data

ref: Science 327:1619-1621,2010



Candidate Criteria:

- Data Quality + Fiducial Volume Cuts
- Muon-veto anticoincident
- Single Scatter (only 1 zip w/ signal)
- Ionization yield inside 2σ nuclear recoil band
- Phonon "timing" cut

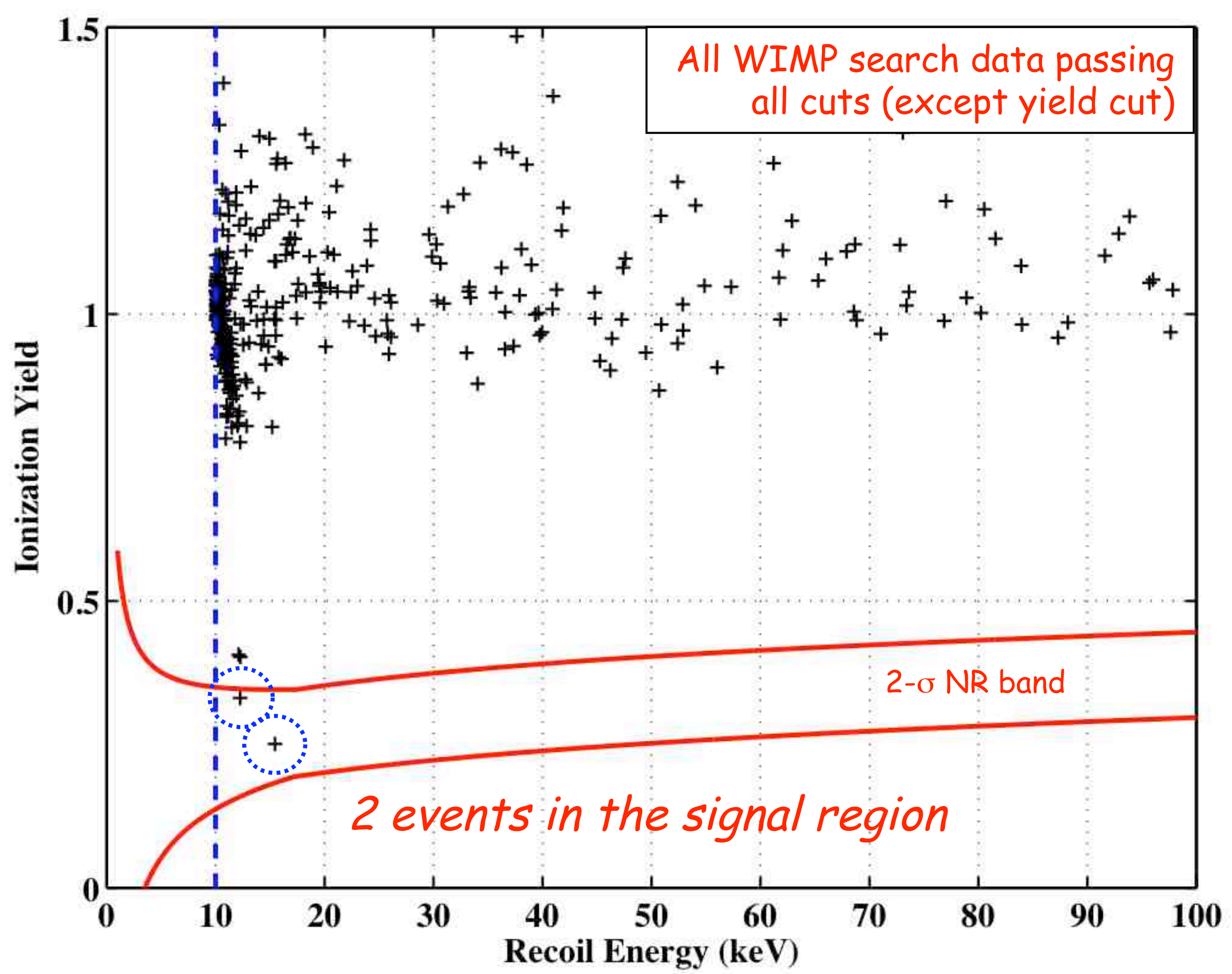


All cuts established before unblinding!

(sidebands and calibration data are used for cut development)

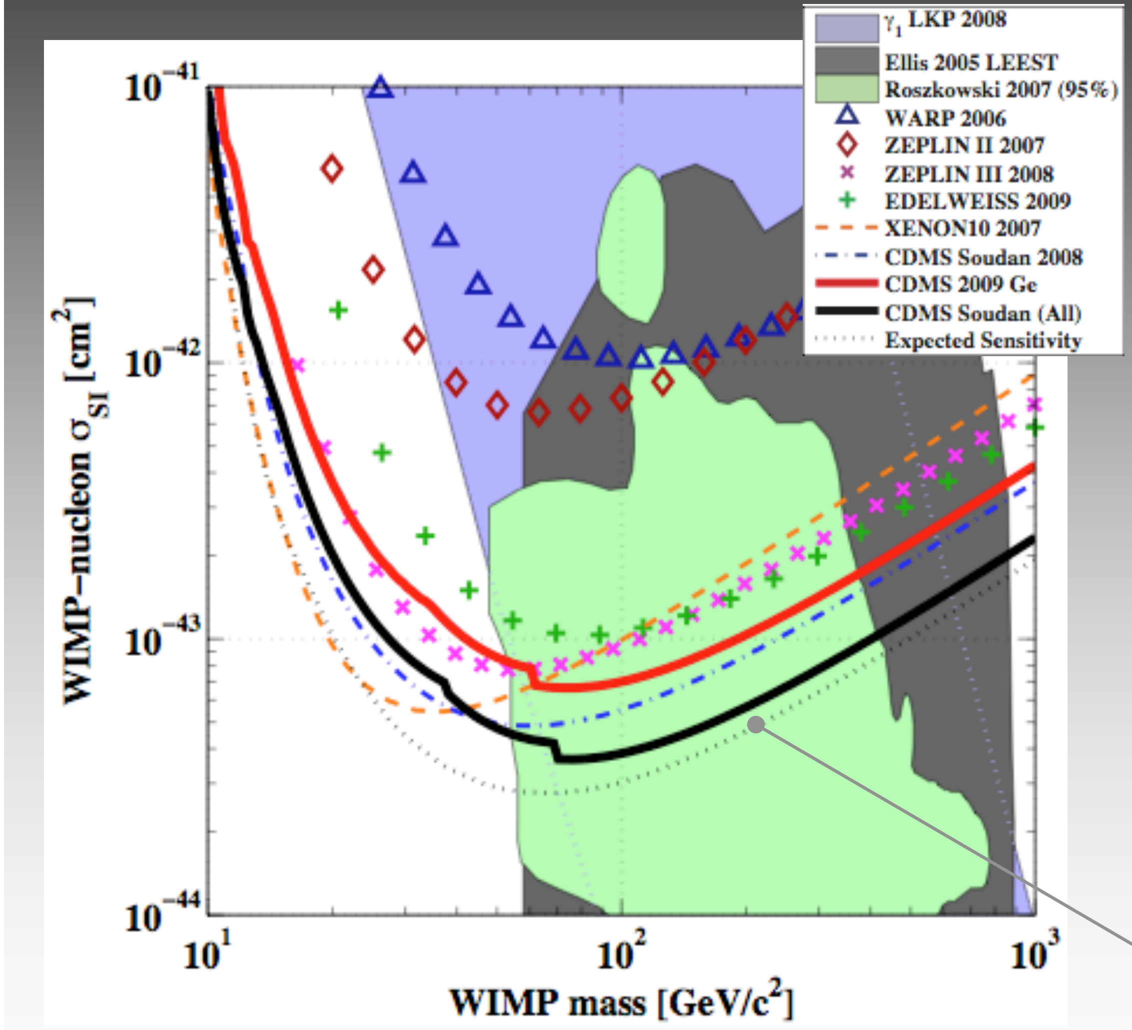
Final Exposure after all cuts: 194.1 kg-days

Unblinded Signal Region (194 kg-days)



expected background:
0.8±0.2(stat)±0.1(sys) surface events and 0.1 neutrons

90% C.L. Spin-Independent Limit



limit calculation: optimal interval method

exposure after all cuts:
194.1 kg-days

In the presence of 2 events (no background subtraction):

CDMS 2009
@WIMP mass 70 GeV
$\sigma = 7.0 \times 10^{-44}$ cm^2 (90% C.L.)

CDMS Combined Soudan Data
@WIMP mass 70 GeV
$\sigma = 3.8 \times 10^{-44}$ cm^2 (90% C.L.)

Sensitivity curve based on final background estimate

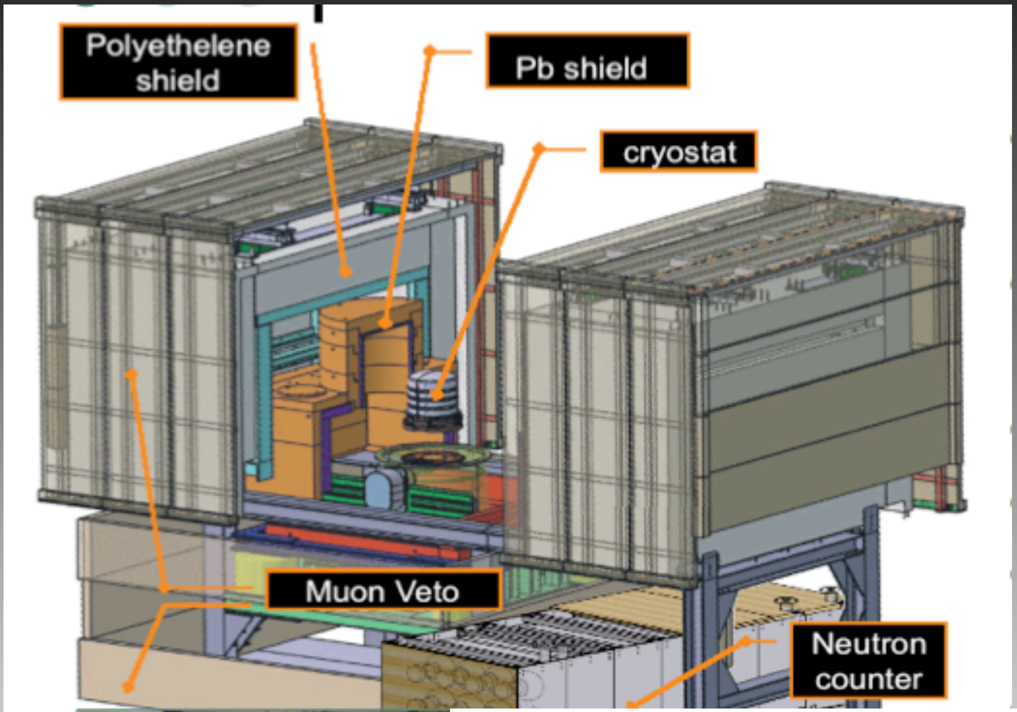
Edelweiss

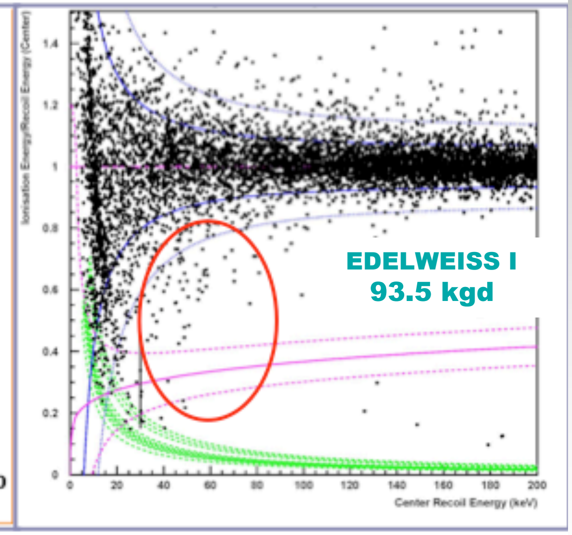
Expérience pour DEtecter Les WIMPs En Site Souterrain

- Located @ Laboratoire Souterrain de Modane (4800 mwe)
- Simultaneous measurement of ionization and heat (NTD)
- EDELWEISS I limited by surface event background

EDELWEISS II running 10x~400g Ge detectors since 2008

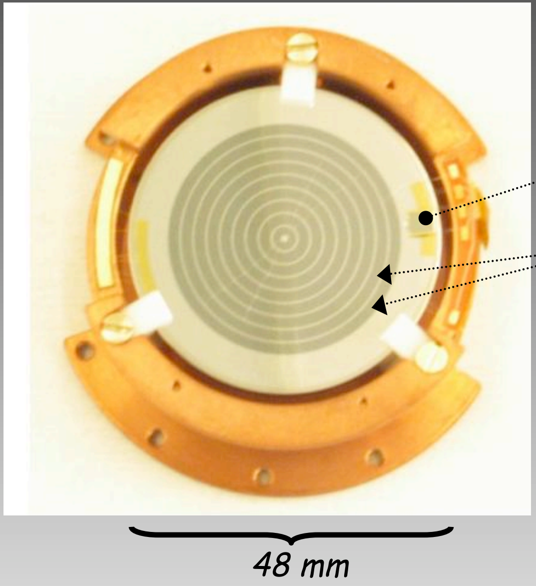
please see parallel session talk by Claudia Nones for more this afternoon





EDELWEISS I
93.5 kgd

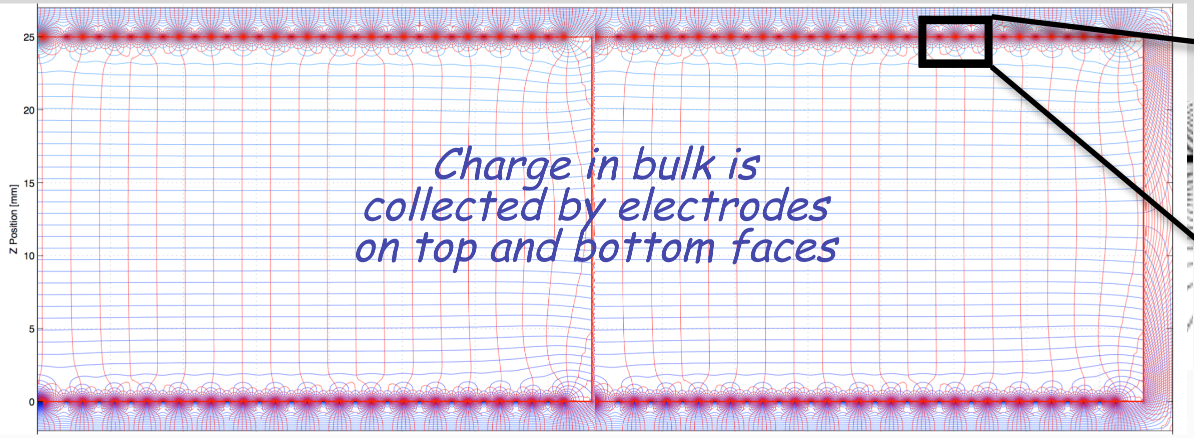
EDELWEISS II: Solving the Surface Event Problem



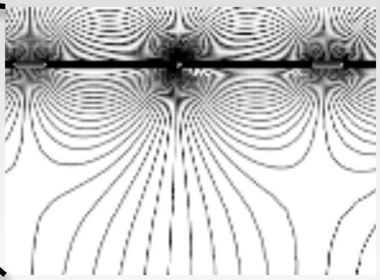
Interleavened Detectors (IDs):

- Keep the EDW-I NTD thermal detector
- Modify the E-field near the surfaces with interleaved electrodes
- First ID built 2007: *conceptual design by CDMS, working demonstration by EDELWEISS II*

1x200g + 3x400g tested in 2008
10x400g running since early 2009

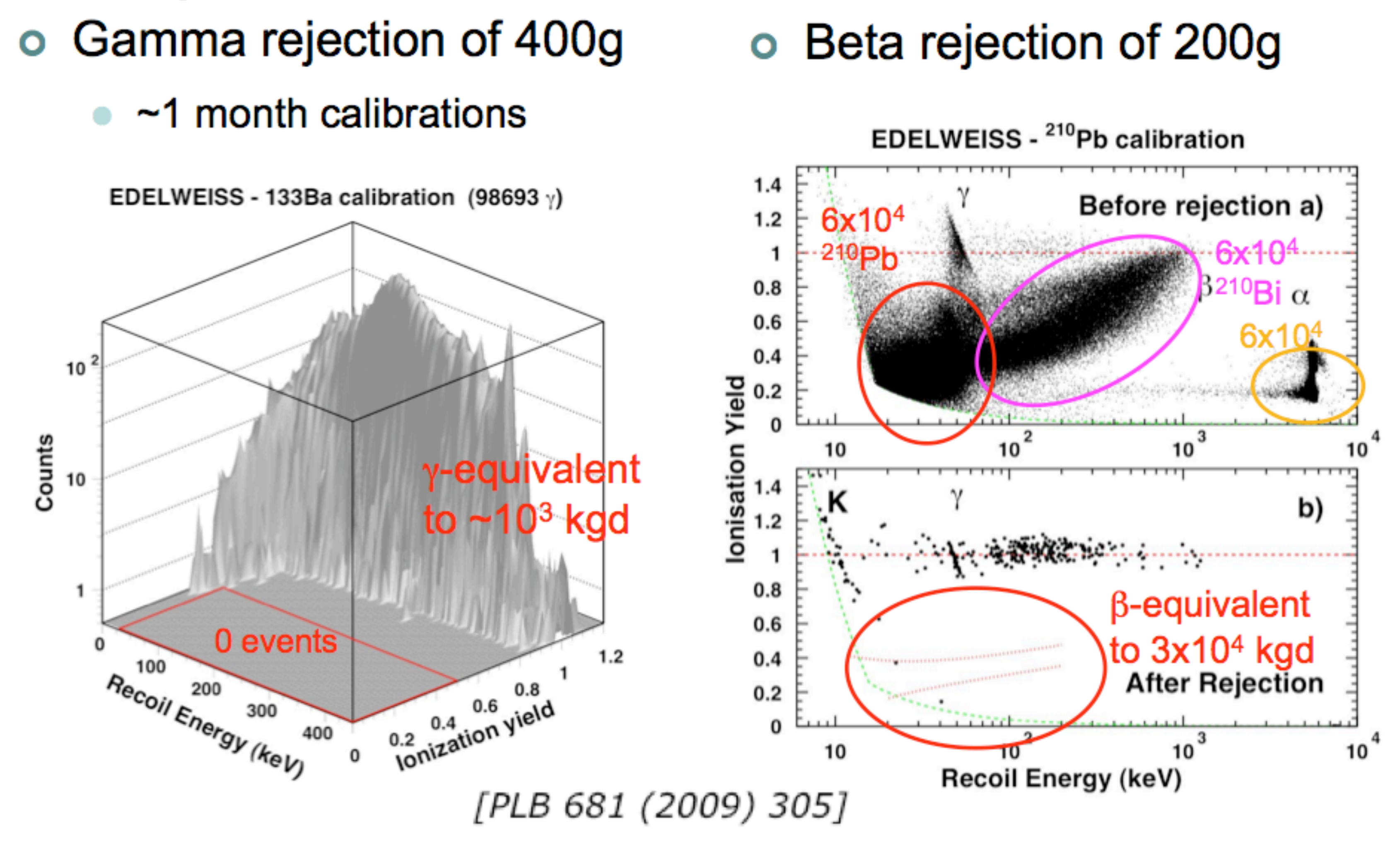


Charge in bulk is collected by electrodes on top and bottom faces



Charge near surface is collected by electrodes on only one side

EDELWEISS II: Background Rejection

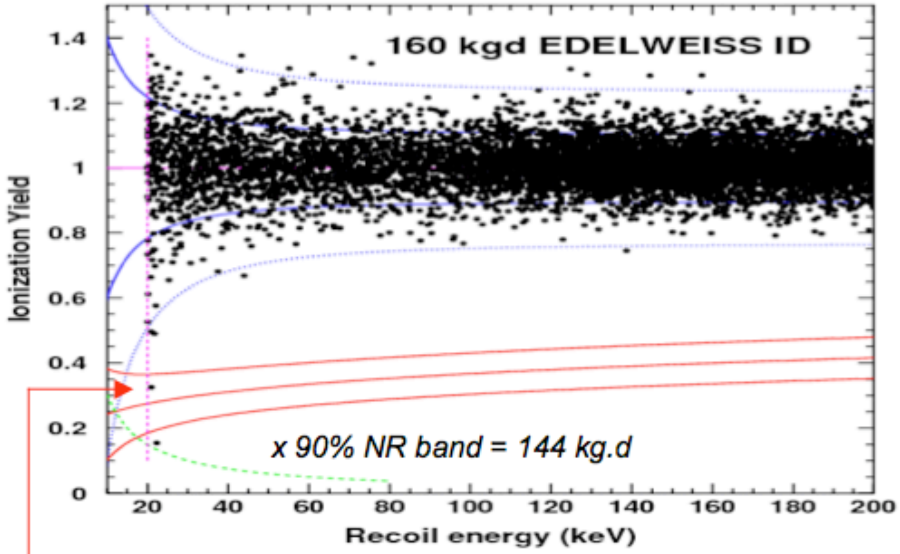


- Gamma rejection of 400g
  - ~1 month calibrations
- Beta rejection of 200g

[PLB 681 (2009) 305]

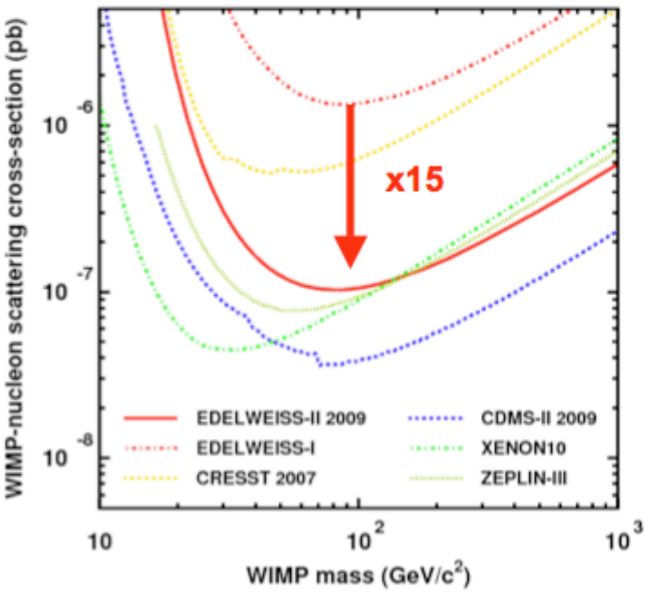
slide from: Moriond EW 2010
by S. Scorza

EDELWEISS-II First Results



« WIMP candidate »
Er = 21 keV

arXiv:0912.0805s



End of January:
~ x1.75 exposure,
Run continues
until spring

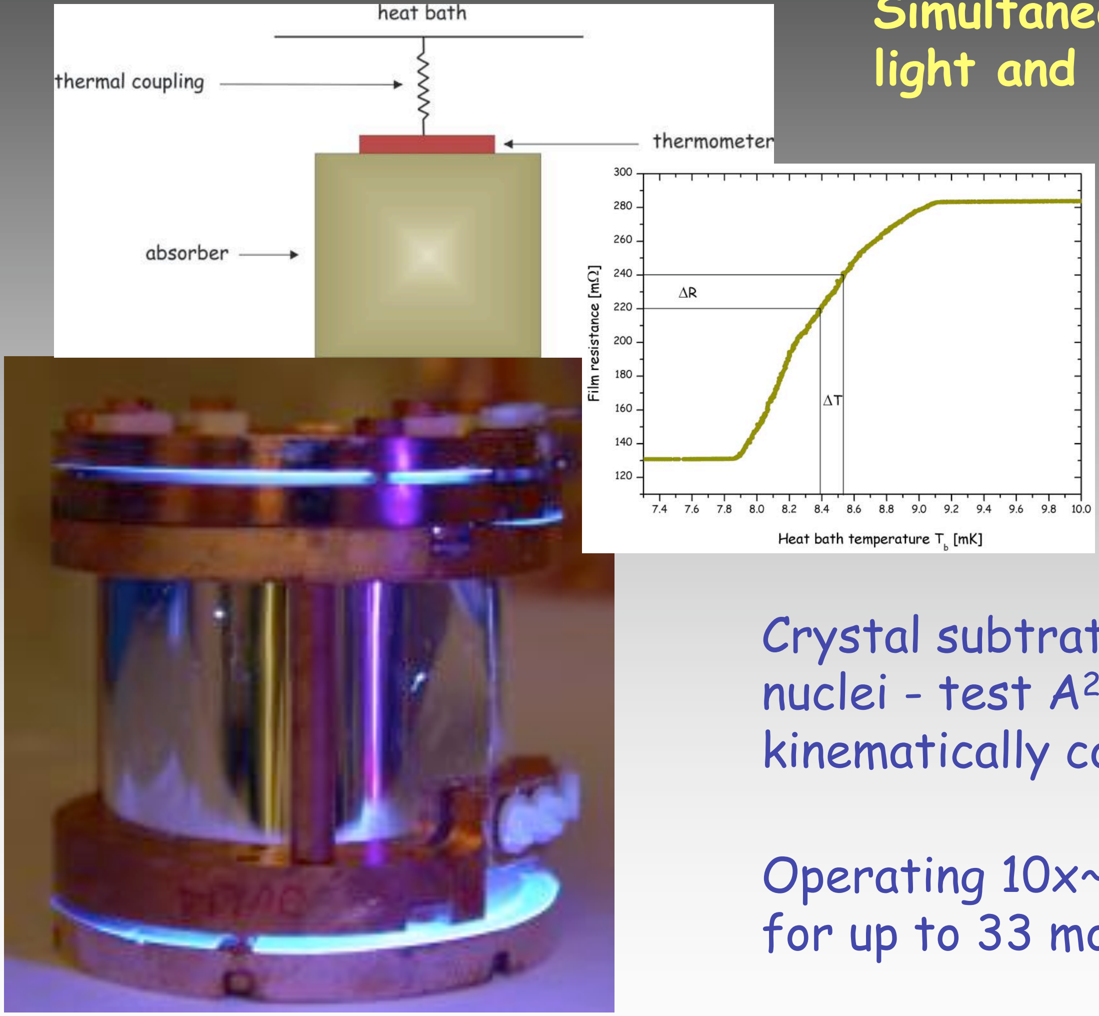
Background estimation from previous calibrations/simulations:

- gamma < 0.01 evt (99.99% rejection)
- beta ~ 0.06 evt (from ID201 calibration+obs. surf. evts)
- neutrons from ^{238}U in lead < 0.1 evt
- neutrons from ^{238}U+(α,n) in rock ~ 0.03 evt
- neutrons from muons < 0.04 evt

} < 0.23 evt

slide from: Moriond EW 2010
by S. Scorza

CRESST II



Simultaneous detection of scintillation light and phonons in $CaWO_4$ crystal

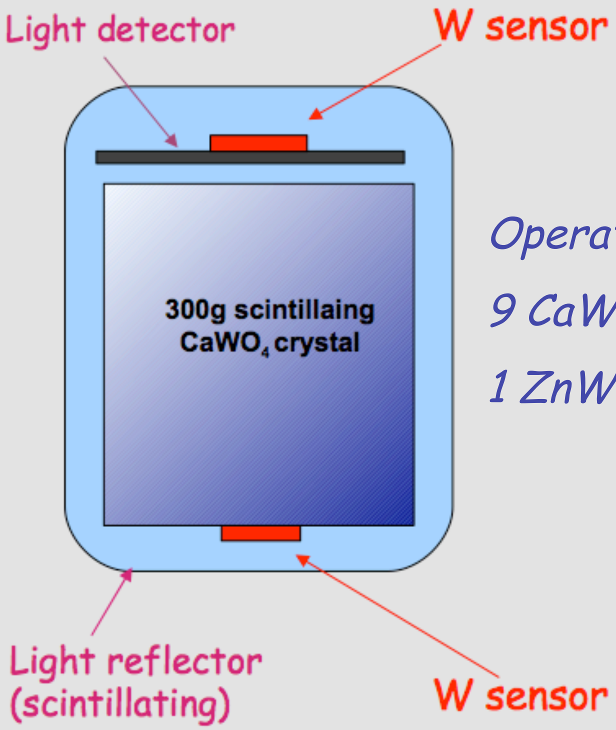
phonon and scintillation detection w/ TES sensors

Crystal subtrate provides multiple target nuclei - test A^2 dependence of σ and kinematically constrain m_χ

Operating 10x~300 g in LNGS with plans for up to 33 modules

Operating Principle

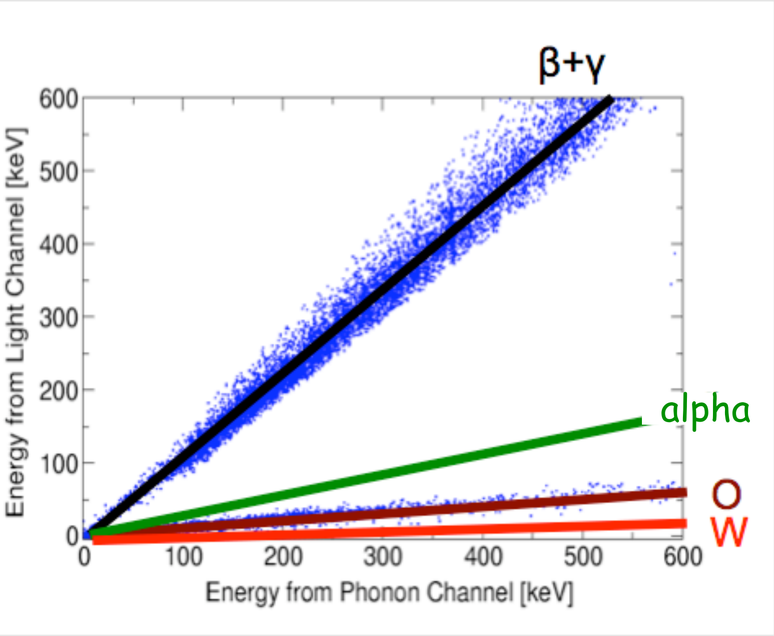
Discrimination of nuclear recoils from radioactive backgrounds by simultaneous measurement of phonons and scintillation light



Operating:

9 $CaWO_4$

1 $ZnWO_4$



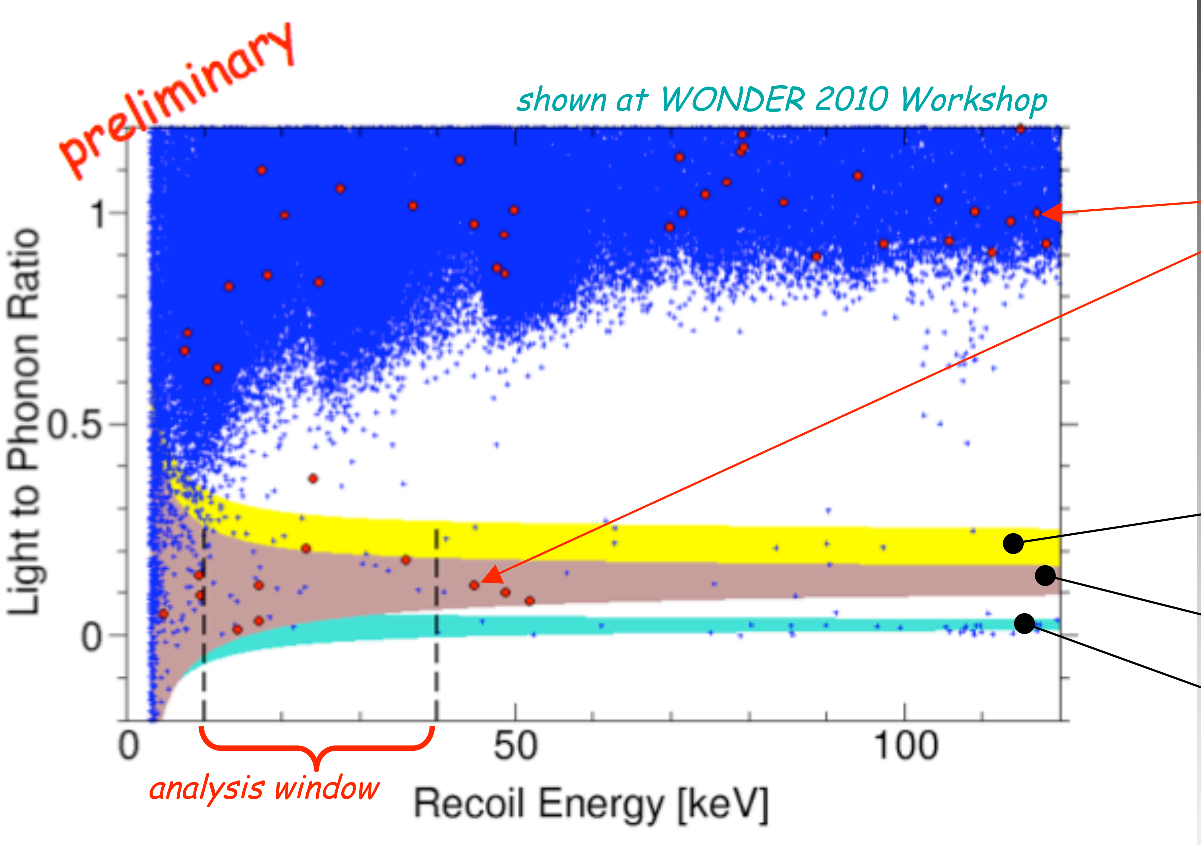
Not only discriminate between nuclear and electron recoils, but also between nuclear recoils of oxygen and tungsten

Recent Progress

- running since summer 2009
- 10 x 300 g detectors running
- Clamps not covered with scintillator
  (worsens background rate from alphas)
- data analysis is still in progress
- recent neutron calibration

Preliminary results on ~300 kg-days (9 $CaWO_4$ detectors) shown recently - stay tuned for more in upcoming summer conferences

Peeking at CRESST Data



Red dots = events in coincidence w/ muon veto

Alpha background band

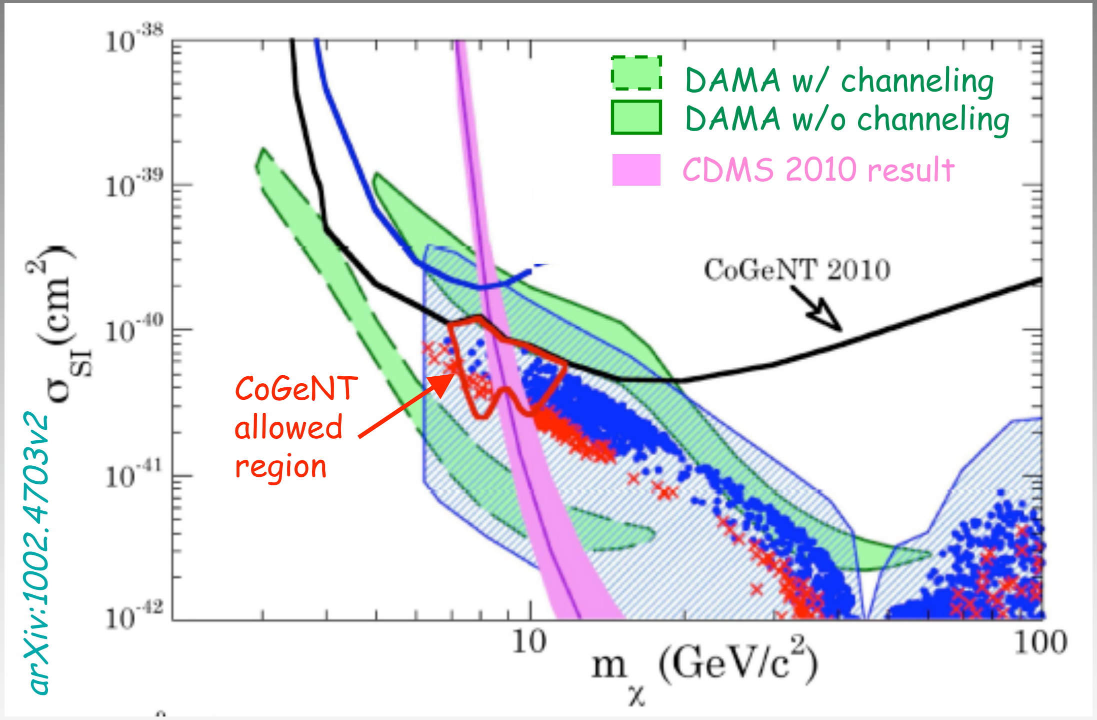
O-recoil band

W-recoil band

- Hint of anomolously high rate of events in the O-band (low-mass WIMP recoil region).
- More data currently being analyzed w/ neutron calibrations

Interesting Time for Low Mass WIMPs

CoGeNT data offered some tantalizing hints this year, BUT ….



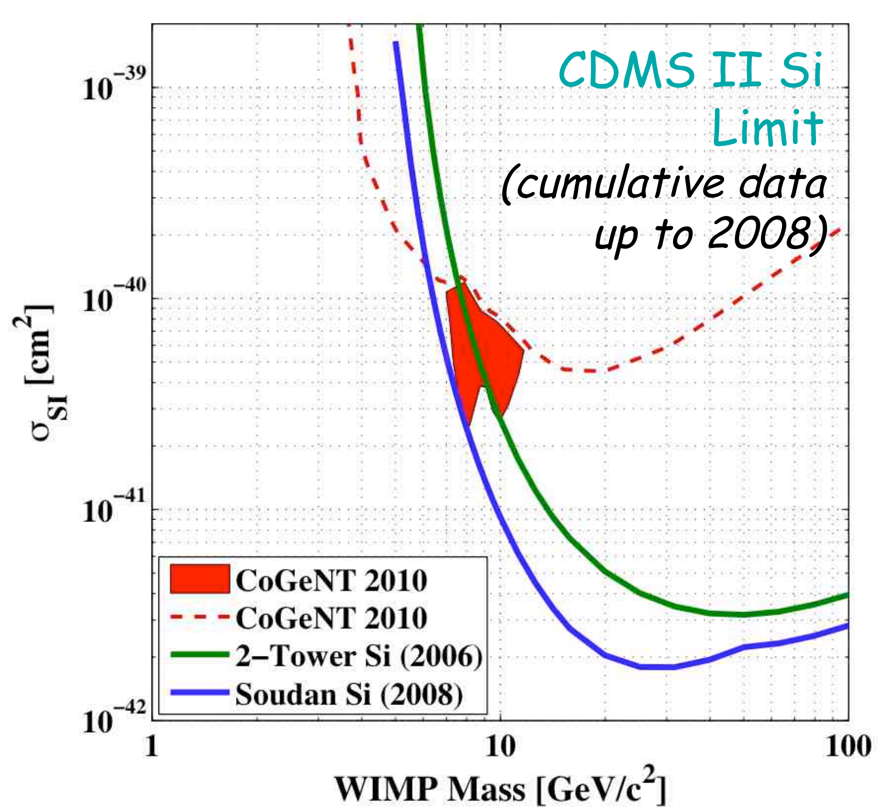
CoGeNT allowed region

arXiv:1002.4703v2

no strong overlap w/ DAMA preferred region (unchanneled)

CDMS and XENON100 See Nothing So Far

BUT how to interpret uncertainties in CDMS Si energy scale and controversy persists over XENON L_{eff} …

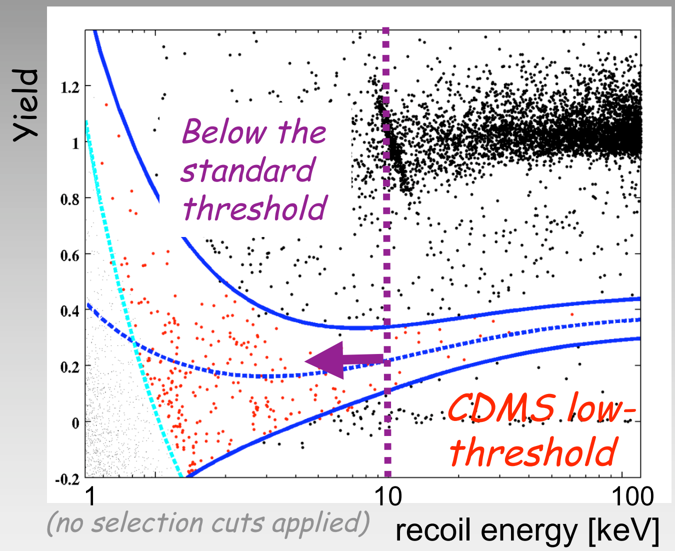


CDMS II Si Limit

(cumulative data up to 2008)

Nuovo Cim.032C:45-52,2009

CDMS (Ge and Si) analysis can be extended to lower thresholds by allowing some additional background



Below the standard threshold

CDMS low-threshold

(no selection cuts applied)

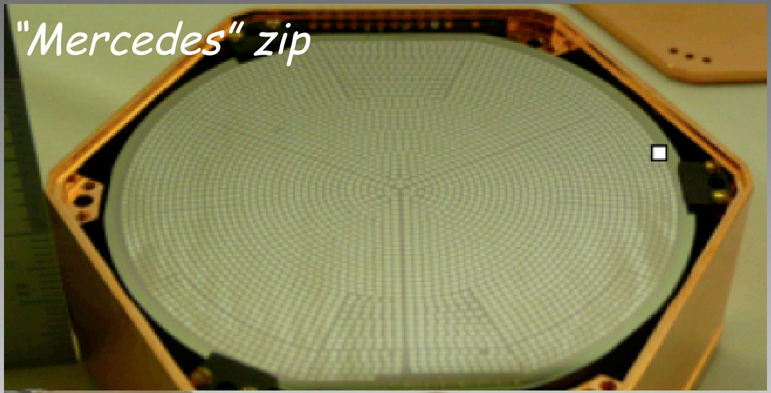
Data from CDMS and CRESST will say more soon - stay tuned!

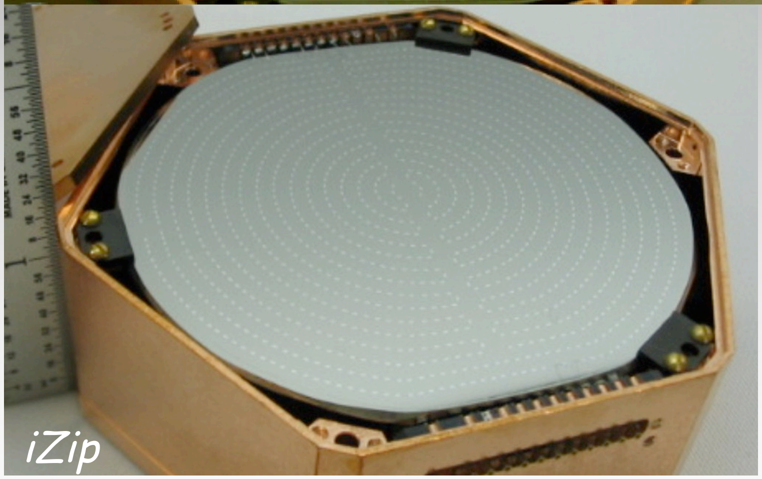
** for a novel technique to detect low mass WIMPs - see Juan Estrada's talk this afternoon*

Future Endeavors

SuperCDMS at Soudan

5 SuperTowers of Ge detectors


"Mercedes" zip


iZip

1-inch thick detectors, 2 designs:

- *Mercedes: older design, 1 ST in operation since June '09, 1 more ready for deployment*
- *iZip: 10X better surface event rejection, better design for the long term*

2.5X thicker (1-inch) Ge crystals

iZIPs for SNOLAB and GeODM

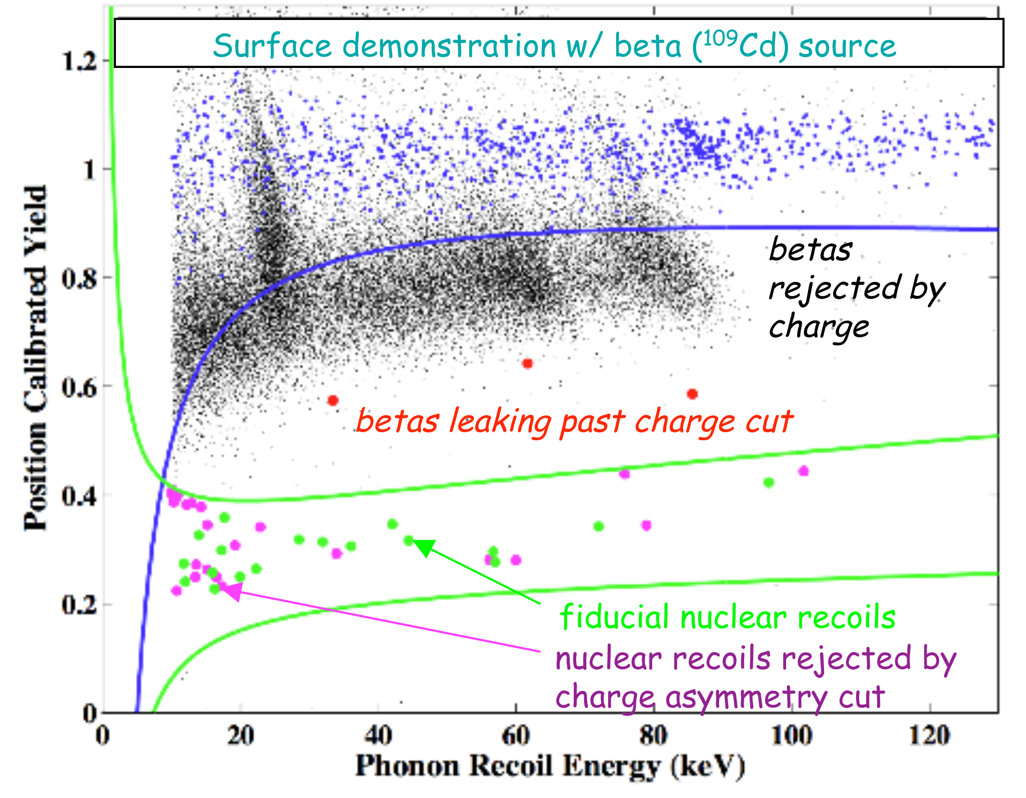
iZIP = interleavened charge and phonon channels
(similar principle to EDELWEISS II detectors)

Based on above-ground testing:

1/1000 rejection of surface events based only on charge symmetry cut (excludes yield and phonon timing)

- full rejection of surface events at least X30 better than CDMSII (!)

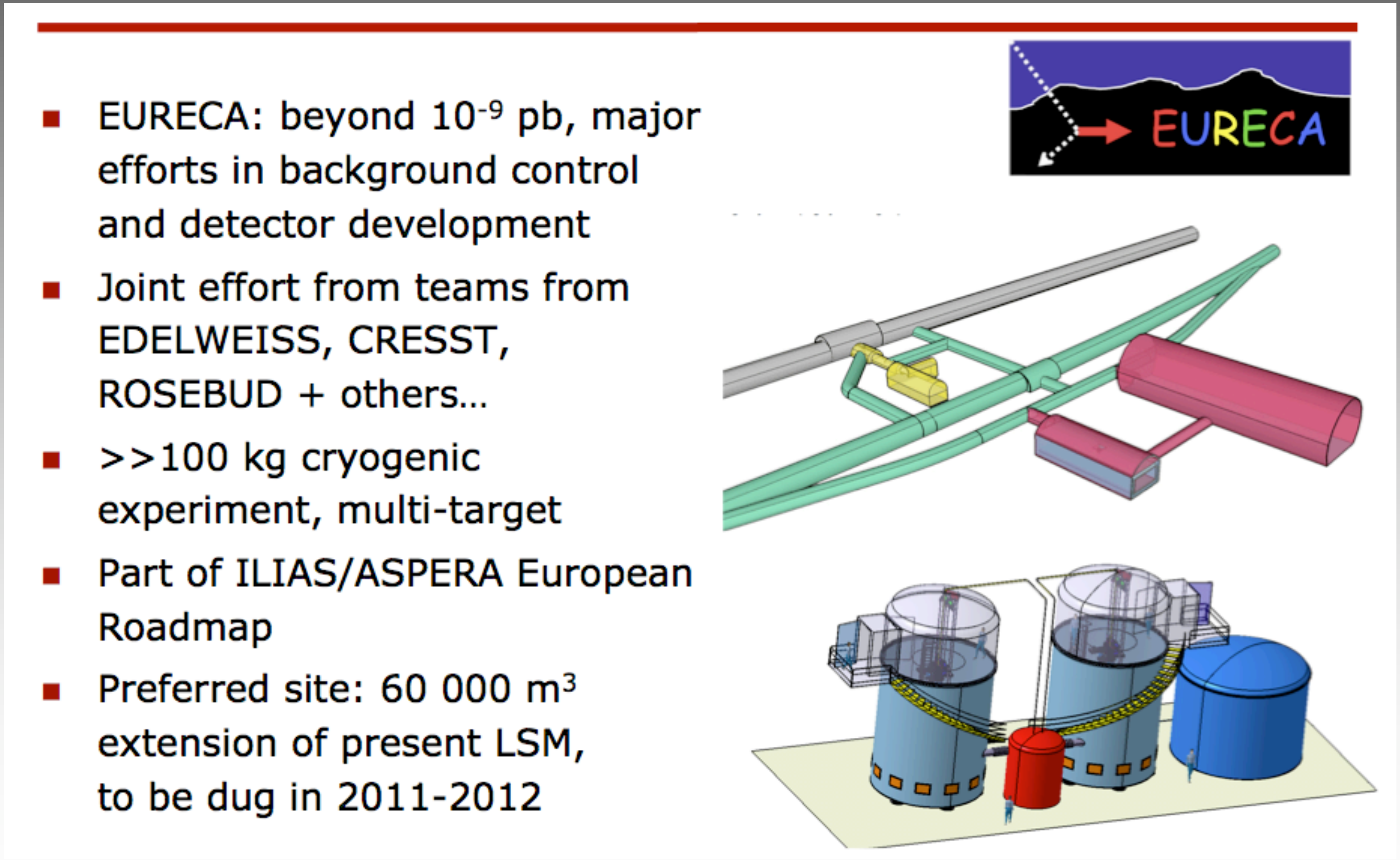
- better efficiency for nuclear recoil selection (~55%)



Backround rejection looks good enough for 100-kg Ge at SNOLAB … and even a ton-scale experiment! (GeODM)

United European Cryogenic Effort: EURECA

multiple target materials, combined effort to reach multi 100kg scale



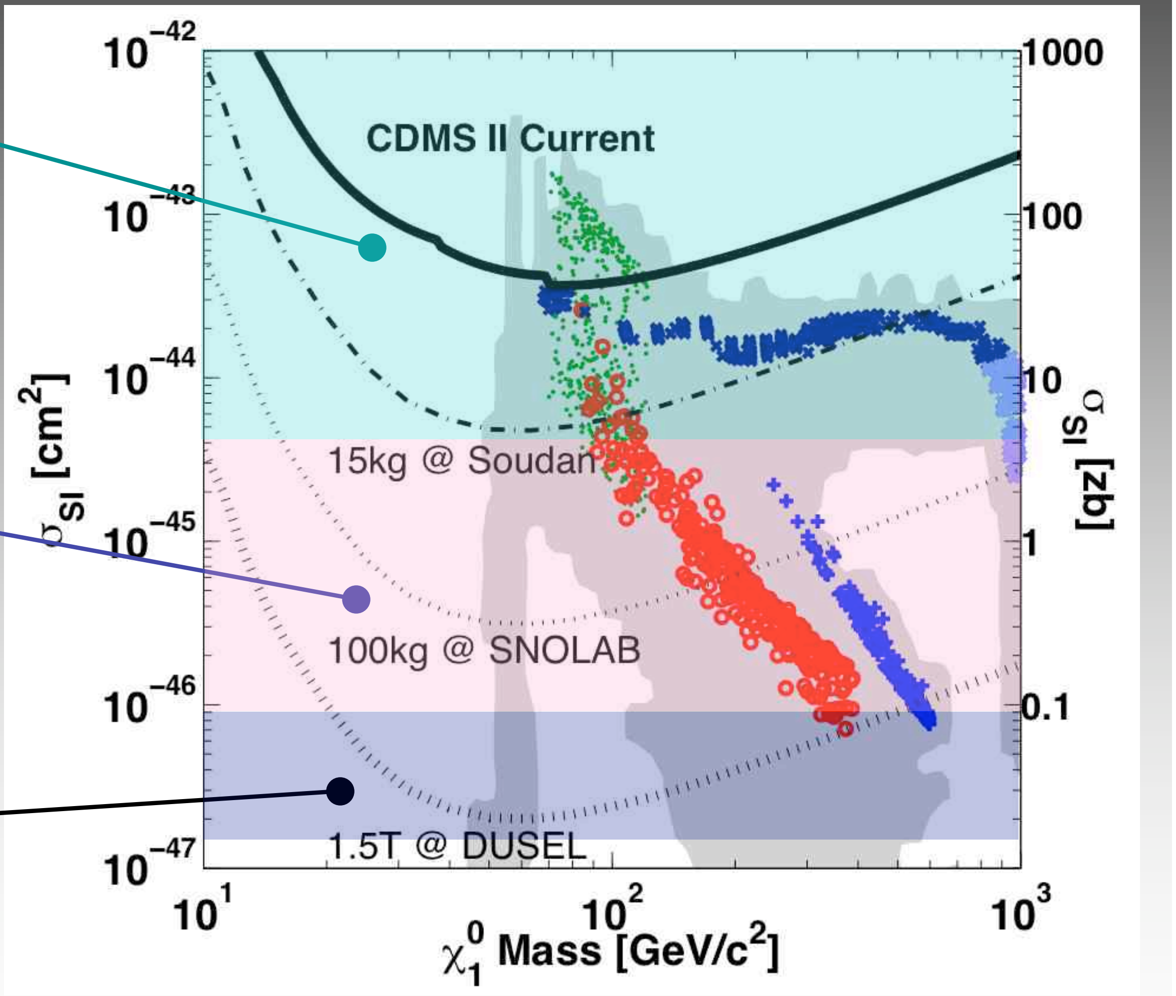
- EURECA: beyond 10^{-9} pb, major efforts in background control and detector development
- Joint effort from teams from EDELWEISS, CRESST, ROSEBUD + others…
- >>100 kg cryogenic experiment, multi-target
- Part of ILIAS/ASPERA European Roadmap
- Preferred site: 60 000 m^3 extension of present LSM, to be dug in 2011-2012

Outlook for Cryogenic Experiments

Region explored by current generation of experiments

100-kg scale
Cryogenic Experiments
SuperCDMS@SNOLAB
EURECA

ton-scale
Cryogenic Experiment
DUSEL/GEODM



Conclusion

Cryogenic dark matter searches are a world-leading technique !

- Superior control of backgrounds - provides event-by-event discrimination - CDMS and EDELWEISS yield expected background rates < 1 event
- Excellent understanding of backgrounds - well characterized with calibration data, precise predictions of expected background made.
- Excellent energy resolution - precisely measure the recoil energy
- Natural implementation of multiple target nuclei (Ca, W, O, Si, Ge)
- Demonstrated rejection factors will work for experiments at the 100kg (EURECA/SuperCDMS@SNOLAB) and even ton-scale level (GeODM)

stay tuned for upcoming results from these experiments!

Thank You!

backup slides

(Ultra) Low Threshold Analysis: CDMSLITE

Luke et al. NIM **A289**, 406 (1990)

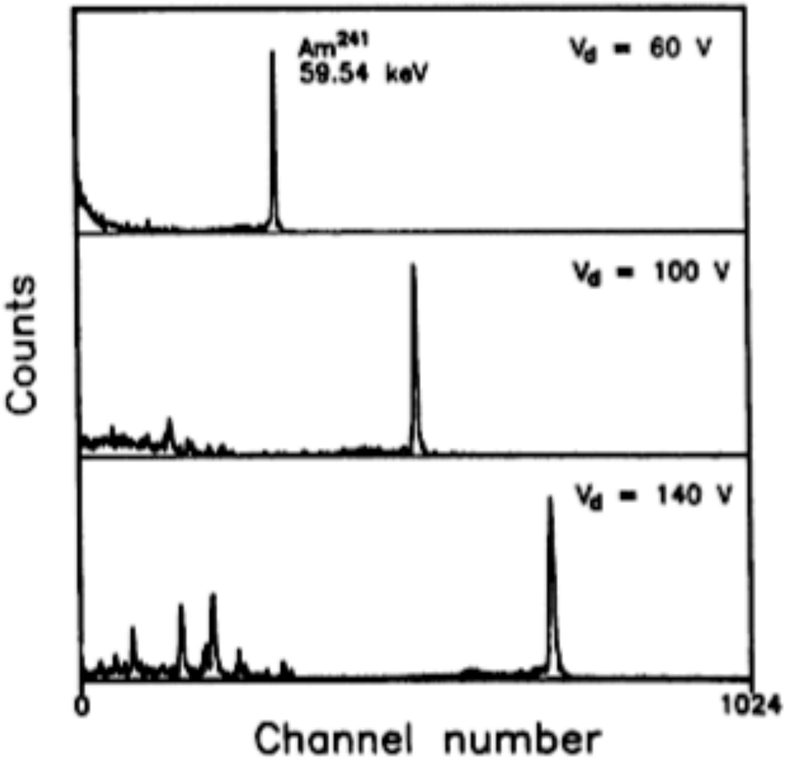
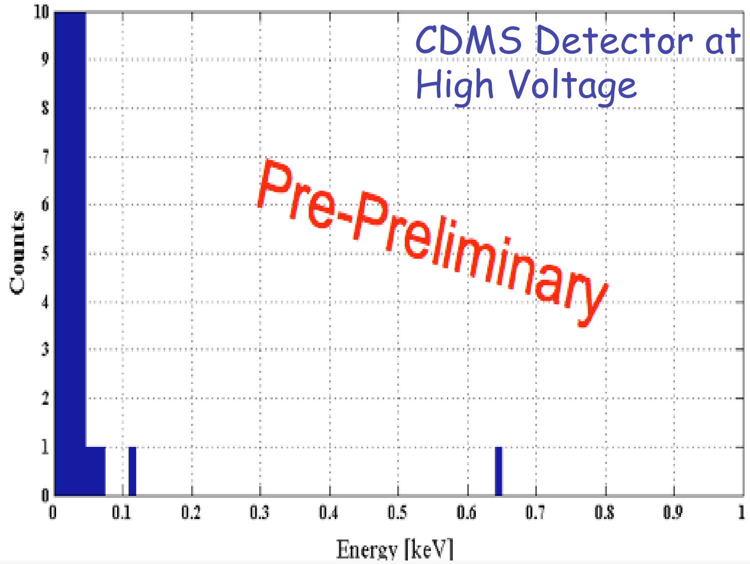


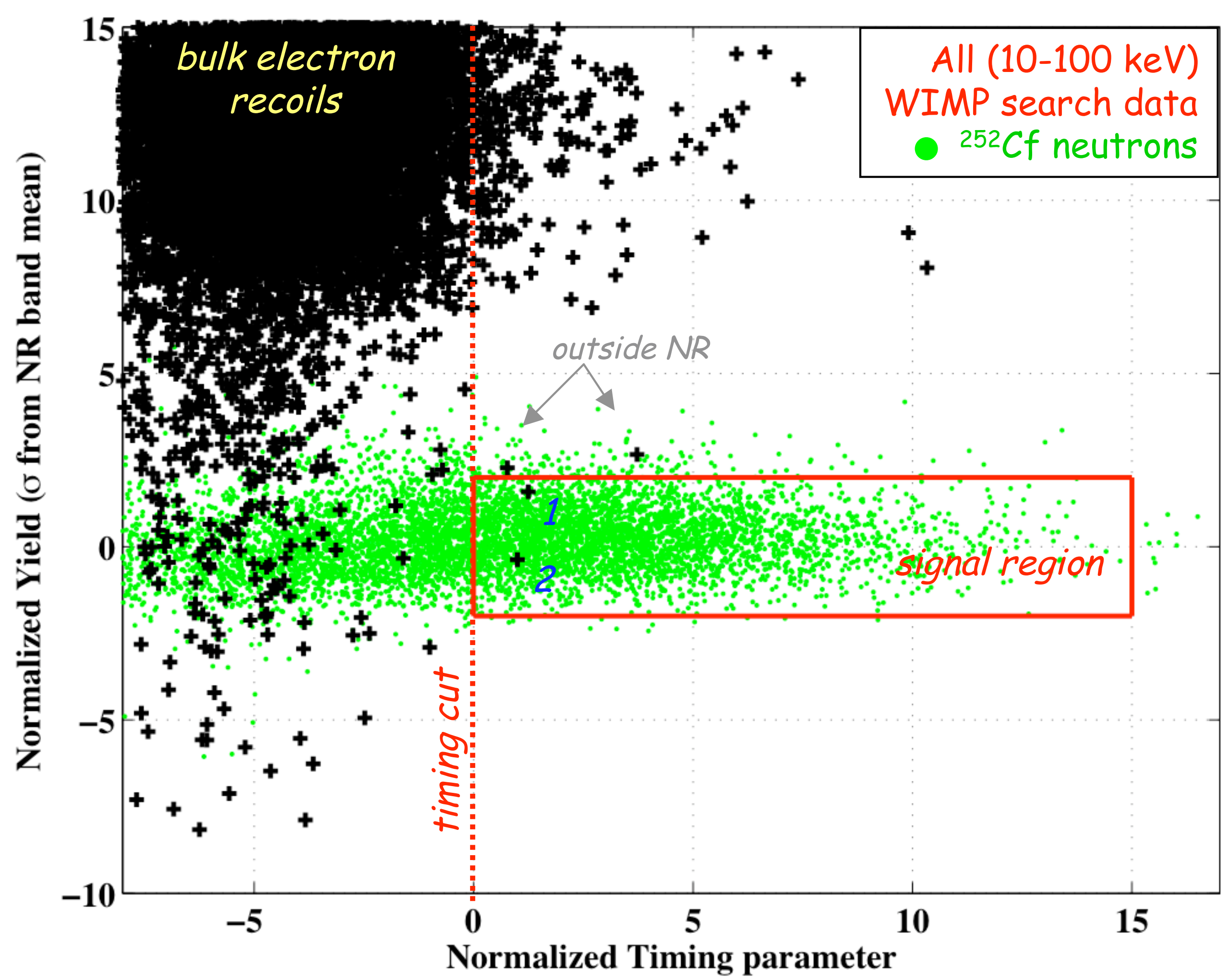
Fig. 3. Spectra obtained using an ^{241}Am gamma-ray source at different diode voltages.

Negonov-Luke amplification of phonon response allows CDMS detectors to operate with a lower energy threshold



Jeter Hall

Alternate View w/ Timing w/ Calibration Data



Yield vs Timing Det-By-Det

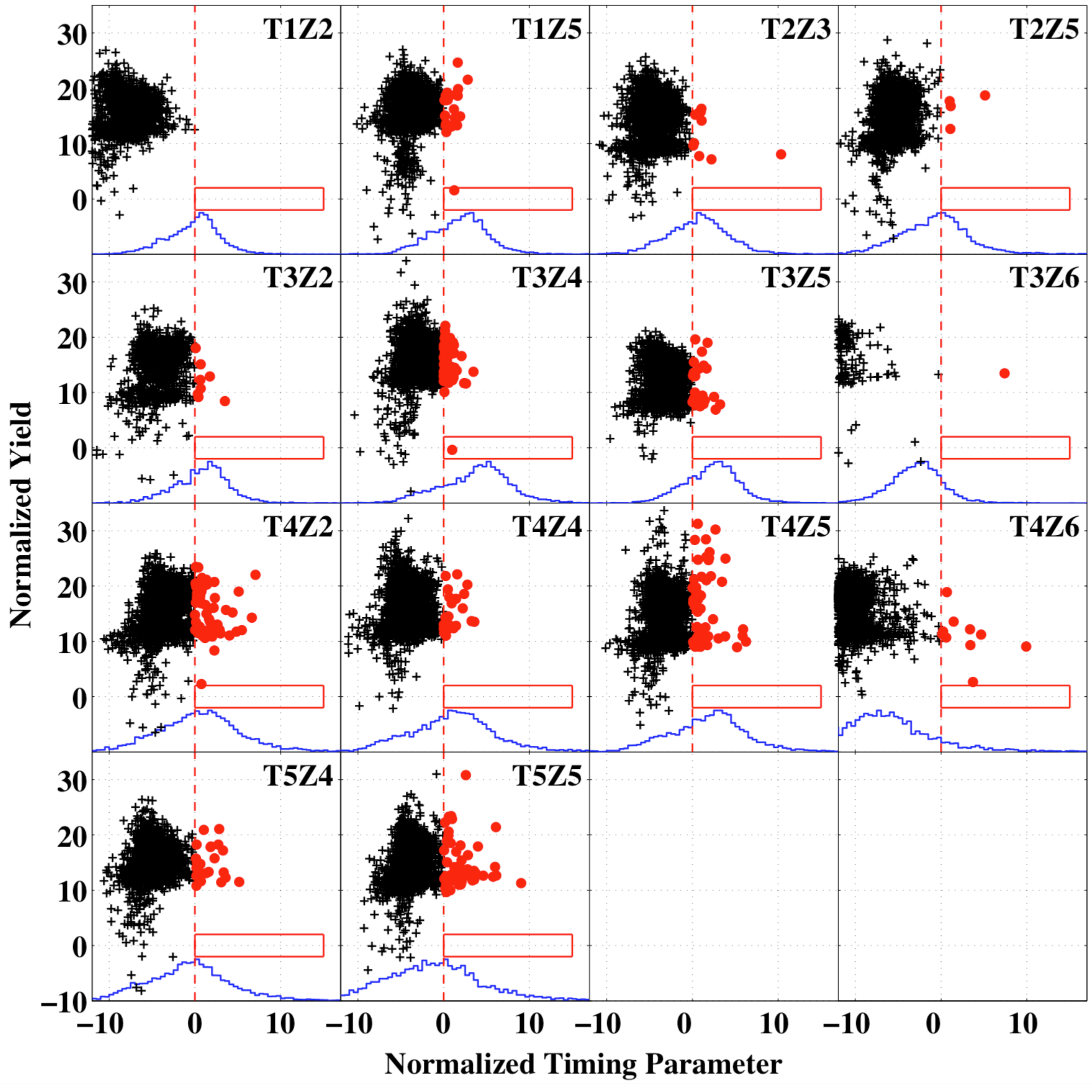
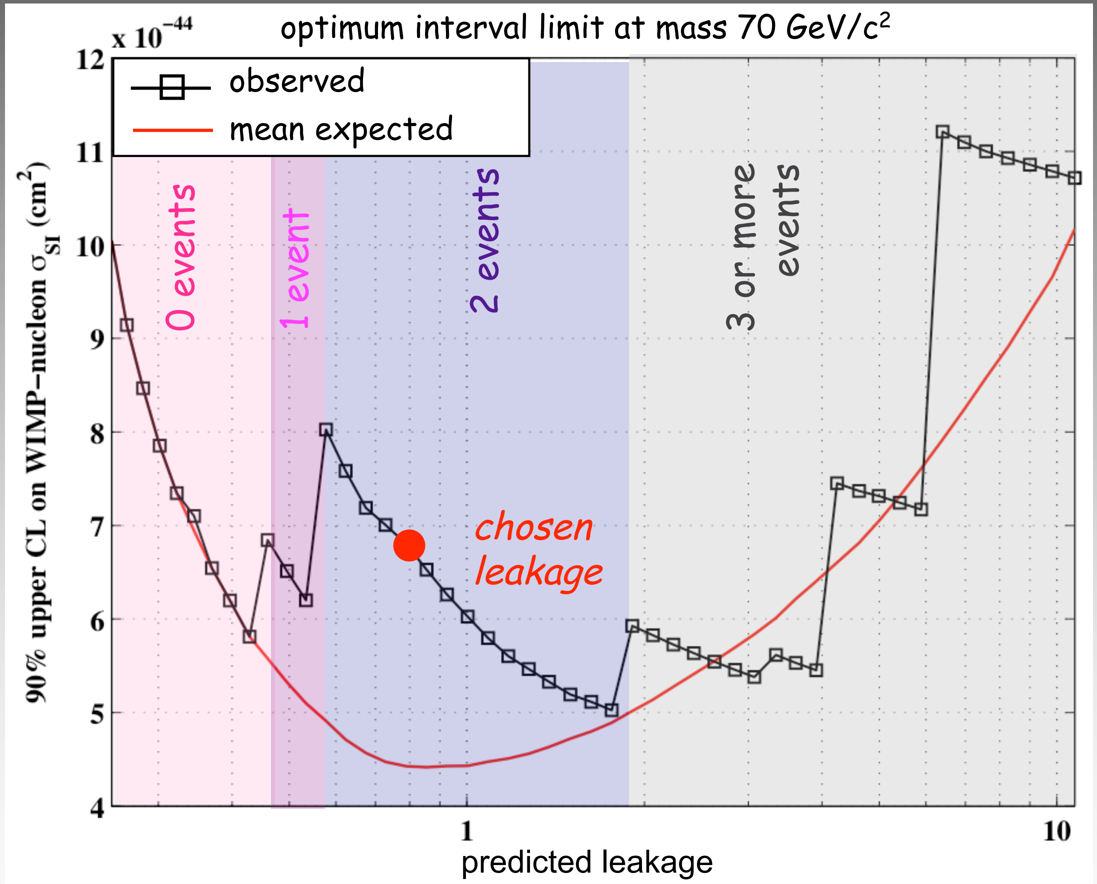


Figure available in supporting online material for Science paper:

http://www.sciencemag.org/cgi/content/full/science.1186112/DC1

What if we had chosen a different cut value?

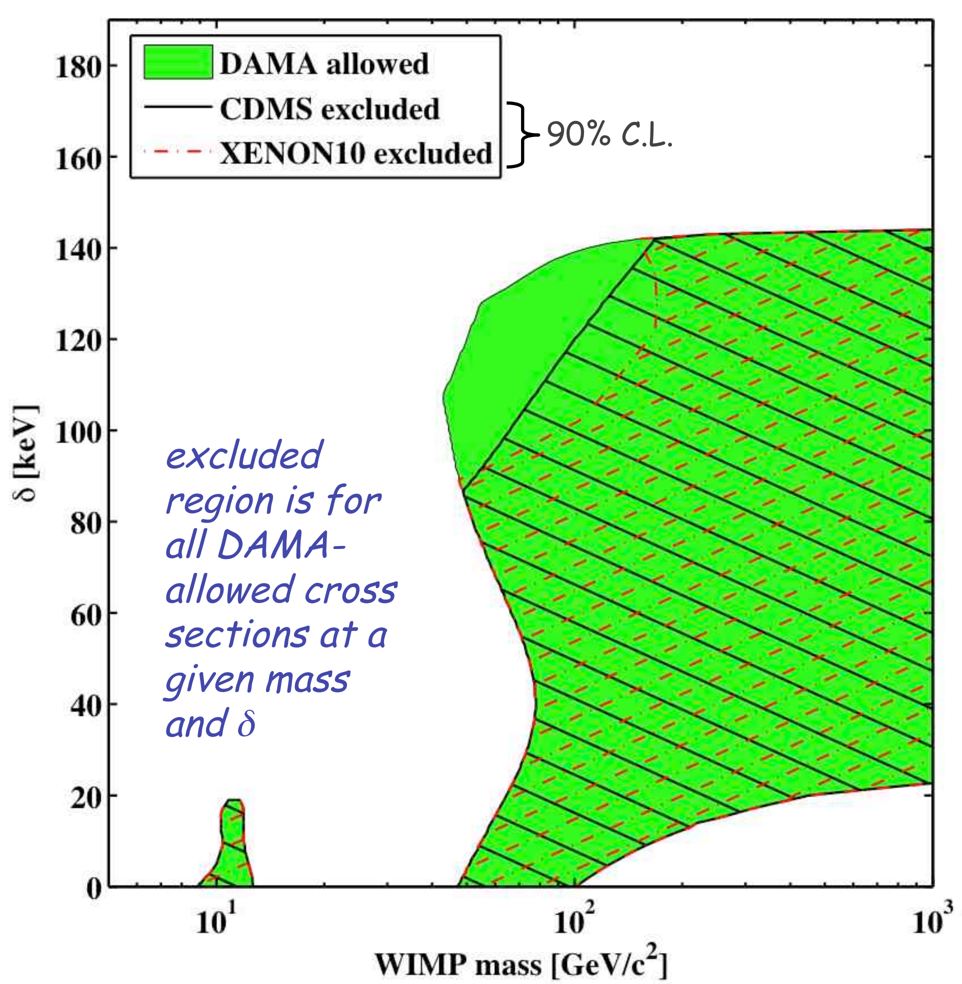


Tightening the cut to yield ~1/2 the expected surface events, removes both events from the signal region and reduces the exposure by ~28%

Additional events appear in the signal region after loosening the cut to ~2X the expected leakage

The observed limit doesn't depend strongly on chosen surface-event rejection cut value

CDMSII - Inelastic Dark Matter



90% C.L.

excluded region is for all DAMA-allowed cross sections at a given mass and δ

channeling not considered here

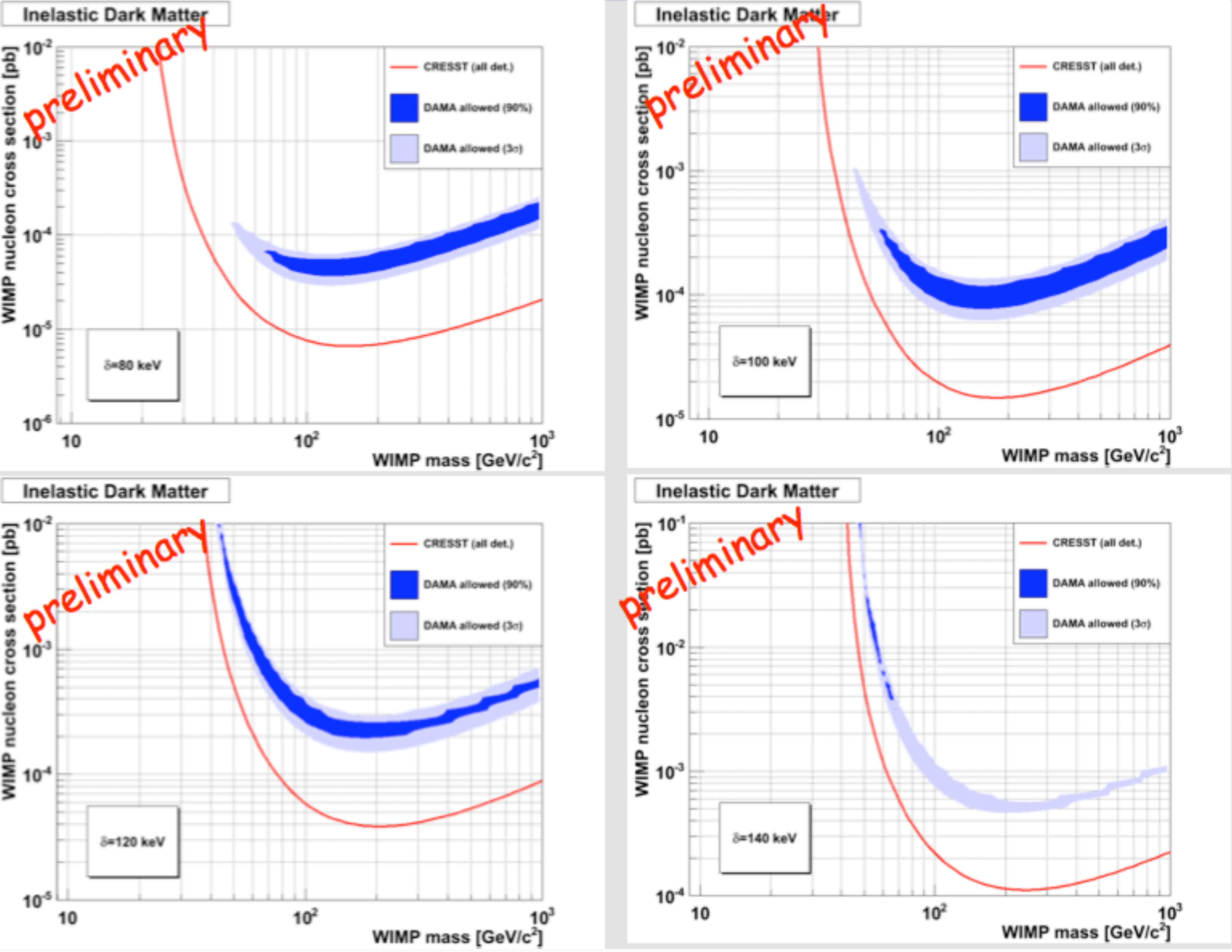
Has been invoked by Weiner et al. to explain DAMA/LIBRA data, among other things.
[Phys. Rev. D 64, 043502 (2001)]

Scattering occurs via transition of WIMP to excited state (with mass splitting δ)

spectrum peaks at higher recoil energies

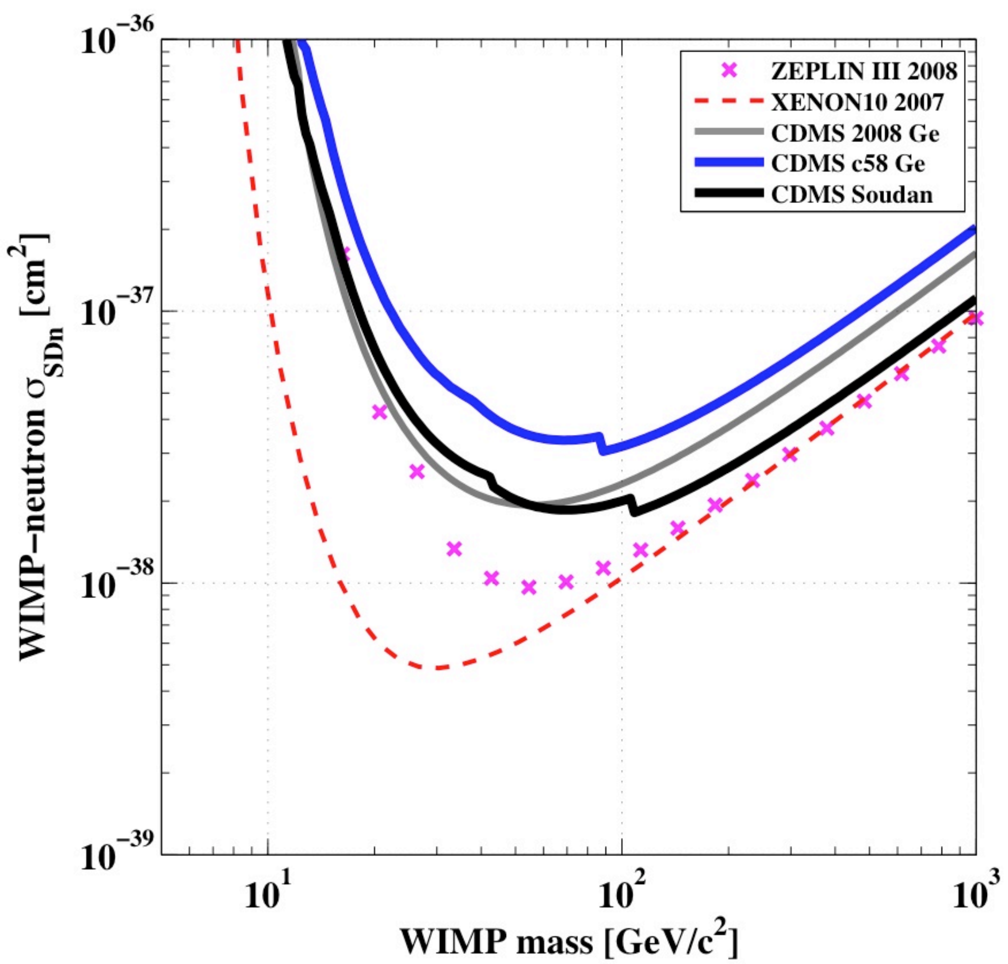
DAMA, allowed regions (at 90% C.L.) computed from χ^2 goodness-of-fit and standard truncated halo-model [JCAP 04 (2009) 010]

CRESST II: Inelastic DM Limits

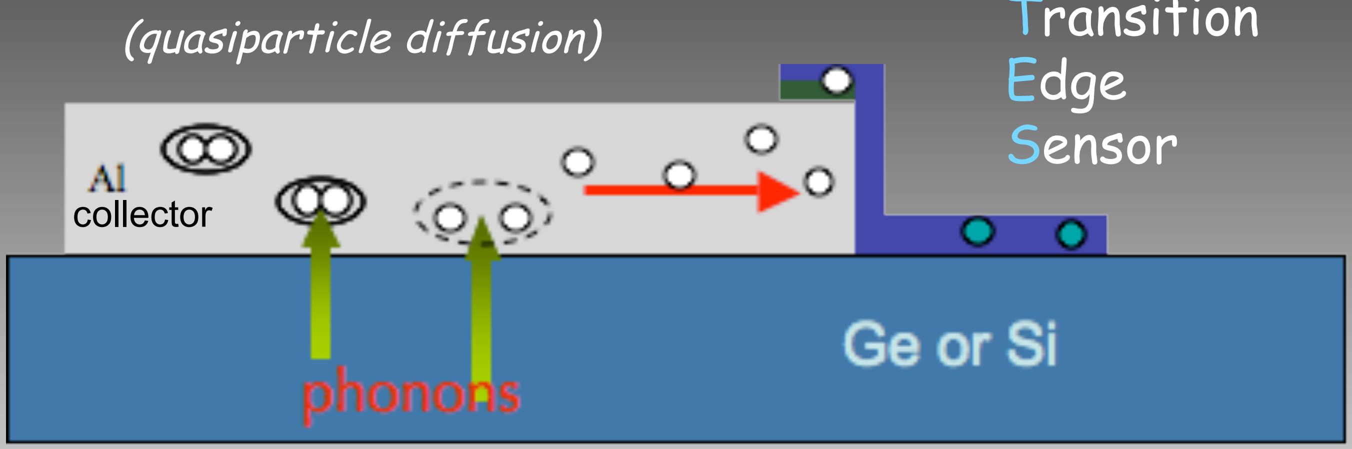


Deduced from full W-band

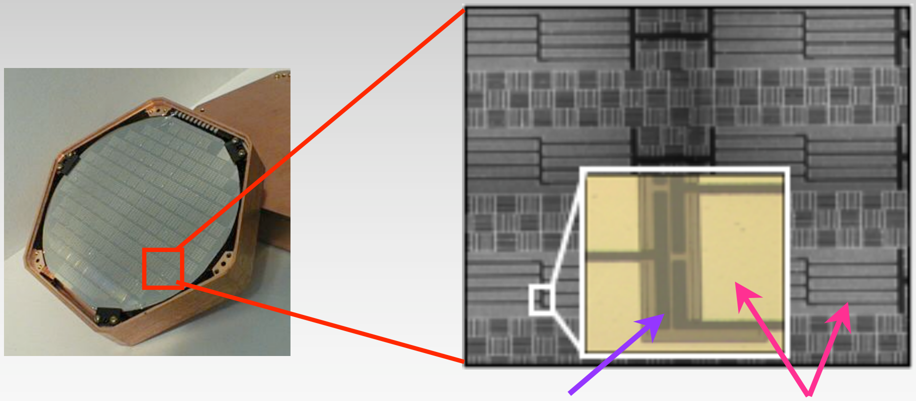
CDMSII 90% C.L. Spin-Dependent Limit

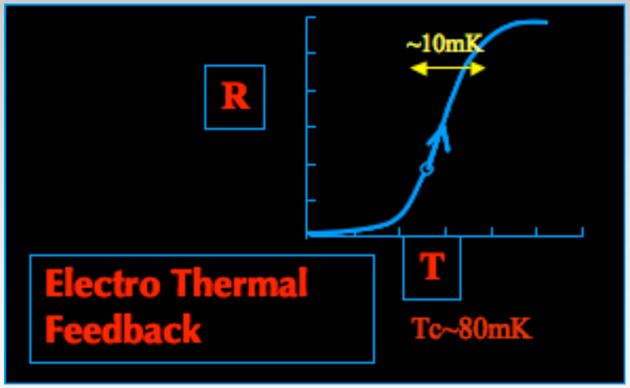


Phonon Detection



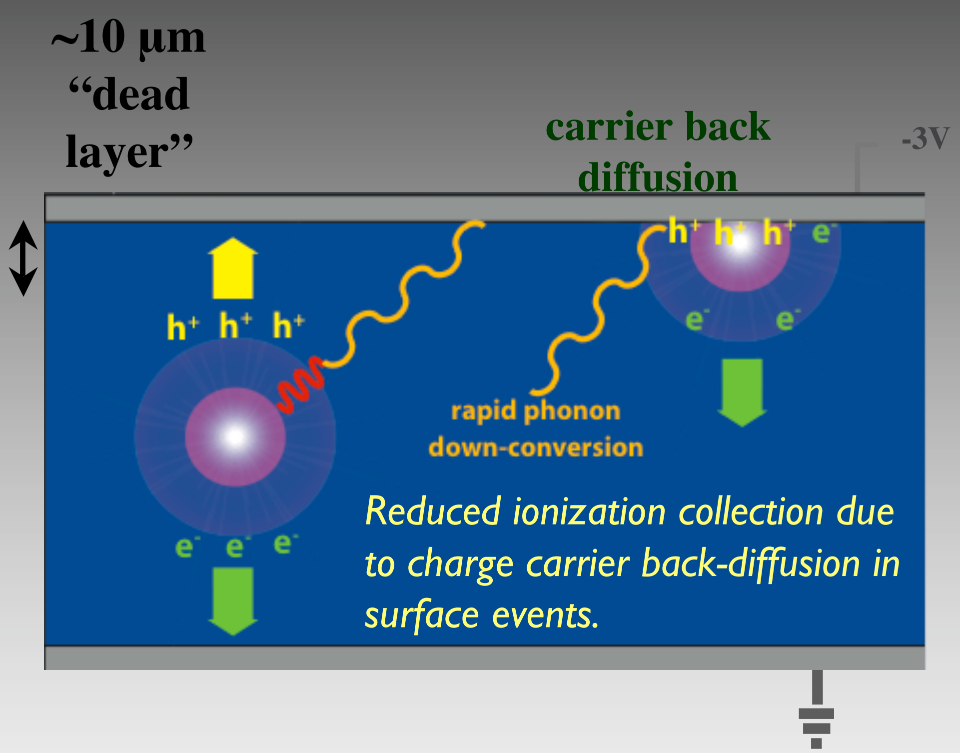
Transition
Edge
Sensor



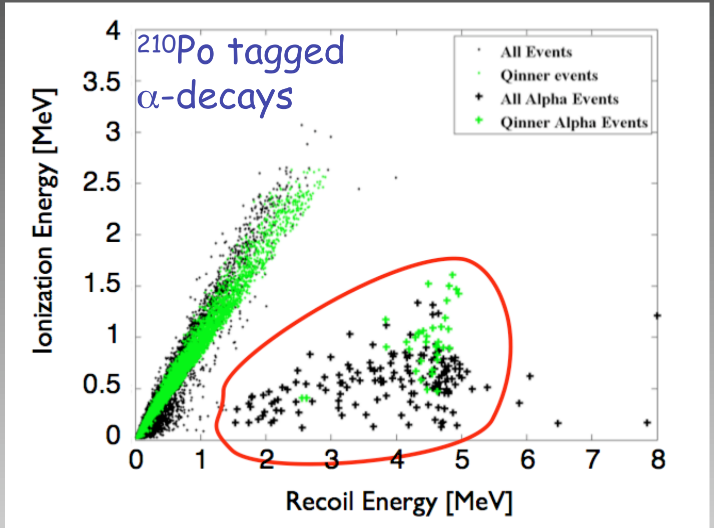


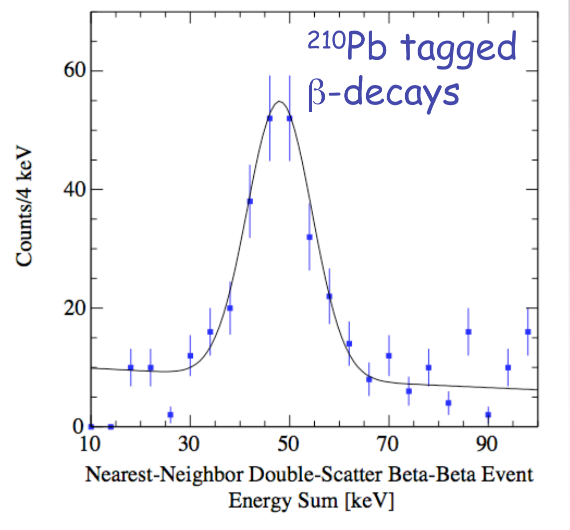
each of 4 phonon channels reads out 1036 TES in parallel

What are Surface Events?



Reduced ionization collection due to charge carrier back-diffusion in surface events.





These events are primarily electrons, and soft x-rays originating from surfaces of the detectors and surrounding materials

Correlations to ^{222}Rn daughter contamination observed

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