Direct Dark Matter Searches

Context

Elastic scattering rates

Detection principle: signal and backgrounds

Review of current experiments

J. Gascon

UCB Lyon 1, CNRS/IN2P3/IPNL

Recommended surfing + browsing

- IDM2012 conference slides

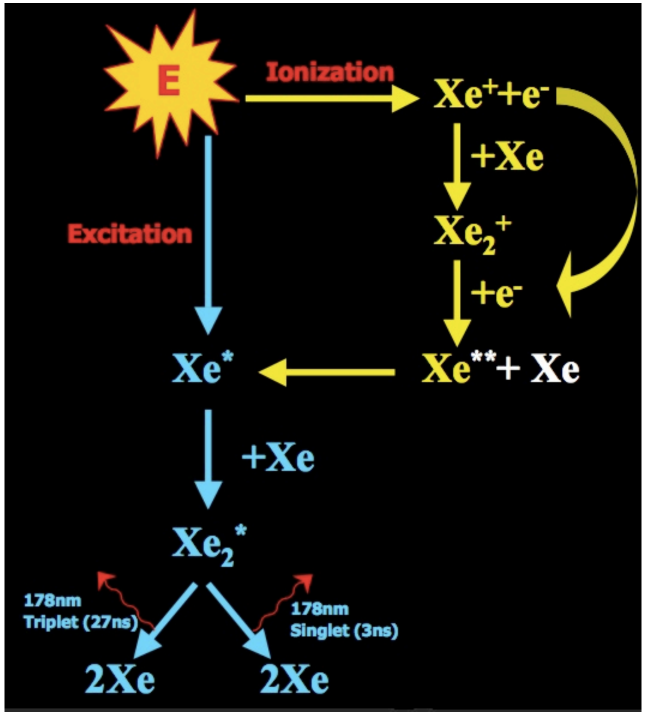
  https://hepconf.physics.ucla.edu/dm12/agenda.html

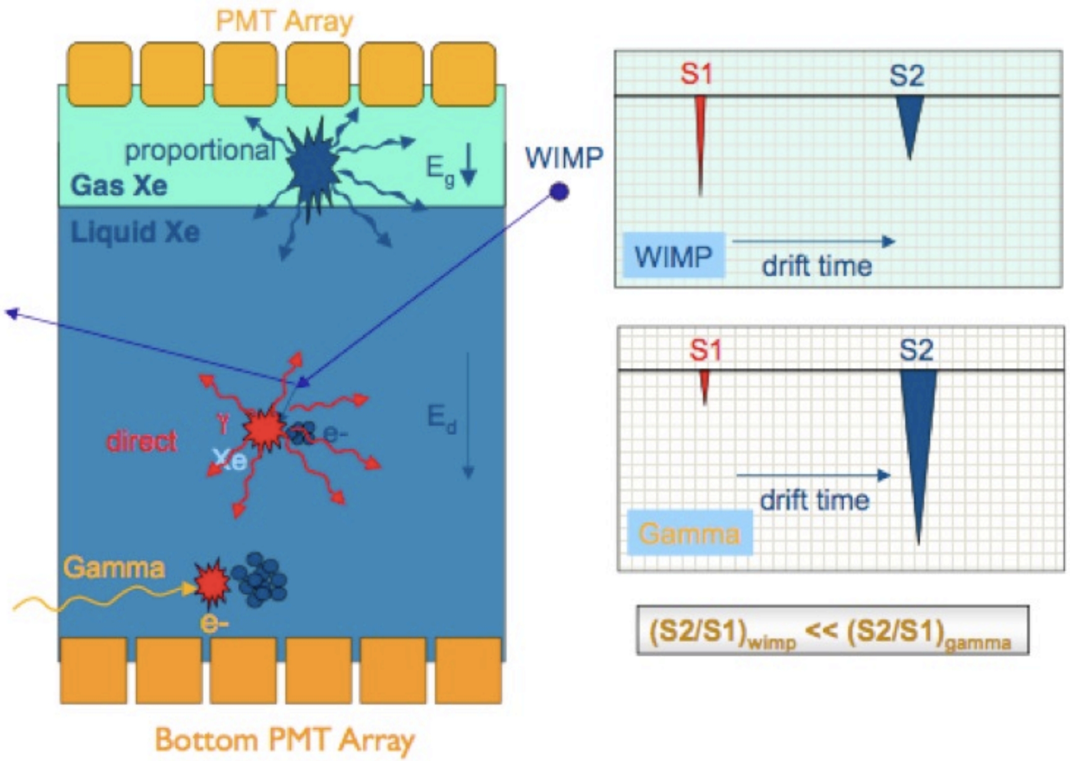
  - Most recent and complete collection of talks on almost all Direct Search experiments and projects

3.1- NOBLE LIQUID + GAS

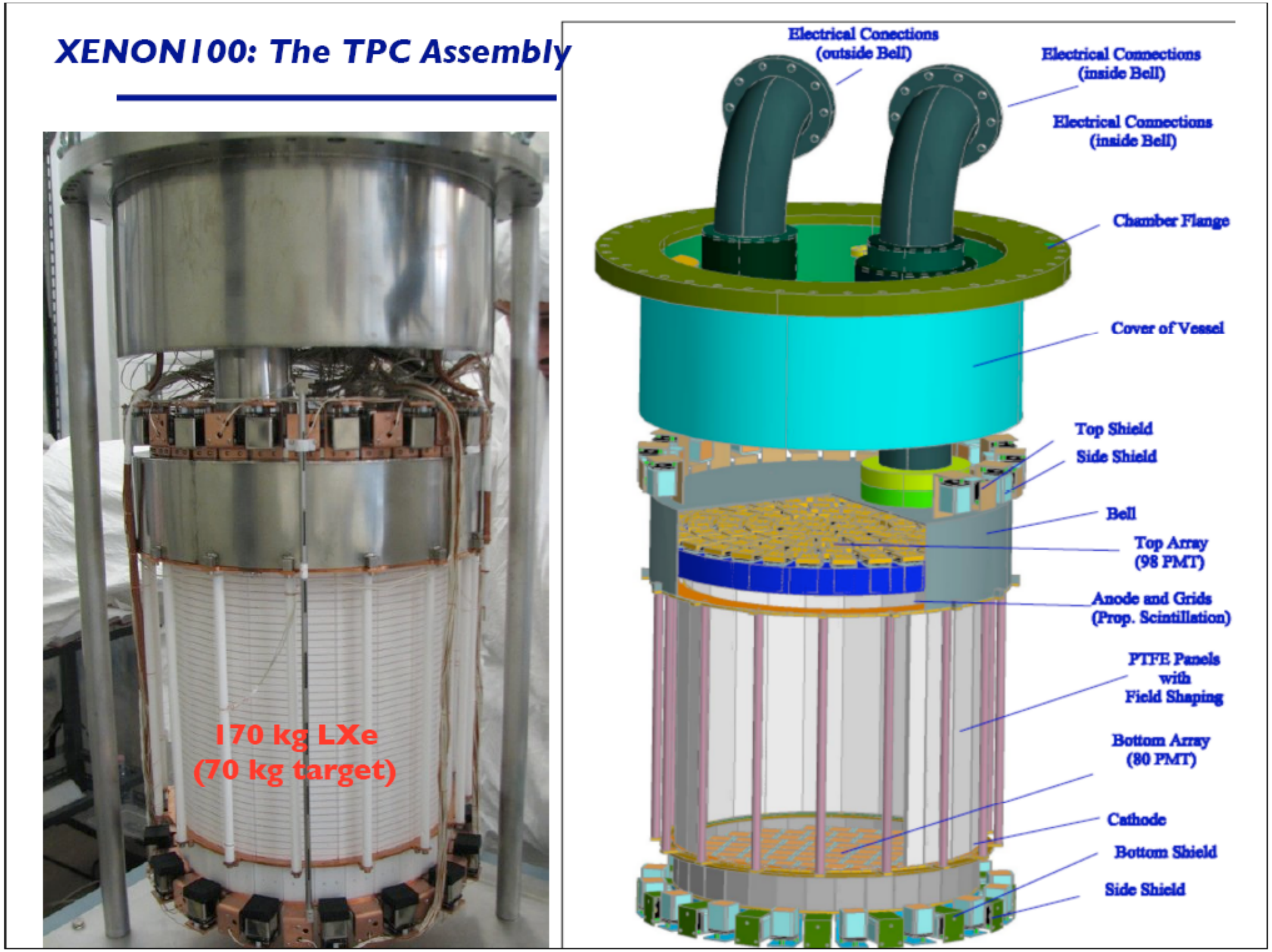
XENON S1/S2 discrimination

- Different scintillation (S1) and ionisation (S2) yields for nuclear / electronic recoils
- PMT array for (x,y), drift time for z : fiducial volume
- **Xenon 100**: 170 kg LXe, 34 kg fiducial, 30 cm drift, 98(top)+80(bottom) PM's
- *Trigger on 3 PM coincidence: bad energy resolution, but excellent noise suppression*
- 10 keV nuclear recoil: S1 ~ 5 P.E.   S2 ~ 800 P.E. (from ~30 ionization e^-)



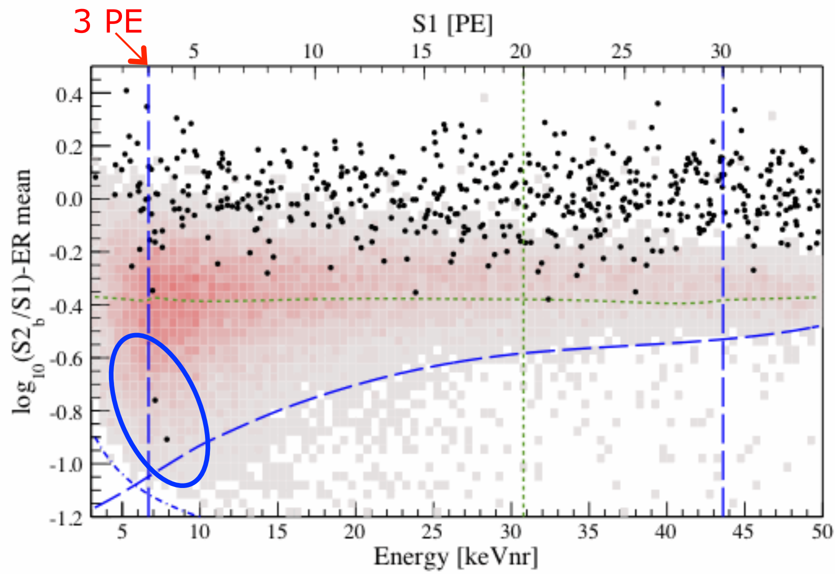


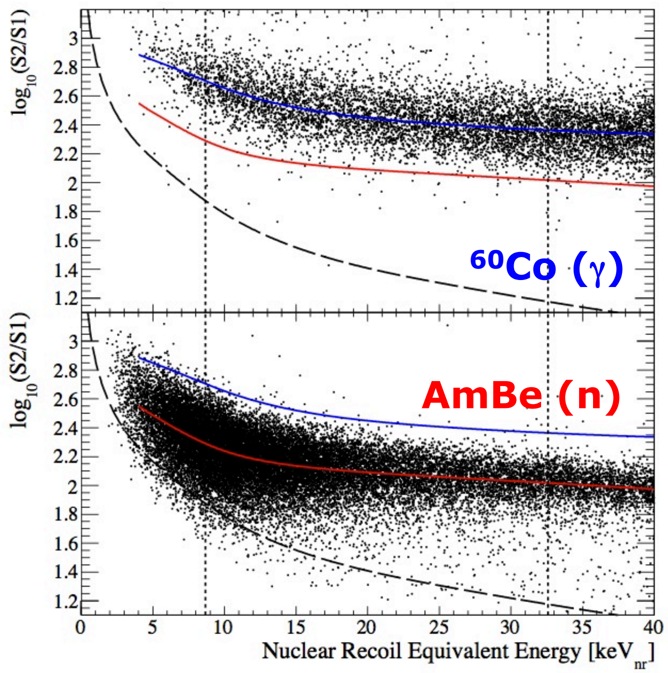
XENON100

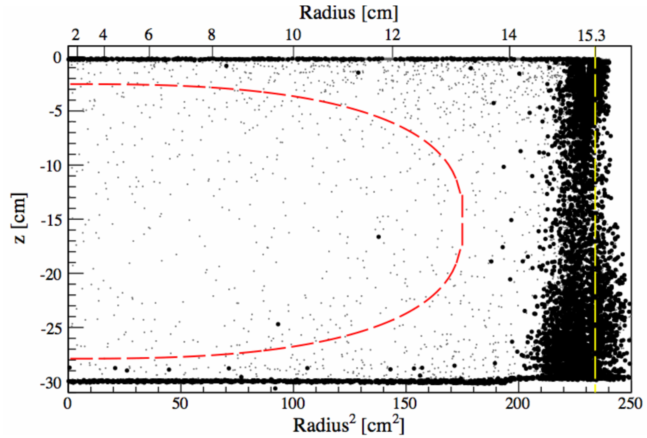

XENON100: The TPC Assembly
170 kg LXe
(70 kg target)
Electrical Conections
(outside Bell)
Electrical Connections
(inside Bell)
Electrical Connections
(inside Bell)
Chamber Flange
Cover of Vessel
Top Shield
Side Shield
Bell
Top Array
(98 PMT)
Anode and Grids
(Prop. Scintillation)
PTFE Panels
with
Field Shaping
Bottom Array
(80 PMT)
Cathode
Bottom Shield
Side Shield

XENON-100 Discrimination

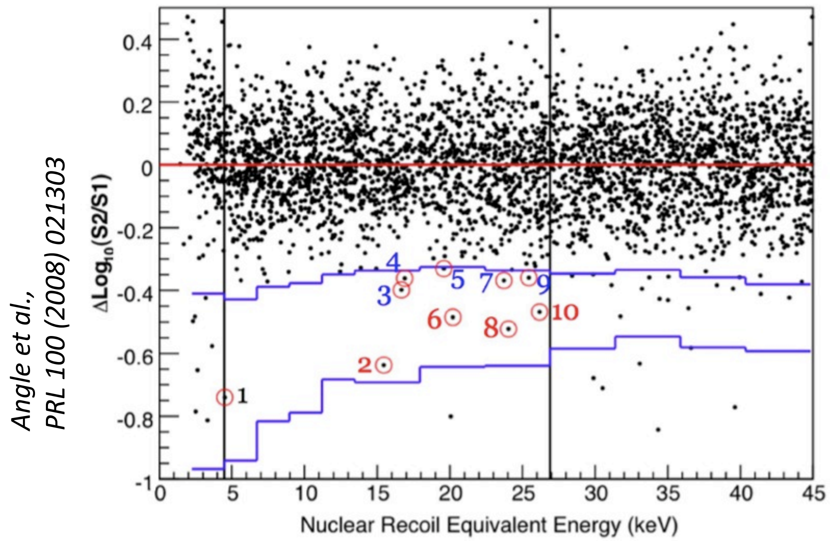
- 34kg Xe fiducial (h~ 25 cm, r ~13 cm)
- 225 day exposure, 3 PE S1 threshold
- Profile Likelihood analysis of ~7600 kg.day
  (Equivalent to ~2300 kg.d max. gap analysis)
- Low g background (19 ppt ^{85}Kr)
- Observe 2 evts, compatible with expected bkg = 1.0±0.2 evt (0.2 n + 0.8 Compton)



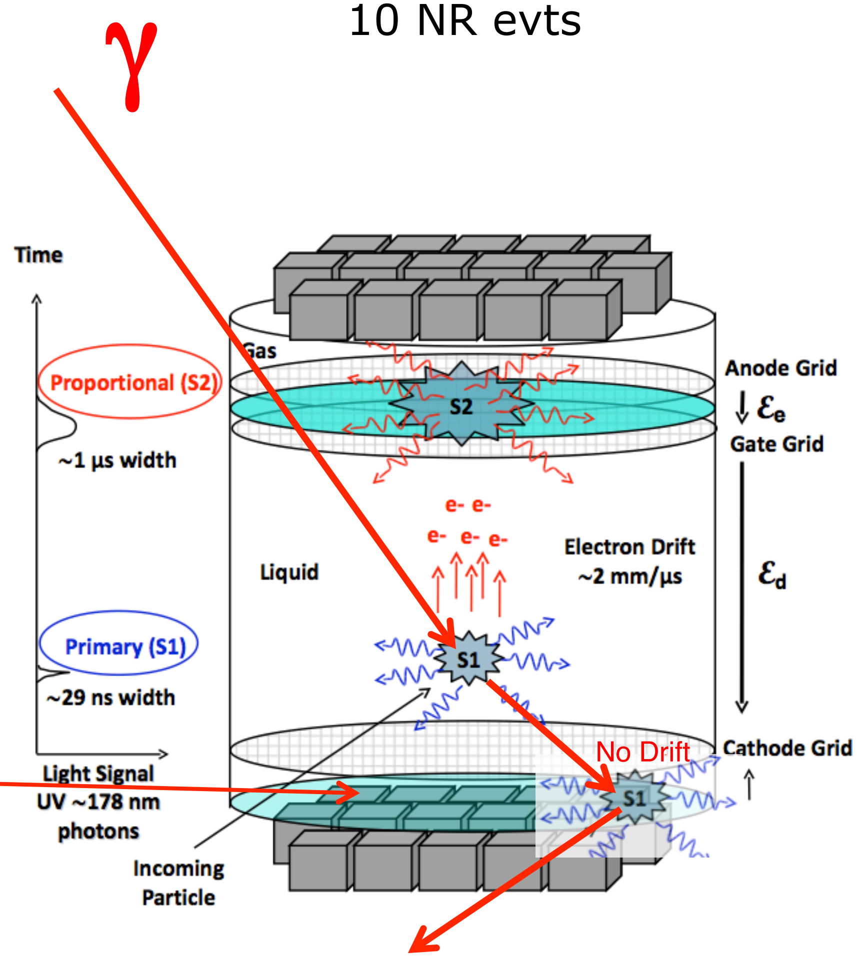




Compton « anomalous leakage » : also in XENON10



XENON-10:
59 d x 5.4 kgfid
10 NR evts

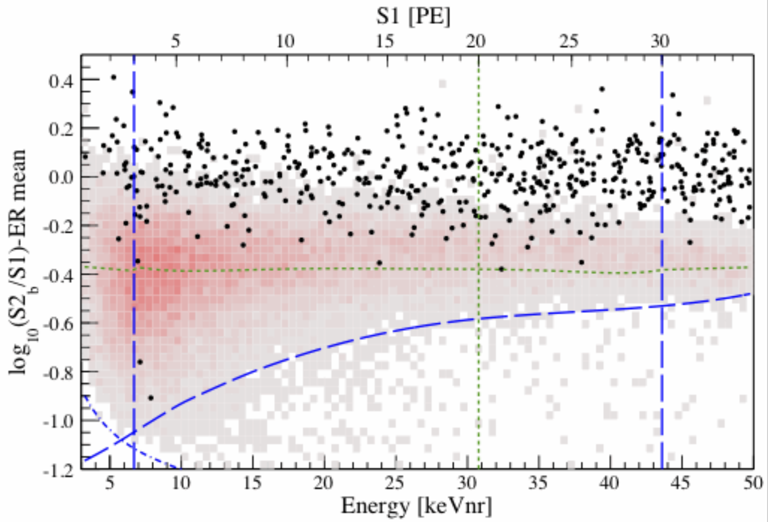


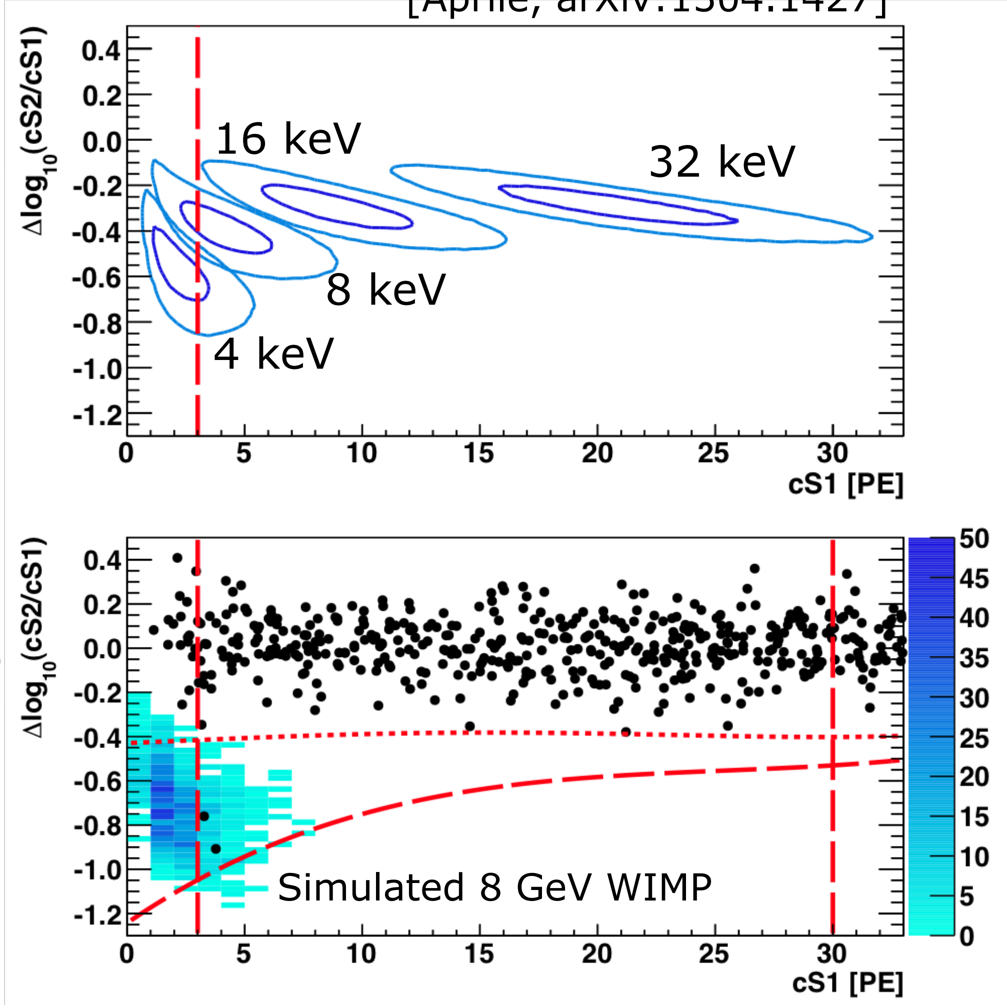
- XENON-10 had a suspected background from Compton interaction with one hit in the zone between the PMs and the cathode grid, where charge can't be drifted to the gaseous phase.

- Reduced size of this zone in XENON-100

XENON events at low energy

[Aprile, arXiv:1304.1427]

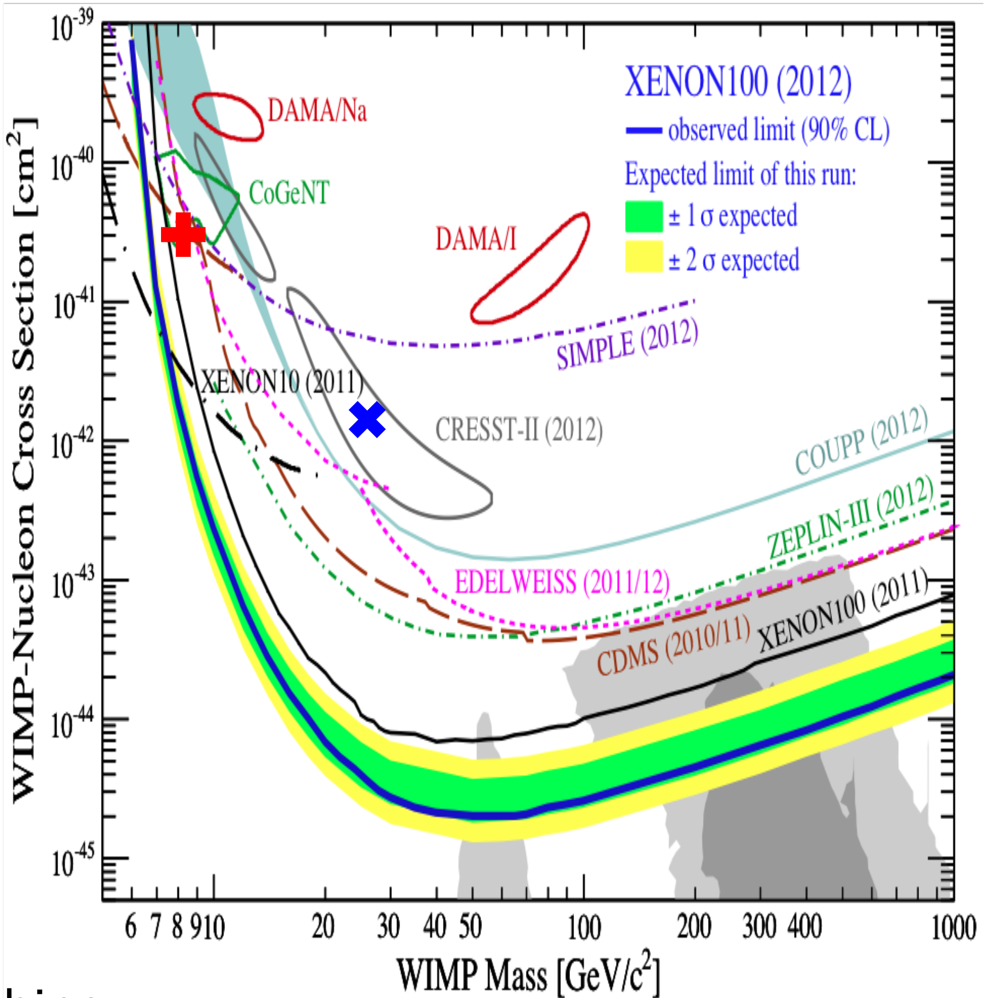




[See also Sorensen, PRD86 (2012) 101301, + Aprile, arXiv:1208.5762]

- $<2\times10^{-9}$ pb at 55 GeV/c^2
- Steep increase at low M_W
- Below ~12 GeV/c^2, efficiency relies on Poisson fluctuations from evts below S1 threshold

- The full simulations of the S1 S2 response of a 8 GeV WIMP at ✚: should have seen $223\pm^{303}_{85}$ evts.
- 25 GeV WIMP at ✖: should have seen $1409\pm^{53}_{4}$ evts
- Uncertainties: S1 S2 Quenching



XENON10 S2-only analysis

1. Intrinsic ratio hν/e⁻ decreases at low energy
2. Higher efficiency to collect electrons than photons

- Difficult to use S1 at low energy

  … but nuclear recoil discrimination may not be required to exclude relevant cross-sections of WIMPs below 10 GeV/c²

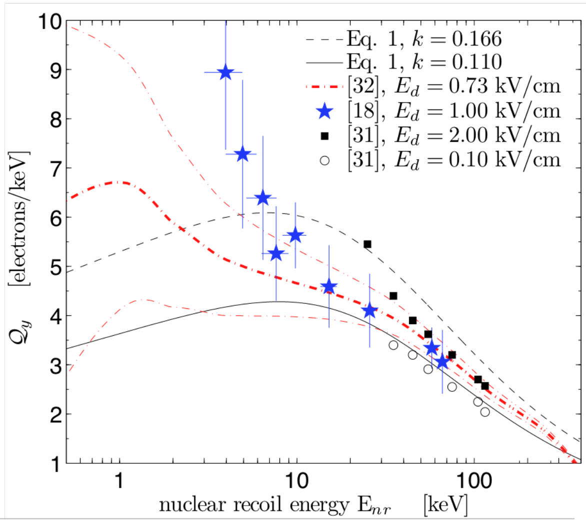
XENON10 analysis using S2 only

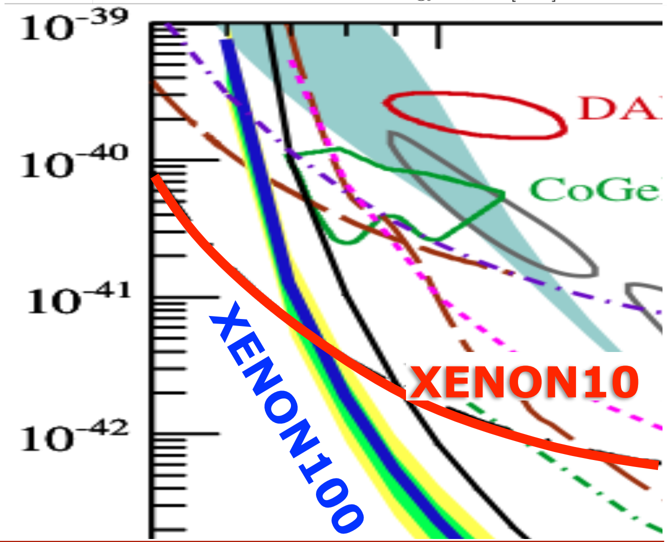
E_{recoil} = S2 / Ionization quenching

- Delicate: not well known below 5 keV
- New bkgs appear (single-photon S2 events)

- For now not very competitive with normal XENON100 analysis > 7 GeV/c²
- XENON100 + improved studies to come

[PRL 107 (2011) 051301]





Some LXe and LAr projects

- XENON 1t: in construction. *Reduction of radioactive background (cryostat, PM, purification)*.
- LUX (Homestake): 300 kg + improved light collection. Calibration starting.
- XMASS (Kamioka): 100 kg + 642 PMs. Monophase, rejection based on fiducialization. Need to study and reduce internal radioactive background.

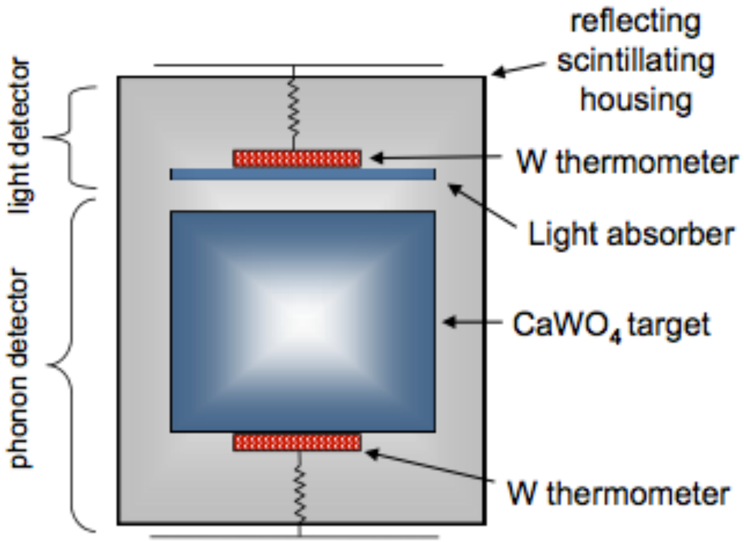
- DEAP-CLEAN (SNOLAB): 100 kg Ar, *need 10^8 rejection of radioactive ^{39}Ar* (pulse shape discr., τ = 1.6 μs)
- DarkSide-50: 33 kg fiducial Ar, *depleted in ^{39}Kr* (underground source, depletion 10^{-2} to 10^{-3})
- ArDM: see poster
- PANDA: Low-mass Xe in JinPing tunnel, China

3.2 - SCINTILLATION+HEAT

- 300 g $CaWO_4$ Crystals with Tungsten film thermometer
- Light detector = thin Si wafer + same type of thermometer
- 3 targets in same detector

  A = 16, 40 and 184

  Q = 0.10, 0.06 and 0.04

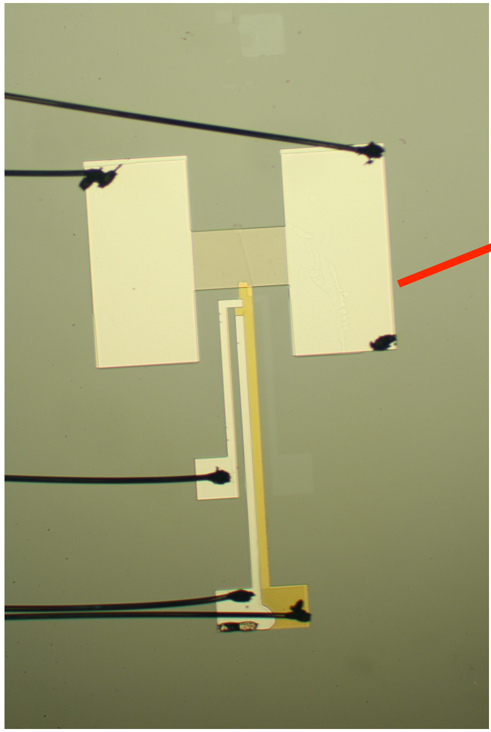


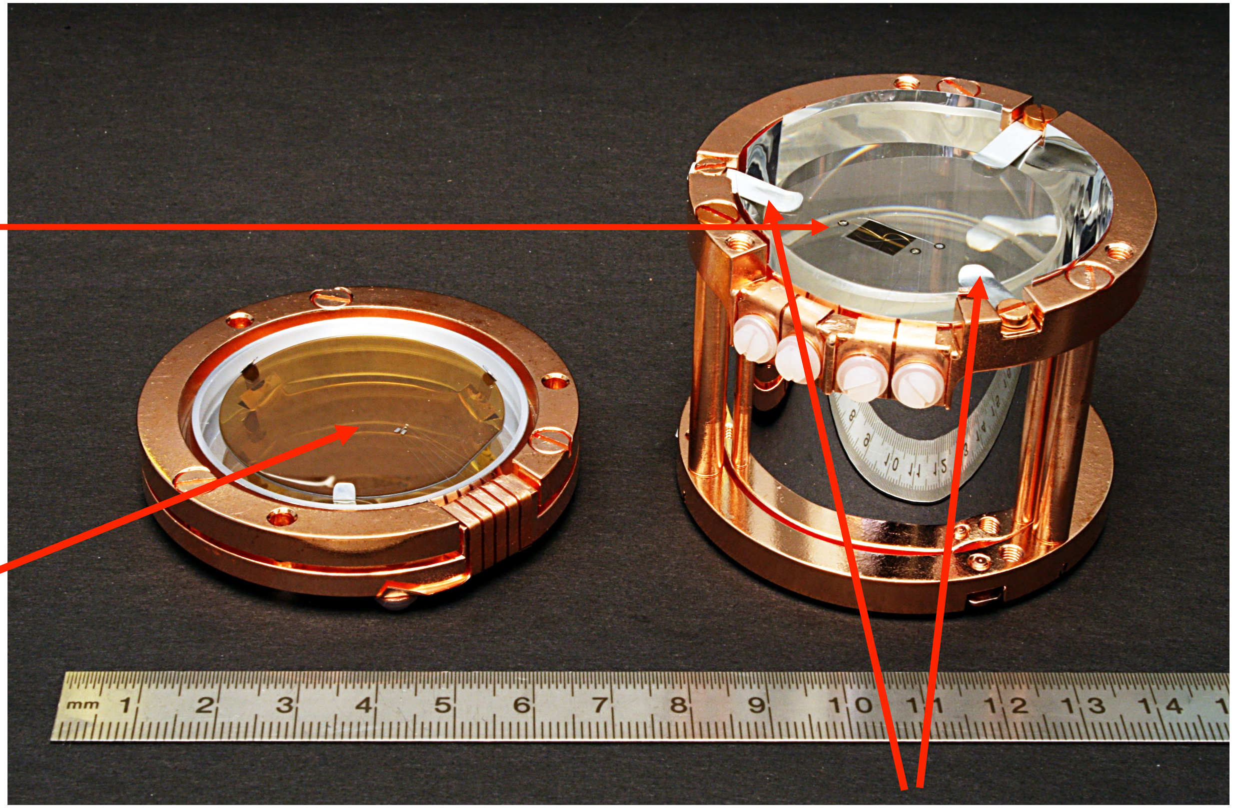
Reflecting scintillating housing to increase light yield

BONUS: tags $^{210}Po \rightarrow \alpha + ^{206}Pb$
two body decay
^{206}Pb recoil ~ W recoil

CRESST detectors

The phonon detector:
300 g cylindrical
$CaWO_4$ crystal.
Evaporated tungsten
thermometer with
attached heater.

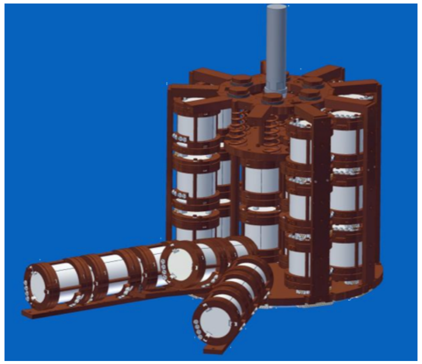




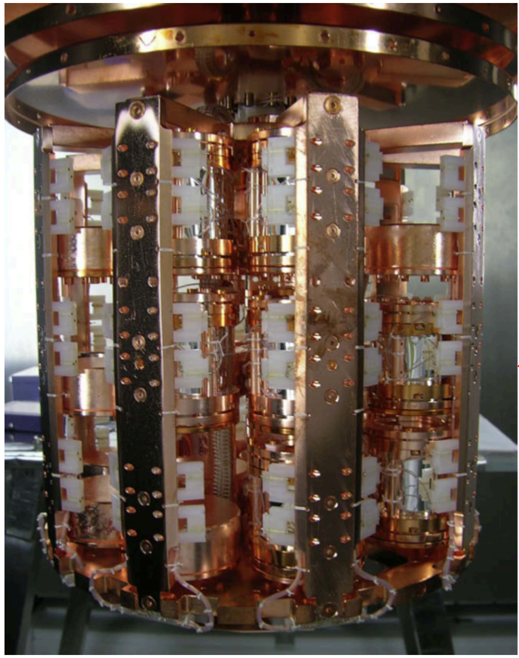
Light detector:
Ø=40 mm silicon on sapphire wafer.
Tungsten thermometer with attached
aluminum phonon collectors and thermal link.
Part of thermal link used as heater

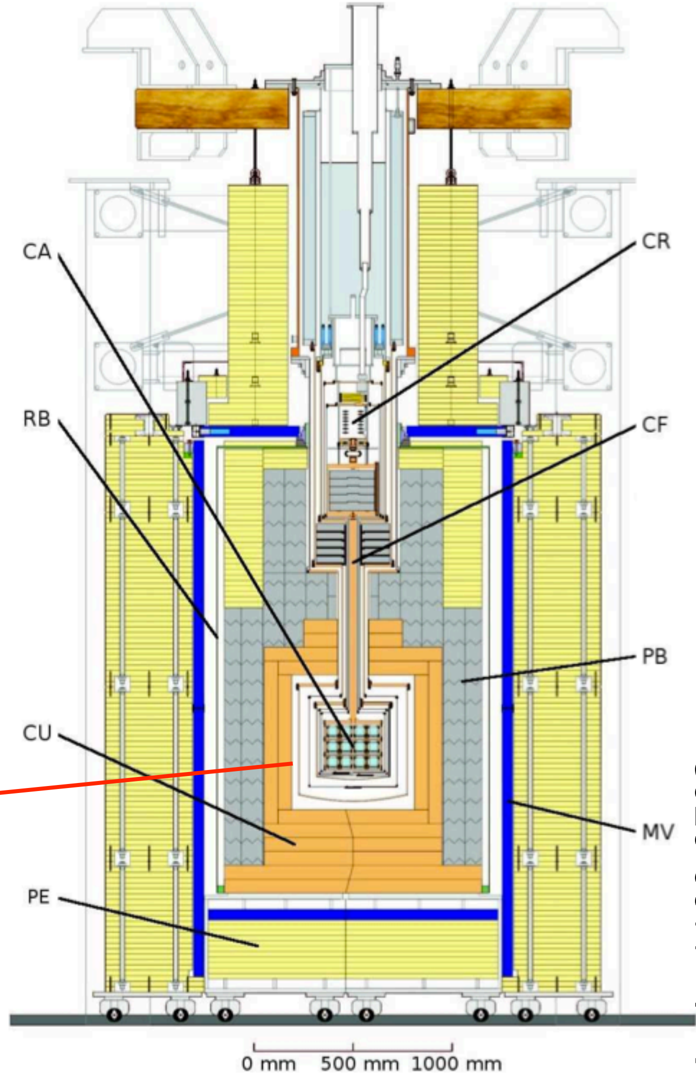
Clamps not
scintillating

66 SQUID channel readout (33 detectors)

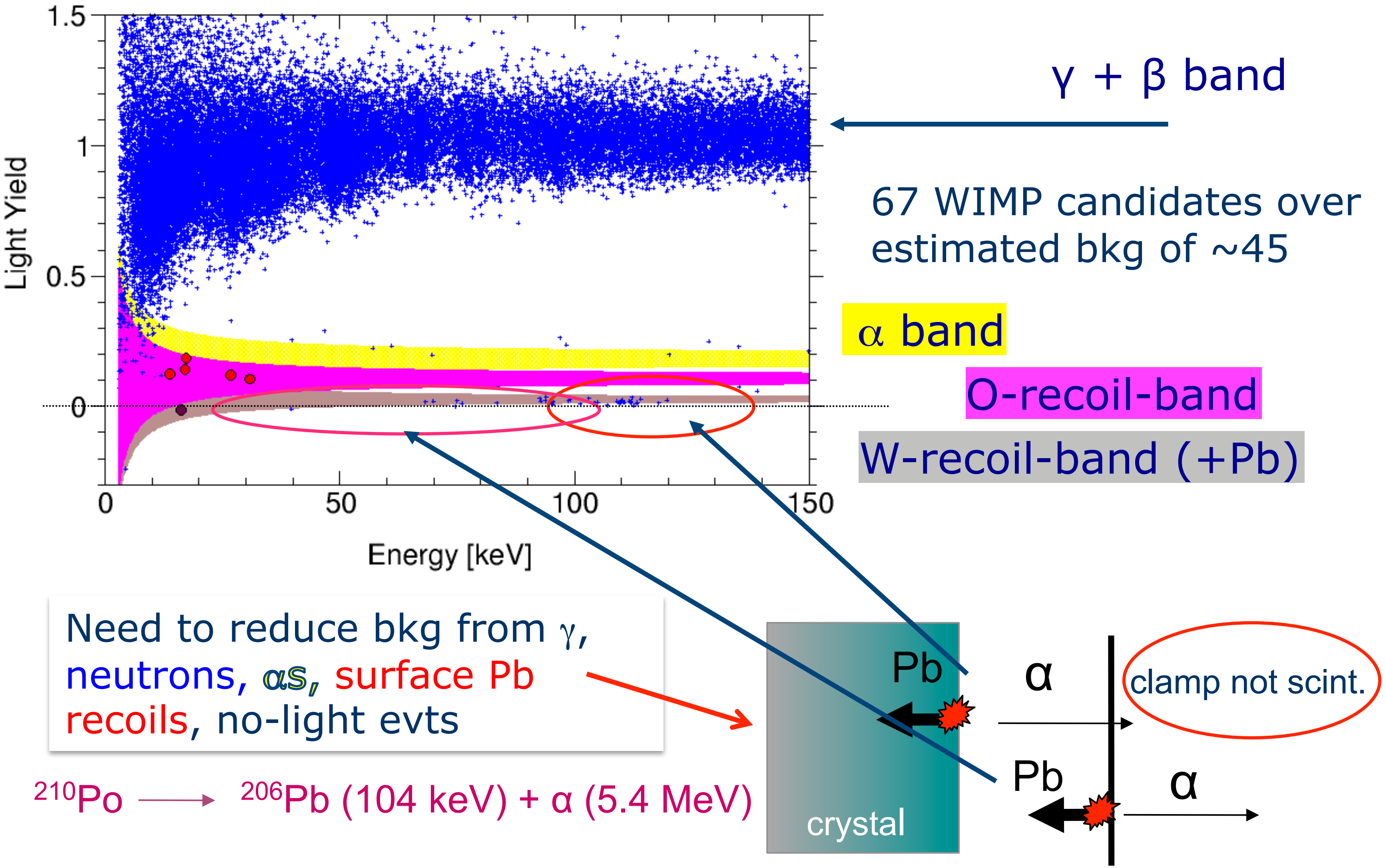


Detector carroussel





Arxiv:1109.0702



67 WIMP candidates over estimated bkg of ~45

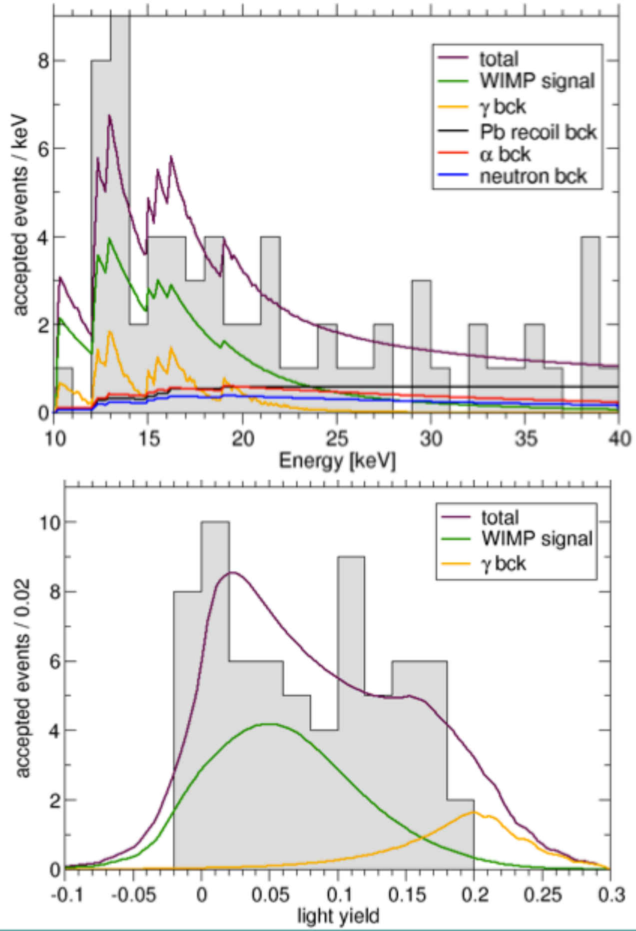
Need to reduce bkg from γ, neutrons, αs, surface Pb recoils, no-light evts

$^{210}Po \longrightarrow$ ^{206}Pb (104 keV) + α (5.4 MeV)

Results of Likelihood Analysis

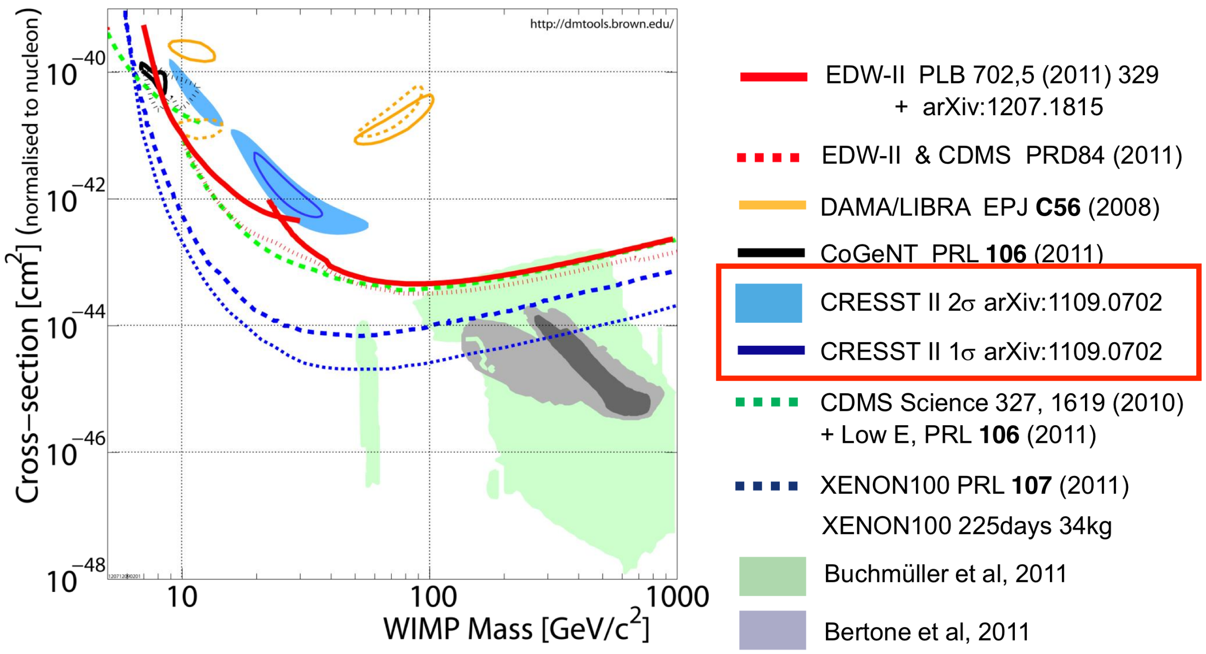
- Energy spectra of α, neutron or Pb backgrounds do not resemble the expected WIMP signal and only the e/γ contribution has a similar shape

- Light yield spectrum of e/γ differs significantly from the expected WIMP signal and thus cannot explain the total LY distribution



06.09.2011 Results from 730 kg days of the CRESST-II Dark Matter Search
Federica Petricca on behalf of the CRESST collaboration 15

- Favored regions not compatible with other direct searches

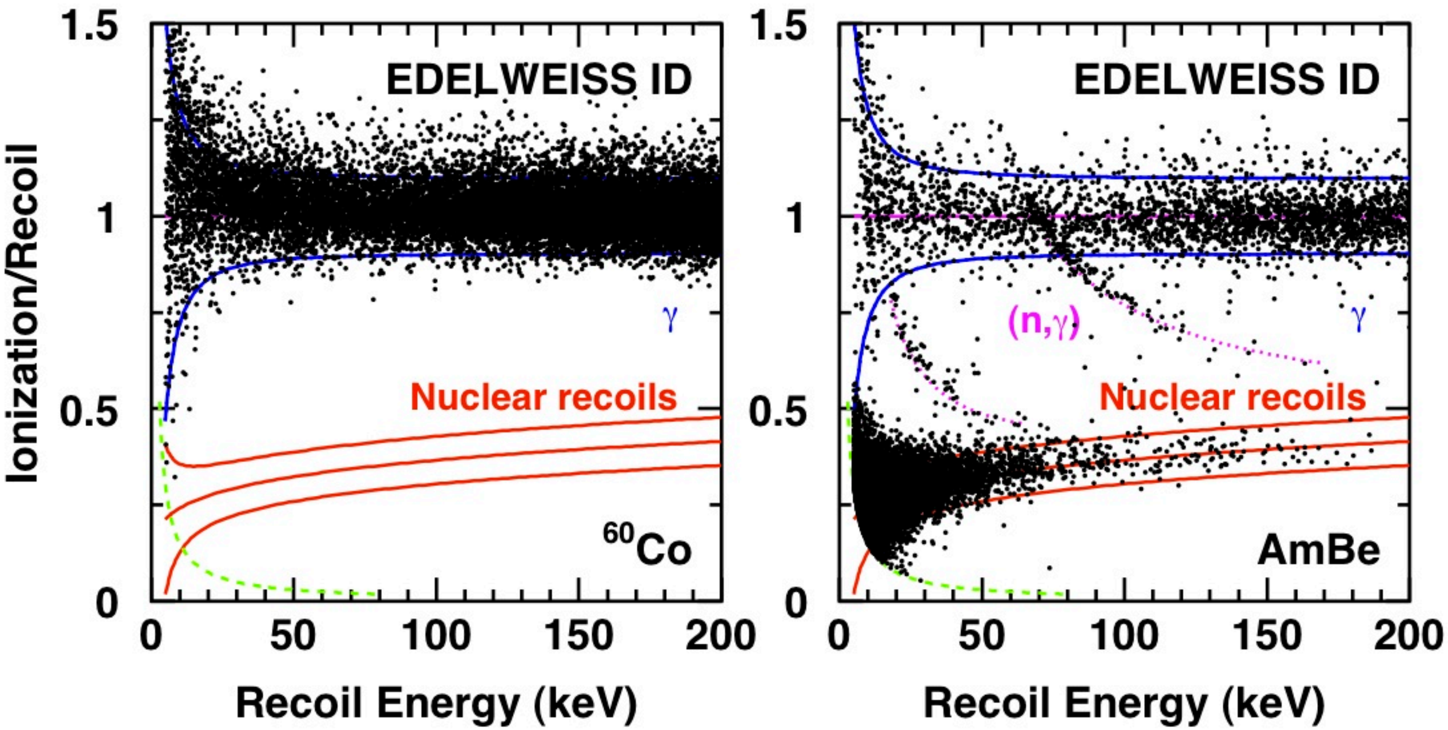


- New run with 33 detectors started
  - Improved neutron shielding
  - Radio-pure clamps + improved scintillation coverage
  - Reduce exposure to radon

3.3 GE IONIZATION + PHONON

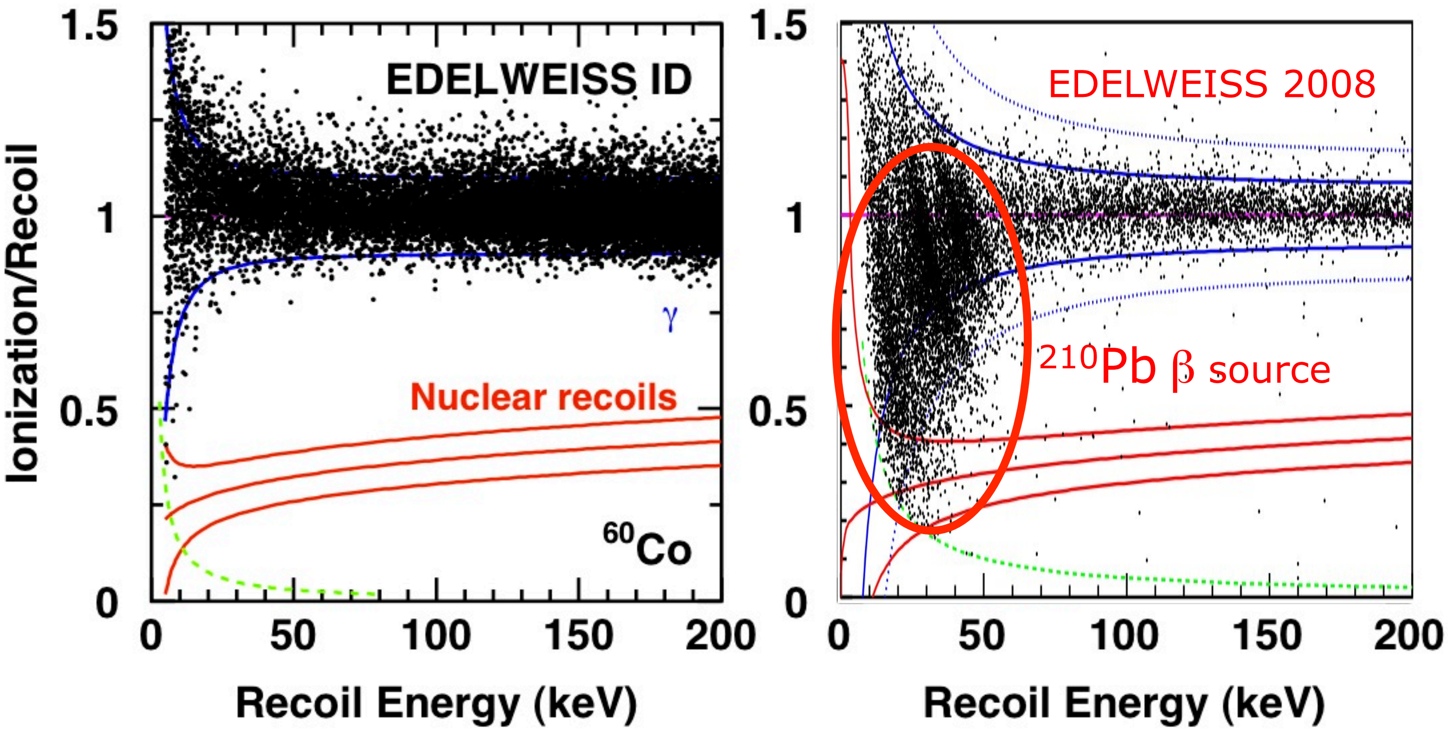
Nuclear recoil / gamma discrimination

- With good resolution on both ionization & heat, very clear discrimination based on the different ionization yields for *nuclear recoils* (WIMP or neutron scattering) and *electronic recoils* (β,γ decays)
  - discrimination of dominant background
  - Stable and reliable rejection performances



Limitation: poor ionization yield for surface events

- With good resolution on both ionization & heat, very clear discrimination based on the different ionization yields for *nuclear recoils* (WIMP or neutron scattering) and *electronic recoils* (β,γ decays)
- *Limitation: deficient charge collection near surface (trapping, dead layer) => different surface rejection strategy for CDMS & EDELWEISS*



(If anone asks…) Luke-Neganov effect

- *The current I corresponding to the charge drift in the potential V heats up the detector with a power VI: Luke-Neganov (~Joule effect)*
- Total work = heat = e N_{charge} x $|V_{polar}|$
- *Amplification* of heat signal:

$$E_{totalheat} = E_{recoil} + eN_{charge} \times |V_{polar}|$$

- Germanium: 3.0 eV/e for electron recoils:
  For ionization signals E_{ion} using gamma-ray source:

$$E_{ion} = N_{charge} \times 3.0\ \mathrm{eV/e}$$

- We can deduce E_{recoil} from de $E_{totalheat}$ et E_{ion}:

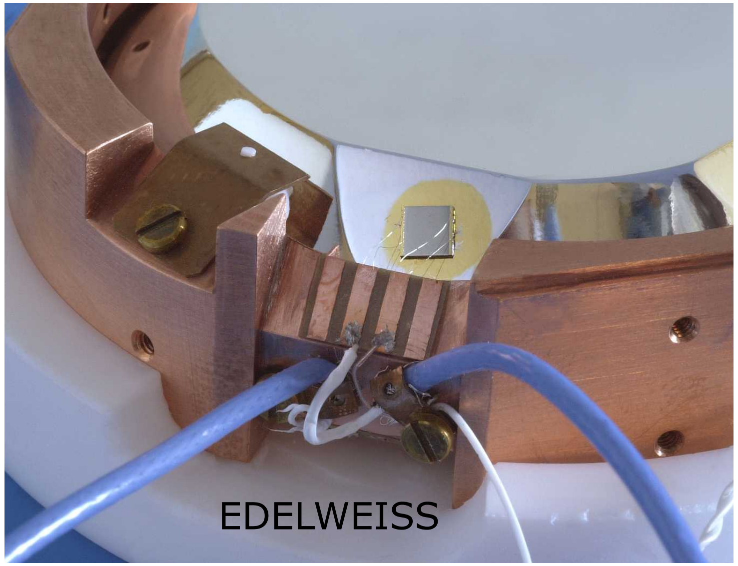
$$E_{totalheat} = E_{recoil} + E_{ion} \times |V_{polar}|/3.0\mathrm{V}$$

$$\mathbf{E_{recoil} = E_{totalheat} - E_{ion} \times |V_{polar}|/3.0V}$$

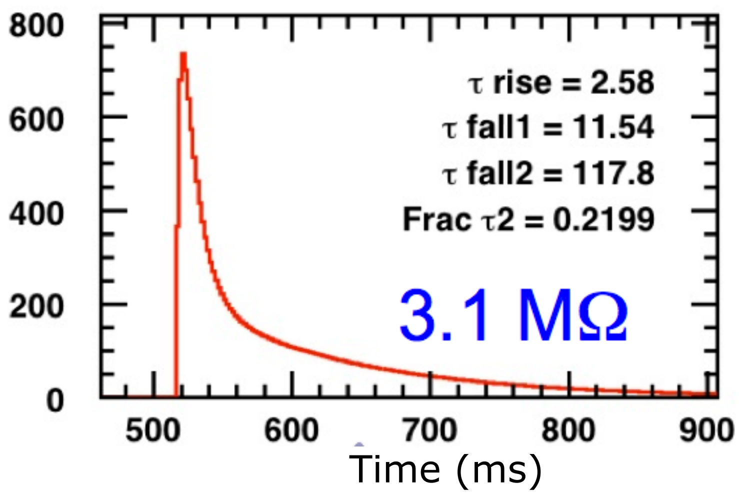
- Increasing V_{polar} improves the charge collection (trapping becomes important below 1 V/cm) and relative heat resolution, but not the nuclear/electronic recoil discrimination which depends on E_{ion}/E_{recoil}
- Compromise: typical V_{polar} 2V to 8V

Heat sensor in EDELWEISS: Ge-NTD

- $\Delta T = E/C$ (après thermalisation)
- Neutron-Transmutation Doped Ge crystal: $R(T) = R_0 \exp[(T_0/T)^{1/2}]$
- Small sensor (~80 mg) glued on 0.4 - 0.8 kg absorber crystals
- Coupling to fully thermalized phonons: $\Delta T = E/C$, independent of position.
- High impedance (1-10 $M\Omega$)
- Current excitation, voltage readout
- Rise time ~ms, Fall time ~100 ms



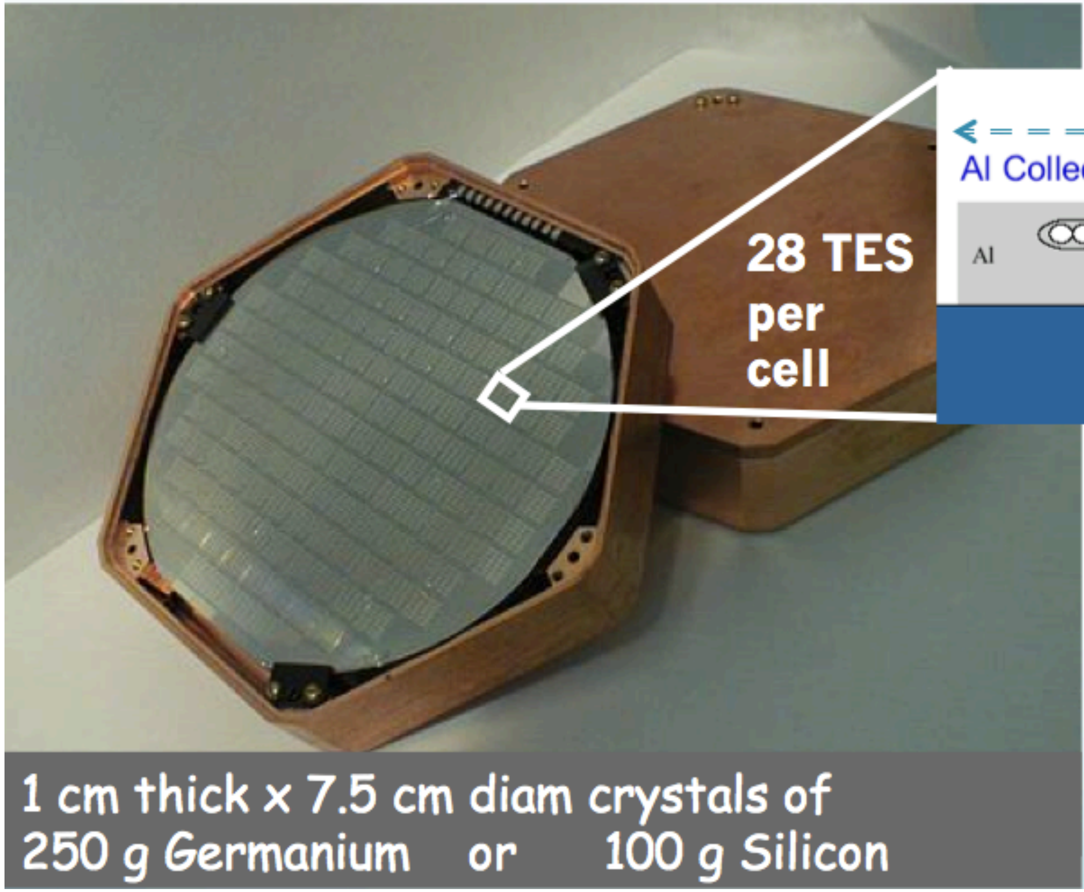
EDELWEISS Ge-NTD
Heat pulse

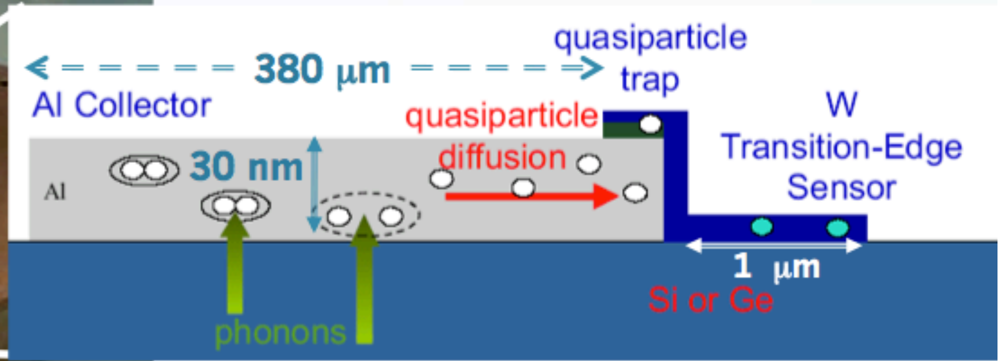


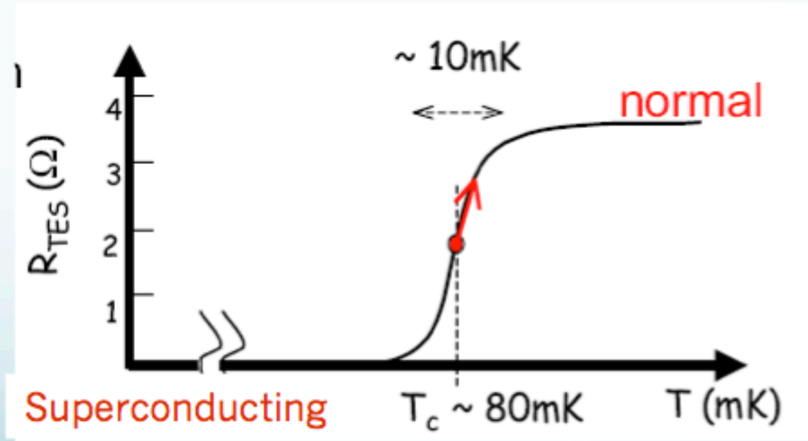
Phonon sensors in CDMS

photolithographic patterning produces 4144 “thermometers”

(quasi-particle-assisted electrothermal-feedback transition-edge sensors)

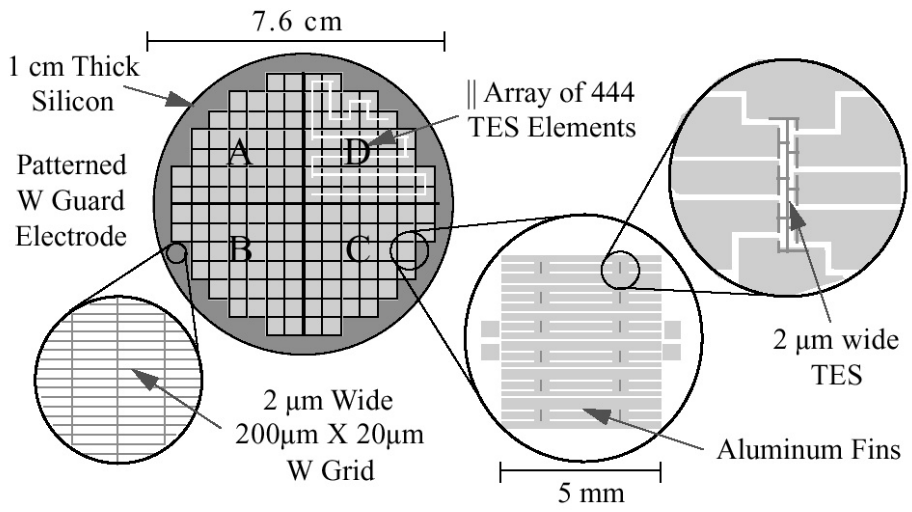


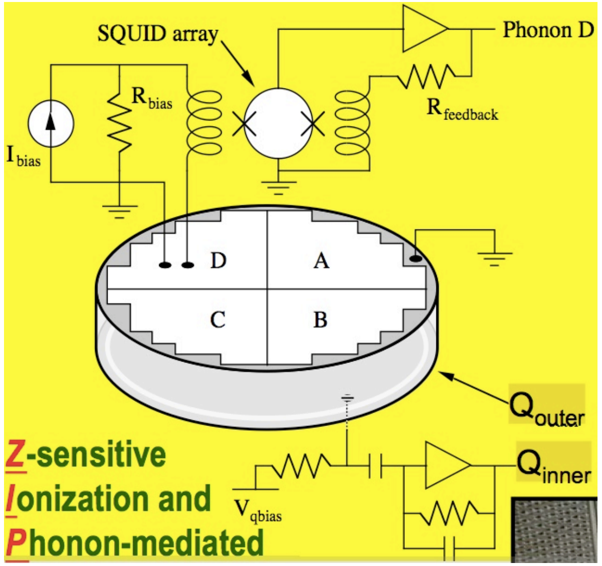




CDMS ZIP detectors

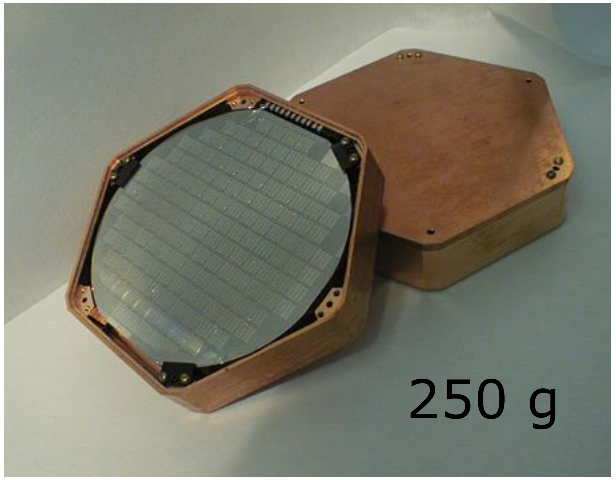
- Large area: sensitivity to athermal phonons
- *Sensitivity to surface interactions*
- Photolithographic patterns of W-TES + Al collector (CDMS)





Heat signals:
4 quadrants

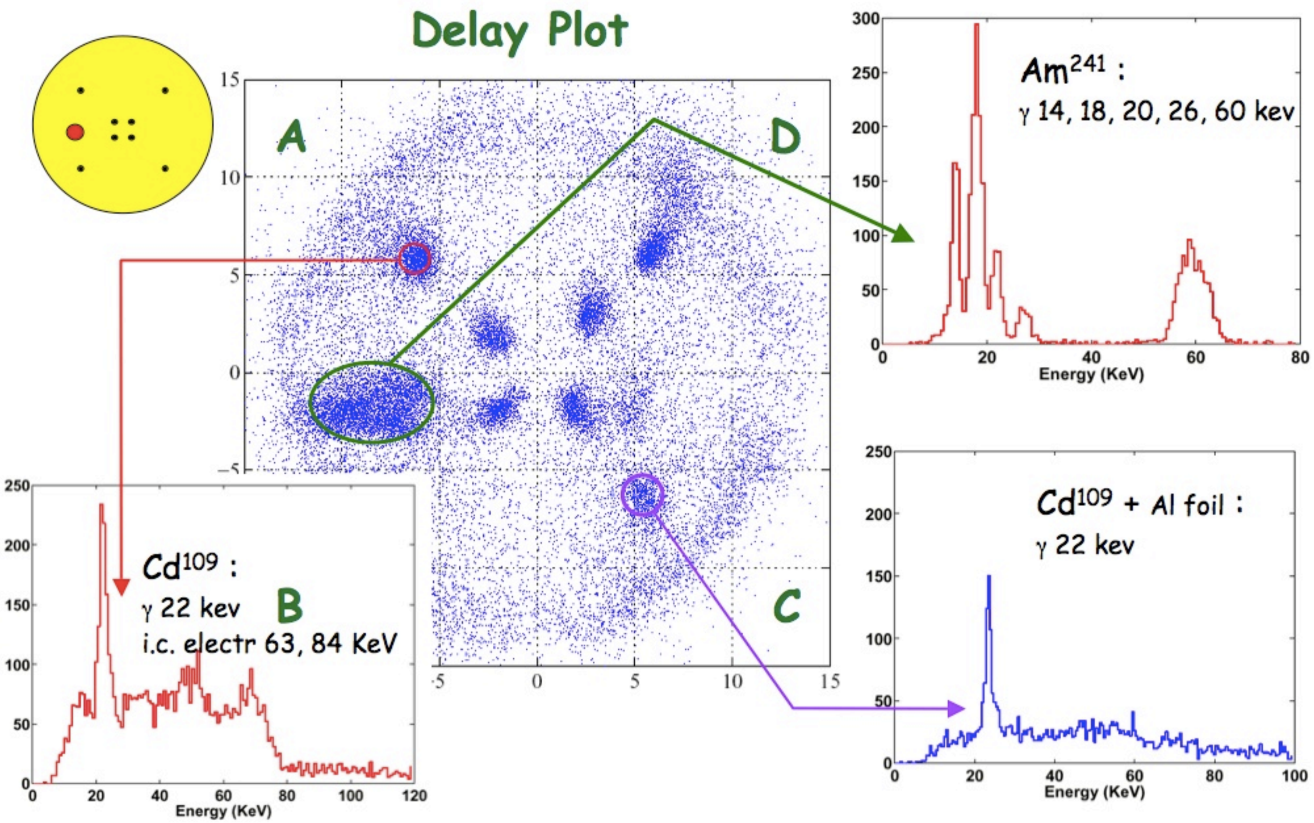
Ionization signals:
Q_inner
Q_outer



ZIP: Radial position of event

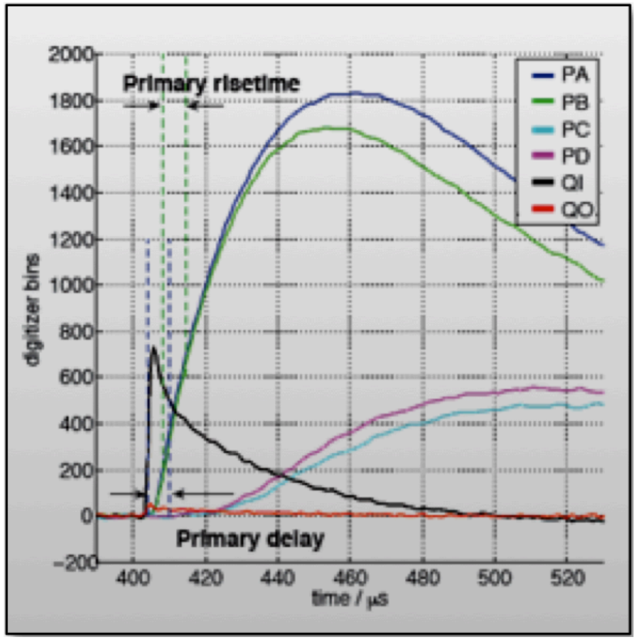
- Athermal phonon signal amplitudes in four quadrants depend on the (x,y) position of the interaction (mm resolution)
- Position-dependent energy calibration

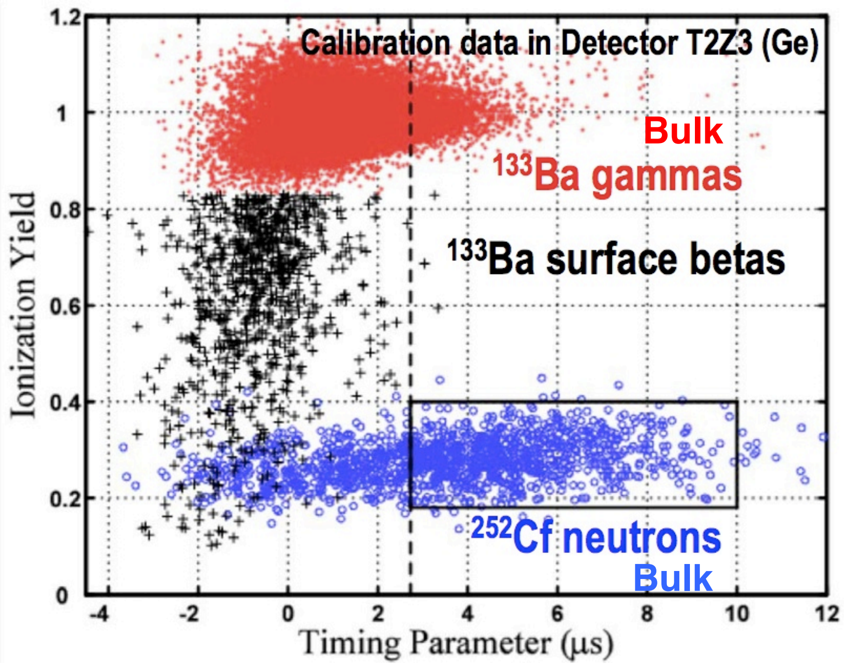
Test with different point sources on the surface of a detector



Phonon time discrimiation

- Phonon risetime < 50 μs
- Ionization risetime < 1 μs
- « Timing parameter » combines *rise time* and *phonon-ionization delay*
- Nuclear/electronic recoil discrimination!

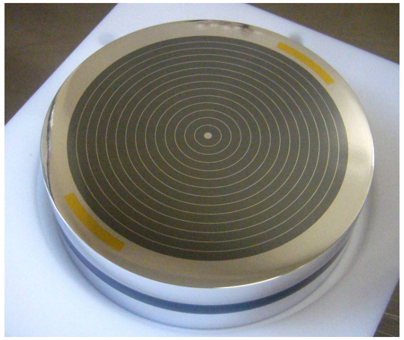


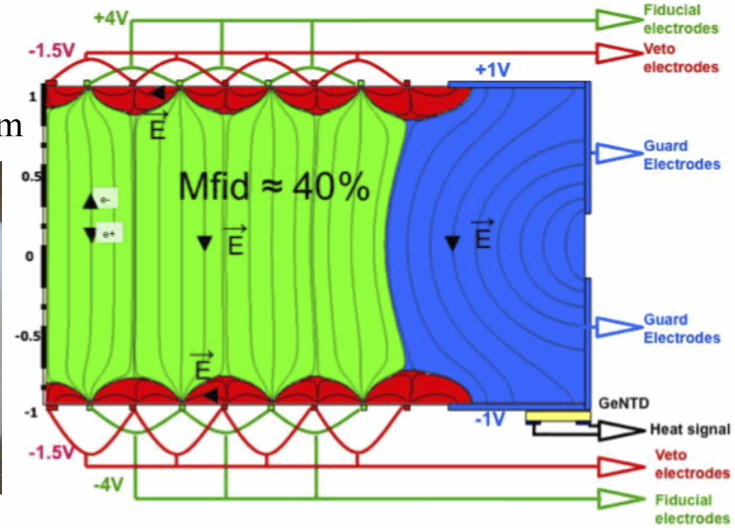


- Sensivity to « z »? (no, works even if sensors on only one side)
- Due instead to a difference between the phonons produced in the primary interaction and in the Luke-Neganov process.

EDELWEISS surface rejection: Interleaved electrodes

Φ 70mm, H 20mm, 410g
14 concentric electrodes
width 100µm, spacing 2mm





Interleaved electrodes + guards rings biased to produce an electric field:

➔ **horizontal near the surface (~1 mm)**

🡻 **vertical in the bulk**

Simple Surface event selection:

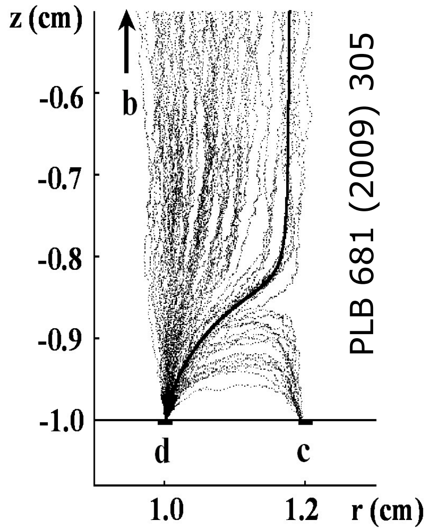
- First criteria: absence of signal on "veto" rings
- ***Redundancy:*** requires equality between "fiducial" rings on both sides

Added bonus: "Grid effect":

- High-field region close to the fiducial electrodes improves charge collection in that critical region close to the surface

Charge transport effects:

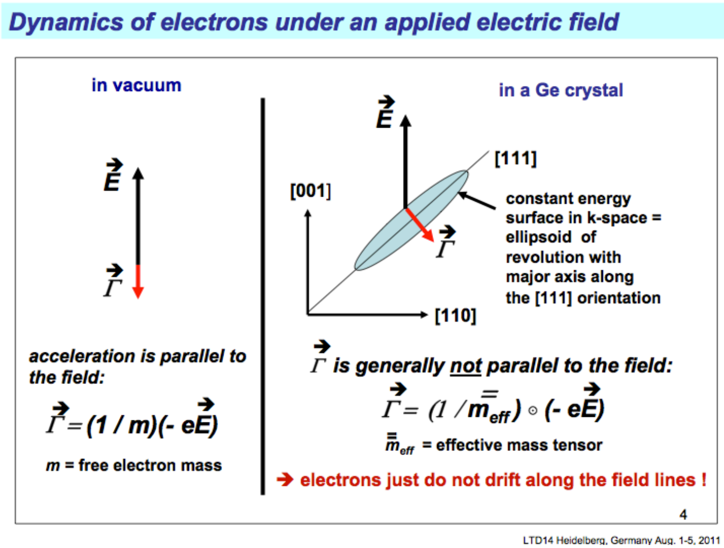
- Diffusion (T=20mK) and charge repulsion insures that charges are never "stuck" in zero-field regions

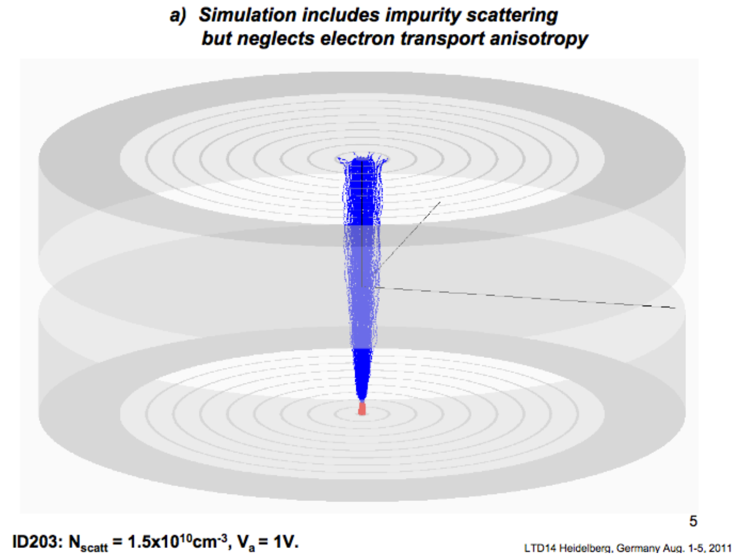


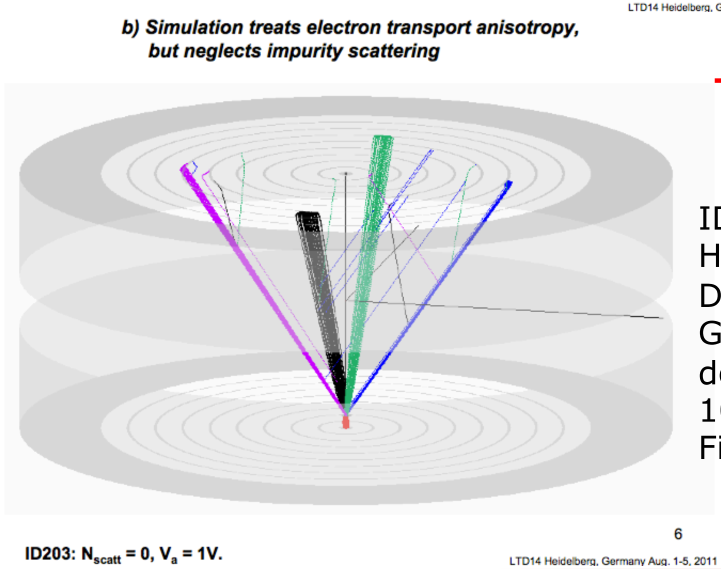
PLB 681 (2009) 305

Understanding charge transport in Germanium

Broniatowski, LTD14

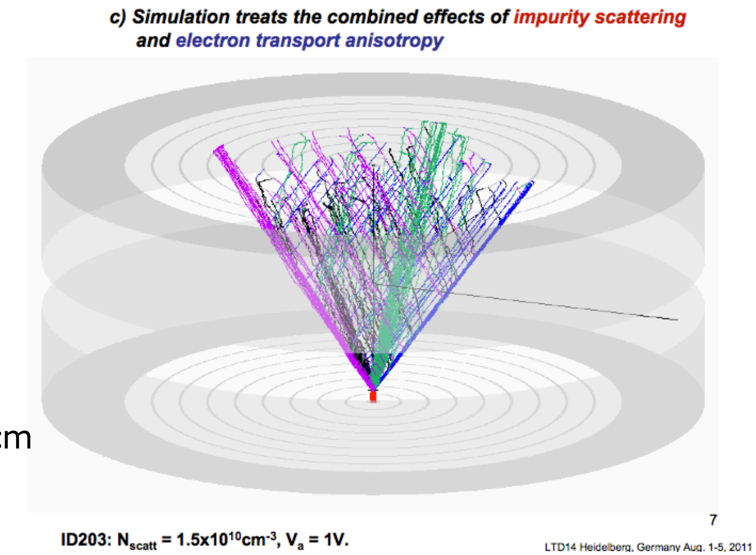






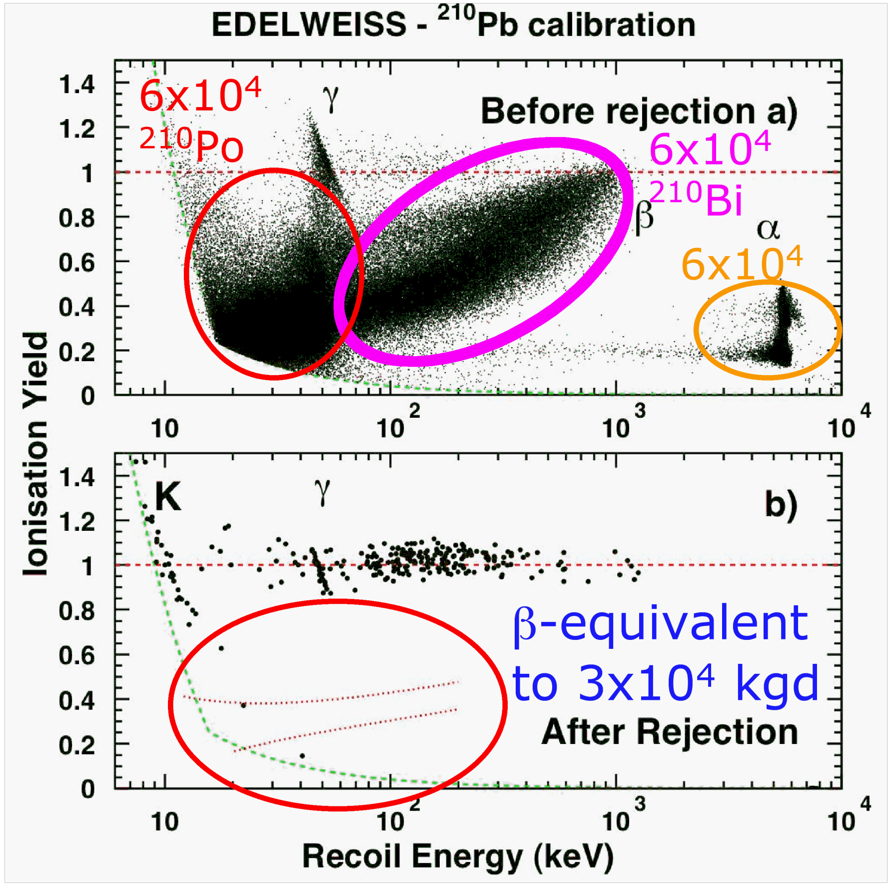
T = 20 mK

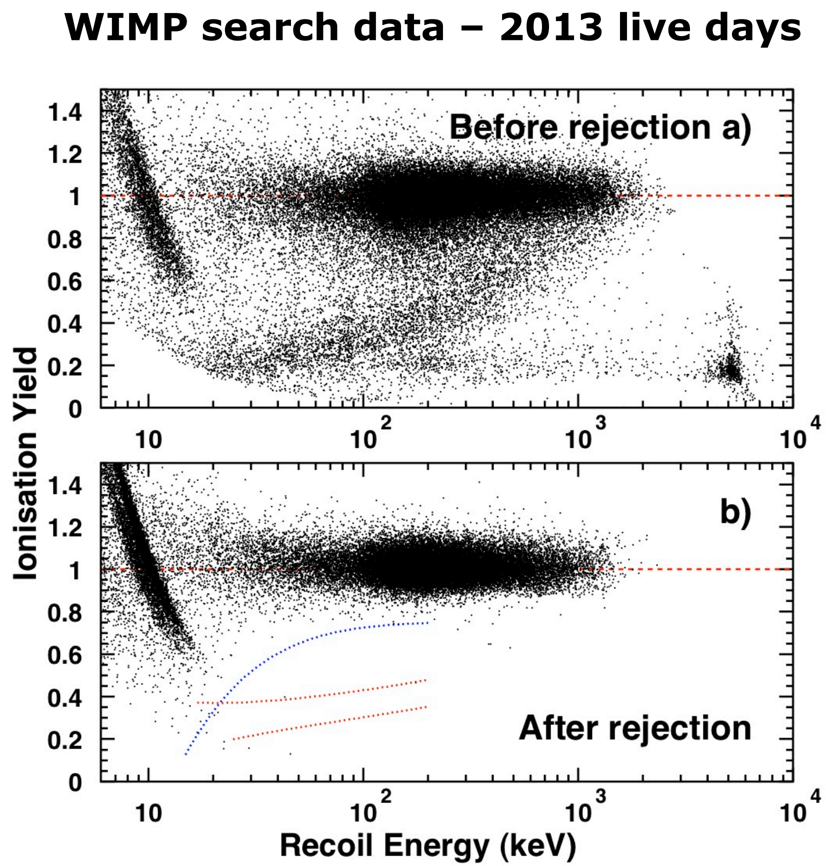
ID203
Height 20 mm
Diam. 50 mm
Ge p-type
doped to
10^{11} cm^{-3}
Field: ~0.5V/cm



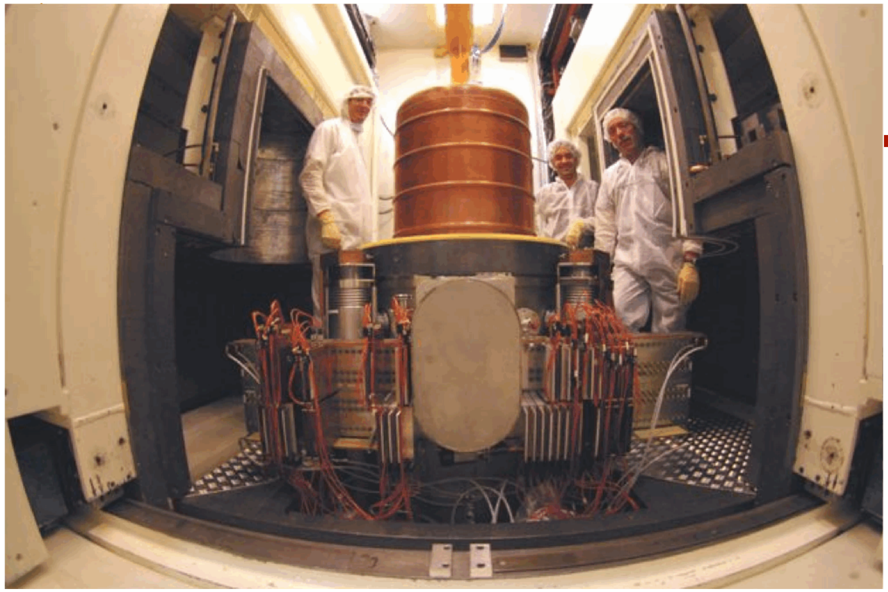
Identification of surface events

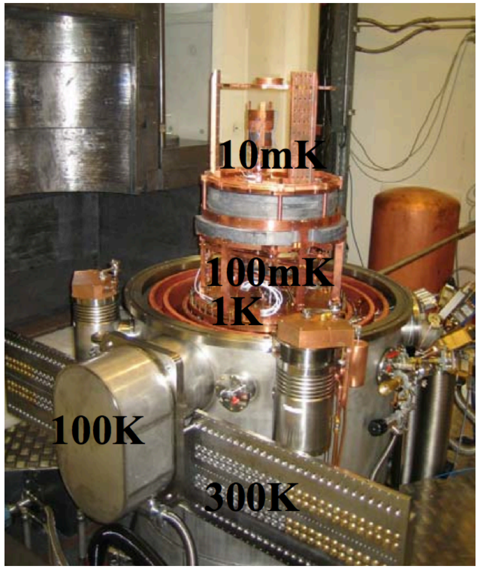
- Surface rejection tested with ^{210}Pb source of surface events
- Technique applied to WIMP search with 10 x 400 g detectors

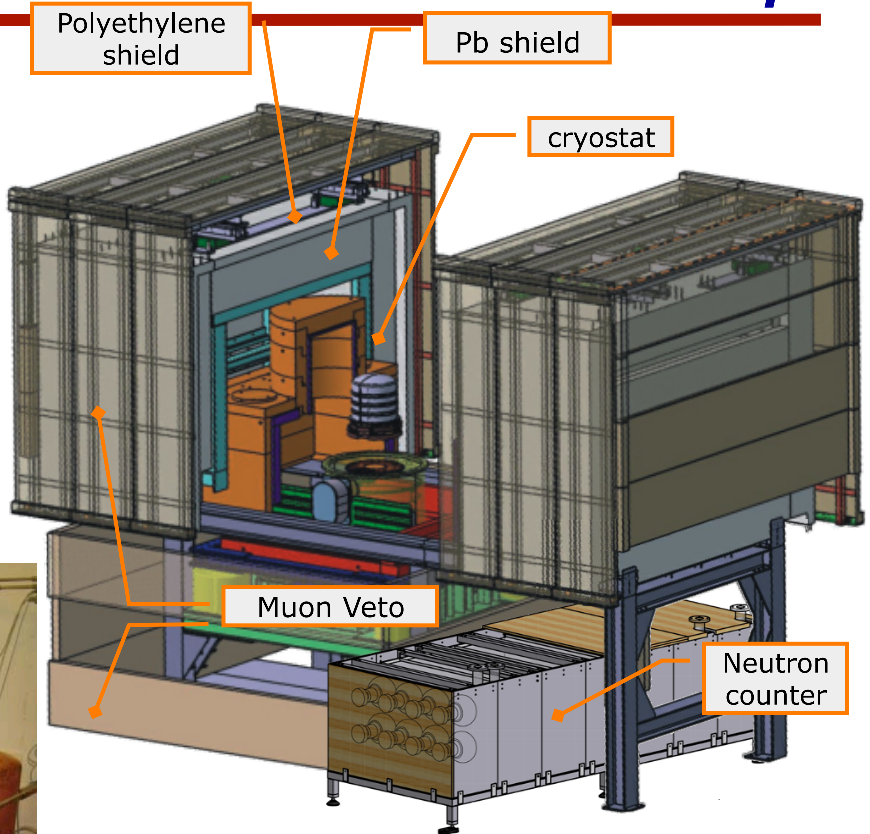


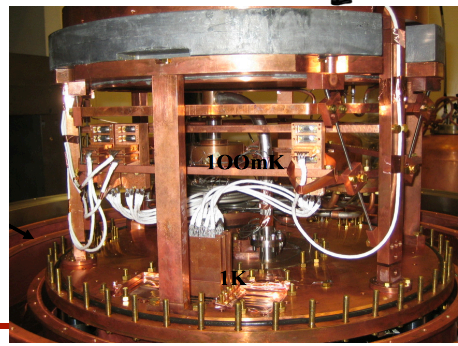


EDELWEISS setup

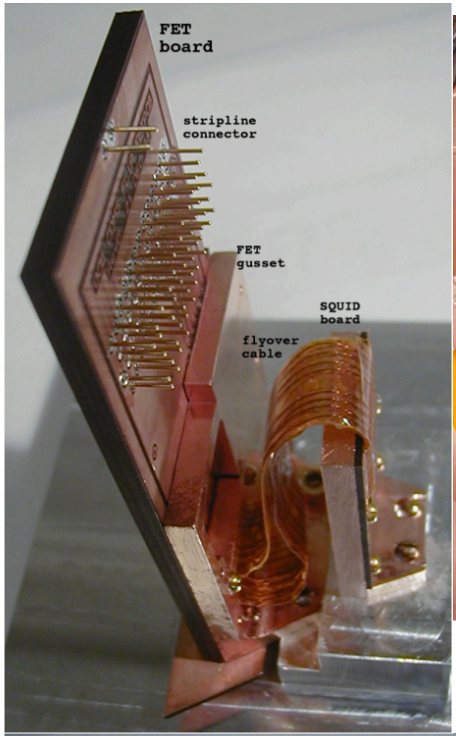




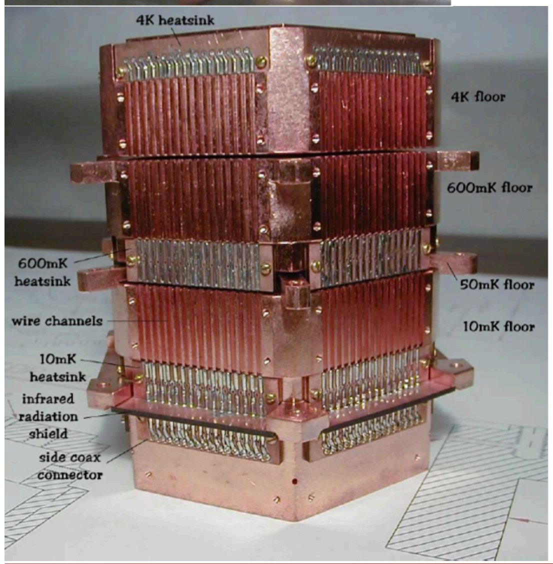




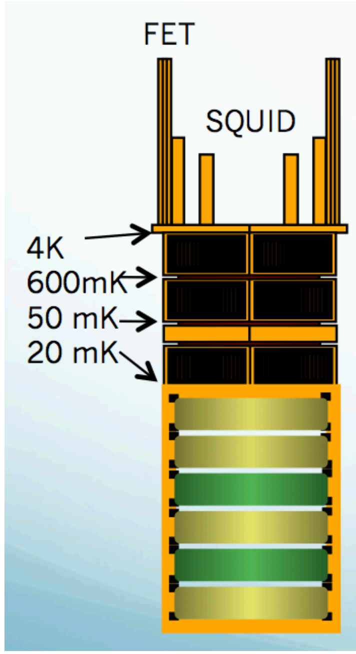
CDMS setup



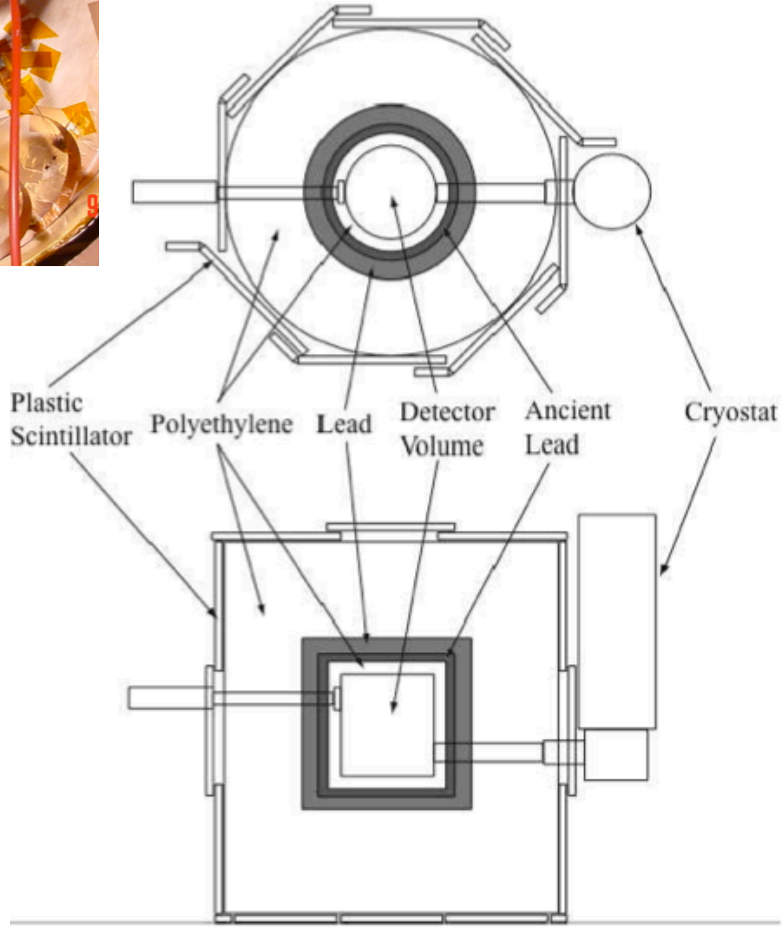
FET board
stripline connector
FET gusset
SQUID board
flyover cable



4K heatsink
4K floor
600mK floor
600mK heatsink
50mK floor
wire channels
10mK floor
10mK heatsink
infrared radiation shield
side coax connector



FET
SQUID
4K
600mK
50 mK
20 mK



Plastic Scintillator
Polyethylene
Lead
Detector Volume
Ancient Lead
Cryostat

CDMS-II and EDELWEISS-II WIMP searches

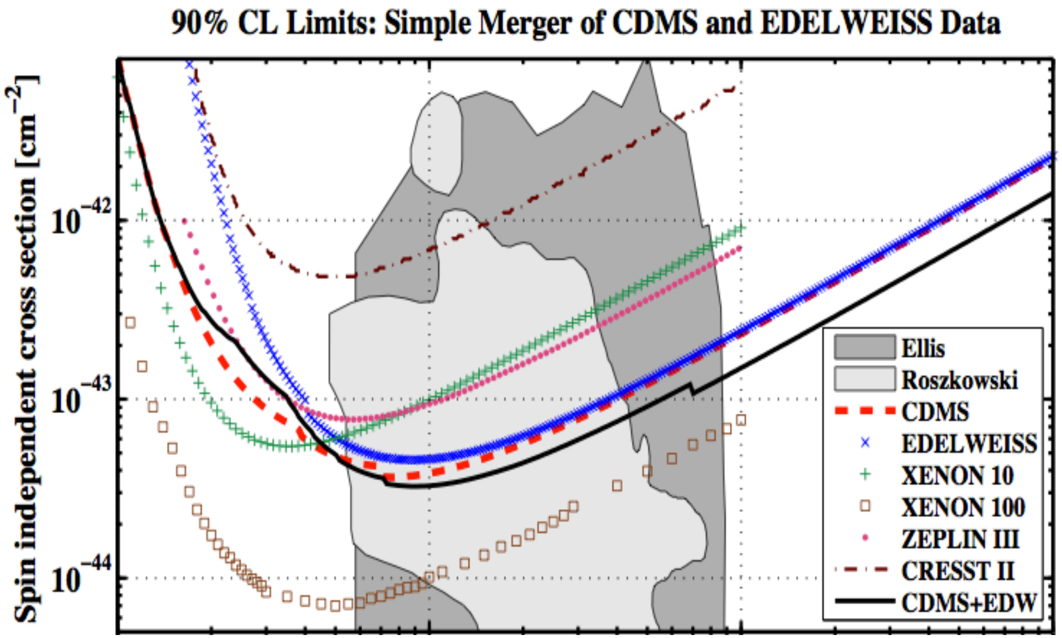
- Combined results: PRD 84 (2011) 011102

	kg.day fiducial	Recoil range (keV)	Ge mass (kg)	NR candidates	Estimated bkg
CDMS	379	5-100	15x0.25	4	~2
EDW	384	20-200	10x0.40	5	~3

* Comparable and consistent results

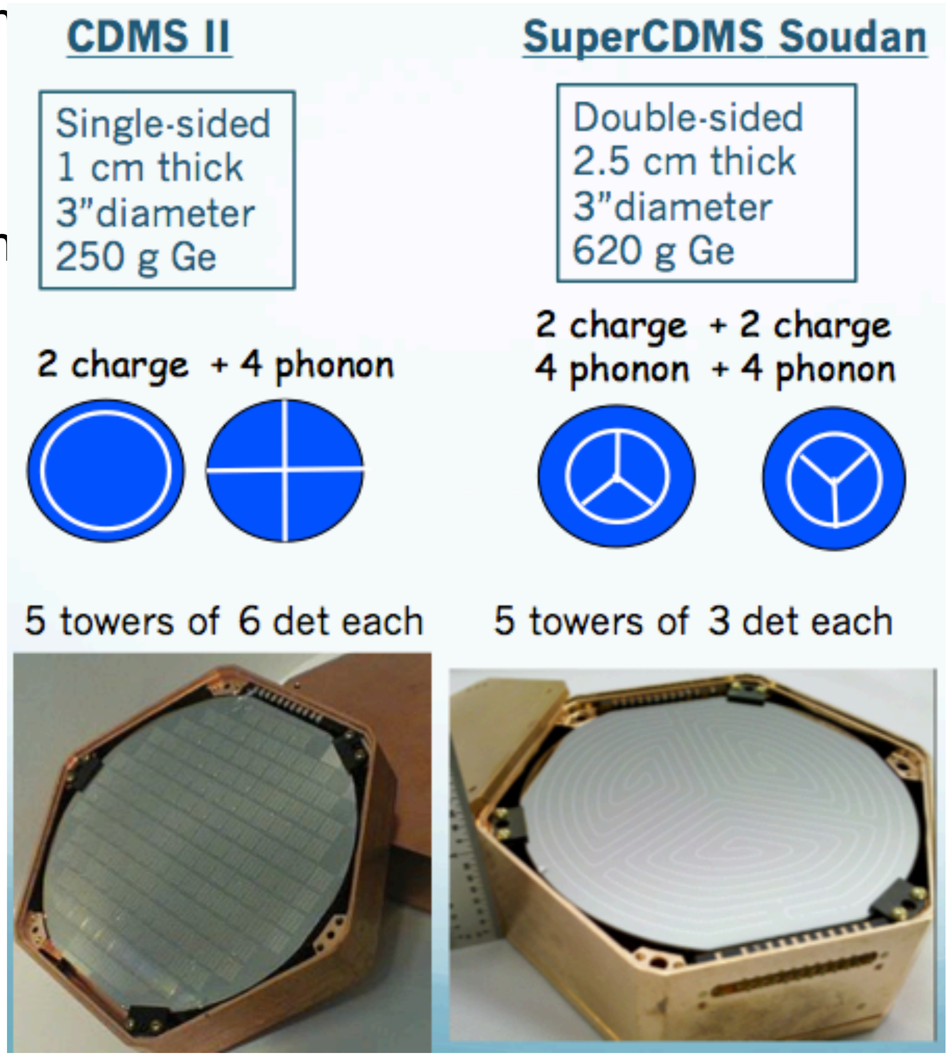
* Limits improved by 1.6 a high mass

* Confirms that bkgs must be present



SuperCDMS Soudan: 650g iZIPs

- ZIP Phonon-based rejection not reliable enough:
  go to bigger detectors,
  more phonon channels with better geometry and **ID electrodes** *(but no "veto" electrode readout)*
- Data started in 2012
  with 9 kg (6 kg fiducial
- 2200 kgd by 2014
  6×10^{-9} pb for 100 GeV/c^2
- Also: goals for lowering thresholds for low-mass WIMPs (at the expense of surface event rejection from phonon timing)



Cushman, IDM2012

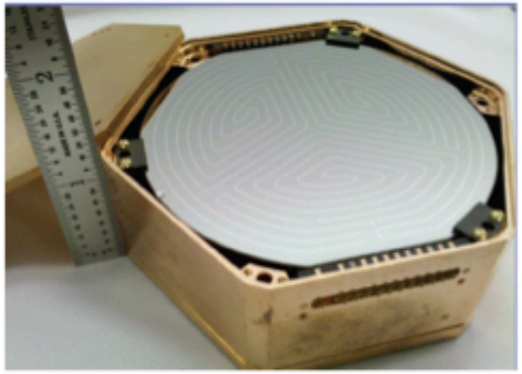
CDMS iZIP

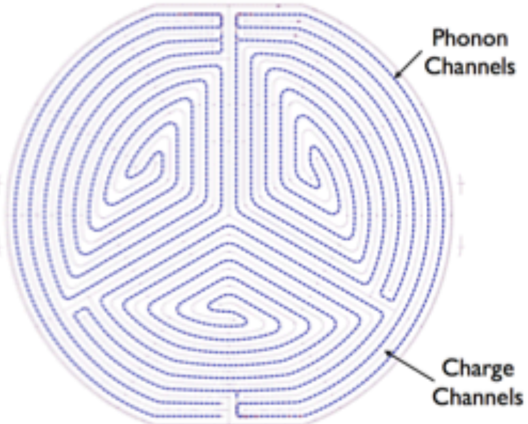
iZIP detector design - II

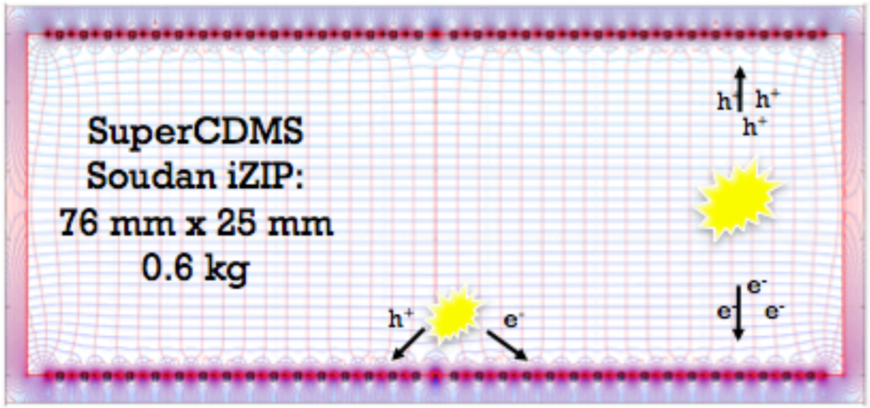
4

Electrode Scheme

- NEW interleaved layout of ionization and phonon sensors
- We now have phonon sensors and ionization sensors on BOTH the top and bottom of the detector
- Major improvements in discrimination from this new technology







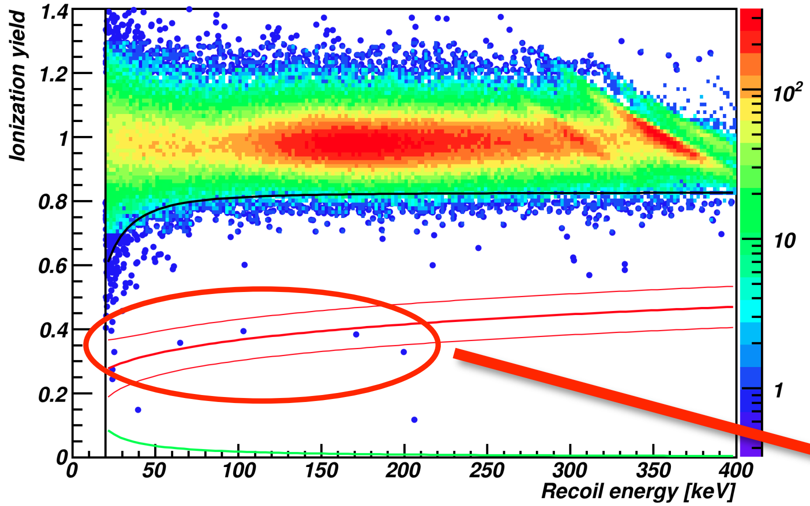
Silvia Scorza

9/6/11

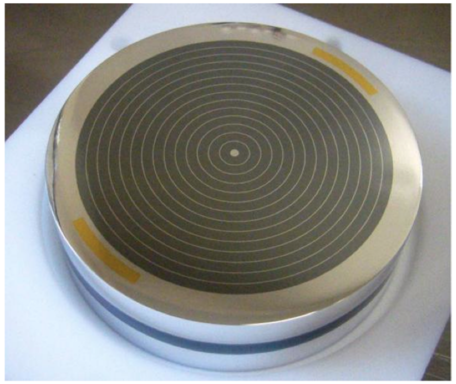
Old EDELWEISS-ID design drawback

- Problem: large non-fiducial volume (blue) with low field under flat guard electrodes

^{133}Ba calib: 350 000 γ



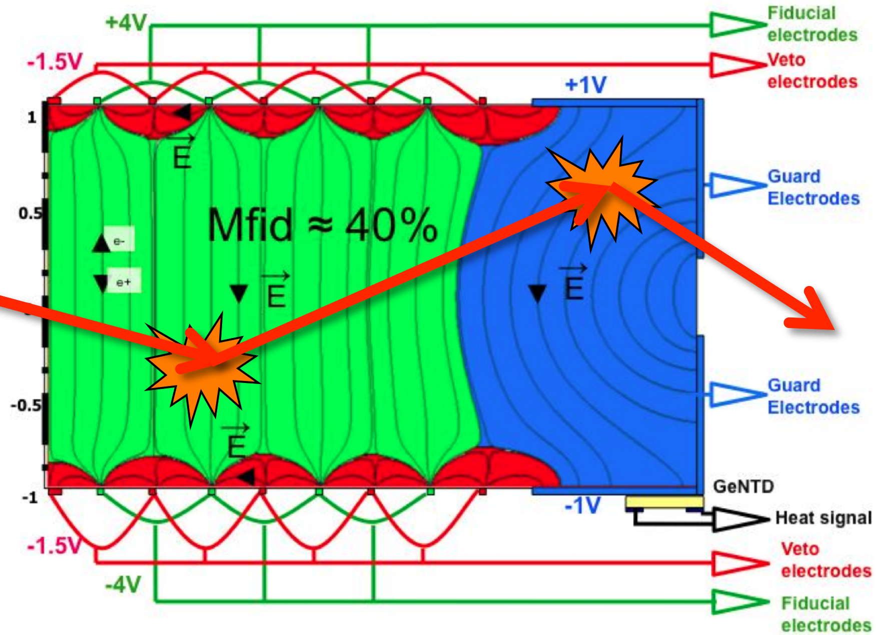
- Compton produces "anomalous leakage" à la XENON
- Large uncertainty from this bkg
- *Only 160 g fiducial / 400 g!*



400g cylindrical ID detector

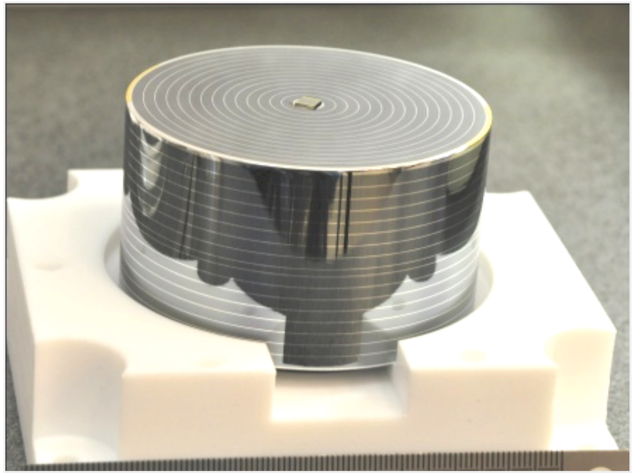
EDELWEISS-II:

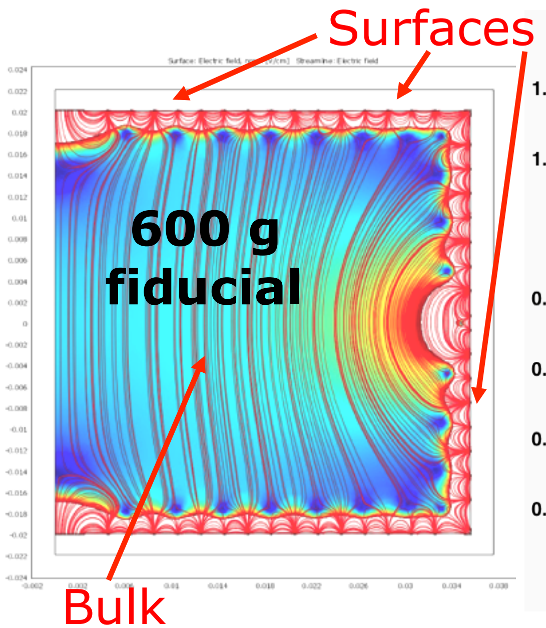
10x400g ID,
1.6 kg tot. fiducial

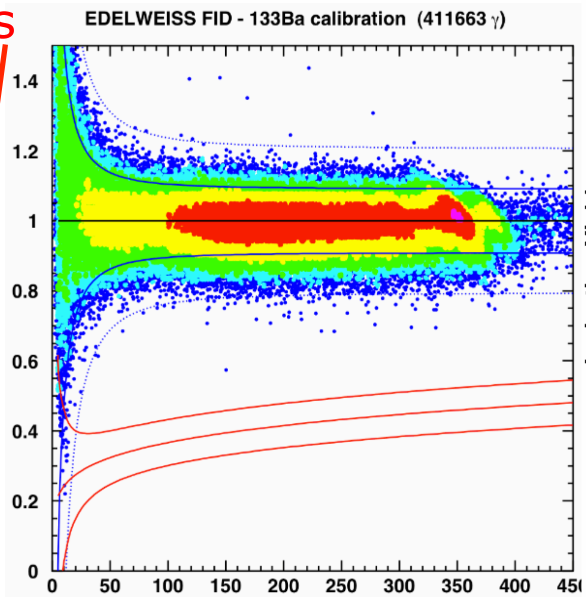


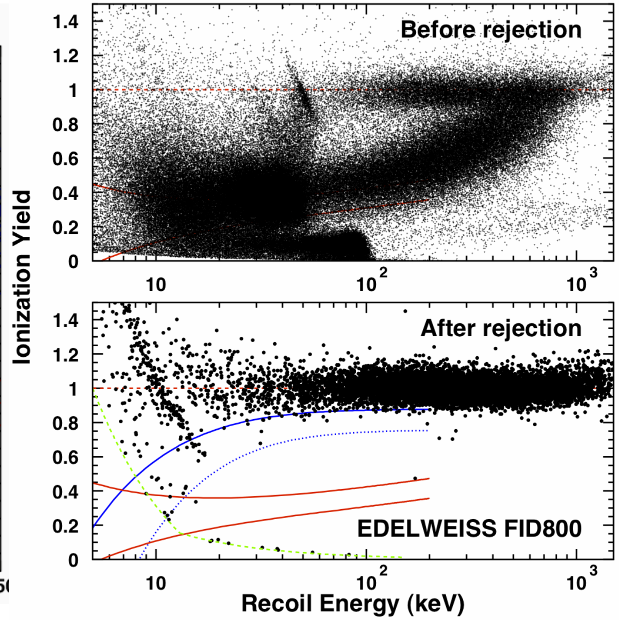
EDELWEISS-III new FID800 design

- FID: detectors FULLY covered with interleaved electrodes (and go from 400 -> 800 g)
- Commissioning 15 FID800
- **Improved γ and surface rejection**
- 40 detectors for end 2013



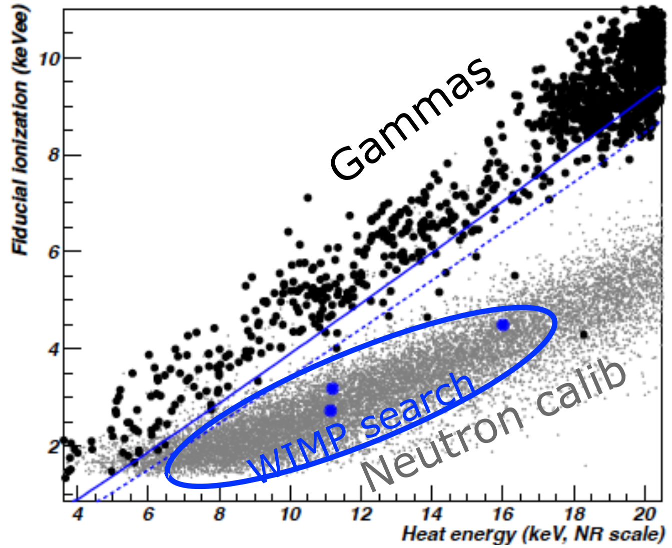


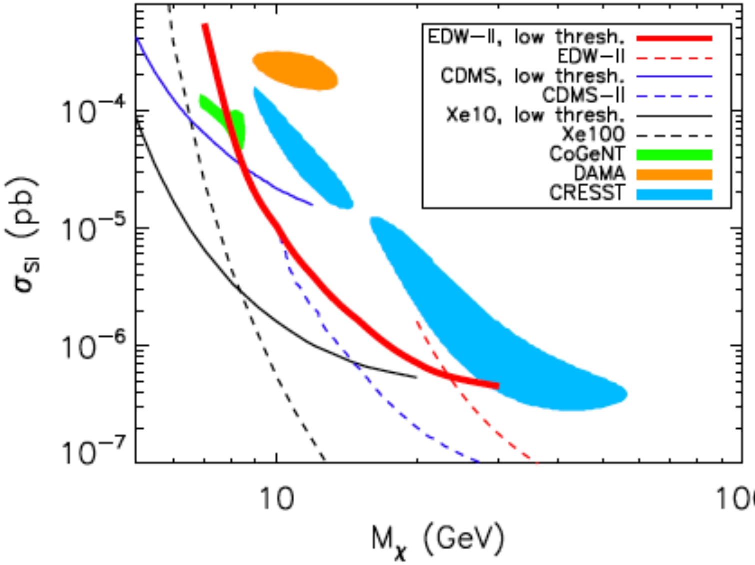




EDELWEISS low mass

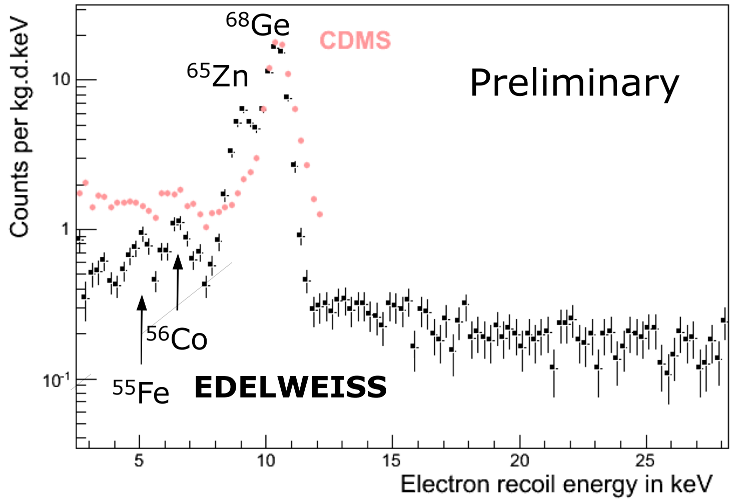
- Avg ID FWHM baselines in 384 kgd sample: 0.9 keV ionization, 1.25 keV heat (acceptable for >50 GeV WIMP search: ~100% eff. for 20 keV recoil threshold)
- Need improvement for ~10 GeV WIMPs
- Low-mass search with 113 kgd with best resolutions [PRD 86 (2012) 051701(R)]
- Fiducial selection applicable down to ~6 keV recoils: Surface event rejections
- Best *Ge* sensitivity at ~9 GeV





arXiv:1207.1815v1

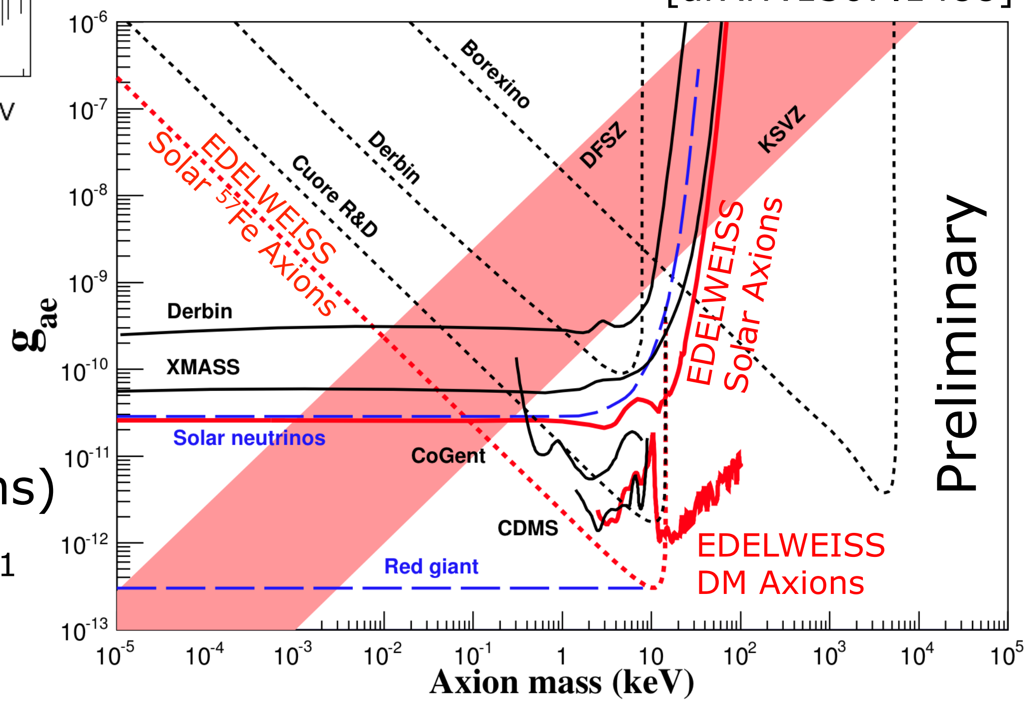
Axions and Axion-Like Particles search



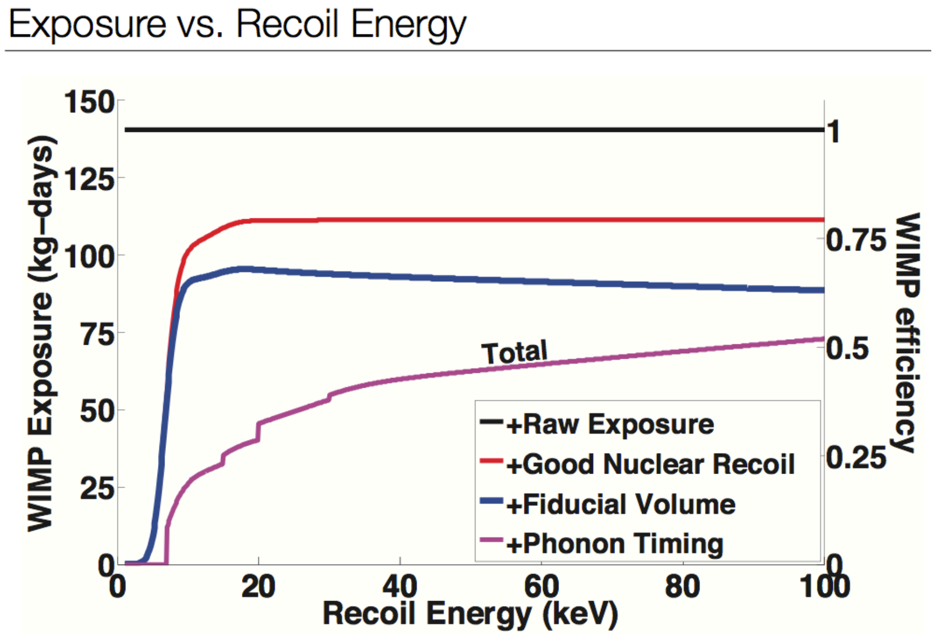
- Low-threshold sample electron recoil also used for axion search
- Fiducial selection helps reduce background at low energy

- Interesting axion limits (via Primakoff or axio-electric detection, solar & dark matter axions) also: $g_{A\gamma} < 2.1 \times 10^{-9}$ GeV^{-1}

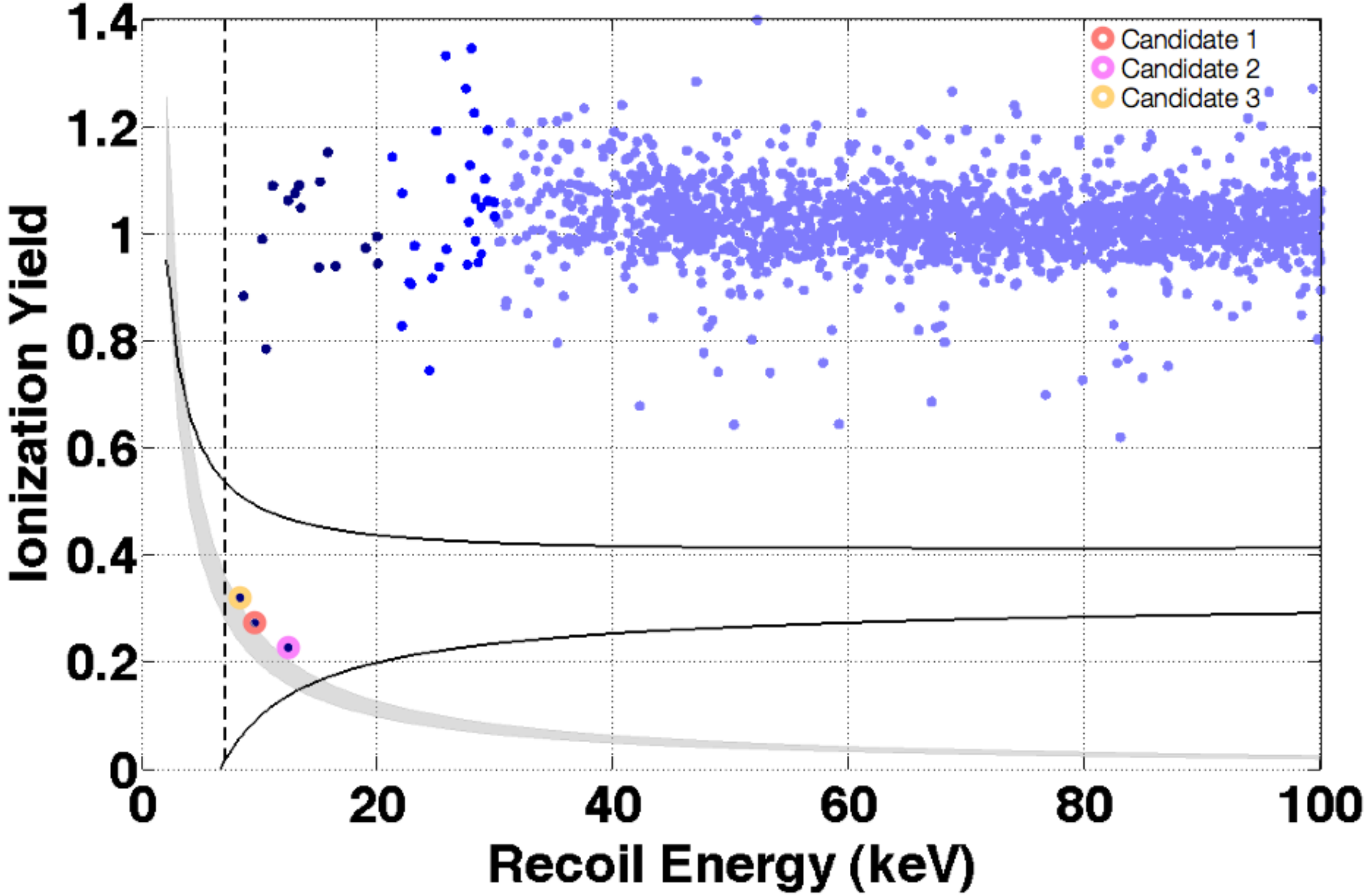
[arXiv:1307.1488]



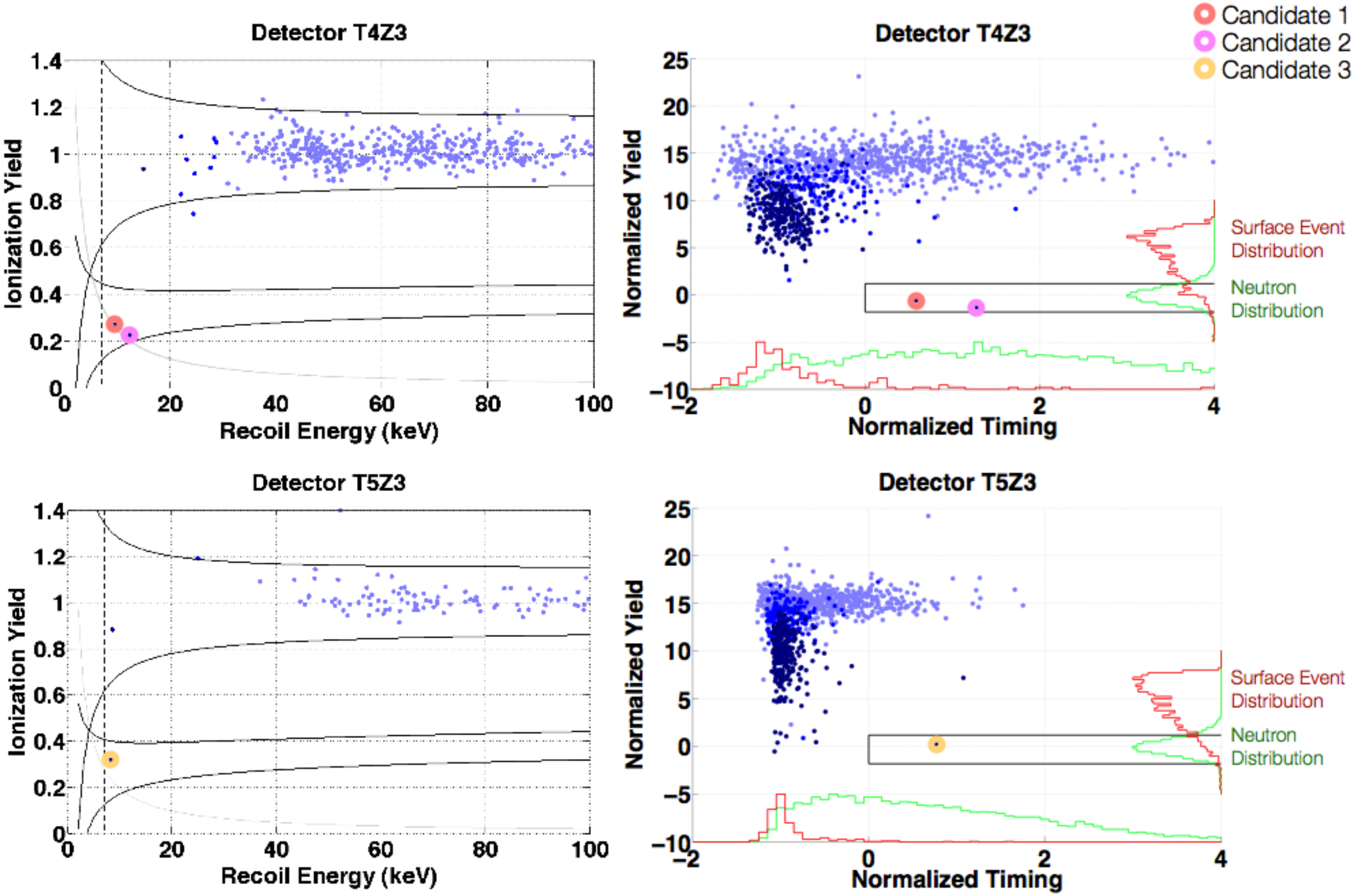
- Analysis of final Soudan exposure: 140 kgd 2007-2008 Si data with better control of background than previous 56 kgd sample. [arXiv: 1304.4279]
- Estimated background: 0.4±0.3 surface events (phonon timing), <0.13 from neutrons, <0.08 from ^{206}Pb



Unblinding Results - after timing cut

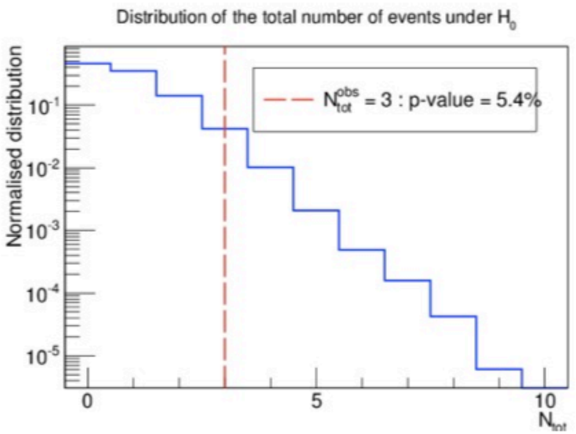


Three Events!



Profile Likelihood of Silicon data

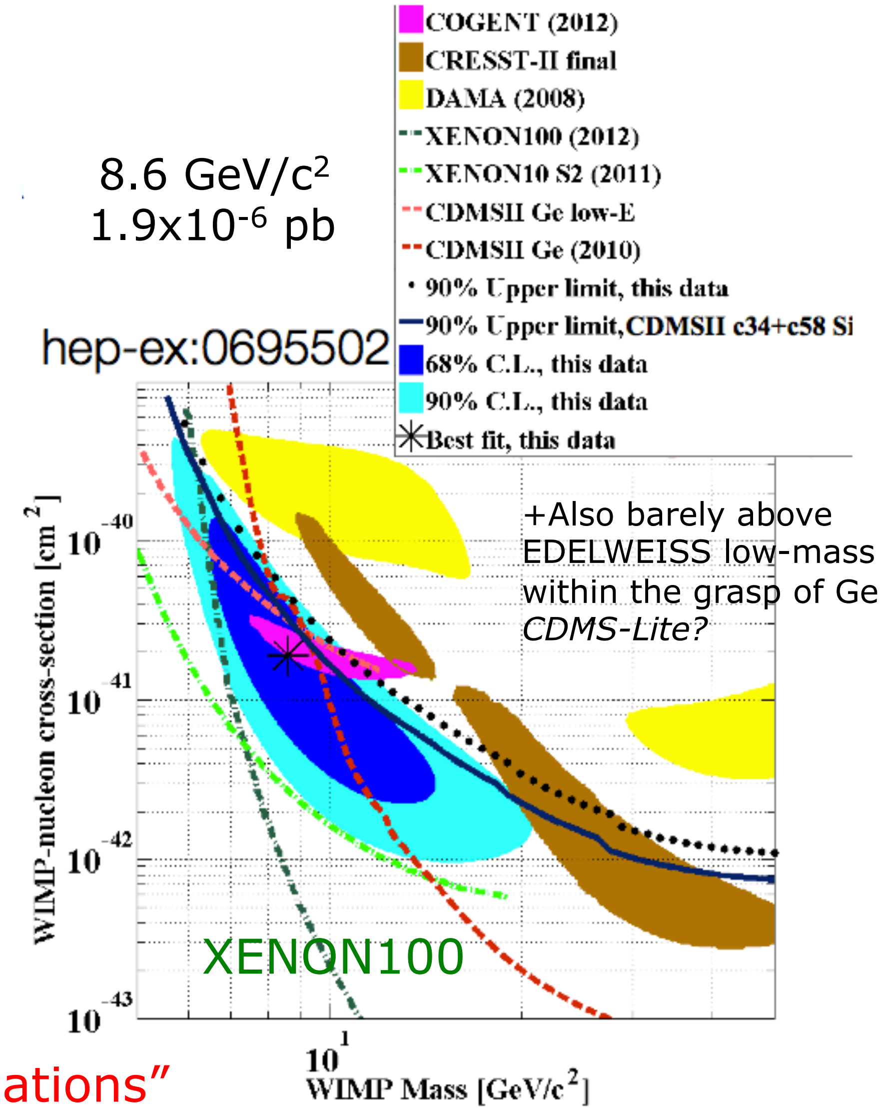
- Monte Carlo simulations of the background-only model indicate the probability of a statistical fluctuation producing three or more events anywhere in our signal region is 5.4%.



But WIMP+bkg hypothesis favored over known bkg estimate by 99.81% CL

8.6 GeV/c^2
1.9x10^{-6} pb

hep-ex:0695502



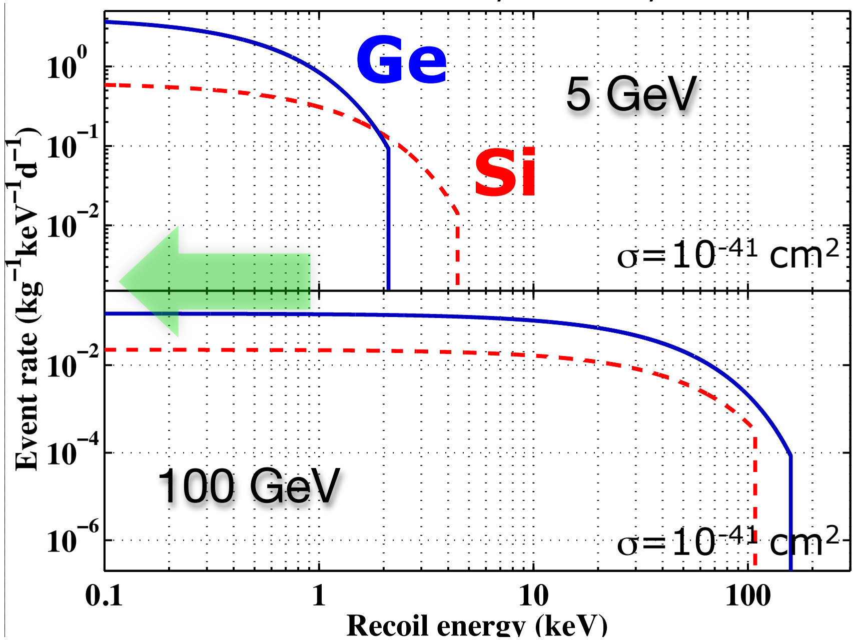
+Also barely above EDELWEISS low-mass within the grasp of Ge *CDMS-Lite?*

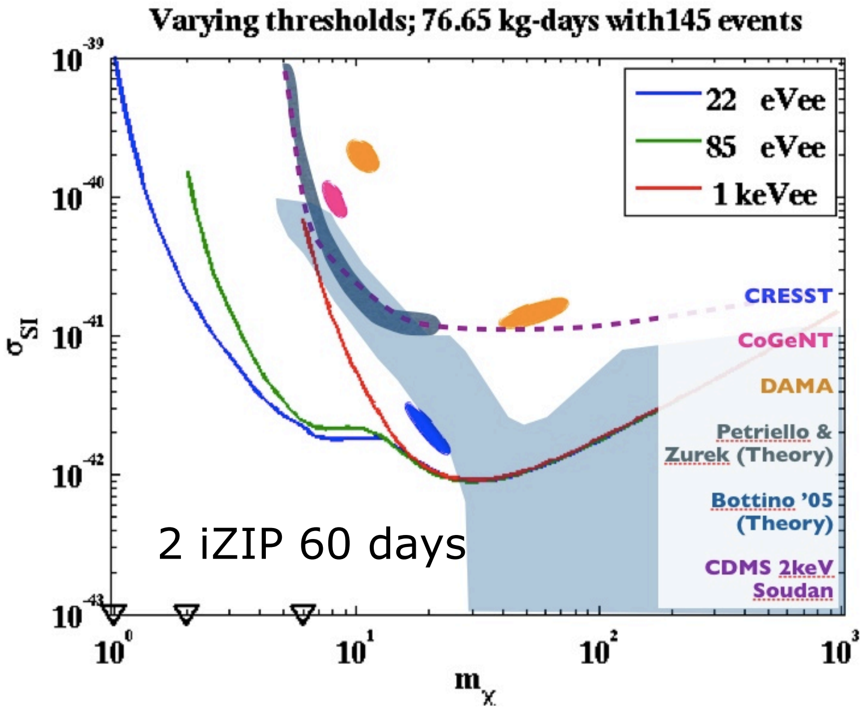
"Calls for futher investigations"

Dedicated low mass WIMPs

- Using Luke-Neganov amplification, can lower the threshold
- Price to pay: no nuclear recoil discrimination (but can test it by varying V_{polar})
- Current threshold on $E_{electron\text{-}equivalent}$ ~ 1 keV_{ee} with V_{polar} = 3.2V
- Biasing at 70V reduces threshold by (1+3.2/3)/(1+70/3) = 12
- 85 eV_{ee} threshold on (standard iZIP) Ge detector

CDMSLite, Thakur, IDM2012





Future projects: USA

- 1.38 kg iZIPs
- R&D to be completed in 2013
- Funding request 2013-2014
- Goal: 200 kg Ge
  140 000 kgd
  (4 year run)
  10^{-10} pb in ~2017

Cushman, IDM2012

Future project EU

- European priority: completion of EDELWEISS-III (physics 2014-2015) and present CRESST runs
- EURECA: ~1 t combining Ge and $CaWO_4$ targets
- EURECA CDR recently completed
- Preferred site: extension of the Modane Laboratory (operational ~2019)
- 2013: discussions with SuperCDMS-SNOLAB (~2015): discussion on common strategy, collaboration for the cryogenics underway.

Recent published spin-independent results

- Little progress between original 80's experiments (~1 evt/ kg/d) until 2000, when discrimination techniques finally got operational. Long development time!
- We're still two orders of magnitude away from the physics goal
- Promising results to come!