Recent Experimental Advances in Direct Dark Matter Searches

LHC is ready for the identification of Dark Matter…

… are Direct Search experiments ready?

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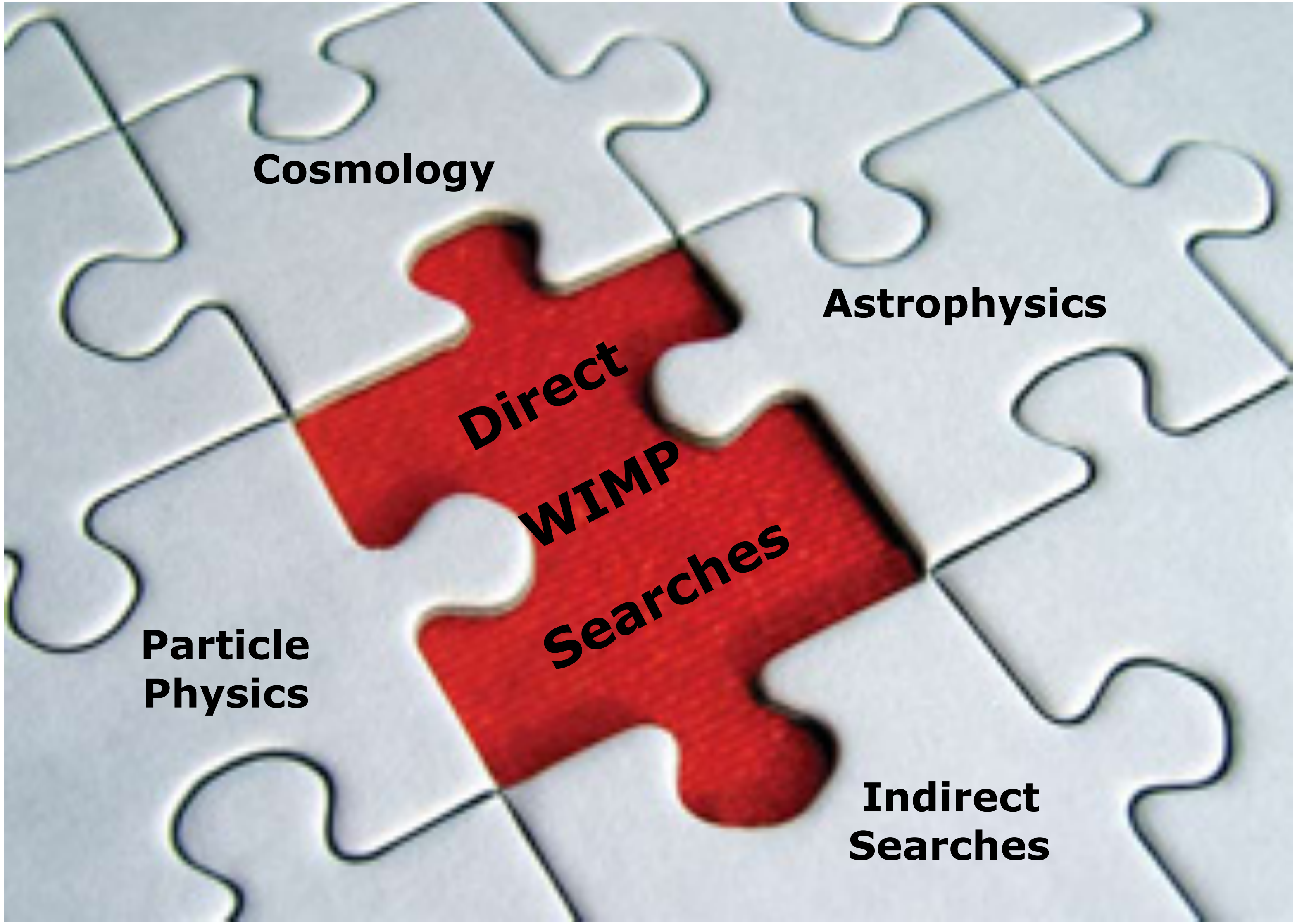
Plan

- Experimental Context

- CMSSM-motivated searches: recent leading results
  - XENON, CDMS, EDELWEISS

- Other searches
  - Low-mass and spin-dependent searches, directional detectors

An important piece of the puzzle



The pieces of the puzzle

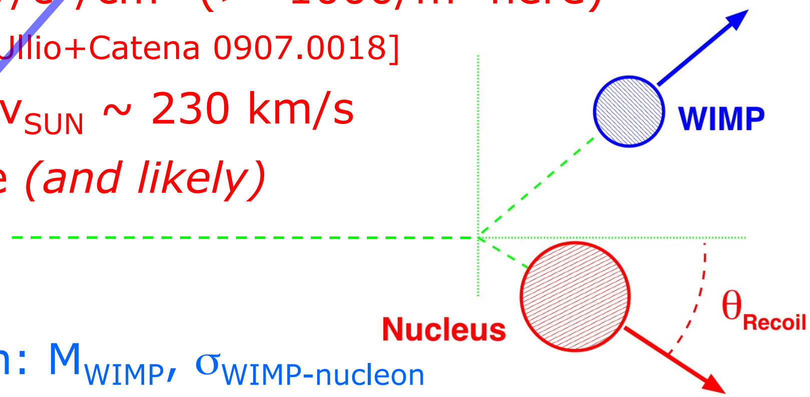
- Cosmology
  - Need for non-baryonic WIMP dark matter in early universe (CMB, large-scale…) *[WMAP, Planck, …]*
- Astrophysics
  - Gravitational probes at galactic/cluster sizes
  - WIMPs present in our Galaxy with density ~0.3 GeV/cm^3
- Particle Physics
  - Thermal relics WIMPs appear as natural consequence of SuperSymmetry (and other theories like Kaluza-Klein, …) *[can be probed by Collider physics]*
- Indirect Searches
  - Annihilation decay products: γ *[HESS, FERMI…]*, ν *[IceCUBE, ANTARES]*, e^+, pbar, dbar *[ATIC, PAMELA, AMS, …]*…
- Direct Searches: galactic WIMP collision with an atom in lab
  - Is the halo of our Galaxy made of the same WIMPs that can be produced at colliders?

WIMP scattering rate

$$\frac{Rate}{Mass} \approx \rho_{wimp} \times f(Velocity) \times \frac{A}{M_{wimp}} \sigma_{wimp-nucleon} \times F(Coherence)$$

Astrophysics:

- *Use Lewin&Smith convention [Astrop 6 (1996) 87] to compare experiments*
- Local WIMP density ρ_{wimp} = 0.3 GeV/c²/cm³ (>~1000/m³ here)
  - … despite more recent estimate: 0.39±0.2 [Ullio+Catena 0907.0018]
- Spherical isothermal Halo: $v_{WIMP} \sim v_{SUN}$ ~ 230 km/s
- More complex Halo models possible *(and likely)*

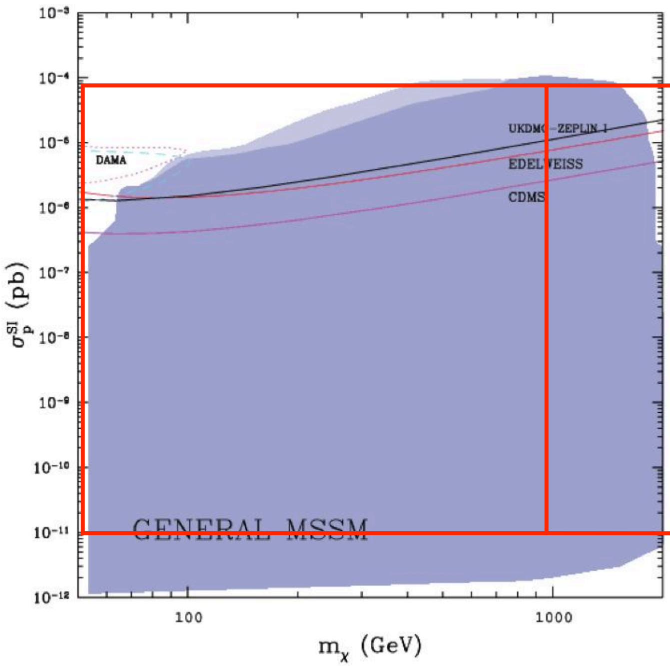


Particle and Nuclear Physics:

- Free parameters / theory prediction: M_{WIMP}, $\sigma_{WIMP\text{-}nucleon}$
  - Extrapolation WIMP-quark -> wimp-nucleon: quark content of nucleons
- Coherence factor:
  - ~A^2 for scalar coupling (spin-indep. interactions, *dominates for A>~20*)
  - ~J(J+1) for axial coupling (spin-dep. interactions)
  - Nuclear Form factor (reduce A^2 enhancement at large A)

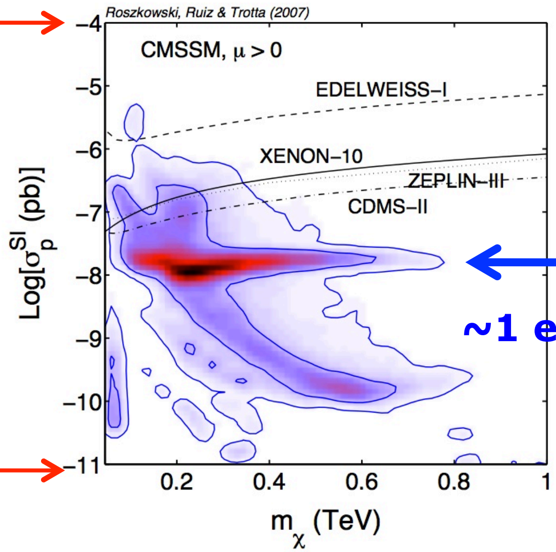
WIMP cross-sections in the CMSSM

- Most general SUSY not very predictive
- CMSSM (M_{GUT}~10^{16} GeV, "benchmark" for LHC): more predictive
- 10^{-8} pb "Focus point" ~"easy" reach for Direct Searches



Kim, Nihei, Roszkowski & Ruiz de Austri 2002

Baysian scan, log priors



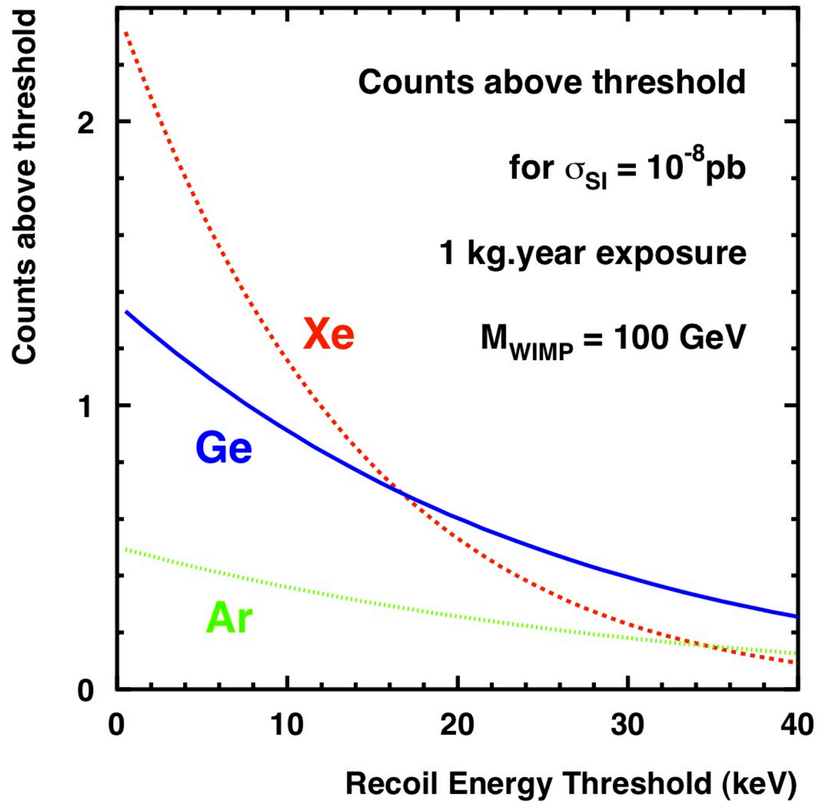
~1 evt/kg/year

- *Focus search on this region, but keep eyes open for alternative models*
- Complementarity: LHC probes M_{WIMP}, direct searches probe $\sigma_{WIMP\text{-}nucleon}$

Rates in detectors

- 10^{-8} pb ~ 1 evt/kg/year
  - Rate depends on *energy threshold* and *atomic mass*

Calculation based on Lewin & Smith convention [Astrop 6 (1996) 87]



Main challenge:

extreme suppression of background from natural radioactivity at low energy

(ex.: people = 10^{10} decay/kg/year)

- *Material selection*
- *Shielding (surround.+cosmics)*
- *Rejection*
- *Detailed understanding of background tails and detector imperfections.*

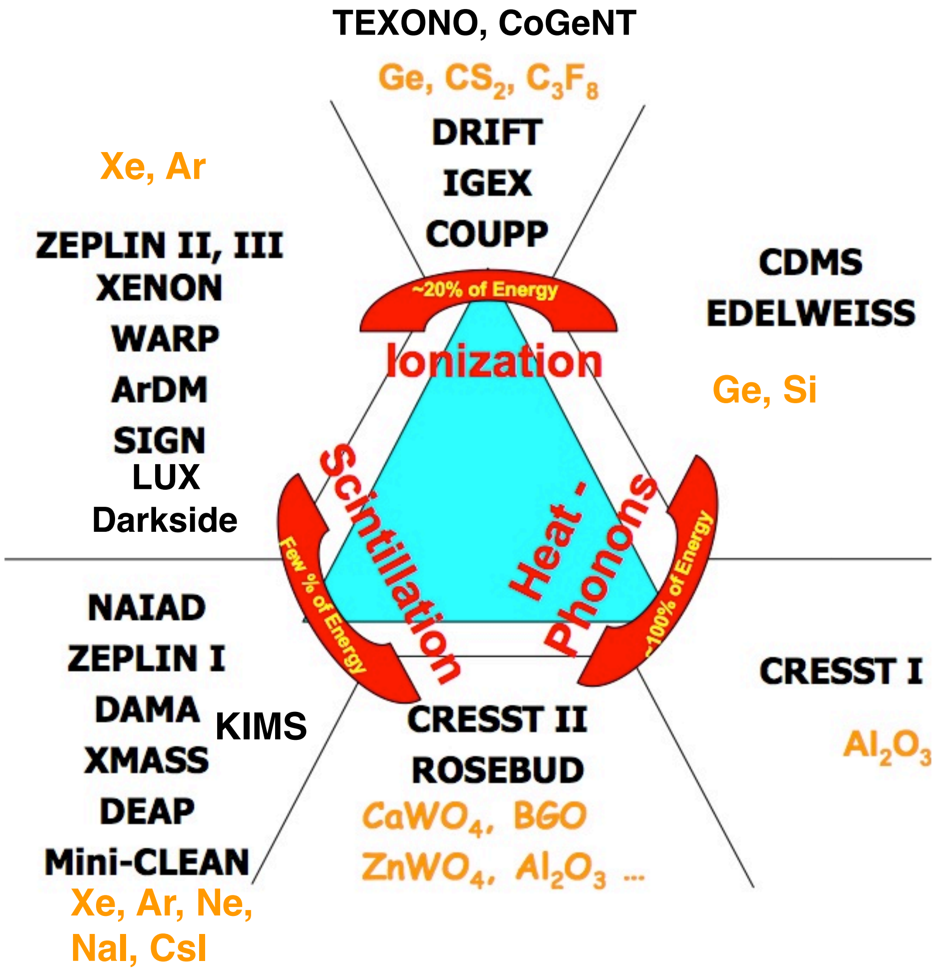
WIMP signatures

- Directionality (correlation with v_{sun})
  - Challenge: ~20 nm recoil in solid, ~30μm in gas
  - Low-pressure TPC? -> Still on R&D
  - *Small annual modulation of flux (~2%) requires large statistics + depends more on velocity distribution details.*
- Nuclear (and not electron = dominant bkg) recoils
  - **Particle identification**
- A^3 dependence of coherent scattering rate/kg
  - Motivates **diversity of target materials**
- Large scattering length
  - **Self-shielding** *[Xenon, Argon]* or **segmentation+multiplicity** *[Ge, Scintillators]*
- Control of systematics also favours target/expt. diversity

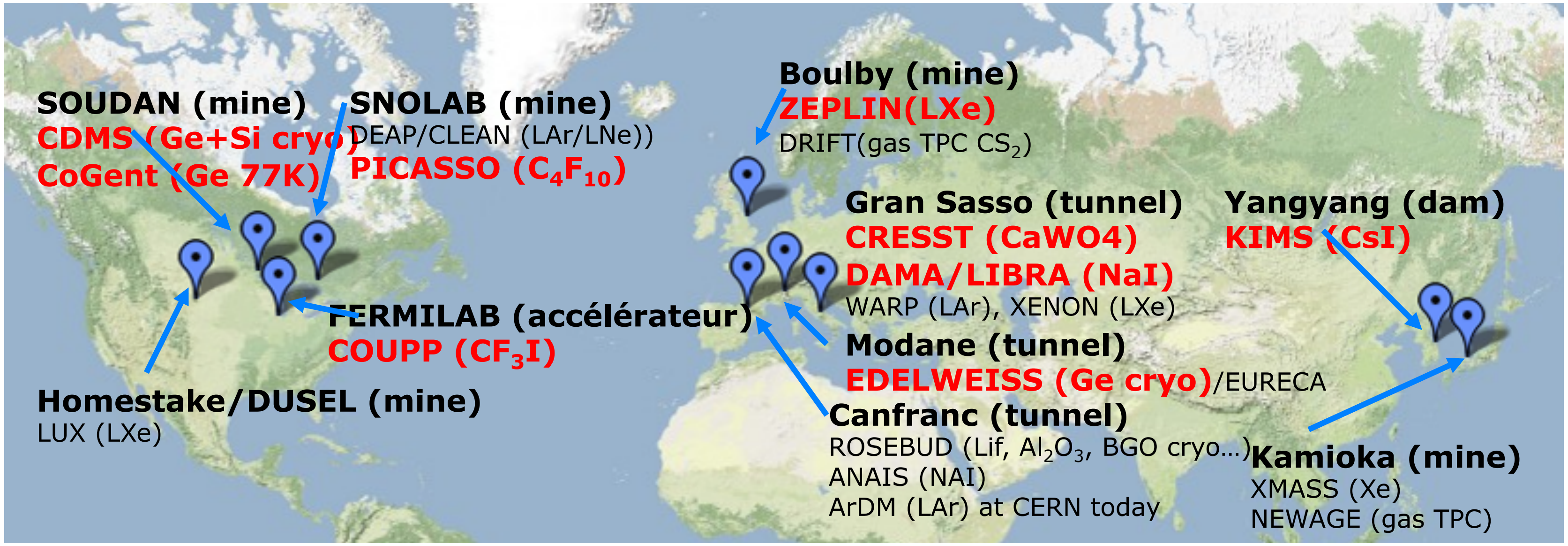
Competing technologies

- Trick: combine signals for ion/electron identification

- Heat (thermalized phonons): "true" calorimetric energy measurement
- Ionization, Scintillation: "Yield" or "Quenching" factor, low-energy calibration required
- Pulse shape discrimination: useful in some cases (Ne, Ar)
- Also: dE/dx in superheated medium: COUPP, PICASSO



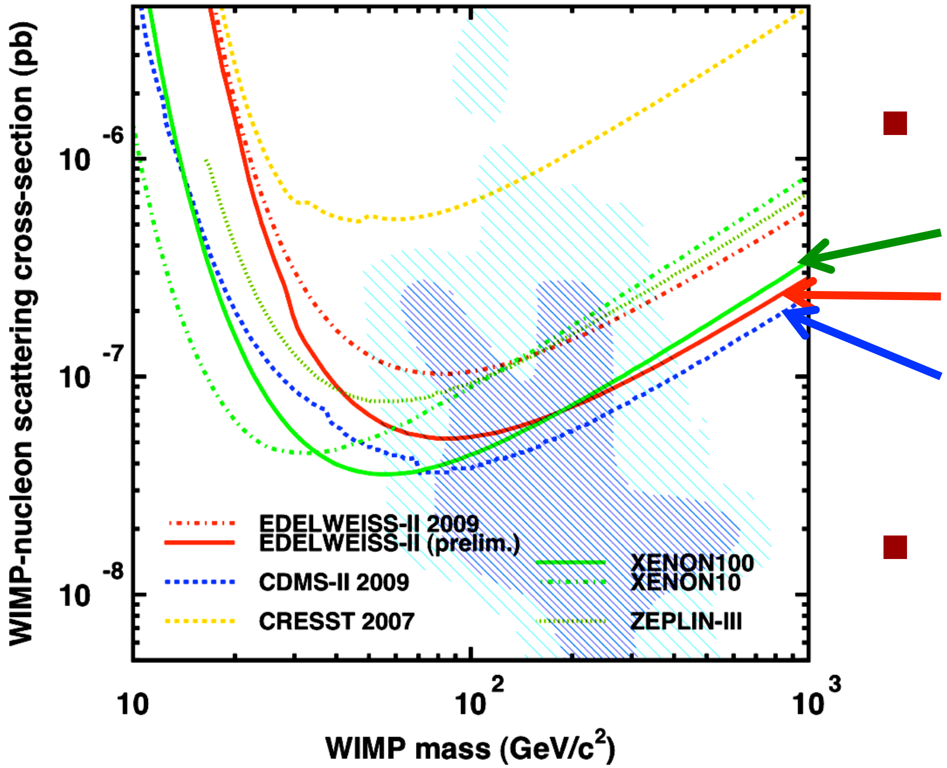
Recent Searches Results since 2008



DAMA	**April 08**	**Solid Scintillator – modulation only**
ZEPLIN III	**Dec 08**	**Double-phase noble gas**
CDMS	**March 08 / Dec 09**	**Cryogenic (Heat-ionization)**
PICASSO	**July 09**	**Metastable C_4F_{10} droplets (low-mass, spin dep.)**
COUPP	**Feb 08/Feb 10**	**Metastable CF_3I bubble chamber (spin dep.)**
CoGeNT	**June 08/Feb10**	**Ge 77K, low-mass WIMP**
XENON100	**March 10**	**Double-phase noble gas**
EDELWEISS	**Dec 09 / July10**	**Cryogenic (Heat-ionization)**

M_{WIMP} > 40 GeV, Spin-independent

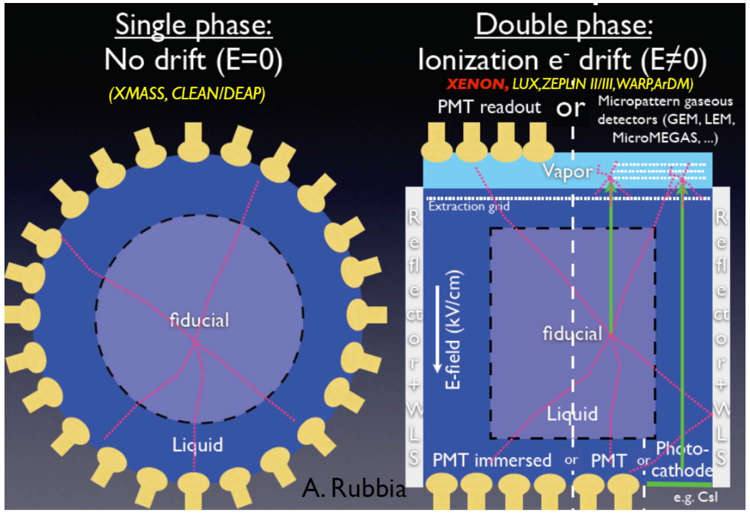
CMSSM scan: Roszkowski, Ruiz de Autri and Trotta, JHEP 07 (2007) 075.



- Achieved sensitivities in CMSSM-inspired searches
- Leading sensitivities: **XENON100** (Xe bi-phase), **EDELWEISS** (cryo Ge) and **CDMS** (cryo Ge)
- Compare techniques:
  - Discrimination techniques
  - Background levels
  - Resolution, thresholds

Noble liquid detectors

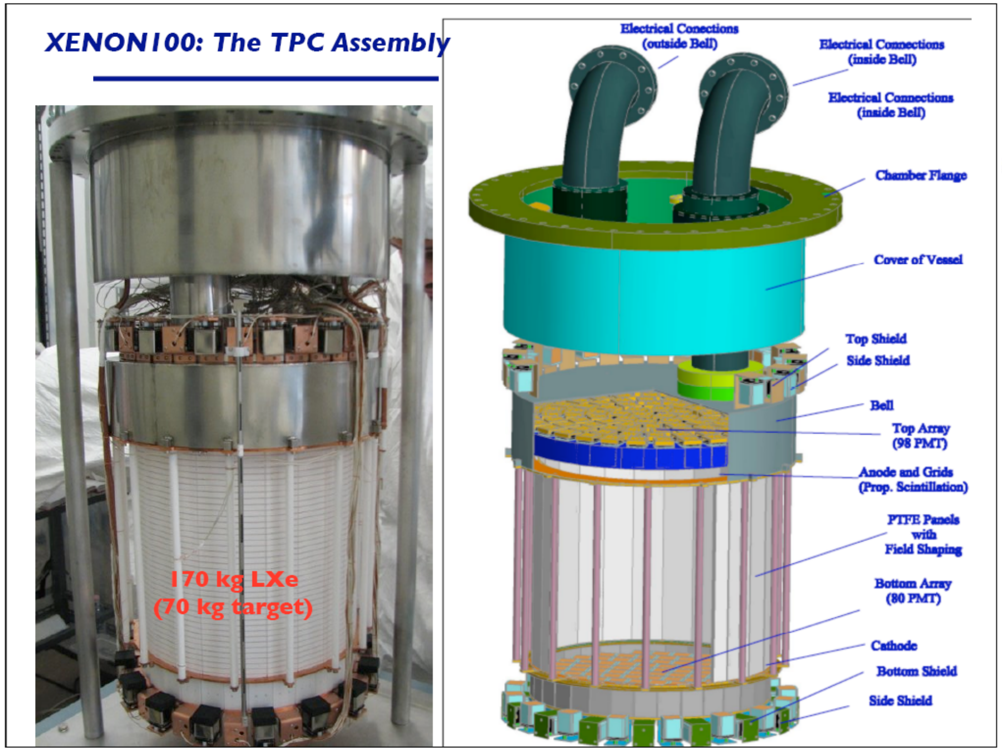
- Xe: large A; Ar: low cost
- High purification (recirculation)
  - ^{39}Ar (1Bq/kg): requires $>10^7$ rejection for 10^{-8}pb, or depleted Ar (DarkSide)

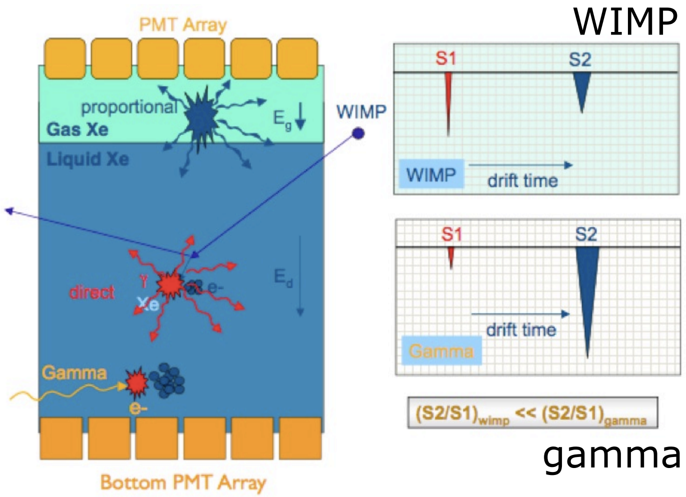


- 3 rejection techniques
  - Self-shielding in large volume [eg: K. Abe, XMASS, this conf.]
  - Ratio (prompt scintillation)/(ionization)
  - Scintillation pulse shape [eg: DEAP/CLEAN, M. Kos, this conf.]
    - Ar $\tau_{singulet}/\tau_{triplet}$ = 7ns/1.6μs (DEAP/CLEAN, WARP...)
    - Xe $\tau_{singulet}/\tau_{triplet}$ = 4ns/22ns (ZEPLIN-I -> poor discrim.)

XENON-100 at Gran Sasso

- **Xenon 10** (2008) 22 kg LXe, 5 kg fiducial, 15 cm drift
- **Xenon 100** (2010) 170 kg LXe, 40 kg fiducial, 30 cm drift
- 98(top)+80(bottom) PM's -> *(x,y)* coordinates <3mm
- Δt (S2-S1): *z* coordinate

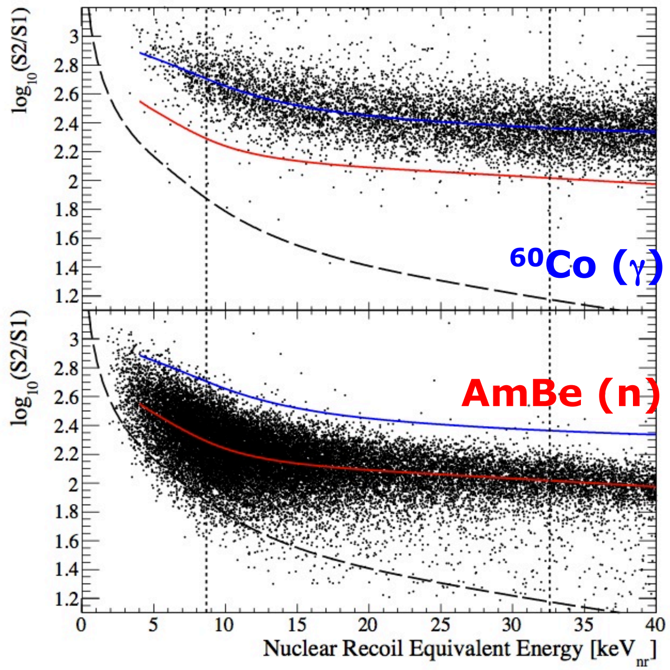


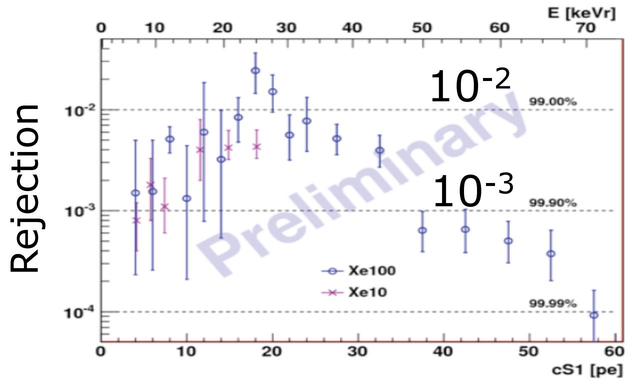


- 10 keV nuclear recoil:
  - S1 ~ 5 P.E.
  - S2 ~ 800 P.E.

XENON discrimination

- Rejection tested with gamma/ neutron sources
- Wide γ distribution: keep lower 50% of nuclear recoils
- ~10^{-2} to 10^{-3} reduction of γ bkg in relevant range



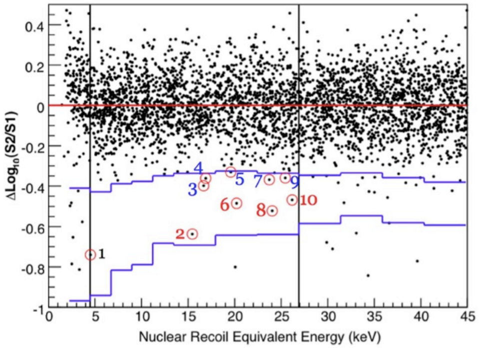


XENON-100 data

- Data between Oct. and Nov. 2009
- 11.2 live days x 40 kg,Fid.:
  172 kg.d after selection
- Gain 100 on fid. γ bkg wrt XENON-10

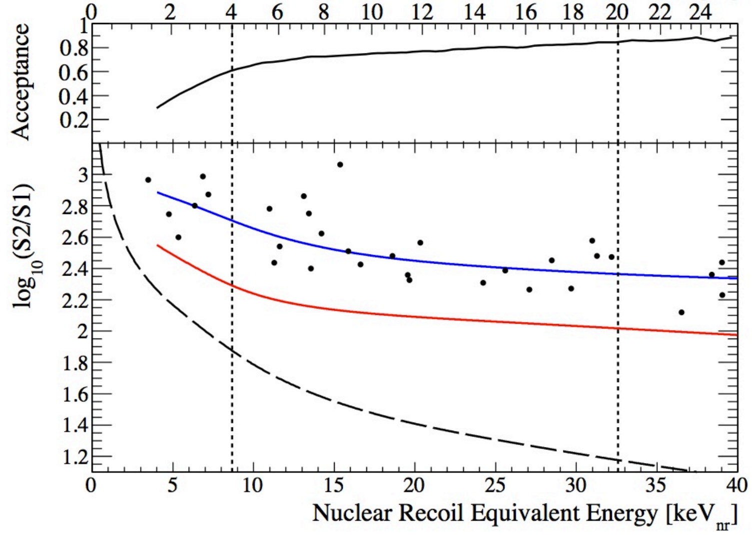
XENON-10:
59 d x 5.4 kgfid
10 NR evts

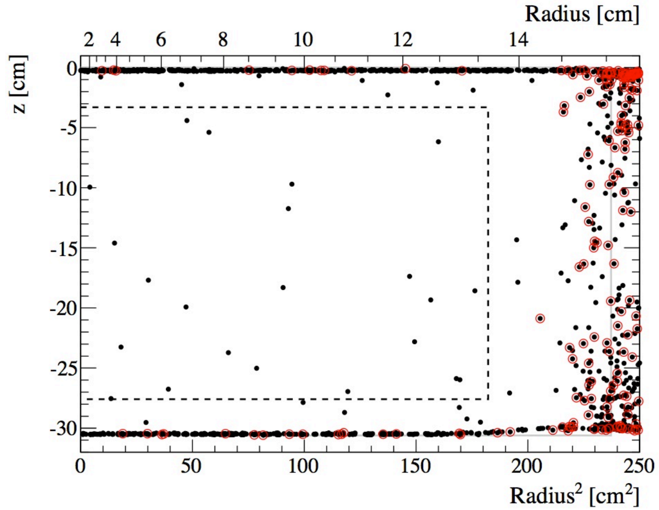
Shielding!



Angle et al., PRL 100 (2008) 021303

Aprile et al, subm. PRL, arXiv:1005.0380

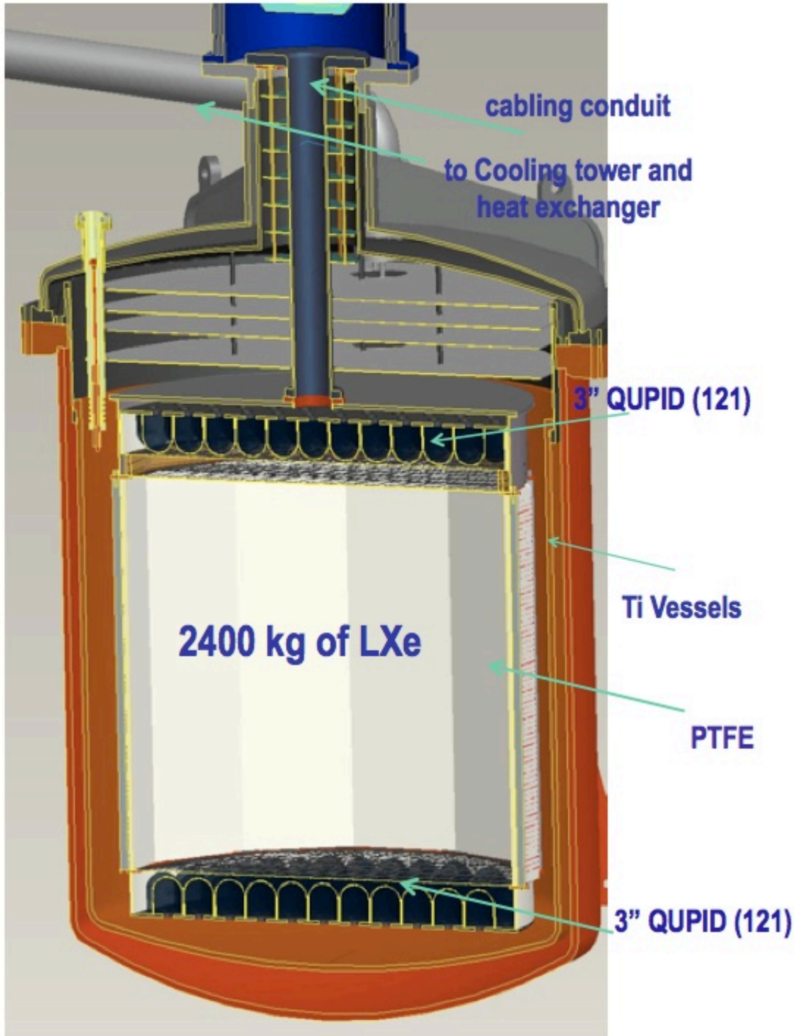




- 0 evt in the recoil zone:
  => 3.4×10^{-8}pb @ 55 GeV/c^2
- Estimated bkg <0.2, limited by rejection of an uniform γ bkg in the fiducial volume
- Acquiring more data (>x11 up to now) for "blind" analysis

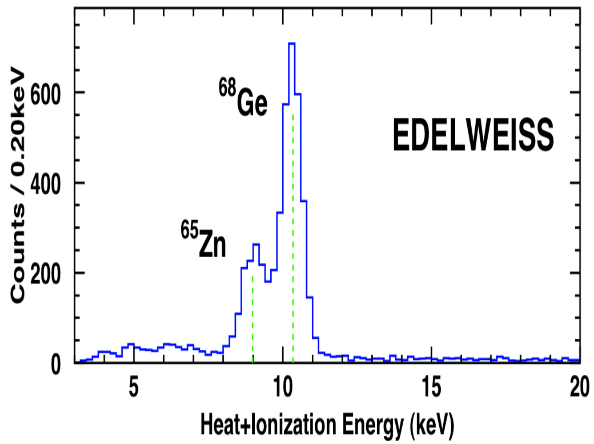
XENON future

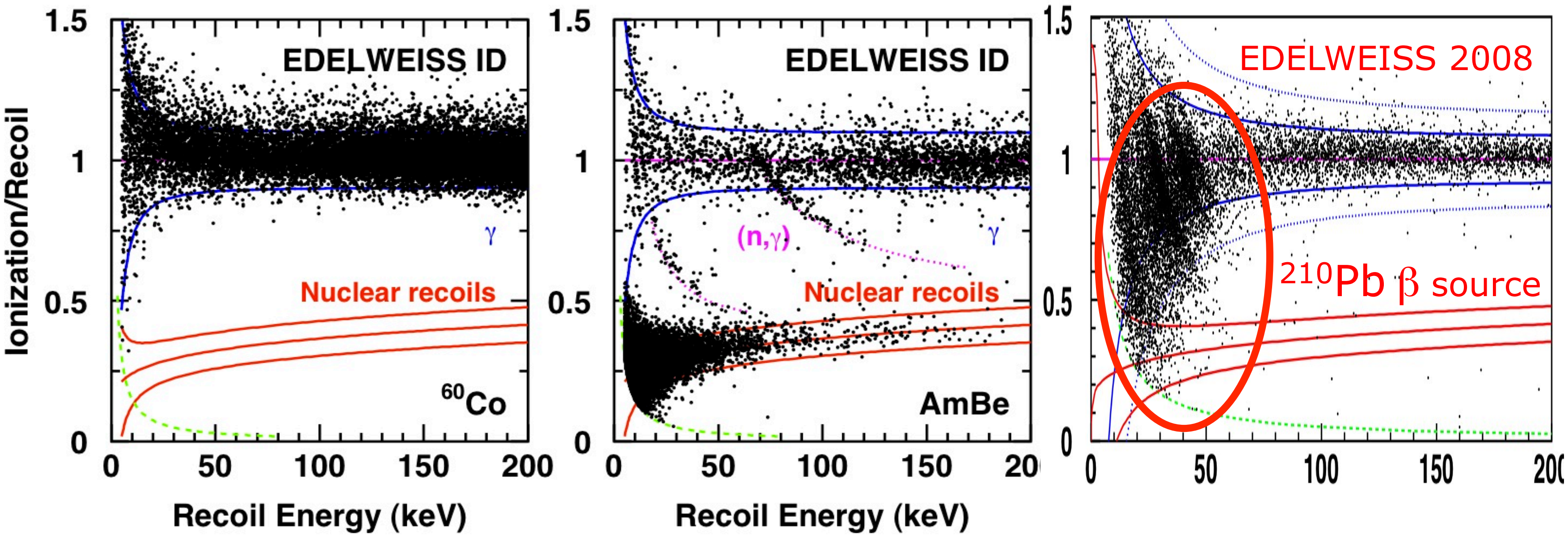
- XENON-100 to run until end 2010
  - goal $2x10^{-9}$pb
  - Improve purification
- XENON-1t (2014, Gran Sasso or LSM)
  - Goal: $3x10^{-11}$ pb
  - Lower radioactivity PMT (QUPIDs) and cryostat, better purification scheme
- Many other Xenon/Argon programs in coming years: LUX, DEAP-CLEAN, WARP, ArDM, DarkSide
- Longer term: multi-ton expts (DARWIN, LZ)



Germanium heat+ionization

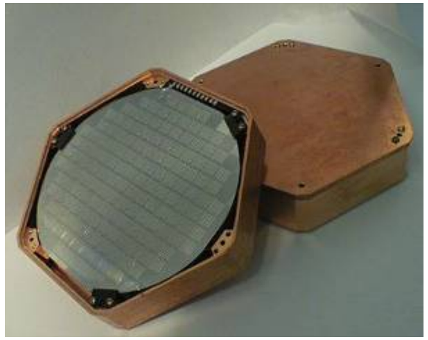
- Germanium = very pure material
- Heat = true calorimetric measurement of recoil energy (independent of slowing-down process)
- Sub-keV resolution for ionization and heat signals is possible
- Ion. yield for nuclear recoils ~1/3 of e^- recoils
- Limitation: charge collection near surface => different rejection strategy for CDMS & EDELWEISS

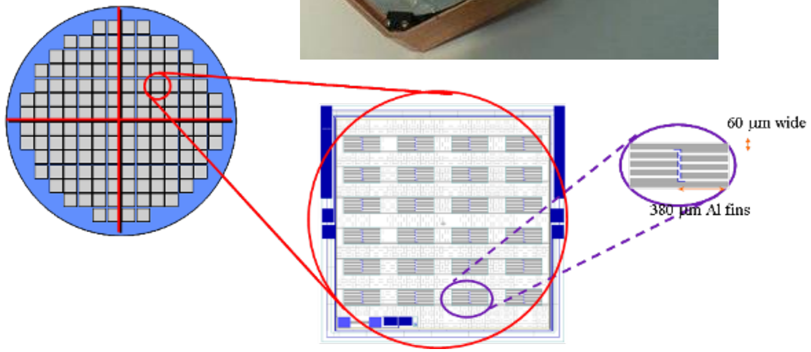


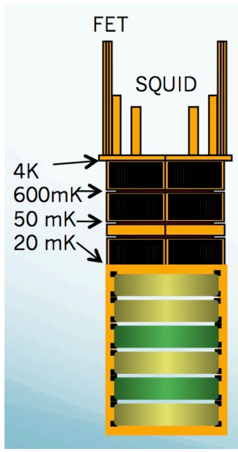


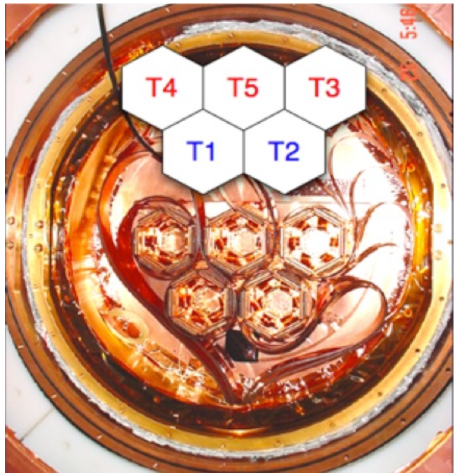
CDMS ZIP detectors

- 250 g Ge or 100 g Si crystal @ 20 mK
- Phonon Sensors : Superconducting W thermometer
  - Photolithographic patterning
  - 4 quadrants, 37 cells per quadrant
  - 6x4 array of 250mm x 1mm W TES per cell
  - Each W sensor "fed" by 8 Al fins (quasiparticle collectors)
- Ionization Sensors: 2 electrodes + ground for rejection of evts in outer ring
- **CDMS-II @ SOUDAN mine**
  - 5 towers x 6 ZIPs
  - 19 Ge x 250 g (4.4 kg)
  - 2006-2008: >1200 kgd before cuts
  - Last 612 kgd analysis released Dec. 2009



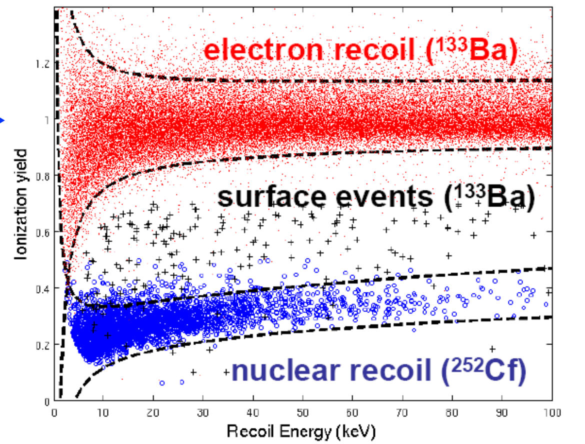




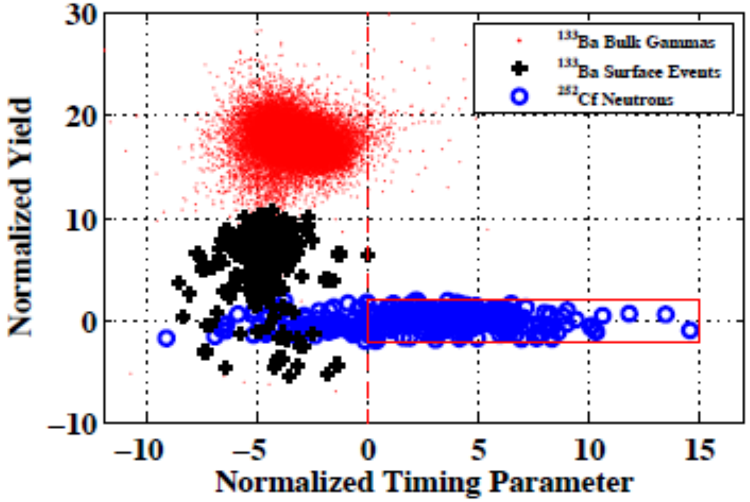


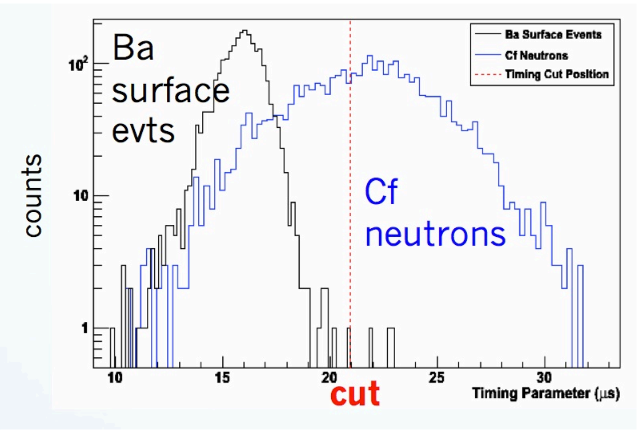
CDMS rejection

- Athermal phonon => 4 quadrant signal give (x,y) coordinates (+energy correction)
- Rejection 1: Ionization Yield



- Rejection 2: Rise-time and time phonon and ionization signal





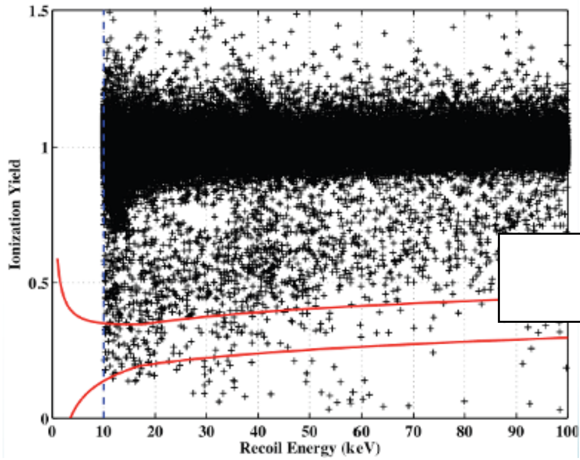
- Selection tuned for <~1 evt bkg event

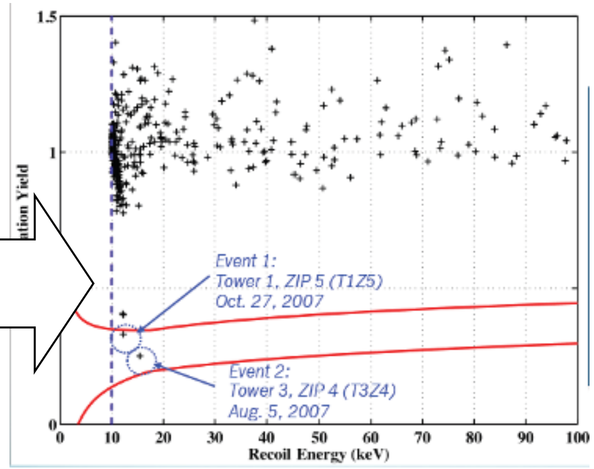
CDMS-II final results

- OPEN the "box" (Nov. 2009) [*Science* 327 (2010) no 5973 p.1619; arXiv:0912.4025]

All data

612 kg.d



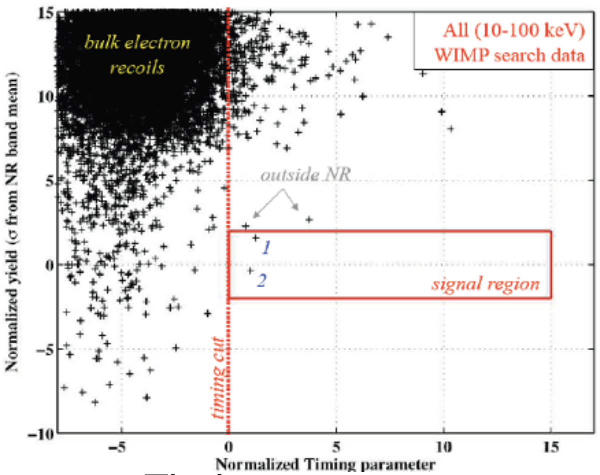


After timing cut

194 kg.d

2 evts

Ion. Yield parameter



Timing parameter

Expected background
0.8 ± 0.1(stat) ± 0.2(sys)

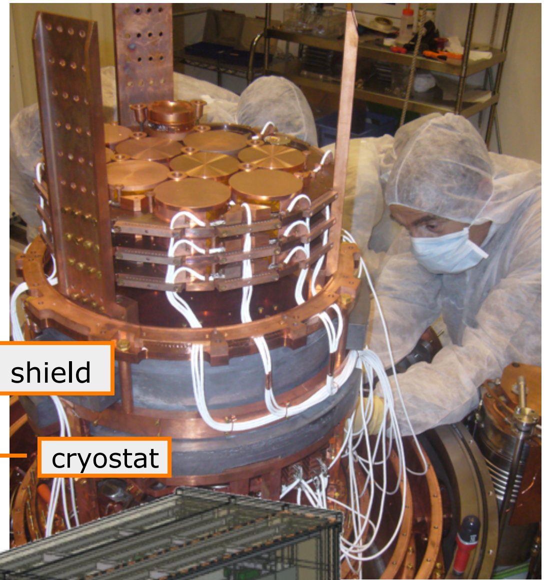
Prob. to observe >=2 events is 23%

"... cannot be interpreted as significant evidence for WIMP interactions. However, we cannot reject either event as signal either."

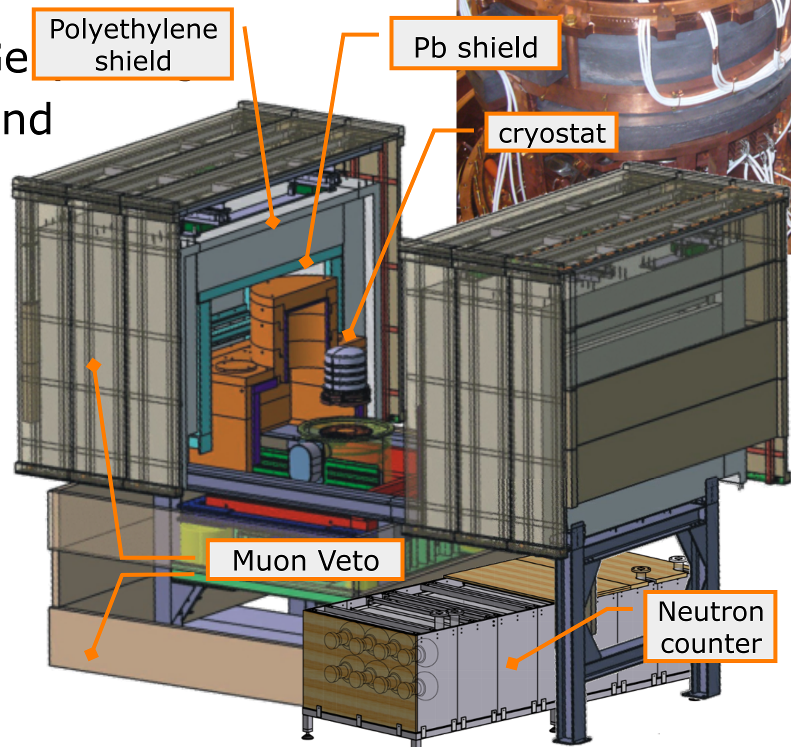
Best limit on σ_{SI}, M_W>70 GeV

EDELWEISS-II ID detectors

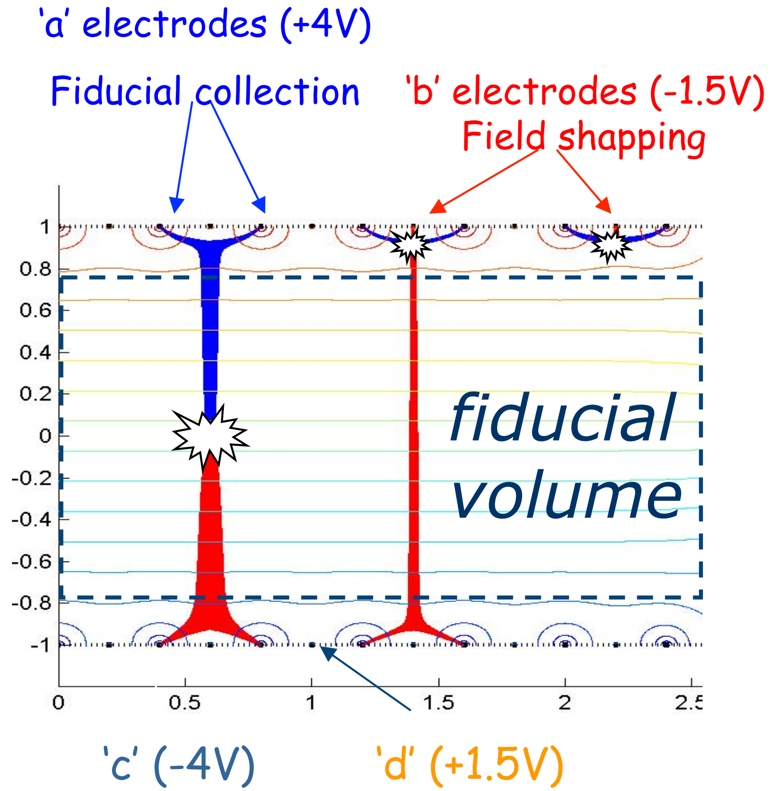
- LSM in Frejus Tunnel (4 μ/day/m^2)
- Goal: <10^{-8}pb, with simple+reliable detectors with an alternative surface events rejection based on *charge signal*



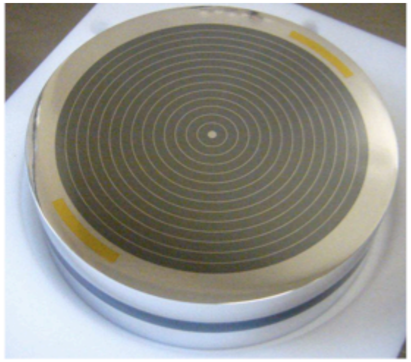
- 2008-2009: 10x400 g new Ge
fiducial mass) build, tested and operated in EDELWEISS-II low-bkg environment
  - 20cm lead + roman lead
  - 50cm polyethylene
  - muon veto



InterDigit detectors



- Keep the EDW-I NTD thermal sensor (true ΔT measurement)
- Modify the E-field near the surfaces with interleaved electrodes
- Use 'b' and 'd' signals as vetos against surface events
- Use |a-c| difference as another veto against surface events



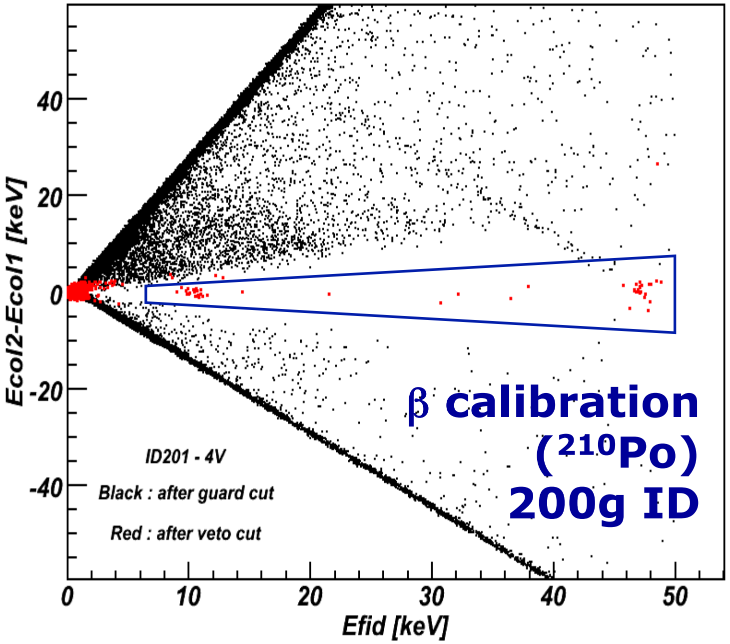
ID401 to 405:
Φ 70mm, H 20mm 410g

ID2 to ID5:
Φ 70mm, H 20mm, 360g

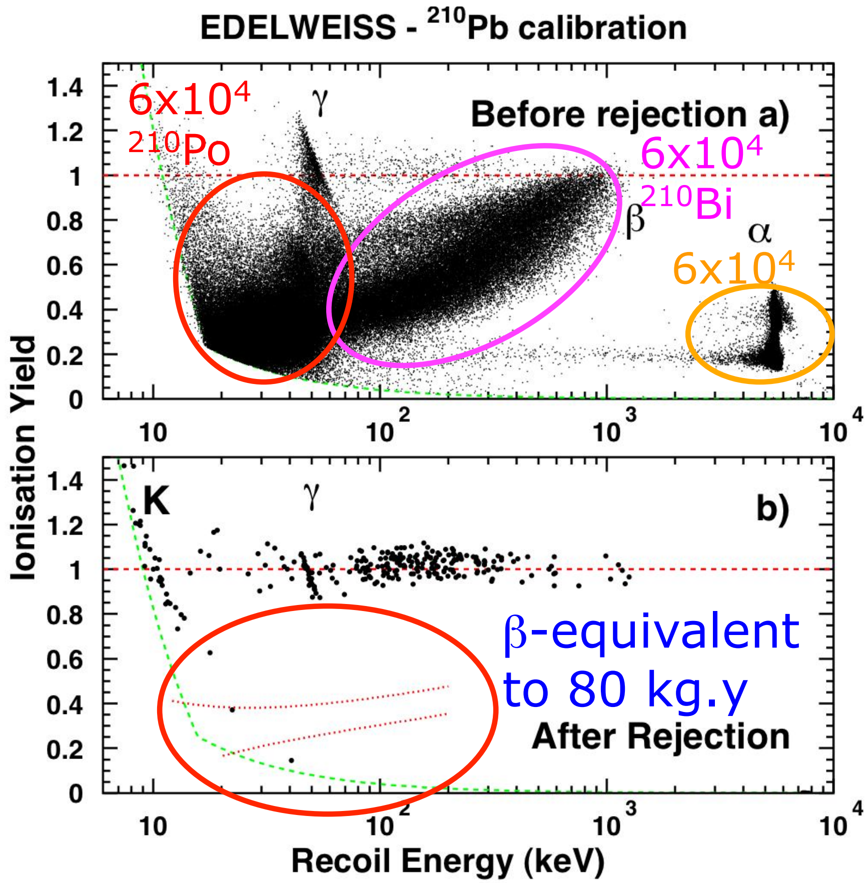
- Concentric electrodes (simple field shape) + ultrasonic Au bonding
- Guard ring electrode on outer edge
- Operated at 20 mK

ID detector surface rejection

- ^{210}Pb β rejection measured with 200g ID *[Broniatowski, PLB 681 (2009) 305]*

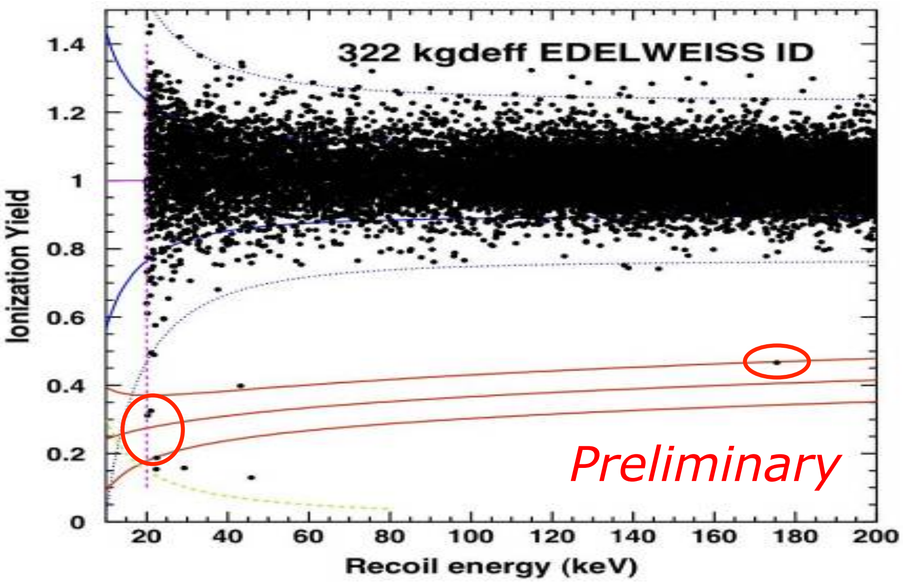


Red: selected after veto electrode cut
=> Good rejection (gap in distribution of difference between 2 fid. electrodes), even in regions of low electric field

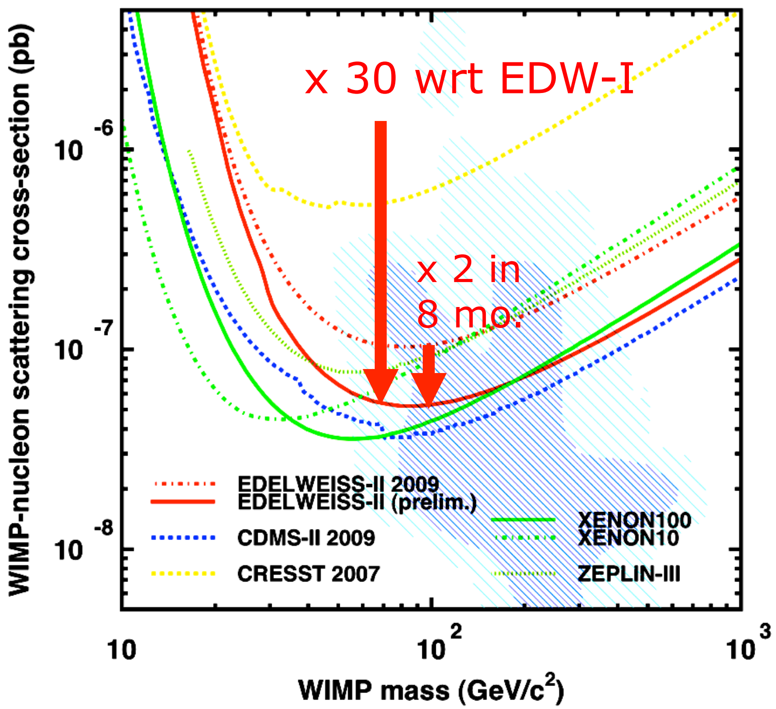


EDELWEISS-II: new updated results

- First results published after ~6 mo. [Armengaud et al, PLB 687 (2010) 294; arXiv:0912.0805]
- *Update with additionnal ~8 months, same cuts as first 6 data set*
- 3 evts near threshold + 1 at 175 keV (est. bkg: <1.6 evt at 90%CL)
- Best limit: $\sigma_{SI(W\text{-}N)} = 5.0\text{x}10^{-8}$ pb at M_W = 80 GeV (90%CL)
- High-stat γ calibrations: new backgrounds start to appear?

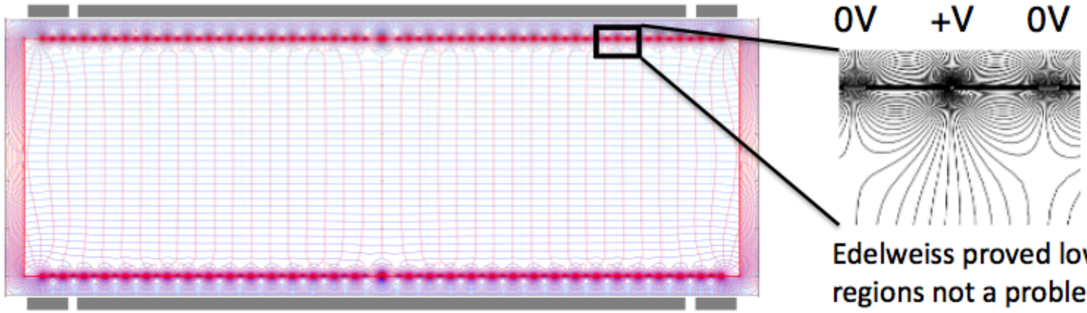


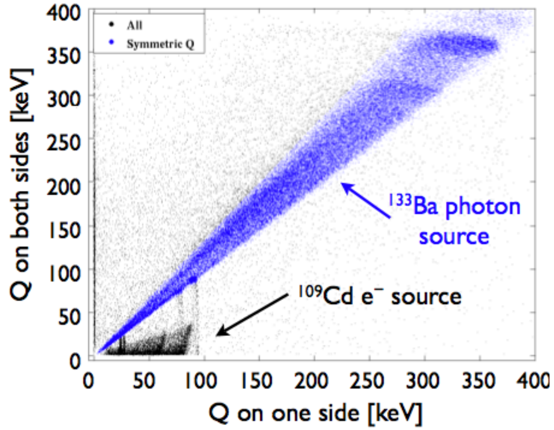
✓ Robust detectors
✓ Good run efficiency



Improving Background Rejection

- Interdigitated ZIP (iZIP) design meets needs for SuperCDMS SNOLAB and GEODM

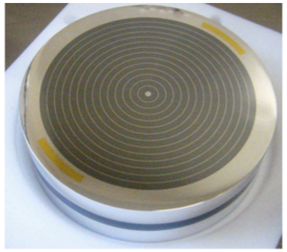


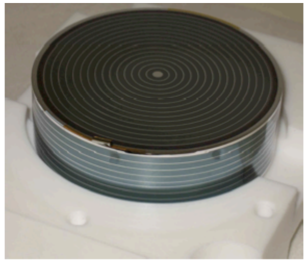


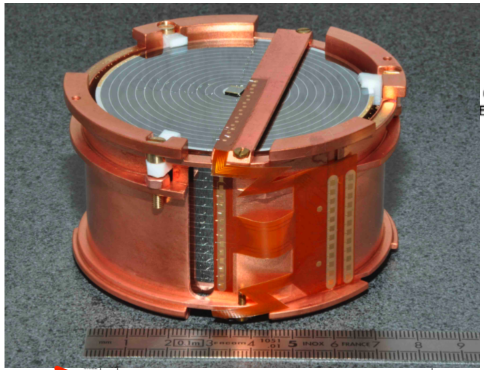
- Larger detectors (cost, bkg): 2.5 cm thickess, tests with ϕ = 10 cm and 15 cm (dislocation-free) => 5 kg units

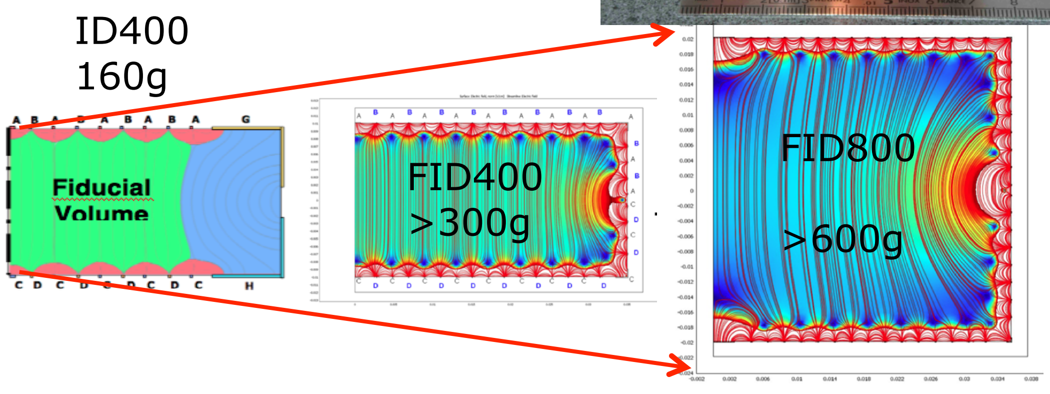
- Super CDMS @ Soudan : 15 kg (2010-2012) runs with 600g i-ZIP
- Super CDMS @ SNOLAB : 100 kg (2012-2017)
- GeoDM @ DUSEL: 5 T (2017-…)

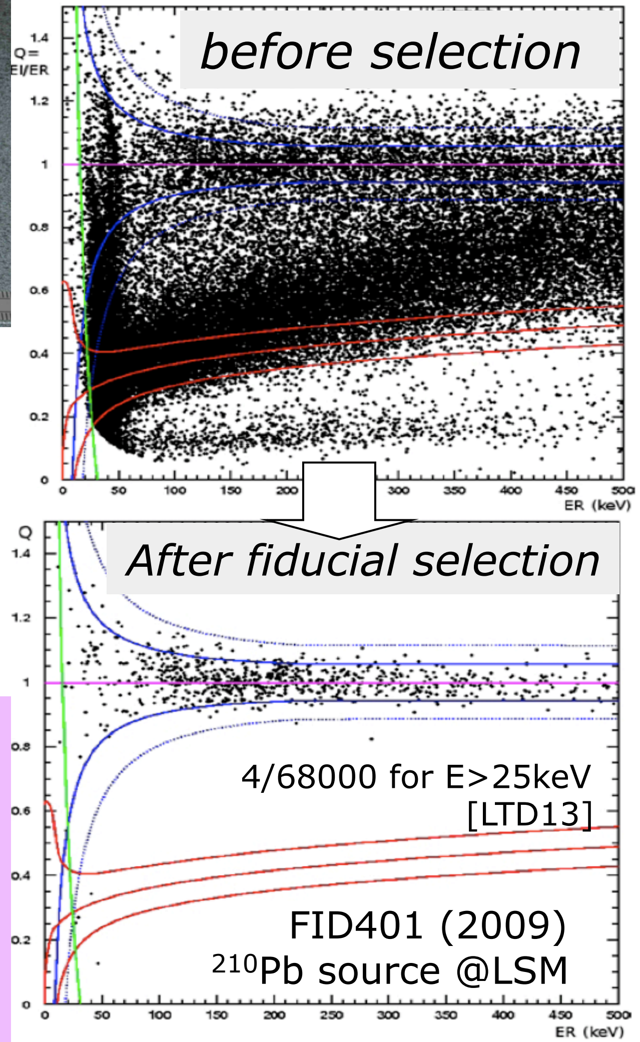
EDELWEISS future


ID401 to 405:
Φ 70mm, H 20mm, 410g


FID401 and FID402:
Φ 70mm, H 20mm, 410g







⇒ Optimization of field map, improved surface treatment and added redundancy

⇒ Doubling/Quadrupling the fiducial mass:
ID400 => FID400 => FID800 (4 at LSM now)
10kg in 2011, 30kg in 2013 -> goal 3000 kgd

⇒ EURECA (LSM): 100 kg -> 0.5t Ge (+scint.)

Alternative searches & techniques

… Omissions:

- Heat+Scintillation (CRESST $CaWO_4$ -> EURECA)
- Directional TPC detectors (DRIFT, Mimac, …)
- Superheated droplets (PICASSO @ SNOLAB)
- CsI Pulse Shape discrimination (KIMS CsI)
- Modulation-only (LIBRA NaI)
- …

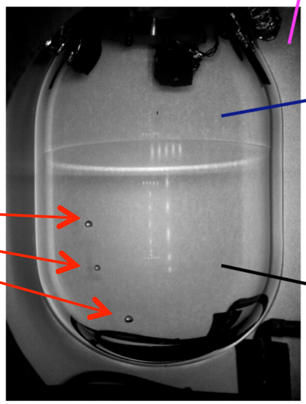
Spin-dependent interactions

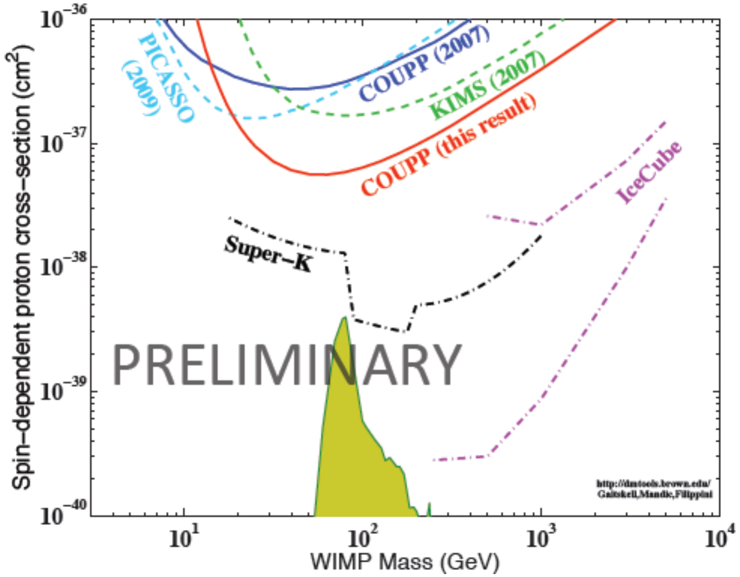
- Models where coherent A^2 enhancement is not present (pure axial interaction)
- Interactions on neutron: XENON best limit ($^{129,131}Xe$)
- Interactions on proton: COUPP best direct limit, but still far from MSSM, and not yet competitive with indirect Super-Kamiokande limit (ν).

Dahl, UCLA DM2010 +arXiv:0804.2886

3 high-dE/dx interactions, few cm apart: n

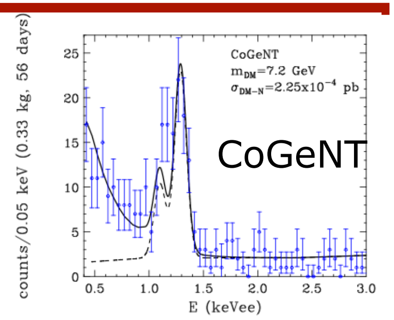
COUPP CF_3I superheated bubble chamber

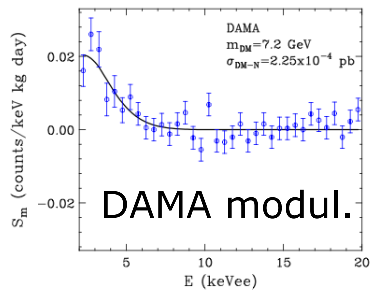




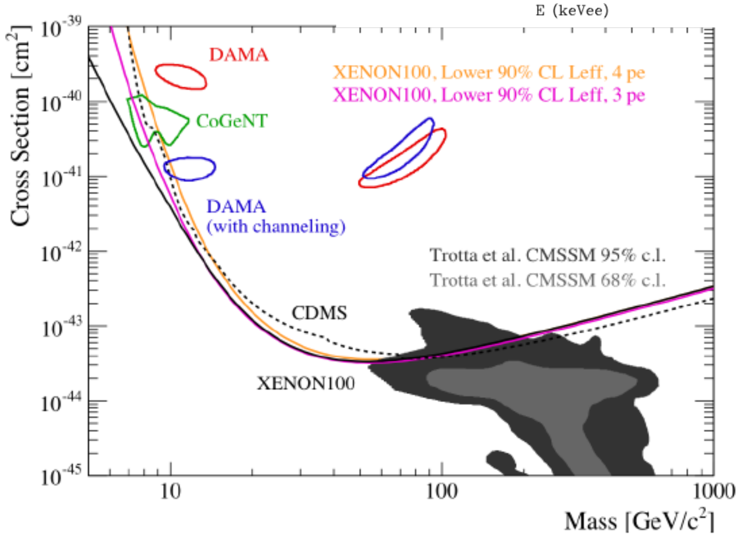
Low Mass WIMPs

- Observed excess at low energy, close to experimental thresholds, in DAMA/LIBRA (annual modulation in NaI) and CoGeNT (high-resolution Ge, ionization-only) [Aalseth et al, arXiv 1002.4703]
- Interpretation as M < 10 GeV WIMP? Inconsistent with XENON-100 [Aprile et al, subm. PRL, arXiv:1005.0380].
- Inconsistency avoided by questioning the precision of the calibration of the light yield for Xe recoils picture [Savage et al, arXiv 1006.0972, Hooper et al, arXiv 1007.1005]



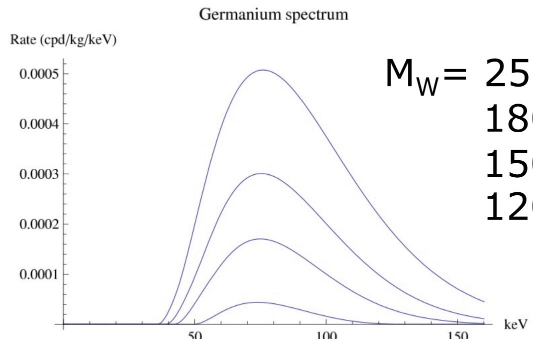


- Contradictory hints, require further investigations (& low thresholds)
- Emerging consensus: channeling of lattice ions no longer relevant [Bozorgnia et al, arXiv 1006.3110]

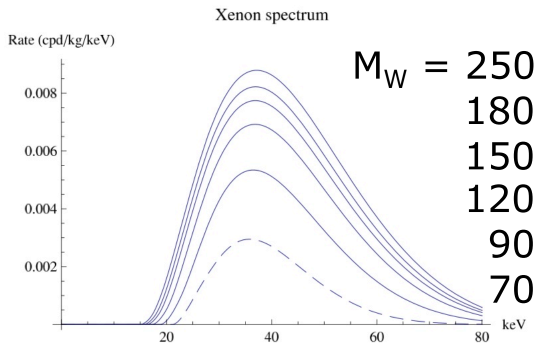


Inelastic Dark Matter

- Originaly Suggested to reconcile DAMA and CDMS
- Suppression of $\chi N \to \chi N$ relative to $\chi N \to \chi^* N$
- Suppression of low-E transfers and of σ on light nuclei
- Annual modulation can be >2% (solving DAMA S_0 problem)



M_W= 250
180
150
120

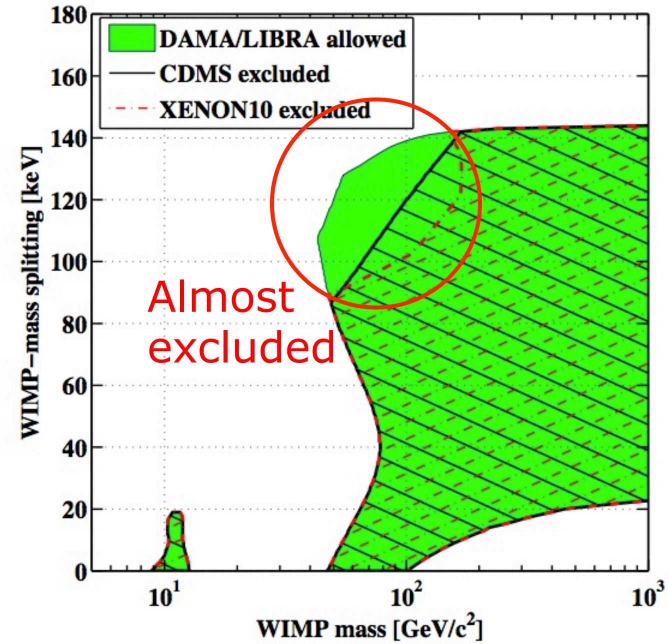


M_W = 250
180
150
120
90
70

Chang, Kribs, Tucker-Smith & Weiner, hep-ph/0807.2250;

Smith & Weiner, PRD 64 (2001) 043502 hep-ph/0101138

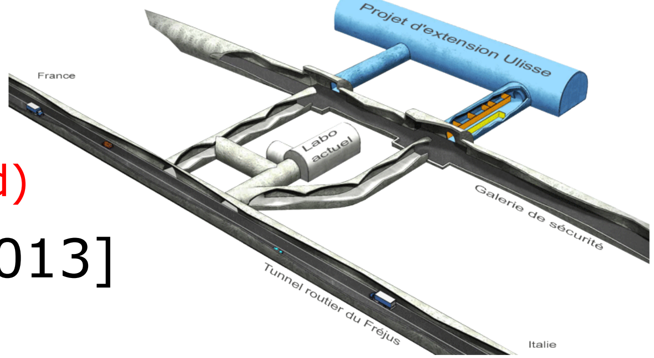
δ~100 keV



New opportunities in Underground Labs

- SNOLAB (Canada) [current]

6000 mwe (0.25 $\mu/m^2/d$)



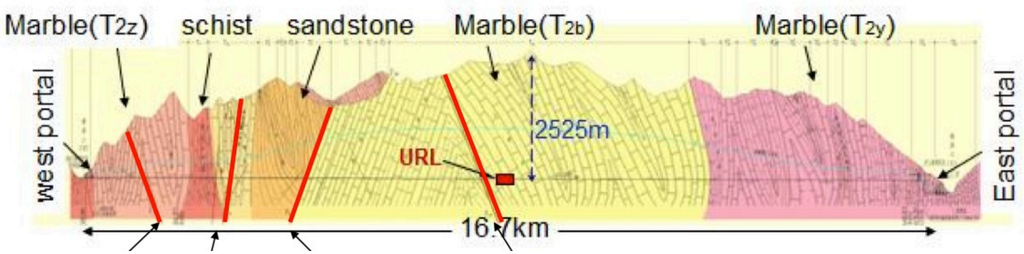
4800 mwe (4.7 $\mu/m^2/d$)

- LSM extension (Frejus, France) [2013]

- JinPing (China)

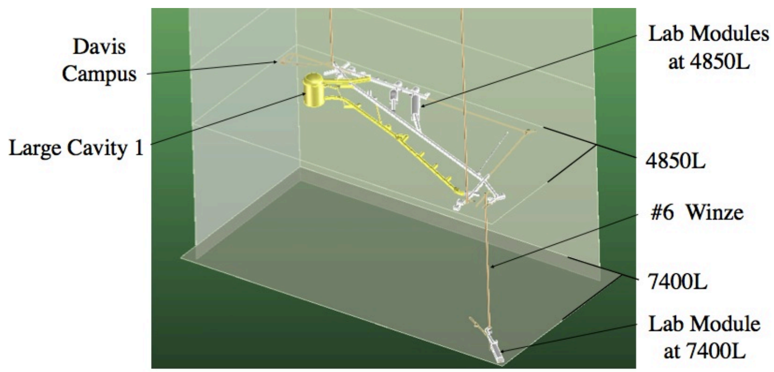
2011-2012

~7500 mwe



- DUSEL (USA) 2017

4200 - 7100 mwe



Conclusions

- Direct Dark Matter Searches: crucial experiments to attest the presence of WIMPs in our environment; strategic complementarity with LHC
- *Apparently simple, but the required extreme low-backgrounds are challenging and they foster constant technological innovations.*

- Need variety of targets *(Ar/Xe, Ge+scintillation in EURECA)*
- Intense world-wide competition of R&D efforts
- Leading technologies (for now):
  - cryogenic Ge (resolution & discrimination)
  - double-phase Xe (large mass, self-shielding & low thresholds)
- New opportunities with extension/build up of underground labs (DUSEL, LSM, JinPing, …)