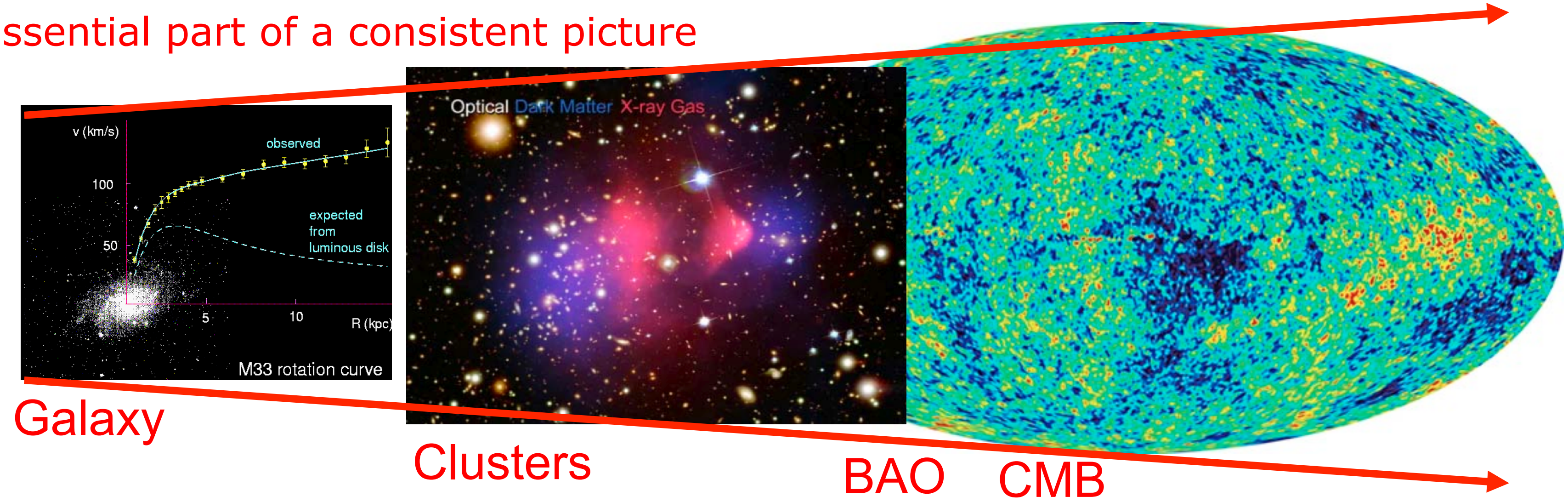
(Direct) Searches for Dark Matter

J. Gascon
UCB Lyon 1, CNRS/IN2P3/IPNL

Dark Matter in the Universe

- Dark Matter present at all scales in the Universe …

Essential part of a consistent picture



- Cosmology: $\Omega_{DarkMatter}$ ~ 0.23 +- 0.02 **(1.3 M_{proton} /m^3)** + most of it is “Cold”
- Astrophysics: Localy, ρ_{DM} ~ 0.4 GeV/cm^3 **(0.3 M_{proton} /cm^3)**

Hypothesis: thermal production in the Big Bang

- *Present Dark Matter density* $\Omega_{DarkMatter}$ is proportionnal to $\sigma_{annihilation}$:

$\langle\sigma_{annihilation} v\rangle$ / ($\Omega_{DM} h^2$) ~ 0.3 x 10^{-27} cm^3/s ~ weak force (“WIMP miracle”)

Look for heavy neutral particle with Weak Force interactions

List of candidates

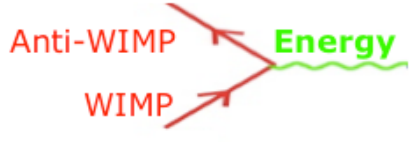
- **Axions**
  - Non-thermal relics (μeV->meV, CDM->HDM)
- **WIMPs**
  - Stable thermal relics
  - Electroweak physics (~ prediction on annihilation/creation/scattering cross-sections)
  - Mass 10-100-1000 GeV/c^2 (atomic nucleus are interesting targets: maximal momentum transfer)
- **Other models**
  - Many are also covered by WIMP search (KK…)
  - Models without detectable particles are not excluded!

Three complementary search strategies

Identification of a Dark Matter particle

1. **Creation at collider - LHC ($\sigma_{creation}$)**

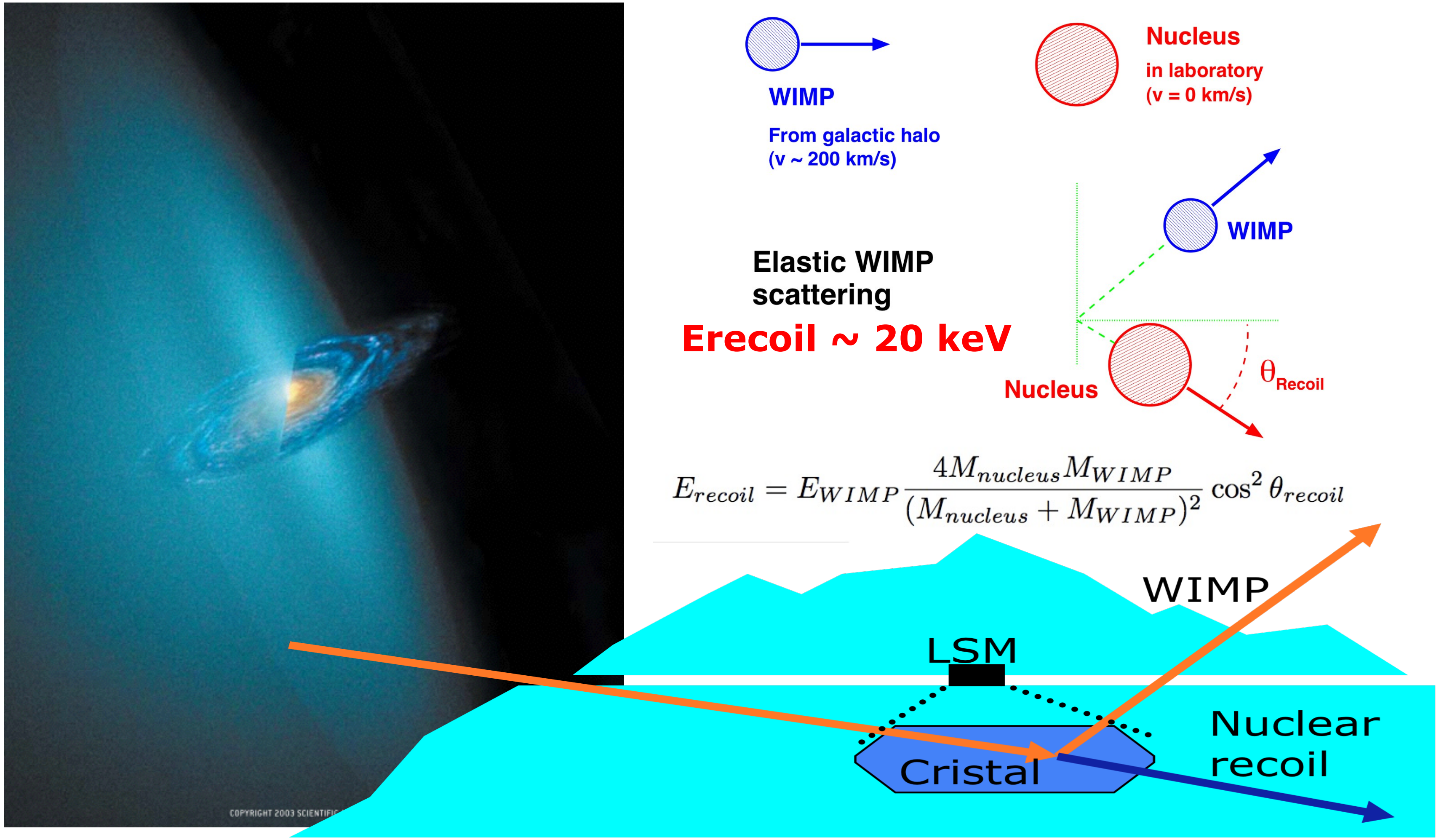
2. **Detect annihilation products** (γ, ν, antimatter)
   in cosmic rays ($\sigma_{annihilation}$)
   [Antares, IceCube, FERMI, HESS, AMS, …]



3. **Scattering on target nuclei**
   in Earth laboratory ($\sigma_{scattering}$)
   [Direct Searches: this talk]

Is the halo of our Galaxy made of the same WIMPs that can be produced at colliders?

WIMP-nucleon collision



$$E_{recoil} = E_{WIMP} \frac{4 M_{nucleus} M_{WIMP}}{(M_{nucleus} + M_{WIMP})^2} \cos^2 \theta_{recoil}$$

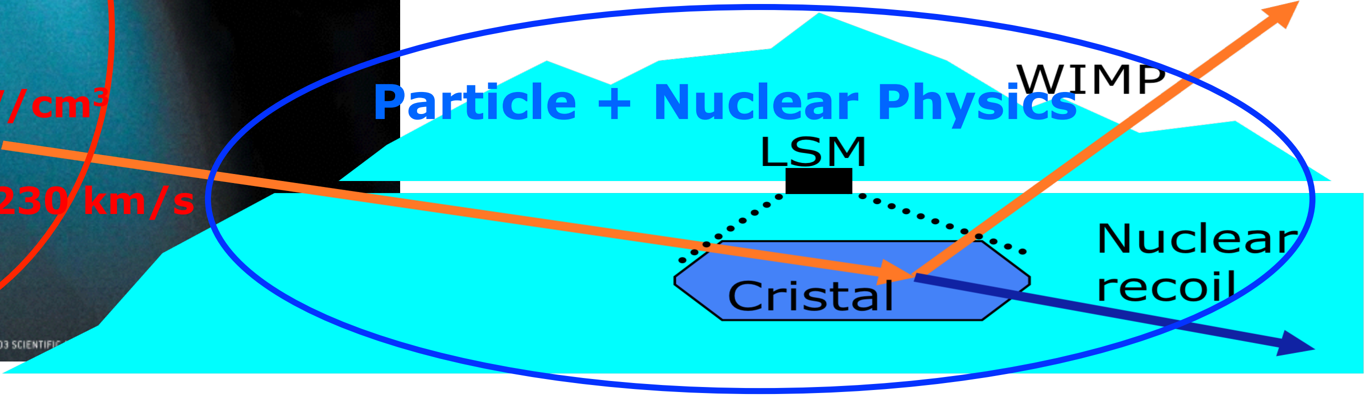
Possible observables: Event rates, Recoil Energy and Range, Scattering angle…

WIMP-nucleon collision

Free parameters: M_{WIMP}, $\sigma_{WIMP\text{-}nucleon}$

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)



Possible observables: Event rates, Recoil Energy and Range, Scattering angle…

First Searches

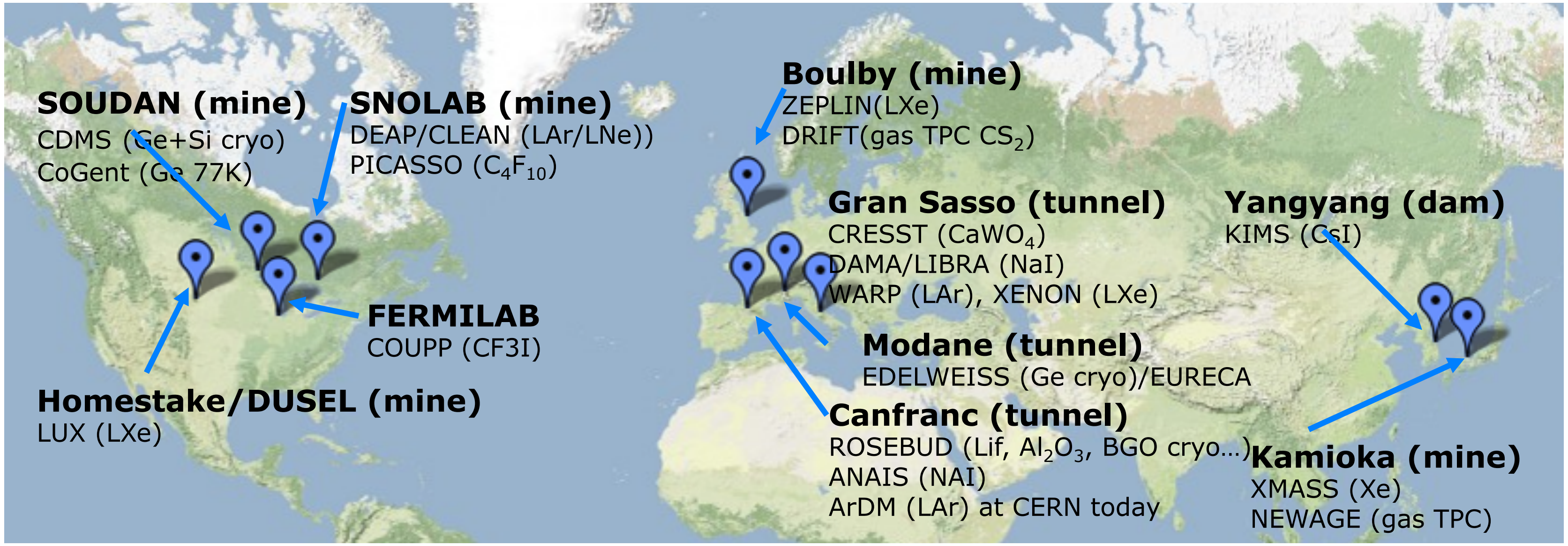
- Method suggested in 1985
  - Goodman + Witten, Phys. Rev. D 31 (1985) 3059

"Sneutrino & Photino & … Dark Matter"

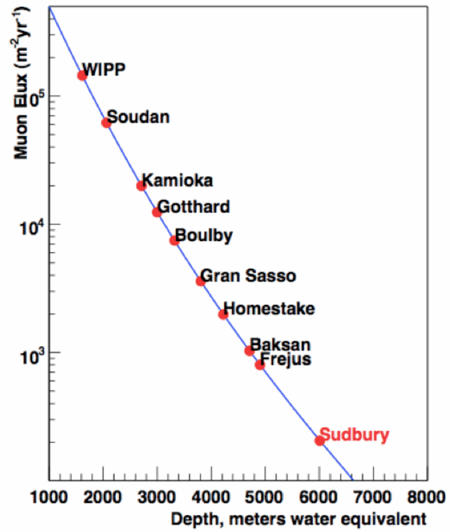
- First significant limits as early as 1987: *exclusion of a heavy neutrino* with germanium et silicon detectors.
  Sensitivity to rates as low as *a few events per kg.day*
  - Ge: S. P. Ahlen, et al., Phys. Lett. B 195 (1987) 603
  - Ge: D. O. Caldwell, et al., Phys. Rev. Lett., 61 (1988) 510
  - Si: D. O. Caldwell, et al., Phys. Rev. Lett. 65 (1990) 1305

- Need for significantly better rejection of radioactive background [in the 1-100 keV range!]: competition between new techniques
  - Pulse-shape discrimination in NaI? Heat and ionization bolometers *[Shutt et al, PRL 69 (1992) 3425+3531]*? CsI? Liquid Argon? Two-phase Xenon? Bubble chambers/superheated droplets? …

Dark Matter Searches around the world



- Underground sites (cosmic rays)
- Combine signals for ion/electron recoil identification
  - Heat (or thermalized phonons): "true" calorimetric energy
  - Ionization Yield
  - Scintillation Yield
  - Pulse shape discrimination: useful in some cases (Ne, Ar)
  - Also: dE/dx in superheated medium: COUPP, PICASSO



Rates in detectors

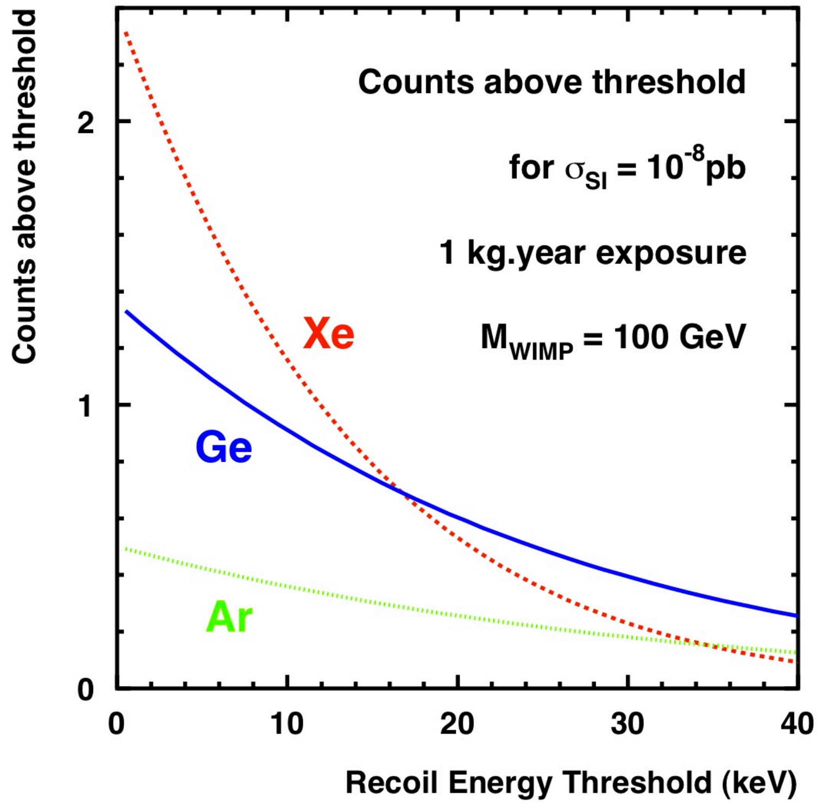
- 10^{-8} pb ~ 1 evt/kg/year
  - Rate depends on *energy threshold* and *atomic mass*

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.*

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



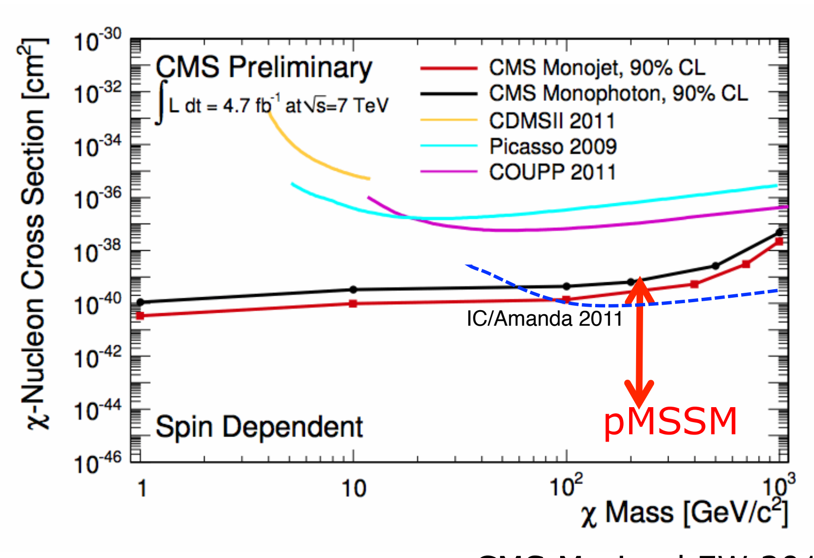
WIMP signatures

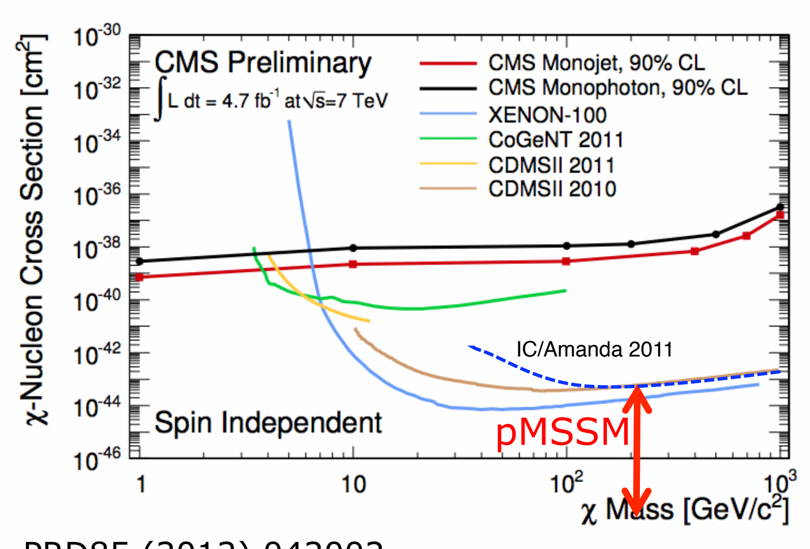
- Directionality (correlation with v_{sun})
  - Challenge: ~20 nm recoil in solid, ~30μm in gas
  - Low-pressure TPC? -> Still in R&D [DRIFT, DMTPC, MIMAC…]
  - *Small annual modulation of flux (~2%) requires large statistics + depends more on velocity distribution details.*
- Nuclear (and not electron = 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

Spin-dependent interactions

- In many models (like SUSY) axial, spin-dependent (SD) interaction are either already excluded, or mixed with spin-independent (SI) component.

  (… but this statement is model-dependent)
- SI component amplified by A^2 coherence tends to dominate.
- SD most efficiently probed by indirect searches (ν detectors) or even LHC, as SD searches don't benefit from A^2 coherence factor.





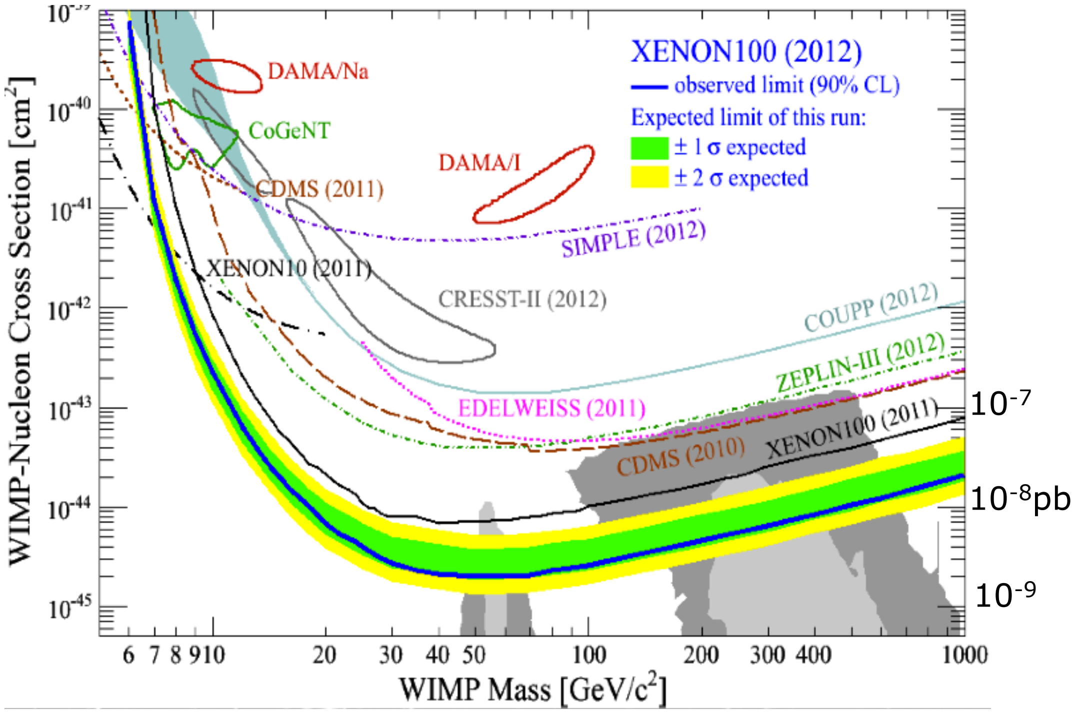
CMS Moriond EW 2012 + PRD85 (2012) 042002

Present spin-independent results

- Best limits today: XENON100 (224 live days, 38 kg Xe fiducial): $2x10^{-9}$pb
- Next best limit: combination of previous CDMS-II+EDELWEISS-II results (~380 kg.day each, with ~2 kg Ge fiducial each): $3x10^{-8}$ pb

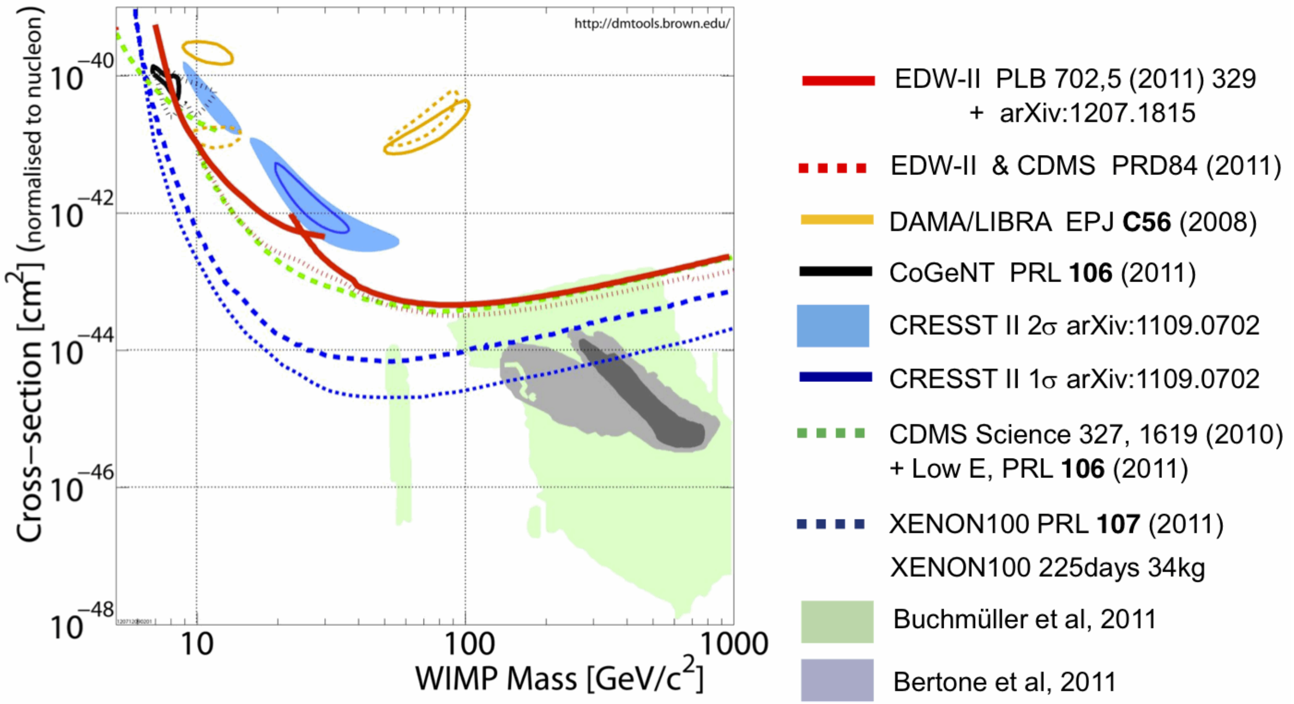
Coming next:

- SuperCDMS Soudan, (6 kg fiducial) started data taking
- EDELWEISS-III (24 kg fiducial) fully assembled mid-2013
- LUX: first op. end of 2012 (mass = XENON100x2)
- XENON 1t = Xe100 X 15
- Challenge: keep backgrounds under control



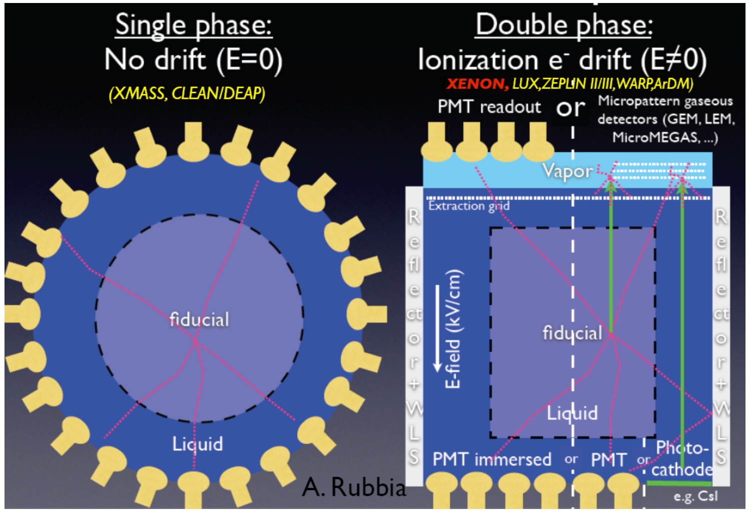
Low Mass WIMPs

- Observed excess at low energy, close to experimental thresholds, in DAMA/LIBRA (annual modulation in NaI) and CoGeNT (high-resolution Ge, ionization-only). Possible interpretation of CRESST (heat+scint.).
- *Interpretation as M < 10 GeV WIMP inconsistent with XENON, CDMS and EDELWEISS (specific low-mass searches)*



Eitel, IDM2012

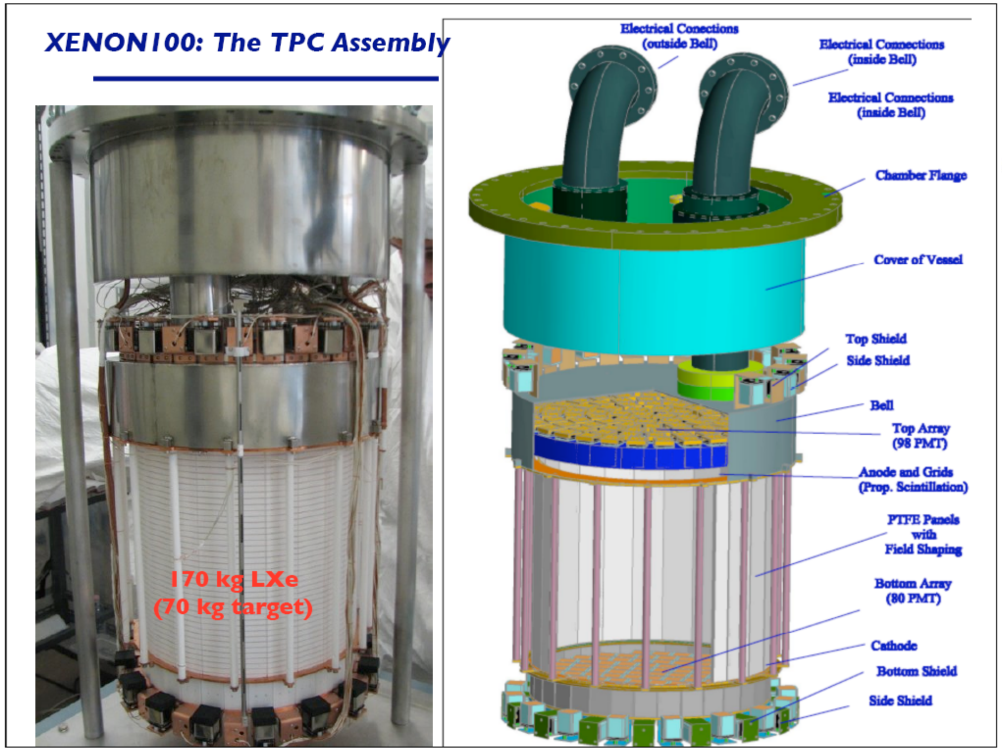
Noble liquid detectors

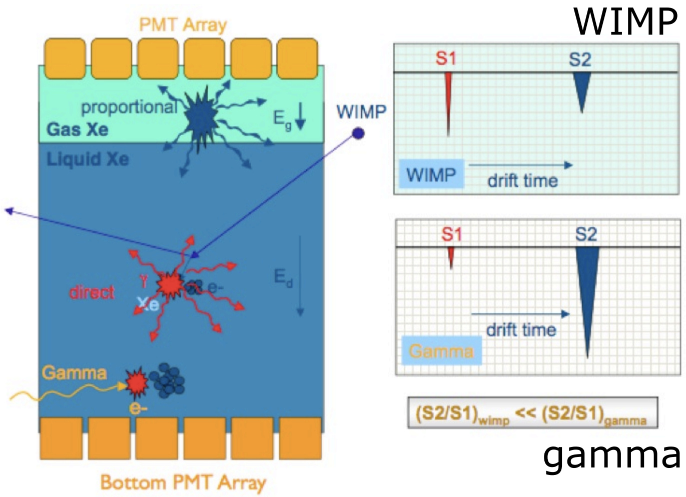


- Xe: large A; Ar: low cost
- High purification (recirculation)
  - ^{39}Ar (1Bq/kg): requires >10^7 rejection for 10^{-8}pb, or depleted Ar (DarkSide)
- 3 rejection techniques
  - Self-shielding in large volume [XMASS]
  - Ratio (prompt scintillation)/(ionization) [XENON, LUX]
  - Scintillation pulse shape [eg: DEAP/CLEAN]
    - 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 100** (2010) 162 kg LXe,   34 kg fiducial, 30 cm drift
- 242 PMT’s (top+bottom) <1mBq, -> *(x,y)* coordinates <3mm
- Δt (S2-S1): *z* coordinate

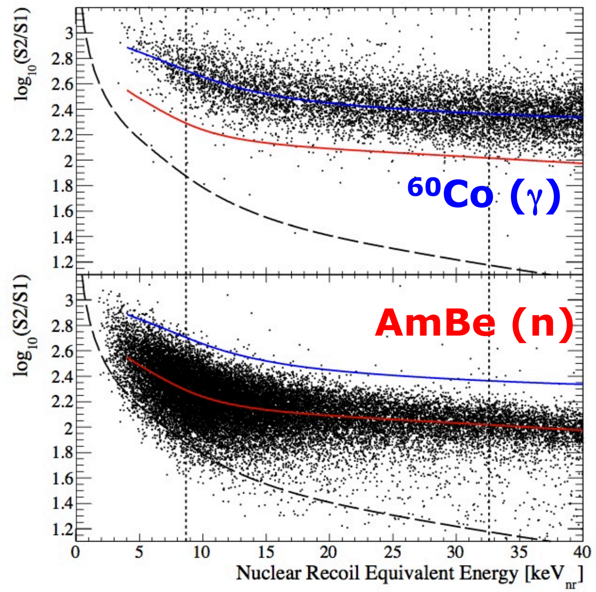




- 10 keV nuclear recoil:
  - S1 ~ 5 P.E.
  - S2 ~ 800 P.E.

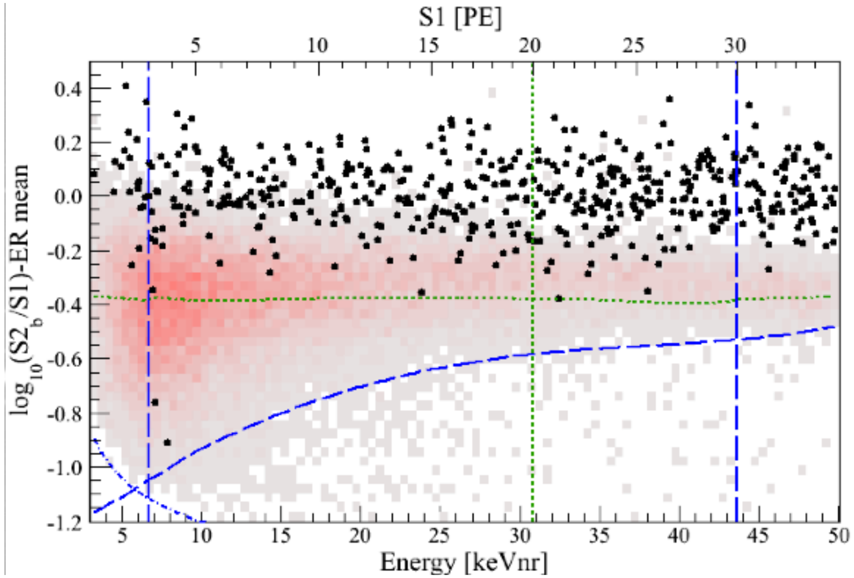
S1 threshold: 3 PE (6.6 keV)

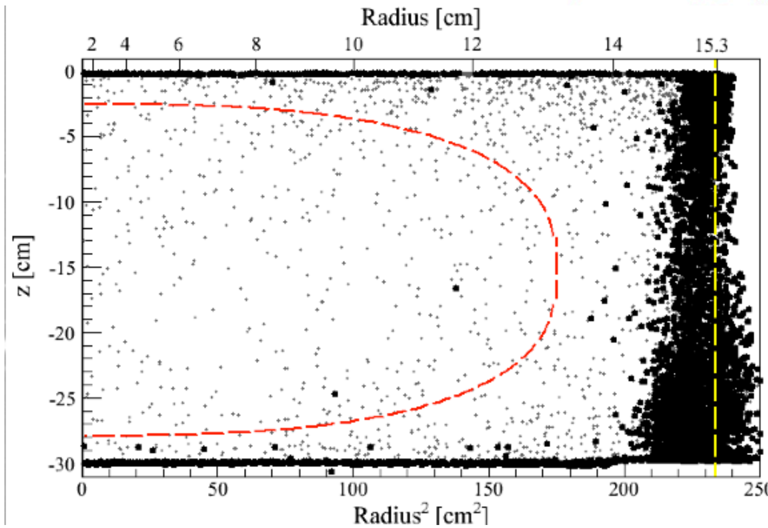
XENON-100 discrimination and results



224 live days, 36 kg fiducial mass

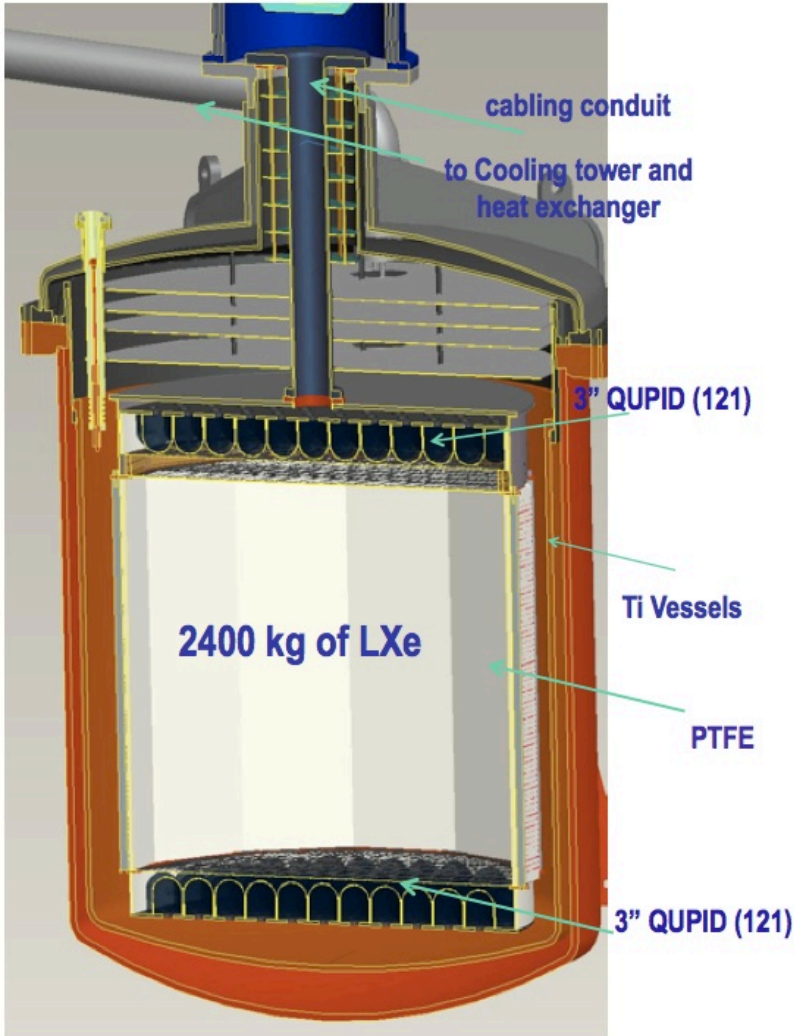
- 3 P.E. threshold on s1 (6.5 keV_NR)
- Estimated background: 0.8 ± 0.2 electron recoil 0.2 ± 0.1 nuclear recoils
- 2 events observed close to threshold
- Improvement relative to previous 100 day run: 700 ppt -> 19 ppt 85Kr, + exposure





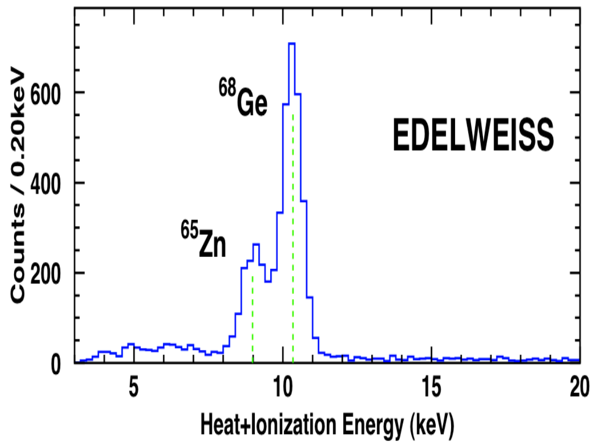
XENON future

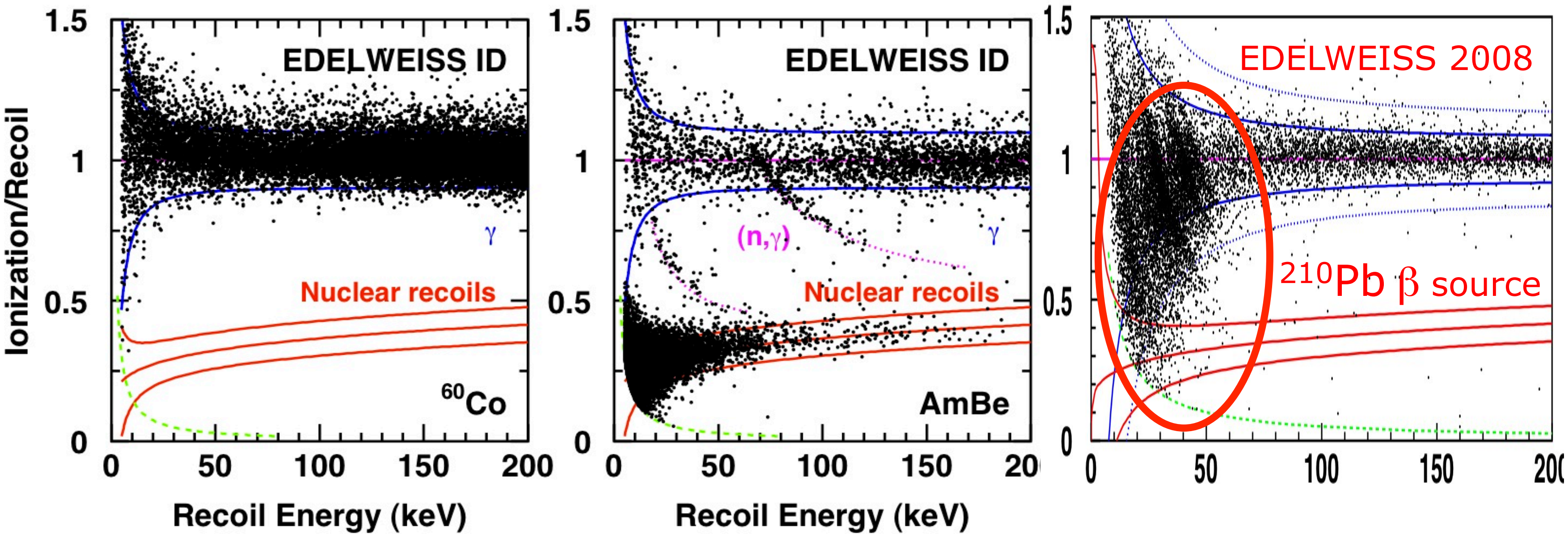
- XENON-1t (2014, Gran Sasso)
  - 2400 kg LXe, drift 100 cm
  - Funded, construction started
  - Goal: 2×10^{-11} pb by 2017
  - Lower radioactivity PMT (QUPIDs) and cryostat, better purification scheme (X100 needed)
- LUX (End 2012, Homestake)
  - 300 kg Lxe
- XMASS (100 kg single-phase)
- Other programs in coming years: DEAP/CLEAN (3.6t LAr) in SNOLab, WARP, ArDM, DarkSide
- Longer term: multi-ton expts (DARWIN, LZ)



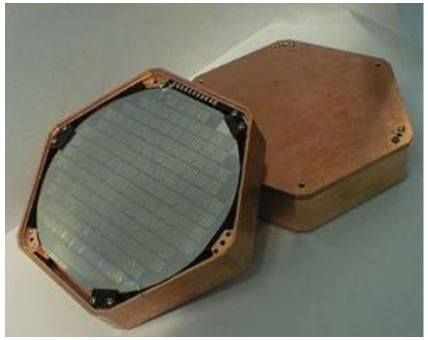
Germanium heat+ionization principle

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

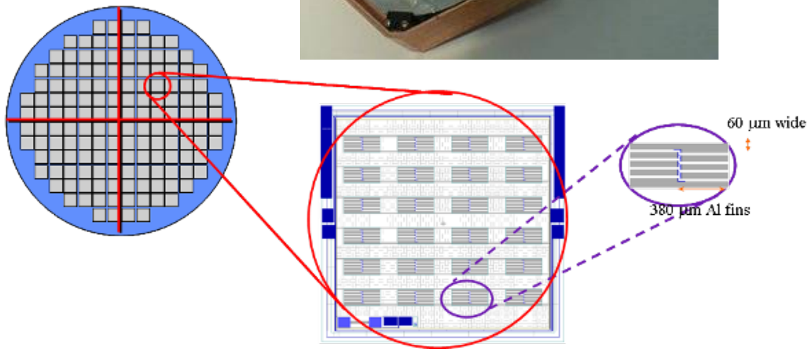




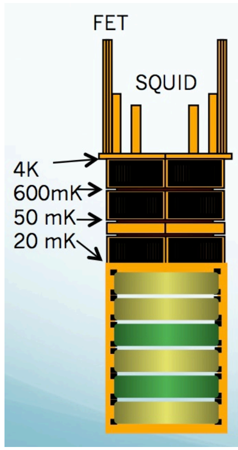
CDMS phonon-sensitive detectors

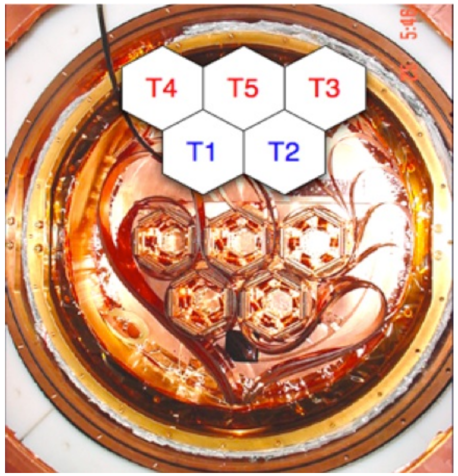


- 250 g Ge or 100 g at 20 mK
- Phonon Sensors : Superconducting W thermometer (array of 4144)
  - Photolithographic patterning
  - 4 quadrants, 37 cells per quadrant
  - 6x4 array of 250mm x 1mm W TES per cell
  - Each W sensor "fed" by 8 Al fins (quasiparticle collectors)



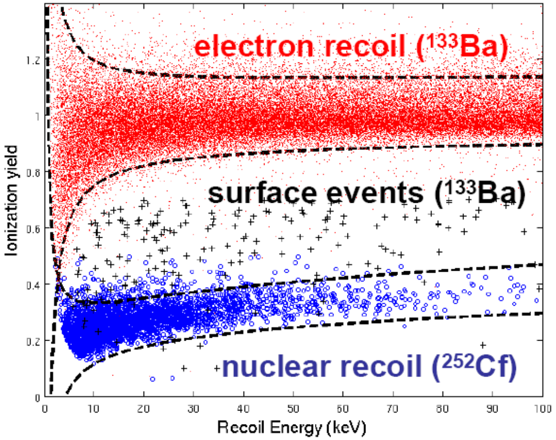
- Ionization Sensors: 2 electrodes + ground for rejection of evts in outer ring
- **CDMS-II @ SOUDAN mine**
  - 5 towers x 6 ZIPs
  - 19 Ge x 250 g (4.4 kg)
  - 2006-2009: >1800 kgd before cuts
  - 379 kg.d total exposure
  - 4 evts, consistent with expected bkg



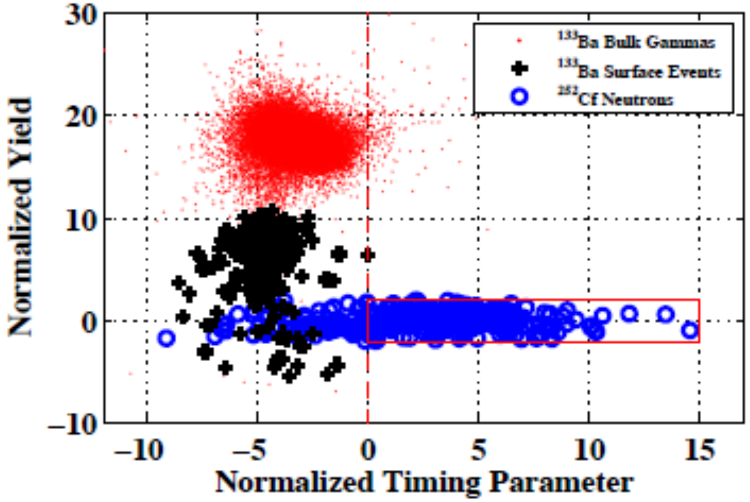


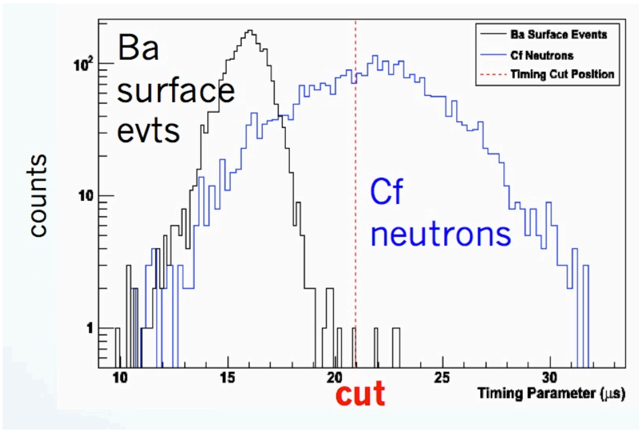
CDMS rejection

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



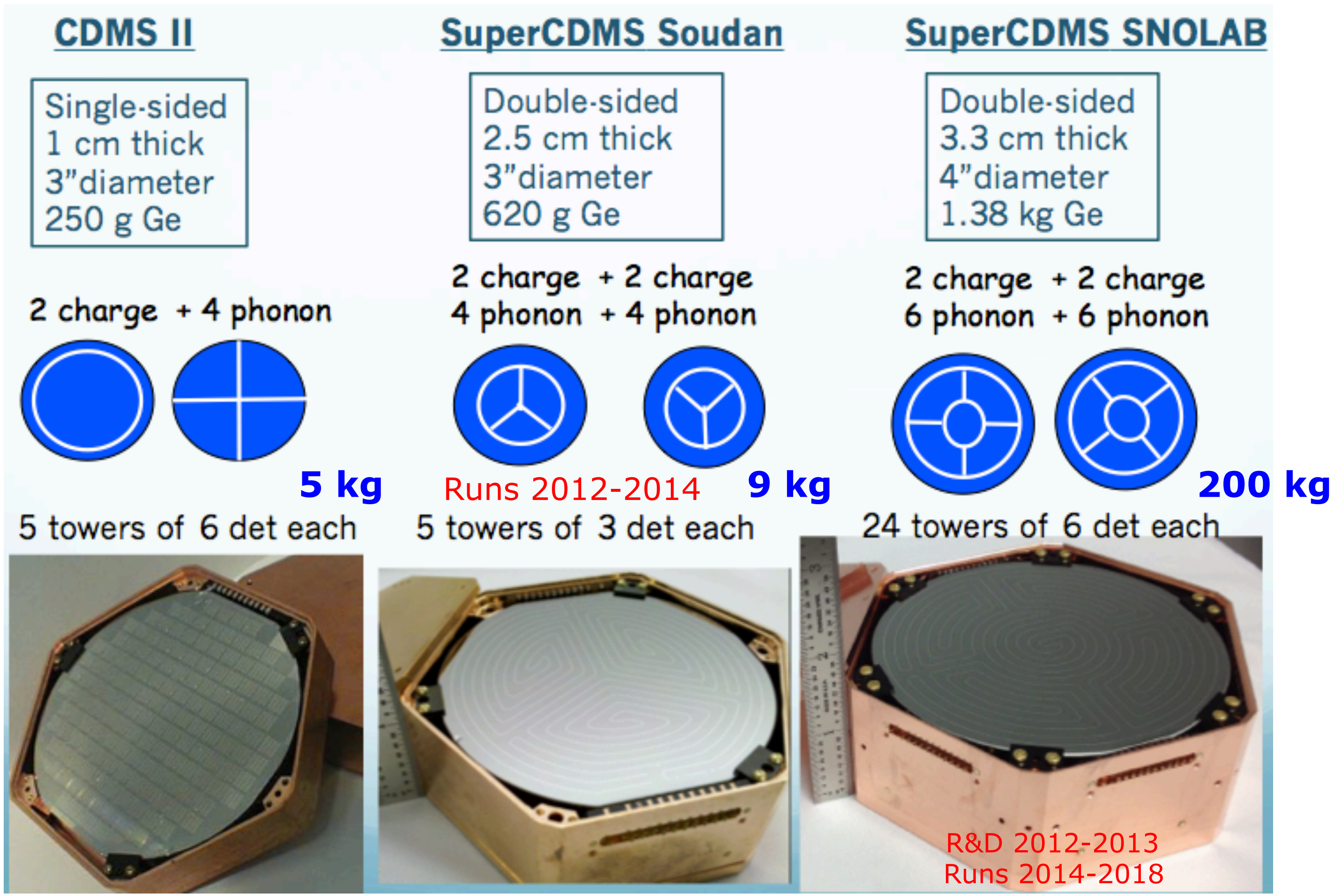
- Rejection 2: Rise-time and time phonon and ionization signal





- Selection tuned for <~1 evt bkg event

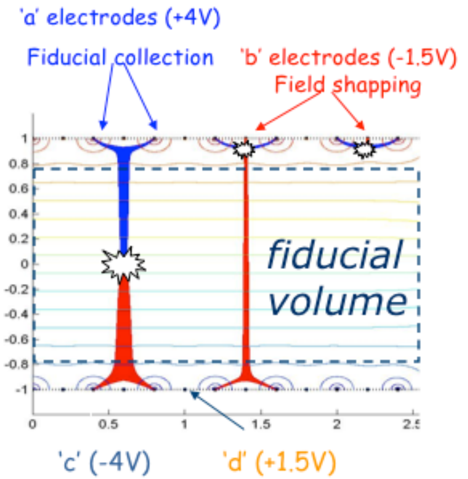
CDMS detector evolution

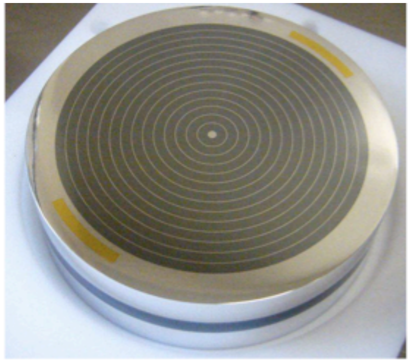


Cushman, IDM2012

EDELWEISS

- LSM in Frejus Tunnel (4 μ/day/m^2)
- Goal: few 10^{-9} pb, with simple + reliable detectors with an alternative (and robust) surface events rejection based on *charge signal*
- EDELWEISS-II (2008-2009) 10x400 g Ge (1.5 kg fiducial mass) with concentric electrodes: demonstration of surface event rejection with interleaved ("ID") electrodes



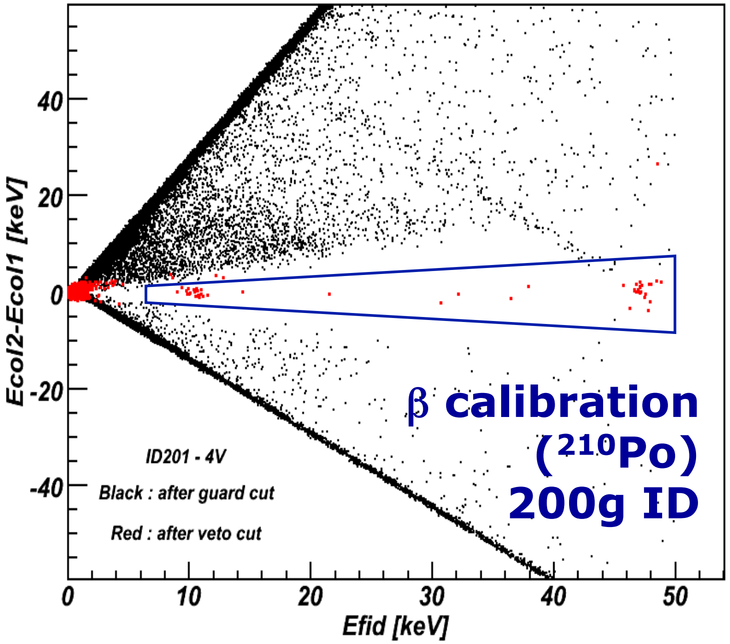


ID401 to 405:
Φ 70mm, H 20mm, 410g

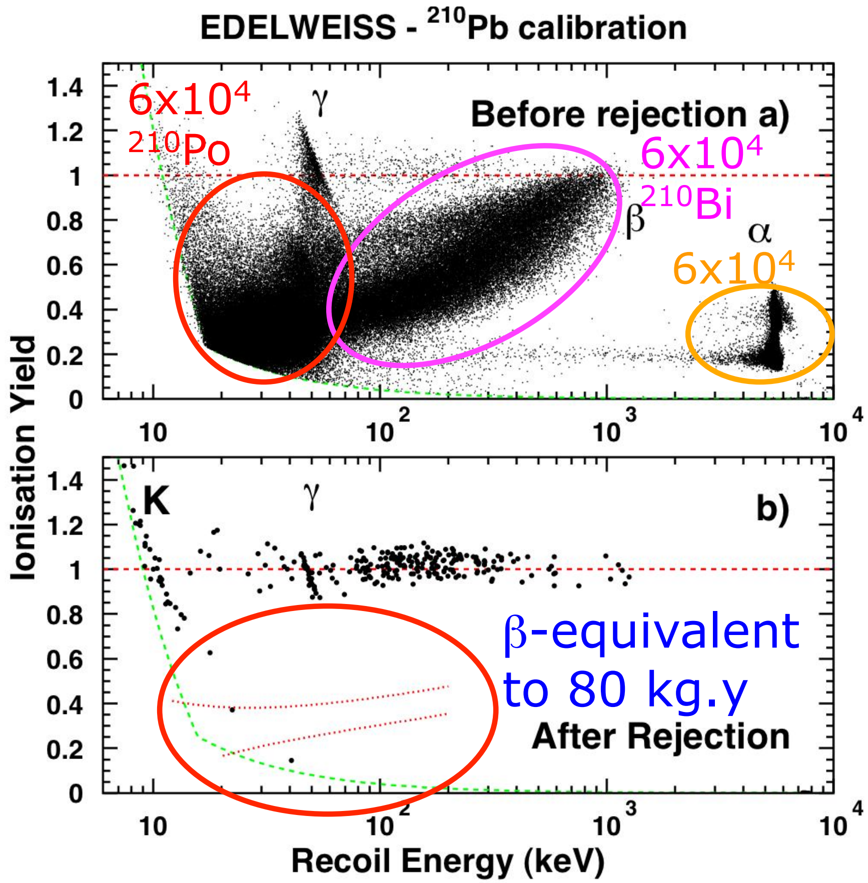
ID2 to ID5:
Φ 70mm, H 20mm, 410g

ID detector surface rejection

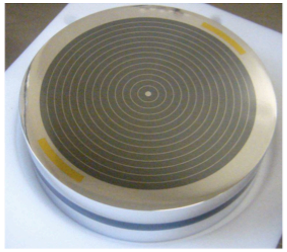
- ^{210}Pb β rejection measured with 200g ID *[Broniatowski, PLB 681 (2009) 305]*



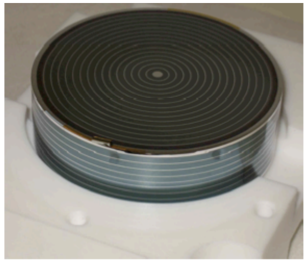
Red: selected after veto electrode cut
=> Good rejection (gap in distribution of difference between 2 fid. electrodes), even in regions of low electric field



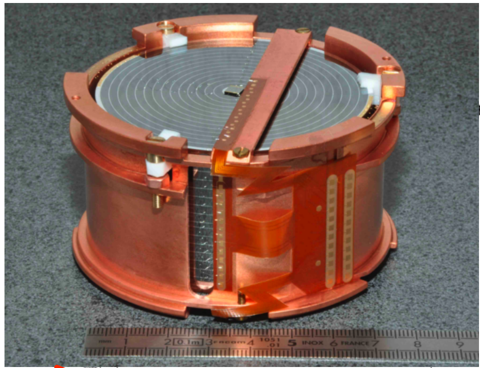
EDELWEISS detector evolution



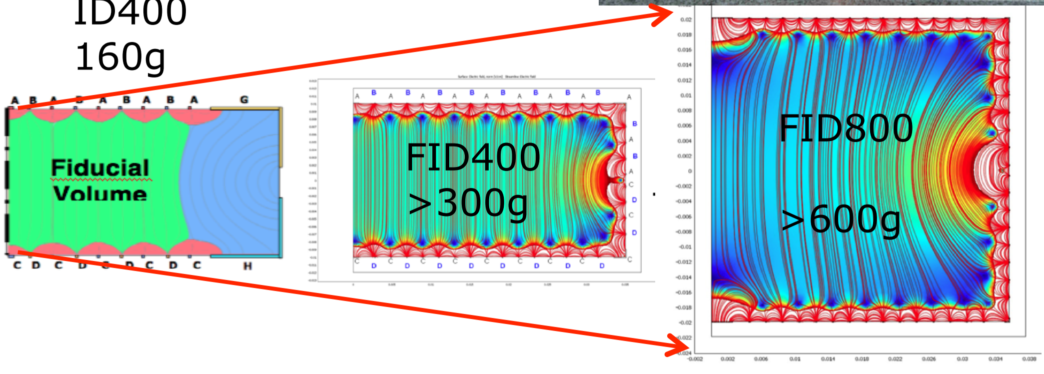
ID401 to 405:
Φ 70mm, H 20mm, 410g

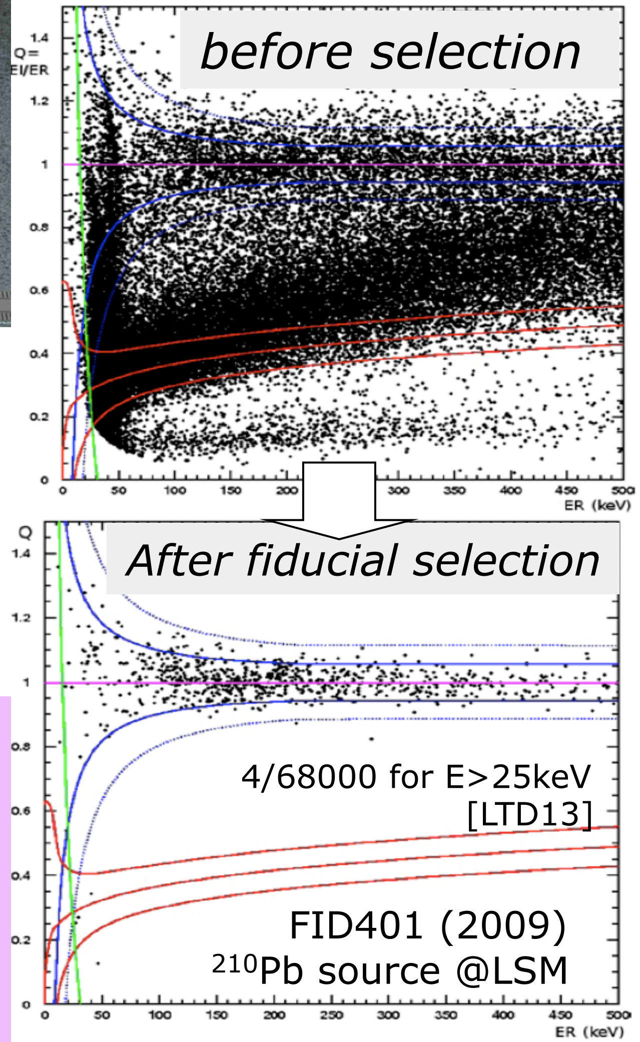


FID401 and FID402:
Φ 70mm, H 20mm, 410g



ID400
160g





⇒ 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.)

Conclusions

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

- Need variety of targets (essential to validate possible discovery)
- Intense world-wide competition of R&D efforts to *reduce backgrounds* and *increase the mass of the arrays*