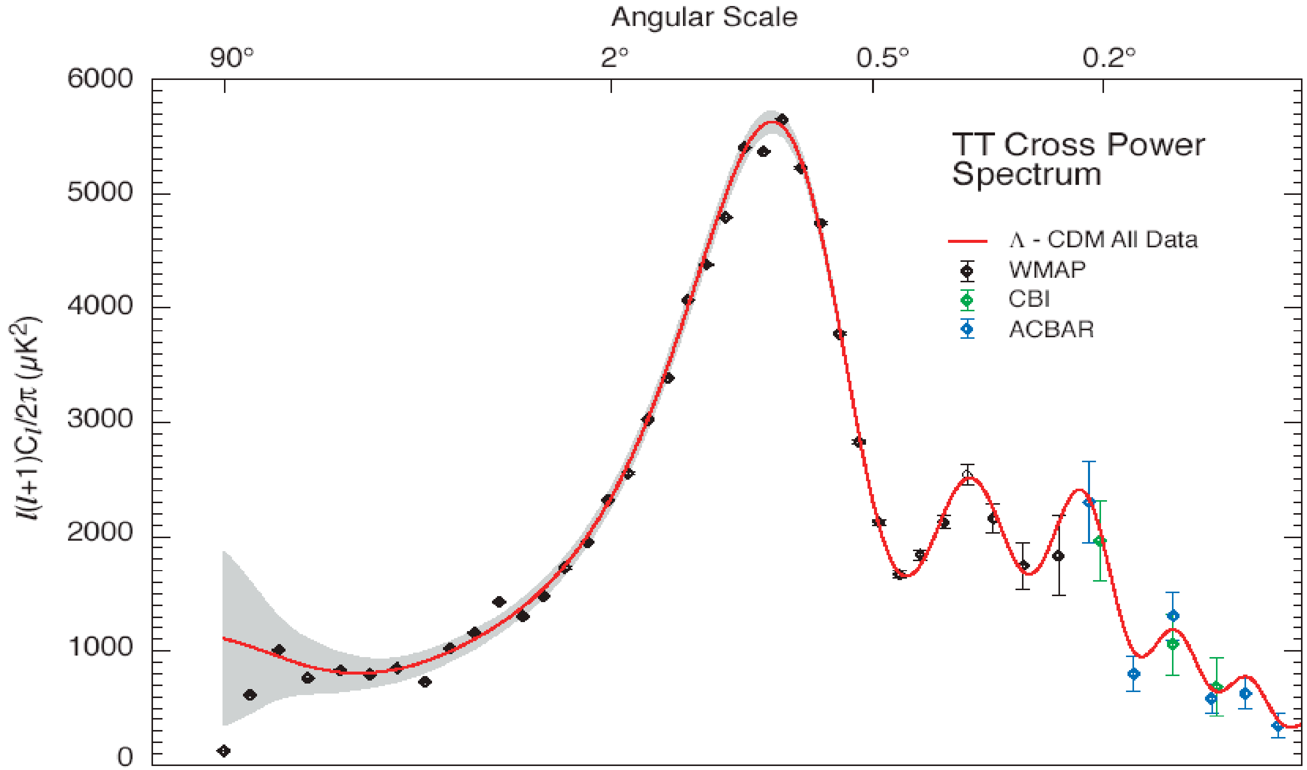
Desperately looking for SUSY…

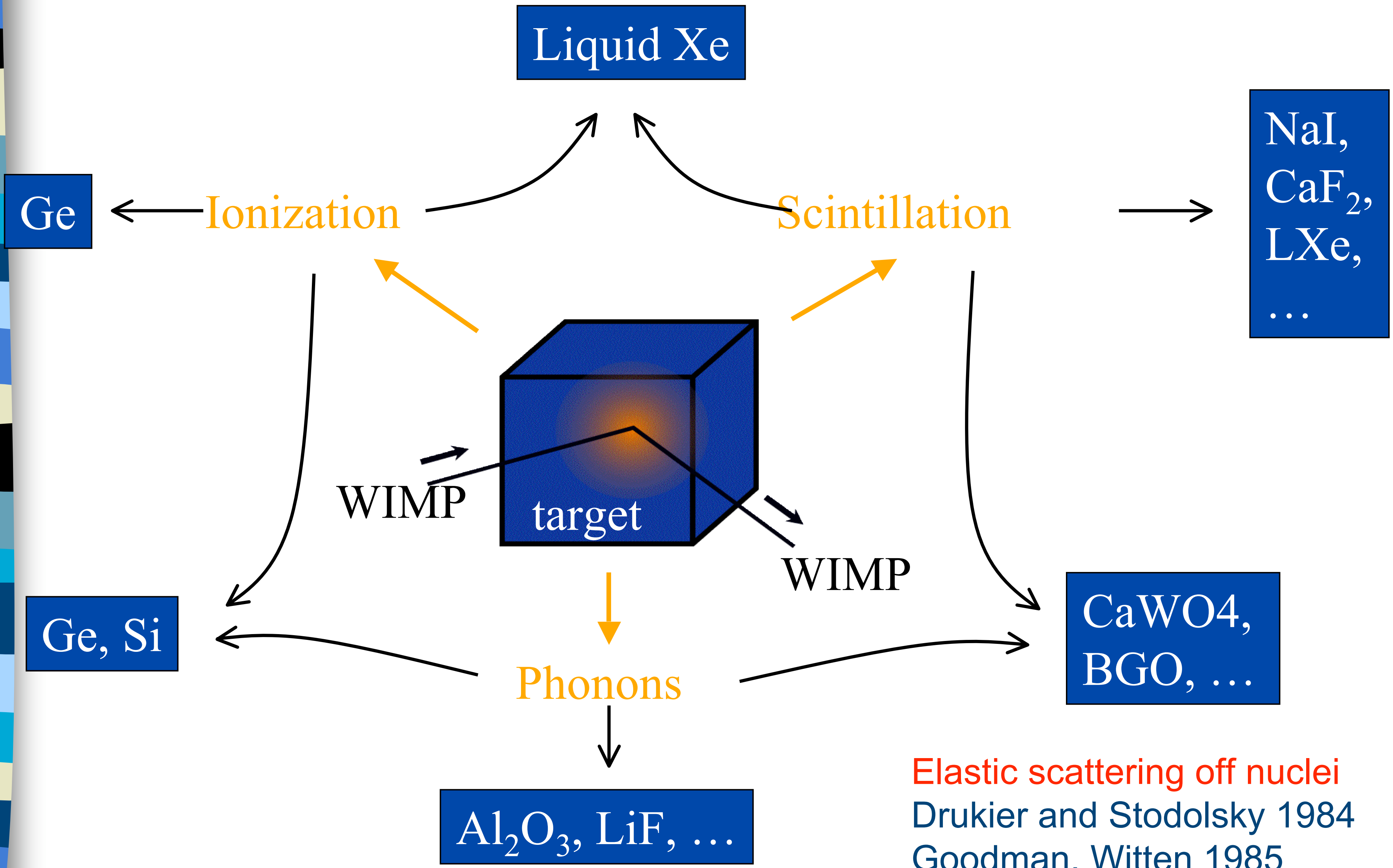
G. Chardin
CEA/Saclay, DAPNIA

Cosmological constraints after WMAP

- $\Omega_{tot} = 1.00 \pm 0.02$
- $\Omega_{baryon} = 0.045 \pm 0.005$
- $\Omega_{matter} \approx 0.30$
- $\Omega_{\Lambda} \approx 0.70$



WIMP detection schemes, with and w/o background rejection



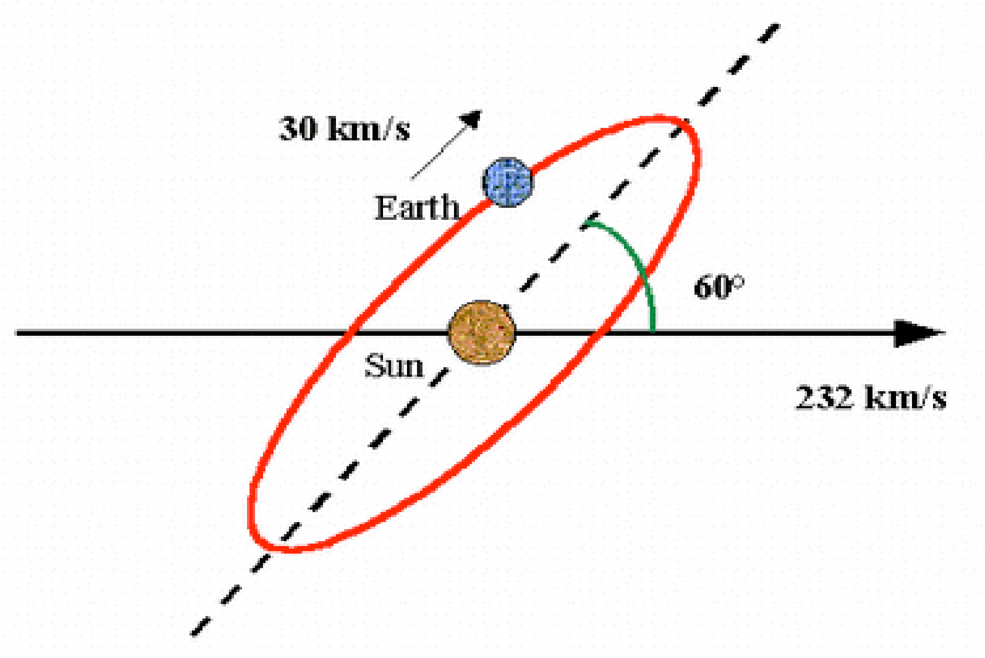
Elastic scattering off nuclei

Drukier and Stodolsky 1984

Goodman, Witten 1985

WIMP signatures are challenging

- Nuclear (NOT electron) recoil
- Annual modulation of event rate:



Maxwell velocity distribution of WIMPs in non-rotating halo superimposed with rotation of galaxy and motion of Earth around the sun

→ modulation of WIMP flux

max. 7% expected

Will soon require > 1 ton target

- Directionality of recoil nucleus:

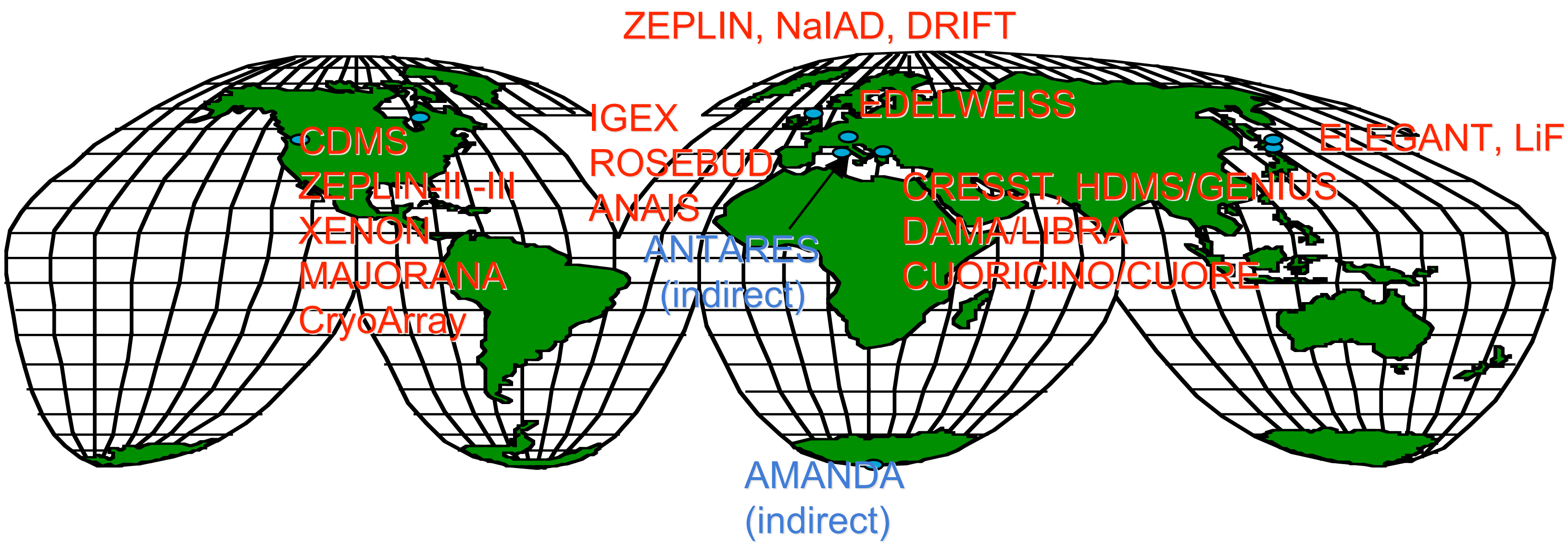
diurnal modulation of recoil direction due to Earth's rotation

→ record track of recoil nucleus in low pressure gas target

1-ton mass range appears barely feasible (x1000 m^3)

Wimps direct detection experiments

- EDELWEISS (cryo Ge @ Fréjus)
- CDMS-I (cryo Ge and Si @ Stanford), CDMS-II @ Soudan Mine
- ZEPLIN, DRIFT, NaIAD @ Boulby Mine)
- CRESST (cryo $CaWO_4$) @ Gran Sasso
- DAMA/LIBRA (NaI, Xe @ Gran Sasso)
- IGEX @ Canfranc, HDMS/GENIUS-TF (Ge) @ Gran Sasso
- ROSEBUD (cryo BGO), ANAIS (NaI)
- CUORICINO/ CUORE ($Te0_2$) @ Gran Sasso
- SIMPLE, MACHe3, ORPHEUS (Bern)
- ELEGANT, LiF @Japan
- Future experiments: CryoArray, XMASS, XENON, MAJORANA…



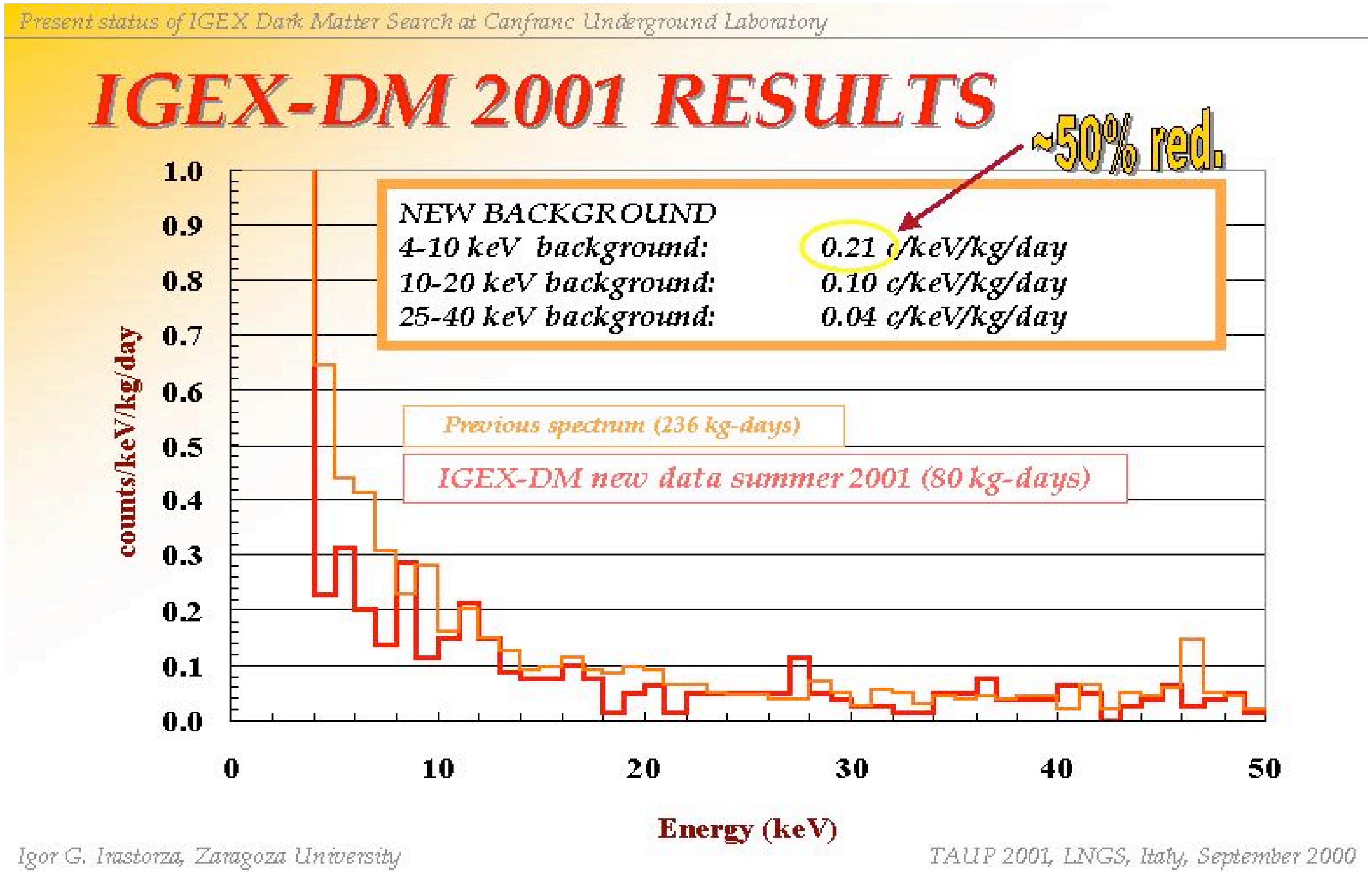
Detector strategies: experiments with and without background rejection

No nuclear recoil discrimination		
CUORICINO/CUORE	42 kg – 760 kg Te02	Gran Sasso
CRESST-I	1kg Al2O3	Gran Sasso
HDMS	0.2 kg Ge in 2.5 kg Ge	Gran Sasso
IGEX	2 kg Ge	Canfranc
Nuclear recoil discrimination : statistical, evt/evt		
NaIAD, ANAIS	50-100 kg NaI	Boulby/Canfranc
DAMA/LIBRA	100-250 kg NaI	Gran Sasso
ZEPLIN I to III	4 kg liq Xe, up to 1 ton	Boulby
EDELWEISS-I and -II	1, 10 to 35 kg Ge	Fréjus Lab (LSM)
CDMS-I and -II	1, 10 kg Ge and Si	Stanford, Soudan mine
CRESST-II	10 kg CaWO4	Gran Sasso
ROSEBUD	0.1-1 kg BGO (CaWO4,…)	Canfranc
Directional and discriminating but digital experiments		
DRIFT	CS2 directional	Boulby
SIMPLE	Freon areogels, digital	Rustrel
MACHe3	Few grams He3, to 1kg	Grenoble

Germanium diodes

High purity: best intrinsic background level
~ 0.05 ev./kg/keV/day (Heidelberg-Moscow)
~ 0.21 ev./kg/keV/day (IGEX), lower E threshold

No electron recoil background rejection possible

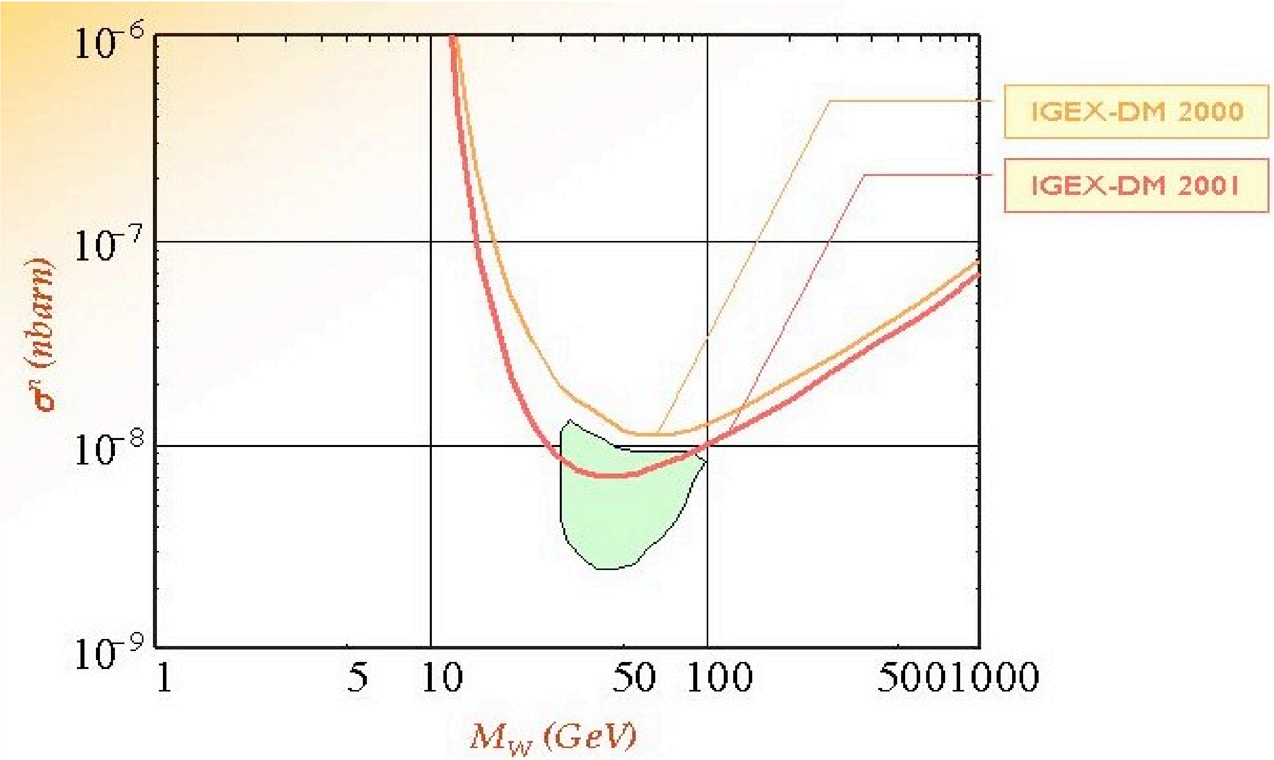


Ge diodes - Quenching factor for nuclear recoils ~ 0.3

→ Energy threshold

9 keV e.e. ⟷ 27 keV recoil (Heidelberg-Moscow)

4 keV e.e. ⟷ 13 keV recoil (IGEX)



IGEX *:

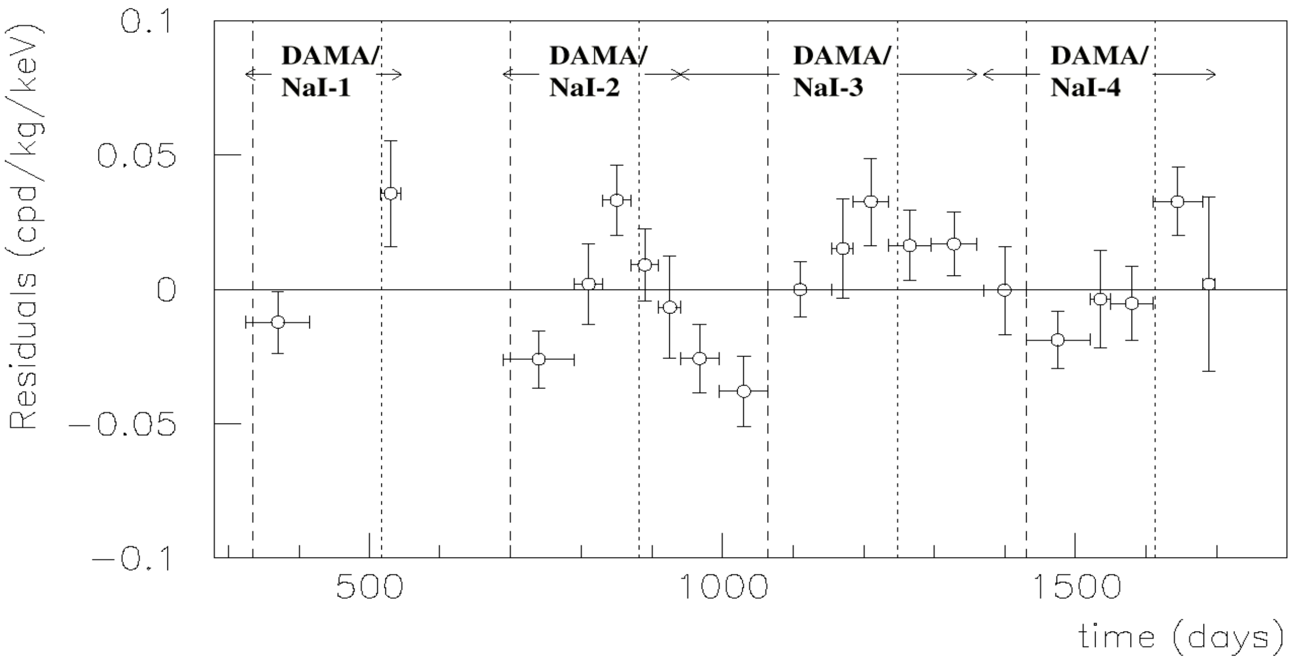
at present highest sensitivity with Ge diodes

Exclusion limit:

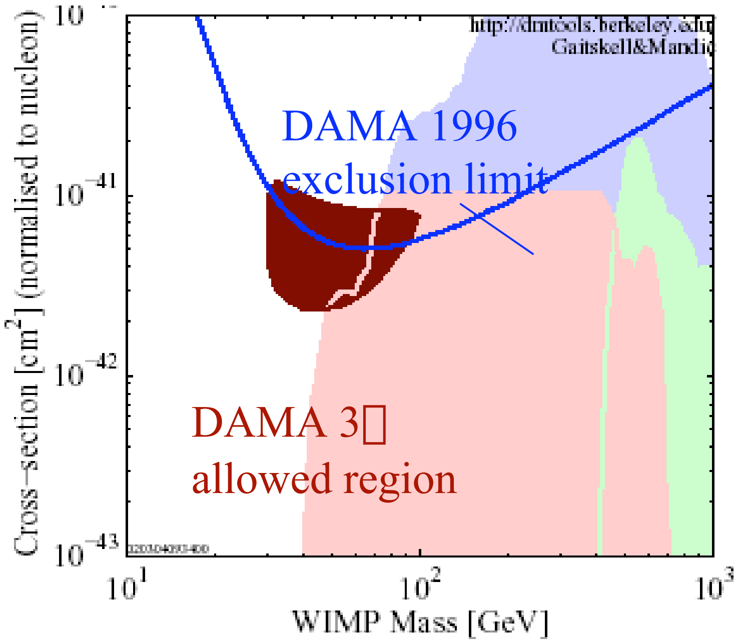
2 kg Ge detector, enriched to 86% ^{76}Ge

80 kg-days

Univ. of Zaragoza; Univ. of South Carolina, Columbia; Pacific Northwest Nat. Lab., Richland WA; ITEP Moscow, Baksan Neutrino Obs., Yerevan Phys. Inst.



Annual modulation compatible in period and phase with WIMP signal observed over four years



~ 100 kg NaI, 9 crystals

~ 58000 kg-days

$M_\chi = (52\ ^{+10}_{-8})$ GeV

$\sigma_{\chi\text{-}N} = (7.2\ ^{+0.4}_{-0.9}) \cdot 10^{-6}$ pb

* Univ. Of Rome, INFN, IHEP Beijing

Should we believe the DAMA claim ?

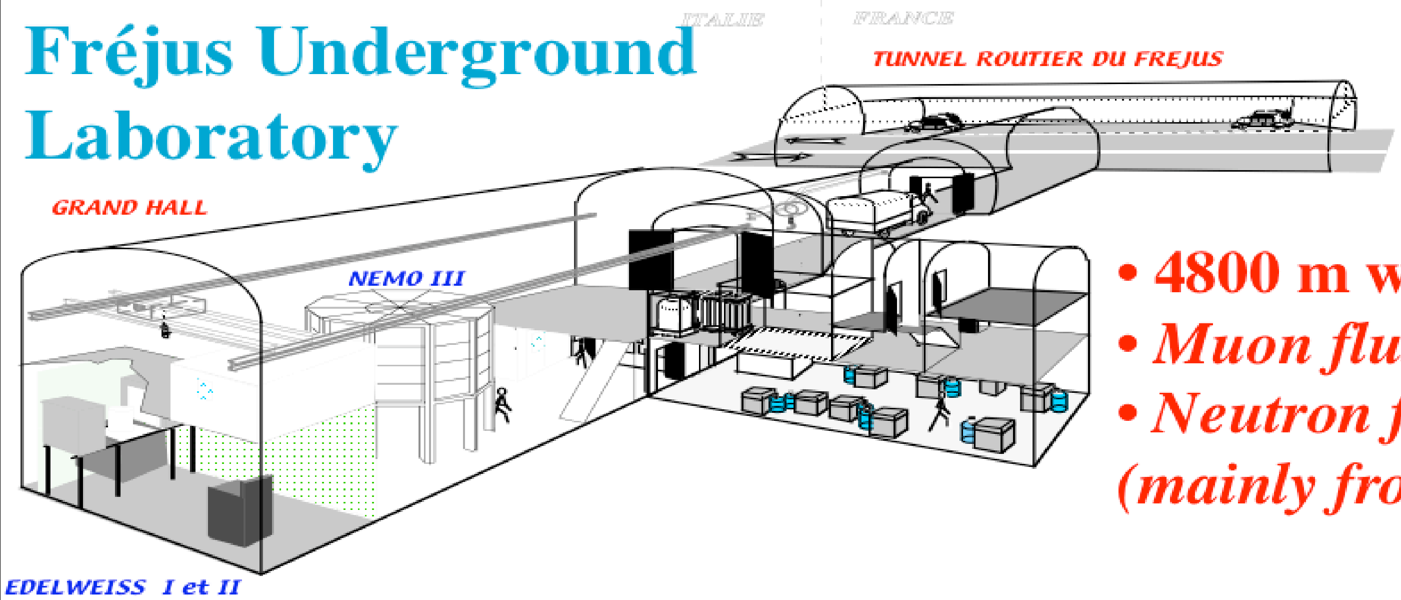
- Annual modulation signature:
  controlling systematics close to threshold
- If correct: a large fraction (>50%) of WIMP events (10^5 events!) in the lowest energy bin (2-3 keV, in fact 25-35 keV recoil)
- The initial DAMA claim (R. Bernabei et al., ROM2F/97/33):
  - Spectrum not consistent with a 60 GeV WIMP
  - Signal seen in only two (out of 9) crystals)
  - Statistical significance in 2000 still at 4 sigma despite exposure increase x15
- Still, checking the DAMA result experimentally is important
- DAMA lesson: annual modulation signature will soon require detector mass in the > 1 ton range
  • experiments with high background rejection now necessary

Edelweiss

-Dark Matter Search -

CEA-Saclay DAPNIA and DRECAM
CRTBT Grenoble
CSNSM Orsay
IAP Paris
IPN Lyon
Laboratoire souterrain de Modane (Fréjus)
FZ-Karlsruhe and Univ. Karlsruhe

Fréjus Underground Laboratory



- 4800 m water eq.
- *Muon flux ≈ 4 muons/m²/day*
- *Neutron flux ≈ 1.5 10^{-6} s^{-1} cm^{-2} (mainly from rock radioactivity)*

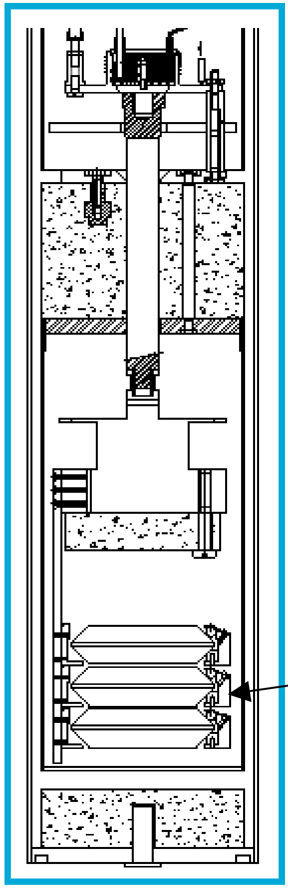
Edelweiss-I: 1 kg stage

Cu screens and without Roman Pb lateral shield

1^{rst} data taking: Fall 2000

2nd data taking : First semester 2002

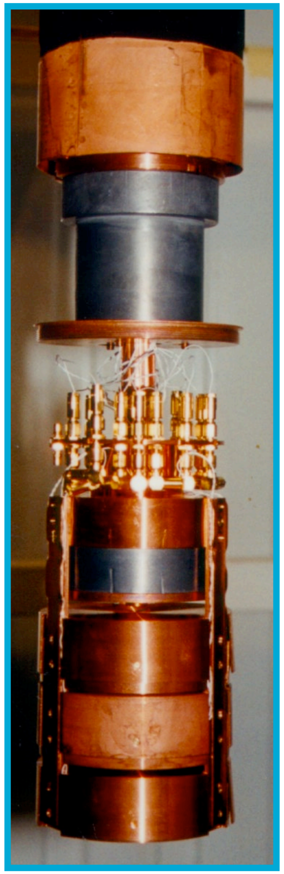
3rd data taking: October 2002 - present



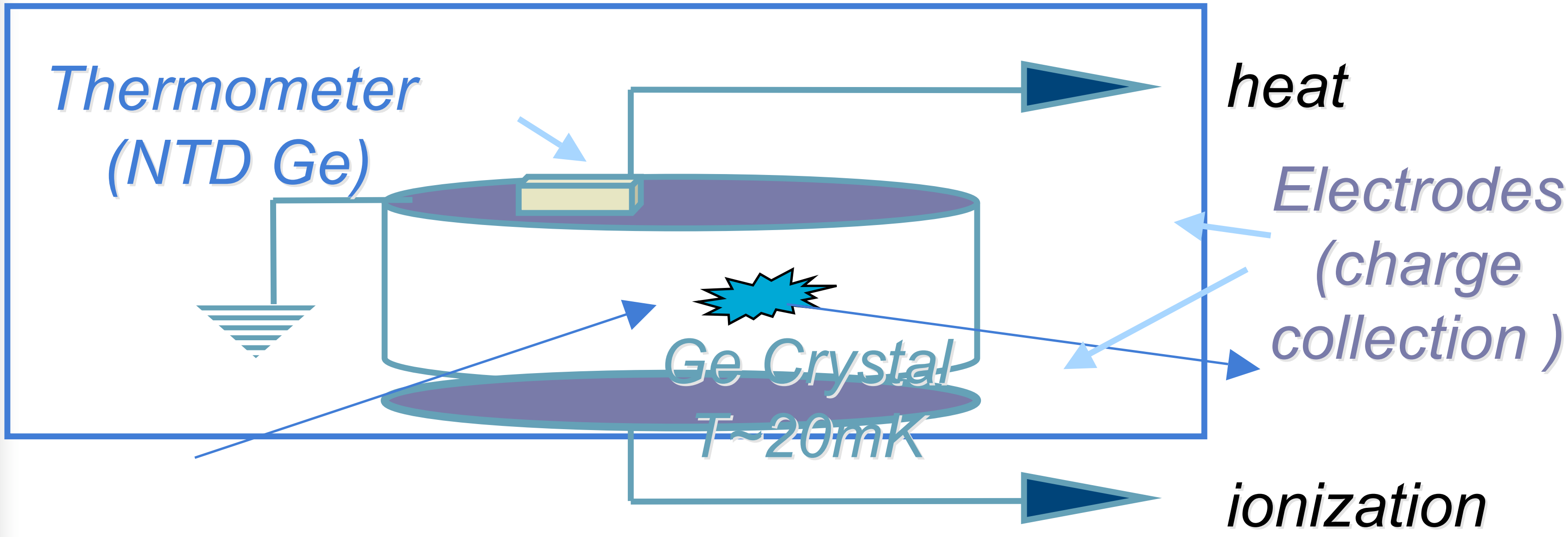
Archeological lead

3 * 320 g Ge detectors

Mai 2002
GGA1,GeAl9,GeAl10



Ionization-heat cryogenic detectors

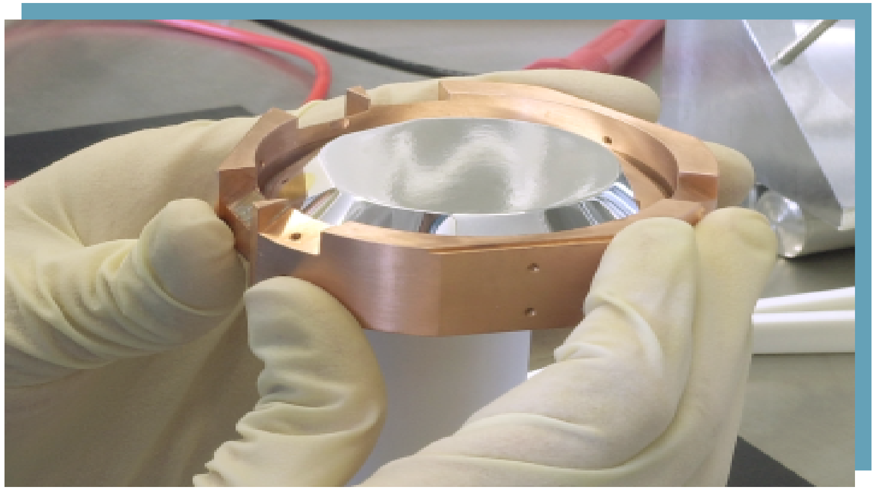


Simultaneous measurement of charge and heat signals for each interaction.

Different charge/heat ratio for nuclear recoils and electronic recoils

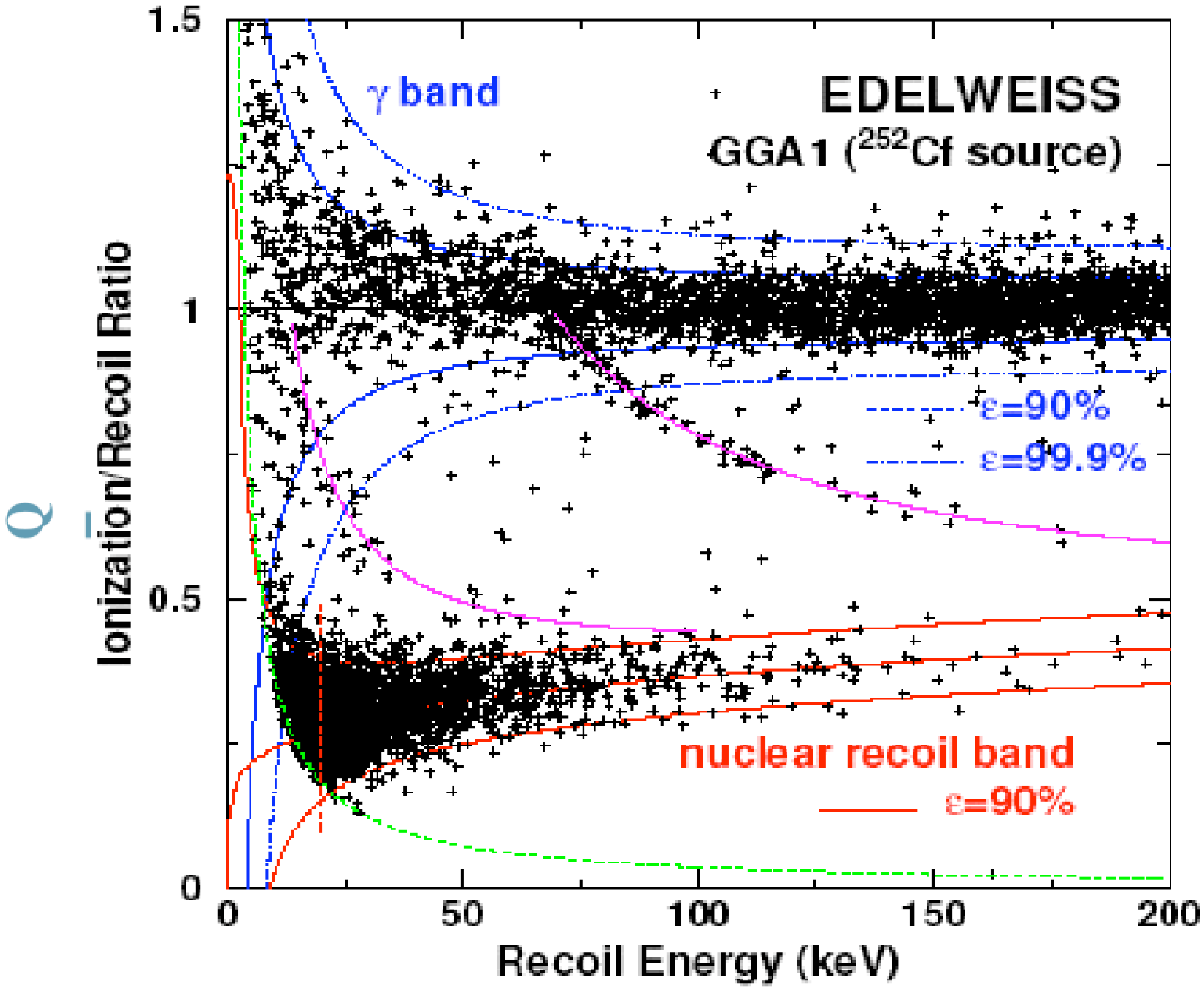
➜ **event by event discrimination**

1kg stage of EDELWEISS-I: 3*320 g Ge.



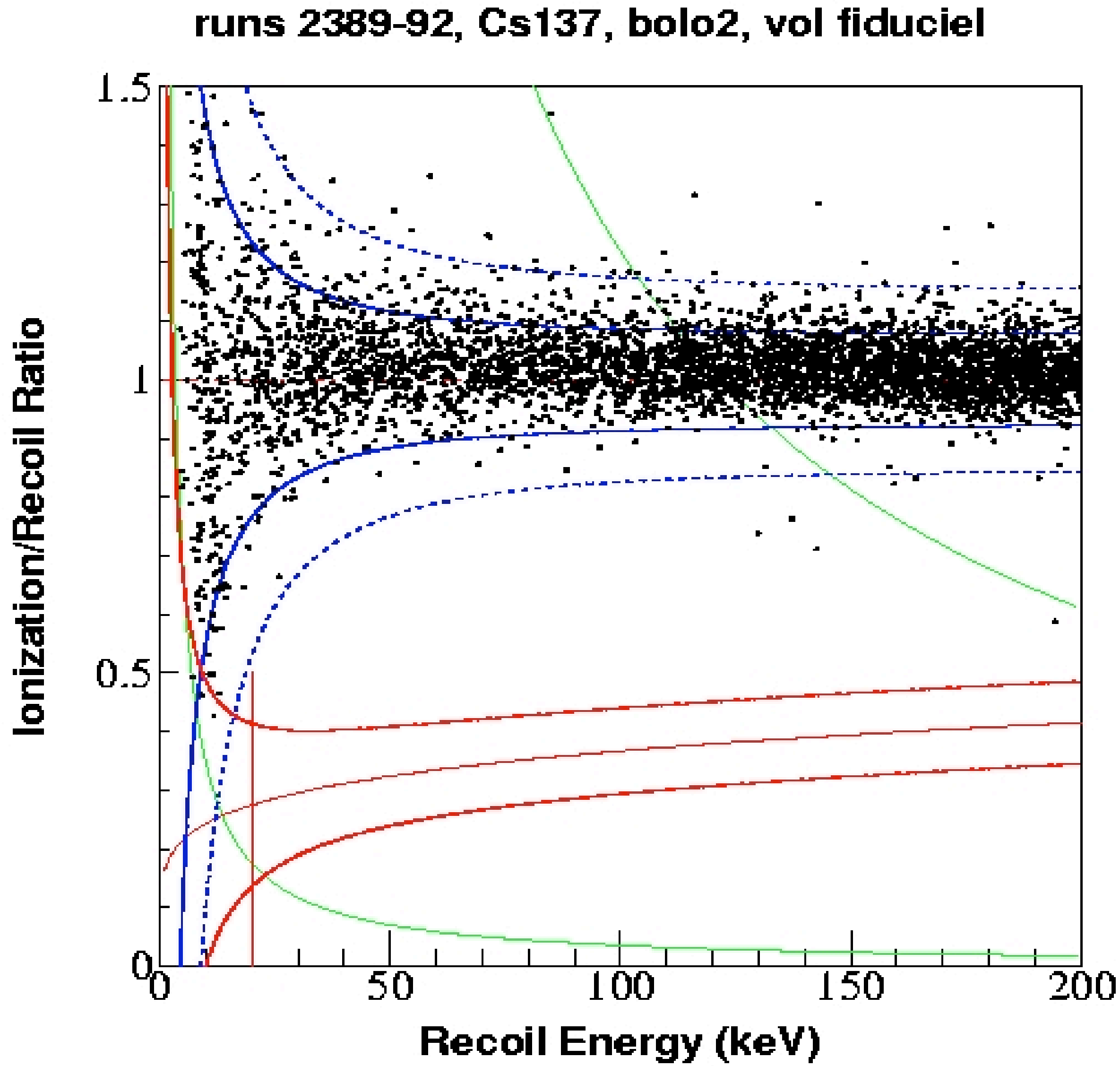
- *GGA1: heat and ionisation Ge detector*
- ***aluminium electrodes*** *(center +* ***guard ring)*** *+* ***Ge amorphous layer***
- *NTD sensor on guard ring electrode*
- *Mass 320 gram*
- *Low radioactivity cryostat*
- *Shield: 30 cm paraffin, 20 cm Pb, 10 cm Cu*
- *Installed in* ***Fréjus Lab*** *4800 mwe*
- *Low neutron background 1.6 10^{-6} n/cm^2/s*
- *Resolutions @ 10 keV (@ 122 keV)*
  - *ionisation : 1.3 keV (2.2 keV)*
  - *heat : 1.0 keV (3.0 keV)*

GGA1 neutron calibration



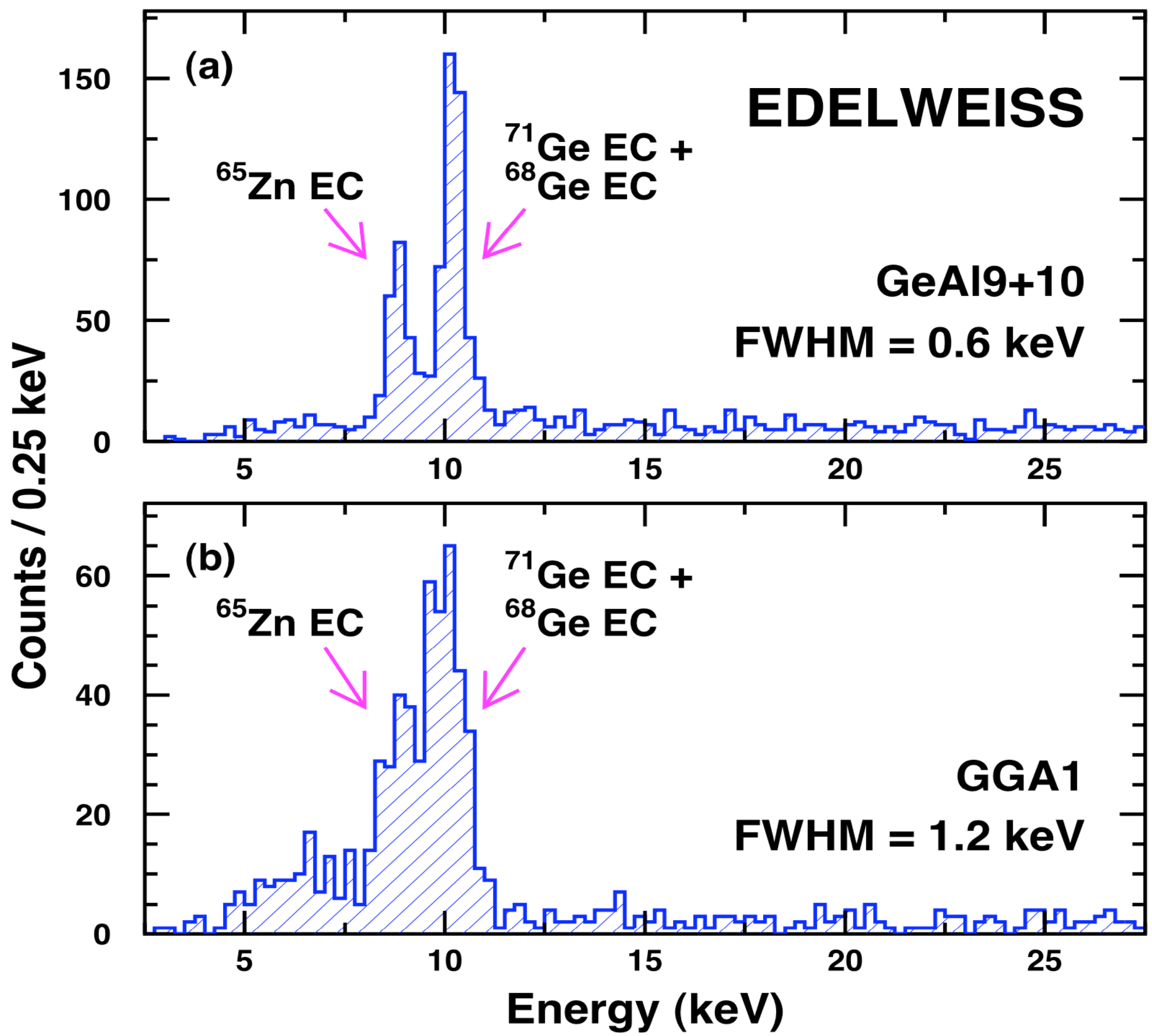
GGA1 gamma calibration

Q =



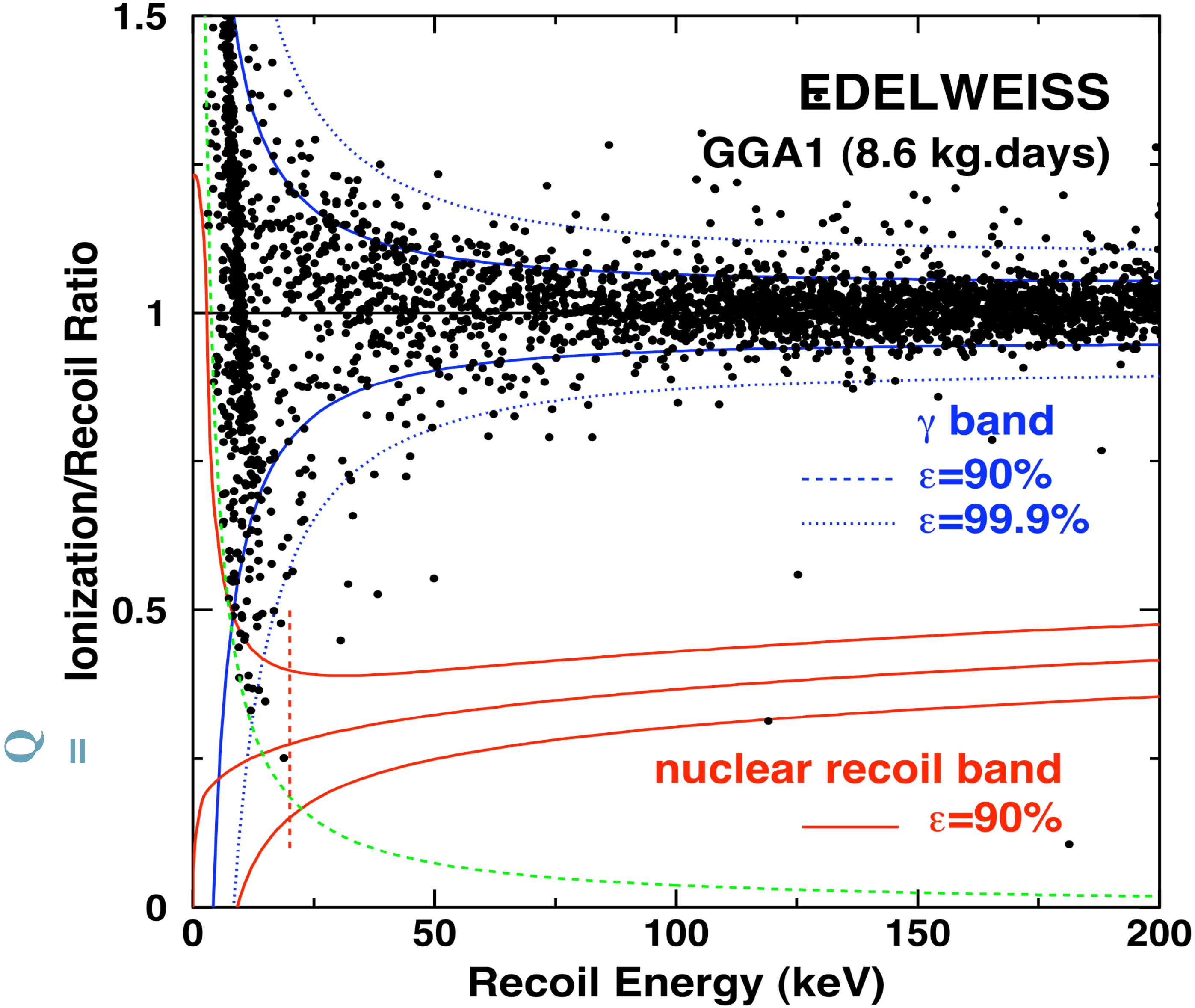
Cryogenic detectors: excellent energy resolution

- Sub-keV energy resolution on phonon
 channels (now down to 300 eV FWHM)
- 400 eV FWHM obtained in lab tests on charge channel



EDELWEISS-I :
2002 data from GGA1 detector

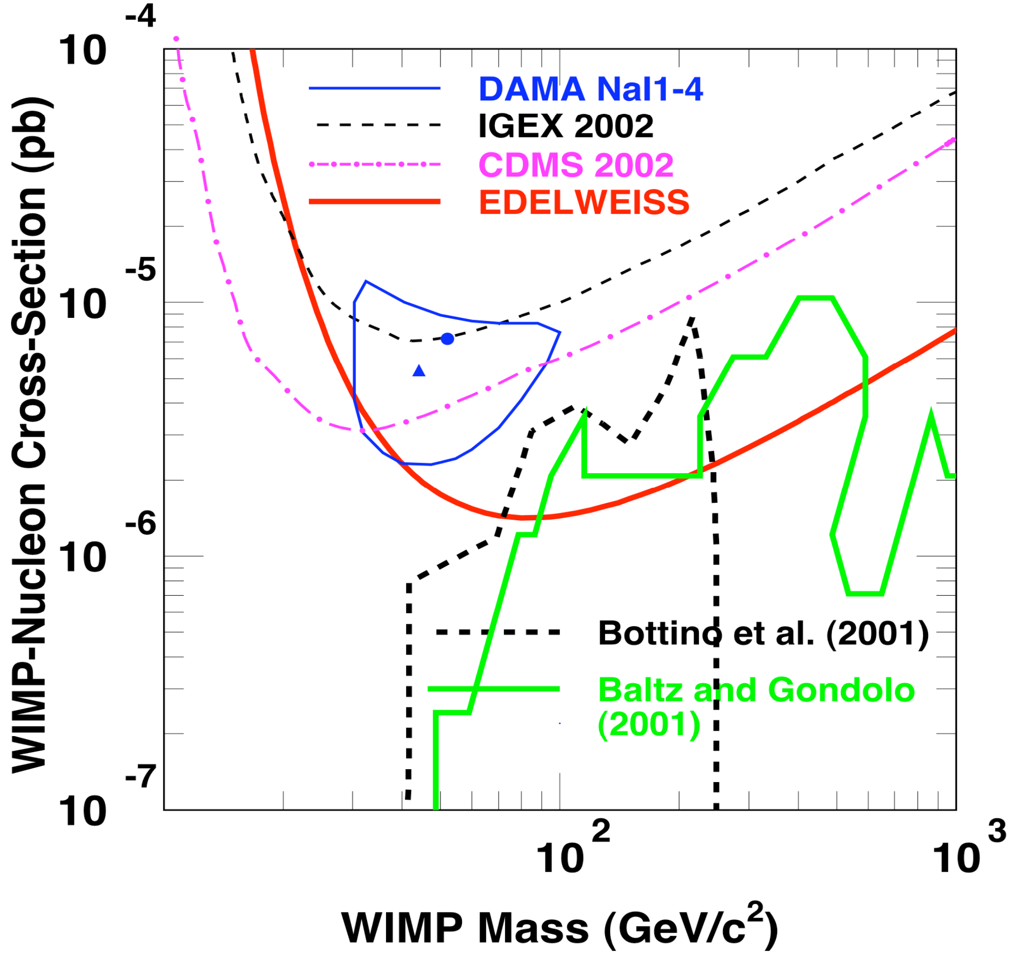
3 months data acq:
0 event (1?)
Present benchmark
Sensitivity:
≈10^{-6} picobarn



EDELWEISS-I 2002
spin independent interaction

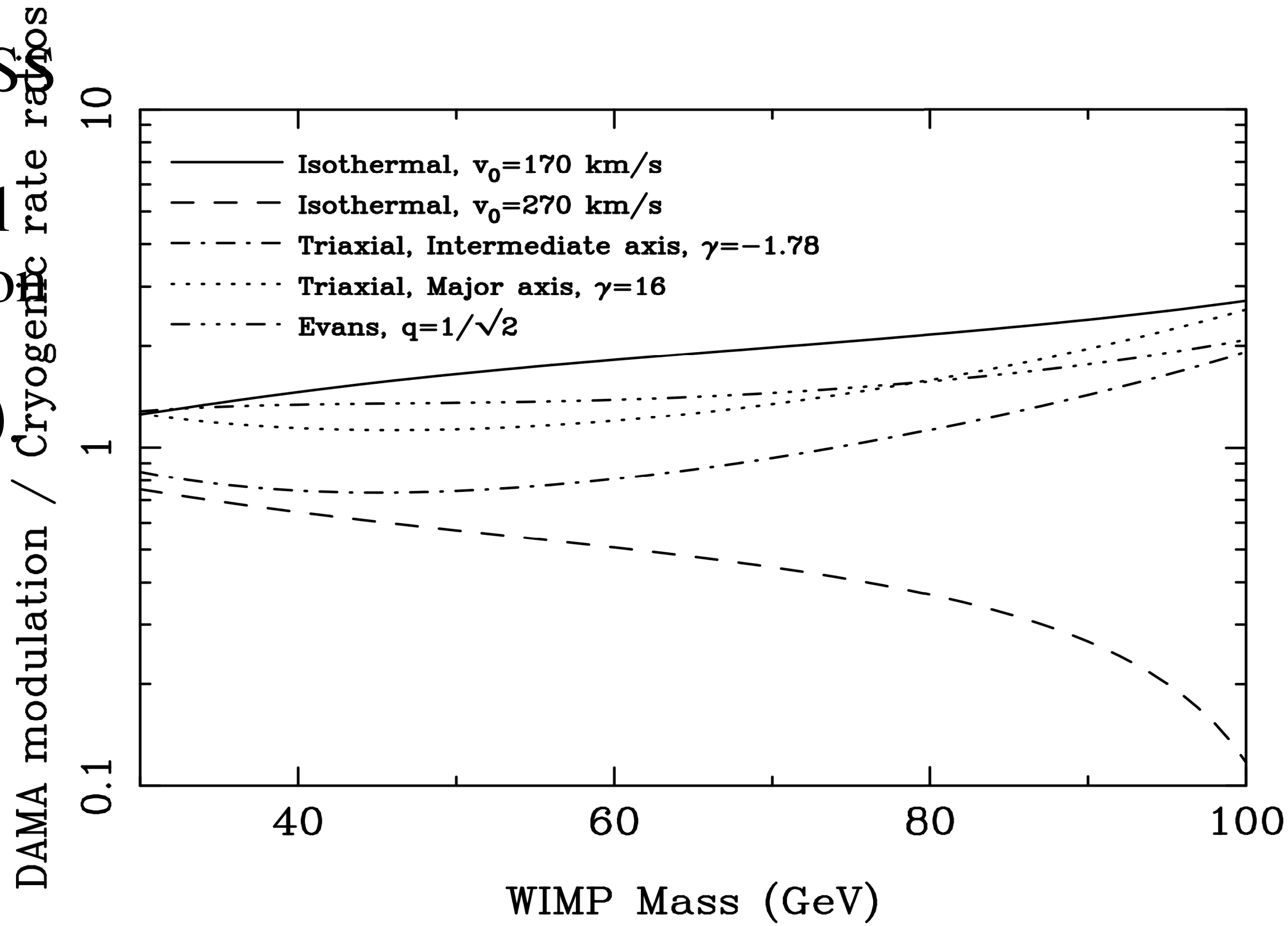
Phys. Lett. B **545**, 43 (2002)

Standard halo assumed, mean velocity of 220 km/s
WIMP signal acceptance = 95 % , the event at 119 keV only contribute marginally to WIMP masses > several TeV
Exploration of first sample of SUSY models compatible with accelerator constraints.



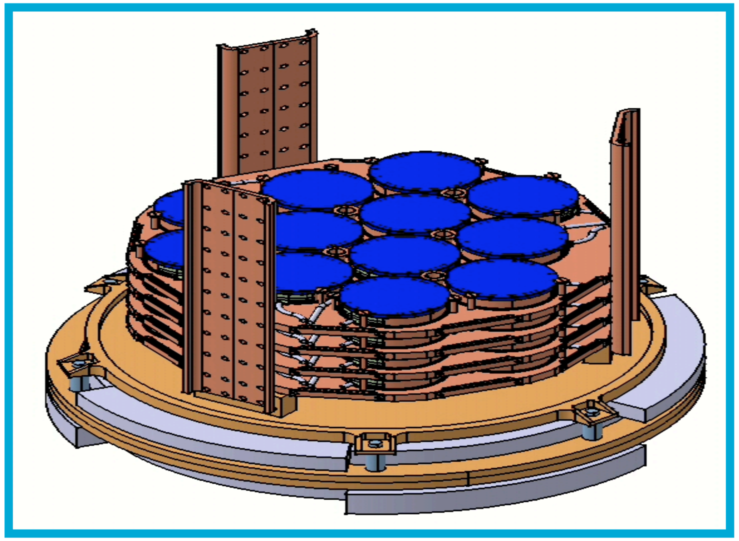
Model independent exclusion

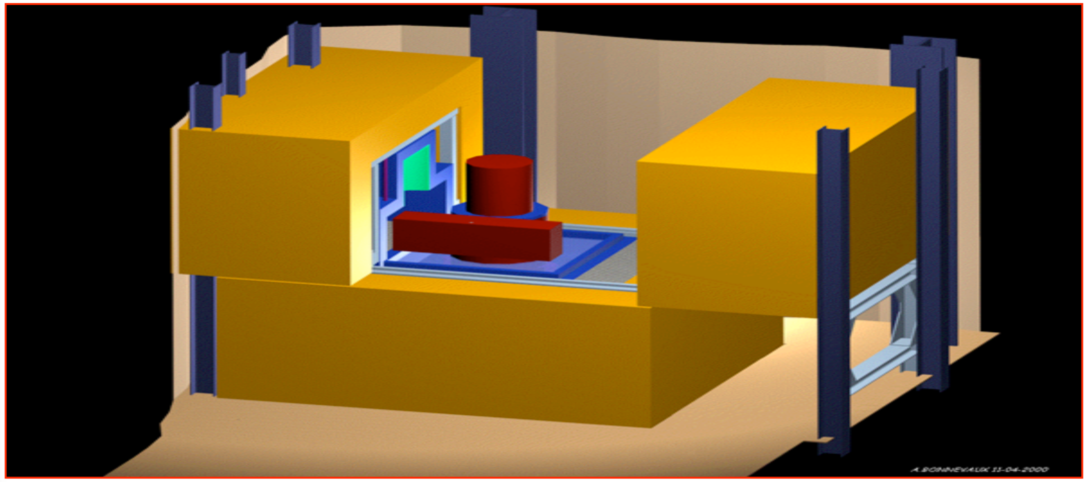
- DAMA exclusion by the EDELWEISS result is stable against halo model parameter excursion *(Copi et Krauss, astro-ph/0208010)*.

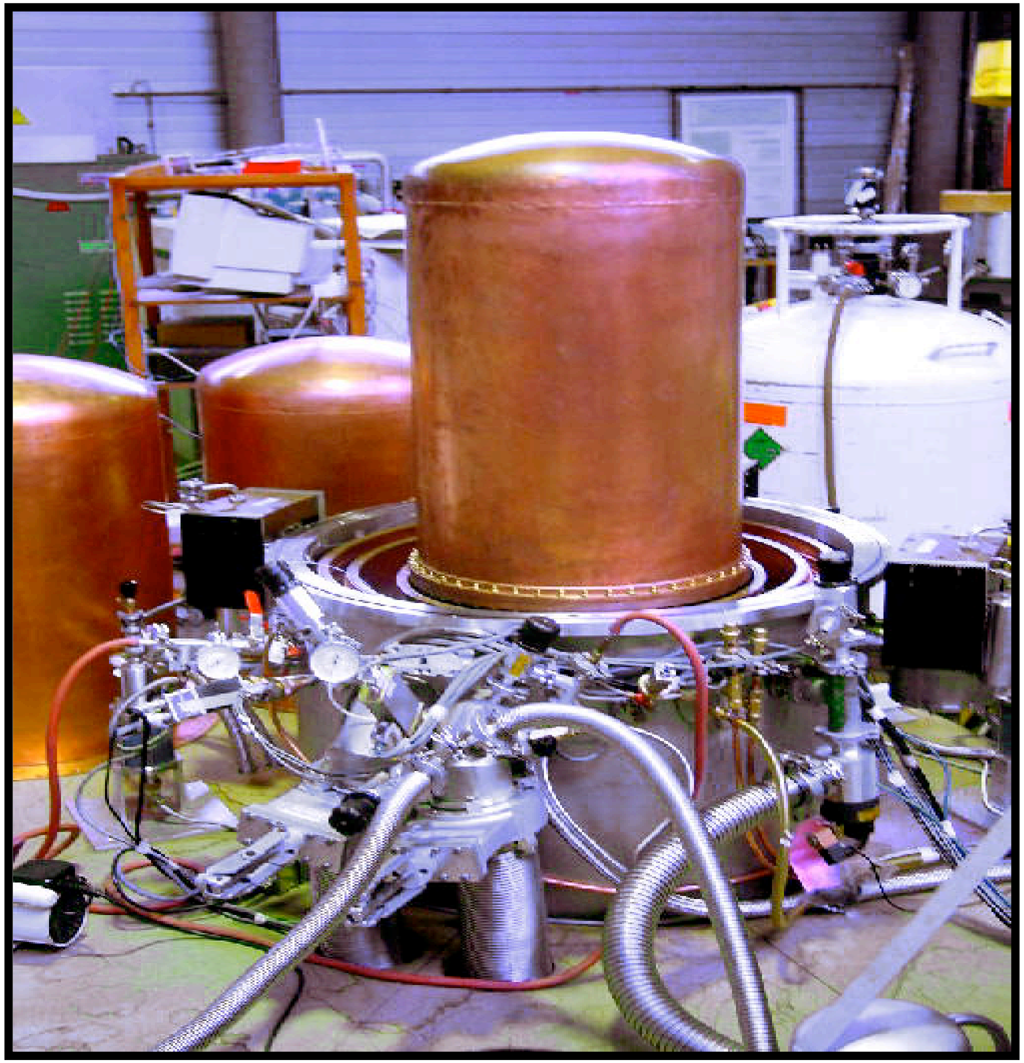


EDELWEISS-II detector setup
(Phase 28*320g detectors approved, 2004)

100 liter cryostat for up to 120 detectors : ≈ 36 kg Ge
Development of NbSi thin layers to eliminate surface events
Improve sensitivity by factor ≈ 100



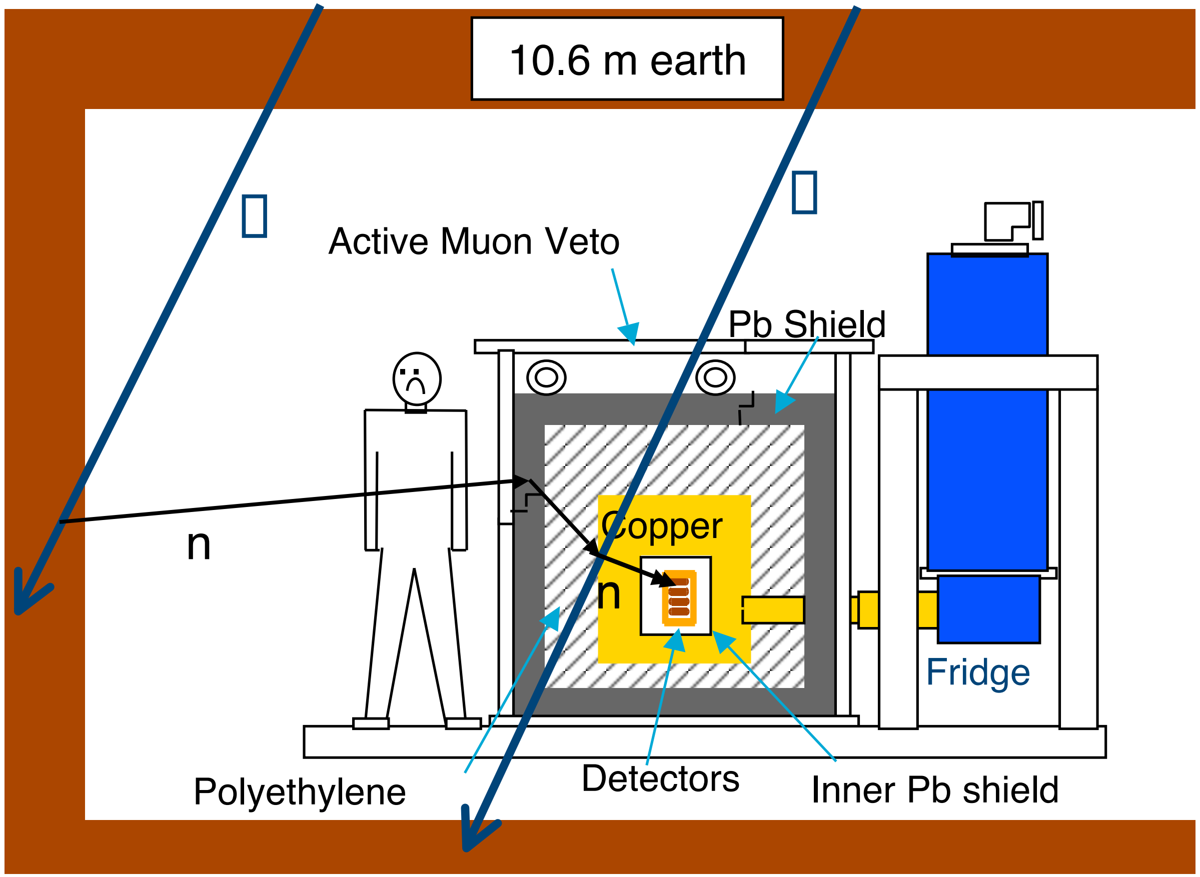




Dilution : 8-10 mK obtained
Wiring and cold electronic test : summer 2003

Current CDMS Site: Stanford

- Shielded, low-background environment
- Shallow (17 mwe rock)
  - Hadronic cosmic-ray flux reduced by >1000x
  - Muons reduced by ~5x
- Active muon veto
  - >99.9% efficient
  - Reject ~100 neutrons per kg-day produced by muons within shield

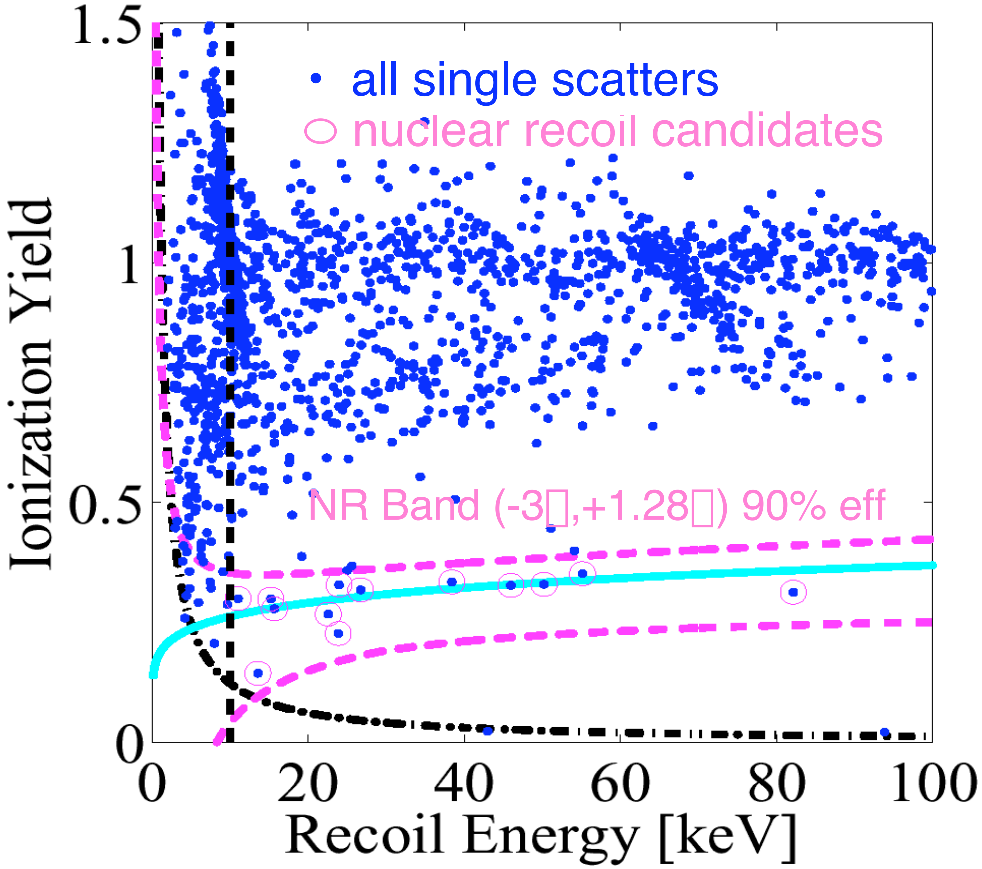


- Expect neutron background ~2 / kg / day produced outside shield; measure using
  – Two materials (Si more sensitive to neutrons, Ge more sensitive to WIMPs)
  – Multiple-detector neutron scatters

1999 Run Ge BLIP Muon-Anticoincident Data Set

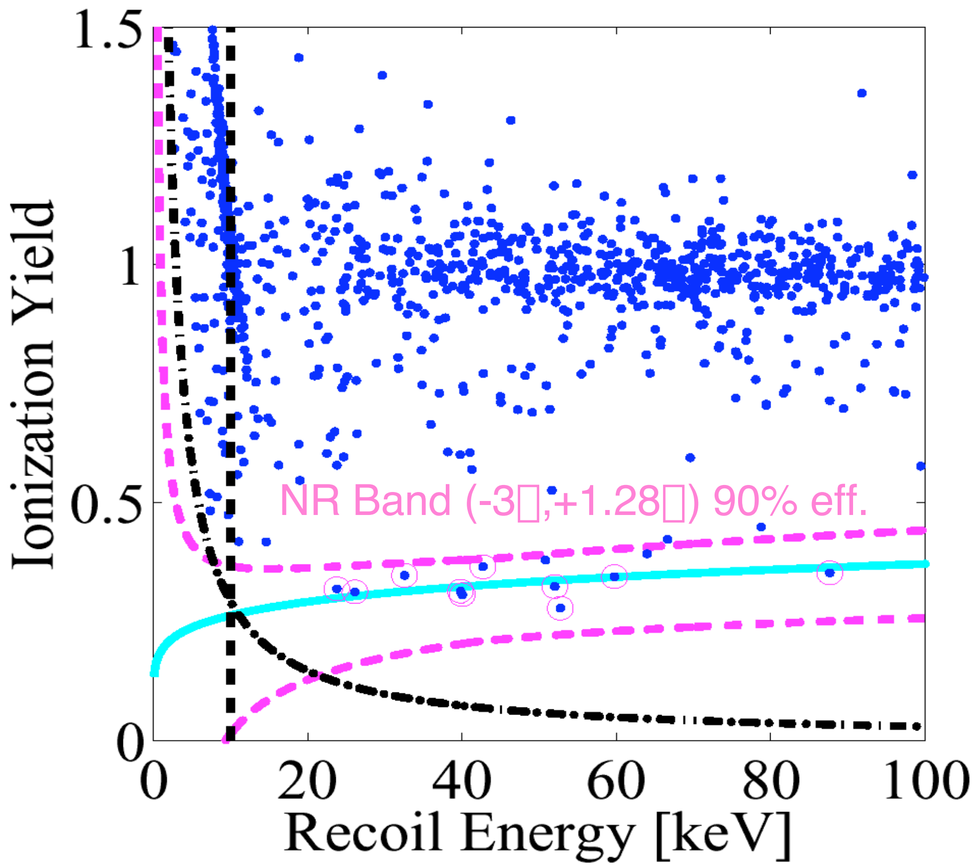
Inner-Electrode

11.9 kg-days for WIMPs
13 nuclear-recoil candidates
(> 10 keV)

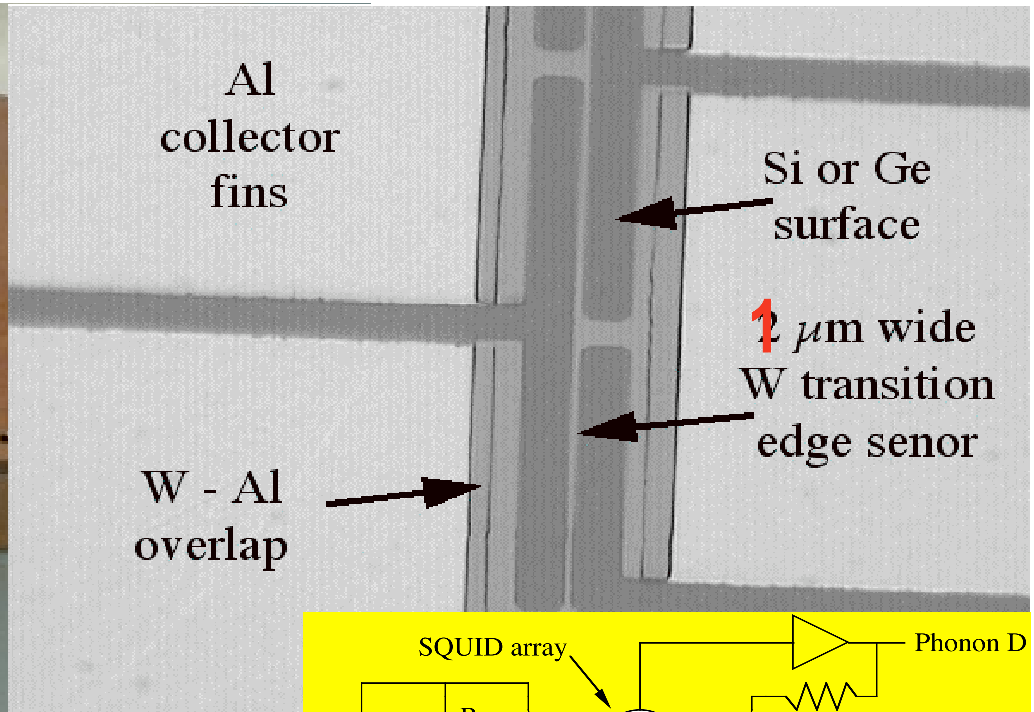


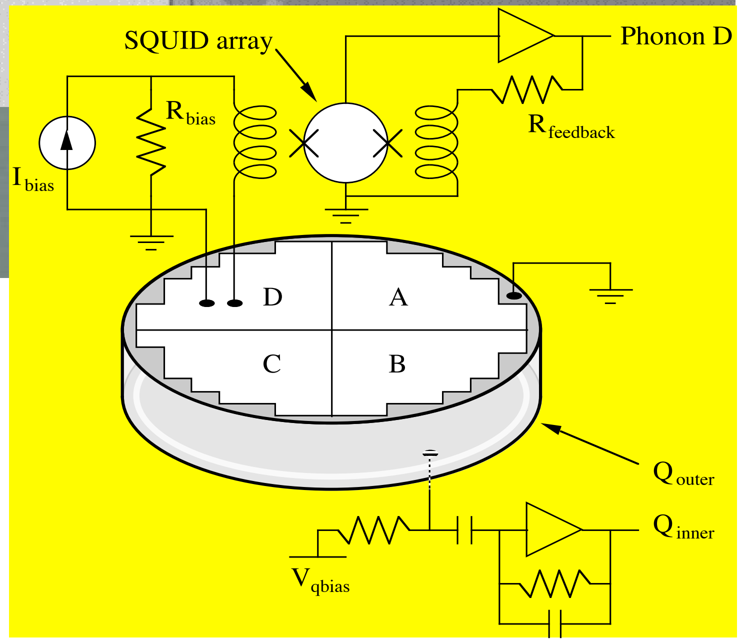
Shared-Electrode

4.4 kg-days for WIMPs
10 nuclear-recoil candidates
(> 10 keV)



ZIP: advanced athermal phonon detectors





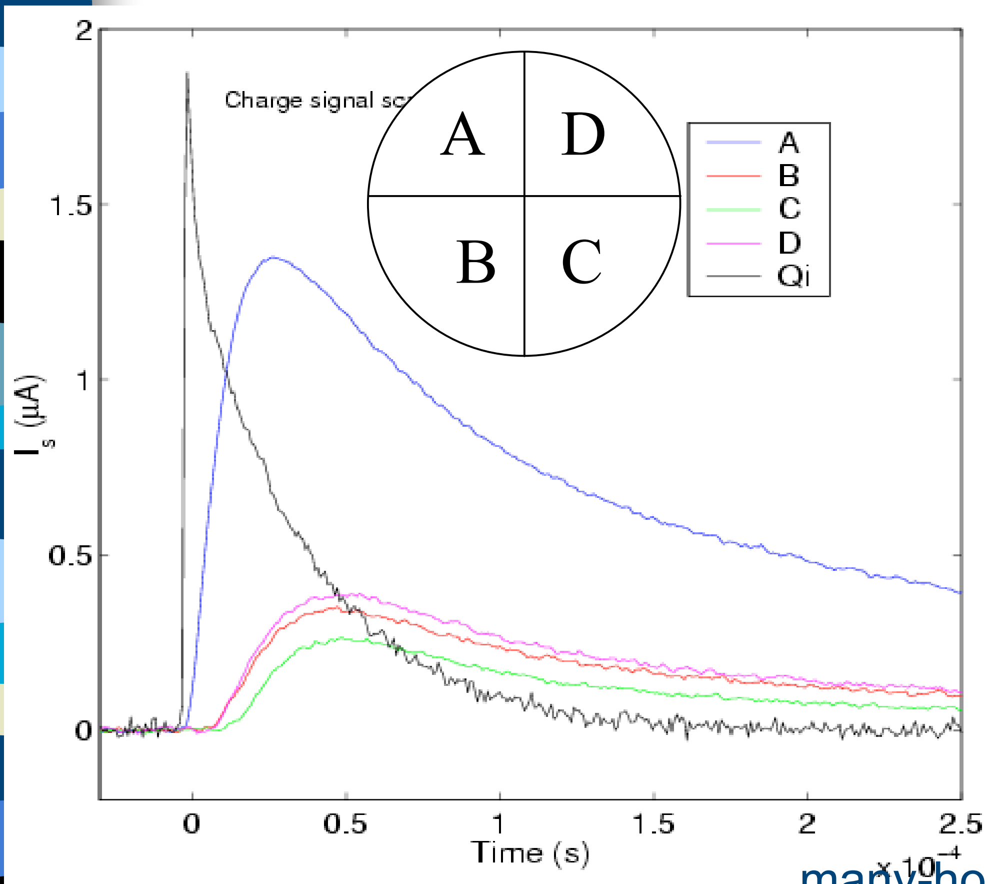
superconducting thin films of W/Al

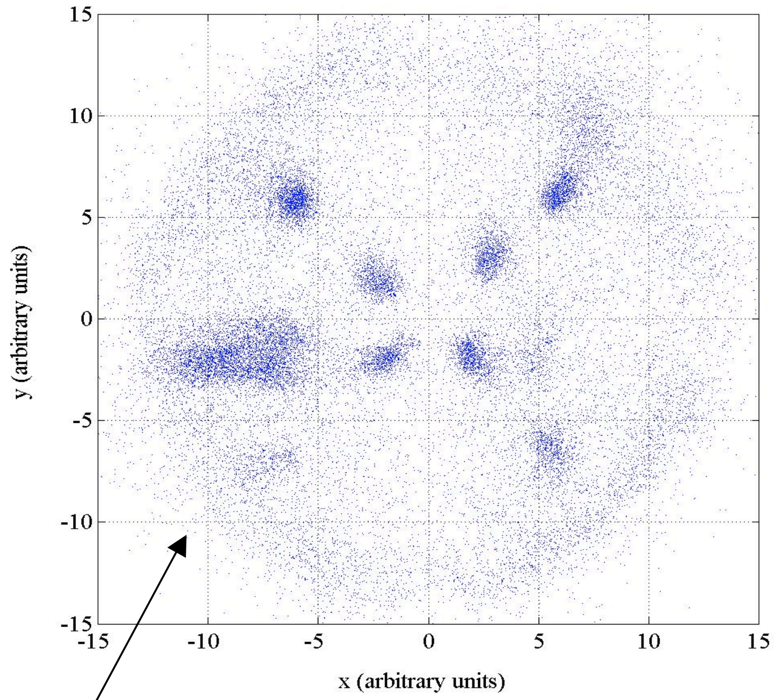
Position Measurement (ZIPs)

Ionization signal is ~ instantaneous: measure of time

Measuring the delays of the 4 phonon signals => (x,y) position of the interaction

(x= delay(A) - delay(D), y = delay(B) - delay(A))





many-hole collimated, large surface Cd-109 source

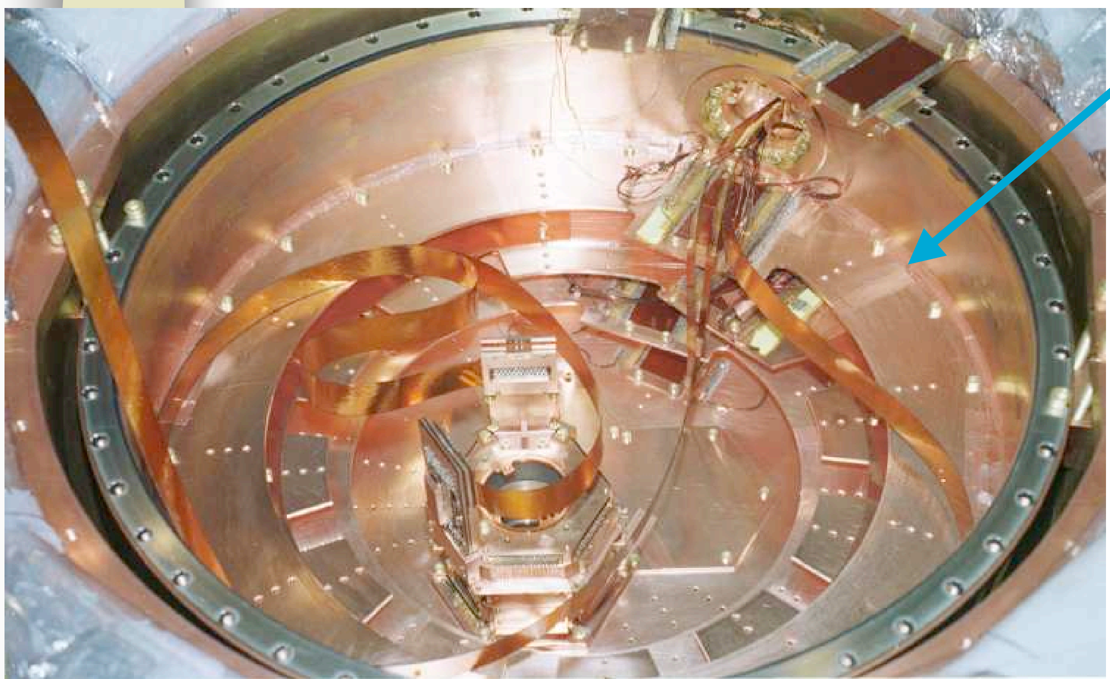
CDMS II: move to Soudan early 2003

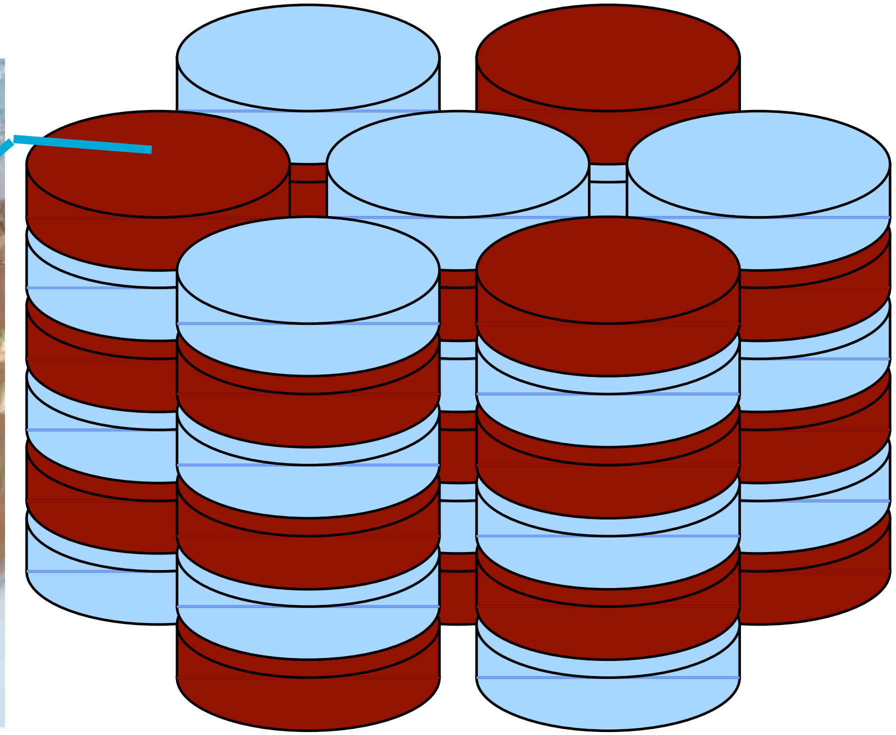
–Identical Icebox:

7 towers each with 3 Ge & 3 Si ZIPs

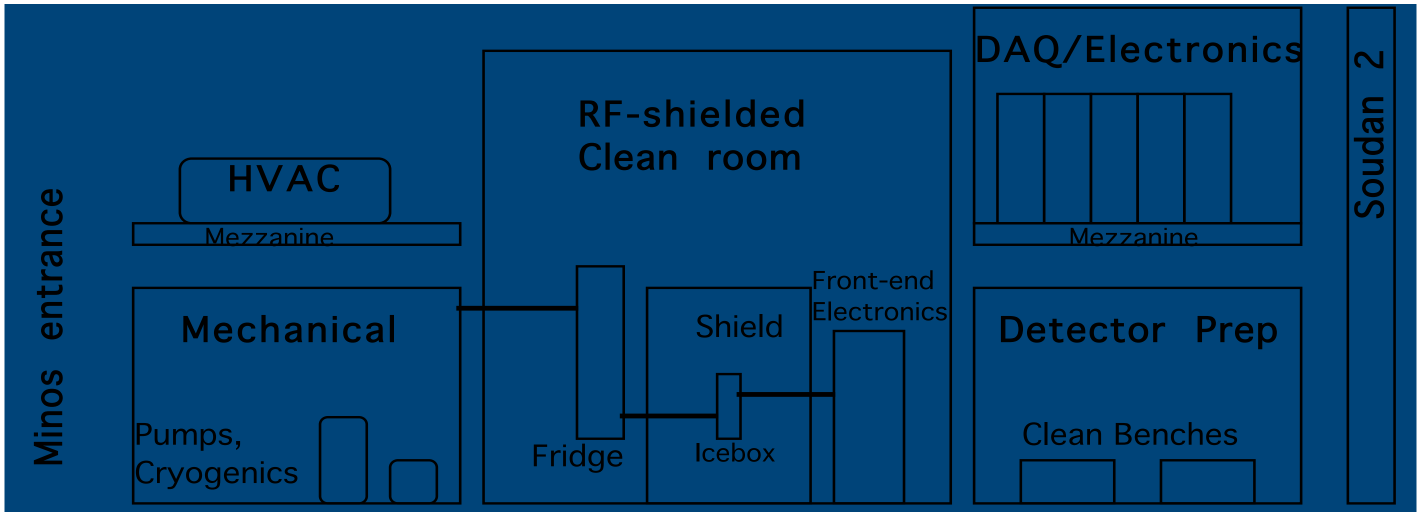
Total mass of Ge = 7 X 3 X 0.25 kg > 5 kg

Total mass of Si = 7 X 3 X 0.10 kg > 2 kg



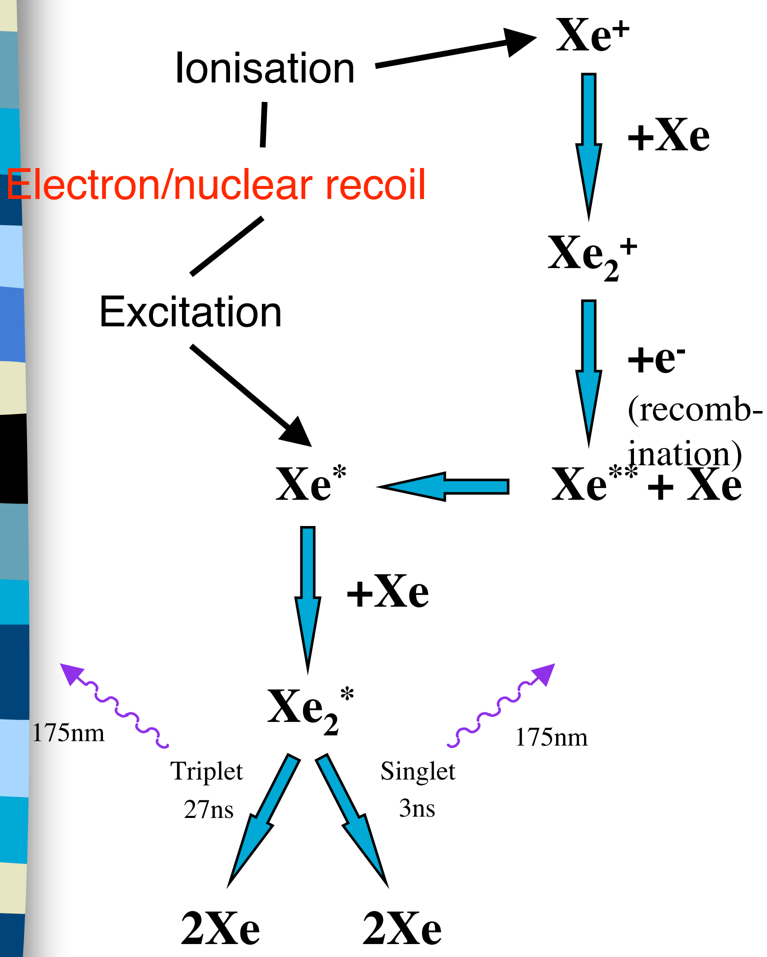


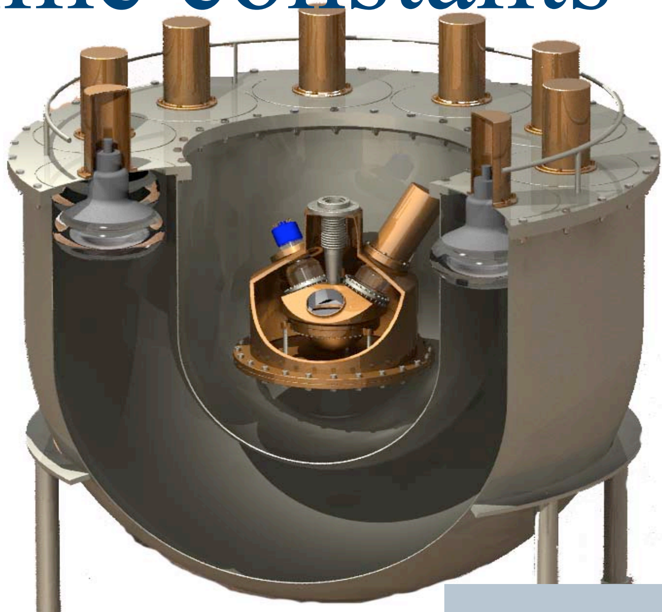
CDMS II experimental enclosure

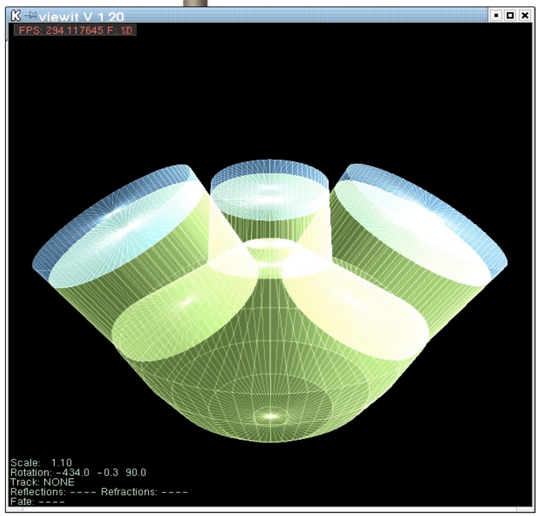


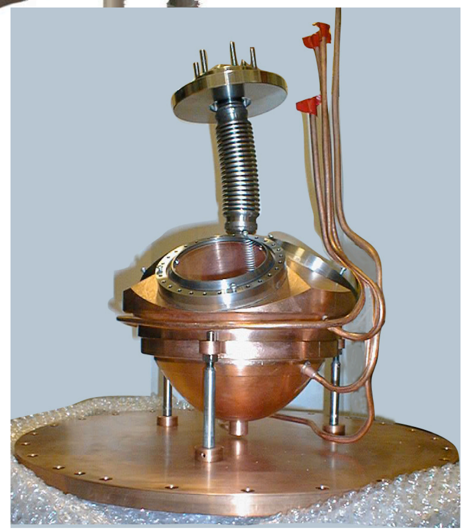
ZEPLIN in Boulby Underground Lab

ZEPLIN I: light time constants

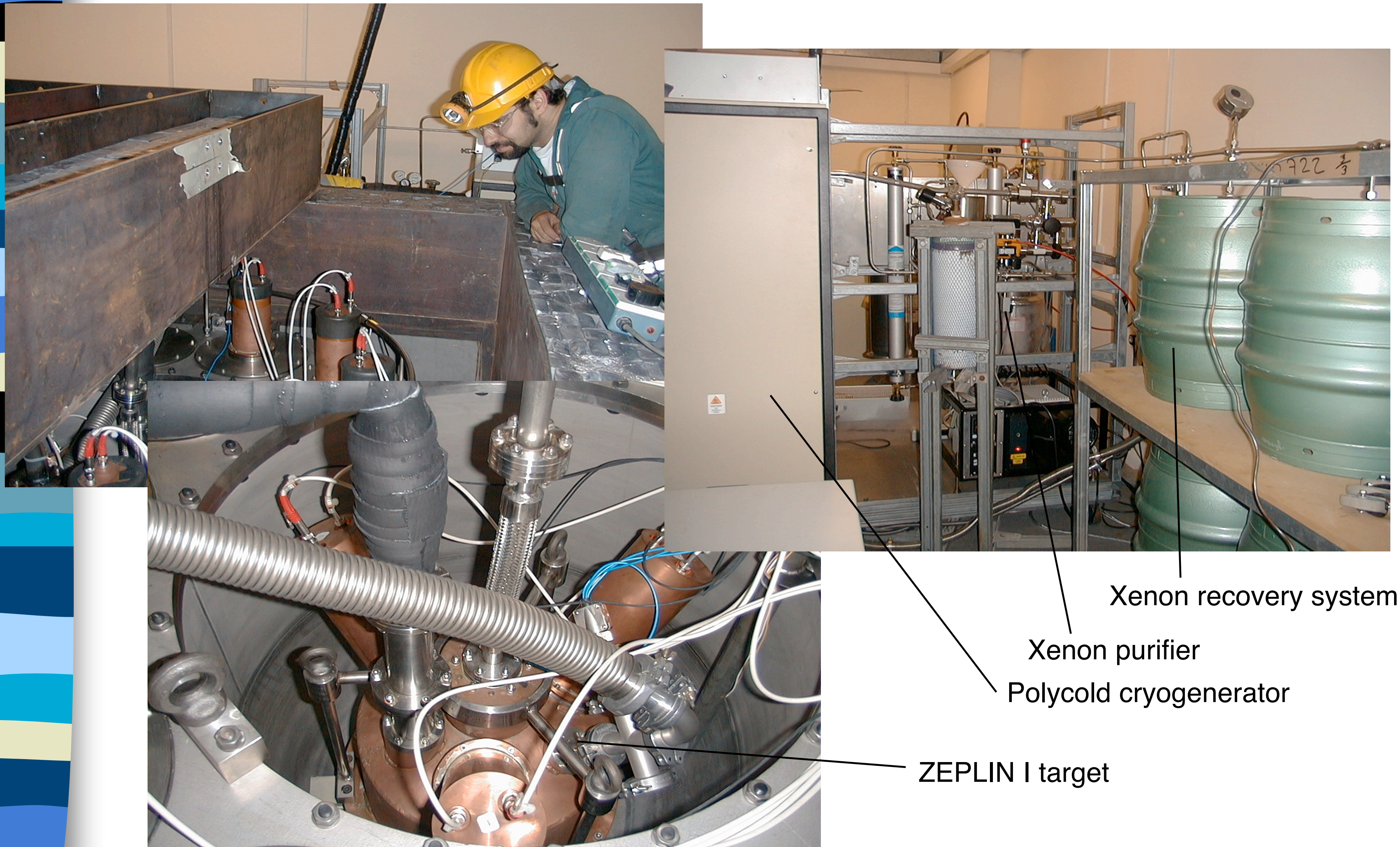




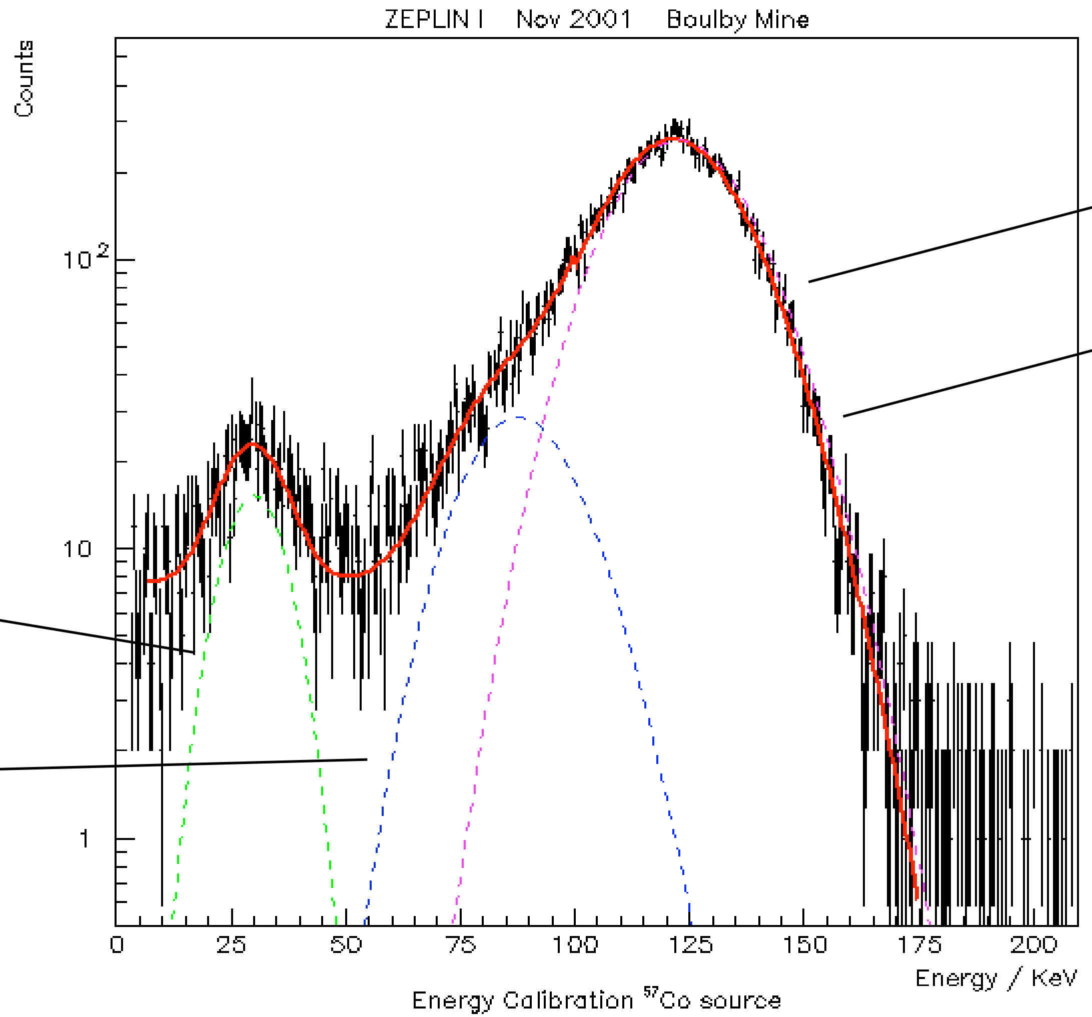




ZEPLIN I Installation



ZEPLIN I Energy Resolution



122 keV peak

136 keV peak (10%)

30 keV X-ray

(150 keV recoil)

90 keV recoil e-

Linear response
1.5 p.e./keV

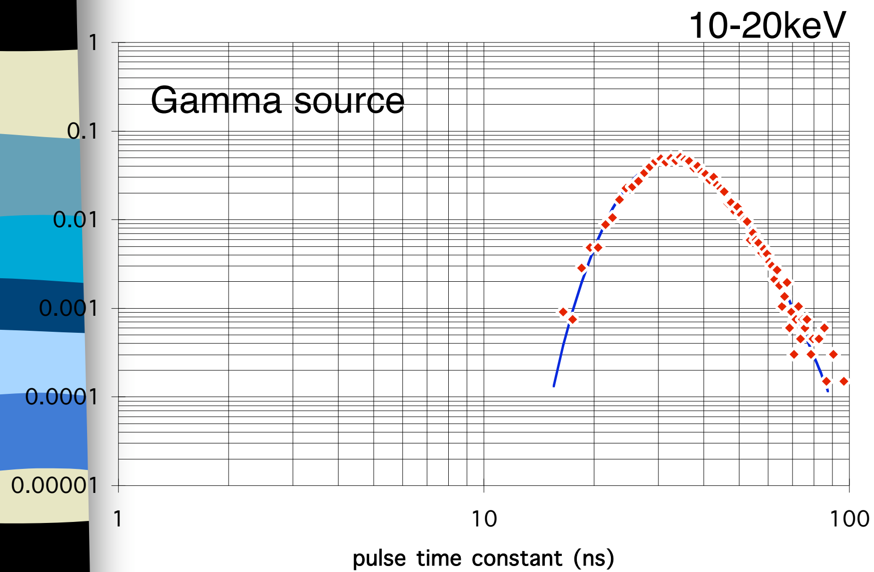
(^{57}Co calibration is effective point source)

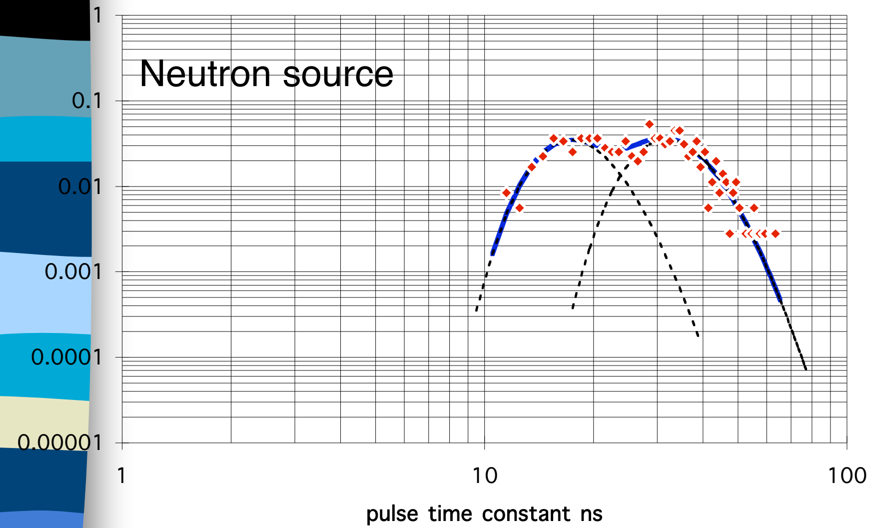
Resolution

$$\sigma(E) = 1.24\sqrt{E}$$

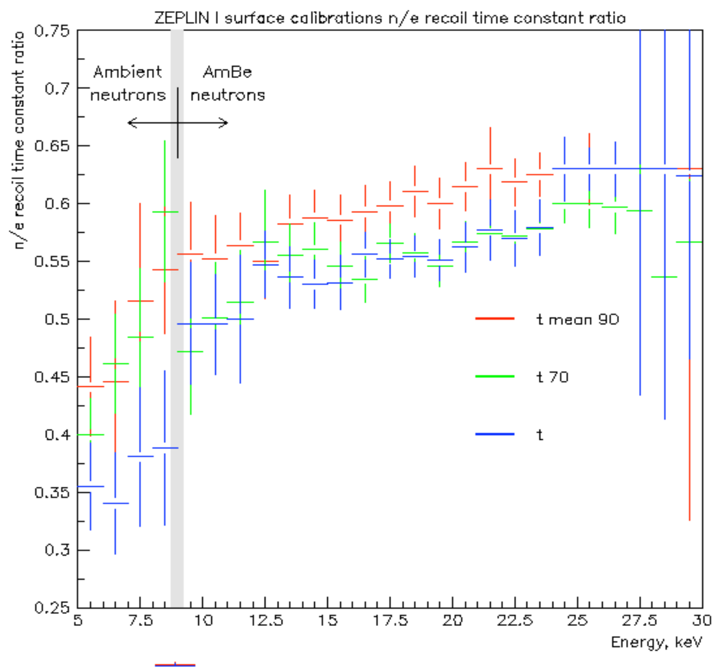
Resolution ≈ 100% at 50 keV recoil energy

ZEPLIN I Discrimination



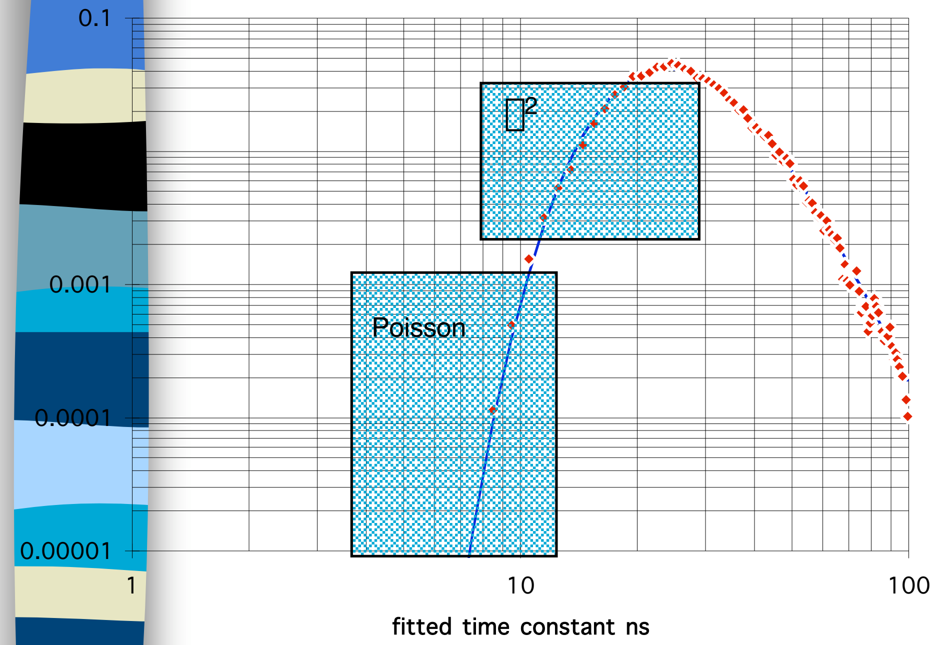


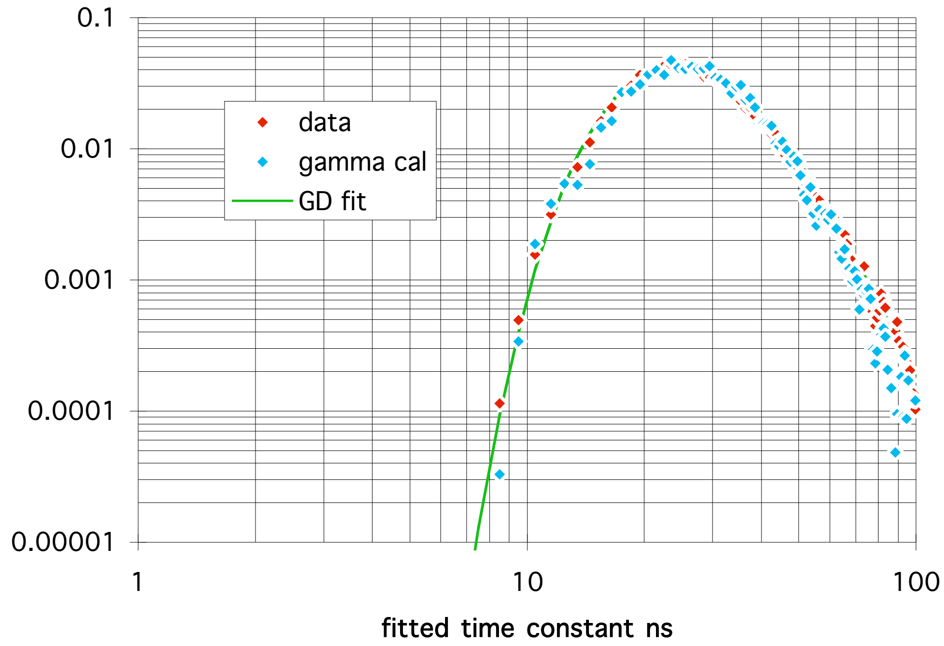
- Using different fitting techniques
  - Exp, Mean, mean to 90%, median
- Fitted 'gamma' density function in 1/
- No reliable calibration with neutrons below 40 keV recoil
- Quenching factor differ x 2 from DAMA



ZEPLIN I Gold Data Run

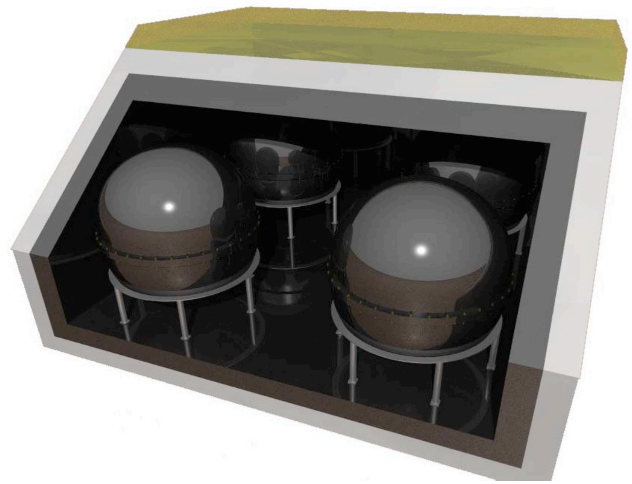
- 75 day livetime, 230kg.days data
- Gamma calibration data from contemporaneous veto events
- ‘Gamma’ density fit (actually in 1/τ) as guide: smooth slope
- Analysis: ML over signal region (tbd), poisson on tail





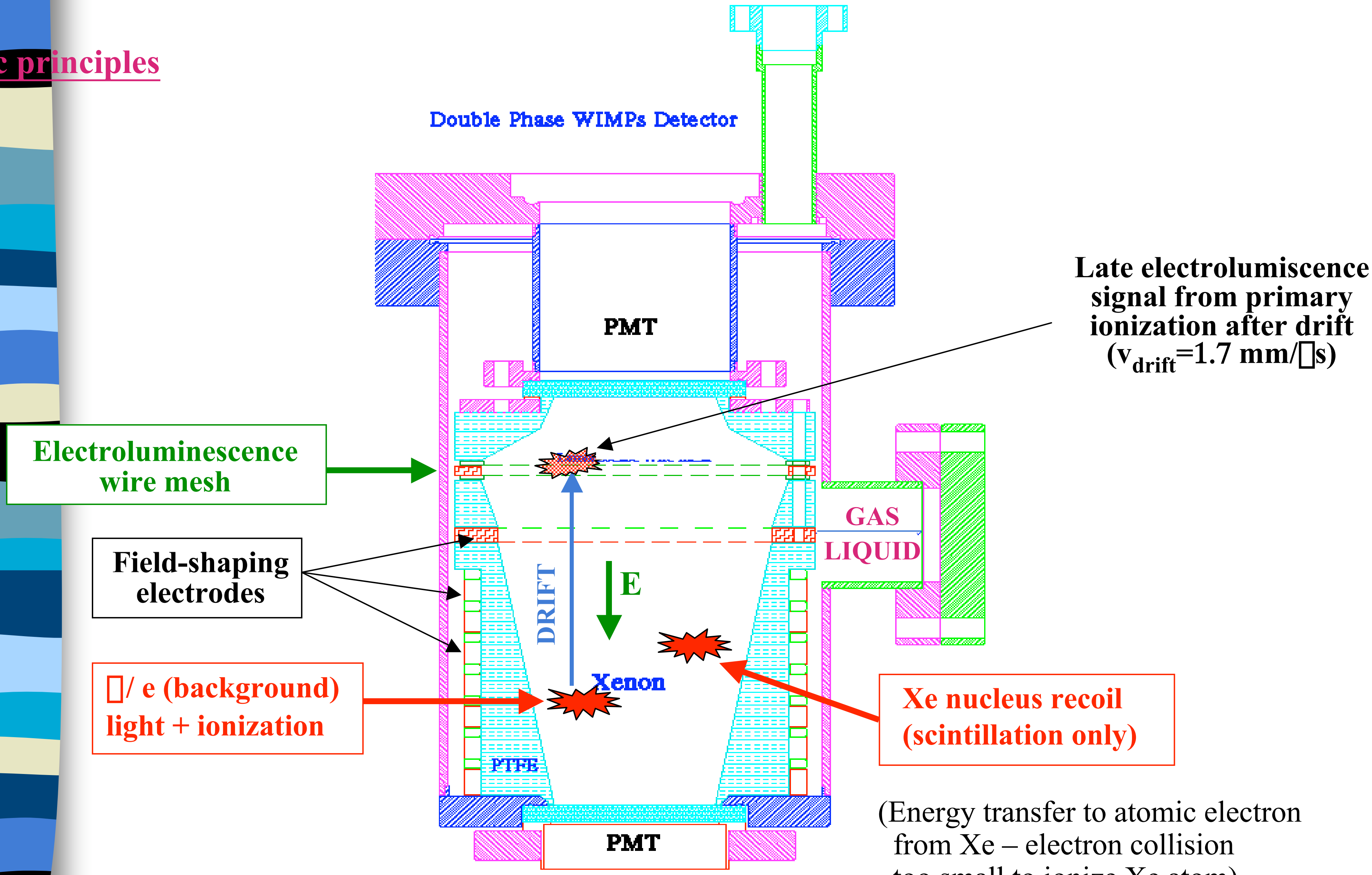
Future programme

- ZEPLIN I
  - – Full CH shielding
  - – Neutron measurements
  - – Low Kr Xenon
  - – ML analysis
  - – More data
- ZEPLIN II/III
  - Better event-by-event discrimination
- ZEPLIN-MAX (IV)
  - – 1 tonne target



ZEPLIN-II: 30 kg two-phase liquid Xenon detector with simultaneous measurement of scintillation and ionization (UKDMC – Italy – U.S.A.)

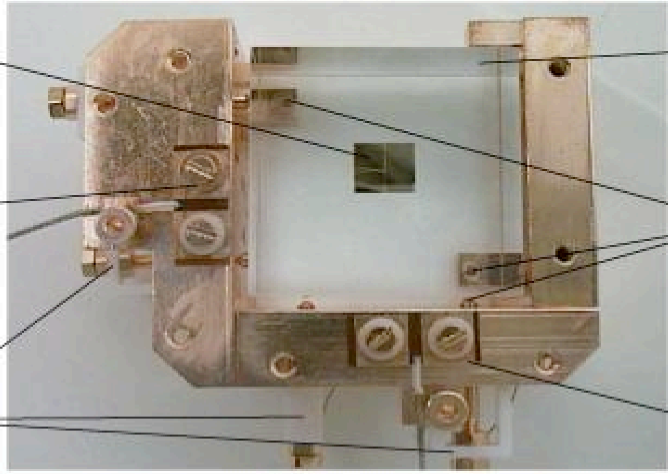
Basic principles

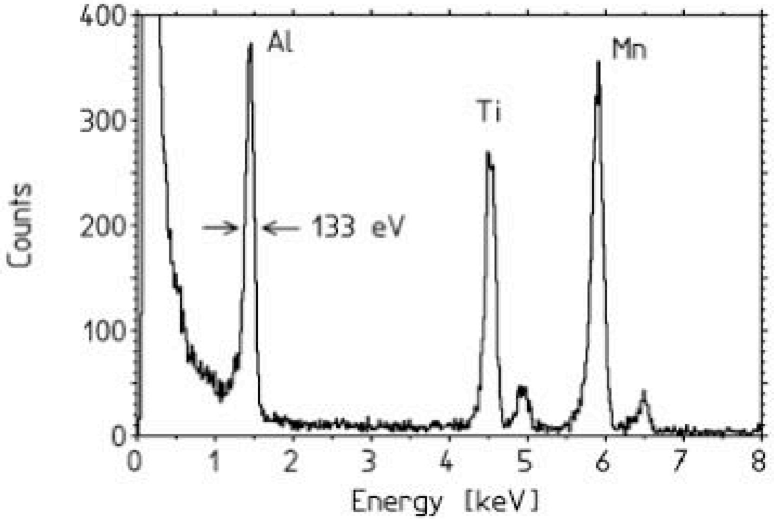


(Energy transfer to atomic electron from Xe – electron collision too small to ionize Xe atom)

CRESST* – I : Sapphire detectors

262 g Sapphire Detector



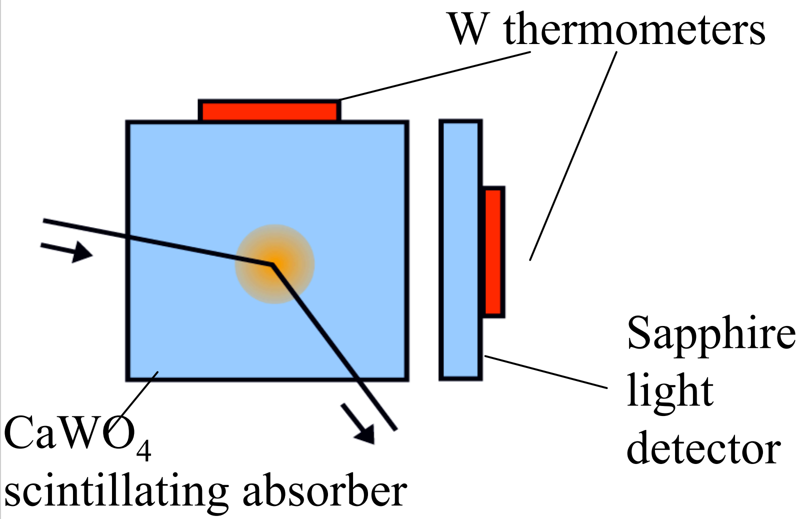


- Energy resolution: 133eV @ 1,5 keV
- Best resolution per mass
- Stable and reproducible operation

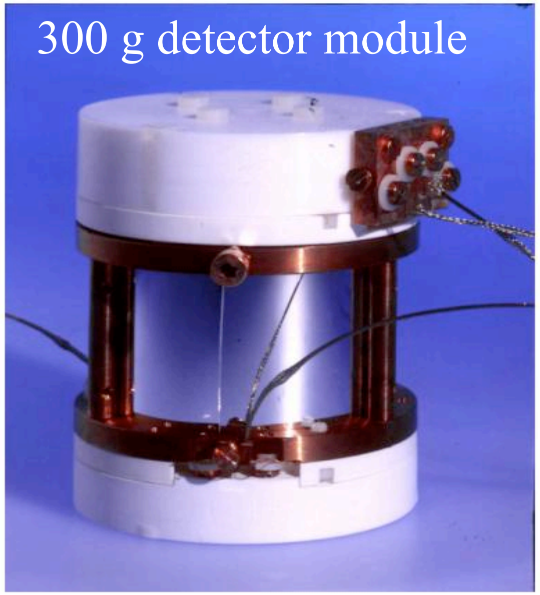
* MPI of Physics, Munich; TU Munich; Univ. Of Oxford; LNGS Assergi, Italy

CRESST – II :

background rejection by phonon + scintillation measurement



6 g test detector: 99.7 % rejection above 15 keV, no surface effects
2 □ 300 g detectors now operating

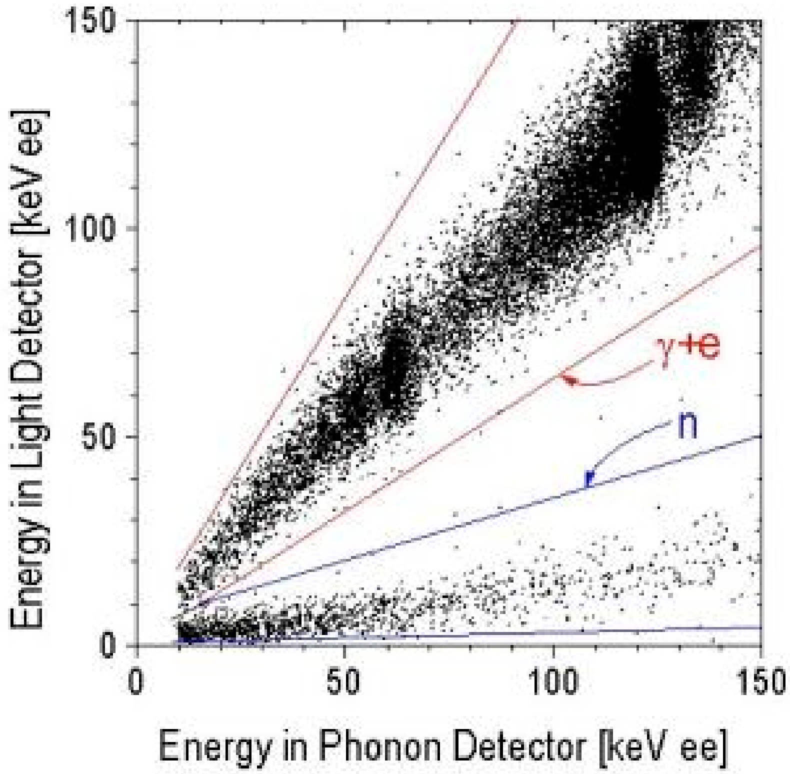


CRESST-II:

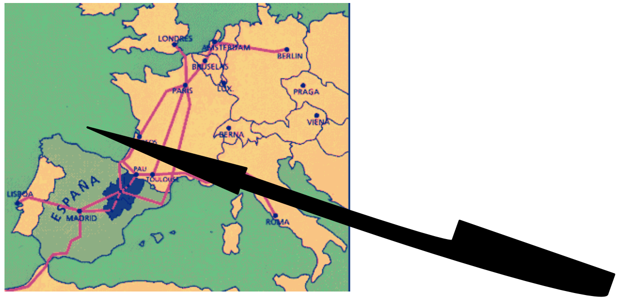
33 x 300 g $CaWO_4$

66 SQUIDs

Present cryostat + cold box

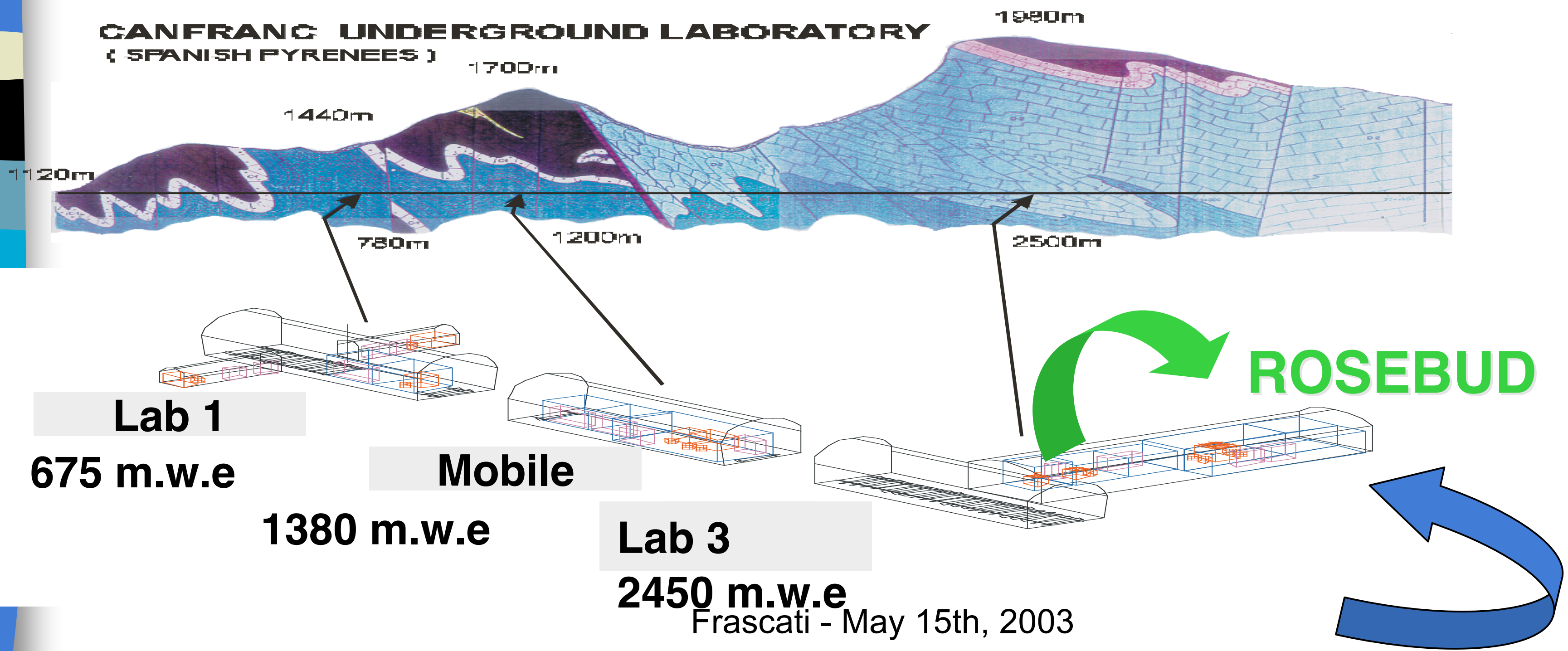


Canfranc Underground Laboratory



Spanish Pyrenees

Railway tunnel (not in use)

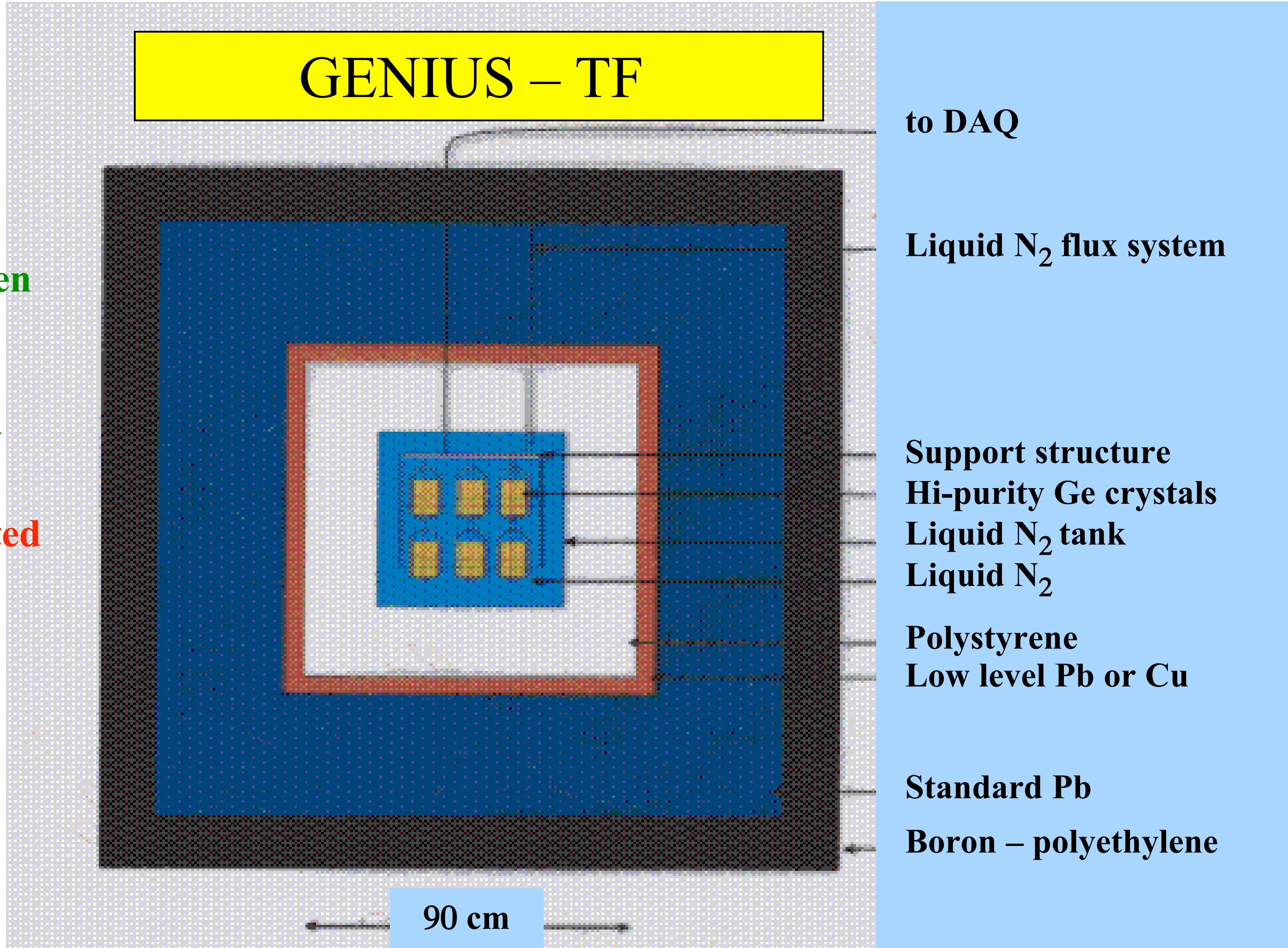


GENIUS Test-Facility being installed in Gran Sasso Underground Lab

GENIUS Test-Facility
14 x 2.5 kg enriched Ge crystals **in liquid nitrogen**
Expected background rate:
0.01 *counts (kg keV d)*$^{-1}$

~ 1000 x the rate expected in GENIUS (1 ton Ge)

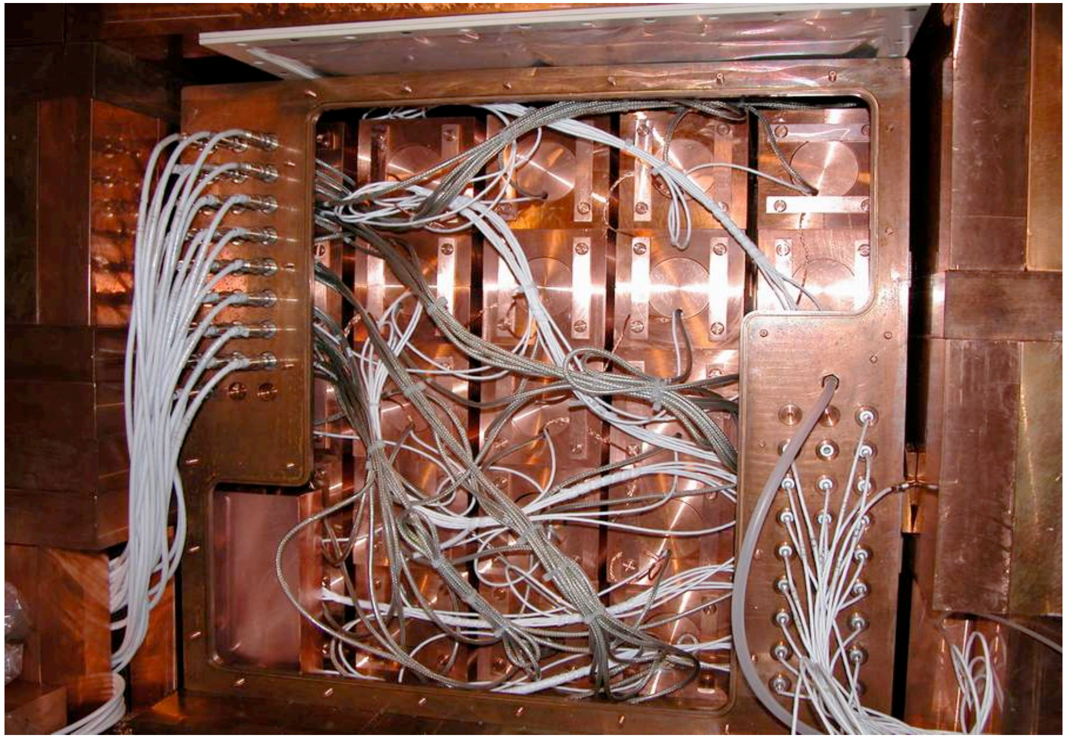
Extrapolation of GENIUS-TF results to GENIUS?



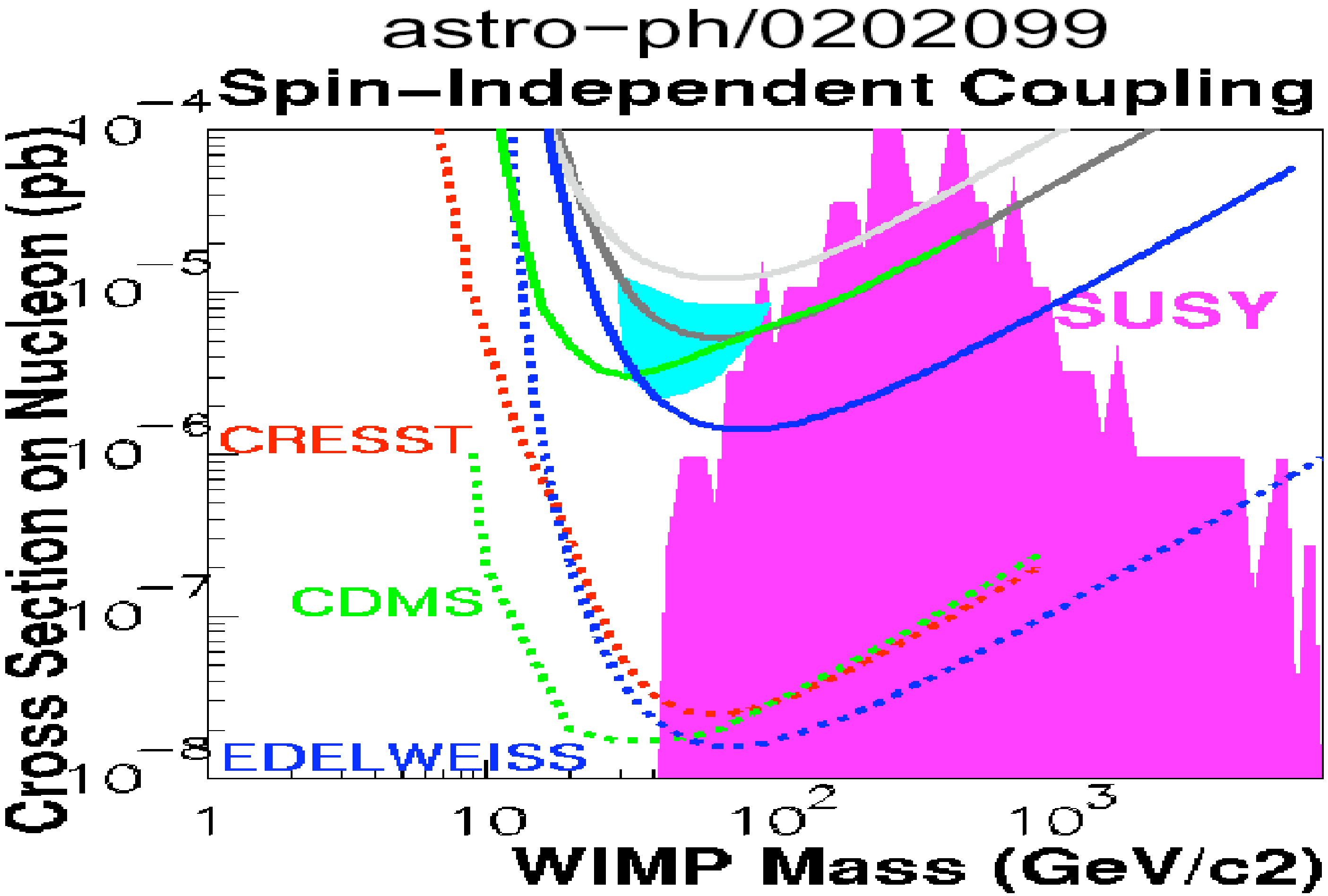
Similarly, CUORICINO (≈ 40 kg) will verify background predictions for CUORE (760 kg)

NaI detectors: LIBRA, NaIAD…

- LIBRA: 250 kg NaI detector
- Installation completed
- Spin-independent couplings: almost no background rejection on iodine
- Annual modulation signature

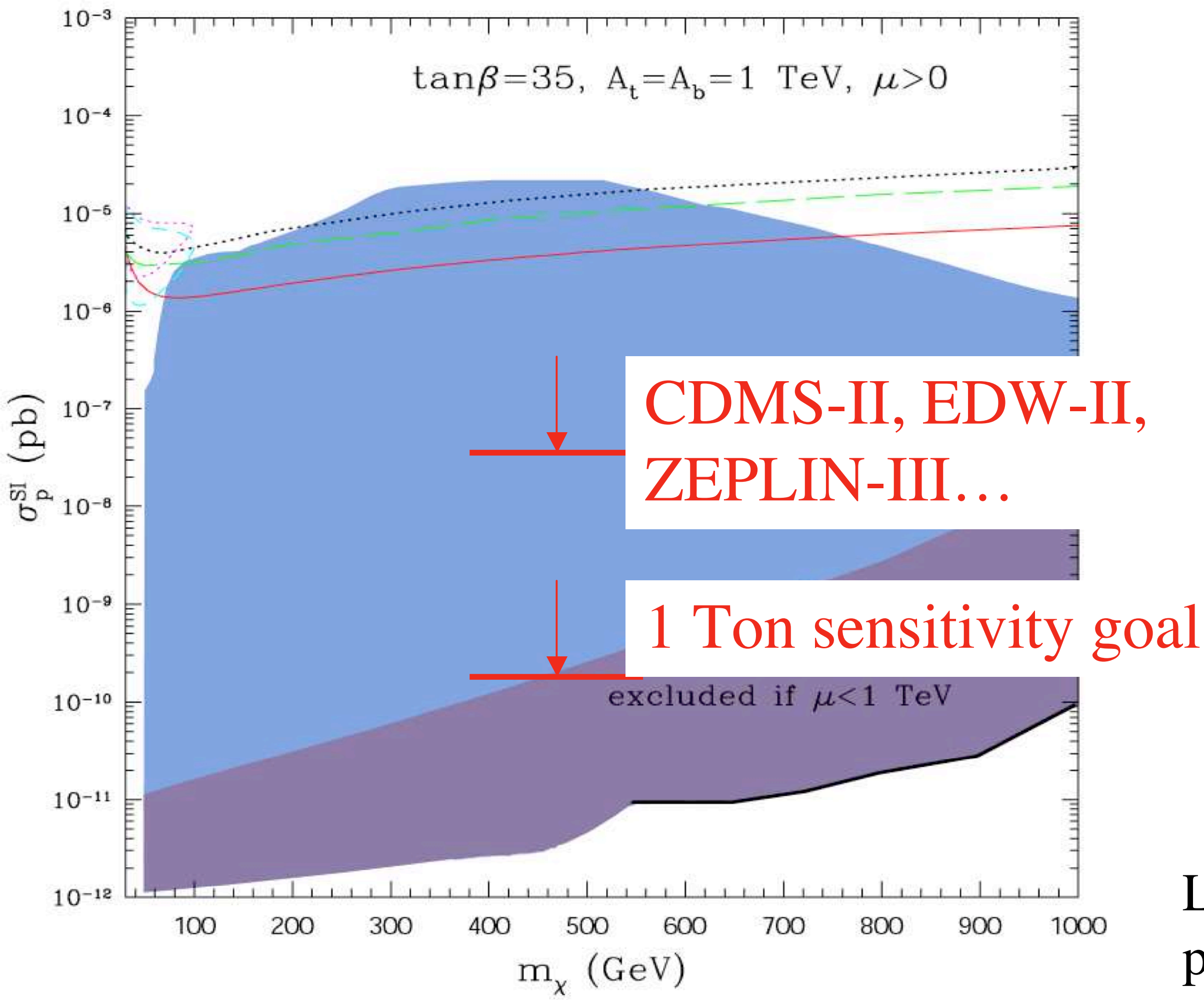


EDELWEISS-II, CDMS-II, CRESST-II, ZEPLIN-II sensitivity goal



- ***Next generation: more than two orders of magnitude improvement over best present limits***

Experimental status and theoretical predictions

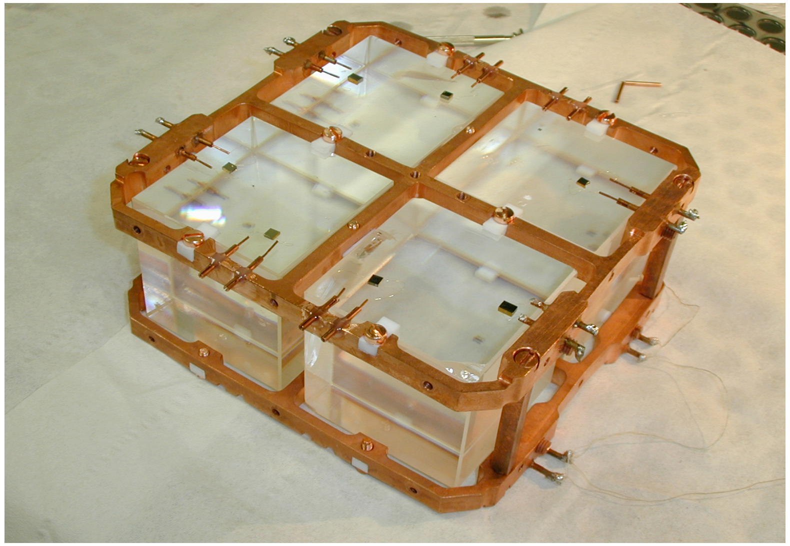


L. Rozkowski et al., hep-ph/0208069

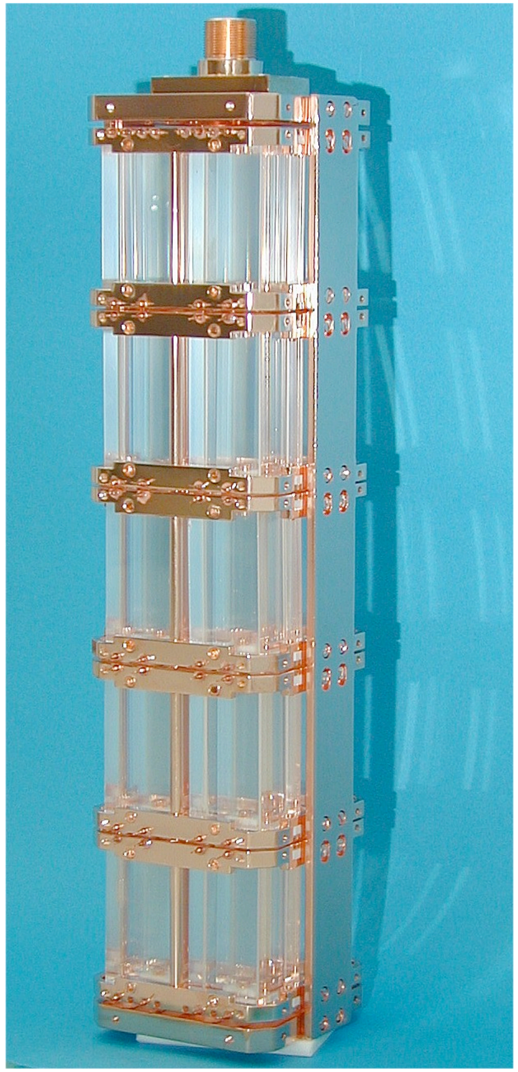
Testing most of SUSY parameter space…

- Predictions for SUSY models
  - 10^{-10} picobarn will test large fraction of SUSY models
- But only a handful of events per ton and per year…
- Gamma-ray background:
  - Extreme background rejection
- Neutron background:
  - (Very) deep site mandatory
  - Efficient muon veto (fast neutrons)
  - Detection of multiple scattering interactions
- Requires >≈ 1000 detectors in very compact design or fine position resolution

Identification of residual neutron interactions (U/Th…) mandatory

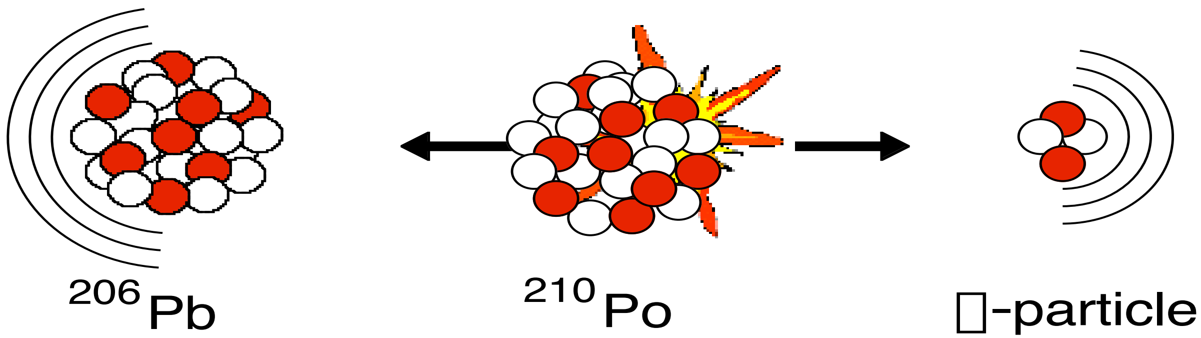


- Identification by multiple scattering interactions
- Requires >≈ 1000 detectors (edge effects)
- CUORICINO starting
- CUORE: 760 kg at 10 mK
- > 95 % neutron identification efficiency possible



Low-energy surface nuclear recoils (not just 2, but 4 populations)

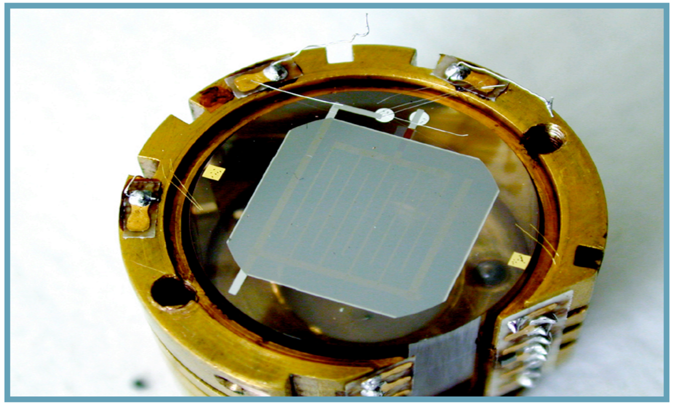
- Take as an example □□ disintegration ^{210}Po □ ^{206}Pb + □ induced by radon pollution:



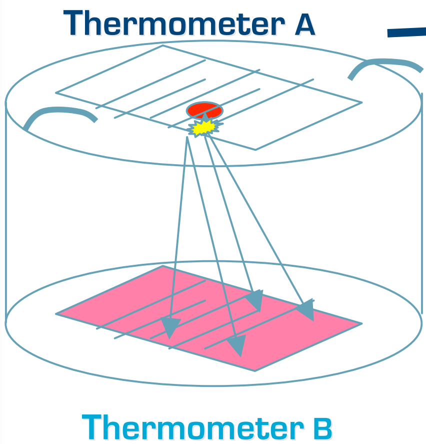
- For a total of 5 MeV, ≈4.9 MeV are carried away by the □ and ≈100 keV by the ^{206}Pb nucleus.
- Alpha particle leaves additional few keV to a few tens of keV:
  - different quenching factors in same event

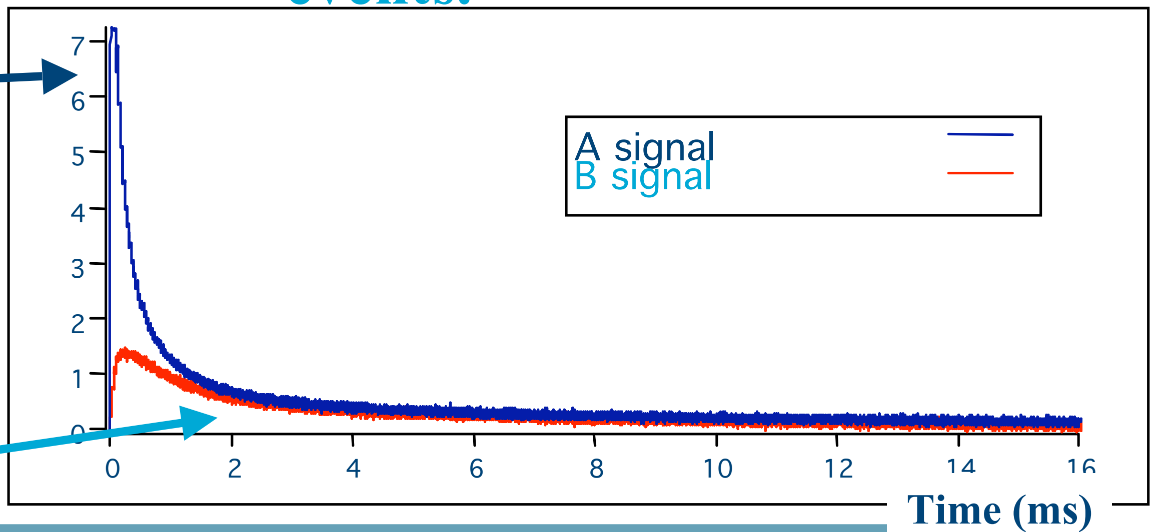
Identification of near surface events (heat channel)

N. Mirabolfathi et al. (CSNSM Orsay)



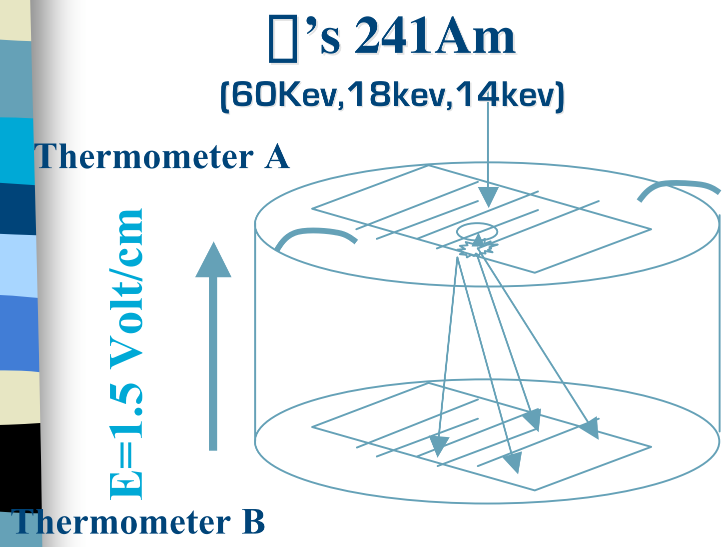
- Co-evaporated NbSi thin film sensors sensitive to athermal phonons : transient regime
- Comb geometry : non linear effect for near thermometer events.

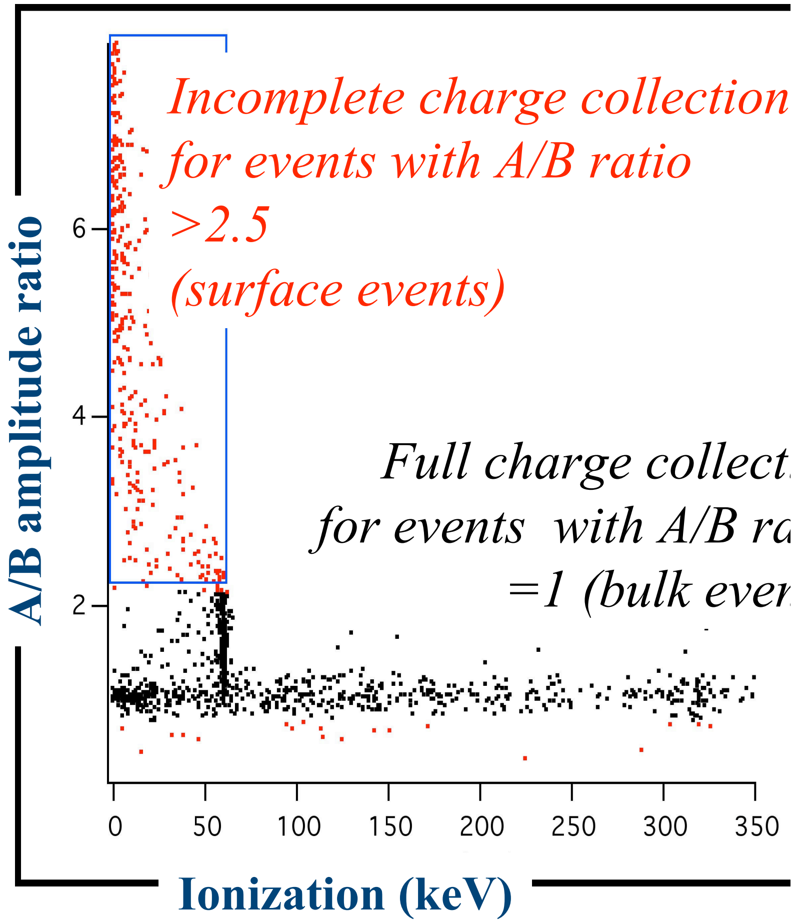


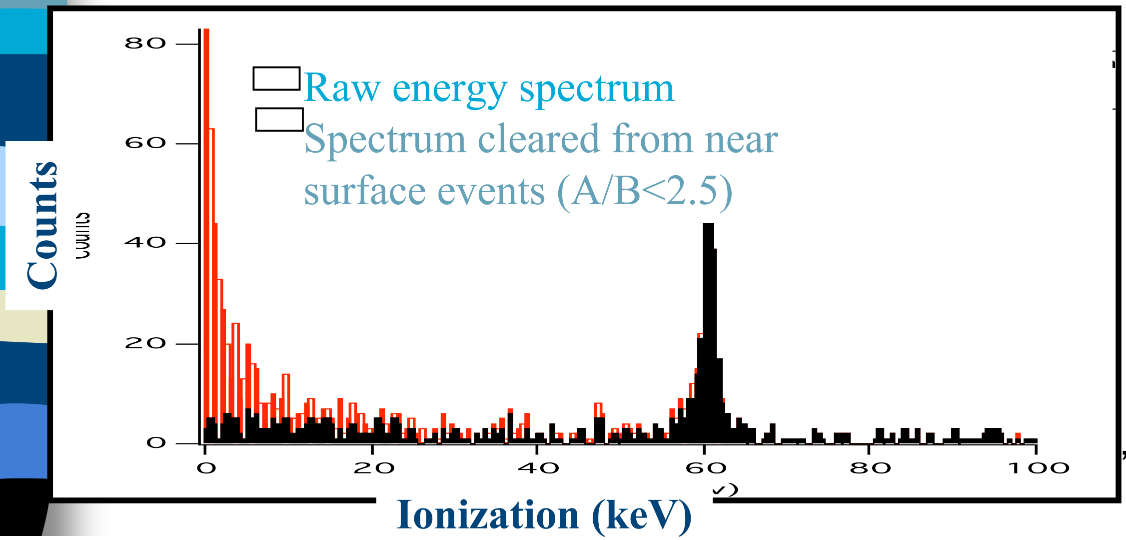


A/B ratio anomaly for surface events

Ge bolometer (35g)
(heat& ionization)



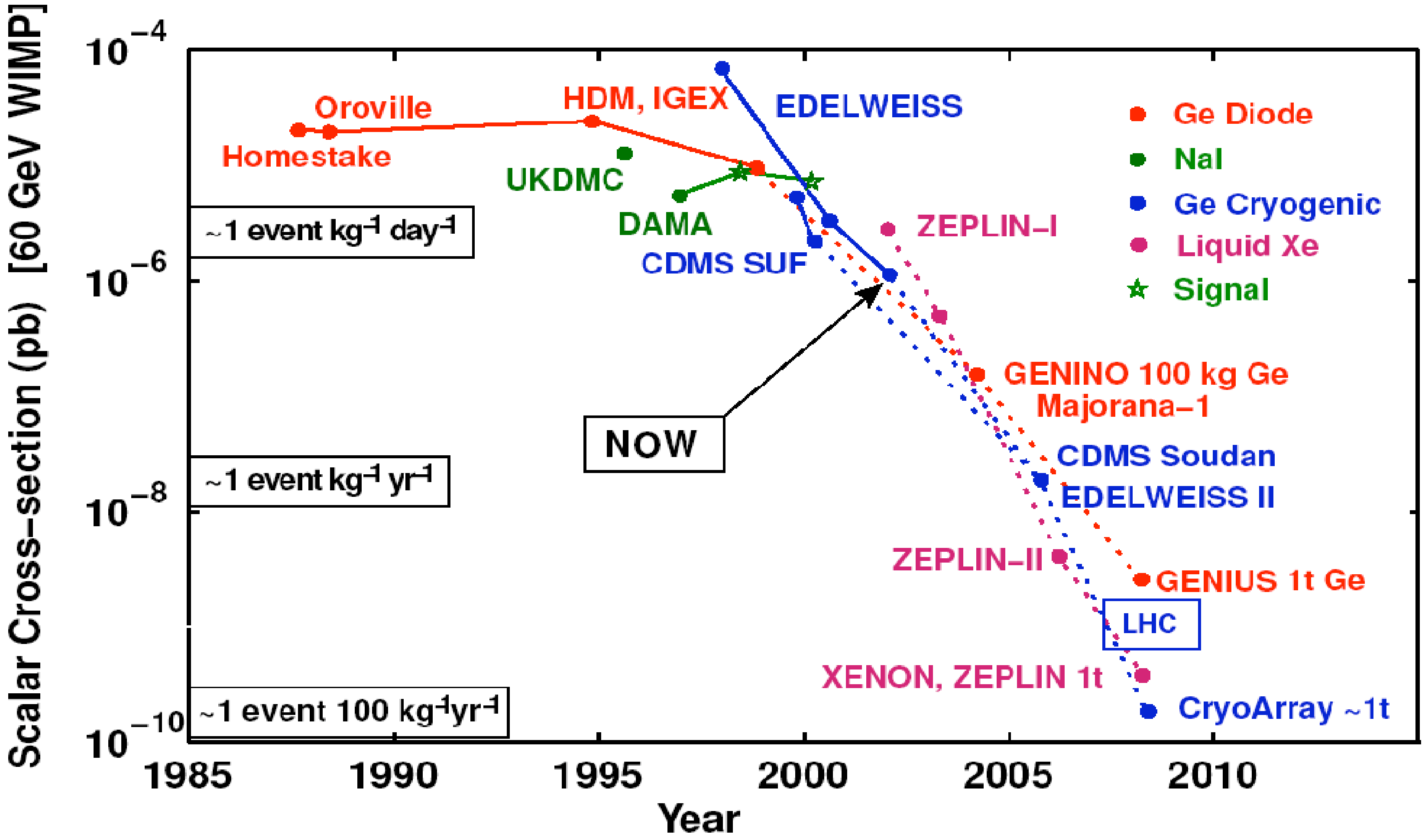




, 2003

- *Allows to reject surface events down to the energy threshold*

Present and Future (expected) sensitivity of main direct detection experiments



III. WIMP indirect detection

WIMPs gravitationally bound in centers of earth, sun, galaxy :

WIMP elastic scattering $\Longrightarrow$ loss of energy ;

$v < v_{escape}$ $\Longrightarrow$ capture

Annihilation $\Longrightarrow$ □; b, c, t quarks; gauge bosons; Higgs bosons

$\Longrightarrow$ high-E □; □; e^{+-}; p

Capture / annihilation balance $\Longrightarrow$ constant density

Indirect search - most promising approach:

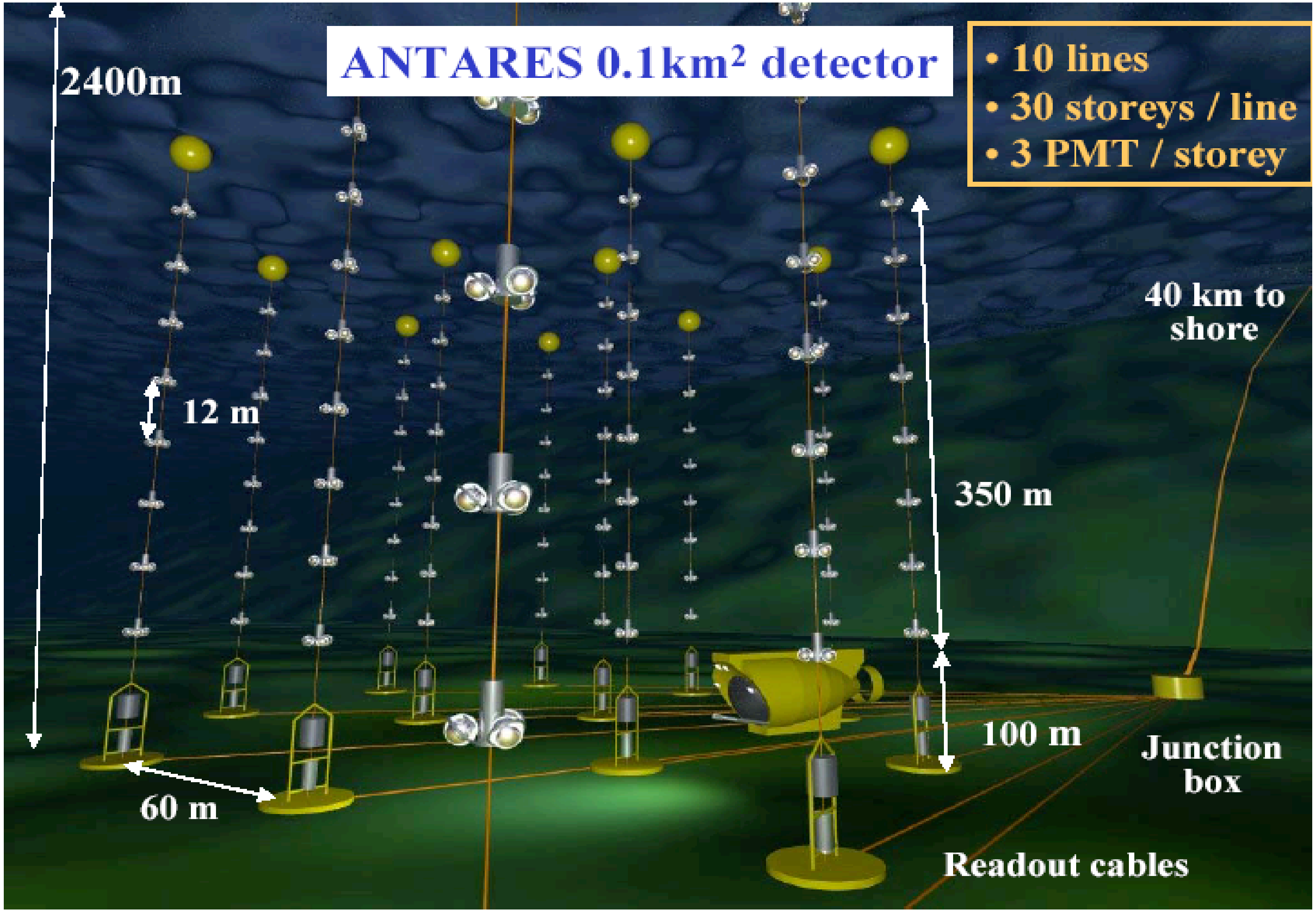
Search for excess of up-going muons from ~ 100 GeV $□_{\mu}$ charged current interactions in the rock under the detector

from direction from centers of earth, sun, galaxy;

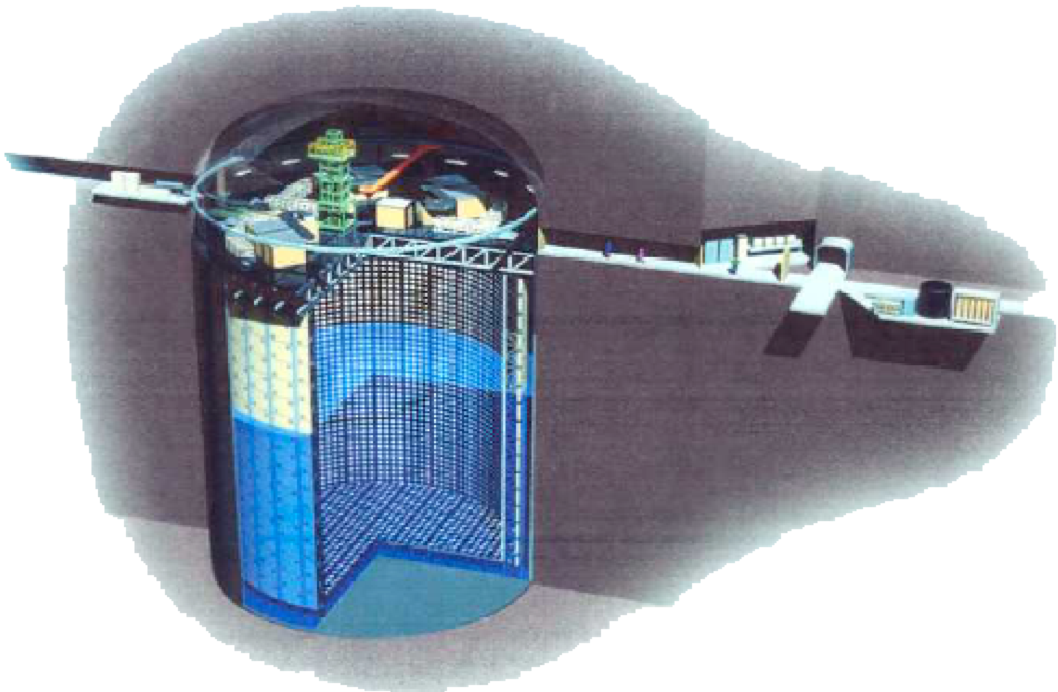
angular distribution of μ's (half-cone angle ~ 5 – 30°) function of WIMP mass.

2005-2010

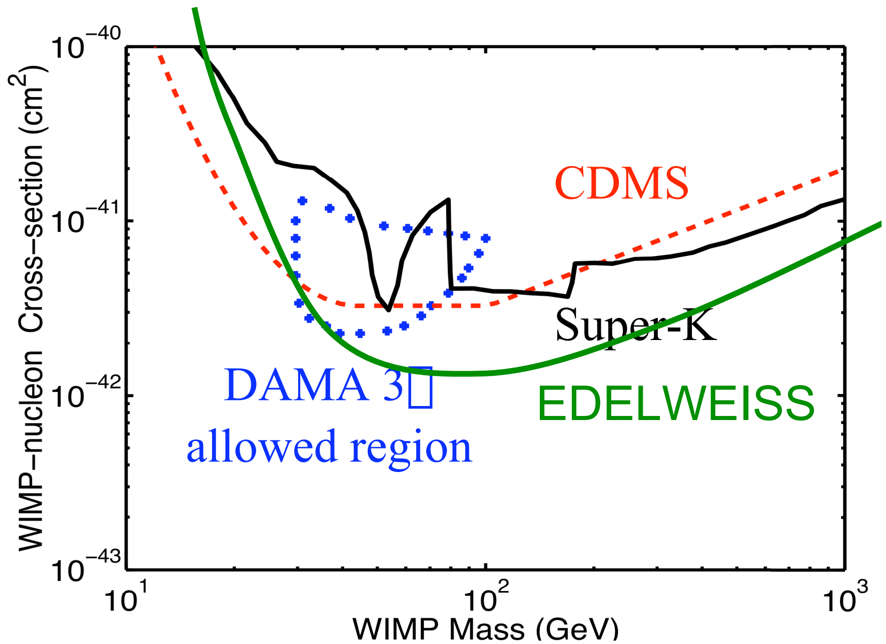
~ km^2 detectors ICECUBE, ANTARES, …



WIMP indirect searches - best present limit from Super-K



Combined analysis for sun, earth and galactic center: no excess over atmospheric neutrino expectation in any cone angle.
Conservative limit comparable with direct searches:



Super-Kamiokande:

50 kT water Cherenkov detector
(22.5 kT fiducial)
11146 inward-facing 20 in. PMTs
1885 outward-facing veto PMTs

Conclusions

- Bad news: the DAMA candidate is not confirmed
- Good news: Direct detection WIMP experiments (EDELWEISS, CDMS, and ZEPLIN) are at last sensitive to (optimistic) SUSY models ($\approx 10^{-6}$ pbarn)
- Next generation experiments (EDELWEISS-II, CDMS-II, CRESST-II, ZEPLIN-II and -III) should allow factor ≈100 improvement in sensitivity (few 10^{-8} pbarn) and begin to test more realistic models
- Testing the bulk of SUSY parameter space (down to 10^{-10} pbarn) will require experiments in the one-ton range and extreme background rejection
- Indirect detection is complementary (spin-dependent couplings), but hardly competitive for low □ models
- Dark Matter solution could be somewhere else (axions, MOND, …) but WIMP solution definitely attractive