Dark Matter Detection with Cryogenic Detectors

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+ Gilles Gerbier, CEA Saclay

The Physics - Identifying Dark Matter particles

Direct Detection and Backgrounds

Why use cryogenic techniques?

Status and results from the experiments
Cryogenic Dark Matter Search (CDMS)
EDELWEISS
CRESST
Rosebud

Future Prospects

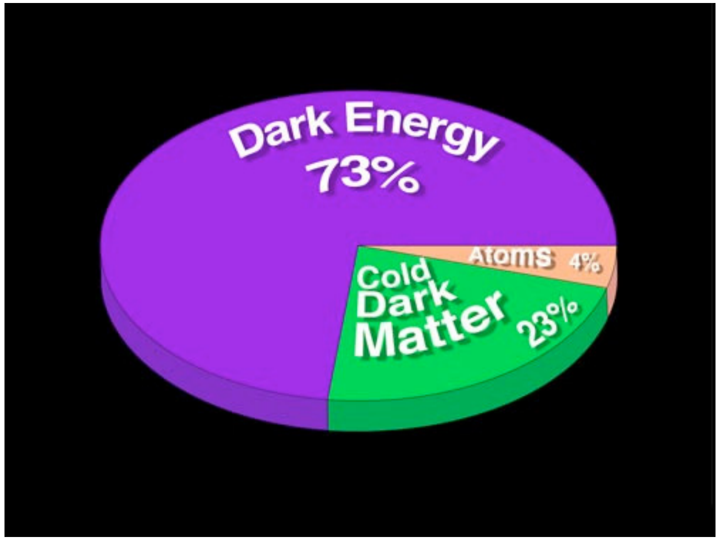
The Physics of Dark Matter

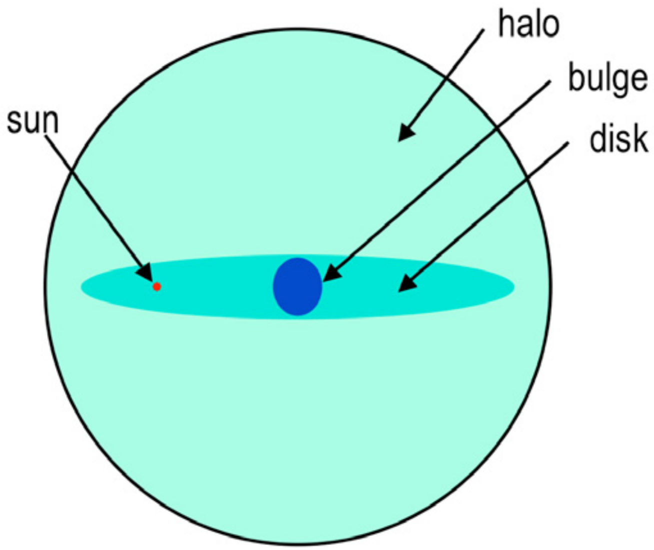
- Cold dark matter makes up nearly 1/4 of the mass/energy of the universe!
- Particle candidates for CDM
  - WIMPs (GeV-TeV masses)
    - SUSY neutralinos
    - Kaluza-Klein excitations
  - Axions (10^{-3} -> 10^{-6} eV masses)
- Dark matter responsible for galaxy formation (including ours)
  - We are moving through a dark matter halo
- Standard halo assumptions

Maxwell-Boltzmann velocity distribution

V_0= 230 km/s, v_{esc}= 650 km/s,

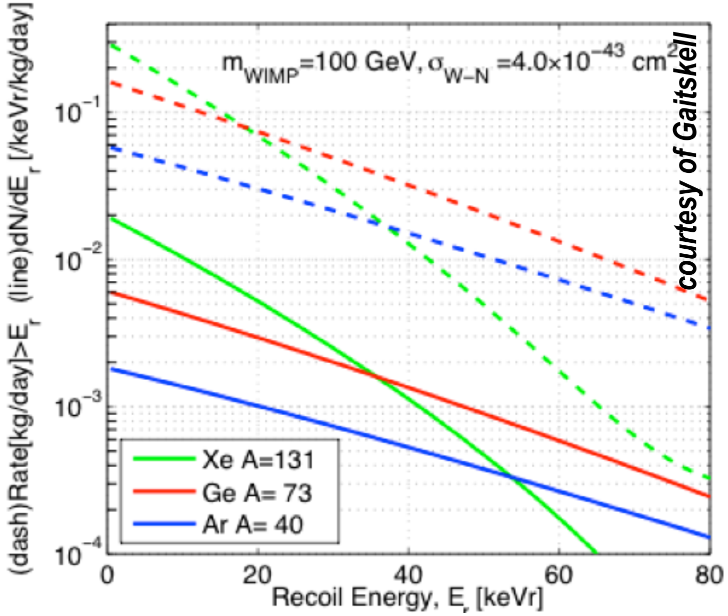
ρ = 0.3 GeV / cm^3

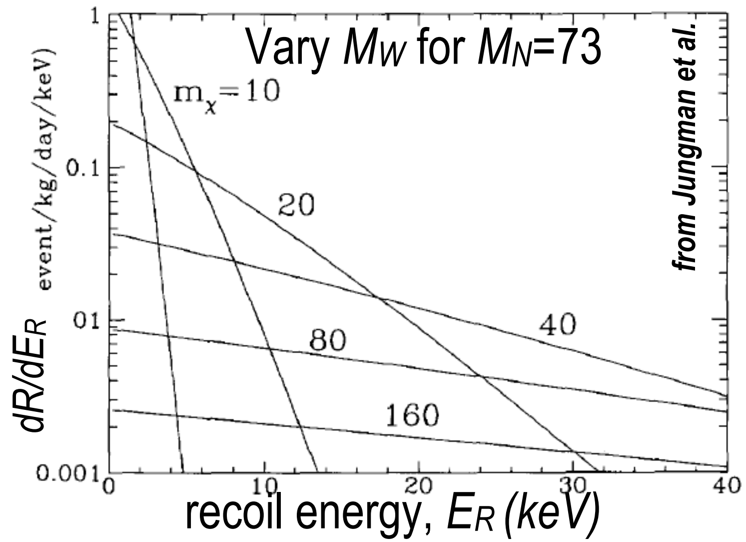




WIMP signal characteristics

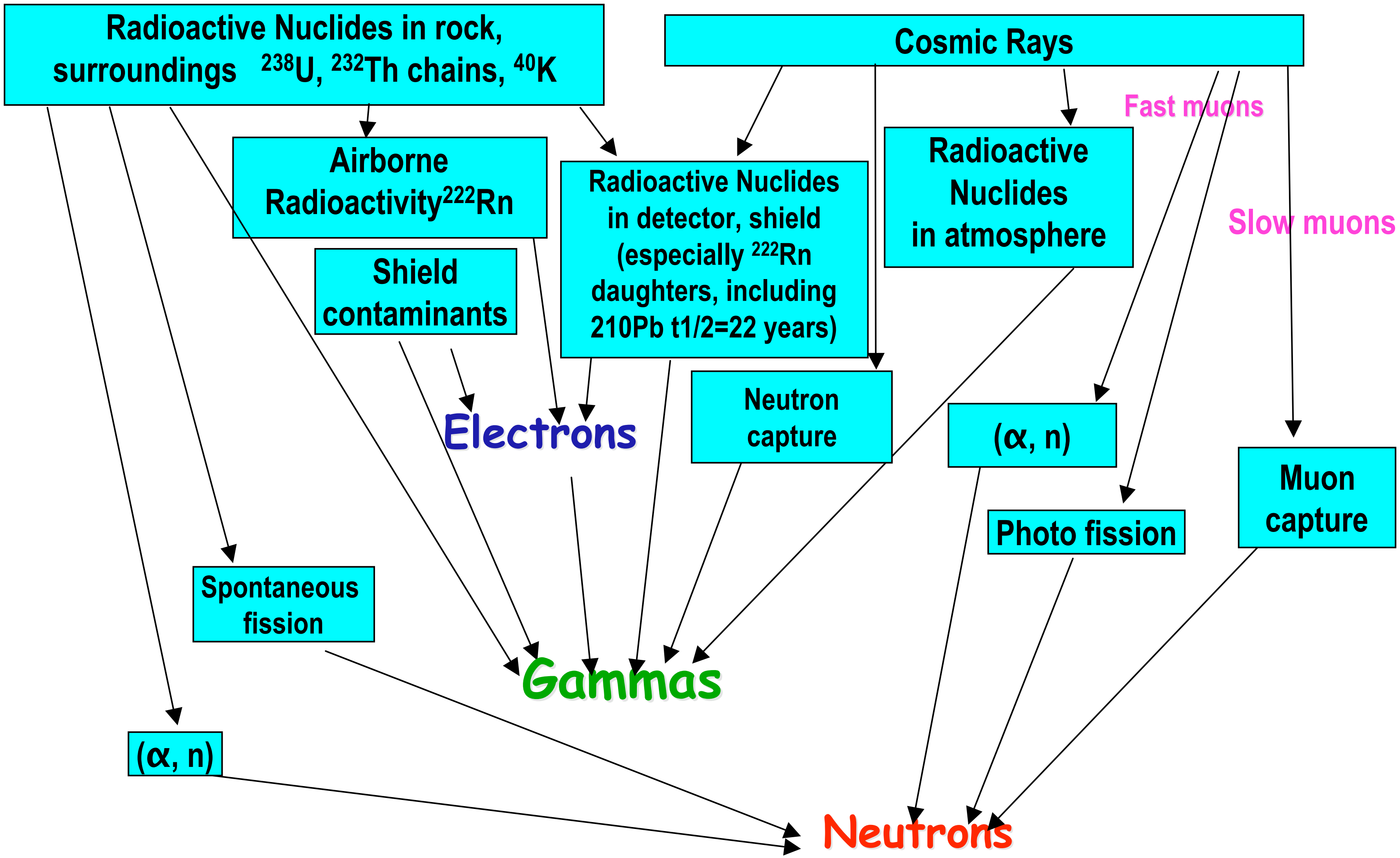
- Scattering off nuclei
- A^2 dependence
  - coherence loss
  - relative rates
- M_W relative to M_N
  - large M_W - lose mass sensitivity
  - if ~100 GeV
- Present limits on rate
- Following a detection (!), many cross checks possible
  - A^2 (or J, if SD coupling)
  - WIMP mass if not too heavy
    - different targets
    - accelerator measurements
  - galactic origin
    - annual
    - diurnal/directional - WIMP astronomy





Backgrounds: cosmic rays and natural radioactivity

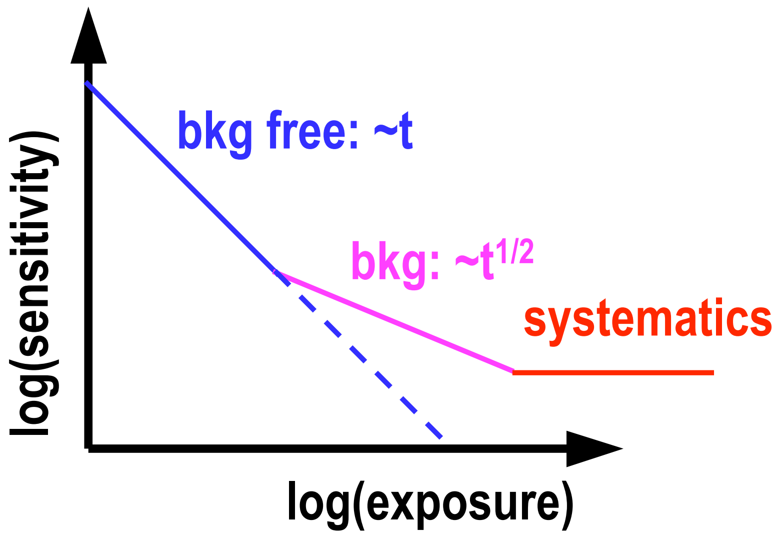
WIMP scatters (< 1 evts /10 kg/ day) swamped by backgrounds (> 10^6 evts/kg-d)

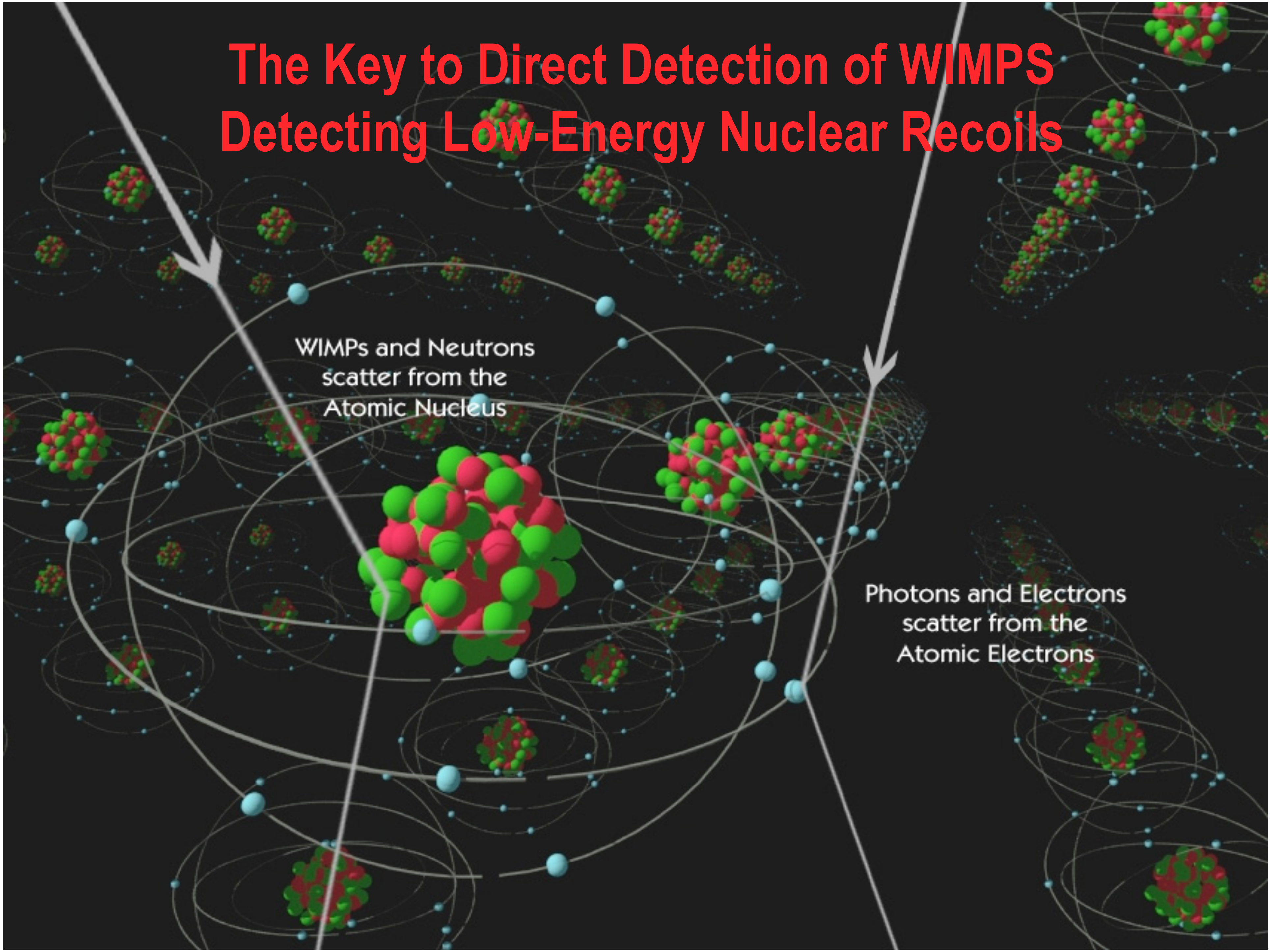


courtesy of S. Kamat

Minimizing backgrounds

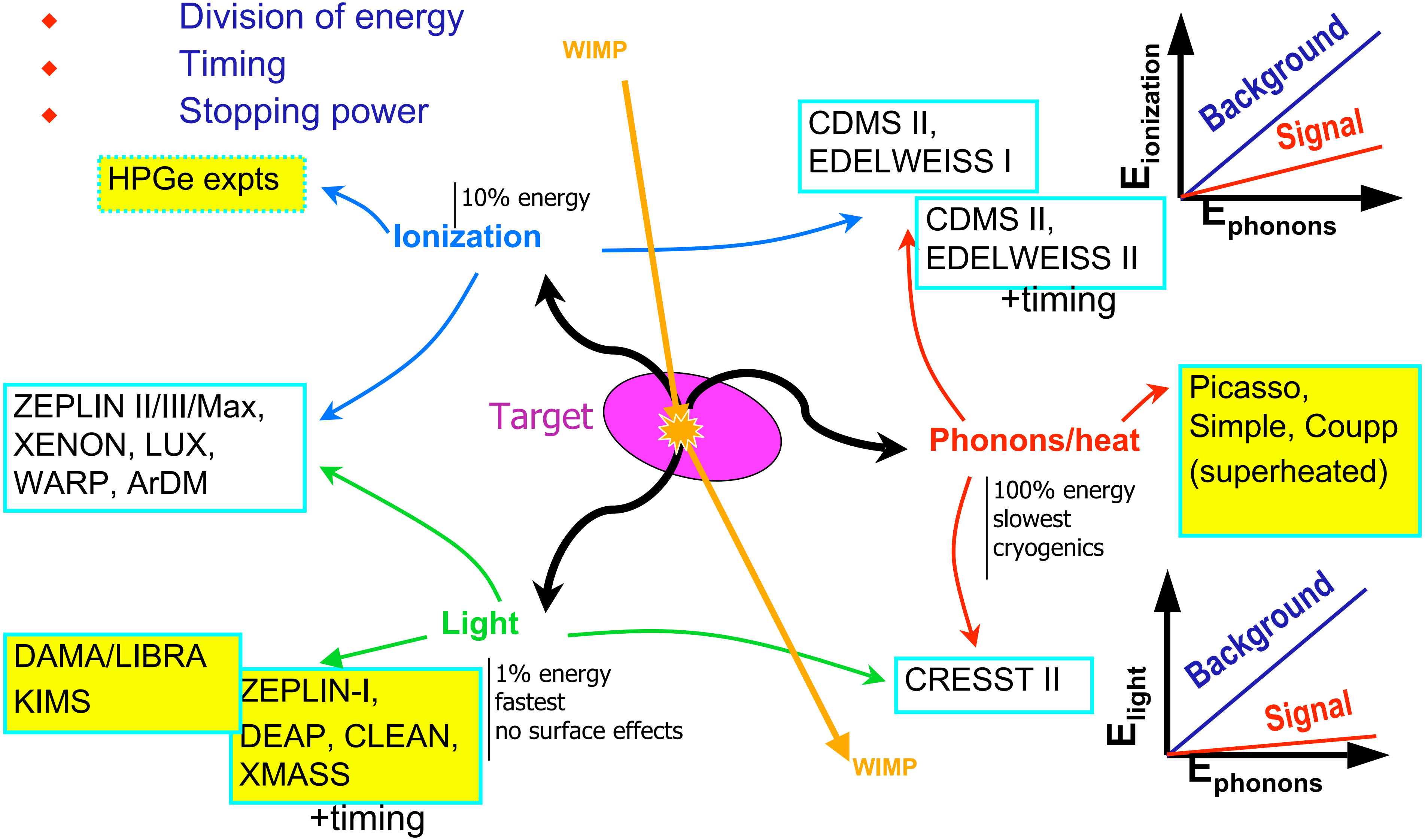
- Critical aspect of any rare event search
- Purity of materials
  - Copper, germanium, xenon, neon among the cleanest with no naturally occurring long-lived isotopes
  - Ancient Lead, if free of Pb-210 ($T_{1/2}$ = 22 years)
- Shielding
  - External U/Th/K backgrounds
- Radon mitigation
- Material handling and assaying
  - surface preparation
  - cosmogenic activation
- Underground siting and active veto
  - Avoid cosmic-induced neutrons
- Detector-based discrimination



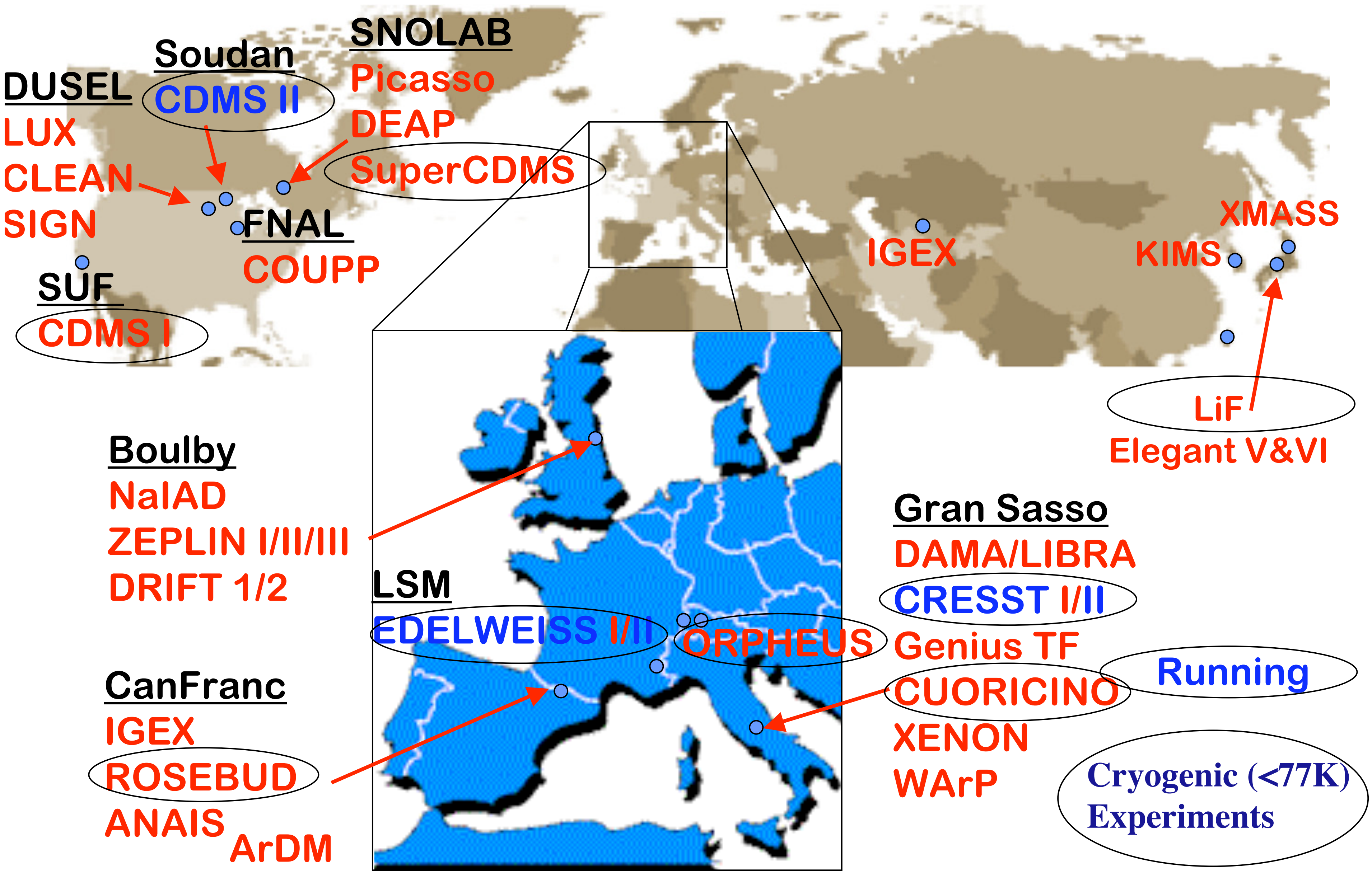

The Key to Direct Detection of WIMPS
Detecting Low-Energy Nuclear Recoils
WIMPs and Neutrons scatter from the Atomic Nucleus
Photons and Electrons scatter from the Atomic Electrons

Nuclear-Recoil Discrimination

- Nuclear recoils vs. electron recoils
  - Division of energy
  - Timing
  - Stopping power

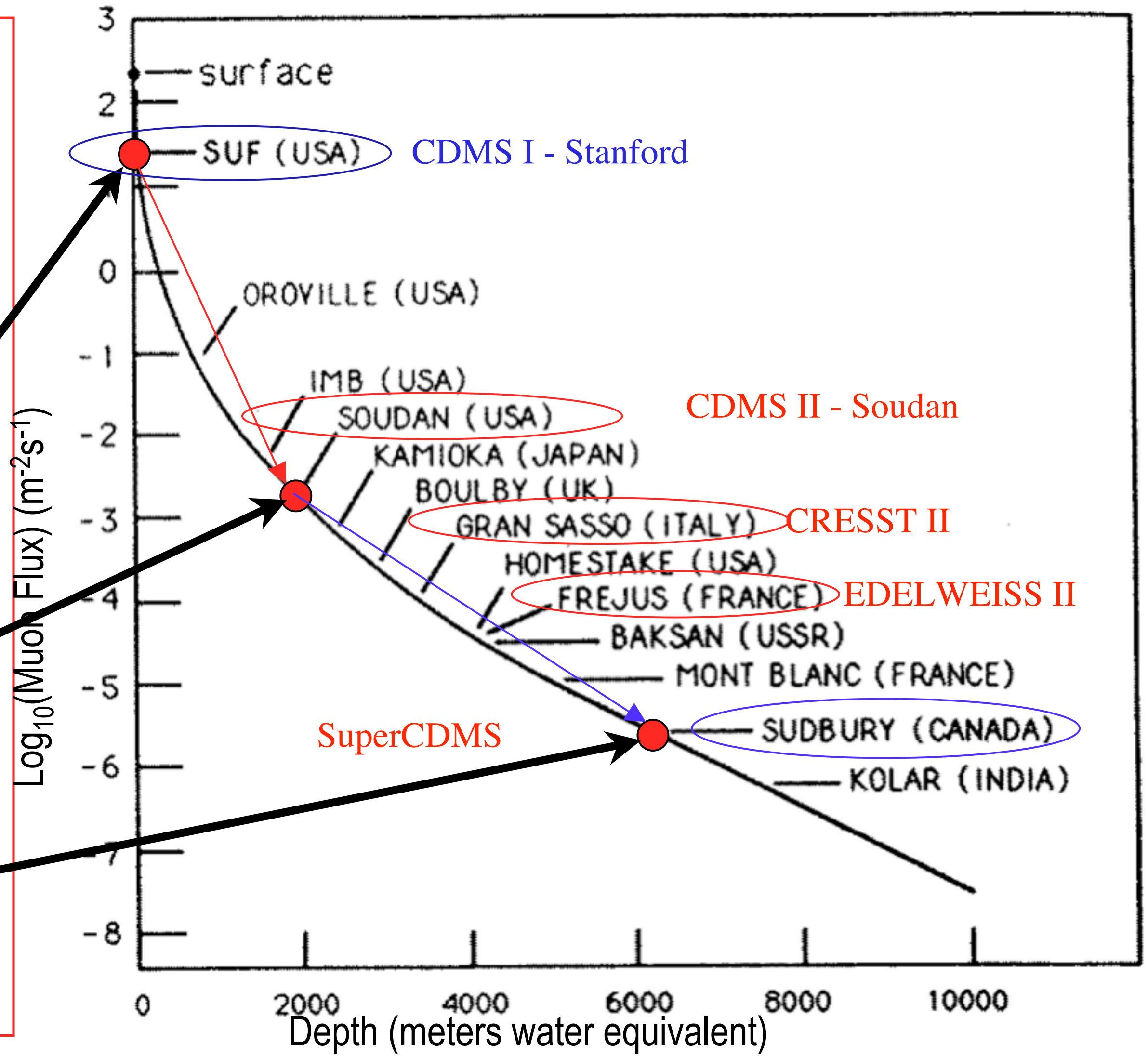


WIMP-detection Experiments Worldwide

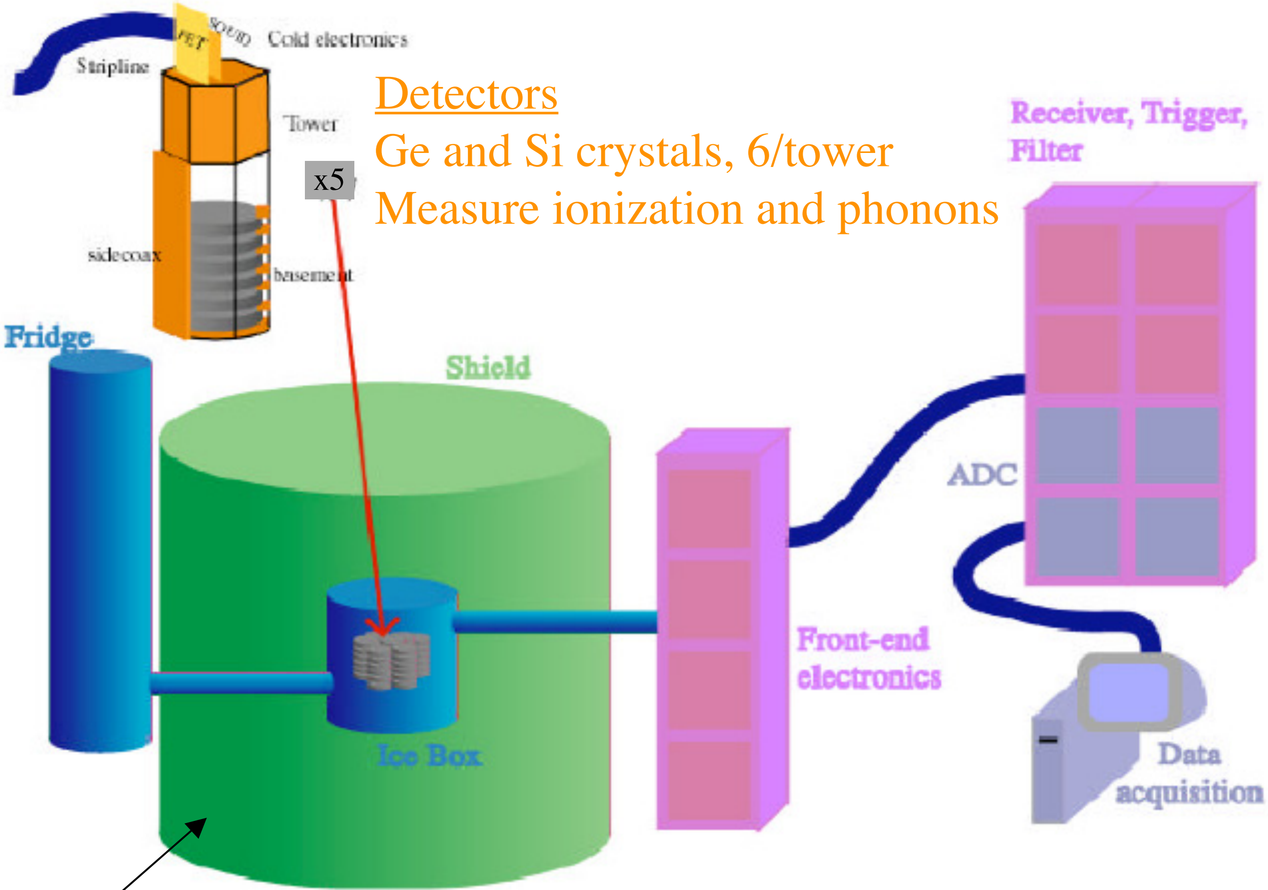


Removing Muon-induced Neutron Background

- Neutrons from cosmic rays are irreducible background
- At SUF
  - 17 mwe
  - 0.5 n/kg-d
- At Soudan
  - 2090 mwe
  - 0.5 n/10kg-y
- At SNOLab
  - 6060 mwe
  - 0.2 n/ton-y



CDMS - A typical cryogenic experiment



Detectors
Ge and Si crystals, 6/tower
Measure ionization and phonons

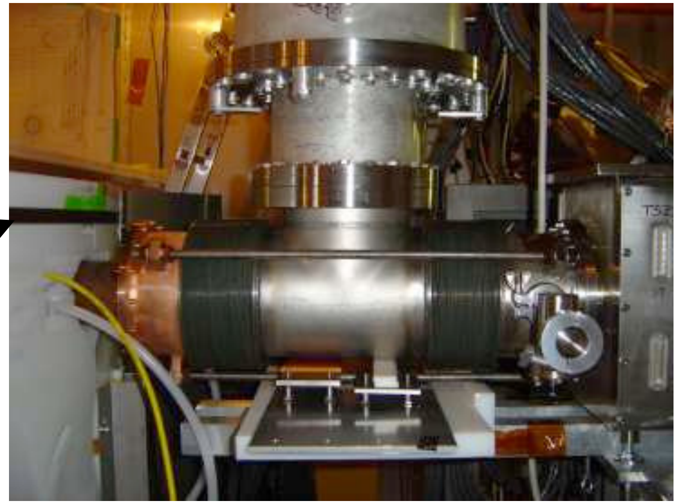
Electronics/ DAQ
Record signals from detectors and veto; form trigger

Cryogenics
Maintain detectors at 50 mK

Shielding
Layered shielding (Cu, Pb, polyethylene) reduces radioactive backgrounds and active scintillator veto is >99.9% efficient against cosmic rays.

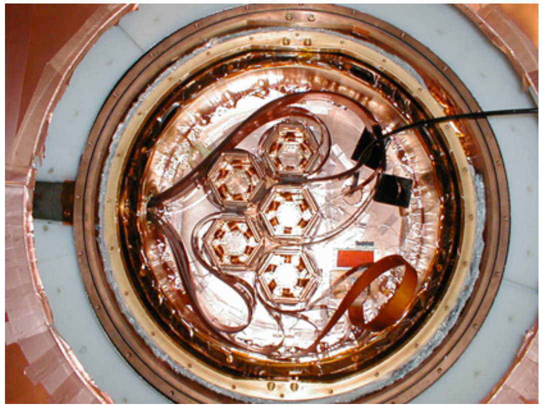
CDMS Cryogenics: How to get really cold!

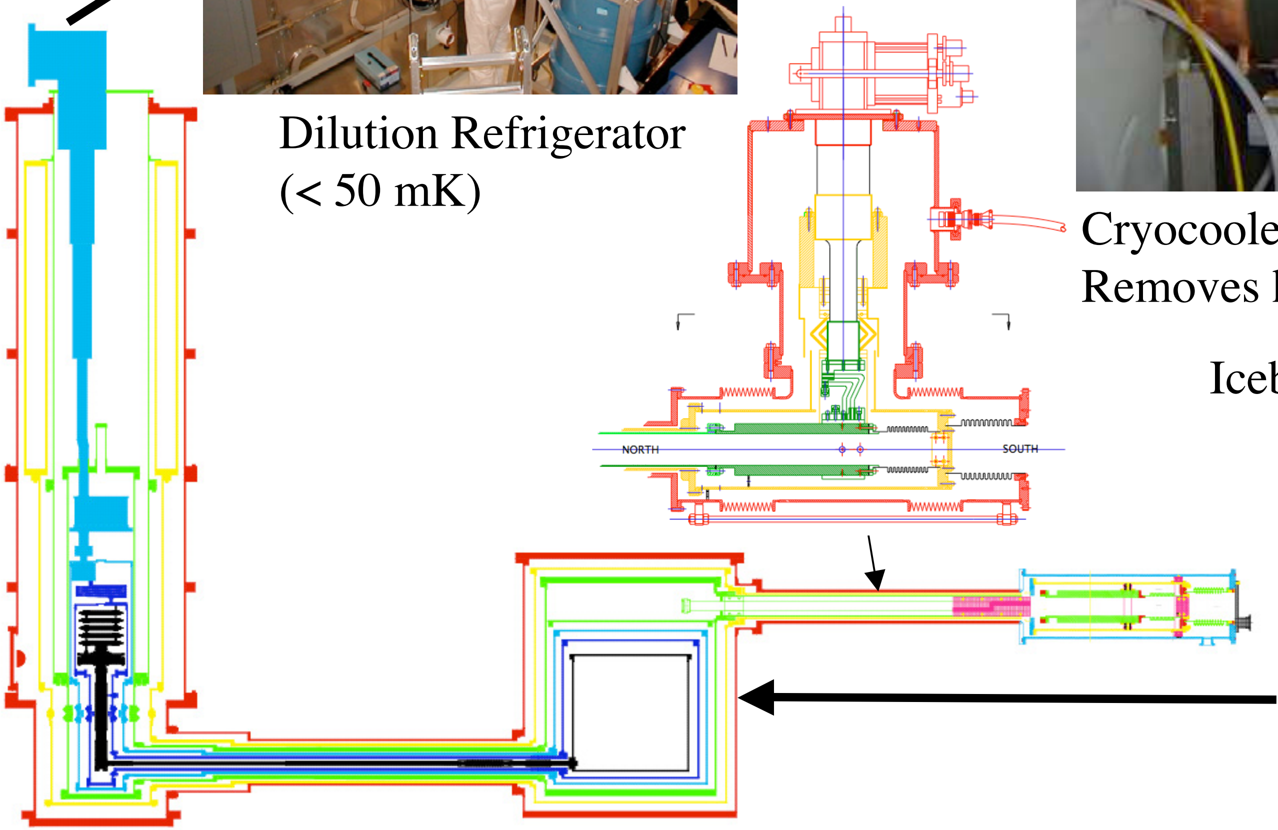
Dilution Refrigerator
(< 50 mK)



Cryocooler (77K and 4K)
Removes heat load from signal cables.

Icebox (Detector Cold Volume)

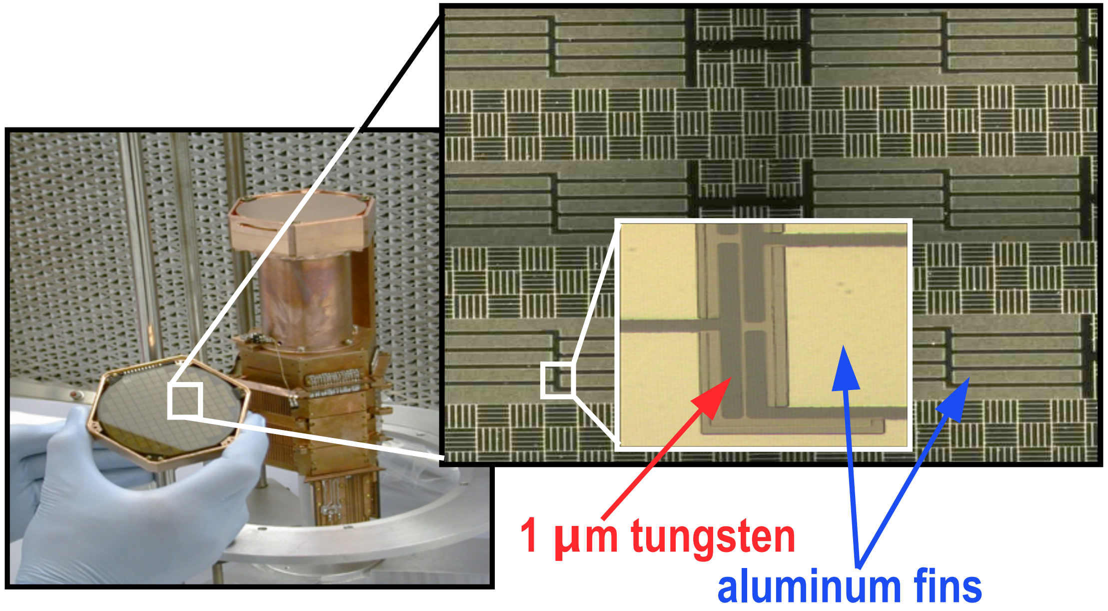


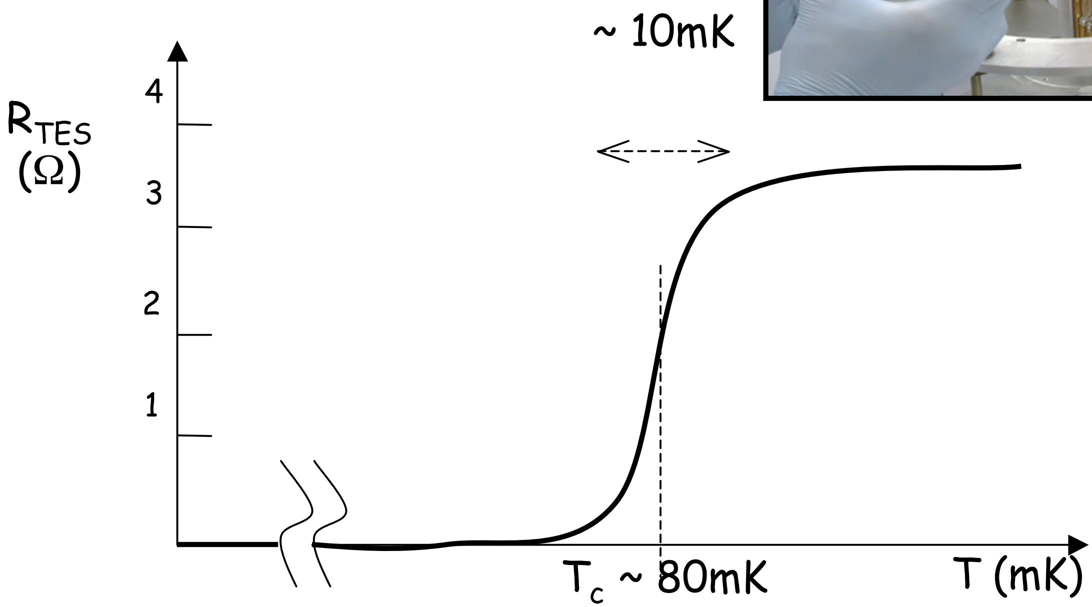


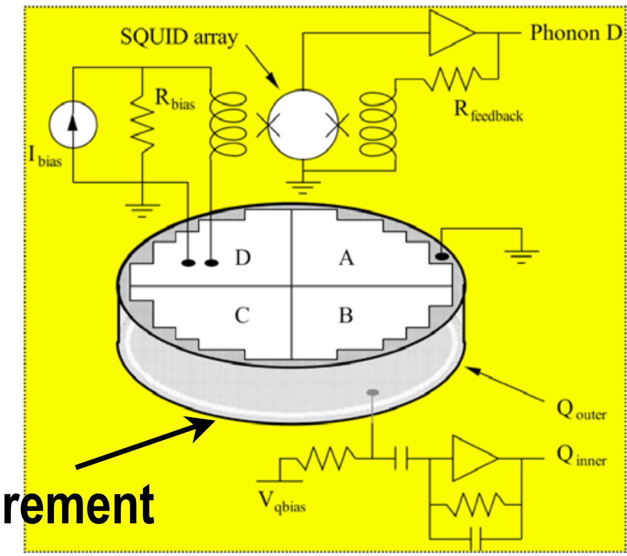
CDMS: Cryogenic “ZIP” detectors

Superconducting films that detect minute amounts of heat

Transition Edge Sensor sensitive to fast athermal phonons



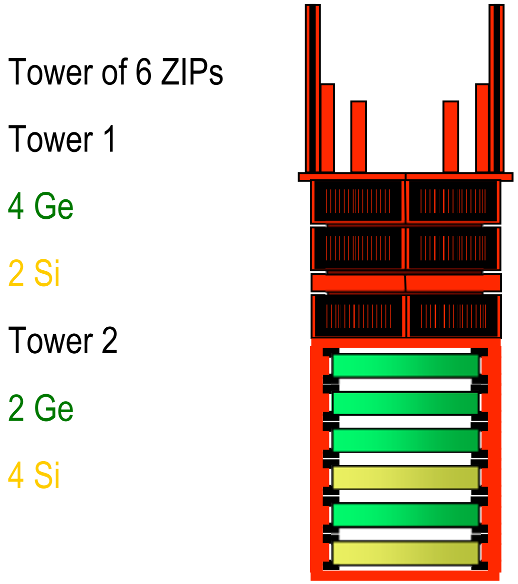


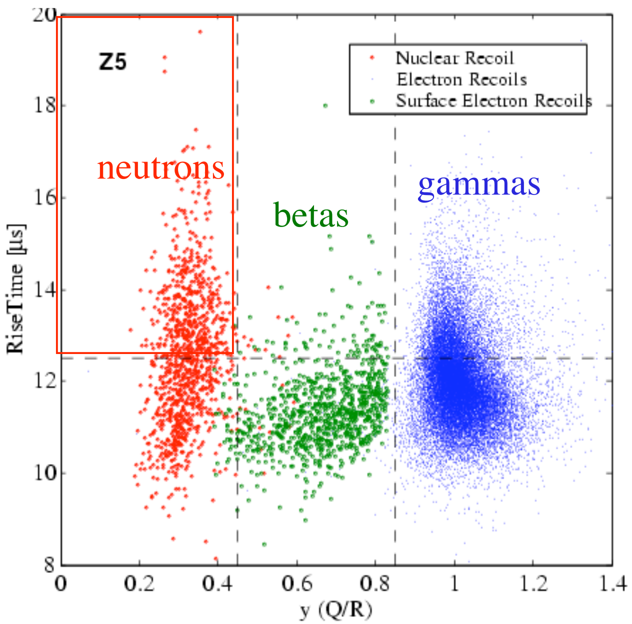


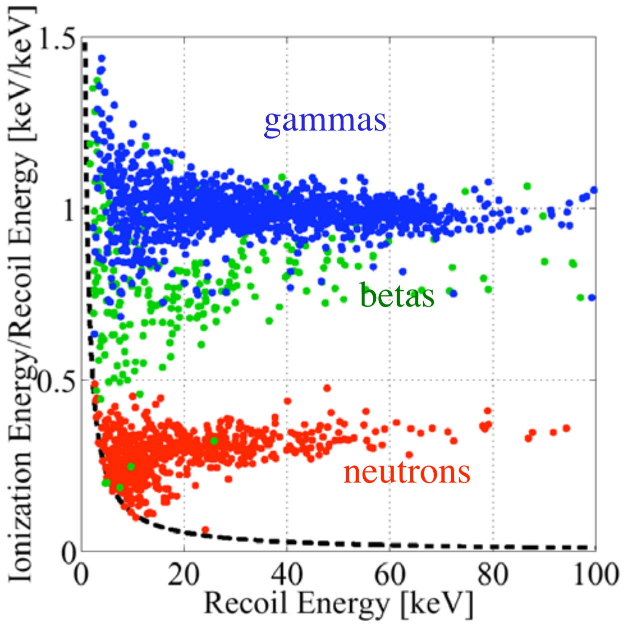
CDMS Techniques for Recoil Discrimination

Detectors with readout of both charge and phonon signals

- Charge/phonon AND phonon timing different for nuclear and electron recoils; event by event discrimination!
- Measured background rejection still improving!
  99.9998% for γ's, 99.79% for β's
- Clean nuclear recoil selection with ~ 50% efficiency
  Can tune between signal efficiency and background rejection

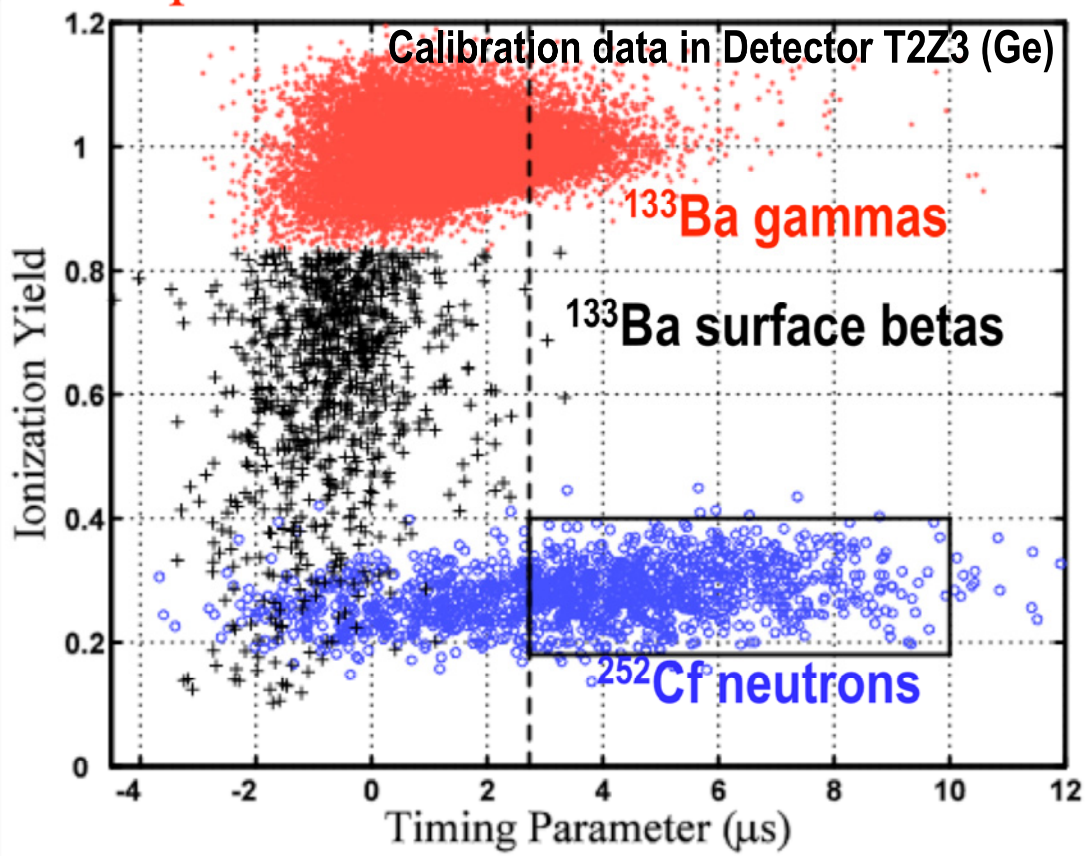


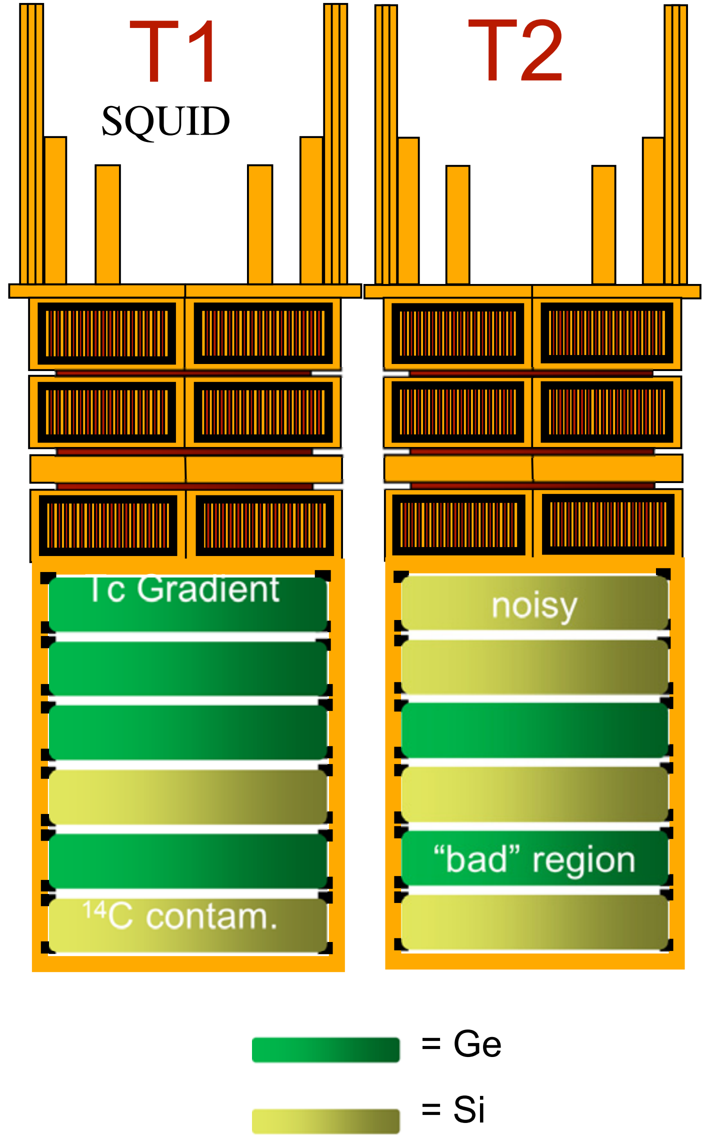




CDMS - Blind analysis to minimize bias

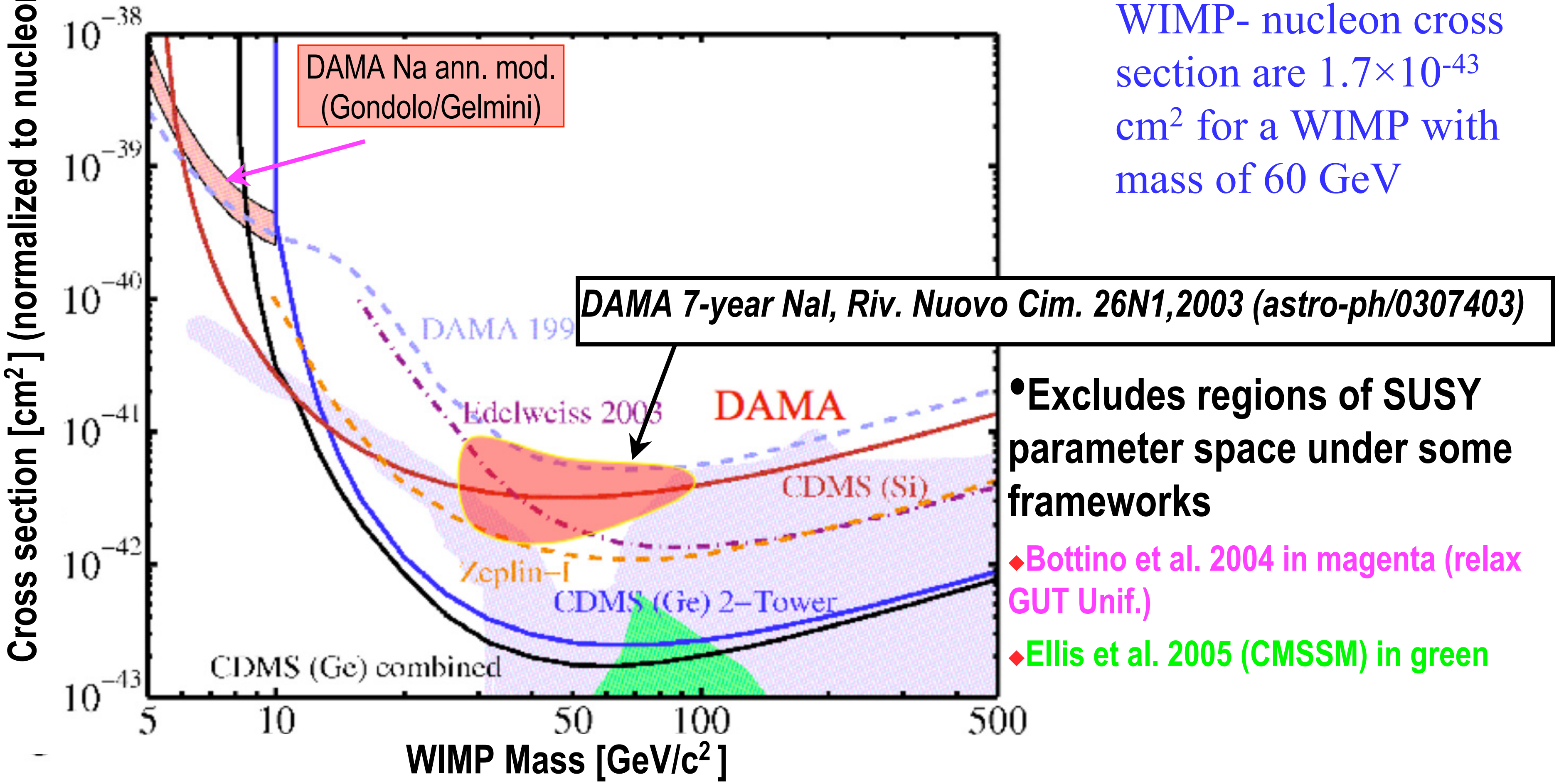
- Cuts set on calibration data and non-masked WIMP-search data
  - timing parameter
  - ionization yield
  - problem detectors/channels





CDMS Soudan Combined Limits

90% CL upper limits assuming standard halo, A^2 scaling (Spin. Ind.)



- Upper limits on the WIMP- nucleon cross section are 1.7×10^{-43} cm^2 for a WIMP with mass of 60 GeV

- **Excludes regions of SUSY parameter space under some frameworks**
  - **Bottino et al. 2004 in magenta (relax GUT Unif.)**
  - **Ellis et al. 2005 (CMSSM) in green**

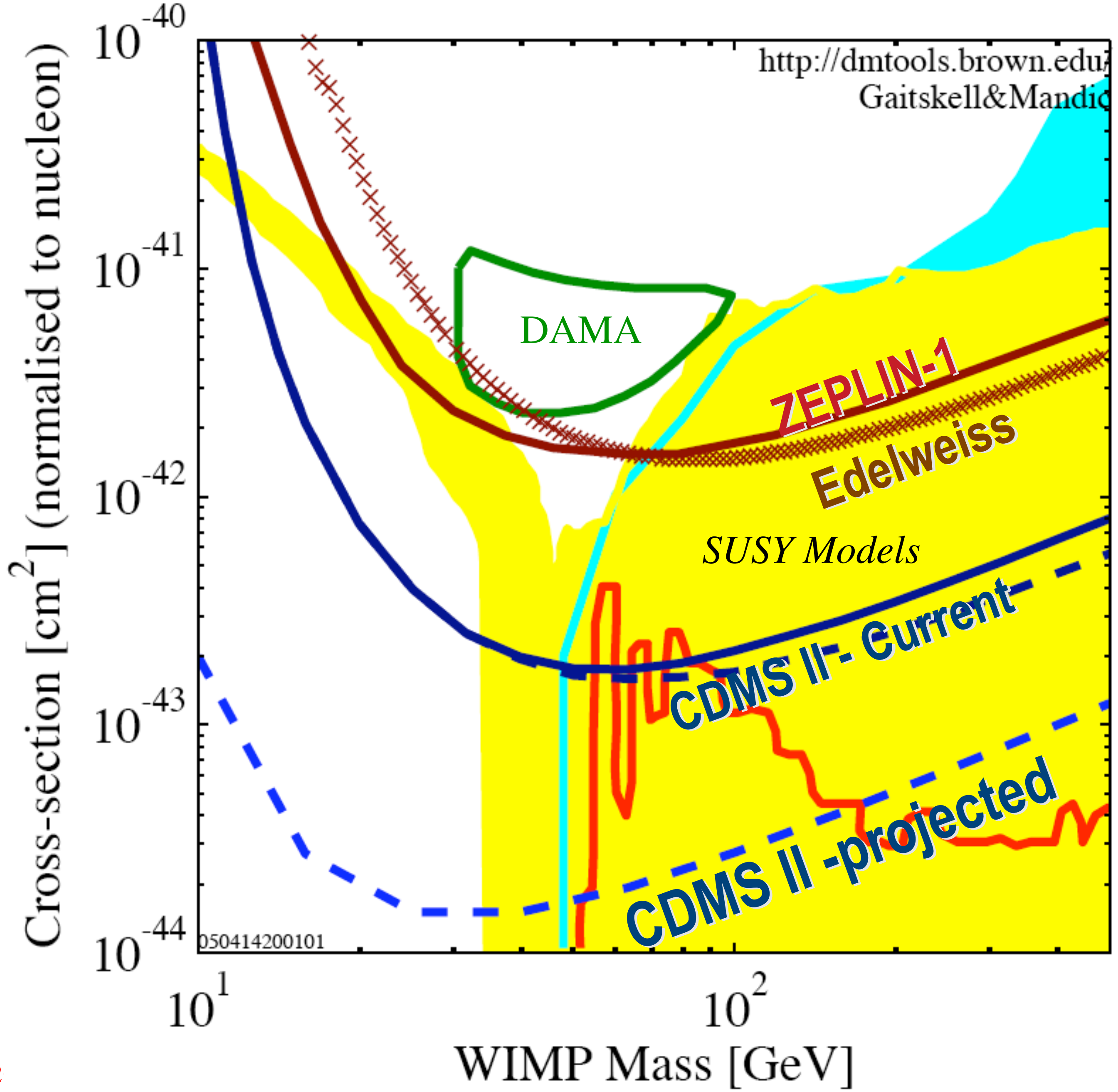
*2-tower and combined (53 kg-d): PRL **96**, 011302 (2006)*

*1-tower (19 kg-d): PRL **93**, 211301 (2004); PRD **72**, 052009 (2005)*

CDMS - Data run with 5 towers
October 2006 - July 2007 - July 2008

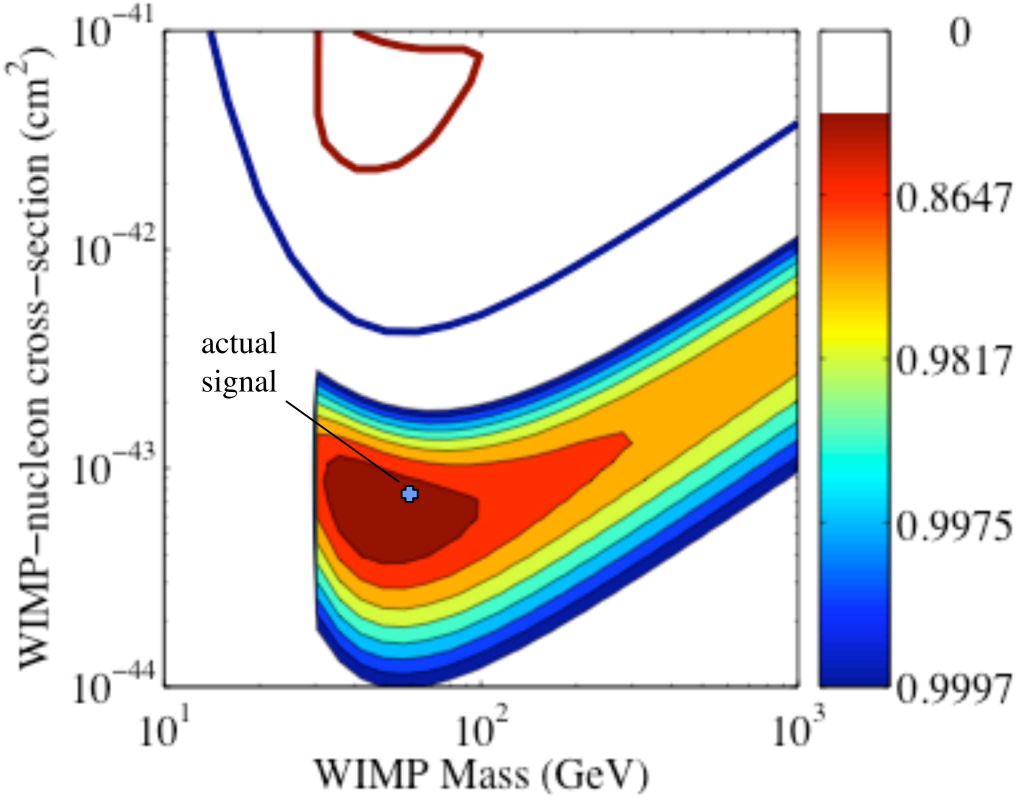
- Vital statistics
  - Base temperature for ~ 9 months
  - 5 months of high-efficiency data taking (**430 kg-days Ge**)
    - 107.4 live days for WIMP search (2.7 million events)
    - 36 (0.76) million gamma (neutron) calibration events
    - 4 TB of data
- Blind analysis underway
  - Cuts set using calibration data
  - Expect to open nuclear recoil region November 2007
  - Sensitivity should be x5 better than previous (3 x 10^{-8} pb for M_W ~ 60 GeV)
- July 2007-July 2008
  - Aim for another x3 improvement in sensitivity (~1300 kg-d)
    - Approaching 10^{-8} pb or perhaps we might start to see a WIMP signal
  - May start to run into backgrounds at Soudan
    - Beta backgrounds on some detectors, Neutrons from cosmic rays
  - If background-free, run 5 towers through 2008
    - Install first SuperCDMS detectors when ready

The Reach of CDMS at Soudan



What do we learn if we see a signal?

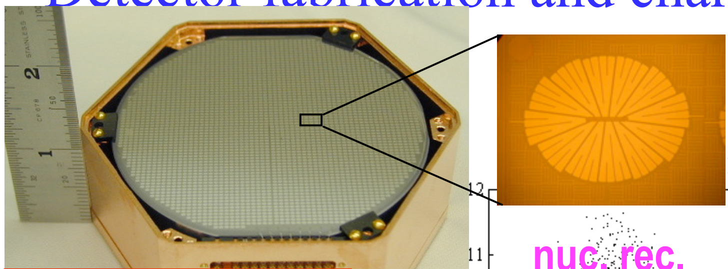
- Current 90% C. L. limit corresponds to < 1 evt per 8 kg-d for Ge
- Most favorable of linear collider SUSY models (LCC2) predicts ~5 events in CDMS II at Soudan!
- WIMP mass & cross section would be determined as shown and SI vs SD determined from different targets



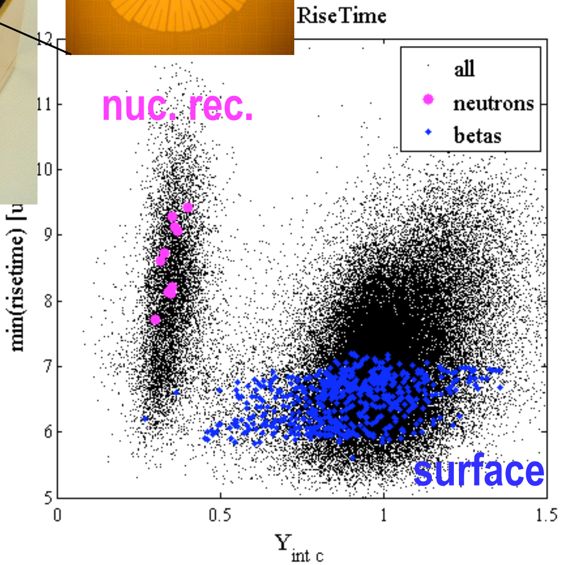
SuperCDMS 25 kg will be ideal for exploring such a WIMP signal on the same time scale as LHC!

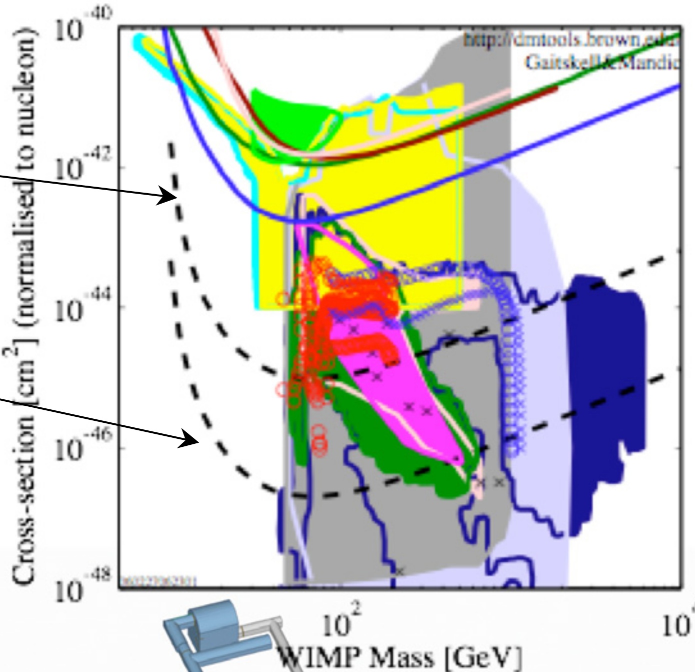
Next for CDMS: SuperCDMS 25 kg

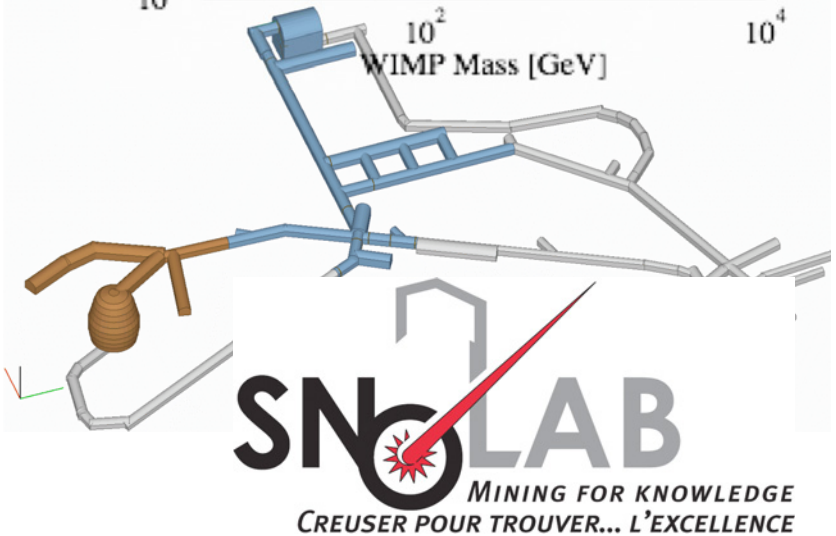
- Proposed 25-kg experiment based on updated 42 x 600-g Ge ZIPs
  - 120x beyond current limits
  - 15x beyond CDMS-II goal
  - Approved for space at SNOLAB
  - Next step towards ton-scale goal
- Detector fabrication and characterization



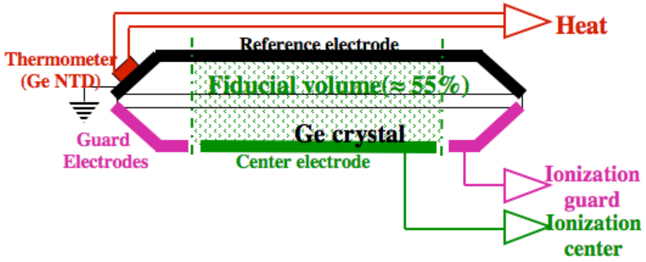
1”-thick 0.6-kg: 3x fiducial mass per s.a.

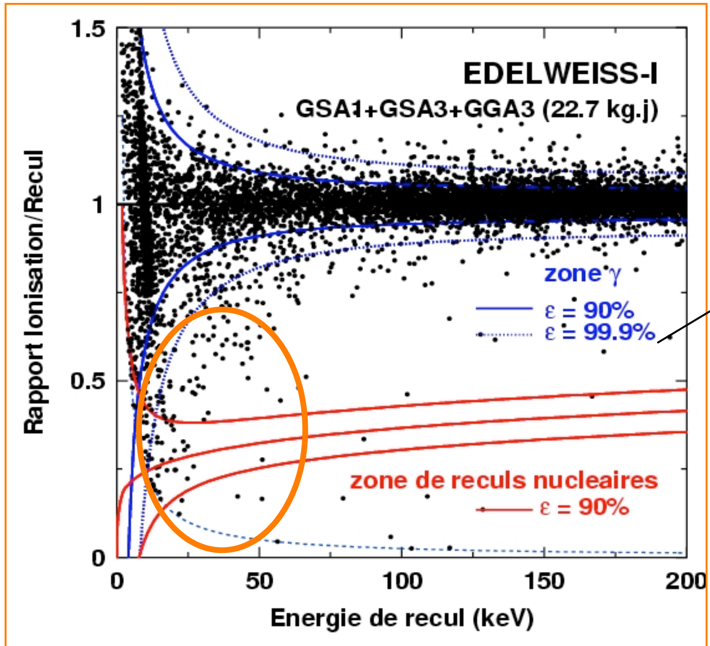


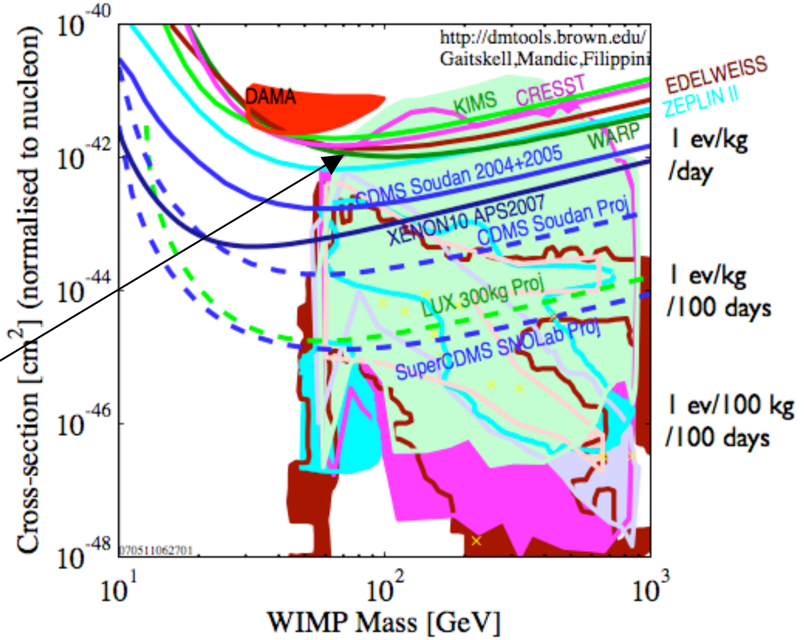




Edelweiss-I @ LSM : background limited



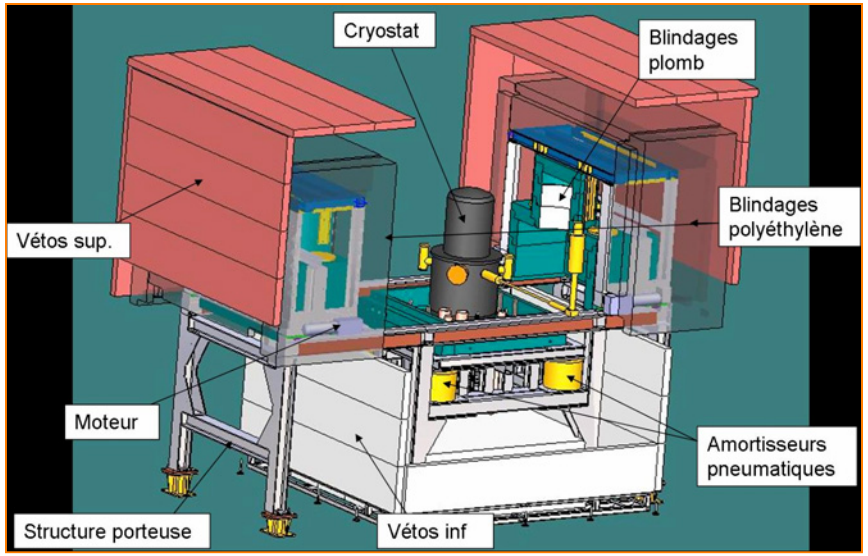




- **No improvment in limits between**
  - First data set of 8.3 kg with 0 event in ROI
  - Final data set of 63 kg.d with 6 events in ROI at E> 30 keV

- **Neutrons** : 2 events expected (MC),
  - 1 n-n coincidence observed
- **Surface electrons recoils** :
  - bad charge collection (trapping and recombination)
- Not visible on coincidence events
- **Evidence of Radon contamination** :
  - α rate ≈ e- rate ≈ ions recoils
    ≈ 5/kg.day

Edelweiss II improvements



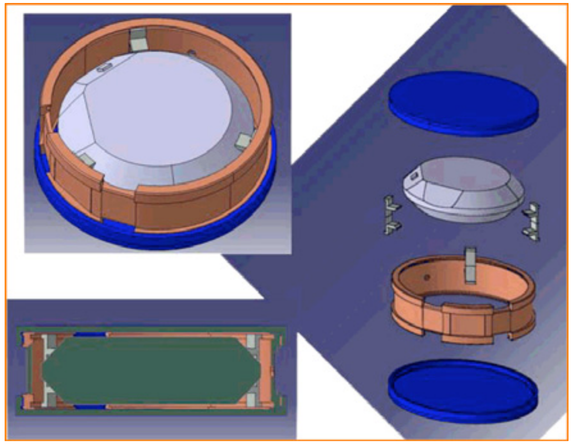
- **Radiopurity**
  - Dedicated HPGe detectors for systematic checks of all materials
  - **Clean Room** (class 100 around the cryostat, class 10 000 for the full shielding
  - **Deradonized air** -from NEMO3 radon trap- from 10 Bq/m3 to 0.1 Bq/m3
  - Thicker shield : 20 cm Pb shieding
- **Neutron Shielding**
  - EDW-I : 30 cm paraffin
  - EDW-II : **50 cm PE** and better coverage
- **μ veto** 120 m^2 (> 98% coverage)
- **Neutron detectors** in coincidence with veto under development (Karlsruhe/Dubna)
- **Cryostat able to shelter 40 kg of detectors**

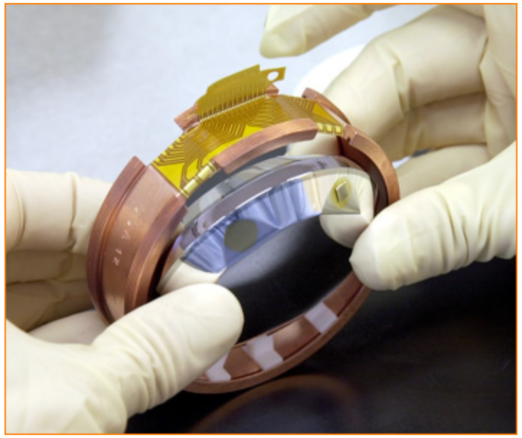
- =>**Aimed sensitivity (EDW-I * 100)**

  σ_{w-n} ≈few 10^{-8} pb with 15 to 20 kg of Ge

  0.002 evt/kg/day (Er>10keV) = neutron coming from not tagged μ interacting in the rock

28 detectors : present “10^{-7} pb” phase





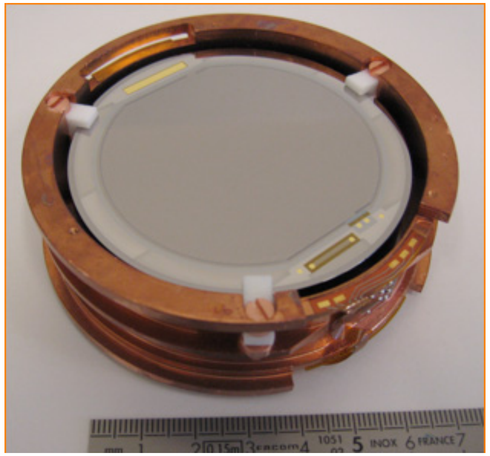
*21*320g Ge/NTD*

♦ Developed by CEA Saclay and Camberra-Eurisys

♦ Amorphous Ge and Si sublayer (**better charge collection for surface events**)

♦ Optimized NTD size (16-18 mK) : **keV resolution**

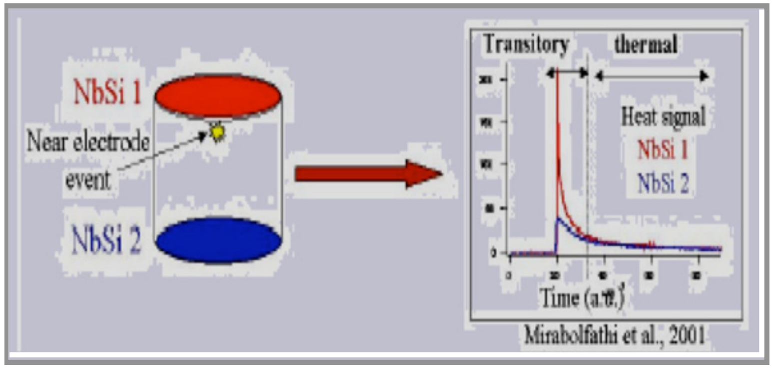
♦ New holder and connectors (Teflon and copper only)



*7*400g Ge/NbSi detectors*

♦ Developped by CSNSM Orsay

♦2 NbSi thin films thermometer for **active surface events rejection**



April-may 2007 commissioning runs : summary

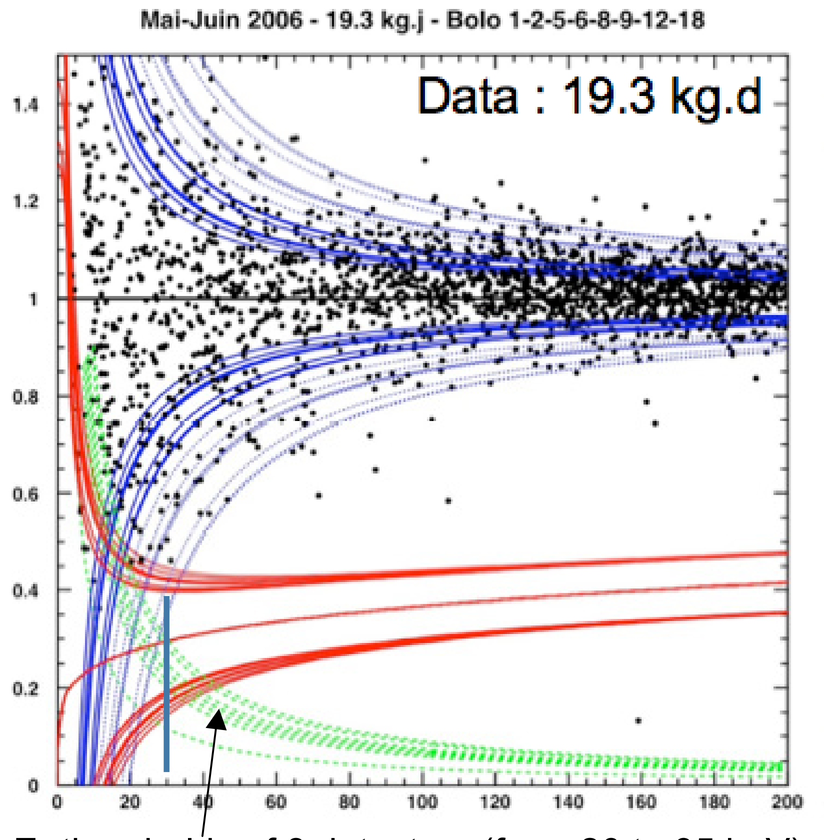
- Resolutions, thresholds at EDWI level for best detectors
- Decoupling of cold machines in progress to decrease noise

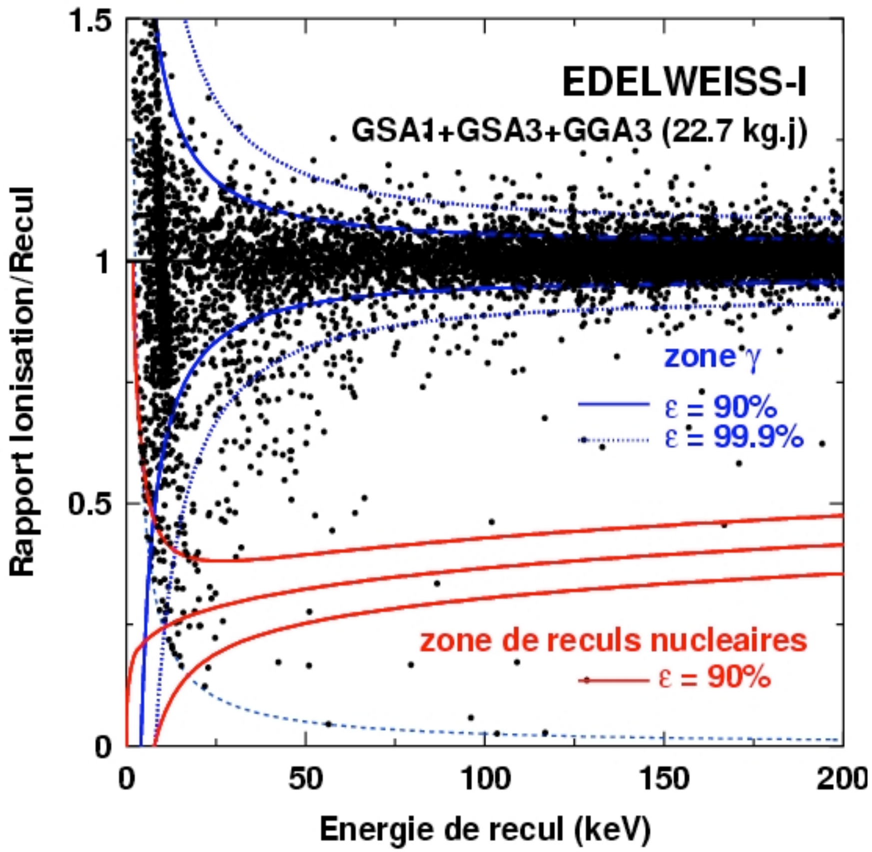
- **NTD : 23 days run result with best 8 detectors**
  - Er threshold 30 keV +- 5 keV =>19.3 kg.d : **no event in ROI**
  - NB : EDW1 runs 8.3 kg.d no event, 62 kg.d : 6 events
- From alpha count rate : surface ^{210}Pb still present at a level 2-3 times lower wrt EDWI

- **Much progress in fight against surface events** :
  - NbSi : 2 * 200g measured in LSM
    - Beta event rejection factor tunable between 90 and 99 %
    - Acceptance for signal measured from 70 to 50 %
    - LSM Data : 1.5 kg.d after cuts : no event in ROI
  - Interdigitised electrodes (ID) and NTD sensor detectors
    - First calibrations at Orsay : behaviour as expected
      - Surface events rejection factor : 95 %
      - Acceptance for signal : of order of 85 %

April-may 2007 commissioning runs
Low energy Q plot for 8 NTD detectors

- 8 lowest threshold detectors selected
- Only « pure center » events selected for better Ei resolution





Er thresholds of 8 detectors (from 20 to 35 keV)

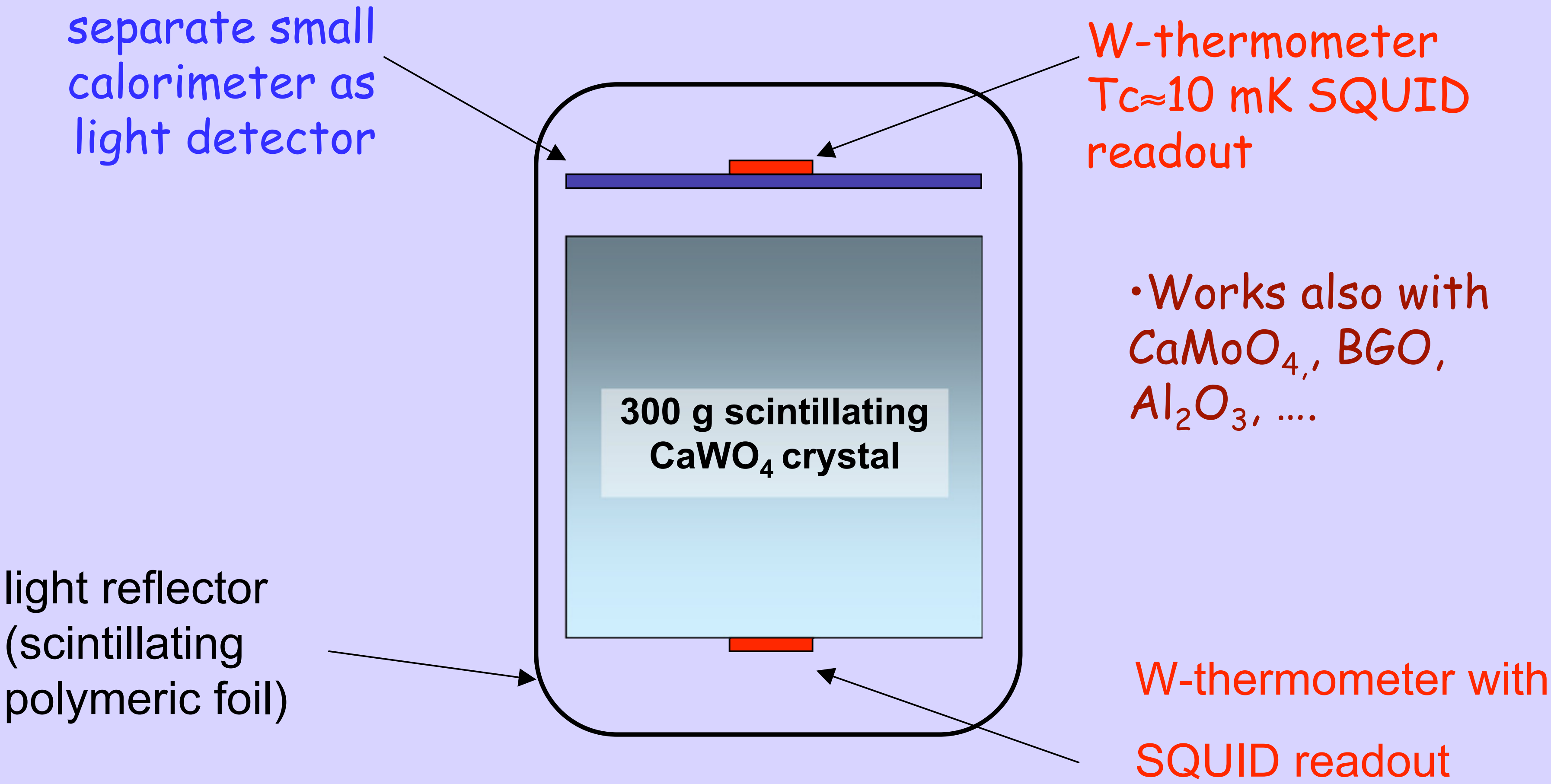
Lower LE background linked to lower alpha count rate ?

Edelweiss II plans

- Now, starting physics runs (when stability of cryogenics OK)
- « 10^{-7} pb» phase
  - Run present 28 detectors (21 NTD, 7NbSi) with duty cycle ~ 50%
  - Should be reached by spring 2008 by both type of detectors
- « 10^{-8} pb» phase « SUSY significant » goal
  - 48 detectors (24 NbSi, 24 NTD/ID, 15 kg total mass)
  - Addition of detectors every 4 months up to mid 2009
  - Program approved by CNRS/CEA scientific councils
  - Sensitivity reached by 2009/2010
- Towards «10^{-9} pb» phase
  - Will be adressed mid 2009
  - Neutron background and VETO efficiency measured at that time
- EDW II is also preparation of «10^{-10} pb» 1T EURECA
- See Gerbier's talk this afternoon + Navick and Nones on thursday

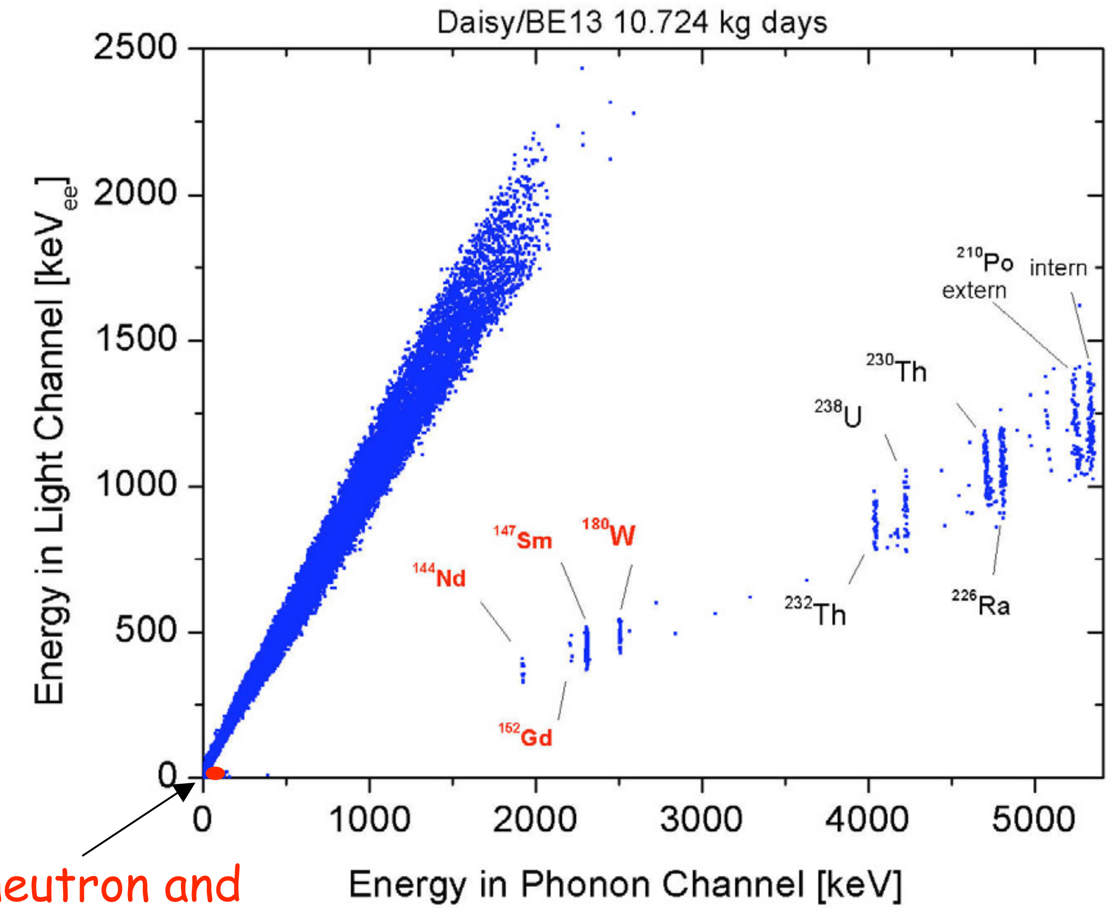
CRESST-II Detector Concept

Simultaneous measurement of **phonons** and **scintillation light** for discrimination of nuclear recoils from radioactive α,β,γ backgrounds.



- Works also with $CaMoO_4$, BGO, Al_2O_3, ….

2004 data with 300g detector in CRESST-I setup

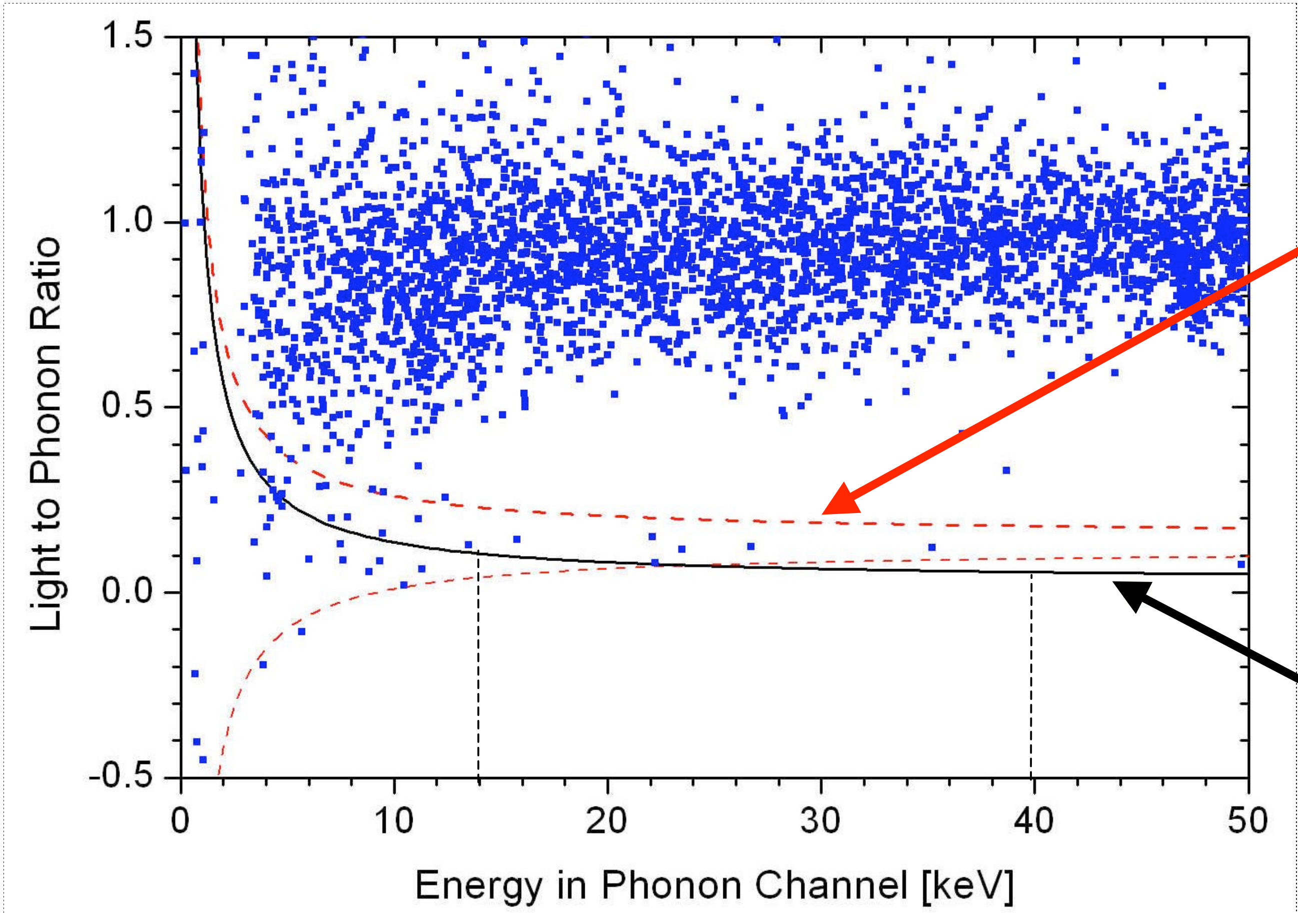


neutron and WIMPS

- 1.5 month run in 2004 before upgrade of CRESST setup
- Excellent linearity and energy resolution in whole energy range
- Perfect discrimination of $\beta+\gamma$ from α's
- Good energy resolution (ΔE=6 keV @ 2.3 MeV) allows identification of alpha emitters
- alphas on surface and in volume give same light

Low Energy Event Distribution in CRESST-I setup without neutron shield

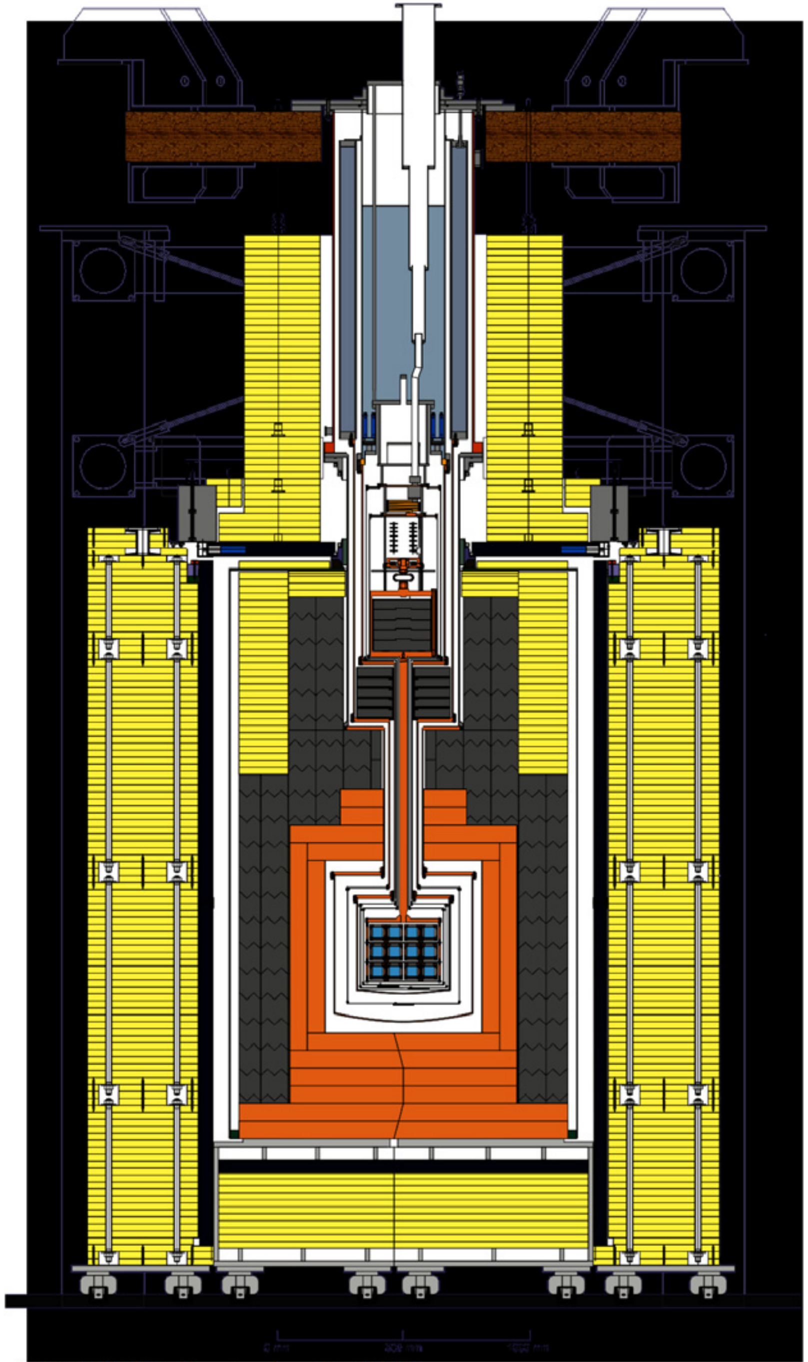
2004 data 10.72 kg days



90% of oxygen recoils below this line. Rate=0.87±0.22 /kg/day compatible with expec-ted neutron background.

90% of W recoils below this line. No W recoils in 12 to 40 keV range

O recoils mostly from neutrons, W recoils mostly from WIMPs
==> good sensitivity despite neutron background



Upgrade for CRESST-II

- **New read out and biasing electronics**:
  66 SQUIDs for 33 detector modules
- **Wiring for 66 channels**
- **Detector integration in cold box**
- **New DAQ and slow control**
- **Neutron shield:** 50 cm PE (12 tons)
- **Muon veto:** 20 plastic scintillator panels outside Cu/Pb shield and radon box. Analog fiber transmission through Faraday cage

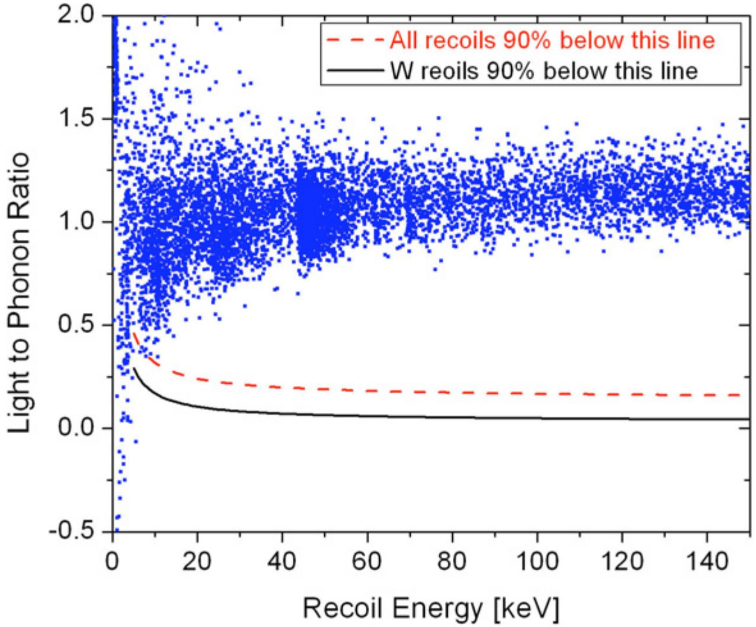
CRESST restart after upgrade

- Cryostat cold since Oct. 2006
- Commisioning run until end of March 2007 to fix issues with SQUID electronics causing disturbances in light channels .
- First physics run with 3 detectors since April 2007. About 60 kg days expected until September ($\sigma \sim 10^{-7}$ pb when no background appears)

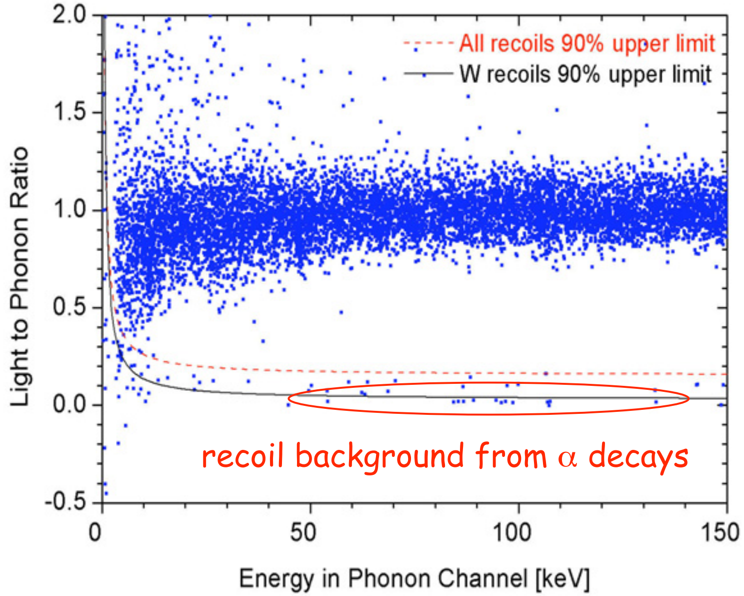
Oct. 2006: Mounting detectors

Preliminary Results from End of CRESST-II Commisioning Run

Data from end of commissioning Run



Run28: 10.5 kg days

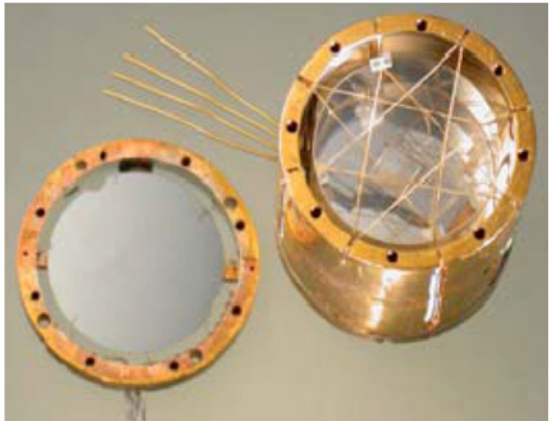


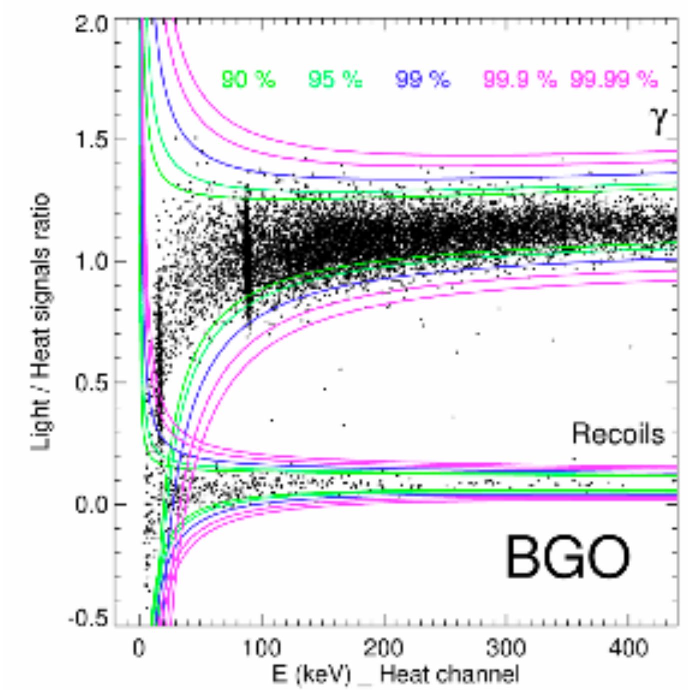
- Neutron background disappered. Installed neutron shield is efficient
- Recoil background from alpha decays completely disappeared (now 100% scintillating inner surface of detector module)
- Width of β/γ band still sufferes a bit from electronic interference in light detectors.
- Check this afternoon session for results by W Seidel

ROSEBUD

Universidad de Zaragoza - Institut d'Astrophysique Spatiale d'Orsay

- R&D for DM search with scintillating cryo detectors
- Test different materials (BGO, Sapphire, LiF, O(50 g) each)
- Thermal measurement with NTD (ca. 20 mK)
- Low BG setup: Laboratorio Subterráneo de Canfranc (LSC; 2450 m w.e.), Cu/Pb shielding, partial PE shield





EURECA

CRESST, EDELWEISS, ROSEBUD, CERN + new groups

United Kingdom

Oxford (H Kraus, coordinator)

Germany

MPI für Physik, Munich
Technische Universität München
Universität Tübingen
Universität Karlsruhe
Forschungszentrum Karlsruhe

Russia

DNLP Dubna

France

CEA/DAPNIA Saclay
CEA/DRECAM Saclay
CNRS/CRTBT Grenoble
CNRS/CSNSM Orsay
CNRS/IPNL Lyon
CNRS/IAP Paris
CNRS/IAS Orsay

Spain

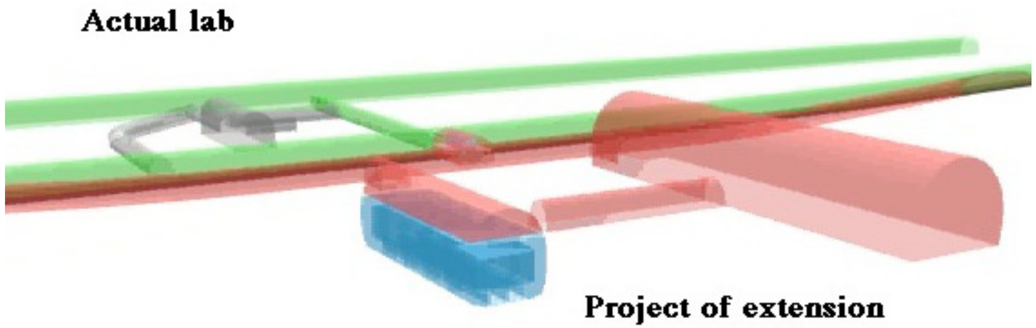
Zaragoza

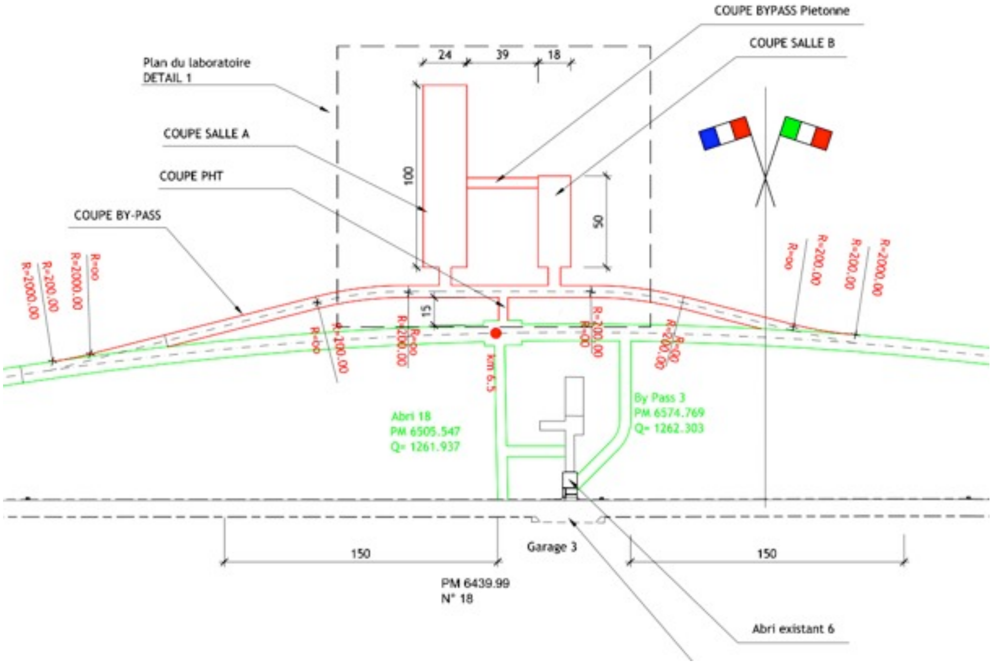
CERN

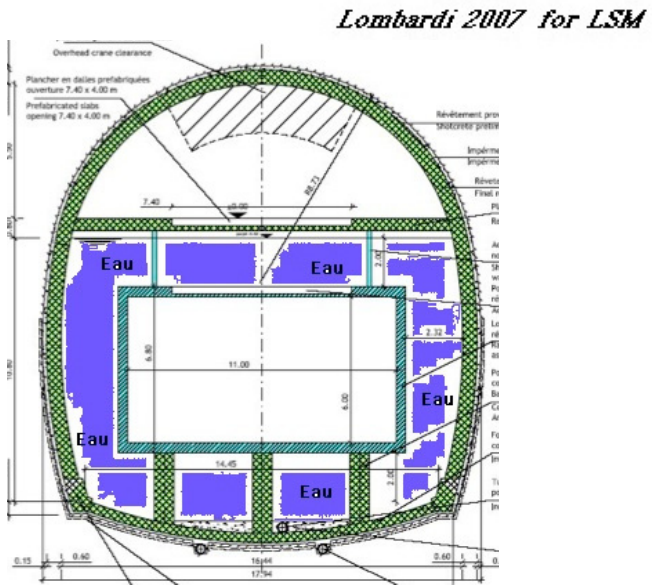
- Reach ultimate sensitivity of 10^{-10} pb to SI interactions
- Facility to host 1 ton of cryogenic detectors
- Multi target approach also for SD WIMp's
- « Open access » facility, to be studied
- A Design Study proposal submitted to European Commission infrastruture support program call
- Statement of Interest distributed, regular meetings hold
- Some funds available for studies at national level

EURECA @ Fréjus site

- Link with future possible extension @ Fréjus site with dedicated low back water shielded hall
- Time scale 2013 start installation







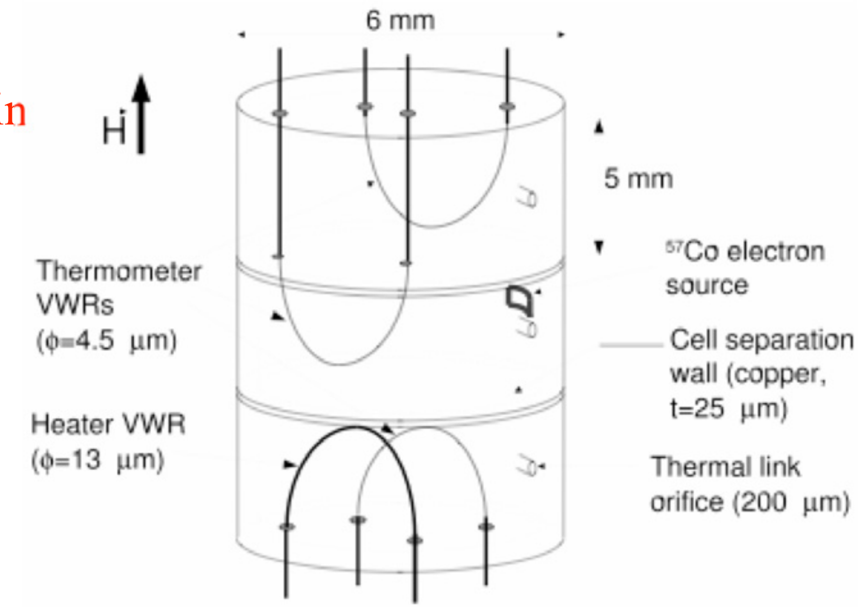
Other Cryogenic Detectors

- Orpheus
  - R&D on superconducting tin granules
  - Shallow site (70 m.w.e.) at University of Bern
  - Initial results showed high backgrounds
  - Experiment appears to be dormant

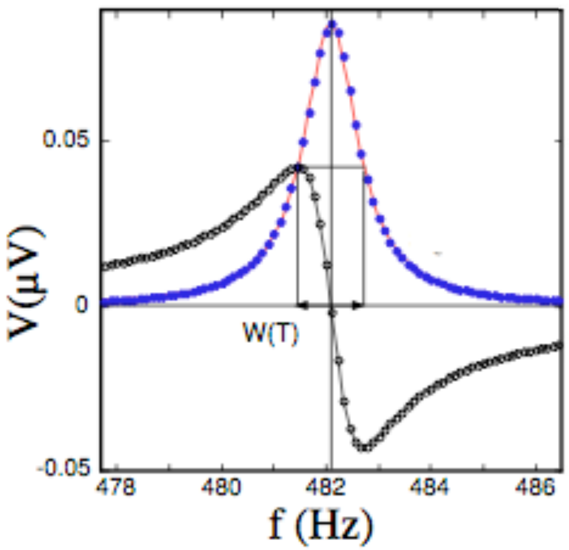
- Cuore
  - TeO_2 crystals, up to 750 kg of target
  - Primarily aimed at double-beta decay (MeV energies)
  - Would have to reduce low-energy backgrounds to be competitive for dark matter search

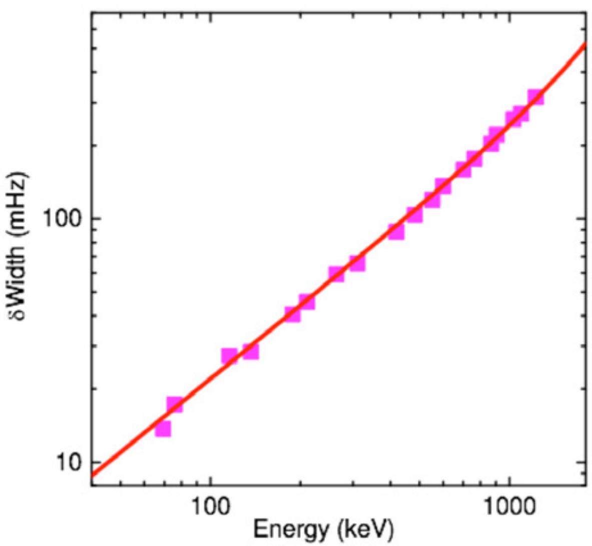
3He Bolometry: MACHe3, ULTIMA

- Bolometric detection using 3He
  - Mechanical wire resonators installed in 100 μK superfluid 3He cell
  - Driven at resonance via Lorentz force in 100 mT uniform B field
  - Energy depositions create quasiparticles that damp resonator motion and thus shift resonance
  - QPs leak out through orifice to main bath; very much like a bolometer

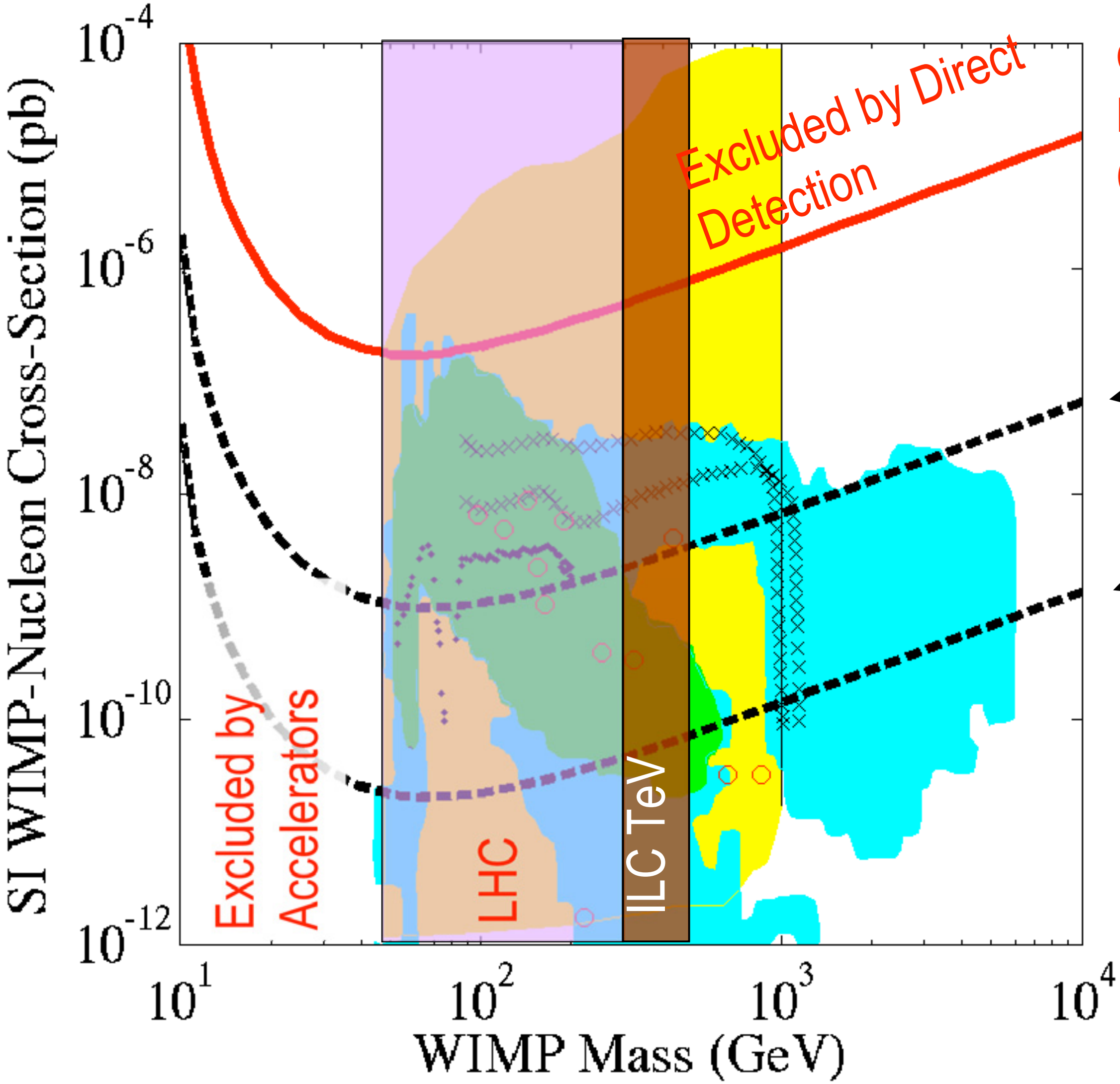


- Eventual NR discrimination via ionization or scintillation
- Still very much in development...





Complementarity with Collider searches for SUSY



Current CDMS II limit
PRL 96, 011302 (2006)
(~20 attobarn^{-1})

Assuming zero-background Sensitivity:
25 kg of Ge (Xe, I, W)
(100 kg Ar, 200 kg Ne)

1000 kg of Ge

Direct detection is cross-section limited.

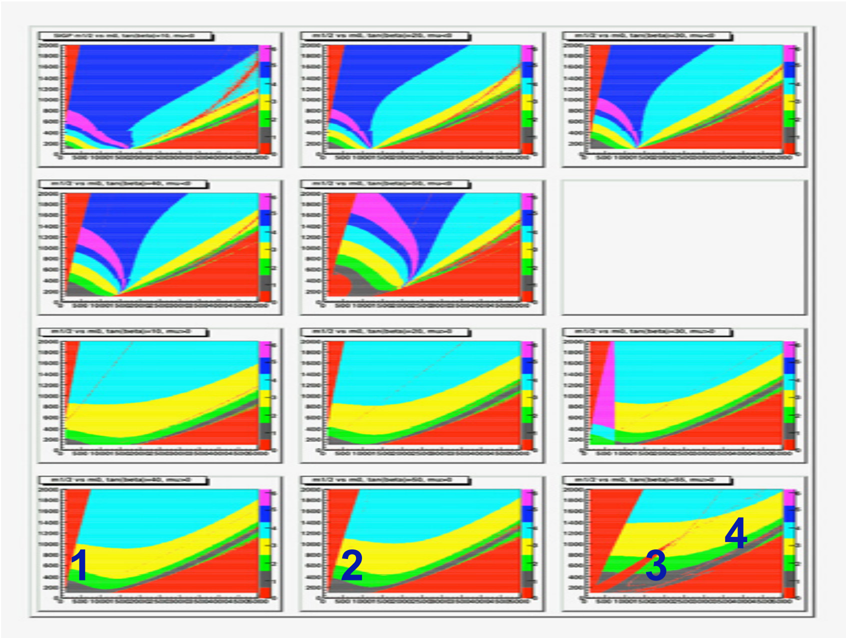
But sensitive to >TeV mass WIMPs

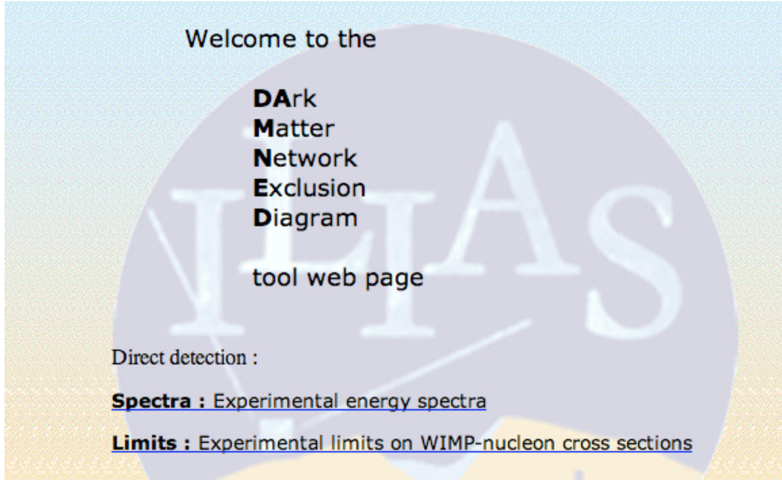
Colliders are mass limited.

And can't determine if WIMP is stable

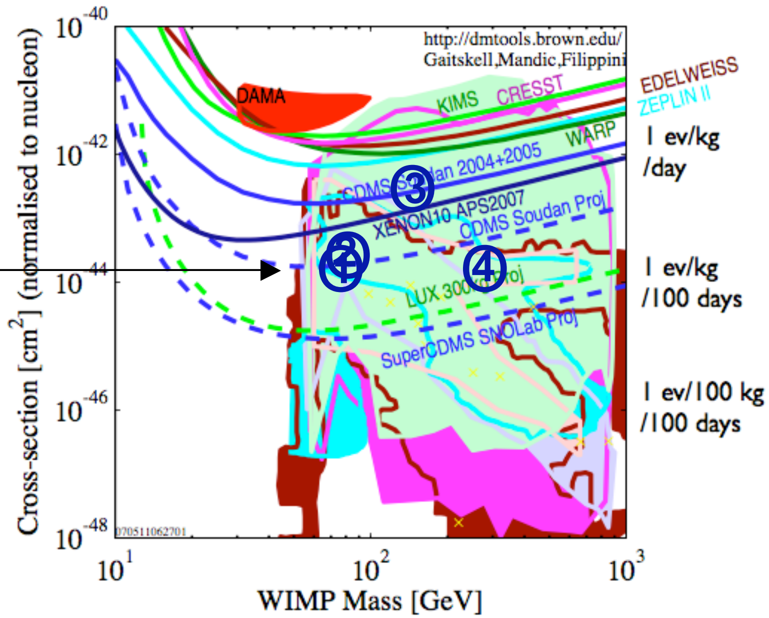
SUSY <=> Exp results calculations web page

http://pisrv0.pit.physik.uni-tuebingen.de/darkmatter/





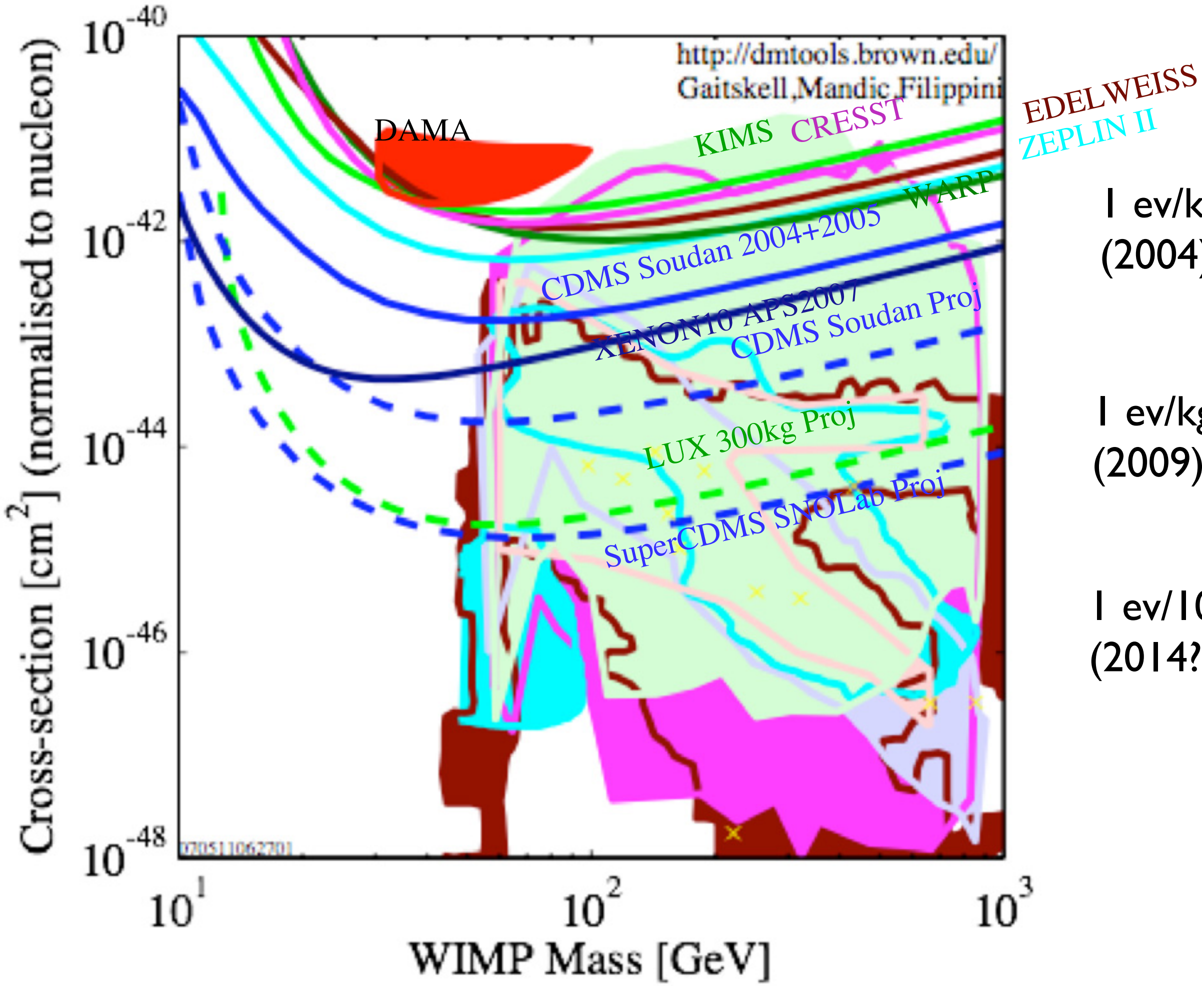
	m0	m1/2	mu sign	tg Beta	σ neutralino mass
1	500	250	+	40	2E-08pb, 97GeV
2	1000	250	+	50	2E-08pb, 98 GeV
3	2000	350	+	55	2E-07pb, 139 GeV
4	4000	900	+	55	4E-08pb, 340 GeV



- Final Goal : integrated interactive analysis of DD, ID and LHC constraints on SUSY models
- Complementary to DarkSusy, DMtools

R Lemrani webmaster

Conclusions



1 ev/kg/day (2004)

1 ev/kg/100 days (2009)

1 ev/100 kg/100 days (2014?)

Cryogenic detectors results and limits will improve in the coming year !
Convincing demonstration of any signal hint will require redondancy !
Large target mass is no guarantee of success, but will help to pinpoint systematics !
Very "anthropically", let's hope that Super WIMPs are less "natural" than SUSY WIMPs !