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Dark Matter
Lecture 3: Direct detection techniques and experiments, I

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Lecture 3: Direct detection techniques and experiments, I

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- Status of experiments, comparison with theory
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  Principles

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  Principles

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  Principles

  Examples: CDMS, CRESST, EDELWEISS

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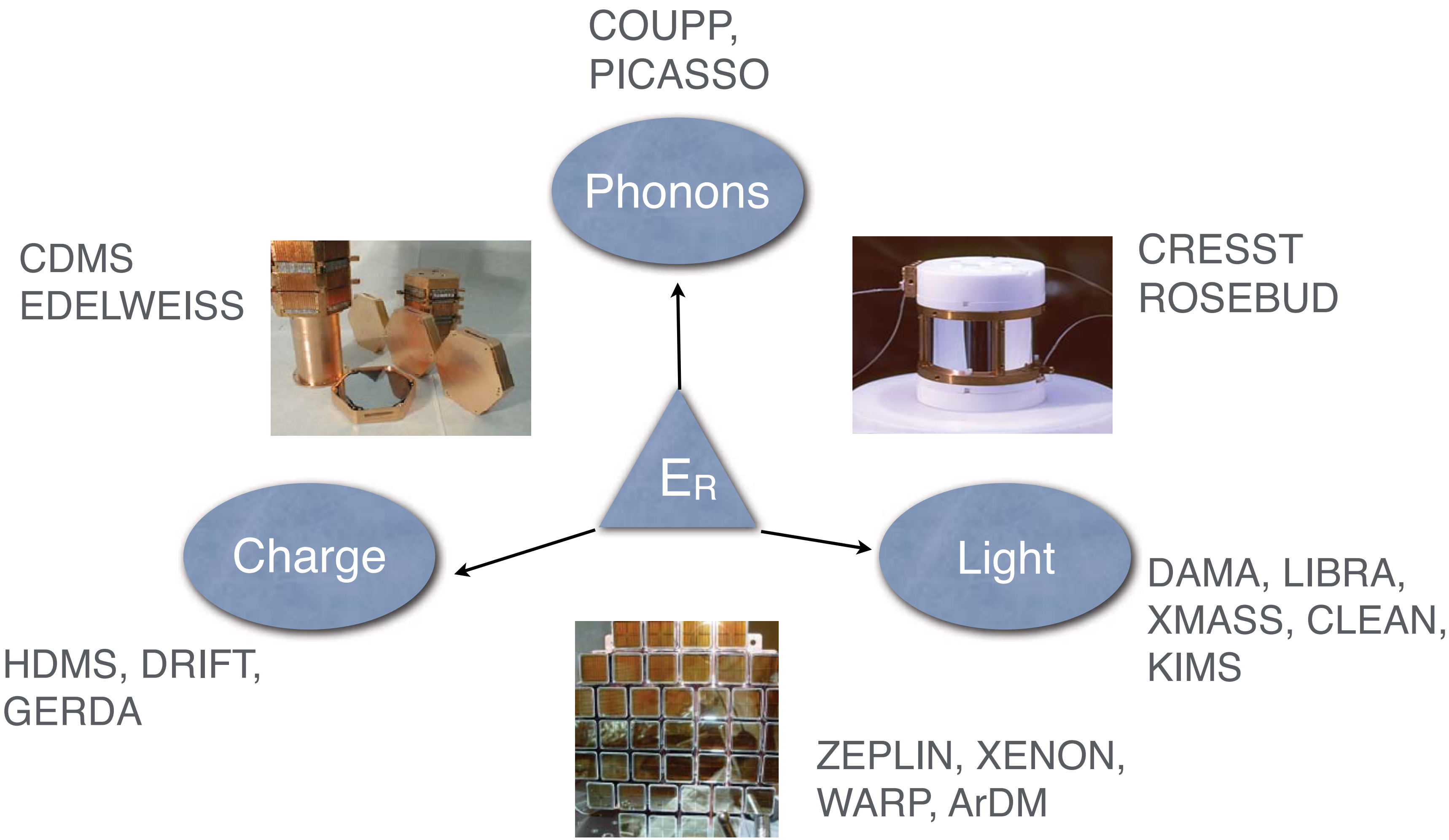
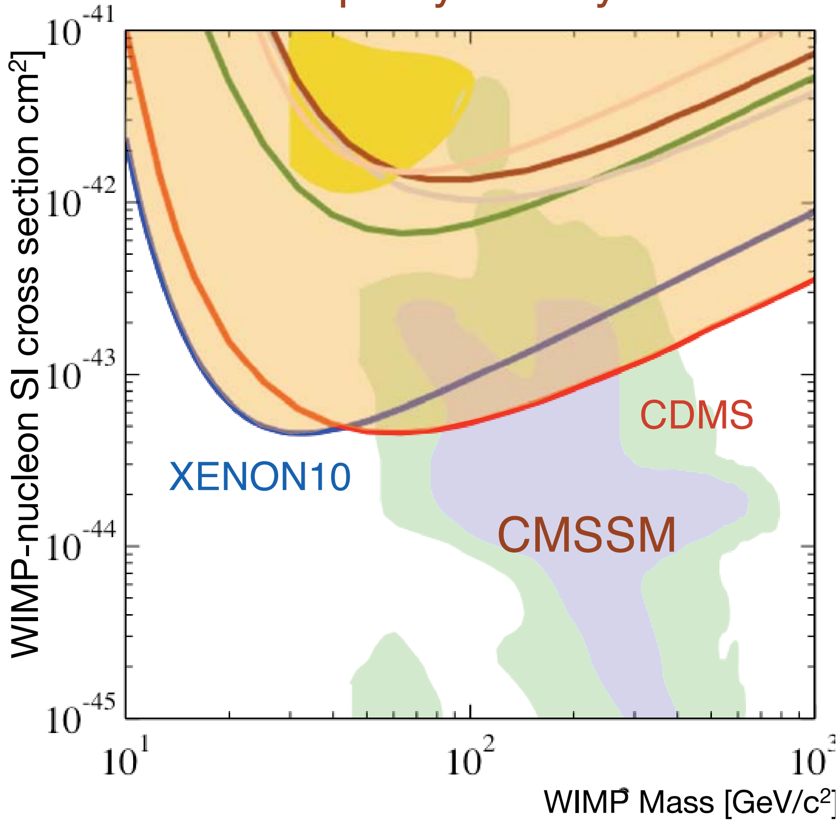
Direct WIMP Detection Experiments

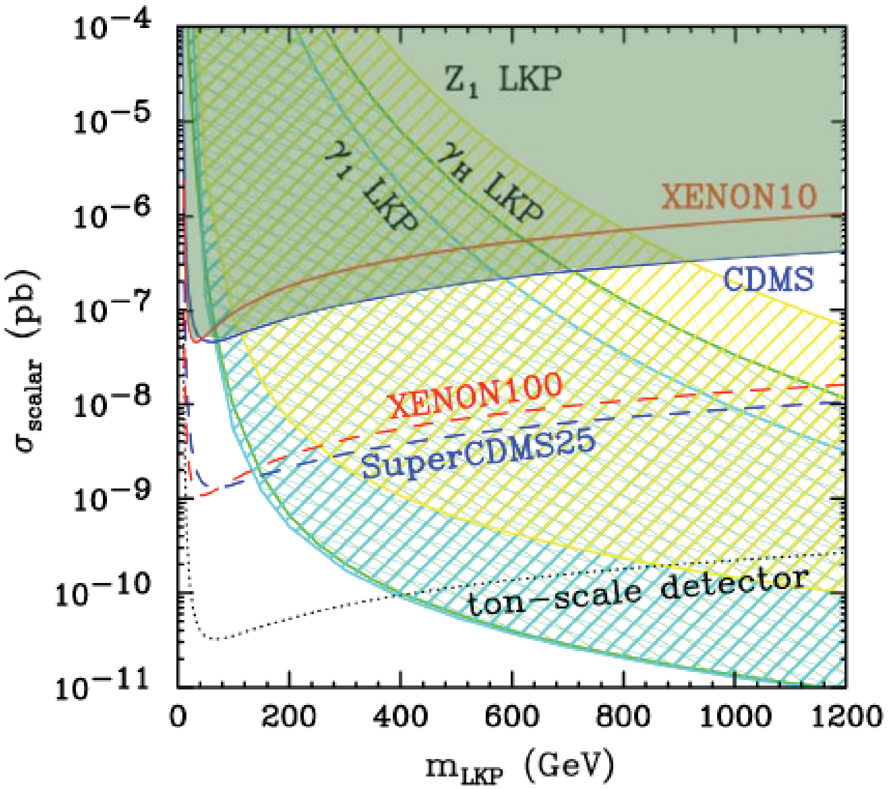


Comparison: Theory and Experiment

Supersymmetry



Universal Extra Dimensions



Vanilla Exclusion Plot

- **Assume we have detector of mass M, taking data for a period of time T**
- The total exposure will be **ε = M × T [kg days]**; nuclear recoils are detected above an energy threshold E_{th}, up to a chosen energy E_{max}. The expected number of events will be:

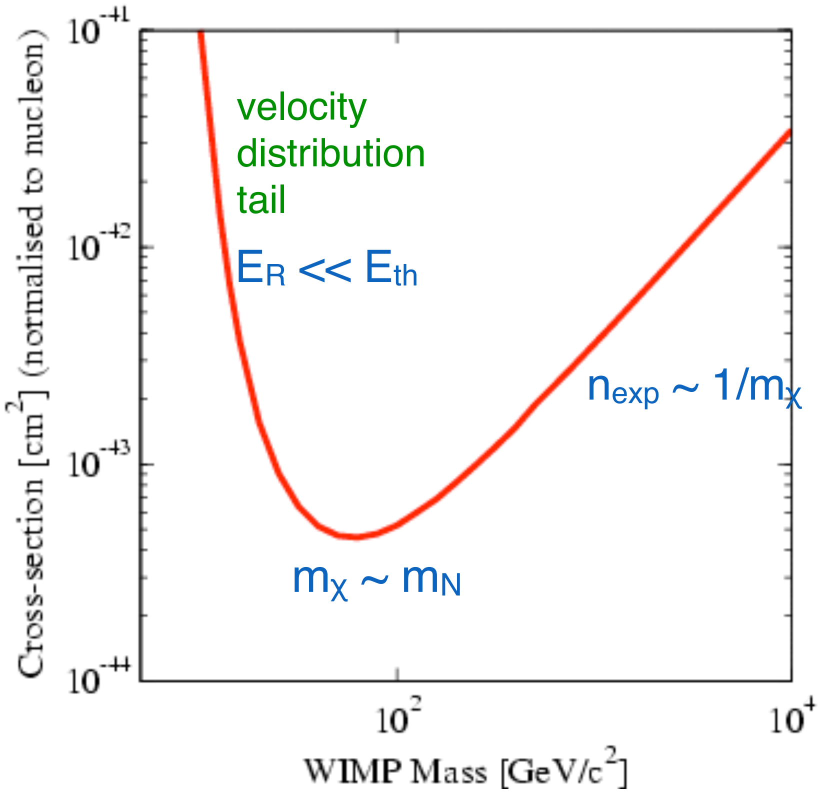
$$n_{\exp} = \varepsilon \int_{E_{th}}^{E_{\max}} \frac{dR}{dE_R} dE_R$$

=> cross sections for which $n_{exp} \sim\geq 1$

can be probed by the experiment

- If ZERO events are observed, Poisson statistics implies that $n_{exp} \leq 2.3$ at 90% CL

=> exclusion plot in the cross section versus mass parameter space



Germanium Ionization Experiments

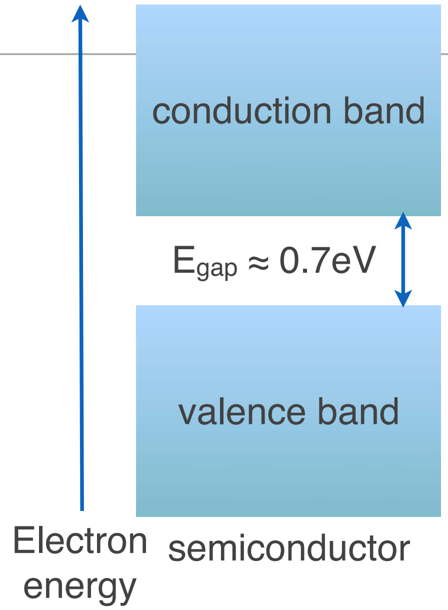
- **Electron-hole pairs in a semiconductor**
- 2.96 eV/e$^-$-h pair at 77 K

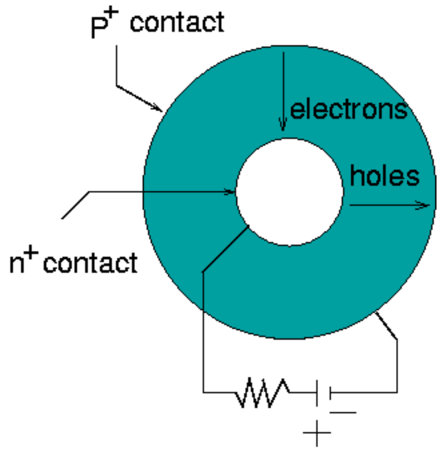
- motion of e$^-$-h in E_{field} => signal

$$Q(t) = Q^-(t) + Q^+(t)$$

  - ➡ relatively slow detectors (μs)
  - ➡ energy thresholds: ~ 2-10 keVee

- In general operated in vacuum-tight cryostats to suppress thermal conductivity between the crystal and the surrounding air
  - ➡ typical energy resolutions: 1 keV at 10 keV, 2-3 keV at 1 MeV
  - ➡ **about 1/3 of energy of a nuclear recoil goes into ionization**





n-type, coaxial HPGe-detector

Germanium Ionization Experiments

- The **full width at half maximum** (of a mono-energetic peak) is given by:

$$W_{tot}^2 = W_{stat}^2 + W_{coll}^2 + W_{noise}^2$$

- **First term:** the inherent statistical fluctuation in the number of charge carriers

$$W_{stat}^2 = (2.35)^2 F\varepsilon E$$

predicts: 1.3 keV at 1.33 MeV

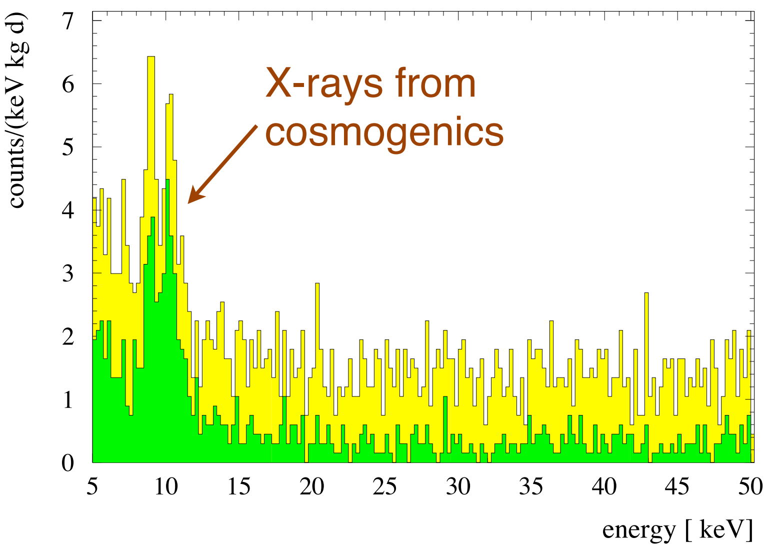
  - ➡ **F = Fano factor**, introduced because the observed statistical fluctuations are smaller than predicted if the formation of charge carriers were a Poisson process (F = 0.08); it arises because the e^--h producing events are not statistically independent
  - ➡ **E = deposited energy**, **ε = energy required to produce one e^--h pair, ε = 2.96 eV**

- **Second term:** accounts for incomplete charge collection
- **Third term:** due to all the electronic components in the system

The Heidelberg Dark Matter Search Experiment

- Has been operated at the Gran Sasso Underground Laboratory
- first enriched ^{73}Ge detector (J = 9/2, for SD couplings)

- **2 concentric HPGe detectors:**
  - ➡ inner = active WIMP target
  - ➡ outer = active veto for gamma background reduction

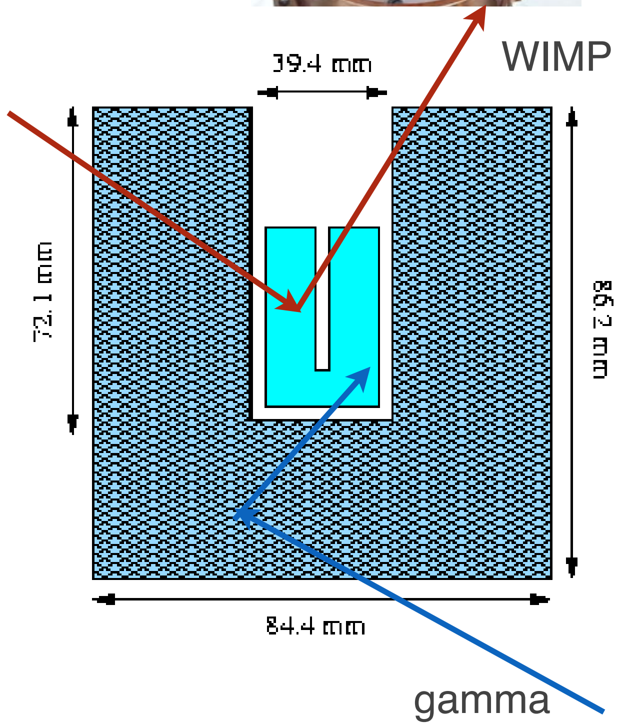


background reduction by anti-coincidence: 4.5

outer detector

inner detector

~27 kg days



The GERDA Experiment

- In construction at the Gran Sasso Laboratory
- Will operate a large amount (40 kg - 500 kg) of HPGe detectors directly in liquid argon, shielded by a water Cerenkov detector
- **Aim:** reduce the backgrounds by using the self-shielding of liquid argon
- Main physics goal: detect the $0\nu\beta\beta$-decay in ^{76}Ge
- However, with an ultra-low BG of ~ 1 event/(kg keV yr) in the low-energy region it may also look for a WIMP annual modulation signature

LAr tank at LNGS

bare HPGe crystal

Room Temperature Scintillation Experiments

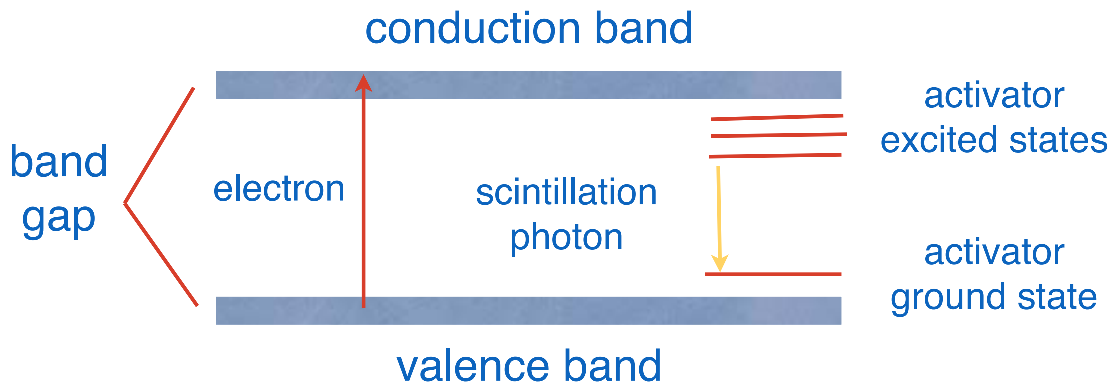
- Detection of scintillation light produced in various materials is a very old technique in particle physics

- **Ideally, the material should:**
  - ➡ convert the kinetic energy of the particle into light with high efficiency, and the conversion should be linear
  - ➡ be transparent to its own emission wavelength for good light collection
  - ➡ have a short decay time for the induced luminiscence for fast detectors
  - ➡ have an index of refraction near that of glass (1.5) for coupling to a PMT or another type of light sensor

- **For dark matter searches:**
  - ➡ mostly inorganic alkali halide crystals (NaI(Tl), CsI(Na,Tl)), operated at room temperature
  - ➡ best light output and linearity
  - ➡ can be produced as high-purity crystals

Room Temperature Scintillation Experiments

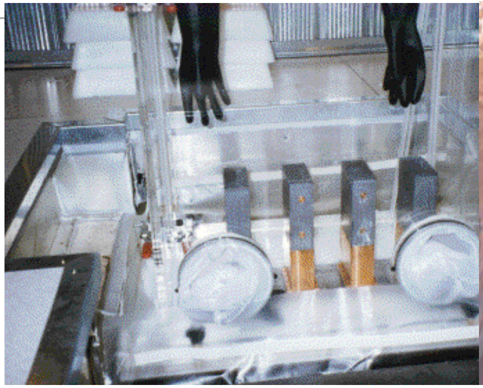
- To enhance the probability of visible light emission: add impurities = “activators”



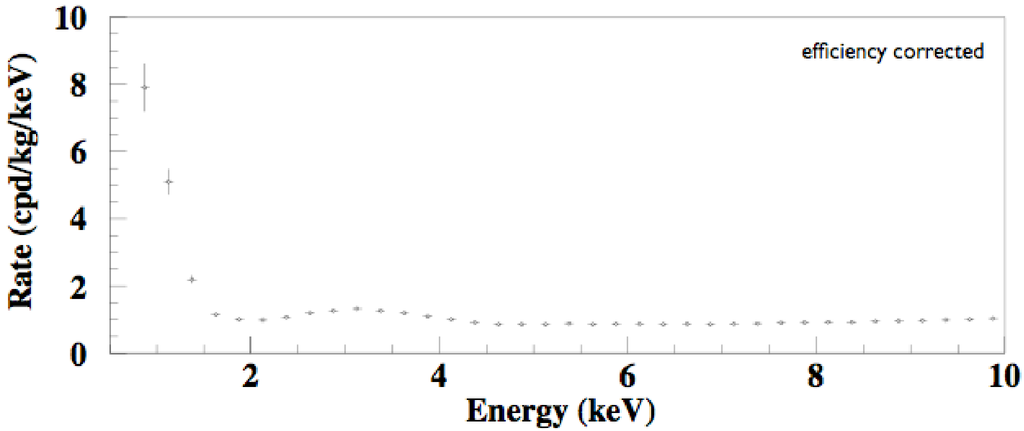
- NaI (Tl): 20 eV to create e^--hole pair, scintillation efficiency ~ 12%
  - ➡ 1 MeV yields 4 x 10^4 photons, with average energy of 3 eV
  - ➡ dominant decay time of the scintillation pulse: 230 ns, λ_{max} = 415 nm

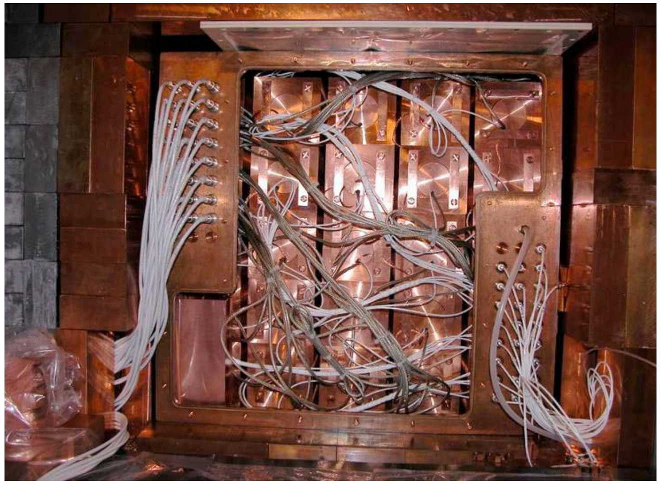
- **No discrimination between electron- and nuclear recoils on event-by-event basis**
- Experiments: **DAMA-LIBRA/Italy,** NAIAD/UK, ANAIS/Spain, **KIMS/Korea**

The DAMA/LIBRA Experiment



- **DAMA:** 9 x 9.7 NaI (Tl) crystals
- BG level: 1-2 events/kg/day/keV
- $E_{threshold} \approx 2keV_{ee} \approx 25\ keV_r$
- **Data period:** 7 annual cycles, until July 2002; 0.29 ton x yr
- **LIBRA:** 25 x 9.7 NaI (Tl) crystals in 5 x 5 matrix
- **Data period:** 4 annual cycles, 0.53 ton x year



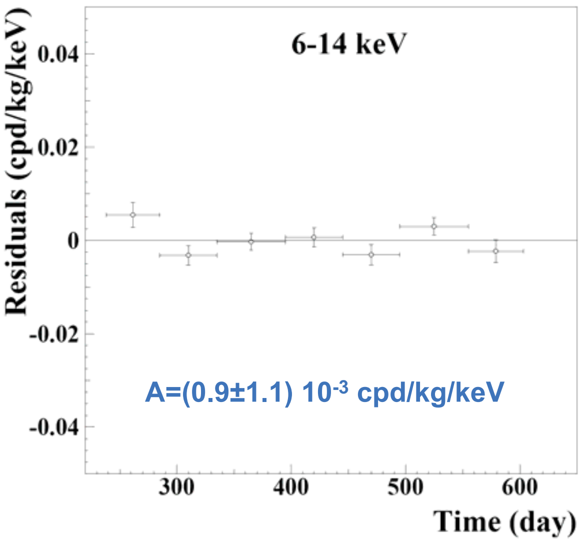


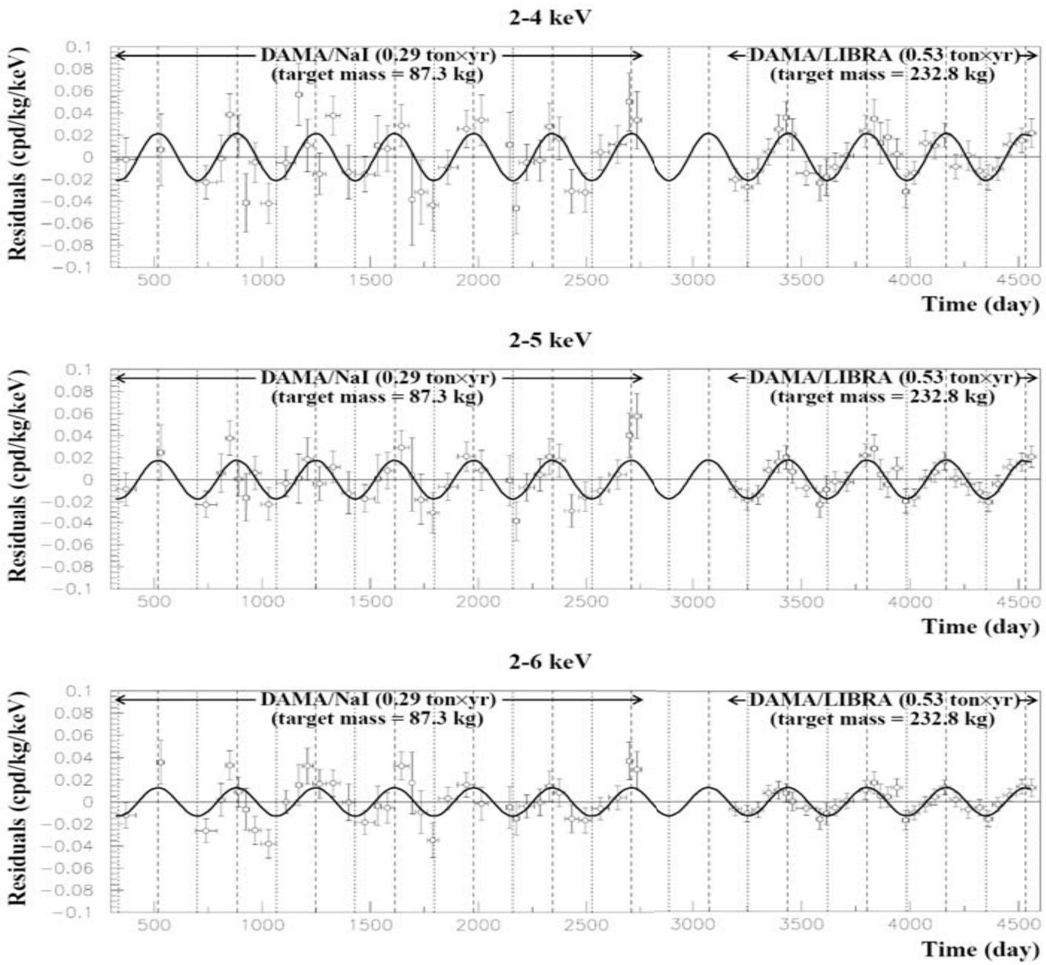
DAMA/LIBRA Results: Evidence for Modulation

- Total exposure: 0.82 ton x year
- **Modulation amplitude:**
- A cos [$\omega(t-t_0)$]

  t_0 = 152.5 d, T = 1 year
- **A = (0.0215 ± 0.0026) cpd/kg/keV**

  (at 8.3 σ CL)
- No modulation above 6 keV



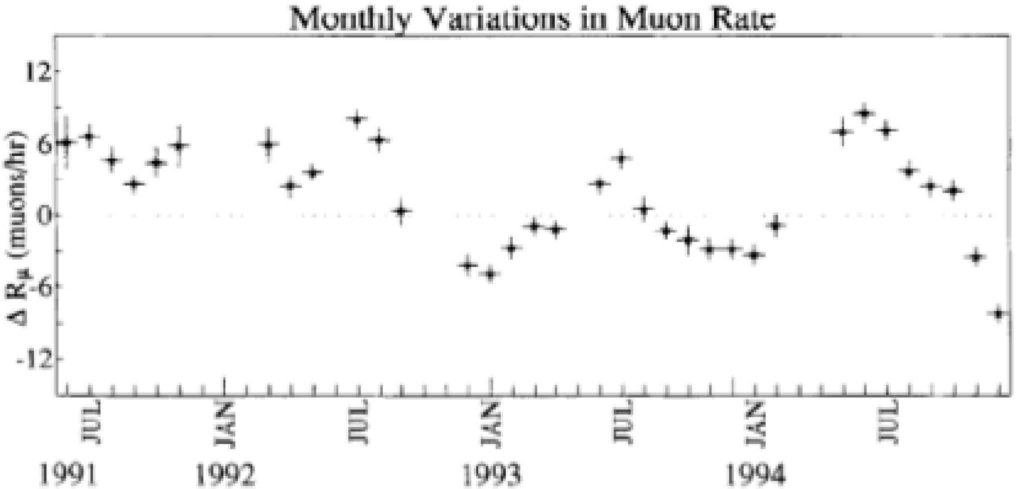


arXiv:0804.2738

arXiv:0804.2741

Annual modulation of muons at LNGS

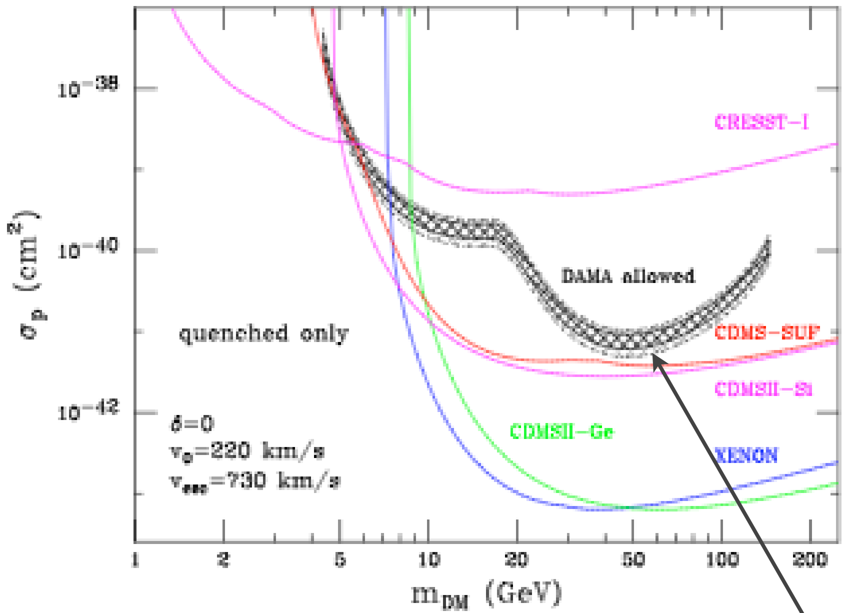
- measured by the MACRO experiment (phase ~ correct, with variations of ~ 1 month)



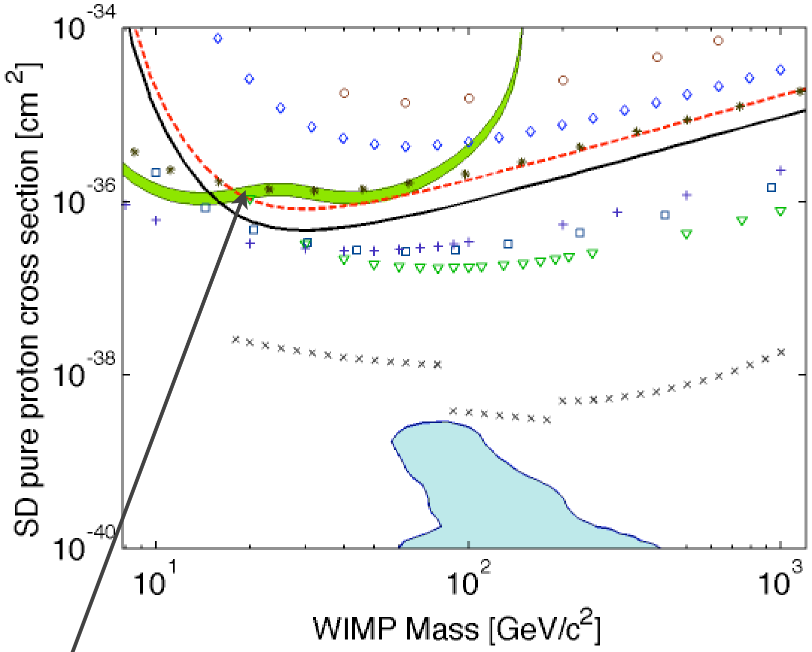
- DAMA: fast, μ-induced n-rate is not sufficiently high to produce observed rate modulation;
- How about metastable isotope production by μ- spallation reactions in NaI? (with $T_{1/2}$ > 500 μs trigger hold-off time, and ~ 3 keV emission) - first estimates show that the effect may be too small considering the 4% modulation measured by MACRO
- Good cross check: measure muon rate versus time in situ (no μ veto, but HE showers)

DAMA Signal and Low WIMP Masses

SI interactions



SD interactions



DAMA allowed region and
upper limits from other experiments for
WIMP interactions

DAMA Signal and a keV Axion

- **One interpretation of DAMA in terms of dark matter:**

➡ pseudoscalar particles χ with keV-like masses

- If these particles couple to electrons similar to axions, their absorption could explain the DAMA signature (see yellow region for allowed parameter space)

- **Axion-like particles with strong couplings $g_{ee\chi}$ to electrons can be emitted from stars, providing additional energy losses**

➡ strong limits from globular cluster stars

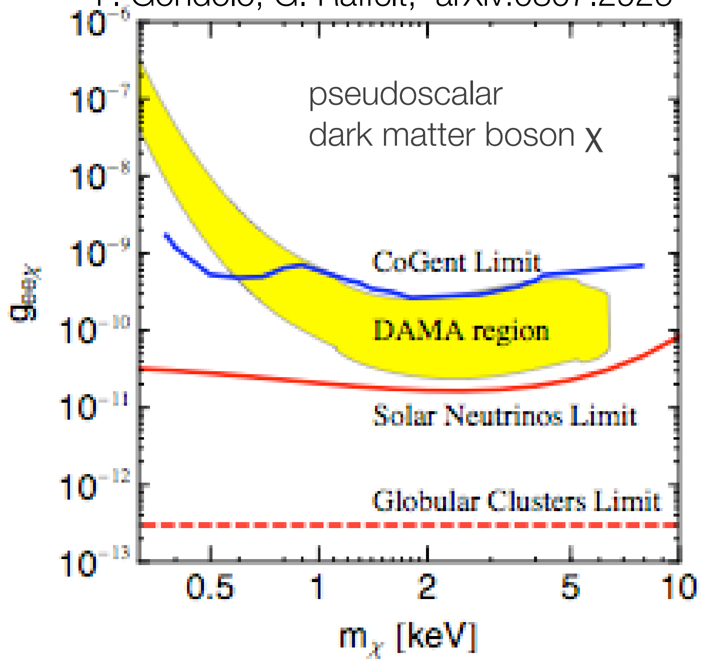
in low-mass red giants, He-ignition would be prevented until the star has reached a higher L than allowed by the observations in GC

➡ new limit from the measured solar ^{8}B neutrinos flux:

the solar emission of axion-like particles would cause the Sun to be hotter, and thus emit a larger neutrino flux

(apart from this, the χ-particles would decay into two photons, thus it is hard for them to be the dark matter)

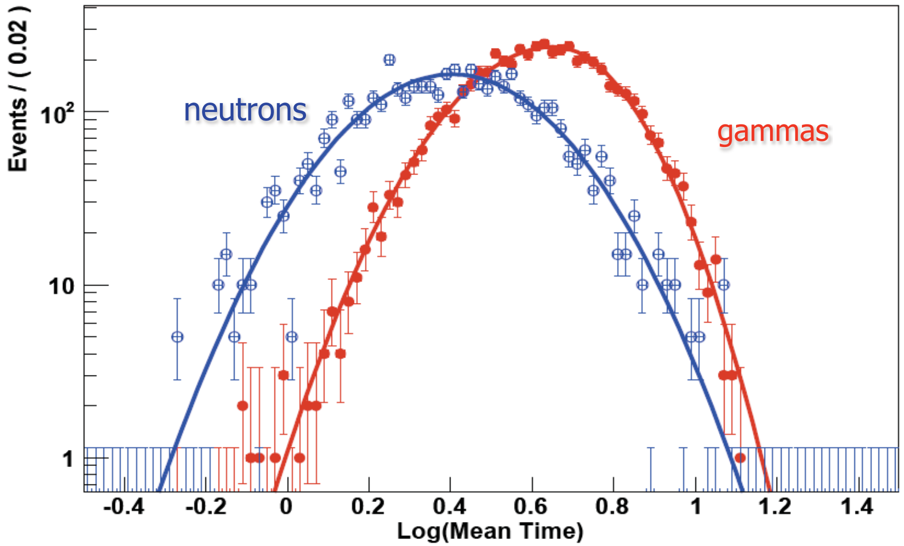
P. Gondolo, G. Raffelt, arXiv:0807.2926

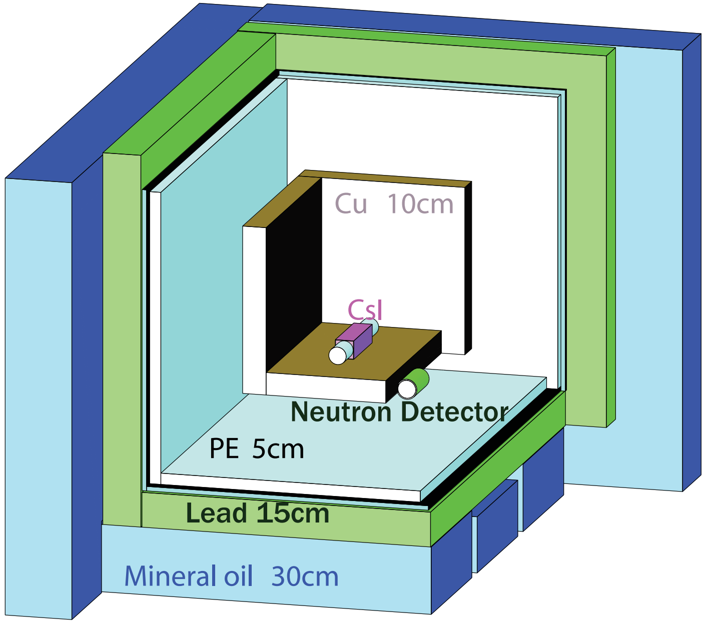


The KIMS Experiment

- At the Yangyang Laboratory in Korea (2000 mwe)
- CsI (Tl) light yield: 5×10^4 photons/keV
- peak emission at 550 nm, decay time ~ 1050 ns
- QF = 8-15% between 10-100 keVe

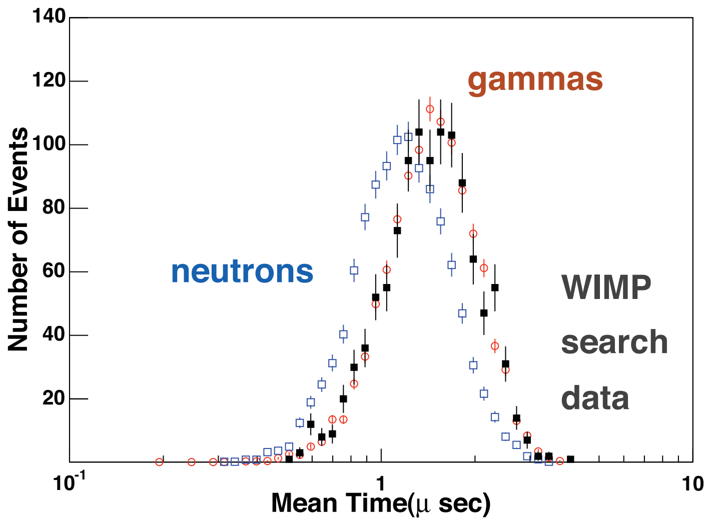
- Background reduction by pulse shape discrimination

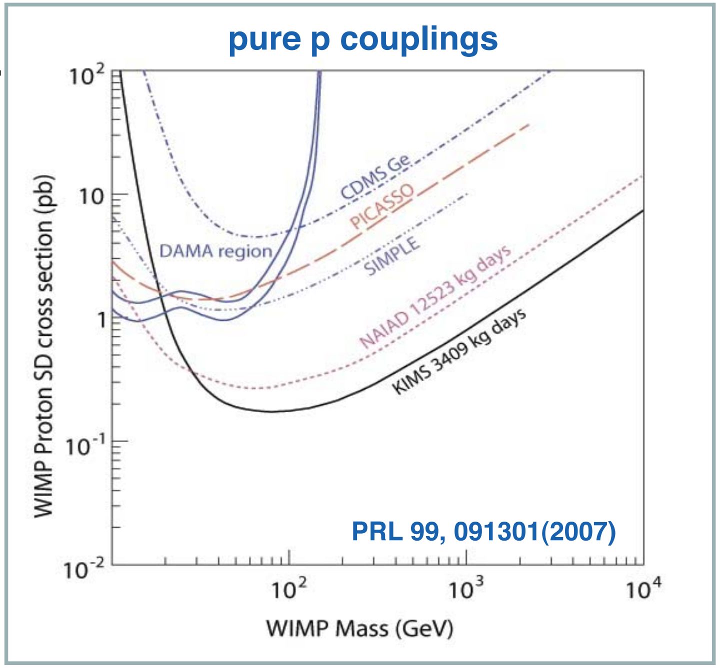




The KIMS Experiment

- **4 x 8.7 kg CsI(Tl) crystals had been operated for 3407 kg yr**
- each crystal is viewed by 2 low-BG quartz window PMTs
- with RbCs photocathode (5.5 pe/KeV)
- results: best SD limit for pure WIMP-p couplings

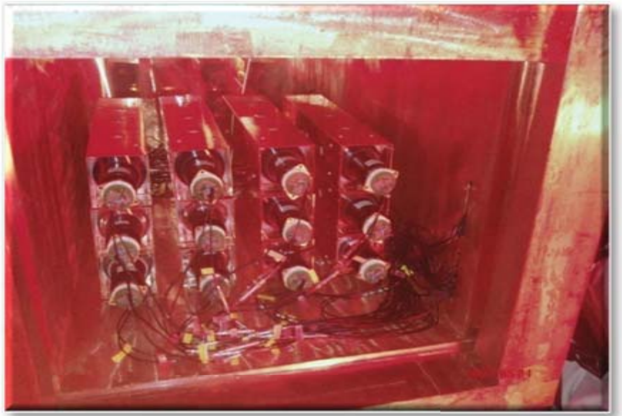




Current status:

12 detectors (104.4 kg) installed
- muon veto (liquid scintillator+56 PMTs)
- optimization runs finished (background rate ~ 1 event/(kg keV d)

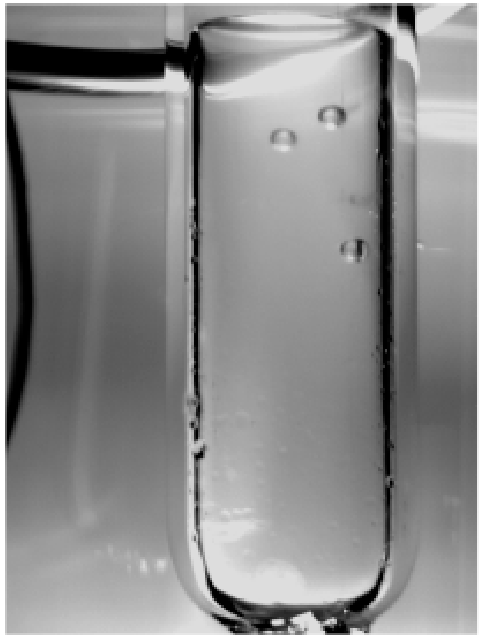
stable operation in progress!
-> probe the DAMA modulation signal
-> study annual modulation of muon associated events



Bubble Chambers as WIMP Detectors

- Principle: detect single bubbles induced by high dE/dx nuclear recoils in heavy liquid bubble chambers (with acoustic, visual or motion detectors)

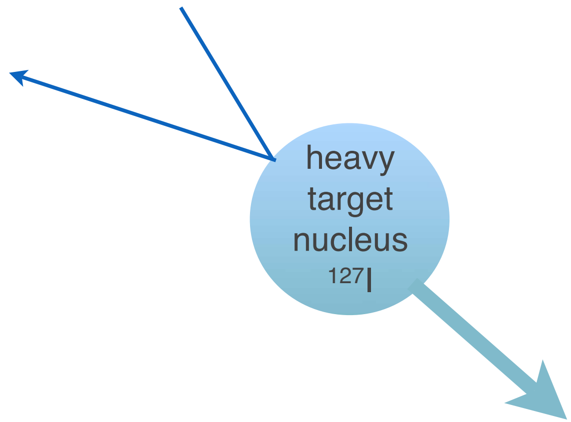
COUPP



n-induced event (multiple scatter)

WIMP: single scatter

WIMP



nuclear recoil
E = 1- 100 keV

Recoil range $\ll 1\ \mu$m in a liquid - very high dE/dx

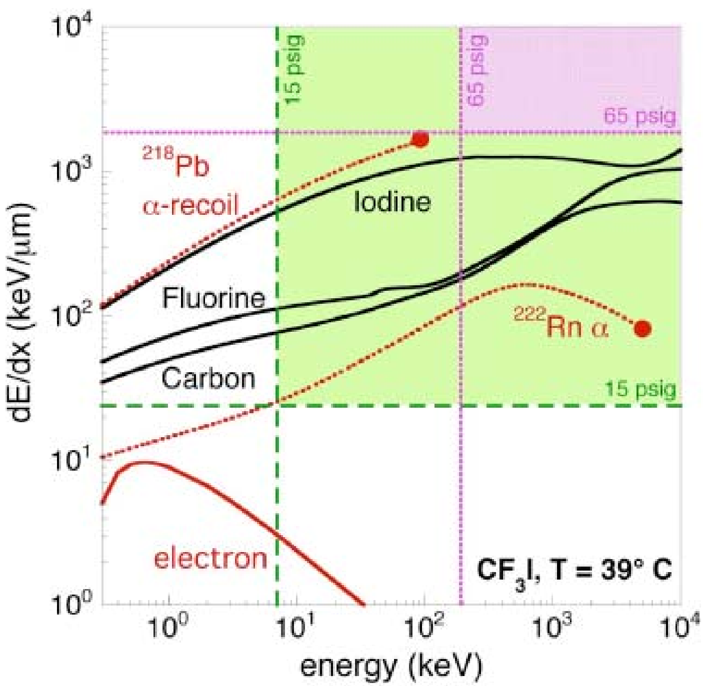
Bubble Chambers as WIMP Detectors

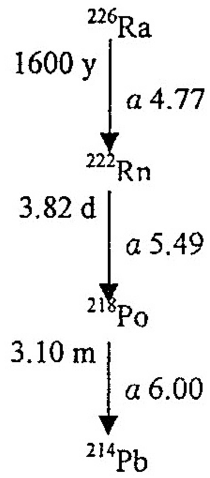
- Advantages
  - ➡ large 'rejection factor' for MIPs (> 10^{10}): in fact 'blind' to these type of particles
  - ➡ can be easily scaled to large masses
  - ➡ nuclei with and without spin => sensitivity to SD and SI interactions
  - ➡ CF_3I, CF_3Br, C_4F_{10} etc
  - ➡ high spatial granularity (reject neutrons -> multiple interactions)
  - ➡ low costs and room temperature operation

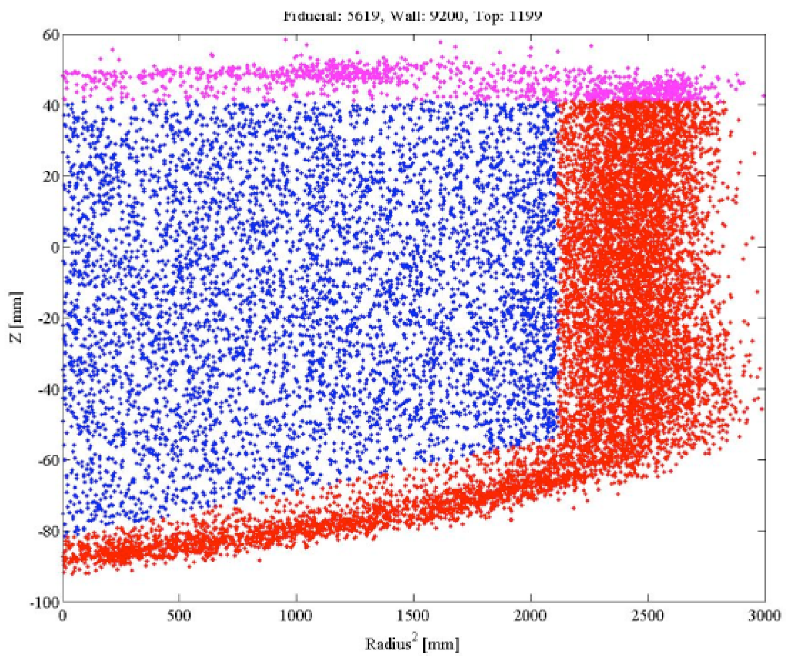
- Challenge: reduce α-emitters in fluids to acceptable levels

The COUPP Experiment

- Located at the NuMI tunnel (300 mwe) at Fermilab
- 2 kg detector operated in 2006
- α background from walls; ^{222}Rn decays -> ^{210}Pb plate-out



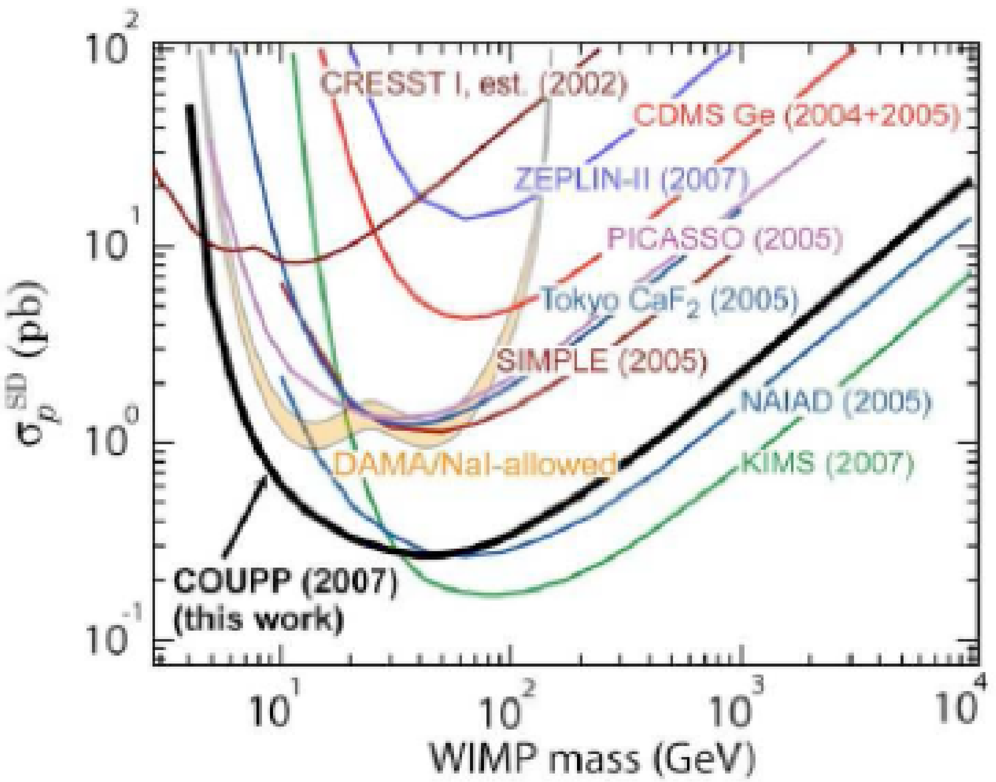




The COUPP Experiment

- current status: larger, low-BG 80 kg module in construction; goal is 3 x 10^{-8} pb
- so far best SD limit for **pure proton couplings at low WIMP masses**

Behnke, Collar et al. Science 319, 15 February 2008, p. 933-936



Cryogenic Experiments

- Principle: phonon (quanta of lattice vibrations) mediated detectors
- **Motivation:** increase the energy resolution + detect smaller energy depositions (lower the threshold); use a variety of absorber materials (not just Ge and Si)
- Remember the energy resolution of a semiconductor detector (N = nr. of e^--h excitations)

$$W_{stat} = 2.35\sqrt{F\varepsilon E} \qquad \left[\frac{\sigma(E)}{E} = \sqrt{\frac{F}{N}} = \sqrt{\frac{F\varepsilon}{E}} \qquad W_{stat} = 2.35\sigma(E)\right]$$

- In Si: ε = 3.6 eV/e^--h pair (band gap is 1.2 eV)
- Max phonon energy in Si: 60 meV
  - ➡ **many more phonons are created than e^--h pairs!**
- For dark matter searches:
  - ➡ **thermal phonon detectors (measure an increase in temperature)**
  - ➡ **athermal phonon detectors (detect fast, non-equilibrium phonons)**
- Detector made from superconductors: the superconducting energy gap 2Δ~ 1 meV
  - ➡ binding energy of a Cooper pair (equiv. of band gap in semiconductors); 2 quasi-particles for every unbound Cooper pair; these can be detected

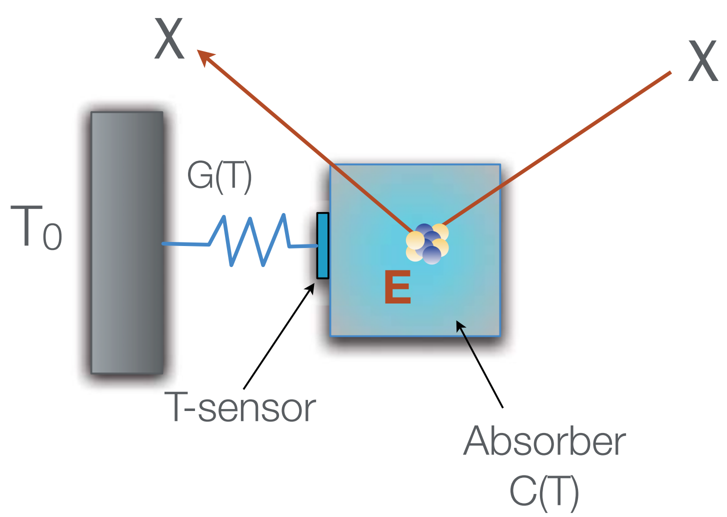
Basic Principles of mK Cryogenic Detectors

- A deposited energy E will produce a temperature rise ΔT given by:

$$\Delta T = \frac{E}{C(T)} e^{-\frac{t}{\tau}}, \qquad \tau = \frac{C(T)}{G(T)}$$

C(T) = heat capacity of absorber

G(T)=thermal conductance of the link between the absorber and the reservoir at temperature T_0



Normal metals: the electronic part of C(T) ~ T, and dominates the heat capacity at low temperatures

Superconductors: the electronic part is proportional to exp($-T_c/T$)

T_c = superconducting transition temperature and is negligible compared to lattice contributions for $T \ll T_c$

Basic Principles of mK Cryogenic Detectors

- For pure dielectric crystals and superconductors at $T \ll T_c$, the heat capacity is given by:

$$C(T) \sim \frac{m}{M}\left(\frac{T}{\Theta_D}\right)^3 JK^{-1}$$

m = absorber mass

M = molecular weight of absorber

Θ_D = Debye temperature

➡ the lower the T, the larger the ΔT per unit of absorbed energy

➡ in thermal detectors E is measured as the temperature rise ΔT

- **Example:** at T = 10 mK, a 1 keV energy deposition in a 100 g detectors increases the temperature by:

$$\Delta T \approx 1\ \mu K$$

- this can be measured!

Thermal Detectors

- Ideal case of a perfect calorimeter: all the energy is converted into heat and the T-rise is measured
- But: a fraction of the energy goes into metastable electronic states and into the breaking of Cooper pairs (for SC), creating electronic excitations called quasiparticles, which will not all recombine on the timescale to be measured as a thermal pulse. In dielectrics: the phonons are far from equilibrium and must first decay to lower energy phonons and become thermalized.
- For a finite **thermalization time τ_{th}**, the time behavior of the thermal pulse is given by:

$$T(t) = T_0 + \frac{E}{C(T)} \frac{\tau}{\tau - \tau_{th}} \left[e^{-t/\tau} - e^{-t/\tau_{th}} \right] \qquad \tau = \frac{C(T)}{G(T)}$$

- **Rise time:** in general μs (limited by detector physics)
- **Decay time:** several ms => < few Hz counting rates for thermal detectors

Thermal Detectors

- The intrinsic energy resolution (as FWHM) of such a calorimeter is given by:

$$W \approx 2.35\sqrt{k_B T^2 C(T)}$$

$$\frac{C(T)}{k_B} = \text{ number of phonon modes}$$

$$k_B T = \text{ mean energy per mode}$$

- **Theoretical expectations:**
  - ➡ a 1 kg Ge crystal operated at 10 mK could achieve an energy resolution of about 10 eV => **two orders of magnitude better than Ge ionization detectors**
  - ➡ a 1 mg of Si at 50 mK could achieve an energy resolution of 1 eV => **two orders of magnitude better than conventional Si detectors**

Temperature Sensors

- **semiconductor thermistor**: a highly doped **semiconducto**r such that the resistance R is strong function of temperature (NTD = neutron-transmutation-doped Ge - uniformly dope the crystal by neutron irradiation)
- **superconduction (SC) transition sensor (TES/SPT):** thin film of **superconductor** biased near the middle of its normal/SC transition

- For both NTDs and TESs/SPTs, **an energy deposition produces a change in the electrical resistance R(T)**. The response can be expressed in terms of the logarithmic sensitivity:

$$\alpha \equiv \frac{d \log(R(T))}{d \log(T)}$$

Typical values:

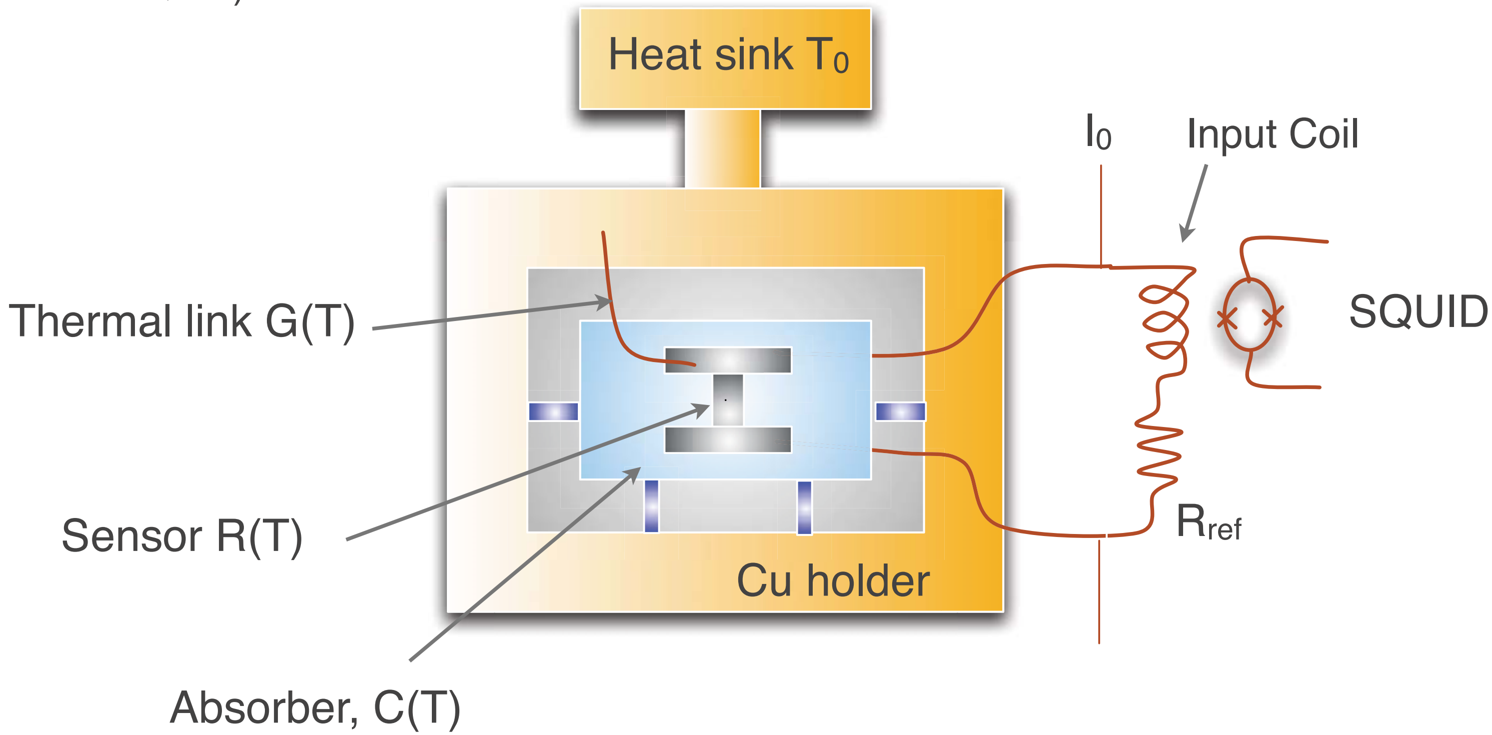
α = -10 to -1 for semiconductor thermistors
$\alpha \sim +10^3$ for TES/SPT devices

→ it is clear that the sensitivity of TES/SPTs can be extremely high (depending on the width of the SC/normal transition)

→ but the temperature of the detector system must be kept very stable

Example: Thermal Detector with SPT-sensor

- The change of resistance due to a particle interaction in the absorber is detected by a superconducting quantum interference device (SQUID) (by the change in current induced in the input coil of the SQUID)



- Thermal detectors: slow -> ms for the phonons to relax to a thermal distribution
- TES can be used to detect fast, athermal phonons -> how are these kept stable?

TES with Electrothermal-Feedback

- $T_0 << T_C$: substrate is cooled well below the SC transition temperature T_C

- **A voltage V_B is placed across the film (TES)**

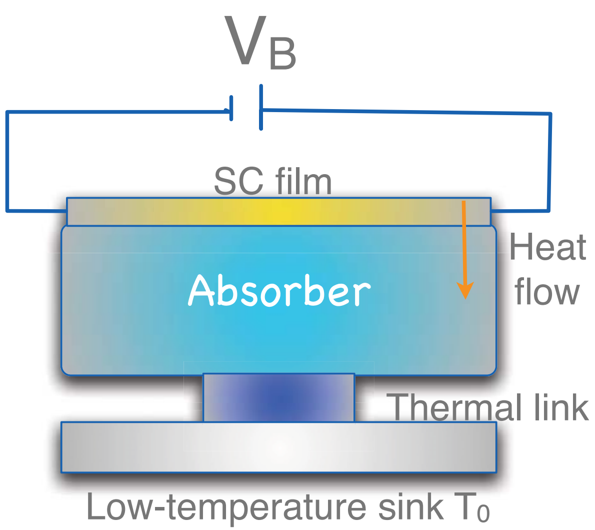
  and equilibrium is reached when ohmic heating of the TES by its bias current is balanced by the heat flow into the absorber

  When an excitation reaches the TES

  → the resistance R increases

  → the current decreases by ΔI

  ⇒ this results in a reduction in the Joule heating



The feedback signal = the change in Joule power heating the film $P=IV_B=V_B^2/R$

The energy deposited is then given by:

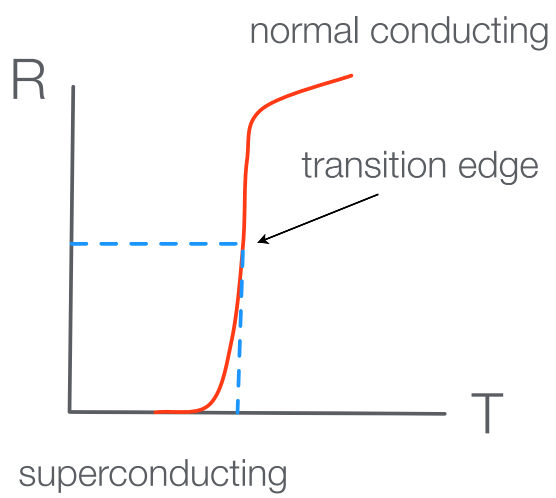
$$E = -V_B \int \Delta I(t)\mathrm{d}t$$

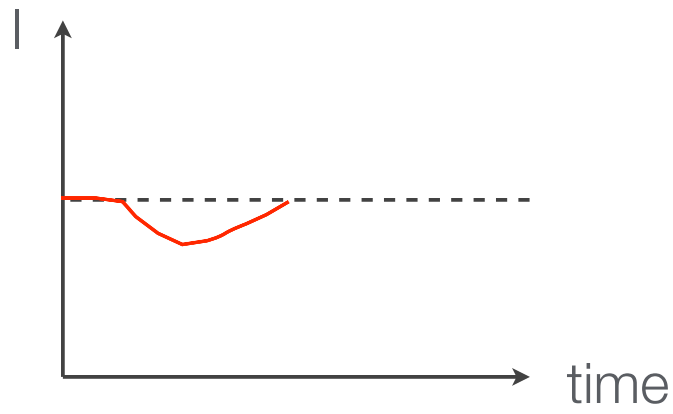
=> the device is self-calibrating

TES with Electrothermal-Feedback

- By choosing the voltage V_B and the film resistivity properly

  => one achieves a stable operating T on the steep portion of the transition edge



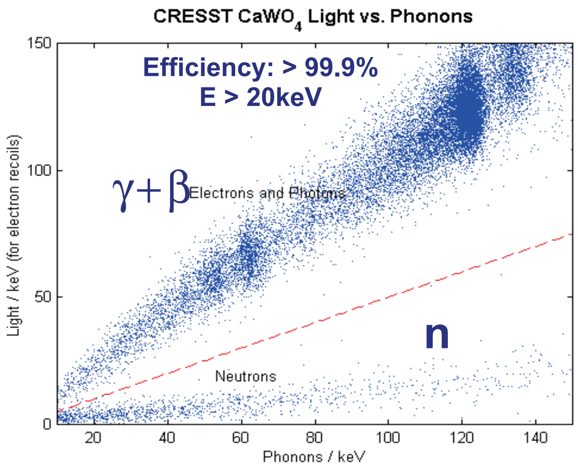


ET-feedback: leads to a thermal response time 10^2 faster than the thermal relaxation time
+ a large variety of absorbers can be used with the TES

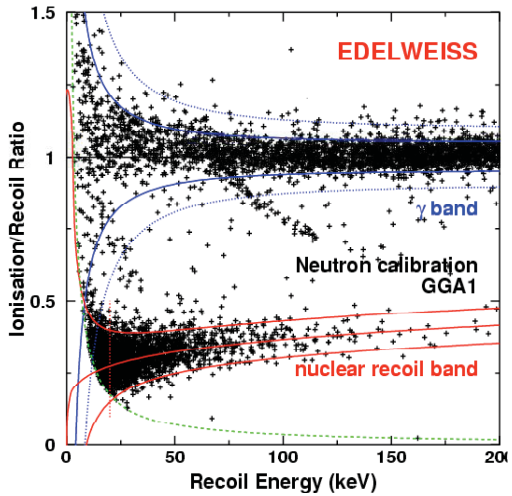
Cryogenic Experiments at mK Temperatures

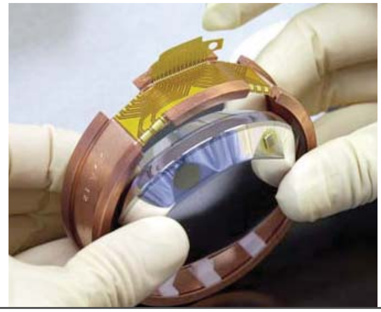
- **Advantages**: high sensitivity to nuclear recoils
  - measuring the full nuclear recoil energy in the phonon channel
  - low energy threshold (keV to sub-keV), good energy resolution
  - light/phonon and charge/phonon: nuclear vs. electron recoil discrimination

CRESST at LNGS

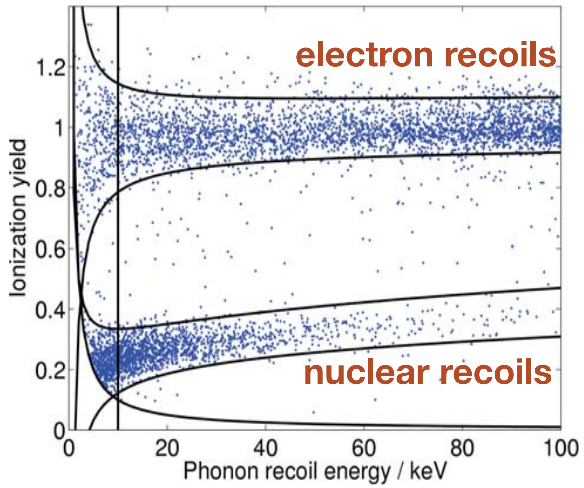


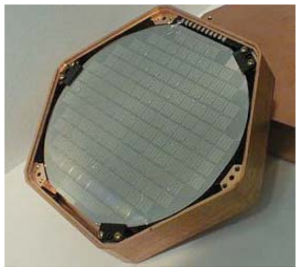
EDELWEISS at LSM





CDMS at Soudan

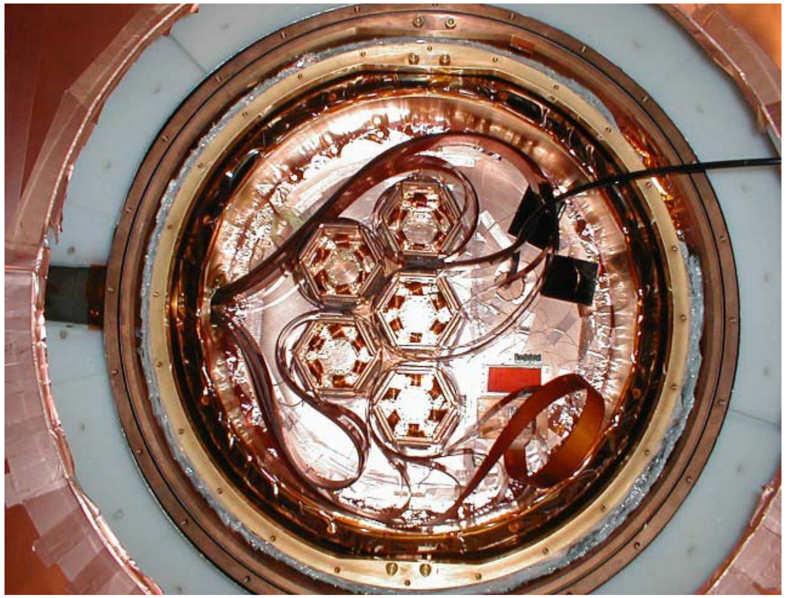




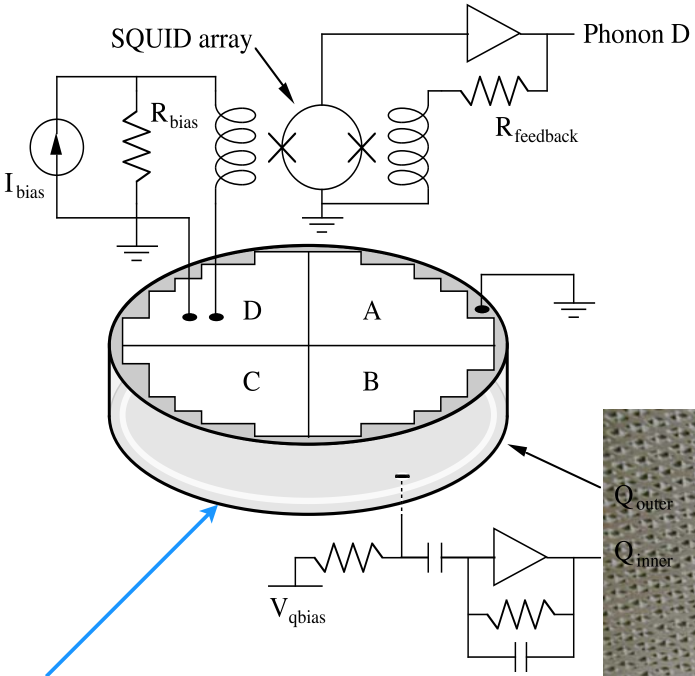
The CDMS Experiment at the Soudan Mine

At the Soudan Lab in Minnesota:
neutron background reduced from
1/kg/day → 1/kg/year

5 towers a 6 Ge/Si detectors
in the 'icebox' at ≈ 20 mK



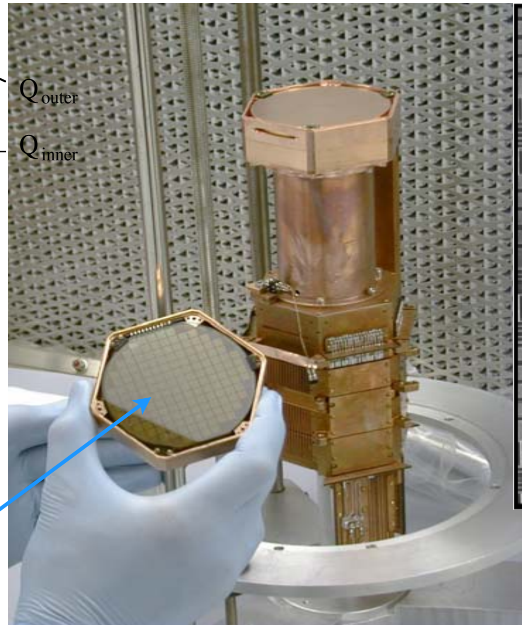
CDMS Detectors

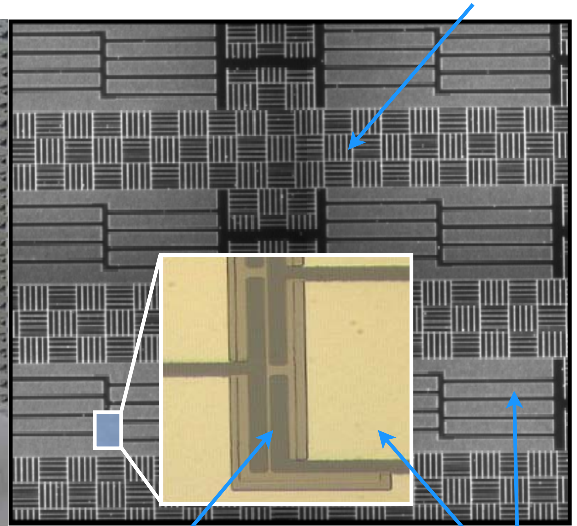


Absorber:
250 g Ge or 100 g Si crystals
1 cm thick x 7.5 cm diameter

T-sensors:
photolithographically patterned thin films of Al +W, collecting athermal phonons

passive tungsten grid





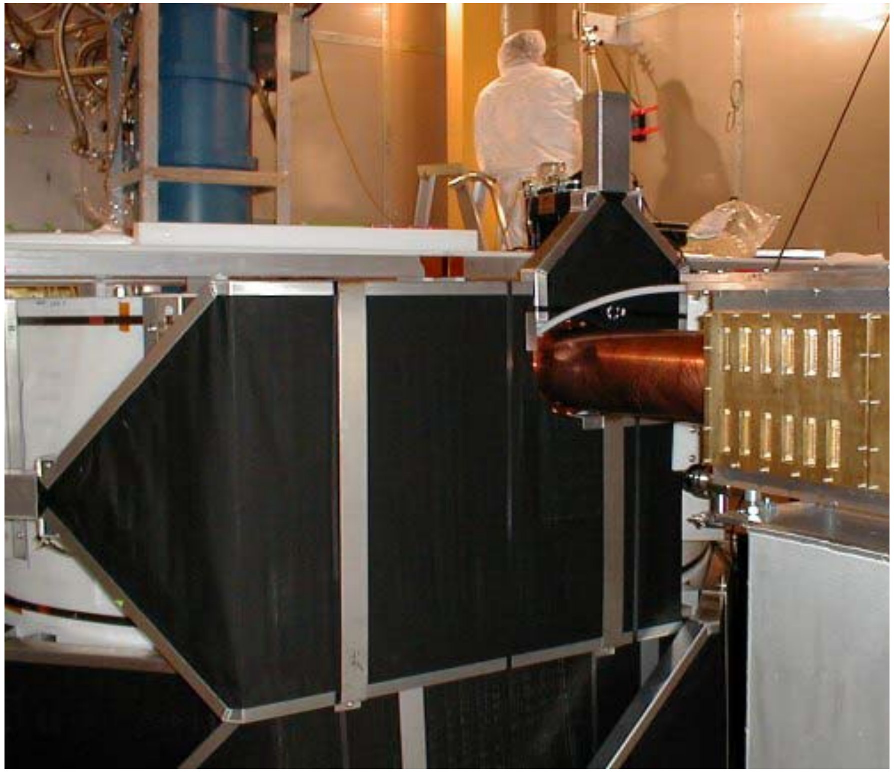
2 charge electrodes:
inner (Q_{inner}) disk shaped
outer (Q_{outer}) ring-like
drift e$^-$-h in E-field: **3 V/cm**

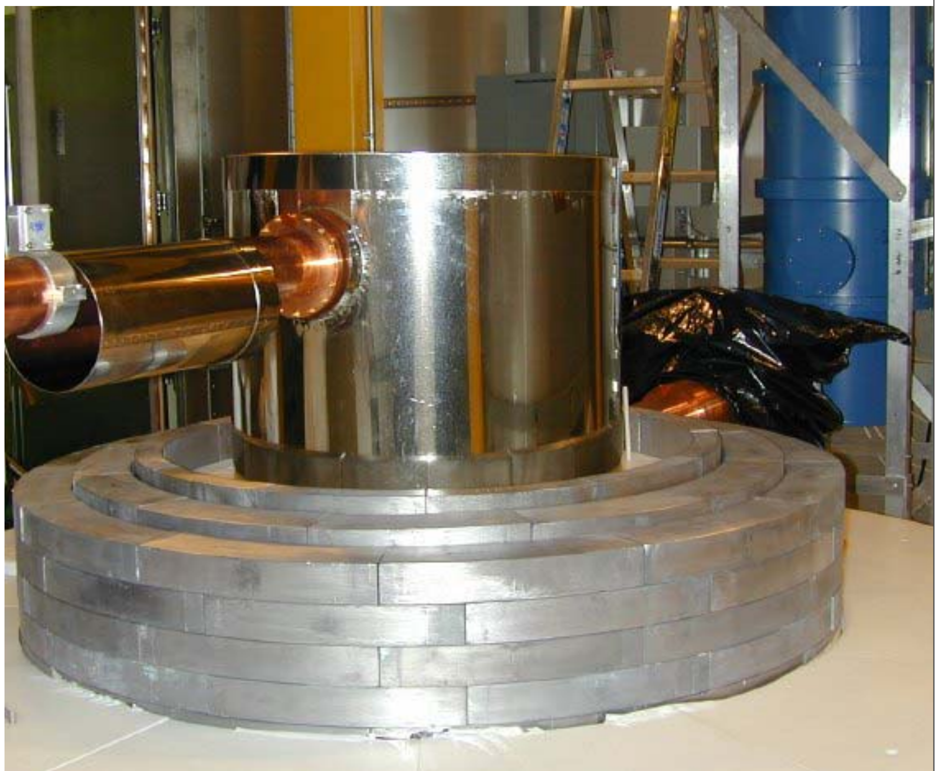
4144 QETs
(4x1036)

250 µm x 1 µm W
(35 nm thick)

380 µm x 55 µm Al
fins (300 nm thick)

CDMS Active and Passive Shields at Soudan



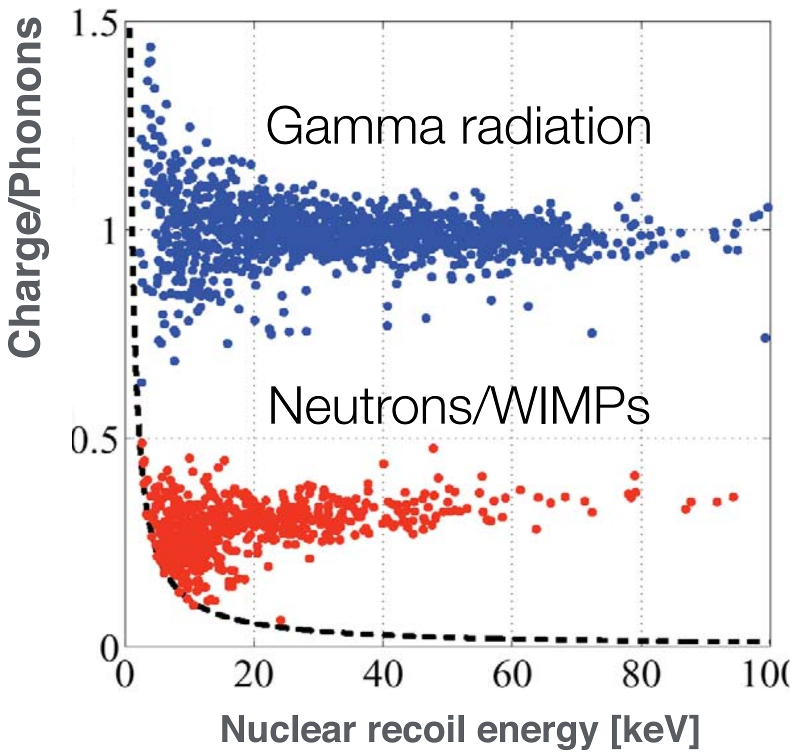


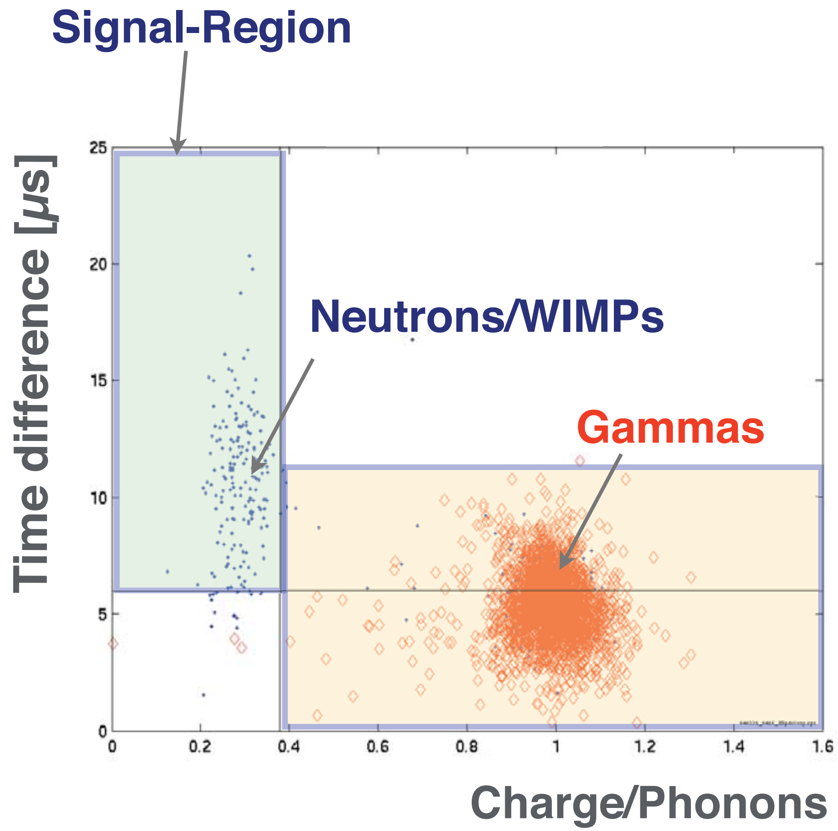
40 × 5 cm thick scintillator panels
read out by 2'' Hamamatsu PMTs
> 99.9% efficiency for through-going μ's
rate ≈ 1 muon/minute

40 cm outer polyethylene
22.5 cm lead
10 cm inner polyethylene
3 cm of copper (Σ_{cans})

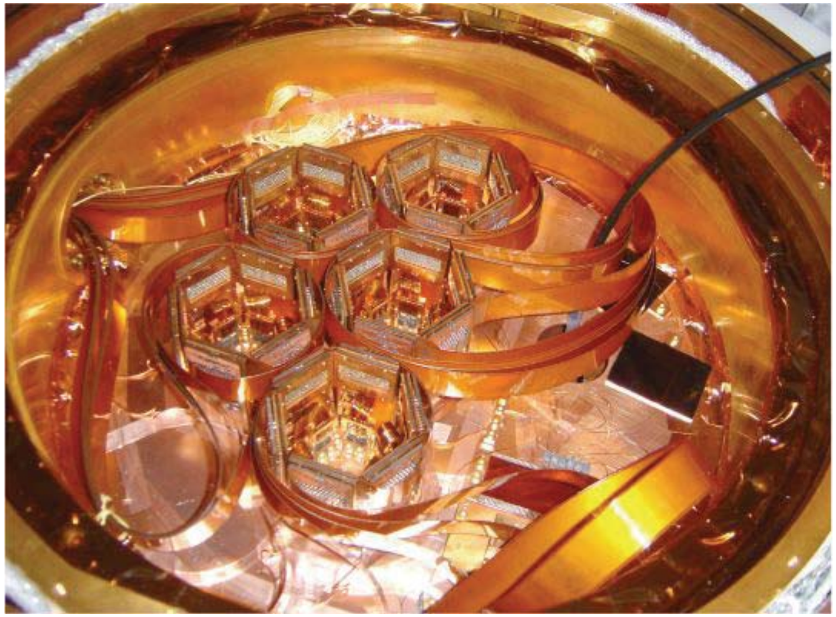
CDMS: Signal versus Background

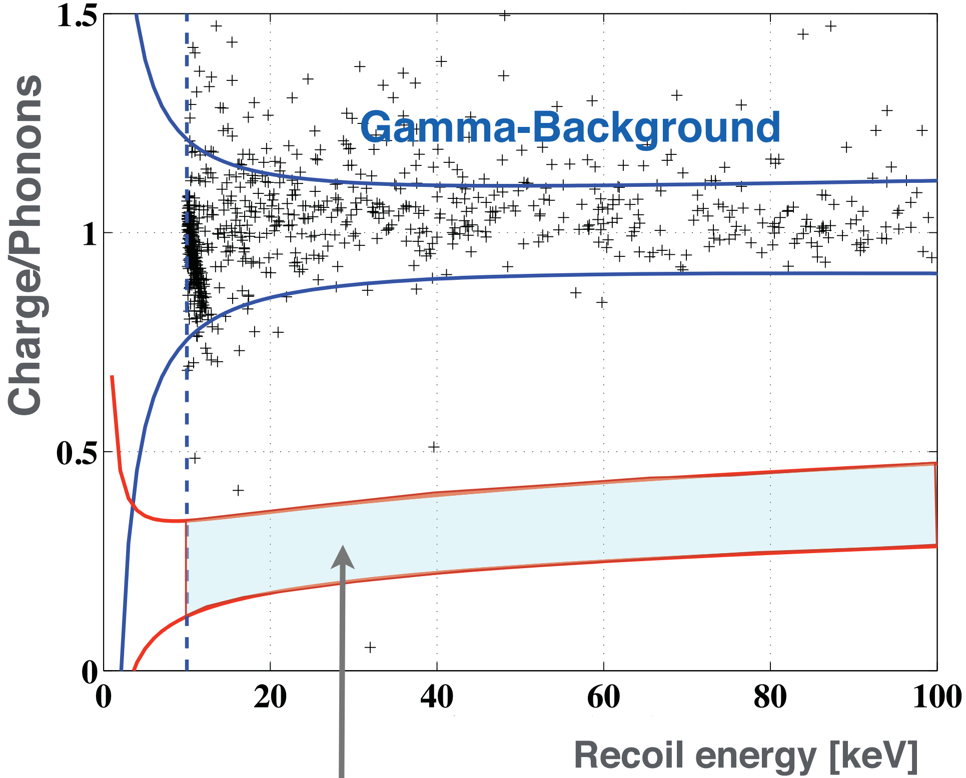
- Ratio of the charge/phonon-signal and time difference between charge and phonon signals => distinguish signal (WIMPs) from background of electromagnetic origin





CDMS WIMP Search Runs





Since October 2006:

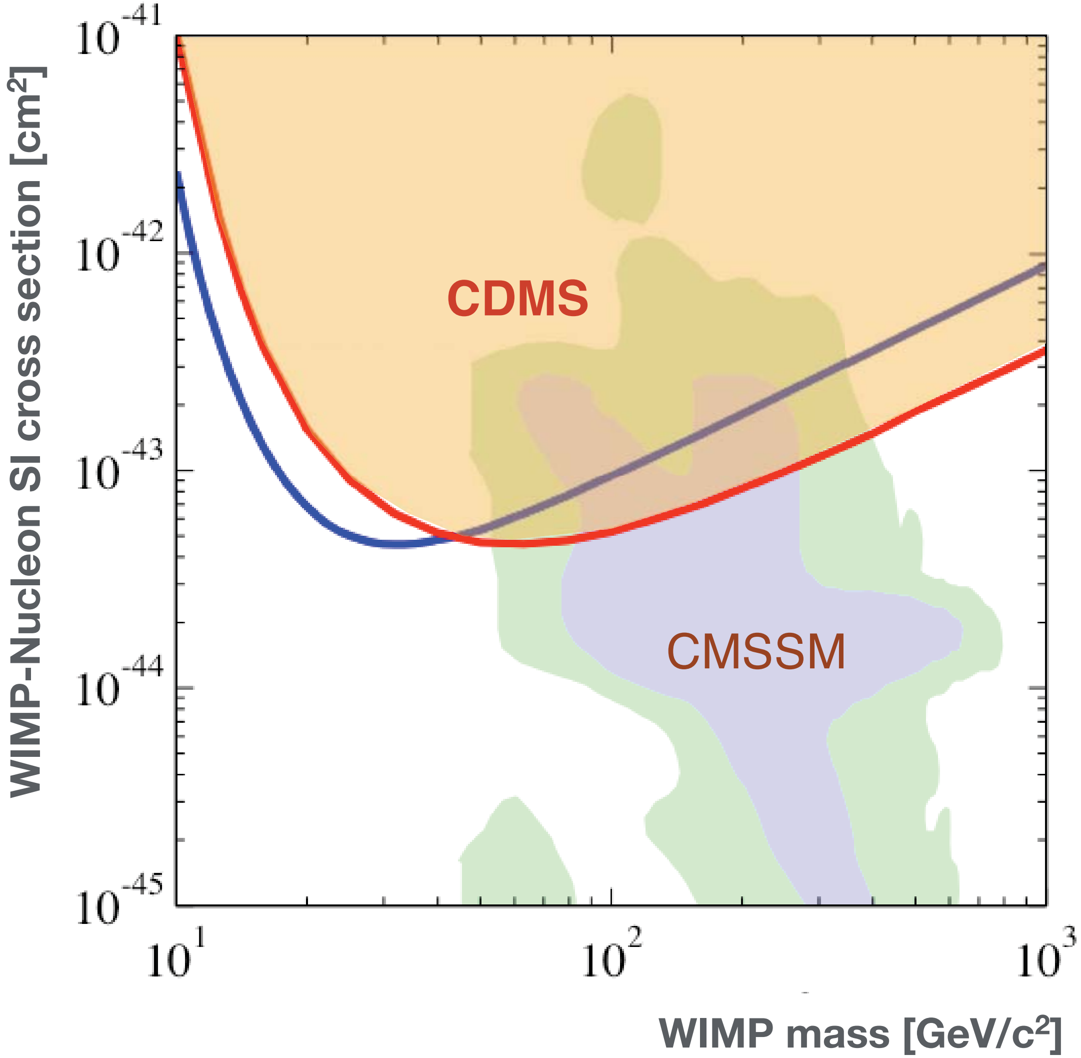
Run 123: 430 kg d Ge
Run 124: 224 kg d Ge
} Data analyzed

Run 125: 465 kg d Ge

Run 126: 17 Jan 08 - ongoing

No WIMP events in the signal region (defined *a priori,* in 'blind' mode, based on calibration and multiple-events data)

CDMS Results for Spin Independent Interactions



Upper limits on WIMP-nucleon cross sections

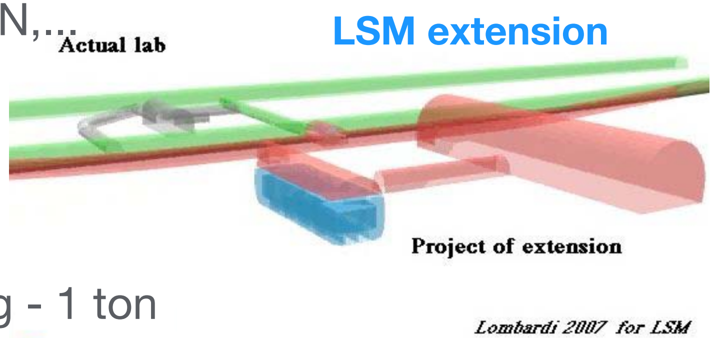
4.0×10^{-44} cm^2

(WIMP mass M_W = 100 GeV)

arXiv: 0802.3530v2

Future mK Cryogenic Dark Matter Experiments

- **EURECA (European Underground Rare Event Calorimeter Array)**
- Joint effort: CRESST, EDELWEISS, ROSEBUD, CERN,...
- Mass: 100 kg - 1 ton, multi-target approach



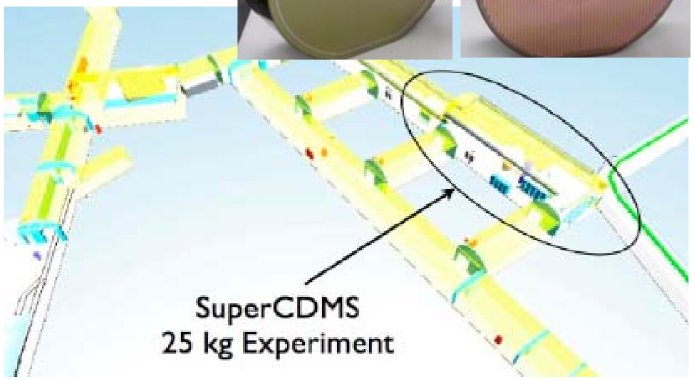
- **SuperCDMS (US/Canada):** 3 phases 25 kg - 150 kg - 1 ton
- 640 g Ge detectors with improved phonon sensors
- 4 prototype detectors built and tested

R&D for SuperCDMS:

1” thick **SuperZIPs** (0.64 kg)

2 SuperTowers at Soudan

7 SuperTowers at SNOLAB



End

The CDMS Phonon Signal

Particle interaction ⇒ THz (~ 4 meV) phonons

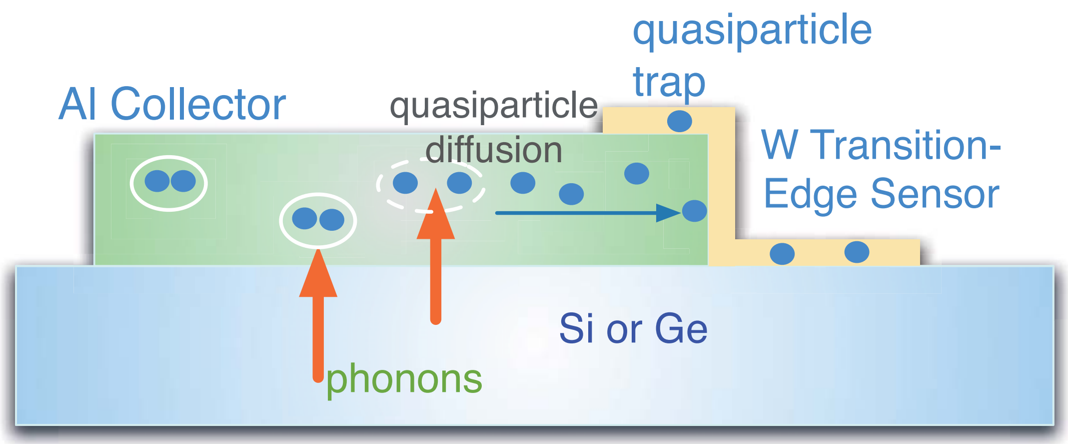
Phonons: propagate to SC Al-fins on the surface, break Cooper pairs ⇒ **quasiparticles**

Quasiparticles: diffuse in 10 μs through the Al-fins and are trapped in the W-TES ⇒ release their binding energy to the W electrons

The electron system T is raised⇒ increased R

The TES is voltage biased and operated in the ETFB-mode

Current change is measured by SQUIDs



The CDMS Charge Signal

Interaction: breaks up the e⁻-hole pairs in the crystal, separated by E-field
=> Charge is collected by electrodes on the surface of the crystal

Two charge channels:

disk in the center (≈85% of surface) + ring at the edge of the crystal surface

Events within few µm of the surface: deficit charge collection (“dead layer”)