Dark Matter
Lecture 3: Direct detection techniques and experiments

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BND Graduate School, Rathen, Germany

Laura Baudis, Universität Zürich

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- **Cryogenic experiments at mK temperatures**

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  Principles

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  Near future projects

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- **Room Temperature scintillators**

  Principles

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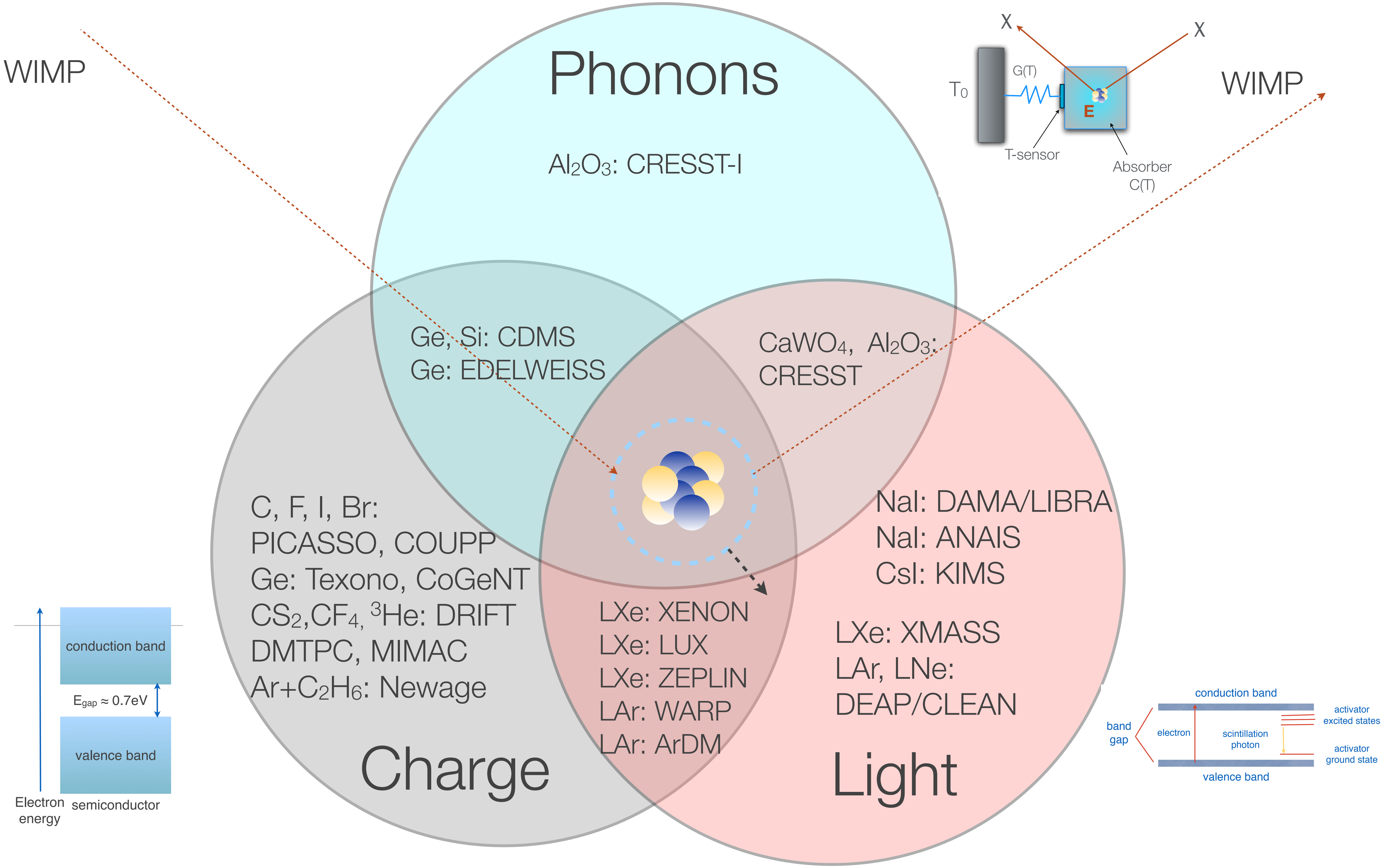
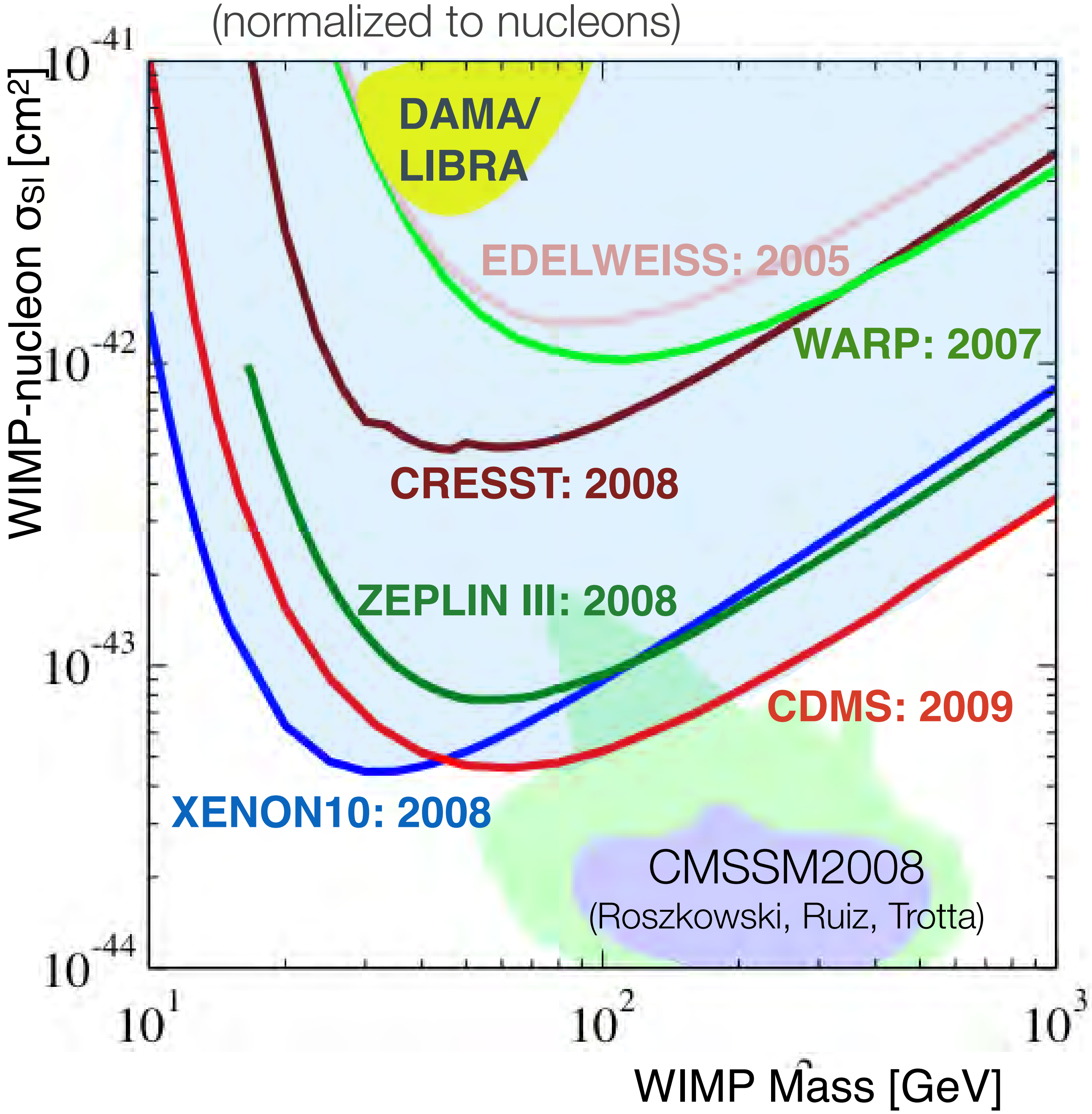
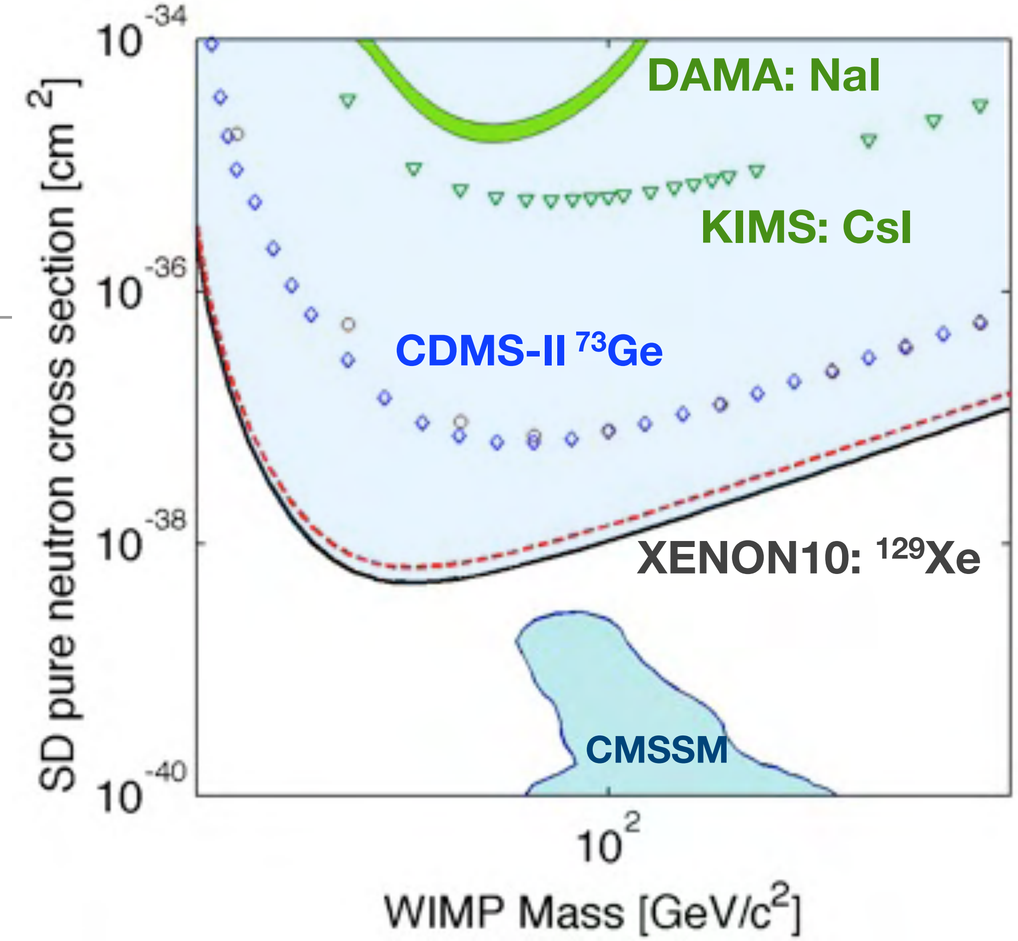
Direct Detection Techniques

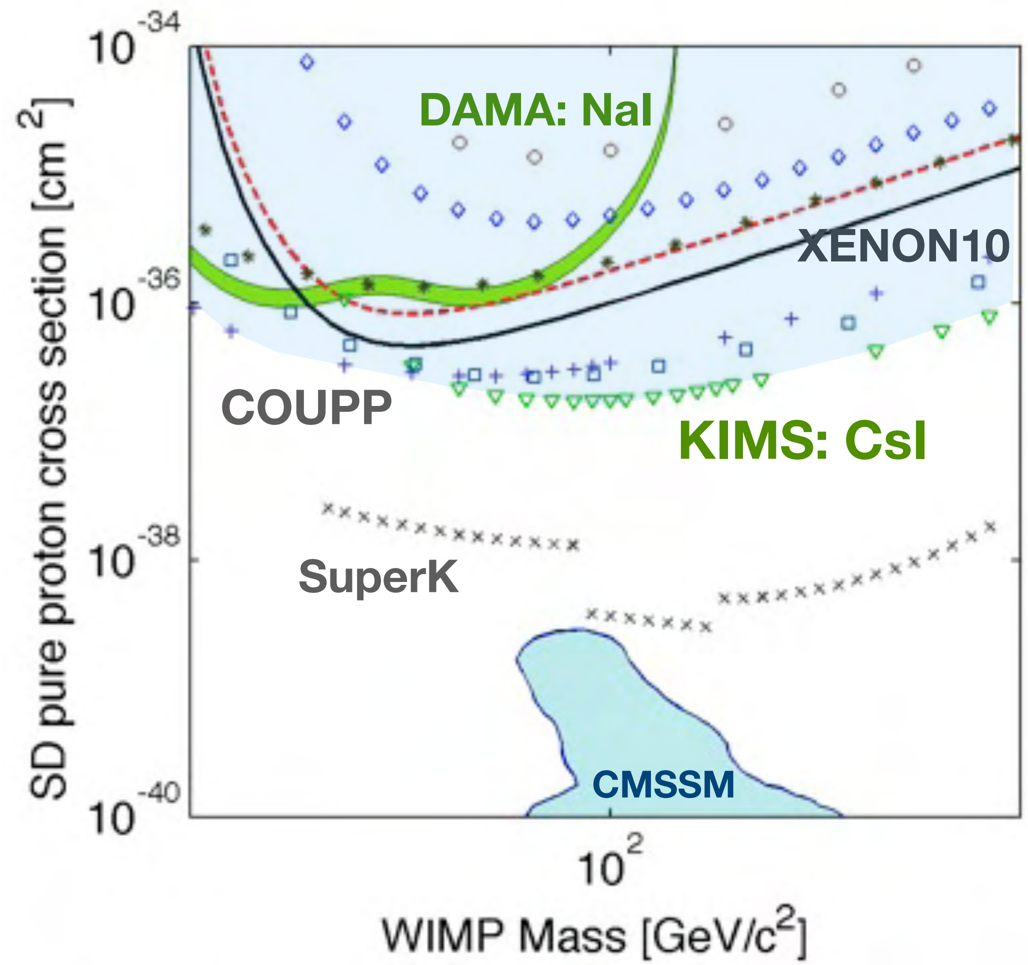


Experimental Results

Spin-independent cross section
(normalized to nucleons)







Spin-dependent

Vanilla Exclusion Plot

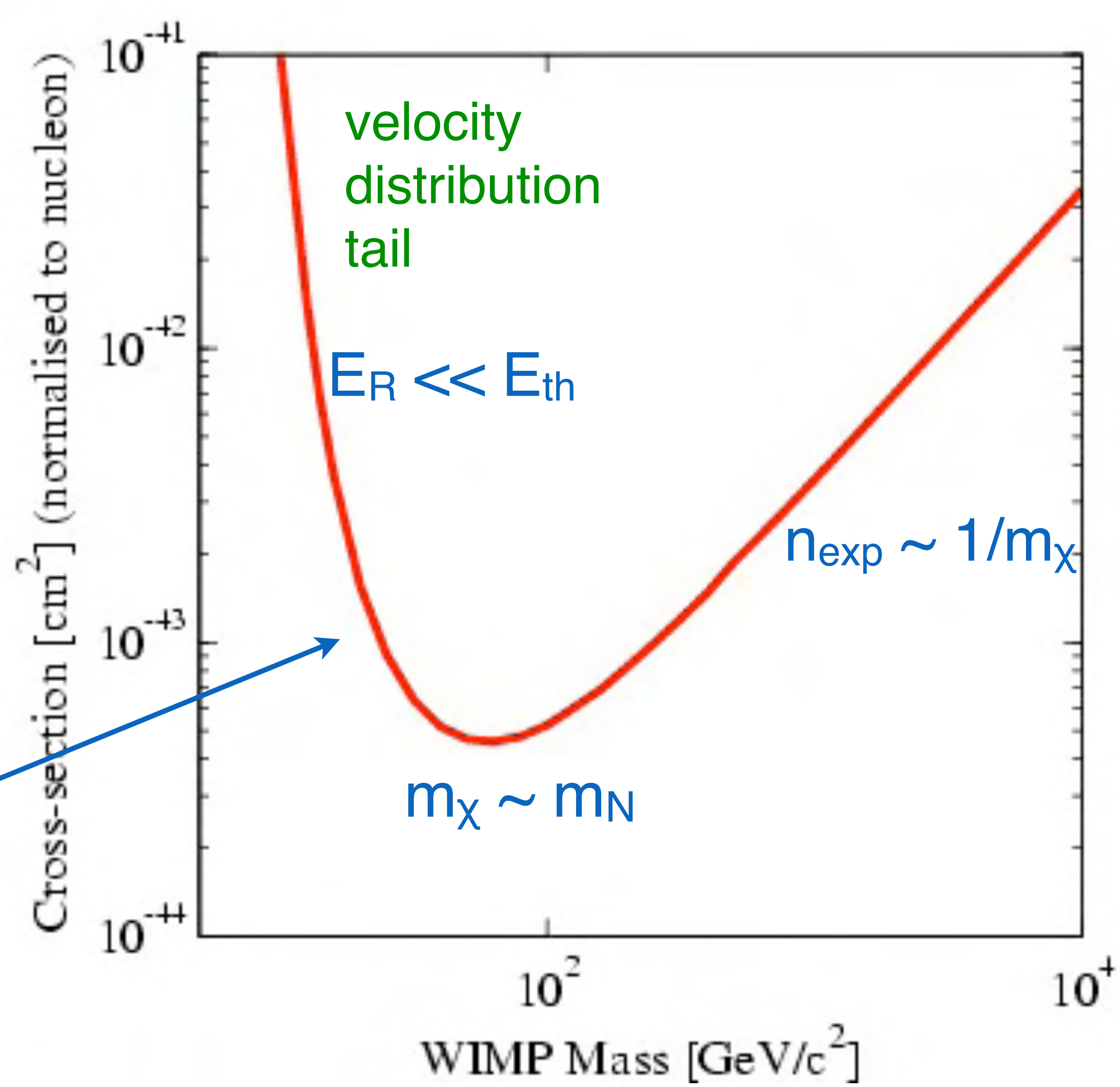
- **Assume we have detector of mass M, taking data for a period of time T**
- The total exposure will be **ε = M × T [kg days]**; nuclear recoils are detected above an energy threshold E_{th}, up to a chosen energy E_{max}. The **expected number of events n_{exp}** will be:

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

⇒ cross sections for which $n_{exp} \geq 1$ can be probed by the experiment

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

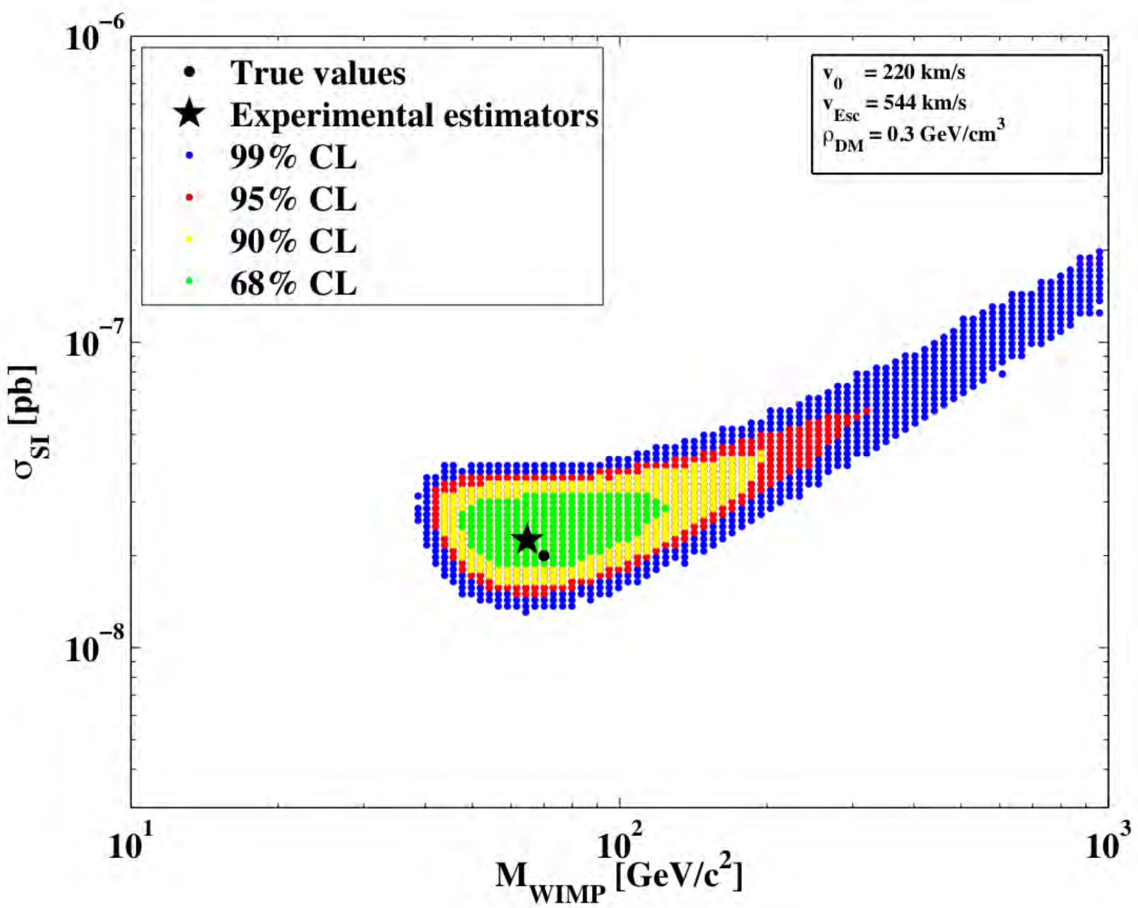
=> exclusion plot in the cross section versus mass parameter space (assuming known local density)



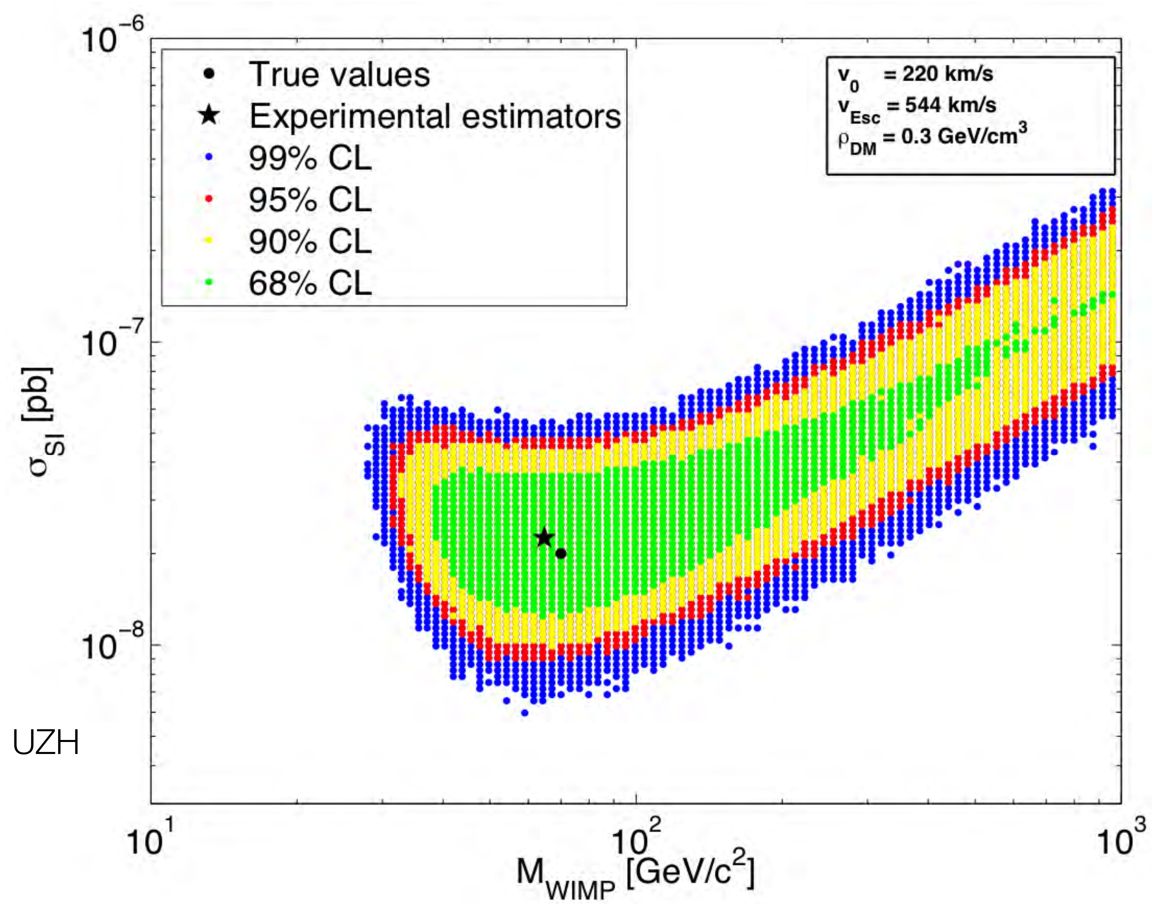
Detection of events above background

- Determination of the WIMP mass and the cross section (assuming one knows the local density of WIMPs)
- The WIMP mass can be determined from the energies of the detected events: we have seen that for a fixed target material the differential event rate depends on the WIMP mass (it decreases more rapidly with increasing recoil energy for lighter WIMPs)
- Example for a 70 GeV WIMP mass: a larger number of detected events will give a more precise determination of the mass of the WIMP

30 events in 12'250 (raw) kg days



8 events in 3'500 (raw) kg days



T. Bruch, UZH

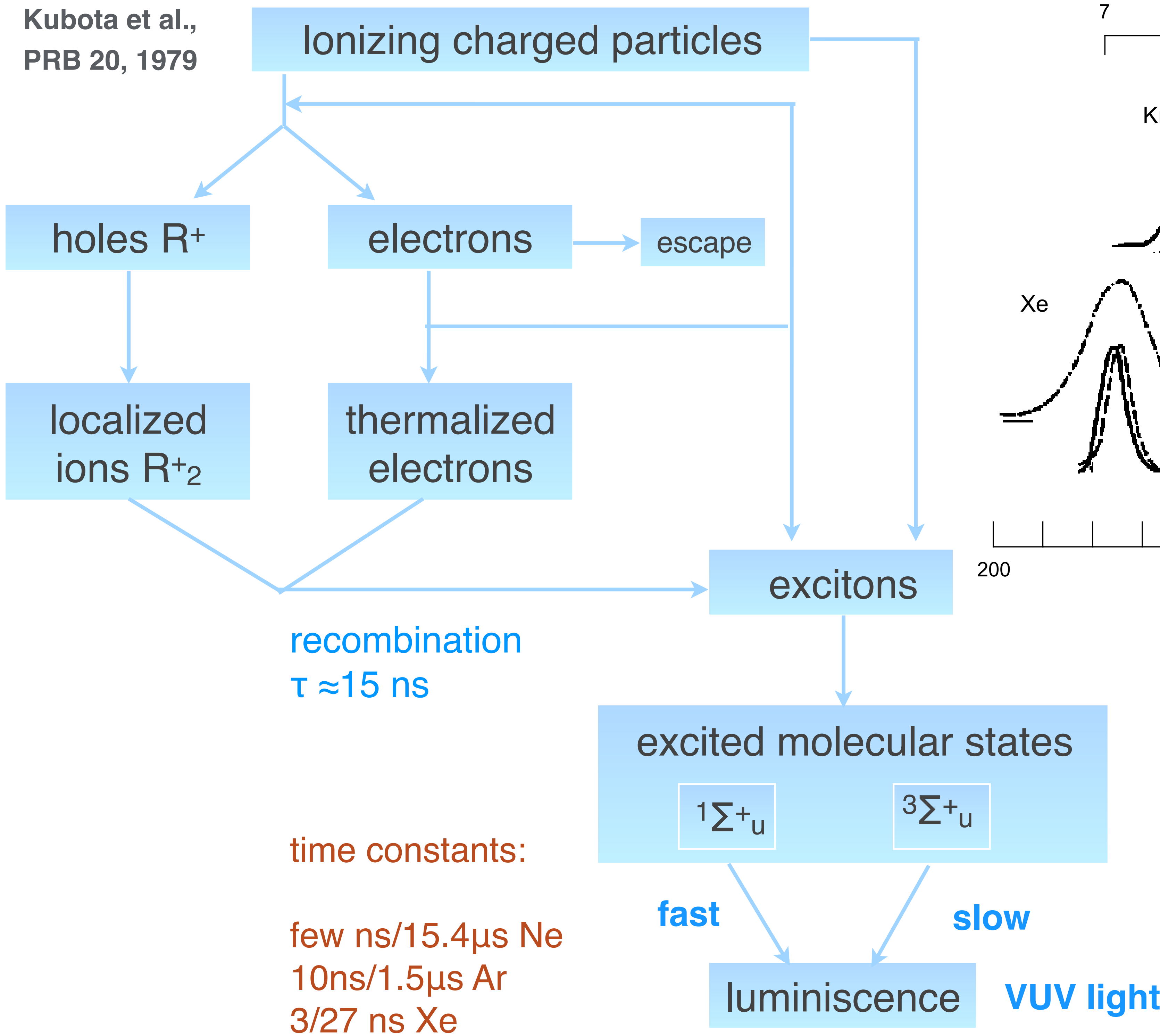
Cryogenic Noble Liquids as WIMP targets: some properties

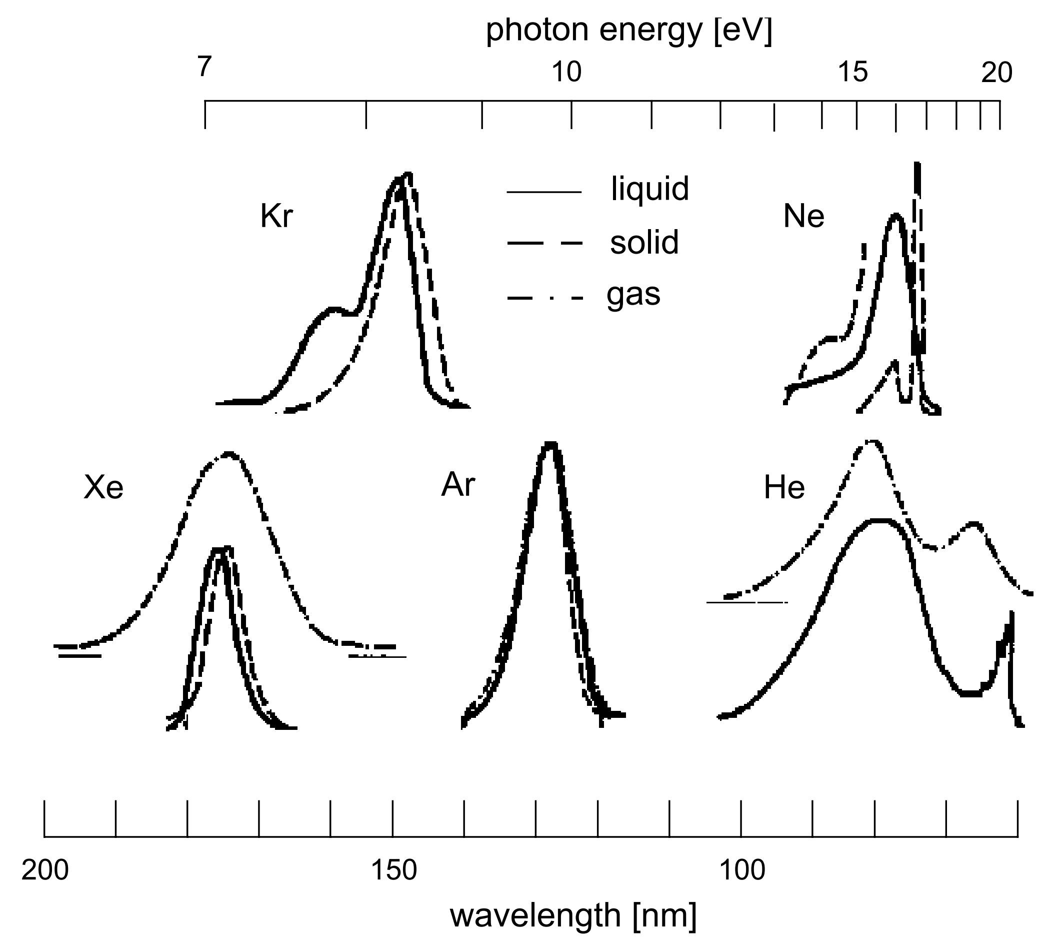
- **Suitable materials for detection of ionizing tracks:**
  - ➡ dense, homogeneous target and also detectors (scintillation and ionization)
  - ➡ do not attach electrons; inert not flammable, very good dielectrics
  - ➡ commercially easy to obtain and purify
- Large detector masses are feasible (at modest costs compared to semiconductors)
- Self-shielding + good position resolution in TPC mode

Element	Z (A)	BP (T_b) at 1 atm [K]	liquid density at T_b [g/cc]	ionization [e^-/keV]	scintillation [photon/keV]
He	2 (4)	4.2	0.13	39	15
Ne	10 (20)	27.1	1.21	46	7
Ar	18 (40)	87.3	1.40	42	40
Kr	36 (84)	119.8	2.41	49	25
Xe	54 (131)	165.0	3.06	64	46

Charge and Light in Noble Liquids

Kubota et al., PRB 20, 1979





$$\lambda_{LNe} \sim 77.5\ nm$$

$$\lambda_{LAr} \sim 128\ nm$$

$$\lambda_{LXe} \sim 175\ nm$$

Existing Experiments and Proposed Projects

	Single Phase (liquid only) **pulse shape discrimination** **(PSD)**	**Double Phase** **(liquid and gas)** **PSD and Charge/Light**
Neon (A=20)	miniCLEAN (100 kg) CLEAN (10-100 t)	SIGN
Argon (A=40)	DEAP-I (7 kg) miniCLEAN (100 kg) CLEAN (10-100 t)	ArDM (1 ton) WARP (3.2 kg) WARP (140 kg)
Xenon (A=131)	ZEPLIN I XMASS (100 kg) XMASS (800 kg) XMASS (23 t)	ZEPLIN II + III (31 kg, 8 kg) XENON10, XENON100 LUX (300 kg), DARWIN (>1t)

- **Single phase:** e^--ion recombination occurs; singlet/triplet ratio is 10/1 for NR/ER
- **Double phase:** ionization and scintillation; electrons are drifted in ~ 1kV/cm E-field

Liquid Xenon Detectors: why Liquid Xenon?

Large A (~131) good for SI interactions, requires low energy threshold E_{th}

^{129}Xe (26.4%, spin 1/2) and ^{131}Xe (21.2%, spin 3/2) for SD interactions

No radioactive isotopes (^{85}Kr reduced to ppt levels, ^{136}Xe: $T_{1/2} > 10^{20}$ yr)

High stopping power (Z=54, ρ=3 g/cm^3) for compact, self-shielding geometry

Efficient and fast scintillator (yield ~ 80% NaI), transparent to its own light

Good ionization yield (W=15.6 eV: energy required to produce an e^--ion pair)

Modest quenching factor (QF) for nuclear recoils (QF ~ 0.2)

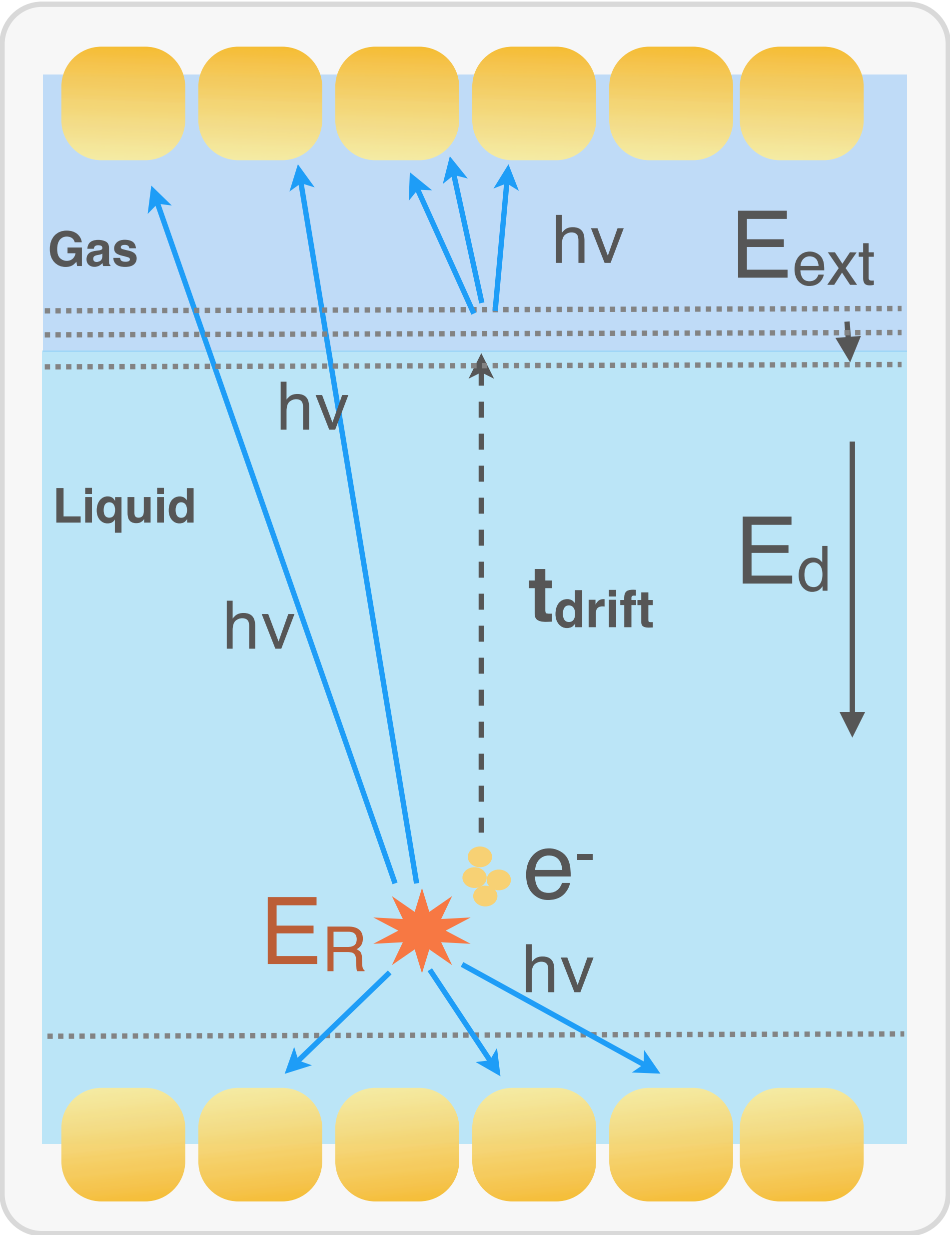
'Easy' cryogenics at ~ 165 K

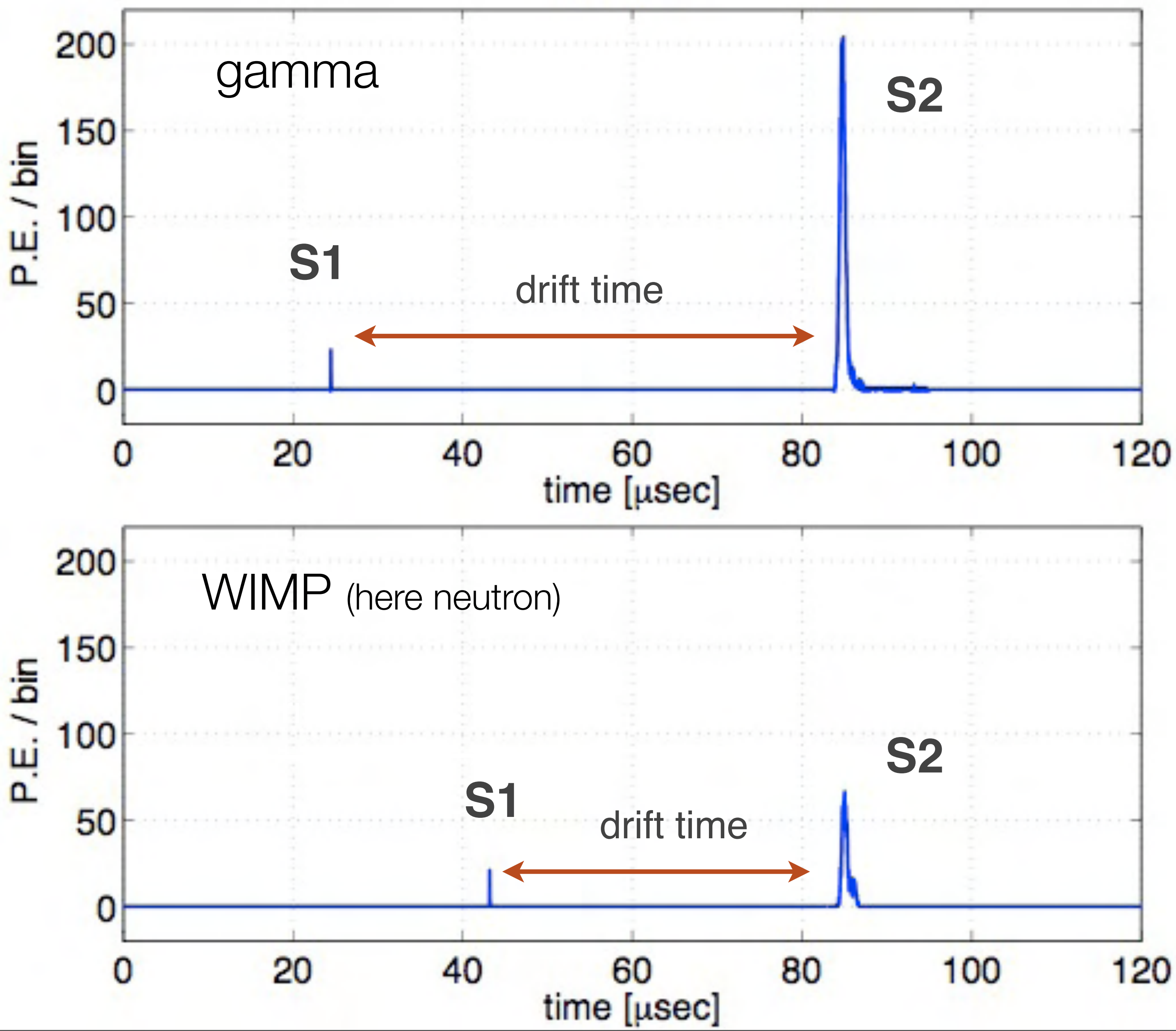
Background rejection: > 99.5% by simultaneous light and charge detection

3D event localization and LXe shelf-shielding => large, homogeneous detectors

The Double-Phase Detector Concept

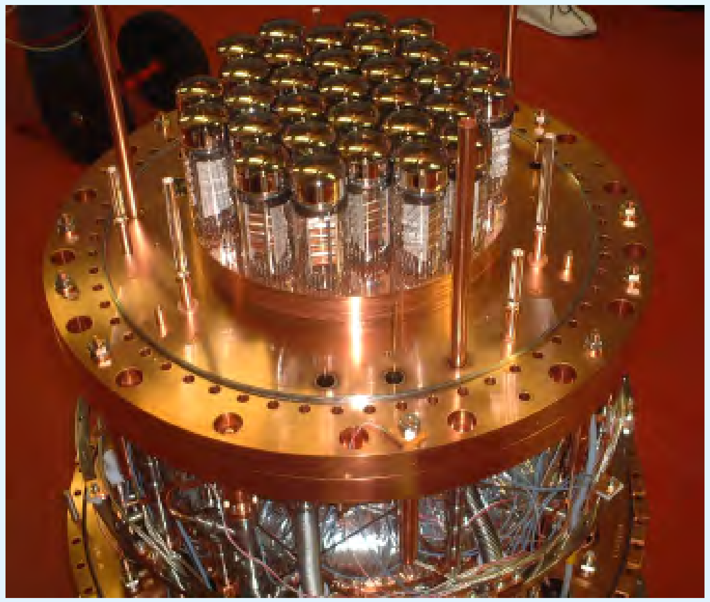
- **Prompt (S1) light signal** after interaction in active volume; charge is drifted, extracted into the gas phase and detected as **proportional light (S2)**
- **Challenge:** ultra-pure liquid + high drift field; efficient extraction + detection of e$^-$





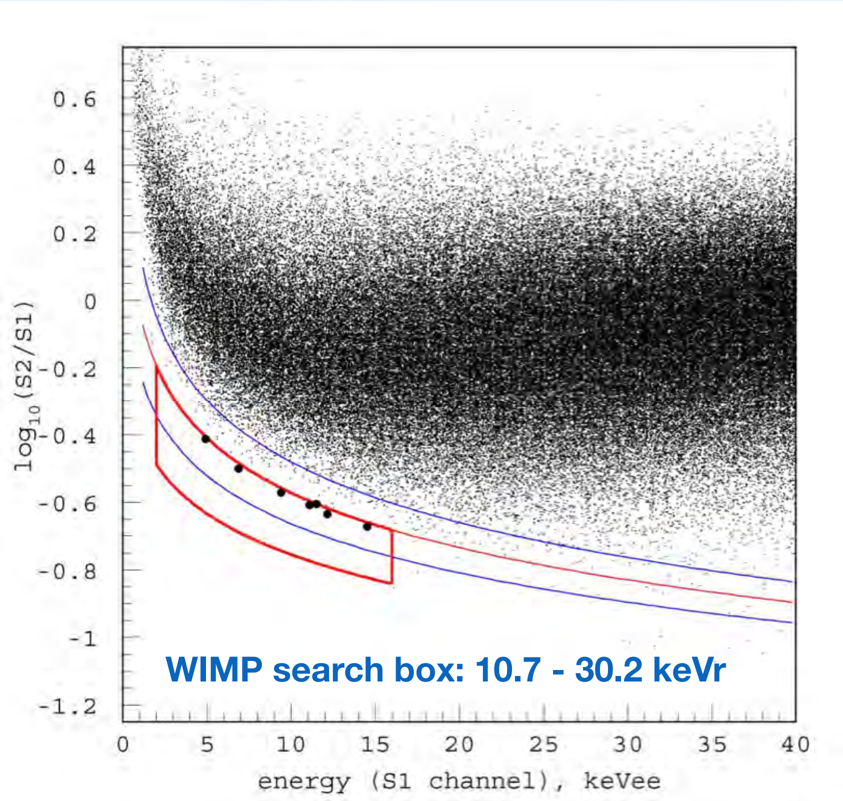
Two-phase Xenon Detectors

ZEPLIN III at Boulby



6.7 kg LXe (fiducial)
31 x 2'' cm PMTs

WIMP search run analyzed: 127 kg d



7 events obs. in WIMP box
11.6±3.0 expected from backgrounds

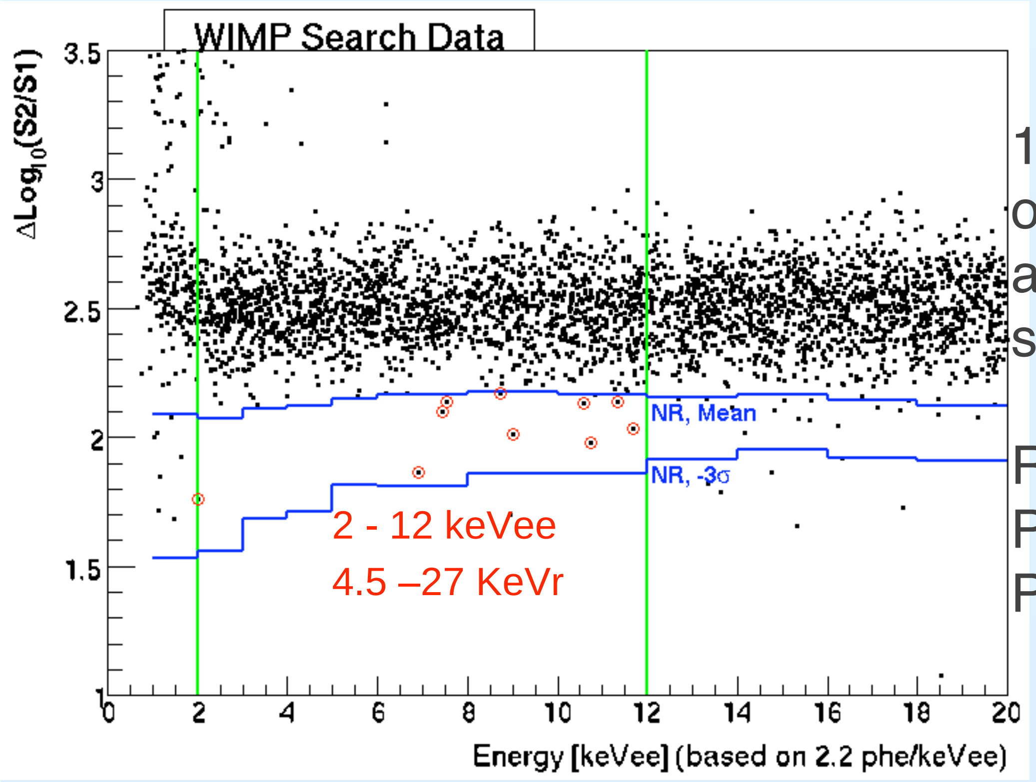
limit with BG subtraction

arXiv:0812.1150v1

XENON10 at LNGS

15 kg (5.4 fiducial), 89 2'' PMTs

136 kg d (after cuts) of WIMP search data

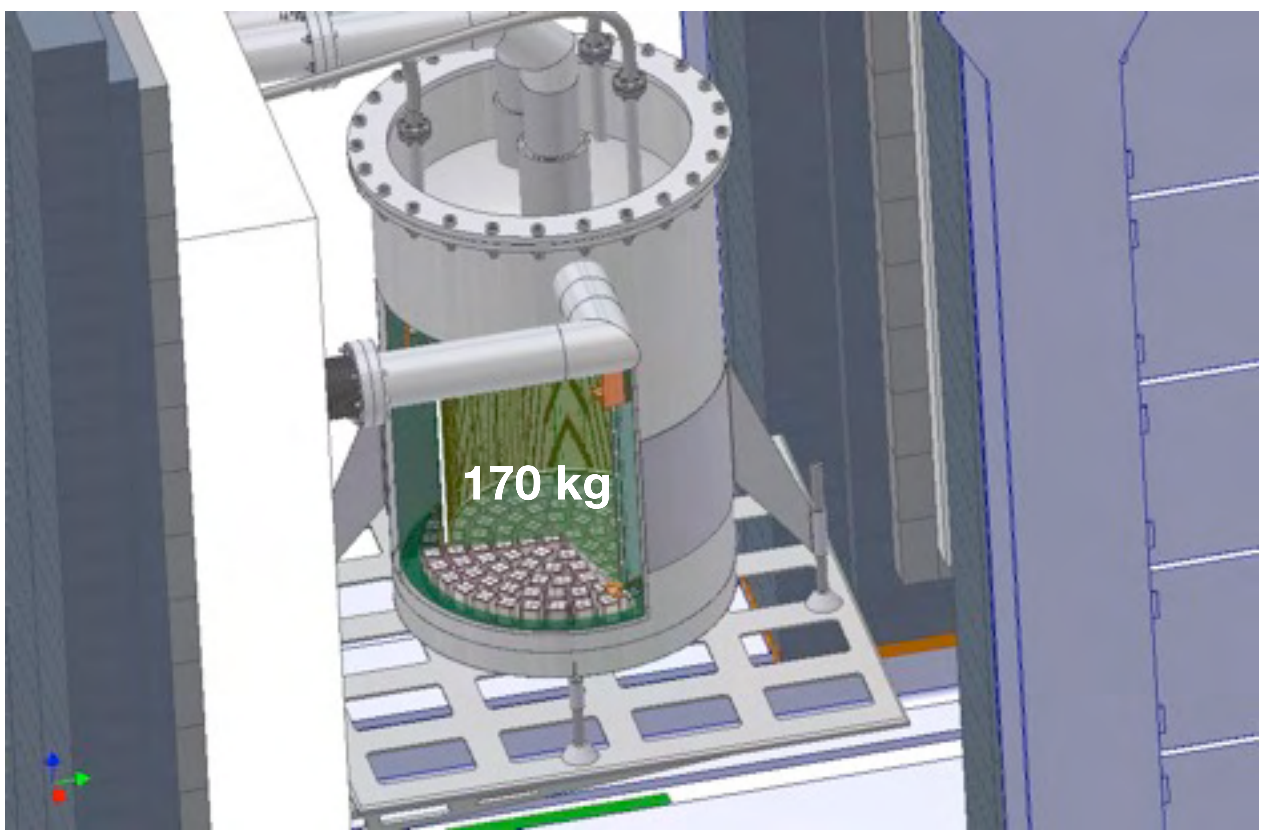


10 events observed, all BG, no subtraction

Results: PRL100, PRL101

The XENON100 Experiment

- **Goals:**
  - ➡ target mass of ~ 50 kg (10 x larger than XENON10)
  - ➡ decrease backgrounds by x 100 (rel. to XENON10)
  - through strong material selection + screening
  - active veto shield and detector design
- Status: under commissioning at LNGS

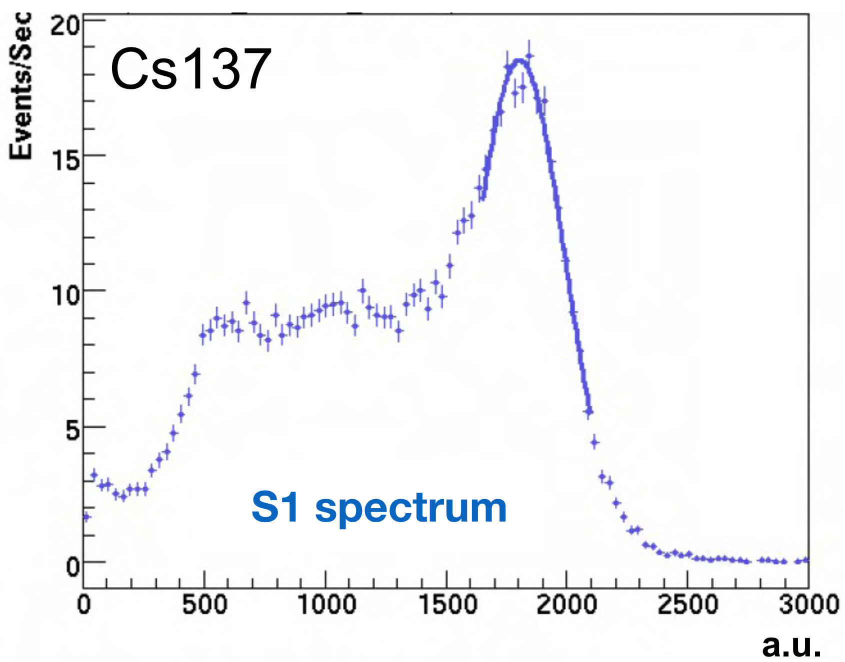


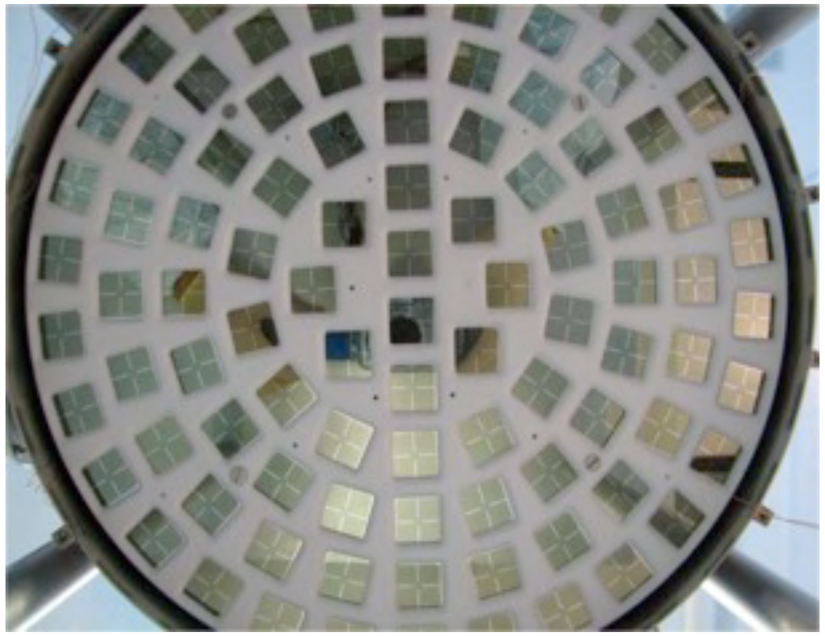
The XENON100 detector in its low-background shield at LNGS

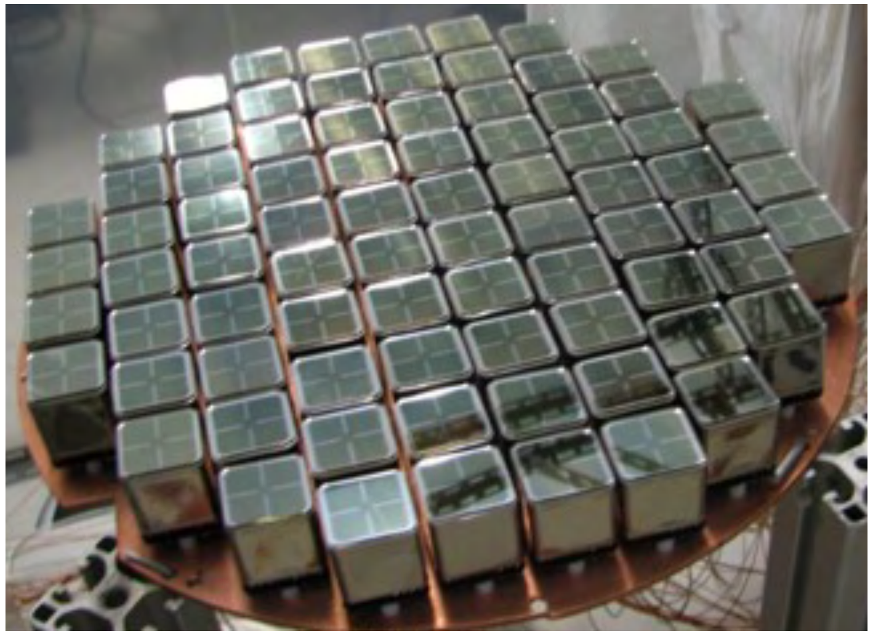
XENON100 Photodetectors and Calibration

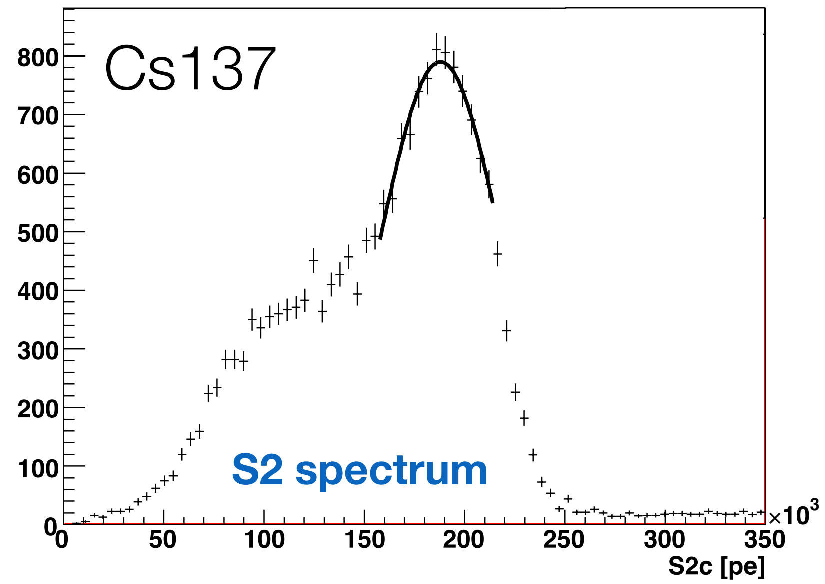
- 242 Hamamatsu R8520 1"x1" PMTs
- low-radioactivity (U/Th < 0.2 mBq/PMT), 80 with high QE of 33%
  - ➡ 98 in top array: optimized for fiducial cut efficiency
  - ➡ 80 in bottom array: optimized for S1 collection -> low E_{thr}
  - ➡ 64 in active veto: BG reduction by factor 3-4
  - ➡ PMT gain calibration: with LEDs, the SPE response measured

- gamma-sources: ^{83m}Kr, ^{57}Co, ^{137}Cs, ^{60}Co, ^{228}Th, ^{83m}Kr, ^{129m}Xe, ^{131m}Xe
- neutron source: AmBe



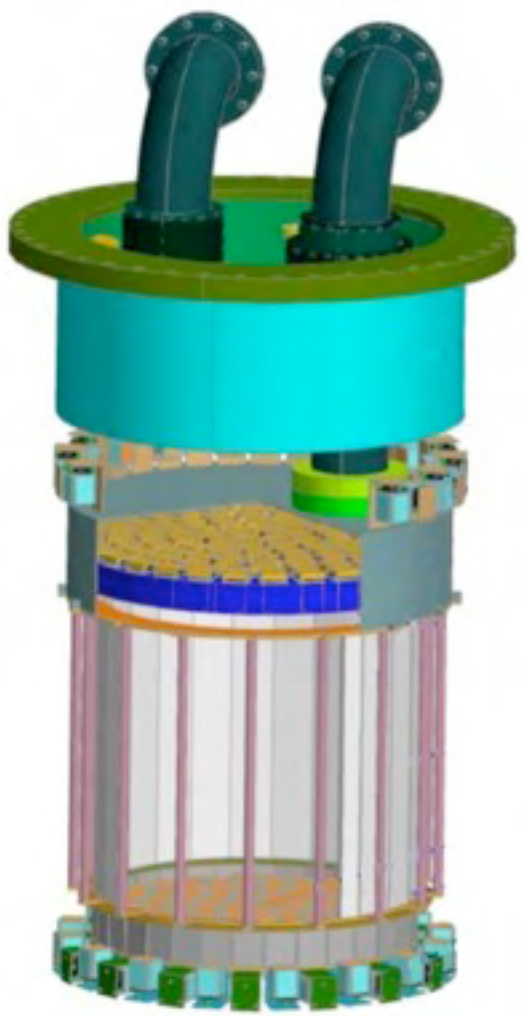


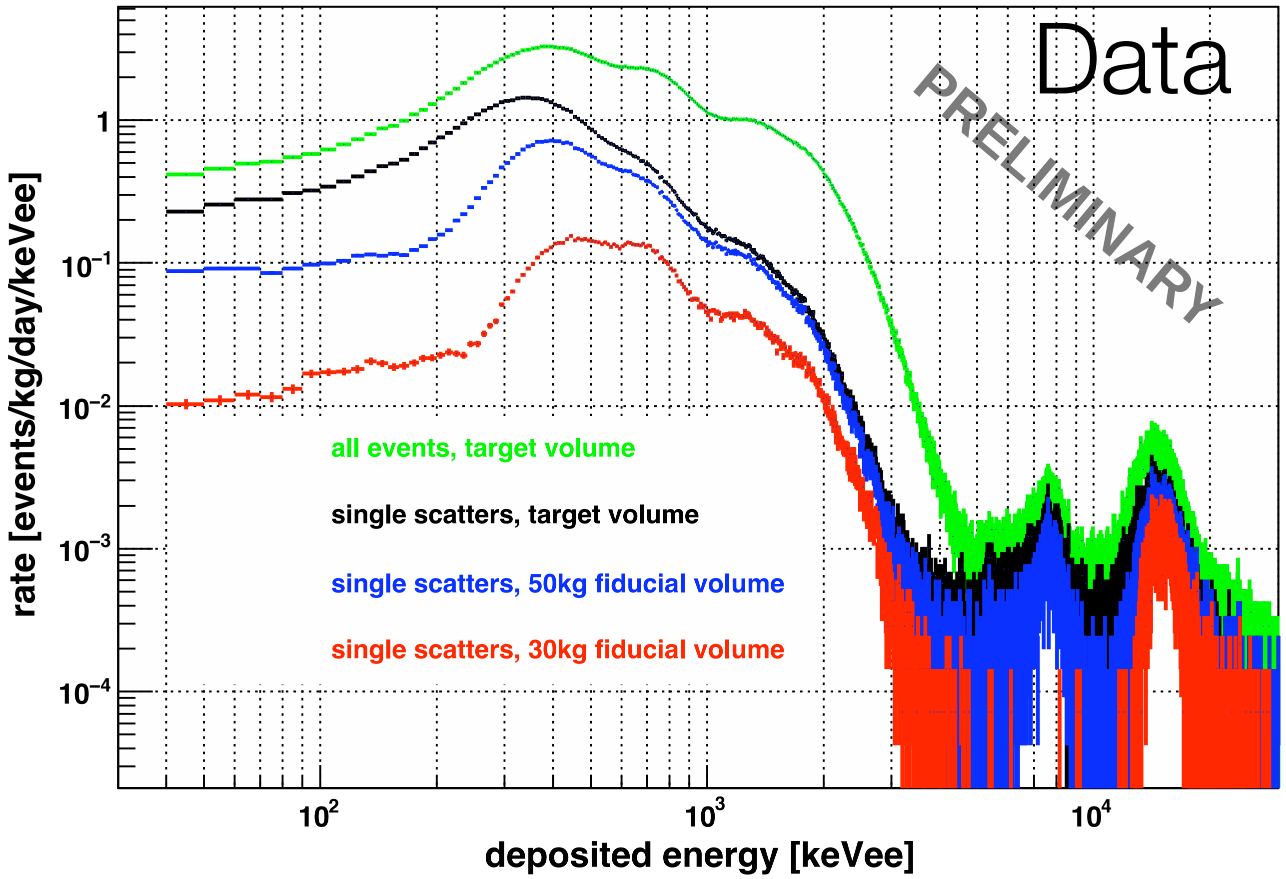




The XENON100 Time Projection Chamber

- TPC (total of 170 kg LXe) with active veto (100 kg LXe) installed underground
- Xe purified to ppt ^{85}Kr-levels ($T_{1/2}$ = 10.7 y, β^- 678 keV)
- Several background and calibration runs taken
- Measured background: factor ~100 lower than in XENON10 (preliminary)
- Expect to start WIMP search by the end of 2009; run until end of 2010



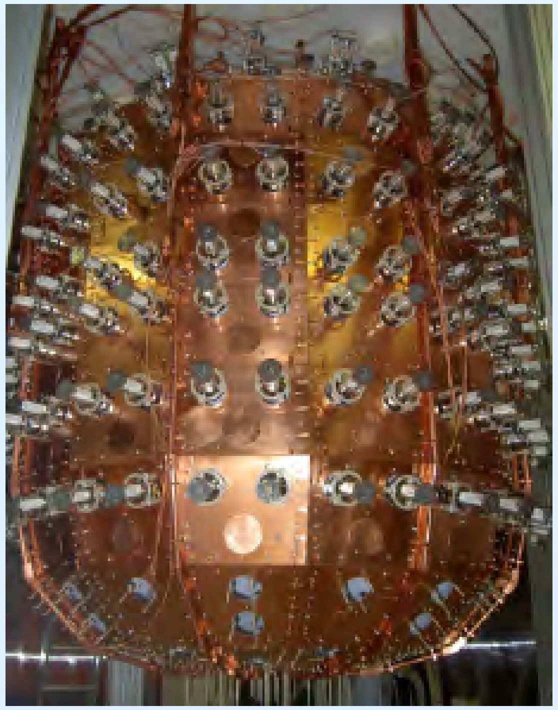


Two-phase Argon Detectors

WARP at LNGS

WIMP target: 140 kg LAr
- S1 and S2 read-out with 41 x 3'' PMTs
- active LAr shield: ~ 8t, viewed by 300 PMTs

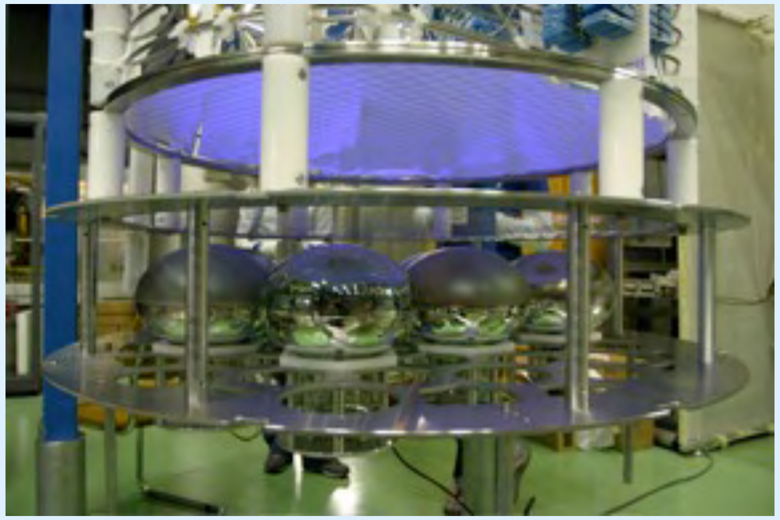
Detector has been installed in December 08
Now under commissioning in Gran Sasso

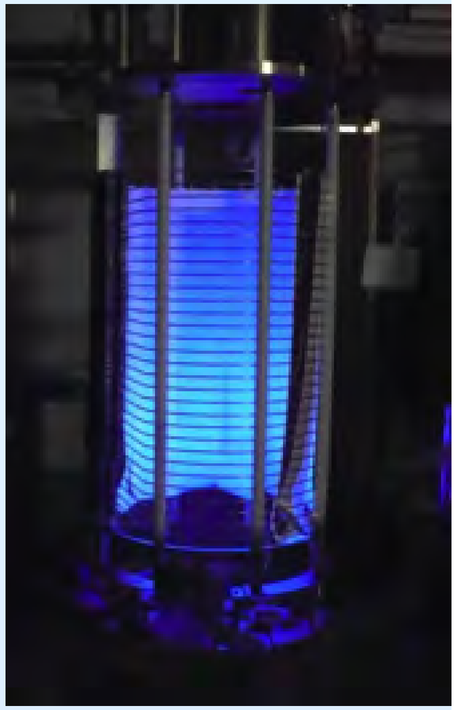


ArDM at CERN

WIMP target: 1 ton LAr
- S1 read-out with 14 x 8'' PMTs
- direct electron readout via LEMs
  (thick macroscopic GEM)

Detector filled May 2009 at CERN
Calibrations with various sources ongoing
Underground operation: LSC or SunLab





DARWIN
(DARk matter WImp search with Noble liquids)

- Design study for **Next-generation noble liquid facility in Europe** submitted (in response to the first ASPERA common call) on June 4th, 2009

- **Goals:**
  - ➡ unify and coordinate extensive existing expertise in Europe (XENON, WARP, ArDM plus new groups, including US groups from XENON and WARP)
  - ➡ study both argon and xenon as WIMP target media and provide recommendation for facility (full technical design report) in 2-3 years from now
  - ➡ submit full proposal in response to second ASPERA call

- **Possible locations**: LNGS (Italy), ULISSE (Modane extension, France), or SUNLAB (Poland)

- **Participants:** Switzerland (ETHZ, UZH), Germany (MPIK, KIT, Münster), France (Subatech), Italy (INFN: L'Aquila, Milano, Napoli, Padova, Pavia, Torino), Netherlands (Nikhef), Poland (IFJ PAN, US, PWr), USA (Columbia, Princeton, Rice, UCLA)

- **Funding:** provided by the national instruments of each participant ('virtual pot')
- **Decision:** expected in October 2009, start in late 2009

Cryogenic Experiments at mK Temperatures

- 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 only Ge and Si)
- Remember the energy resolution of a semiconductor detector (N = nr. of e^--h excitations)

$$W_{stat} = 2.35\sqrt{F\varepsilon E}$$

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

- E = deposited energy; F = Fano factor; in Si: ε = 3.6 eV/e^--h pair (band gap is 1.2 eV)

- Maximum 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

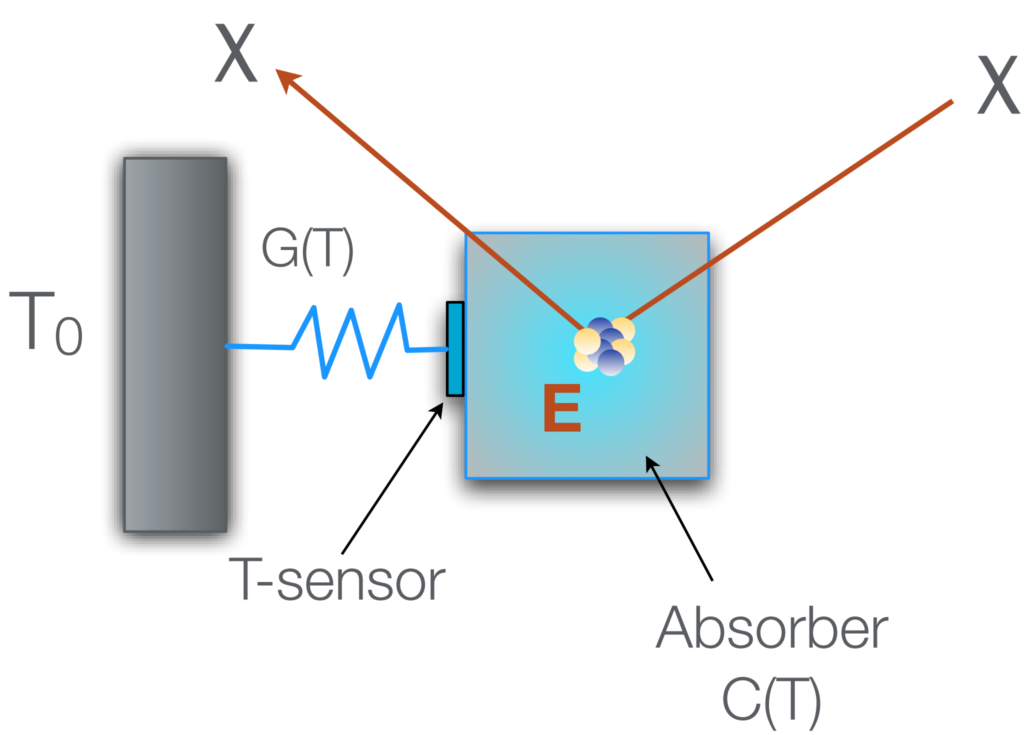
Basic Principles of mK Cryogenic Detectors

- 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 $T << T_c$, 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 $\Rightarrow$ < 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 **semiconductor** such that the **resistance R** is a 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

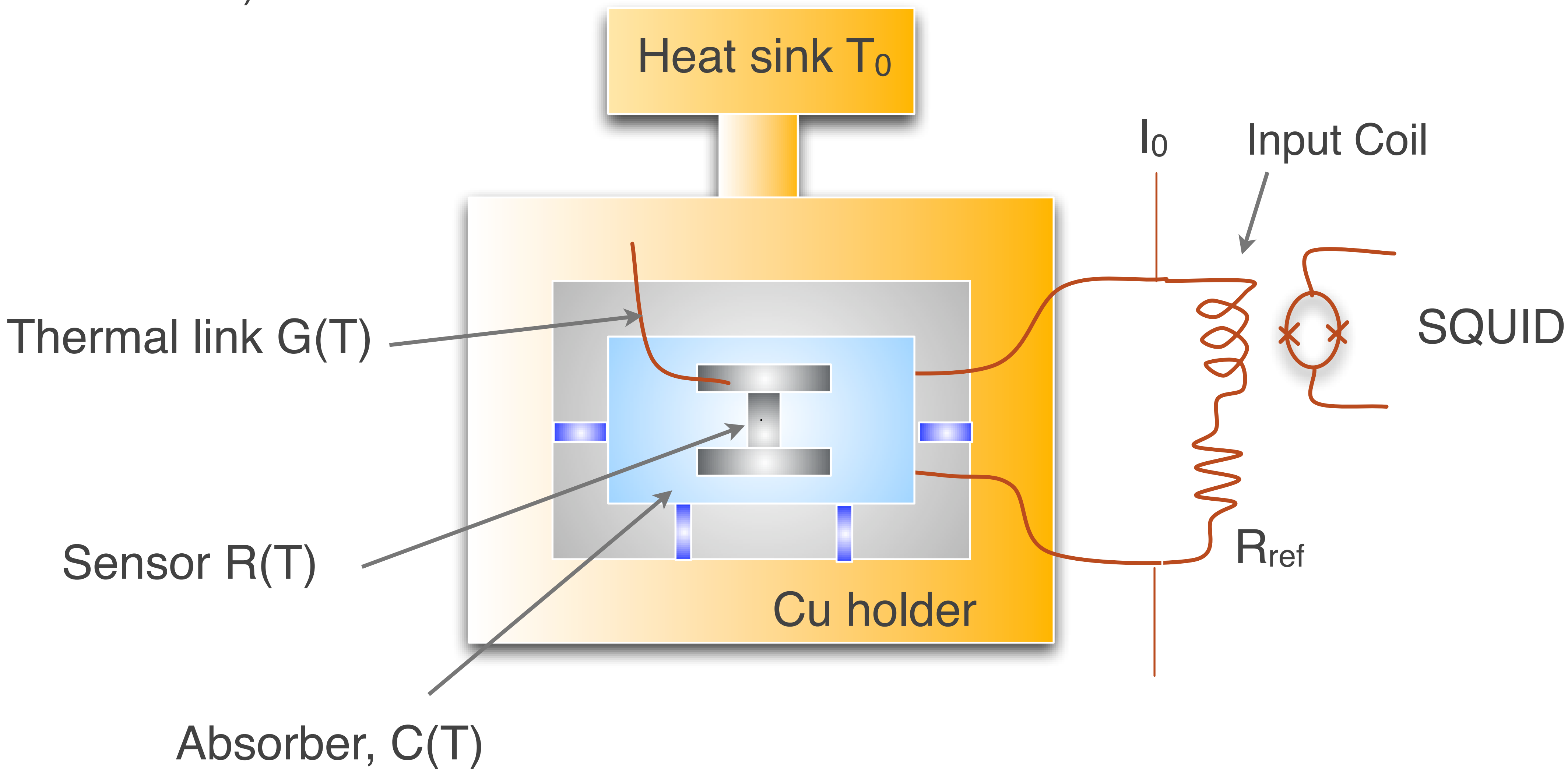
$\alpha \sim +10^3$ for TES/SPT devices

→ 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)**

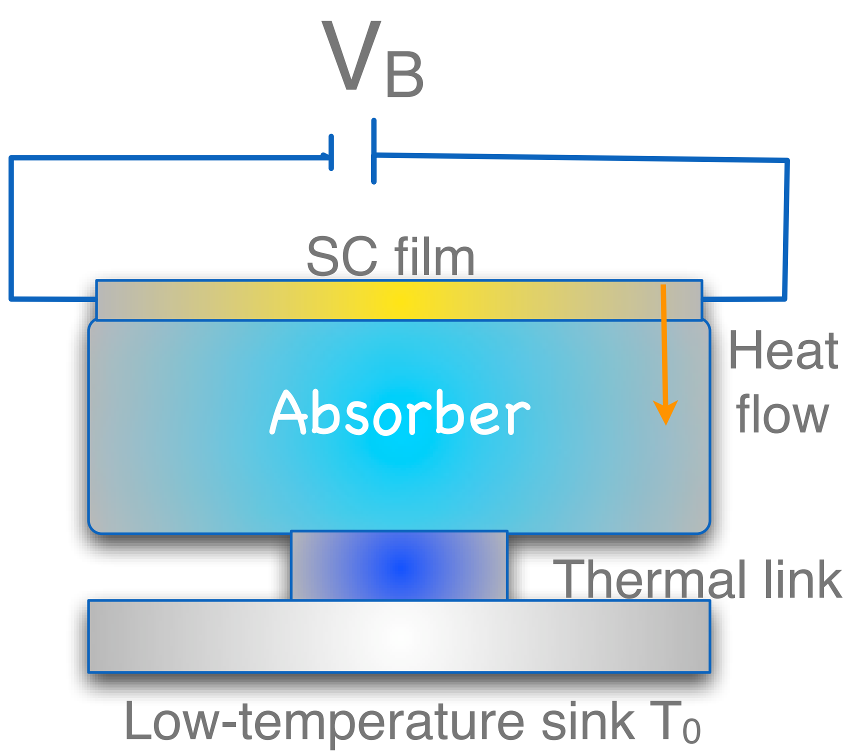
  and equilibrium is reached when ohmic heating of the TES by its bias current is balanced by the heat flow into the absorber

  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:

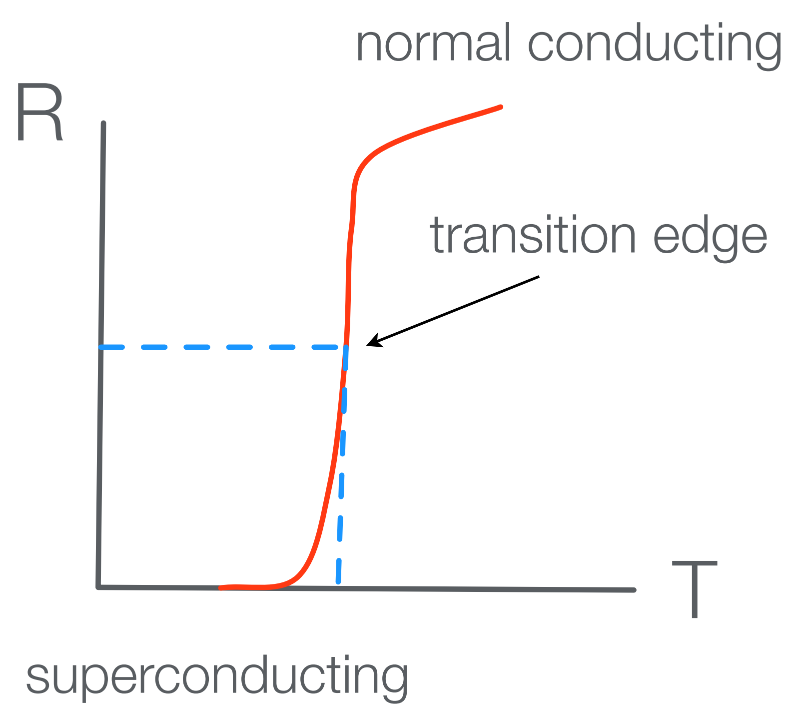
$$E = -V_B \int \Delta I(t)\,\mathrm{d}t$$

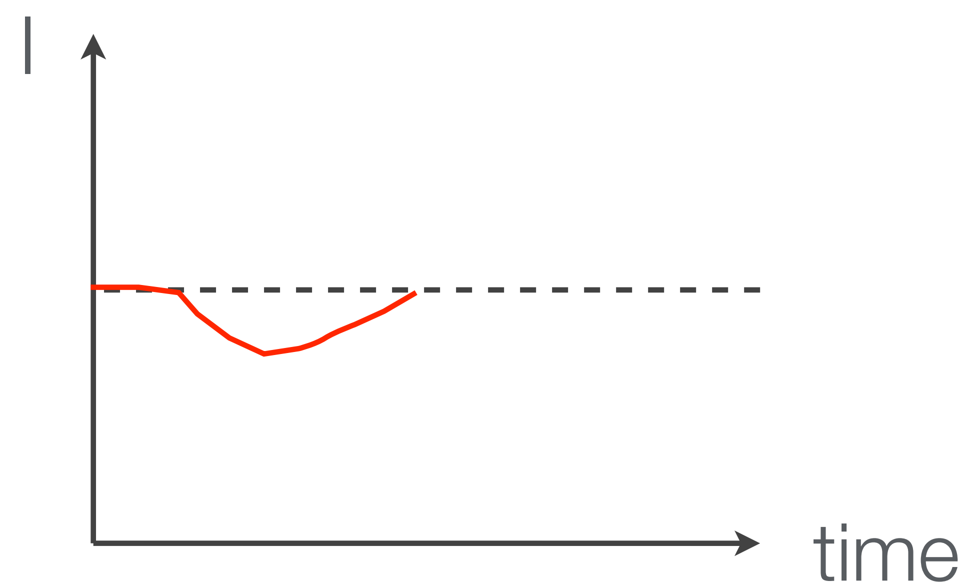
=> the device is self-calibrating

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



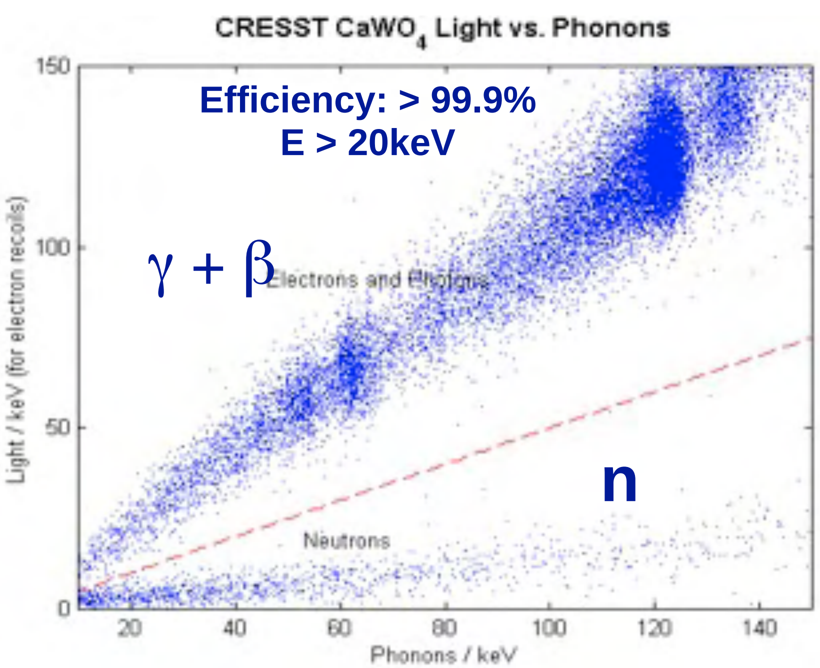


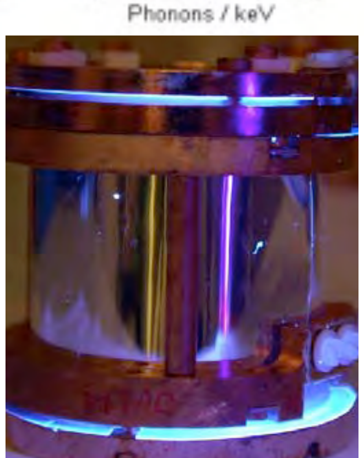
ET-feedback: leads to a thermal response time 10^2 faster than the thermal relaxation time
+ a large variety of absorbers can be used with the TES

Cryogenic Experiments at mK Temperatures

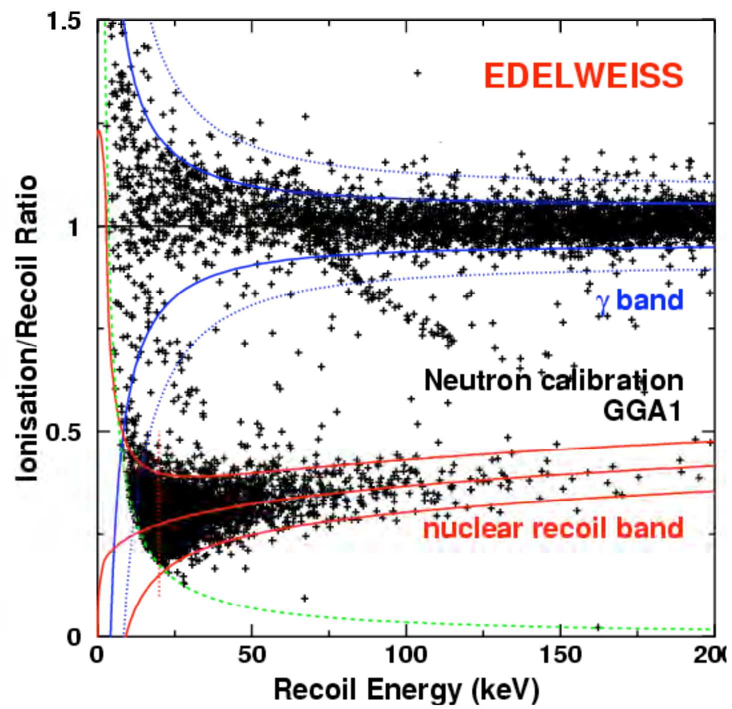
- **Advantages**: high sensitivity to nuclear recoils
  - measuring the full nuclear recoil energy in the phonon channel
  - low energy threshold (keV to sub-keV), good energy resolution
  - light/phonon and charge/phonon: nuclear vs. electron recoil discrimination

CRESST at LNGS

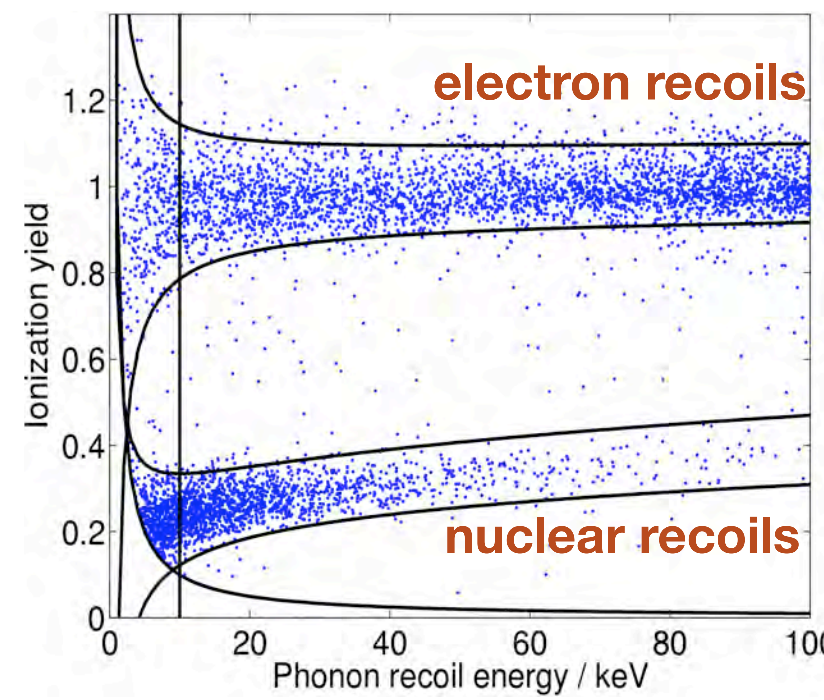


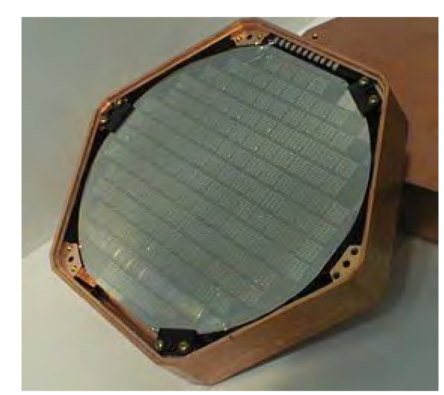


EDELWEISS at LSM



CDMS at Soudan

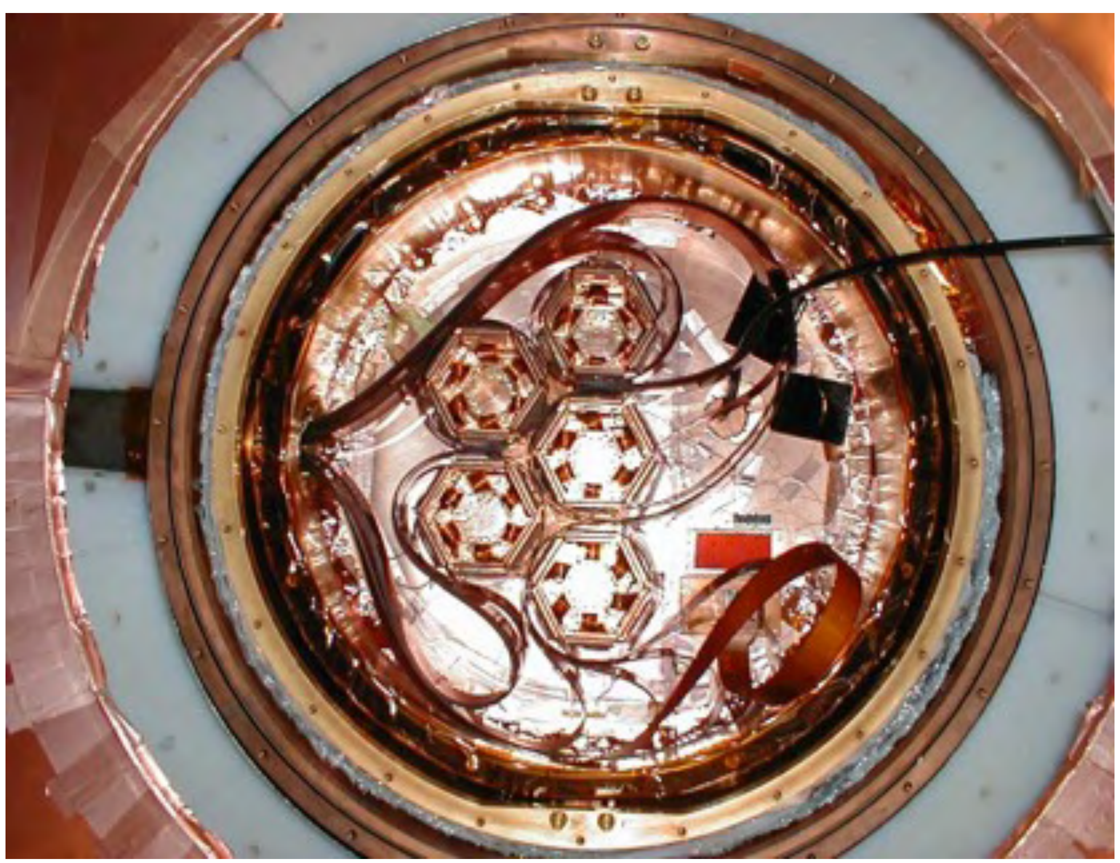




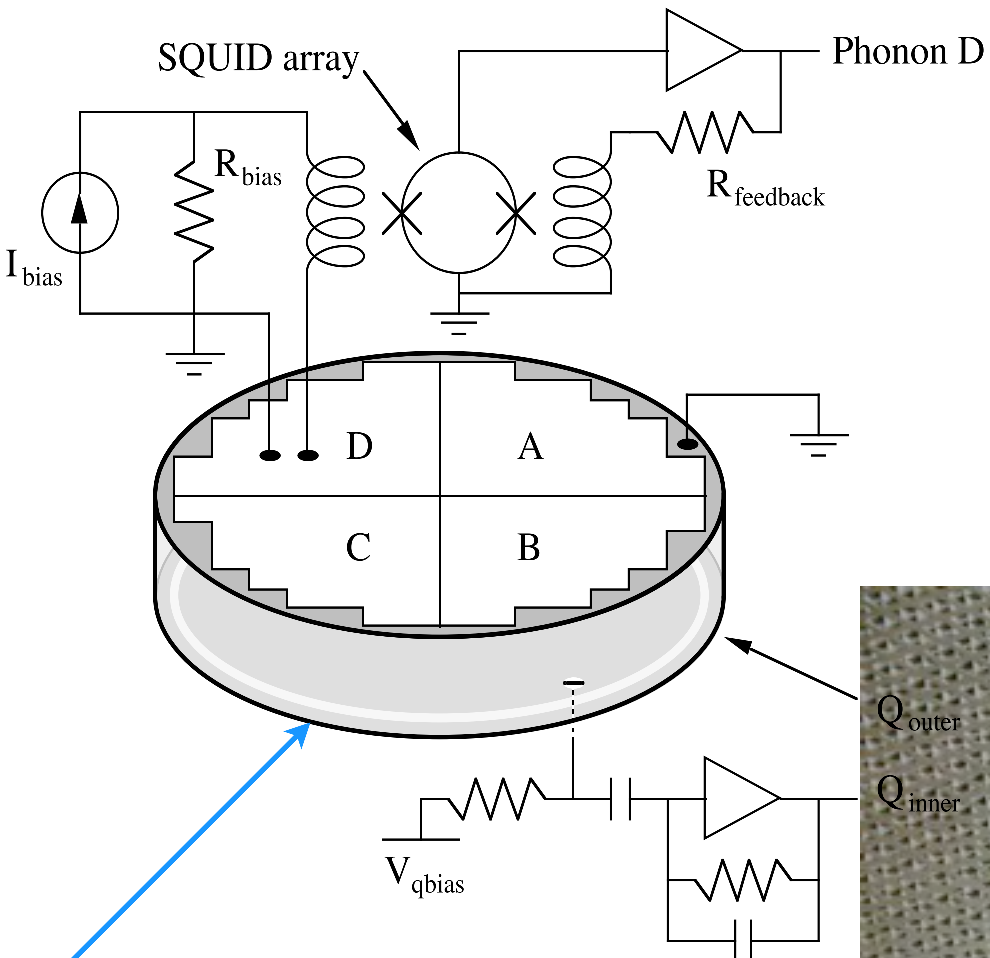
Example: the CDMS Experiment at the Soudan Mine

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' kept at ≈ 20 mK



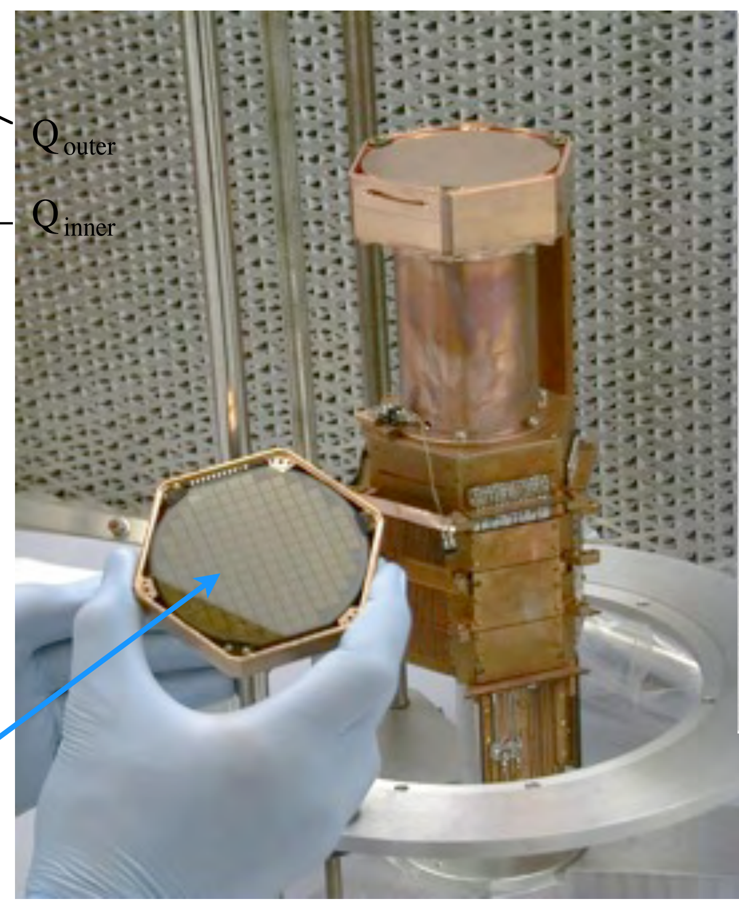
CDMS Detectors: charge and phonon sensors



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

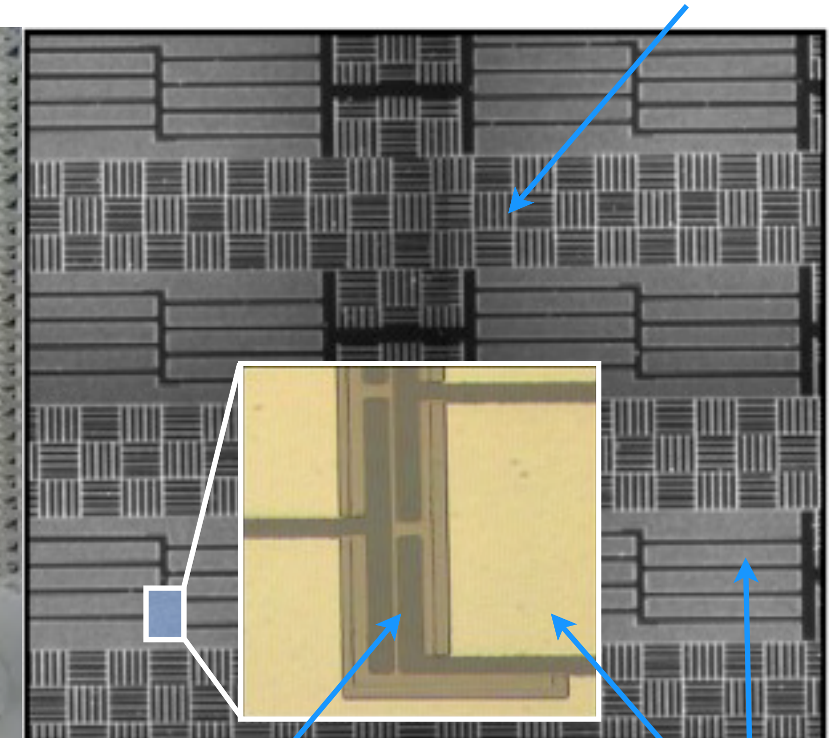
T-sensors:
photolithographically patterned thin films of Al +W, collecting athermal phonons

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)

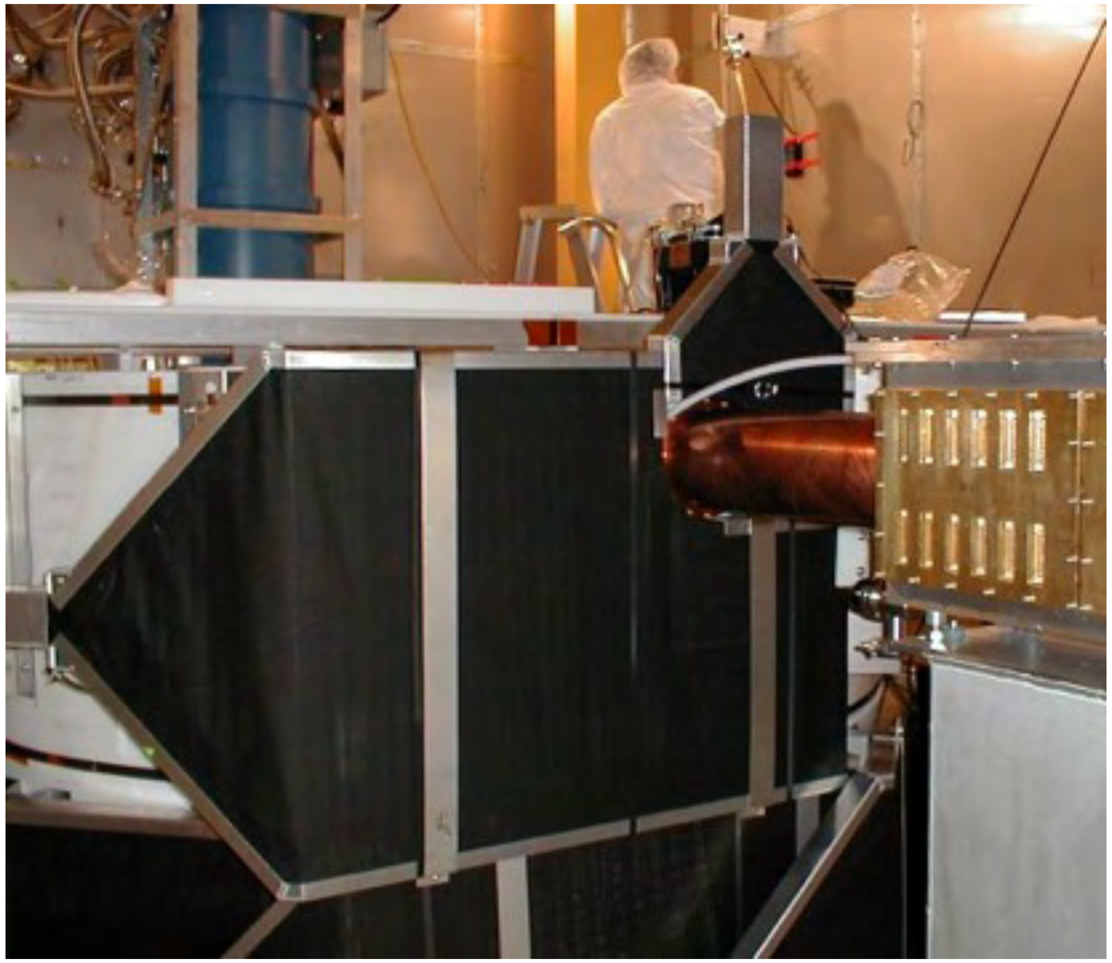
passive tungsten grid

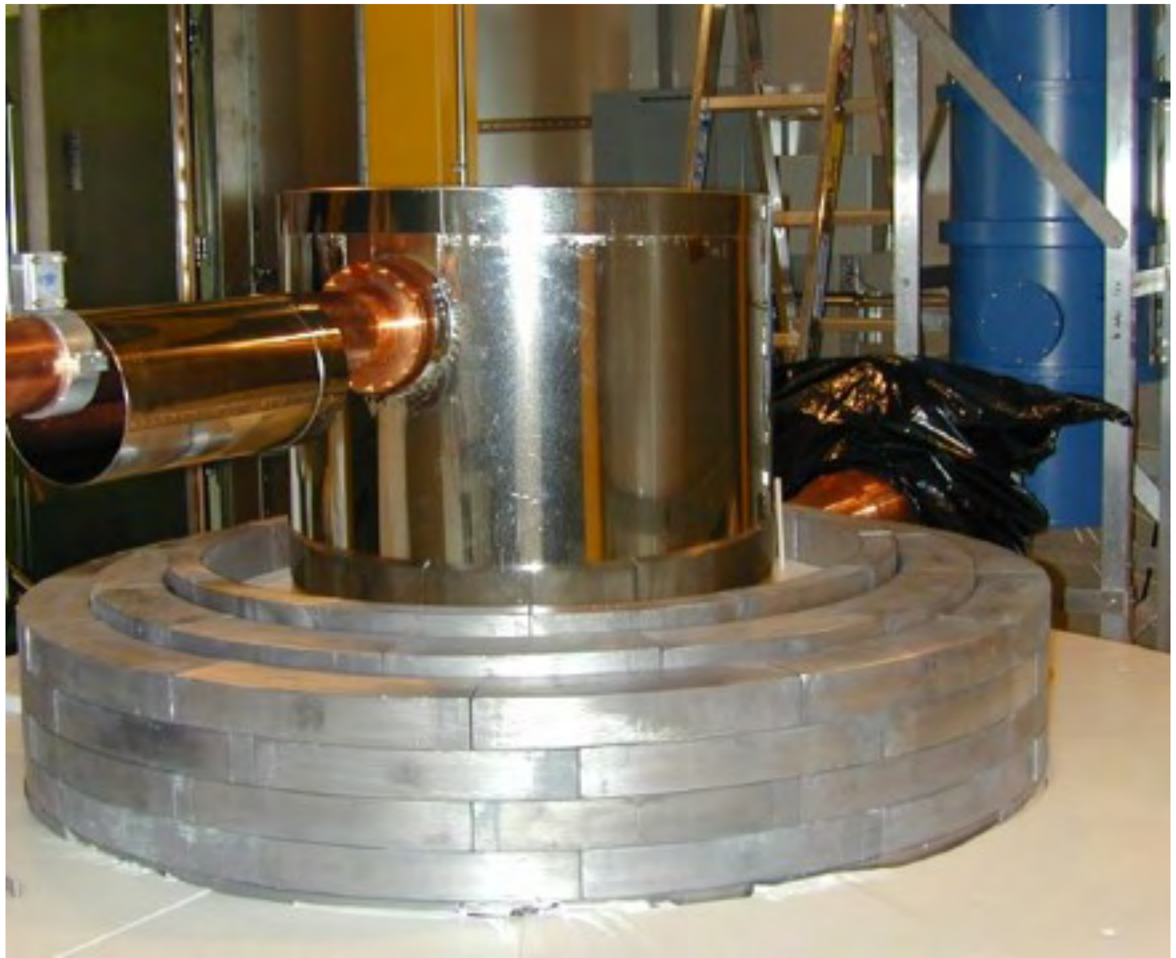


250 µm x 1 µm W
(35 nm thick)

380 µm x 55 µm Al
fins (300 nm thick)

CDMS Active and Passive Shields (typical shields for a dark matter experiment)



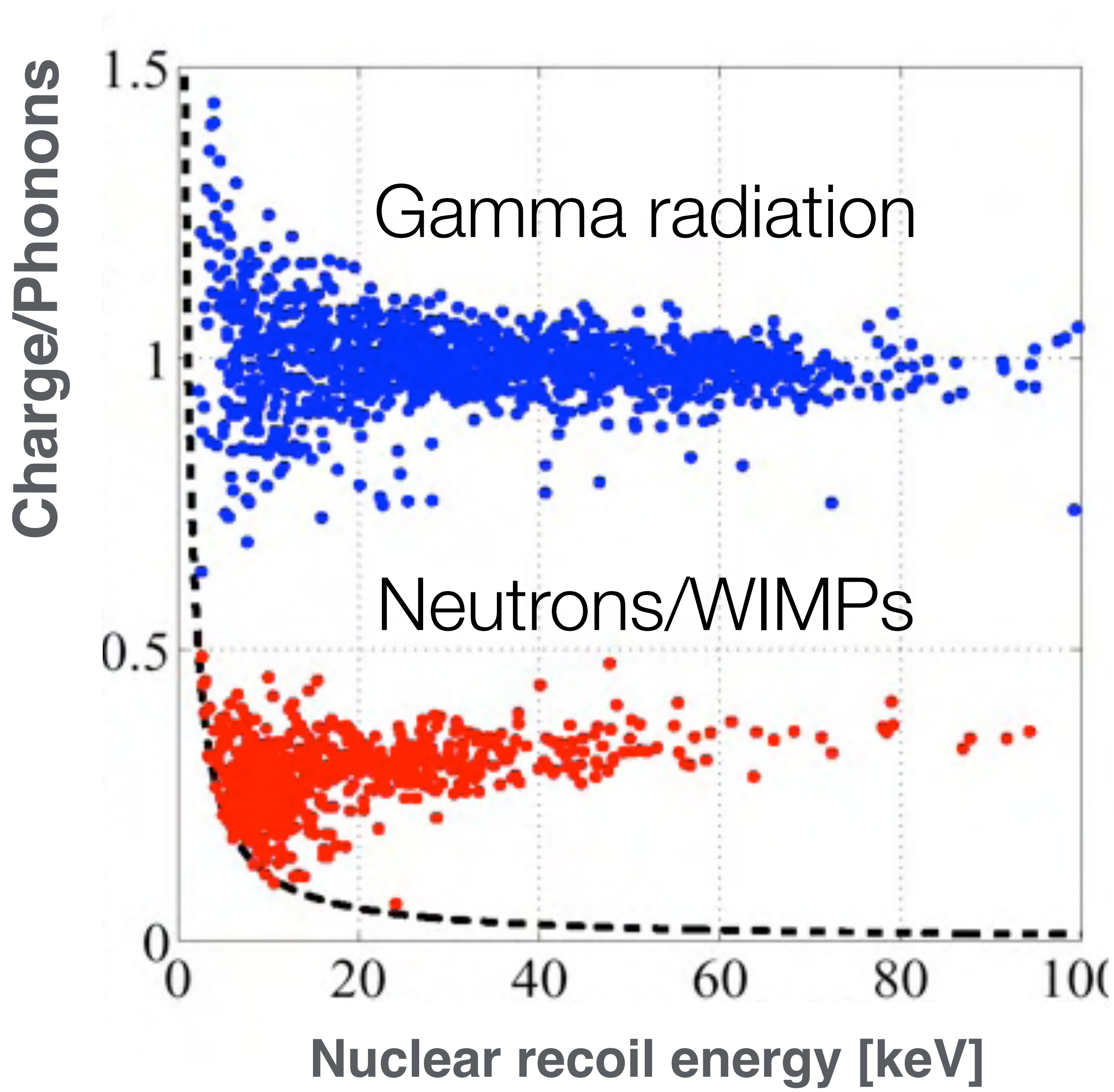


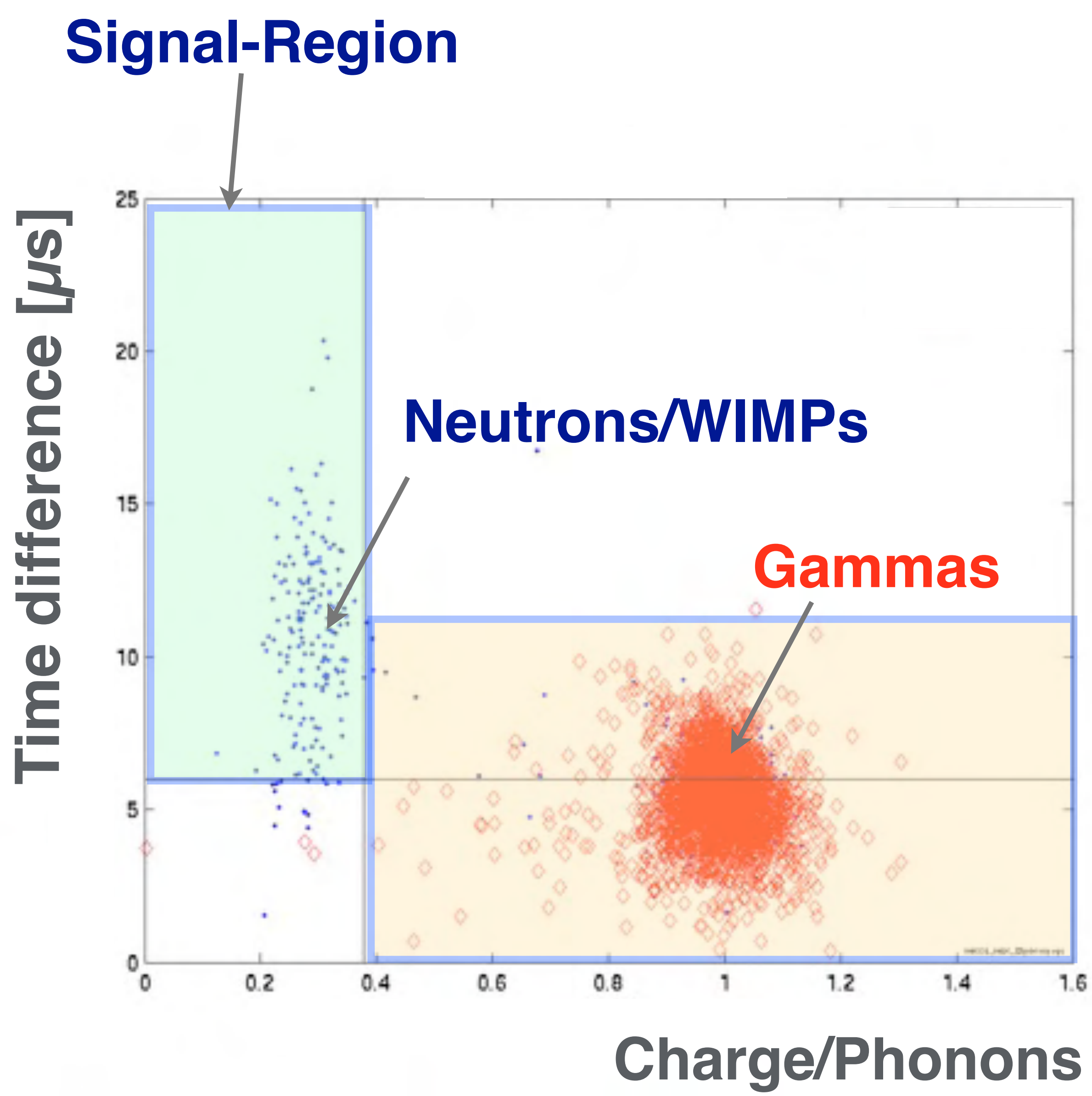
40 × 5 cm thick scintillator panels
read out by 2'' Hamamatsu PMTs
> 99.9% efficiency for through-going μ's
rate ≈ 1 muon/minute

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

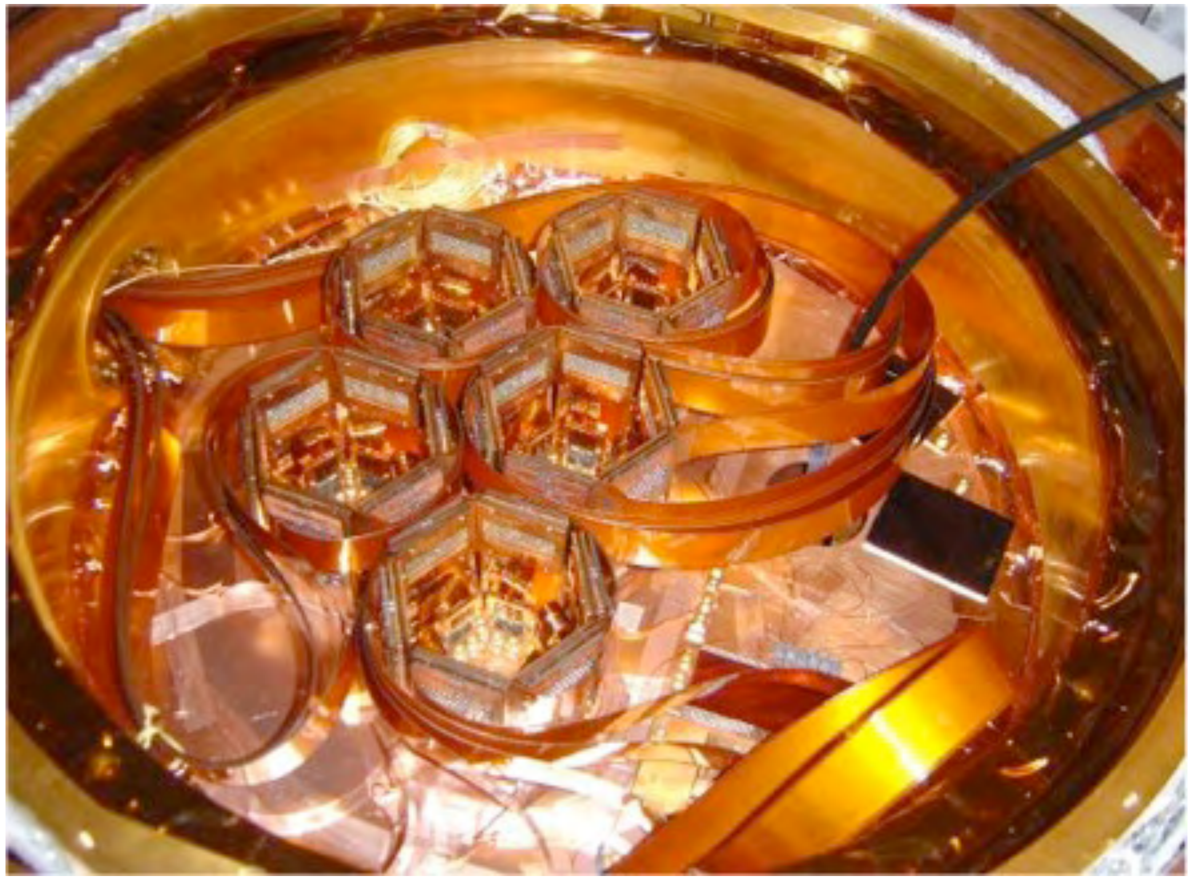
CDMS: Signal versus Background

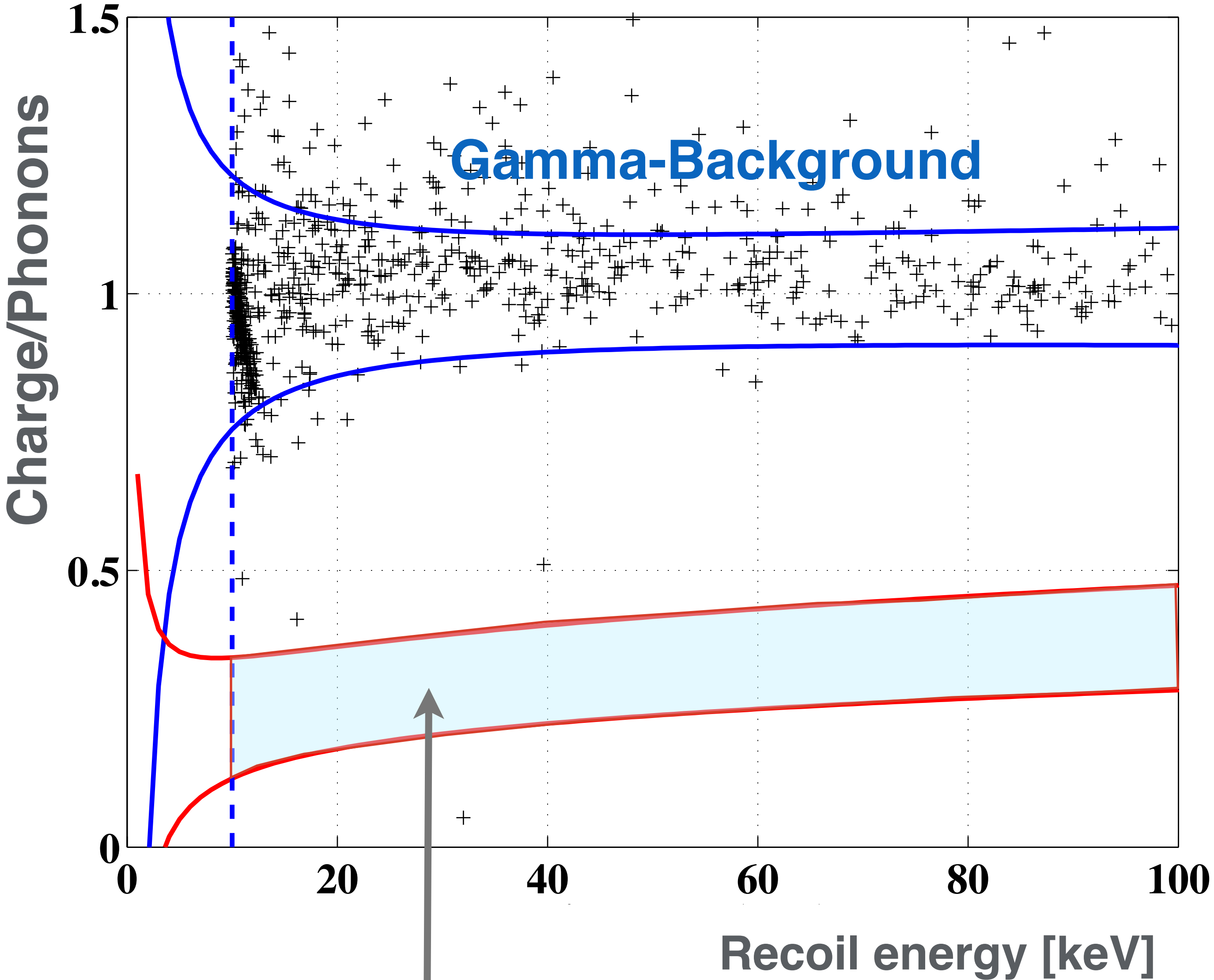
- Ratio of the charge/phonon-signal and time difference between charge and phonon signals => distinguish signal (WIMPs) from background of electromagnetic origin





CDMS WIMP Search Runs





Run 123 -124: 163 live days results published in PRL

Run 125-128: > 270 live days

Under analysis, results in late 2009

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

Cryogenic mK Experiments: Near Future

CRESST at LNGS

10 kg array of 33 $CaWO_4$ detectors
- new 66 SQUID channel array
- **new limit from operating 2 detectors (48 kg d) published in 2008,** arXiv:0809.1829v1
- **new run in progress**

EDELWEISS at LSM

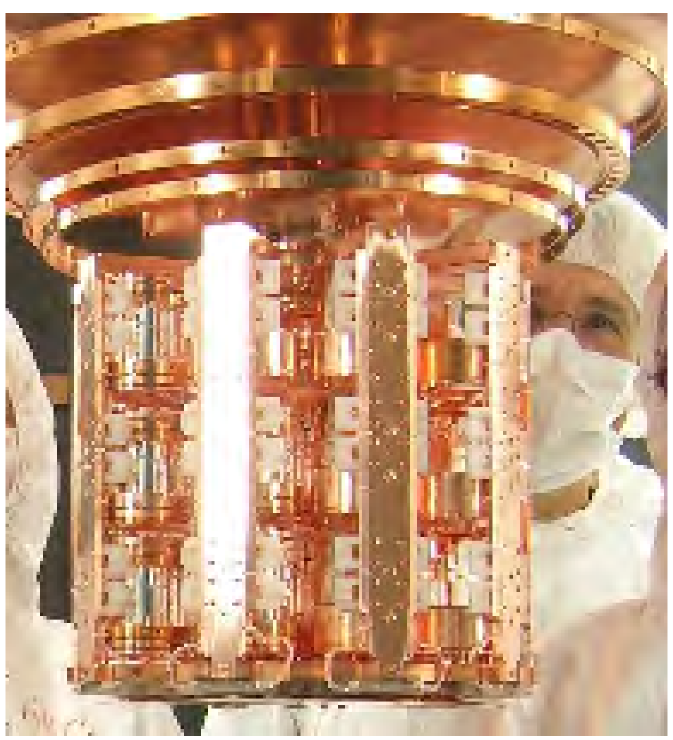
Goal: 10 kg (30 modules) of NTD and ID (new charge electrodes) Ge detectors in new cryostat
- **data taking (with 19 detectors) in progress**
- **reach: 4 x 10^{-44} cm^2**

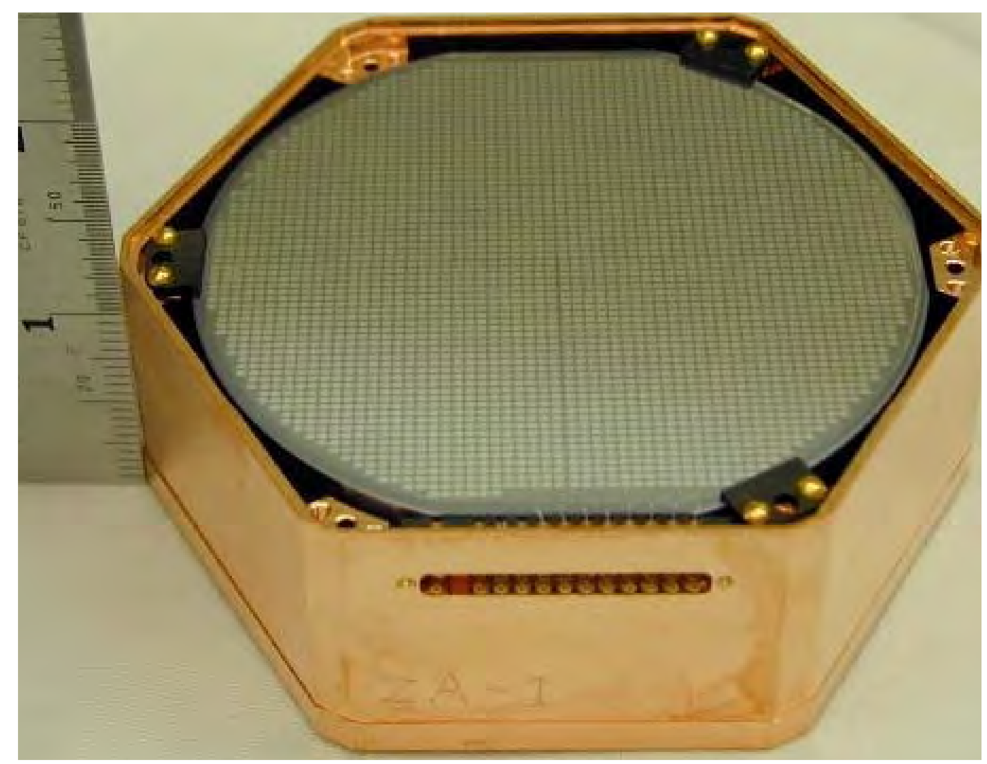
CDMS/SuperCDMS at Soudan

SuperCDMS detectors (1" thick ZIPs, each 650 g of Ge) have been tested

First SuperTower installed at Soudan (3 kg of WIMP target) and working

Goal: 5 x 10^{-45} cm^2 with 16 kg Ge





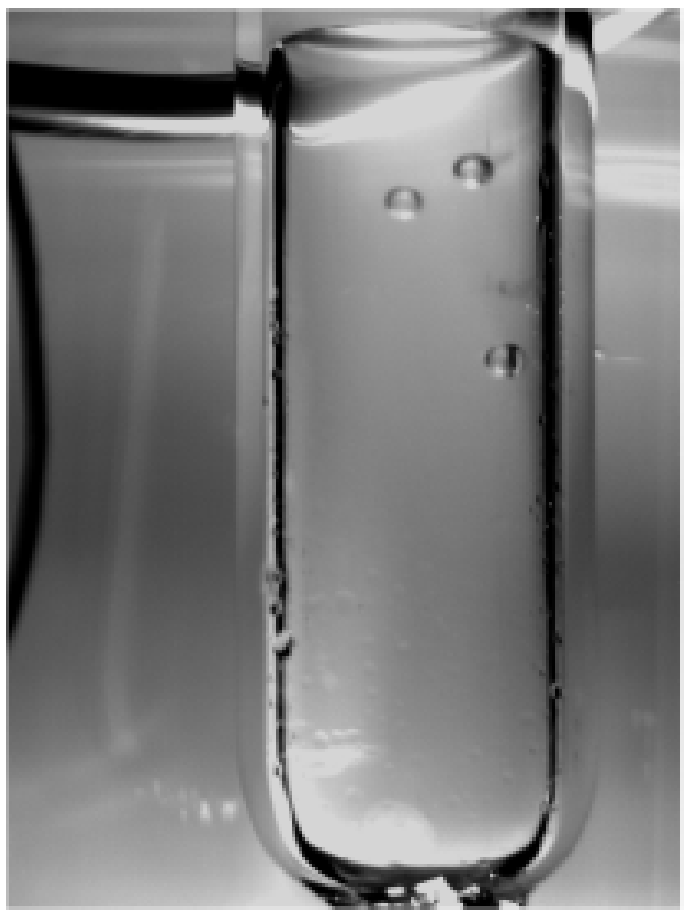
EURECA: joint effort for 100 kg-1t experiment in Europe

Goal: 7 SuperTowers at SNOLAB

Bubble Chambers as WIMP Detectors

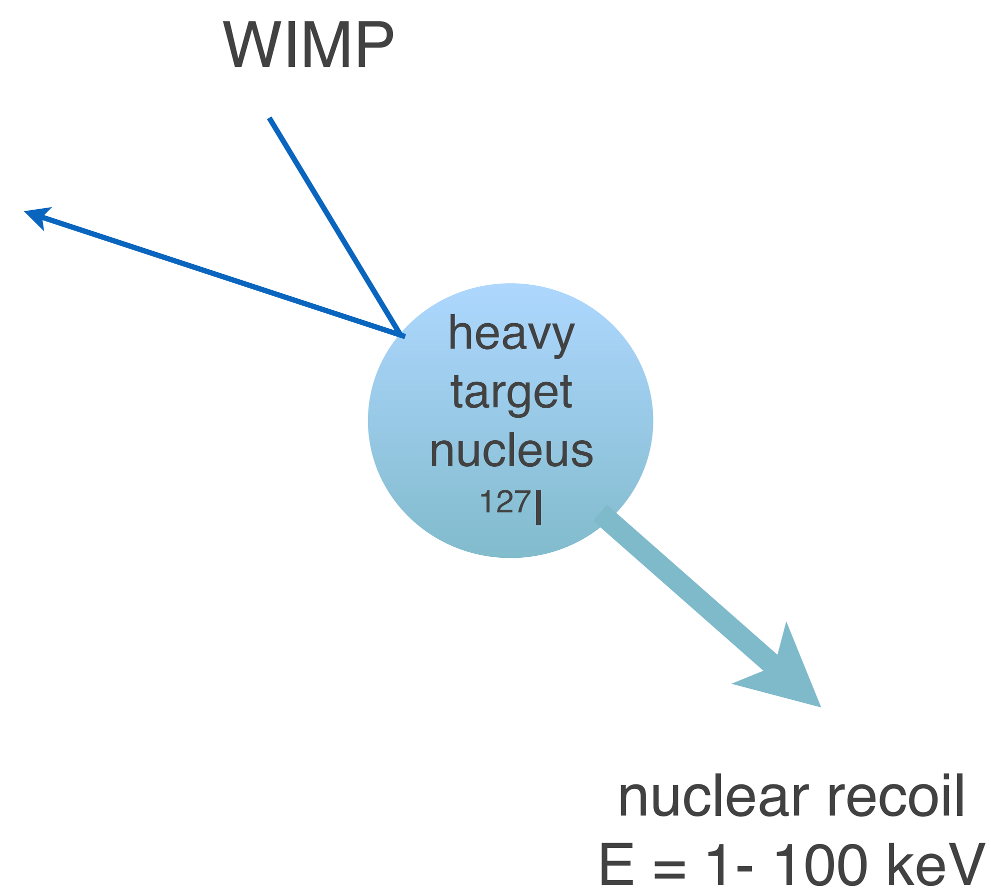
- **Principle:** detect single bubbles induced by high dE/dx nuclear recoils in heavy liquid bubble chambers (with acoustic, visual or motion detectors)

COUPP



n-induced event (multiple scatter)

WIMP: single scatter



Recoil range << 1 μm in a liquid - very high dE/dx

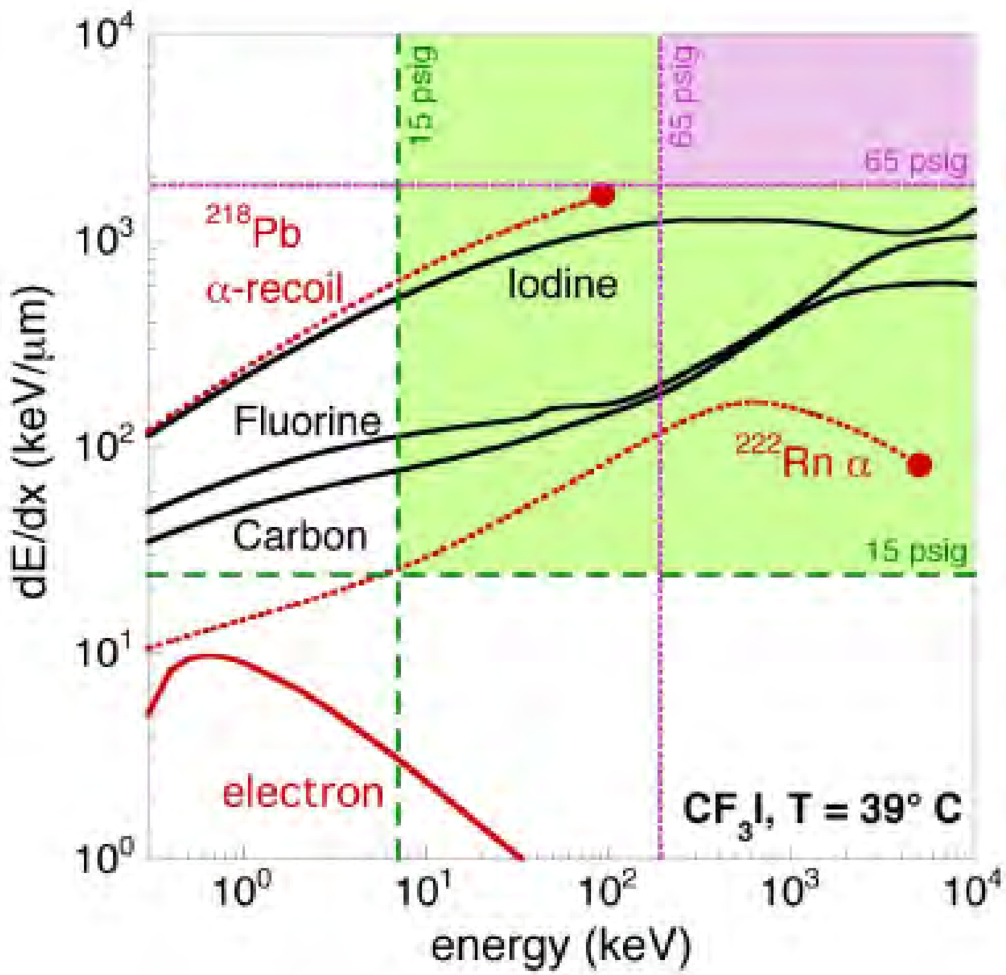
Bubble Chambers as WIMP Detectors

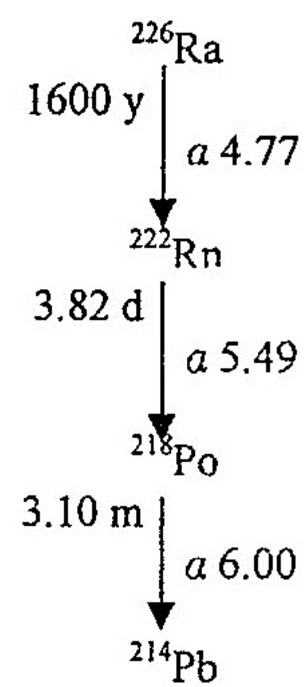
- **Advantages**
  - ➡ large 'rejection factor' for MIPs (> 10^{10}): in fact 'blind' to these type of particles
  - ➡ can be easily scaled to large masses
  - ➡ nuclei with and without spin => sensitivity to SD and SI interactions
  - ➡ CF_3I, CF_3Br, C_4F_{10} etc
  - ➡ high spatial granularity (reject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

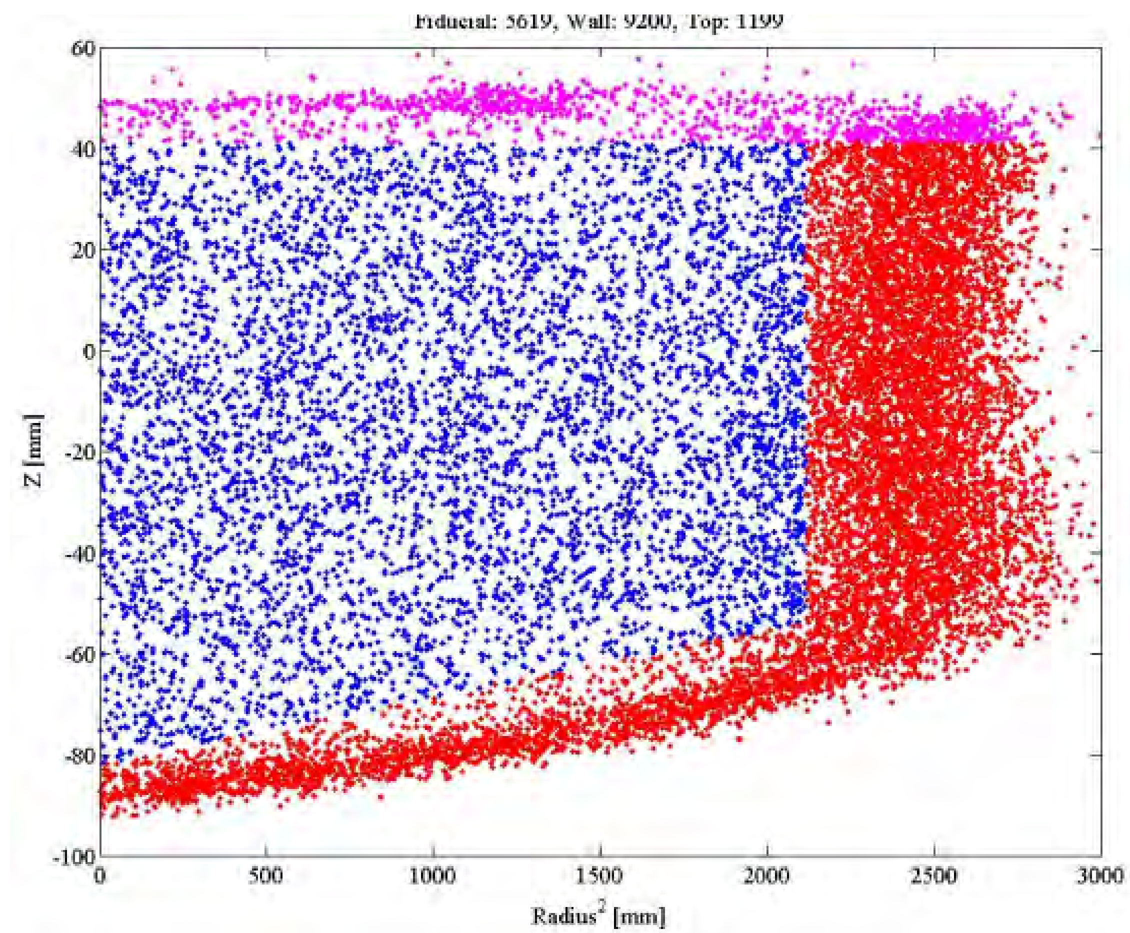
- **Challenge**: reduce α-emitters in fluids to acceptable levels

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

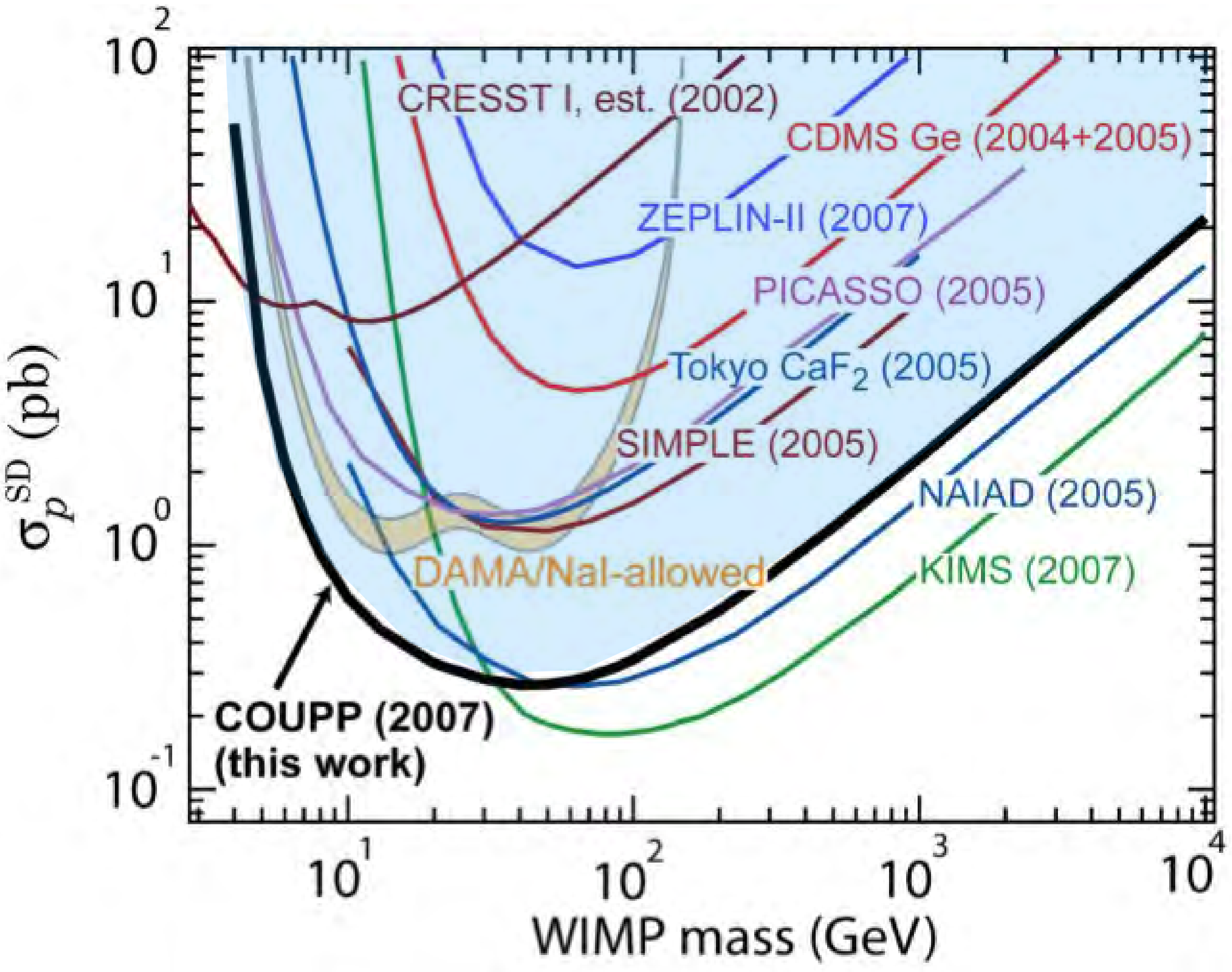






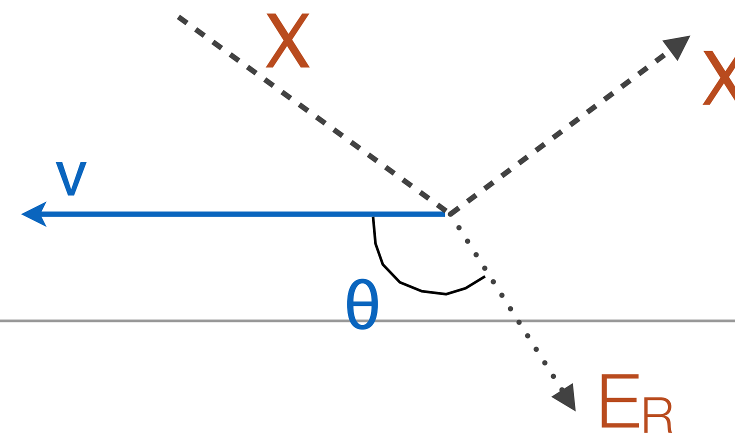
The COUPP Experiment: results and status

- Run with 2 kg detector and reduced backgrounds in 2007/2008
- Larger, low-BG 60 kg module in construction at Fermilab; goal is to reach 3 x 10^{-8} pb for SD WIMP-nucleon cross sections
- Result from 2 kg detector: best SD limit for **pure proton couplings at low WIMP masses**

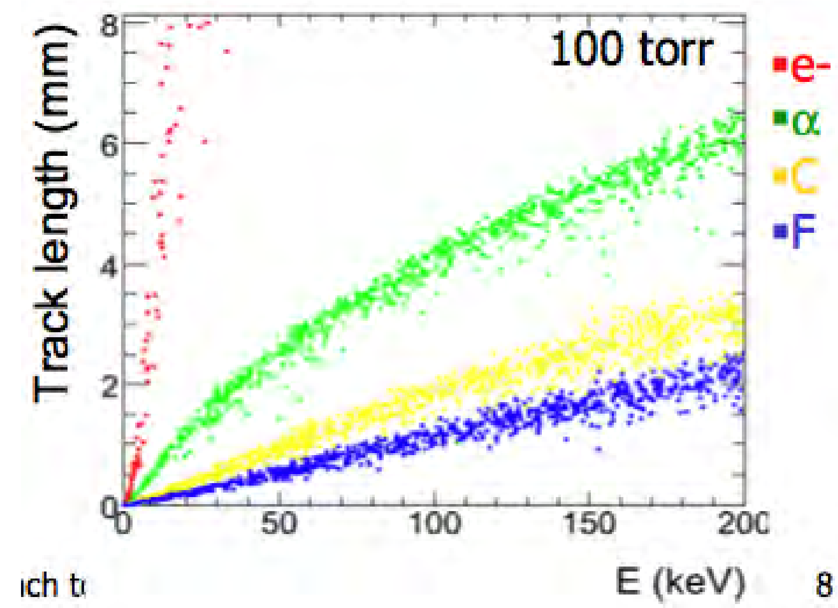


60 kg detector under construction at FNAL

Directional Detectors

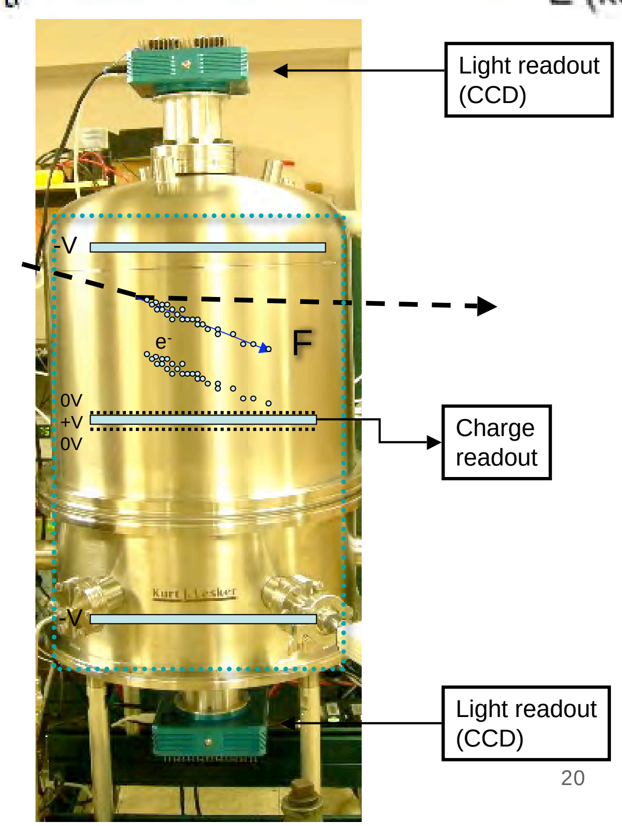


- Would provide robust signature
- 10-100 events needed, depending on direct. capability
- These detectors are still in R&D phase



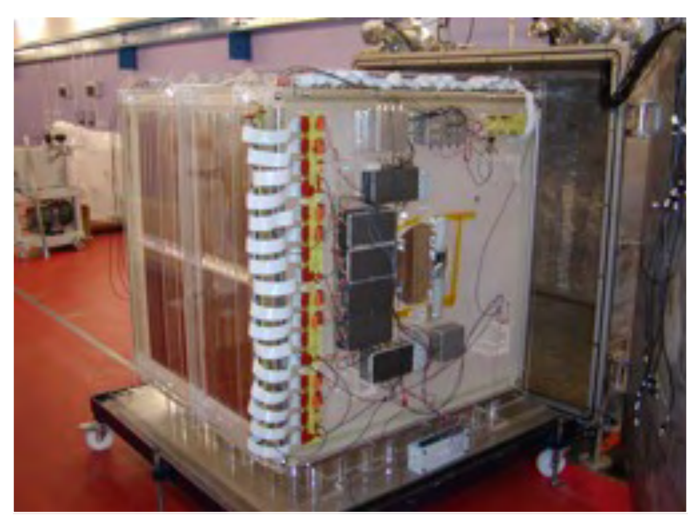
- **DRIFT-II:** negative ion (CS_2) TPC, 1 m^3 40 Torr CS_2 gas (0.17 kg)
- MWPC readout; running at Boulby with reduced Rn backgrounds

- **DMTPC:** CF_4 gas TPC at 50 Torr, 2 x 10^{-2} m^3 at MIT
- PMTs + CCD read-out => 3D-info + E
- 1 m^3 detector being designed (0.25 - 0.5 kg/m^3) for WIPP



- **NEWAGE:** Ar + C_2H_6 micro-TPC
- micro-pixel chamber readout
- test cell at Kamioka

- **MIMAC:** ^3He and CF_4 micro-TPC
- goal: measure tracks + ionization
- test chamber at CEA-Saclay



DRIFT-IIa @ Boulby

Room Temperature Scintillation Experiments

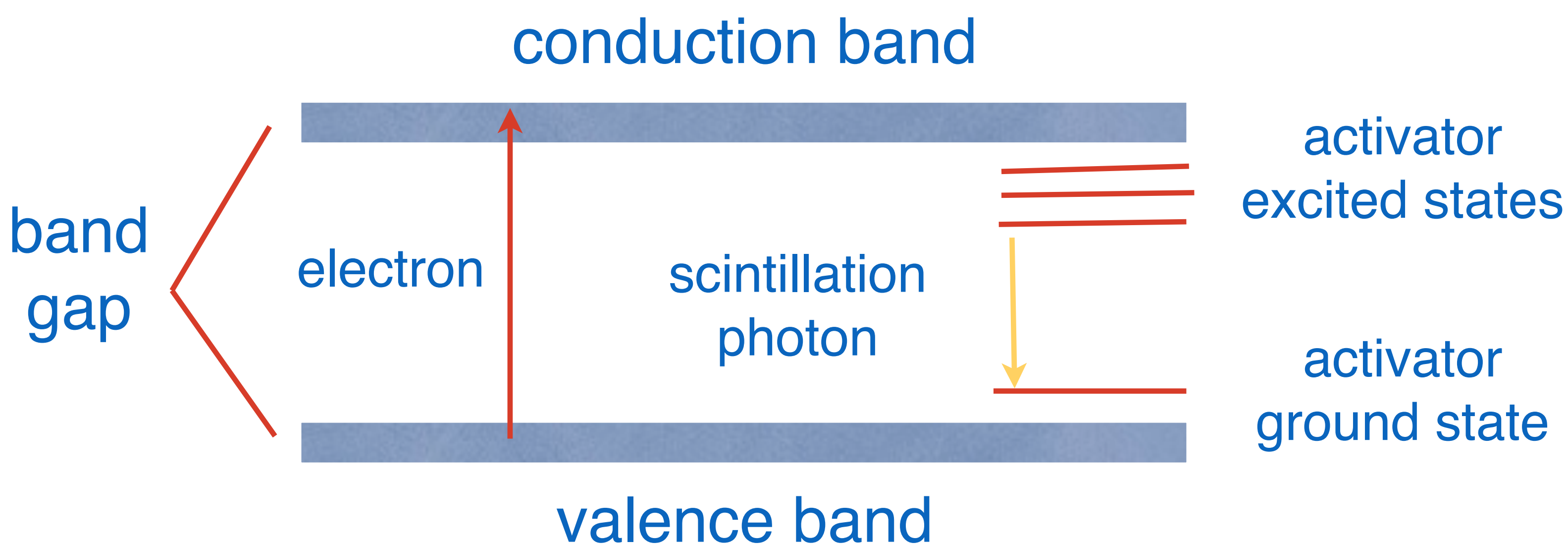
- Detection of scintillation light produced in various materials is a very old technique in particle physics

- **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

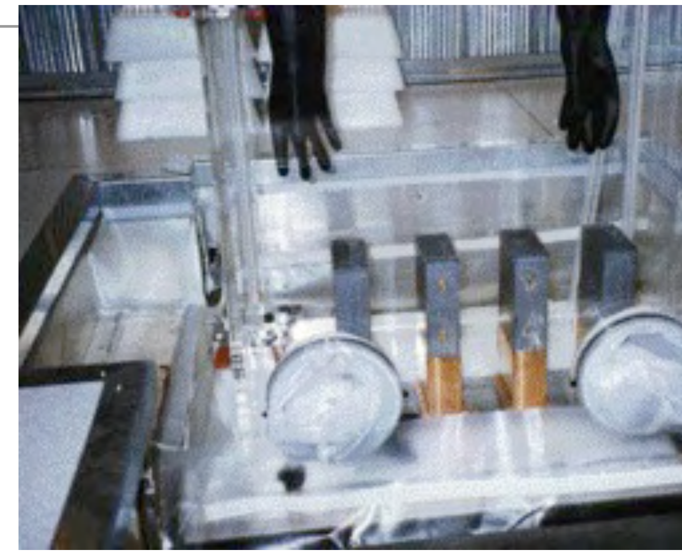
Room Temperature Scintillation Experiments

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

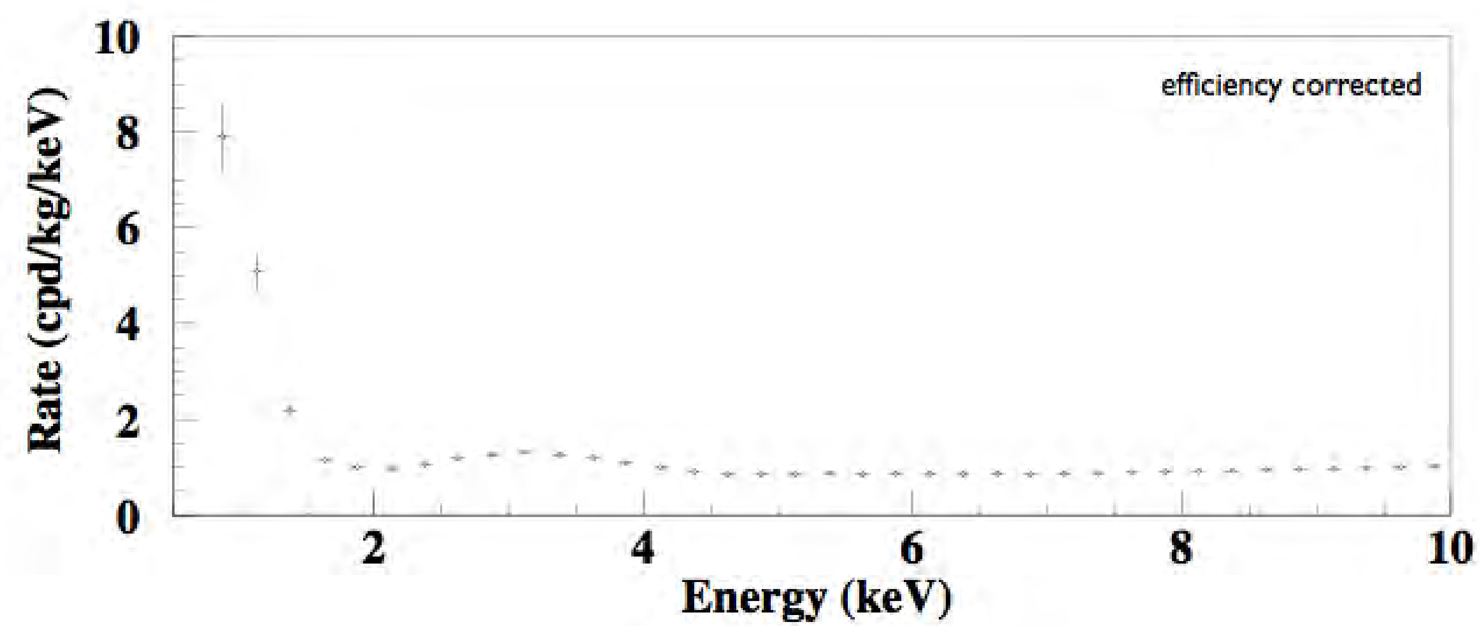


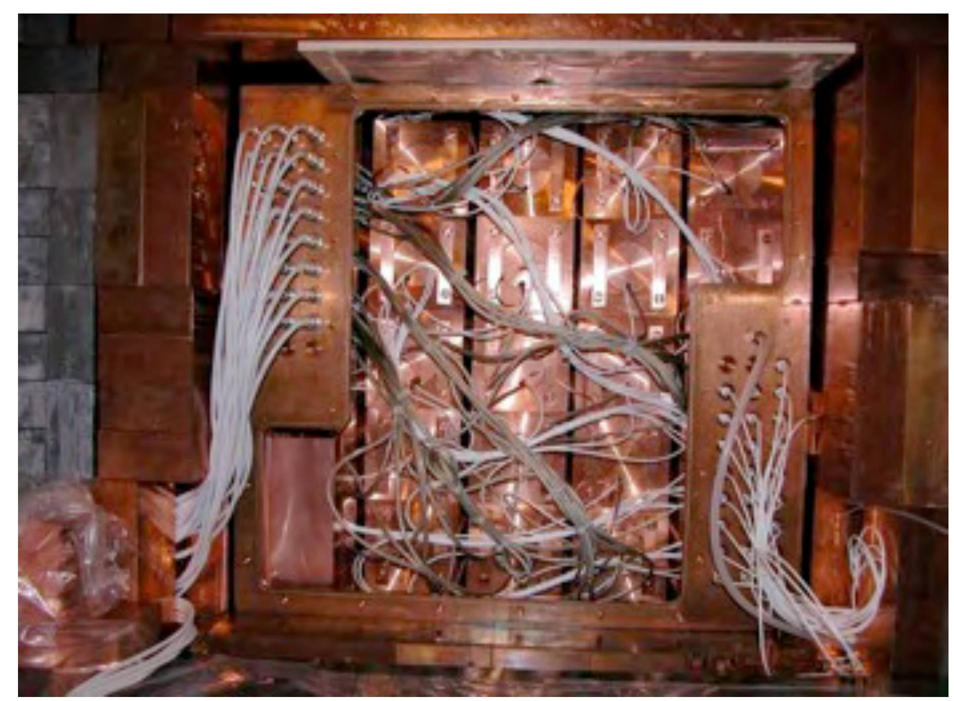
- NaI (Tl): 20 eV to create e^--hole pair, scintillation efficiency ~ 12%
  - ➡ 1 MeV yields 4 x 10^4 photons, with average energy of 3 eV
  - ➡ dominant decay time of the scintillation pulse: 230 ns, λ_{max} = 415 nm
- **No discrimination between electron- and nuclear recoils on event-by-event basis**
- 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

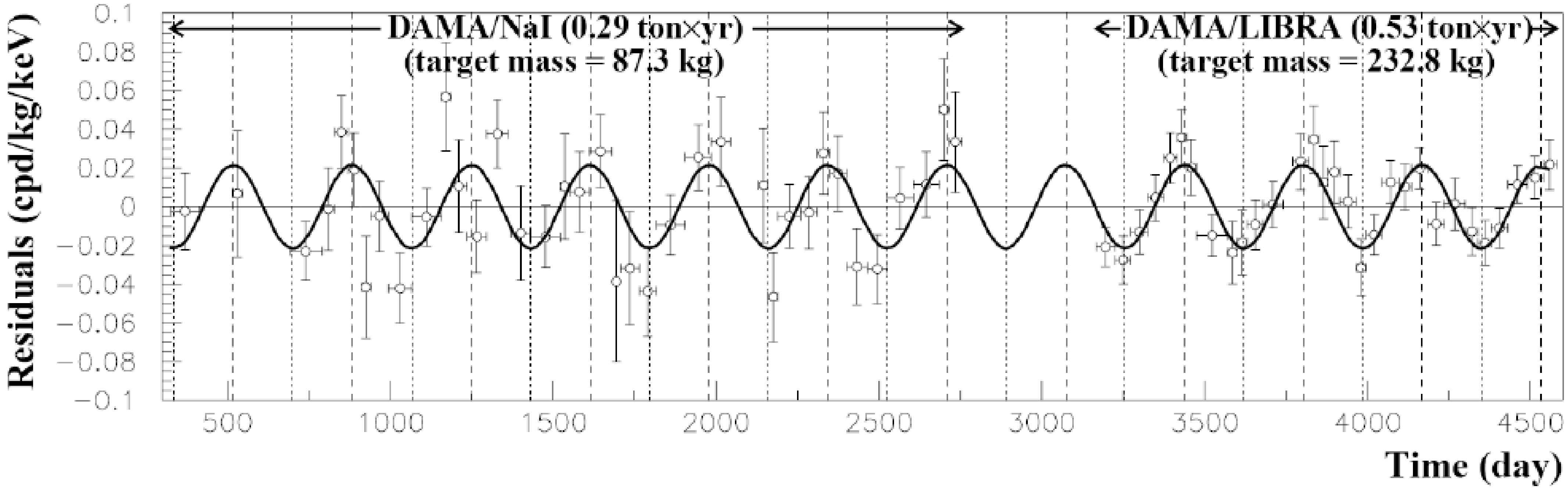




DAMA/LIBRA

- **Modulation of observed event rate confirmed in 2008**
- 25 NaI detectors a 9.7 kg; each viewed by 2 PMTs (5.5-7.5 p.e./keVee)
- 4 years of data taking: 192 x 10^3 kg days

residuals from average rate **2-4 keV**



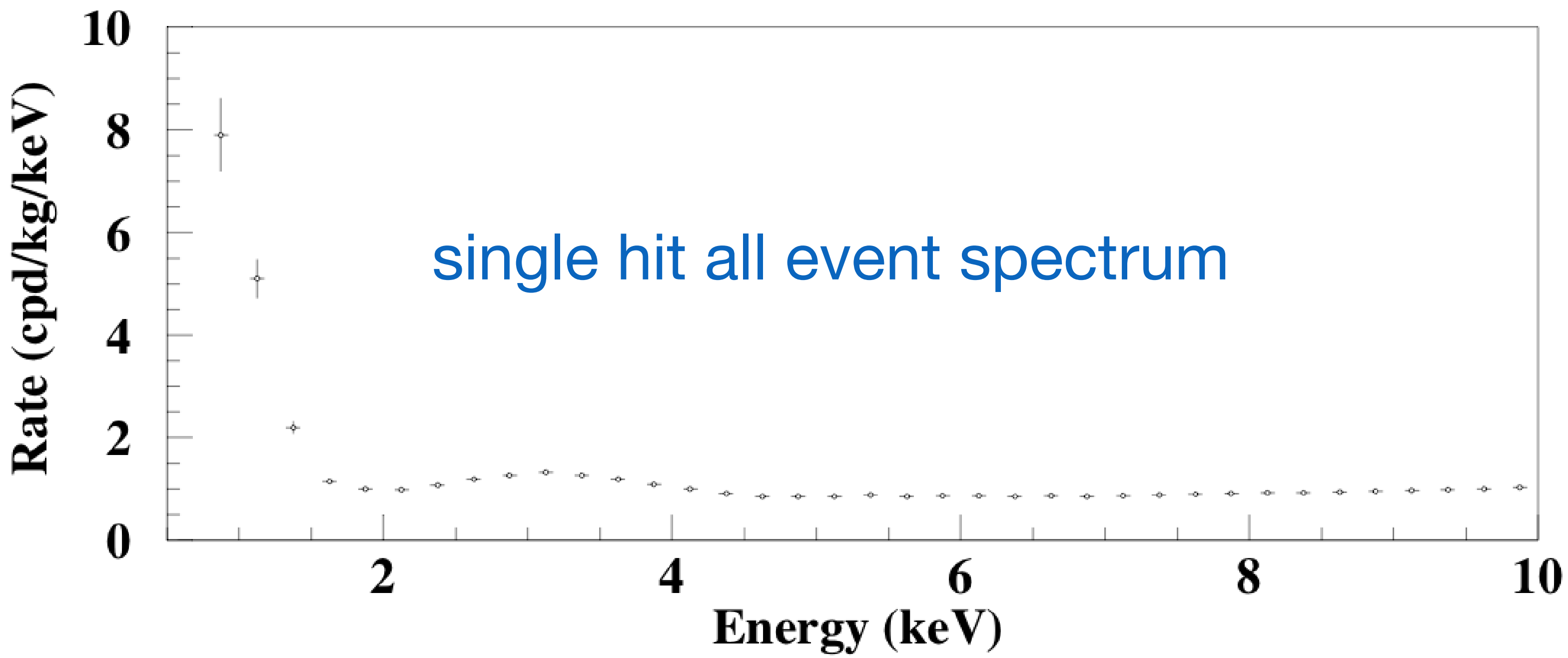
$$\frac{dR}{dE}(E,t) \approx S_0(E) + S_m(E)\cos\omega(t - t_0)$$

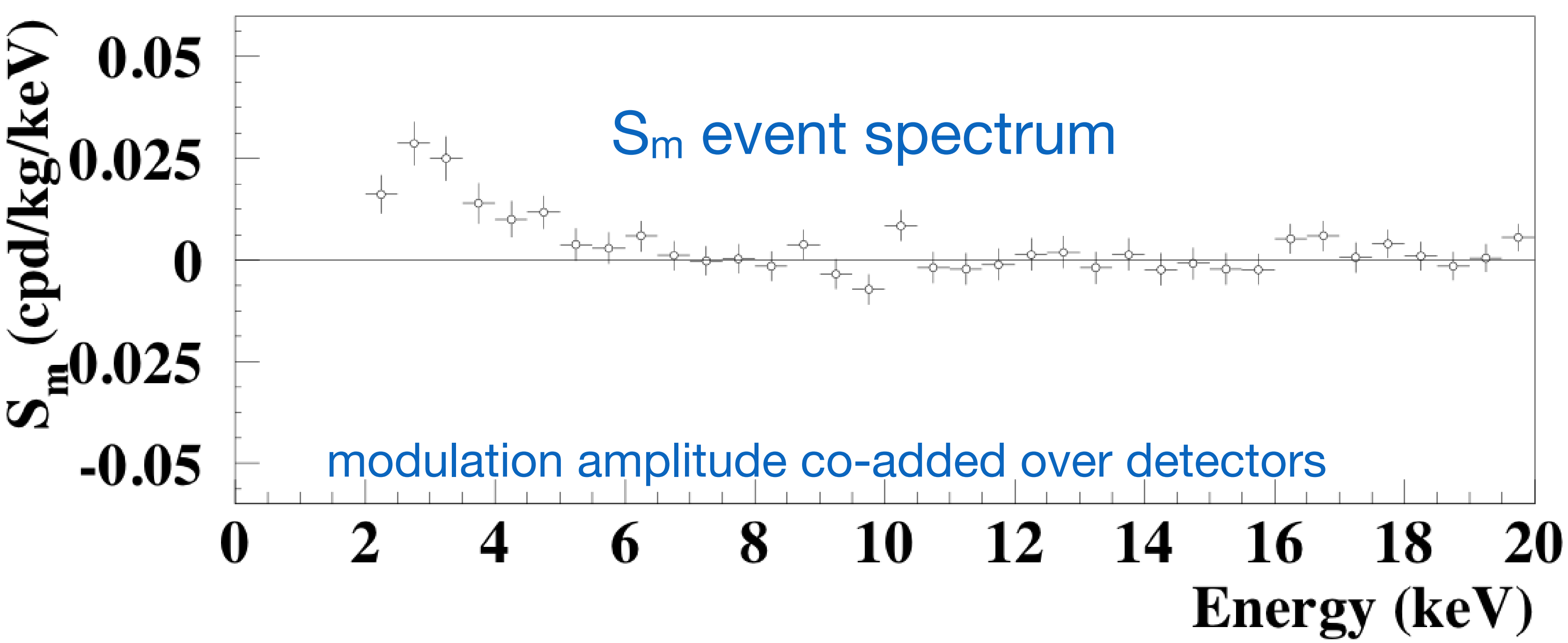
S_m = (0.0215 ± 0.0026) counts/(day kg keV)

t_0 = 144 ± 8 days

T = 0.998±0.003 year

DAMA/LIBRA





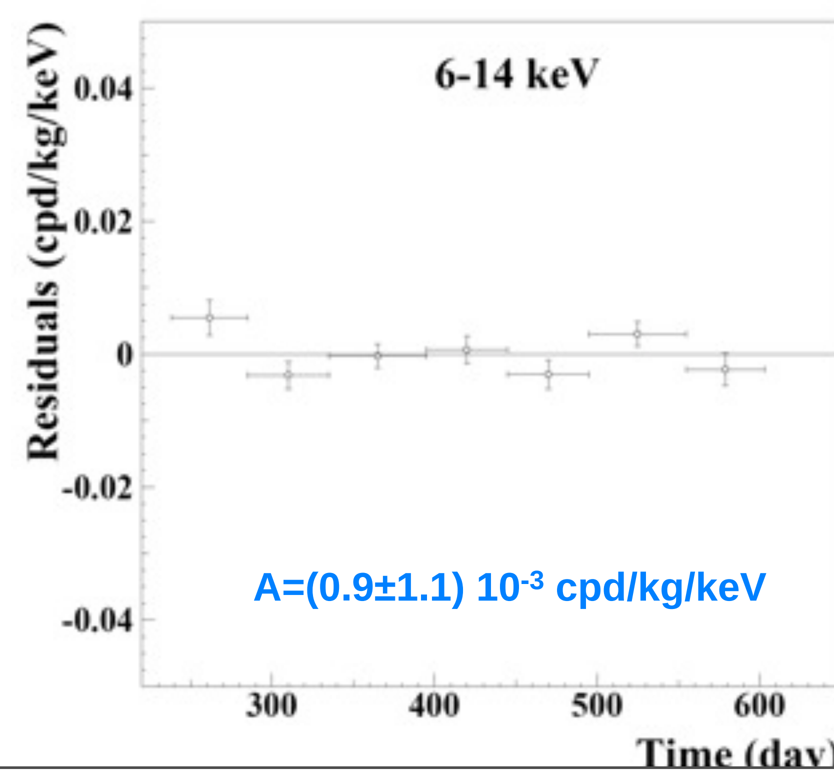
signal in region dominated by PMT noise (does the tail of the noise distribution modulate?)

signal very close to threshold; how stable is the software threshold?

modulation of a peak around 3 keV?

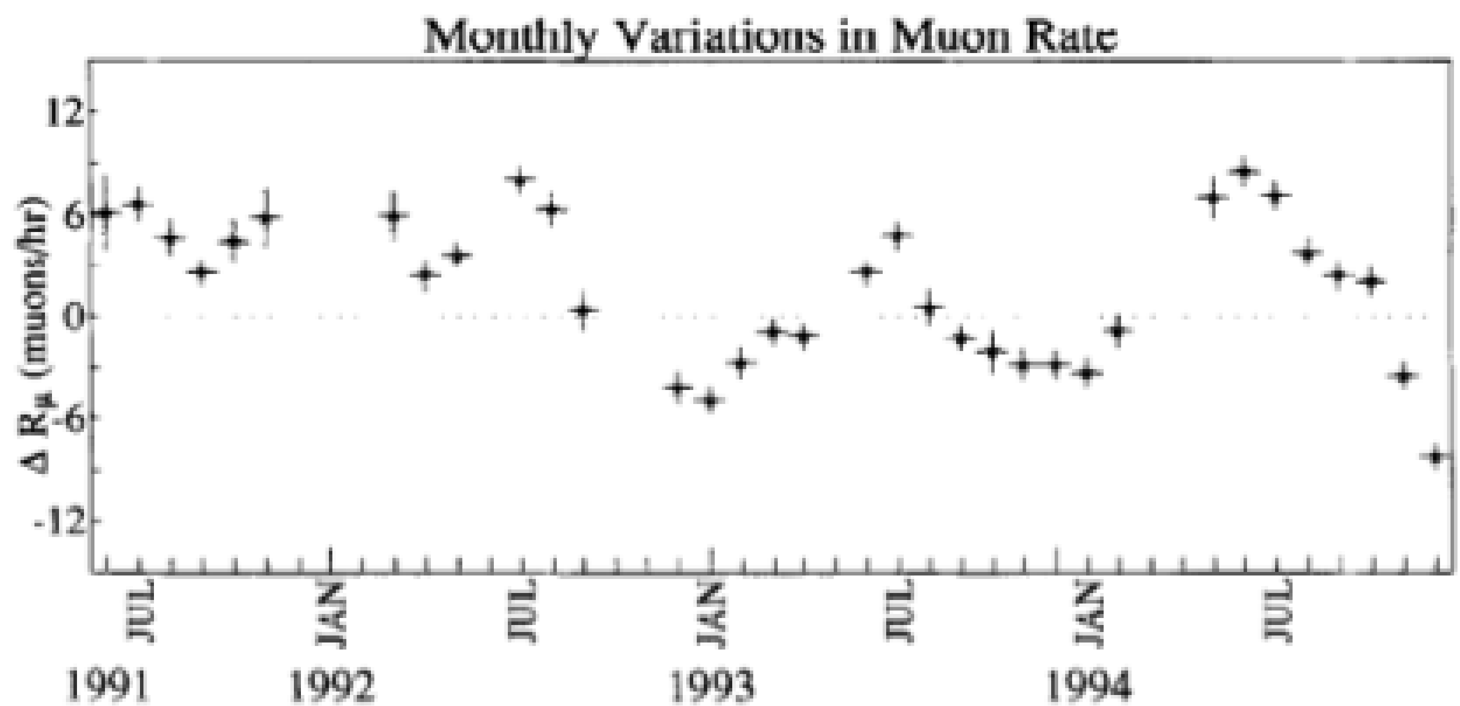
what is the contribution of the ^{40}K 3 keV X-ray in the singles spectrum?

no modulation above 6 keV



Annual modulation of muons at LNGS

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

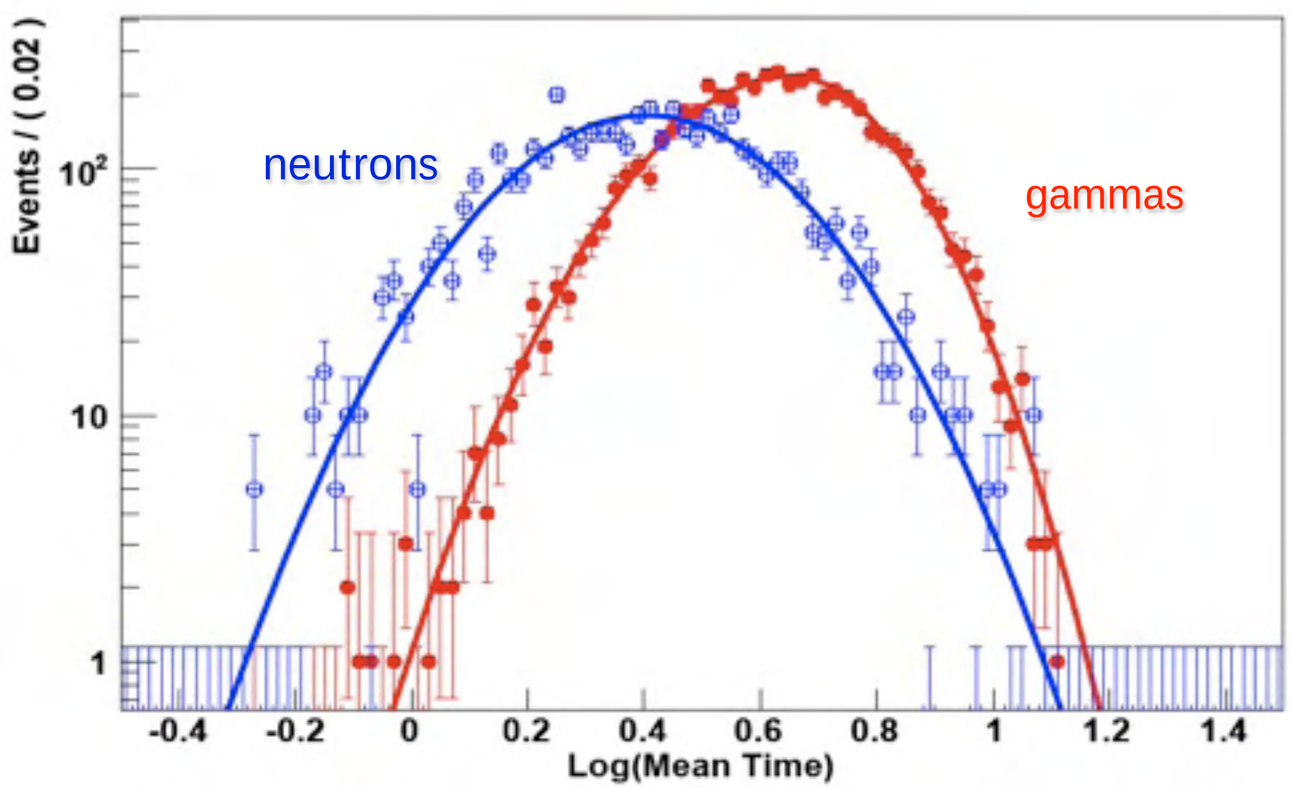


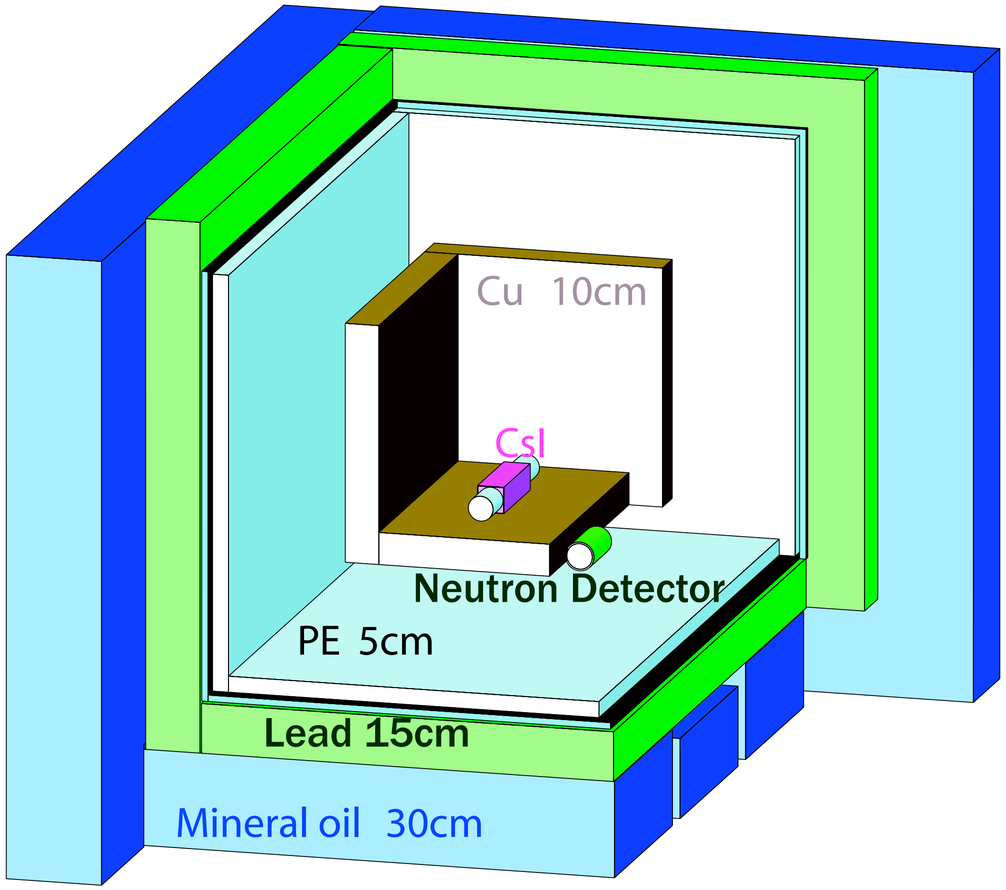
- DAMA: fast, μ-induced n-rate is not sufficiently high to produce observed rate modulation;
- How about metastable isotope production by μ- spallation reactions in NaI? (with $T_{1/2}$ > 500 μs trigger hold-off time, and ~ 3 keV emission) - first estimates show that the effect may be too small considering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

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

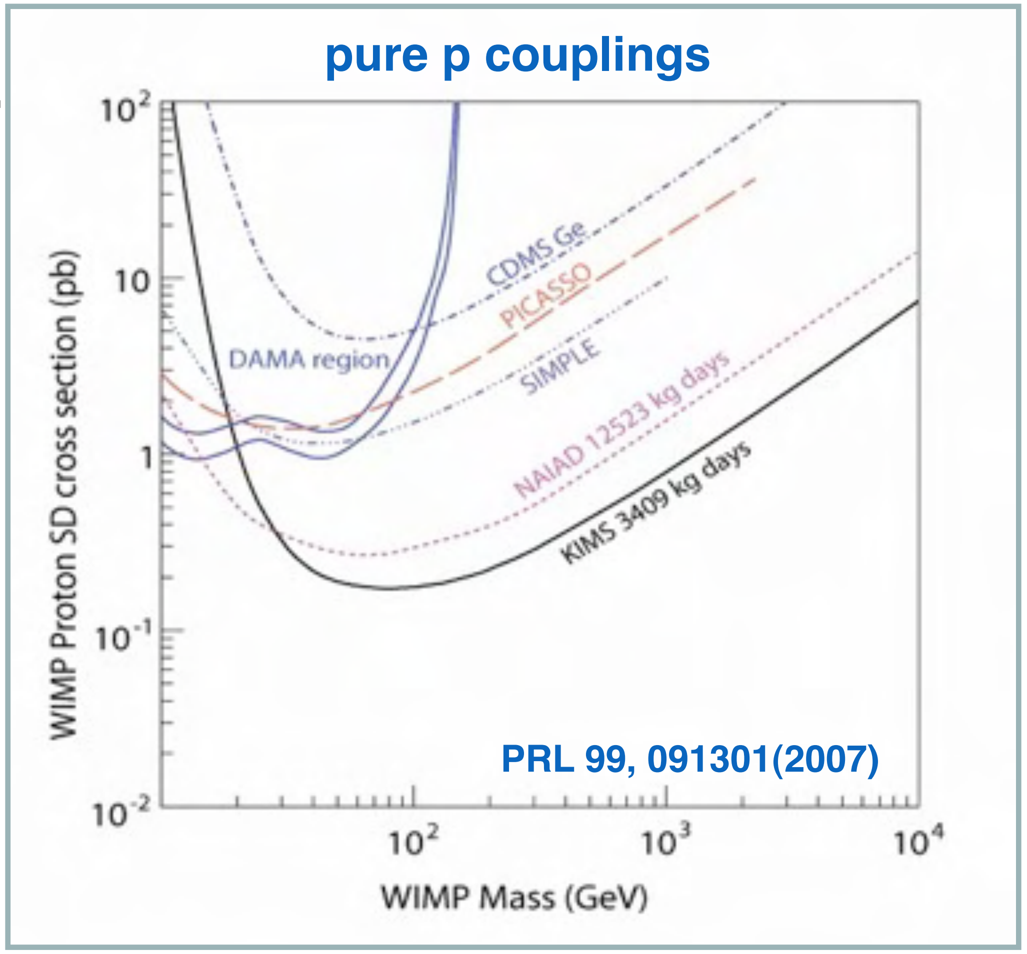
- Background reduction by pulse shape discrimination

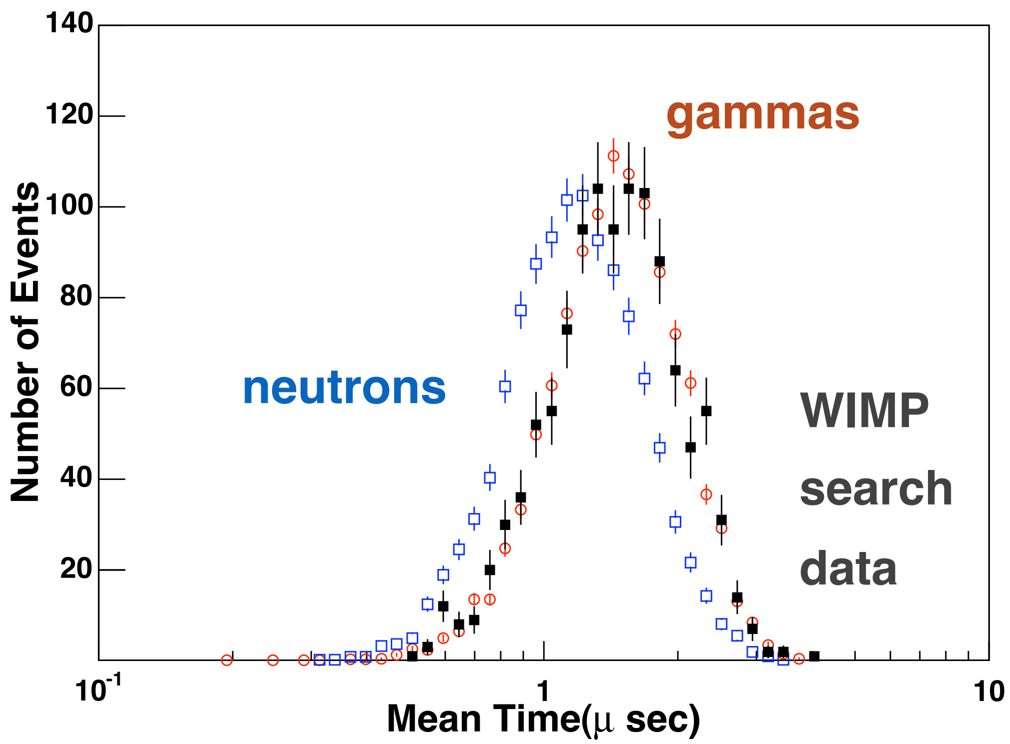




The KIMS Experiment

- **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





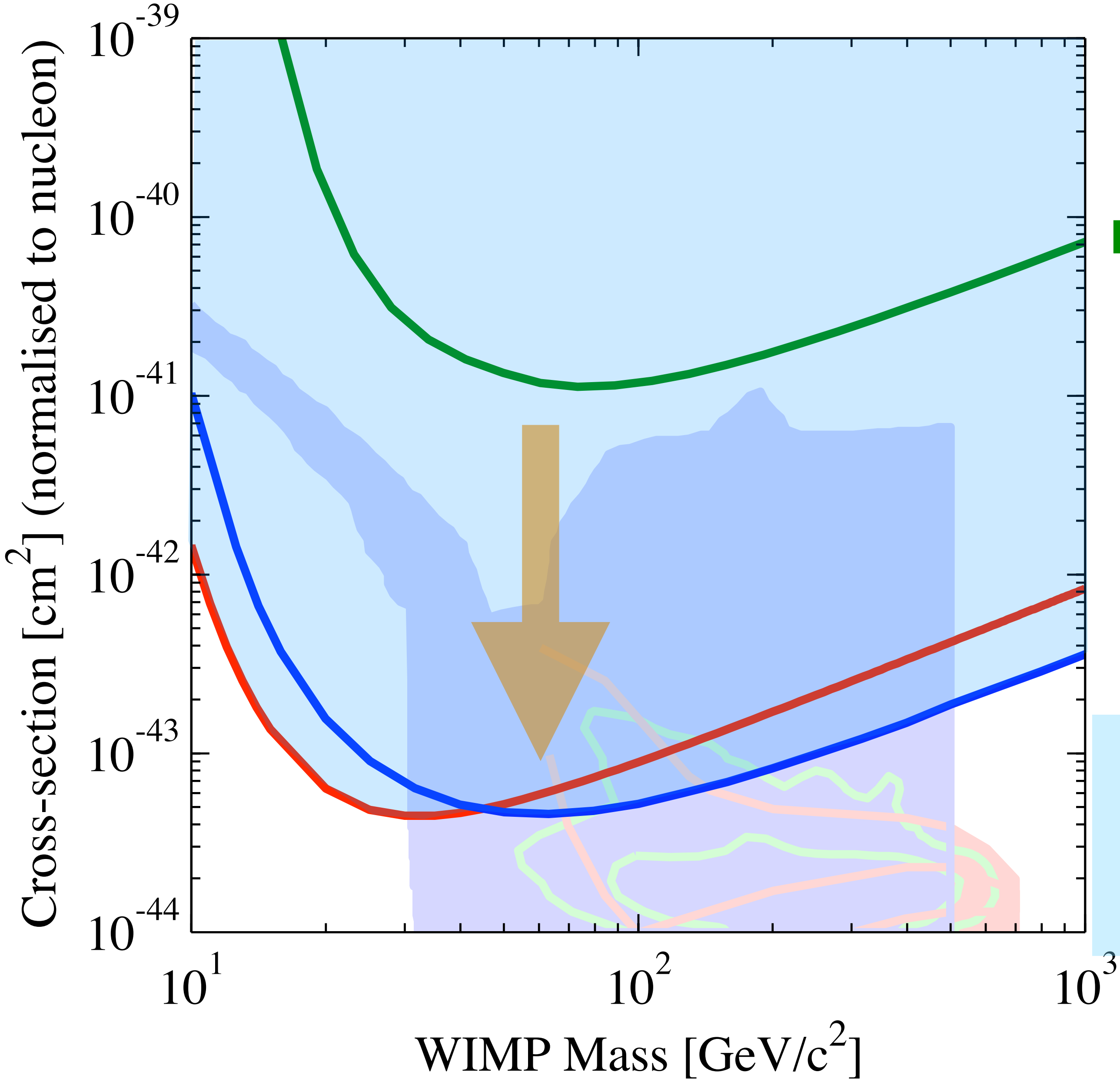
Current status:

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

Summary/Outlook (I)

- Many different techniques/targets are being employed to search for dark matter particles
- Steady progress in the last ~ 10 years: **> factor 100 increase in sensitivity!**



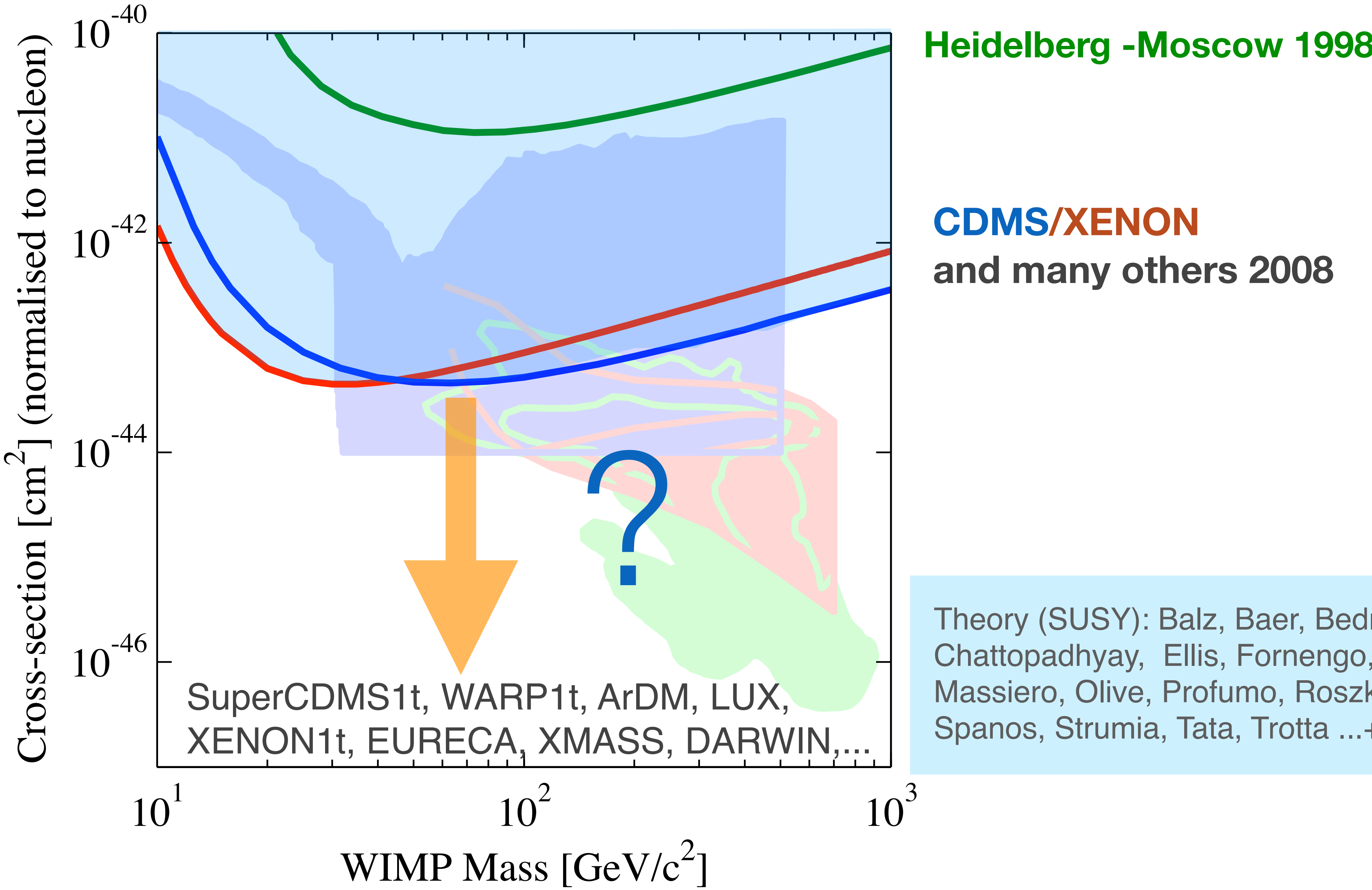
Heidelberg -Moscow 1998

CDMS/XENON
and many others 2008

Theory (SUSY): Balz, Baer, Bednyakov, Bottino, Cirelli, Chattopadhyay, Ellis, Fornengo, Giudice, Gondolo, Massiero, Olive, Profumo, Roszkowski, Ruiz, Santoso, Spanos, Strumia, Tata, Trotta ...+ many others

Summary/Outlook (II)

- Experiments are probing some of the theory regions for WIMP candidates
- Next generation projects: should reach the ≲ 10^{-10} pb level => WIMP (astro)-physics



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General Conclusions

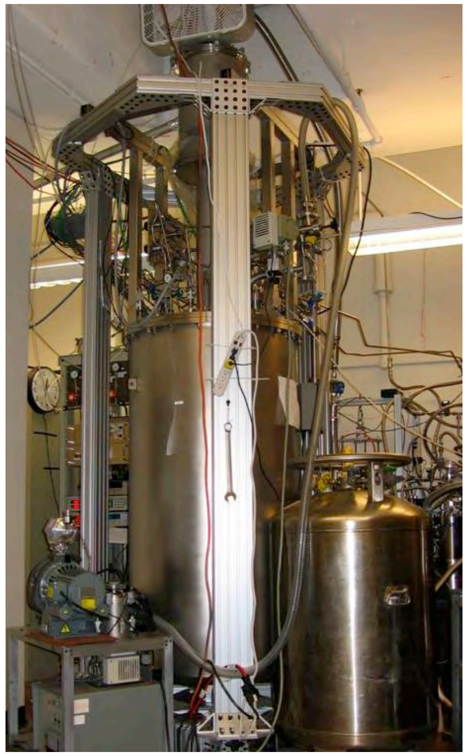
- Strong evidence for Cold Dark Matter (galaxies, clusters, LSS, CMB, etc)
- Cold Dark Matter: likely new, long-lived particles produced in the early Universe
- Neutral, massive and weakly interacting particles are independently predicted by physics beyond the standard model, needed to stabilize the weak scale
- Dark matter particles of galactic origin can elastically scatter from nuclei in ultra-low background, low energy threshold terrestrial detectors
- The energy of the recoiling nucleus is transformed into a charge, light or phonon signal and could be detected with ultra-sensitive devices operated in underground laboratories
- A possible signal has to be consistent with a series of predicted 'signatures' in order to qualify as WIMP dark matter
- So far there is one claim for a signal, not confirmed by other, independent experiments
- Existing experiments can probe WIMP-nucleon cross sections down to ~ 10^{-7} pb
- Experiments under construction and future, ton-scale detectors should probe most of the theoretically interesting parameter space

End

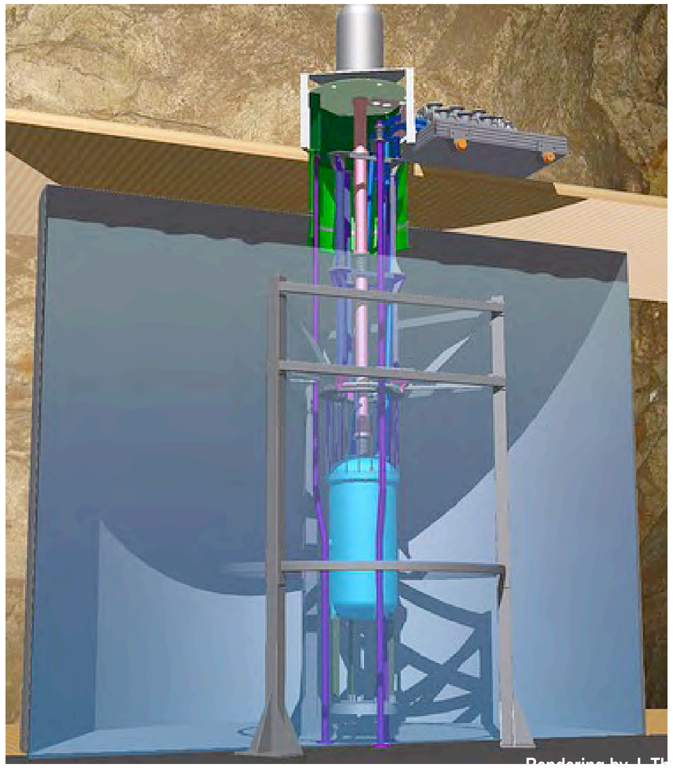
The LUX Experiment

- **350 kg dual phase LXe TPC (100 kg fiducial), with 122 PMTs in large water shield with muon veto**
- LUX 0.1: 50 kg LXe prototype with 4 R8778 PMTs was assembled and tested at CWRU
- PMTs: 2” diameter, 175 nm > 30% QE; radioactivity: U/Th ~ 9/3 mBq/PMT
- LUX 1.0: full detector to be operated above ground at Homestake in fall 2009
- LUX 1.0: to be installed at Homestake Davis Cavern, 4850 ft in spring 2010 (in 8 m ∅ water tank)
- **Predicted WIMP sensitivity: 7×10^{-10} pb after 10 months**

R8778 PMT



LUX 0.1



In water shield @ Homestake 4850 ft level

The CDMS Phonon Signal

Particle interaction ⇒ THz (~ 4 meV) phonons

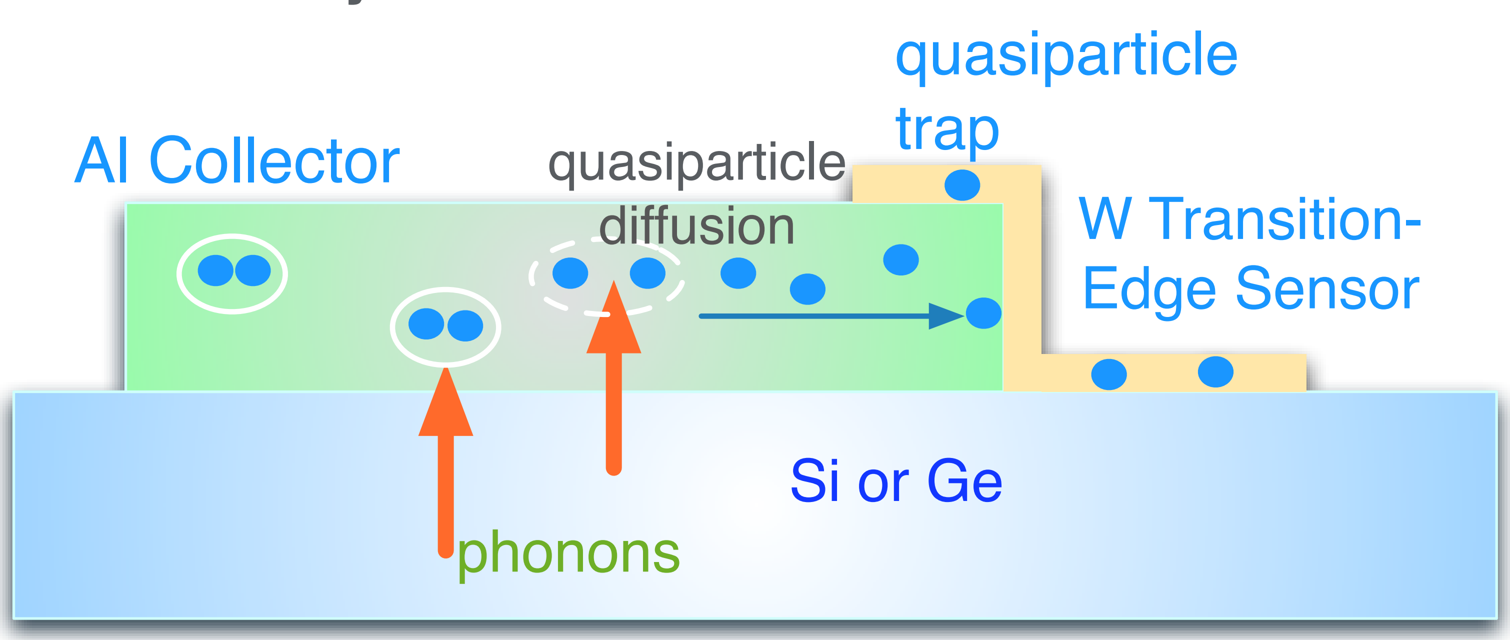
Phonons: propagate to SC Al-fins on the surface, break Cooper pairs ⇒ **quasiparticles**

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")