# Direct Detection using Other Techniques

Sunil Golwala

Caltech

The Hunt for Dark Matter

May 11, 2007

## or,
## Direct Detection without PMTs

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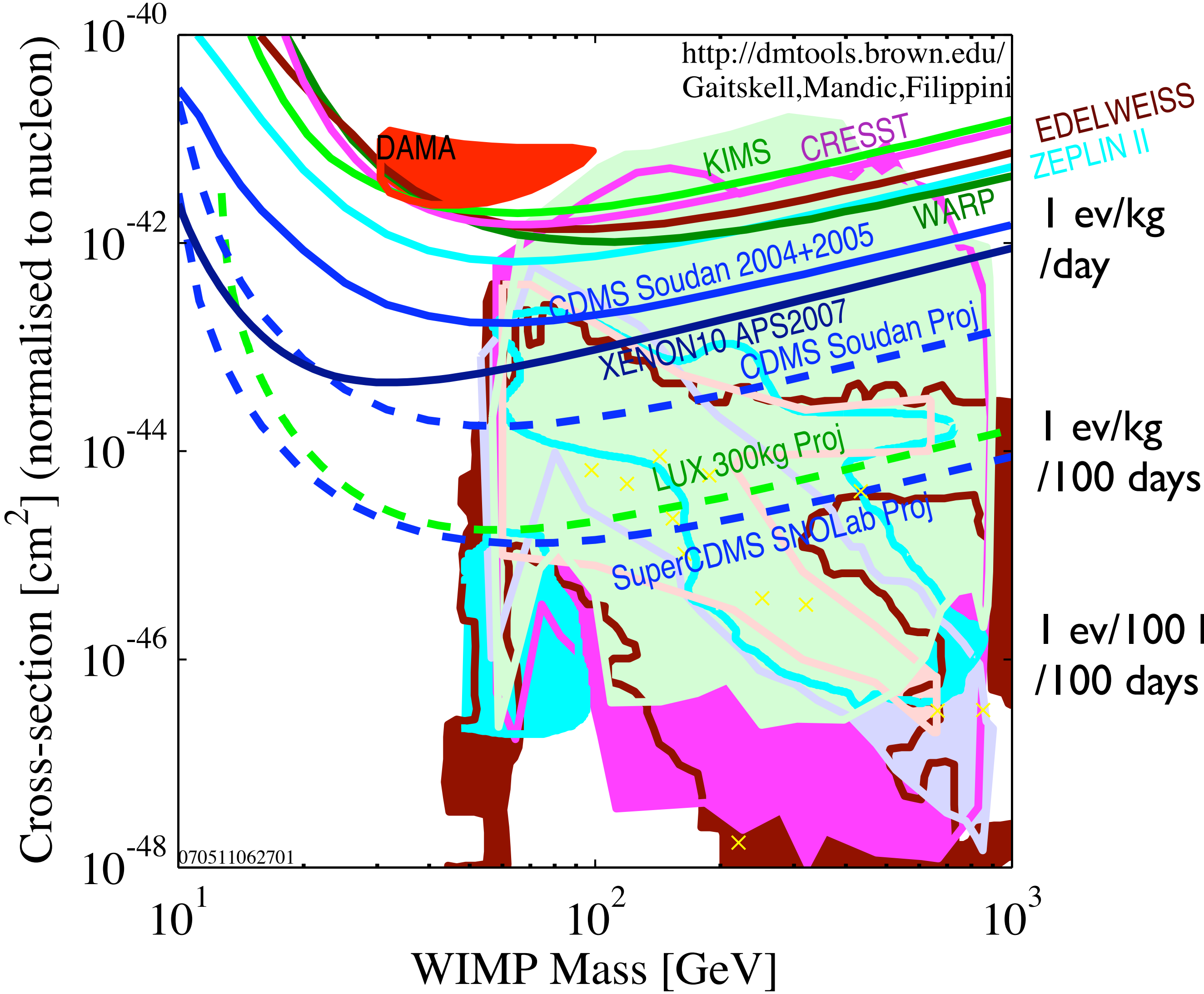
# Overview




1 ev/kg /day

1 ev/kg /100 days

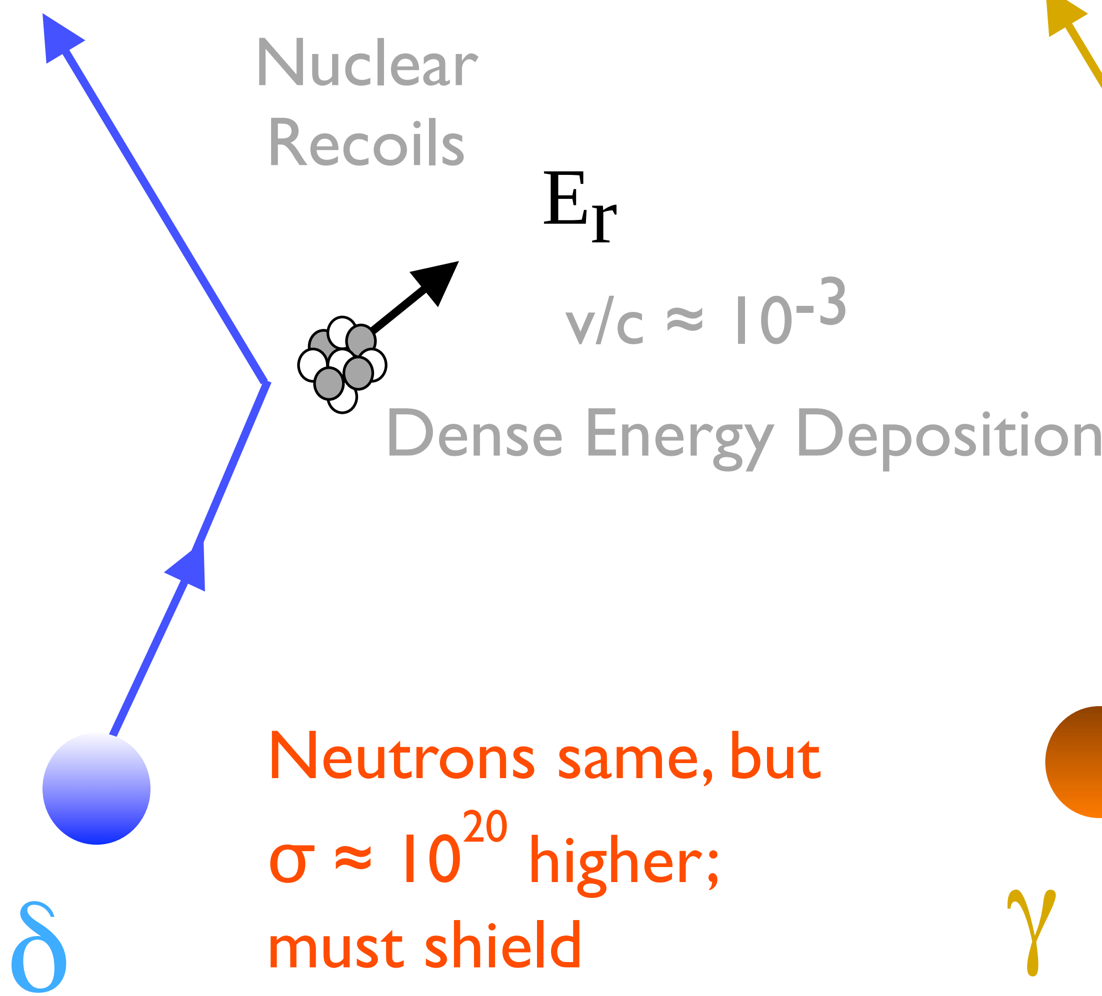
1 ev/100 kg /100 days

where the coming generation is aiming, $10^{-9}$-$10^{-8}$ pb

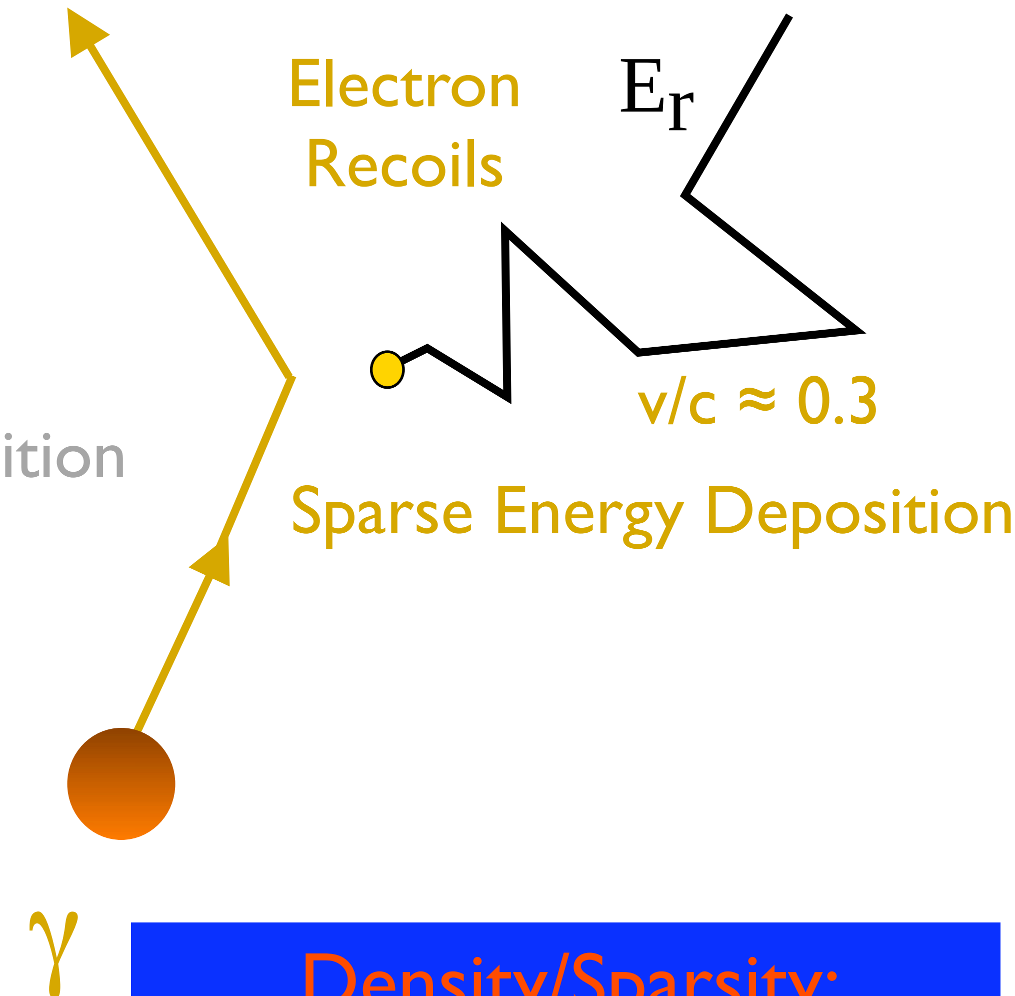
- Many techniques are competitive
- Most use nuclear recoil discrimination
- Apologies in advance: see experiment talks for full collaboration lists, etc.

# Nuclear Recoil Discrimination

## Signal




## Background



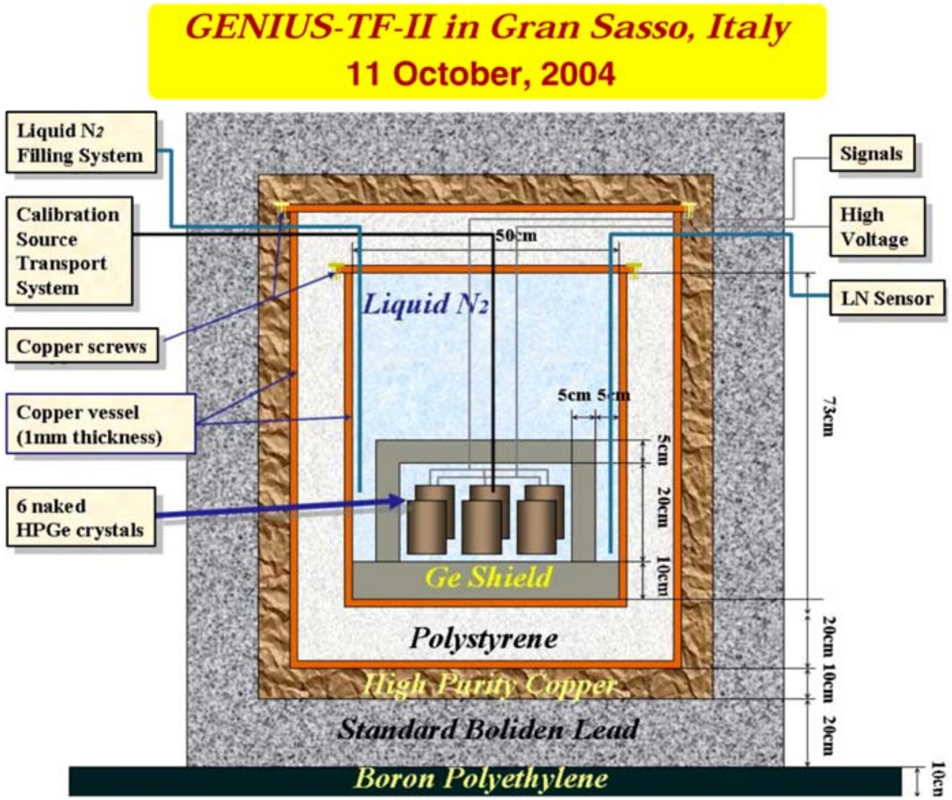

**Density/Sparsity: Basis of Discrimination**

# Non-PMT Experiments

- High-purity Ge spectrometers: GENIUS
  - No discrimination, but reduce bgnds and exploit multiple scattering to reject.
- Metastable bubble-chamber detectors: COUPP, PICASSO
  - Transition out of metastable state only occurs for dense energy depositions.
- Phonons + Ionization, Scintillation: CDMS, EDELWEISS, CRESST, ROSEBUD
  - Phonons provide total energy.
  - Electronic excitation channel provides measure of energy deposition density: electronic signal usually smaller/suppressed by higher recombination rate at high density
- Time Projection Chambers: DRIFT, MIMAC-He3
  - Track morphology very good measure of density of deposition.
  - Additional prospect of directionality via recoil track.
- 3He bolometers

# GENIUS

- Reduce the backgrounds
  - Suspend standard Ge spectrometers in very pure cryogenic liquid (LN) with minimal support structure.
  - Ultrapure medium and minimal non-detector mass reduces bgnds.
- 15 kg Ge detectors installed and run into 2006

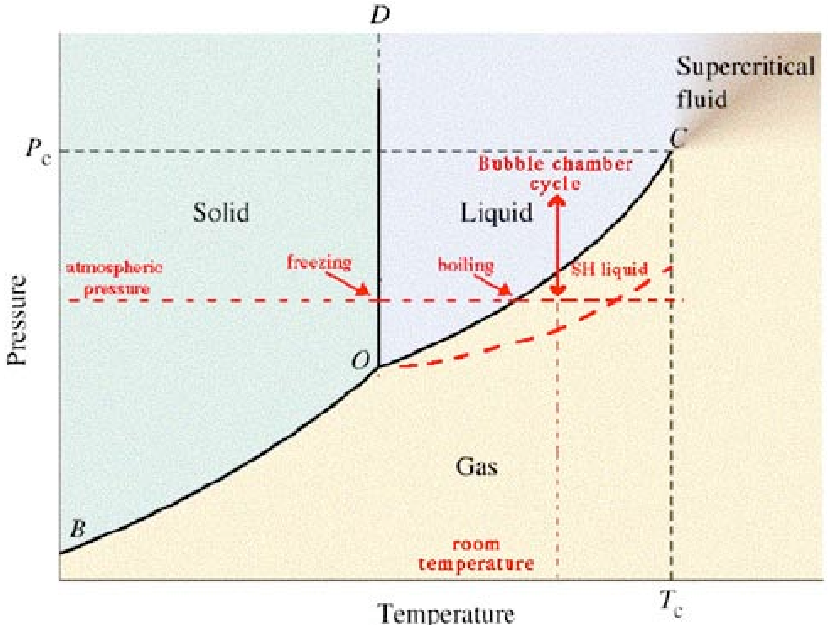


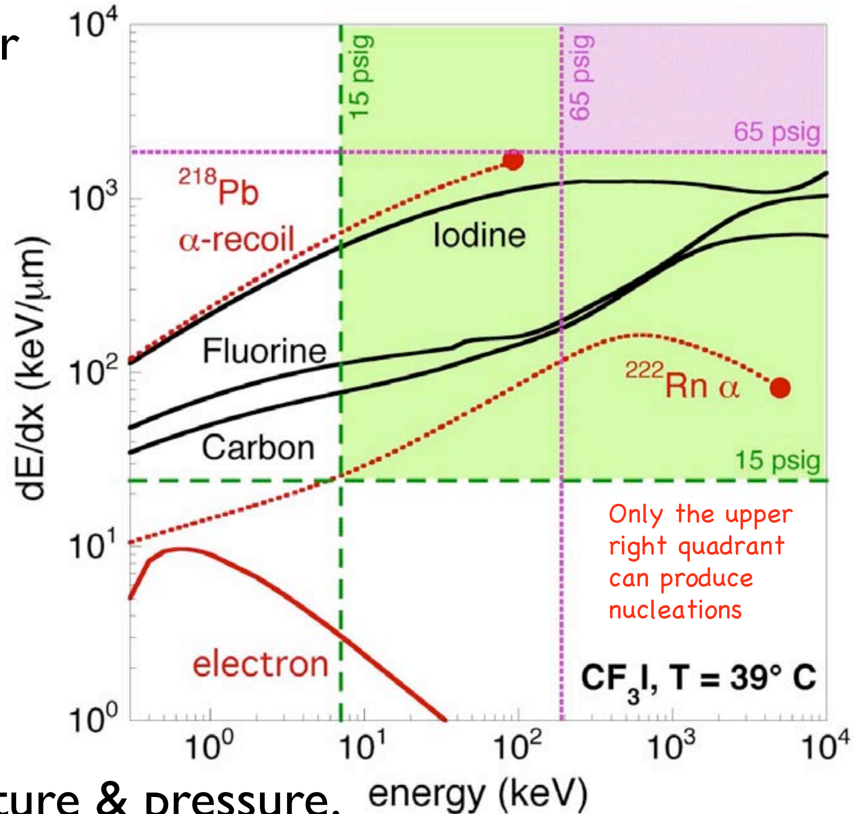
# GENIUS

- GENIUS-TF ran 2003-2006 in various modes
- Difficulties:
  - Bgnd surprisingly high: 0.2 cts/kg/day, 33-150 keVr (~0.05 cts/kg/day over 30 keVr). Due to $^{222}$Rn diffusion into LN supply?
    - Corresponds to 0.25 mBq/m$^3$ in precursor $N_2$ gas.
    - LN purified by low-temperature adsorber system built with Borexino.
    - Radon content in purified LN expected to yield bgnd 400x lower.
    - Diffusing into transport lines on the way from Borexino plant?
  - Leakage currents show degradation over time; detectors' max HV degrading
    - Degradation of electrodes due to ion gettering by Ge from LN?
    - GERDA has seen similar degradation due to removal of detectors from cryostat between runs, can be prevented with right handling.
- GENIUS seems to be stalled due to these and other problems; but GERDA collaboration has formed and is making good progress toward $0\nu\beta\beta$ experiment
  - Proposed to LNGS 2004
  - Vessel and cryostat delivery in late 2007, begin running in early 2009
  - LAr instead of LN to improve shielding; but $^{39}$Ar $\beta$ at 1 Bq/kg will render experiment insensitive to DM; fine for $0\nu\beta\beta$ at 2 MeV

# Metastable Bubble Chamber Detectors: COUPP

- Superheated liquid
- Energy density effect: ER deposition density too small to nucleate bubbles
- Excellent rejection of ERs: $>10^{10}$ @ 10 keVr threshold demonstrated for COUPP

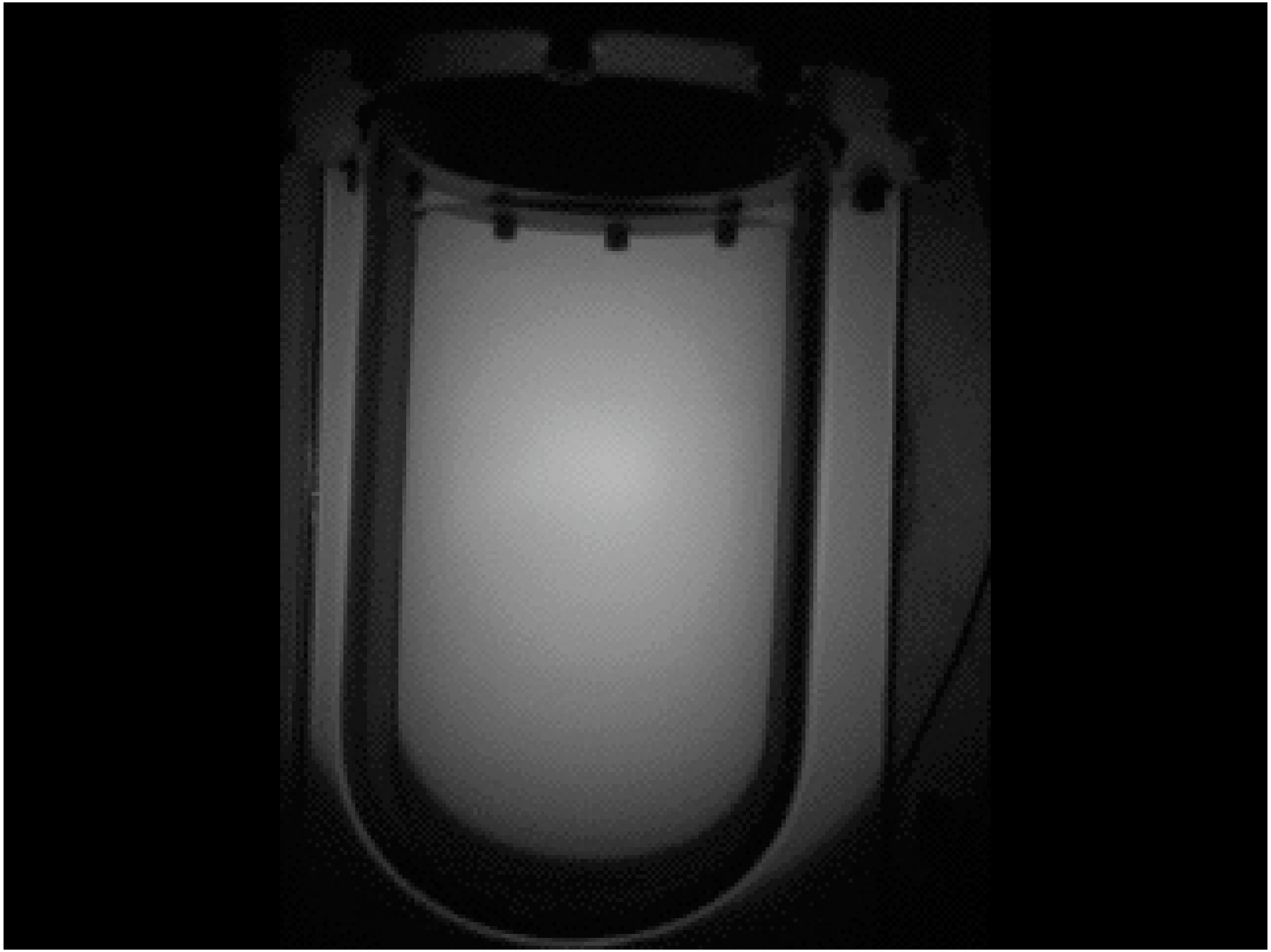



- Threshold detector, controlled by temperature & pressure.
- Video and/or acoustic readout.
- Spin-independent (I and Br) and spin-dependent (F) targets work, changing target to check rate scaling with nucleus relatively easy.
- Scalable; many inexpensive modules to do energy scan

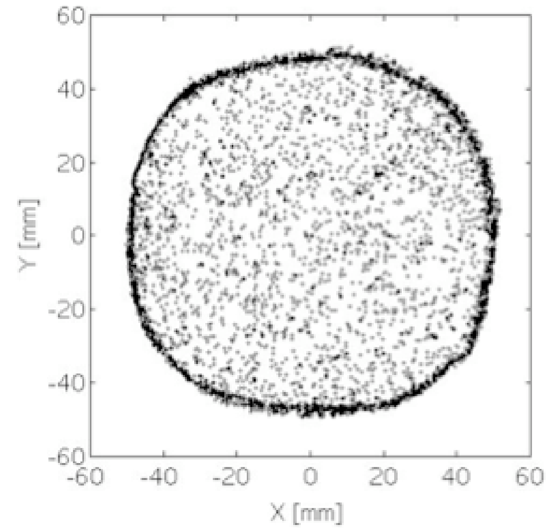
# COUPP

- In action: triple neutron scatter.

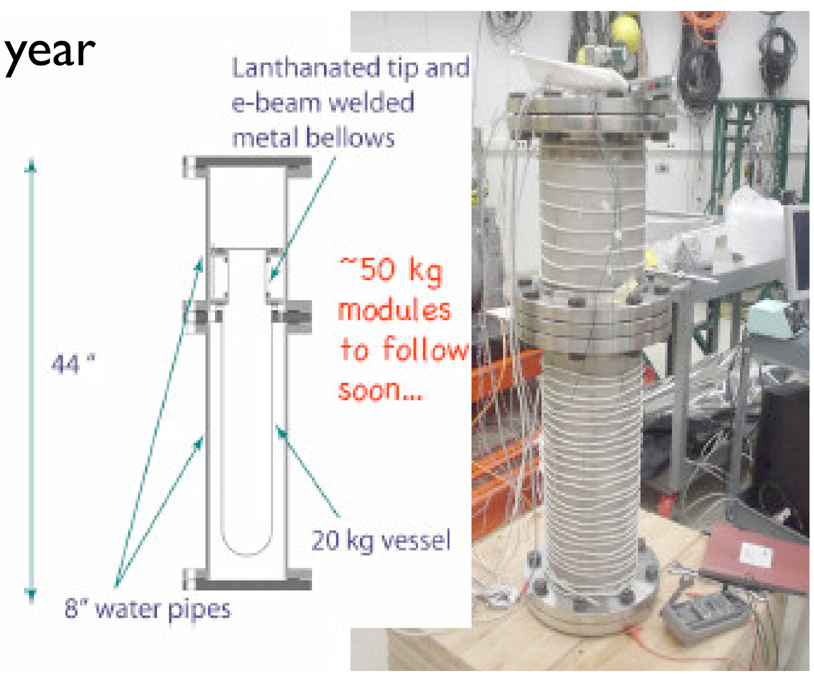


# COUPP

- Ran 2 kg detector at 300 mwe in MINOS near detector hall during 2006
- Vessel background: $\alpha$'s emitted from walls
  - $^{222}$Rn exposure of glass vessel; presumably $^{210}$Pb plateout
  - Easily cut by position, but decreases live time.
- Liquid background: ~16 ev/kg/day > 10 keVr
  - Continuous $^{222}$Rn emanation from materials (O-rings, weld joings), diffuses into liquid and $\alpha$-decays.

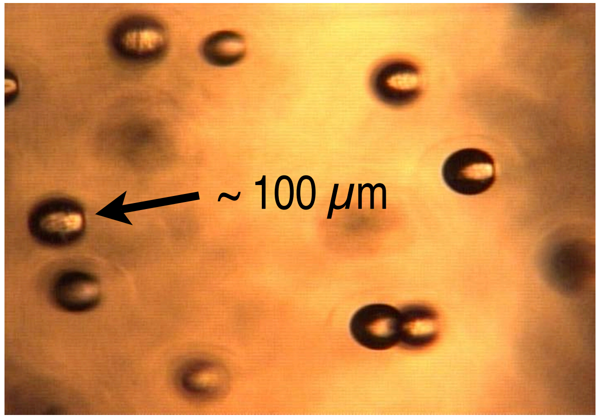


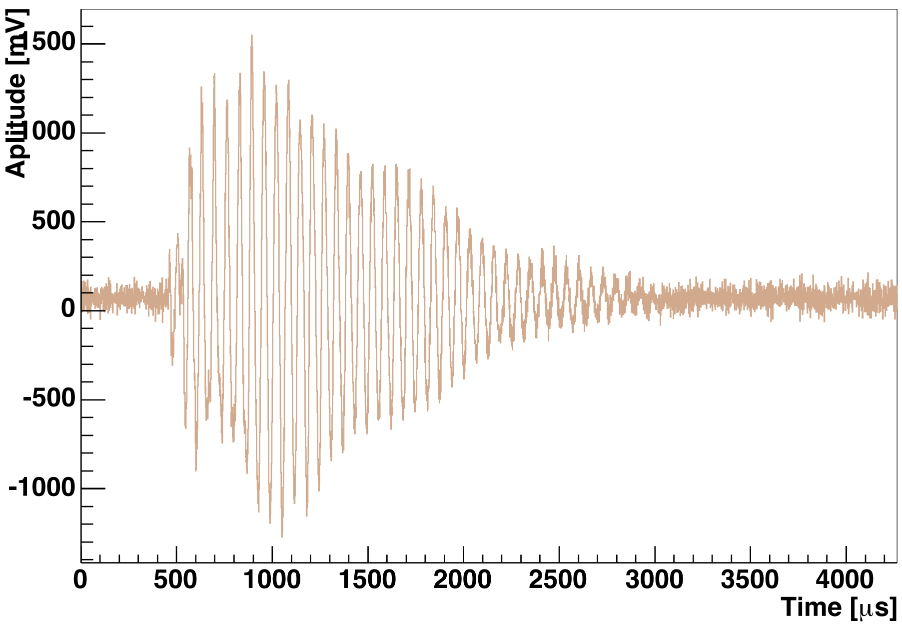

- Cleaning up these problems, new 2 kg run this year
- Sensitivity:
  - Spin-ind: competitive with current best limits if U/Th can be brought down to $10^{-15}$; $10^{-17}$ has been achieved by SNO and Borexino
  - Spin-dep: can do as much as 2.5 orders of magnitude better than current limits with same U/Th reduction
- Approved for construction of 80-kg module, ready at end of 2007, can reach $3 \times 10^{-8}$ pb




- Beginning to explore deeper sites, but need to clean up Rn before n bgnd is limiting

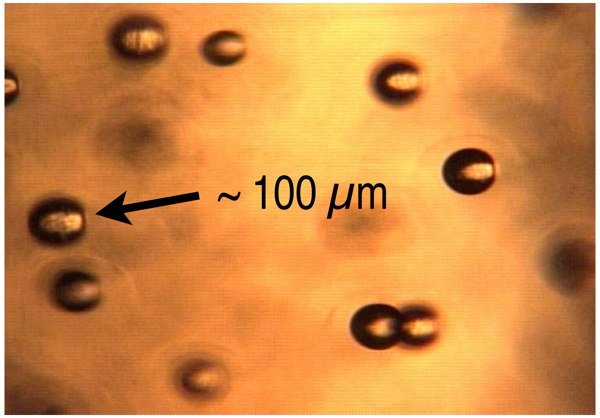
# PICASSO

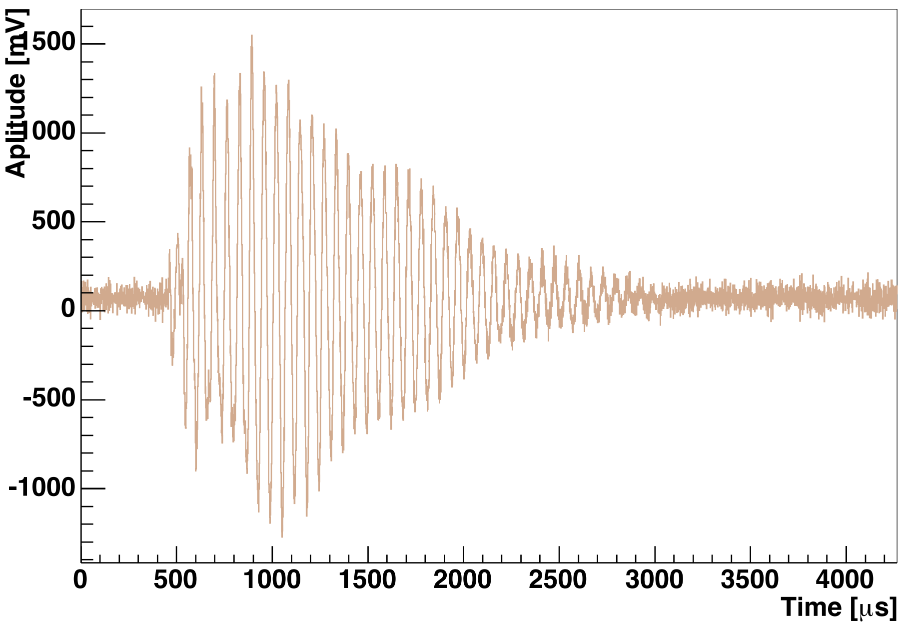



- Design
  - Bubbles of liquid $C_4F_{10}$ in matched-density CsCl gel (like dosimeters)
  - Acoustic readout with piezos
  - >107 rejection of MIPs demonstrated
  - geared to spin-dep interactions
- 2004 data set: 2 kg-d
  - 6 x 1 liter detectors, 7 months running
  - SNOLab + neutron shield
  - α bgnd from CsCl
  - 1 pb spin-dep proton limit, within x2 of best available
  - 20 pb spin-dep neutron limit

# PICASSO

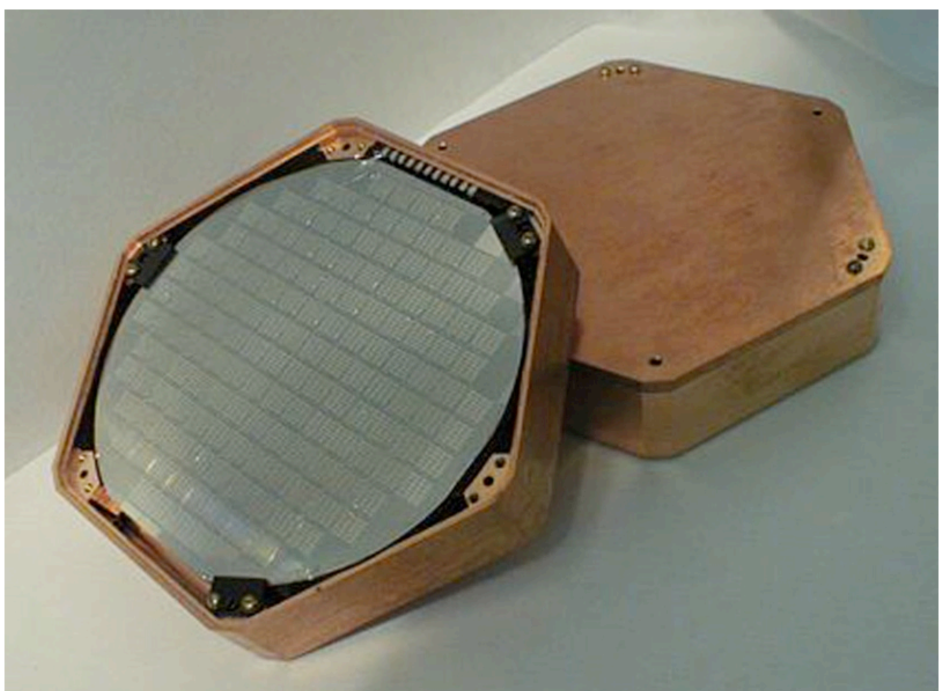


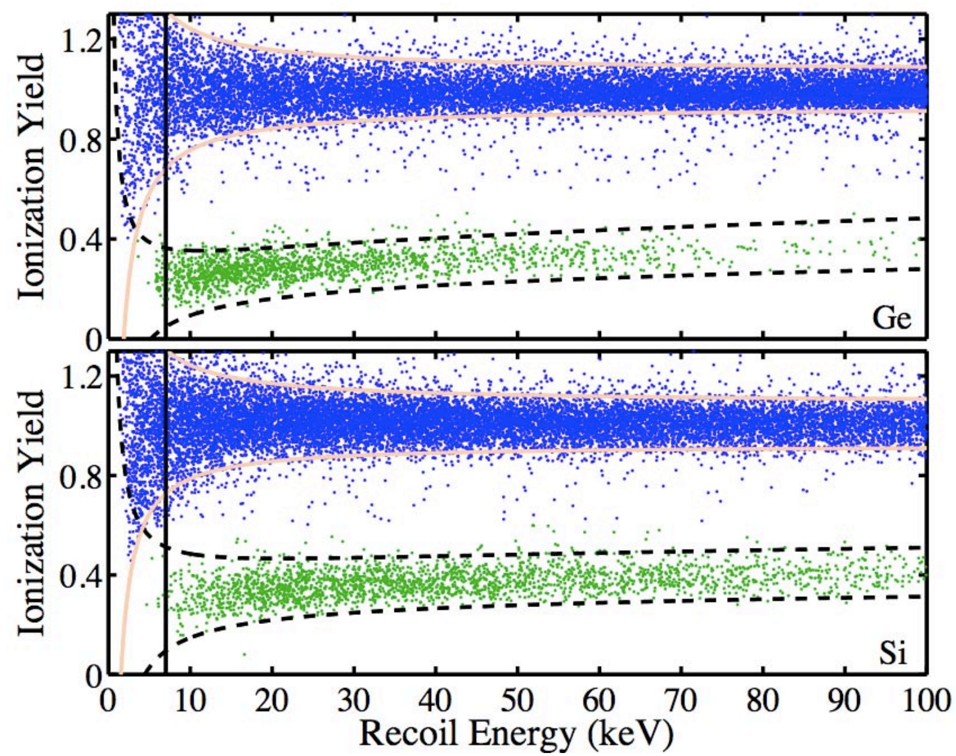




- Upgrades:
  - Screen materials + HZrO purification removes U/Th/Pb: expect bgnd reduced by x300
  - bubble size: 10 μm → 100 μm
- Installing 32 x 4.5 l detectors = 2.6 kg
  - 4 in place and running
  - 6-month run: 280 kg-d exposure
  - Should be very big improvement over 2 kg-d data set if bgnds reduced as expected.
- Scalable?
  - not as easy as COUPP, but easier than cryo detectors

# CDMS

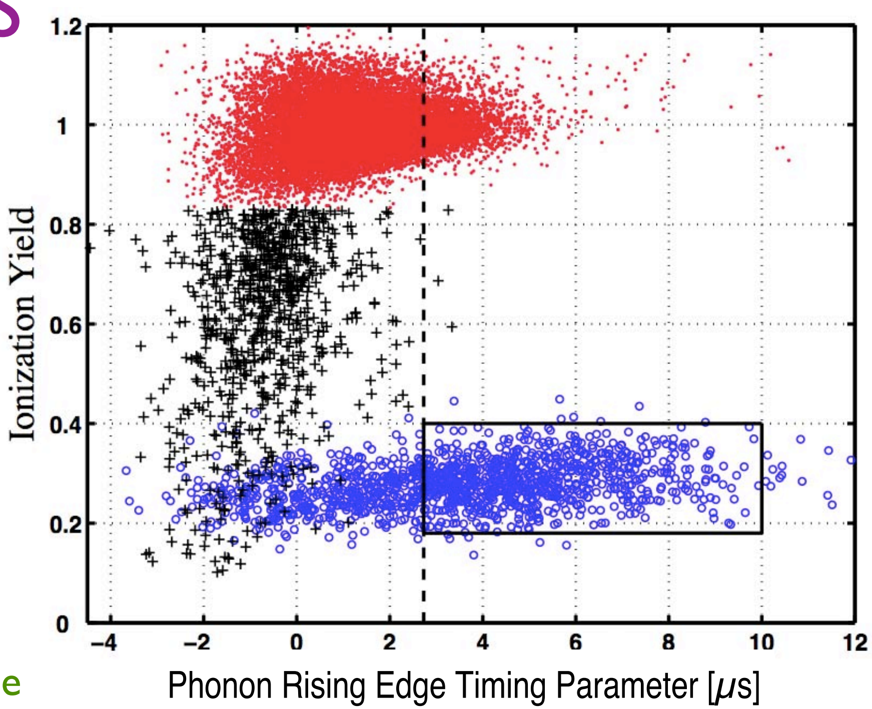
- NR discrimination via total recoil energy + ionization + phonon timing/position:
  - phonon signal provides total recoil energy (athermal phonon sensor using tungsten transition-edge sensors attached to aluminum phonon absorbers)
  - ionization signal depends on density of deposition, ionization yield ~ 1/3 for NRs in Ge
    - Read out using H-a-Si electrodes to minimize dead-layer effects
  - close-packed stacking of detectors with no intervening material minimizes exposure to outside radiation sources
  - radial segmentation of ionization electrode provides guard ring to reject events at outer edge of detector

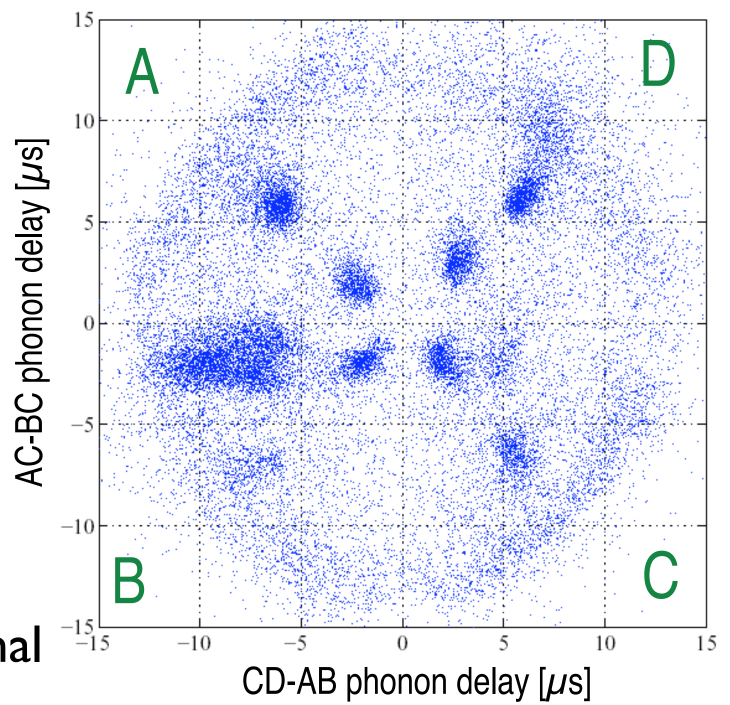




# CDMS

- Dead layer and athermal phonons
  - tens of μm deep "dead layer" due to loss of hot charges into "wrong" electrode before drift field takes over: surface electron events misd probability ~10%
  - athermal phonon sensor provides rejection
    - phonon signal rising edge provides 2-d imaging and sensitivity to z position; latter provides rejection of ionization dead-layer events
    - Close-packing and guard ring ionization electrode minimize flux of outside contaminants
- Background rejection (15-45 keV, 50-70% acceptance)
  - in CDMS II:
    $2 \times 10^{-6}$ misid of gamma events
    $2 \times 10^{-3}$ misid of surface electron events
  - SuperCDMS, see Cooley and Mahapatra talks:
    $1 \times 10^{-7}$ for gammas,
    $2.5 \times 10^{-4}$ for surface electrons
- Steady improvement in bgnd rejection expected over time by further exploitation of phonon signal



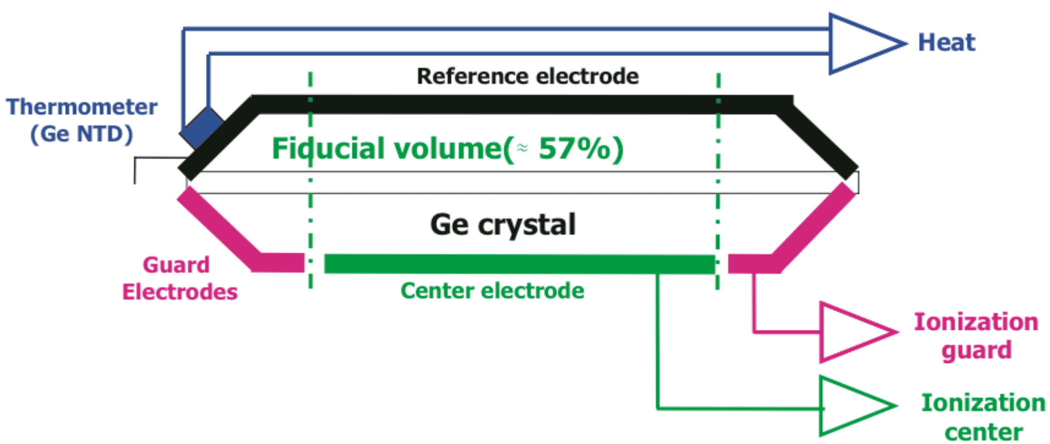



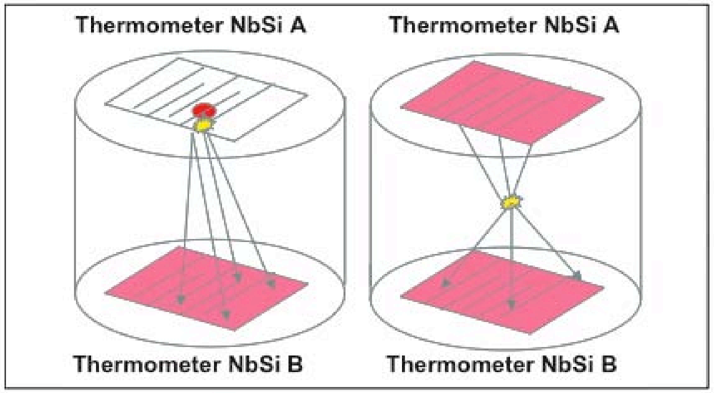
# CDMS

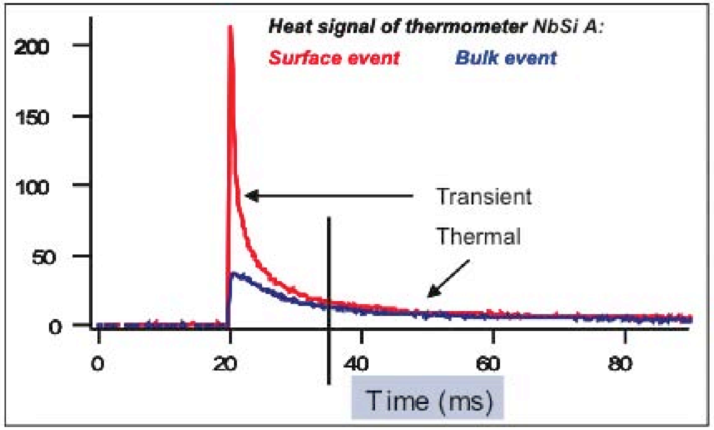
- Experimental setup/Status
  - Backgrounds:
    - Sited at Soudan underground lab
    - HPGe screening of all materials used
    - Class 10000 clean room
    - Old-air purge around cryostat minimizes gamma rate from radon
    - 8.6 cm polyetylene + 22.5 cm Pb shield + 40 cm polyethylene + 99.9% efficient muon veto
    - Copper cryostat separated from commercial dilution refrigerator by extension
  - Detectors
    - First run: 4 x 250g Ge, 2 x 100g Si. 52 kg-d raw (Ge),19 kg-d post-cuts (Ge) (published, 2004)
    - Second run: 6 x 250g Ge, 4 x 100g Si. 97 kg-d raw (Ge) , 34 kg-d post-cuts (Ge) (published, 2006)
    - Third run: full set of detectors, 19 x 250g Ge, 11 x 100g Si, 430 kg-d raw (Ge), analysis ongoing
    - Fourth run underway with same detectors, expect > 870 kg-d raw (Ge) by Spring 2008.
- Expect to reach $2 \times 10^{-8}$ pb with 1300 kg-d raw (Ge) exposure with full set of detectors
  - Ongoing improvements in analysis provide better background rejection at comparable or increased nuclear recoil effiiciency
- Scaling: challenging, but plan in place for 25 kg, another factor of 6 to 150 kg seems feasible

# EDELWEISS

- NR discrimination via total recoil energy + ionization + phonon timing
  - thermal: NTD Ge thermistors for recoil energy, ionization readout for NR discrimination
    - H-a-Si and H-a-Ge electrodes reduce effect of ionization dead layer (99.9% rejection of gammas)
    - thick Al electrodes to stop betas
  - athermal: NbSi thermometer for recoil energy + athermal phonon signal
    - athermal phonon signal discriminates against surface events, reducing impact of dead layer.
  - sub-keV energy resolution



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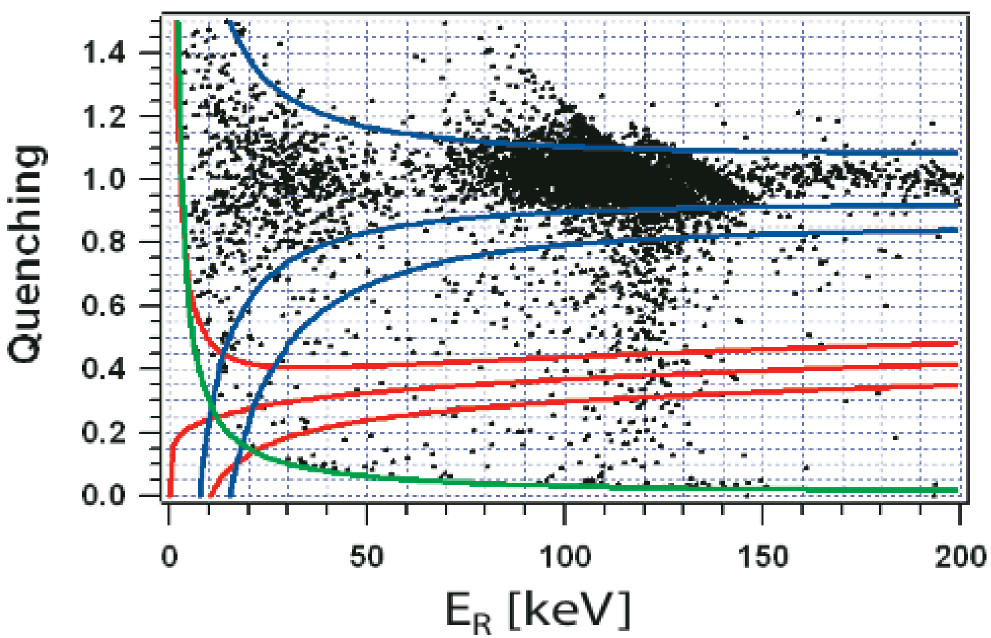
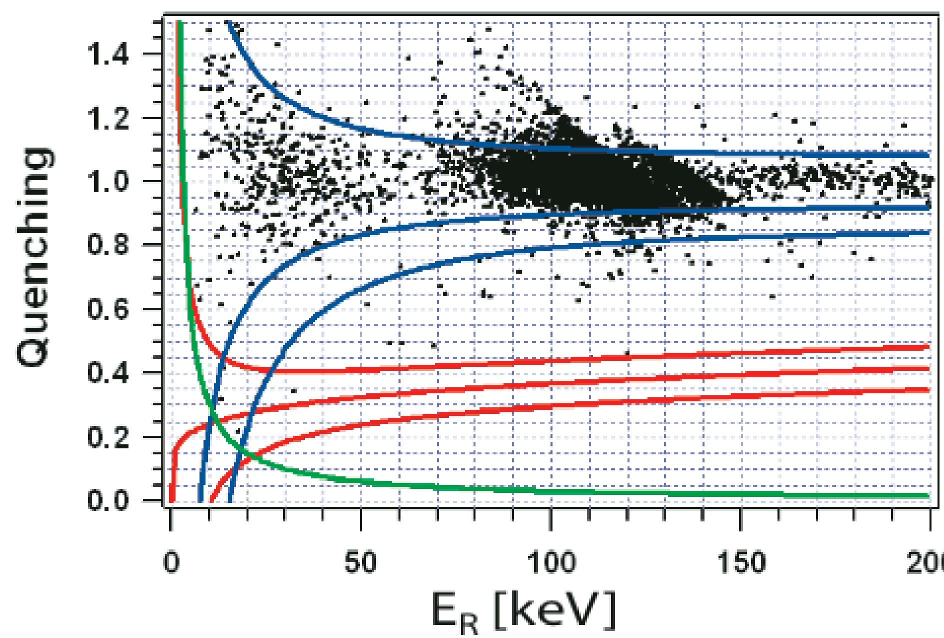



Before rejection



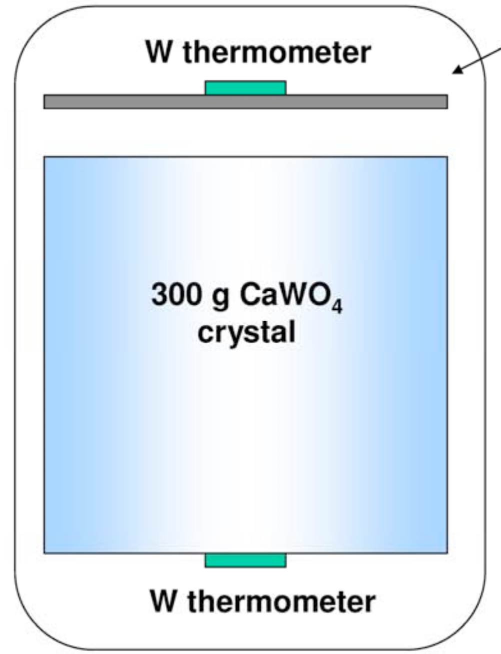

After rejection (1mm cut)

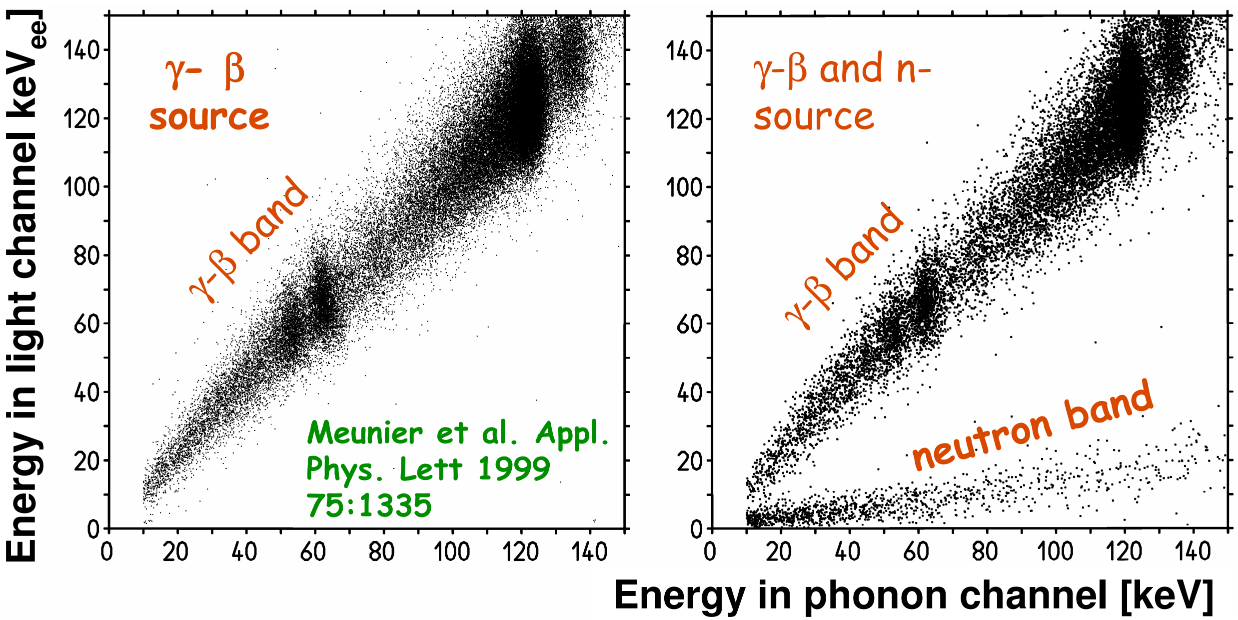
# EDELWEISS

- EDELWEISS-I
  - 3 x 320 g detectors
  - significant surface electron bgnd, clear Rn contamination: $^{210}$Pb, 6 events seen in 62 kg-d
- EDELWEISS-II
  - Setup:
    - Sited at Modane underground lab (Frejus) 4800 mwe
    - HPGe screening of all materials used
    - Class 100 clean room at cryostat, class 10000 around shield
    - Deradonized air, 0.1 Bq/m$^3$ (vs. ~50 Bq/m$^3$ surface, 10s-100s Bq/m$^3$ typical in underground labs)
    - 20 cm Pb shield + 50 cm polyethylene + 98% coverage muon veto
  - Status:
    - Summer 06 test run: 6 x 320g Ge/NTD, 1 x 200g and 1 x 400g Ge/NbSi, 1 x 50g heat+scint
    - Upcoming run: 21 Ge/NTD, 7 Ge/NbSi
      - 8 detectors installed and run through Feb 2007
      - 23 x 320g Ge/NTD installed and running: expecting x5 reduction in surface electron bgnds
      - 7 x 400g Ge/NbSi to be installed by end of 2007: expecting x5 better rejection of surface electron bgnds
      - Expect to reach $10^{-7}$ pb if bgnd-free in 30-90 day post-cuts exposure
    - Cryostat can hold up to 100 detectors; if $^{210}$Pb reductions + NbSi rejection can be combined, then can reach 2 x $10^{-8}$ pb in 60-day post-cuts exposure
- Scalability: challenges comparable to CDMS

# CRESST

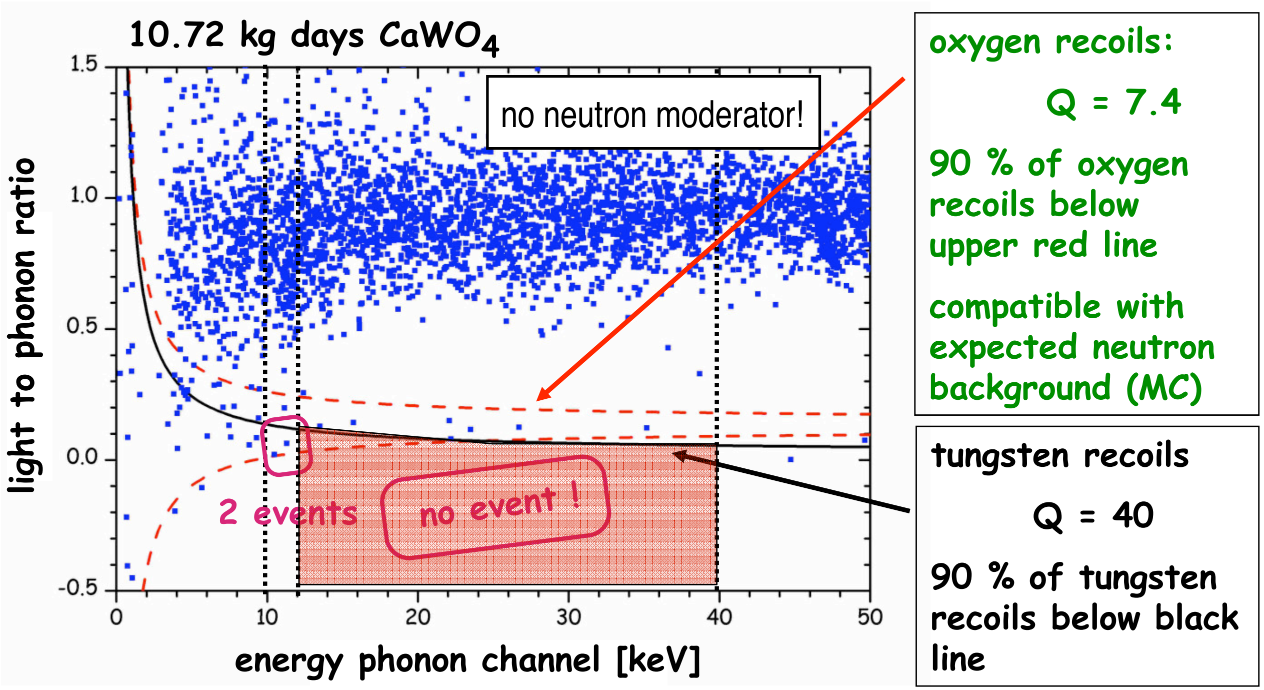
- NR discrimination by phonon energy + scintillation
  - target detector is transparent scintillator; energy left in target detector sensed with tungsten superconducting phase-transition thermometer
  - scintillation photons detected by phonon signal in ~black partner light detector (silicon + sapphire)
  - no apparent dead layer effects
  - 3 x $10^{-3}$ misid of gamma/electron background above 15 keV



# CRESST

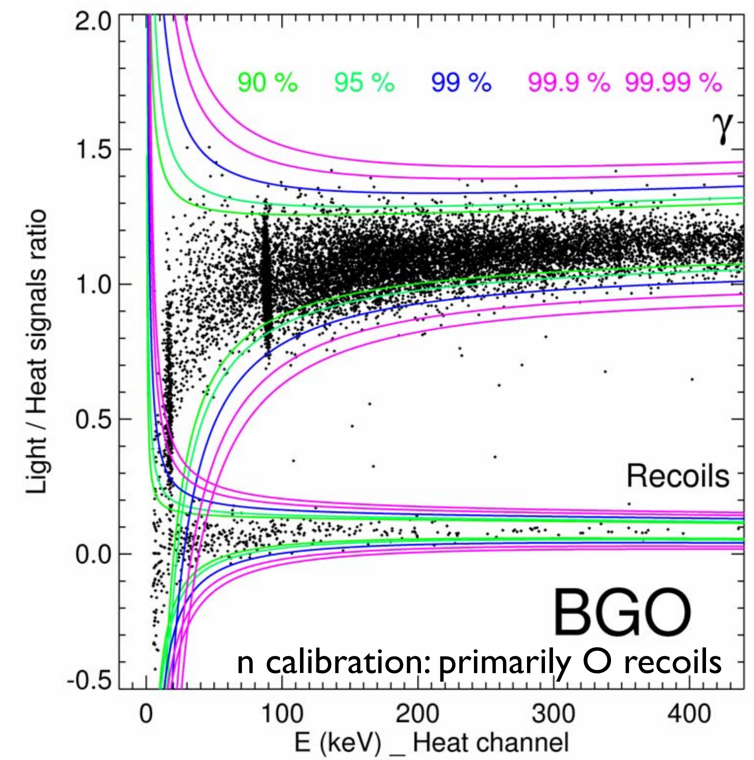
- NR discrimination by phonon energy + scintillation
  - WIMPs will produce "no-light" W recoils
  - O serves as built-in neutron monitor
  - Other scintillators possible ($ZnWO_4$, $CaMoO_4$, $Al_2O_3$)
  - First run with light detectors at LNGS limited by n bgnd because no moderator




- Experimental Setup
  - Gran Sasso (4000 mwe); 10-cm Cu, 20-cm Pb, 50-cm polyethylene shield, muon veto
  - 33-detector carousel and cold electronics in place; can hold up to 10 kg target mass
- Status:
  - 3 detectors installed in late 2006; zero no-light events in 3 kg-d commissioning data
  - 2 detectors running in WIMP-search mode since Spring, 2007; expect 10 kg-d to date,
  - Will run into summer before opening to install more detectors
- Scalability: like CDMS and EDELWEISS, though scintillation may scale better

# ROSEBUD

- Similar approach to CRESST
  - sapphire ($Al_2O_3$) and BGO ($Bi_4Ge_3O_{12}$) scintillator
  - Ge wafer as photon detector
  - NTD Ge thermistors attached to each crystal
- Performance
  - 0.1 misid prob > 23 keV
  - 1 x $10^{-4}$ misid prob > 51 keV
  - *not calibrated for Bi or Ge recoils*
- Experimental Setup/Status
  - Canfranc underground lab, 2450 mwe
  - Pb shield in place for earlier runs of non-discriminating detectors; gamma backgrounds ~ 10x higher than, e.g., CDMS
  - n shield installed during 2006?
  - Setup only capable of handling a couple of detectors; much work needed to scale up to competitive target masses

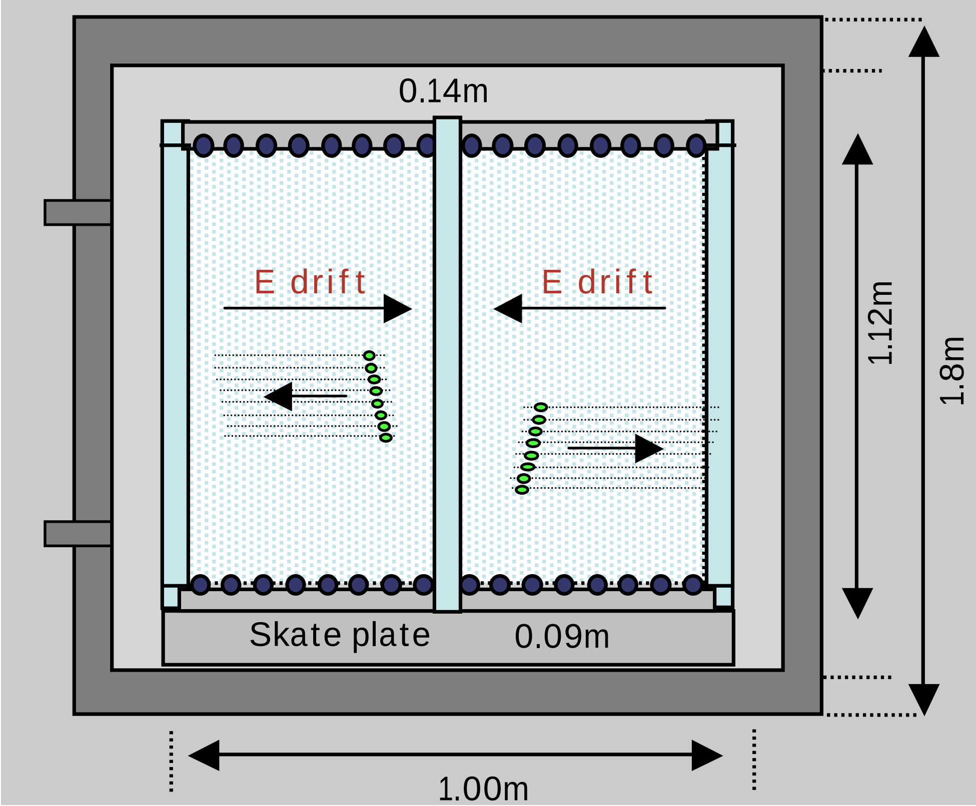


# EURECA

- European initiative toward 100-kg and ton-scale NR-discriminating cryodetector experiment
- Joins together EDELWEISS and CRESST efforts
- Aims for multi-target experiment to test for A dependence
- Can move forward when competitive science results available from EDELWEISS and CRESST

# DRIFT

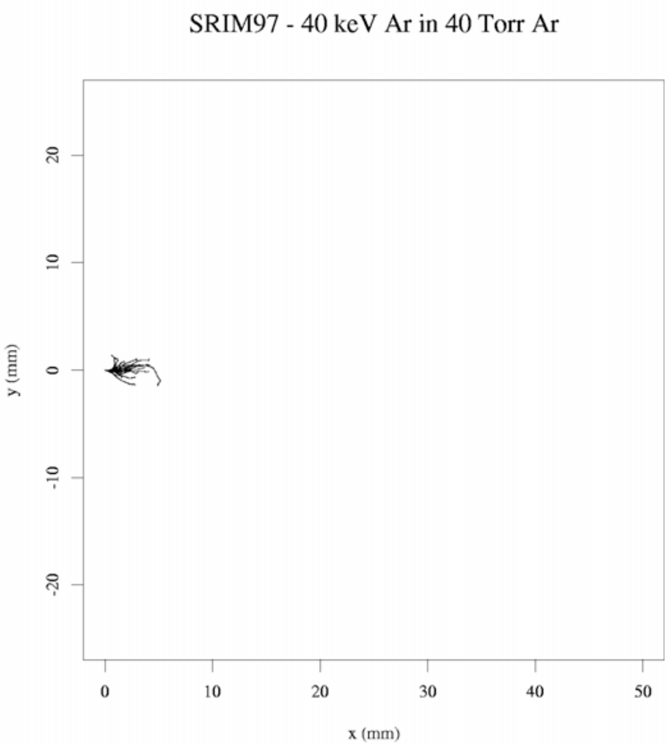
- Negative Ion Time Projection Chamber
  - $e^- + CS_2 \rightarrow CS_2^-$: drifting of heavy ion suppresses charge diffusion
  - 1 $m^3$ 40 Torr $CS_2$ gas (0.17 kg)
  - 2 mm pitch anode + crossed MWPC grid give 2D imaging
  - 700 V/cm drift field



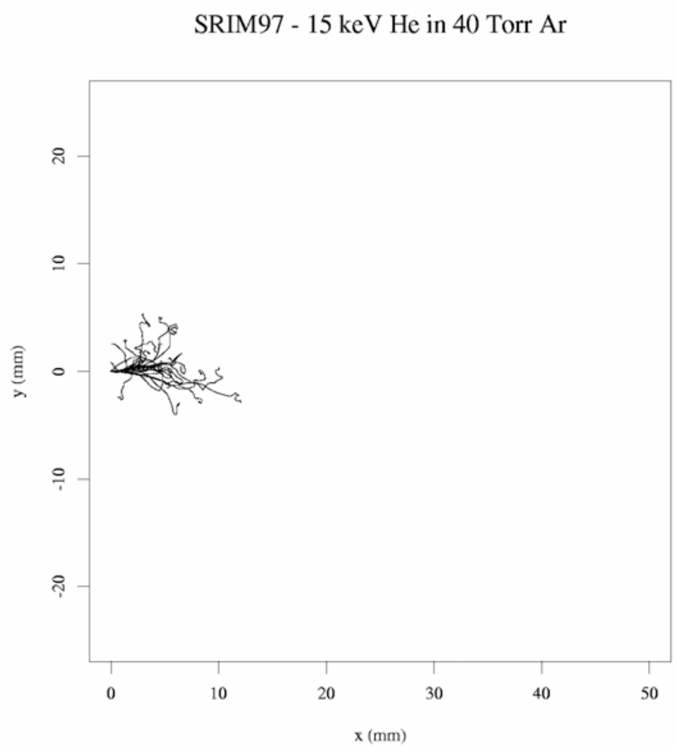

# DRIFT

- Nuclear recoil discrimination via track morphology in gas target
  - NRs: few mm
  - MeV alphas: 100-100s of mm
  - gammas: tens of mm

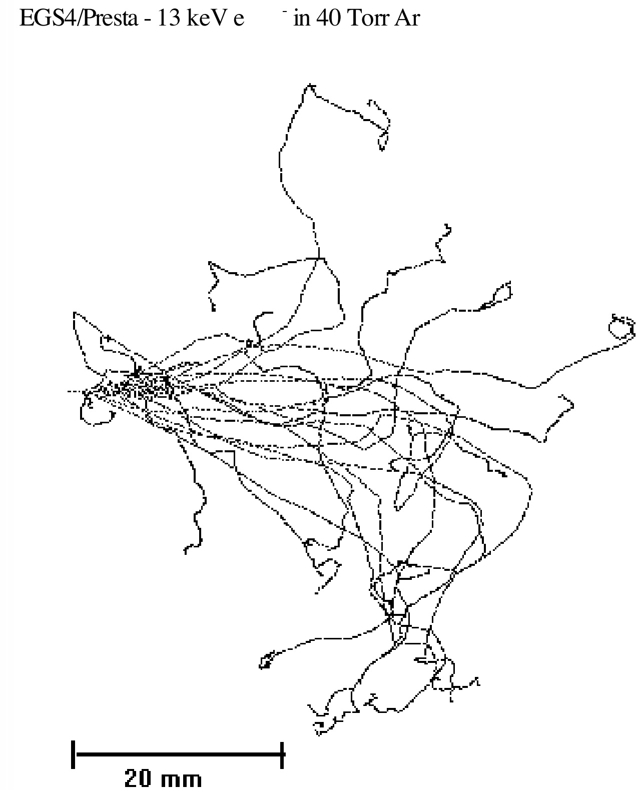
40 keV nuclear recoils
500 electron-ion pairs




15 keV αs
500 electron-ion pairs

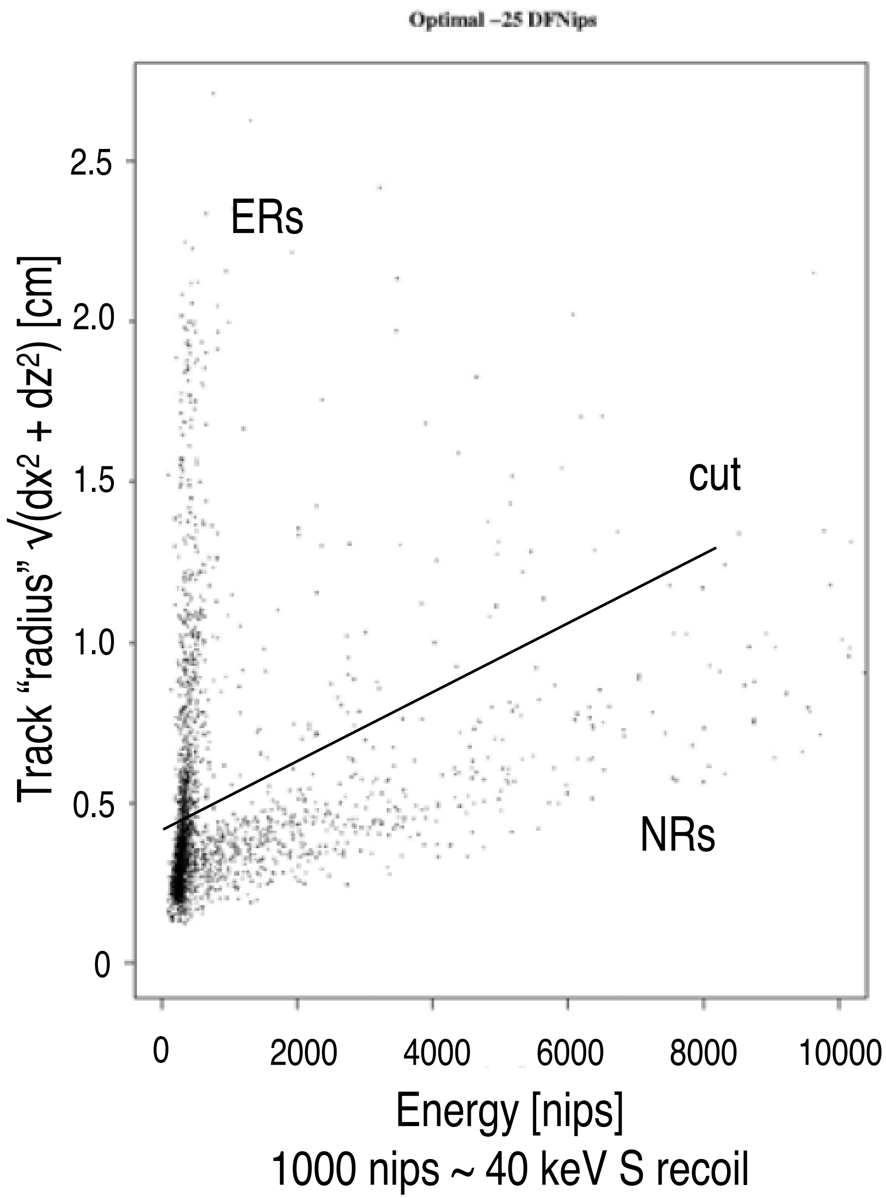



13 keV e$^-$
500 electron-ion pairs



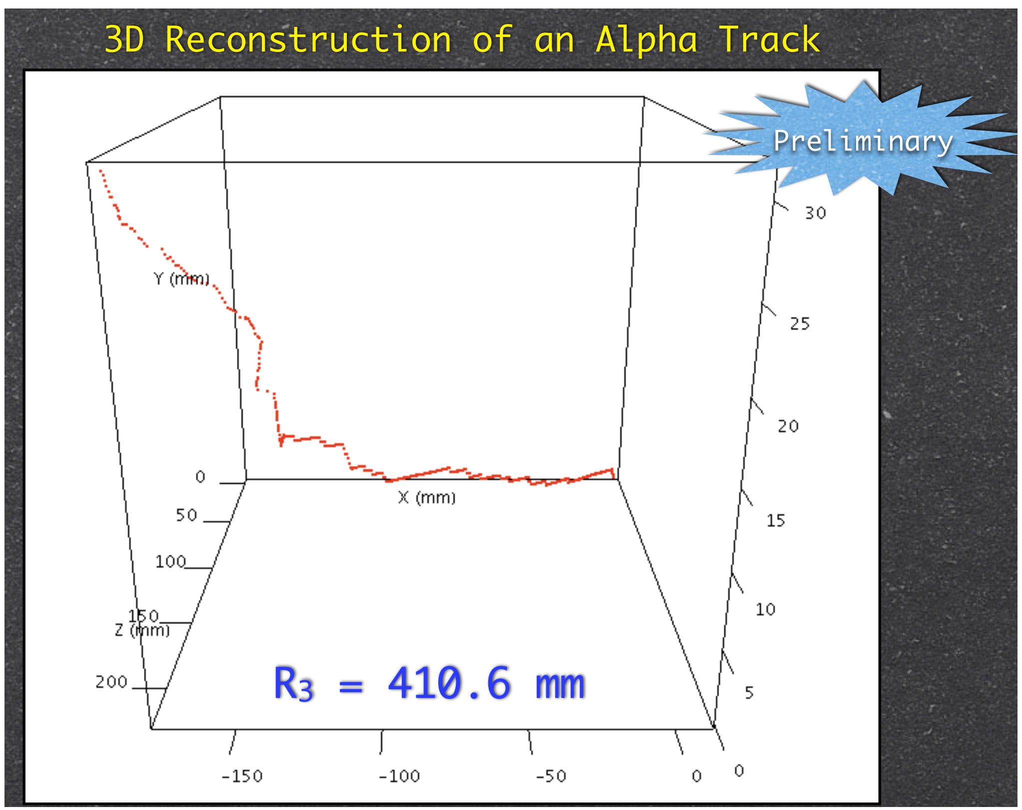
# DRIFT

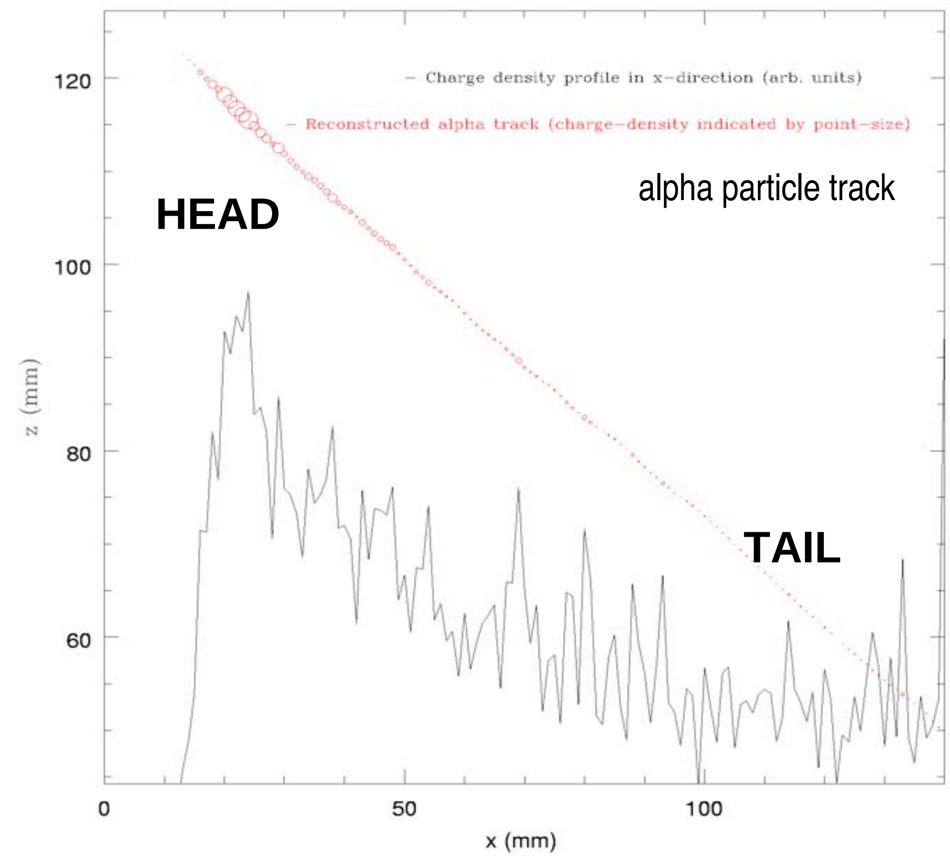
- Nuclear recoil discrimination via track morphology in gas target
  - NRs: few mm
  - MeV alphas: 100-100s of mm
  - gammas: tens of mm
  - Initially use $\sqrt{(dx^2 + dz^2)}$ because y reconstruction (induced charge on MWPC cross cathode) not developed due to smaller signal size; y reconstruction now working for $\alpha$s
  - demonstrated gamma misid prob. upper limit of ~5 x $10^{-6}$, limited by gamma exposure statistics, not real misid'd events



# DRIFT

- 3D track reconstruction for determination of recoil direction
  - Diurnal modulation signal: head-tail discrimination can provide x10 sensitivity improvement
  - Use dE/dx (Bragg peak) to find head and tail of recoil
  - Demonstrated for $\alpha$s with 100-mm-long tracks, but can it be done with NRs that deposit 100x less charge over a track only a few mm long?



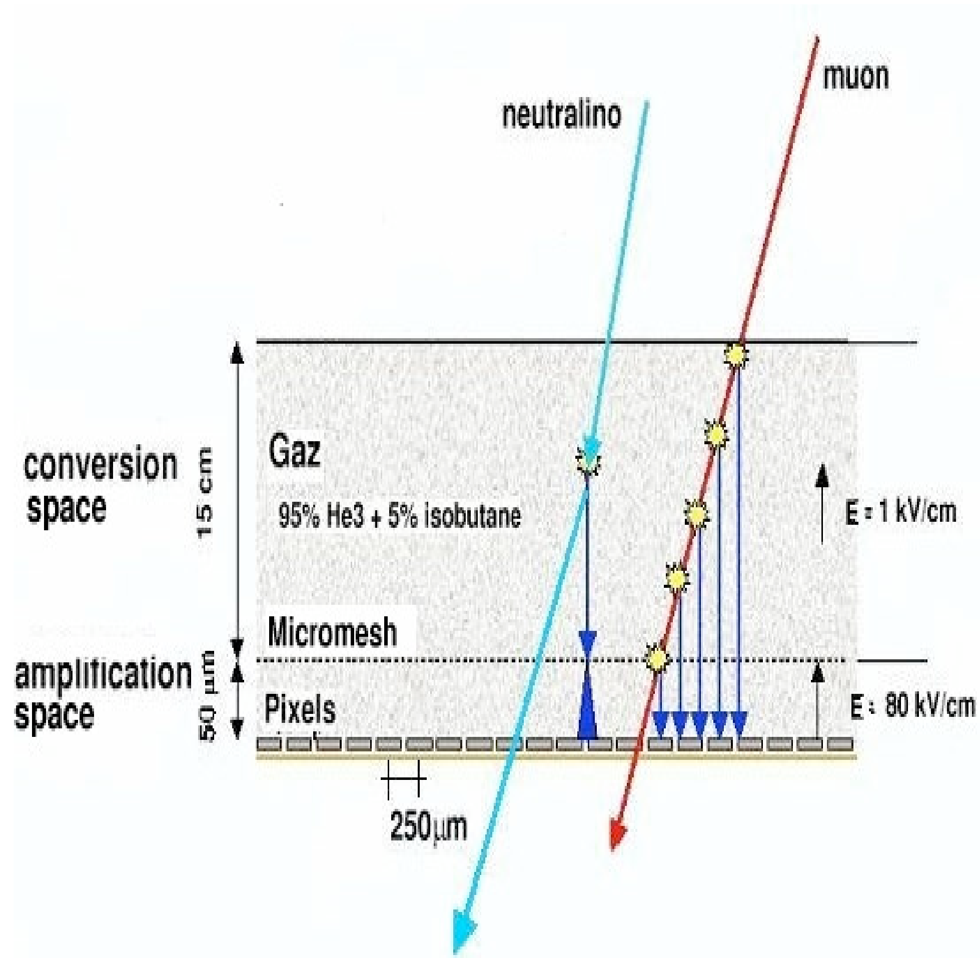



# DRIFT

- Experimental Setup
  - Sited at Boulby underground lab, 3000 mwe, n shielding only because of gamma rejection
  - DRIFT IIa commissioned and operated in 2005, DRIFT IIb installed in summer 2006
- Status
  - MC can reproduce observed rates when exposed to gamma and n sources
  - Background source: Radon progeny embedded in cathode wires
    - $^{222}$Rn daughters emanating from detector elements become attached to cathode
    - $\alpha$ decay of daughter sends recoiling nucleus into detector,
  - 6 kg-d data during late 2005 in this configuration taken. Being analyzed.
  - New run summer 2007 with expectation of much reduced Rn background
    - replaced Rn-emanating components
    - increased CS2 flow
    - clean cathode
- R&D
  - Working with Saclay to develop micromegas for reading out drifted charge:
    Much finer position resolution, necessary to get good reconstruction of n events
  - BU/MIT group (Ahlen, Fisher, Monroe) working on CCD readout of scintillation light
- Scaling: $100k/module cost can be brought down, then perhaps not too far off from cryodetector scaling.

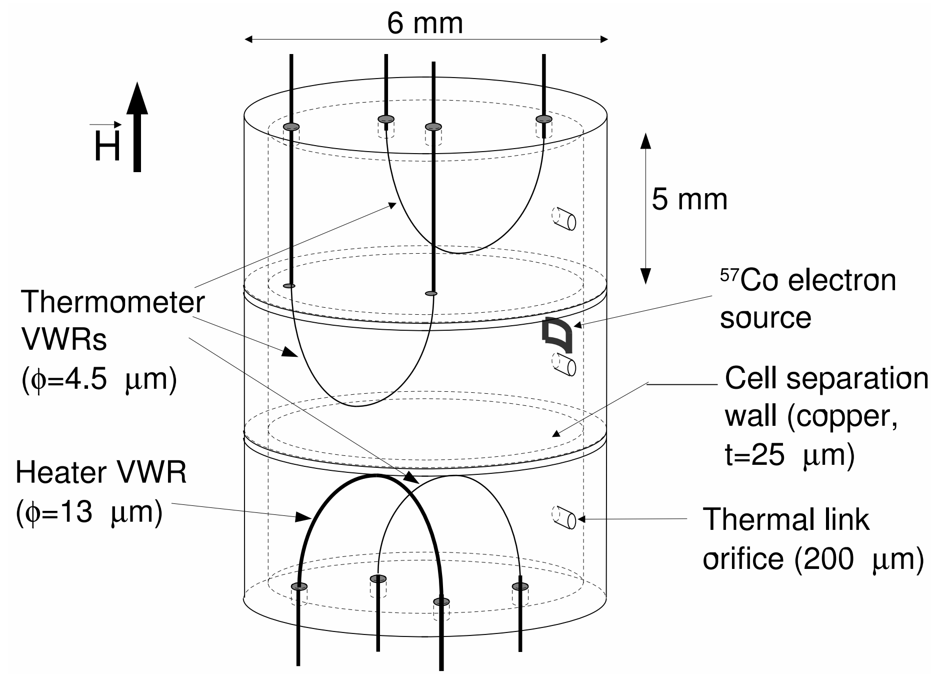
# MIMAC-He3

- MIcromegas MAtrix of Chambers of He3
  - $^3$He TPC with micromegas readout: very fine position resolution
  - sensitive to spin-dep interactions
  - low gamma cross-section
  - Upper limit on recoil energy of 6 keV restricts the energy range of interest, compresses the entire rate into small energy range (1-6 keVr)
  - n-capture signature for monitoring *thermal* neutrons
  - high-pressure (1-3 bars) for NR discrimination by track length, low pressure (0.1 bar) for directionality

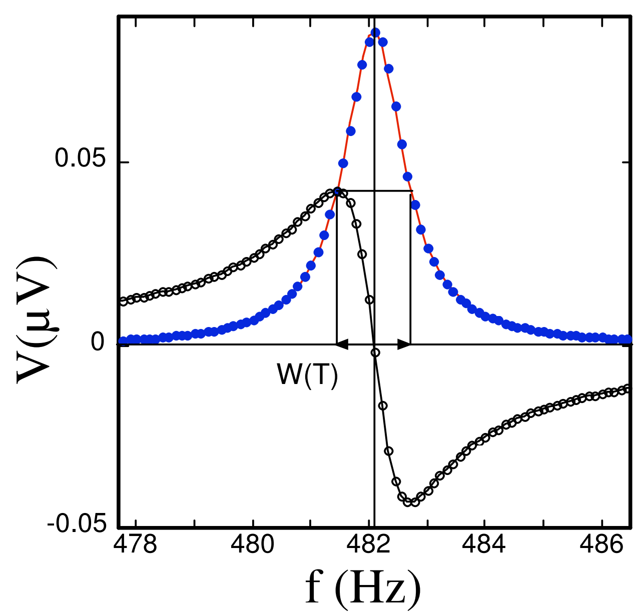


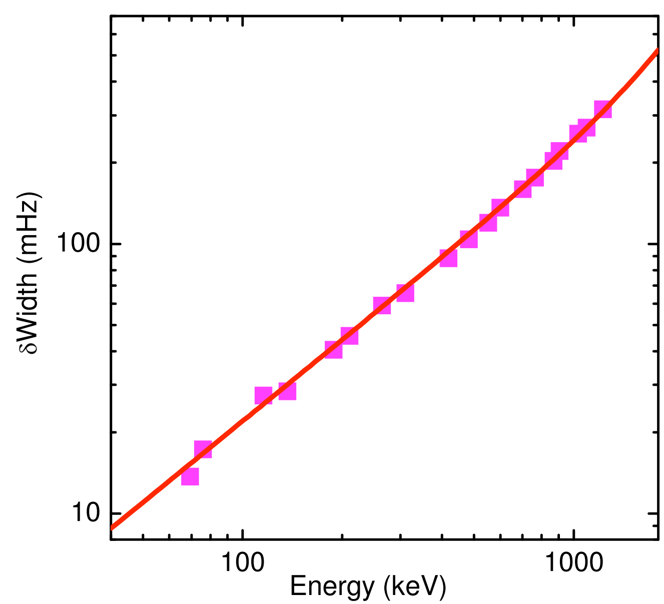
# 3He Bolometry: MACHe3, ULTIMA

- 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

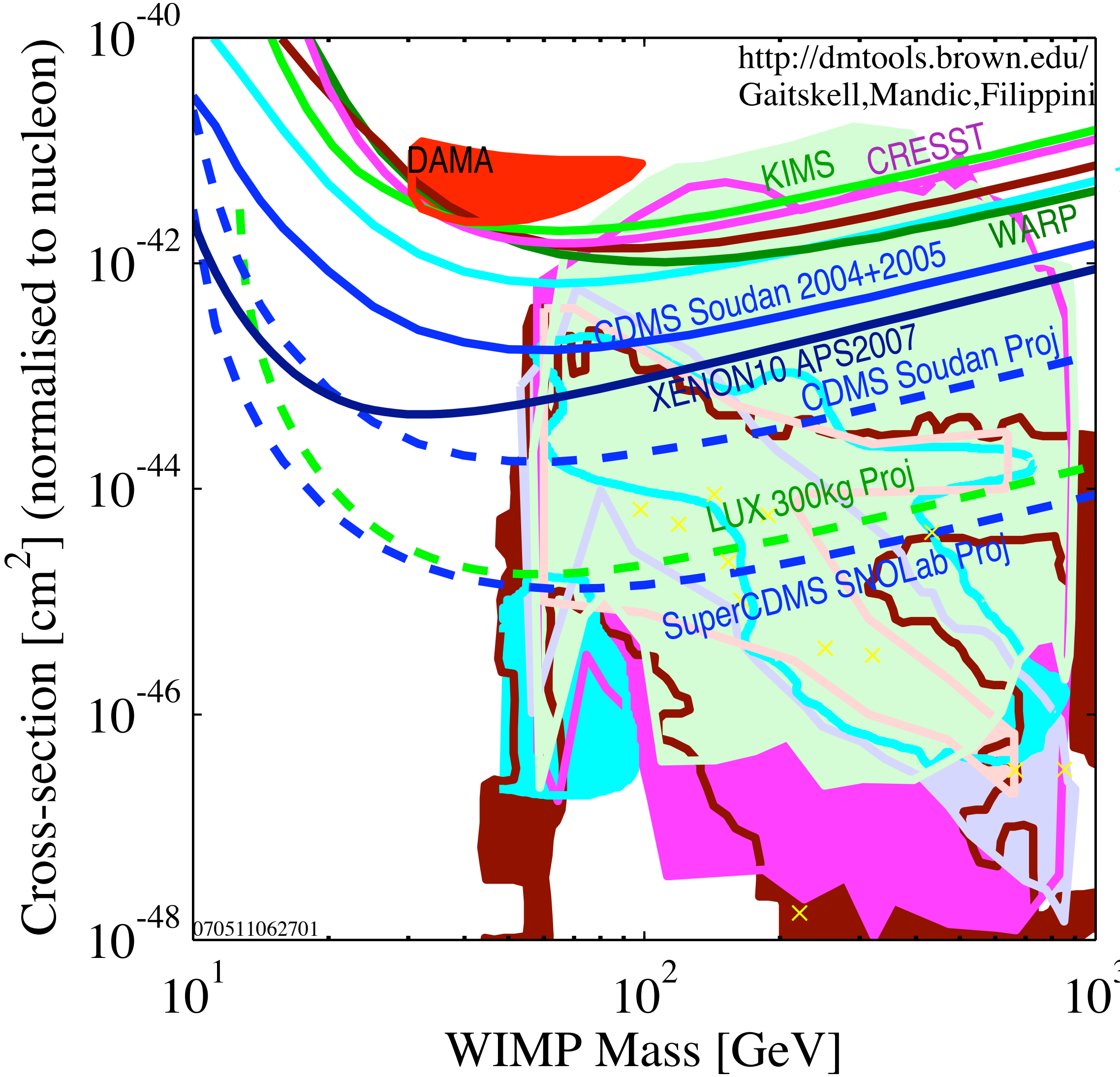



- Eventual NR discrimination via ionization or scintillation
- Still very much in development…



# Conclusions




1 ev/kg /day

1 ev/kg /100 days

1 ev/100 kg /100 days

- A wide variety of techniques being employed to search for WIMP dark matter, many with interesting sensitivities
- Many have the potential to reach $10^{-8}$ pb and possibly to $10^{-10}$ pb