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Direct Detection of CDM: The challenge ahead

- Non-baryonic Galactic Dark Matter close to a paradigm (certainly in the mind of many) but yet to be detected.

- ~20-30% Cold (non-relativistic) DM presently favored (we don't seem to be able to explain large scale structure of the universe without WIMPs –Weakly Interacting Massive particles-, relics of early stages)

- Cautious strategy: start by looking first for non-ad hoc particle candidates, i.e., those already invoked by particle theories (E.g., neutralino ↔ MSSM, axions ↔ strong CP problem)

- WIMPs: dominant interaction via low-energy nuclear elastic scattering, expected rates << 1 kg target / day in the keV region. (local ρ~0.4 GeV/cm^3, <v>~300 km/s, $\sigma<10^{-42}$ cm^2).
Supersymmetric WIMPS can have rates as low as 1 recoil/tonne/yr!

- The challenge: build cost-effective tonne or multi-tonne detectors sensitive exclusively to WIMP-induced nuclear recoils (down to 1/year) and nothing else. Not even neutron recoils. Nada. Zilch.

- The scale of things: a 1-kg Ge detector fires in this room at the tune of ~1 kHz (OK to giggle at this point).

WIMP searches: a quixotic fight against backgrounds

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Particle dark matter? The number of candidates is comparable to the ~30 experiments to detect it.

- Standard model neutrinos
- Sterile neutrinos
- **Axions**
- **Supersymmetric dark matter** (**neutralinos**, sneutrinos, gravitinos, axinos)
- Light scalar dark matter
- Little Higgs dark matter
- Kaluza-Klein dark matter
- Superheavy dark matter (simpzillas)
- Q-balls
- CHArged massive particles (CHAMPS)
- Self-interacting dark matter
- D-matter
- Cryptons
- Superweakly interacting dark matter (SWIMPS)
- Brane-world dark matter
- Heavy 4^{th} generation neutrinos
- Mirror particles
- Etc. etc.

Patient compilation by C. Hailey (Columbia)

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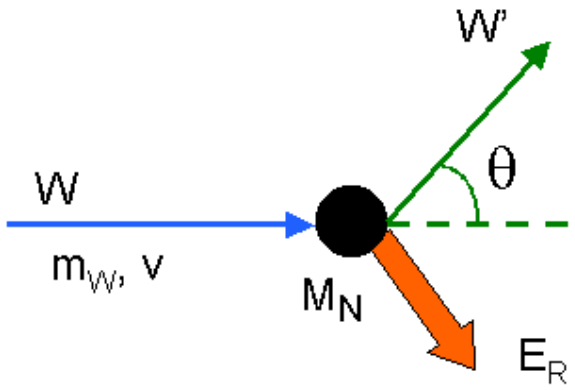
Do we know anything about these particles?

- Some are expected in particle theories having nothing to do with the dark matter problem.
(E.g., neutralino ↔ supersymmetry, axions ↔ strong CP problem)

- Supersymmetry attempts to find a common explanation to all known forces in nature. It predicts the existence of new stable particles with the right mass range and stability to make up the galactic dark matter.

- We expect these to interact (very rarely!) with known matter via "nuclear recoils" = billiard ball collisions. Known particles (e.g. neutrons) can produce the same.



(click on frame to run movie)

QuickTime™ and a
Video decompressor
are needed to see this picture.

Things that go bump in the night.

Few keV iodine recoils injected into CF3I. Movie available from http://cfcp.uchicago.edu/~collar/IonCF3I_1.mov

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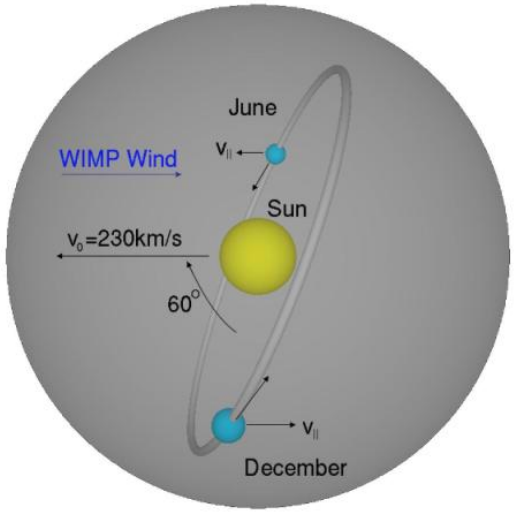
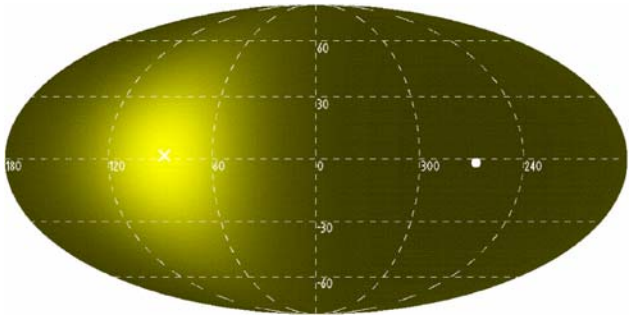
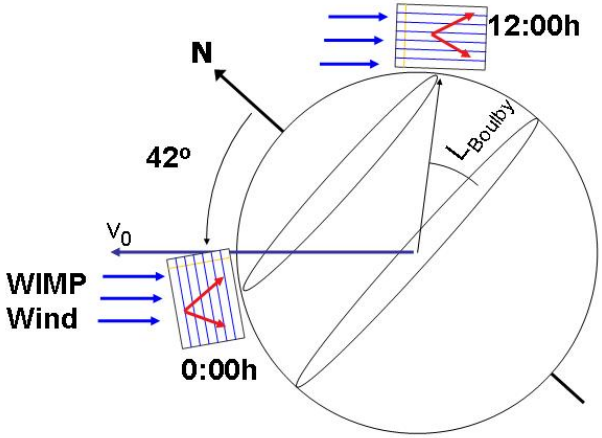
WIMP Phenomenology: a way to avoid embarrassment (or is it?)

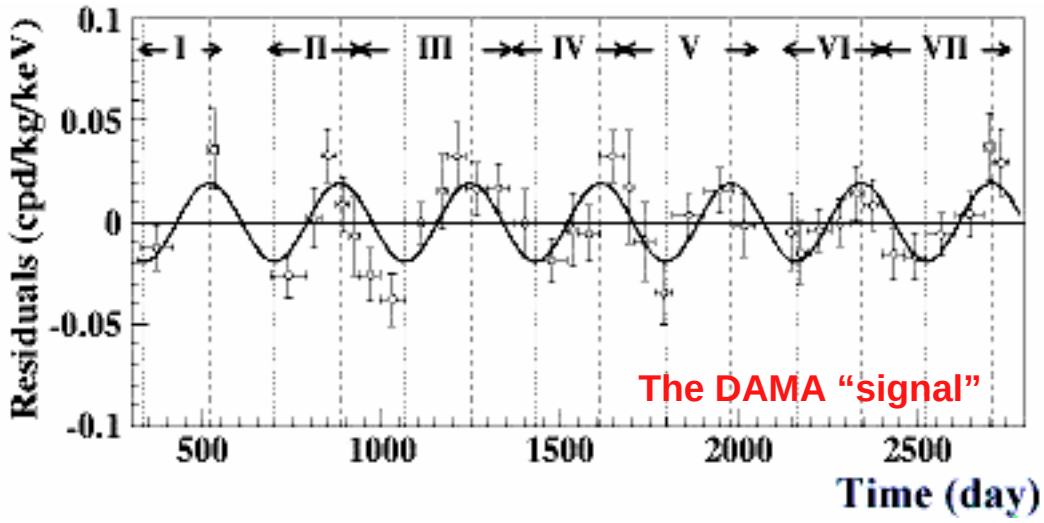
A "WIMP wind" from Cygnus



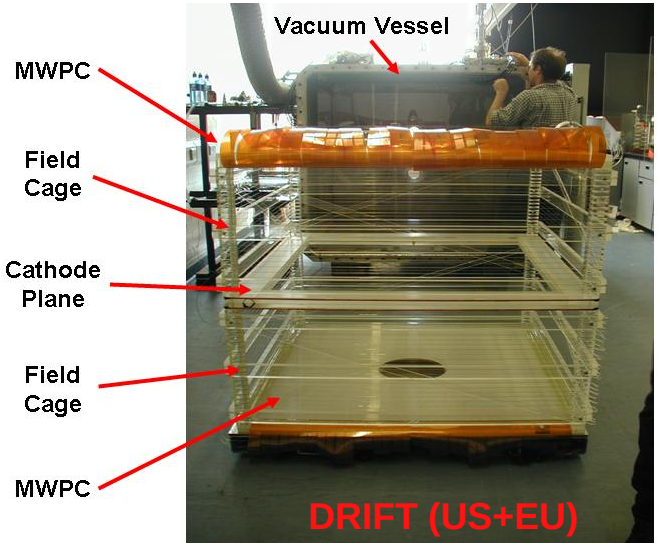




Directional detectors, a dream come true



The DAMA "signal"



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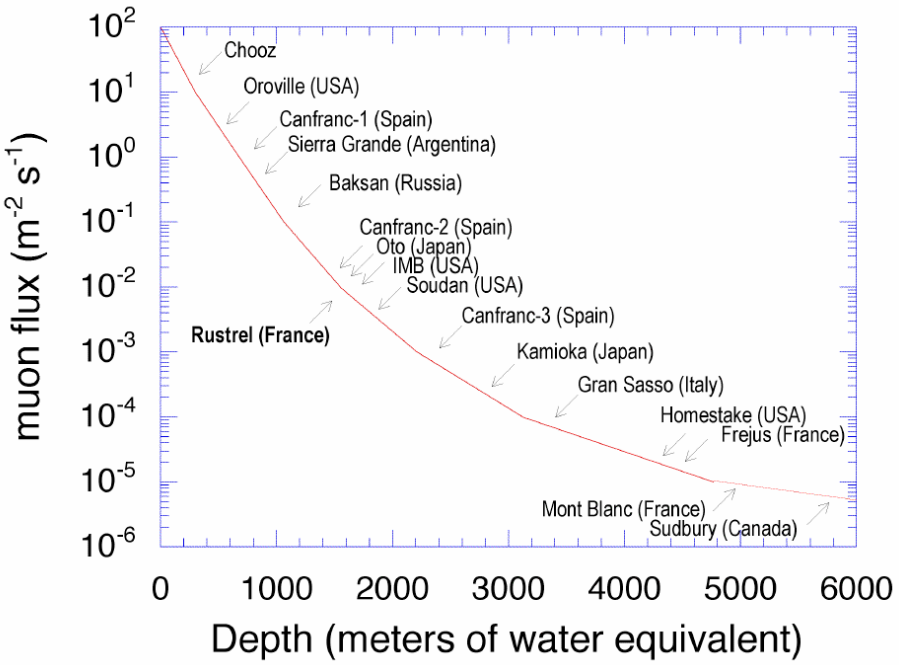
From ~1000/kg/s to ~1/ton/year (you have to be kidding me)

- Deep bag of tricks: radiation shielding, radiopurity of materials (careful selection), underground sites, and background rejection.

Cozy (1 mile underground)



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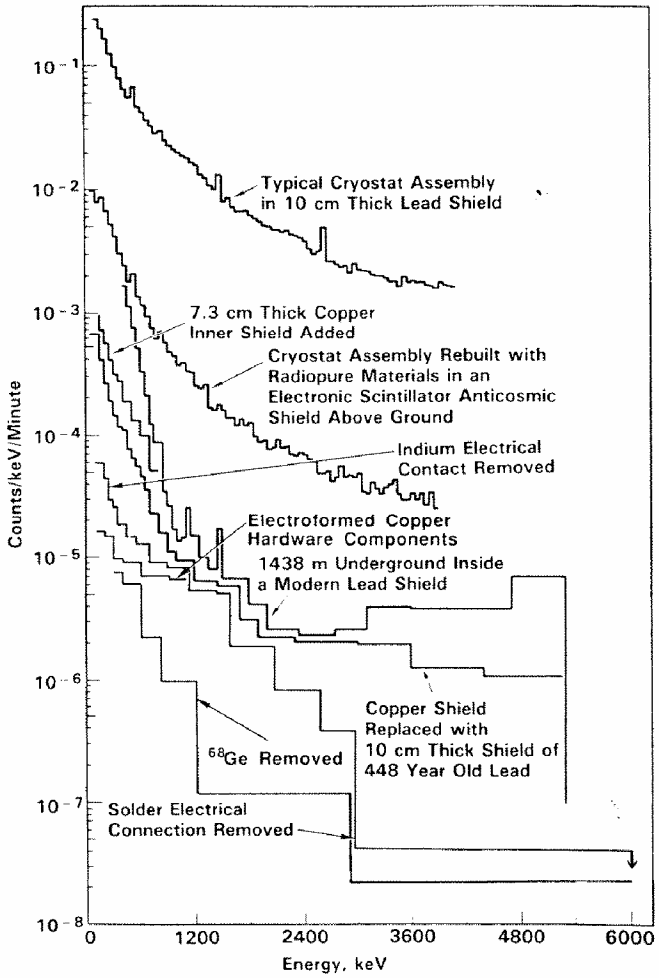

Fig. 1. Improvements in low-background technology.

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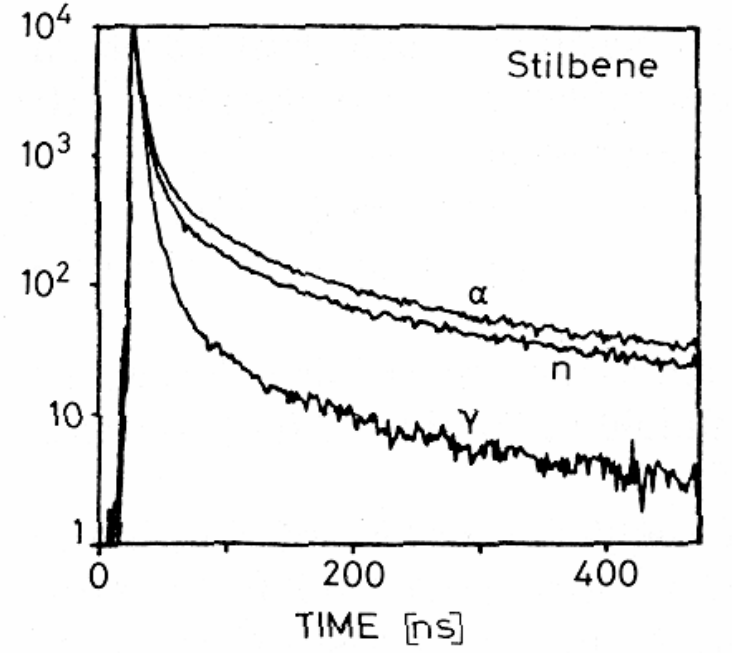
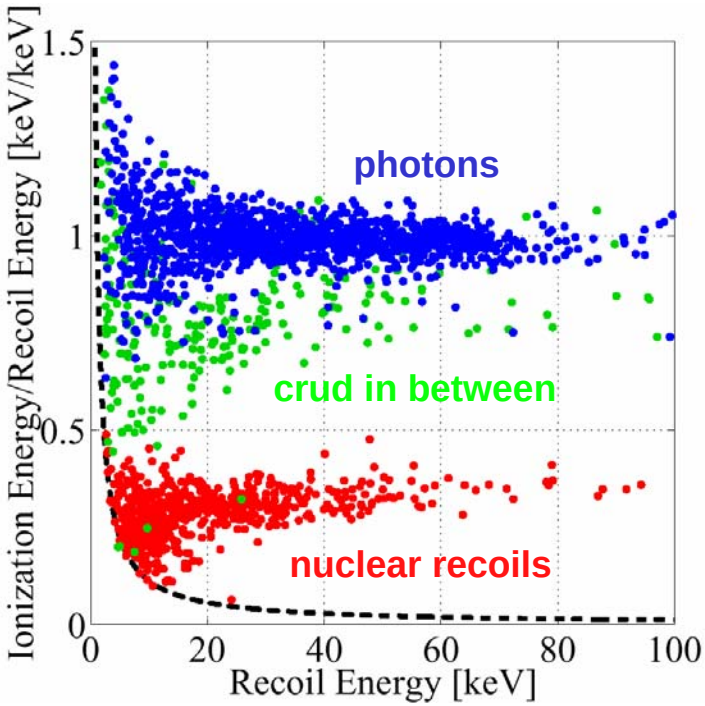
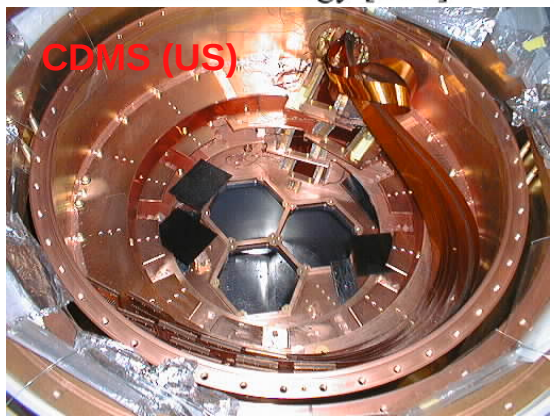
- Deep bag of tricks: radiation shielding, radiopurity of materials (careful selection), underground sites, and background rejection.







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Parental advisory:

What follows is not an unbiased review

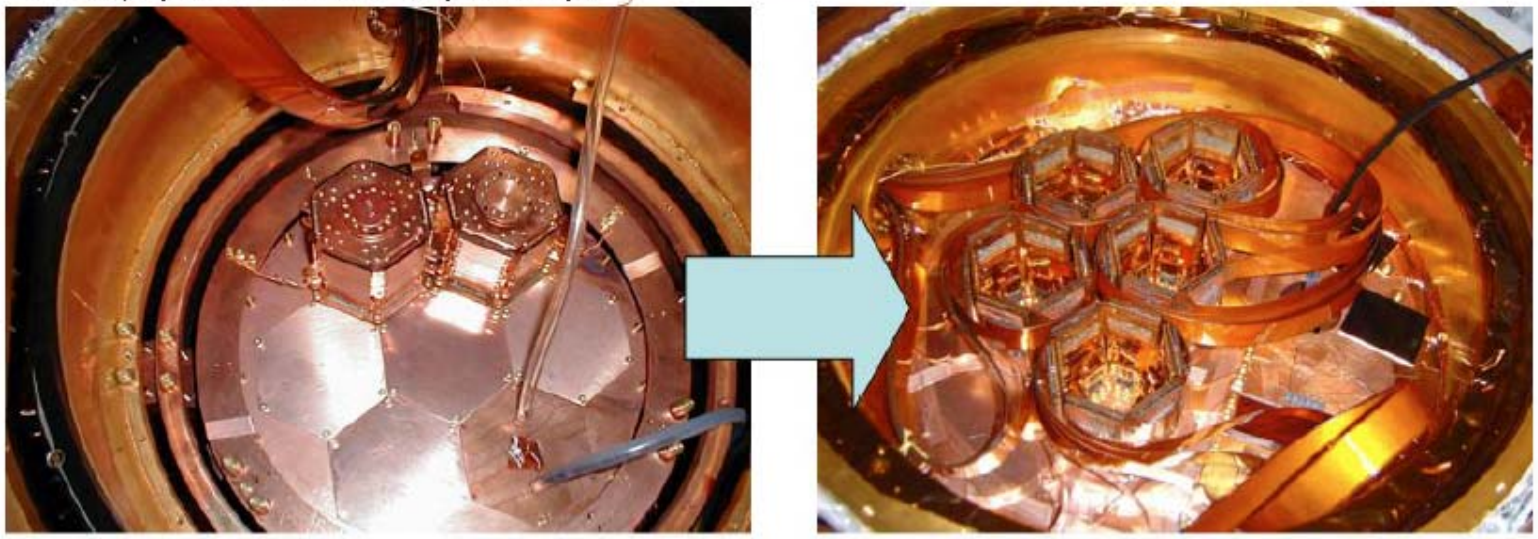
Inside the icebox,

Towers of 6 ZIPs in a stack are kept at 50 mK

Data from the 1 and 2 tower runs

Astro-ph 0509259 (Spin-Ind)
Astrp-ph 0509269 (Spin-Dep)
} Just submitted

5-tower run is starting now



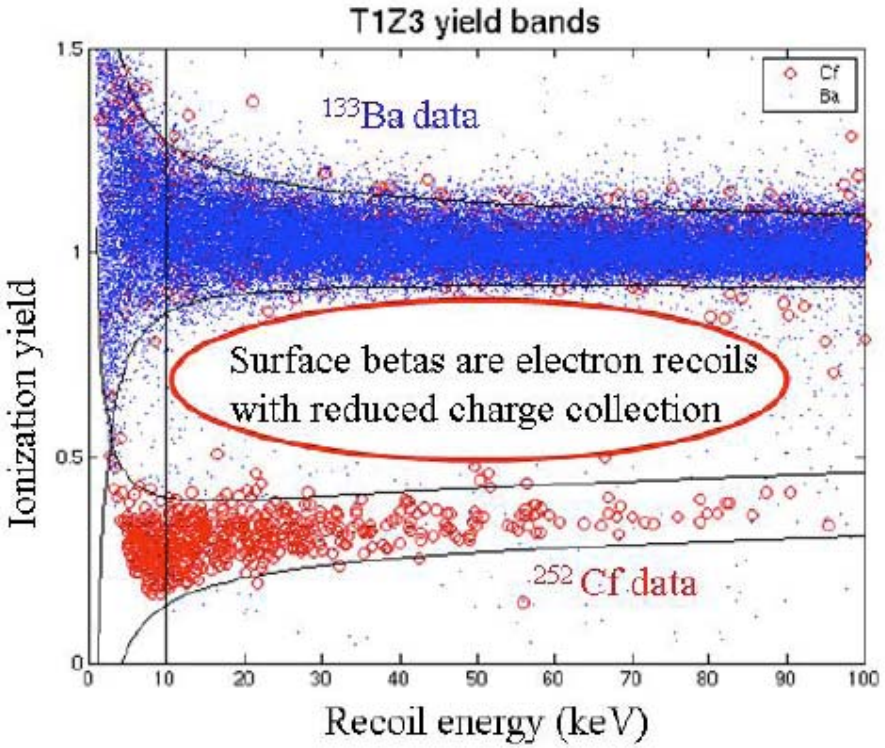
CDMS gets rid of most gammas and betas using the YIELD: ratio of ionization to phonon signal

WIMPs and neutrons produce nuclear recoils with small ionization yield.

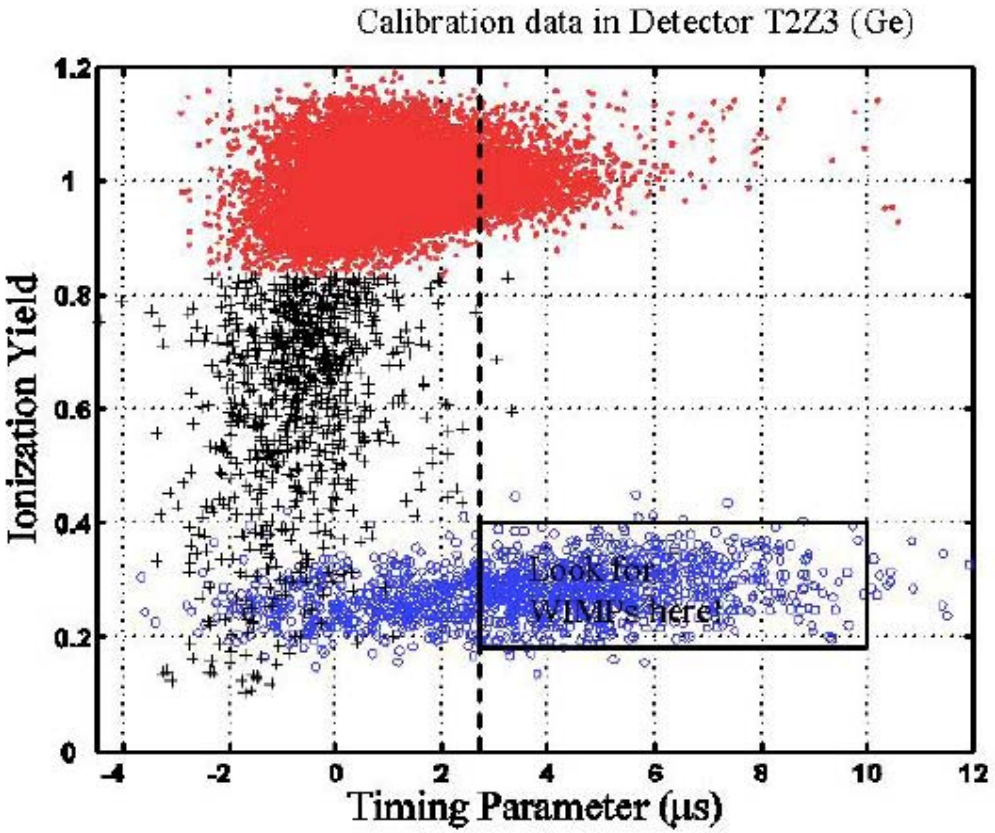
Gammas and electrons in the bulk produce electron recoils with ionization yield centered on 1

Calibration source data is used to define 2σ bands (Lindhard functional form)

Surface betas can leak down into the nuclear recoil band



Timing provides further discrimination



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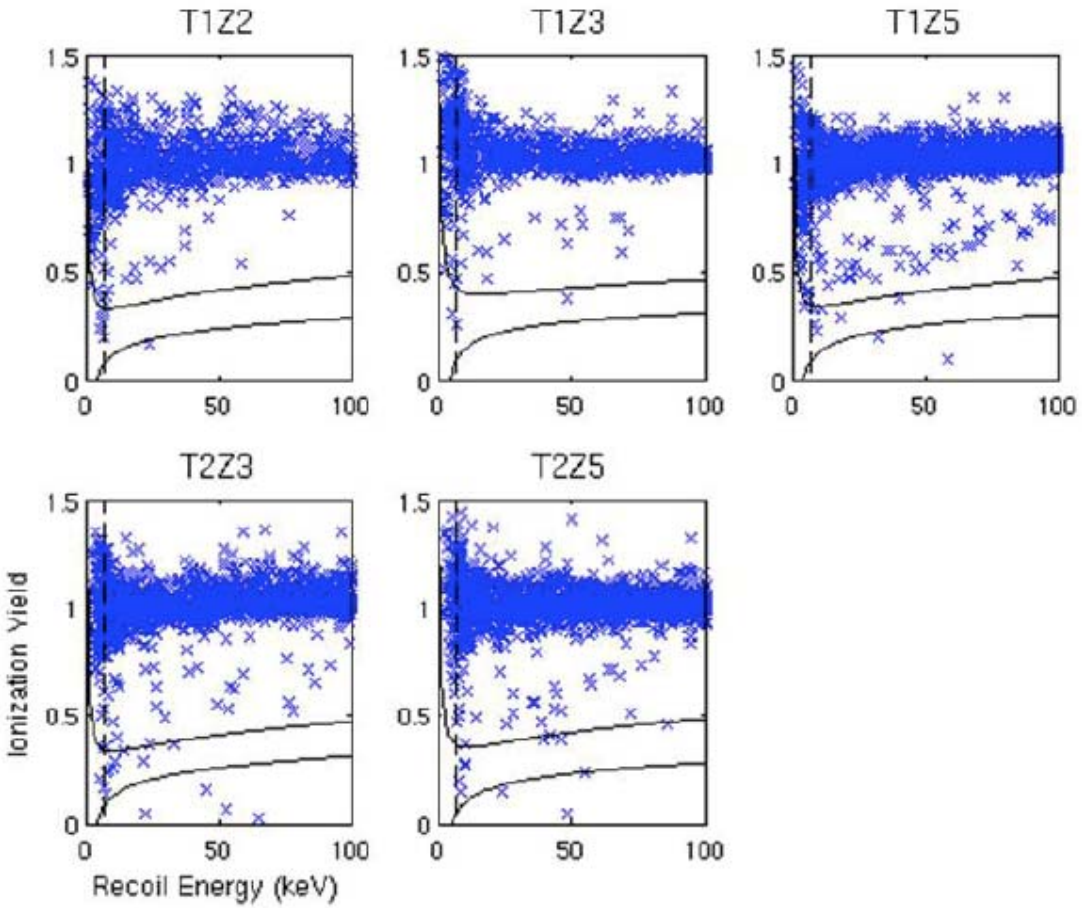
Iron Chef: Chop, chop, chop...

WIMP search data for the Germanium Detectors Before timing cut



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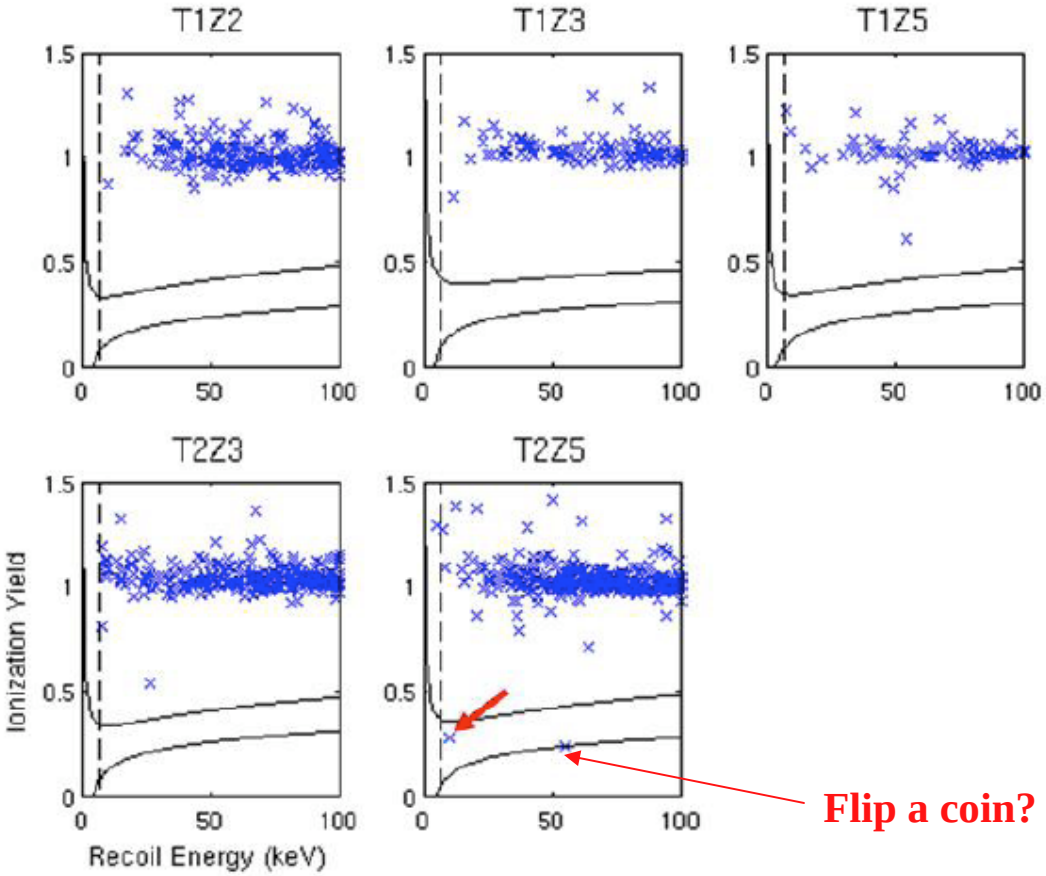
chop-chop-chop-chop-chop-chop...

WIMP search data for the Germanium Detectors After timing cut



Flip a coin?

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Two towers of 6 ZIPs each

Close-packed multiple detectors allow identification of multiple scatters
➔ neutrons, NOT WIMPs !

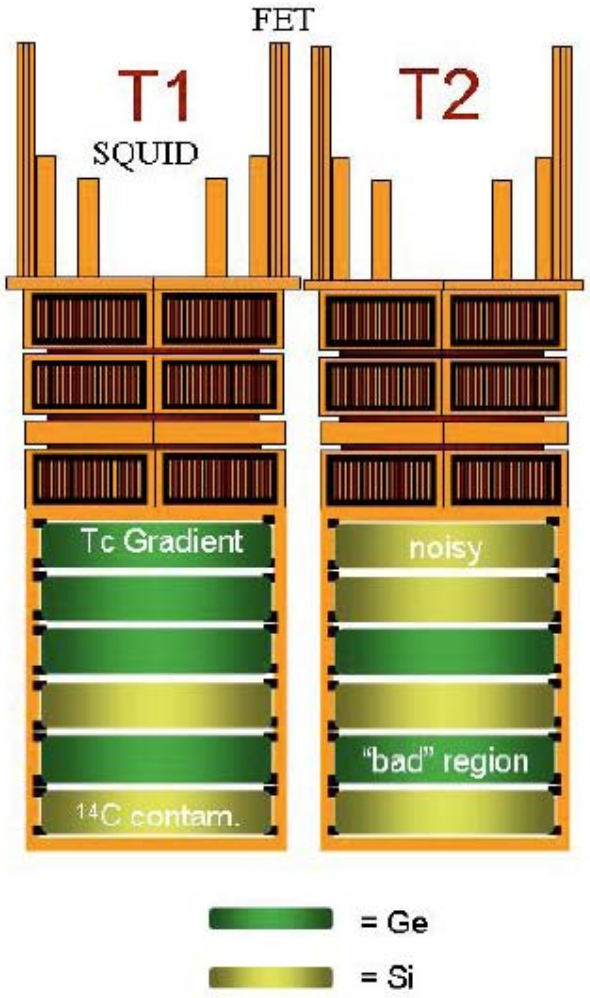
Used 5 Ge (250 g) and 4 Si (100 g)

(Others still provide self-shielding)

Why Silicon if Ge gives best exposure?

WIMP ID

Si has 5-7 times lower WIMP-nucleon rate
(but same neutron scattering rate)
except for lowest mass WIMPs



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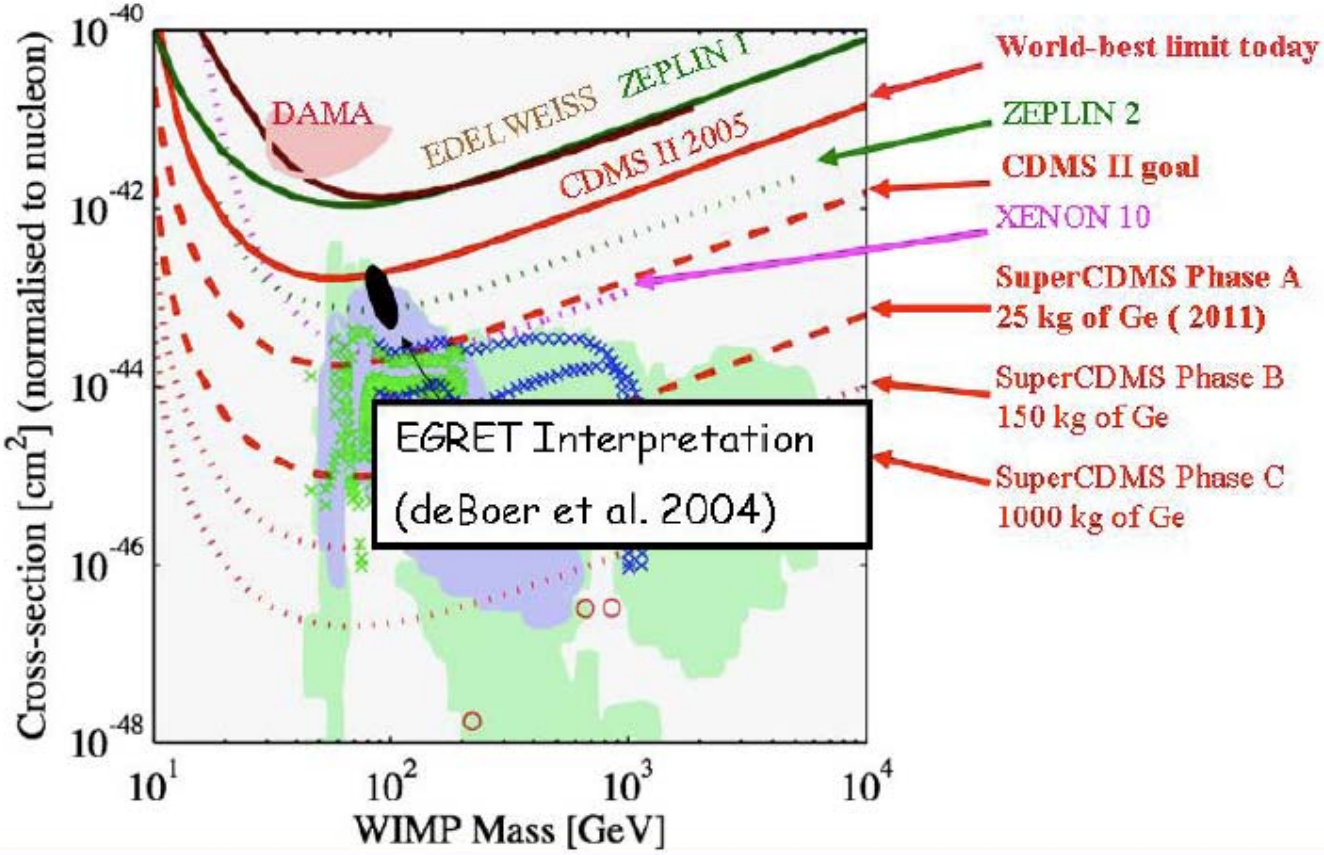
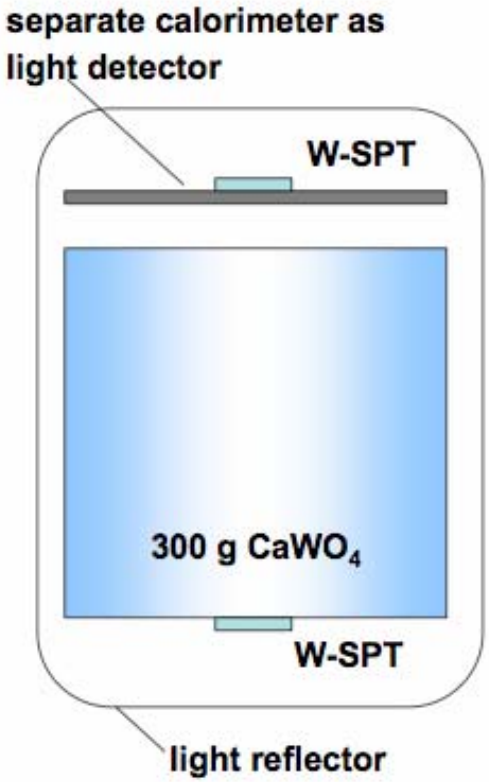
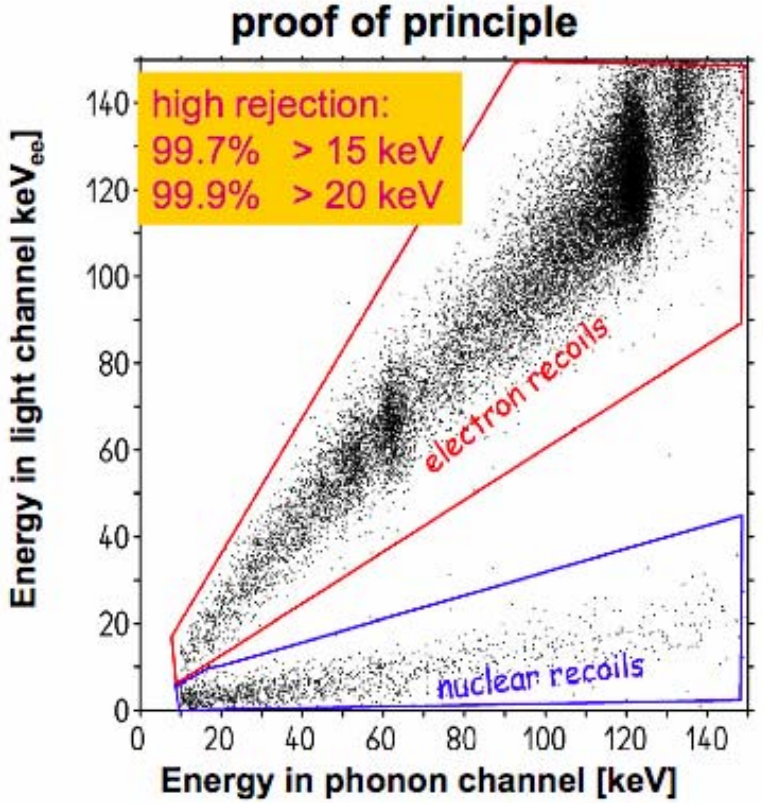
Continuing to probe SUSY space using CDMS



Phonon – Scintillation

Discrimination of nuclear recoils from radioactive backgrounds (electron recoils) by simultaneous measurement of phonons and scintillation light





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Life is too short.

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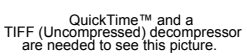
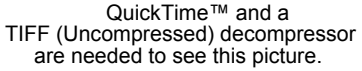
Life is too short.

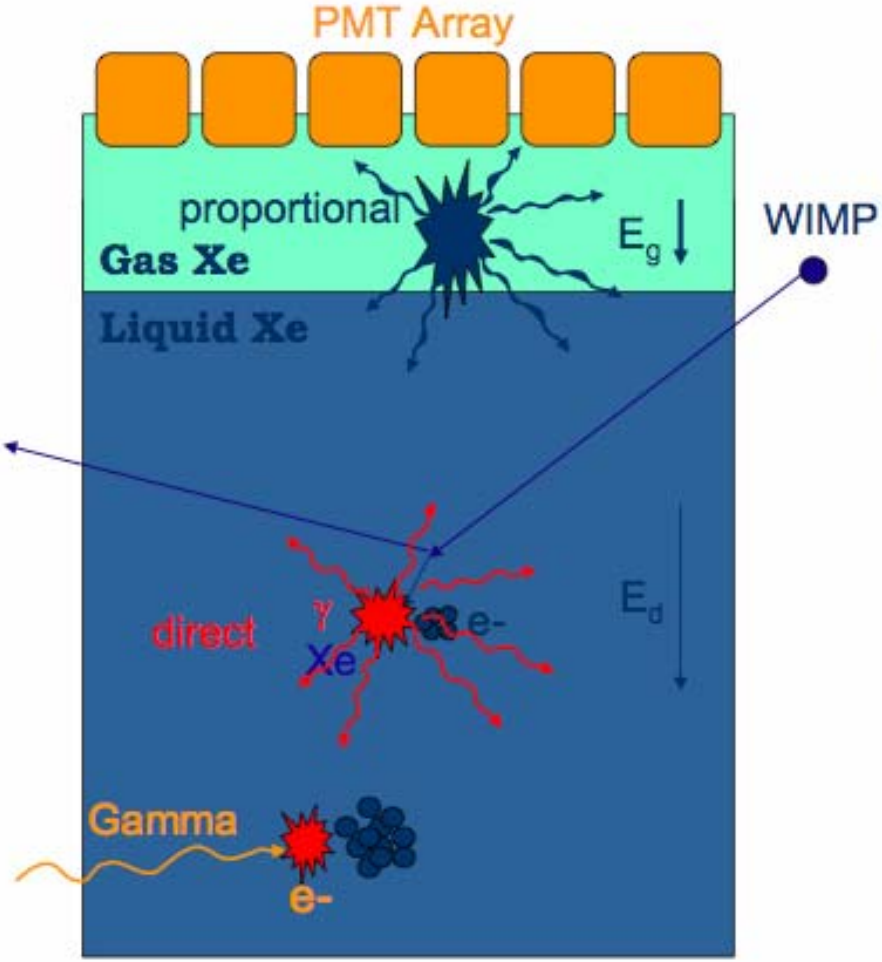


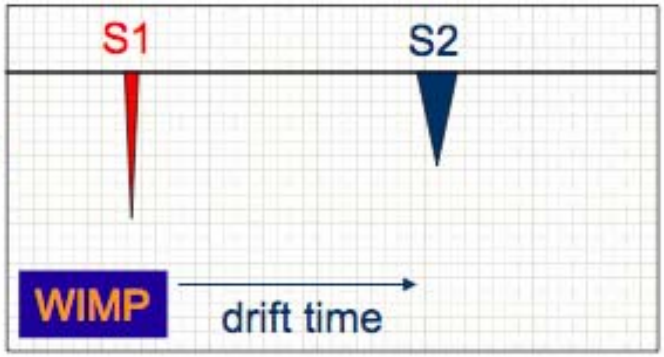


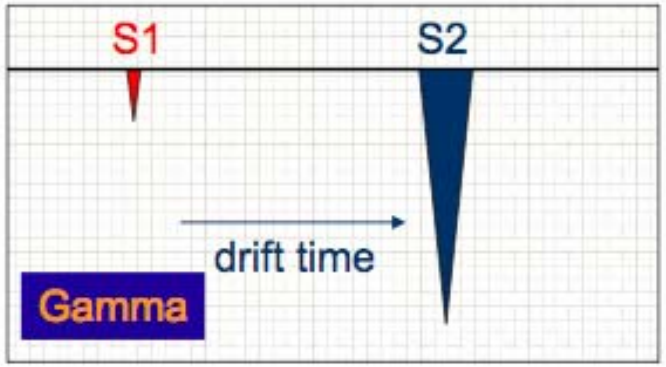
You can chisel…

…or you can pour.

XENON: Event Discrimination



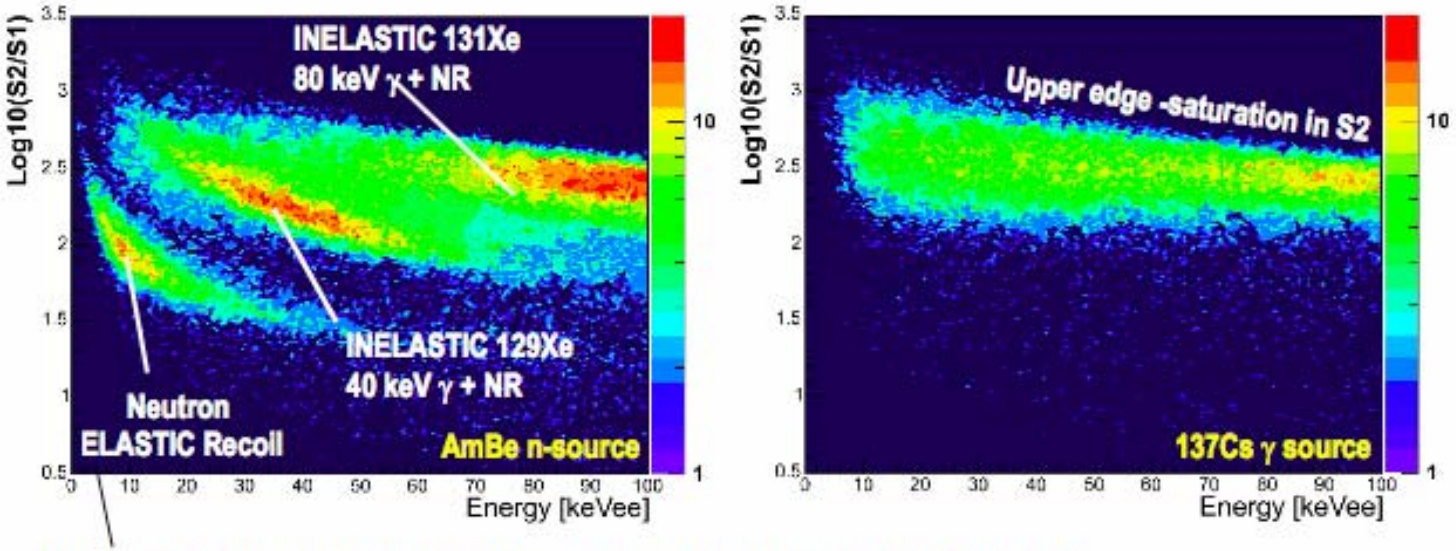




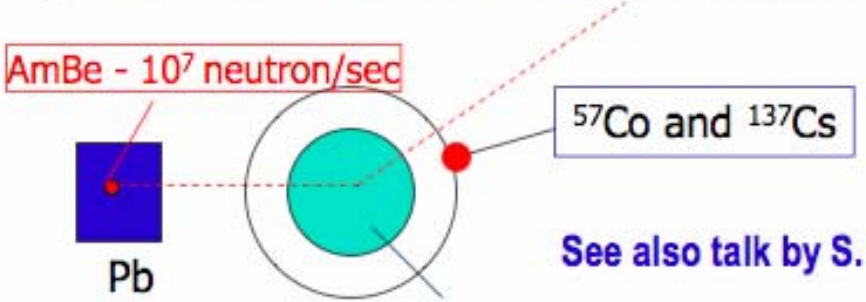
$(S2/S1)_{wimp} << (S2/S1)_{gamma}$

EVERY PHOTON IS SACRED

Gamma and Neutron Recoils Discrimination

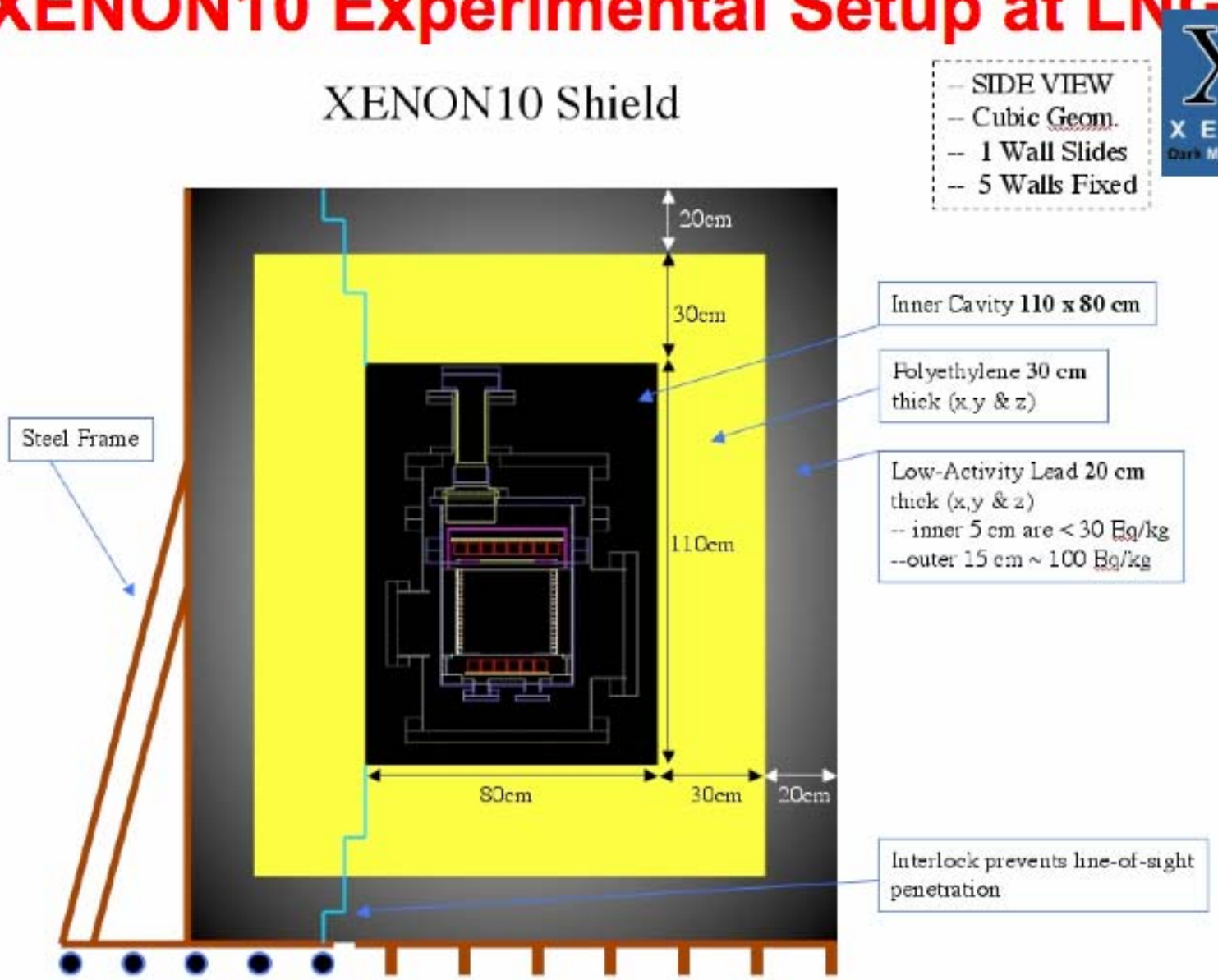


Energy Threshold ER~5 keVee →Recoil Threshold NR~10 keVr



See also talk by S. Kamat for LXe response to neutrons

XENON10 Experimental Setup at LNGS



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From the people that brought you this beauty...

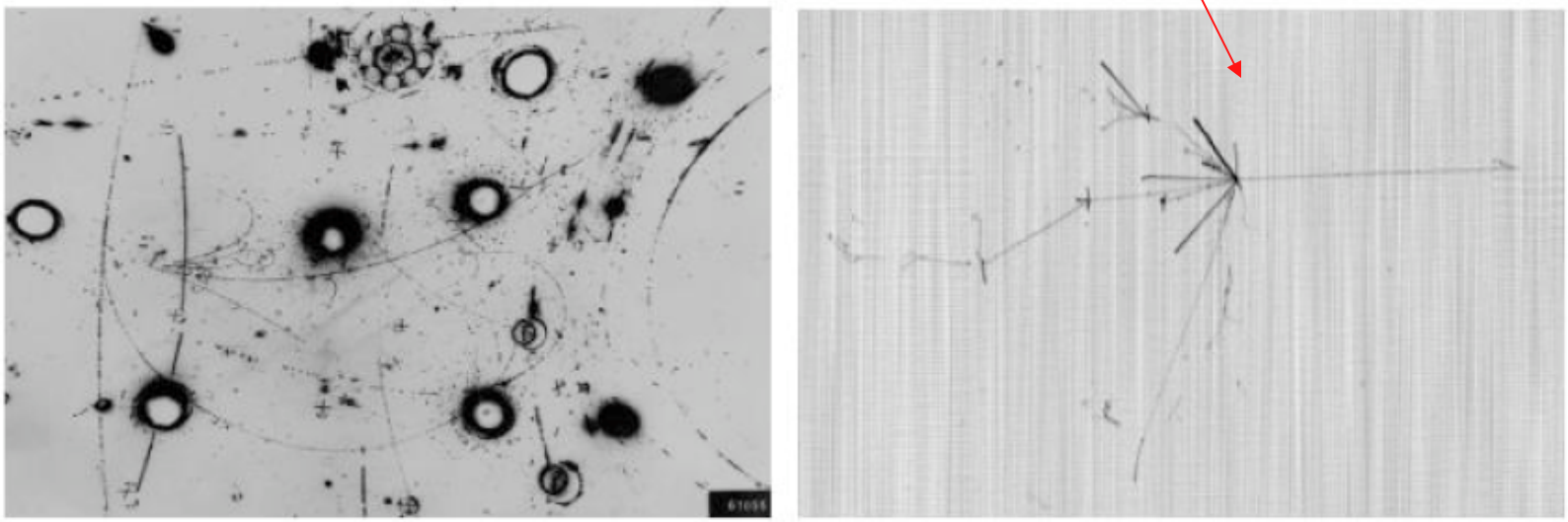
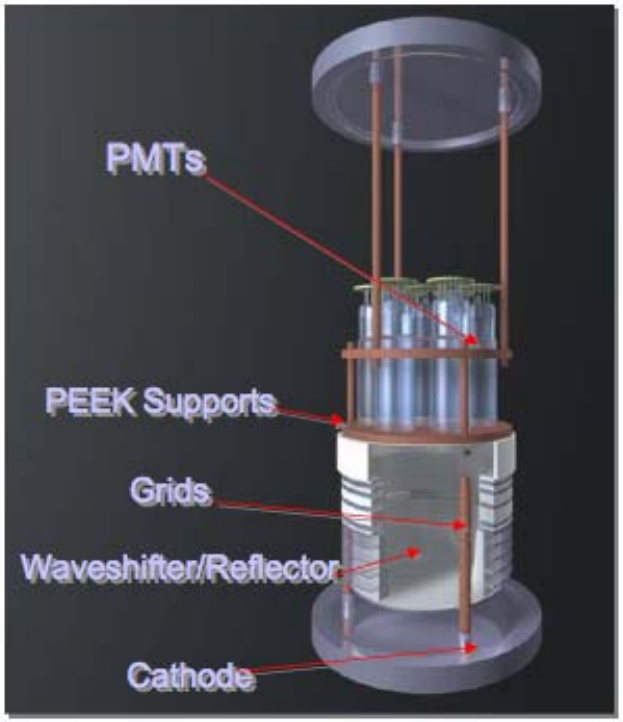


Figure 1. Electronic bubble chamber: an event recorded by the Gargamelle bubble chamber (left) compared to an hadronic interaction collected in the ICARUS TPC during the technical run on the surface (right).

The WARP 2.3 liters test

- The 2.3 liters prototype has been equipped, in subsequent phases, with 2" and 3" PMs made of low background materials.
- The structure is a (down) scaled version of the 100 liters detector, with field-shaping electrodes and gas to liquid extraction and acceleration grids.
- The equipment is contained in a high-vacuum tight container immersed into an external, refrigerating, liquid argon bath.
- The chamber is filled with ultra-purified argon in order to allow for long drift times of free electrons.
- Puritiy is maintained stable by means of continuous argon recirculation.



Schematic view of the 2.3 liters chamber

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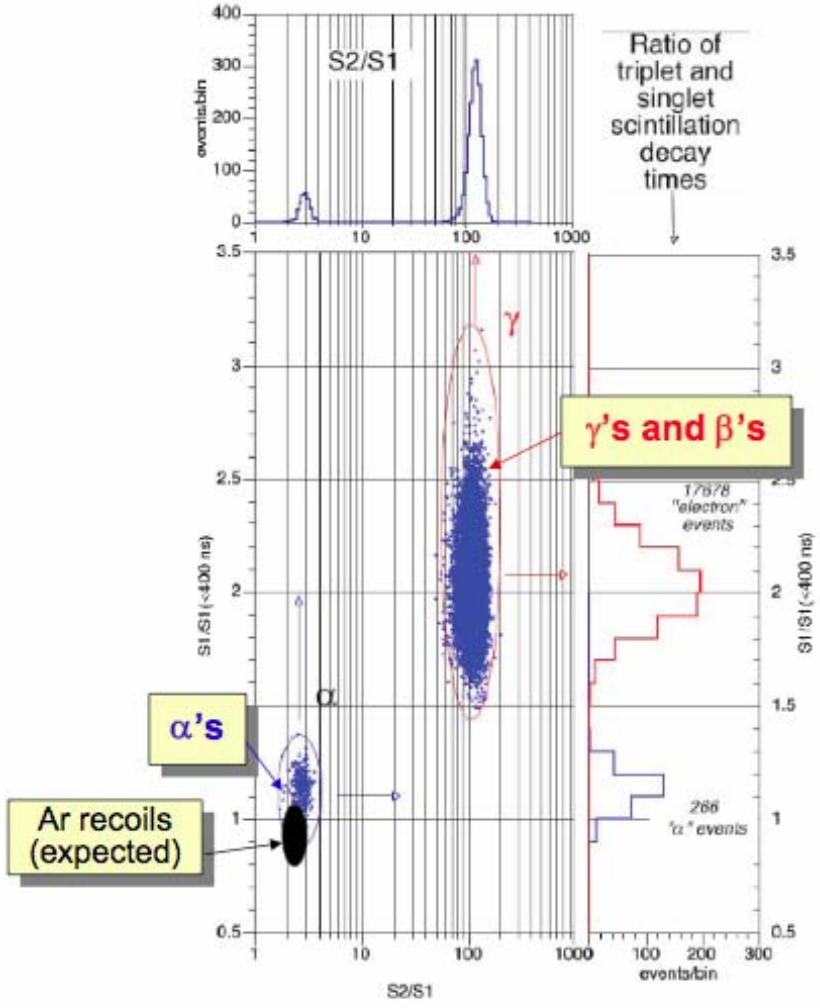
What's a couple of kilos next to 600T?
(in less than 2 yr, >10^7 rejection!!!)



The combination of a selection based on S2/S1 ratio and rise time of primary scintillation gives an extremely poweful rejection power for the search of WIMPs signals.

No event outside the two circled regions

Complete agreement up to an observed level of ≈ 1/20000 → combined rejection < $1/10^8$

TAUP 2005 - September 11, 2005 - Saragoza - Spain

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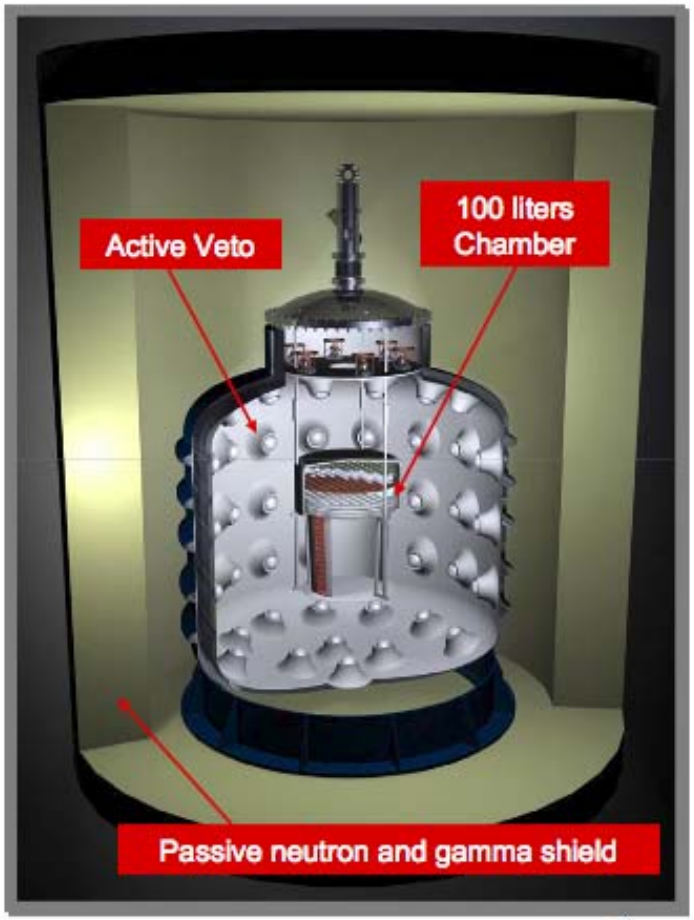
The WARP 100 liters chamber

- The liquid argon final detector with a sensitive volume of 100 liters is expected to be operational by 2006.
- In order to perfect the detection method, a 2.3 liters test jig is in operation at the LNGS, since April 2004.
- It is expected that the test detector may already reach competitive sensitivity levels.
- The 100 liters detector will provide, in addition to the increased sensitive mass:
  - → the active VETO system, completely surrounding the 100 litres sensitive volume;
  - → 3-D event localization by means of:
    - Drift time recording (vertical axis);
    - Centroid of PM's secondary signal amplitudes (horizontal plane).



Less is more: XMASS
(this from the people that brought you Super-K…)

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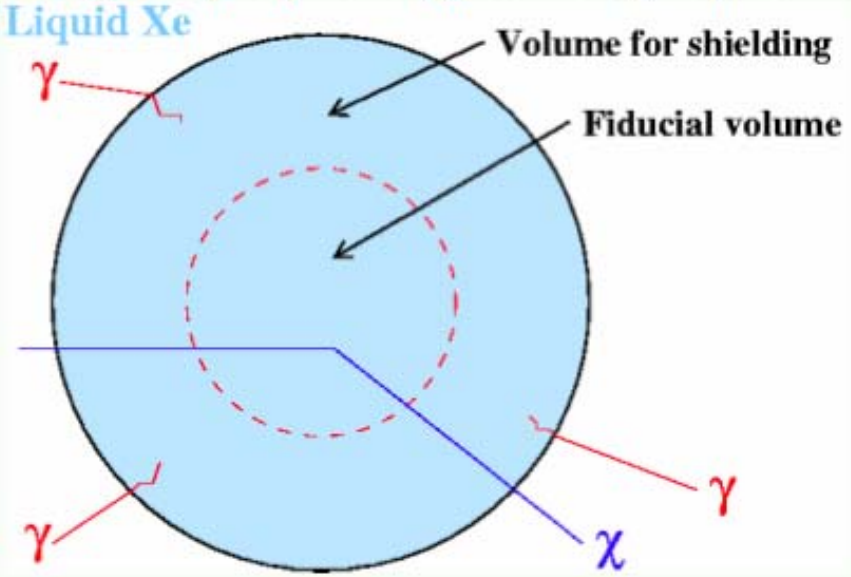
- Key idea

Self shielding for γ ray background by liquid Xe (Z=54)



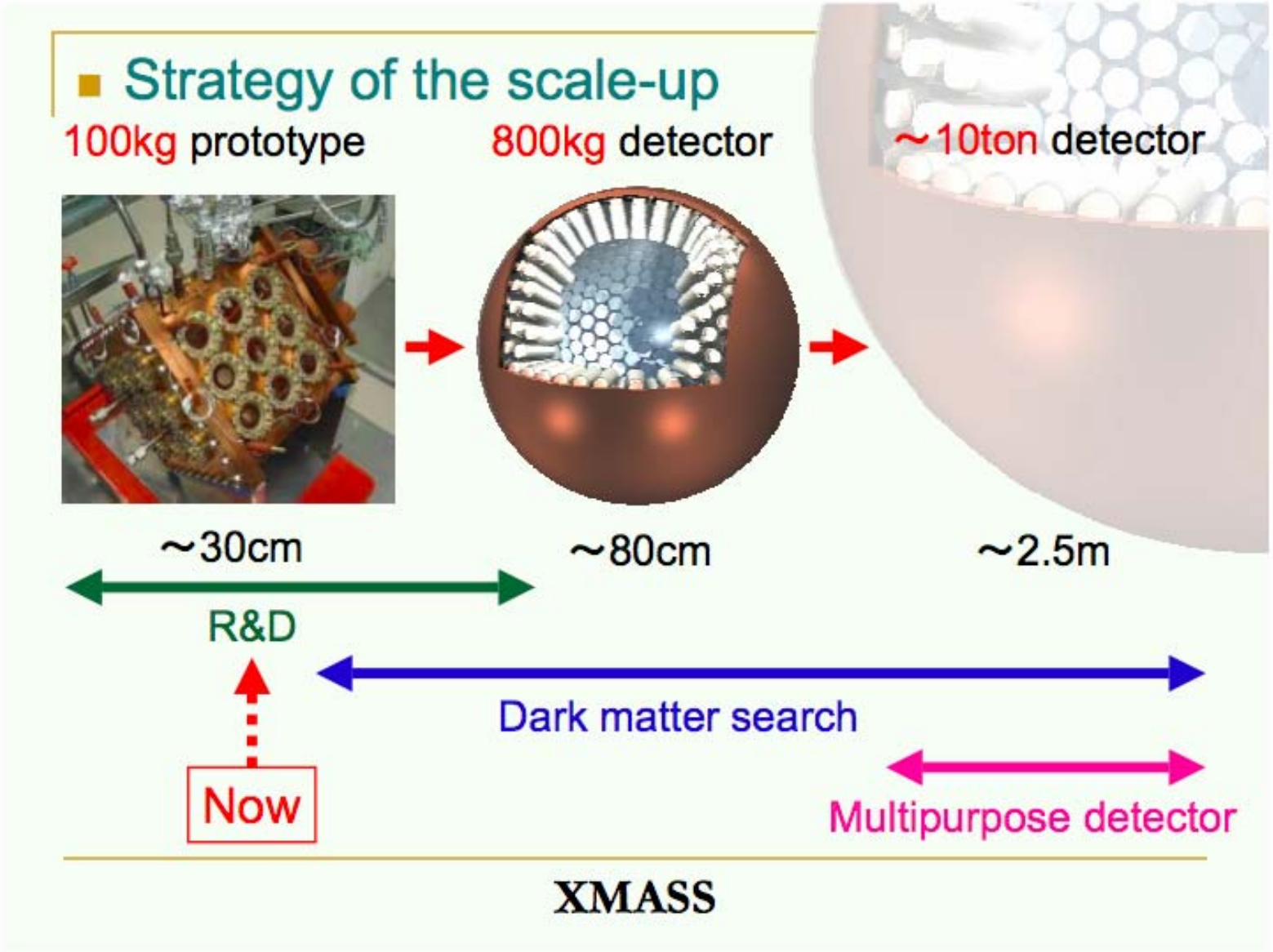
Reconstruct the vertex of events from PMTs information

→ γ ray backgrounds are absorbed in outer volume

→ Dark matter can go into fiducial volume

XMASS

Be scared. Be really, really scared.



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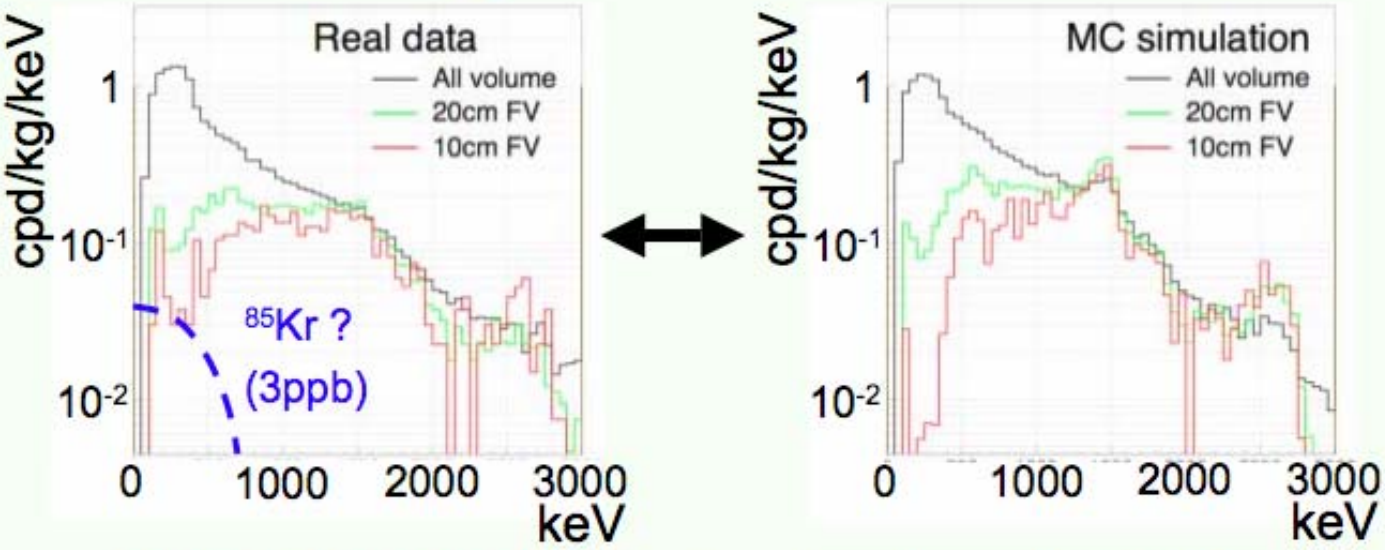
Self shielding for real data and MC



☆ Low background at inner volume by self shielding

→ Good agreement real data and MC estimation

☆ Something exists in low energy region of the real data

→ Internal background (^{85}Kr?)

XMASS

Yes, they do.

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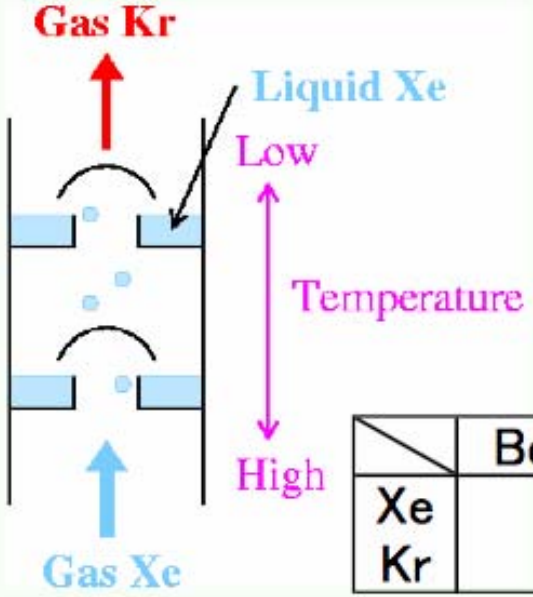
Purification of Xe by distillation

☆ Test using 1.6kg Xe in September 2003

☆ XMASS succeeds to reduce Kr concentration in Xe from 310[ppb] to < 5[ppb] with one cycle (~1/100)



	Boiling point
Xe	165K
Kr	120K

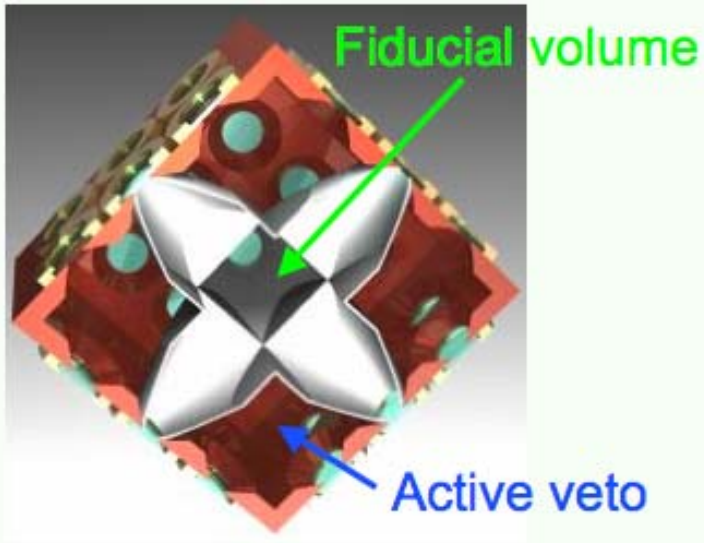
→ Full process of 100kg Xe next week!

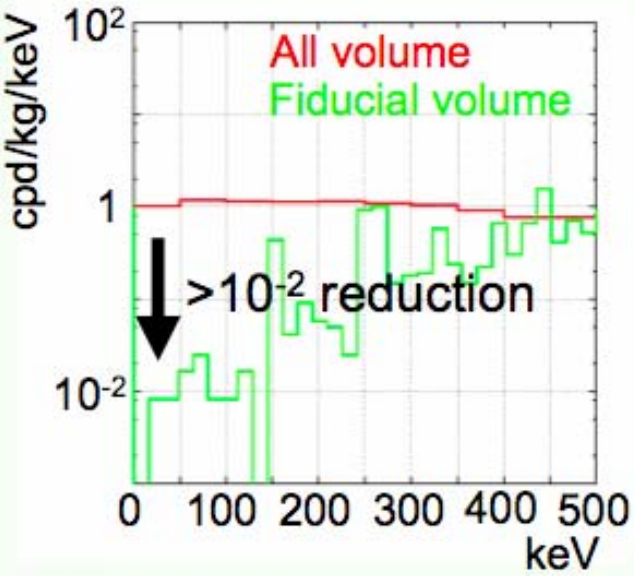
XMASS

Next plan of 100kg detector (2)

☆ Dark matter search with PTFE light guide

- 0.6 p.e./keV → 1.2 p.e./keV
- Difficult to fit the wall events → No need to fit





→ Reach the sensitivity of DAMA, CDSM,…

XMASS

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Local efforts: COUPP

- **KICP charge (of many!):**
  –> What is Dark Matter?
  –> Is it PARTICLES at the galactic level?
  –>WIMPs?
  –> SUSY WIMPs? (advantage: non ad hoc)

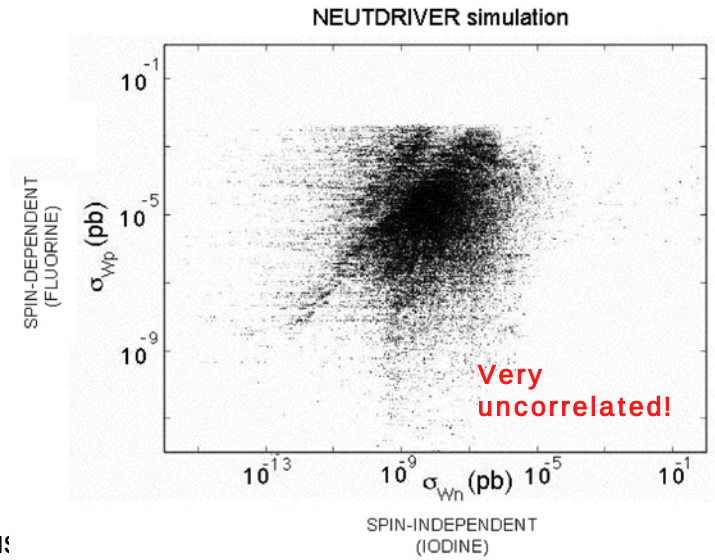
NEEDS SWIFT AND THROUGHOUT EXPLORATION (WITH A REALISTIC PRICE TAG)

- **THE PROBLEM:**

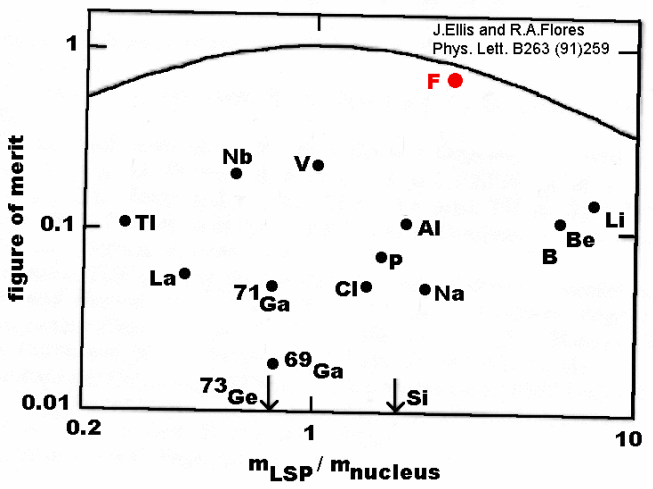
Extremely small SUSY WIMP interaction rates require TON or even MULTI-TON targets, with near PERFECT background rejection: Mus keep exclusively nuclear recoils, and of these only those WIMP-induced

- **OUR SOLUTION AT KICP:**

–> Use inexpensive, safe, superheated industrial refrigerants
–> Operate detectors at room temperature and modest pressure
–> Choose optimal SUSY WIMP target (CF_3I), maximally sensitive to both spin-dependent and -independent WIMP couplings
–> Demonstrate intrinsic MIP rejection power of $>10^9$ (best anywhere)
–> Design detector with unique neutron rejection abilities and sensitivity To WIMP smoking guns
–> Insist on simplicity: local detector fabrication, keep collaboration lean
–> Concentrate on alpha emitter purification to levels already achieved (single goal, will lead to throughout SUSY phase space exploration)



An old precept:
Attack on both fronts



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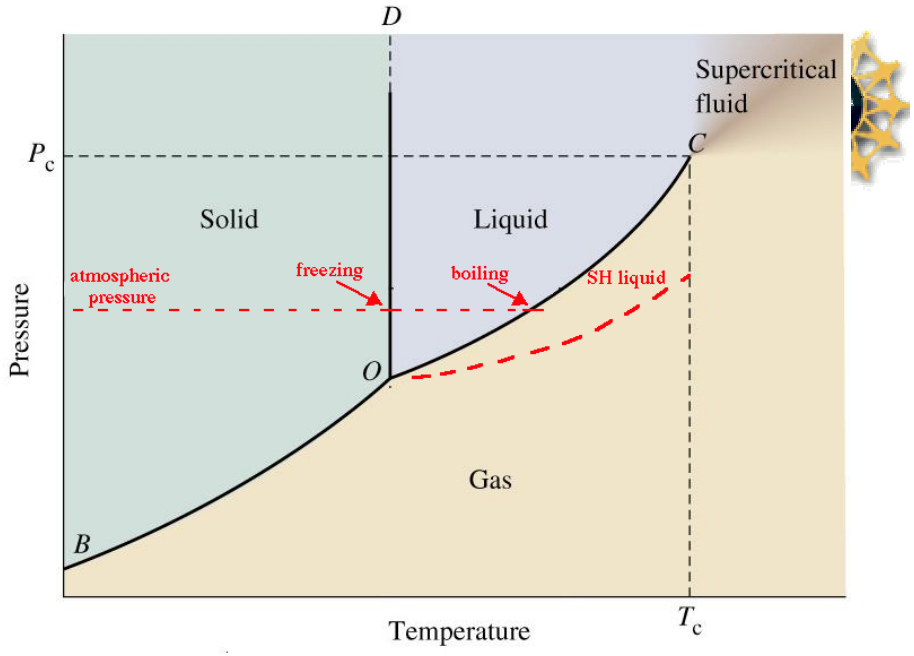
A risky maneuver:

⇒ Two ongoing experiments (SIMPLE, PICASSO) exploit Superheated Droplet technique (SDD)

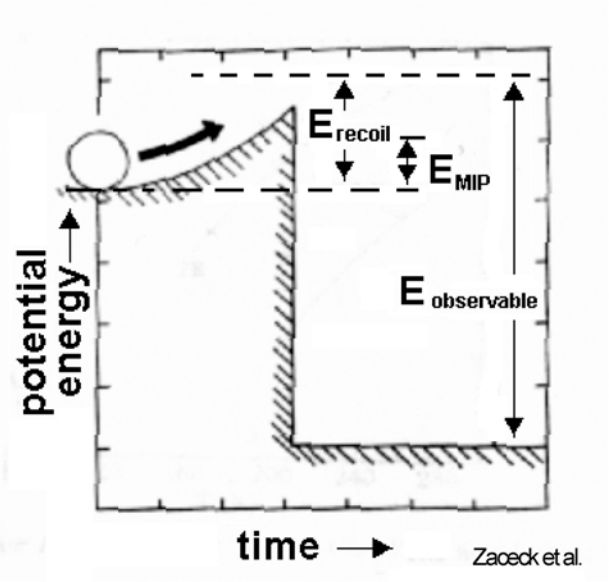
⇒ Interesting heavy-liquid targets such as **CF_3I** hard to introduce in SDDs; also, α-emitters migrate to droplet boundary ⇒ try bulk (=Bubble Chambers, a much trickier endeavor). KICP seeded this transition: taking risks seemingly pays.

⇒ Total insensitivity to MIPs, yet sensitive to low-E nuclear recoils (via tunable dE/dx and E thresholds)

⇒ ~$140/kg, room T …a fast path to tonne detectors?



neutron-induced nucleation in 20 c.c. CF_3Br (0.1 s real-time span)
Movie available from http://cfcp.uchicago.edu/~collar/bubble.mov



QuickTime™ and a
MPEG-4 Video decompressor
are needed to see this picture.

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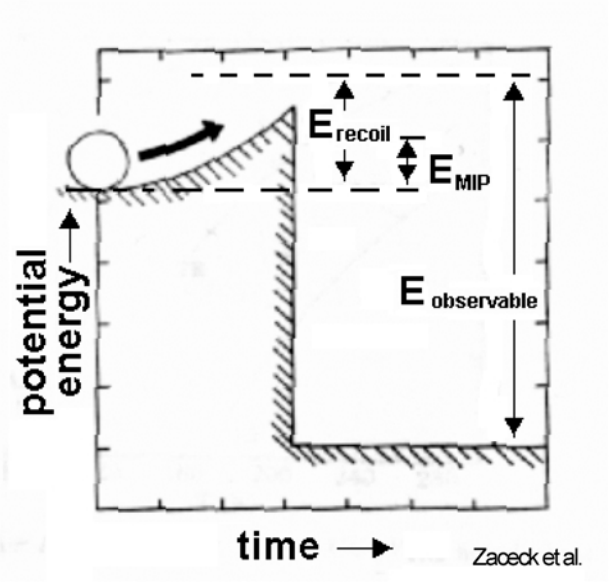

Seitz model of bubble nucleation:

$$E > E_c = 4\pi r_c^2 \left(\gamma - T\frac{\partial\gamma}{\partial T}\right) + \frac{4}{3}\pi r_c^3 \rho_v \frac{h_{fg}}{M} + \frac{4}{3}\pi r_c^3 P \quad , \quad r_c = 2\gamma/\Delta P$$

$$\mathrm{d}E/\mathrm{d}x > E_c/(ar_c)$$

Threshold also in stopping power, allows for efficient INTRINSIC background rejection

neutron-induced nucleation in 20 c.c. CF_3Br (0.1 s real-time span)
Movie available from http://cfcp.uchicago.edu/~collar/bubble.mov

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Can Bubble Chambers be made stable enough?

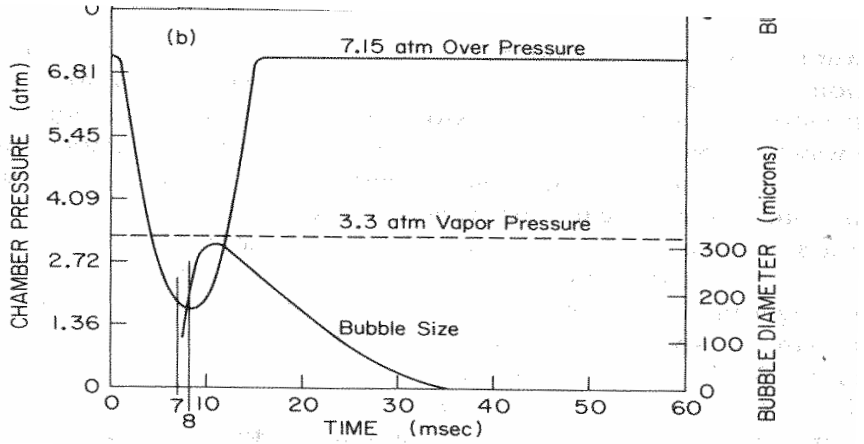
SEE -> arXiv:astro-ph/0503398 v1 17 Mar 2005

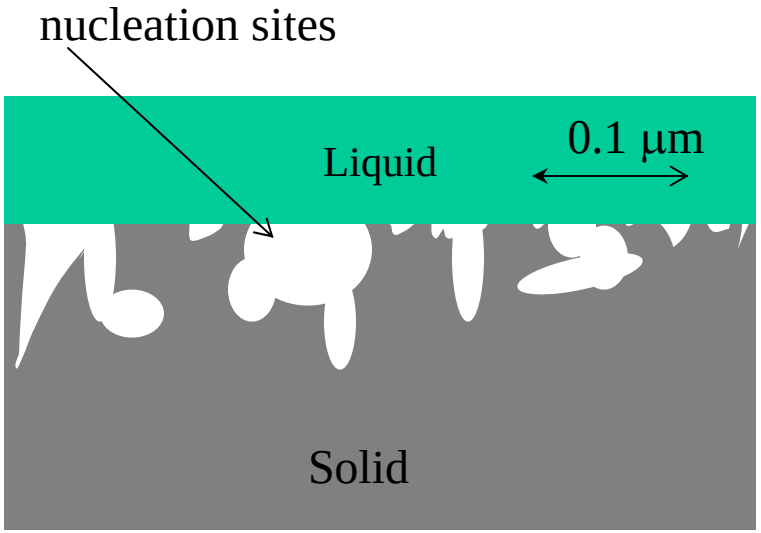
- Old Bubble Chambers radiation-ready for only few ms at a time (coincident with beam spill)

- Gas pockets in surface imperfections and motes can act as inhomogeneous nucleation centers.

- A WIMP BC must remain superheated indefinitely, except for radiation-induced events. Low superheat helps, but is not enough.

- *Recent* progress in neutralization of inhomogeneous nucleation sites (from work unrelated to bubble chambers!). E.g. use of liquid "lid", outgassing in presence of buffer liquid, cleaning techniques and wetting improvement via vapor deposition.





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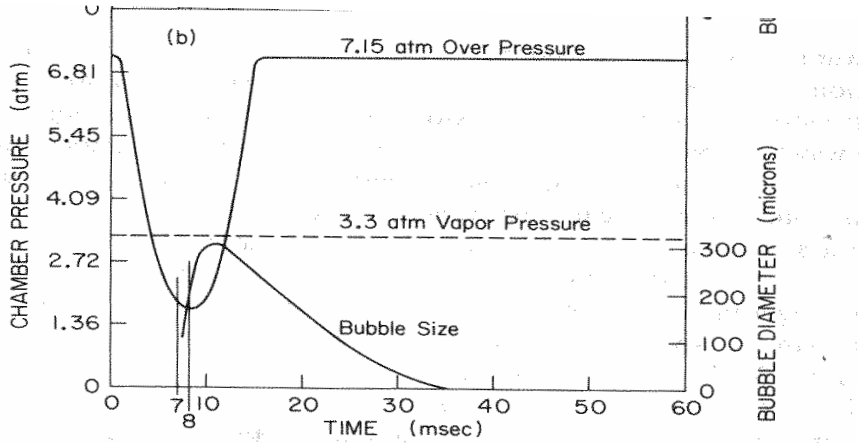

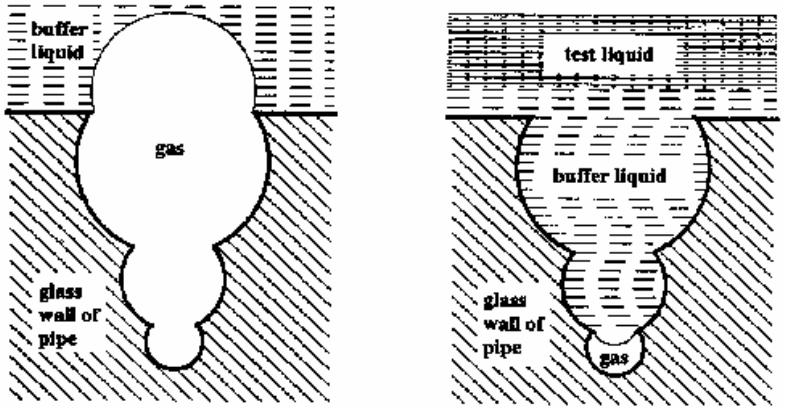

Figure 1. Schematic representation of the deactivation of nucleation sites by degassing (1), pressurization and replacement of buffer liquid by test liquid (2).

P. Reinke, Exp. Heat Transf. 10 (1997) 133

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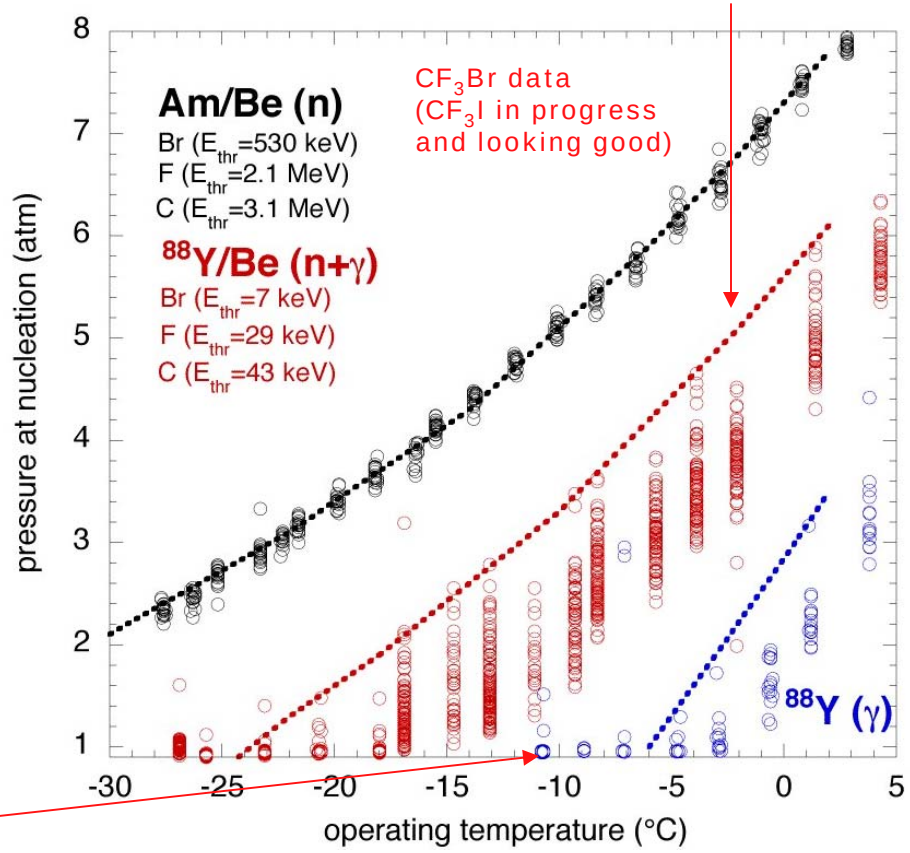
Well-defined low energy threshold

Sensitivity to < 7 keV recoils demonstrated (while having no response to 3mCi γ source). In agreement with models.

Sensitivity to ~1 keV recoils in progress (Sb-124/Be source)

Further studies in progress (efficiency, sharpness of threshold, disentanglement of I and F response).

Lines show Seitz model prediction for top boundary of data point distribution (onset of sensitivity during decompression)



Detector is insensitive to gammas (see previous transparency) yet fully responsive to low-E recoils

Background Counting Rate at ~ 6 m.w.e.

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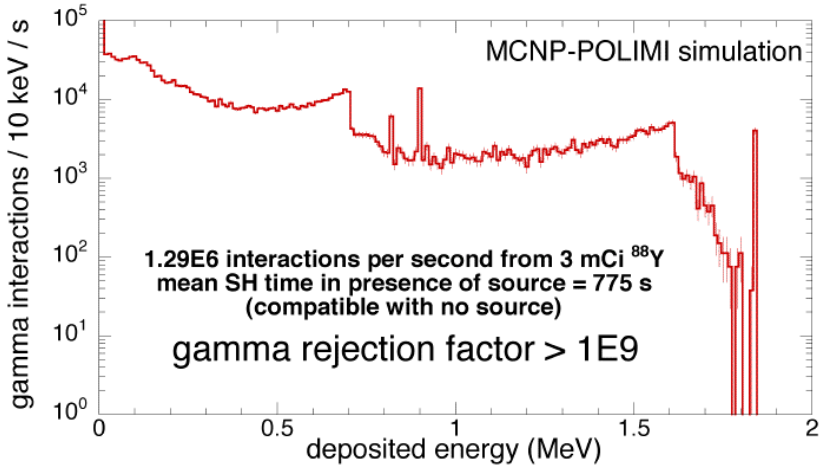
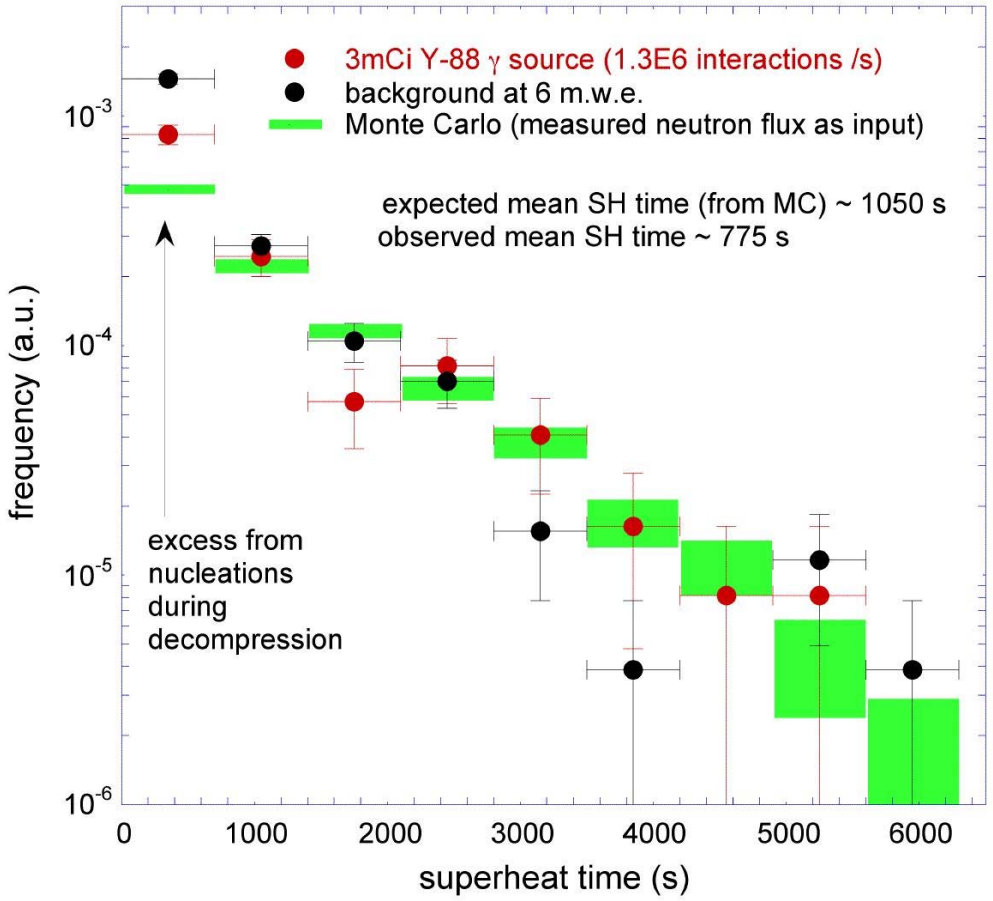
- Mean survival time for superheated state varies due to periodic episodes of nucleation on chamber walls, but is usually ~ 10 minutes.
- Live time (due to long recompression cycle) is already 62%.
- Counting rate for "real events" is 4/hour (compatible with measured fast neutron flux in the lab).
- **Intrinsic gamma rejection factor (from absence of excess nucleation rate in presence of Y-88 ⇒ 1.3E6 γ interactions / s) is ≥ 1E9 (⇒ ^{14}C not a concern even at the multiton level)**

Energy	Neutron Flux (n/cm^2/s) Ground Level	6mwe Lab	50 mwe Pit
<.5 eV	0.00394	4.65E-04	4.37E-05
.5eV-100keV	0.00384	5.61E-04	1.60E-04
100keV-10MeV	0.0015	6.87E-04	1.48E-04
10 MeV-50MeV	0.00454	0.00E+00	0.00E+00
Total	0.01382	1.71E-03	3.52E-04





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Where we are

⇒ 2 kg CF_3I chamber stable and dominated by environmental neutrons at 6 m.w.e. Still learning some of the interesting peculiarities of this new system (see astro-ph/0503398): systematic study of effect of recompression time, decompression speed, "direction" of heating, etc.

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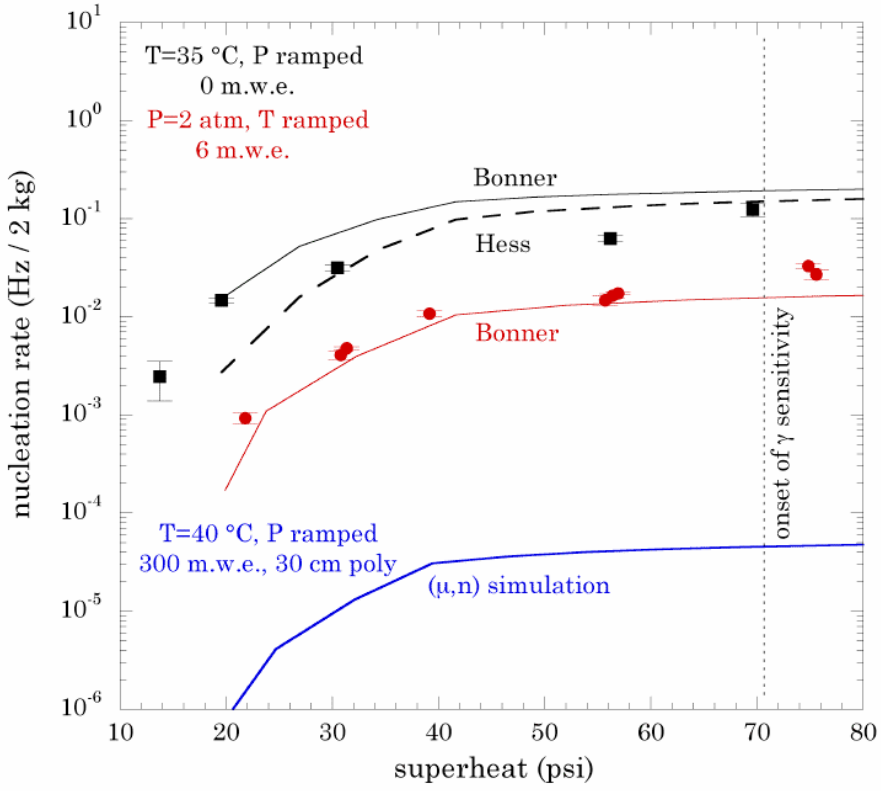
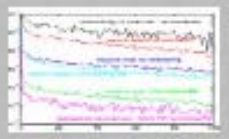
nucleation rate in 2 kg chamber compared with MC (response to measured environmental n spectrum)

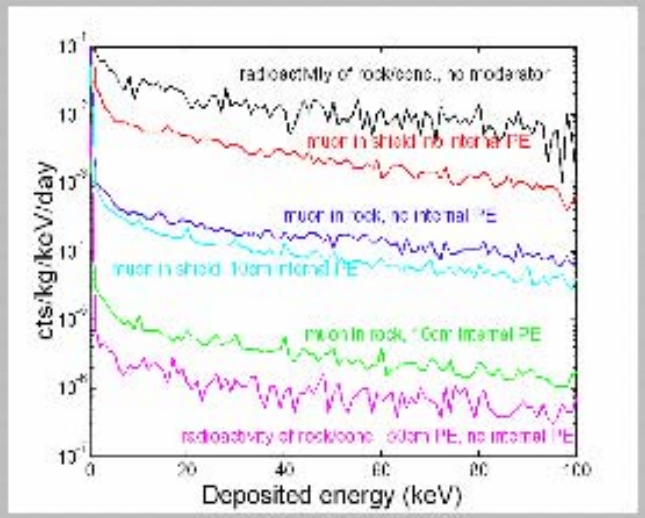


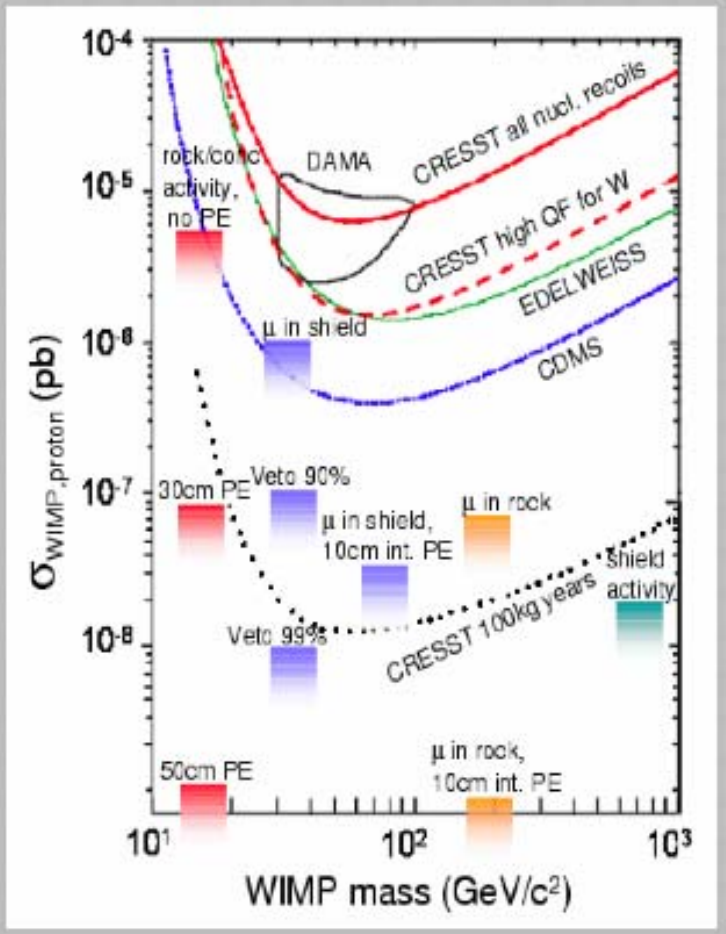


Neutron Simulations

MC simulations of neutrons from different sources:

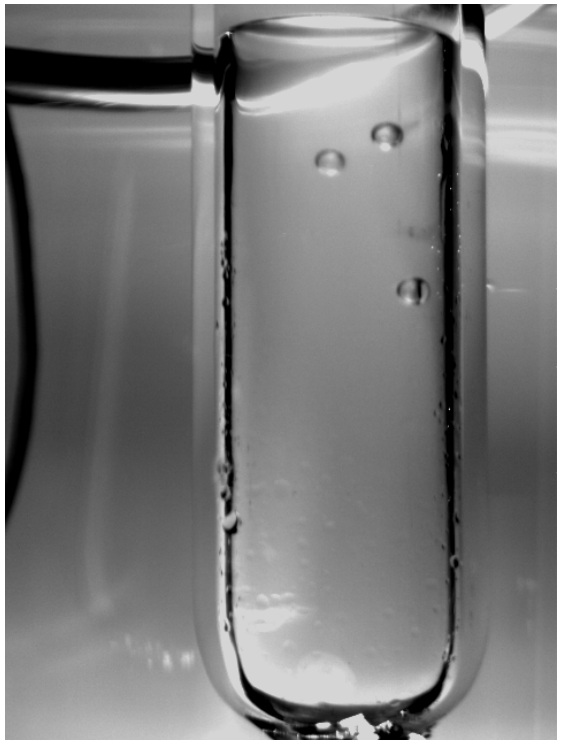
- Radioactivity: fission, (α,n) → 0.6 cts/kg/day
- Muons in the shield (Pb)
- Muons in the rock



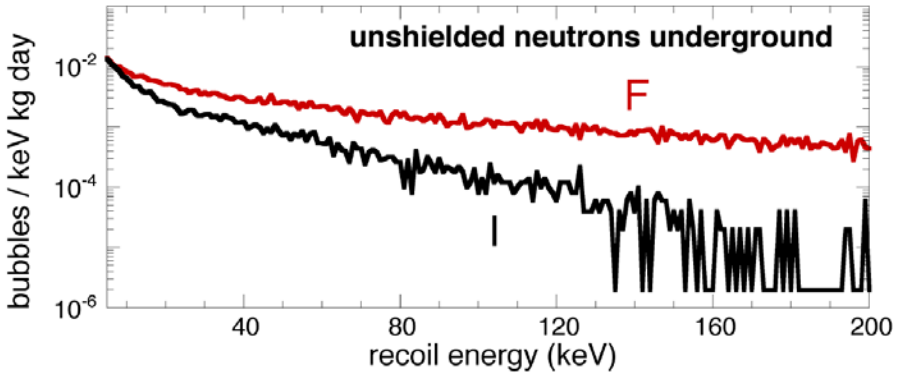


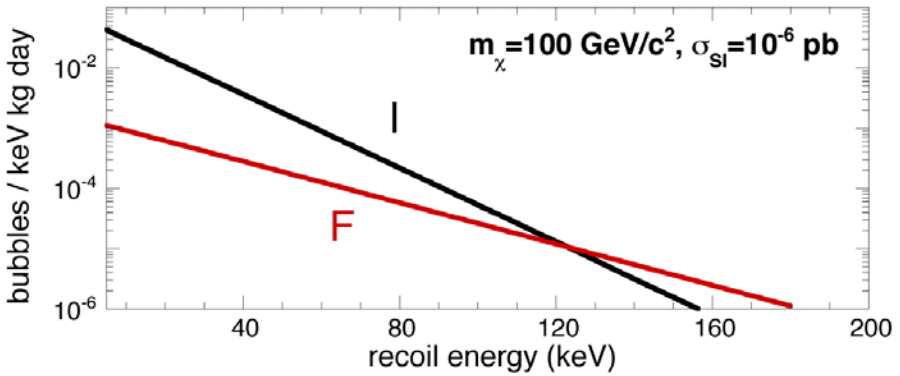
Neutron Background Rejection Potential

- Multiple simultaneous bubbles are present in ~4% of events in our "background" data set. Neutrons can do this, WIMPs cannot.



- The response to neutrons and WIMPs interacting mostly via SI is *very* different for refrigerants containing F only (C_3F_8) and F+I (CF_3I); more favorable situation than Ge/Si to verify a WIMP signal





Neutron Background Rejection Potential (bis)

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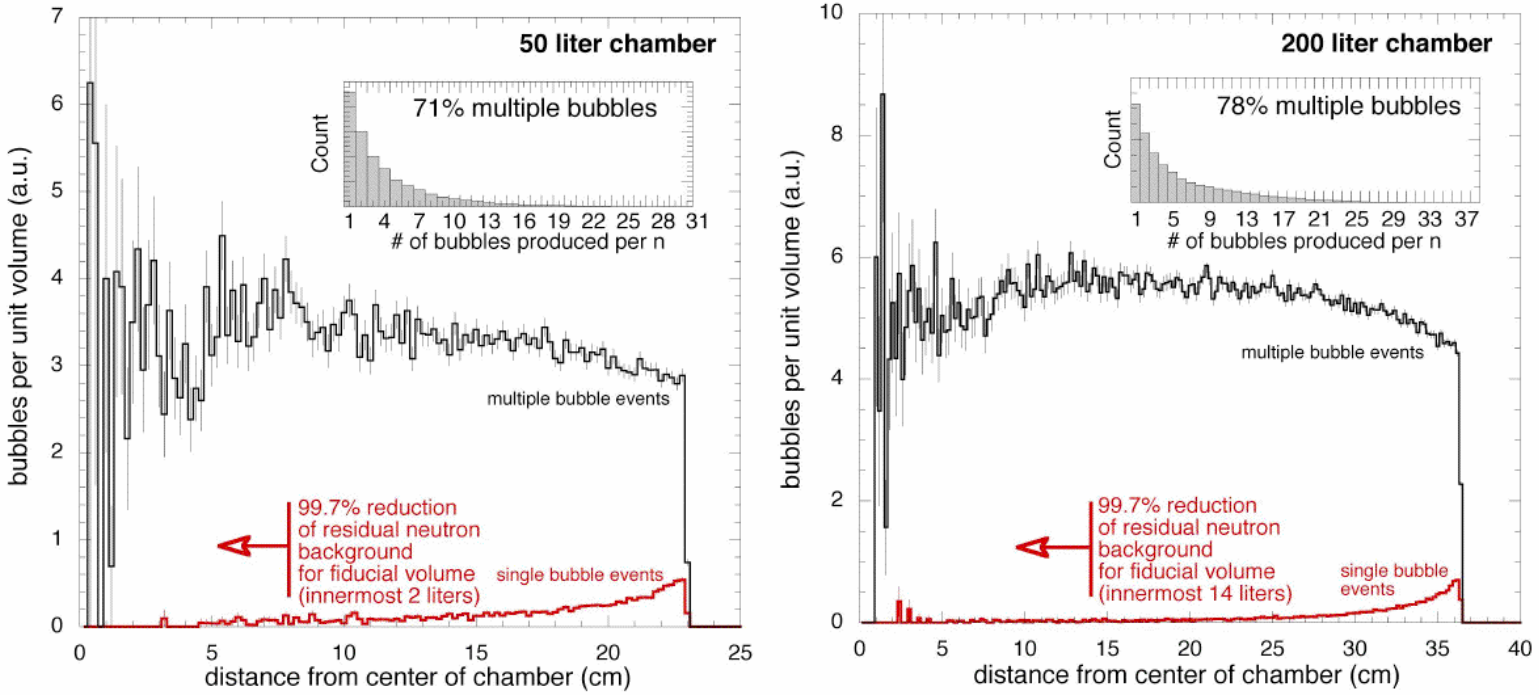
•Larger chambers are “self-shielding” (innermost fiducial volume will have good rejection of energetic neutrons able to penetrate moderator <- chances of a single n-induced bubble deep within detector volume are very small)

This helps reduce sensitivity to dreaded high energy “punch through” neutrons down to the ~1 count/tonne/month range ⇒ allowing for exhaustive exploration of supersymmetric WIMP models.

MCNP-POLIMI simulations



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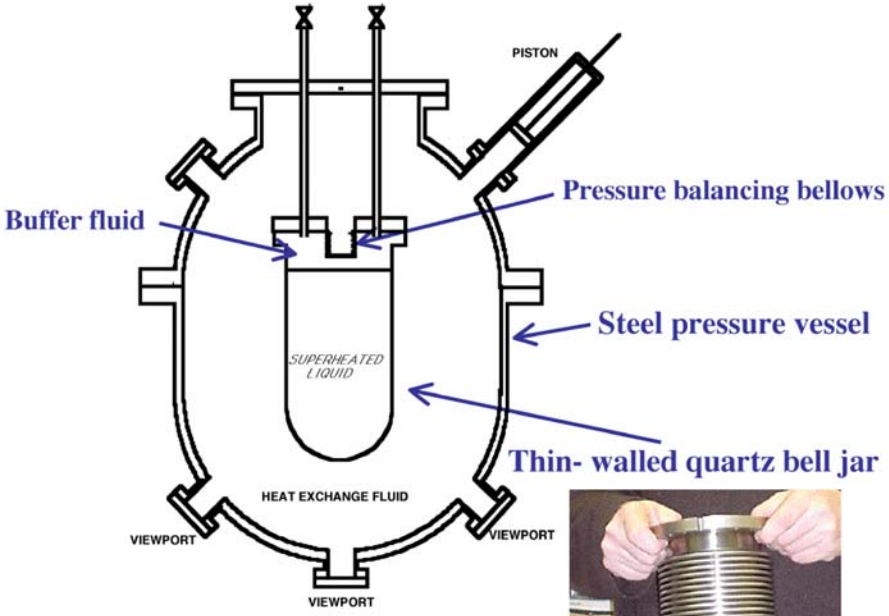
Meet COUPP-2 kg
(2 kg CF_3I target, installation at 300 m.w.e. (FNAL) Feb. 2005)

- Central design issue is how to avoid metal contact with superheated liquid.
- Bellows mechanism compensates pressure inside and outside of inner vessel



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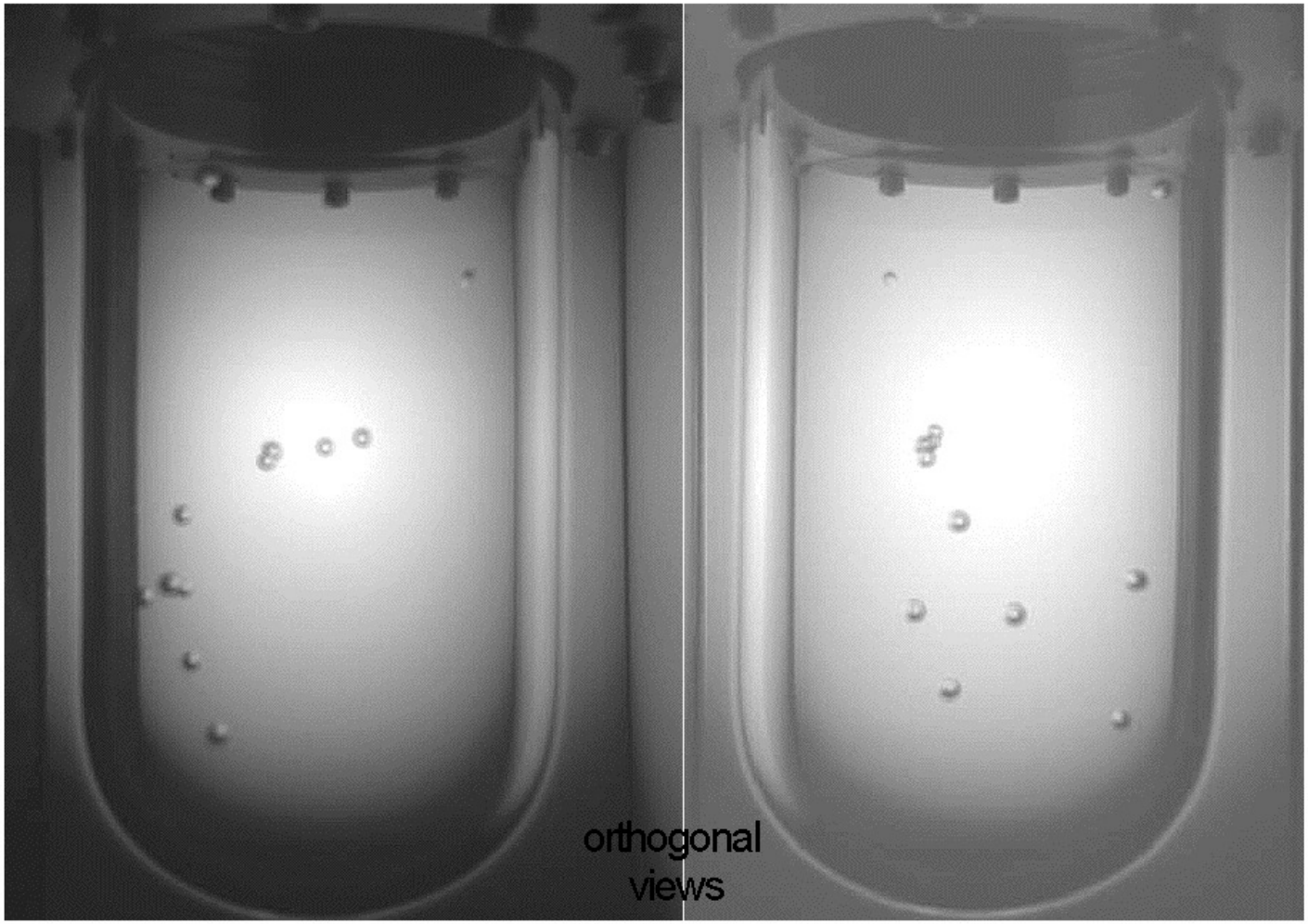
Record holder: high multiplicity (μ,n) event (12 bubbles)



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Present status at ~300 m.w.e. (July 2005)

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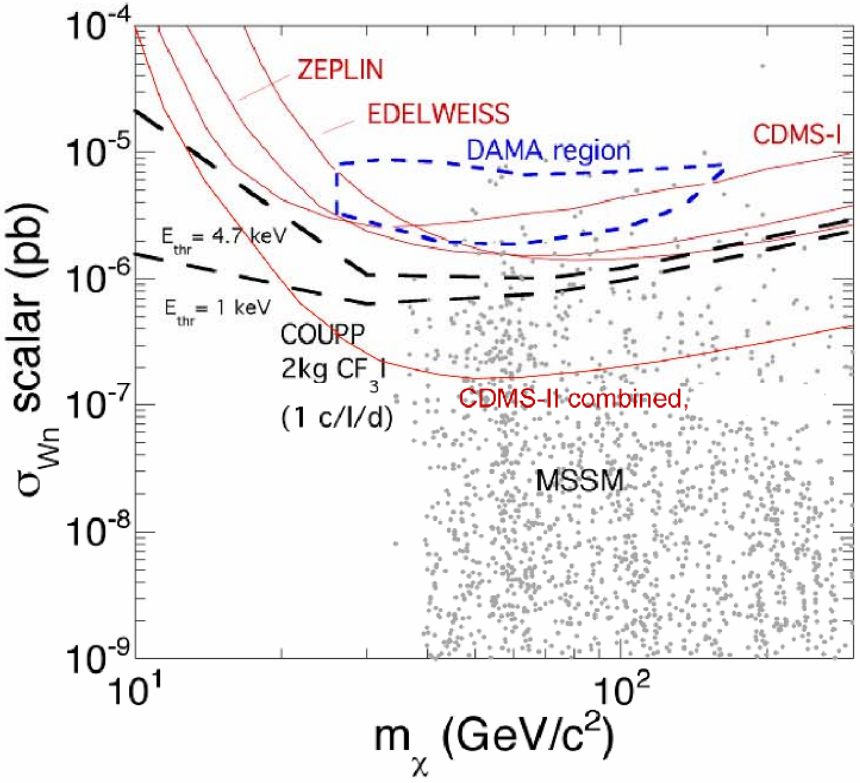
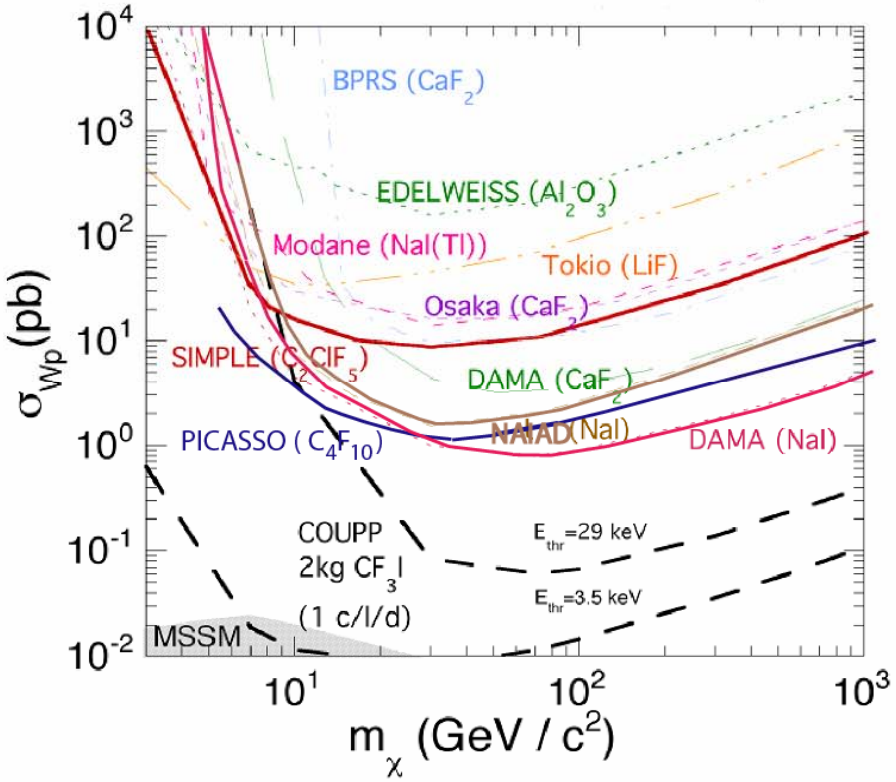
Where we are

Physics potential of 2 kg prototype at the 300 mwe NuMi site (FNAL), prior to addition of muon veto. Lines are labeled according to achievable energy threshold





Same target material as DAMA for spin-independent (no arguing about target effects)

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Moving FAST towards the 1 Ton frontier
Goal ~100 kg deep underground during 2006

⇒2 kg CF_3I demonstration "blind" chamber under construction (Dec. 2005). Bubble position/multiplicity determined exclusively via ultrasound detection (mm precision possible)

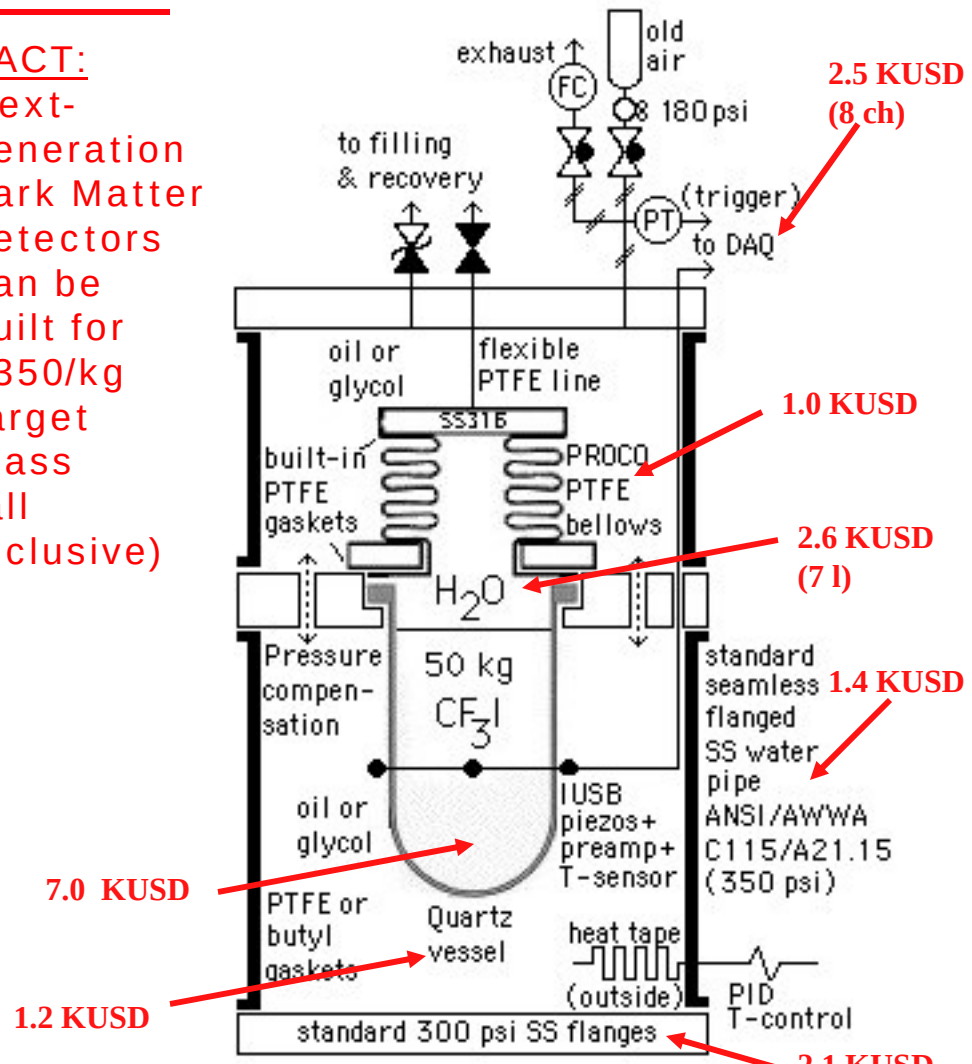
⇒No welding nor machining necessary, all commercially-available parts (uses standard pressure-rated water pipes).

⇒ Simplest possible assembly (all in-house, infrastructure -clean room, etching (FNAL)- already in place)

⇒<u>Addresses alphas already:</u> double Rn barrier, absence of Rn emanation sources in inner vessel, use of 1E-3 ppt U,Th water, CF_3I scrubbing column, measures against Rn plating.

⇒Absence of inspection windows and 50 kg modular size enhance safety in an underground environment. Modular deployment provides immediate physics results and enables progressive improvements.

<u>FACT:</u>
Next-generation dark Matter detectors can be built for $350/kg target mass (all inclusive)



A "blind" Bubble Chamber
(and yet it can see)

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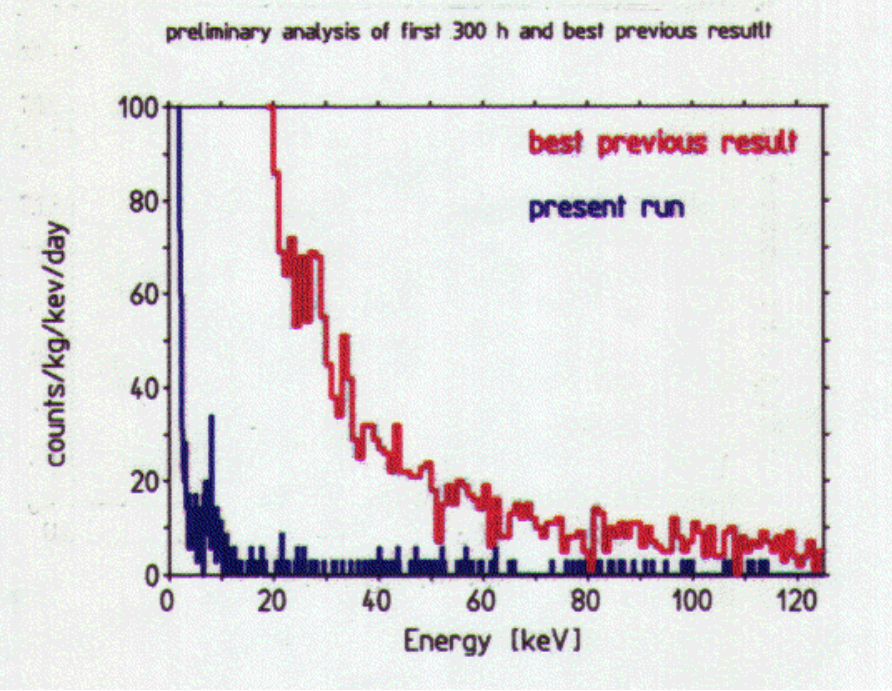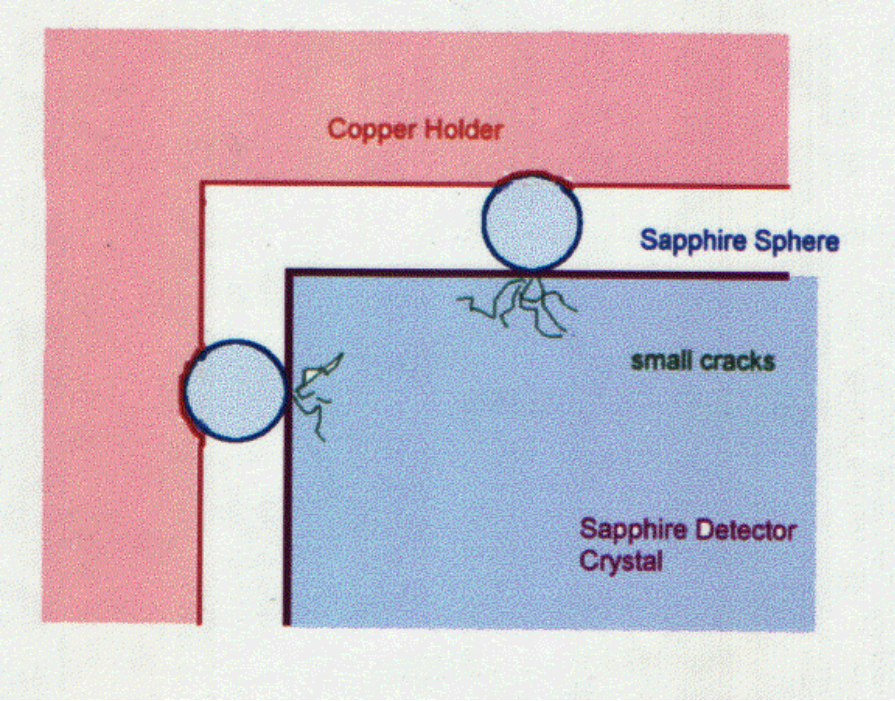
Let us be humble for a second (try!)