Things that go bump in the dark

Outline of (this component of) the course:

- Brief introduction to low-background techniques
- What do we expect from WIMPs and axions?

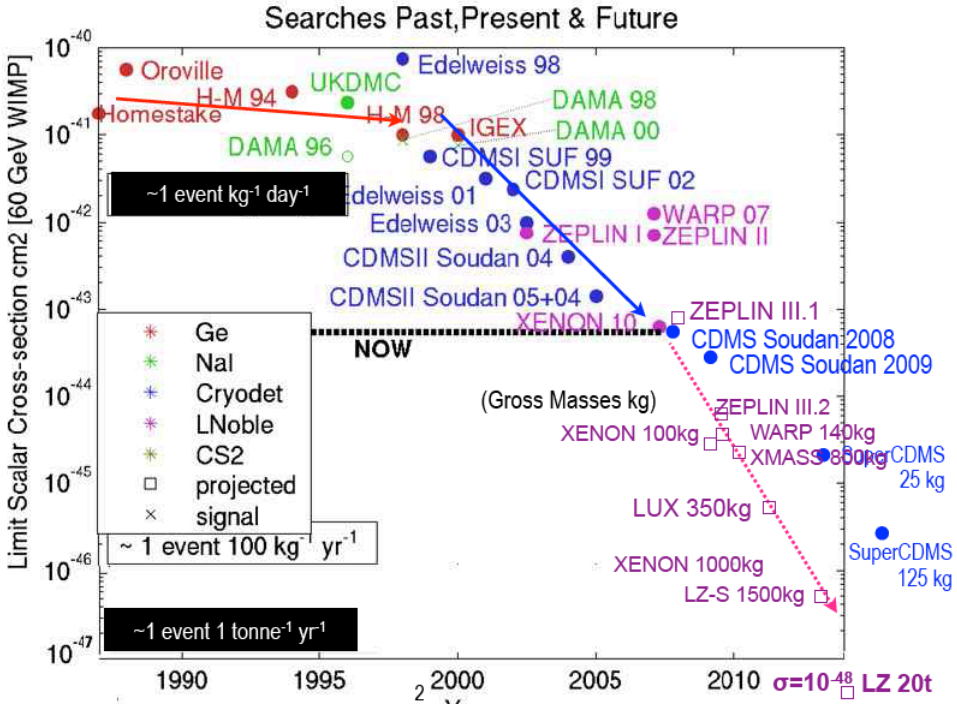
(what do we think we know about them, basic phenomenology)

- Detailed discussion of direct search methods
- Have we found them yet?
- What will it take to call it "dark matter"?

Experiment	Technology	β,γ rejection	Comments
CDMS	Cryo Ge/Si	ionization/phonon	surface β's, timing helps
Edelweiss	Cryo Ge	ionization/thermal	surface β's, NbSi helps
CRESST, Rosebud	Cryo $CaWO_4$	scintillation/thermal	low light for WIMP on W
Zeplin, XENON,	LXe 2-phase	charge/scintillation	low light, PMT radioactivity
WArP, ArDM,	LAr 2-phase	charge/scintillation	purification (^{39}Ar,^{42}Ar,^{85}Kr)
XMASS	LXe	scint,self-shielding,	No E-field, good scaling
CLEAN	LAr/LNe	scint,pulse shape disc.	also solar ν, no E-field
Majorana, Gerda	HPGe counting	energy resolution	primarily ββ-decay
Genius, GEDEON	HPGe counting	extreme purity	large mass, ann mod.
Cuoricino	Cryo TeO_2	stat. subtraction	
DAMA,LIBRA, ANAIS	NaI scint.	pulse shape disc. extreme purity	large mass, ann mod. also ββ-decay
Picasso, COUPP	bubble chambers	nucleation thresh	large mass, alpha bkgd
DRIFT	drift chmbr (gas)	track length	directionality/low density

P. Cushman

DM Direct Search Progress Over Time (2009)



R.Gaitskell

We live in a radioactive medium

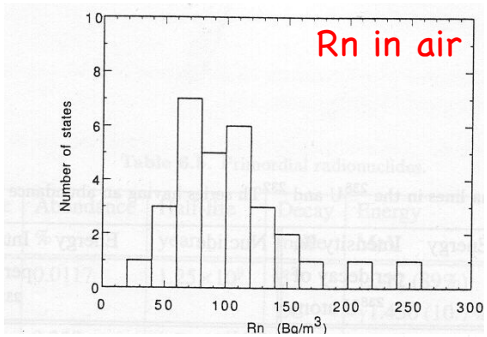
(and one day, "dark matter" will be regarded as just another source of natural radioactivity)

Many sources:

- Primordial (U, Th, K)
- Cosmogenic
- Man-made

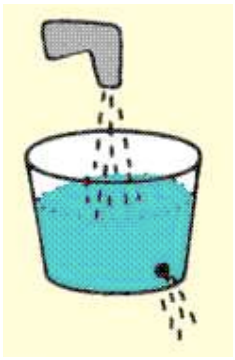
Rule-of-thumb: ~1 ppm in Earth's crust

	Half-life, years	Activity Bq/kg	γ/dis (>50 keV)
Potassium, ^{40}K	1.25×10^9	2.98×10^4	0.11
Thorium, ^{232}Th	14.0×10^9	4.02×10^6	2.08*
Uranium, ^{238}U	4.5×10^9	12.3×10^6	1.80*



"Equilibrium" not always there (chemical affinities, mobility)

$$N_B = \frac{\lambda_A}{\lambda_B} N_A$$



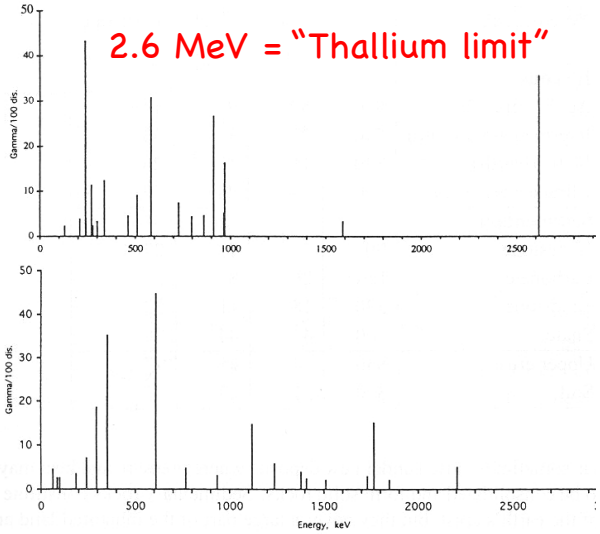


Fig. 6.2. Abundance of main gamma lines of the ^{232}Th and ^{238}U ser

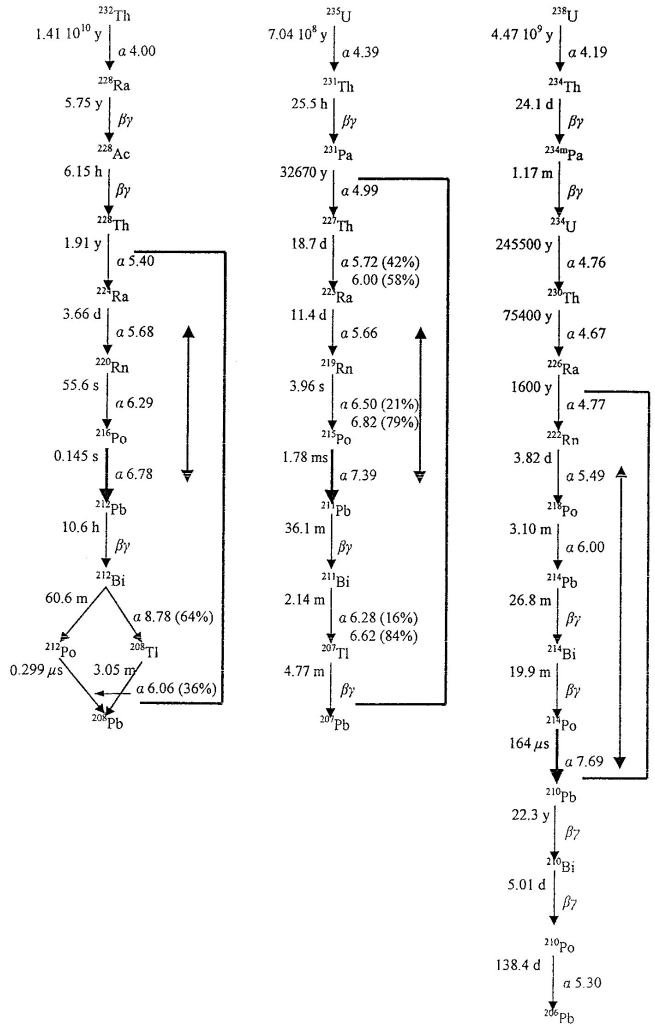


Fig. 4. Decay series of ^{232}Th, ^{235}U and ^{238}U; rare (< 1%) branches are ignored, and average energies given for alpha decays with fine structure. Bold arrows indicate decays of short-lived alpha-emitters included in the selected α–α or β–α coincidences, double-headed arrows the sequences of prior decays that can be observed and counted. The rectangular bars enclose those nuclei which have half-lives short compared with the duration of the experiment.

We live in a radioactive medium

(and one day, "dark matter" will be regarded as just another source of natural radioactivity)

Many sources:

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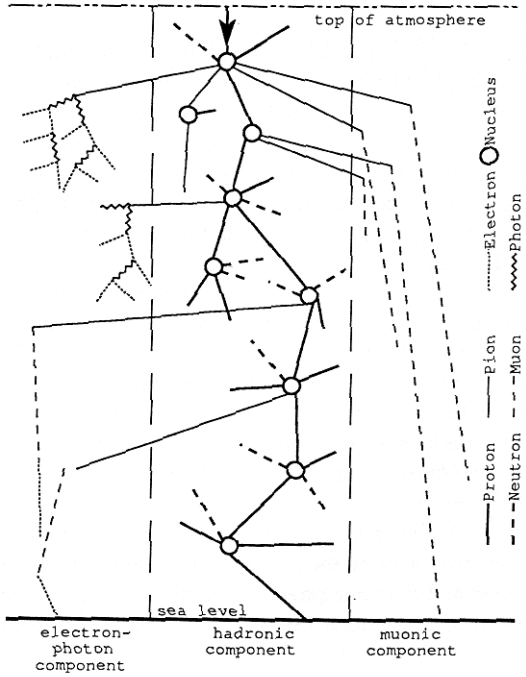
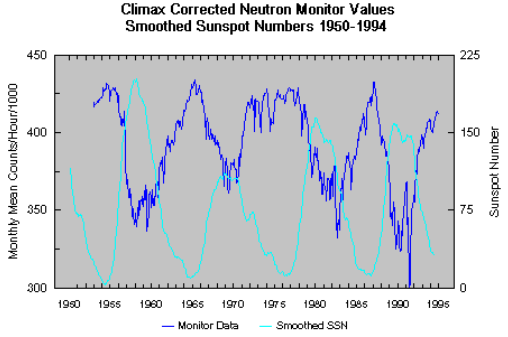
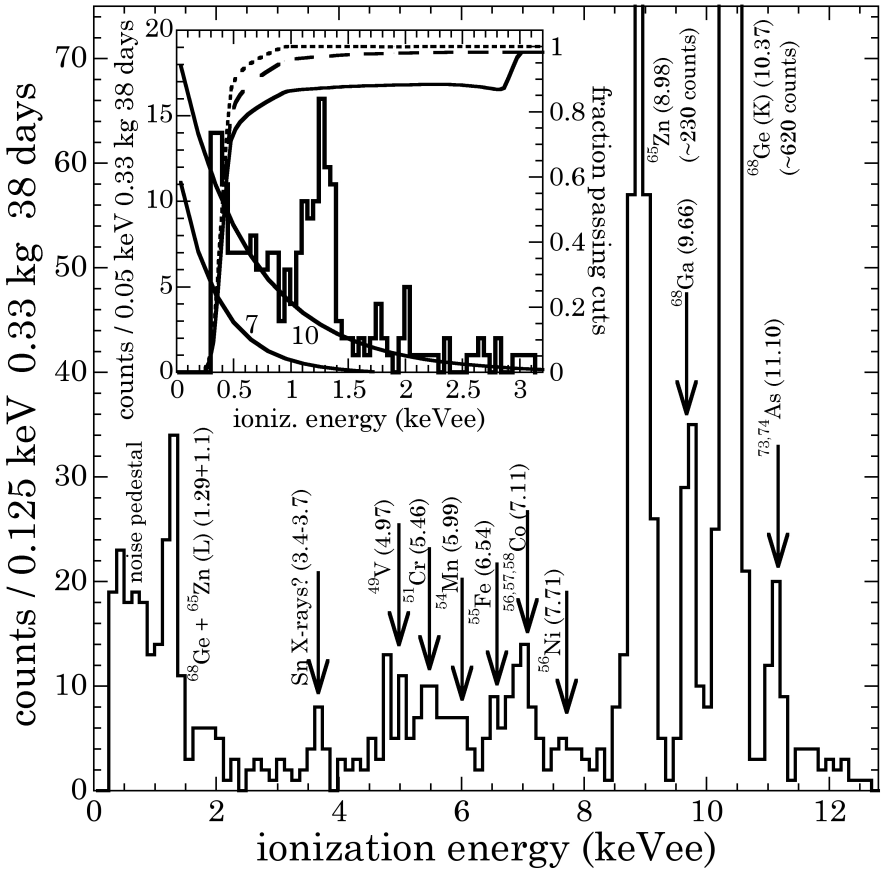


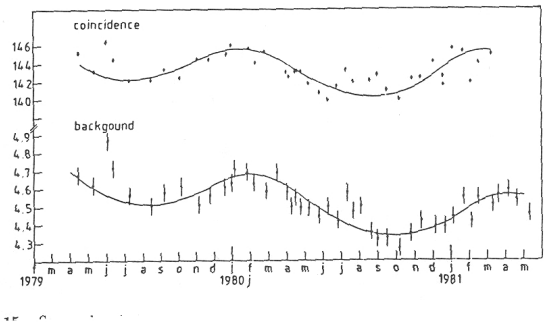
Fig. 7.3. A schematic description of the production and fate of cosmic ray particles in the atmosphere and upper layer of the Earth.



Cosmogenics in CoGeNT



Not a stationary situation! (atm depth, solar activity)



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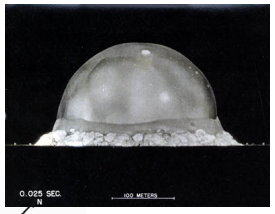
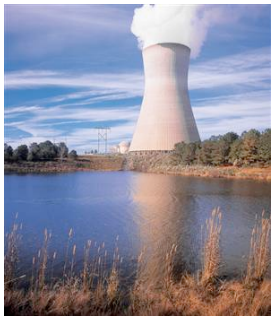
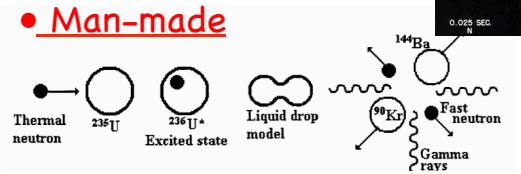
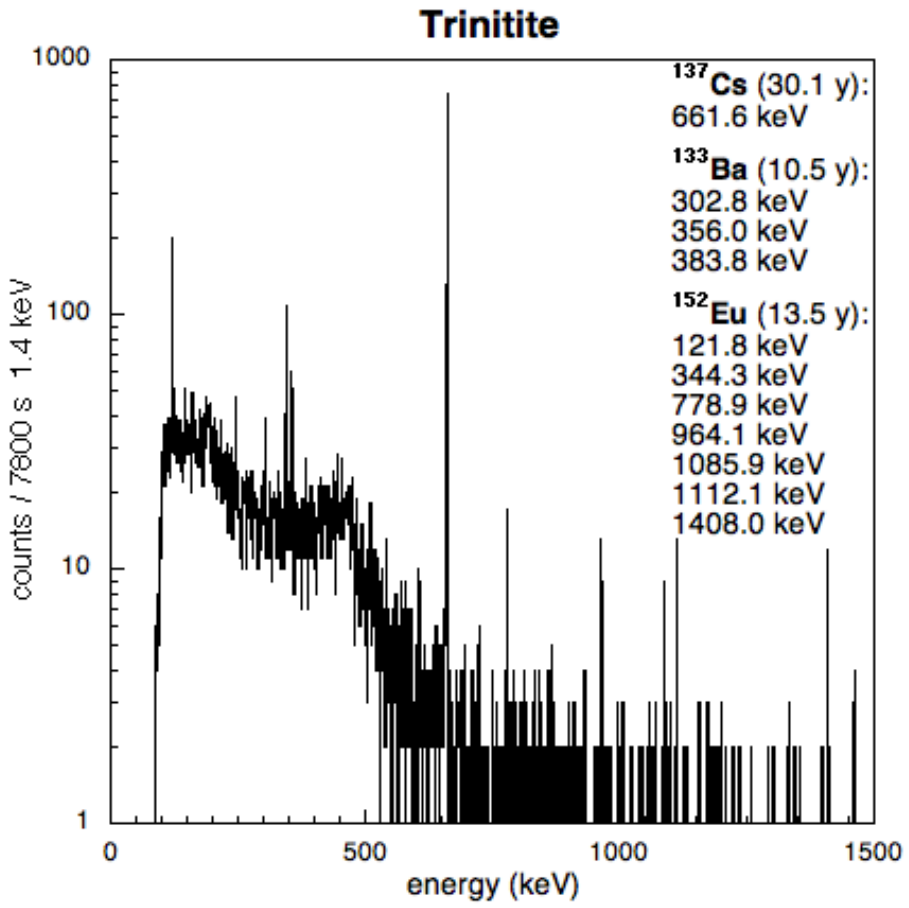








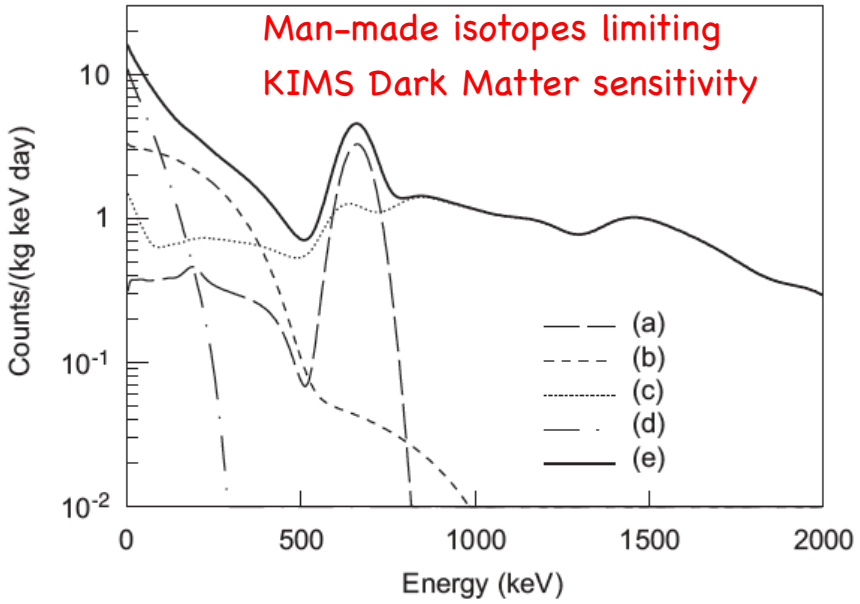
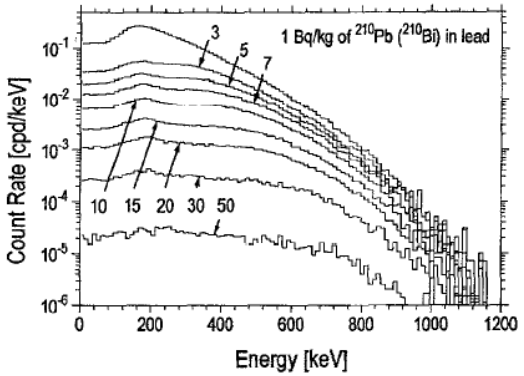


Fig. 3. Background spectra obtained using GEANT4 simulation for the $8 \times 8 \times 30\,\mathrm{cm}^3$ CsI(Tℓ) crystal with 10 mBq/kg ^{137}Cs contamination, 30 mBq/kg ^{134}Cs contamination, and 10 ppb ^{87}Rb contamination: (a) spectrum of ^{137}Ba*; (b) beta-ray spectrum of ^{137}Cs; (c) ^{134}Cs spectrum; (d) ^{87}Rb spectrum; and (e) total summed spectrum.



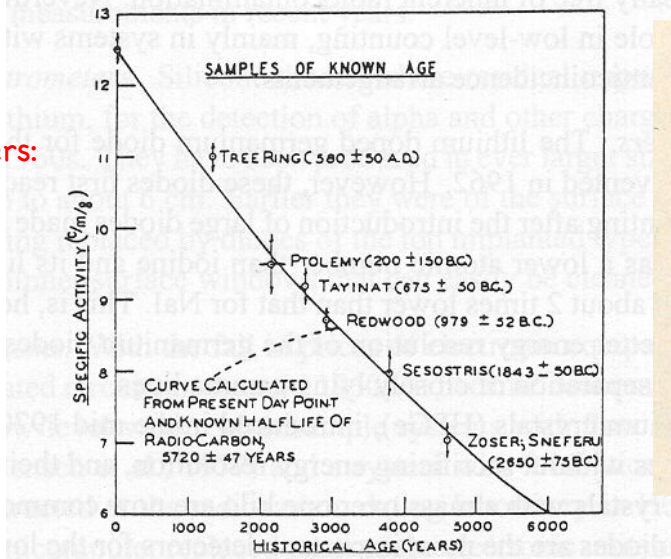
ulated for increasing thickness of absorbing layer made of radio-pure lead. The numbers at arrows indicate the layer thicknesses in mm. The uppermost spectrum was obtained without any layer of radio-pure lead.

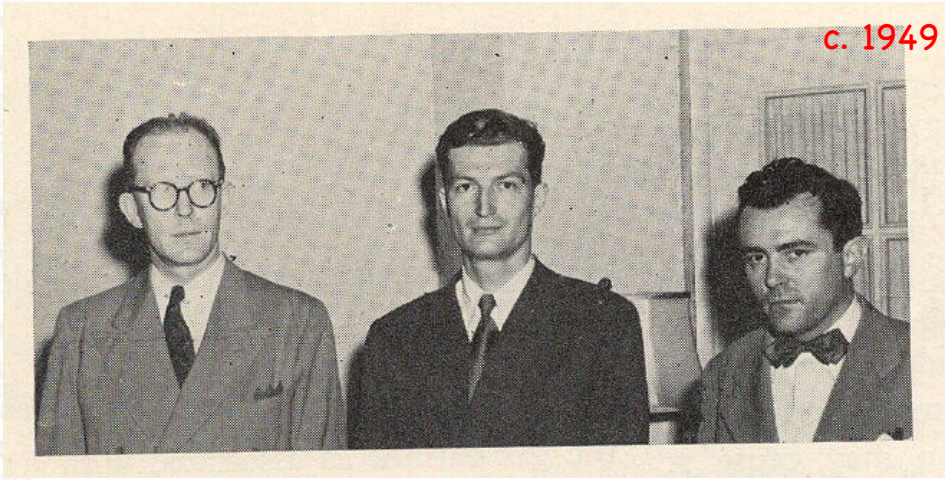
Chemical affinity:
a real pain
in the tuckus

Low-background techniques

Problem for early C-14 counters:

Background rates ~100c/min regardless of shielding:
Birth of the anticoincidence veto

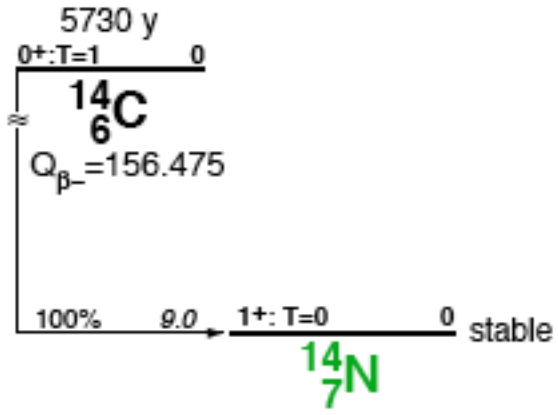




Pioneered at UC by W. Libby
(tradition continued by J. Simpson, T. Turkevich, etc.)

Cosmogenic origin: $n_{th} + {}^{14}N \rightarrow {}^{14}C + H$

Fixed by plants via photosynthesis



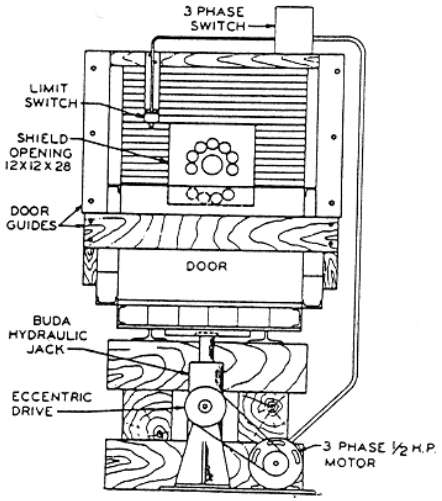
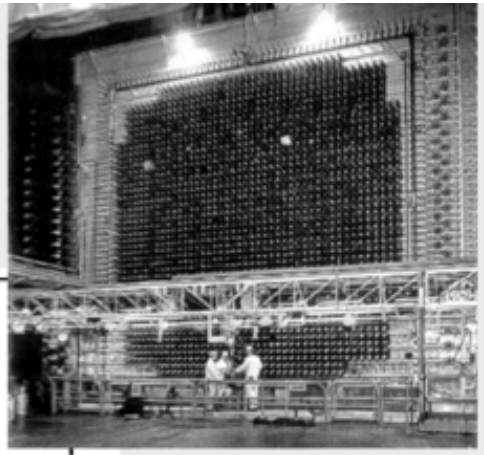


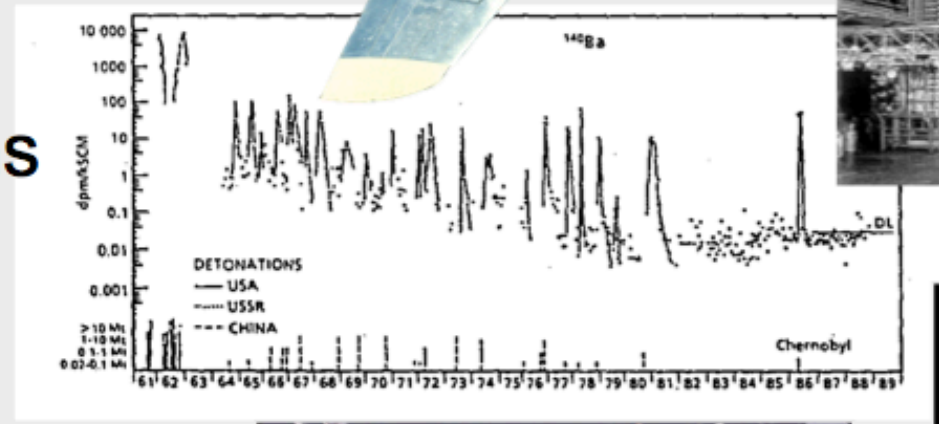
Fig. 1.1. Low-level counting started with this system. Libby's radiocarbon system with which he and his co-workers established the radiocarbon dating technique in 1947–1949.

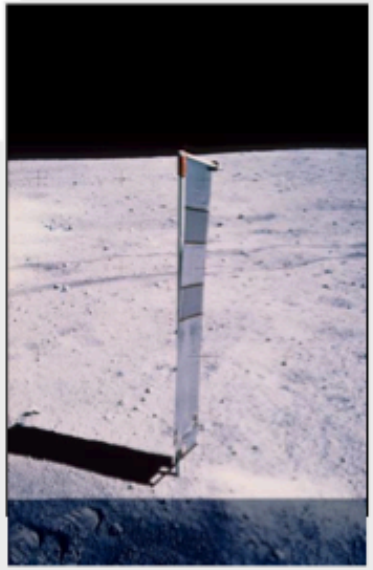
Low-background techniques

Pure science apps

- The atmosphere
- The oceans
- Cross sections
- Meteorites
- Lunar studies
- Astronaut studies

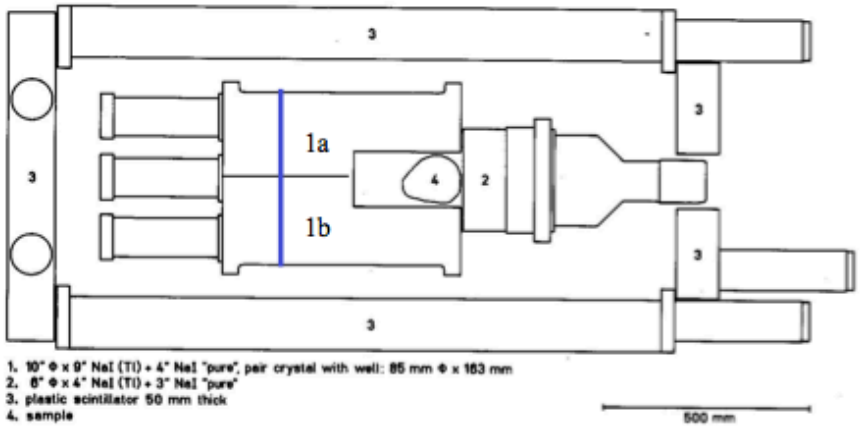






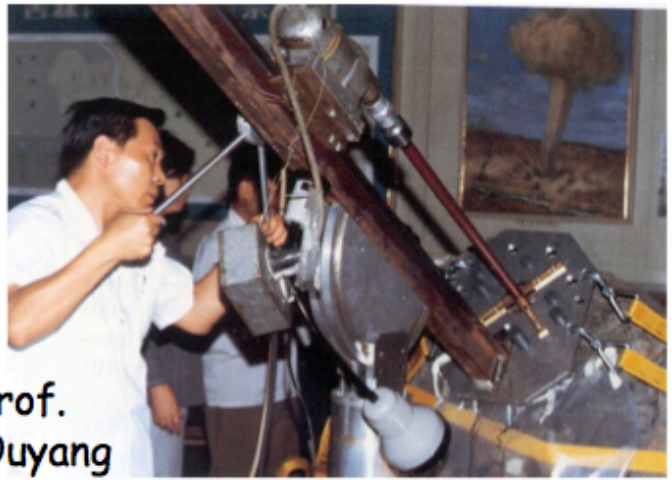
H. Miley

Low-background techniques



1. 10" Φ x 9" NaI (Tl) + 4" NaI "pure", pair crystal with well: 85 mm Φ x 163 mm
2. 6" Φ x 4" NaI (Tl) + 3" NaI "pure"
3. plastic scintillator 50 mm thick
4. sample

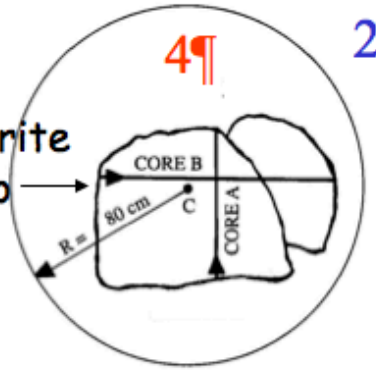
detector + coincidence condition	total count rate [cpm] (> 100 keV)	
	no anticoinc.	with anticoinc.
half of 10"Ø x 9"	537	167
6"Ø x 4"	201	67
2 fold coinc. 1a + 1b	214	22
3 fold coinc. 1a + 1b + 2	1.6	0.16



Prof. Ouyang

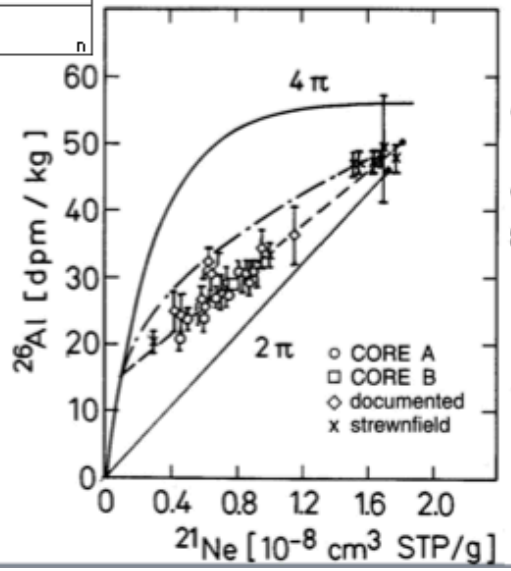
Jilin meteorite
1.77 to

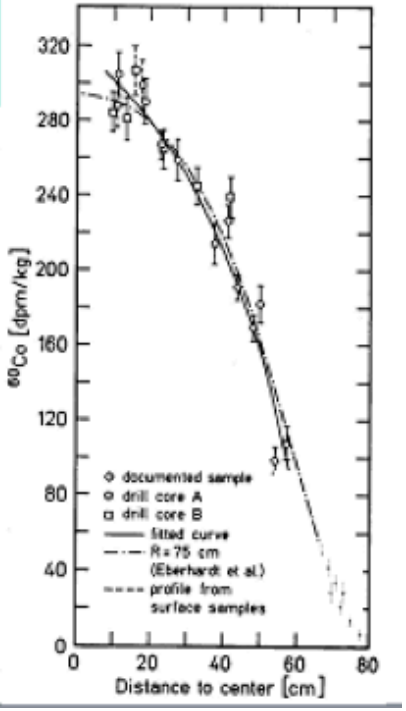
Fall
1976



$T_{2\pi} = 7.2 \pm 1.2$ My

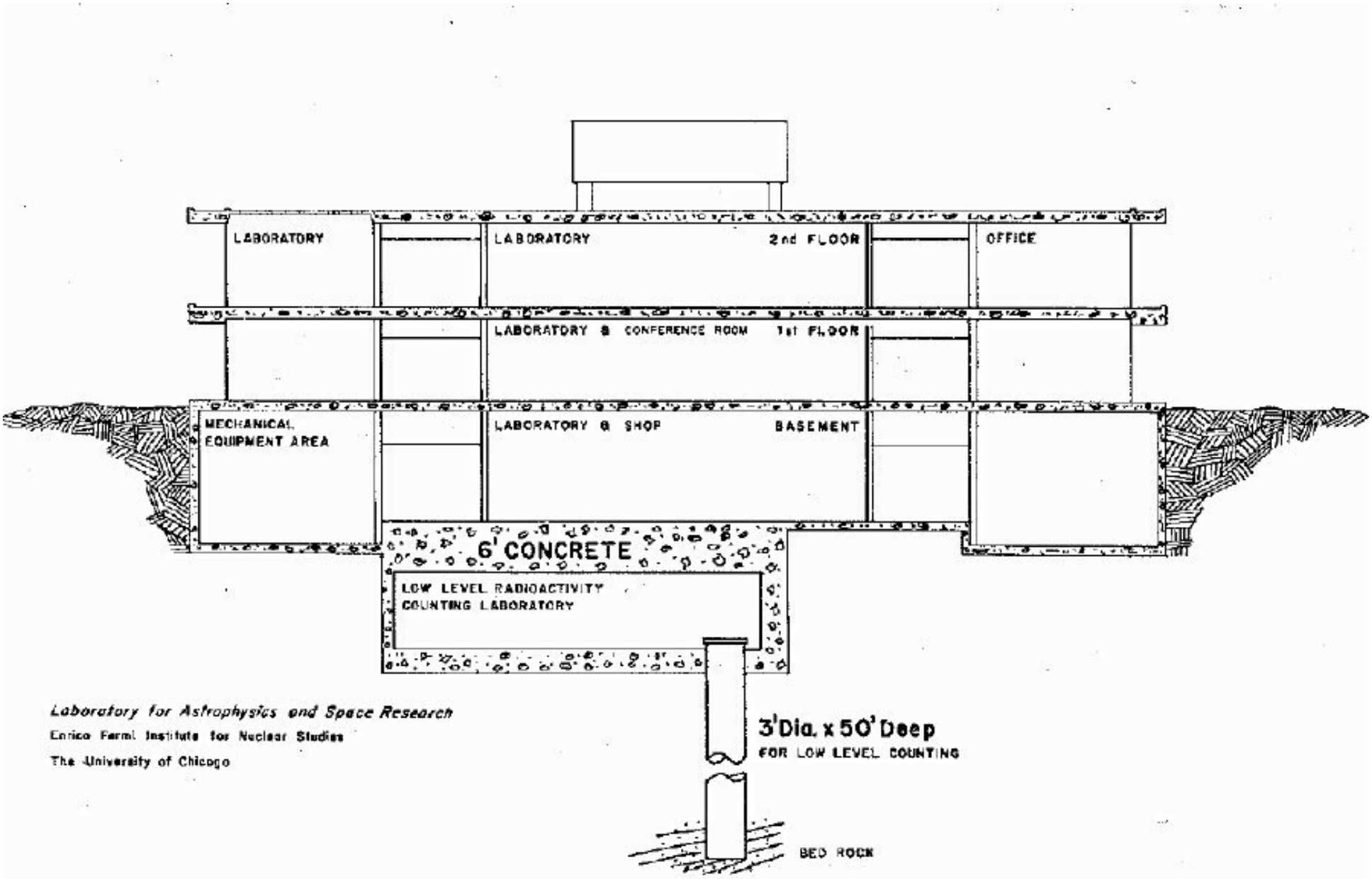
$T_{4\pi} = 0.31 \pm 0.07$ My





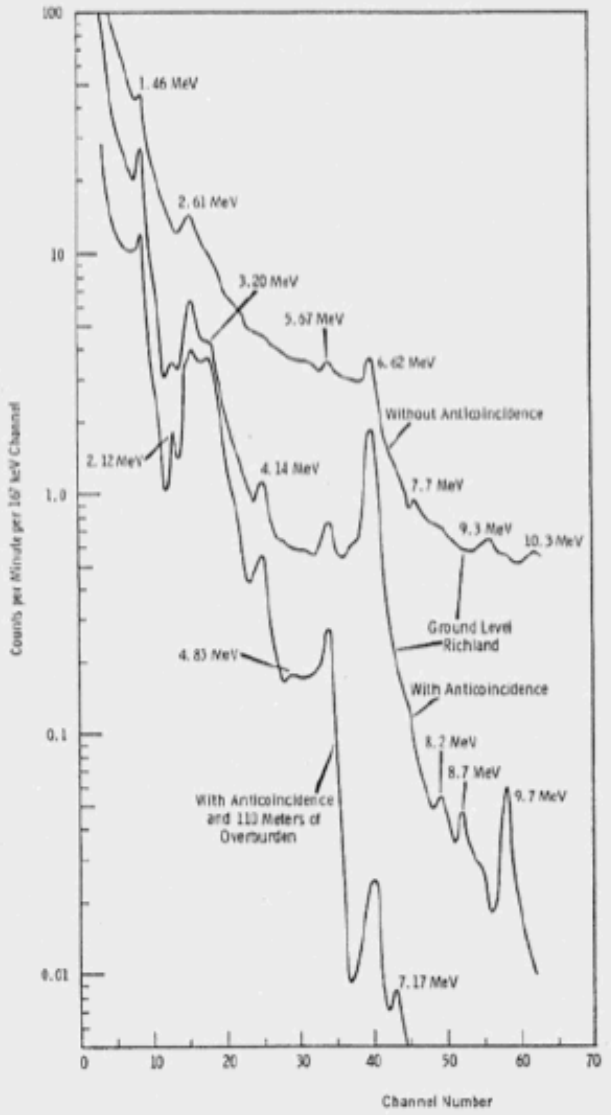
G. Heusser

Low-background techniques

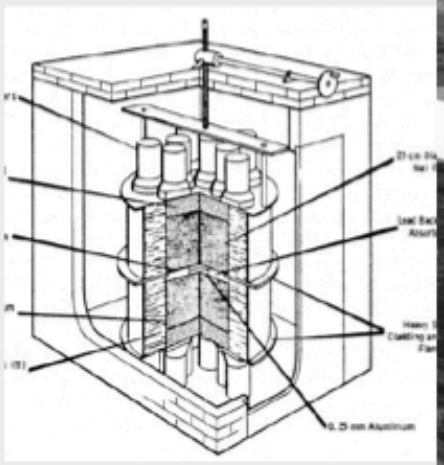


LASR basement lab: a remnant of this era

Low-background techniques



- Hanford Works environmental surveillance
- Early high-sensitivity radiation detection using NaI underground
- Methodical bkg reduction & sensitivity increase for environmental samples



Lots to clean up after Manhattan project… (e.g., watch "Deadly Deception")

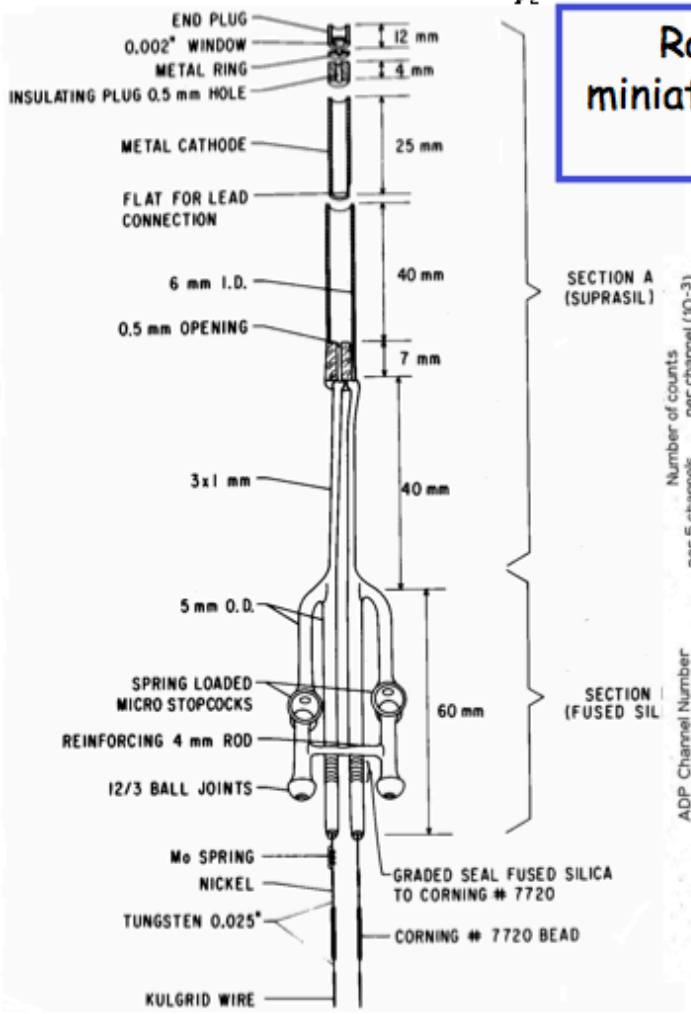
H. Miley

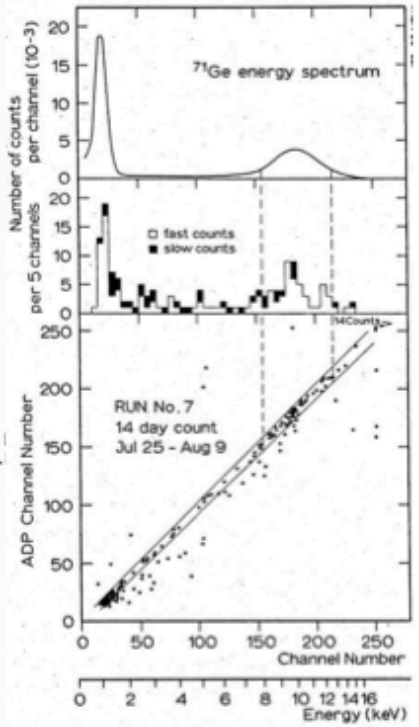
Low-background techniques

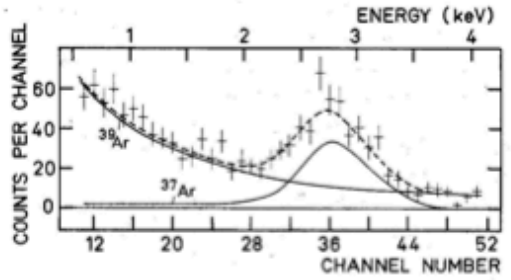
$^{71}Ga\ (\nu_e, e^-)^{71}Ge$

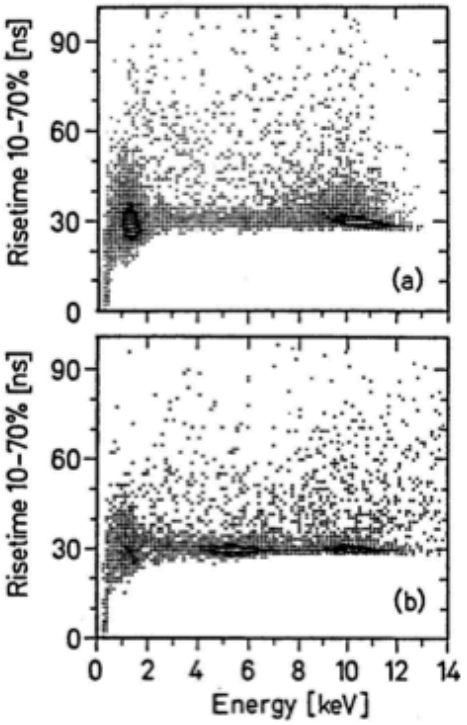
$T_{1/2}$= 11.4 d

Ray Davis type miniature proportional counter









Techniques not restricted to Dark Matter searches
(by now common to most non-accelerator particle physics)

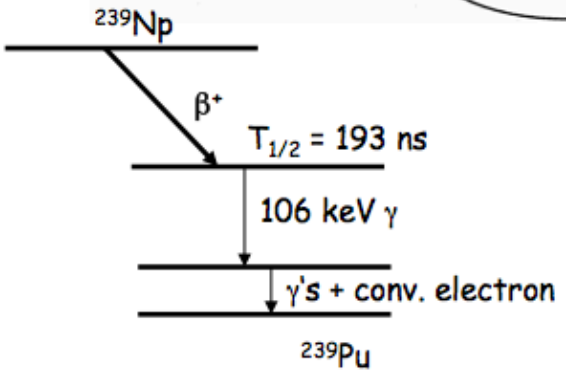
G. Heusser

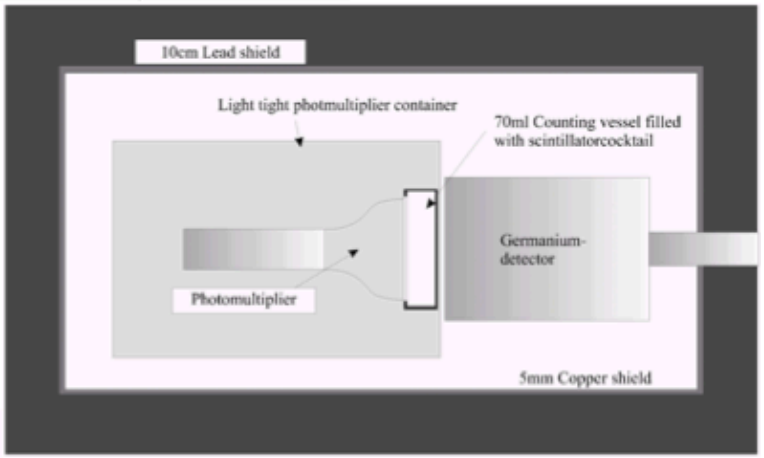
Low-background techniques

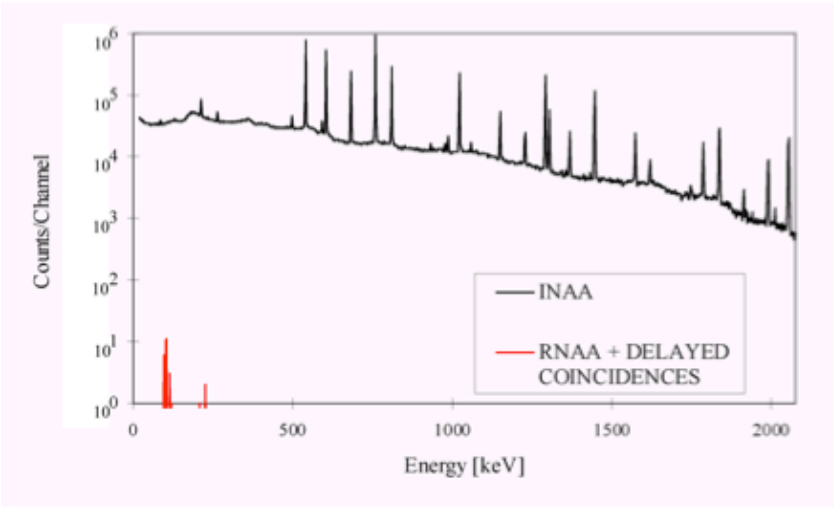
NAA (TU Munich)

Peruse if you want:
http://kicp.uchicago.edu/~collar/Heusser.pdf
http://kicp.uchicago.edu/~collar/martoff.pdf

$$n + {}^{238}U \rightarrow {}^{239}U \xrightarrow[23.5\,m]{\beta^-} {}^{239}Np \xrightarrow[2.36\,d]{\beta^-} {}^{239}Pu, \quad \sigma_{th} = 2.3\,b\ (7.9\,b)$$







PXE plus 1.5 g/l PPO

^{40}K $<7\cdot10^{-16}$ g/g	≤ 0.19 μBq/kg
^{232}Th $<2\cdot10^{-16}$ g/g	≤ 8x10^{-4} μBq/kg
^{238}U $<1\cdot10^{-17}$ g/g	≤ 1x10^{-4} μBq/kg

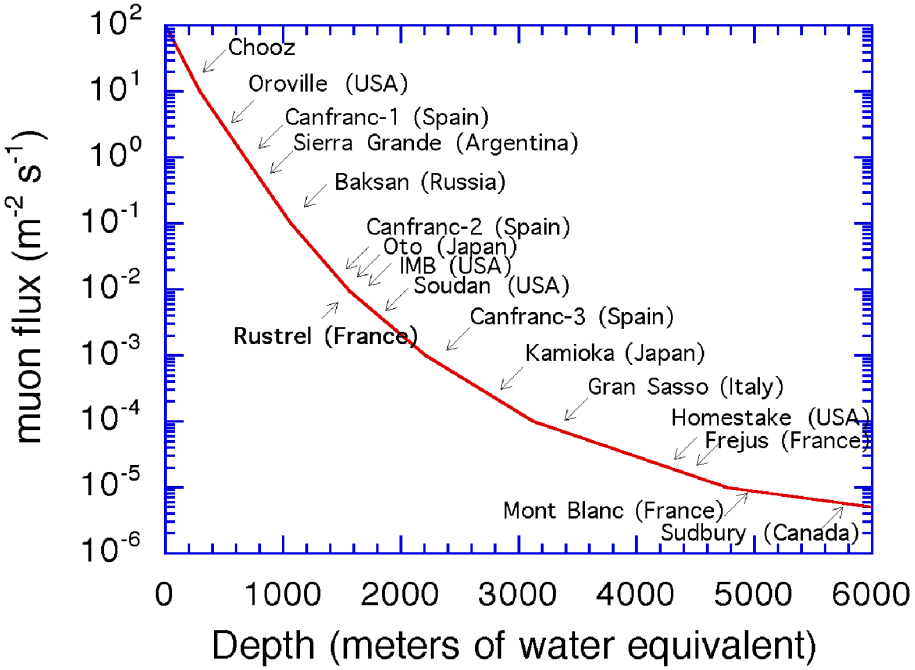
Techniques have reached a sobering level of maturity
(in this example, state-of-the-art radioassay)

G. Heusser

Low-background techniques
(as applied to DM searches)

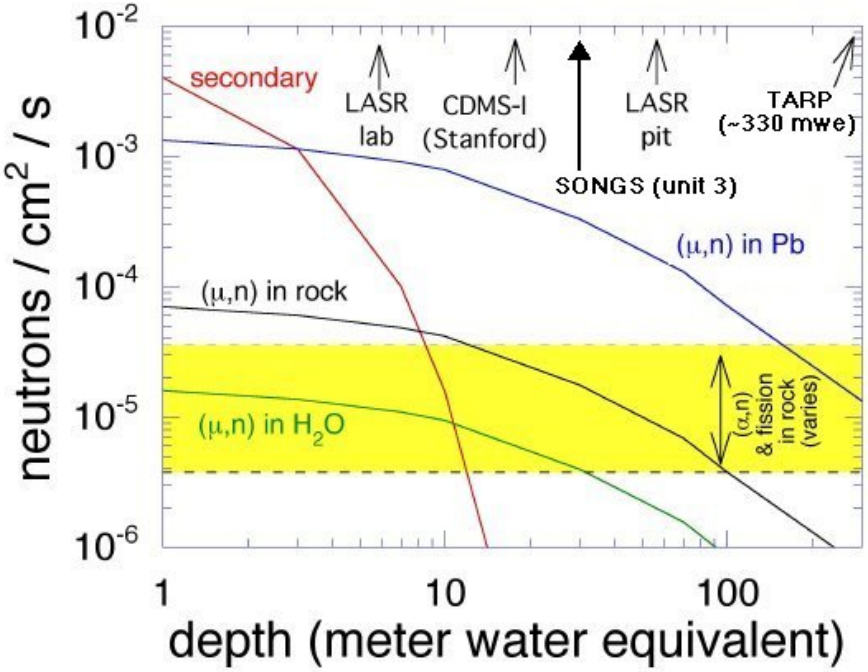
Bag-of-tricks:

- Depth
- Shielding (active & passive)
- Radiopurity
- Background rejection
- Special detector properties



Four sources of neutrons to control:

- secondaries (modest overburden)
- environmental (hydrogenated shielding)
- (μ,n) in detector and shield (active veto)
- "punchthrough" (depth, massive moderator)



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(as applied to DM searches)

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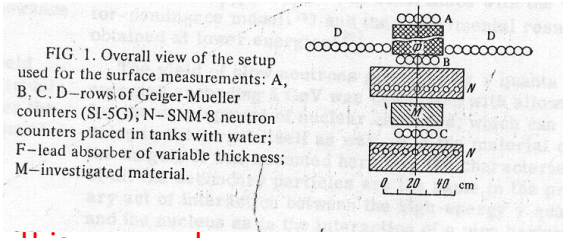
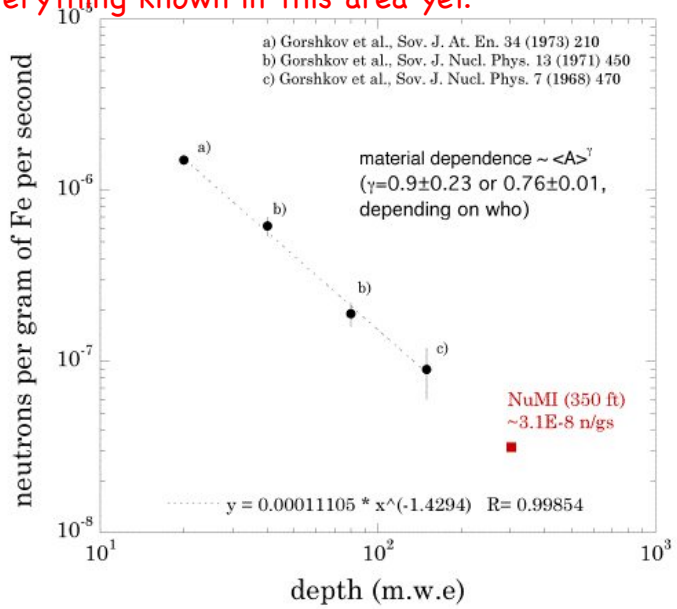


FIG. 1. Overall view of the setup used for the surface measurements: A, B, C, D—rows of Geiger-Mueller counters (SI-5G); N—SNM-8 neutron counters placed in tanks with water; F—lead absorber of variable thickness; M—investigated material.

"muon telescope"

Not everything known in this area yet.



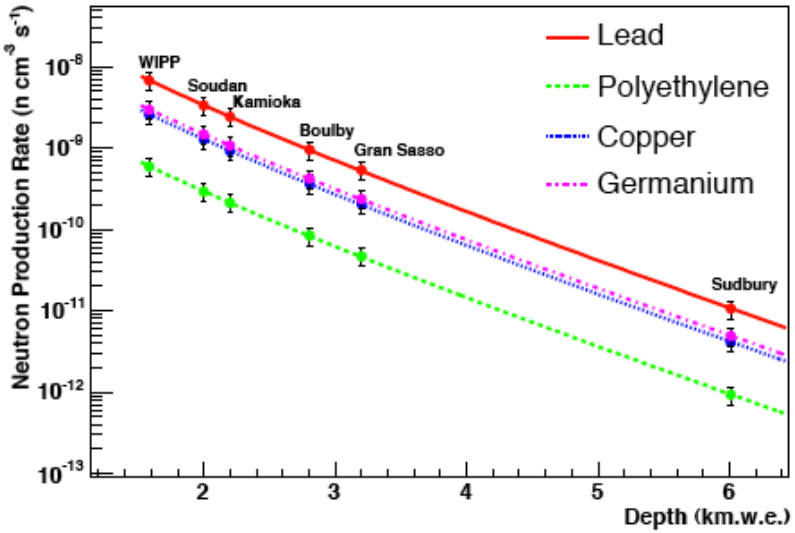
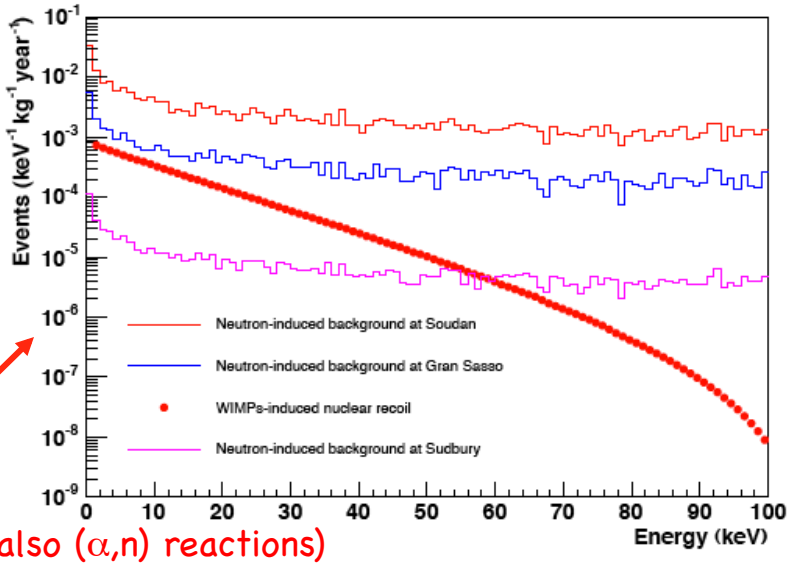


FIG. 15: The muon-induced neutron production rate predicted for some common detector shielding materials. Note that minor variations due to neutron back-scattering have been neglected in these calculations. Mei + Hime



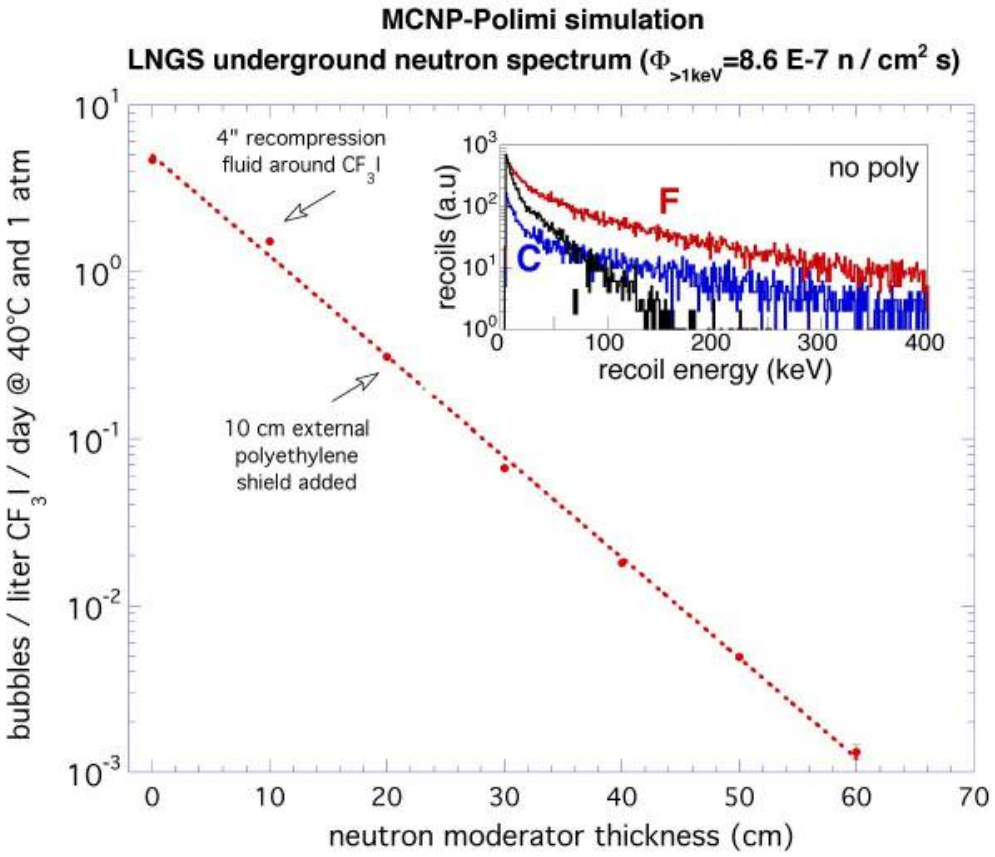
Long-term concerns:

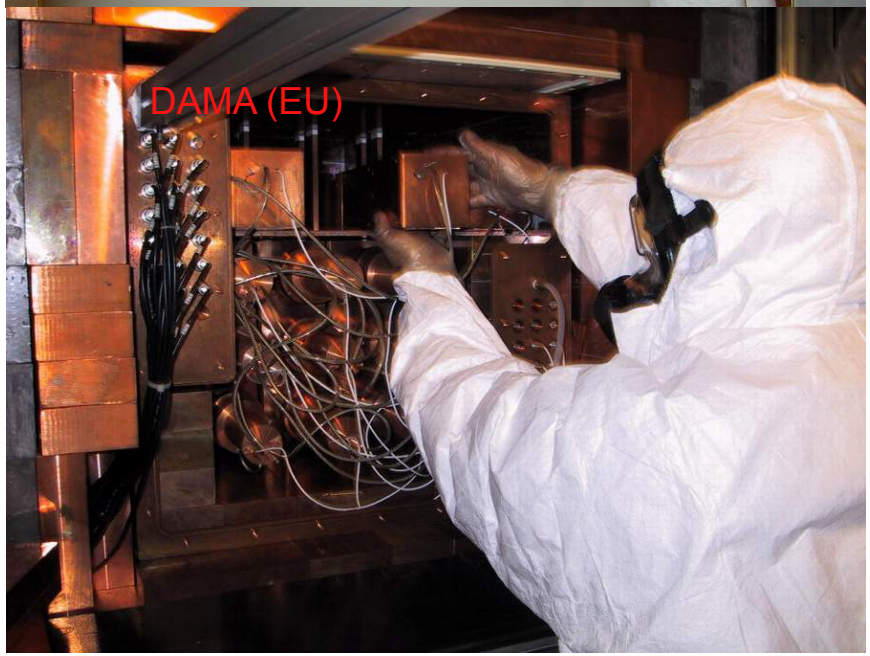
"punchthrough" neutrons (also (α,n) reactions)

Low-background techniques
(as applied to DM searches)

Bag-of-tricks:

- Depth
- Shielding (active & passive)
- Radiopurity
- Background rejection
- Special detector properties





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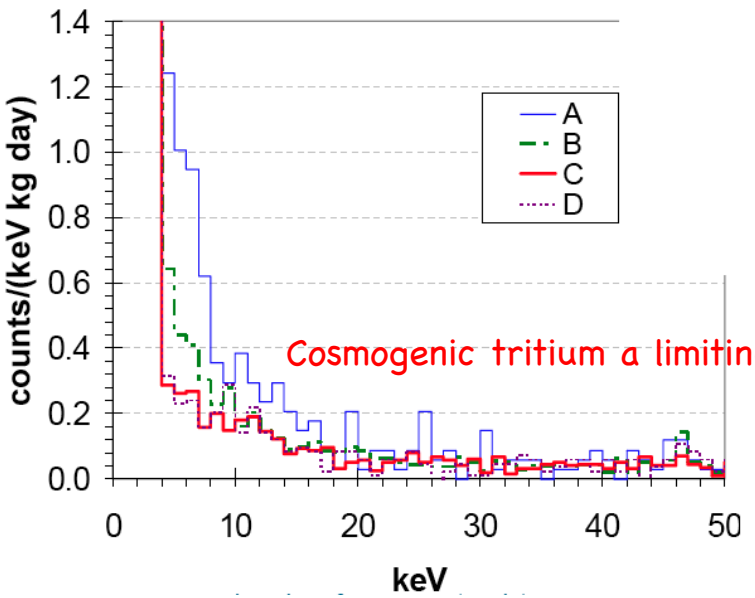
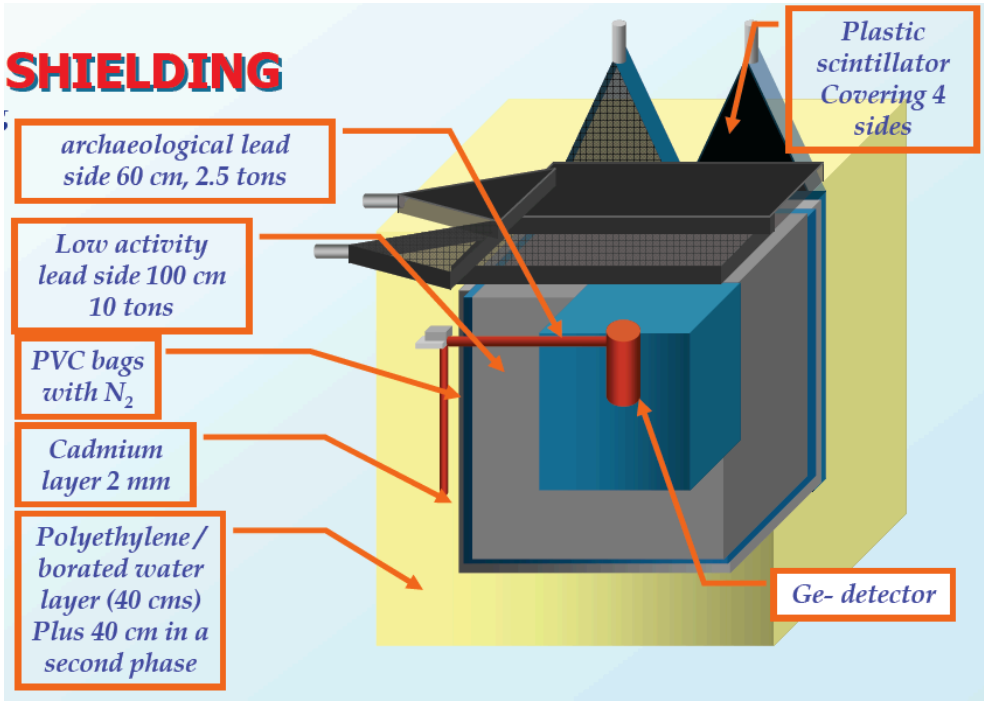
Sets properties	A	B	C	D
Thickness of moderator (cm)	0	20	40	80
Statistics time (days)	17	118	97	41
Counts/(keV kg day)	0.74(6)	0.39(2)	0.22(1)	0.24(2)





G. Luzon

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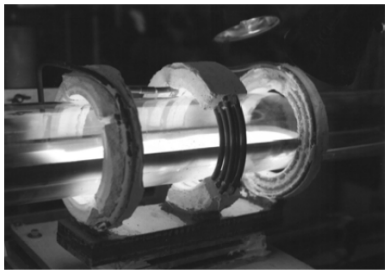
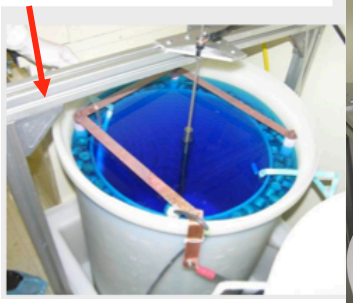


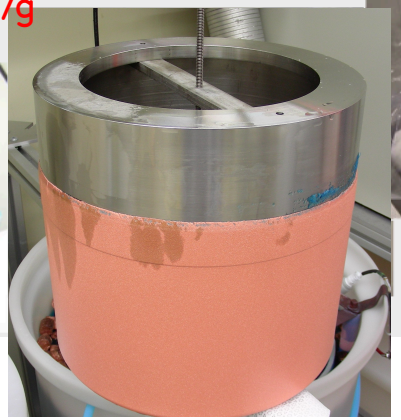
Fig. 2. A 3-Coil Zone Refiner.

Fig. 3. A Zone-Refined Ingot.

Ge zone refinement

impurities ~1E-13 g/g





Electroformed
Cu cryostat

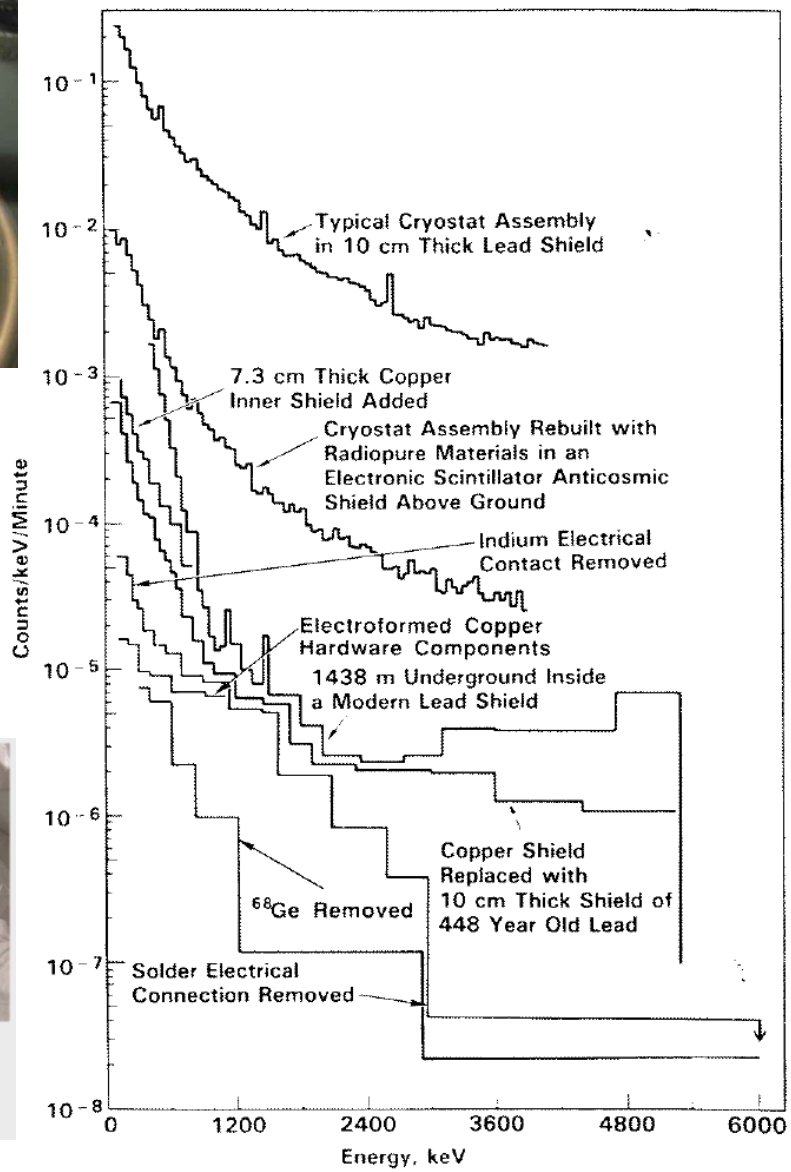


Fig. 1. Improvements in low-background technology.

...and yet not enough *per se* to catch a WIMP...

Low-background techniques
(as applied to DM searches)

Bag-of-tricks:

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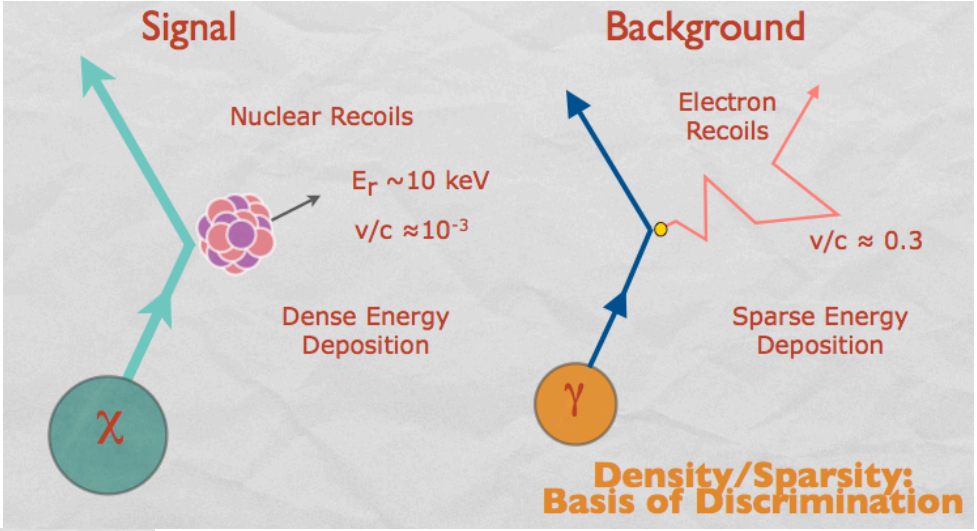

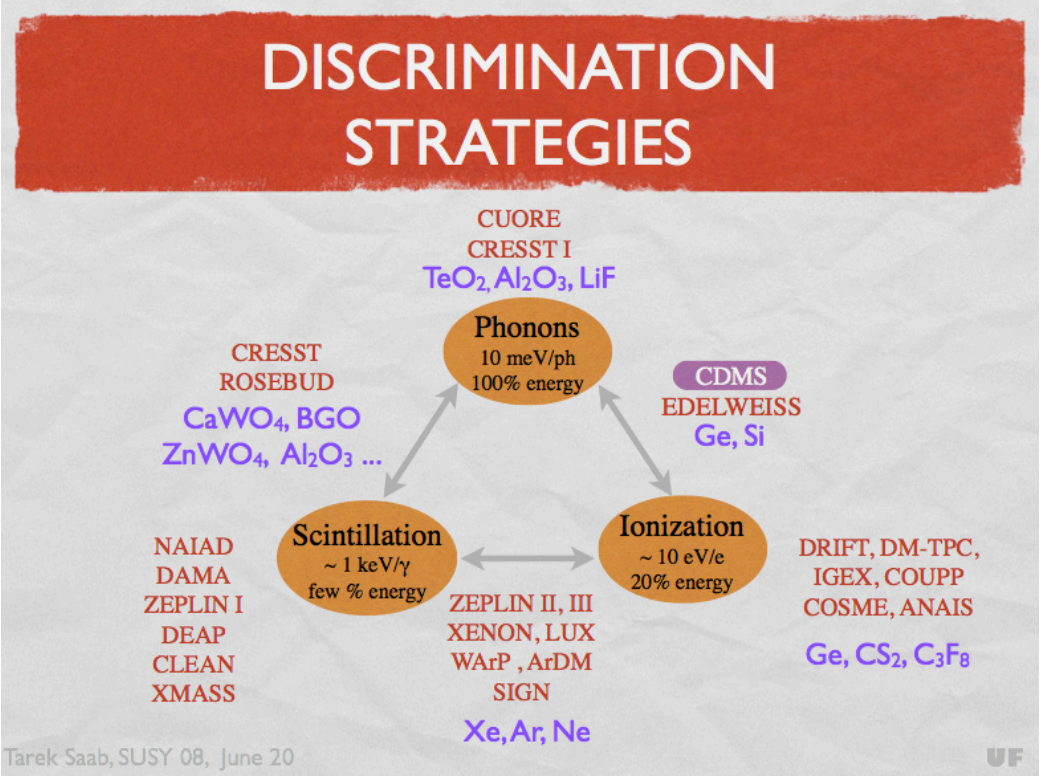

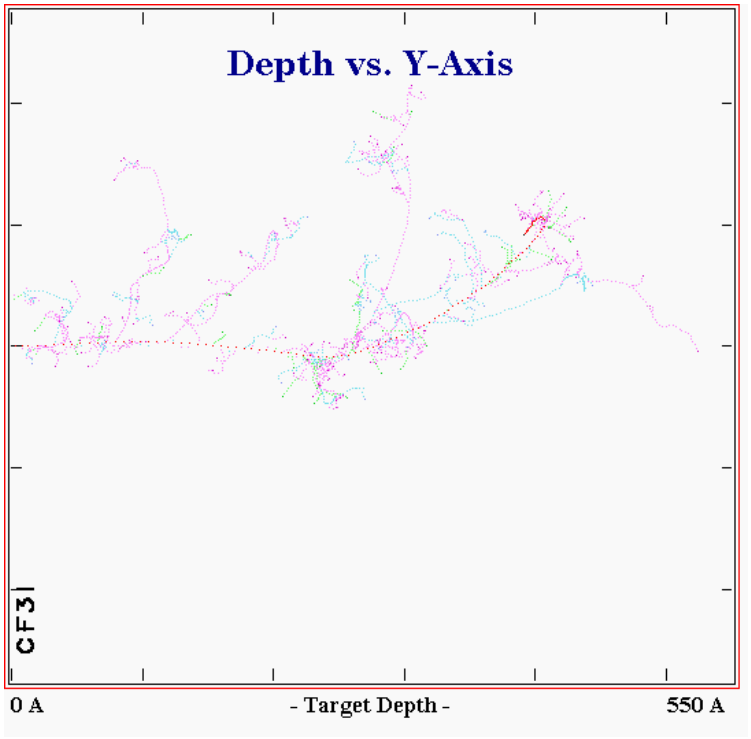

Low-background techniques
(as applied to DM searches)

Bag-of-tricks:

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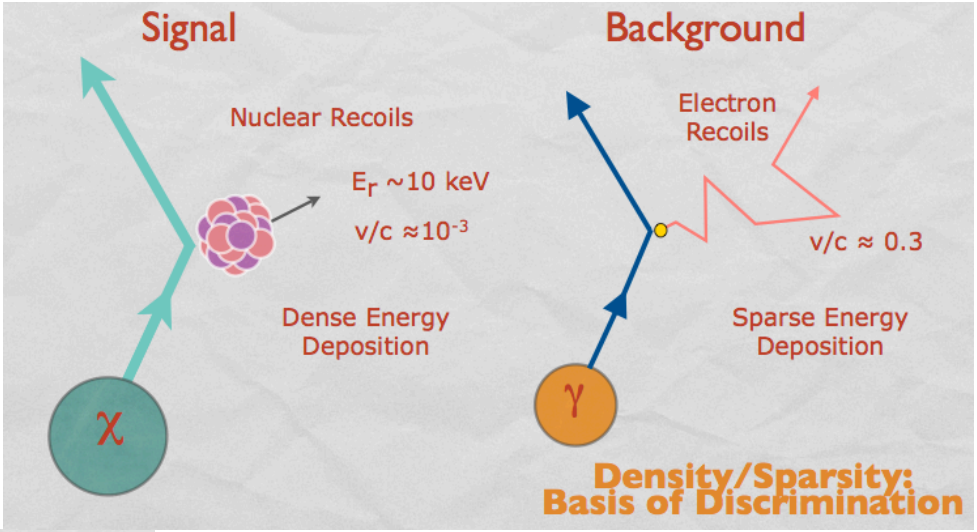
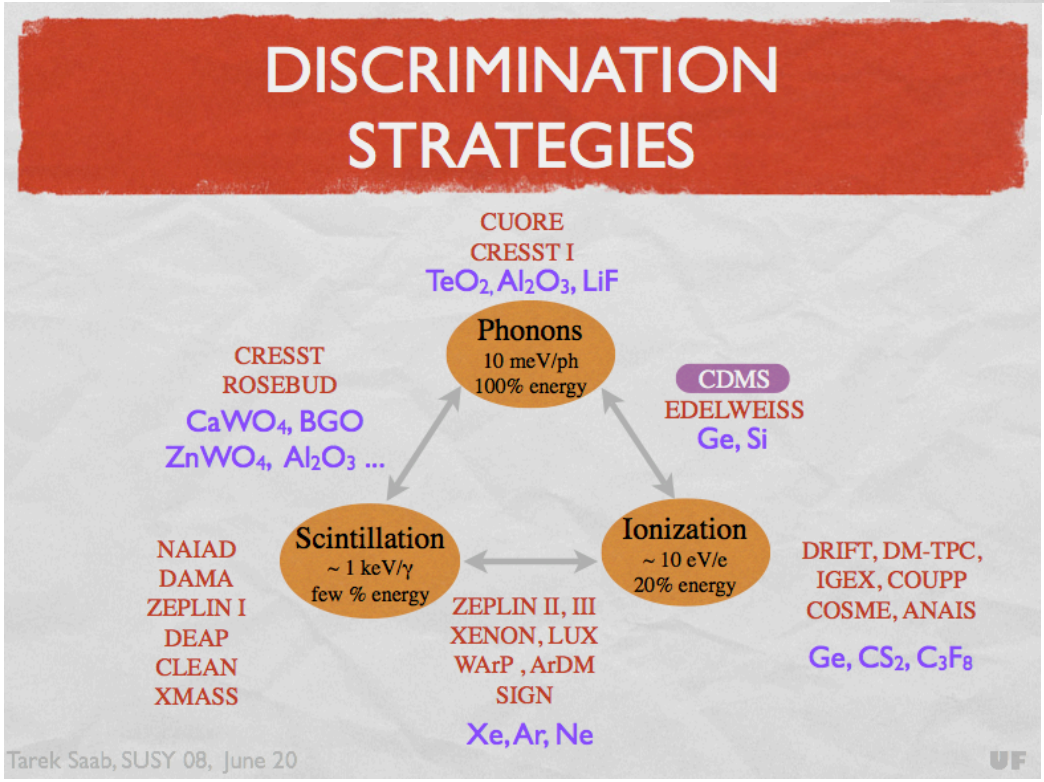
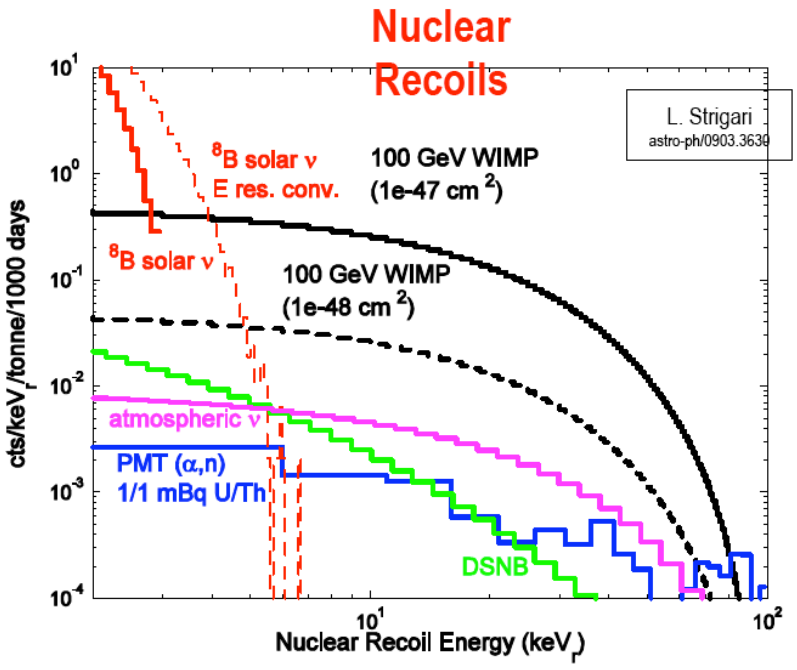
E.g., COUPP's choice of target
CoGeNT's dynamic range and E resolution





Ridiculous or sublime?



L

A few words about your project

- 5-page "white paper" (i.e., a pre-proposal) + references + "Quad chart"
- Usual sections: motivation, implementation, projected sensitivity, deliverables (reach). Skip funding...
- Will adapt to your finals schedule (deadline flexible)
- Show some creativity!!! (grading DARPA-style)
- GET STARTED NOW

Particle dark matter? The number of candidates is comparable to the ~30 experiments out 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 (wimpzillas)
- 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.

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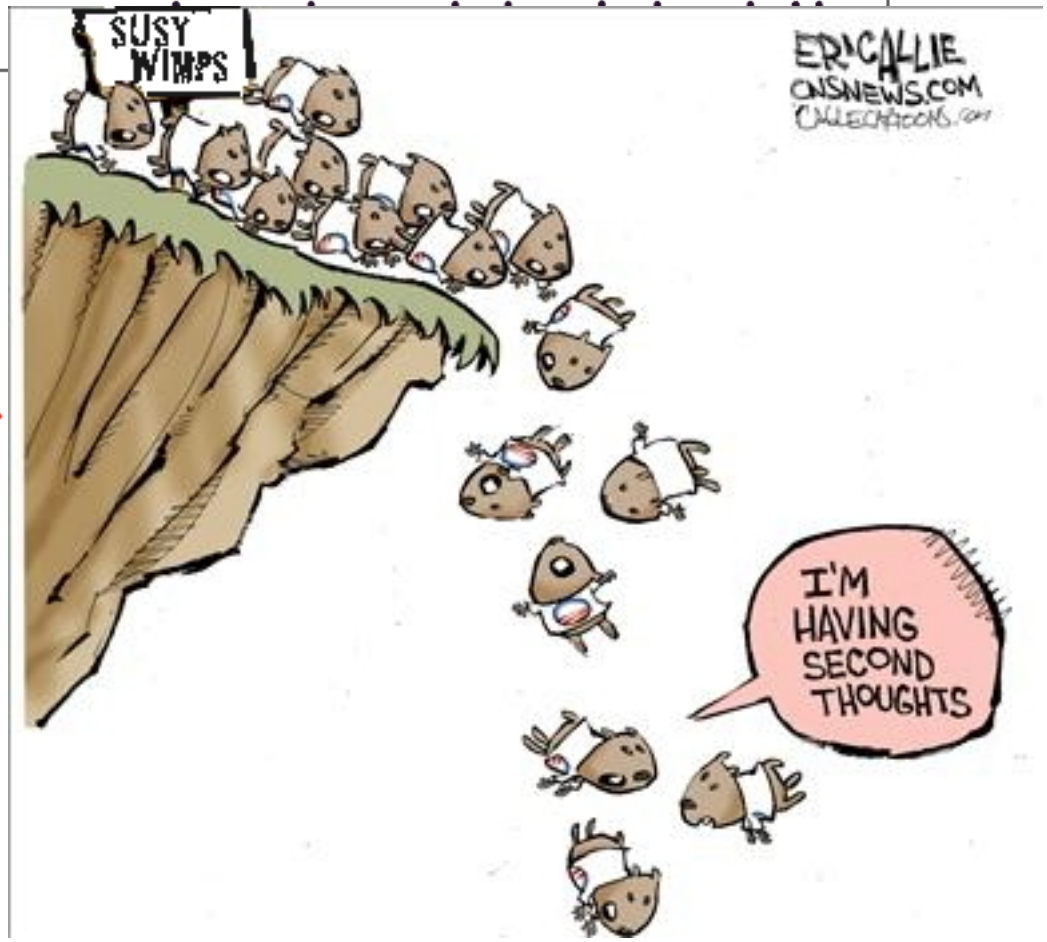

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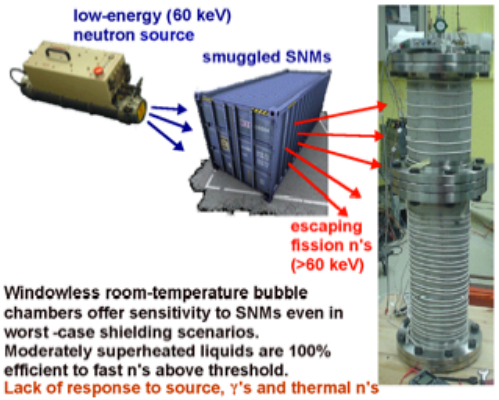
Broad Agency Announcement 06-01
Mission Area: ERT-01 Innovative Detection Materials

Leading Institution: Enrico Fermi Institute, Univ. of Chicago
06/01/06

Proposal Title: **Compact, moderately-superheated bubble chambers: the most sensitive fast neutron detector?**



Windowless room-temperature bubble chambers offer sensitivity to SNMs even in worst -case shielding scenarios. Moderately superheated liquids are 100% efficient to fast n's above threshold. Lack of response to source, γ's and thermal n's

Operational capability to be provided:

• Low-cost, moderately superheated bubble chambers can be built with sufficient stability and design simplicity to permit use as portal monitors.

• Prototype chambers have demonstrated a predictable neutron energy threshold below which nucleations cannot take place. A gamma rejection factor of >1E+9 and total insensitivity to thermals has also been shown. This allows to operate the chamber in the presence of a low-energy interrogating neutron source, responding only to fission neutrons from smuggled SNMs escaping with energies higher than that of the source.

• Simulations show that the ability to detect the few prompt fission neutrons able to reach the chamber with excellent efficiency, while being insensitive to source-induced backgrounds, leads to an unparalleled sensitivity to SNMs, even in the worst possible shielding conditions (a cargo container full of hydrogenated moderator). Use of a low-energy neutron source and the short exposures required also results in a negligible activation of cargo, safe operation and fast screening.

Proposed technical Approach:

PHASE 1 TASKS (1st year, medium risk):
• Development of 4 kg CF3I prototype
• Proof-of-principle tests at Sandia and LLNL, using SNMs and a variety of simulated cargo configurations. Use of optimal Li-7(p,n) 60 keV neutron generator (LLNL) as the interrogating source.
• Demonstration of insensitivity to (n,g) and (p,g) E>12 MeV gammas.
PHASE 2 TASKS (2nd year, low risk):
• Using simulations validated in previous tests, generate accurate predictions of expected sensitivity in a variety of cargo configurations
• Development of fastest possible cycling of the chambers (less than present 5 s) to minimize dead time.
• Development of triggering schemes compatible with the above
• Development of 2 to 4 large portal monitors (chambers ~2m tall)
PHASE 3 TASKS (3rd year, low risk):
• Continued development of 2 to 4 large portal monitors (chambers ~2m tall)
• Installation and tests within a "nuclear car wash" context.

Cost & Schedule:

• Total project cost: 899 kUSD (1st year 291 kUSD, 2nd year 350 kUSD, 3rd year 256 kUSD)
• Highest risk involved during first task (first year). Demonstration of total insensitivity to interrogating source with a low-enough threshold for sufficiently high-efficiency detection of escaping fission n's is crucial. The decision to proceed with phases 2 & 3 will be taken after prototype tests at Sandia/LLNL during task 1.

Deliverables:

• A tested bubble chamber design ready for transfer to industry by the third year. A complete demonstration portal monitor with sensitivity to O(100)g smuggled HEU, even in the worst-case shielding scenarios.

Contact Information:

• Asst. Prof. Juan I. Collar, Enrico Fermi Institute, University of Chicago, 5640 S. Ellis Ave., LASR 214, Chicago IL 60637.
• Phone: (773) 702 4253, Fax: (773) 834 8279
• E-mail: collar@uchicago.edu www: collargroup.uchicago.edu

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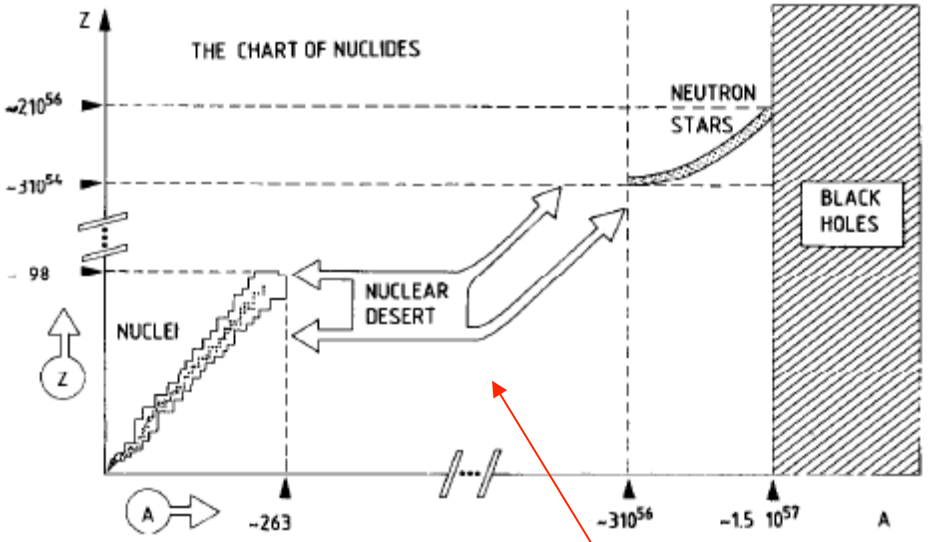


FIGURE 4
Chart of nuclides, hopefully incomplete.

OTHER MYTHICAL BEASTS: Monopoles, Nuclearites, Q-balls, D
(all HEAVILY ionizing)

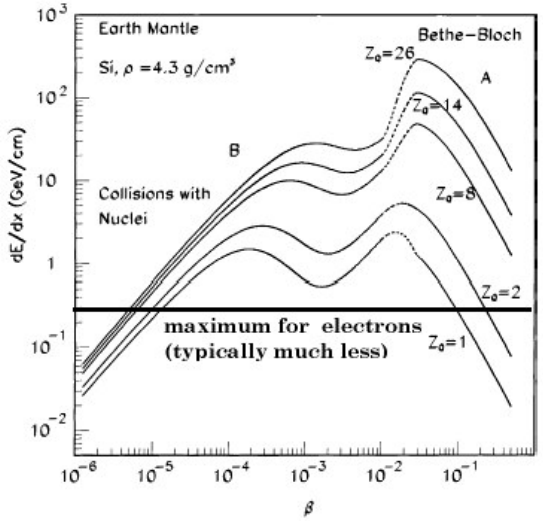
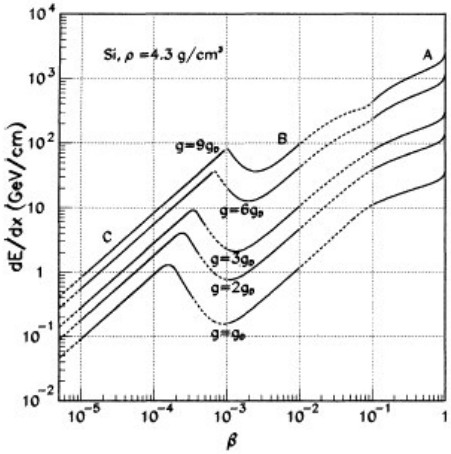


Fig. 5. Energy losses of SECS versus β in the earth mantle; Z_Q is the electric charge of the Q-ball. The dashed parts of the lines indicate interpolations.

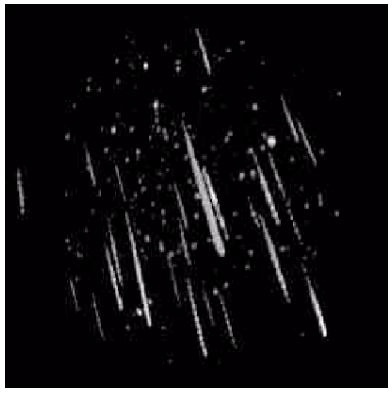
Bakari et al, Astropart. Phys. 15, 137 (2001)



idem for monopoles

Can be enormous for Nuclearites:
dE/dx~(1E-8)x(A^(2/3))... A up to 1E56 !!!

"ASTROBLEMS" (de Rujula & Glashow)
"LINEAR EARTHQUAKES"...



Faux meteorites?

Read about these "Aborigines of the nuclear desert"
(usual path+)
alvaro1.pdf <-Beauty!
alvaro2.pdf
vigdor1.pdf
vigdor2.pdf <-!!!
vigdor3.pdf <-ho-hum
(let that be a lesson…)

Many other ways to look for these, e.g., fullerene.pdf , MACRO detector, macro.pdf
http://www.bo.infn.it/macro/pub_refj.htm
etc.

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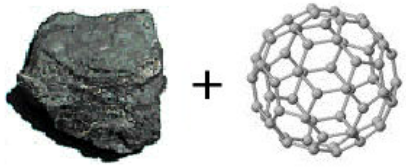


= Dark Matter?

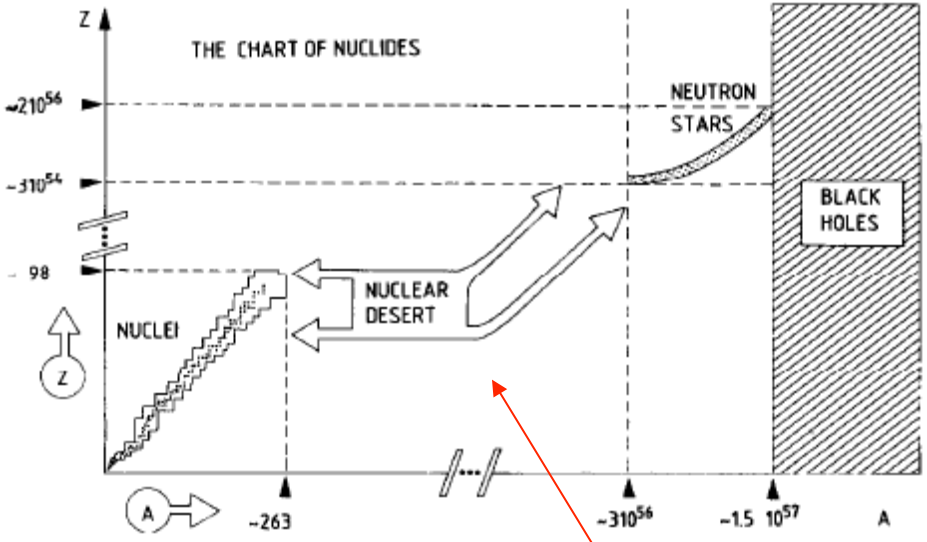
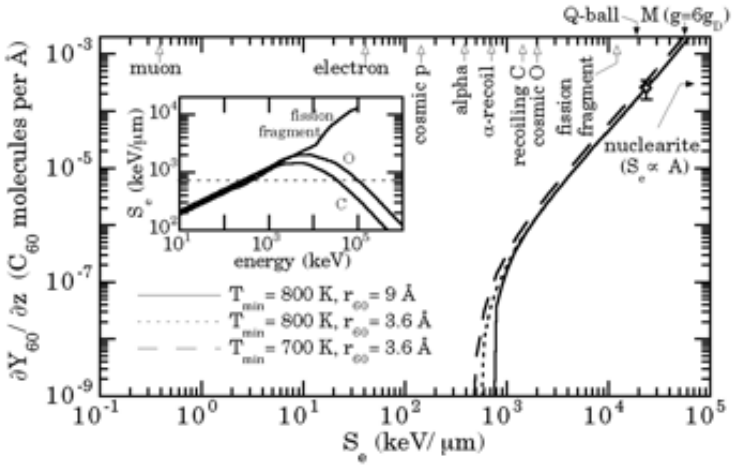


FIGURE 4
Chart of nuclides, hopefully incomplete.

- True threshold "detector": natural radioactivity cannot produce enough (if any) fullerenes due to short tracks and feeble dE/dx.
- C-60 takes a beating and keeps on ticking: it does survive over geological ages once formed (in rocks known to have undergone episodes of intense heating). Extremely stable.
- Fullerenes absent from "middle-of–the-road" carbonaceous rocks (good sensitivity immediately possible)



J.I.Collar and K. Zioutas, Phys. Rev. Lett. 83 (1999) 309

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(let that be a lesson…)

Many other ways to look for these, e.g., fullerene.pdf , MACRO detector, macro.pdf
http://www.bo.infn.it/macro/pub_refj.htm
etc.

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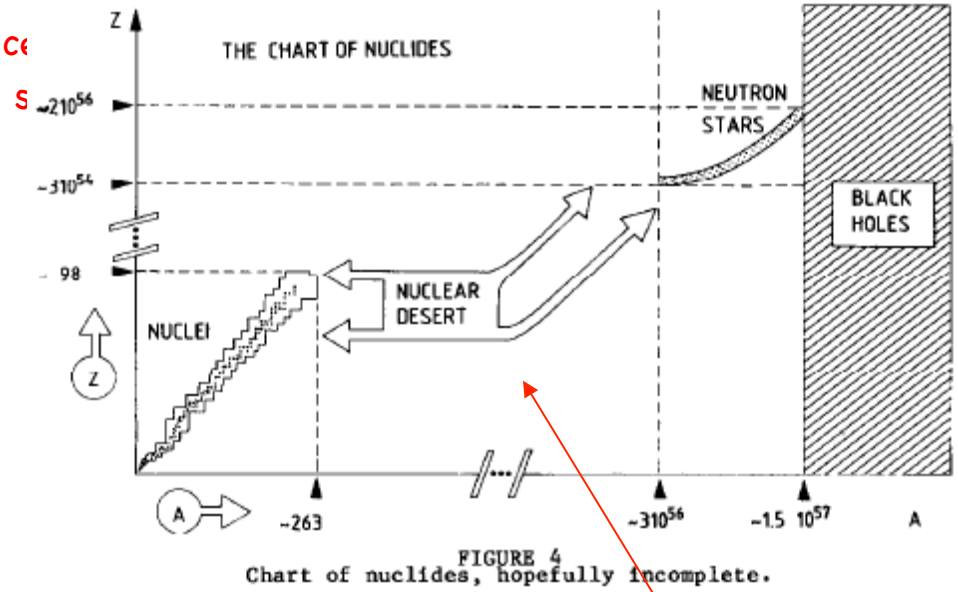

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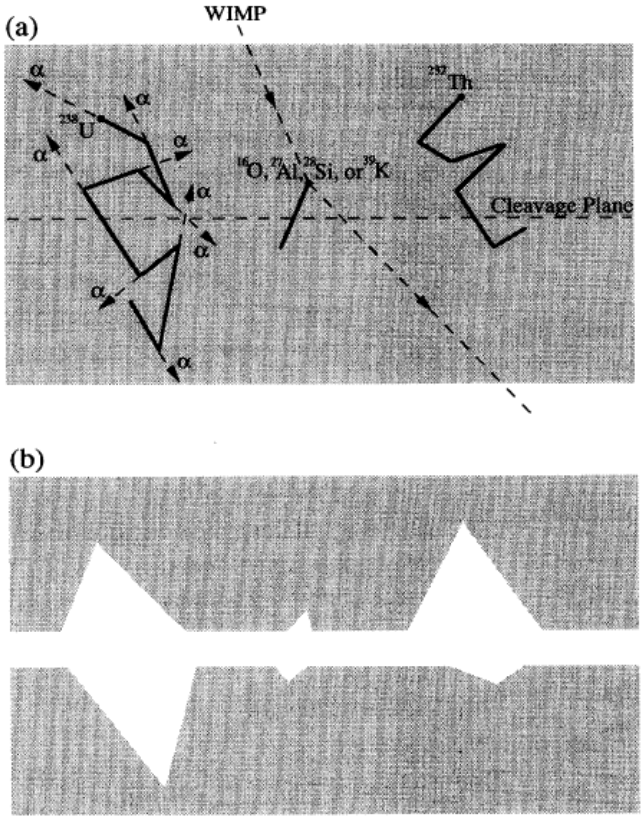

FIG. 1. An illustration of the etching technique. (a) If WIMPs exist they would cause the constituent atoms of muscovite mica, mainly ^{16}O, ^{27}Al, ^{28}Si, and ^{39}K, to recoil across a cleavage plane. (b) When both halves of the cleavage plane are etched matching pits will appear. The illustration also shows the development of α-recoil tracks and that these tracks will have longer summed depths than WIMP-recoil tracks.

Geochemical approach
To WIMP detection
(Exposure = Nt)
Snowden-Ifft *et al.* PRL 74 (1995) 4133
Collar & Avignone NIM B95 (1995) 349
Collar PRI 76 (1996) 331

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