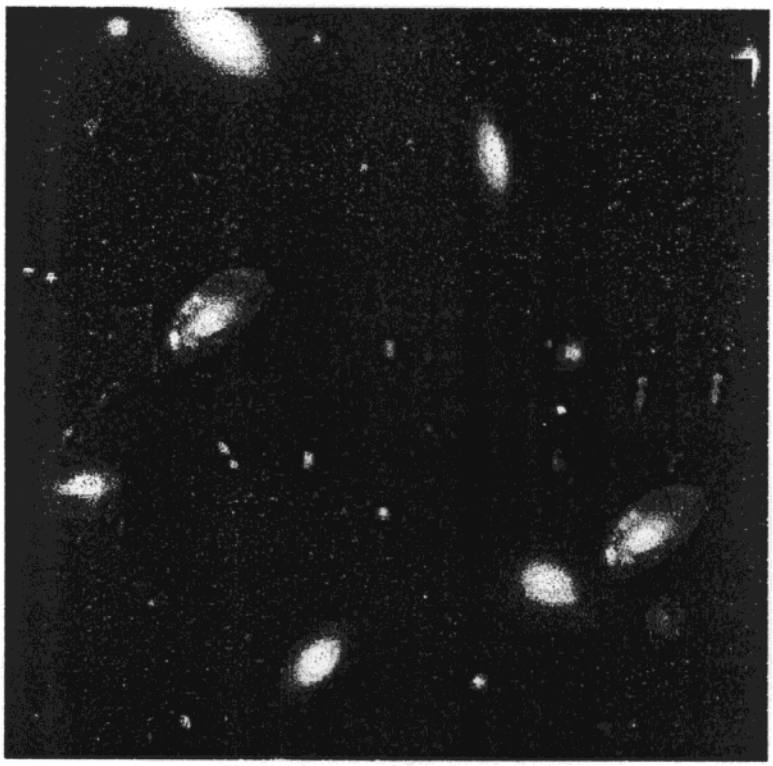
DARK MATTER SEARCHES



> 90% of the Universe is dark
What is its nature?

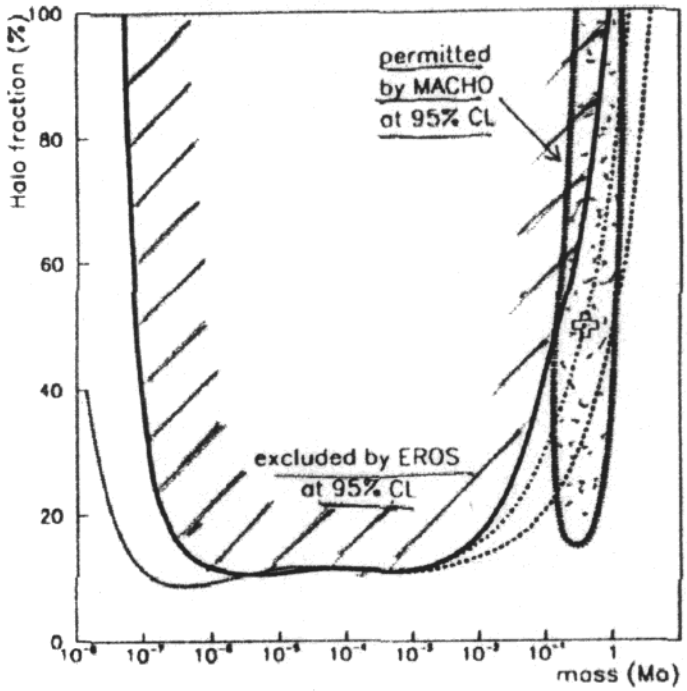
R. BERNABEI
Venice, February 1999

Searching for the baryonic part .....

MACHOs — **from Gravitational microlensing**

signature: **light amplification should be: symmetrical, achromatic and aperiodical**

Relatively recent situation considering the candidates in LMC:



from Nucl.Phys. B (Proc. Sup) 70 (1999), 14

competing background? e.g. LMC stars can do μlensing (Nature,370(1994),278) + too much events in the bulge

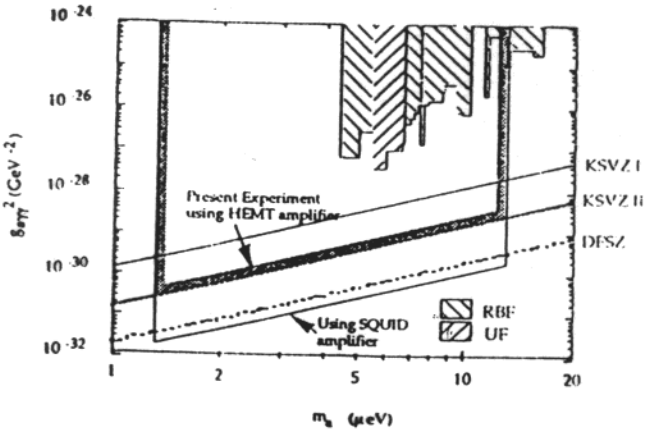
how much D.M. in Galaxy is accounted for? Interpretation model dependent

Present evalutions credit: Halo fraction in MACHOs <0.1

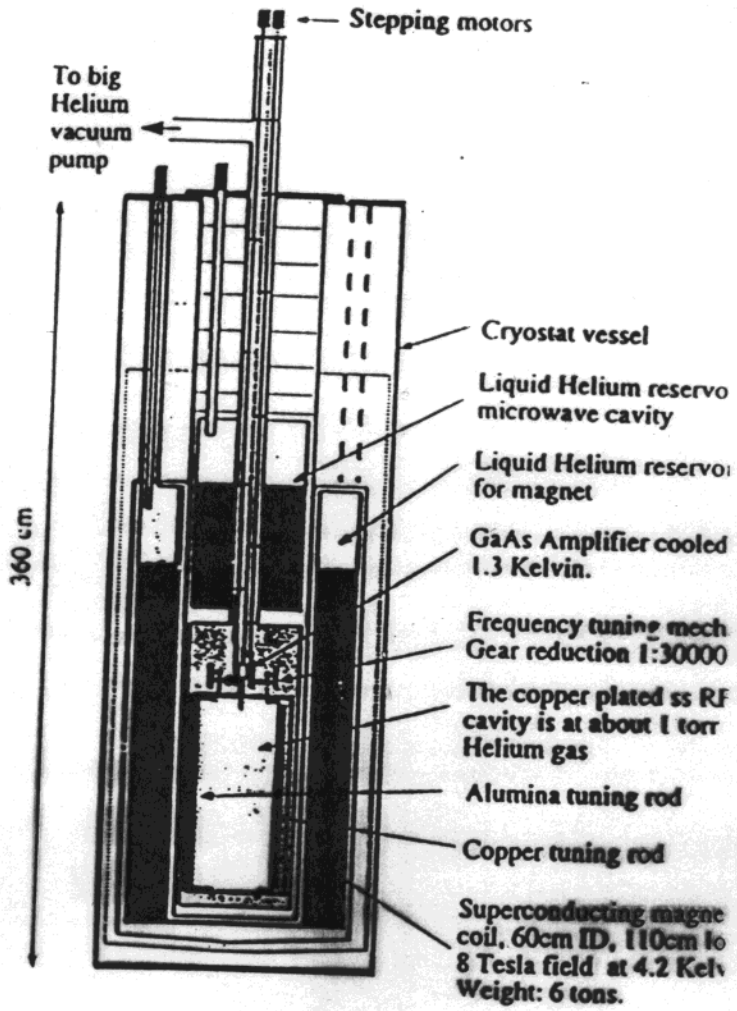
Searching for the axions .....

- Postulated by Peccei-Quinn to explain the absence of CP violation in strong interaction.
- Interesting range of mass for D.M. $10^{-6}<m_a<10^{-3}$ eV.
- Detection method: axion conversion to photons in the strong magnetic field in an electromagnetic cavity

RBF: $B_0^2V=0.36\ T^2m^3$
UF: $B_0^2V=0.45\ T^2m^3$
LLNL: $B_0^2V=12\ T^2m^3$



Still space for investigation



Searching for the WIMPs .....

Properties:

- Particles in thermal equilibrium in the early stage of the Universe, decoupling at freeze out temperature.
- $\langle \sigma_{ann} \times v \rangle \sim 10^{-26} / \Omega_W h^2$ cm^{2}s^{-1} $\rightarrow$ σ on ordinary matte of the order of weak interaction cross section
- Expected flux: $\Phi \sim 10^7 \times (1\text{GeV}/M_W)$ cm^{-2} s^{-1} $(0.2 < \rho_{halo} < 0.6$ GeV cm$^{-3})$
- They form a dissipationless gas trapped in the gravitational field of the Galaxy ($v \sim 10^{-3}$ c).

Most favoured candidate:
the lightest SUSY particles: the neutralino

Searches:

indirect:	in space, water, ice $\rightarrow$ see previous talks & underground
Direct	underground

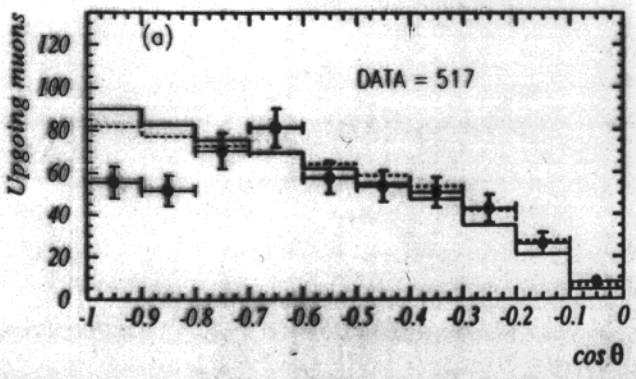
MACRO

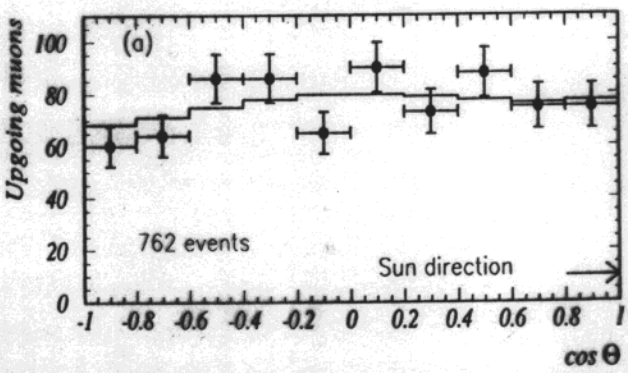
6 supermodules

° **latest result:** **data from 3/89 to 3/98**

° **total measured upgoing muons from Sun: 762**
° **total measured upgoing muons from Earth: 517**

° **expected from athmosferic ν:** **no osc. 662±113**
with osc. 462±79

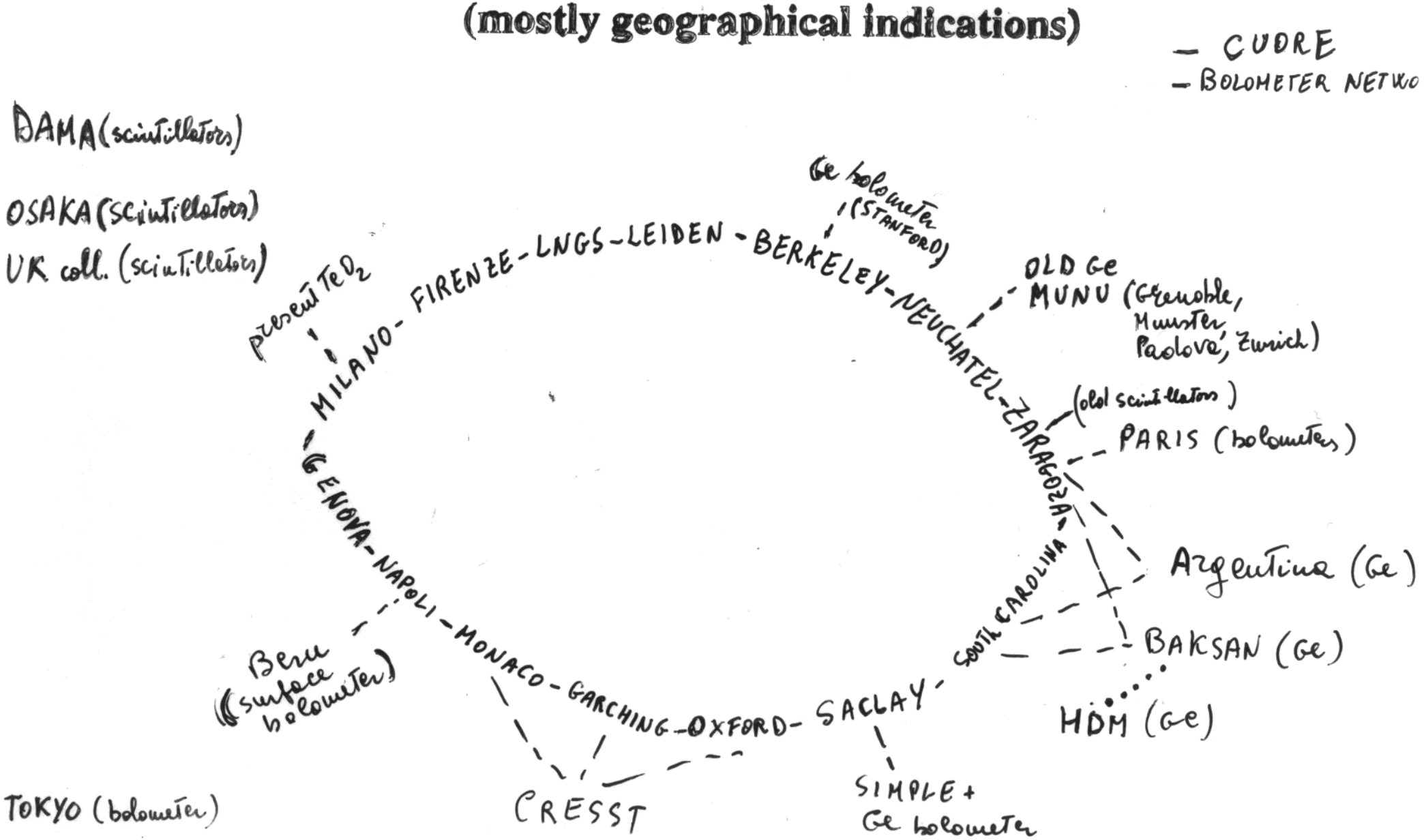


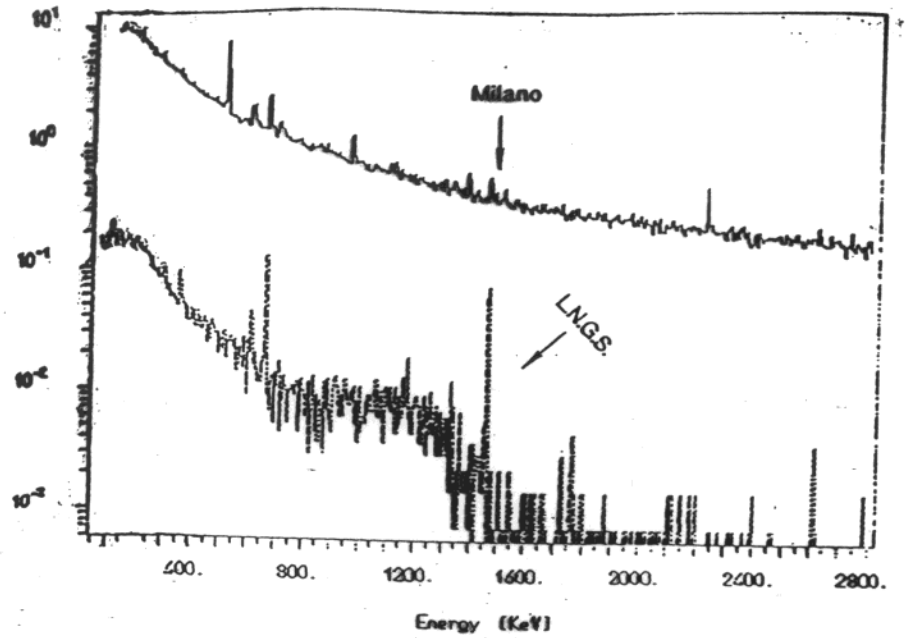


Earth Nadir distribution

cos of the angle from the Sun direct

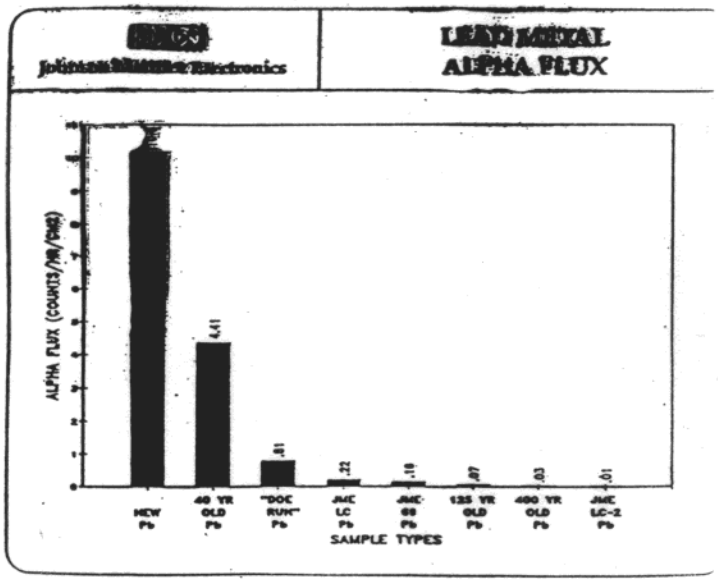
Main part of the D.M. direct searches
(mostly geographical indications)

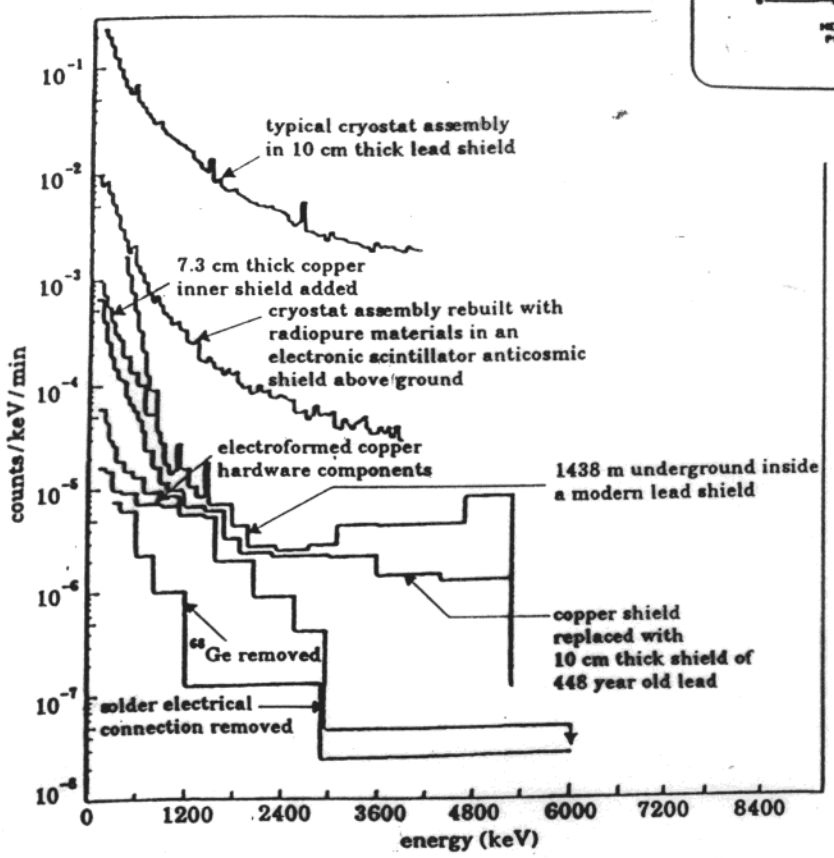




← underground site

low radioactive materials →





Improvement in low background technology over several years (Avignone Jal)

← continuous efforts for rate reduction on detector on electronic on environment

↓

ALWAYS POSSIBLE FOR ANYKIND OF DETECTORS

Examples of improvements with time

Ge detectors

	1988 Caldwell-Moriond (cpd/kg/keV)	1996 TWIN fax Morales (cpd/kg/keV)	1998 HDM latest result (cpd/kg/keV)
9 keV	~ 3.0	~ 1.0	~ 0.2
18 keV	~ 0.5	~ 0.2	~ 0.04

Reduction factor ~ 10

Bolometer

	EDELWEISS-91 24 g sapphire (cpd/kg/keV)	EDELWEISS -TAUP95 24 g sapphire (cpd/kg/keV)
15 keV	~ 400	~ 25

Reduction factor ~ 16

CaF2(Eu)

	Astrop.Phys. 94 - detector (best commercial), running and event analysis by DAMA + quenching factors on different detector (+higher polluted detector test) by SACLAY & LYON [BPRS] (cpd/kg/keV)	Astrop.Phys. 96 - DAMA after R&D + strong environmental improvement + q.f. from literature (UK&Osaka) (cpd/kg/keV)
4 keV	~ 26	~ 8
12 keV	~ 15	~ 1.3

Reduction factor ~ 3-10

OTO ~ at similar sensitivity

NaI(Tl)

	PLB92 - detector (best commercial), running and event analysis by DAMA + quenching factors on different detector by SACLAY [BRS] (cpd/kg/keV)	PLB96 - DAMA results after R&D + strong improvements on noise reduction and environmental quality + q.f. ENEA (cpd/kg/keV)
4 keV	~ 12	~ 1

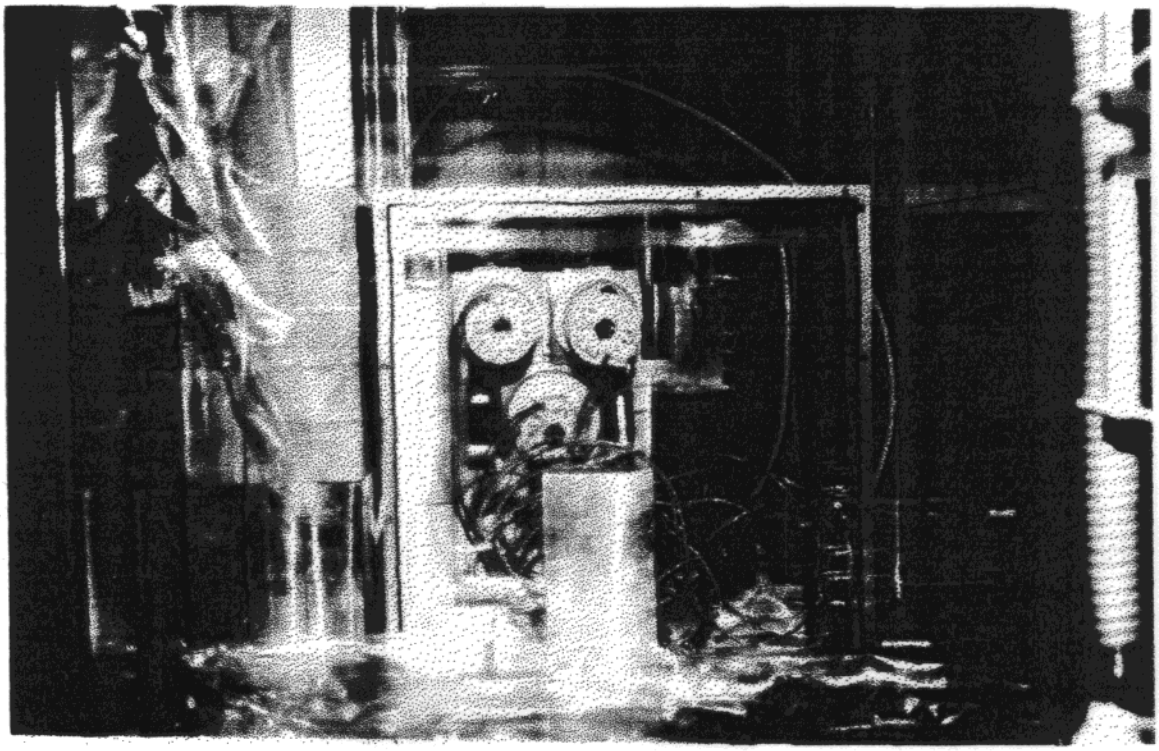
Reduction factor ~ 10

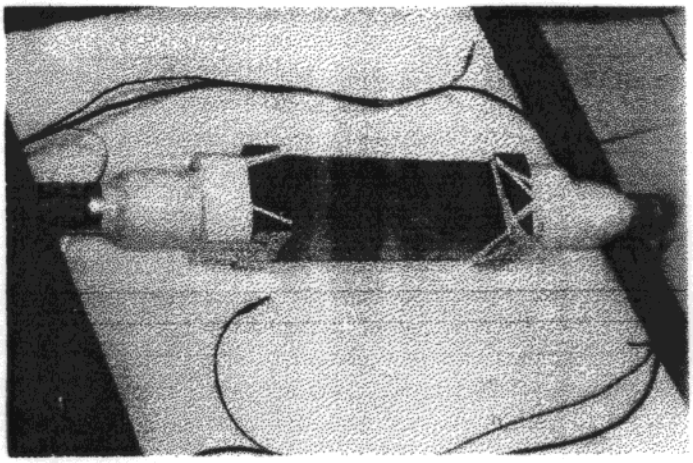
(improvements arises from the SI A^2 behaviour + threshold reduction due to light collection improvement, noise reduction & rejection, environment improvement, etc.)

UK coll. at similar sensitivity with PSD

An old example for comparison with present improvements

The 20 days exercise in 94





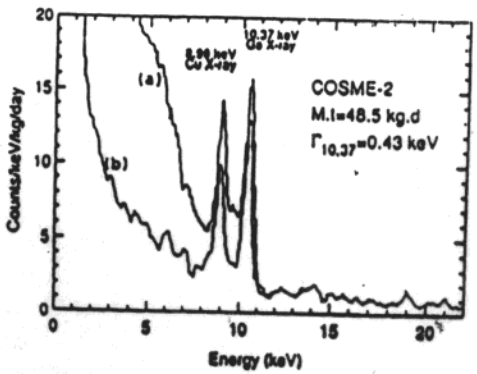
- **shield not fulfilled**
- **some small holes present in it**
- **plexi inner box (unsuitable for light+radon)**
- **unsuitable housings**
- **central detectors highly polluted → refused and given back to industry**
- **short life contaminants still important**
- **cabling, voltage divider, light guides, electronics etc. to be further developed**
- **etc. etc.**

..... easy to improve ...

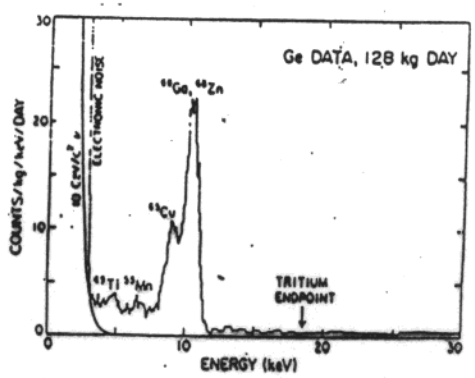
→ only an interesting test of human resources

The Ge case

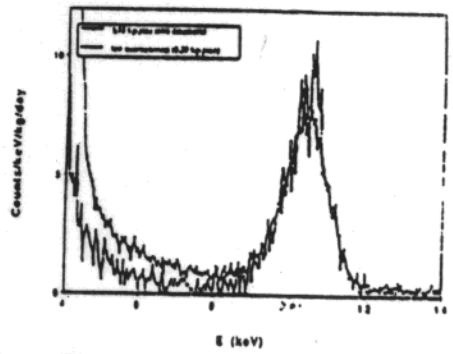
Example of old results to compare improvements



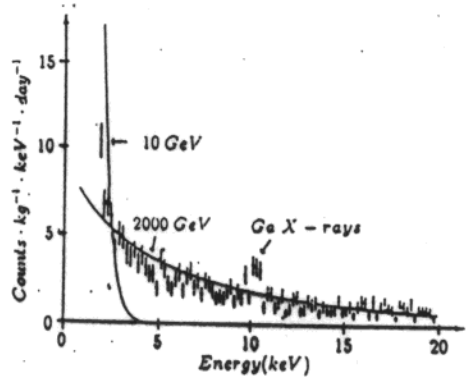
(1) COSME at Canfranc
(a) raw data (b) filtered data



UCSB/LBL



(2) Twin at Homestake
[redacted]NL/USC/UZ Collaboration



Caltech/PSI

(TAUP93)

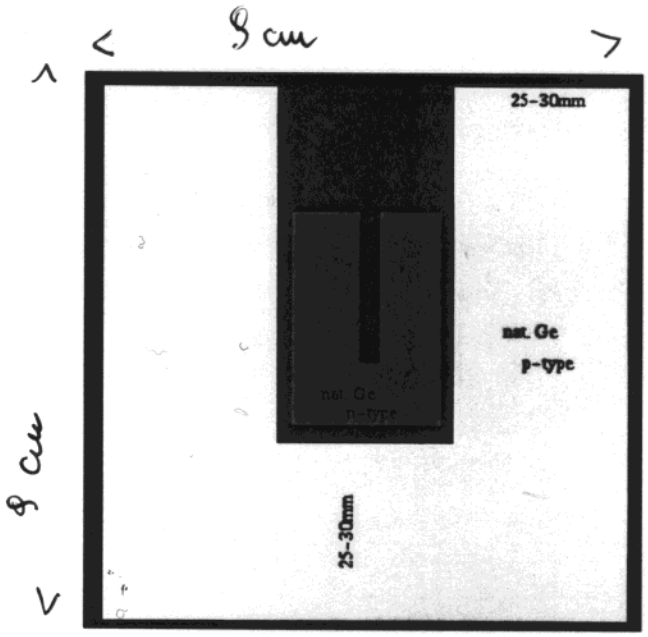
Further improvements by Twin and HDM (see exclusion plots)

In recent determinations (such as e.g. HDM) quenching factor at Lindhard upper limit (→ necessary to account for significant energy behaviour)

HDM, HDMS

(ionizing detector)

- coaxial intrinsic p-type HP-Ge
- HDM latest result with 2.758 Kg detector
- HDMS small natural Ge-crystal surrounded by a well type Ge crystal running in anticoincidence. Both crystals are mounted in a common cryostat system



Example of minimal information to be fulfilled and suitably compared before setting any comment on thresholds, rates and behaviours near energy threshold in various NaI(Tl) cases

(quoted values from published data)

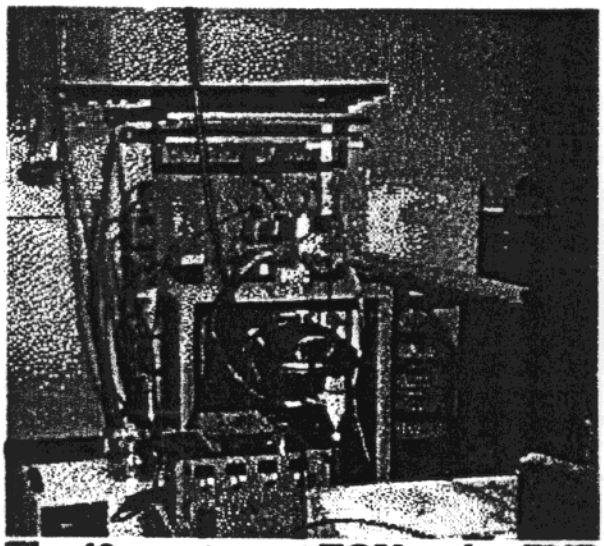
expt	techno-logy	single/ multi det.	#PMT / detector	noise rejection	info on res. contaminants in detectors/ added materials/ shield/ radon etc.	photoel ./keV	total hardware rate above single photoel. threshold	neutron source in under-ground installation	^{210}Pb peak height (mainly ext?) cpd/kg/ keV	threshold on single PMT	coinc. window + afterglo w rejection	σ/E
CANFRANC	old	Multi	1	?	NO	?	NO	NO	20	?	–/?	~14% @ 46.5 keV
DAMA	new	Multi	2 (window and 10 cm u/l.g. the same)	pulse shape info.	YES (+more in near future)	5.5.-7.5	YES	NO	3-6	single photoel.	given	7.5% @ 59.5 keV
OSAKA	old	Multi	2 (but very long l.g.)	?	OLD ELEGANT V paper	?	NO	NO	40	?	?	~14% @ 46.5 keV
UK	new	Single	2 (but 30 cm l.g.)	?	NO	1.7	NO	YES	?	2.4 Photoel.	?	?

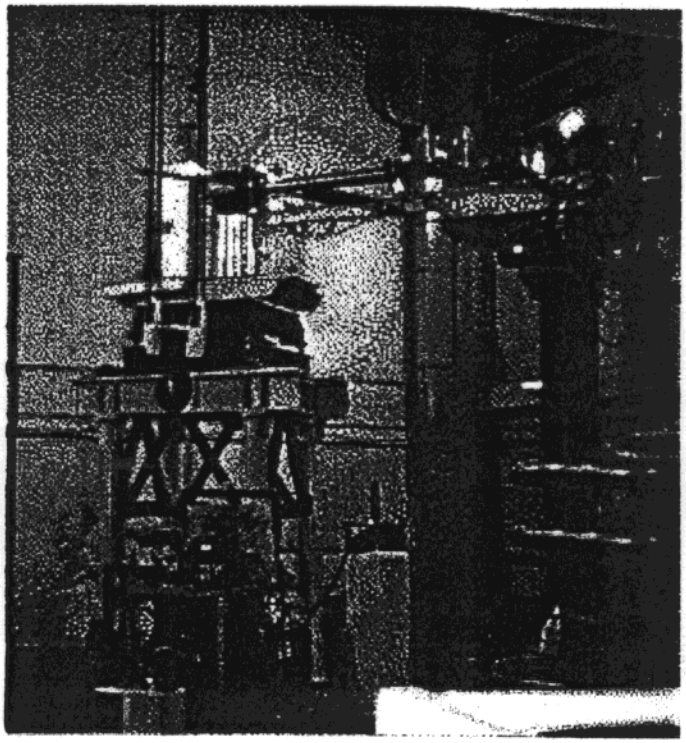
General REMARK: if the same (or higher) number of photoelectrons/keV is claimed → obviously (!) the energy resolution also should be the same (or better)....

LXe experiment

~2 liter LXe detector running at LNGS
filled with Kr-free Xenon enriched at 99.5% in ^{129}Xe

- **Published results** *(PLB 436 (1998), 379)*
  - *new limits on the WIMP-^{129}Xe elastic scattering*
  - *quenching factor*
  - *PSD*
  - *data analysis on 1763.2 kg·day*





The 40 cc set-up at TOV and at ENEA

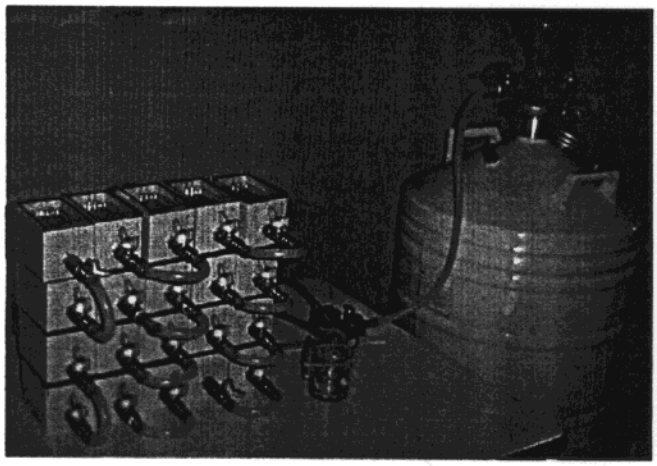
- **Planned upgradings:**
  - *external box + new Radon trap*
- **Planned measurements in incoming years:**
  - *data taking with ^{129}Xe and ^{136}Xe and at neutron beam*

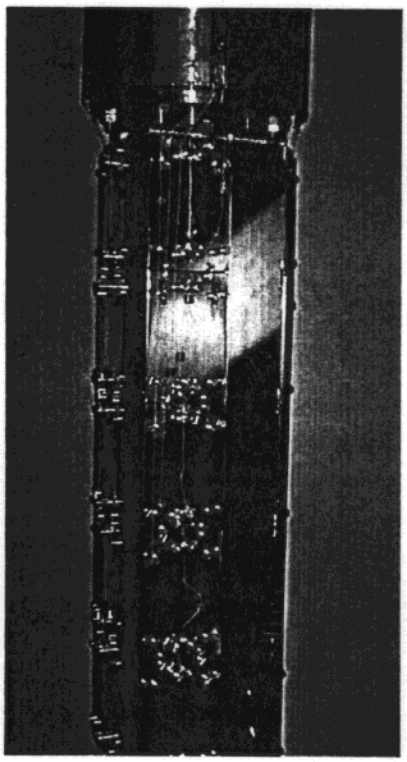
NOW:
A 6 Kg LXE DETECTOR ALSO AT WORK IN BOULBY MINE

Milano - TeO_2

(Double Beta Decay & Dark Matter)

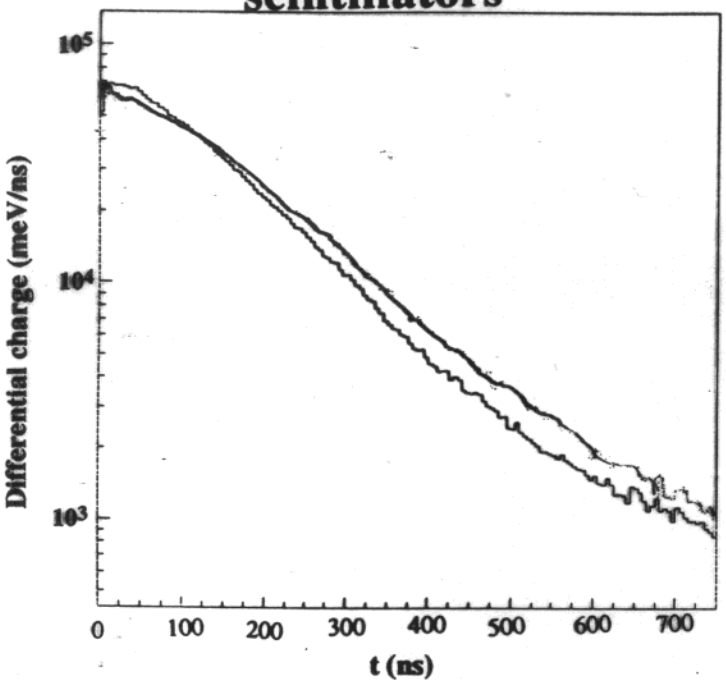
- Bolometers approach
  (NTD Ge thermistor)
- First result with ~340 g crystal
- Now a 20 detector array operating in the Hall A at LNGS → 6.8 Kg + energy resolution ~ 5 keV FWHM @ low energy
- planned expansion: Cuoricino (~ 100 kg)

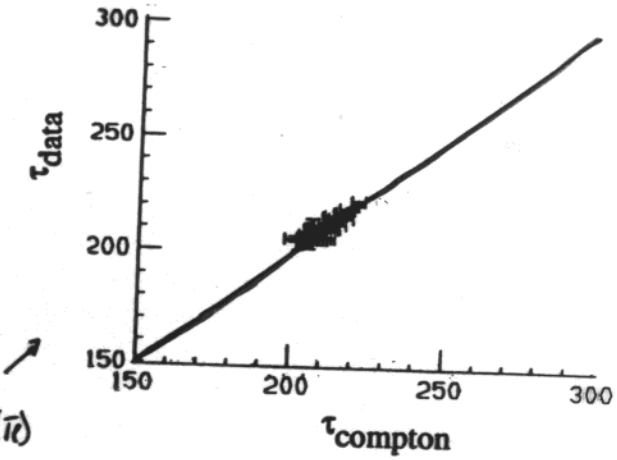




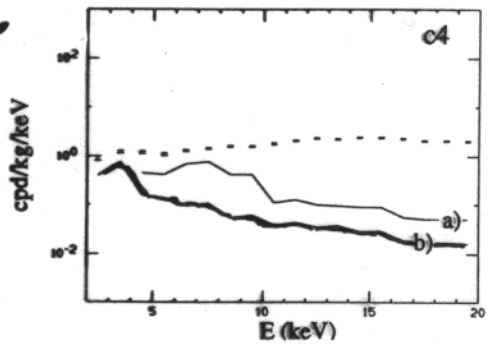
Improvements from PSD .....

A) Studying the different pulse time decay in scintillators

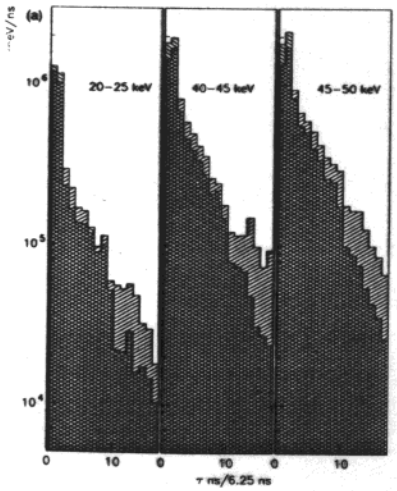




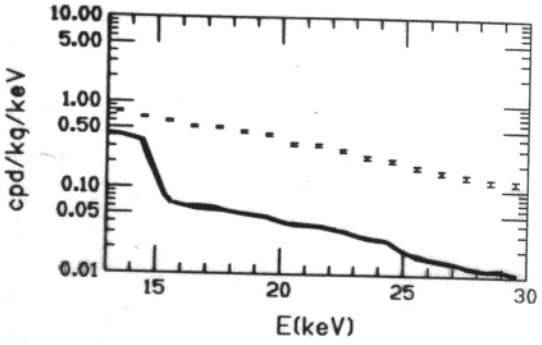
NaI(Tl)



Example on 1 olei



LXe



LXe

successfully realized e.g. by DAMA and UK in NaI(Tl) and by DAMA in LXe

Note on PSD in doped scintillators

possible concurrent processes:

physical: recoils from neutrons; end-range α's; fission processes, etc.

instrumental: from possible dopant drift in the surface layers of a given detector (e.g. Tl in NaI(Tl) - peculiar, mainly when long time passed from the growth of the crystalline bulk and the detector creation) $\rightarrow$ effect e.g. on pulse shape from external source (and more...)

⇩

° indistinguishable from the recoil pulses searched for: a candidate recoil fraction should be quoted, unless each contribution quantitatively identified (unlikely to perform in reliable manner at the needed precision!)

° incompatibility between data and all the reference pulses (due to malfunctioning or to inconsistency between reference and production data taking) can be always accounted as systematic contribution

⇩

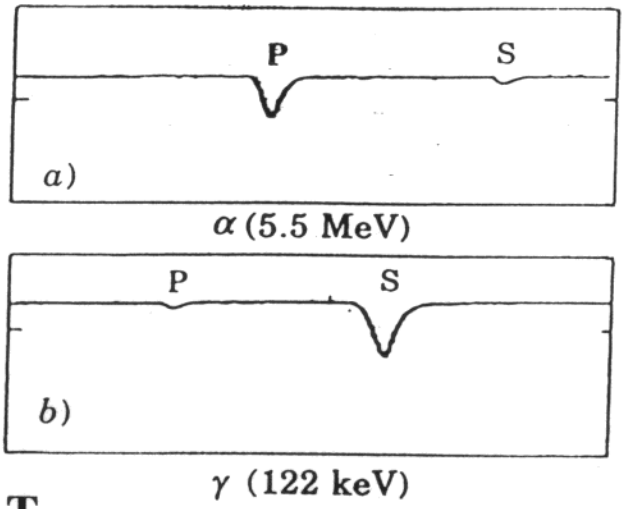
For a successfull PSD e.g. in NaI(Tl) (when concurrent processes contributions are negligible with respect to statistical uncertainties):

- ° high Temperature stability
- ° full compatibility of Compton, neutron and production data running conditions
- ° efficient rejection of residual PMT noise and not relevant contribution from afterglow events and electronic line noise.

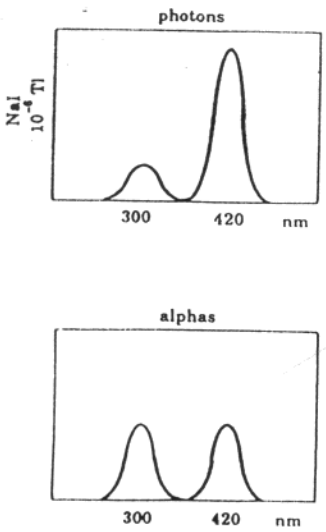
$\rightarrow$ PSD not a WIMP signature for any kind of detector and strategy $\leftarrow$

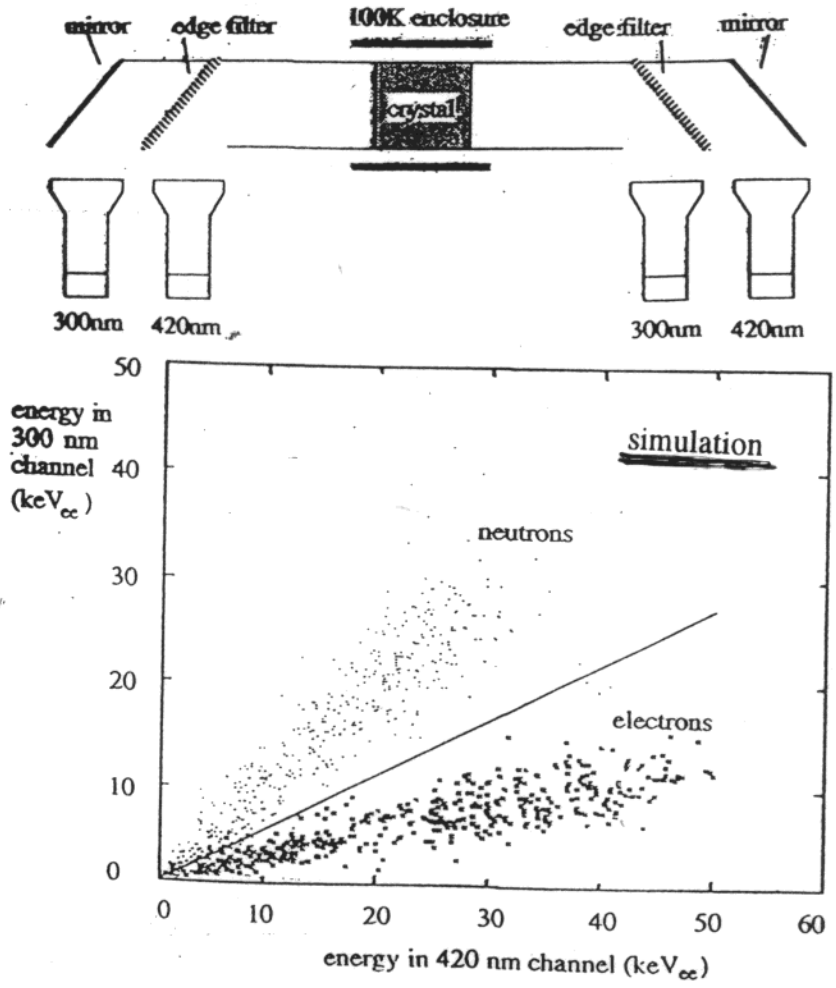
Other kind of recoil discrimination?

- **CERN/ITALY/UK/USA: LXe proportional scintillation**



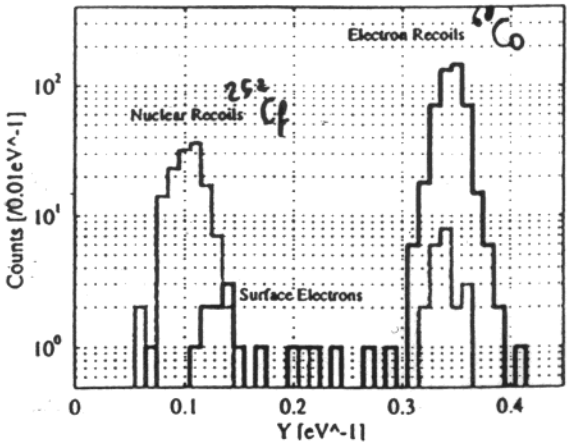
- **UK: *pure* NaI at low T**

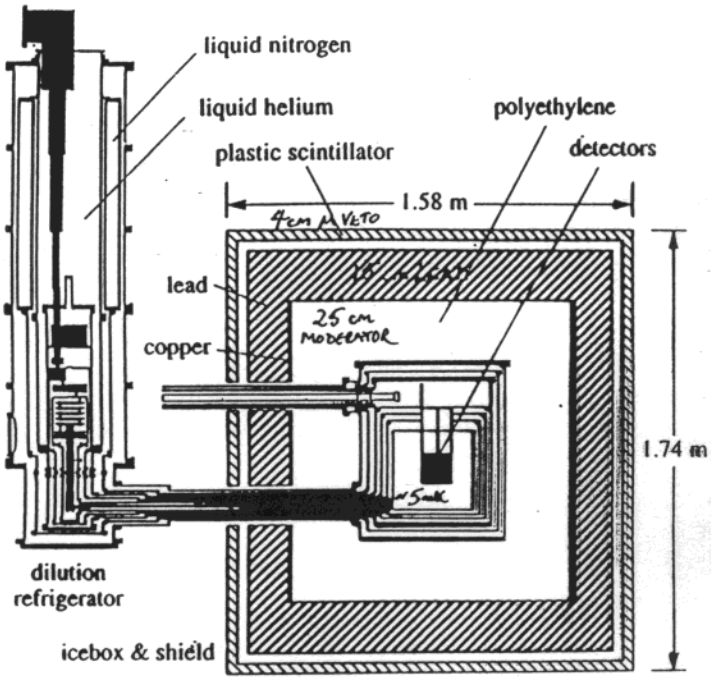


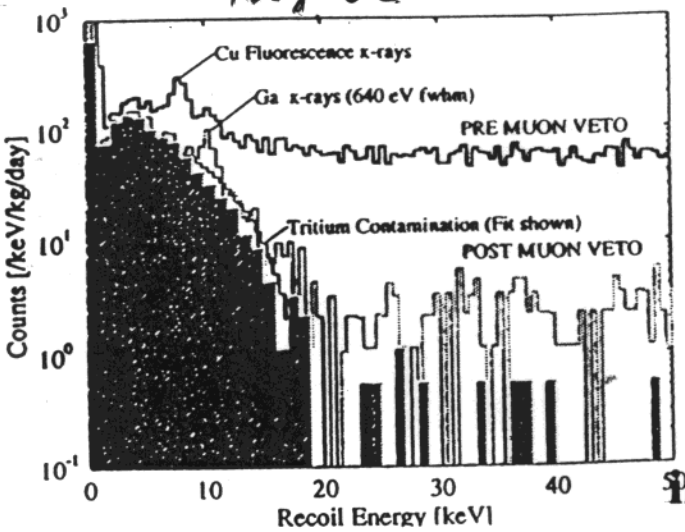


B) Comparying different signals from the same event

* ionization vs heat Ge bolometer case







1.6 Kg d

CDMS

In progress at Berkeley

*** scintillation vs heat ?** — **threshold, resolution?**

*** scintillation vs ionization** — **long R&D done (performances?)**

more on:

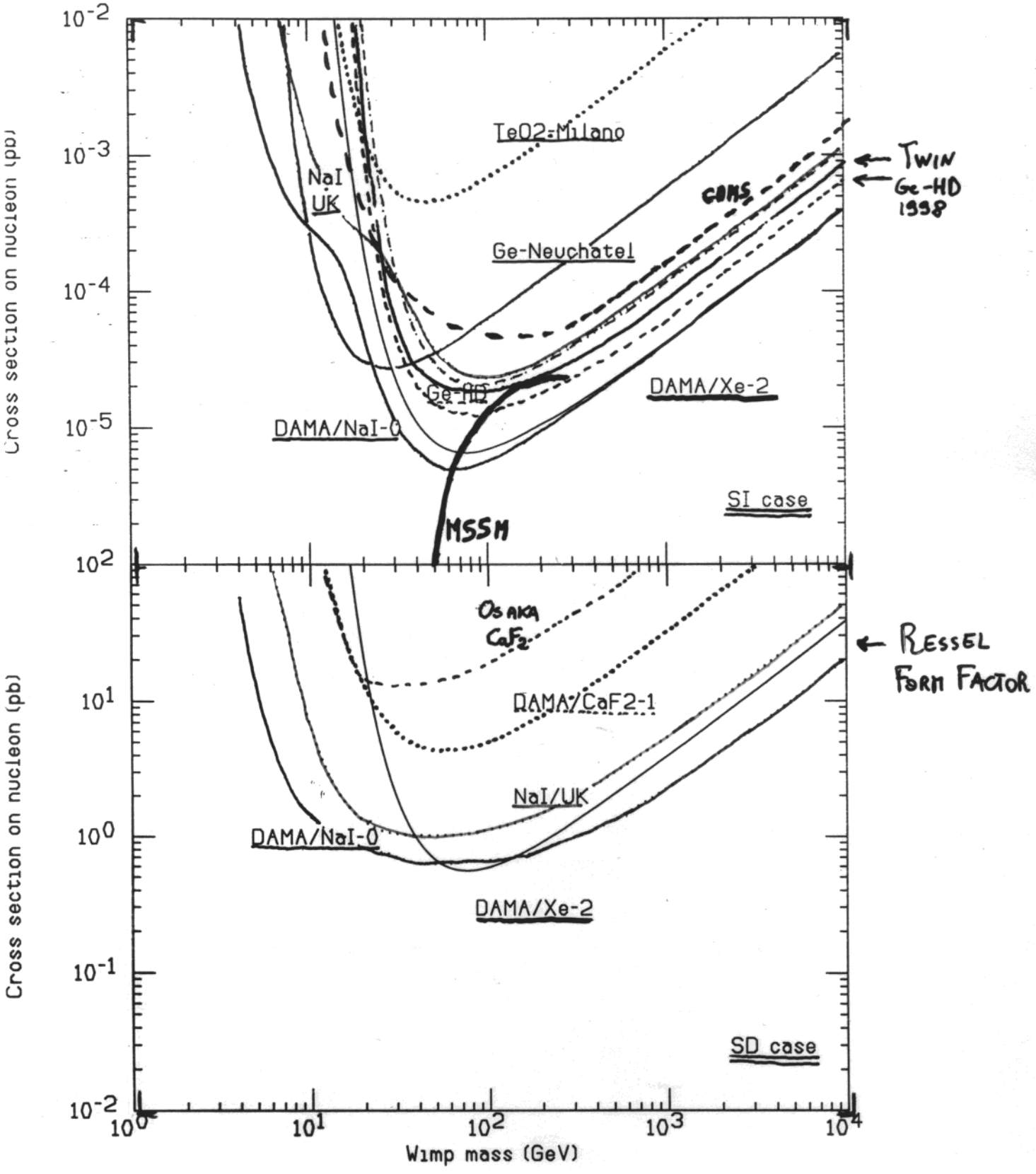
- **quenching factors,** ← with neutrons
- **identity of the sensitive volume for two different signals,**
- **concurrent processes...**

NEEDED

- rejection factor uncertainty
- efficiencies, sensitive volumes
- noise rejection eff.

etc. etc..

Recent Limits On σ_p vs M_w



A signature is needed !

- **Comparison of the results from different experiments.**

  (SI: $R \propto A^2$; SD: $R \propto C\lambda^2 J(J+1)$; $\langle Er \rangle = f(M_N)$ for each M_W)

  ← unlikely

- **Directionality.**

  Correlation of nuclear recoil track with the Earth's galactic motion due to the distribution of WIMP velocities

  ← too difficult

- **Diurnal modulation**

  Daily variation of the rate due to different Earth depth crossed by Wimps

  ← very small effect (Rio Grande)

- **Annual modulation of the signal**

  annual variation of the rate due to Earth motion around the Sun

  - Dama/NaI project started 90
  - First "exercises" Confuse (old NaI) + DAMA
  - Recent lower sensitivity (+ overall conditions ?
    Rio Grande (1 Kg Ge) ≳ OSAKA (old NaI)
  - UK coll. efforts with PSD

  → in progress The ~100 Kg DAMA/NaI

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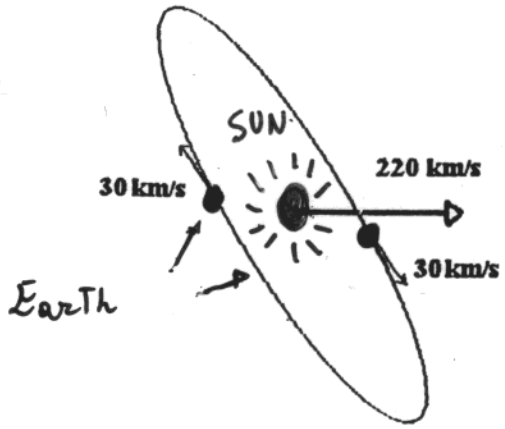
  → in progress The ~100 kg DAMA/NaI

• Drukier, Freese Spergel, PRD86
• Freese et al, PRD

Annual modulation of the rate

- **Correlation of the signal with the Earth galactic motion**



- $v_e(t) = v_{sun} + v_{earth} \cos\gamma \cos\omega(t-t_0)$

v_{sun}=232km/s Sun velocity in halo
v_{earth}=30km/s Earth velocity around the Sun
$\gamma = 60^o$
$\omega = 2\pi/T$ and T=1 year
$t_0 \approx 2^{nd}$ June

- **Expected Signal in the k^{th} energy bin:**

$$S_k[v_e(t)] = S_{0,k} + S_{m,k} \cos\omega(t-t_0)$$

- $S_{m,k}/S_{0,k} \approx 7\%$ **where** $S_{m,k}$ **is maximum**

- **ONLY large detectors (mass > 50 kg) can single out such a signal** *(with suitable counting rate and energy threshold)*

ANNUAL MODULATION → CLEAR SIGNATURE

Requirements

1) Single hit events in a multidetector set-up

2) Modulated rate

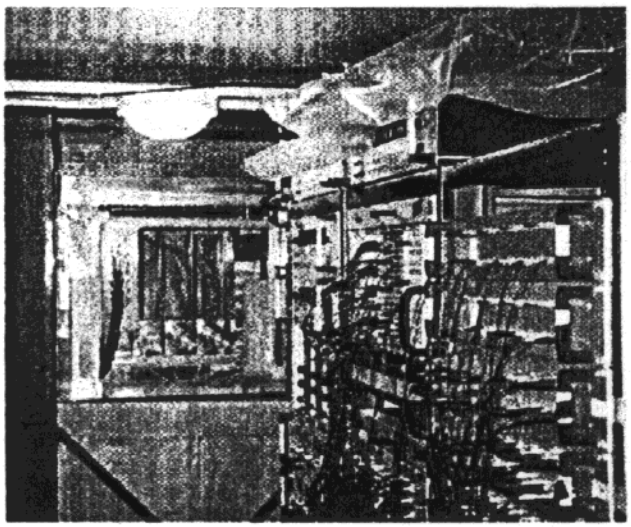
3) with proper period (1 year)

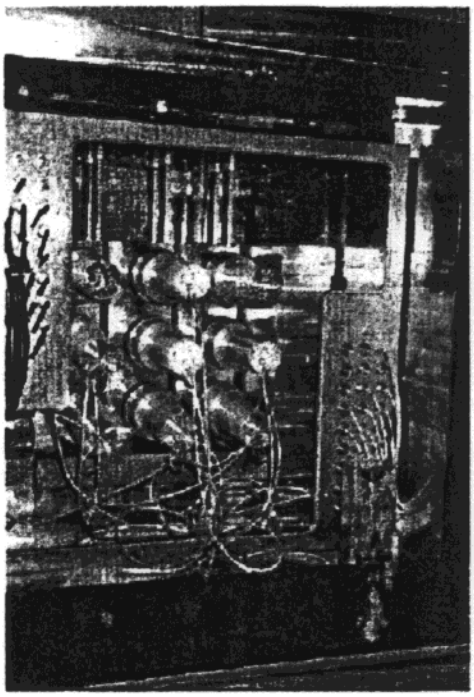
4) with proper phase (about june 2nd)

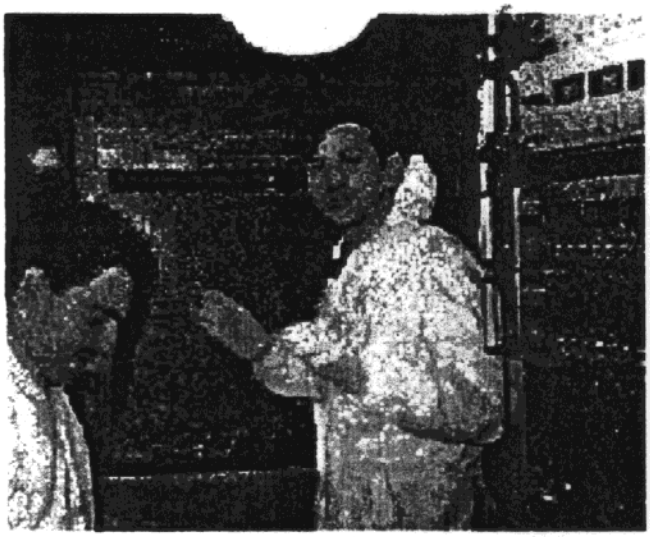
5) only in a defined low energy range

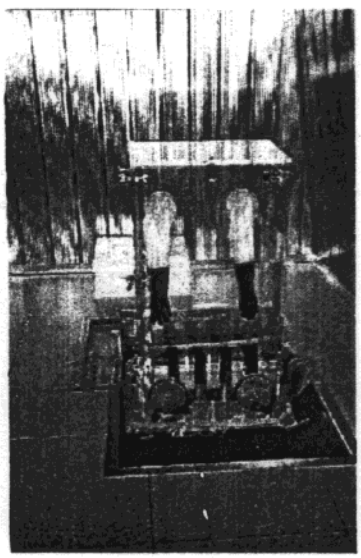
6) with modulated amplitude in the region of maximal sensitivity $\lesssim$ 7%.

The ~100 kg NaI(Tl) experiment



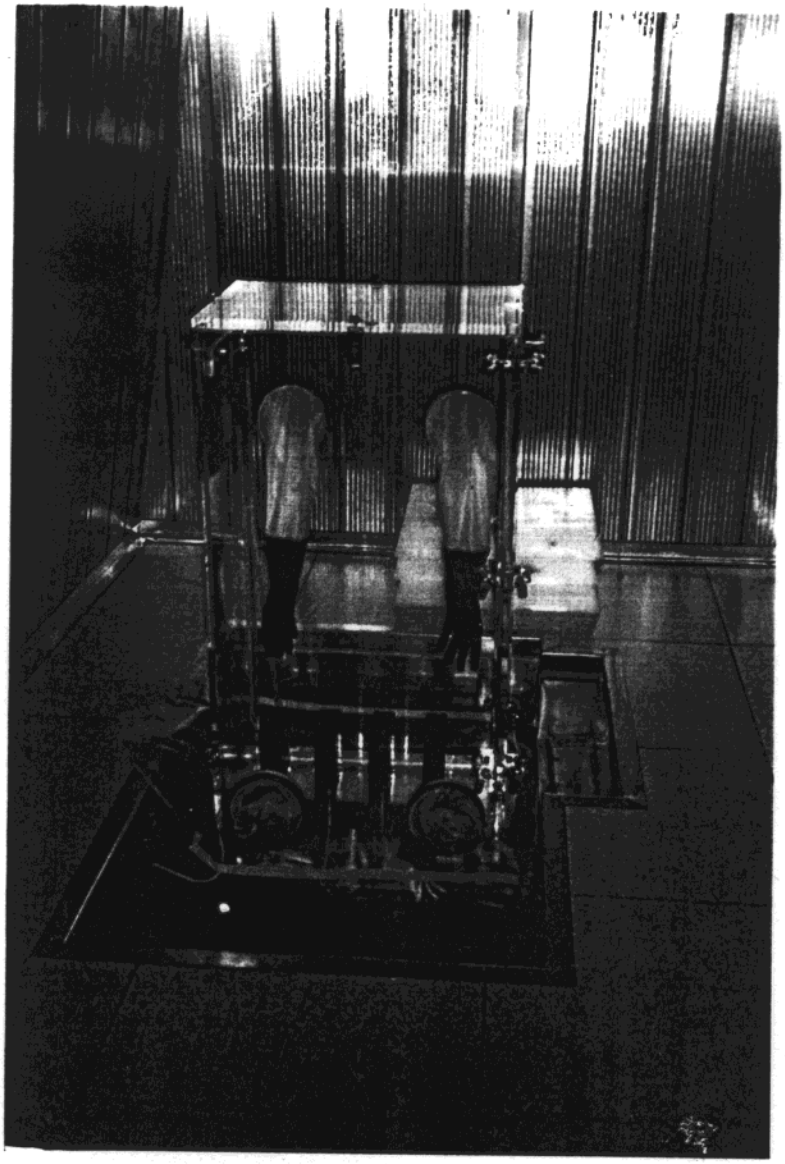


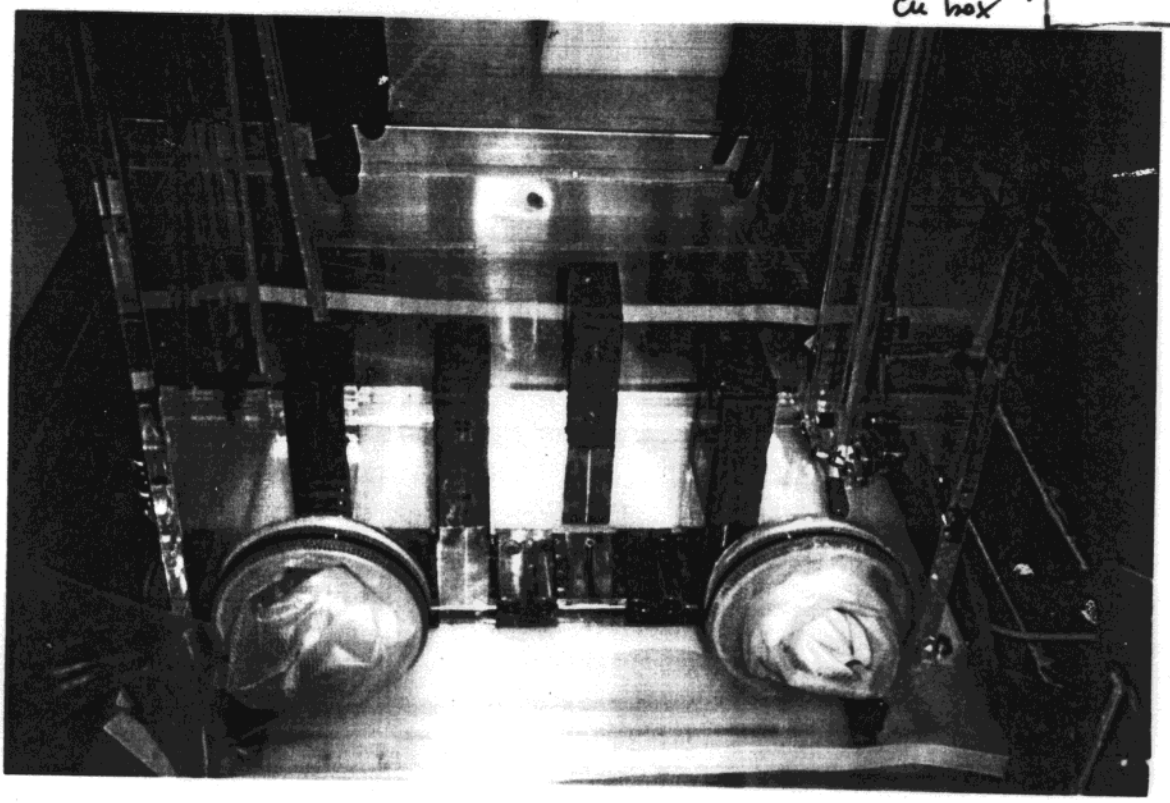


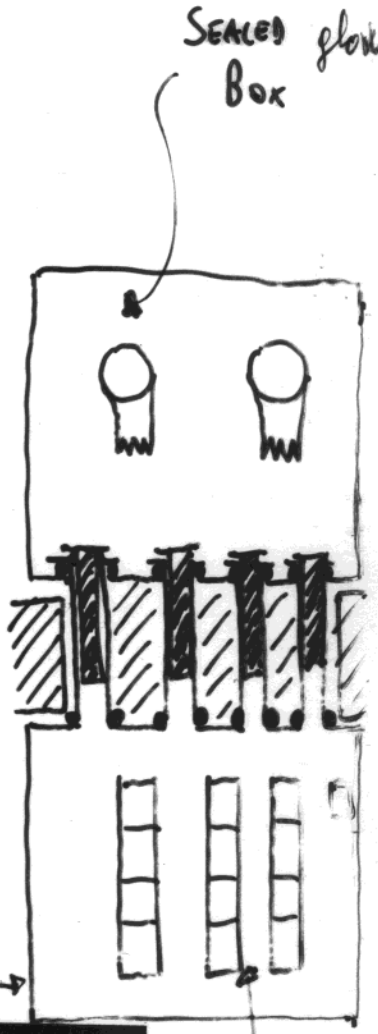


Detailed description on ROM2F/98/27 and INFN/AE-98/23

on http://mercury.lngs.infn.it/lngs/preprint/preprint.html






SEALED glove-
BOX
NaI
DETECTOR

Present results

Analysis method endorsed by the collaboration:
Maximum likelihood method with data grouped in {ijk} cells of 1 day(i), 1 keV(k) for each detector (j):

experimental $N_{ijk} \Leftrightarrow \mu_{ijk}$ expected from the model

running period	statistics (kg d)	stability parameters	M_W (GeV)	$\xi\sigma_p$ (pb)	C.L. (m.l.r)
DAMA/ NaI-1	3363.8 winter + 1185.2 summer	good	59^{+36}_{-19}	$(1.0^{+0.1}_{-0.4})\,10^{-5}$	90%
DAMA/ NaI-2	14962 from middle november to the subsequent july	good	59^{+22}_{-14}	$(7^{+0.4}_{-1.7})\,10^{-6}$	98.5%
DAMA/ NaI1&2	19511	"	59^{+17}_{-14}	$(7^{+0.4}_{-1.2})\,10^{-6}$	99.6%

← PL B424(1998), 195

IN FN/AE-98/20
To appear on PL B

Further data analysis, data taking and upgradings in progress **wait for more....**

Statistical evaluations

DAMA/NaI-2

- **Test of maximum likelihood ratio:**
  favours the hypothesis of presence of modulation according to the best fitted $\xi\sigma_p$, M_w **at 98.5% C.L.**

- **Test of z variable** $z=\frac{1}{N}\sum_{ijk}\left[2\left(\mu_{ijk}-N_{ijk}\right)+2N_{ijk}\ln\left(\frac{N_{ijk}}{\mu_{ijk}}\right)\right]$ (PDP)

  (a χ^2/d.o.f. for sufficiently large N_{ijk})
  N number of considered {ijk} cells (d.o.f.)

  gives a probability of 7.4% to get a $z > 1.08$ (expt value)

- **Test of z variable on the data of each detector:**
  test passed by 8 detector over 9 for 95 % C.L.

- **Consistency check of this result (fixed M_w):**
  considering both $\xi\sigma_p$ and the modulation period T as free parameters

  $\xi\sigma_p$ as before
  $T = 1.3\pm0.4$ year to compare with 1 year

  considering both $\xi\sigma_p$ and the phase t_0 as free parameters

  $\xi\sigma_p$ as before
  $t_0 = 140\pm20$ day to compare with $\approx$ 2nd June($\approx$152.5 day)

DAMA/NaI-2

Systematics

Systematics which can affect the <u>whole energy spectrum:</u> e.g.

- **Temperature variations**

  (<< 0.1% random variation in the light response along the year + calibration and energy resolution)

- **Radon variations**

  (Detectors excluded from environmental air. However, time correlation analysis gives modulated contribution compatible with zero)

- **Energy calibration**

  (Uncertainties negligible with the respect to the energy resolution at low energy: overall additional relative energy spread $<3\ 10^{-4}$ @ 2 keV and $<3\ 10^{-3}$ @ 20 keV)

- **Background variations**

  (No evidence of modulation on: i) total hardware rate; ii) rate above 90keV, $R_{90}<0.2$ cpd/kg; iii) S_m (7-20 keV) = -0.0045 ± 0.0047 cpd/kg/keV. Increasing bckg with time excluded from R_{90})

→ Systematics $< 10^{-3}$

<u>"Side reactions":</u>

- They must simulate the WIMP signal features: yearly modulation of "single hit" rate with t_0 and only in the lowest energy region.

- Up to now no candidate has been found; in particular, the muon modulation studied by MACRO experiment would account roughly only for modulated amplitude << 10-4 cpd/kg/keV, which is much lower than the ones found here.

(+ fails some requirements!)

??Suggestions??

DAMA/NaI 1&2

- Consistency of the results DAMA/NaI-1 and DAMA/NaI-2 running periods.
  Although they have been performed in different operating conditions.

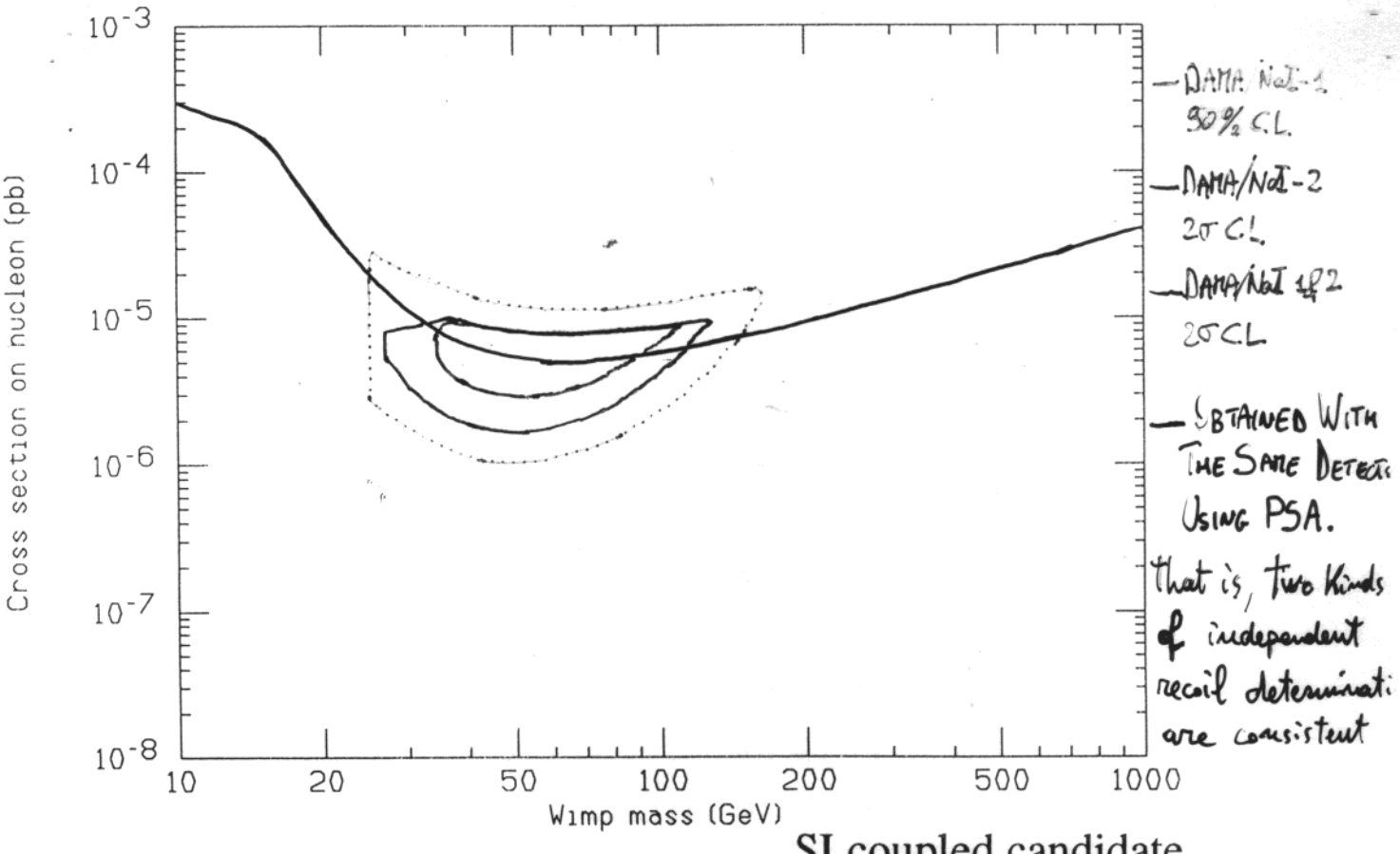
- Combined analysis of the two data sets together by maximum likelihood method, properly taking into account that the b_{jk} for the two running periods can be slightly different.

- The total statistics is **19511 kg day**.

- Minimum value of the y function is found for: $M_w = (59^{+17}_{-14})$ GeV

$$\xi\sigma_p = (7.0^{+0.4}_{-1.2})\ 10^{-6}\ \text{pb}$$

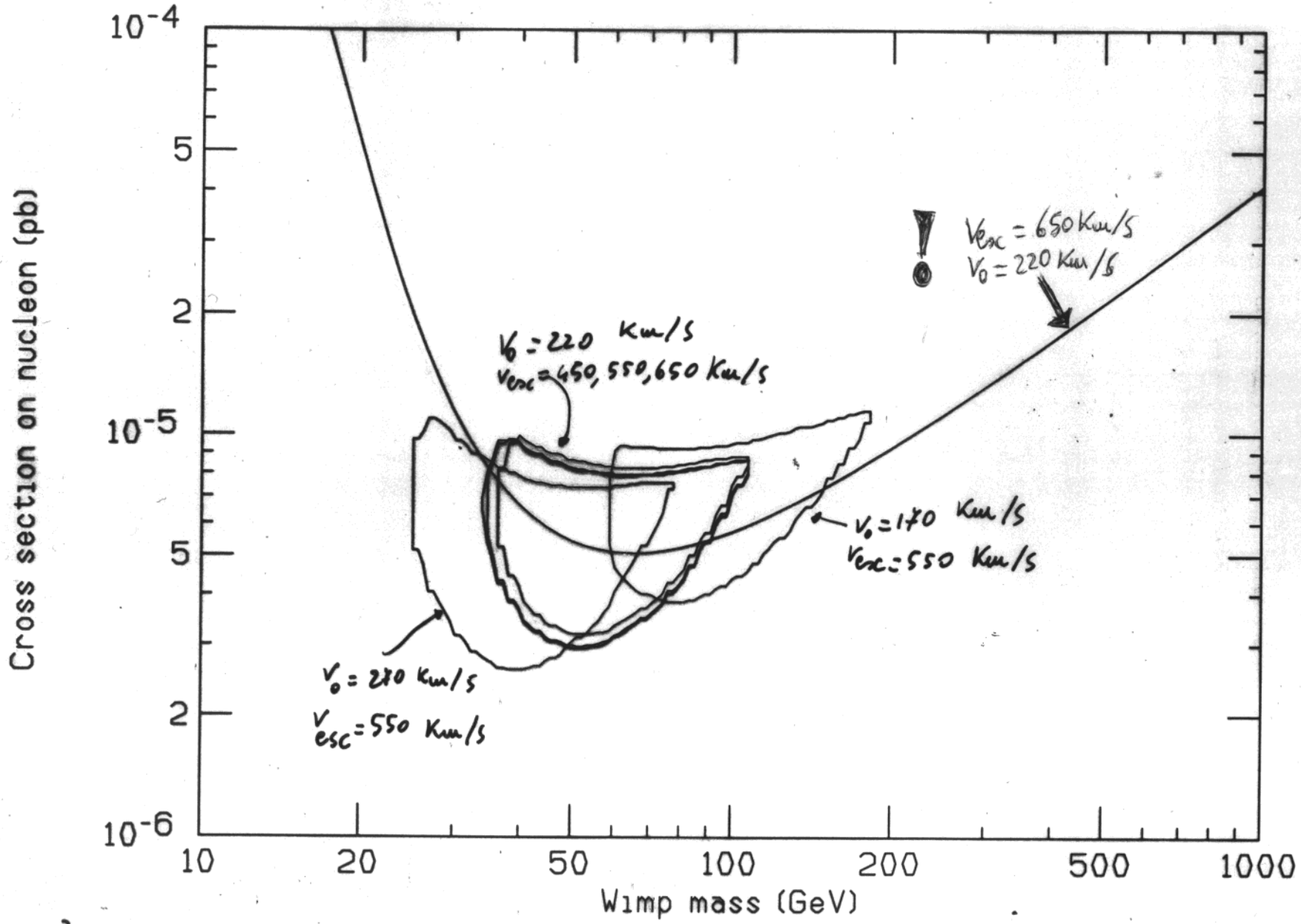
- The variable **$(-2\ \ln\lambda) = 8.23$**, that is in favour of the hypothesis of the presence of a modulation with the given M_w and $\xi\sigma_p$ at **99.6% C.L.**



SI coupled candidate

Effect

of uncertainties on the local (v_0) and escape velocities (v_{esc}) on the DAMA/NaI-1&2 allowed region



$\rho = 0.3$ GeV/cm^3, $v_e = 15.3$ Km/s
$v_0 = v_0 + (12 \div$ Km/s)

limits at 2σ C.L.

What next for the DAMA/NaI annual modulation search ?

° improvement of external shielding
september 98

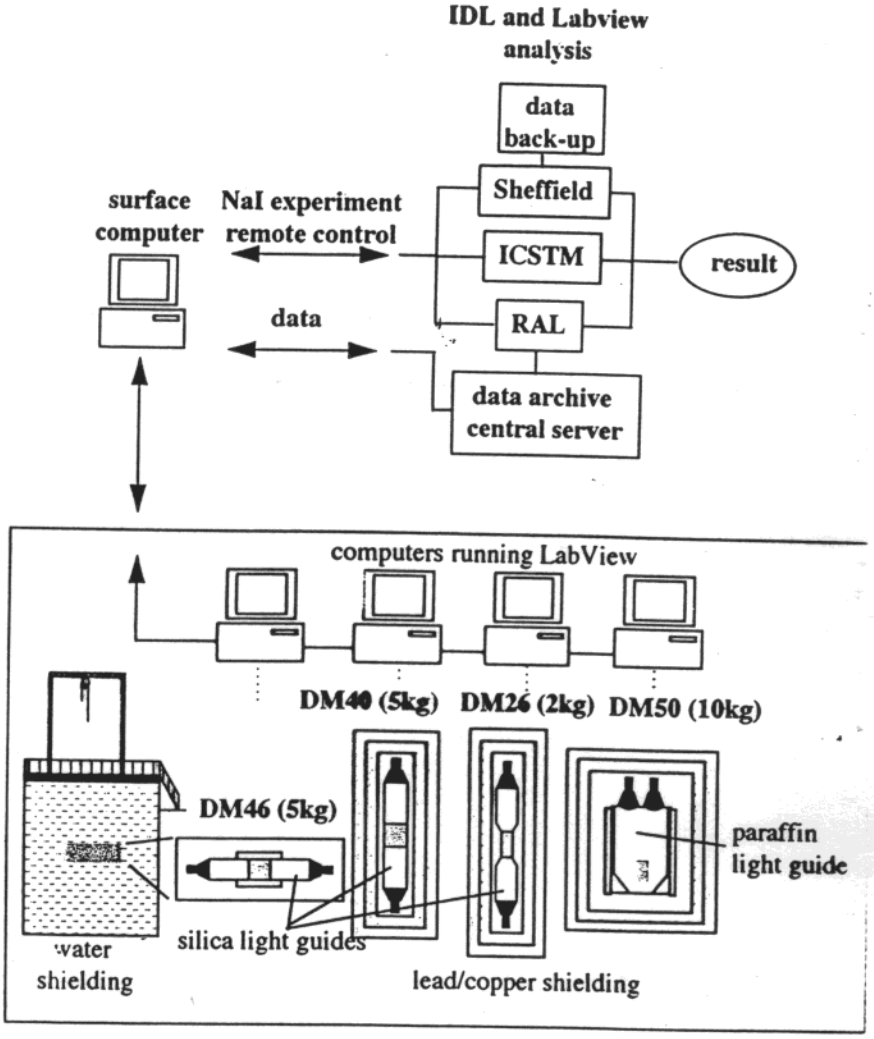
° new data release
october/november 99

° new electronics and DAQ installation
september 99
(exploiting further peculiarities)

+ new R&D in progress → if successful
→ fulfill the present installation up to 250 kg

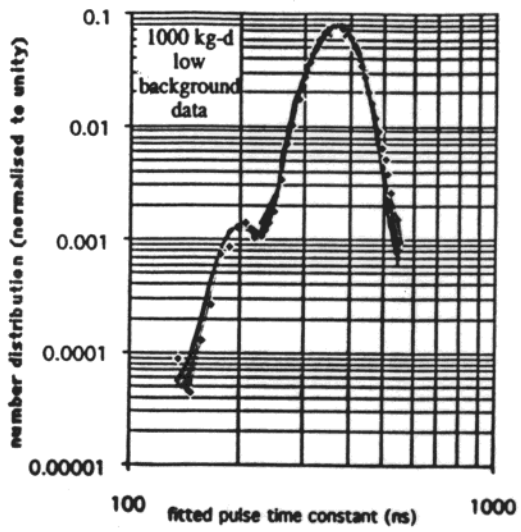
The UK coll. set-up

'he 22 kg NaI "diagnostic array"

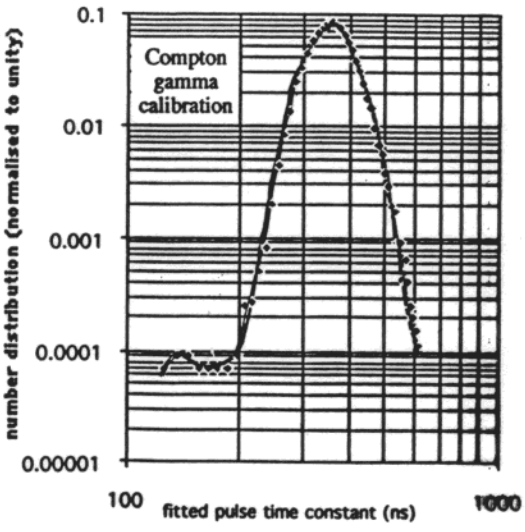


Bump subtraction

production data.



Compton



Further investigation in progress . . .

Conclusion

- D. M. problem well set
- multicomponent nature accepted
- hints for possible solutions in this scenario?

  from Macho ?
  from suitably low ν mass ?
  from WIMP ?

..... work in progress .....

+ new results from indirect searches coming soon?

..... from the "dark" to the "light" again? .....