DARK MATTER

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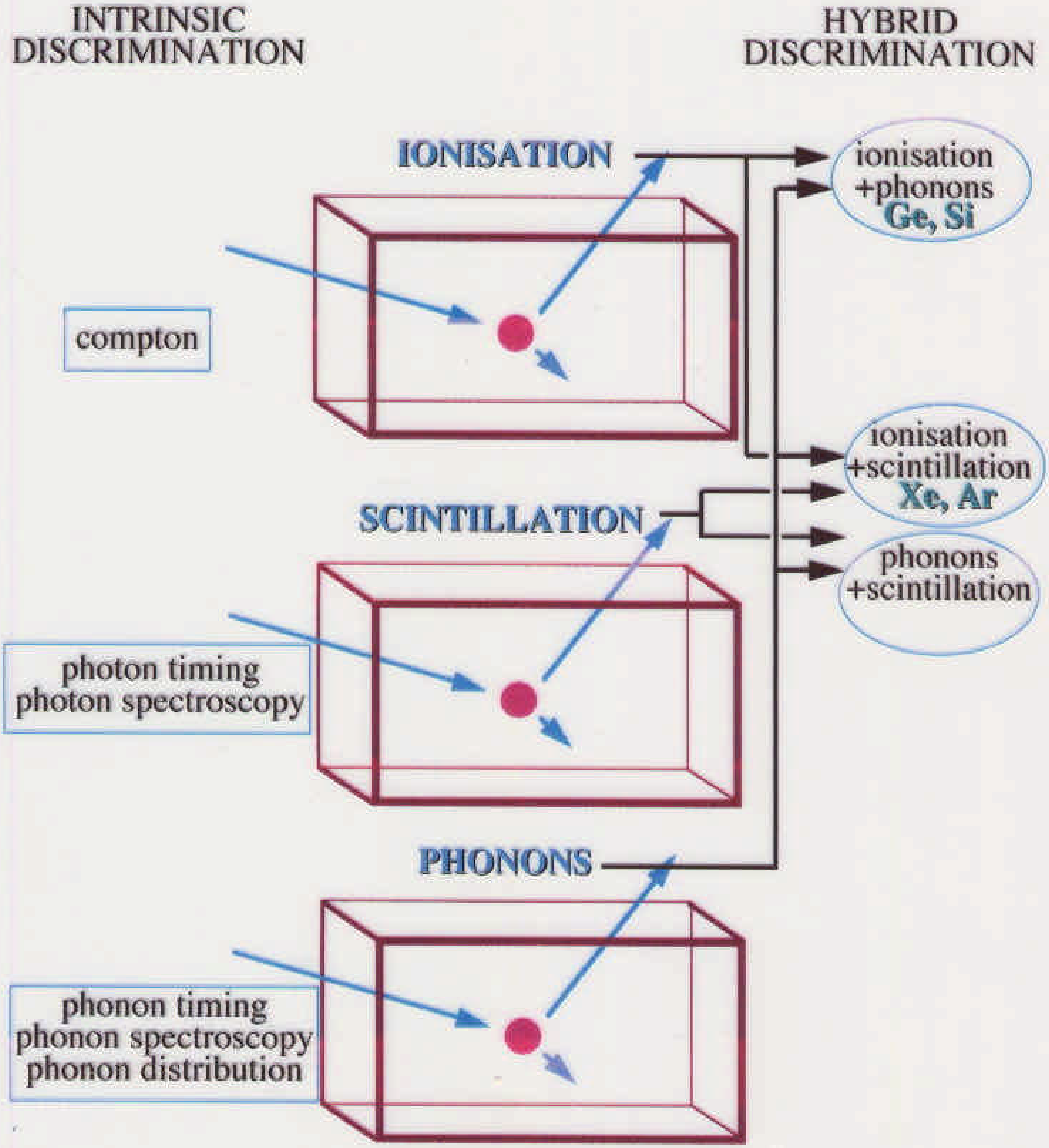
WIMP Searches by Direct Detection

- overview of detector strategies
- recent results --> DAMA, CDMS, UKDMC
- the UKDMC programme (and JIF)
- future developments --> directional

WIMP Detection - Recoil Discrimination



Some past, present and future experiments

	Experiment	Site	Target	
E	USC-PNL-Zaragoza	Homestake	Ge	
E	Neuchatel-Caltech-PSI	St. Gottard	Ge	
US	UCSB-UCB-LBL		Si, Ge	ion
E	HDMS (Heidelberg-Moscow)	Gran Sasso	Ge	
E	GENIUS (Heidelberg)		Ge	
E	TANDAR-USC-PNL-Zaragoza	Sierra Grande	Ge	
E	GEDEON (MOZA collaboration)	Canfranc	Ge	
E	UKDMC (IC-Sheffield-RAL)	Boulby	Na, I	
E	NAIAD (UKDMC)	Boulby	Na, I	
E	DAMA (Rome)	Gran Sasso	Na, I	
	ELEGANTS	Kamioka	Na, I	
E	SACLAY	Frejus	Na, I	scint
E/US	USC-PNL-Zaragoza	Canfranc	Na, I	
E	ANAIS (Zaragoza)	Canfranc	Na, I	
E	DAMA (Rome)	Gran Sasso	Ca, F	
	ELEGANTS VI (Osaka, Otho)	Oto-Cosmo	Ca, F	
E	CASPAR (Sheffield)	Boulby	Ca, F (C,H)	
E	DAMA (Rome)	Gran Sasso	Xe	
E	ZEPLIN I (UKDMC)	Boulby	Xe	
E/US	ZEPLIN II (UK-UCLA-Torino)	Boulby	Xe	
US/E	DRIFT (UK-UCSD-Oxy-Temple)	Boulby	Xe, Ar	gas
E	SIMPLE (Paris VII-Lisbon)	Paris	freon	sdd
E	Montreal Droplet Detector	Montreal	freon	
E	CRESST-I (MPI-TUM-Oxford)	Gran Sasso	sapphire	
E/US	CUORCINO(Italy-US collab)	Gran Sasso	TeO_2	bol
E/US	CUORE (Italy-US collab)	Gran Sasso	TeO_2	
E	ROSEBUD (IAS-IAP-Zaragoza)	Canfranc	sapphire	
US/E	PASS (UBC-Bayreuth)	UBC	In/Sn	
E	ORPHEUS(Bern)	Bern	Sn	ssg
E	SALOPARD(Lisbon-Paris-Zaragoza)	Canfranc	Sn	
US	CDMS-I (US collaboration)	Stanford	Ge, Si	
US	CDMS-II (US collaboration)	Soudan	Ge, Si	ion/
E	EDELWEISS-I (French collab)	Frejus	Ge	therm
E	EDELWEISS-I (French collab)	Frejus	Ge	
E	CRESST-II (MPI-TUM-Oxford)	Gran Sasso	$CaWO_4$	

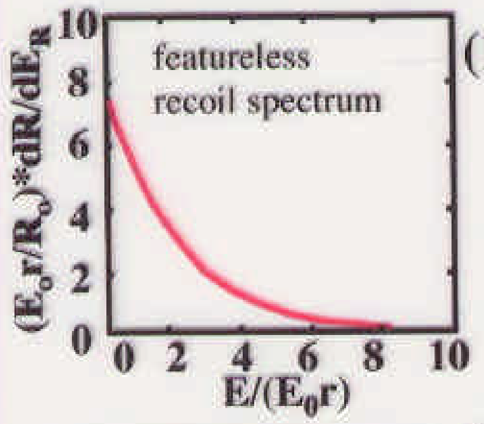
Towards an Ideal WIMP Detector

OBJECTIVE: obtain maximum information on all events

⇓

- **Unambiguous IDENTIFICATION of WIMPS** (control systematics..)
- **Maximum INFORMATION about WIMPS** (mass, velocity..)
- **Maximum ASTRONOMY with WIMPS** (halo, galactic structure..)

what information is available and how can it be used?

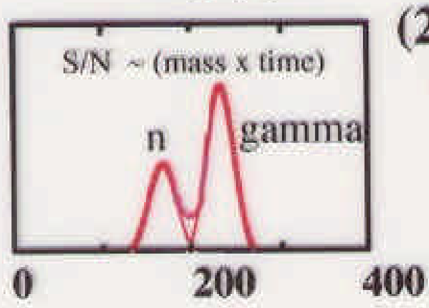


(1) measure recoil energy spectrum

simple counting experiments (Ge, CaF_2..)

⇓

limits only (no discrimination)
some A dependence



(2) add statistical electron discrimination

experiments with some discrimination (NaI, Xe)

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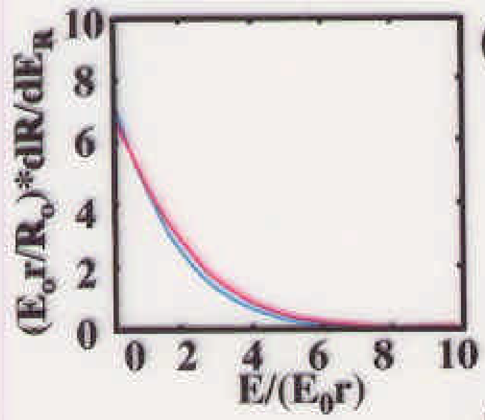
better limits, but sytematics? (no event x event)
to confirm detection still difficult



(3) add annual modulation

Discrimination + annual modulation (NaI, Xe..)

⇓

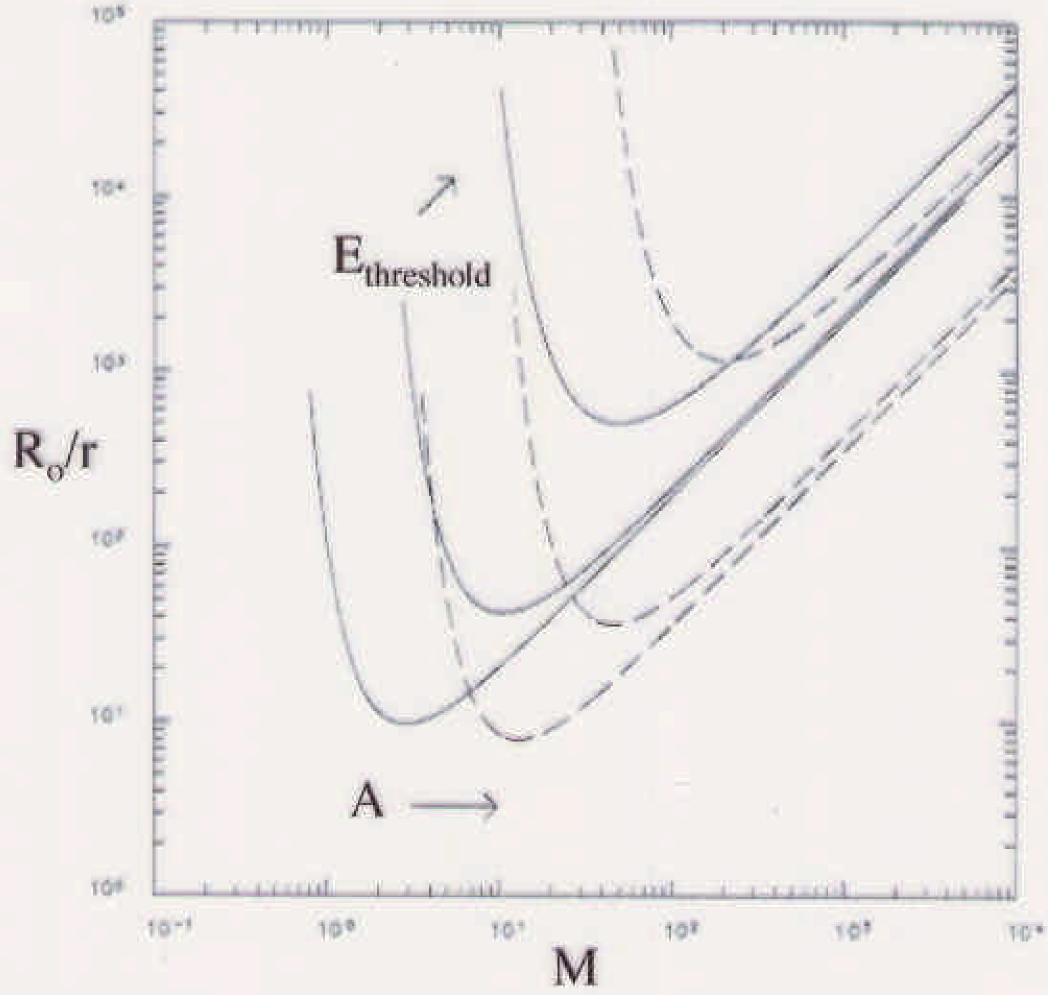
now link to astronomy to confirm PSD
but control of annual systematics difficult

(4) measure direction of recoils

new powerful discrimination closely linked to astronomy

• Limit curves

- shows effect of energy threshold and A
- CAUTION - is this a limit curve or a detector sensitivity curve?



• What determines a valid detector

- target (spin matrix, A)
- mass available
- intrinsic background
- discrimination
- threshold
- systematics

• **But strategy is now dominated by the need for active rejection of electron recoil background**

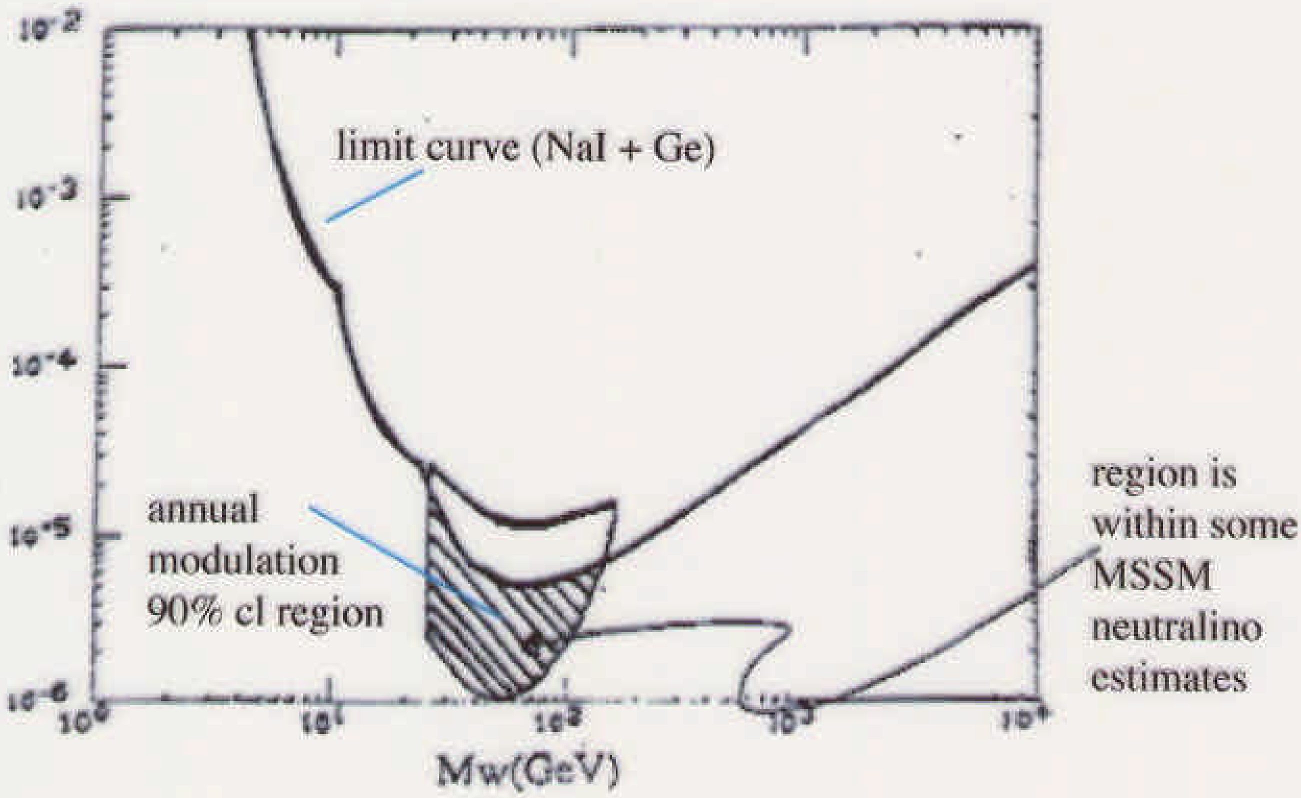
• DAMA - NaI(Tl), annual modulation

"intriguing" result from annual modulation (TAUP97)
spin independent WIMP case

Region allowed at 90% c.l.

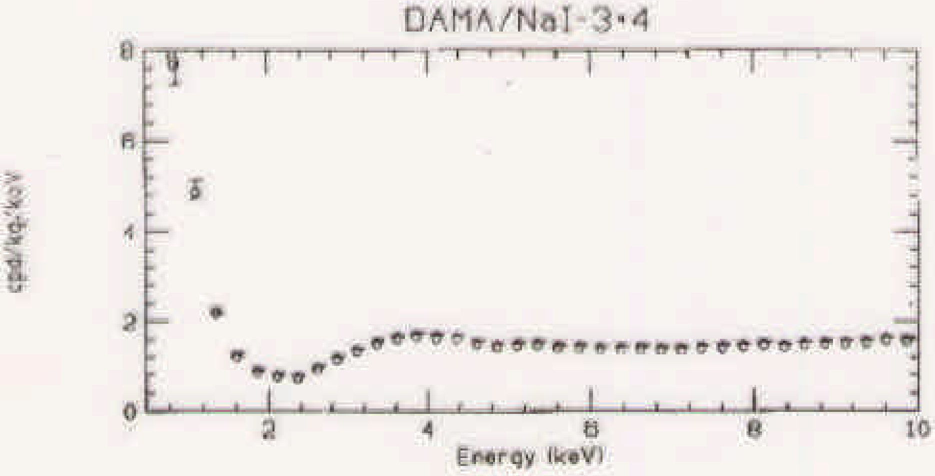
$$M_W = 59^{+36}_{-19}\ \text{GeV} \quad \text{and} \quad \xi\sigma_p = 1.0^{+0.1}_{-0.4}\ 10^{-5}\ \text{pb}$$

- 4549 kg.days (3363.8 kg.days winter - 1185.2 kg.days summer)
- part of 115 kg detector
- no PSD

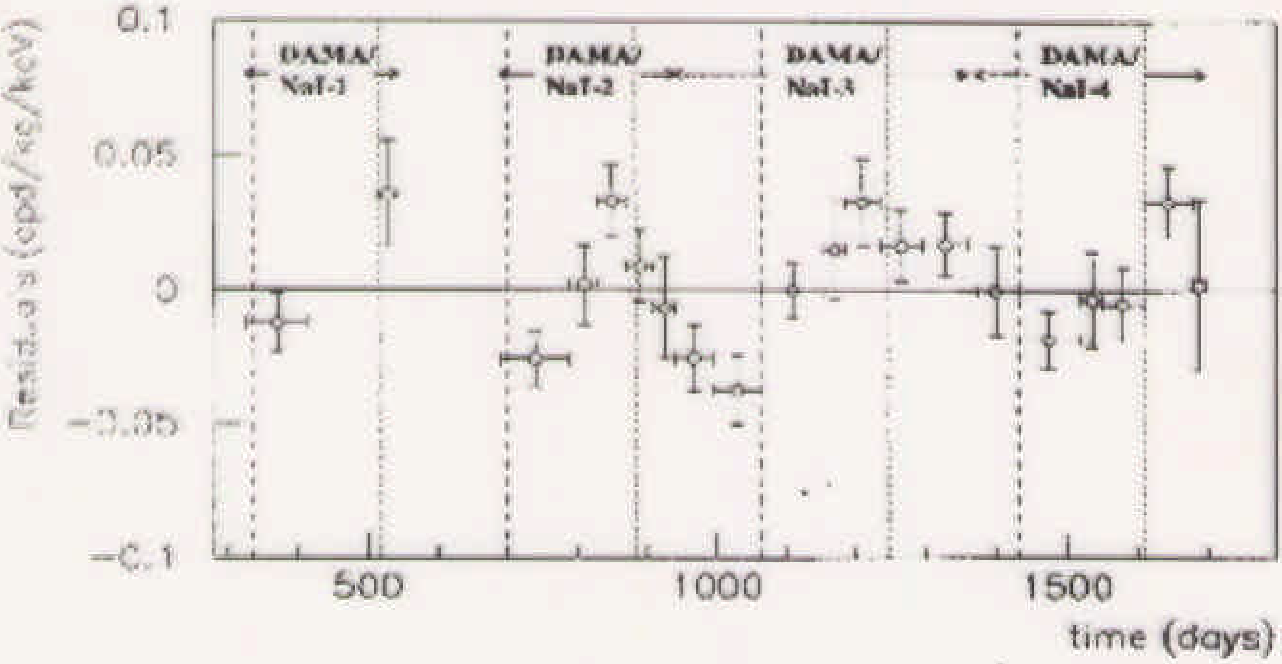


• DAMA - NaI3/4 modulation results
[Rome]

- NaI 3/4 -38475 kg.days
- total 4 years annual modulation data 57986 kg.days

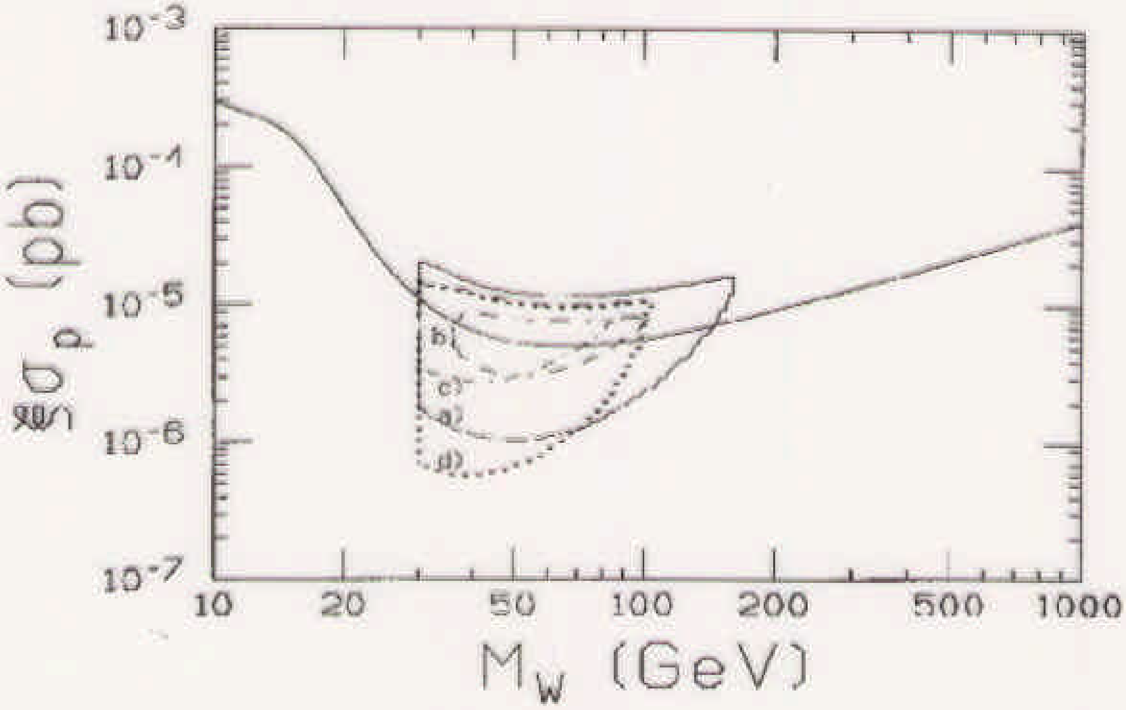


Residuals from 2-6 keV region



DAMA - modulation signals

90% CL regions for spin independent neutralinos for each year

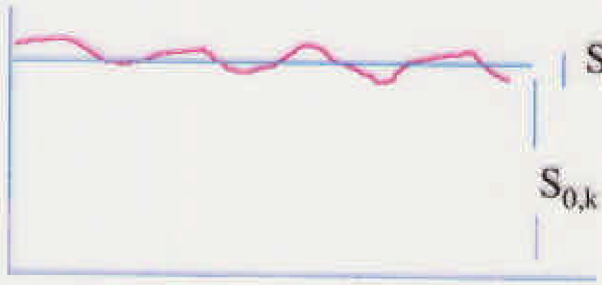


running period	statistics (kg d)	M_W (GeV)	$\xi\sigma_p$ (pb)	C.L. (m.l.r)
DAMA/NaI-1&2	19511	59^{+17}_{-14}	$(7.0^{+0.4}_{-1.2})10^{-6}$	99.6%
DAMA/NaI-3	22455 from middle August to end of September	56^{+18}_{-26}	$(9.7^{+0.3}_{-3.5})10^{-6}$	98.3%
DAMA/NaI-4	16020 middle October to second half of August	44^{+32}_{-14}	$(6.9^{+3.9}_{-3.8})10^{-6}$	92.8%

running period	statistics (kg d)	M_W (GeV)	$\xi\sigma_p$ (pb)	C.L. (m.l.r)
DAMA/NaI-1 to DAMA/NaI-4	57986	52^{+10}_{-8}	$(7.2^{+0.4}_{-0.9})10^{-6}$	4σ

DAMA - analysis

sketch



$S_{m,k} \cos\omega(t_i - t_o)$ modulated component

$S_{0,k}$ - unmodulated component

Table 1: The $S_{0,k}$ and $S_{m,k}$ values — in the region of maximum interest for the possible signal — as obtained by using the above quoted results of the maximum likelihood method, are shown. Above 6 keV negligible $S_{m,k}$ values are present.

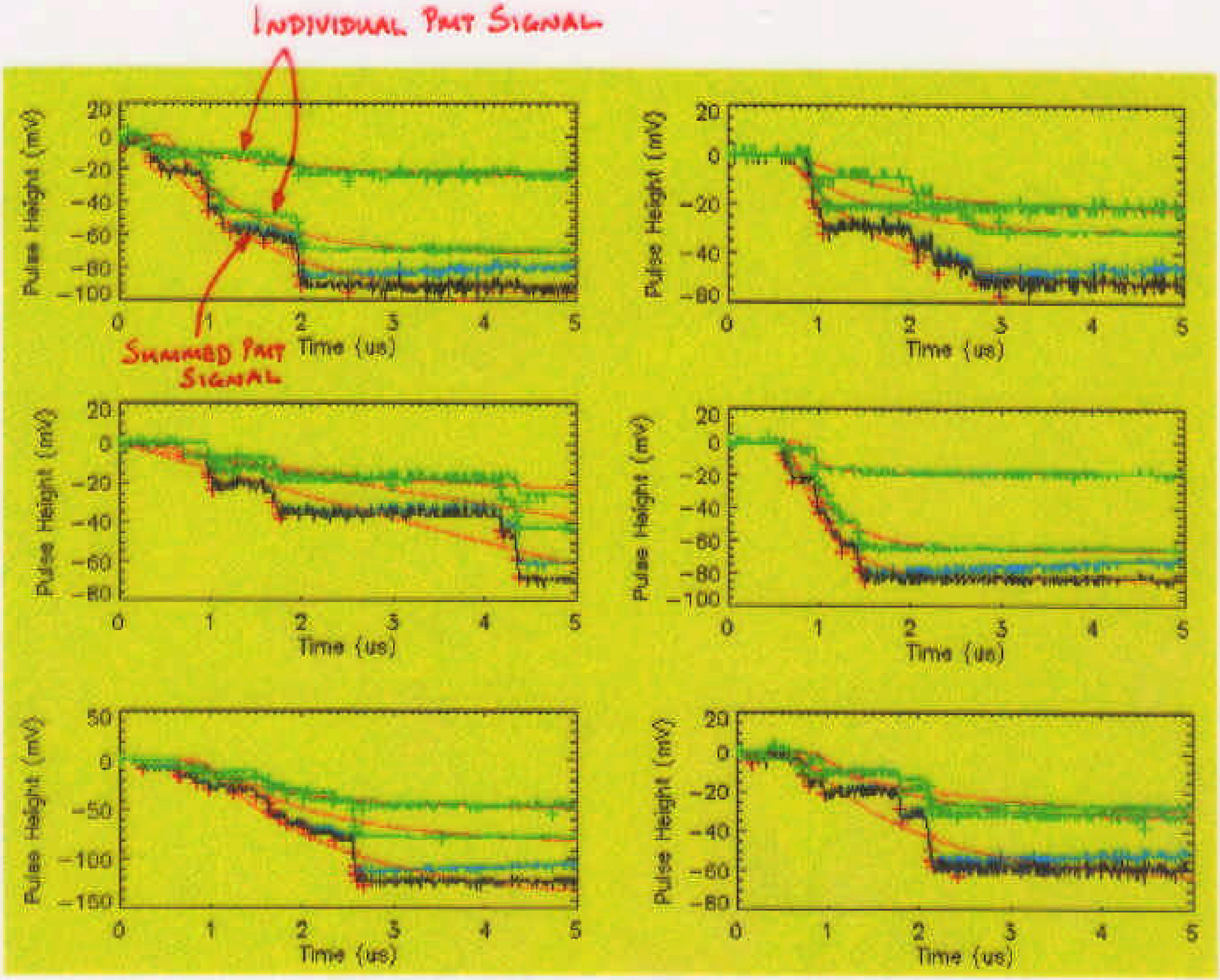
Energy (keV)	S_o (cpd/kg/keV)	$S_{m,k}$ (cpd/kg/keV)
2-3	0.54 ± 0.15	0.018 ± 0.009
3-4	0.23 ± 0.08	0.012 ± 0.004
4-5	0.09 ± 0.04	0.006 ± 0.002
5-6	0.04 ± 0.02	0.003 ± 0.001

INFN AE-98-20

- fit assumes neutralino mass and cross section.
- what is the influence of constraints on the mass?
- what other solutions are possible?

Various Noise Pulses

- Light Guide Only Data

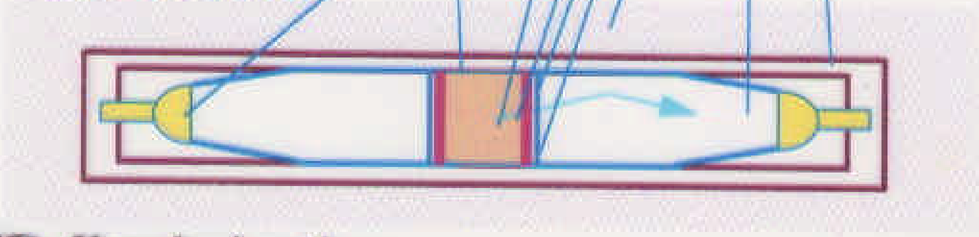


SCINTILLATION - NaI

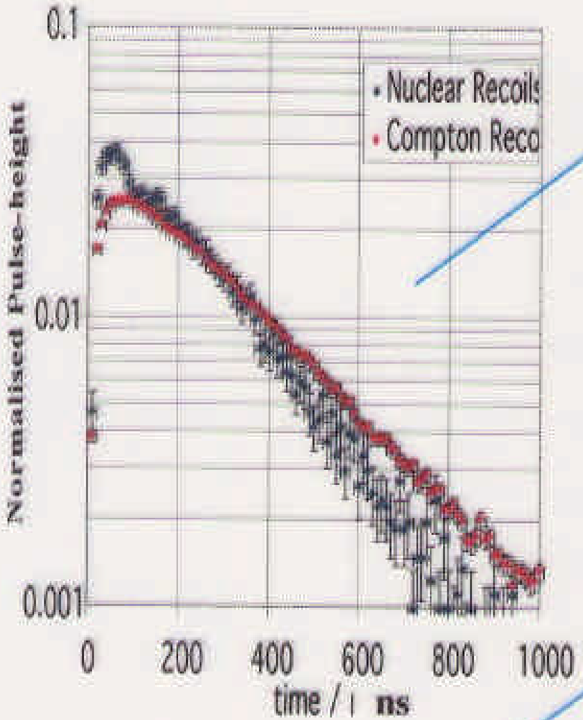
• UKDMC - NaI(Tl) with PSD, ~270K

Typical design

- low activity copper pmt shields and containers
- low activity silica light guides & PMT shield
- 3m low activity/high purity water shielding
- low activity selected optical grease/glue
- pre-selected quartz windows and glue
- double zone refined NaI(Tl) crystal
- pre-selected Merck NaI powder
- selected PTFE wrapping
- EMI9265A PMTs

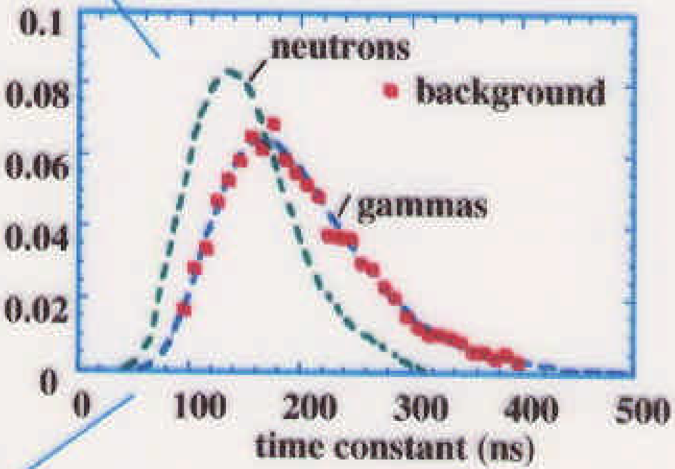


PSD discrimination



~15 keV events

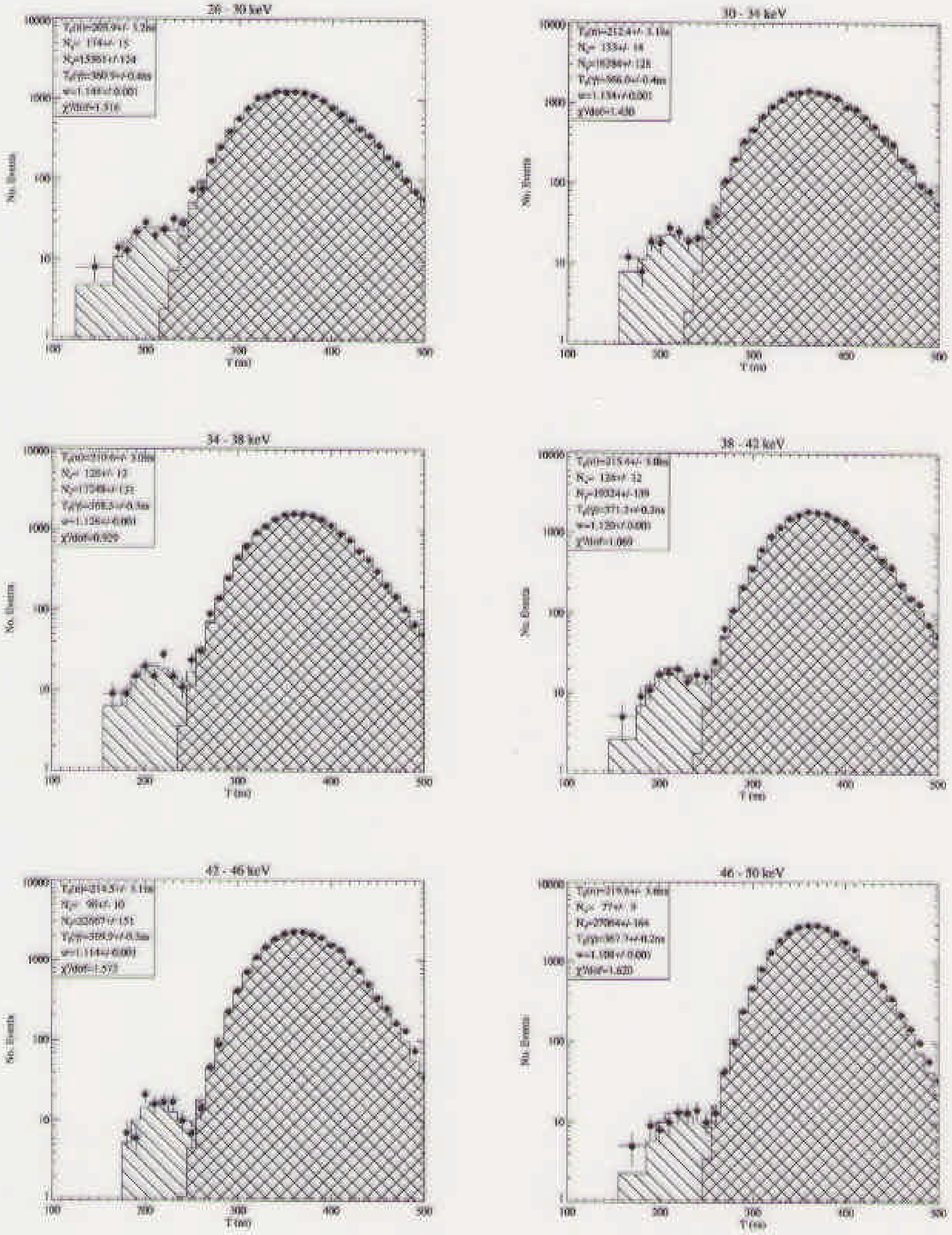
statistical discrimination



FIT: $$\frac{dN}{d\tau} = \frac{1}{(2\pi)^{1/2}} \frac{1}{\tau \ln w} e^{-\frac{(\ln \tau - \ln \tau_0)^2}{2(\ln w)^{-2}}}$$

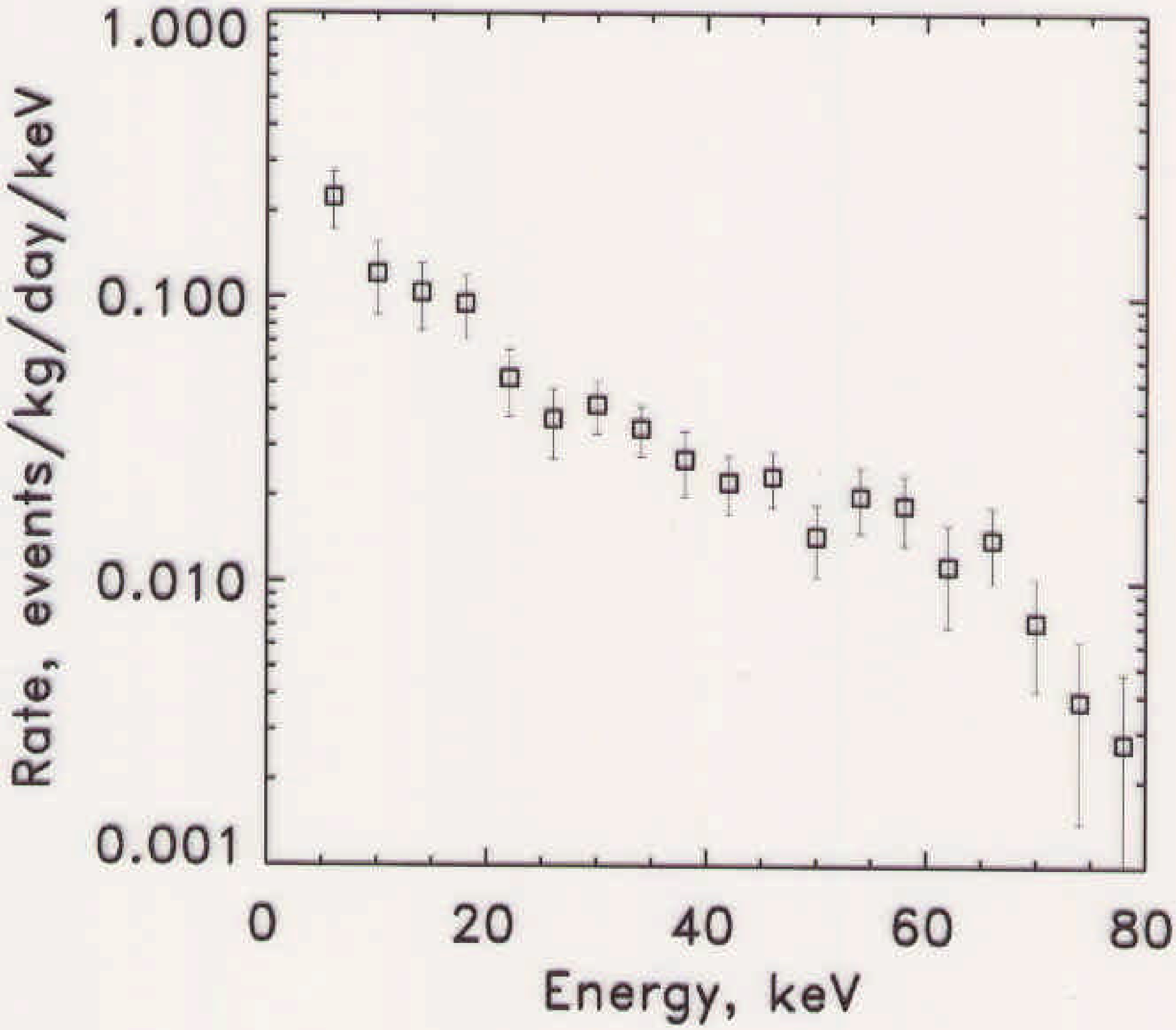
error in τ_0 : $$\Delta\tau_0 = \frac{\tau_0 \ln w}{\sqrt{N}}$$

example NaI DM 46 data bump fits



UKDMC - NaI detector DM46 "bump" spectrum

UKDMC publication: Phys Rep 307 (1998) 275-282

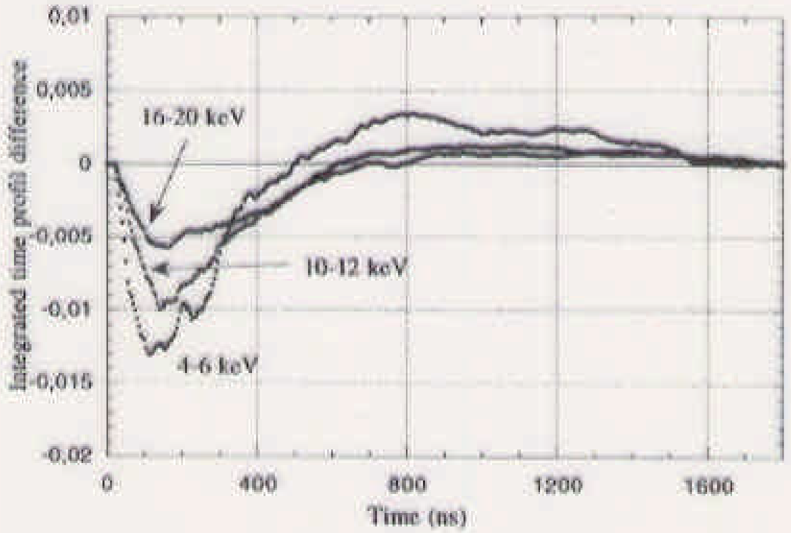


• Saclay - NaI(Tl) with PSD

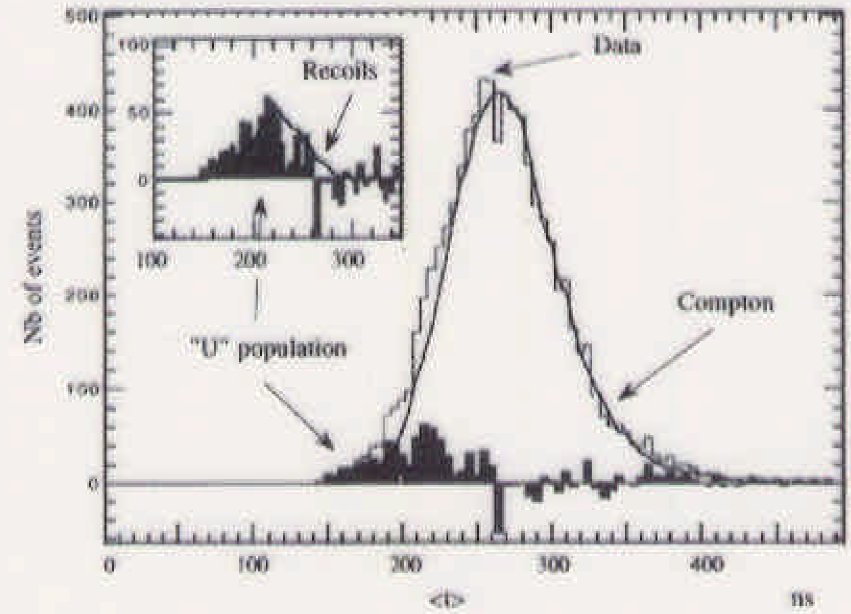
[Saclay/LPCC/IPN Lyon - Modane site]

- operating 2 x 9.7 kg ex-BPRS NaI crystals (same type as DAMA)
- 805 kg.d data, 2 ct $keV^{-1}kg^{-1}d^{-1}$@ 5 keV with PSD
- see population of fast rise time events not compatible with any mixture of Compton, recoils, x-rays or betas

integrated time profile difference analysis



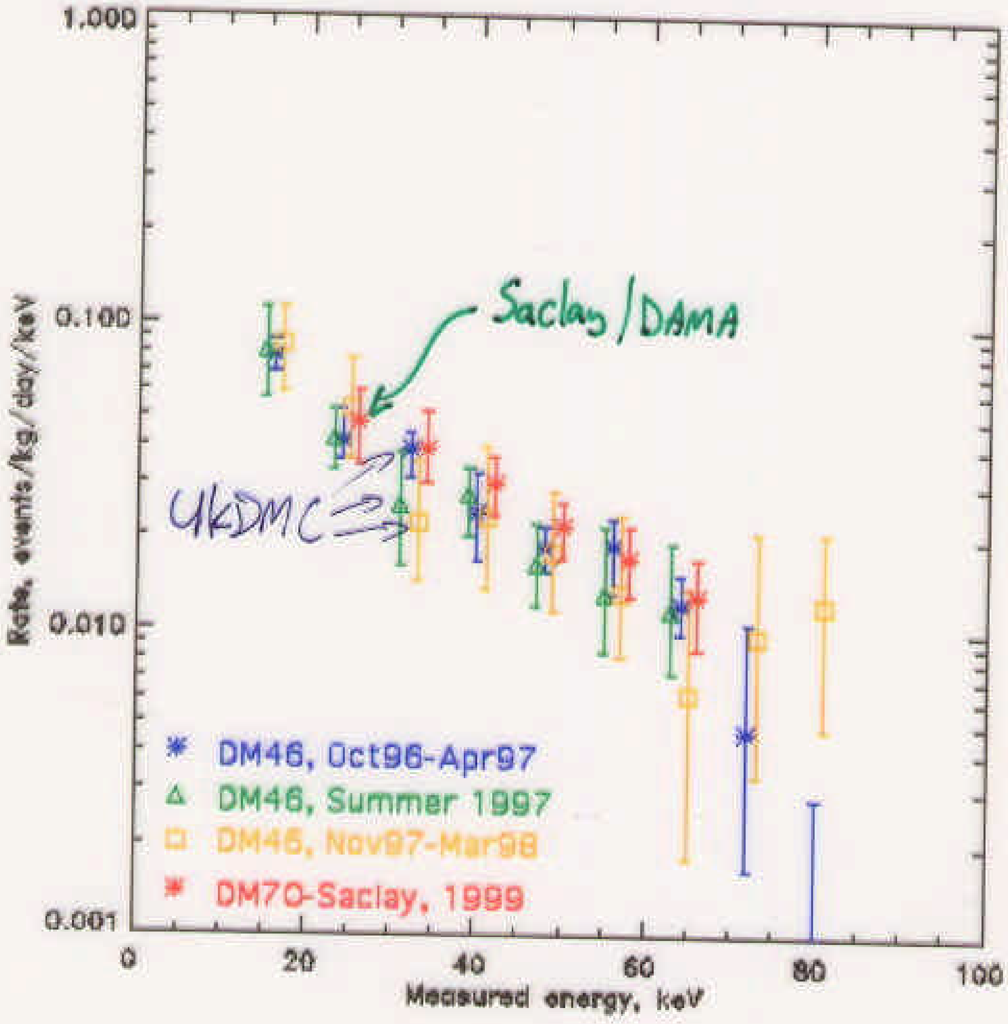
- TC Analysis **appears to confirm UKDMC "bump" results**



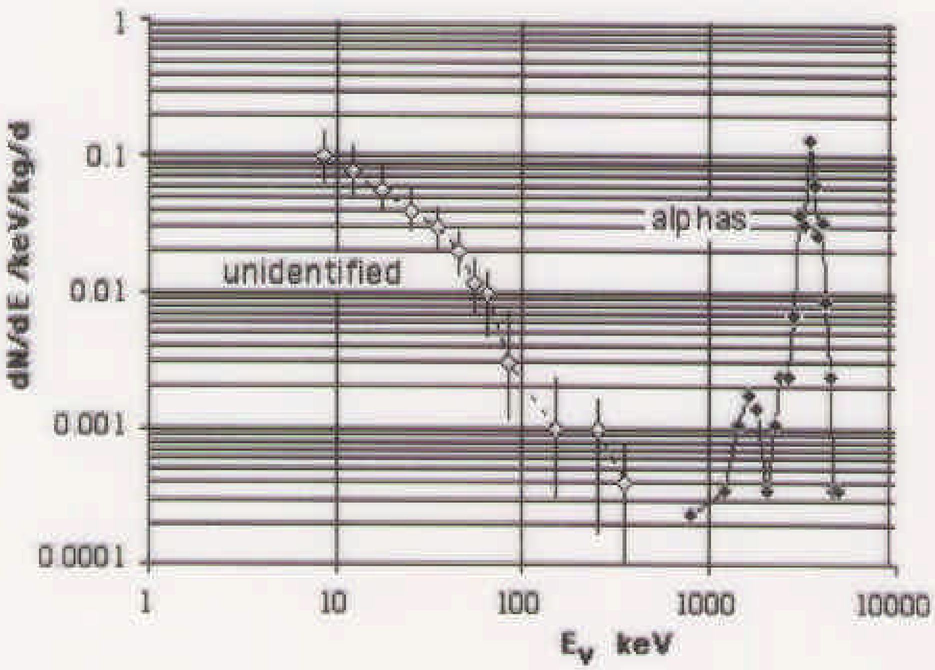
Spectra of 'bump-U' events

DM70 (Saclay) versus DM46

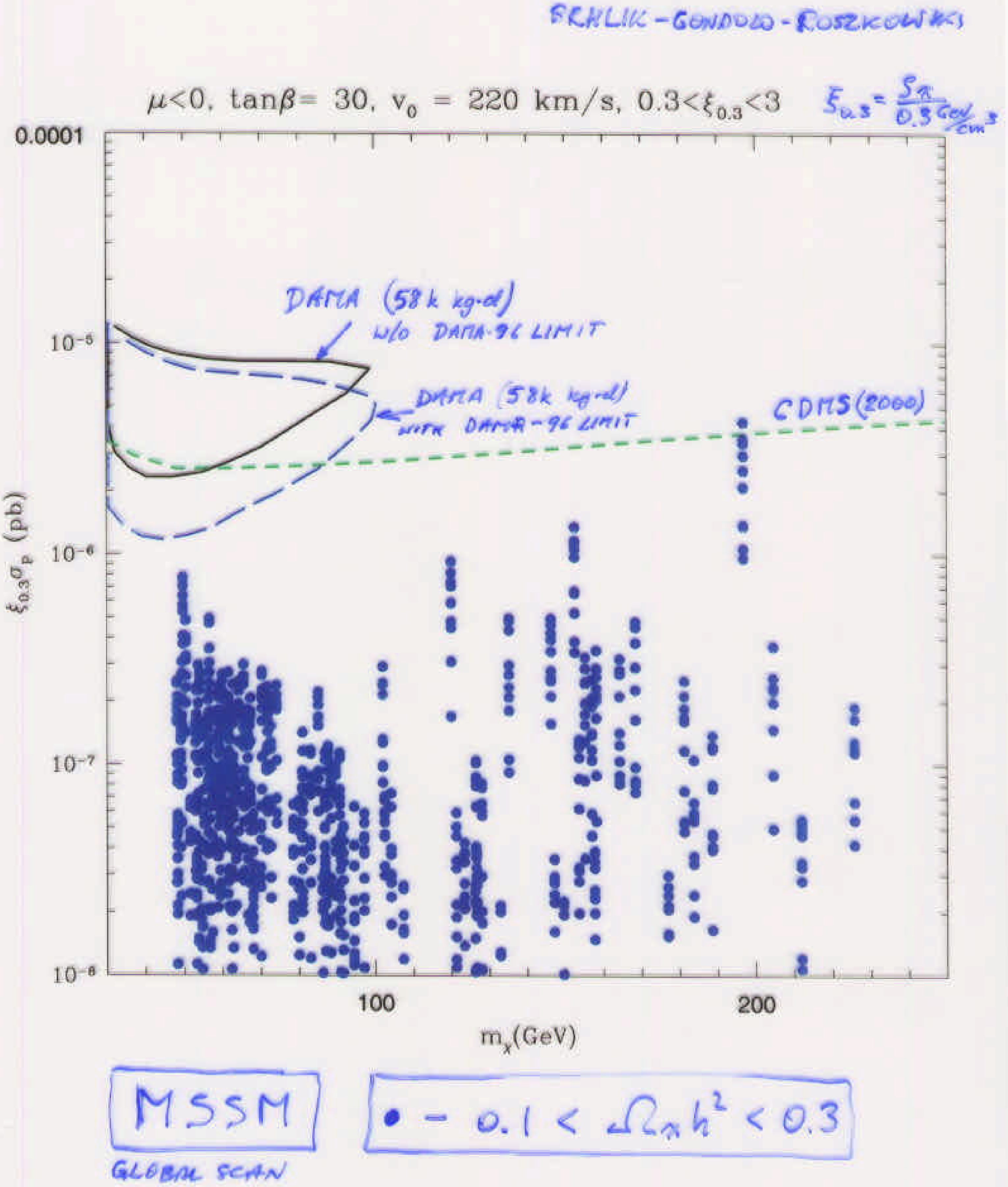
= DAMA



DM26 (NaI) spectrum: fast component (low energies) + alphas



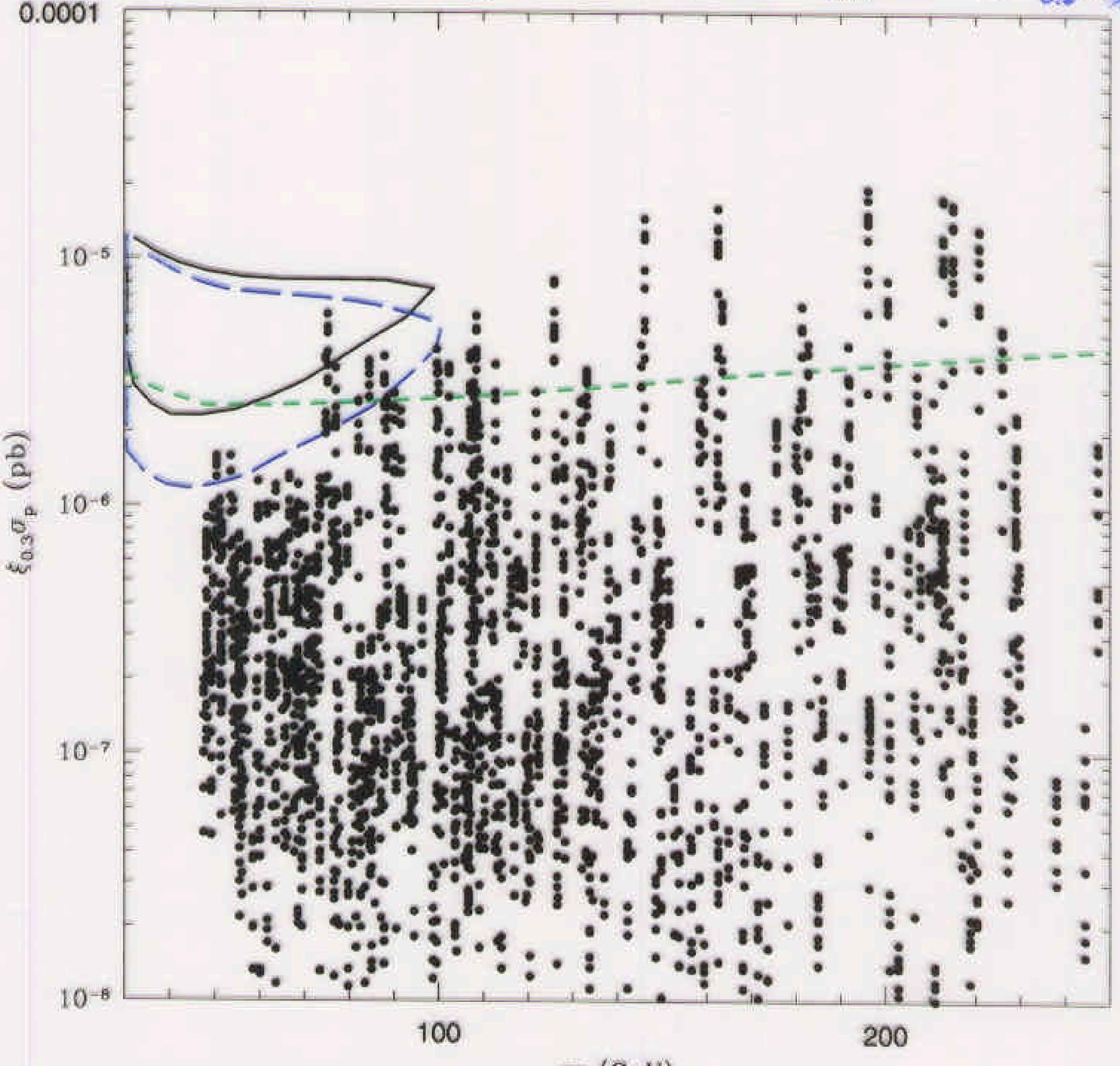
Spectrum of anomalous fast events in DM26 2kg crystal from data covering several energy spans. The MeV range peaks correspond to the expected alpha spectrum from U/Th
Graph from P. F. Smith et al. Phys. Rep., **307** (1998) 275



BRHLIK - GONDOLO - ROSZKOWSKI
μ<0, tanβ= 30, v₀ = 220 km/s, 0.3<ξ₀.₃<3
ξ₀.₃ = ρχ / 0.3 GeV/cm³
0.0001
10⁻⁵
10⁻⁶
10⁻⁷
10⁻⁸
ξ₀.₃σₚ (pb)
100
200
mχ(GeV)
DAMA (58k kg·d)
w/o DAMA-96 LIMIT
DAMA (58k kg·d)
WITH DAMA-96 LIMIT
CDMS (2000)
MSSM
GLOBAL SCAN
• - 0.1 < Ωχh² < 0.3

BRHLIK + GONDOLO + ROSZKOWSKI

$\mu<0$, $\tan\beta = 30$, $v_0 = 220$ km/s, $0.3<\xi_{0.3}<3$ $\xi_{0.3} = \frac{\rho_\chi}{0.3\ \mathrm{GeV/cm^3}}$



MSSM

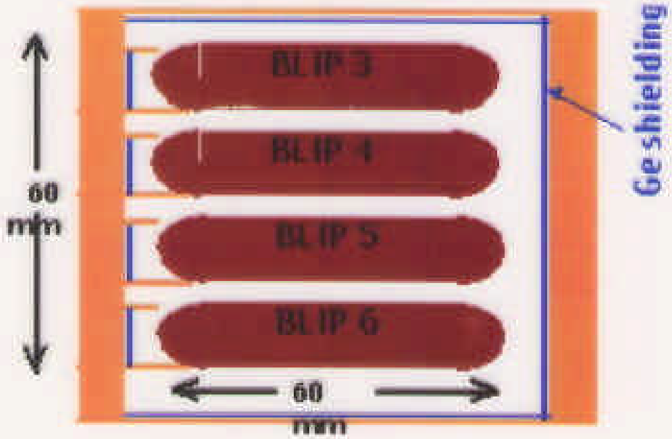
$0.025 < \Omega_\chi h^2 < 0.1$

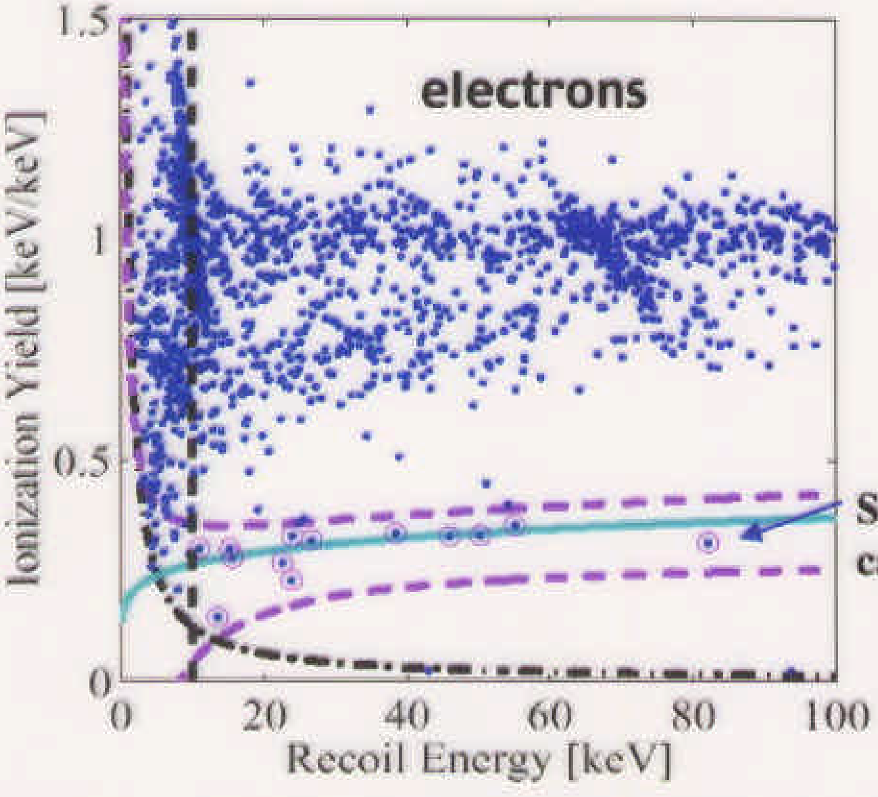
- **CDMS - low temperature**

  [CfPA et al - Stanford site]

Present experiment - Ge and Si ionisation +thermal

- **1998 - 1.6 kg.days Si ZIP (4 recoil events observed)**
- **1999 - 10.6 kg.days Ge BLIP (17 nuclear recoil events observed)**

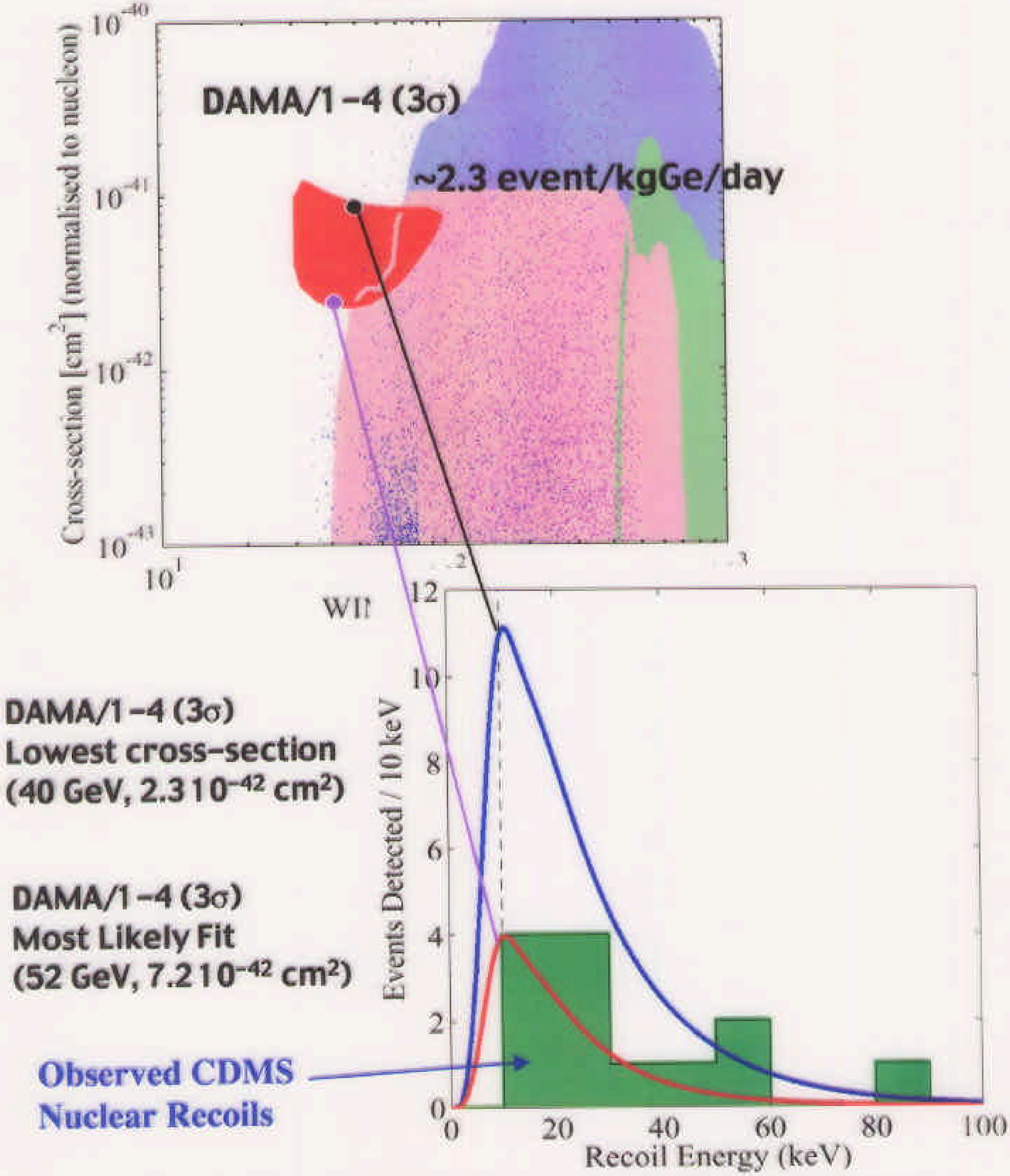




See a total of 13 recoil candidates events > 10 keV

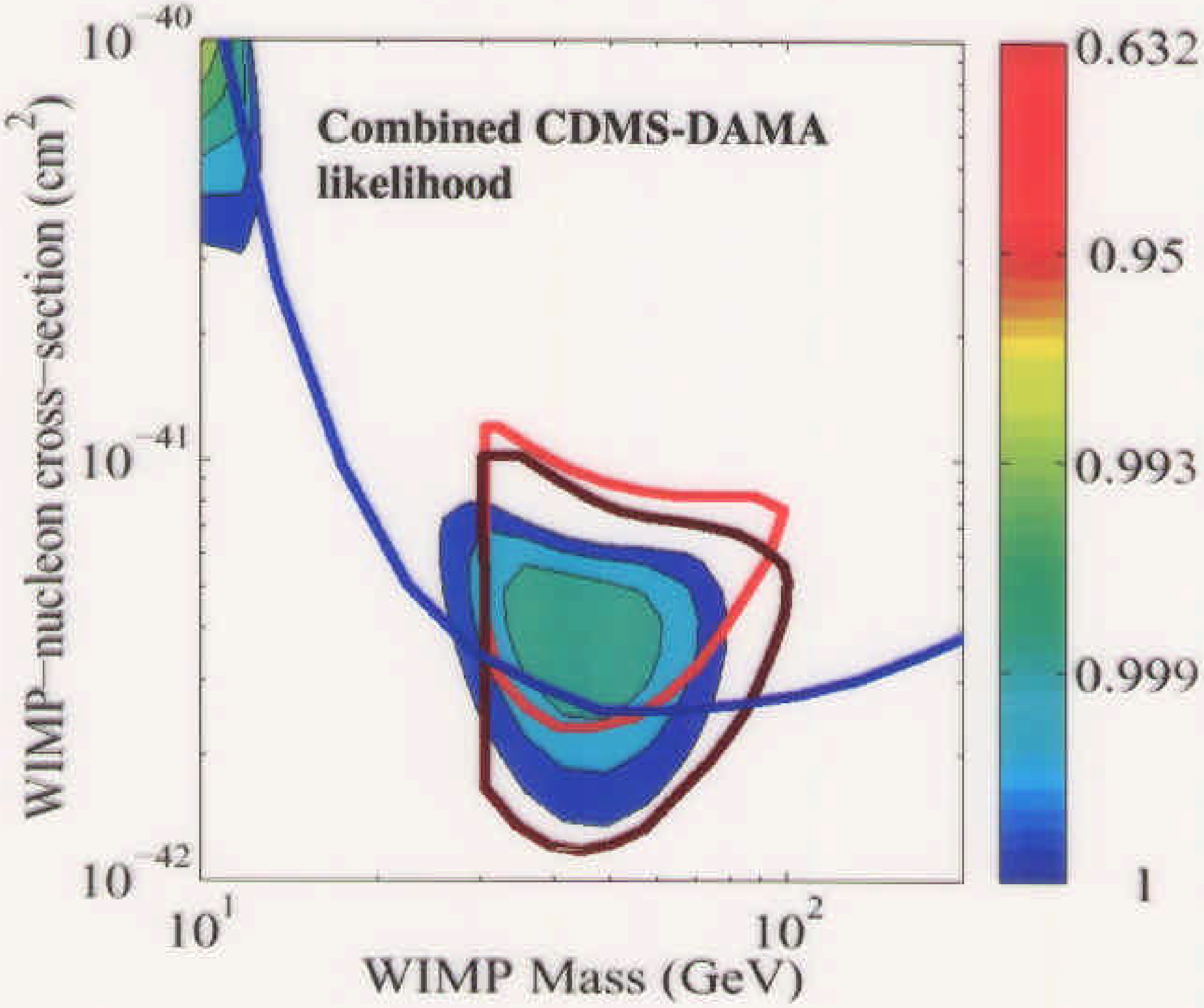
event rate is in region of DAMA signal

CDMS - expected WIMP spectra for DAMA allowed region



CDMS - limit

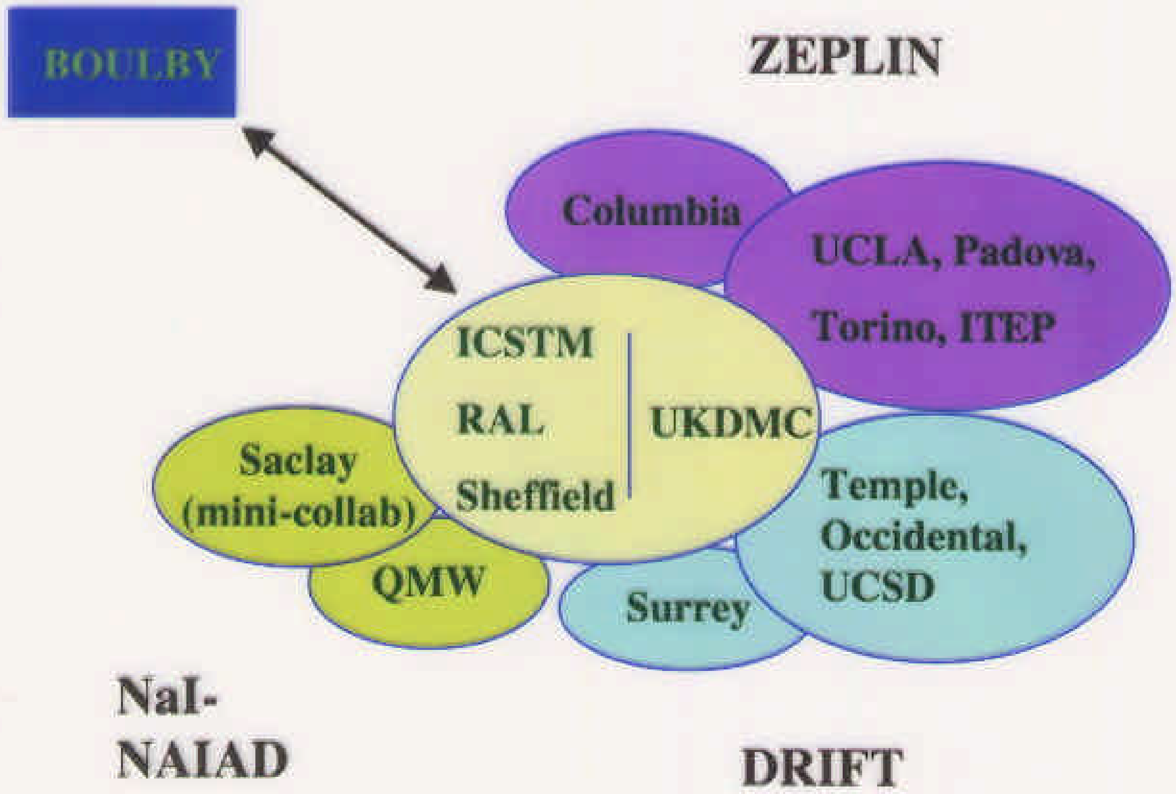
13 single NRs similar to that expected for DAMA
BUT
strong evidence that these events are caused by neutrons
--> 4 multiple scatter recoils observed in Ge in same data



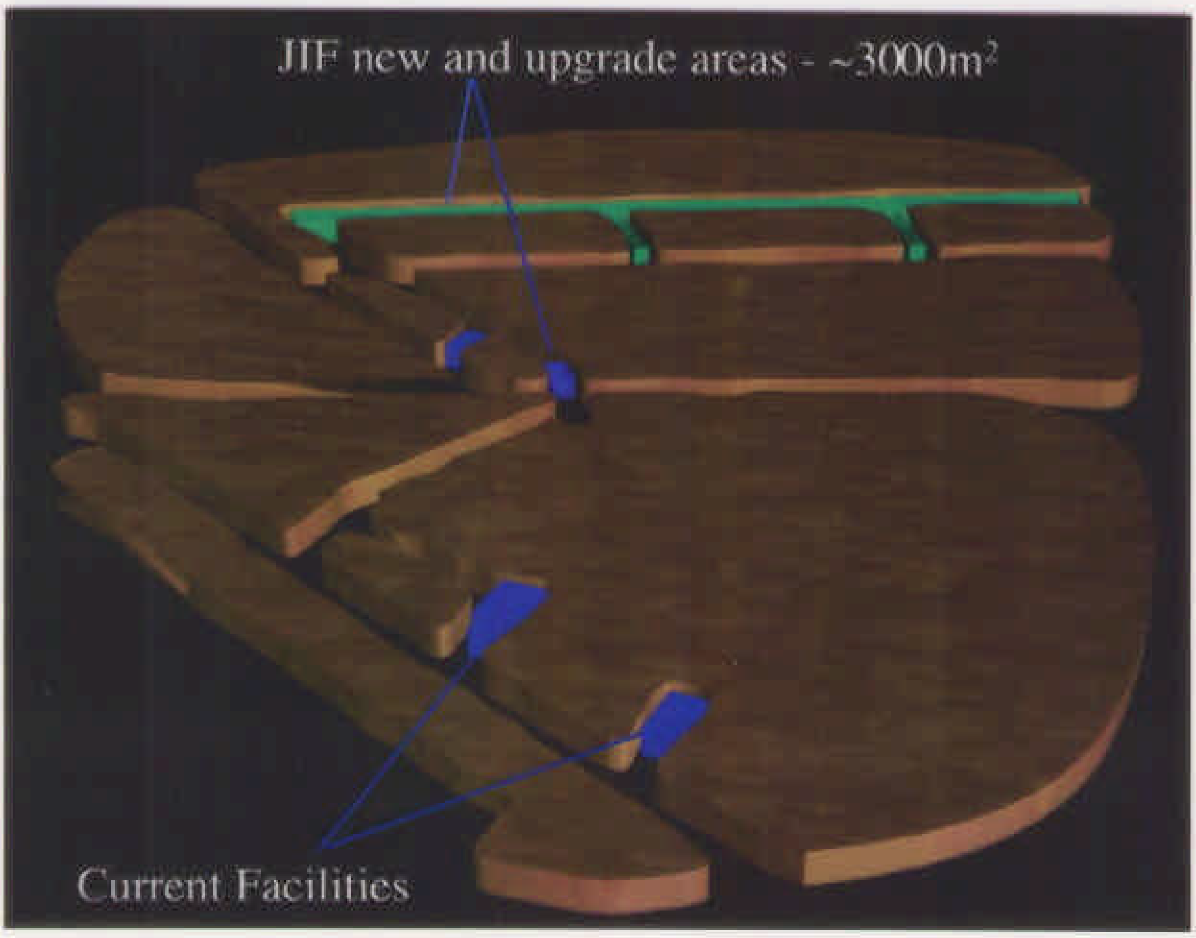
- Two experiments are incompatible at 99.76% CL

UkDMC

A Wider Collaboration

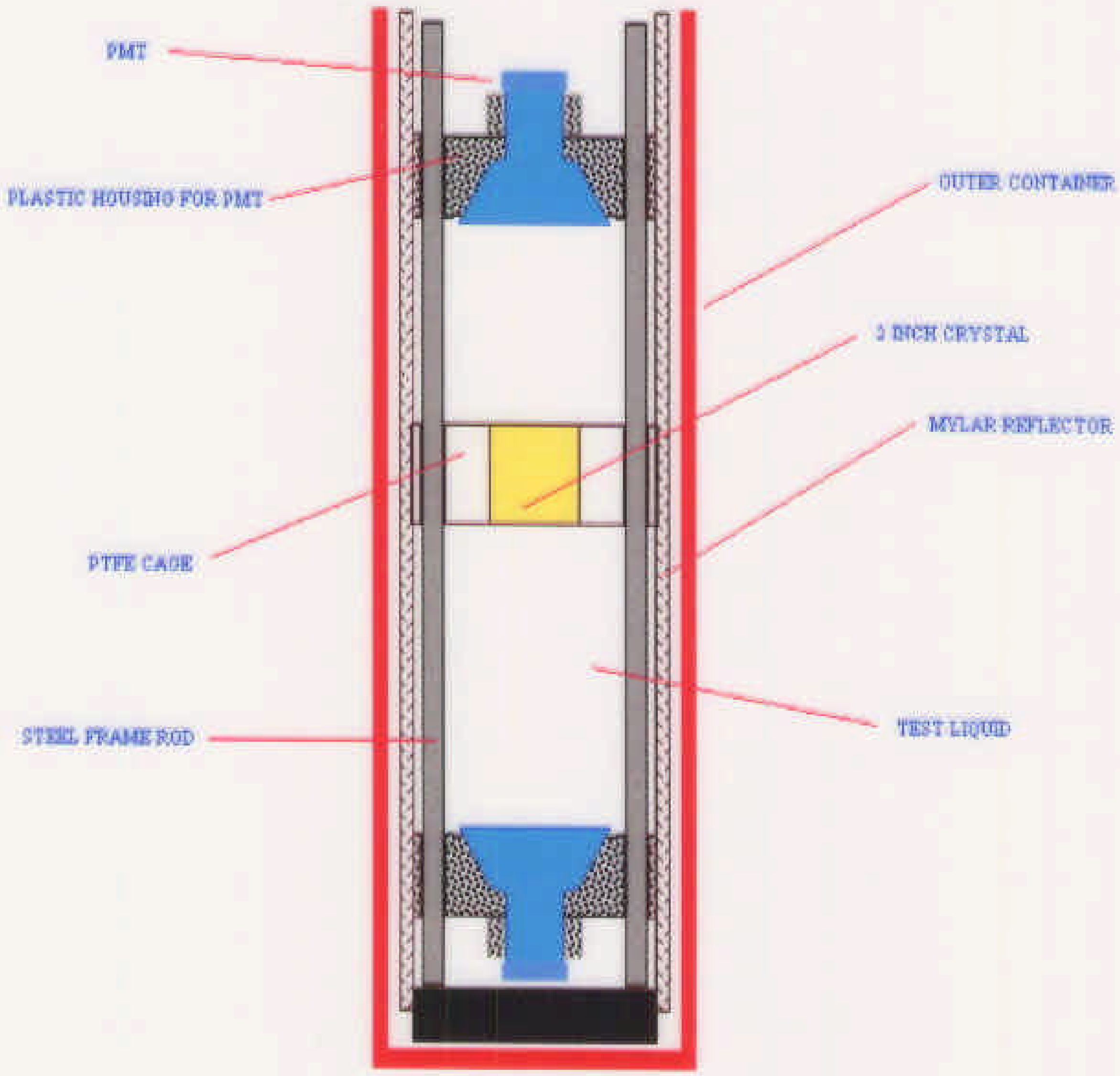


JIF
a new underground laboratory



- **Dust control**
- **Temperature control**
- **Laboratory facilities**

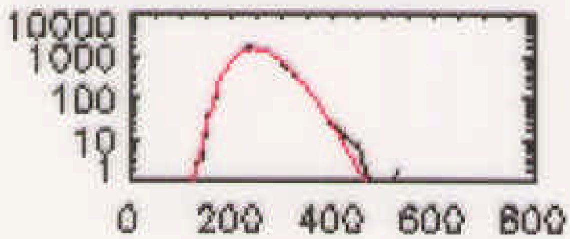
Design of an unencapsulated detector



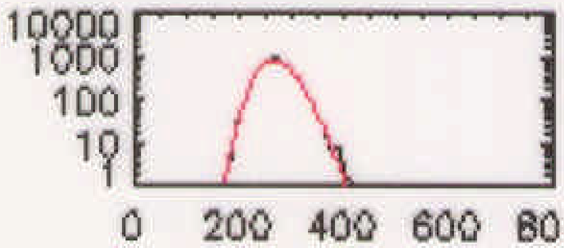
NAIAD-4 horizontal unit

NAIAD-1 preliminary data

initial 120 kg.days data

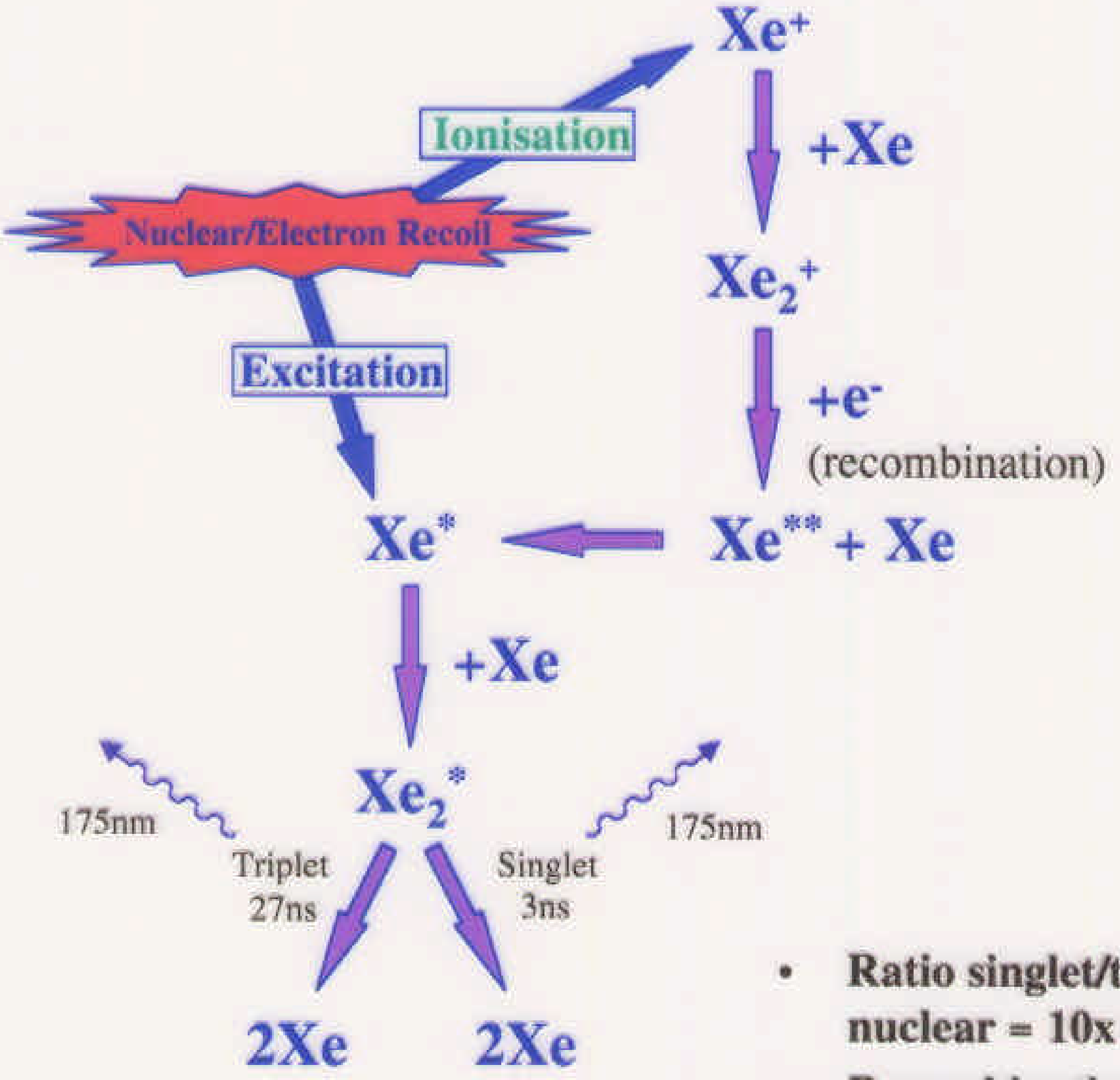


24-28 kev



56-60 kev

Liquid Xenon Scintillation Mechanism

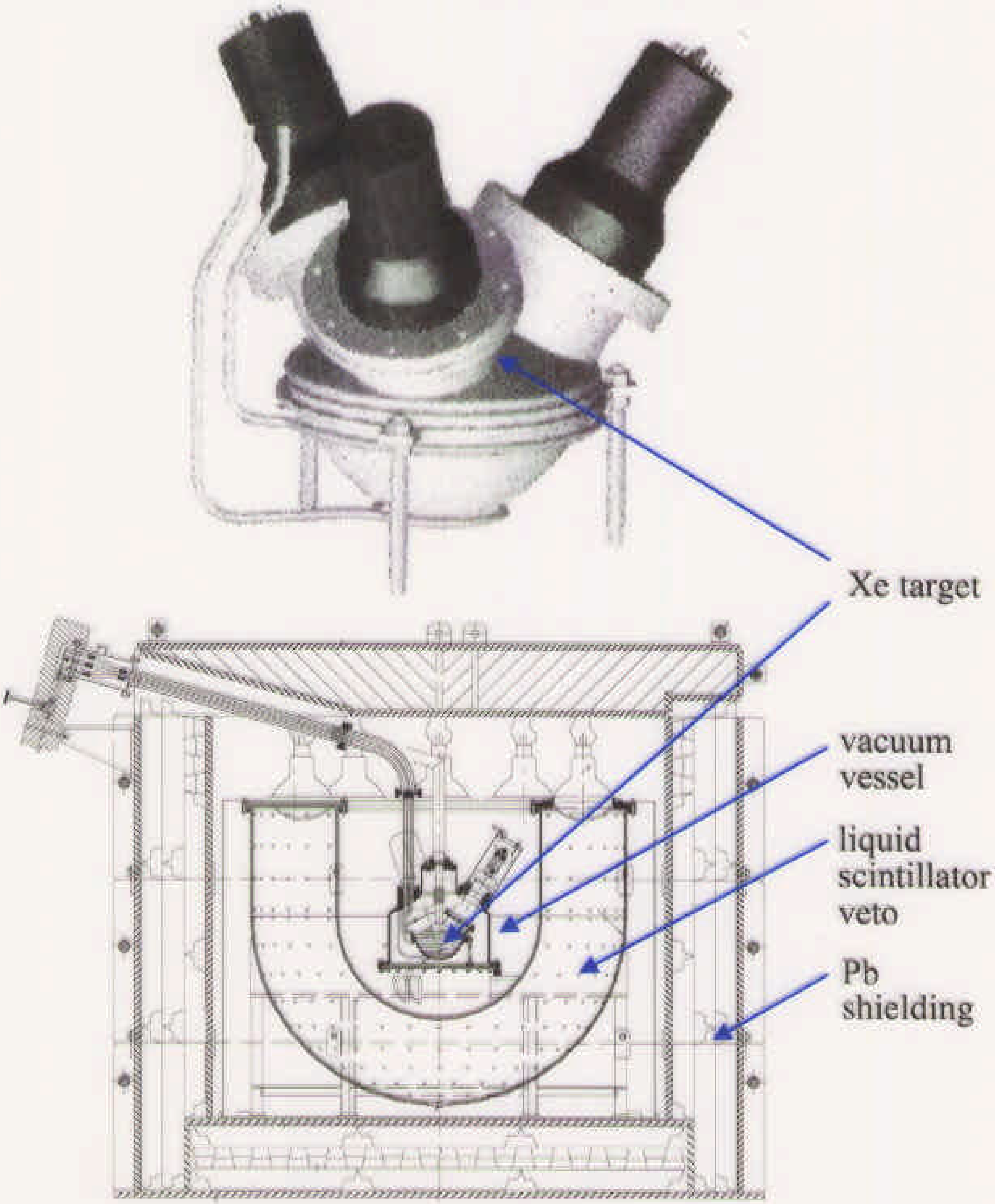


- **Ratio singlet/triplet nuclear = 10x electron**
- **Recombination time (~45ns) only for electron recoils**

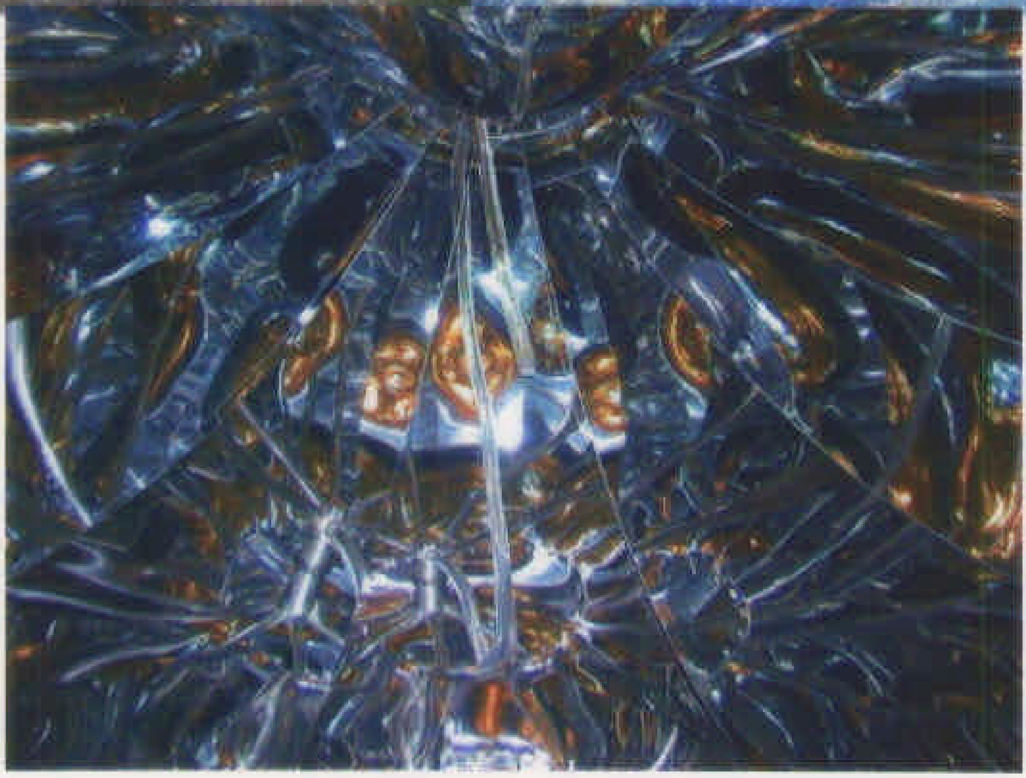
ZEPLIN I
No recombination

[UKDMC]

liquid Xe with PSD ready for installation at Boulby



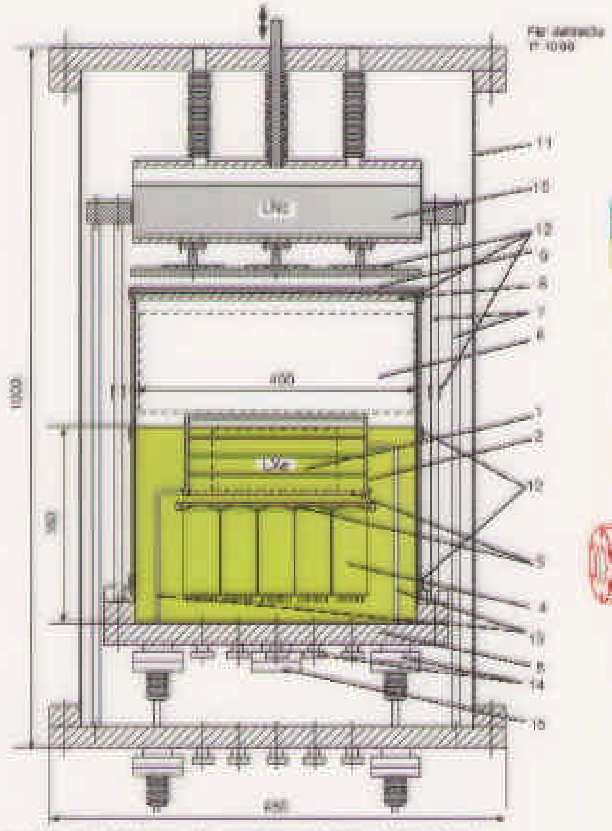
ZEPLIN I detector in veto and shielding

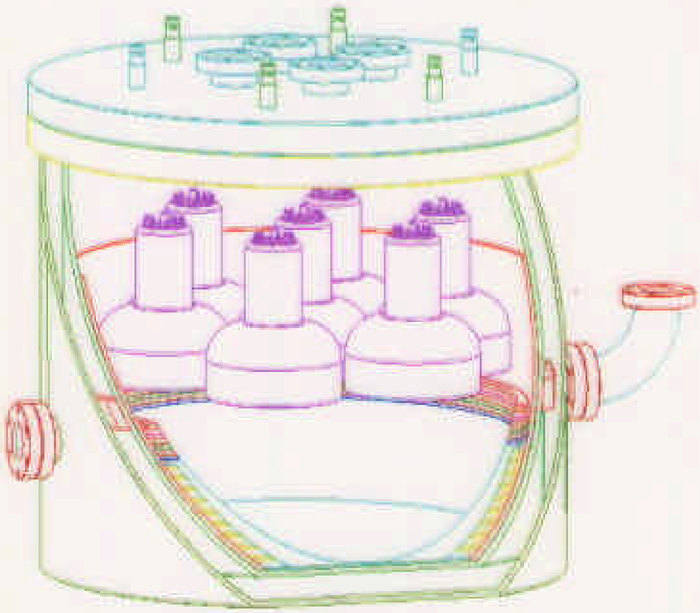


ZEPLIN II experiments

- UKDMC/UCLA/Padova/Torino/ITEP
- 10-40kg LXe targets
- Two phase discrimination

  - (i) Direct electroluminescence in high-E field
  - (ii) CsI plate to convert light->charge





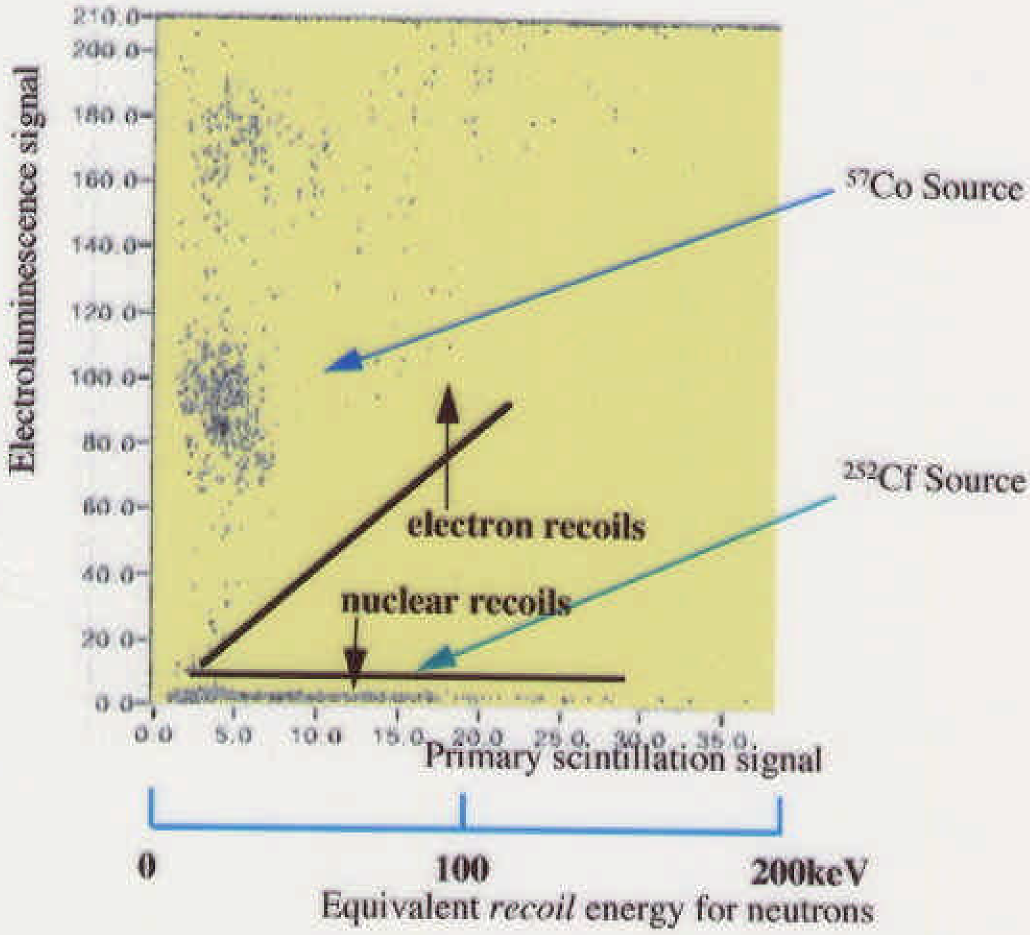
UKDMC
First stage
(5-10 kg)

UCLA/CERN
Second stage advanced
(higher mass, CsI)

ZEPLIN II - 2nd stage design

[UCLA, Torino, UKDMC and ITEP]

UCLA/CERN Test Results



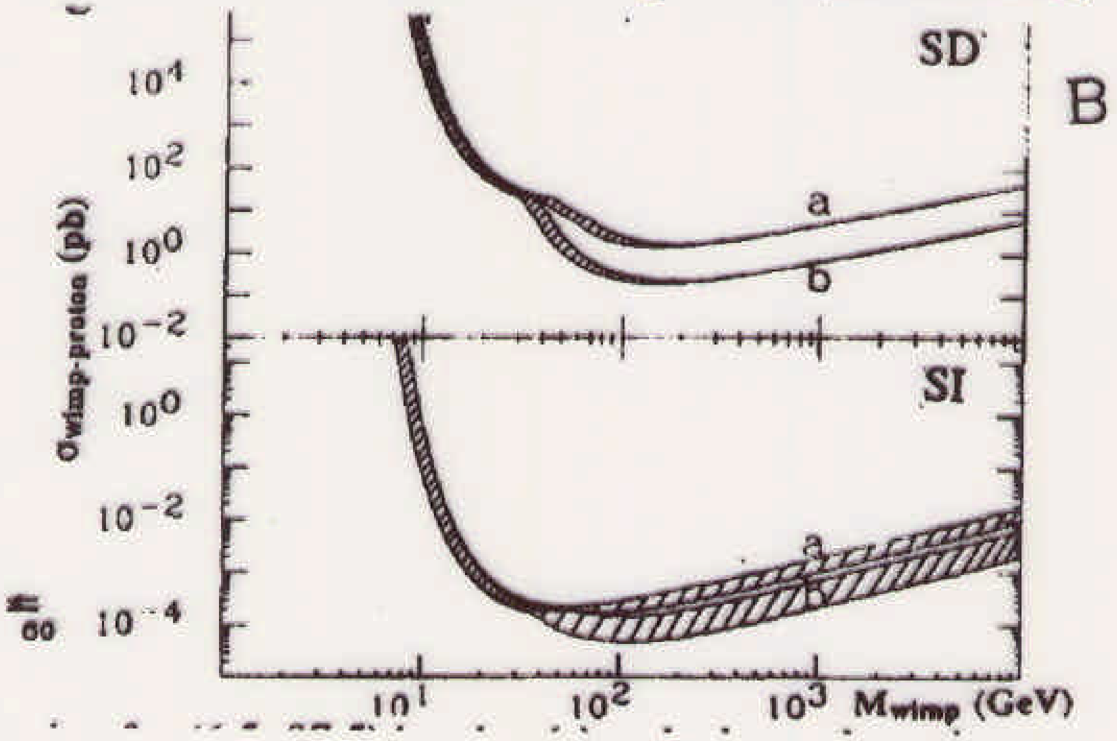
- **Discrimination possible below 10 keV**
- **Order of magnitude improvement over current NaI**

• DAMA Xe - Rome

- Xenon experiments, first go counting only (no discrimination)

Xe_{-0} 6.5 kg x 97.5 days

- with/without attempted background subtraction
- assumed q.f. 0.6-0.8 (Susuki et al. gives 0.2 (2nd RESCEU)



Xe_{-1} 823 kg.days

- ^{129}Xe inelastic search (39.58 keV and 236.14 keV lines) (but depends on q.f.)
- planned annual modulation and pulse shape analysis

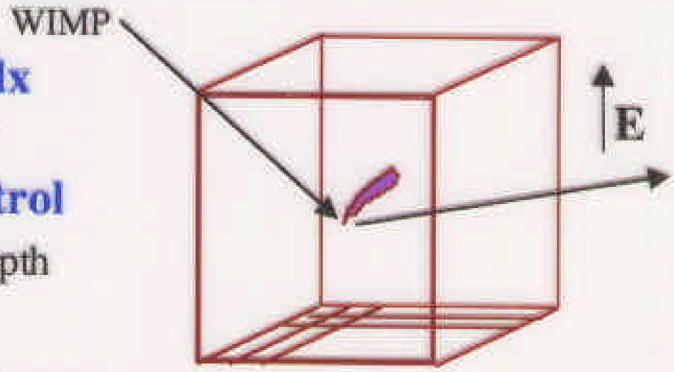
DRIFT

Directional detector with Xe, Ar gas

[UKDMC, Temple, Occidental, Surrey, RAL]

ultimate in event identification (background rejection)

- **4 π reconstruction**
- **track orientation and dE/dx**
- **observe true recoil energy**
- **complete background control**



(1) neutrons --> H shielding and depth

(2) Compton e^- --> low dE/dx

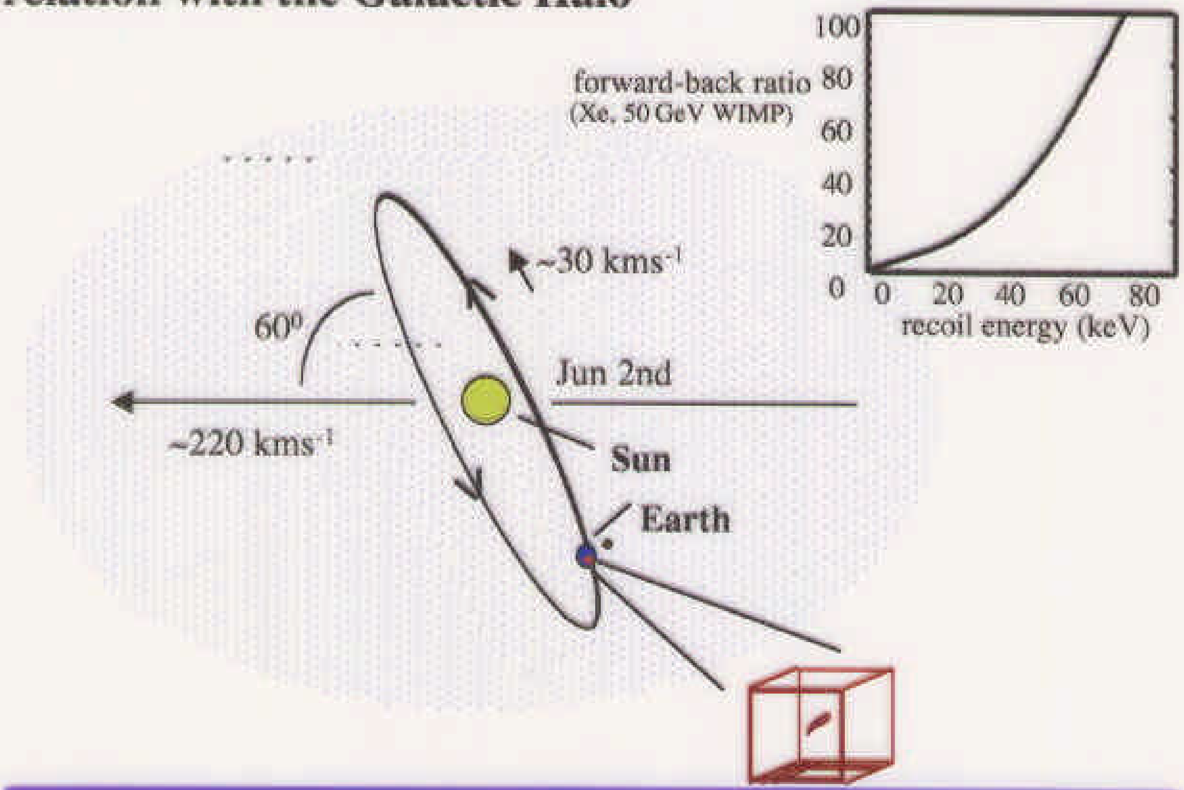
(3) vessel beta e^- --> low dE/dx, fiducial cut

(4) vessel/radon alphas --> high E, fiducial cut

(5) readout alphas --> low activity materials
(e.g. MC results for 0.1 ppb U,Th --> ~1 event/year/10^3m)

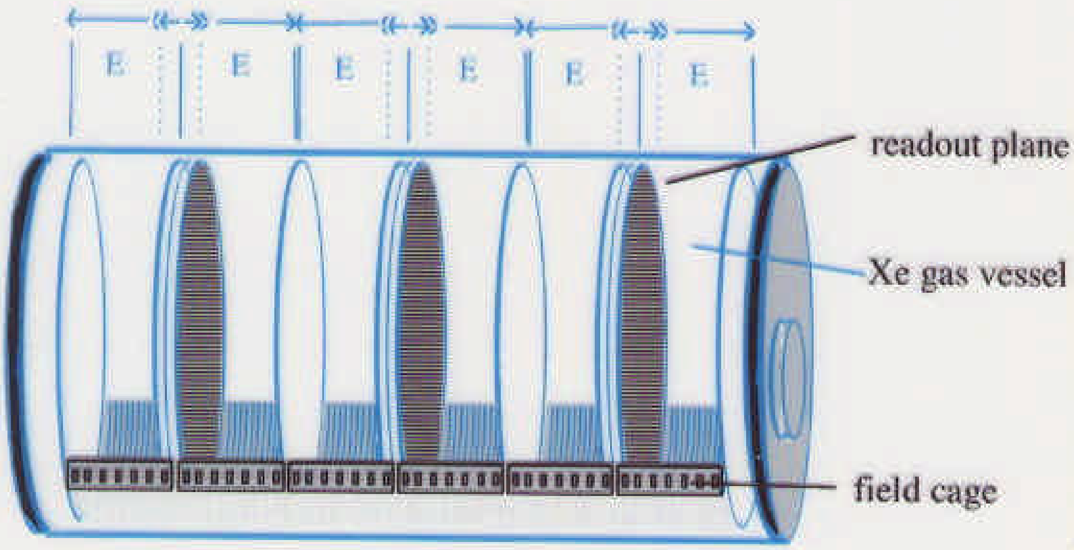
- **potential sensitivity proportional to T (not $T^{1/2}$)**

correlation with the Galactic Halo



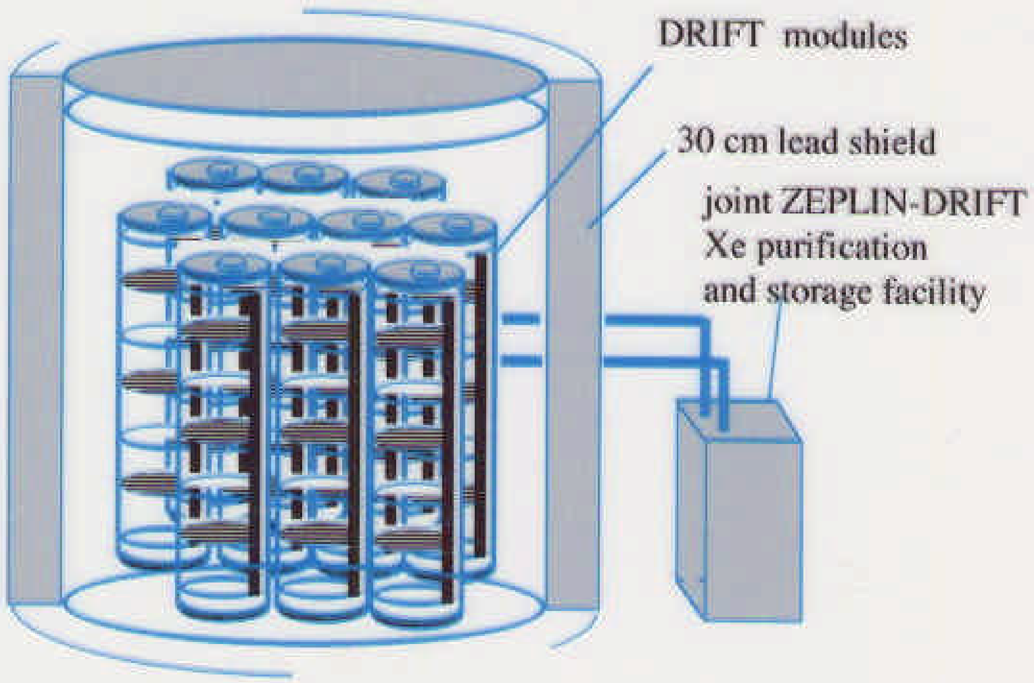
DRIFT programme

- **DRIFT module under construction (OxyLA-Temple-UKDMC)**



OBJECTIVE: $10 m^3$ with competitive sensitivity below 1 $kg^{-1}d^{-1}$

- **DRIFT scale up by simple multiplication of drift volumes**

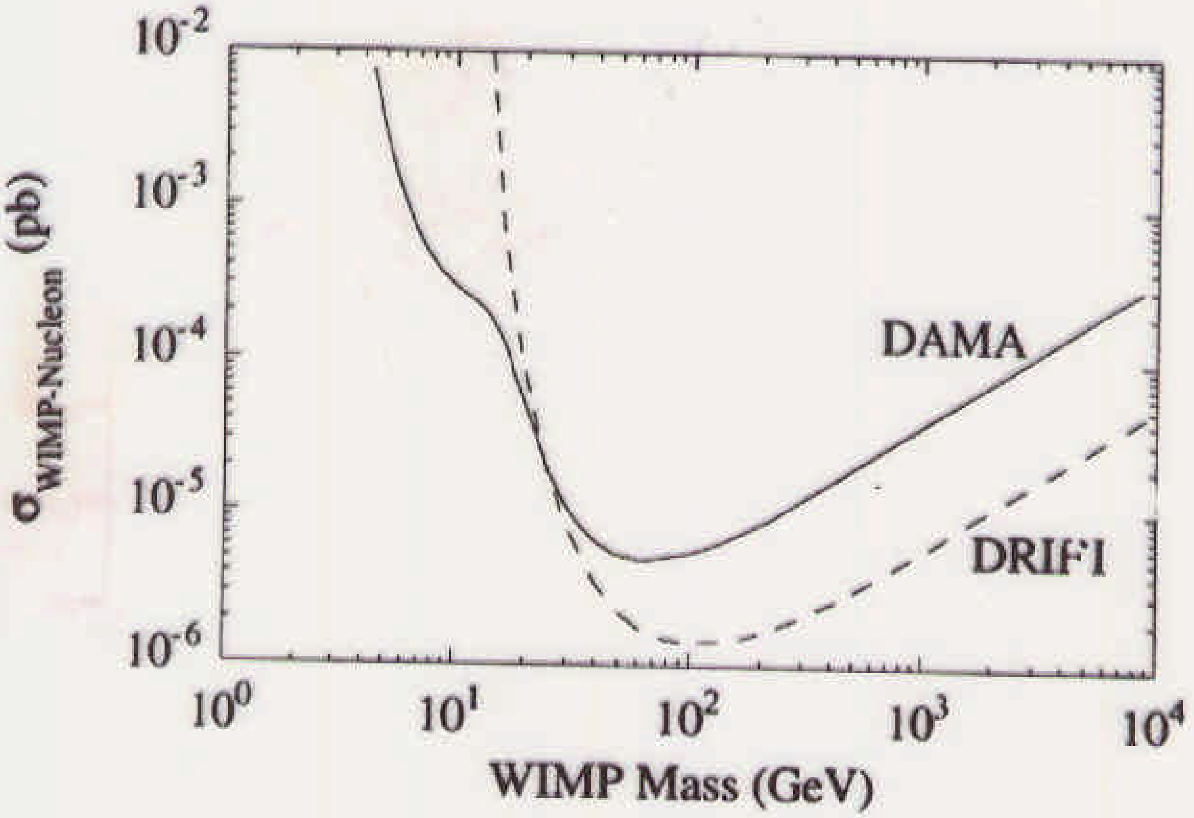


OBJECTIVE: $100 m^3$ scale up with upgraded 3d readout, sensitivity at 0.01 $kg^{-1}d^{-1}$ (coherent)

Stage 1 DRIFT sensitivity

Stage 1 prototype

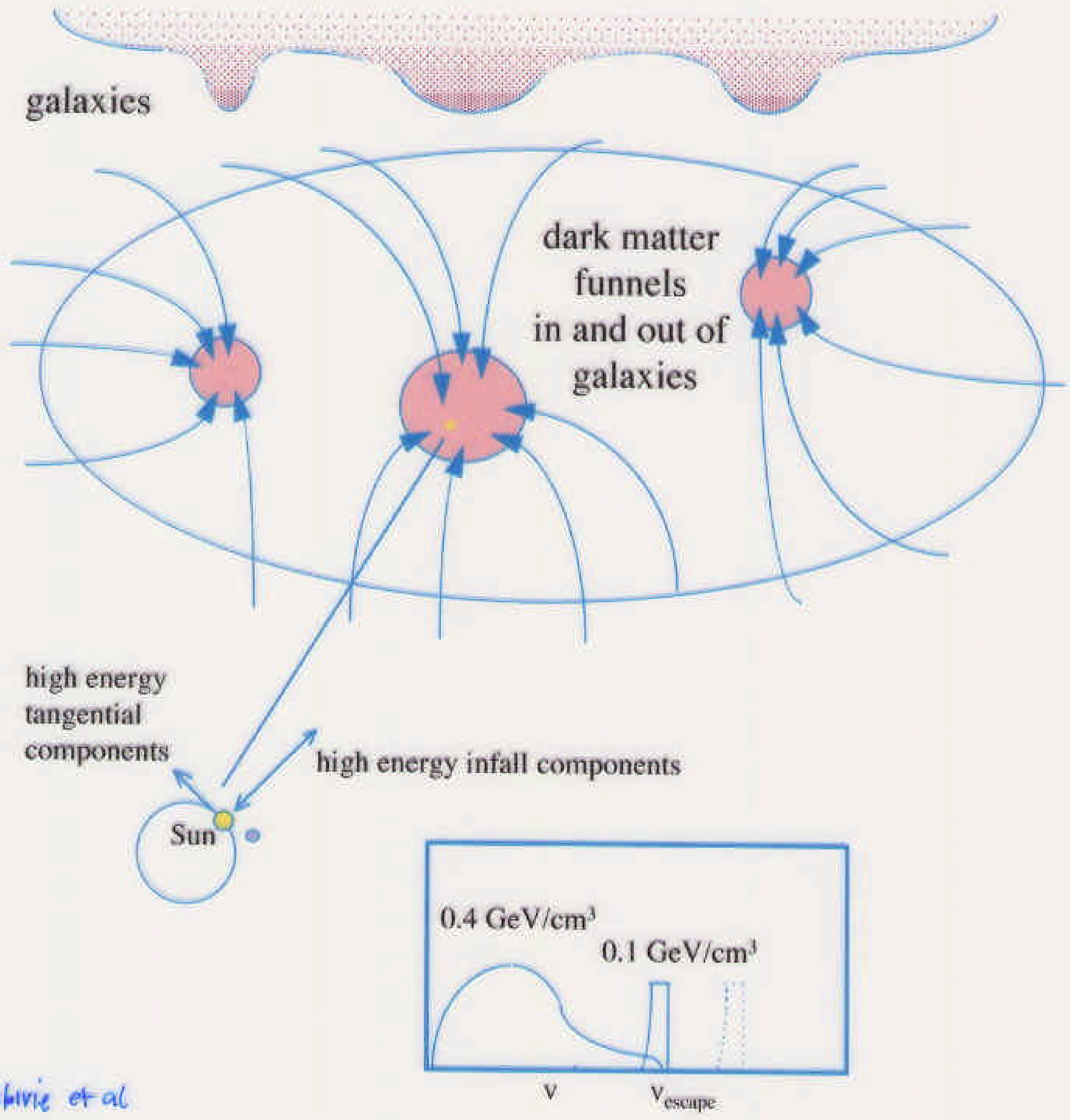
- 1 year 1 m^3, 40 Torr Ar (Xe) 36 kg.d
- improves as $(Mt)^1$
- direction sensitive



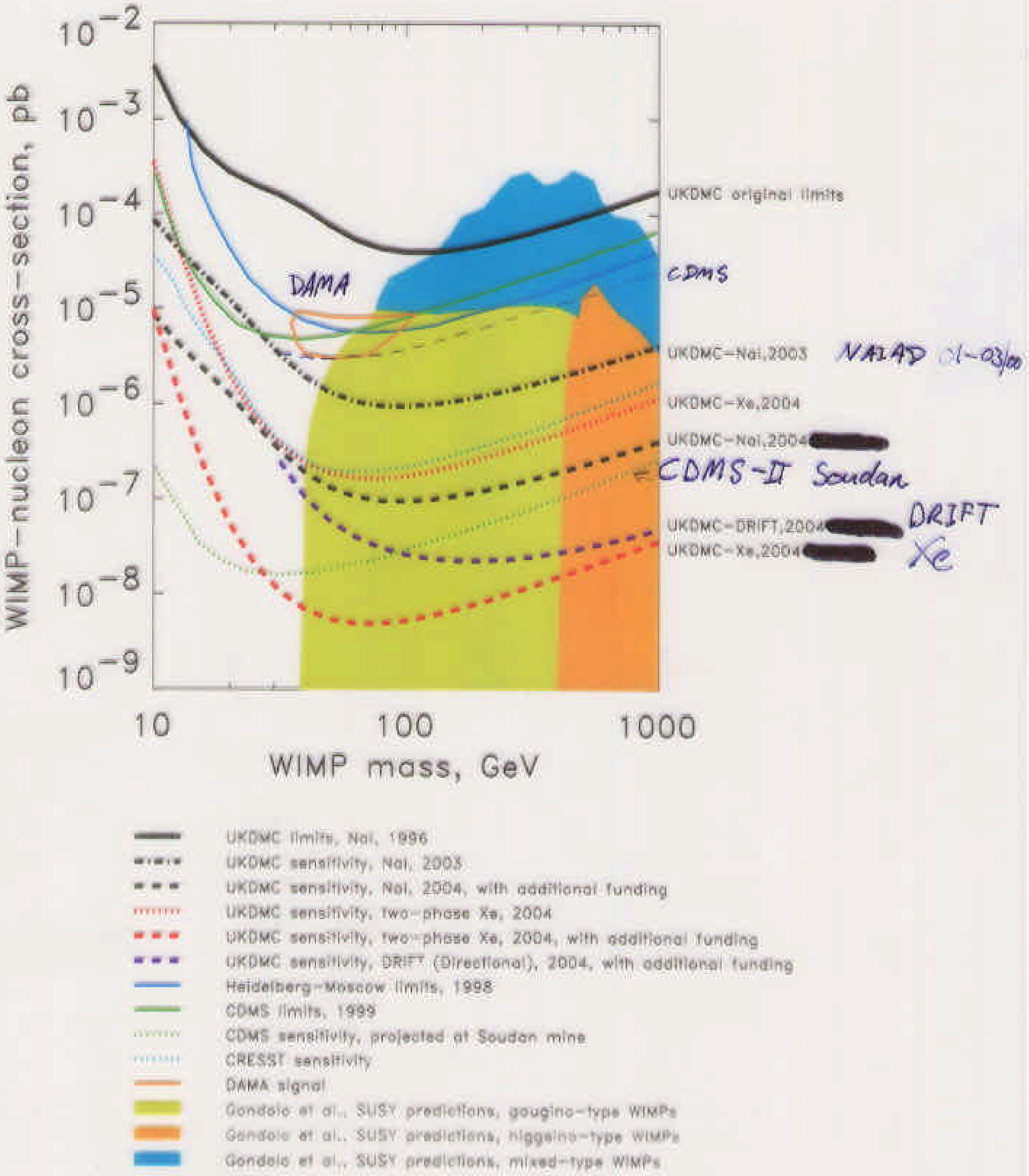
Full DRIFT experiment

- scale-up x 10-100
- 3d pixel readout

Infall components of Galactic, Cluster and Supercluster dark matter



Sikivie et al
Gondolo et al
Smith et al

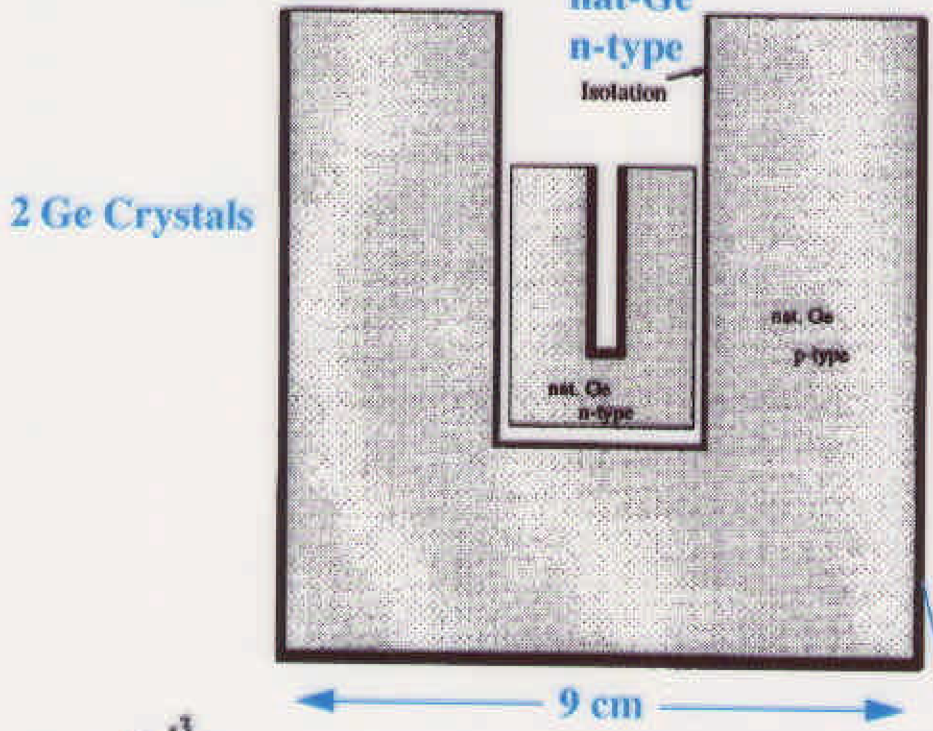

WIMP-nucleon cross-section, pb
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8
10^-9
10
100
1000
WIMP mass, GeV
UKDMC original limits
CDMS
DAMA
UKDMC-NaI,2003
NAIAD
UKDMC-Xe,2004
UKDMC-NaI,2004 [redacted]
CDMS-II Soudan
UKDMC-DRIFT,2004 [redacted]
DRIFT
UKDMC-Xe,2004 [redacted]
Xe
UKDMC limits, NaI, 1996
UKDMC sensitivity, NaI, 2003
UKDMC sensitivity, NaI, 2004, with additional funding
UKDMC sensitivity, two-phase Xe, 2004
UKDMC sensitivity, two-phase Xe, 2004, with additional funding
UKDMC sensitivity, DRIFT (Directional), 2004, with additional funding
Heidelberg-Moscow limits, 1998
CDMS limits, 1999
CDMS sensitivity, projected at Soudan mine
CRESST sensitivity
DAMA signal
Gondolo et al., SUSY predictions, gaugino-type WIMPs
Gondolo et al., SUSY predictions, higgsino-type WIMPs
Gondolo et al., SUSY predictions, mixed-type WIMPs

IONIZATION

• Heidelberg-Moscow - Ge

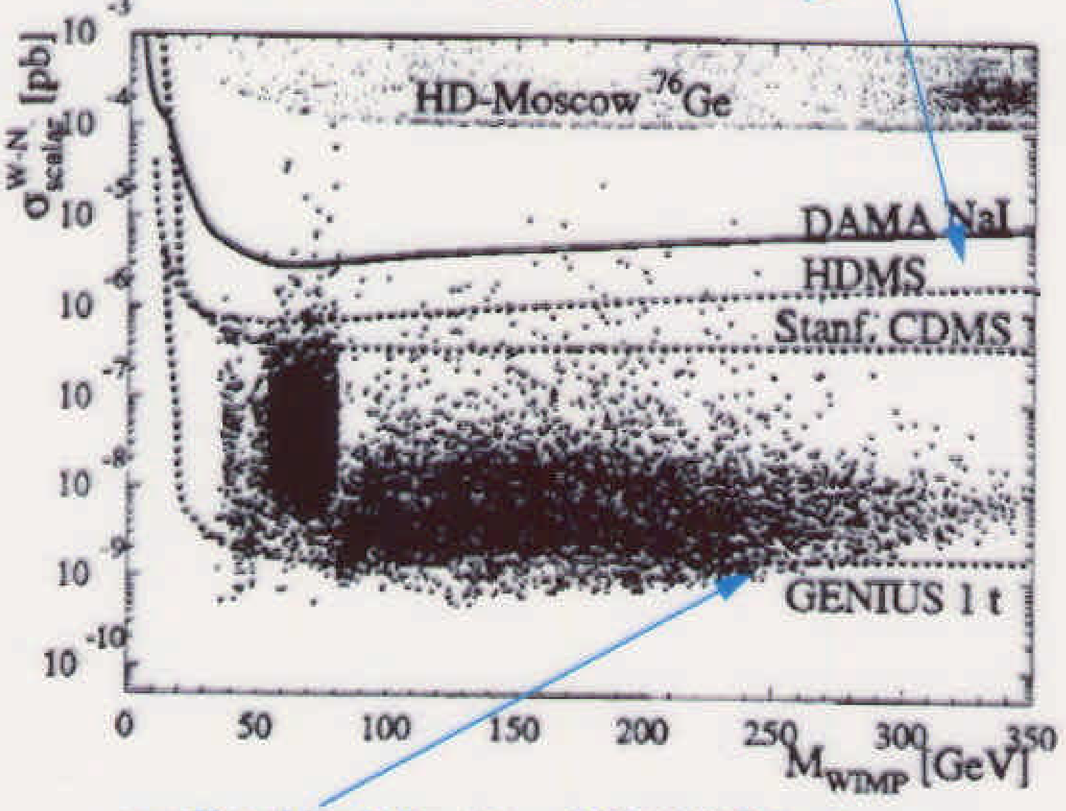
- new compton vetoing
- <u>no recoil discriminatoin</u>

see e.g. IDM'96



Next Heidelberg Experiment

predicted limit



predicted limit for 1 ton GENIUS ^{76}Ge detector

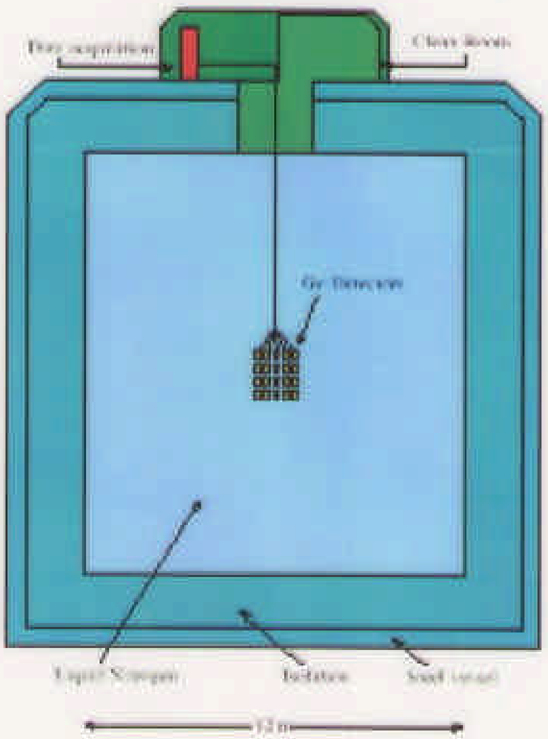
Heidelberg-Moscow - future

GENIUS

Reduction of background by 3-4 orders of magnitudes:

→New technology:

'naked' HPGe-crystals in LN_2



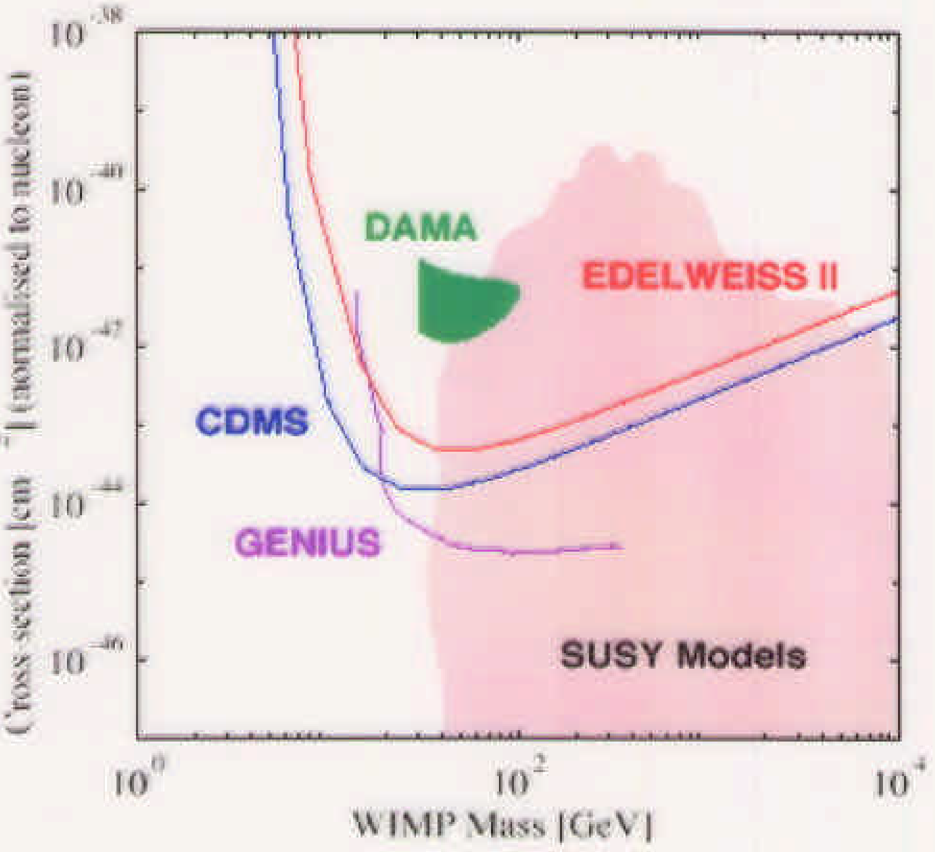
- LN_2 can be produced very clean
- Removement of all dangereous contaminations
- Shielding from external activity
- Efficient cooling of detectors

H.V. Klapdor-Kleingrothaus, L. Baudis, G. Heusser, B. Majorovits,
H. Päs, MPI-Report MPI-H-V26-1999 and hep-ph/9910205

Edelweiss - future

Edelweiss II goals :

- 500 kg days Ge
- neutron shielding : 50 cm polyethylene with boron
- neutron simulations extrapolated
- expected rate : 8 evts or 5.10^{-4}evts/kg/keV/day after back-ground rejection in the interval 8 - 40 keV



EDELWEISS II
500 kg.d
0.0005 evt/kg/d/keV

CDMS (Soudan)
2500 kg.d
0.0003 evt/kg/d/keV
(Gaitskell, TAUP99)

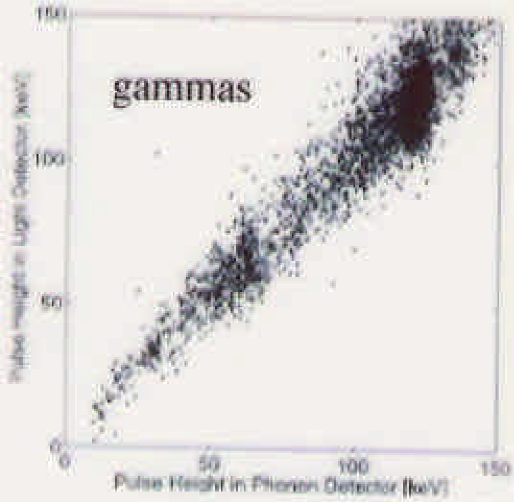
• CRESST - low temperature
[MPI/TUM/Oxford/LNGS - Gran Sasso]

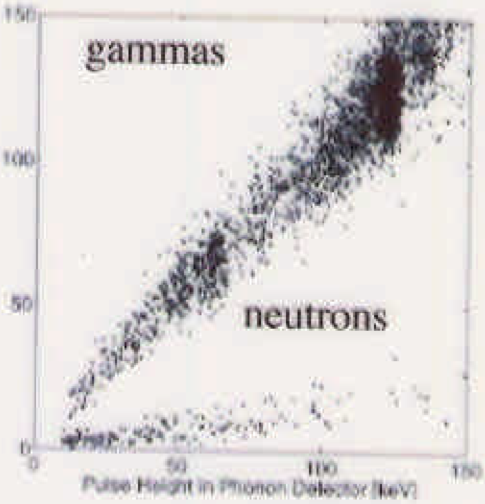
Phonon experiment - low mass WIMPs

- superconducting film on dielectric crystal (W on Al_2O_3) @15 mK
- special cold box, separate from cryostat, 20cm Pb + 14 cm Cu
- 262 g installed: 133 eV @ 1.5 keV, few ct $keV^{-1}kg^{-1}d^{-1}$ >30 keV
- 342 g Ge detector being prepared

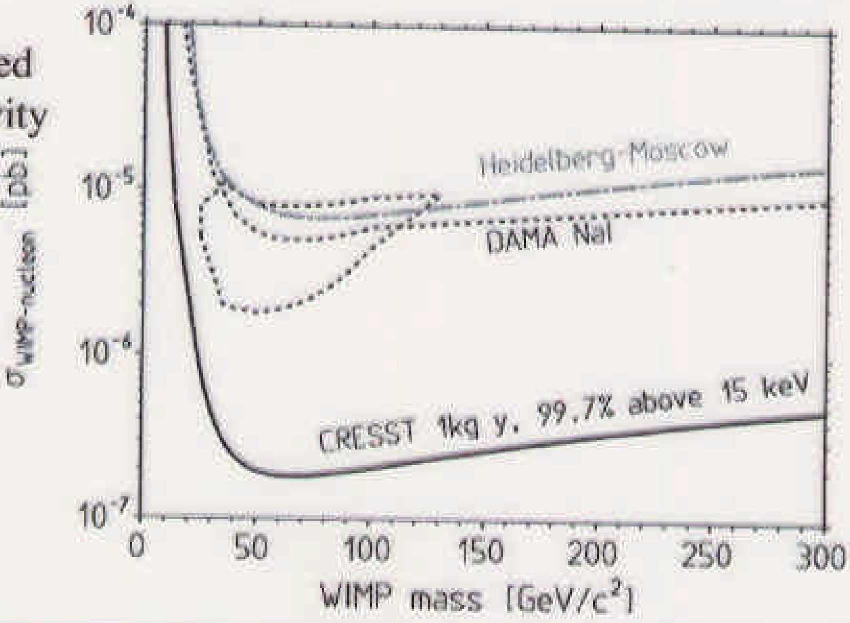
Phonon + scintillation experiment - high mass WIMPs

- new $CaWO_4$ target with scintillaiton, threshold ~10 keV
- 98% rejection, 10-20 keV



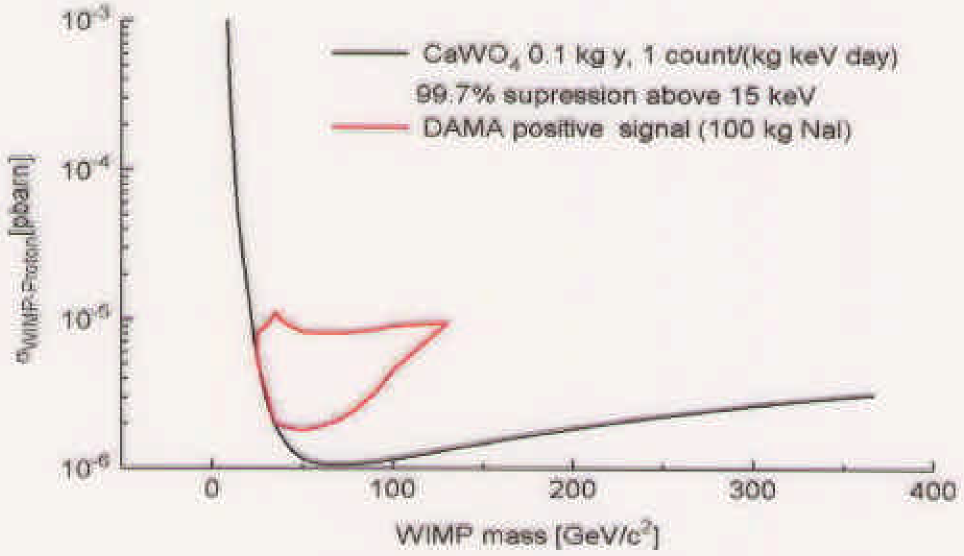


predicted sensitivity

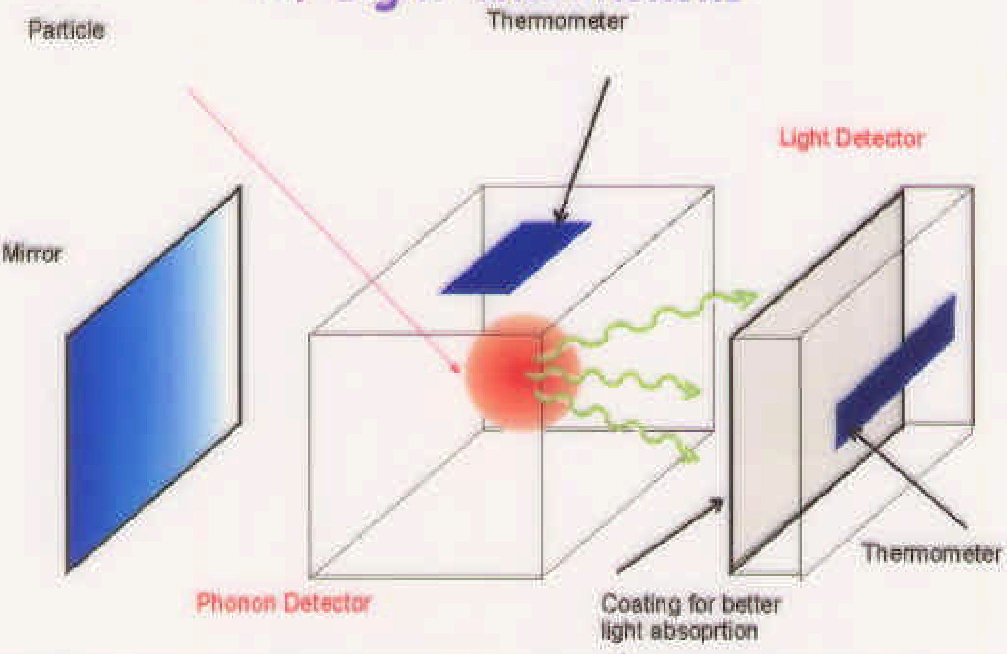


CRESST - next two years

- continue running sapphires, find and remove background
- installation $CaWO_4$ (probably 300 g) detectors in 2000
- during 2001 upgrade to 60 channels -> 10kg detector



Simultaneous Measurement of Light and Phonons



END