Searches for SUSY Dark Matter at Boulby Mine.

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&

UK Dark Matter Collaboration

Search Technique

- Many theories Beyond the Standard Model, including R_{pc} SUSY models, predict the existence of stable Weakly Interacting Massive Particles (WIMPs).

- Relic WIMPs from the Big Bang provide ideal candidates for the invisible 'Dark Matter' inferred to exist throughout our universe.

- WIMPs are predicted to interact occasionally with atomic nuclei via elastic scattering.

- WIMPs within our galaxy could be detected by searching for anomalous sources of nuclear recoils.

Recoil Energy Spectra

- Predicted nuclear recoil energy spectrum depends upon astrophysics (DM halo model), nuclear physics (form-factors, coupling enhancements) and particle physics (WIMP mass and coupling).

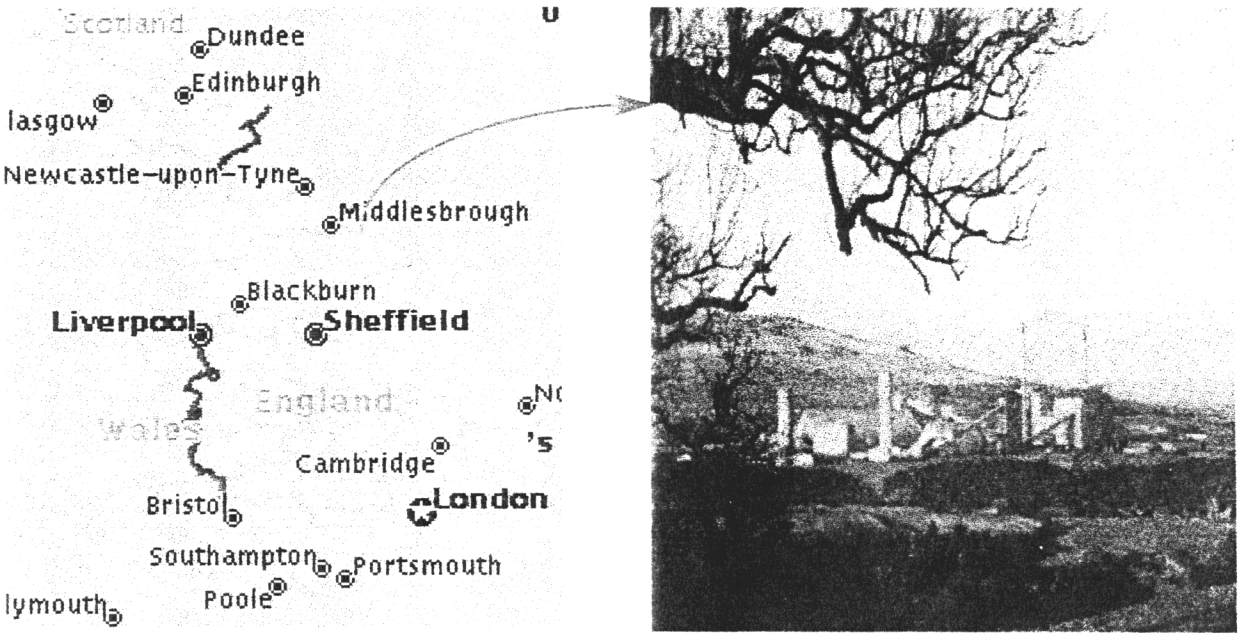
$$\frac{dR}{dE_v} = \sigma_0 \,.\, \Sigma_A \, f(A) \,.\, S(A,E_R) \,.\, I(A) \,.\, F^2(A,E_R) \,.\, g(A) \,.\, \varepsilon(E_v)$$

σ_0 = WIMP scattering cross-section,
$f(A)$ = mass fraction of element A in target,
$S(A,E_R) \sim \exp(-E_R/E_0 r)$ for recoil energy E_R,
$I(A)$ = spin/coherence enhancement (model-dep.),
$F^2(A,E_R)$ = nuclear form-factor,
$g(A)$ = energy detection efficiency (E_v/E_R),
$\varepsilon(E_v)$ = event identification efficiency.

- To first order *shape* of predicted spectrum independent of WIMP model (e.g. MSSM).

Boulby Mine

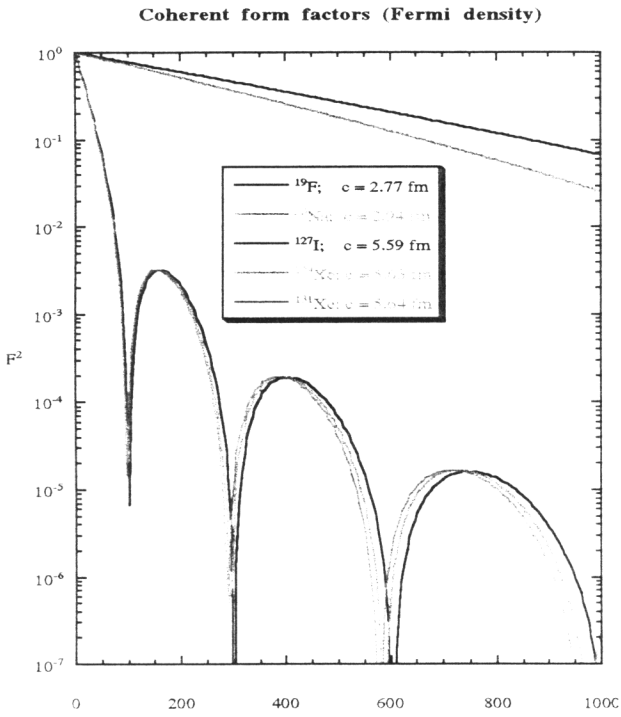
- σ_0 small (spin-ind. WIMP-proton $\sigma < 10^{-4}$ pb)
  => Predicted event rate low (< 1 /kg/day).
  => Go underground to shield detectors from background events due to radioactivity / cosmic rays.
- The UK Dark Matter Collaboration (Sheffield, Imperial College, RAL, Birkbeck) operates detectors at the Boulby Mine (3600 mwe), a working Potash mine in the North of England.

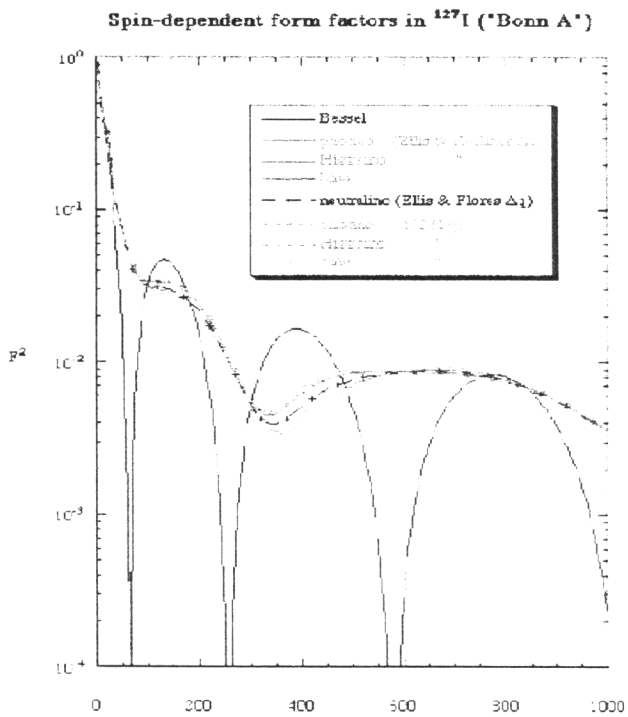


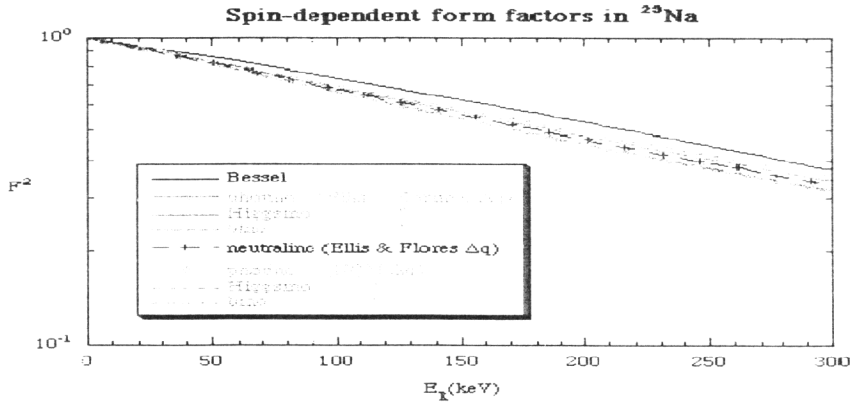
Form-Factors

- Nuclear form-factors determined from theory

(e.g. Ressell *et al.* Phys. Rev. **C 56** No.1 (1997) 535).

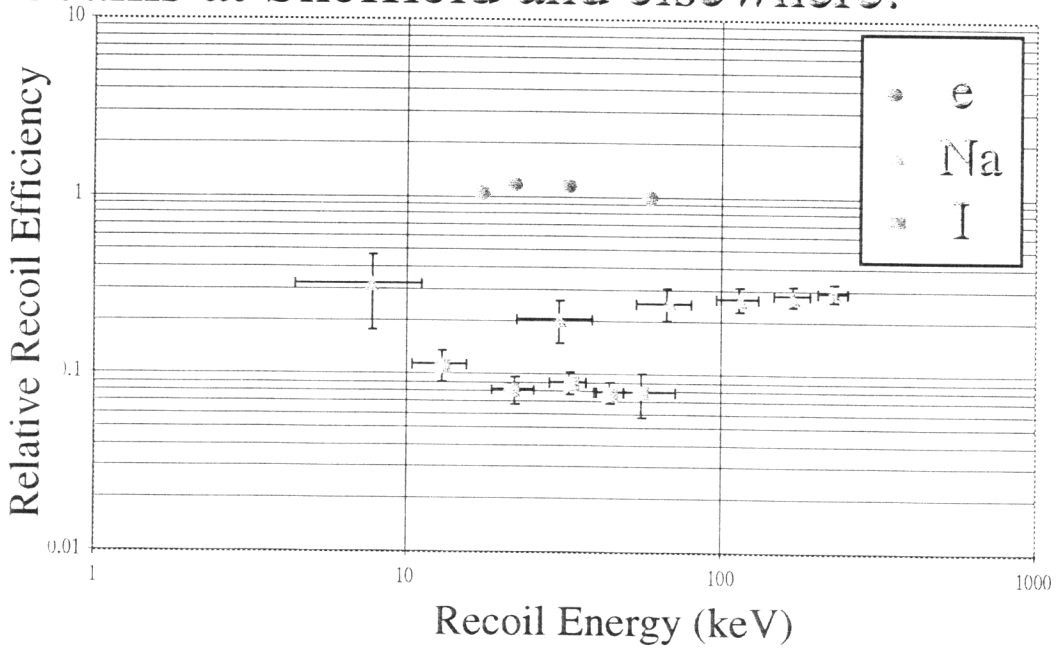






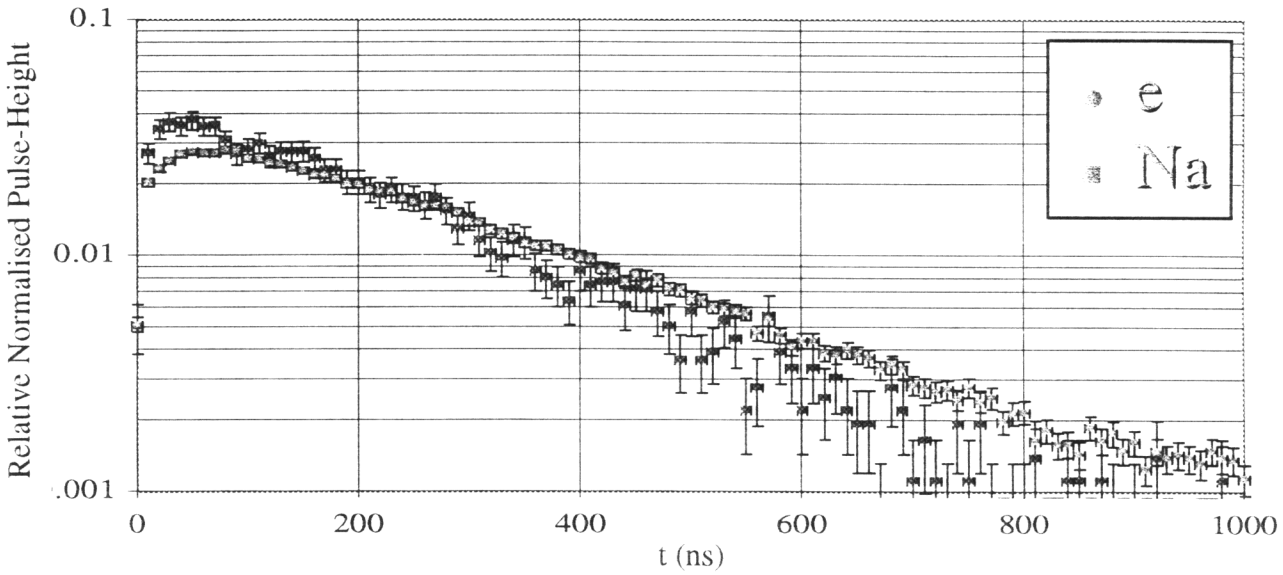
NaI(Tl)

- The UKDMC uses NaI(Tl) scintillator crystals => high light-output => low E_v threshold.
- I nuclei heavy (A=127) => large coherent rate enhancement ($I \sim A^2$).
- Na nuclei have reasonable spin coupling rate enhancement (e.g. $I_{higgsino} \sim 0.089$).
- Iodine form-factor poor => low recoil energy threshold important.
- Na, I efficiencies g(A) measured using neutron beams at Sheffield and elsewhere:



Pulse-Shape Discrimination

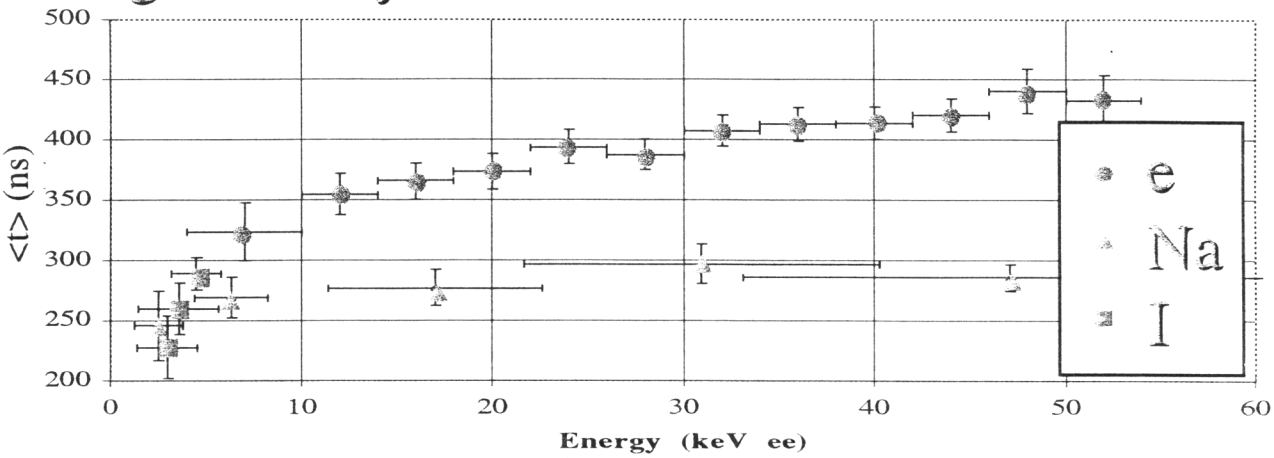
- MAJOR additional advantage of NaI(Tl) is the ability to distinguish nuclear recoils from background electron recoils using Pulse-Shape Discrimination.
- Time spectrum of scintillation photons function of recoil type:



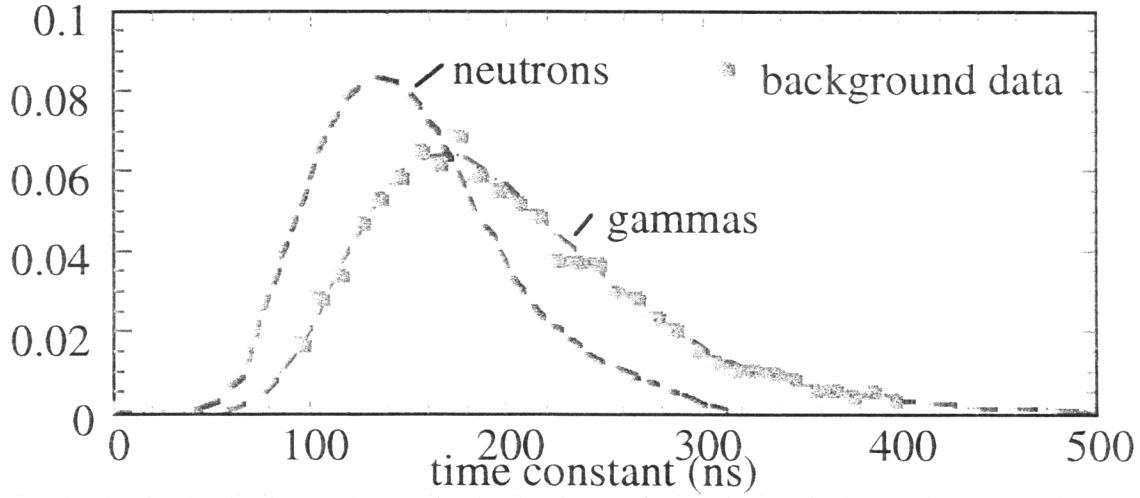
- Approximate scintillation pulse with exponential function and analyse digitised pulse-shape using χ^2 fit or Maximum Likelihood technique => use fitted decay time constant to discriminate.

Pulse-Shape Discrimination

- Means of time constant distributions differ significantly for electron and nuclear recoils:

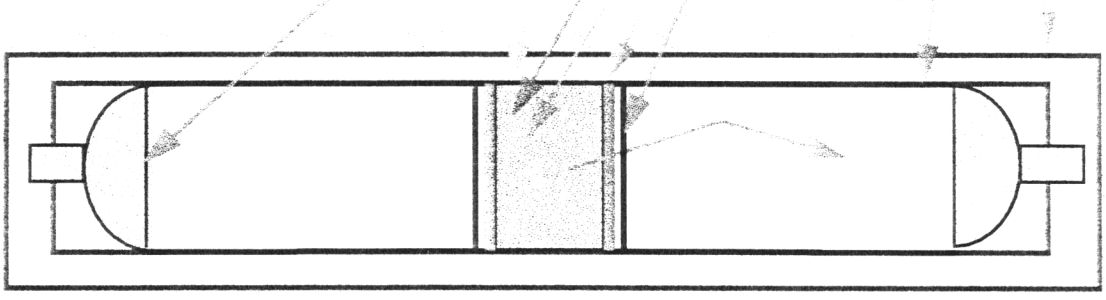


- Distributions overlap but discrimination possible on statistical basis by fitting to distributions using theoretical log-Normal curve (derived from ML treatment).



5.2 kg NaI(Tl) Detector

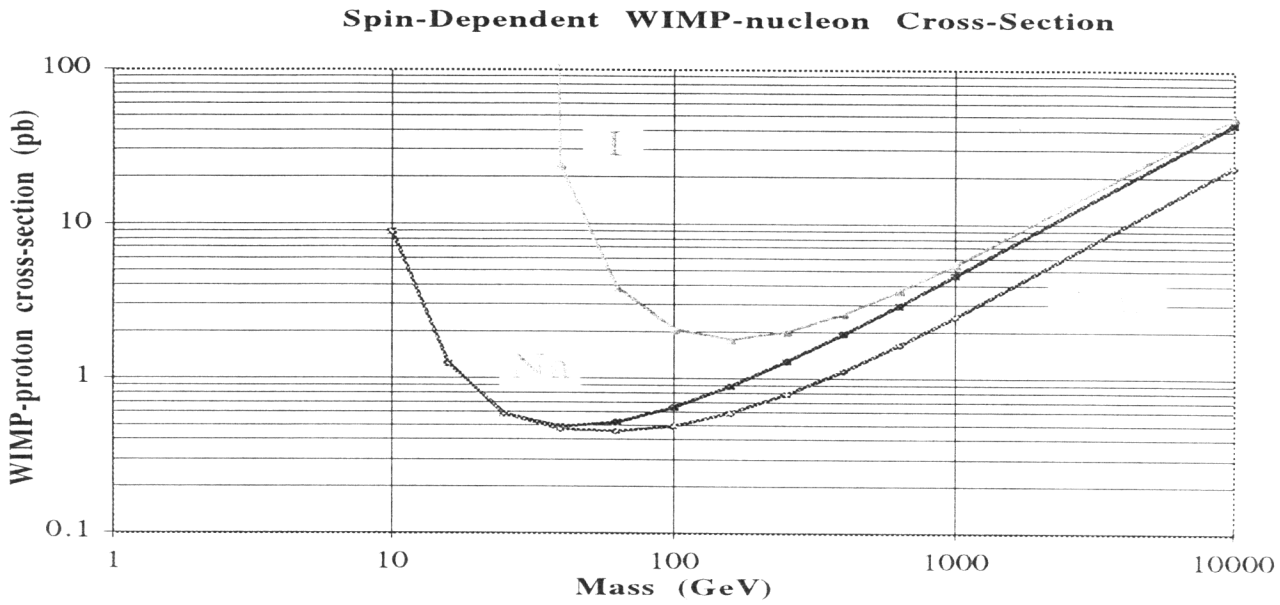
- Particular attention paid to reducing energy threshold and level of radio-impurities (source of electron recoil background via compton scattering of gammas).
  - low activity copper pmt shields and containers
  - low activity silica light guides & PMT shield
  - 3m low activity/high purity water shielding
  - 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
  - EMI 9265A PMTs

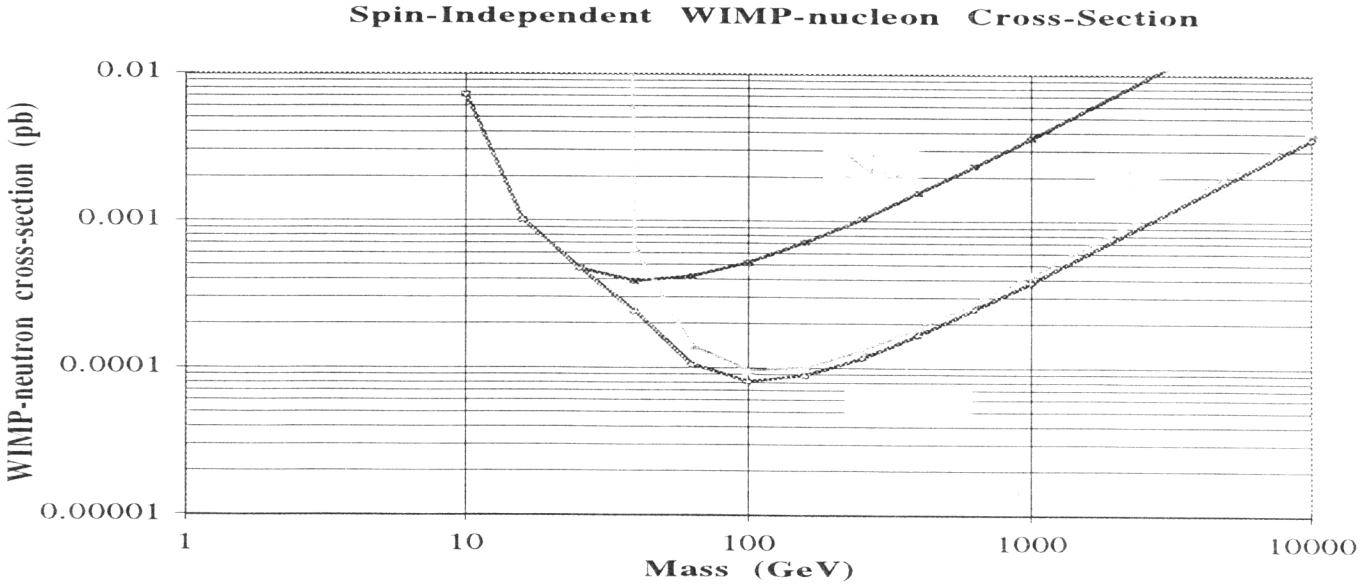


Cross-Section Limits

- PLB 379 (1996) 299 with new $F^2(A,E_R)$ & I(A)

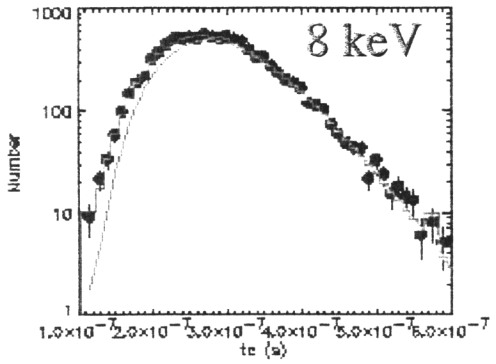
(e.g. Ressell *et al.* Phys. Rev. **C 56** No.1 (1997) 535).

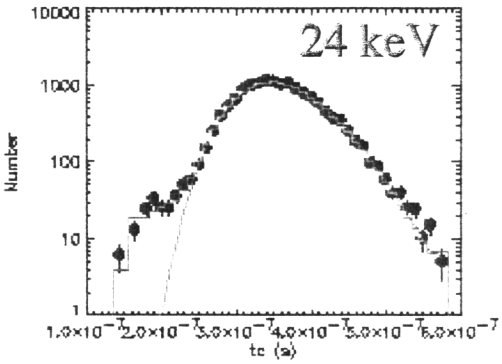


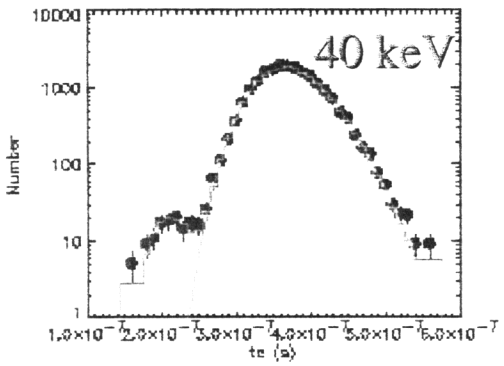


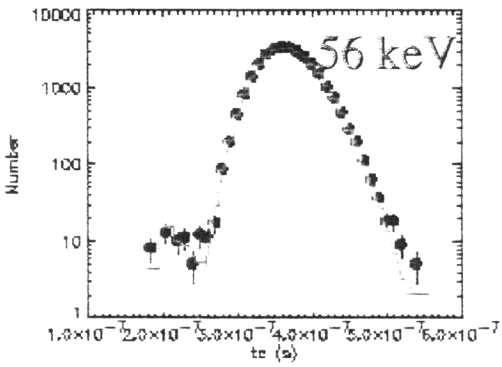
Latest Data

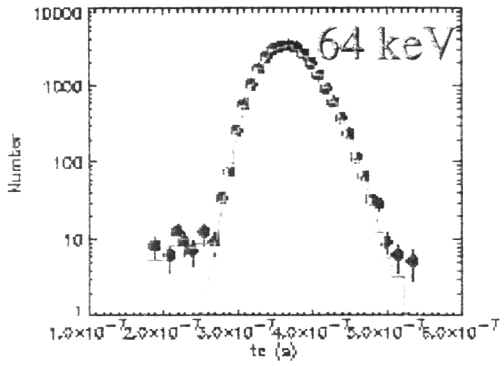
- Latest data shows evidence for 'anomalous' events at short time constant (*preliminary*).

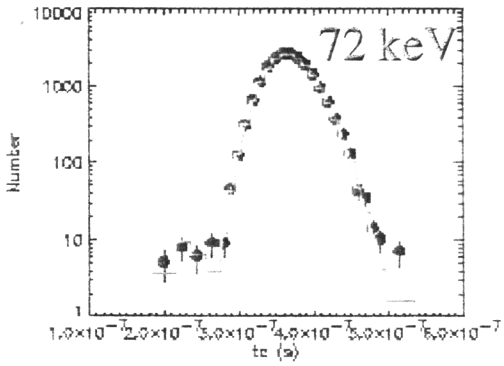






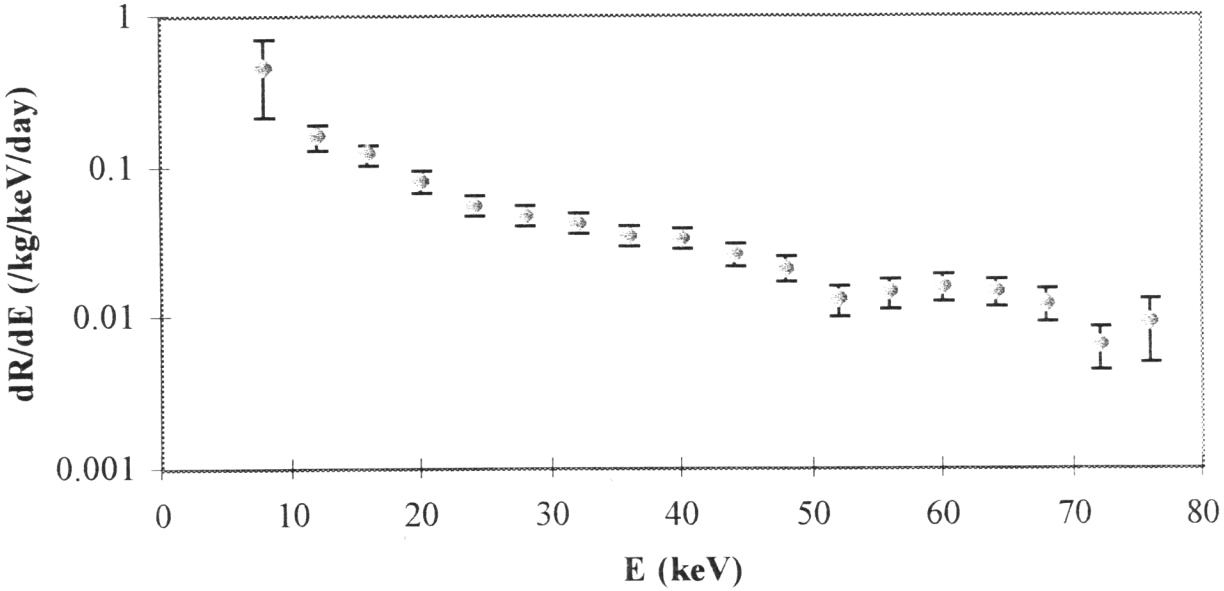




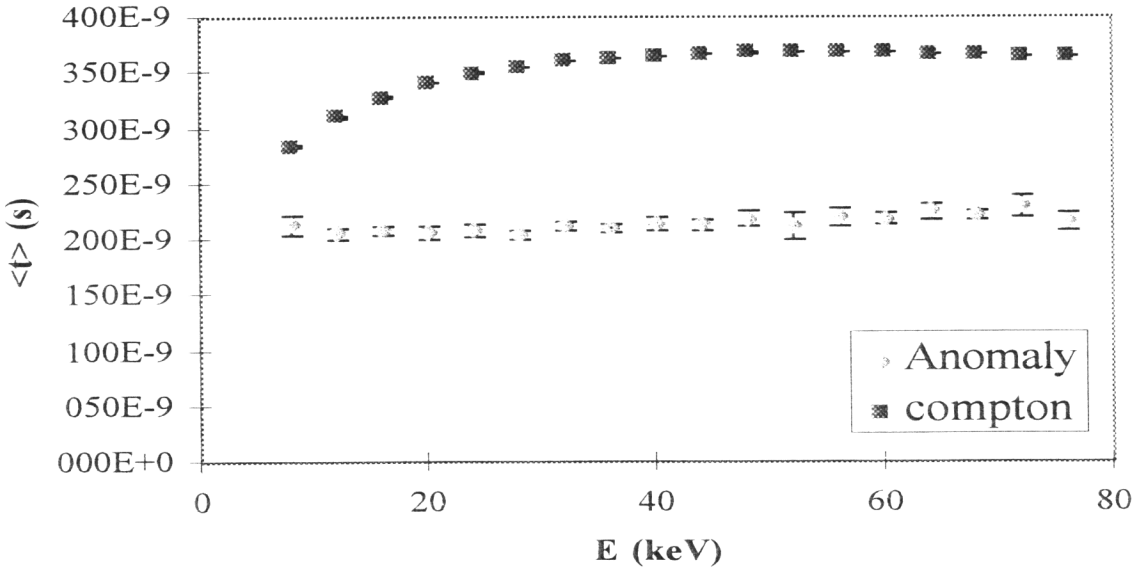


Anomaly Spectra

- *Preliminary* energy spectrum:

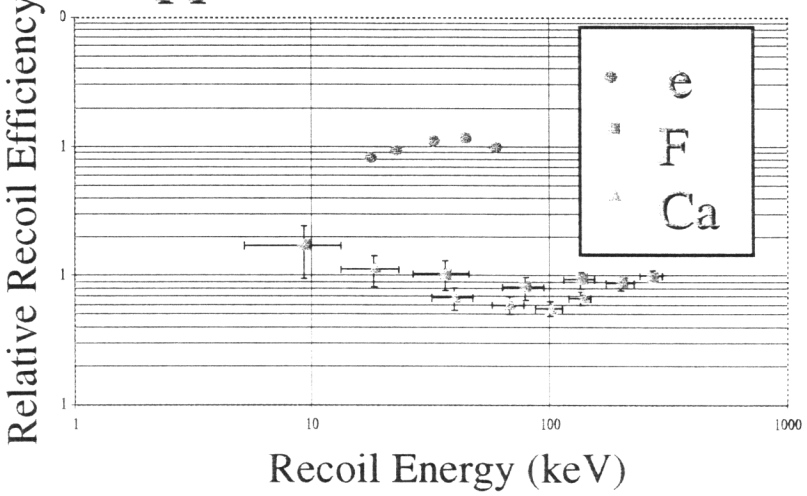


- *Preliminary* time constant spectrum (apparently inconsistent with Na / I recoils):

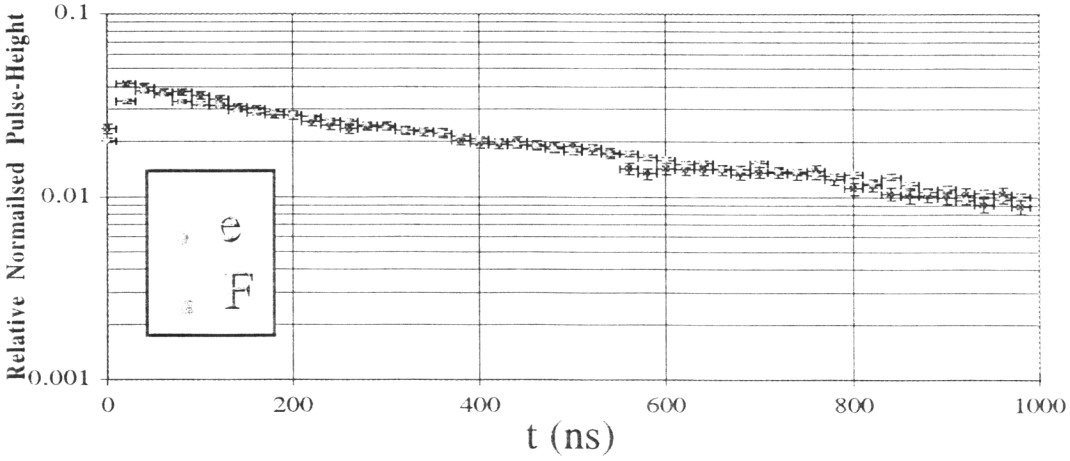


Spin-Dep. Improvements

- $CaF_2(Eu)$ is an efficient scintillator (~60% NaI(Tl)) and has a nuclear recoil efficiency g(A) which appears to rise at low energy:

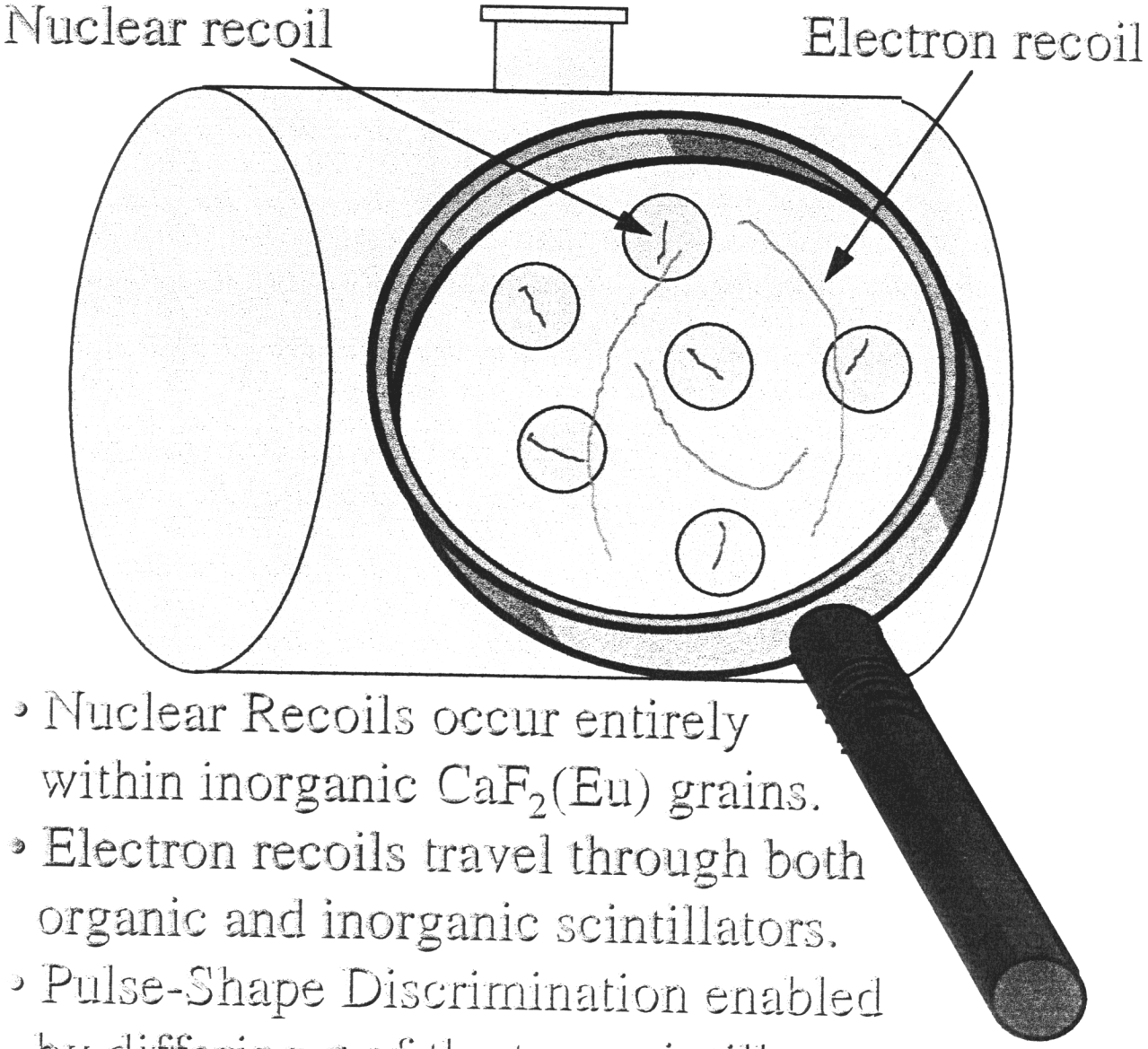


- Contains ^{19}F (has excellent spin enhancement e.g. $I_{higgsino}$~0.7).
- *But*, $CaF_2(Eu)$ has no intrinsic PSD properties:



CASPAR

(currently not part of main UKDMC programme)

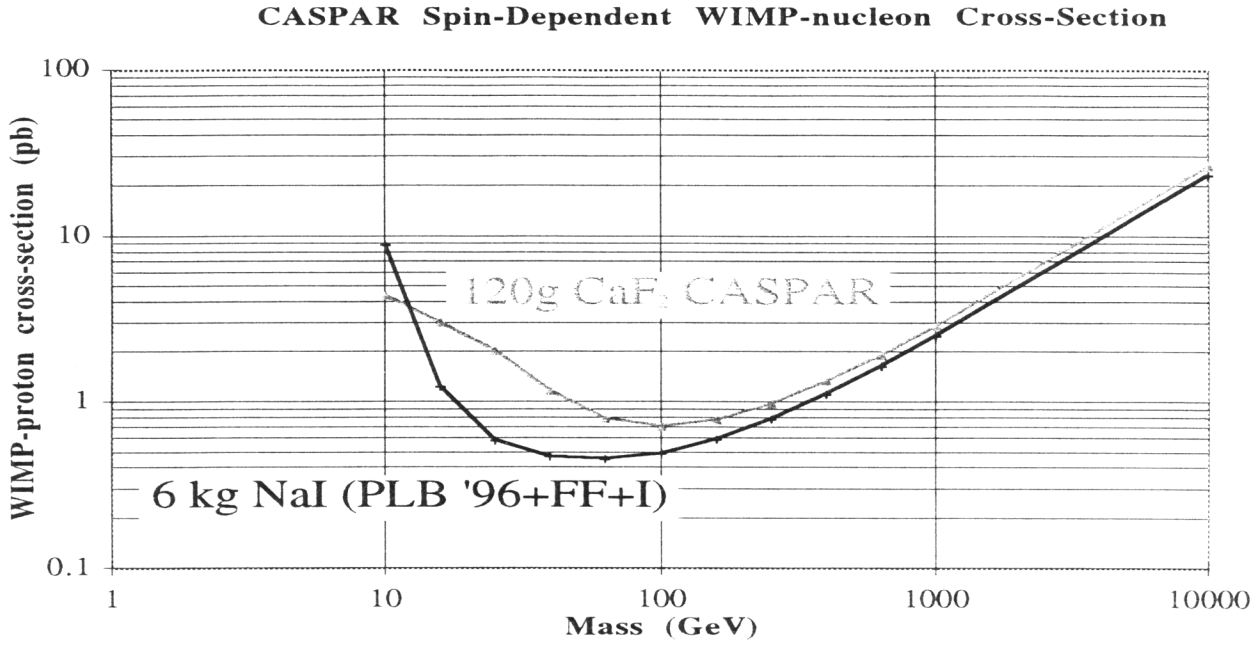


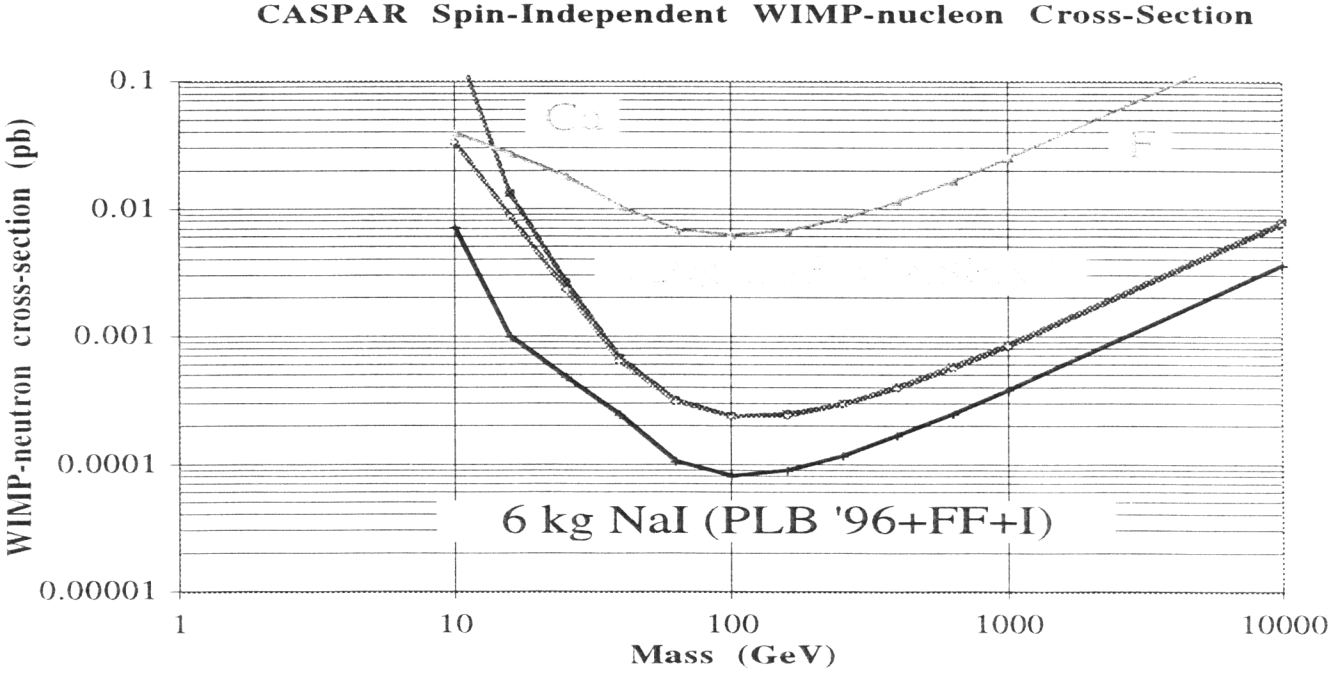
- Nuclear Recoils occur entirely within inorganic $CaF_2(Eu)$ grains.
- Electron recoils travel through both organic and inorganic scintillators.
- Pulse-Shape Discrimination enabled by differing τ of the two scintillators.

D.R.Tovey *et al.*, Astroparticle Phys. **8** (1997).

CASPAR MC Sensitivity

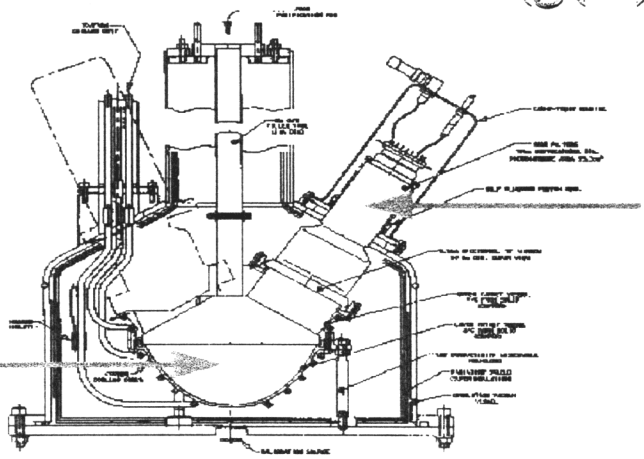
- MC predictions of CASPAR sensitivity.



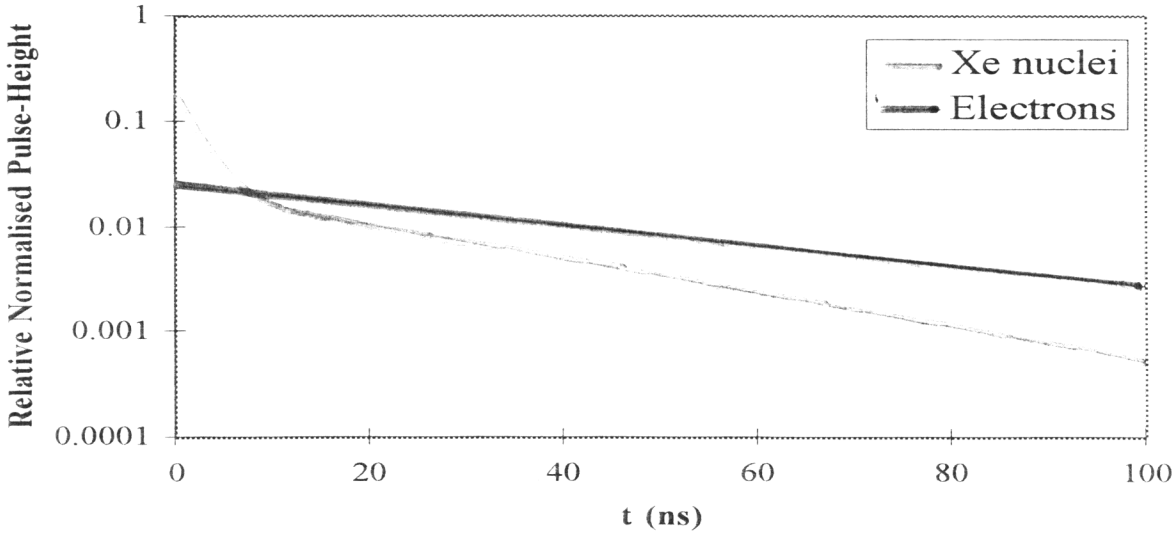


Coherent Improvements

- Increase g(A) and event identification eff. $\varepsilon(E_\gamma)$.
- Latter requires greatly increased PSD efficiency.
- Use Liquid Xenon scintillator (g(A)>20%).



- Significant intrinsic PSD properties:

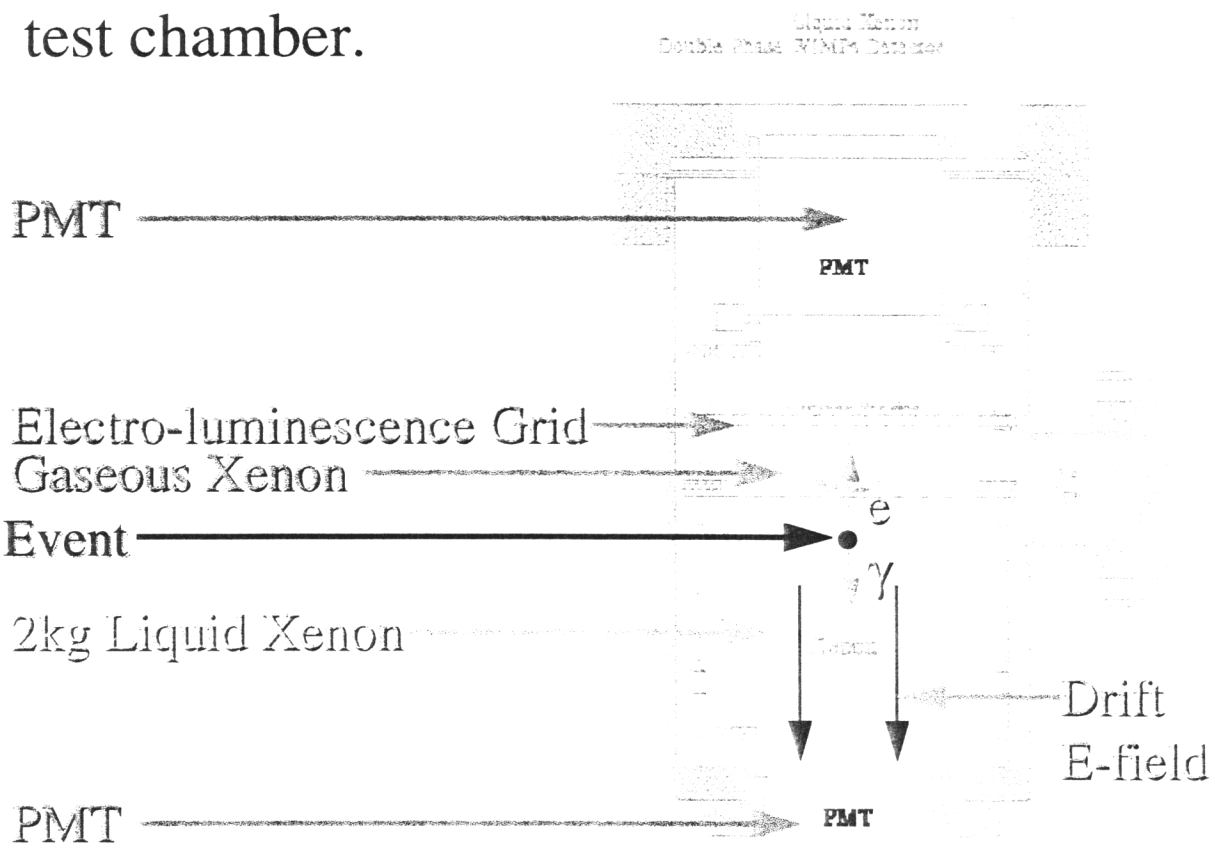


- ^{129}Xe also gives excellent s-dep. sensitivity.

Double-Phase Xe Chamber

- Still better discrimination provided by measuring relative amounts of charge and scintillation in event.
- Ratio depends sensitively on recoil type.

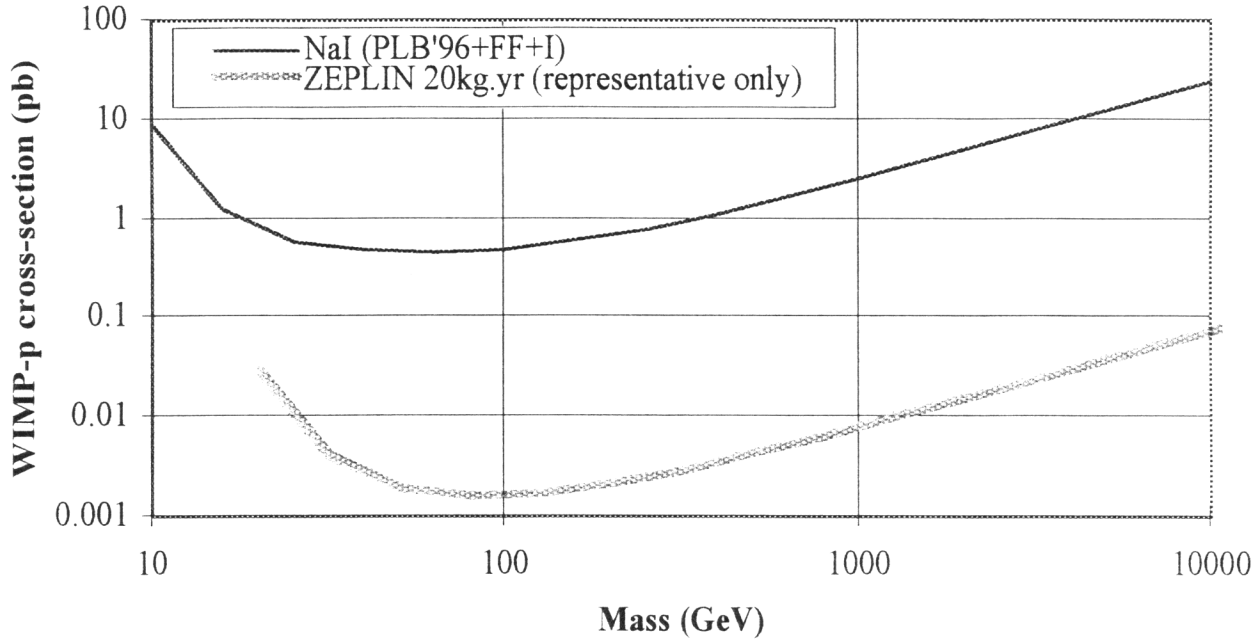
e.g. UCLA/Torino/CERN test chamber.



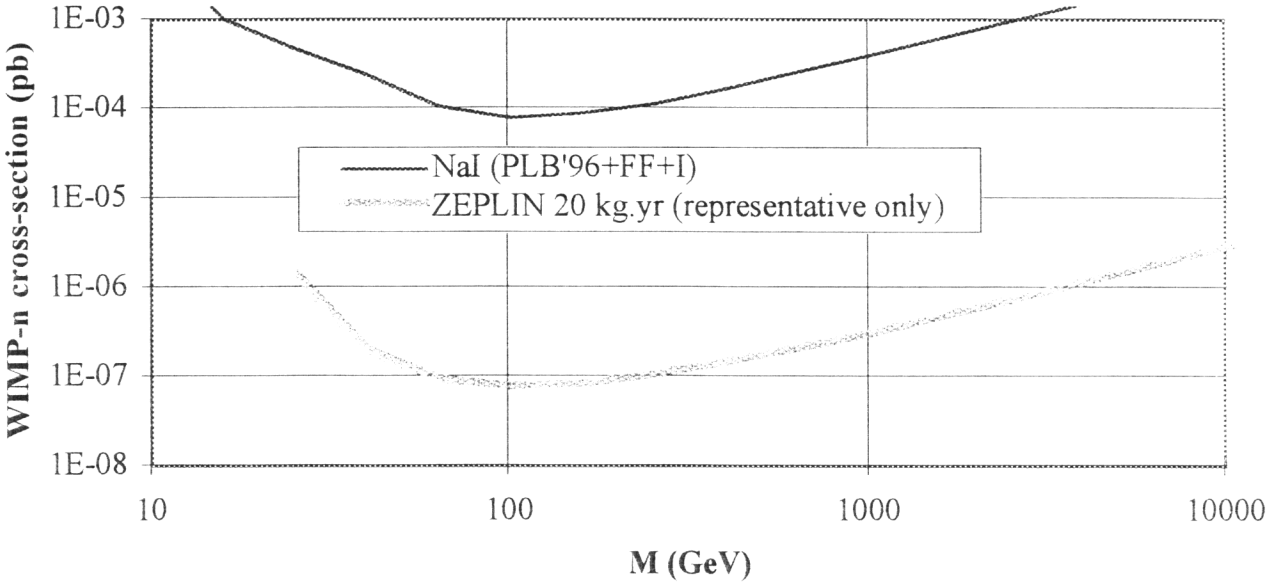
(H.Wang, proc. Cosmo '97)

Predicted Xe Sensitivity

- Spin-dependent Wimp-proton cross-section:

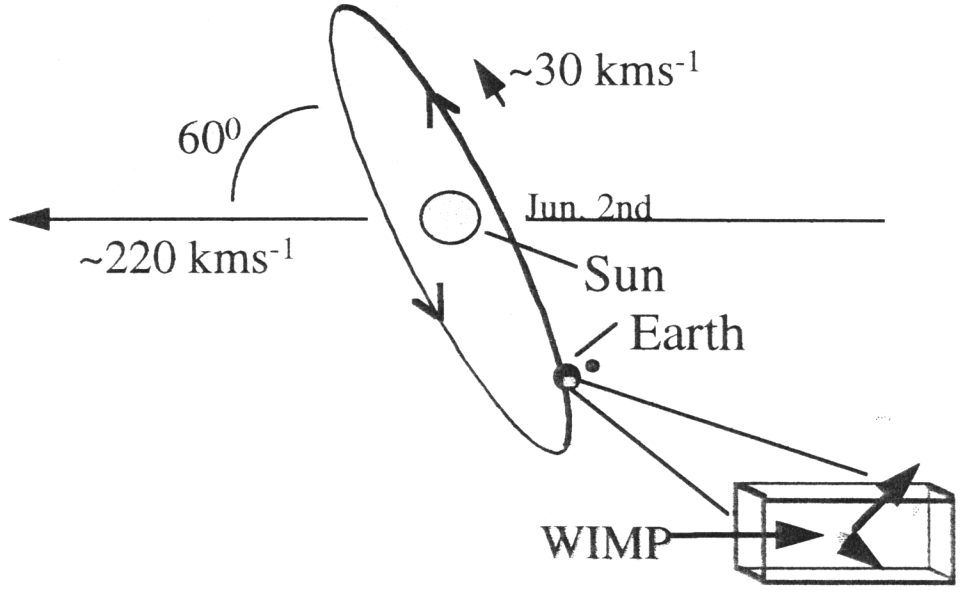


- Spin-independent Wimp-neutron cross-section:



Directionality

- Q: What else can we do ?
- A: We can be more clever: $S(A,E_R)$ is in fact also function of recoil direction due to earth's motion through DM halo.



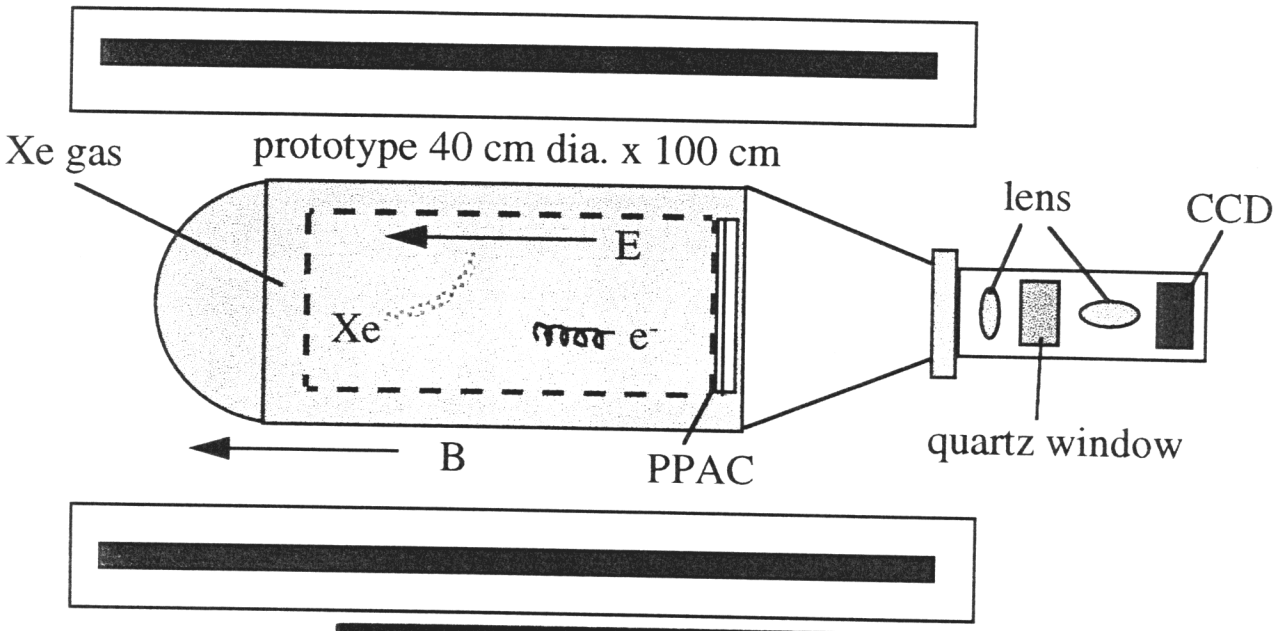
$$S(A,E_R) \Rightarrow S(A,E_R,\psi) \sim \exp(-((v_E \cos\psi - v_{min})/v_0)^2)$$

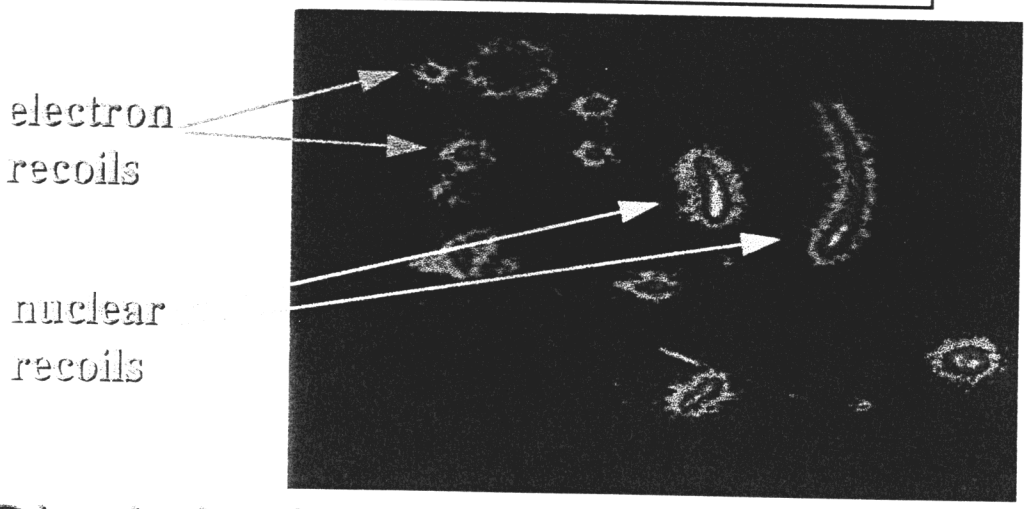
D.N. Spergel, Phys. Rev. **D 37** (1988) 1353

- => Search for diurnal modulation to signal in directional detector.

Directional TPC

- One idea is to use a low-pressure TPC (UCSD).



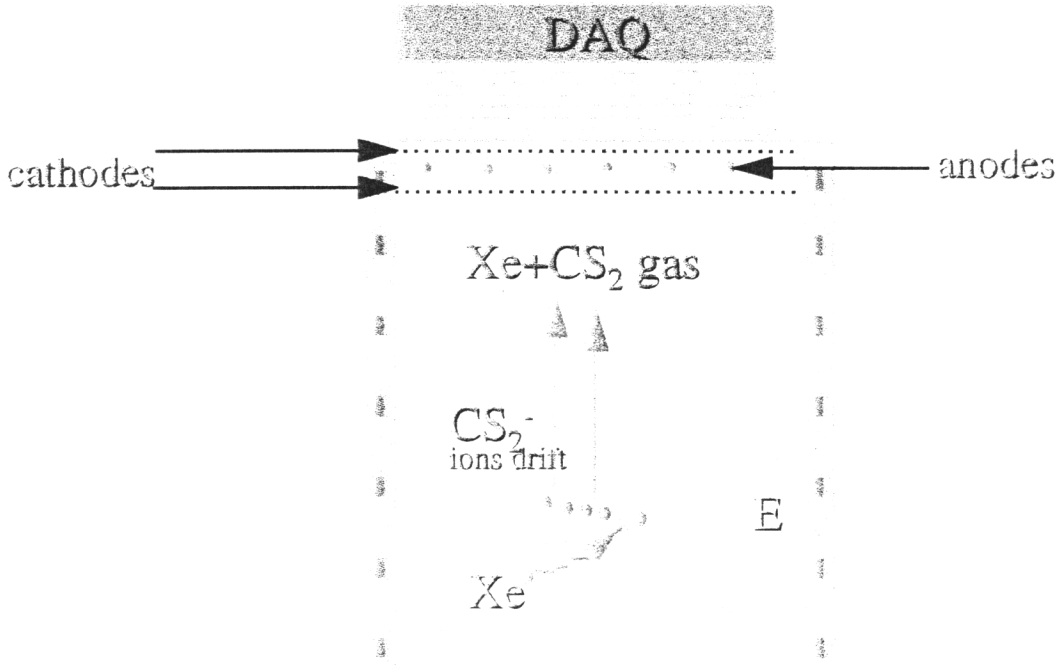


- Discrimination using track length / curvature.

Buckland *et al.* PRL **73** No.8 (1994) 1067-1070

DRIFT

- Need for magnet to limit diffusion problem for UCSD detector.
- New collaboration (Sheffield, Temple, LA Occidental, UCSD, Surrey) proposing to use negative ion drift to solve this problem => Directional Recoil Identification From Tracks.



- High mass of CS_2^- ions limits diffusion.
- Discrimination on basis of track length.

Summary & Conclusions

- Detectors currently being operated by the UKDMC at Boulby Mine are providing interesting new results.

- These results emphasise the importance of understanding the background processes at work within the detectors.

- It is proposed to build and operate new classes of detector with significantly improved WIMP sensitivity in the near future.

- This sensitivity should be sufficient to push limits deep into those regions of parameter space predicted by Theory (e.g. SUSY), *or* (preferably), discover Dark Matter!