An International Collaboration on New Liquid Xenon Detectors for the Detection of Neutralino Dark Matter

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RAL
ICSTM
Sheffield
UCLA
Torino

• The Dark Matter Problem

Galactic Rotation Curves

Large Scale Structure + Dynamics

Primordial Nucleosynthesis

Inflation

-> ***The Baryonic DM Problem***

-> ***The Non-baryonic DM Problem***

• Possible Solutions

Baryonic

MACHOs or Dark Stars

Non-baryonic

Neutrinos	ν_τ	**m ~ 10 eV**	**hot**
WIMPS	χ	**m > 22 GeV**	**cold**
Axions	**a**	**m ~ 10^{-5} eV**	**cold**

Hybrid Solution: $\Omega = \Omega_b + \Omega_{CDM} + \Omega_{HDM}$

$0.05 + 0.75 + 0.20$

MSSM (Minimal Supersymmetric extension of the Standard Model)

- Boson – Fermion symmetry
  ⇒ predicts $\underbrace{\tilde{q}, \tilde{\ell}}_{J=0}, \underbrace{\tilde{g}, \tilde{W}_3^0, \tilde{B}^0, \tilde{H}_1^0, \tilde{H}_2^0, \tilde{H}^{\pm}}_{J=\frac{1}{2}}$

- $\underbrace{\tilde{W}_3^0, \tilde{B}^0, \tilde{H}_1^0, \tilde{H}_2^0}$ mix to give 4 mass eigenstates

$$\Downarrow$$

$\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3, \tilde{\chi}_4$ ← Neutralinos

e.g. $\tilde{\chi}_1^0 = c_1\tilde{\gamma} + c_2\tilde{Z} + c_3\tilde{H}_1^0 + c_4\tilde{H}_2^0$

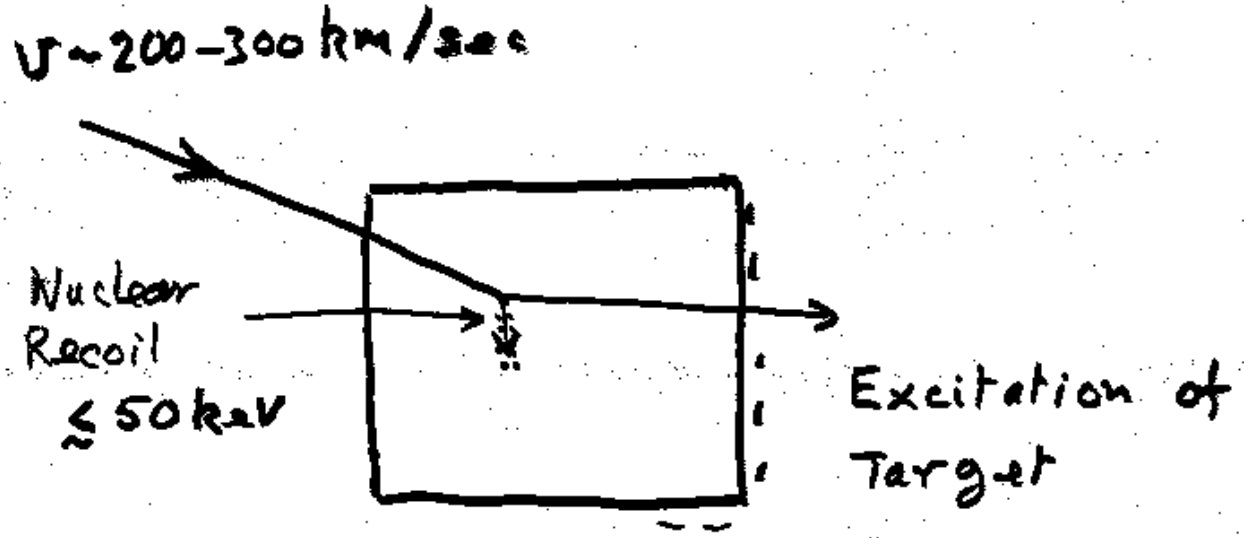
where $\tilde{\gamma} = \cos\theta_W \tilde{B}^0 + \sin\theta_W \tilde{W}_3^0$ = photino

- Mixing Parameters are: $M_1, M_2, \mu, \tan\beta = \frac{v_2}{v_1}$, m_0, m_{ν_2}

R parity = +1 for supersymmetric particles (SP's)
= −1 " normal particles

R conserved ∴ only make–destroy SP's in pairs
∴ Lightest SP is stable ⇒ LSP

WIMP Detection



Ionization :

Scintillation :

Phonons :

General Features of WIMP search

Expected Interaction Rate ~ 1 - 10^{-3} /(kg day)

Expected Recoil Energy < 50 keV

Backgrounds from
- **(a) cosmic rays**
- **(b) radioactivity in environment**
- **(c) radioactivity in detector**

General Requirements of Detector

Target Mass 1 - 1000 kg

Sensitive to Recoil Energies ~ 10 keV

Very good shielding

Constructed from low radioactivity materials

Good background discrimination

UKDMC (RAL, ICSTM, Sheffield)
+ UCLA + Torino + ITEP (?)

at

Boulby Mine

- **Depth about 1100 m**
- **Working Salt and Potash Mine**
- **Low Natural Radioactivity**
- **Hot and Dusty !**
- **Three Caverns (not permanent but > 15 Yrs)**
- **Large Water Tank + Pb, Cu Castles**

Different Approaches

Small Mass, very low threshold, no discrim.

Germanium bolometer	**Heidelberg**
Low Temp bolometer	**CREST**
	Berkeley, Stanf'rd

Medium Mass and discrimination

NaI Scintillator	**UKDMC**
	BPRS
Si, Ge	**Berkeley, Stanf'd**

Large Mass and discrimination

NaI Scintillator	**DAMA (Rome)**

Medium Mass and v. good discrimination

Xe	**UKDMC+UCLA**
	DAMA (Rome)

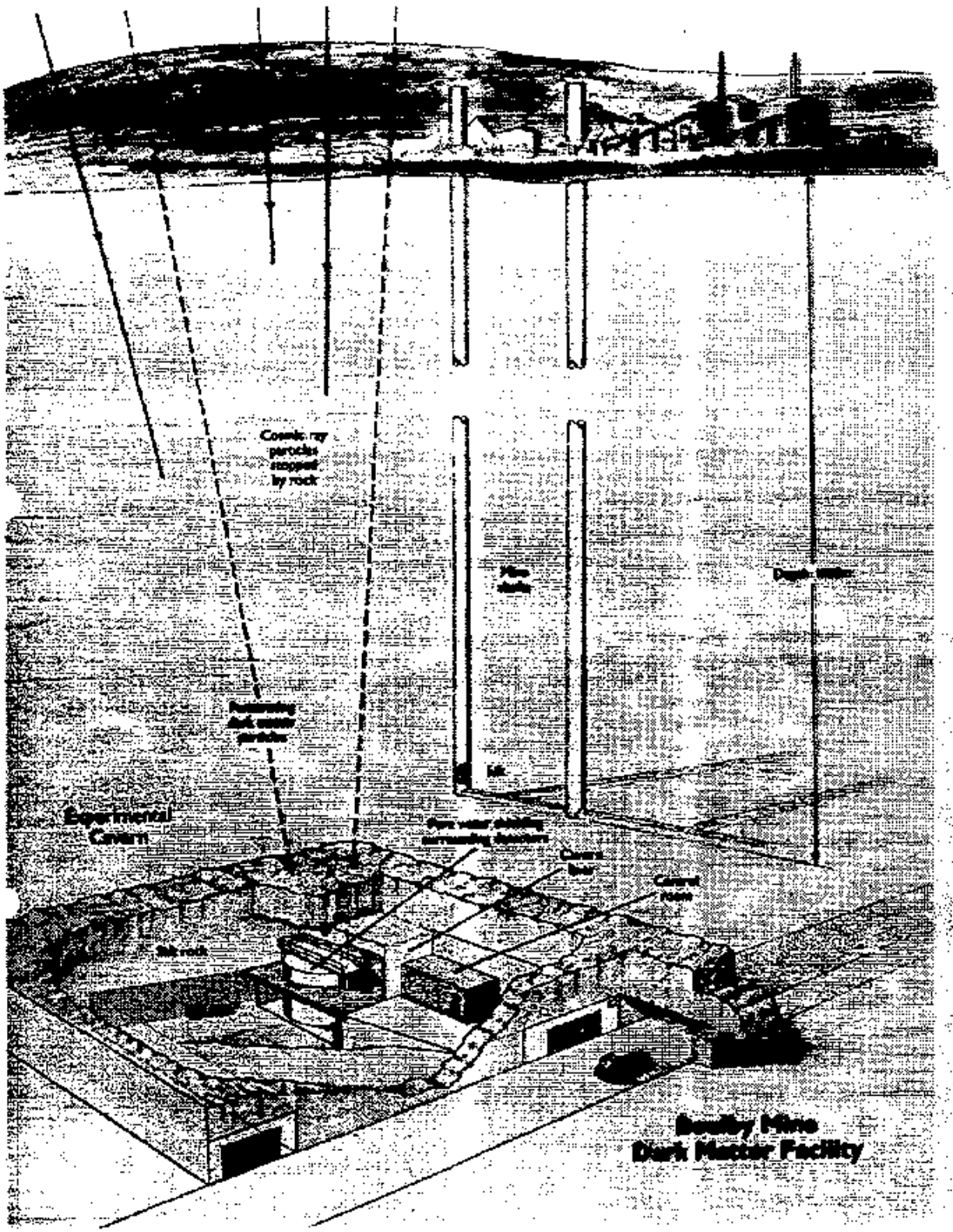


Fig 2.1 Artist's impression of Boulby Mine and Dark Matter Facility

Predicted Recoil Spectrum

$$\frac{dR}{dE_R} = c_1 \left(\frac{R_0}{E_0 r}\right) e^{-(c_2 E_R / E_0 r)} \; |F(E_R)|^2$$

$$= \text{Events} / (\text{kg} \cdot \text{day}) / \text{keV}$$

$$r = 4 \frac{M_D A}{(M_D + A)^2}, \quad M_D = \text{Mass of DM particle}, \quad A = \text{Mass of Nucleus}$$

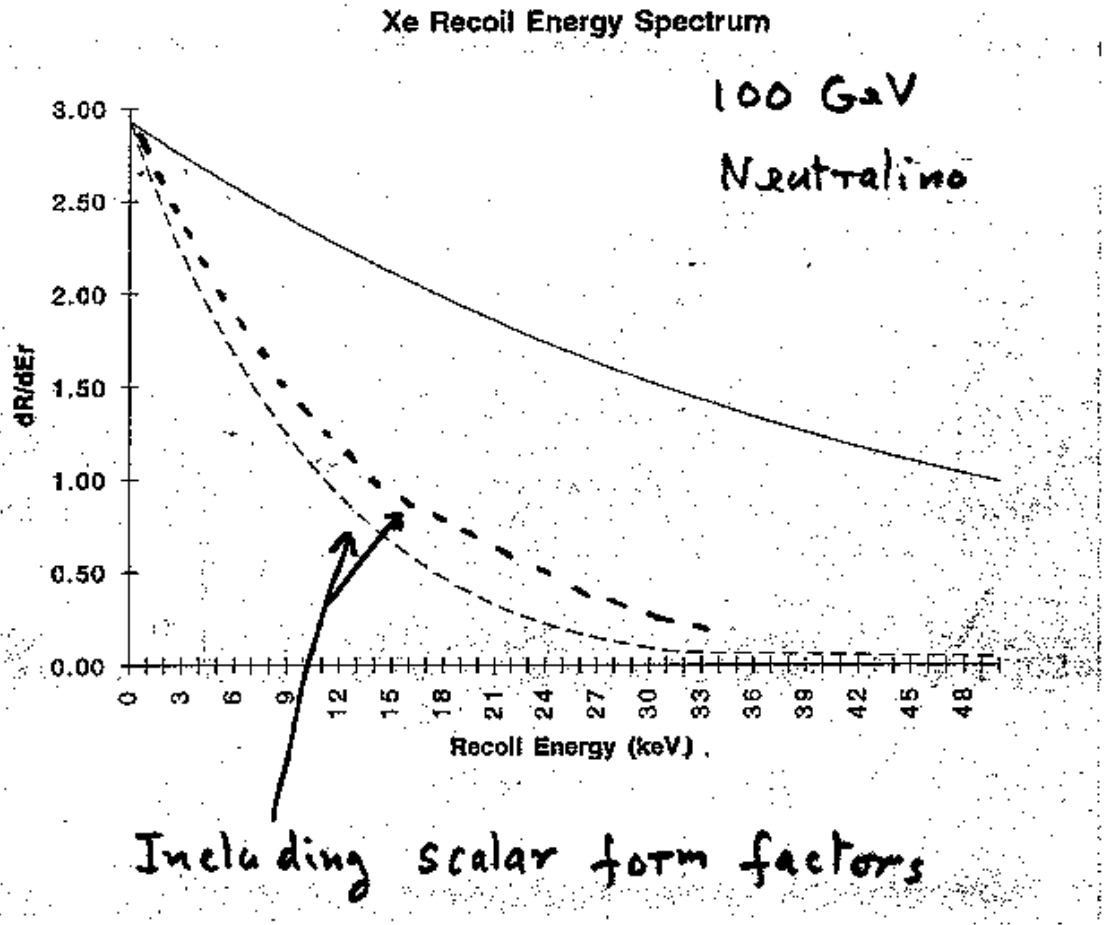
Assumes Gaussian DM flux dist'n

R_0 depends on Supersymmetry parameters + need to give right annihilation σ to give Ω_{CDM}

$\Rightarrow \quad 1 - 10^{-3} \; / \text{kg} \cdot \text{day}$

The key requirement is to discriminate against background

γ / e^- background $\sim 10 / \text{kg} \cdot \text{day}$


Xe Recoil Energy Spectrum
100 GeV
Neutralino
dR/dEr
3.00
2.50
2.00
1.50
1.00
0.50
0.00
0
3
6
9
12
15
18
21
24
27
30
33
36
39
42
45
48
Recoil Energy (keV)
Including scalar form factors

Scintillation and Ionization in Li Xe

Two mechanisms are at work:

P1: Production of excited atom Xe*
-> excimer Xe^*_2 -> 175nm photons
with time constants of 3ns and 27ns

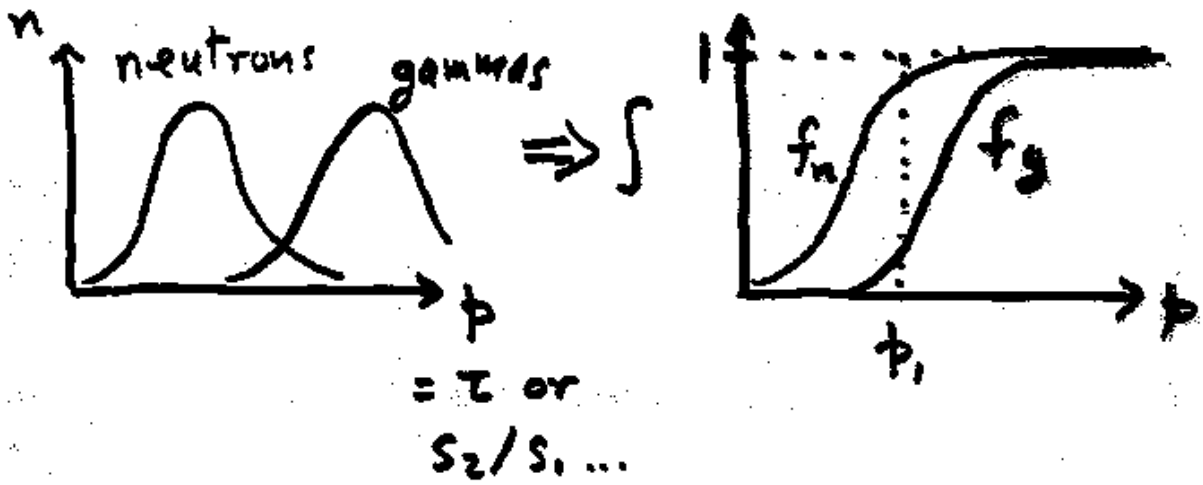
P2: Production of ionized state Xe^+
-> Xe^+_2 -> Xe^*_2 -> 175nm photons
but delayed by recombination time

For incident electrons (e.g. from gamma absorption) the 3ns component is small but recombination time is long -> ~ 45ns time constant.

For alphas and nuclear recoils the 3ns component is larger and the recombination time is small (high ionization density) so very few slow photons.

(See Kubota et al, Hitachi et al, Doke et al, Aprile et al)

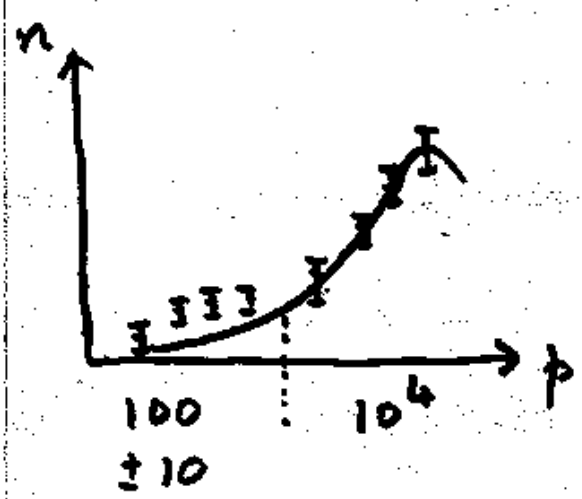
Discriminating Detectors



Statistical fluctuation in BG (= N) below cut at $p = p_1$.

$\Rightarrow$ 90% CL on Signal $= 1.3 \dfrac{\sqrt{f_g(1-f_g)}}{(f_n - f_g)\sqrt{N}}$

or better to fit to calibration spectra



e.g. 10^4 events with

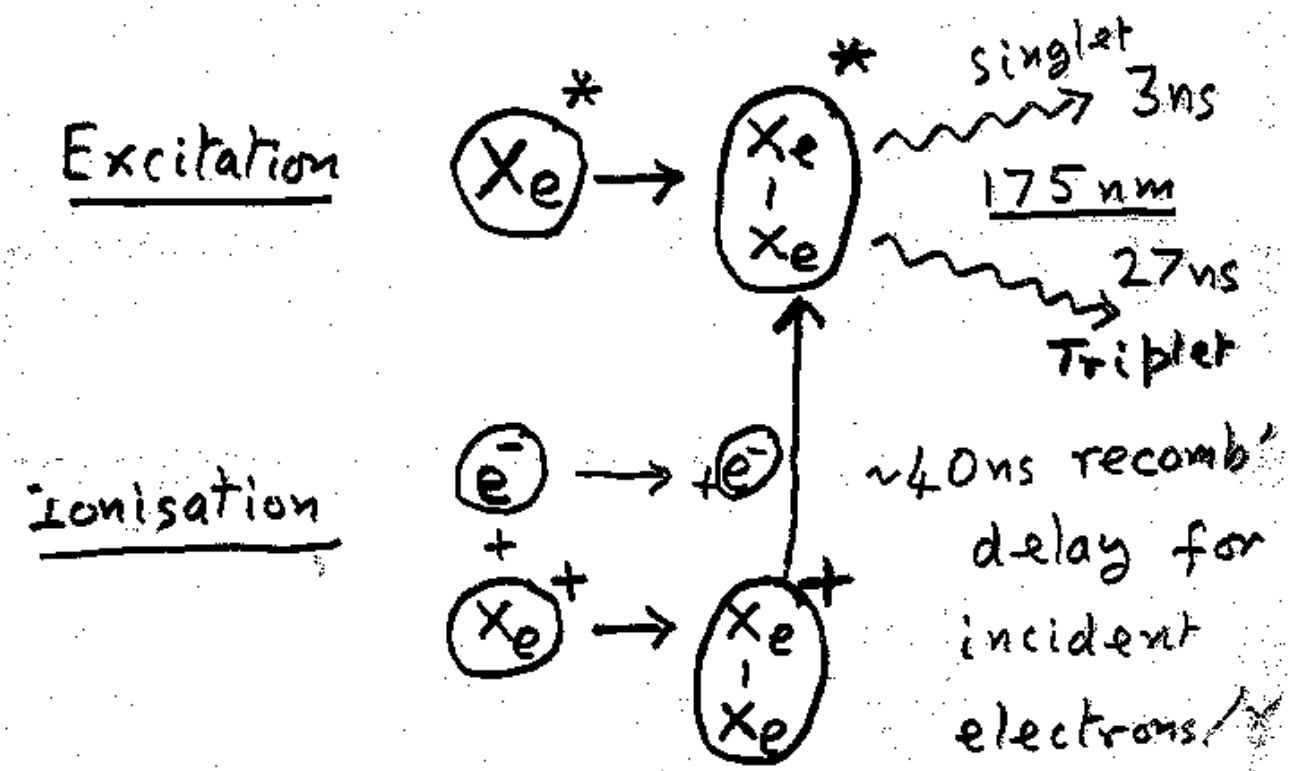
$f_g = 0.01$

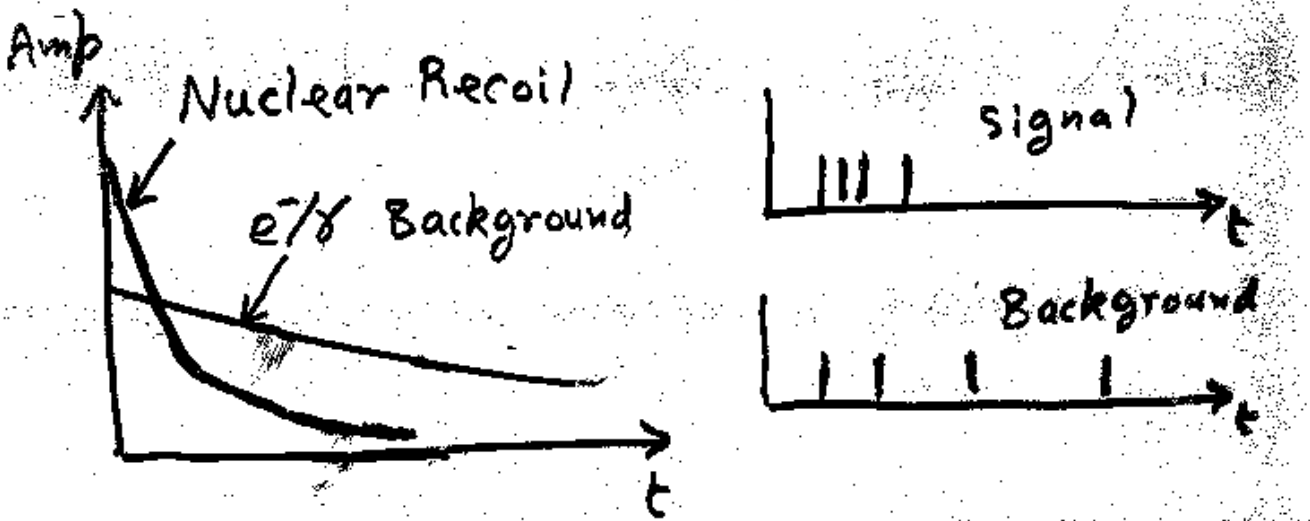
$\Rightarrow 100 \pm \sqrt{100}$

↑

fake signal

Discrimination by Photon Timing





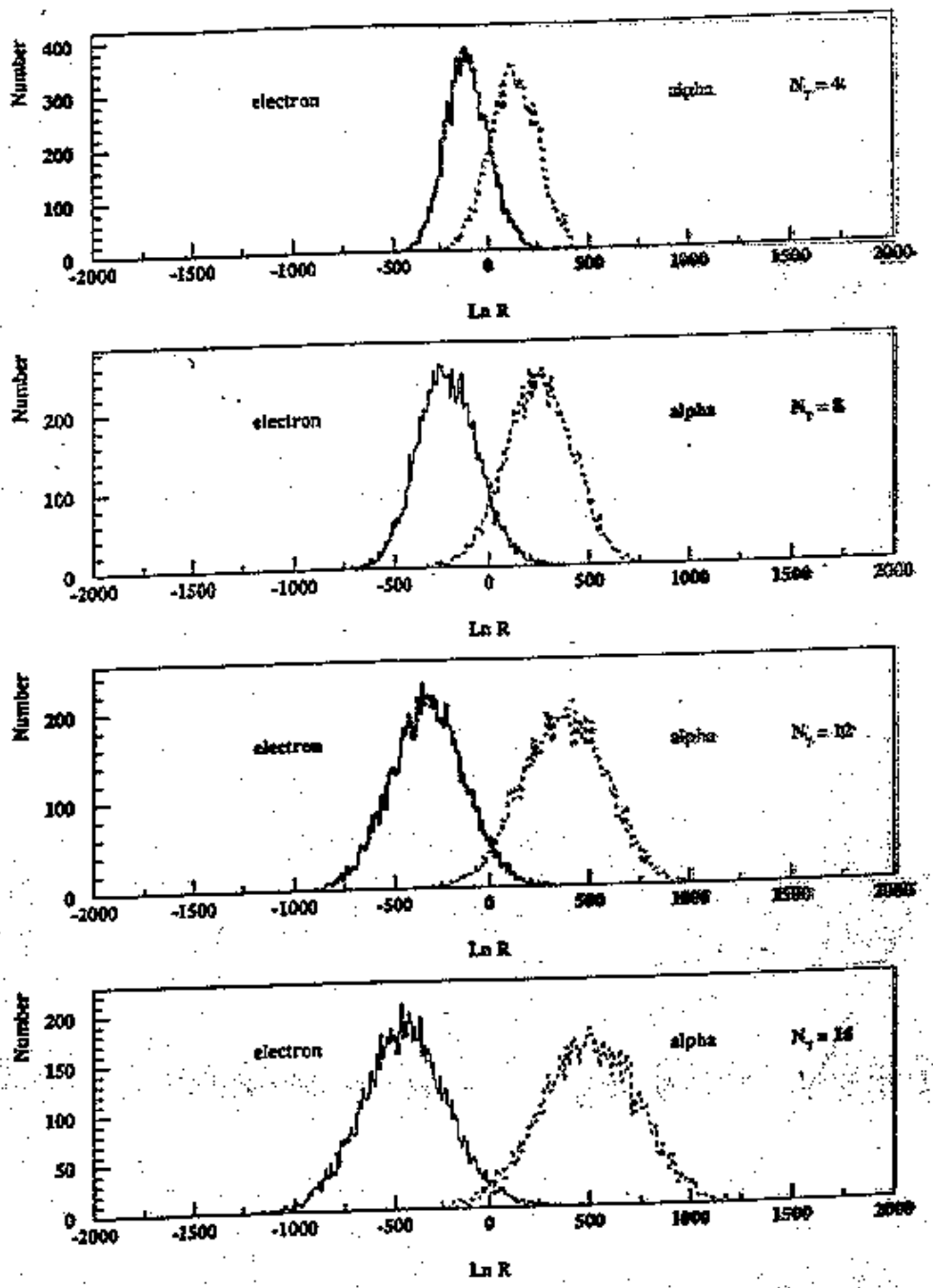
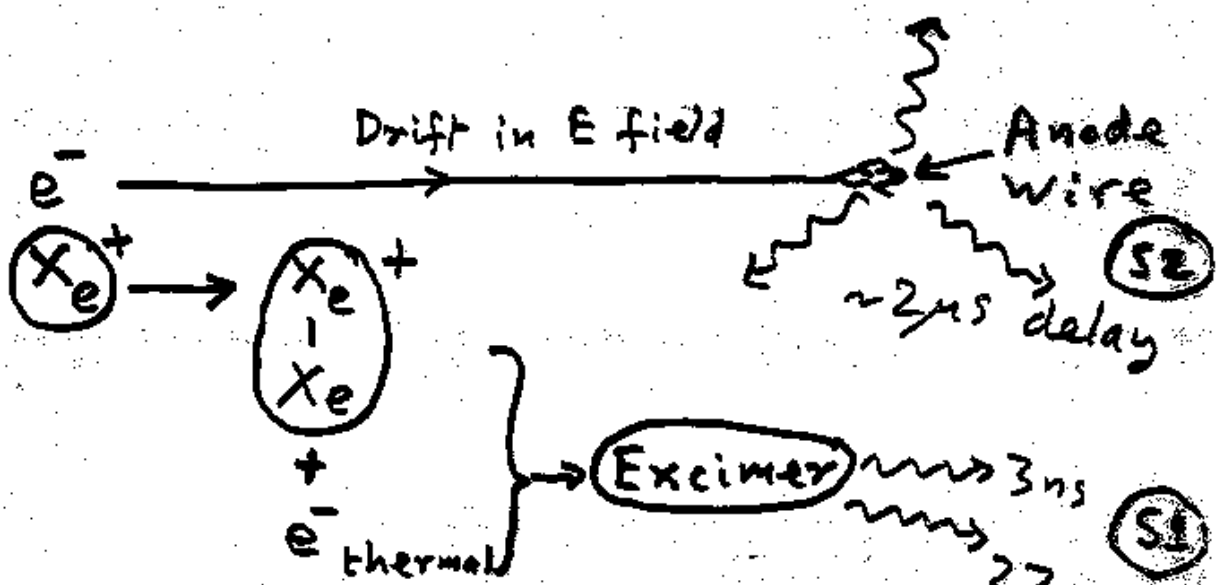


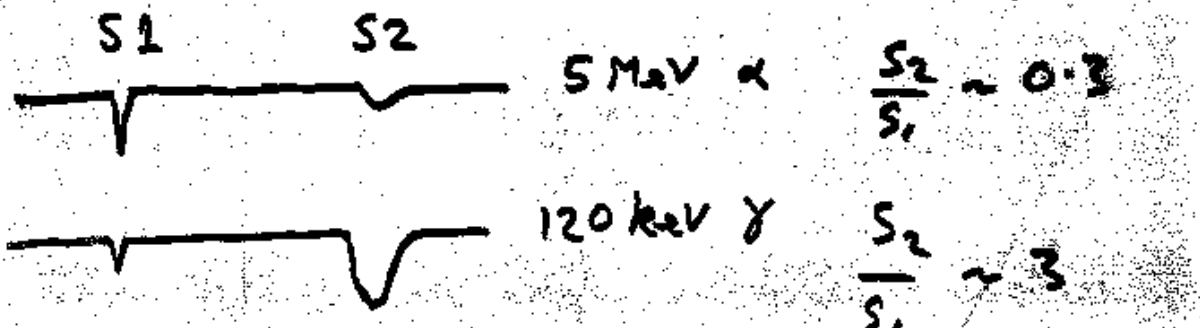
Fig. 7.21 Likelihood distribution with PMT single photoelectron pulse shape included

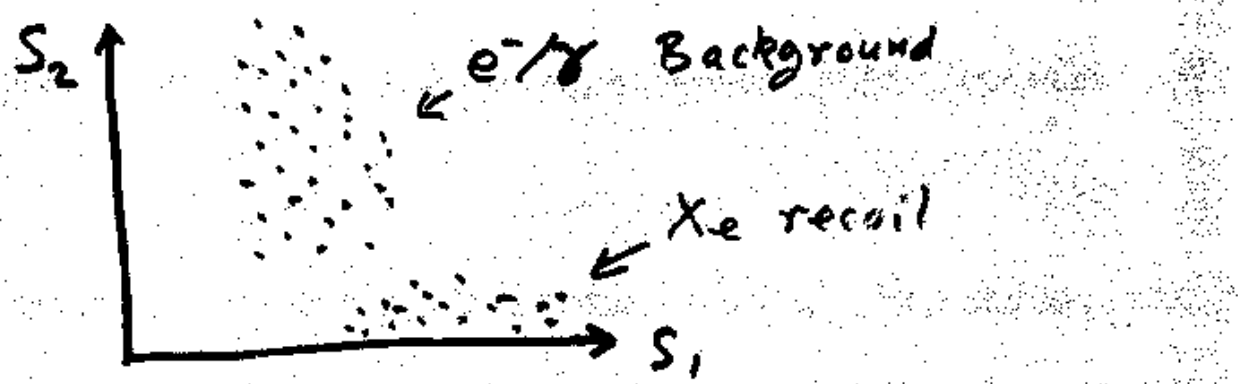
Discrimination by Drifting Ionisation

NIM A 327, 203

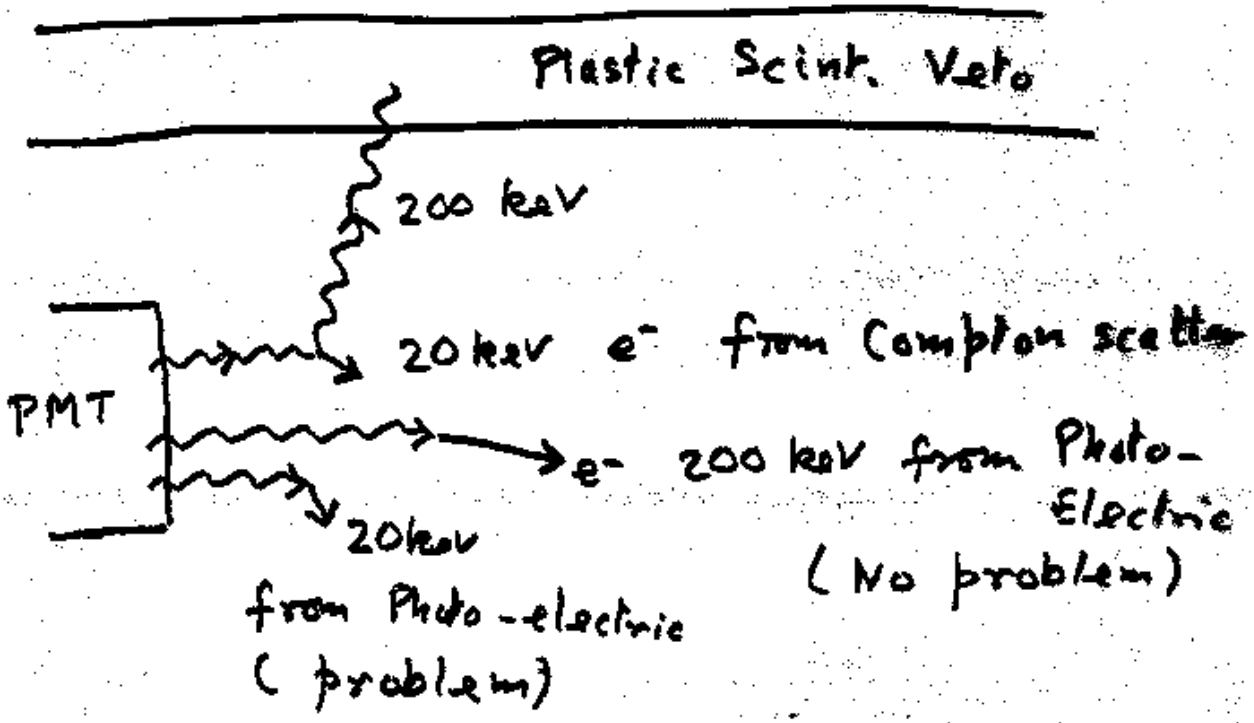
Icarus



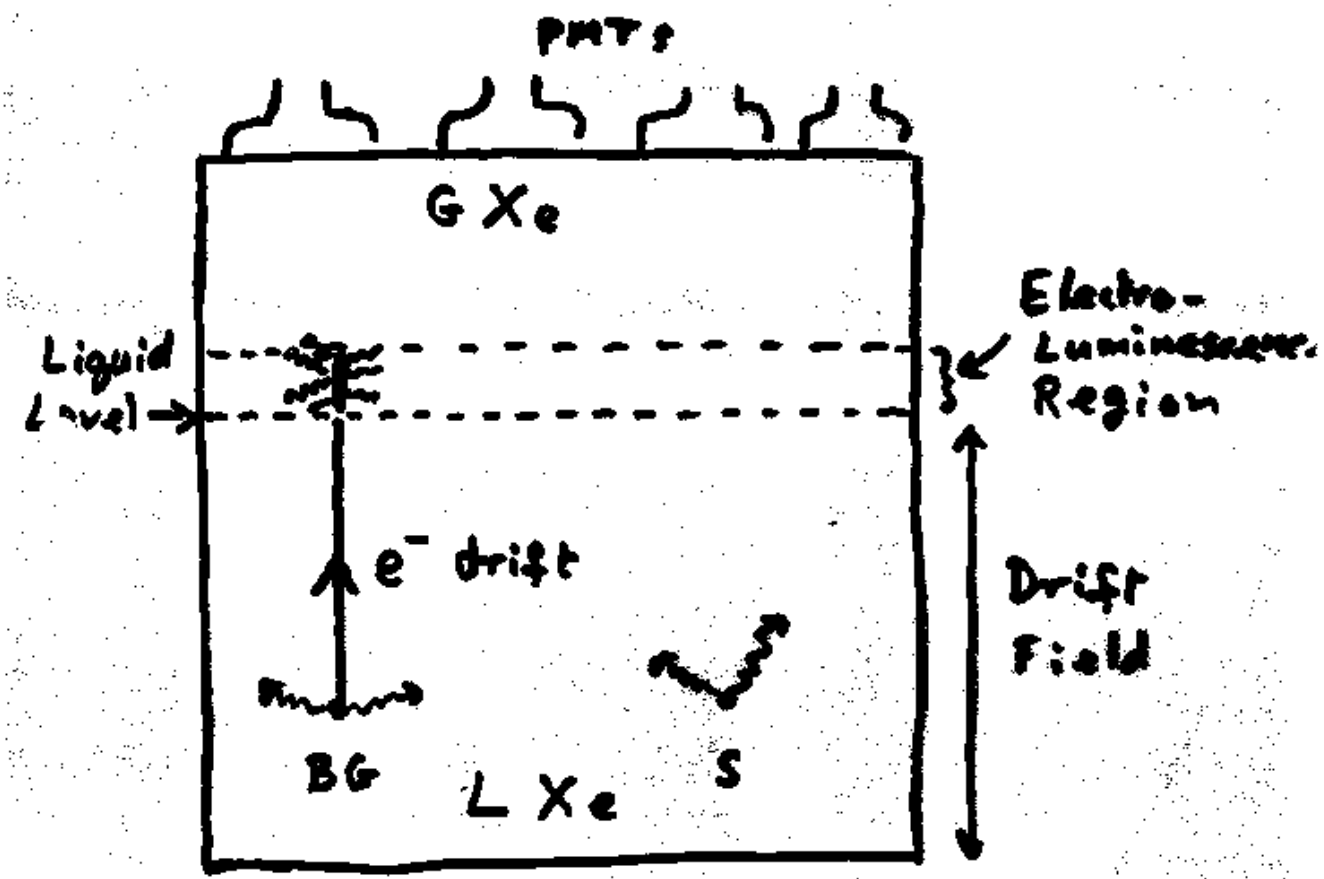




Backgrounds from PMT's



Principle of Two Phase Design



Electroluminescence Light Yield

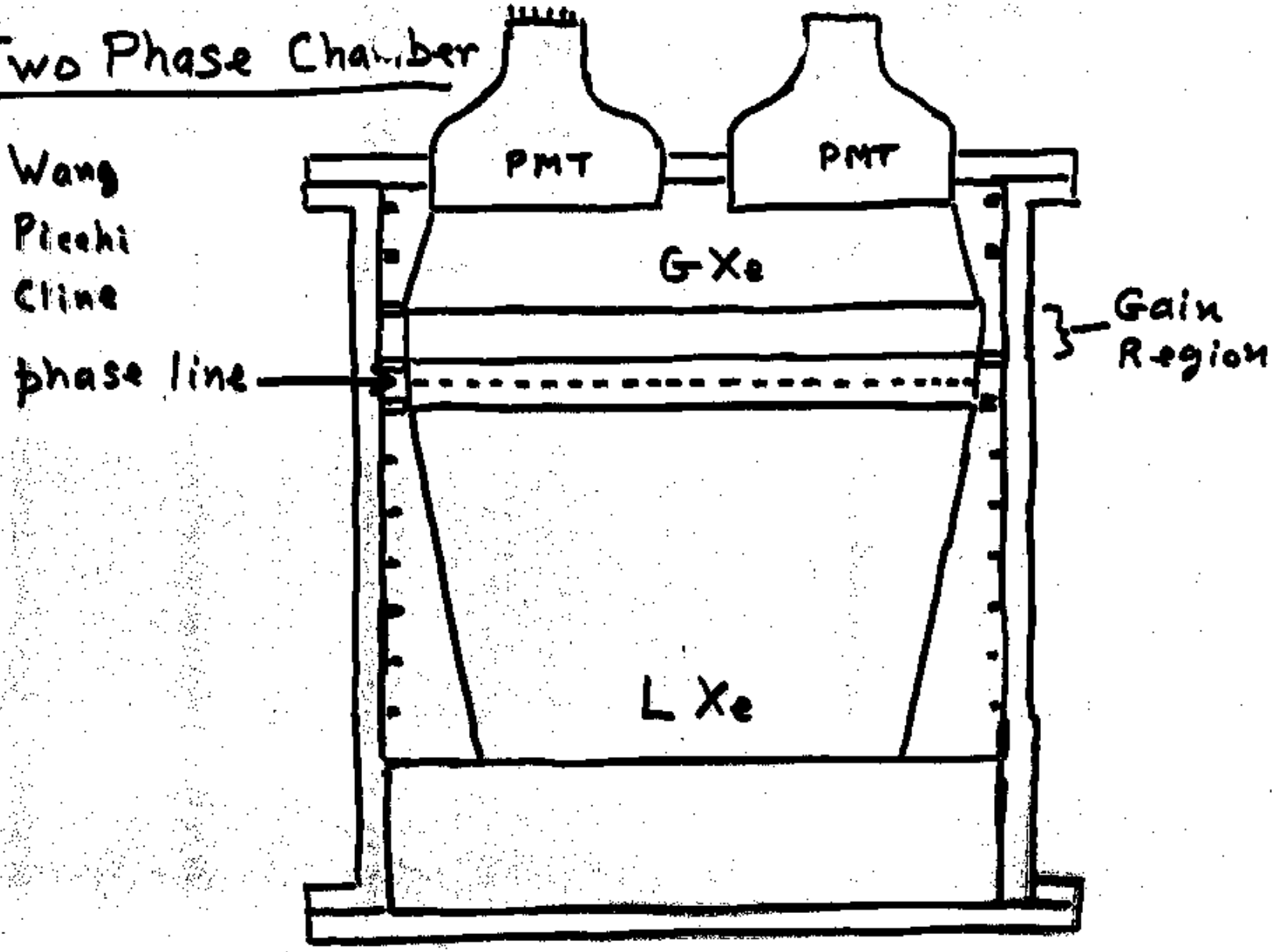
$$N_{ph} = 70\left(\frac{E}{P} - 1\right) x \cdot P$$

x in cm, P in bar

E in kV/cm

Two Phase Chamber

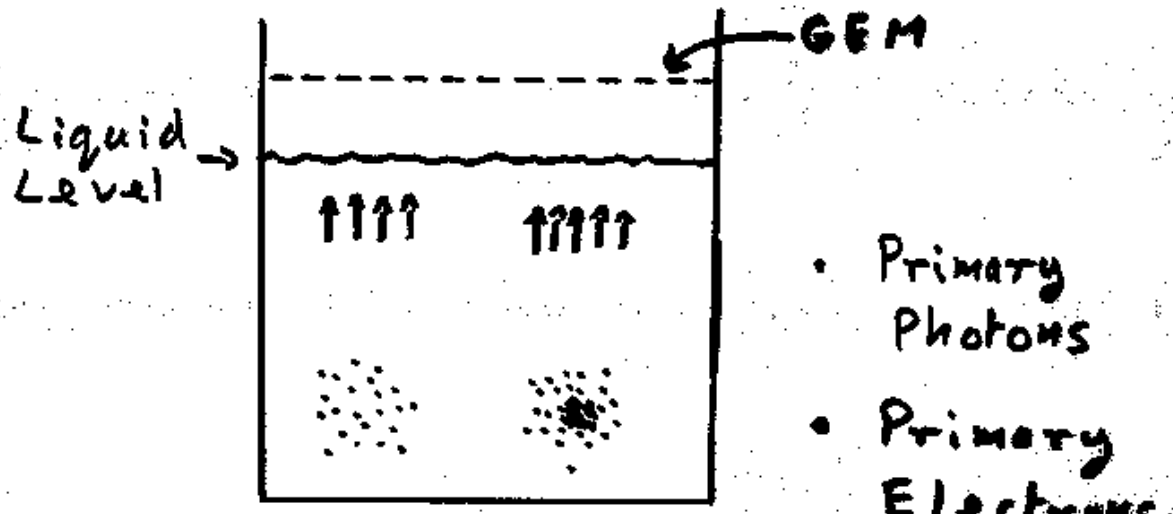
Wang
Piechi
Cline



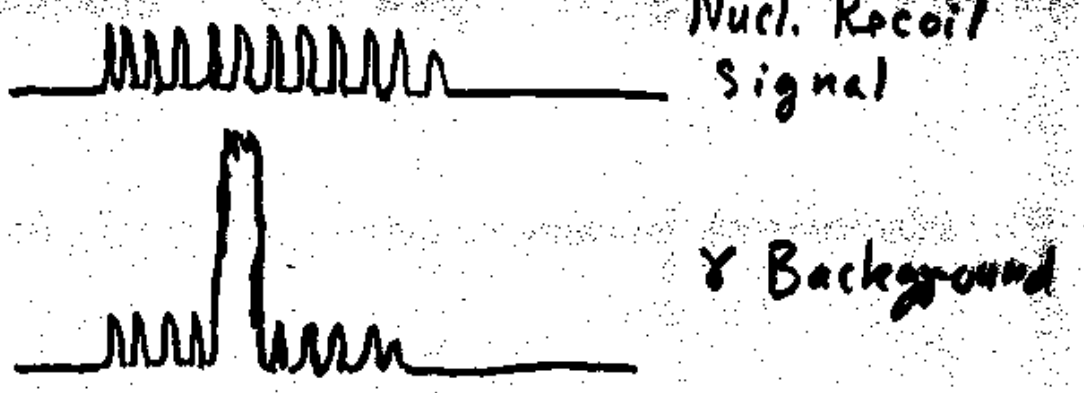
Further Developments

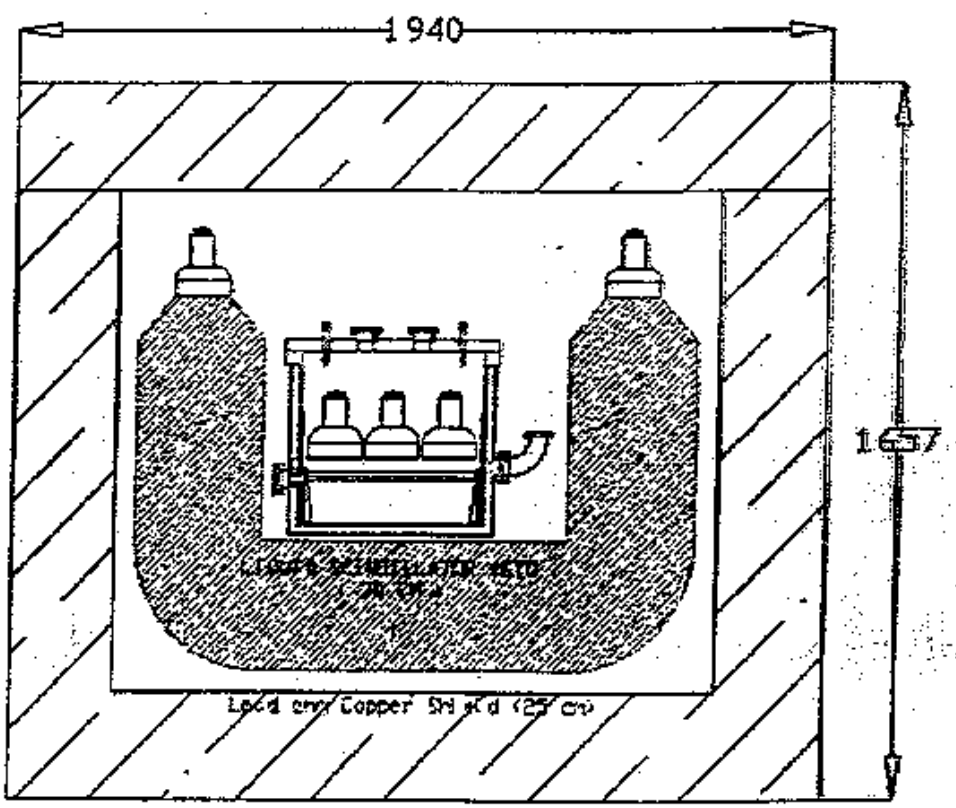
- Use APD's instead of PMT's
- Use HPD's
- Use GEM (Gas Electron Multiplier) idea in Two Phase Chamber

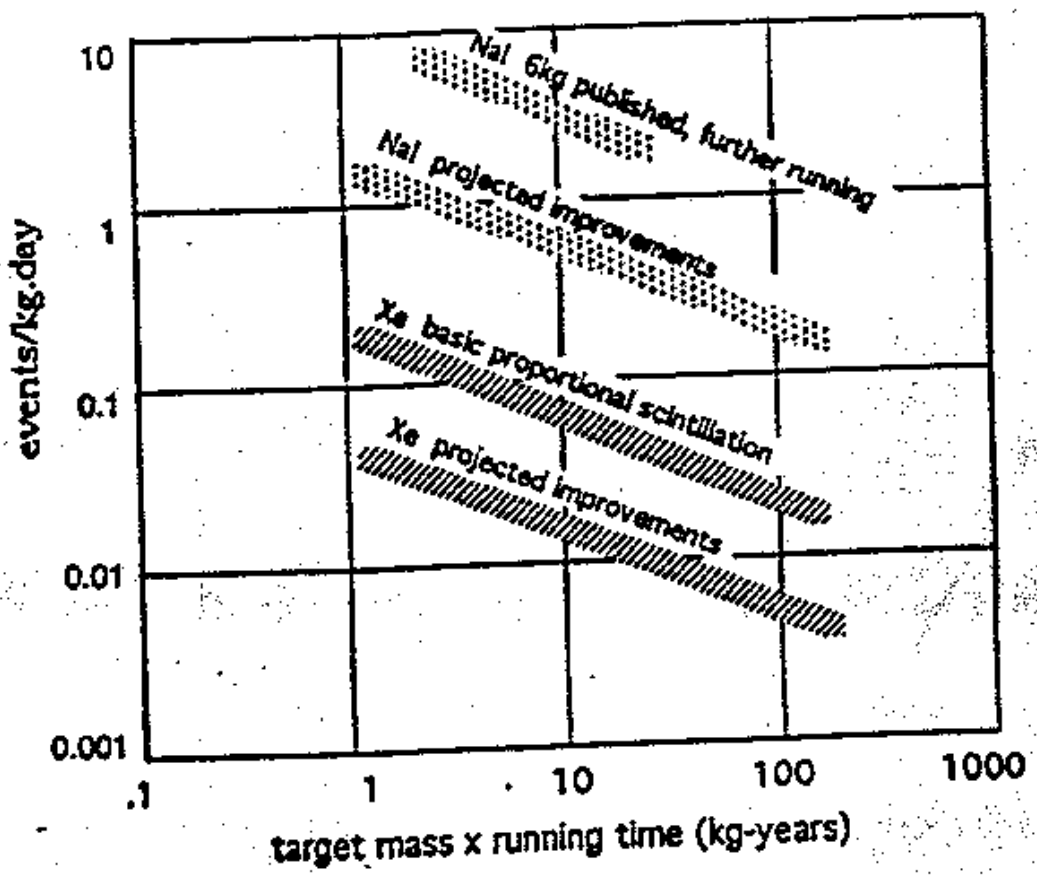
Doping with TEA



Nuc. Rec. Signal γ BG




1940
1657


NaI 6kg published, further running
NaI projected improvements
Xe basic proportional scintillation
Xe projected improvements
events/kg.day
10
1
0.1
0.01
0.001
.1
1
10
100
1000
target mass x running time (kg-years)

Possible Pitfalls

- All Halo DM may be in MACHOs
- R parity may not be conserved
- WIMP mass may be too high (or too low?)
- Backgrounds may be too high