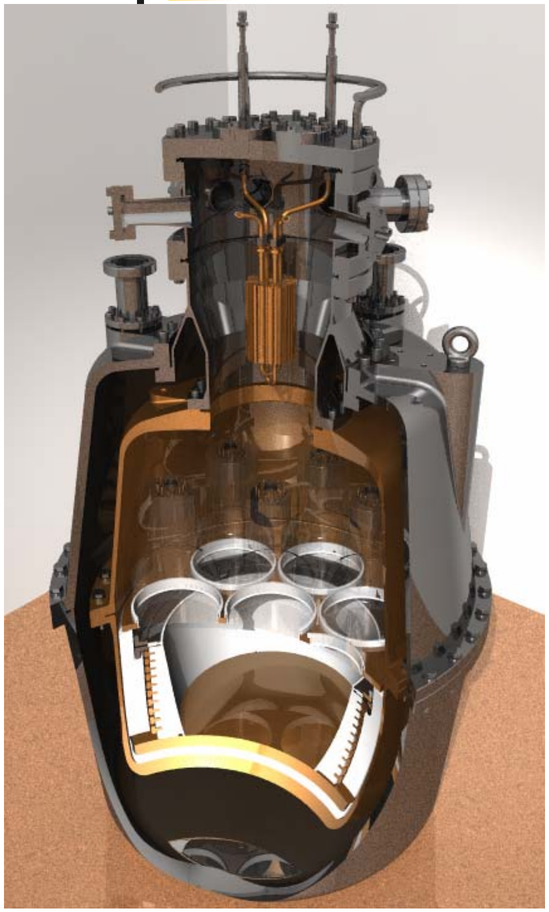
Search for Dark matter with ZEPLIN II Liquid Xenon Detector and LUX

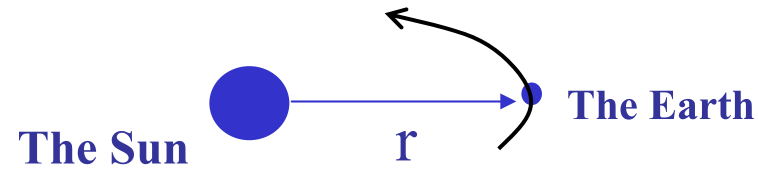
xenon two phase dark matter direct detection



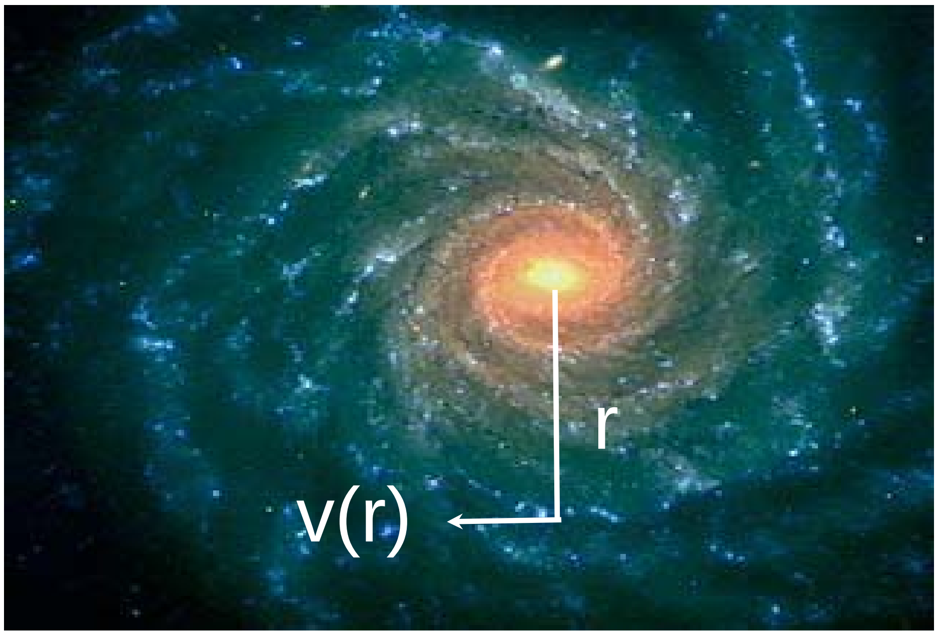
Hanguo Wang,
UCLA, Physics and Astronomy
UC Davis HEP Seminar , Feb. 13, 2007

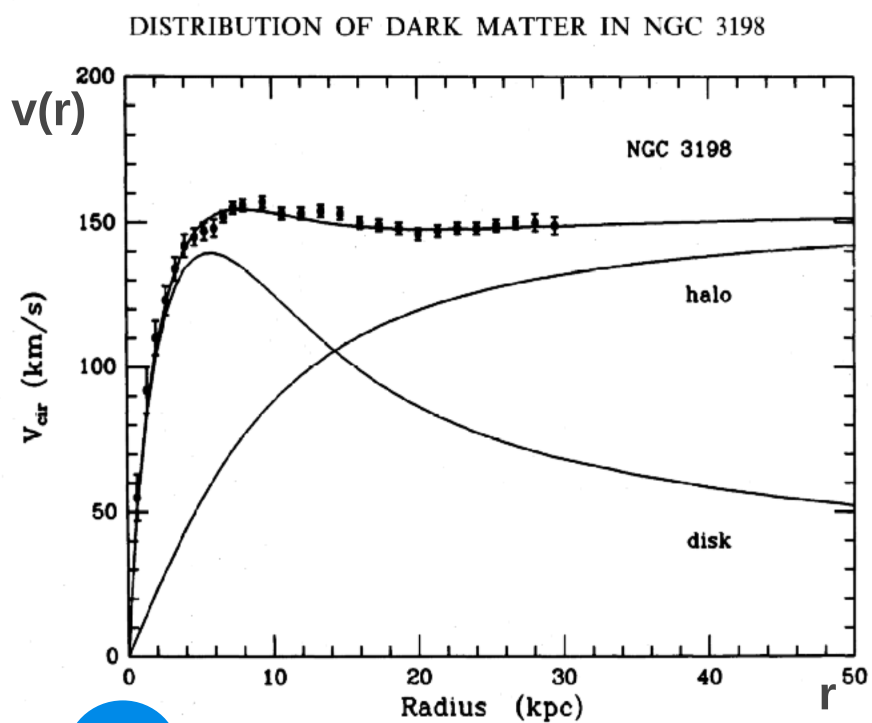
1. **Brief Introduction**
2. **Direct Detection**
3. **The ZEPLIN II Detector**
4. **Performance and Results**
5. **The LUX Detector**

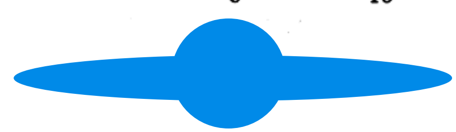
Evidence for dark matter



$$v = \sqrt{\frac{GM}{r}}$$



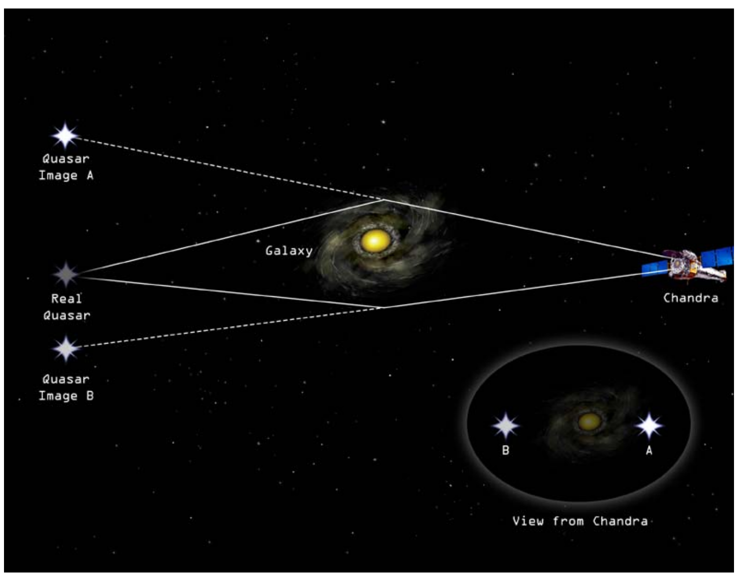


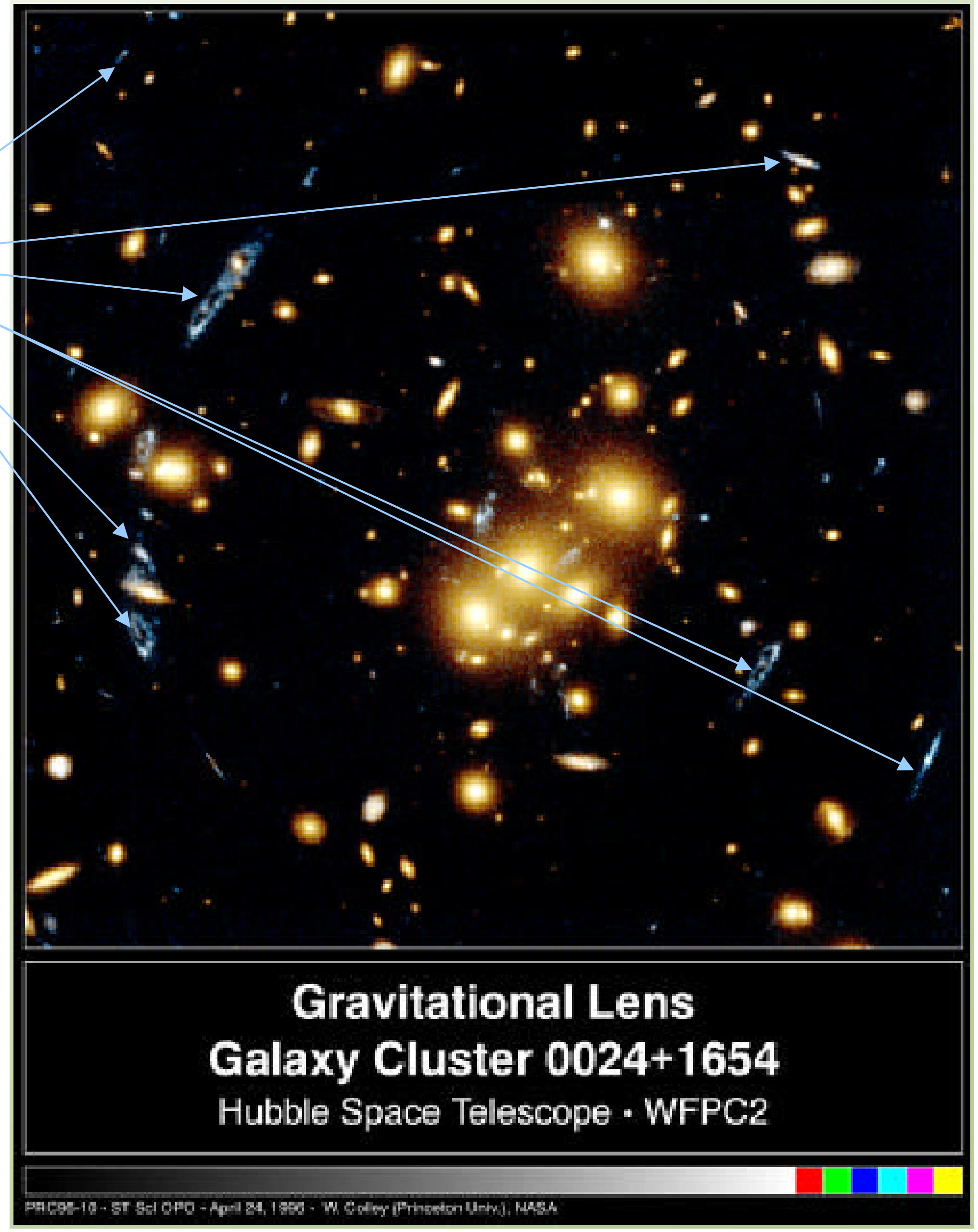


Rotation curves of spiral galaxies

Gravitational lenses:

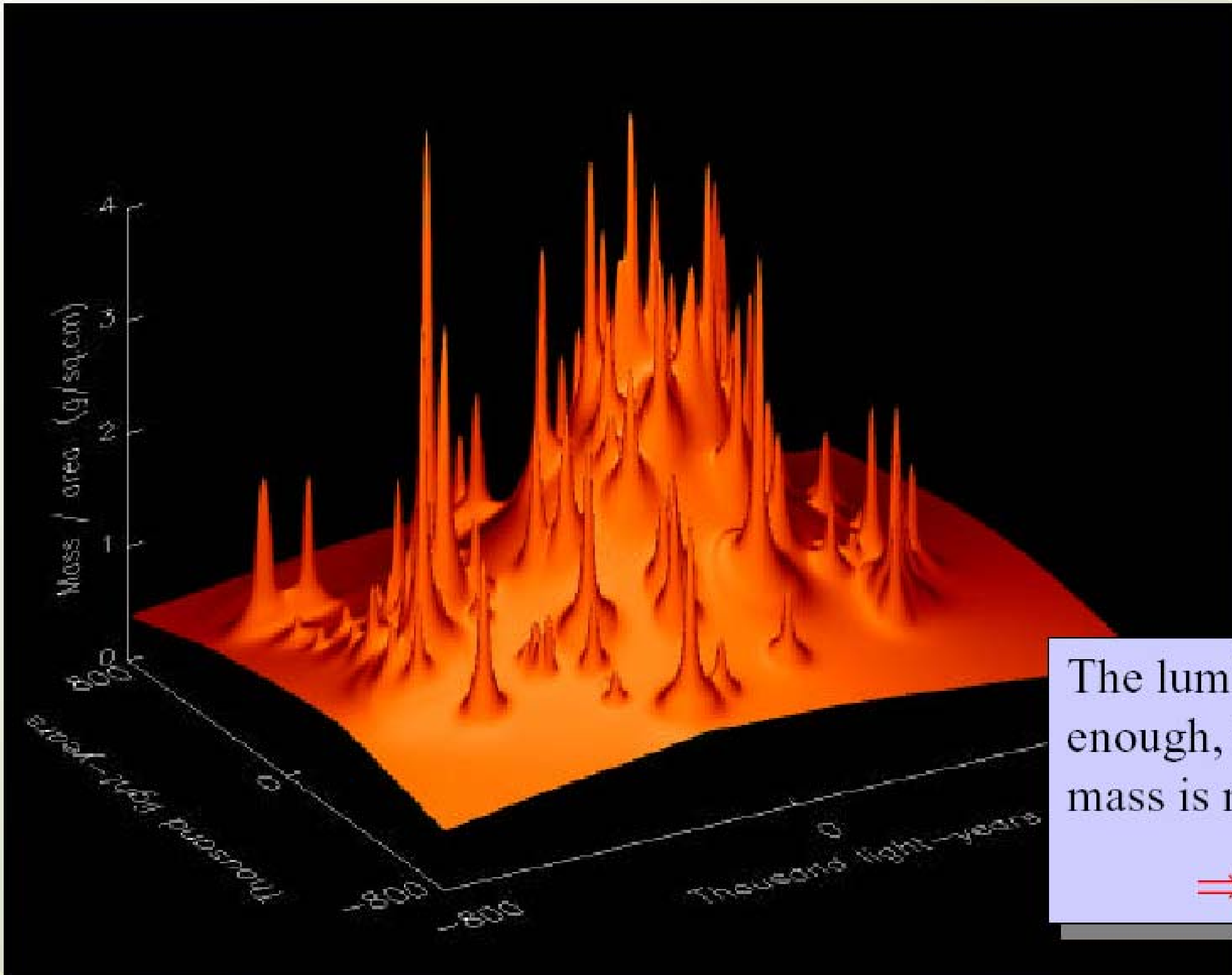
The blue arcs are light from a distant galaxy whose light has been deflected by the galaxy cluster in the foreground.





Dark matter - gravitational lenses

Reconstruction of the mass distribution in the galaxy cluster

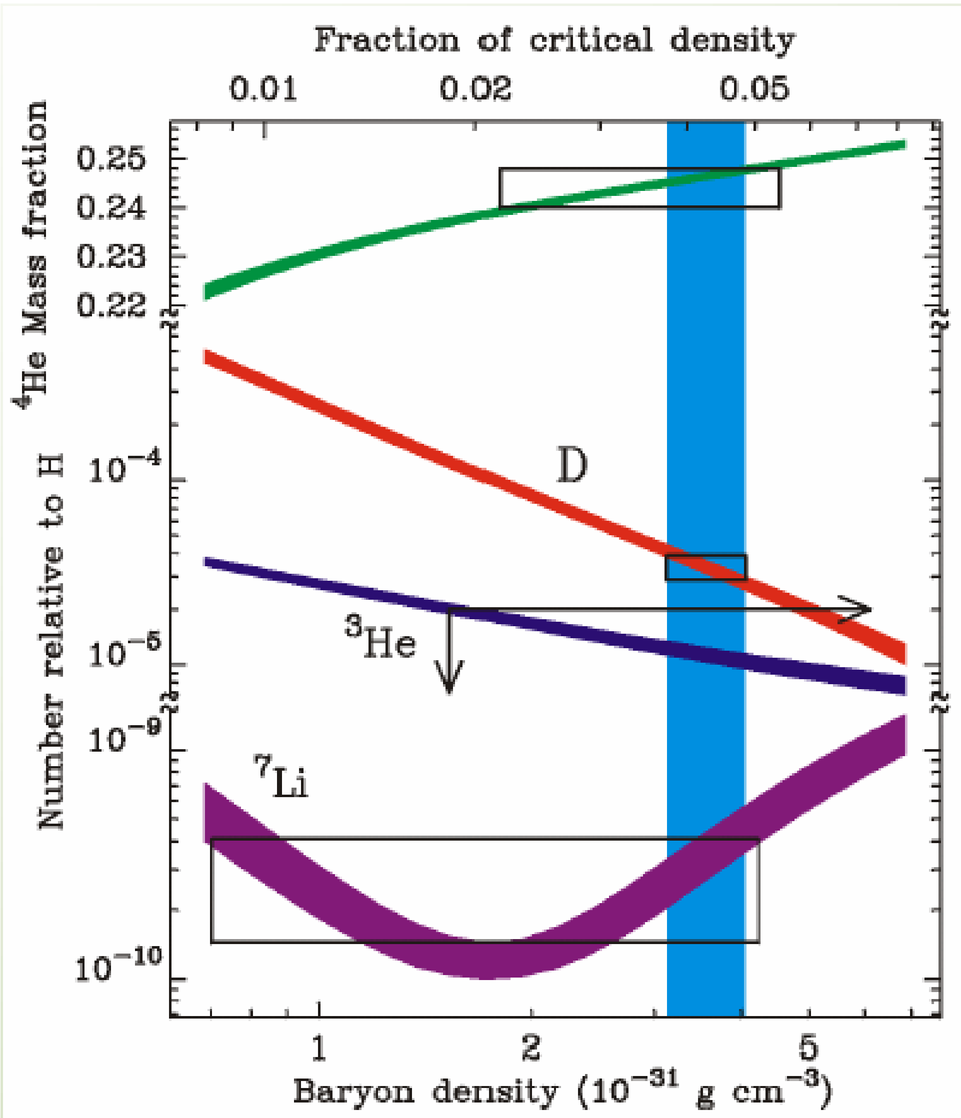


The luminous mass is not enough, the reconstructed mass is much larger!

⇒Dark Matter!

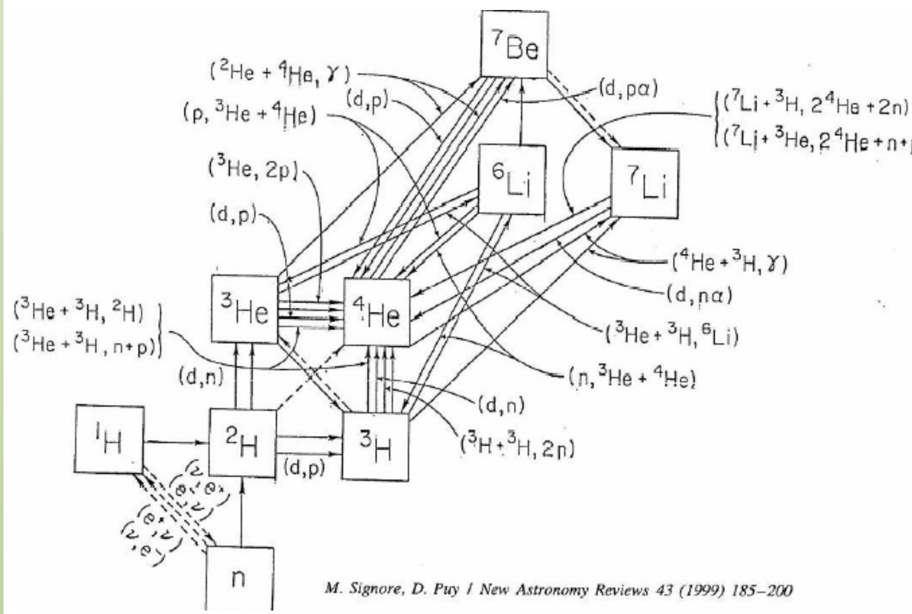
Från Tyson, Bell Labs.

Big Bang Nucleosynthesis



- Light elements up to 7Li are produced in the Big bang
- Nuclear reactions are known
- The amount of light elements can be calculated
- Compare with observations

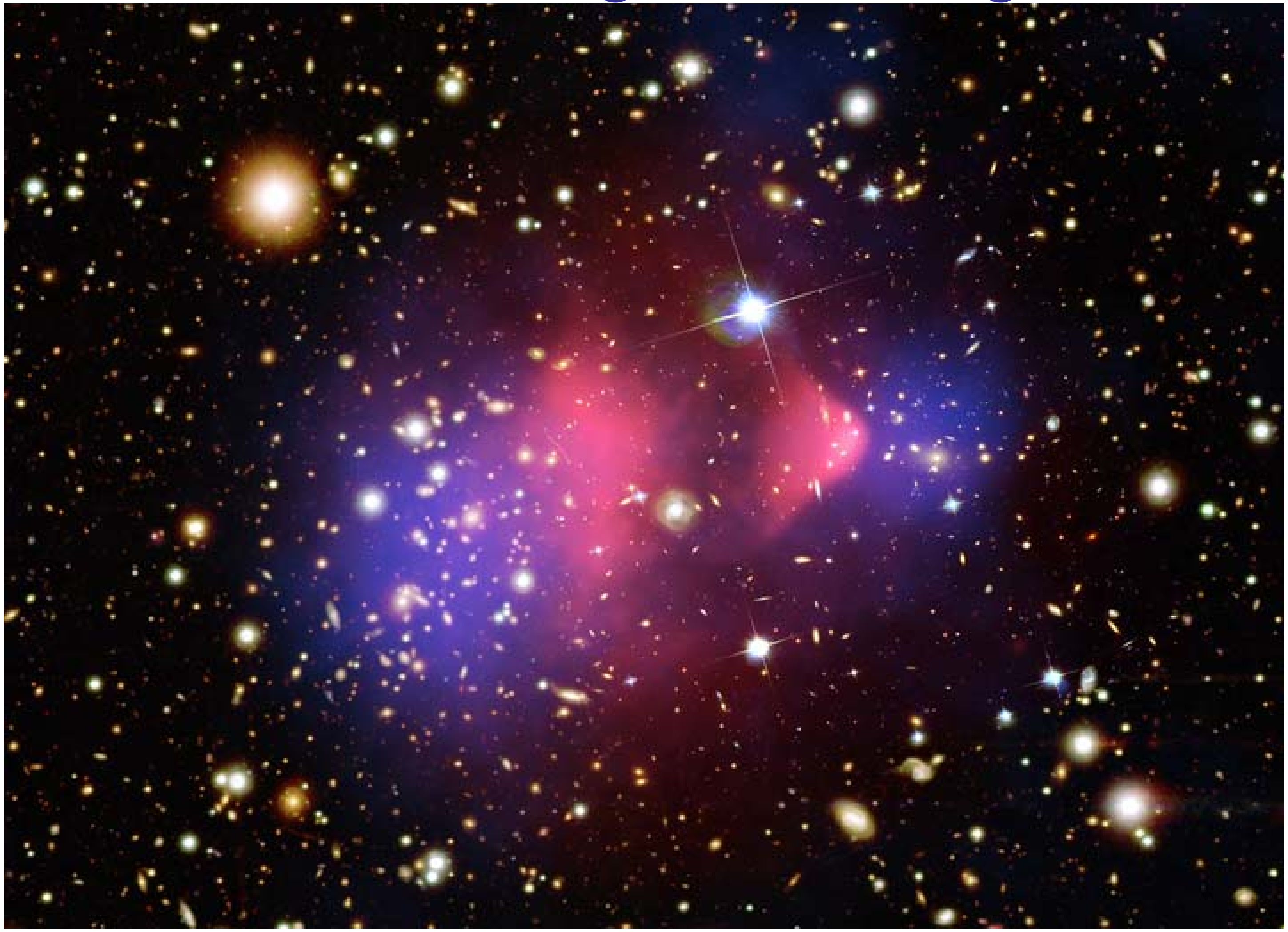
- The baryons can only make up a small fraction of the dark matter



From Turner et al.

M. Signore, New Astro. Rev. 1999

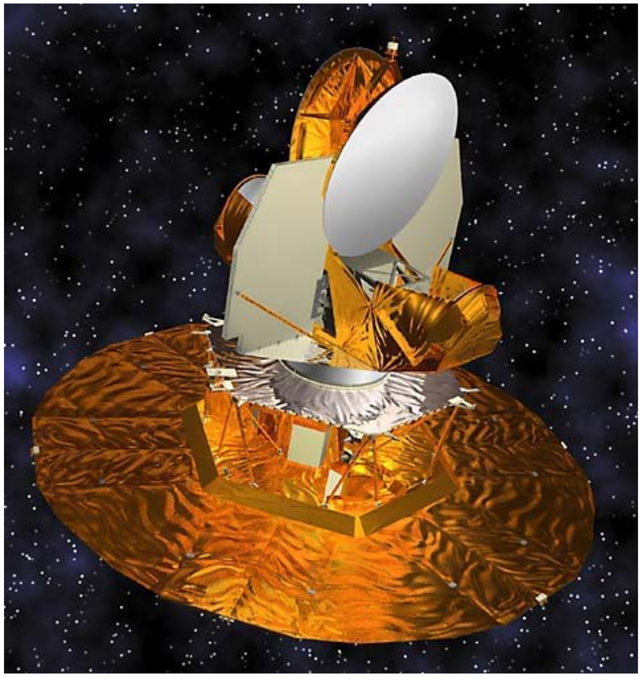
collision of two large clusters of galaxies

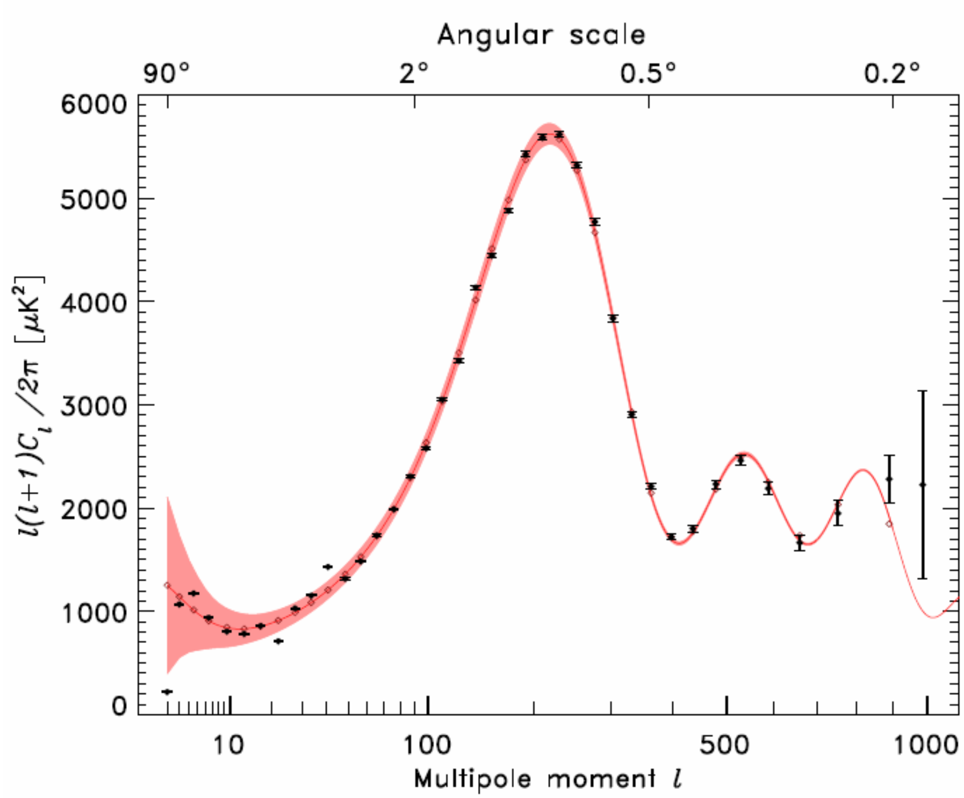


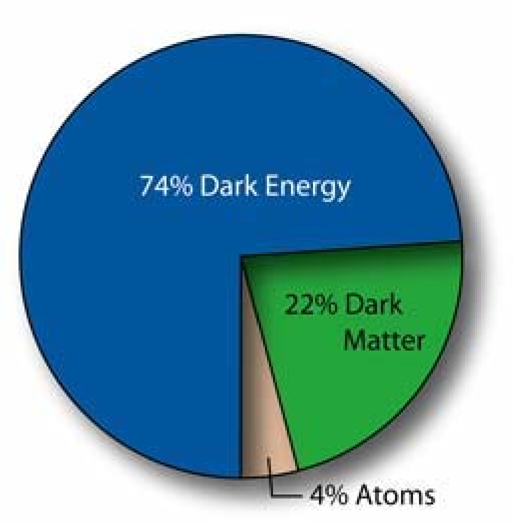
The discovery, using NASA's Chandra X-ray Observatory and other telescopes, gives direct evidence for the existence of dark matter.

Pink: Hot gas, Blue: Dark Matter

Wilson Microwave Anisotropy Probe (WMAP)



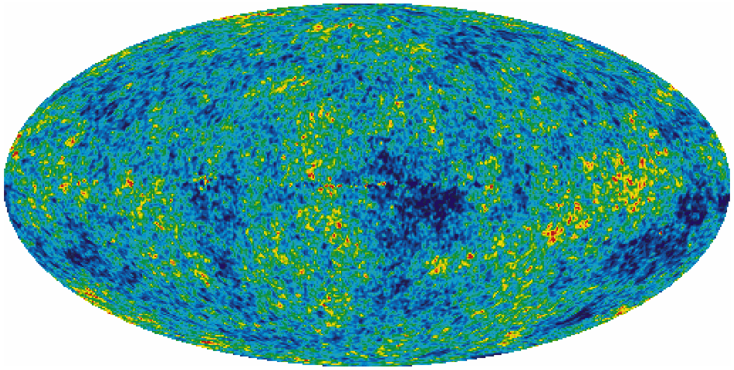




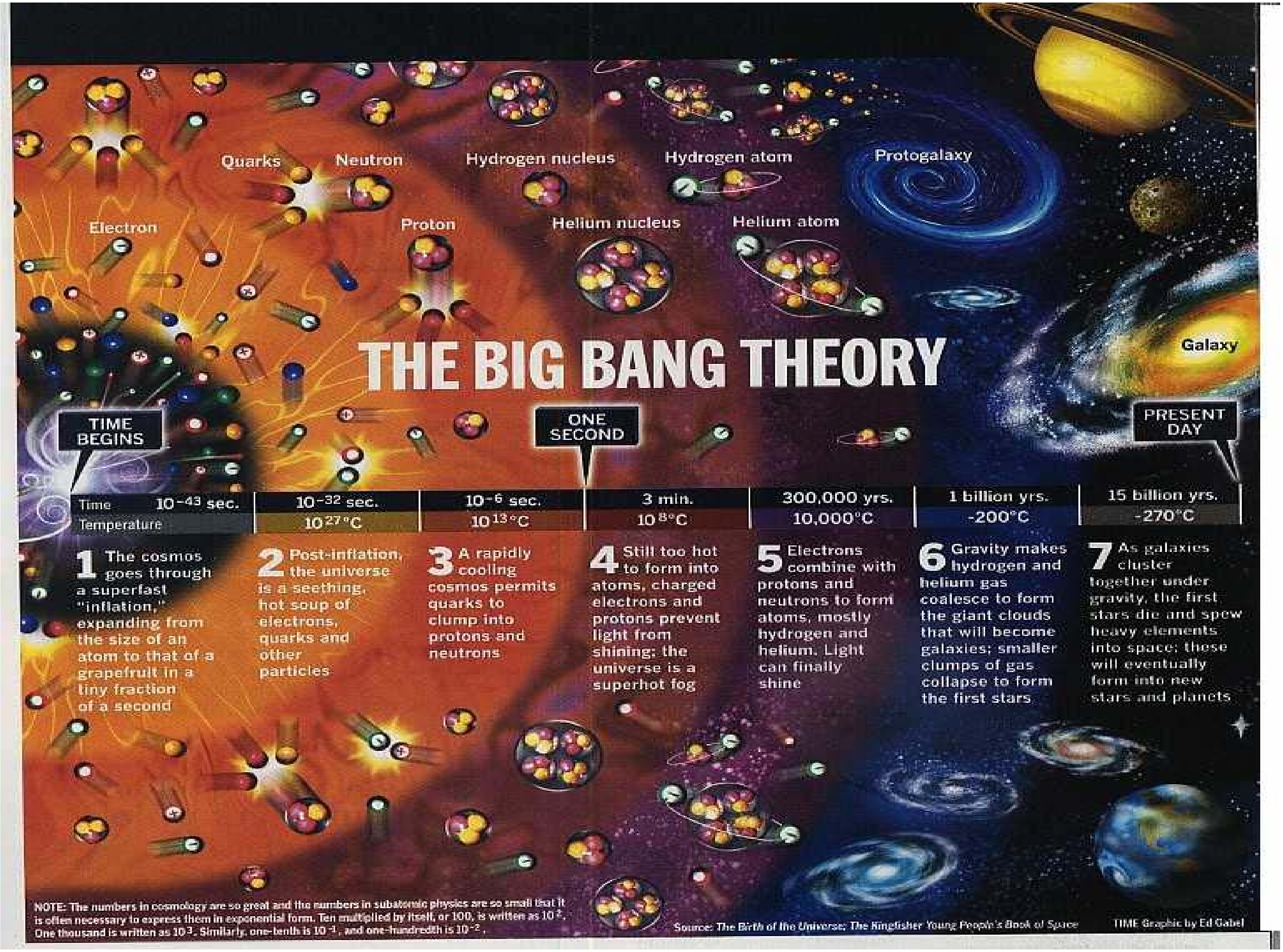
$$\Omega_m h^2 = 0.127^{+0.007}_{-0.013}$$

$$\Omega_b h^2 = 0.0223^{+0.0007}_{-0.0009}$$

$$h = 0.73^{+0.03}_{-0.03}$$

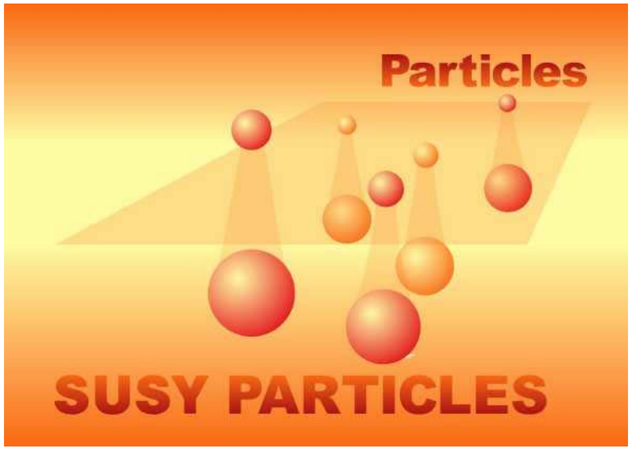


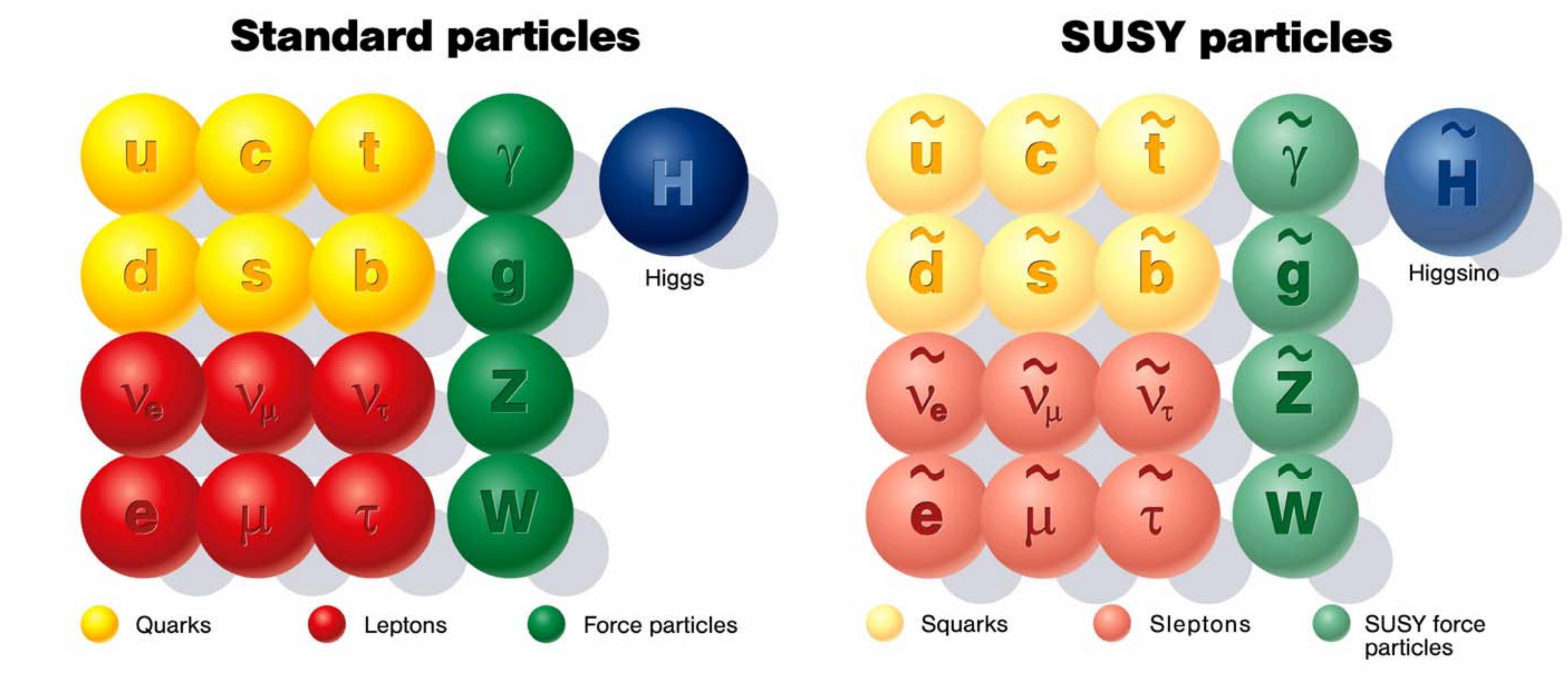
Dark Matter: Everything here is only <1% of the whole story



A WIMP χ (Weakly Interacting Massive Particle)
Created in the Bug Bang:
Is predicted in Supersymmetric theory of particle physics:
Lightest particle, **neutralino**, with a mass
~ 100 x proton mass and stable

Has exactly the right properties to be the dark matter!

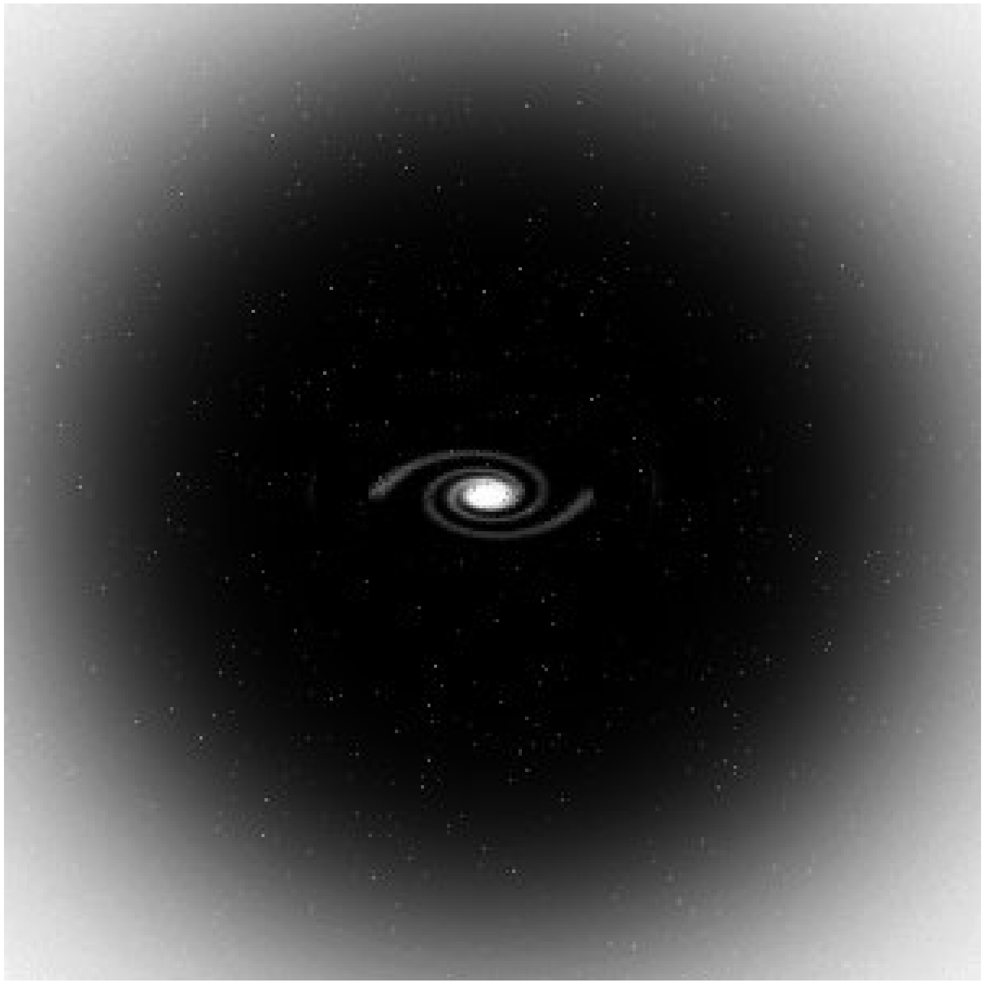




We see only SM particles Today Symmetry break at higher M scale

Relative size of luminous galaxy and the dark matter halo

$$v = \sqrt{\frac{GM}{r}}$$



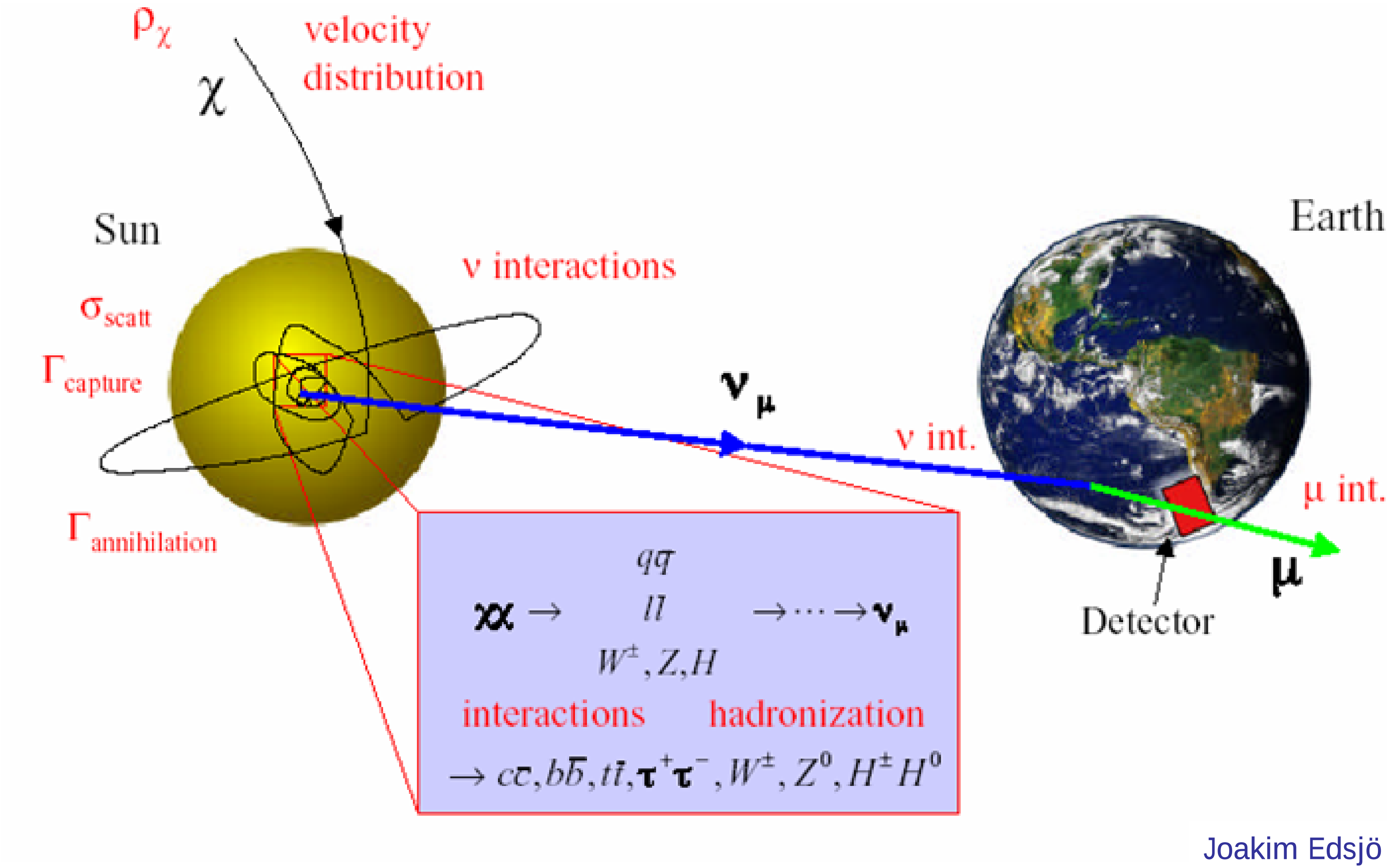
Cored spherical isothermal halo

$$\rho(r) = \rho_0 \frac{a^2 + r_0^2}{a^2 + r^2}$$

With Maxwelian local distribution

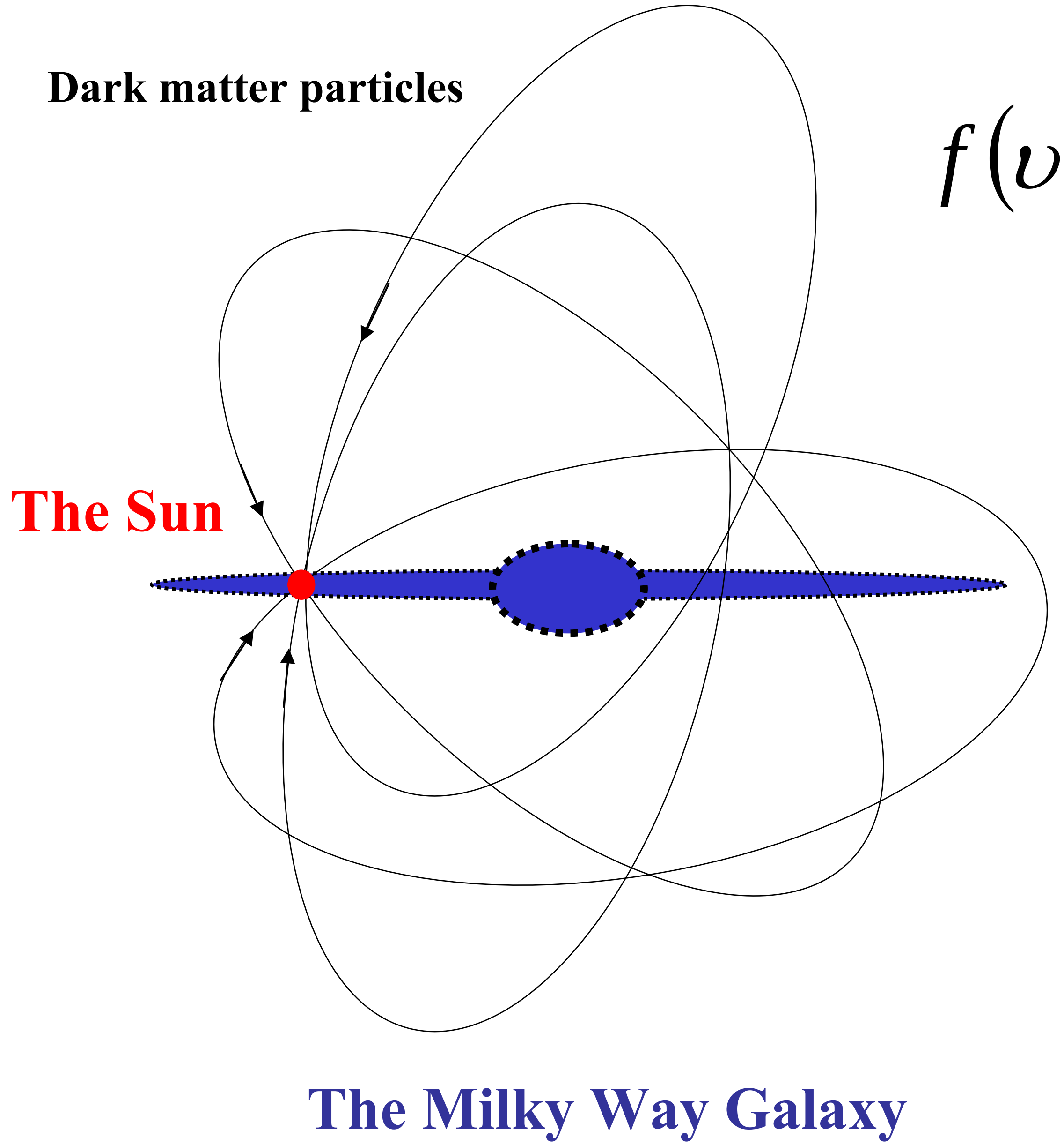
$$f(\upsilon)d^3\upsilon = \frac{e^{-\upsilon^2/\upsilon_0^2}}{\pi^{3/2}\upsilon_0^3} d^3\upsilon$$

Indirect searches: CDF & D0 at Fermilab (TeV-tron)
CMS & Atlas at CERN (LHC)



Joakim Edsjö

Direct Detection Strategy



$$f(\upsilon)d^3\upsilon = \frac{e^{-\upsilon^2/\upsilon_0^2}}{\pi^{3/2}\upsilon_0^3}d^3\upsilon$$

$$v_{\max} = 650 km/s$$

$$\rho = 0.3\ GeV/cm^{-3}$$

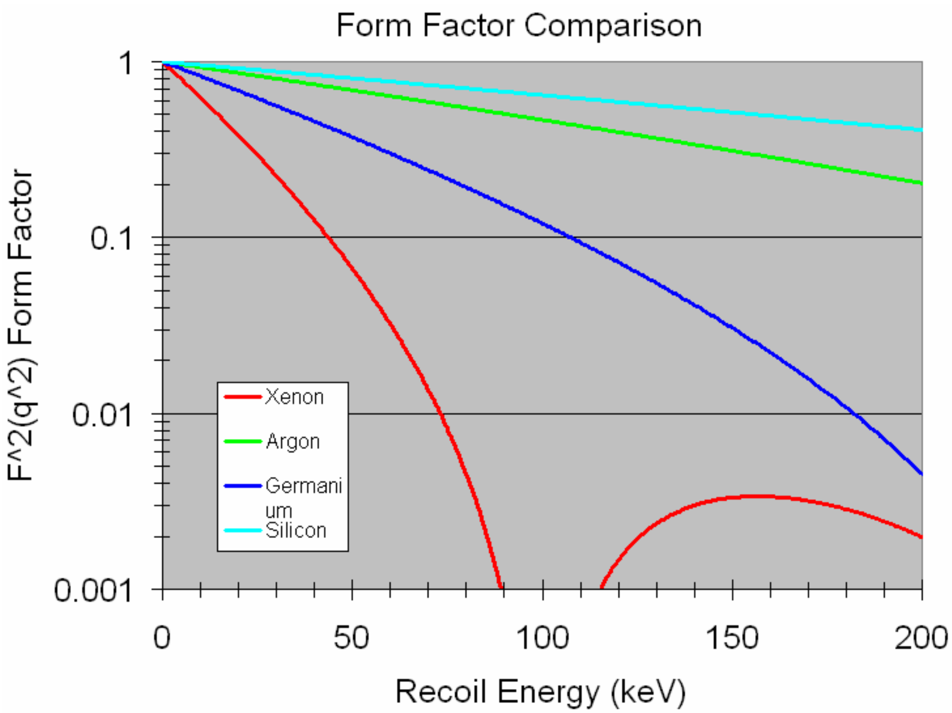
$$v \approx 220 km/s$$

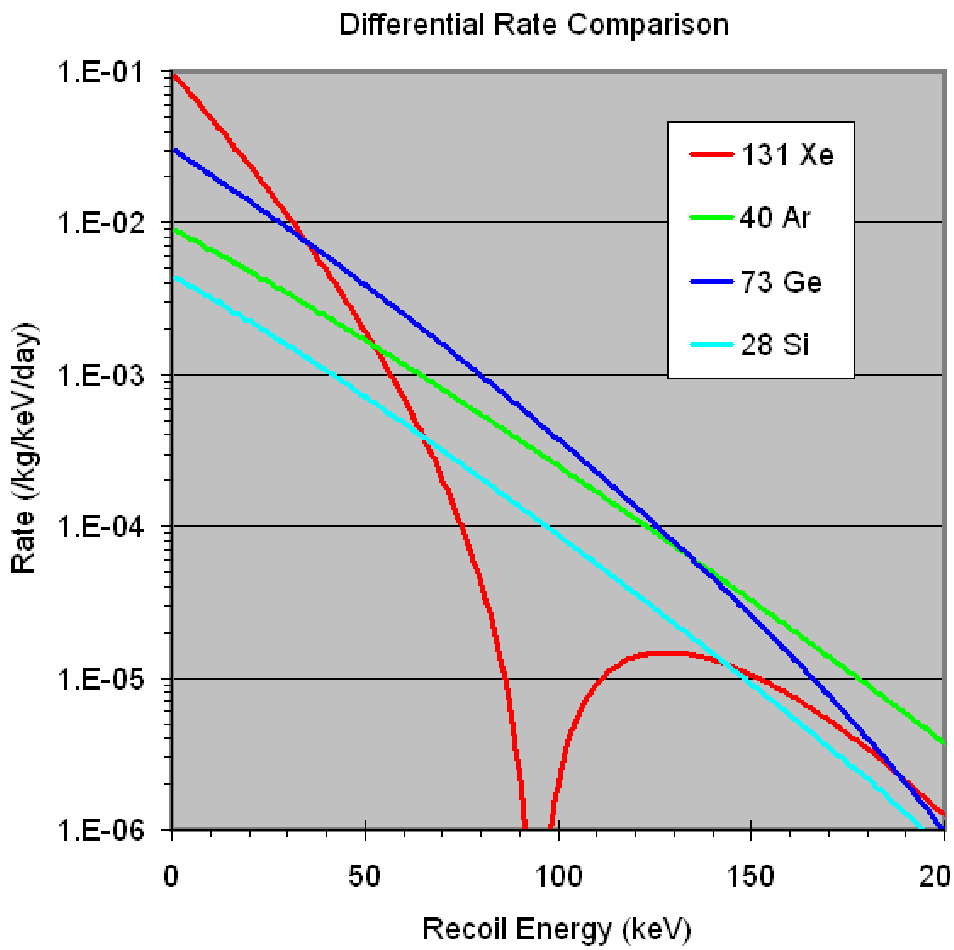
$$flux \approx 10^5 s^{-1} cm^{-2}$$

form factor effect with various targets

Coherent enhancement on event rate

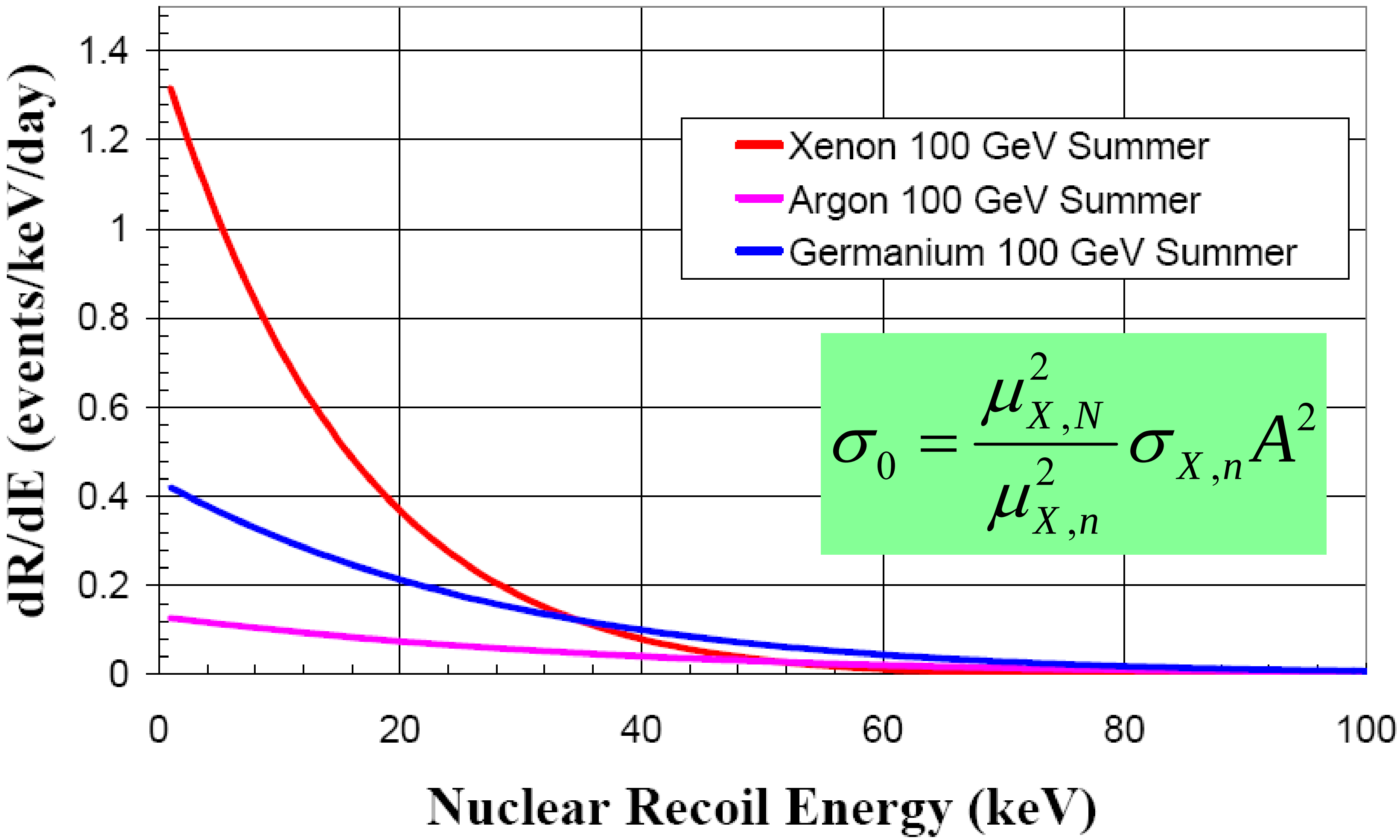
$$\sigma_c = \frac{\mu_{X,N}^2}{\mu_{X,n}^2} \sigma_{X,n} A^2$$





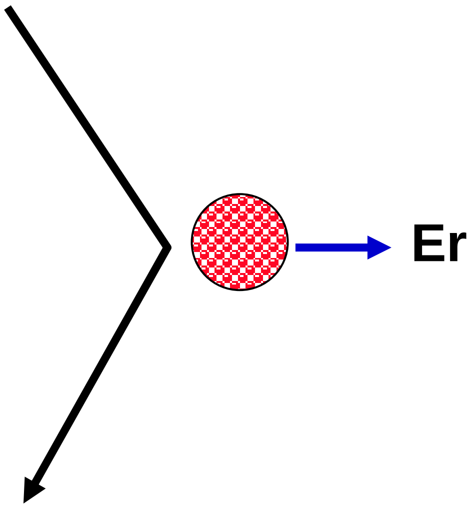
Recoil Spectra of different Targets

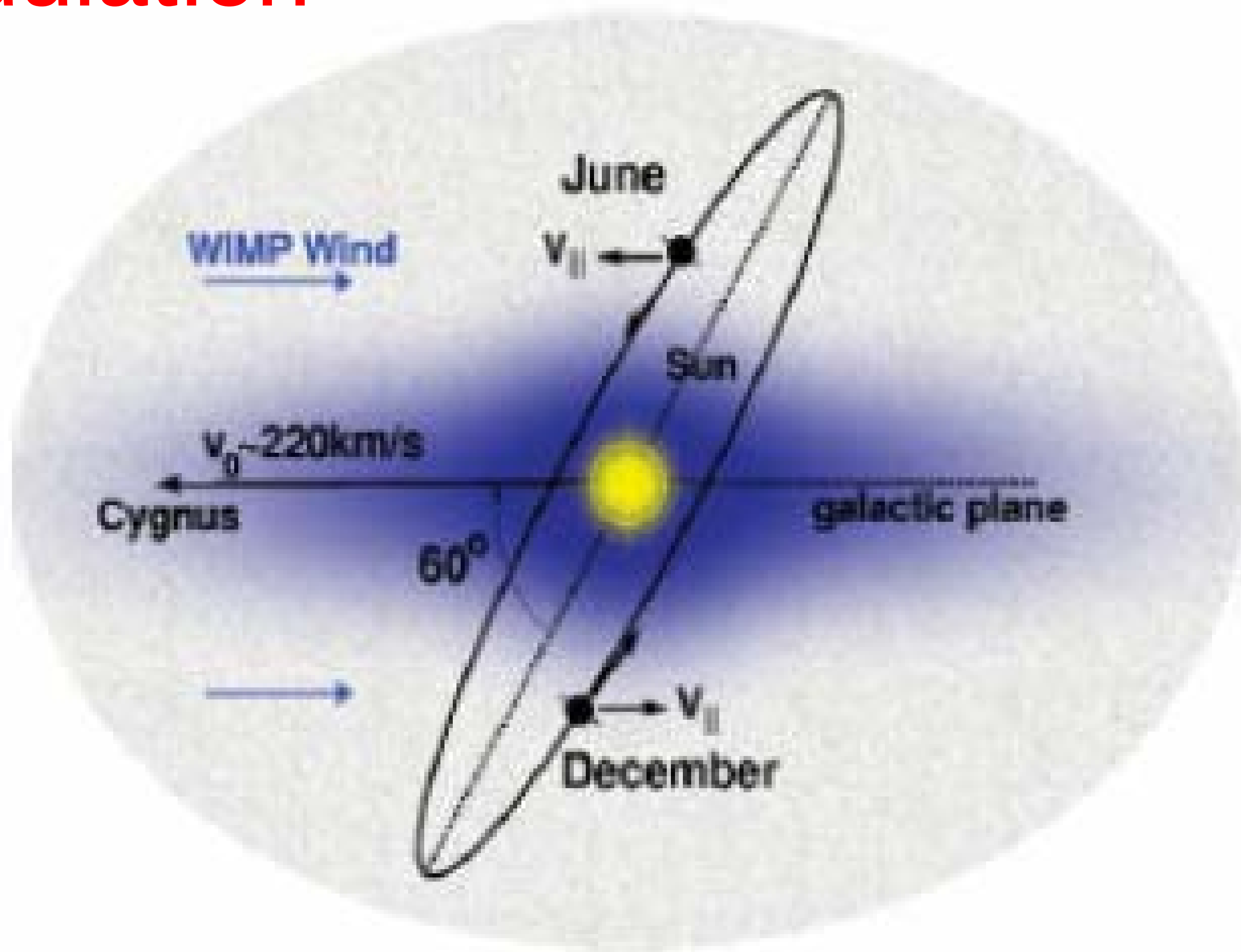
$$\frac{dR}{dE_R} = \frac{\sigma_0 \rho_x}{4\upsilon_e m_x \mu_{x,N}^2} F^2(E_R) \left[\mathrm{erf}\left(\frac{\upsilon_{\min} + \upsilon_e}{\upsilon_0} \right) - \mathrm{erf}\left(\frac{\upsilon_{\min} - \upsilon_e}{\upsilon_0} \right) \right]$$



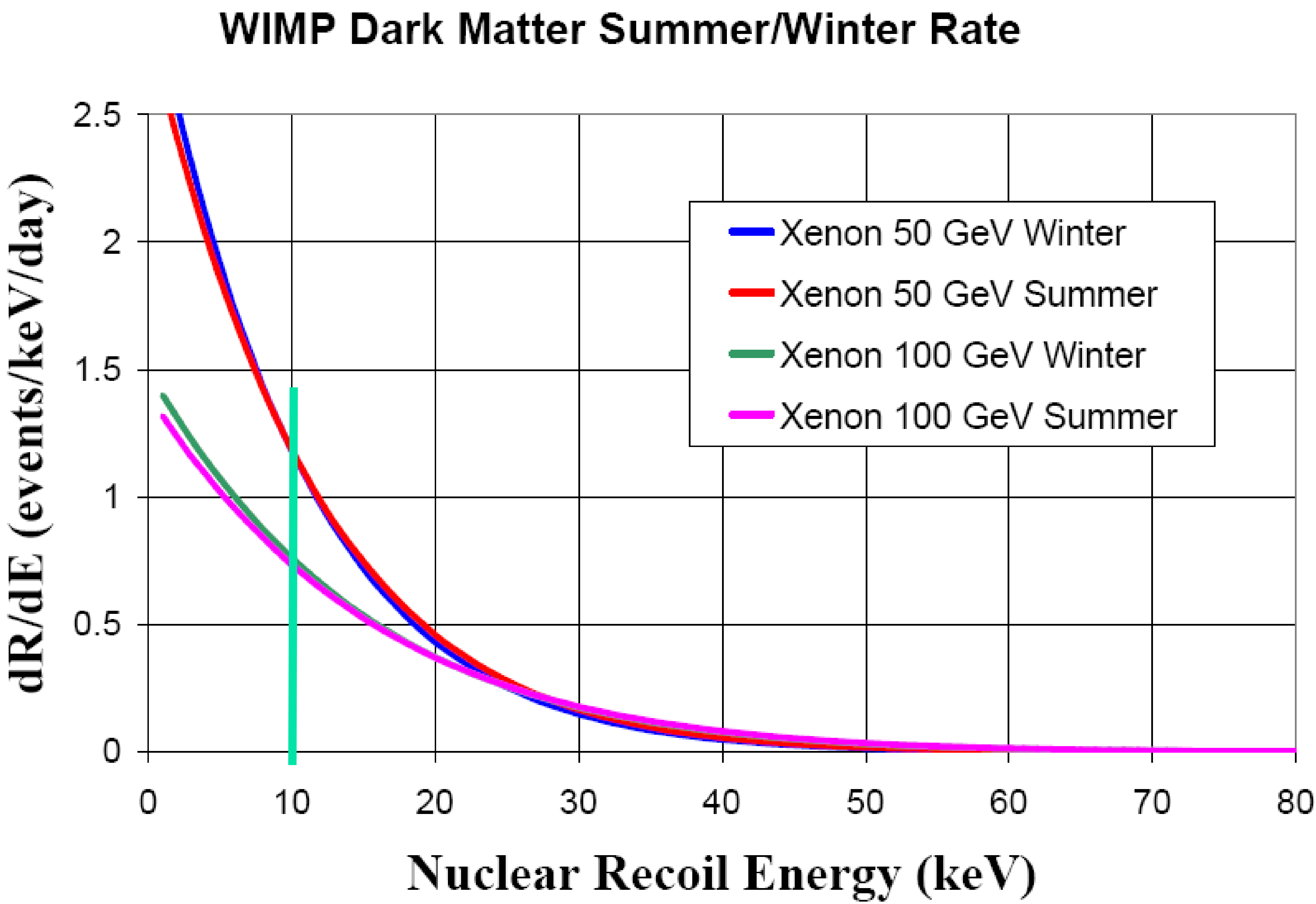
$$\sigma_0 = \frac{\mu_{X,N}^2}{\mu_{X,n}^2} \sigma_{X,n} A^2$$

Annual Modulation



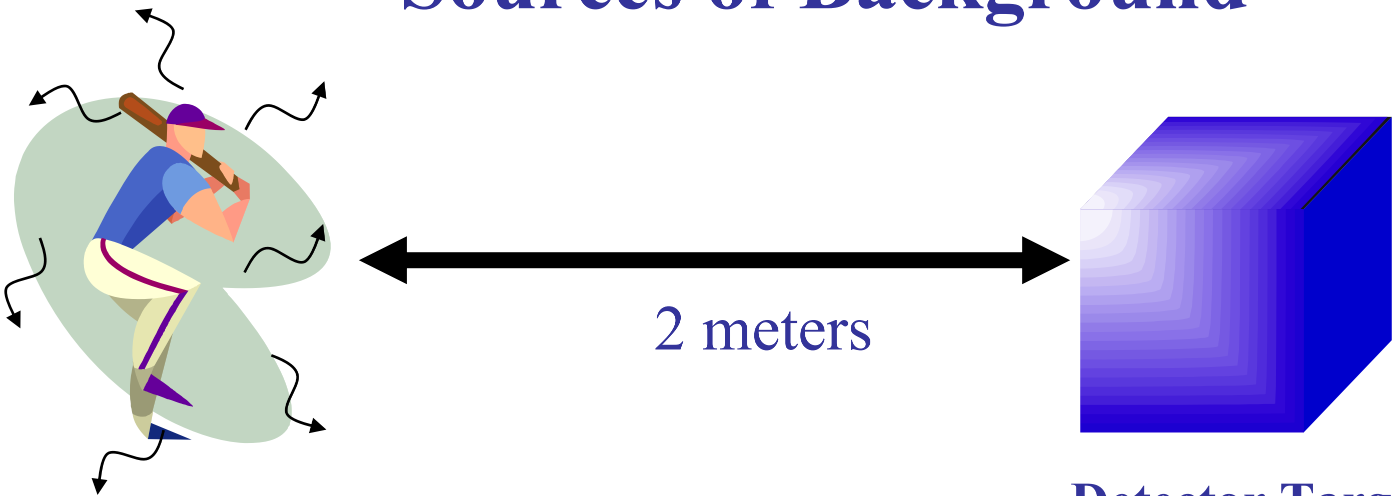


$$\frac{dR}{dE_R} = \frac{\sigma_0 \rho_x}{4\upsilon_e m_x m_r^2} F^2(E_R)\left[\mathrm{erf}\left(\frac{\upsilon_{\min} + \upsilon_e}{\upsilon_0}\right) - \mathrm{erf}\left(\frac{\upsilon_{\min} - \upsilon_e}{\upsilon_0}\right)\right]$$



WIMP Dark Matter Summer/Winter Rate
dR/dE (events/keV/day)
2.5
2
1.5
1
0.5
0
0
10
20
30
40
50
60
70
80
Nuclear Recoil Energy (keV)
Xenon 50 GeV Winter
Xenon 50 GeV Summer
Xenon 100 GeV Winter
Xenon 100 GeV Summer

Sources of Background



Detector Target

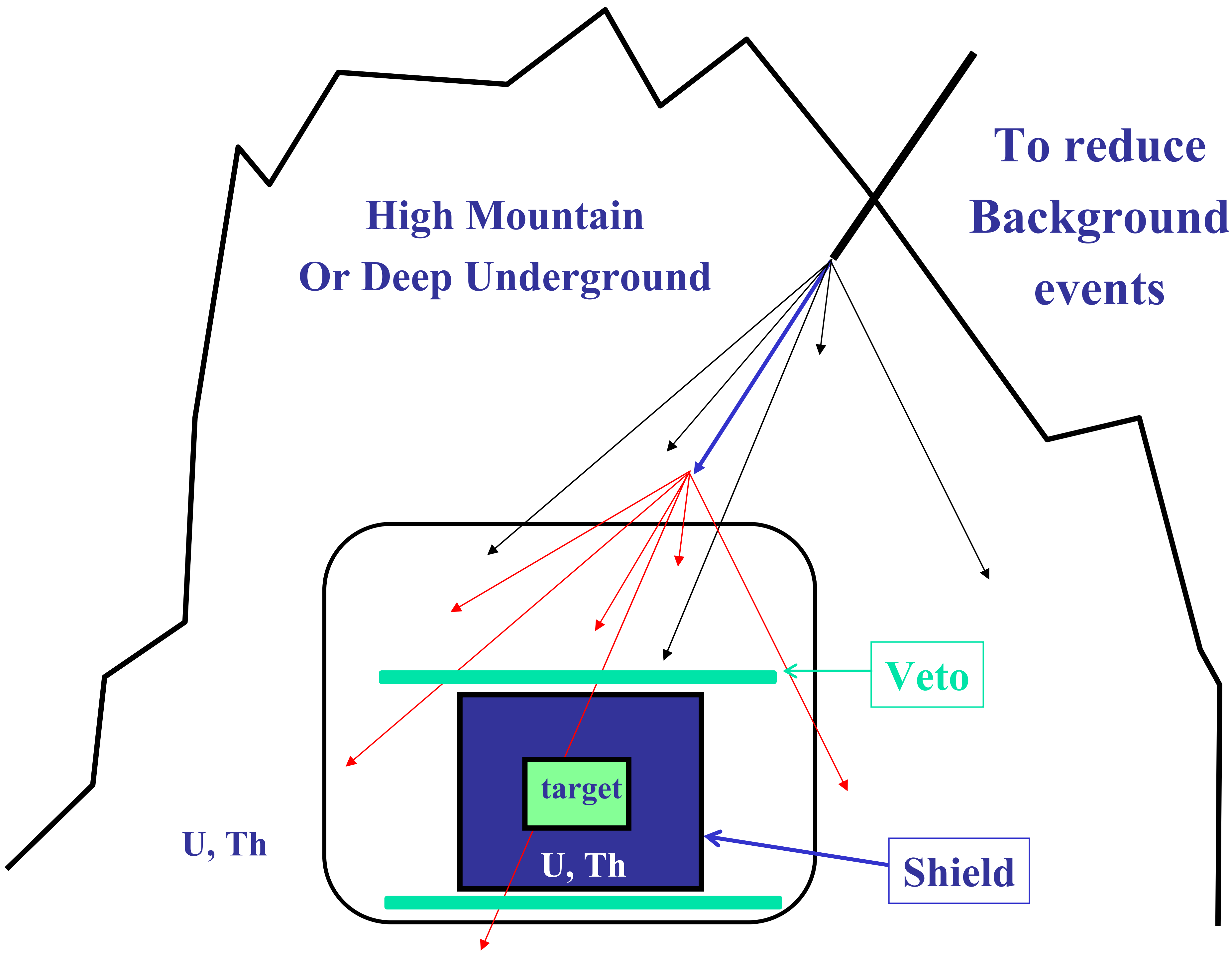
^{40}K: 4*10^{7} γ/day (~1.5MeV)

10^{3} /(kg-day)

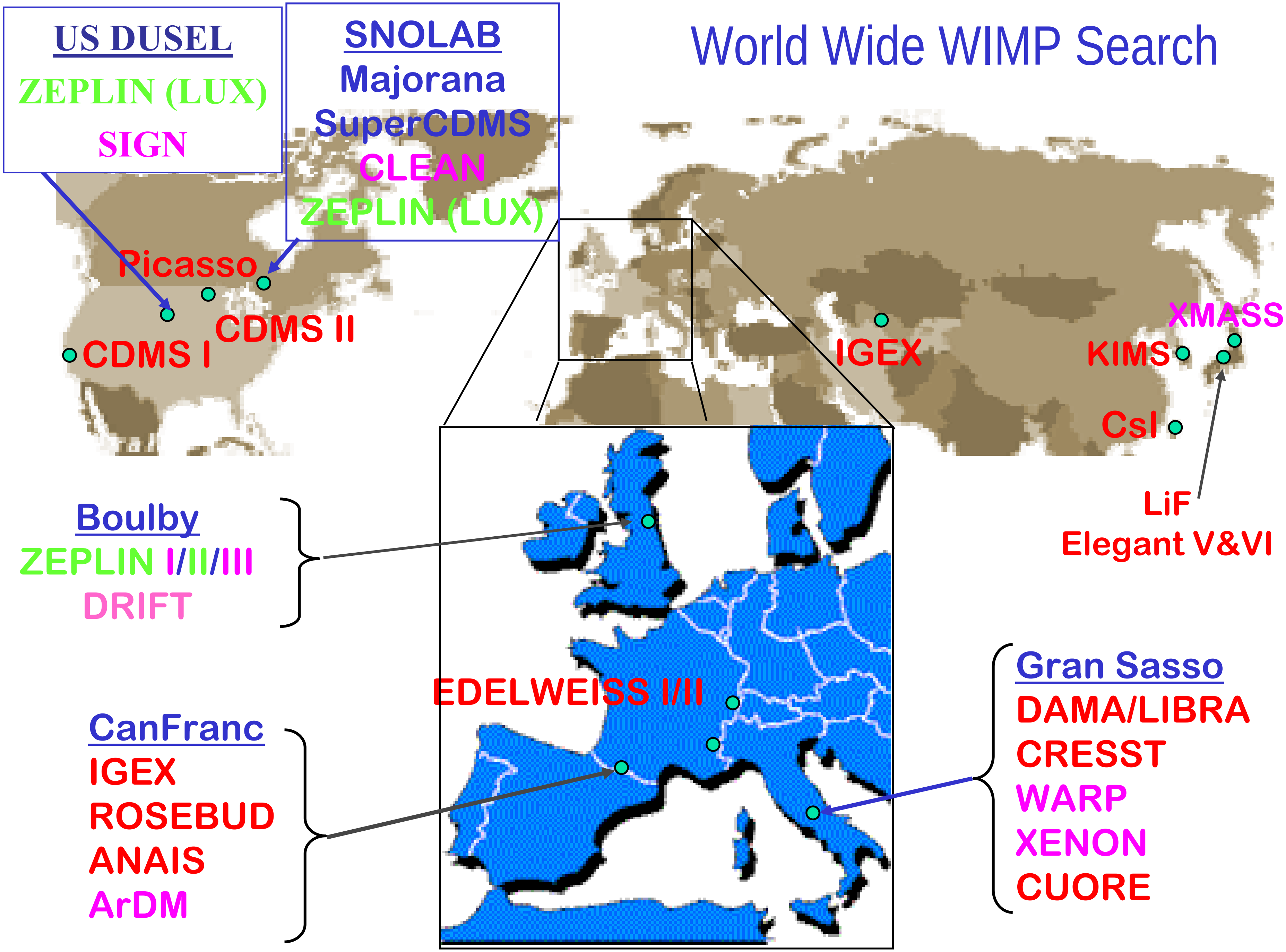
all materials used for detector construction are contaminated by Uranium and Thorium

Cosmic rays produce large rate in detector too

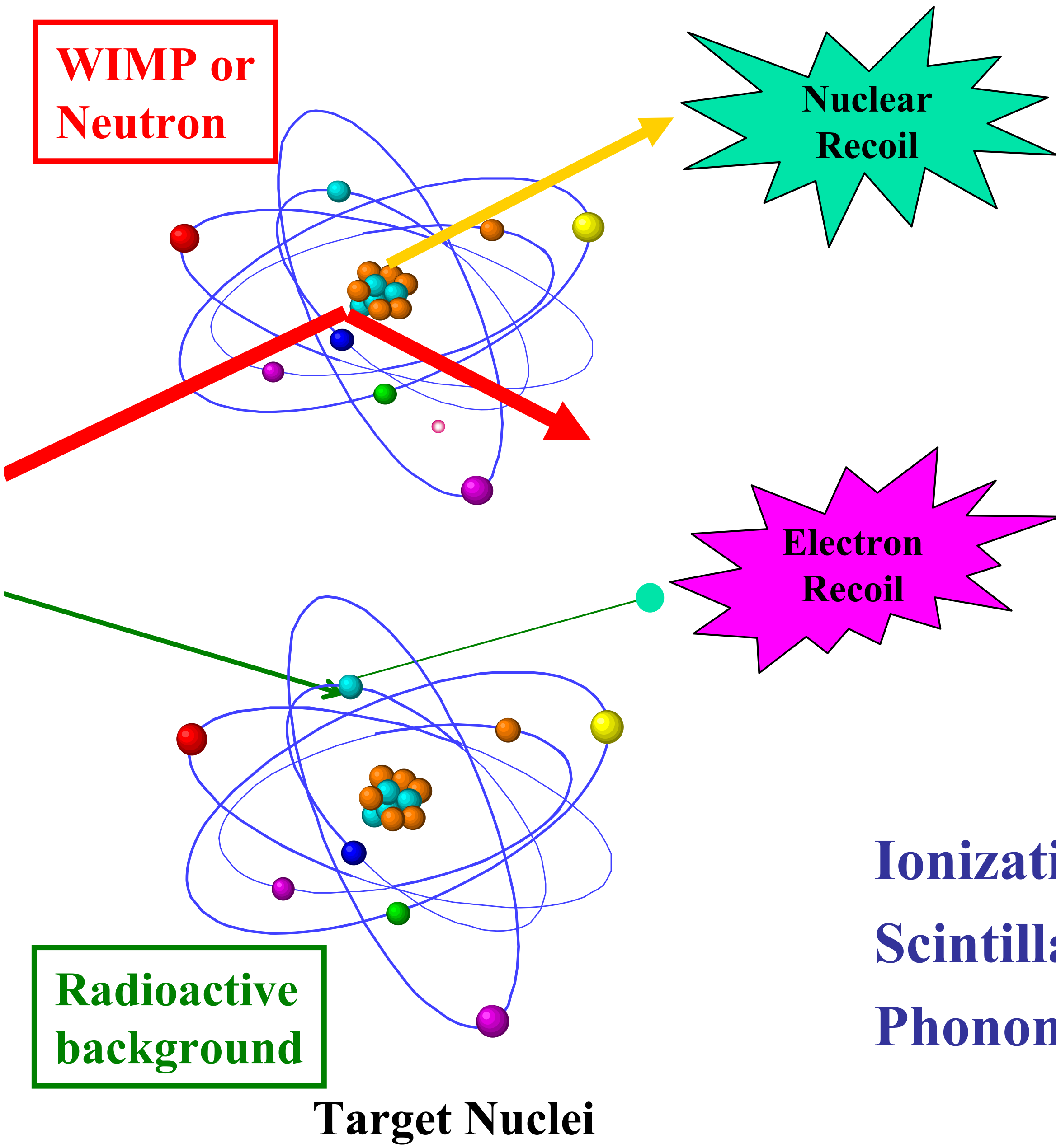
Current limit ~ 0.1 event/kg/day

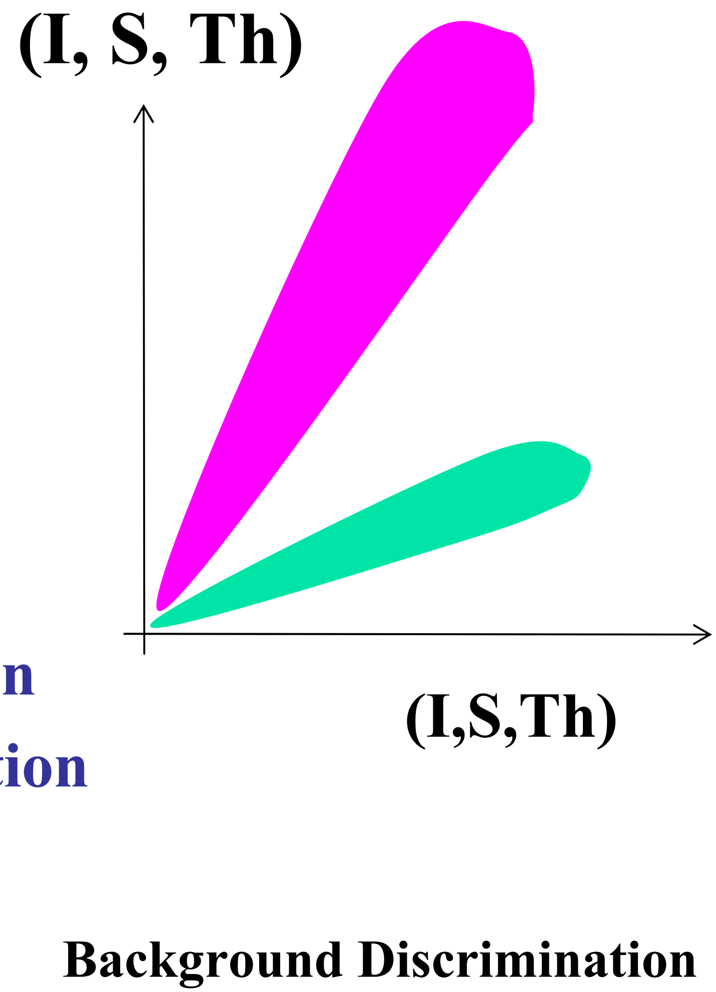

High Mountain
Or Deep Underground
To reduce
Background
events
Veto
target
U, Th
U, Th
Shield

World Wide WIMP Search



Detector response to WIMPs and Background



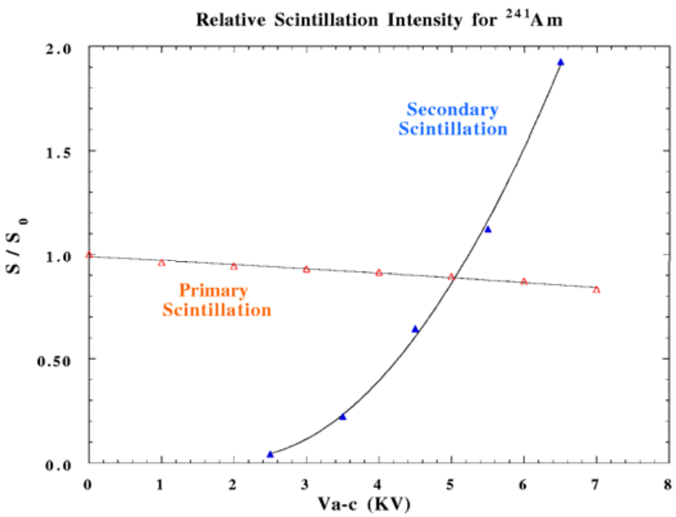


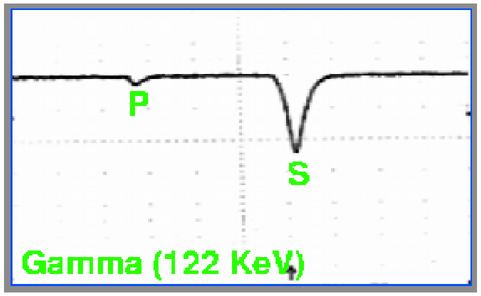
Ionization

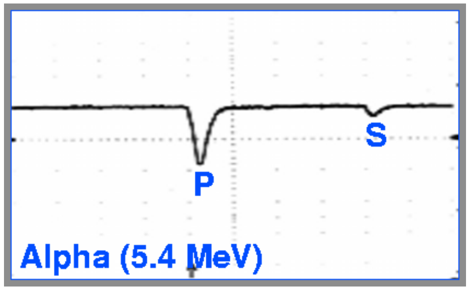
Scintillation

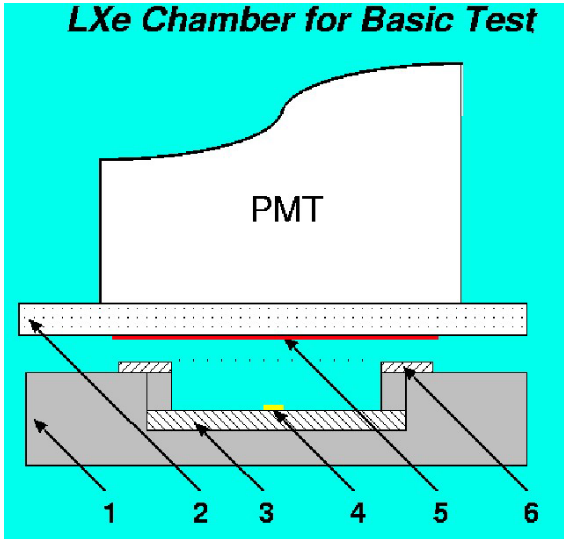
Phonon

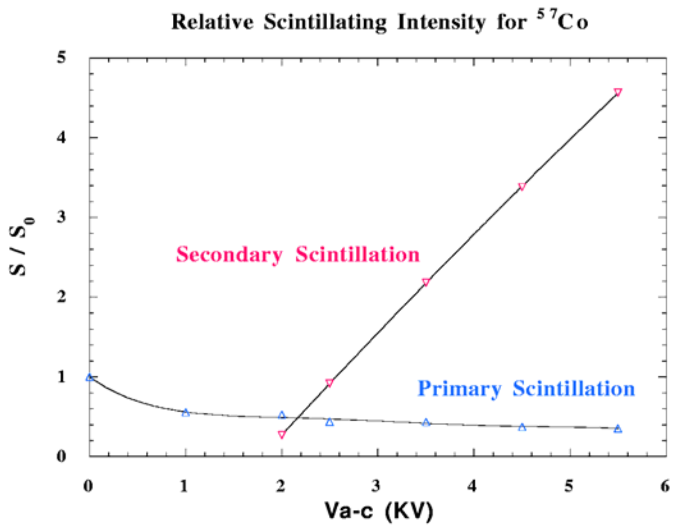
Principle Tests Setup & Results

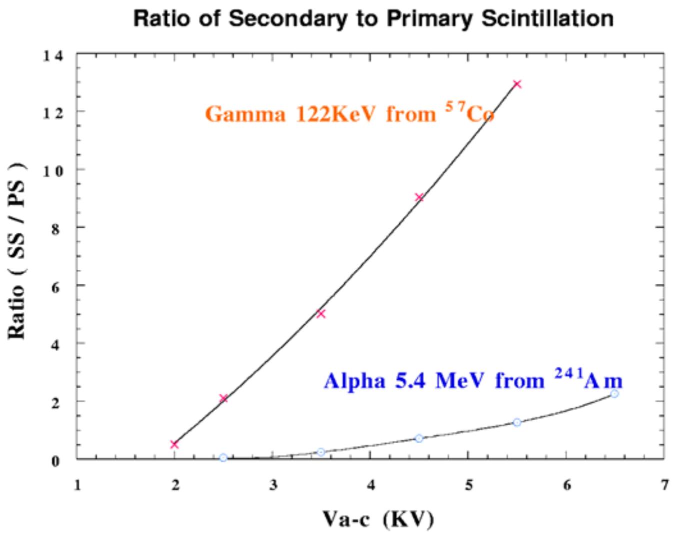








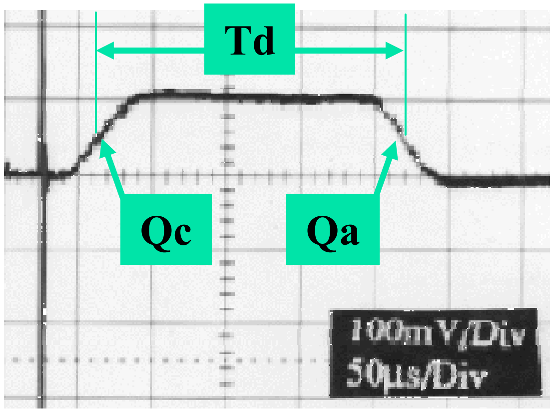




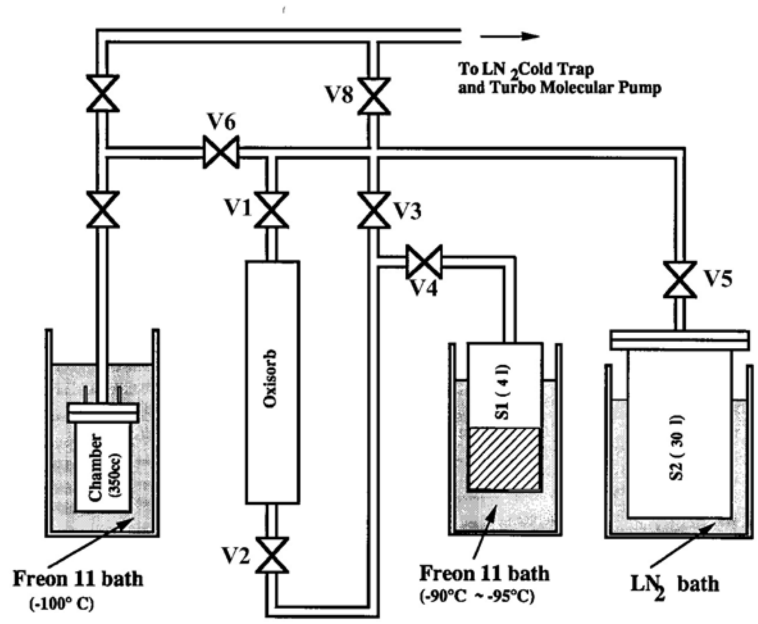
1. Ceramic.
2. Quartz Window,
3. Stainless Steel Cathode.
4. Source.
5. Grounded Grid.
6. Anode wire frame

NIM A327 (1993) 203

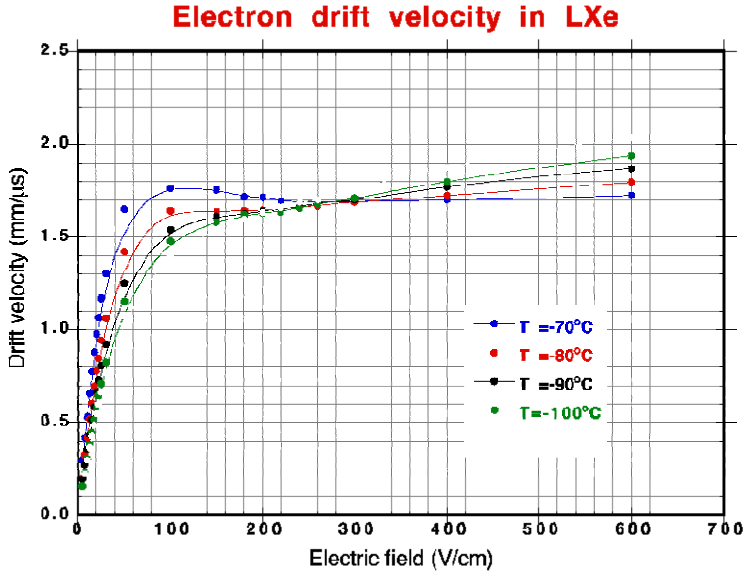
A simple purification process developed to achieve 5ms electron lifetime in liquid xenon



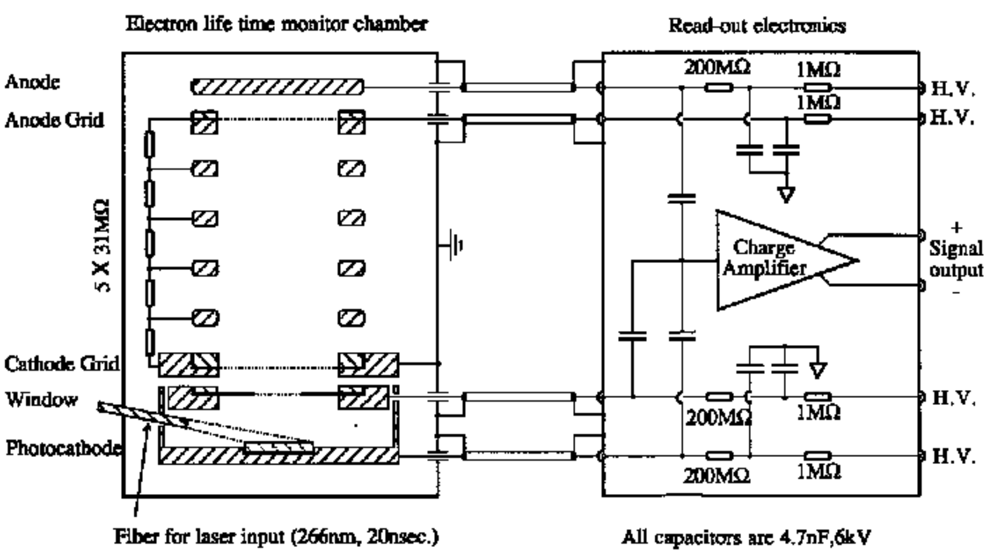
$$\tau = T_d / \ln(Q_c / Q_a) > 5ms$$



Purification system



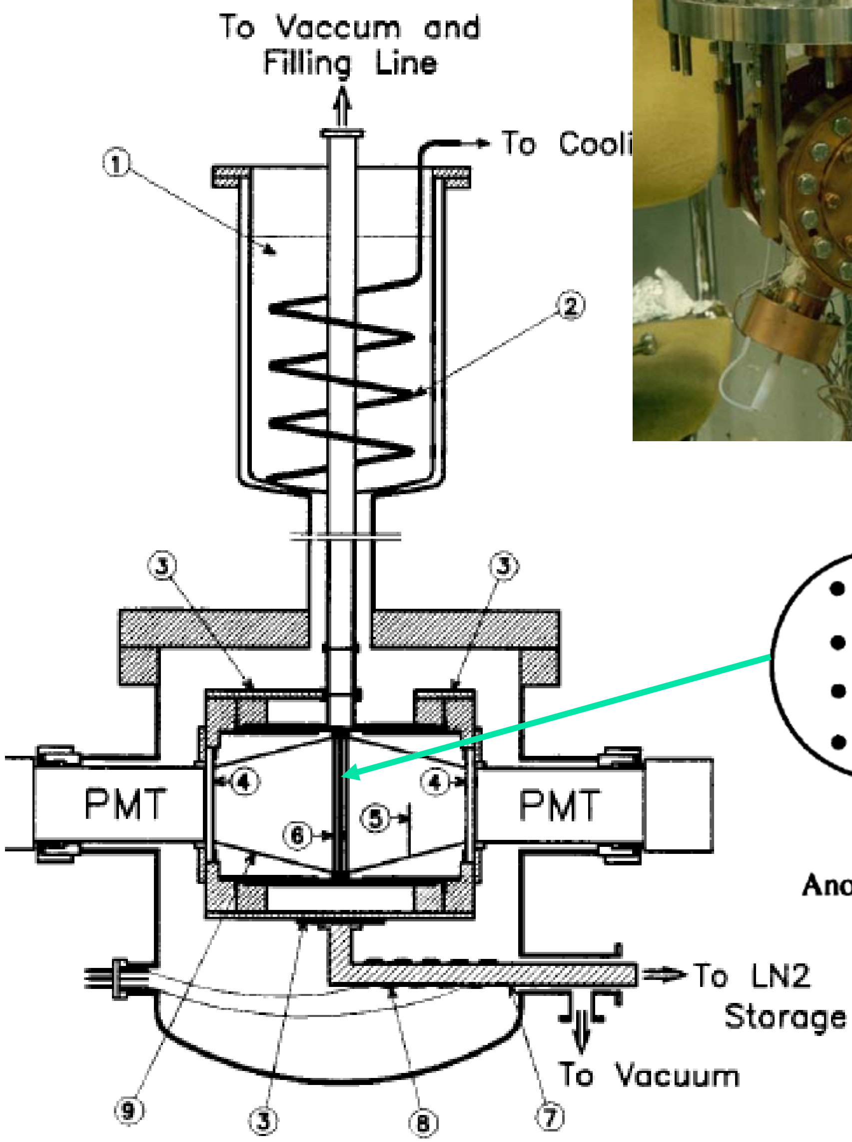
NIM A329 (1993) 361-36

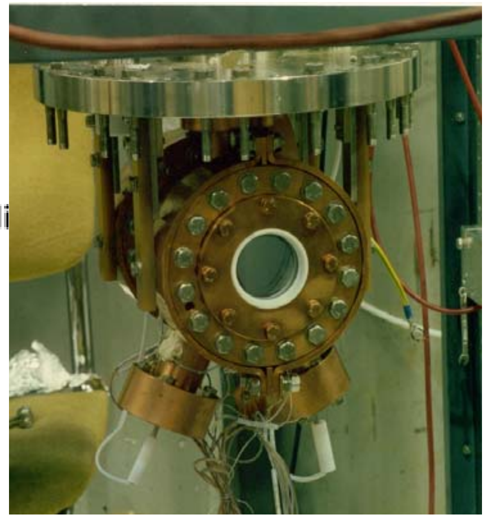


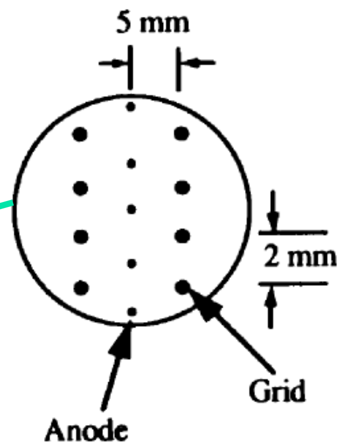
Lifetime measurement

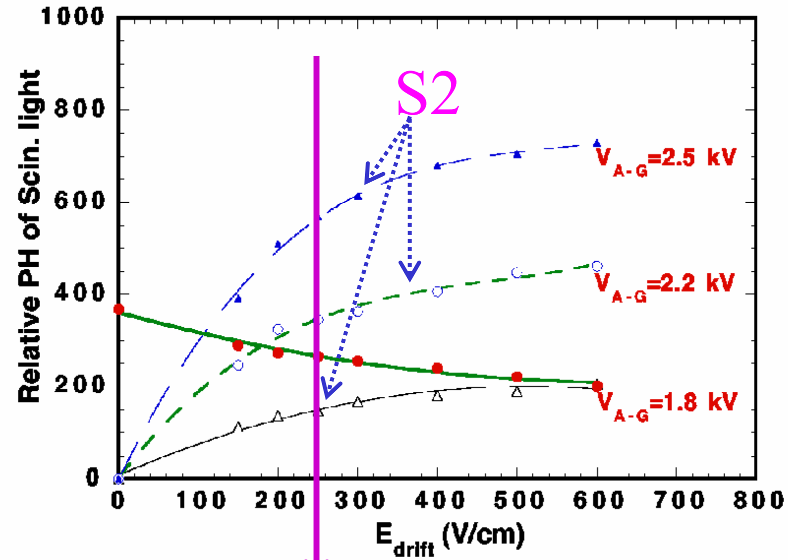
single phase studies using a 2kg liquid xenon detector

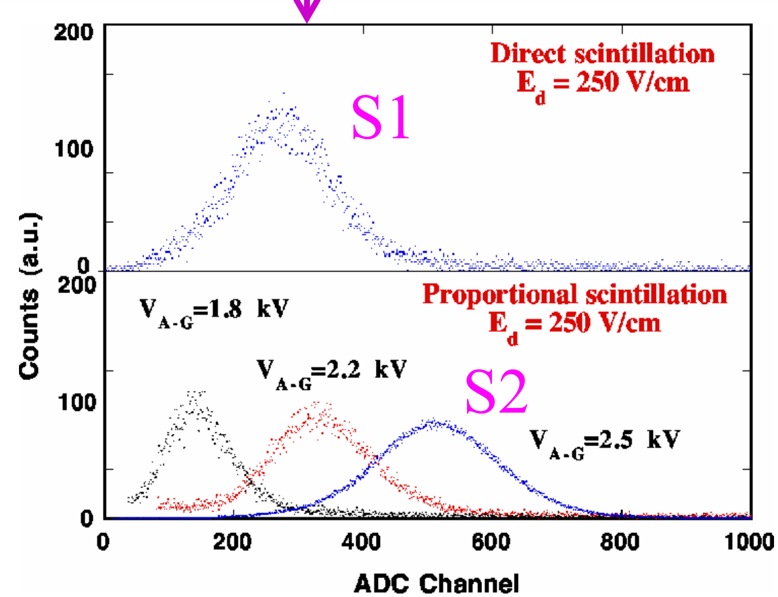
1995-1996







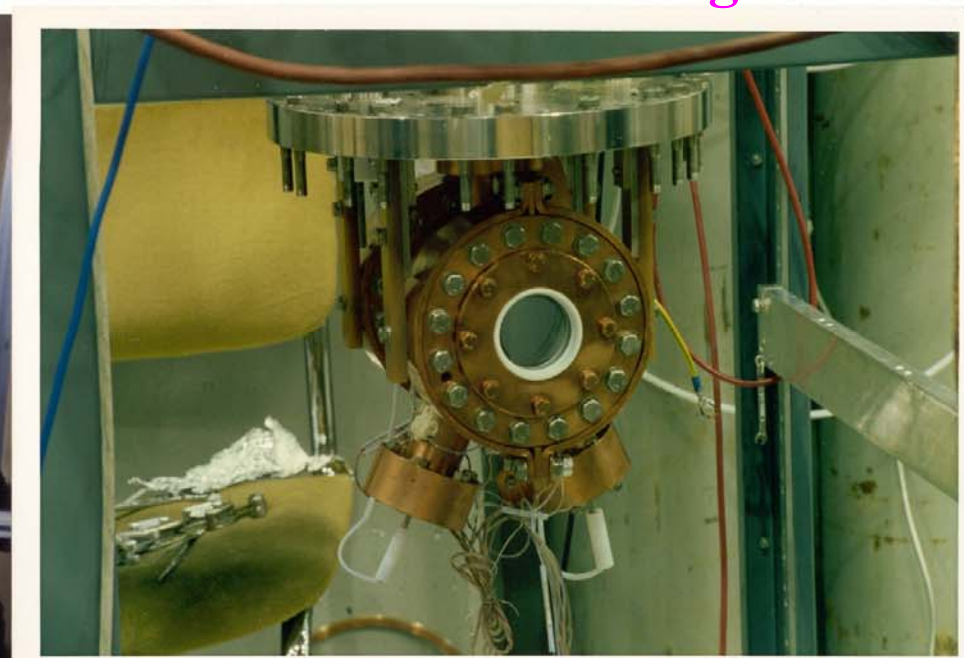




H Wang UCLA thesis 1998

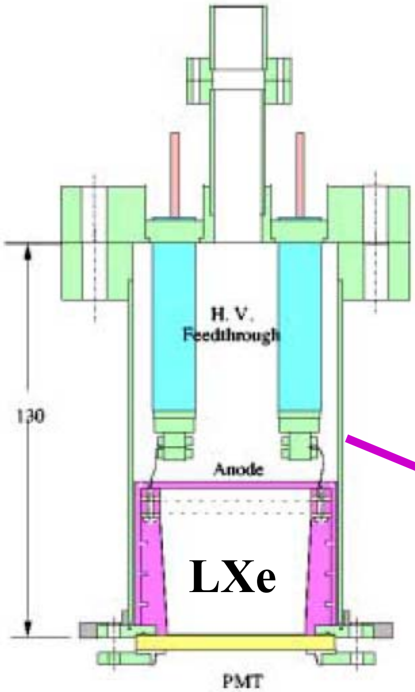
2kg single phase detector @ Mt. Blanc LAB

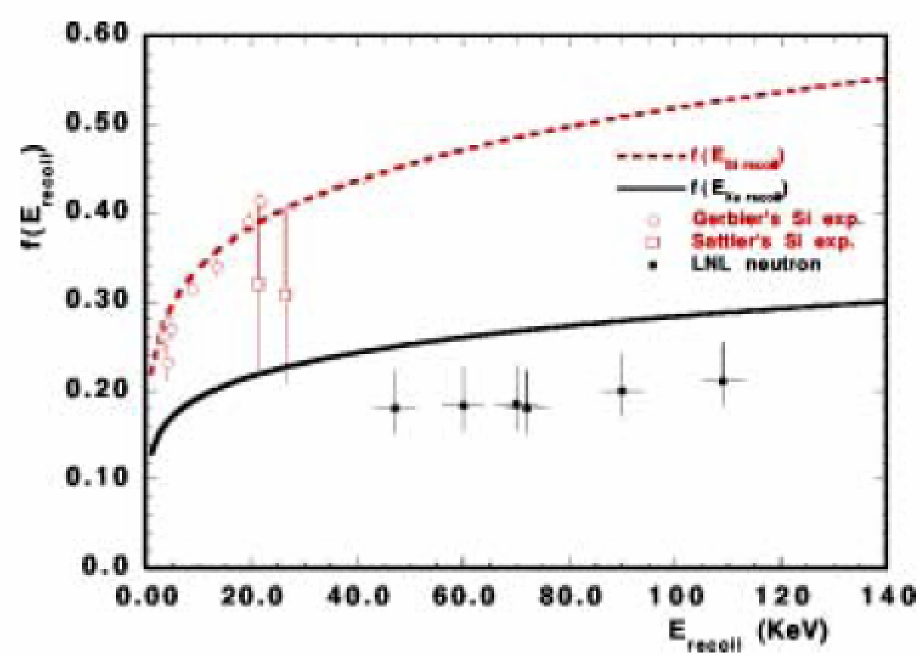
Aug. 1996



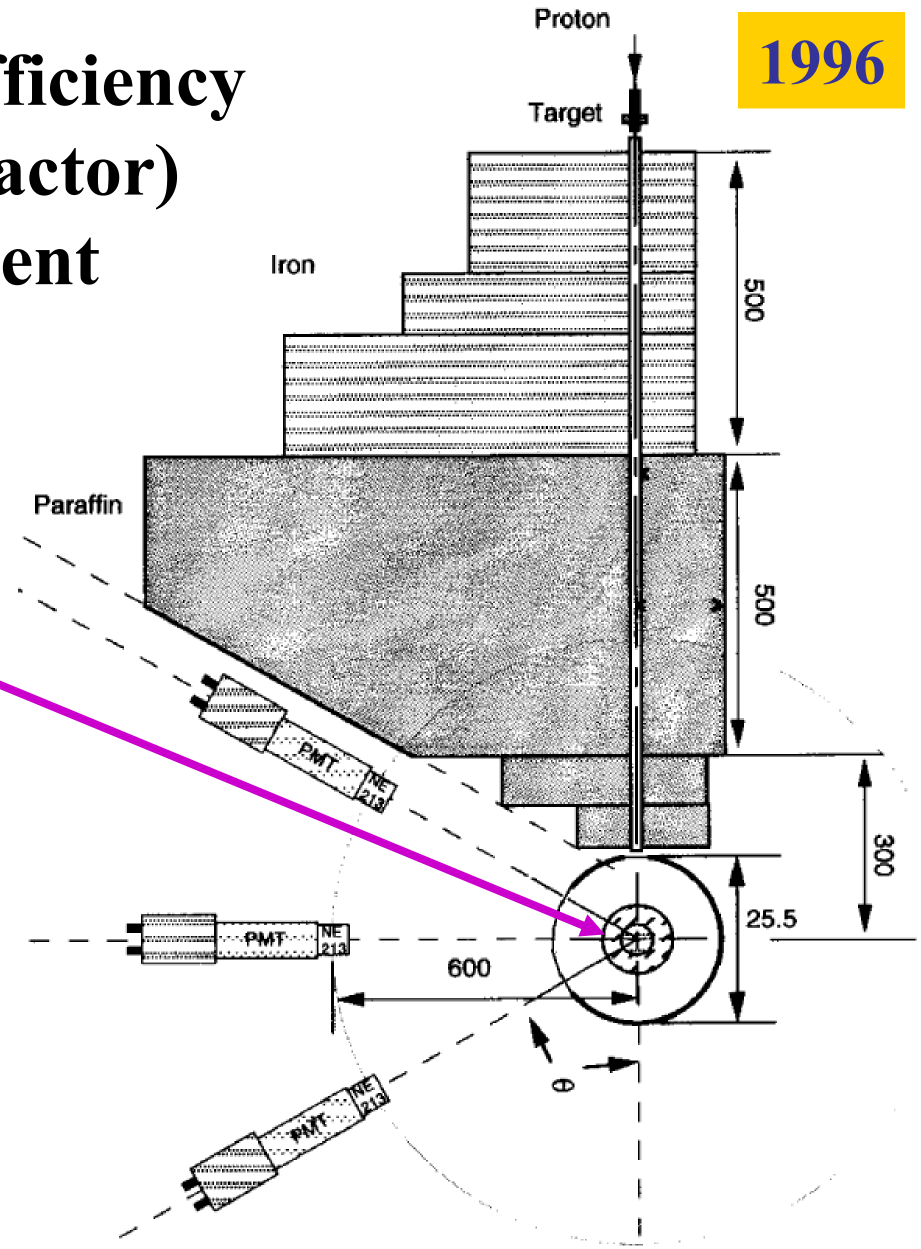
Scintillation Efficiency (quenching factor) measurement

1996



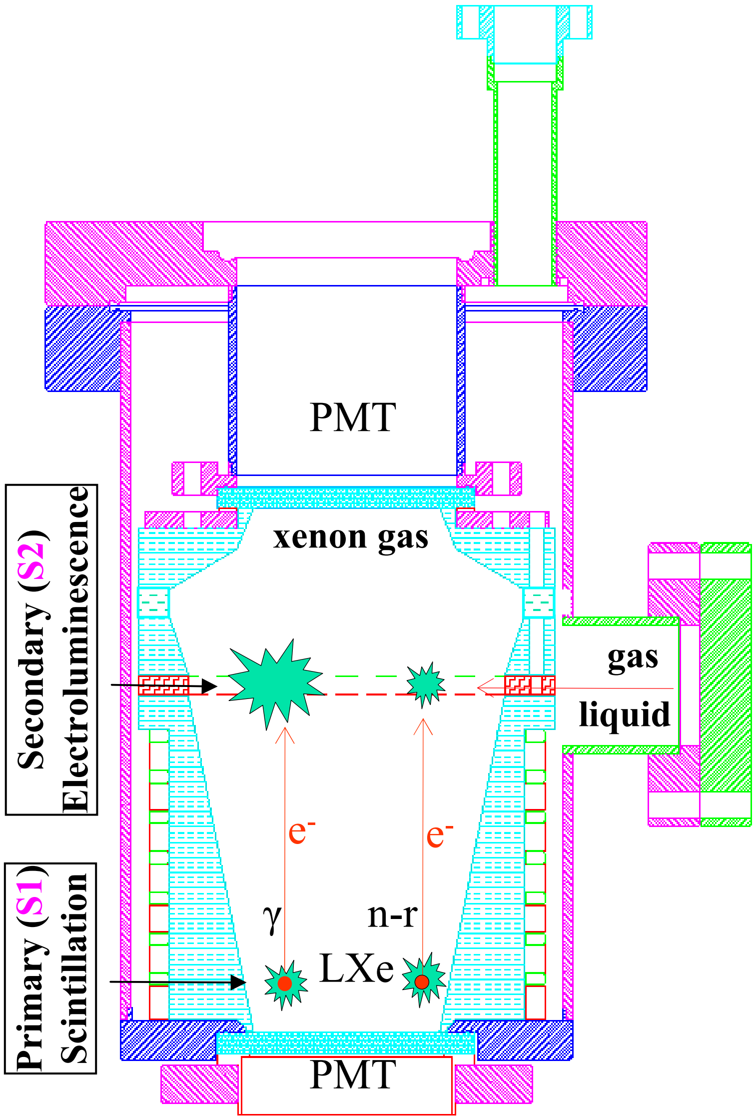


NIM A 449 (2000) 147-157



7MeV Proton on Li target (1-4mg/cm²)
Van de Graaff accelerator
Legnaro (Padova Italy)

1kg two-phase study setup



$$N_{ph/e} \approx 70 \bullet \left(\frac{E}{P} - 1.3 \right) \bullet X \bullet P$$

1997

E: Electric field (kV/cm),
P: Gas Pressure (Bar),
X: electron Drift Distance (cm)

Why Xenon

- Available in Large Quantities
- Large abundance for both $s_{1/2}$ (^{129}Xe~26%) and s_0 (^{132}Xe~27%)
- High Atomic Number ($\sigma_{WIMP\text{-}Nucleon} \propto A^2$, $Z_{Xe}=54$, $A=131$)
- High Density (~ 3g/cm^3 liquid) (compact detector design)
- High Scintillation Light (175nm) & Ionization Yield
- Small fano factor ($F = 0.041$ Energy Resolution $\frac{\Delta E}{E} = 2.35\sqrt{\frac{FW}{E}}$)
- Scintillation decay profile difference (primary) (PSD)
- Large quenching factor (observed energy/e.e.Energy)
- Can be Highly Purified

    long light attenuation length (~m)

    long free electron life time (~5ms)
- Gamma & Recoil signal Discrimination
- Capable of Scale up to Large Volume (ton)
- No Long Lived Radioactive Isotopes (low background)

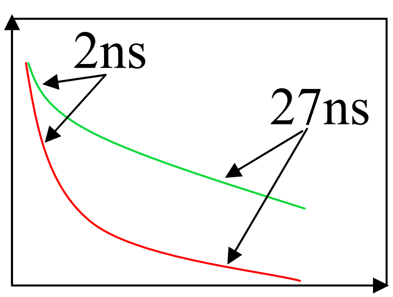
Liquid Xenon Scintillation Mechanism

(A) Pulse Shape discrimination: due to decay profile difference between nuclear recoil & electron recoil

(B) When E_{drift} applied, and measure E_i & E_s, Very good background rejection due to $(E_i/E_s)_{M.I.P.} >> (E_i/E_s)_{H.I.P.}$

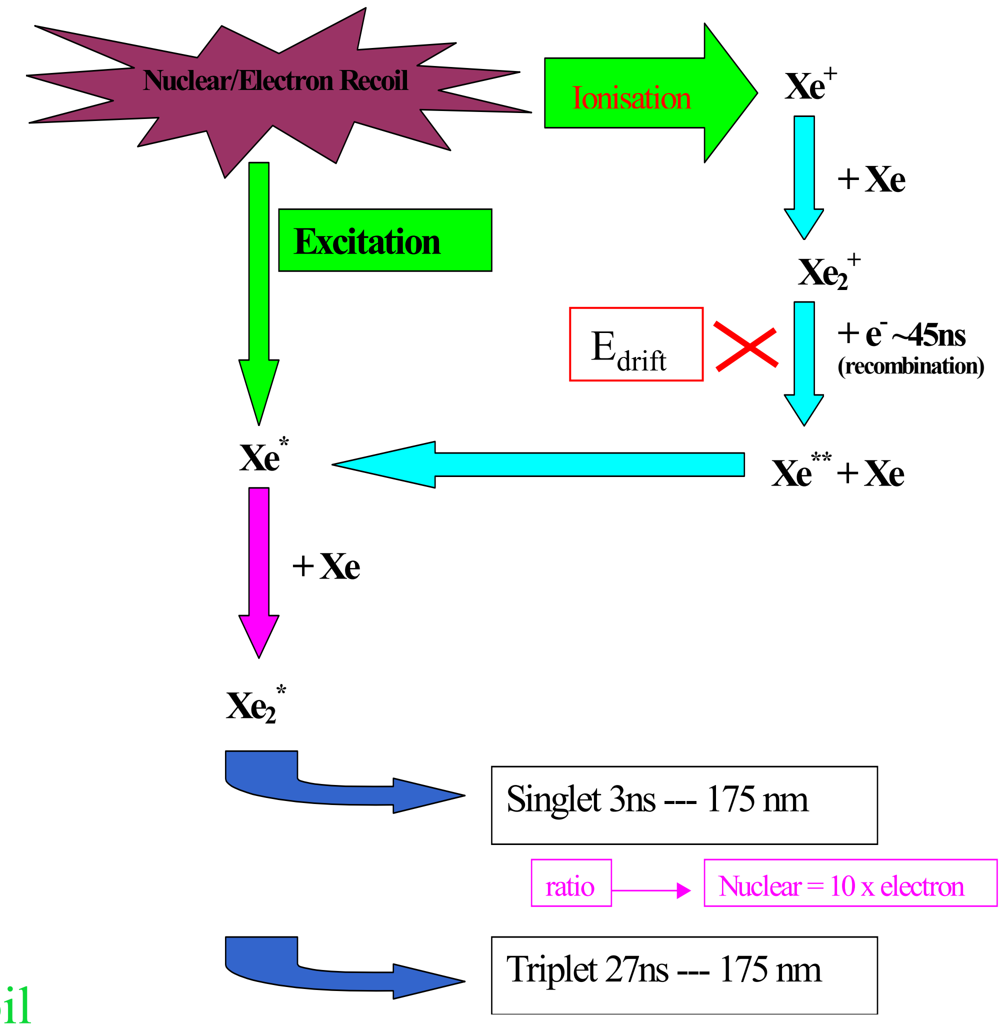
ZEPLIN I (A)

ZEPLIN II (A&B)

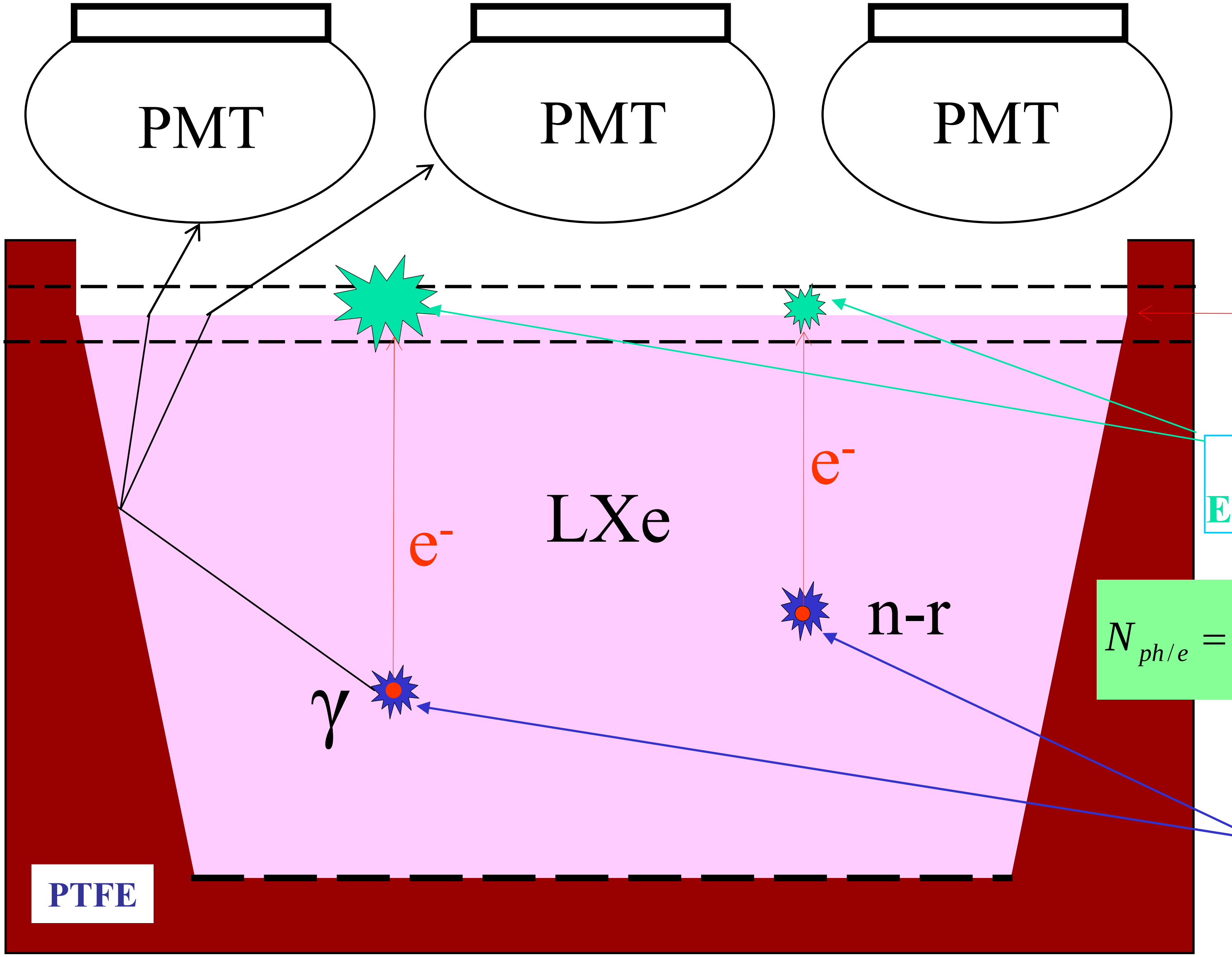


Nuclear recoil

Electron recoil



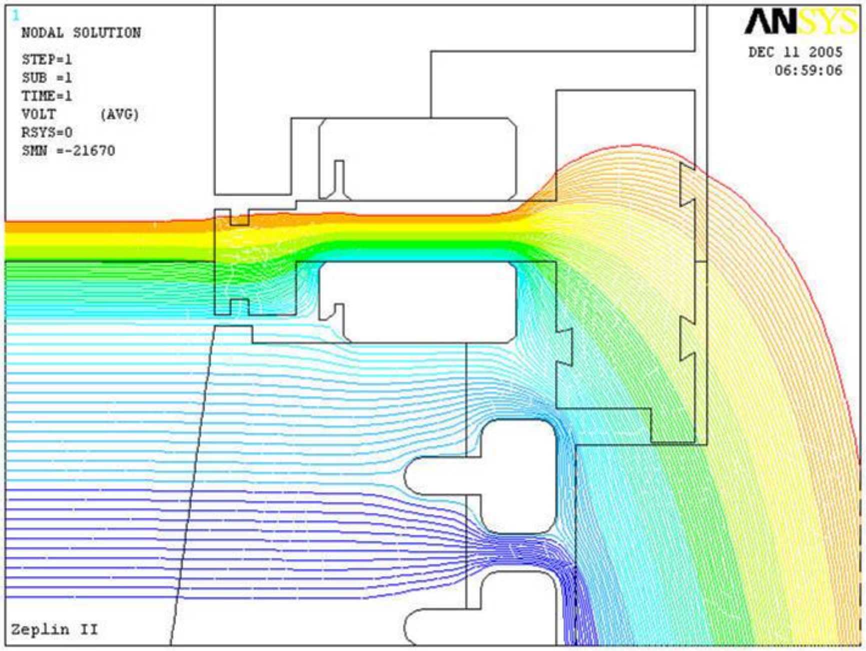
ZEPLIN II Design Principle



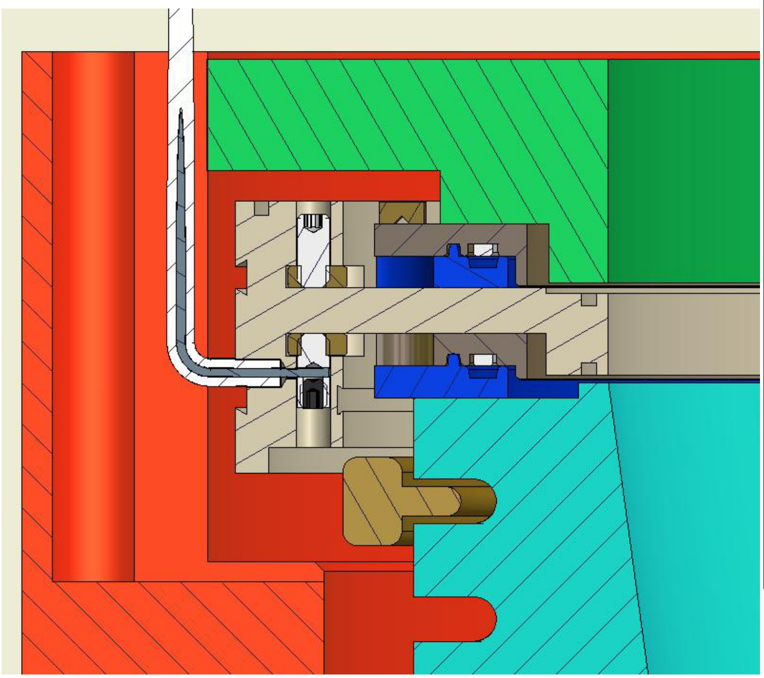
$$N_{ph/e} = 70\left(\frac{E}{P} - 1.3\right) X \bullet P$$

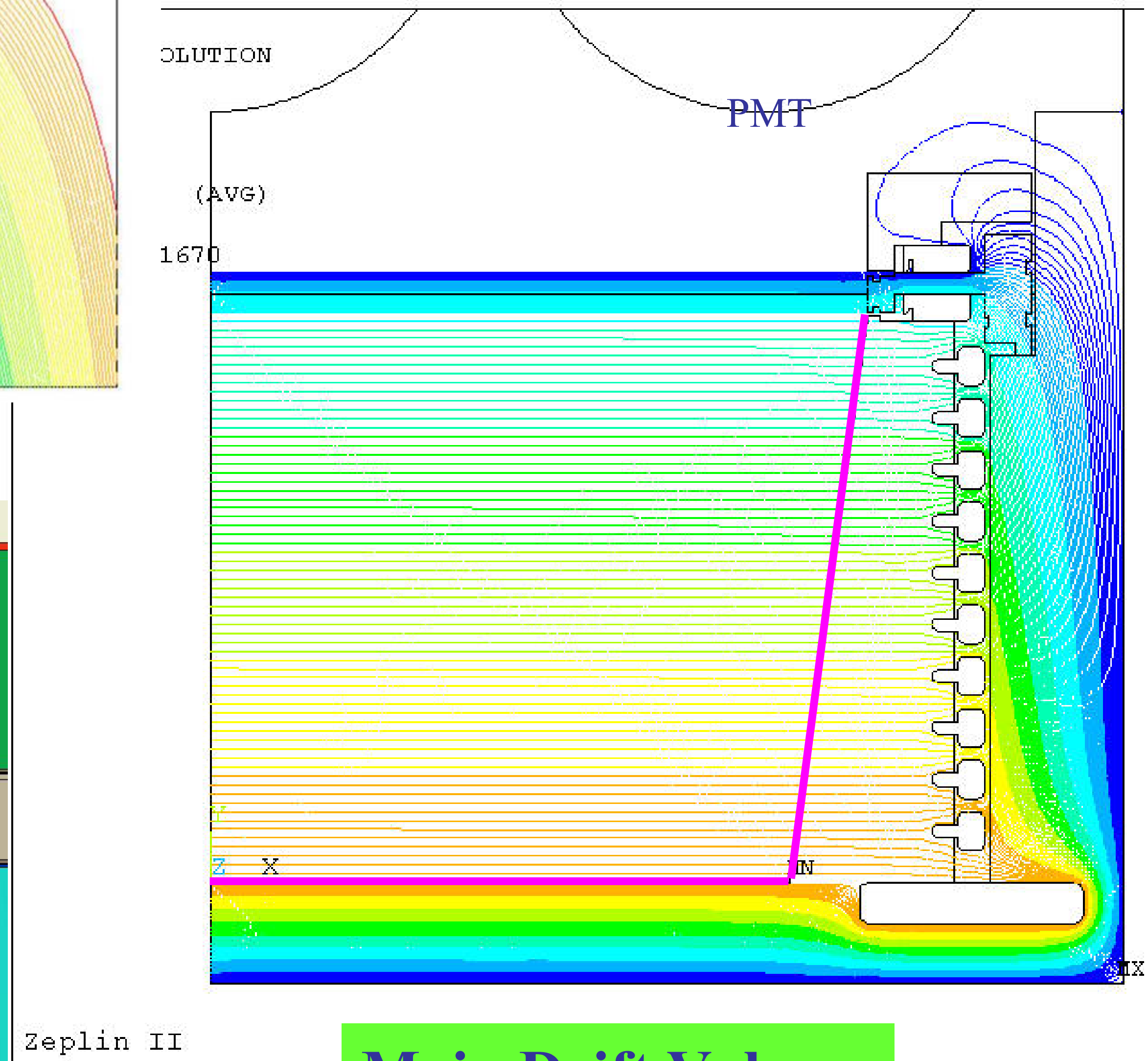
~9p.e./e

Drift and Luminescence Field Modeling



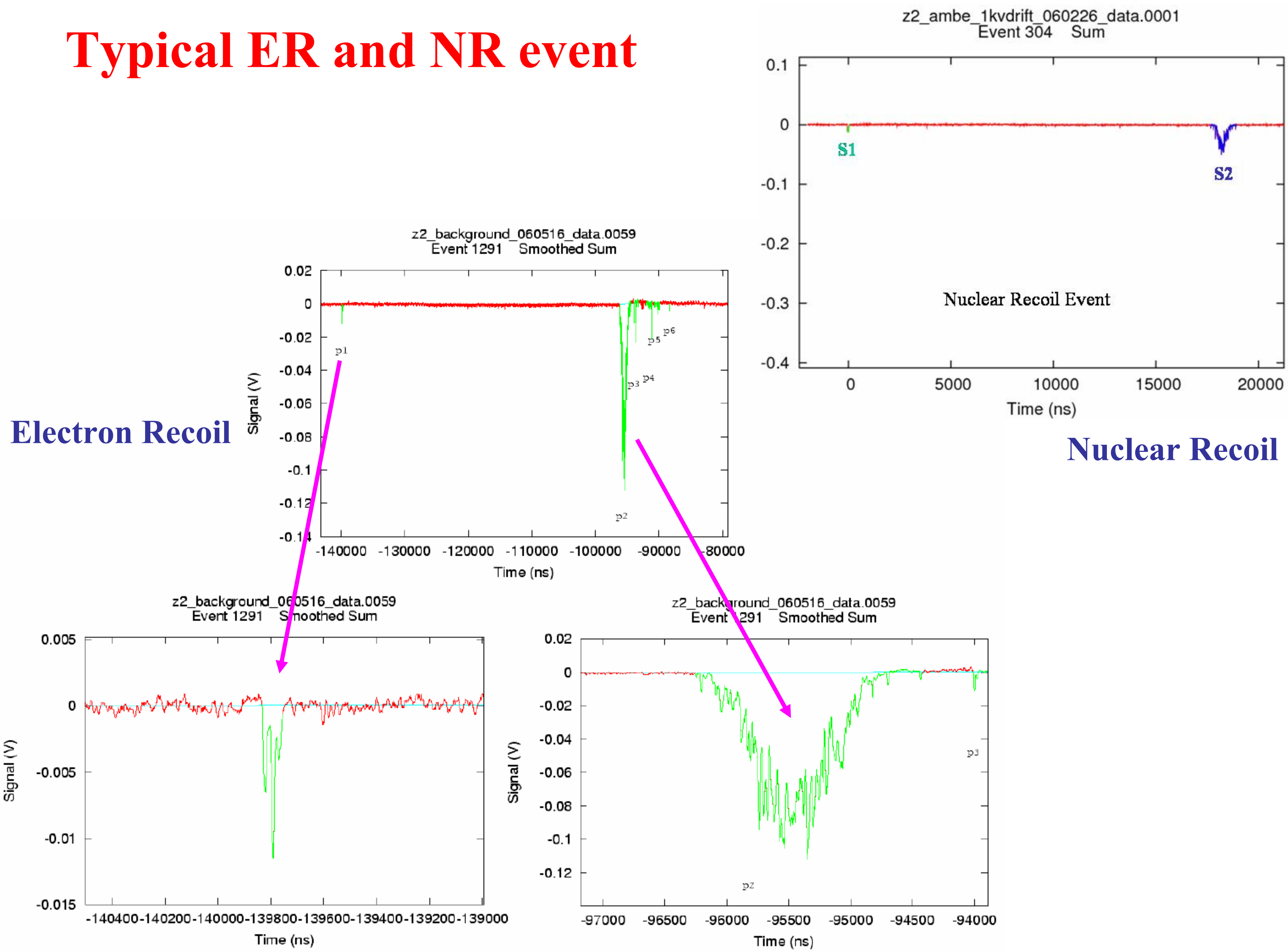
Mesh Structure





Main Drift Volume

Typical ER and NR event

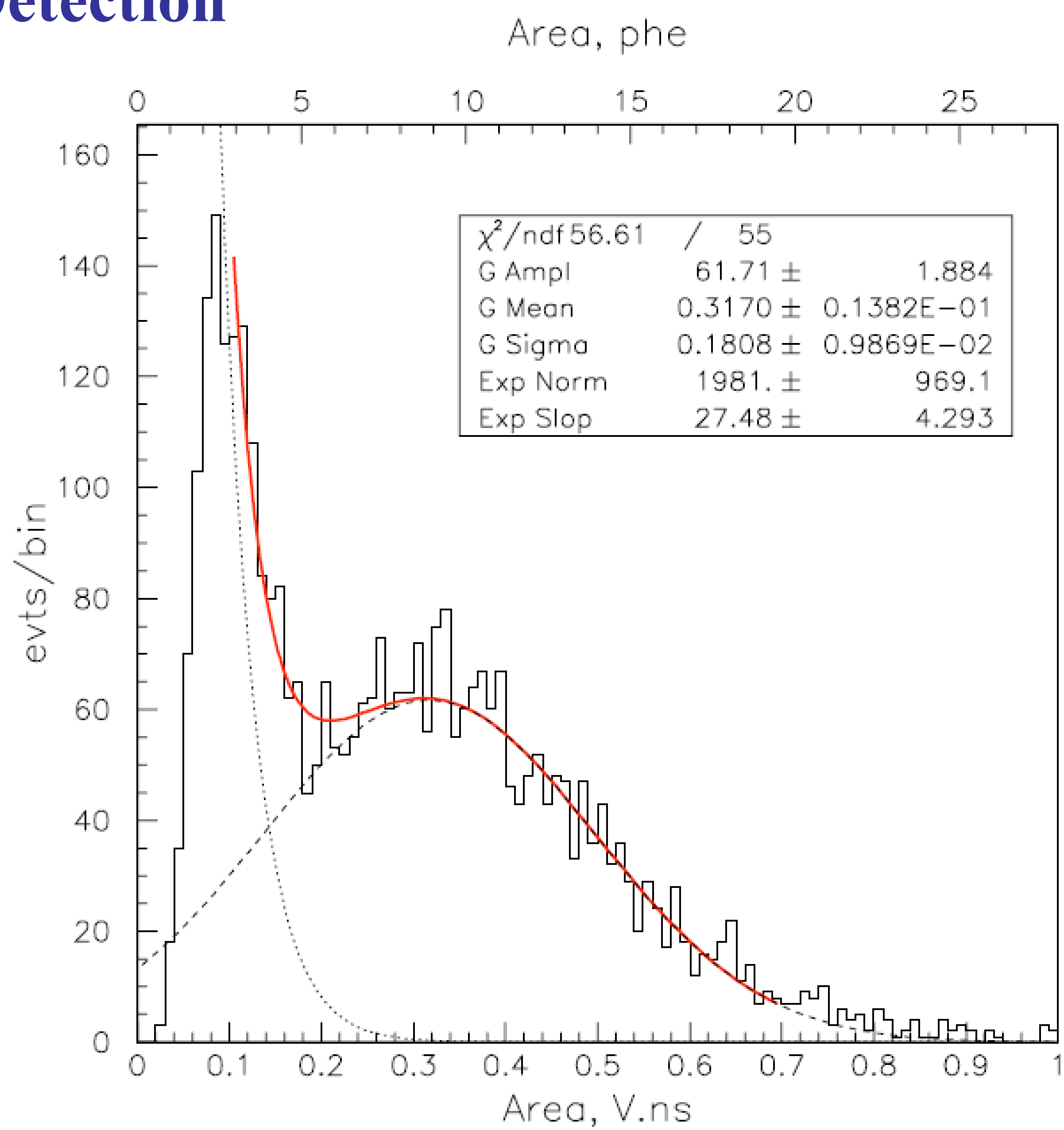


Electron Recoil

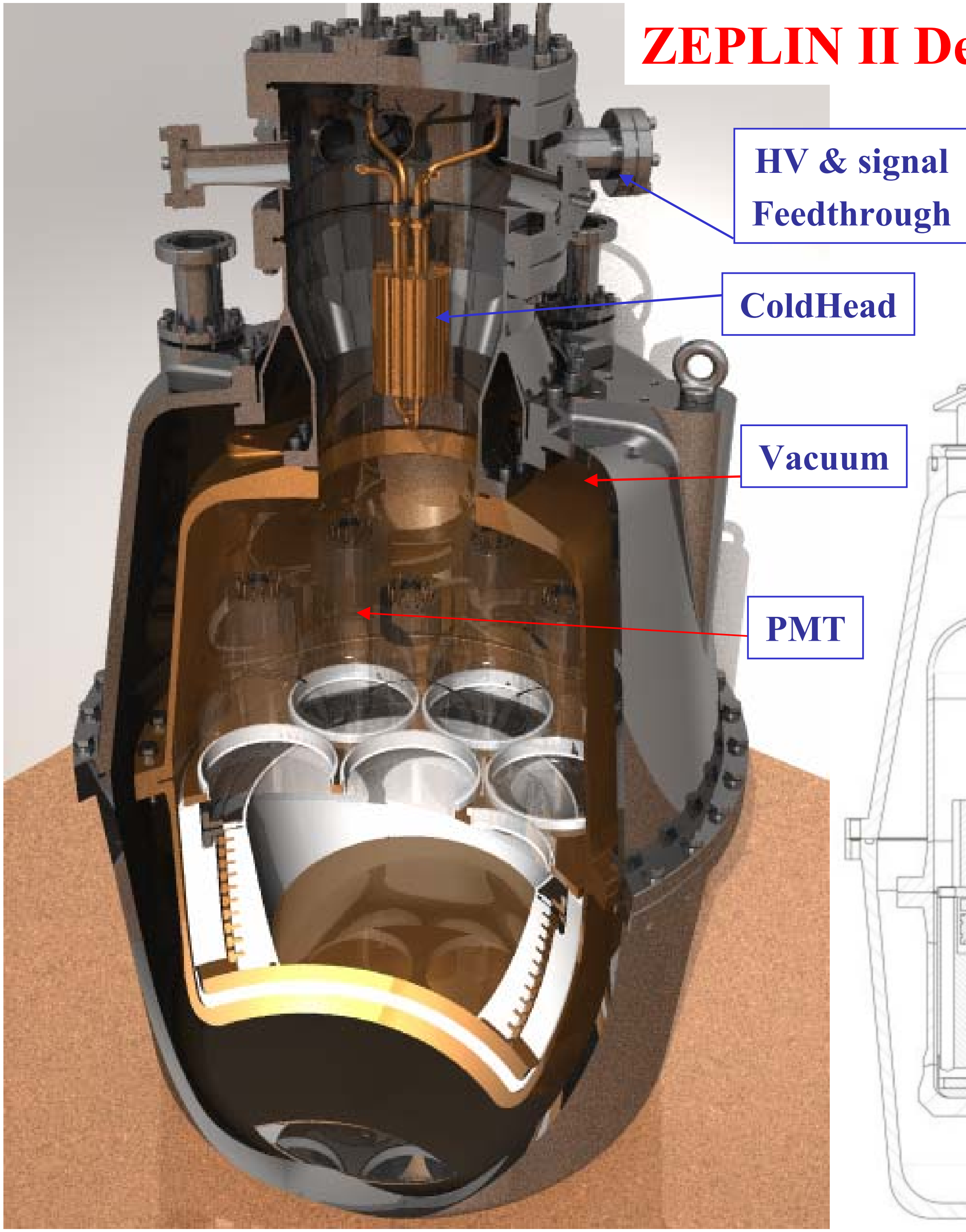
Nuclear Recoil

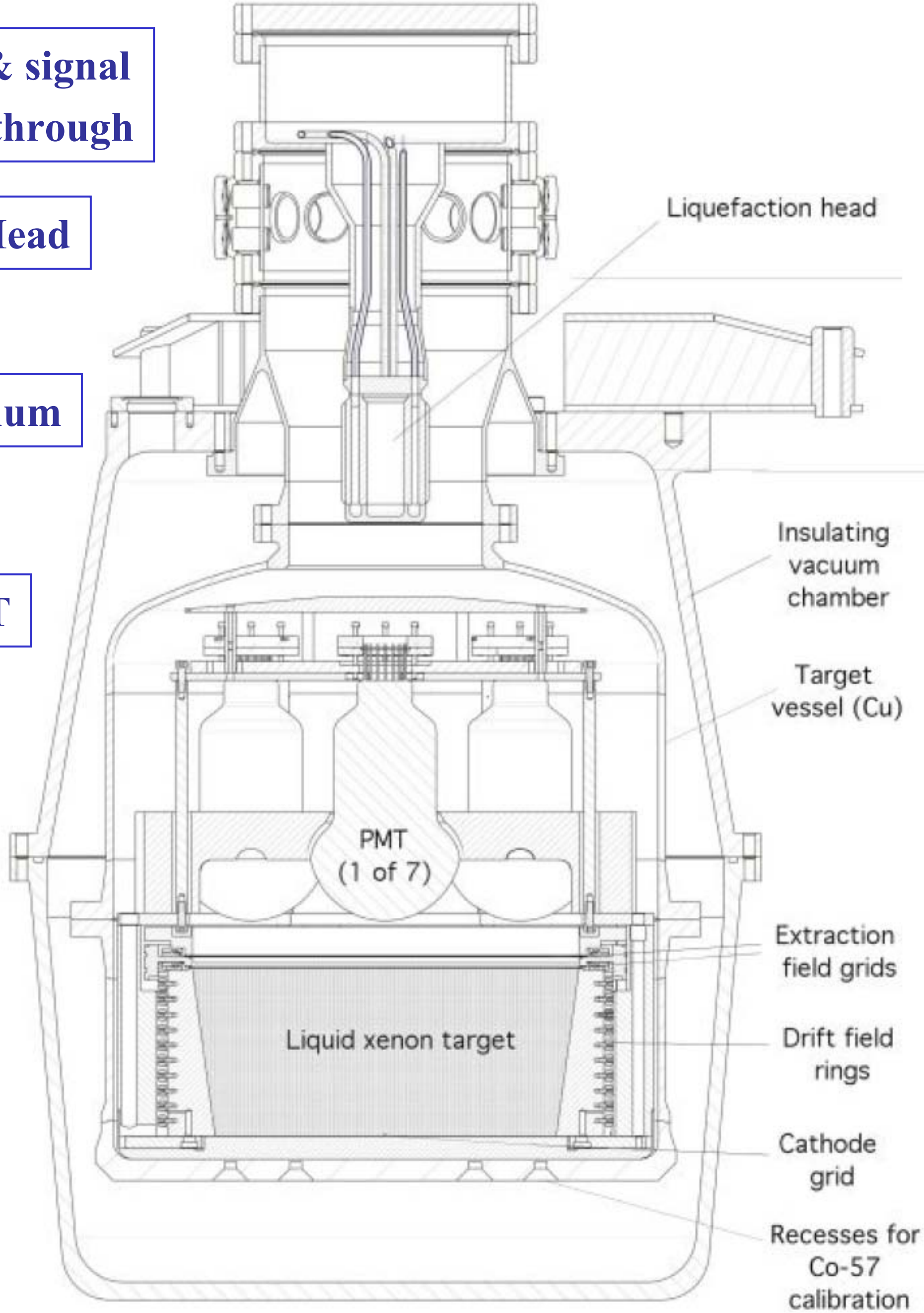
Single Electron Detection

A single electron leaving liquid surface can be detected using S2! (~9p.e./e)



ZEPLIN II Detector

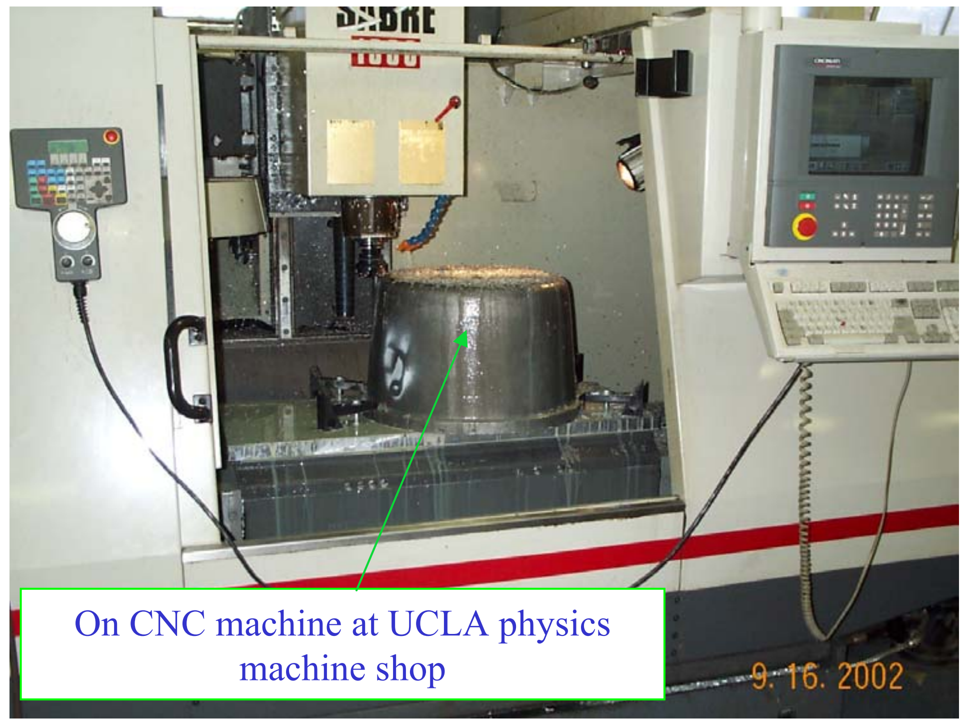




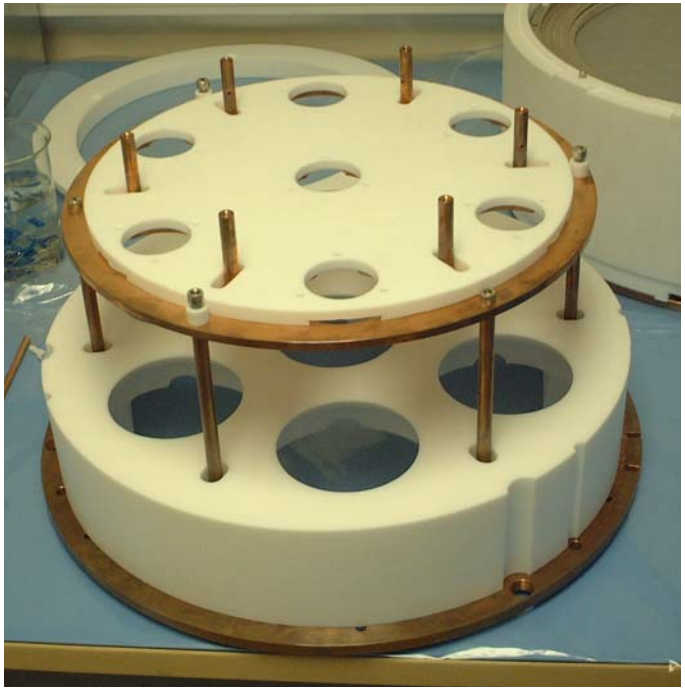
The first piece being made at UCLA Physics Machine shop in 2001!

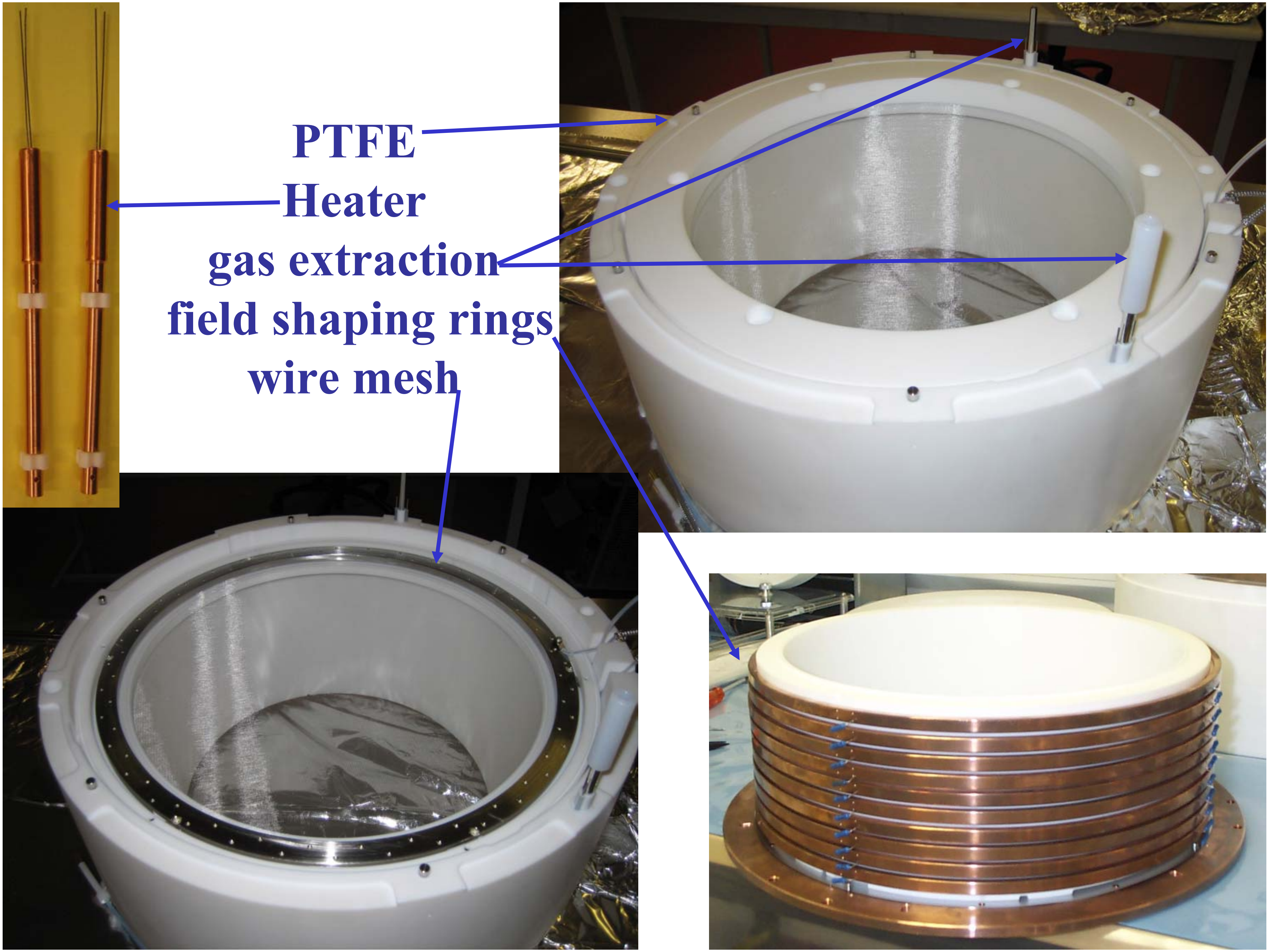
PTFE cone and field ring holder

Stainless Steel cast Vacuum Vessel



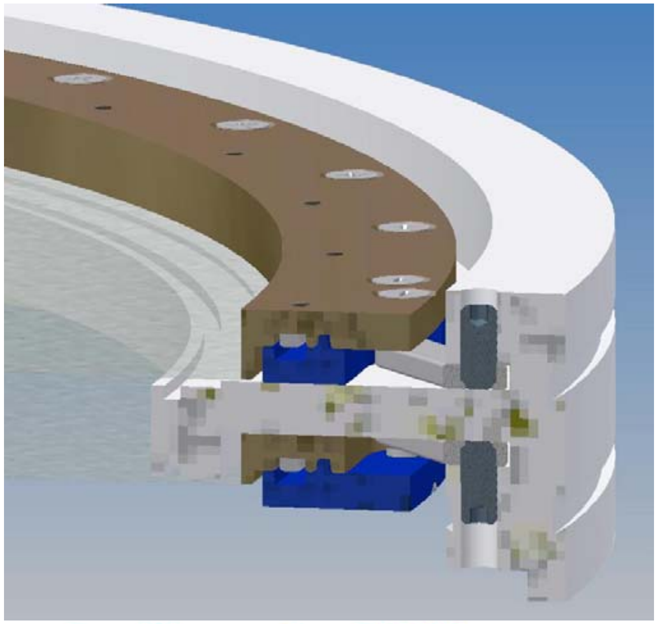
ZEPLIN II
PMT Assembly
7 UV sensitive low temperature PMTs (by ElectronTubes Inc.)

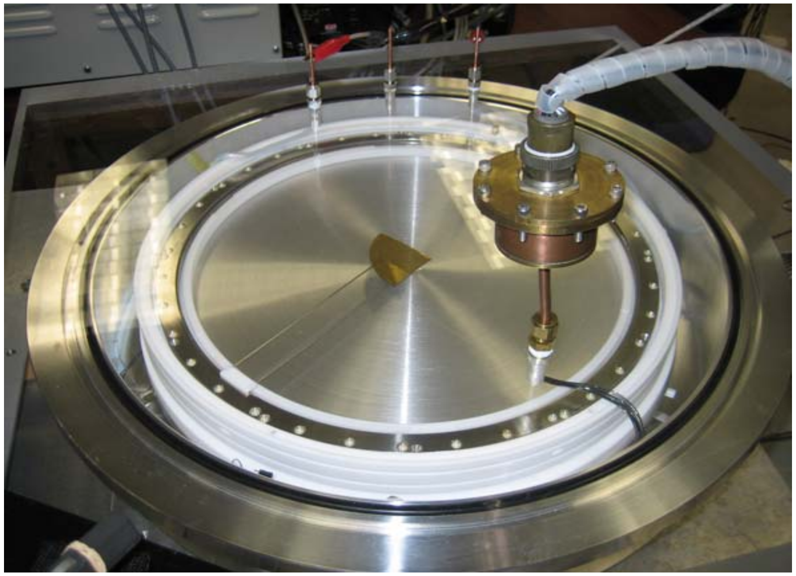



PTFE
Heater
gas extraction
field shaping rings
wire mesh

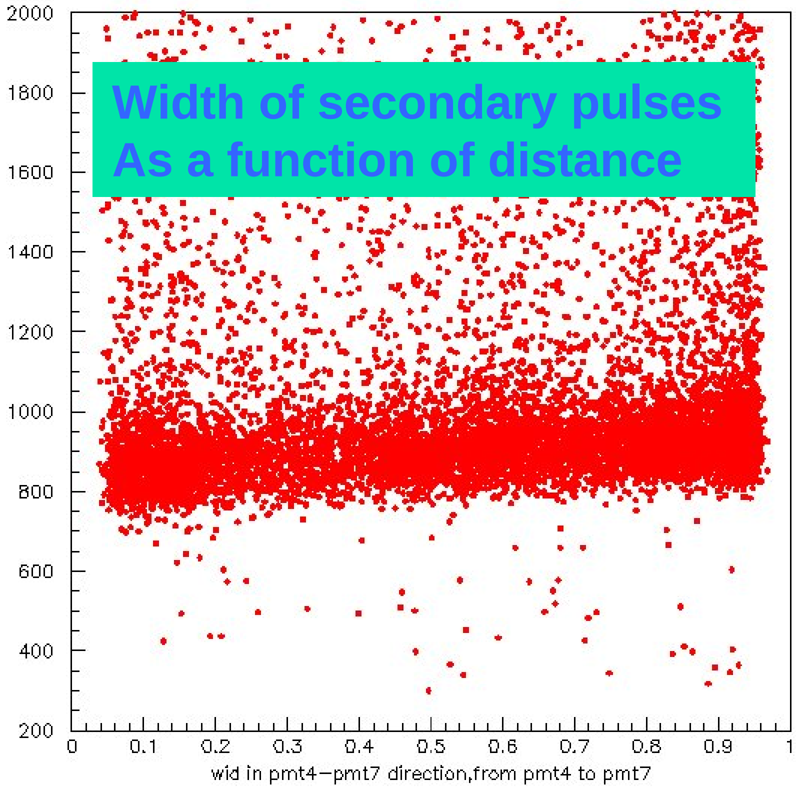
Zep II Charge Extraction & Luminescence Field Grid

88% transparency

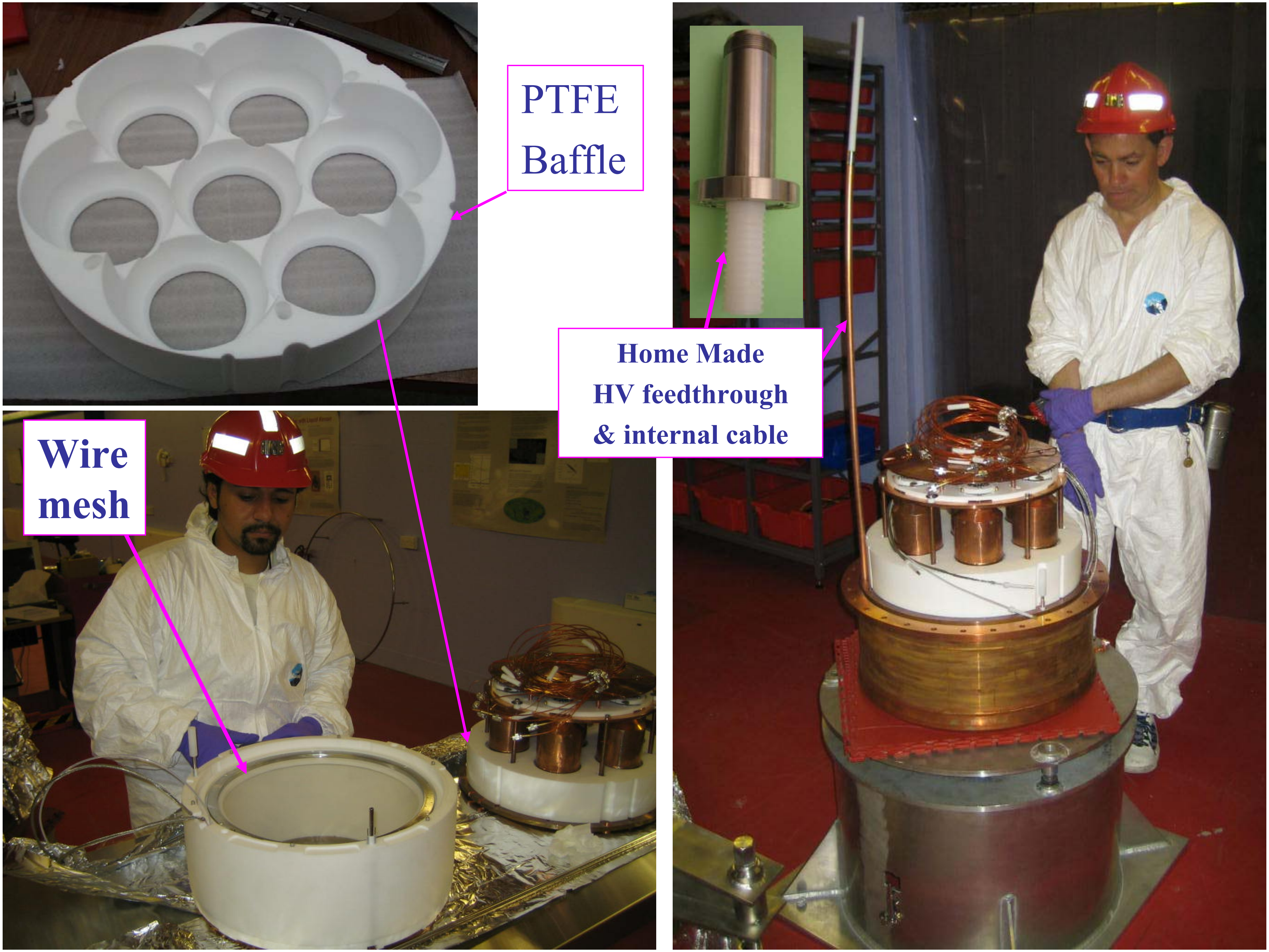




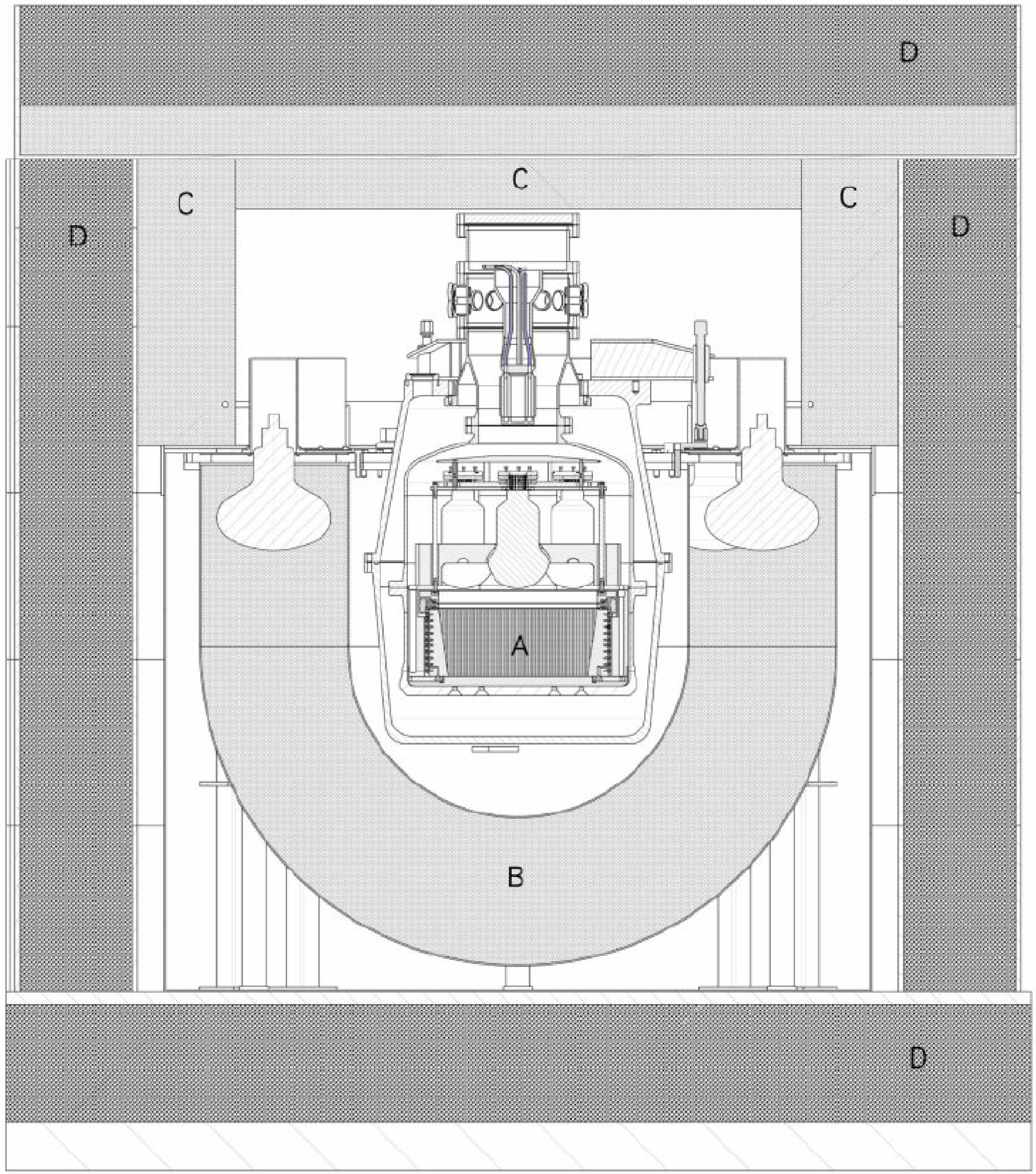
Cold deflection test



Width of secondary pulses
As a function of distance


PTFE
Baffle
Wire
mesh
Home Made
HV feedthrough
& internal cable

Detector Shielding Set up



A: Xenon Target

B: Veto

C: Neutron Shield

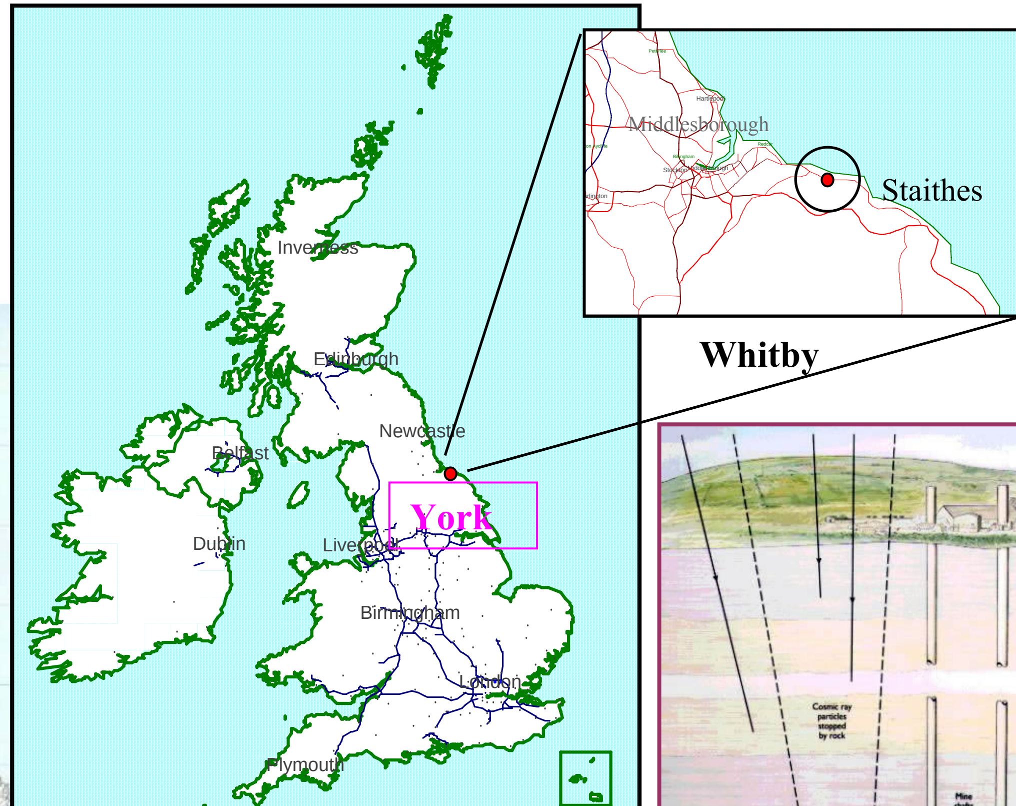
D: Lead

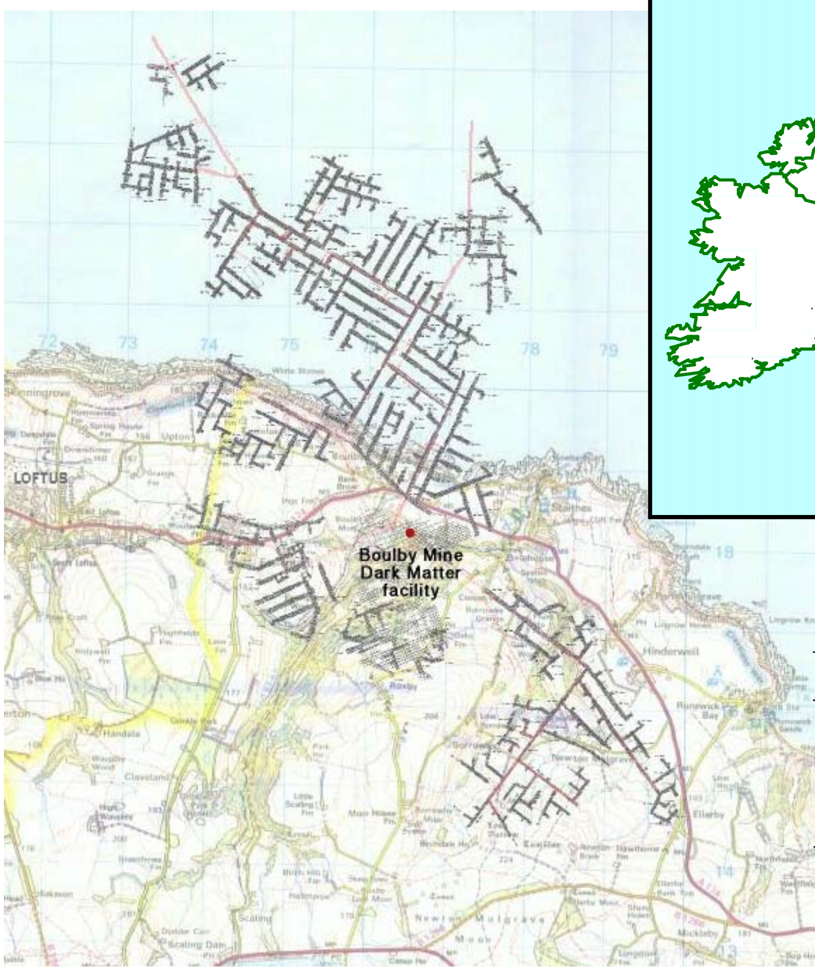
ZEPLIN II
Underground Operation
at Boulby Mine

First science run:

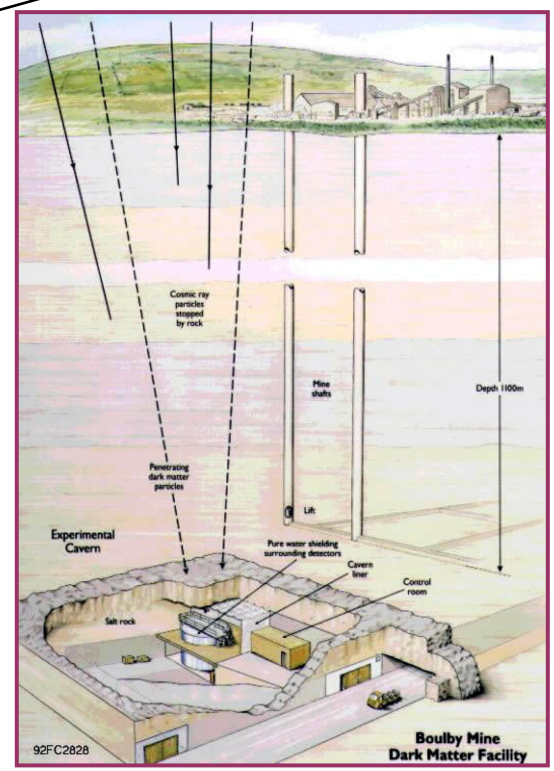
- 5 months continuous operation
- 1.0t*day of raw DM data
- Results submitted to Astropart. Phys.

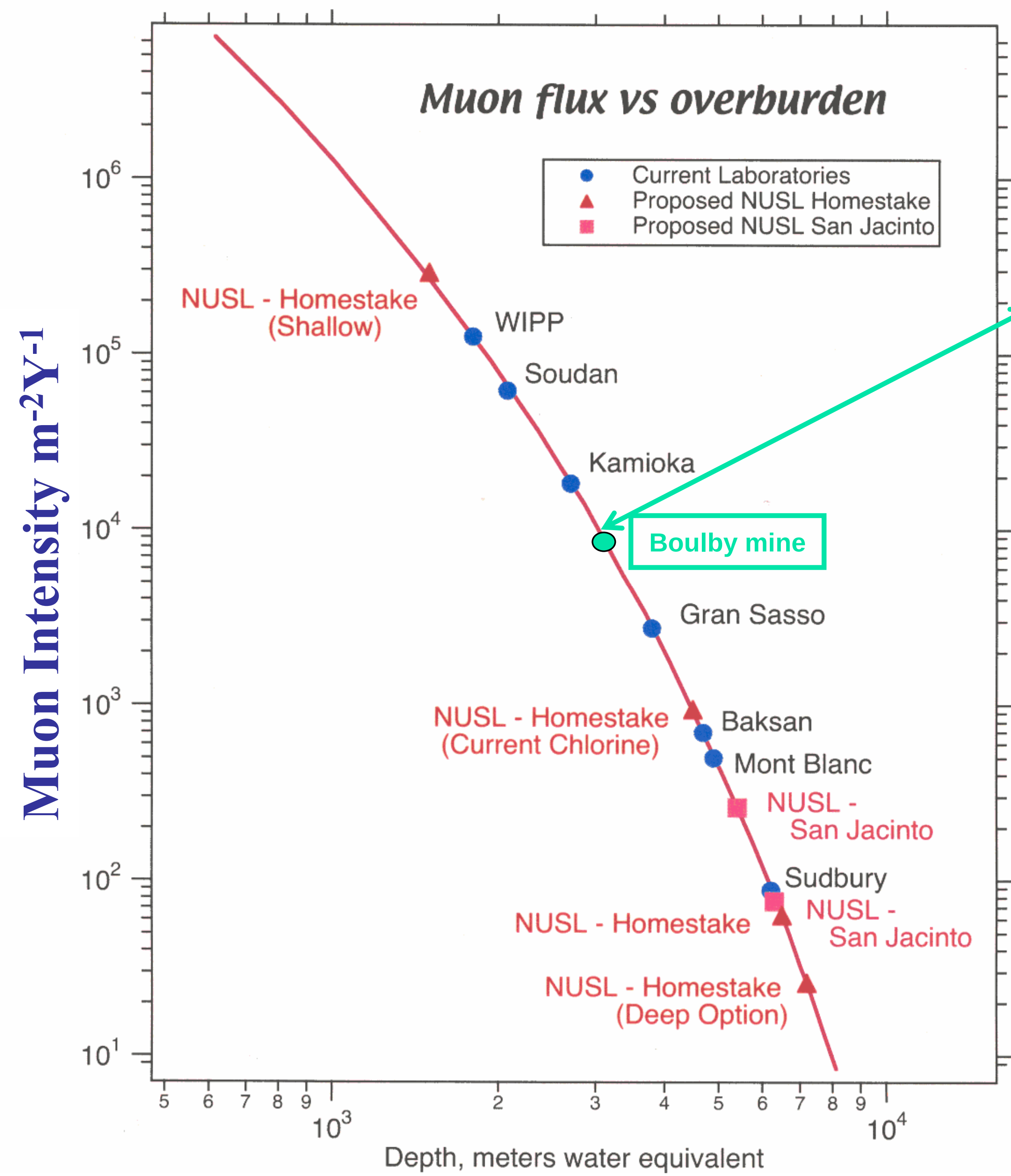
Location of ZEPLIN II Detector





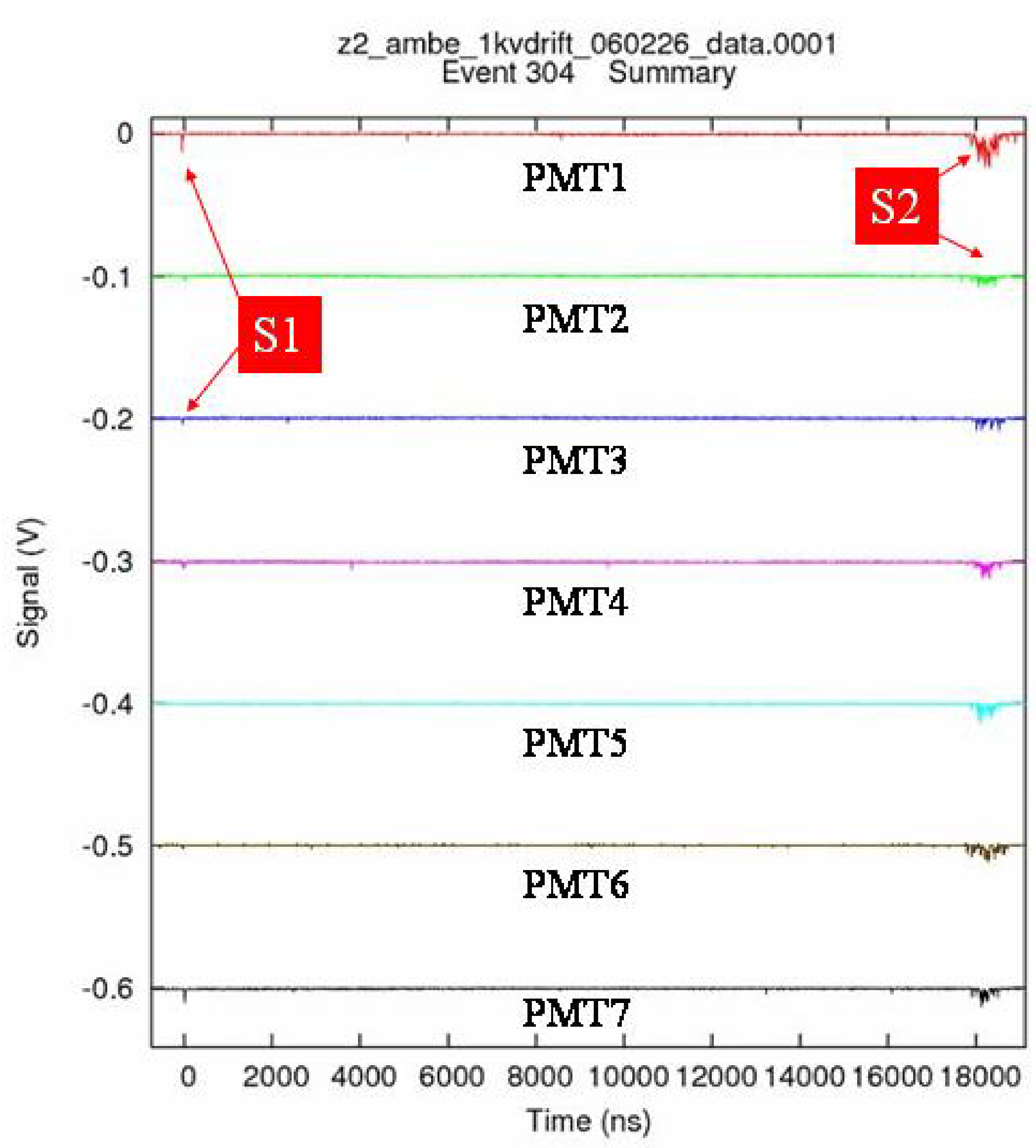
Boulby Site
1,100-m deep underground

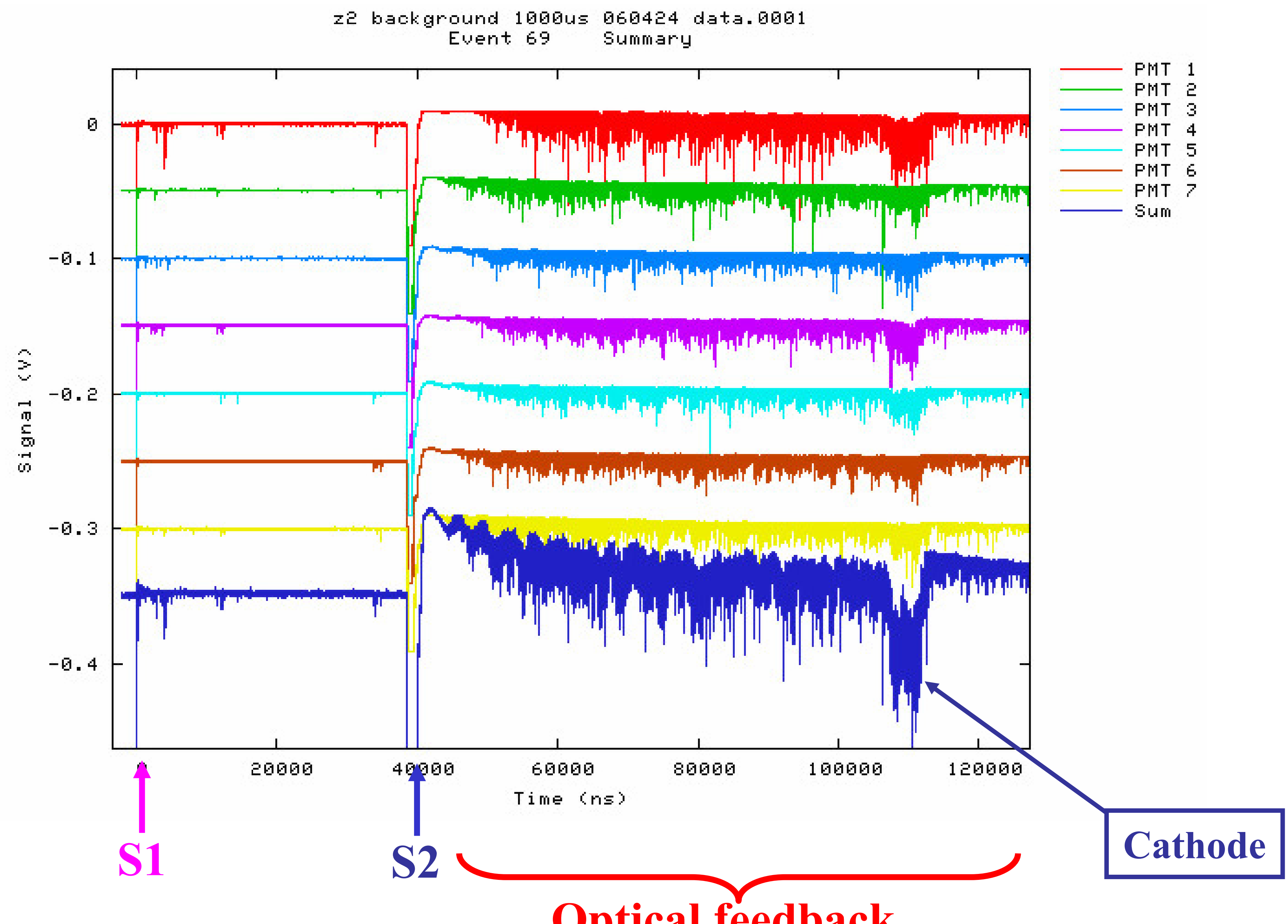




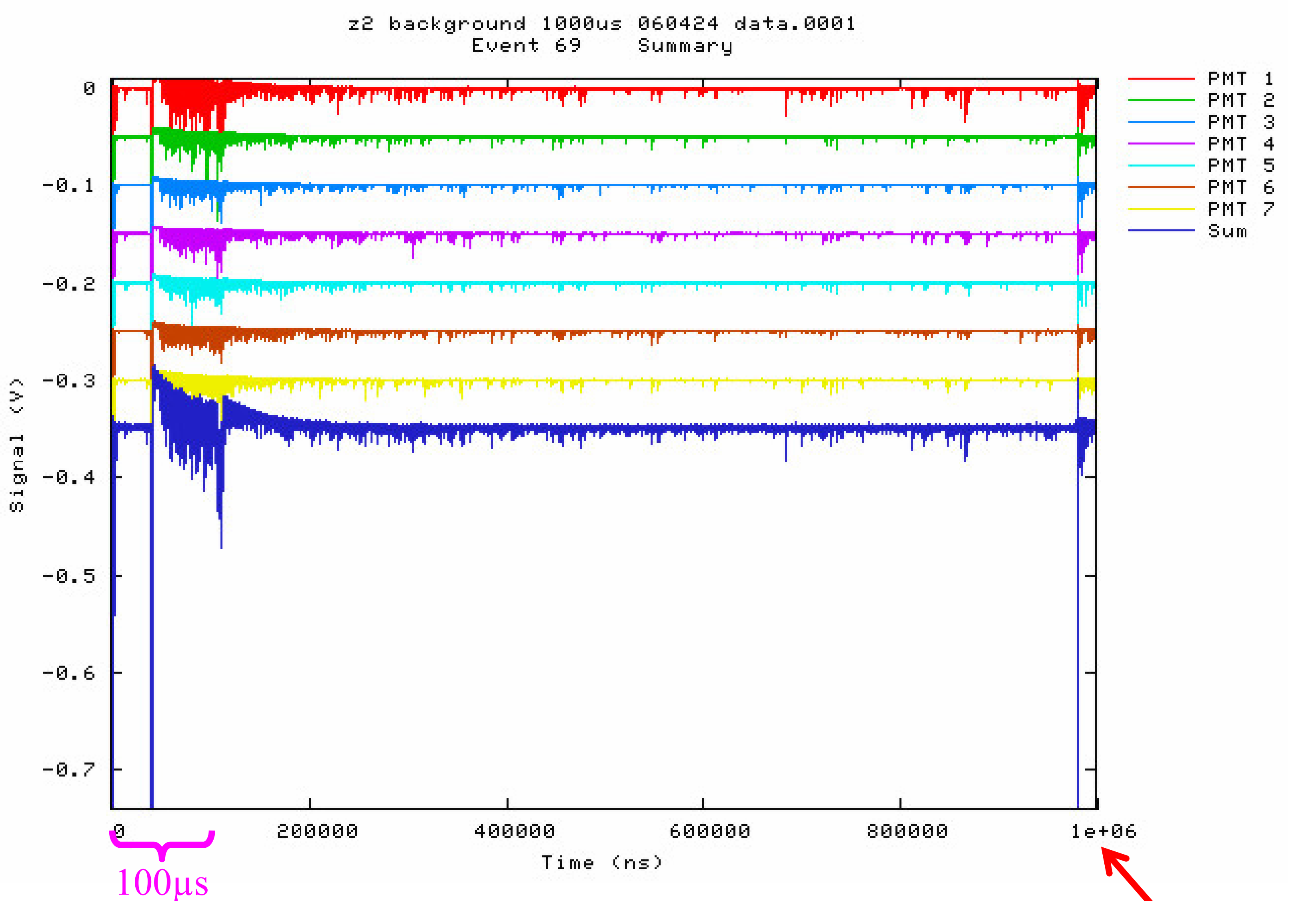
	Depth (m.w.e.)
WIPP	1600-2300
Soudan	2200
Boulby	3300
Gran Sasso	3800
Sudbury	6200 (SNOLAB)
Homestake	7200 (deep opt.)
San Jacinto	5400-6300

Recoil Event

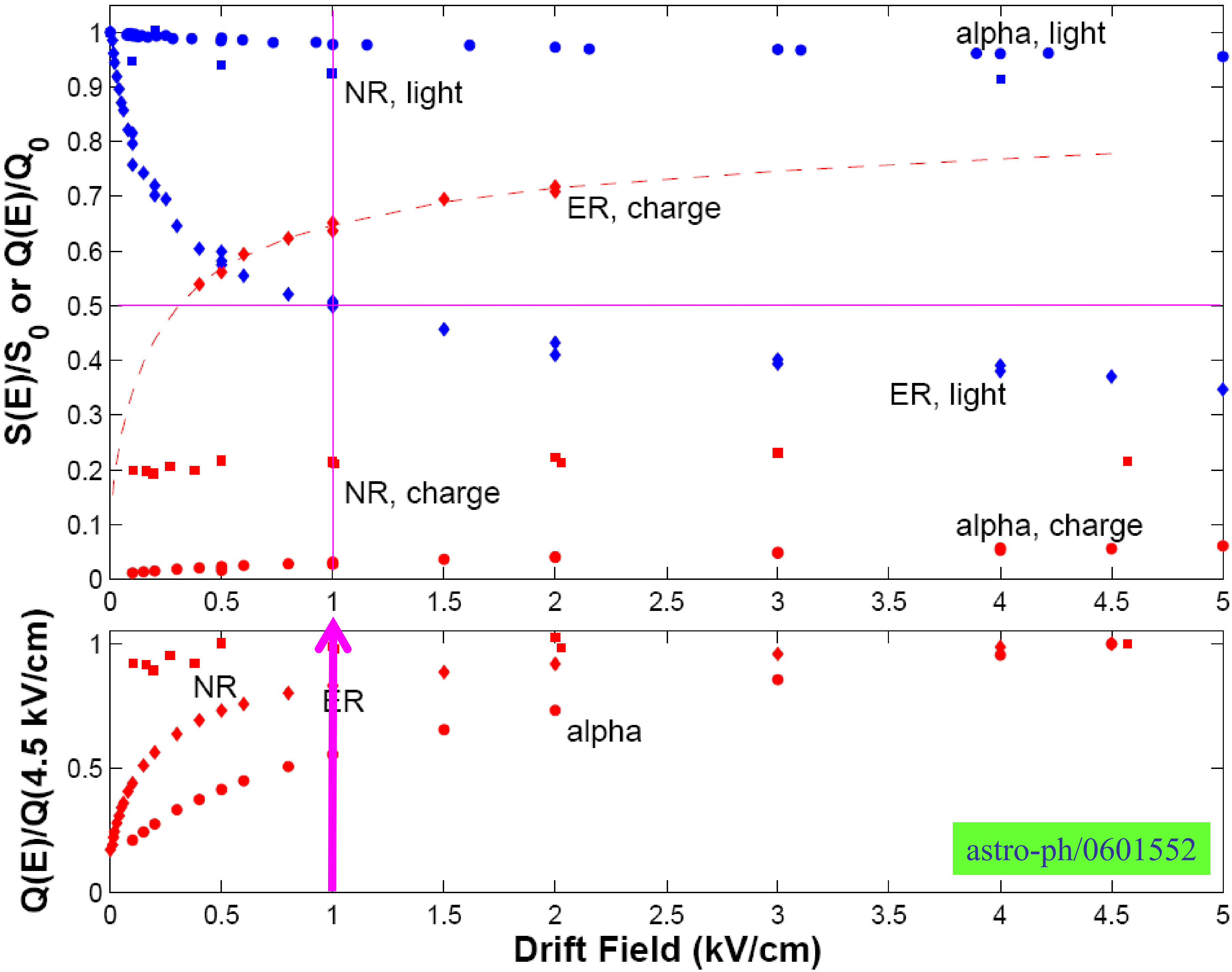




A high energy gamma event

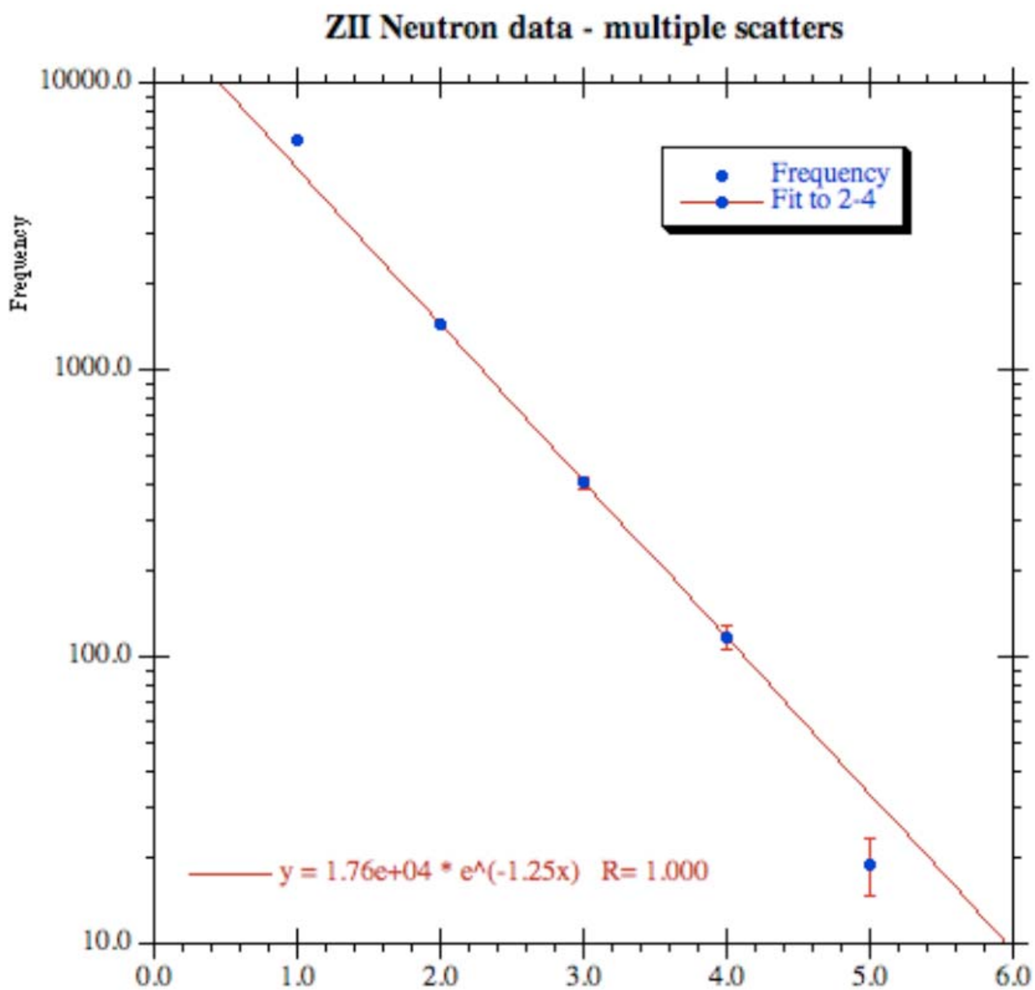


Optical feedback: A detailed look with wider window

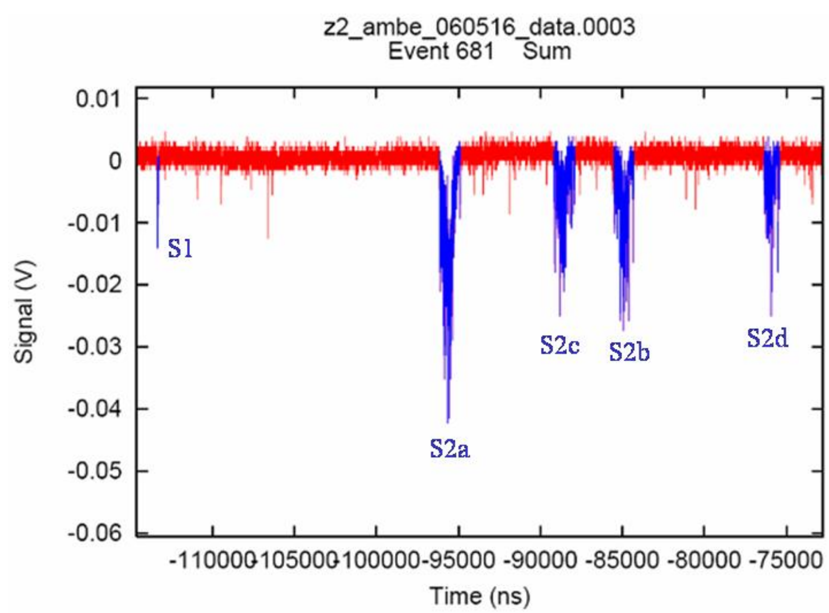


alpha, light
NR, light
ER, charge
ER, light
NR, charge
alpha, charge
S(E)/S0 or Q(E)/Q0
Q(E)/Q(4.5 kV/cm)
NR
ER
alpha
astro-ph/0601552
Drift Field (kV/cm)

Neutron multi-scatter In ZEPLIN II



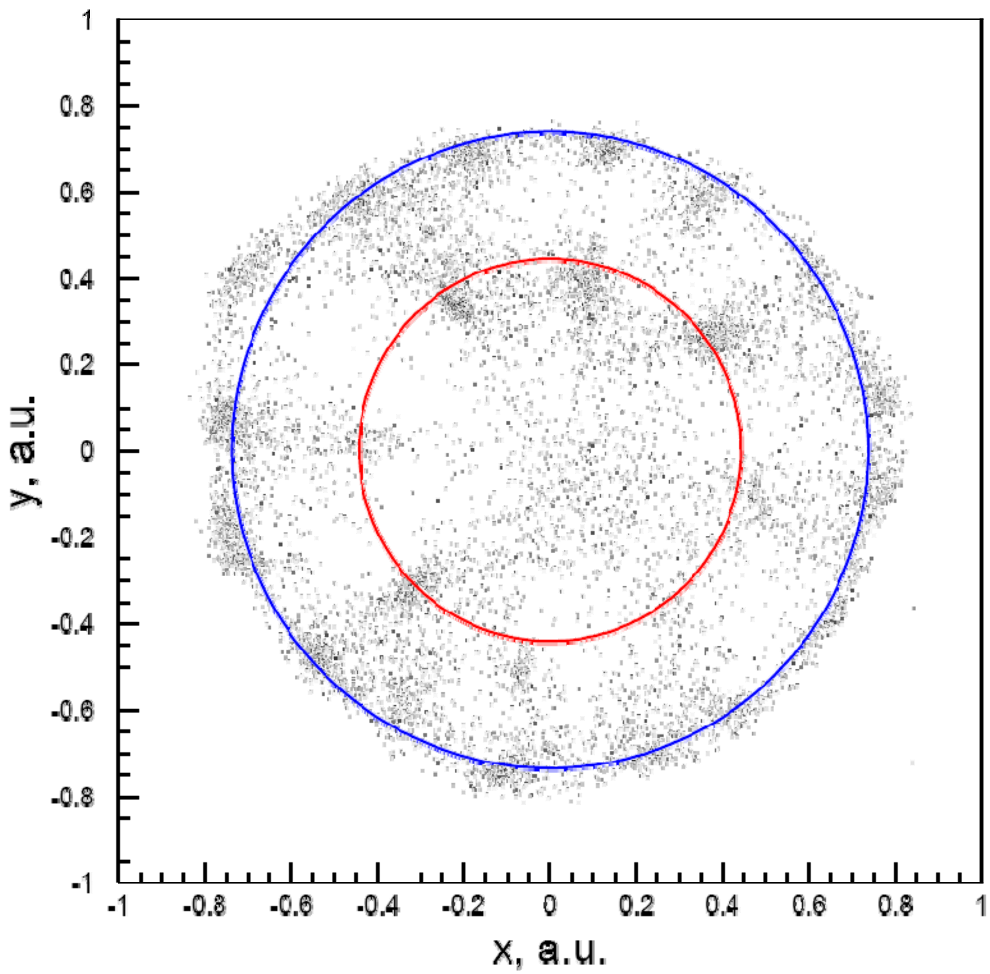
Number Of Scatters

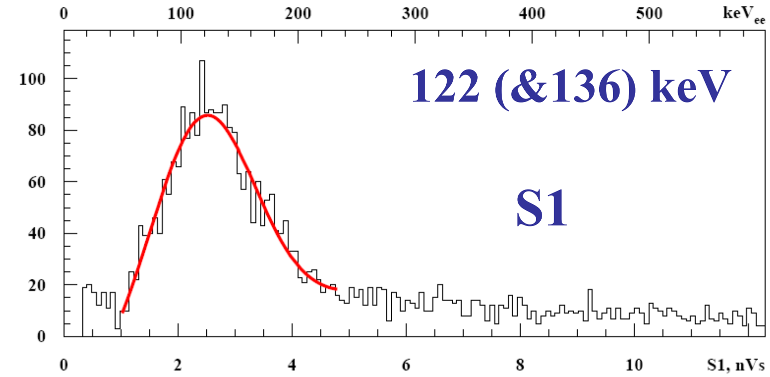


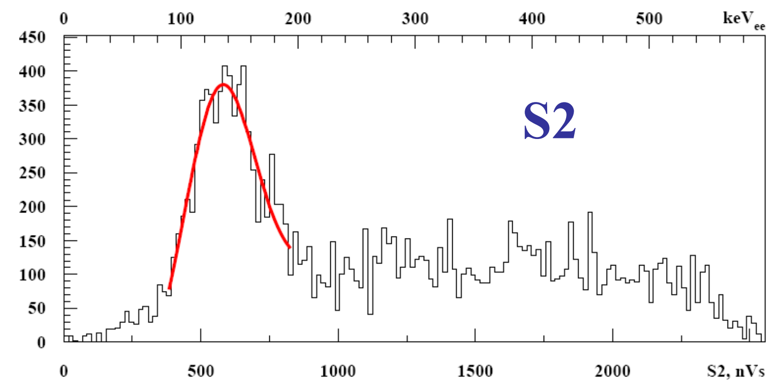
^{57}Co source data from bottom

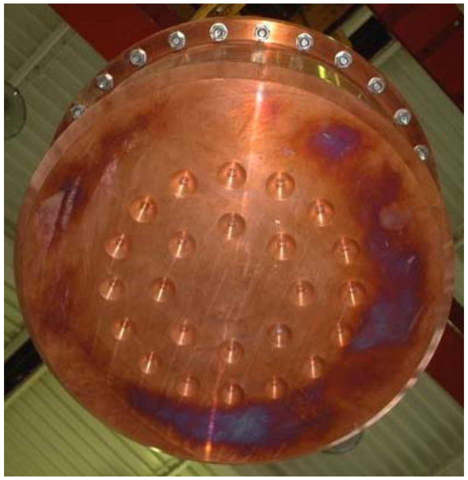
0.55p.e./keV @1kV/cm

Using S2 from each PMT to Determine the X-Y location



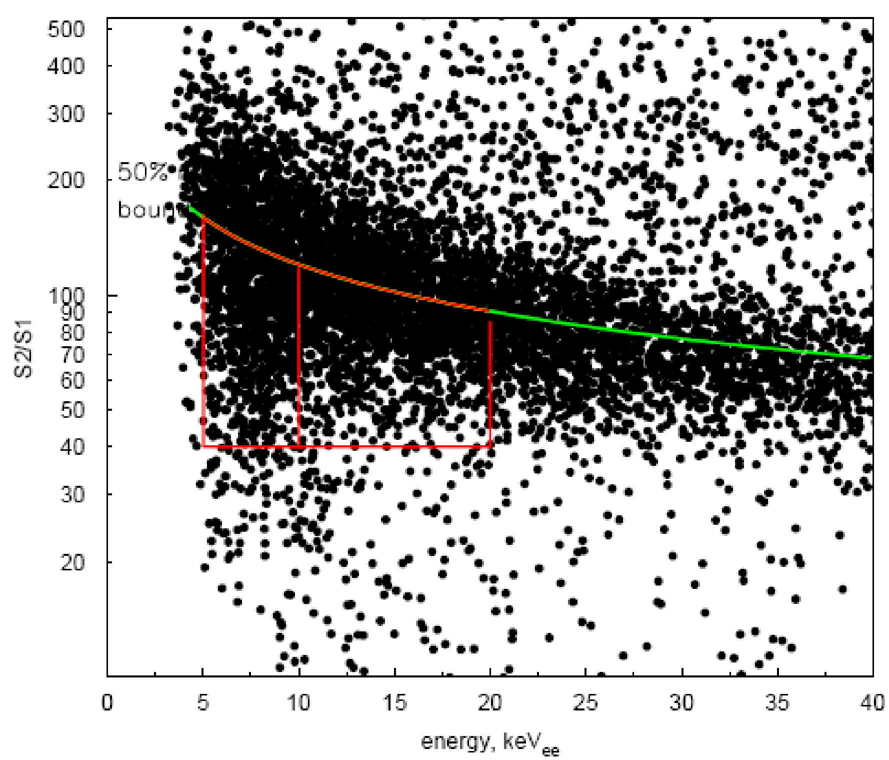




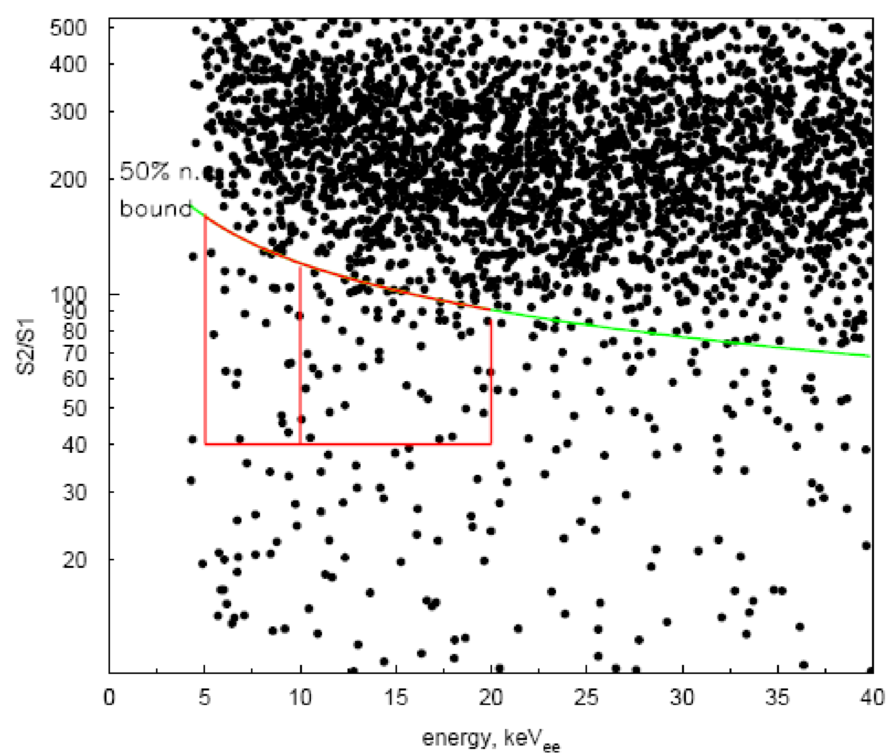


Discrimination and acceptance box determination

AmBe source calibration

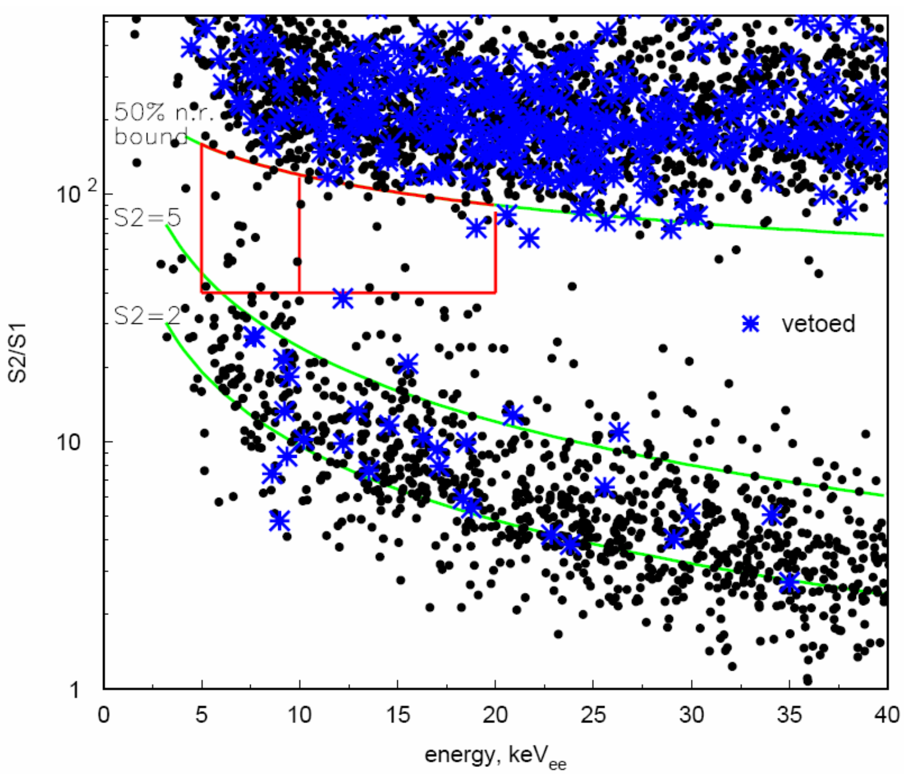


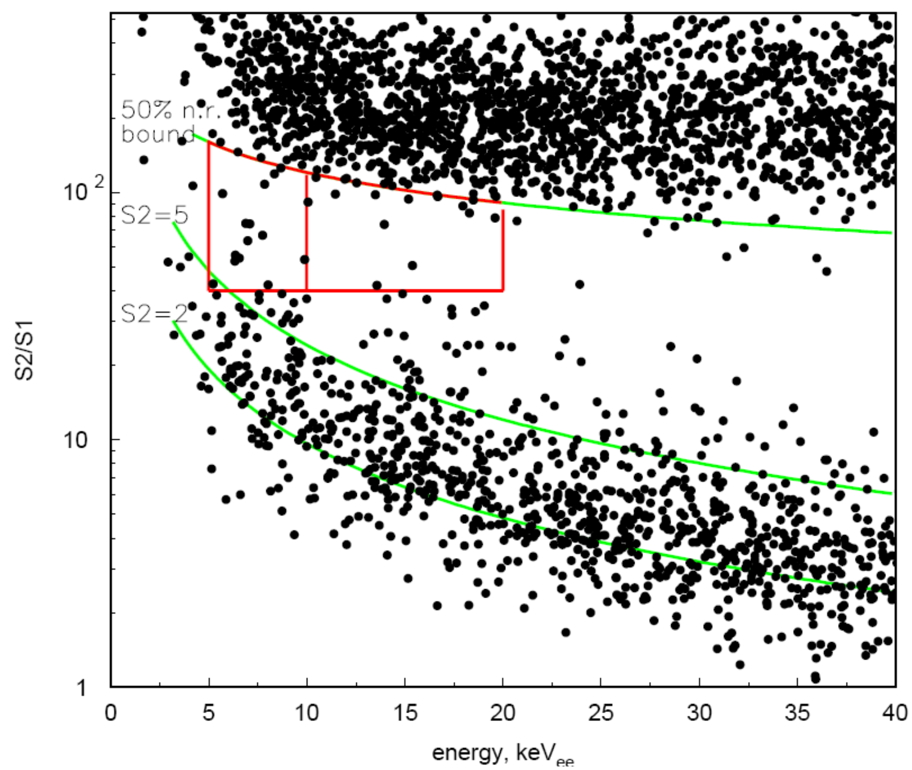
^{60}Co calibration



- Upper bound set at 50% n.r. acceptance
- Fixed S2/S1 lower bound
- Energy range from 5 to 20keVee
- 98.5% γ discrimination

Science Run Results

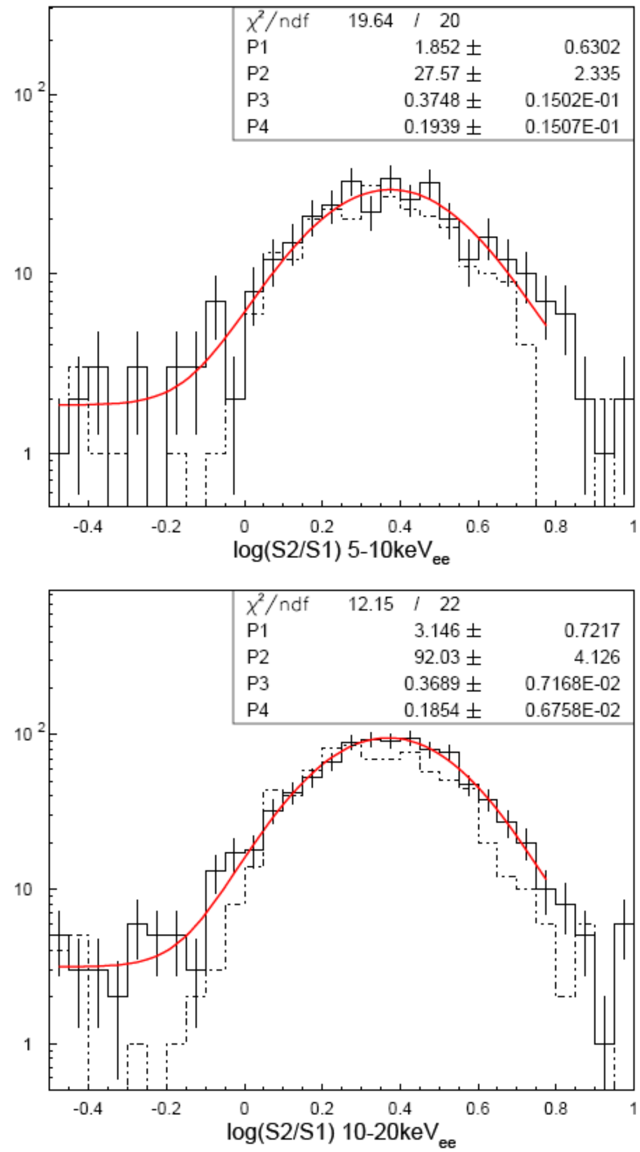




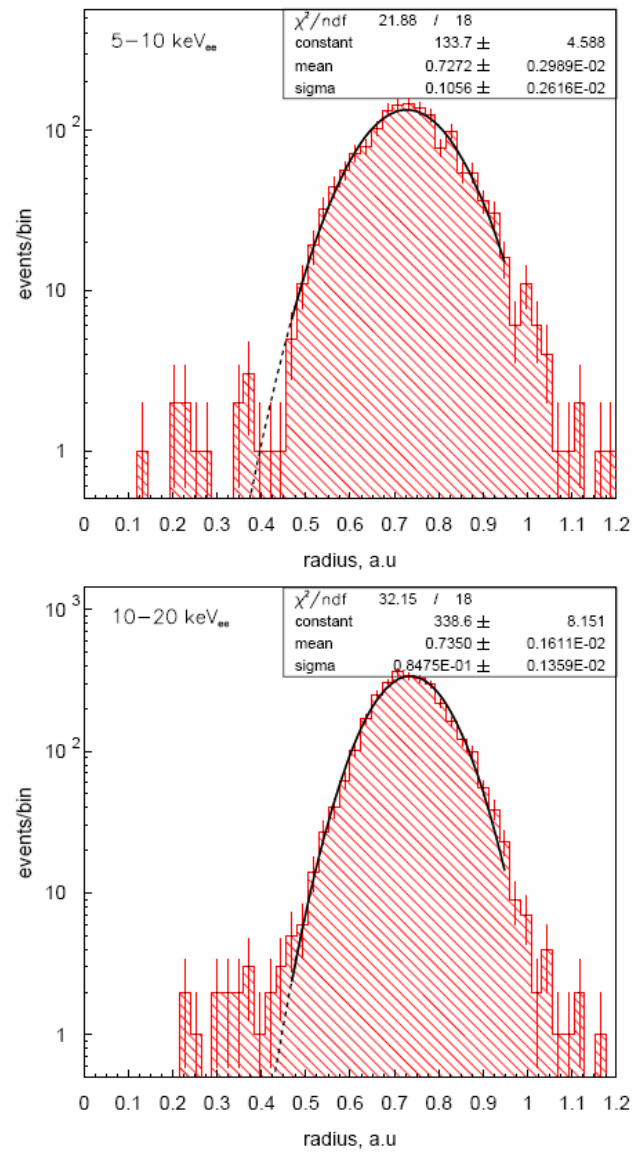
Blue star: Even in coincident with veto

Lower band due to Radon daughters on side walls

Background expectations



Gamma from Co-60



Radon Daughters

Cross-Section results, first run

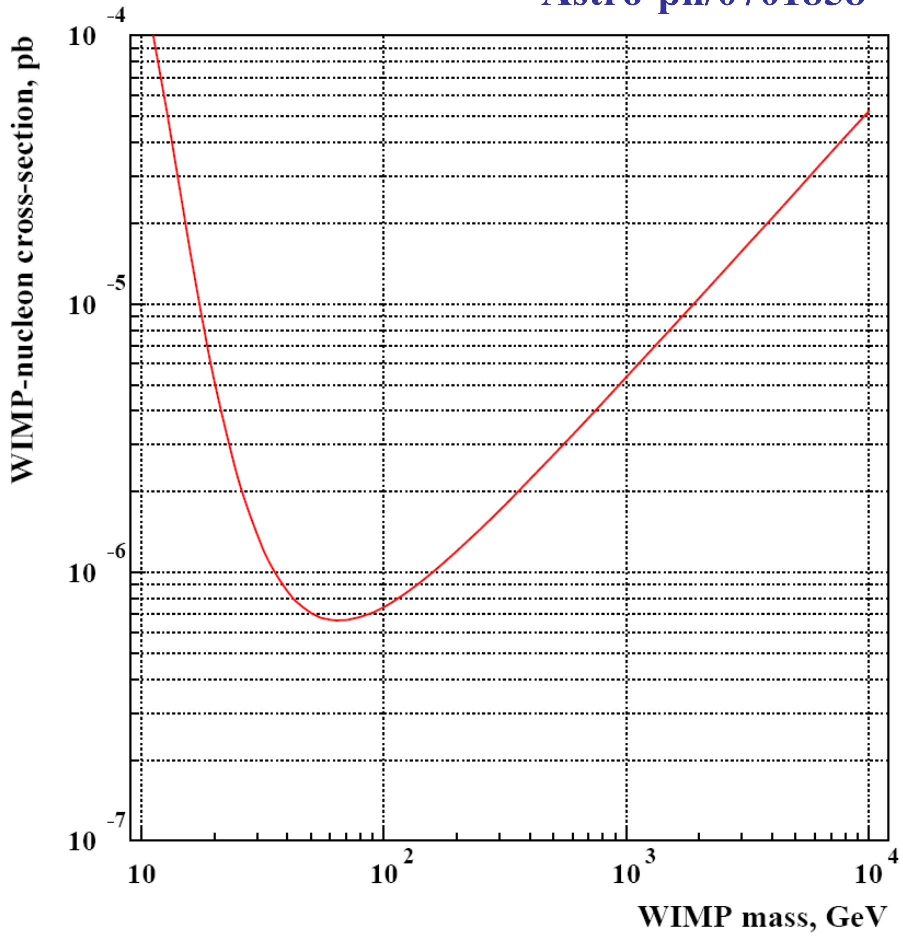
In review: submitted to Astropart. Phys.

- 29 events seen in box
- 28.6±4.3expected (total)
- 10.4 upper limit to n.r.
- 225 kg*days
- 7.2kg fiducial

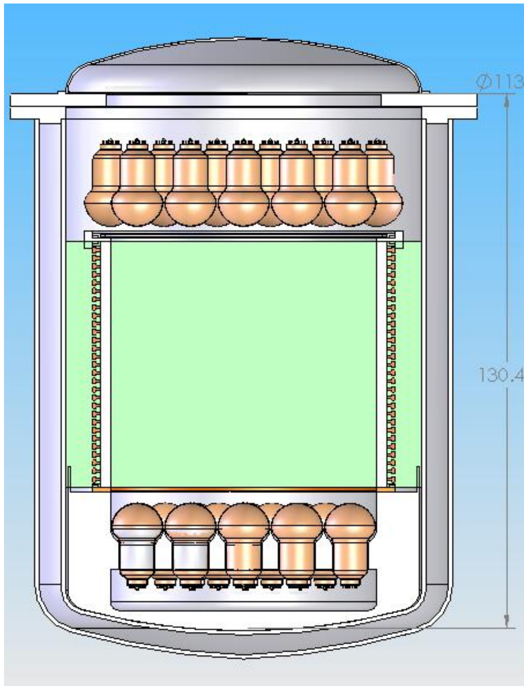
Standard Halo

Scalar Interaction

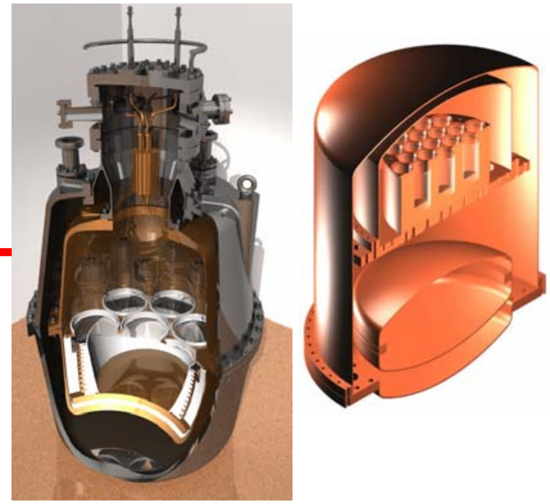
Astro-ph/0701858



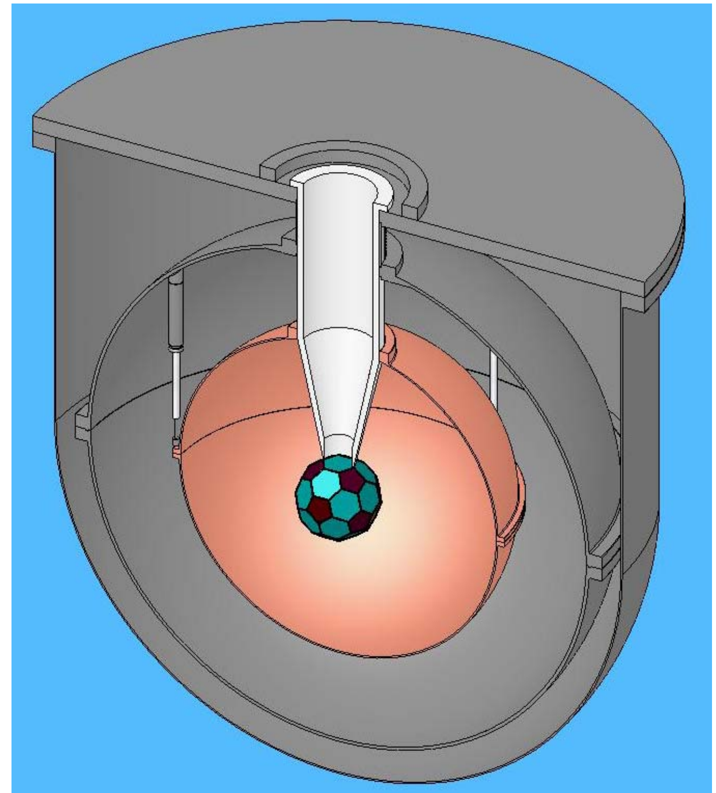
WIMP-nucleon cross section limits for 31 days (225 kg-days): 6.6 x 10^{-7} pb (@65GeV)



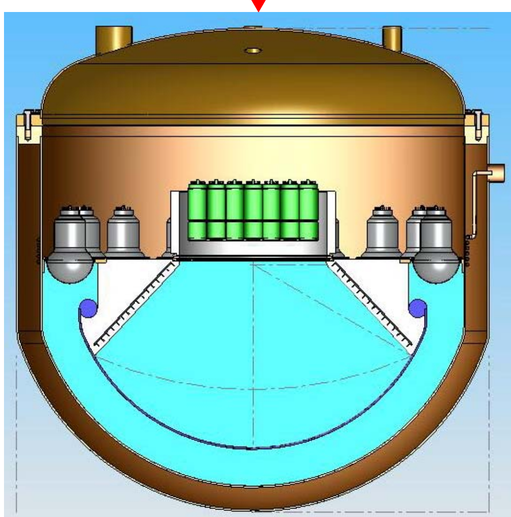
0.5-ton



ZEPLIN II/III

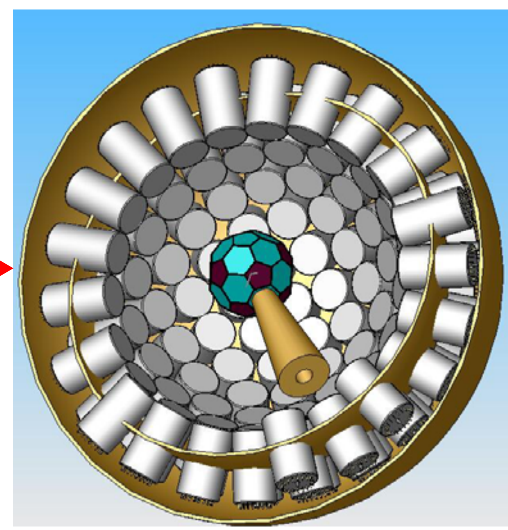


1.6-ton
5.8-ton total



1-ton

ZEPLIN IV?

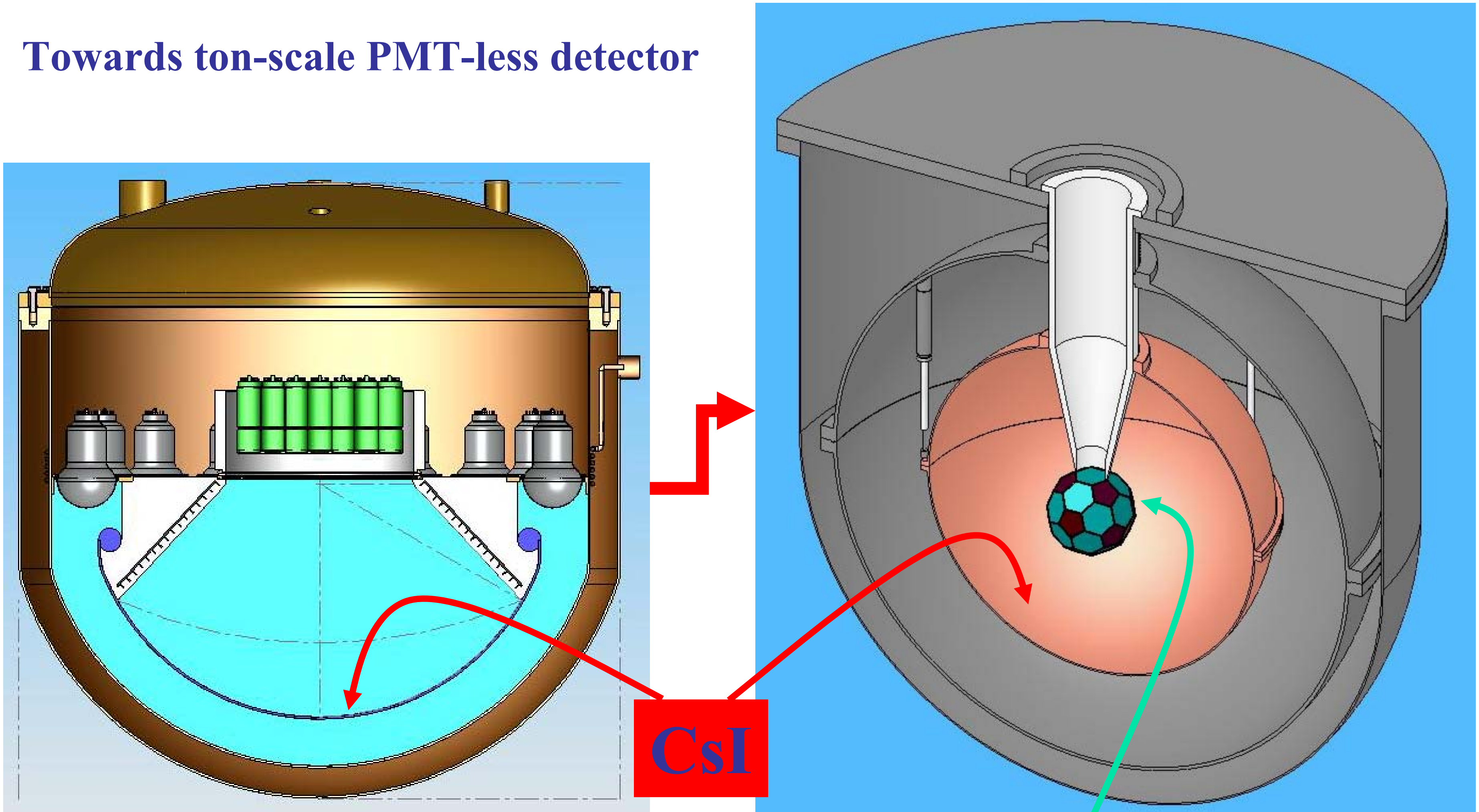


My Dream Detector

ZEPLIN long term strategy II

5-ton

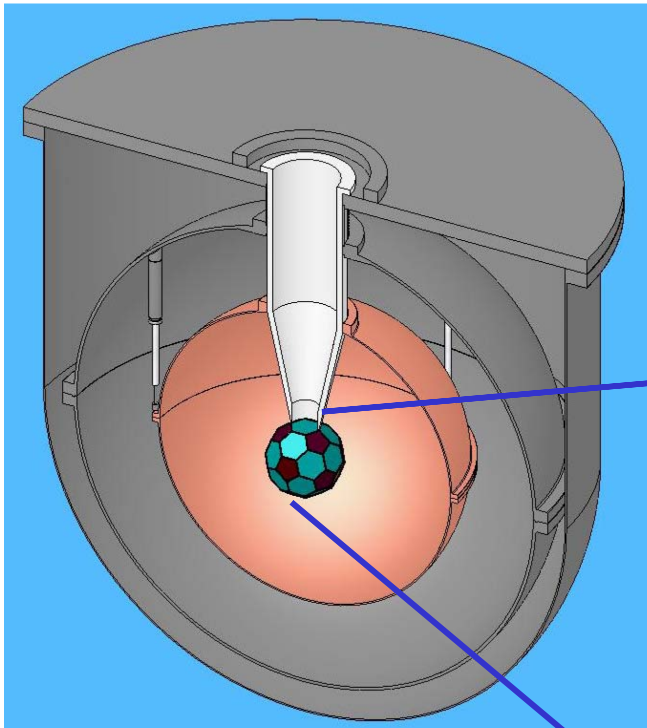
Towards ton-scale PMT-less detector



1-ton

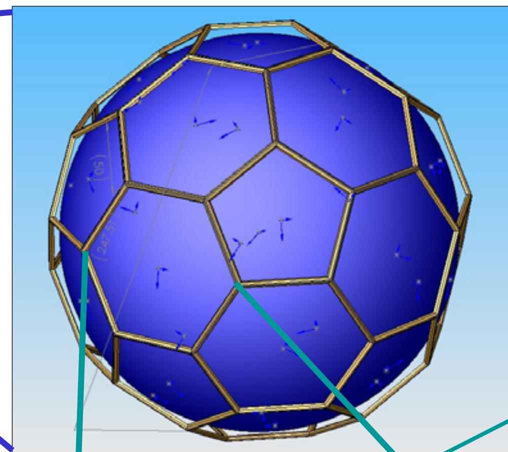
Nano-Tip Charge Readout

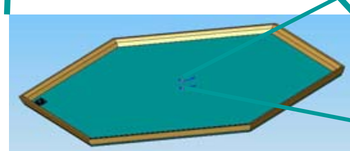
Future Multi-Ton detector

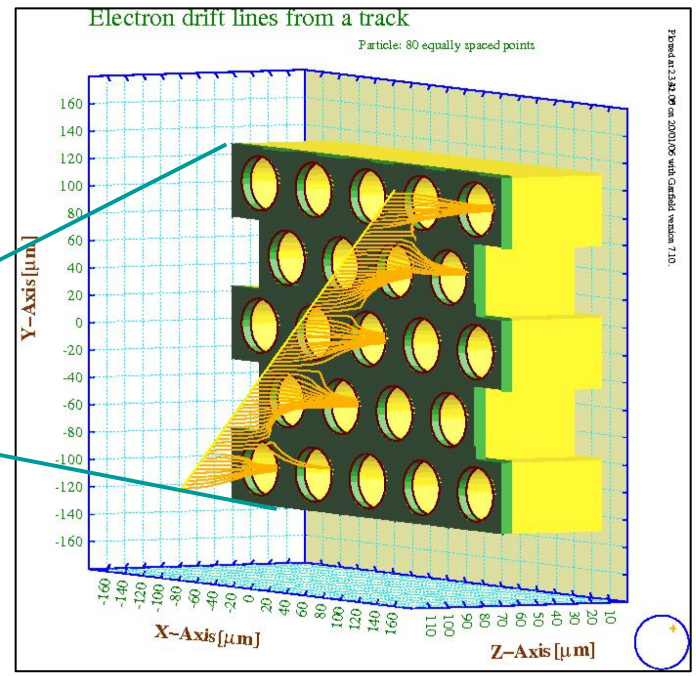


Central ball 4pi covered with charge collecting and amplifying micro-structure

Nano-Tip Structure for Charge Readout



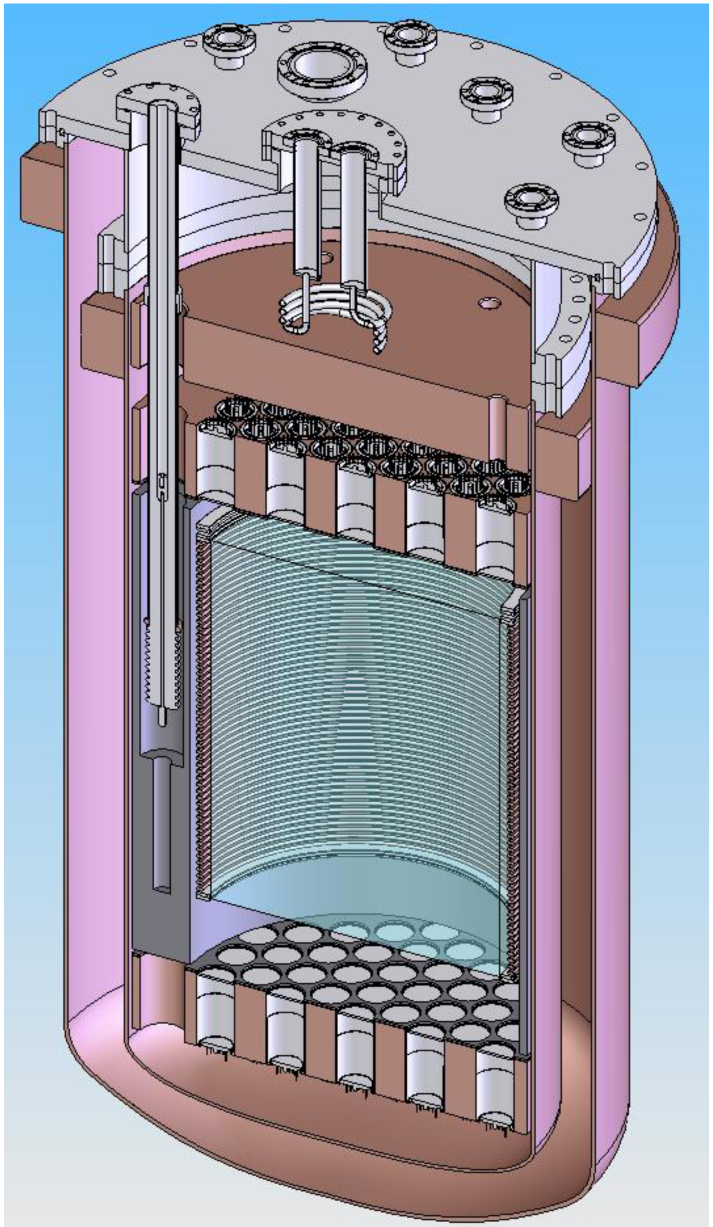




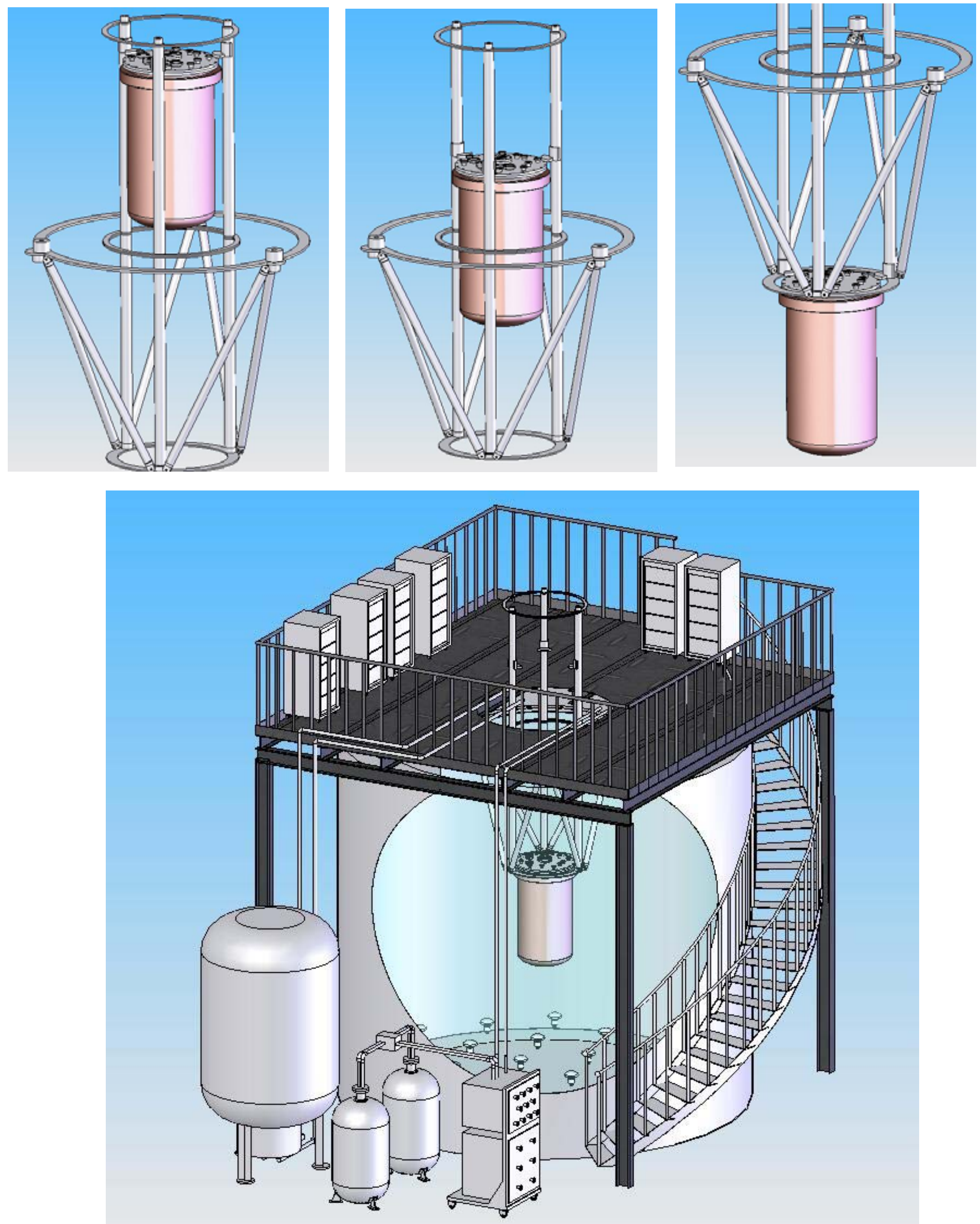
Requirements:

- **Sensitivity to single electron**
- **High readout segmentation for position information**

The LUX Detector



One Possible System for Installation

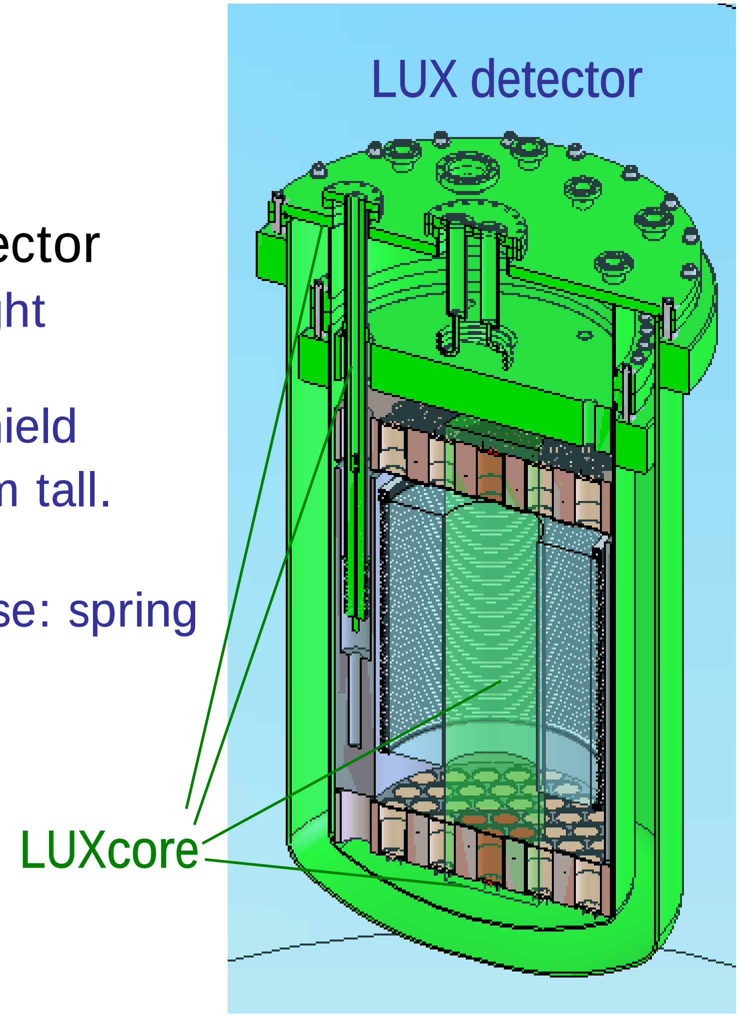


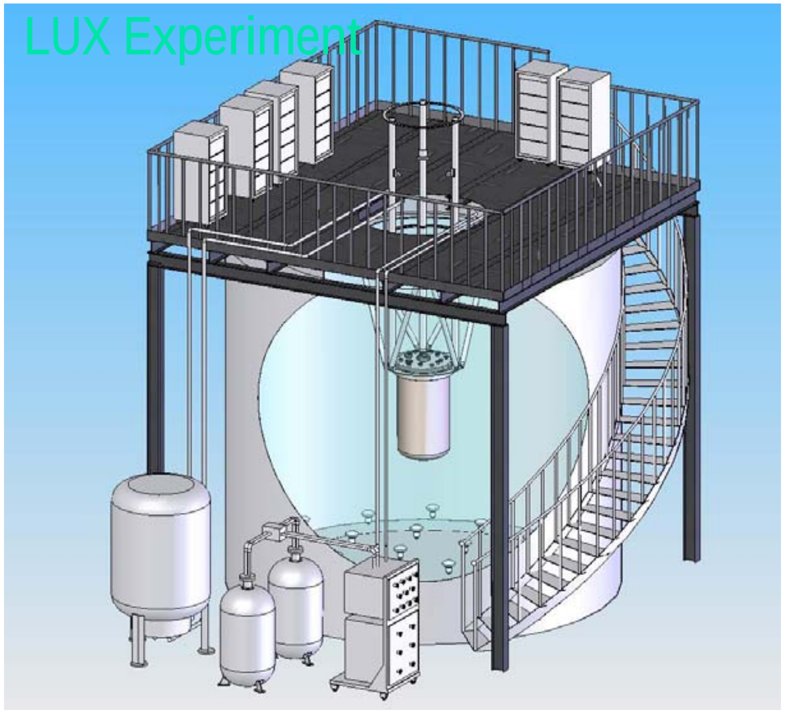
LUX Dark Matter Experiment - Summary

- Brown, Case, LLNL, LBNL, Rochester, Texas A&M, UC Davis, UCLA
  - XENON10, ZEPLIN II (US) and CDMS; ν Detectors (Kamland/SuperK/SNO/Borexino); HEP/γ-ray astro
  - (Also ZEPLIN III Groups after their current program completed)
- 300 kg Dual Phase liquid Xe TPC with 100 kg fiducial
  - >99% ER background rejection for 50% NR acceptance, E>10 keVr
    (Case+Columbia/Brown Prototypes + XENON10 + ZEPLIN II)
  - 3D-imaging TPC eliminates surface activity, defines fiducial
- Backgrounds:
  - Internal: strong self-shielding of PMT activity
    - $\gamma/\beta < 7\times10^{-4}$ /keVee/kg/day, from PMTs (Hamamatsu R8778 or R8520).
    - Neutrons (α,n) & fission subdominant
  - External: large water shield with muon veto.
    - Very effective for cavern γ+n, and HE n from muons
    - Very low gamma backgrouns with readily achievable $<10^{-11}$ g/g purity.
- DM reach: 2×10^{-45} cm^2 in 4 months
  - Possible ~5×10^{-46} cm^2 reach with recent PMT activity reductions, longer running.

LUX program: exploit scalability

- LUXcore: Final engineering for large-scale detector
  - Cryostat, >100 kV feedthrough, charge drift, light collection over large distance
  - Full system integration, including ~1m water shield
  - 40 kg narrow “core”, 14 PMTs, 20 cm Ø x 40 cm tall.
    - Radial scale-up requires full-funding.
  - Under construction, Jan 2007, operations at Case: spring 2007.



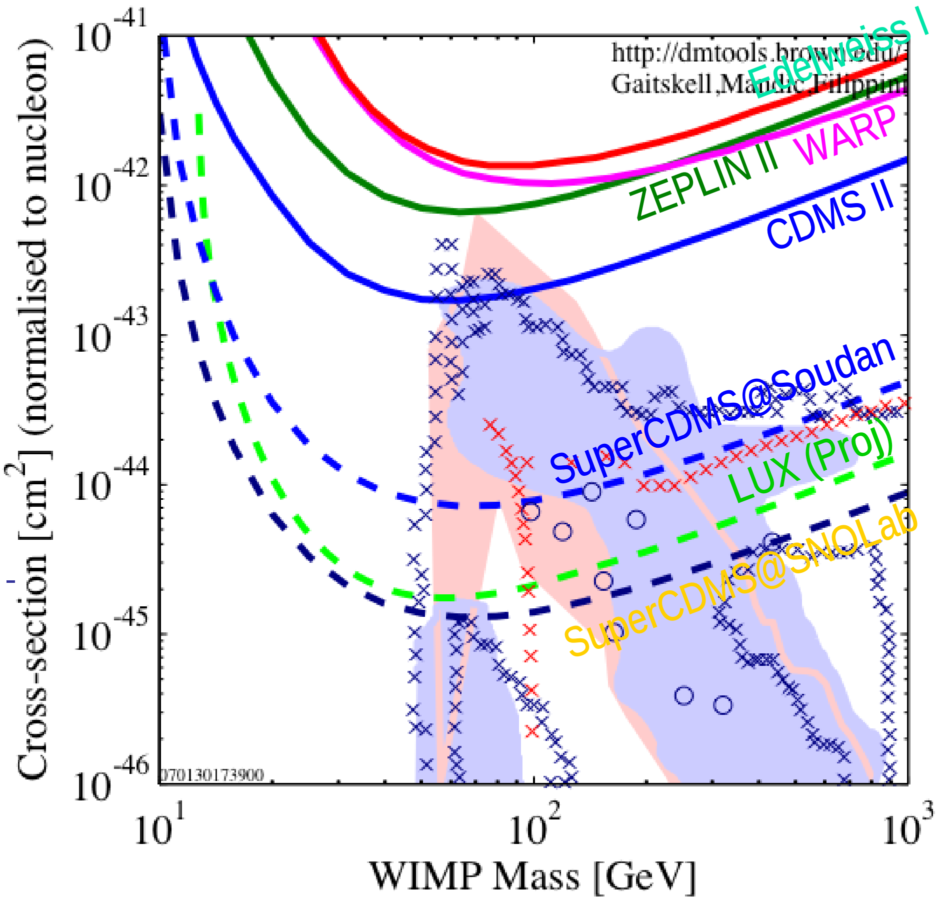


- LUX in ~ 6m Ø water shield
- Very good match to early-implementation DUSEL (e.g., Homestake “Davis” cavern)
  - SNOLAB LOI
- System scalable to very large mass.

Cryostat arrived at Case (Feb. 12 2007)

LUX Dark Matter Goal

- Dark Matter Goals
  - LUX - Sensitivity curve at $2x10^{-45}$ cm^2 (100 GeV)
    - Exposure: Gross Xe Mass 300 kg
      Limit set with 120 days running
      x 100 kg fiducial mass x 50% NR acceptance
      - If candidate dm signal is observed, run time can be extended to improve stats
    - ~1 background event during exposure assuming most conservative assumptions of
      ER $7x10^{-4}$ /keVee/kg/day and 99% ER rejection
      - ER bg assumed is dominated by guaranteed Hamamatsu PMT background (R8778 or R8520) - recent PMTs from Hamamatsu achieving lower backgrounds, but not guaranteed
      - Improvements in PMT bg (and rejection power) will extend background free running period, and DM sensitivity
  - Comparison
    - SuperCDMS Goal @ SNOLab: Gross Ge Mass 25 kg
      (x 50% fid mass+cut acceptance)
      Limit set for 1000 days running x 7 SuperTowers



XENON10 Results will be announced at APS April Meeting