R&D of Liquid Xenon TPCs for Dark Matter Searches

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CHIPP 2008 Workshop on Detector R&D

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Overview

- What already works: examples from XENON10
  - Basics of a LXe Dual phase TPC
  - S2 and its many applications
- Challenges and Developments in future LXe detectors
  - Nuclear recoil Energy scale in S1
  - Nuclear recoil Energy scale in S1 + S2
  - Gamma-x events
  - Getting rid of backgrounds: Self shielding

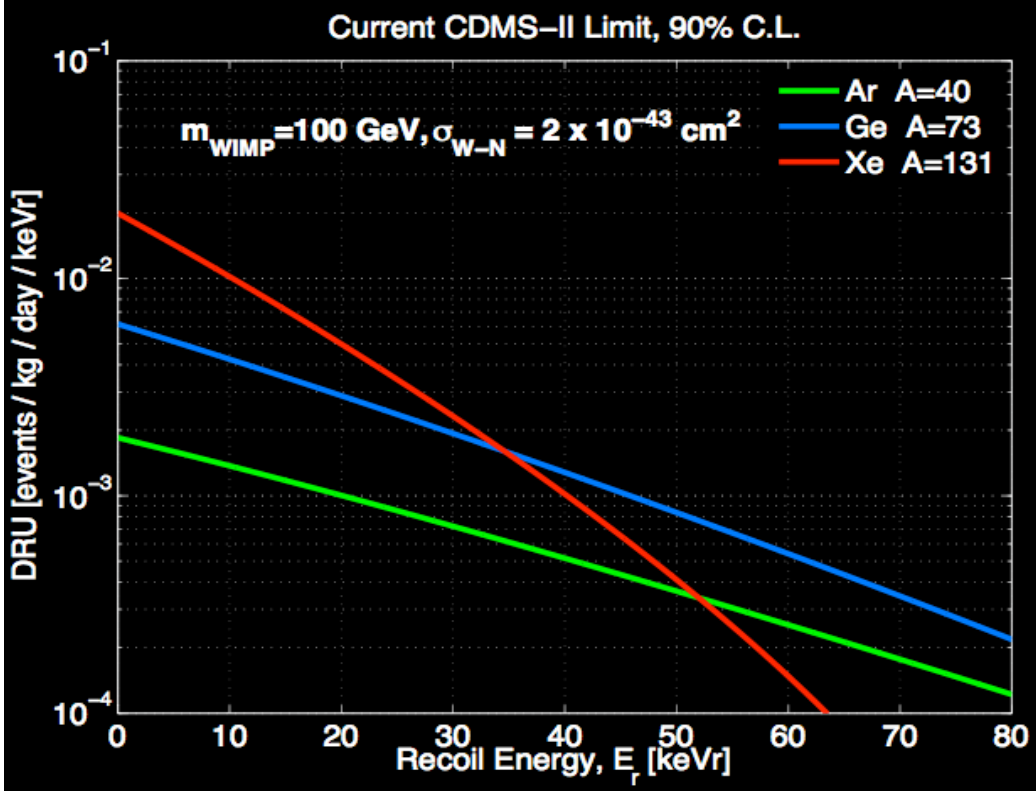
Why use Liquid Xenon to look for DM?

54

Xe

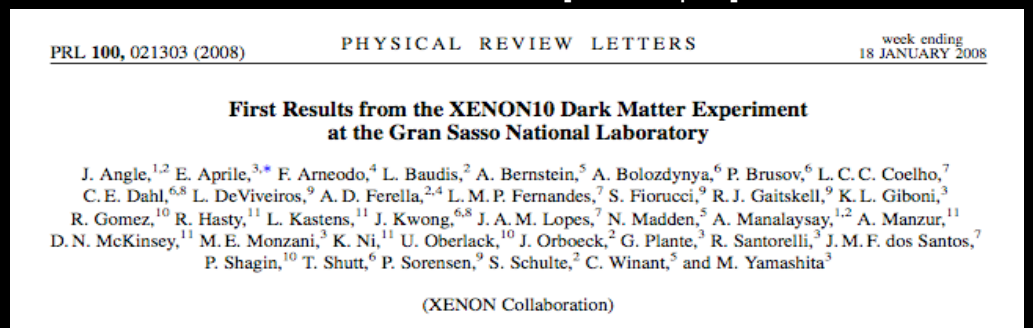
131.29

- Large A (~131), great for SI ($\sigma \sim A^2$) if NR threshold is low.
- ~50% odd isotopes (^{129}Xe, ^{131}Xe), for SD interactions.
- No long lived radioisotopes.
- High stopping power means active volume is self-shielding.
- Cryogenics at ~180 K quite easy.
- Efficient intrinsic scintillator (80% light-yield of NaI), with fast time-response.
- BG Rejection/reduction -- NR discrim through simultaneous measurement of light and charge, 3-D even localization and self shielding.
- Electro-negative impurities easily reduced to << 1ppb level (for high electron drift lengths.
- Easily scaled up in mass.
- Inter gas, safe to work with.
- Relatively inexpensive (~ 2 KEuro/kg).



As seen in PRL **100**, 021303 (2008)

Or arXiv:0706.0039 [astro-ph]



PRL **100**, 021303 (2008) PHYSICAL REVIEW LETTERS week ending 18 JANUARY 2008

First Results from the XENON10 Dark Matter Experiment at the Gran Sasso National Laboratory

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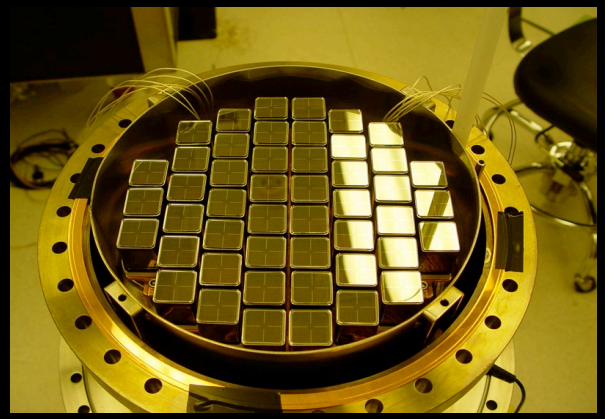
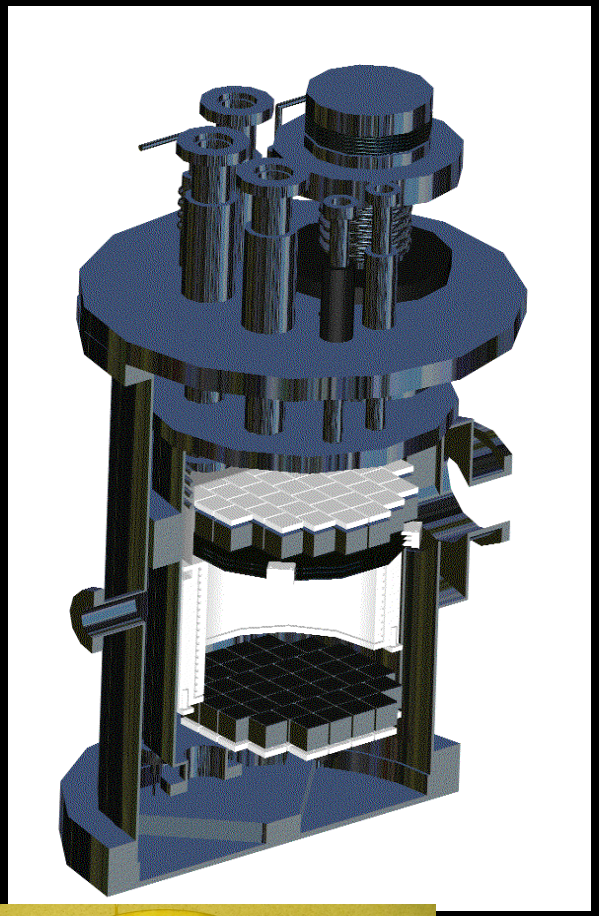
(XENON Collaboration)

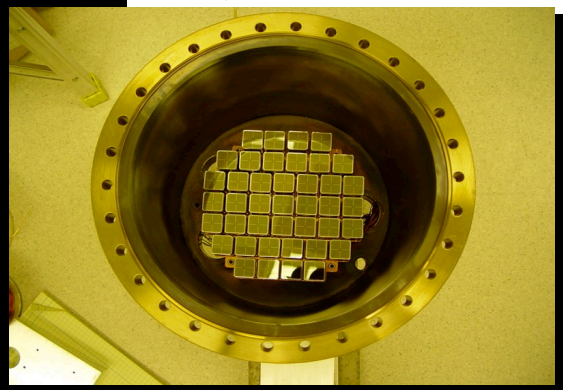
XENON10 Detector Specifics

- **Dimensions**
  - 22 kg LXe , 15 kg active, 5.4 kg fiducial
  - Cylinder, r = 10 cm, z = 15 cm
- **PMTs**
  - Hamamatsu R8520 Al, 1" x 3.5 cm
  - Bialkali-photocathode Rb-Cs-Sb,
  - Quantum efficiency > 20% for 178 nm

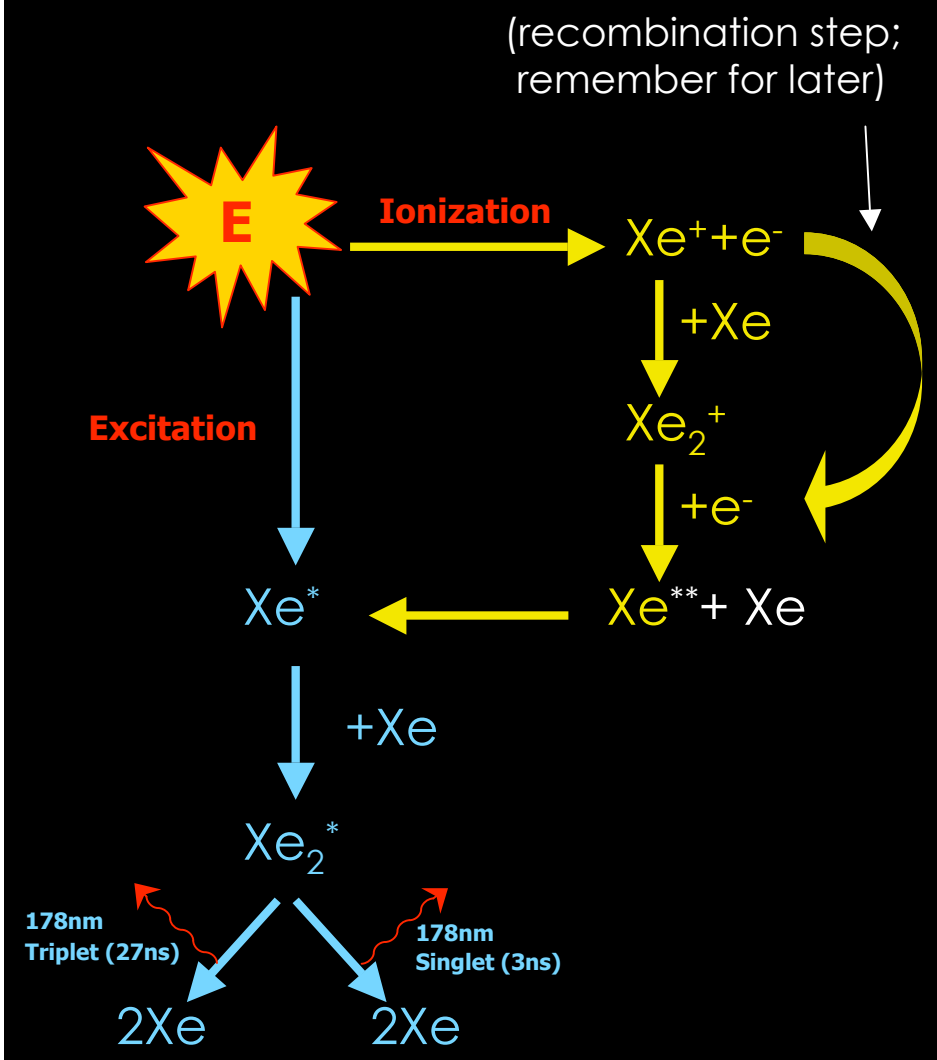


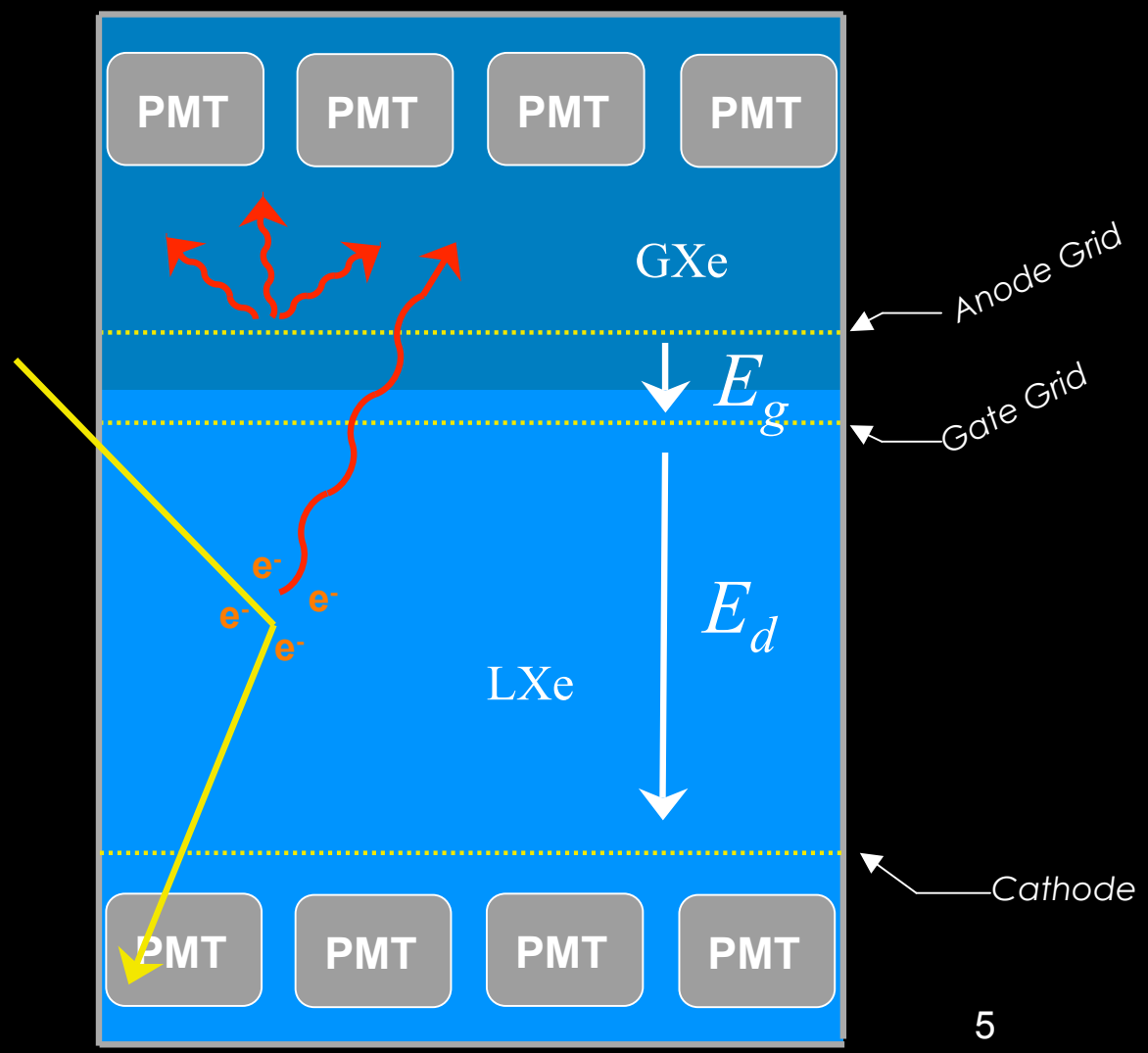


- **Detector Readout**
  - 48 PMTs top, 41 PMTs bottom
  - x-y position from top PMT hit pattern. $\sigma_{x\text{-}y} \sim 1$ mm
  - z - position from electron drift time. $\sigma_z \sim 0.3$ mm
- **Cryogenics**
  - 90W Pulse Tube Refrigerator (PTR) (LN_2 backup for emergencies)
  - Extremely stable T = 180 K at P = 2.2 bar
- **Electric Fields**
  - Drift Field = 730 V/cm (drift), Extraction Field = 9 kV/cm



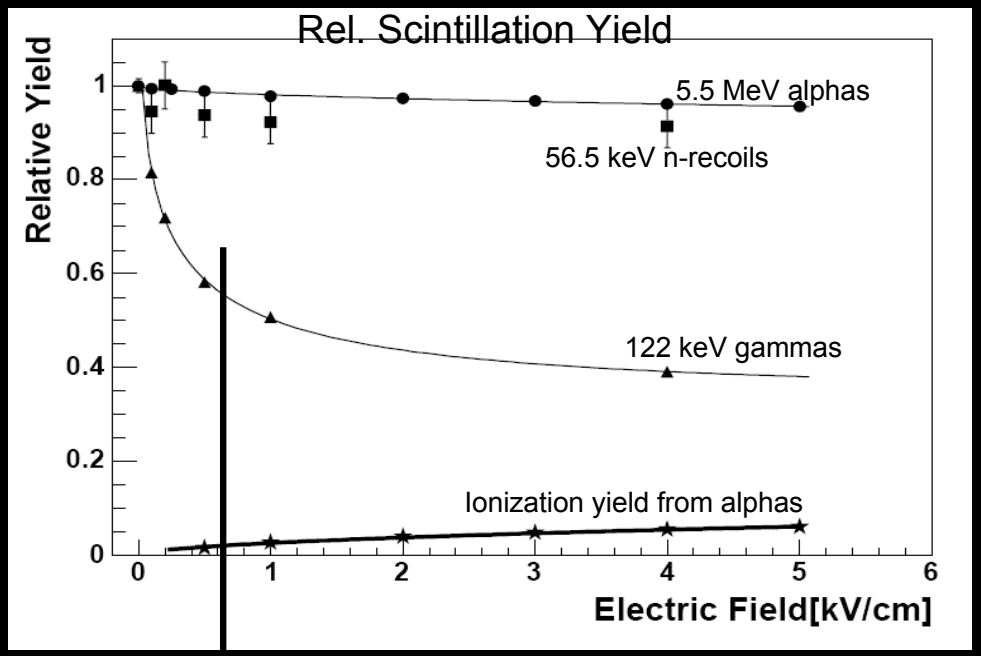
Interaction and Detection



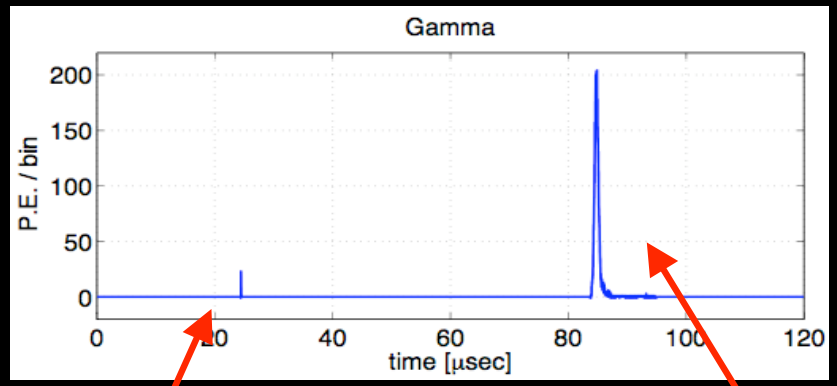


Field Quenching -

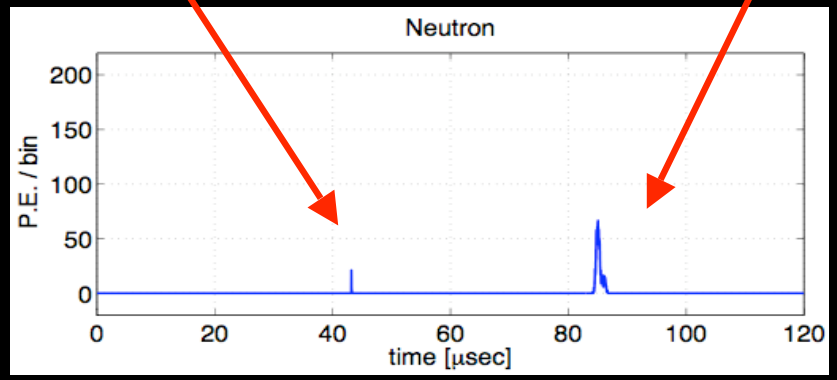
As the drift field is increased, fewer and fewer electrons recombine with their parent ions. Due to differences between the track structures of recoiling electrons and recoiling nuclei, the two species experience different amounts of quenching.



E. Aprile et al, Phys. Rev. D **72** (2005), 072006



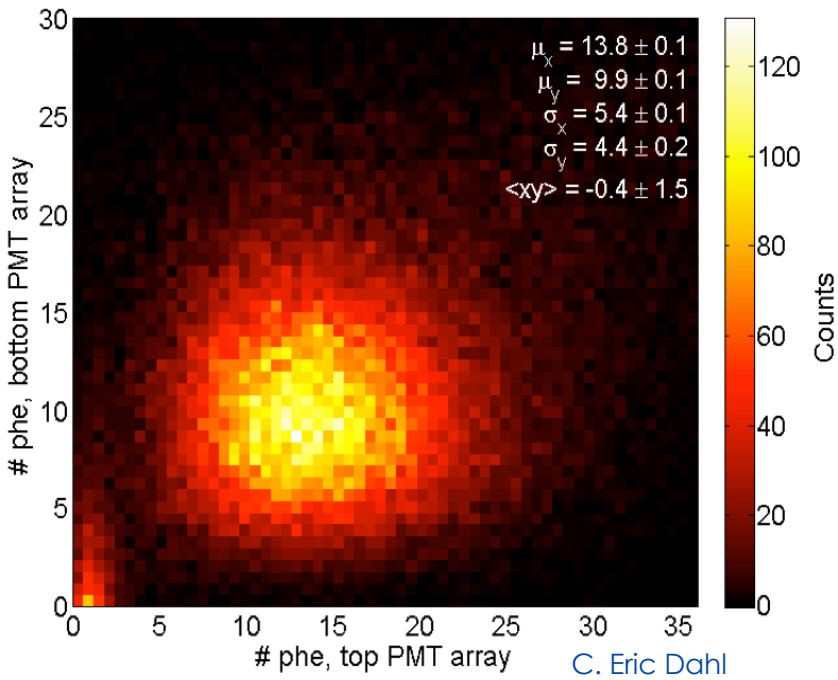
S1 (PMT Output) S2



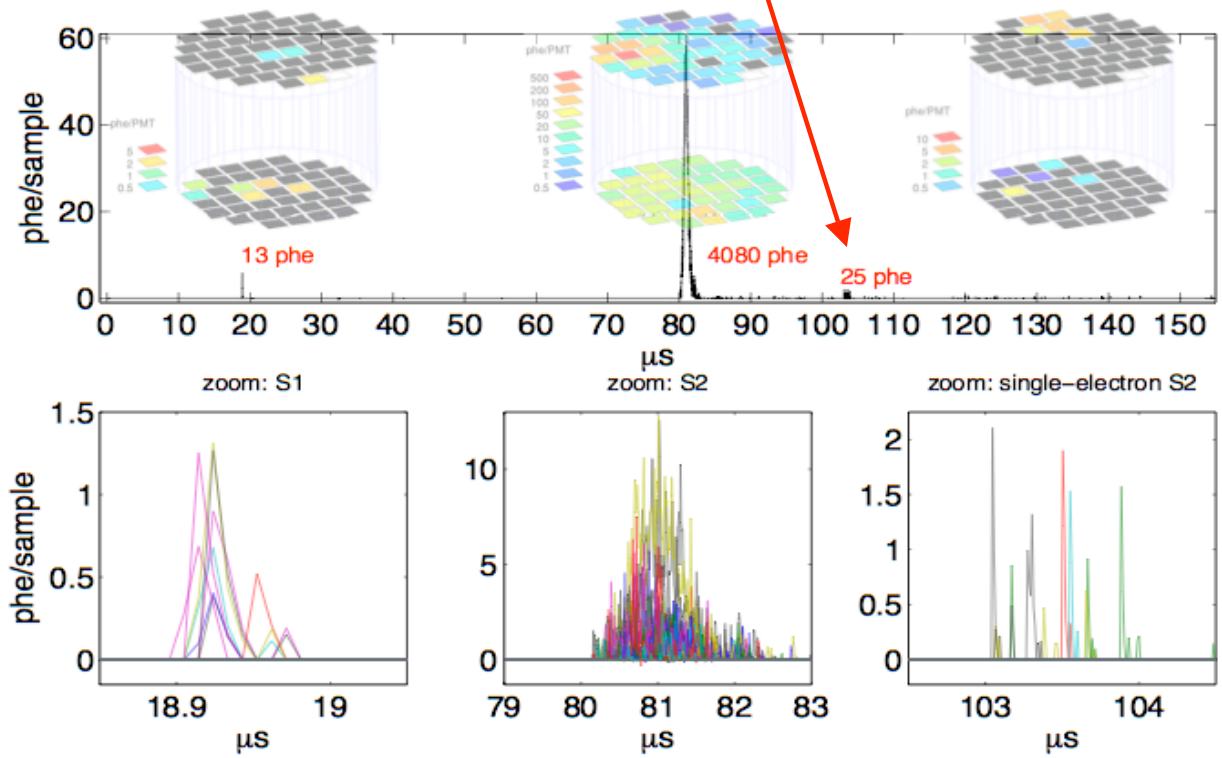
Question: Just how good is the ionization signal amplification with dual-phase?

Answer: Good enough to see single electrons!

2-D Histogram of small S2 signals



C. Eric Dahl

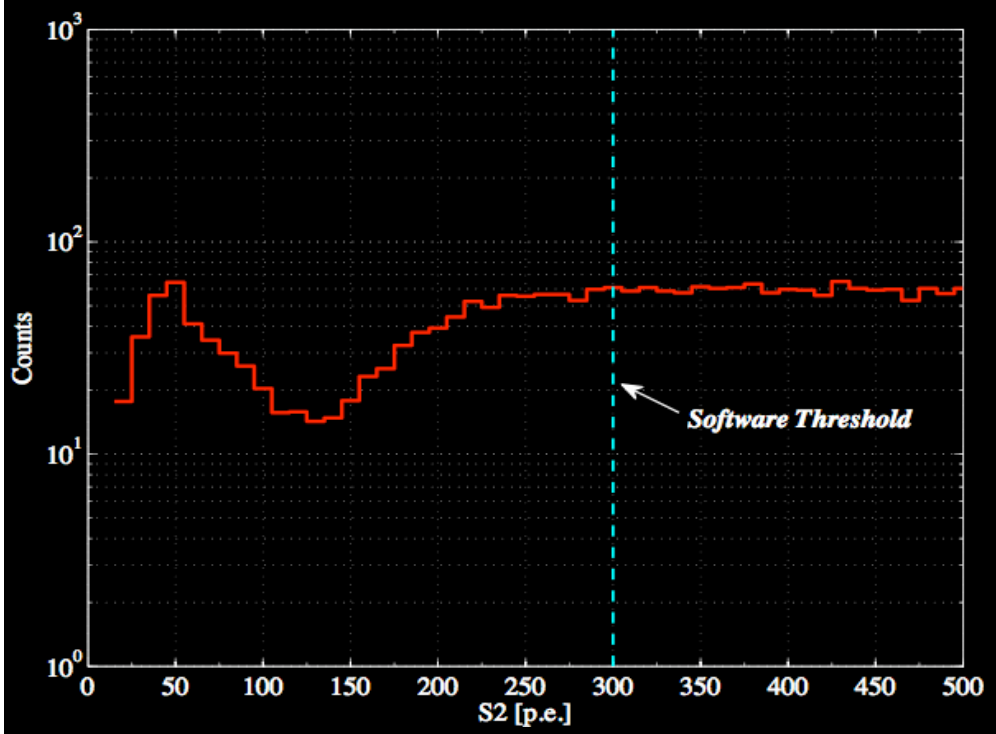


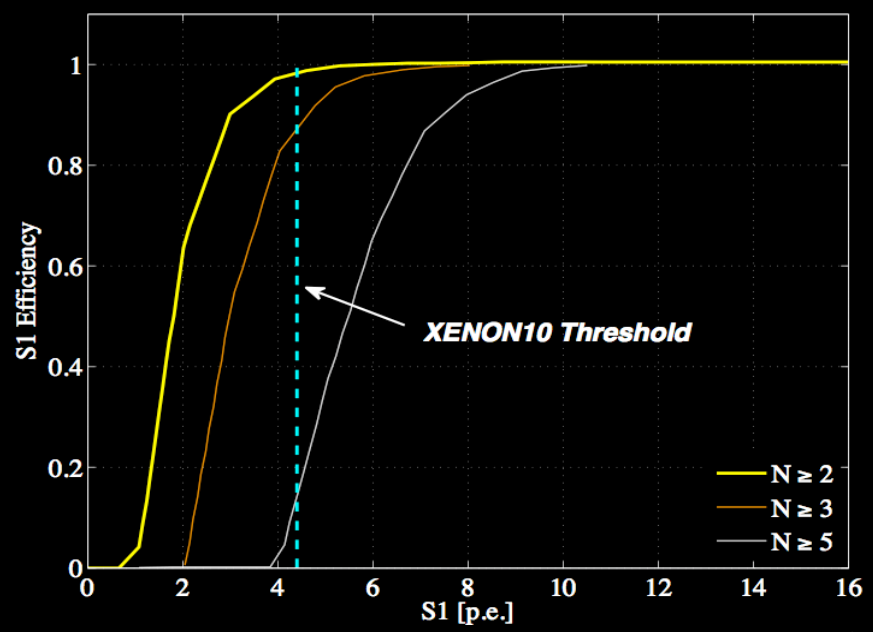
Peter Sorensen

What else can we do with S2?

Trigger on S2

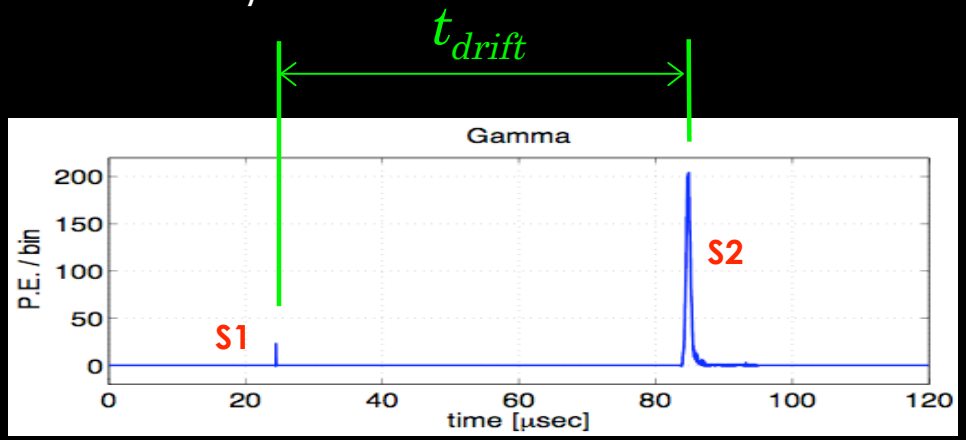
- Trigger: S2 sum signal from top PMTs. A software threshold of 300 p.e. is imposed.
- S1 is searched for in the offline analysis, requiring a coincidence of at least 2 channels.



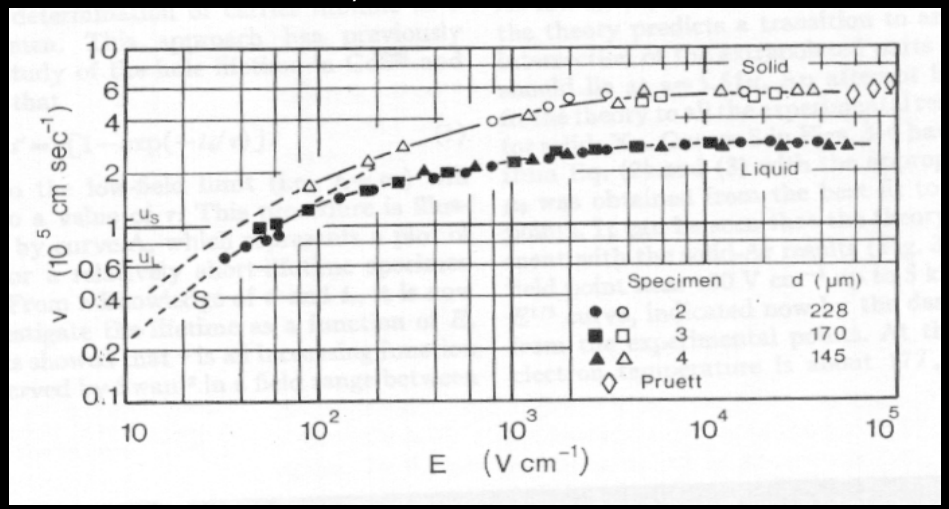


Position Reconstruction

Z-position from drift time (0.3 mm resolution)

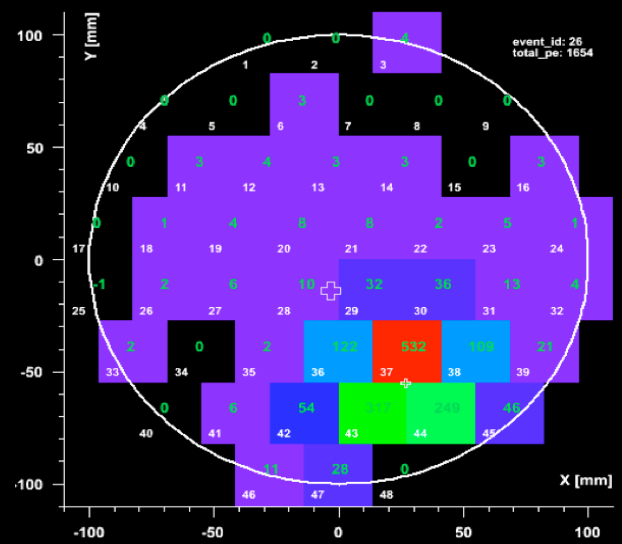


electron drift velocity vs. field



L. S. Miller et al, Phys. Rev. **166** (1968), 871

x-y position from PMT hit pattern (1 mm resolution)



– 0th order: position of most-hit PMT

– 1st order: "center of gravity" of PMT hits

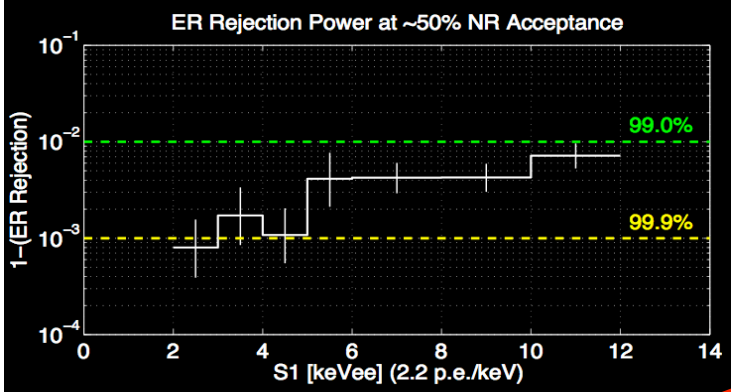
– higher order: Use a monte carlo to make a template hit-pattern for every point in x and y

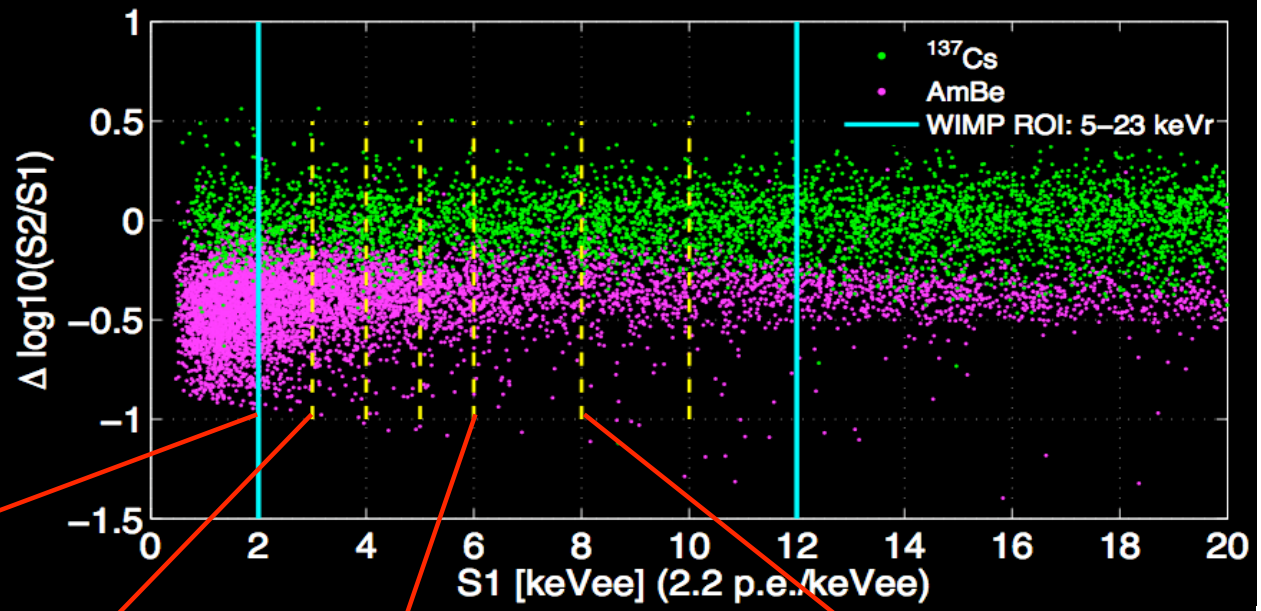
–Search for a position of "best fit" between actual hits and MC map (Max. Liklihood, χ^2-minimization)

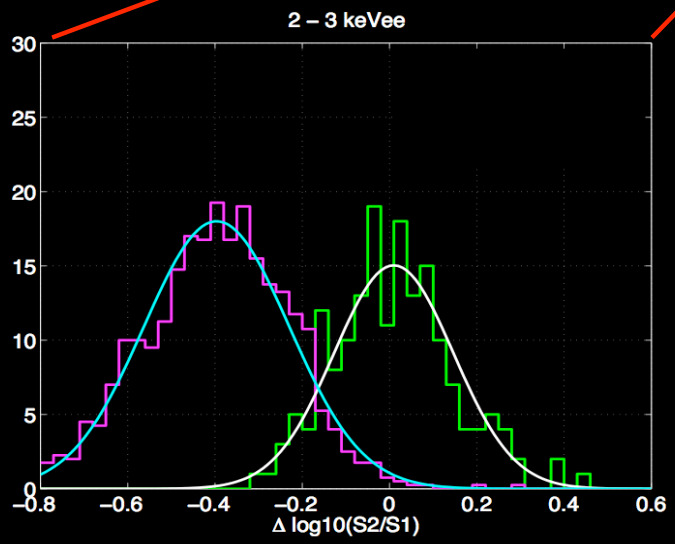
–Use MC map to train a Neural Network

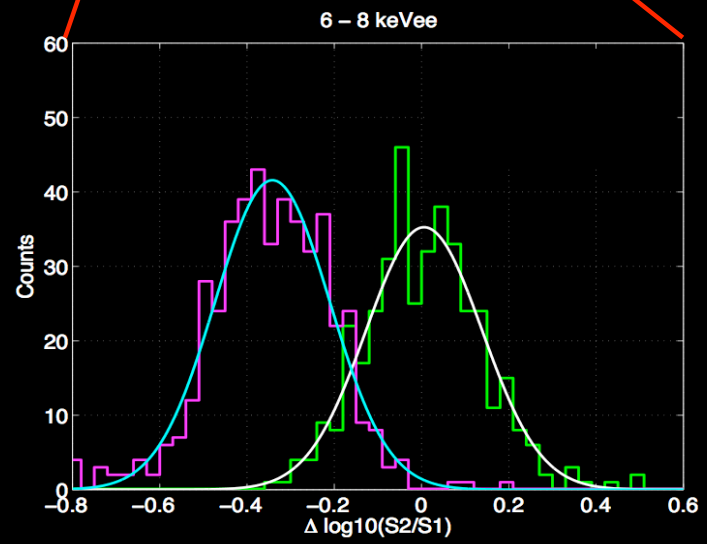
Nuclear Recoil Discrimination (in one slide…)

Electronic and nuclear recoils have characteristically different track structures, which lead to differing ratios of S2 to S1. This gives >99% ER rejection at 12 keVee, and >99.9% ER rejection at 2 keVee.









What are some challenges and developments we see for the future?

Nuclear Recoil Energy Scale : S1

energy of nuclear recoil (NR)

measured signal in p.e.

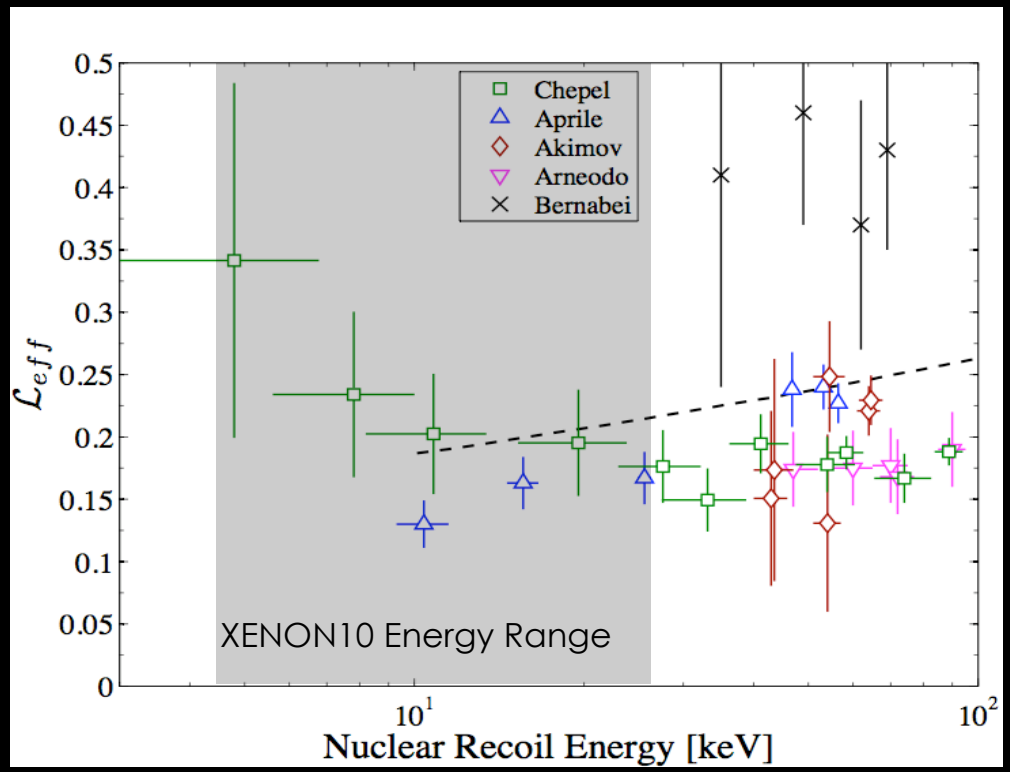
quenching of scintillation yield for 122 keV γ due to drift field

$$E_{nr} = \frac{S1}{L_y \mathcal{L}_{eff}} \times \frac{S_e}{S_r}$$

light yield for 122 keV γ in p.e./keV

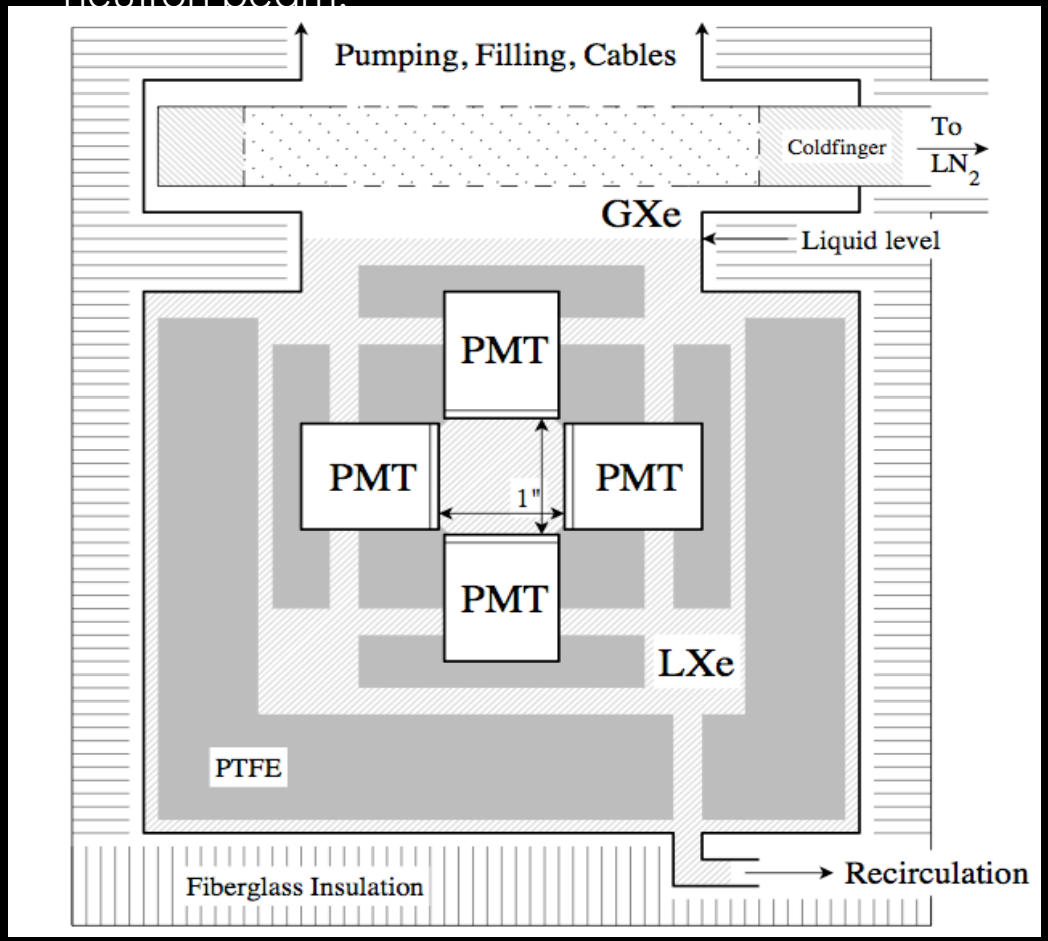
relative scintillation efficiency of NR to 122 keV γ at zero field

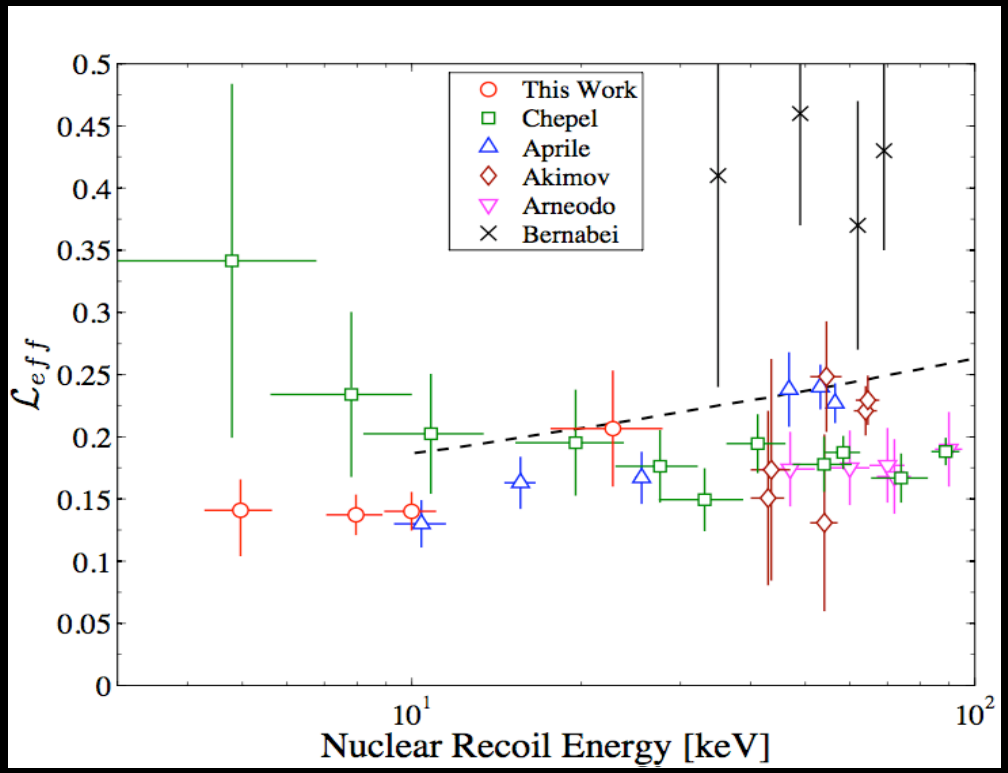
quenching of scintillation yield for NR due to drift field



Nuclear Recoil Energy Scale : S1

"xecube" single-phase detector: 6 square PMTs form a cube of LXe, placed in a neutron beam.

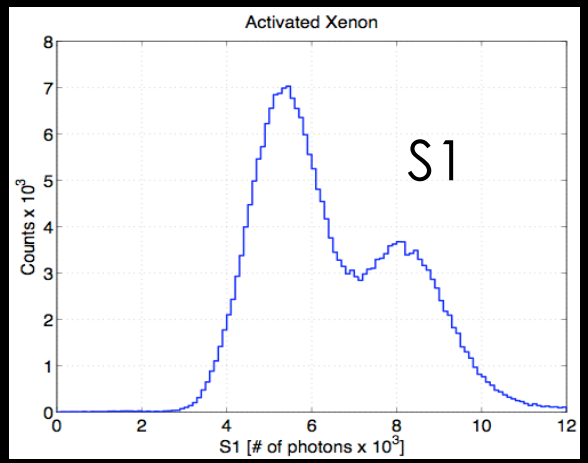


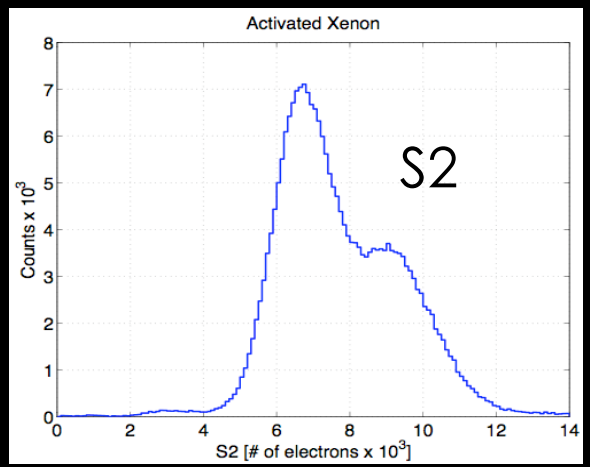


These results soon to be submitted to PRD

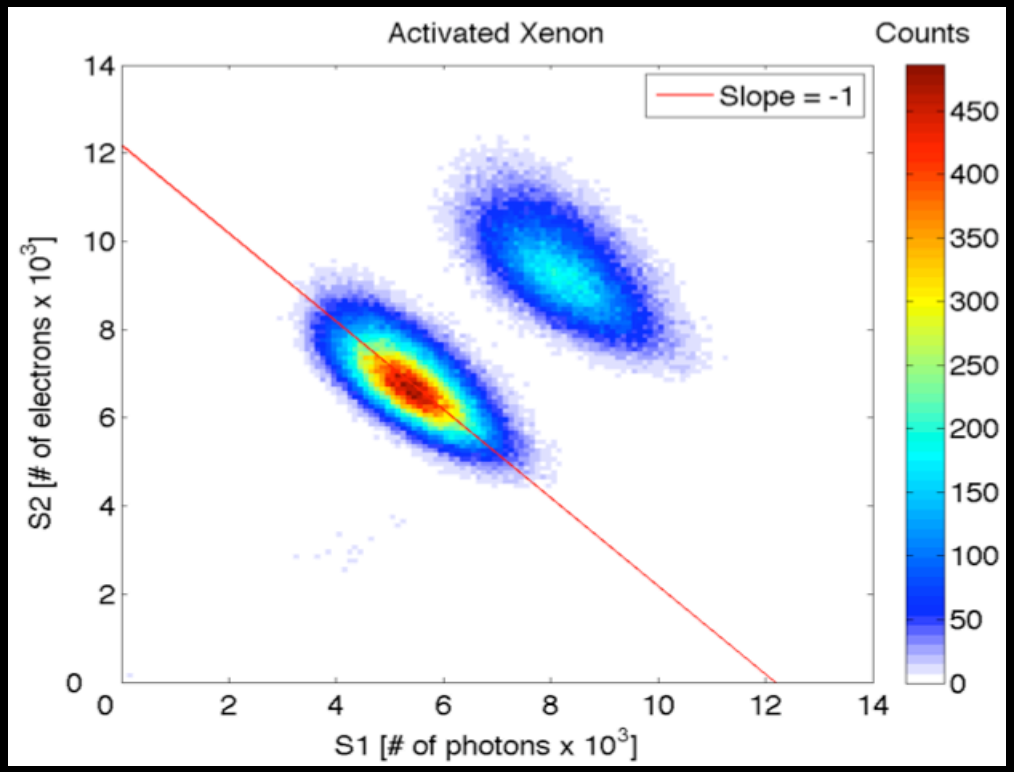
Nuclear Recoil Energy Scale: S1 + S2

^{129m}Xe (236 keV) + ^{131m}Xe (164 keV)





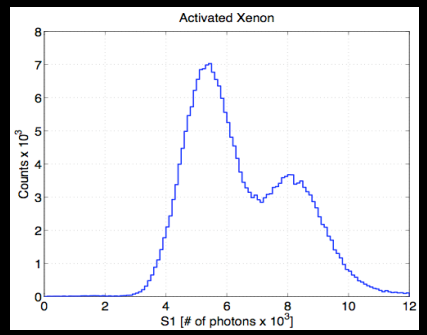
When an ionized electron recombines with its parent ion, a scintillation photon is produced as the Xe atom de-excites. As a result, S1 and S2 are anticorrelated.



The resolution of S1 is dominated by anticorrelated fluctuations between S2 and S1, which are fluctuations in the amount of electrons which recombine.

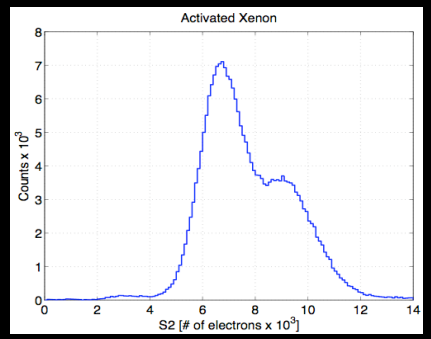
Nuclear Recoil Energy Scale: S1 + S2

S1



+

S2



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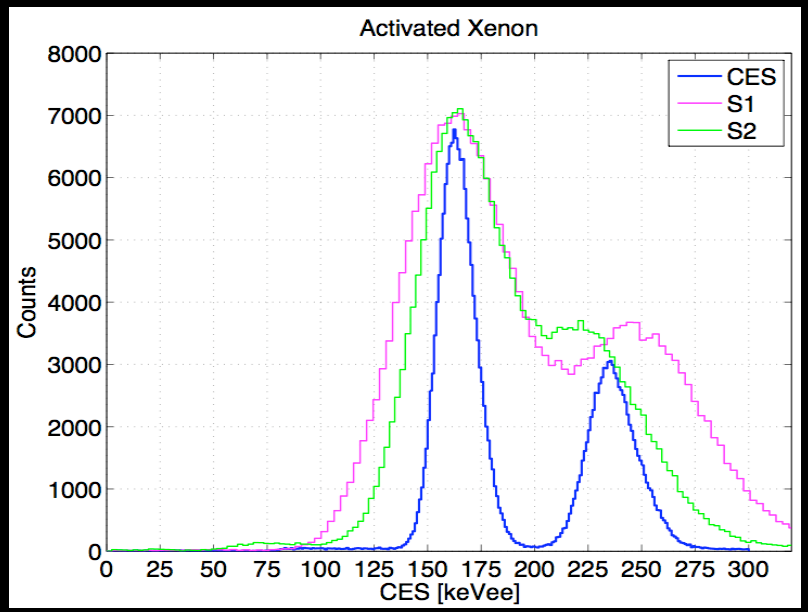
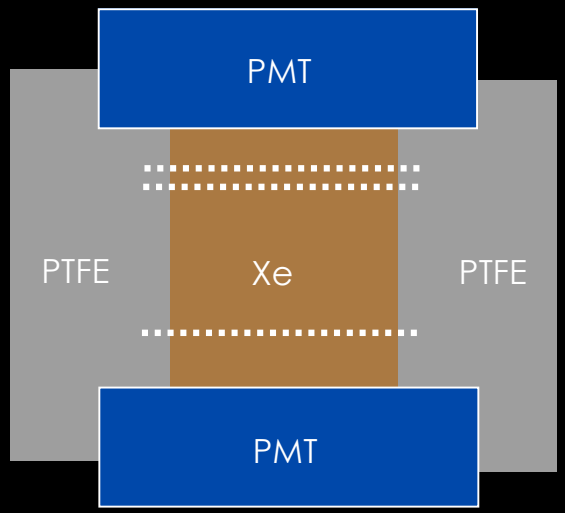


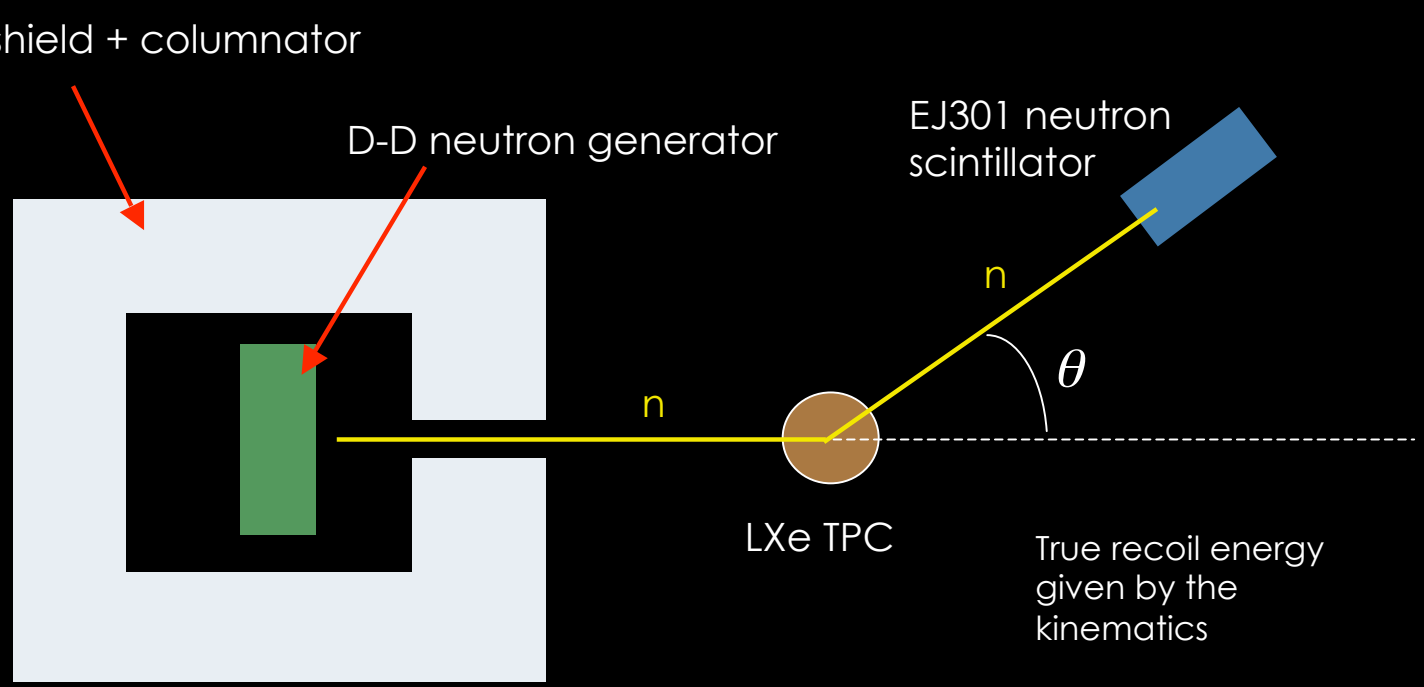
The combined S1&S2 energy scale gives much better resolution than S1 alone, is not affected by recombination fluctuations, is independent of the applied field (assuming E is large enough to see S2), but <u>we do not know the corresponding quenching factor for nuclear recoils in this energy scale.</u>

Nuclear Recoil Energy Scale: S1 + S2

We are developing a small dual-phase TPC at UZH to measure this quenching factor. Simple design, using just one PMT on top and bottom, Hamamatsu R9869 11-stage. Bottom PMT has "Ultra-Bialkali" photocathode with ~40% Q.E.



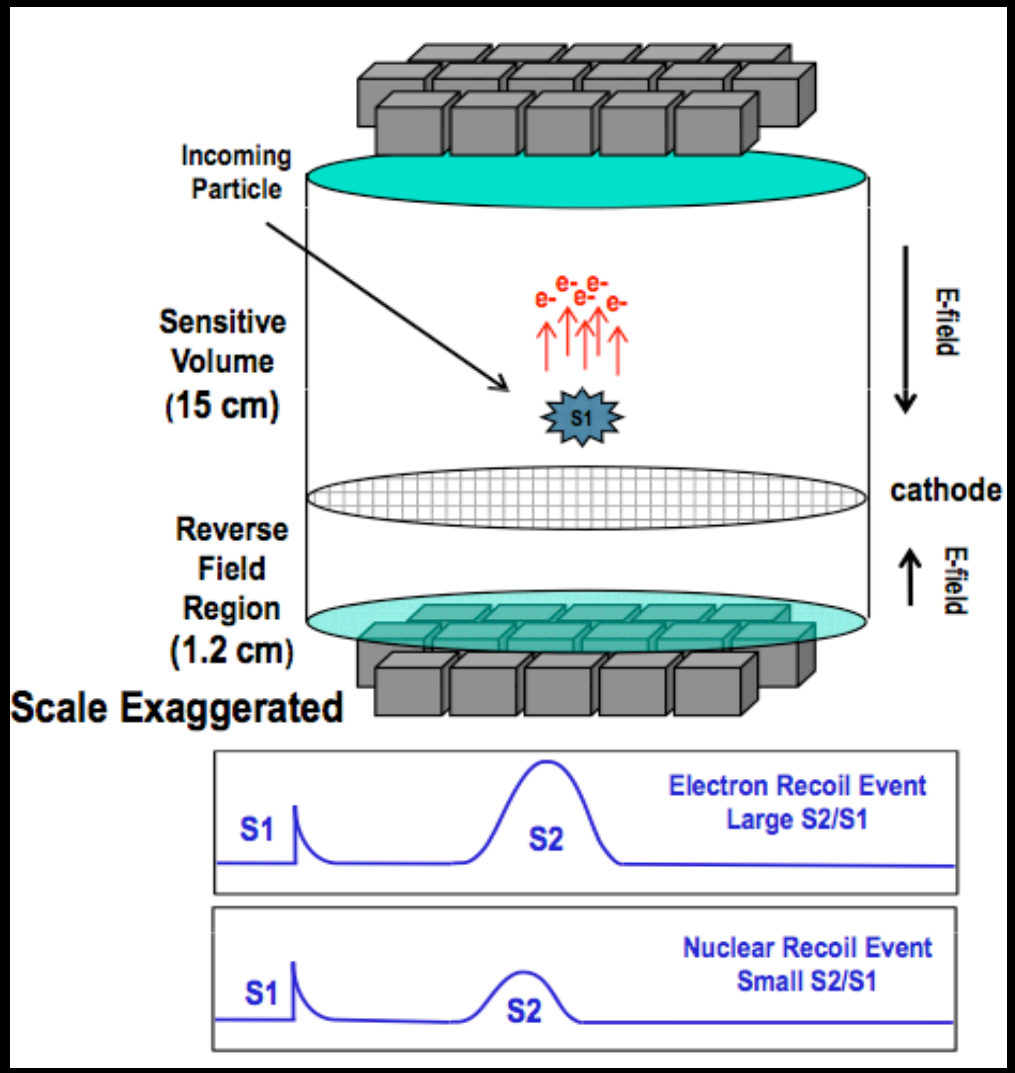
Cryostat already built and tested: copper cold finger coupled to a liquid nitrogen bath.



Gamma-x Events

There are always regions in the detector from which S1 can be extracted but not S2. Multiple-scatter events with one vertex in such a region mimics a single scatter, but as a result has a lower value of S2/S1 and can be reconstructed as a nuclear recoil (4 of the 10 bg events in XENON10 were later identified with this phenomena).

Cut schemes based on the S1 hit-pattern in the bottom PMTs are useful, and hopefully the powerful self-shielding in larger detectors will help alleviate this issue. An additional strategy in XE100 is to extra PTFE pieces to block PMTs from "seeing" large areas of LXe which do not yield S2.



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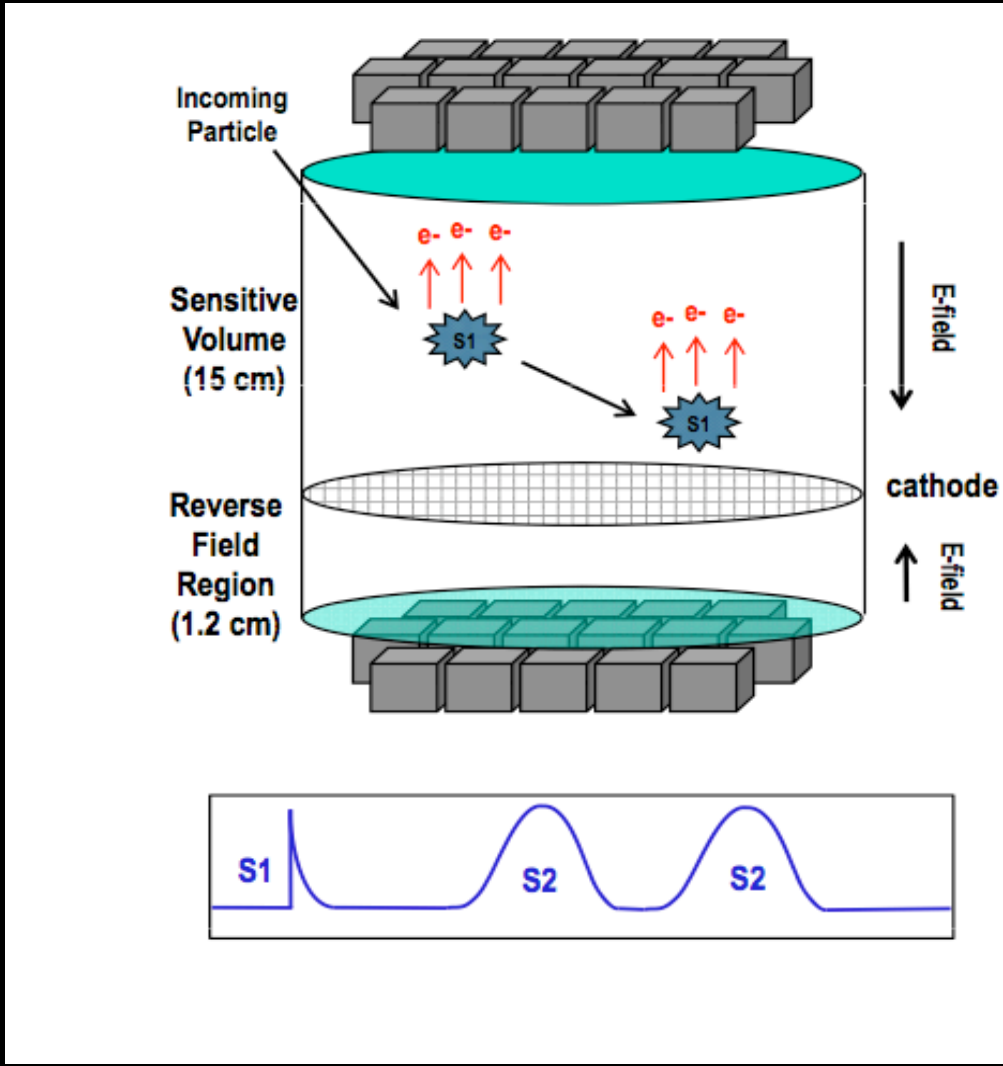

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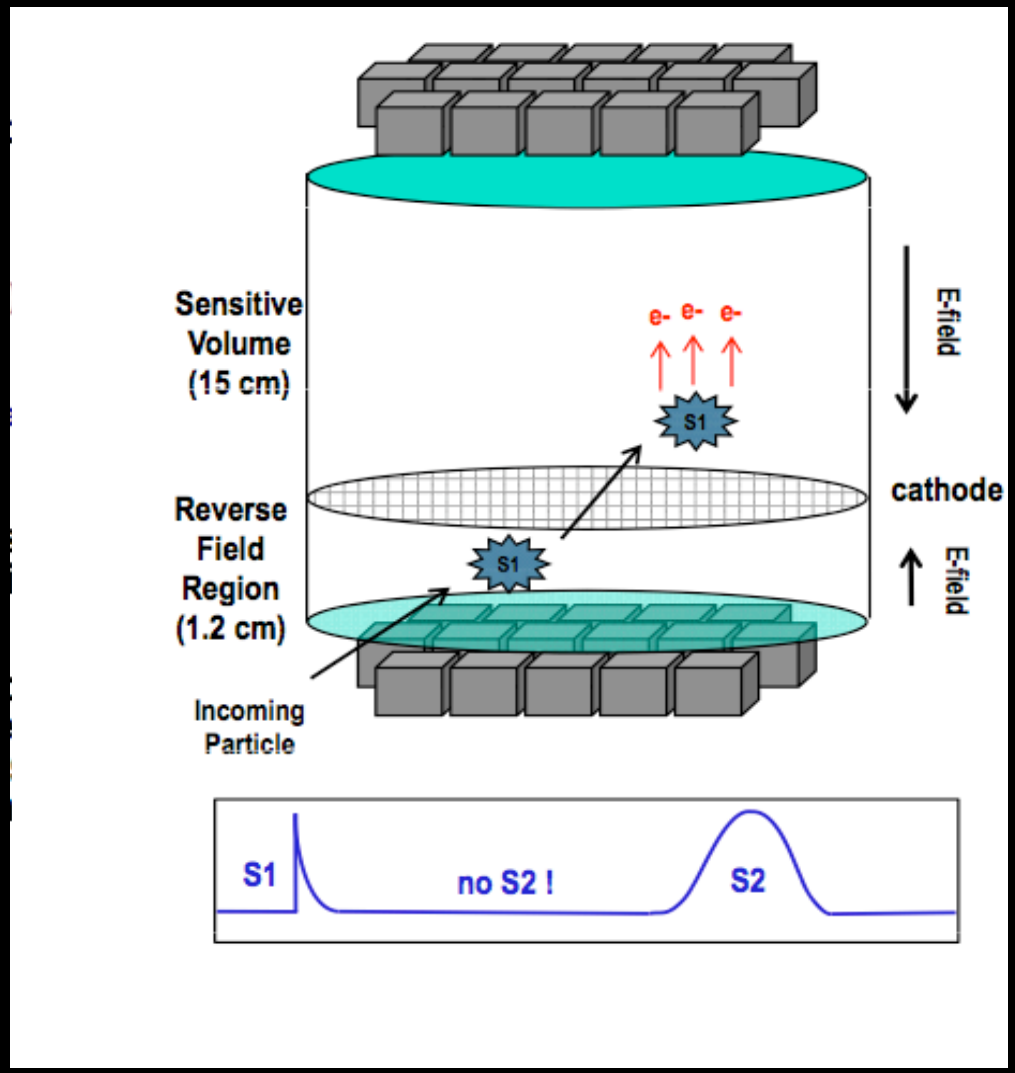
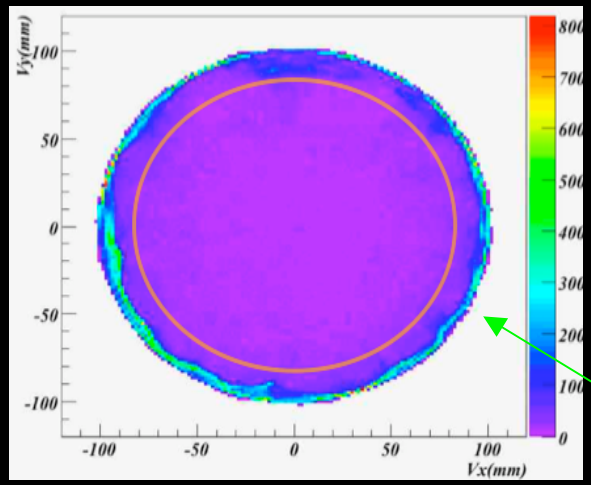
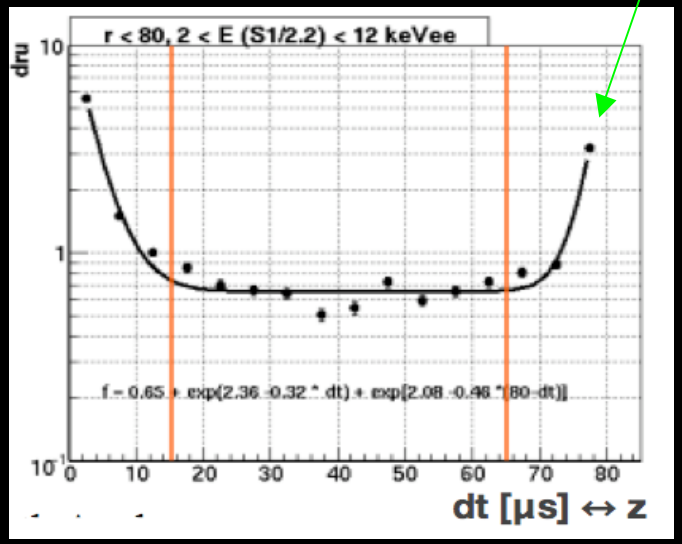


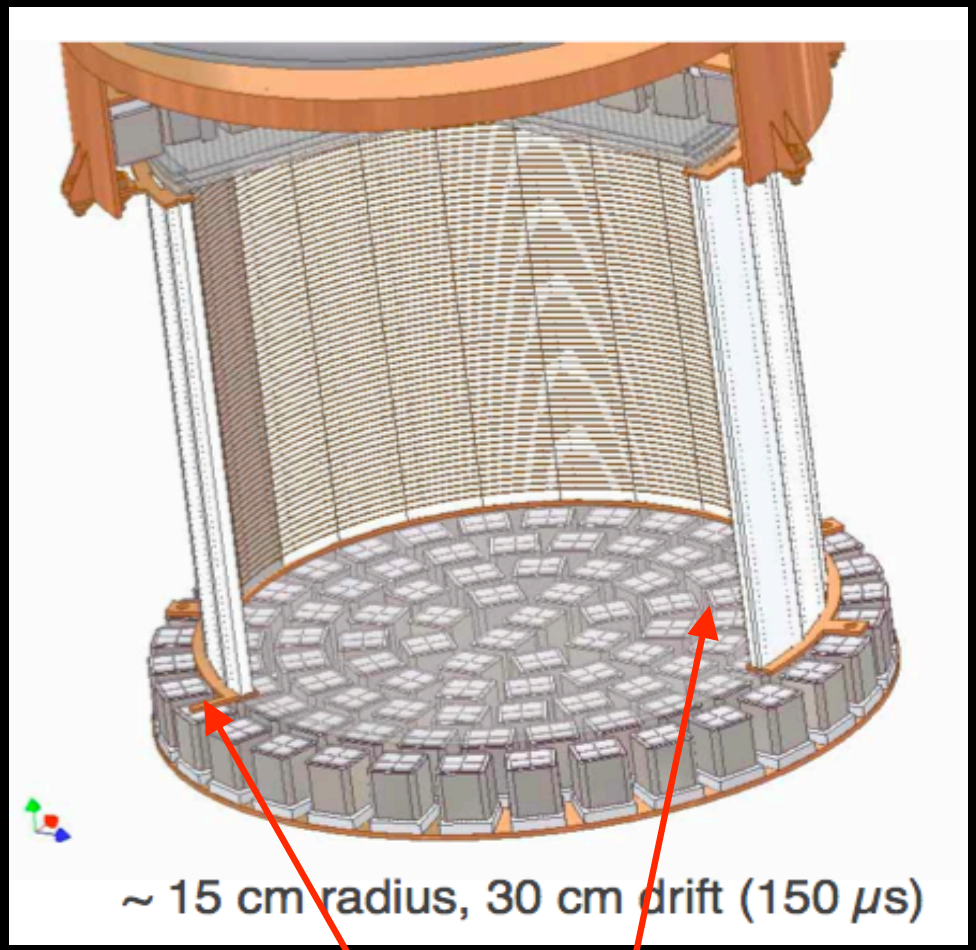
Xe self-shielding



XENON10 - passive only

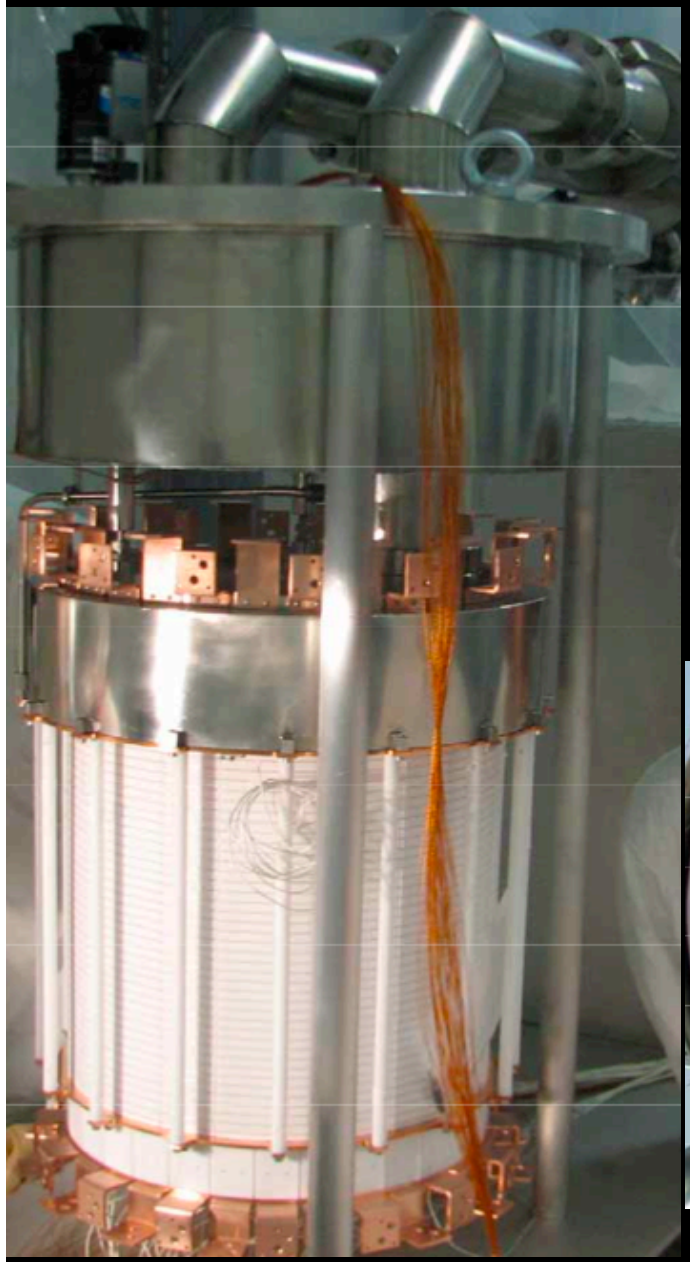
Majority of BG events at the edges



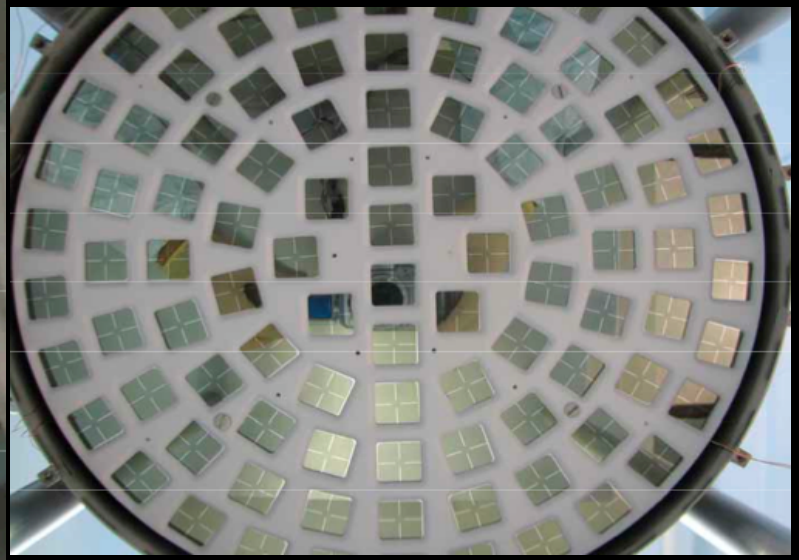


XENON100 - active and passive shielding

XENON100

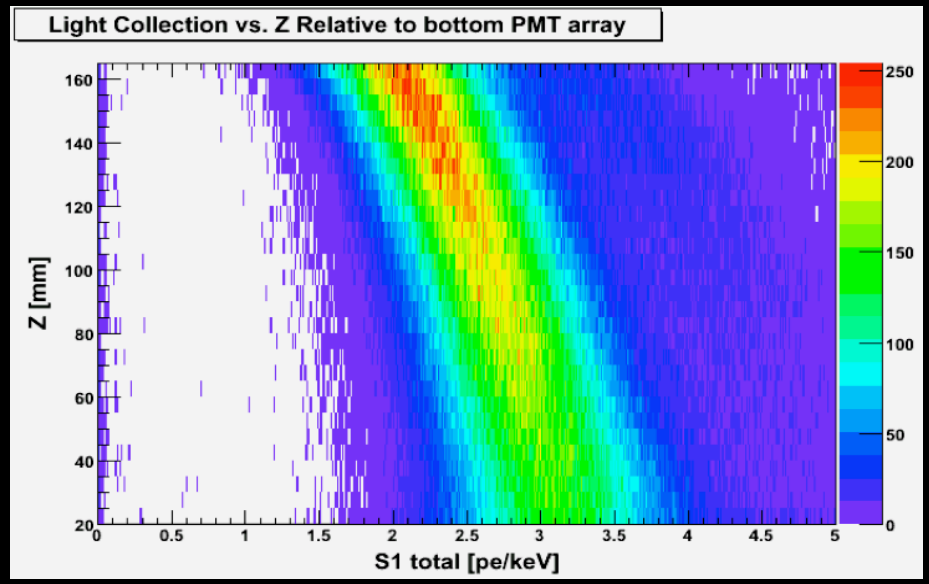


XE100 not just on paper; it is already built and installed. No DM data yet, currently characterizing PMTs, calibrating sensors, streamlining DAQ/processing/analysis.

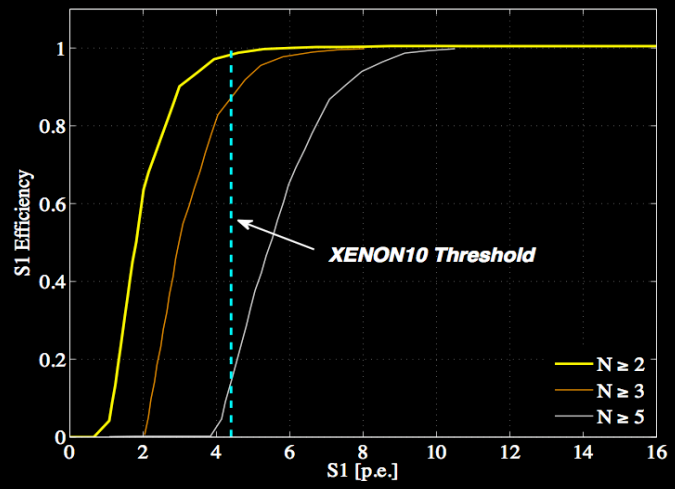


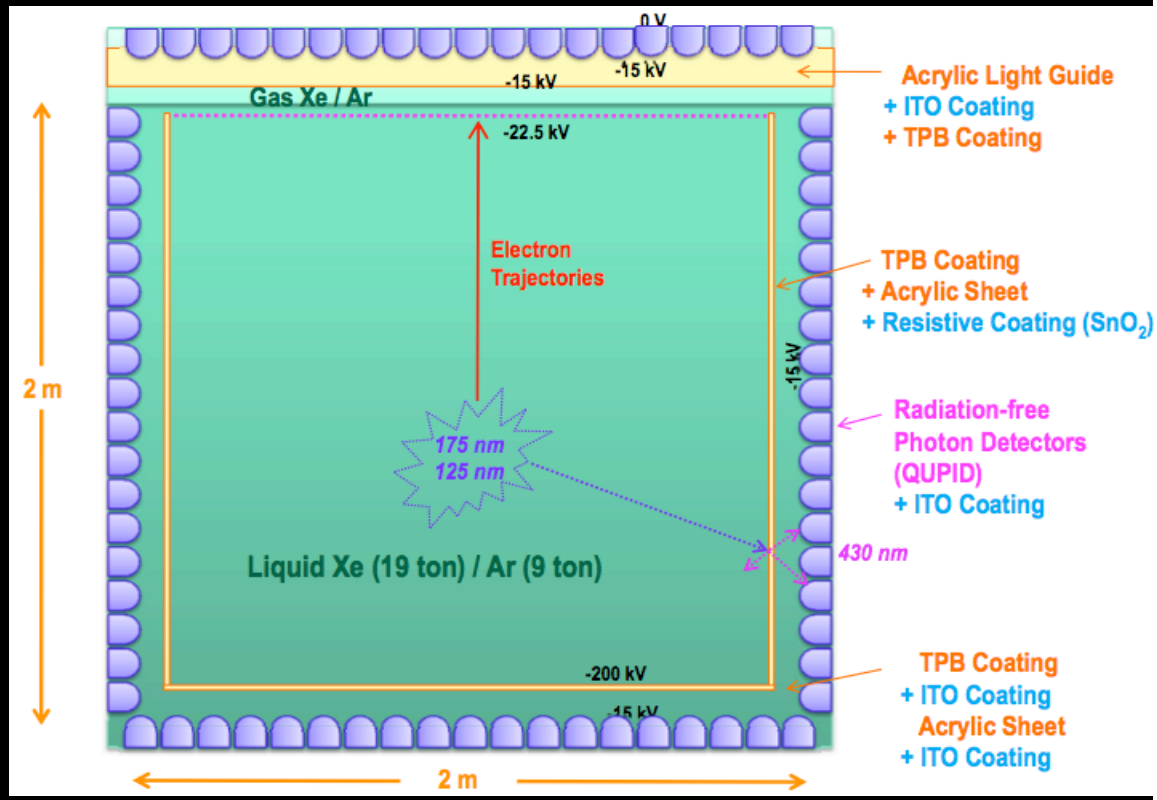
S1 Light Collection

Roman Gomez



The S1 response is strongly z-dependent. As a result, in larger detectors (several tonnes), the S1 yield may significantly cut into the energy threshold. One idea is to surround the active region with a clear, acrylic sheet with a resistive coating (to ensure a uniform electric field) and then instrument the entire interior surface with photon sensors (similar to Super-K).





Katsushi Arisaka

Summary

- Dual-phase design originally motivated by need for clean ionization signal amplification, but provides many other advantages (clean trigger, position reconstruction, etc.)
- Measured value of S1 quenching for low energy (<10 keV) nuclear recoils is beginning to converge.
- Developing a dual-phase prototype at Uni. Zürich to facilitate the use of combined-energy scale in future detectors.
- XENON100 has been born, currently in the characterization process.

Fin.