Physics of LXe dark matter detectors

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UZH Seminar on Particle and Astrophysics

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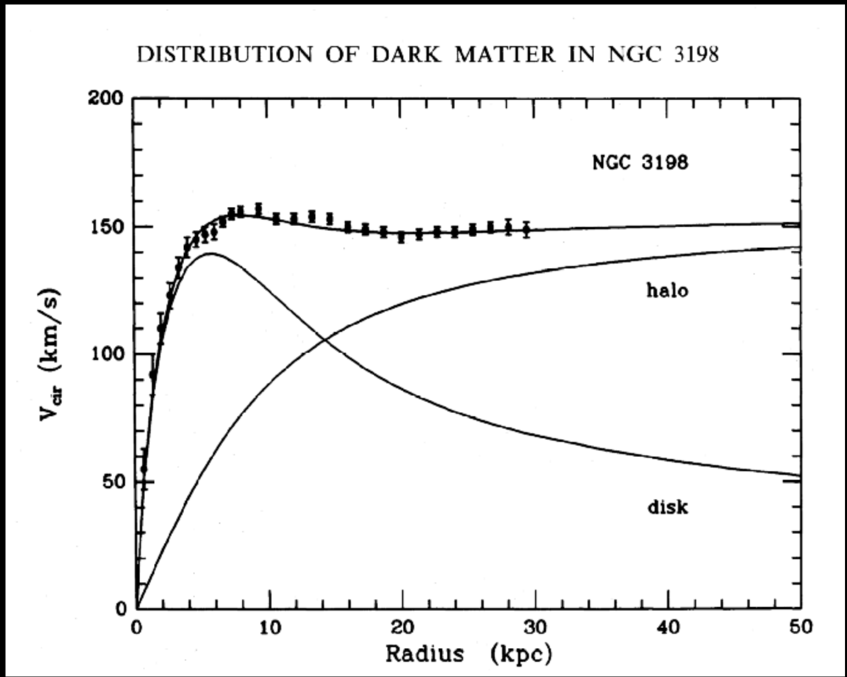
Overview

- Background (DM, candidate, direct detection)
- Nuclear recoil discrimination in LXe
- Problems in calibrating LXe detectors
- Measurement of L_{eff}
- Xürich Detector at UZH
- ^{83}Rb motivation and results.

Evidence for Dark Matter

(on local-ish scales)

Galactic Scale: rotation curves

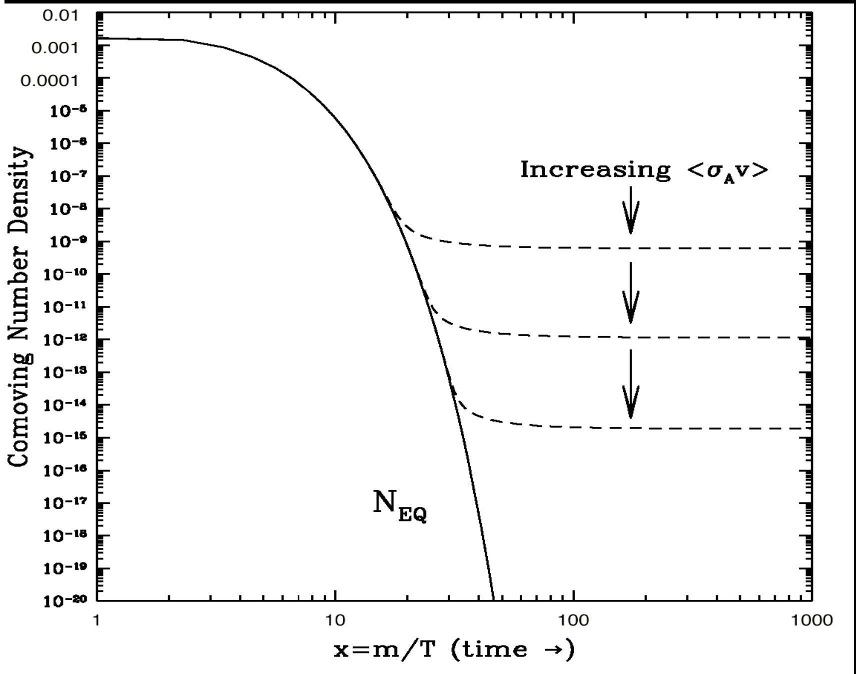


Current picture of galactic structure is that a roughly spherical cloud pervades all of galactic space, including our solar system with a local density of ~0.3 GeV/cm^3.

Galaxy Cluster Scales: grav. lensing

One DM candidate: the WIMP

The weakly interacting massive particle (WIMP) is produced in large quantities in the early universe by the generic mechanism of thermal freezeout if nature even allows for the existence of such a particle.



$$\chi + \overline{\chi} \longleftrightarrow q + \overline{q}$$

Most popular WIMP candidate is SUSY's neutralino

However, stable WIMPs naturally arise in almost ALL theories beyond the standard model (at the weak scale)

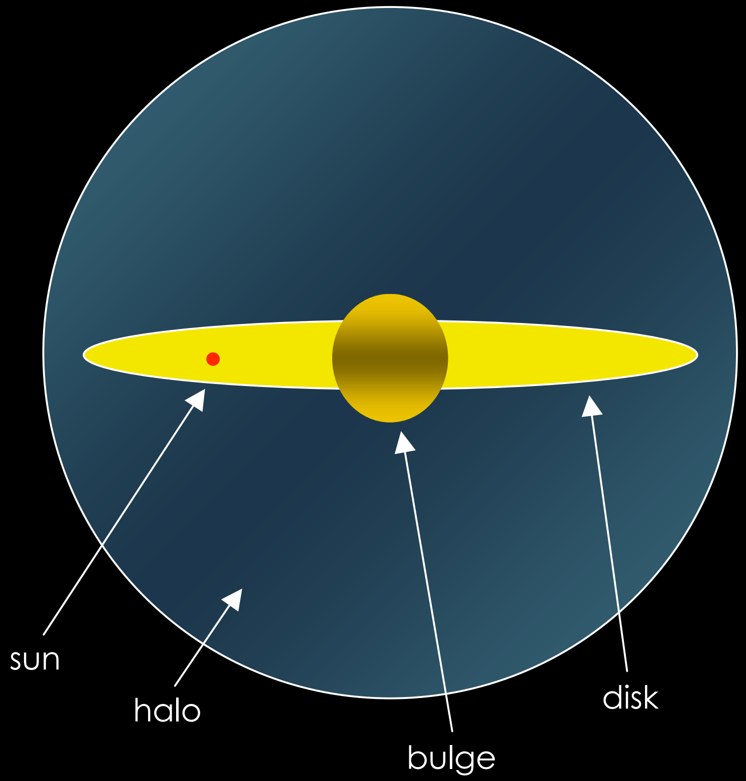
See talk by N. Weiner,

http://www-conf.slac.stanford.edu/ssi/2007/lateReg/program.htm

Dark Matter Direct Detection

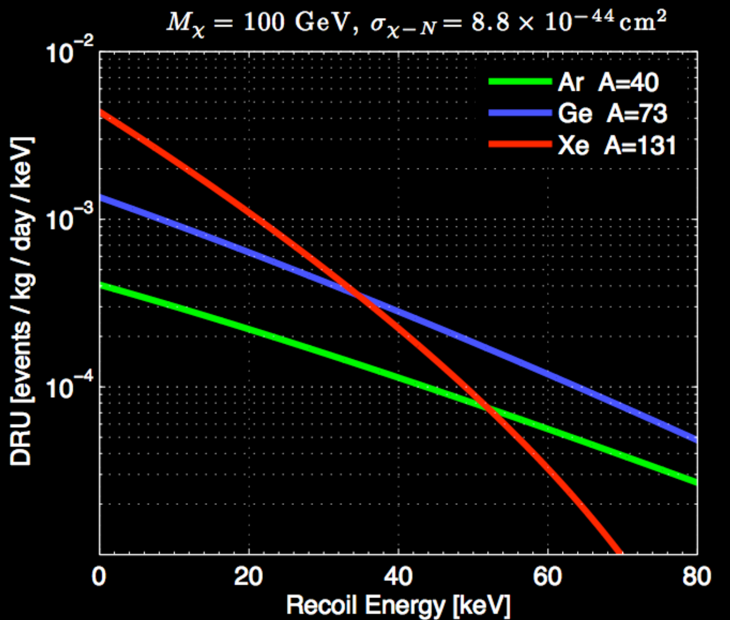
Our solar system is 'flying' through a gas of WIMPs that make up the dark matter halo. One looks for interactions between these WIMPs and [Xe, Ar, Ge, etc.] nuclei.

The Milky Way



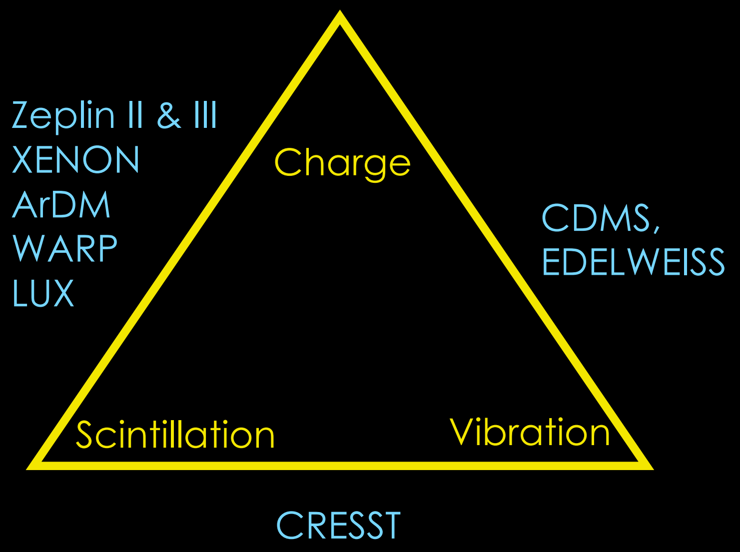
The actual differential rate depends on the mass, density and velocity distribution of the WIMPs, and on the nuclear form factors and couplings governing the interactions. But as a first approximation we can write a simplified rate:

$$\frac{dR}{dE_R} = \frac{R_0}{E_0 r} e^{-E_R/E_0 r}$$



Dark Matter Direct Detection

Typically,* to distinguish nuclear recoils from electronic recoils, one needs to record energy deposition in two of three channels: charge, scintillation, and vibration. Particle identification then comes from the ratio of the two channels.



* Although there are other possibilities…

54
Xe
131.29

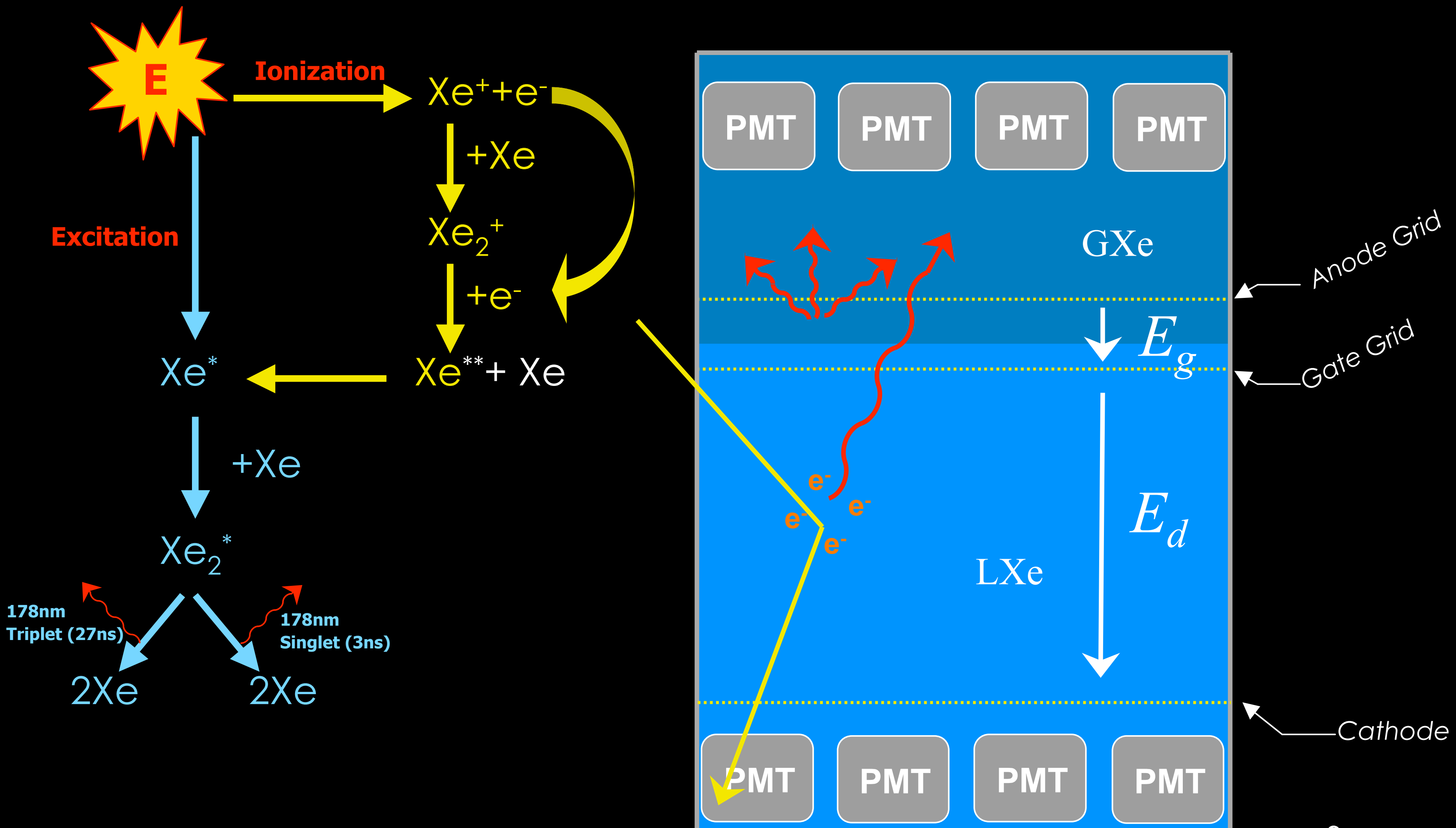
Why use Liquid Xenon?

- Large A (~131), great for SI (s ~ 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).

Two important questions:

- How do we identify the type of interaction (nuclear recoil vs. electronic recoil)?
- How do we accurately measure energy deposition in liquid xenon?

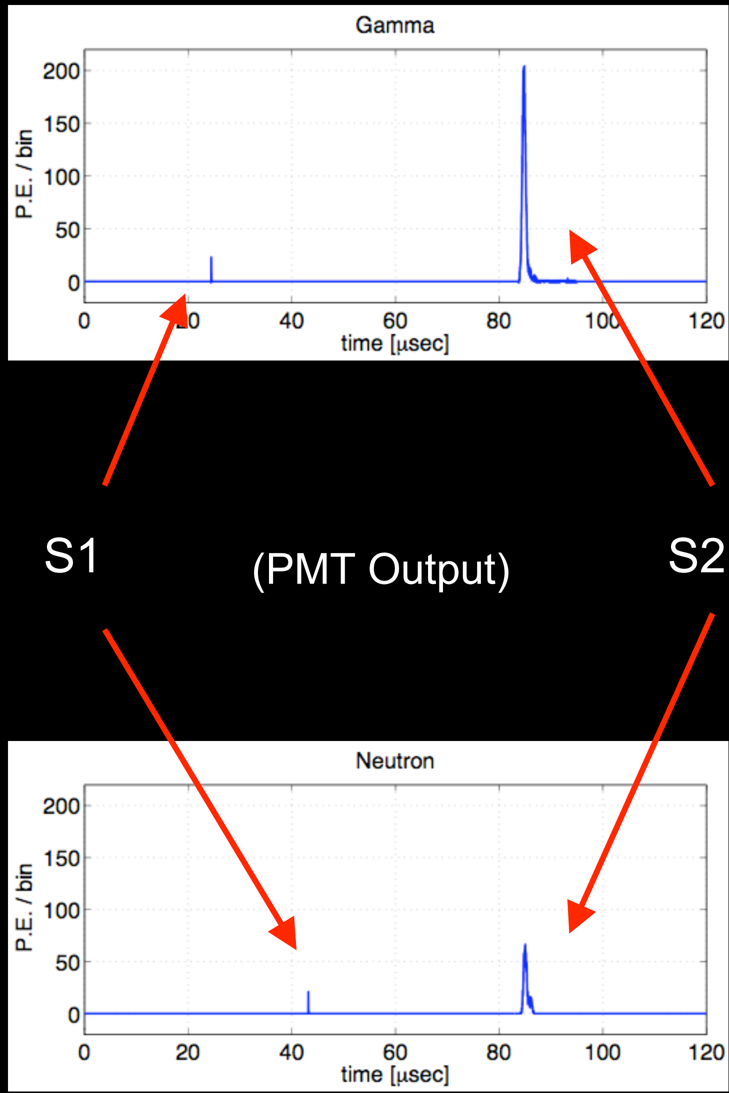
Energy deposition and measurement

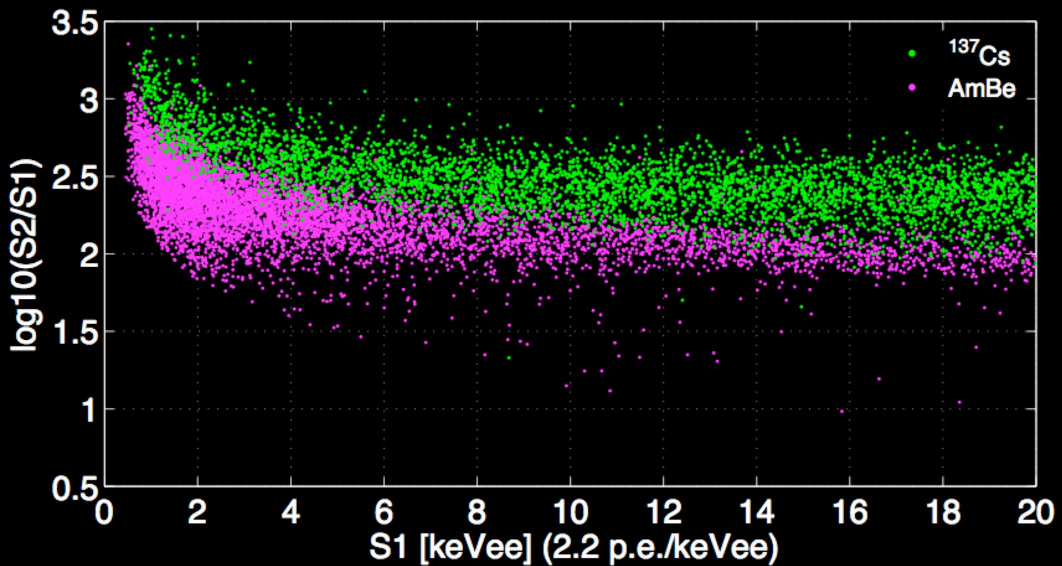


Nuclear Recoil Discrimination in LXe

The dual-phase design of such detectors produces two signals in the PMTs: S1, the primary scintillation light; S2, the proportional scintillation (charge signal).

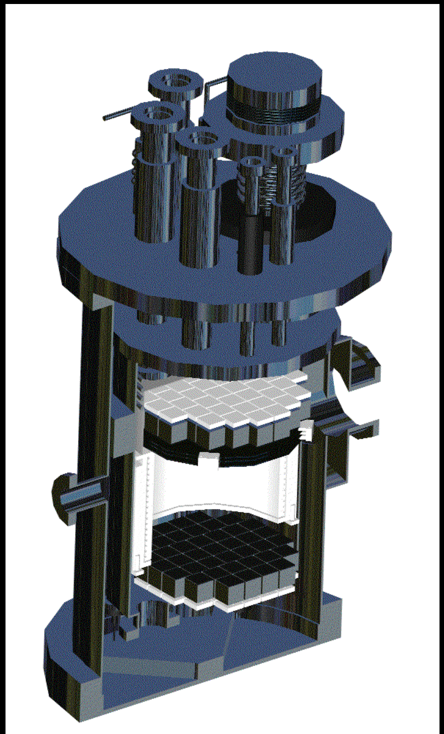
Recombination is stronger for nuclear recoils, and thus gives a smaller S2/S1 ratio than for electronic recoils.

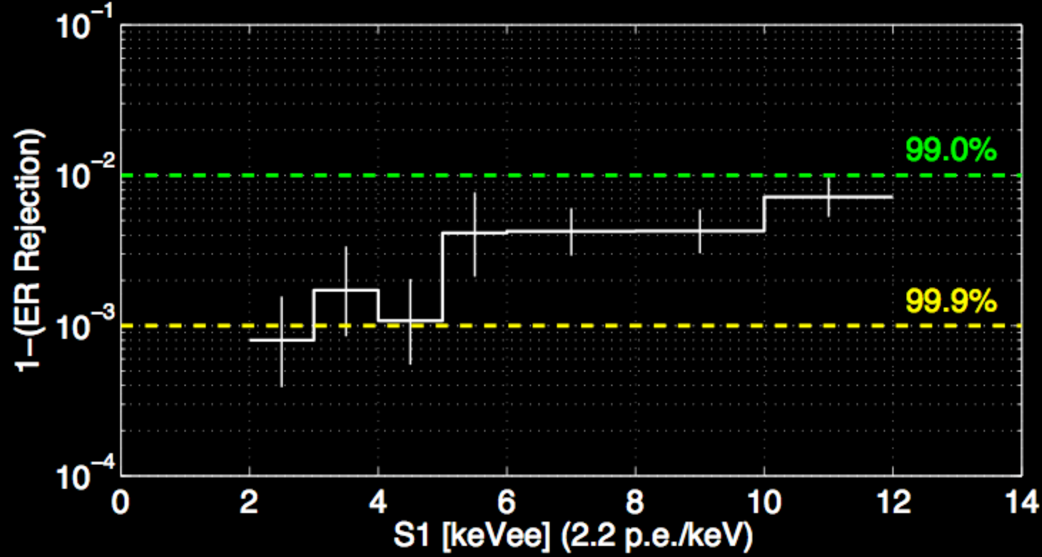


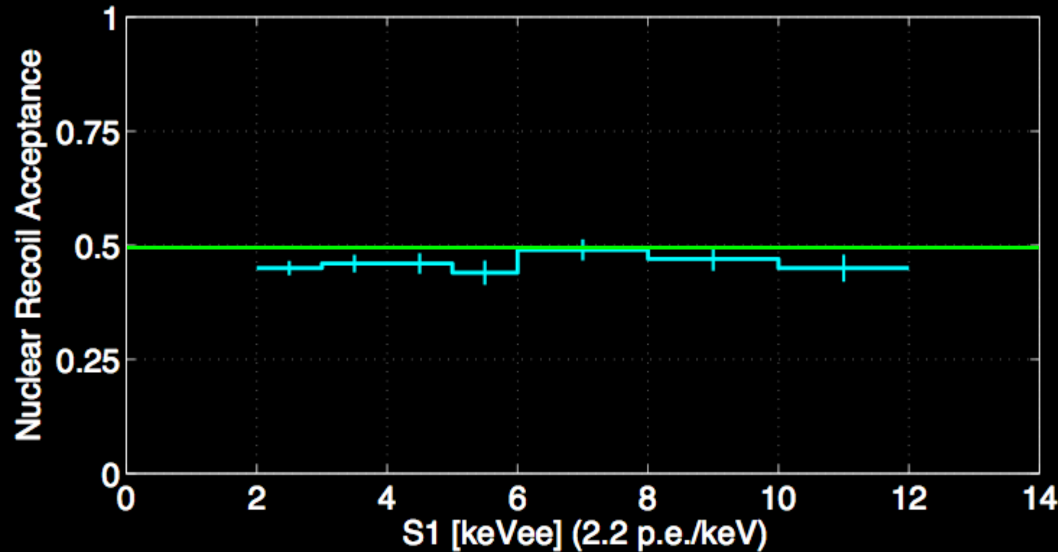


Nuclear Recoil Discrimination in LXe

The XENON10 detector achieved upwards of 99.9% rejection of EM backgrounds with ~50% cut acceptance.







Two important questions

- How do we identify the type of interaction (nuclear recoil vs. electronic recoil)?
- How do we accurately measure energy deposition in liquid xenon?

The light yield (Q_{out} per deposited energy) depends on…

…many many things, so we calibrate with known sources

-W_{ph}, energy required to produce one scintillation photon

Only important parts that change in a given detector:

-LET (linear energy transfer)
- -Particle species
- -Energy of the particle

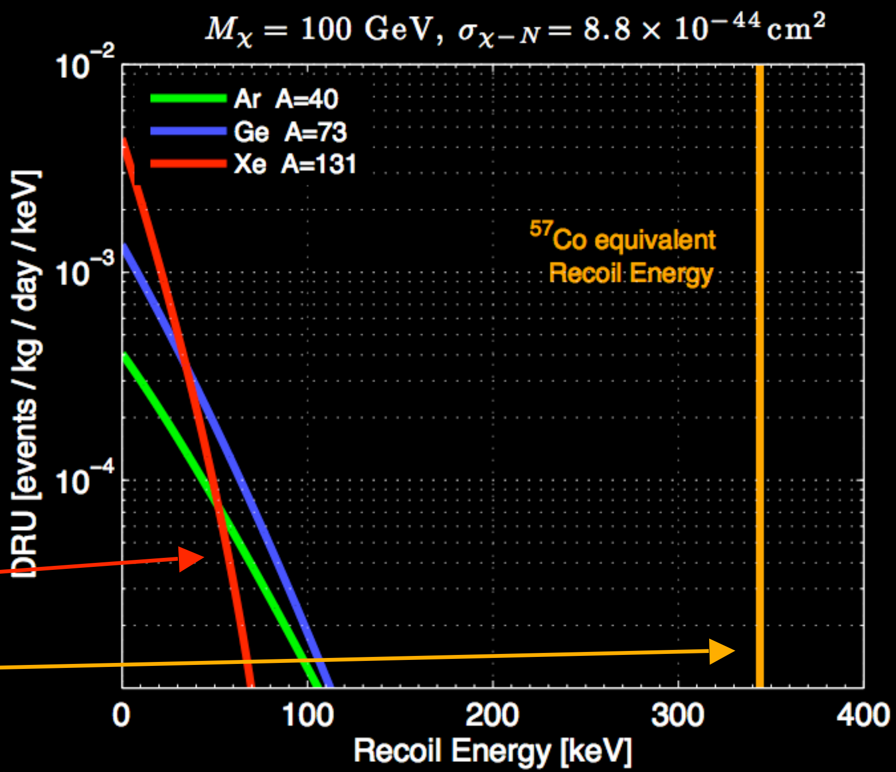
- Applied electric field
- LCE (light collection efficiency)
  - -Solid angle subtended by PMTs
  - -Reflectivity of detector materials
  - -Scattering length of the photons in LXe
    - -Inherent absorption of LXe to it's own scintillation
    - -Impurities
- Transmission efficiency of PMT windows at 178 nm
- QE of PMT photocathodes at 178 nm
- Collection efficiency of the first dynode in the PMTs

Calibrated *in situ* , so light yield is given in units of p.e. / keV:

- Gain of the PMTs
- Output impedance of the on-board PMT electronics

Calibration of Nuclear Recoil Energy Scale

^{57}Co, giving 122 keV gammas, is very common for calibration, and is typically a very easy source to obtain.



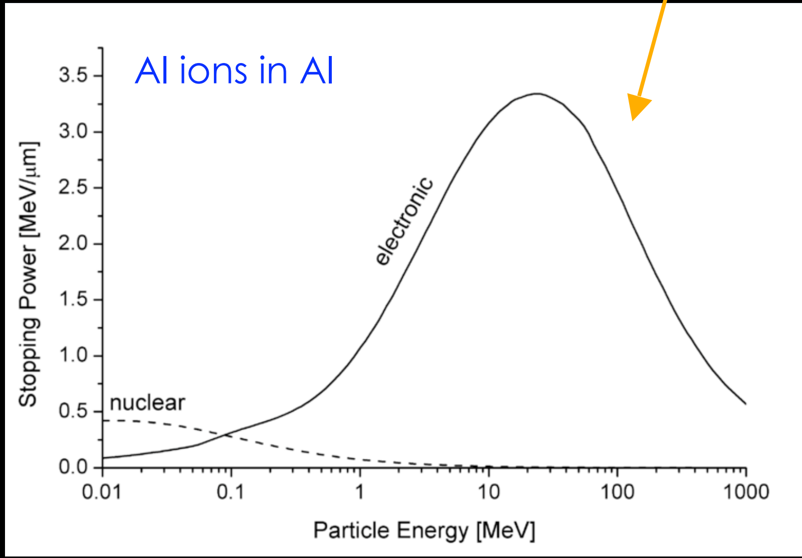
But clearly this calibration is not enough. We need to know how the light yield of these events compares with the light yield from ^{57}Co

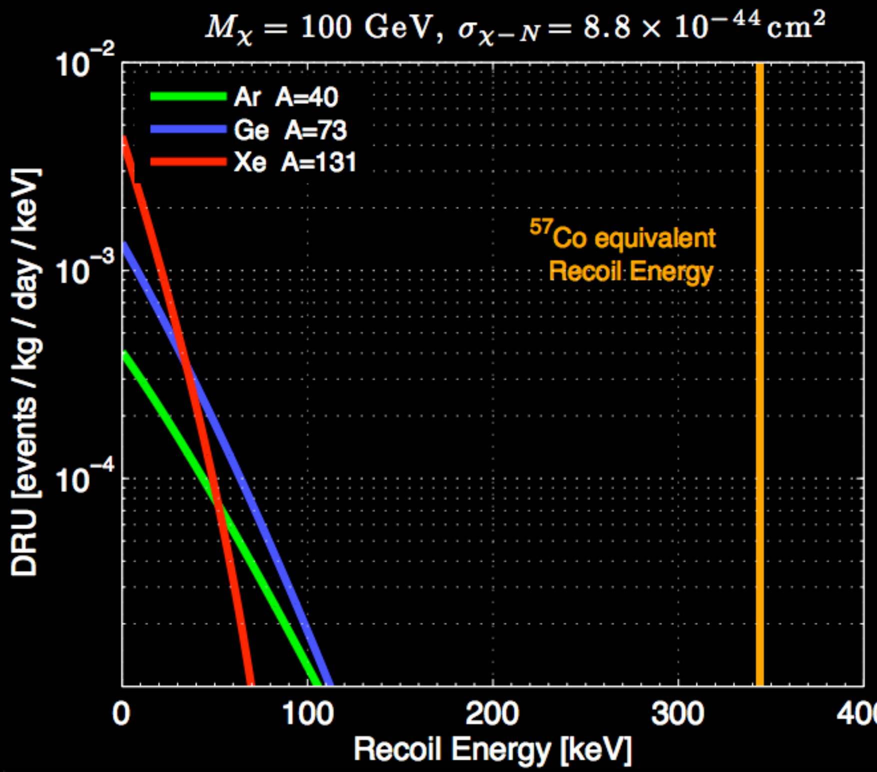
WIMP recoils are both different energy and different particle species

So we have to ask, how do different particles lose energy in matter?

Calibration of Nuclear Recoil Energy Scale

Gamma rays calibrate only the electronic recoil energy scale; we measure only energy going into this channel, but low energy interactions lose significant energy through elastic, atomic interactions.



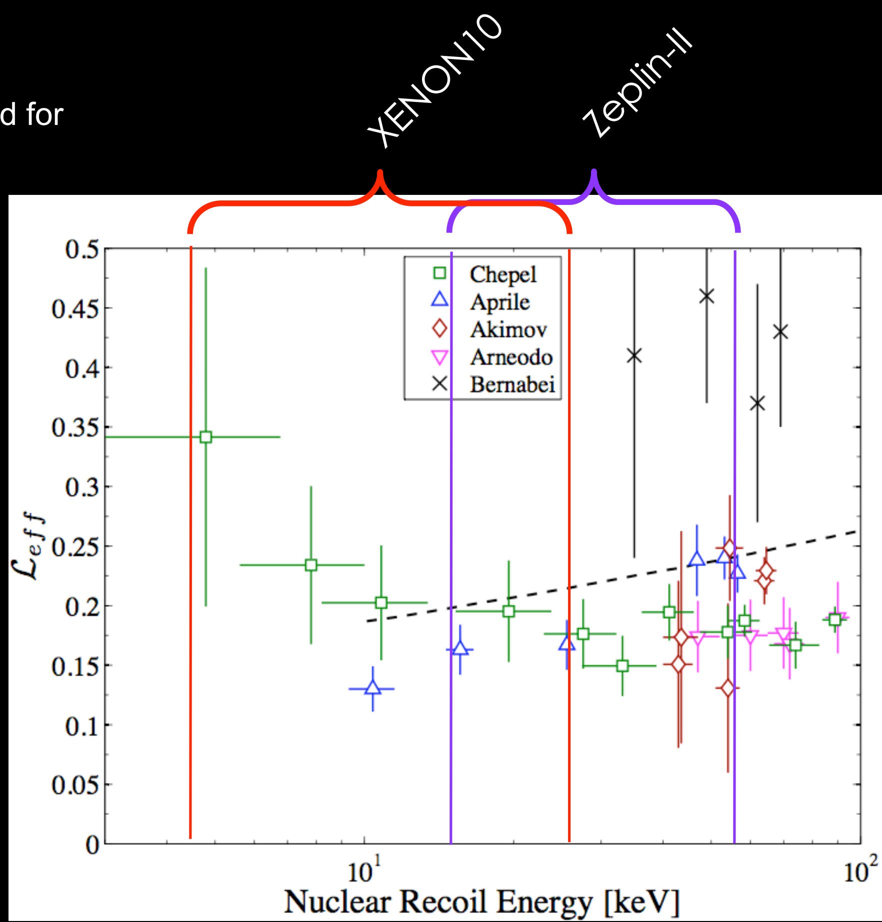


The ratio of the light yield from nuclear recoils to the light yield from ^{57}Co is called L_{eff}, and has been measured by many groups at recoil energies above 20 keV. But measurements at lower recoil energies has been sparse.

Reconstruction of the Nuclear Recoil Energy Scale with L_{eff}

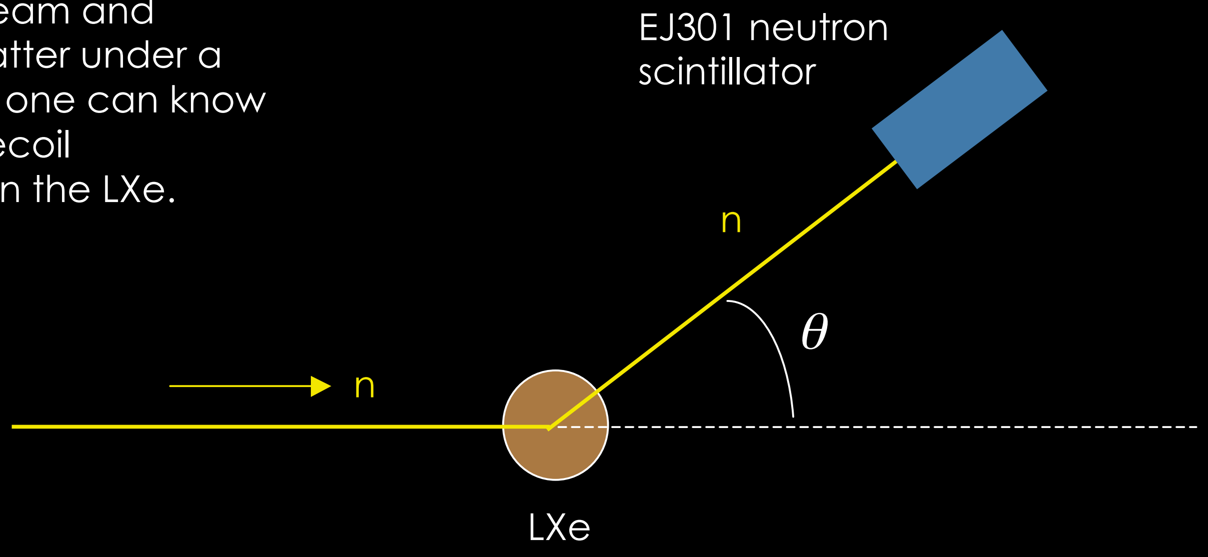
$$E_{nr} = \frac{S1}{L_y \mathcal{L}_{eff}} \times \frac{S_e}{S_r}$$

- E_{nr}: energy of nuclear recoil (NR)
- $S1$: measured signal in p.e.
- S_e: quenching of scintillation yield for 122 keV γ due to drift field
- L_y: light yield for 122 keV γ in p.e./keV
- $\mathcal{L}_{eff}$: relative scintillation efficiency of NR to 122 keV γ at zero field
- S_r: quenching of scintillation yield for NR due to drift field



Measurement of L_{eff}

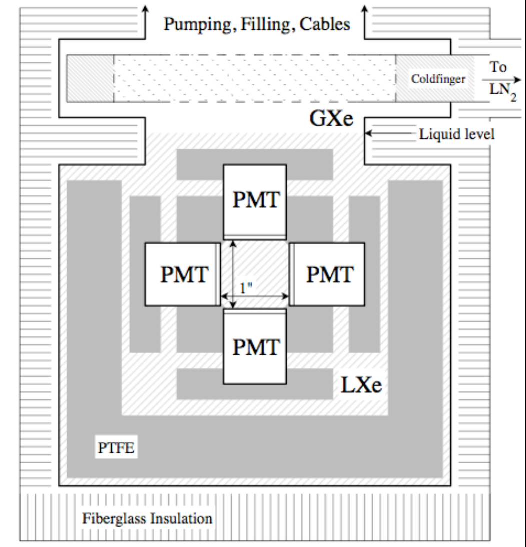
L_{eff} is measured by placing a LXe chamber in a monoenergetic neutron beam and 'tagging' neutrons which scatter under a chosen angle. By doing this, one can know the absolute energy of the recoil independent of its response in the LXe.



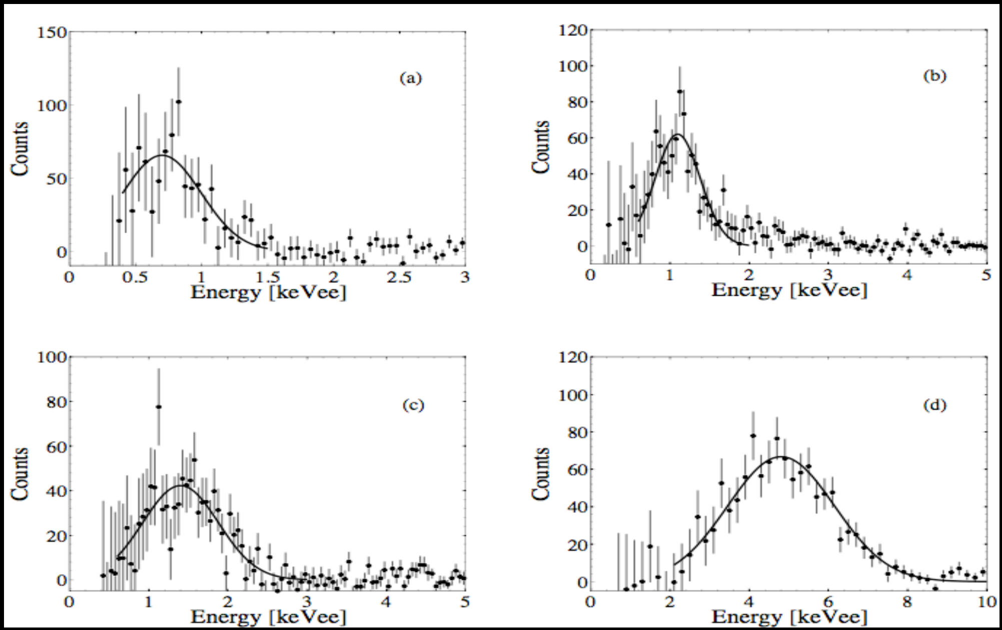
True recoil energy given by the kinematics

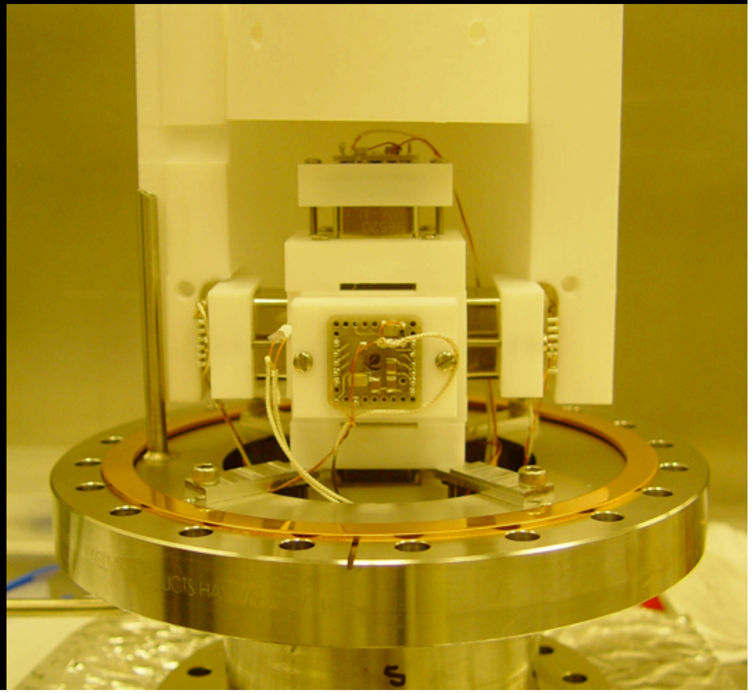
$$E_r \approx 2E_n \frac{m_n M_N}{(m_n + M_N)^2}(1 - cos\theta)$$

Measurement of L_{eff}: the XeCube detector



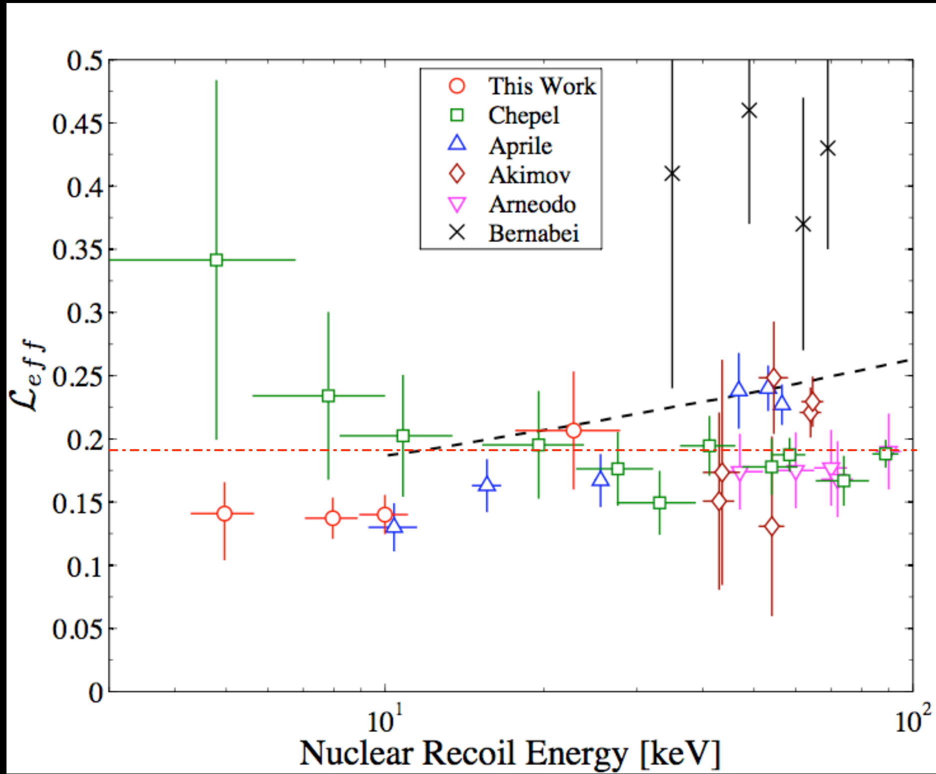
The XeCube detector was constructed specifically to measure L_{eff}. The design provides a zero-field measurement with high light collection (>95% LCE, ~20 p.e./keVee at 122 keVee), and the measurements done in collaboration with the XENON100 group at Columbia University. The detector was placed in the neutron beam of the RARAF at Columbia's Nevis Lab. Each tagged angle gives a different [known] recoil energy.

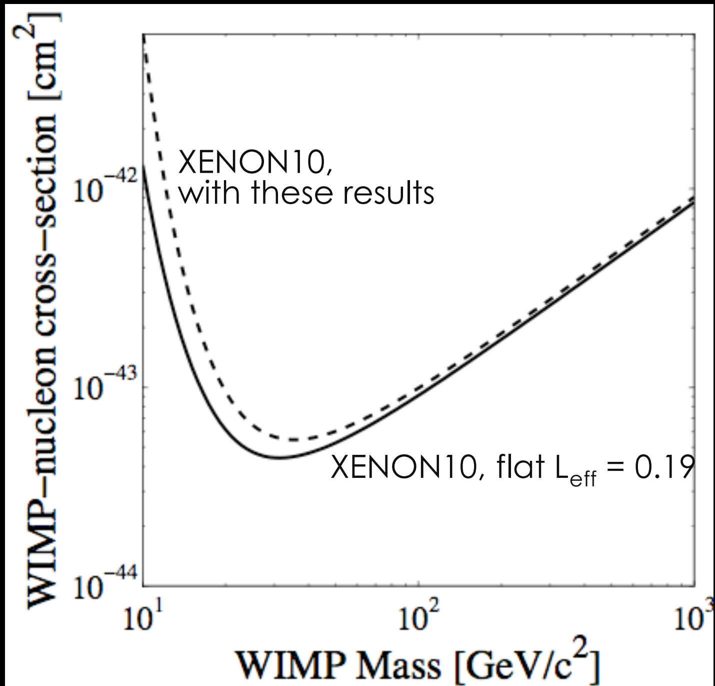




Measurement of L_{eff}

Results [Phys. Rev. C **79**, 045807 (2009)] show a drop in L_{eff} below 20 keV to ~0.14 at 10 keV and below. XENON10's upper limit is changed by ~12.5% at M_{WIMP} = 100 GeV/c^2





PHYSICAL REVIEW C **79**, 045807 (2009)

New measurement of the relative scintillation efficiency of xenon nuclear recoils below 10 keV

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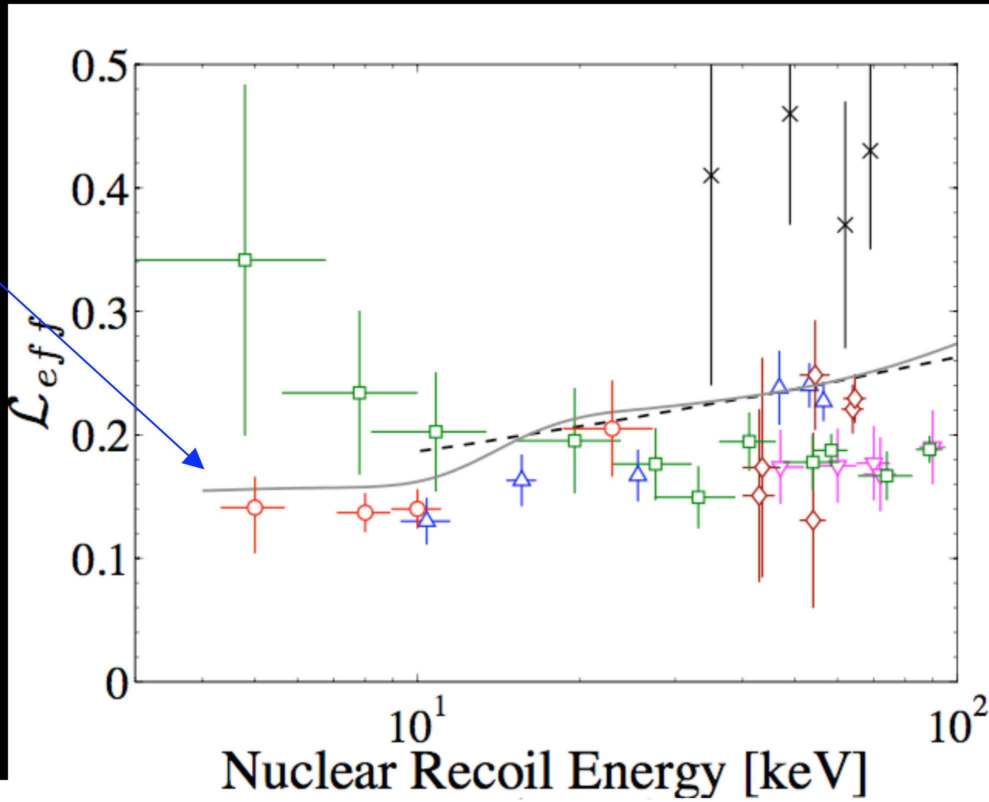
Liquid xenon is an important detection medium in direct dark matter experiments, which search for low-energy nuclear recoils produced by the elastic scattering of WIMPs with quarks. The two existing measurements of the relative scintillation efficiency of nuclear recoils below 20 keV lead to inconsistent extrapolations at lower energies. This results in a different energy scale and thus sensitivity reach of liquid xenon dark matter detectors. We report a new measurement of the relative scintillation efficiency below 10 keV performed with a liquid xenon

Measurement of L_{eff}

Best-fit of XENON10 between neutron calibration (AmBe) and Monte Carlo

(P. Sorensen et al., NIM A 601, 339 (2009))



So it seems our resolution on L_{eff} is improving….

… but then …

Contents lists available at ScienceDirect

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journal homepage: www.elsevier.com/locate/nima

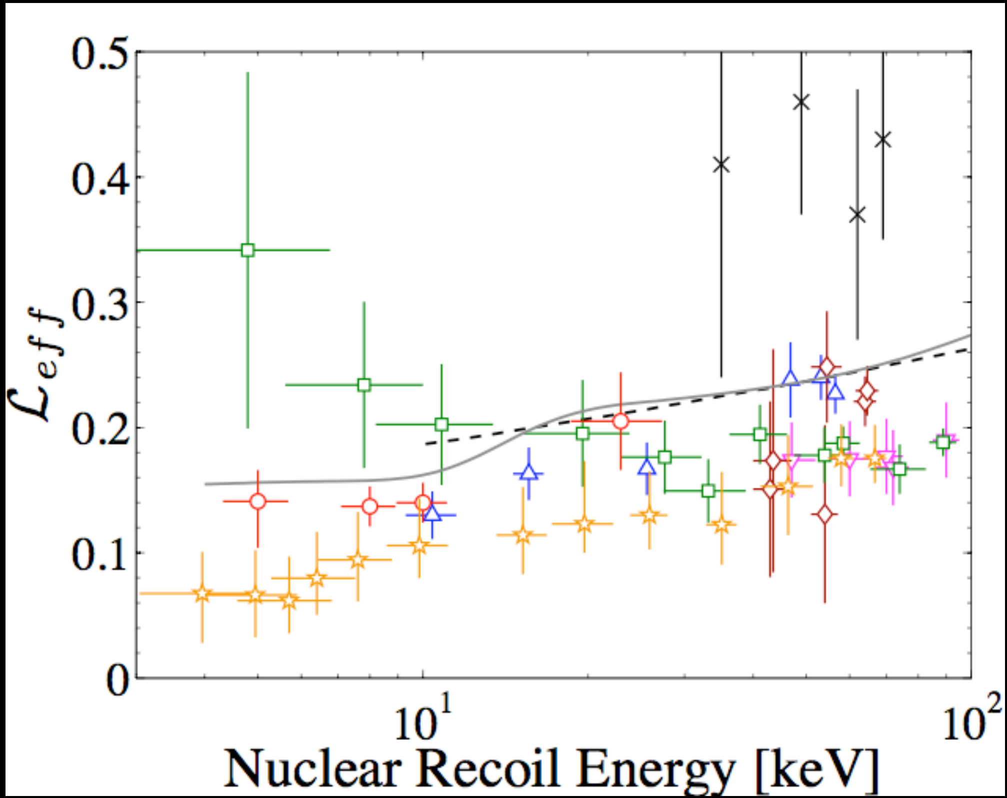
The scintillation and ionization yield of liquid xenon for nuclear recoils

P. Sorensen[a,*], A. Manzur[i], C.E. Dahl[f], J. Angle[l,j], E. Aprile[c], F. Arneodo[d], L. Baudis[l], A. Bernstein[e], A. Bolozdynya[b], L.C.C. Coelho[k], L. DeViveiros[a], A.D. Ferella[l,d], L.M.P. Fernandes[k], S. Fiorucci[a], R.J. Gaitskell[a], K.L. Giboni[c], R. Gomez[g], R. Hasty[i], L. Kastens[i], J. Kwong[f], J.A.M. Lopes[k], N. Madden[e], A. Manalaysay[l,j], D.N. McKinsey[i], M.E. Monzani[c], K. Ni[i], U. Oberlack[g], J. Orboeck[h], G. Plante[i], R. Santorelli[c], J.M.F. dos Santos[k], P. Shagin[g], T. Shutt[b], S. Schulte[h], C. Winant[e], M. Yamashita[c]

Measurement of L_{eff}

… but then …

these results came out.

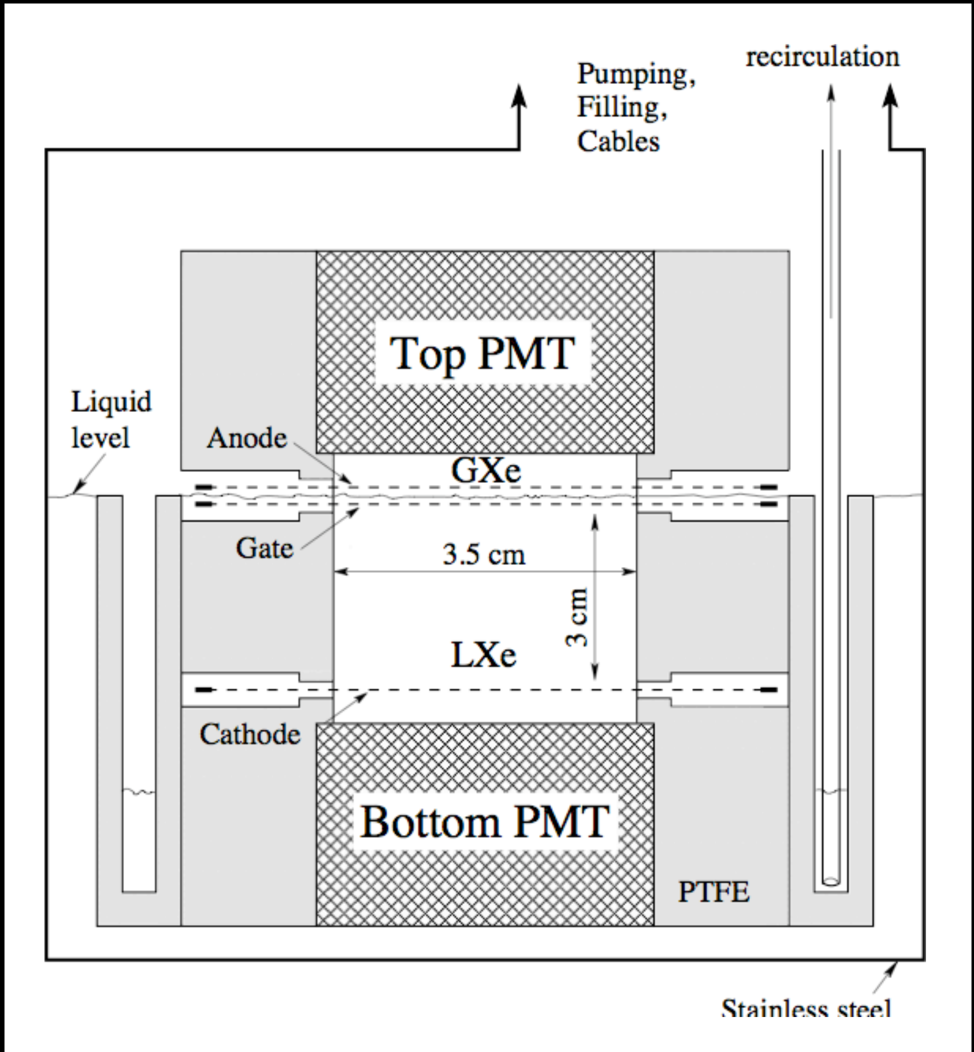


In a recent talk at the TAUP 2009 conference this past July, a new L_{eff} measurement by D. McKinsey et al was reported

http://taup2009.lngs.infn.it/parallel_1.html

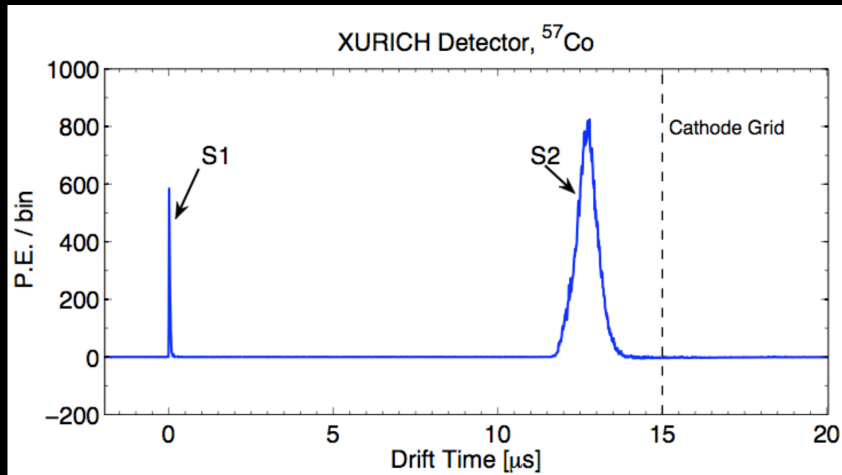
… so it seems more studies of L_{eff} are needed

Further Studies: the Xürich Detector

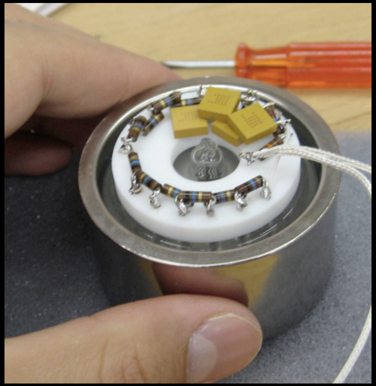


We have developed a small dual-phase LXe TPC for measuring additional properties of LXe under low-energy particle interactions. In a dual-phase TPC:

- The initial "primary" scintillation light is detected. (S1)
- Electrons are drifted to the liquid surface where they are extracted to the gas by an extraction field
- As the electrons are accelerated through the gas onto the Anode, they produce proportional scintillation (S2), which is also detected by the PMTs

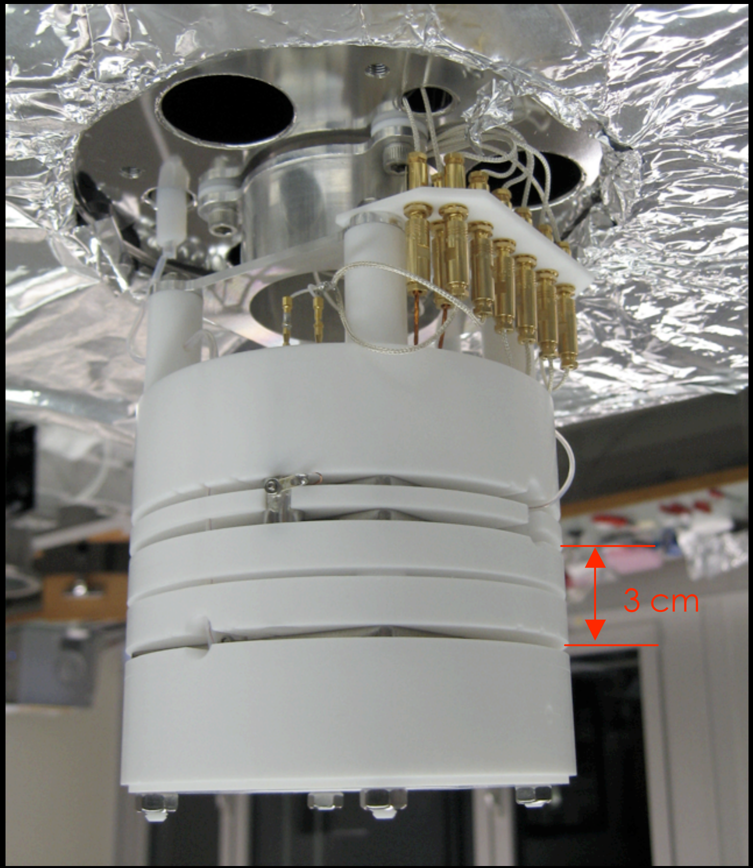


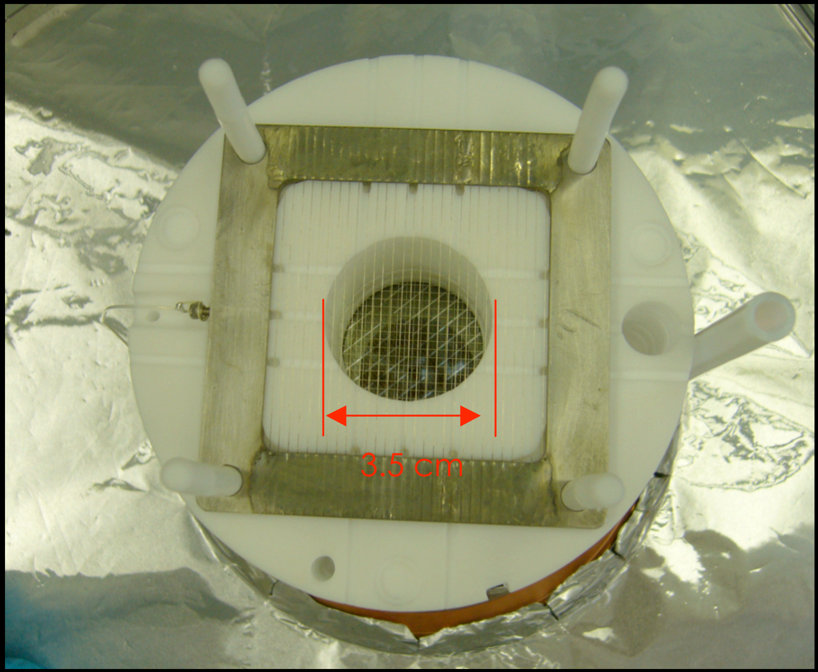
Xürich Detector



R9869 PMTs, Hamamatsu

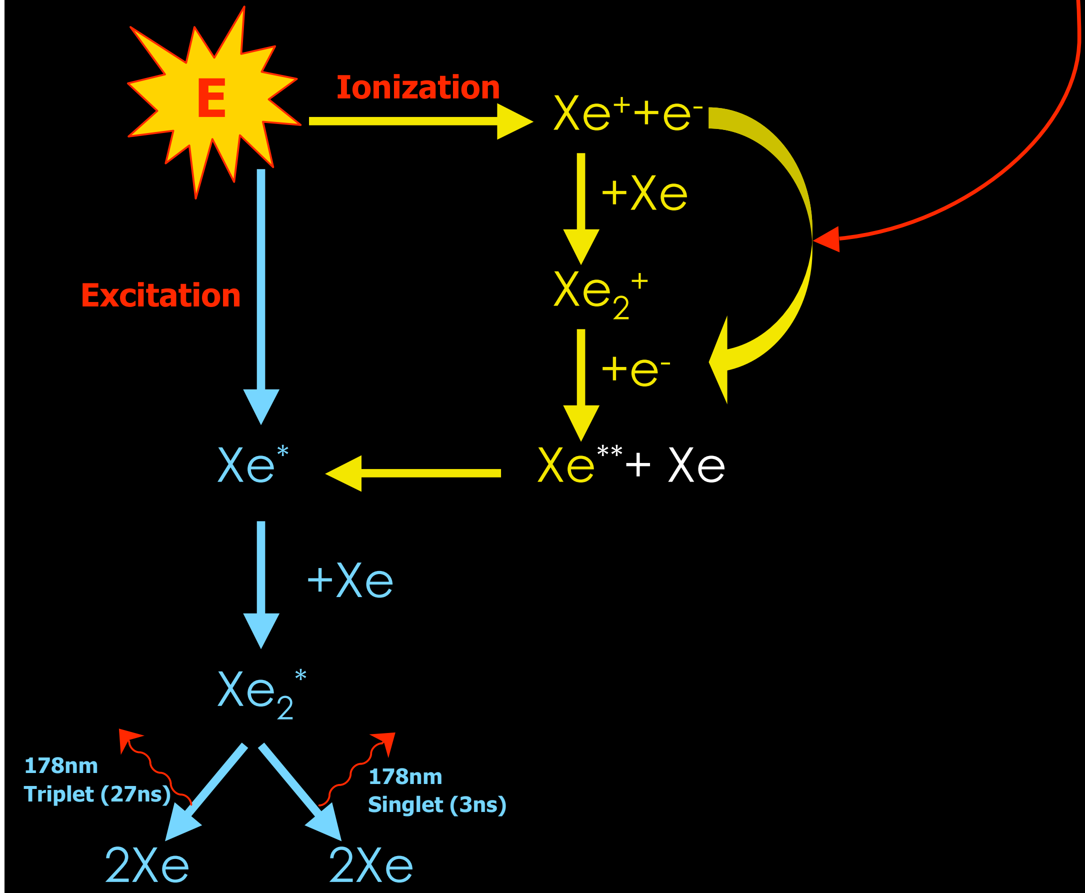
- 3 x 3.5 cm active region
- Active region defined by PTFE
- PTFE is useful because:
  - Good insulator
  - Similar dielectric constant as LXe
  - Good reflector of VUV photons
- Two-pmt design (top-bottom)
- Everything made in-house

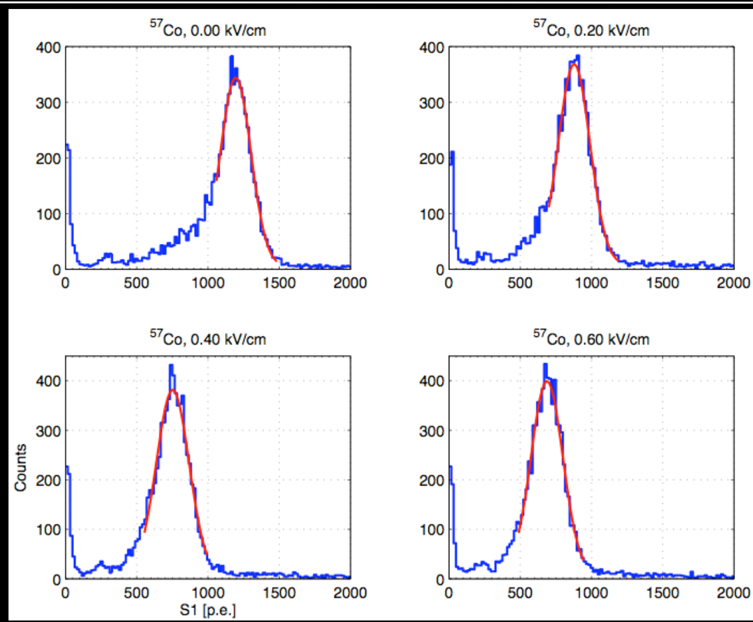




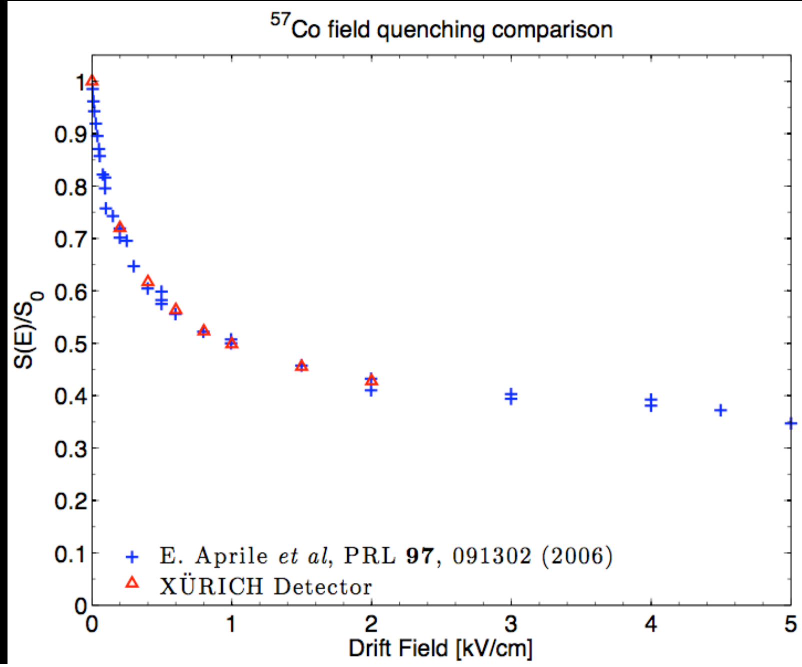
Field Quenching of ^{57}Co

As the applied electric field is increased, free electrons are stolen from the interaction site, and the recombination process becomes more and more suppressed. Each electron escaping recombination means one fewer scintillation photon.





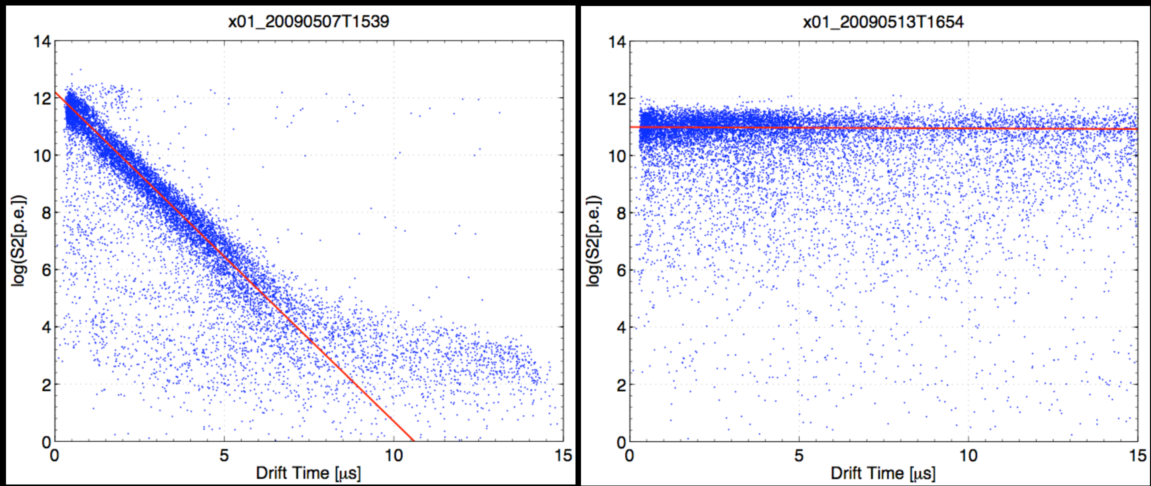
Peak position shifts lower with increasing field

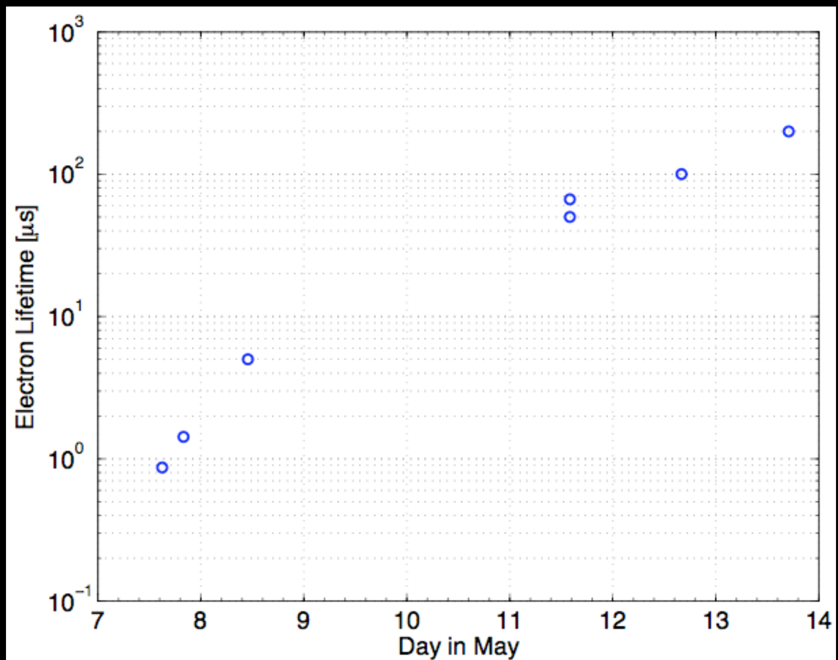


LXe purity and Electron Lifetime

Various electronegative impurities can steal electrons as they drift through the LXe.

- Xe is constantly vaporized, passed through a hot getter (purifier), and recondensed.
- Electron lifetime can be monitored by looking at the S2 size from a photopeak as a function of drift time.
- With a lifetime of several 100's of us, we suffer less than 5% charge loss over our 15 us drift.



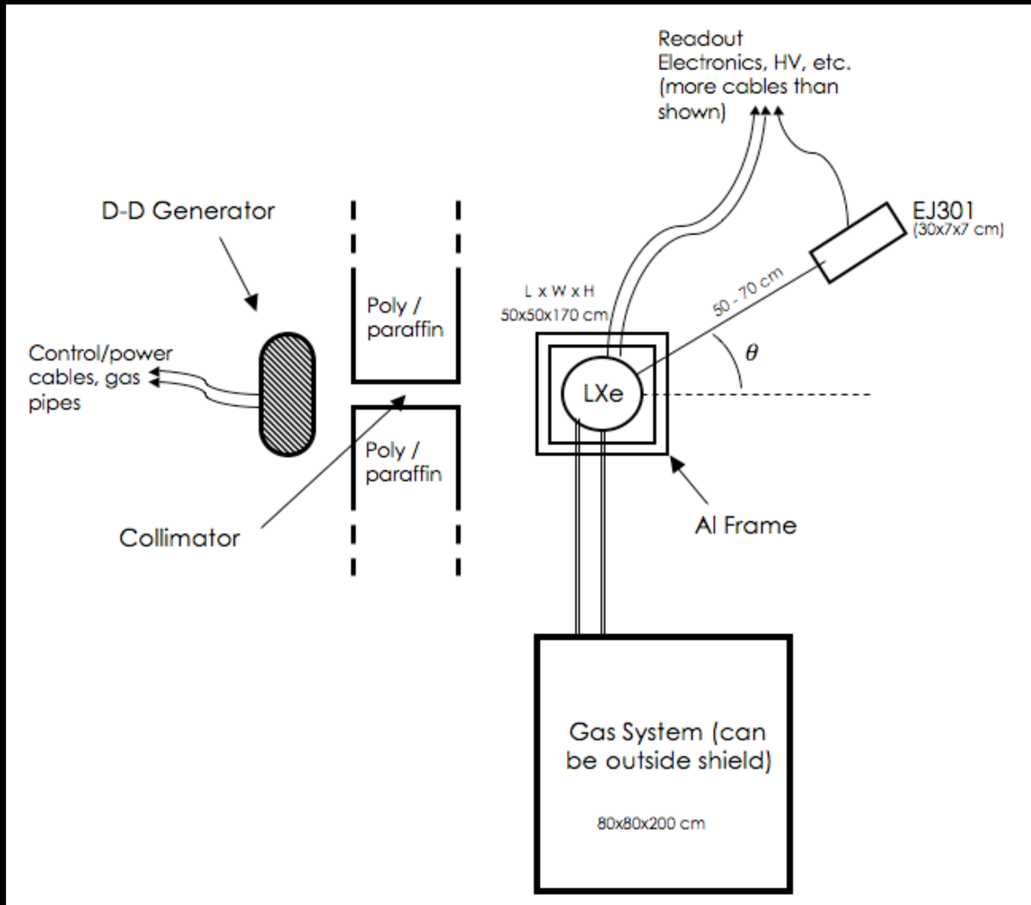


Xürich detector& cryostat

purifier

recirculation pump

Plans for an improved L_{eff} measurement, with a D-D neutron generator, already ordered for the Physik Institut.



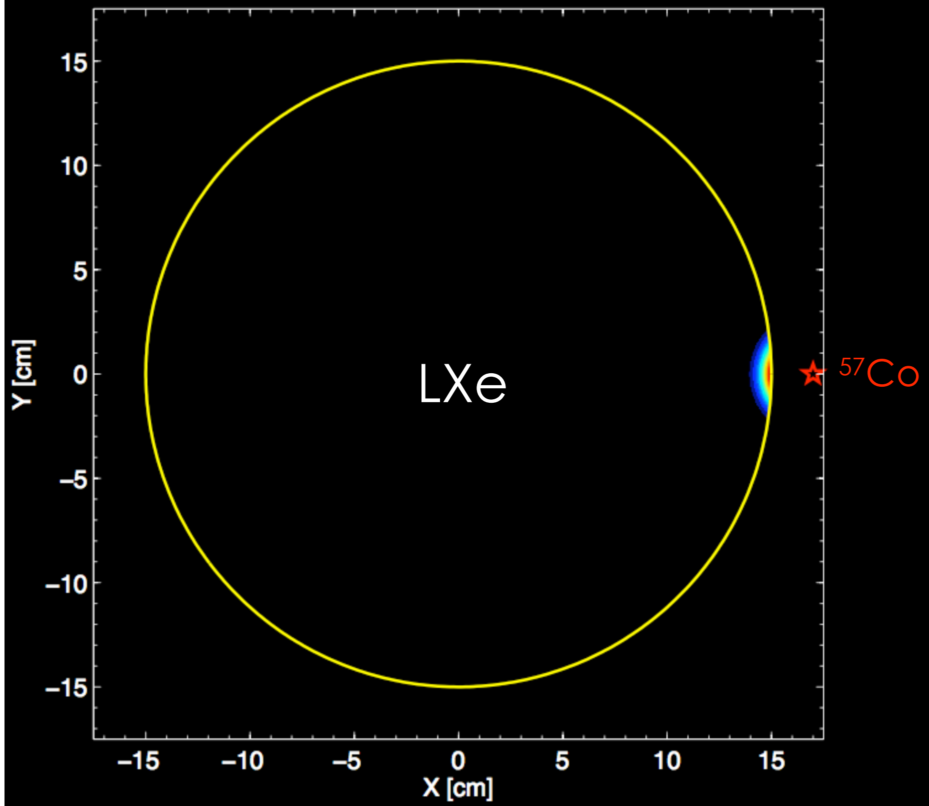
What is wrong with ^{57}Co as a calibrator?

What is wrong with ^{57}Co as a calibrator?

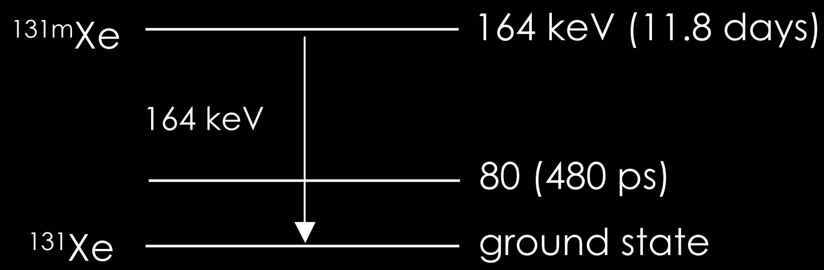
-Energy is much higher than the WIMP-search region of interest.

-Produces different interaction than WIMPs

-No spatial uniformity (~2.5 mm attenuation length)

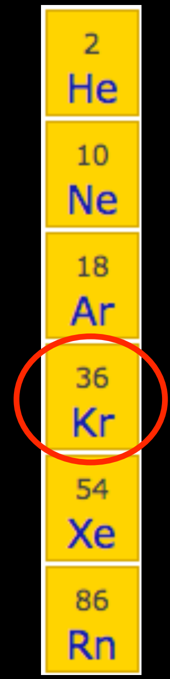


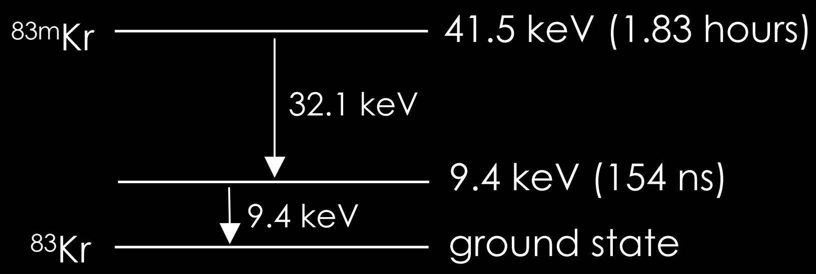
In order to have a calibration source with spatial uniformity, noble gas sources are popular. For example, ^{131m}Xe gives a 164 keV gamma/IC and lives for only 12 days. This solves the issue of spatial uniformity, but not of an appropriate energy.



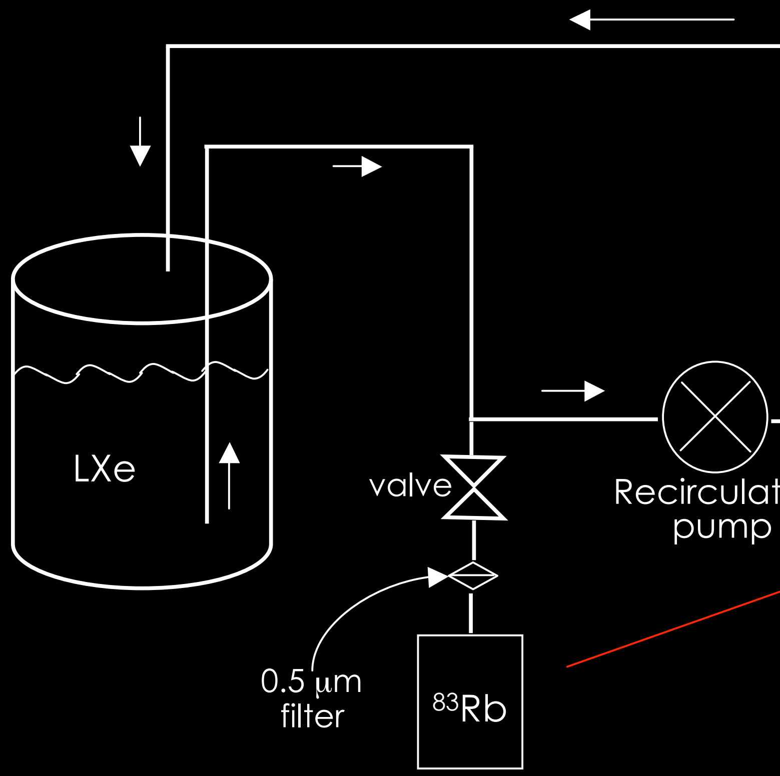
Q: Are there other metastable noble gases that can be used, and are they better than ^{131m}Xe?

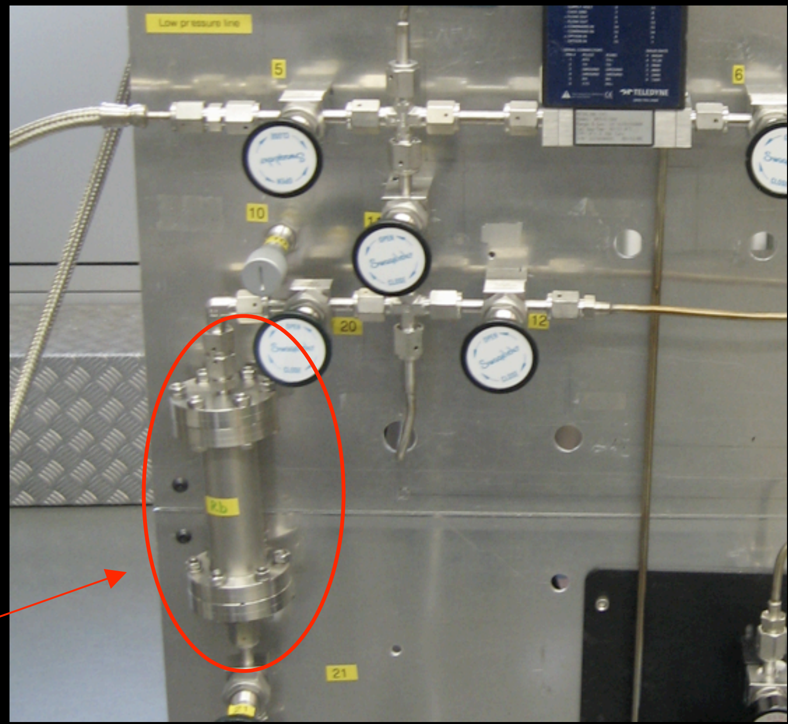
A: Yes! ^{83m}Kr has two lines, at 32 keV and 9.4 keV (low energy), and is living less than 2 hours. It is produced by the decay of ^{83}Rb.





Adding ^{83m}Kr to the system



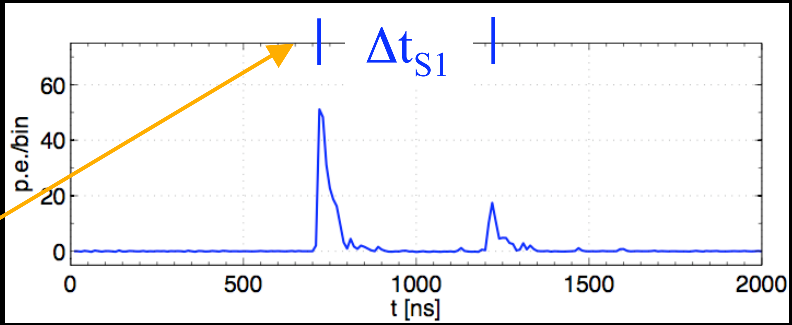


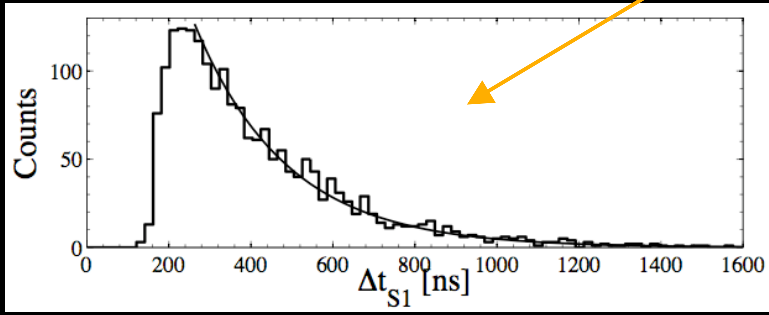
The ^{83m}Kr is the decay product of a 6 kBq ^{83}Rb which decays by EC ($t_{1/2}$ = 86.2 days), produced by O. Lebeda at NPI, Prague and deposited into zeolite ceramic beads. It is placed in a chamber attached to the recirculation loop. A 0.5 μm filter is placed on the Rb chamber, to prevent Rb aerosols from entering the system.

^{83m}Kr Results

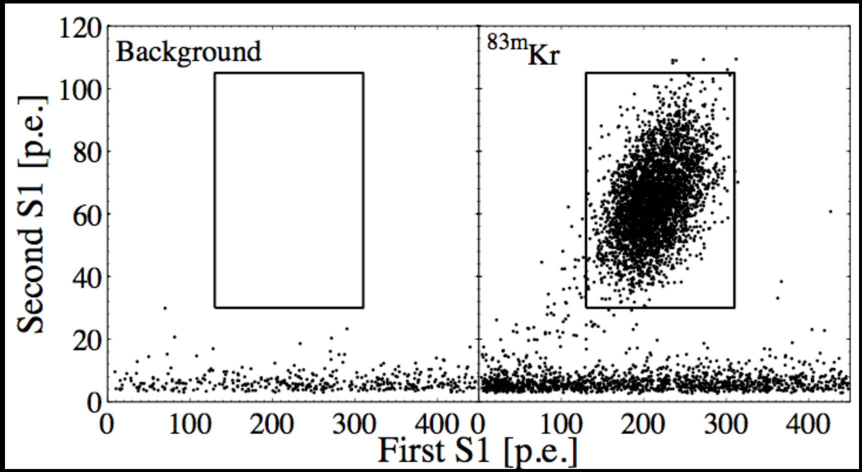
see arXiv:0908.0616 [astro-ph.IM]

The double-S1 structure of the PMT traces provides an unambiguous way to identify the 83mKr decays, that is free of background.

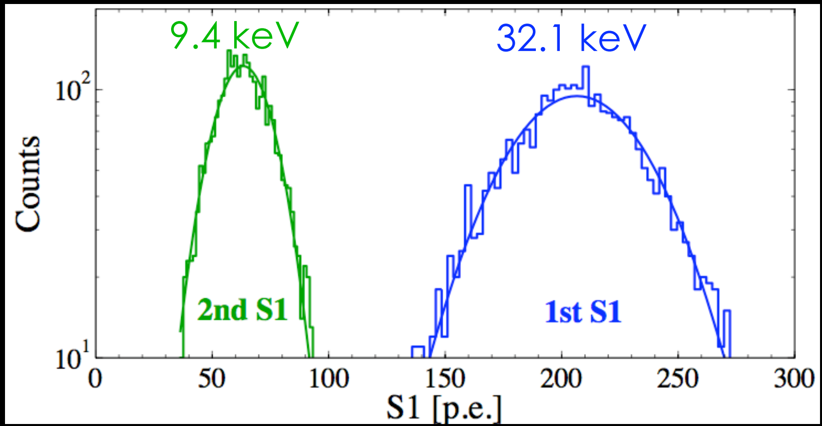




Exponential fit gives $t_{1/2}$ = 156+/-5 ns (value in literature is 154 ns)



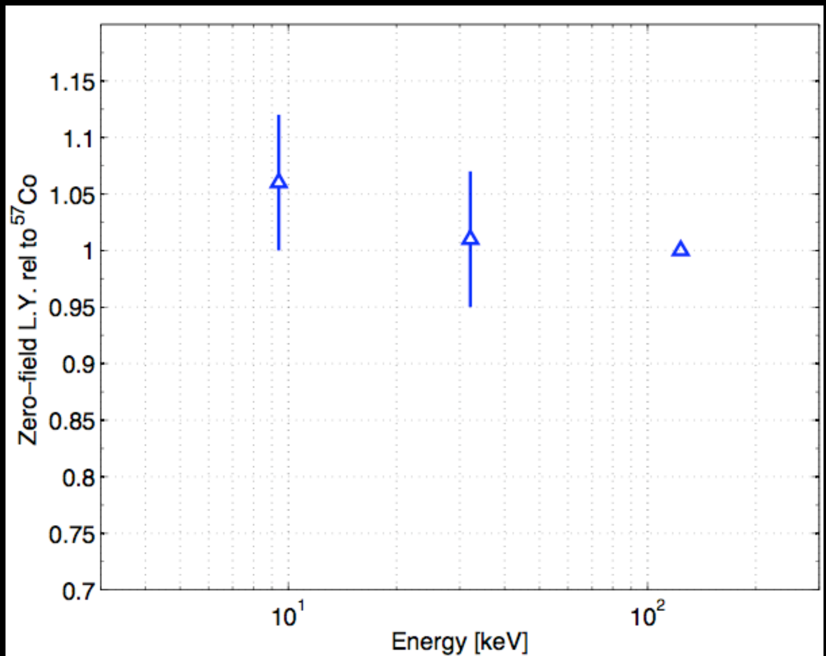
^{83m}Kr Results



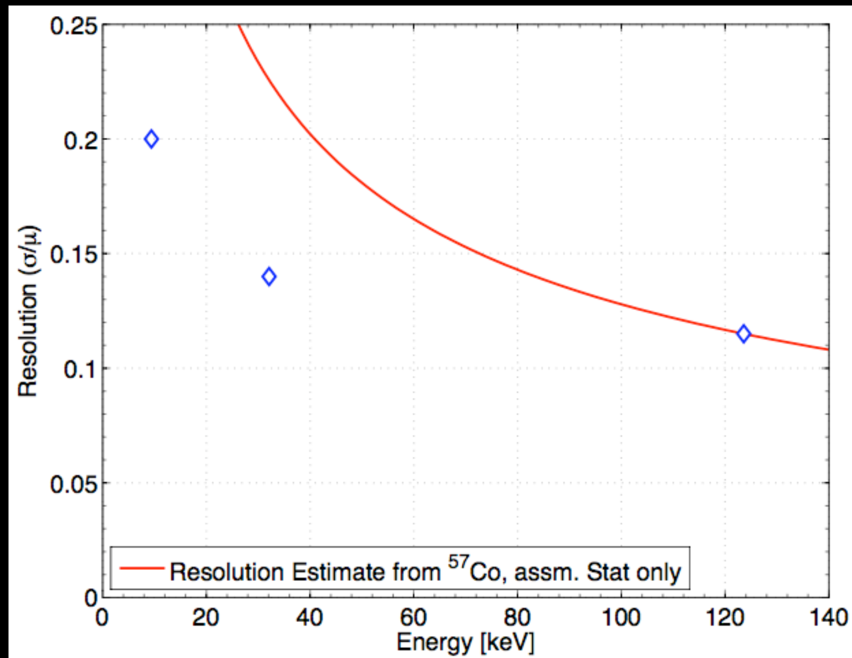
LXe's behavior at these energies suggests an increase in the light yield relative to ^{57}Co

Normaly one estimates the detector's energy resolution by measuring at 122 keV and assuming it is proportional to $E^{-1/2}$ (red curve)

Light yield, relative to ^{57}Co

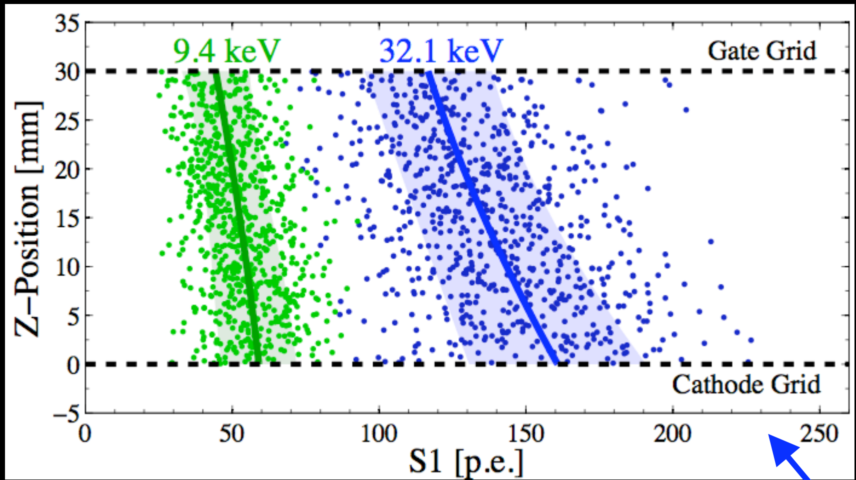


Energy Resolution

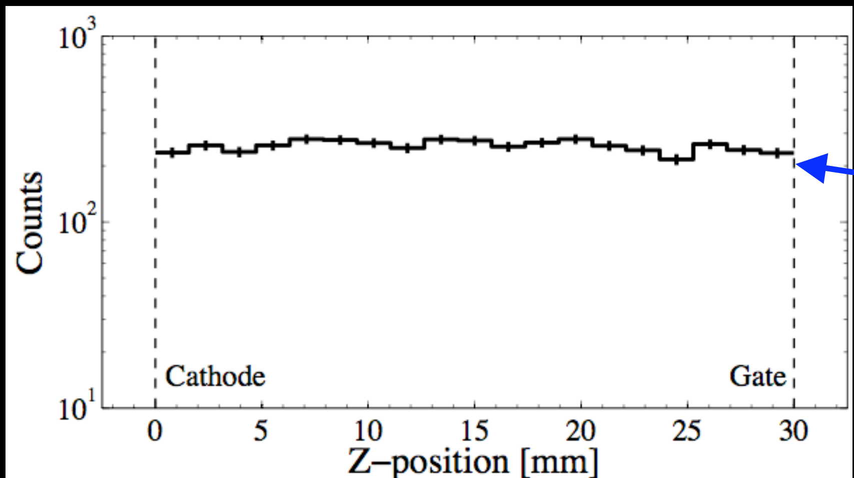


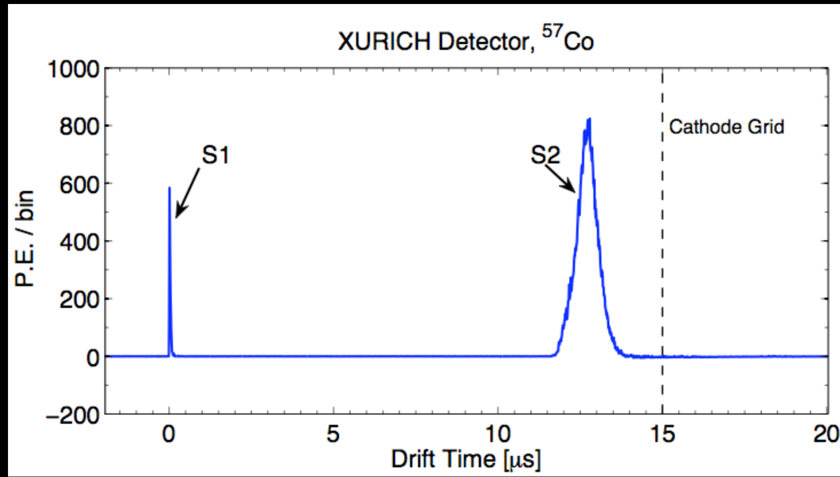
^{83m}Kr Results

S1-position dependence -- centroid differs by factor of ~1.3 from bottom to top



Z - distribution of hits

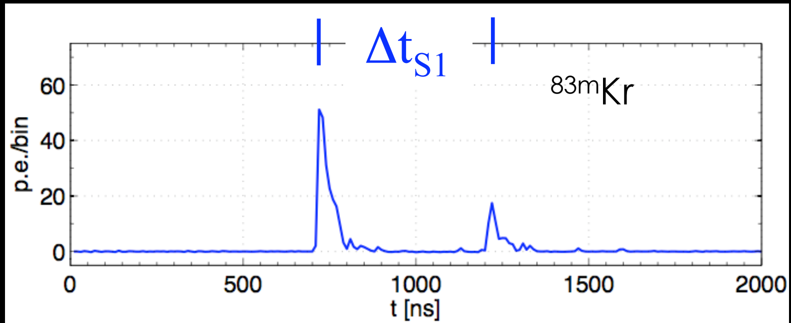




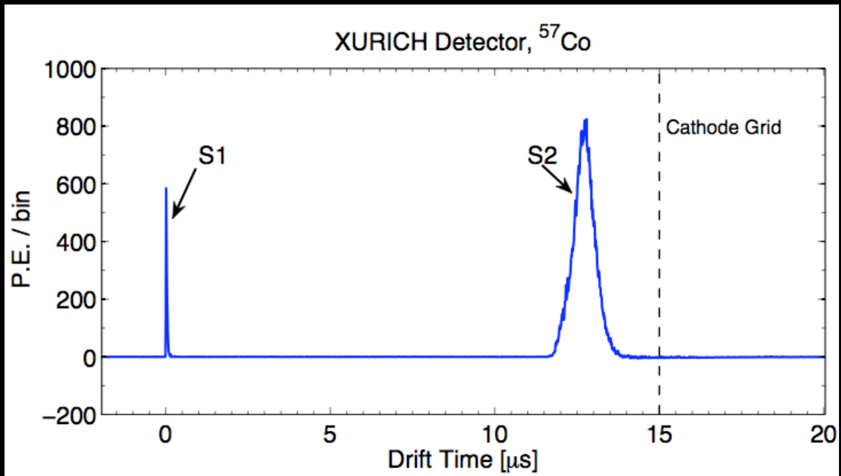
The drift velocity of electrons in LXe as a function of electric field is well known, ~ 2 mm/μs at 1 kV/cm. The z-position of the event can thus be measured from the delay time between S1 and S2. With this information, we can measure:

- Position dependence of S1
- Uniformity of the energy deposition

^{83m}Kr Results

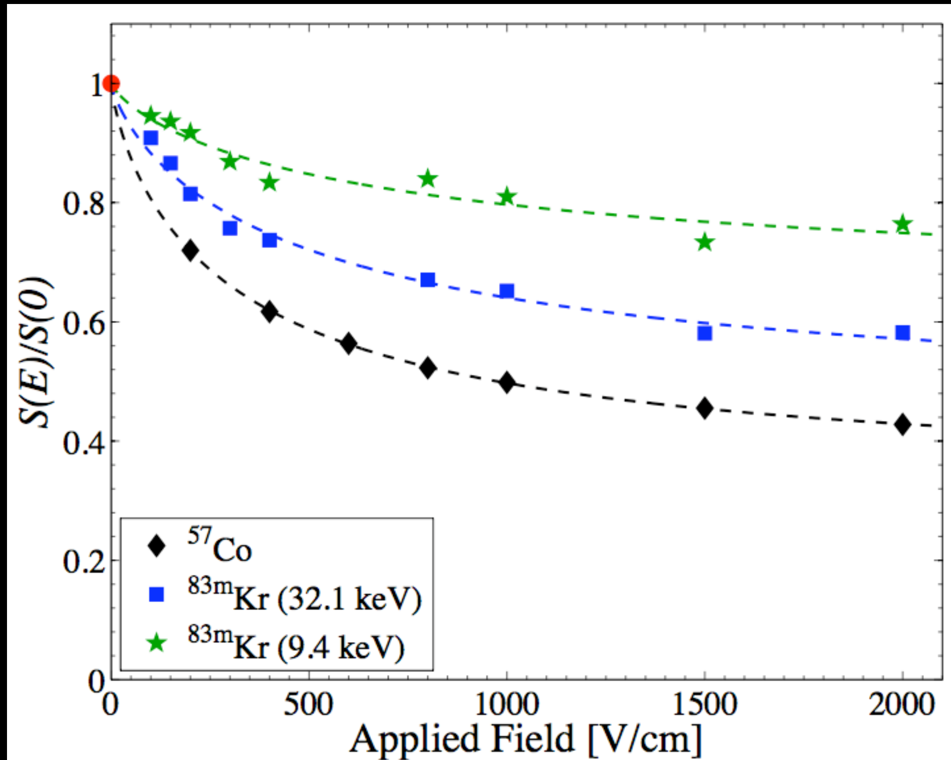


Unfortunately, with $t_{1/2}$=154ns, the two S2 signals (typically ~1μs wide) created by the ^{83m}Kr decay cannot be separately distinguished, and so the charge collection cannot be measured.



Additionally with the applied field, we can measure the field-quenching behavior of LXe at these energies. Knowledge of this is essential if we wish to compare these interactions with those of other types.

Field Quenching

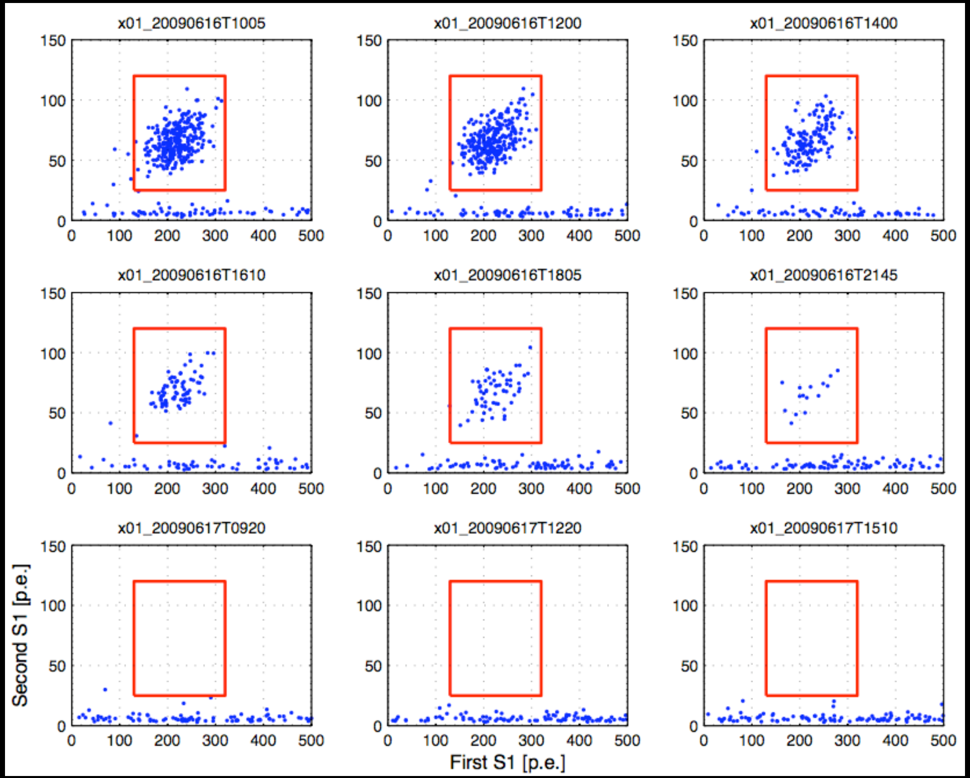


Does any ^{83}Rb enter the system?

^{83m}Kr decays away in a matter of hours, but ^{83}Rb has a half-life of 86 days -- not good in a low-background experiment!

Residual Rb

After ~150 h total exposure, we close the valve to the Rb chamber and watch the Kr rate decrease…



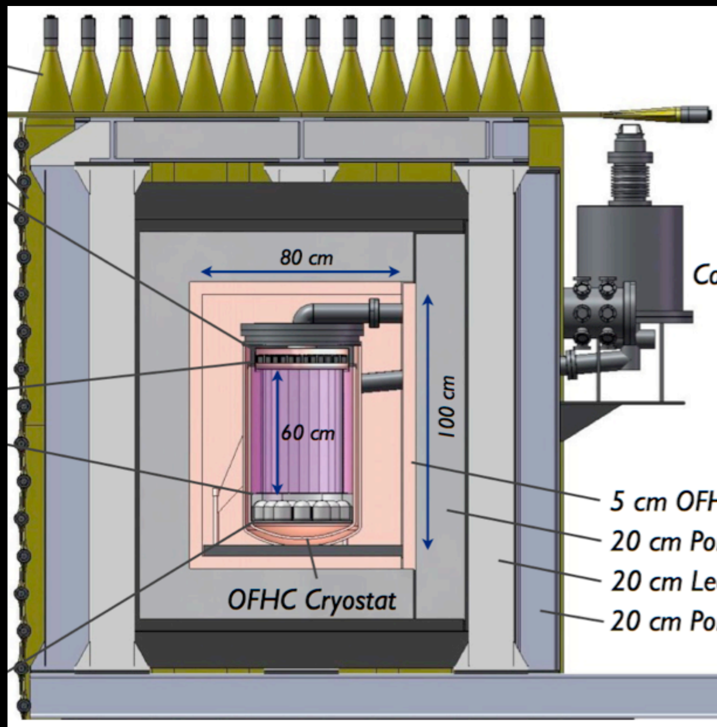
0 events in 2.5 hours gives an upper limit (90% C.L.) of 800 μBq in the active region

Residual Rb

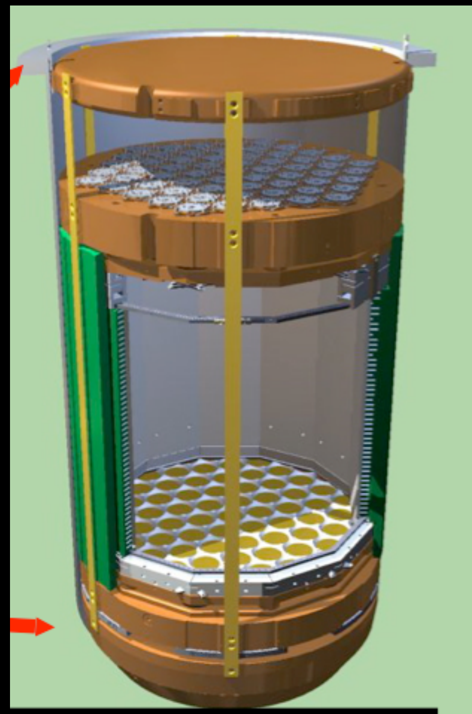
Next generation of dual-phase LXe dark matter detectors will contain ~300 kg LXe (~100 kg fiducial), and project intrinsic radioactive backgrounds at the level of 1 mDRU (1 DRU = 1 evt/kg/day/keV).

Our limit of 800 μBq would produce a background of less than 50 μDRU in such a detector, a factor of 20 below their intrinsic backgrounds.

XENON100 Upgrade



LUX



Summary

- Possible to reject upwards of 99.9% of EM backgrounds in LXe detectors
- Difficult to understand the energy scale of WIMP interactions in LXe. Large uncertainty in L_{eff} remains and requires further study.
- Calibration of LXe detectors using ^{57}Co is common, but not practical especially for large detectors.
- ^{83m}Kr will be important for calibration of LXe dark matter detectors because it is low-energy, spatially uniform, and short-lived.
- A small dual phase LXe TPC (Xürich detector) has been constructed at UZH for tests of the low-energy response of LXe. Will measure L_{eff} with a D-D neutron generator.
- We have recently demonstrated the introduction and use of ^{83m}Kr in our detector.

Fin.