Rubidium 83: A low-energy, spatially uniform calibrator for xenon TPCs

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2009 UniZH/ETH Doktorandenseminar

June 5, 2009

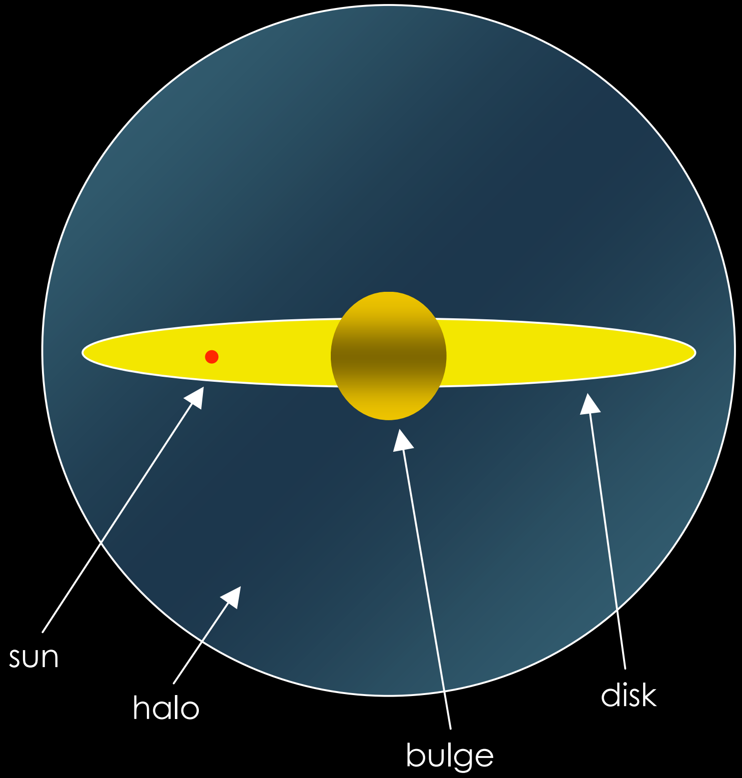
Brief Overview

- Short (1-slide) overview of DM direct detection
- Problems in calibrating LXe detectors
- Measurement of L_{eff}
- Xürich Detector at UZH
- ^{83}Rb motivation and preliminary tests.

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.

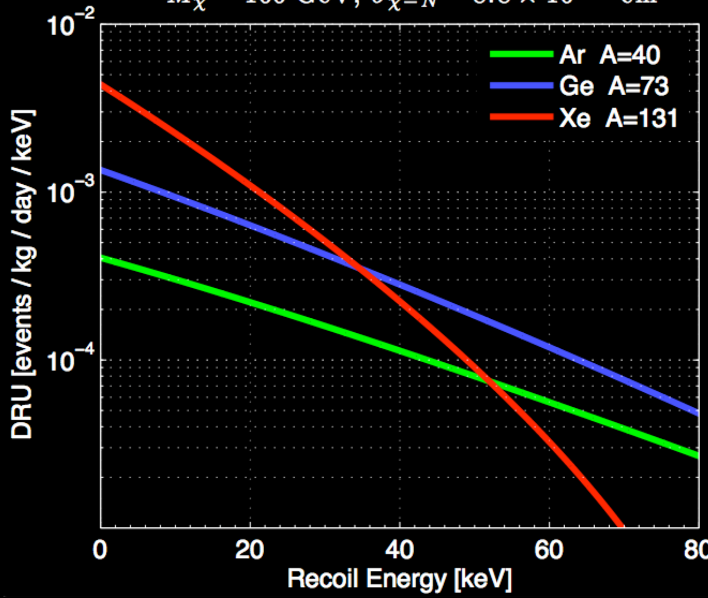
The Milky Way



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:

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

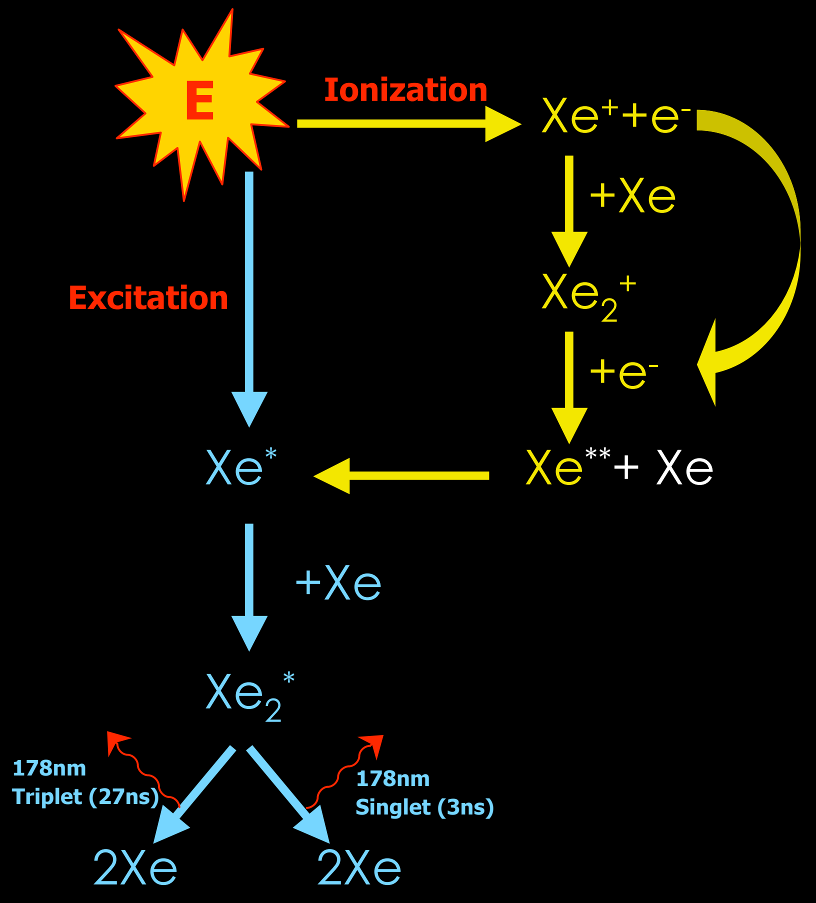
$M_\chi = 100$ GeV, $\sigma_{\chi-N} = 8.8 \times 10^{-44}\,\mathrm{cm}^2$



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



E

Ionization

$Xe^+ + e^-$

+Xe

Xe_2^+

$+e^-$

Excitation

$Xe^{**} + Xe$

Xe^*

+Xe

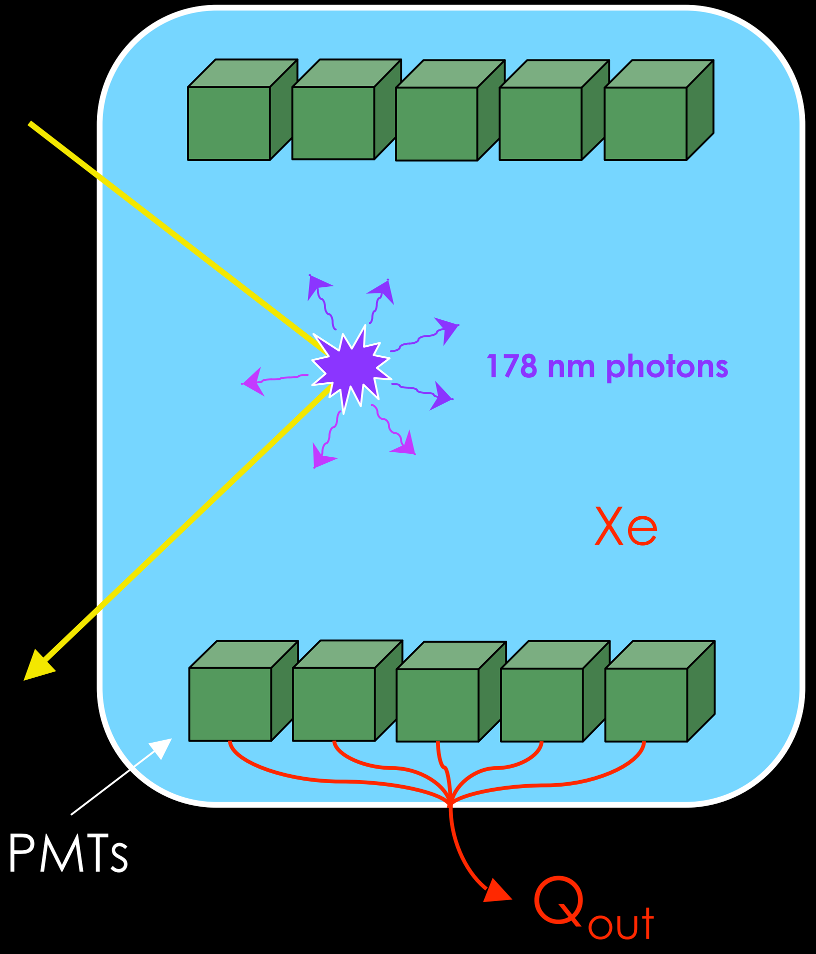
Xe_2^*

178nm Triplet (27ns)

178nm Singlet (3ns)

2Xe

2Xe



178 nm photons

Xe

PMTs

Q_{out}

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

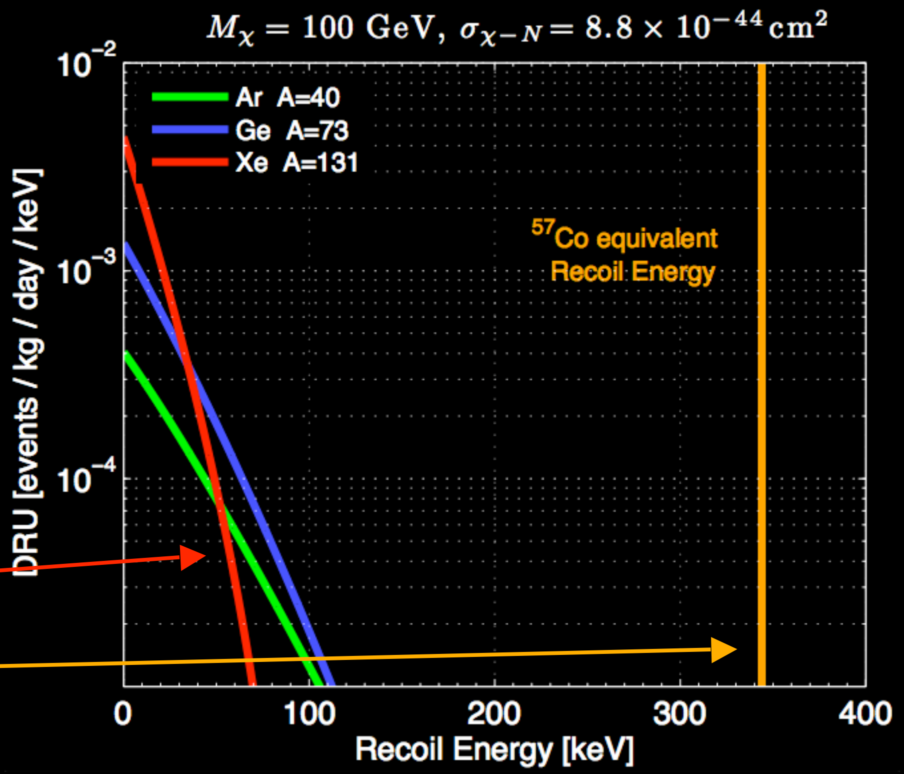
- - Applied electric field
- - LCE (light collection efficiency)
  - -Solid angle subtended by PMTs
  - -Reflectivity of detector materials
  - -Scattering length of the photons in LXe
    - -Inherent absorption of LXe to it's own scintillation
    - -Impurities
- - Transmission efficiency of PMT windows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

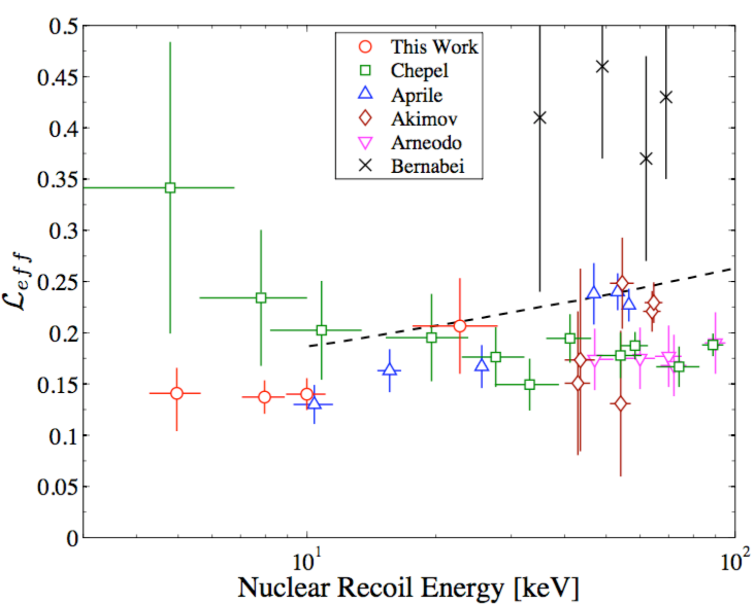
WIMP recoils are both different energy and different particle speices

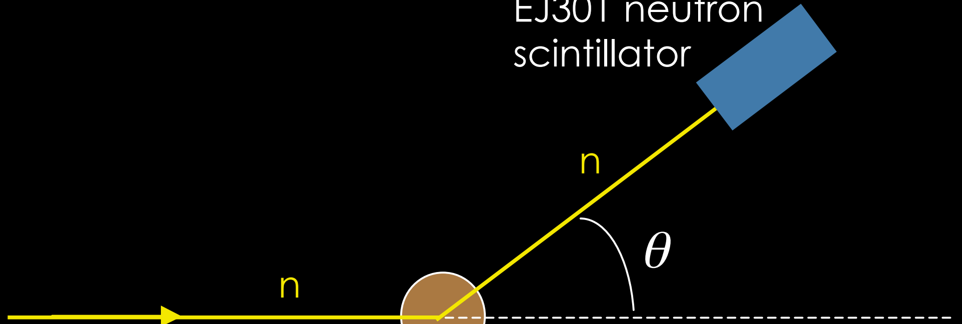
The ratio of the light yield from nuclear recoils to the light yield from ^{57}Co is called L_{eff}, and has been measured by many groups at recoil energies above 20 keV. But measurements at lower recoil energies has been sparse.

Calibration of Nuclear Recoil Energy Scale

L_{eff} is measured by placing a LXe chamber in a monoenergetic neutron beam and ‘tagging’ neutrons which scatter under a chosen angle.

The most interesting region for WIMP searches is <20 keV, which has the least coverage from beam measurements. This was the source of XENON10’s largest systematic uncertainty, and was a source of complaint from many in the community.

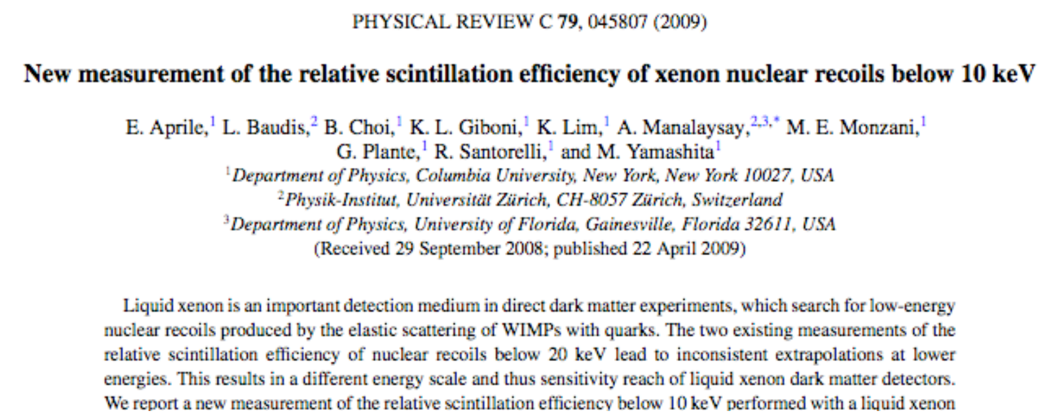




EJ301 neutron scintillator

LXe

True recoil energy given by the kinematics



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

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

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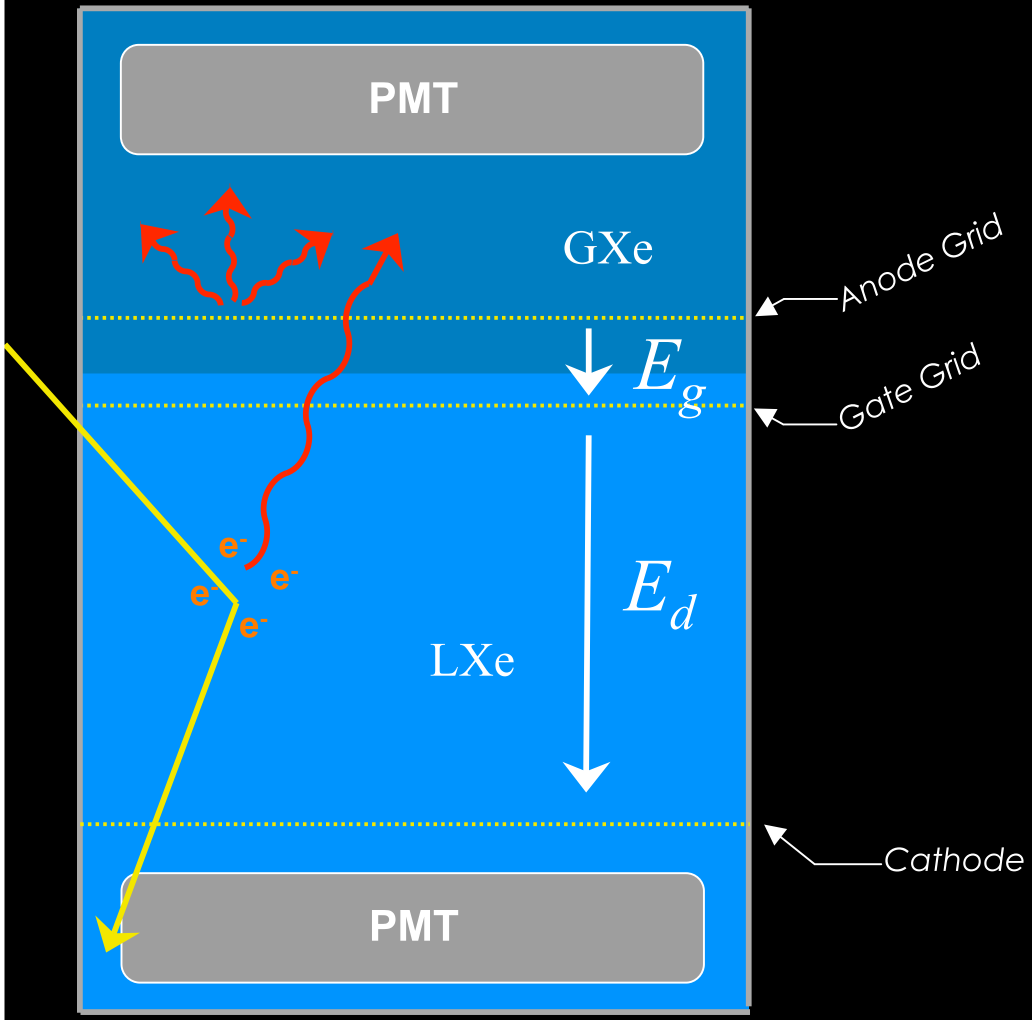
(Received 29 September 2008; published 22 April 2009)

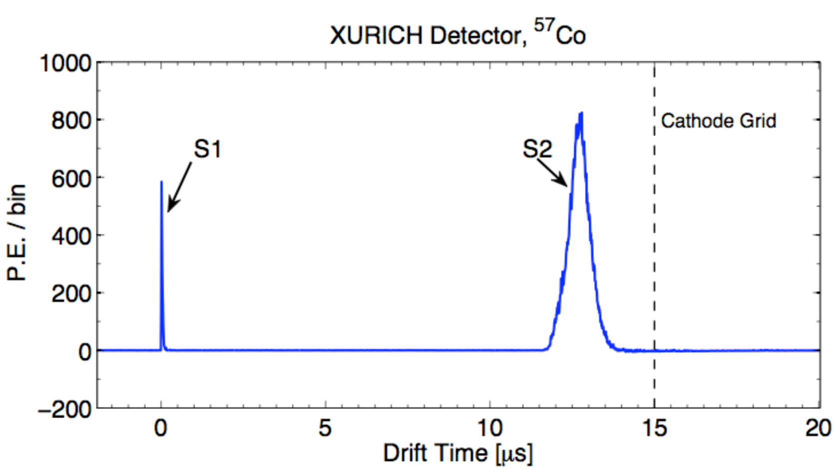
Liquid xenon is an important detection medium in direct dark matter experiments, which search for low-energy nuclear recoils produced by the elastic scattering of WIMPs with quarks. The two existing measurements of the relative scintillation efficiency of nuclear recoils below 20 keV lead to inconsistent 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

Further Studies: the Xürich Detector

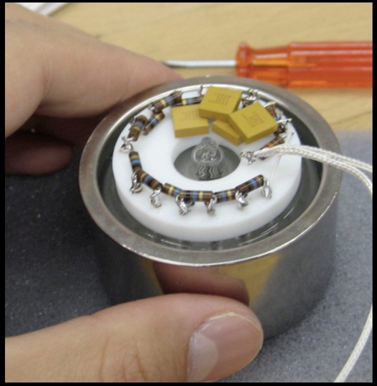


We have developed a small dual-phase LXe TPC for measuring additional properties of LXe under low-energy particle interactions. In a dual-phase TPC:

- 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

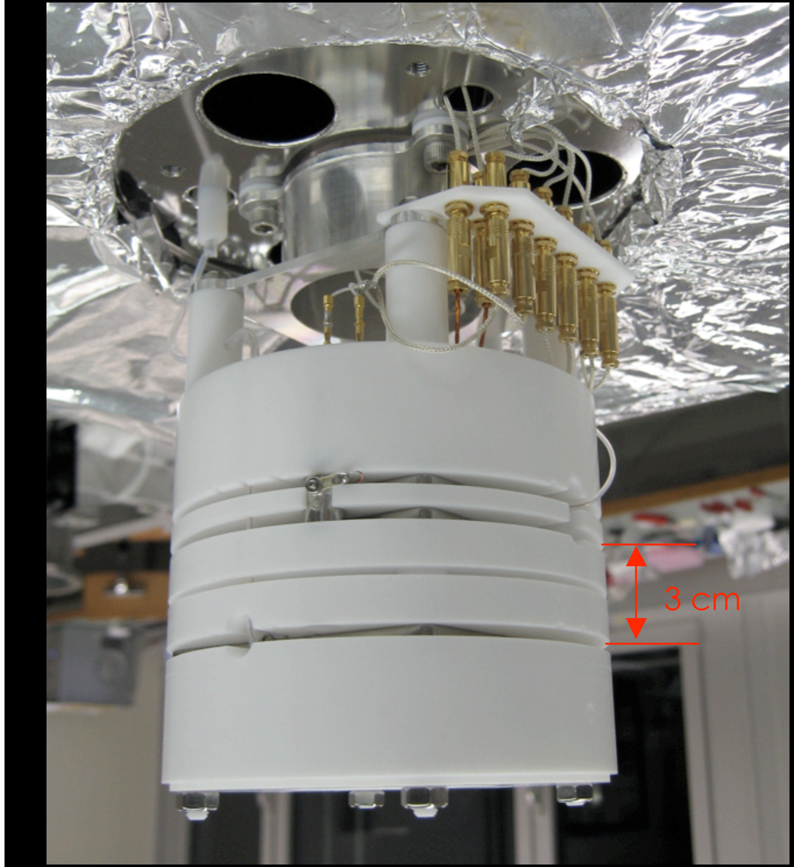


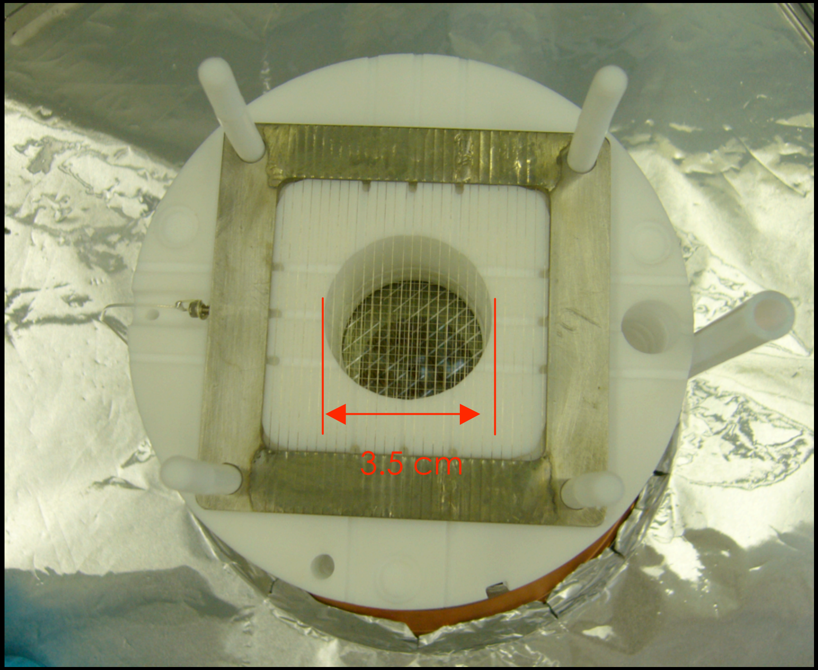
Xürich Detector



R9869 PMTs, Hamamatsu

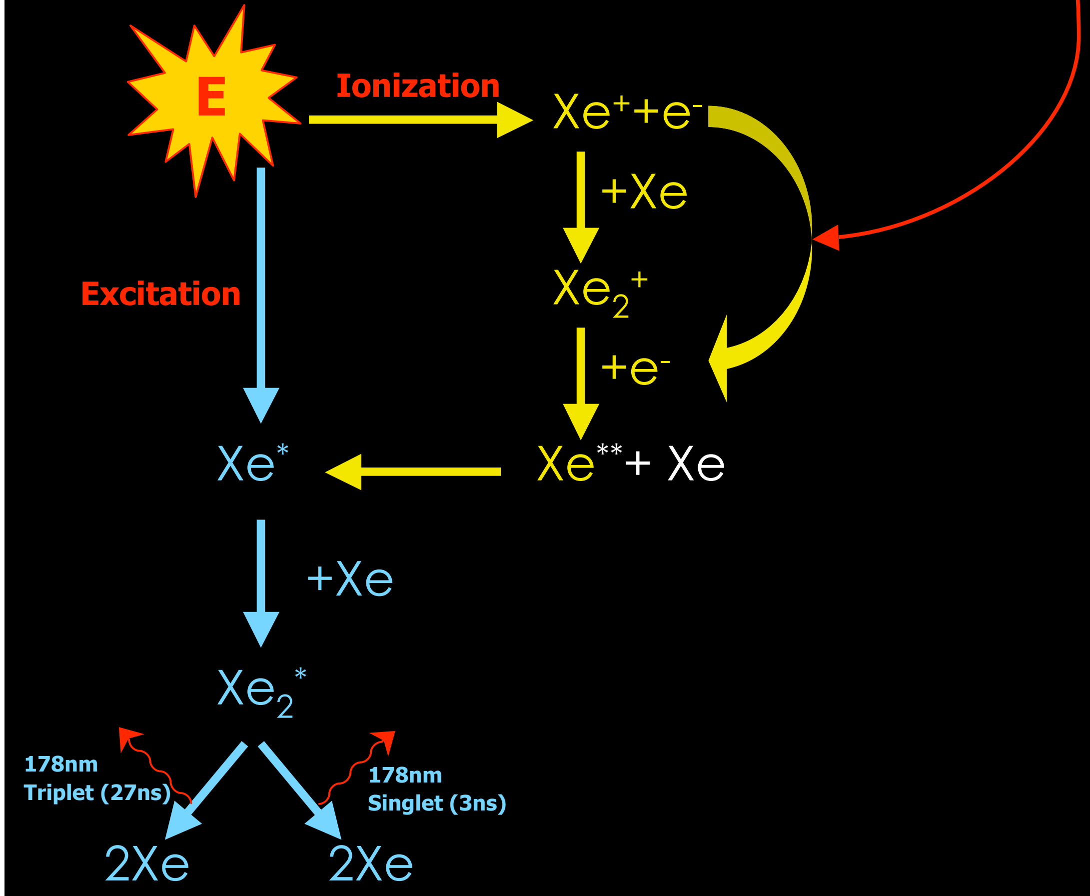
- 3 x 3.5 cm active region
- Active region defined by PTFE
- PTFE is useful because:
  - Good insulator
  - Similar dielectric constant as LXe
  - Good reflector of VUV photons
- Two-pmt design (top-bottom)
- Everything made in-house





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.



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Ionization

$Xe^{+}+e^{-}$

$+Xe$

Xe_2^{+}

$+e^{-}$

$Xe^{**}+Xe$

Excitation

Xe^{*}

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2Xe

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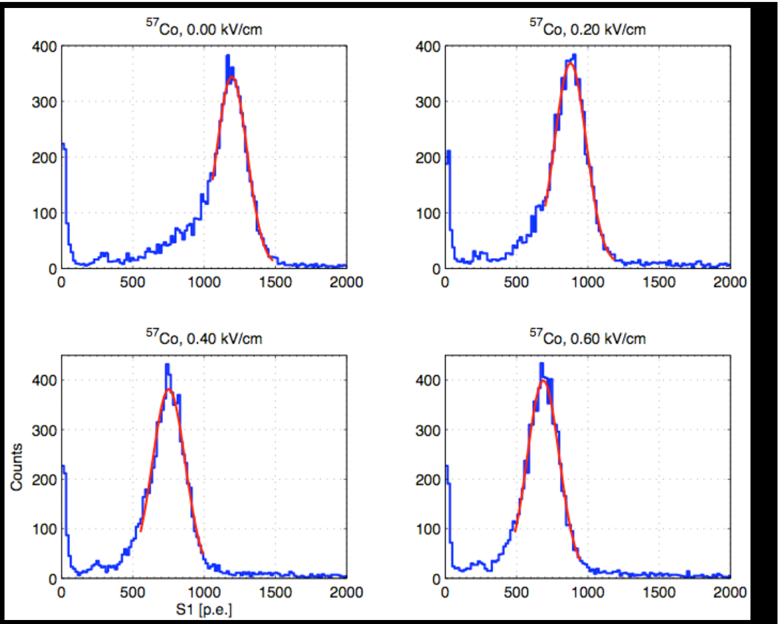
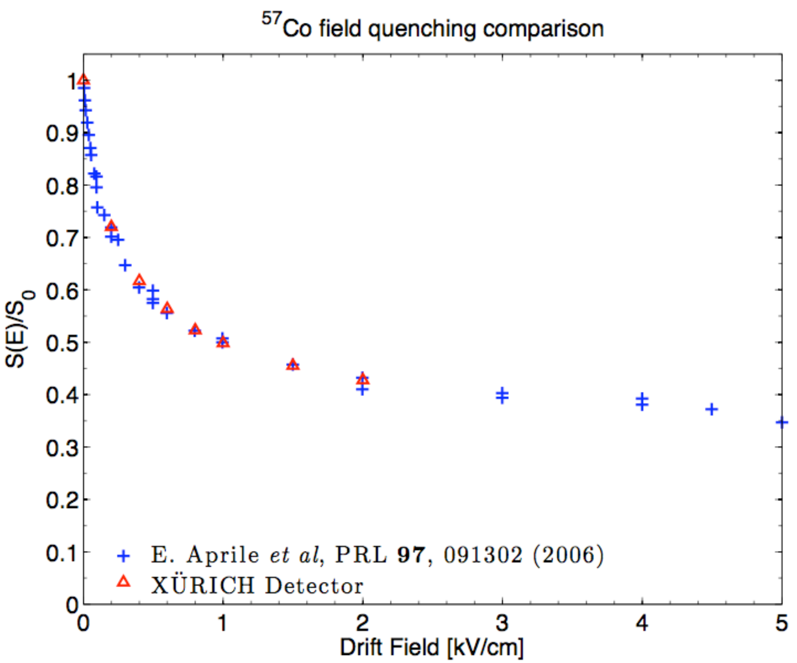
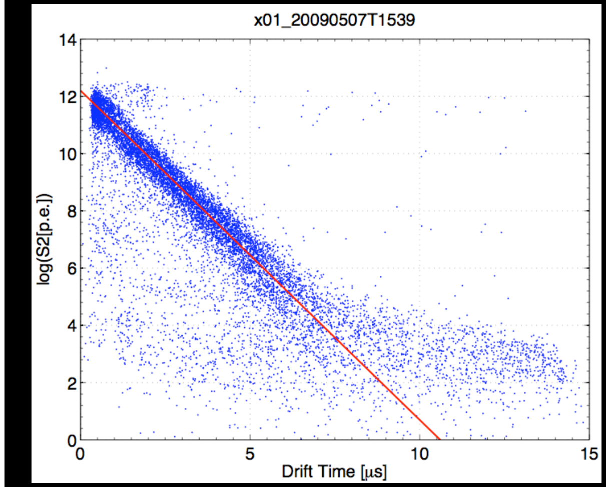
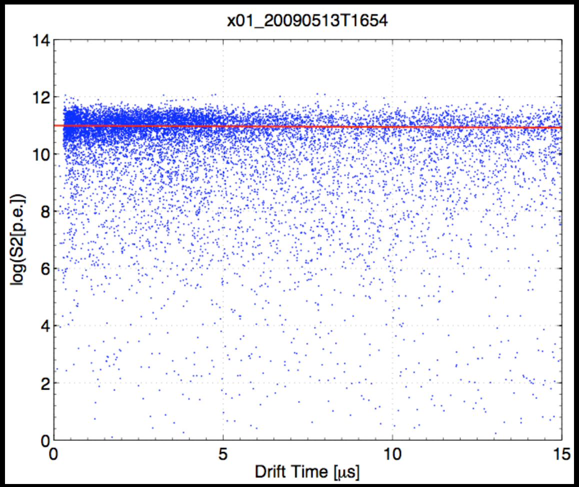


Peak position shifts lower with increasing field



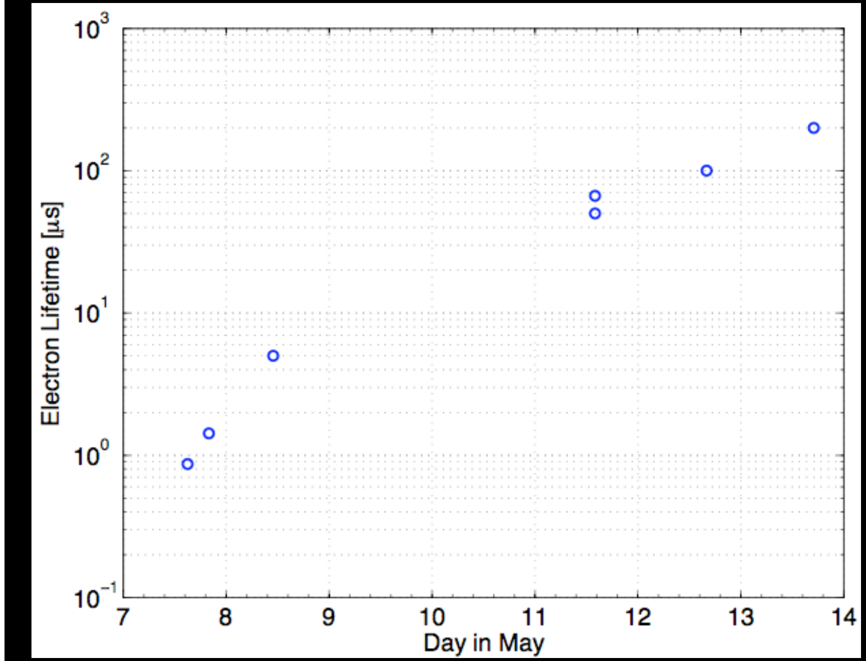
LXe purity and Electron Lifetime



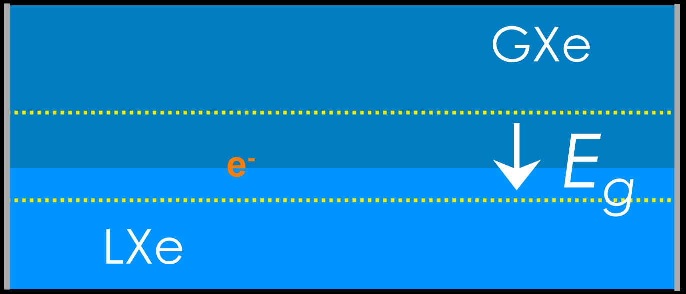


Various electronegative impurities can steal electrons as they drift through the LXe.

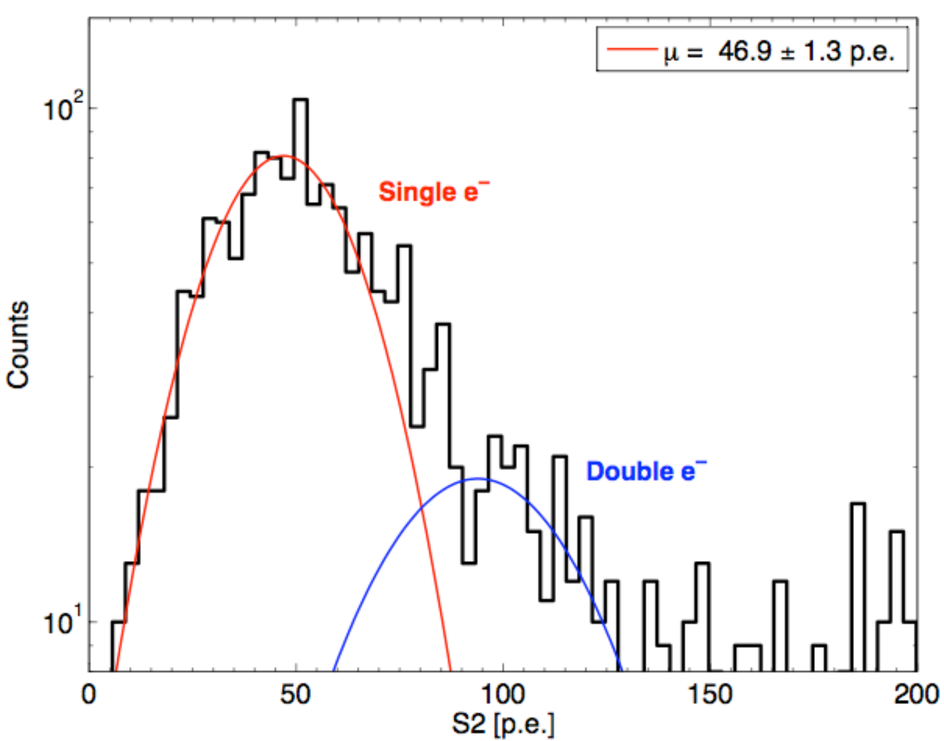
- Xe is constantly vaporized, passed through a hot getter (purifier), and recondensed.
- Electron lifetime can be monitored by looking at the S2 size from a photopeak as a function of drift time.
- With a lifetime of several 100’s of us, we suffer less than 5% charge loss over our 15 us drift.

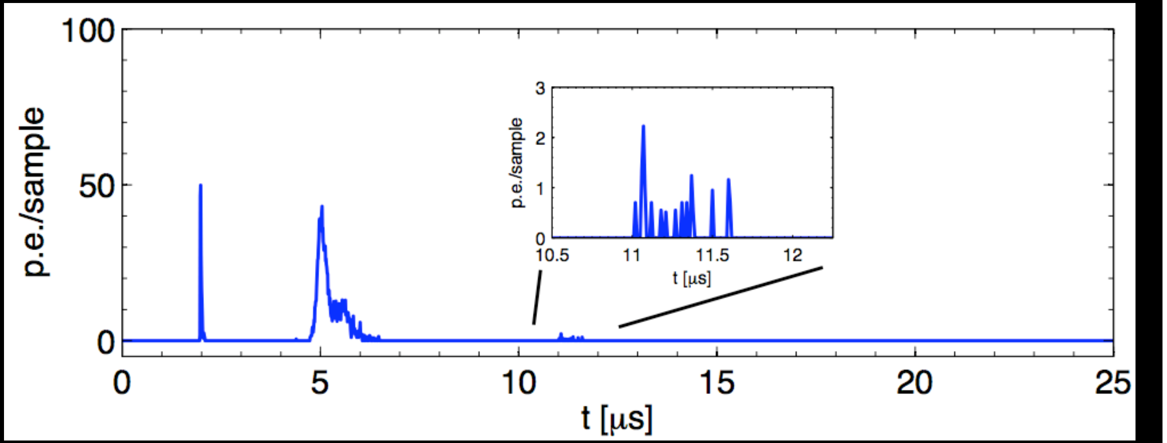


S2 Charge Amplification



The amplification of charge by proportional scintillation provides a very clean method of charge readout. One particular strength is the ability to cleanly amplify tiny amounts of charge. A phenomenon that was observed in the XENON10 detector, single electrons spontaneously evaporating off the liquid surface, is also seen in our Xürich detector. These single-electron S2 events provide a calibration of the S2 signal to an absolute quantity of charge.



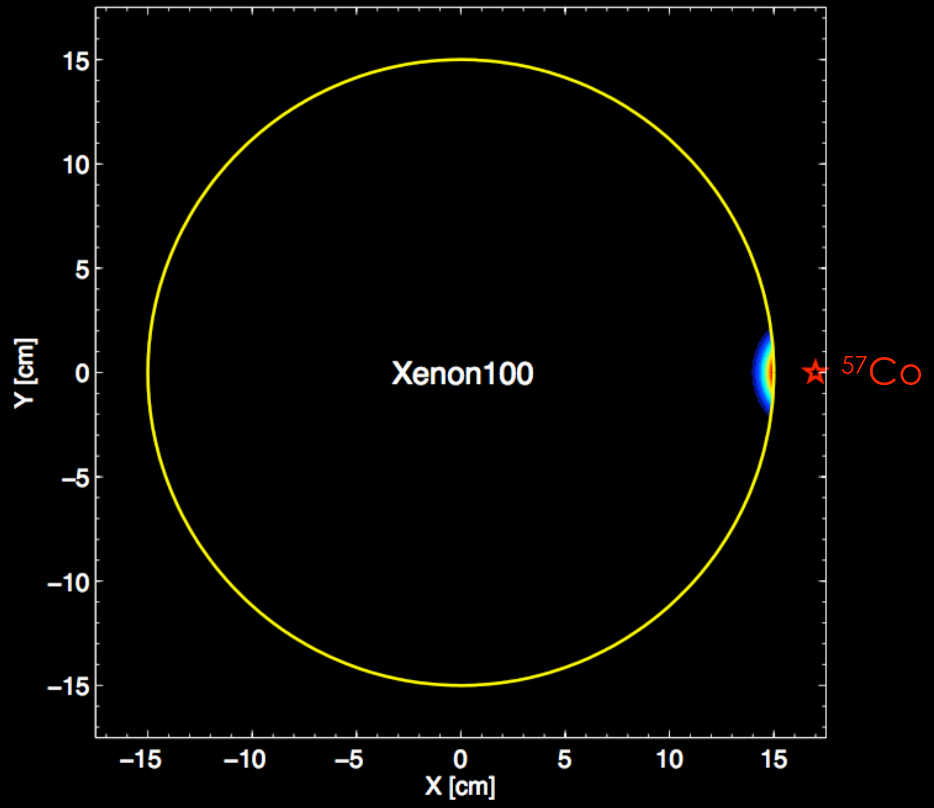


What is wrong with ^{57}Co as a calibrator?

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

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

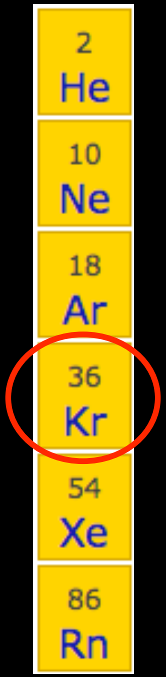
-Spatial uniformity (~2.5 mm attenuation length)



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 problem 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.



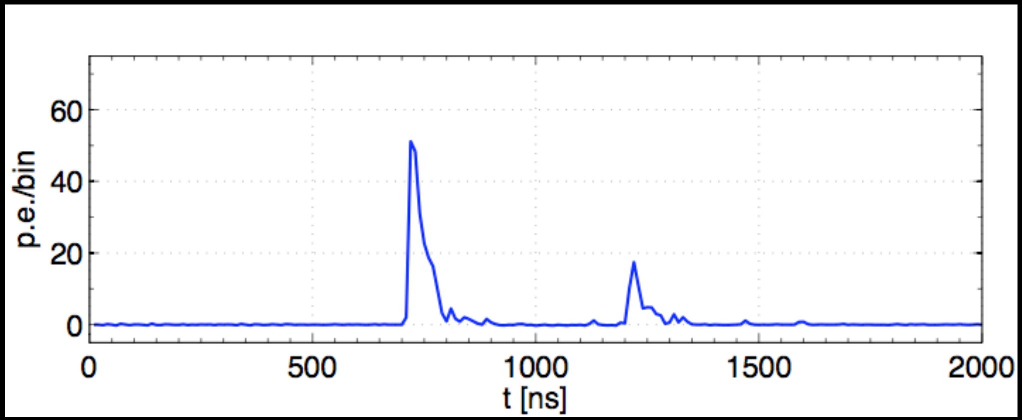
^{83m}Kr — 41.5 keV (1.83 hours)

32.1 keV

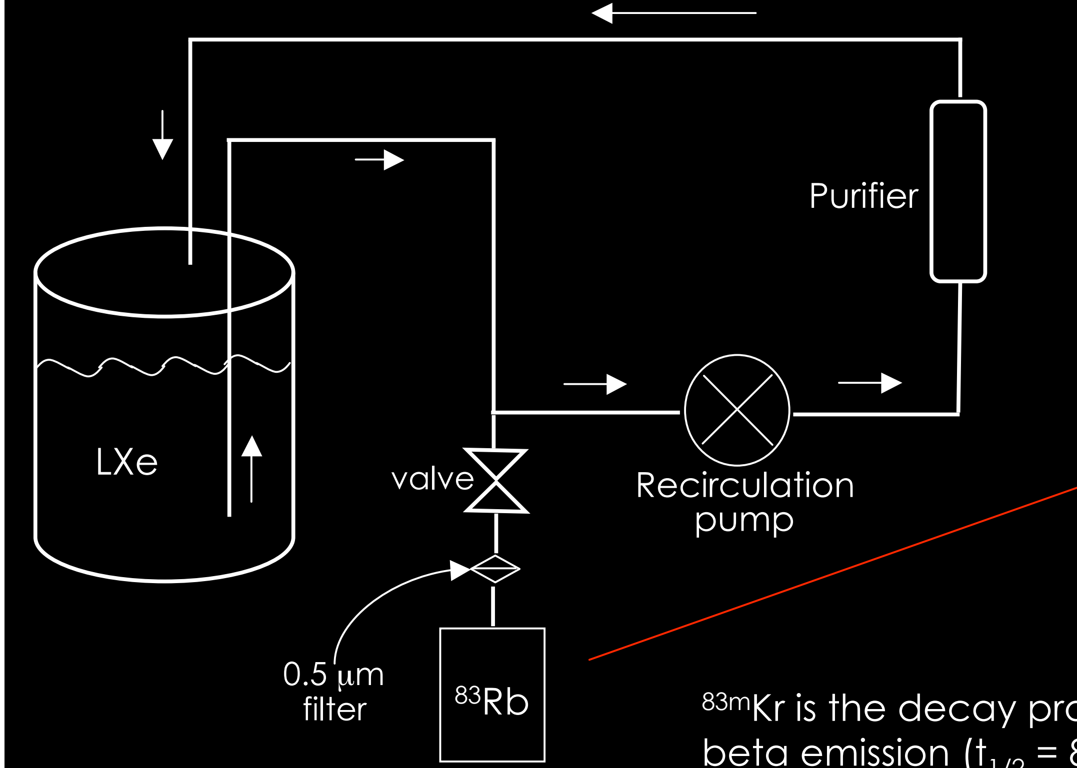
9.4 keV (154 ns)

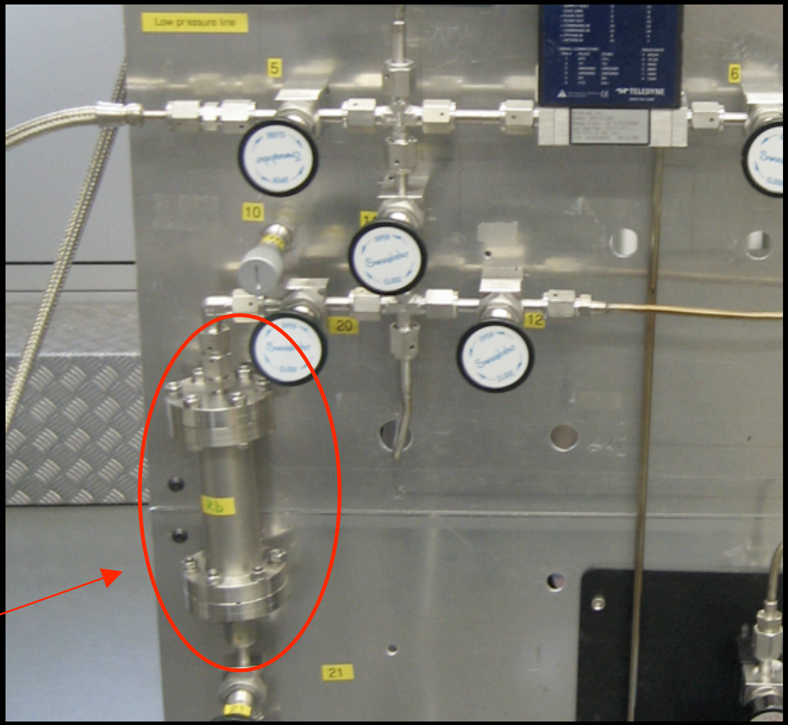
9.4 keV

^{83}Kr — ground state



Adding ^{83m}Kr to the system



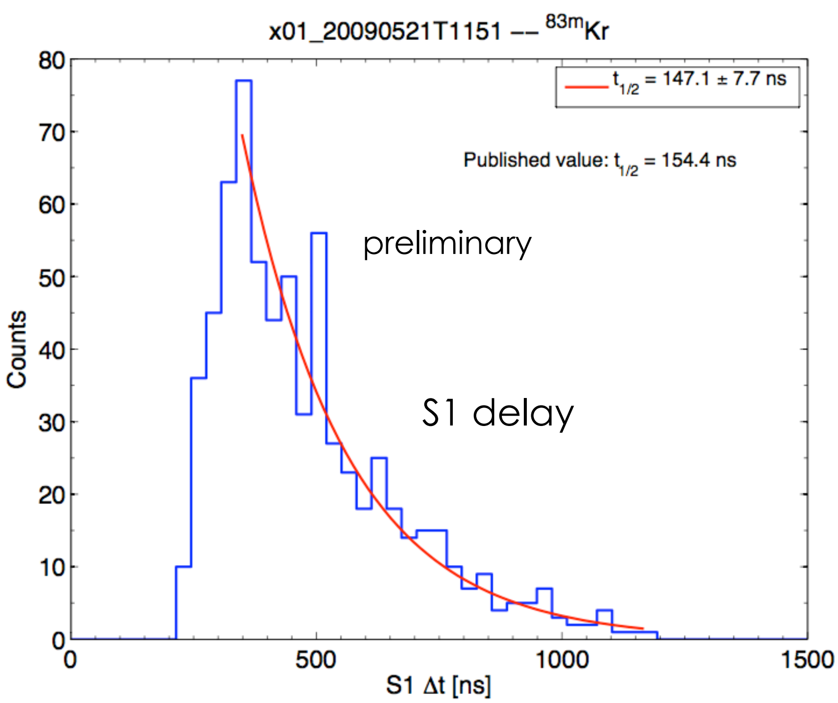


^{83m}Kr is the decay product of ^{83}Rb which decays by beta emission ($t_{1/2}$ = 86.2 days), produced by O. Lebeda at NPI, Prague. It is placed in a chamber attached to the recirculation loop. A 0.5 μm filter is placed on the Rb chamber, to prevent Rb from entering the system.

Very preliminary (~1 week old) results

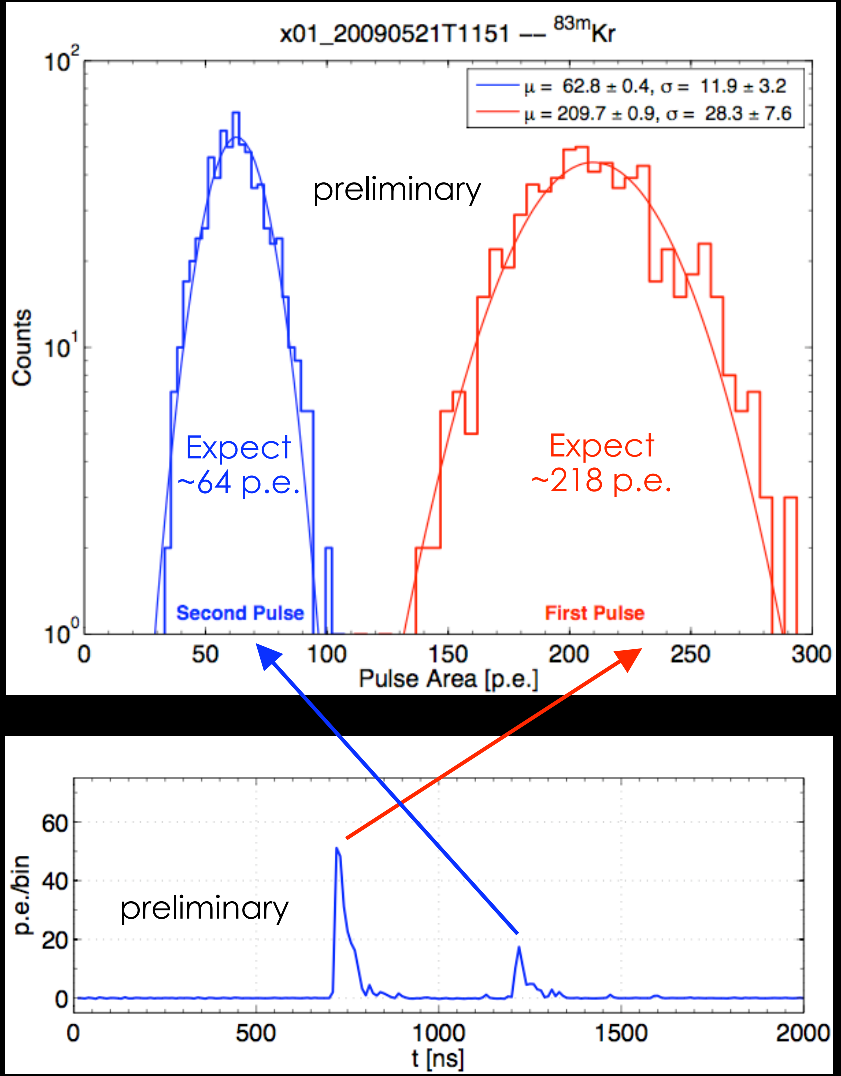
Have demonstrated that we can produce, deploy, and measure the ^{83m}Kr. For the future:

- Measure the field quenching and charge yield
- Measure the linearity of the light yield (with more stats)
- Verify that no ^{83}Rb is entering the system.



preliminary

S1 delay



preliminary

Expect ~64 p.e.

Expect ~218 p.e.

preliminary

Summary

- Difficult to understand the energy scale of WIMP interactions in LXe.
- 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.
- We have recently demonstrated the introduction and use of ^{83m}Kr in our detector. More measurements to follow soon.

Fin.