Improved understanding of liquid xenon's response in dark matter searches

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Overview

- 1-slide discussion of DM direct detection
- Problems in calibrating LXe detectors
- Measurement of L_{eff}
- Metastable 83-Krypton

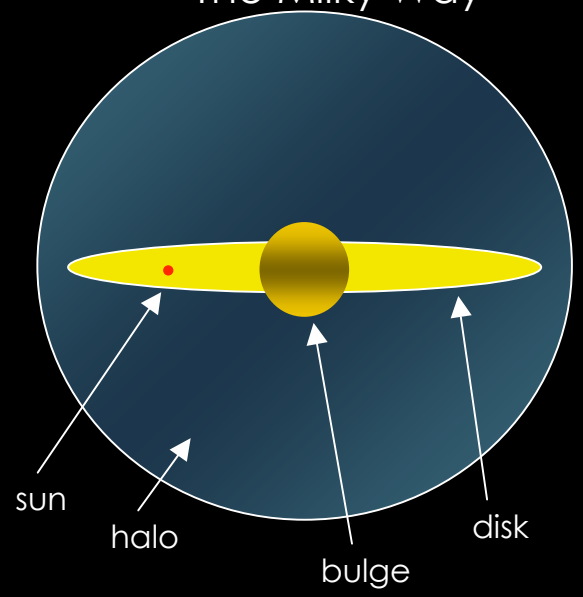
Dark Matter Direct Detection

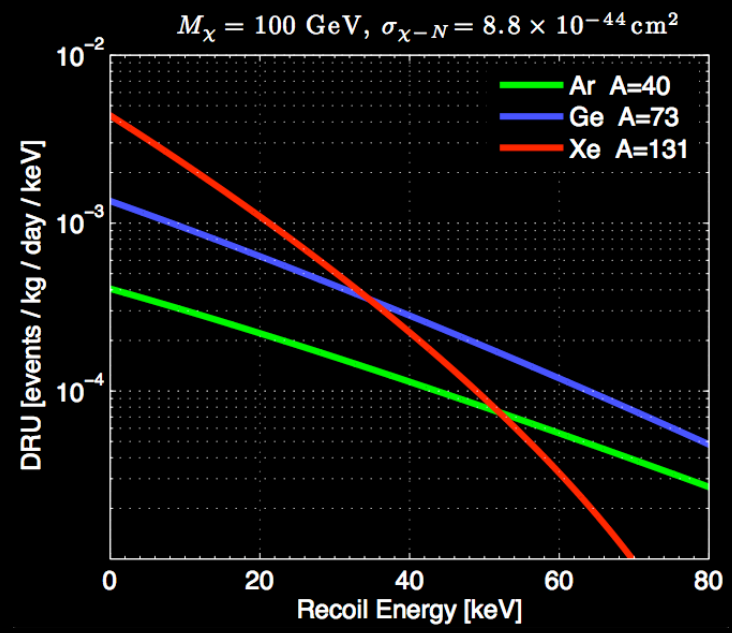
Our solar system is 'flying' through a gas of WIMPs that make up the dark matter halo. One looks for interactions between these WIMPs and [Xe, Ar, Ge, etc.] nuclei.

The 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:

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

The Milky Way



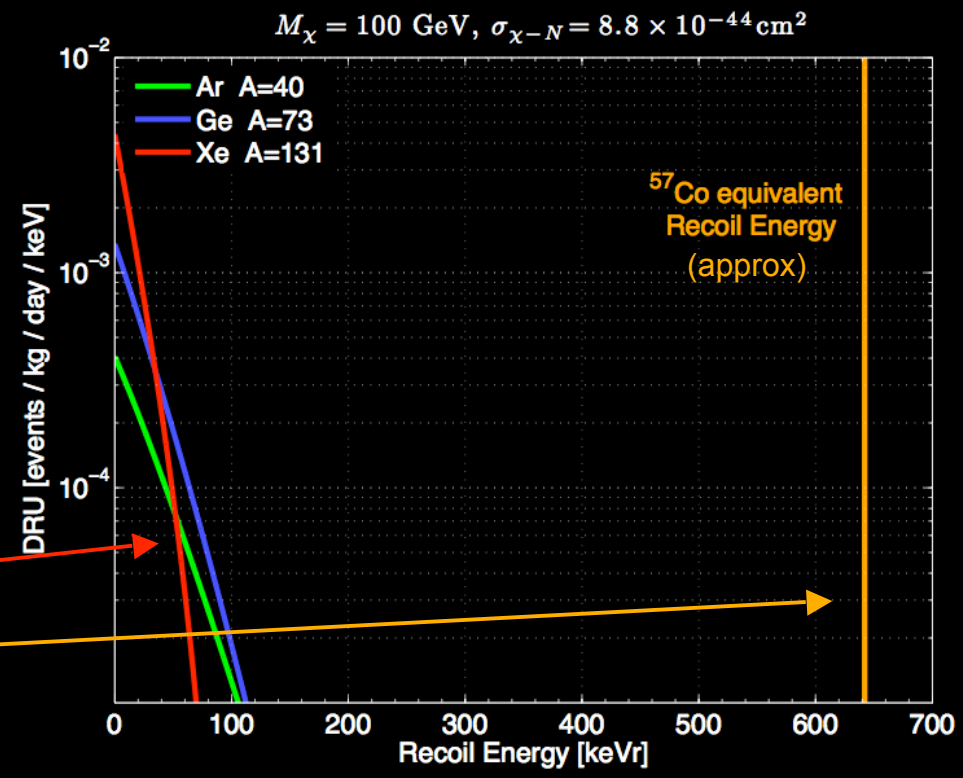


Two important questions:

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

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.

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

energy of nuclear recoil (NR)

measured signal in p.e.

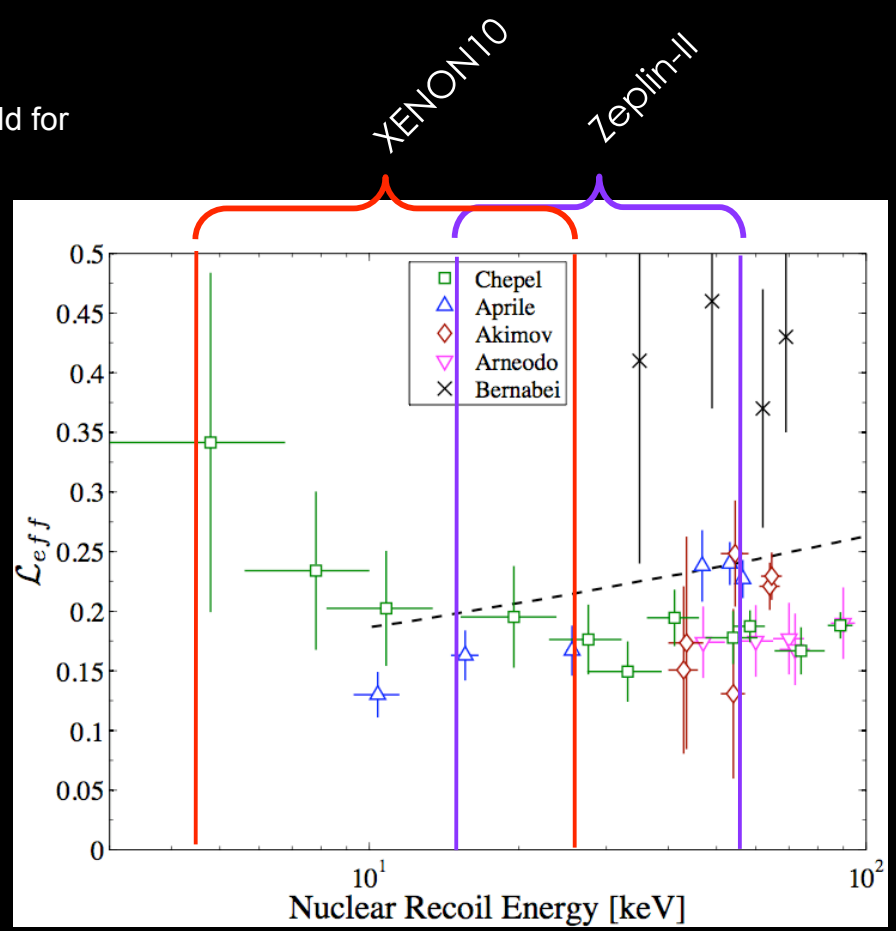
quenching of scintillation yield for 122 keV γ due to drift field

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

light yield for 122 keV γ in p.e./keV

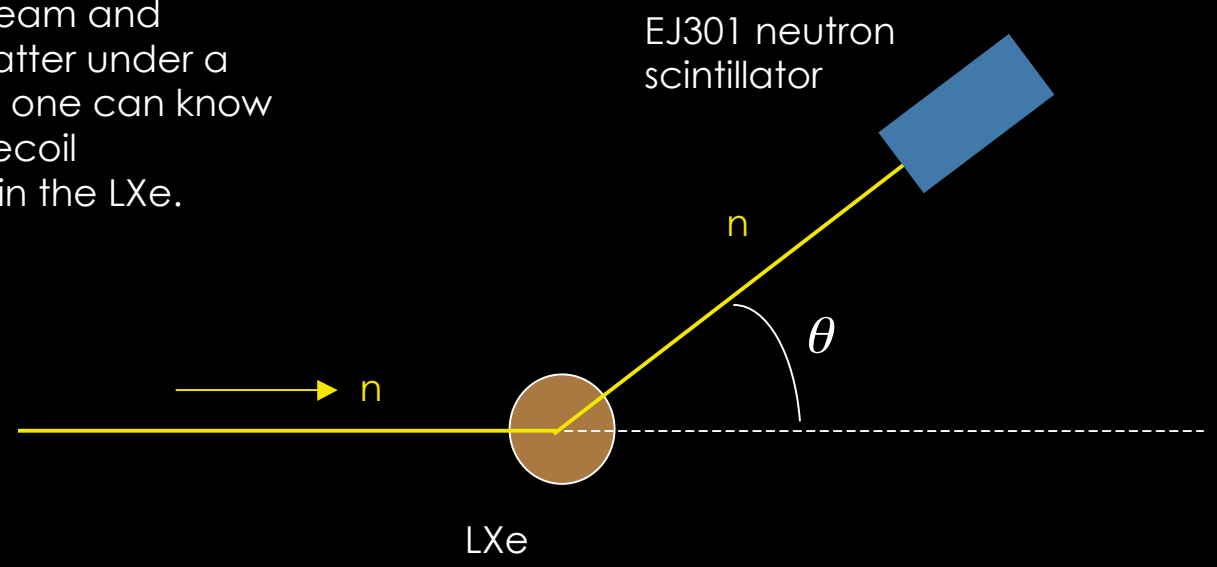
relative scintillation efficiency of NR to 122 keV γ at zero field

quenching of scintillation yield for NR due to drift field



Measurement of L_{eff}

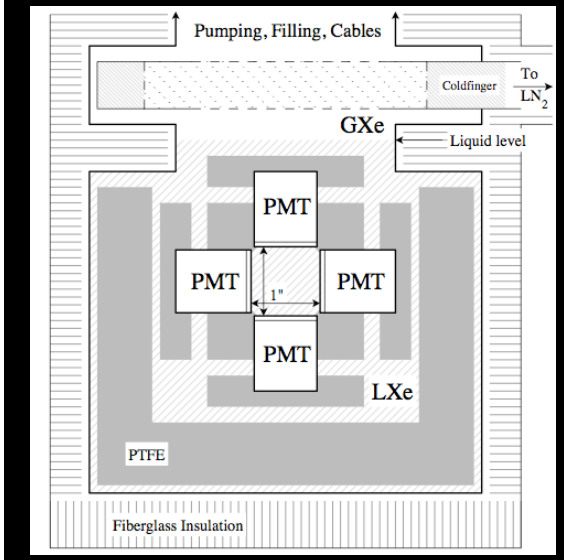
L_{eff} is measured by placing a LXe chamber in a monoenergetic neutron beam and 'tagging' neutrons which scatter under a chosen angle. By doing this, one can know the absolute energy of the recoil independent of its response in the LXe.



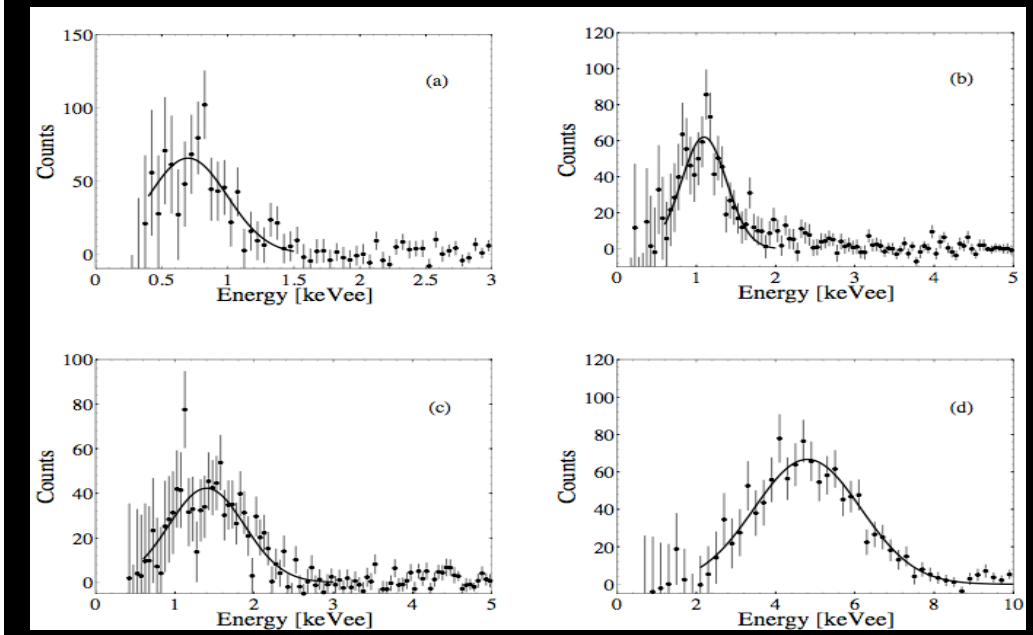
True recoil energy given by the kinematics

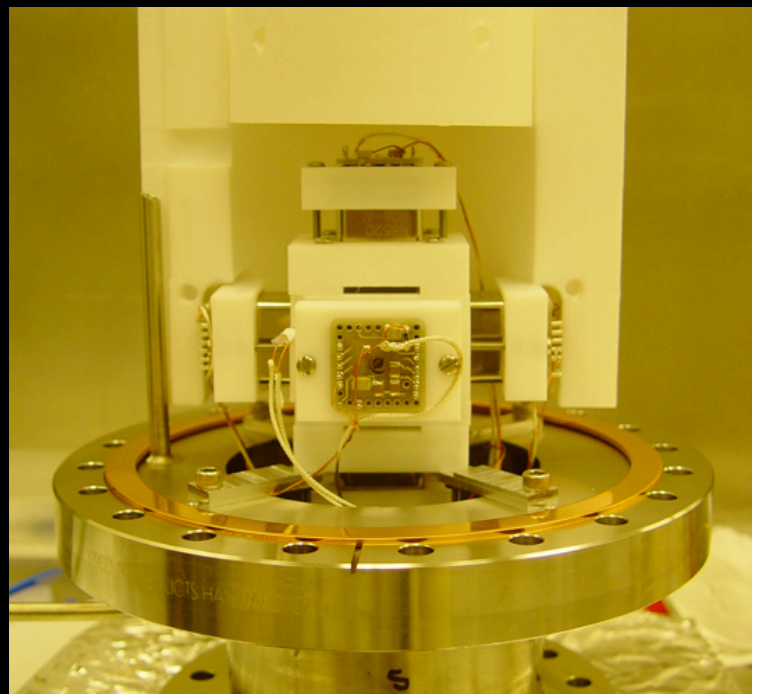
$$E_r \approx 2E_n \frac{m_n M_N}{(m_n + M_N)^2}(1 - cos\theta)$$

Measurement of L_{eff}: the XeCube detector



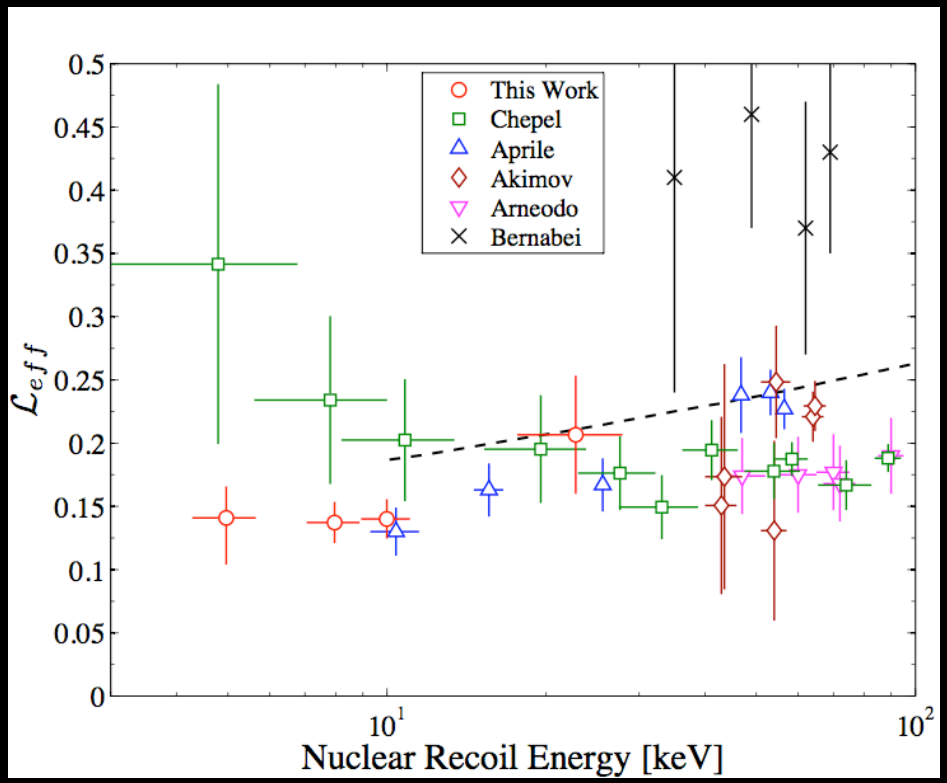
The XeCube detector was constructed specifically to measure L_{eff}. The design provides a zero-field measurement with high light collection (~20 p.e./keVee at 122 keVee), and the measurements done in collaboration with E. Aprile's group at Columbia University. The detector was placed in the neutron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

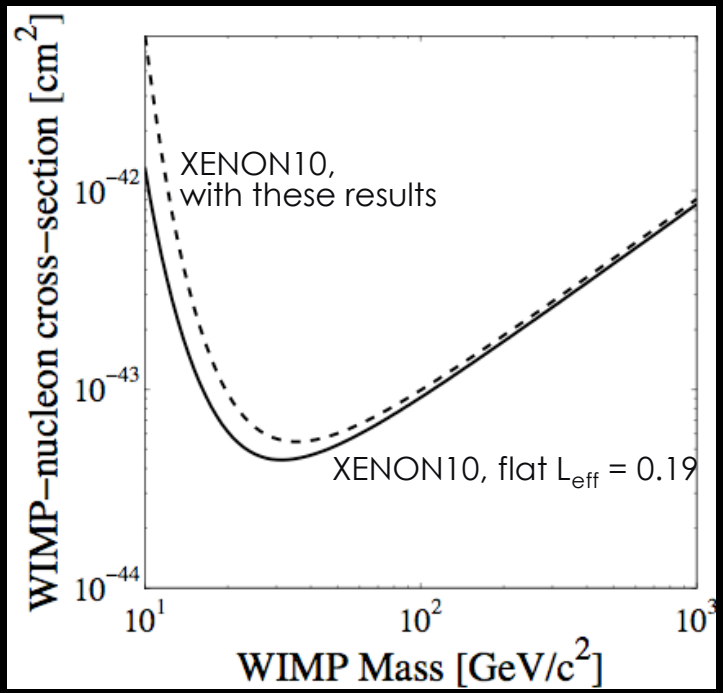




Measurement of L_{eff}

Results (see PRC) 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





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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

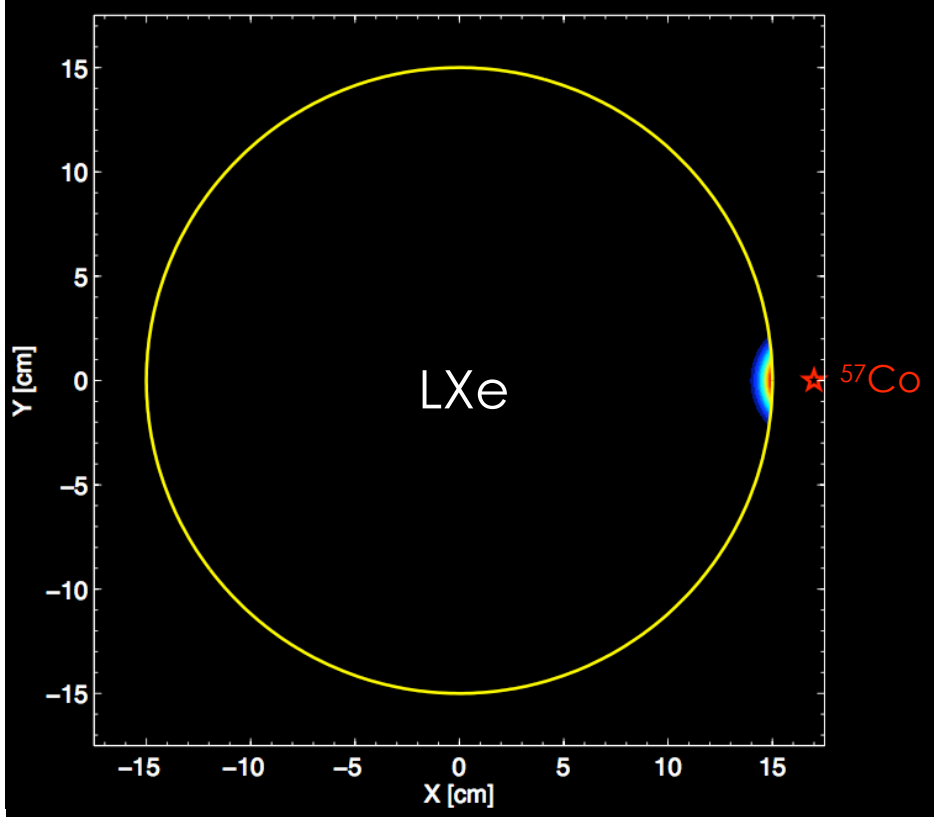
What is wrong with ^{57}Co as a calibrator?

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

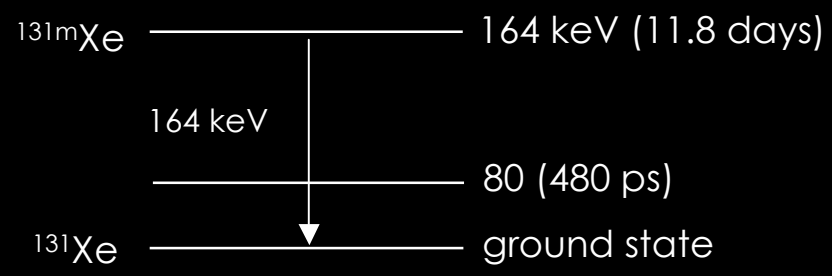
-Energy is much higher than the WIMP-search region of interest.

-Produces different interaction than WIMPs

-No spatial uniformity (~2.5 mm attenuation length)

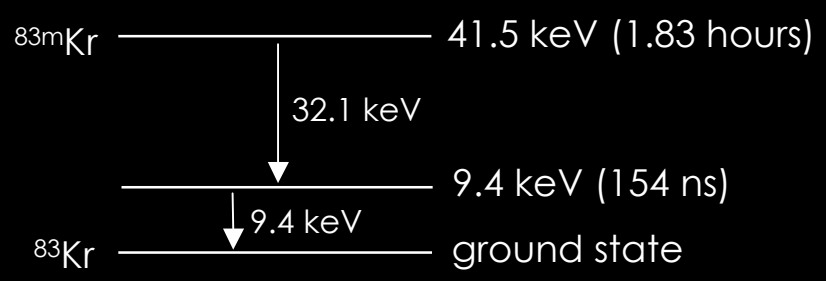


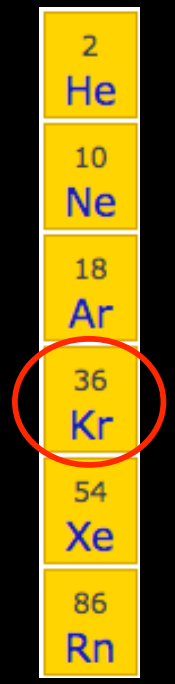
In order to have a calibration source with spatial uniformity, noble gas sources are popular. For example, ^{131m}Xe gives a 164 keV gamma/IC and lives for only 12 days. This solves the issue of spatial uniformity, but not of an appropriate energy.



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

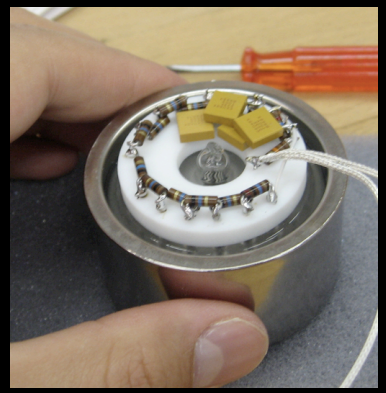
A: Yes! ^{83m}Kr has two lines, at 32 keV and 9.4 keV (low energy), and is living less than 2 hours. It is produced by the decay of ^{83}Rb.



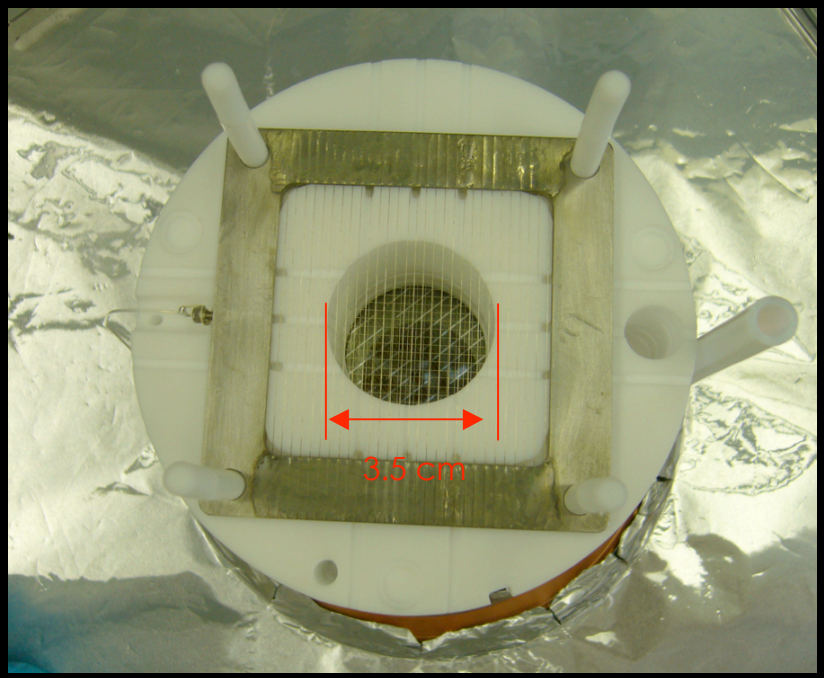


Xürich dual-phase LXe TPC at Universität Zürich

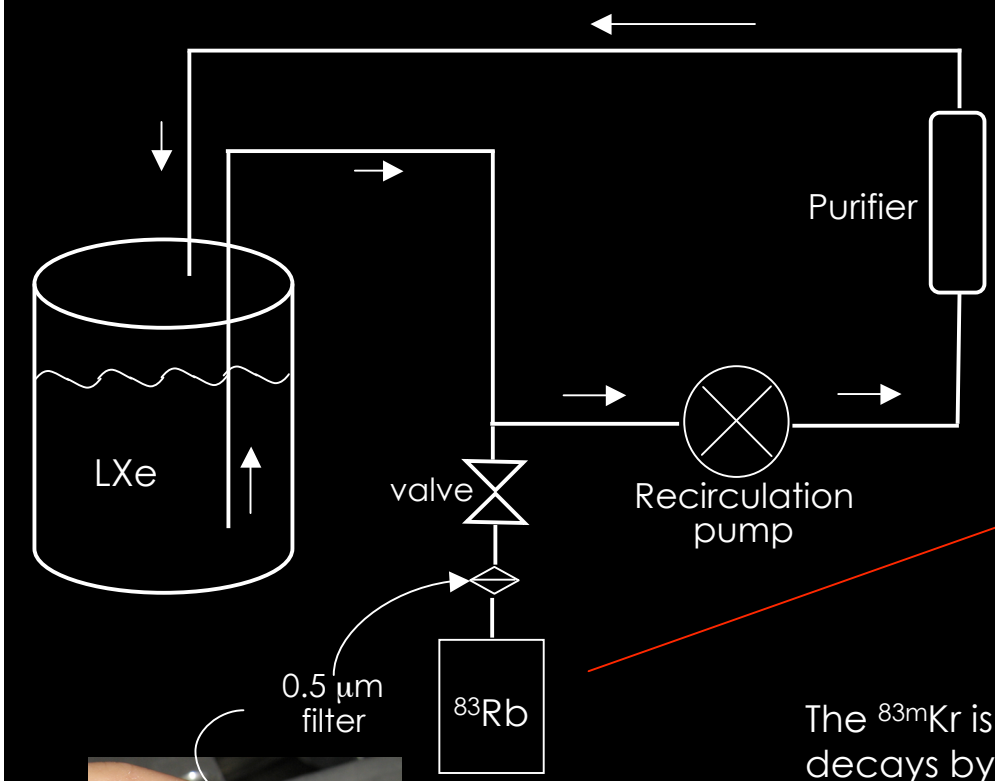
- 3 x 3.5 cm active region
- Active region defined by PTFE
- PTFE is useful because:
  - Good insulator
  - Similar dielectric constant as LXe
  - Good reflector of VUV photons
- Two-pmt design (top-bottom), Hamamatsu R9869 (2" diameter)
- Everything made in-house
- Z-position reconstruction

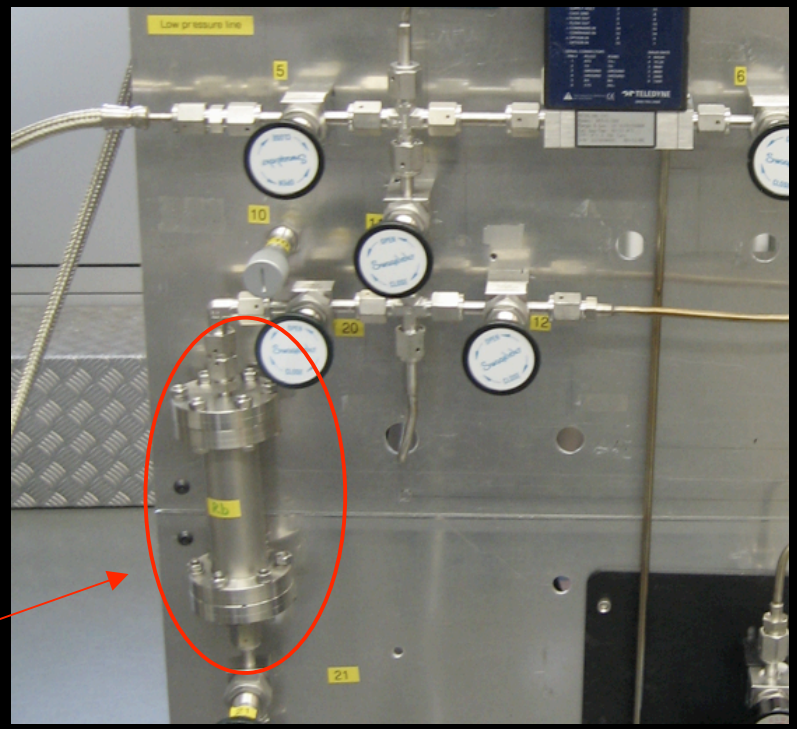


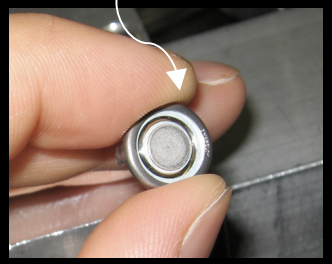
R9869 PMTs, Hamamatsu



Adding ^{83m}Kr to the system

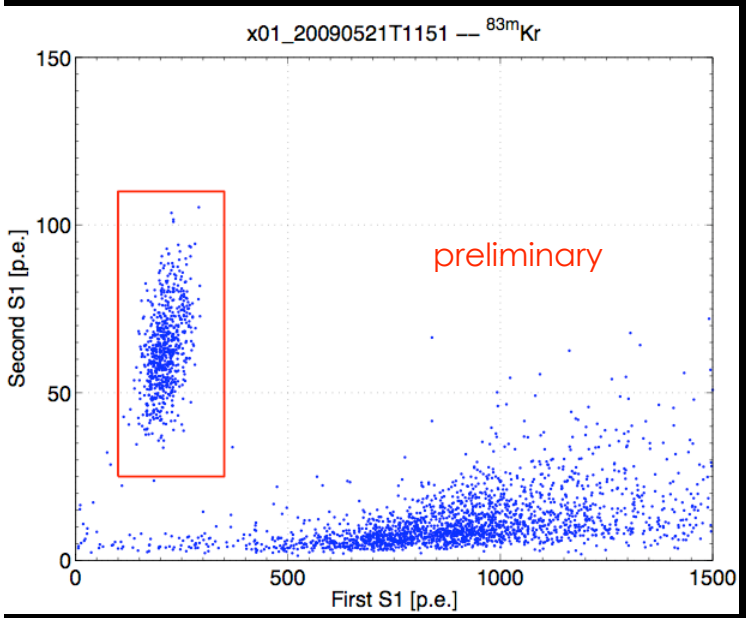


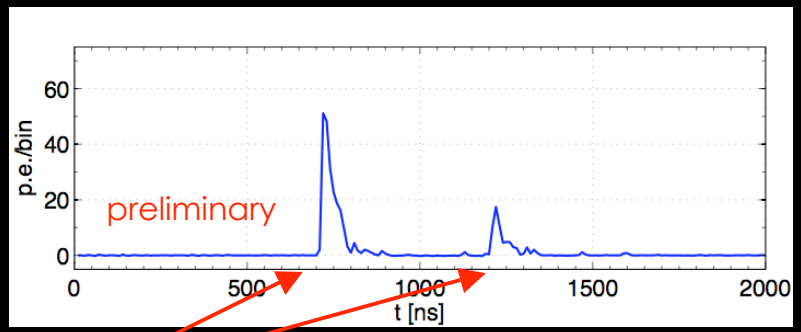




The ^{83m}Kr is the decay product of a 6 kBq ^{83}Rb which decays by EC ($t_{1/2}$ = 86.2 days), produced by O. Lebeda at NPI, Prague and deposited into zeolite ceramic beads. It is placed in a chamber attached to the recirculation loop. A 0.5 μm filter is placed on the Rb chamber, to prevent Rb aerosols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

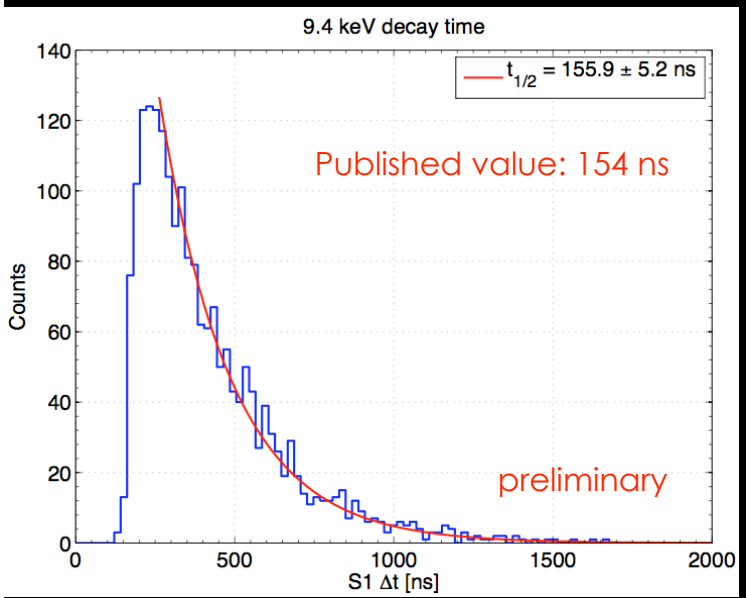
Preliminary results

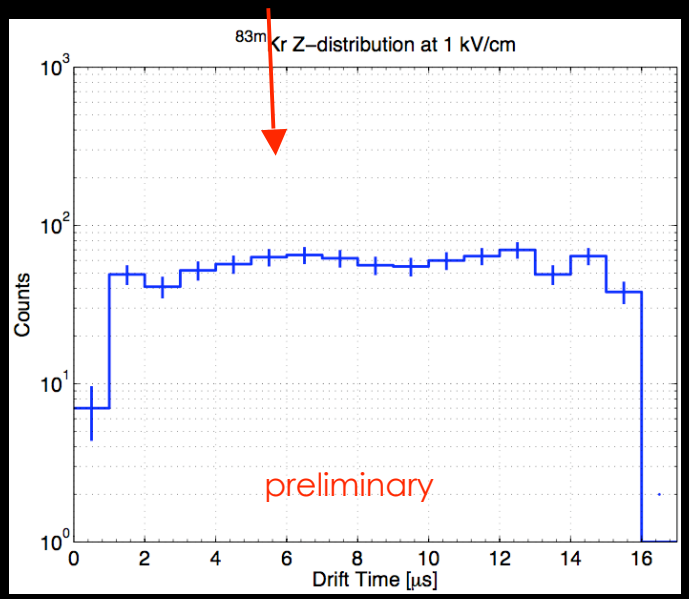




The double pulse signature of 83mKr decay provides a ready way to identify these events.

The dual-phase detector allows measurement of the Z-position of the events, confirming this is a spatially-uniform source.

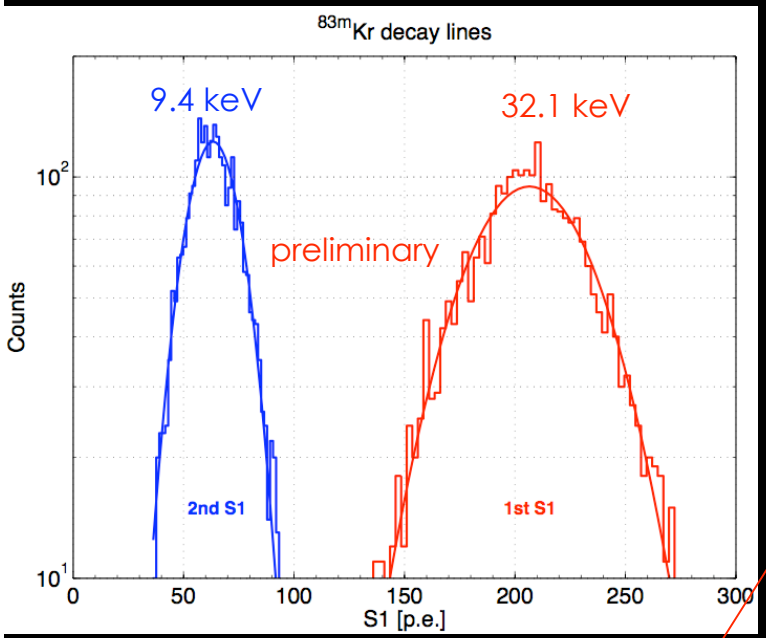


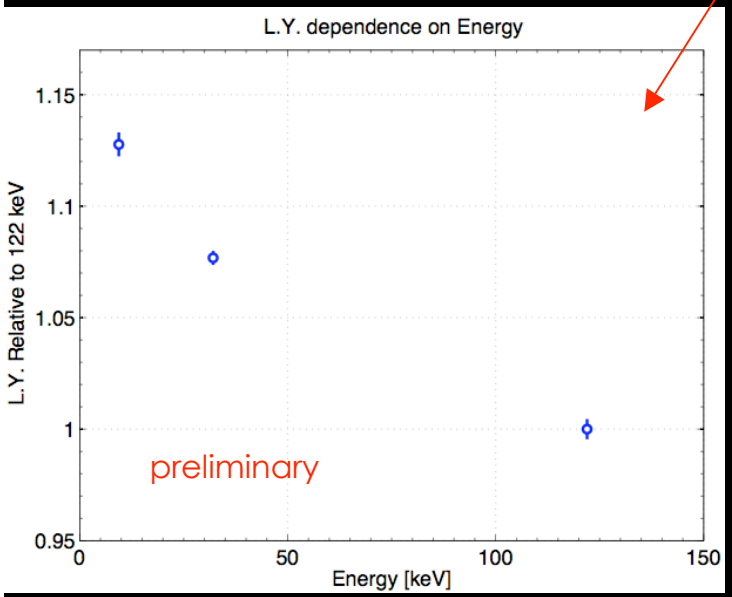


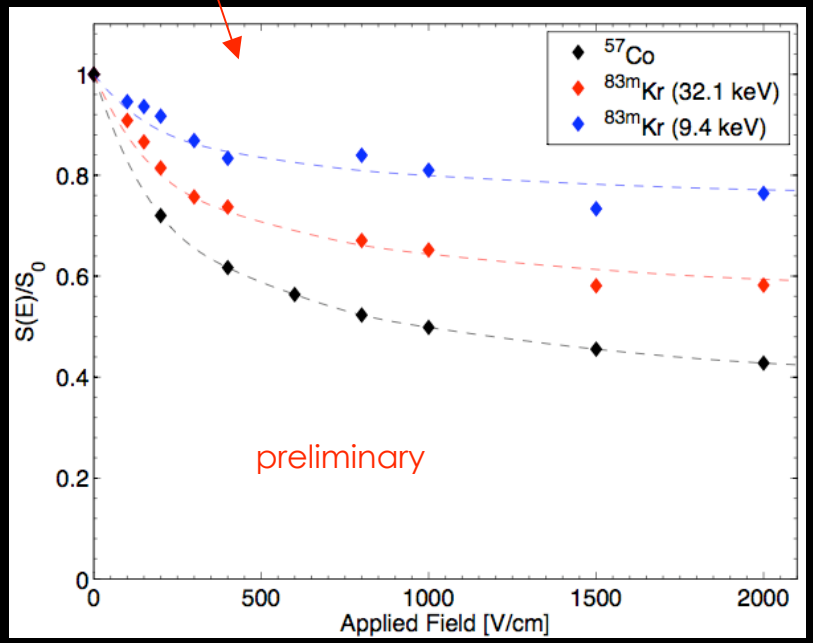
See also L. W. Kastens *et al*, arXiv:0905.1766 [physics.ins-det], done in parallel with these measurements, with a single-phase detector.

Preliminary results

The double-pulse events readily give very clear spectra of the two transitions. These peaks can be used to determine the linearity of the scintillation energy scale, and also to investigate the electric field quenching at these energies.

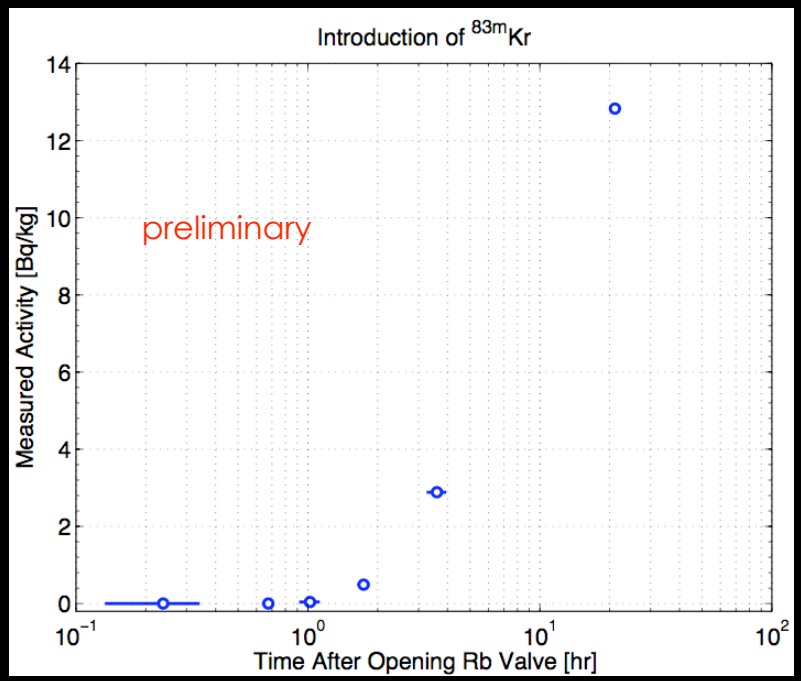




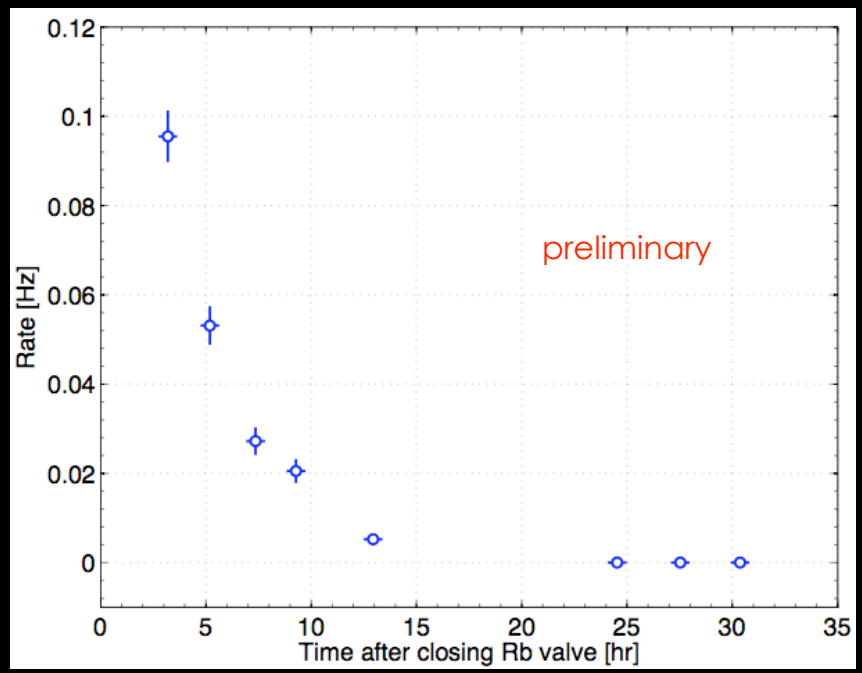


Diffusion rates, decay, and residual ^{83}Rb

The diffusion of ^{83m}Kr into the liquid from the Rb chamber is on the time scale of 5-10 hours, most likely dominated by the diffusion of Kr from the gas into the liquid.



Does an Rubidium enter the system? Our measurement of the ^{83m}Kr decay allows us to set an upper limit of <10 mBq/kg (90% C.L.) residual Rb. This is consistent with D. Venos *et al*, App. Rad. and Isotopes **62**, 323 (2005) measurement of Rb release from zeolite. Some of the residual 83Rb will be easily cut (eff ~ 35%) by rejecting multiple S1 events.



Summary

- Difficult to understand the energy scale of WIMP interactions in LXe. A new measurement of L_{eff} has been completed, which helps to understand LXe's response in this regime.
- 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.
- ^{83m}Kr has been introduced and its lines observed, with no measured Rb contamination.

Fin.