Mirror Dark Matter Search with LUX Electron Recoil Data

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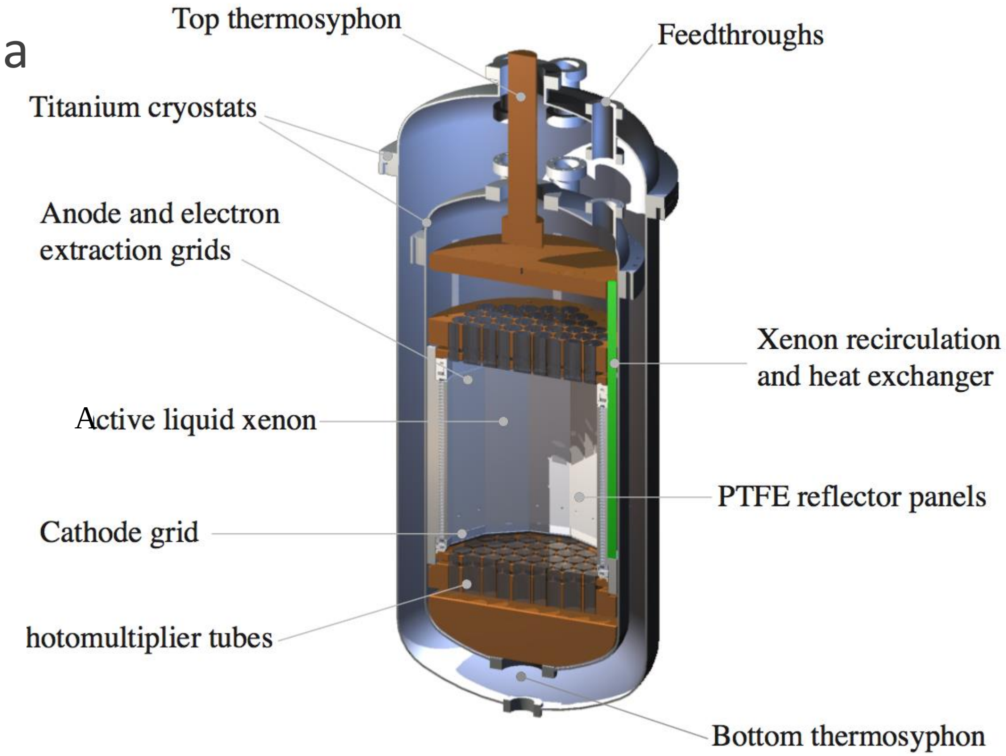
Outline

1. **LUX**
   - LUX experiment
   - LUX data
   - Electron recoil signal
2. **Mirror Dark Matter**
   - Theory
   - Signal model and detection
3. **Analysis**
   - Analysis overview
   - Outlook

The LUX Experiment

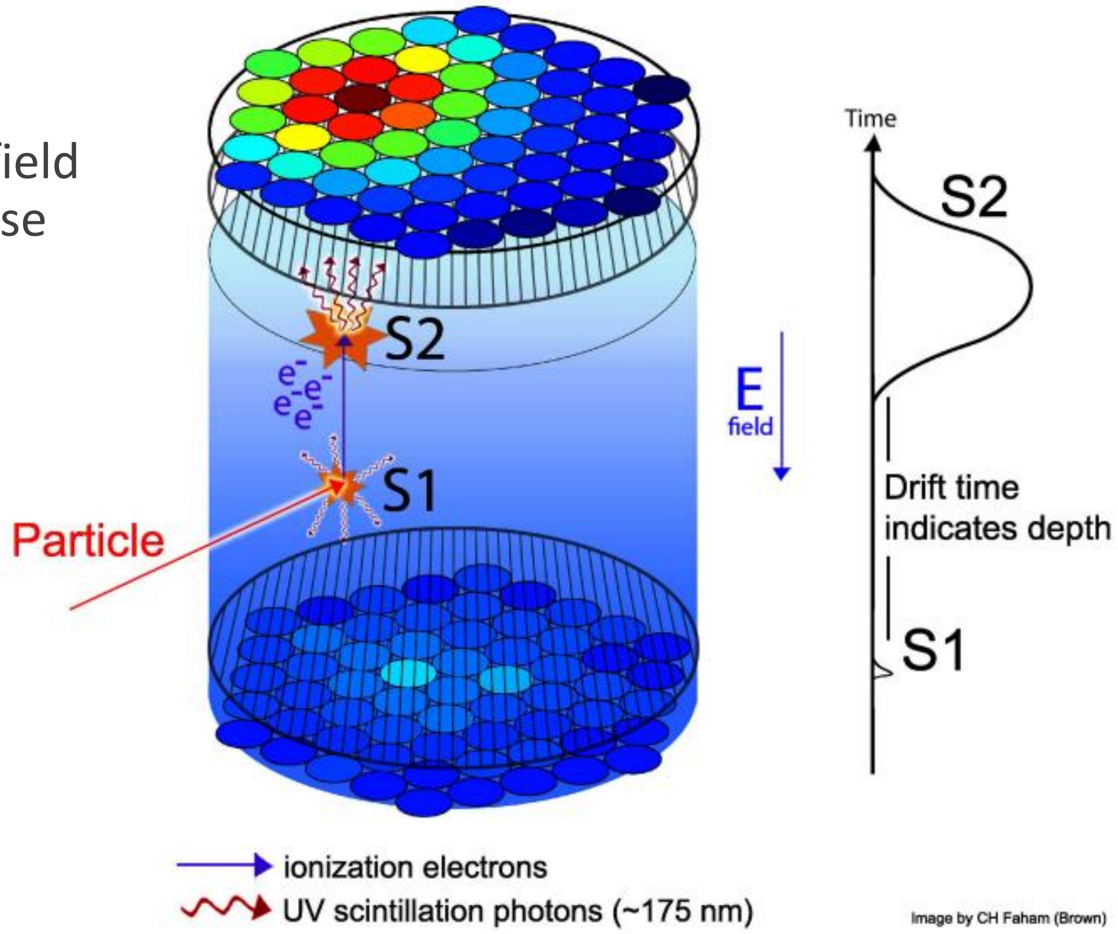
- 4850ft underground at Stanford Underground Research Facility
- 370kg xenon, 250kg active mass
- Dual phase time projection chamber – layers of gaseous a liquid xenon, with vertical electric field applied



The Large Underground Xenon (LUX) Experiment

LUX Data

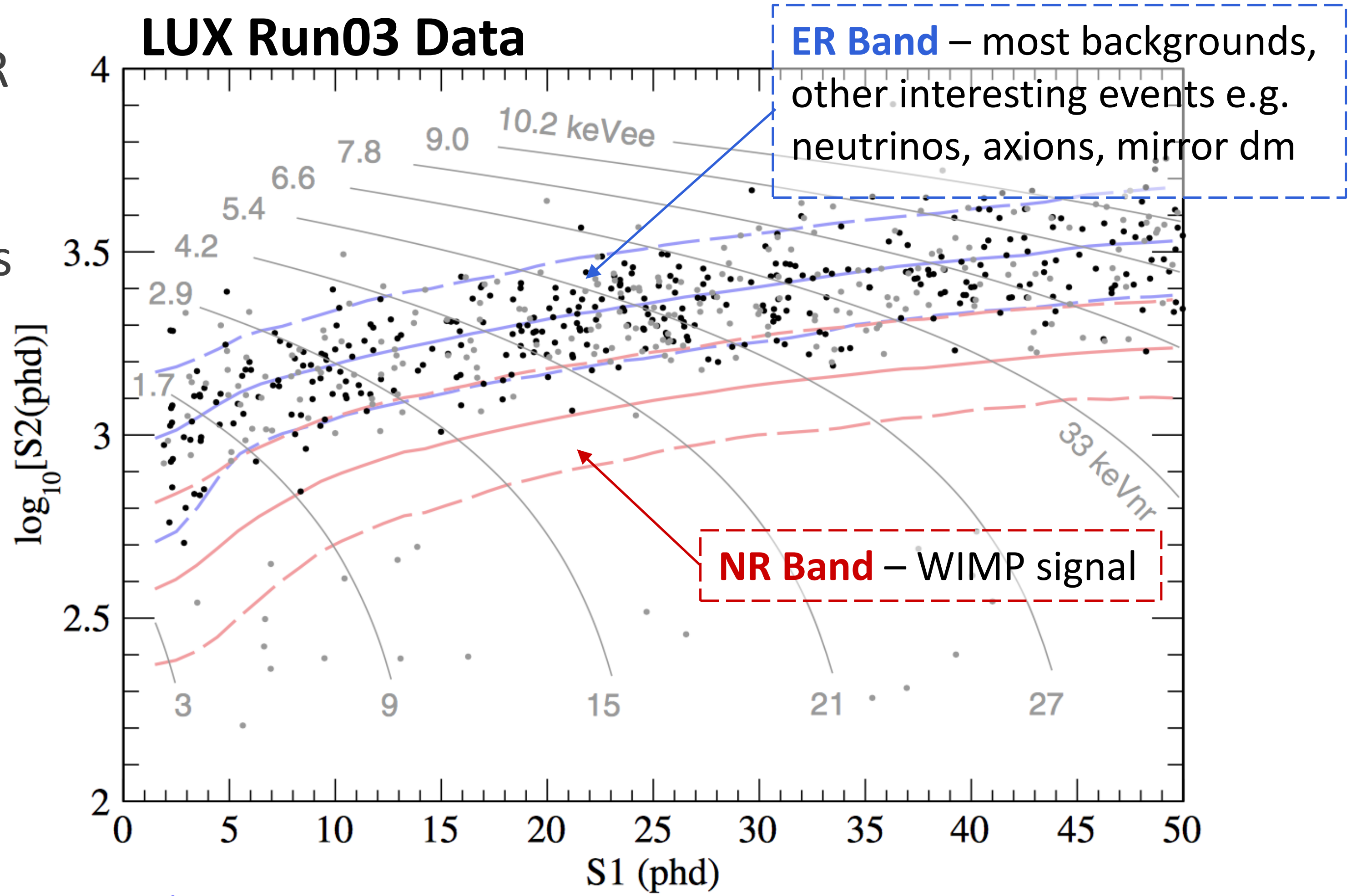
- Particle interaction with Xe atom produces:
  - scintillation light (**S1**)
  - ionization electrons - drifted vertically by electric field and produce electroluminescence signal in gas phase (**S2**)
- x, y from S2 position
- Depth, z, from drift time between S1 and S2



Electron Recoil Signal

- WIMP signal: Nuclear Recoil, NR
- Also have: Electron Recoil, ER
- ER band search more difficult as it contains all the backgrounds

LUX Run03 Data

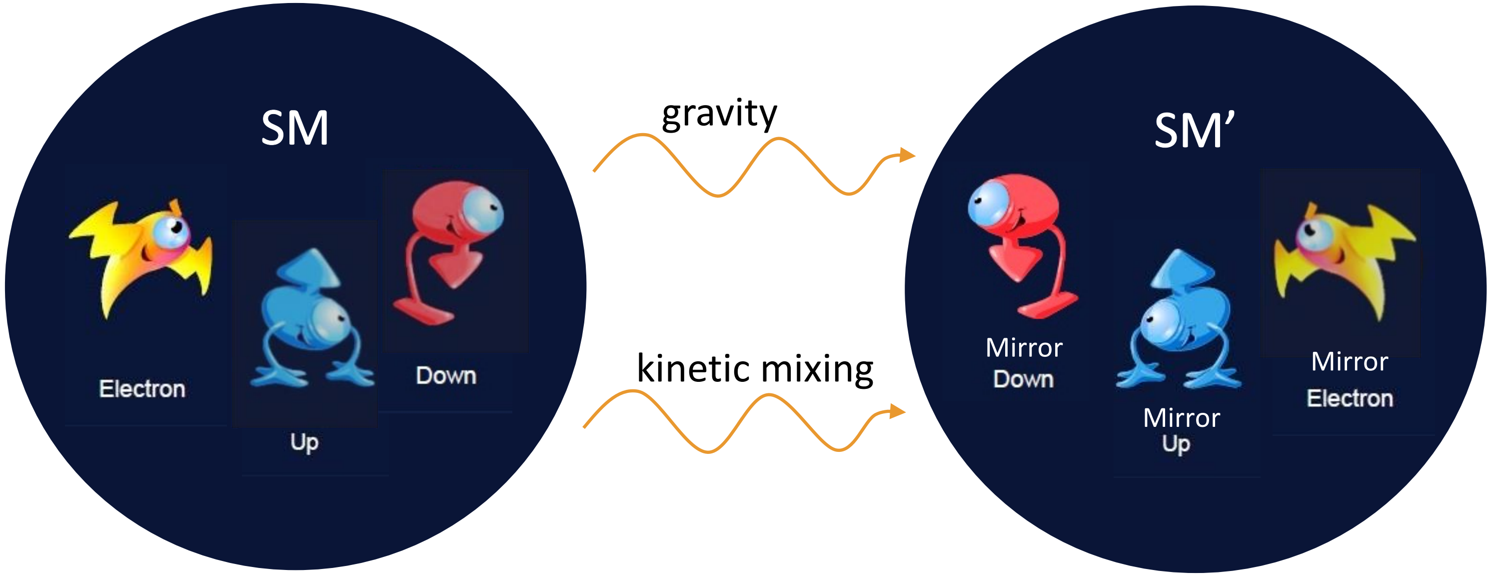


PhysRevLett.116.161301

Mirror Dark Matter

- Hidden sector dark matter (does not interact via SM gauge boson forces), with hidden sector isomorphic to SM.
- Mirror sector contains mirror version of each SM particle; with same masses, lifetimes and self-interactions.
- Mirror dark matter forms a multi-component plasma halo.
- Lagrangian: $\mathcal{L} = \mathcal{L}_{SM}(e, u, d, \gamma, W, Z, ...) + \mathcal{L}_{SM}(e', u', d', \gamma', W', Z', ...) + \mathcal{L}_{mix}$

R.Foot, IntJModPhysA.29.1430013,
J.Feng, JCAP 0907:004



Symmetry allows two interactions:

$$\mathcal{L}_{mix} = \frac{\epsilon}{2} F^{\mu\nu} F'_{\mu\nu} + \lambda \phi^{\dagger} \phi \phi'^{\dagger} \phi'$$

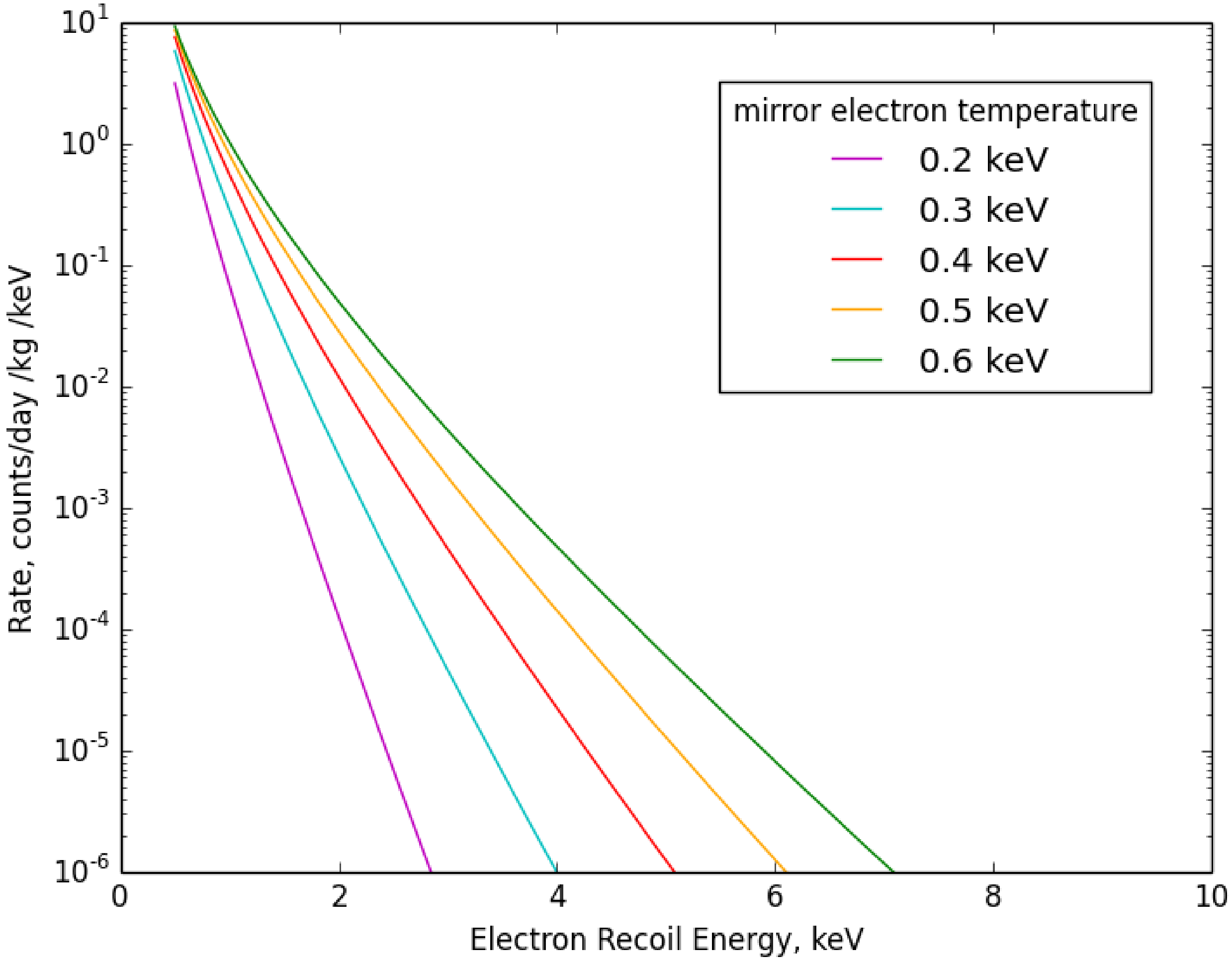
$\gamma - \gamma'$ kinetic mixing allows interaction with $\pm\epsilon e$ effective charge

ϵ = kinetic mixing term

Theory to Detection

- Kinetic mixing term allows electromagnetic interactions with effective charge $\pm\epsilon e$
- Mirror electrons scatter off atomic electron in xenon – ER event
- Rate depends on ϵ and local mirror electron temperature, T
- Theoretical limit from astrophysics and cosmology: $10^{-11} \lesssim \epsilon \lesssim 4 \times 10^{-10}$

  J.Clarke R.Foot, PhysLettB.2016.12.047
- Signal model uncertain below 1keV due to atomic effects.



Mirror DM electron recoil spectrum, for $\epsilon = 10^{-10}$

Analysis

Use same framework as LUX axion analysis [PRL.118.261301]:

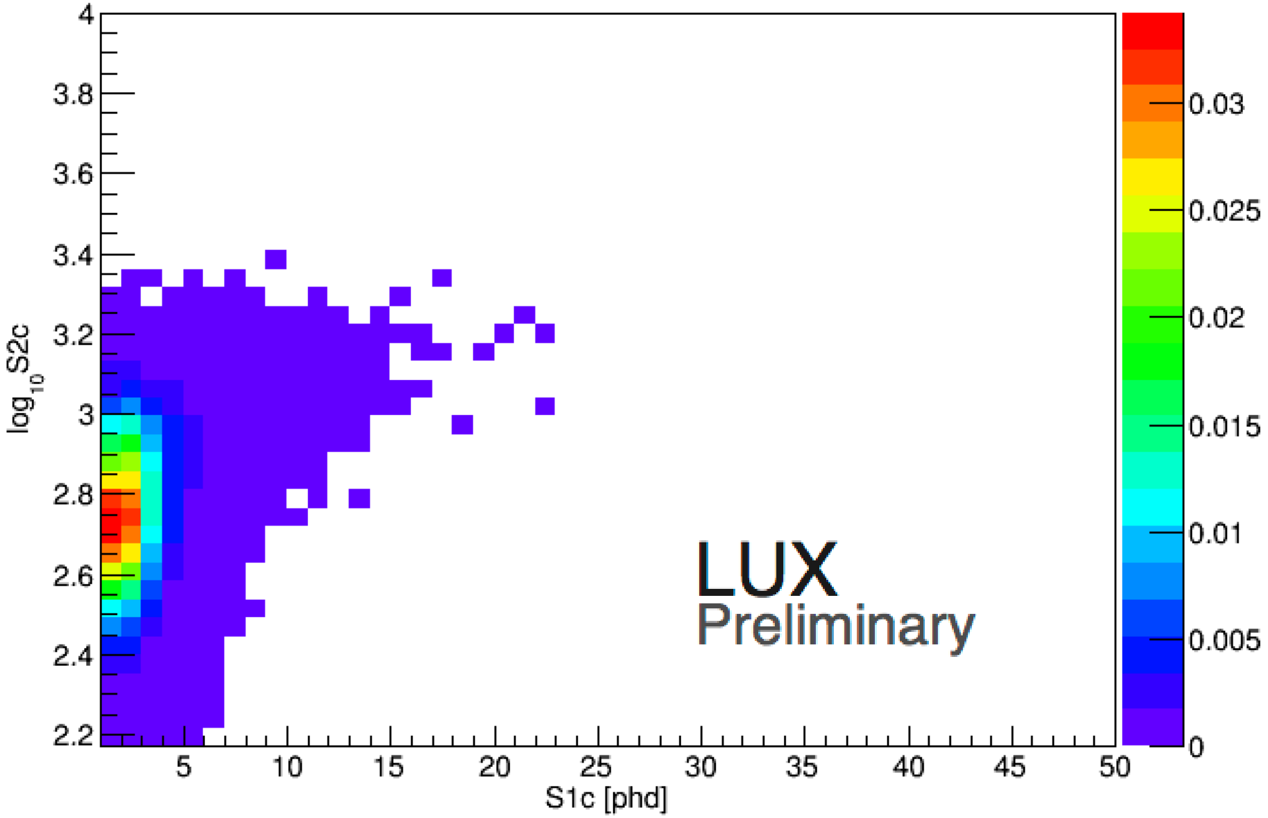
1. Make signal model – ER energy spectrum with arbitrary ϵ
2. Simulate energy deposition in detector: E, x, y, z
3. Convert to detector observables: S1, S2, r, z (4D pdf)
4. Statistical test – Profile Likelihood Ratio (PLR), find 90% confidence limit (CL) on number of signal events and use to find limit on ϵ

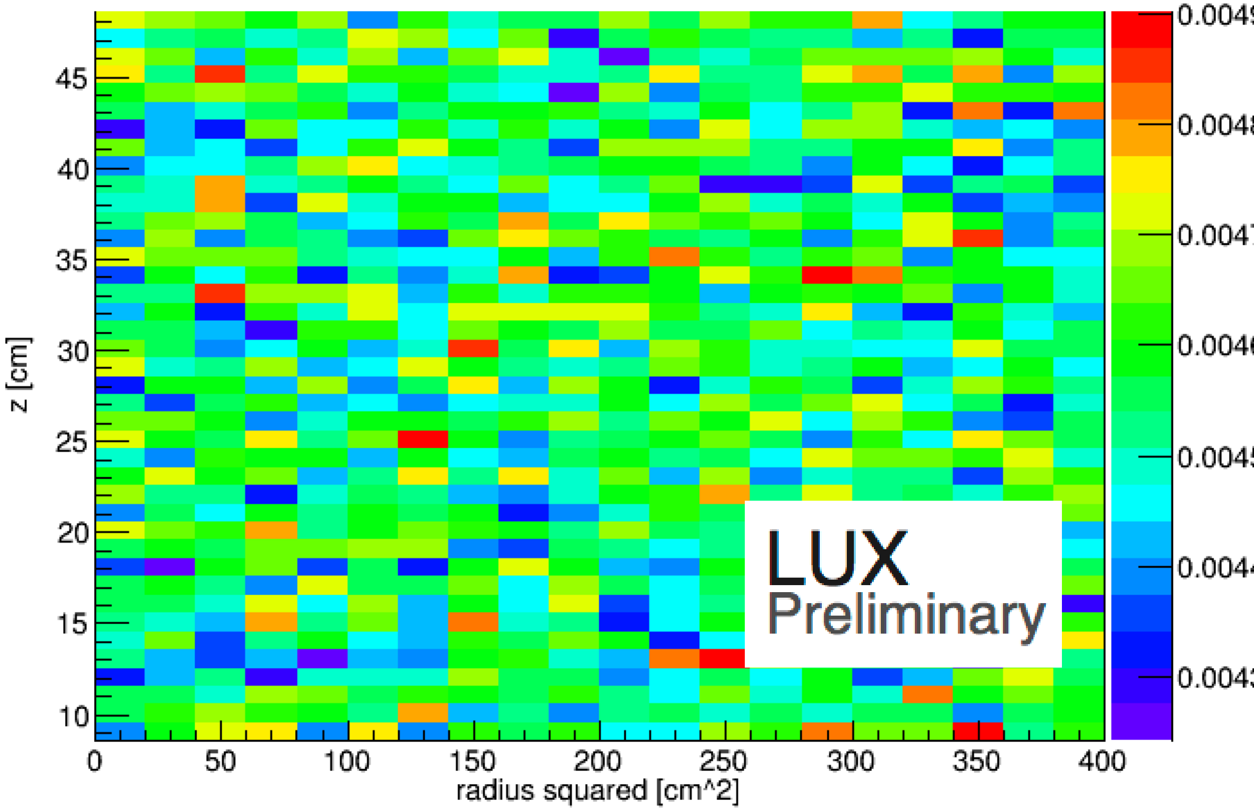
Analysis Details

- Use LUX Run03 data taken 24th April – 1st September 2013, 95 days × 118kg fiducial mass.
- Cross section calculation [J.Clarke R.Foot, JCAP01(2016)029] assumes atomic electron is stationary relative to incoming mirror electron - 1keV threshold for electron recoil energy.
- PLR result, 90% CL number of signal events, must be scaled to find 90% CL on ϵ.

Signal Model

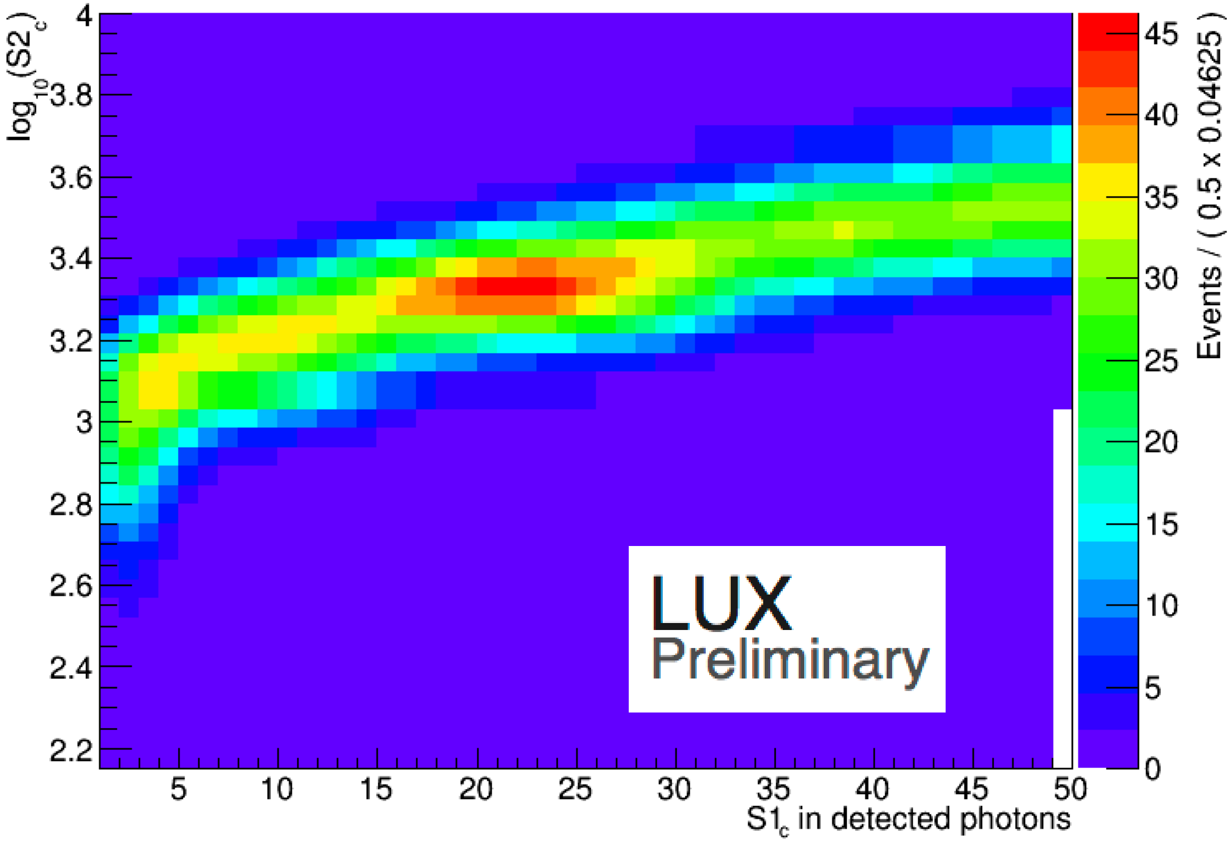
- Signal model projections in detector observables, before any cuts
- T = 0.3 keV, $\epsilon = 10^{-10}$

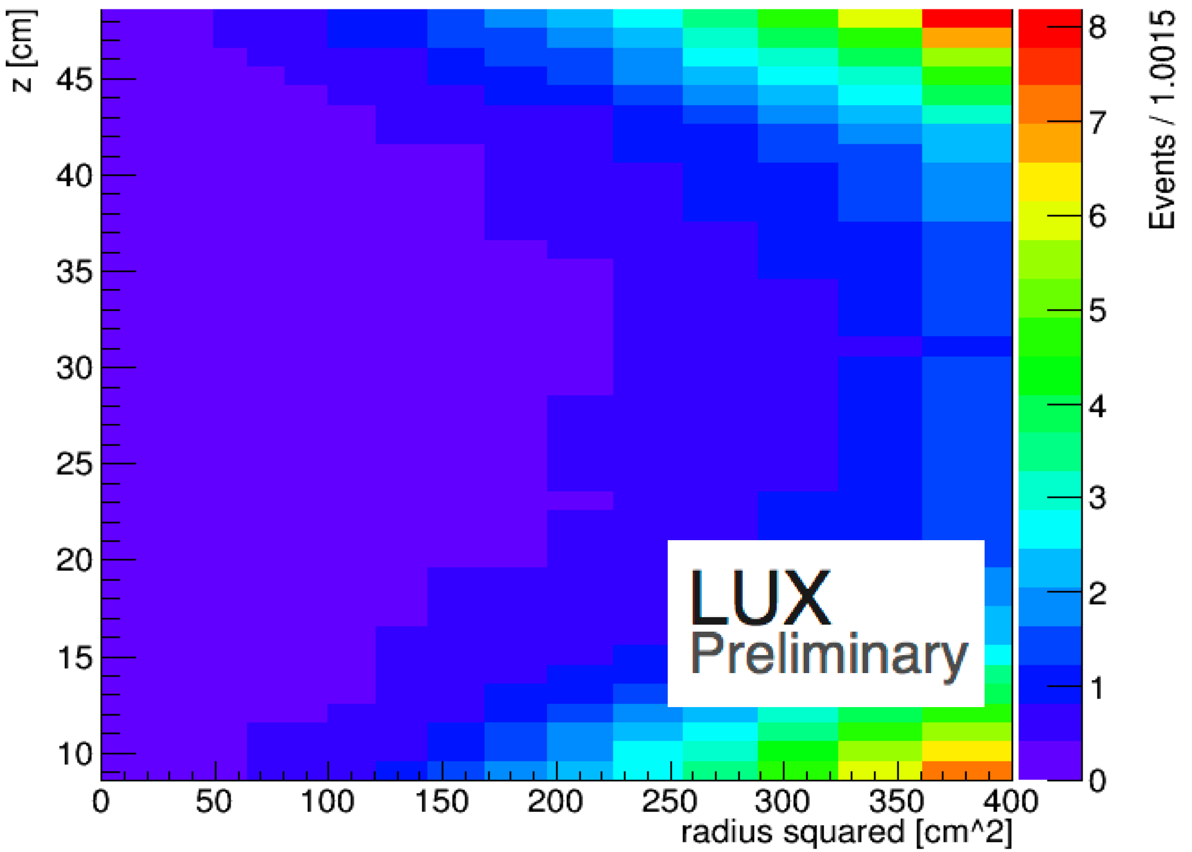




Background Model

- Backgrounds from: β decay of Rn and Kr, Xe^{127} electron capture, γ rays from detector components AND Ar^{37} electron capture, PTFE wall





Outlook

- Complete Run03 analysis
  - look into low energy behaviour and required cuts
  - plot ϵ limit against T

Results coming soon!

- Next
  - LUX Run04 analysis
  - projected LZ sensitivity

Thank you

Backup slides

Mirror DM Theory

Mirror-ordinary electron scattering rate:

$$\frac{dR_e}{dE_R}(x,t) = N_e n_{ed}(x, v_E) \int_{|v|>v_{min}}^{\infty} \frac{d\sigma}{dE_R} f_e(v; x, v_E)|v| d^3v.$$

Spin independent Coulomb scattering cross-section:

$$\frac{d\sigma}{dE_R} = \frac{\lambda}{E_R^2 v^2}, \quad \lambda = \frac{2\pi\epsilon^2\alpha^2}{m_e}.$$

Maxwellian velocity distribution:

$$f_e(v) = \left(\frac{1}{\pi v_0^2}\right)^{\frac{3}{2}} \exp\left(\frac{-(v - v_E)^2}{v_0^2}\right), \qquad v_0 = \sqrt{2T/m_e},$$

Evaluate velocity integral:

$$\frac{dR_e}{dE_R} = \frac{N_T g_T n_e \lambda}{2E_R^2|v_E|}\left[\mathrm{erf}\left(\frac{v_{min} + |v_E|}{v_0}\right) - \mathrm{erf}\left(\frac{v_{min} - |v_E|}{v_0}\right)\right]$$

J.Clarke R.Foot, JCAP01(2016)029

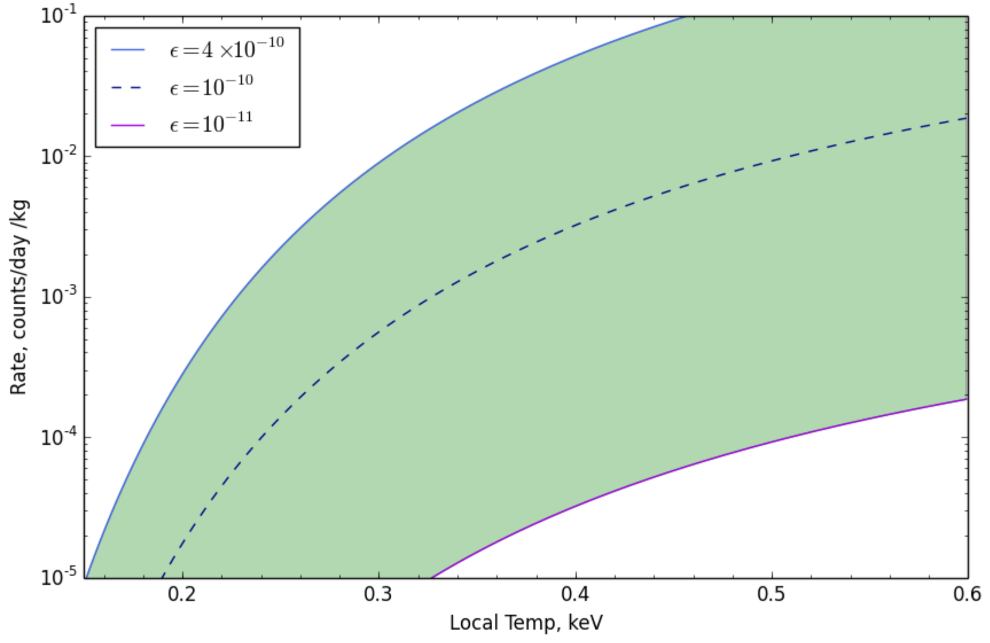
Interaction Rate

Differential rate: $$\frac{dR_e}{dE_R} = \frac{N_T g_T n_e \lambda}{2E_R^2 |v_E|}\left[\mathrm{erf}\left(\frac{v_{min}+|v_E|}{v_0}\right) - \mathrm{erf}\left(\frac{v_{min}-|v_E|}{v_0}\right)\right], \quad \lambda = \frac{2\pi\epsilon^2\alpha^2}{m_e}.$$

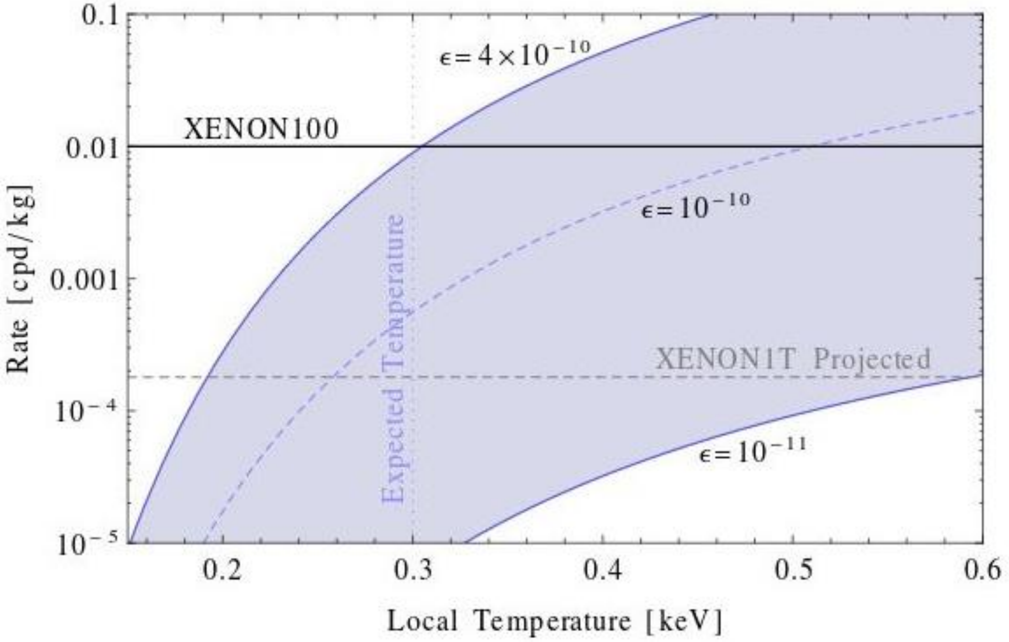
Integrating over recoil energies from threshold, E_t, to infinity:

$$R_e = N_T g_T n_e \lambda \left(\frac{2m_e}{\pi T}\right)^{\frac{1}{2}} \left(\frac{e^{-\frac{E_t}{T}}}{E_t} - \frac{\Gamma[0, E_t/T]}{T}\right).$$

My plot:



Plot from PhysLettB.2016.12.047:



Theoretical ϵ Limit

- $10^{-11} \lesssim \epsilon \lesssim 4 \times 10^{-10}$
- **Lower limit** from limit required for halo equilibrium - heating from supernovae (e , e', γ' -> γ' -> absorbed by mirror nuclei in halo) must balance energy loss from dissipative processes, R. Foot, IntJModPhysA.29.1430013
- **Upper limit** from cosmic structure formation - if ϵ is too high structure formation is too heavily damped by acoustic oscillations, R. Foot S. Vagnozzi, JCAP07(2016)013

1keV Threshold

- Uncertainties in the signal model exist sub keV electron recoils.
- Theory (cross section calculation) assumes the atomic electrons are free and at rest relative to the incoming mirror electrons. This approximation is valid for loosely bound electrons, with binding energy much less than electron recoil energy, Er.
- There are taken to be 44 loosely bound electrons in Xe, with binding energy <1keV. So Er must be >1keV for the theory to hold.
- See Section 6 of J.Clarke R.Foot, JCAP01(2016)029], for details.

PLR

- Statistical test to compare modelled signal + background to observed data.

- Test statistic: $q_\mu = -2ln\frac{L(\mu,\hat{\hat{\theta}})}{L(\hat{\mu},\hat{\theta})},$

Likelihood maximized with fixed μ, θ free.

Likelihood maximized with μ, θ free.

full model = $\mu \cdot signalPDF + \sum_i(\theta_i \cdot bkgPDF_i)$

- Use the pdf of this test statistic to find p-value for a given value of μ. Scan over values to find μ corresponding to 90% CL (p-value<0.1).

Scaling the PLR Result

- PLR result must be scaled to constrain ϵ - 90% CL number of signal events used to find 90% CL on ϵ. Rate $\propto \epsilon^2$, so use the inverse relationship to convert limit on number of signal events to limit on rate:

$$\epsilon(90\%CL) = \epsilon(0)\left(\frac{nSig(90\%CL)}{nPDF(0)}\right)^{\frac{1}{2}}$$

where: $\epsilon(0)$ is the initial (arbitrary) value of ϵ
nPDF(0) is the initial number of signal events
nSig(90%CL) the 90% CL on the number of signal events returned by the PLR