Extending searches for light WIMPs to single scintillation photons in LUX

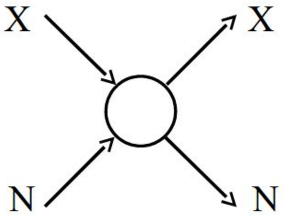
IOP HEPP Meeting - April 2019

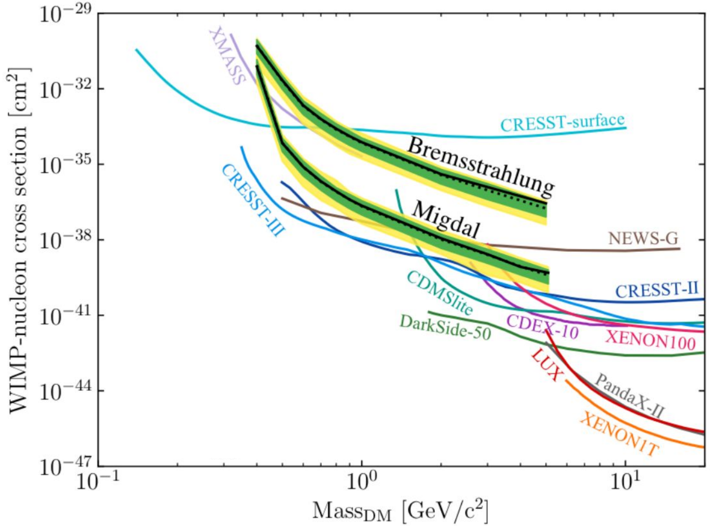
Nellie Marangou

Imperial College London

Motivating low mass dark matter searches

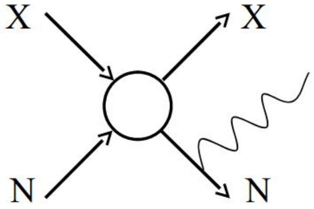
- Dark matter direct detection experiments probe a variety of rare processes leading to O(keV) energy transfers to ordinary matter:
    - Light thermally-produced WIMPs
    - Asymmetric DM
    - Mirror DM
    - Astrophysical neutrino fluxes through coherent neutrino-nuclear scattering (CνNS): solar (B8) atmospheric, supernova neutrinos



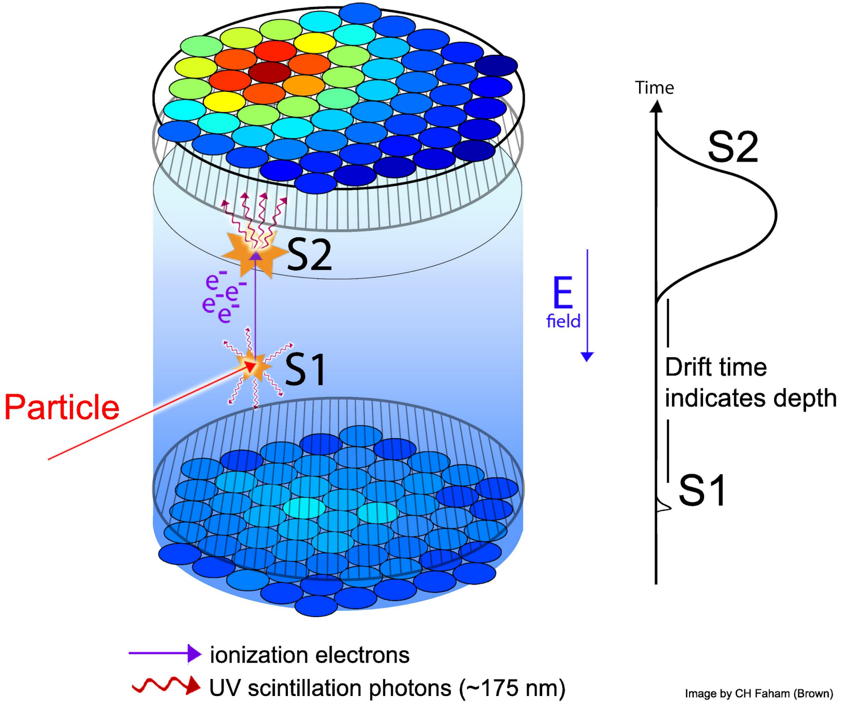


PRL, 122, 131301

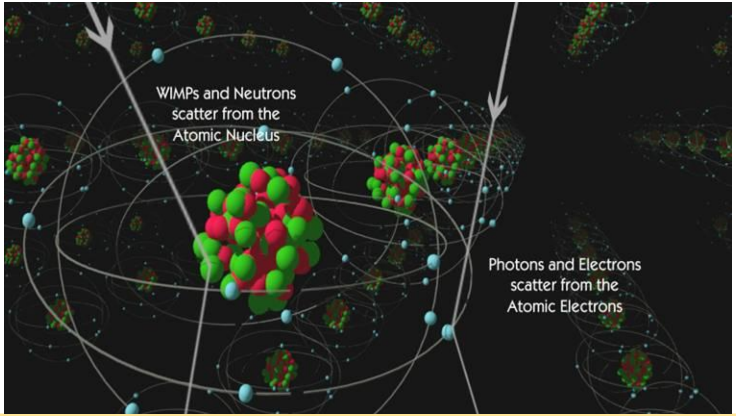
- Direct detection experiments can also probe sub-GeV DM models through nuclear bremsstrahlung and Migdal effect signals



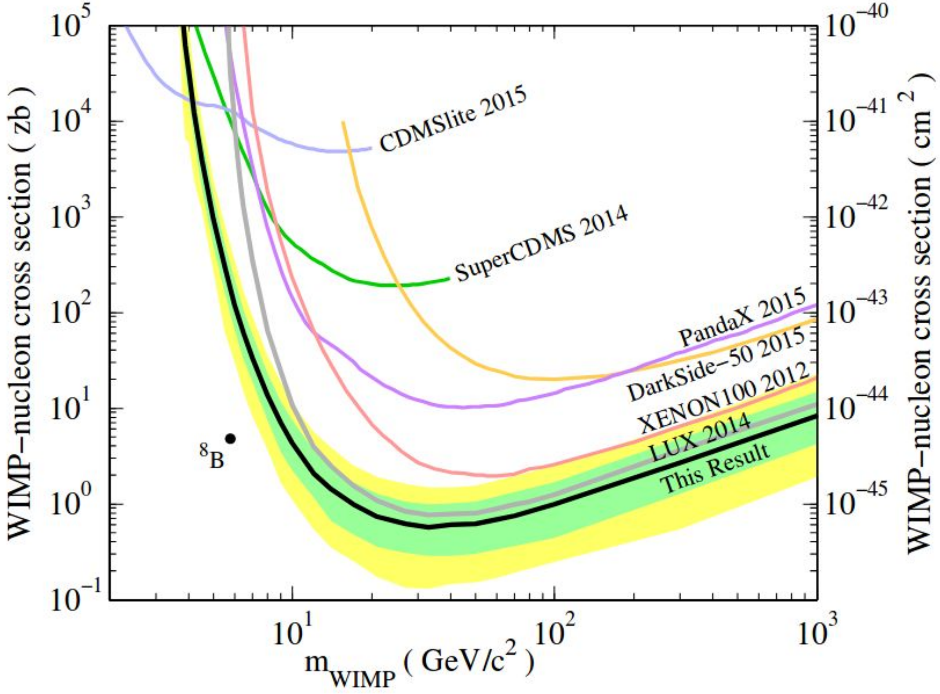
The Large Underground Xenon (LUX) experiment



- 4850’ level of the Sanford Underground Research Facility
- 2-Phase (liquid/gas) xenon TPC sensitive to light (S1) and charge (S2)
  - Particle ID: electron recoil (ER) vs nuclear recoil (NR)
  - 3-D position reconstruction
- Total LXe mass of 370 kg - active mass 250 kg
- S1 and S2 detected by two arrays of 122 photomultiplier tubes (PMTs)

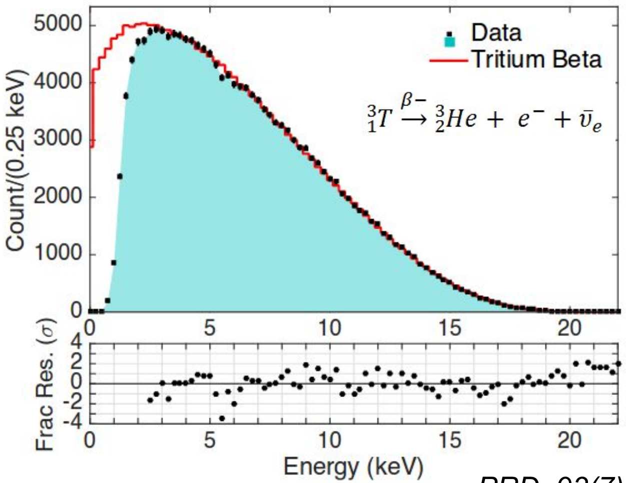


LUX WIMP searches



PRL, 116(16), 161301

- LUX completed two successful science runs (Run 3 and Run 4)
- Run 3 final WIMP search result included 95.3 live-days of data with 145 kg fiducial volume - this is the dataset we use here
- Many calibration campaigns to measure the detector response to NR and ER signals: ^{83m}Kr, ^{14}C, ^{131m}Xe, DD- neutron, CH_3T



PRD, 93(7), 072009

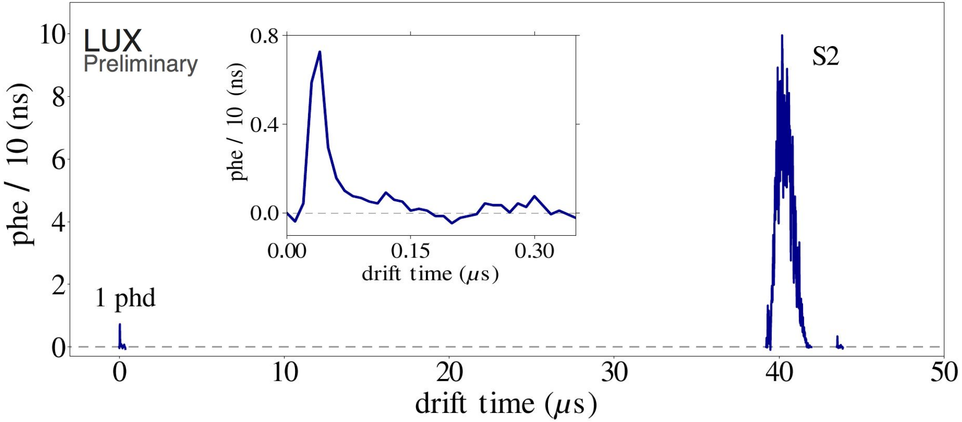
Low energy limitations

- In LUX both the S1 and S2 channels are sensitive to low recoil energies but the ionization channel is more sensitive and hence standard S1+S2 analyses are limited in energy by the S1 signal

- The smallest S1 signal previously used in LUX included 2 photons (2-fold coincidence requirement)
    - ***Why not go to an S1=1 photon?***
        - PMT dark counts
        - S2-only events

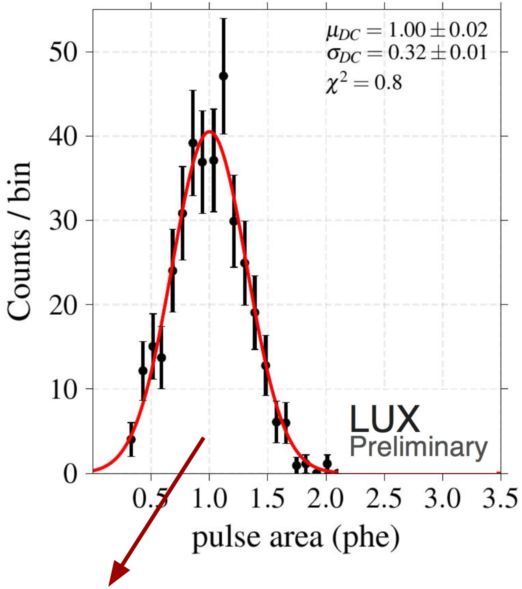
      → accidental coincidences

    - ***Aim:***
      Extend the standard ‘2-fold’ LUX analysis to include interactions in which the S1 consisted of single photons without contaminating our search with a huge background rate

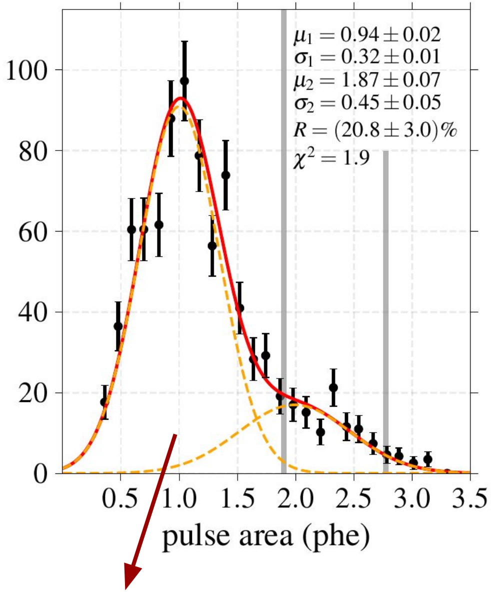


Using single scintillation photons

- Question remains: *How do we distinguish genuine single scatters with an S1 of one photon to accidental coincidences between PMT dark counts and S2-only events?*

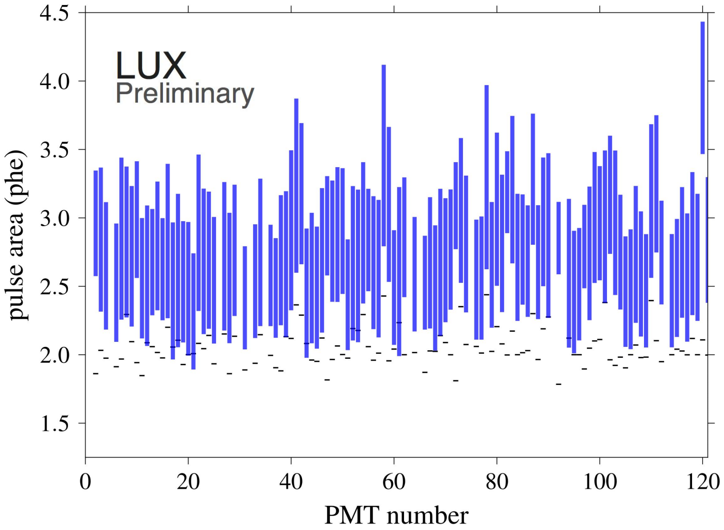


PMT response to visible photon or dark counts

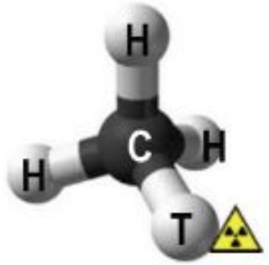


PMT response to single VUV photons (double photoelectron emission - DPE)

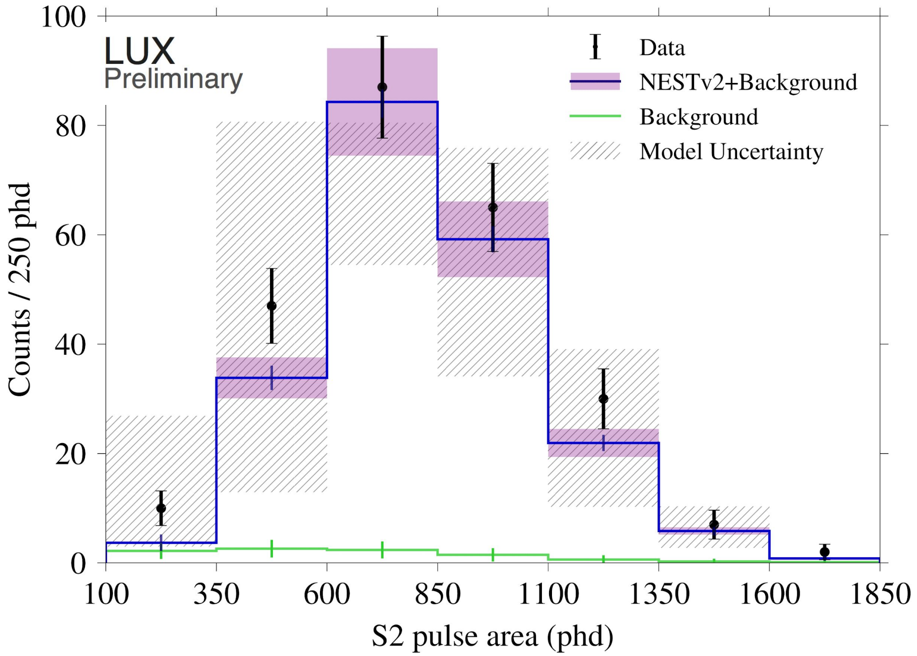
- Calibrating dark count and single VUV photon responses on a PMT by PMT basis and defining a signal region:



Extending the tritium ER calibration



- The electron recoil response was calibrated using Tritium (CH_3T), a single-beta emitter with a Q-value of 18.6 keV, which was dissolved in the LXe providing spatially-uniform events
- Performed a tritium calibration with **only single S1 photon events (2-phe)**



- Used the Noble Element Simulation Technique (NEST) package we predict the number of events

(NEST Simulation package: http://doi.org/10.5281/zenodo.1314669)

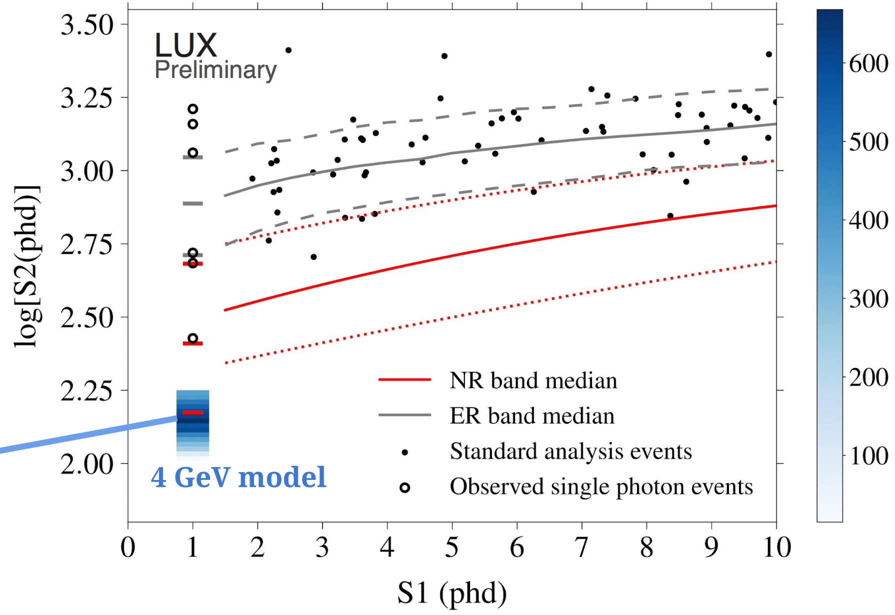
- Expectation: **211 ± 24**$_{\text{syst.}}$ **±** $^{26}_{11\ \text{mod.}}$.
- Observation: **248** events.
- Background expectation included: 10.8 ± 1.1 events
- Energy range: **0.25-1.75 keV**

Run 3 single photon search

- Performed a single photon search using the Run 3 reanalysis dataset of 95.3 live-days and a 118 kg fiducial volume

Signal model for 4 GeV WIMP, 10^6 kg-days exposure and 10^{-40}cm^2 cross section

Background expectation is 0.9 counts and observation is 0



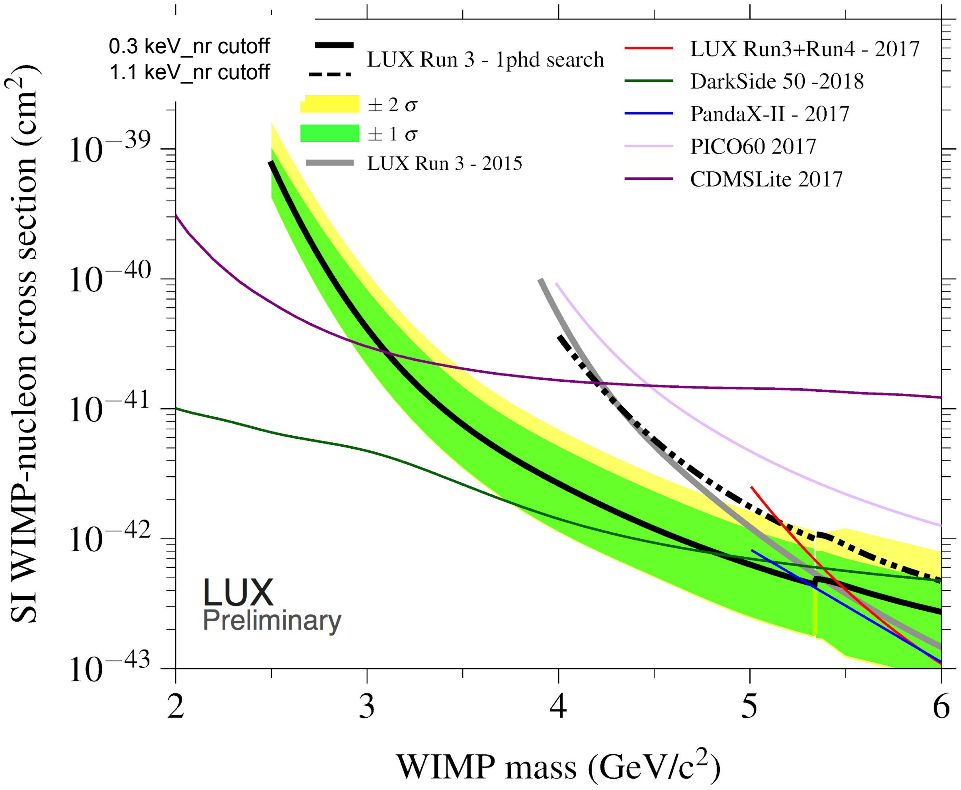
- Expected backgrounds and observed counts:

S2 region	*S2 size (phd)*	*Coincidences*	*ER*	*NR*	*Wall events*	*Total*	*Observed*
> 90% ER	1100-5000	2.0 ± 0.2	0.02 ± 0.01	<0.01	<0.01	**2.0 ± 0.2**	**3**
10%-90% ER	515-1100	0.9 ± 0.1	0.4 ± 0.2	<0.01	<0.01	**1.3 ± 0.2**	**1**
< 10% ER	~120-515	1.7 ± 0.3	0.02 ± 0.01	0.01 ± 0.01	0.05 ± 0.02	**1.8 ± 0.3**	**2**
Total	**~120-5000**	**4.6 ± 0.4**	**0.4 ± 0.2**	**0.01 ± 0.01**	**0.05 ± 0.02**	**5.1 ± 0.4**	**6**

Run 3 WIMP analysis

- Rolke statistical analysis used to set 90% C.L upper limits on the number of signal counts at each mass and calculate the spin-independent elastic scattering cross section
- New result fully consistent with the background-only hypothesis
- Improvement between previous run 3 analysis result and single photon limit includes mainly 2 effects:
    - Relaxing model cutoff and
    - Lowering analysis thresholds

At 4 GeV these are approximately equally important

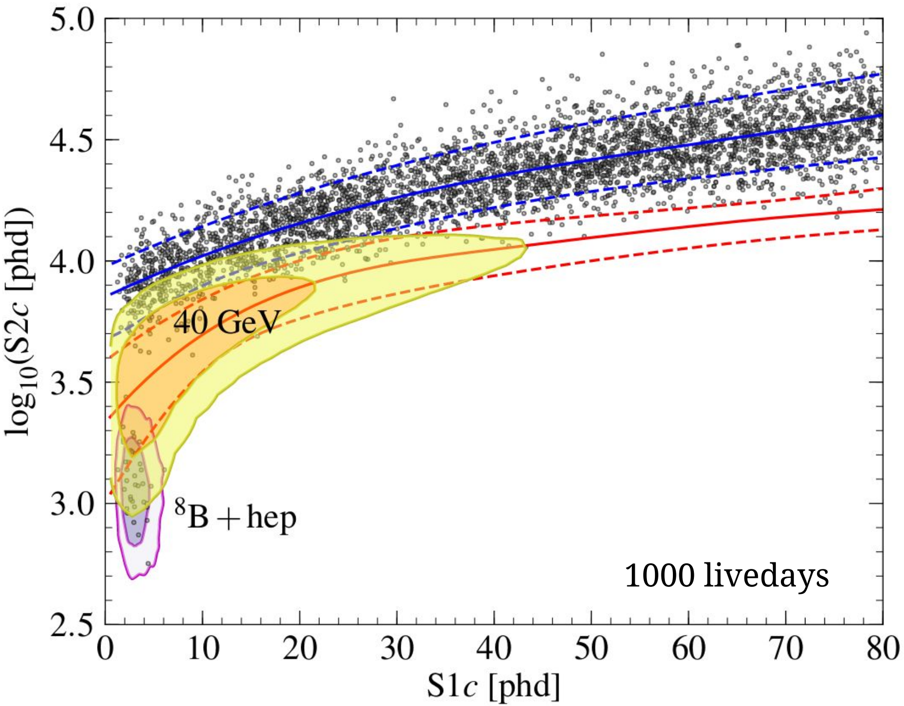


LZ

- More efficient analysis:
  - S1 threshold from 3-fold to 2-fold (and possibly to 1-fold) - either or both detected photons can undergo double photoelectron emission
  - LZ PMTs have a higher DPE rate

- LZ study ongoing

- Using the technique described the rate of CνNS B8 neutrinos observed by LZ is expected to double



arXiv:1802.06039

Summary and perspectives

- Presented a new data analysis technique to search for rare ER and NR interactions at sub-keV energies in LXe-TPCs, based on the efficient detection of single VUV photons that sometimes generate two photoelectrons in some PMT models

- Demonstrated accurate reconstruction of single photon ER events and applied technique to search low energy NRs, improving the spin-independent scattering cross section limits for very light WIMPs - working towards a publication of the LUX analysis presented here

- A separate LZ analysis is being performed with promising sensitivity enhancement

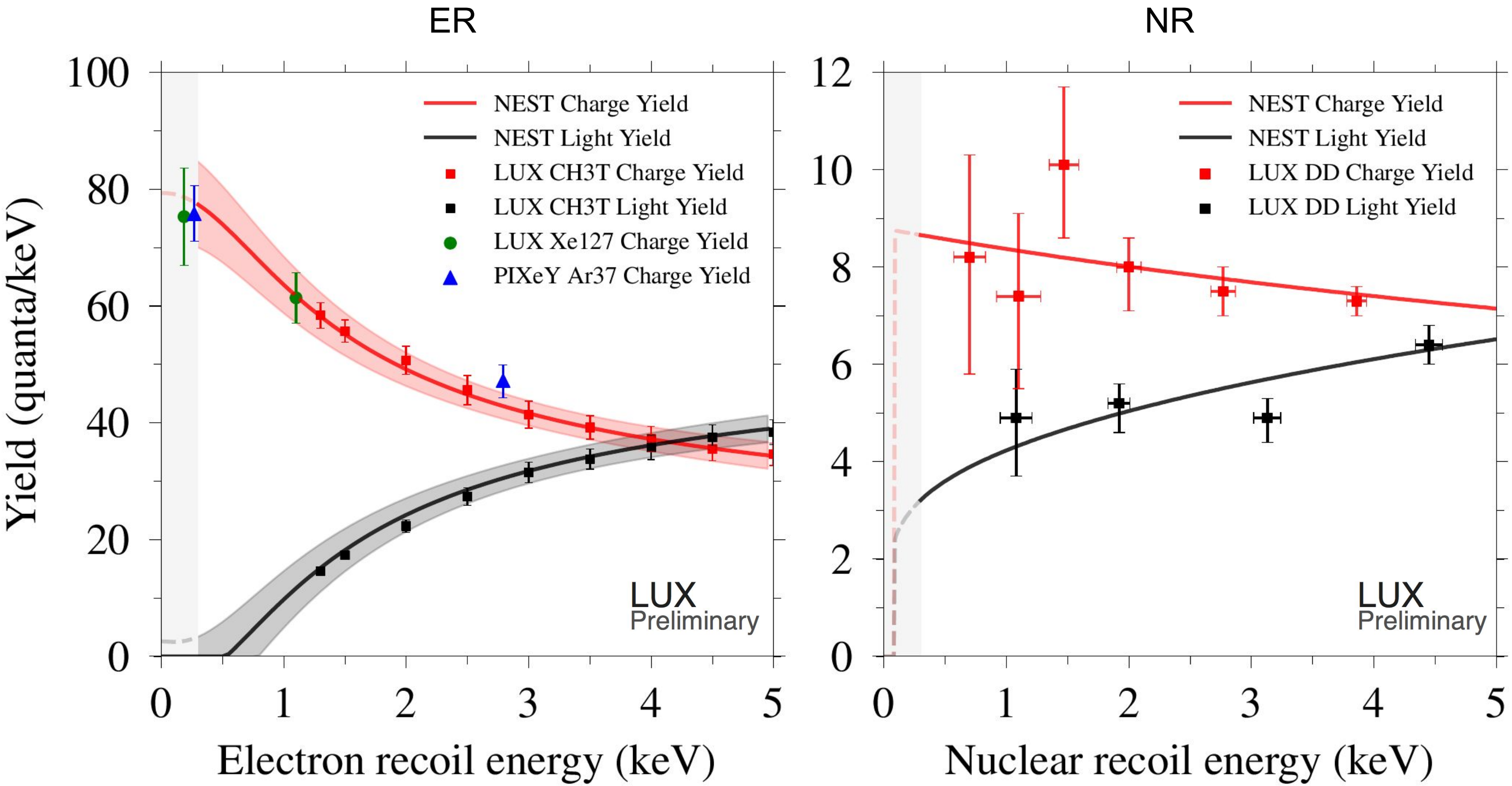
- Good prospects for enhancing sensitivity to very light WIMPs or other low recoil energy models

Thank you!

Imperial College London

Backup

Yield variations and energy cutoff

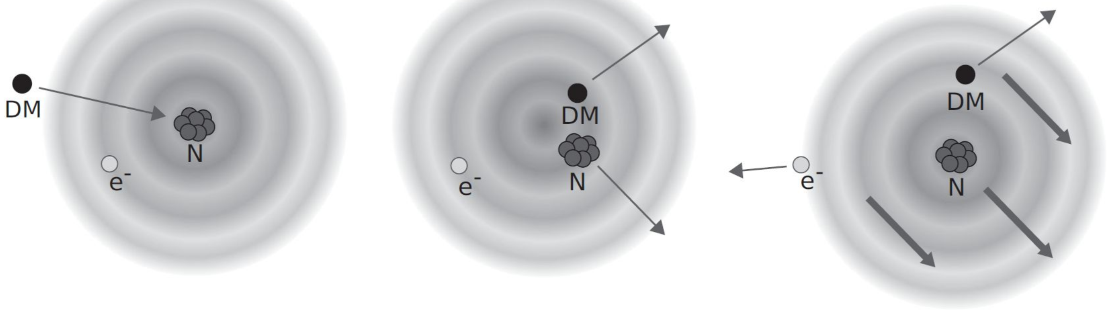


NEST Simulation package: http://doi.org/10.5281/zenodo.1314669

LUX sub-GeV searches

Migdal effect:

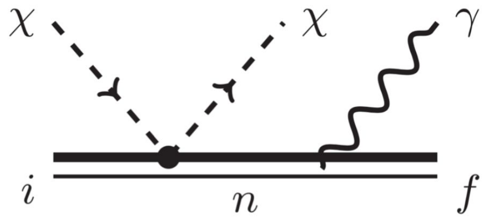
Image credit: Dolan *et al*, PRL 121, 101801



- DM-nuclear non-elastic scattering in which ionized electrons (low-energy) are emitted
- NR signal is below threshold but ER signal is above threshold

Bremsstrahlung:

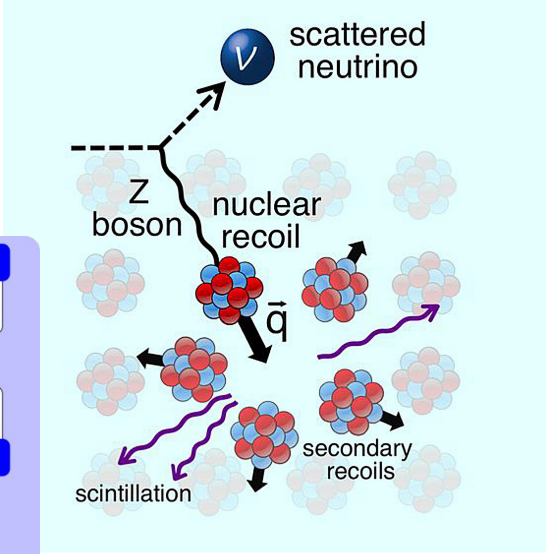
Photon emission resulting from DM-nucleus scattering



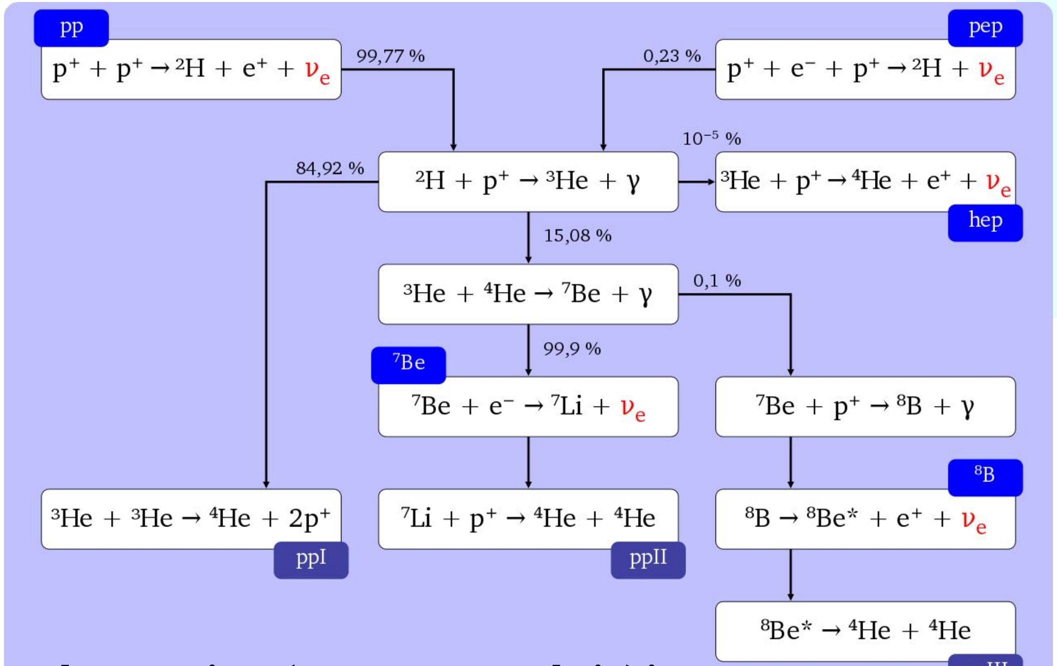
PRL 118, 031803 (2017)

- Low energy NR interaction seen in the ER band
- Photon emitted due to acceleration of the recoiling nucleus after DM interaction

Coherent neutrino nucleus scattering



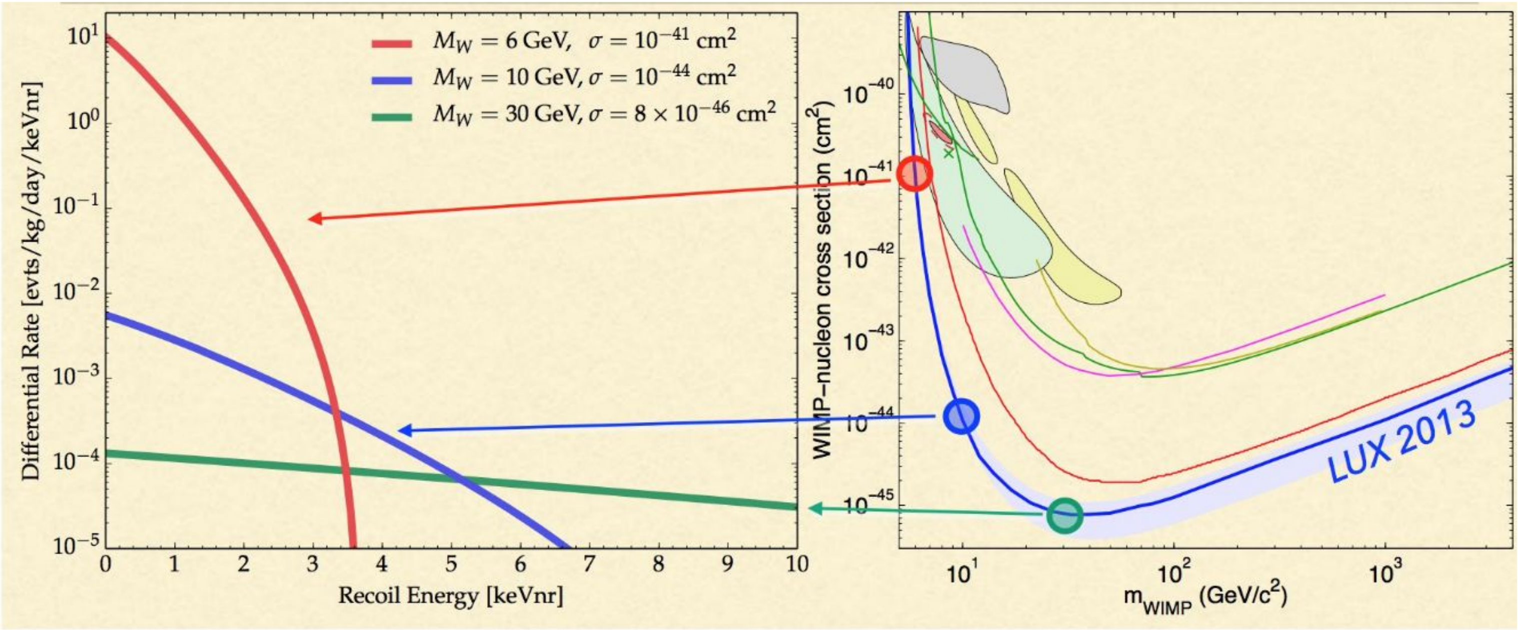
- Recently observed for the first time by the COHERENT collaboration for a pulsed neutrino beam with rates consistent with SM
- Solar neutrinos:



Solar neutrinos (proton-proton chain) in SM

- Atmospheric neutrinos, supernova neutrinos

Importance of energy threshold



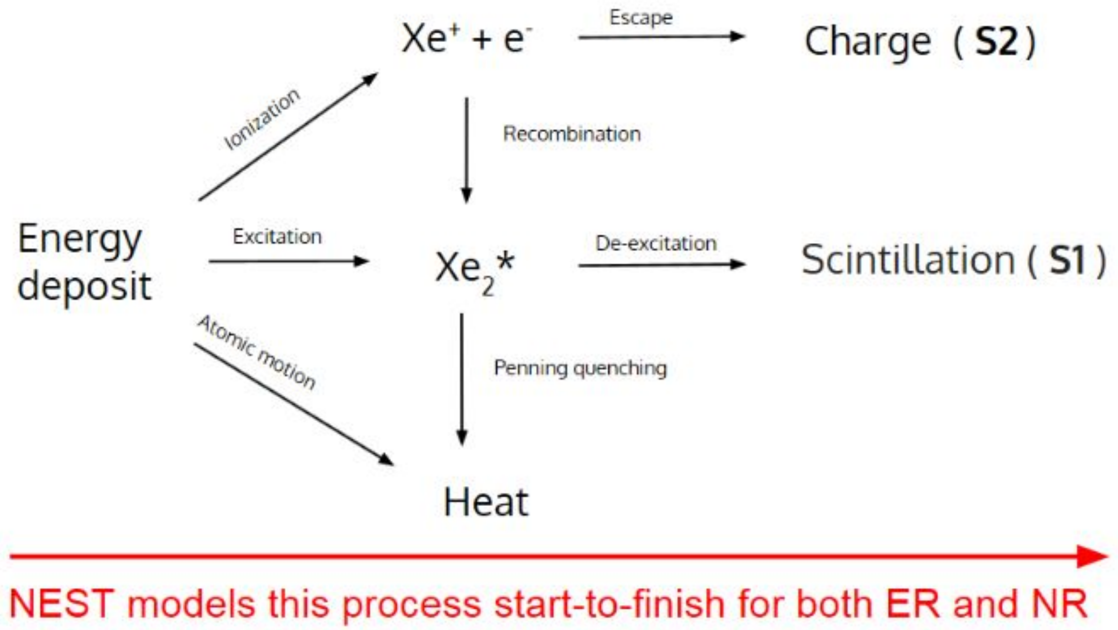
Low mass dark matter models

- WIMPs:
  - Lowest mass ~ 2GeV - Lighter WIMPs would mean a lower annihilation cross section and hence an earlier freeze out and a higher DM relic density, inconsistent with observations

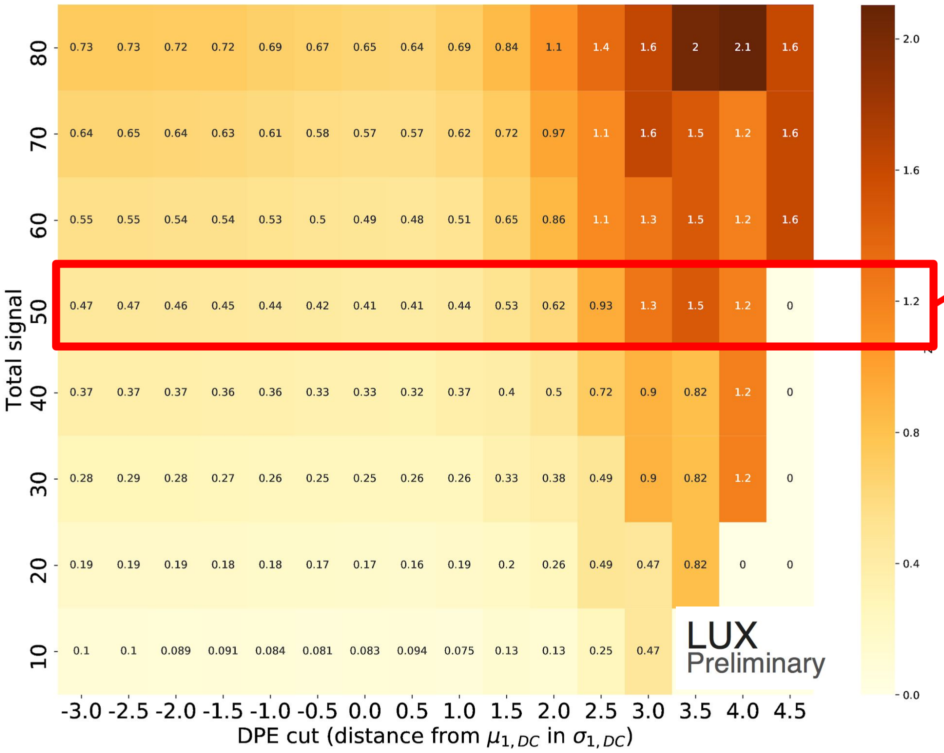
- Asymmetric dark matter:
  - 1-15 GeV
  - Present-day abundance of dark matter has the same origin as the abundance of visible matter: an asymmetry in the number densities of particles and antiparticles.
  - Motivation: present-day mass density of DM is about a factor of five higher than the density of VM suggesting a common origin

- Mirror Dark Matter:
  - Asymmetric dark matter with dark sector isomorphic to visible sector
  - Two sectors interact gravitationally through kinetic mixing
  - Allows interactions between charged mirror e- and atomic electron in Xe –ER signal in LUX

Xenon Physics & NEST



Accessing DPE cut



2.3 counts after DPE cut

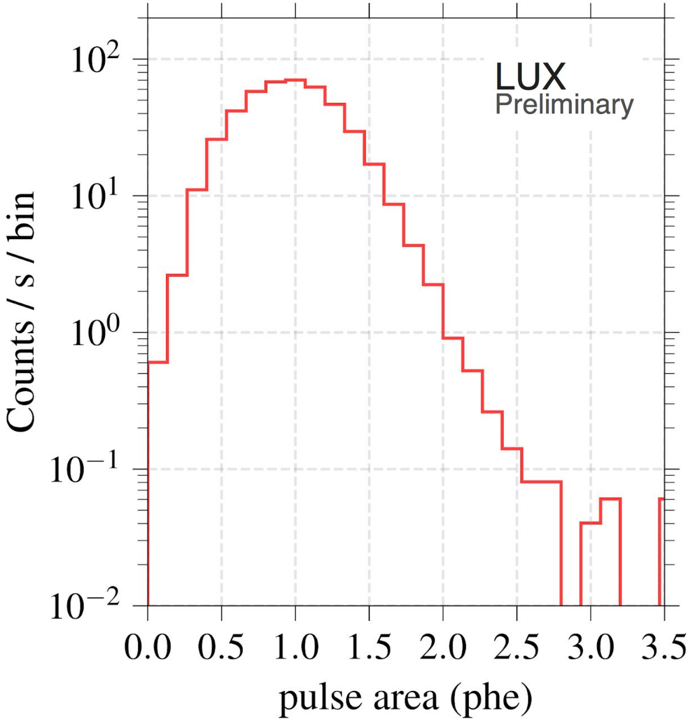
Z - poisson significance

$$Z_A = \left[2\left((s+b)\ln\left[\frac{(s+b)(b+\sigma_b^2)}{b^2+(s+b)\sigma_b^2}\right] - \frac{b^2}{\sigma_b^2}\ln\left[1+\frac{\sigma_b^2 s}{b(b+\sigma_b^2)}\right]\right)\right]^{1/2}$$

Is this technique viable?

- In other words are there any major new backgrounds that would jeopardise a rare event search?
- Examine summed dark count leakage within signal region

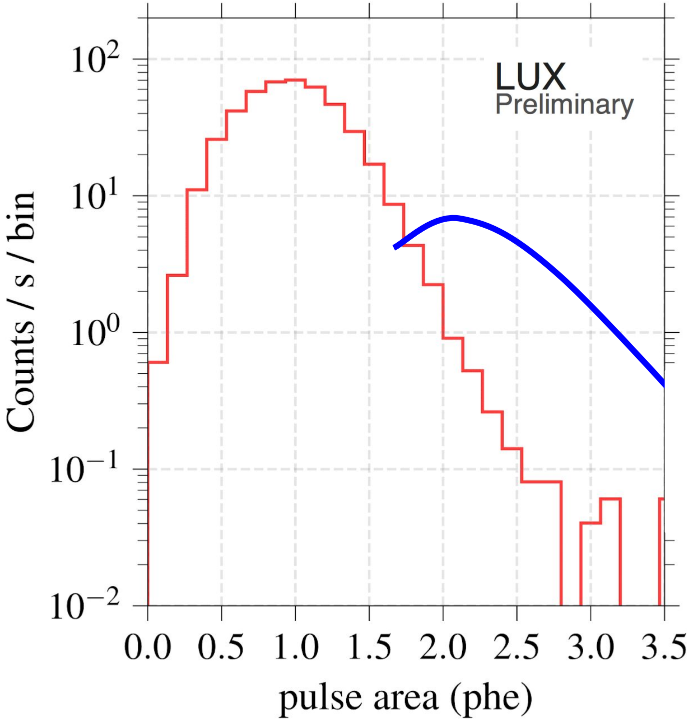
Summed distribution of single photon like pulses found before S1



Is this technique viable?

- In other words are there any major new backgrounds that would jeopardise a rare event search?
- Examine summed dark count leakage within signal region

Summed distribution of single photon like pulses found before S1



Predicted leakage in signal region from one-gaussian fits (summed):

- 2.4 ± 0.2 counts/s

Observed leakage:

- 2.0 ± 0.2 counts/s

=> i.e. mostly due to dark counts - no significant extra VUV sources

We assume all observed leakage counts in background expectation