Light dark matter in LUX

Aaron Manalaysay, U.C. Davis
on behalf of the LUX Collaboration

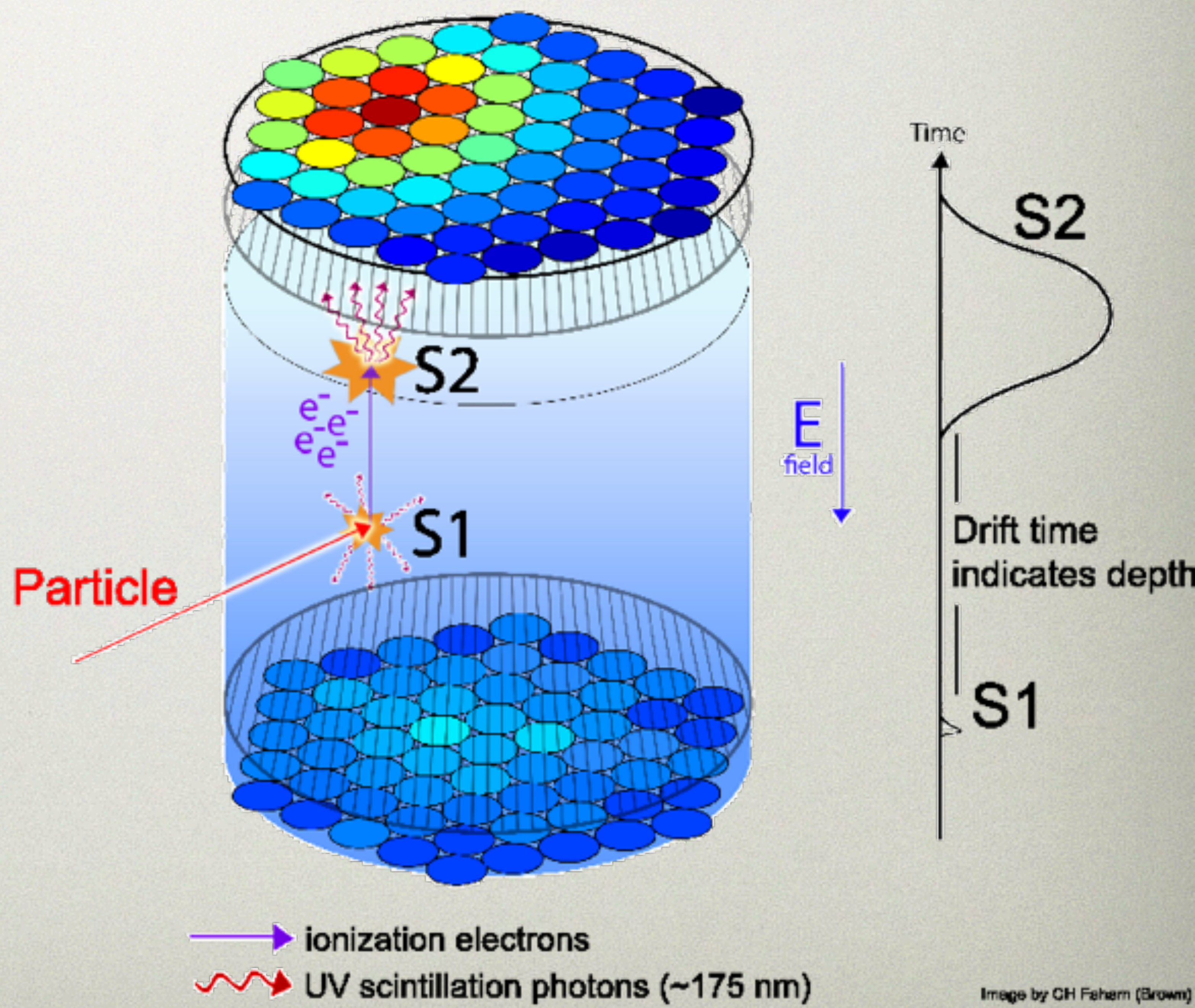
Beyond WIMPs: From Theory to Detection
May 30th, 2015, Hagoshrim Kibbutz, Israel

The LUX hand soap in the restrooms here is infused with moisturizing liquid xenon, that cools your hands as it cleans them.

But this isn’t a talk about soap

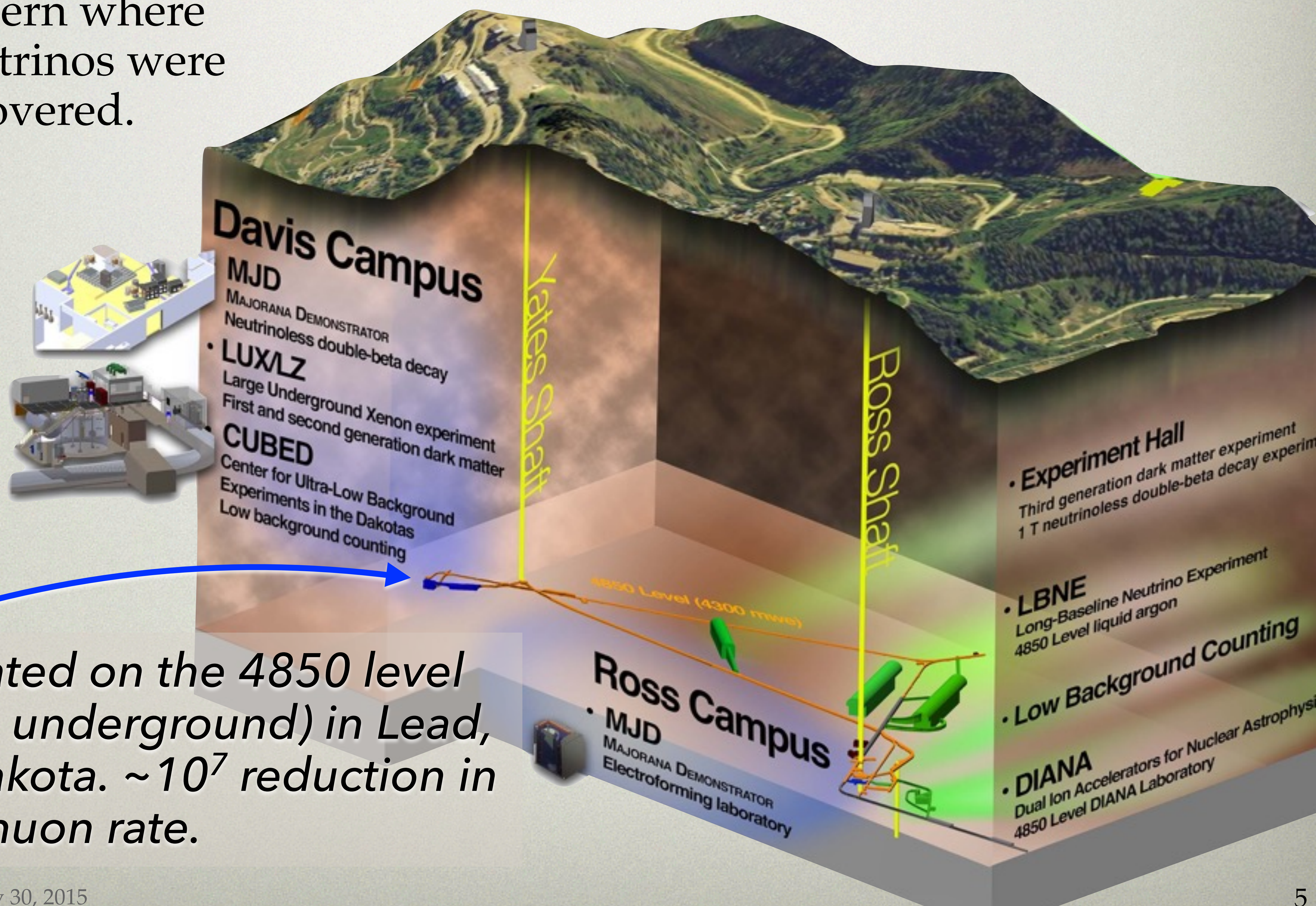
LUX Detector

- LUX is a dual-phase time projection chamber (like most other liquid-noble DM experiments); essentially a cylinder of LXe.
- Primary scintillation light ("S1") is emitted from the interaction vertex, and recorded by an array of PMTs on top and bottom.
- Electrons emitted from the interaction are drifted by and applied field to the surface and into the gas, where they emit proportional scintillation light ("S2"), also recorded by the PMTs.
- This design permits:
  - **Identification of multiple scatters (via S2 count).**
  - **3-D localization of each vertex.**
  - **ER/NR discrimination (via S2/S1)**
  - **Sensitivity to single electrons.**



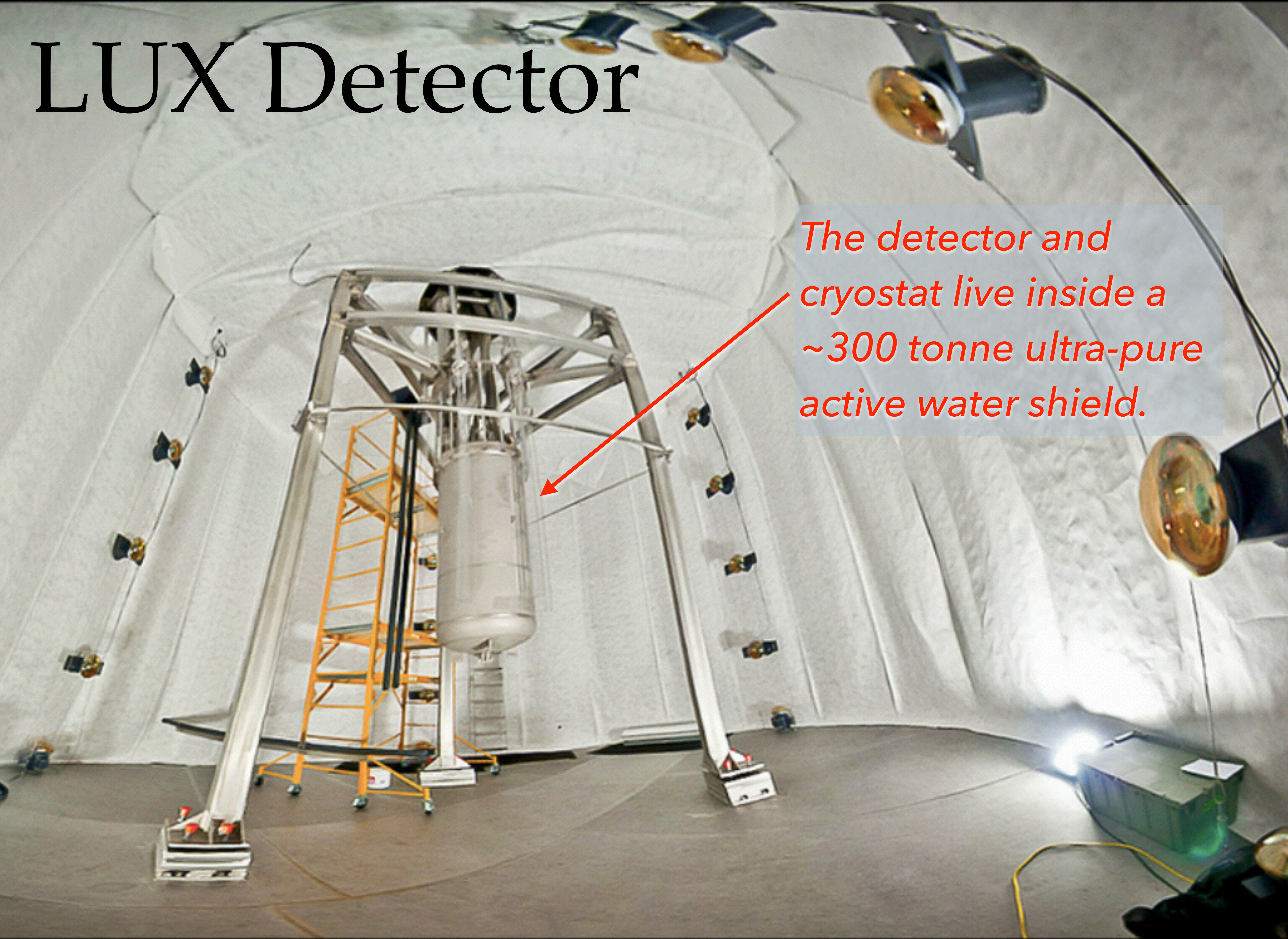
Sanford Underground Research Facility

Same cavern where solar neutrinos were first discovered.



LUX, located on the 4850 level (~1.5 km underground) in Lead, South Dakota. ~10^7 reduction in cosmic muon rate.

LUX Detector



LUX Detector

- 47cm diameter by 48 cm height dodecagonal “cylinder”.
- 370 kg LXe total, 250 kg active region
- 61 PMTs on top, 61 on bottom, specially produced for low radiogenic BGs and VUV sensitivity.
- Xenon was pre-purified via chromatographic separation, reducing residual krypton levels to 3.5±1 ppt (g/g).
- Liquid is continuously recirculated (¼ tonne per day) to maintain chemical purity.
- Ultra-low BG titanium cryostat.

The LUX Collaboration

Brown

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Simon Fiorucci	Research Associate
Samuel Chung Chan	Graduate Student
Dongqing Huang	Graduate Student
Will Taylor	Graduate Student
Casey Rhyne	Graduate Student
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Sergey Uvarov	Graduate Student
Jacob Cutter	Graduate Student

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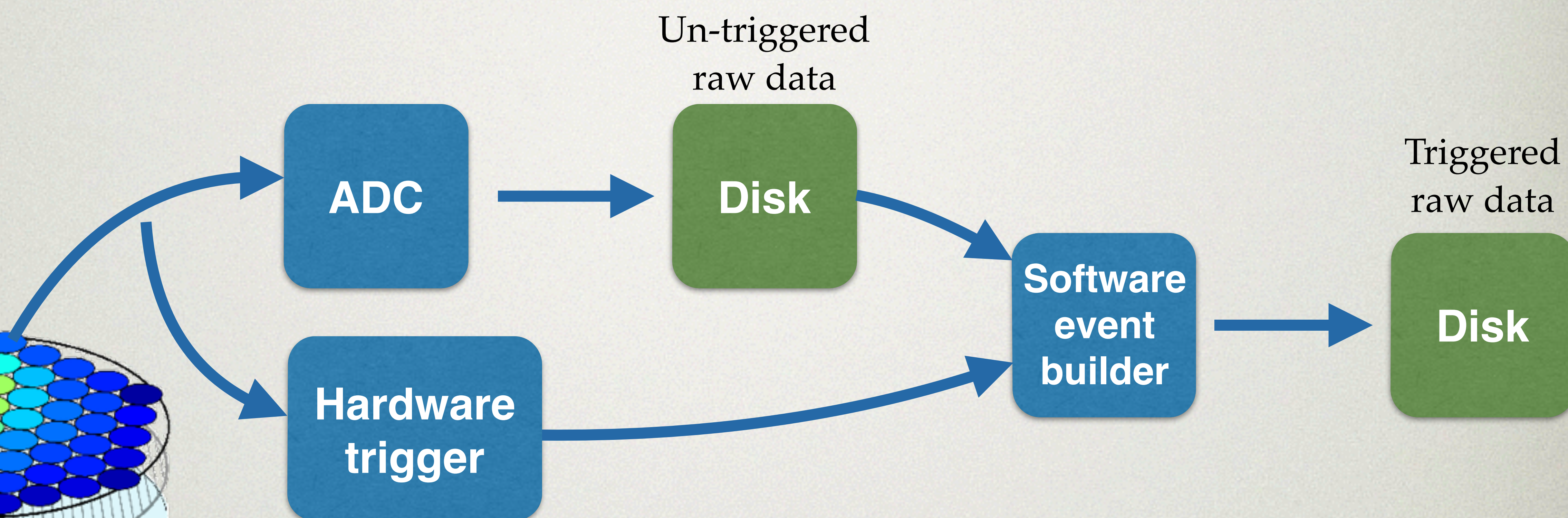
Scott Hertel	Postdoc
Kevin O'Sullivan	Postdoc
Elizabeth Boulton	Graduate Student
Nicole Larsen	Graduate Student
Evan Pease	Graduate Student
Brian Tennyson	Graduate Student
Lucie Tvrznikova	Graduate Student

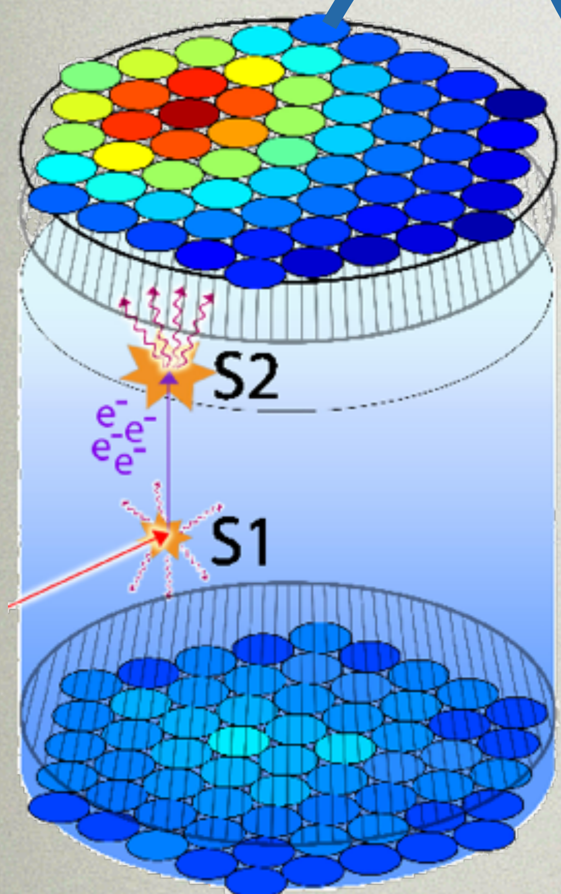
LUX on the horizon

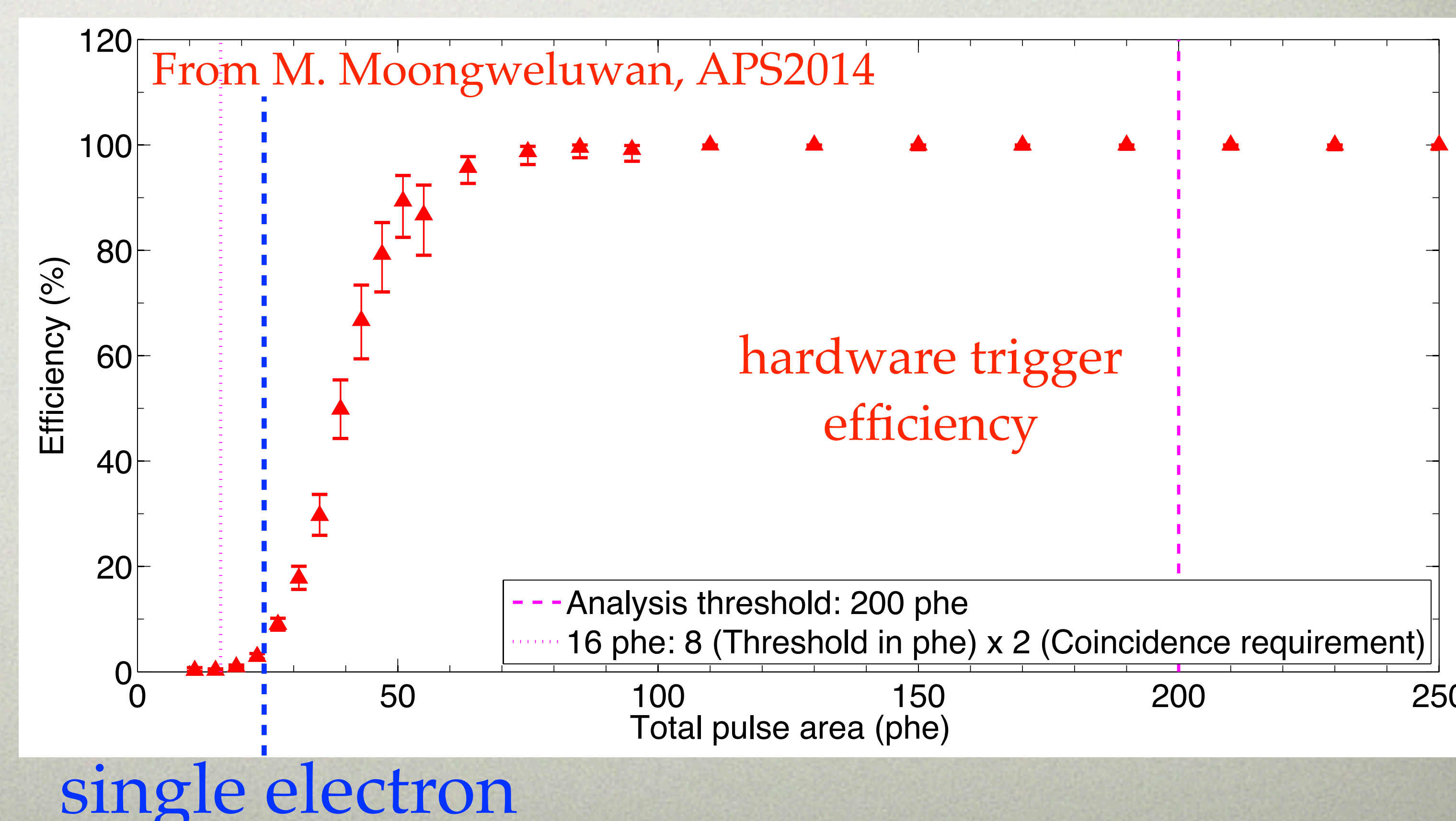
There are several upcoming LUX [DM] papers in the pipeline:

- Vanilla re-analysis (i.e. S1+S2) of the already released data.
- Ionization-only search for low-mass WIMPs.
- Axion (solar) and axion-like particles.

LUX ionization sensitivity







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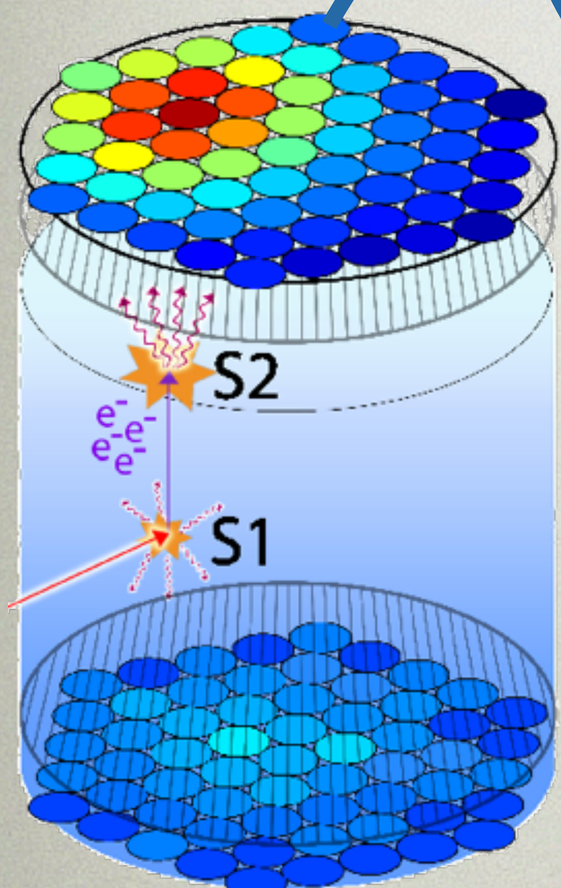
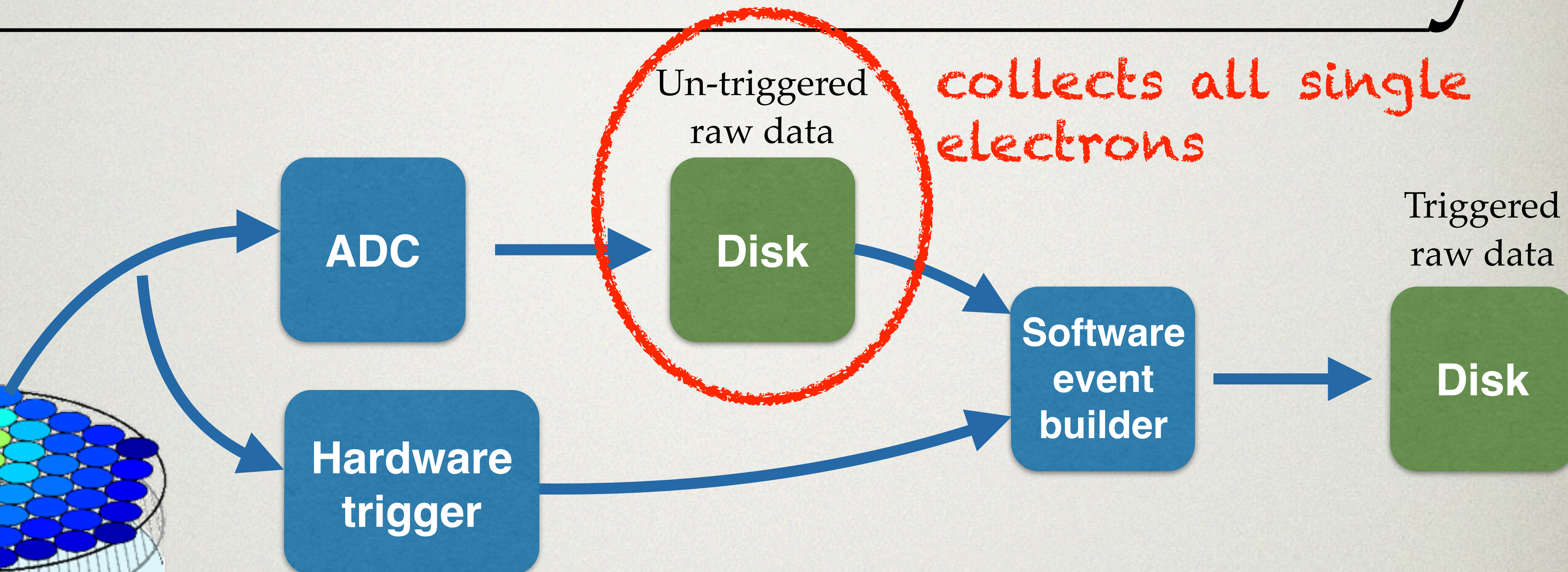
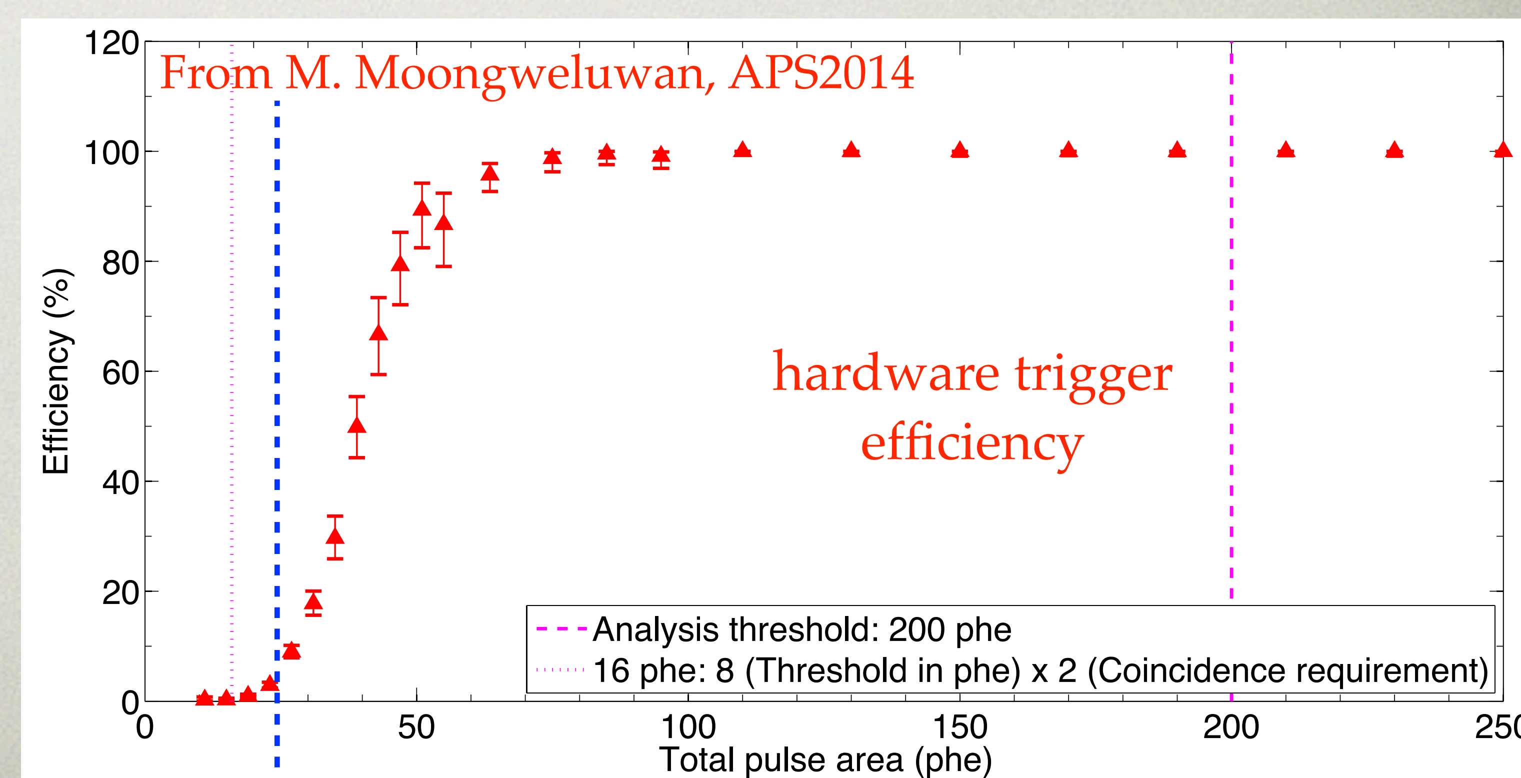






single electron

Light dark matter

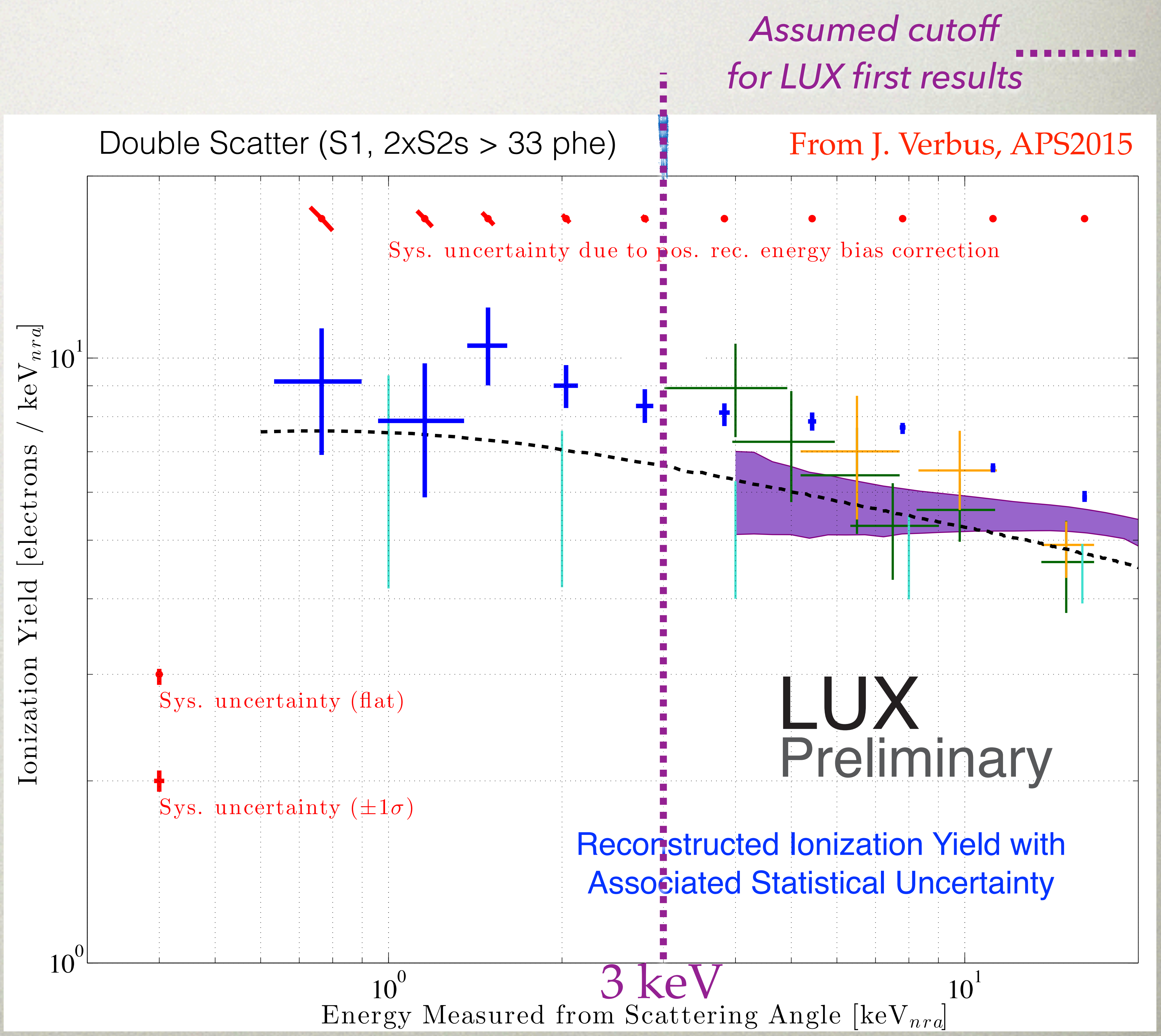
- Light O(1 GeV) vanilla WIMPs or asymmetric DM*
- ~keV axion-like particles†
- subGeV hidden-sector U(1)′ models*†

* Gives up on scintillation signal

† Looks for electronic recoils

Light WIMP search

- The published LUX results assumed LXe's response has a hard cutoff below 3 keV (conservative choice due to ignorance).
- We have since measured LXe's ionization response down to ~0.75 keV*!*
- How much of a difference this make vis-à-vis light-WIMP sensitivity?



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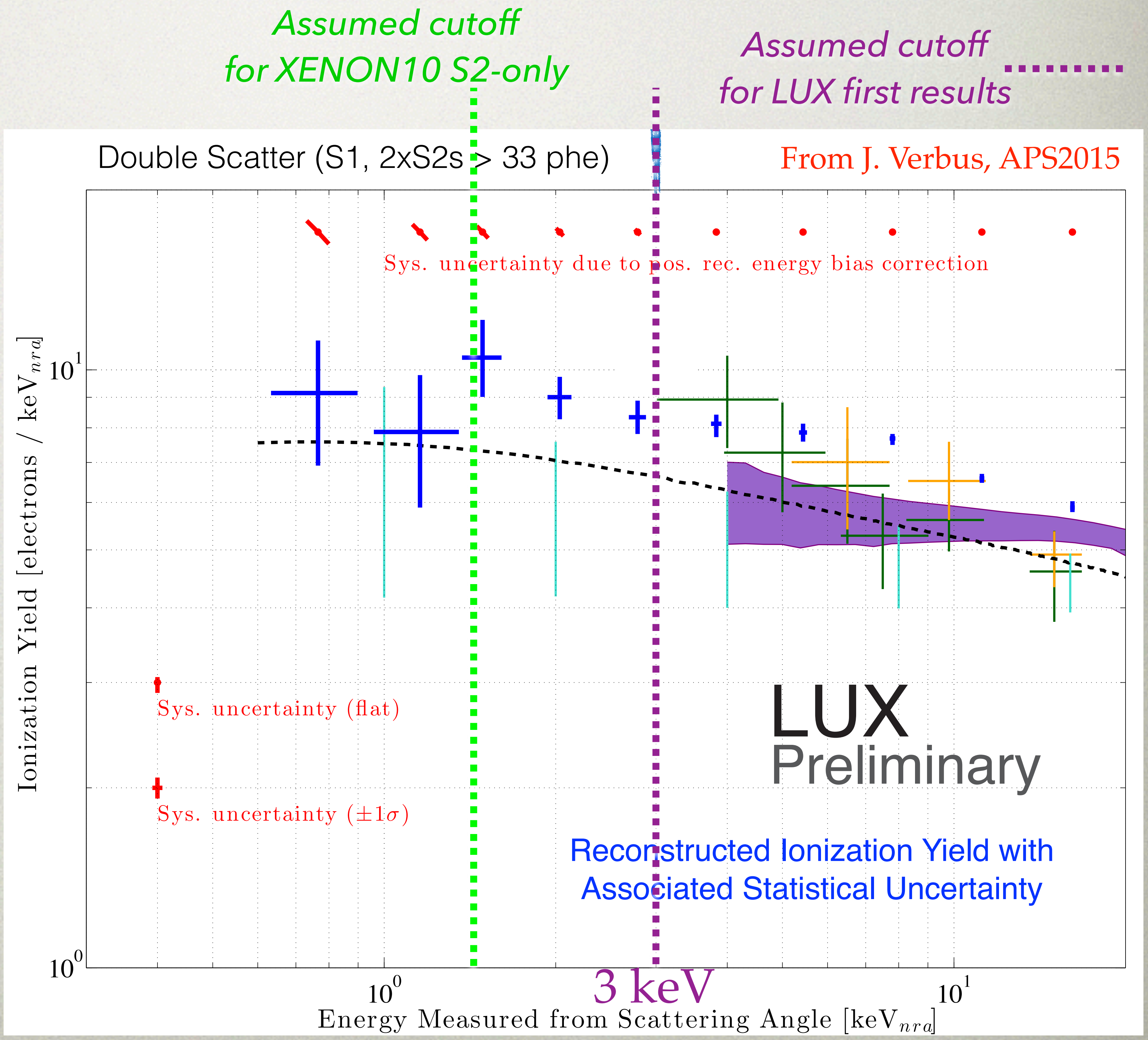

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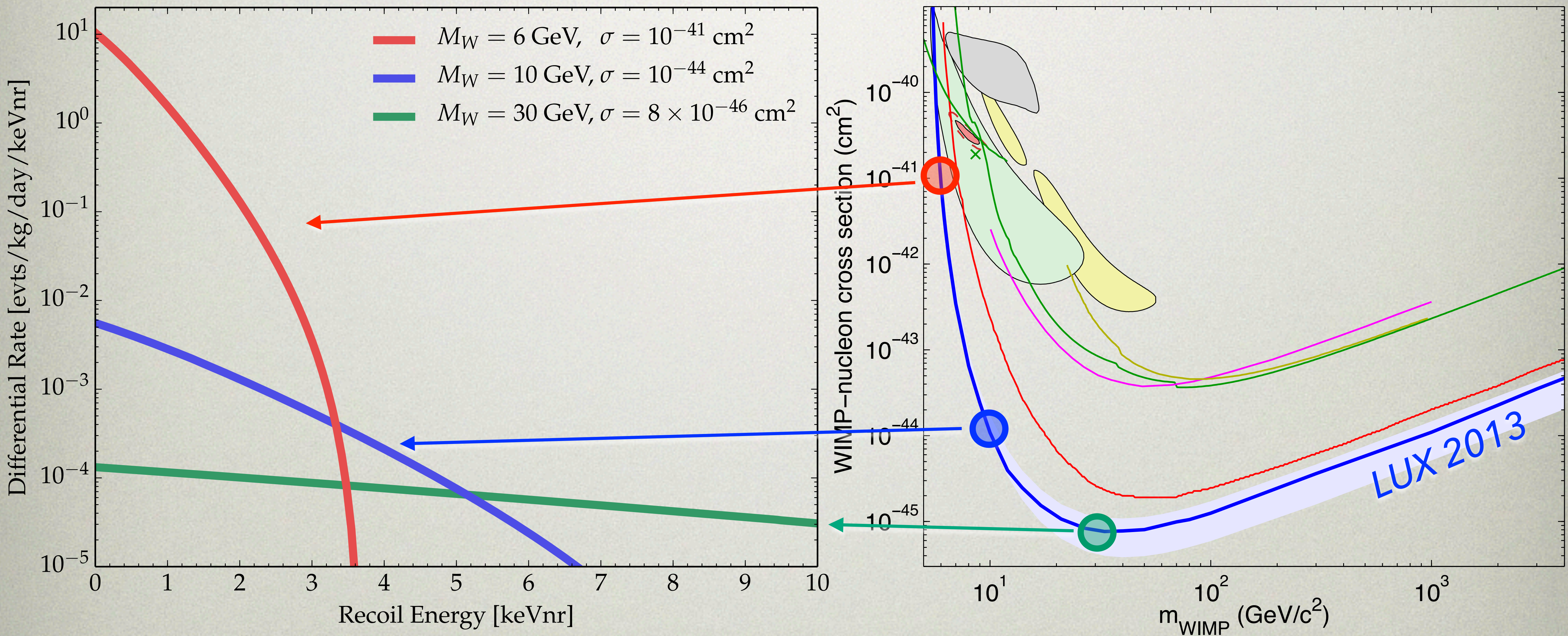

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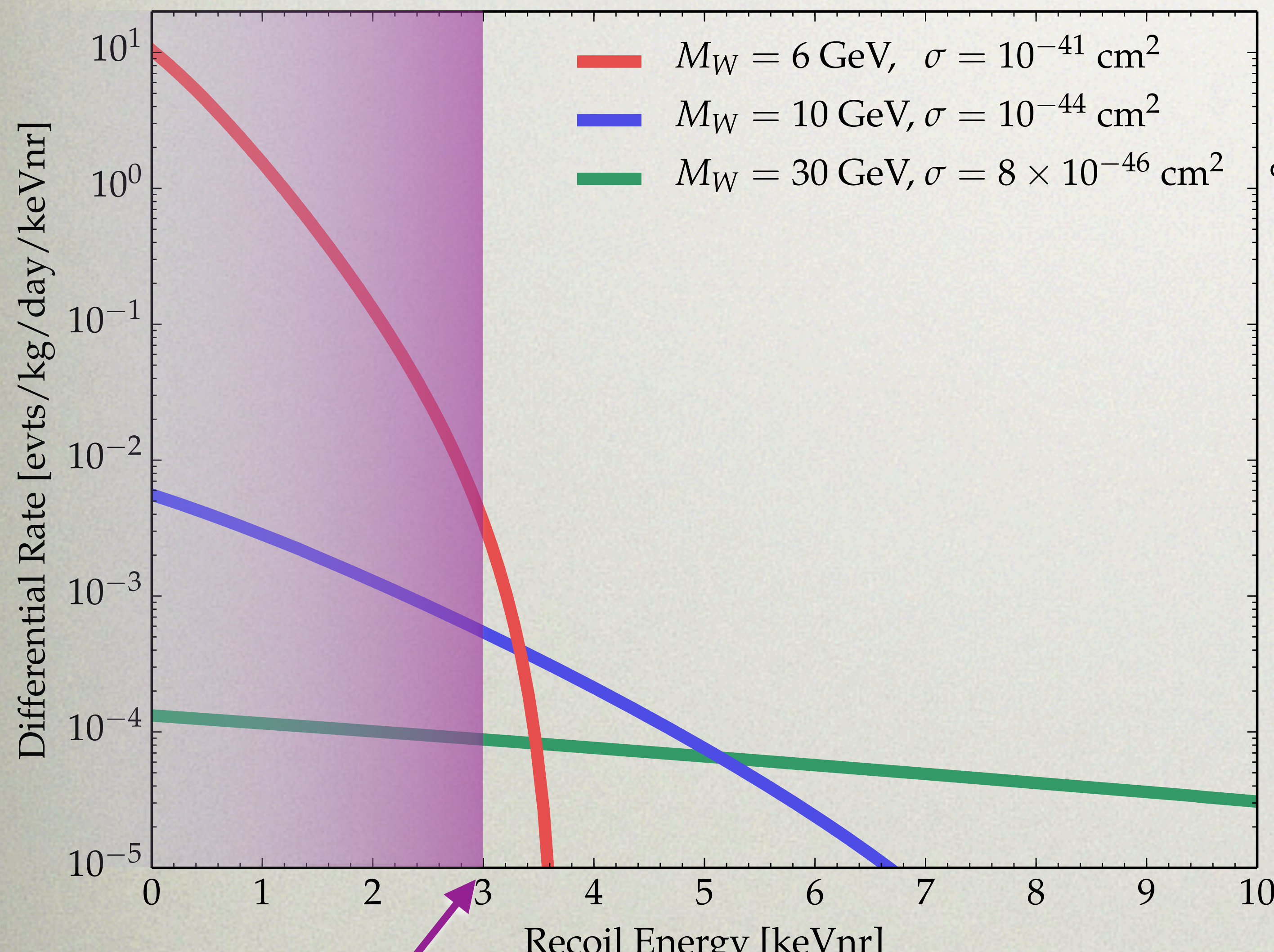
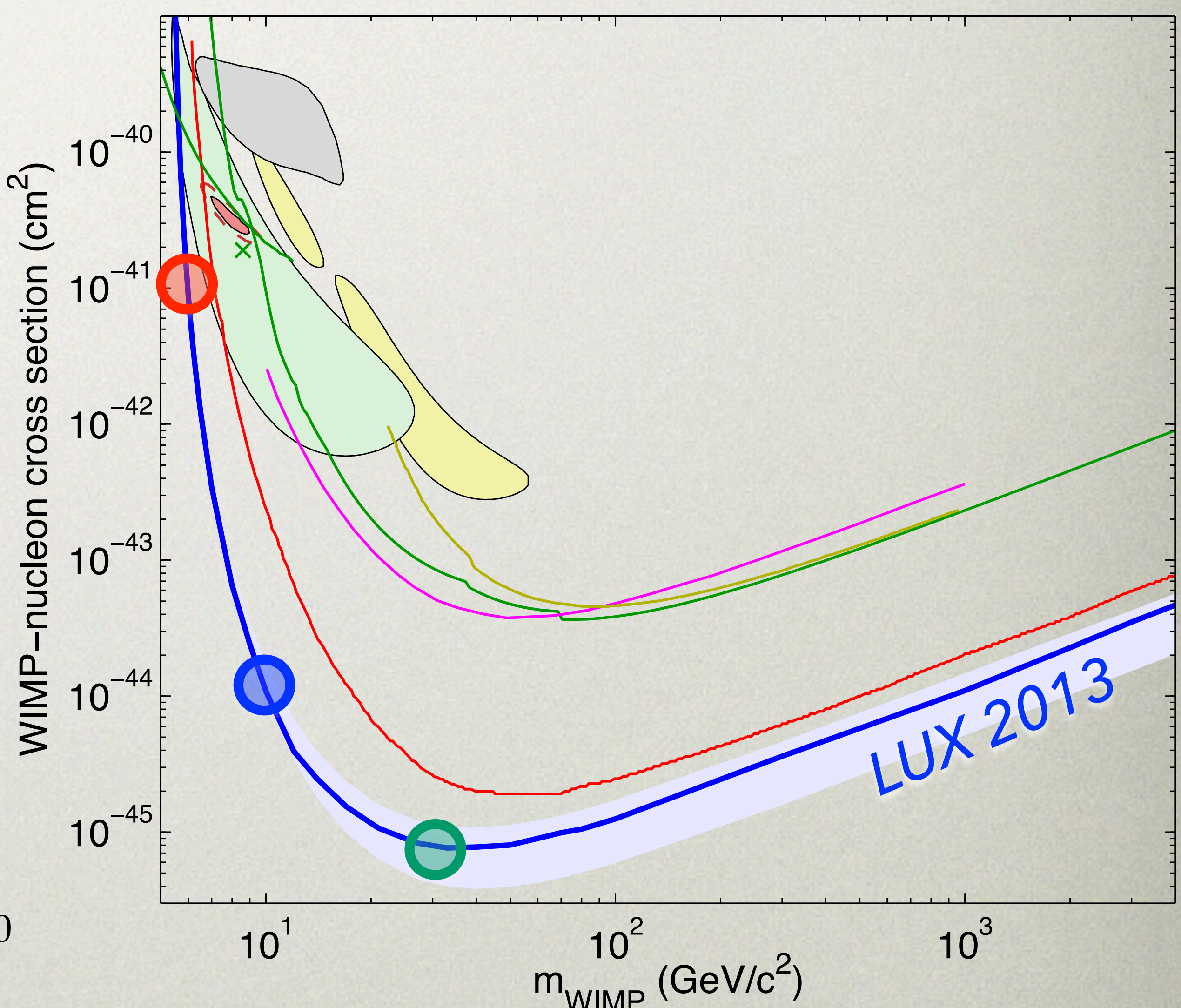
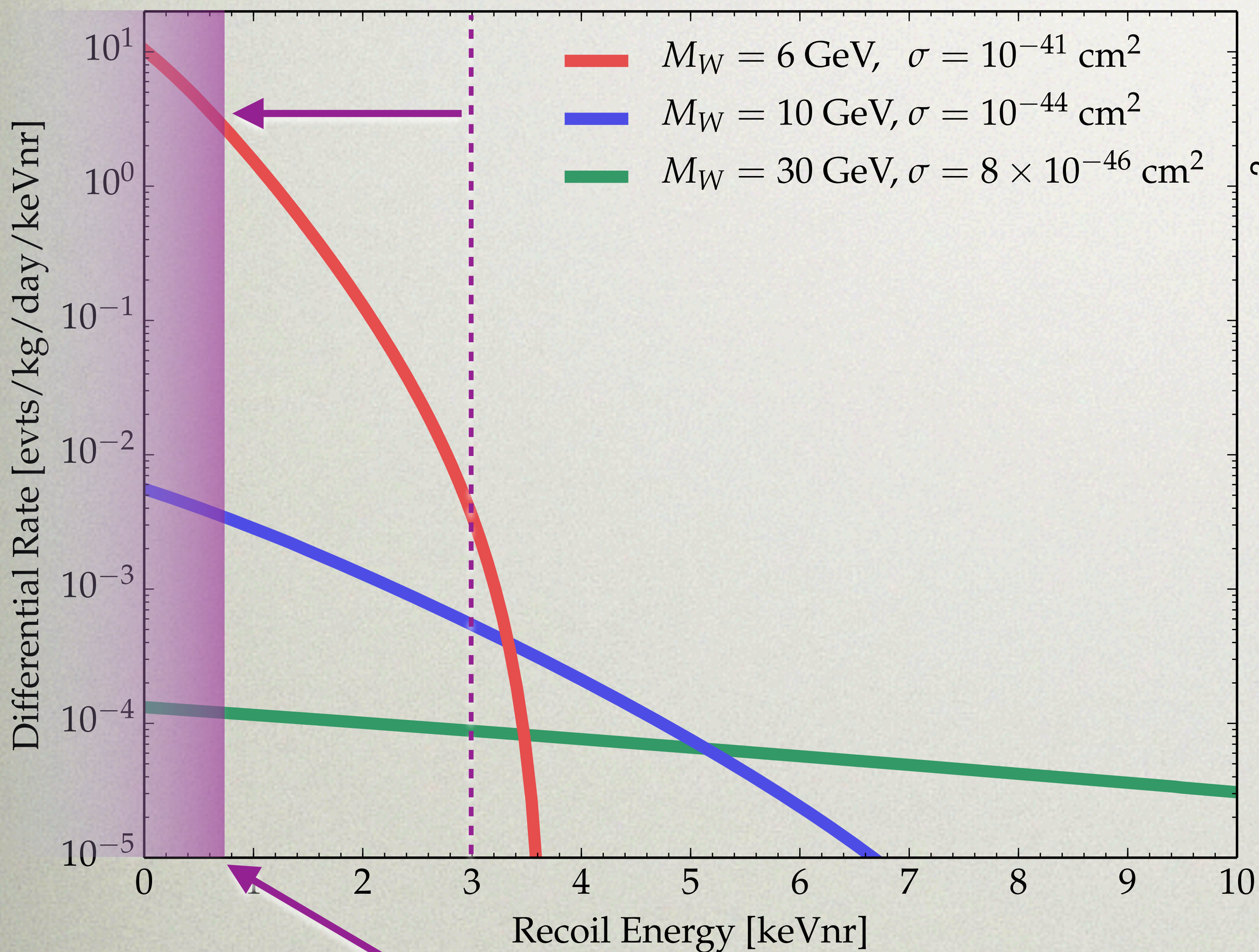
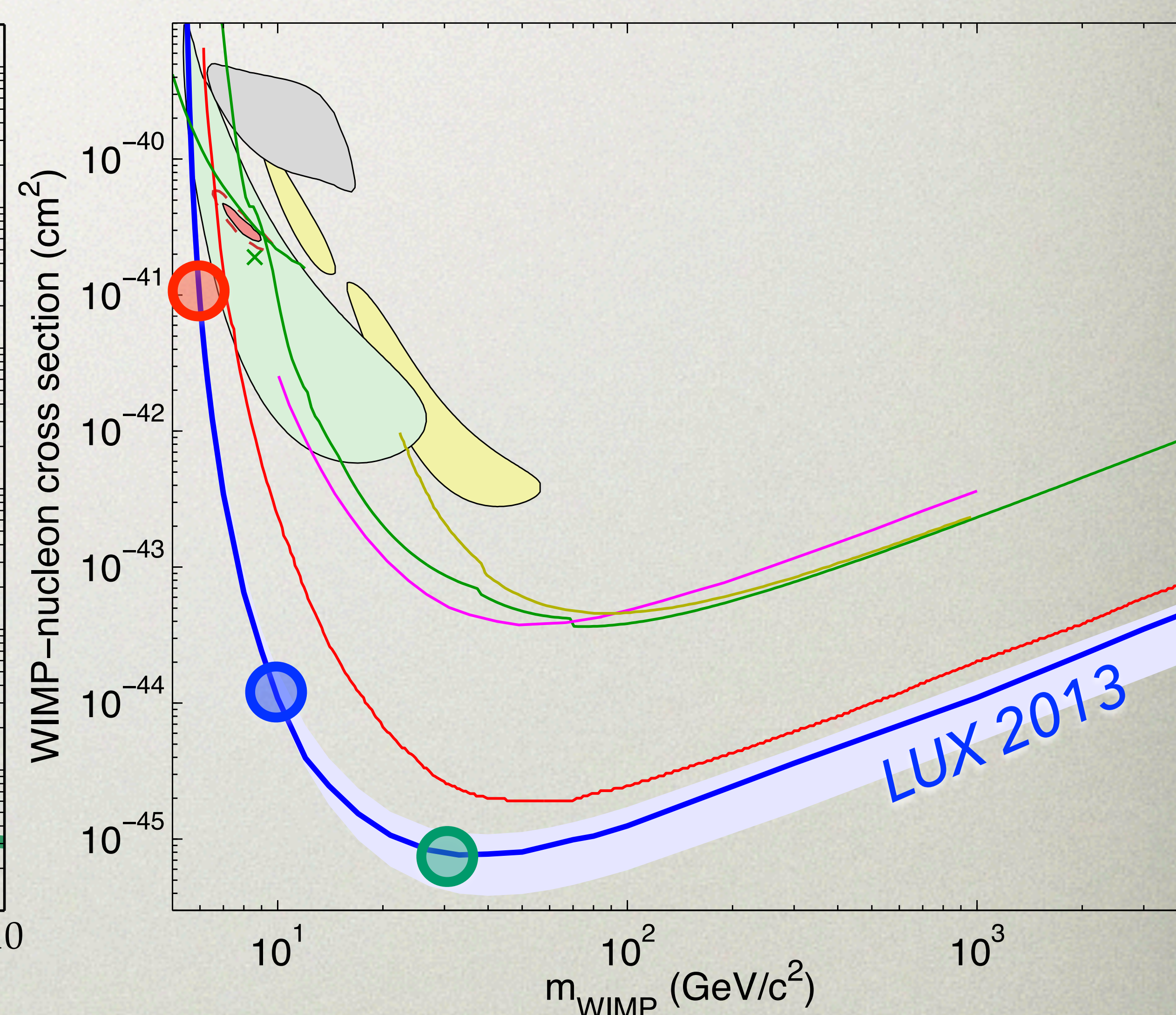




LUX 2013 upper limits assumed NO SENSITIVITY to recoils below 3 keV

Light WIMP search



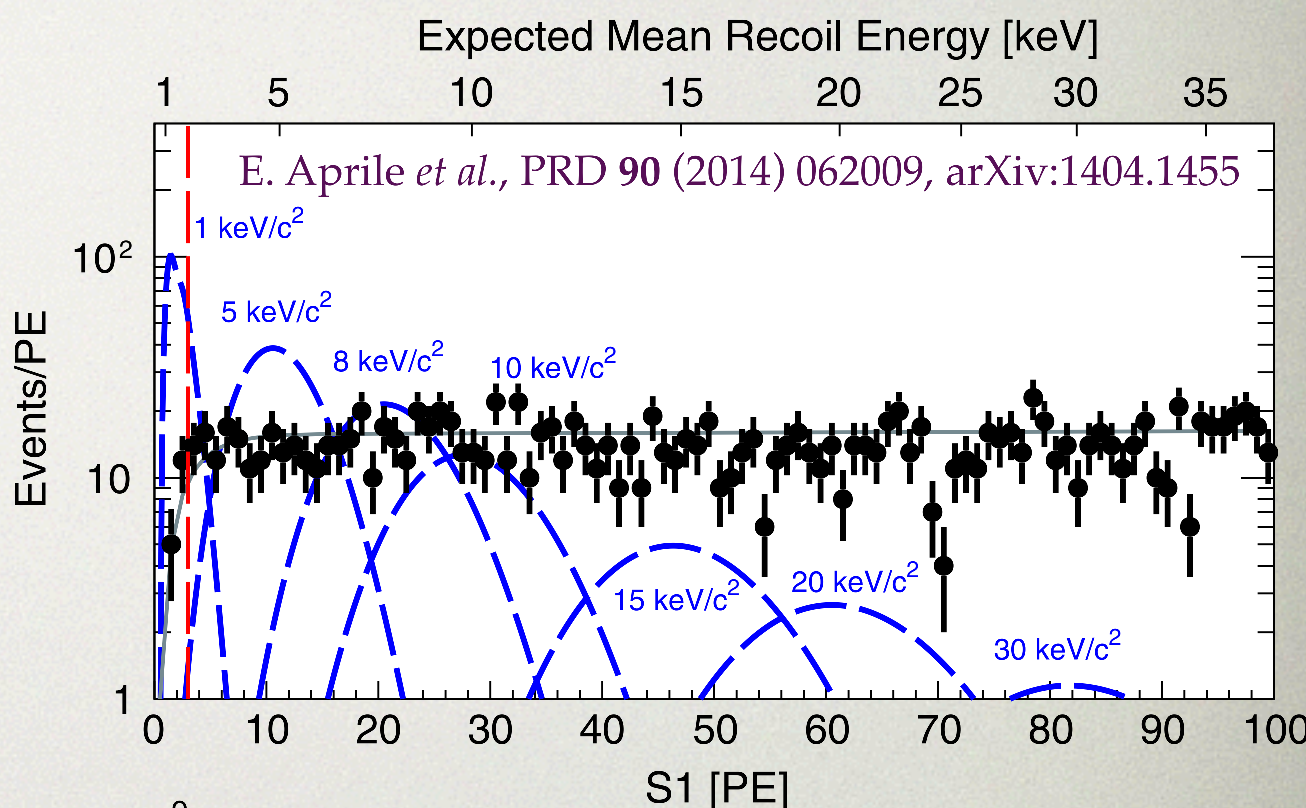


Decreasing this response cutoff from 3keV to 0.75keV
provides access to a factor of **8000*** **more signal** at M = 6 GeV

*Before folding in detection efficiencies

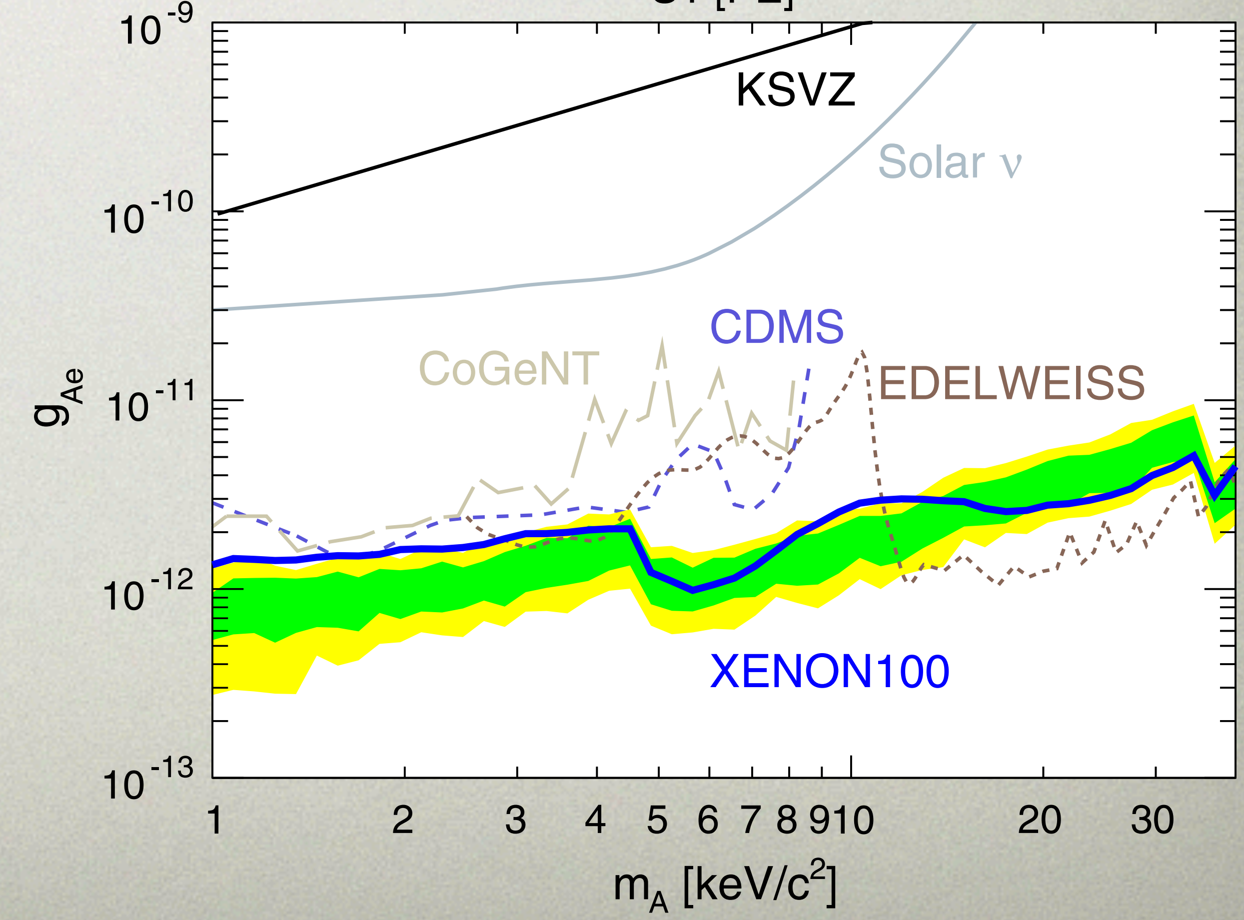
keV axion-like particles

- XENON100 has searched their data for evidence of axio-electric conversion of DM candidates in the O(1-10) keV mass range.
- Easy to search for: looking for a monoenergetic line given by $m_{DM} - E_b$



See talks by:

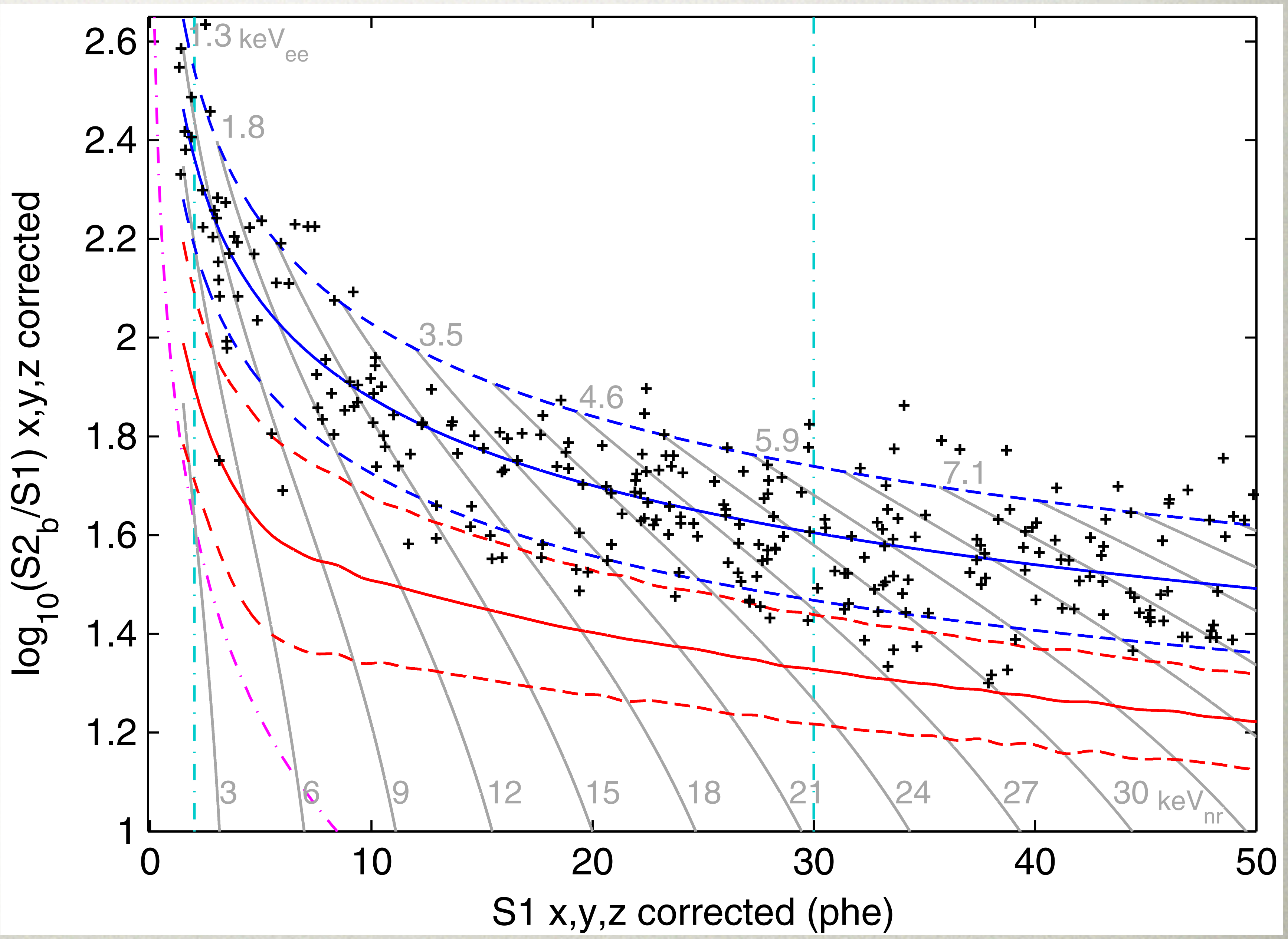
- Ranny Budnik
- Rafael Lang



keV axion-like particles

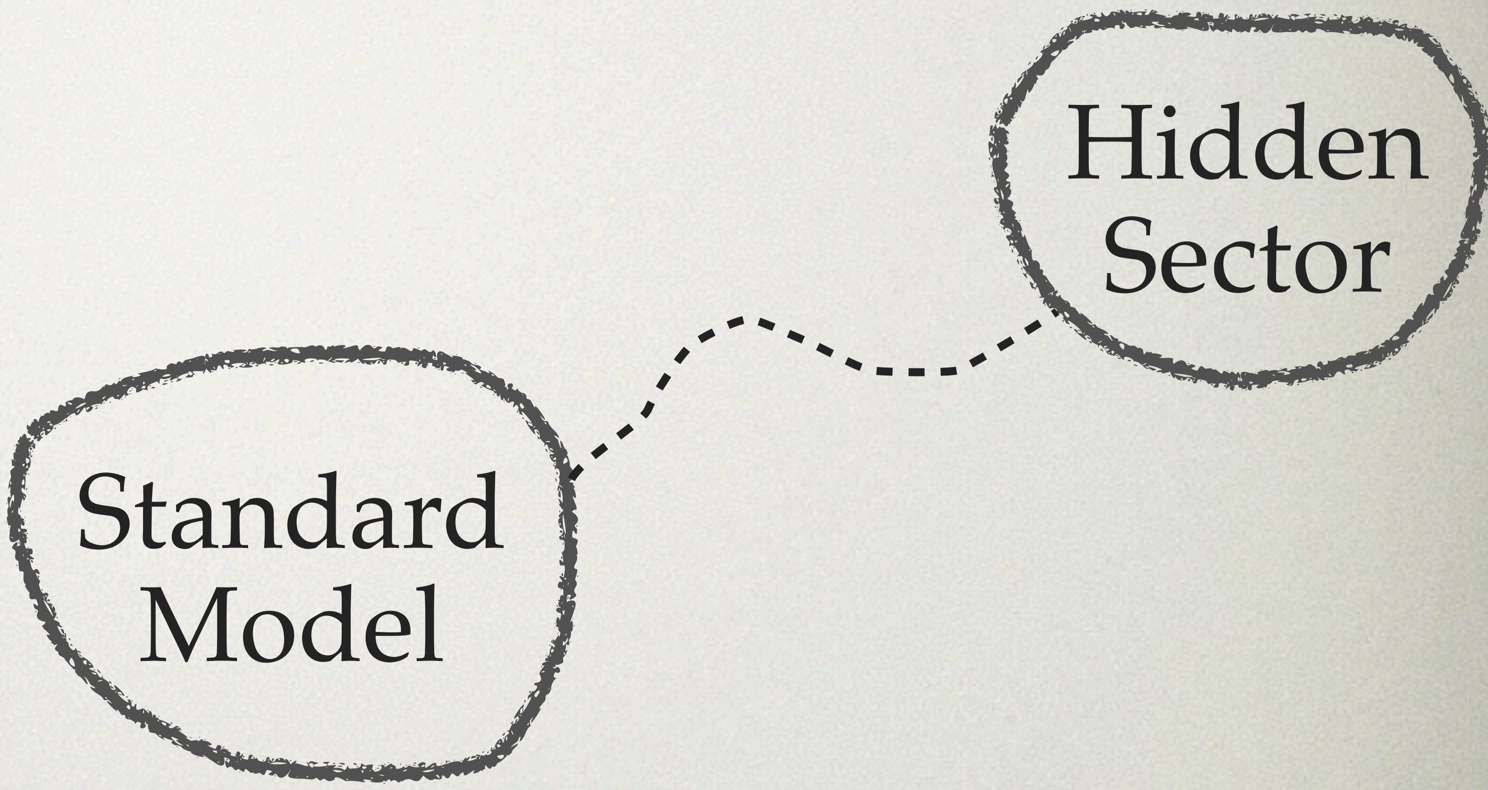
Existing DM WIMP search:

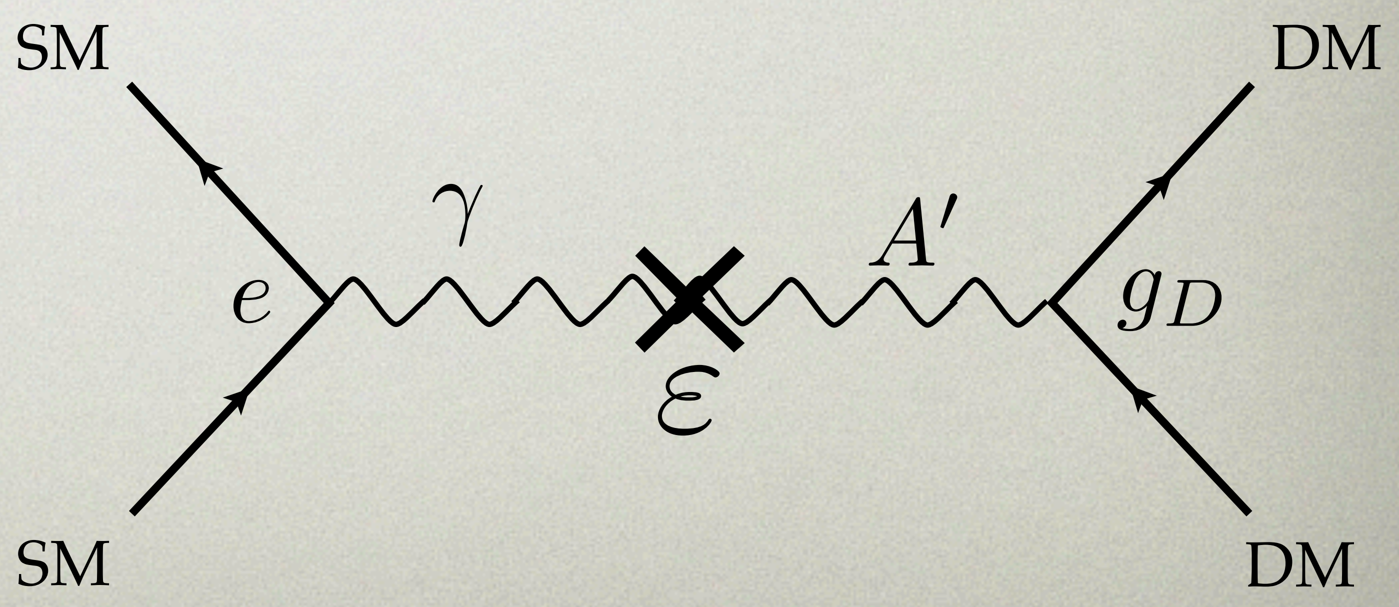
- 160 events between ~1 keV and ~5 keV (electronic-recoil energy)
- 118 kg fiducial mass, 85.3 days
- Lower background than XENON100: can expect improved sensitivity.



Detection of light DM

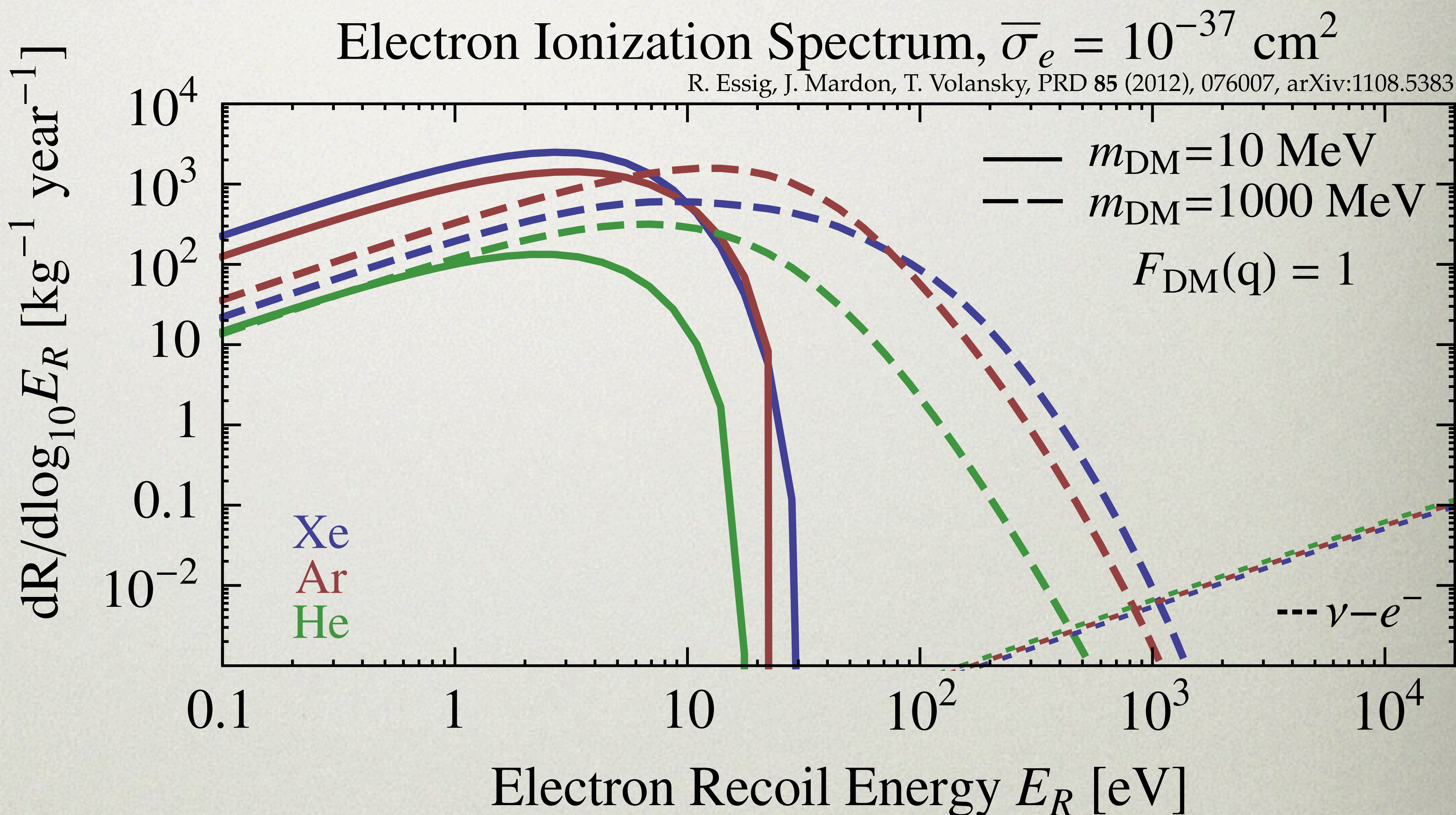
- Hidden sector with its own U(1)′ gauge symmetry.
- The hidden gauge boson, *A′*, kinetically mixes with our photon.
- The DM interacts with SM particles in this way.
- DM masses in the range *O*(1-1000 MeV)
- Kinematics precludes looking for this as nuclear recoils: we look instead for electronic recoils.





Hidden sector on electrons

Expect electronic recoils in the eV to keV range.

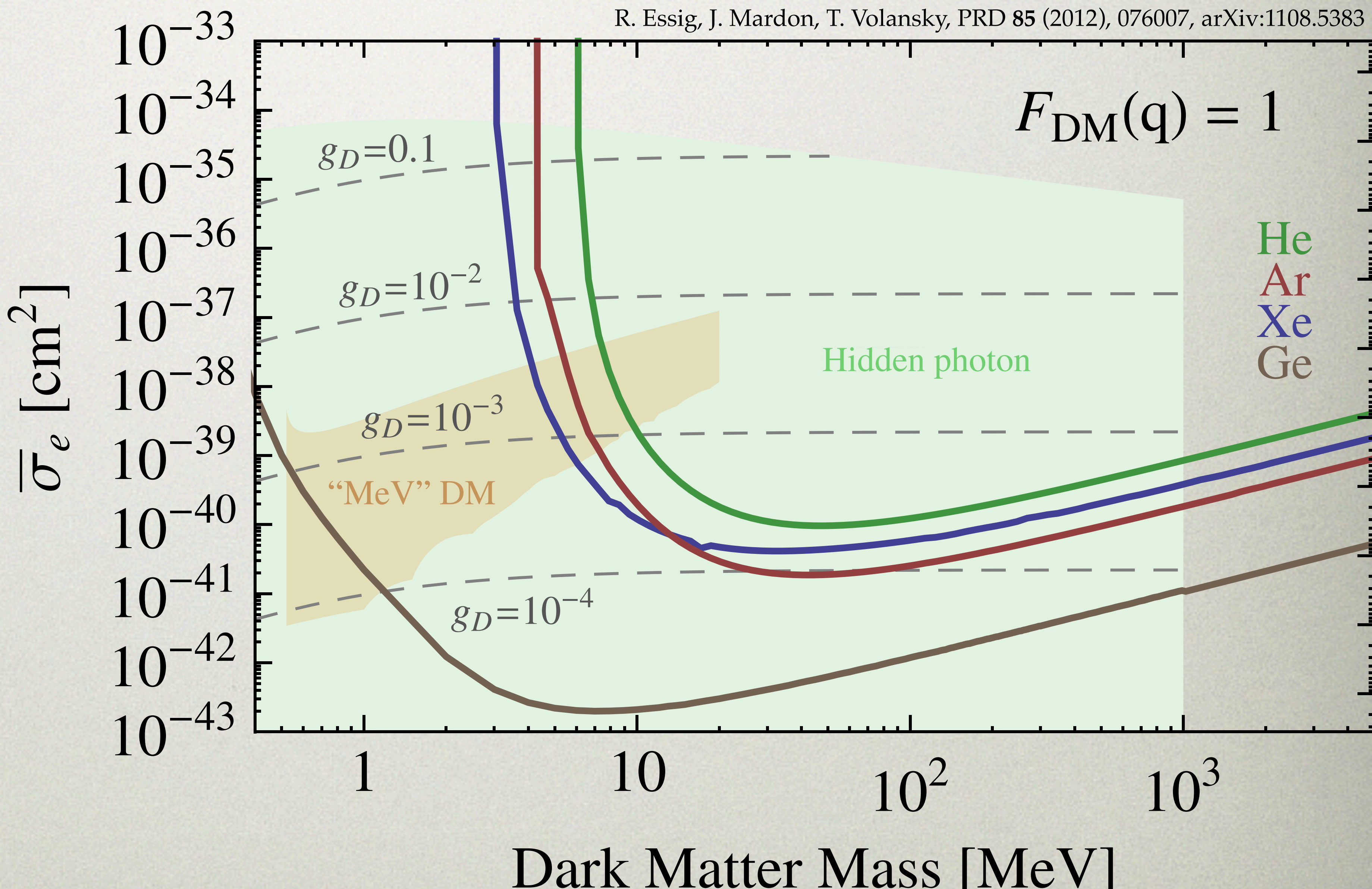


Possible sensitivity

Sensitivity here based on:

- 1 kg detector
- 1 year exposure
- Single-e- threshold
- No background

Cross section Sensitivity and Event Rate (per kg·yea



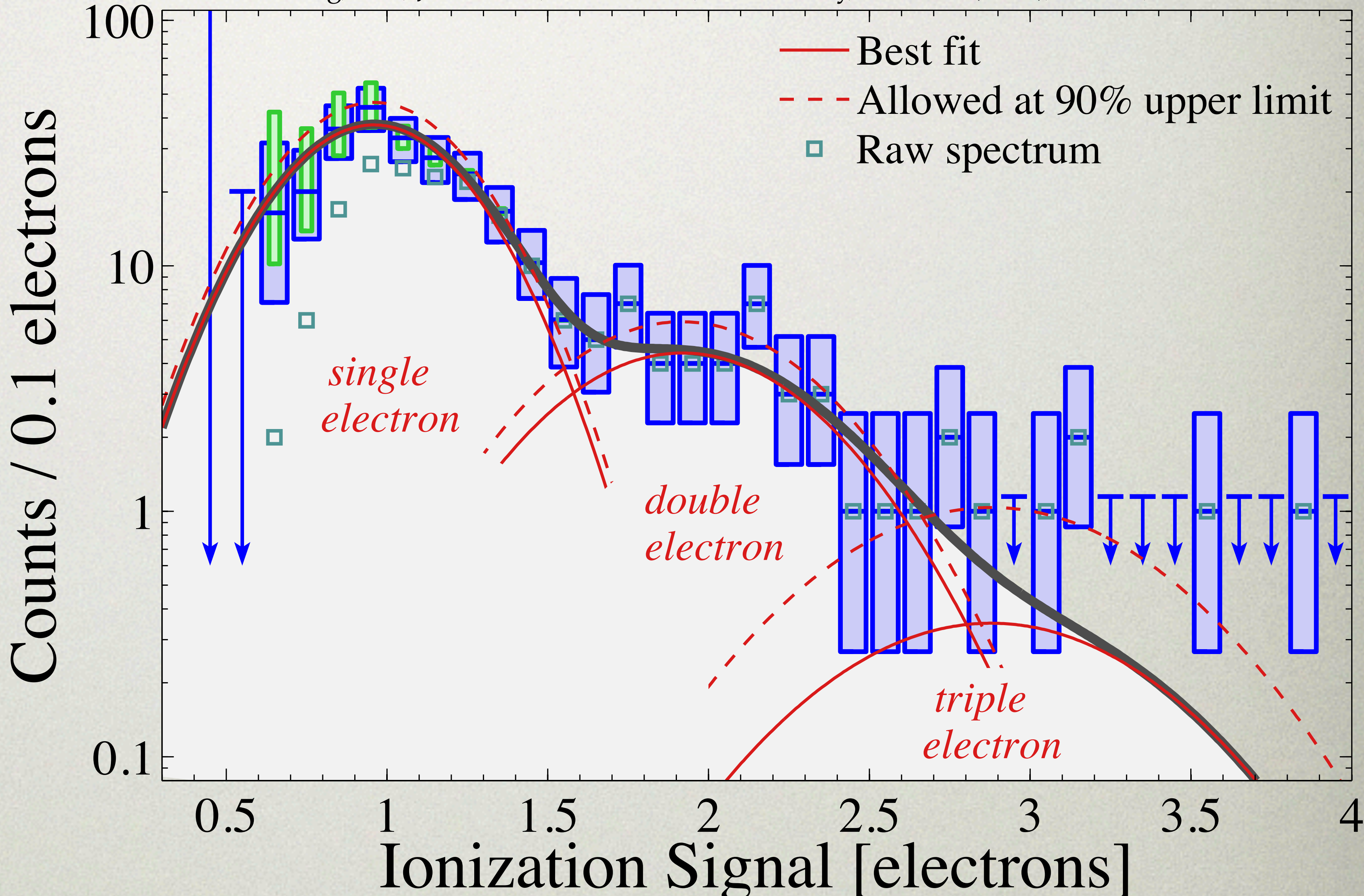
XENON10

90% C.L. Upper Limits
(cts/kg/day)

Single e^-	< 23.4
Double e^-	< 4.23
Triple e^-	< 0.90

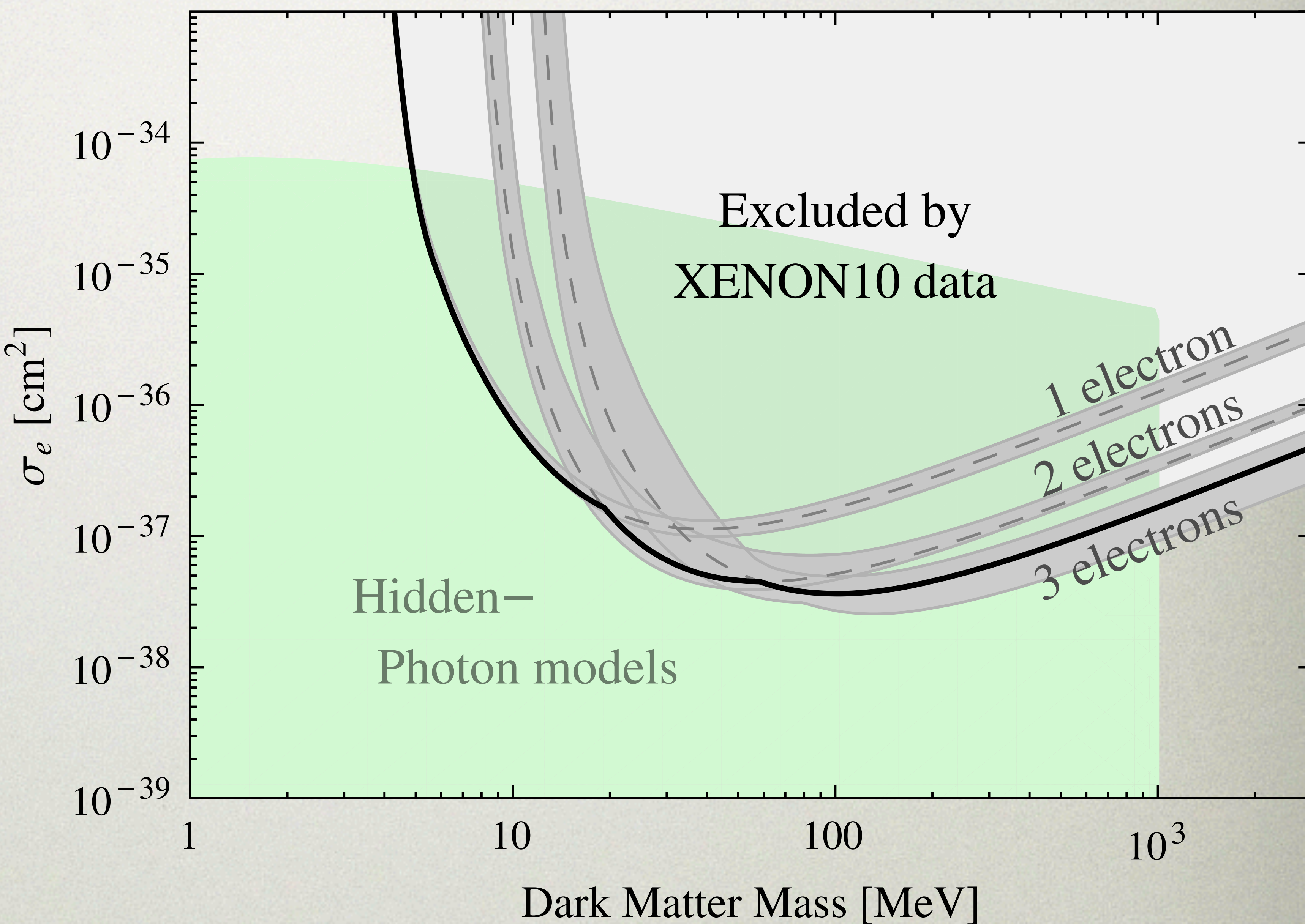
(no BG subtraction)

R. Essig, AM, J. Mardon, P. Sorensen, T. Volansky, PRL **109** (2012), 021301, arXiv:1206.2644



XENON10

- Here for $m_{A'} \approx 10$ MeV, $F(q) = 1$
- 12.5 live-day data set, 1.2 kg, no BG subtraction, can already probe un-touched parameter space.



PRL **109,** 021301 (2012) PHYSICAL REVIEW LETTERS week ending 13 JULY 2012

First Direct Detection Limits on Sub-GeV Dark Matter from XENON10

Rouven Essig,[1,2,*] Aaron Manalaysay,[3,†] Jeremy Mardon,[4,‡] Peter Sorensen,[5,§] and Tomer Volansky[6,||]
[1]*C.N. Yang Institute for Theoretical Physics, Stony Brook University, Stony Brook, New York 11794, USA*
[2]*School of Natural Sciences, Institute for Advanced Study, Einstein Drive, Princeton, New Jersey, USA*

XENON10

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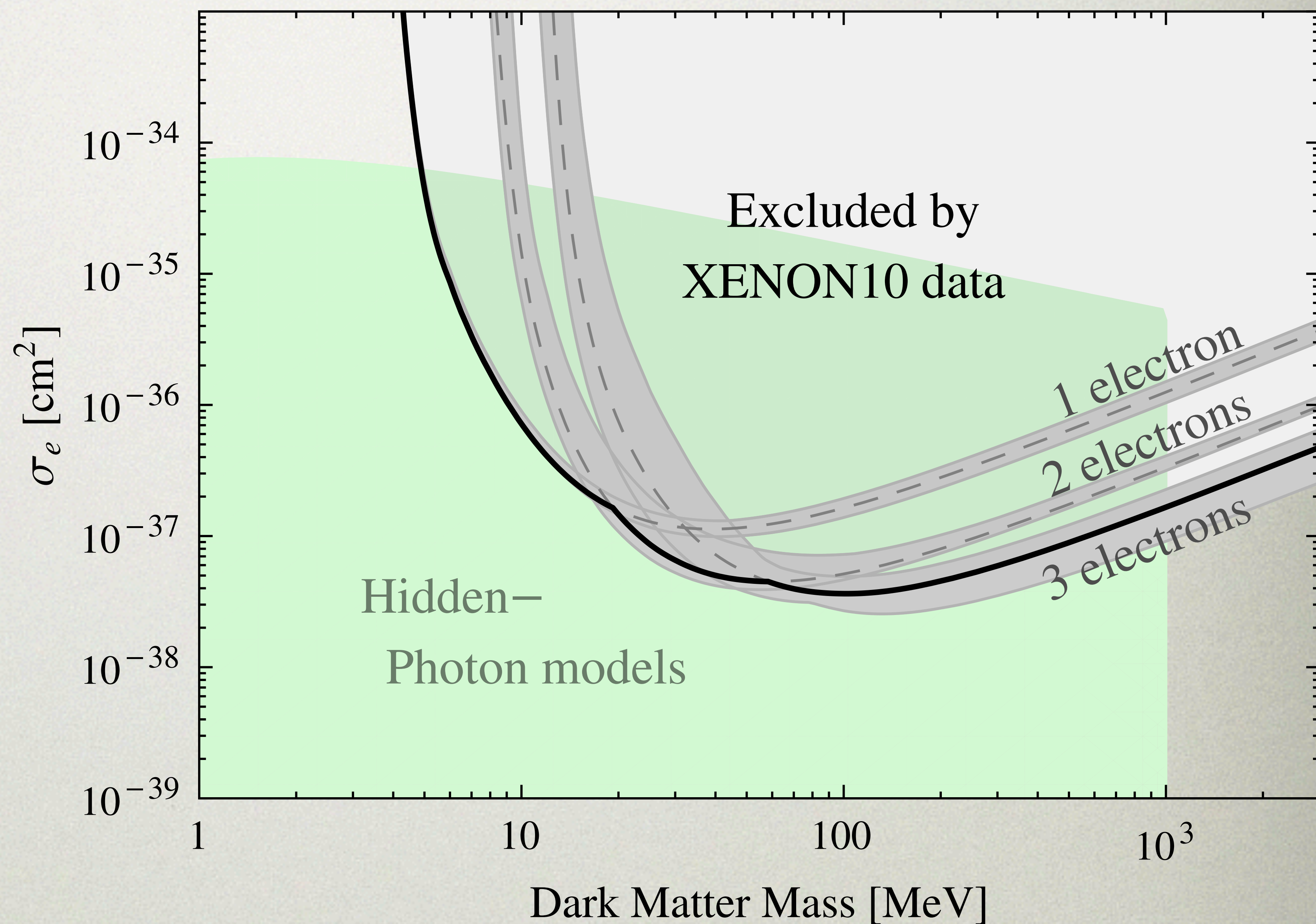
- 12.5 live-day data set, 1.2 kg, no BG subtraction, can already probe un-touched parameter space.

"Proof of principle"



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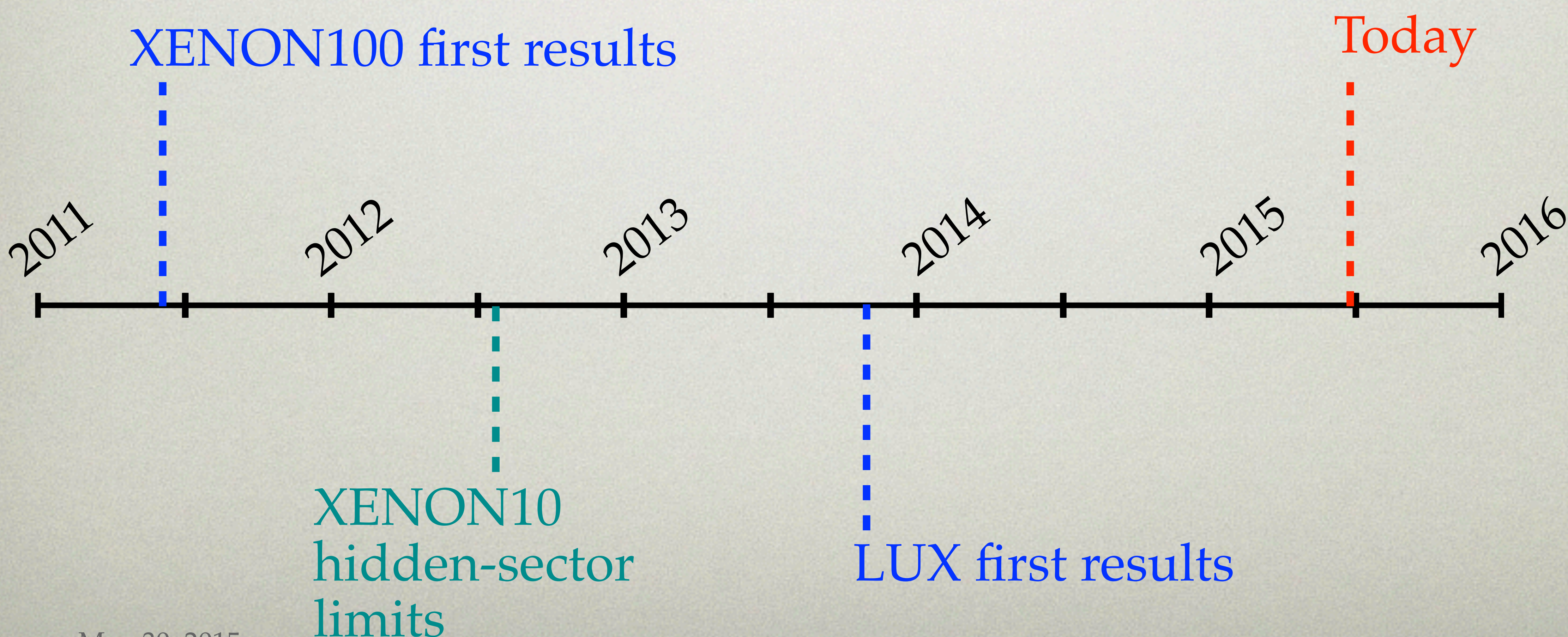
[1]C.N. Yang Institute for Theoretical Physics, Stony Brook University, Stony Brook, New York 11794, USA
[2]School of Natural Sciences, Institute for Advanced Study, Einstein Drive, Princeton, New Jersey, USA

Is it really that easy?

Timeline

If it’s so easy, then why have we seen no results yet from XENON100 or LUX?



Challenges

Why is this type of search challenging?

Two problems:

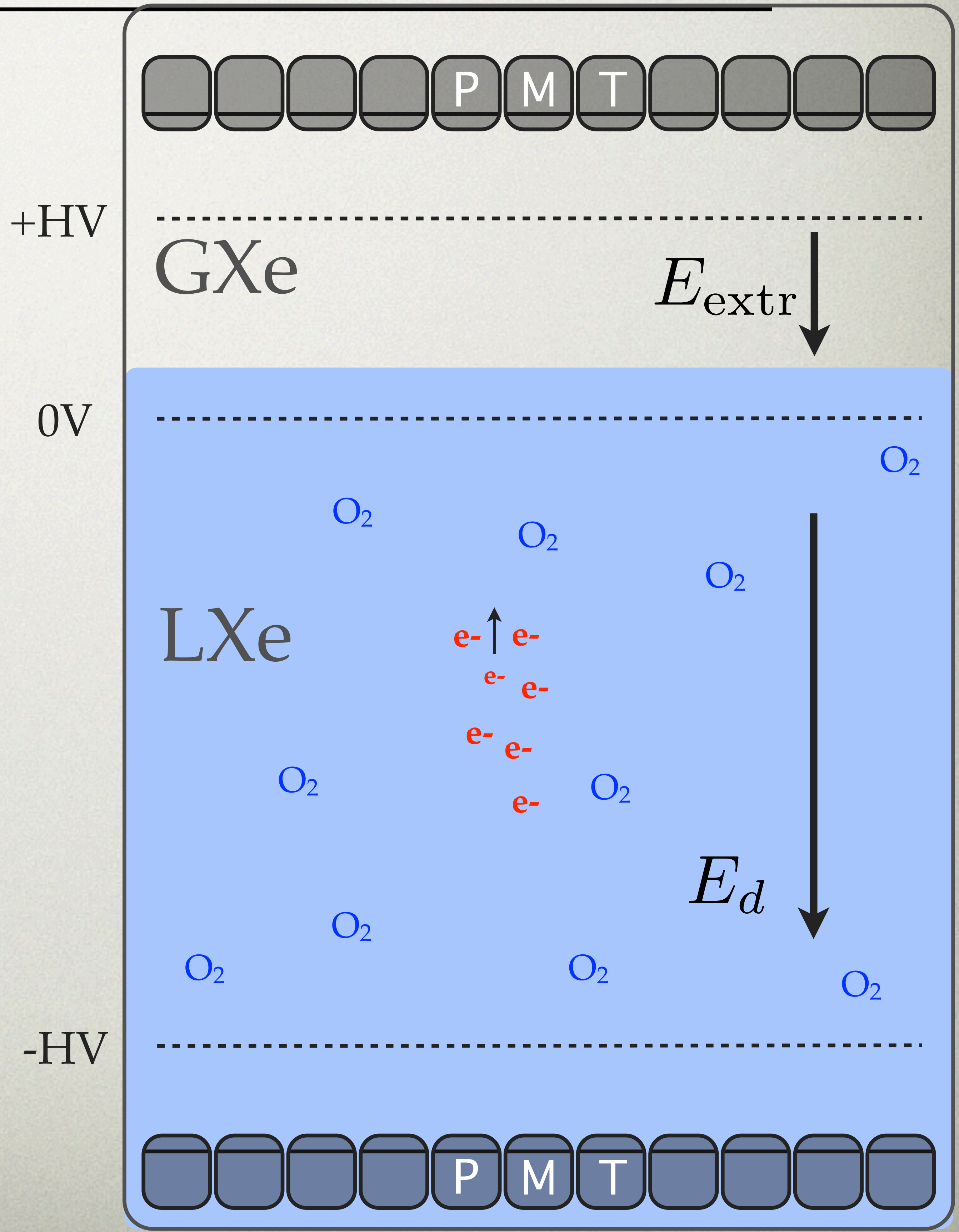
1. Detector details:
   - Detector “features” lead to difficulties in interpreting ionization-only searches.

2. Backgrounds:
   - In normal mode (ionization and scintillation), BG can be rejected either by particle ID, or vertex position. This is not possible with ionization-only.

Problem 1

Large detectors are harder to build than small detectors

Experiment	Charge loss to impurities*
XENON10	~0%
XENON100	~40%
LUX	~30%



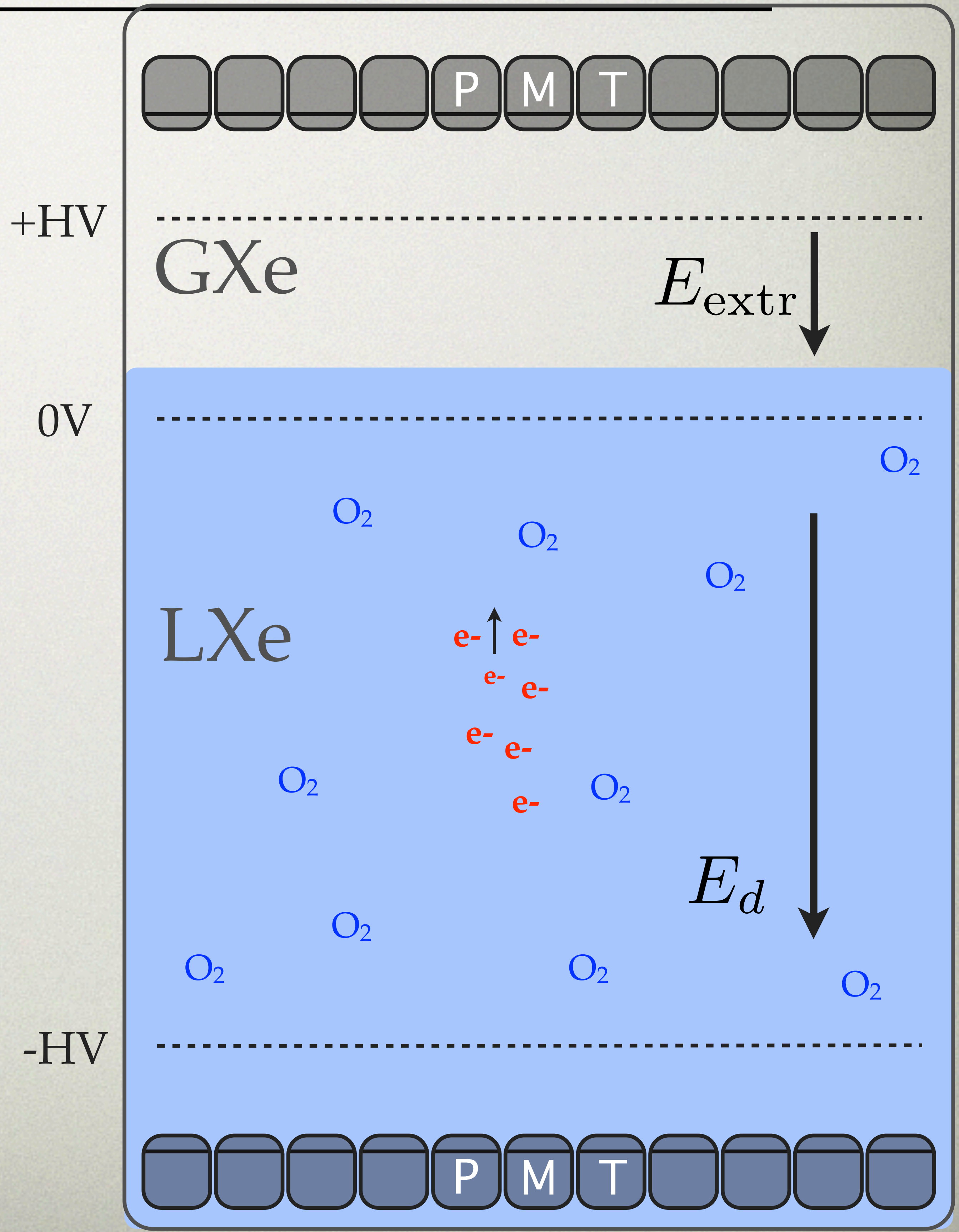
*For events on the bottom

Problem 1

Large detectors are harder to build than small detectors

Experiment	Charge loss to impurities*
XENON10	~0%
XENON100	~40%
LUX	~30%

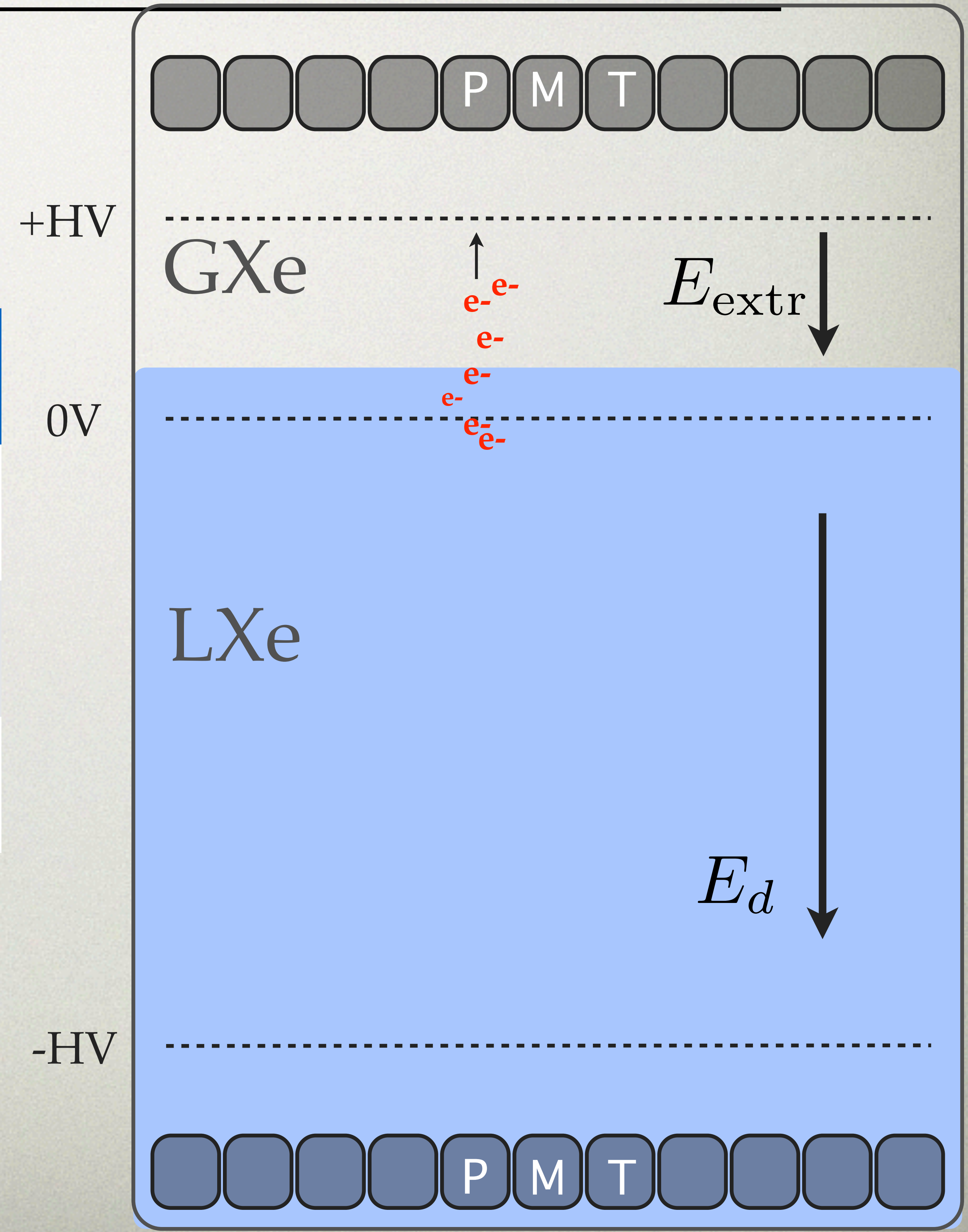
The amount of charge loss depends on the depth of the event. Without a scintillation signal, we cannot reconstruct the depth.



Problem 1

Large detectors are harder to build than small detectors

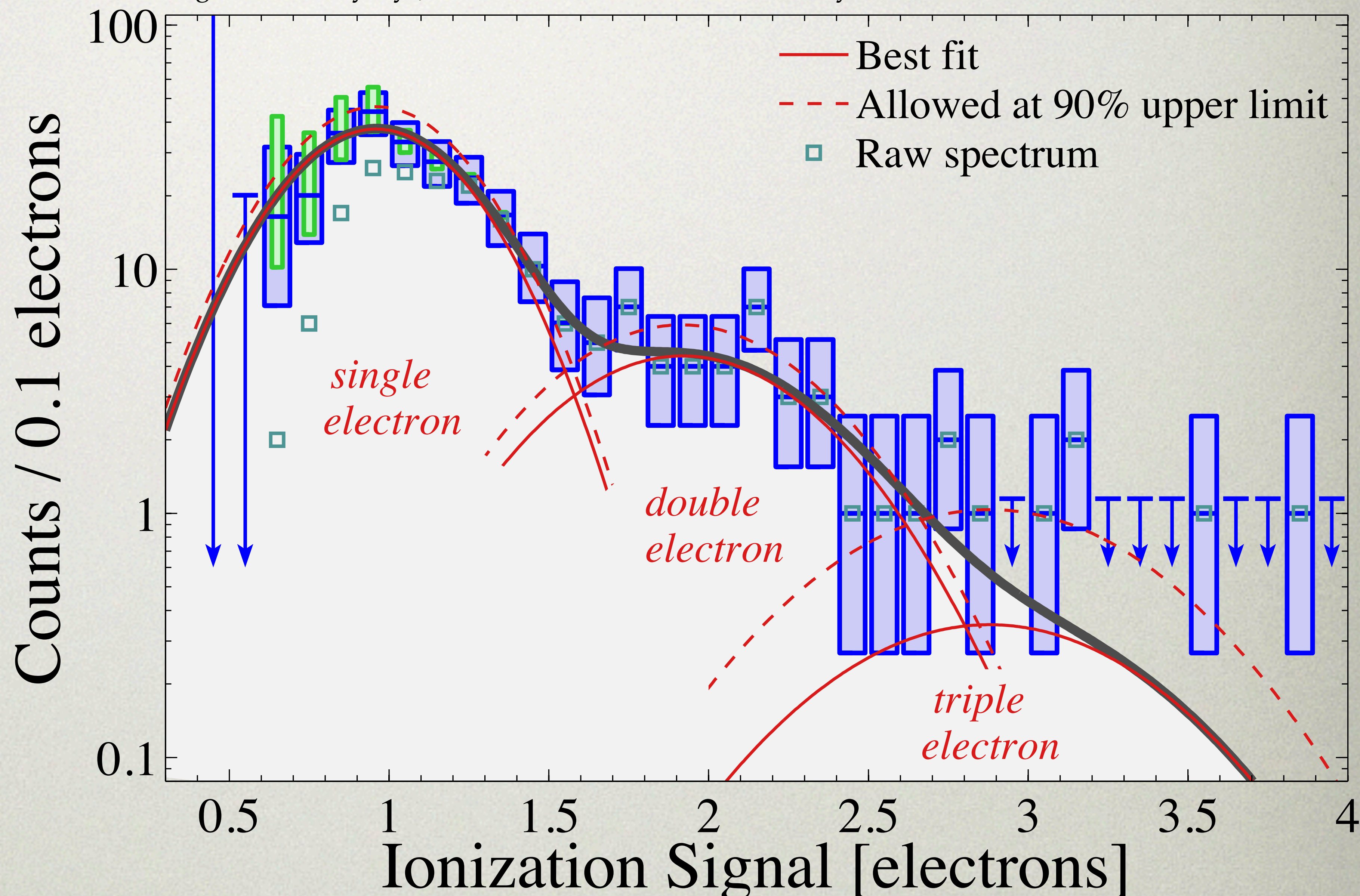
Experiment	Liquid-gas electron extraction efficiency
XENON10	~100%
XENON100	~100%
LUX	~50%



Problem 2: single electrons

"Background-free"
is a pipe dream

R. Essig, A. Manalaysay, J. Mardon, P. Sorensen, T. Volansky, PRL **109** (2012), 021301, arXiv:1206.2644



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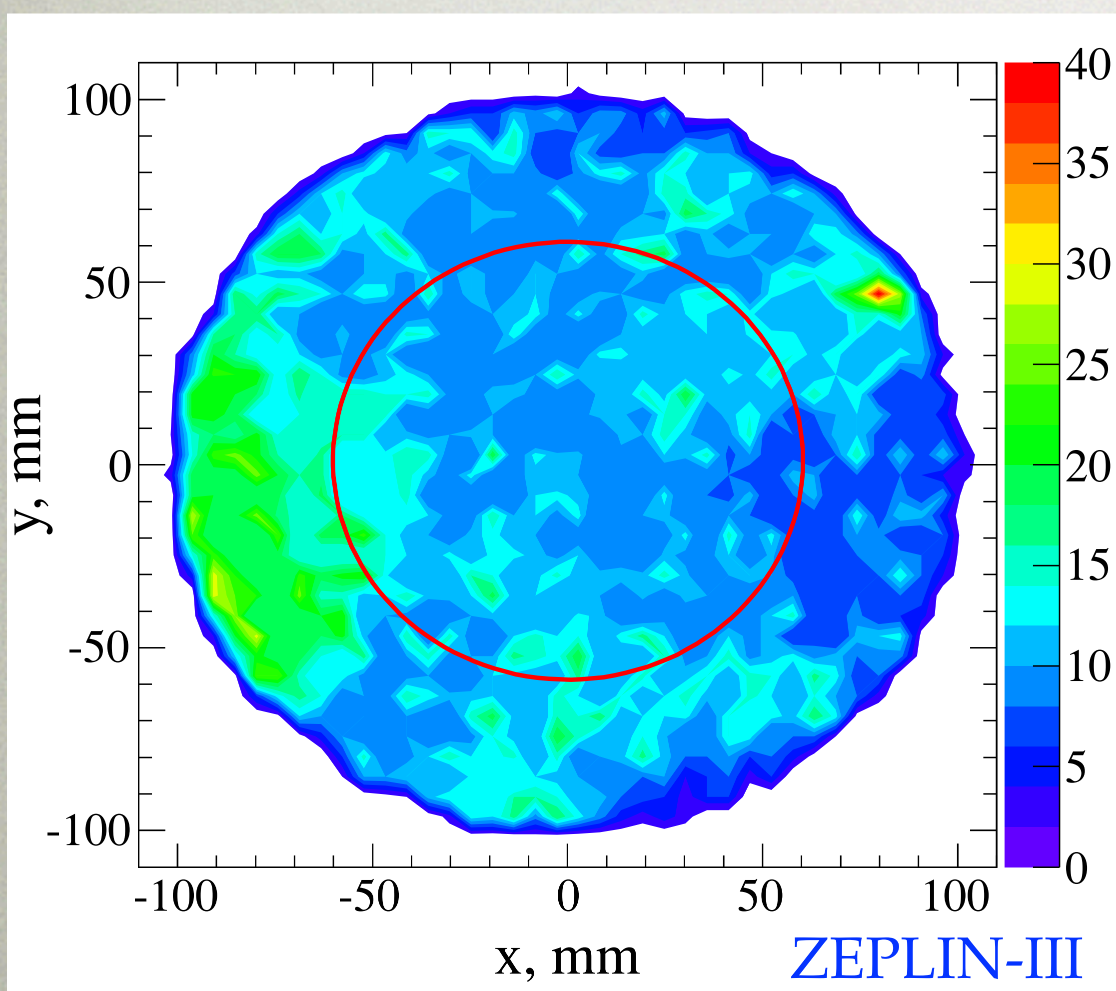
"Background-free" is a pipe dream

All dual-phase LXe DM experiments have observed single-e⁻ backgrounds that are difficult to model. LUX is no different



E. Santos *et al*. JHEP**12** (2011) 115

B. Edwards *et al*. Astropart. Phys. **30** (2008) 54

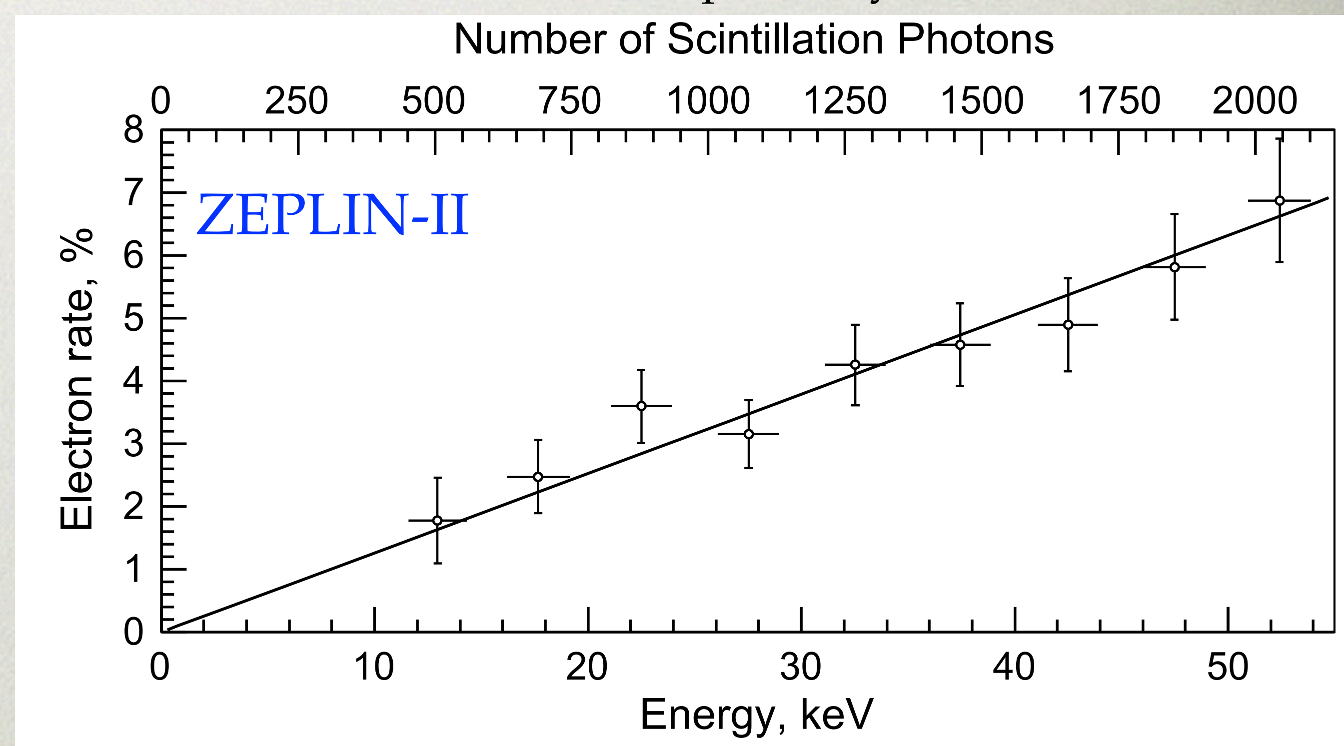


Fig. 6. Fraction of primary triggers where a single electron is observed as a function of primary signal size (normalized to γ-ray energy), calculated as the fraction of timelines checked containing single electron signals.

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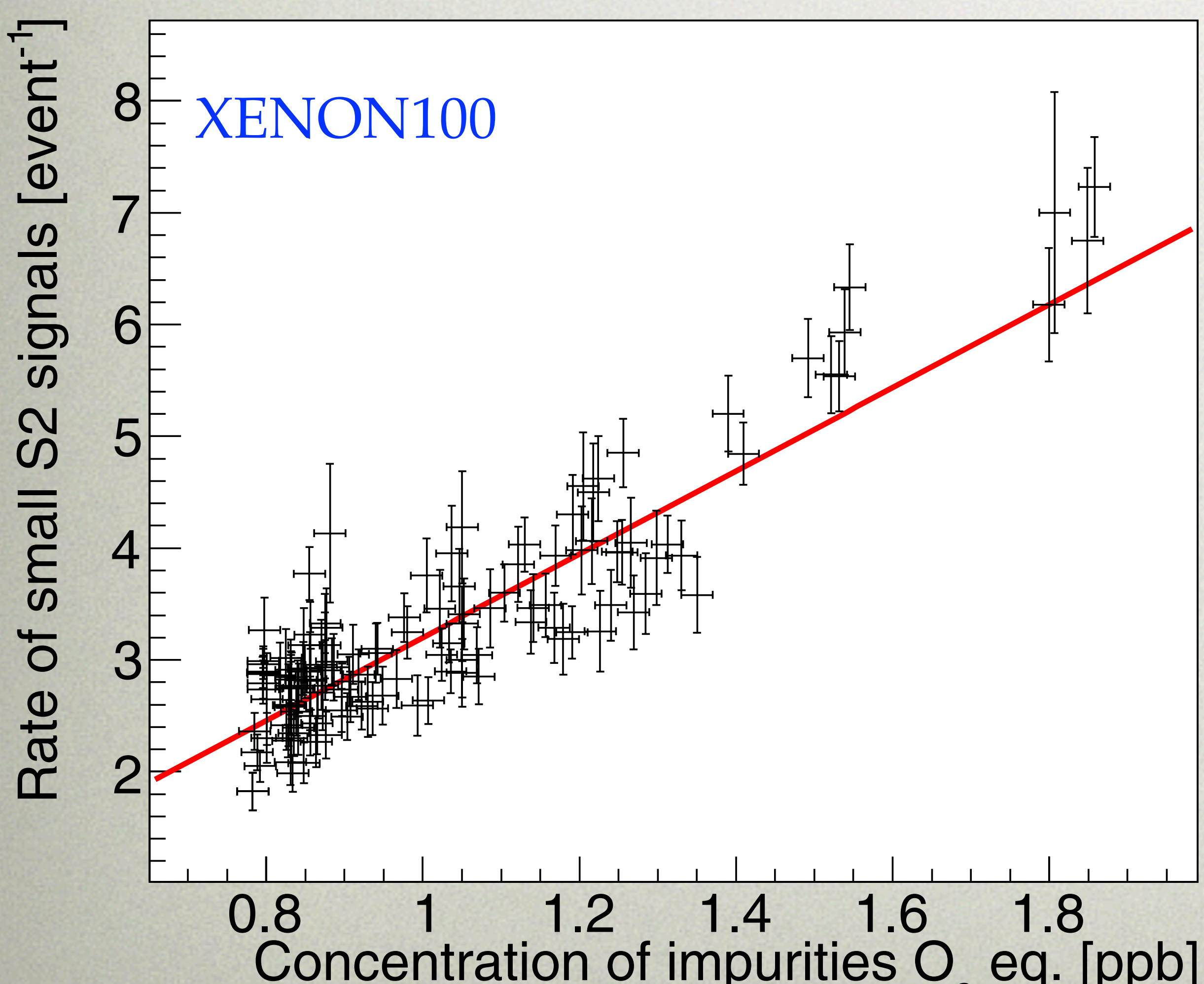
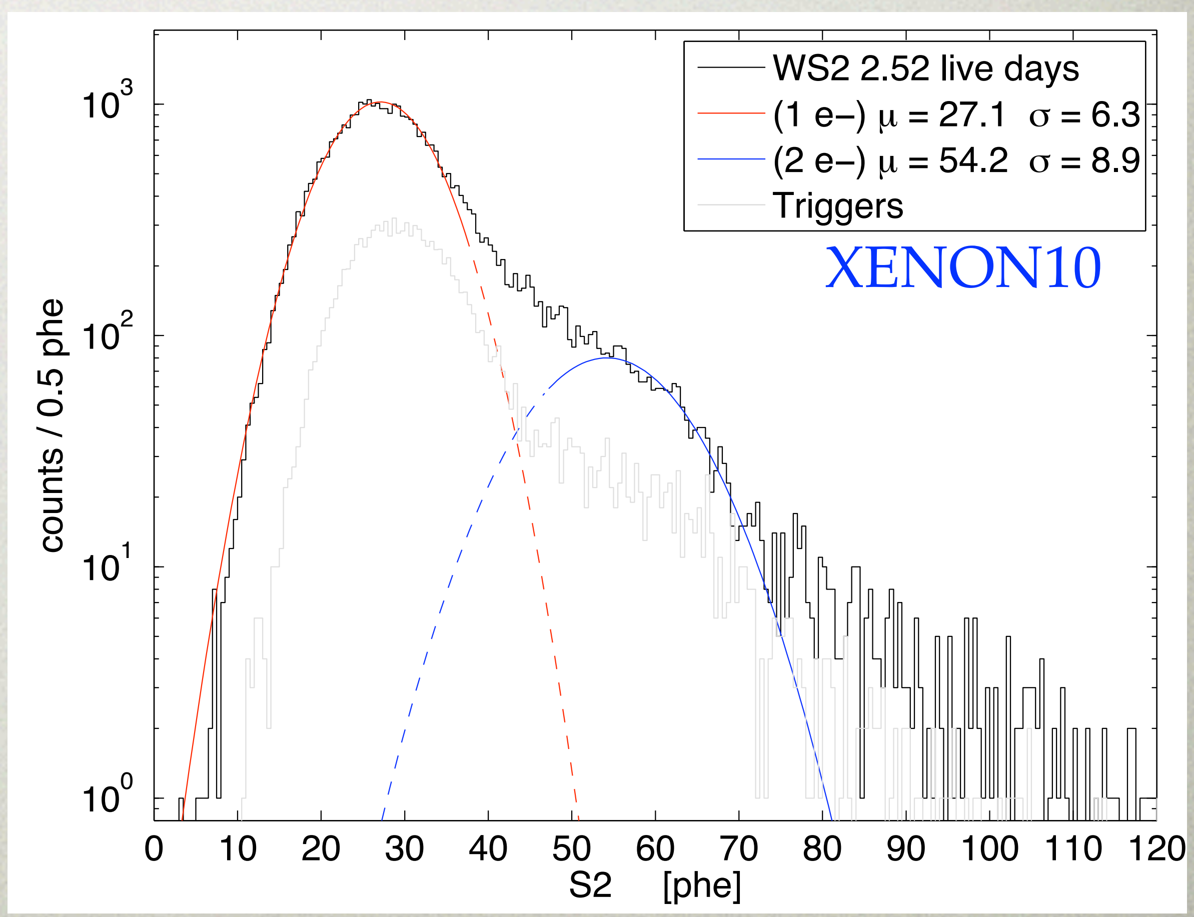


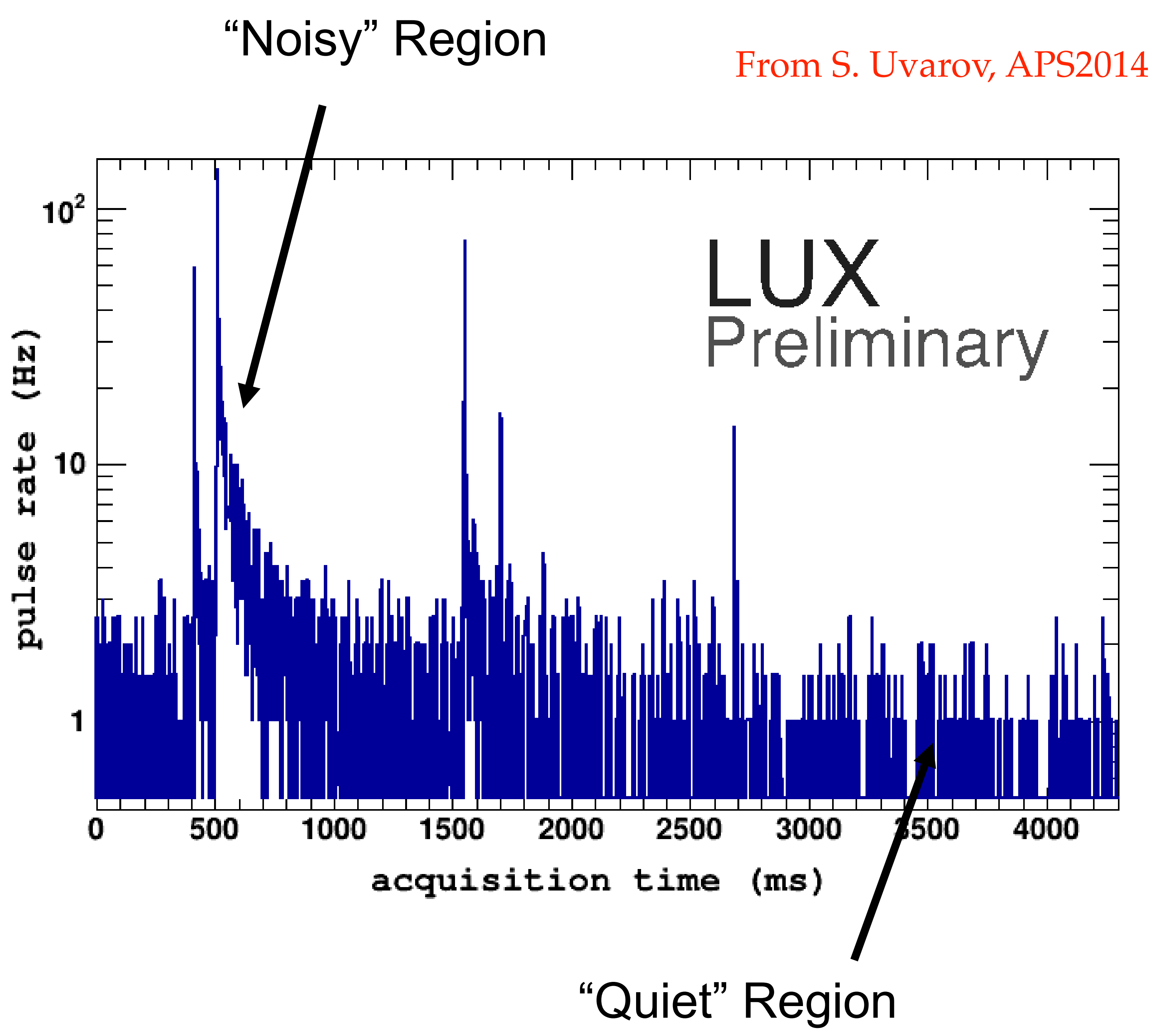
E. Aprile *et al*. J. Phys. **G 41** (2014) 035201



P. Sorensen, Ph.D. Dissertation (2008), Brown University

Problem 2: single electrons

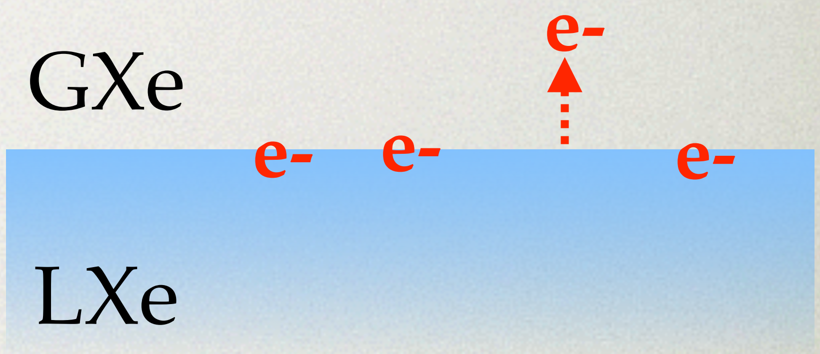
- Because LUX's acquisition system is triggerless (i.e. we record everything), we can monitor these events as well.
- Following a large event, we see elevated pulse activity, which decays through several different time constants.



Problem 2: single electrons

These observations teach us that multiple mechanisms contribute to single-electron background signals.

- The electrons see a potential barrier at the surface and can get trapped there, to later “evaporate” off.



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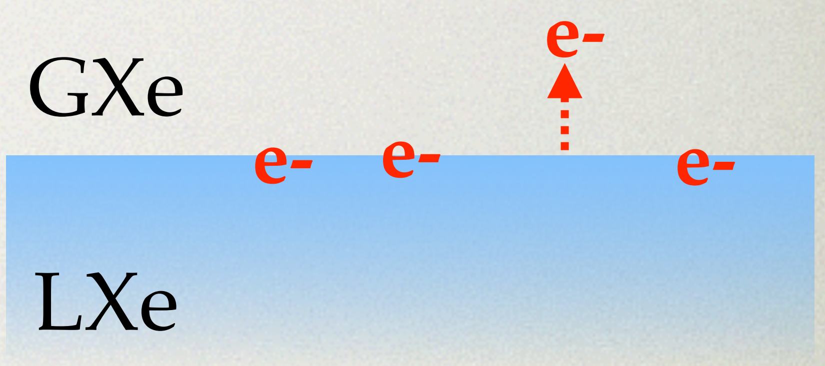
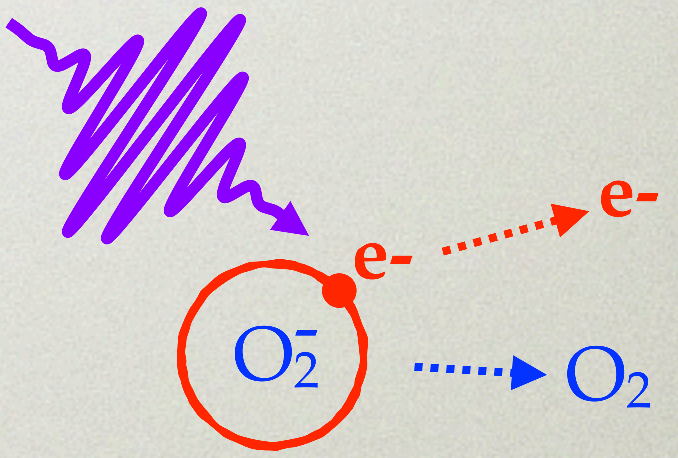


- O_2 impurities that have captured an electron can be ionized by a Xe scintillation photon.



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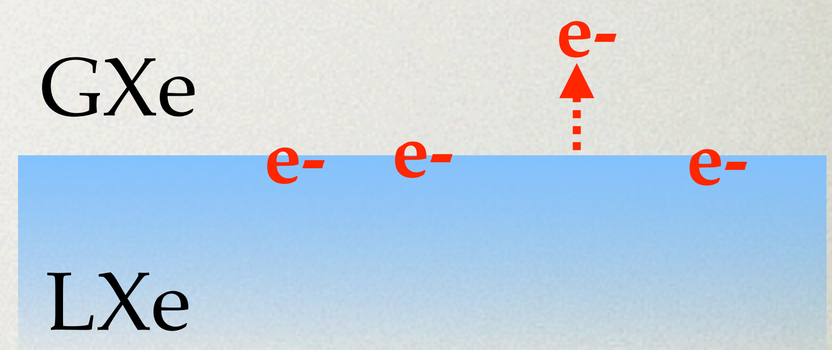

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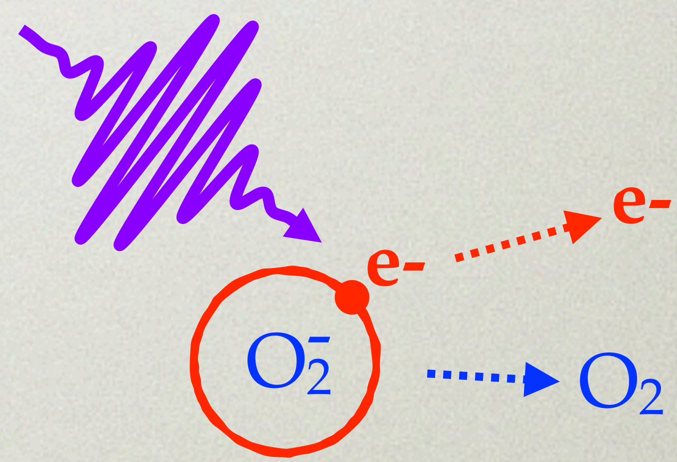
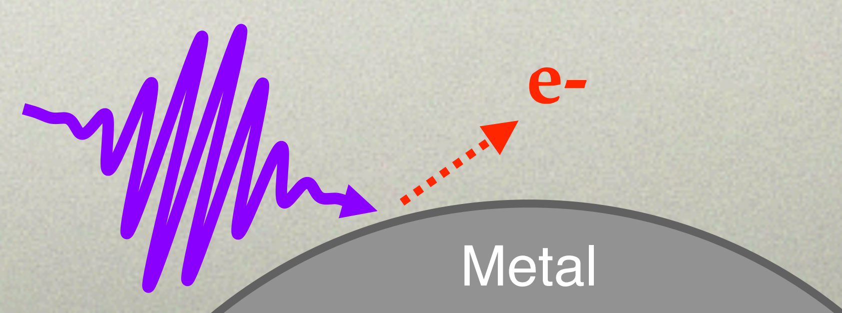
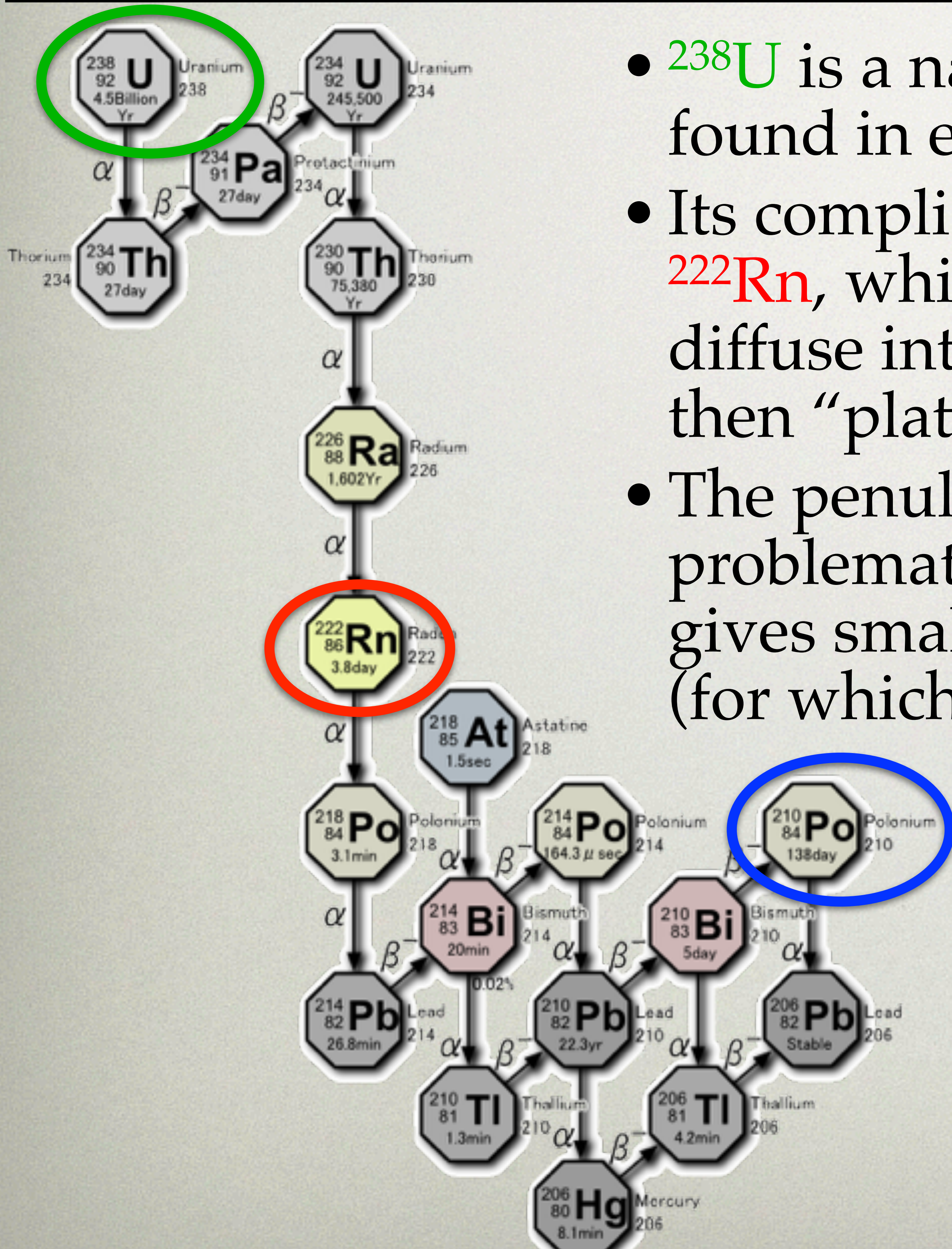


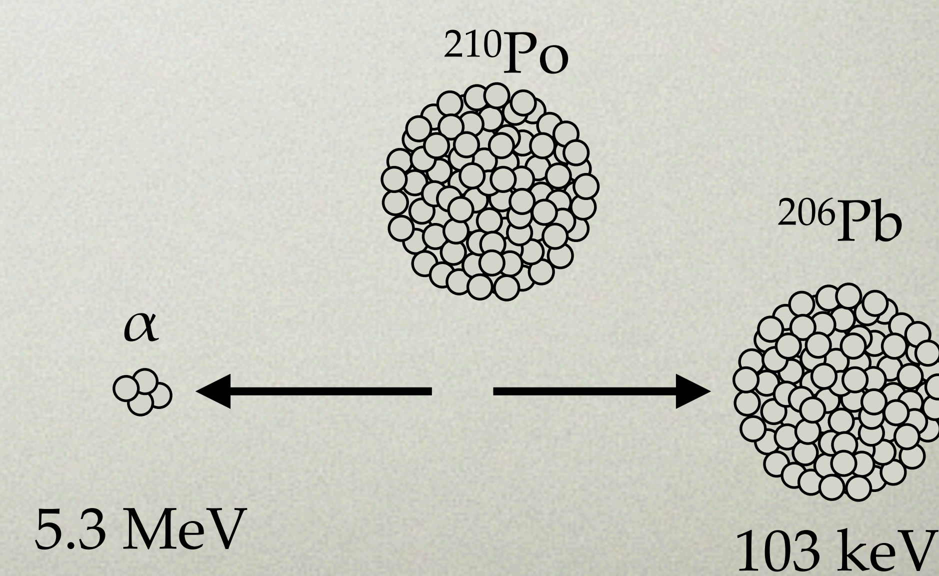
- A Xe scintillation photon (7 eV) can eject an electron from the surface of a metal (i.e. one of the electrodes).



Problem 2: surface backgrounds

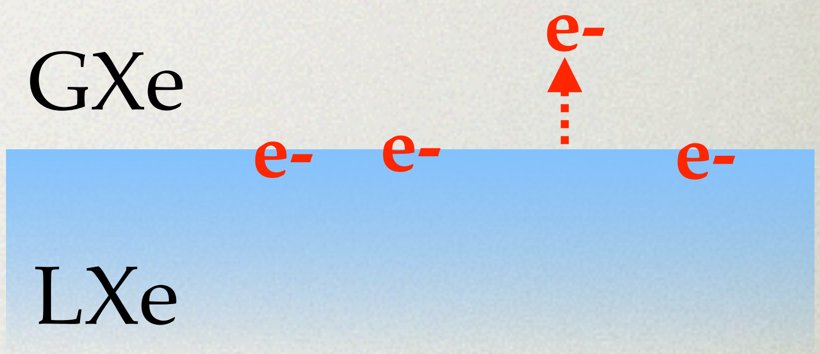


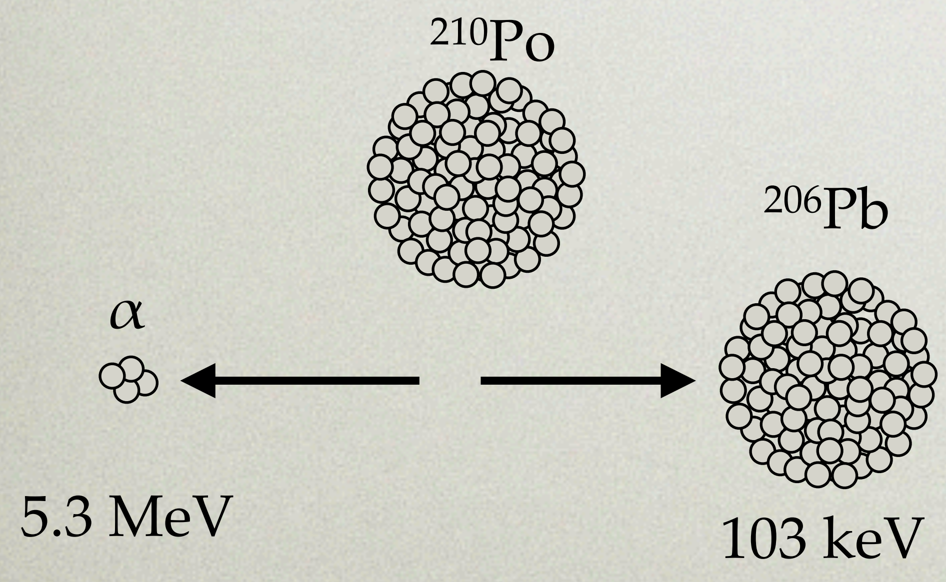
- ^{238}U is a naturally occurring radioisotope, found in every material in nature.
- Its complicated decay chain takes it through ^{222}Rn, which is a noble gas, and can therefore diffuse into the air and get everywhere. It will then “plate out” once it decays.
- The penultimate daughter, ^{210}Po, is problematic: low energy, heavy projectile, gives small ionization and scintillation signals (for which we don’t yet have measurements).



Problem 2: wrap up

- We are currently unable to model these processes, and hence unable to form a background model. No background model -> limits only
- Several LUX/LZ groups are building dedicated setups to study these processes thoroughly*.





*An empirical model can be made in some, but not all situations.

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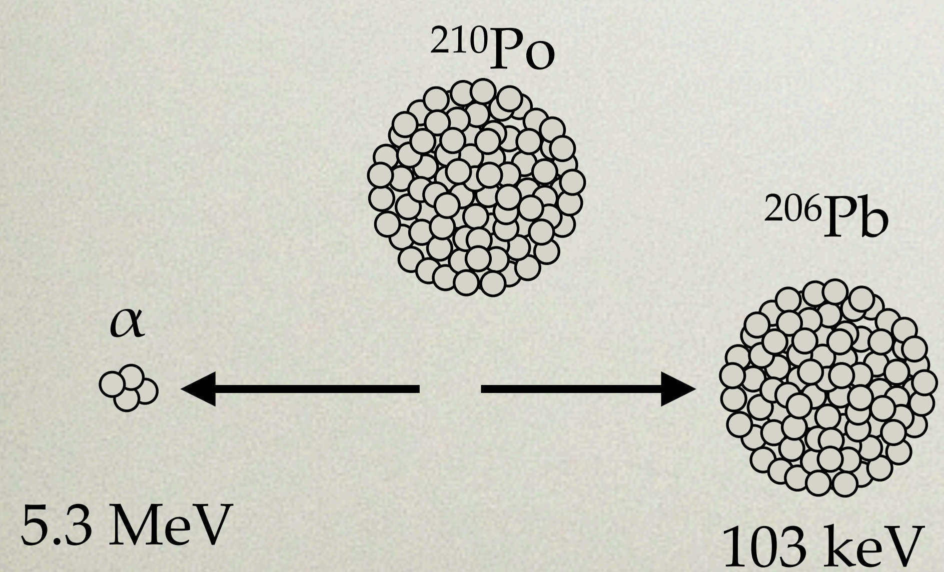

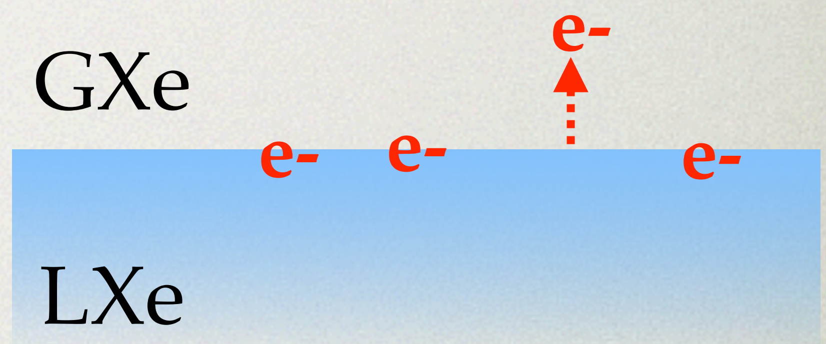

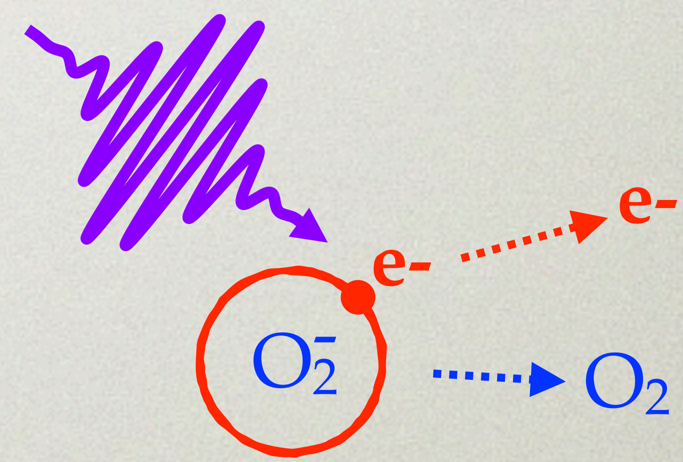

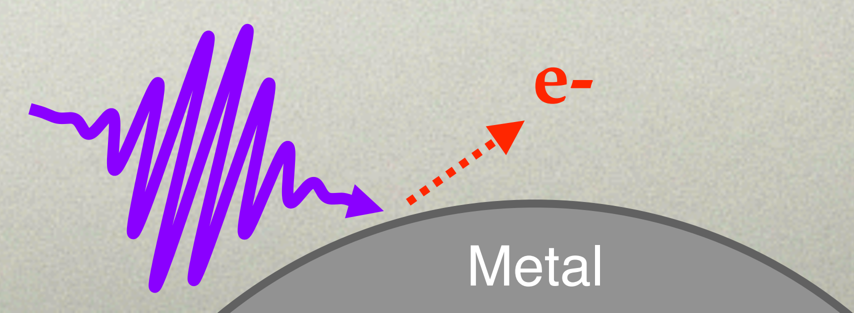

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Summary

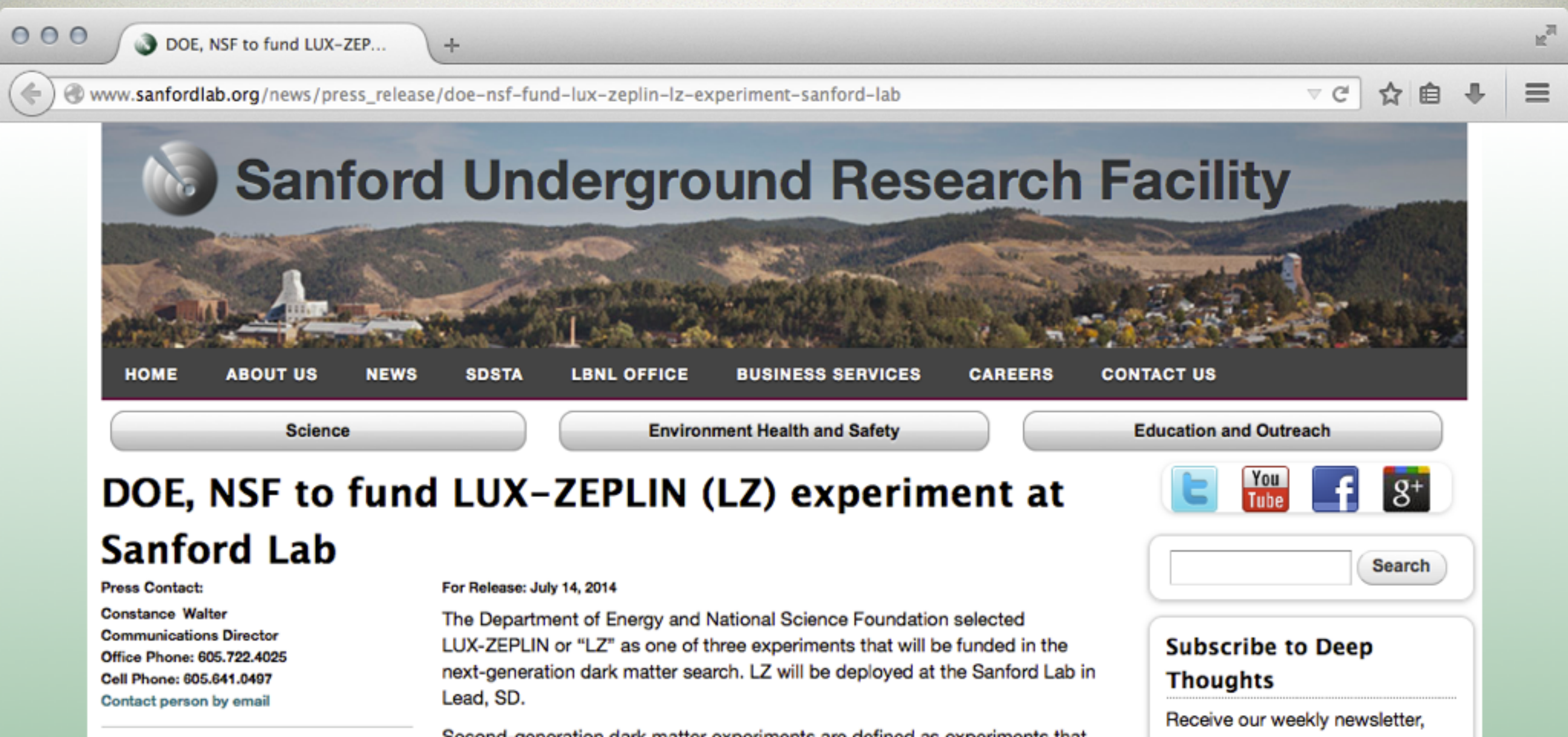
- LUX re-analysis coming out soon. Currently collecting data for the 300-day run.
- Several DM papers in the pipeline (not just vanilla WIMP).
- Ionization-only searches are good at targeting light DM candidates, but are fraught with backgrounds we don't yet understand.
- Several LUX/LZ groups currently working to better understand these details.

Stay tuned!

Backup Slides

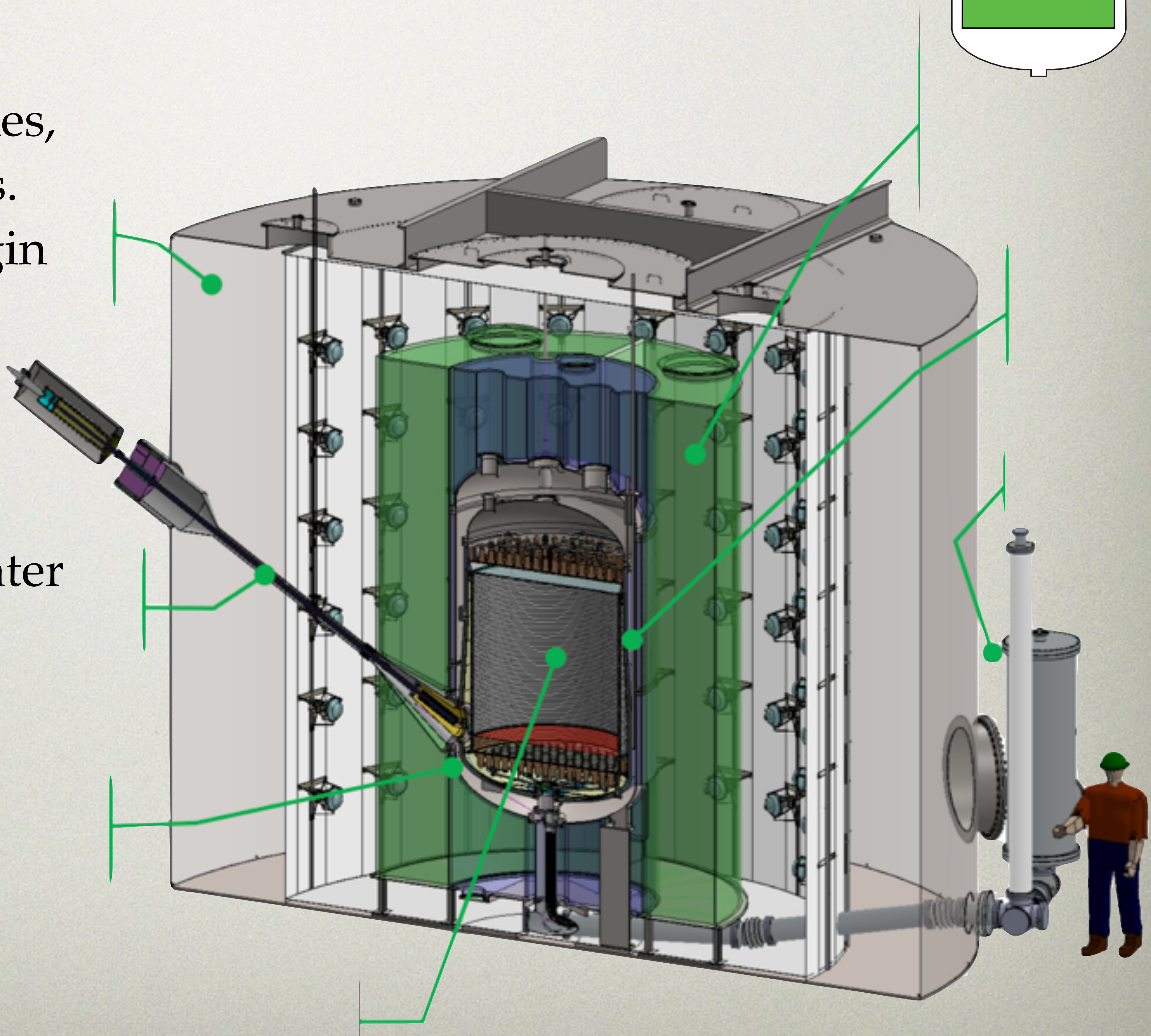
LUX-ZEPLIN (LZ)

Next generation, the LUX-ZEPLIN (LZ) experiment, recently selected as one of three "G2" DM projects! Projected for 2016-2020, 100-fold sensitivity improvement over LUX.



LUX-ZEPLIN (LZ)

- Successor to LUX
- Active LXe mass of 7 tonnes, fiducial mass of 5.6 tonnes.
- Construction slated to begin in 2016.
- To be placed in the LUX water shield.
- LXe, inside 4π liquid scintillator veto, inside water shield.



The WIMP Landscape — past and future