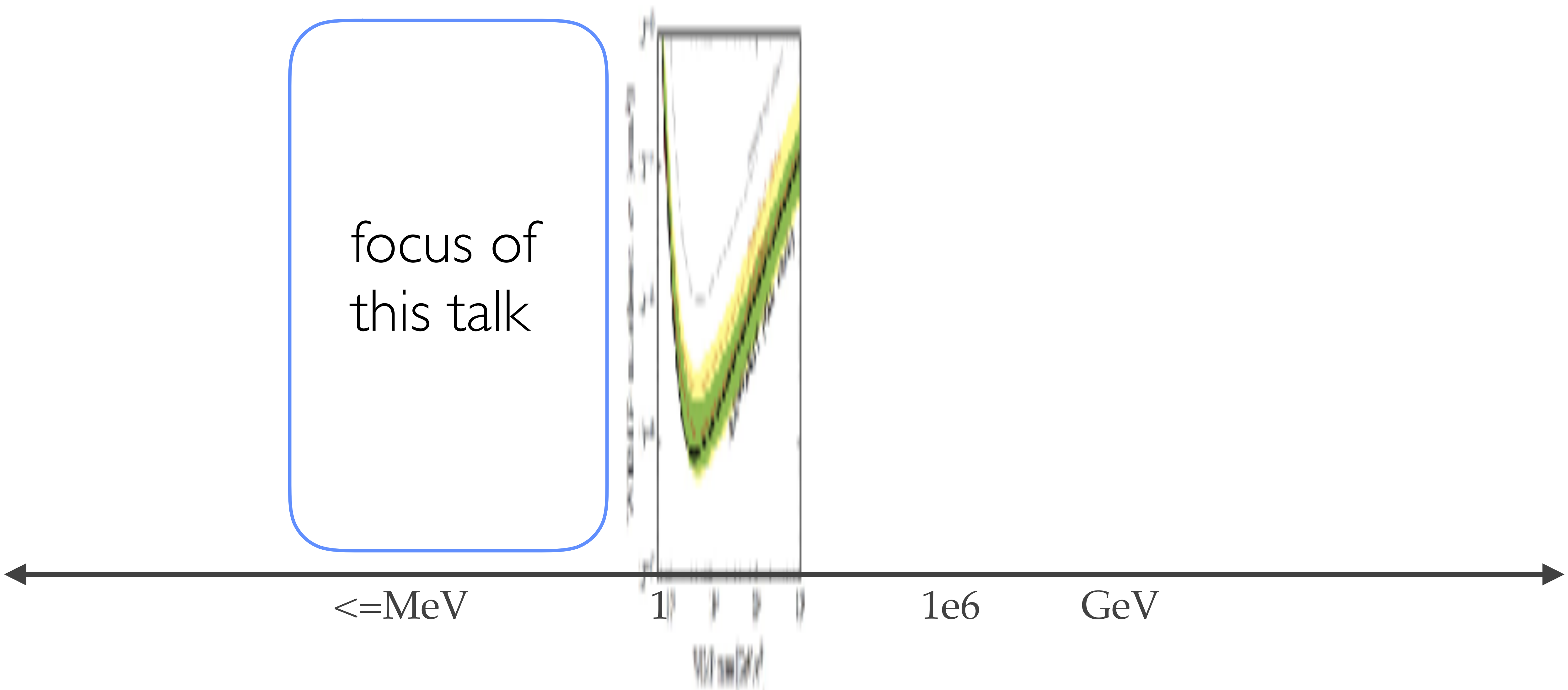
Return of the large liquid xenon detectors

LZ cryostats
LZ scientist

Return?

as in,
"great success in spite of great odds?"

BSM particle candidate mass range



Why use choose liquid xenon:

As a target for sub-GeV dark matter:

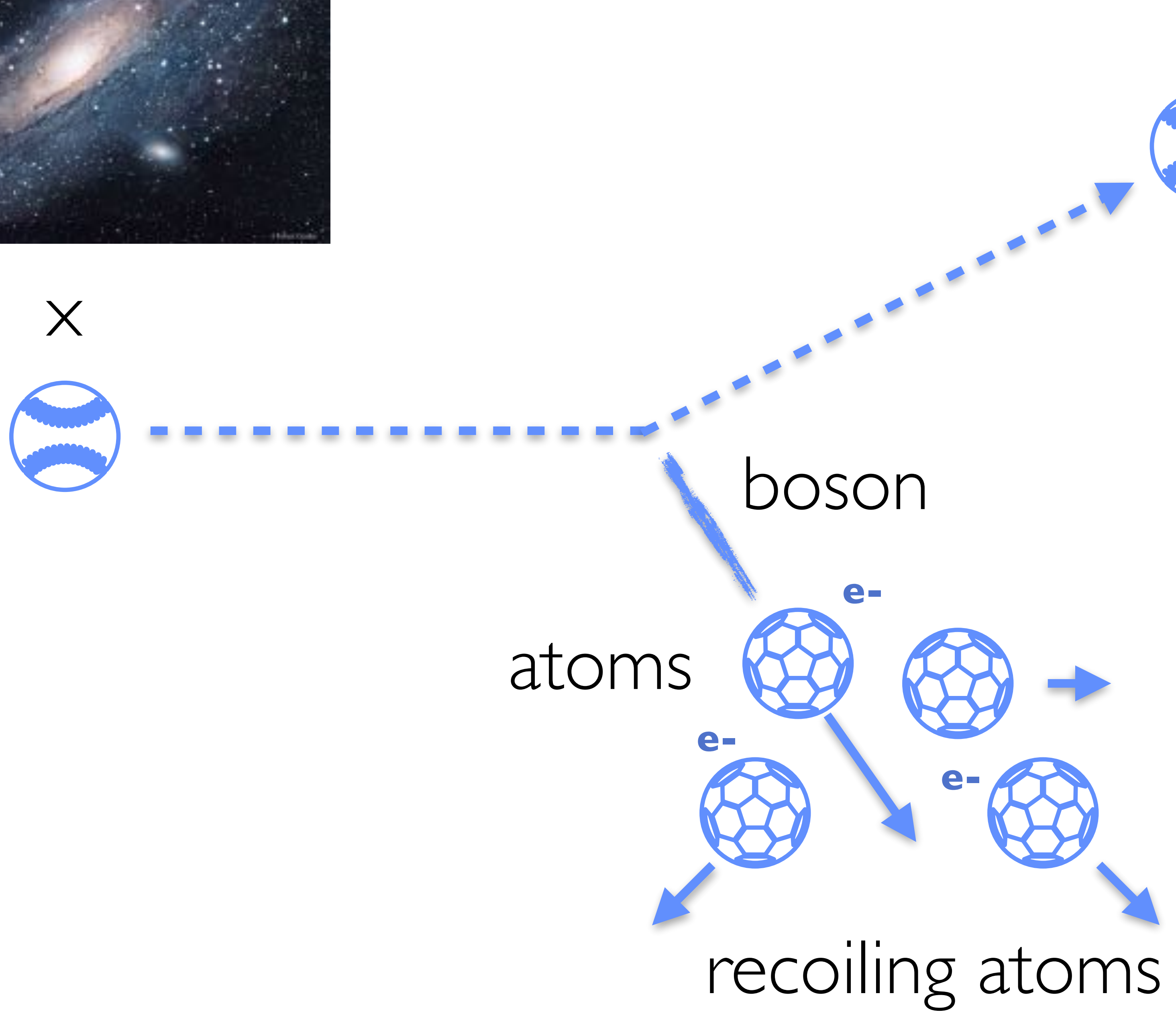
- it has a large nucleus, A~131
- it has a large band gap, ~9 eV

Ugh. unfavorable kinematics!

- On the other hand, we've got a few **tonnes** of it instrumented for other purposes (WIMPs)

LZ: observe elastic scattering of DM with nucleons

e.g. Goodman, Witten, PRD 31 3059 (1985)



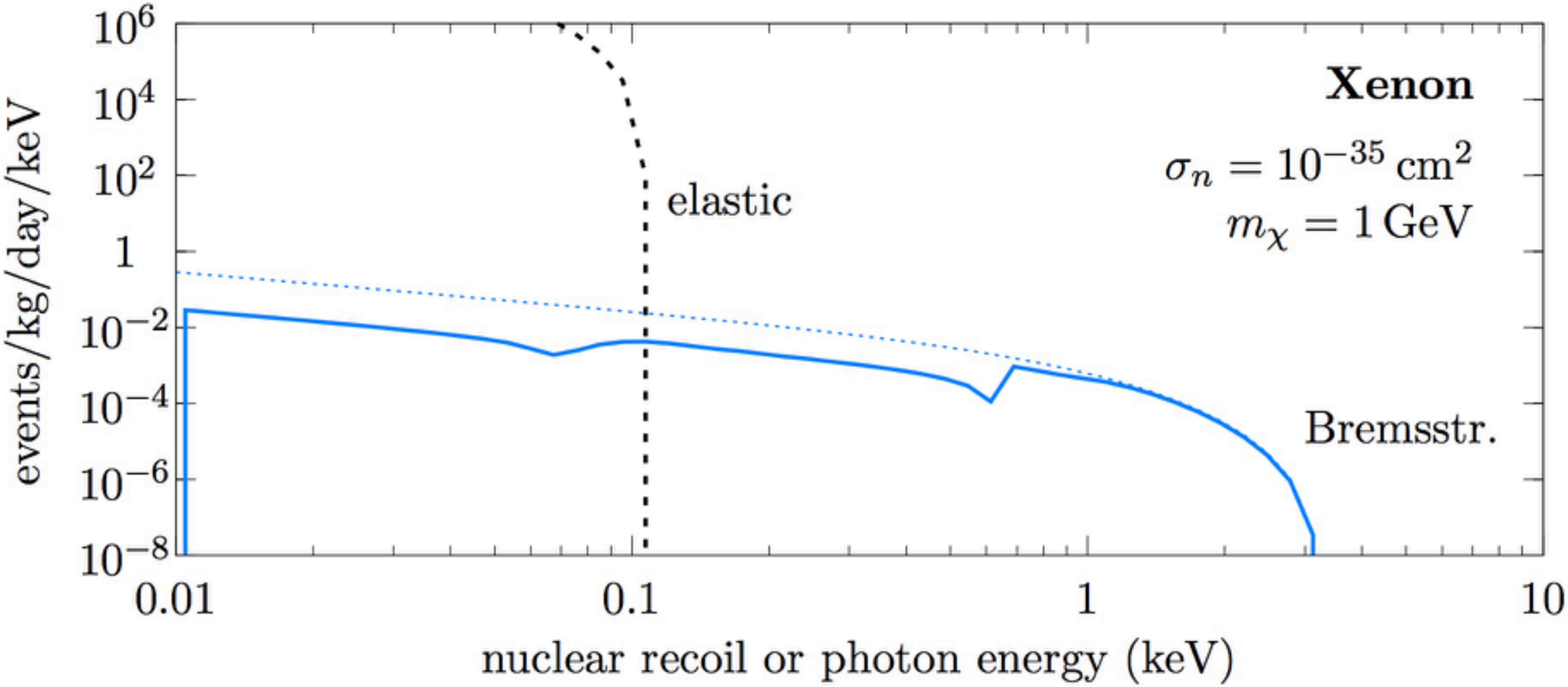
if $m_X \sim 1$ GeV,
$E_R < 1$ keV

and

atomic cascade inefficient for production of e-, γ

new probe: "Brem"

Kouvaris, Pradler, arXiv:1607.01789

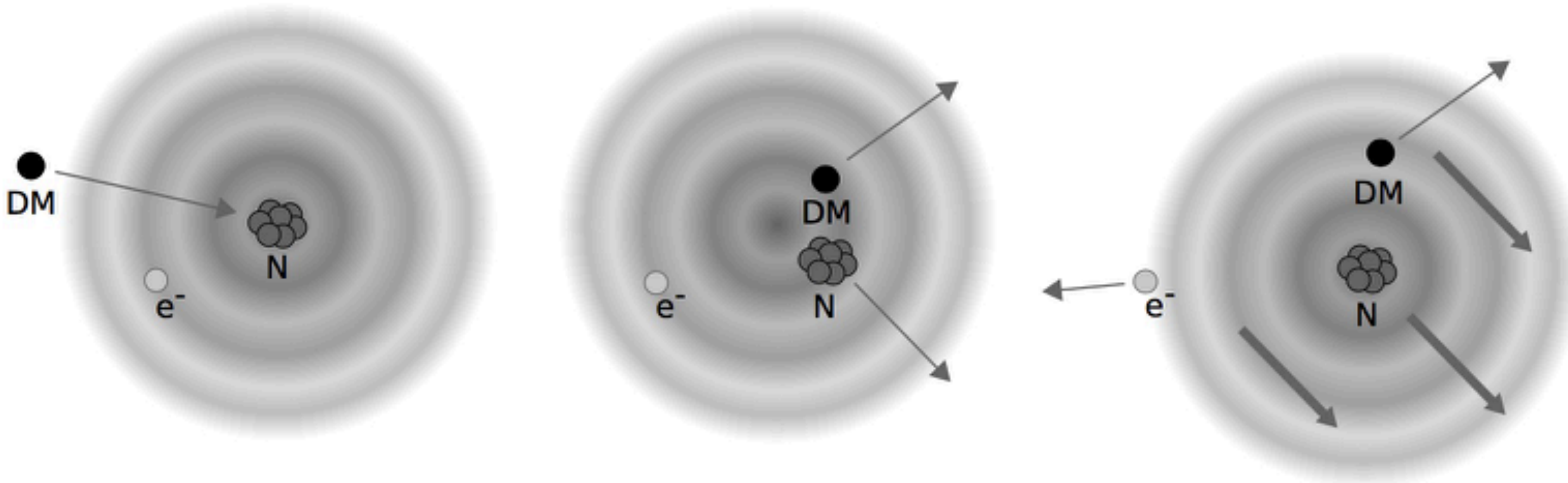


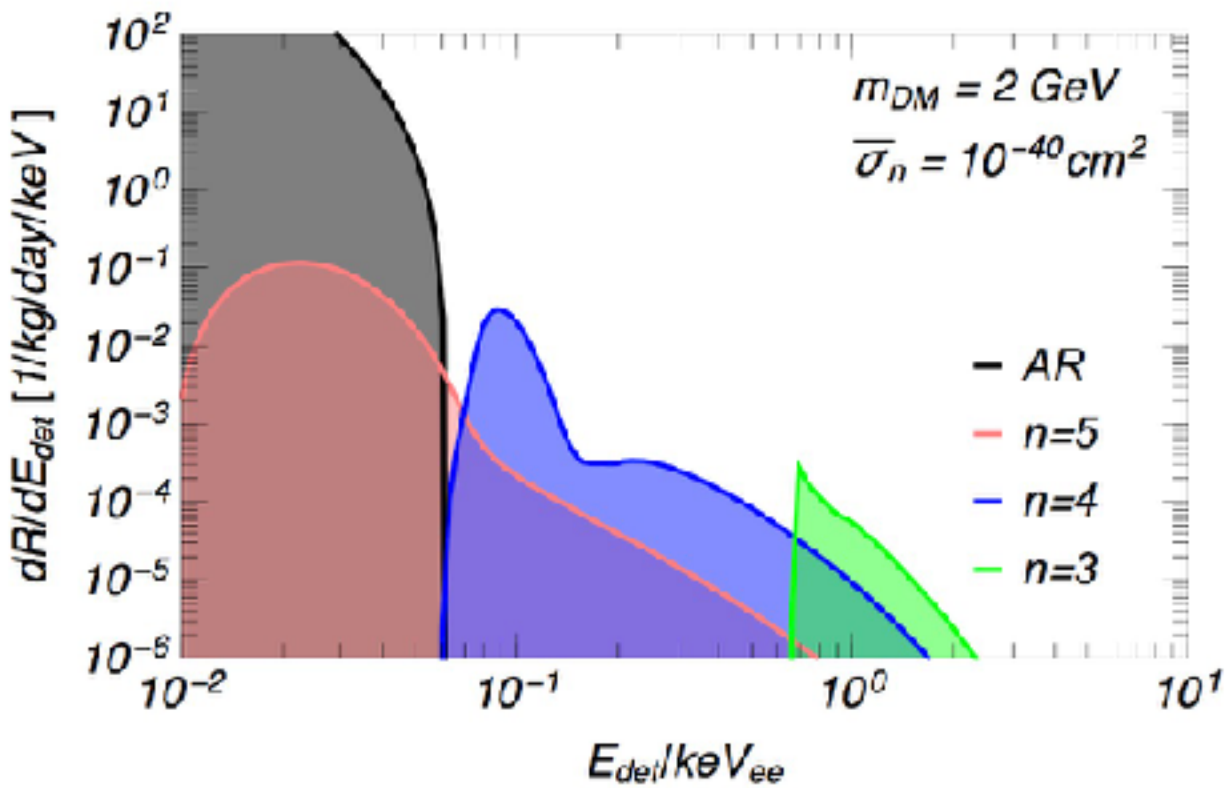
$$\chi + N \to \chi + N(E_R) \qquad \text{(elastic)},$$

$$\chi + N \to \chi + N(E'_R) + \gamma(\omega) \qquad \text{(inelastic)}$$

new probe: "Migdal Effect"

Dolan, Kalhoefer, McCabe, arXiv:1711.09906

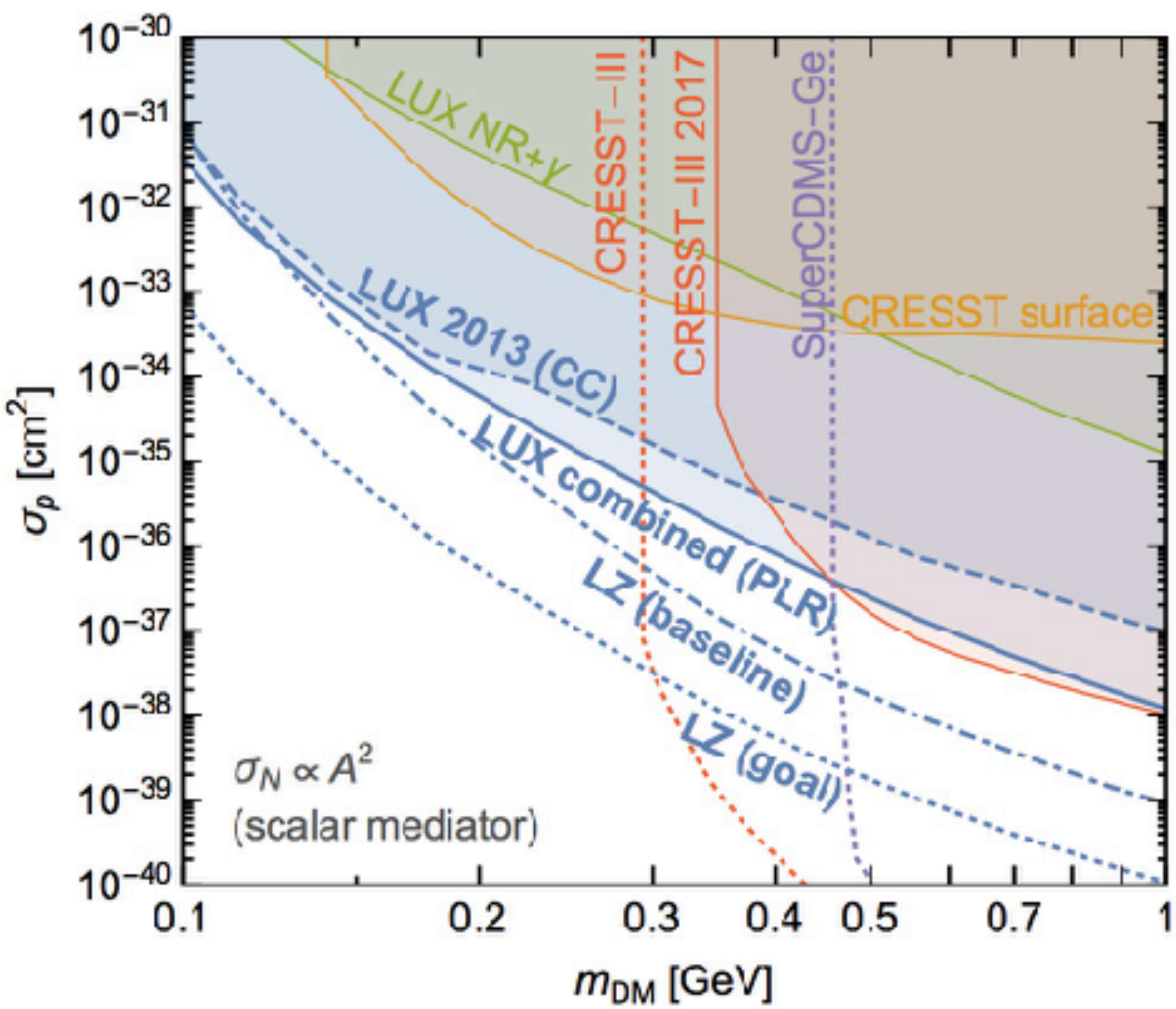


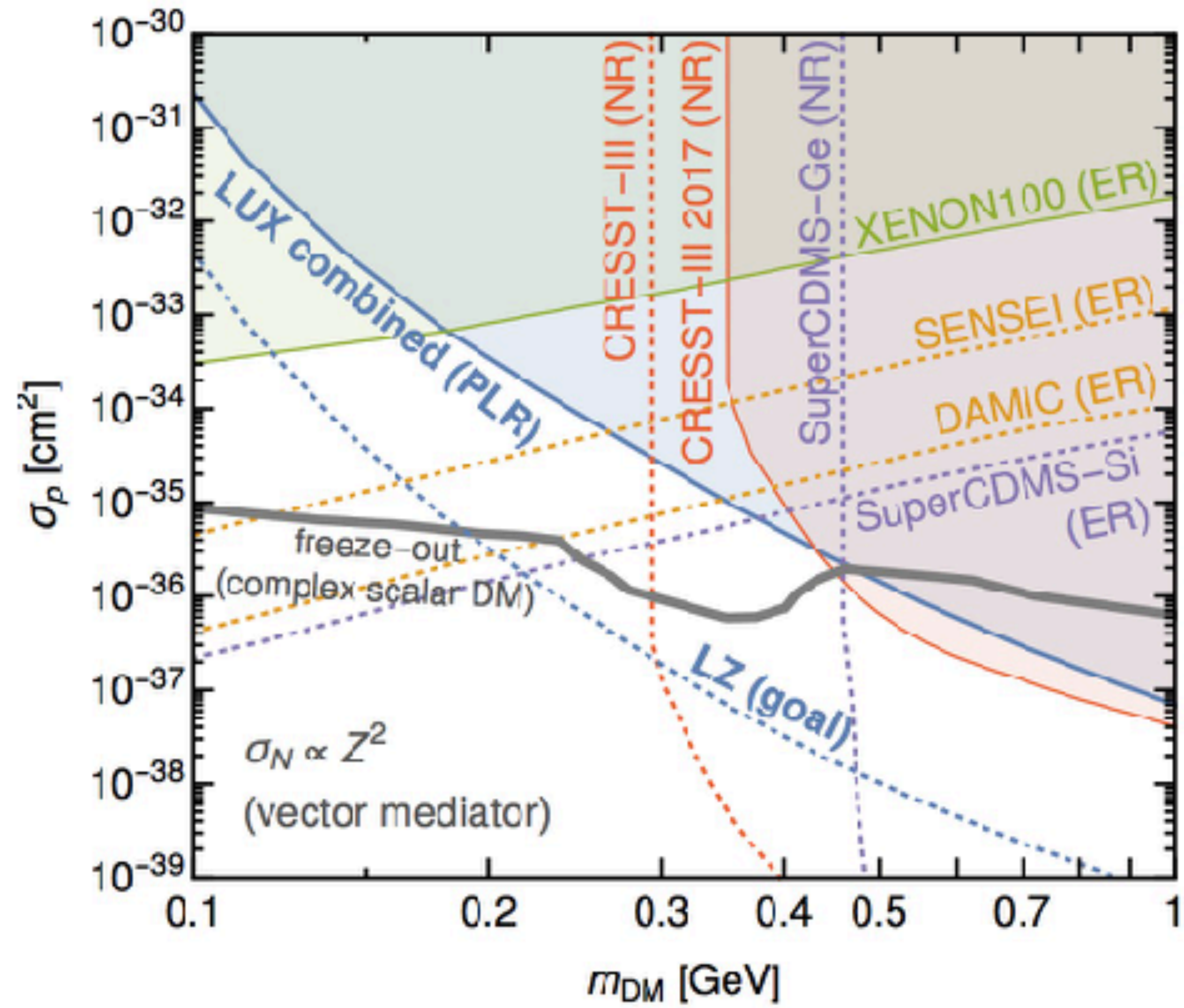


Ibe et al, arXiv:1707.07258

Sensitivity to DM-proton scattering

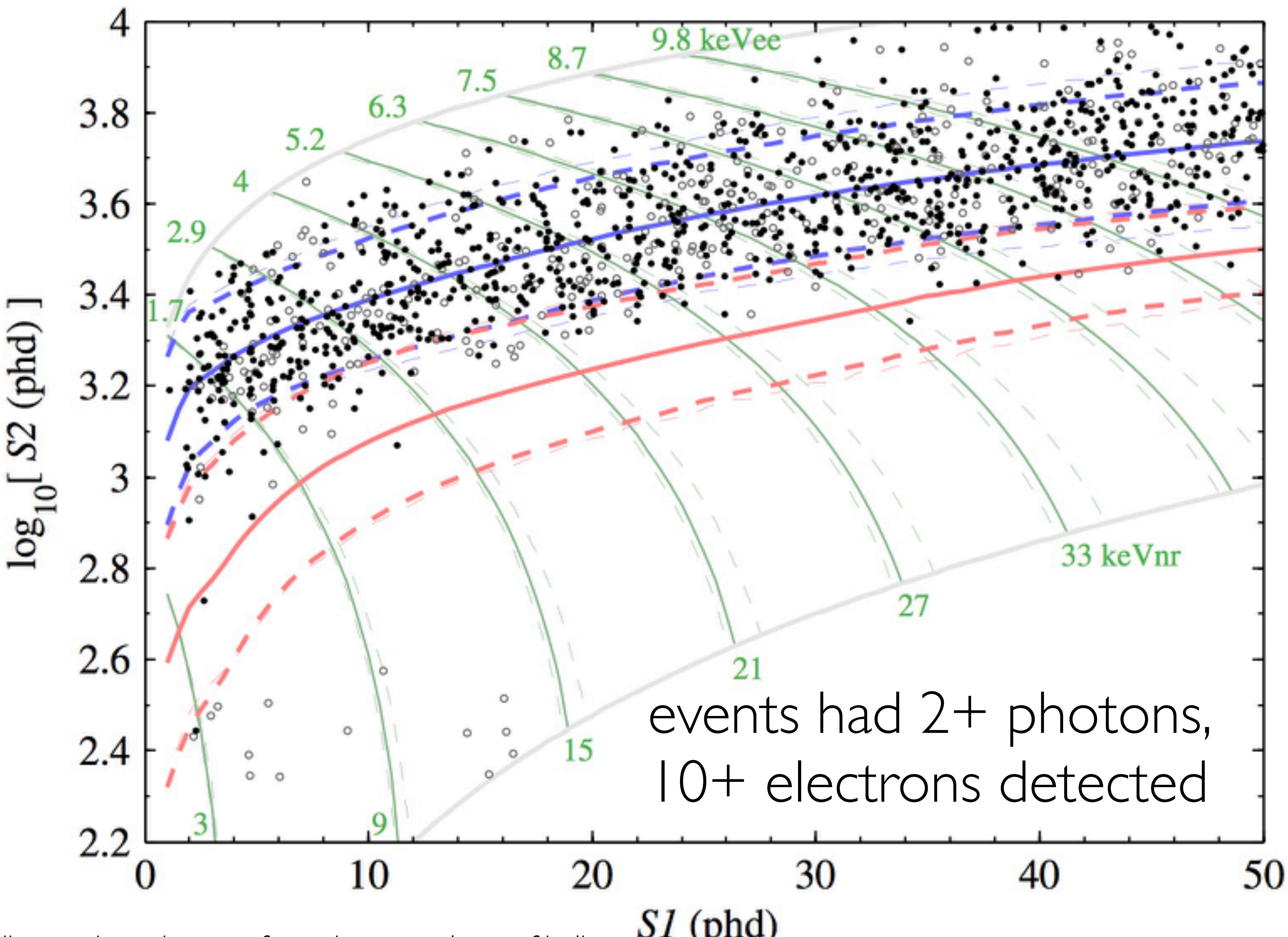
Dolan, Kalhoefer, McCabe, arXiv:1711.09906





The LUX data behind those limits

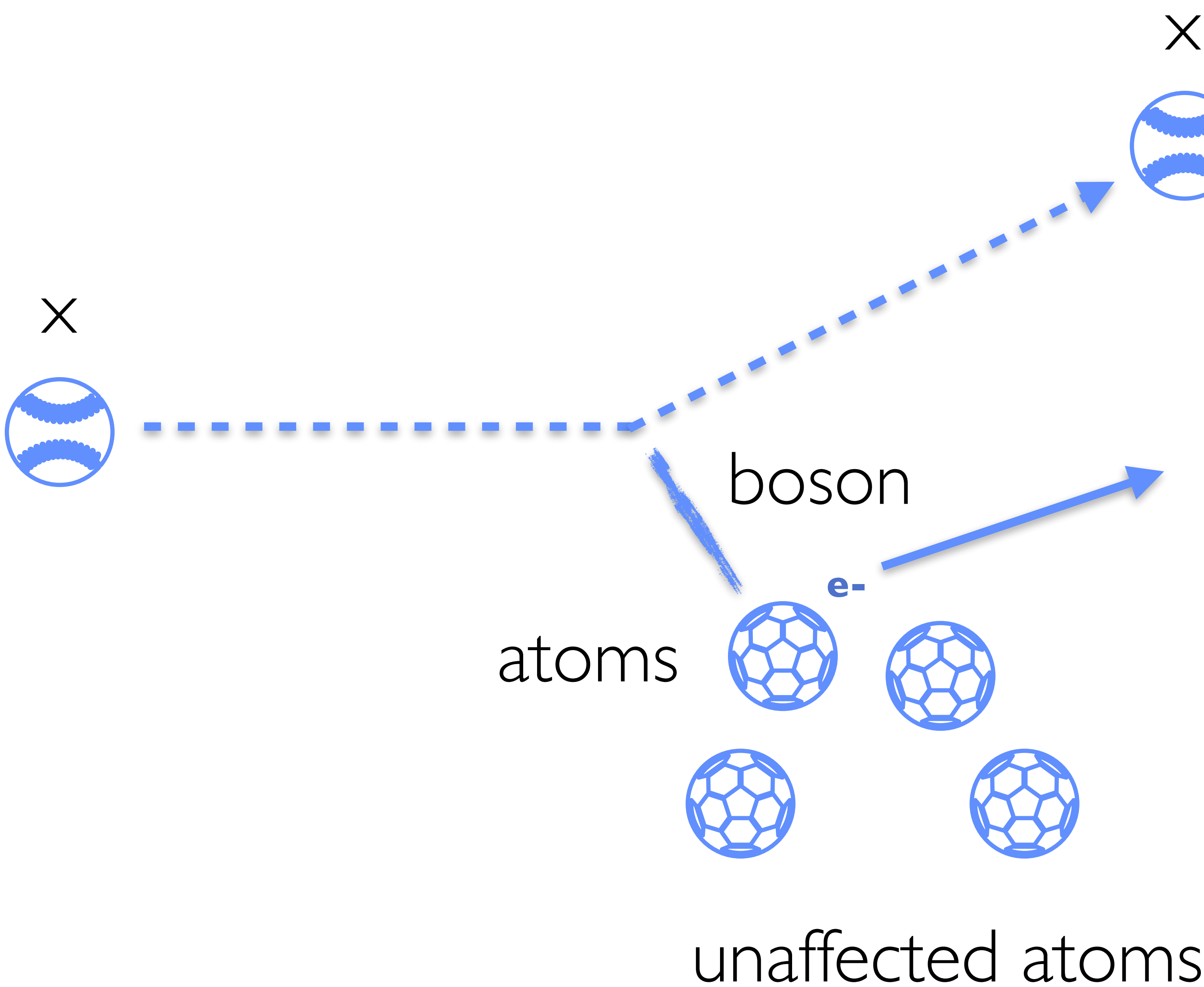
Phys. Rev. Lett. 118, 021303 (2017)



open circles indicate rejected events from the outer 1 cm of bulk

Elastic scattering of DM with electrons

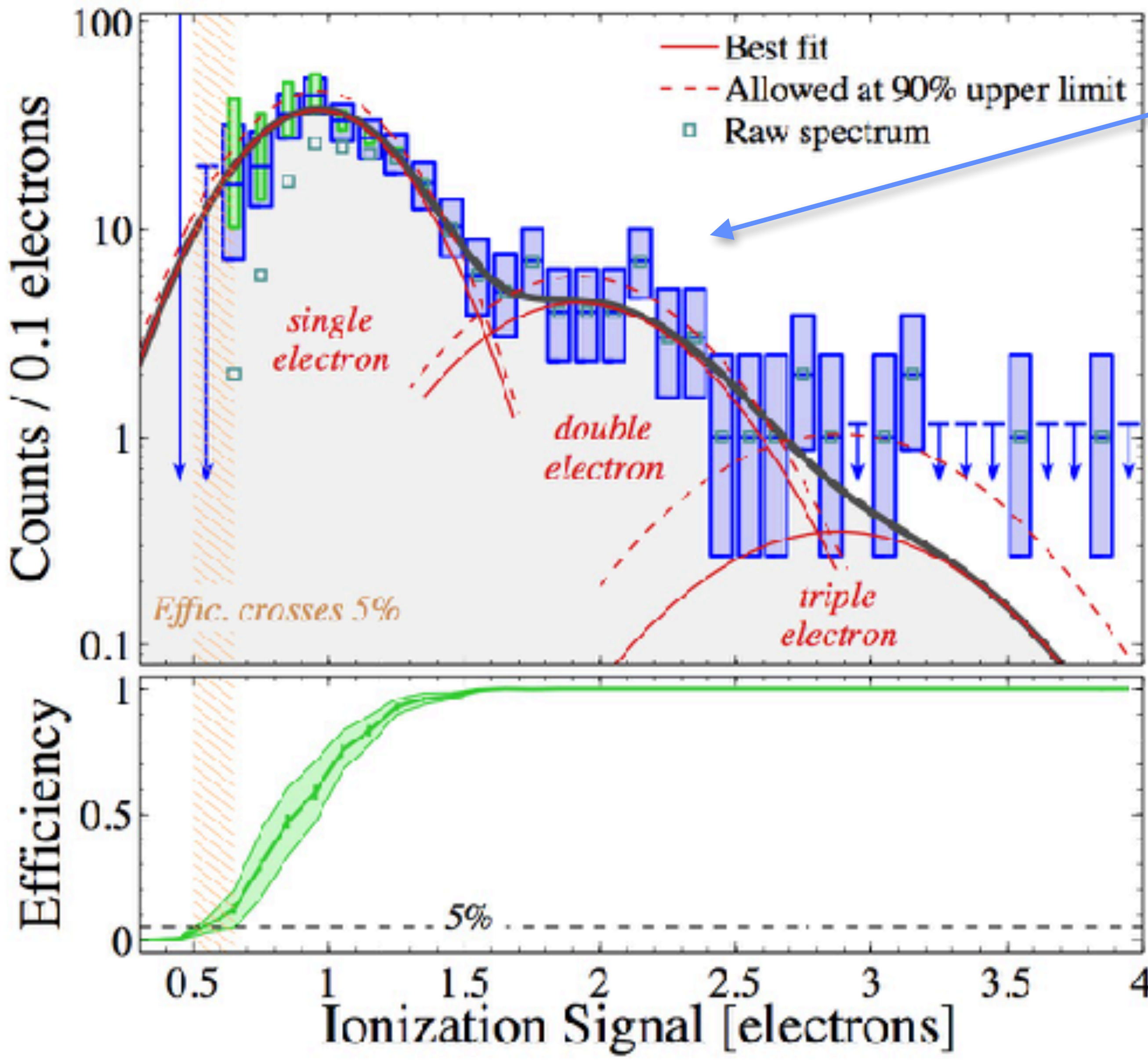
Essig, Mardon, Volansky, arXiv:1108.5383



$$E_{R,e} \sim 50 \text{ eV}(m_X/100 \text{ MeV})$$

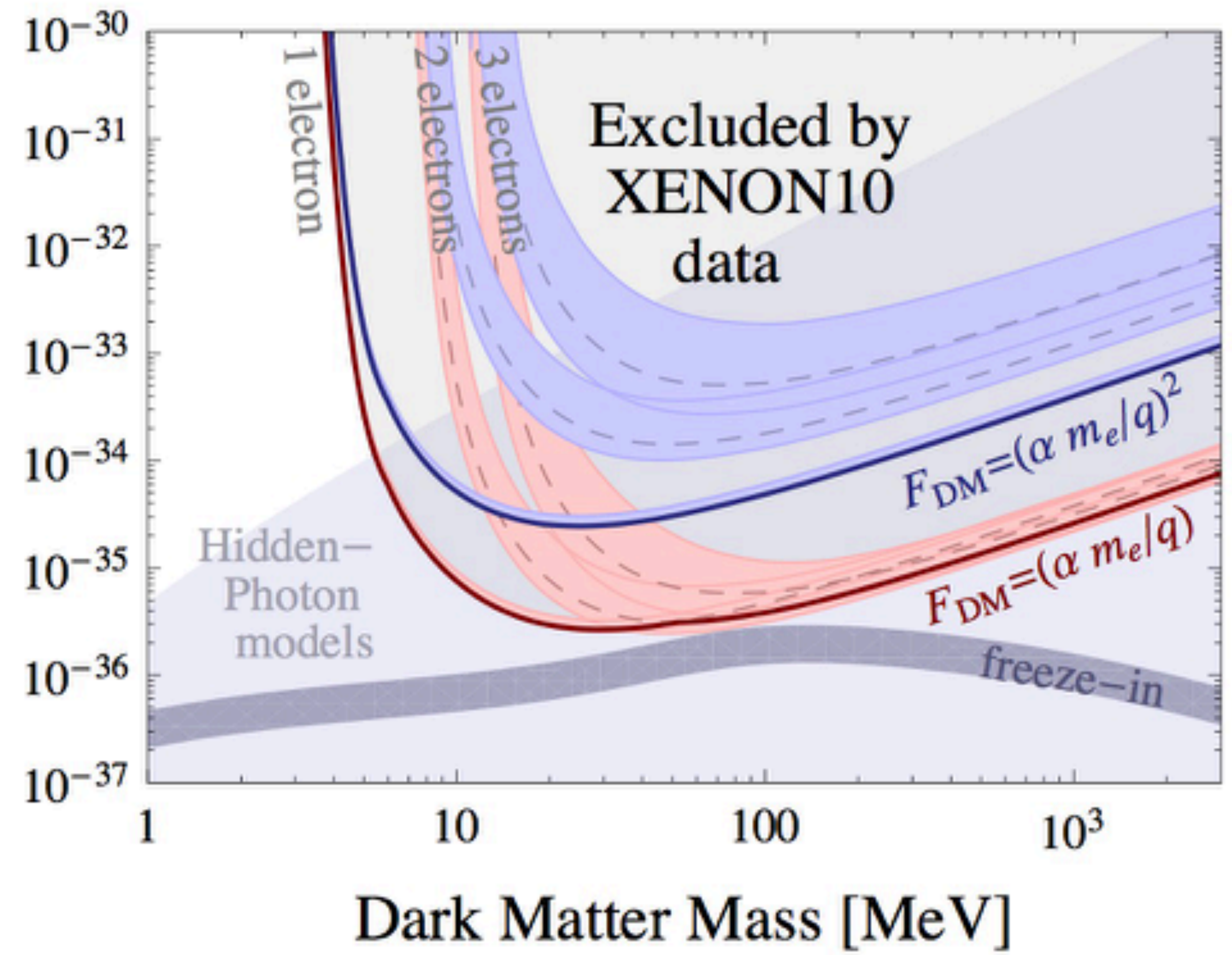
Liquid xenon TPCs can detect single quanta

Essig et al, arXiv:1206.2644



data from XENON10

PRL 107 051301 (2011)



Achille's heel: electron noise

PRL **107,** 051301 (2011) PHYSICAL REVIEW LETTERS week ending 29 JULY 2011

Search for Light Dark Matter in XENON10 Data

"A possible origin is from excess free electrons trapped at the liquid surface. This could occur because the emission of electrons from the liquid to the gas is nearly— but likely not exactly—unity [35]. As a result, every S2 signal could be a potential source of a small number of trapped electrons."

PHYSICAL REVIEW D **94,** 092001 (2016)

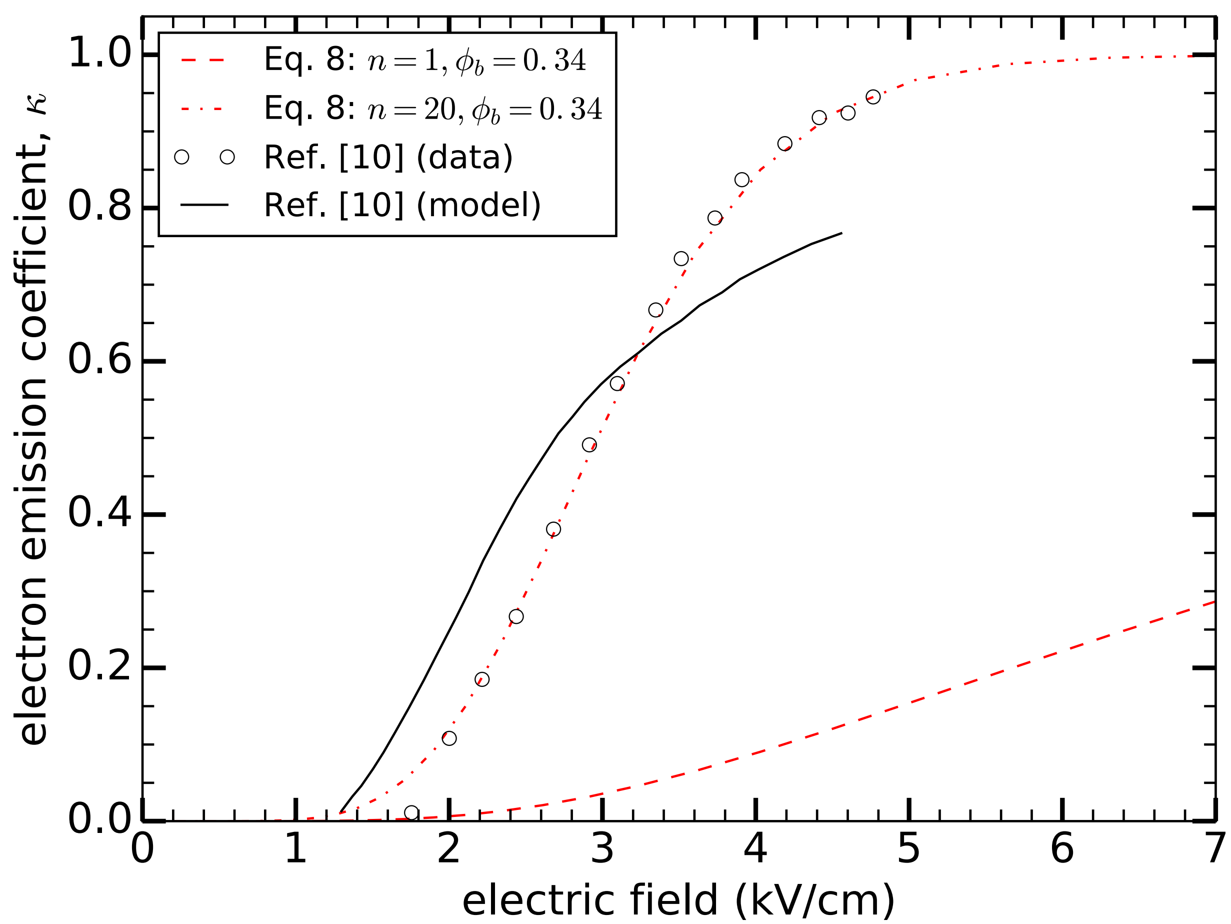
Low-mass dark matter search using ionization signals in XENON100

"In the absence of a full background model, which cannot be constructed, as the origin of the small-S2 background in the detector cannot be reliably quantified, we assume that every event passing the analysis cuts could be due to a DM interaction."

We thought un-extracted electrons were the problem

- a 9 eV bandgap strongly disfavors spontaneous thermal ionization (good)
- long-held suspicion of trapped electrons at the liquid-gas interface

(model) Sorensen, arXiv:1702.04805
(data) Gushchin et al, JETP 55 5 (1982)



- They are not the primary problem

Let's review the basics

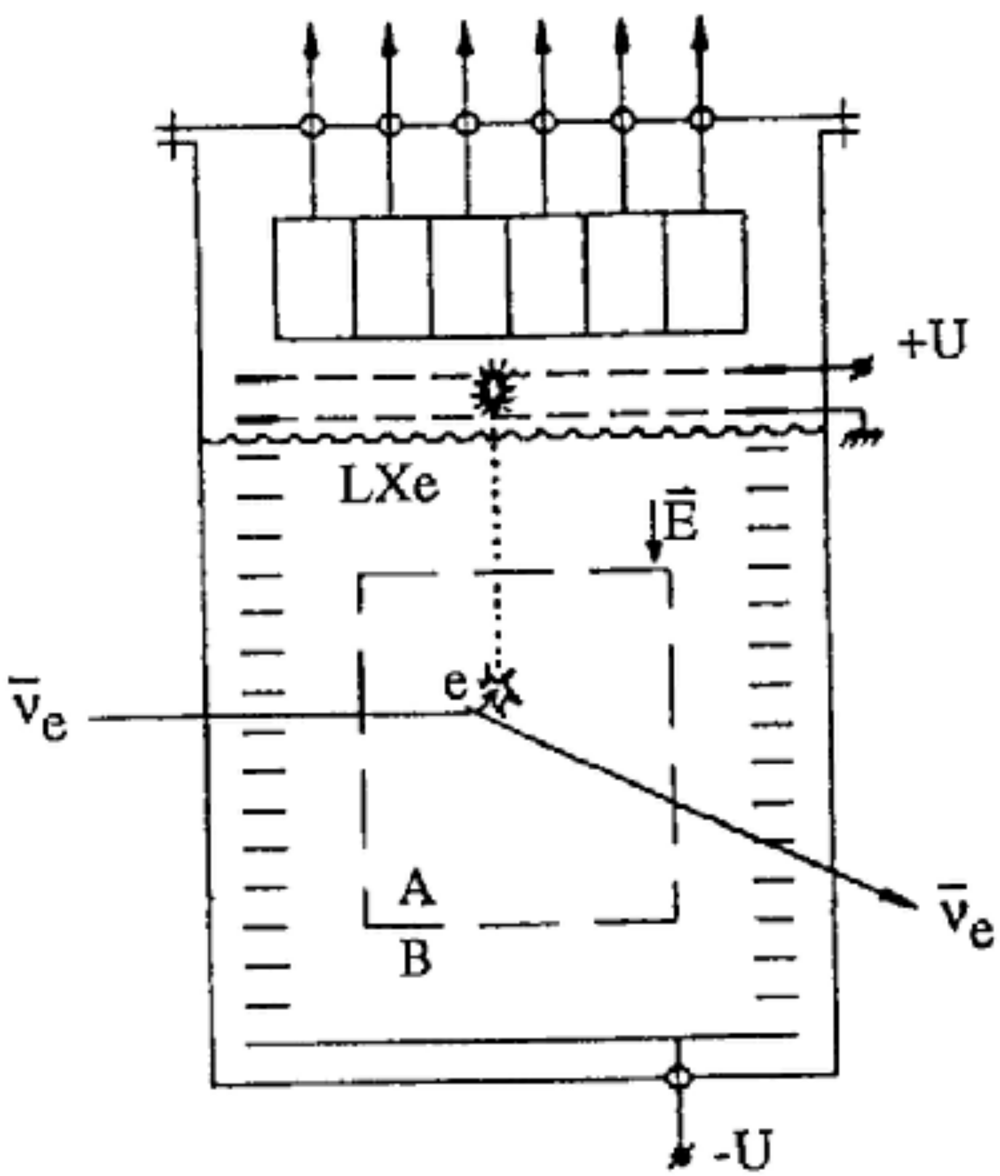


Fig.4. LXe time-projection scintillating drift chamber as wall-less detector for measurements of magnetic momentum neutrino.

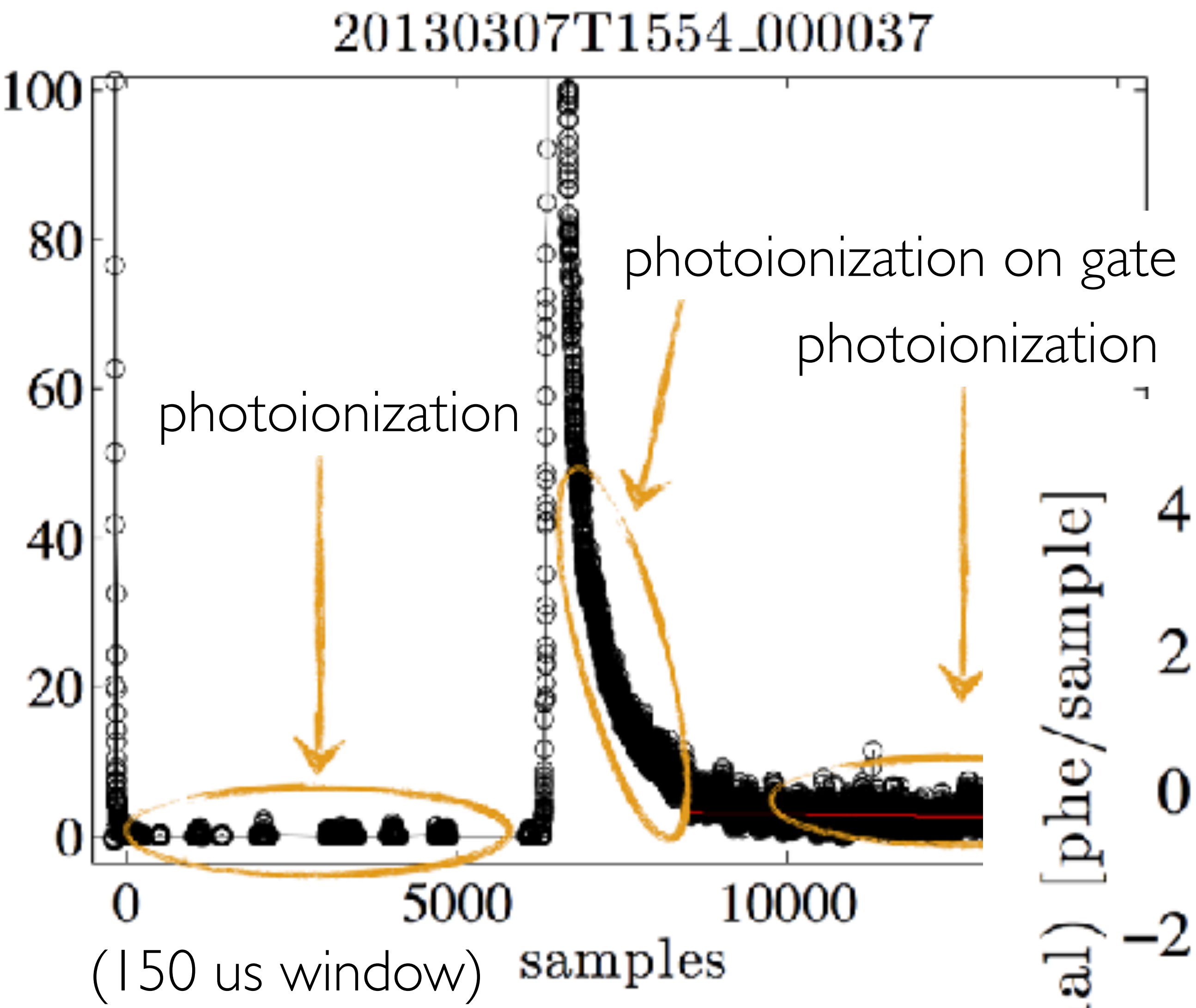
Bolozdyna et al., IEEE Trans. Nucl. Sci. 42 (1995) 565

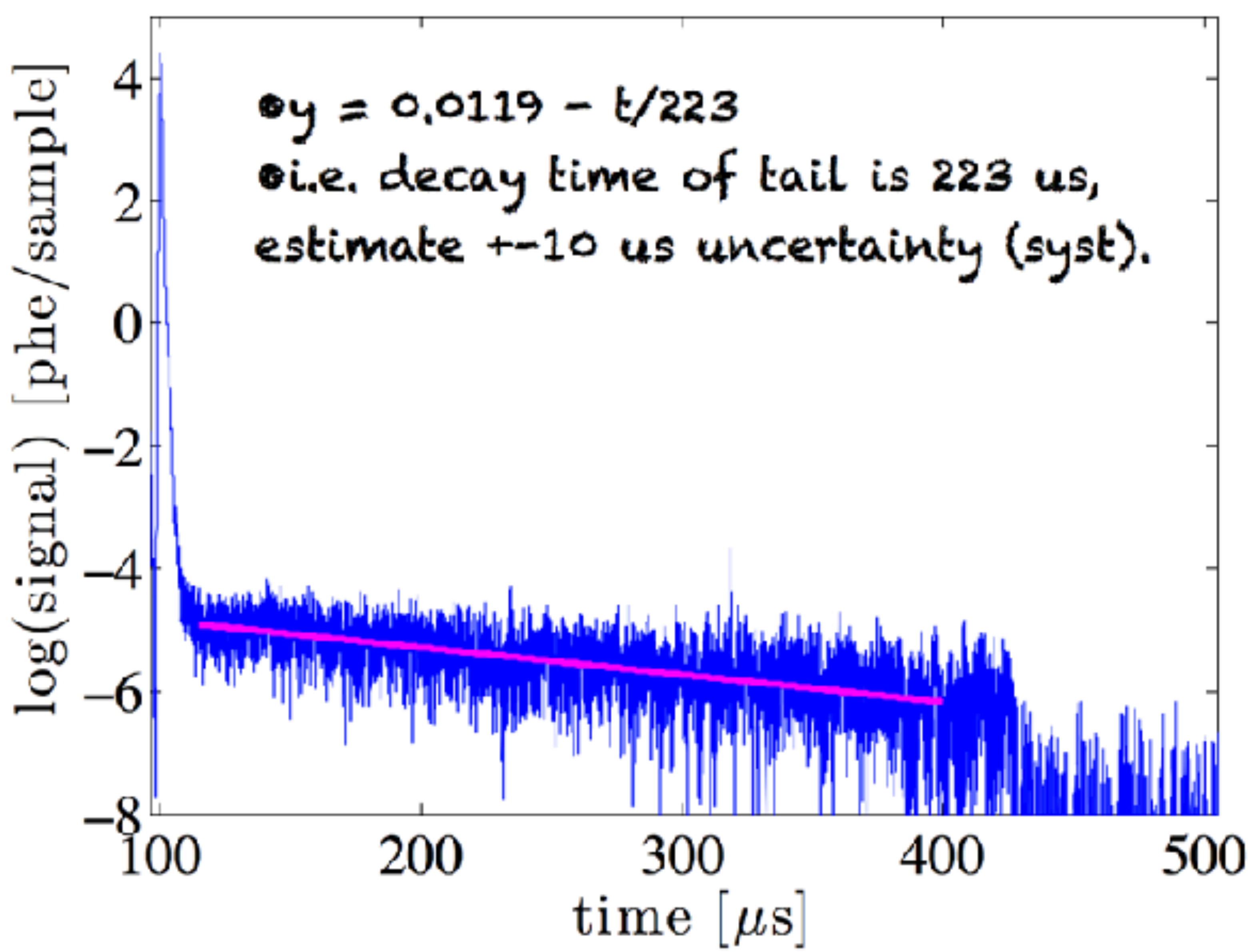
- t ~100 ns. initial scintillation
- electronegative impurities capture some e-
- t ~100 us. electrons drift (v~mm/us), secondary scintillation

- O(100 us) electron trapping at surface
- O(100 us) photoionization

- impurities drift (v~mm/s)
  NIM A 555 205 (2005)
- positive ions drift (v~cm/s)
  Chem Phys 183 147 (1994)

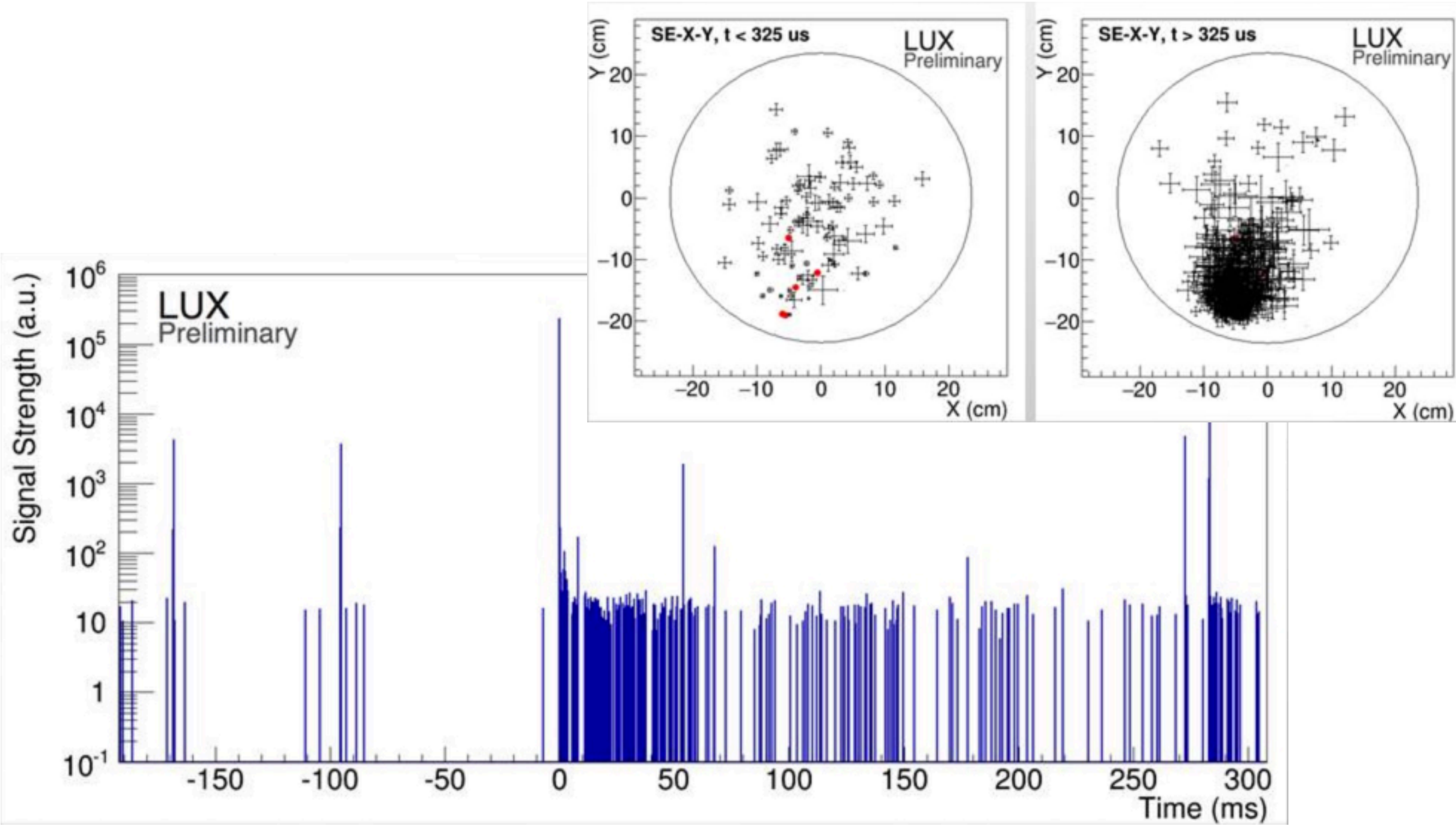
Early LUX event (low purity)





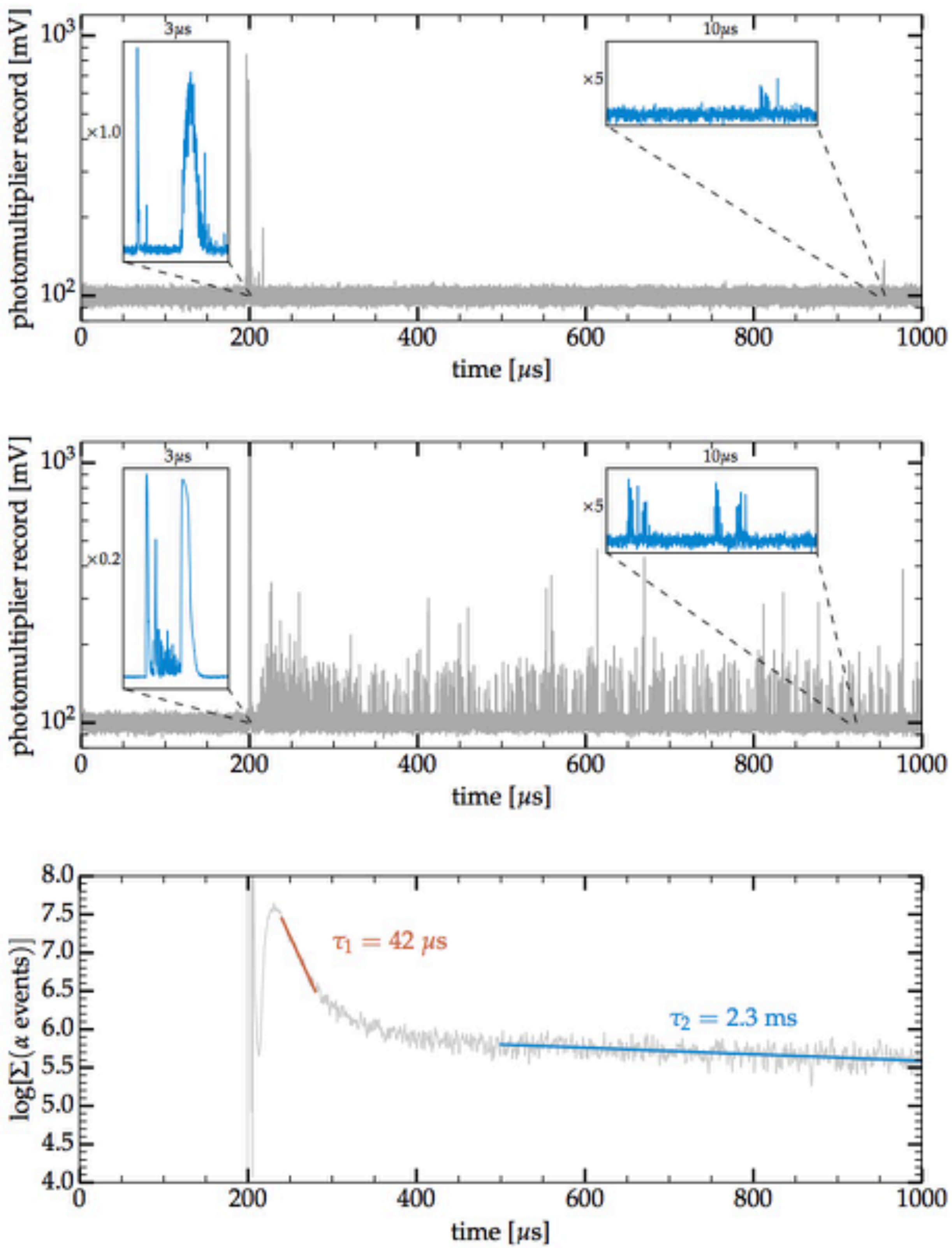
Strong position correlation of noise

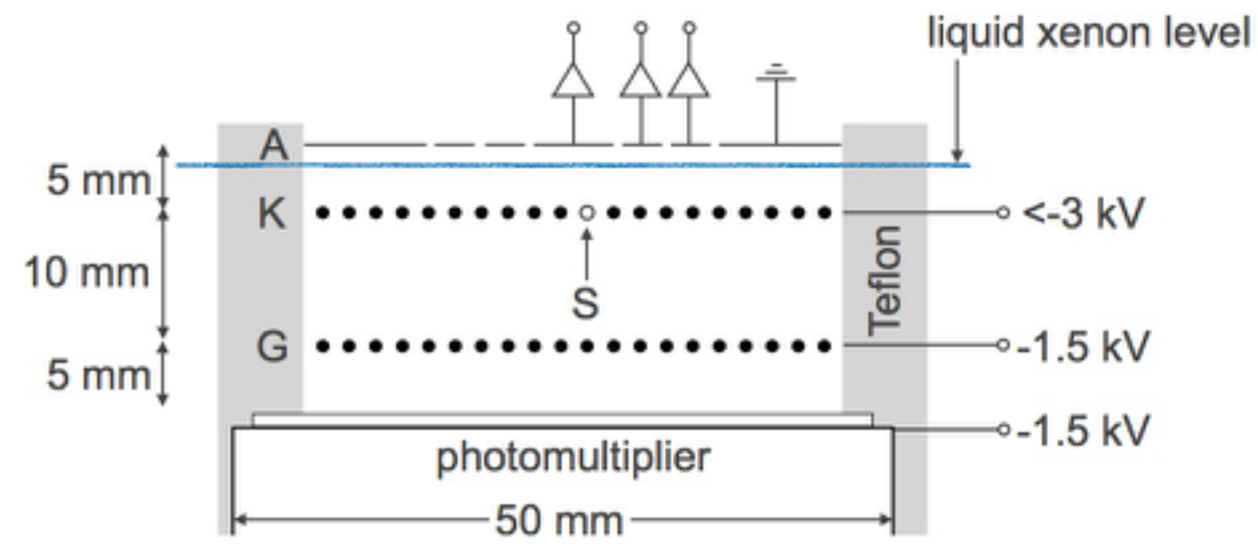
J. Xu (for LUX), https://meetings.aps.org/Meeting/APR16/Session/B16.5

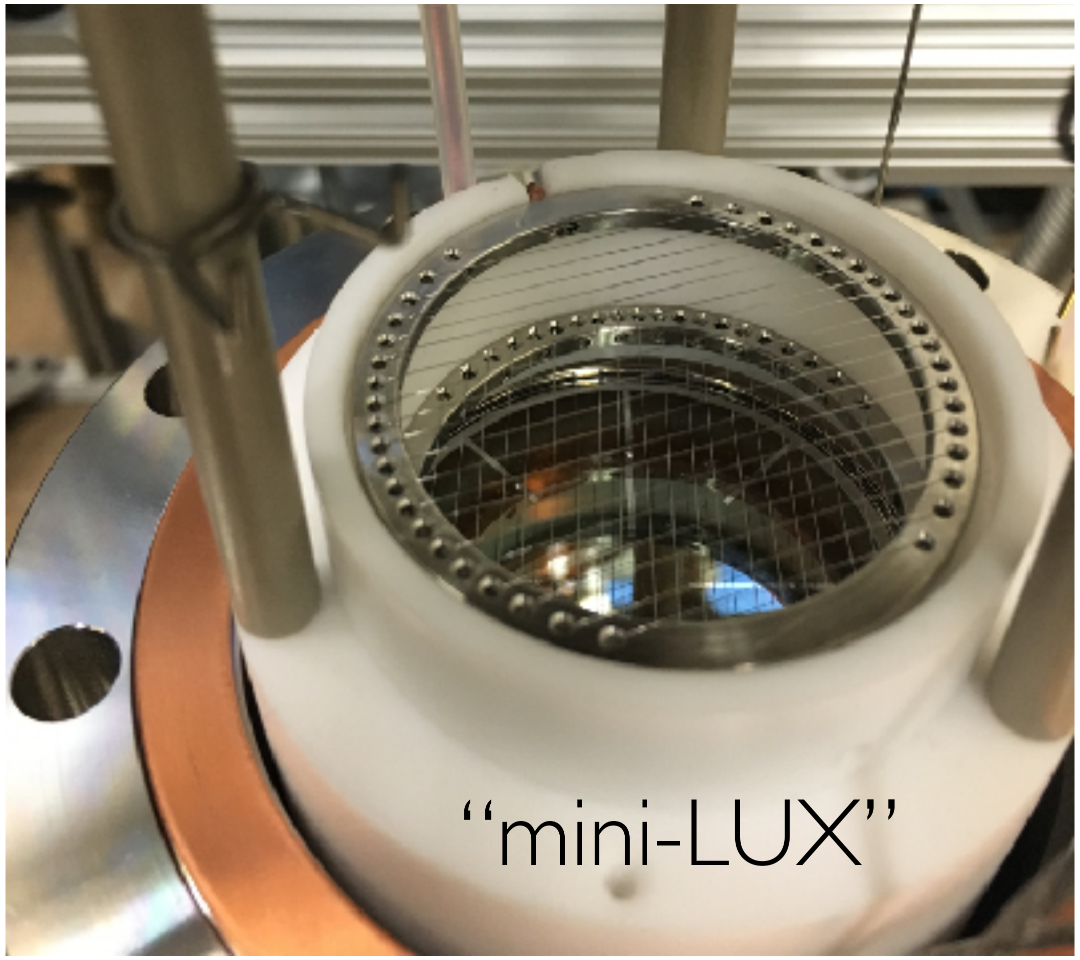


Recent R&D

Sorensen and Kamdin, JINST 13 P02032 (2018)



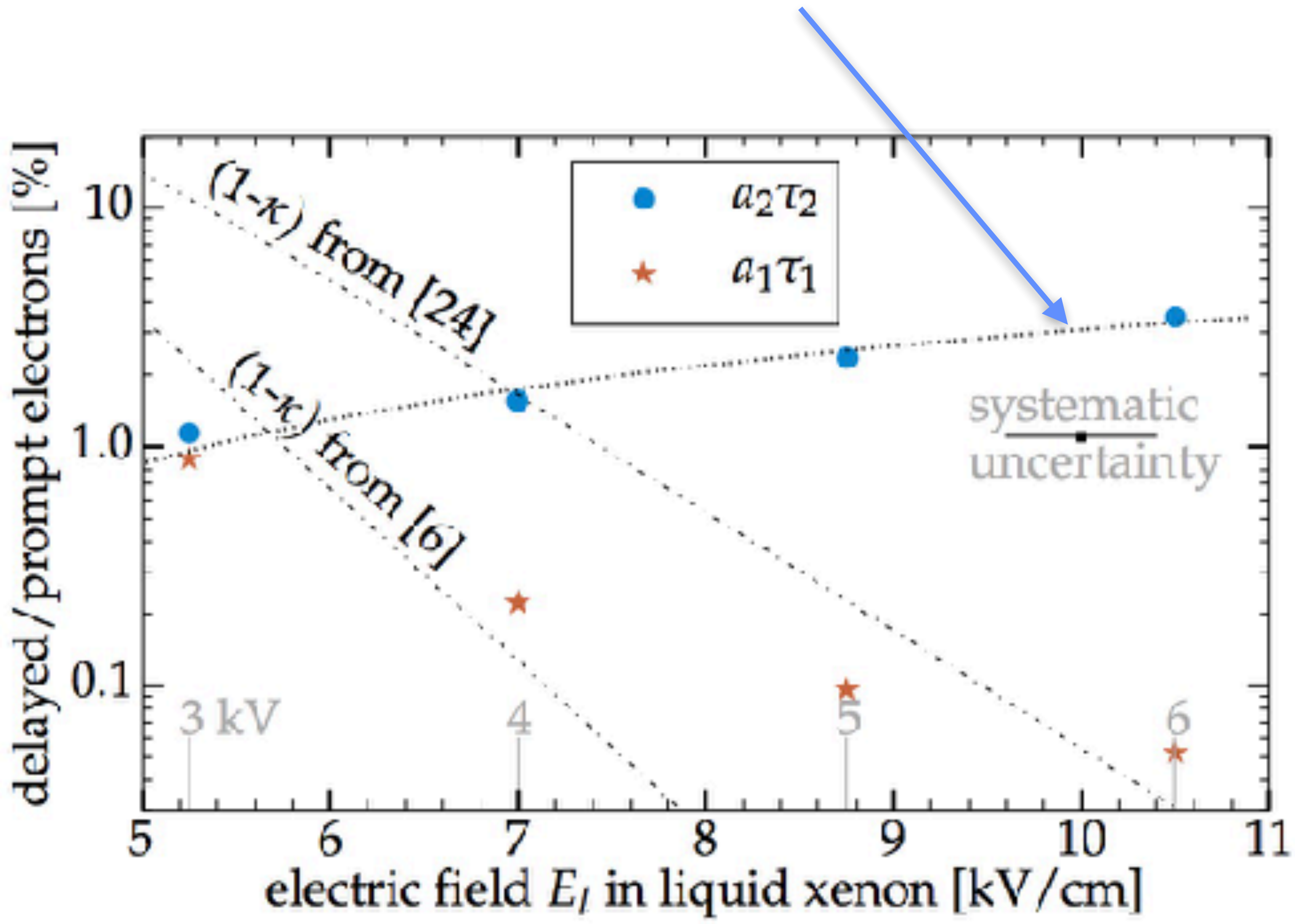


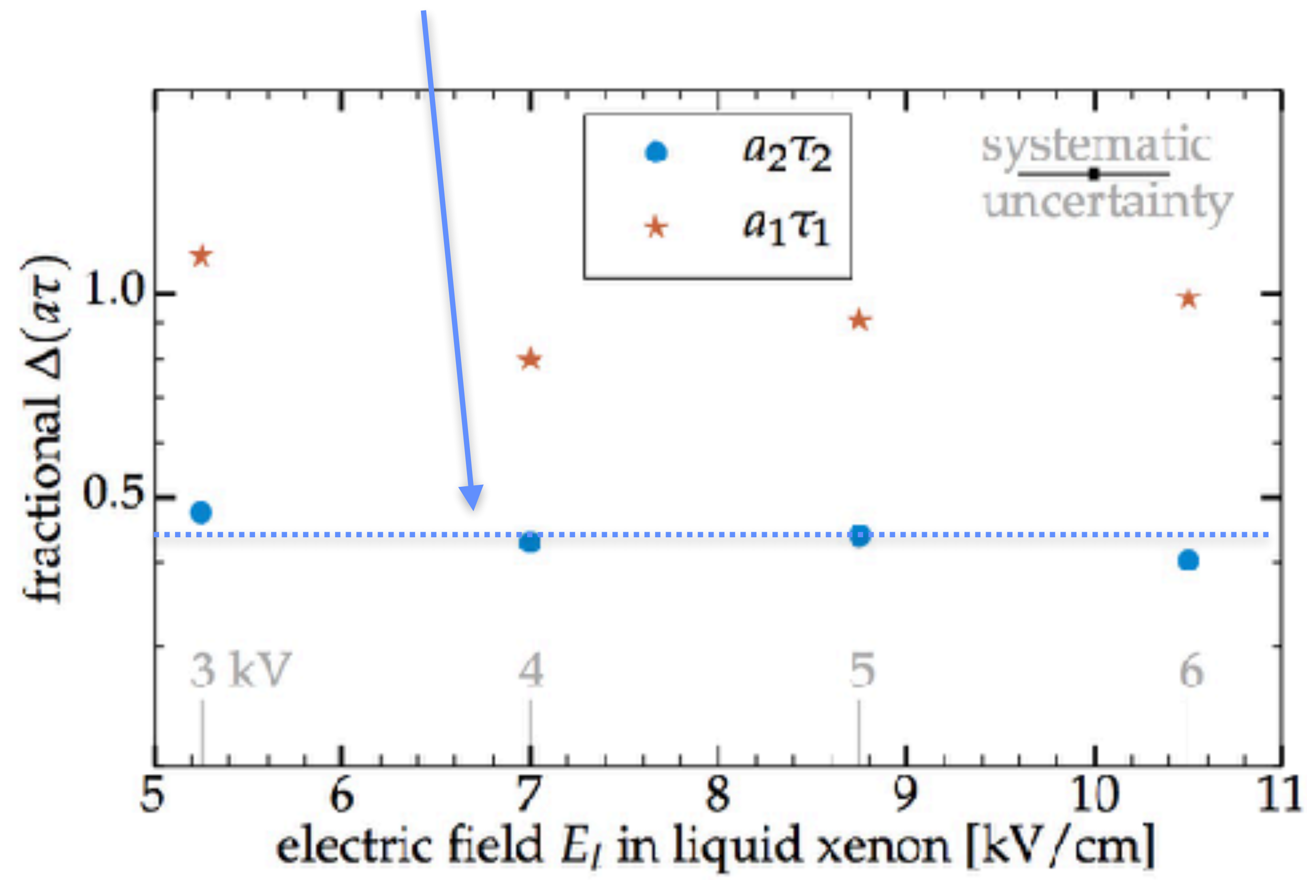


R&D, emphasis on "R", pronounced "Arrr"

"Arrr"

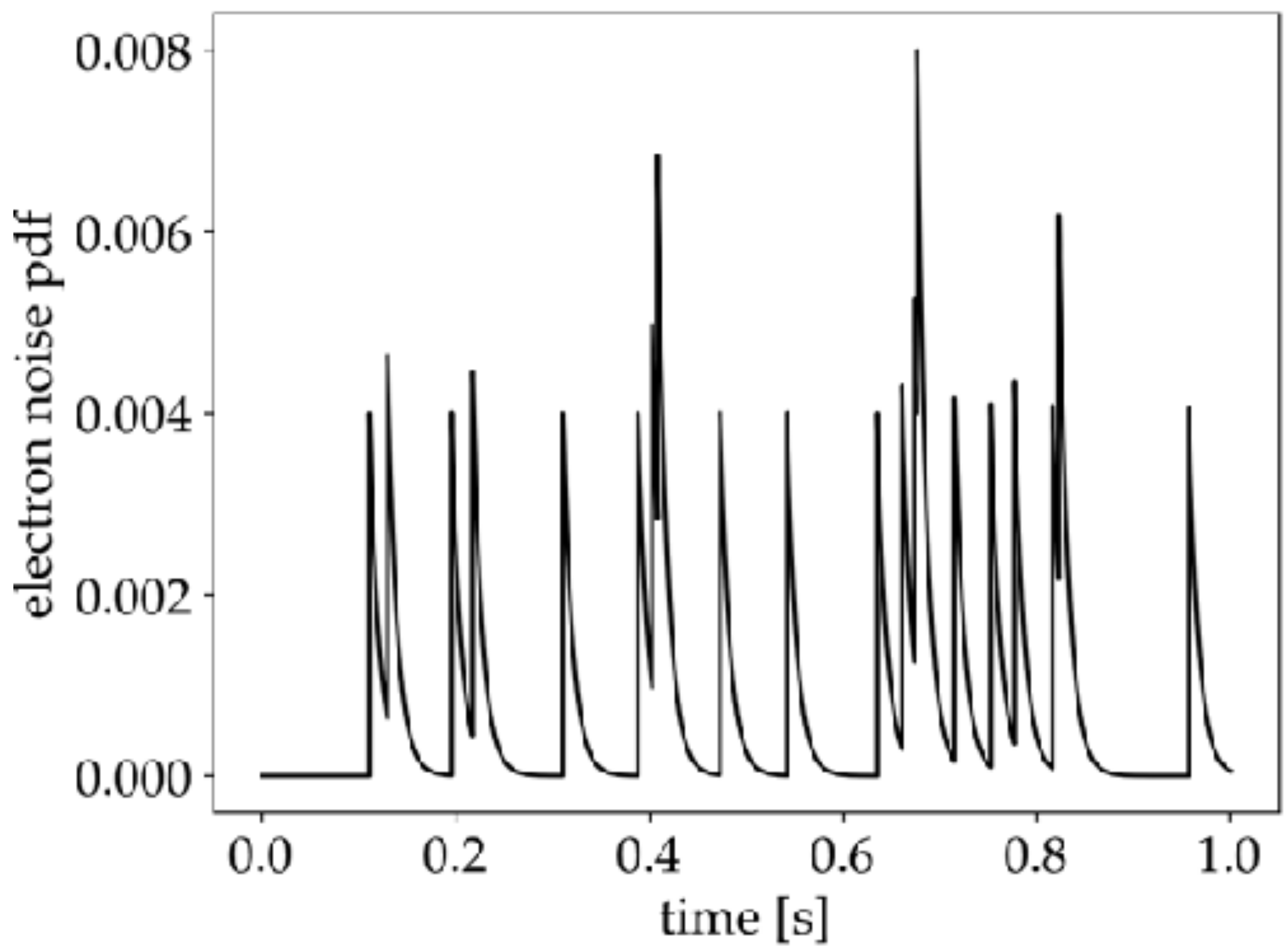
higher purity, smaller delayed noise



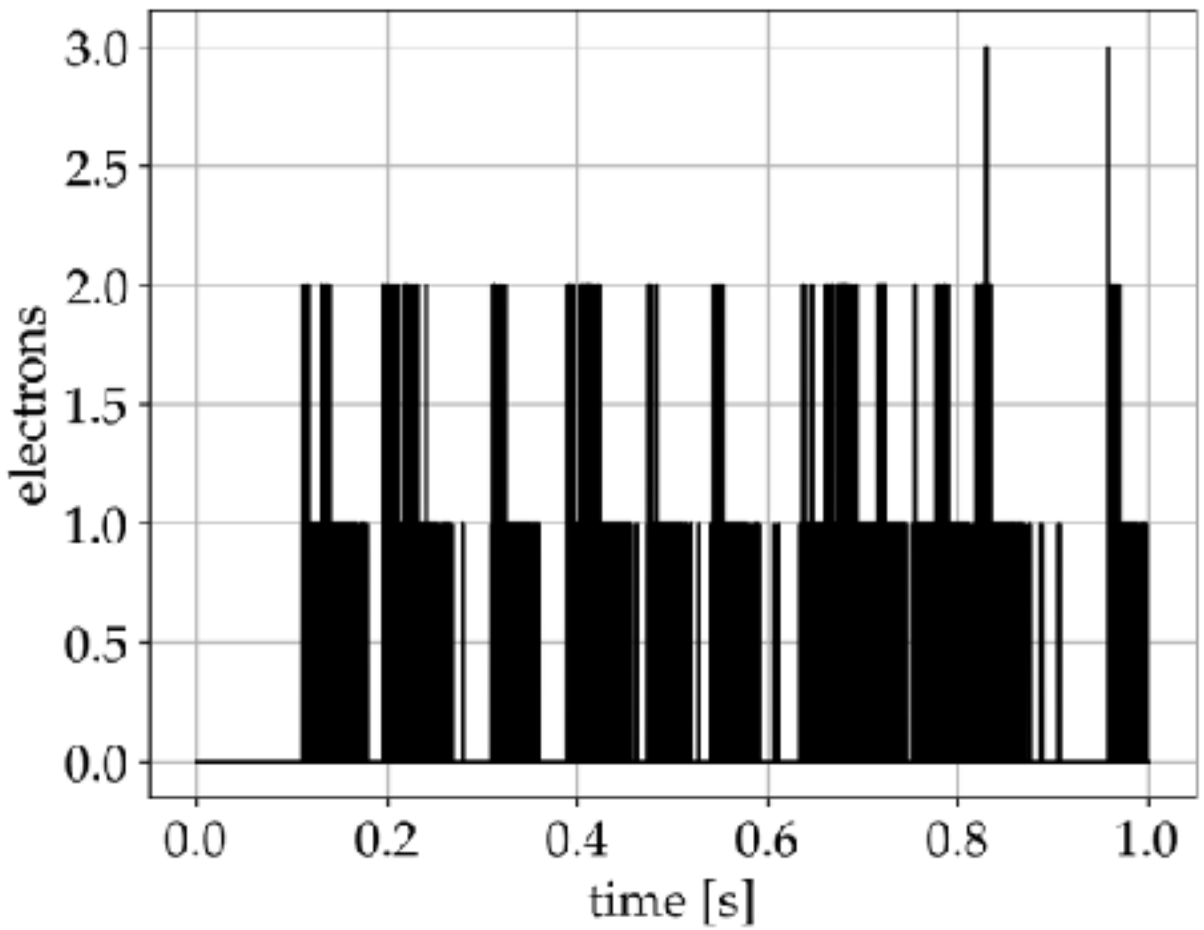


Darkside observed this, too

Simulation of electron noise



Assume:
* 20 Hz of 1 MeV events
* 20 ms decay time of e- noise

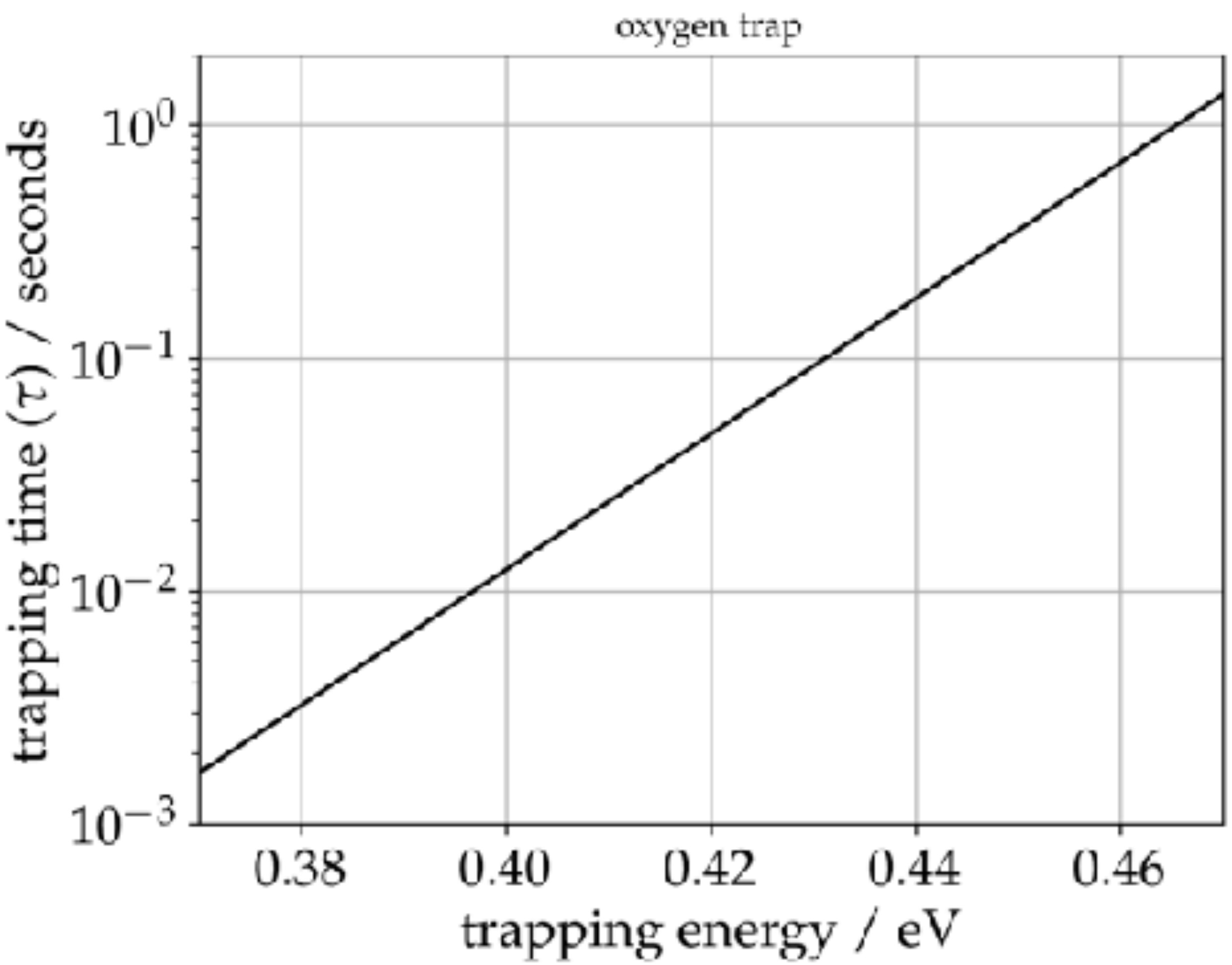


voila: nonzero rate of
2 and 3 e- events

My favored hypothesis

- impurities eventually release their captured electron
- the time scale for this release is 10-100 ms ** and a primary mechanism is thermal agitation (collisions)
- may change with electric field

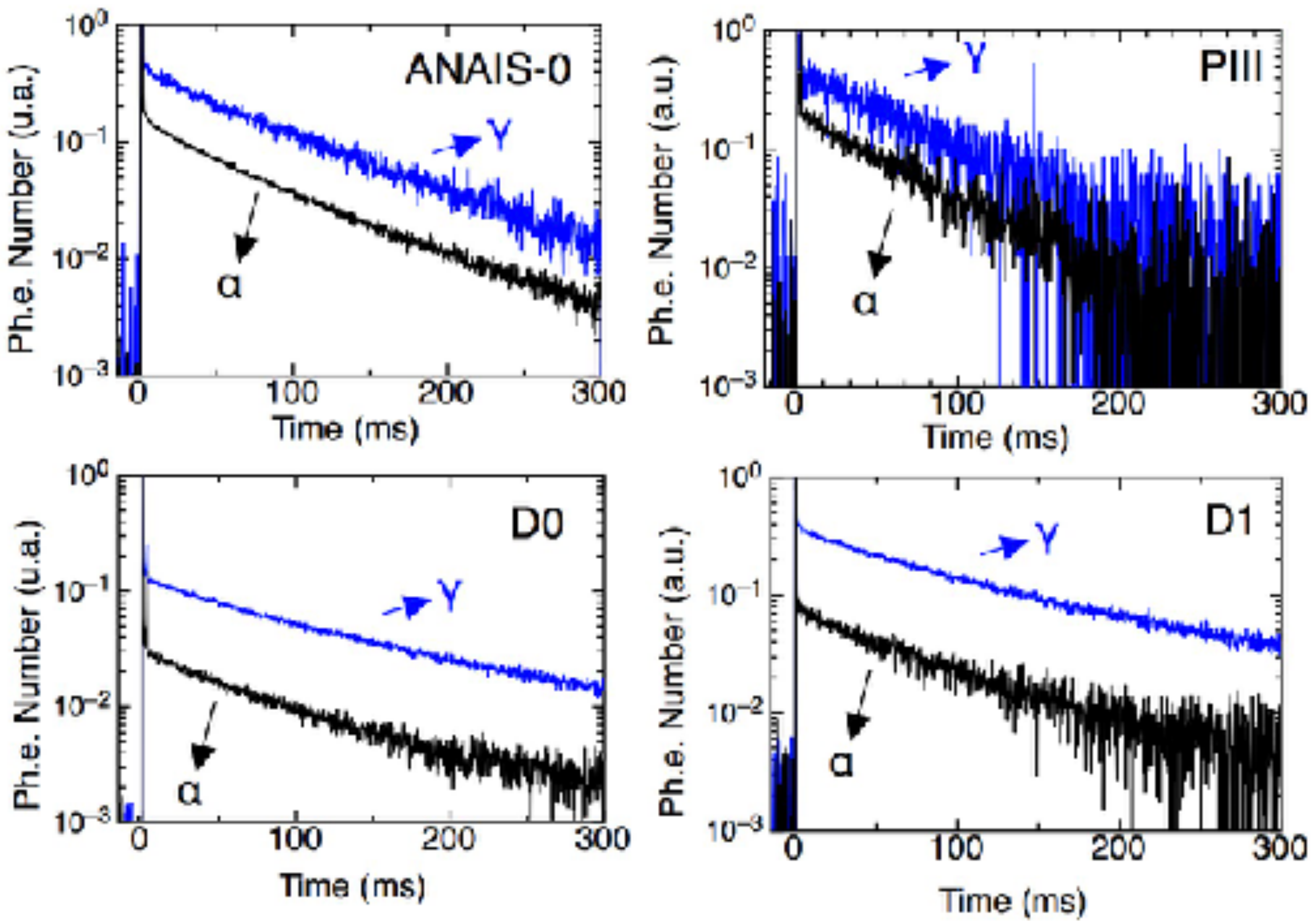
- an impurity only moves O(10) um in this time!!
- leaving it in the bulk, ready to cause future misery



** calculation is incorrect in our paper :)

Trapping with delayed release

Cuesta et al, arXiv:1307.1398



"Significant differences … among … different NaI(Tl) crystals, pointing at an origin of such scintillation related to **impurities or defects** more than to the thallium doping."

- generic cautionary tale
- also relevant for semiconductors, E=0 scintillators
- where do all the electrons go?
    1. recombination
    2. trapping
- impurities are always there :(

from UA'(1) to LBECA

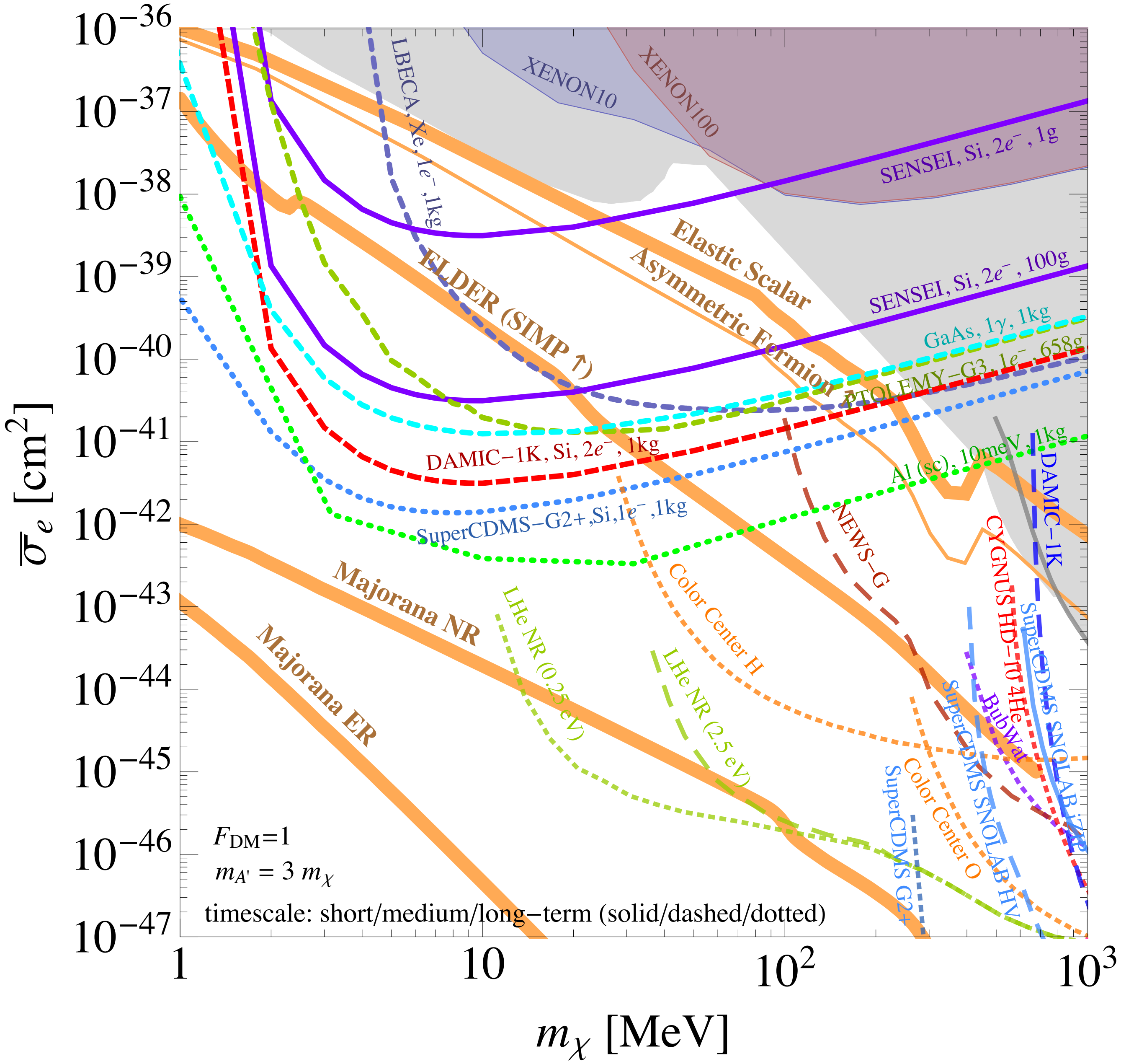
- should we deploy a low-background e- counting apparatus (LBECA)? cf. Cosmic Visions white paper
- ***A liquid xenon demonstrator clearly makes sense:*** *show that we can obtain ultra high purity, obtain interesting new limits on dark sector DM!*

—Bernstein, Essig, Fernandez-Serra, Ni, Lang, Sorensen, Xu

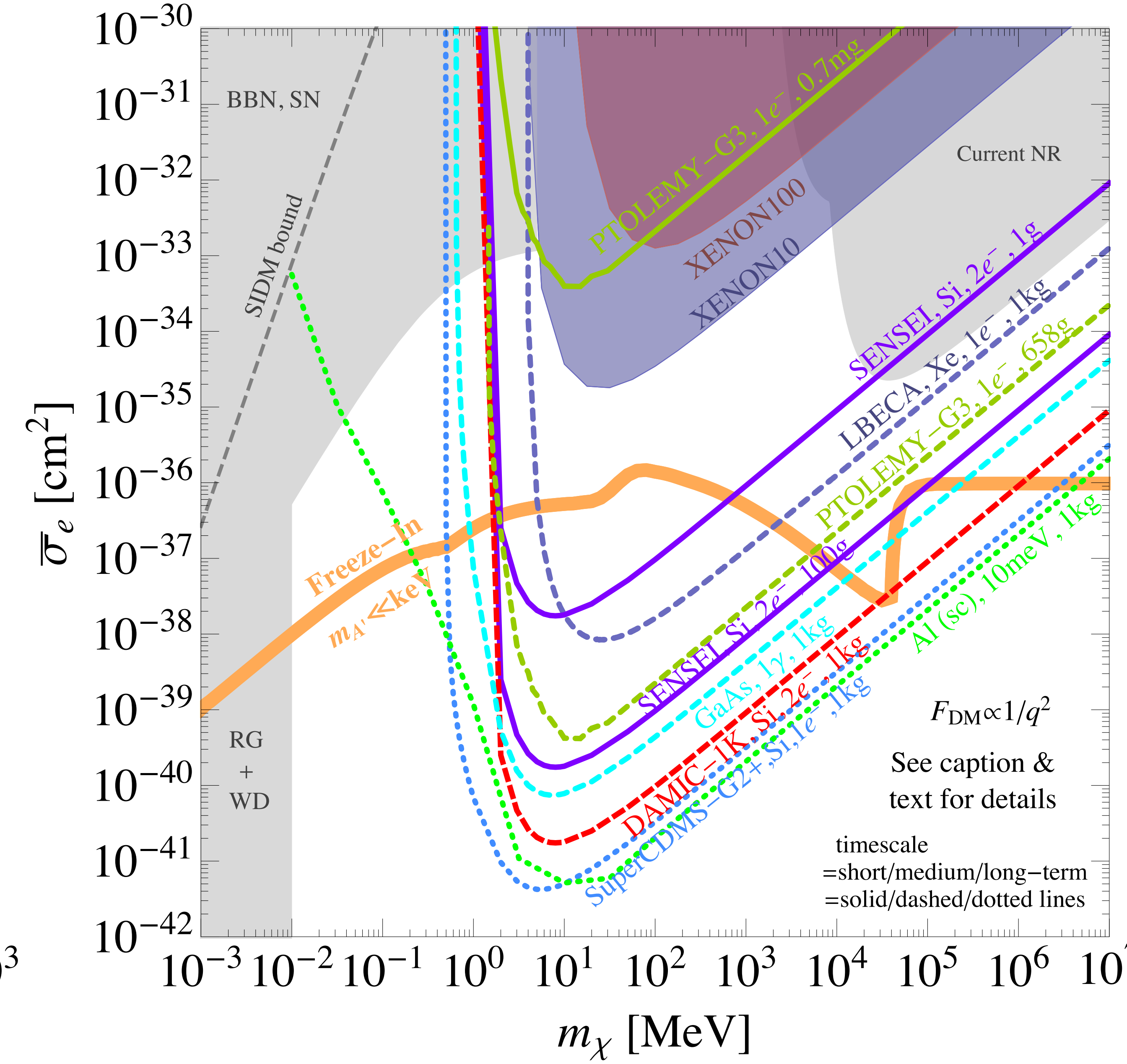
- kilograms are better than grams for rare event searches
- what is different from LZ/XENONnT? mostly: remove the plastics and PMTs
  - they trap impurities, diffusion time scales are slow

Sensitivity to dark sector models

heavy A'



light A'



Summary points

- Impurity trapping of electrons is a generic background issue for technologies which measure photons or electrons
- Significant reduction in electron noise looks possible
- Interesting limits on BSM candidates despite significant one-electron noise
- LBECA could herald the "return" of the large liquid xenon detectors for sub-GeV — an excellent medium-term search strategy