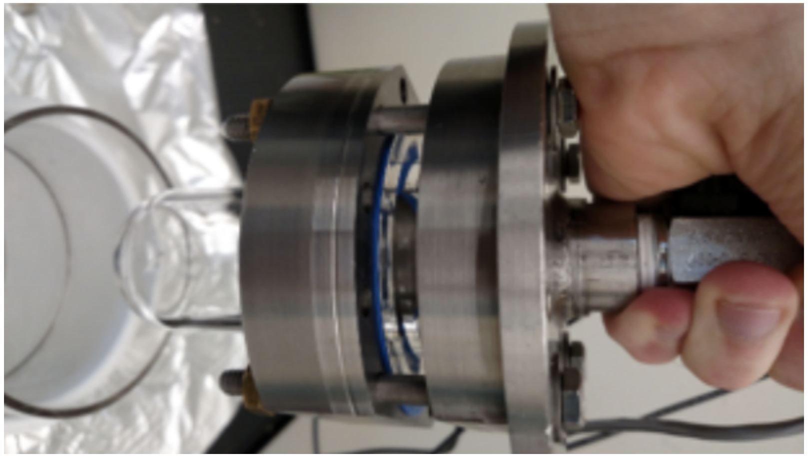
Searching for Dark Matter

with the Noble Element Simulation Technique (NEST)
and with "BubXe" - a xenon bubble chamber detector

Matthew Szydagis

NEST



10 October 2016 ICPPA Moscow, Russian Federation

http://www.albany.edu/physics/NEST.shtml

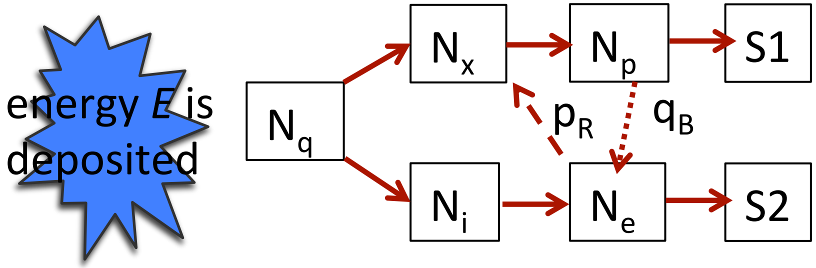
Noble Element Simulation Technique

- NEST: What is it? Free software for Geant4 (standalone coming)
  - Monte Carlo simulation model/algorithm collection and framework
- Semi-empirical, absorbing/fitting existing best world data and uncertainties, to make predictions/extrapolation for newer data
  - In the future: greater degree of first-principles approaches
- Crucial for LUX & LZ: tool to understand/interpret, plan
  - See my plenary session talk on Thursday for these collaborations
- Easy, fast models of light (S1) and charge (also light, S2) yields
  - Photon/electron counts output as functions of incoming energies, electric fields, and particle types (neutrons and electrons)

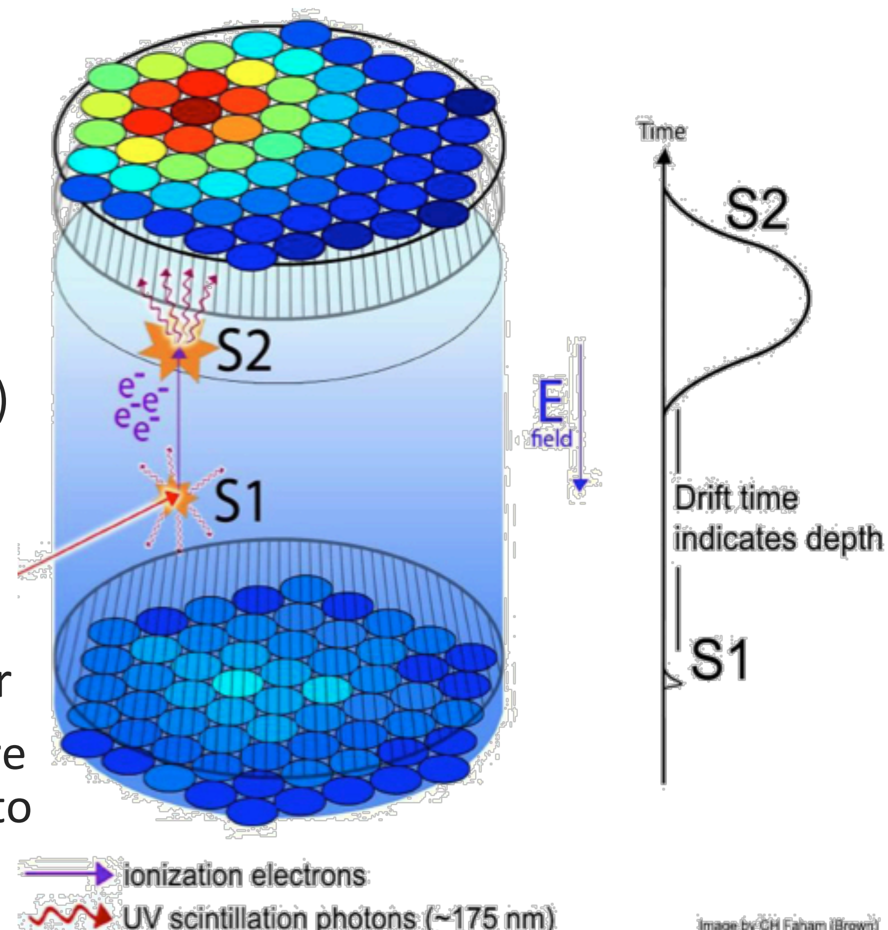
Outline

- The microphysics of the scintillation and ionization processes
  - Recent improvements in our understanding with new calibrations
- Examples of both the postdictive and predictive power of NEST
  - Focusing exclusively on liquid xenon now due to time constraint. Vetted/justified with past data sets so can trust in present+future
- This work is crucial to many different fields of research not just dark matter: any rare event search, at low threshold (or not)
  - Coherent neutrino-nucleus scattering: discovery and monitoring
  - More nuclear physics: Neutrinoless Double-Beta Decay search
  - BSM HEP like MEG, plus LAr TPCs for neutrino physics. So much!

Overview of the Physics



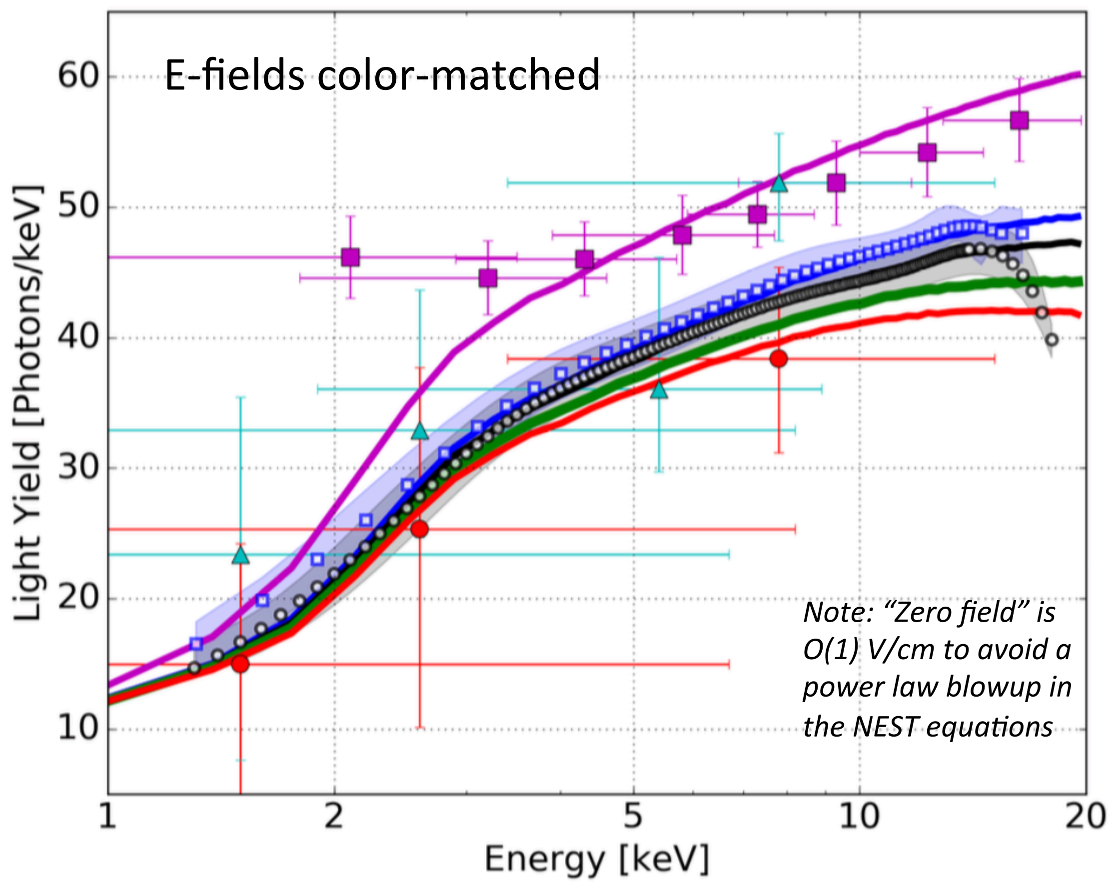
- Energy is first partitioned into both excitation and ionization (and heat)
  - Last is big deal for nuclear recoils (NR)
- Recombination probability is key: re-shuffles the channel division as some ionized electrons are captured into excited states. Physical "free" parameter
  - And 2nd-order effect (high-E NR) where some photons "lost," or converted into e's (Penning & biexcitonic quenching)
- S1 and S2 result from the γ's and e^-'s



Electron Recoil (ER) Absolute Light Yield

Figure 1.3.6: Absolute ER scintillation yield in LXe. Purple squares are from Compton-scattering measurements at Columbia [53] and cyan triangles from [54] – both at zero field. Blue/black squares/circles are from LUX tritium beta emission measurements in situ at 105 and 180 V/cm respectively [55]. Red circles are from Compton-scattering measurements performed in Zürich at 450 V/cm [54]. The NEST model (updated from [56, 57] but using the same framework and formulae still) is shown in purple, blue, black, green, and red for 0, 105, 180, 310 (LZ baseline), and 450 V/cm, respectively.

- LUX has led the way in the direct WIMP detection field for producing fantastic new calibrations with lower uncertainties and down to lower energies than ever for both the ER and NR. Here CH_3T

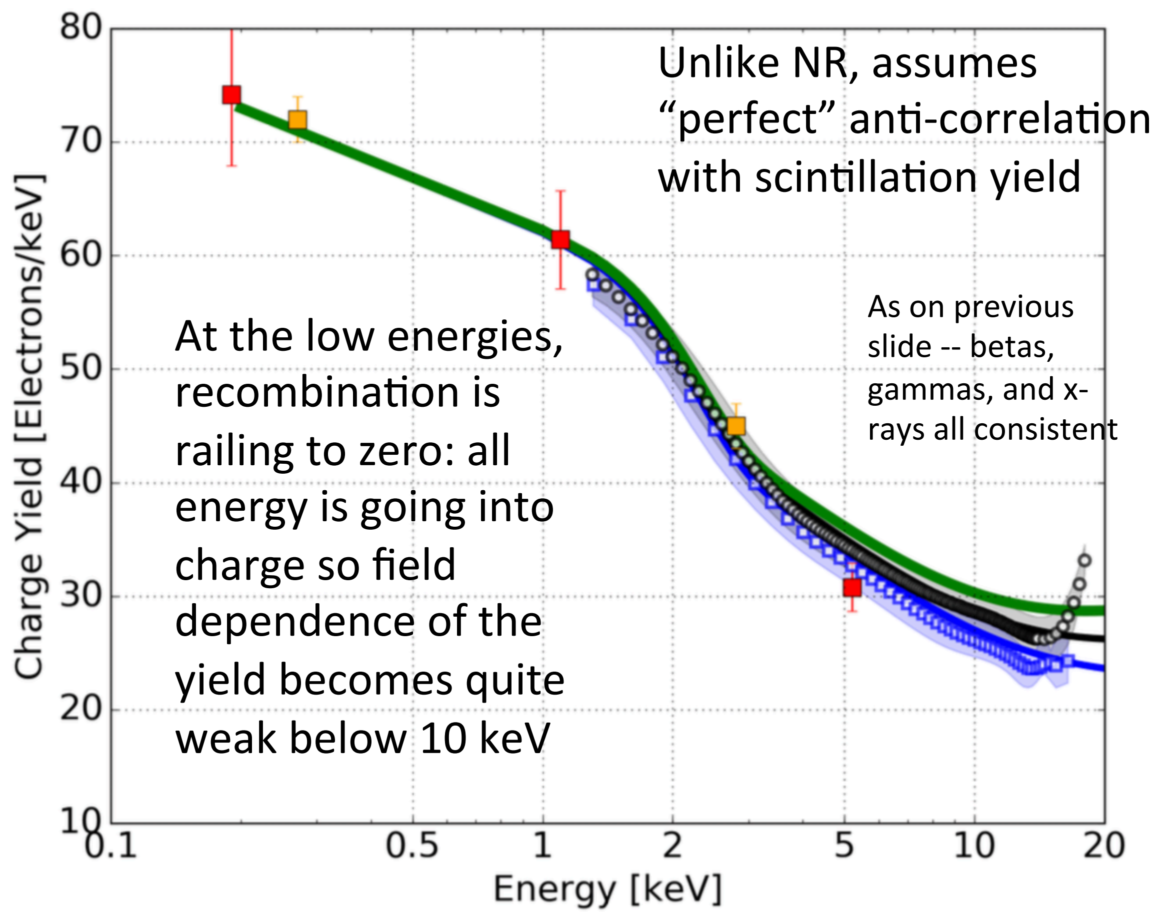


Assume ~5% uncertainty on yields in NEST across energy and field

ER Absolute Charge Yield

Figure 1.3.7: ER ionization yield in LXe. Data are as follows: blue squares from LUX tritium data beta spectrum matching at 105 V/cm [55]; red and orange squares from ^{127}Xe activation lines in LUX and ^{37}Ar in PIXeY, respectively, all at 180 V/cm [F,G]; black circles from LUX at 180 V/cm once again [55]. The NEST model is shown in blue, black, and green for 105, 180, and 310 V/cm (LZ baseline), respectively. The green curve in each plot is what is used for all of the ER background modeling in LZ. Low-energy beta particles and gamma-rays are treated equivalently as both generating ER in the context of the simulation. Increasing the magnitude of the drift electric field reduces the recombination probability, thus raising the charge yield at the expense of light, as with NR.

- A NEST version based on the most cutting-edge results taken from the most recent ER & NR calibrations: LUX tritium, PIXeY, Shanghai/PandaX



NR State of the Art Now (LZ TDR Figs)

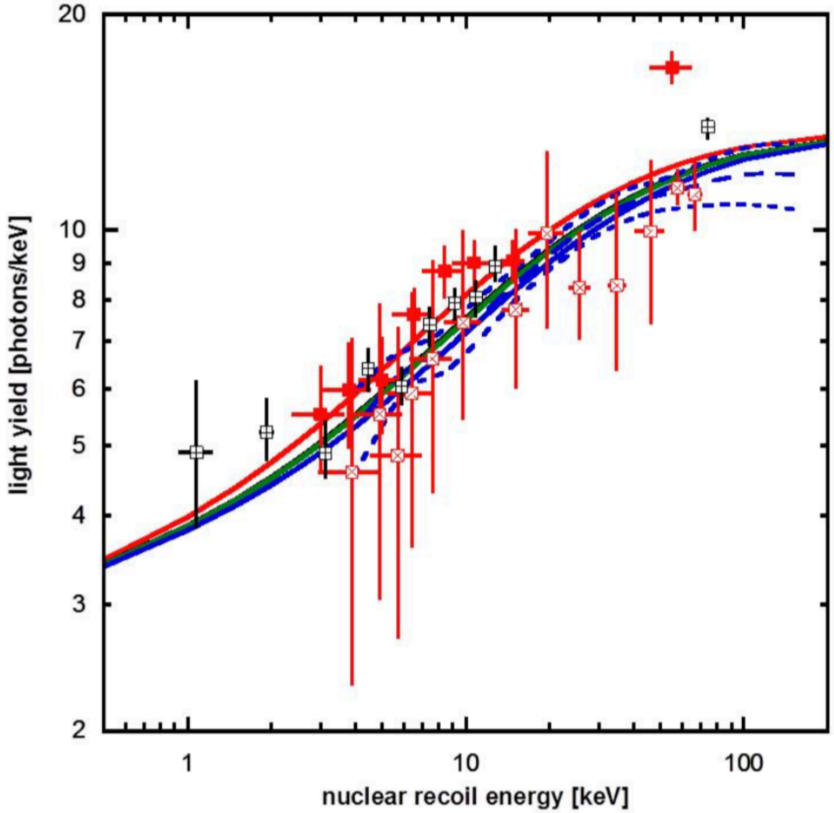


Figure 1.3.8: Absolute NR scintillation yield in LXe. Hollow red markers are from neutron-beam measurements at Yale [60] and filled markers from [61]—both at zero field. Black squares are from LUX DD neutron gun measurements in situ at 180 V/cm [23]. Blue dashed lines are the combined mean and 1-σ curves from two in situ measurements with Am-Be neutron sources via fitting to MC simulation from ZEPLIN-III [62] (3,650 V/cm). The NEST model (updated from [59] but using the same framework and formulae) is shown in red, black, green, and blue for 0, 180, 310 (LZ baseline), and 3,650 V/cm, respectively. The green curve is used for LZ sensitivity calcula-

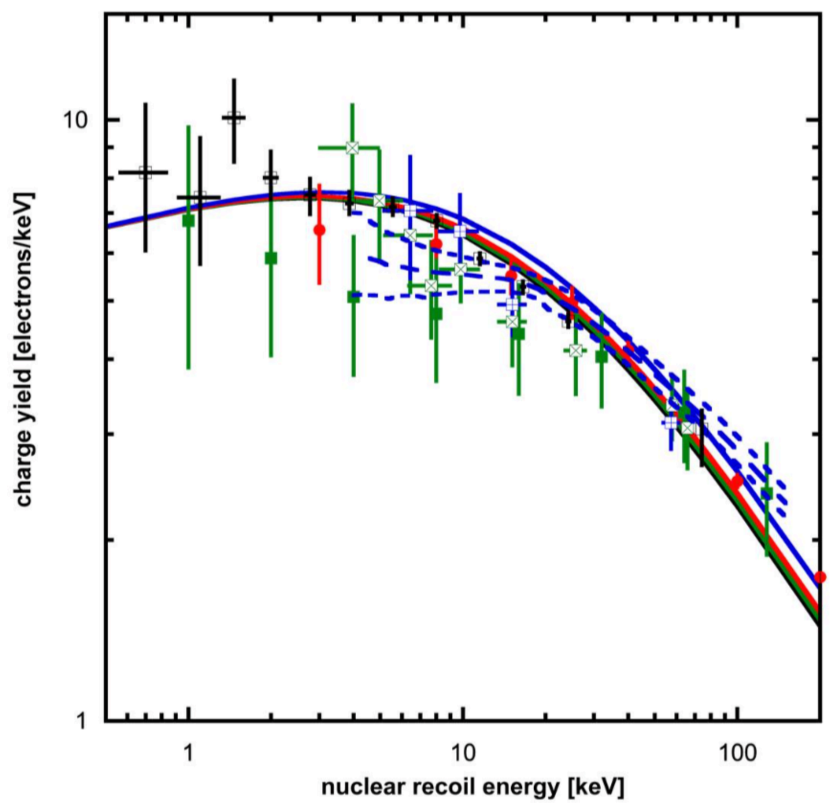
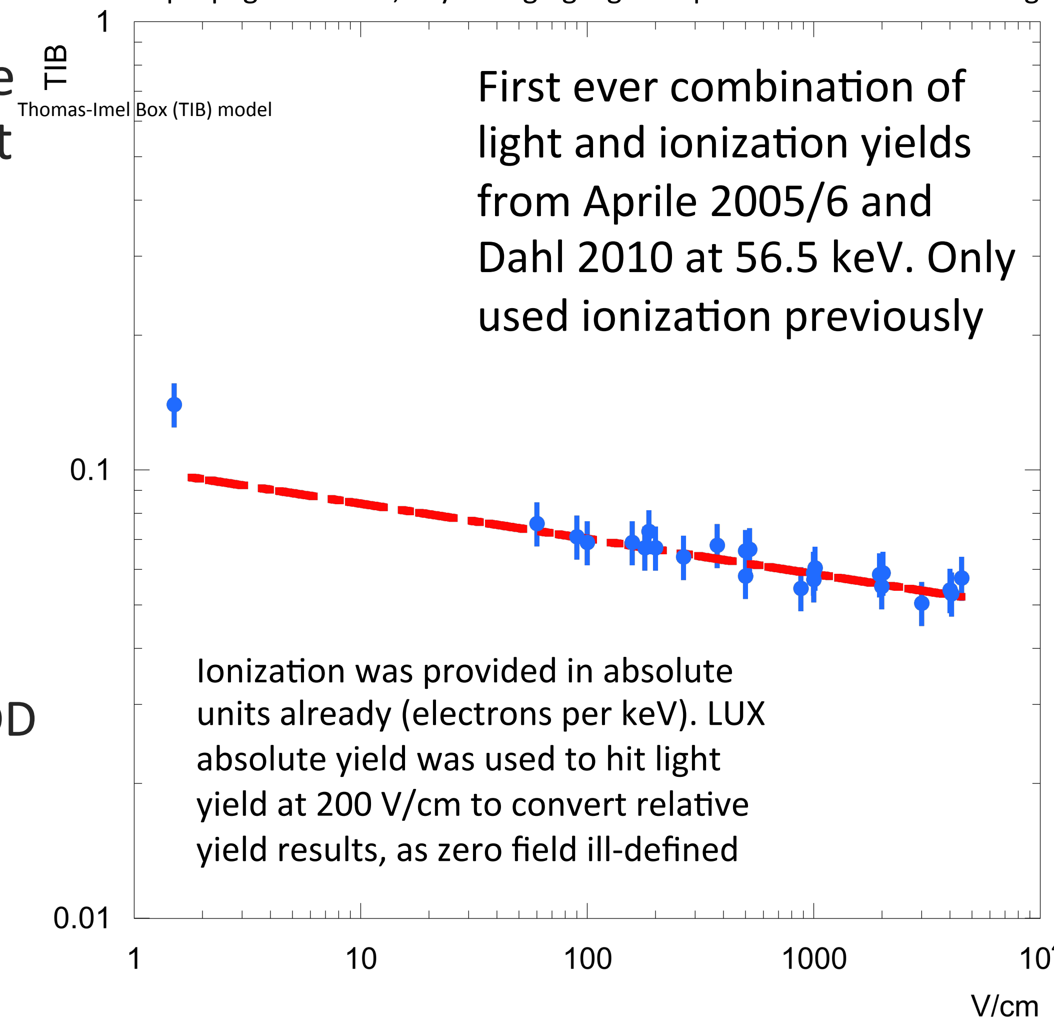


Figure 1.3.9: Absolute NR ionization yield in LXe. Data are as follows: blue and green hollow squares from neutron beam data from Yale at 4 kV/cm and 1 kV/cm, respectively [60]; dashed blue curves from MC matching from ZEPLIN-III [62] at 3,650 V/cm; solid green squares from XENON10 at 730 V/cm[63]; red markers from XENON100 at 530 V/cm [64]; black squares from LUX DD neutron gun measurements in situ at 180 V/cm [23]. The NEST model is shown in black, green, red, and blue for 180, 310 (LZ baseline), 530, and 3,650 V/cm, respectively. The green curve is used for LZ sensitivity calcula-

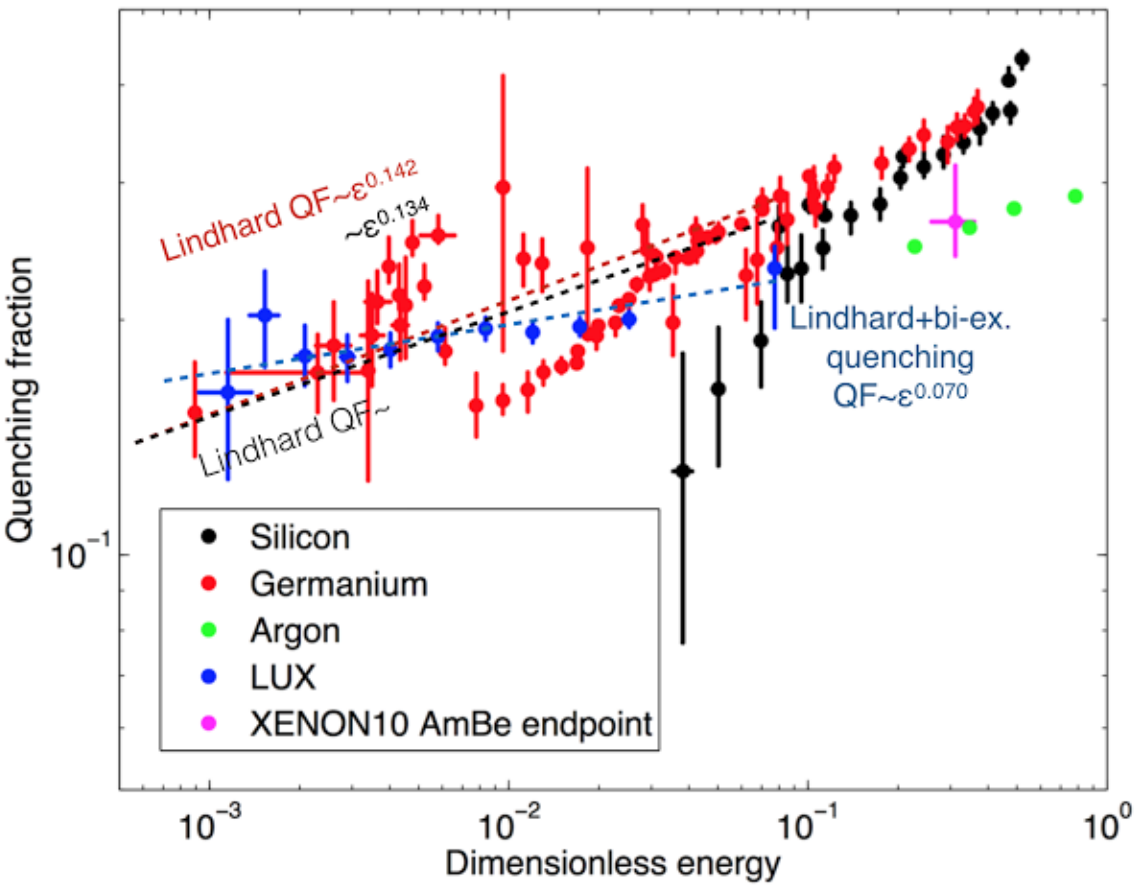
How to Get at NR Field Dependence

- Even if small, important to include and get right because subtleties here change/affect the discrimination (ER v. NR)
- Used famous high-E data, to introduce 1 additional free parameter, a power law in Thomas-Imel recombination
  - Reduces e⁻ recombination probability with rising field
  - Forced to agree with LUX DD data perfectly at 180 V/cm
  - A power of -0.078 that is consistent with previous results (~ 0.05 to 0.1, Dahl)

Effect "propagates down," by changing a global parameter across all energies

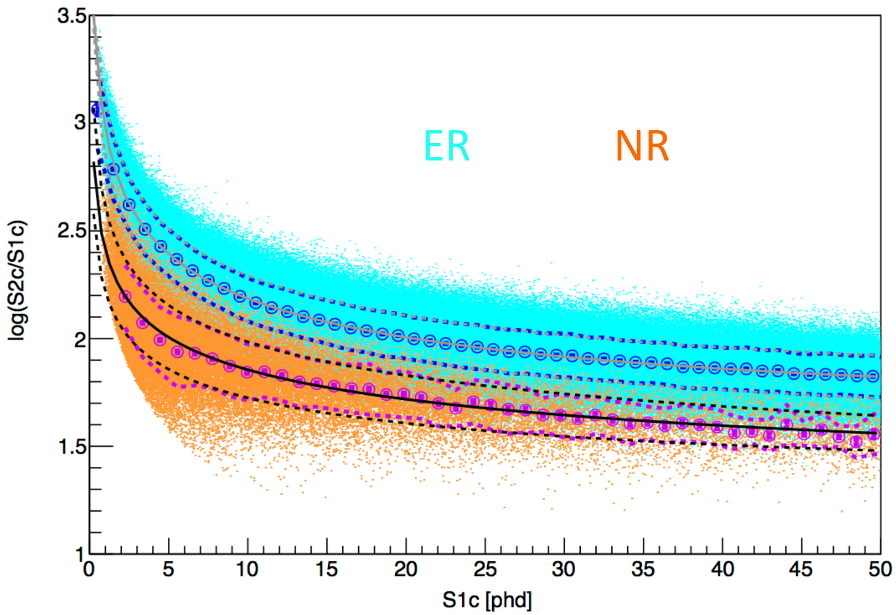


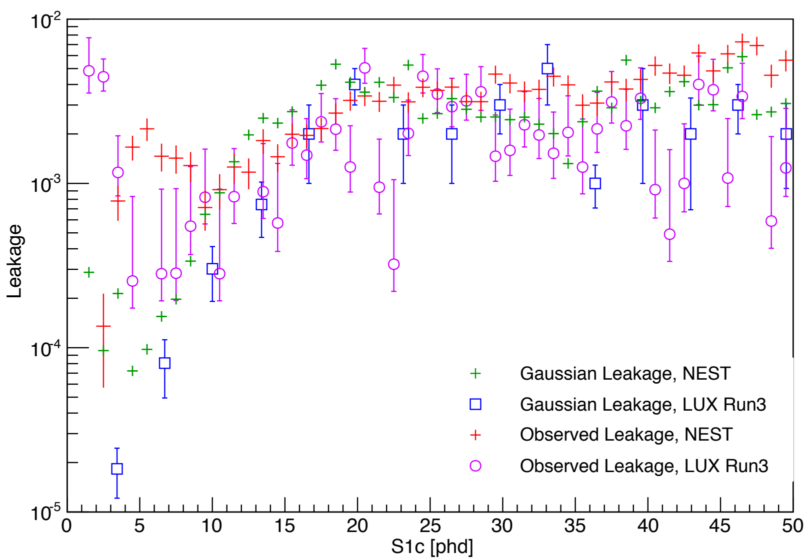
The Lindhard Factor in Liquid Xenon



- Sum of photons/ light and charge/ ionization now close match to Lindhard theory: see the LUX DD n "gun" paper
- Xe (well-behaved!) has achieved same understanding level as other elements such as Ge or Si, if not better! (lower)

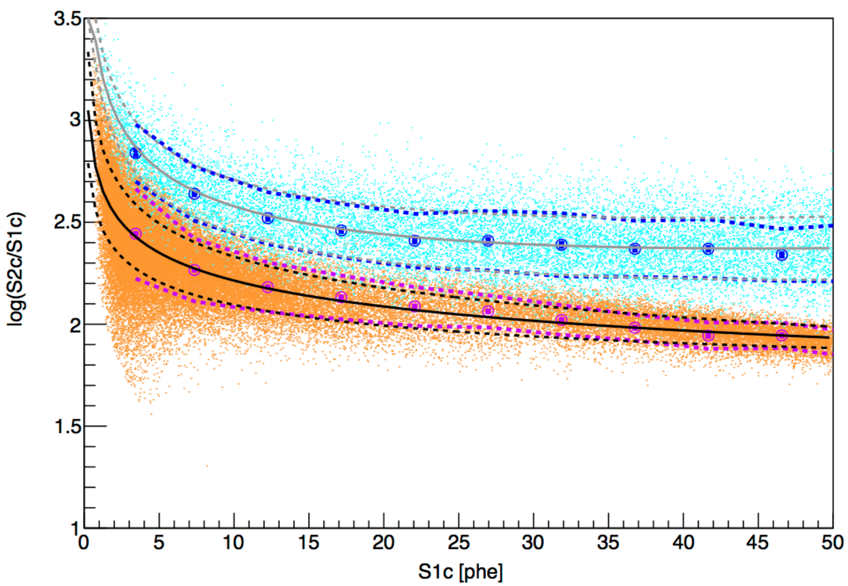
Validation: LUX Run03 Re-analysis

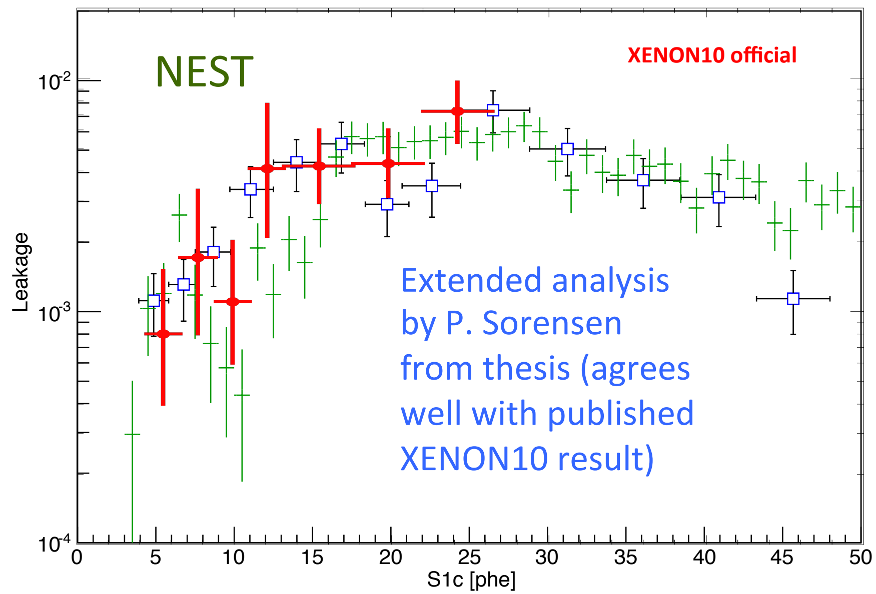




NR band is from DD and ER band is from tritium. Profile Likelihood was used to determine limit so the ER background discrimination is only a figure of merit for how well bands are separated. Slight NR band disagreement conservative: towards ER band, manifest at right. Still, great match on means/widths in general, for both interaction types. Notoriously hard to get all wiggles right (low S1 disagreement not that bad)

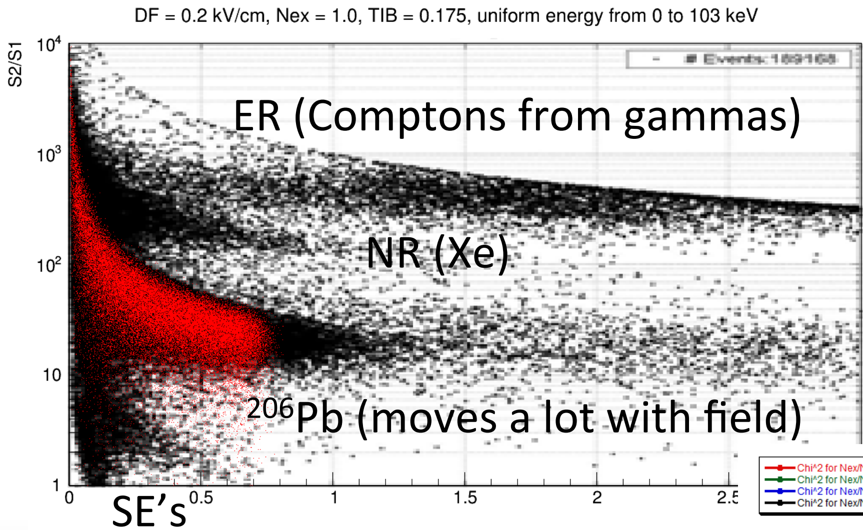
Validation: XENON10

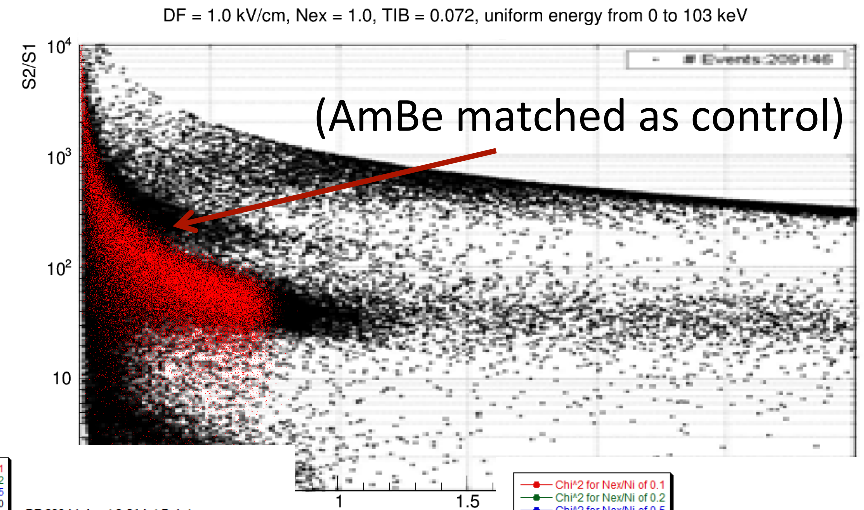


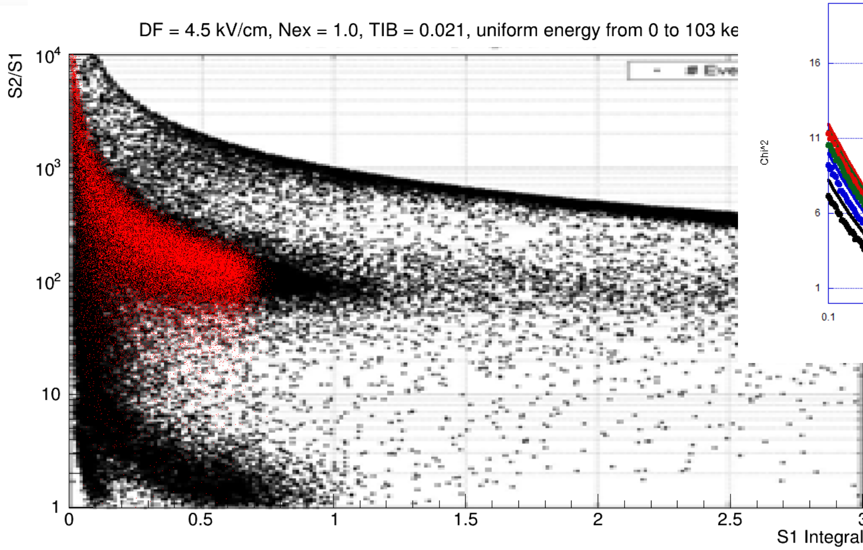


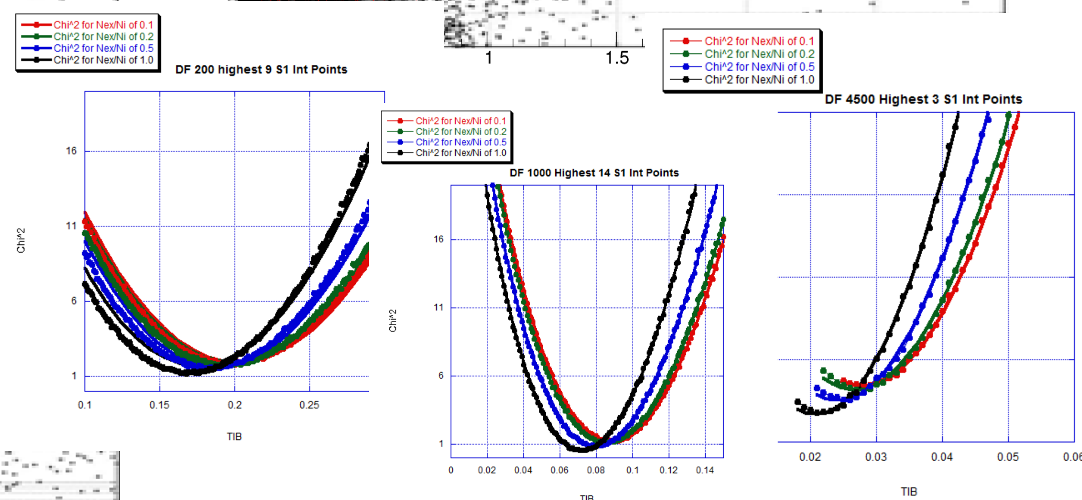
This important cross-check worked on nearly the first try, using ER yields' field dependence from PIXeY (which agrees within error with Shanghai publication) modified (within error) to match the LUX tritium data perfectly at 180 V/cm. For NR, famous 2005-6 Case/Columbia 56.5 keV field dependence used and forced to match DD vs. energy. Energy spectra: AmBe, flat ER. Electric field higher than LUX (730 V/cm), but S1 photon detection efficiency lower

Pb-206 (Xed @CWRU: Shutt, Dahl, & co.)



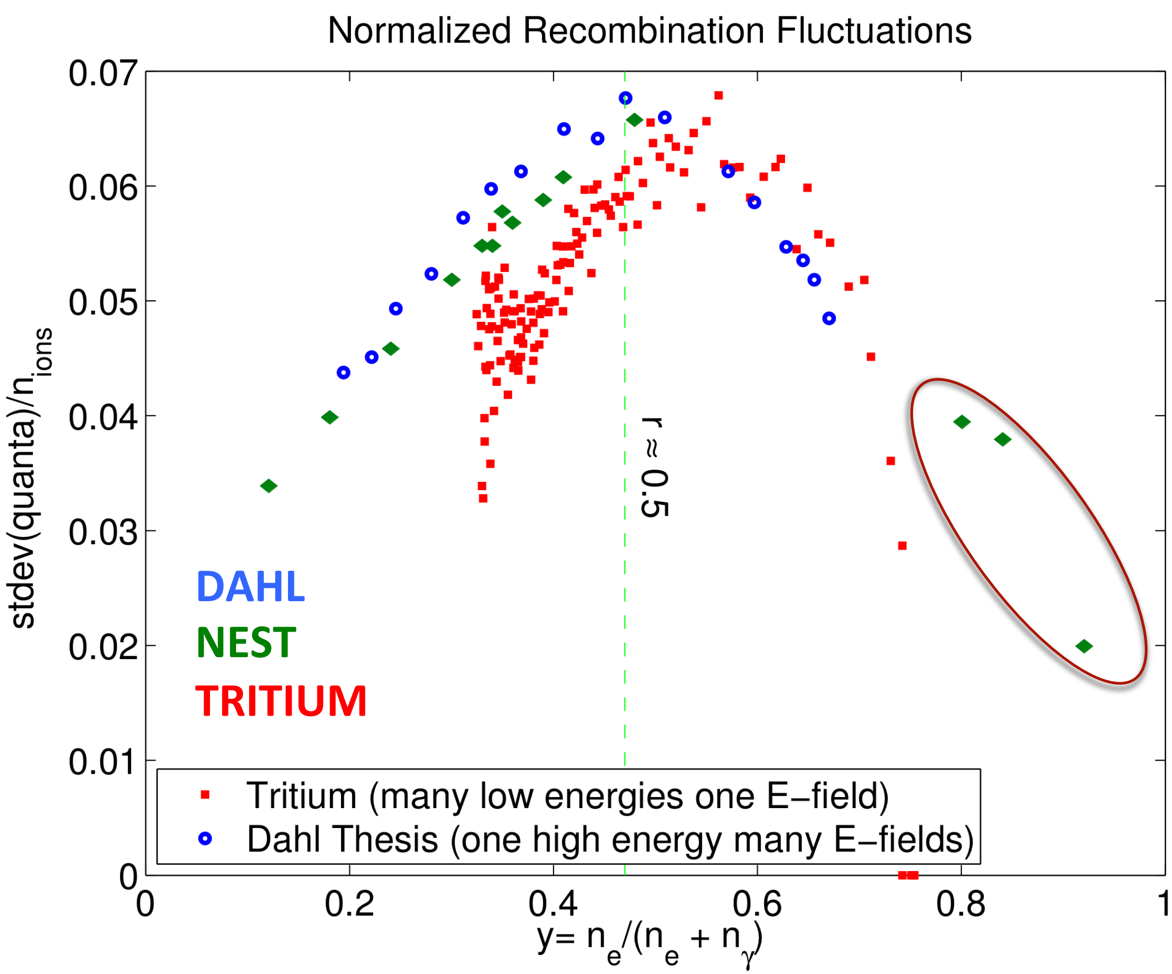






Field dependence is general, i.e., detector-independent. Once found, can be re-applied

Recombination Fluctuations (E Resol.)



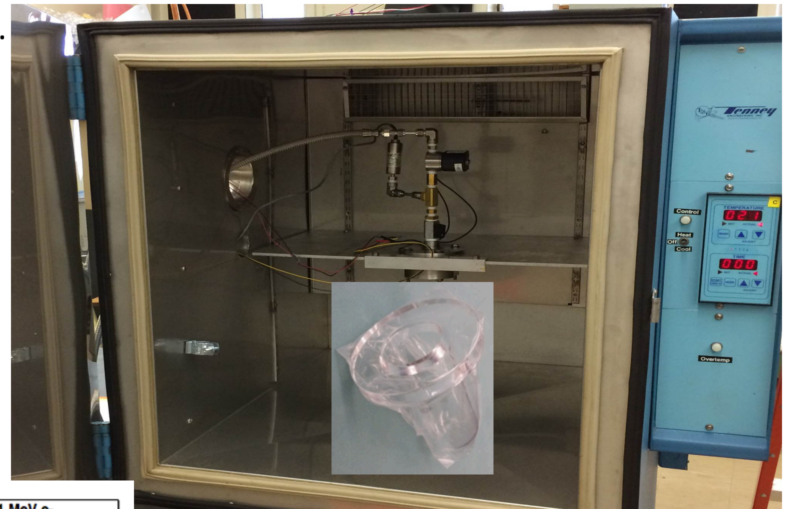
- NEST has got only the left side correct
  - Sails off the scale above ~0.5
  - These are low energies (sub-keV) and very high fields (~1+ kV/cm)
- Solve-able (circle) by making the fluctuation more purely *binomial*
  - Currently under investigation…

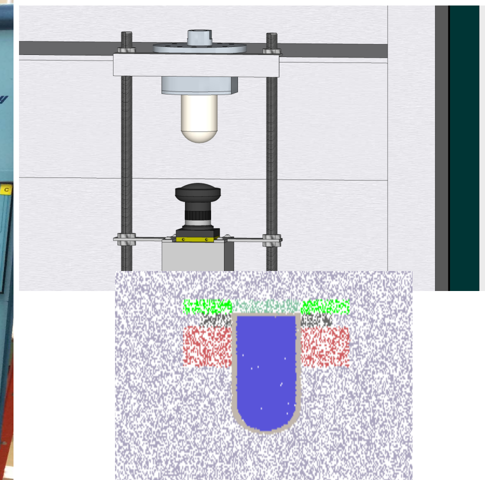
Switching Gears: *BubXe*

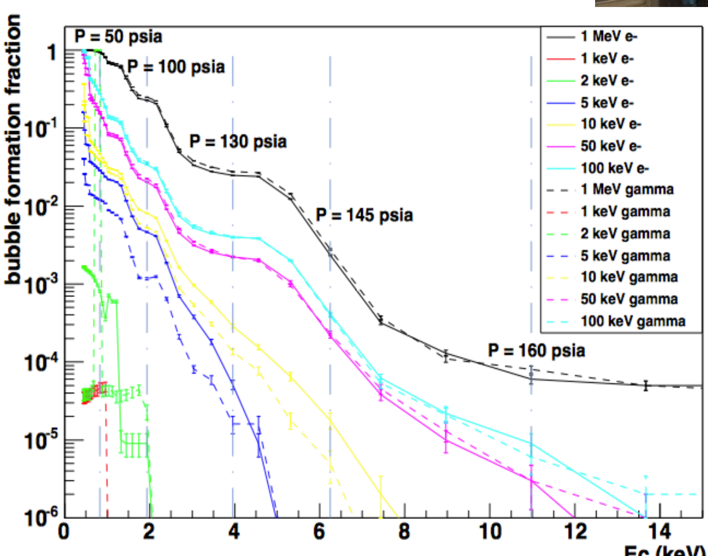
- A new idea, as Generation-3 direct dark matter search R&D
  - Can also help planned G2 experiments especially LZ, and last G1
- Combines the mains advantages of LXe TPCs (energy reconstruction, density) with bubble chambers (blindness to ER backgrounds, visibility of the heat channel)
  - Nearly-100% of an active volume can be fiducial
  - First dark matter detector with 3 channels: light, charge, heat
- Idea: may be possible to punch through the neutrino floor with directionality coming from the S2 light within the bubbles
  - Also, cleaner rare-event detector with unique filter system
- 100 d hits 10 GeV LUX limit with 100 kg (0.5 keV threshold)

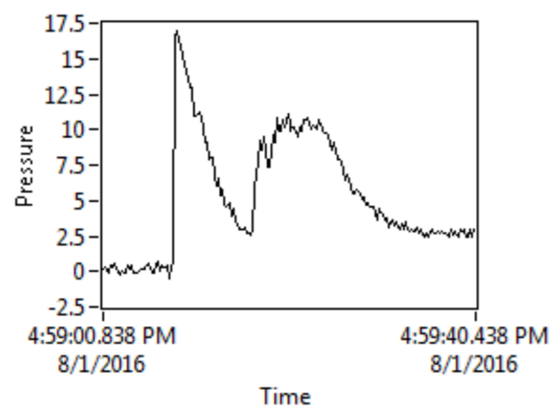
Under Development at UAlbany

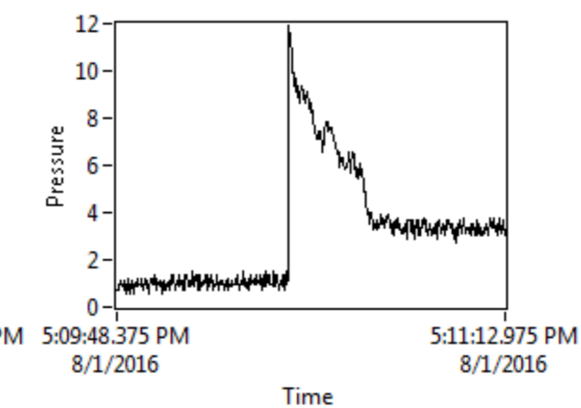
Temperatures and pressures are tunable.
Starting with -40 °C, > 250 psia pressure





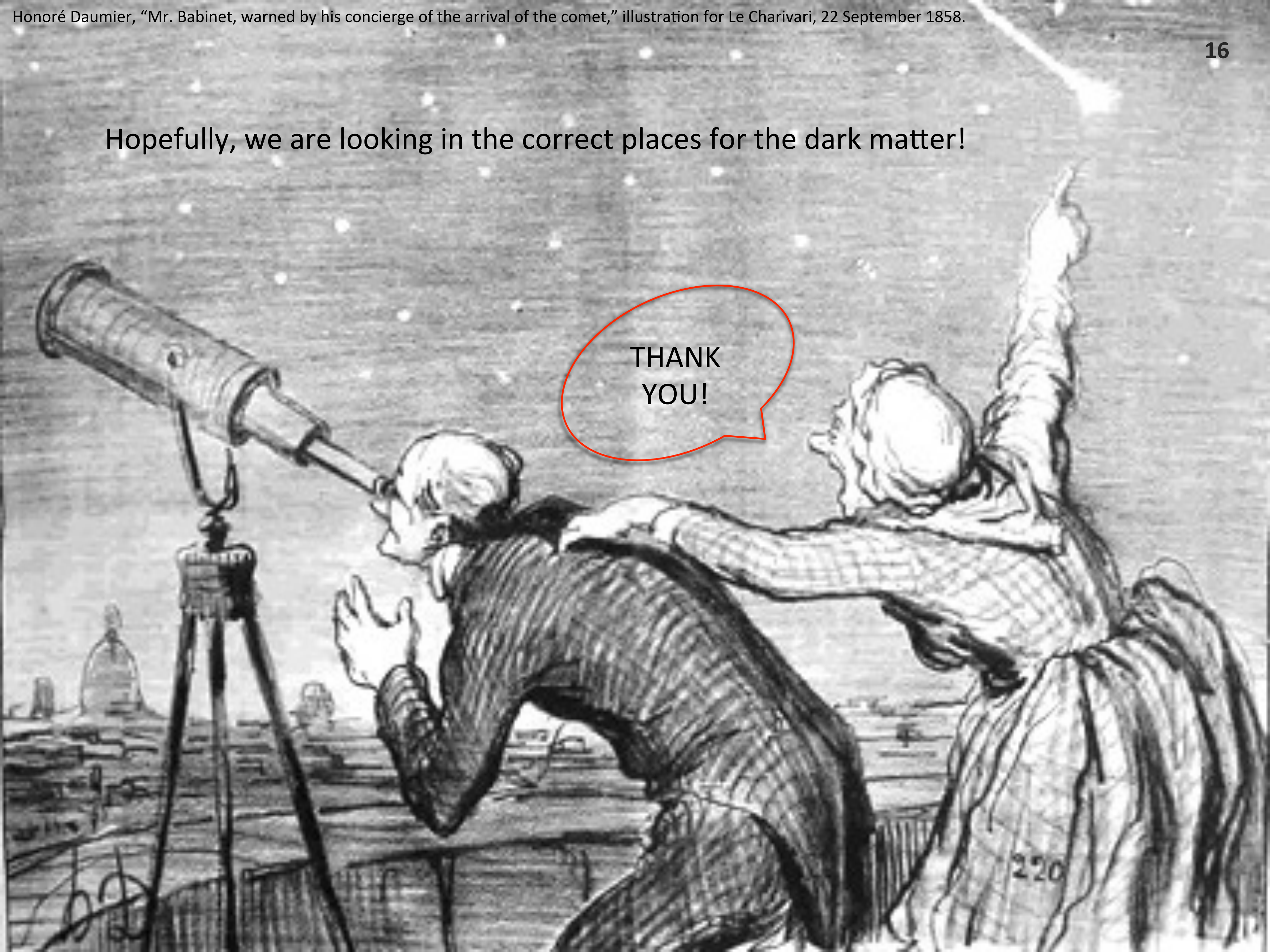






Double- and single-bubble events from system test with water this summer.
First prototype is water Cerenkov chamber, then scintillating bubble chamber

Hopefully, we are looking in the correct places for the dark matter!



Honoré Daumier, “Mr. Babinet, warned by his concierge of the arrival of the comet,” illustration for Le Charivari, 22 September 1858.