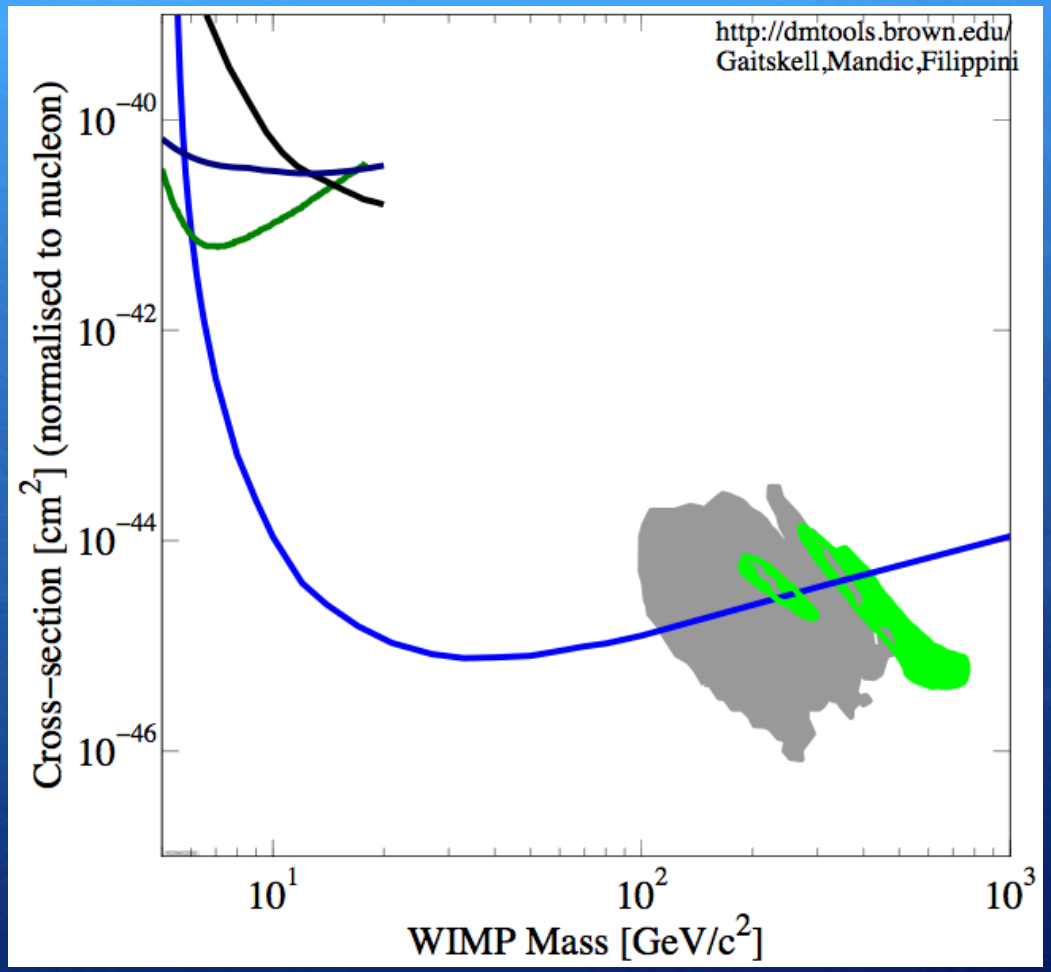
Time Progression of Sensitive Experiments

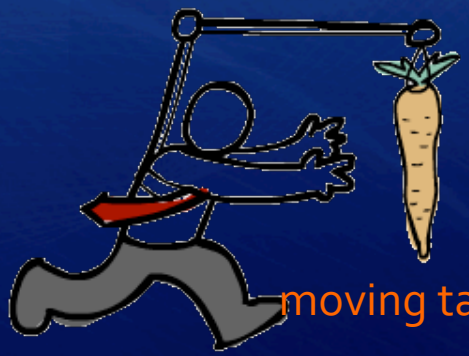


Animation courtesy of Aaron Manalaysay, UC Davis

Years '00-13

Where is all the dark matter? There is so much evidence for it (revolution of stars in galaxies, gravitational lensing, CMB, BBN, cluster collisions) So, why no direct detection??

Closing in on a 1 TeV Higgsino? (See talk by L. Roszkowski 6/3)



moving target?

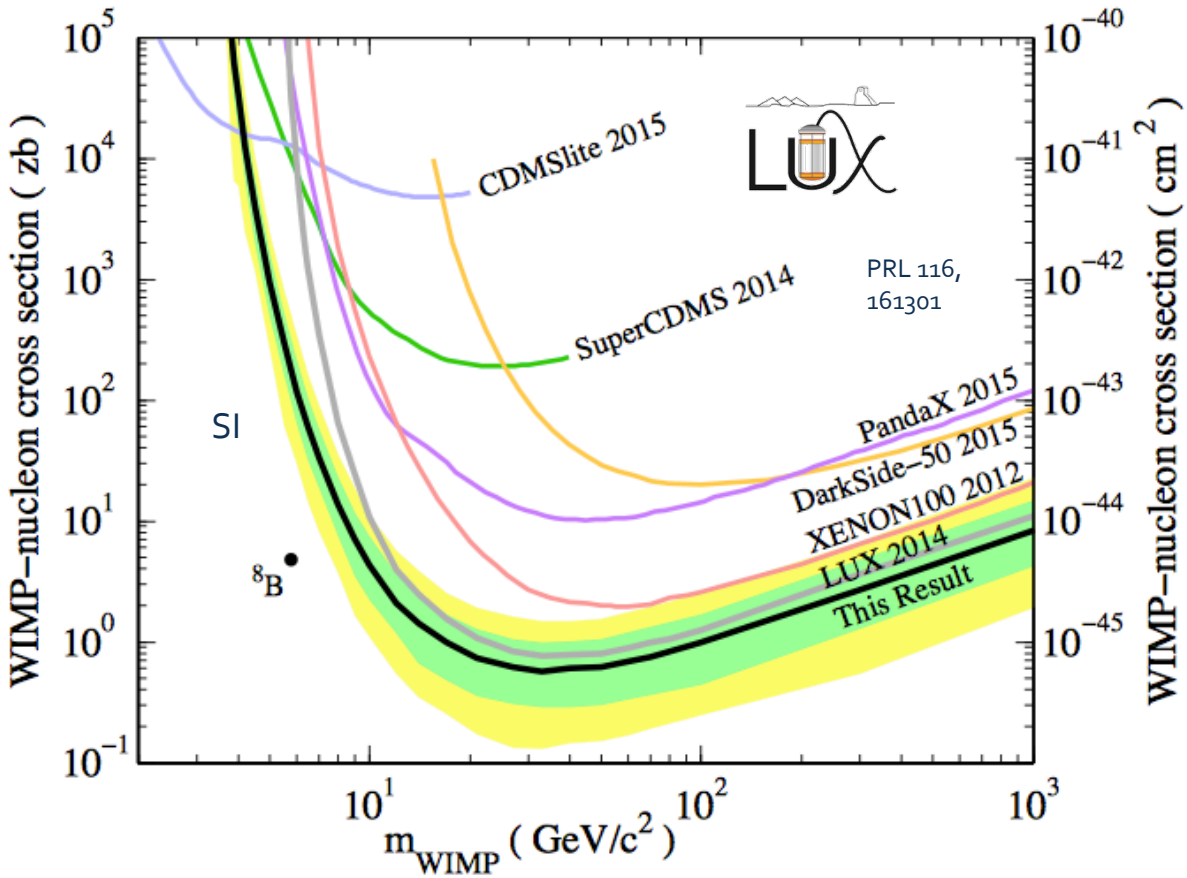
Higgs-mediated coupling coming up?

Status of Field of Direct WIMP Detection

Some claims of discovery exist (for few-GeV WIMPs)

- But NOT discovering something (or, something else) is many a time equally as valuable as your original goal (think Michelson-Morley and aether or Columbus)

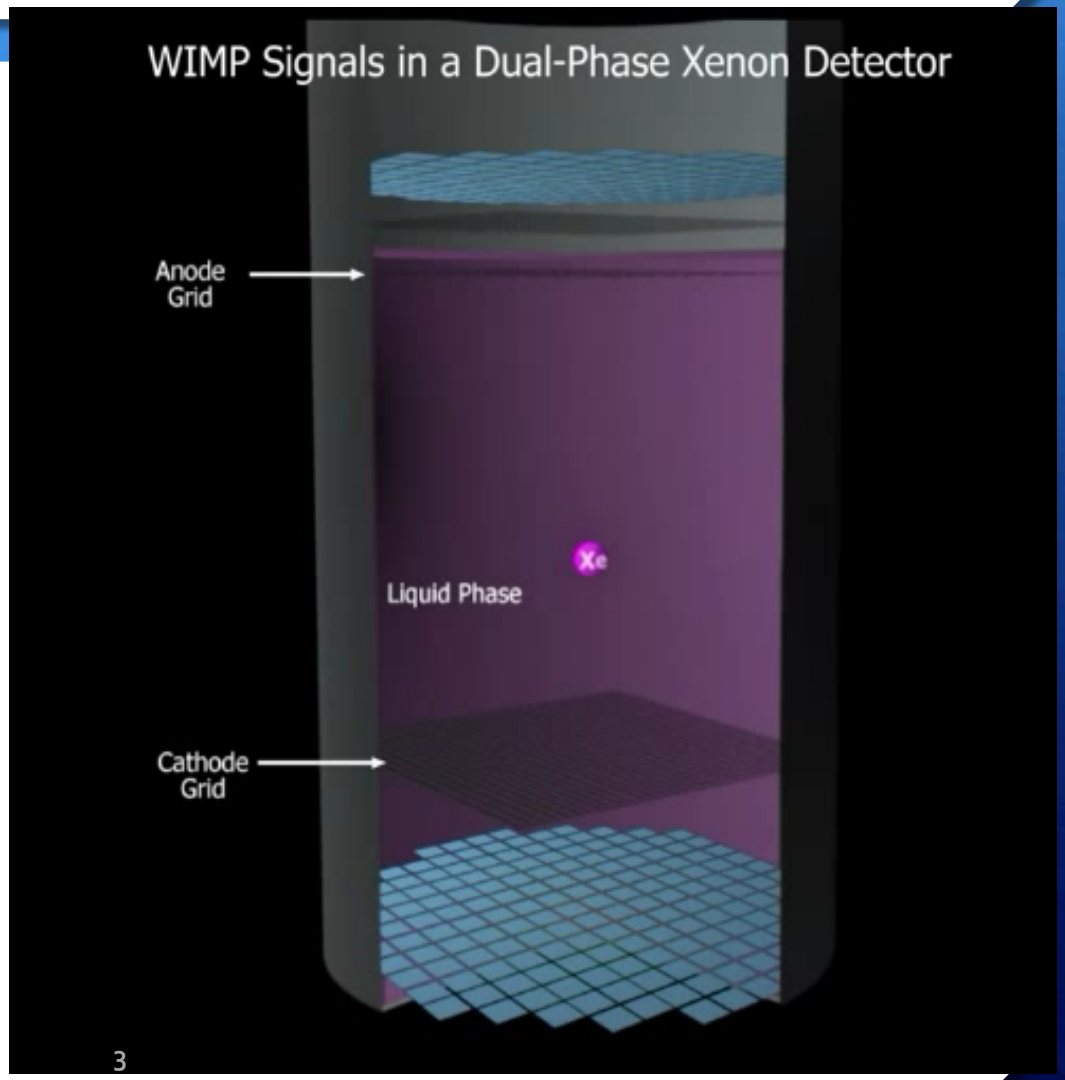
LUX still leads the pack at most WIMP masses as of this talk, having re-analyzed its original data in light of new calibrations (Getting close also to solar ν coherent scattering, ^{8}B, at level of 0.3 events/year)

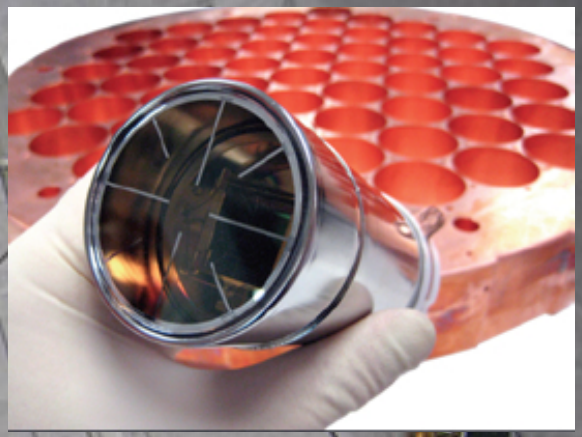


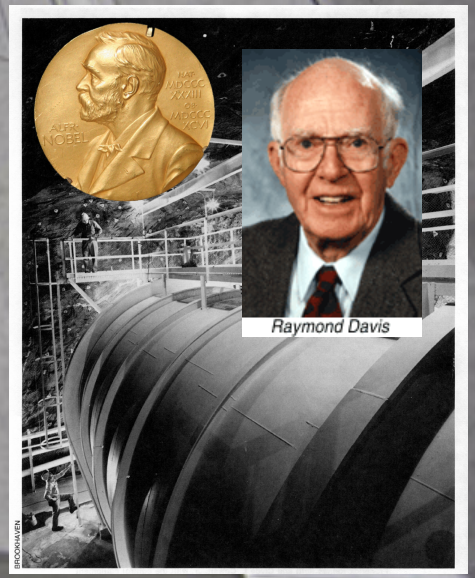
LUX (2015/6) 90 live-day exclusion limit curve

How a Two-Phase Xe TPC Works

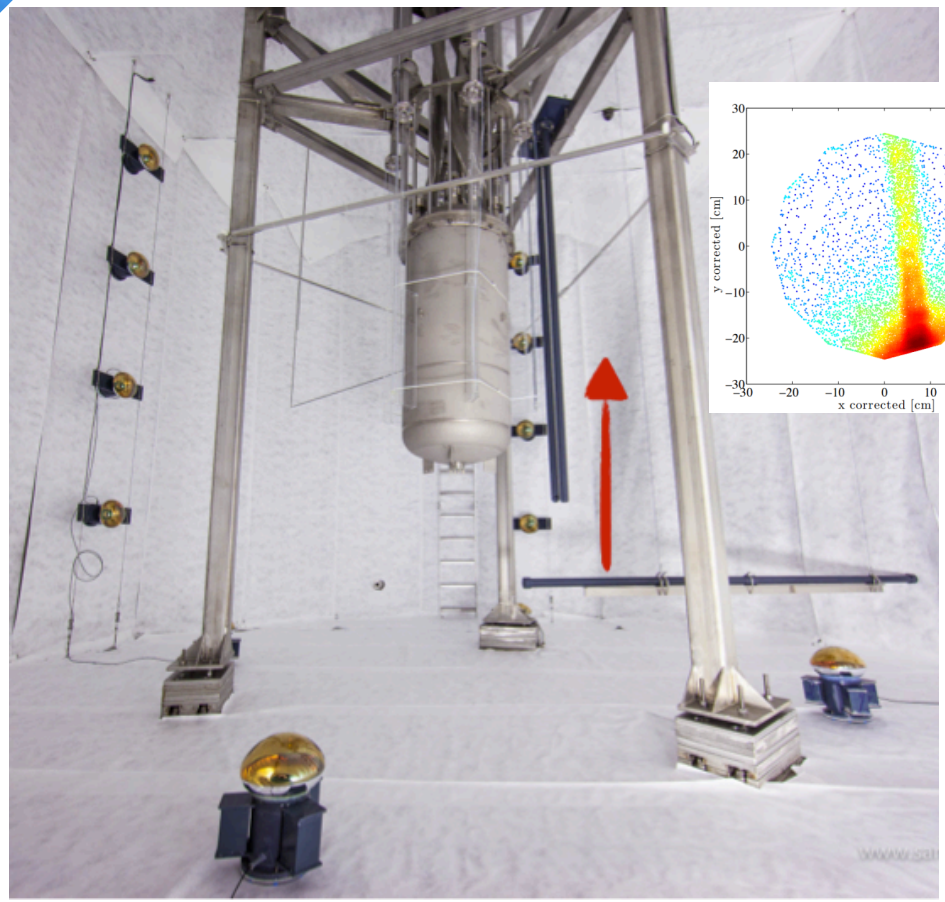
- Collaborations with Xe-based TPCs have been leading pack for ~10 years
  - XENON10 / 100, now LUX
- PMTs convert single photons into photo-electrons (phe)
  - phd = photons detected, term coined by LUX (better-resolution counting method)
- Time between S1 and S2 gives you depth (Z), and S2 top hit pattern is radial position (XY)
- LUX is at Sanford Lab, SD

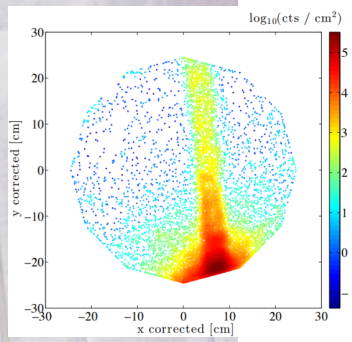


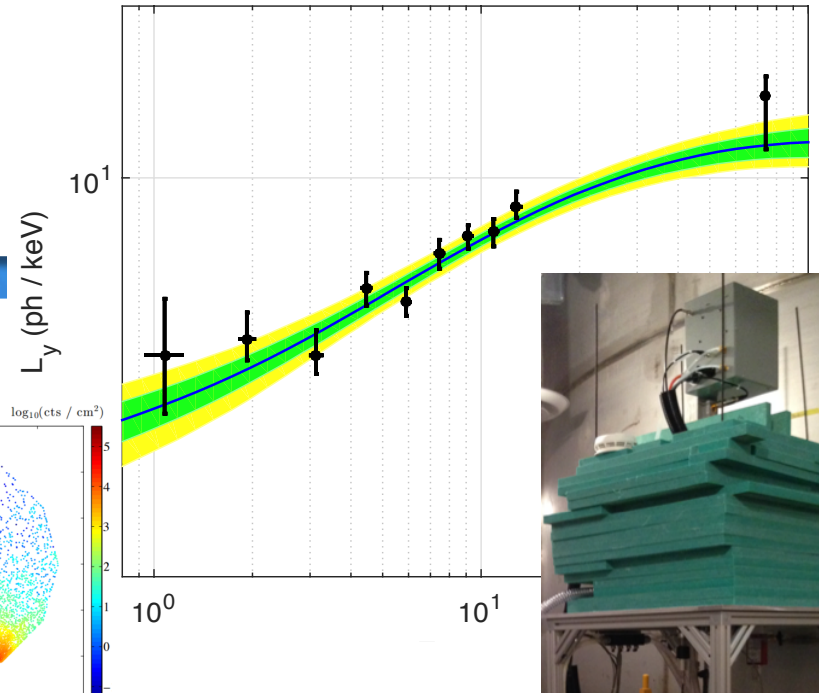


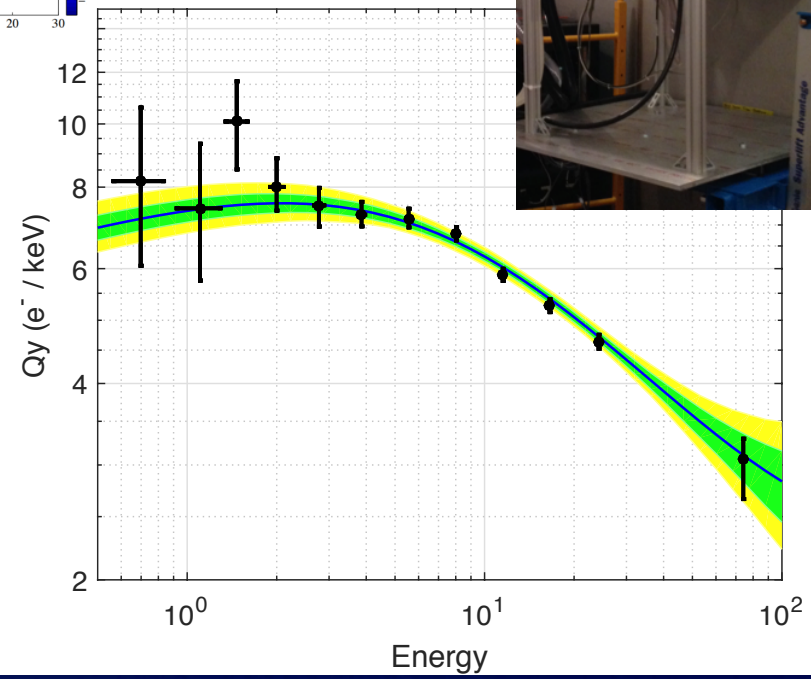

Raymond Davis
BROOKHAVEN

Calibration (LUX DD)

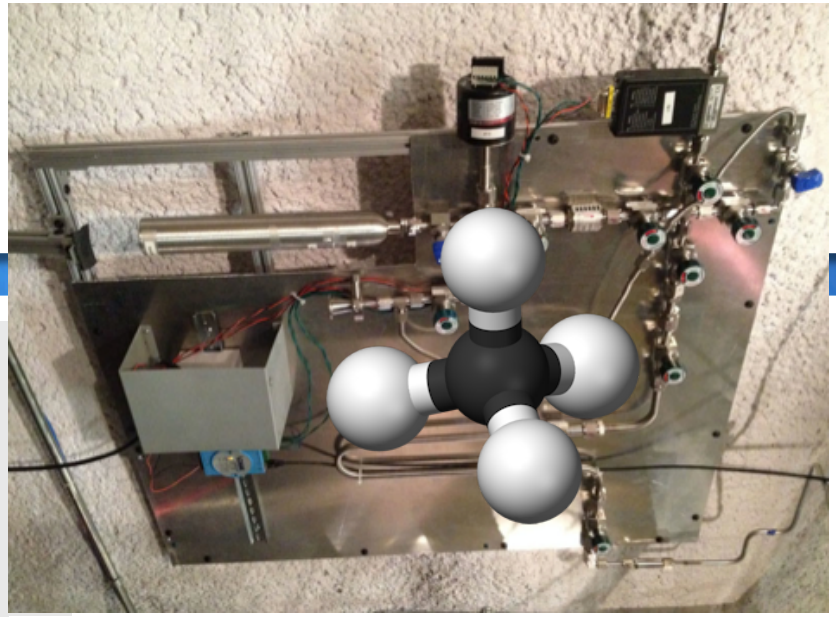


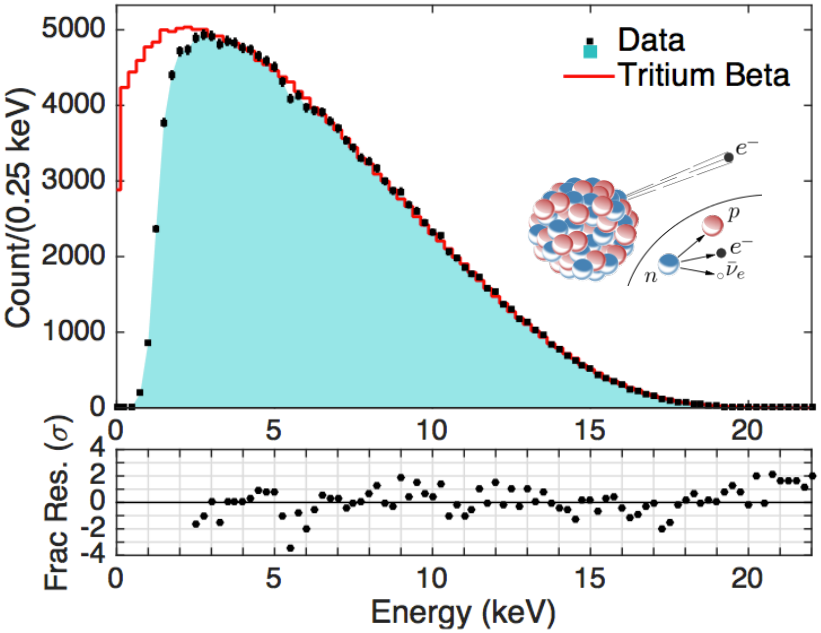




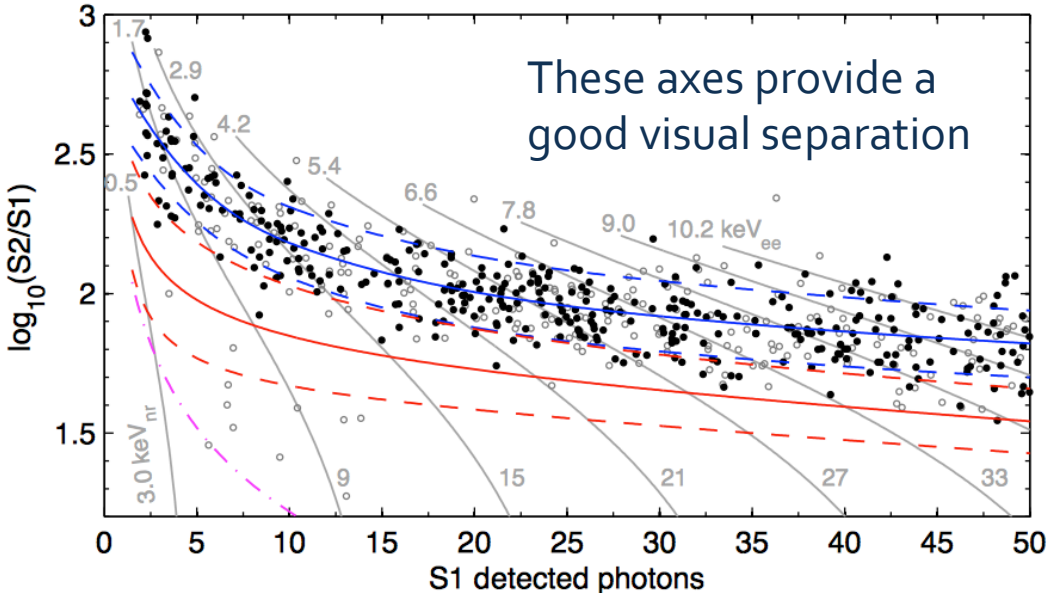


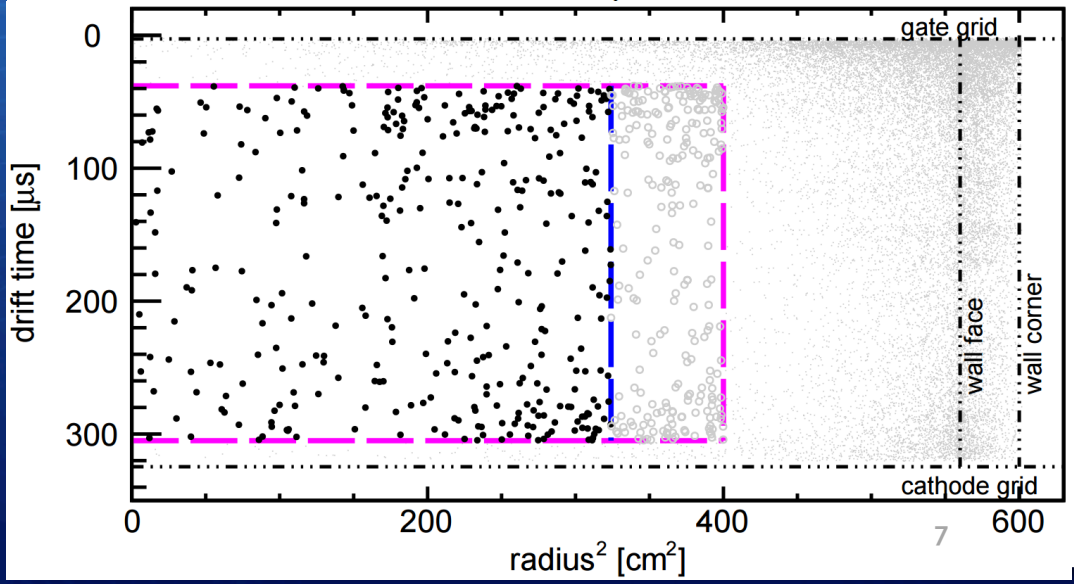
Calibration (LUX CH_3T)

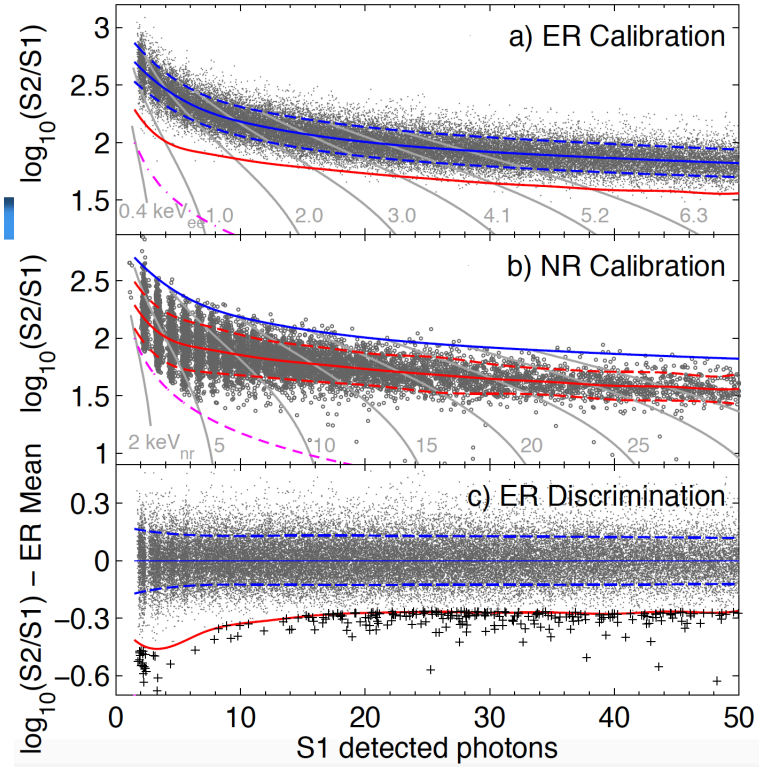




Putting It All Together

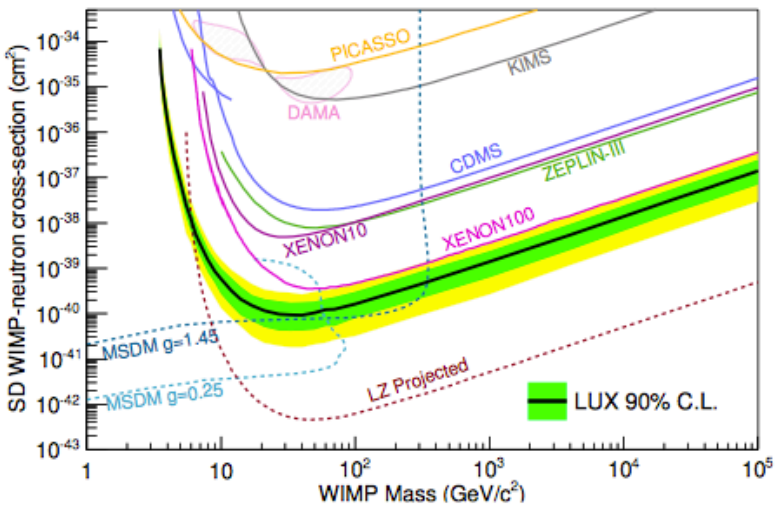


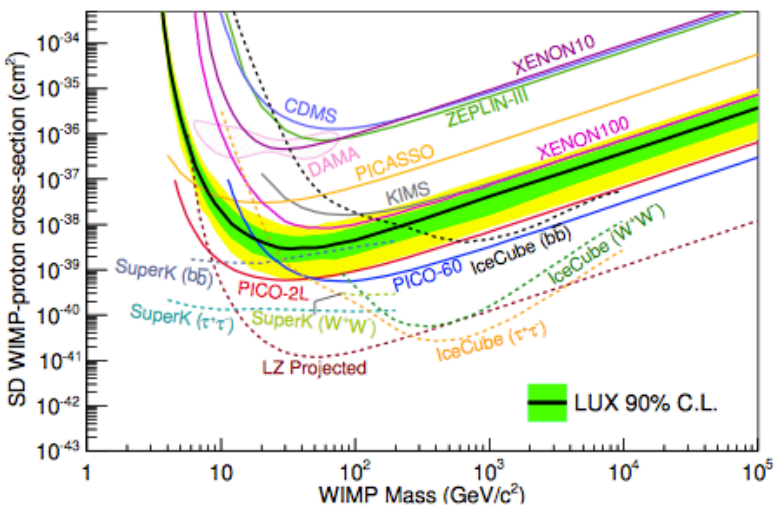




- The S1 (first), and the S2 (the second) scintillation light, latter coming from charge
  - Log ratio says ER or NR
  - Sum provides us energy
- "Wall events" are gray points

New SD Exclusion Bounds

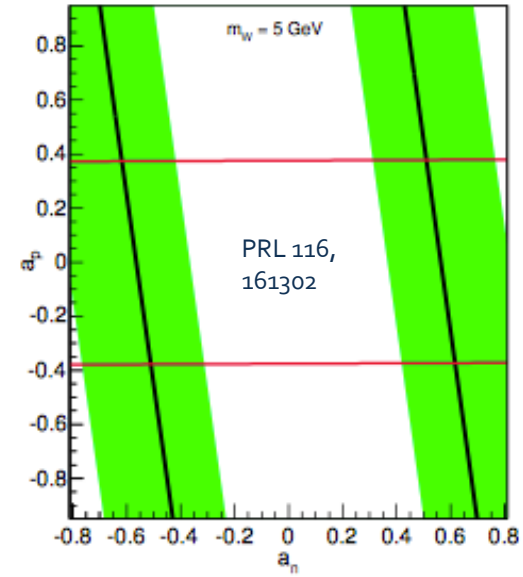


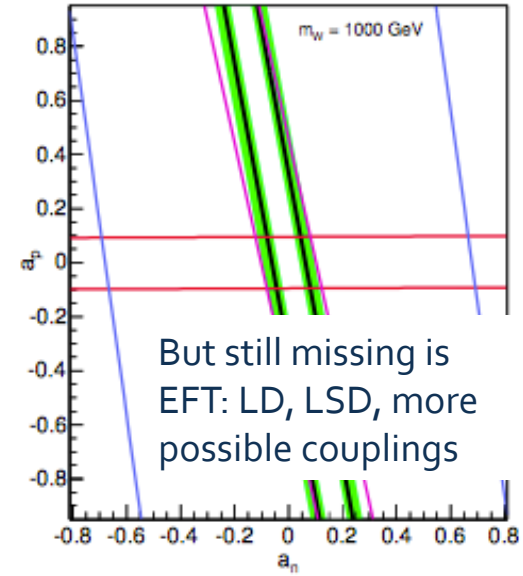


WIMP spin-spin interaction (axial-vector coupling): best when there is an odd number of nucleon under study in nucleus

Xenon is the best element for neutrons, while fluorine is best* for protons based upon nuclear form factor (but Xe can still win via sheer mass)

*Exception = IceCube

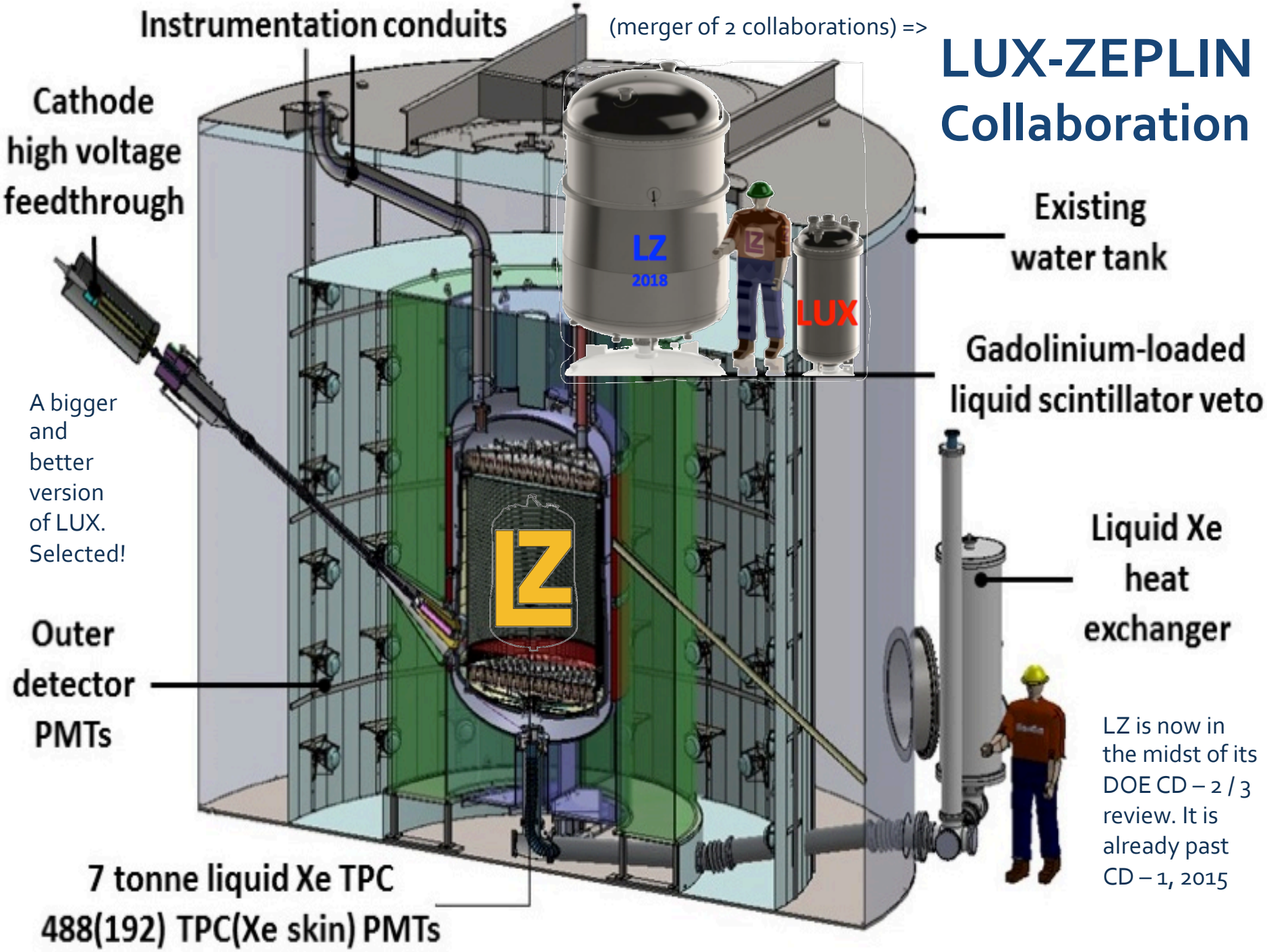




But still missing is EFT: LD, LSD, more possible couplings

LUX-ZEPLIN Collaboration

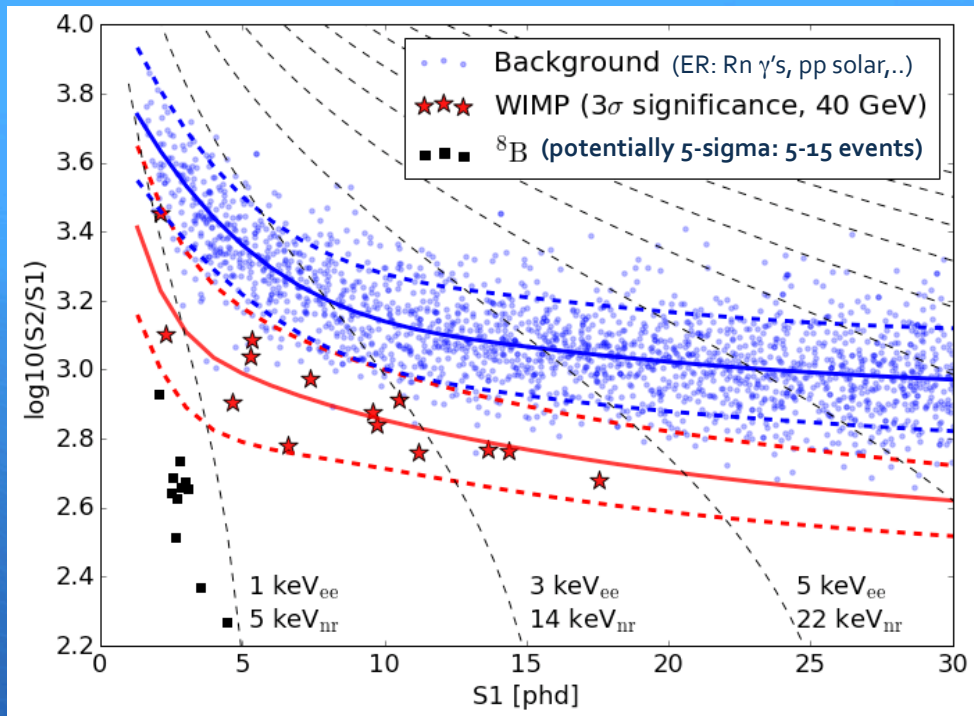
(merger of 2 collaborations) =>

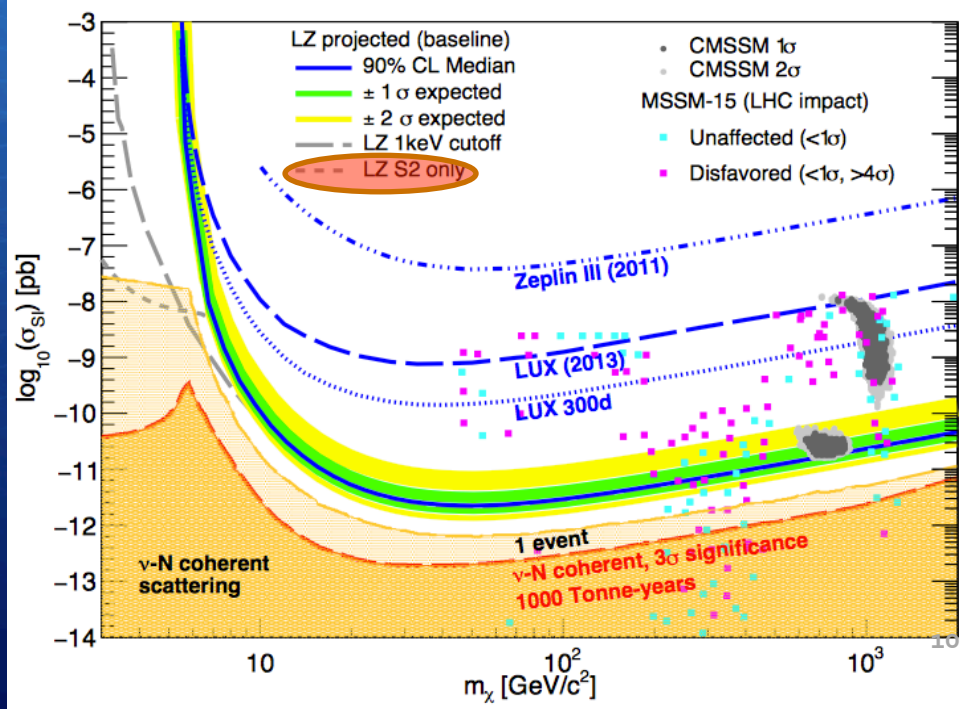


A bigger and better version of LUX. Selected!

LZ is now in the midst of its DOE CD – 2 / 3 review. It is already past CD – 1, 2015

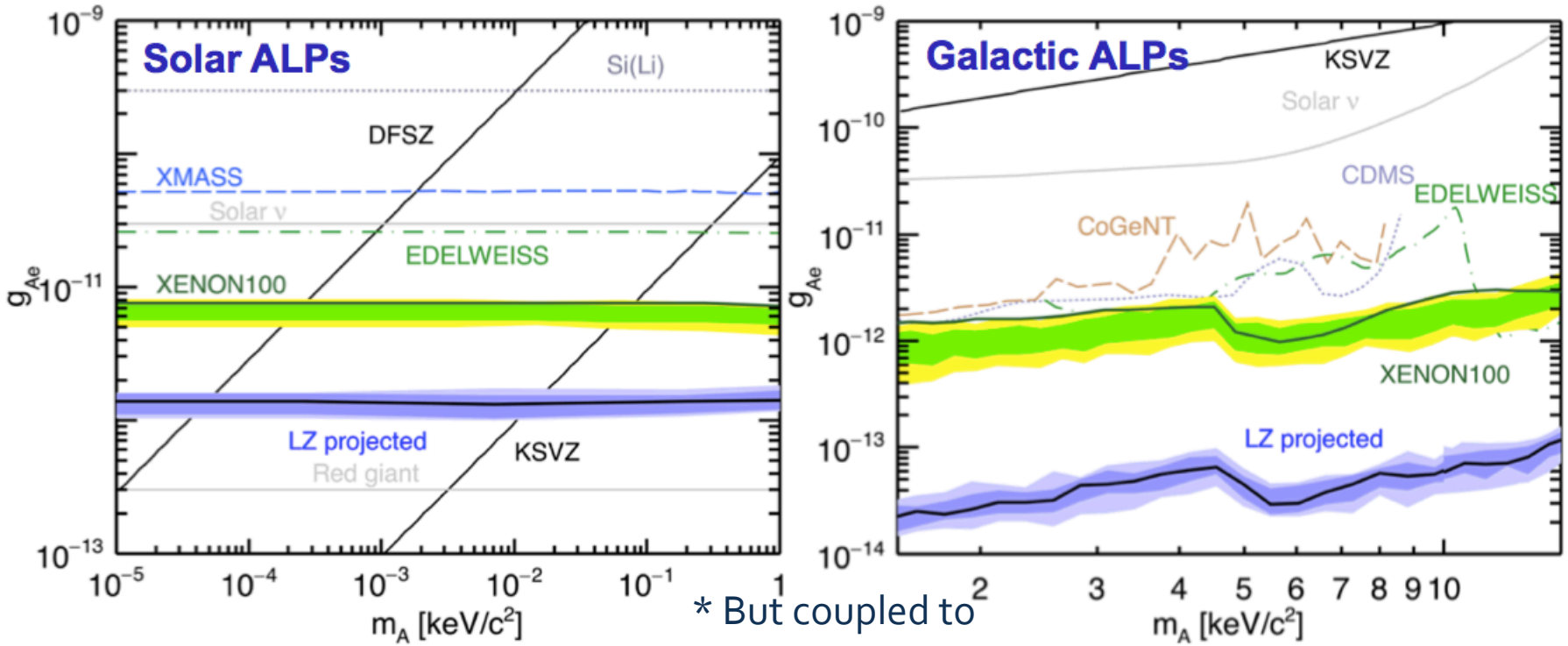
Projected Results





- Turning on by the end of the decade: LUX-ZEPLIN (LZ)
  - Follows after the 300-live-day LUX definitive result this year
- Planning on 3 live-years' data at least with ~5.6-ton fiducial mass
- *O*(100) times more sensitive than present-day LUX results
  - 3×10^{-48} cm^2 or better @40 GeV
- arXiv:1509.02910 CDR. TDR now
- Multi-faceted machine: WIMPs, axions, neutrinoless double-beta decay, solar neutrinos (including coherent scattering)

Axions, in LZ: Distinct From* $g_{A\gamma}$ Probing

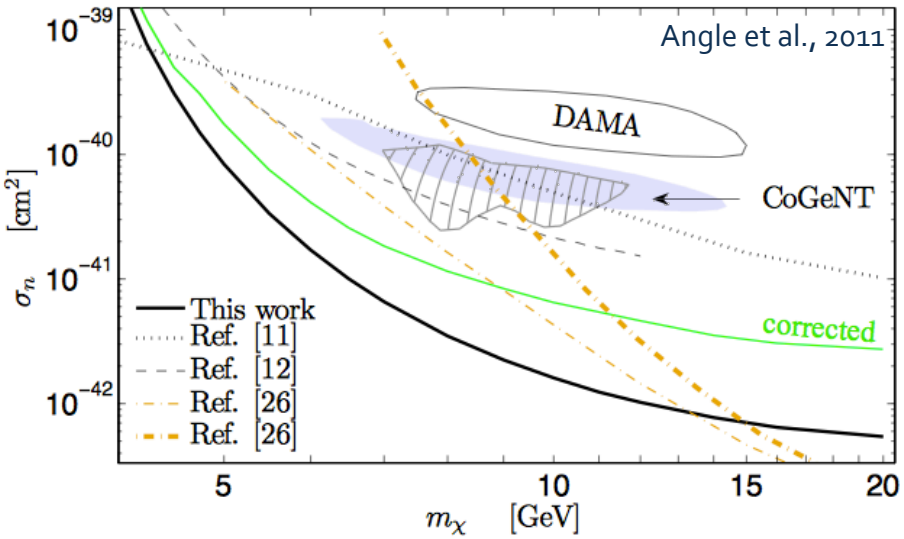


* But coupled to

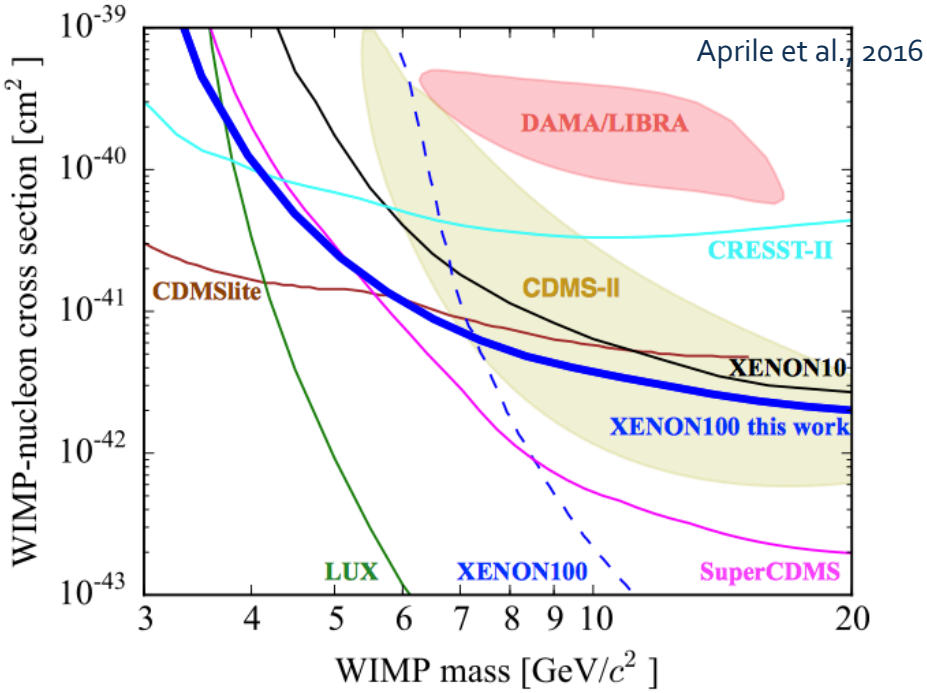
Solar axion limit, at left, and on galactic ALPs (axion-like particles) at right. Y-axis indicates coupling strength to electrons, so looking for ER in these cases not NR like for WIMPs. Former has rich energy spectrum, from axioelectric conversion of the significant source of photons that is our Sun, and latter is dark matter candidate and would be mono-energetic peak <u>above ER background</u> based on mass (must contend with ^{37}Ar BG). *Note LUX 2016 not included but coming soon: similar to Xe100, lower*

S2 -Only (Ionization Channel) Sensitivity

- First ever limit found using this method in XENON10 (2011)
  - Pioneered by Peter Sorensen
- Sacrifices discrimination (S2/S1) and the depth for fiducialization (thus, surface BGs a problem) and correcting electron losses
  - Depth ~known from S2 width
  - But gains much lower threshold: down to sub-keV!!!
- Focus on low-mass DM possible
  - Light vanilla WIMPs O(1) GeV
  - Asymmetric DM models as well

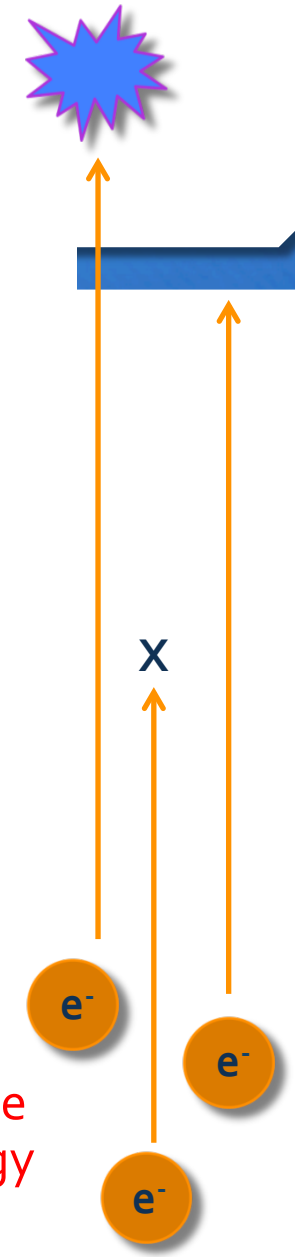


Proof of principle (above)

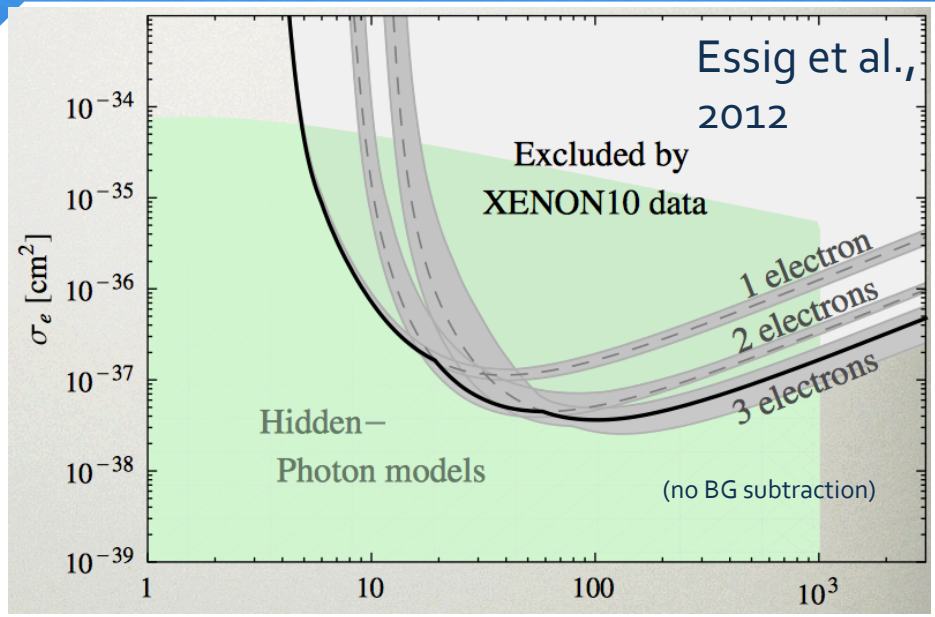


Why Not Better, Sooner, More?

- Competitive, CoGeNT/DAMA "killing" at first go
  - But can discovery be reliably claimed, even if "all" BGs modeled?
- Also, harder to do well with larger detectors, even though larger masses, longer exposures, better calibrations
  - More single-electron and few-electron BGs exist (EVERY XeTPC)
- Potential explanations for the roadblocks encountered
  - Late-extracted e-'s due to lower gas electric field than desired
  - Unavoidable/random, as surface area scales up, and S2s large?
  - Charge build-up e.g. on PTFE, or e- ejection from metal (grids)
  - Photo-ionization on impurities such as O2, encountering VUV
- LUX still planning on trying, and soon, emboldened by new charge yield measurements (DD), showing the ionization from low-energy recoils better than we had even expected/hoped



Back to ER (like axions) not NR



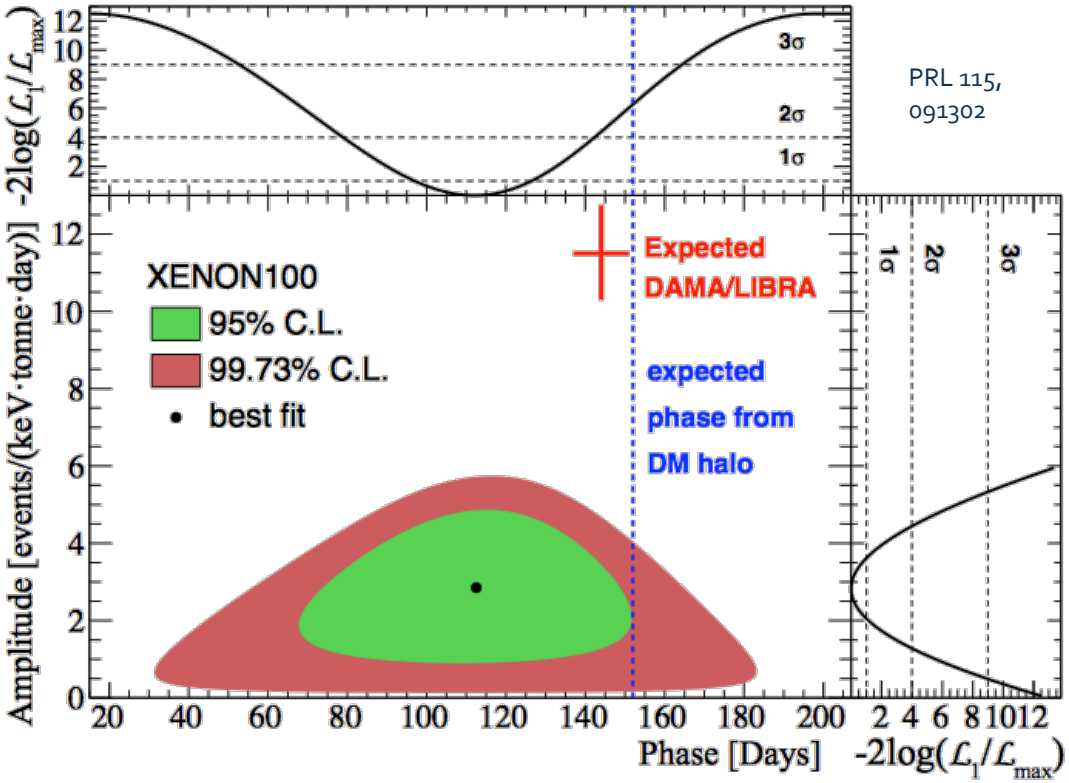
LUX (later LZ) can trigger on such events, even SINGLE-ELECTRON ones, easily: ~25 phd per electron, or 50+ (LZ)

- *So the problem is the background, not the threshold, not the efficiency—can look at ER, NR events agnostically, addressing criticism of focus on NR*

- What about relativistic, ultra-light-mass WIMPs? (Thermal?)
- Hidden/dark sector mediators? Dark photons, gauge bosons?
  - Not dark matter itself but the particles it uses to "talk" to the Standard Model potentially!
- Too light and fast to interact with nuclei significantly
  - Must look at ER events, including few-electron ones
- Sub-MeV masses. keV even harder to see; need new tech?

XENON100 Annual Modulation Result, or Credit Where Due to the Main Competition of LUX/LZ-

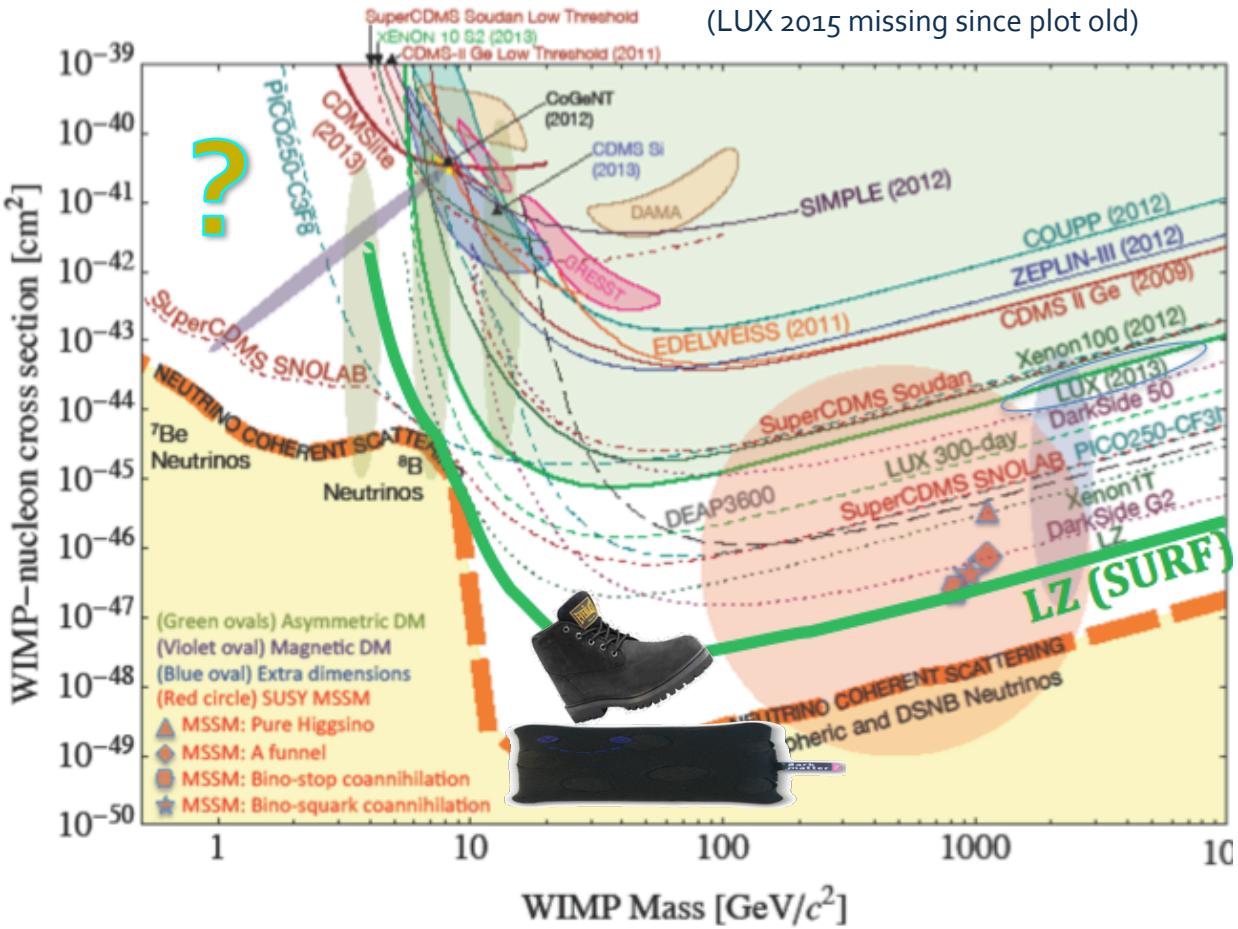
- DAMA/LIBRA signal just keeps getting re-killed (but returning)
- Killed for SI (LUX is latest), killed for SD-p (COUPP), killed for SD-n (XENON100, LUX)
  - Channeling not it
  - COUPP, KIMS have ^{127}I
- Killed for NR (LUX, others), and killed for ER (XENON100 best)



Only apples to apples with NaI, and same crystals, missing, though DM-Ice working on it, in Southern Hemisphere (Antarctica). Also, isospin violation getting squeezed from strictness of results like LUX

The Famous, Very Busy SNOWMASS Plot

(LUX 2015 missing since plot old)



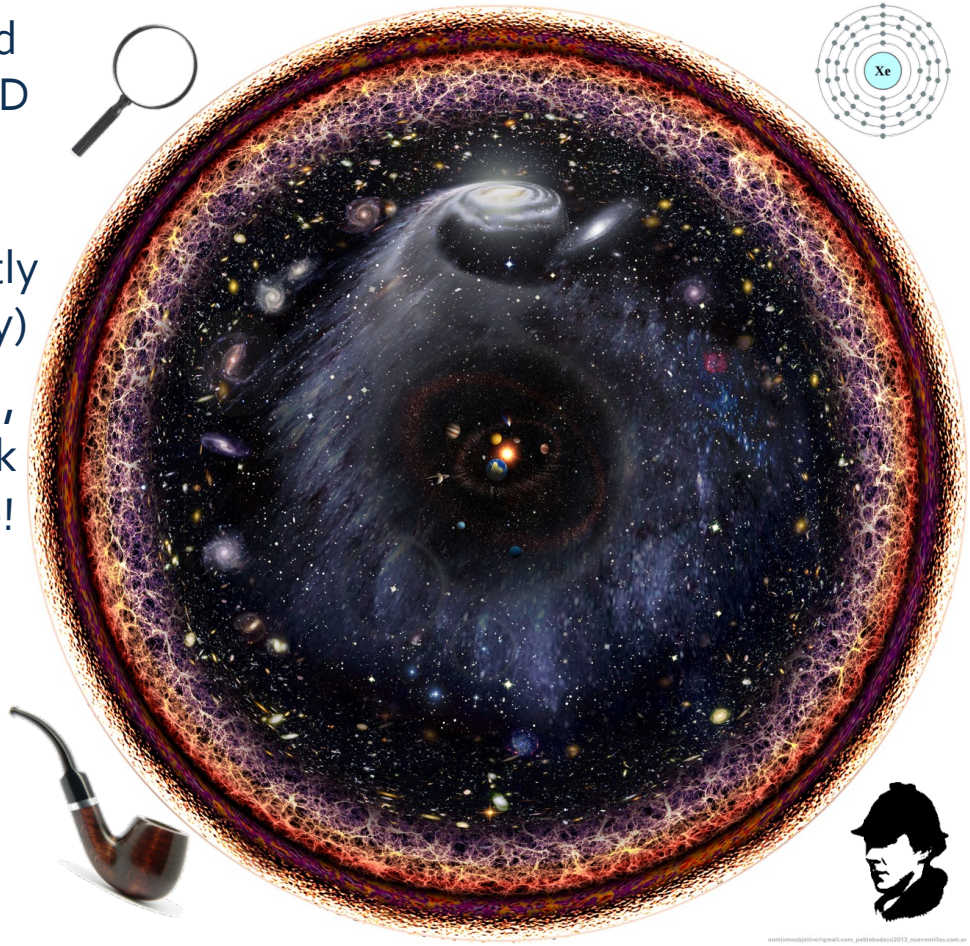
- Almost obligatory ☺
- Low-mass region is kind of lonely, but between both LZ and SuperCDMS is mostly covered-ish
- sub-GeV WIMPs no ('ordinarily' – see talk by J. Pradler from this morning)
- But, LZ limit is old! Better…

A Concluding Summary and Outlook

* LUX has published limits from SI and SD perspective for standard WIMPs on 90-day data (recently reanalyzed carefully)

* 1-yr result coming, and non-WIMP work currently in pipeline!

* LZ holds the promise to be the ultimate Generation-2 (DOE G2) DM project. Great discovery not just limit potential



* Detection claims uncorroborated, but still sure DM exists, "around the corner" as we search in a nearly-independent way with many well-calibrated, same OR complementary direct detectors

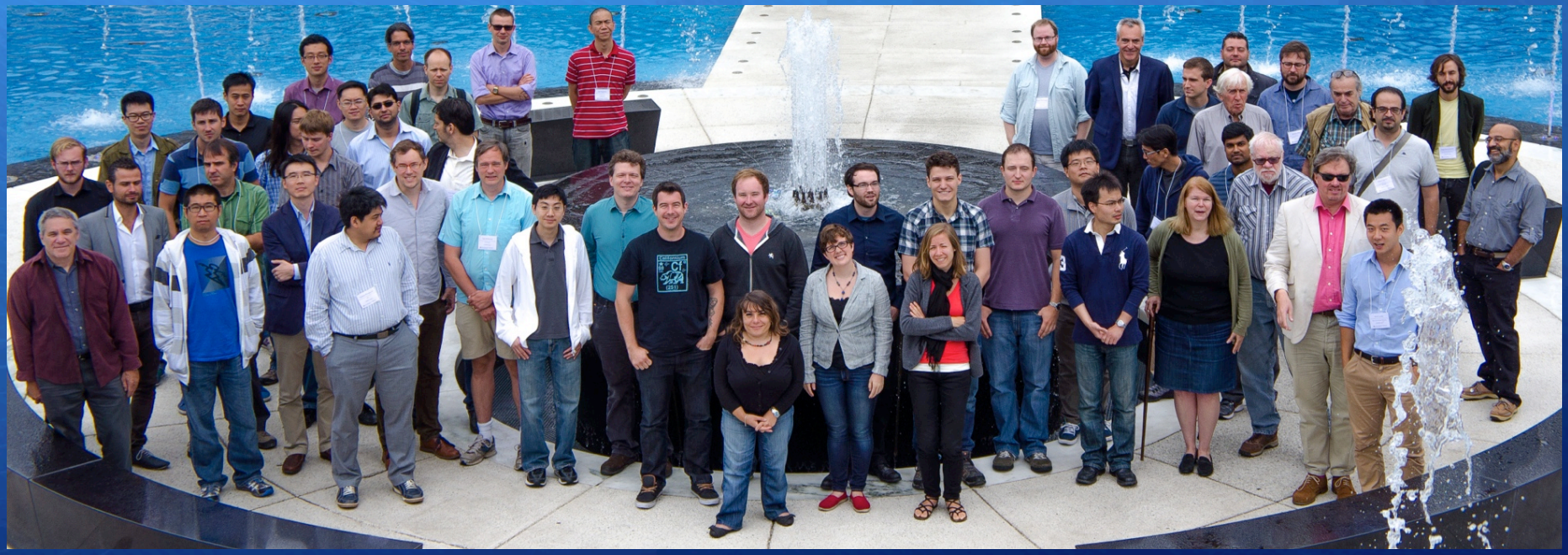
* Future looks bright (at least for WIMPs!)

* No time to cover: new G3 ideas like LHe (McKinsey), LXe bubble chamber (me), ionization limit in semi-conductors, and single-photon limit in scintillators

- Thank you for your attention

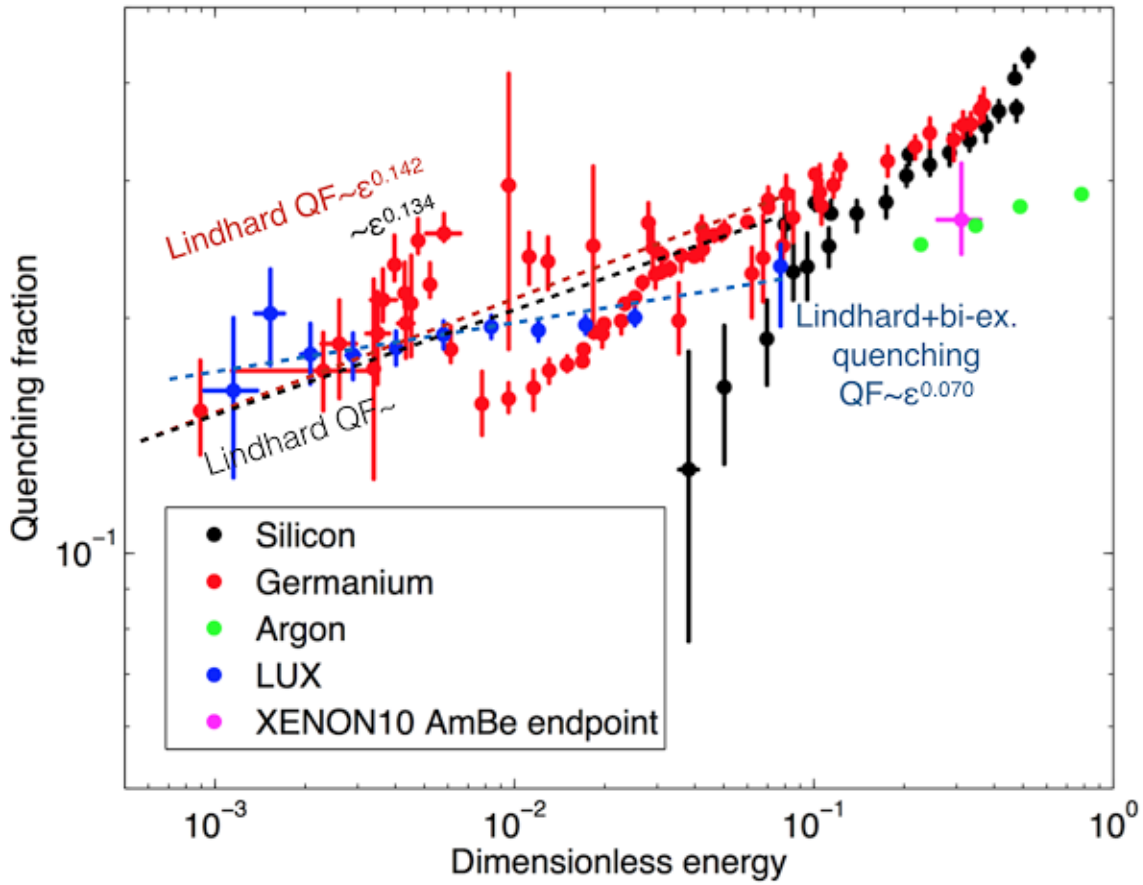
- (Note, my license plate is for element not experiment)

LIDINE (Light Detection in Noble Elements)

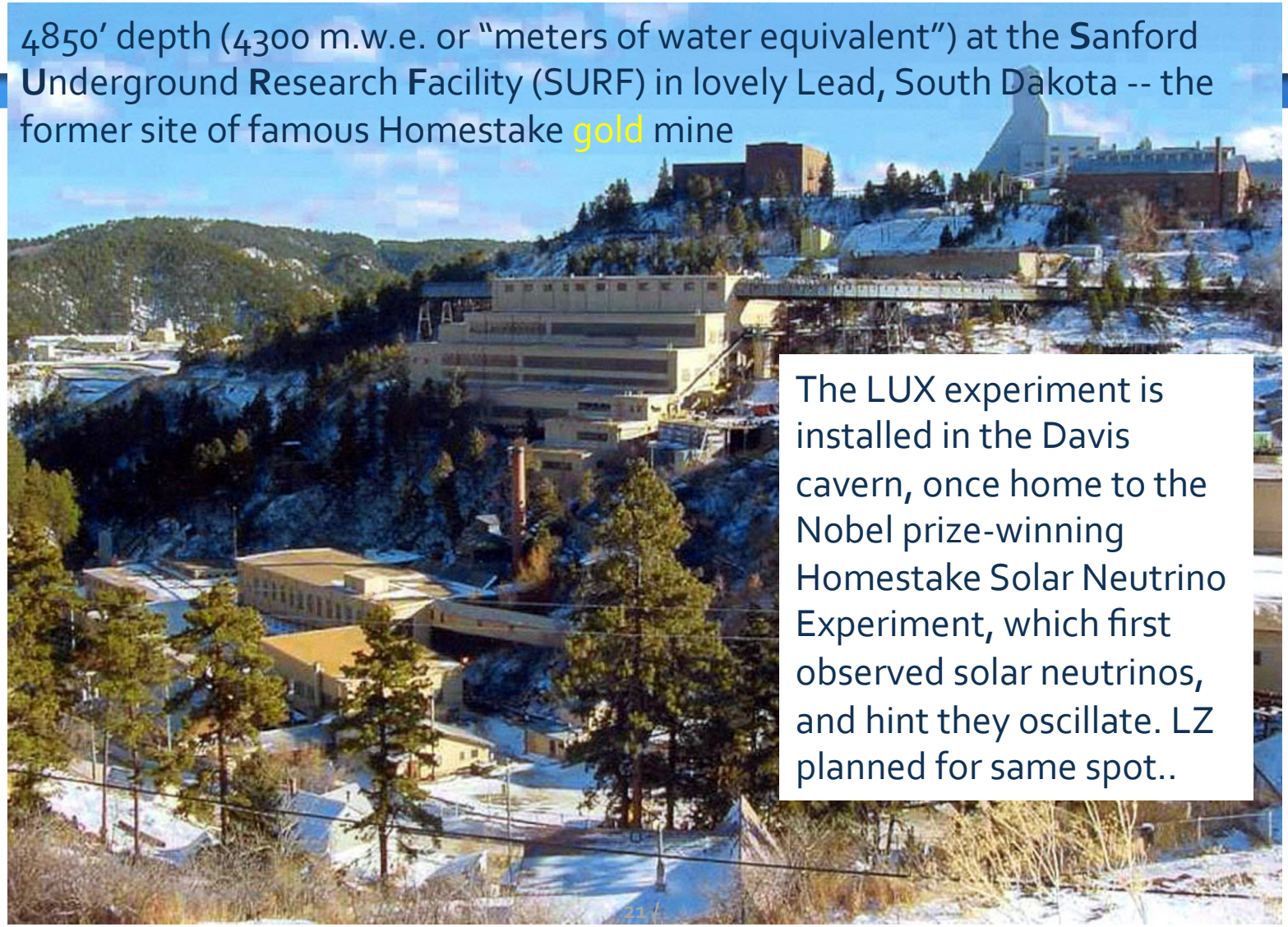


Conference at the University at Albany, State University of New York, my home institution, this past August (2015). The users of Xenon, Argon, Helium, etc. (WIMPs, neutrinos…) met

The Lindhard Factor in Liquid Xenon



Underground at Sanford Lab



4850′ depth (4300 m.w.e. or "meters of water equivalent") at the **S**anford **U**nderground **R**esearch **F**acility (SURF) in lovely Lead, South Dakota -- the former site of famous Homestake gold mine

The LUX experiment is installed in the Davis cavern, once home to the Nobel prize-winning Homestake Solar Neutrino Experiment, which first observed solar neutrinos, and hint they oscillate. LZ planned for same spot..