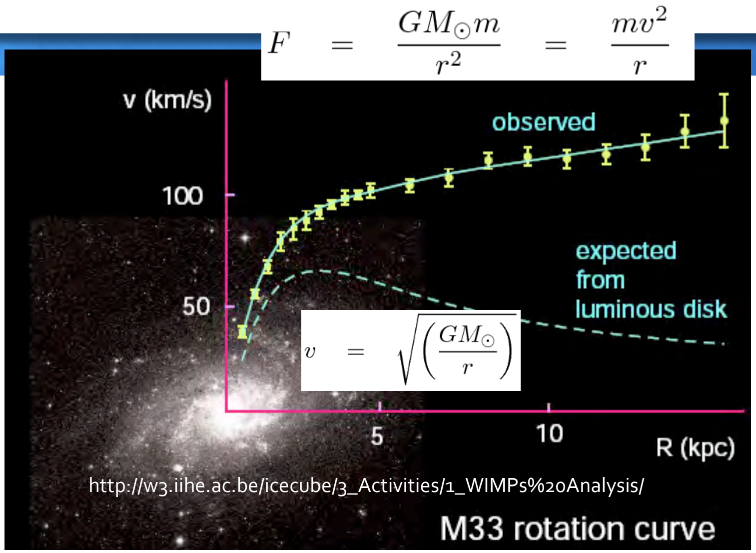
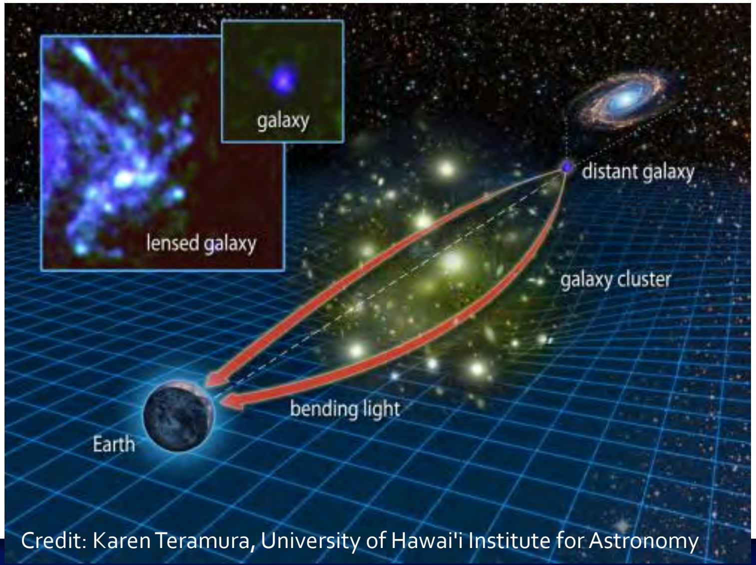
The Case for *Dark Matter*

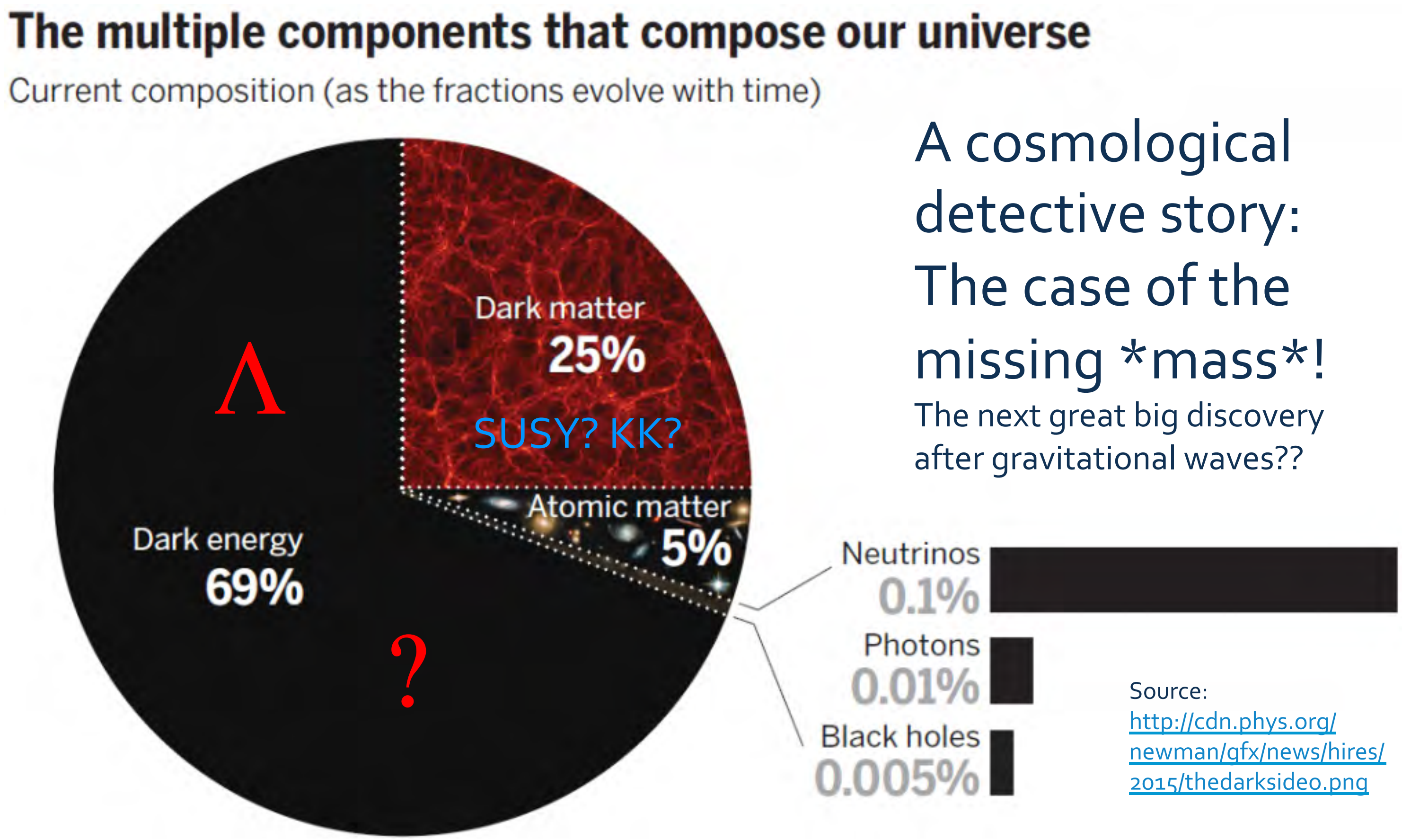
- Wealth of observational evidence now but conclusive direct detection remains elusive
- Galactic rotation curves exhibit behavior consistent with significant missing mass
- Gravitational lensing studies concur with rotation curves, as with the Bullet Cluster
- Cosmic Microwave Background favors model with ~25% energy content of universe in matter but non-baryonic
- Big Bang Nucleosynthesis implies the same
- Large-scale structure simulations indicate this *dark matter* is rarely interacting and non-relativistic, implying that it is heavy
- Term, Weakly Interacting Massive Particle (WIMP), coined to cover just vanilla traits





Credit: Karen Teramura, University of Hawai'i Institute for Astronomy

A Gaping Hole in Our Knowledge!



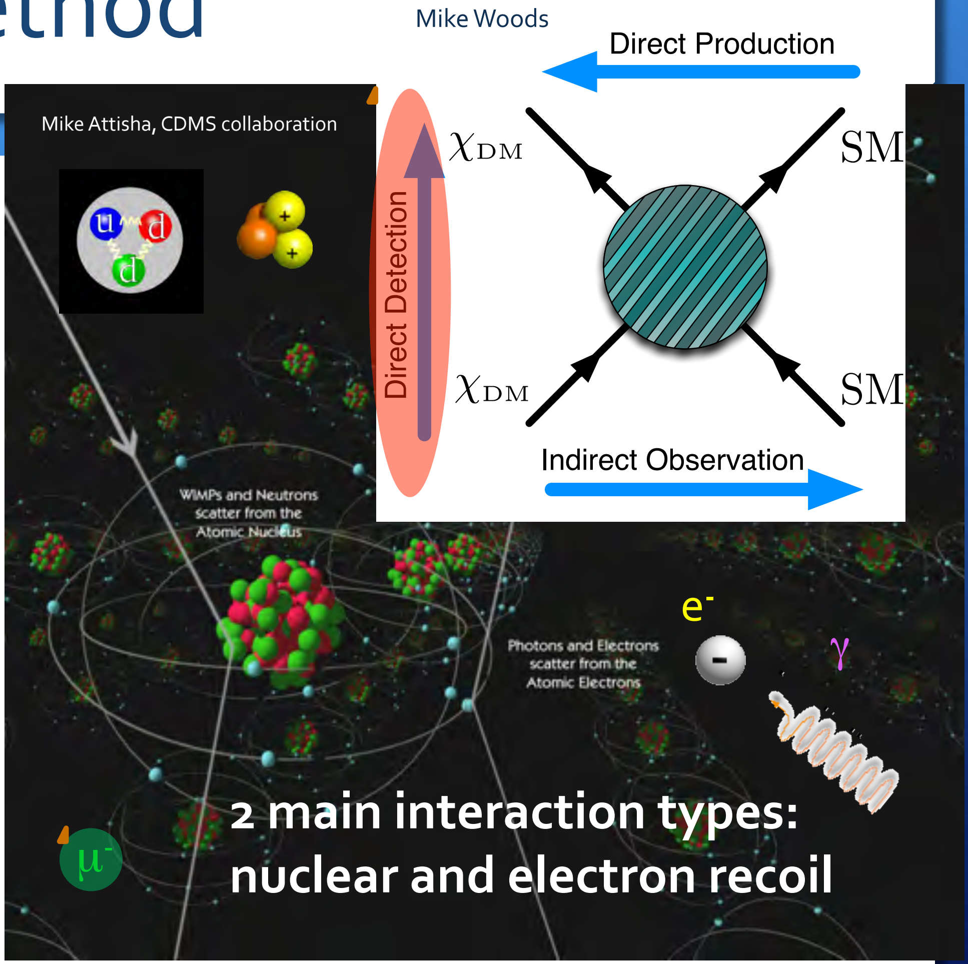
A cosmological detective story: The case of the missing *mass*!

The next great big discovery after gravitational waves??

Source: http://cdn.phys.org/newman/gfx/news/hires/2015/thedarksideo.png

Direct Detection Method

- Most searches are geared towards finding the WIMP in a model-independent fashion
  - Something going bump in the night above LOW background
- In most models, massive WIMPs scatter elastically off nucleons, not the electrons
- Experiments deployed deep underground, because depth reduces the overwhelmingly high rate of cosmic radiation



Low-energy, few-keV (exponentially favored) nuclear recoils (NR) expected from WIMPs; electron recoils (ER) constitute primary backgrounds, to actively avoid. (Exception: ultra-light WIMPs relativistic, making ER.)

The Major Experimental Backgrounds

Reduce radiological ones with radio-pure materials

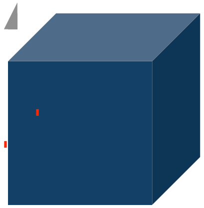
- Neutrons: Go bump in the night just like WIMPs. Can be remediated by cutting multiple scatter events and by aggressively fiducializing detector volume, if it is self-shielding, and by simulating all of the neutrons sources you've determined.
- Alphas: Can also produce nuclear recoil like WIMPs. Radon events near detector walls can be removed from data by good fiducialization. However (α,n) events remain problematic (above) even for scintillators, even if α' s themselves bright
  - As with n's above material selection/screening and simulations help a great deal here
- Gammas and electrons: Not problem if your detector is insensitive to electron recoil, or can discriminate between electron and nuclear recoils well (between 1 part in 10^3-10^{11} level discrimination/acceptance possible with current detectors)
  - High energies -> multiple-scattering; self-shielding -> fiducialization. But few e-'s??
- Muons: Will induce neutrons in nearby material. Will also produce (energetic) electron recoils. Can go deep underground to help shield. Can also tag them with muon veto (Cerenkov-capable water tank, plastic scintillator panels, etc.)
- Neutrinos: New enemy. ER, NR. Can't be shielded against. From solar fusion.

Detector Response Possibilities

light from de-excitation (scintillation)

charge from ionization (electrons liberated)

excitations within crystalline structures



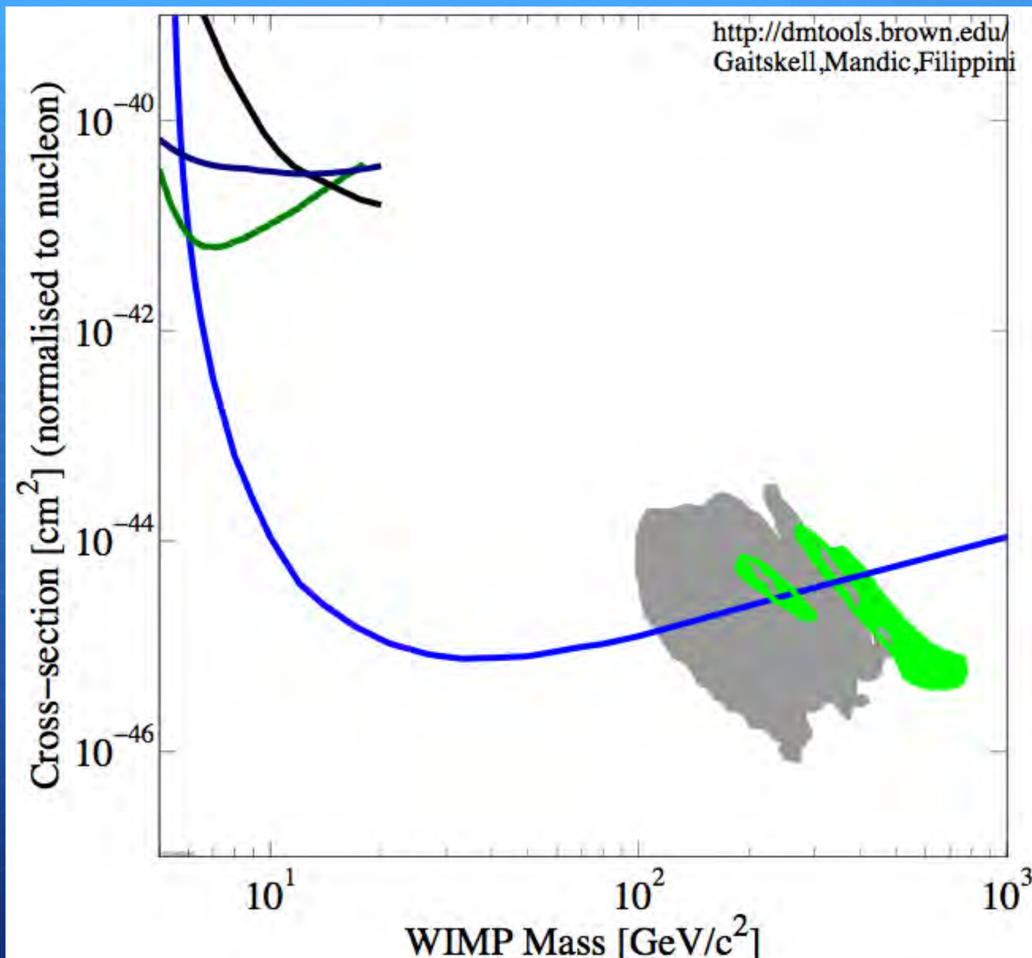
Or, phonons

bubbles, boiling

heat (atoms move)

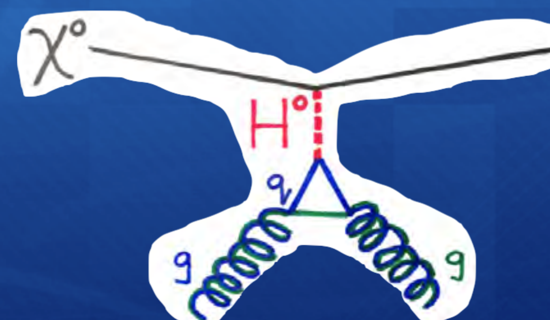
- Atoms can be excited and scintillate and/or be fully ionized by NR/ER
- Recoils can also cause lattice vibrations, or boil superheated liquids
- Many searches will combine two methods
- Given rare interaction, figure of merit = target mass X exposure time

Time Progression of Sensitive Experiments



Years
2000-2013

Closing in on Higgs coupling?

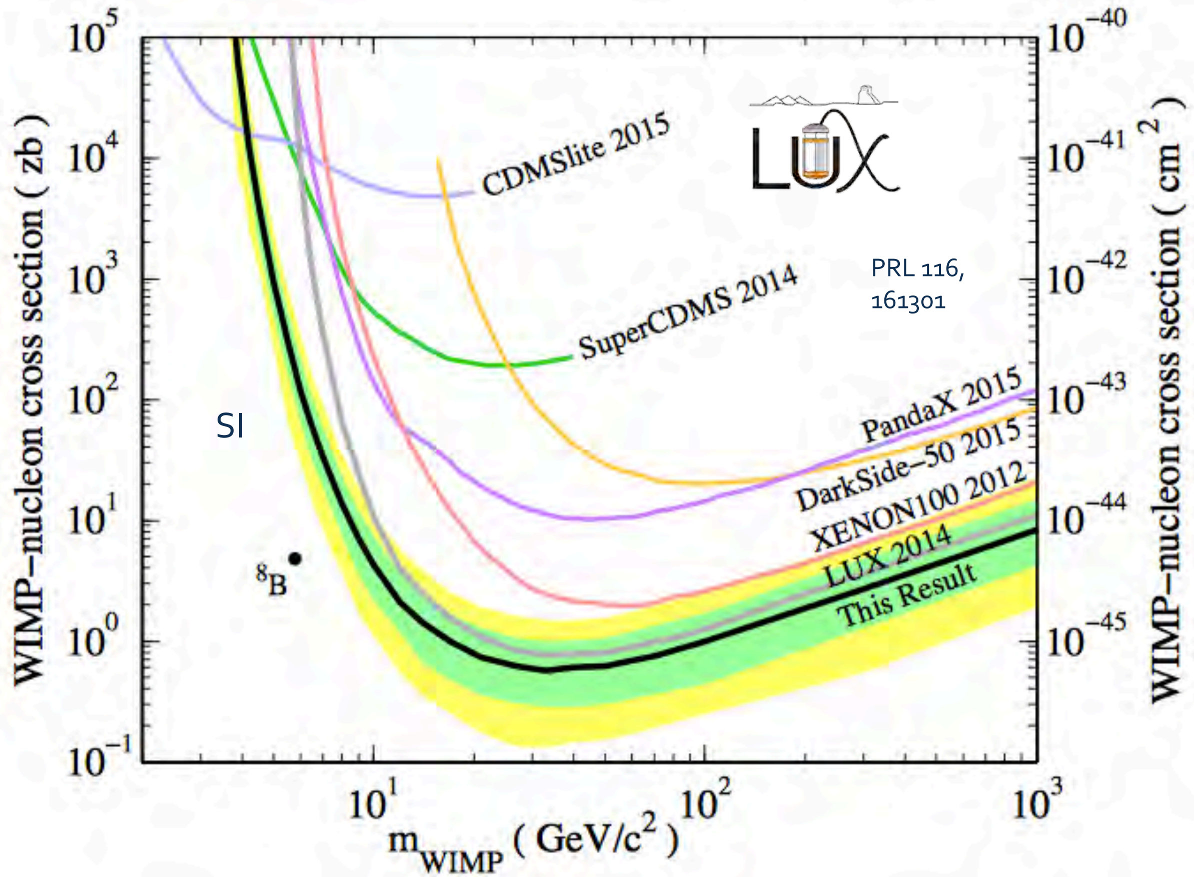


moving target?

Animation courtesy of Aaron Manalaysay, UC Davis

Status of Field of Direct WIMP Detection

- Some claims of discovery exist (for few-GeV WIMPs)
  - But not discovering something (or, something else) is oftentimes equally as valuable as your original goal (think Michelson-Morley ether, 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)

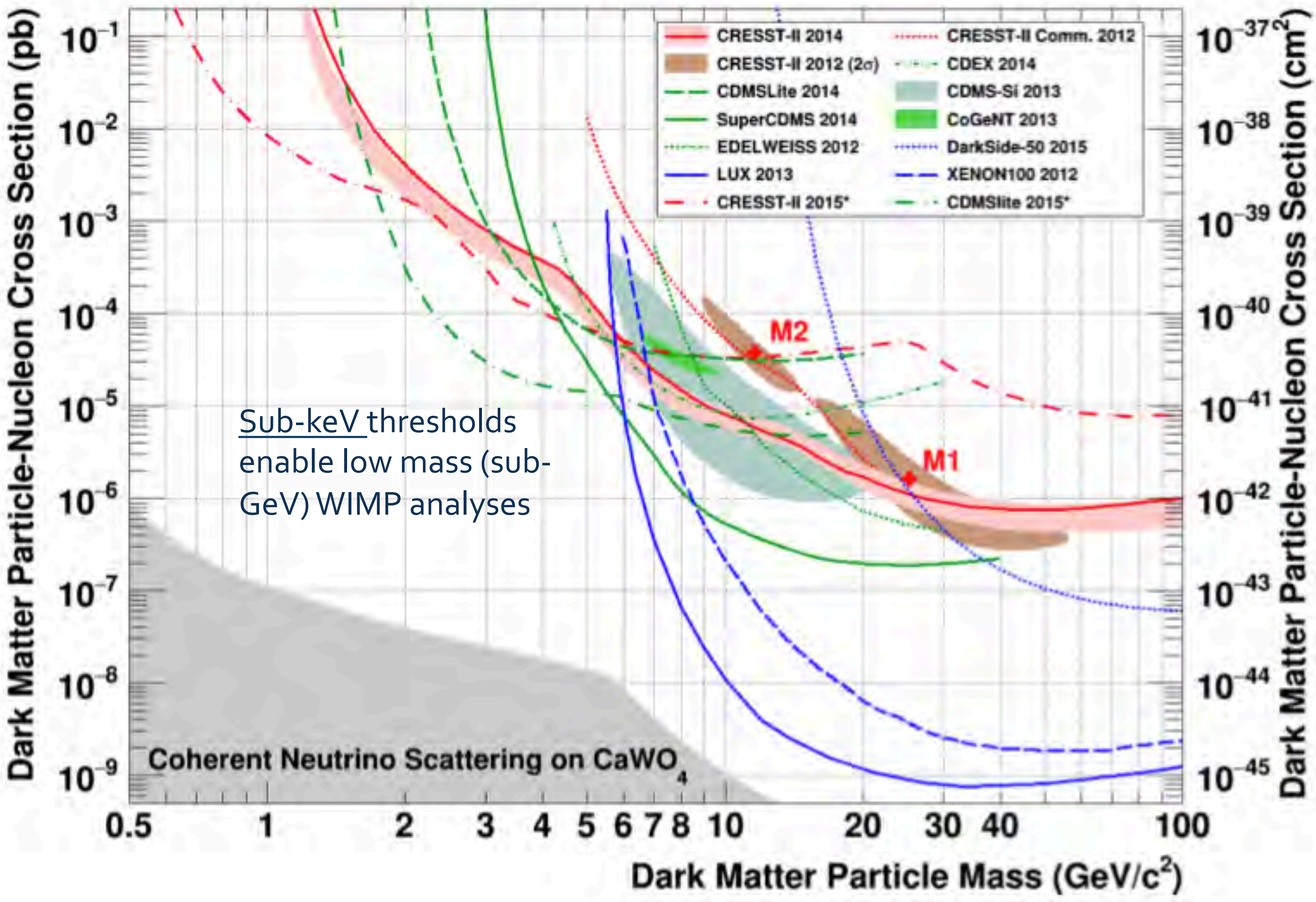


LUX (2015/6) 90 live-day exclusion limit curve

Potential Signals and Detection Claims

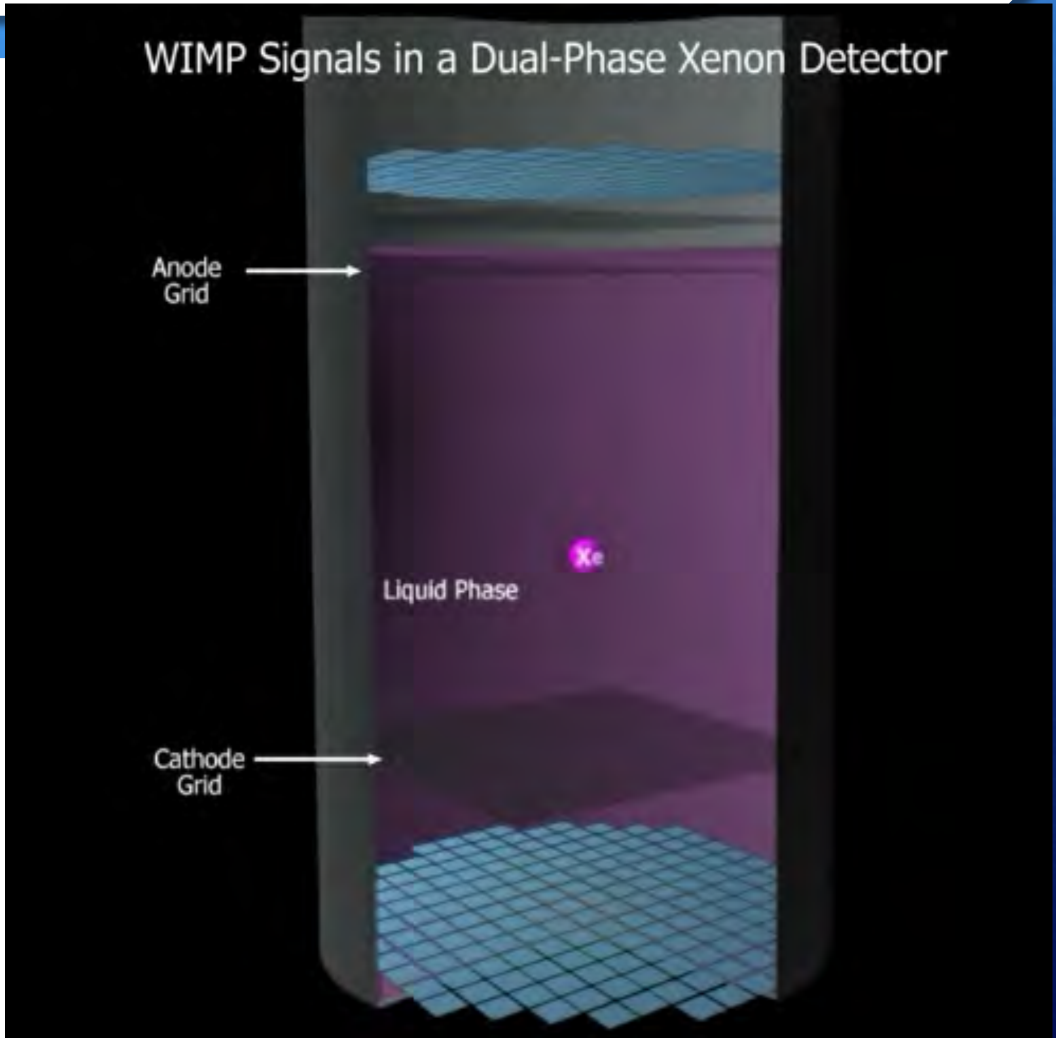
- DAMA / LIBRA: The earliest, most famous, most statistically significant, and most persistent, resisting explanations to make it go away, but very difficult to reconcile with other results
  - Annual modulation signal seen over many years in NaI detectors in scintillation channel (just 1: not sensitive to whether ER v. NR)
- CoGeNT: Annual modulation again, this time in Ge, but single channel again (ionization) and low threshold. A possible explanation of a forgotten background of L-shell decays?
  http://research.dsu.edu/cetup/documents/2015-talks/dark-matter/06-16-Tuesday/Chris%20Kelso.pdf (Talk by Chris Kelso, CETUP 2015)
- CDMS Si: Ruled self out fast. Few events. More *thresholdinos*?
- CRESST: First 2-channel claim (photons + phonons) but resolved itself (Pb alpha background). Now best limit <2 GeV

CRESST, and the Very Low Mass Picture



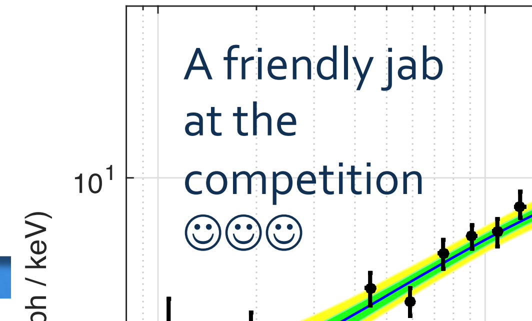
How Any Two-Phase Xe TPC Works

- Collaborations with 2-phase xenon-based time-projection chambers have been leading the pack for over a decade now
  - XENON10 / 100, LUX
  - 2-phase Ar similar principle: DarkSide, ArDM
- Photomultiplier tubes (PMTs) convert single photons into photo-electrons (phe or PE)
- Lead, SD for LUX (while Gran Sasso Italy for XENON): underground vs. mountain



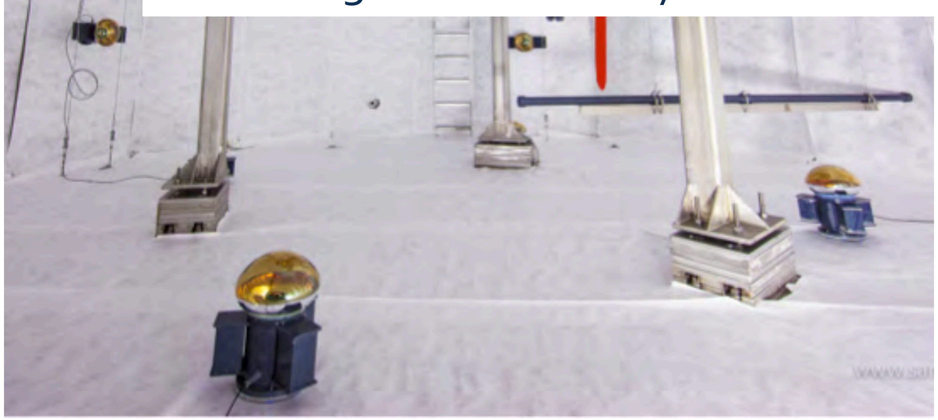

Raymond Davis

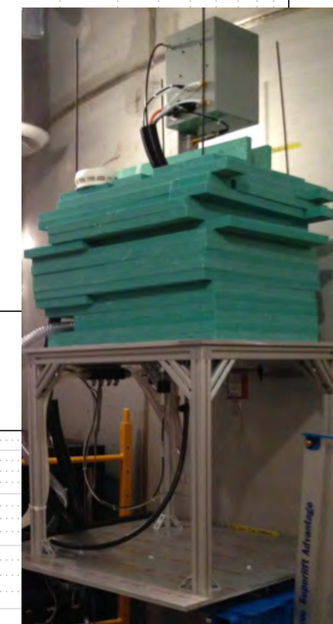
Calibration (LUX DD)

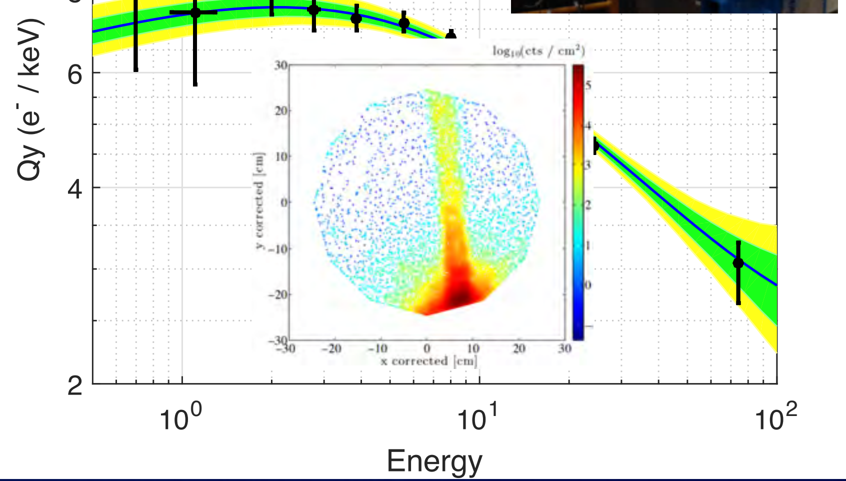


Plante et al. 2011 LXe light yield measurement-- Considering that this LXe detector has the highest light detection efficiencies achieved in a LXe detector, measuring $\mathcal{L}_{\text{eff}}$ in the near future at lower energies is probably impractical and will be subject to a considerably higher systematic uncertainty from the trigger efficiency roll-off. NOT SO!

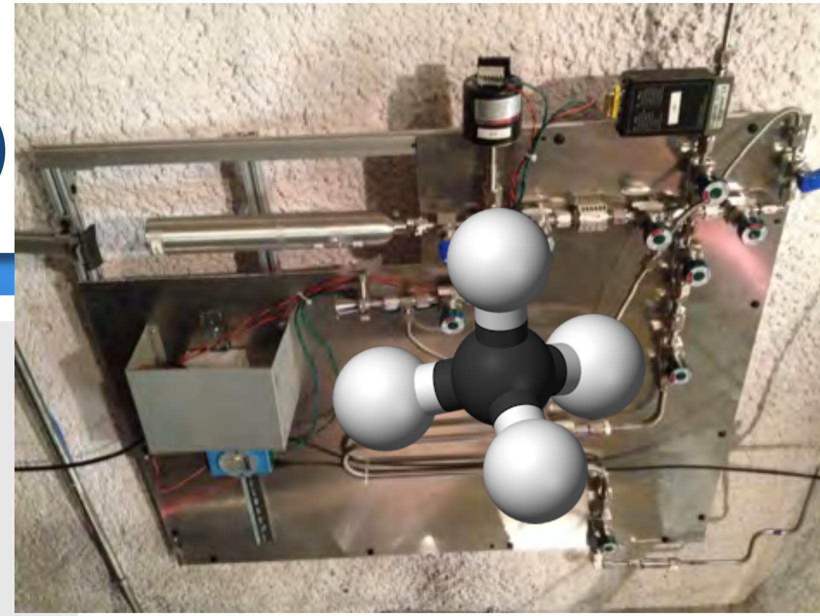
Plante made an excellent, crucial measurement, but we managed to find a way to reach even lower energy

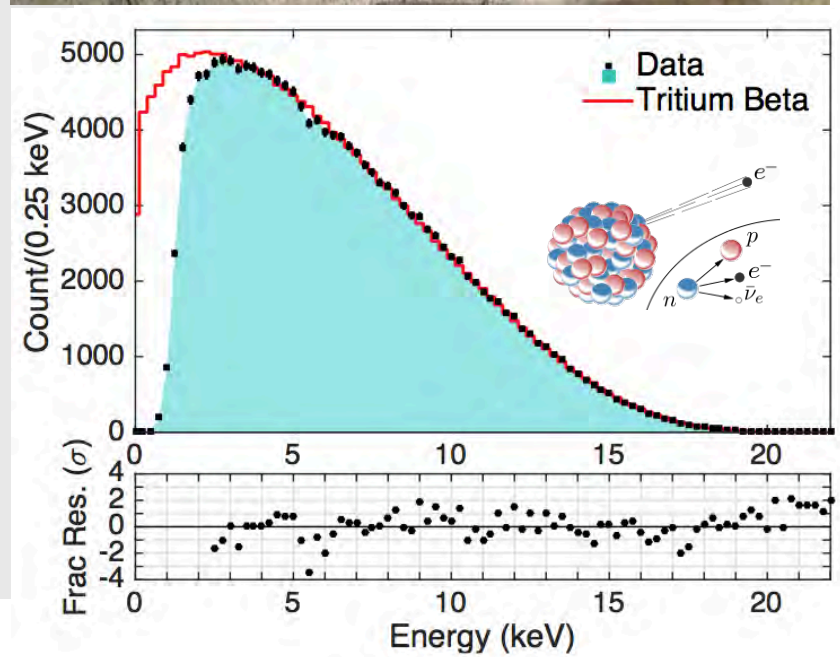




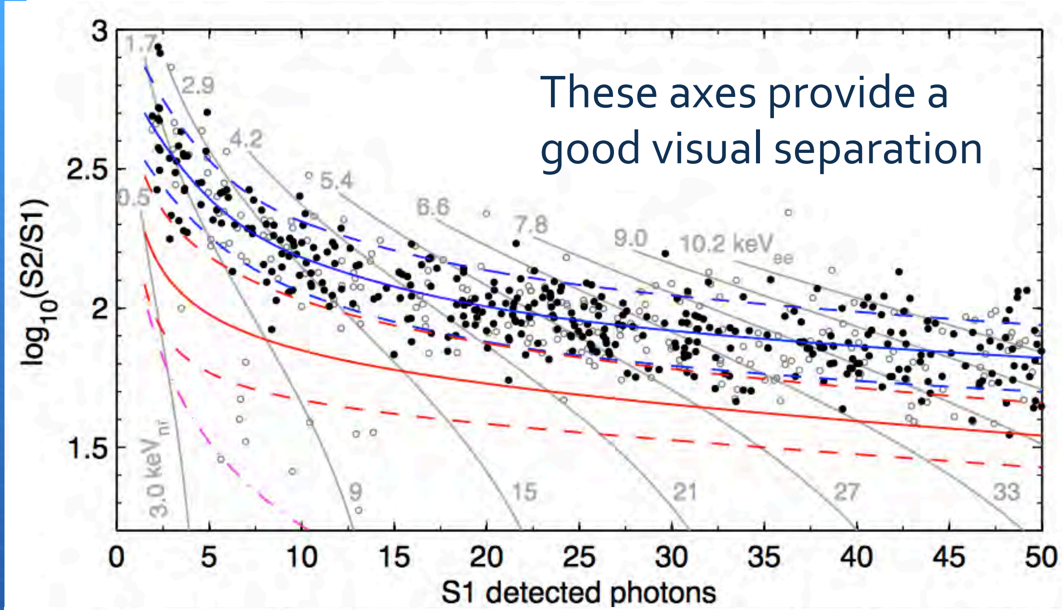


Calibration (LUX CH_3T)

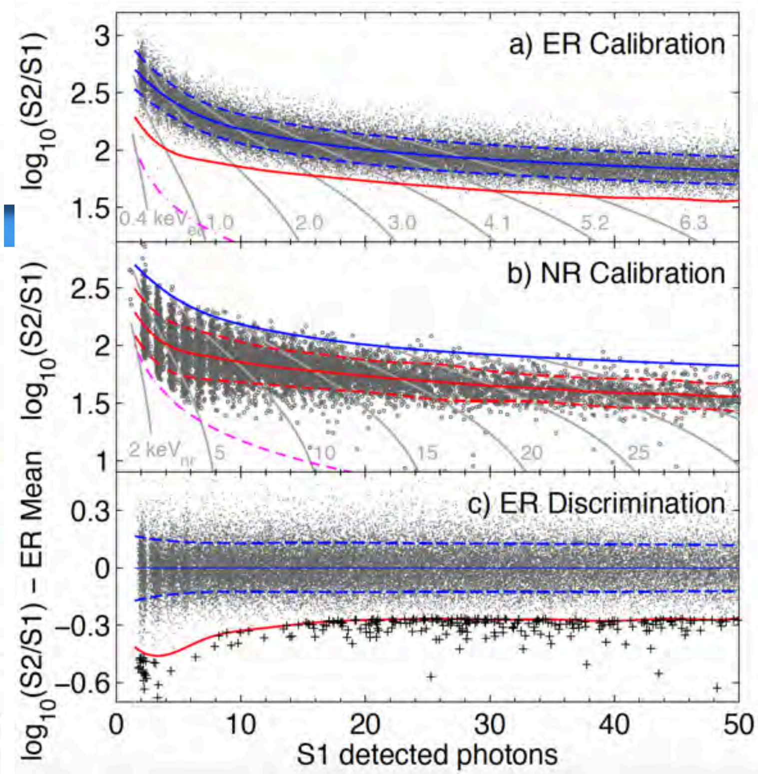


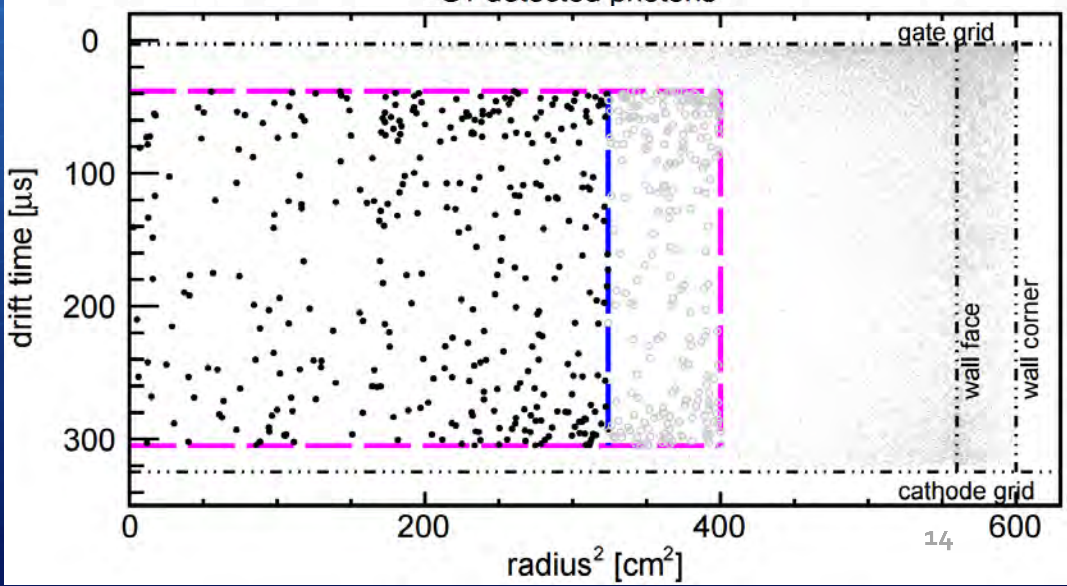


Putting It All Together



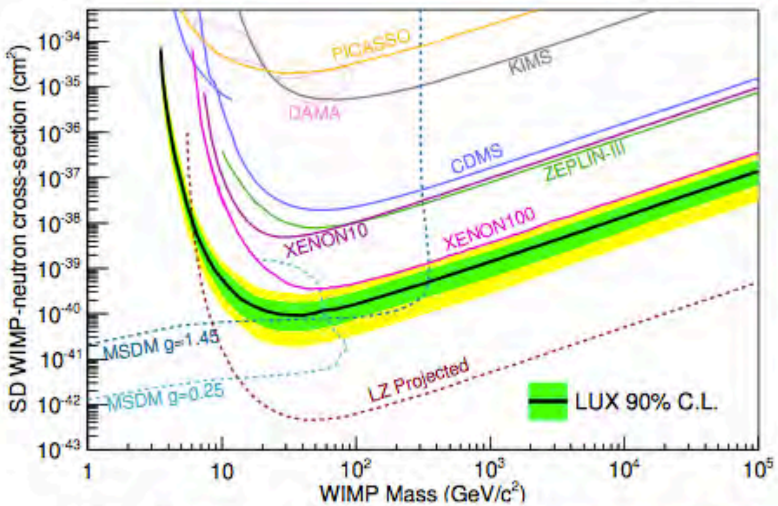
These axes provide a good visual separation

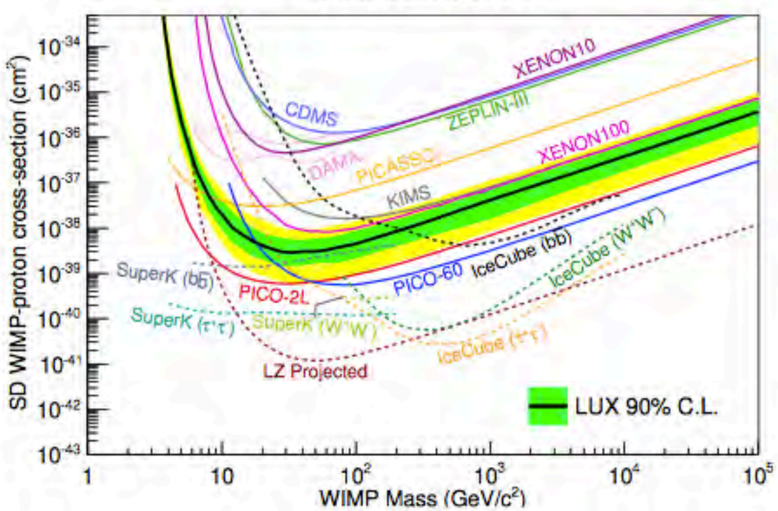




- The S1 (first), and S2 (the second) scintillation light - latter coming from charge
  - Log ratio says ER or NR
  - Sum provides us energy
- Wall events are gray points

New SD Exclusion Bounds

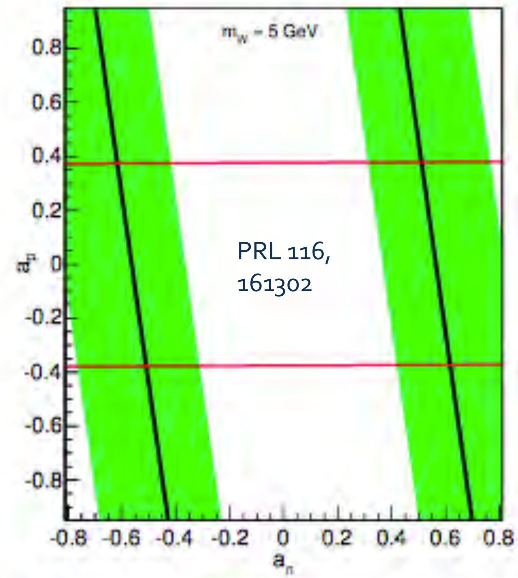




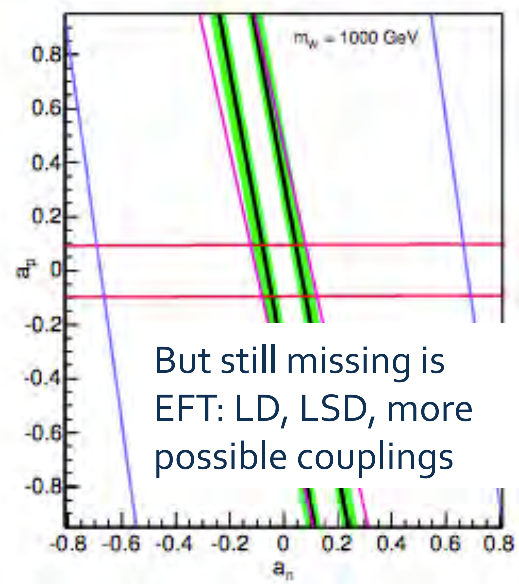
WIMP spin-spin interaction (axial-vector coupling): best when there is an odd number of nucleon under study in nucleus

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

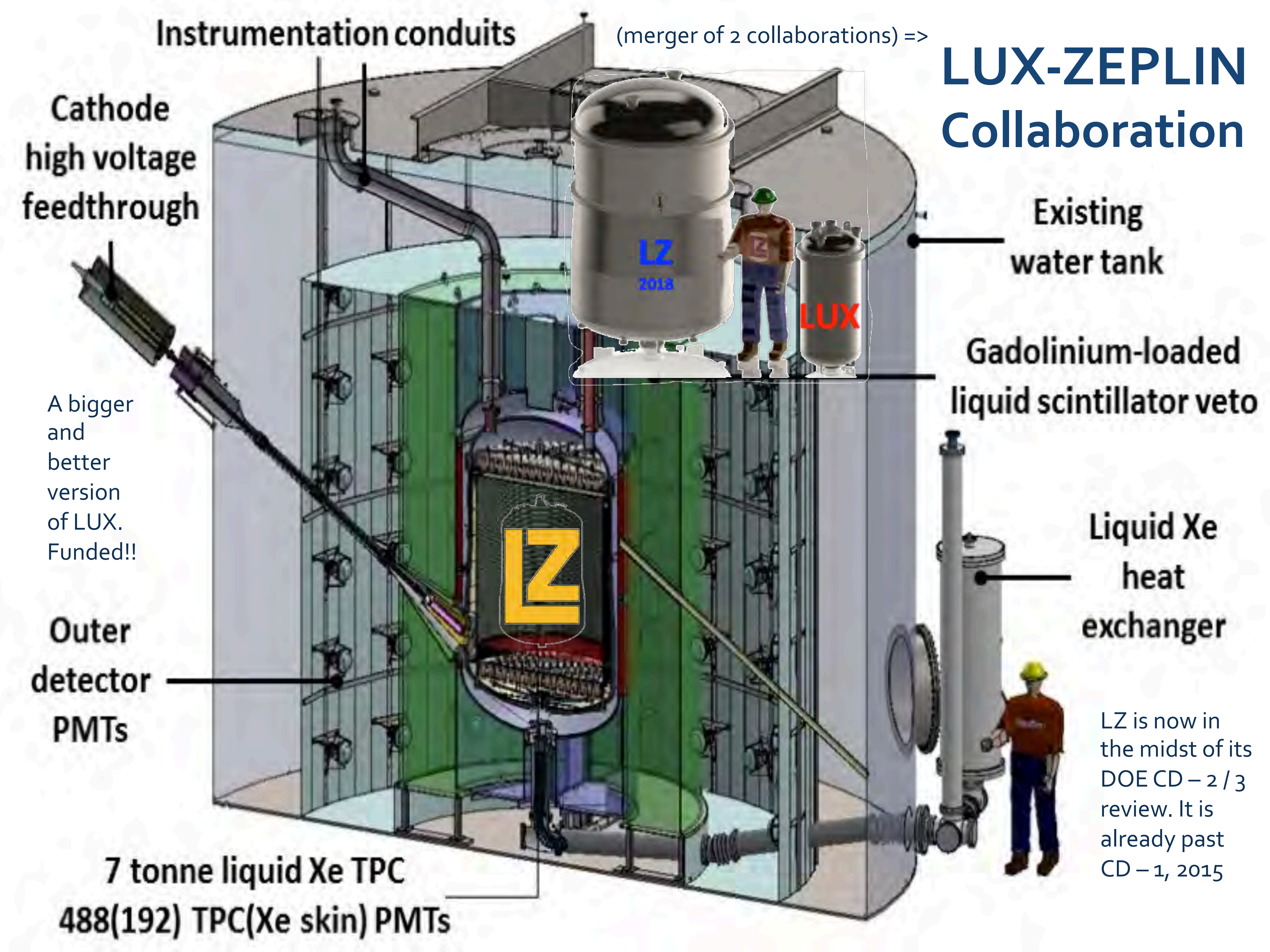


PRL 116, 161302



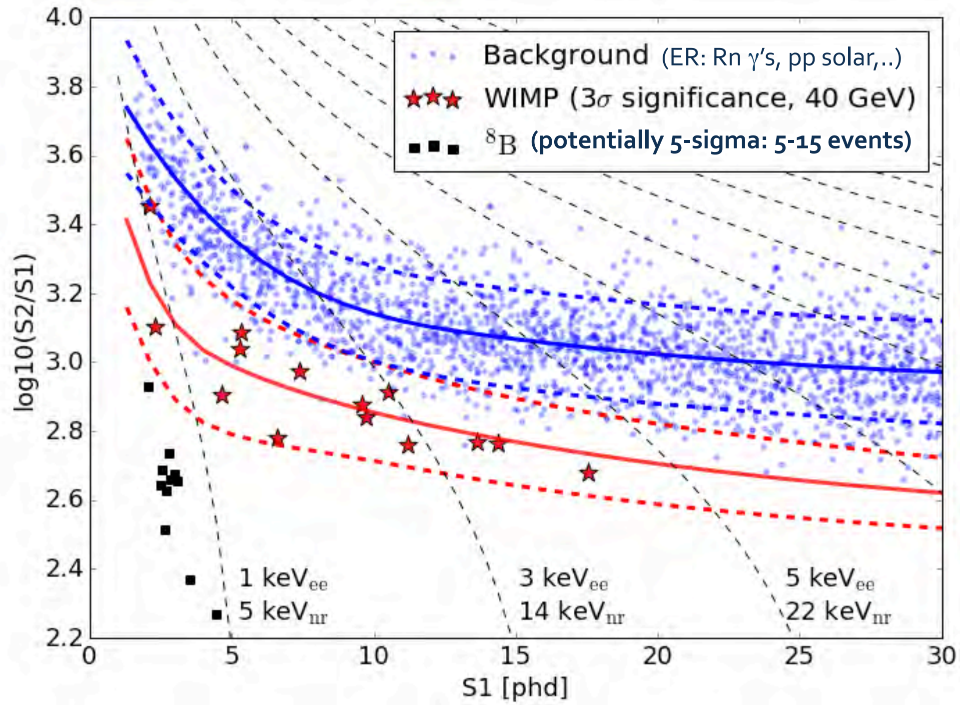
But still missing is EFT: LD, LSD, more possible couplings (merger of 2 collaborations) =>

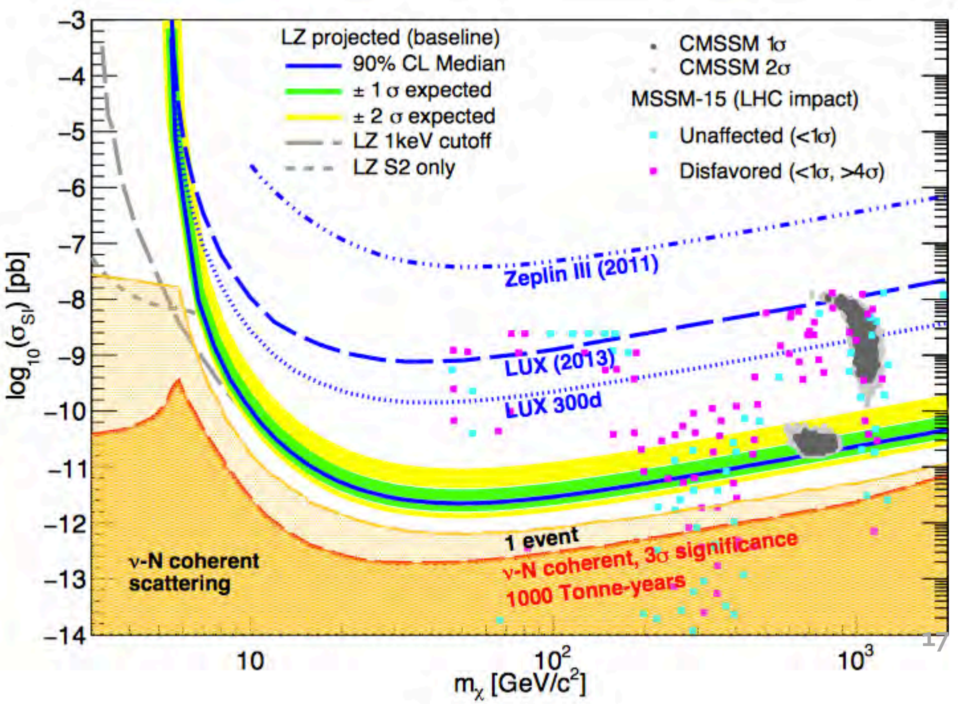
LUX-ZEPLIN Collaboration



A bigger and better version of LUX. Funded!!

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



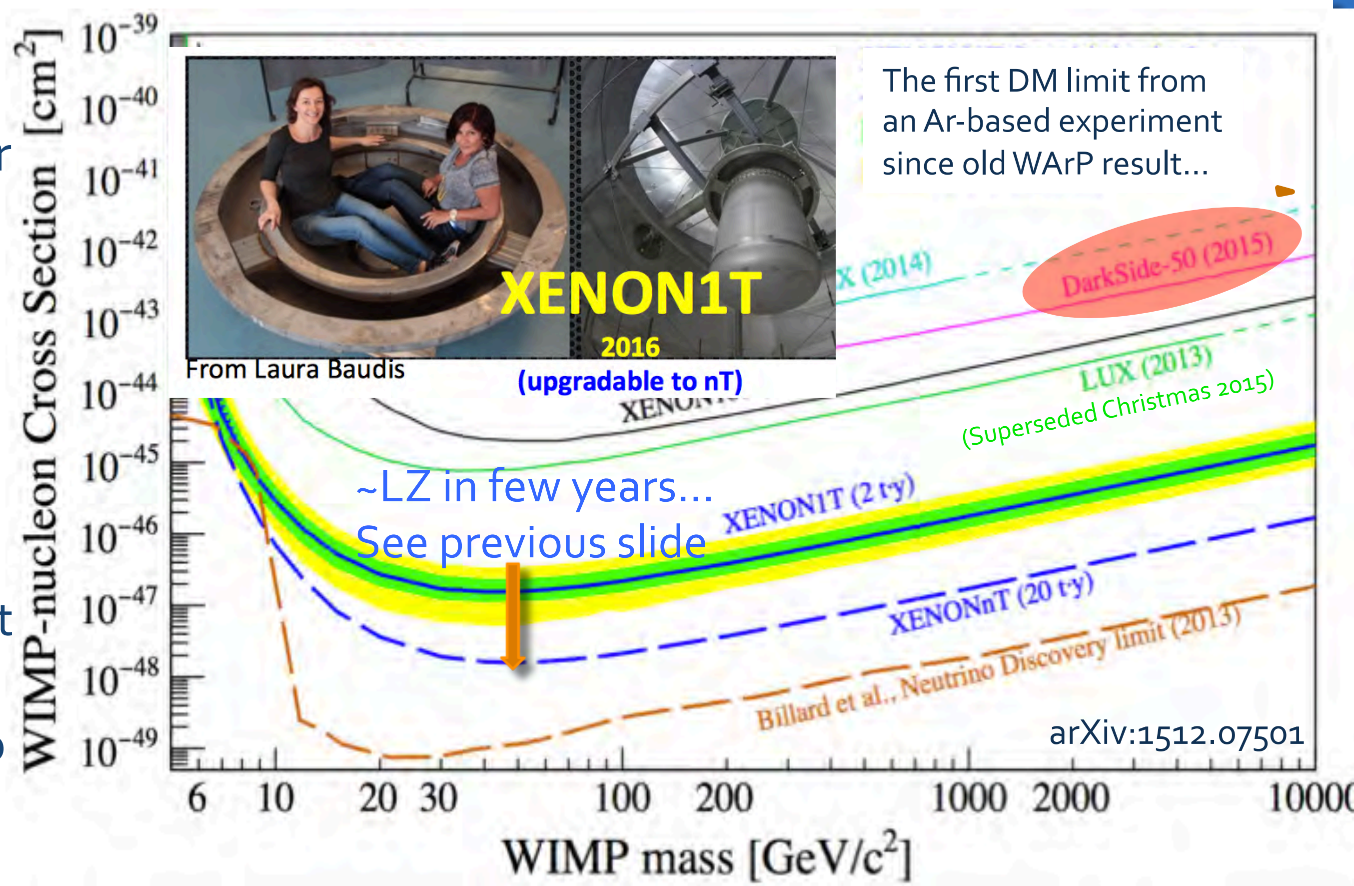


Projected Results

- 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)

Review of Future (and Present) of Competing Noble-Based Projects

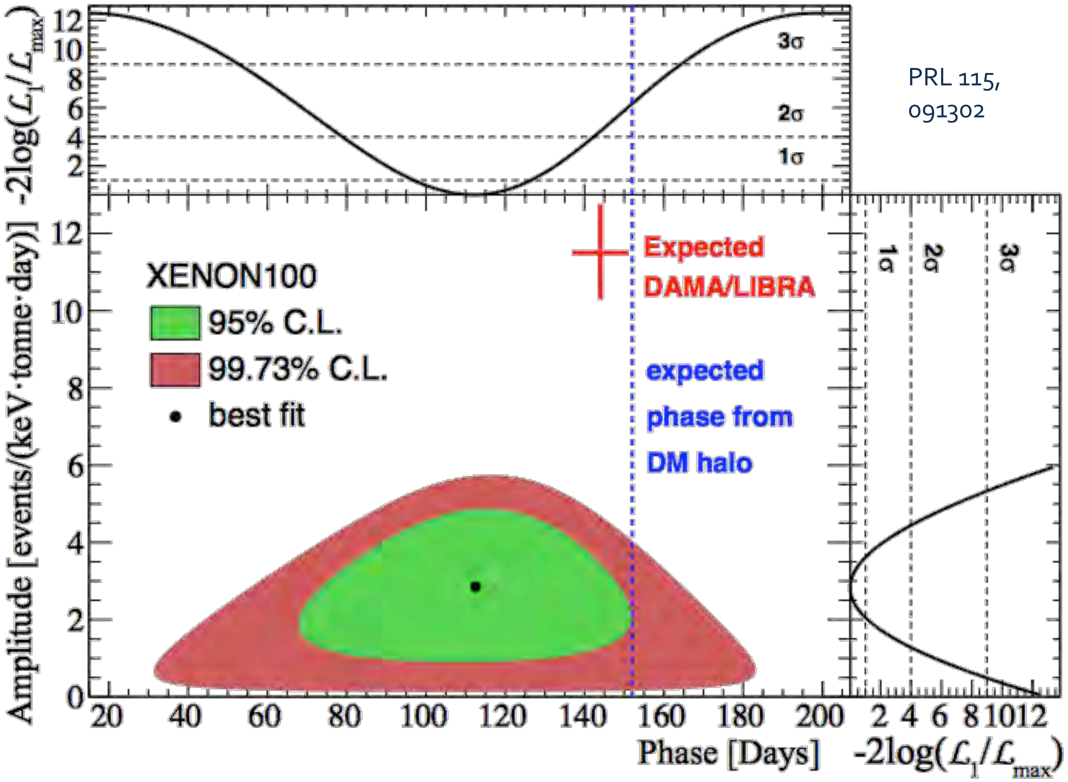
- See XENON100 (competitive results very similar to LUX) followed by XENON1T in Italy. Turning on!
- Panda-X in China
  - Appears better at lower mass (due to different assumptions!)
  - Beaten by DS50
- The competing experiments using same technology



Note also: DarkSide 2-phase Ar, less good @low mass but intrinsically lower ER leakage (PSD) than Xe BUT catch-up

XENON100 Annual Modulation Result (ER)

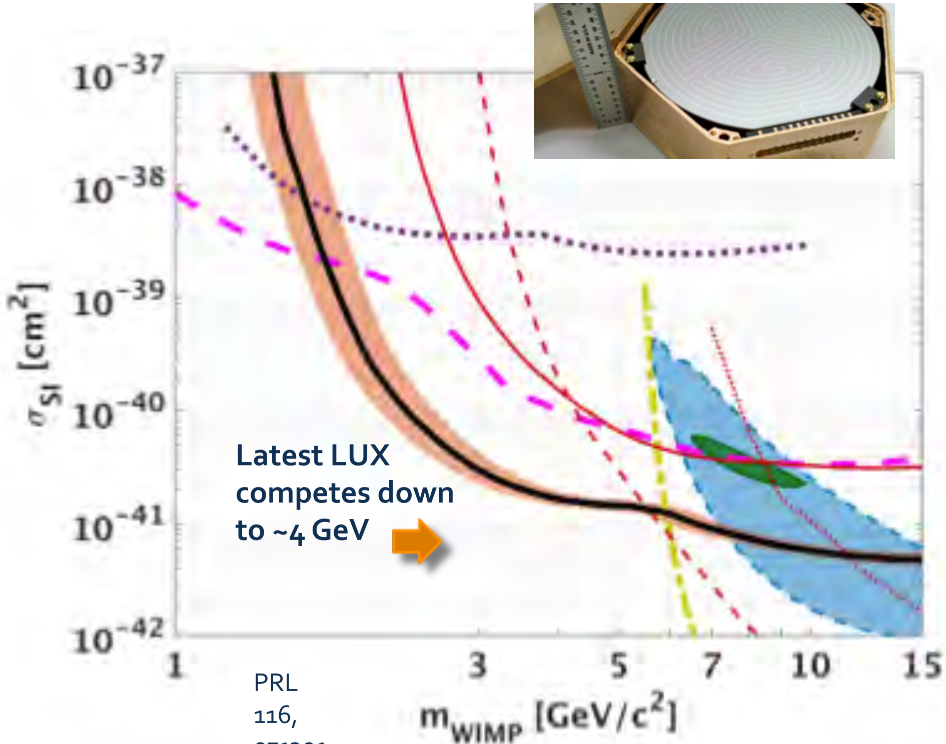
- DAMA/LIBRA signal just keeps getting re-killed (but returning)
- Killed for SI (LUX is latest), killed for SD-p (COUPP), killed for SD-n (XENON100, LUX)
  - Channeling not it
  - COUPP, KIMS have ^{127}I
- Killed for NR (LUX, others), and killed for ER (XENON100 best)



PRL 115, 091302

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

CDMS, CDMSlite, SuperCDMS: Ge, Si



PRL 116, 071301

FIG. 4. (color online) Median (90 % C.L.) and 95 % interval of the WIMP limit from this analysis (black thick solid surrounded by salmon-shaded band) compared to other selected results. Other 90 % upper limits shown are from the first CDMSlite run (red thin solid curve) [23], SuperCDMS (red thin dashed curve) [24], EDELWEISS-II (red thin dotted curve) [25], LUX (dark-yellow thick dashed-dot curve) [5], CRESST (magenta thick dashed curve) [27], and DAMIC (purple thick dotted curve) [28]. Closed regions are CDMS II Si 90 % C.L. (blue dashed shaded region) [17], and CoGeNT 90 % C.L. (dark-green shaded region) [19].

- One of the only two DOE Generation-2 aka G2 WIMP Cosmic Frontier projects
  - Plus, ADMX, for the axion
  - And: XENON (NSF funds)
- One of leaders, low WIMP masses (***with CRESST***) due to extreme in low threshold (ionization channel alone)
  - Early leader at every mass
  - Trouble competing at high masses nowadays (vs. Xe!)
  - Focuses on Luke phonons

PICO: Superheat – Bubble Chambers

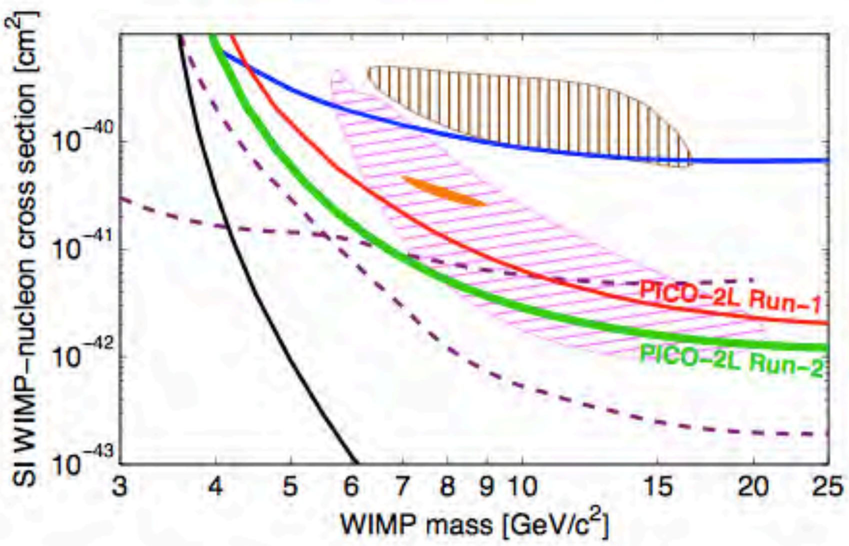
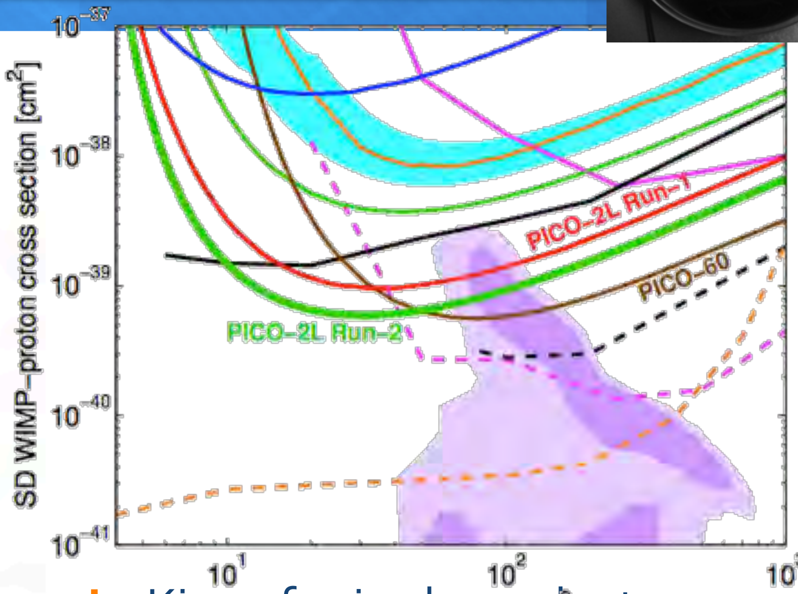


FIG. 4. (Color Online) The 90% C.L. limit on the SI WIMP-proton cross-section from Run-2(Run-1 [8]) of PICO-2L is plotted in green(red), along with limits from PICASSO (blue), LUX (black), CDMSlite and SuperCDMS (dashed purple) [12, 38–40]. Similar limits that are not shown for clarity are set by XENON10, XENON100 and CRESST-II [41–43]. Allowed regions from DAMA (hashed brown), CoGeNT (solid orange), and CDMS-II Si (hashed pink) are also shown [44–46].

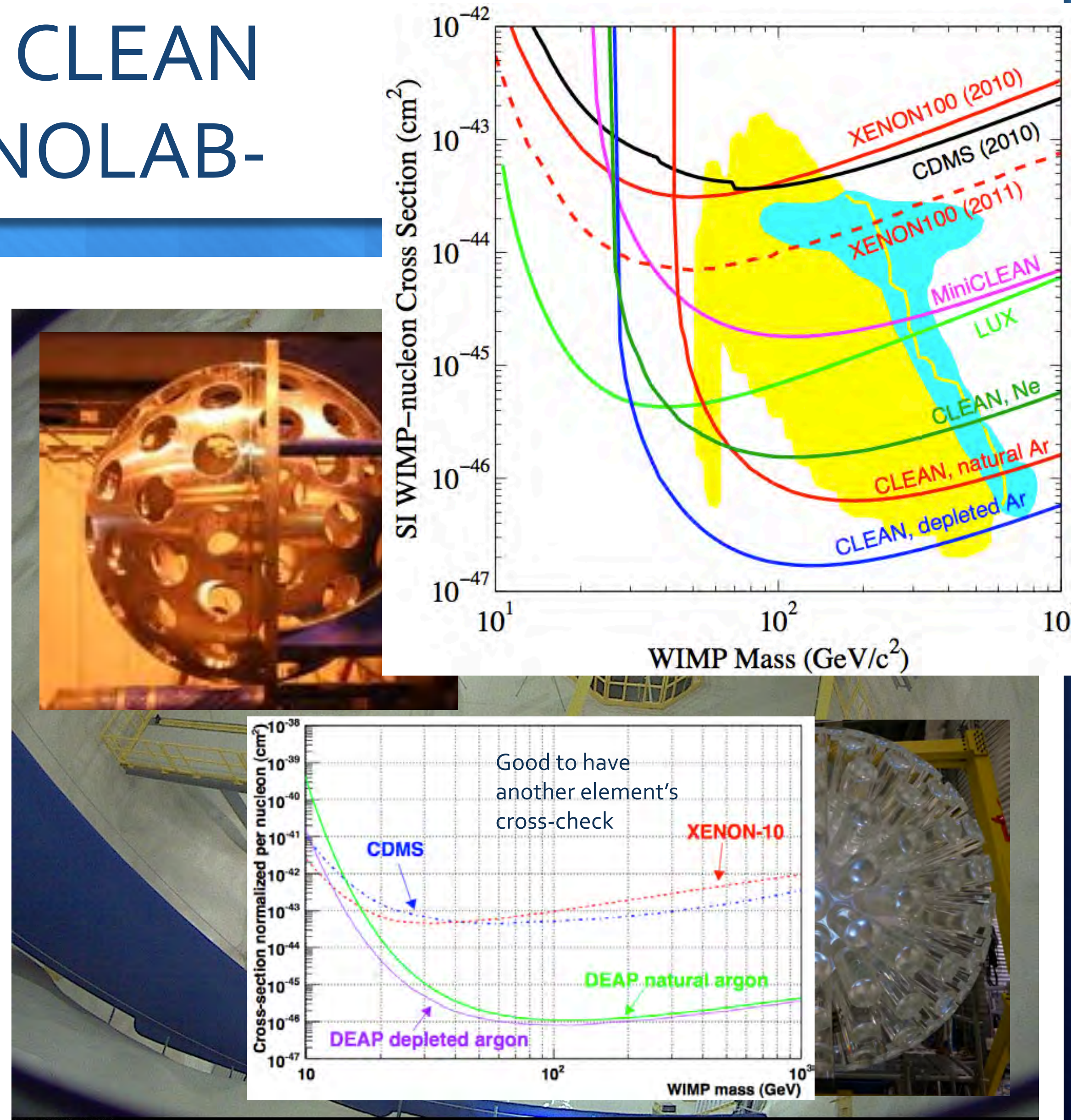
PRD 93, 061101



- King of spin-dependent p+
- Rapidly catching up on SI front especially at low mass
- No energy info, but ER-blind to highest degree of any experiment
- Future: 250 L in the works?

Down the road: CLEAN and DEAP, at SNOLAB-

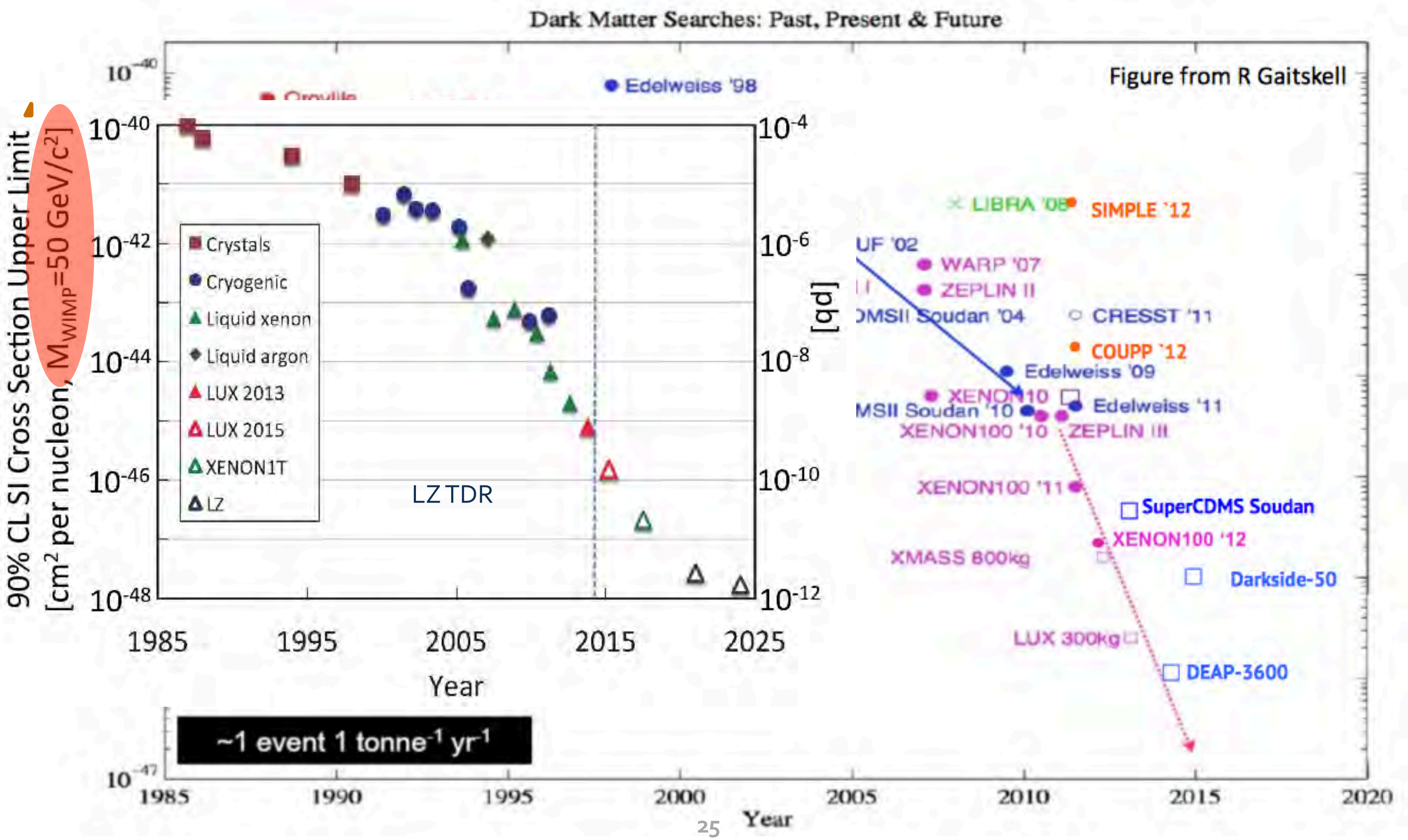
- Single-phase liquid argon with no E-field. miniCLEAN, DEAP-3600 deployed now, running
- Strengths
  - PSD better than S2/S1 discrimination by orders of magnitude
  - Argon = cheap
  - High mass WIMPs
- Weaknesses
  - Argon not dense, so less self-shielding
  - Underground Ar more expensive (^{39}~~Ar~~)
  - Threshold not low



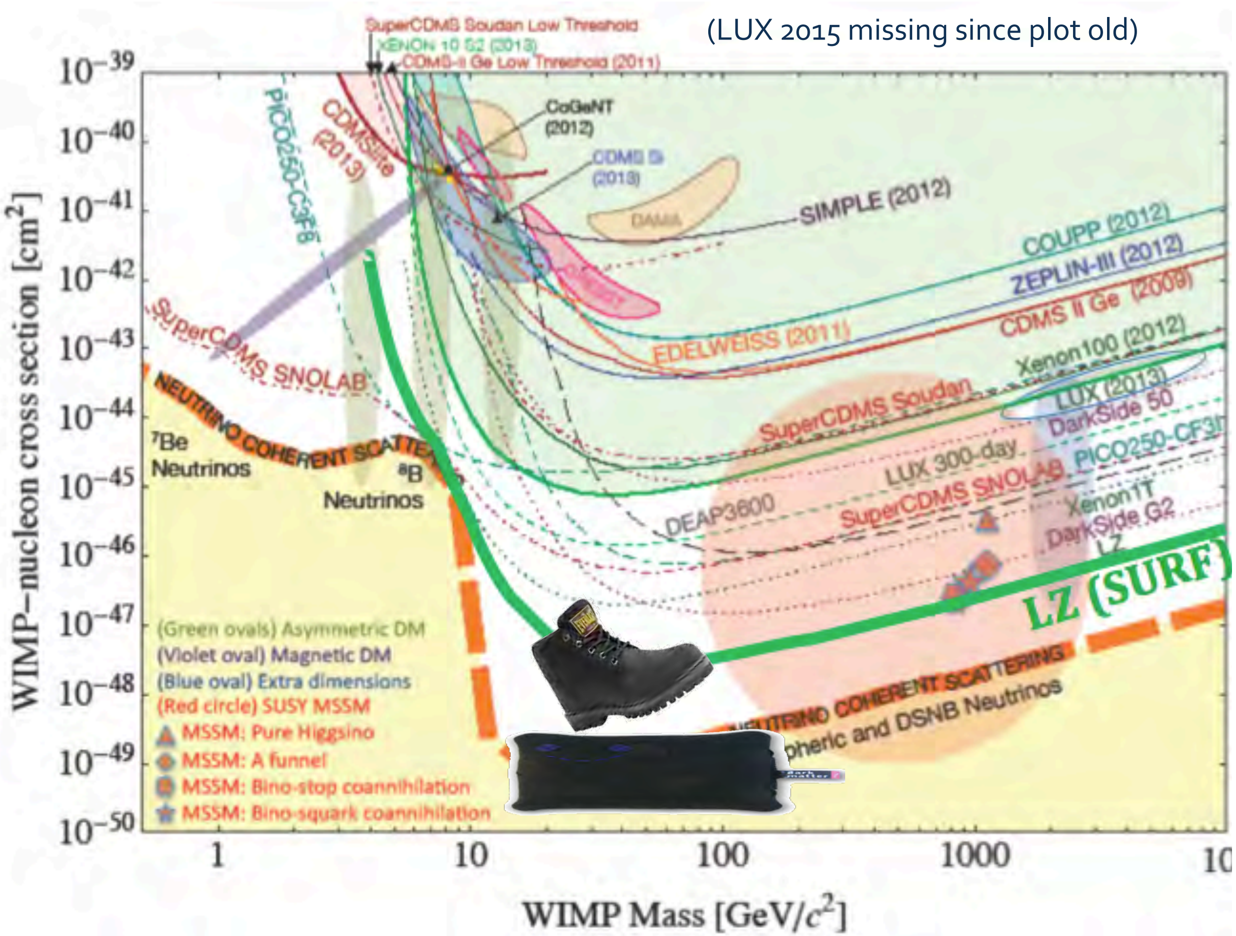
More Dramatis Personae (Incomplete)

- XMASS: Only 0-field, single-phase, spherical Xe detector, and largest mass Xe one in current operation. Attempting PSD.
- CoGeNT: First to push Ge threshold low: ionization only. Potential signal at low masses, in conflict with other results.
- DAMIC: Putting the extreme in extremely low threshold, O(10) eV!! Uses CCDs. Not world-best yet, but catching up.
- SABRE: Princeton (also DarkSide) leading charge. Reproduce DAMA / LIBRA with ultra-low-background NaI, in Australia!
- Directional detector ideas: NEXT (GXe), DMTPC, DRIFT, et al.
- Apologies if your favorite experiment hasn't been mentioned! There are dozens around the globe, even after "down-select."

Past, Present, and Future Trending



The Famous Busy SNOWMASS Plot



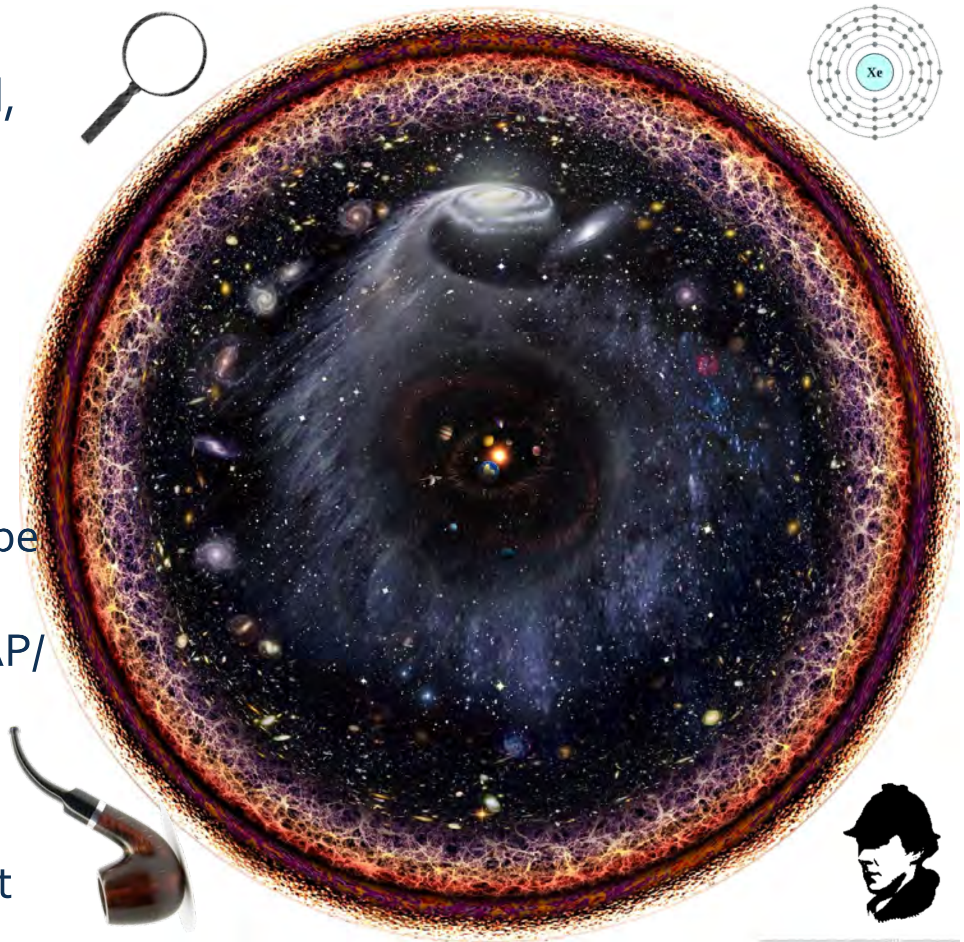
(LUX 2015 missing since plot old)

- Almost obligatory ☺
- Not ignoring the extremely competitive XENON1T / nT (see earlier slides) but are not present here
  - Because not a part of Snowmass nor DOE G2 down-selection processes
  - Already funded by NSF, plus deployed in Europe; partially funded by Euro $$
- Low-mass region is kind of lonely, but between LZ and SuperCDMS covered
  - And, LZ limit is old!

A Concluding Summary and Outlook

* Low mass, high mass, nuclear recoil, electron recoil, annual mod, SI and SD both flavors are all at least kind of covered for WIMPs

* U.S.A. (G2: LZ, SuperCDMS), Europe (XENON, CRESST), Canada (PICO, DEAP/CLEAN), China (Panda-X), Japan (XMASS), others all in the game, of next generation DM.



* 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 up to ν floor at least…

* 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

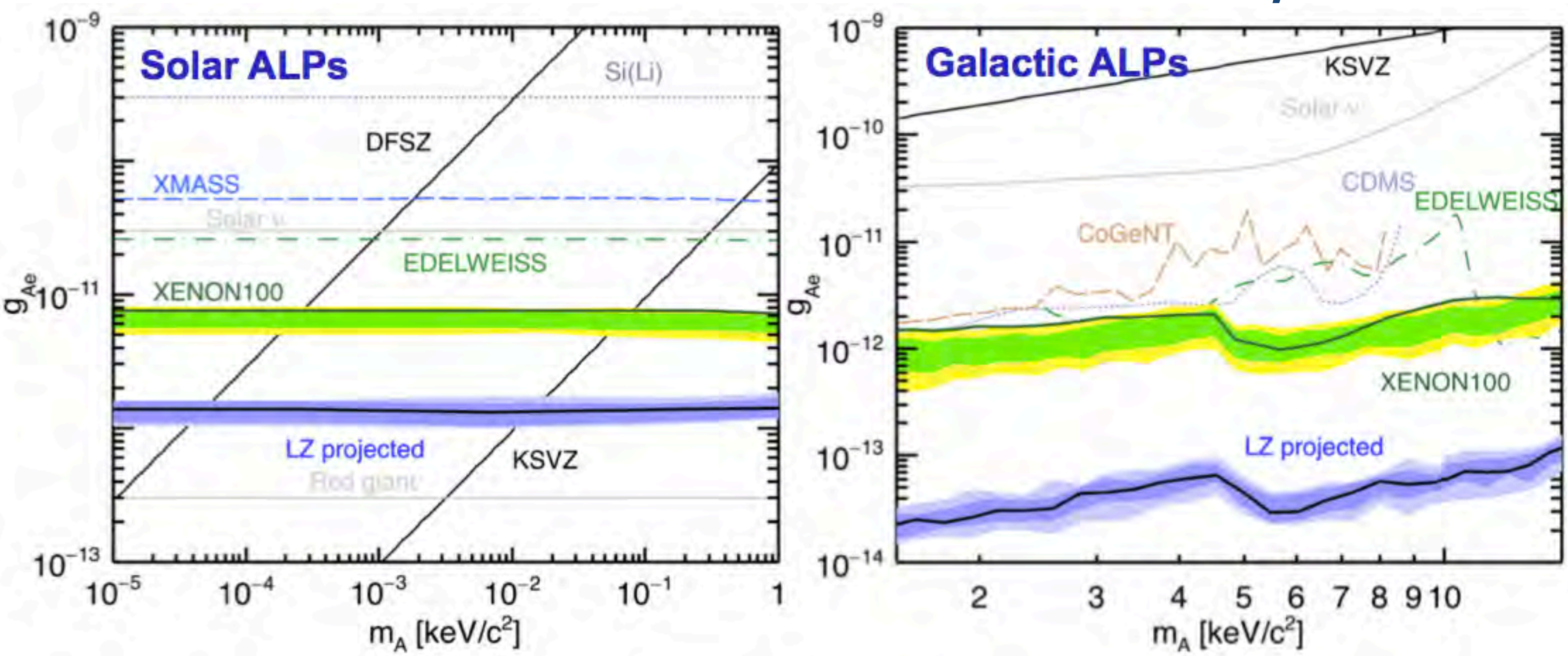
- Thank you for your attention

- (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

Axions, in LZ



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 above ER background based on mass (must contend with ^{37}Ar BG). Note LUX 2016 not included but coming soon: similar to Xe100, lower

The Lindhard Factor in Liquid Xenon