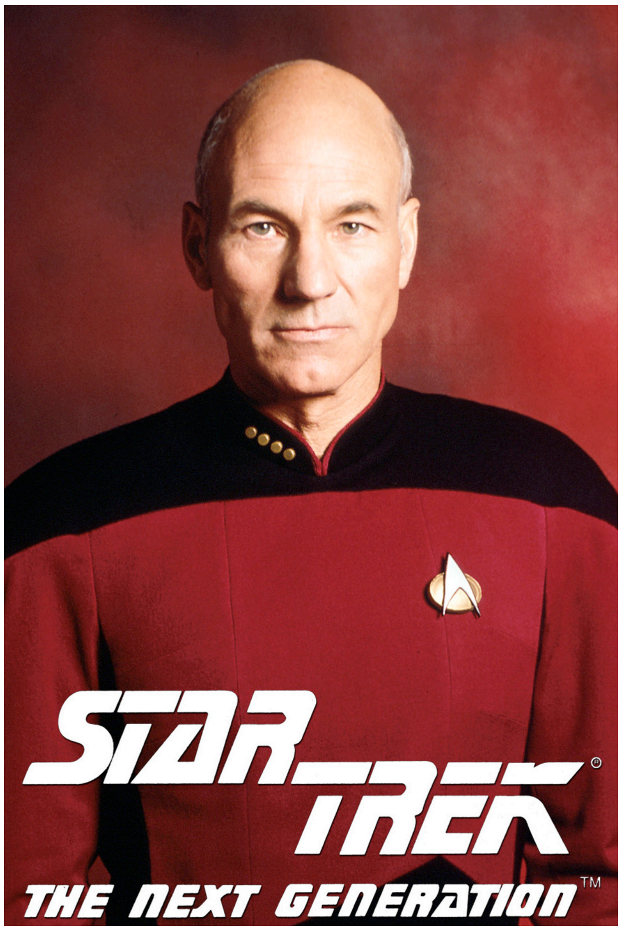
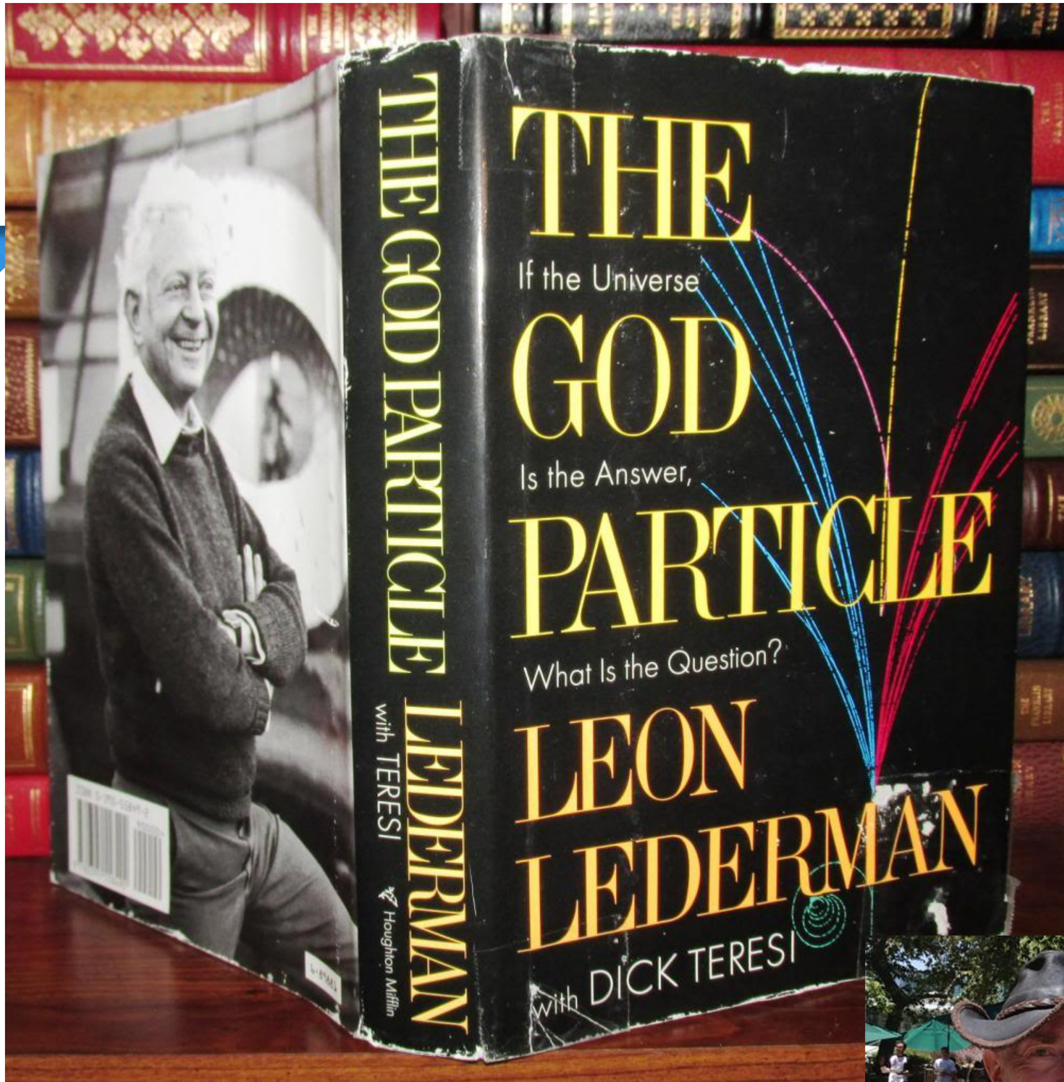
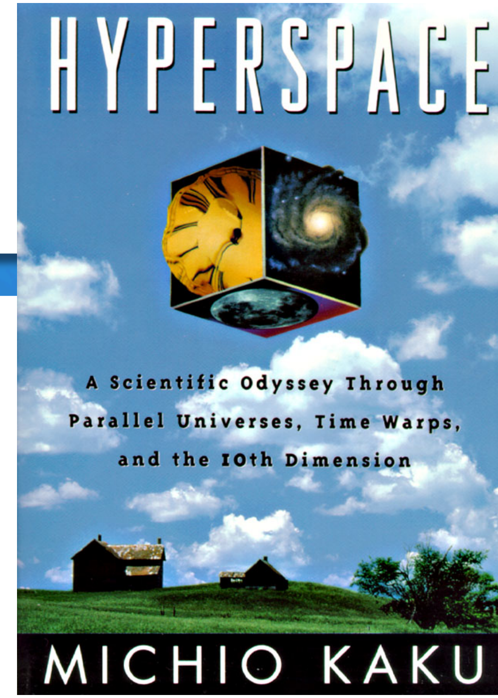
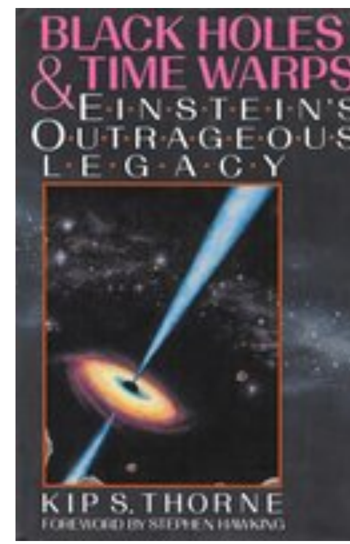
How I Got Interested in Science



- I wanted to be involved with and engage with the sublime, fantastical, or even the "impossible"!
- Like time travel, faster than light travel, etc. etc. Though I got sucked into "more practical" things…





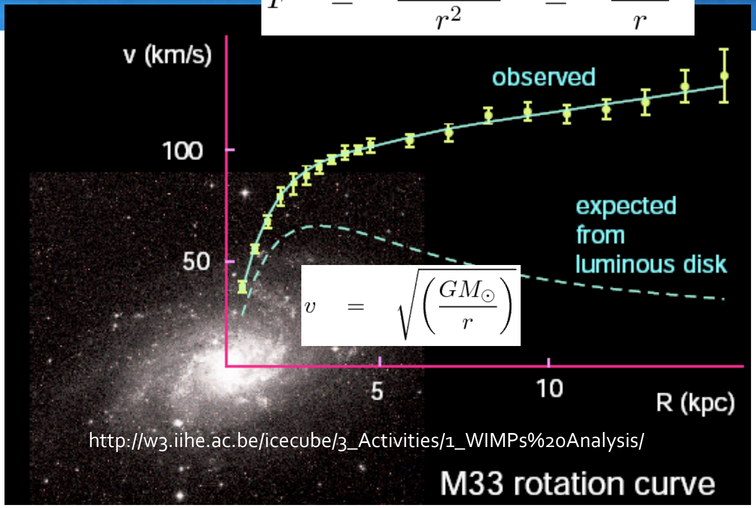


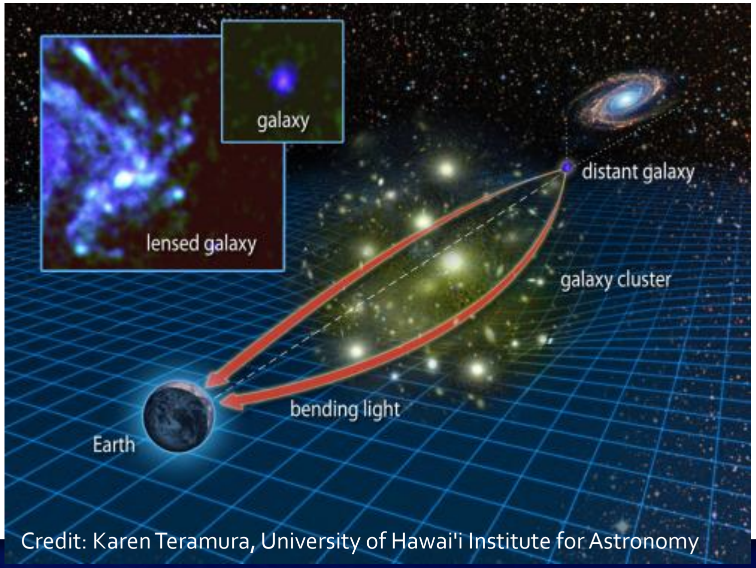
I read these 3 books in the 4^{th} and 5^{th} grades!

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

$$F = \frac{GM_{\odot}m}{r^2} = \frac{mv^2}{r}$$

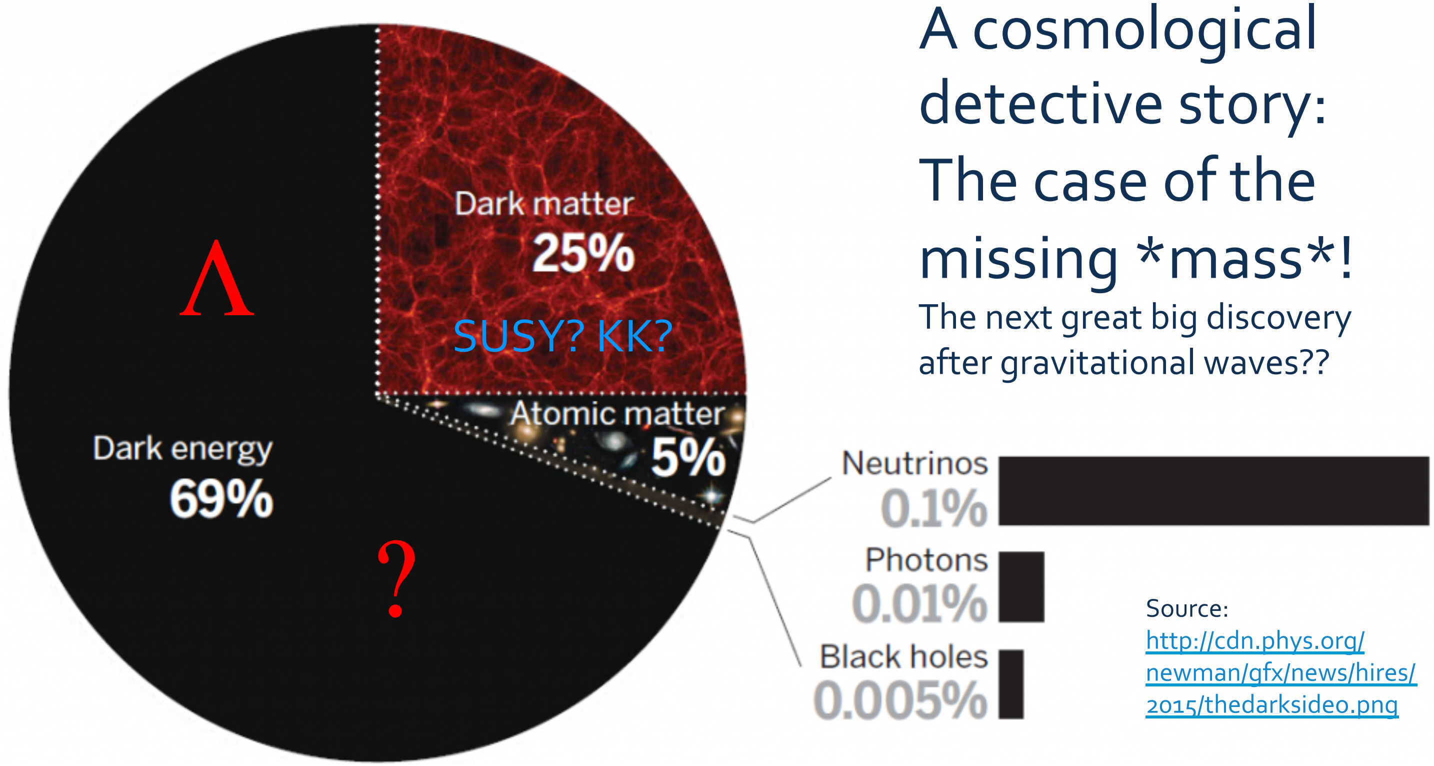




A Gaping Hole in Our Knowledge!

The multiple components that compose our universe

Current composition (as the fractions evolve with time)



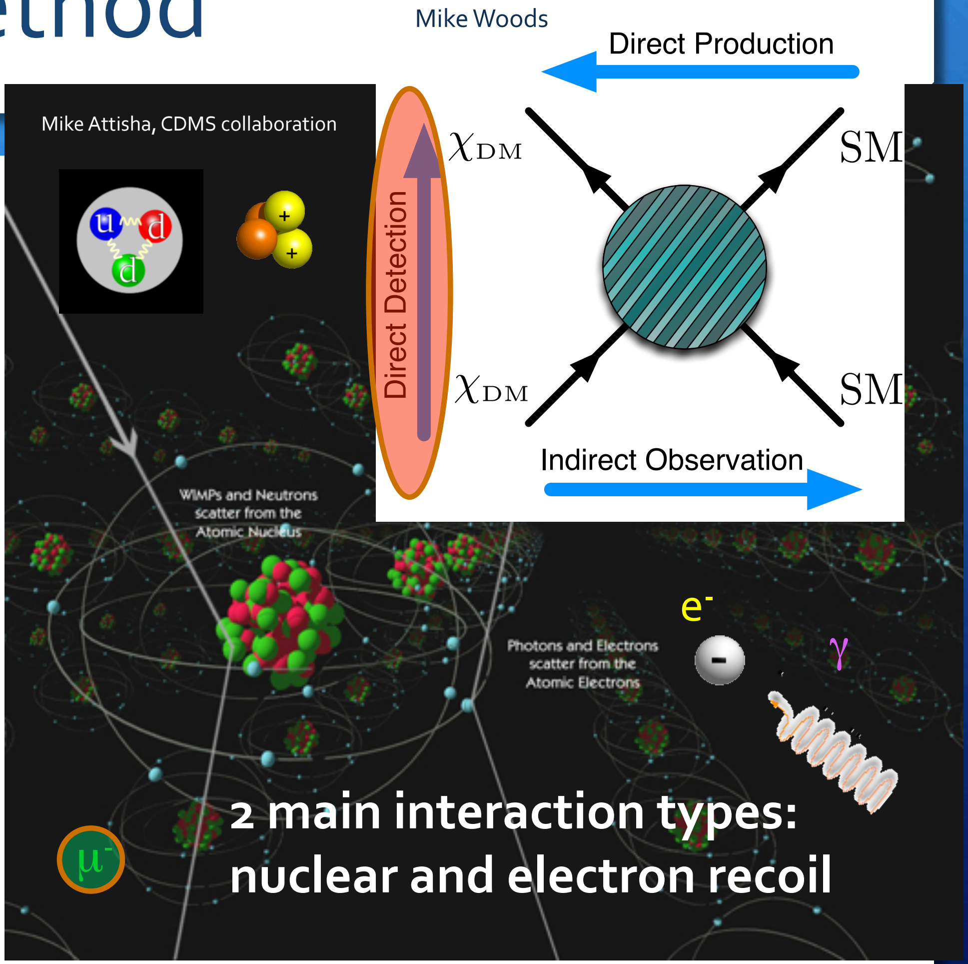
A cosmological detective story: The case of the missing *mass*!

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 Math

- Use Chris McCabe 2010 as reference! arXiv:1005.0579 Phys. Rev. D82, 023530 (2010) "The Astrophysical Uncertainties of Dark Matter Direct Detection Experiments"
  - Update to seminal work of Lewin and Smith (2006)

$$\frac{dR}{dE_R} = \frac{\rho_0}{m_\chi m_A} \int_{v>v_{min}} v f(\vec{v}) \frac{d\sigma}{dE_R} d^3v$$

Nicole Larsen, LUX

Differential event rate with respect to recoil energy (events/keV/kg/day)

Differential cross-section

Average over WIMP velocity distribution

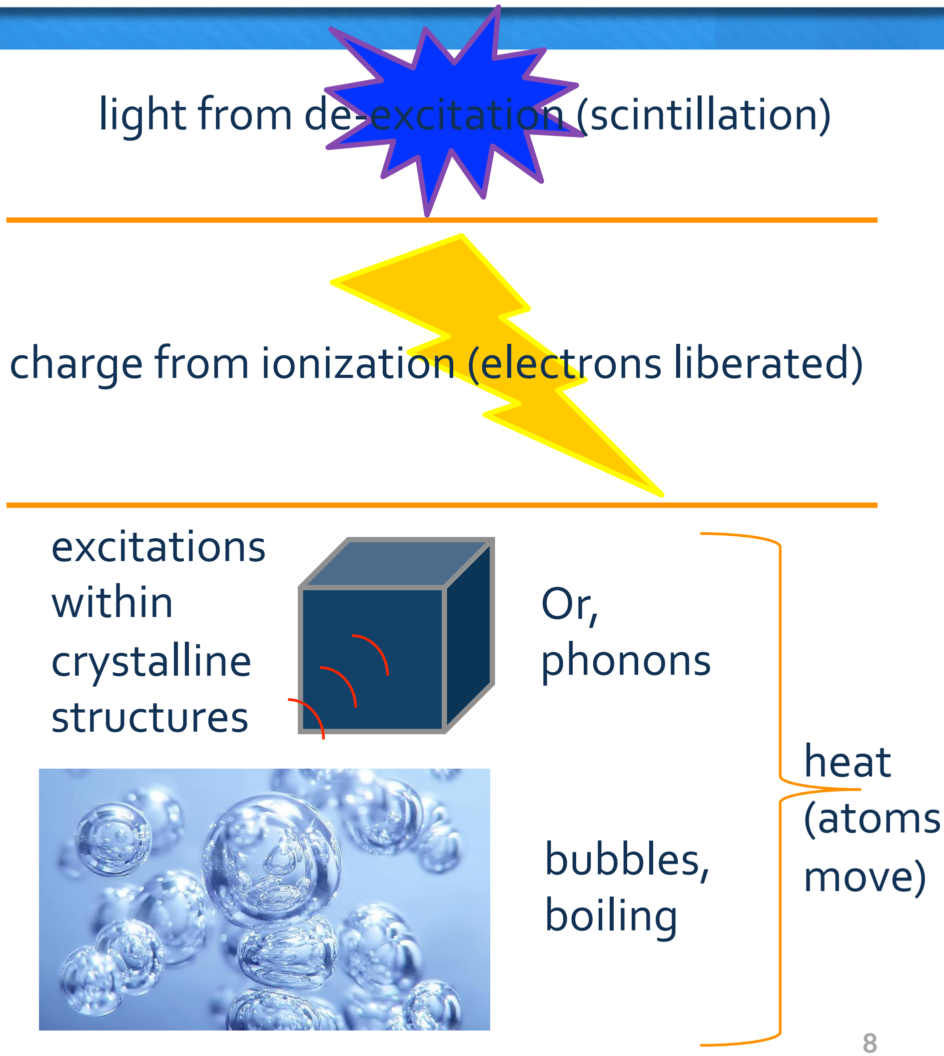
- Some key numbers: Earth velocity, dragged by sun around center of galaxy, is ~230-240 km/s depending on time of year
  - Plus: v_escape = 544 km/s, v_WIMP (mean) 220 km/s; rho ~ 0.3 GeV/cm^3

The Major Experimental Backgrounds

Reduce radiological ones with radio-pure materials

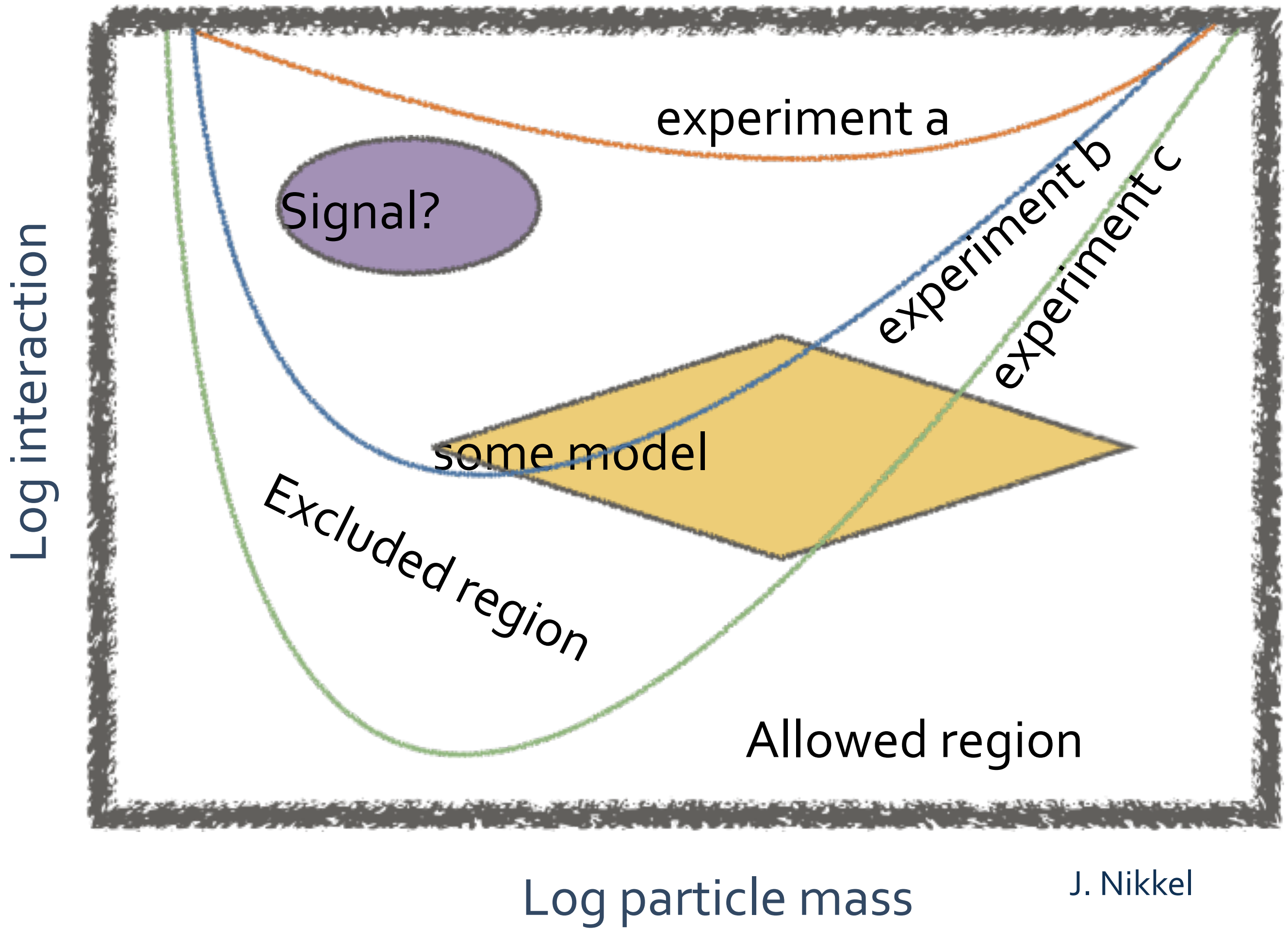
- Neutrons: Go bump in the night just like WIMPs. Can be remediated by cutting multiple scatter events and by aggressively fiducializing detector volume, if it is self-shielding, and by simulating all the neutrons sources you've determined.
- Alphas: Can also produce nuclear recoil like WIMPs. Radon 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



- 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

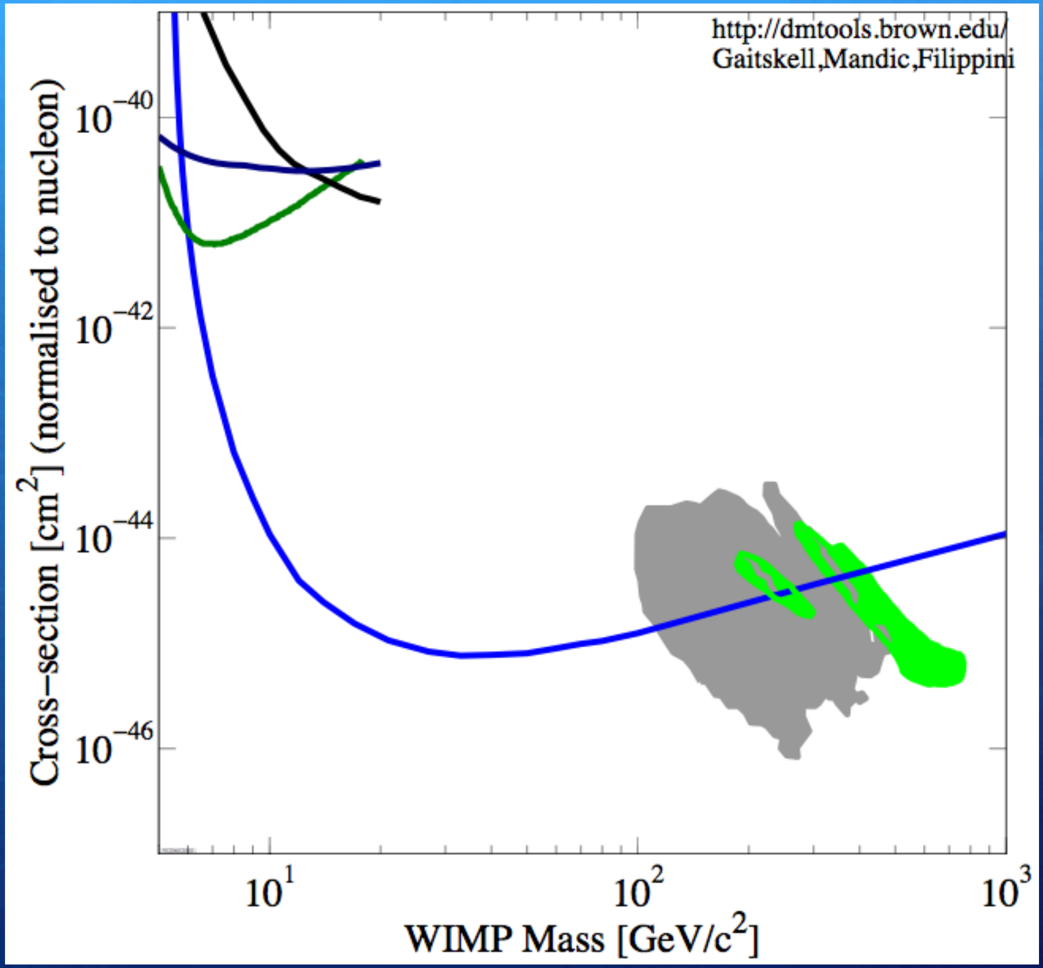
A Generic Search Plot



The result of a search may be an exclusion region if nothing is found, or an allowed region in phase space if a positive signal is observed.

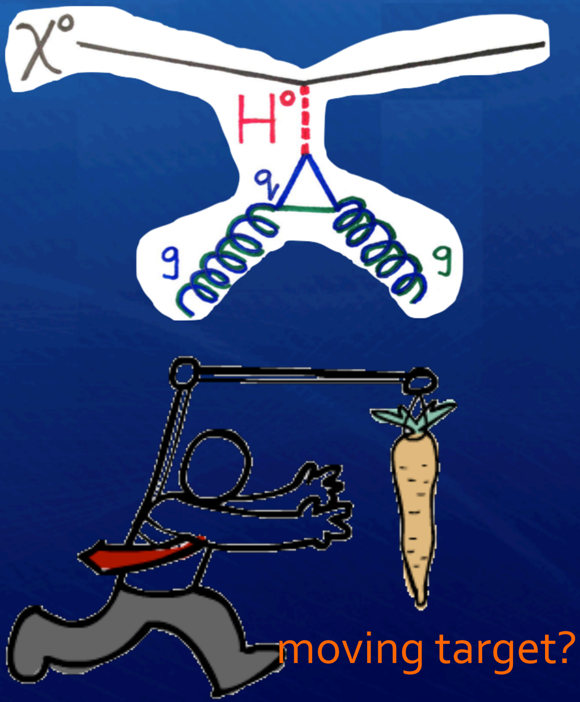
Since we still do not know a lot about dark matter, the allowed phase space is large.

Time Progression of Sensitive Experiments



Years
2000-2013

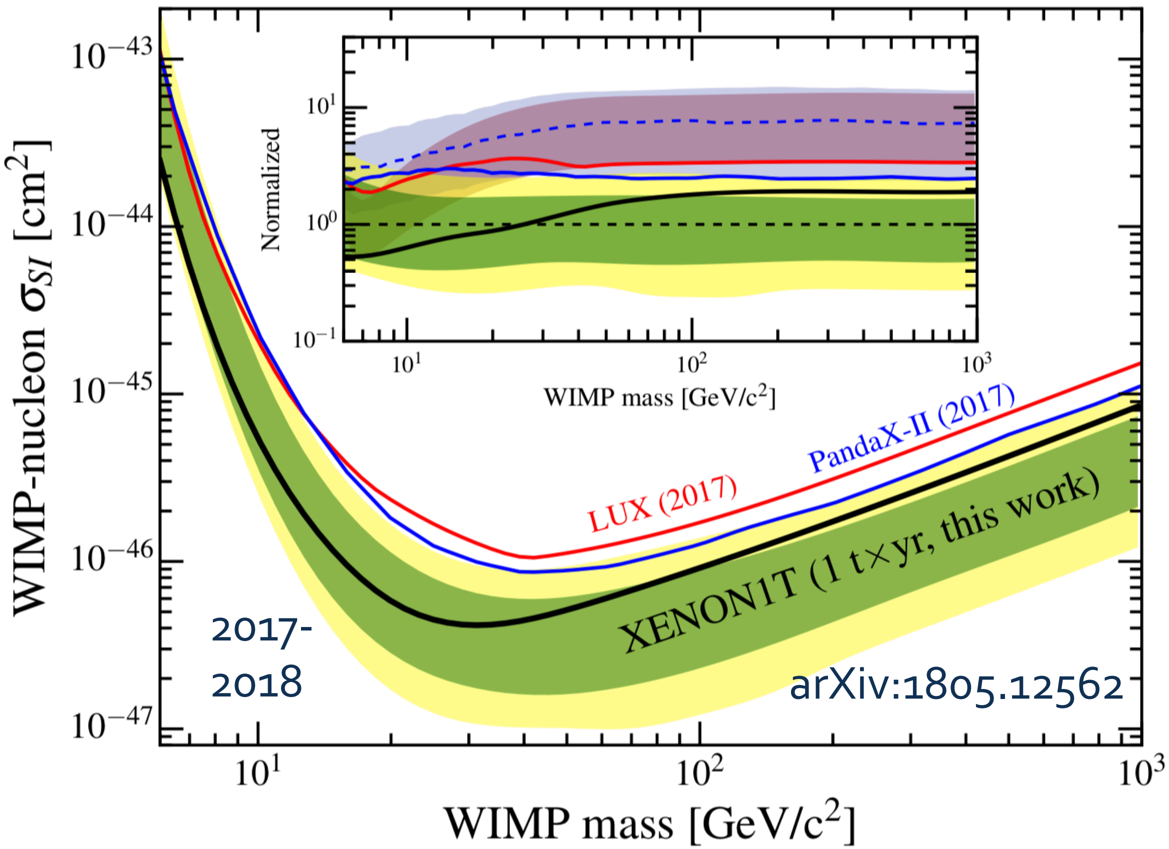
Closing in on Higgs coupling?



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)
- XENON has pulled ahead at most WIMP masses as of this talk, having re-analyzed its original data and taken lot more data (Getting close also to solar ν coherent scattering, ^{8}B, at level of ~1 events/year)

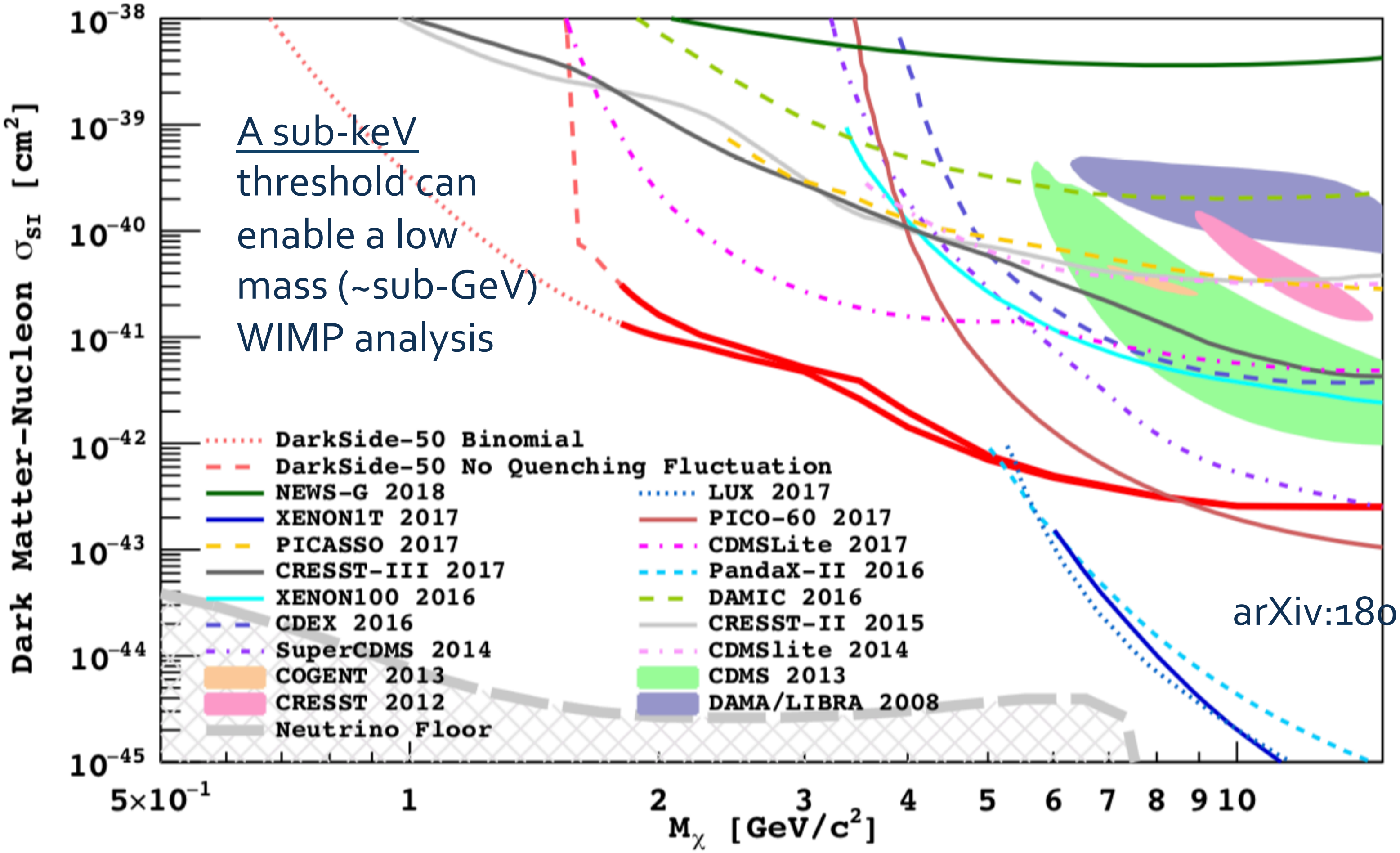


XENON1T 278.8 live-day exclusion limit curve

Potential Signals and Detection Claims

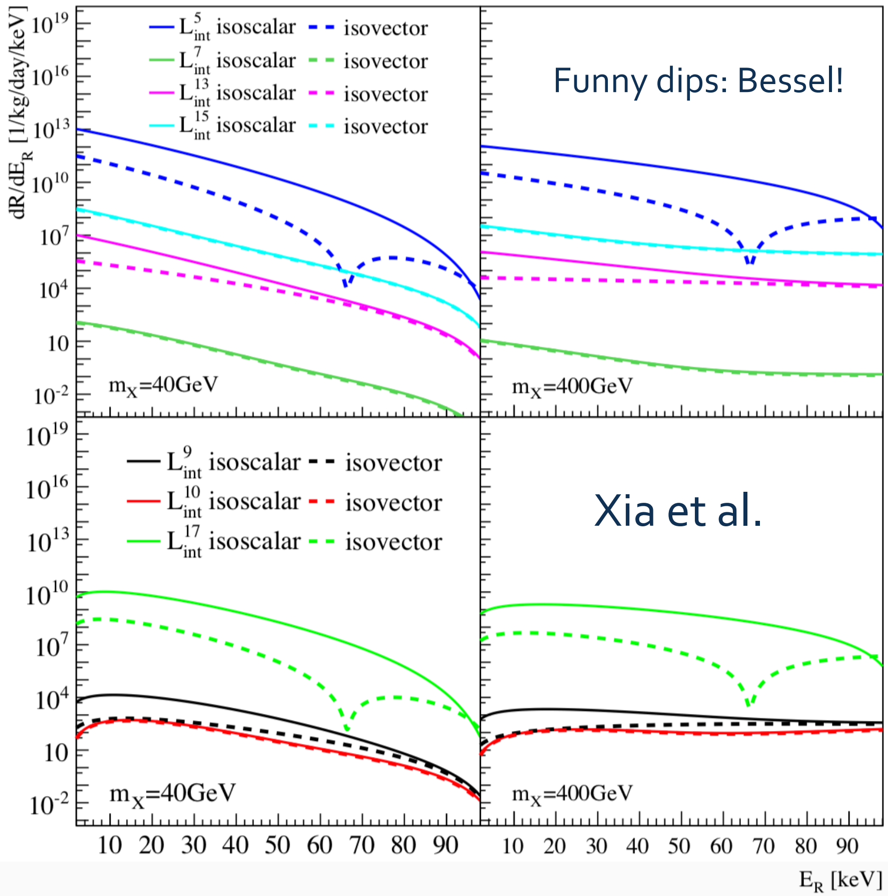
- DAMA / LIBRA: The earliest, most famous, most statistically significant, and most persistent, resisting explanations to make it go away, but very difficult to reconcile with other results
  - Annual modulation signal seen over many years in NaI detectors in scintillation channel (just 1: not sensitive 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 great limit <2 GeV

DarkSide, and the Very Low Mass Picture



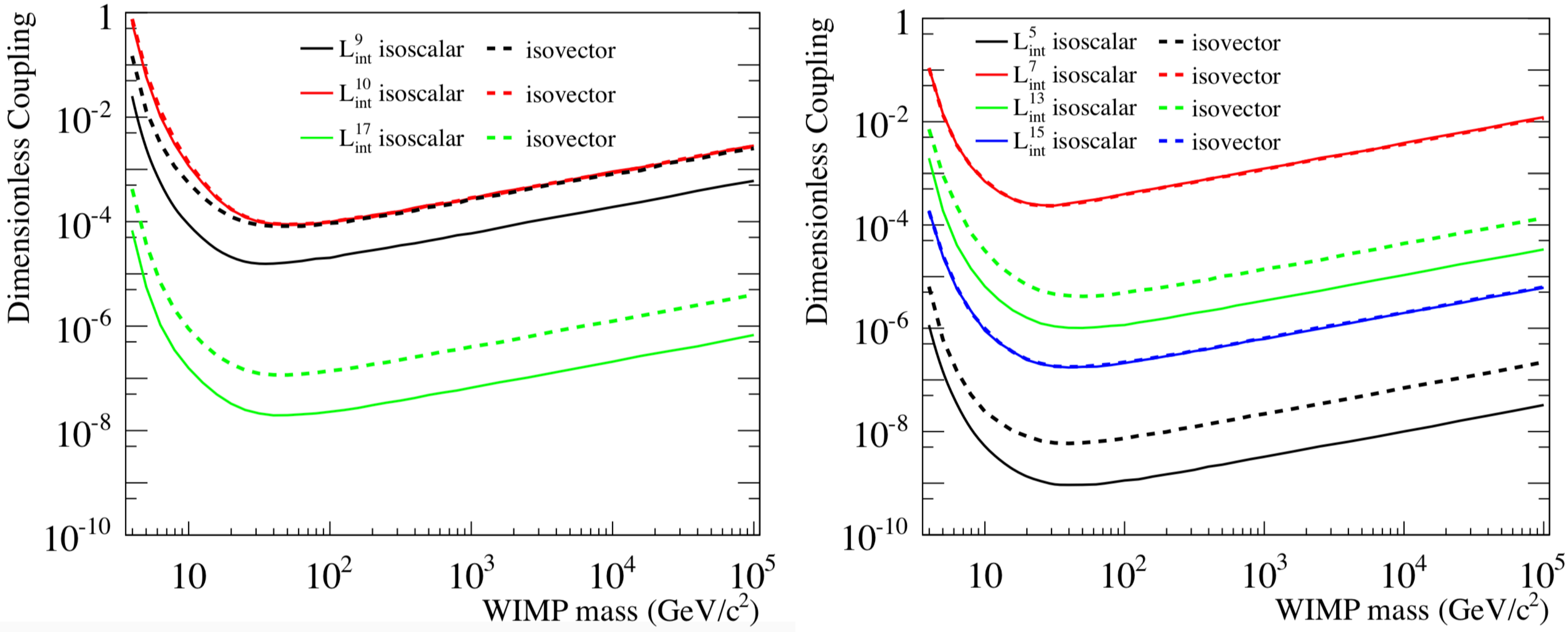
arXiv:1802.06994

Effective Field Theory (EFT) Operators



- Going out to higher energies than ever before too. But why?
- New operators could add corrections including interference terms to traditional SI (spin-independent) and SD (spin-dependent) interactions
- Individual proton, neutron, and quark momenta are not necessarily negligible
- Restrict to Galilean or Lorentz invariant and Hermitian

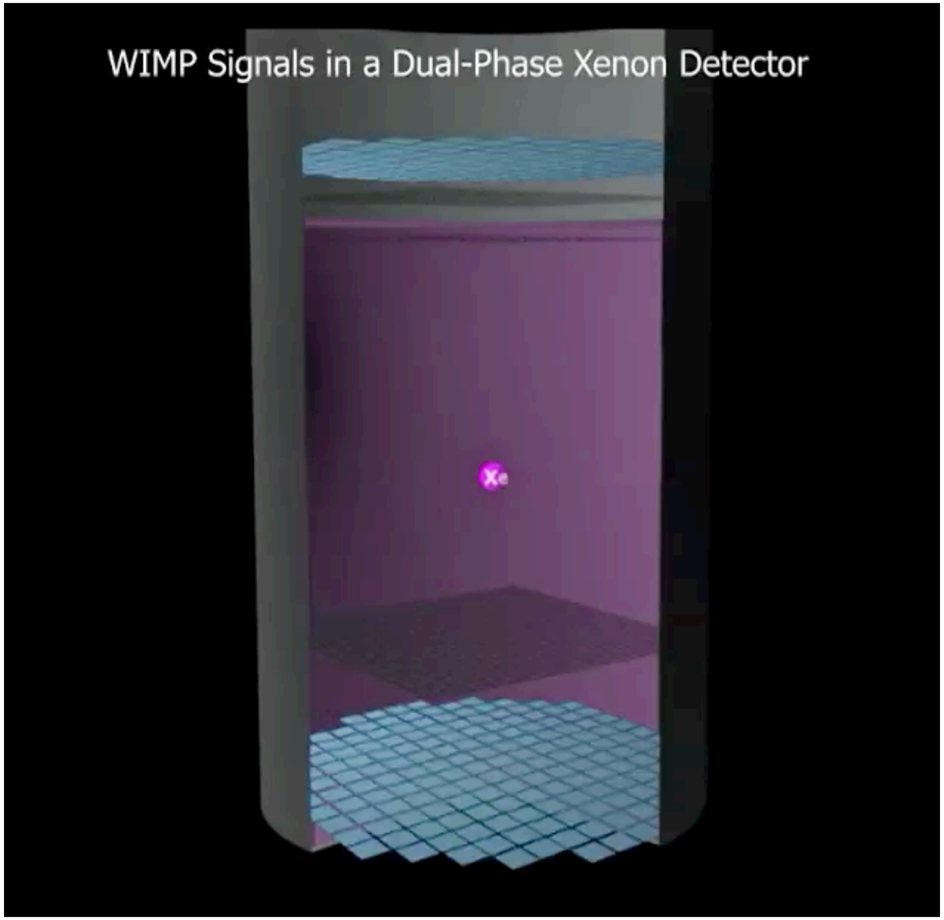
Right Now PandaX is Latest/Greatest



PandaX-II Experiment + Wick Haxton. arXiv:1807.01936

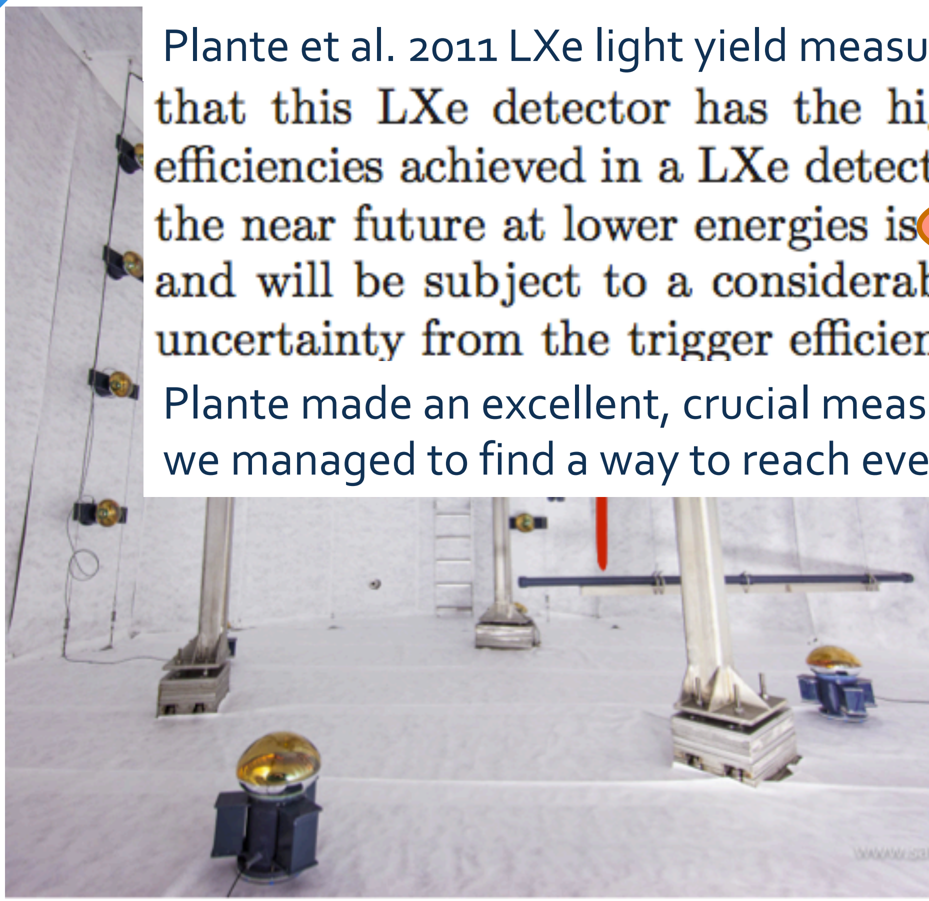
How Any Two-Phase Xe TPC Works

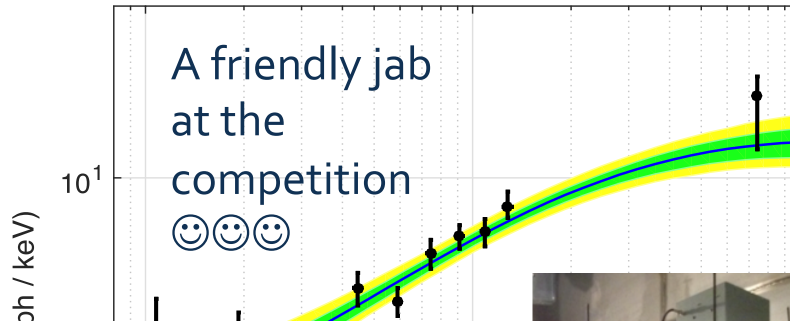
- Collaborations with 2-phase xenon-based time-projection chambers have been leading the pack for over a decade now
  - XENON10/100/1T, LUX
  - 2-phase Ar similar principle: DarkSide, ArDM
- Photomultiplier tubes (PMTs) convert single photons into photo-electrons (phe or PE)
- Lead, SD for LUX (while Gran Sasso Italy for XENON): underground vs. mountain




Raymond Davis
BROOKHAVEN

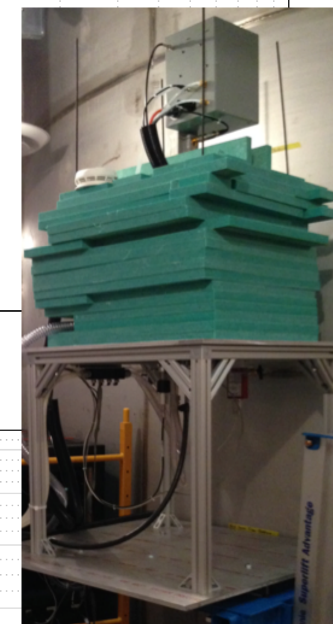
Calibration (LUX D-D)

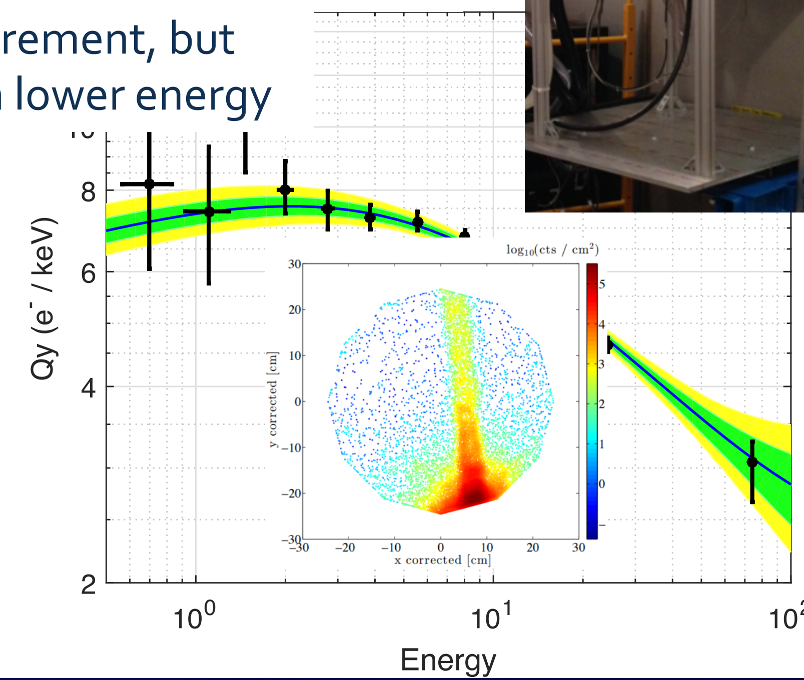




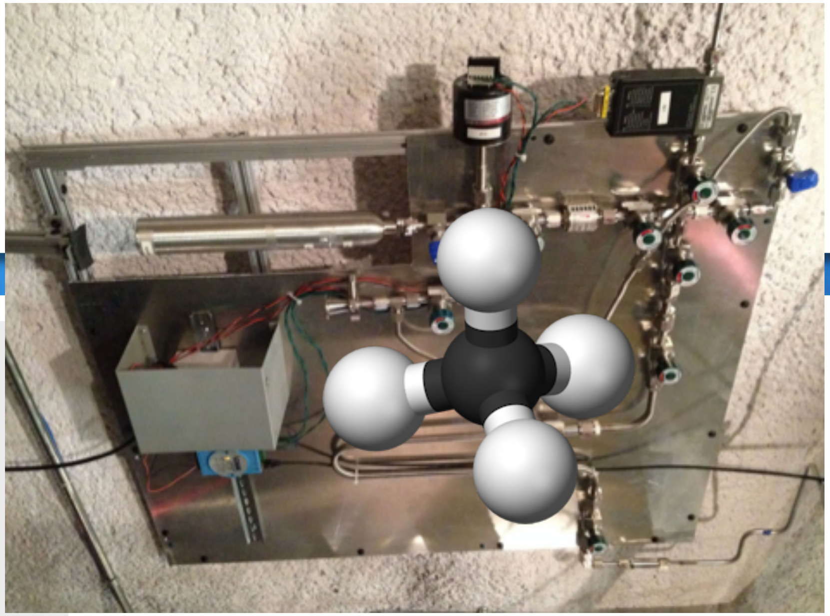
Plante et al. 2011 LXe light yield measurement-- Considering that this LXe detector has the highest light detection efficiencies achieved in a LXe detector, measuring $\mathcal{L}_{\rm eff}$ in the near future at lower energies is probably impractical and will be subject to a considerably higher systematic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

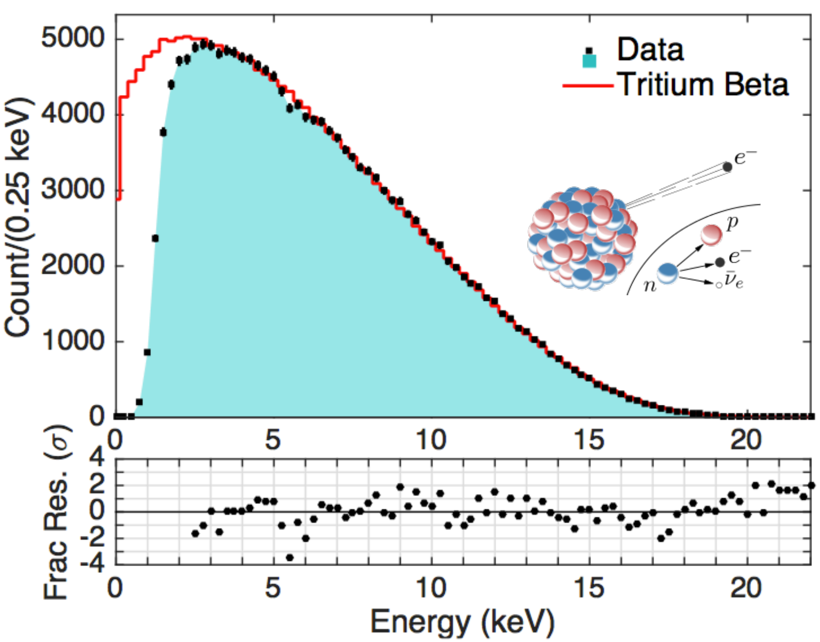
Plante made an excellent, crucial measurement, but we managed to find a way to reach even lower energy





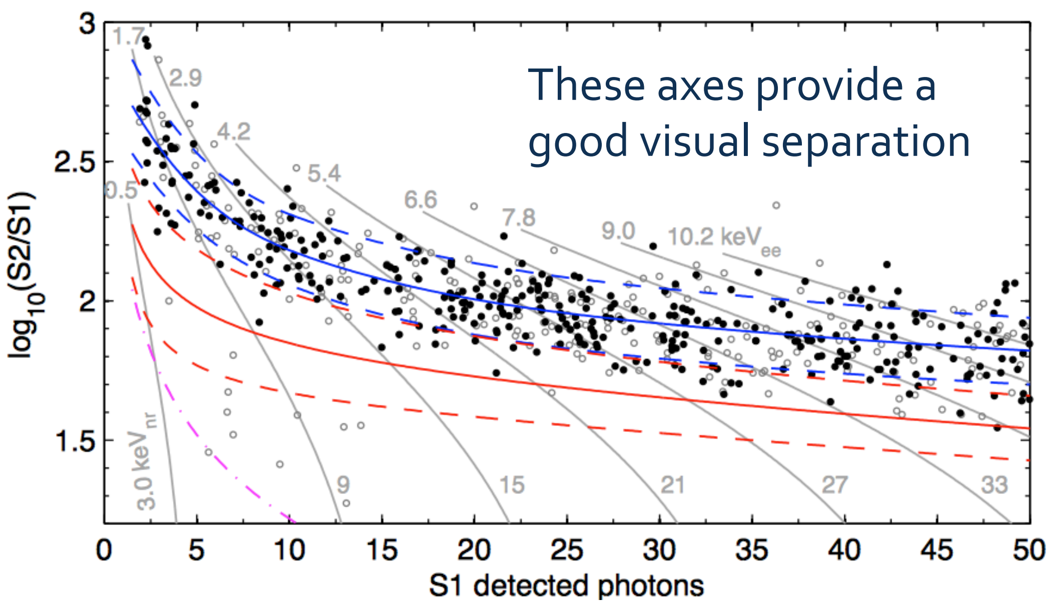
Calibration (LUX CH_3T)

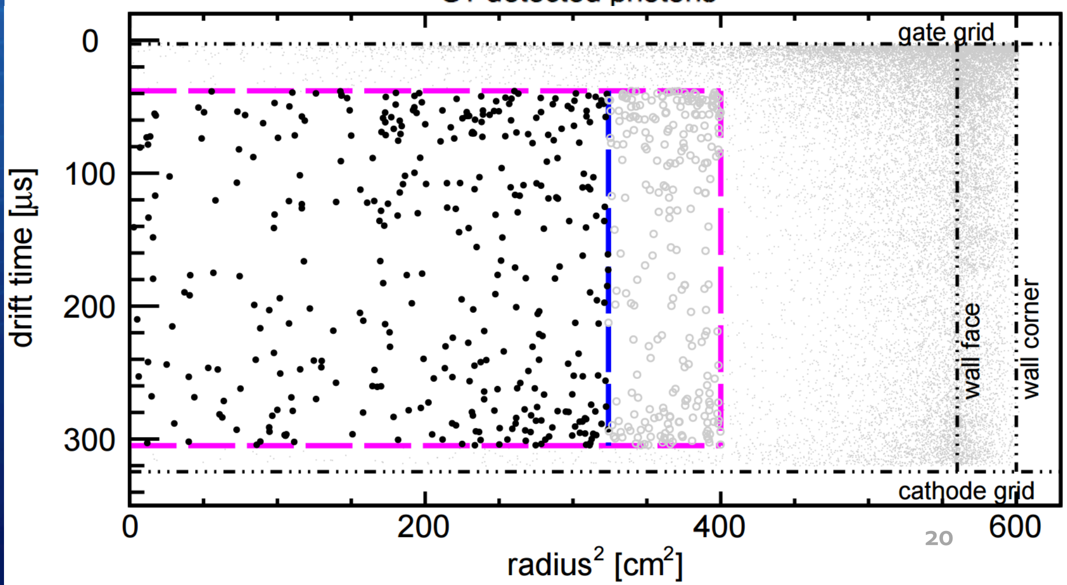


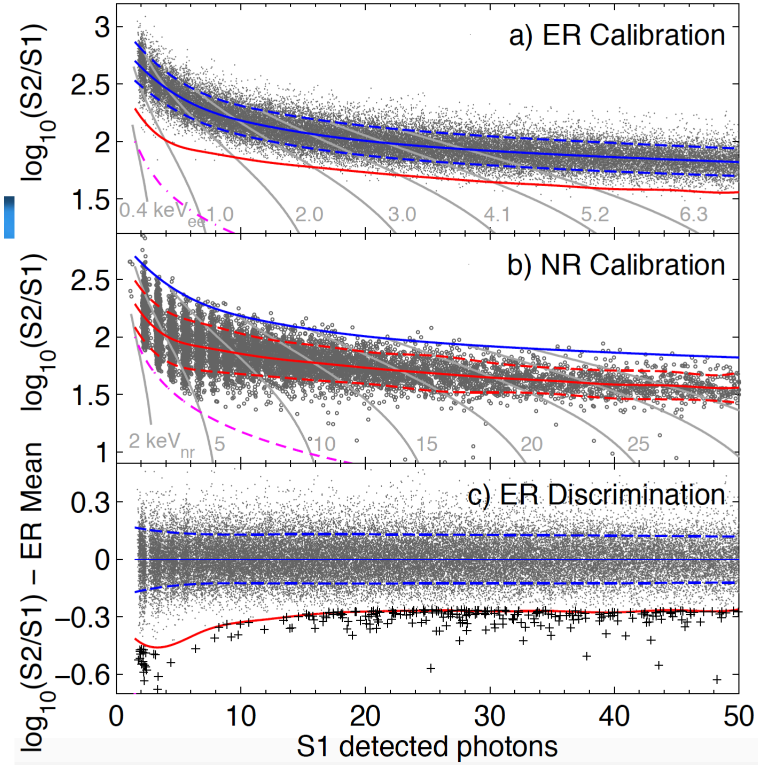


Example only, outdated: first LUX WIMP search result (only 95 live-days)

Putting It All Together

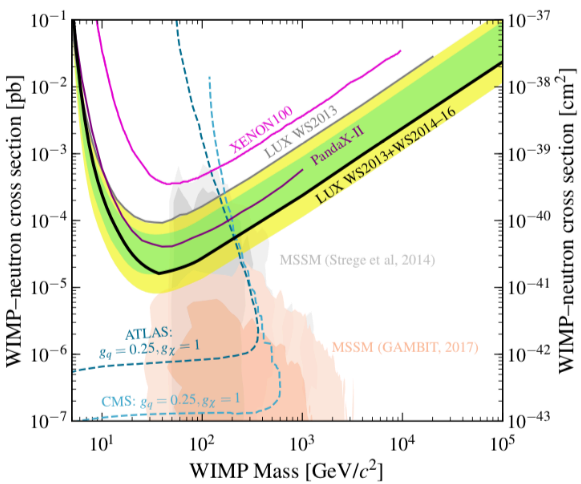


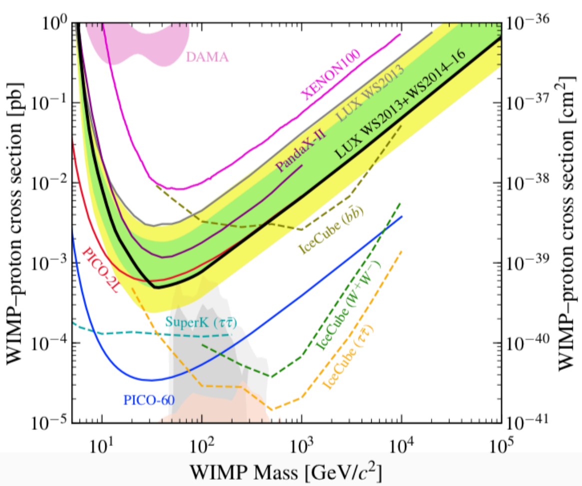




- The S1 (first), plus S2 (the second) scintillation light, latter coming from charge
  - Log ratio says ER or NR
  - Sum provides us energy
- Wall events are gray points

“New” SD Exclusion Bounds (427 days)



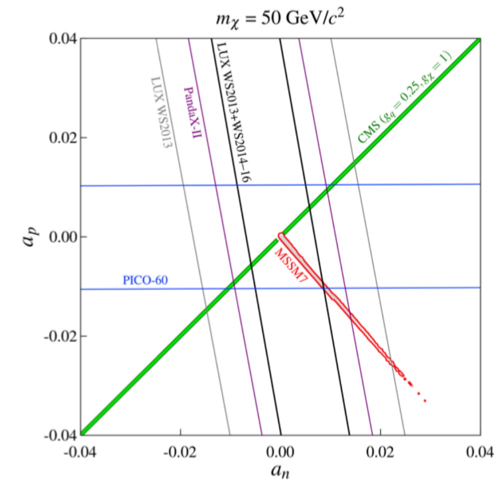


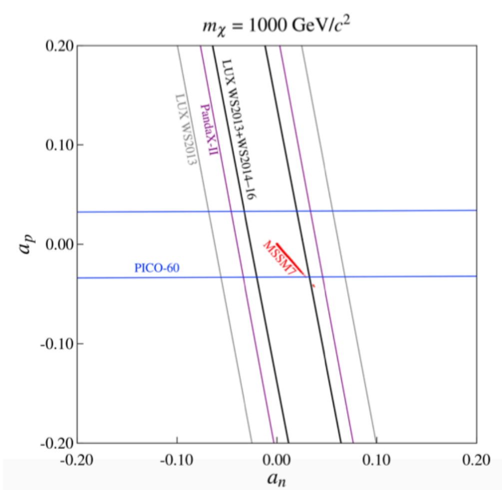
WIMP spin-spin interaction (axial-vector coupling): best when there is an odd number of nucleons under study in nucleus

PRL 118, 251302

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)

(But still missing is EFT: more possible couplings)

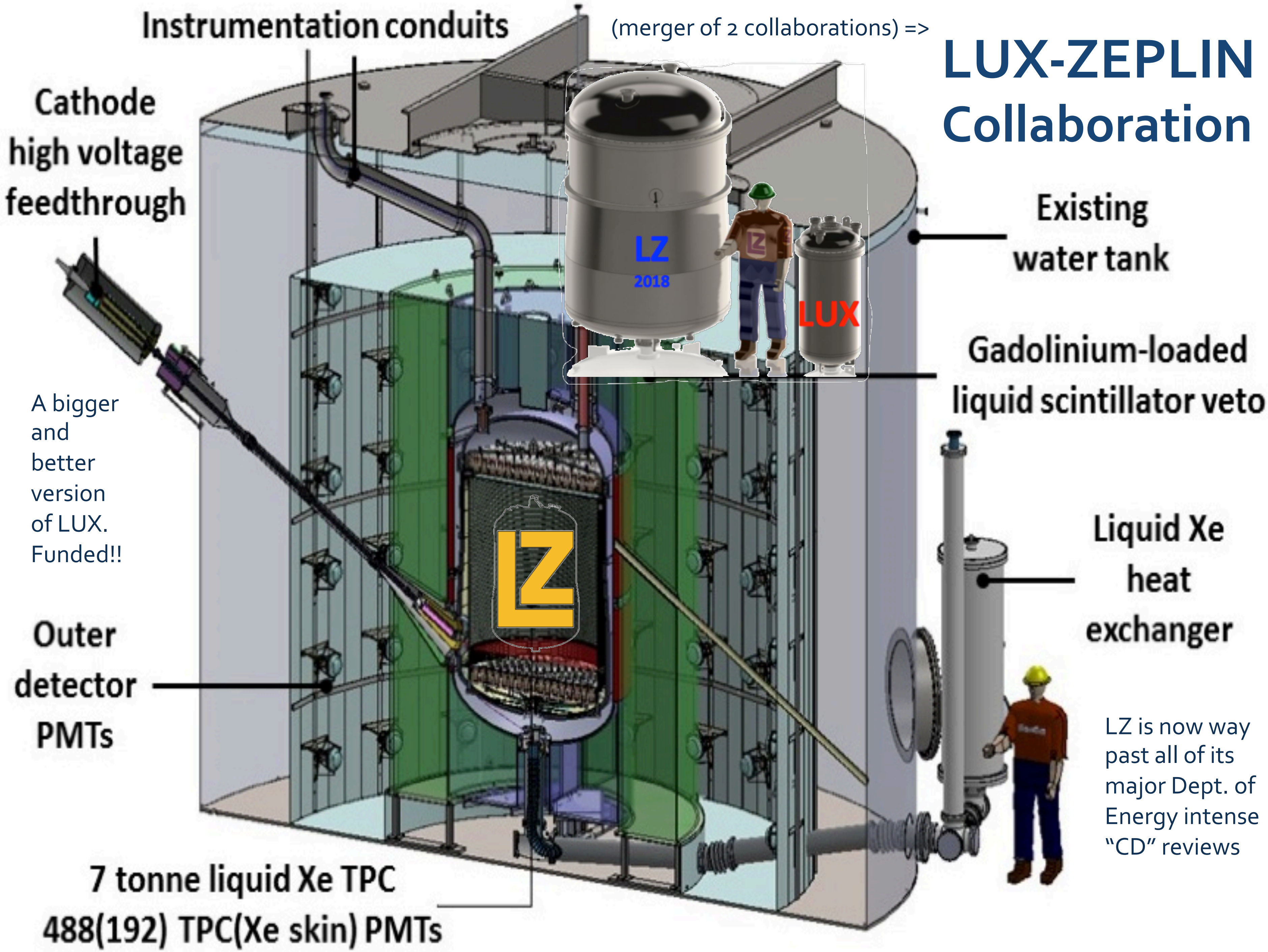




*Exception = IceCube

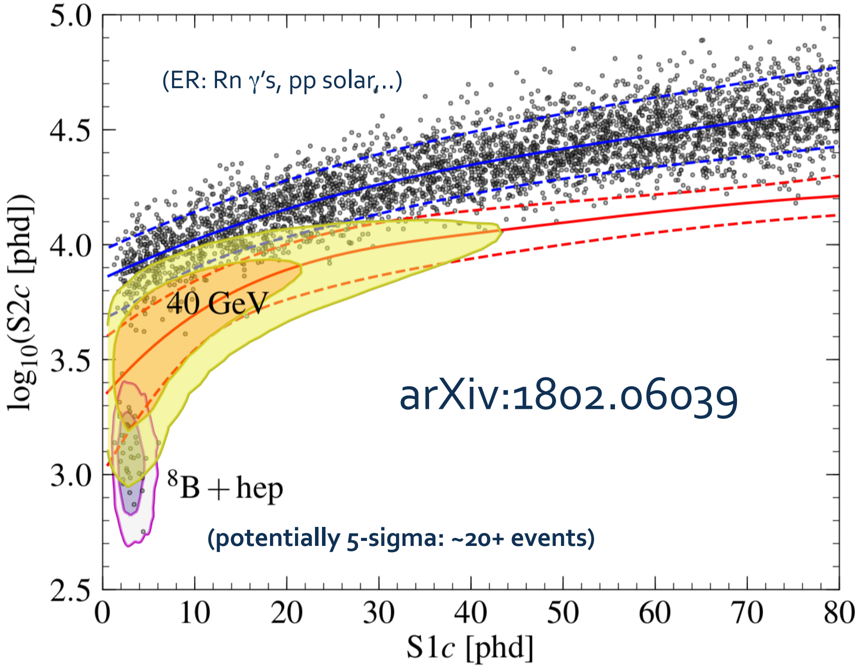
LUX-ZEPLIN Collaboration

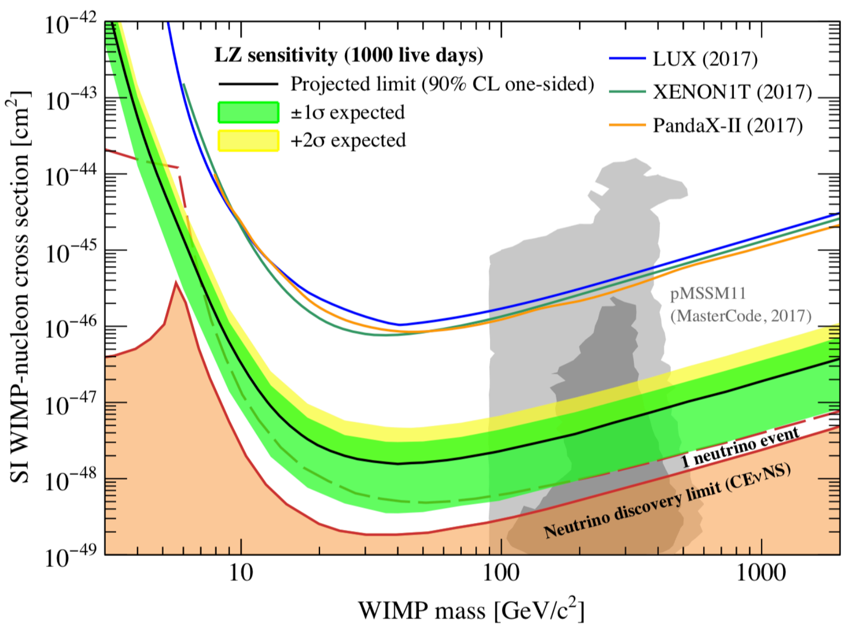
(merger of 2 collaborations) =>



A bigger and better version of LUX. Funded!!

LZ is now way past all of its major Dept. of Energy intense "CD" reviews





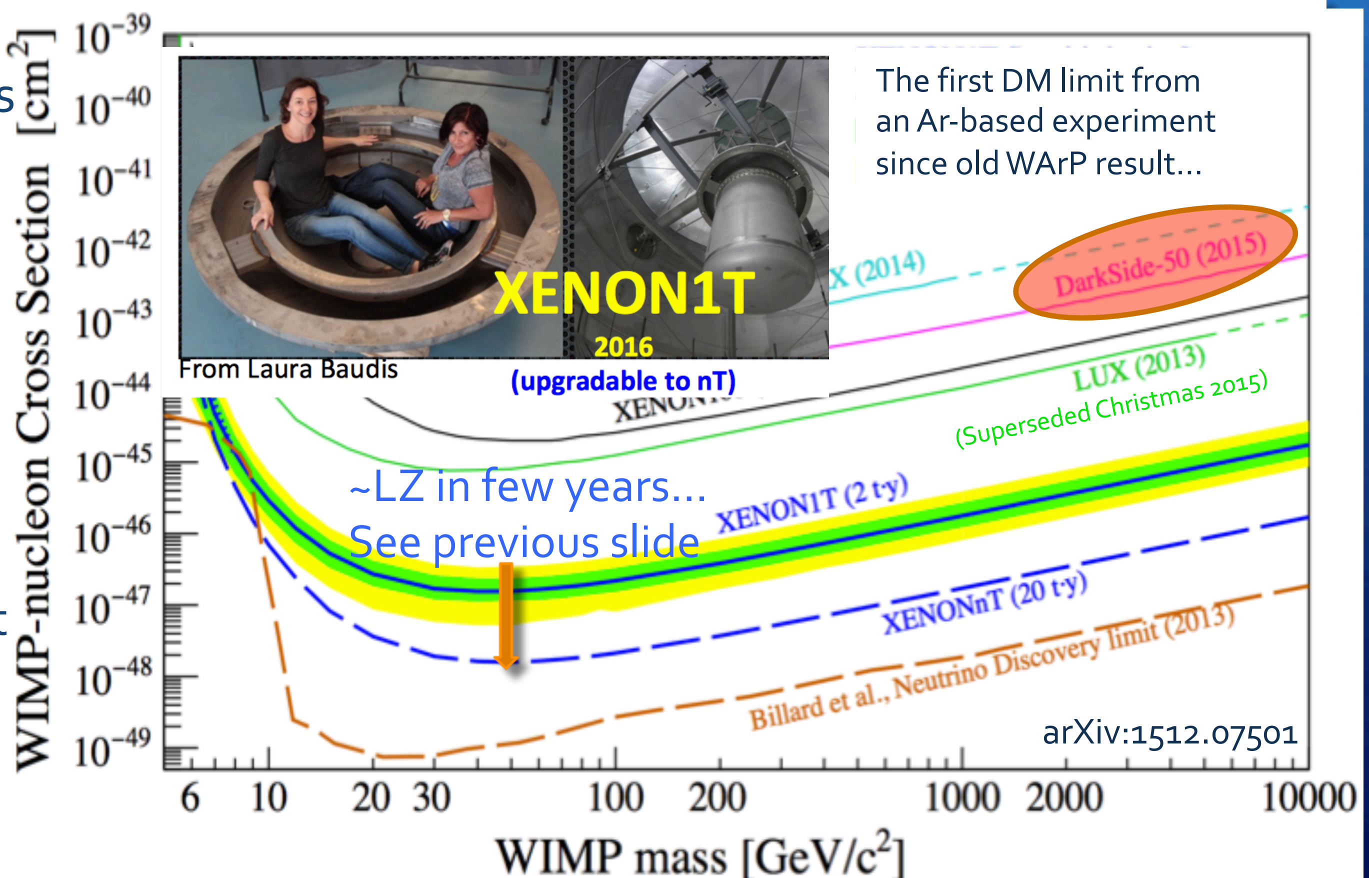
Projected Results

- Turning on by the end of the decade: LUX-ZEPLIN (LZ)
  - Follows after 400+-live-day LUX definitive result last year
- Planning on 3 live-years' data at least with ~5.6-ton fiducial mass
- *O*(10) times more sensitive than present-day best results (p. 11)
  - 2×10^{-48} cm^2 or better @40 GeV
- arXiv:1703.09144 TDR post CDR
- Multi-faceted machine: WIMPs, axions, neutrinoless double-beta decay, solar neutrinos (including coherent scattering)

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

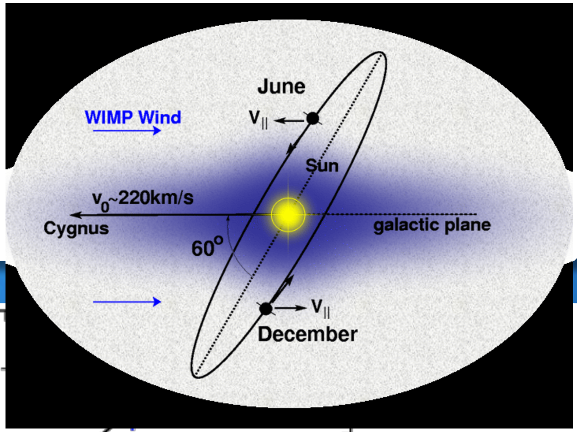
(sensitivity is now a real limit for XENON1T)

- See XENON1T (world-class results that beat LUX) followed by XENONnT in Italy. Turning on!
- Panda-X in China
  - Appears better at lower mass (due to different assumptions!)
  - Leap-frogging
- The competing experiments using same technology

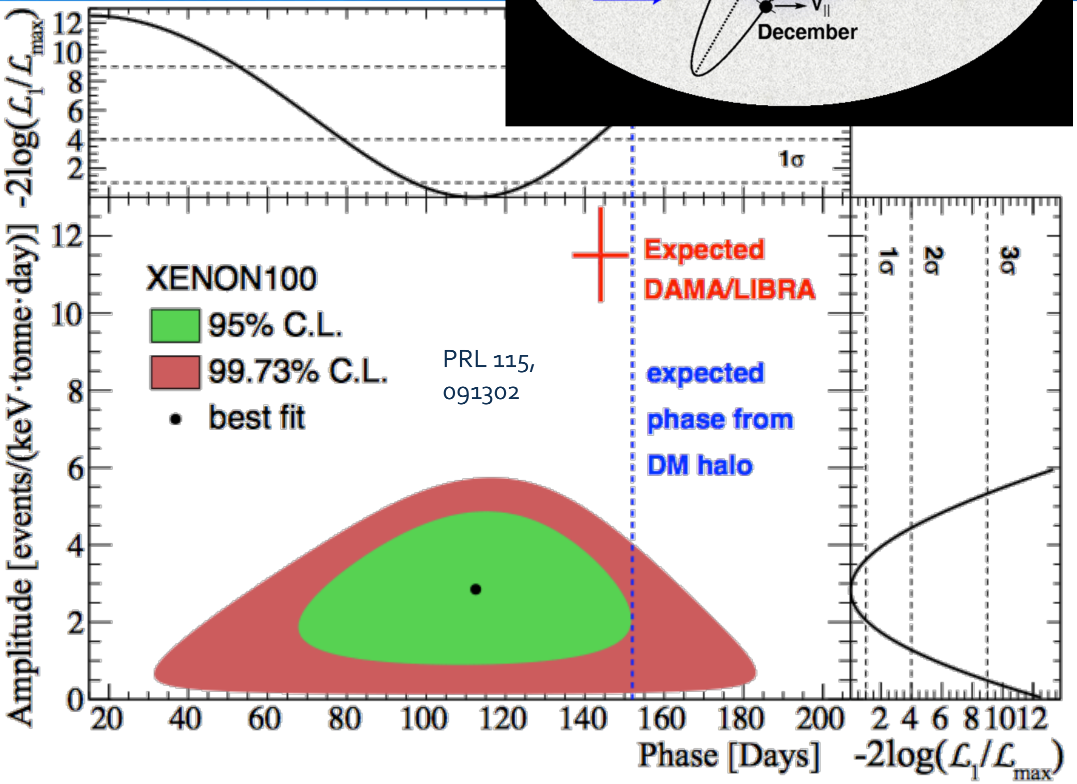


Note: DarkSide 2-phase Ar standard, less good @low mass but intrinsically lower ER leakage (PSD) than Xe -- catch-up

XENON100 Annual Modulation Result (ER) (LUX result coming soon, w/ diurnal)



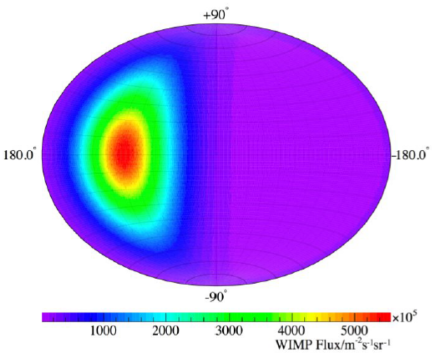
- DAMA/LIBRA signal just keeps getting re-killed (but returning)
- Killed for SI (LUX is latest), killed for SD-p (COUPP), killed for SD-n (XENON100, LUX)
  - Channeling not it
  - COUPP, KIMS have ^{127}I
- Killed for NR (LUX, others), and killed for ER (XENON100 best)



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

(slide blatantly stolen from Cecilia Levy)

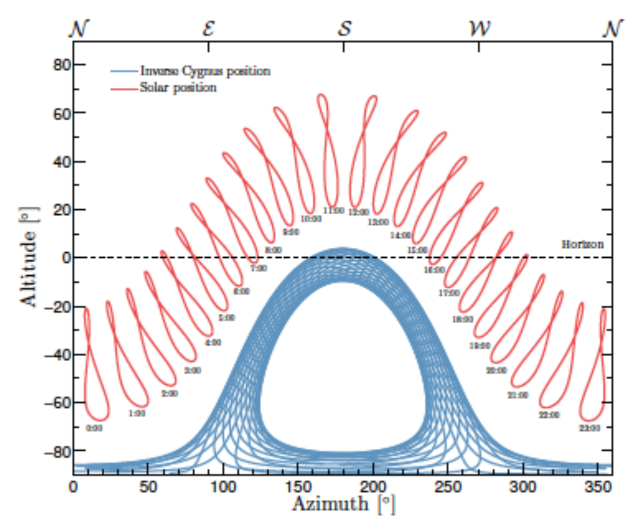
Directional Dark Matter

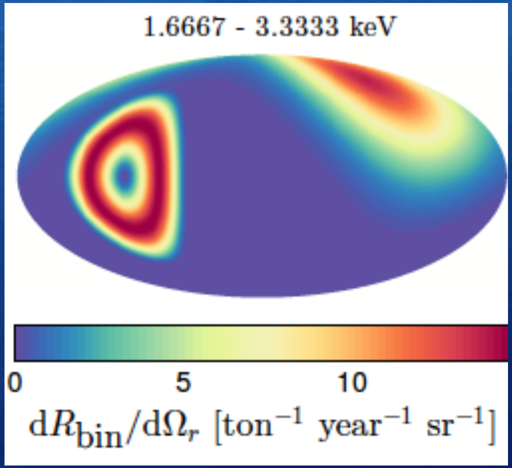


Ahlen et al. arXiv:0911.0323 (2009)

<u>**Directionality**</u>: only known way to get through the neutrino floor
⟶ looks at the direction of the incoming particle
⟶ has already been proposed to detect DM
⟶ interesting idea, but never successful because not competitive enough

DM comes from the direction of the Cygnus constellation (direction of solar motion)
Solar neutrinos come from the Sun



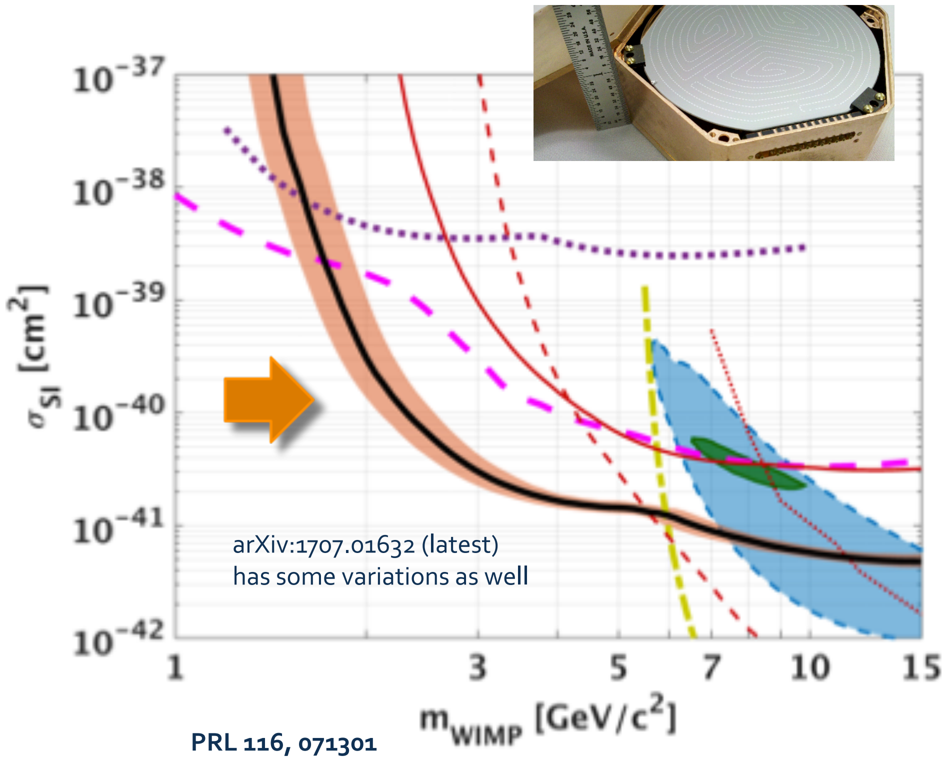


- ✧ Unfortunately directionality **only useable in gas detectors** (length of electron tracks)
- ✧ But gas is too light ⟶ will never reach the neutrino floor

O'Hare et al arXiv:1505.08061 2015

✦ Yes, one **can differentiate** between WIMPs and neutrinos

CDMS, CDMSlite, SuperCDMS: Ge, Si

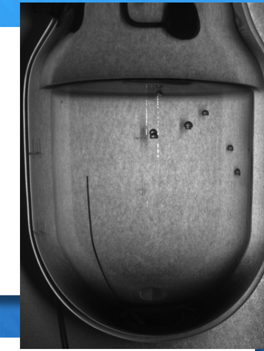


PRL 116, 071301

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 + EU)
- 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



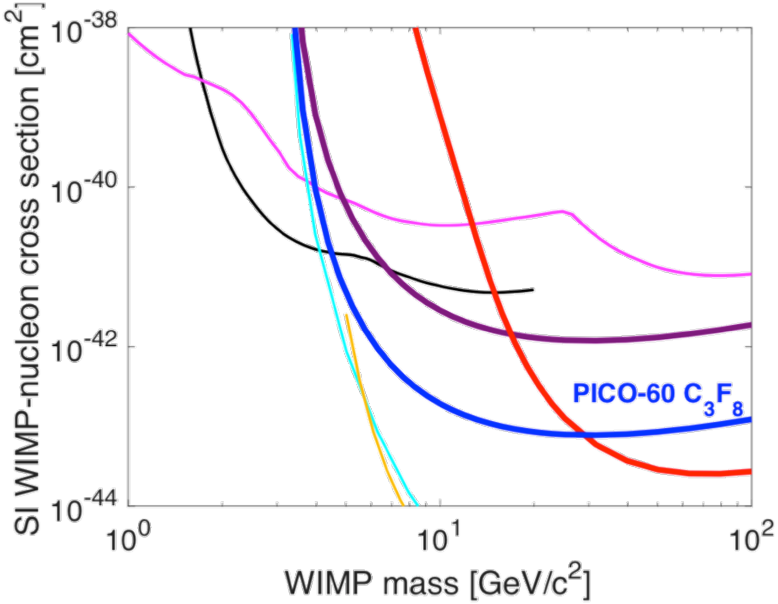
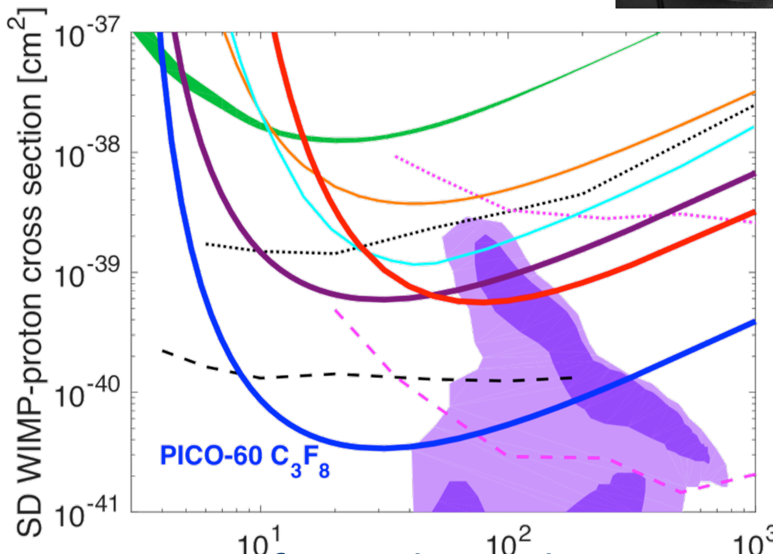


FIG. 4. The 90% C.L. limit on the SI WIMP-nucleon cross-section from PICO-60 C_3F_8 plotted in thick blue, along with limits from PICO-60 CF_3I (thick red) [10], PICO-2L (thick purple) [9], LUX (yellow) [44], PandaX-II (cyan) [45], CRESST-II (magenta) [46], and CDMS-lite (black) [47]. While we choose to highlight this result, LUX sets the strongest limits on WIMP masses greater than 6 GeV/c^2. Additional limits, not shown for clarity, are set by PICASSO [14], XENON100 [41], DarkSide-50 [48], SuperCDMS [49], CDMS-II [50], and Edelweiss-III [51].

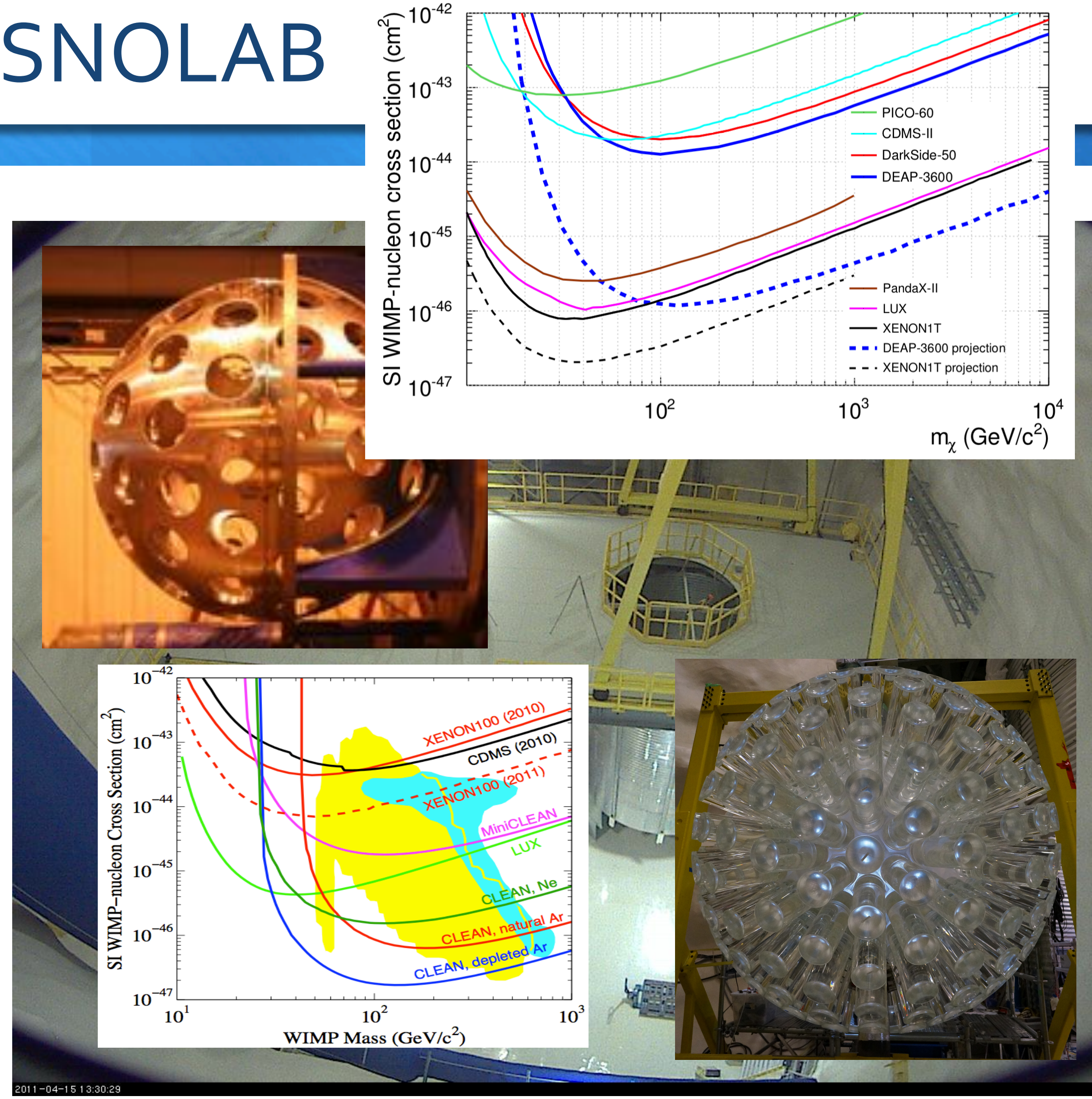
PRD 118, 251301



- King of spin-dependent proton
- Rapidly catching up on SI front especially at low mass
- No energy info, but ER-blind to highest degree of any experiment
- Future: 250-500 L or kg in works?

Down the Road -->DEAP and CLEAN, @ SNOLAB

Good to have another element's cross-check



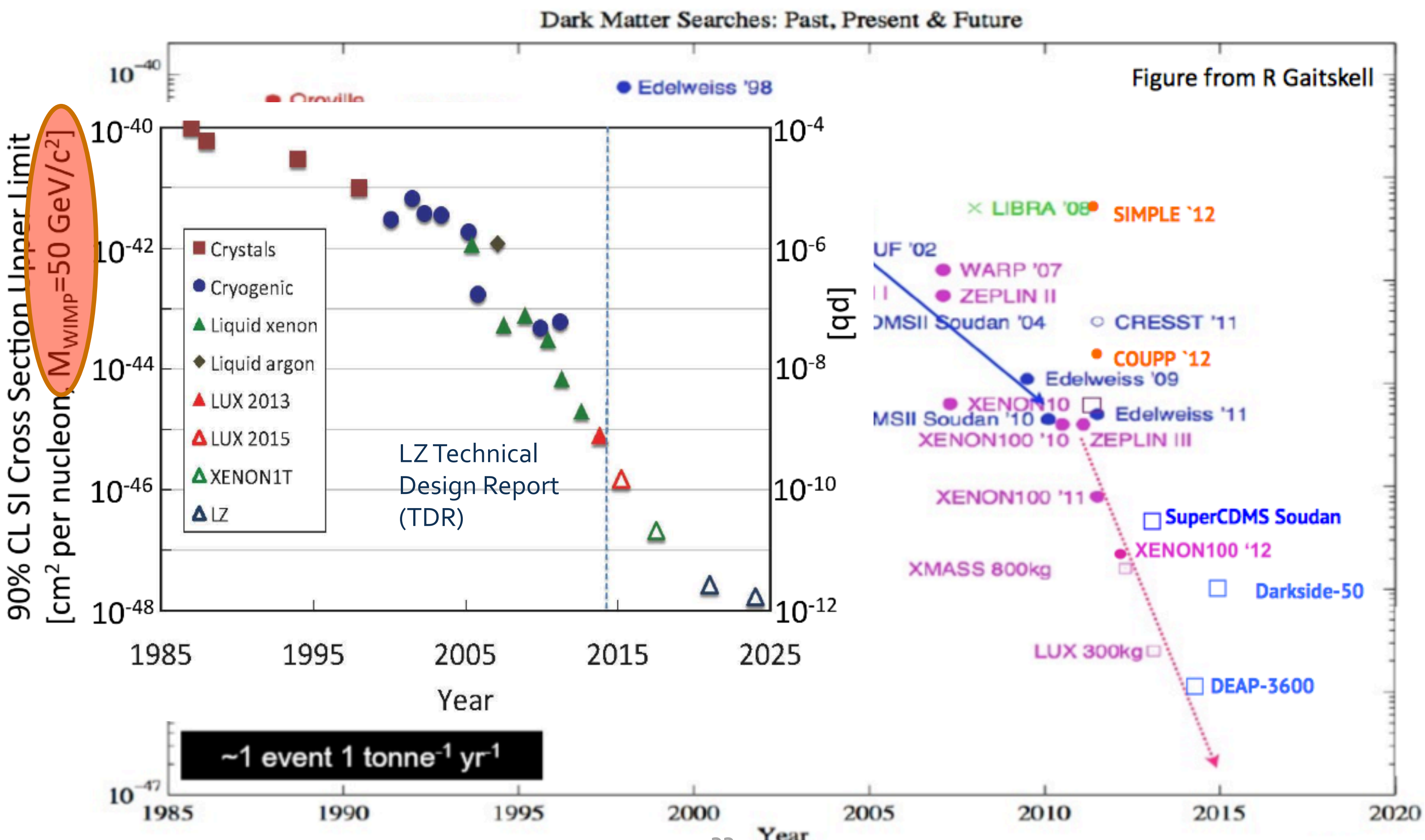
- Single-phase liquid argon with no E-field. miniCLEAN, DEAP-3600 deployed now, running
- Strengths
  - PSD better than S2/S1 discrimination by orders of magnitude
  - Argon = cheap
  - High mass WIMPs
- Weaknesses
  - Argon not dense, so less self-shielding
  - Underground Ar more expensive (~~^{39}Ar~~)
  - 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/SENSEI: Putting the extreme in extremely low threshold, O(10) eV!! Uses CCDs. Not world BEST, 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."

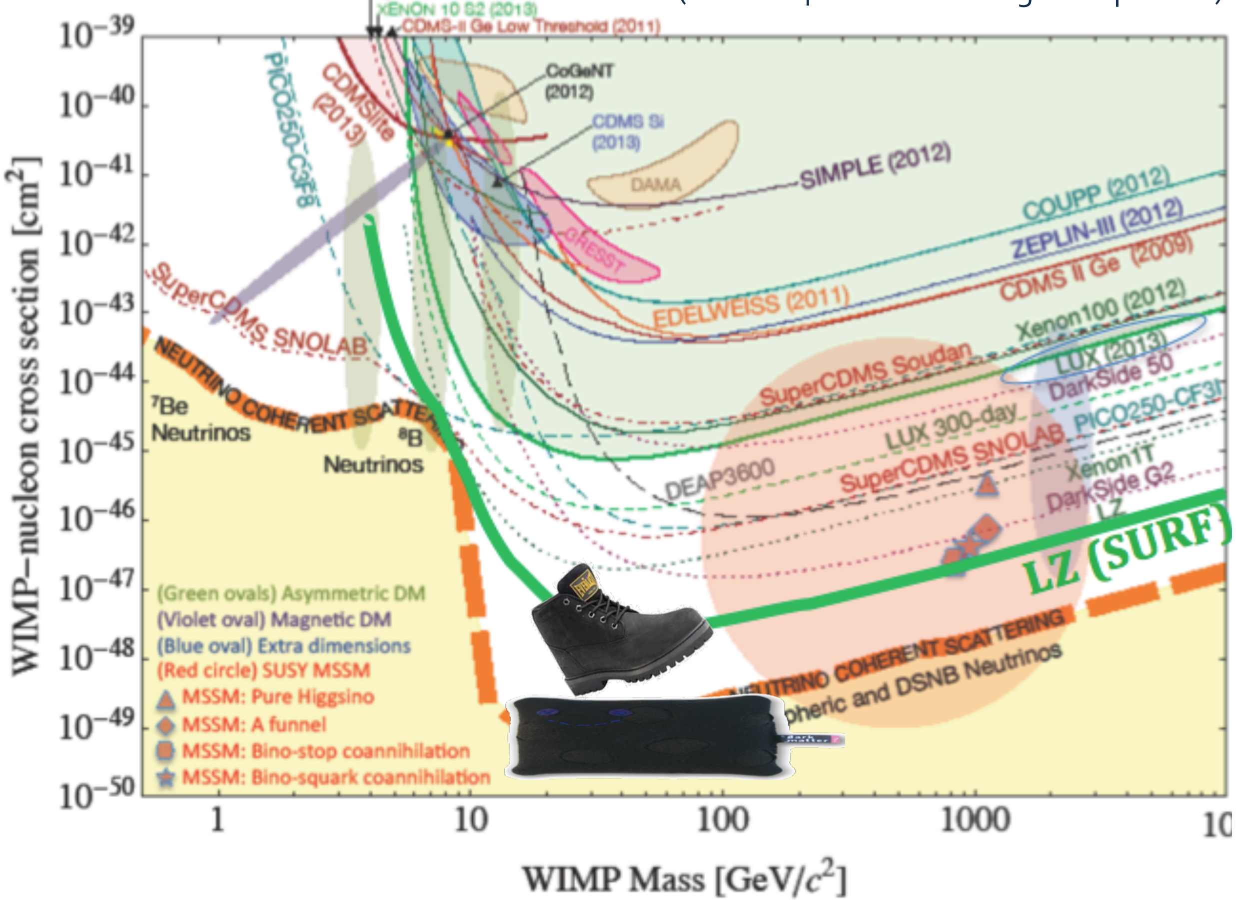
Game of Thrones or Hunger Games

Past, Present, and Future Trending



The Famous Busy SNOWMASS Plot

(LUX 2014-16 et al. missing since plot old)

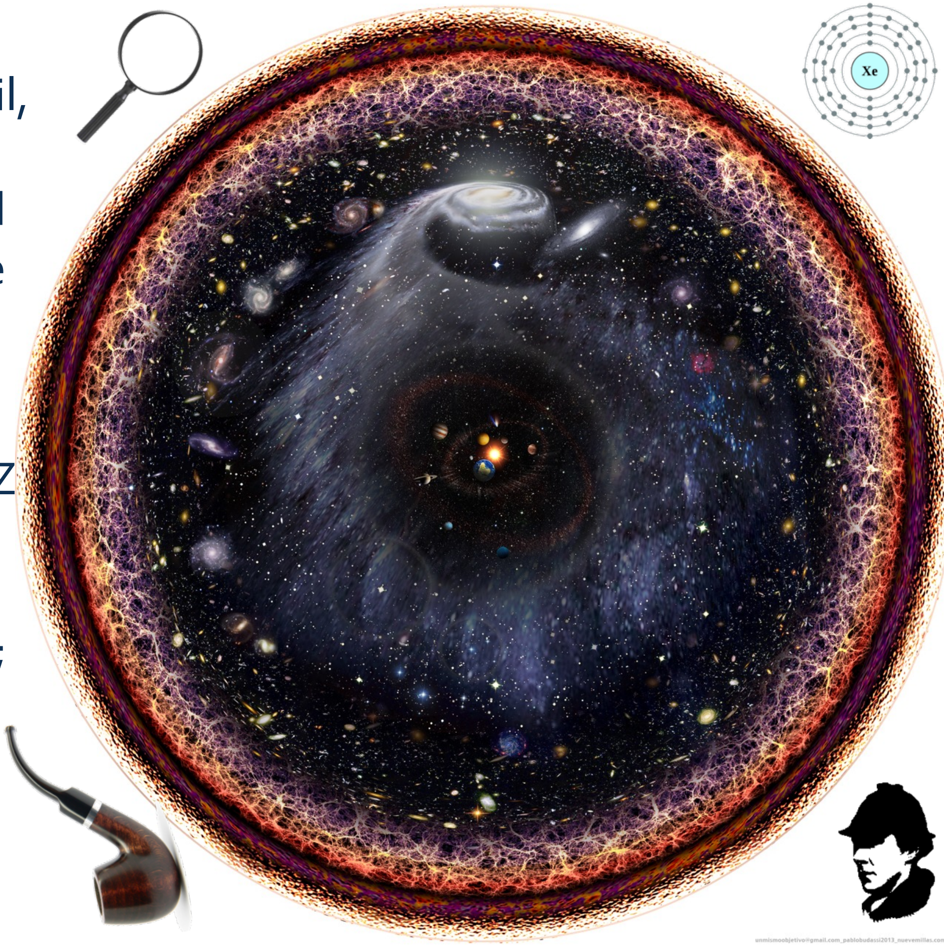


- Almost obligatory ☺
- Not ignoring the extremely competitive XENON1T / nT (see earlier slides) but are not present here
  - Because not a part of Snowmass nor DOE G2 down-selection processes
  - Also too new as well
- Low-mass region is kind of lonely, but between LZ and SuperCDMS covered
  - And, 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

* US SuperCDMS, LZ G2; Europe XENON, CRESST; Canada PICO, DEAP/CLEAN; China Panda-X, CDMX; others all in next-gen game. Experiments like COSINE test DAMA



* 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 (Dahl), ionization limit in semi-conductors, and single-photon limit in scintillators

- Thank you for your attention
- (Note that my license plate is *element* not experiment)

Hopefully, we are all looking for dark matter in ALL the places that we can