LZ Electron Recoil Calibrations & NEST-Based Simulations

Matthew Szydagis, UAlbany SUNY + LZ / NEST

UNIVERSITY AT ALBANY
State University of New York

CPAD Workshop 2022

LZ (LUX-ZEPLIN) Collaboration

35 Institutions: 250 scientists, engineers, and technical staff

@lzdarkmatter

https://lz.lbl.gov/

- Black Hills State University
- Brookhaven National Laboratory
- Brown University
- Center for Underground Physics
- Edinburgh University
- Fermi National Accelerator Lab.
- Imperial College London
- Lawrence Berkeley National Lab.
- Lawrence Livermore National Lab.
- LIP Coimbra
- Northwestern University
- Pennsylvania State University
- Royal Holloway University of London
- SLAC National Accelerator Lab.
- South Dakota School of Mines & Tech
- South Dakota Science & Technology Authority
- STFC Rutherford Appleton Lab.
- Texas A&M University
- University of Albany, SUNY
- University of Alabama
- University of Bristol
- University College London
- University of California Berkeley
- University of California Davis
- University of California Los Angeles
- University of California Santa Barbara
- University of Liverpool
- University of Maryland
- University of Massachusetts, Amherst
- University of Michigan
- University of Oxford
- University of Rochester
- University of Sheffield
- University of Sydney
- University of Wisconsin, Madison

US UK Portugal Korea Australia

Thanks to our sponsors and to participating institutions!

U.S. Department of Energy Office of Science

UKRI Science and Technology Facilities Council

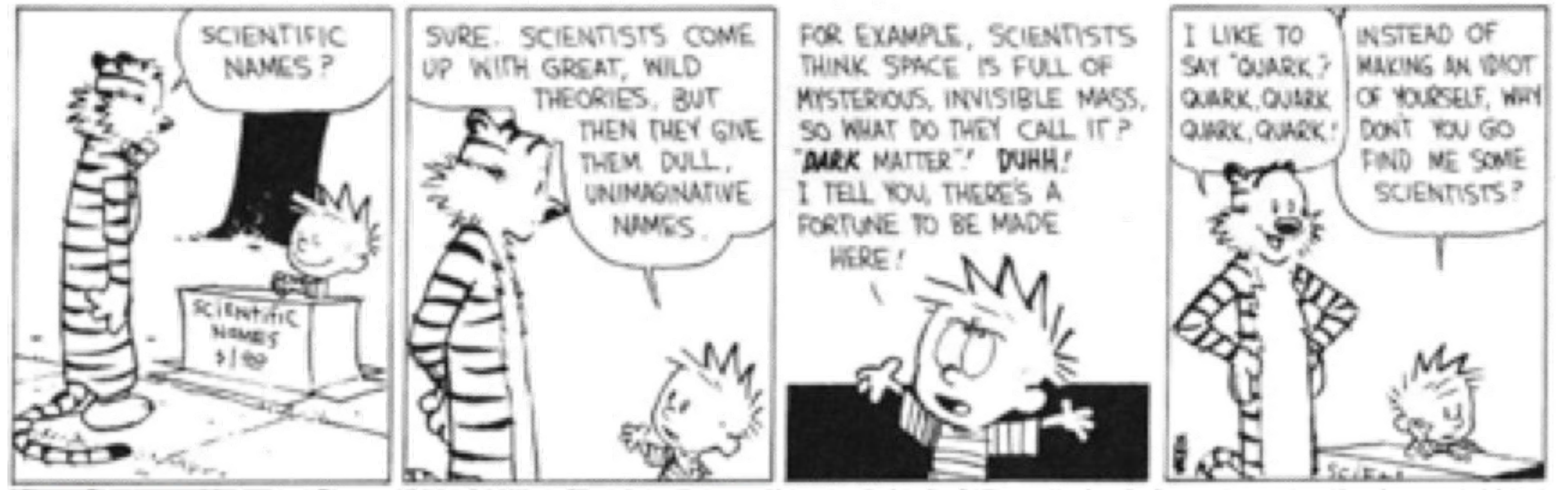
Sanford Underground Research Facility
South Dakota Science and Technology Authority

FCT Fundação para a Ciência e a Tecnologia
Ministério da Educação e Ciência

ibs Institute for Basic Science

Dark Matter

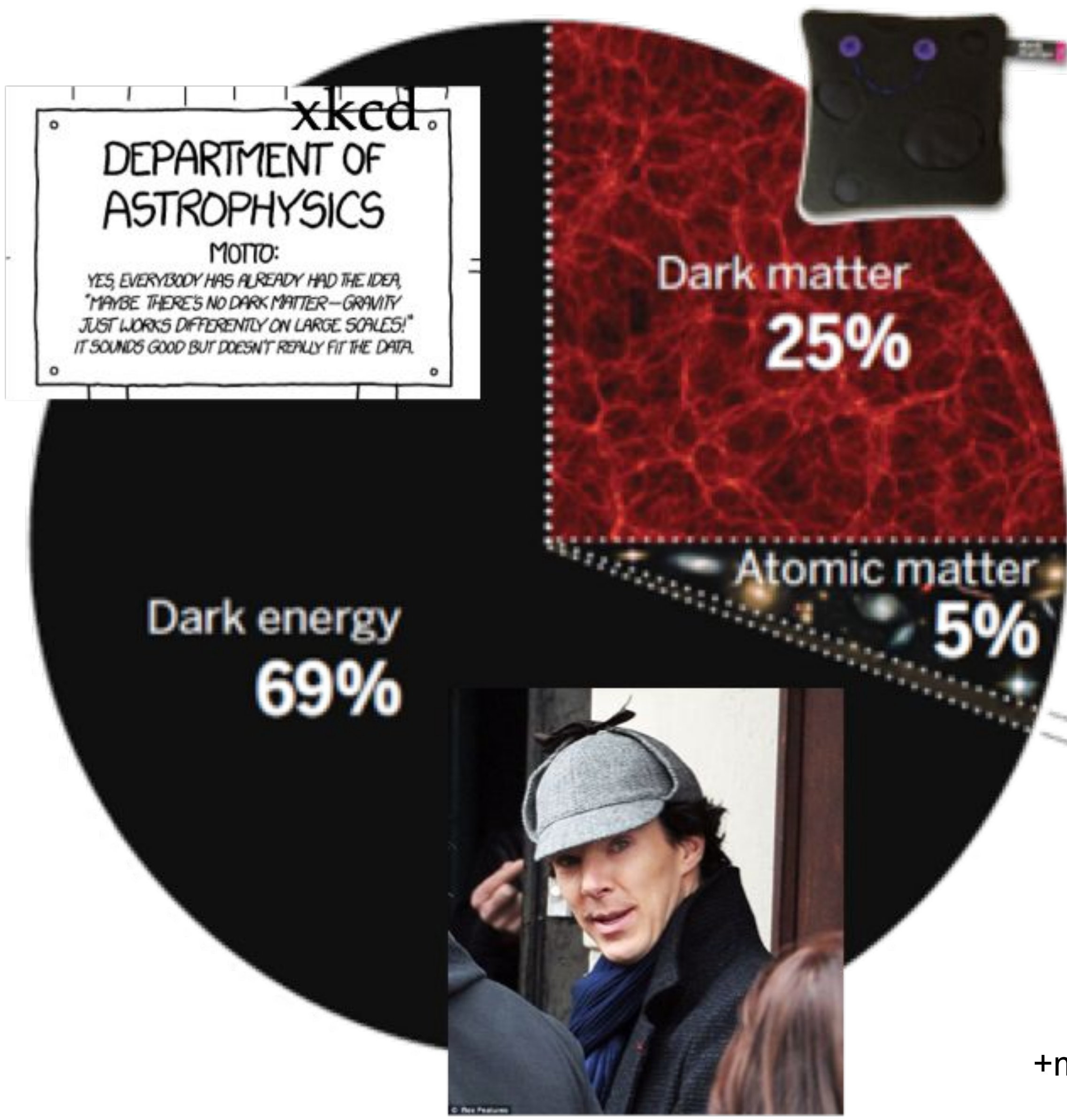
= ??????????



Calvin & Hobbes, by Bill Watterson

The multiple components that compose our universe

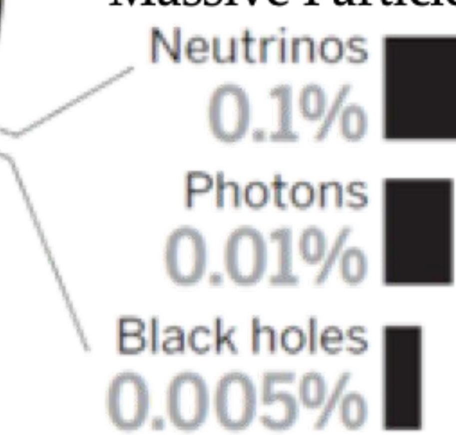
Current composition (as the fractions evolve with time)



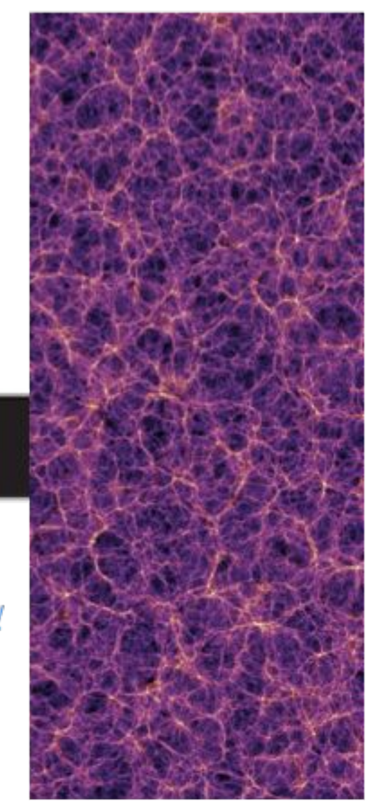
A Big Hole in Our Knowledge

What is this **dark matter?**

WIMPs? (Weakly Interacting Massive Particles)

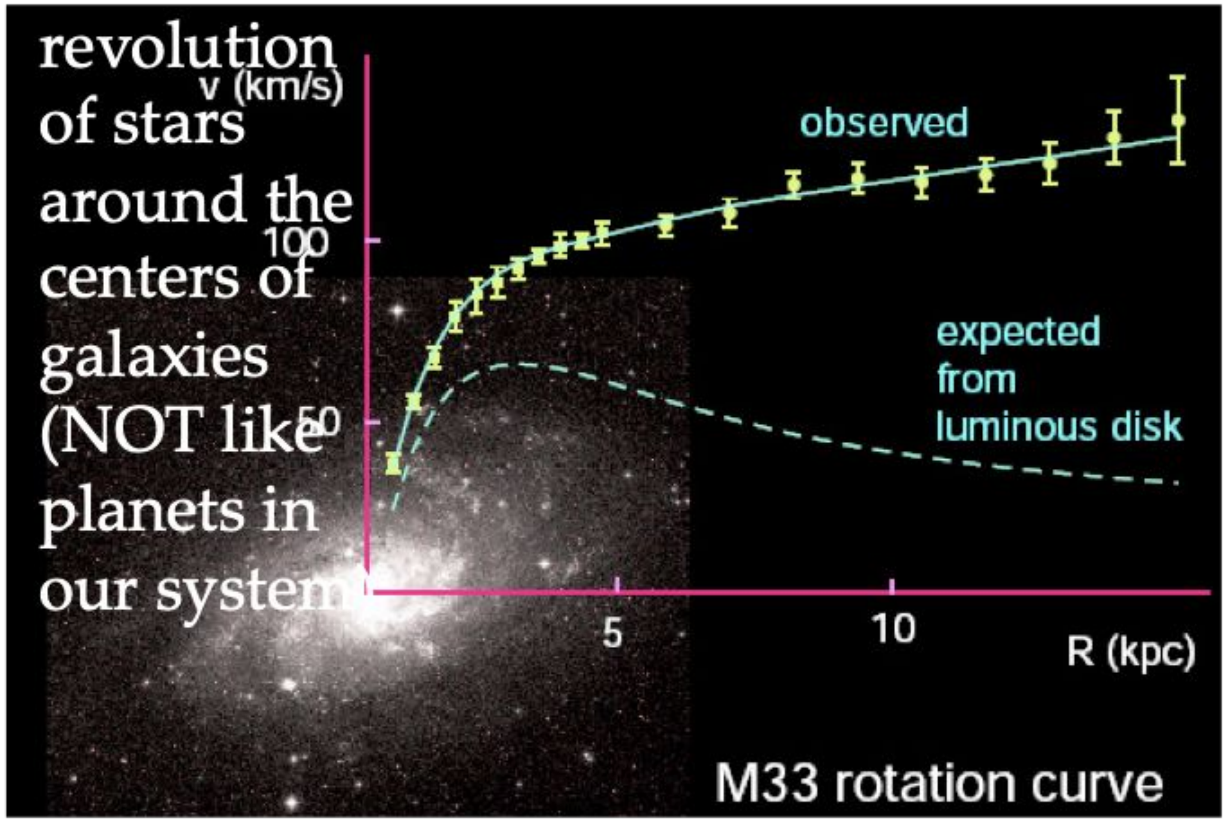


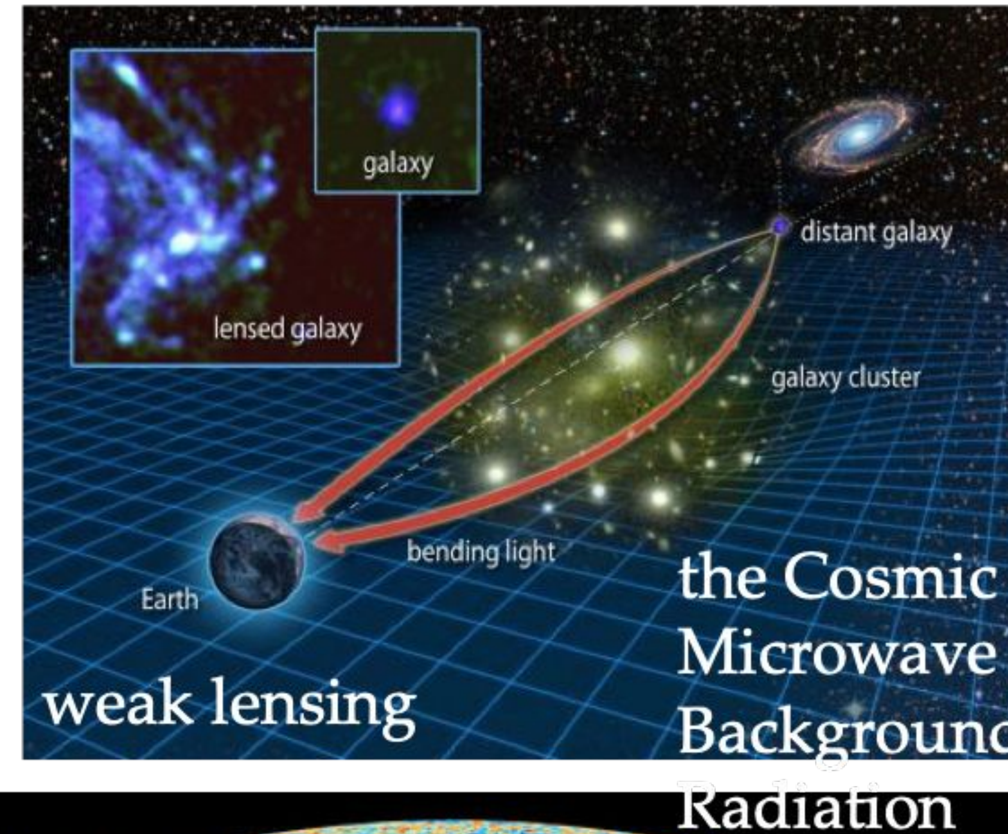
http://cdn.phys.org/newman/gfx/news/hires/2015/thedarksideo.png

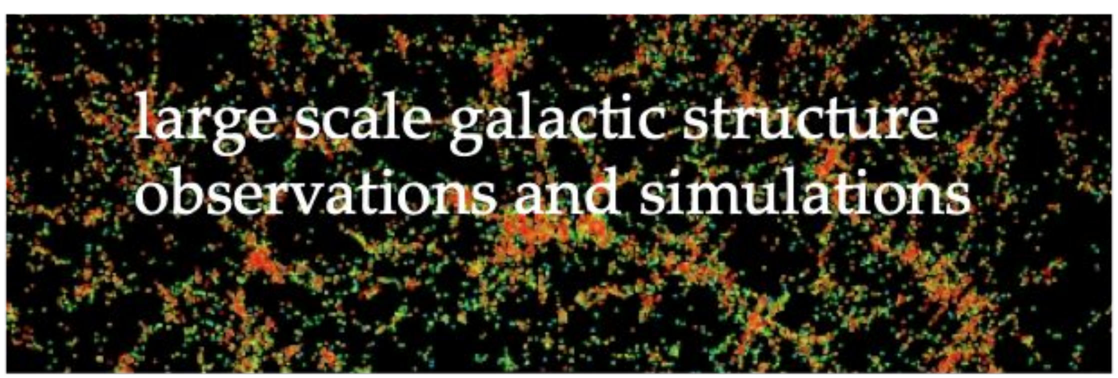


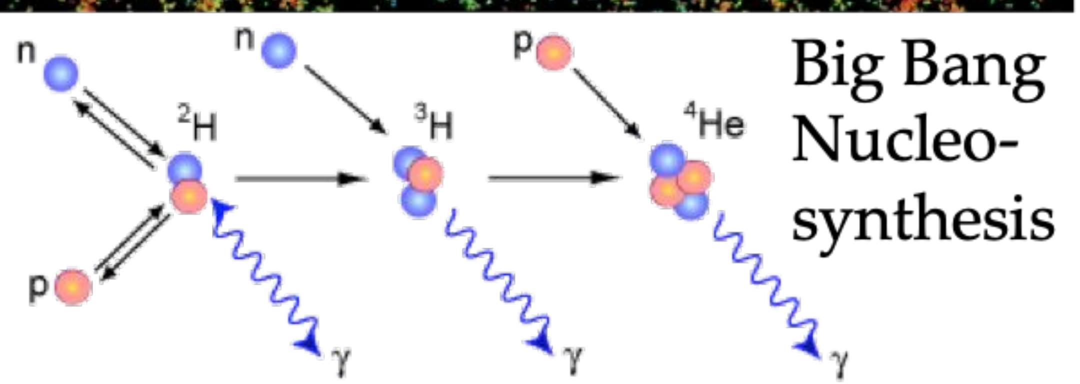
+more "dregs," (adding up to ~1%)

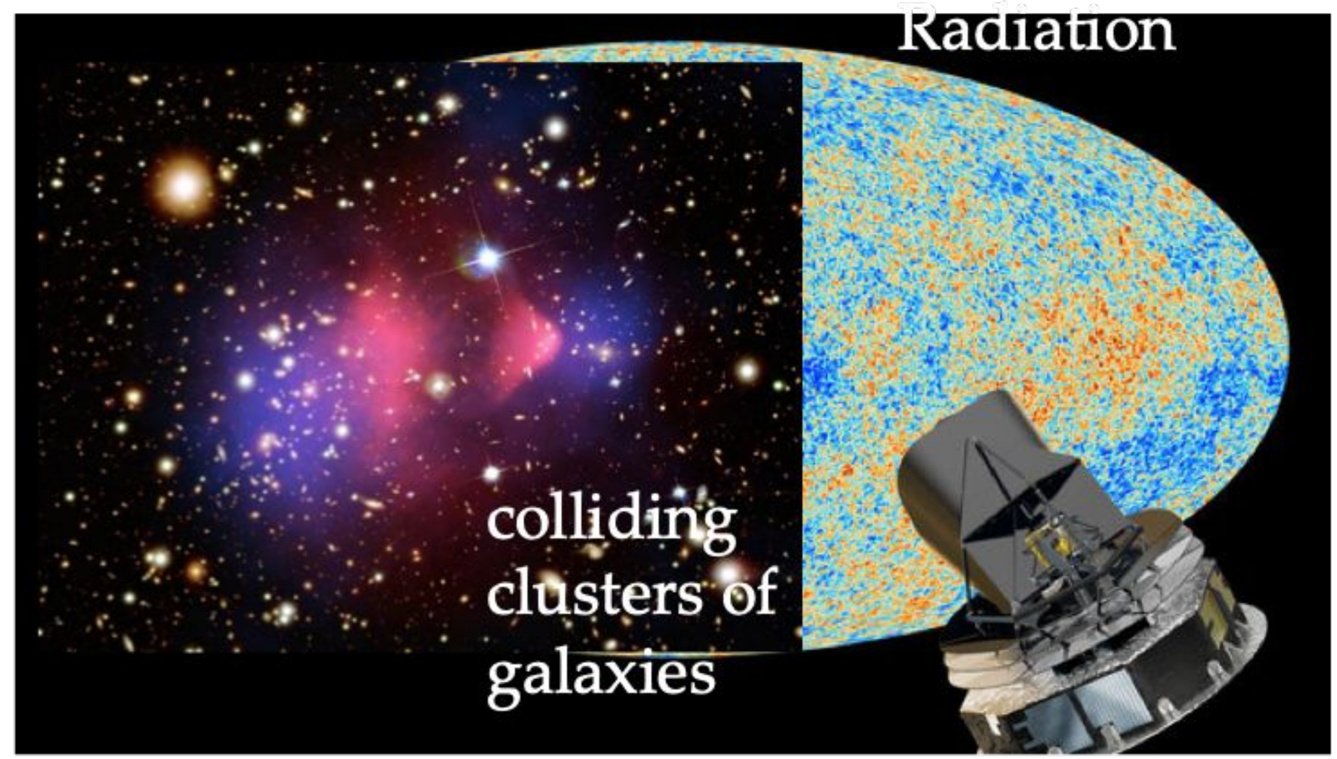
The Observational Evidence







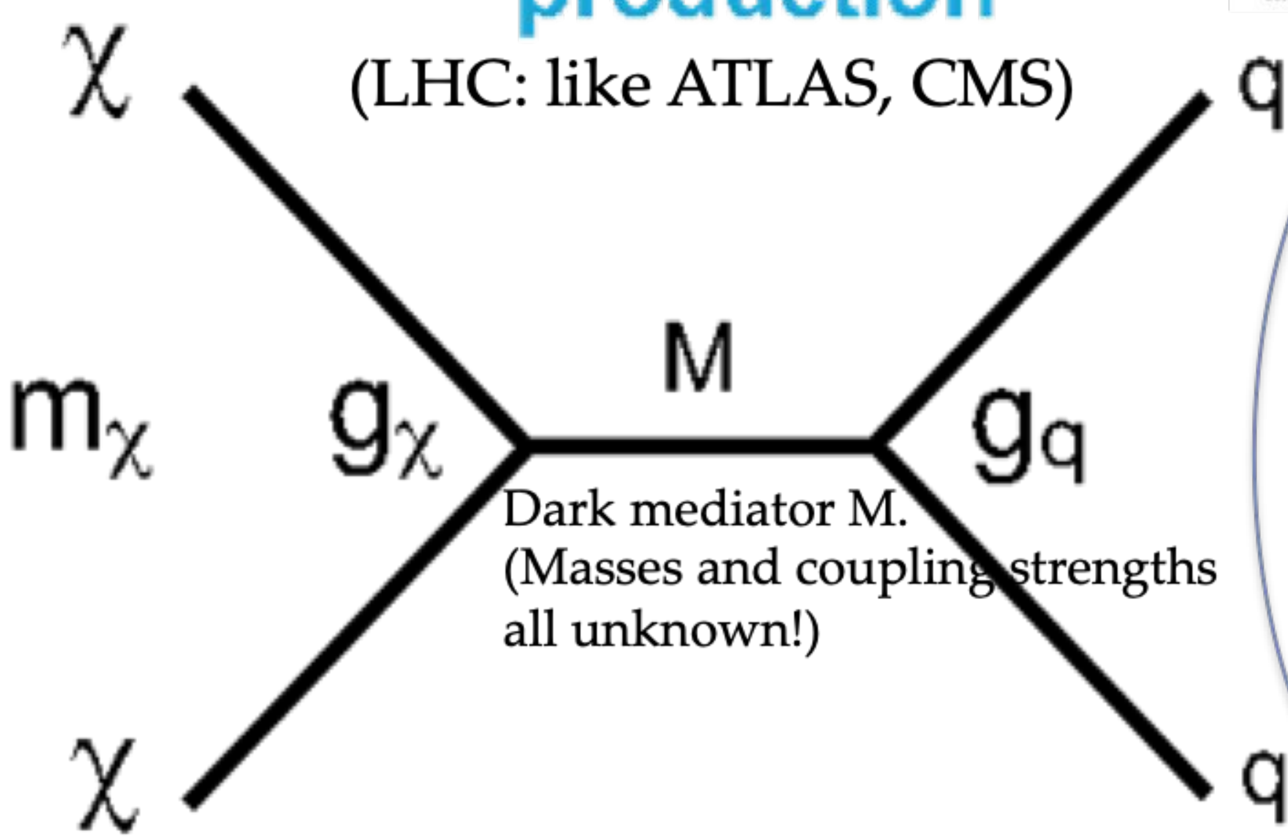




How to Look? Directly

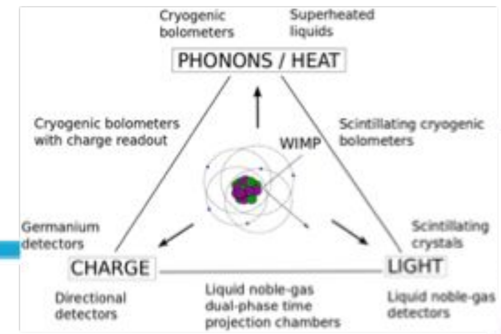
Collider production

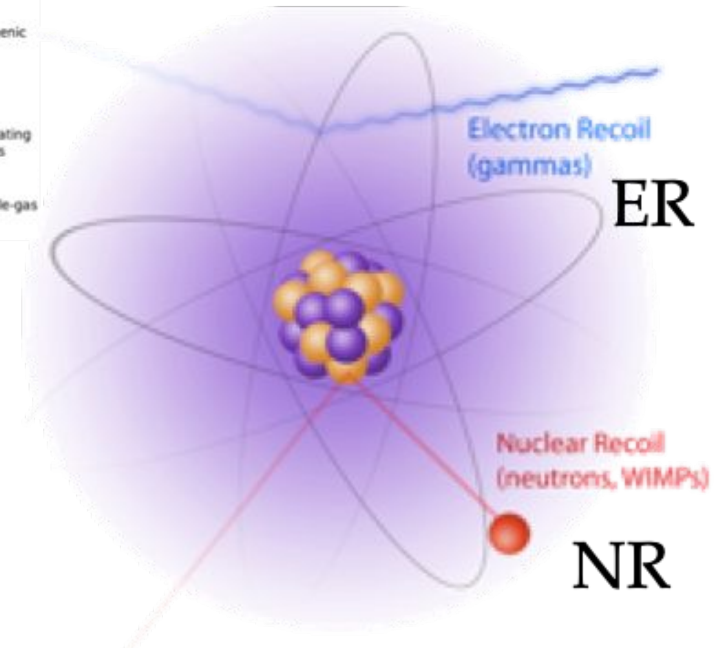
(LHC: like ATLAS, CMS)



Dark mediator M.
(Masses and coupling strengths all unknown!)

Direct detection



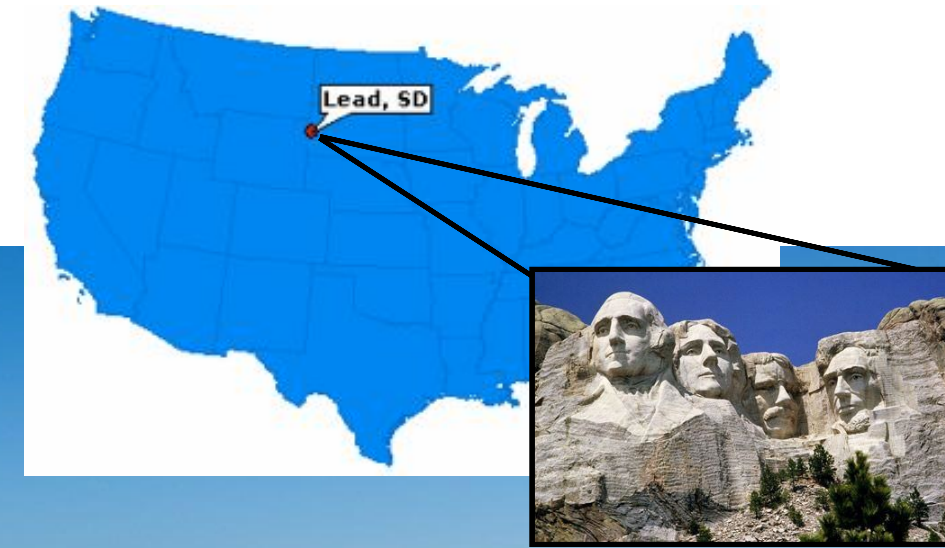


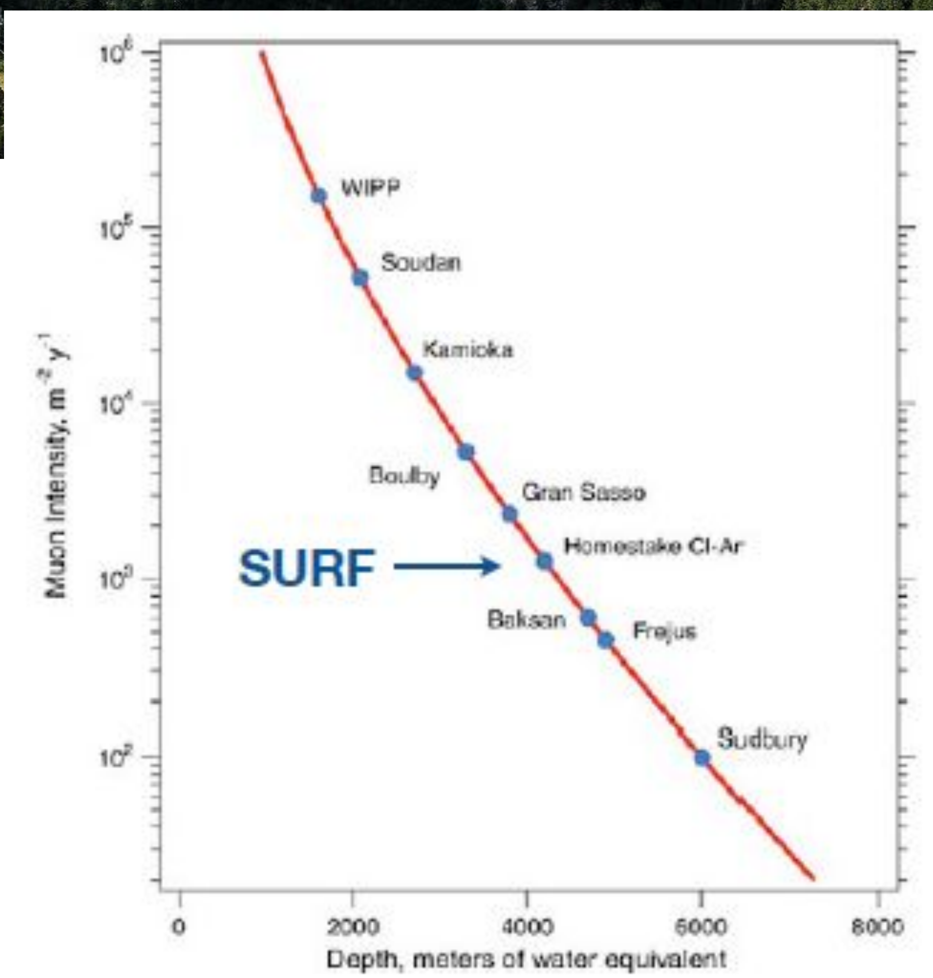
("billiard ball" collisions. Still need mediator. Higgs perhaps?)

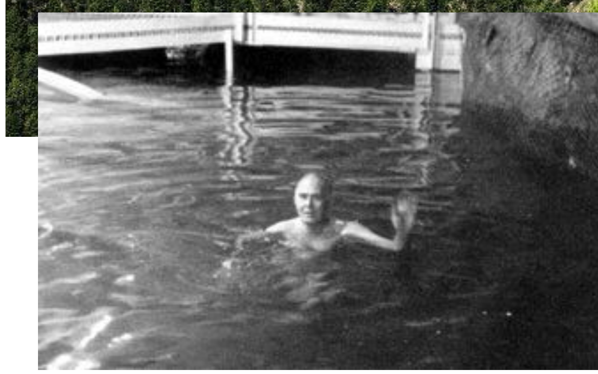
Freeze-out, indirect detection

(e.g., NASA! FERMI Telescope, AMS)

Sanford Underground Research Facility (SURF) in Lead, SD



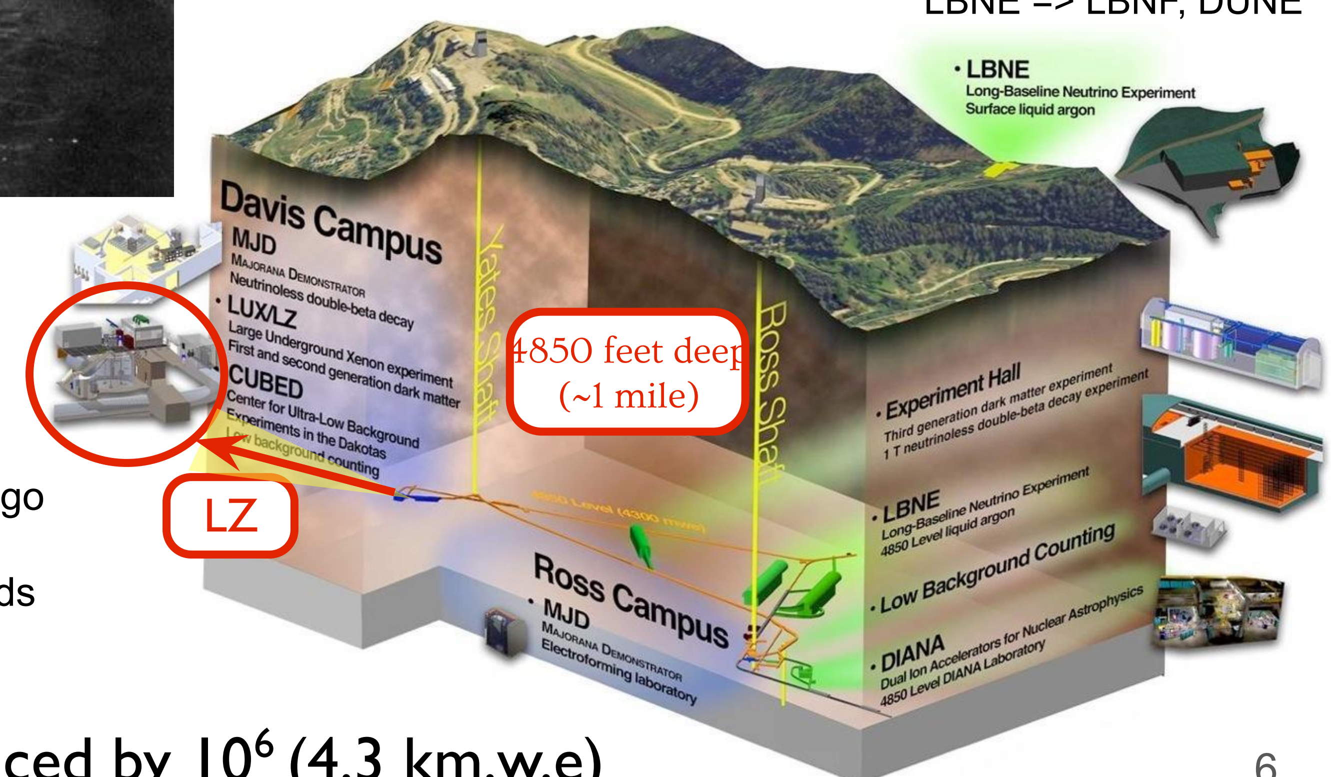




Ray Davis, nobel prize winner

Direct detection experiments must go underground to reduce backgrounds

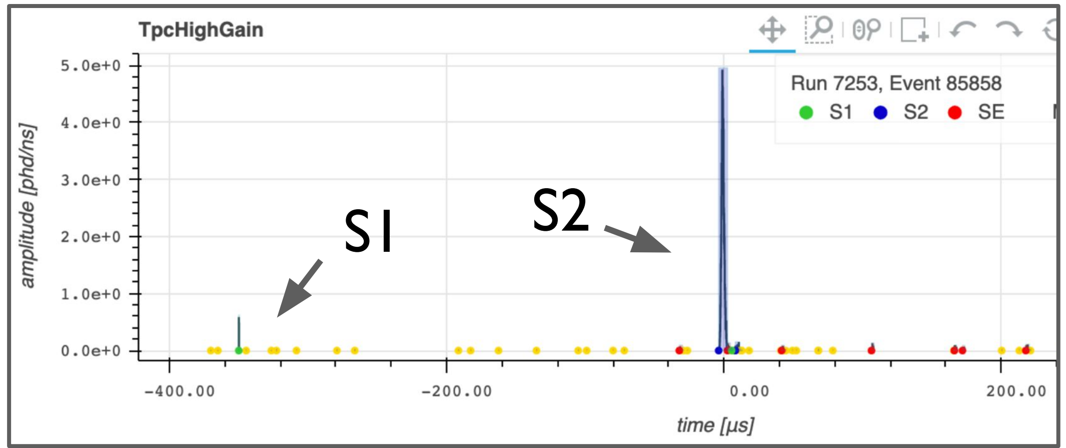
LBNE => LBNF, DUNE

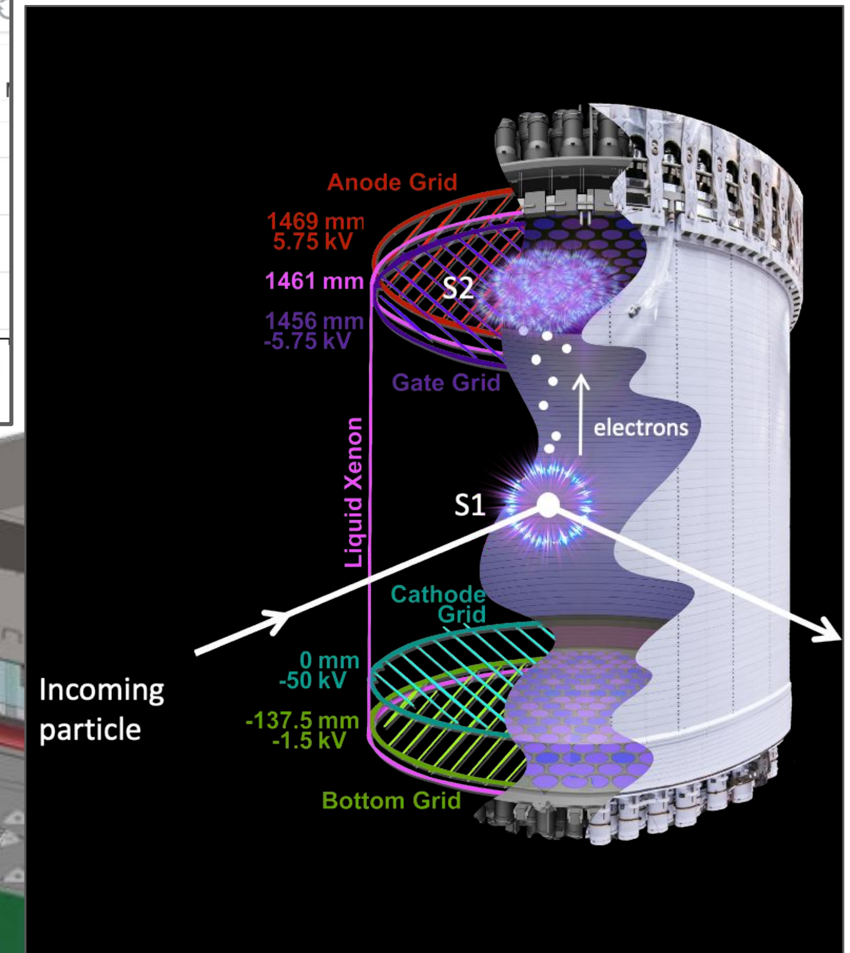


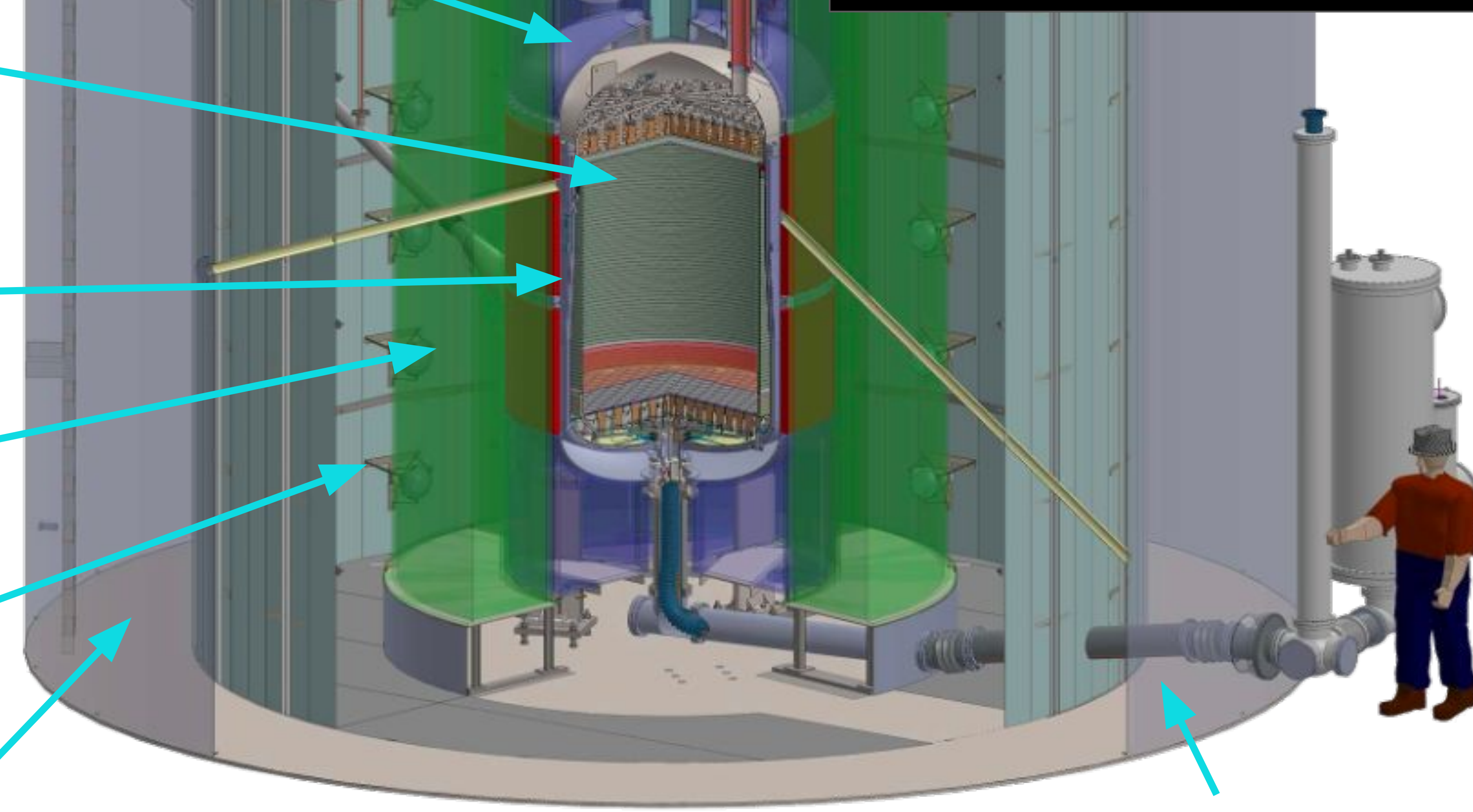
Muon flux reduced by 10^6 (4.3 km.w.e)

LZ Detector Overview

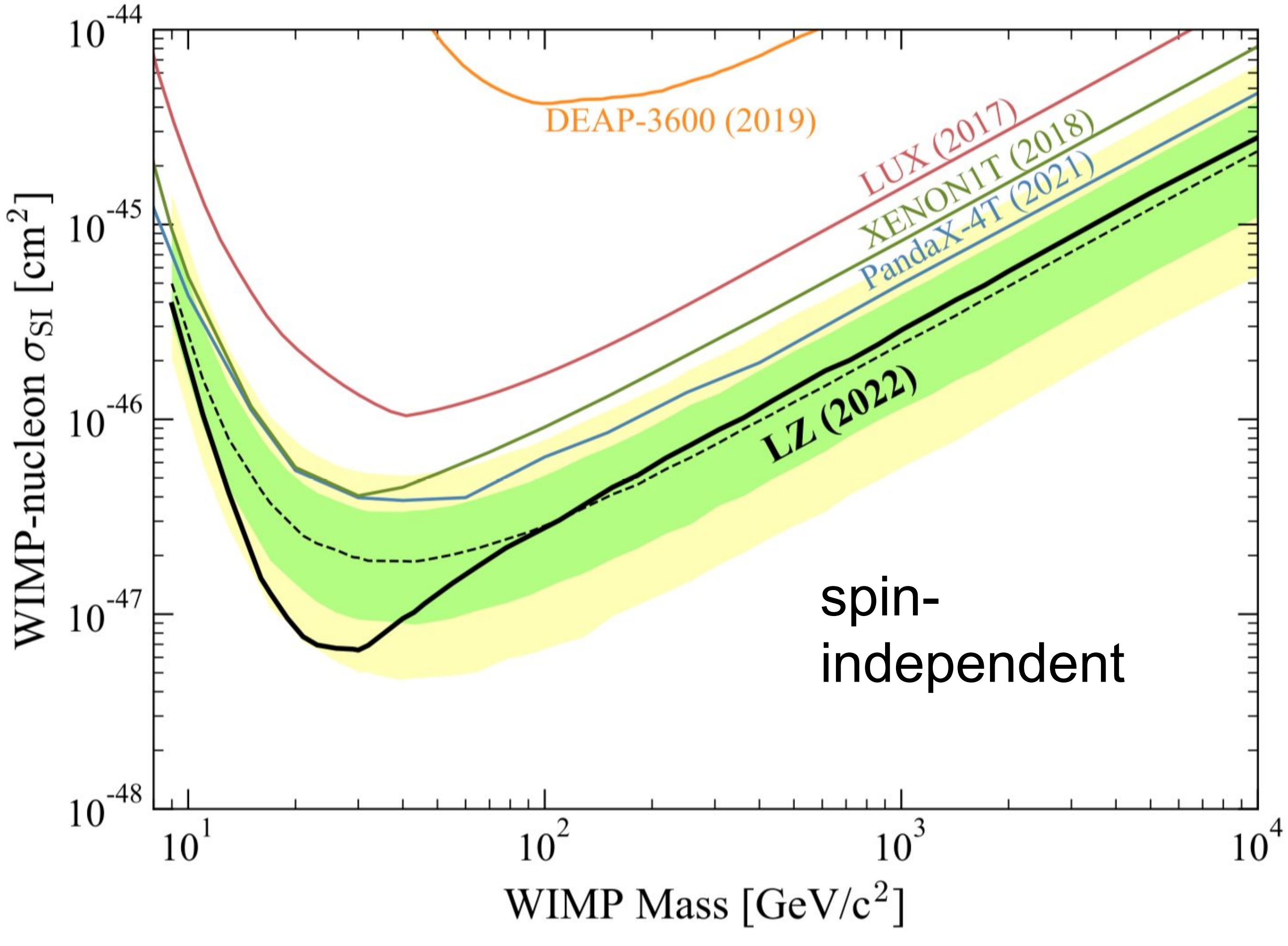
LZ detector design:
[NIM A, 163047 (2019)](#)

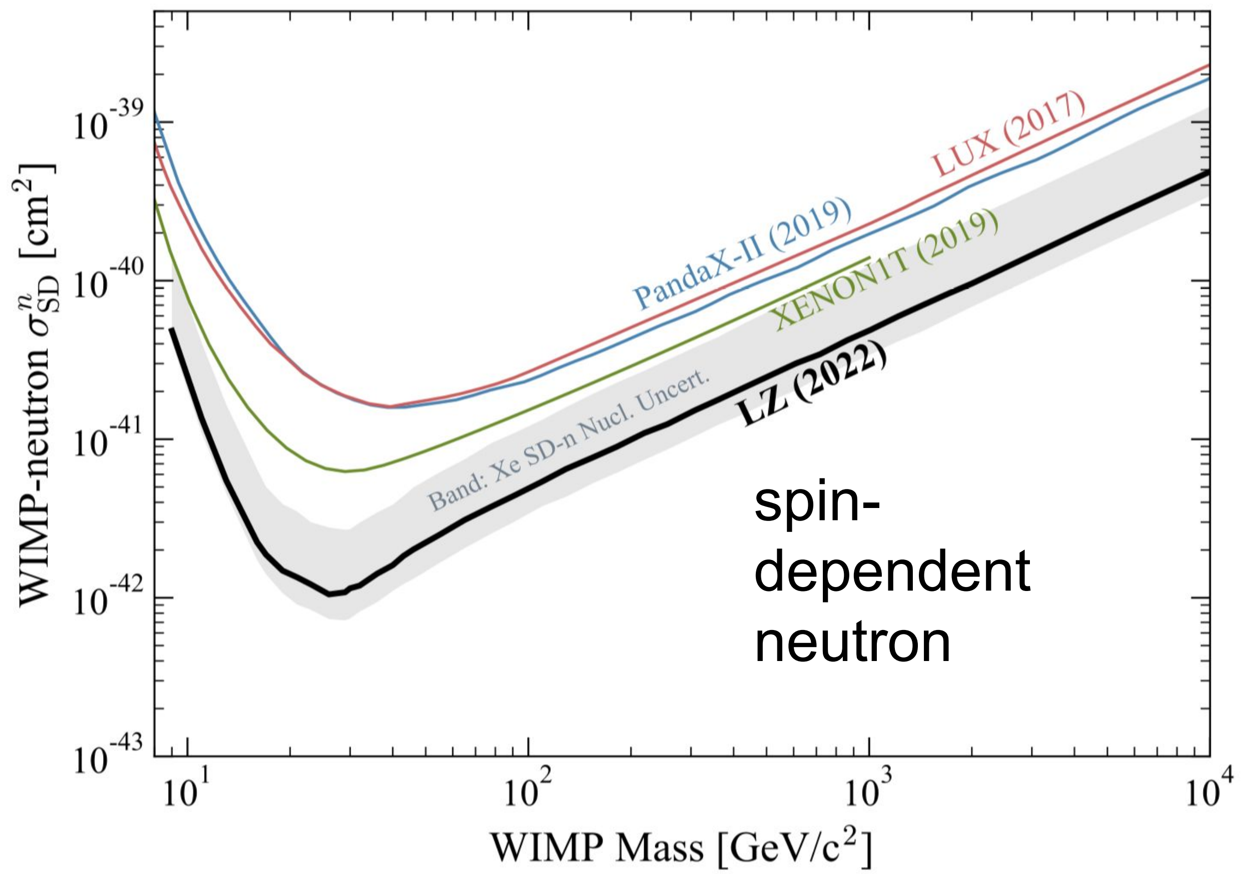


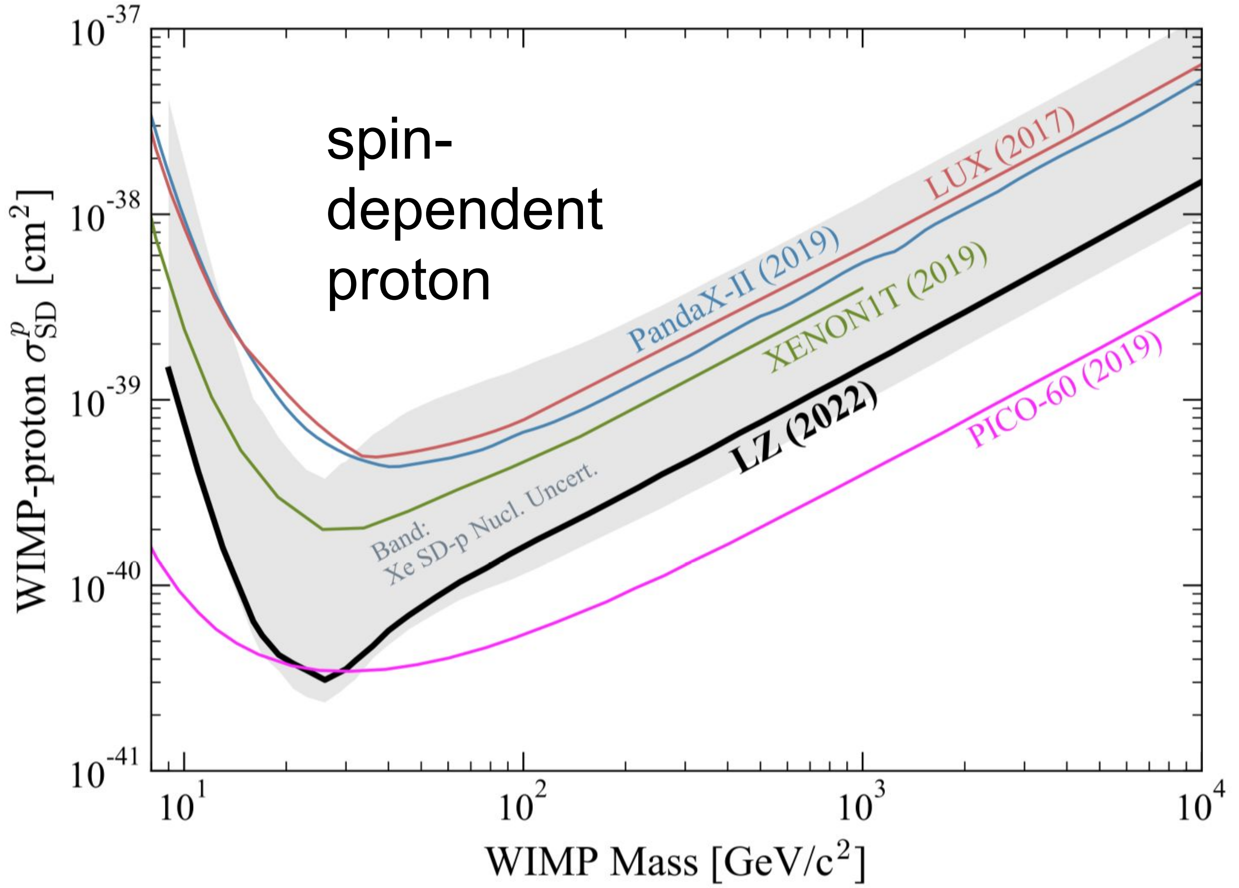




First Major WIMP Dark Matter Results From LZ (arXiv:2207.03764)





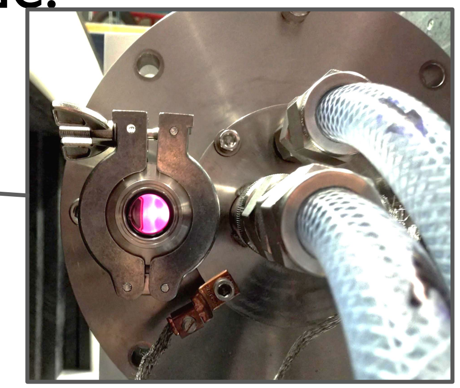


SR1 = Science Run 1 (not blinded; next run will be salted)

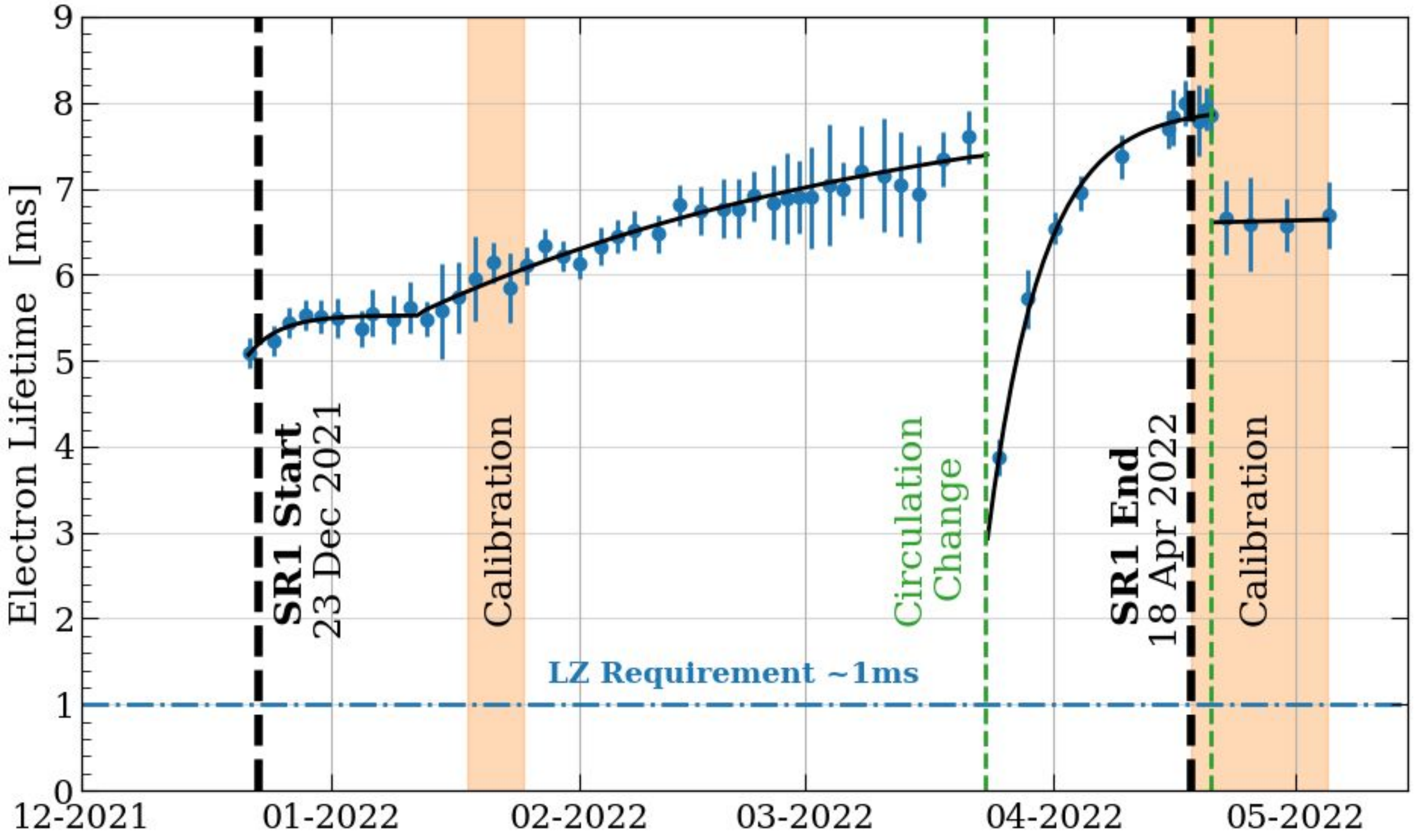
Calibrations First are How We Got There

We utilize a variety of calibration sources in LZ. Our main ones include:

- D-D neutron generator: 2.45 MeV neutrons, collimated ***Agustin Vaitkus's talk NEXT***
  - Used for: NR band, trigger efficiency, S1 cut acceptance
- Am-Li: continuum neutrons, isotropic
  - Used for: Outer Detector (OD), neutron-tagging efficiency, S2 cut acceptance
- CH_3T: continuum betas up to 18.6 keV
  - Used for: ER band, fiducial volume, S1 cut acceptance
- ^{83m}Kr: monoenergetic ERs, 32.1 and 9.4 keV
  - Used for: energy scale, xy spatial corrections
- ^{131m}Xe: monoenergetic ER, 164 keV
  - Used for: energy scale, electron lifetime
- Additional background sources (e.g. alphas and cosmics)
  - Used for: energy scale, electron lifetime



Excellent Electron Lifetime



- Drifting electrons can become trapped on impurities such as O_2 and N_2
- Purity is typically quantified by the electron lifetime: the mean time a free electron will live before becoming trapped.
- LZ requirement: >1.0 ms (*i.e.*, the maximum drift time from the cathode to the liquid surface)
- During SR1, e^- lifetime consistently greater than 5 ms (given field, this is also a long length)

Other calib parameters: What are g_1 and g_2?

This is called keVee

- Reconstructed energy (for electron recoils) is E = (S1c / g1 + S2c / g2) * W
  - S1c and S2c are the primary (liquid) and secondary (gas) scintillation signals, corrected for position, though sometimes the 'c' comes in front, or is not stated at all
  - g1, g2 are called gains not efficiencies. g1 is < 1 but g2 > 1 (1e- makes many photons)
  - W is work function, in eV units, averaged over the scintillation and ionization processes
- g2 is a bit complicated
  - Product of many factors!
  - Most simply SE * E_ext
  - SE => single e- pulse area
  - Epsilon or E_ext is ext eff
  - SE is broken down into g1_gas analogous to g1 (term invented on NEST) and photons/e- (Y_e)

$$g_2 = SE \cdot \epsilon_{ext}(\mathcal{E}_{gas})$$
$$= g_1^{gas} \cdot Y_e(\mathcal{E}_{gas}, \Delta z_{gas}) \cdot \epsilon_{ext}(\mathcal{E}_{gas})$$

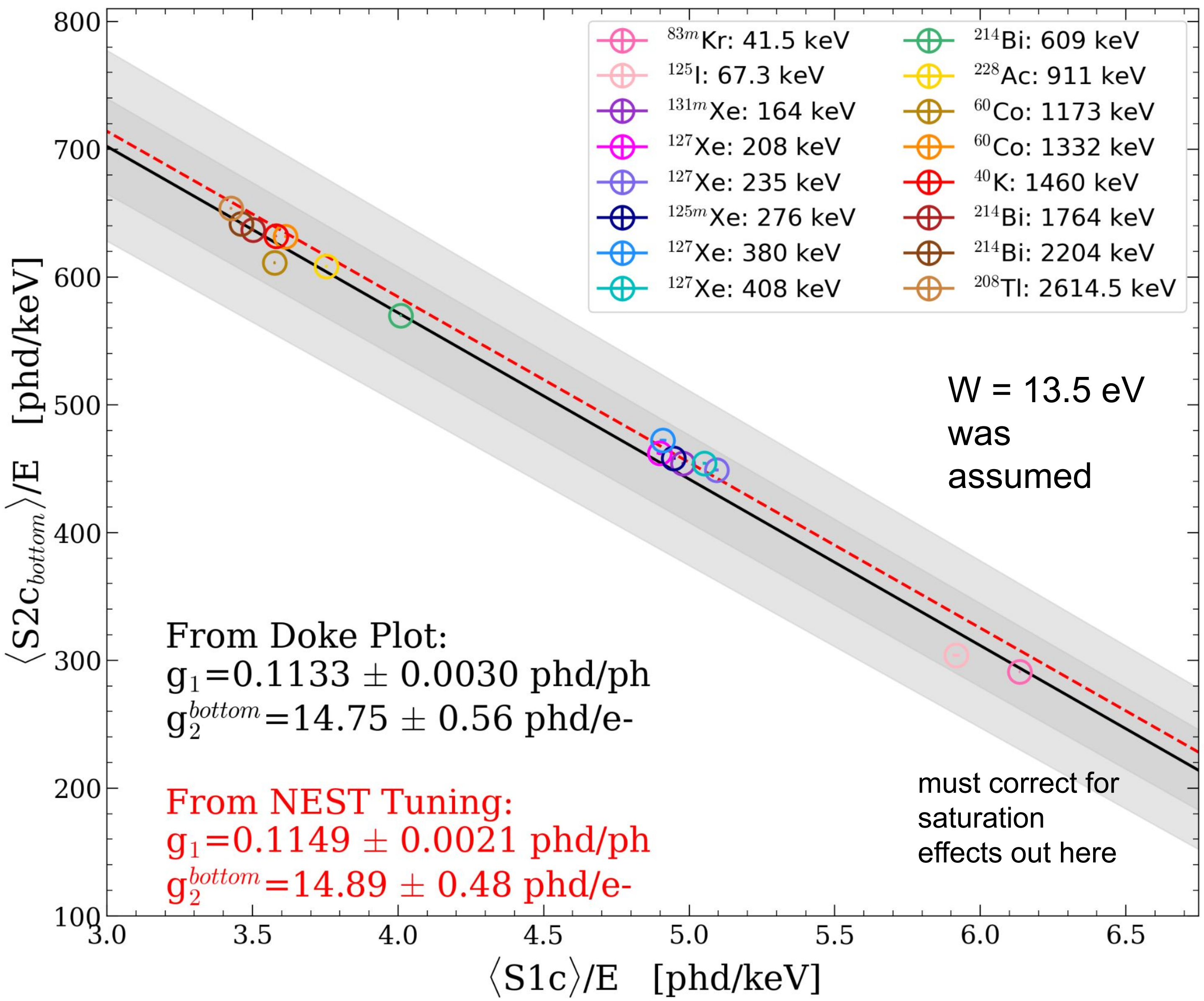
arXiv:1910.04211

- g1 & g2 are determined by a "Doke Plot" named after the late T. Doke
  - Alternative methods are: "mini" Doke plot (anti-correlation inside of 1 peak) i.e. EXO style
  - Comparison of S1 and S2 peaks to a (predictive) NEST simulation is another way
  - Optical (ray-trace) sims (G4, Garfield for S2, etc.) provide independent predictive means

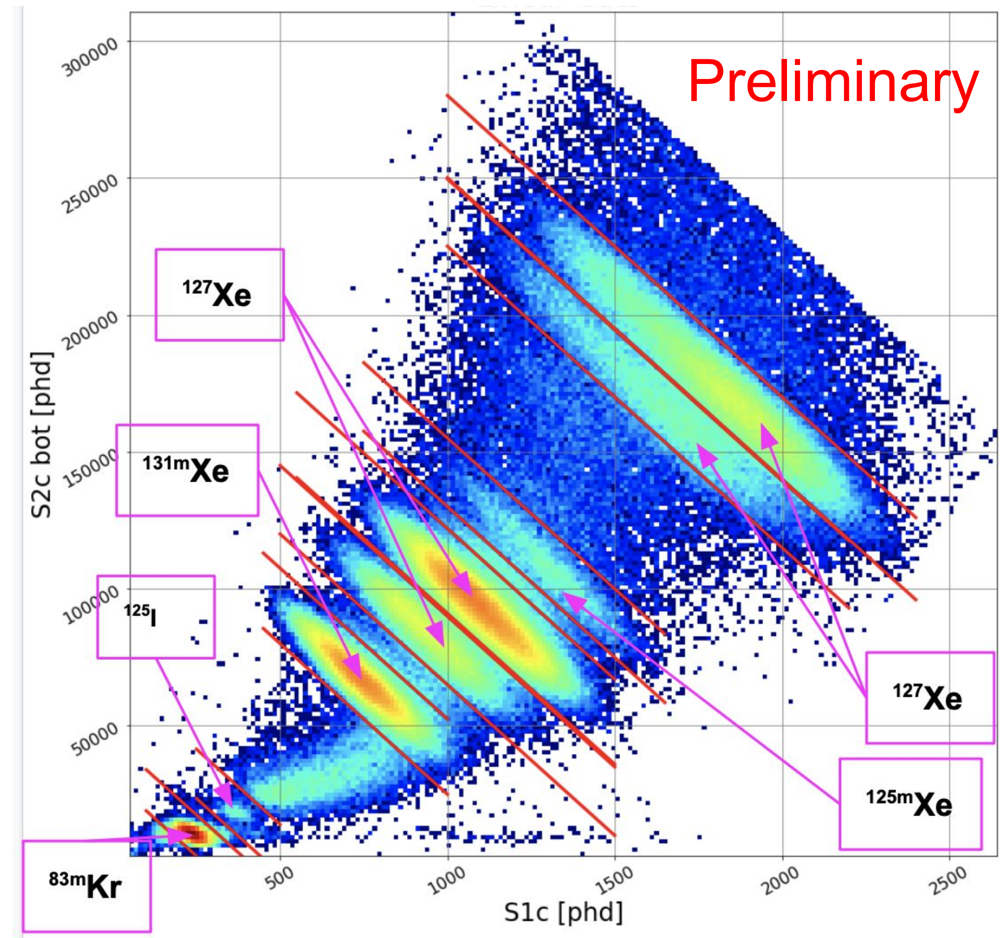
G4 = GEANT4

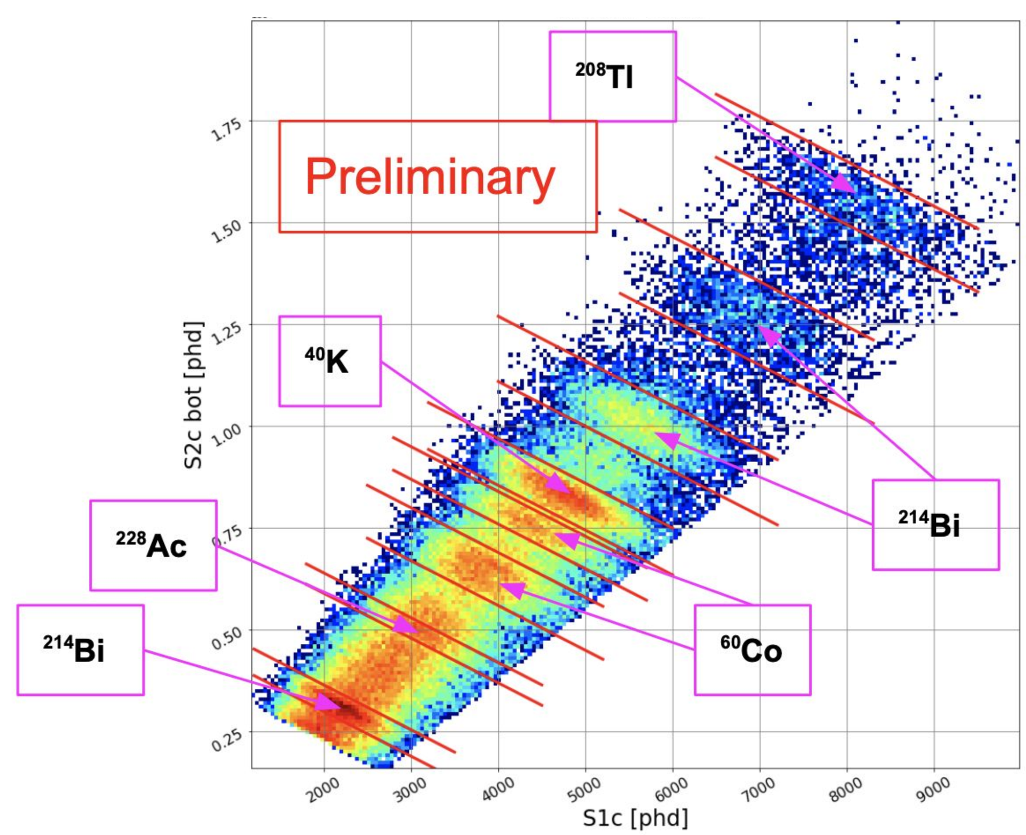
LZ SR1's "Doke Plot"

If you assume a W value, you can get g1 & g2 using the slope and intercept of a plot of the S1, S2 central values from a series of peaks



Photons detected = phd





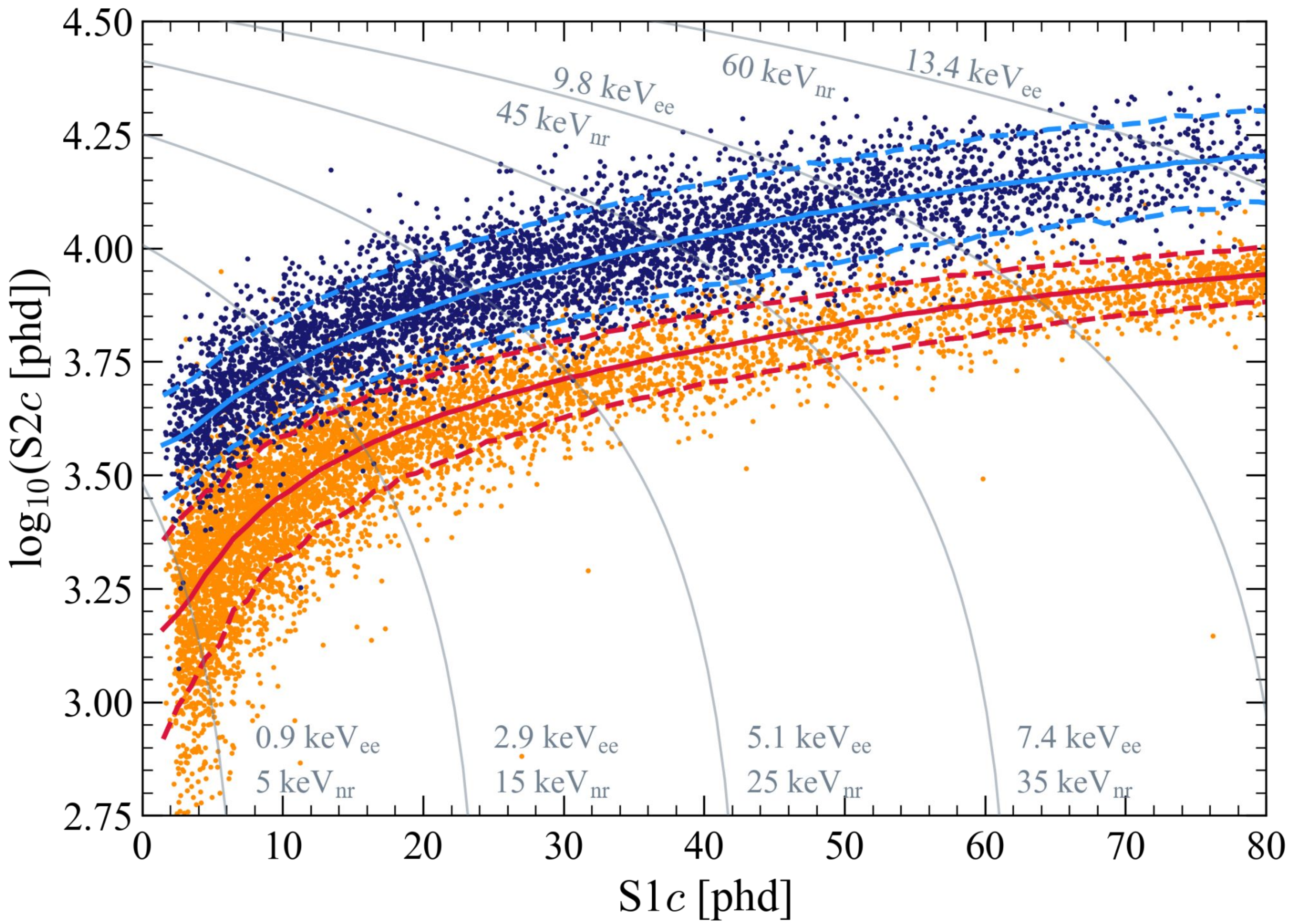
Calibration Bands

- We use the Noble Element Simulation Technique (NEST)* to model LXe response
- At right:
  - Blue pts: CH_3T data
  - Orange pts: DD (neutron) data
- Fit data to model for detector-performance parameters

Parameter	Value
g_1^{gas}	0.0921 phd/photon
g_1	0.1136 phd/photon
Effective gas extraction field	8.42 kV/cm
Single electron	58.5 phd
Extraction Efficiency	80.5 %
g_2	47.07 phd/electron

- In SR1, we have 99.9% rejection of ER leakage below the median quantile of a 40 GeV/c^2 WIMP. (99.75% for a flat-E NR response)

O(1)%->O(0.1)% on means; ~20% -> ~10% on widths

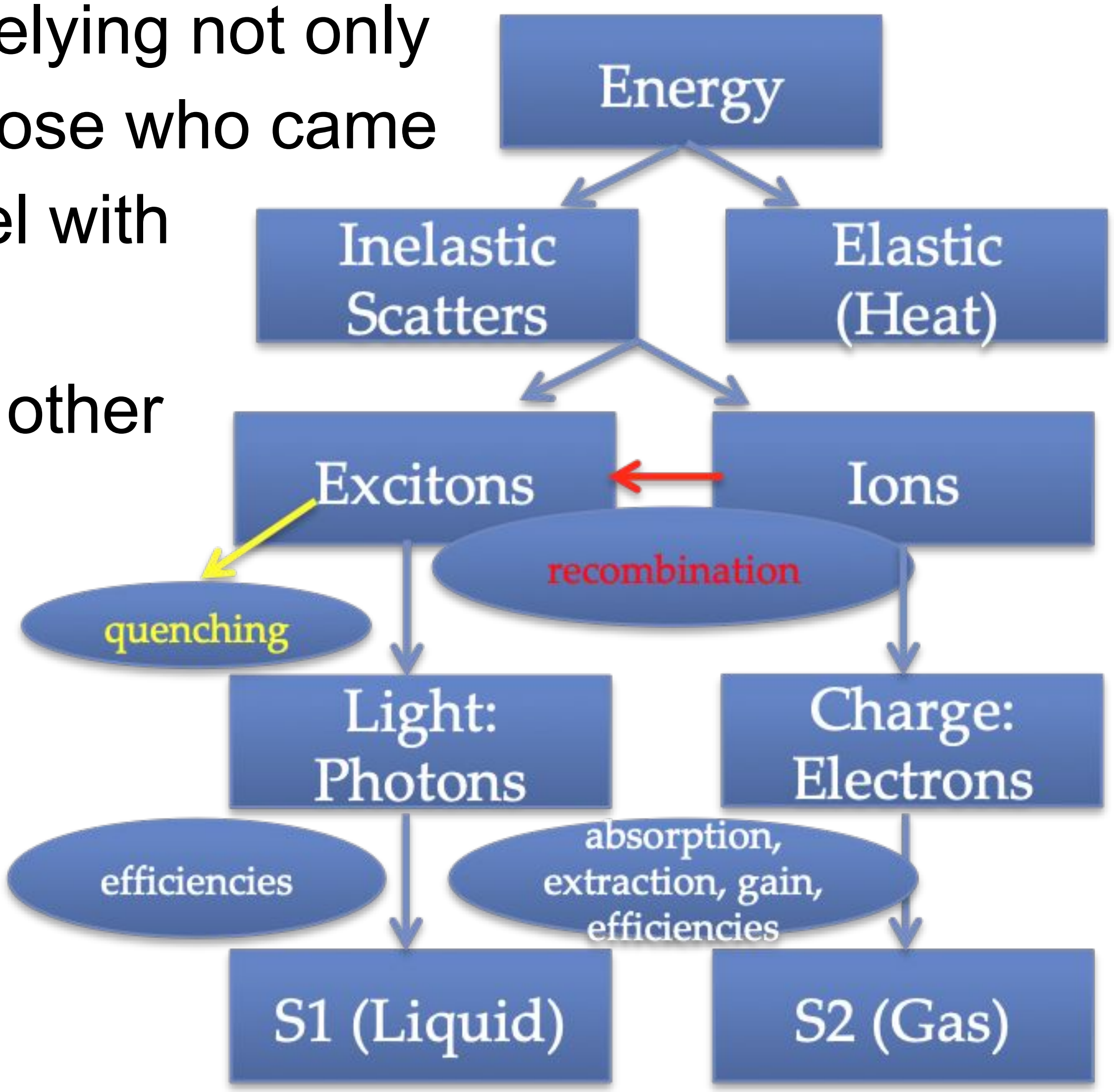


- The CH_3T calibration allowed us to validate the accuracy of our ER leakage model out to 4 standard deviations.

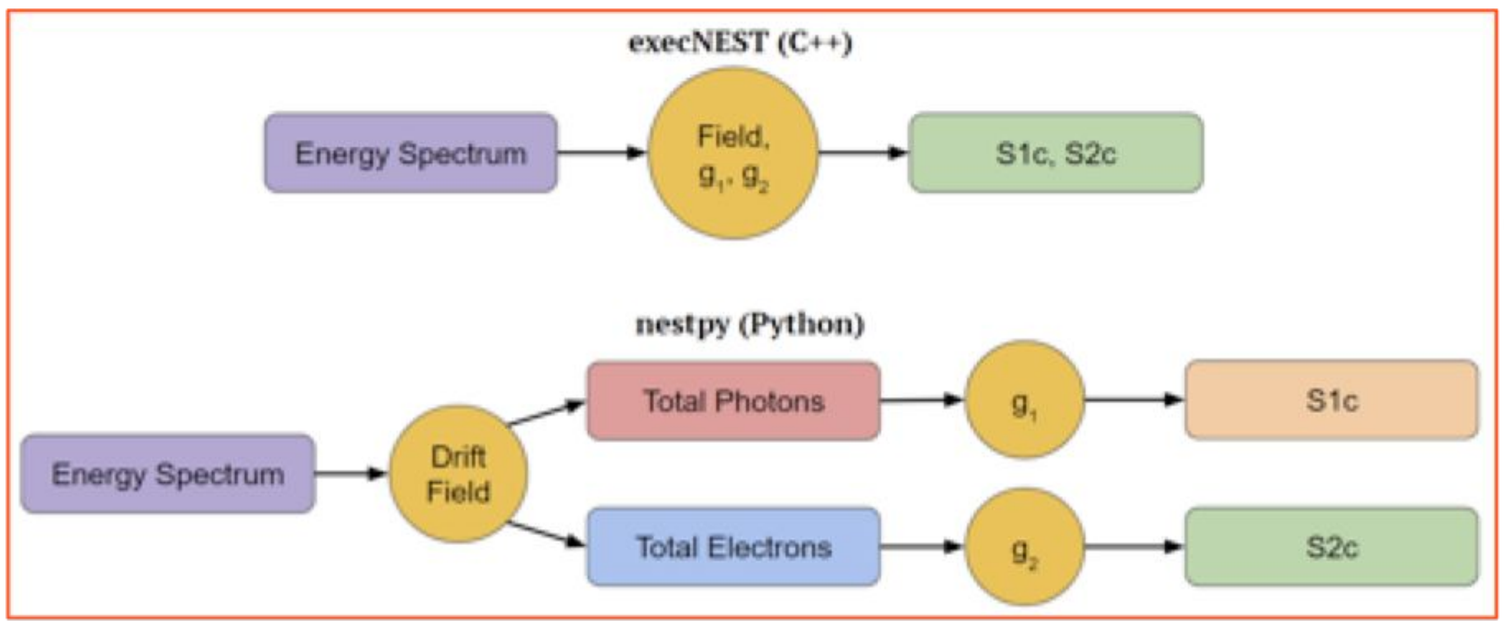
(*) https://github.com/NESTCollaboration/nest

What is NEST? And its Benefits

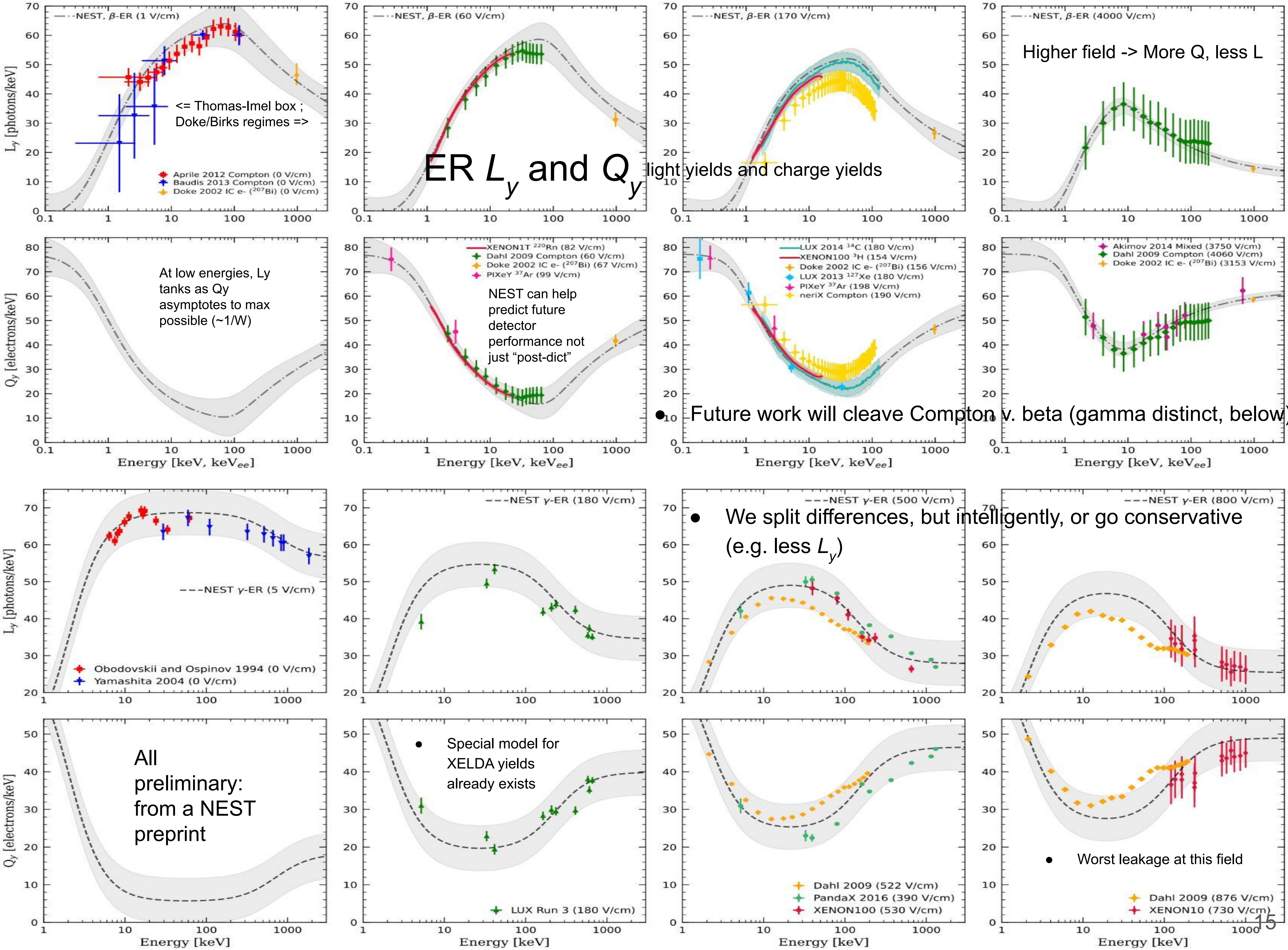
- It's neutral, open source. Inter-collaboration collaboration (similar to G4 collab)
- Software does LXe, GXe, SXe, LAr, from sub-keV to MeV
- Primary parameters: particle or interaction type, electric fields, density or phase, and energy
- Using it means reducing your systematics by relying not only on your own calibration data, but upon all of those who came before you. One can stop reinventing the wheel with "NEST-like" but private / secret software
- Integrated into both Geant4 and Garfield. Also other languages: ROOT, Python (nestpy)



Everything depends on particle and interaction type, energy, E-fields, and density

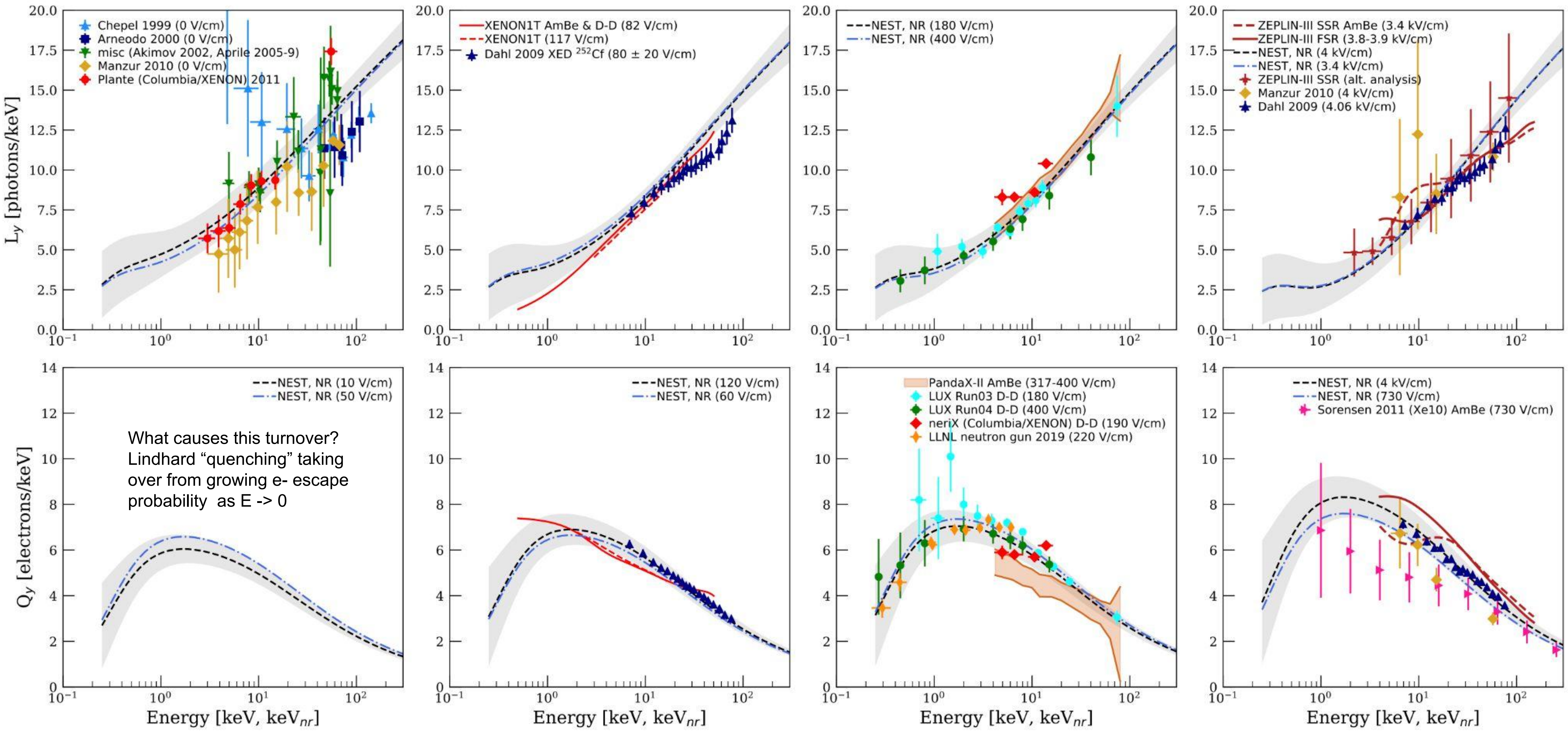


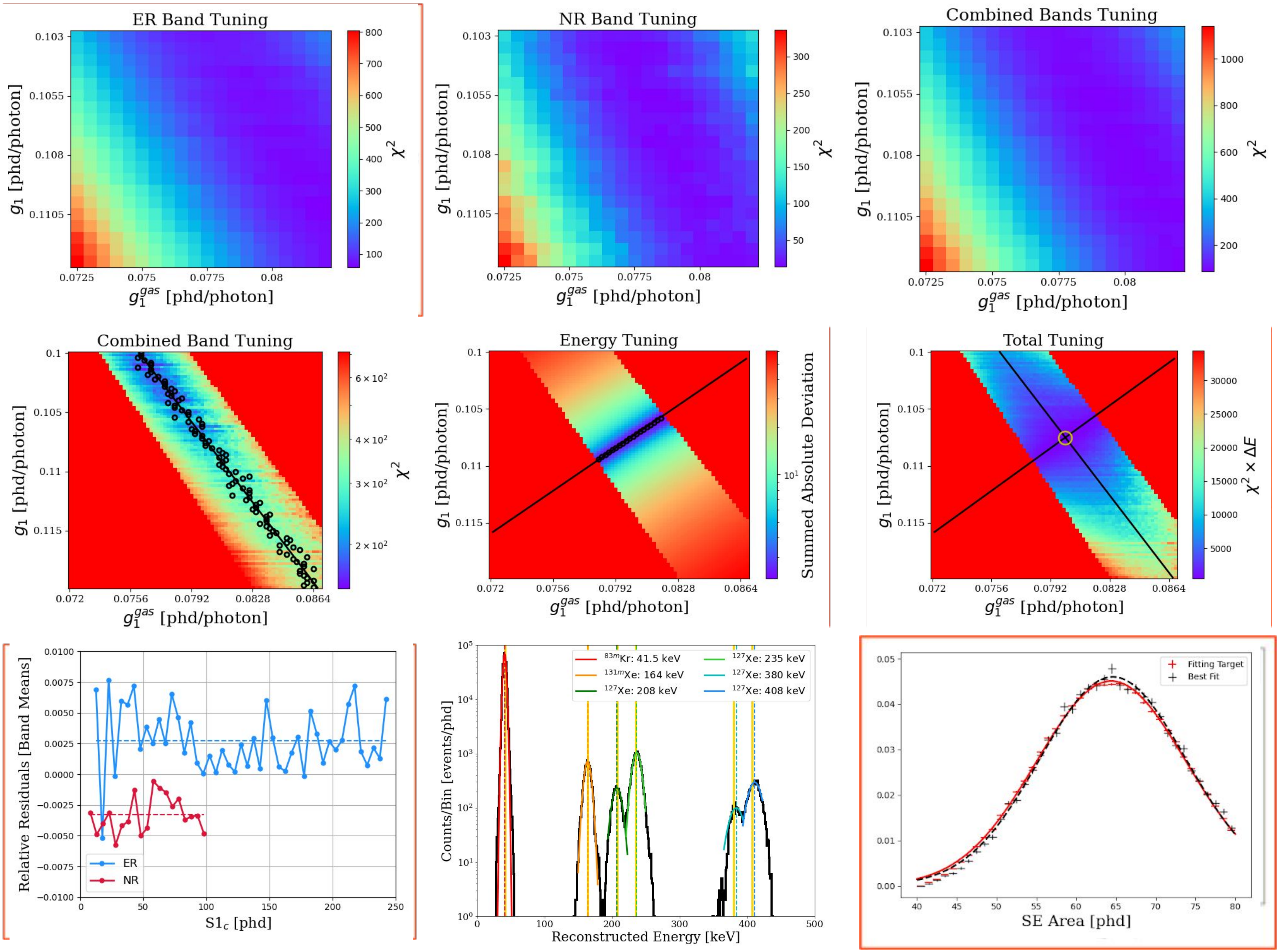
ER L_y and Q_y light yields and charge yields

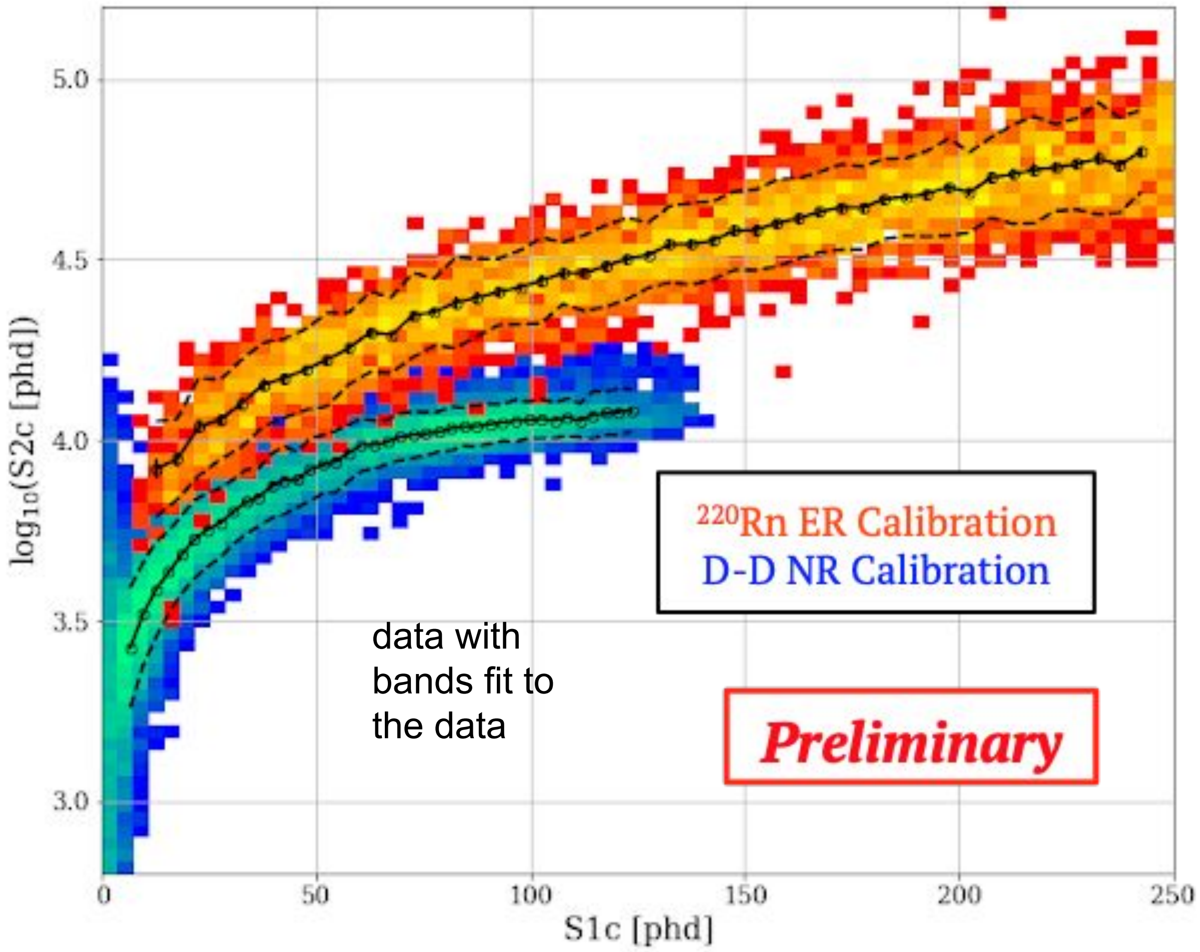


NR L_y and Q_y

- Threading the needle -- between fully theoretical and fully empirical
- Providing users good defaults, but also great flexibility (NEST is customizable)




ER Band Tuning
NR Band Tuning
Combined Bands Tuning
Combined Band Tuning
Energy Tuning
Total Tuning
g_1 [phd/photon]
g_1^{gas} [phd/photon]
χ^2
Summed Absolute Deviation
$\chi^2 \times \Delta E$
Relative Residuals [Band Means]
ER
NR
$S1_c$ [phd]
Counts/Bin [events/phd]
Reconstructed Energy [keV]
^{83m}Kr: 41.5 keV
^{131m}Xe: 164 keV
^{127}Xe: 208 keV
^{127}Xe: 235 keV
^{127}Xe: 380 keV
^{127}Xe: 408 keV
Fitting Target
Best Fit
SE Area [phd]



<= PRIOR TO TUNING

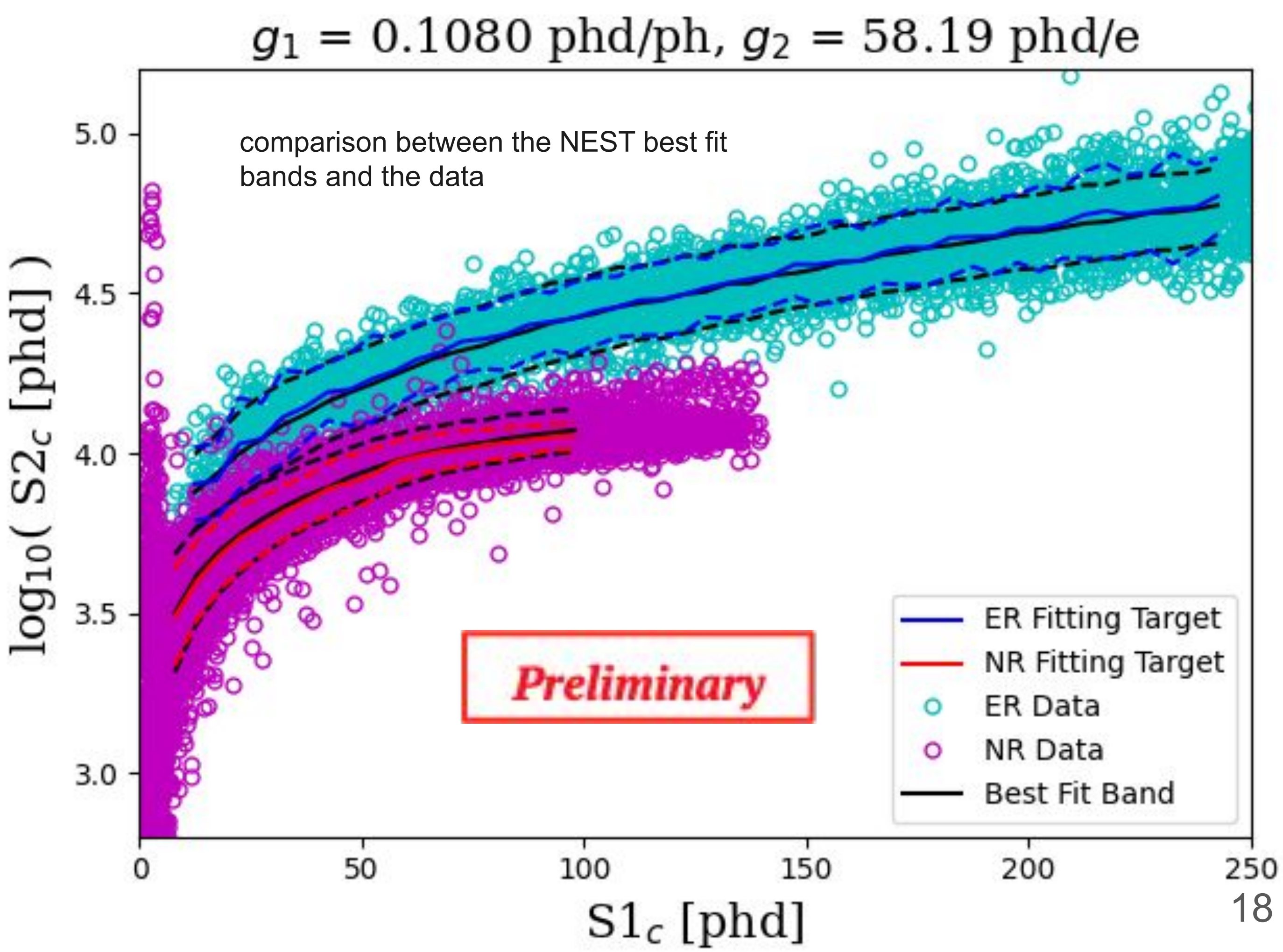
Radon-220! https://arxiv.org/abs/1602.01138
We didn't only do tritium ER!

Crucial for EFT operator based searches (high-*E* NR group)

AFTER TUNING =>

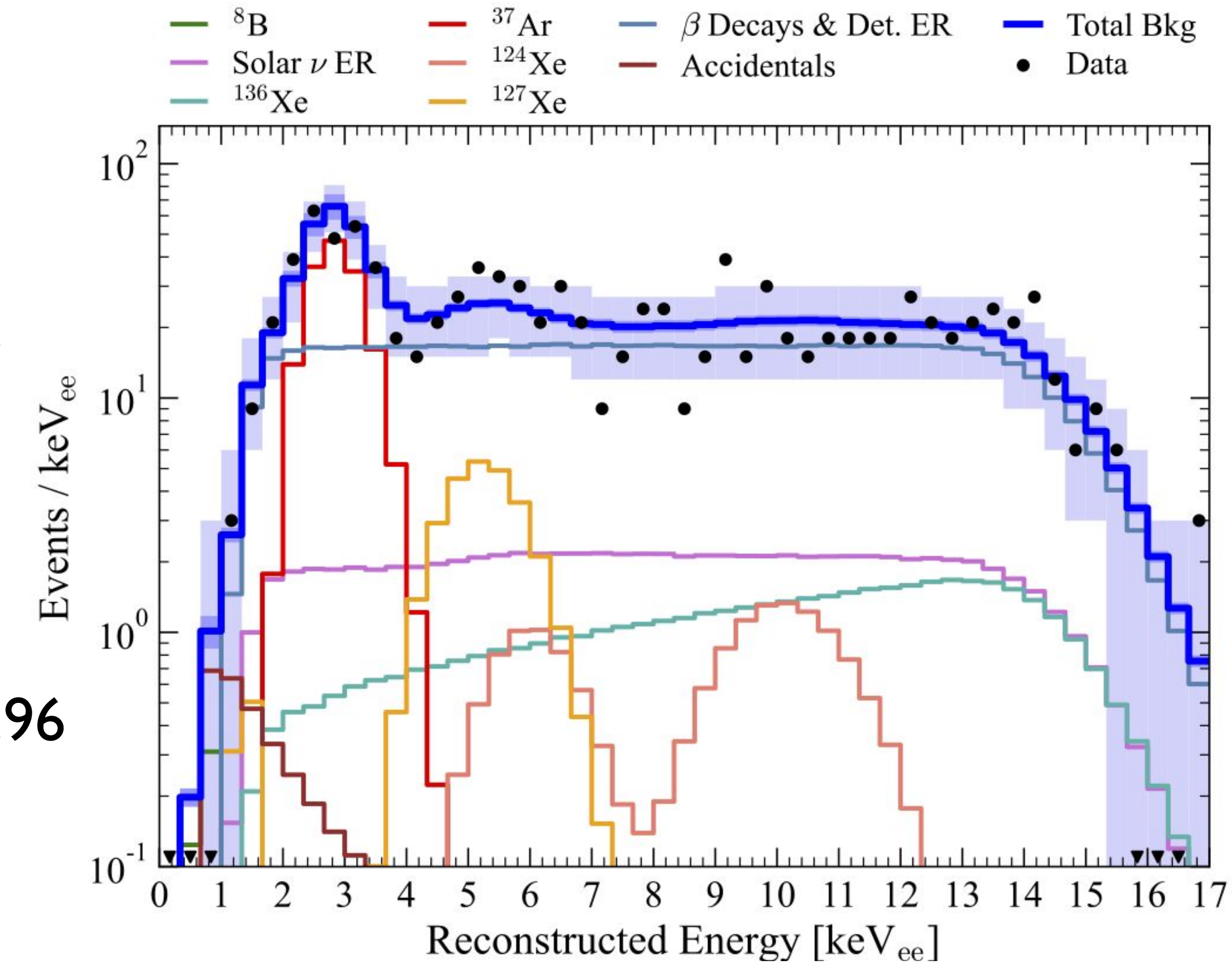
(an early example: commissioning data when we had different grid (Gate-Anode) voltages so different g_1 and g_2;

also because an earlier 3D XYZ correction map used)

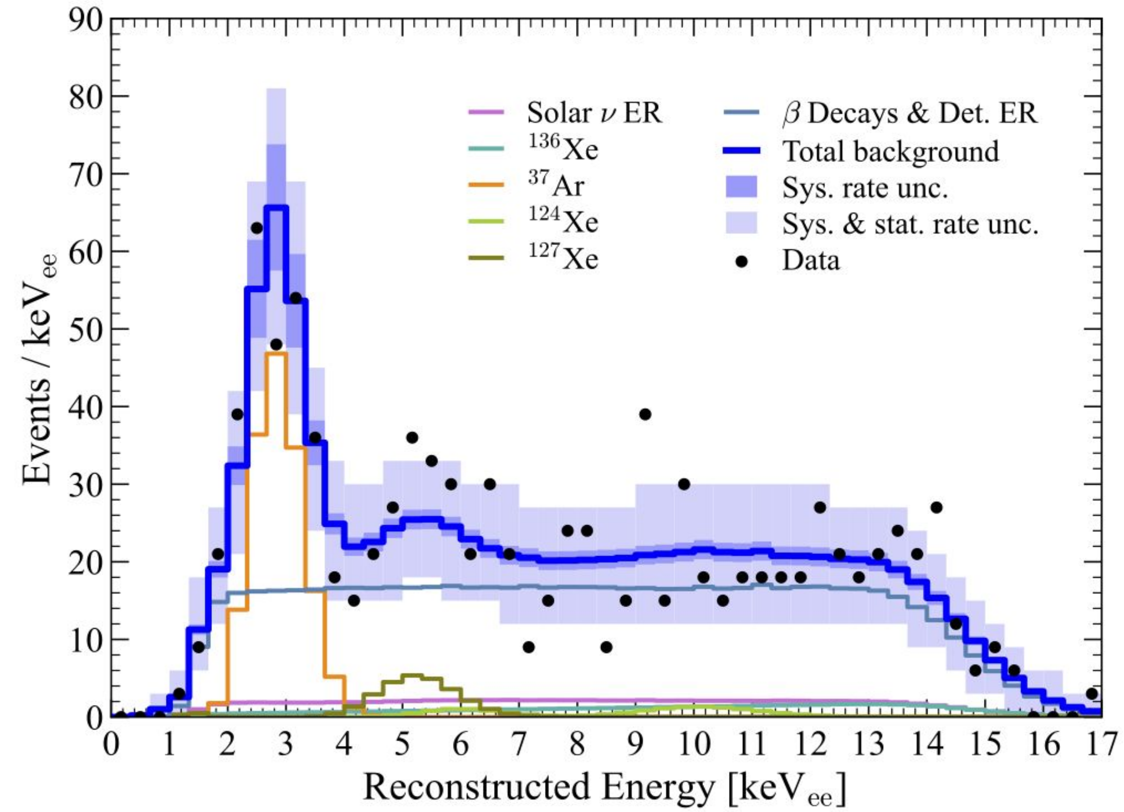


Final SR1 Data: The Backgrounds

- Projecting onto electronic-equivalent reconstructed energy ("keVee")
- Data histogram shown as black points
- Best fit with *no* WIMP signal yields p-value = 0.96
- Expected range of statistical fluctuations for best-fit: light-blue boxes



no evidence of WIMPs at any mass (so the best fit WIMP component was 0 everywhere)



Source	Expected Events	Best Fit
β decays + det ER	218 ± 36	222 ± 16
ν ER	27.3 ± 1.6	27.3 ± 1.6
^{127}Xe	9.2 ± 0.8	9.3 ± 0.8
^{124}Xe	5.0 ± 1.4	5.2 ± 1.4
^{136}Xe	15.2 ± 2.4	15.3 ± 2.4
^{8}B CEνNS	0.15 ± 0.01	0.15 ± 0.01
Accidentals	1.2 ± 0.3	1.2 ± 0.3
Subtotal	276 ± 36	281 ± 16
^{37}Ar	[0, 291]	$52.1^{+9.6}_{-8.9}$
Detector neutrons	$0.0^{+0.2}$	$0.0^{+0.2}$
30 GeV/c^2 WIMP (only one example mass of course, out of many)	–	$0.0^{+0.6}$
Total	–	333 ± 17

Summary and Outlook

- LZ is online and taking high-quality physics data
  - All detectors are performing well not just the TPC (skin, OD, water)
  - Backgrounds well within expectations
- With 60 live-days, LZ is the most sensitive dark matter detector for NR
- NEST provides a robust simulation package for reproducing primary scintillation light and charge yields, as well as TPC observables
  - Allows you to work with absolute yields, and contrast experiments
- Future work
  - Tune to band widths and energy resolution to verify fluctuations and noise are modeled appropriately
  - Tune to individual S1c and S2c distributions as another way to break band tuning degeneracy
  - Repeat as LZ continues to collect more data and data quality evolves

Questions??