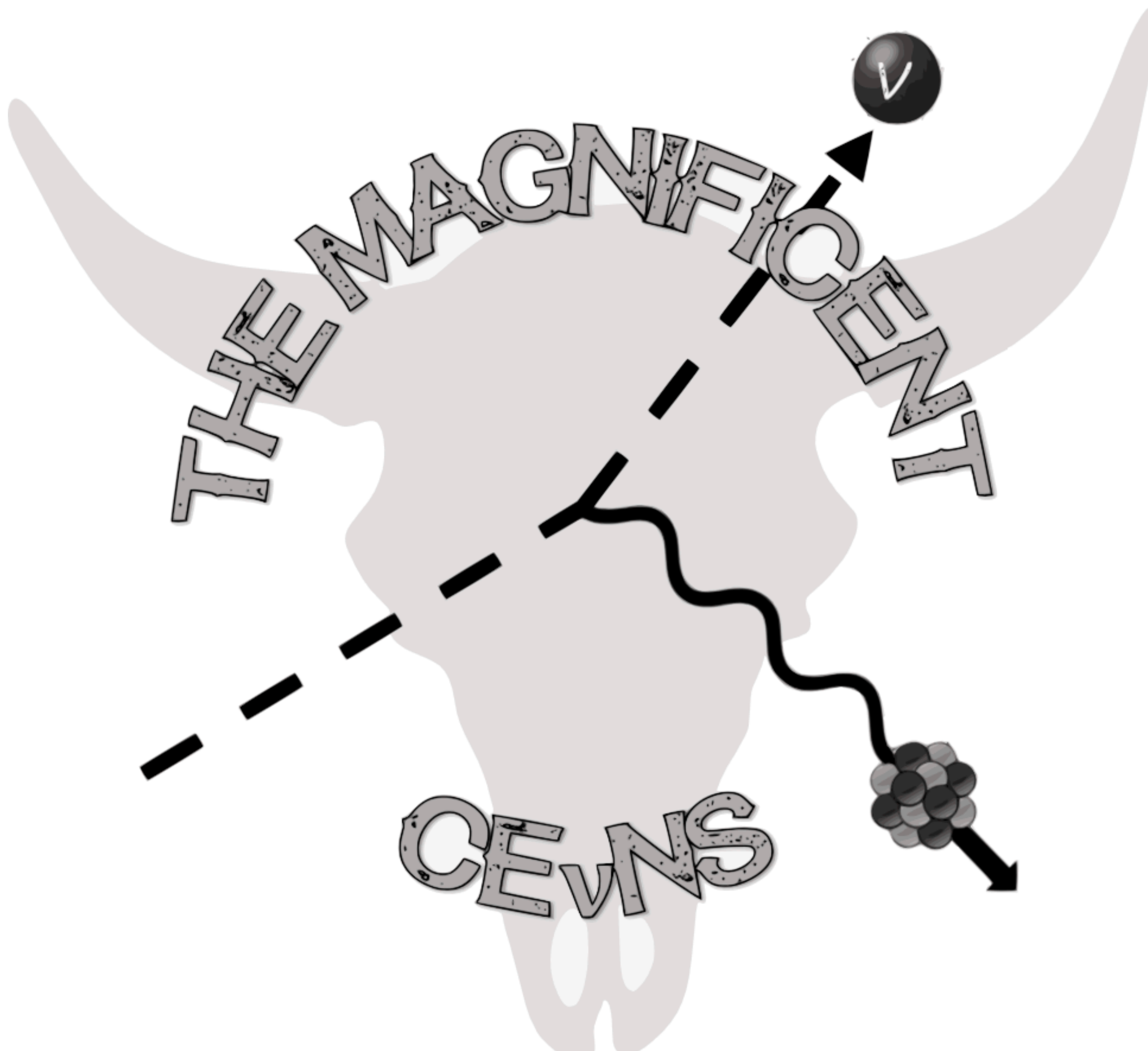
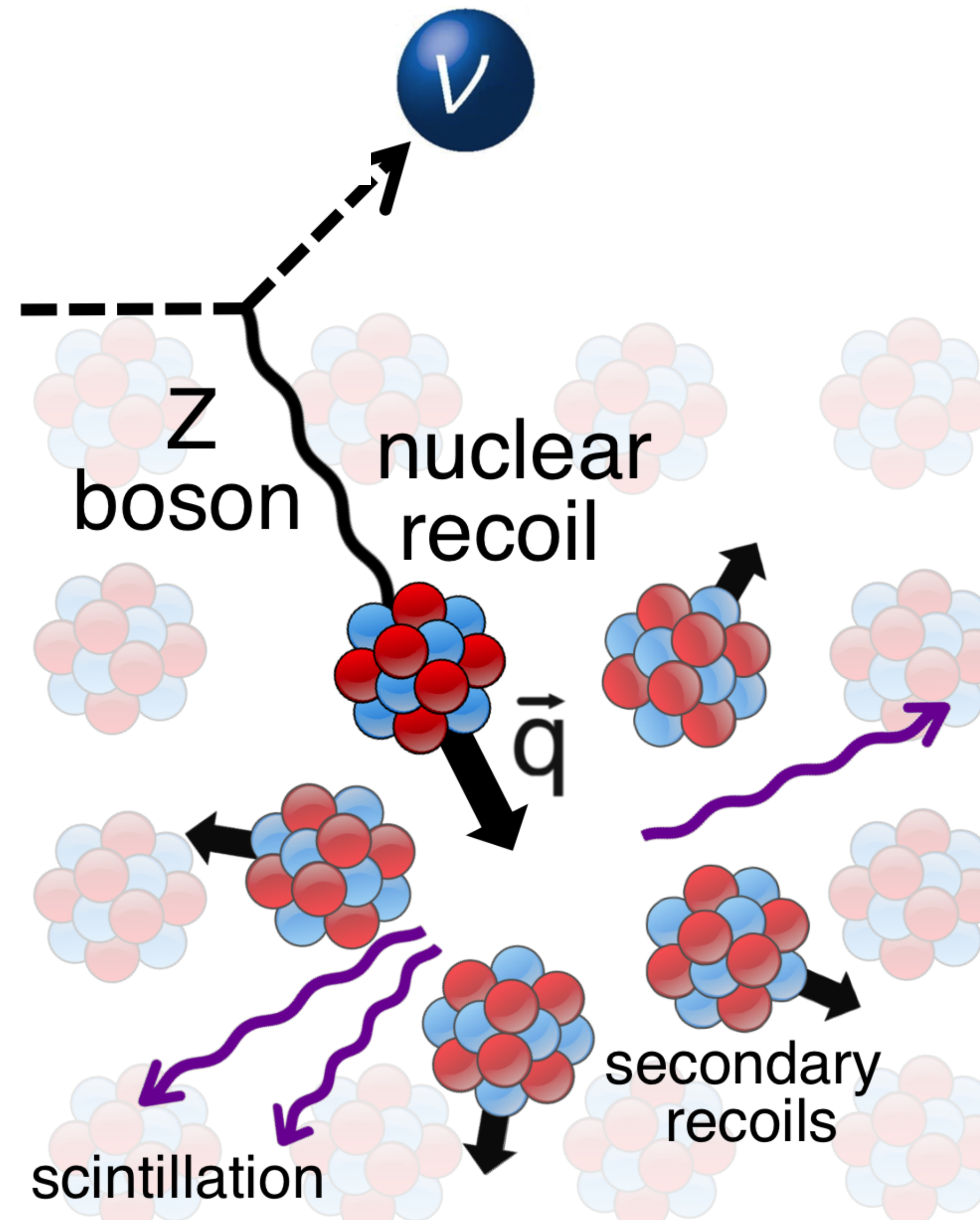
Detection and Calibration of Low-Energy Nuclear Recoils for Dark Matter and Neutrino Scattering Experiments





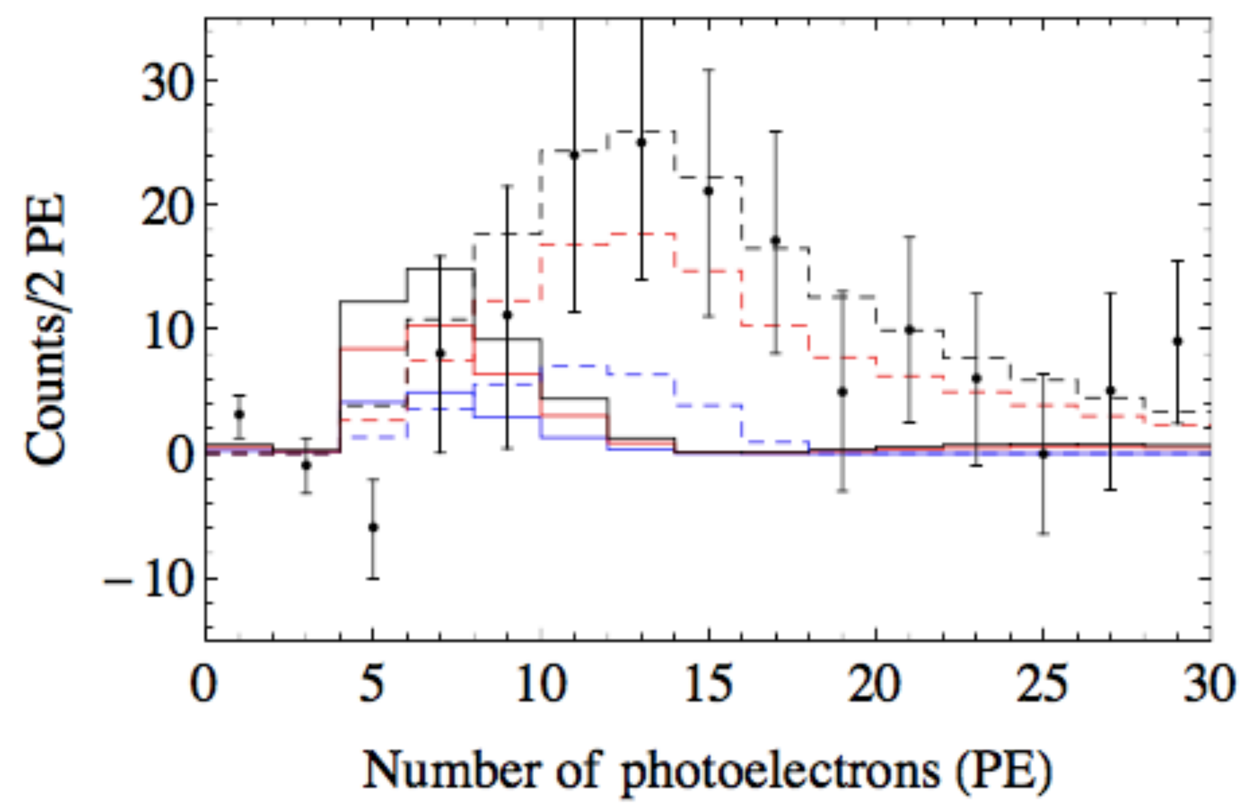
Phil Barbeau (he/him/his)

I would also like to acknowledge the work of *Jingke Xu & Ziqing Hong*

Critical for CEvNS

- Demonstrating sensitivity to nuclear recoils is critical for any CEvNS detector
- Beyond this, precision calibrations are critical for next generation searches
  - NSIs, Form Factors, recoils near threshold

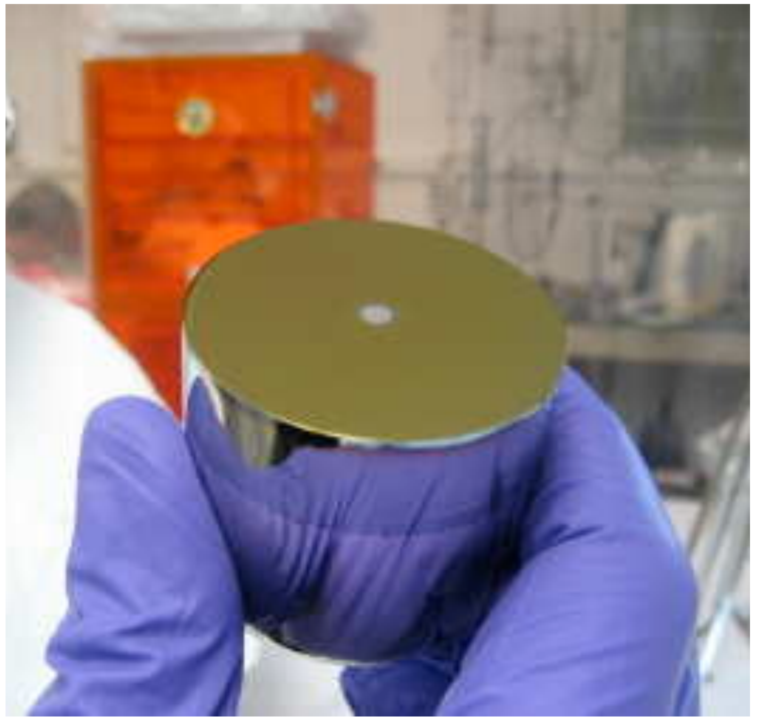
Liao and Marfatia, arXiv:1708.04255v1



light-mass Z' dark mediator fit to COHERENT 1st gen CsI result

Nuclear Recoil Detection Methods

- Detectors with ionization and scintillation signal channels only measure a small fraction of the recoil energy
- Bolometric detectors don't suffer this signal loss, but detectors should still be calibrated
- I will not have time to discuss detectors that
  - change phase (e.g. superheated droplet, bubble-chambers or supercooled liquids)
  - or detectors that record their signals as crystal defects or nuclear tracks in crystal lattices



Models

- A heavy nucleus is an inefficient way to transferring energy to electrons

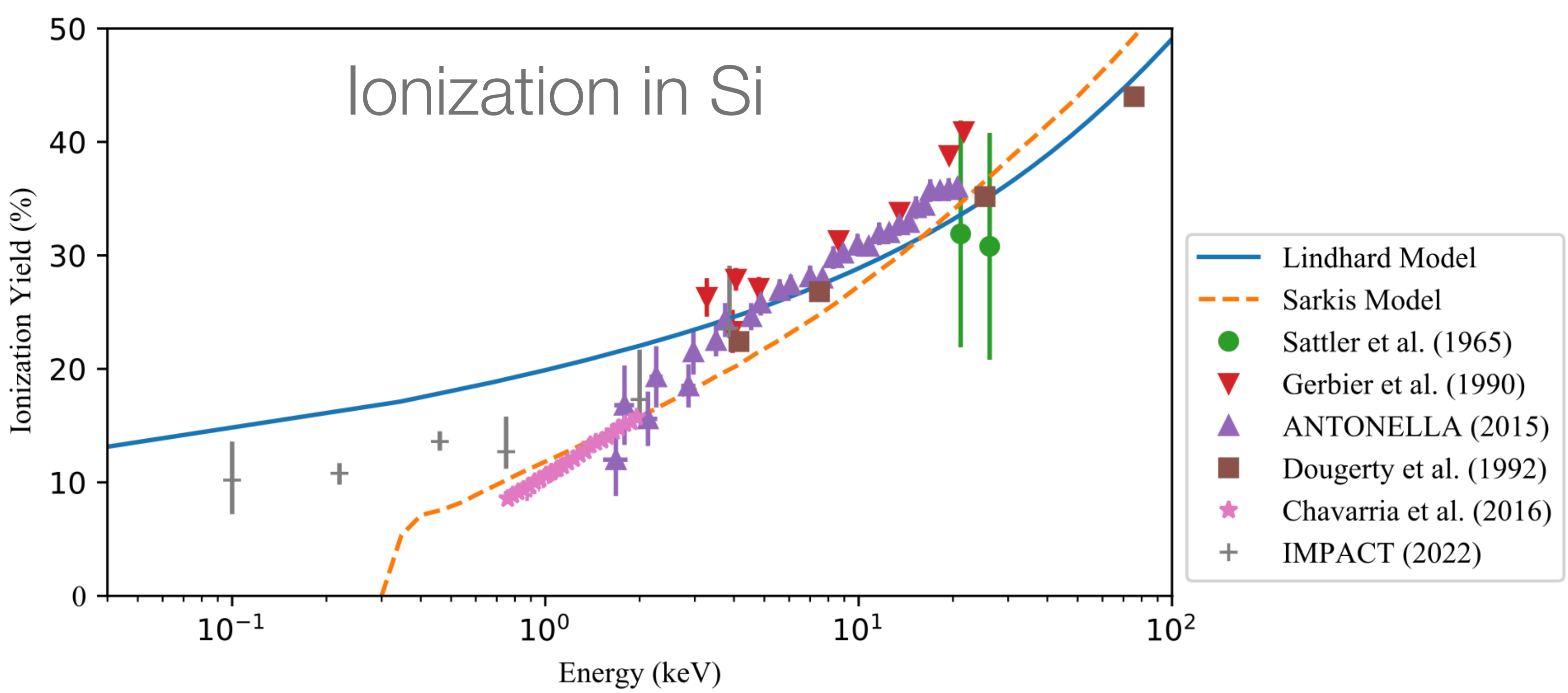
Ionization: Lindhard Model

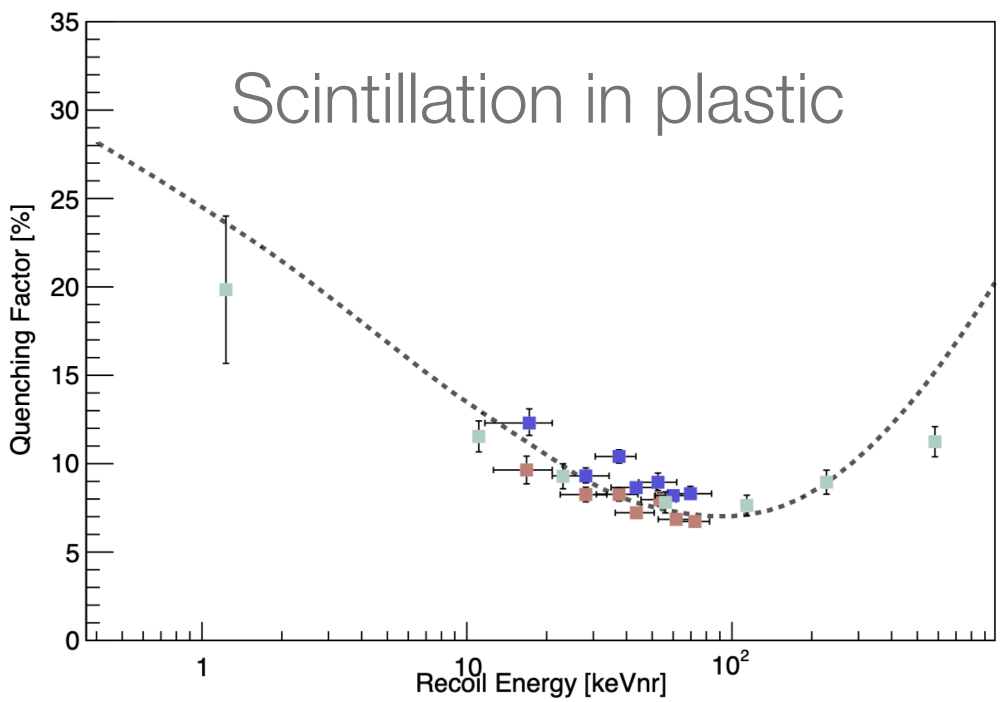
$$f = \frac{kg(\epsilon)}{1 + kg(\epsilon)}$$

Scintillation: Lindhard Model

$$\frac{dL}{dx} = \frac{S}{1 + kB\frac{dE}{dx}}\frac{dE}{dx}$$

But: there are deviations, non-linearities, Fano factors, variances…



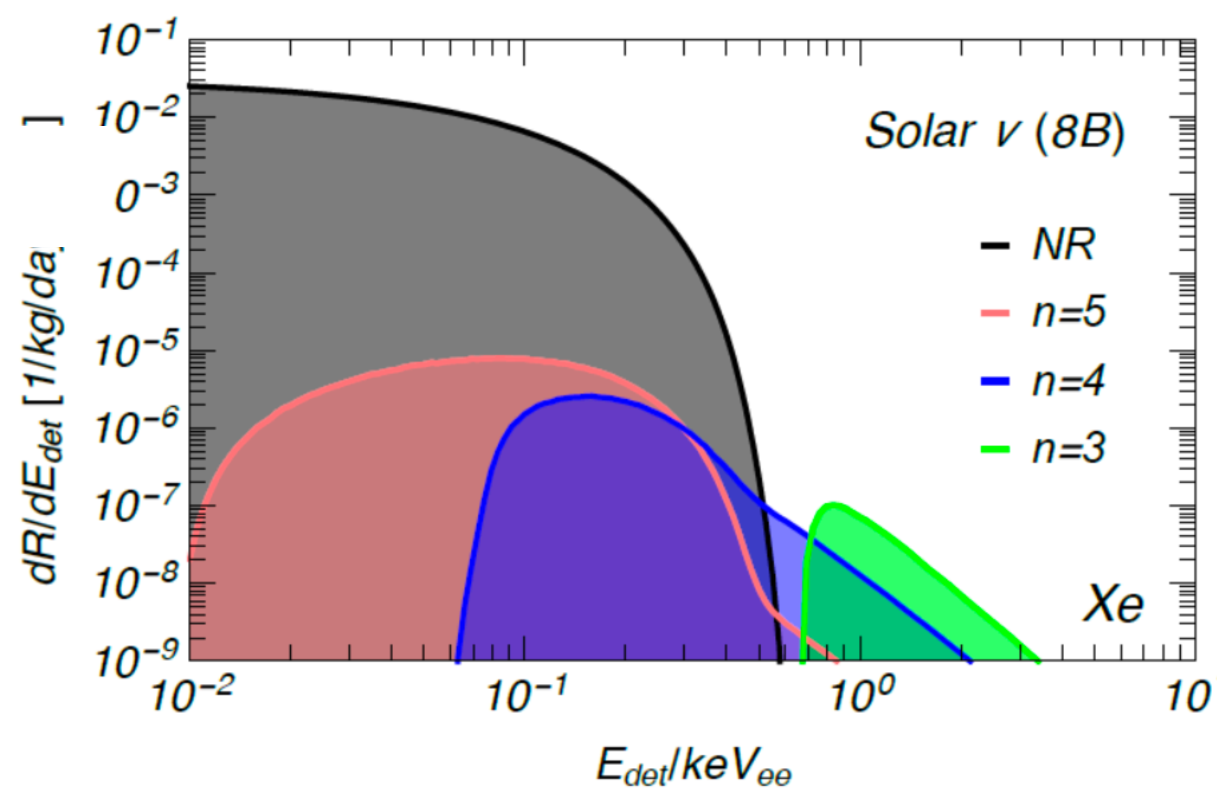


Subdominant Effects

Many effects can modify response

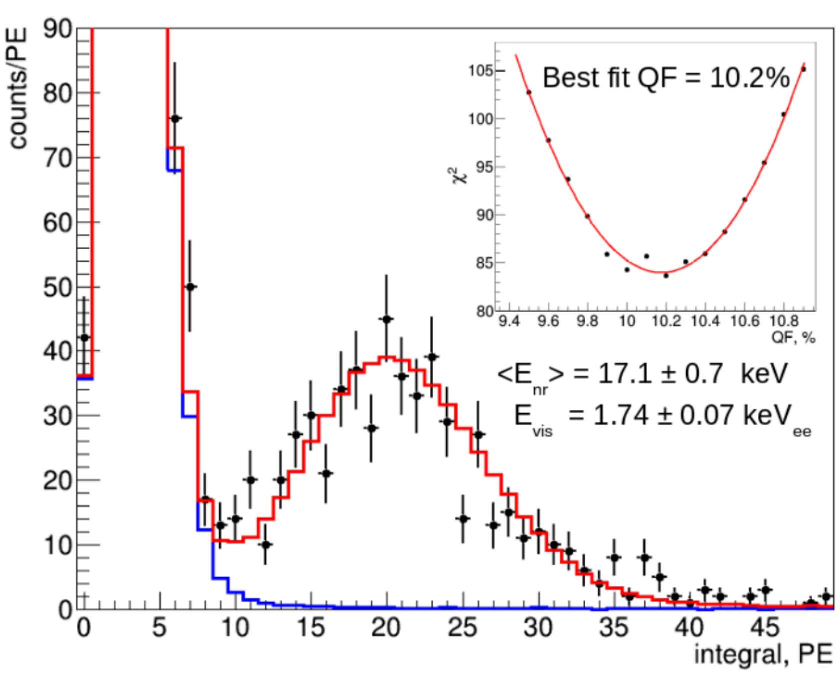
- Migdal Effect: electron cloud displacement
- Channeling: recoils oriented along crystal lattice channels
- Columnar Recombination: e-ion recombination when charge is drifted along track direction

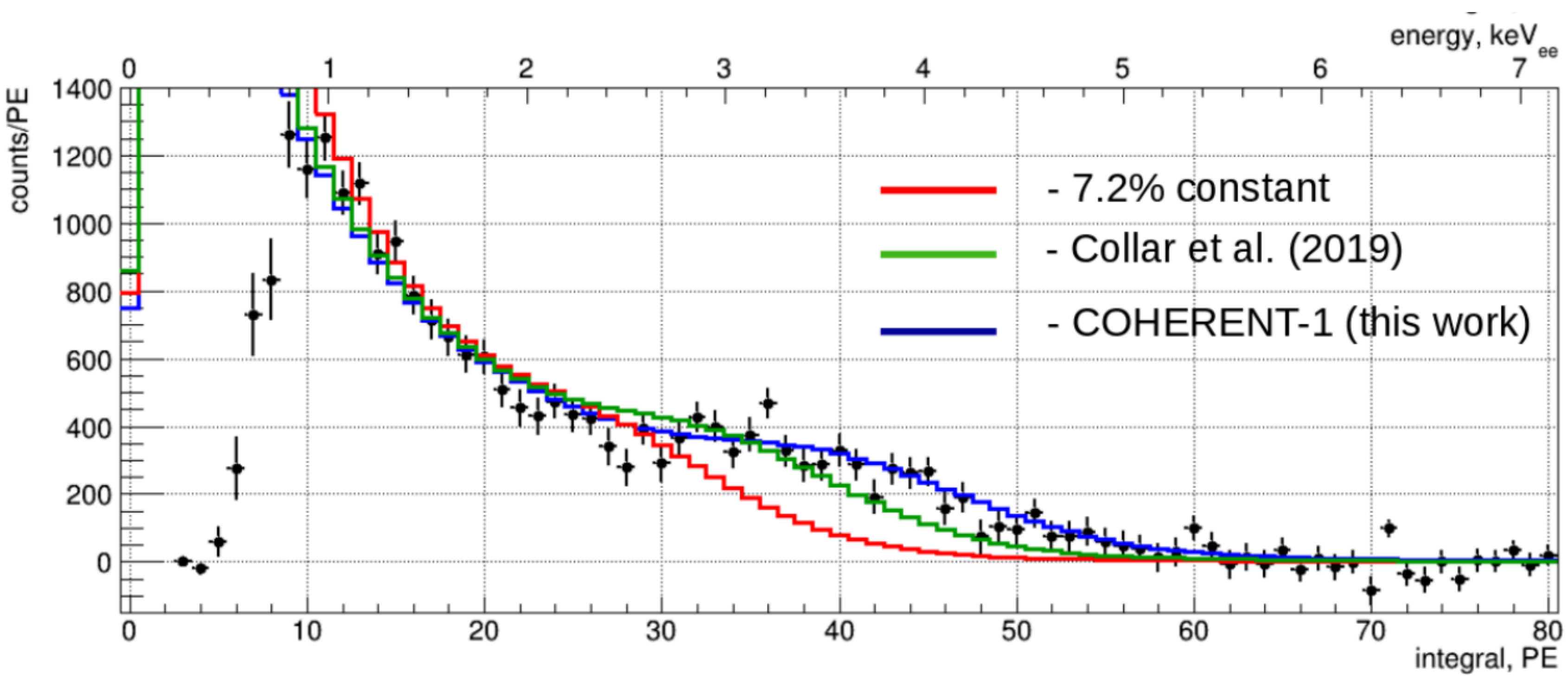
Ice, et al, JHEP 2018, 194 (2018)



Calibration Techniques

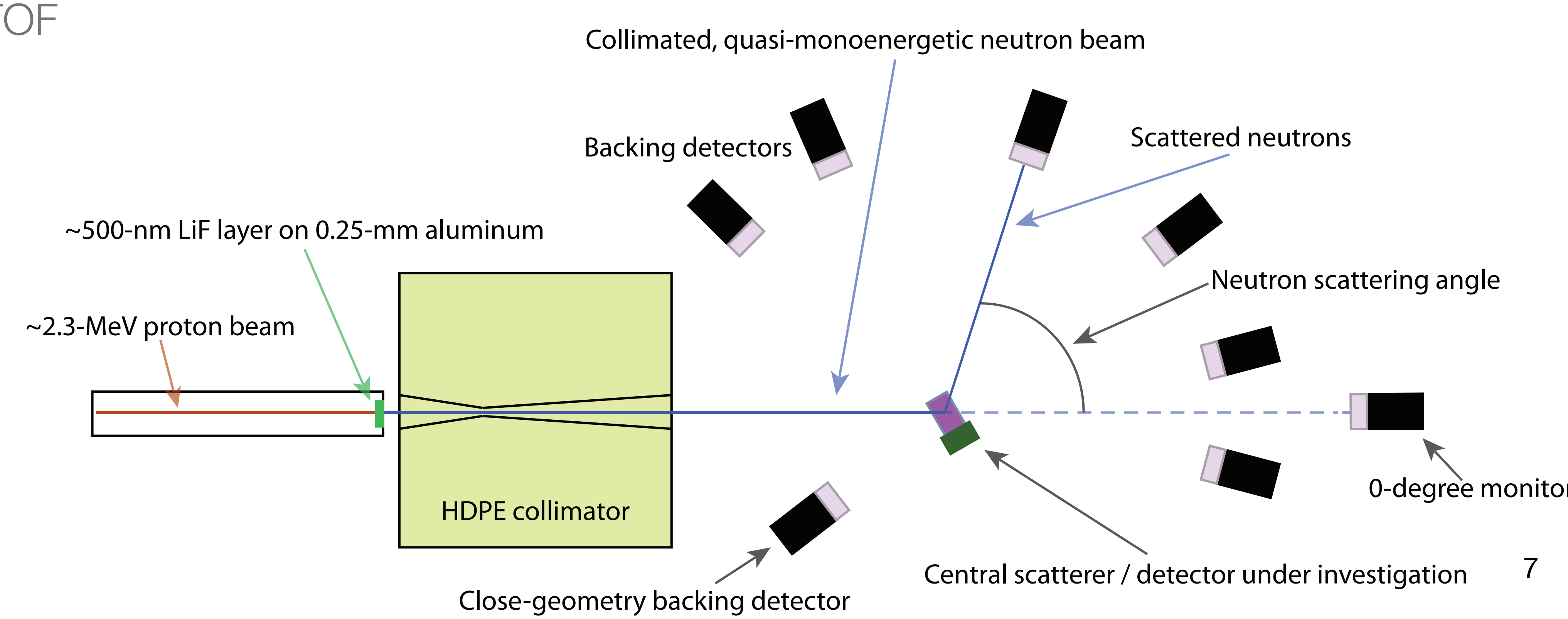
- We mimic neutrino (and neutrinalino) interactions by scattering neutral particles off detectors of interest:
  - **neutrons, photons, pions & neutrinos**
- Scatters can be elastic or inelastic.
- Measurements can be direct, or indirect (composite sum signal)
- Kinematics can be constrained, or unconstrained (endpoint measurements)





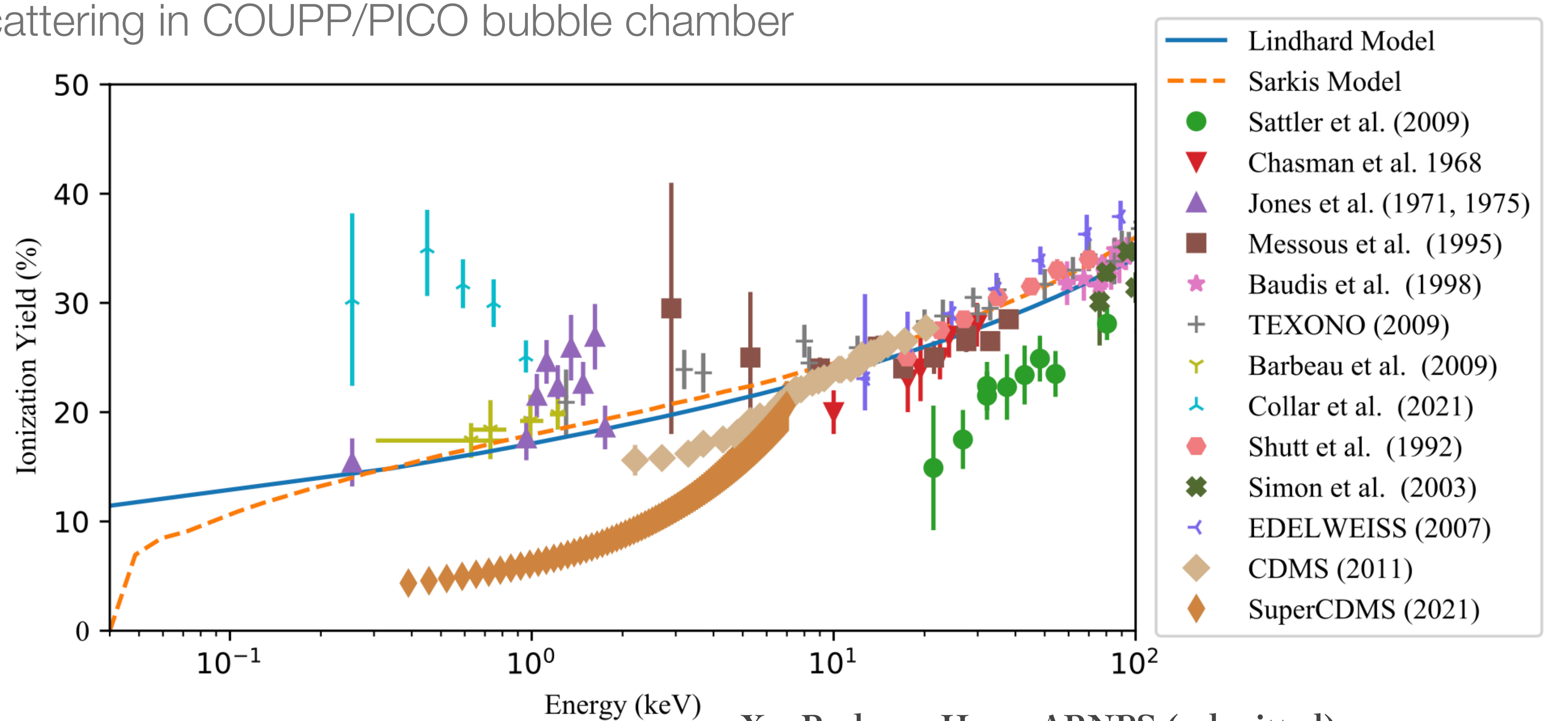
Neutron Elastic Scattering "best way"

- Use a well defined energy neutron
- Compact target (reduces multiple scattering & geometric uncertainties)
- It's best to over constrain the system by measuring the recoiling neutrons
- Pulsed neutron beams monitor beam energy, reject stray neutrons, and over constrain the kinematics using NTOF
- Collimated neutron beams reduce background
- Tunable beams allow systematic cross checks
- Symmetrically placed neutron detectors do as well
- Always a challenge to scale from calibration detector to larger scale



Alternative methods

- Inelastic methods can measure either coincidences or sum-peaks. Nucleus recoils against emitted gamma.
- Thermal capture: low energy in germanium. Depends on isotopes. Nucleus recoils against emitted gamma.
- Using photon capture from NRF proposed by Tenzing Joshi with HIGS gamma ray source.
- Pion-iodine scattering in COUPP/PICO bubble chamber



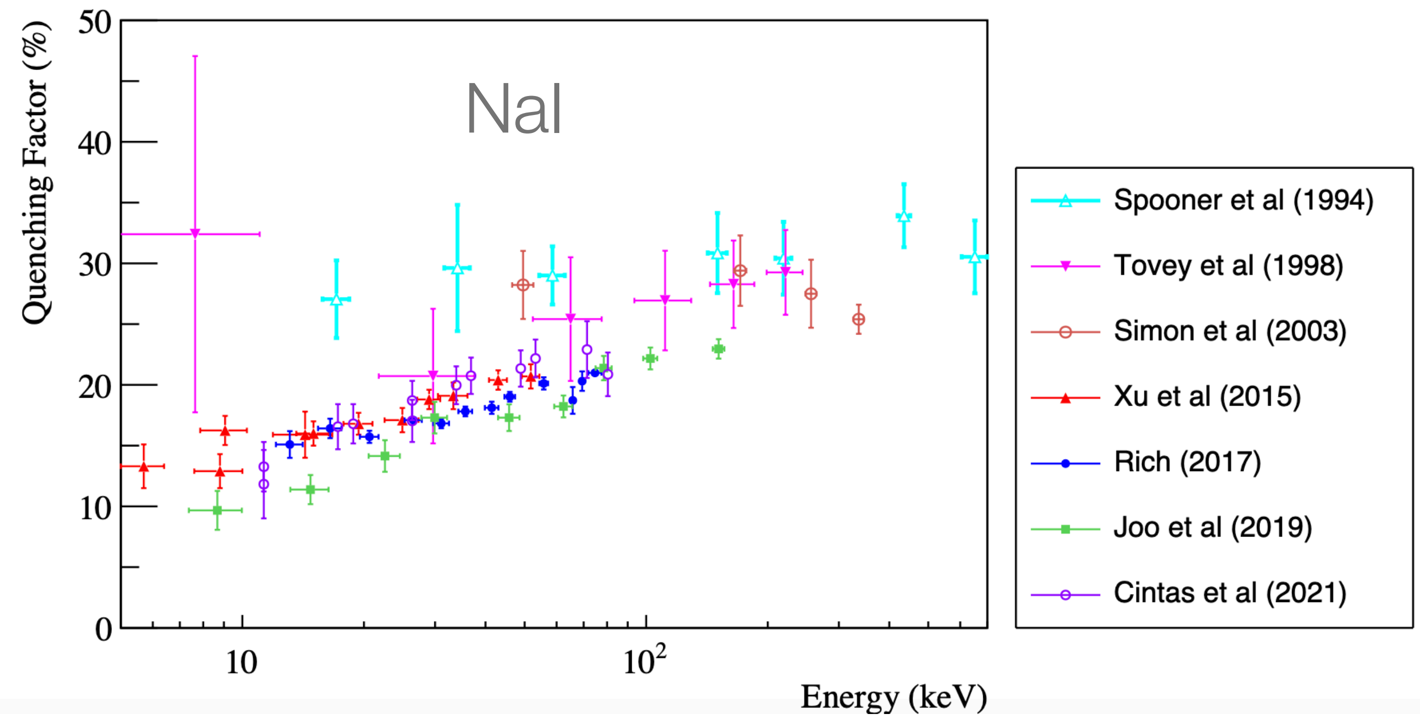
Xu, Barbeau, Hong, ARNPS (submitted)

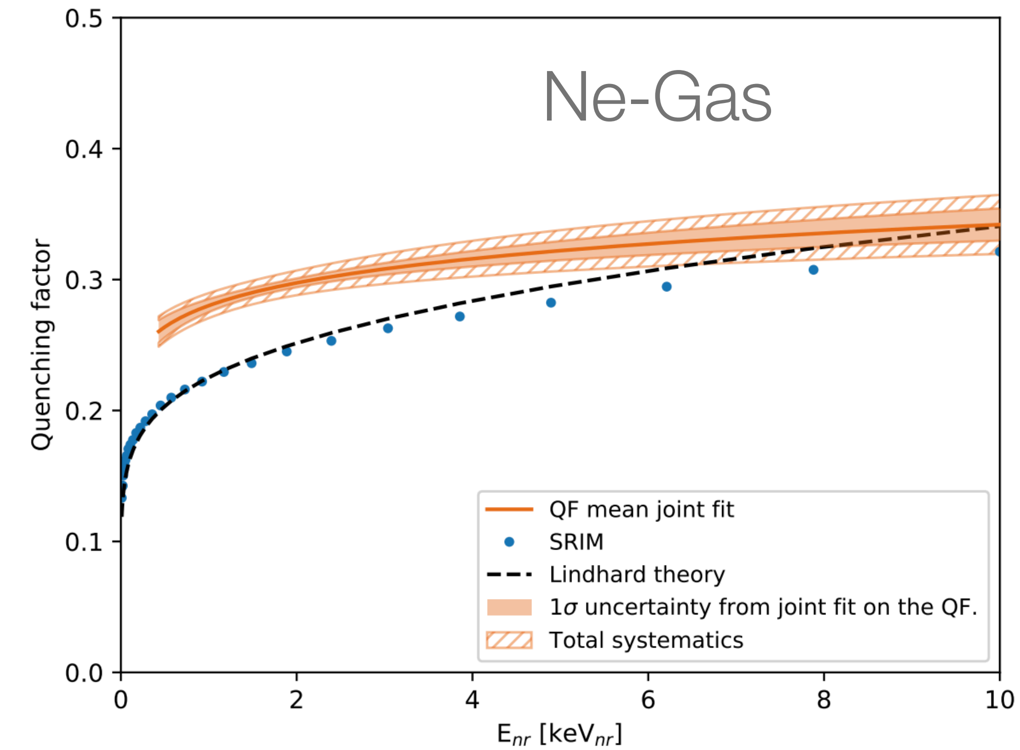
Typical Neutron Sources

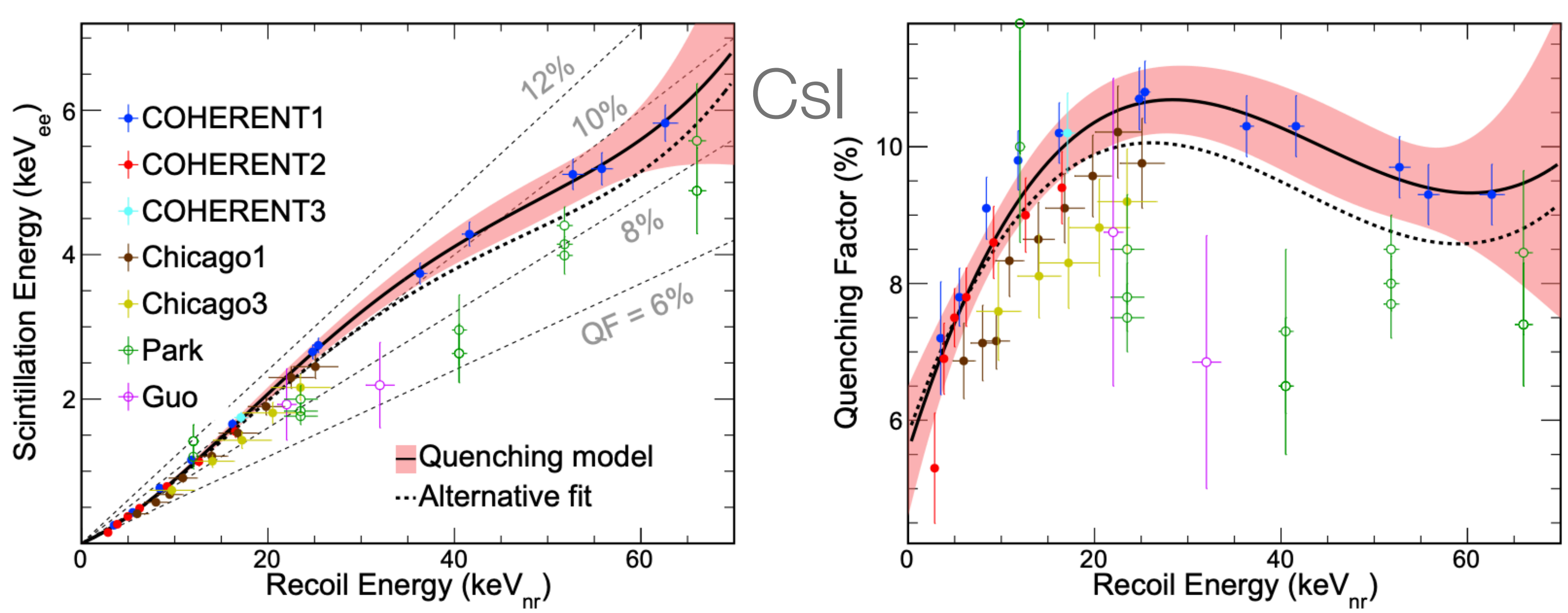
Source	Energy Range (MeV)	Energy Distribution	Yield	Timing
^{252}Cf	0–10 (aver. 2)	continuous	10^3 n/s/μCi	γ-tagging
Fission reactors	0–10 (aver 2) or thermal	continuous	10^{12}-10^{16} n/s/MW_{th}	-
AmBe	0–10	continuous	$\sim5\times10^{-5}$ n/α	γ-tagging
PuBe	0–10	continuous	$\sim5\times10^{-5}$ n/α	γ-tagging
AmLi	0–1.5 (aver. 0.45)	continuous	$\sim10^{-6}$ n/α	
SbBe	0.023	mono-energetic	$\sim10^{-5}$ n/γ	
YBe	0.152	mono-energetic	$\sim10^{-5}$ n/γ	
D-D	2–3	mono-energetic	$\lesssim 10^9$ n/s	$\lesssim$10 µs
D-T	13–15	mono-energetic	$\lesssim 10^{10}$ n/s	$\lesssim$10 µs
p-Li	0–2	mono-energetic	vary	$\gtrsim$1 ns
p-V	0-0.2	mono-energetic	vary	$\gtrsim$1 ns

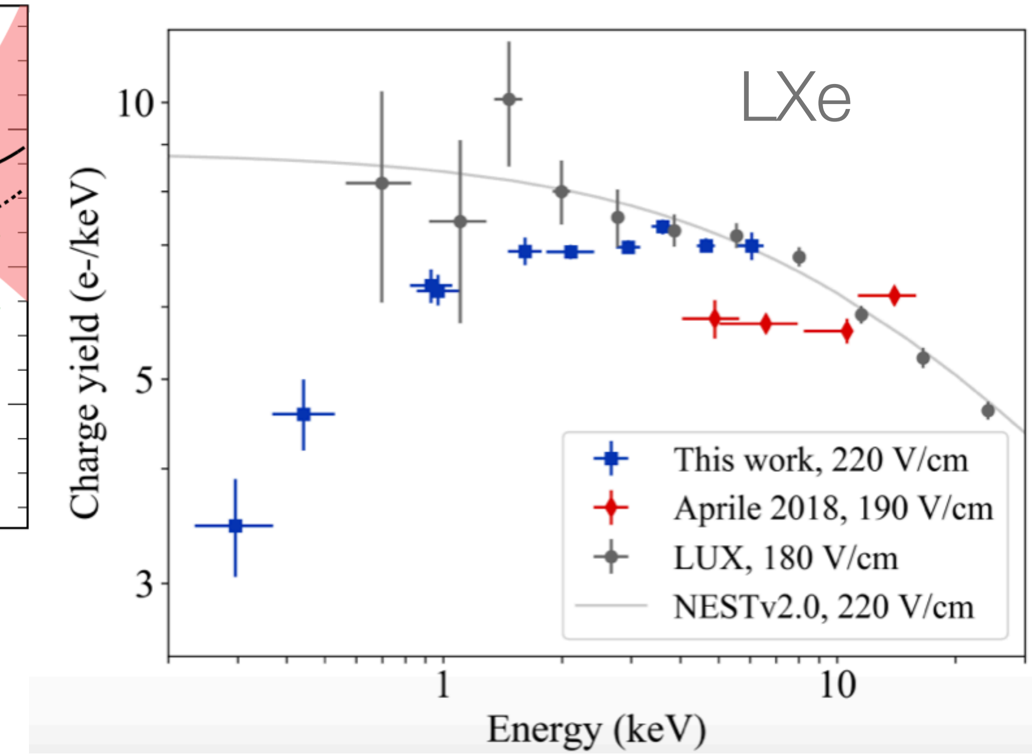
Xu, Barbeau, Hong, ARNPS (submitted)

Survey of Results





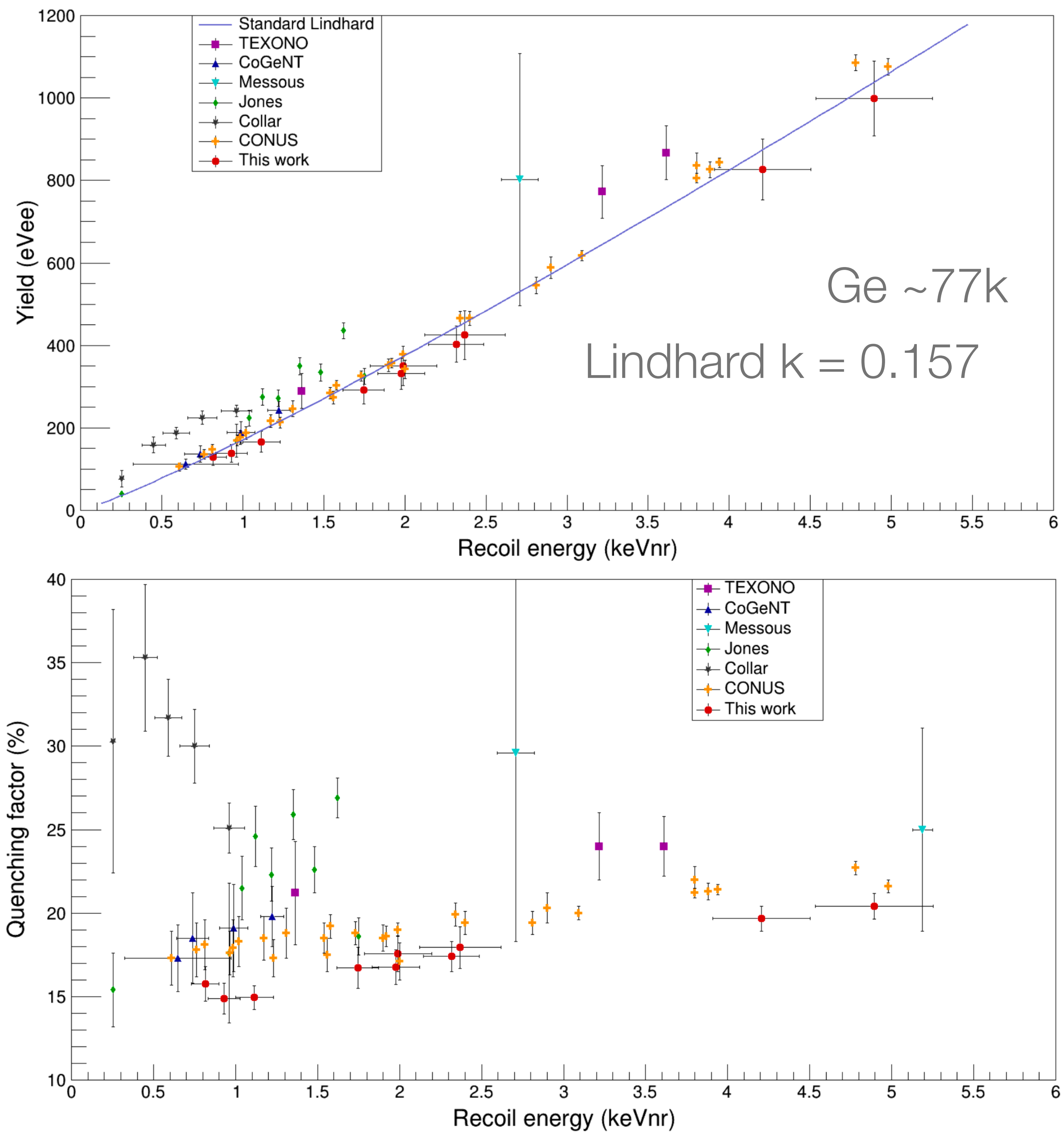




Survey of Results

Long Li PhD Dissertation, Duke

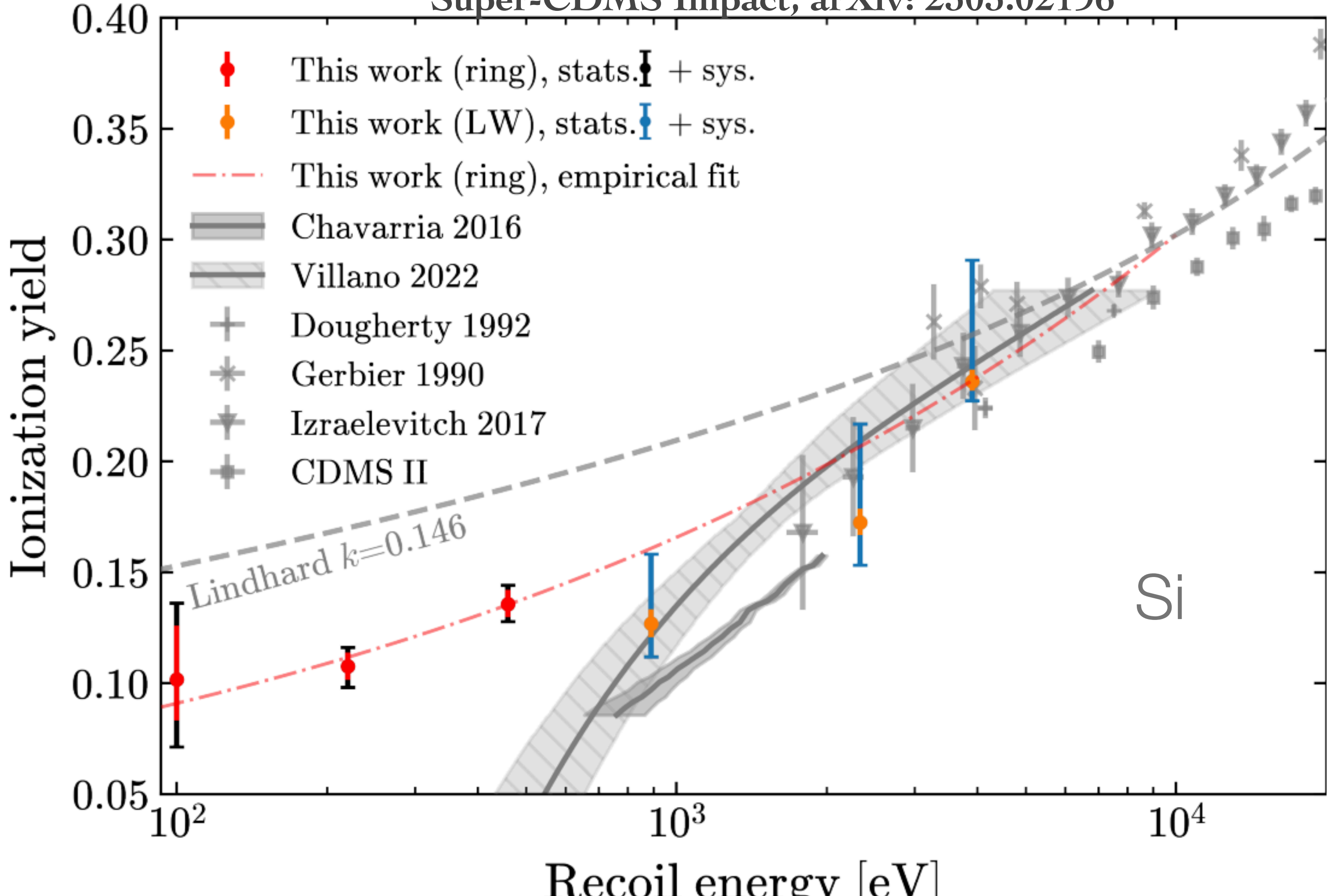
- Ge the elephant in the room
- IMHO: CONUS exceptionally well done
- COHERENT result (Long Li's thesis on N-type detector—red points)
- General disagreement with Collar calibration

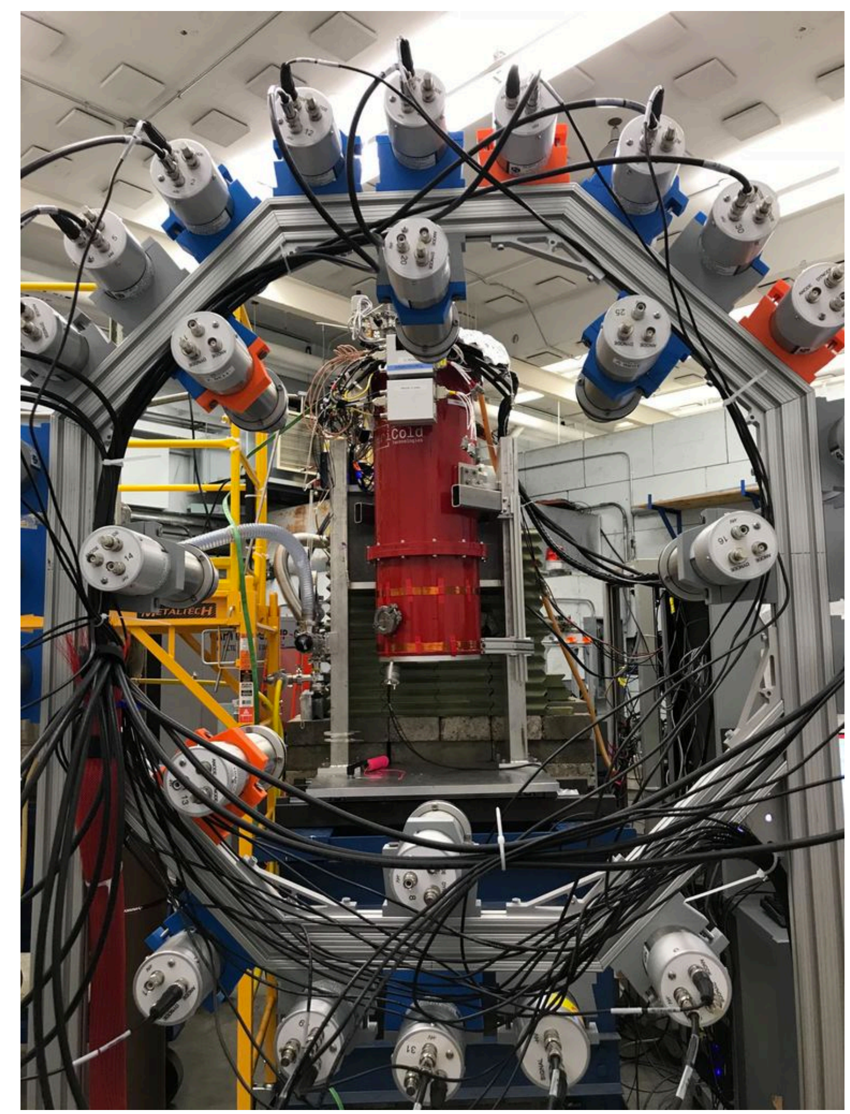


Mitigation of biases

- Using a trigger-less DAQ is ideal for near-threshold events. Rates and energies can be shifted by presence of threshold.
- Avoid small angle scattering where energies change rapidly
- If possible, blind data (see Super-CDMS result)

Super-CDMS Impact, arXiv: 2303.02196

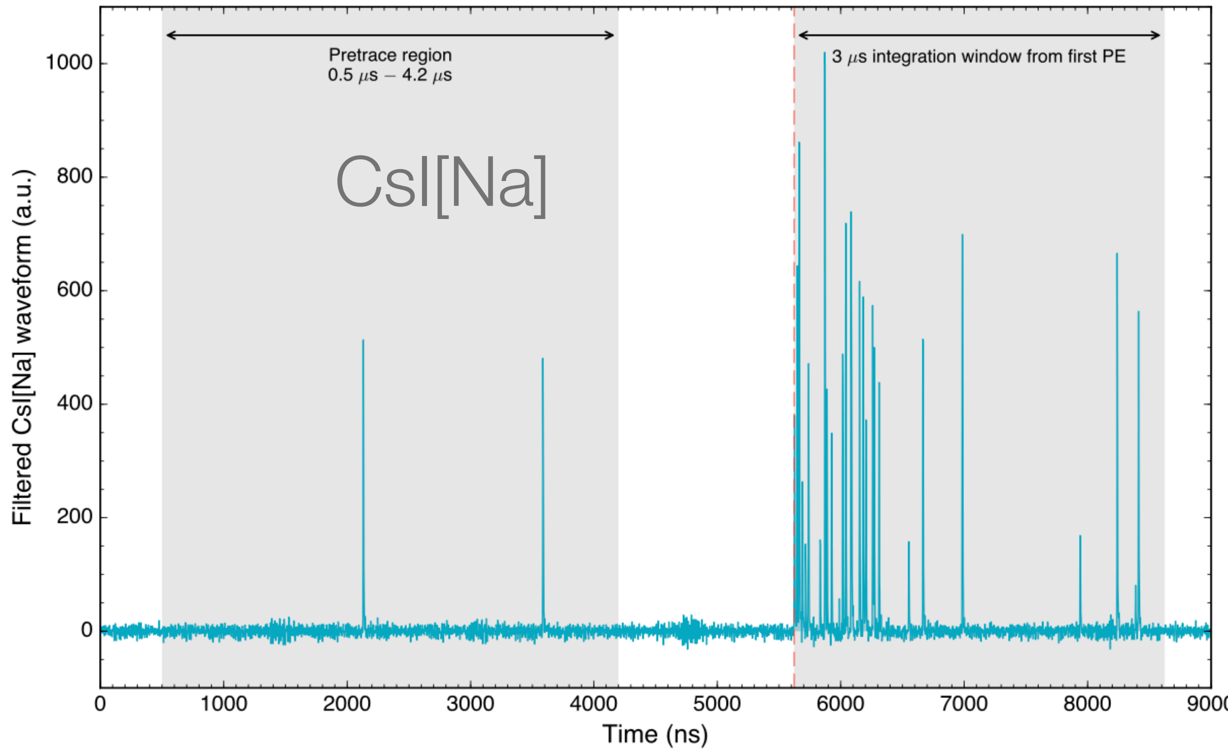




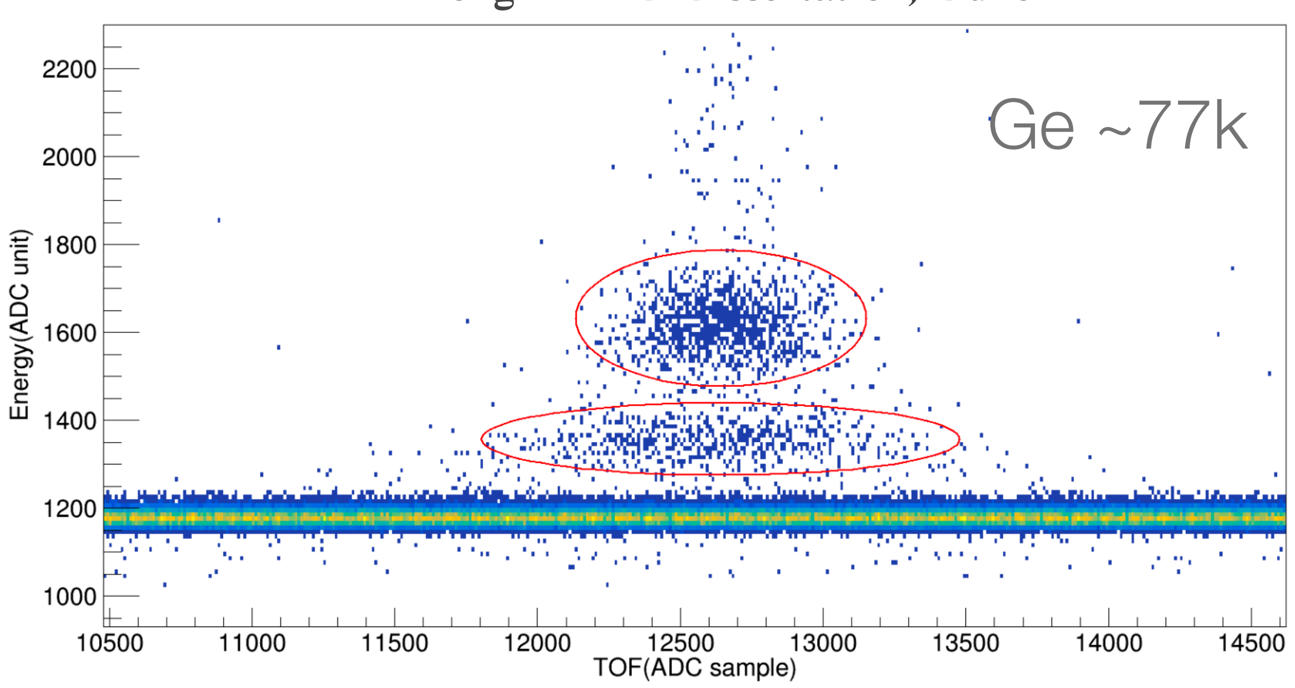
Mitigation of biases

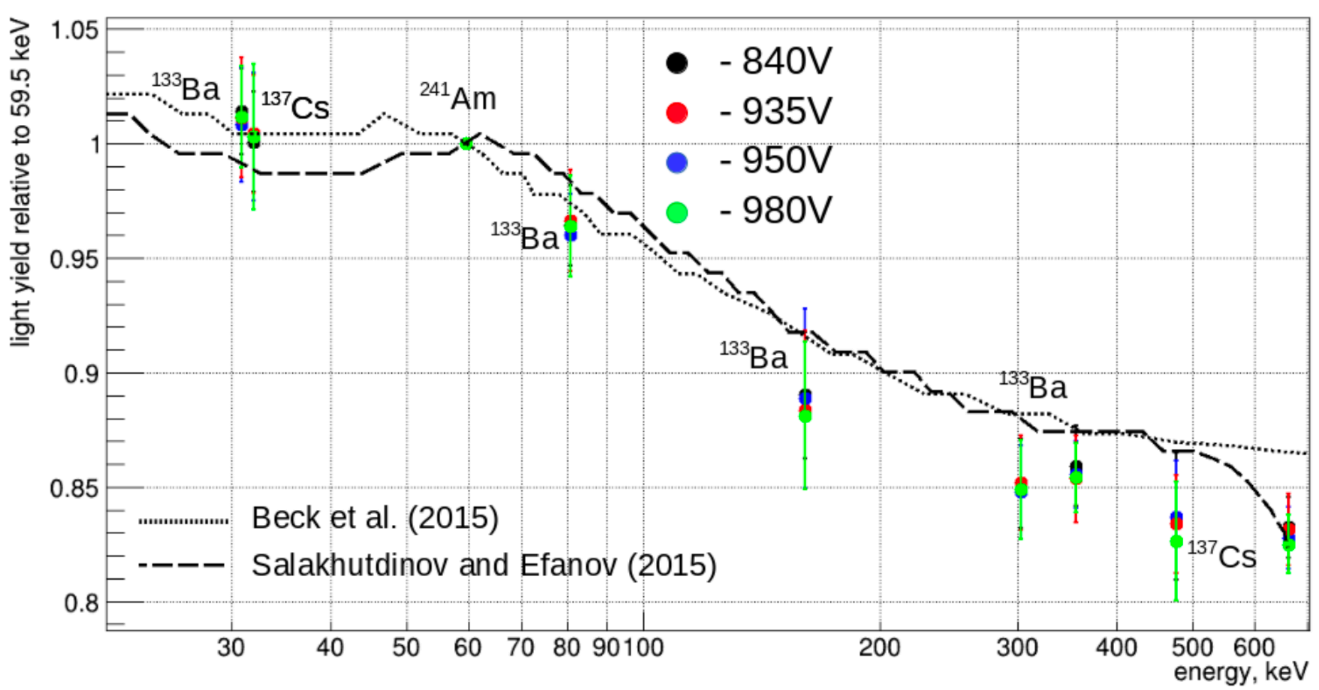
- Timing: 1st photon or recoil time? Effects of noise…
- Nonlinearities (PMTs, scintillation, threshold effects)
- Scaling of waveform analysis algorithms from low to high amplitudes

Grayson Rich PhD Dissertation, UNC



Long Li PhD Dissertation, Duke

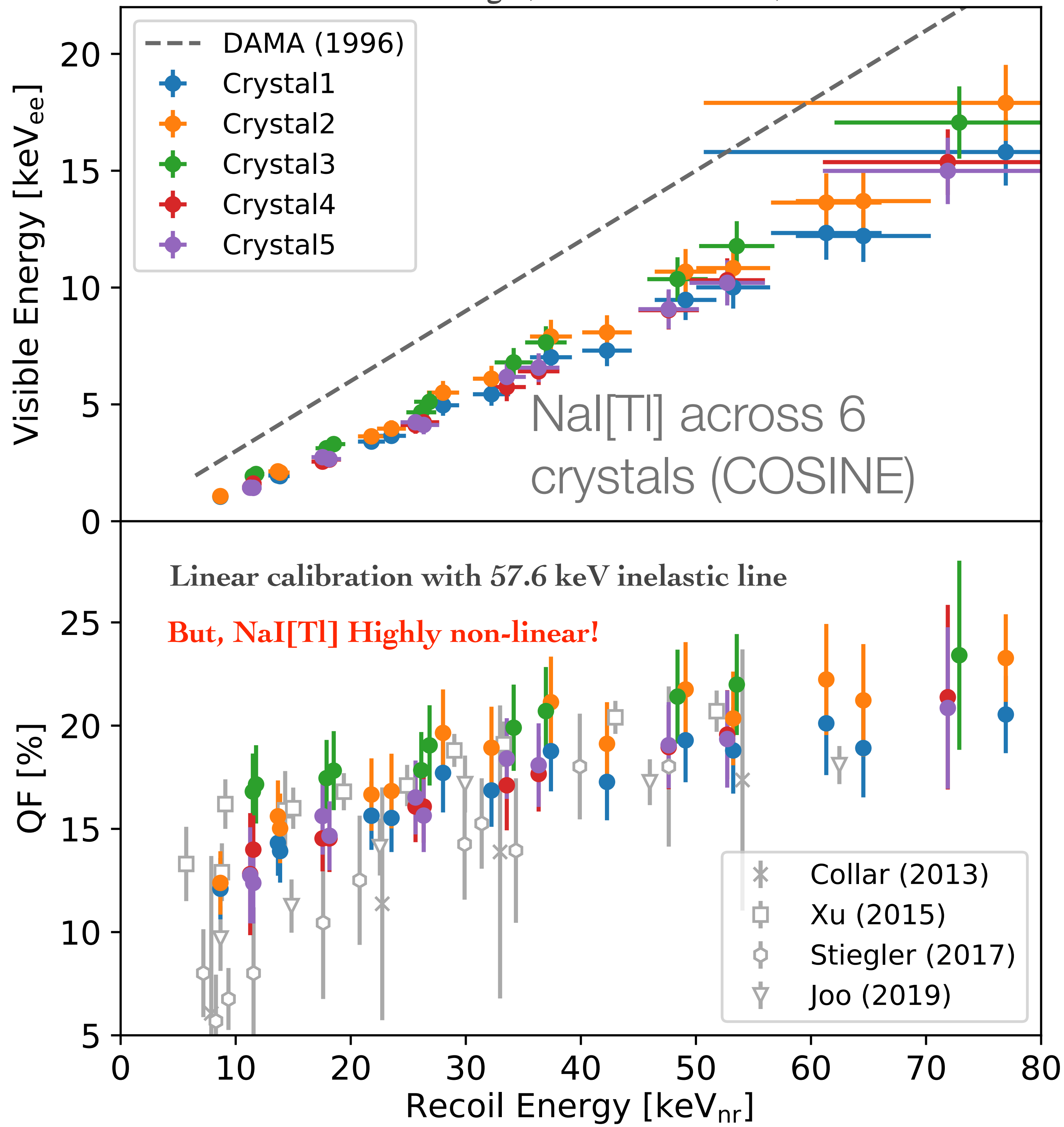




Presentation of results

- Number of quanta: ideal, but challenging to normalize
- Yield value: second best, but susceptible to your "energy" normalizer. (e.g. what peak are you calibrating to? Are there nonlinearities? Need consistency)
- Quenching factor: least ideal. Can see important microphysics, but sources of uncertainty can be obscured. Difficulty to reconcile "spreads" with errors. Horizontal errors end up in vertical errors.

Sam Hedges, PhD Disseration, Duke



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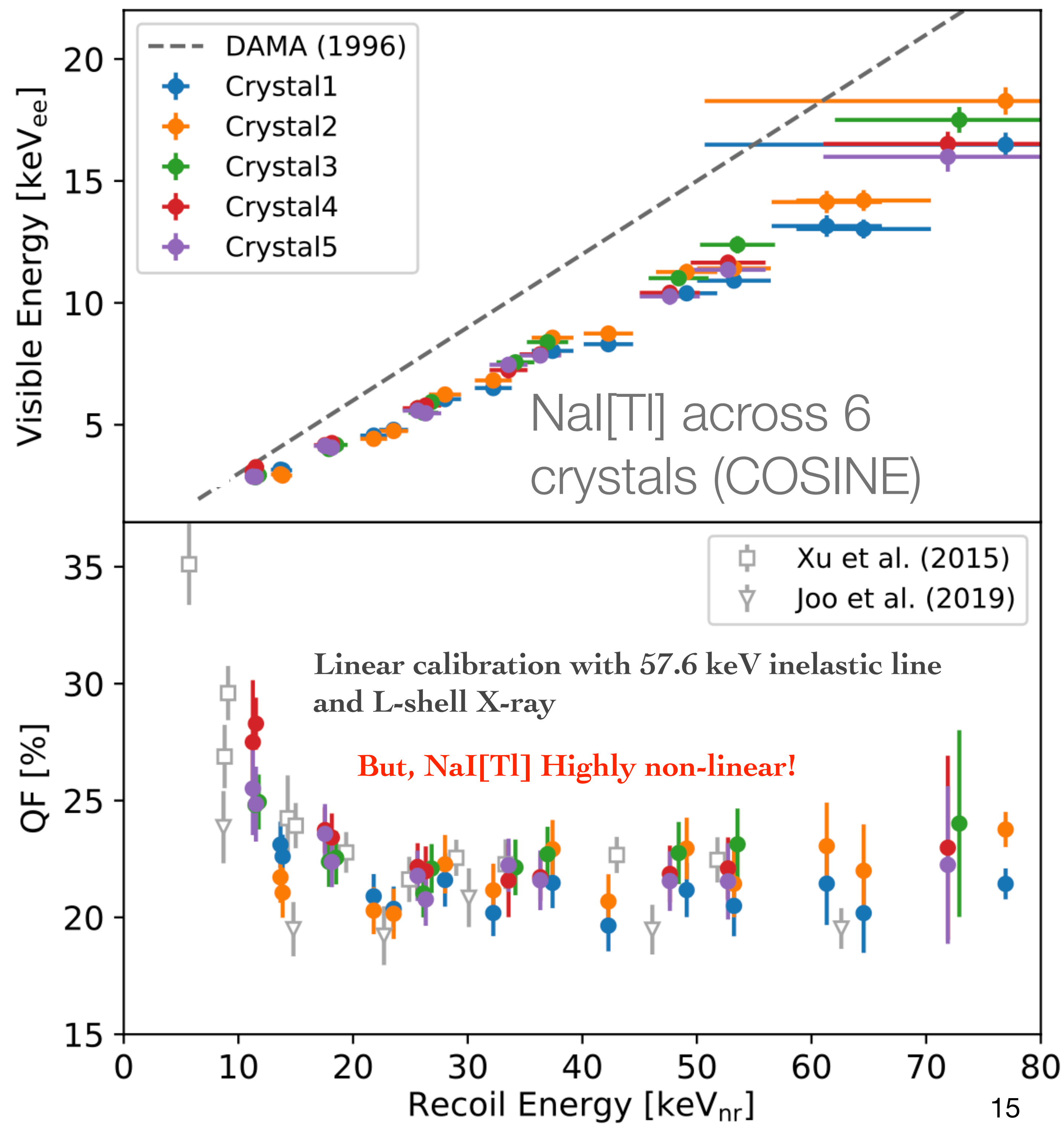

Presentation of results

- Most useful: Full accounting of correlated & uncorrelated errors

LXe **Leonard et al, arXiv:1908.00518**

BD	E (keV)	ΔE		Q_y				Scaling syst.	Modeling syst.
		Uncorr.	Corr.	220V/cm	550V/cm	2.2kV/cm	6.3kV/cm		
1	$6.08^{+0.42}_{-0.52}$	±3.3%	$^{+0.04}_{-0.04}$	$6.98^{+0.08}_{-0.08}$	$7.382^{+0.09}_{-0.11}$	$7.63^{+0.11}_{-0.14}$	$8.00^{+0.12}_{-0.13}$	-	-
2	$4.65^{+0.25}_{-0.24}$	±0.8%	$^{+0.04}_{-0.04}$	$6.99^{+0.12}_{-0.11}$	$7.46^{+0.14}_{-0.14}$	$7.46^{+0.14}_{-0.14}$	$7.95^{+0.21}_{-0.23}$	-	-
3	$3.61^{+0.23}_{-0.22}$	±0.9%	$^{+0.04}_{-0.03}$	$7.33^{+0.11}_{-0.13}$	$7.74^{+0.15}_{-0.15}$	$8.03^{+0.17}_{-0.15}$	$8.08^{+0.20}_{-0.20}$	-	-
4	$2.95^{+0.21}_{-0.20}$	±1.1%	$^{+0.04}_{-0.03}$	$6.96^{+0.10}_{-0.10}$	$7.53^{+0.13}_{-0.16}$	$7.77^{+0.11}_{-0.12}$	$8.17^{+0.11}_{-0.15}$	-	-
5	$2.11^{+0.31}_{-0.28}$	±1.3%	$^{+0.03}_{-0.03}$	$6.88^{+0.09}_{-0.09}$	$7.26^{+0.10}_{-0.10}$	$7.31^{+0.08}_{-0.10}$	$7.63^{+0.14}_{-0.09}$	-	-
6	$1.61^{+0.16}_{-0.15}$	±1.5%	$^{+0.03}_{-0.03}$	$6.89^{+0.21}_{-0.22}$	$7.13^{+0.16}_{-0.21}$	$7.36^{+0.15}_{-0.18}$	$7.764^{+0.18}_{-0.17}$	-	-
7	$0.97^{+0.13}_{-0.11}$	±2.0%	$^{+0.03}_{-0.03}$	$6.23^{+0.22}_{-0.18}$	$6.66^{+0.25}_{-0.32}$	$6.26^{+0.26}_{-0.21}$	$6.84^{+0.23}_{-0.29}$	-	-
8	$0.93^{+0.12}_{-0.11}$	±2.0%	$^{+0.03}_{-0.03}$	$6.32^{+0.23}_{-0.24}$	$6.48^{+0.27}_{-0.25}$	$6.47^{+0.26}_{-0.30}$	$6.84^{+0.27}_{-0.35}$	-	-
9	$0.442^{+0.088}_{-0.074}$	±3.0%	$^{+0.016}_{-0.018}$	$4.58^{+0.39}_{-0.38}$	$4.94^{+0.38}_{-0.36}$	$4.80^{+0.41}_{-0.43}$	$5.47^{+0.43}_{-0.43}$	-5.9%	5.5%
10	$0.296^{+0.074}_{-0.062}$	±3.6%	$^{+0.018}_{-0.014}$	$3.47^{+0.41}_{-0.40}$	$4.50^{+0.48}_{-0.45}$	$4.31^{+0.40}_{-0.37}$	$4.46^{+0.50}_{-0.50}$	+6.4%	11.0%
Electron lifetime systematic				±2.9%	±2.5%	±2.1%	-		
Extraction efficiency systematic				+2.0% / −1.5%					

Future challenges

- Lower energies: see next talk. Much of the best advice may change!
- Migdal: Several experiments motivated to search for this
- Precision: Next-phase CEvNS experiments will need to do better than ~5%-level
- Complexity: With more detectors comes more variance from channel to channel (e.g. across multiple NaI detectors in an array)
- Directionality: CYGNUS style detectors may be able to give us a new observable for CEvNS (recoil angle). Detector responses will need calibrating.

Sven Vahsen, SNOWMASS, July 2022