SABRE South and the search for dark matter in Australia

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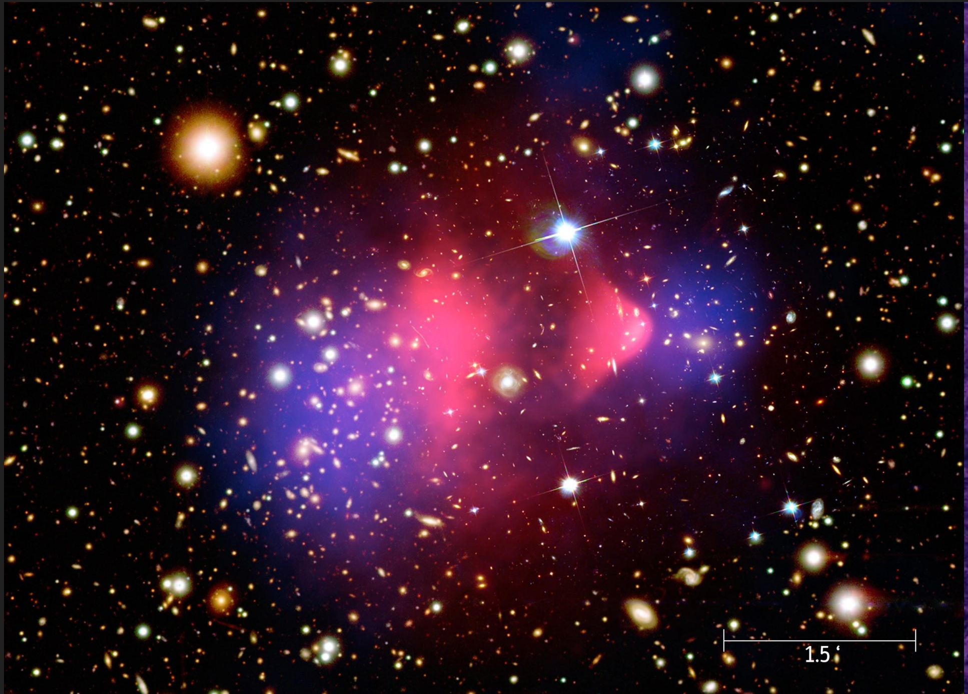
Dark Matter Recap

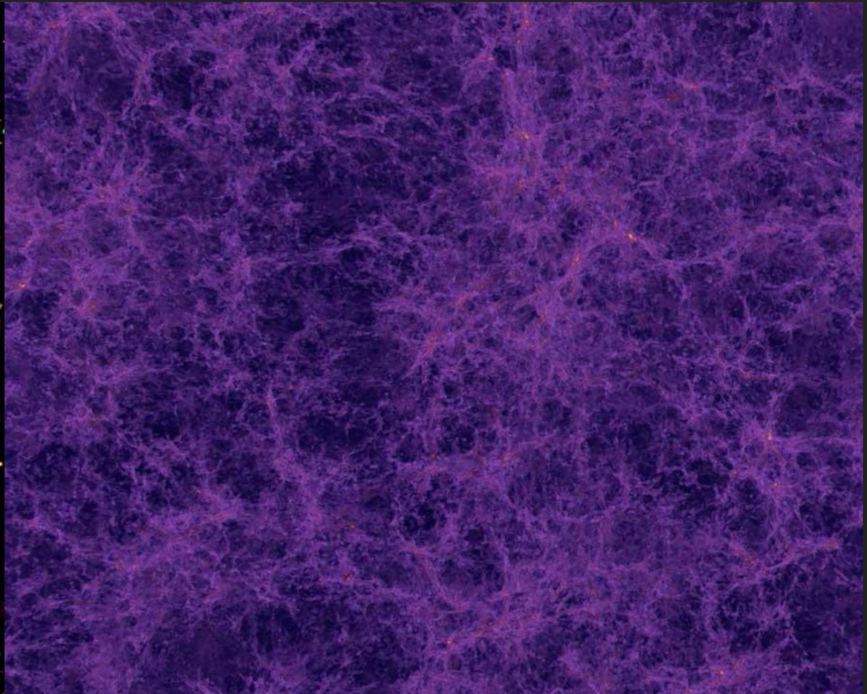
Gravitationally bound systems (eg. galaxy clusters, rotation curves)

Gravitational lensing (eg. galaxy mergers)

Cosmology (eg. CMB, nucleosynthesis, large scale structure)

A new particle? WIMP?



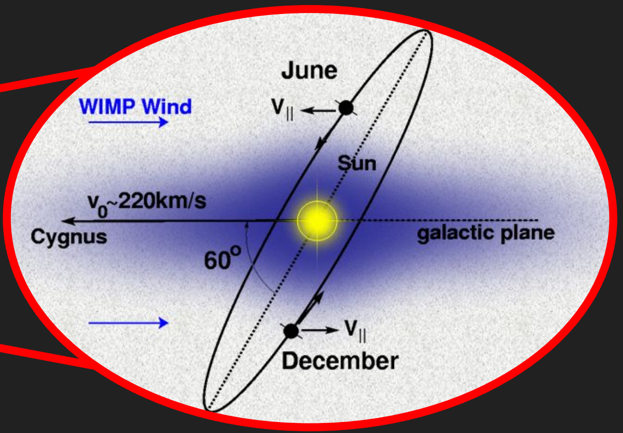


Annual Modulation

Dark matter ‘wind’ from galactic orbit.

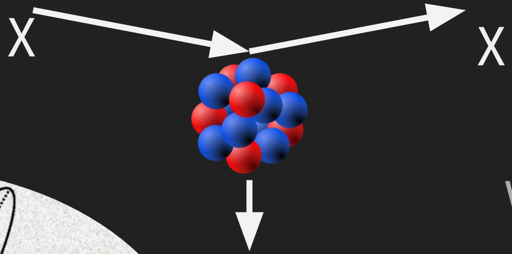
Earth’s orbit modulates the flux.

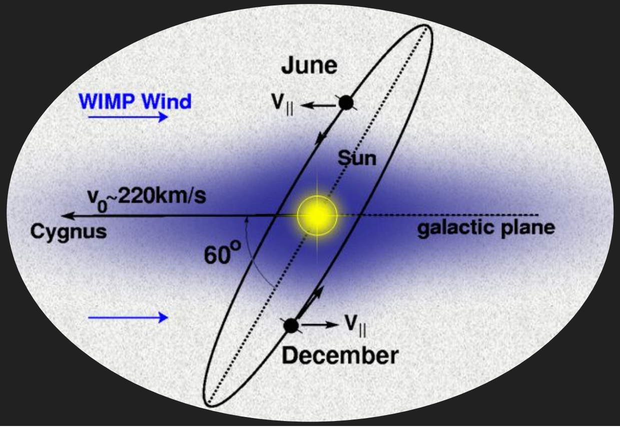
Modulation fraction ~1-10% [1] of total flux.



[1] Freese *et al.*, arxiv:1209.3339

Annual Modulation



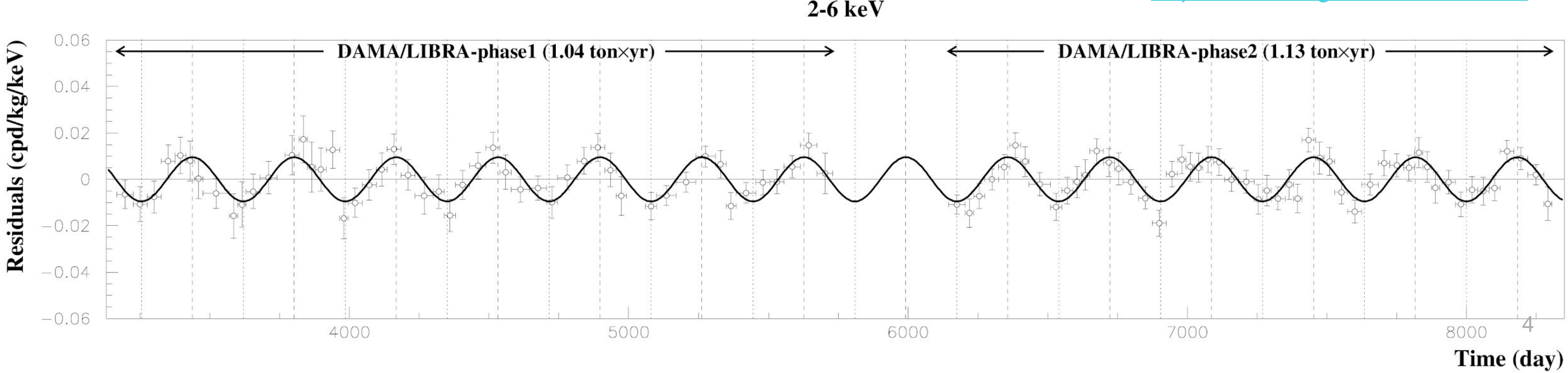


WIMP detection: coherent elastic scattering.

Expect the event rate to modulate through the year.

DAMA: reports a highly significant (12.9 σ) modulation signal consistent with dark matter in their NaI:Tl detector.

https://arxiv.org/abs/1805.10486



No-one else has seen DAMA's signal

Latest results →~5 orders of magnitude better sensitivity than DAMA.

Model-dependent

$$\frac{dR}{dE_r}(E,t) = \frac{\rho_\chi}{m_N m_\chi}\int_{v_{min}}^{v_{max}} v f(\vec{v},t)\,\frac{d\sigma(v,E_r)}{dE_r}\,d^3v$$

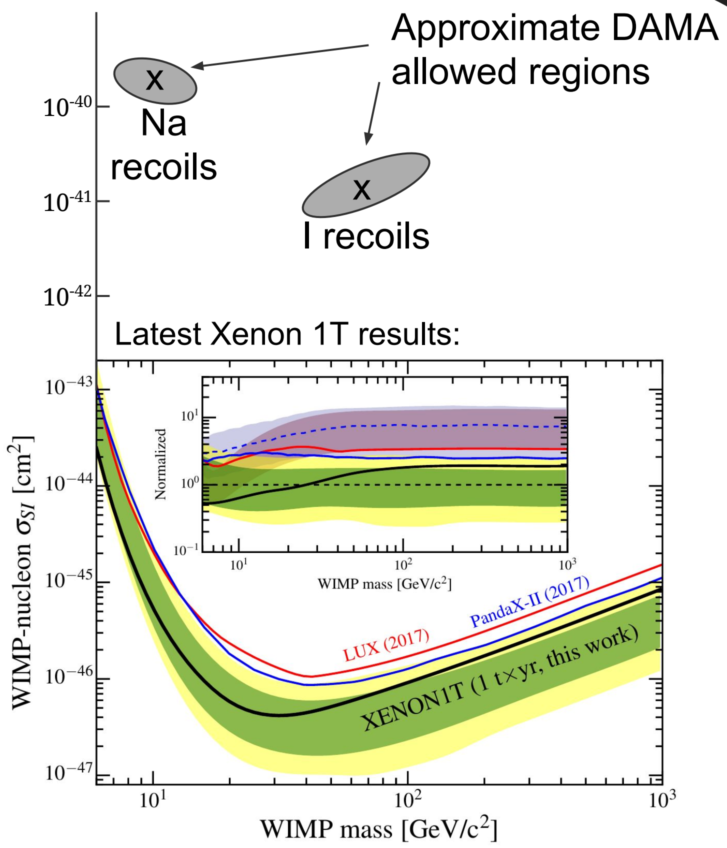
Do WIMPs like Na?

Does DAMA have a seasonal systematic?

Need a model-independent test of DAMA.

Same target material.

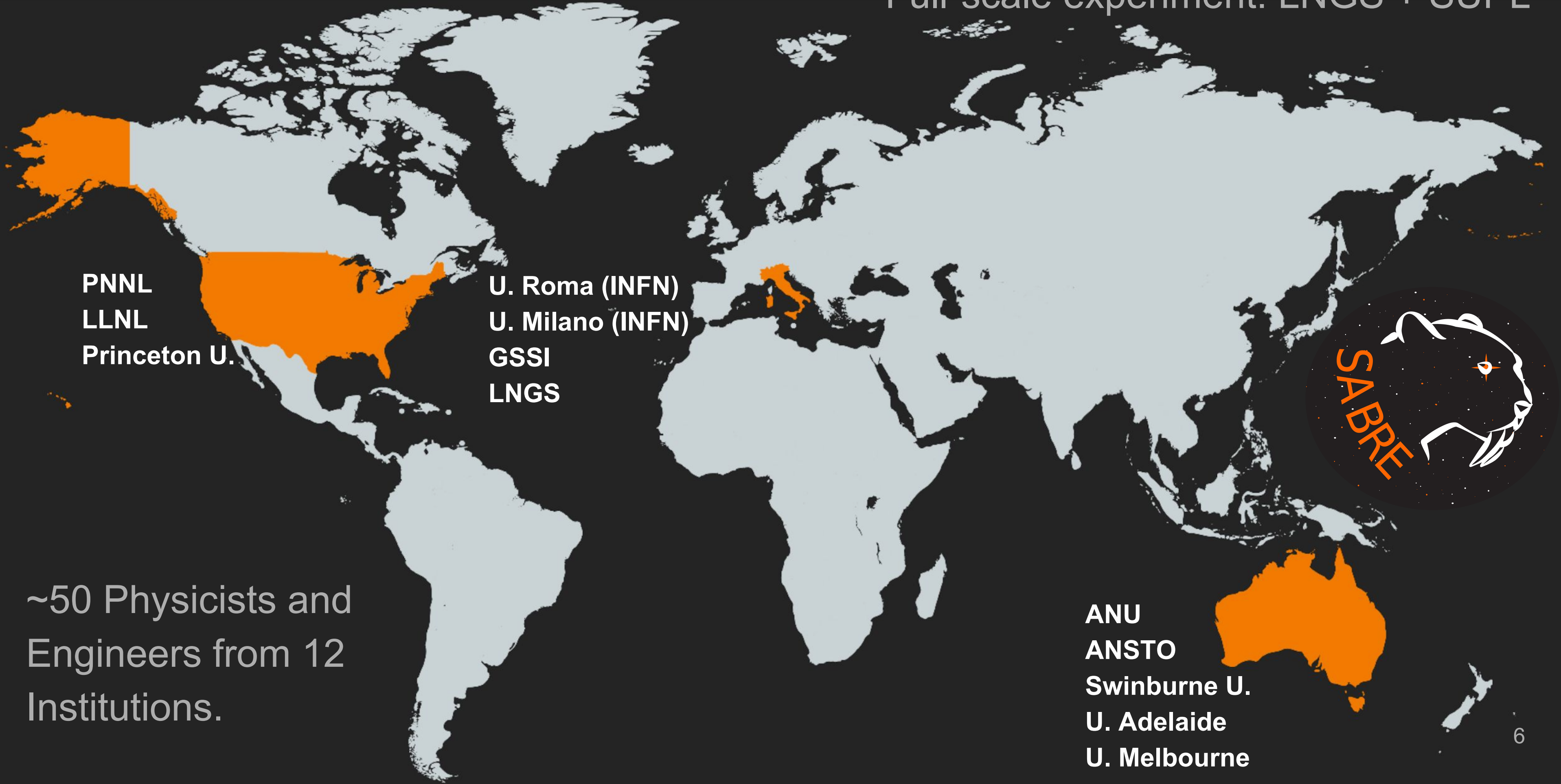
Modulation analysis.



SABRE Collaboration

Proof-of Principle: LNGS

Full-scale experiment: LNGS + SUPL



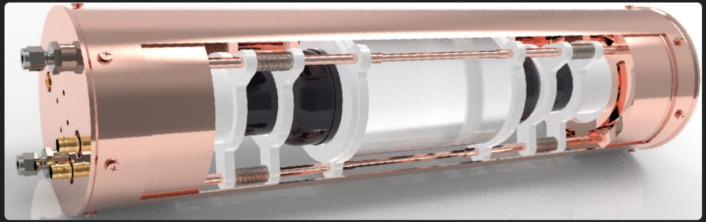
~50 Physicists and Engineers from 12 Institutions.

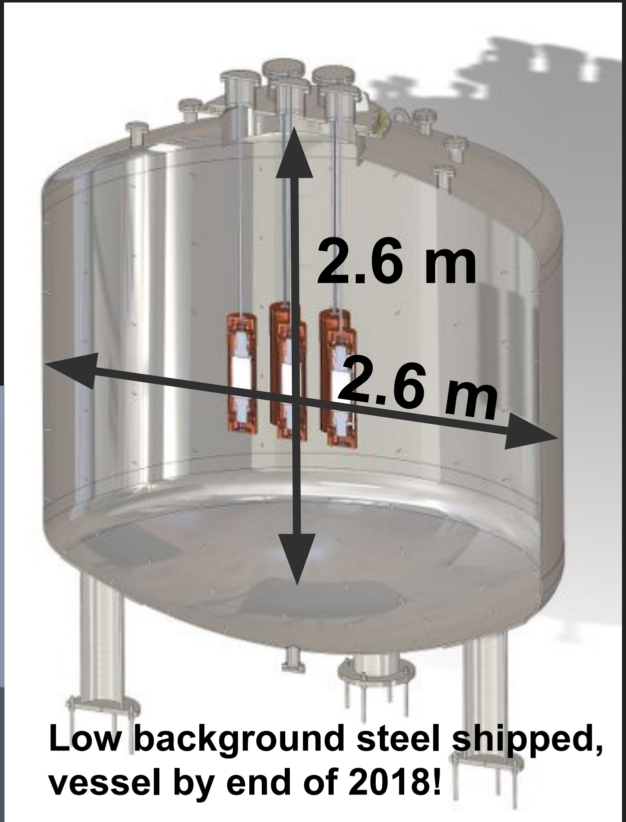
SABRE South Design

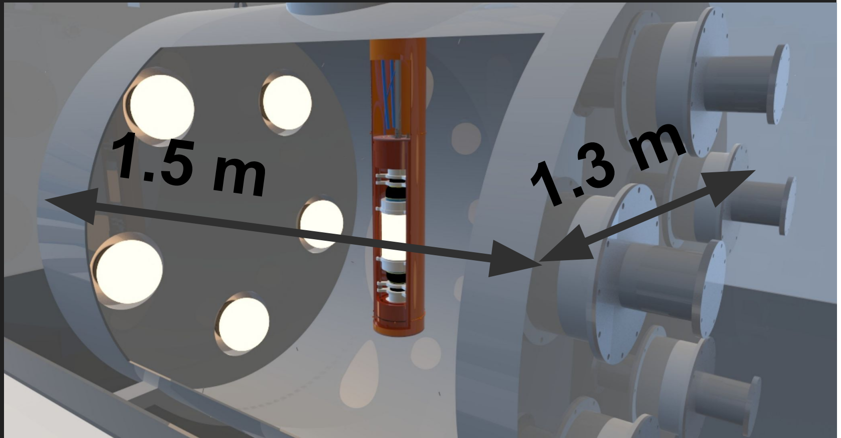
Proof-of-Principle detector: 5.2 kg NaI:Tl.
- Test veto and background performance,
- Validate simulation model.

South Full Scale detector: 7 PoP crystals.
- Ultrapure NaI:Tl target (~40 kg)
- Liquid Scintillator Veto (10.5 T)
- Two Sites

Goal:
More sensitivity than DAMA

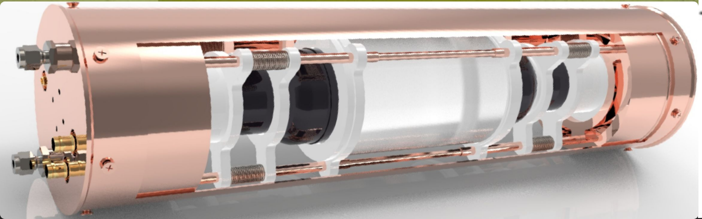






SABRE Design


First Production Crystal! (June 2018)



Intrinsic radioactivity limits WIMP sensitivity.

'Astrograde' powder (Sigma Aldrich).
Powder preparation + growth (Princeton + RMD).

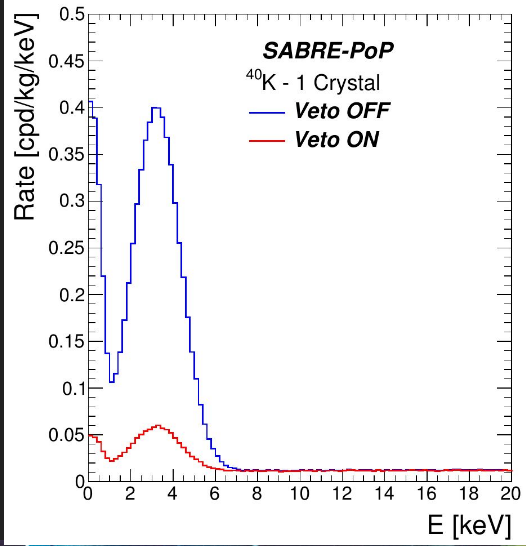
Lower radio-impurity than DAMA.

^{210}**Pb**: important background, hard to quantify!
Accelerator mass spectrometry: new method improved limits by 10^2. Aiming for <1 mBq/kg.

Element	DAMA powder [ppb]	DAMA crystals [ppb]	Astro-Grade [ppb]	SABRE crystal [ppb]
K	100	$\sim$13	9	9
Rb	n.a.	<0.35	<0.2	<0.1
U	$\sim$0.02	$0.5\text{-}7.5\times10^{-3}$	$<10^{-3}$	$<10^{-3}$
Th	$\sim$0.02	$0.7\text{-}10\times10^{-3}$	$<10^{-3}$	$<10^{-3}$

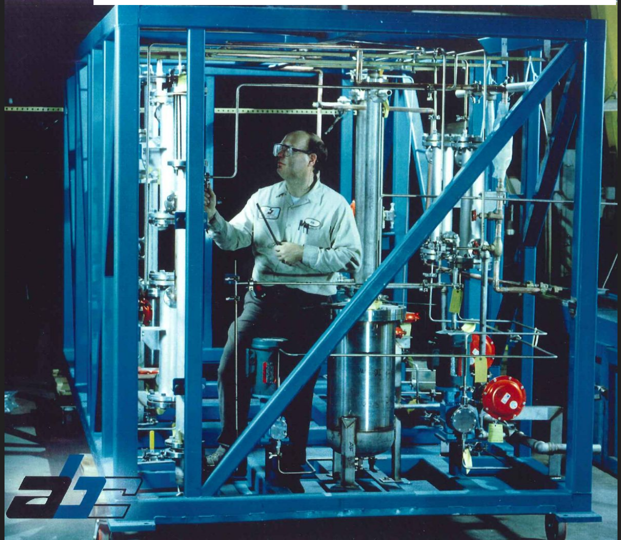
Liquid Scintillator Veto

Proof-of-Principle veto 84% of ^{40}K in signal range.



Radiopure Shielding and background tagging. External neutrons/gammas, internal decay-correlated gamma rays (especially ^{40}K).

SABRE North: Pseudocumene-based LS.
SABRE South: Linear alkylbenzene-based LS, ex-CTF purification system? Production at ANU.



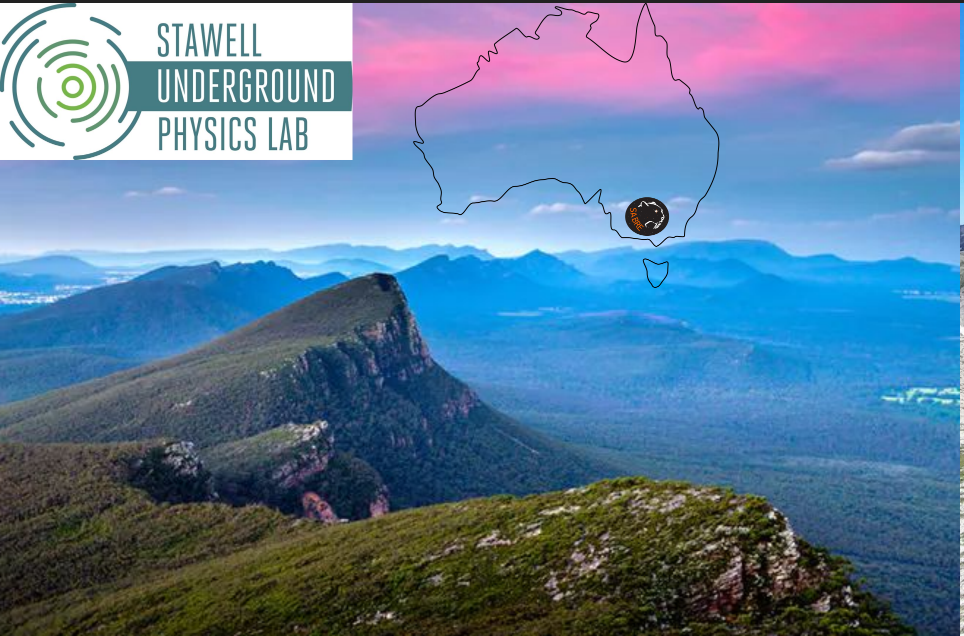
Two Hemisphere Experiment

SABRE will be at two underground sites in the Northern/Southern Hemisphere.

Seasonal background modulations are out of phase

Dark matter modulations are in phase (and strong evidence for DM).

Stawell (SABRE South)



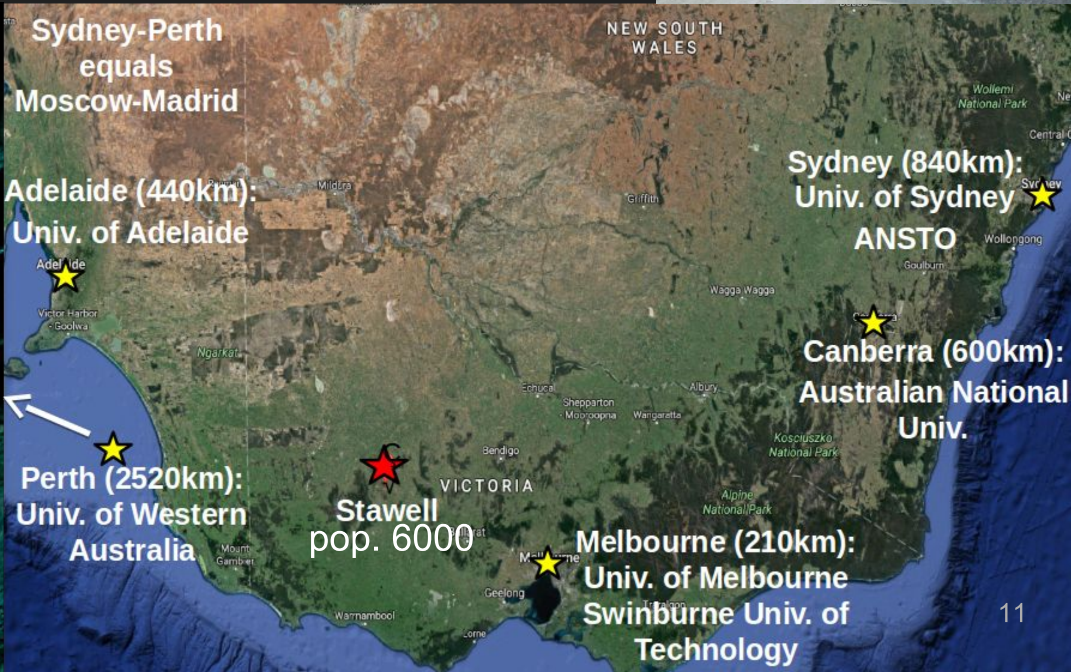
Gran Sasso (SABRE North)

Stawell Underground Physics Laboratory

The first underground laboratory in the Southern Hemisphere.

Decline-type gold mine (basalt rock). Laboratory planned for 1025 m.

Environmental condition: 40°C!



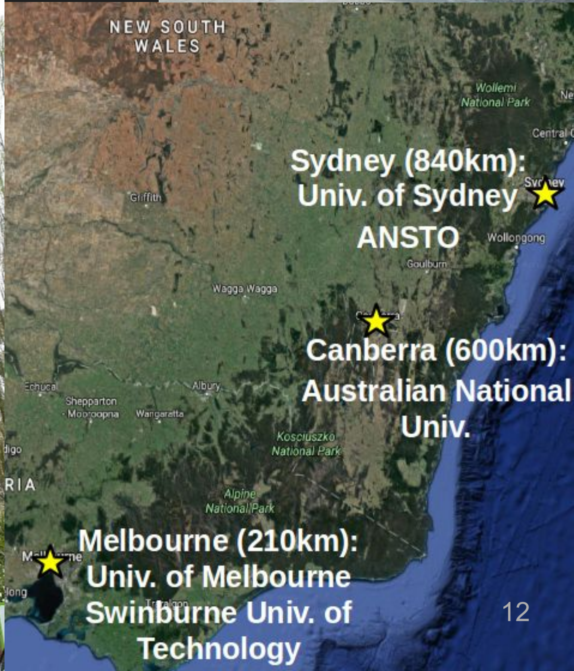
Stawell Underground Physics Laboratory

The first underground la

Decline-type gold mine

5 m.

Environmental conditi



The Stawell Underground Physics Laboratory

Backgrounds comparable to other LNGS:

Flux [$cm^{-2}s^{-1}$]	Thermal neutrons	Fast neutron
Rosebery	4.5E-05	1.1E-05
Stawell	3.0E-05	6.6E-06
LNGS	4.0E-06	<4.0E-06

Flux [$\gamma cm^{-2}s^{-1}$]	E>100 keV	E>600 keV	^{40}K (1461 keV)	^{208}Tl (2614 keV)
Rosebery	7.6E-01	3.3E-01	4.7E-02	1.2E-02
Stawell	2.3E-01	8.9E-02	1.3E-02	2.1E-03
LNGS (Hall C)*	4.0E-01	1.5E-01	4.8E-03	9.4E-04

	Gran Sasso	Stawell 1025m	Rosebery 1200m
^{232}Th (ppm)	<0.1	0.1 - 5.6	4 - 17

Stawell 1025m (results from Alan Robinson, the University of Chicago)

	Sample	White Rock	Dark Rock	Concrete
232 Th	Conc. [ppb]	5,610	88	4,450
238 U	Conc. [ppb]	3,360	330	900
232 Th	Activity [Bq/kg]	22.8	0.4	18.1
238 U	Activity [Bq/kg]	41.5	4.1	11.1

LNGS (https://arxiv.org/pdf/hep-ex/0503054.pdf

	Sample	Hall B Rock	Hall C Rock	Concrete
232 Th	Conc. [ppb]	62	66	656
238 U	Conc. [ppb]	420	660	1,050
232 Th	Activity [Bq/kg]	0.3	0.3	2.7
238 U	Activity [Bq/kg]	5.2	8.1	13.0

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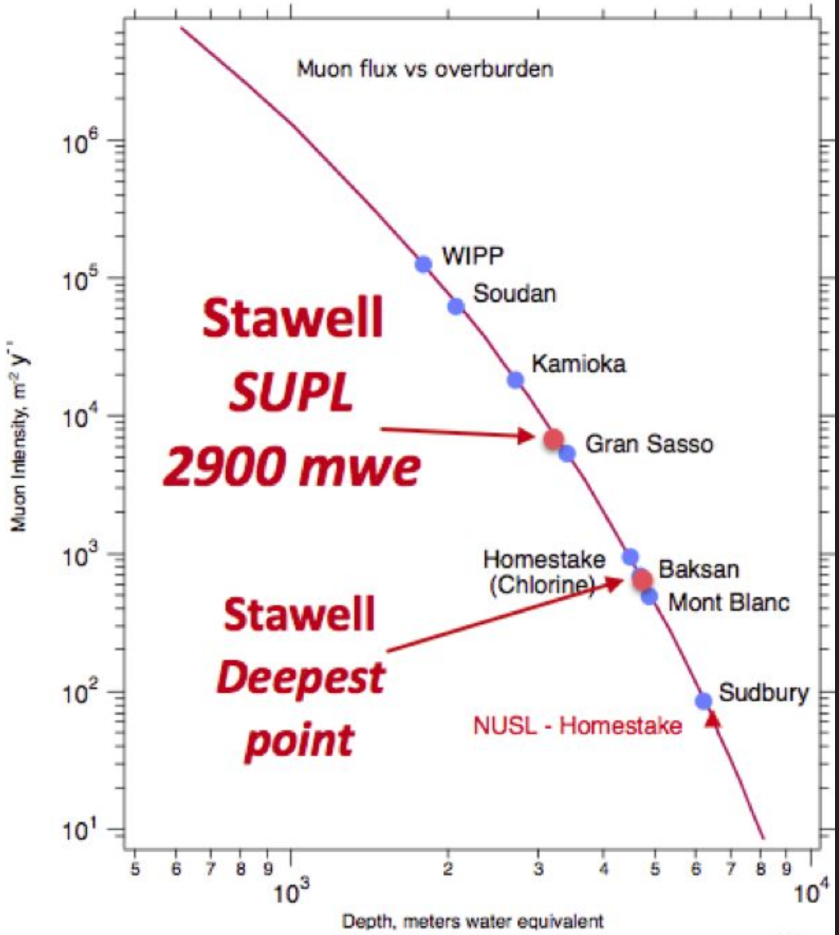
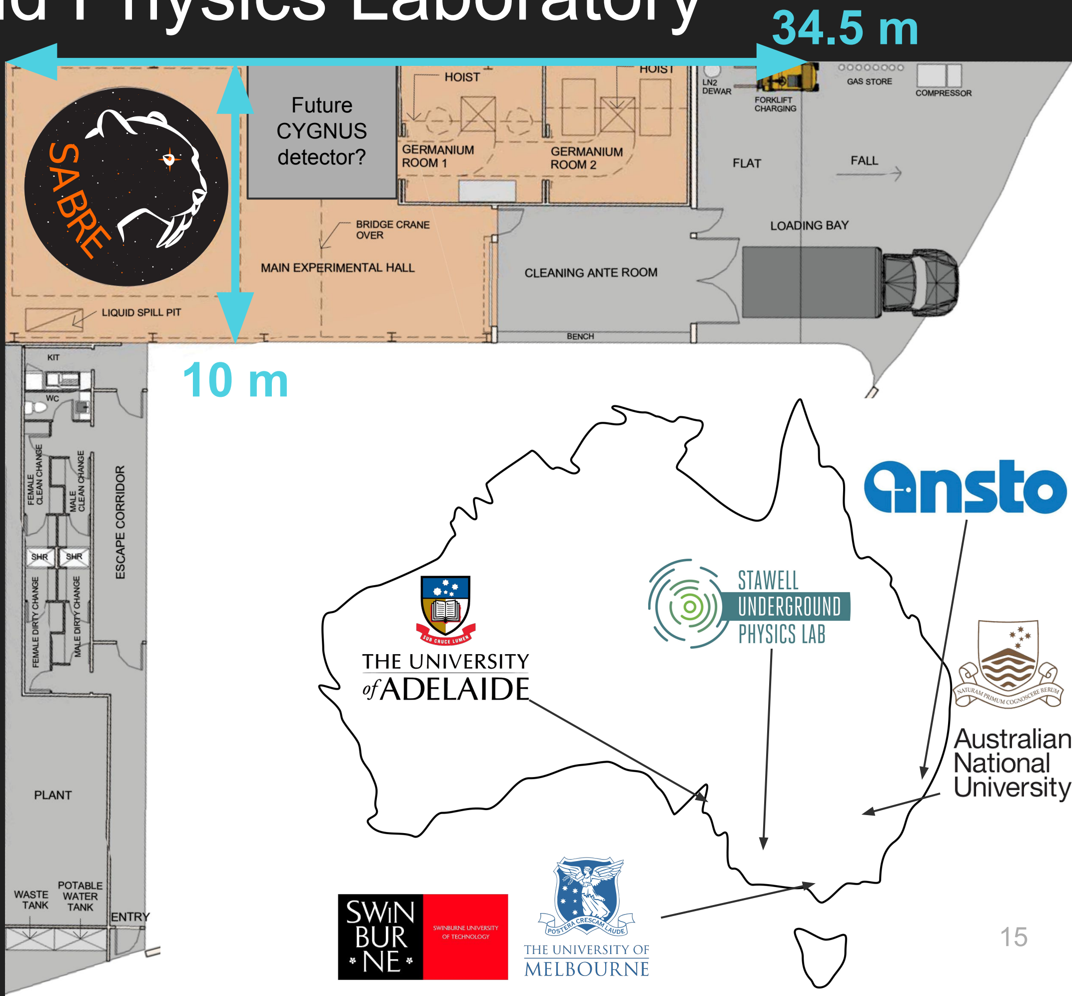
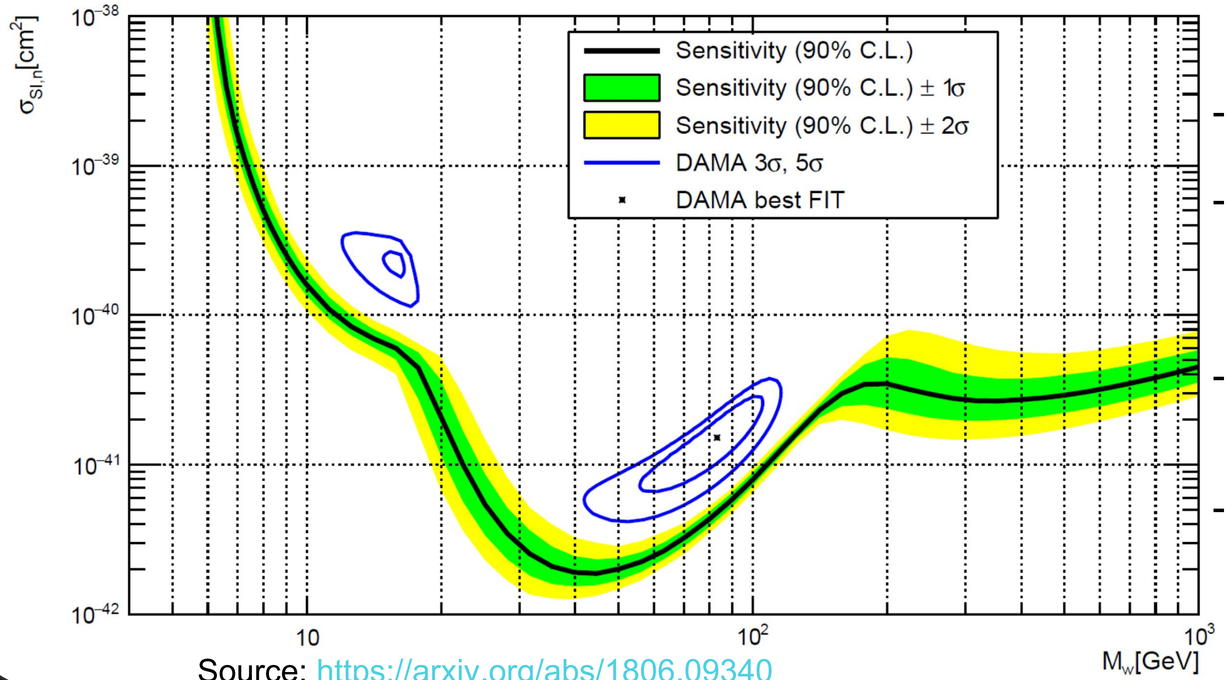




Projected SABRE Sensitivity

- Can rule DAMA in/out in 3 years, using modulation.
  - Confirm at 6 σ, reject at 5 σ. **Model independent**.
  - Measured contamination + detector MC + toy MC of modulation measurement.



Source: https://arxiv.org/abs/1806.09340

- 50 kg NaI:Tl, for 3 years of measurement.
- 0.22 counts day^{-1} kg^{-1} keV^{-1} (PoP simulation) across [2, 6] keV signal region.
- Quenching factor of Xu (https://arxiv.org/abs/1503.07212).
- Standard halo model and spin-independent interaction.

Quenching Factor Measurements

LY (Nuclear Recoil) < LY (Electron Recoil)

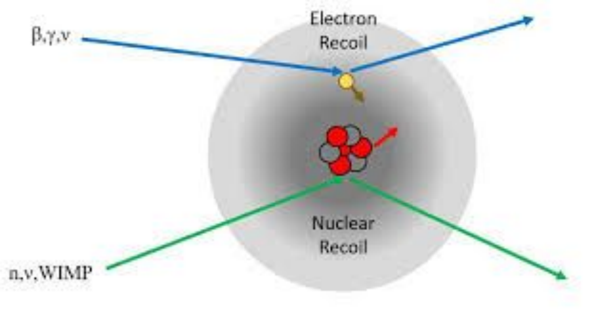
Why?

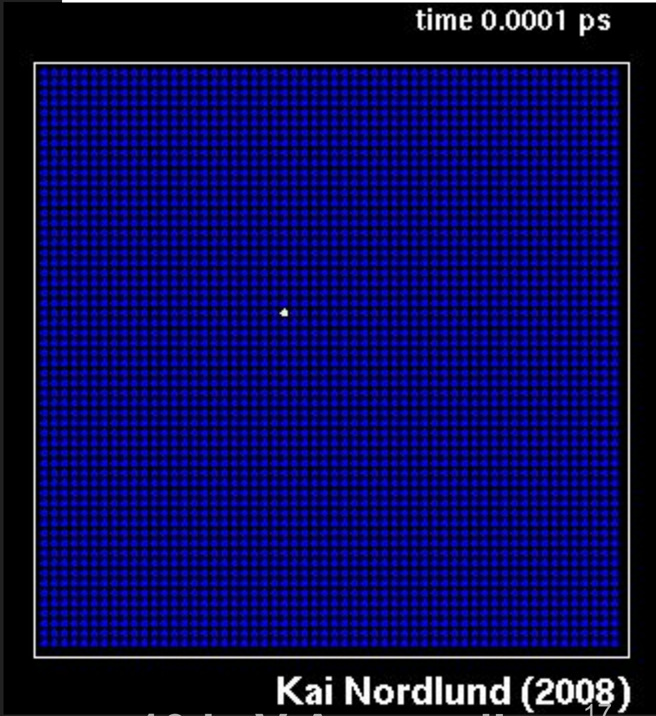
Nuclear stopping power: more energy lost to lattice displacements and phonons.

dE/dx 'Birks' quenching: high excitation densities -- non-radiative de-excitation becomes more probable. Also faster decay time (particle ID).

In a detector, ER is convenient for calibration, so we need to know:

$$QF = LY_{NR} / LY_{ER}$$

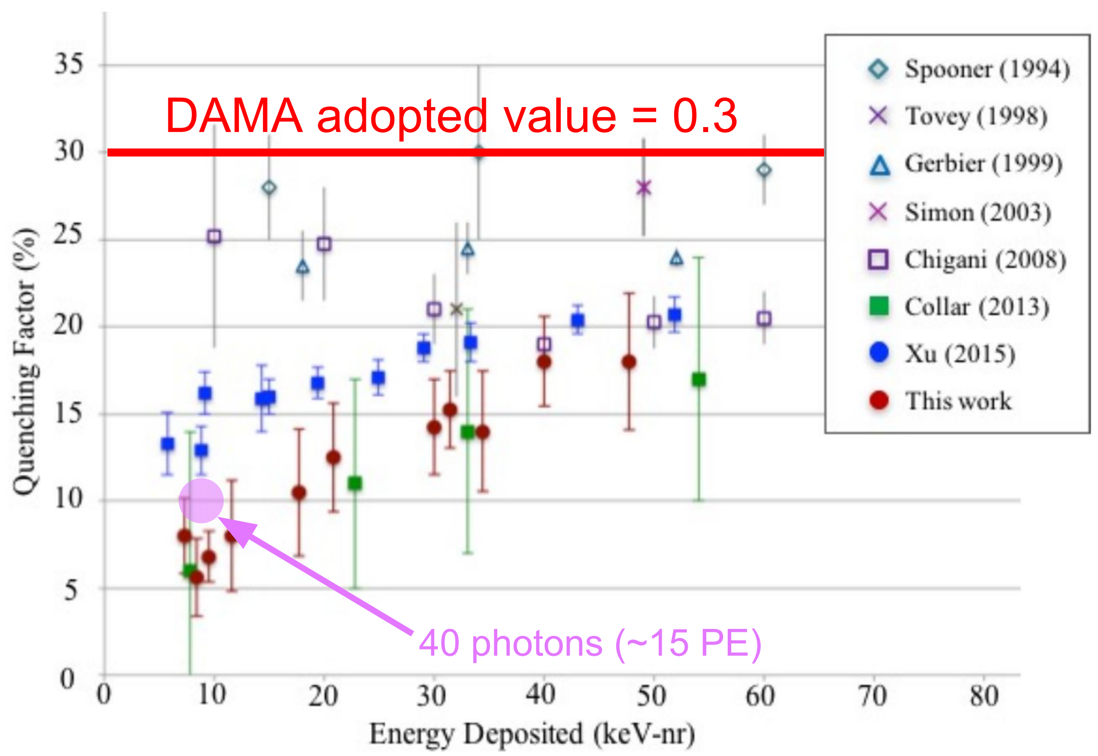




10 keV Au recoil

Quenching Factor Measurements

NaI:Tl quenching factor results are inconsistent.

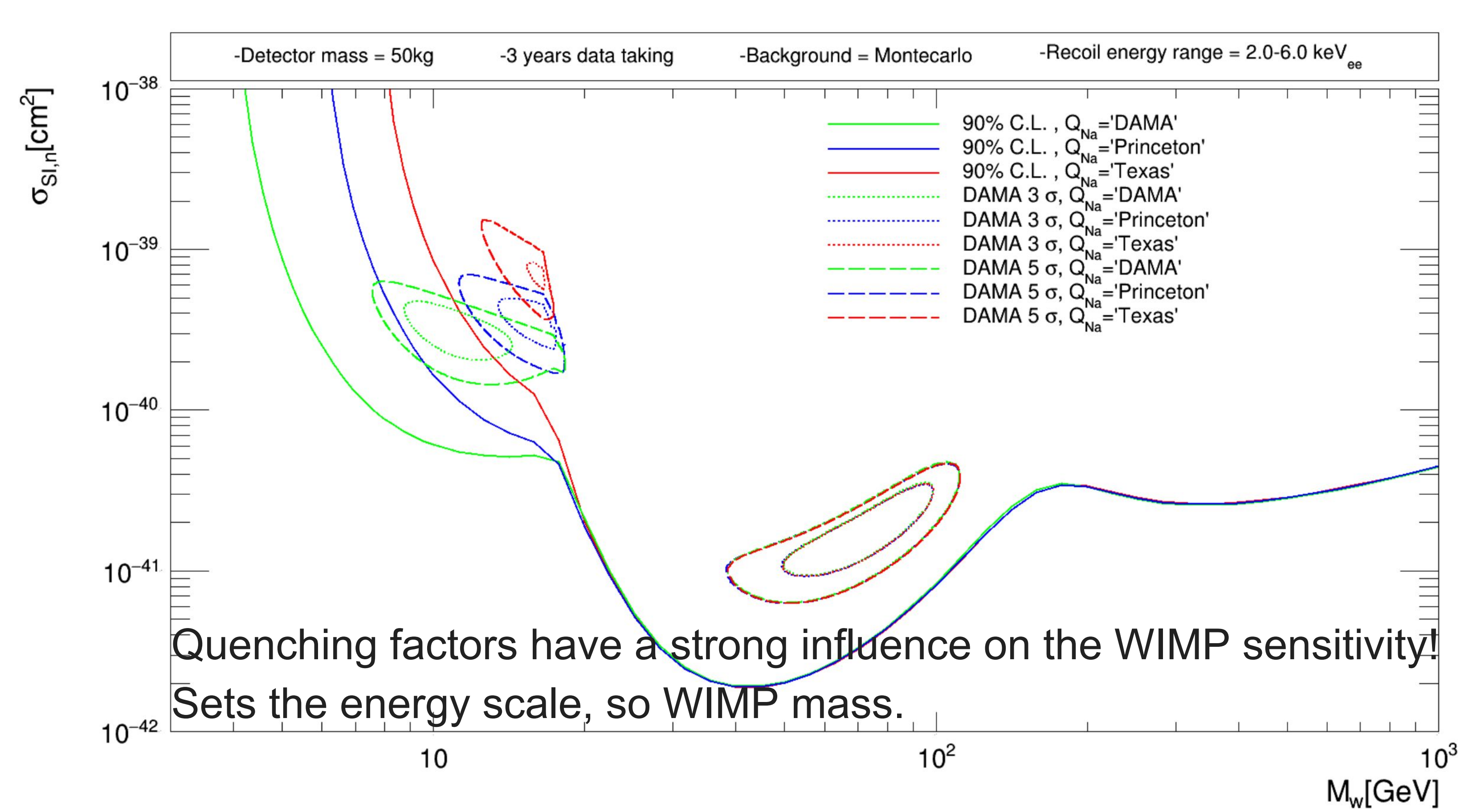


Why?

1. Difficult measurement. Poorly understood systematics?
2. Crystal variations. (Growth type dependence, Tl variation)?
3. Measurement conditions (temperature, angle/channeling)?

Na recoil measurements in NaI:Tl [arXiv: 1706.07494]

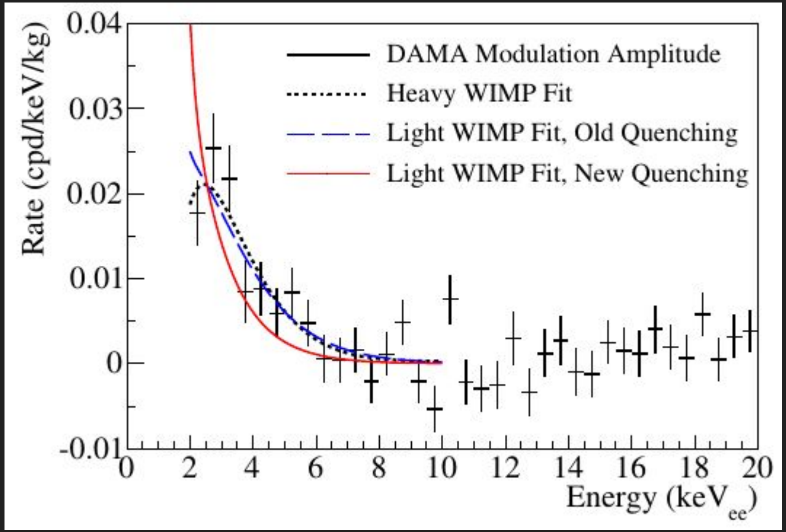
Quenching Factor Measurements

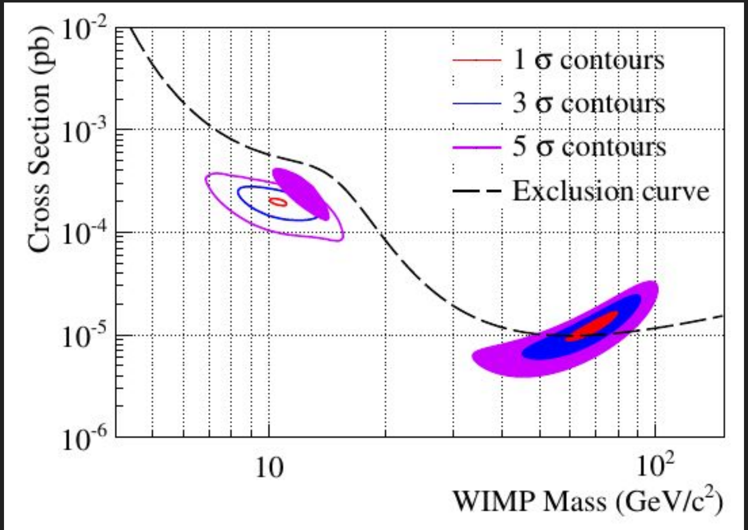


Quenching factors have a strong influence on the WIMP sensitivity!

Sets the energy scale, so WIMP mass.

Quenching Factor Measurements





Xu *et al*: DAMA phase 1 spectra are not consistent with the low mass SI-SHM WIMPS (>3 σ, arXiv:1503.07212).

Quenching factor is really important for understanding model exclusion!

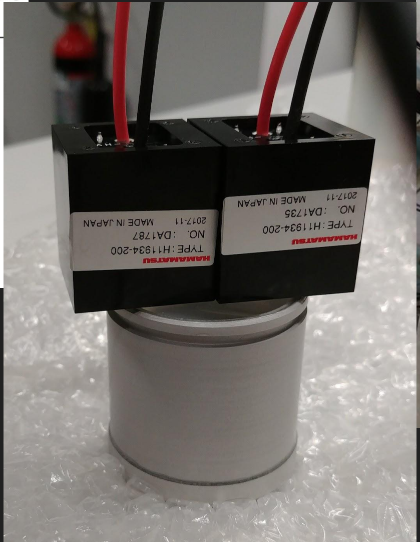
Quenching Factor Measurements at the ANU

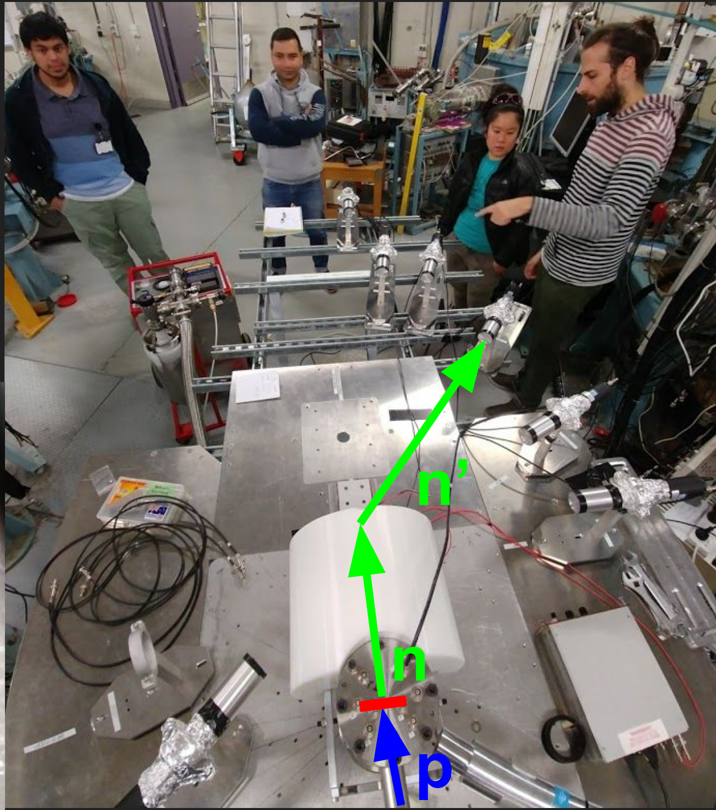
* Pulsed proton beam (1.5 ns bunches).
* 0.5 mg/cm^2 LiF target, Ta backing.
* $^7Li(p,n)^7Be$ reaction, 1.64 MeV threshold.
* Custom PTFE-lined EJ-309 neutron detectors.
* 43% peak QE PMTs for NaI:Tl readout.

Angle (deg)	Distance from NaI (cm)	Relative Energy Uncertainty (%)
5	150	31
12	100	19
22	75	13
40	75	7
67.5	50	6
90	50	6
112.5	30	4
135	30	2

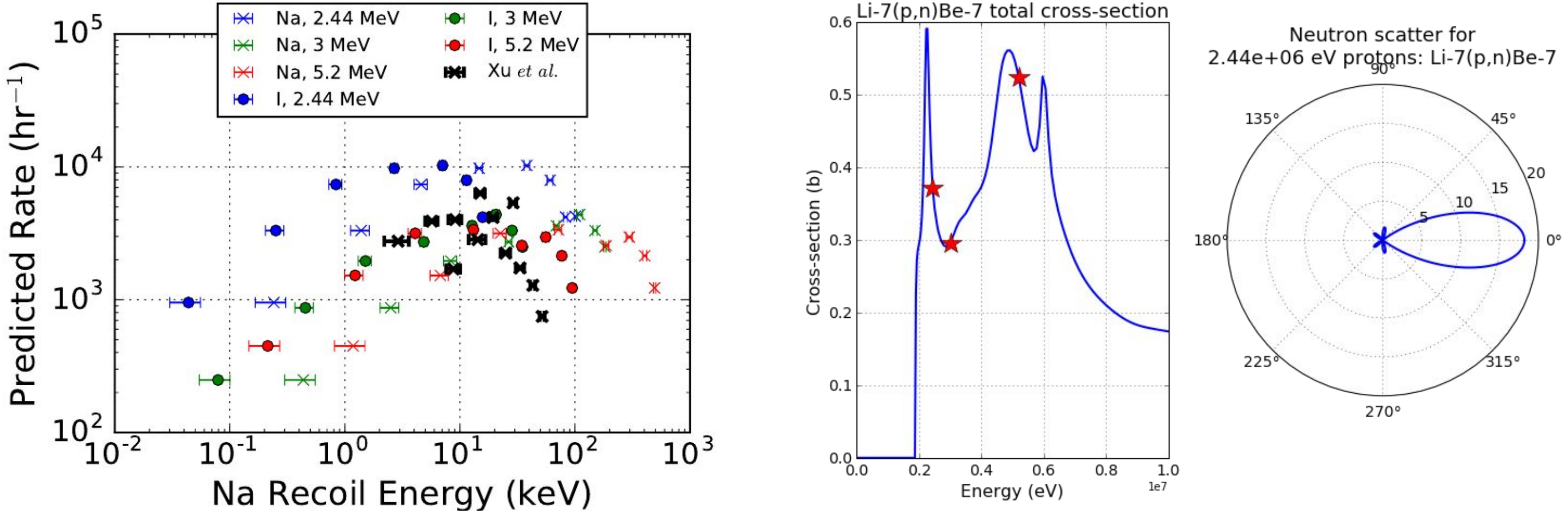
Bad PMT, not used

Test Crystal:
40 mm x 40 mm cylindrical
NaI:Tl (ca 1980's USSR, from Swinburne U)





Quenching Factor Measurements at the ANU



Beam energies: 2.44, 3, 5.2 MeV → decent spread of energies with some overlapping values.

Preliminary: calculations assume nominal neutron energies, don't account for slowing in LiF.

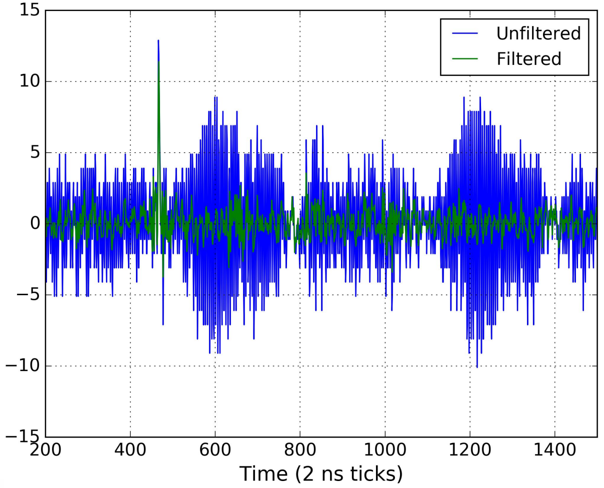
Signal Processing

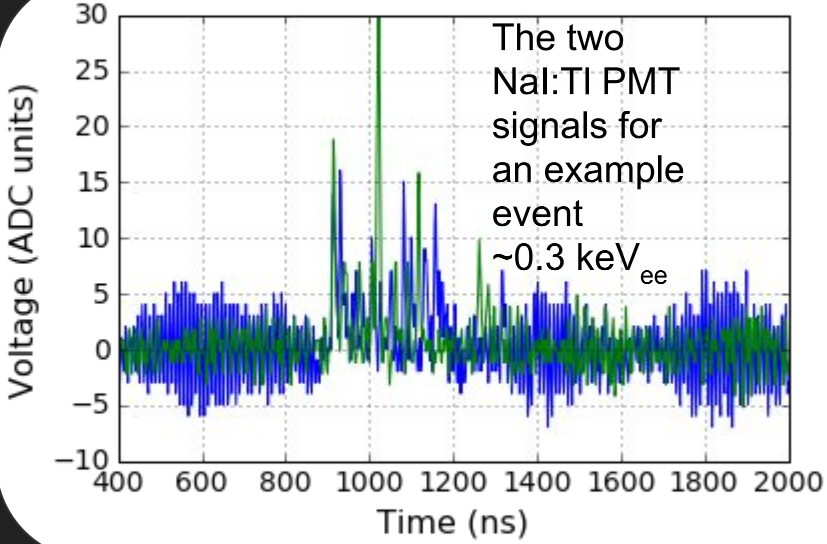
Data Acquisition:

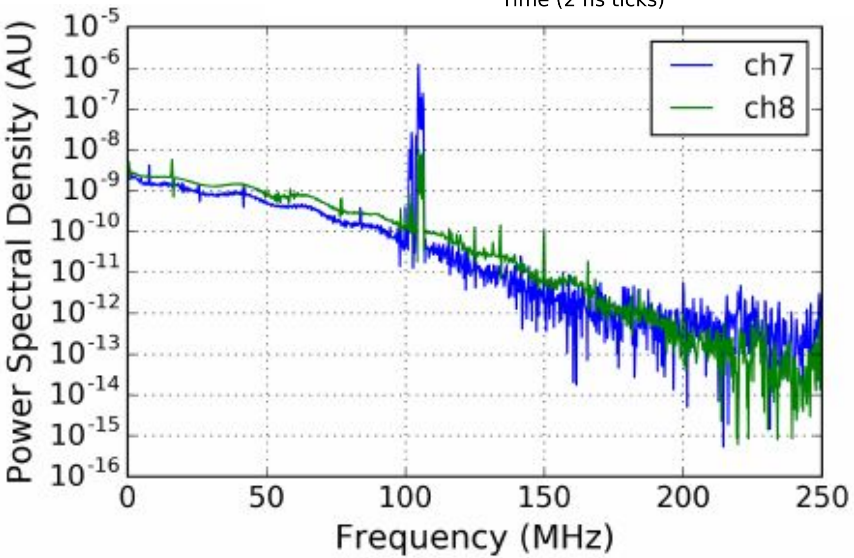
PIXIE16 system: 500 MSPS @ 12 bit

No global trigger, common clock. **10 TB of data.**

Noisy NaI channels, recovered by filtering.



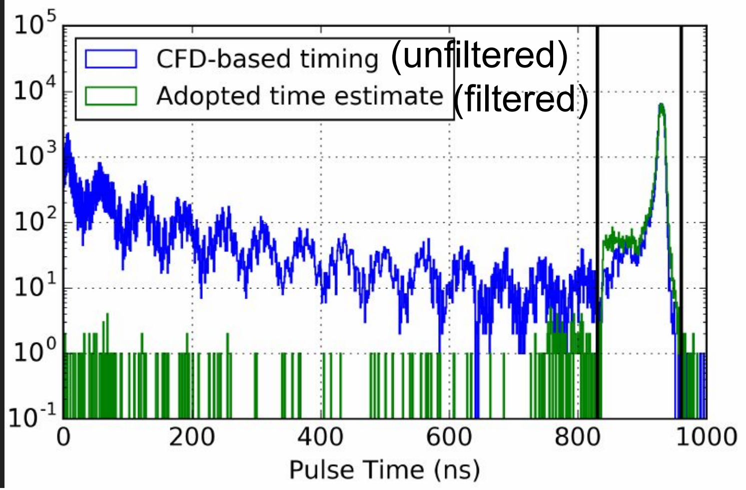


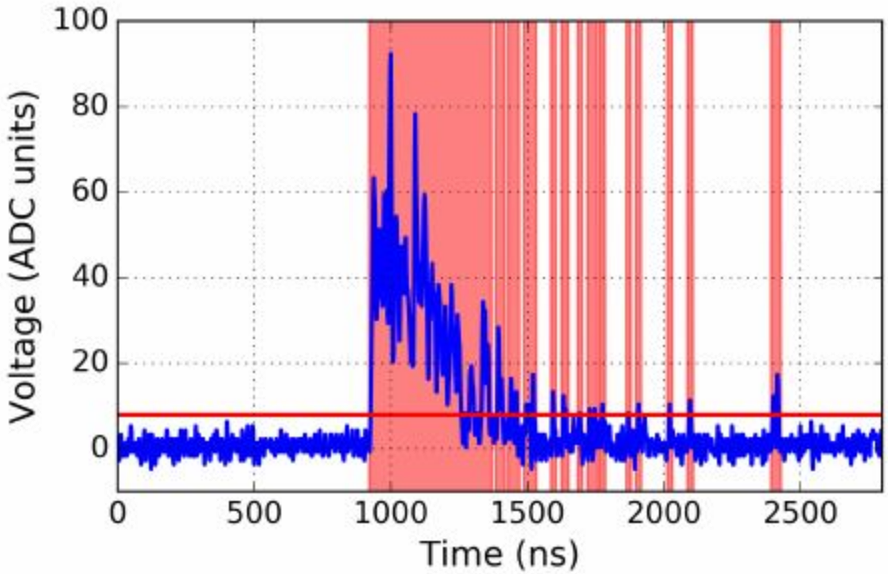


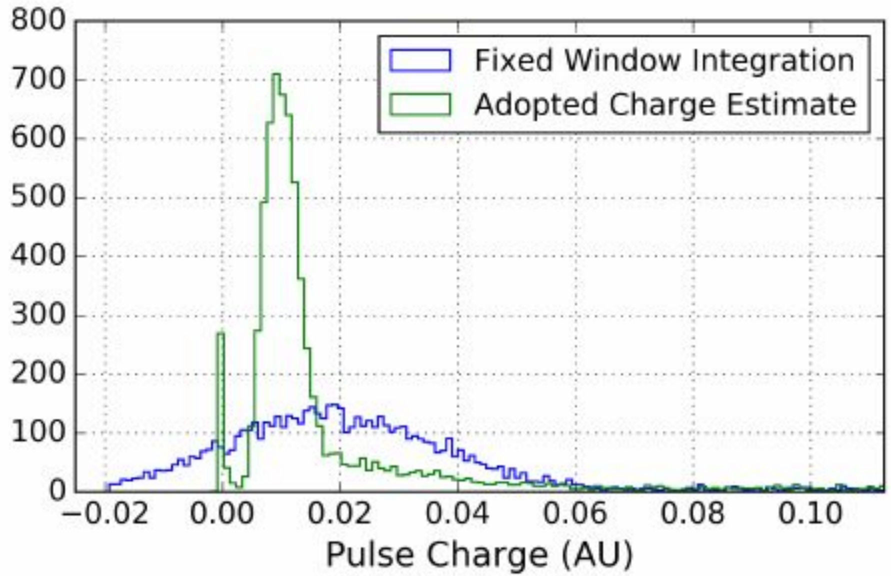
More Signal Processing

Filtering is necessary for determining pulse time →

The charge distribution was actually better unfiltered, by using the **spread-out charge over threshold.**



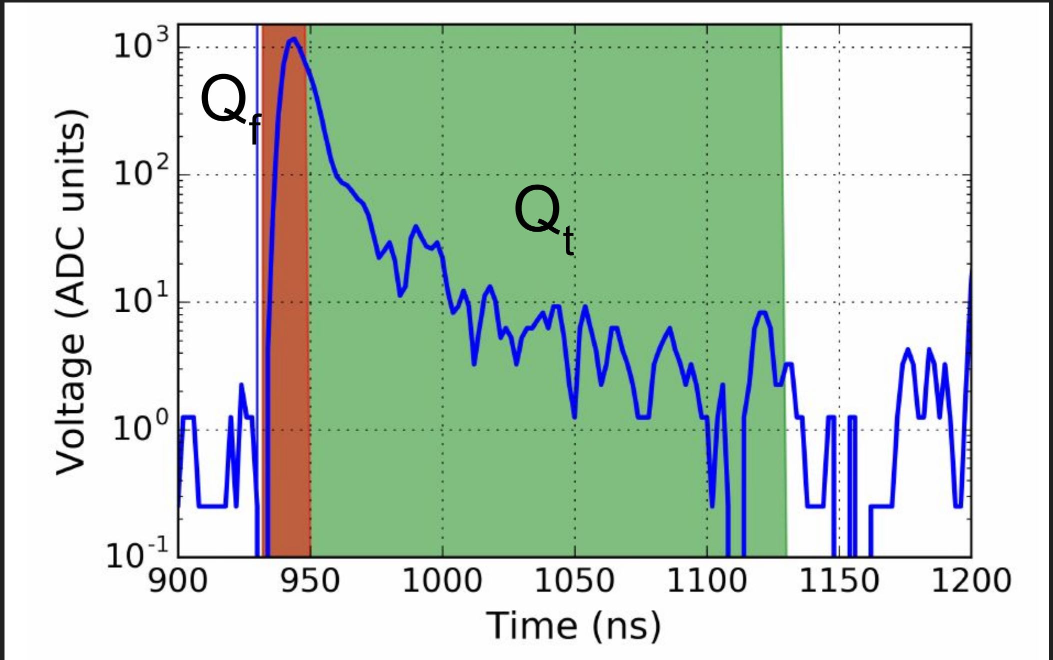




Liquid Scintillator Signal Processing

The liquid scintillator channels had less noise (and the low energy events were less important.

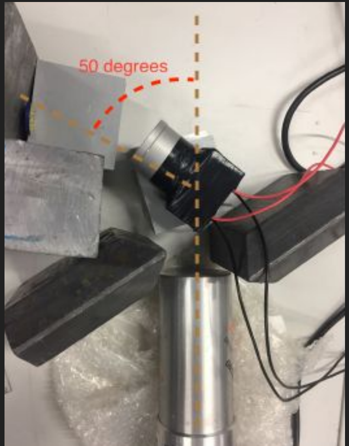
Fixed window integration with two timing gates for particle ID.

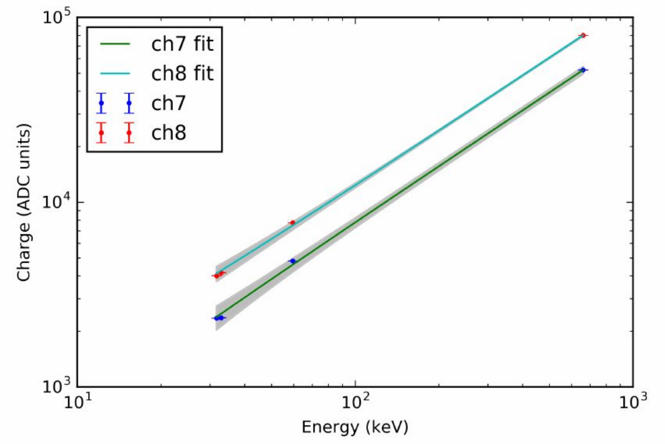


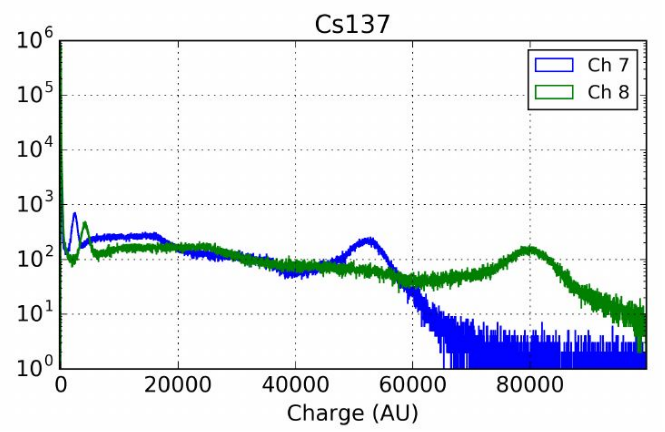
ER Energy Calibration

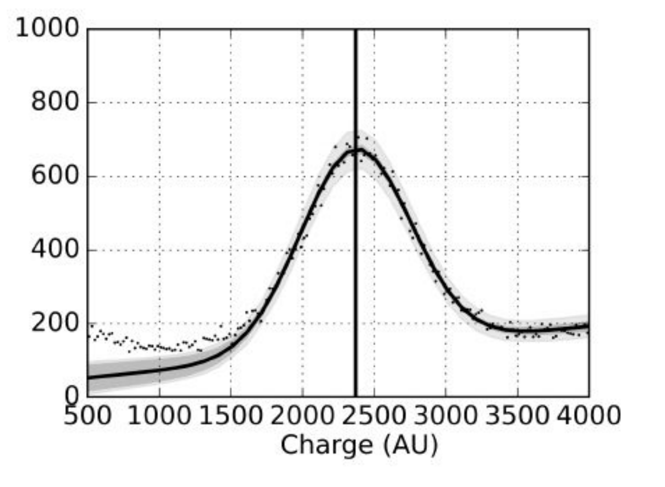
Gamma ray measurements:

- Am-241, Ba-133, Cs-137
- Limited at low energies by available sources and (ultimately) the thickness of the housing.
- Compton electron measurements to measure low energies and account for electron non-linearity.
- Need to measure efficiency at low energy[1].



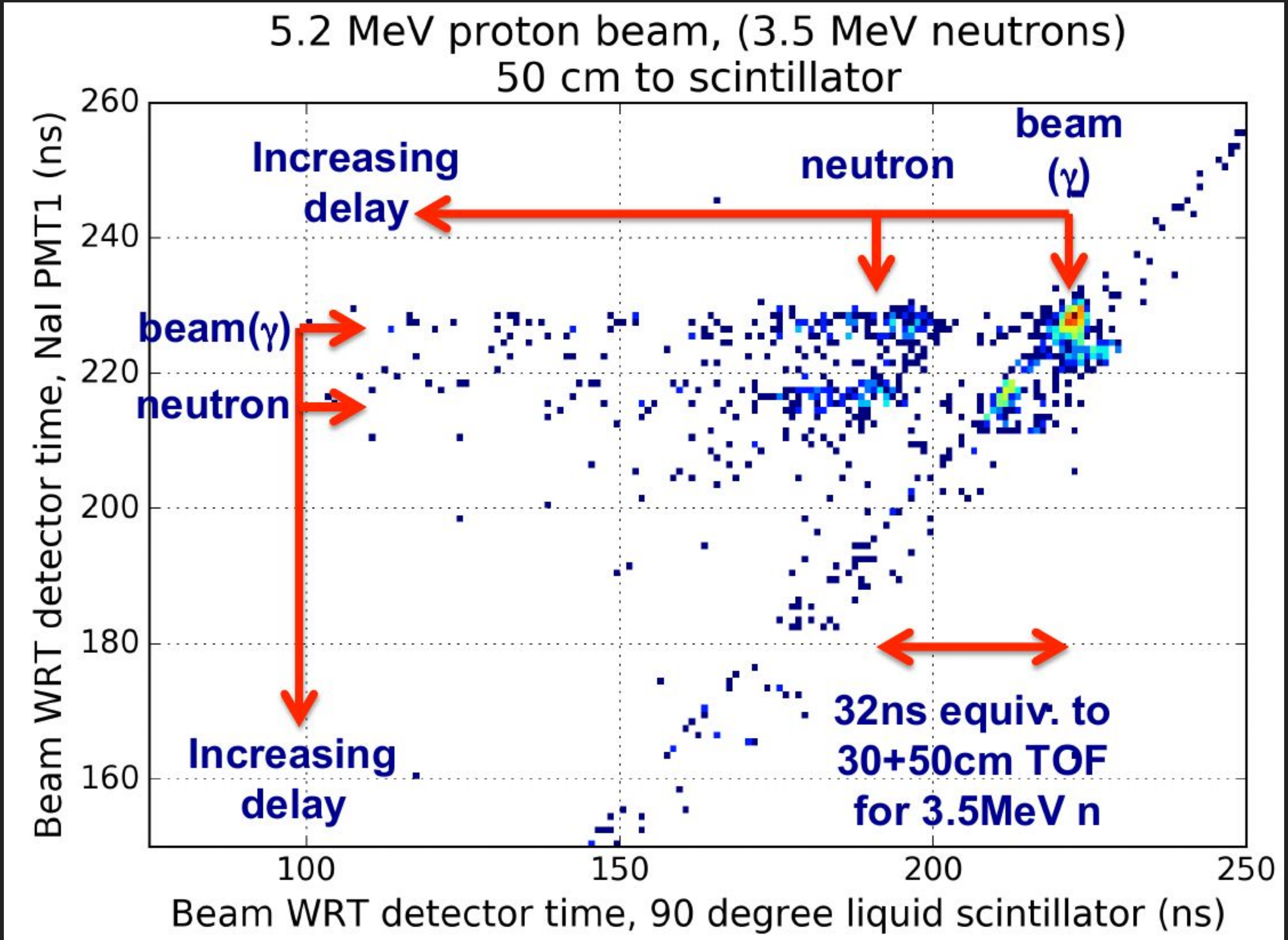






Collar (2010) arXiv:1010.5187

Results - Time of Flight



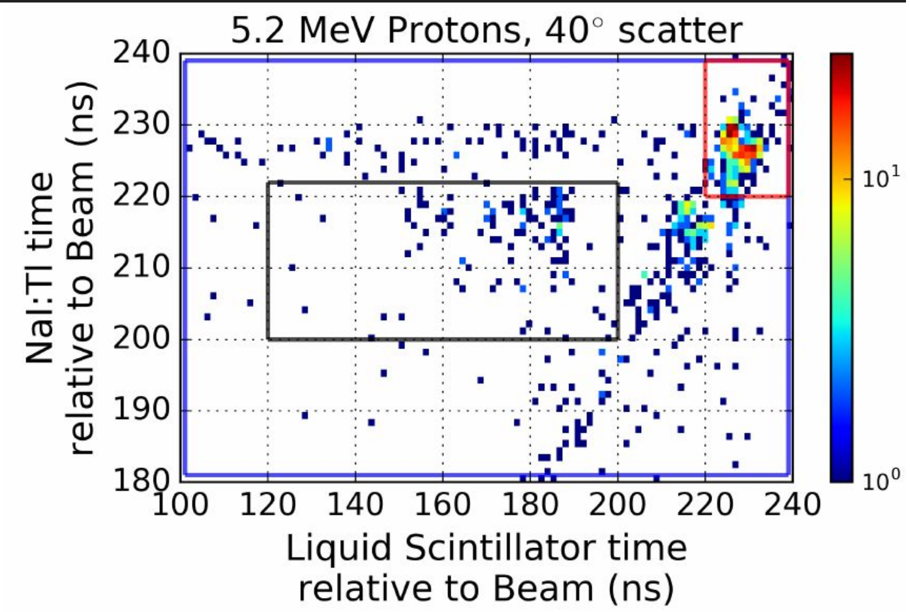
Diagonal line is coincident gamma rays/cosmic events.

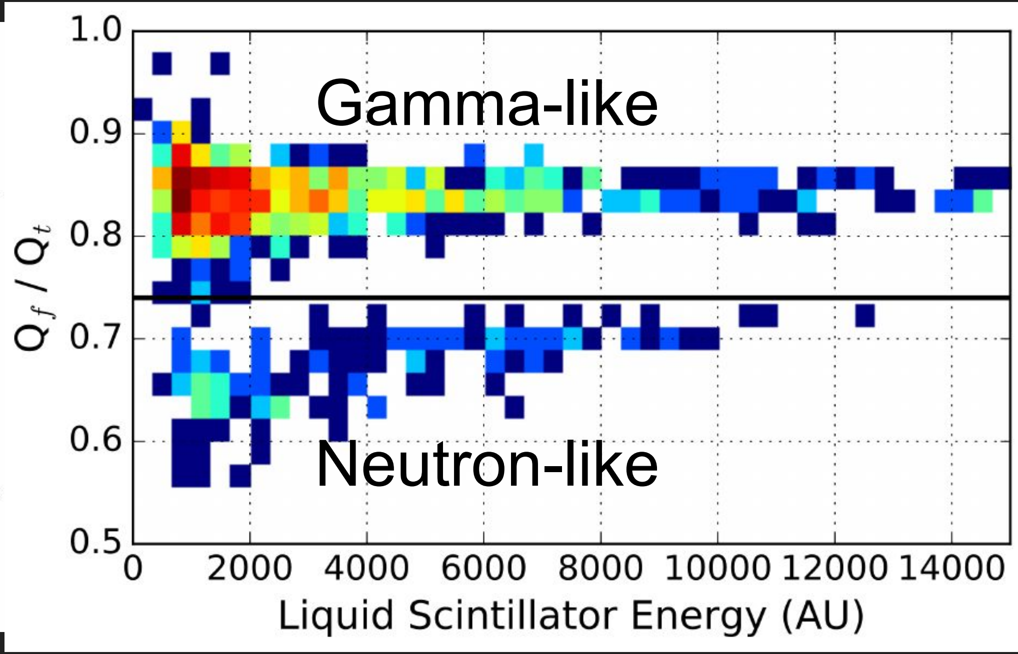
TOFs make sense.

Statistics are low :-(

PSD Results

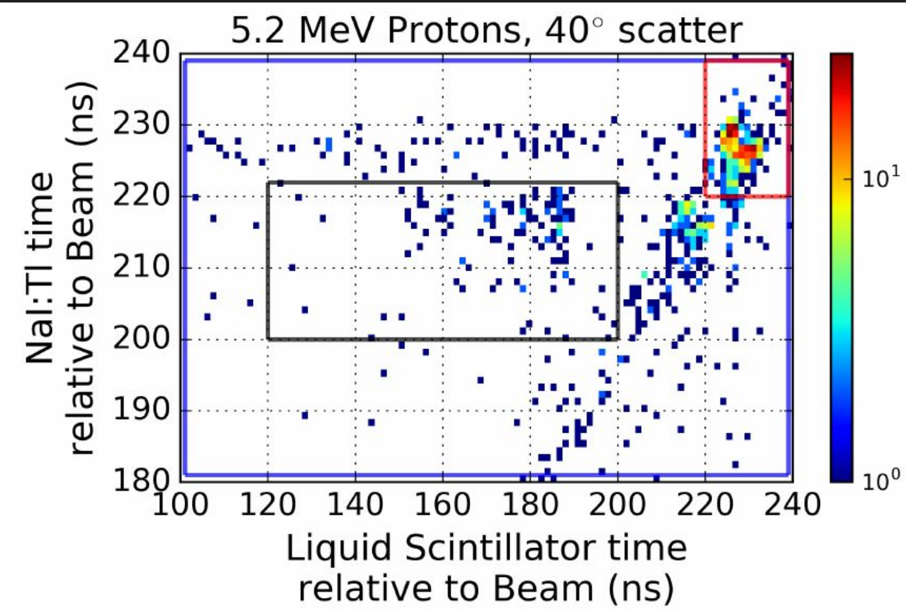
Select all times (blue box): neutron-like and gamma-like events in LS.

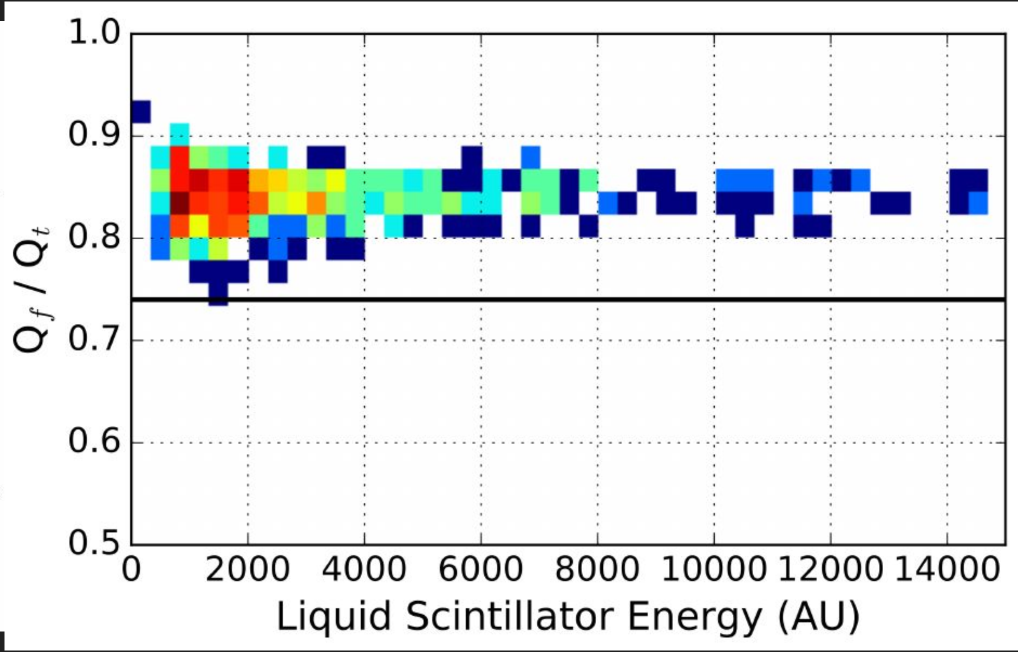




PSD Results

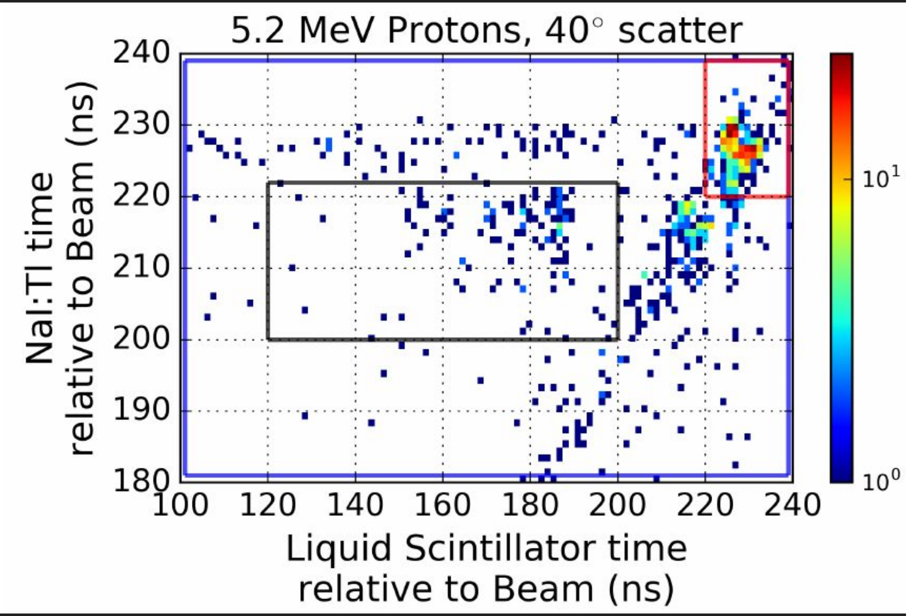
Select gamma-gamma times (red box): gamma-like events in LS

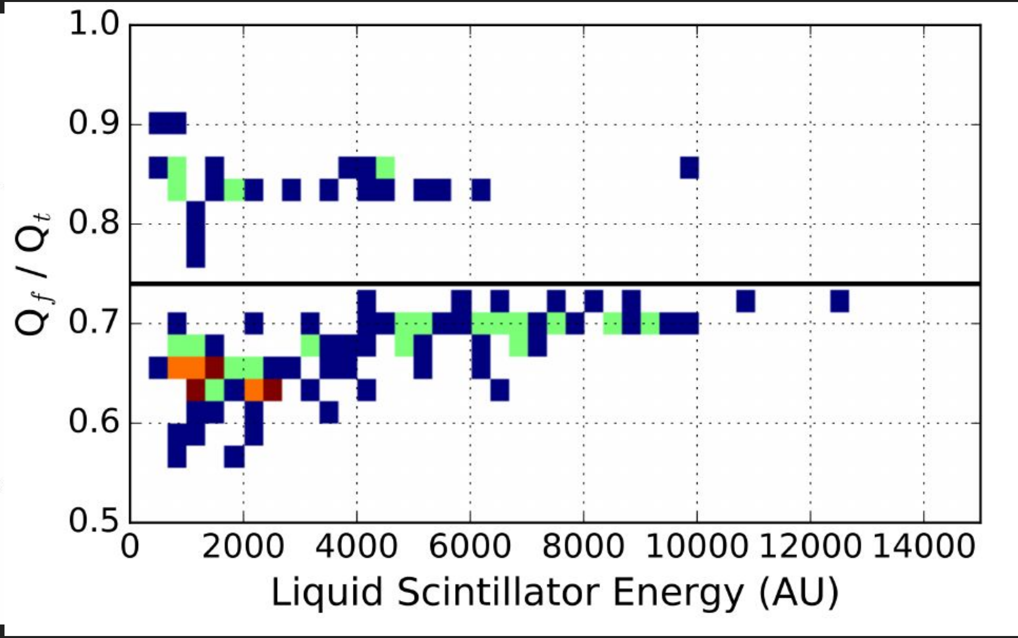




PSD Results

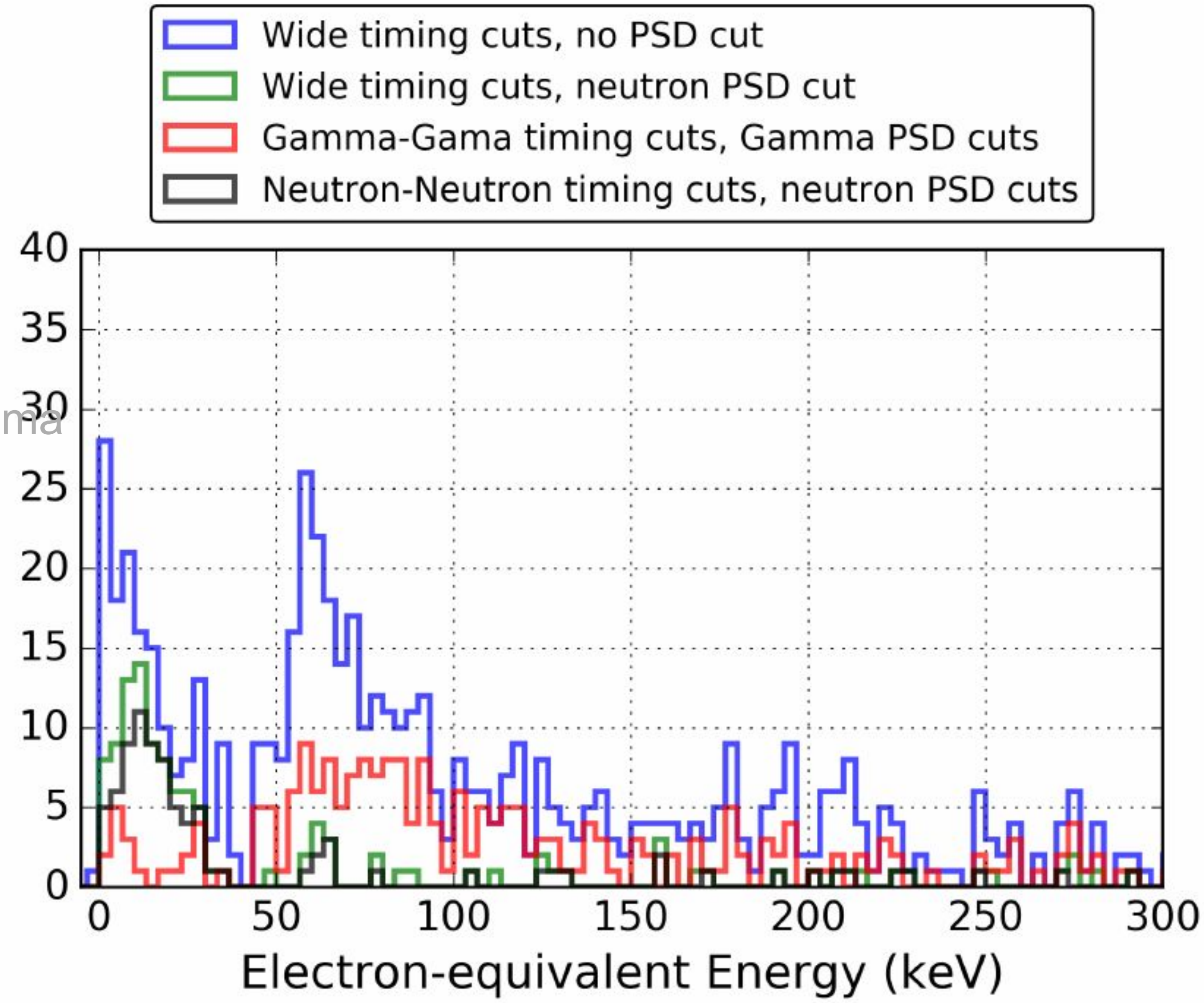
Select neutron-neutron times (black box): preferential neutron events in LS





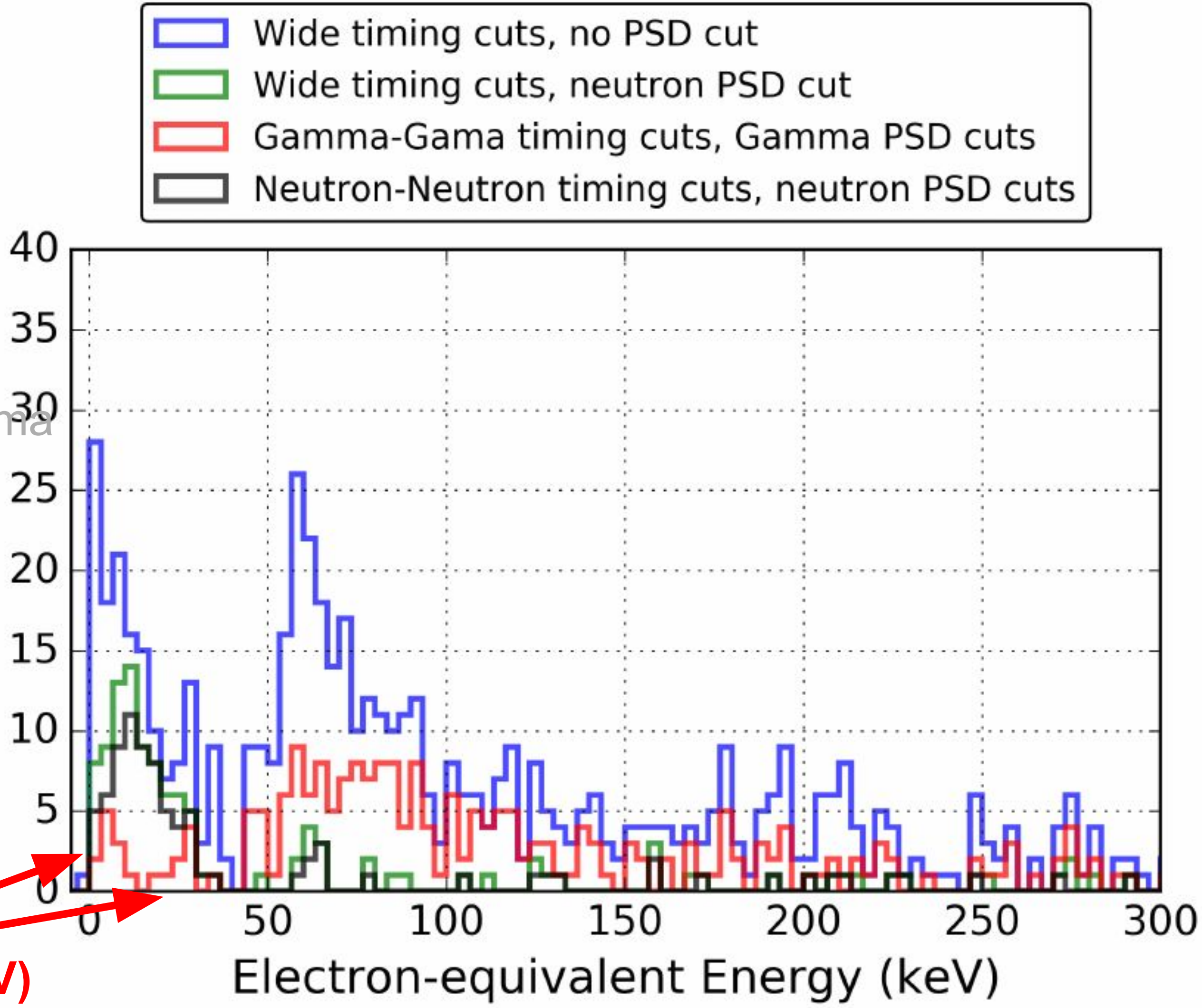
Significant difference between the gamma-gamma timing
cut and the neutron-neutron cut.

PSD cut is very effective!



Significant difference between the gamma-gamma timing
cut and the neutron-neutron cut.

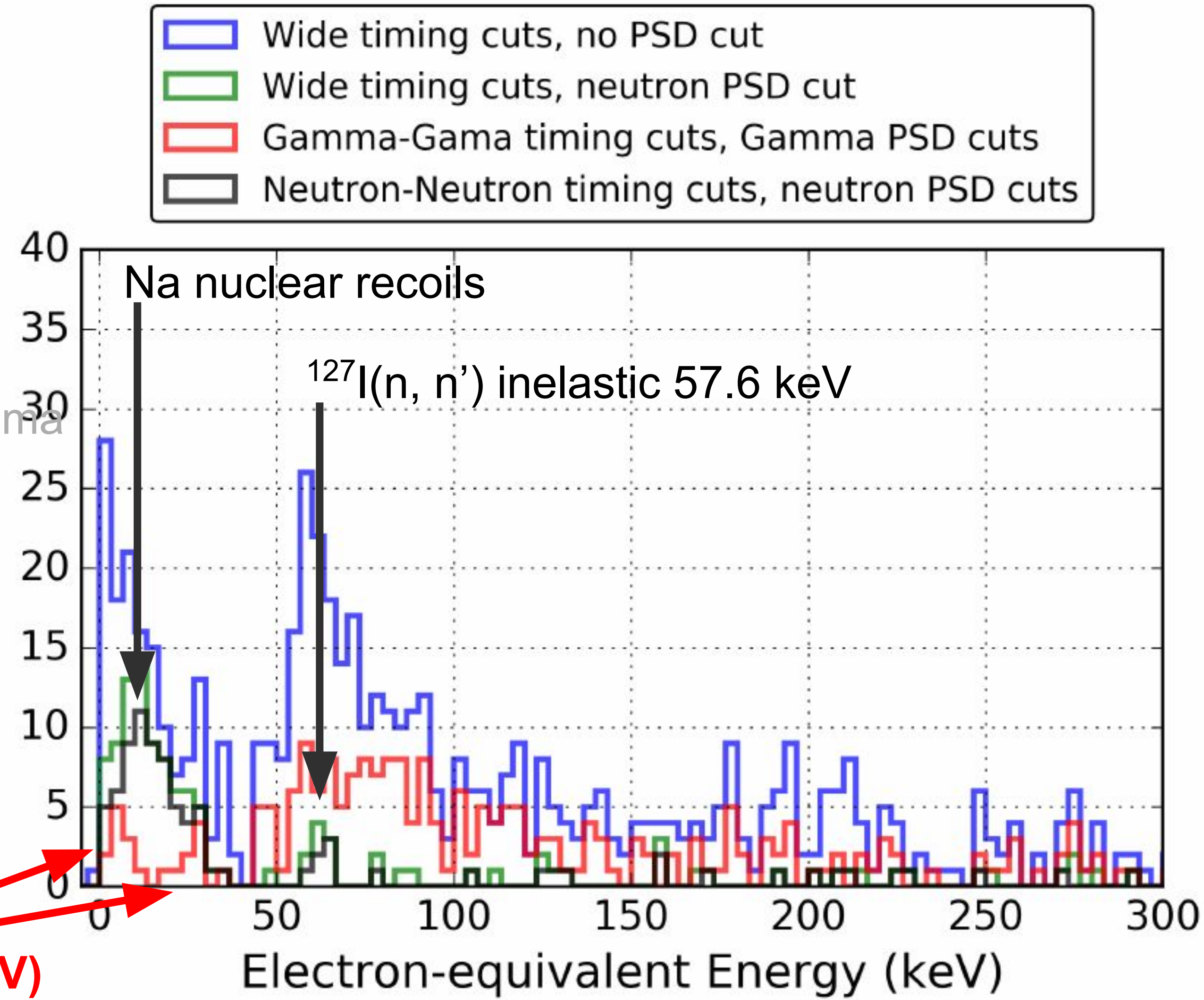
PSD cut is very effective!



Iodine x-rays (33 + 5 keV)

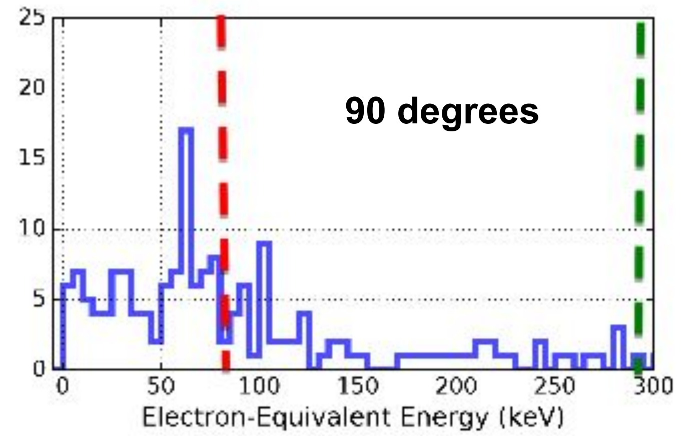
Significant difference between the gamma-gamma timing cut and the neutron-neutron cut.

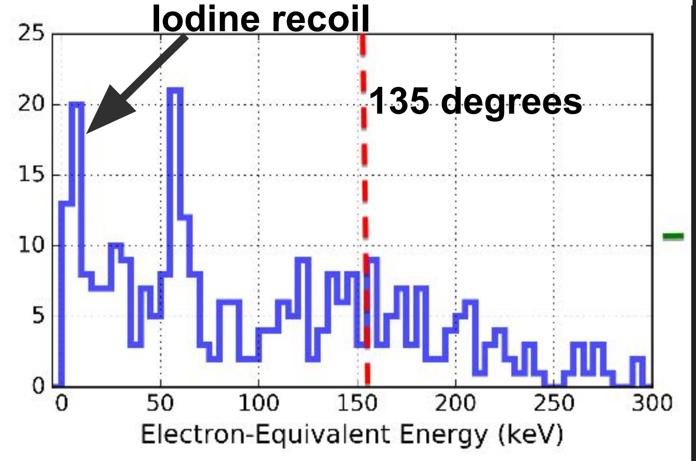
PSD cut is very effective!



Iodine x-rays (33 + 5 keV)

5.2 MeV data





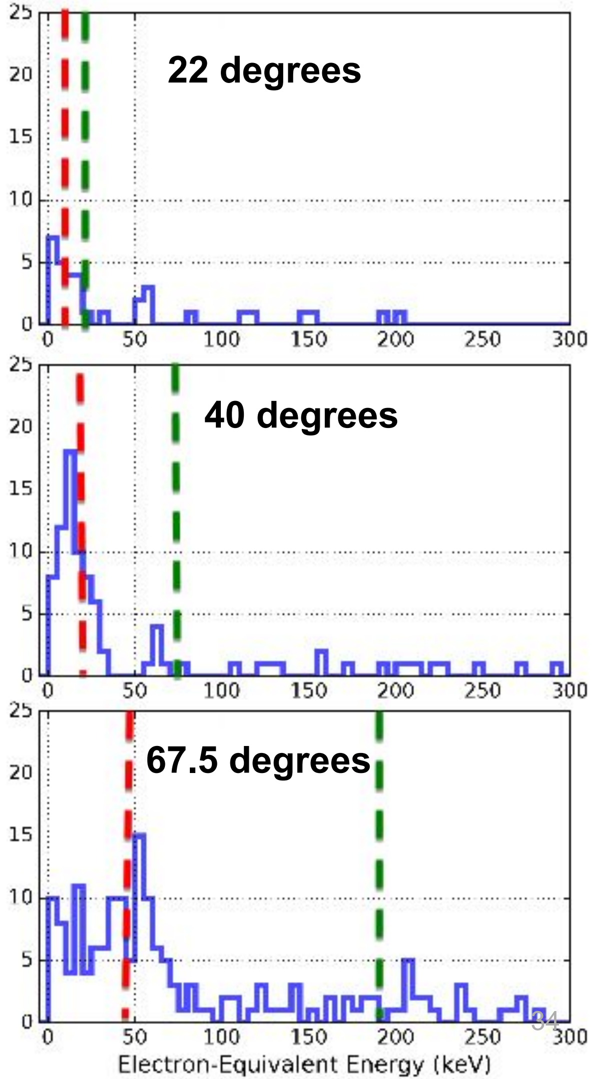
Not all channels had enough statistics

Unbinned fit to Gaussian.
Fit range is a systematic.

Green lines: Nuclear recoil energy

Red lines: fitted Na peak location.

→ 492 keV



3 MeV data

Poorer statistics than 5.2 MeV data.

Less background than 5.2 MeV data.

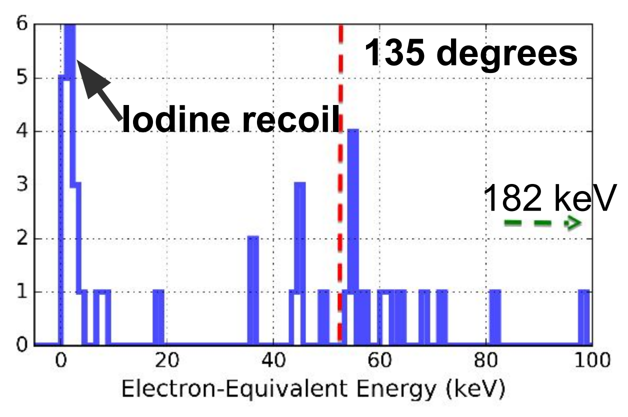
Unbinned fit to Gaussian. **Fit range is a systematic.**

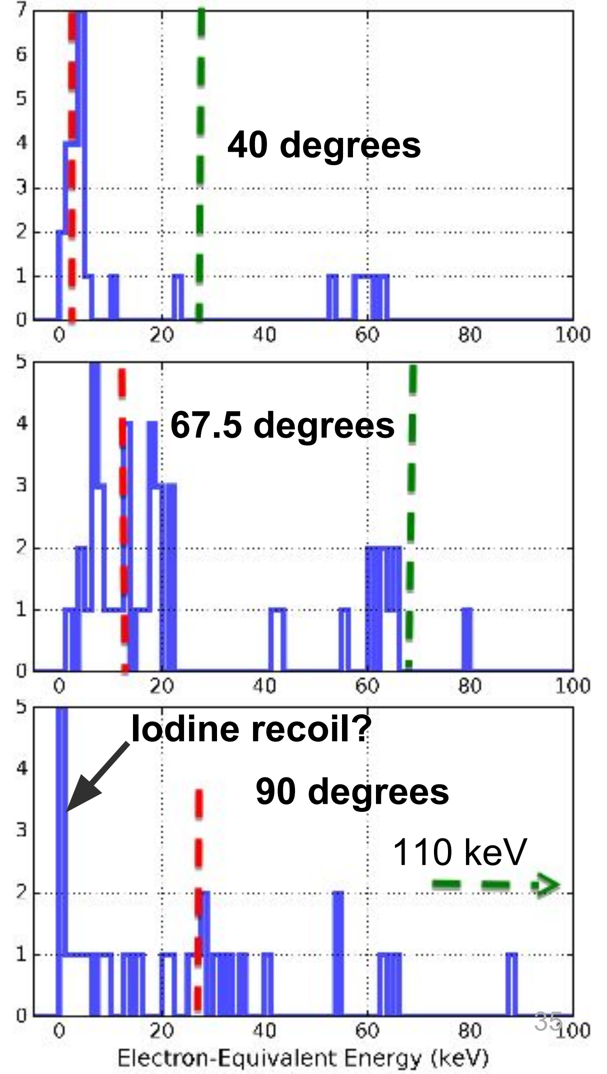
Green lines: Nuclear recoil energy

Red lines: fitted peak location.

No detectors at 2.44 MeV had enough statistics!

:,-(

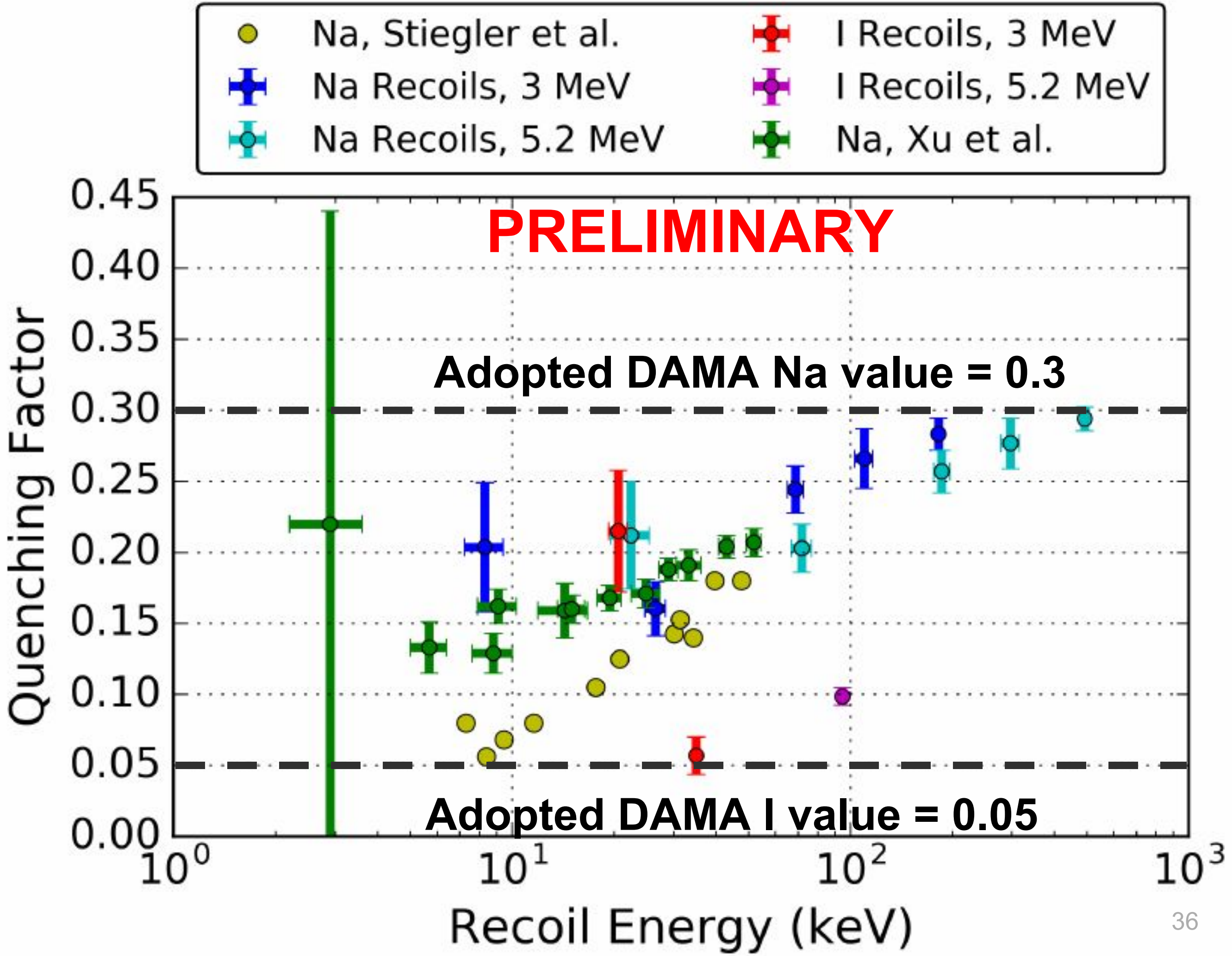




Similar to recent quenching factor measurements.

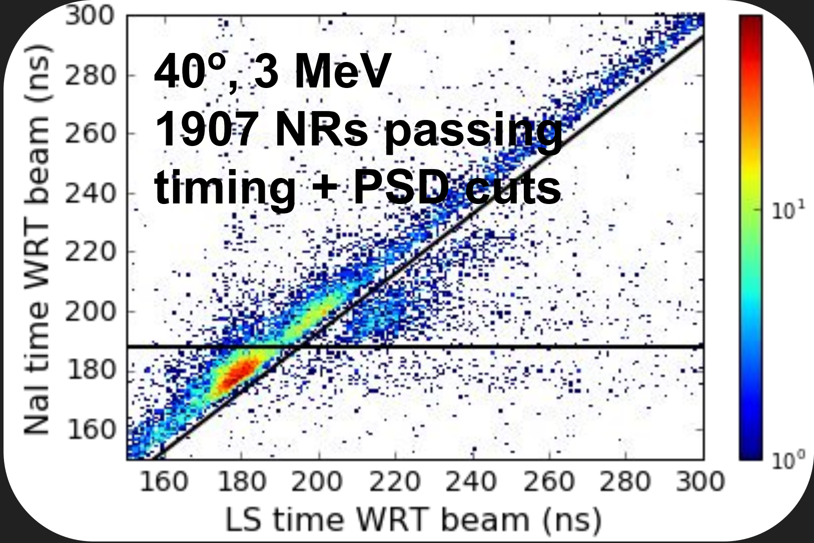
Lower energy points are particularly prone to systematics[1]

Not accounting for slowing of proton in LiF → will tend to converge 5.2 and 3 MeV data



1. Collar (2010) arXiv:1010.5187

Future QF measurements



Follow-up measurements in new geometry.
→ Preliminary analysis ~100x more NRs.

SABRE NaI crystal: small (~1” cube) sample from tip/tail of a crystal.

Systematic NaI studies: temperature, doping, impurities, and crystal axis.

Other materials:

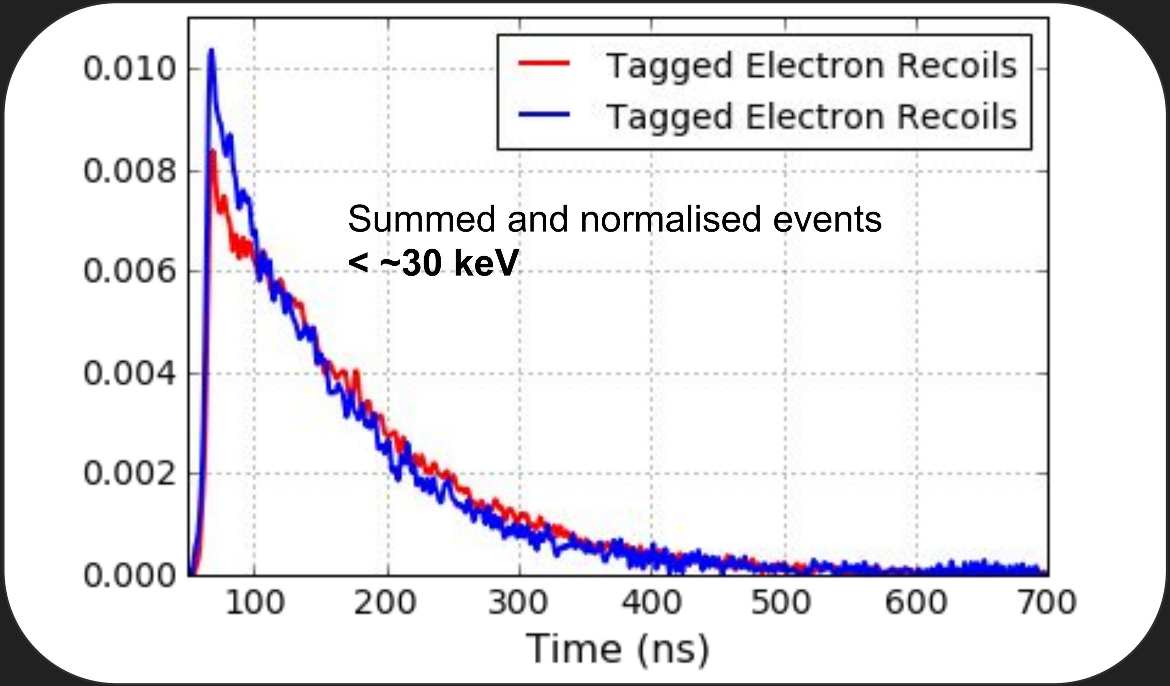
- SABRE LS
- gas TPC (various gases) for CYGNUS directional dark matter collab
- Water-based LS (future neutrino detector material) -- highest reported Birks quenching of 0.7 mm/MeV (typical value ~0.1 mm/MeV)[1].

1. arXiv:1508.07029

Particle Identification

dE/dx (Birks) quenching modifies the time distribution of the scintillation.

This is another handle to reduce background (mostly electron recoils).

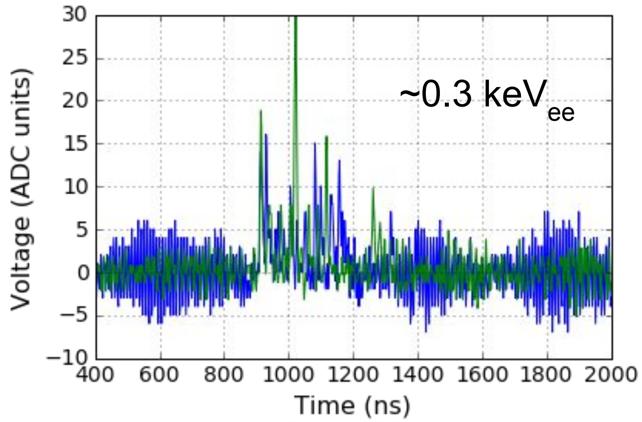


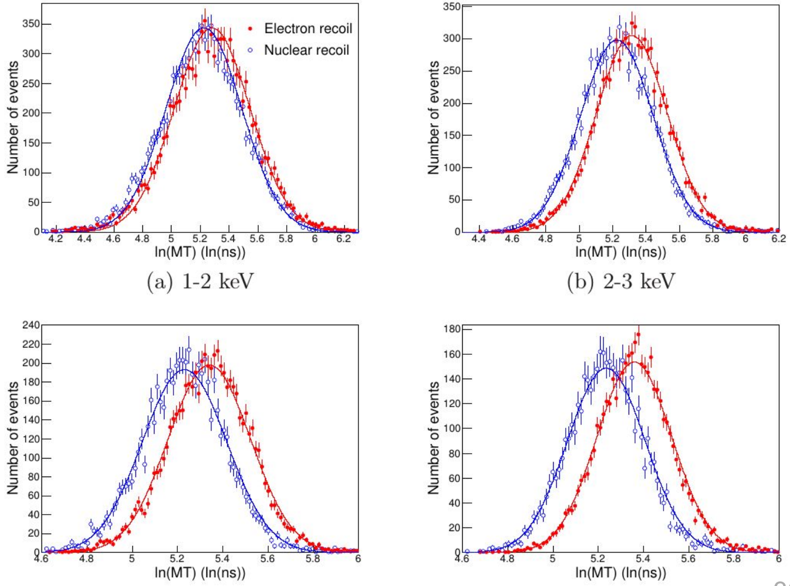
Particle Identification

Unfortunately, the low energy events of interest consist of separated single photoelectrons.
The approach used for the LS detectors is less effective.

Standard particle ID metric (NAIAD, KIMS, and COSINE):

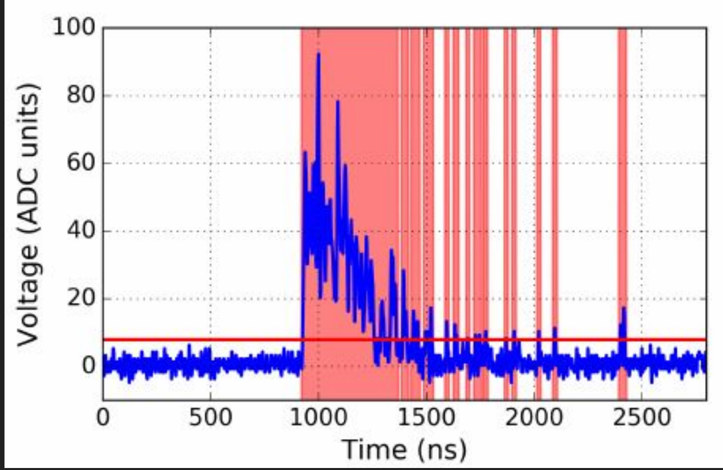
$$\ln(\mathrm{MT}) = \ln\left(\frac{\sum A_i t_i}{\sum A_i} - t_0\right)$$



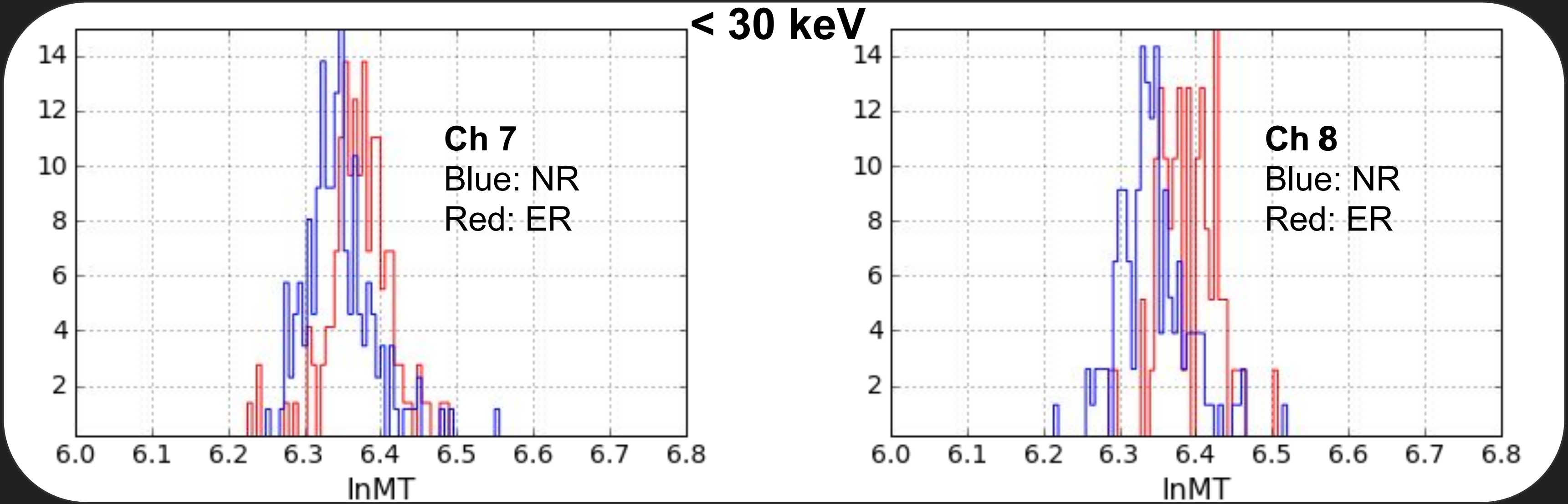


(a) 1-2 keV (b) 2-3 keV (c) 3-4 keV (d) 4-5 keV

Particle Identification: lnMT



Metric is susceptible to noise and errors in the baseline estimate.
Using the mean time of the spread out charge over-Threshold gave much better results.



Particle Identification: NR likelihood

Alternate approach, try to calculate the likelihood that waveform is a NR

$$\mathcal{L}(\mathtt{NR}|w(\vec{t})) = \frac{\prod_i w(t_i)\mathtt{NR}(t_i)}{\prod_i w(t_i)\mathtt{NR}(t_i) + \prod_i w(t_i)\mathtt{ER}(t_i)}$$

Use the averaged and normalised ER and NR waveforms as priors.

Particle Identification: NR likelihood

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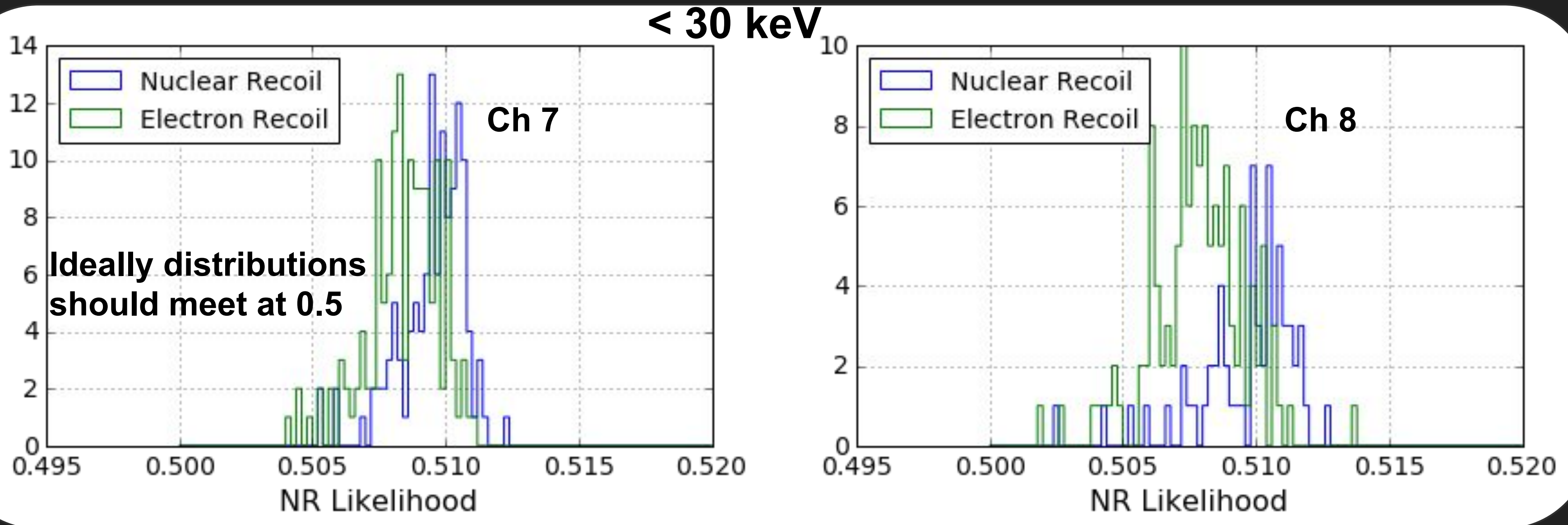


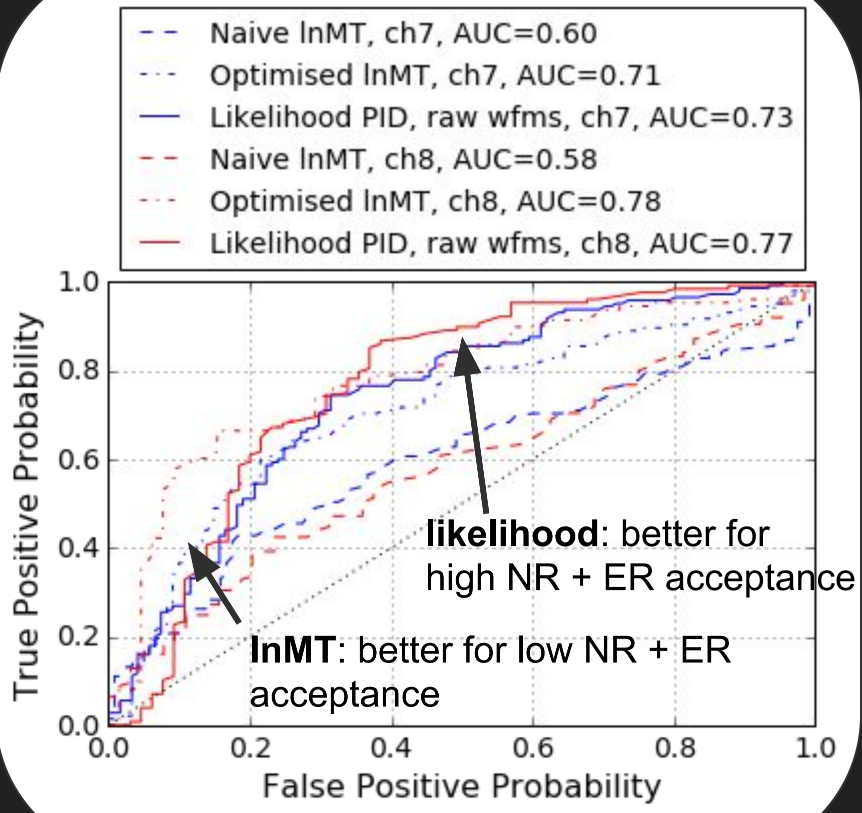
Comparison of lnMT and Likelihood

Receiver operating characteristic plot, useful for comparing classification models.
→ CDF of false positives plotted against CDF of true positives.

Are the differences significant?

Similar overall performance. Maybe a combination of the metrics would improve the performance?

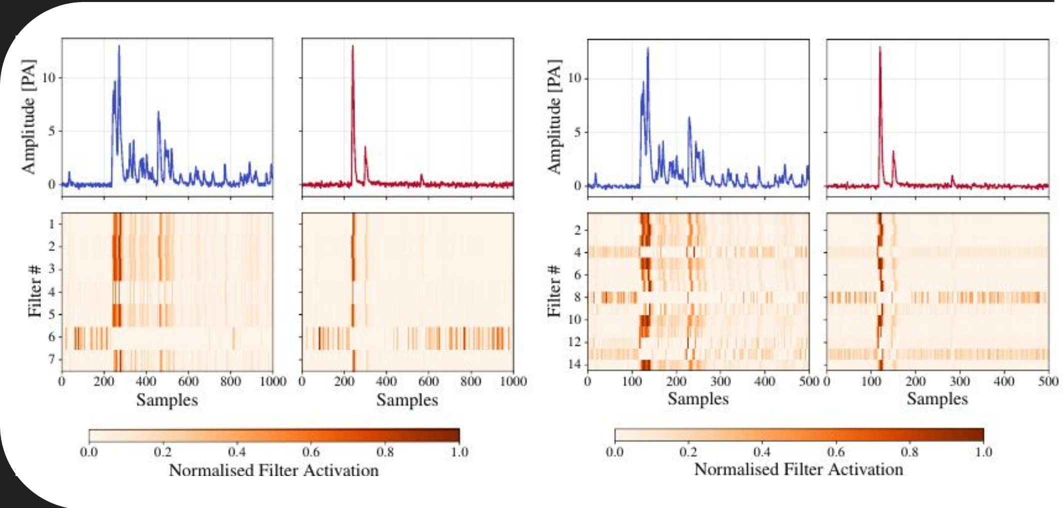
More data needed!

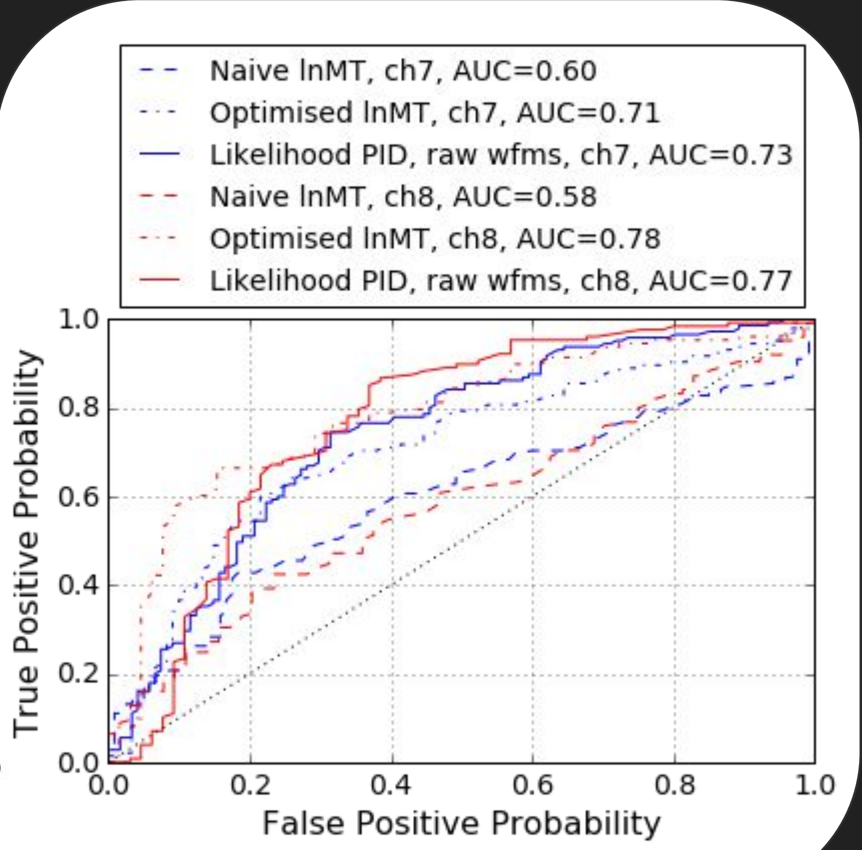


Comparison of lnMT and Likelihood

Receiver operating characteristic plot, useful for comparing classification models.
→ CDF of false positives plotted against CDF of true positives.

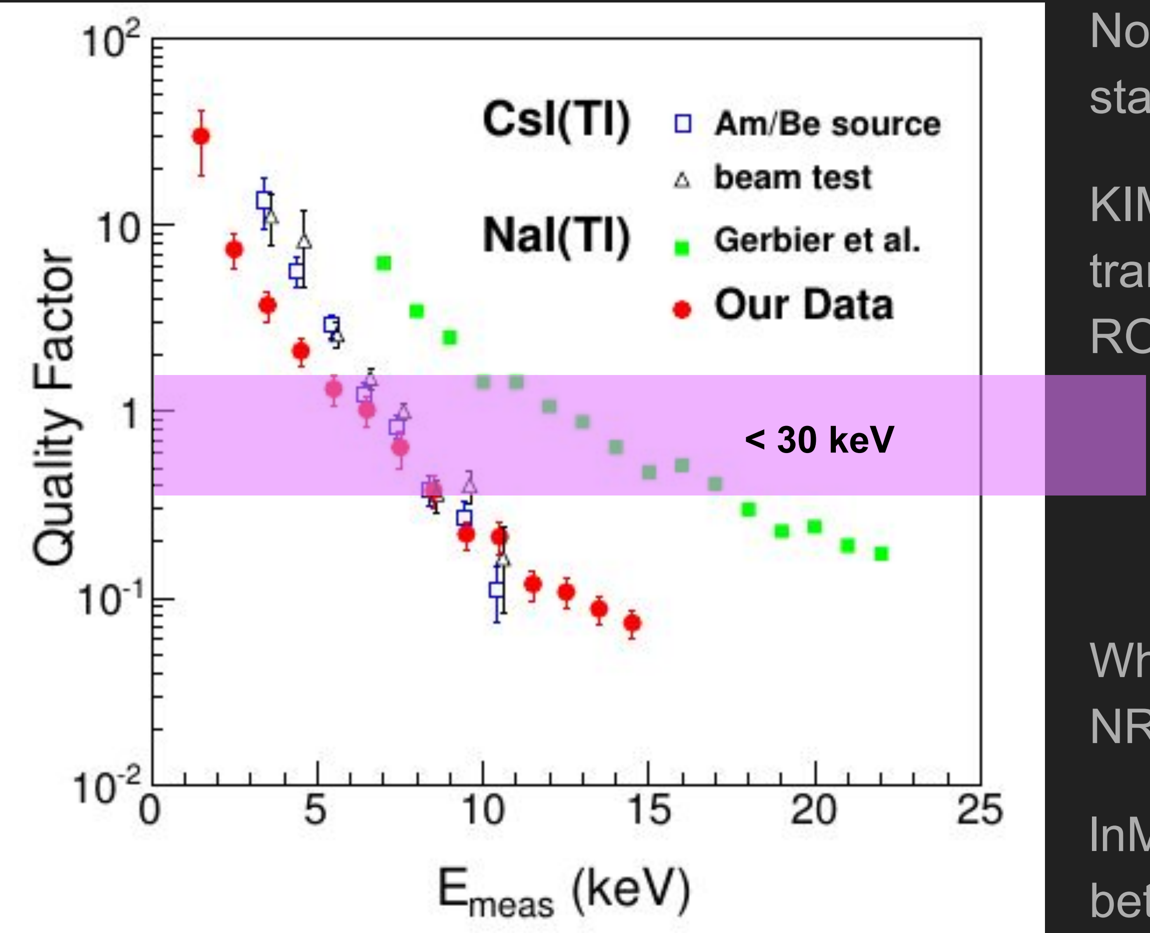
With more data, also try machine learning[1].





1. arXiv:1807.06853

Comparing with KIMS Particle Identification



Not straightforward due to poor statistics.

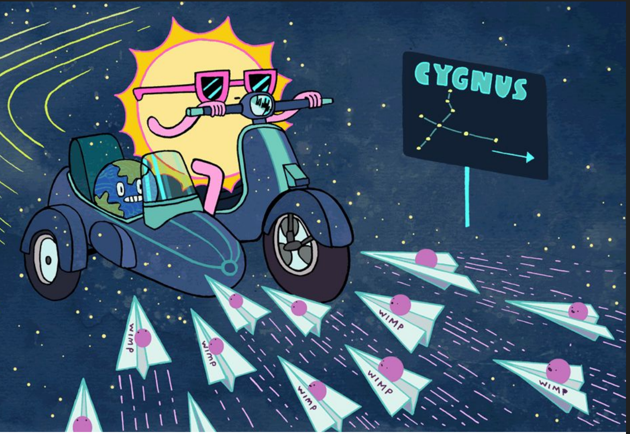
KIMS 'Quality Factor': effectively a transformation of a point along the ROC curve.

$$K \equiv \frac{\beta(1-\beta)}{(\alpha-\beta)^2}$$

Where alpha/beta are the fractions of NR/ER passing the cut.

InMT and likelihood give a minimal K between 0.35 and 1.3.

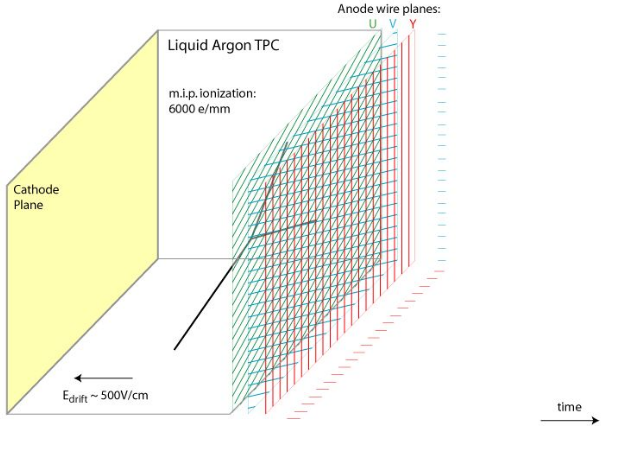
CYGNUS: Directional Detection



Multi-site directional experiment (Boulby, LNGS, SUPL, Kamioka, Jinping)
CYGNO(@LNGS) recently funded!

Micropatterned gas TPC, negative ion.
Readout technology TBD → active R&D phase.
Granular readout for directionality.

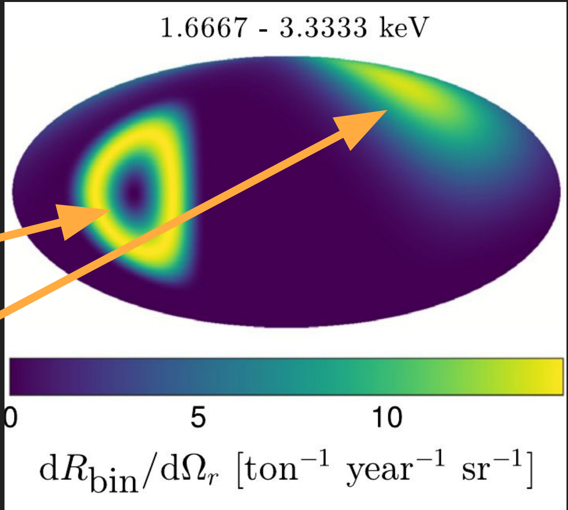
Liquid Argon TPC (CYGNUS→ gas)



Directionality allows searches below the neutrino floor!

Solar neutrinos

WIMPs



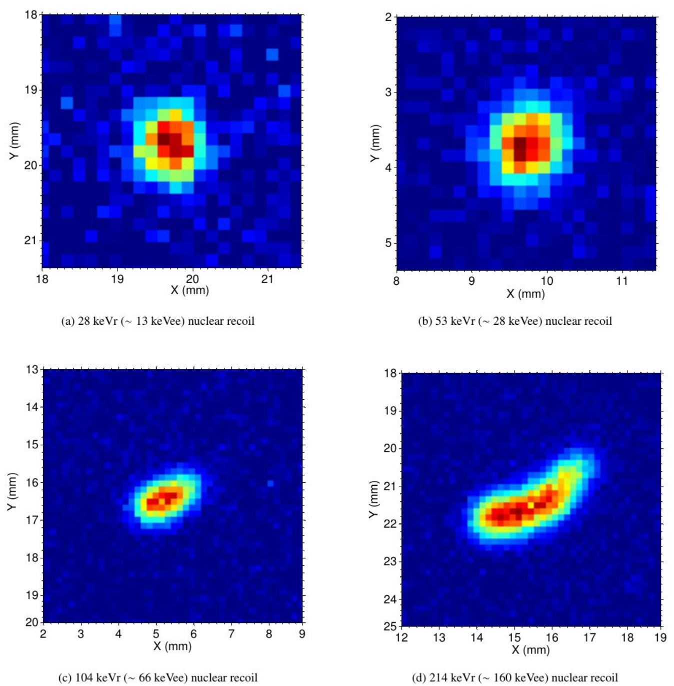
Gas? Really??

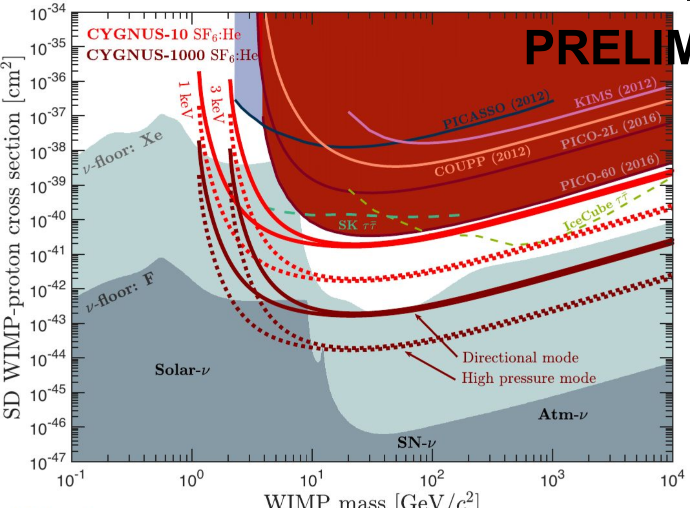
Rich event information makes up for low target mass.

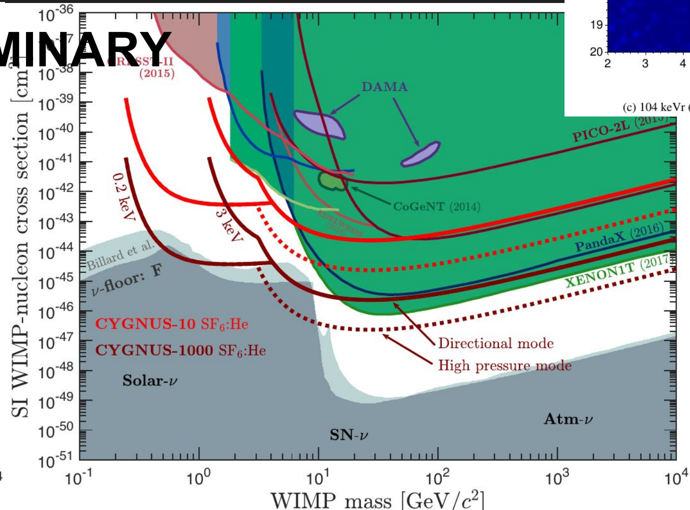
Low threshold for energy, absolute positioning, directionality and vector sense, and particle ID

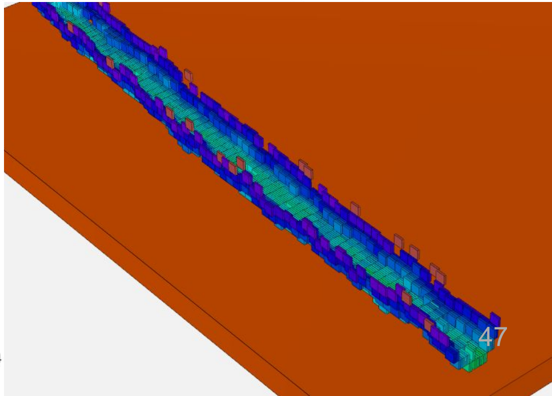
All have been demonstrated at ~10 keV or less, but not simultaneously.

R&D is needed.





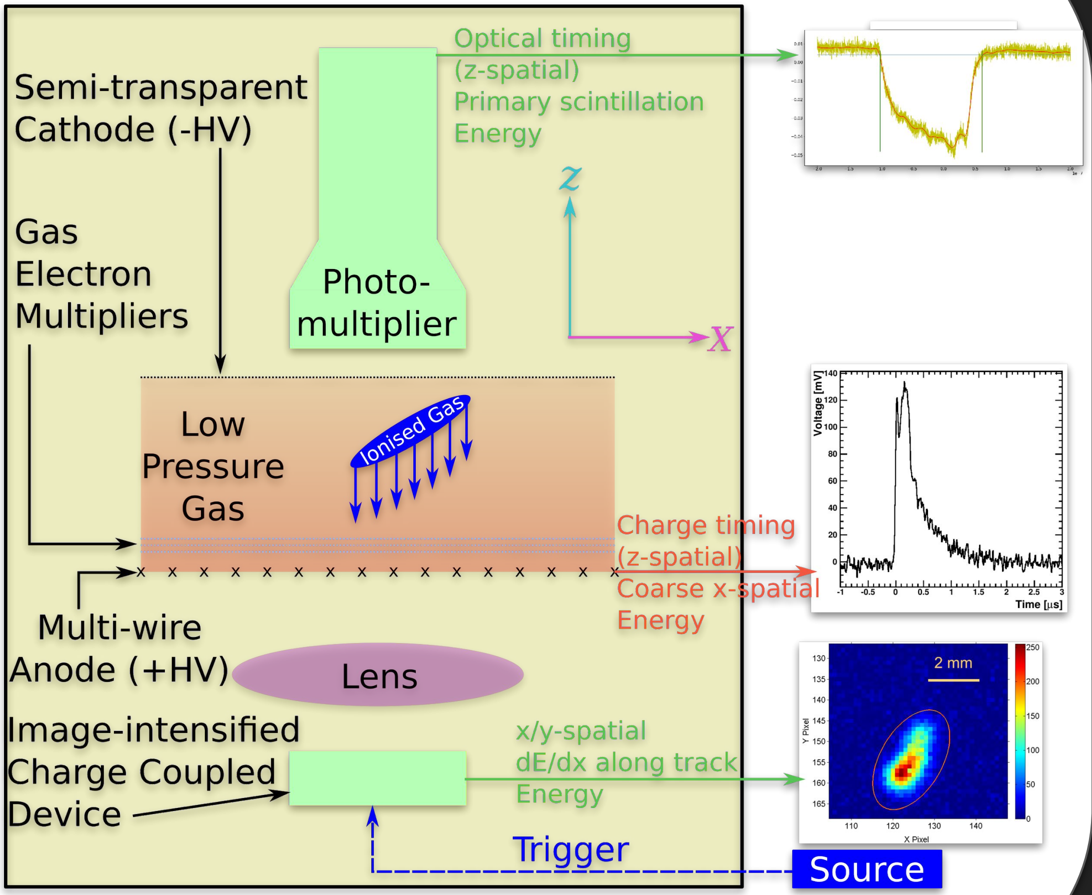




ANU CYGNUS prototype

Detector characterisation/testing platform.

- First dual charge/optical readout with 3D event reconstruction.
- First triggered optical readout, facilitates characterisation and interesting self-triggering schemes.



Conclusion

SABRE will confirm or refute the DAMA signal.

Housed in the first deep underground laboratory in the Southern Hemisphere.

R&D for post-SABRE program is already

Bonus Slides

Gas? Really??

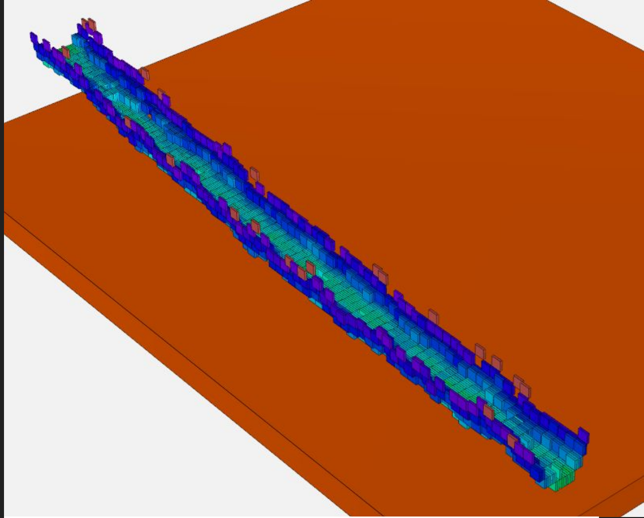
Rich event information makes up for low target mass.

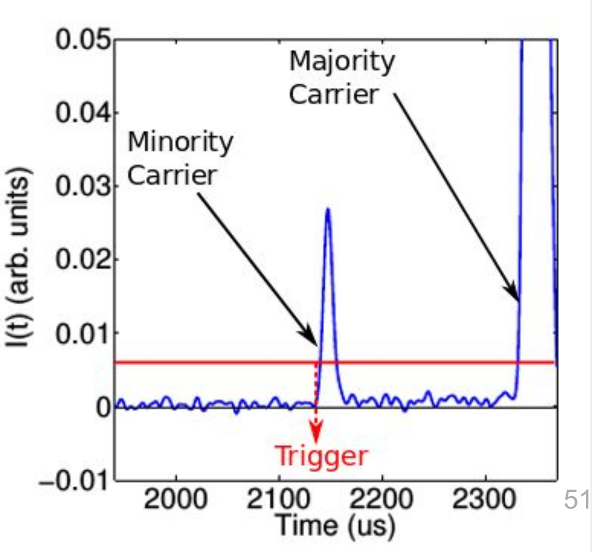
Fiducialisation (absolute Z position):

Negative ion drift[1] → velocity difference between minority carriers (SF_5^-) and majority carriers (SF_6^-).

Negative ions also diffuse less than electrons -- preserves directionality in bigger detectors / to lower energies.

Diffusion → infer Z by the amount of track diffusion[2]





1. arXiv:1609.05249, 2. arXiv:1410.1131

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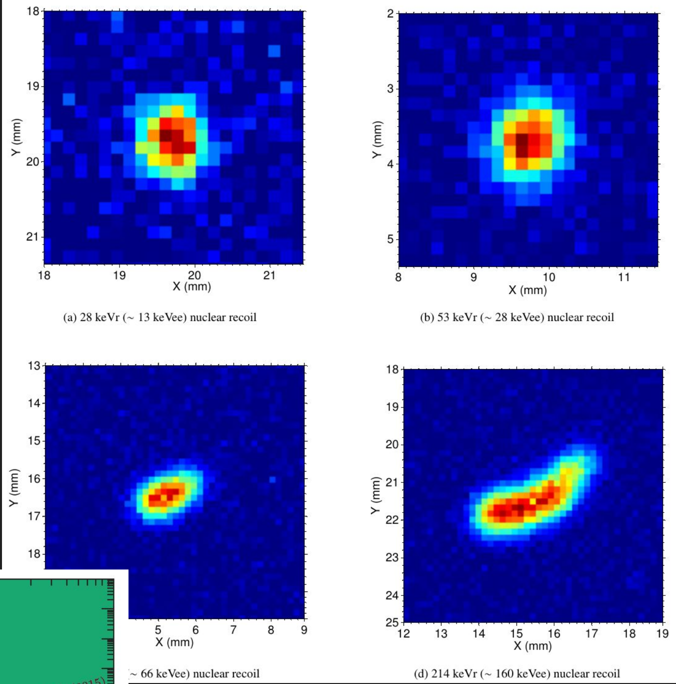
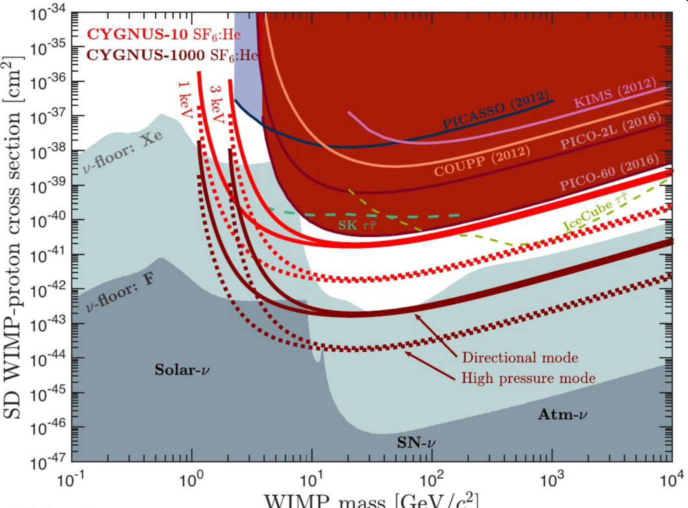
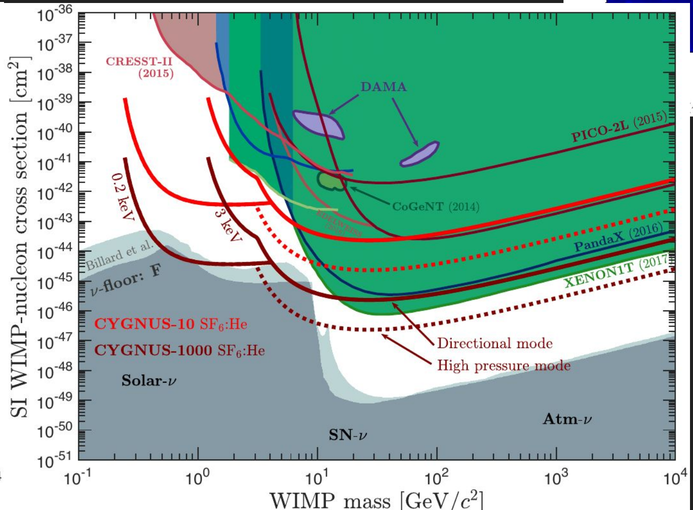
R&D is needed.



(a) 28 keVr (~ 13 keVee) nuclear recoil
(b) 53 keVr (~ 28 keVee) nuclear recoil
~ 66 keVee) nuclear recoil
(d) 214 keVr (~ 160 keVee) nuclear recoil





10 m^3 detector
Competitive SD sensitivity
10^3 m^3 detector
Below neutrino floor!

Waveform Processing (Too much detail?)

Filtering:

Necessary for timing, charge estimates worked better on the raw waveforms.

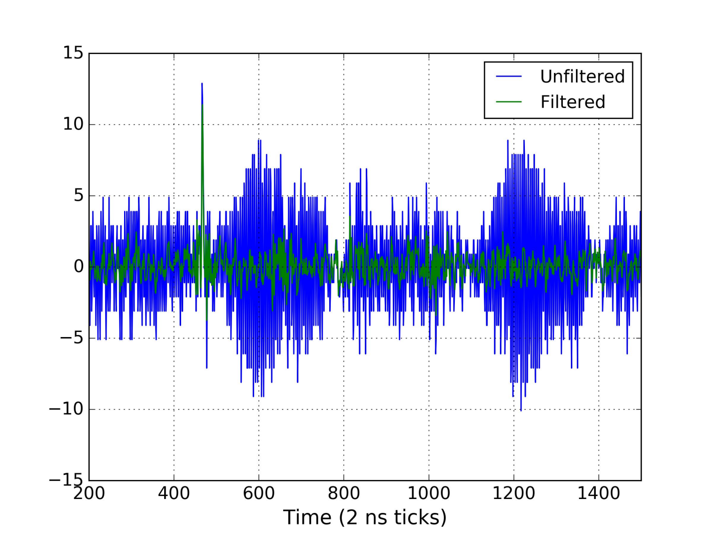
Used a Wiener filter

H = S / (S + N) = (S/N) / [(S/N) + 1]

High S/N gets passed, low S/N gets attenuated.

'Signal' was determined by finding 1 PE Waveforms (identified by time-over threshold).

Timing cut to select S and N regions.



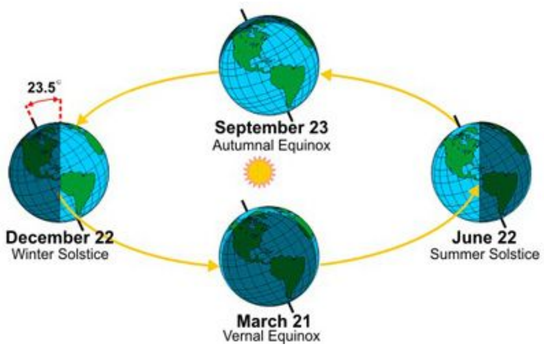
S was additionally filtered using median filter on power spectral density.

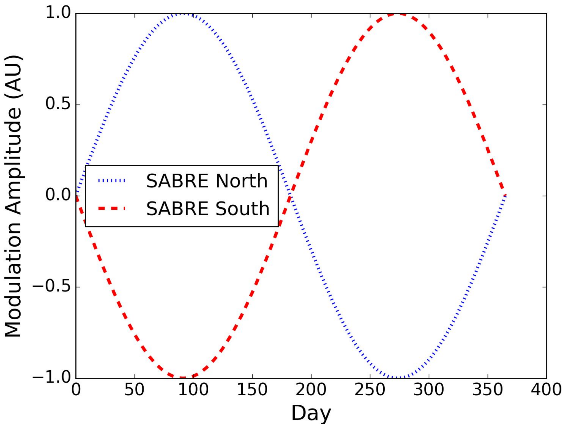
Detector	Nucleus	Recoil Energy, 2.44 MeV beam (keV)	Recoil Energy, 3 MeV beam (keV)	Recoil Energy, 5.2 MeV beam (keV)
LS0	Na	0.24 ± 0.07	0.44 ± 0.13	1.2 ± 0.3
LS0	I	0.04 ± 0.01	0.08 ± 0.02	0.21 ± 0.06
LS1	Na	1.39 ± 0.25	2.5 ± 0.5	6.8 ± 1.2
LS1	I	0.25 ± 0.05	0.45 ± 0.08	1.2 ± 0.2
LS2	Na	4.61 ± 0.60	8.3 ± 1.1	22.5 ± 2.9
LS2	I	0.84 ± 0.11	1.5 ± 0.2	4.1 ± 0.5
LS3	Na	14.7 ± 1.0	26.5 ± 1.8	71.8 ± 5.0
LS3	I	2.7 ± 0.2	4.9 ± 0.3	13.1 ± 0.9
LS4	Na	38.2 ± 2.1	68.9 ± 3.8	186 ± 10
LS4	I	7.1 ± 0.4	12.8 ± 0.7	34.5 ± 2.0
LS5	Na	60.8 ± 3.7	109.8 ± 6.7	297 ± 18
LS5	I	11.4 ± 0.7	20.6 ± 1.3	56.0 ± 3.5
LS6	Na	100.7 ± 2.4	182 ± 4	492 ± 12
LS6	I	19.4 ± 0.5	35.0 ± 0.9	94.6 ± 2.4

Table 2: The predicted nuclear recoil energies for the measurement.

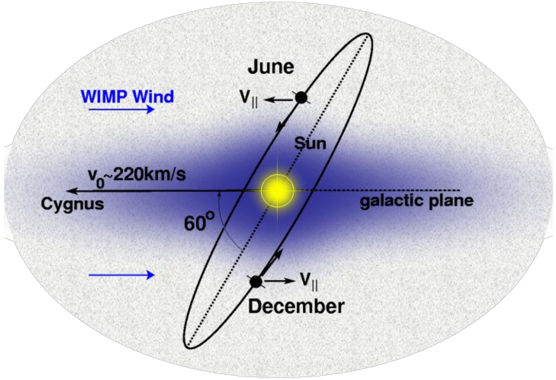
Two Hemisphere Experiment

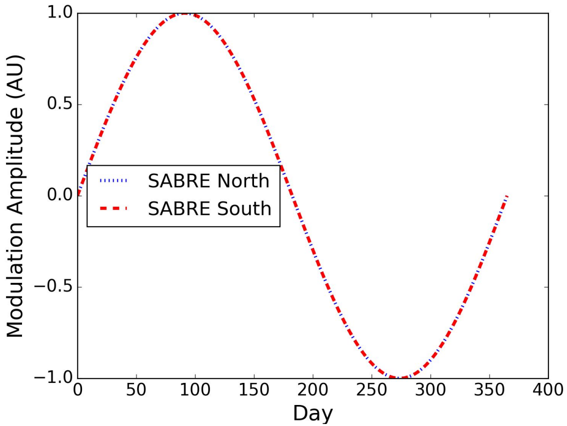
Seasonal Effect:





Dark Matter:

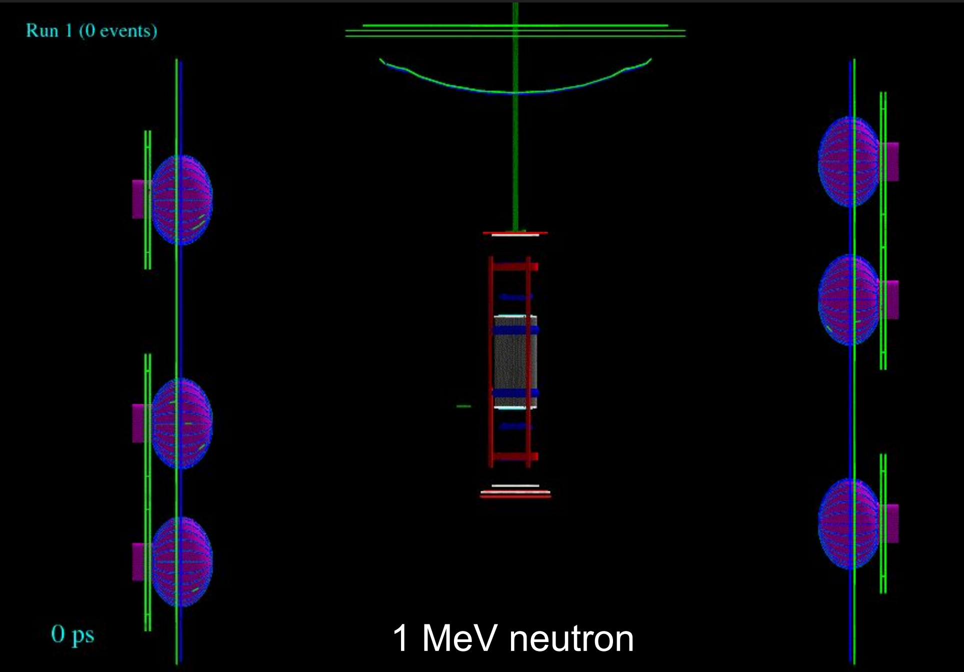




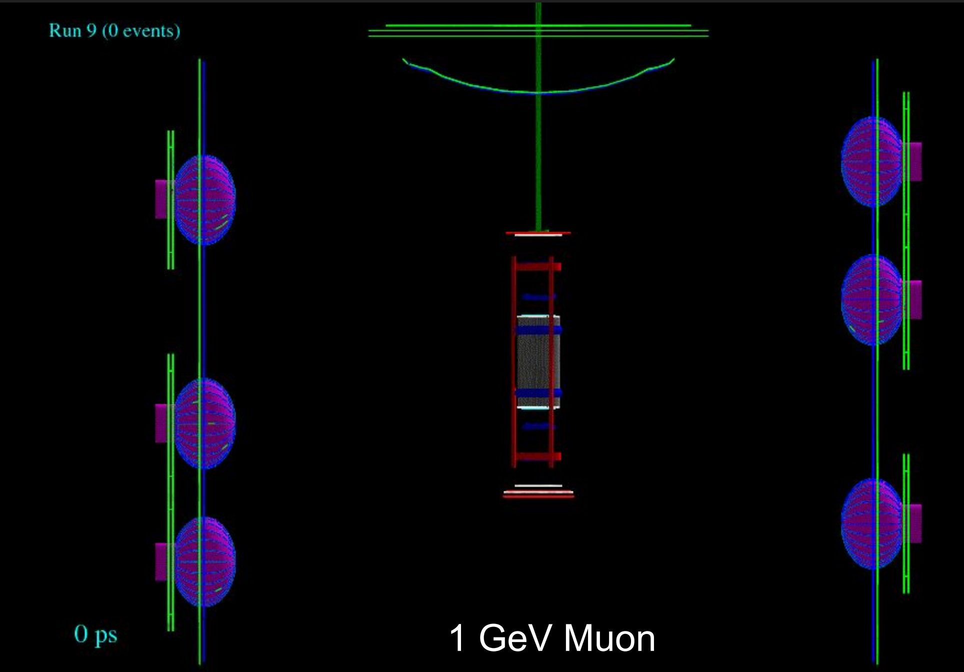
Proof-of-Principle Simulations

Uses known internal contamination levels and predicted cosmogenic activation.

Optical photon physics has recently been added → improved calculations soon.

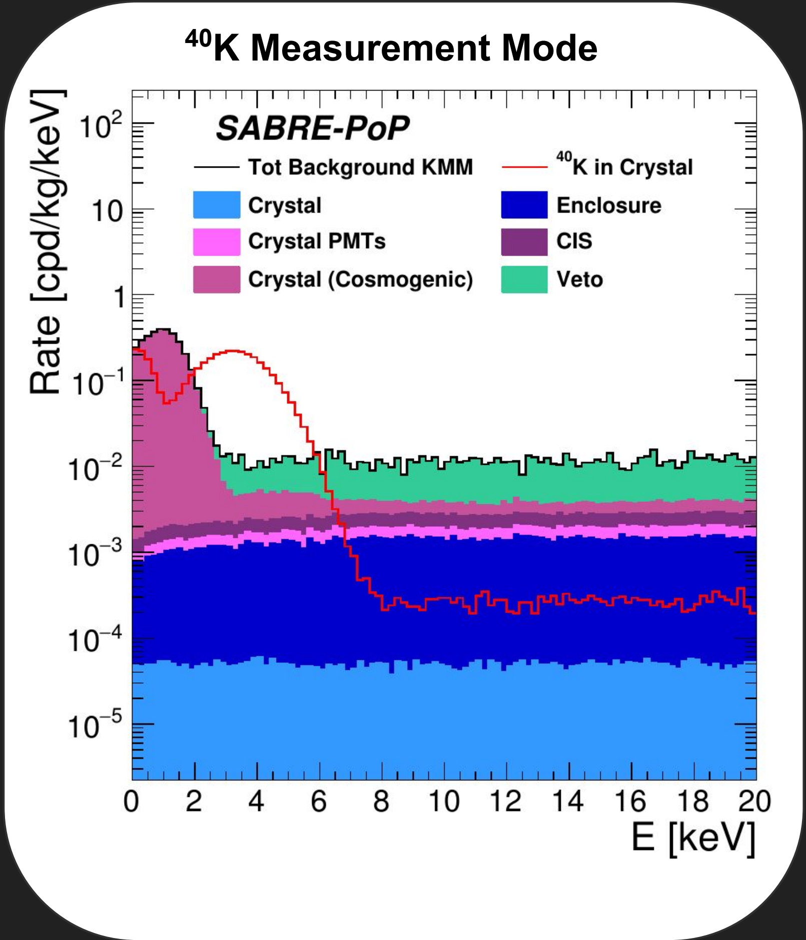


1 MeV neutron



1 GeV Muon

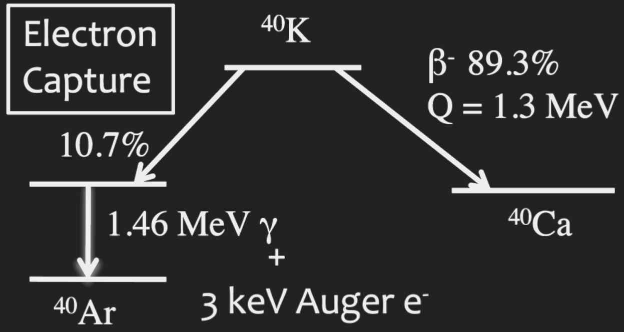
Simulations: K-40 measurement mode



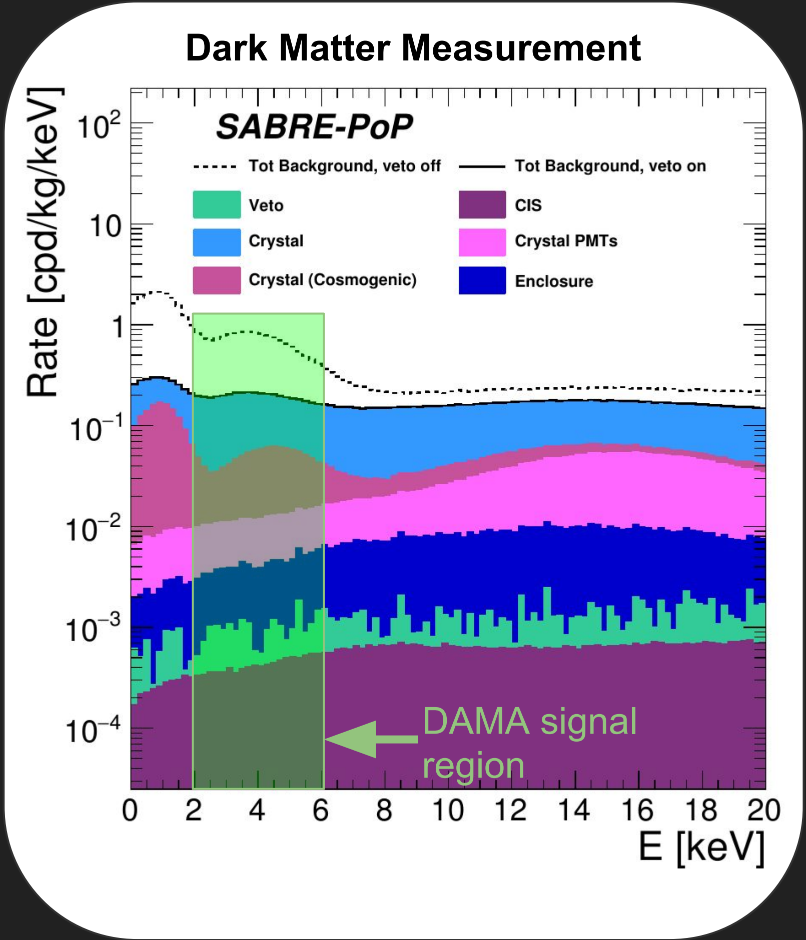
Crystal-veto coincidences tag ^{40}K Auger electron + gamma events.

Backgrounds assume 2 months of cosmogenic decay.

10 ppb ^{40}K in crystal (red trace) is detectable above background; 10% precision after 2 months of measurement.



Simulations: Dark Matter Mode



Isotope	Rate, veto OFF [cpd/kg/keV]	Rate, veto ON [cpd/kg/keV]
Intrinsic		
^{87}Rb	$6.1 \cdot 10^{-2}$	$6.1 \cdot 10^{-2}$
^{40}K	$2.5 \cdot 10^{-1}$	$4.0 \cdot 10^{-2}$
^{238}U	$2.0 \cdot 10^{-2}$	$2.0 \cdot 10^{-2}$
^{210}Pb	$2.0 \cdot 10^{-2}$	$2.0 \cdot 10^{-2}$
^{85}Kr	$1.9 \cdot 10^{-3}$	$1.9 \cdot 10^{-3}$
^{232}Th	$1.9 \cdot 10^{-3}$	$1.7 \cdot 10^{-3}$
Tot Intrinsic	$3.5 \cdot 10^{-1}$	$1.5 \cdot 10^{-1}$
Cosmogenic		
^{121}Te	$2.6 \cdot 10^{-1}$	$3.3 \cdot 10^{-2}$
^{22}Na	$3.6 \cdot 10^{-2}$	$2.7 \cdot 10^{-3}$
^{125}I	$1.8 \cdot 10^{-3}$	$1.8 \cdot 10^{-3}$
^{129}I	$3.4 \cdot 10^{-4}$	$3.4 \cdot 10^{-4}$
^{126}I	$2.0 \cdot 10^{-4}$	$1.3 \cdot 10^{-4}$
^{121m}Te	$1.3 \cdot 10^{-4}$	$7.0 \cdot 10^{-5}$
^{123m}Te	$7.6 \cdot 10^{-5}$	$5.1 \cdot 10^{-5}$
^{127m}Te	$5.0 \cdot 10^{-5}$	$4.9 \cdot 10^{-5}$
^{125m}Te	$5.3 \cdot 10^{-6}$	$5.1 \cdot 10^{-6}$
^{24}Na	-	-
Tot Cosmogenic (180 days)	$3.0 \cdot 10^{-1}$	$3.9 \cdot 10^{-2}$

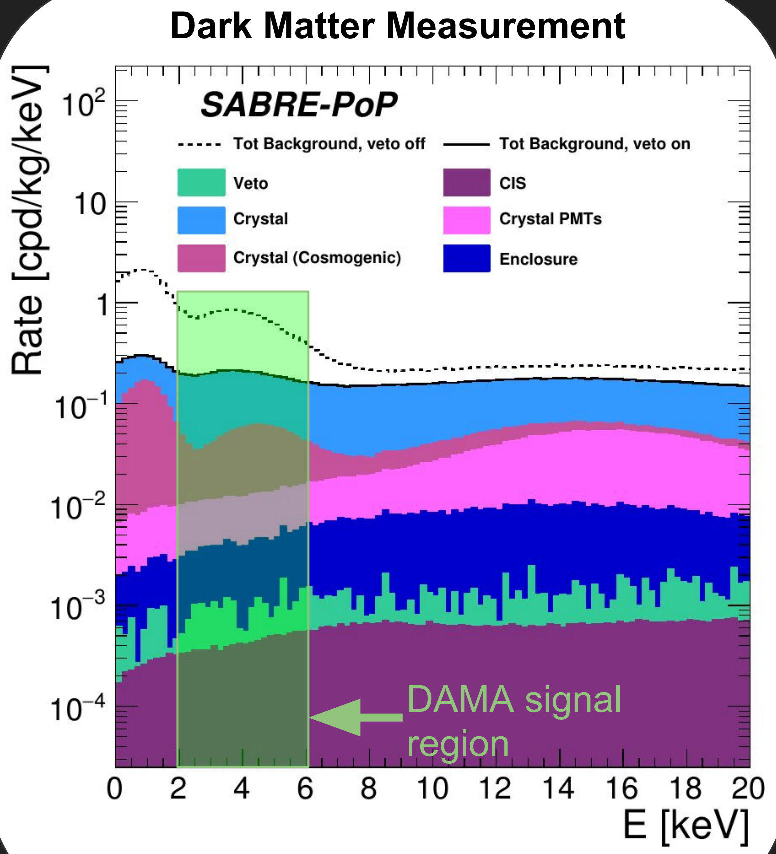
Veto threshold: 100 keV.

Total background rejection efficiency = 70%.

Signal region: 0.22 counts day^{-1} kg^{-1} keV^{-1}.

More details: https://arxiv.org/abs/1806.09344

Simulations: Dark Matter Mode



~50% ^{87}Rb, which is a measurement limit!

Isotope	Rate, veto OFF [cpd/kg/keV]	Rate, veto ON [cpd/kg/keV]
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^{126}I	$2.0 \cdot 10^{-4}$	$1.3 \cdot 10^{-4}$
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^{123m}Te	$7.6 \cdot 10^{-5}$	$5.1 \cdot 10^{-5}$
^{127m}Te	$5.0 \cdot 10^{-5}$	$4.9 \cdot 10^{-5}$
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Total background rejection efficiency = 70%.

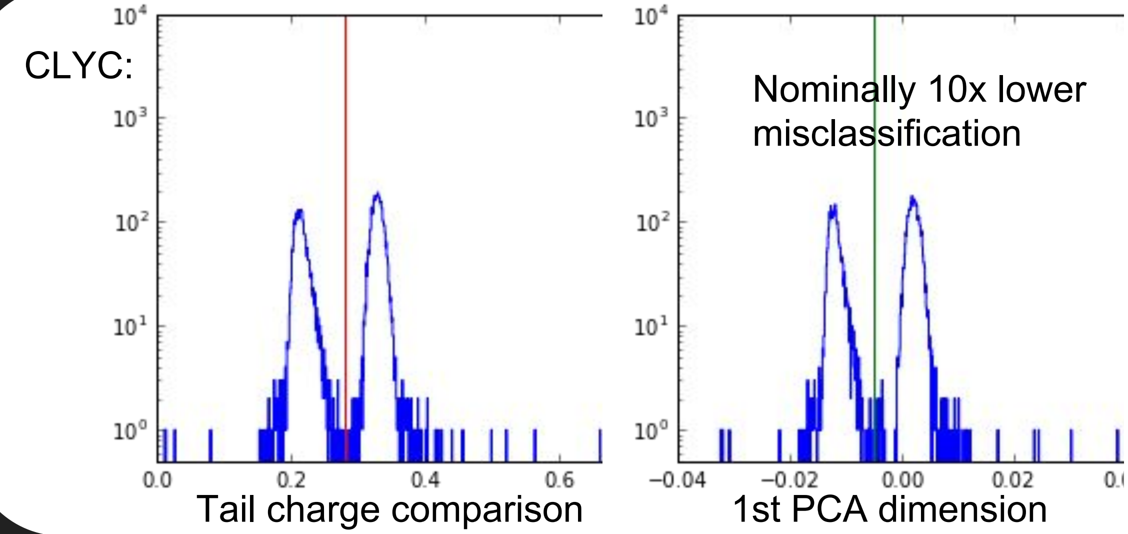
Signal region: 0.22 counts day^{-1} kg^{-1} keV^{-1}.

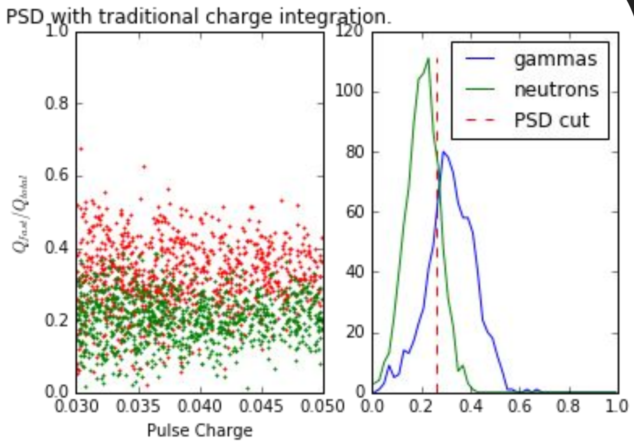
More details: https://arxiv.org/abs/1806.09344

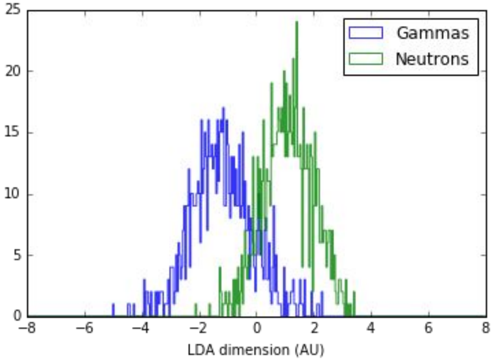
Pulse Shape Discrimination

Optimise NaI:Tl PSD?

- Principal component analysis-based approach, with optimal cuts from linear discriminant analysis.
- Difficult for low energy NaI:Tl signals due to low numbers of photoelectrons.
- Quenching factor measurements → training set.



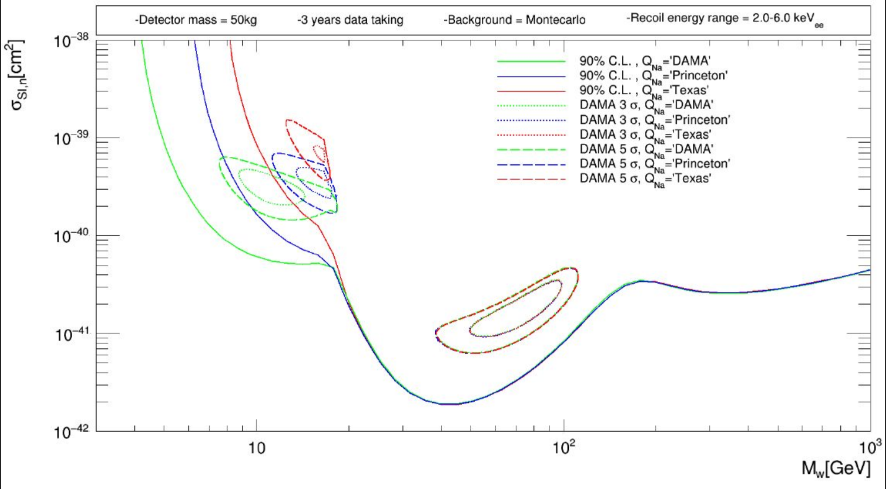


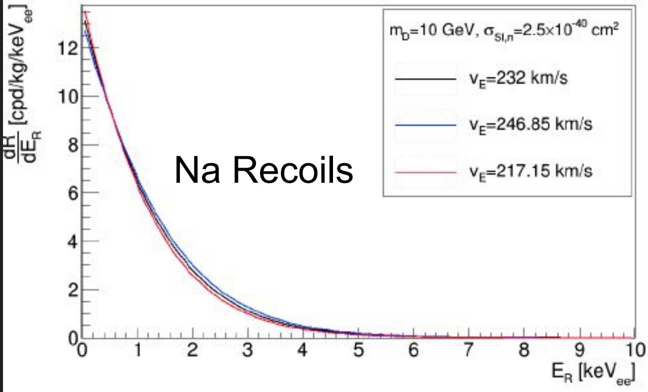


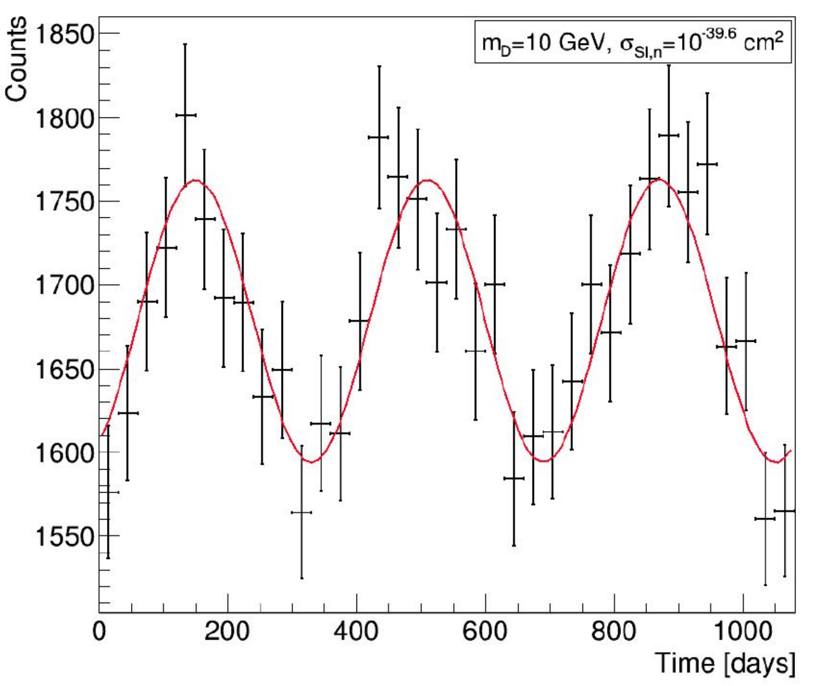
Sensitivity Calculation

Two independent analyses, both predict similar sensitivities

Effect of varying the quenching factor:







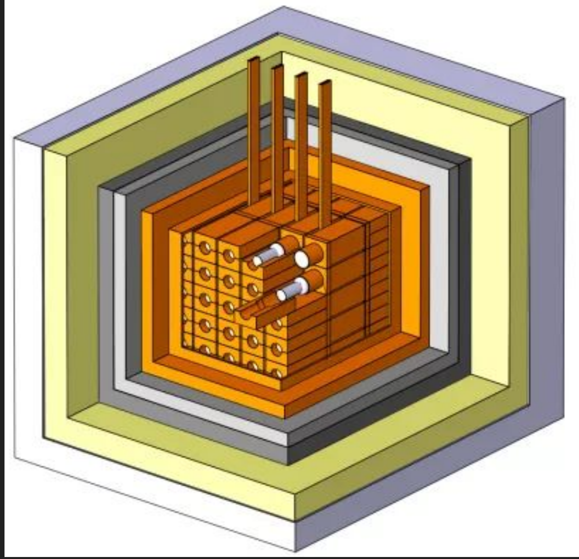
Characterisation Measurements
Liquid scintillator testing

- Purification, compatibility testing, etc.

DAMA Design

25 x 10 kg of NaI:Tl target, double-sided readout, high QE PMTs, ~10 PE/keV.

Cu/Pb/Cd/HDPE/paraffin/concrete shield flushed with N_2.



Temperature, gas flow, HV, and radon monitoring.

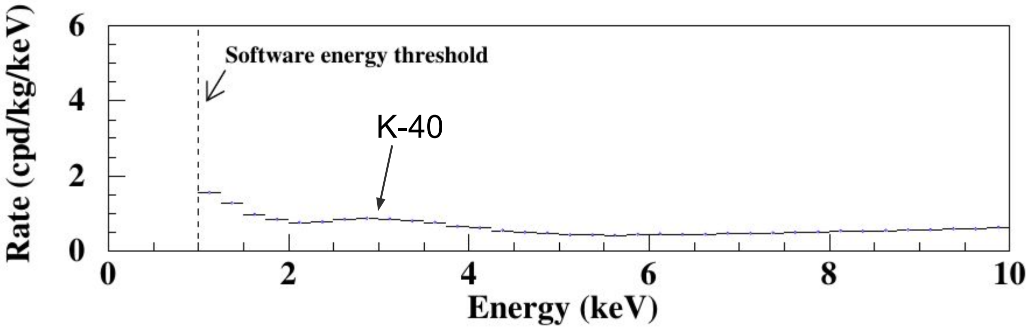
Temperature control through A/C.

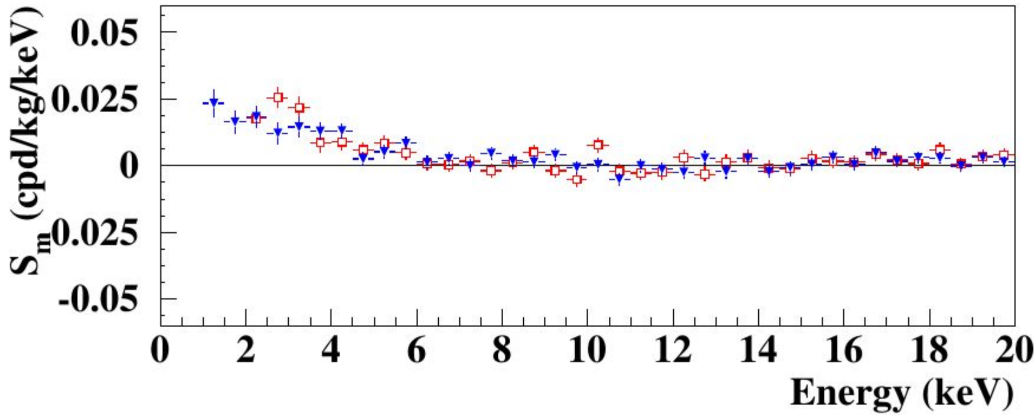
Alternate modulation systematics (temperature, muons, etc.) claimed to be insignificant by DAMA.

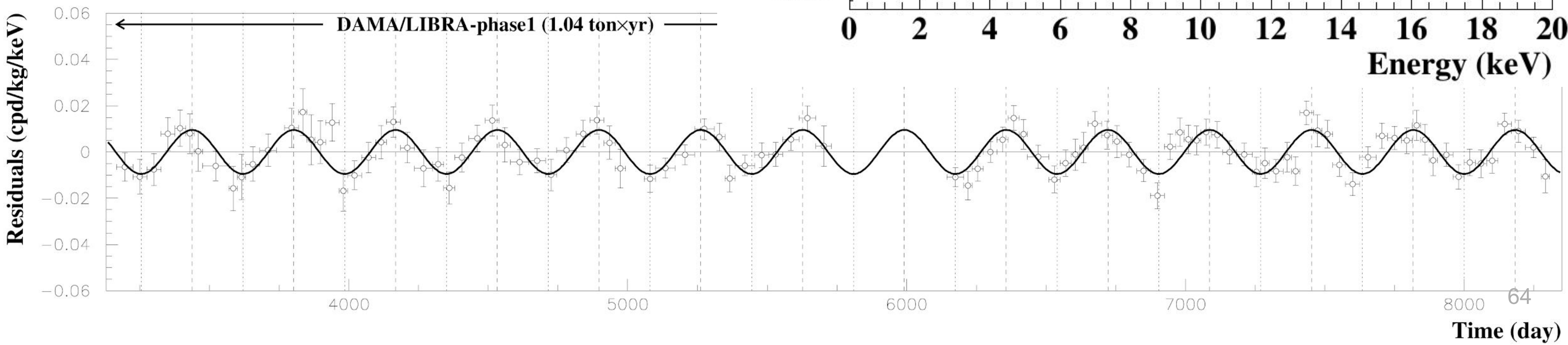
Annual Modulation

Modulation range was 2 - 6 keV, recently pushed to 1 keV threshold.

No comprehensive background model, but K-40 appears to be most important for signal region.





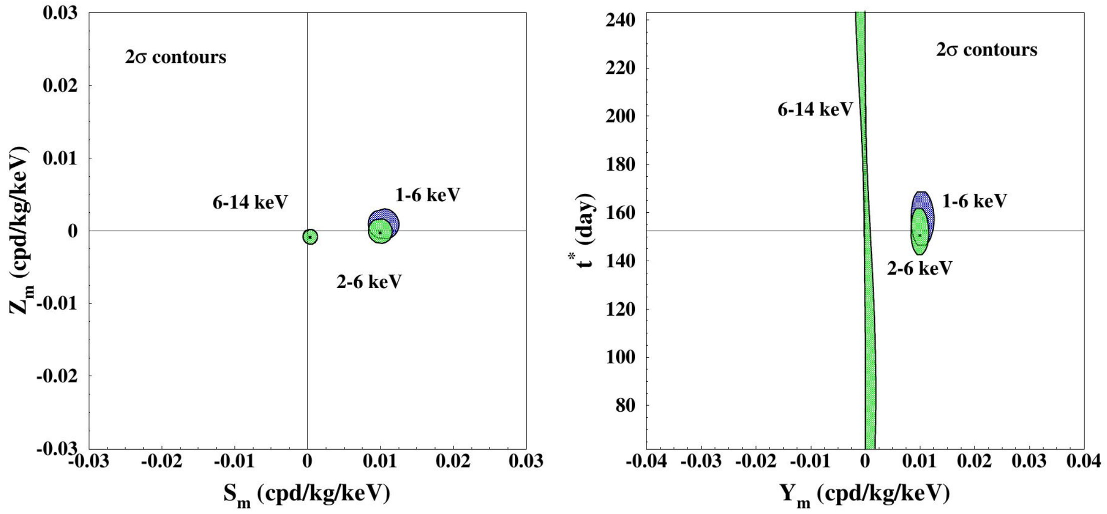


DAMA Result

Phase matches standard halo model prediction.

Amplitude ~0.01 cpd keV^{-1} kg^{-1} ~ 1% of background

$$
\begin{aligned}
S_i(E) &= S_0(E) + S_m(E)\cos\omega(t_i - t_0) + Z_m(E)\sin\omega(t_i - t_0) \\
&= S_0(E) + Y_m(E)\cos\omega(t_i - t^*).
\end{aligned}
$$



Ultrapure NaI:Tl Target Detector

Intrinsic radioactivity limits WIMP sensitivity.

‘Astrograde’ powder (Sigma Aldrich).
Carefully-developed powder preparation and growth protocols (Princeton + RMD).

Lower radio-impurity than DAMA.
Production growth underway.

High QE + low background PMTs: 1 keV threshold design.

Accelerator Mass Spectrometry

^{129}I: similar level to DAMA (1 mBq/kg)

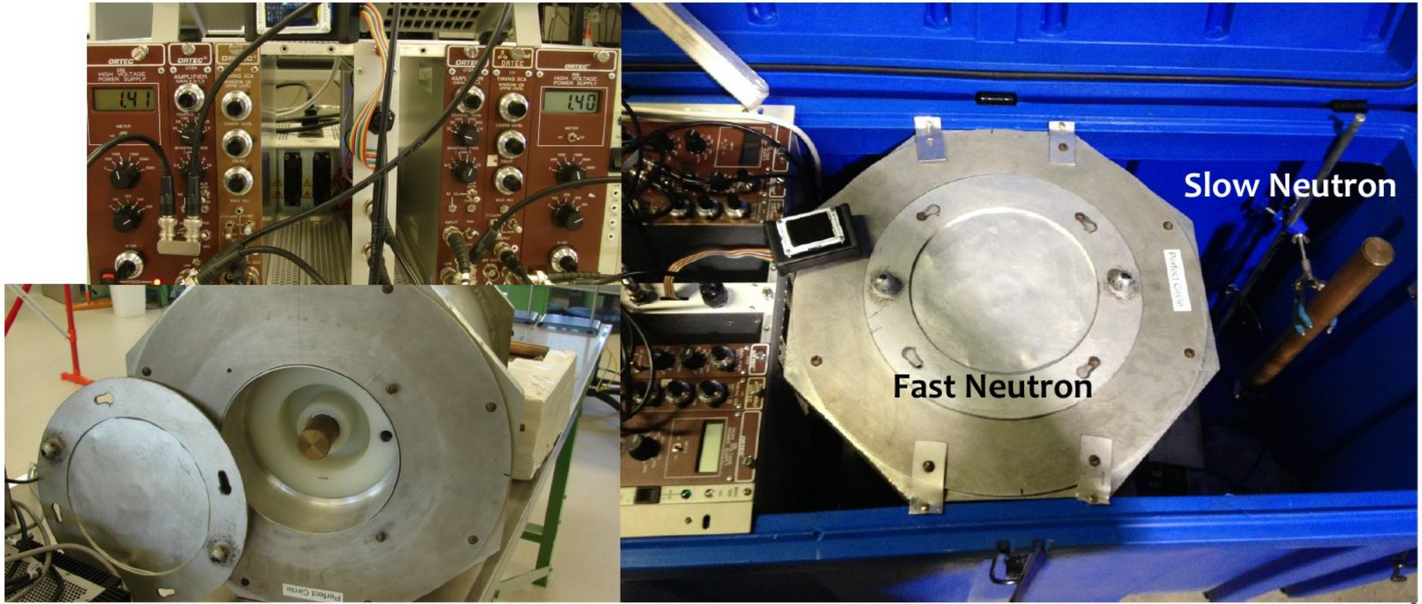
^{210}Pb: new methodology, 2 orders of magnitude better sensitivity. Working towards < 1 mBq/kg.

ICP-MS measurements

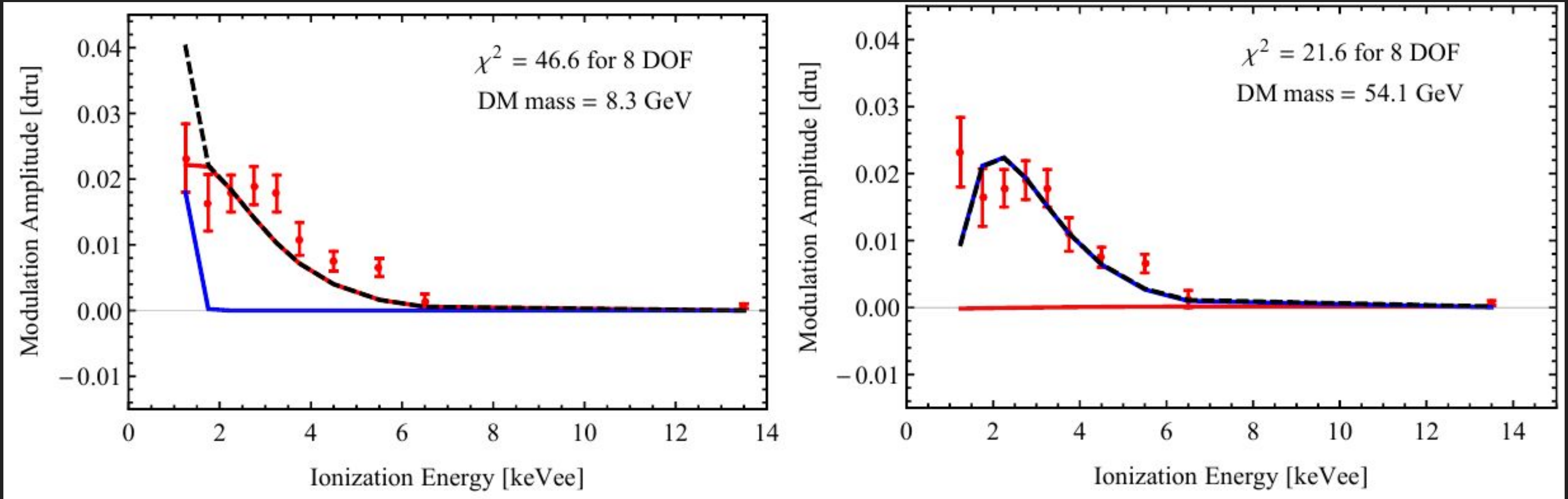
Element	DAMA powder [ppb]	DAMA crystals [ppb]	Astro-Grade [ppb]	SABRE crystal [ppb]
K	100	$\sim$13	9	9
Rb	n.a.	<0.35	<0.2	<0.1
U	$\sim$0.02	$0.5\text{-}7.5\times10^{-3}$	$<10^{-3}$	$<10^{-3}$
Th	$\sim$0.02	$0.7\text{-}10\times10^{-3}$	$<10^{-3}$	$<10^{-3}$

Neutron flux measurement

- Thermal neutron (<0.5 eV) and fast neutron (MeV energies) are measured with two BF_3 proportional tubes (V=295 cm^3 and P = 0.33 atm).
  - One naked BF_3 tube for thermal neutrons
  - One BF_3 tube surrounded by a Polyethylene cylinder to detect slowed down fast neutrons



Quenching Factor Measurements



Recent paper: DAMA phase 2 spectra are not consistent with SI-SHM WIMPS (>5.2 σ and >2.5 σ, arXiv:1804.01231), but quenching factor affects this!

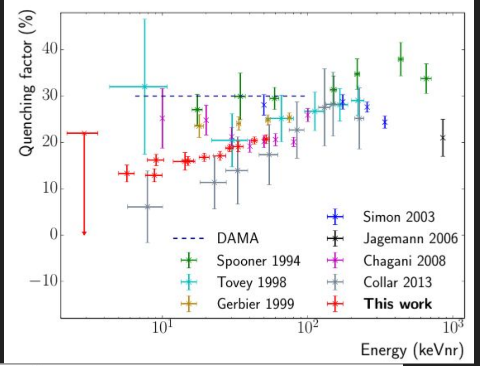
Model dependent/constrains possible models

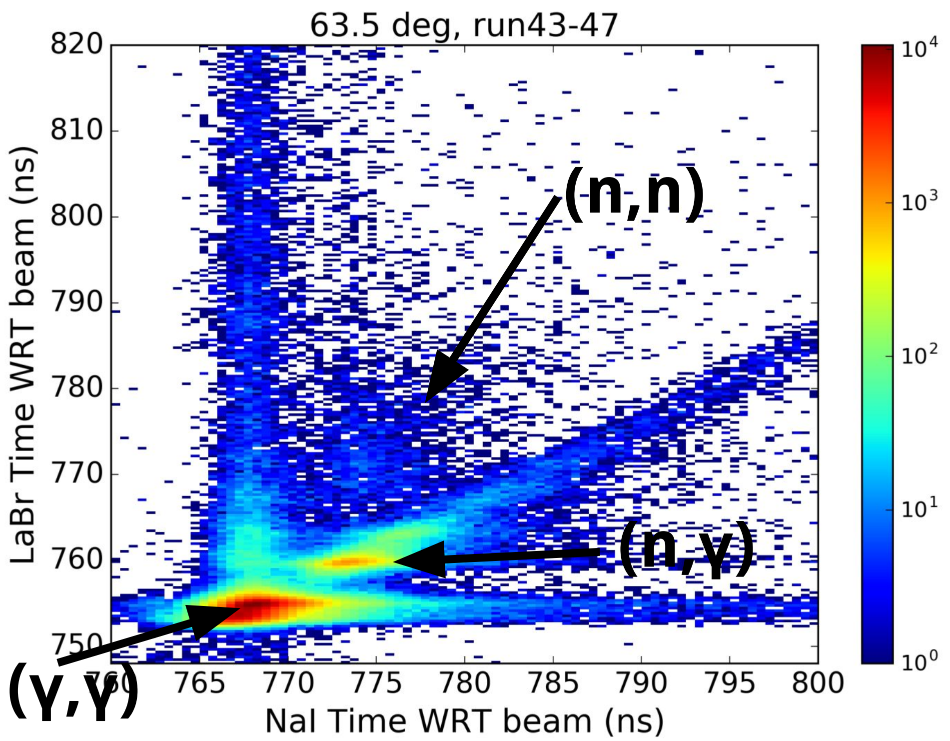
Quenching Factor Test Run

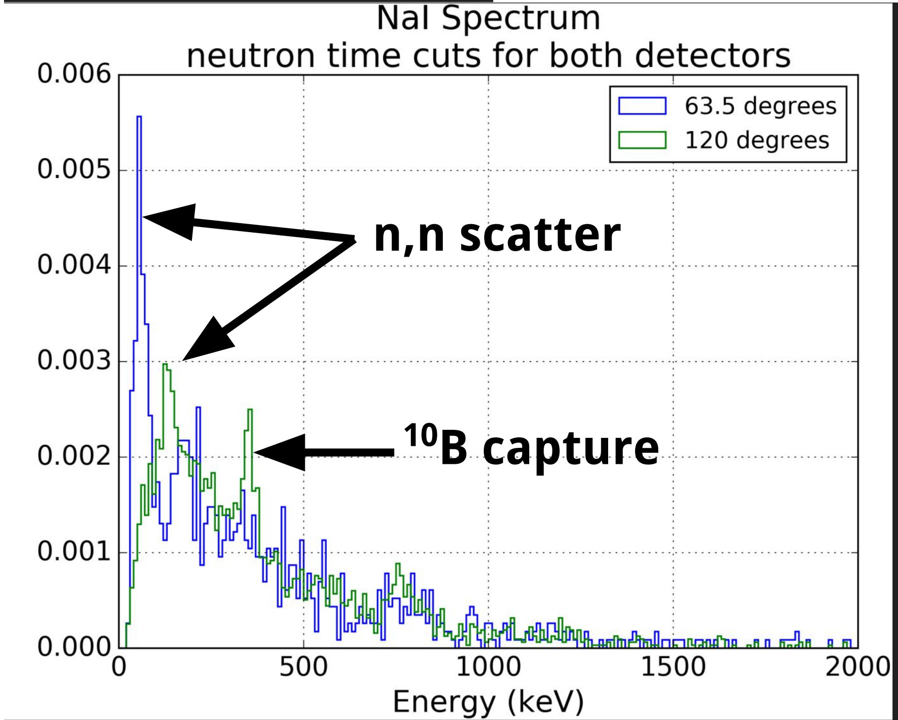
Test measurement:

NaI:Tl target, $LaBr_3$ for tagging neutrons.

~393 keV and 168 keV NR → QF ~ 0.33.





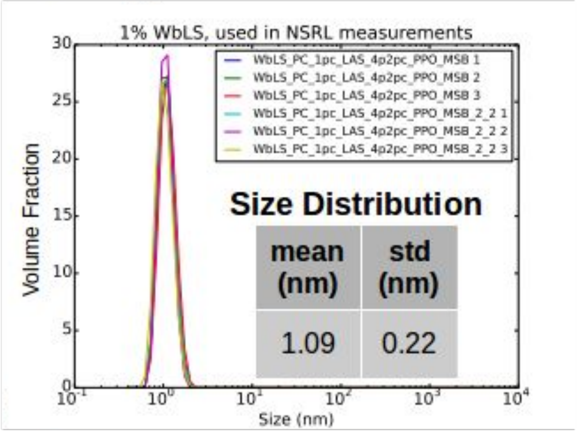


WbLS Quenching

- Why does WbLS have high quenching?
  - Exciton diffusion length over lifetime:

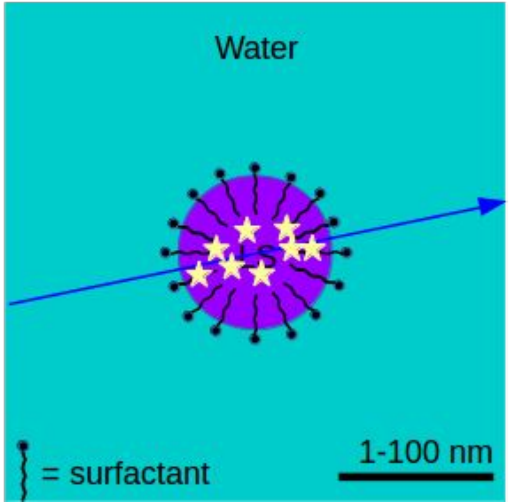
$$l = \sqrt{D\tau} \sim 2\,\text{nm} \qquad \tau \sim 10\text{ ns} \quad D \sim 4\times10^{-6}\text{ cm}^2/\text{s}$$

    - This is a lower-limit estimate, as D is the molecular diffusion length.
  - The micelle size for the WbLS used in the NSRL study is less than the diffusion length.
  - We have plans to do more measurements of WbLS quenching.



Size Distribution

mean (nm)	std (nm)
1.09	0.22



WbLS Development

- Optical properties:
  - Absorption:
    - Primarily due to impurities in stock material.
      - Column purification, vacuum distillation.
  - Scattering:
    - Primarily determined by the micelle size.
    - Rayleigh scattering ~ d^{-6}, but number of scatterers ~ d^{3}.
      - Optimize amount of surfactant, and use co-surfactant.

Figure: Unpurified solvent from the manufacturer