

Spectroscopy of VUV luminescence in dual-phase xenon detectors

[arXiv:2512.20935](https://arxiv.org/abs/2512.20935)

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On behalf of Albert B, Elisa J, Tim S, Henrique A and the Imperial Dark Matter Group

CPAD 2026 Instrumentation and Detector R&D Workshop

Dual-phase xenon time projection chambers (TPCs)

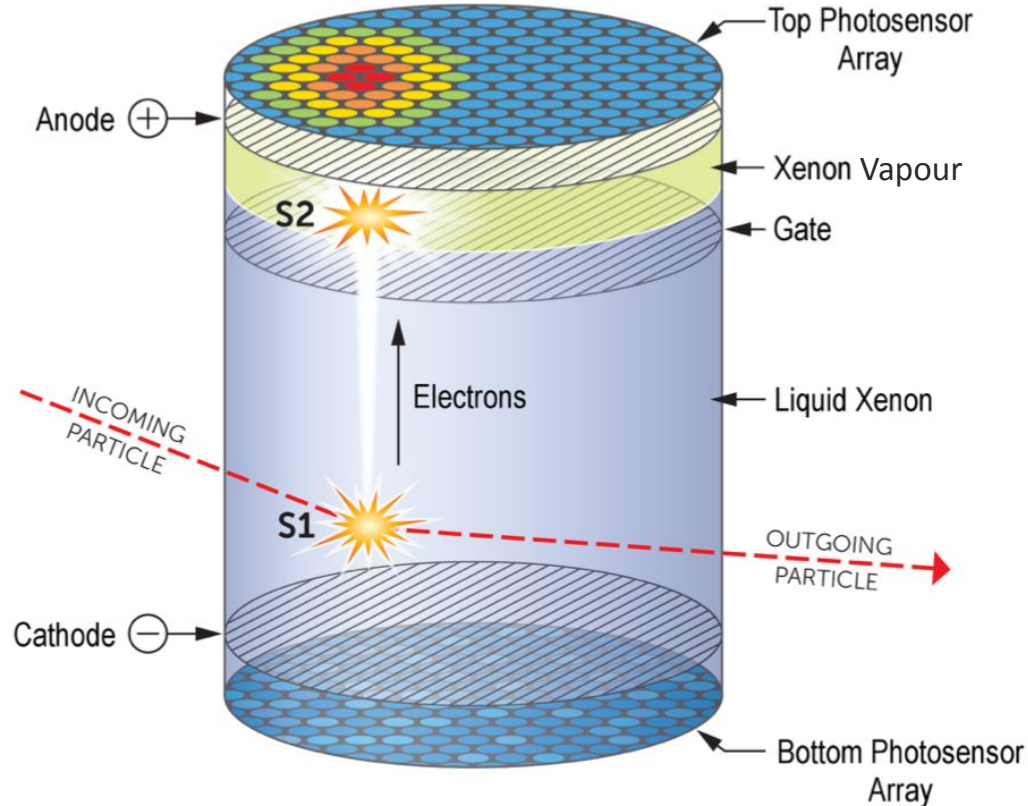
S1: VUV scintillation in liquid

S2: VUV electroluminescence in vapour

Current LZ experiment is leading the search for WIMPs with 7 tonnes of liquid xenon [[Phys. Rev. Lett. 135, 011802 \(2025\)](#)]

Next-generation XLZD experiment will probe WIMP parameter space down to neutrino fog with ~70 tonnes of liquid [[Eur. Phys. J. C 85, 1192 \(2025\)](#)]

Precise measurements of the S1 & S2 wavelength spectra are needed to accurately simulate the optical response of such detectors



Dual-phase xenon time projection chambers (TPCs)

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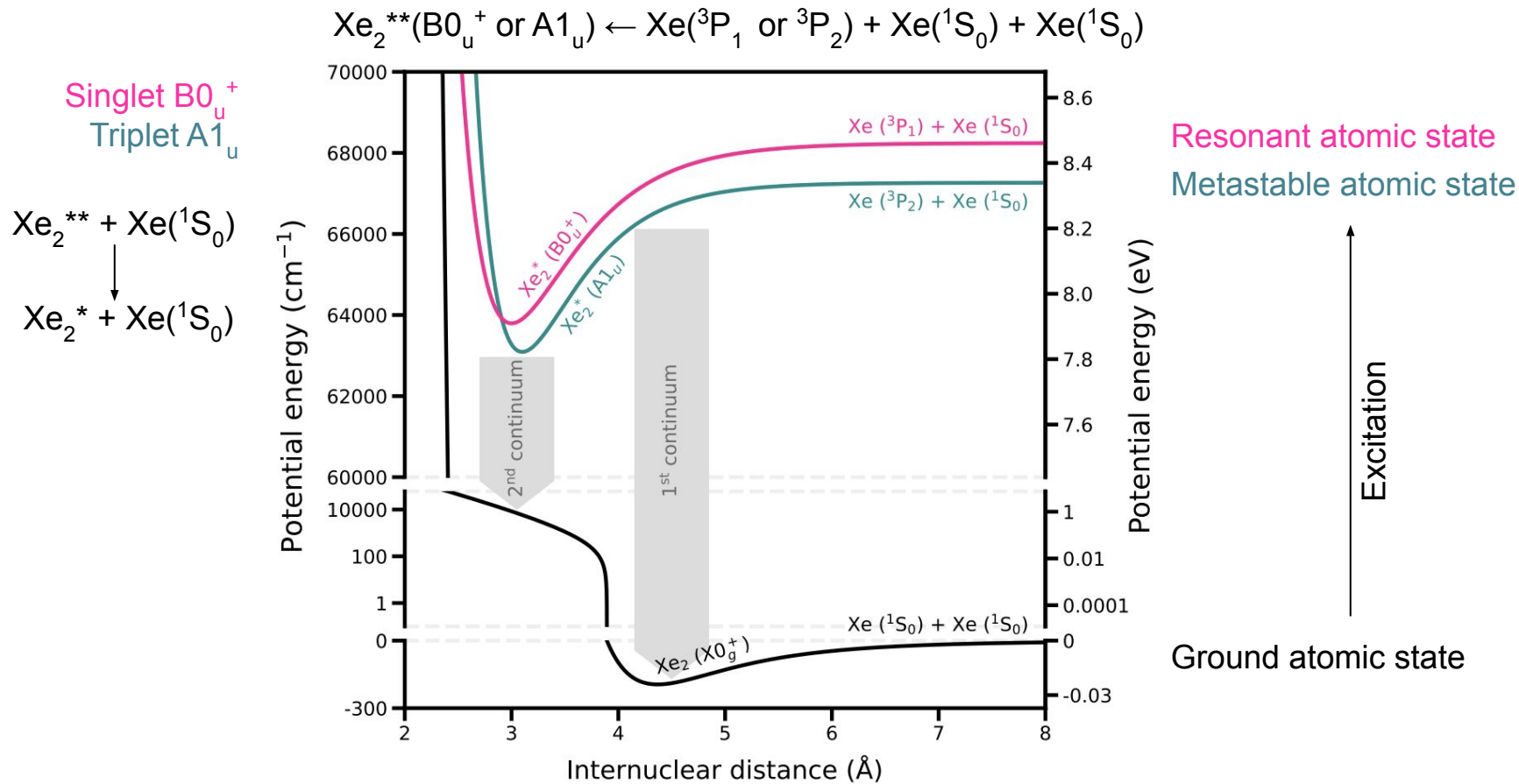
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Origin of xenon luminescence



Previous xenon luminescence measurements

	Paper	P (bar)	T (K)	Excitation method	Peak wavelength (nm)	FWHM (nm)
Liquid	Jortner 1965		168	^{60}Co gammas	178 ± 0.6	14.2 ± 1.6
	Fuji 2015		160	^{210}Po alphas	174.8 ± 0.1	10.2 ± 0.2
	Wahl 2021	180	17.3	2-photon	175.3 ± 0.1	13.3 ± 0.2
Cold gas	Murayama 2014	1.38	174	^{60}Co gammas	173.4 ± 0.3	14.4
Room-temp gas	Jortner 1965	1	299	^{210}Po alphas	174 ± 0.6	13 ± 1.6
	Koehler 1974	2	295	Relativistic electron burst	169 ± 0.9	15.0 ± 0.3
	Suzuki 1979	0.5	Room	Electroluminescence	173	10
	Takahashi 1983	1	Room	^{241}Am alphas	171	12
	Messing 1990	3.9	Room	Optical pumping triplet fit	171.4 ± 0.6	12.2 ± 0.2
	Messing 1990	3.9	Room	Optical pumping singlet fit	170.4 ± 0.6	13.1 ± 0.3
	Wahl 2021	40	17.3	2-photon	172.2 ± 0.1	13.3 ± 0.2

Variety of pressures and temperatures comparable to those in dual-phase xenon TPCs

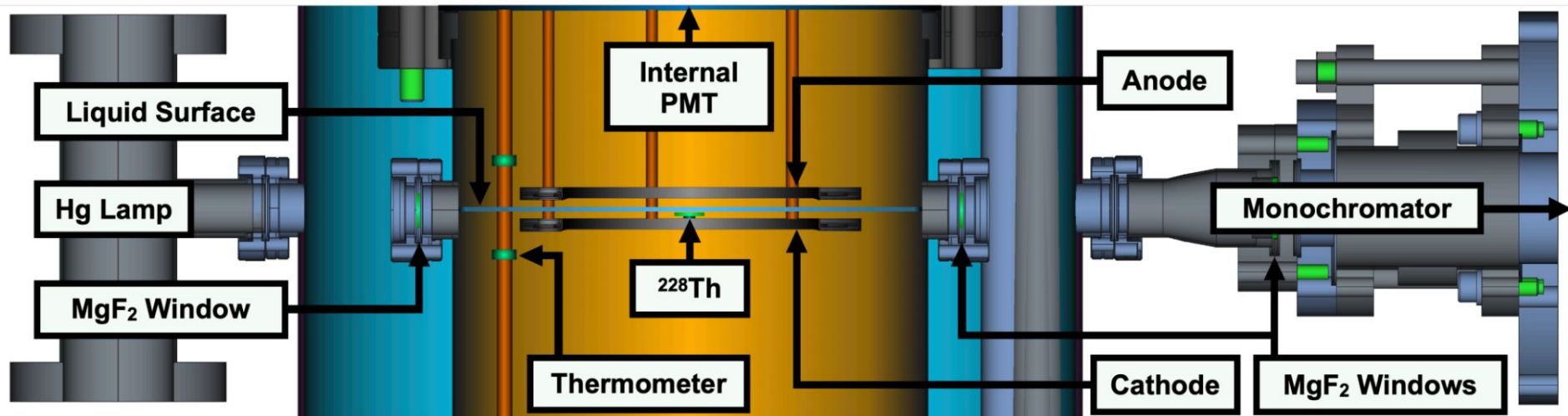
Optically relevant differences (e.g. $\lambda_{\text{Rayleigh}} \sim 20\text{--}40$ nm over $170\text{--}180$ nm)

Liquid results are, on average, several nanometers (0.1 eV) longer than those in the gas

Minimal purity information: O_2 & H_2O can absorb on the short wavelength side

Different methods used to excite xenon $\rightarrow$ different ratio of singlet to triplet states

Minimal TPC



Low-pressure Hg arc lamp for calibration

Light follows similar path as xenon luminescence (through TPC to monochromator)



Monochromator views ²²⁸Th α -decay induced liquid scintillation (S1) at the same time as the gas electroluminescence (S2)

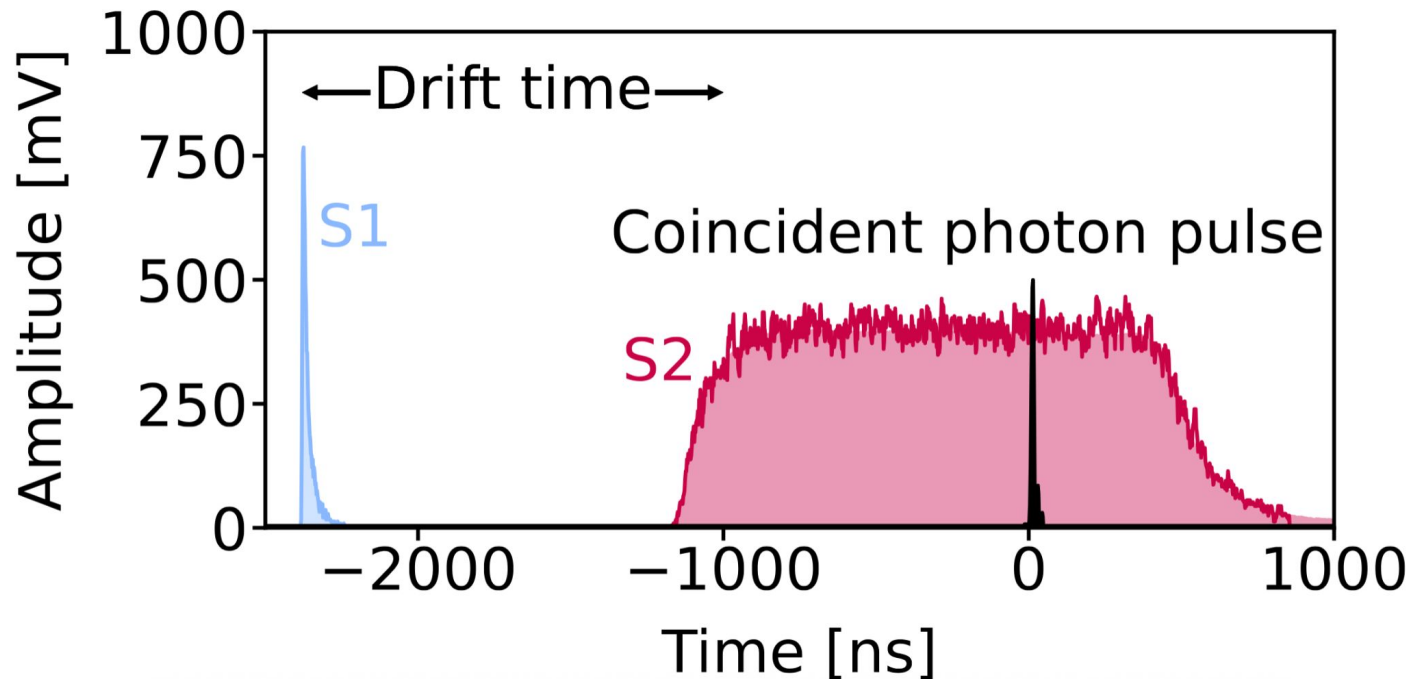
Spectroscopy PMT (not shown) detects light at the outlet of the monochromator

Coincident photon counting

Digitise individual
photons from
spectroscopy PMT

Coincident with S1
or S2 pulses from
the internal PMT

Minimises
background from
thermionic dark
counts

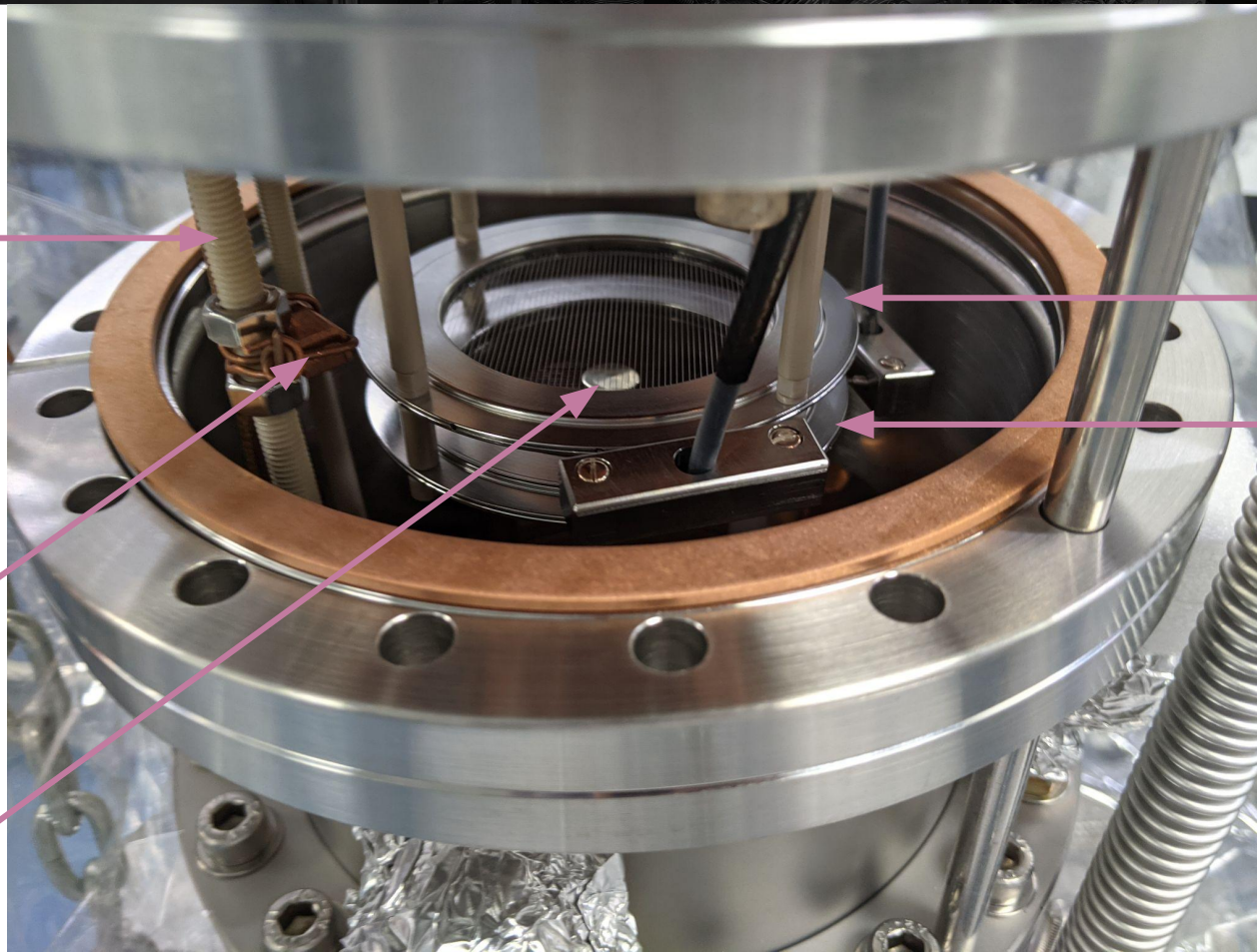


Minimal time projection chamber (TPC)

PEEK supports
positioned outside
monochromator
line-of-sight to
minimise any PEEK
scintillation
backgrounds

Thermometer

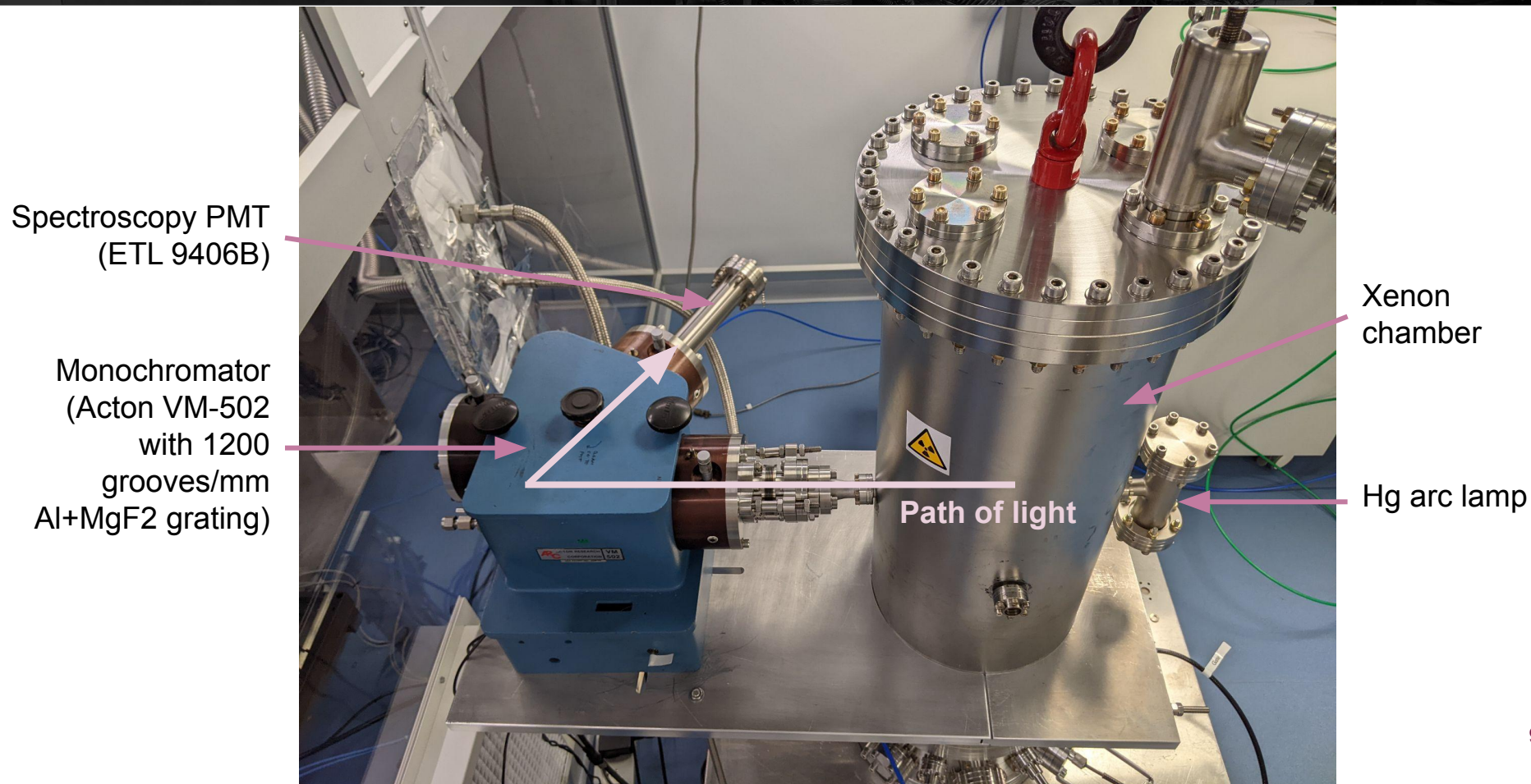
^{228}Th source



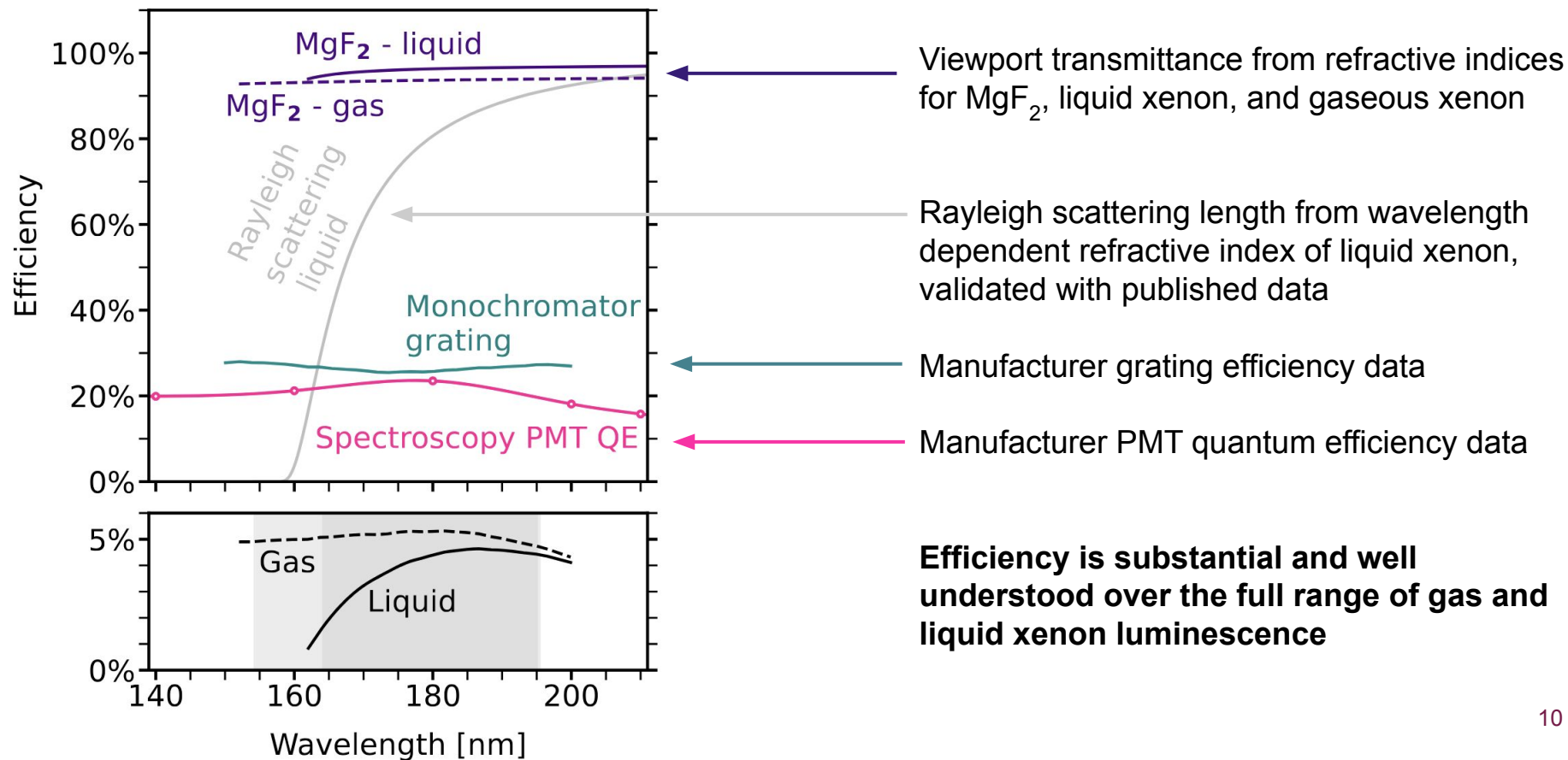
Anode

Cathode

Path of light



Optical efficiency corrections

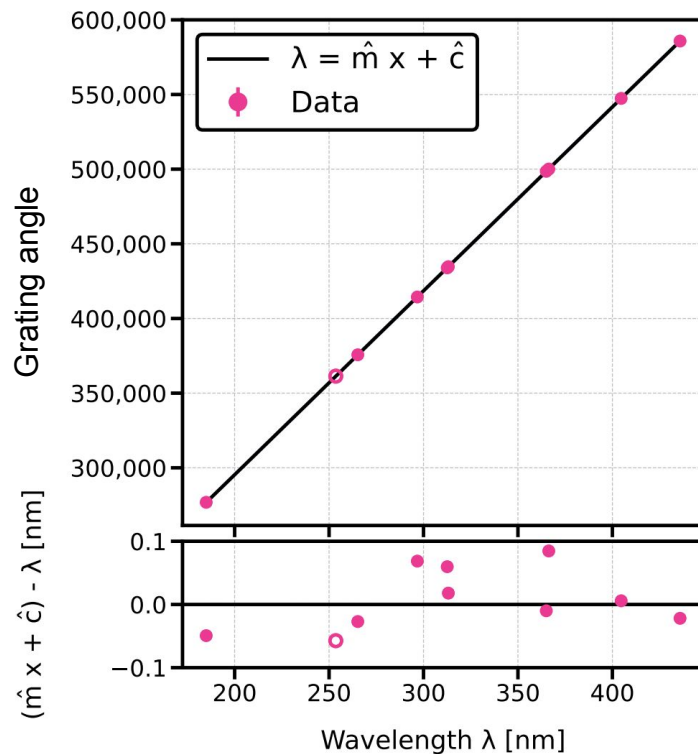
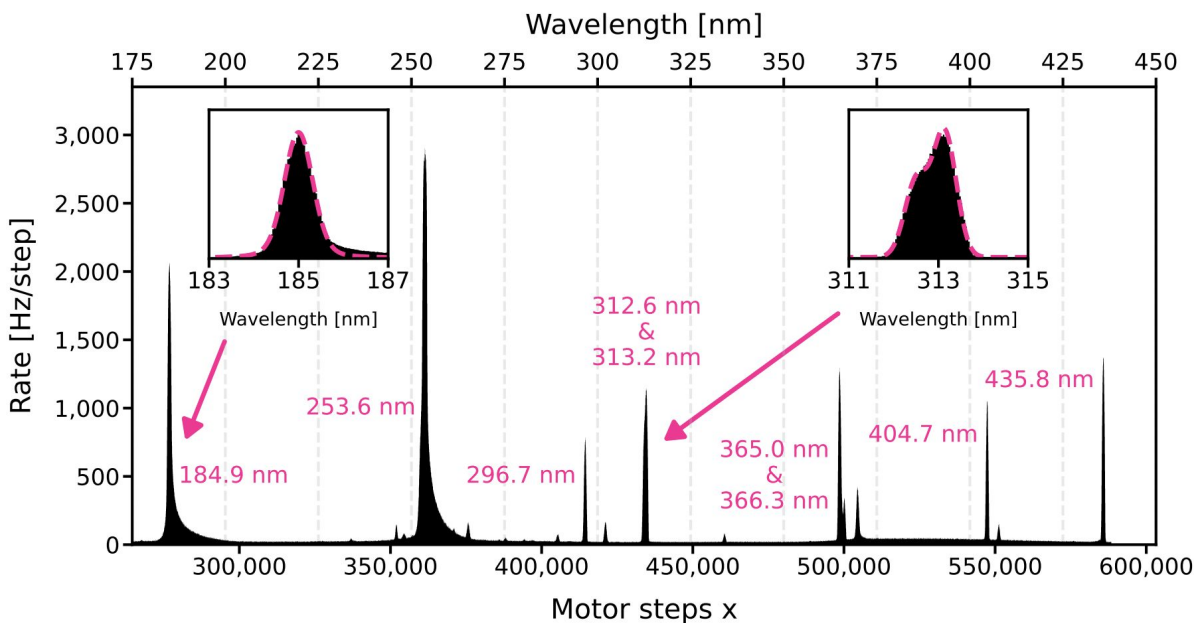


Calibration with low-pressure Hg arc lamp

FWHM resolution of 0.8–1 nm from 184.9 nm Hg atomic emission line

312.9 & 313.2 nm doublet demonstrates our ability to nearly resolve subnanometre spectral features

Datapoints deviate from linear fit by <0.1 nm



Data collection

For ~1 month, three vapour pressures span the range of modern LXe dark matter experiments

- LZ ~ 1.8 bar
- XENONnT ~ 1.9 bar
- Triple point ~ 0.8 bar

Collected hundreds of photons in coincidence with S1s

Collected tens-of-thousands of photons in coincidence with S2s

	Detector				Spectroscopy				
	Press. (bar)	Temp. (K)	Liquid height (mm)	Reduced E-field (Td)	Slit width (mm)	Scanning range (nm)	Livetime per nm (min)	No. S1s (#)	No. S2s (#)
Liquid	2.15	179 ¹	6.4	10	0.25	110–210	15	879	18,376
&	1.73	175 ¹	5.8	12	0.18	145–205	92	2,270	60,013
Vapour	1.34	170 ¹	4.7	14	0.18	110–210	22	267	12,234
Gas	2.21	293 ²	-	0, 5.6 ³	0.18	145–205	42, 5 ³	1,027	8,935
	0.29	296 ²	-	33	0.18	135–205	52	0	10,054

For several days, room temperature gas data

- 2.21 bar for comparison with liquid & vapour data
- 0.29 bar to search for evidence of 1st continuum

S1s with the electric field turned off

S2s with the electric field established

Liquid & vapour in equilibrium

Signal	Function	Peak wavelength (nm)	FWHM (nm)
S1	Gaussian	$176.5 \pm 0.1_{\text{stat}} \pm 0.4_{\text{sys}}$	$11.7 \pm 0.2_{\text{stat}}^{+0.5}_{-0.3\text{sys}}$
	Spline	-	-
S2	Gaussian	$173.27 \pm 0.02_{\text{stat}} \pm 0.2_{\text{sys}}$	$10.57 \pm 0.03_{\text{stat}} \pm 0.2_{\text{sys}}$
	Spline	-	-

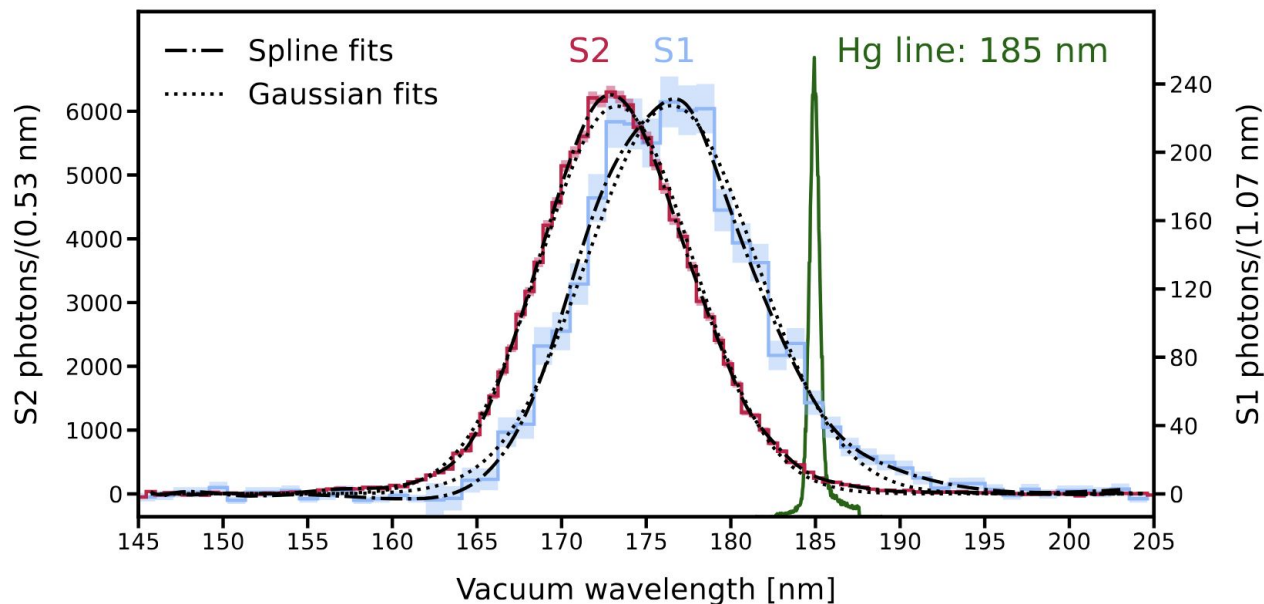
Combining data from all three vapour pressures

~3 nm difference in liquid & vapour peak wavelength

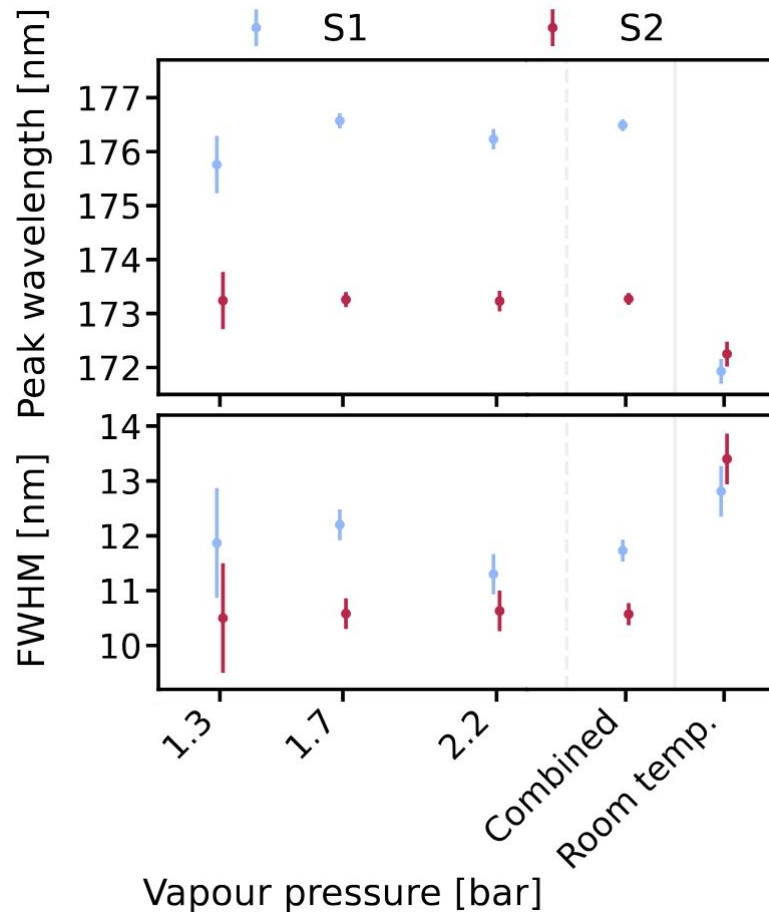
~1 nm difference in liquid & vapour FWHM

→ Influence of the surrounding liquid on potential energy surfaces is significant

Gaussians accurately model center of distributions while splines better characterise tails



Pressure/temperature dependence



Peak wavelength and FWHM are consistent across all three vapour pressures

Room-temperature gas measurements have peak wavelengths ~1 nm shorter and FWHMs ~2 nm wider than those in cold vapour

→ Higher temperatures result in a greater proportion of excimers in higher-energy vibrational/rotational states following thermalisation

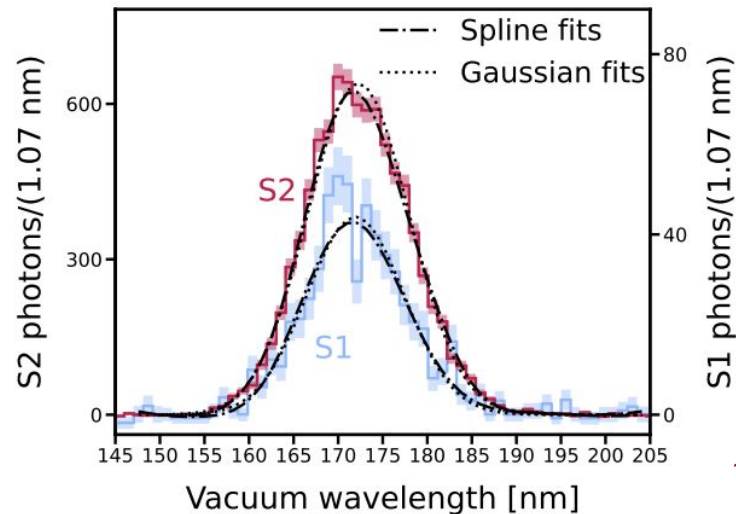
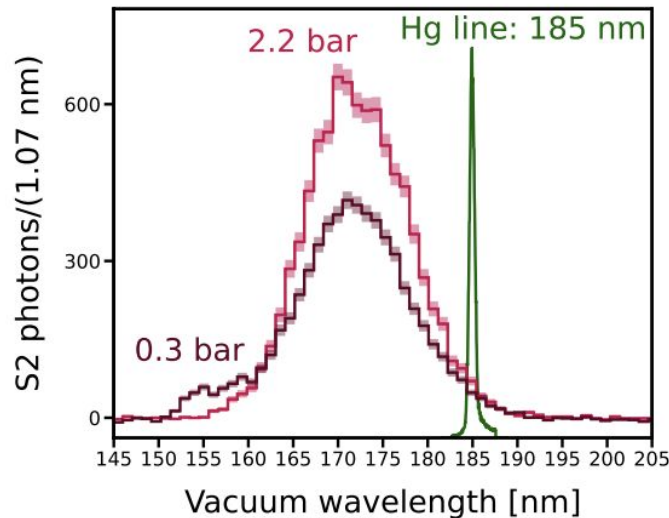
Room-temperature gas

2.2 bar data show 2nd continuum while 0.3 bar data shows additional contribution from the 1st continuum

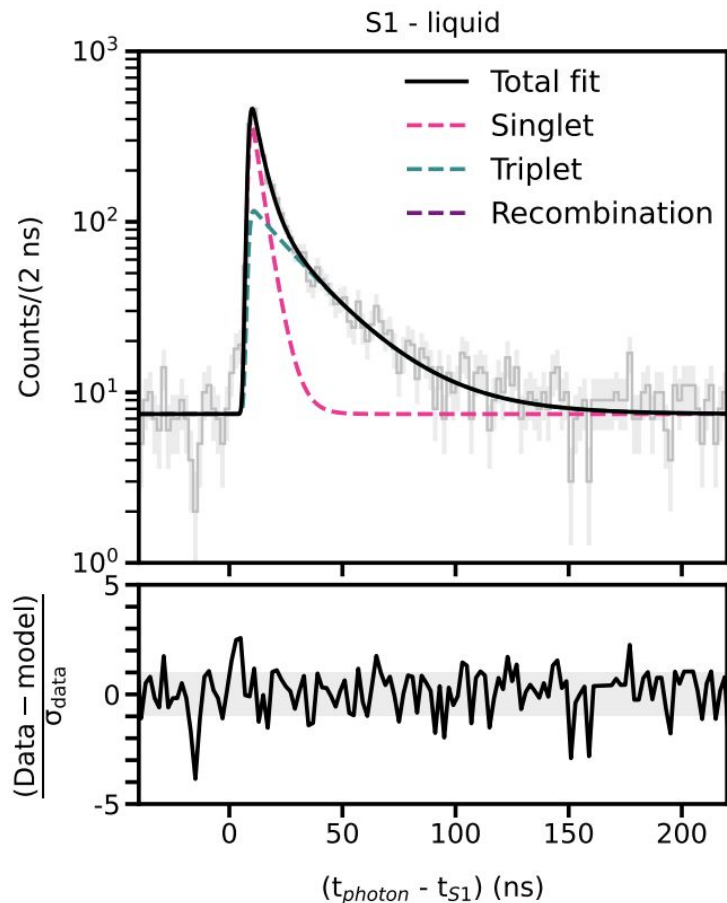
Signal	Function	Peak wavelength (nm)	FWHM (nm)
S1	Gaussian	$171.9 \pm 0.2_{\text{stat}} \pm 0.3_{\text{sys}}$	$12.8 \pm 0.5_{\text{stat}} \pm 0.5_{\text{sys}}$
S2	Gaussian	$172.25 \pm 0.06_{\text{stat}} \pm 0.2_{\text{sys}}$	$13.4 \pm 0.1_{\text{stat}} \pm 0.2_{\text{sys}}$

S1 & S2 distributions are consistent in shape

→ ~3 nm shift between S1 in liquid & S2 in vapour is associated with the phase of the medium, rather than the method of excitation



Singlet-triplet ratio (liquid)



$$Y(t) = B + \sum_{i=s,t \text{ or } r} C_i \exp\left(\frac{\sigma^2}{2\tau_i^2} - \frac{t-t_o}{\tau_i}\right) \left(1 + \operatorname{erf}\left(\frac{t-t_o}{\sigma\sqrt{2}} - \frac{\sigma}{\tau_i\sqrt{2}}\right)\right)$$

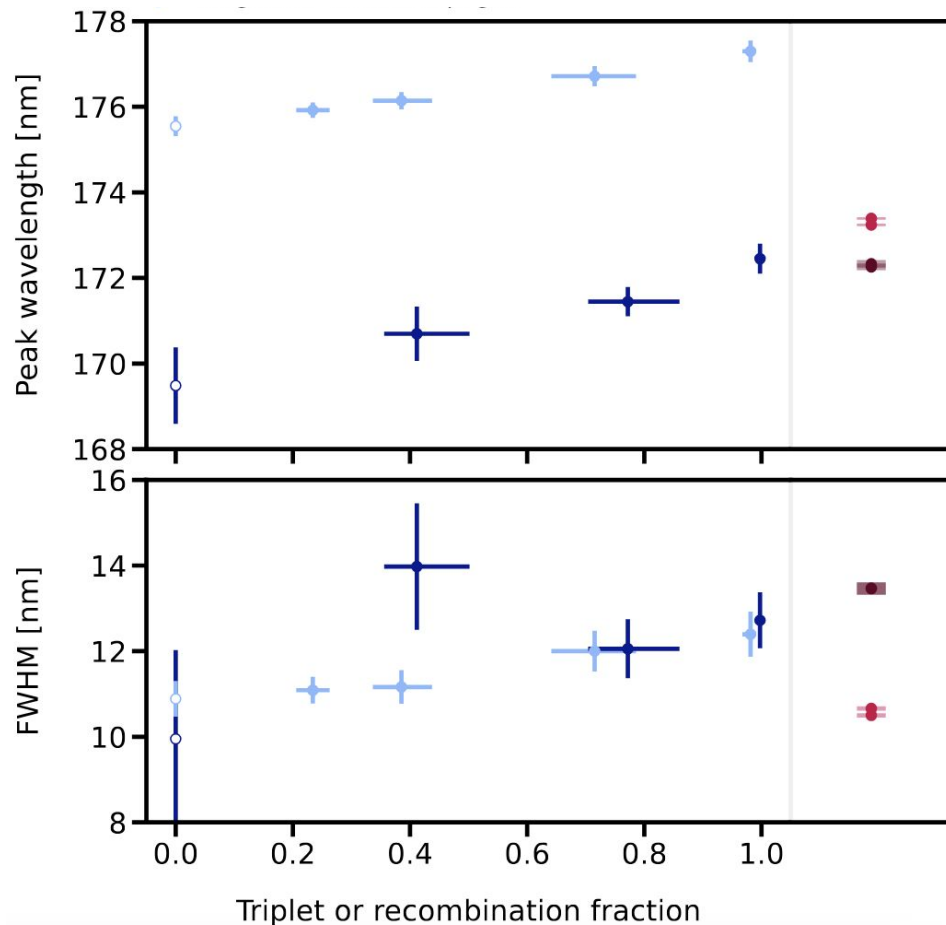
Two exponentials convolved with Gaussian instrument response function + constant background

$$\tau_s = 4.9 \pm 0.6 \text{ ns} \quad \leftarrow \text{Singlet}$$

$$\tau_t = 26.8 \pm 2.1 \text{ ns} \quad \leftarrow \text{Triplet}$$

Calculate triplet fraction in four bins

Dependence on singlet-triplet ratio



- S1 - liquid
- S1 - room temp. gas
- Singlet fit - liquid
- Singlet fit - room temp. gas
- S2 front/back - cold vapour
- S2 front/back - room temp. gas

Peak wavelength increases by:

- 1.4 ± 0.3 nm (liquid)
- 1.7 ± 0.7 nm (room-temp gas)

FWHM increases by:

- 1.2 ± 0.5 nm increase of (liquid)

S1 changes are large compared to differences in first & second half of S2s

→ Trend is a genuine effect, rather than an unanticipated consequence of selecting different sections of waveforms

Singlet & triplet

Extracted separate models

Triplet model from time bin with highest triplet/recombination fraction

- Spline for liquid tail
- Gaussian for room-temp gas

Fit full dataset to triplet/recombination function + Gaussian singlet

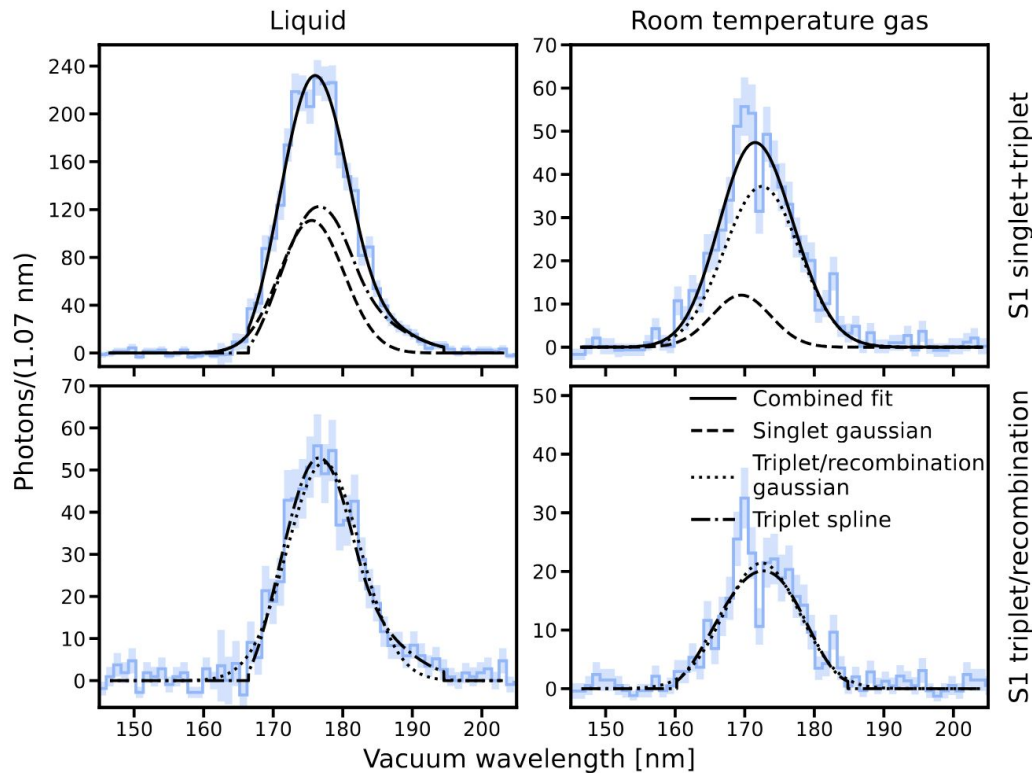
Singlet peak wavelength shorter by:

- $1.8 \pm 0.3_{\text{stat}}$ nm (liquid)
- $3.0 \pm 0.9_{\text{stat}}$ nm (room-temp gas)

Singlet FWHM narrower by:

- $1.5 \pm 0.6_{\text{stat}}$ nm (liquid)

	Signal	Function	Peak wavelength (nm)	FWHM (nm)
Liquid	S1 singlet	Gaussian	$175.5 \pm 0.2_{\text{stat}} \pm 0.5_{\text{sys}}$	$10.9 \pm 0.4_{\text{stat}}^{+0.8}_{-0.6_{\text{sys}}}$
	S1 triplet	Gaussian Spline	$177.3 \pm 0.2_{\text{stat}} \pm 0.4_{\text{sys}}$ -	$12.4 \pm 0.5_{\text{stat}}^{+0.5}_{-0.3_{\text{sys}}}$ -
Gas	S1 singlet	Gaussian	$169.5 \pm 0.9_{\text{stat}}^{+1.9}_{-1.1_{\text{sys}}}$	$9.9 \pm 2.1_{\text{stat}}^{+4.3}_{-1.8_{\text{sys}}}$
	S1 recombination	Gaussian	$172.5 \pm 0.3_{\text{stat}} \pm 0.3_{\text{sys}}$	$12.7 \pm 0.7_{\text{stat}} \pm 0.5_{\text{sys}}$



Conclusion



Only simultaneous spectroscopic measurements of liquid scintillation (S1) & gas electroluminescence (S2)

First spectroscopy measurements of singlet and triplet emission in the liquid phase

Important for precisely characterising dual-phase xenon detectors such as LZ, XENONnT, and XLZD

Special thanks to Alex L, Chico N, and Andrew S for significant assistance with data acquisition, software development, and operation of the detector

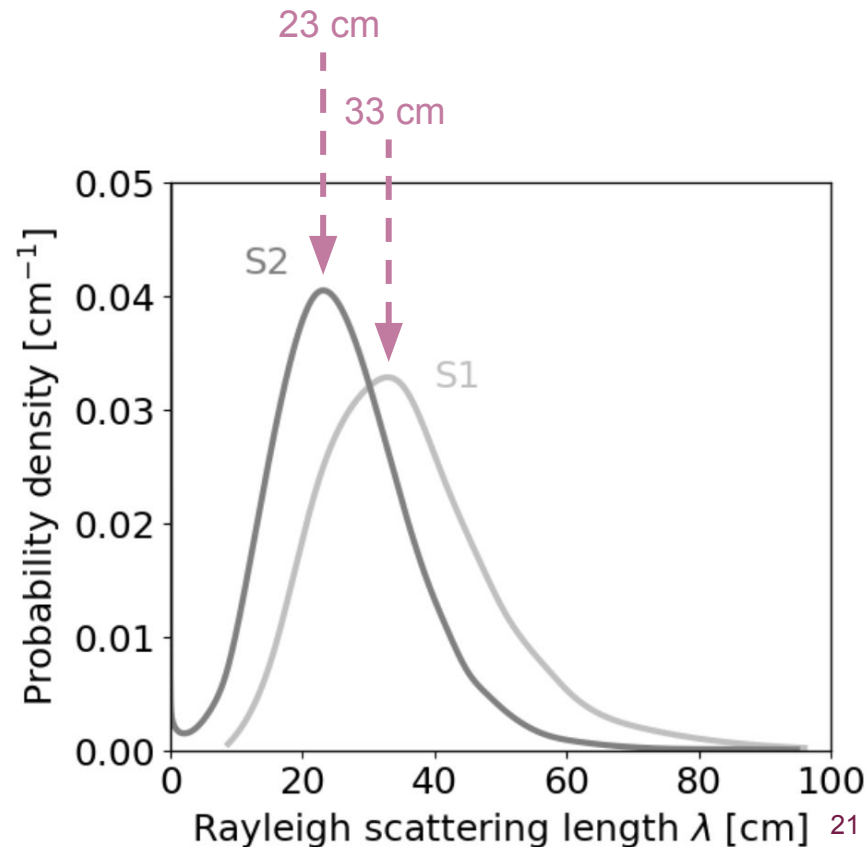
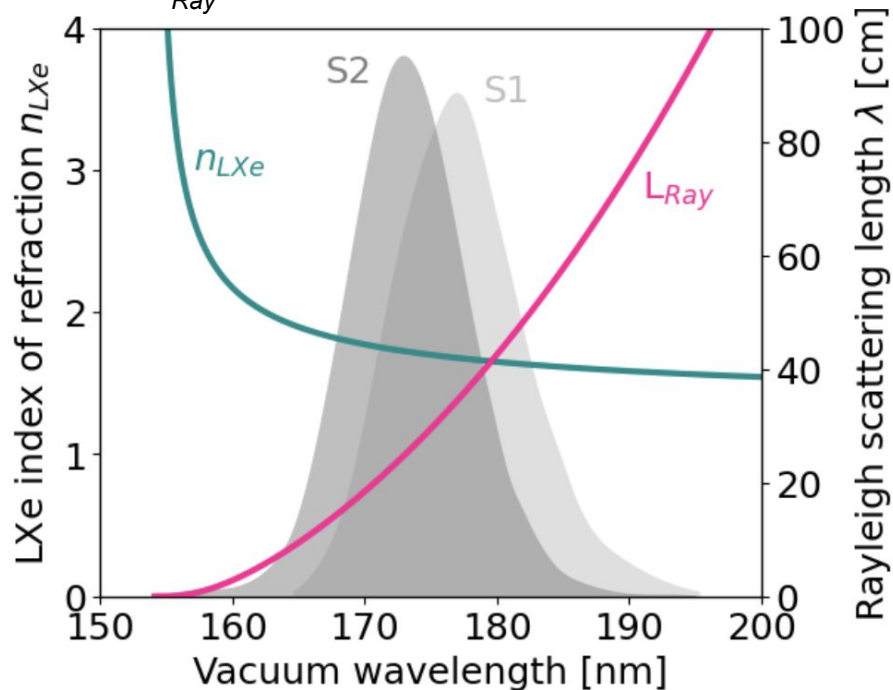


Thank You

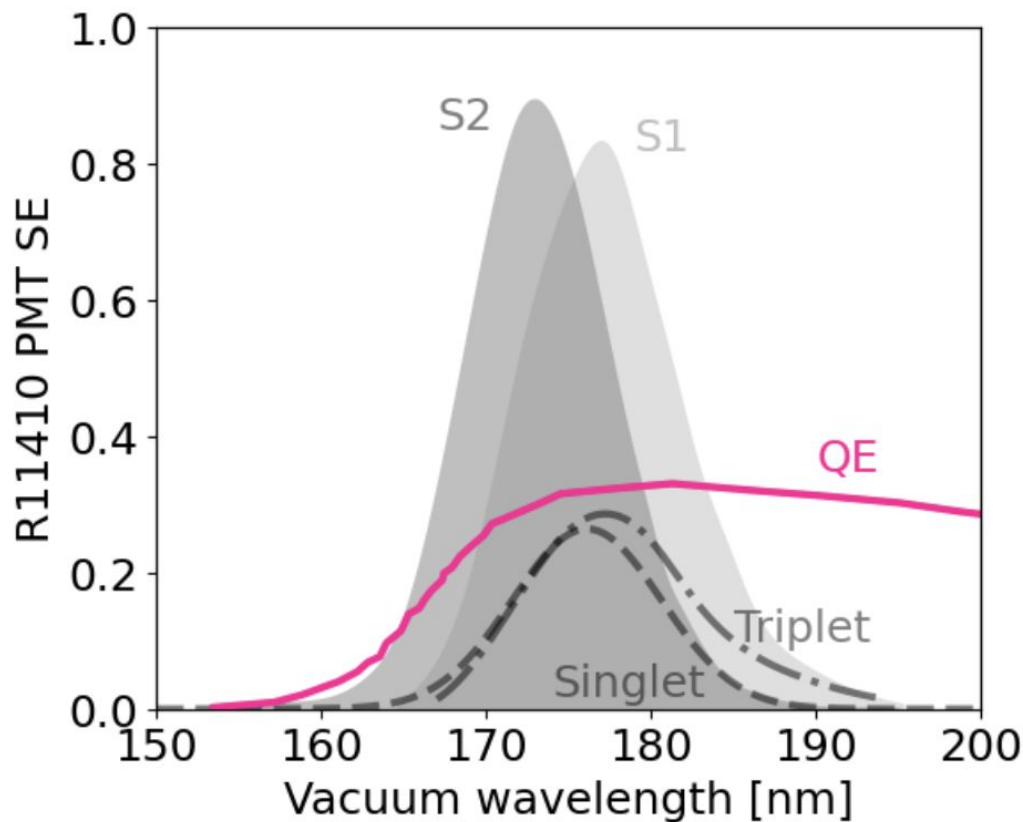
Rayleigh scattering length

Calculation for rare-gas liquids:

- [Nuc. Instr. and Meth. A, 489 \(2002\), p. 189](#)
- [J. Chem. Phys. 123, 234508 \(2005\)](#)
- $L_{Ray} \sim \lambda^4 n^{-8}$



Quantum efficiency (QE)



QE for R11410 PMTs used in LZ rises from 0-30% across the low wavelength side of the spectra as a consequence of absorption in the quartz window

	QE (%)
172 nm	29
174 nm	32
178 nm	32
S2 (cold gas)	28
S1 (liquid)	31
S1 singlet	30
S1 triplet	31

~10% difference in light collection efficiency

Negligible difference in light collection efficiency

Table 2: Stability of the pressure, drift time, S1 pulse area, and S2 pulse area. The drift time acts as a proxy for the liquid level, which affects the solid angle coverage of the monochromator for the S1 and S2 light. The S1 and S2 pulse areas recorded by the internal PMT serve as indicators of the xenon purity; notably, the S2 area is highly sensitive to the presence of electronegative contaminants. The liquid-vapour datasets acquired at 2.2 and 1.7 bar, and the room-temperature gas dataset acquired at 2.2 bar, demonstrated excellent stability. Greater variability was observed for the 1.3 bar liquid-vapour dataset and the 0.3 bar room-temperature gas dataset.

	Pressure (bar)	Pressure (% RMS)	Drift time (% RMS)	S1 area (% RMS)	S2 area (% RMS)
Liquid	2.15	0.2	0.5	0.8	1.0
&	1.73	0.3	0.5	0.8	0.9
Vapour	1.34	6.9	44	3.2	17
Gas	2.21	0.7, 0.1 ¹	-	4.8	0.4
	0.29	1.2	-	-	41

¹ The electrodes were powered off for 2 days to collect S1 data, then biased for 6 hr to collect S2 data.

Systematic uncertainties

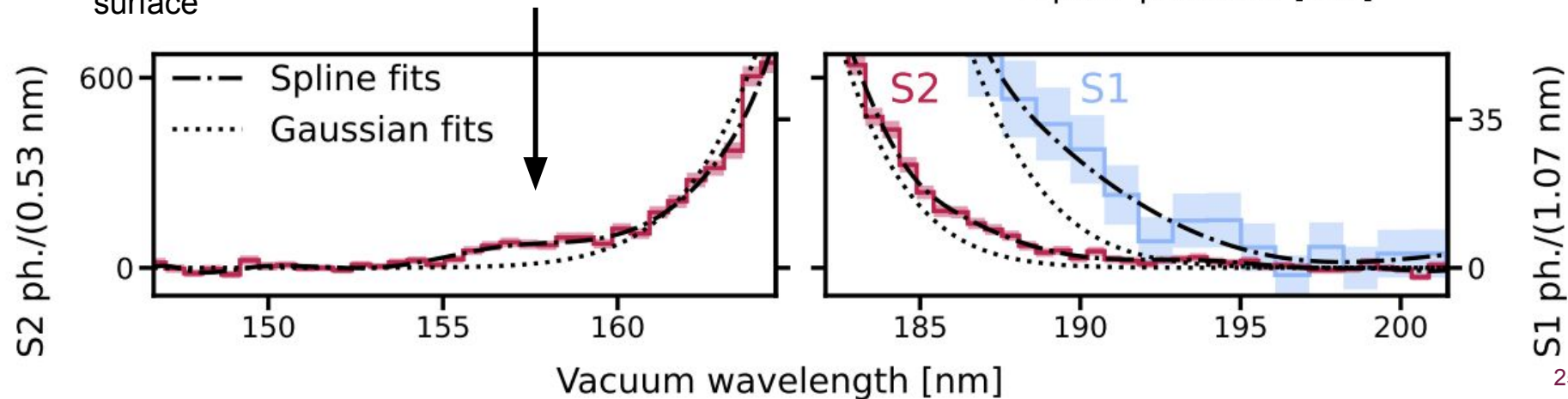
Systematic uncertainty	Signal	Gaussian Peak wavelength (nm)	Gaussian FWHM (nm)	S2 tail (%)
Calibration non-linearity	All	± 0.1	-	-
Calibration variability	All	$-0.06/+0.04$	-	-
Singlet fitting procedure	S1 singlet liquid	± 0.31	$-0.52/+0.65$	-
	S1 singlet room-temp. gas	$-1.1/+1.9$	$-1.7/+4.3$	-
Efficiency Rayleigh scattering	S1 liquid	± 0.29	± 0.29	-
Efficiency MgF ₂ viewports	All	-0.05	$+0.03^*$	$+0.06$
Efficiency monochromator grating	All	± 0.09	$\pm 0.03^*$	$\pm 0.04^*$
Efficiency spectroscopy PMT	All	± 0.09	$\pm 0.03^*$	$\pm 0.04^*$
Diffuse reflections on source	S1 liquid	-0.11^*	$+0.22^*$	-
Contaminant ingress	S1 room-temp. gas	$\pm 0.23^*$	$\pm 0.46^*$	-
Grating scattering angle	All	± 0.14	± 0.14	-

* For certain calculations of the systematic uncertainty, no significant effect was observed. In these instances, an upper limit was established at the level of the statistical uncertainty.

S2 short-wavelength tail in cold vapour

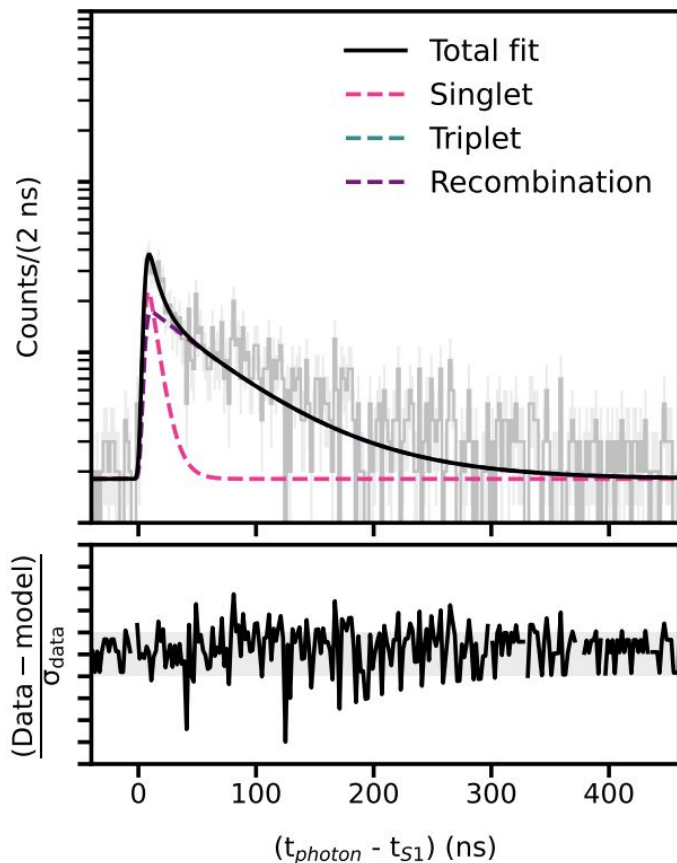
Subtle bump from 155–160 nm, extending well beyond the main body of the S2 spectrum

- $\sim 0.6\%$ of the total area
- $2\text{--}5\sigma$ greater than the flat background rate of thermionic dark counts in spectroscopy PMT
- Consistent in size from first to second half of the S2s $\rightarrow$ doesn't vary with height above the liquid $\rightarrow$ likely not an effect related to angle of light entering the monochromator or reflection of light on the liquid surface



Singlet-triplet ratio (gas)

S1 - room temperature gas



$$Y(t) = B + \sum_{i=s,t \text{ or } r} C_i \exp\left(\frac{\sigma^2}{2\tau_i^2} - \frac{t-t_o}{\tau_i}\right) \left(1 + \operatorname{erf}\left(\frac{t-t_o}{\sigma\sqrt{2}} - \frac{\sigma}{\tau_i\sqrt{2}}\right)\right)$$

Recombination time constant is not negligible
in the gas phase

$$\tau_s = 8.3 \pm 2.4 \text{ ns}$$

← Singlet

$$\tau_r = 71 \pm 7 \text{ ns}$$

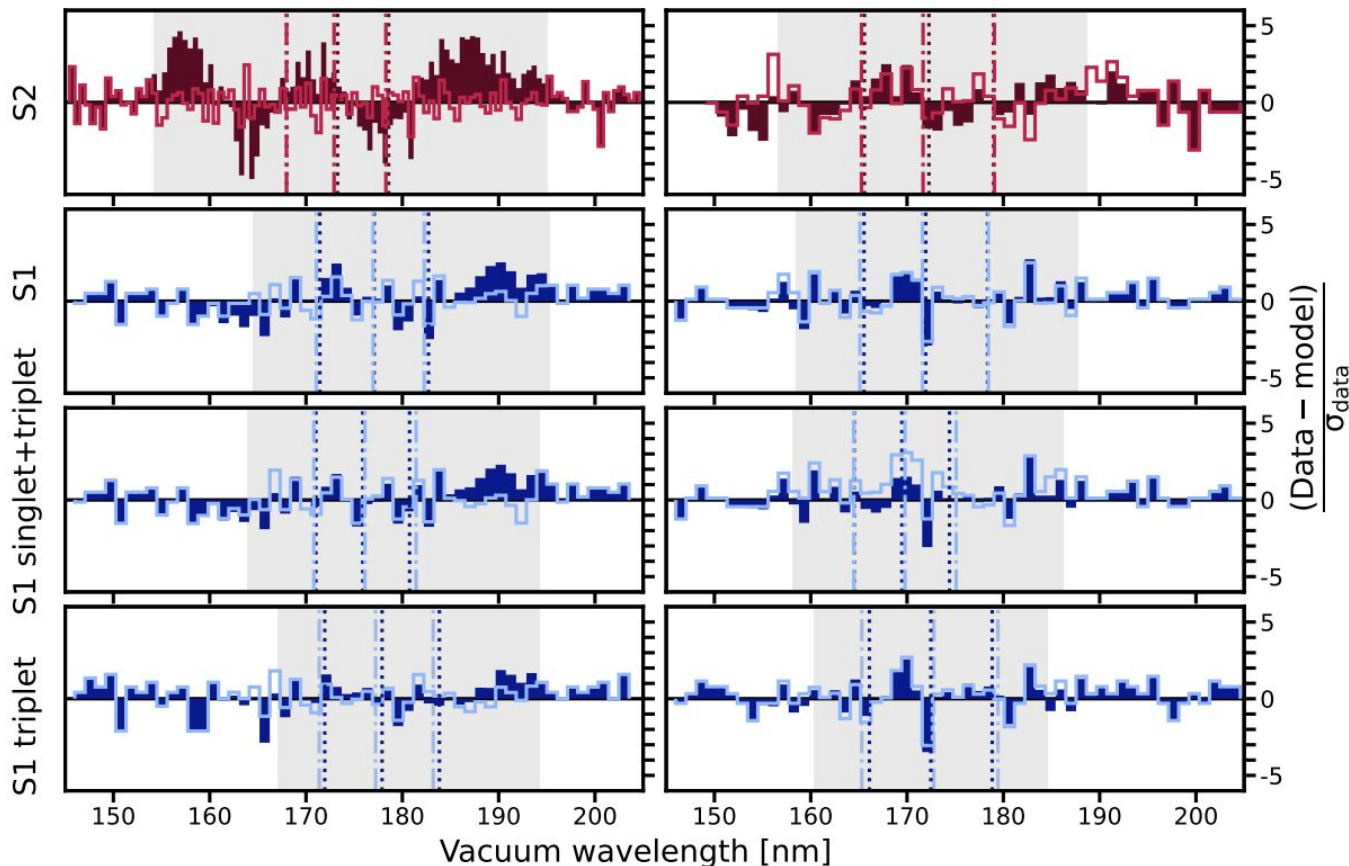
← Recombination

Calculate recombination fraction in four bins

Goodness of fit

Liquid or cold vapour

Room temperature gas



Filled – Gaussian
Line – Spline

Vertical lines – peak
wavelength and FWHM

Grey shading – region
where spline is greater
than constant background
rate

Spline better models S1,
S2, and S1-triplet tails in
liquid

Singlet+triplet model is a
good fit to S1 data