Observational Analysis of Lyman-alpha Emission in Equivalent Magnitude Solar Flares

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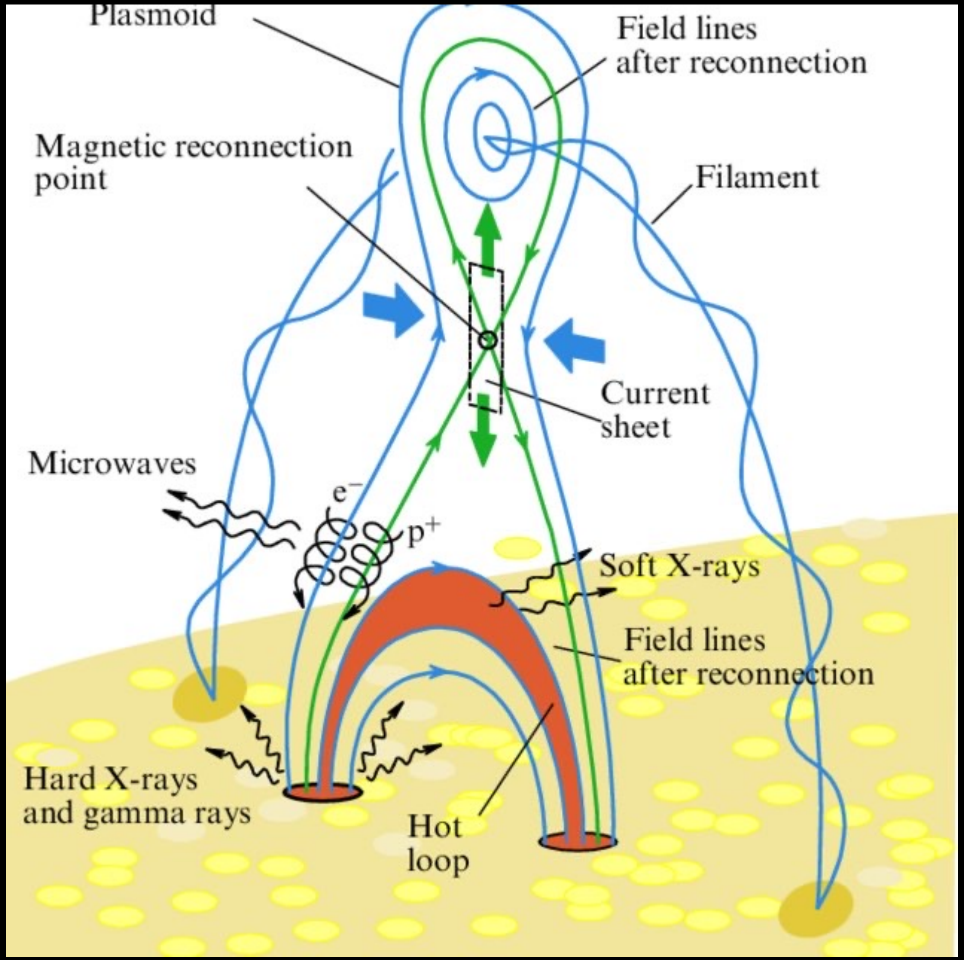
Standard Flare Model: *Simplified Breakdown*

- Magnetic reconnection
- Accelerated particles
- Energy deposited in chromosphere
  - ➢ UV/EUV/Optical
- Plasma heating + chromospheric evaporation
  - ➢ Soft X-ray
- Bremmstrahlung
  - ➢ Hard X-ray [nonthermal & thermal]

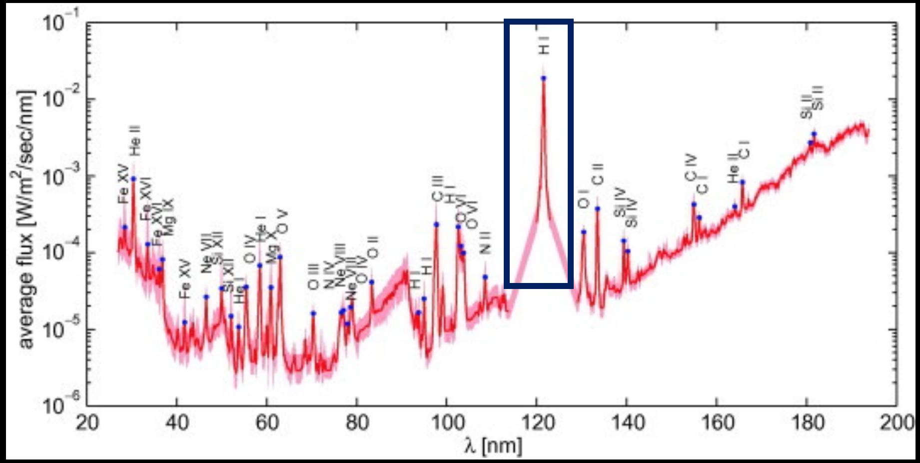


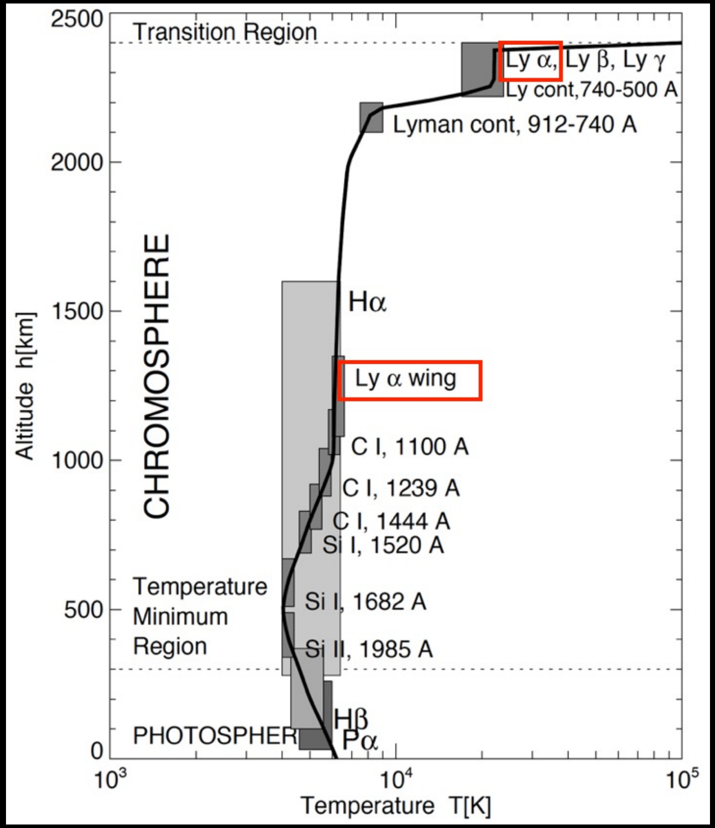
Adapted from Shibata et al. (1995)

Lyman-alpha (Lyα; 1216Å)

- Emitted from 2p-1s transition in neutral Hydrogen
- Brightest line in quiet Sun solar spectrum
- Line core formed in transition region/upper-chromosphere. Wings formed in mid-chromosphere
- Emitted from footpoints during solar flares

Dudok de Wit+ (2005)



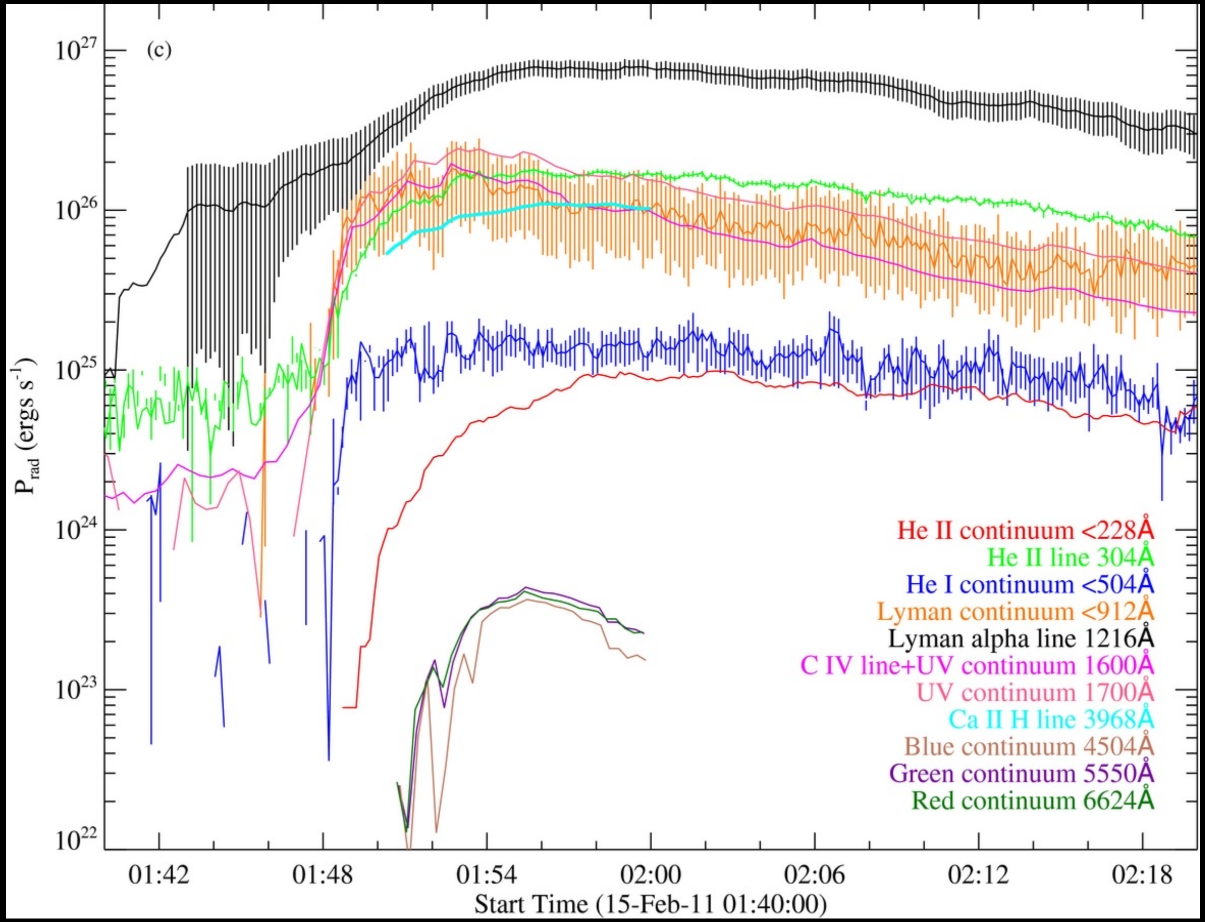


Aschwanden (2005)

Why Lyman-alpha?

Flare Energy Budget

- Radiated energy budget of solar flares still an ongoing topic of research:
    - Milligan+ 2014: 15% flare energy accounted for in optical and UV/EUV
    - Kleint+ 2016: 10-20% flare energy accounted for in NUV continuum
- Lyα found to radiate 5-8% of the total energy deposited in the chromosphere during an X-class flare. (*Milligan+ 2014*)



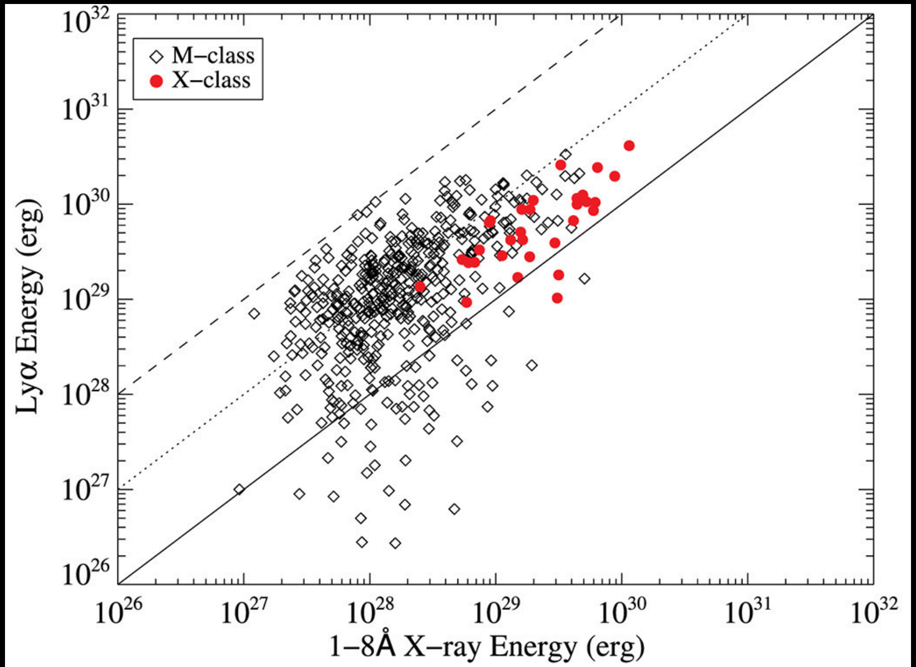
Milligan+ (2014)

Flare Variability:

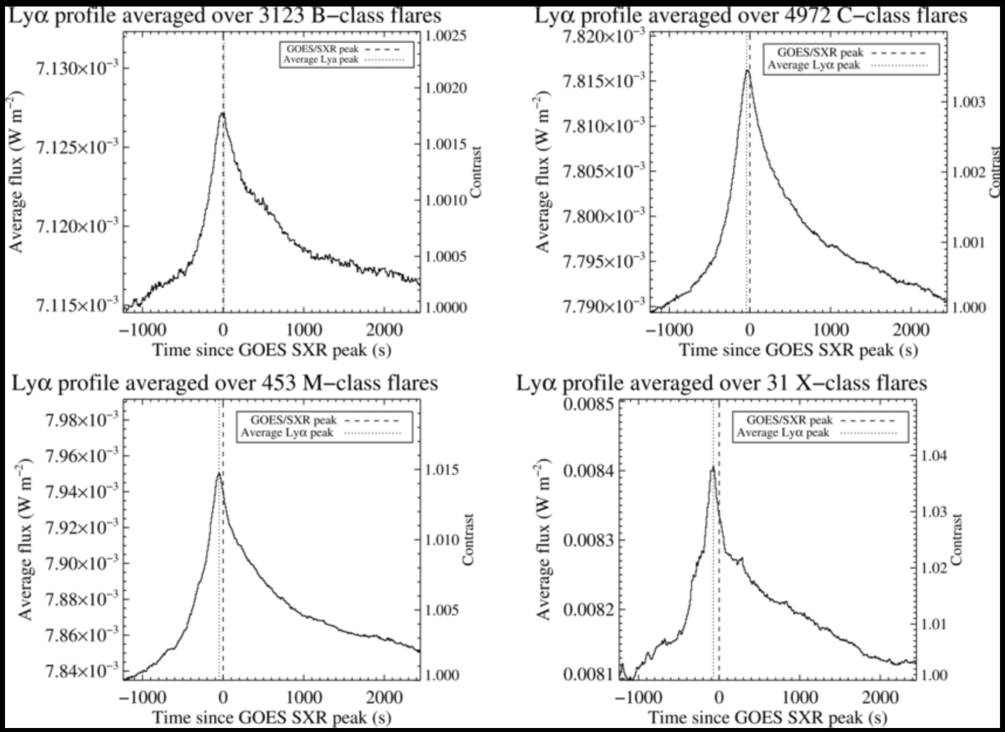
The changing behaviour of Lyα

- Milligan+ 2020 found Lyα energy to increase with GOES class
- Average flux enhancements: 0.18% [B], 0.35% [C], 1.5% [M], 3.8% [X] (Milligan 2021)

1. How does Lyα emission vary in equivalent magnitude flares?
2. Do the properties of accelerated electrons drive variation in Lyα emission?
3. What is the contribution of Lyα to the radiated energy budget? Does this change between equivalent magnitude flares?



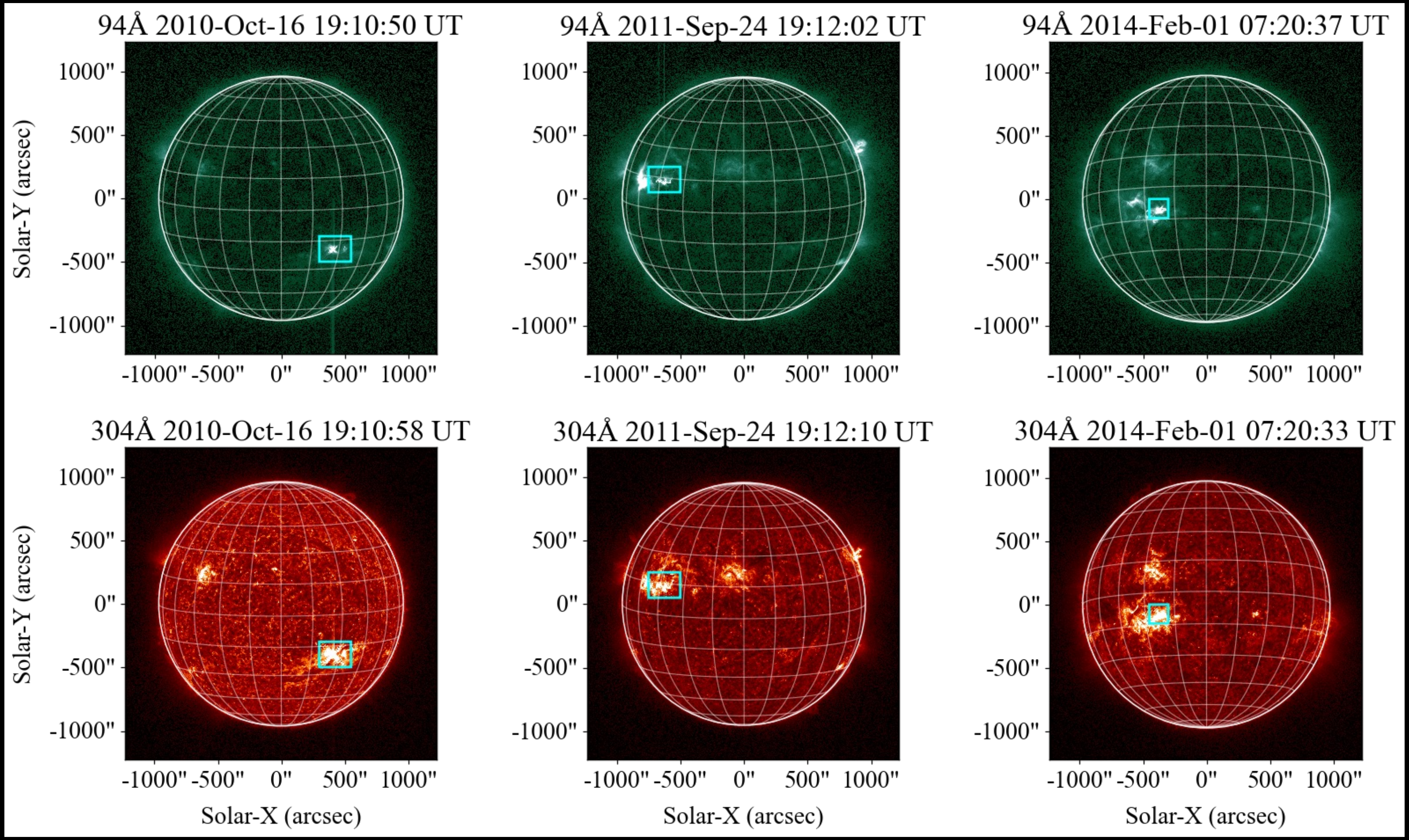
Milligan+ (2020)



Milligan (2021)

The Flare Sample: *Why these flares?*

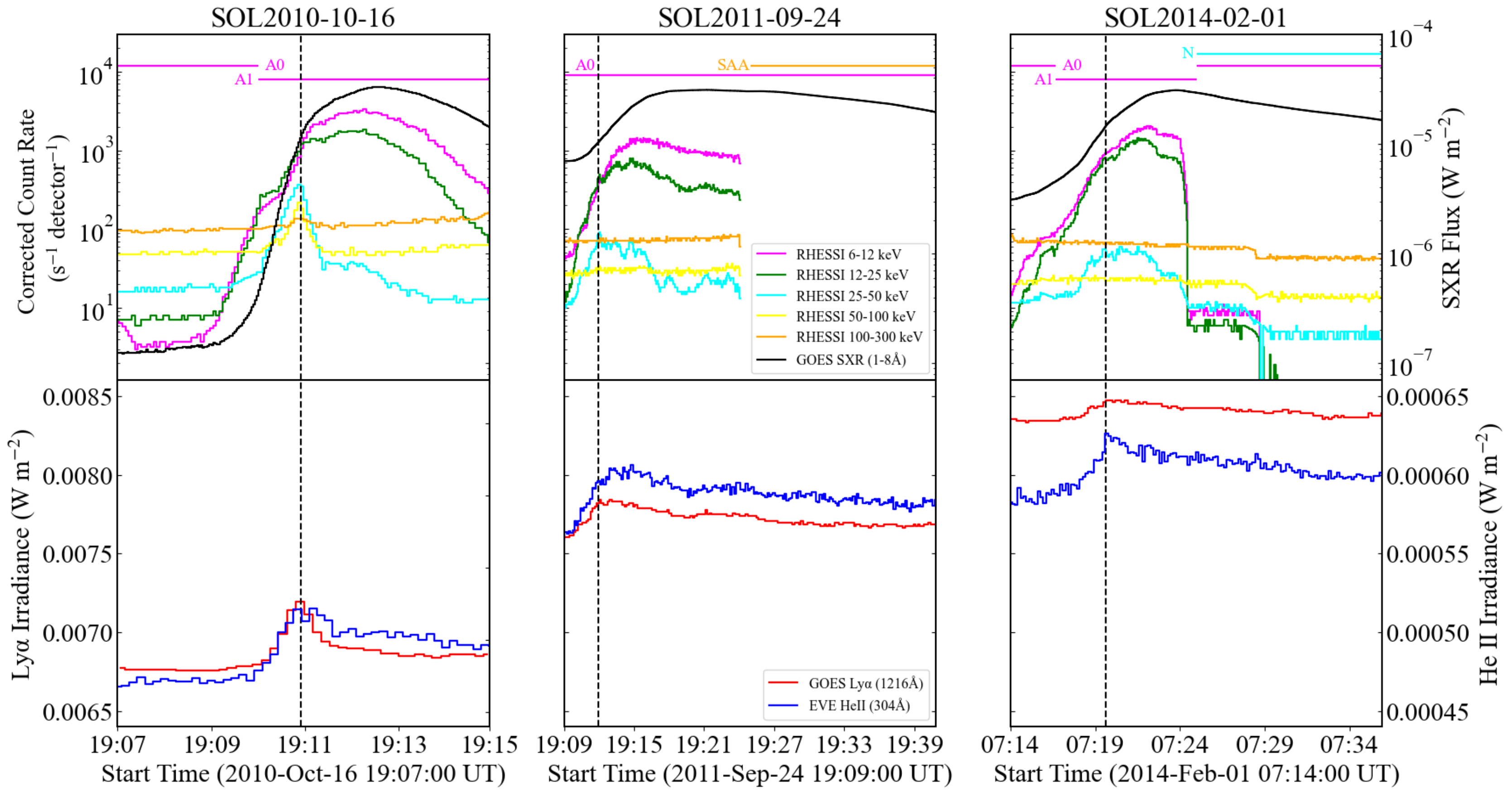
- Three M3 flares in solar cycle 24
- Intermediate size removes complexities of larger (X-class) flares but retains sufficient magnitude for spectral analysis



Greatorex+ (2023)

Observational Data

- RHESSI – HXRs
  - 6-12 keV [Thermal]
  - 12-25 keV [Thermal]
  - 25-50 keV [Nonthermal]
  - 50-100 keV [Nonthermal]
  - 100-300 keV [Nonthermal]
- GOES-15/XRS – SXRs (1-8Å)
- GOES-15/EUVS-E – Lyα
- SDO/EVE – He II (304Å)
  - Recently suggested that He II could be used as proxy for Lyα



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Part A | Irradiance Enhancements

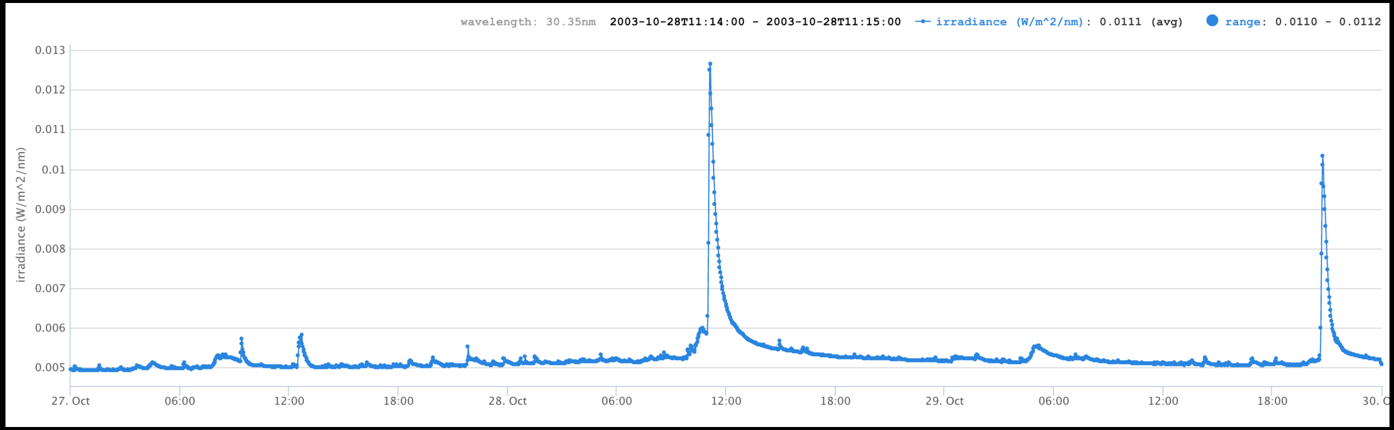
How do the Lyα and He II profiles vary between flares?

How do our observations compare to predictions from spectral models?

Part A | Irradiance Enhancements:
How do spectral models compare to observations?

What is FISM2?

- Flare Irradiance Spectral Model (Chamberlin+ 2007, 2008, 2020)
- Designed to fill temporal gaps in irradiance data using observations from periods of similar activity
- FISM products applied in terrestrial atmosphere models (WACCMX), mission development (FISM-M: MAVEN/EUVM).



Laboratory for Atmospheric and Space Plasma / LASP Interactive Solar Irradiance Datacentre

Part A | Irradiance Enhancements:
How do spectral models compare to observations?

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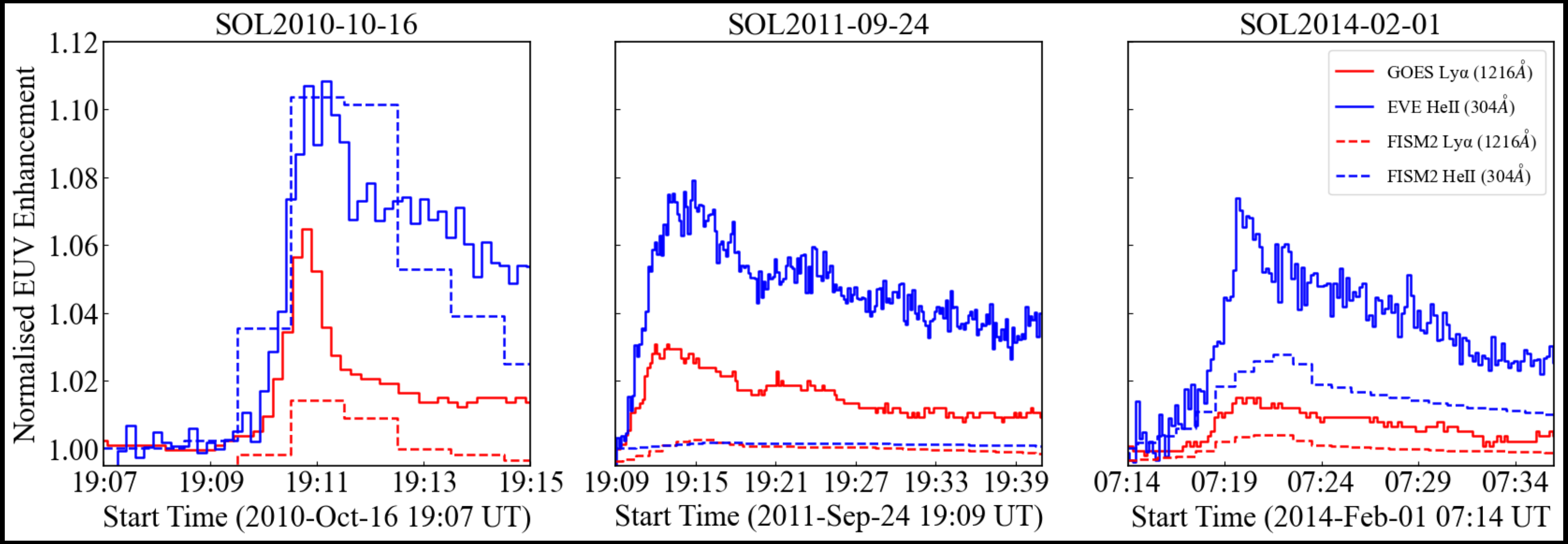
- Peak enhancement varied despite equivalent magnitude
- 2/3 have enhancements greater than the M-class average [1.5%] found by Milligan+ (2020)
- He II enhancements greater than Lyα in all cases
- FISM2 underestimates the Lyα and He II irradiance enhancements in all three flares.



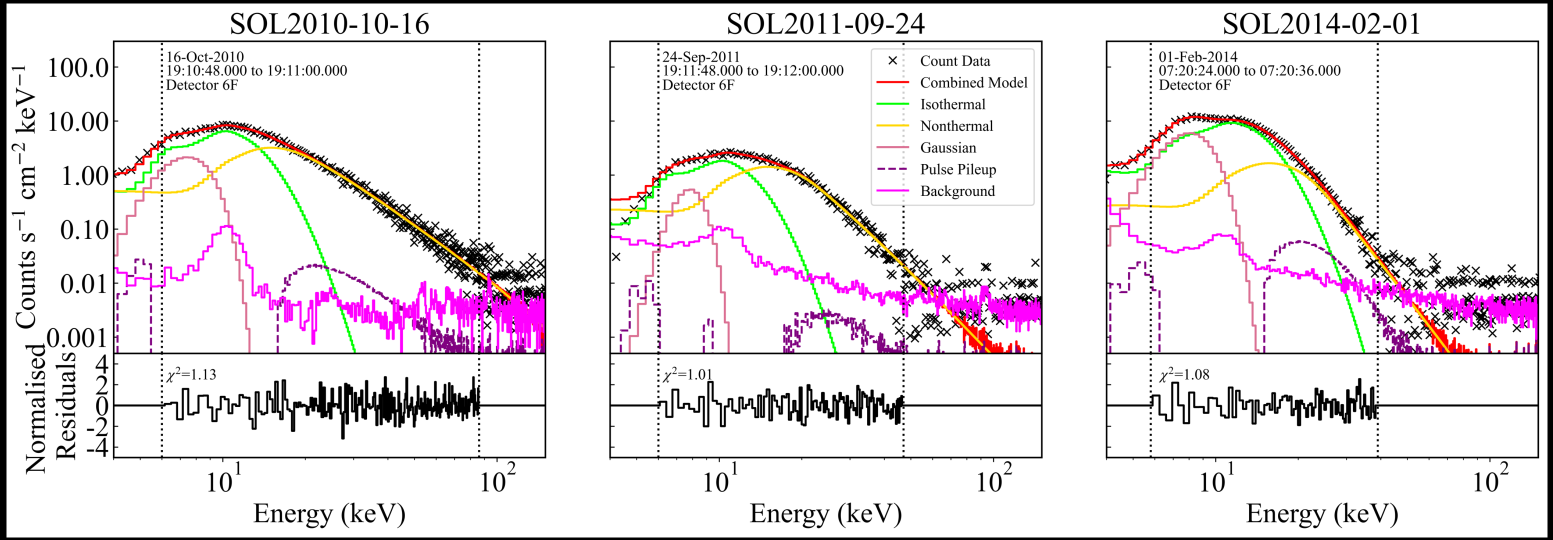
Flare	Peak Enhancements			
	Lyα		He II	
	GOES/EUVS-E	FISM2	SDO/EVE	FISM2
SOL2010-10-16	*6.4%*	*2.2%*	*10.8%*	*10.7%*
SOL2011-09-24	*3.3%*	*0.7%*	*7.4%*	*0.4%*
SOL2014-02-01	*1.5%*	*0.8%*	*7.3%*	*3.3%*

Part B | HXR Spectral Analysis

Do the properties of the nonthermal electron distribution drive the variable emissions in our flares?

Part B | HXR Spectral Analysis:
Discerning electron energy distribution

- Cannot directly observe accelerated electrons but can infer properties from the HXRs they produce



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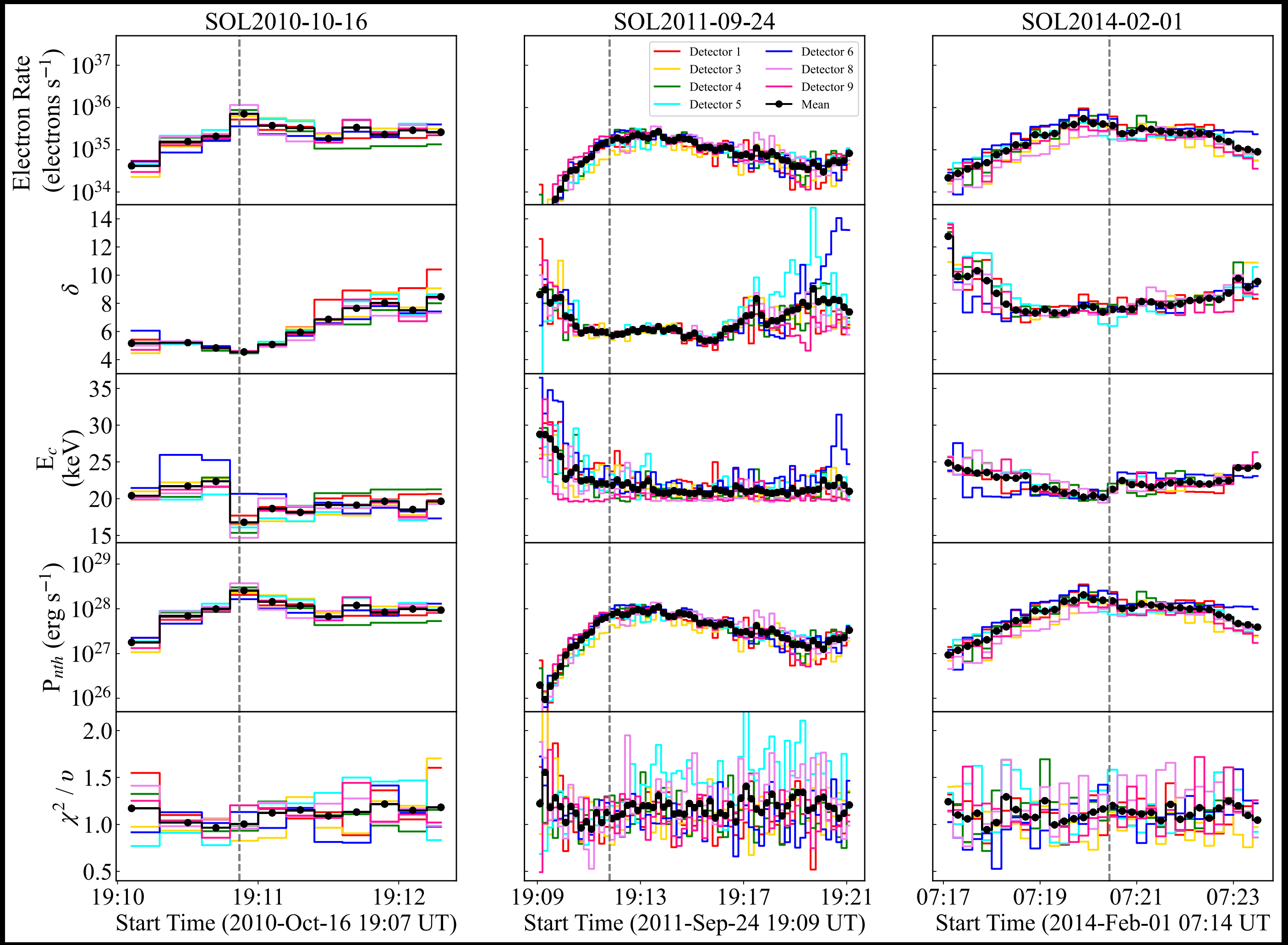
- Nonthermal parameters:
  - Spectral Index - δ
  - Energy Cutoff - E_c
  - Electron Rate - A

Electron Power

$$P_{nth}(E \geq E_c) = \frac{\kappa_E A}{(\delta - 2)} E_c^{(2-\delta)} \text{ erg s}^{-1}$$

Part B | HXR Spectral Analysis:
Temporal evolution of nonthermal parameters

- SOL2010-10-16:
  $\delta = 4.6 \pm 0.1$
  $E_c = 16.8 \pm 1.8\ (keV)$
  A = $4.2 \pm 1.3\ (10^{35}\ electrons\ s^{-1})$
- SOL2011-09-24:
  $\delta = 5.7 \pm 0.2$
  $E_c = 21.8 \pm 1.3\ (keV)$
  A = $1.1 \pm 0.3\ (10^{35}\ electrons\ s^{-1})$
- SOL2014-02-01:
  $\delta = 7.4 \pm 0.4$
  $E_c = 20.2 \pm 0.5\ (keV)$
  A = $2.7 \pm 1.2\ (10^{35}\ electrons\ s^{-1})$



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Part C | Flare Energetics

What portion of the flare energy deposited in the chromosphere is radiated in Lyα and He II?

Part C | Flare Energetics:
Comparing nonthermal and radiated energy

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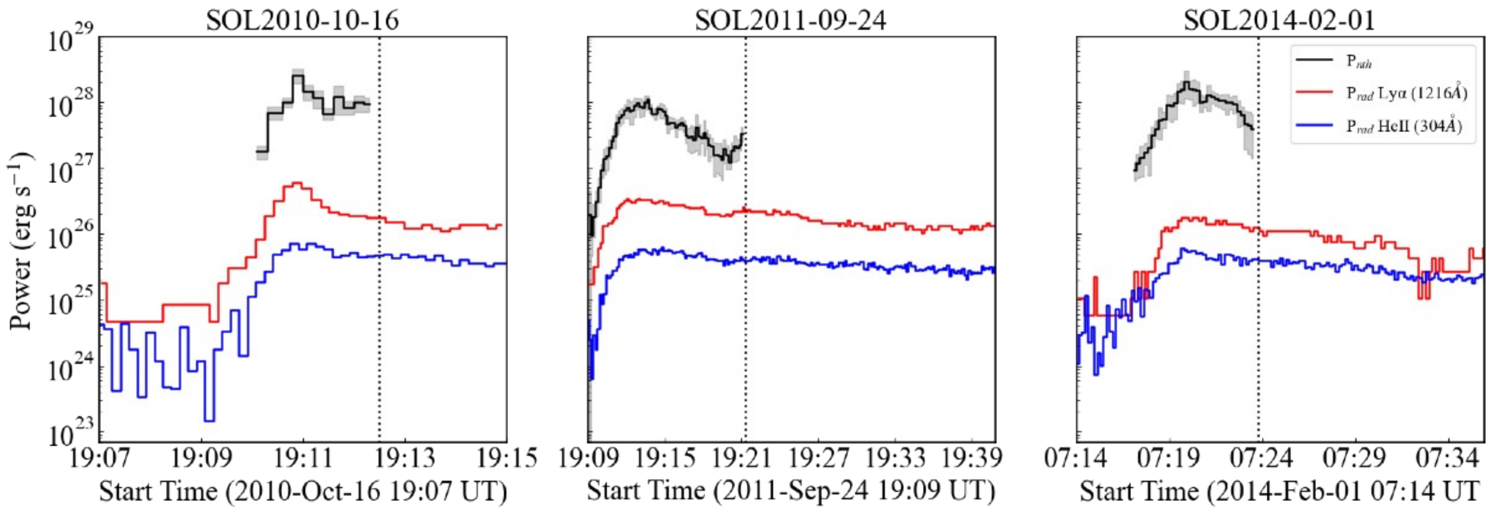
- Lyα radiates ~ 2-8% of nonthermal energy
- He II significantly less energetic than Lyα
- In total we account for a maximum of 9.4% of the flare energy



Flare	Total Energy (erg)			E_{rad}/E_{nth} (%)	
	Nonthermal Electrons	Lyα	He II	Lyα	He II
SOL2010-10-16	$9.7 \pm 1.6{\times}10^{29}$	$4.3{\times}10^{28}$	$7.1{\times}10^{27}$	4.4 ± 0.7	0.7 ± 0.1
SOL2011-09-24	$2.0 \pm 0.3{\times}10^{30}$	$1.6{\times}10^{29}$	$2.9{\times}10^{28}$	7.9 ± 1.1	1.4 ± 0.2
SOL2014-02-01	$2.3 \pm 0.7{\times}10^{30}$	$4.7{\times}10^{28}$	$1.5{\times}10^{28}$	2.0 ± 0.6	0.6 ± 0.2

Summary:

- Irradiance enhancements in Lyα and He II found to be variable across flares of equivalent magnitude. Enhancements found to vary from 1.5-6.4% - larger than average found by Milligan+ 2014 for M-class flares.
- FISM2 significantly underpredicts Lyα and He II flux enhancements during solar flares. Significant implications for atmospheric modelling.
- Apparent tendency for the enhancement in Lyα to scale with spectral index.
- Lyα and He II may radiate up to a combined total of up to 9.4% of the flare energy during the impulsive phase.

Considerations

- Small sample size, cannot claim a firm correlation.
- Disk integrated measurements do not allow spatial deconstruction of irradiance contribution, therefore not possible to determine the chromospheric and coronal components individually.

Future of Lyα Study: *Upcoming Missions & Projects*

Missions:

- **Solar Orbiter** – Extreme Ultraviolet Imager (**EUI**) features Lyman-alpha channel in High Resolution Imager (**HRI**)
- **ASO-S** – Lyman-alpha Solar Telescope (**LST**) features an imager and coronagraph
- **Solar-C** – EUV High-throughput Spectroscopic Telescope (**EUVST**) and Solar Spectral Irradiance Monitor (**SoSpIM**) for spectroscopy and irradiance
- Solar eruptioN Integral Field Spectrograph (**SNIFS**) sounding rocket featuring spectrograph
- **GOES-R** – Extreme Ultraviolet and X-ray Irradiance Sensor

Modelling:

- NASA HSR funding to carry out **RADYN** Modelling of Lyman-alpha: [*PI Milligan, Co-I's Graham Kerr (NASA/GSFC) and Paulo Simões (McKenzie, Sao Paulo)*]

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