

# Transition region spectroscopy with the Hinode/EIS instrument



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# About Me



## Career

1998: PhD, Cambridge University (UK)

1999: Harvard-Smithsonian CfA (US)

2002: Rutherford Appleton Laboratory (UK)

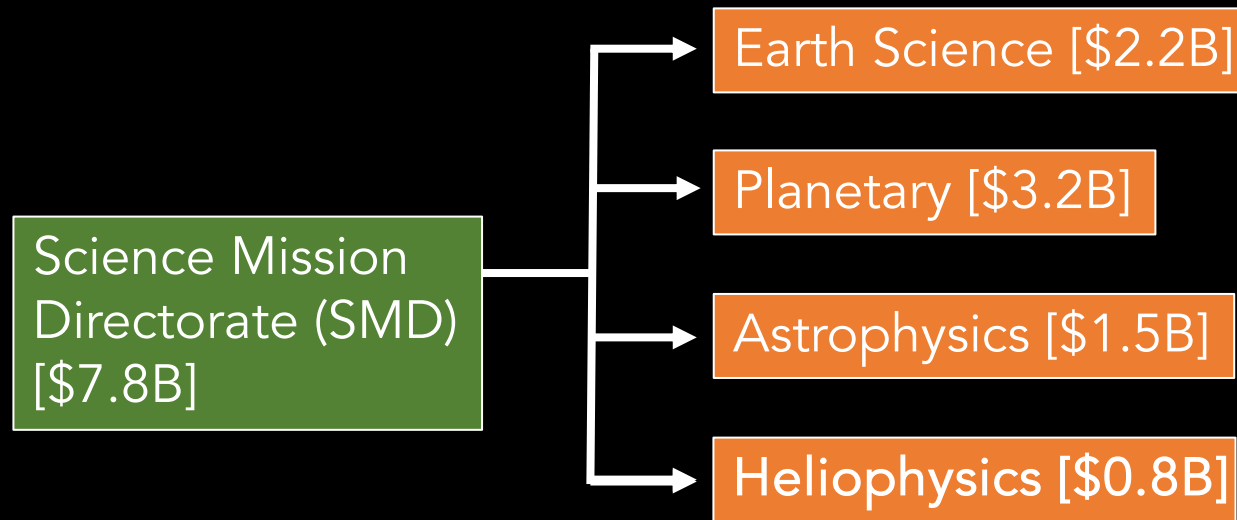
2008: Naval Research Laboratory (US)

2015: NASA Goddard (US)

## Interests:

- UV/EUV spectroscopy
- CHIANTI atomic database
- Solar atmosphere
- Missions: SOHO, *Hinode*, SDO, IRIS, Solar Orbiter

# Structure of science at NASA



Good news: Solar Physics is “protected” within the SMD Heliophysics Division



## Heliophysics sub-fields

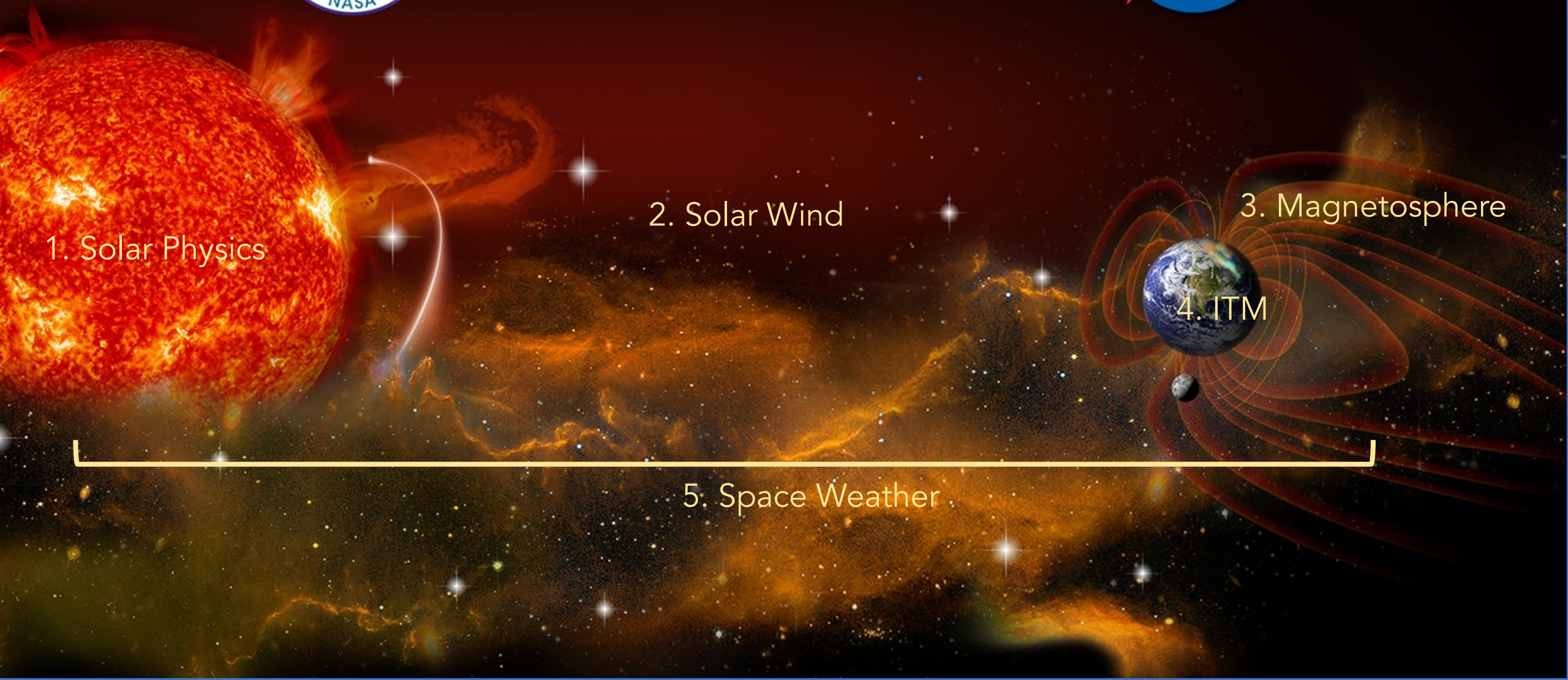
1. Solar Physics

2. Solar Wind

3. Magnetosphere

4. ITM

5. Space Weather



# Solar Physics Demographics

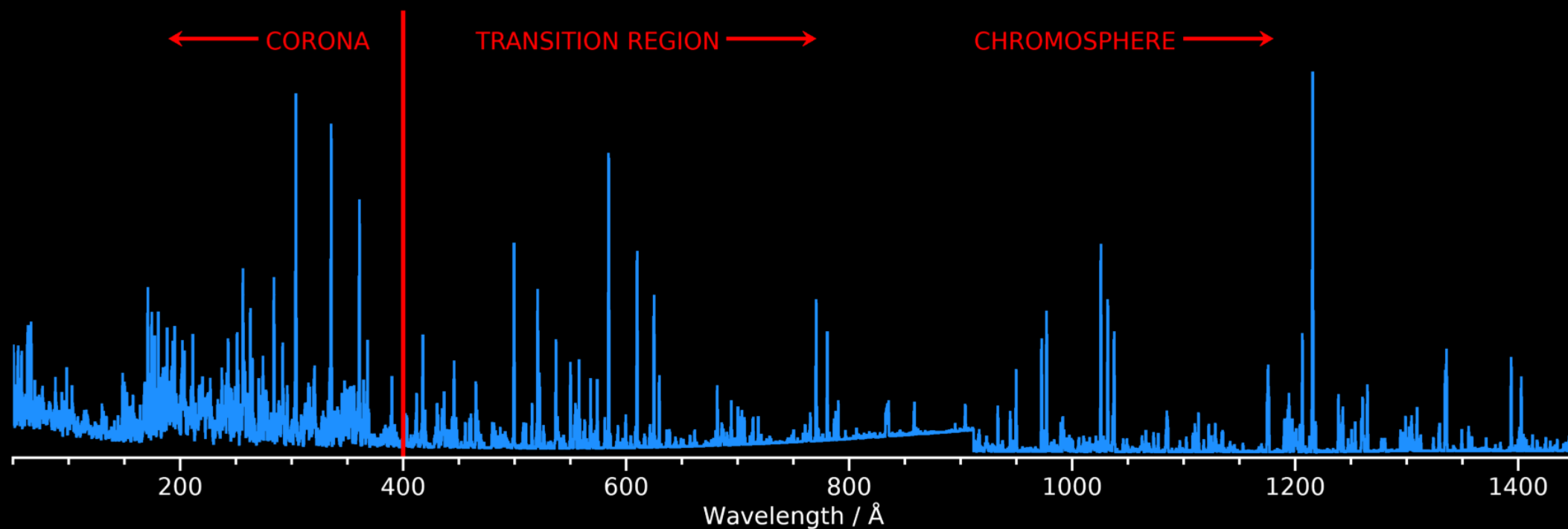
No. of researchers: 1521

No. of countries: 50

Country	Researchers
USA	30%
China	14%
UK	8%
Germany	5%
Italy	5%
ESA member states	38%

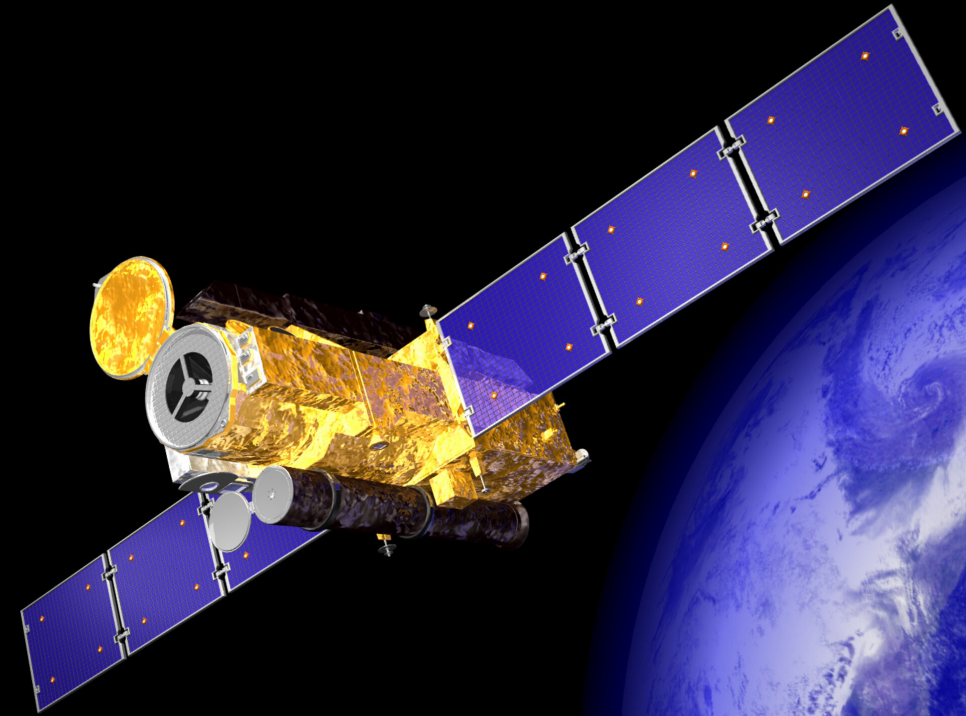
# The Solar EUV Spectrum

- Contains large number of emission lines from ionized atoms



# Hinode/EIS

- Hinode was launched in 2006
- EIS is an EUV imaging spectrometer operating in the 171-212 and 246-292 Å wavelength ranges
- EIS is led by UK (MSSL)



# The CHIANTI database

- Atomic database and software package for Astrophysics
- Principal datasets are
  - Electron excitation rates
  - Radiative decay rates
  - Energy levels
- Data are mostly obtained from the literature and a quality assessment is performed



Named after wine-growing region  
in Tuscany

<https://chiantidatabase.org>

# Spectroscopy

## 1. Line identification

- What are the lines?
- What are their precise wavelengths?
- Use to measure Doppler velocities

Project 1

## 2. Line diagnostics

- What can we measure with the lines?
- Emission measure, element abundances, temperature, density

Project 2

# Project 1: updated wavelengths for Mg VII & Si VII

Young, 2023, ApJ, 958, 40

# NIST Atomic Spectra Database

- The ASD is the standard resource for wavelengths and energy levels used in Astrophysics
- The ASD team was very active in 1960's-1980's
- Many ions have not been updated since then
- Many wavelength measurements from space missions (Solar & Astro) have not been incorporated



NIST, Gaithersburg, Maryland

## Bengt Edlén (1906-1993)

- Made lab measurements at Uppsala in 1930's and 40's
- Helped resolve the "coronium" problem, giving a high temperature for the solar corona
- Final work in 1980's was to provide wavelengths and energies along a number of isoelectronic sequences
- These data are not in the NIST ASD



## Large discrepancies between ASD and Edlén

Consider two lines:

Line	NIST ASD	Edlén	Difference
Si VII 275.3 Å	275.353	275.361	+9 km/s
Mg VII 276.4 Å	276.154	276.138	-17 km/s

EIS absolute accuracy is 5 km/s; relative precision is 1 km/s

Doppler velocities in coronal loops: 10-40 km/s

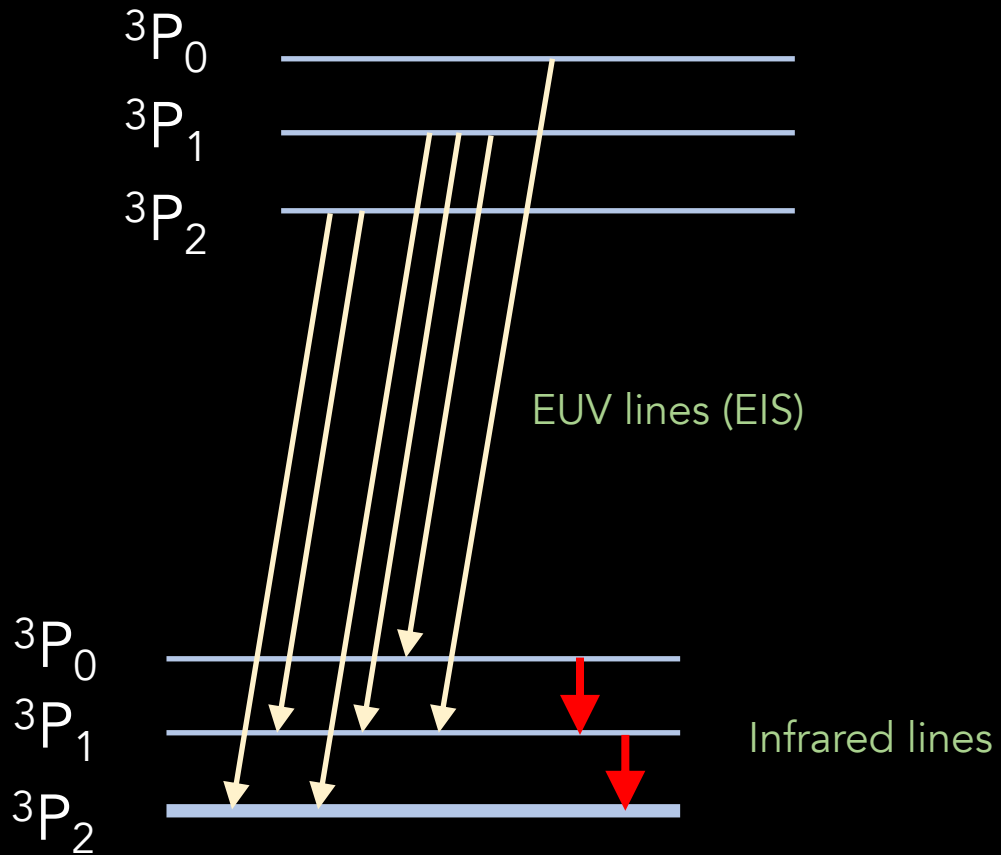
## Use EIS to derive new reference wavelengths

- No expectation of new laboratory wavelength measurements
- Use the EIS spectra to derive new wavelengths
- Mg VII has four lines; Si VII has six lines
- All lines in the range 272-281 Å

### Potential problems

- EIS does not have an absolute wavelength calibration
- Solar plasma often shows Doppler shifts

## Example: Si VII



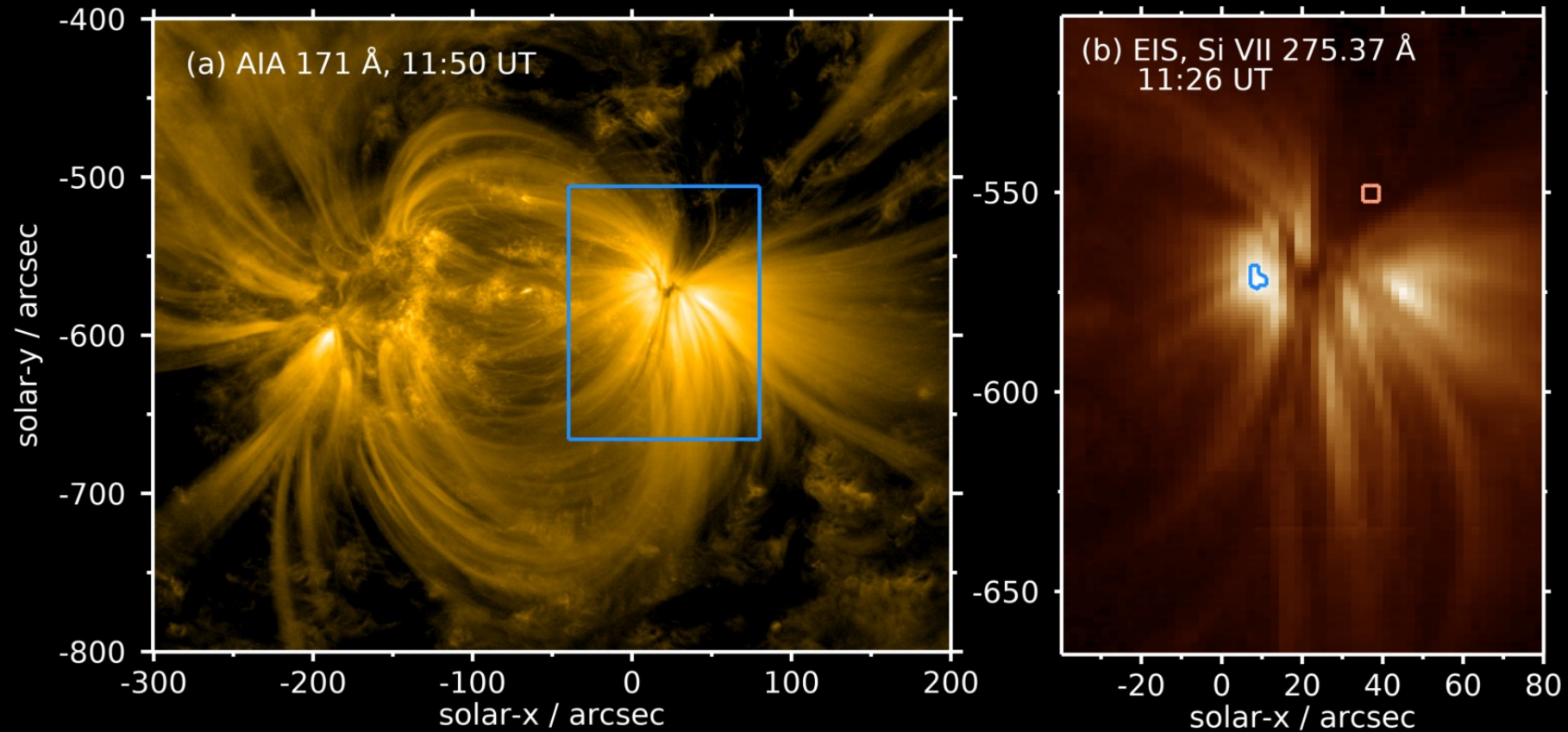
- The six EIS lines constrain energies for five atomic states.
- For ground  $3P$  state, more accurate energies come from astronomical IR spectra (see later).

# EIS does not have an absolute wavelength calibration

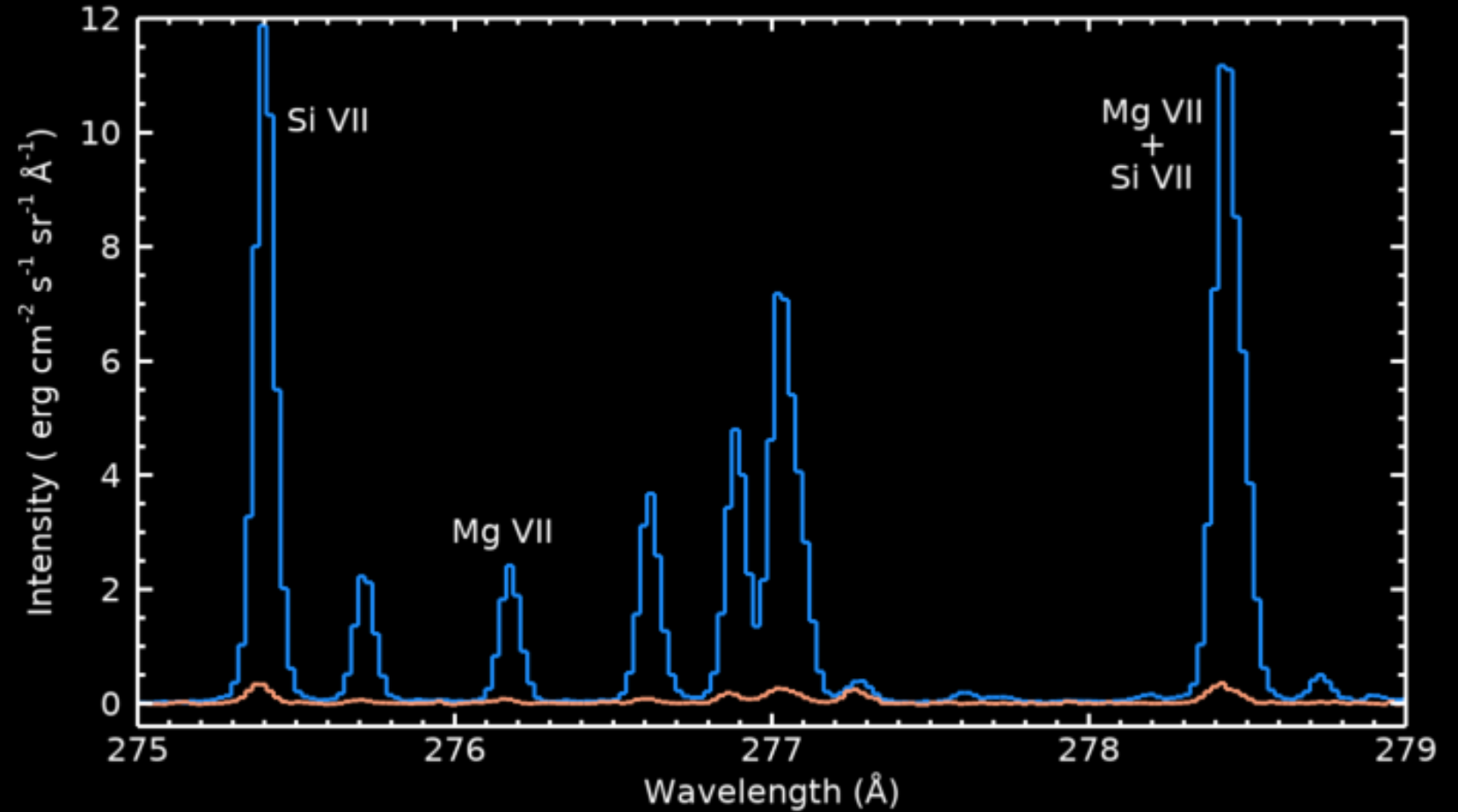
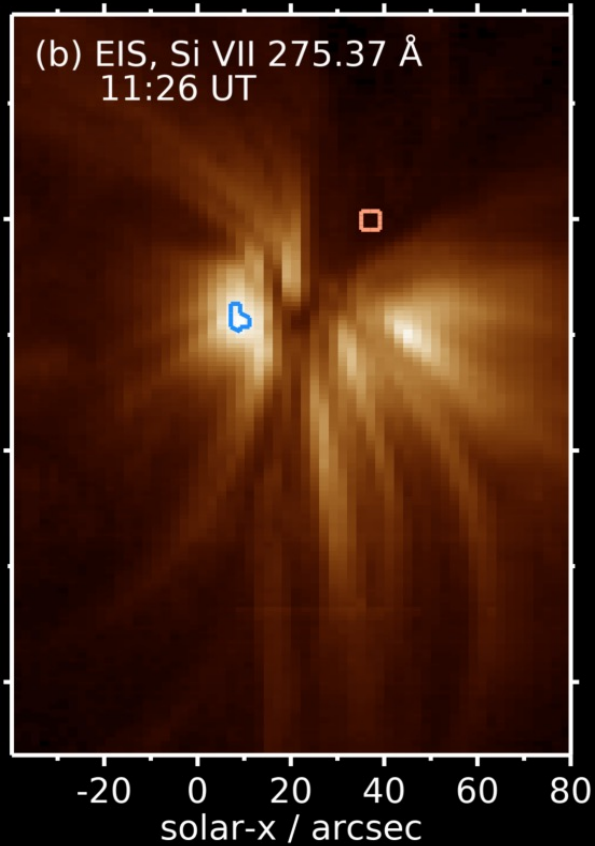
## Procedure

- The Behring et al. (1976) rocket spectrum is well-calibrated in wavelength (to 4 mÅ)
- Assume plasma above the solar limb observed by EIS has no Doppler shift
- Calibrate EIS limb spectrum against Behring rocket spectrum
  - Gives a reference wavelength for strong Si VII 275.36 Å line
- Use coronal loop spectrum (where Mg VII & Si VII are strong) to obtain reference wavelengths for all Mg VII & Si VII lines

# Mg VII & Si VII are bright in active region loops



# Lines x30 stronger in loop compared to background



## Datasets and measurements

- 13 sets of loop spectra between 2007 and 2017.
- RMS spread of measured wavelengths varies from 0.8 to 2.7 mÅ
  - gives confidence in EIS wavelength calibration
- Mg VII – Si VII separation RMS variation is < 1.5 mÅ
  - Mg VII and Si VII formed at same temperature

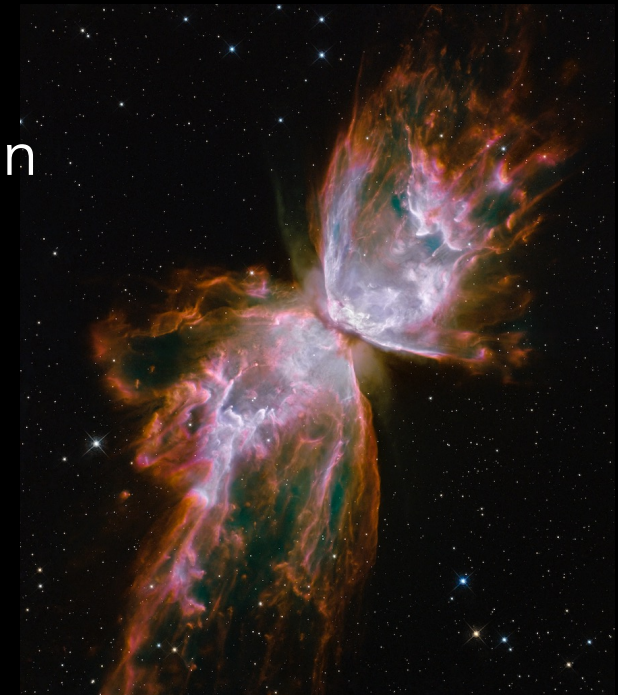
# Wavelengths measured from EIS spectra

**Table 2**  
Si VII and Mg VII Transitions and Wavelengths

Ion	Configurations	Terms	$\Delta\lambda^a/\text{\AA}$	Wavelengths ( $\text{\AA}$ )			
				Measured <sup>a</sup>	Ritz <sup>a</sup>	ASD	Edlén
Si VII	$2s^22p^4-2s2p^5$	$^3P_2-^3P_1$	-2.7105(9)	272.658 (4)	272.658 (3)	272.639	272.647
		$^3P_1-^3P_0$	-1.1804(13)	274.188 (4)	274.188 (4)	274.175	274.180
		$^3P_2-^3P_2$	0.0000	275.368 (4)	275.368 (3)	275.353	275.361
		$^3P_1-^3P_1$	+0.3158(8)	275.684 (4)	275.685 (3)	275.667	275.675
		$^3P_0-^3P_1$	...	...	276.860 (3)	276.839	276.850
Mg VII	$2s^22p^2-2s2p^3$	$^3P_1-^3P_2$	+3.0877(27)	278.456 (5)	278.456 (3)	278.443	278.449
		$^3P_0-^3S_1$	+0.7739(10)	276.142 (4)	276.142 (3)	276.154	276.138
		$^3P_1-^3S_1$	...	...	276.993 (3)	277.001	276.993
		$^3P_2-^3S_1$	+3.0261(18)	278.394 (4)	278.394 (3)	278.402	278.393
		$^1D_2-^1P_1$	+5.3613(14)	280.729 (4)	280.729 (4)	280.737	280.722

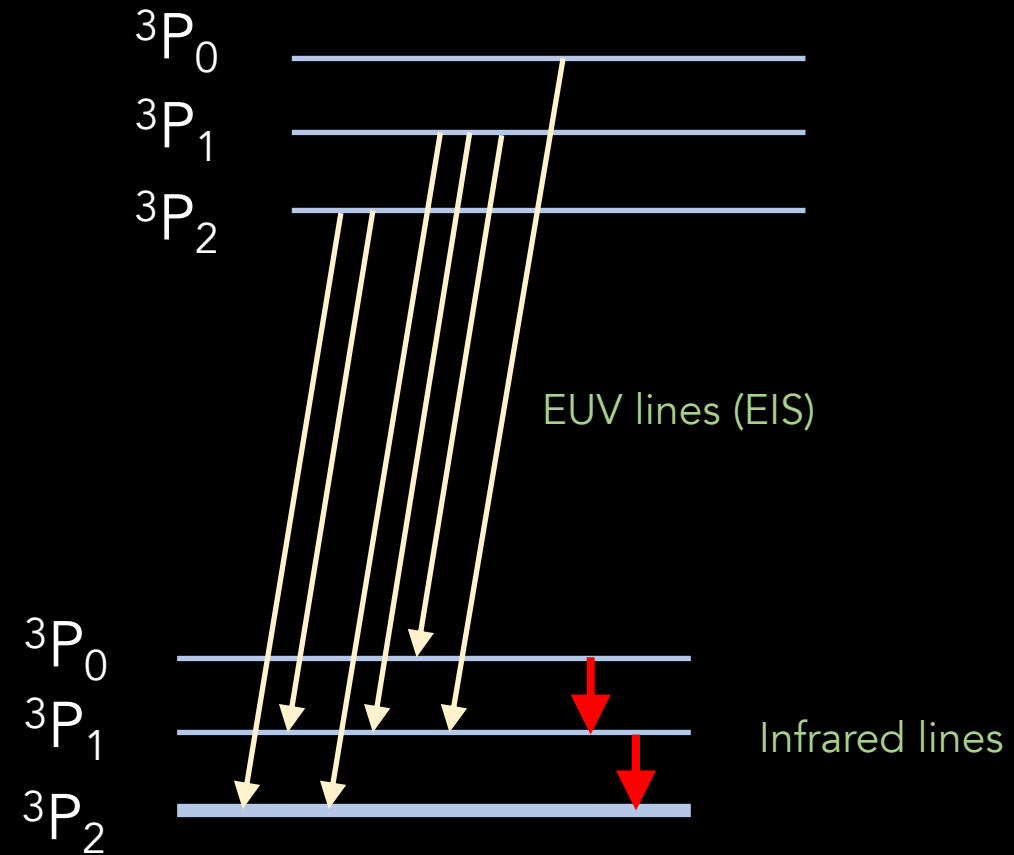
# Infrared Lines

- For low-Z elements, fine-structure transitions in the ground term are found at infrared wavelengths
  - Mg VII:  $^3P_1$ - $^3P_2$  and  $^3P_0$ - $^3P_1$  at 5.5  $\mu\text{m}$  and 9.0  $\mu\text{m}$
  - Si VII:  $^3P_2$ - $^3P_1$  and  $^3P_1$ - $^3P_0$  at 2.5  $\mu\text{m}$  and 6.5  $\mu\text{m}$
- These lines were first measured by ISO (1995-1998) from an unusually hot planetary nebula (NGC 6302)



# Ritz wavelengths

- A level's energy can be constrained by multiple lines
- An optimization procedure (e.g., LOPT code) is used to find the set of energies that best reproduce the measurements
- The Ritz wavelength is derived from the optimized energies



# Final recommended wavelengths

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Si VII and Mg VII Transitions and Wavelengths

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		$^1D_2-^1P_1$	+5.3613(14)	280.729 (4)	280.729 (4)	280.737	280.722

## Final comment: Mg/Si abundance

- Mg VII and Si VII formed at same temperature
- Ratio of Mg VII 276.14 Å to Si VII 275.37 Å varies between 0.17 to 0.21 in cool loop spectra (i.e., almost constant)
- Implies Mg/Si relative abundance is 50% higher than photospheric abundance
  - Not consistent with the “FIP effect”

## Summary

- New reference wavelengths for Mg VII and Si VII EUV lines derived from EIS and infrared measurements
- Improvement over earlier NIST and Edlén values
- Will allow more precise Doppler velocity measurements from EIS
- Work is underway to derive new energies and wavelengths for complete set of Mg VII atomic states

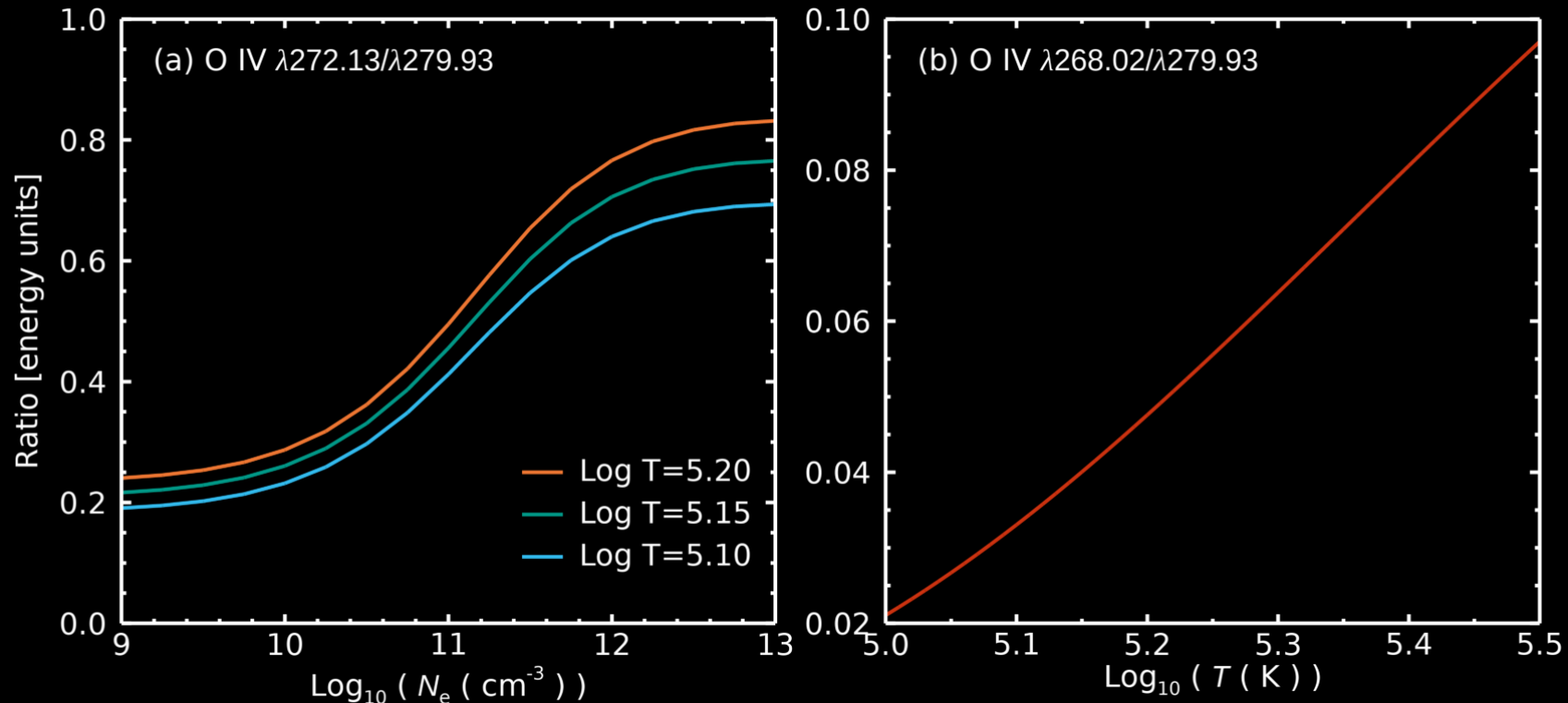
## Project 2: new diagnostics for O IV

Young, 2023, ApJ, submitted (arXiv:2401.12390)

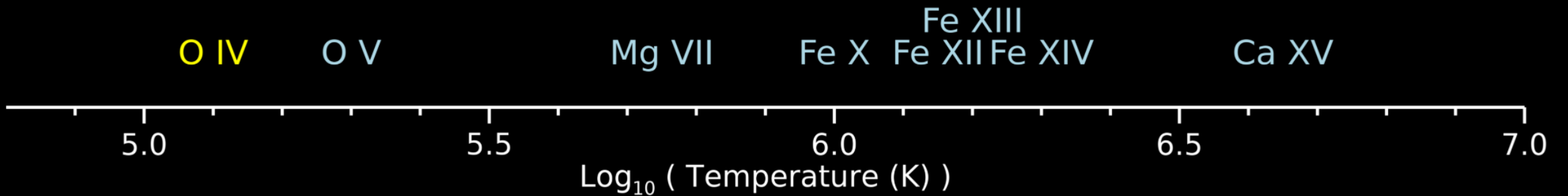
Use O IV emission lines to measure temperature and density of flare plasma

# Line ratio diagnostics

- The populations of an ion's atomic states can respond differently to changes in temperature and density
- Ratios of lines from different states can be used as diagnostics



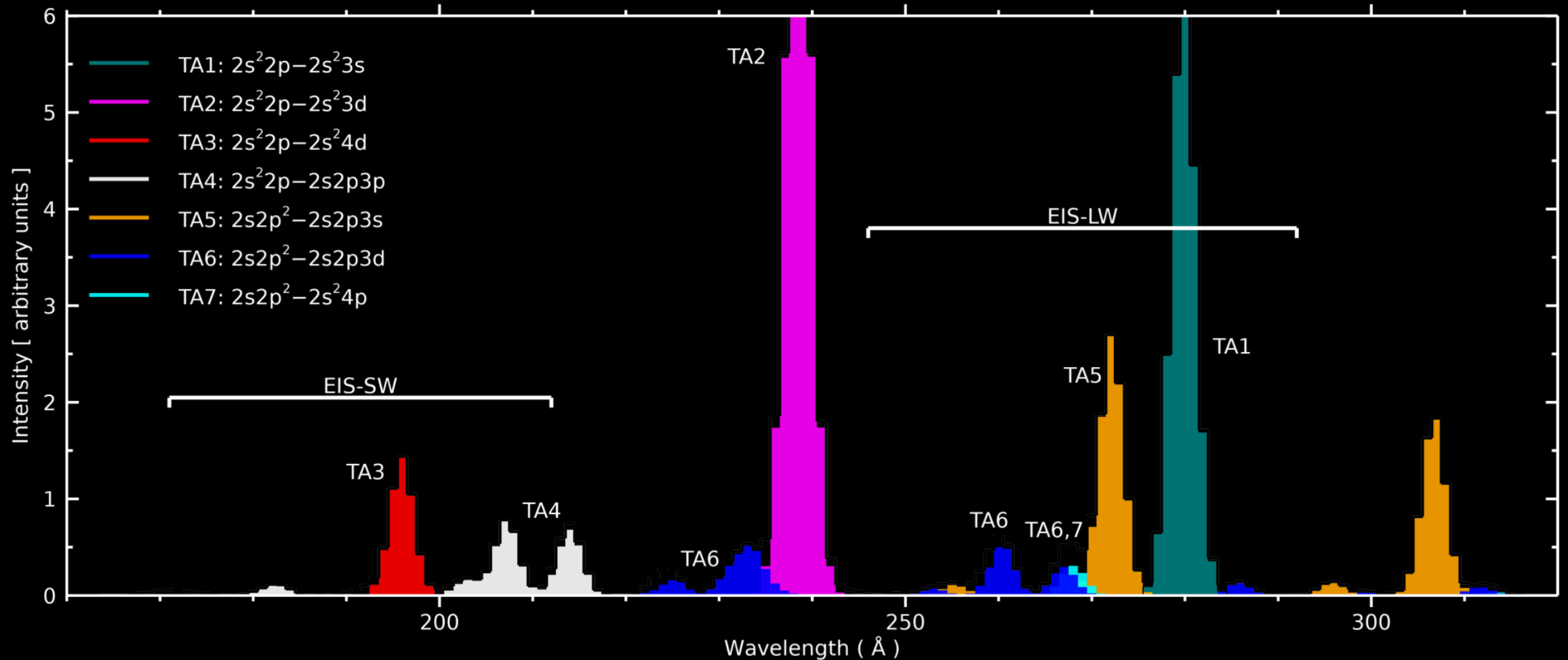
# EIS density diagnostic ions are mostly coronal



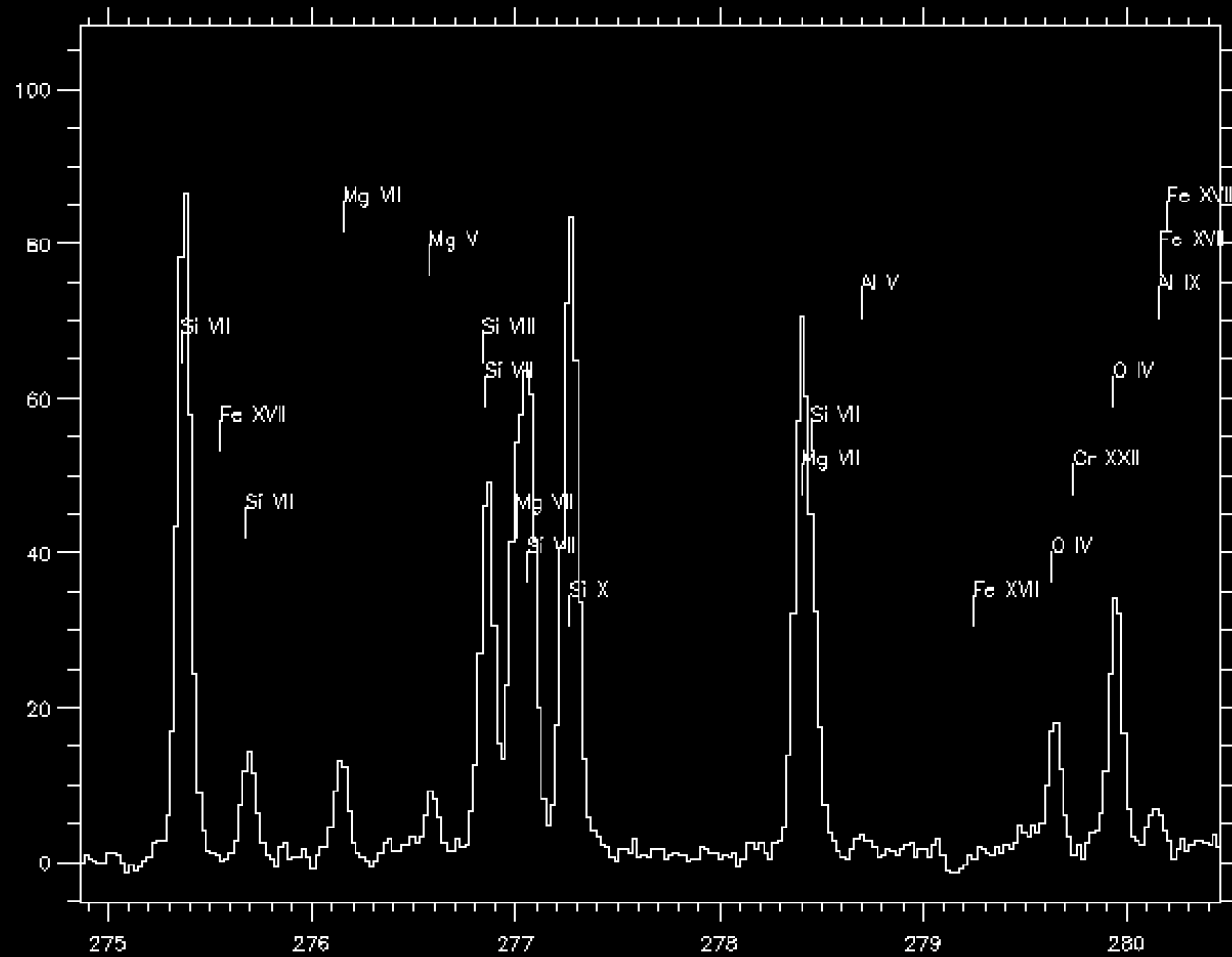
O IV has coolest density diagnostic accessible by EIS

# O IV has a rich spectrum in EIS range

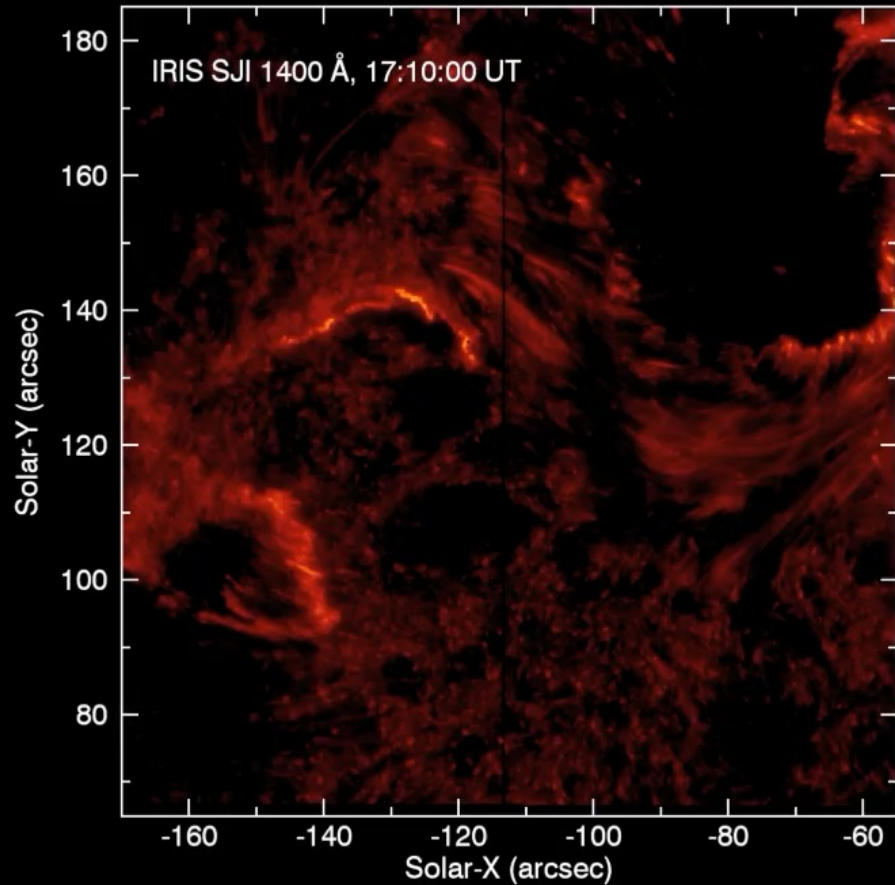
...but lines normally very weak



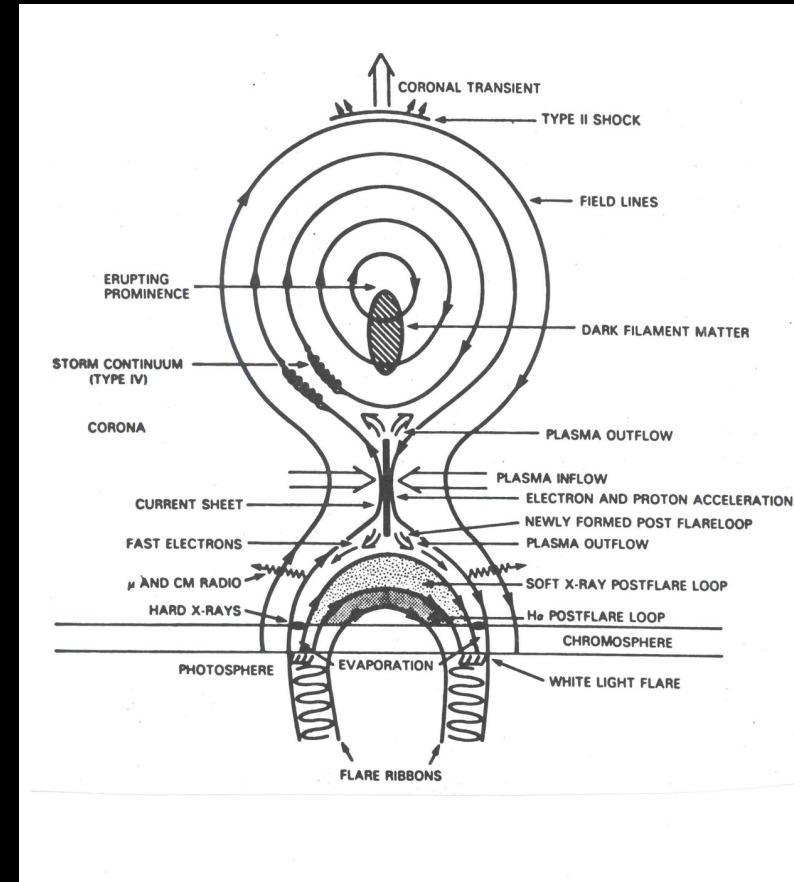
# Strongest lines can be clearly seen in quiet Sun



# Flare Ribbons

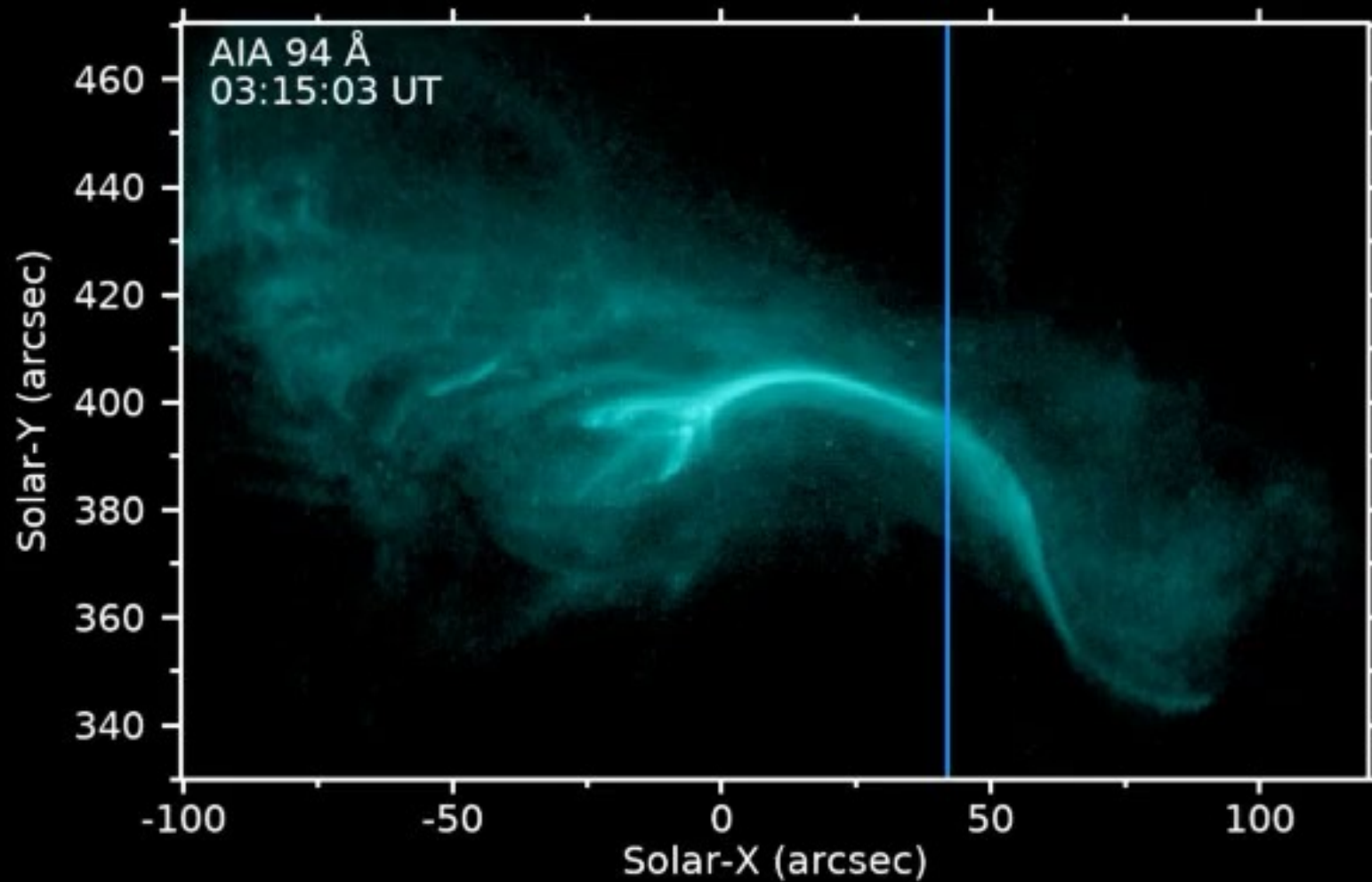


Flare ribbon development,  
IRIS, 10-Sep-2014



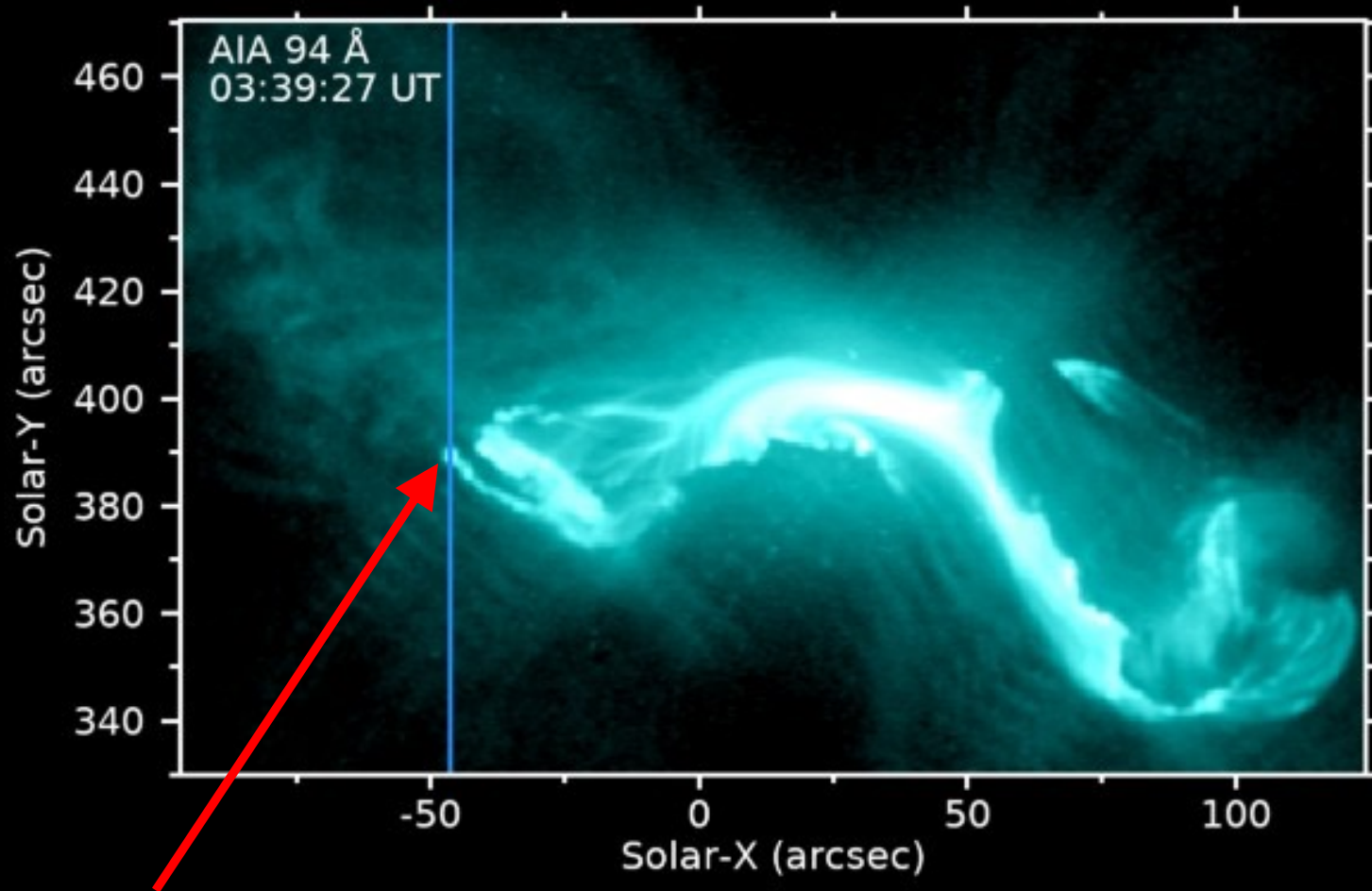
Flare cartoon (Martens & Kuin, 1989)  
[from Hudson cartoon archive]

# M6 Flare, 9-Mar-2012: AIA 94 Movie with EIS Slit

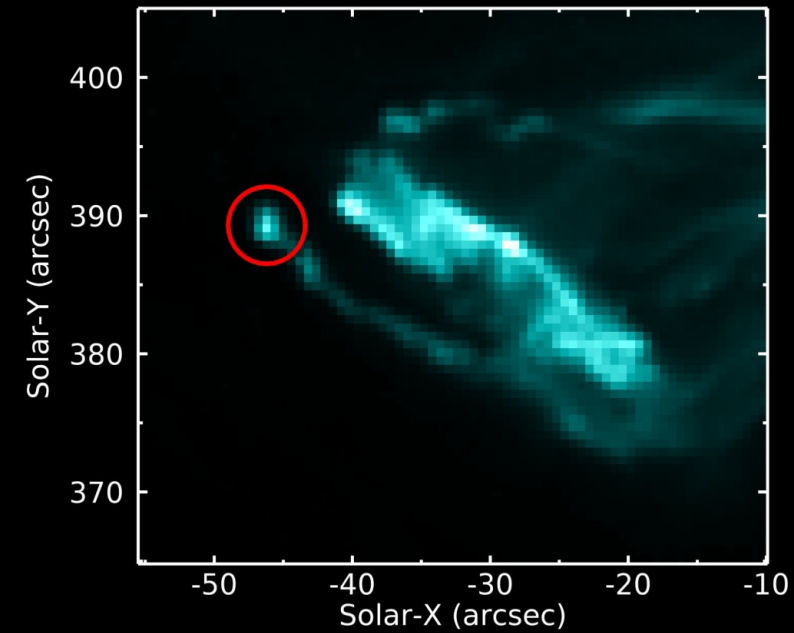


Blue line shows  
location of EIS slit

# Flare ribbon & kernel

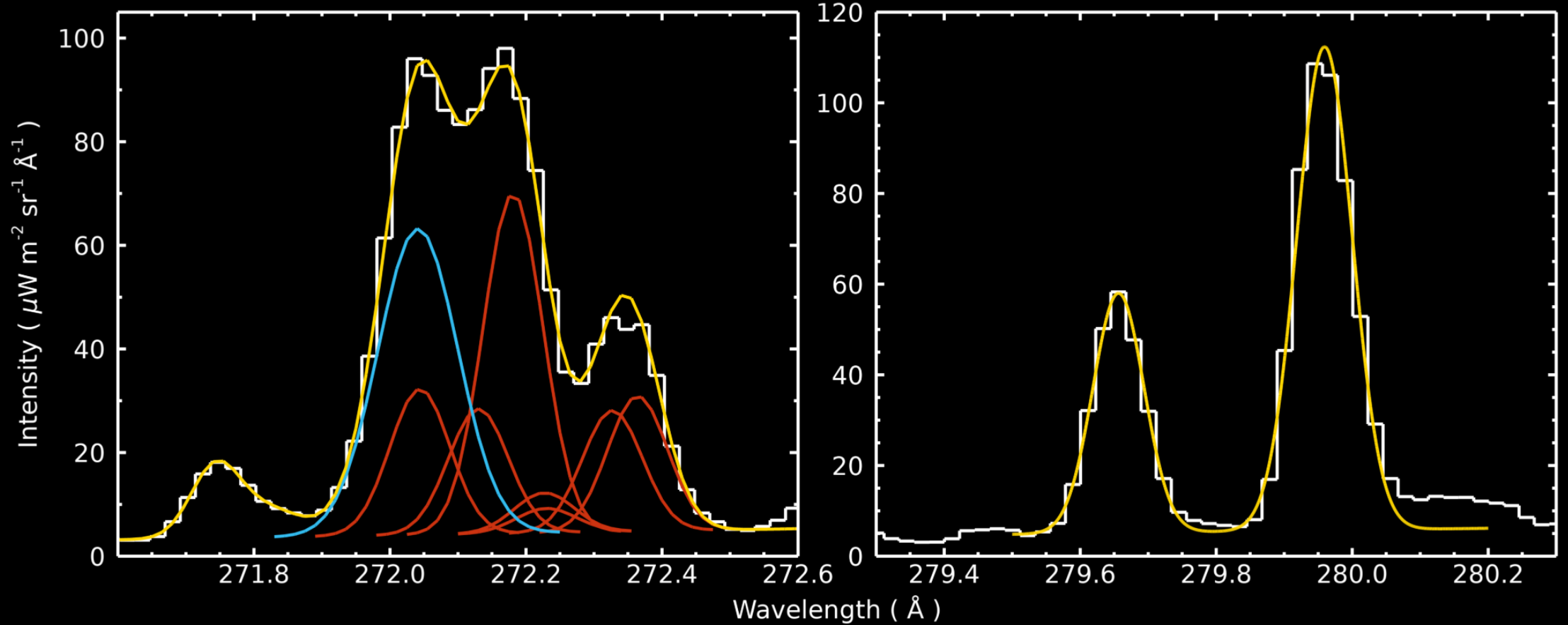


Slit captures a bright flare kernel within 1min of it appearing



Linear scaling shows "kernel" is significantly brighter than rest of ribbon

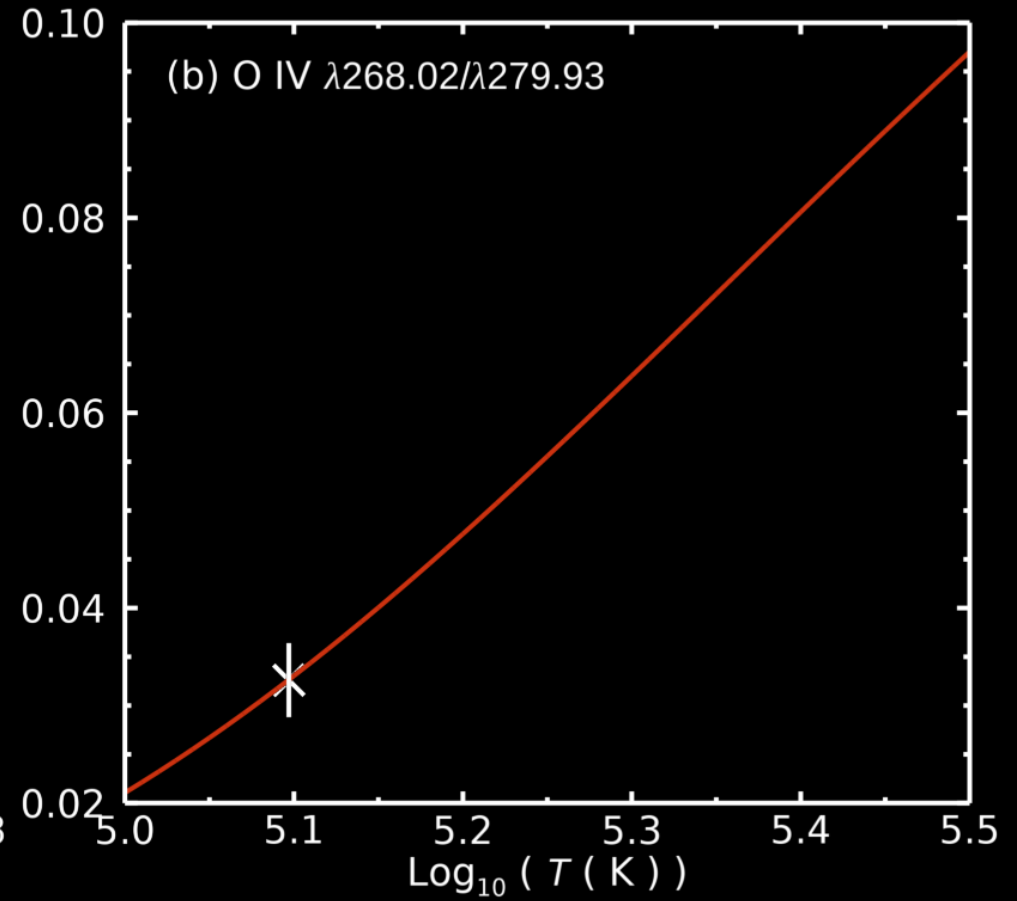
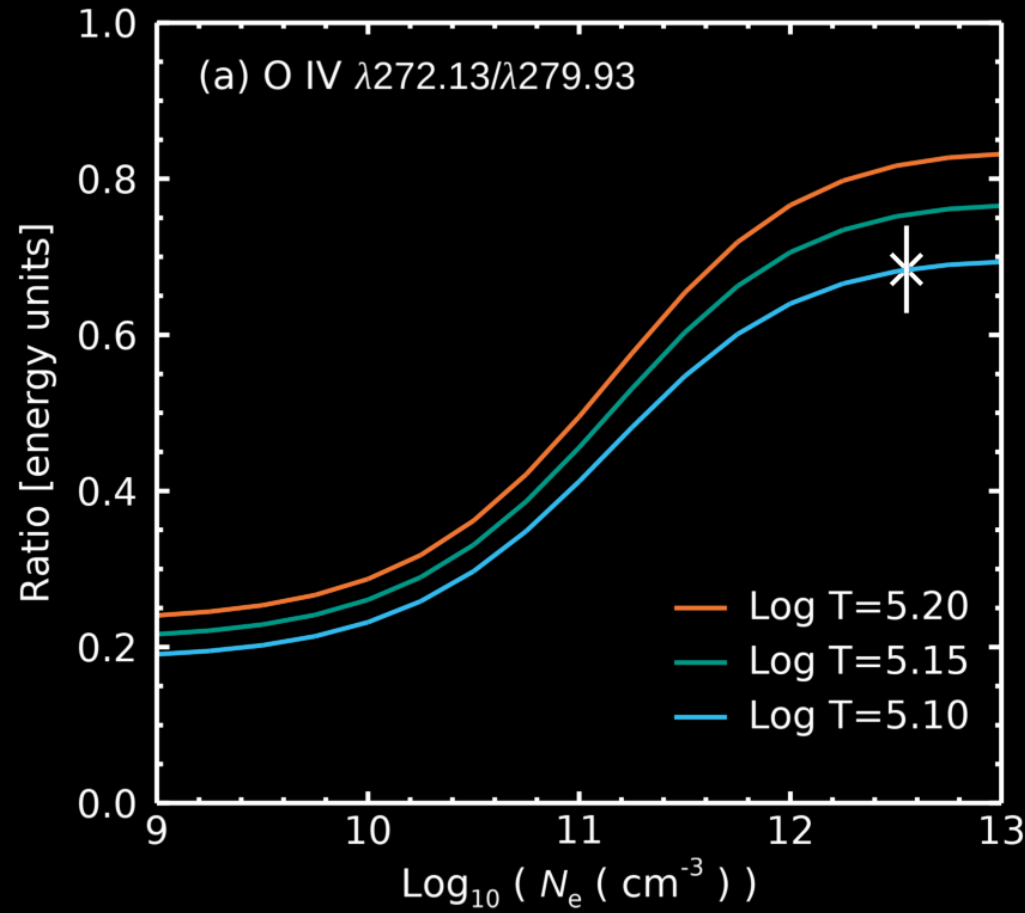
# Line profiles & fitting



Seven O IV components (red) at 272  $\text{\AA}$ , but they all behave the same

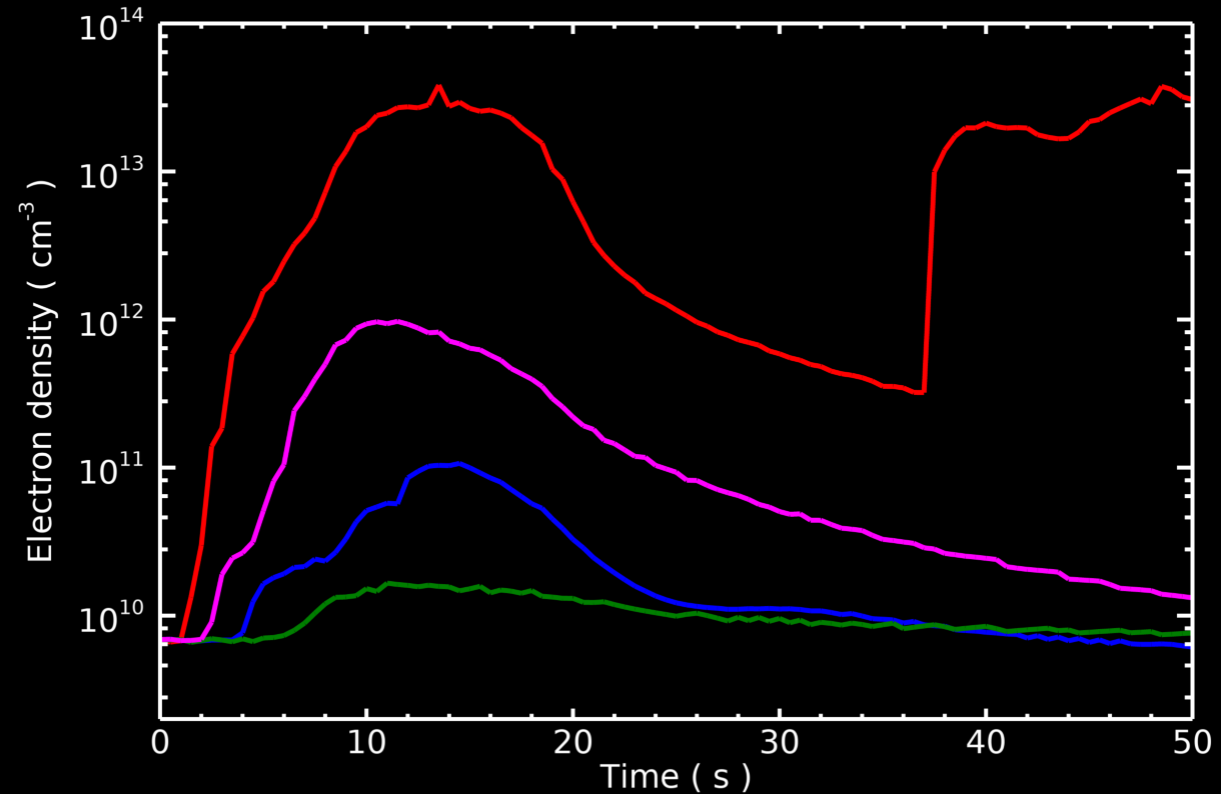
Two O IV lines in 2:1 ratio

# Diagnostics



# Density: comparison with a flare model

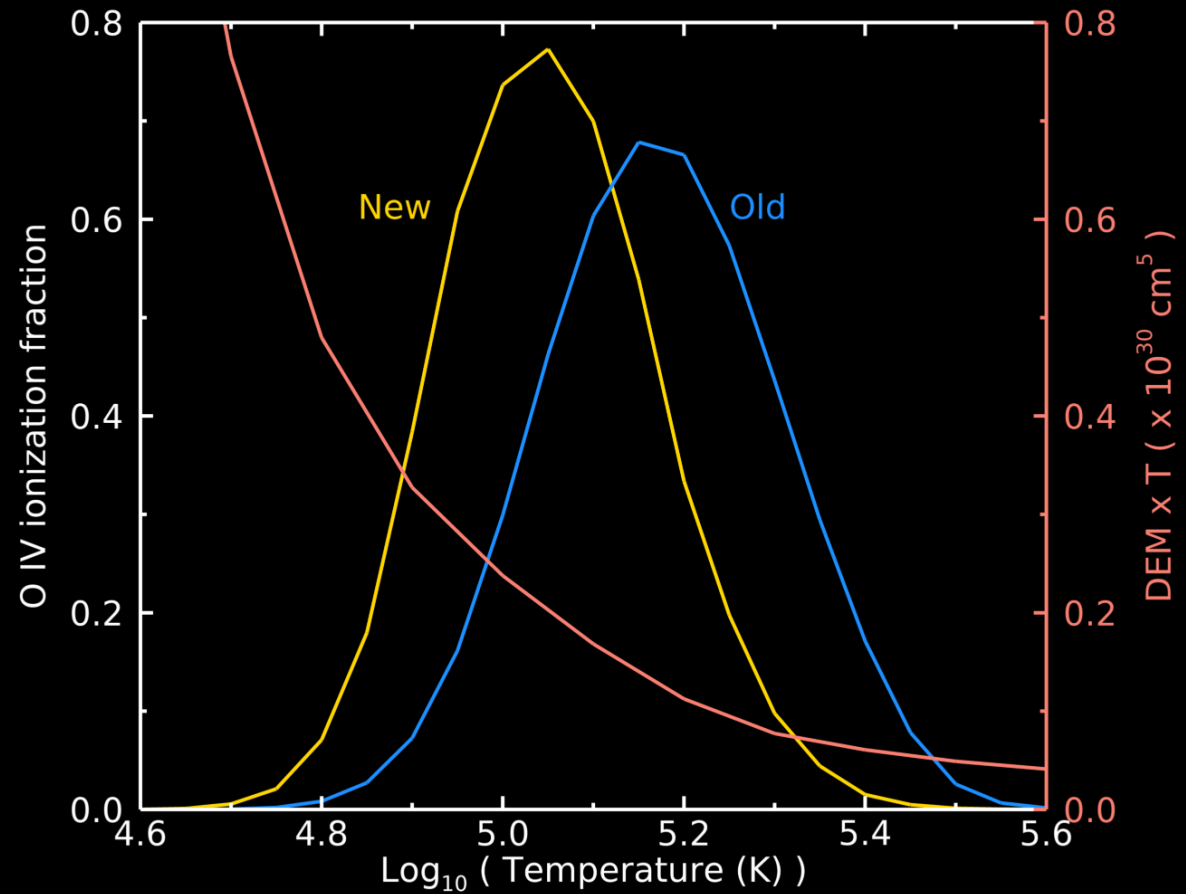
- The RADYN code models response of chromosphere to flare heating in a 1D loop
- Plot shows density variation for O IV plasma as function of time
- Densities  $> 10^{12} \text{ cm}^{-3}$  obtained for largest energy input



Energies from  $3 \times 10^{10}$  (green) to  $1 \times 10^{12}$  (red)  $\text{erg cm}^{-2}$

# Temperature: consistent with new ionization models

- Temperature:  $\log T = 5.10 \pm 0.04$
- The lines' contribution functions peak at  $\log T \approx 5.25$  (CHIANTI)
- Can be explained by sloped DEM distribution and new ionization balance calculations (Dufresne et al. 2020)



## Summary

- Previously unexplored line ratio diagnostics for O IV have been applied to EIS spectra of a flare kernel.
- Density:  $\log N_e = 12.55$  (upper limit 14.40; lower limit 11.91)
- Temperature:  $\log T = 5.10 \pm 0.04$
- Extends EIS diagnostic coverage to mid transition region

Contact: [peter.r.young@nasa.gov](mailto:peter.r.young@nasa.gov)

This talk: <https://pyoung.org/talks/>

**END OF TALK**