Nonthermal Line Broadening and Velocities Observed by EUNIS-2021 and EIS in the Core of AR 12824

Jeff Brosius (Catholic U at NASA/GSFC)

Adrian Daw (NASA/GSFC)

Enrico Landi (U Michigan)

Doug Rabin (NASA/GSFC)

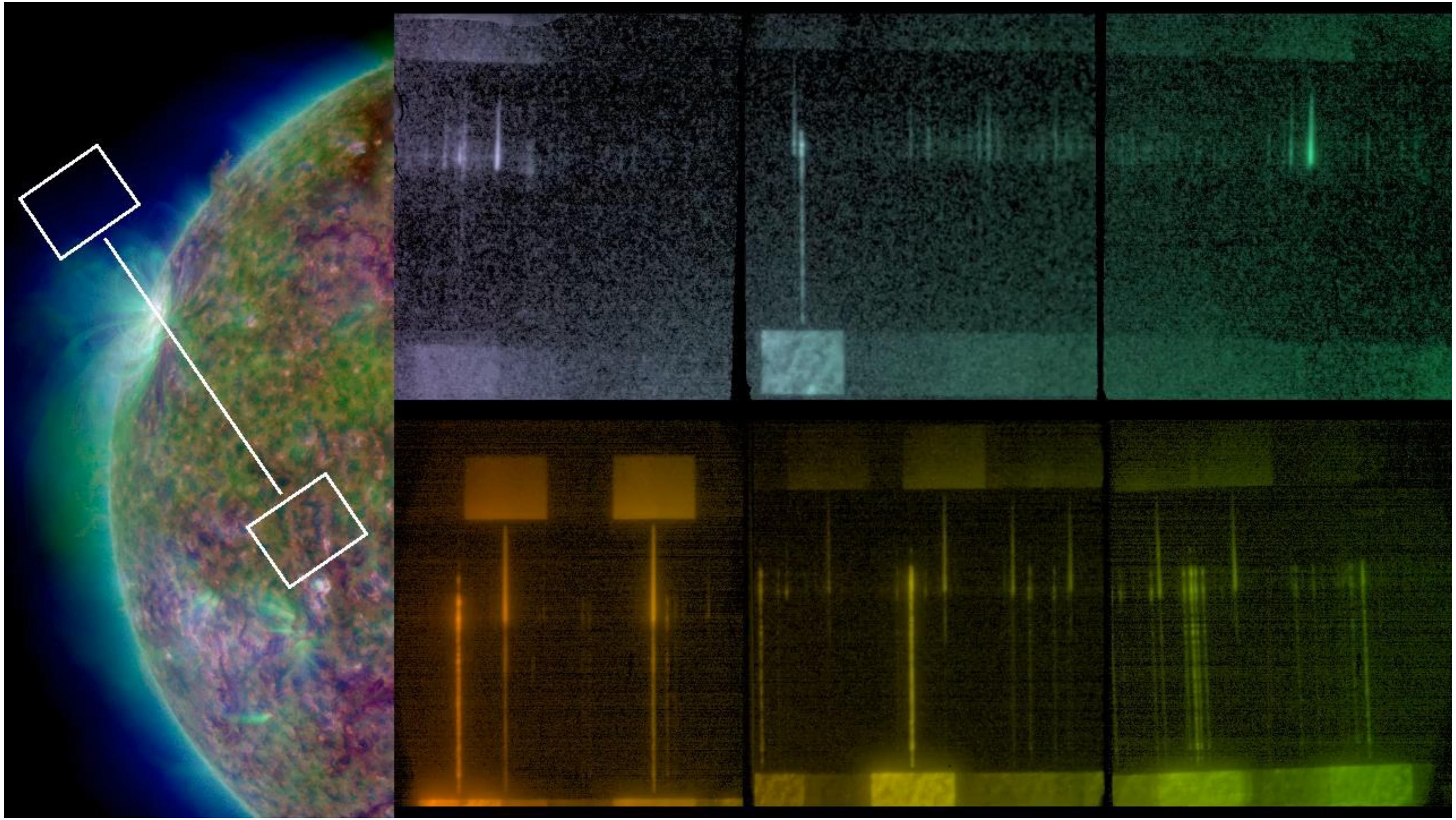
Don Schmit (U Colorado)

Can V_{nonth} Help Constrain Coronal Heating Mechanisms?

- Nanoflare reconnection jets suggest $V_{nonth} \approx 250$ km/s (Cargill 1996).
- Nanoflare high-speed upflows suggest nonthermal broadening ≈ 16 – 37 km/s (Patsourakos & Klimchuk 2006).
- Alfven wave energy dissipation through shocks yield mean V ≈ 50, max V > 200 km/s (Antolin *et al.* 2008).
- 3-D MHD model of coronal loop heating by Alfven wave turbulence and dissipation yield coronal velocity amplitudes 20 – 40 km/s (van Ballegooijen *et al.* 2011).
- Ponderomotive force to produce FIP effect yields Alfven amplitudes ≈ 50 – 100 km/s (Laming *et al.* 2012).
- Plasma response to reconnection strand heating using 2DCAM-EBTEL (Lopez Fuentes & Klimchuk 2022): $9 < V_{nonth} < 16$ km/s for T up to 3 MK.

EUNIS Observations of AR 12824 on 2021 May 18

New SW channel at 92-115 Å in 3rd order superimposed on 277-345 Å in 1st, plus LW channel at 525-639 Å; 17:32 - 17:38 UT. GOES recorded one C1 flare early in day, otherwise nothing greater than B2; last pre-launch microflare ended ≈80 m before flight.



Extreme Ultraviolet Normal Incidence Spectrograph: EUNIS-2021

- Designed to observe line emission from Fe XVIII (T_{max} = 7.1 MK) & Fe XIX (T_{max} = 8.9 MK): key to assessing nanoflare model.
- Overall, EUNIS observed 100s of lines formed at $0.03 < T < 10$ MK.
- Fe XVIII & Fe XIX detected over extended portion of AR. These lines constrain EM at high T, with preliminary results indicating small amount of plasma around 6 MK.
- Ongoing work: finalize flat fielding, radiometric calibration, and instrumental width; assemble AR and QS line lists.
- Here focus on instrumental width and nonthermal velocities.

Measuring Nonthermal Velocities

$F^2_{obs} = F^2_{therm} + F^2_{inst} + F^2_{nonth}$

F_{therm} = (λ/c)(2akT/m)^(1/2), where a=4ln2, m=atomic mass

F_{inst} : measured in laboratory

$F^2_{nonth} = F^2_{obs} - F^2_{inst} - F^2_{therm}$

V_{nonth} = (cF_{nonth})/[λa^(1/2)]

Instrumental Widths

EUNIS-2021

- Lab spectrum with Ar II, Ar III, & He I at 530-640 Å reveal F_{inst} independent of λ in long wavelength (L) channel.
- Strongest, well separated lines yield F_{inst} = 189.8 ± 11.7 mÅ in L channel.
- Gaussian profiles fit well.
- Uncertainties:

  * Best focus around 578 Å.

  * He I 584.3 alone: F_{inst} = 205.5 mÅ.

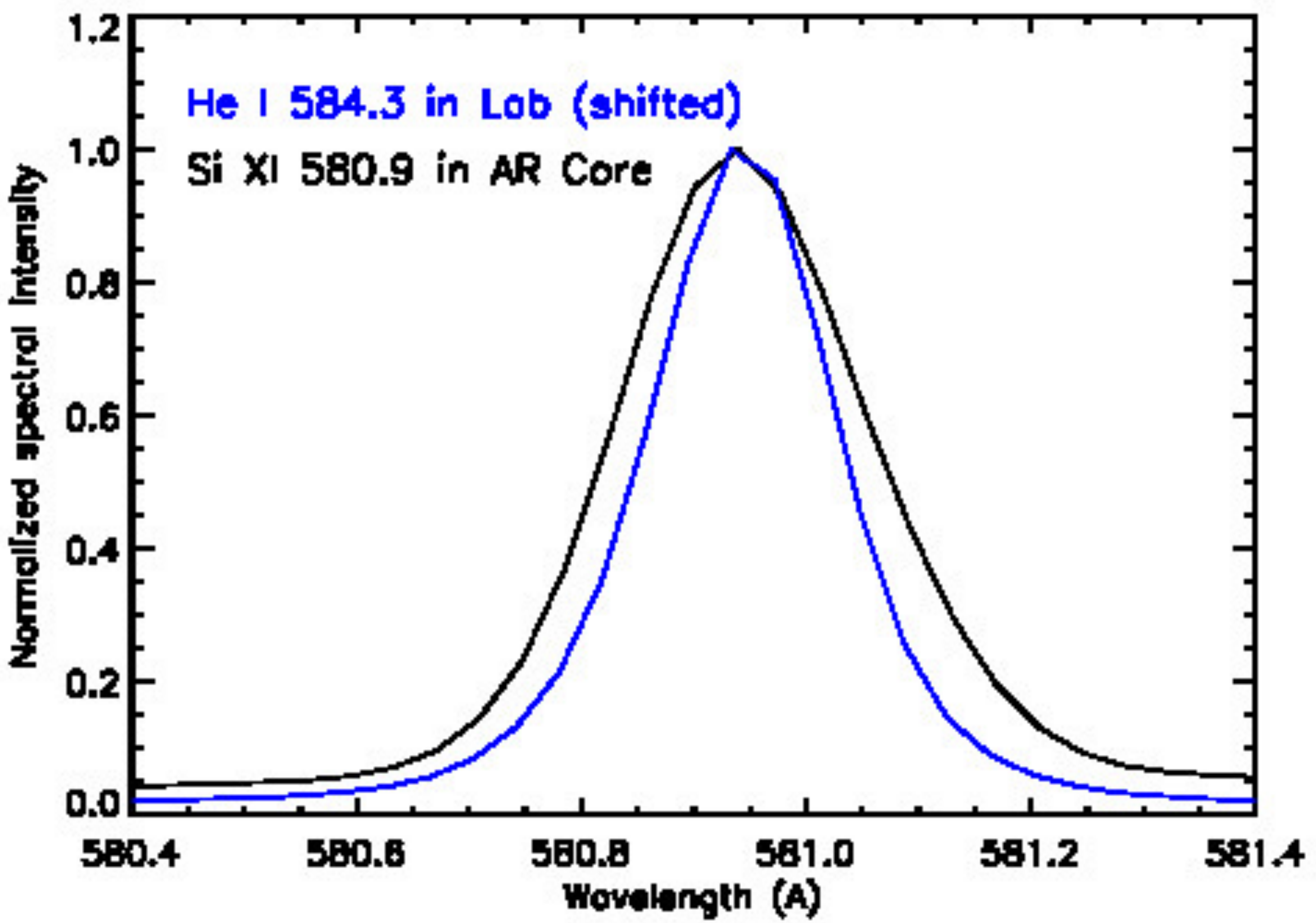
  * Widths slightly depend on λ range of profile fit.

  * Lab *vs.* solar illumination.

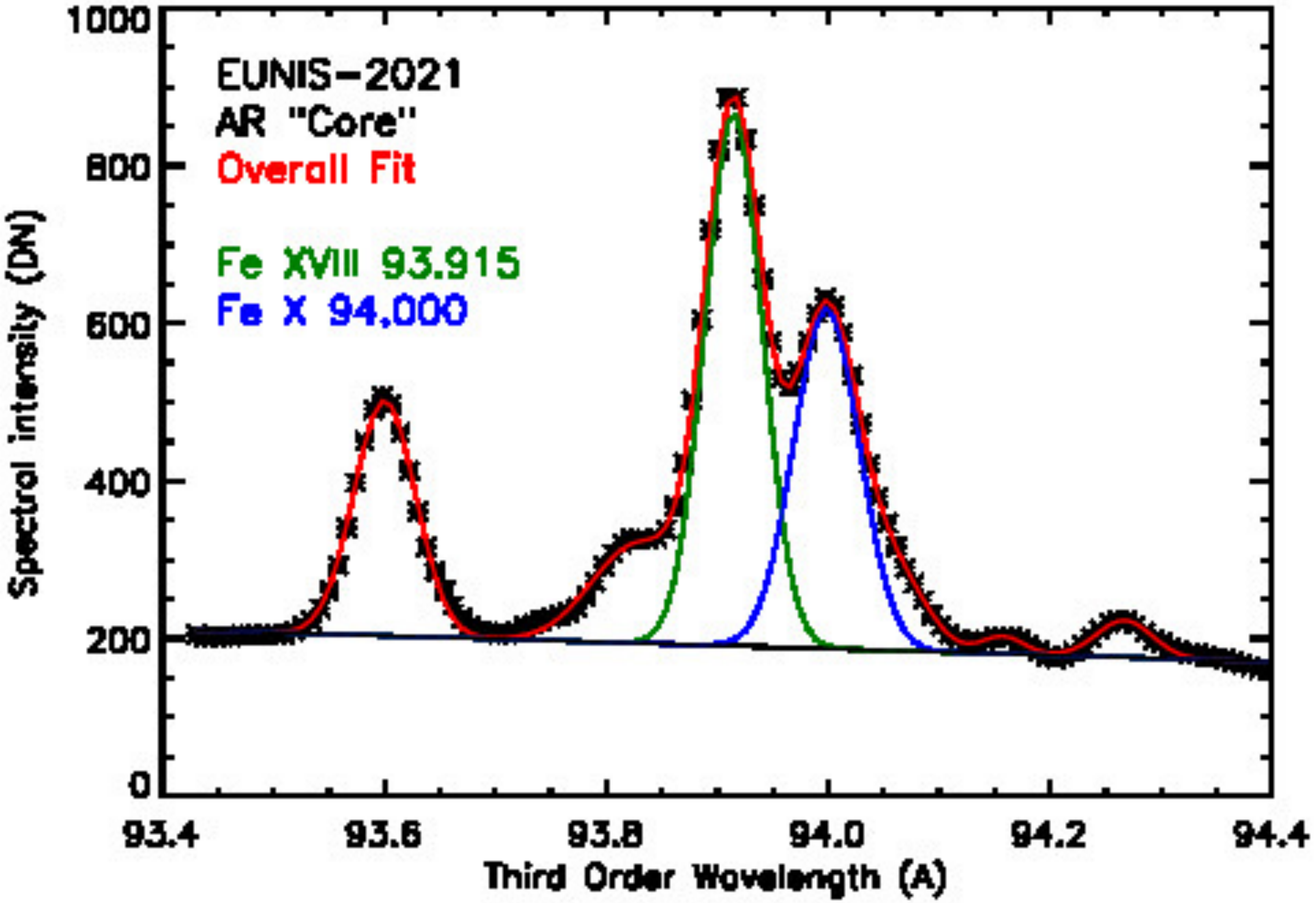
Hinode/EIS

- Korendyke *et al*. (2006): Mg III 187 Å → F_{inst} = 47 mÅ in SW (170-210 Å); He II 256 & Ne III 267 → F_{inst} = 55-57 mÅ in LW (250-290 Å).
- Brown *et al*. (2008): F_{inst} = 54 mÅ in SW based on solar obs and V_{nonth} ≈ 30 km/s.
- Young (2011): Quantify F_{inst}(Y-pixel) based on off-limb solar obs of Fe XII 193.5; removed F_{therm} but **not** F_{nonth}.
- Brooks & Warren (2016): Gaussian profiles fit well.
- Widths slightly depend on λ range of profile fit.
- Uncertainty on F_{inst} ≈ 3.1 mÅ (Young 2011).

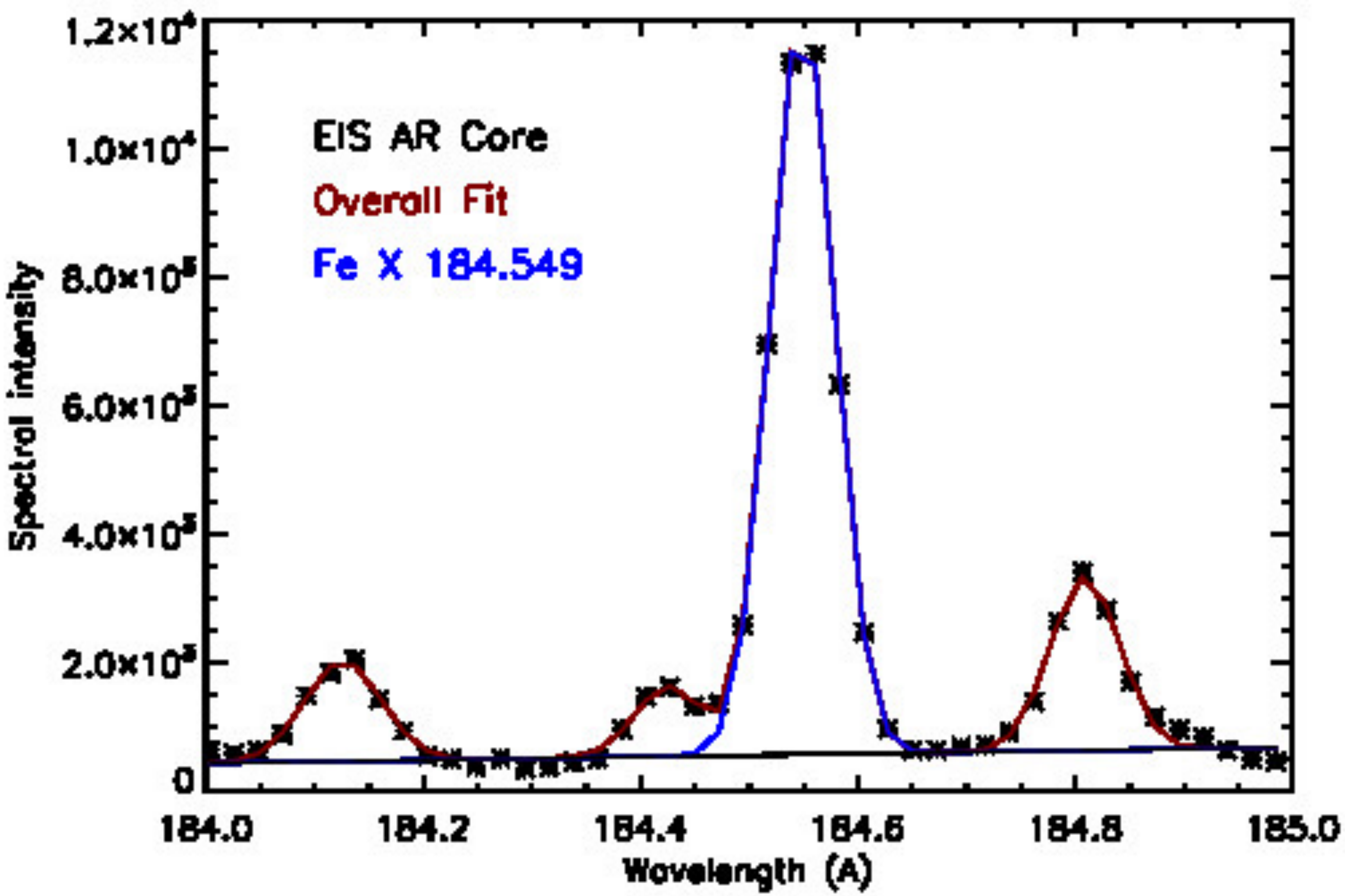
Comparison of Normalized Solar Profile of Si XI 580.9 Å With Normalized Shifted Lab Profile of He I 584.3 Å



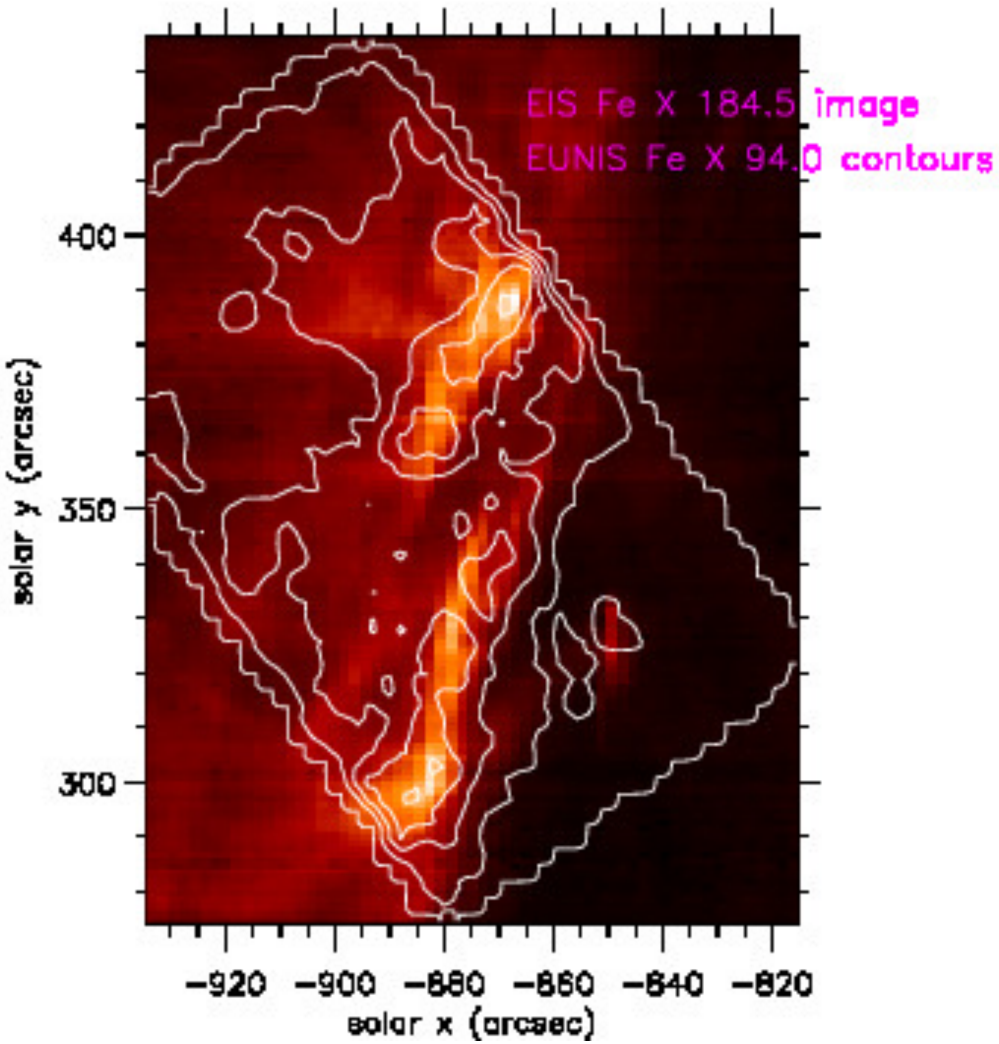
EUNIS Profile fits to Fe XVIII 93.9, Fe X 94.0 Å

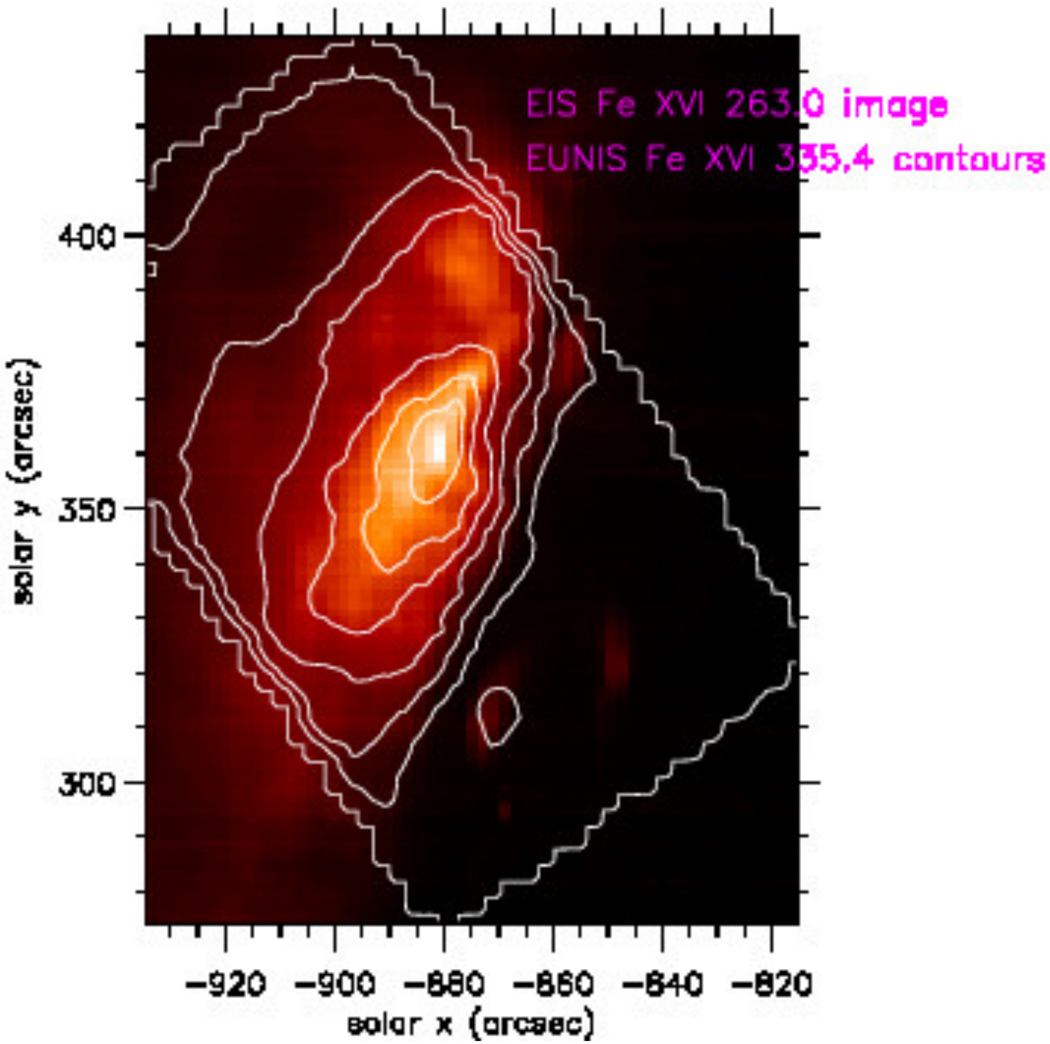


EIS Profile fits to Fe X 184.5 Å and Neighbors

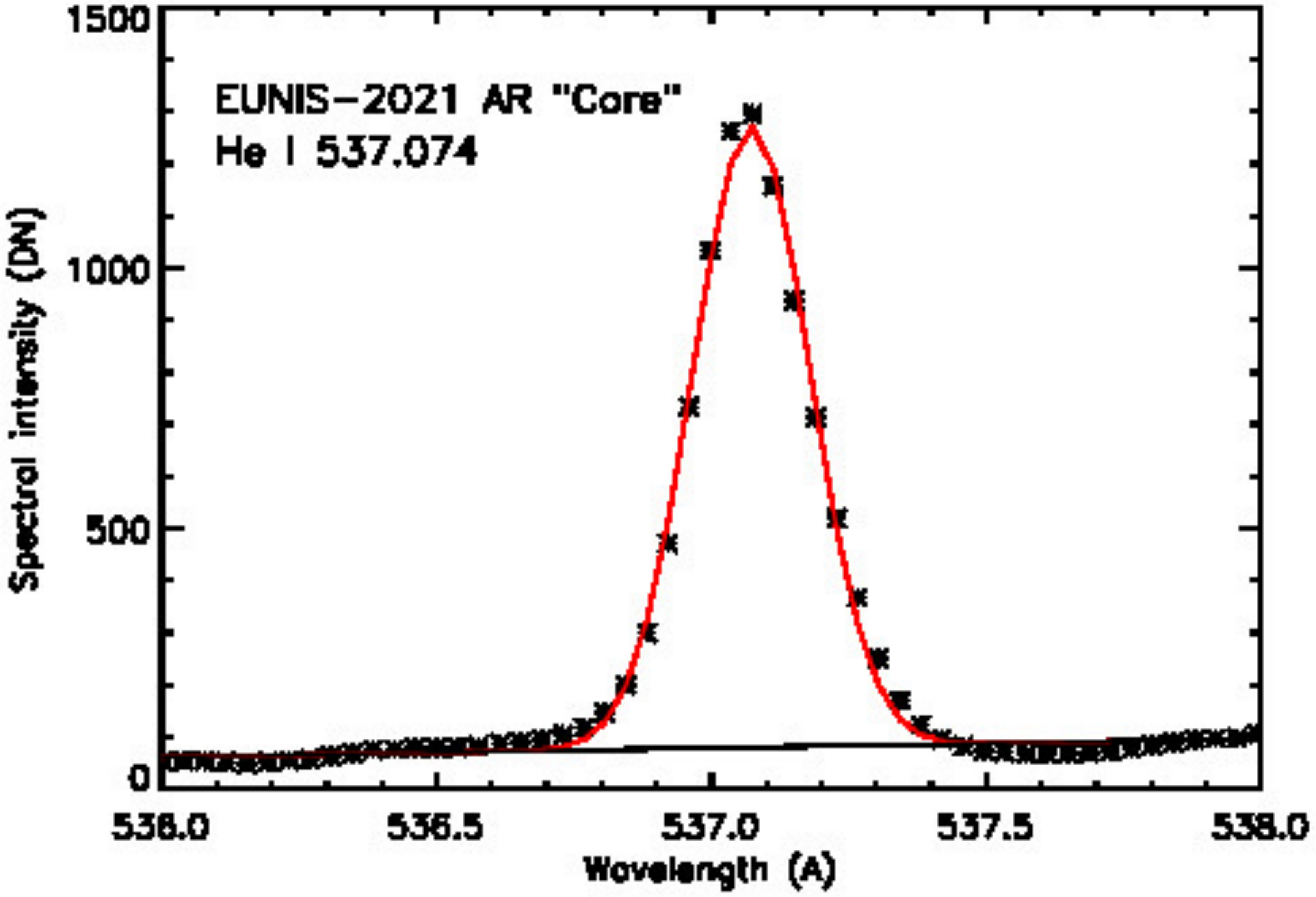


Coalignment of EUNIS & EIS



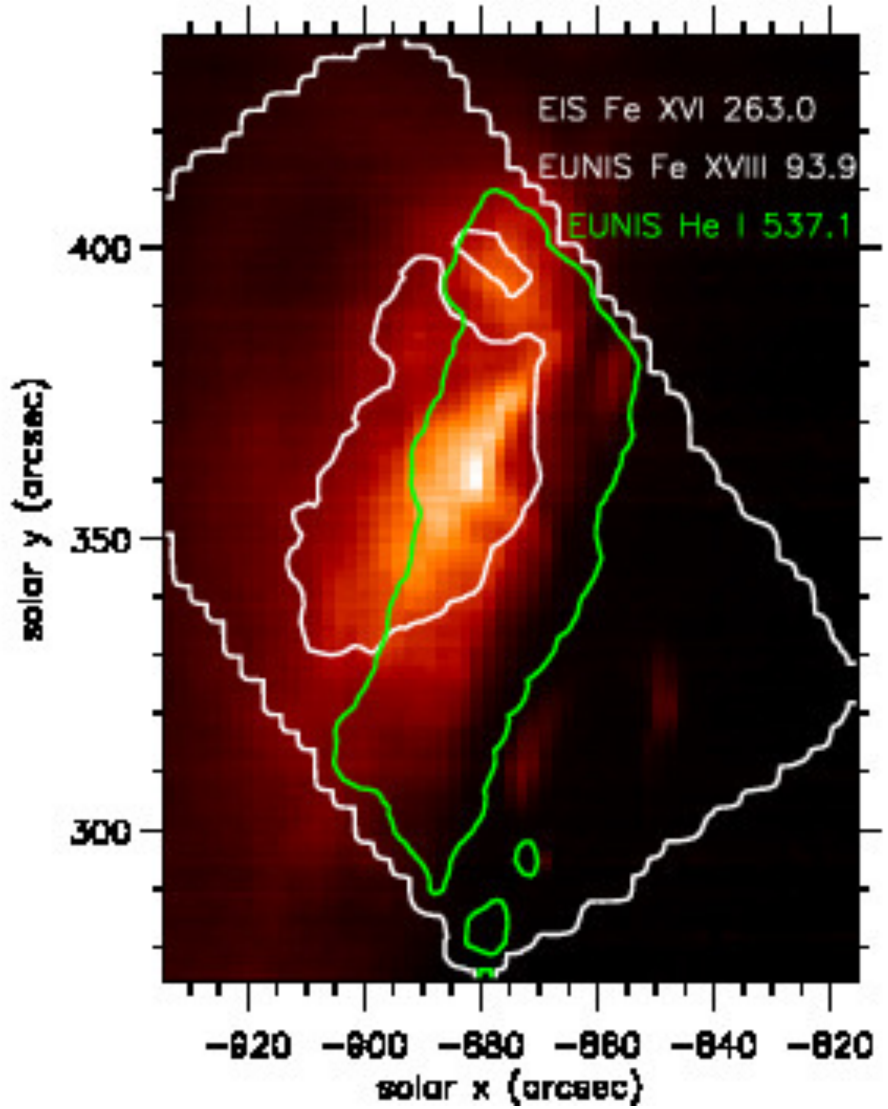


EUNIS Profile Fit to He I 537.1 Å

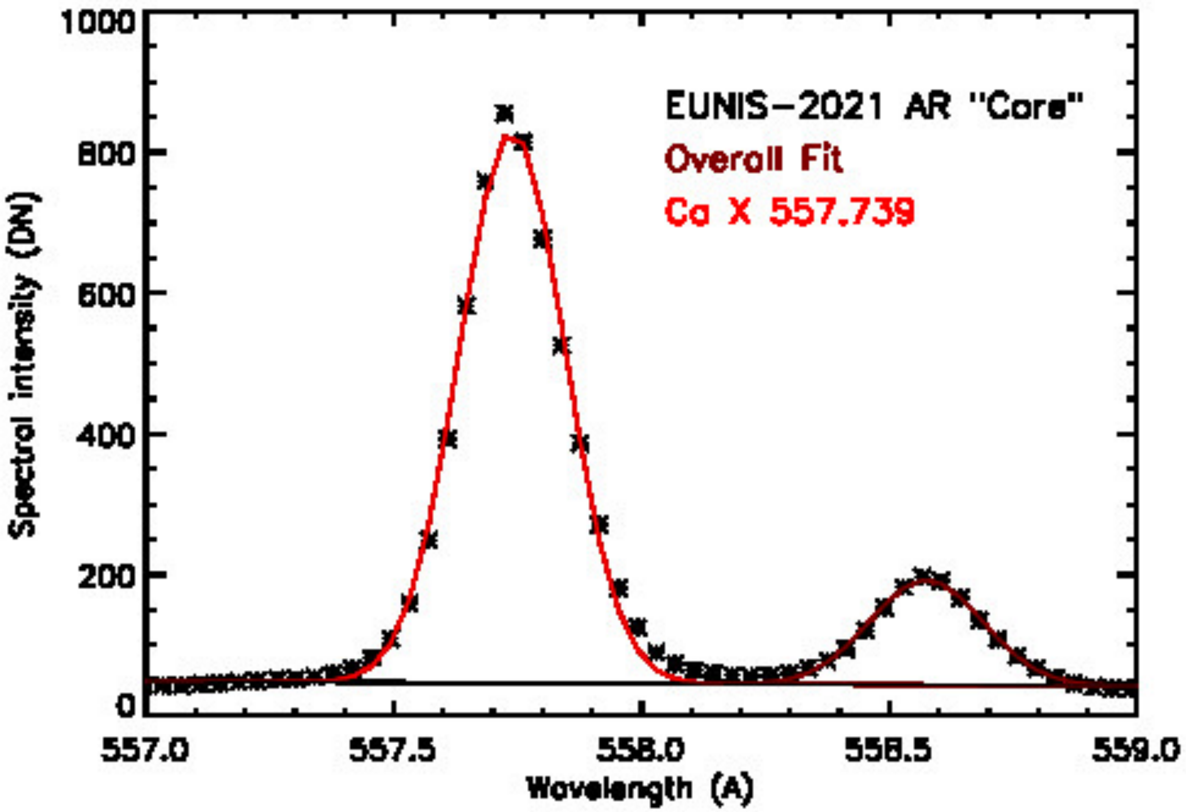


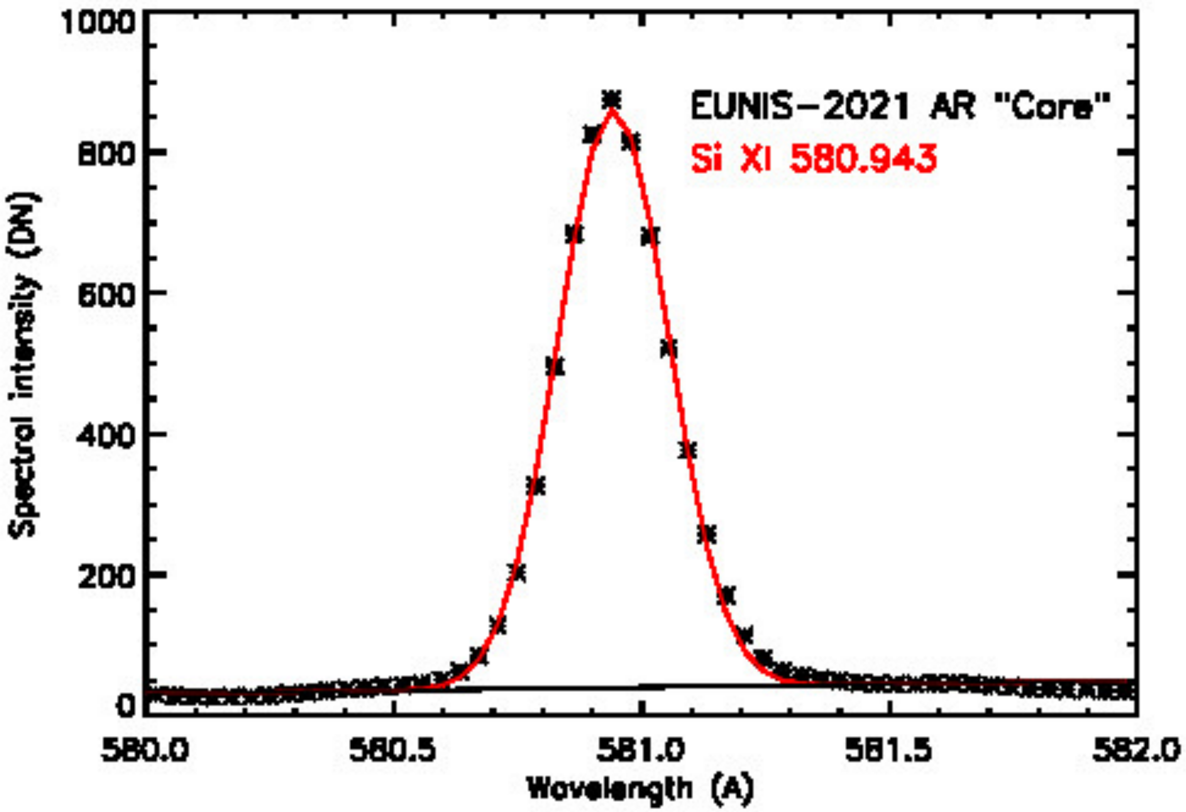
Fe XVIII and He I Contours Outlining AR Core

EIS raster image of Fe XVI at 263.0 Å. White contour is where Fe XVIII 93.9 Å intensity exceeds 33% of its max; green contour is where He I 537.1 exceeds 20% of its max. Overlap of these contours outlines AR "Core" (884 arcsec²).



More EUNIS Profiles in Core: Ca X 557.7 & Si XI 580.9





EUNIS V_{nonth} for Strong, Separate Lines with F_{inst} = 189.8 ± 11.7 mÅ.

Here, T_{eff} is temperature at which most emission originates based on preliminary DEM.
Range of measured values is V_{nonth} = 49.9 ± 6.6 km/s ; average ± 1σ = 48.9 ± 3.7 km/s.

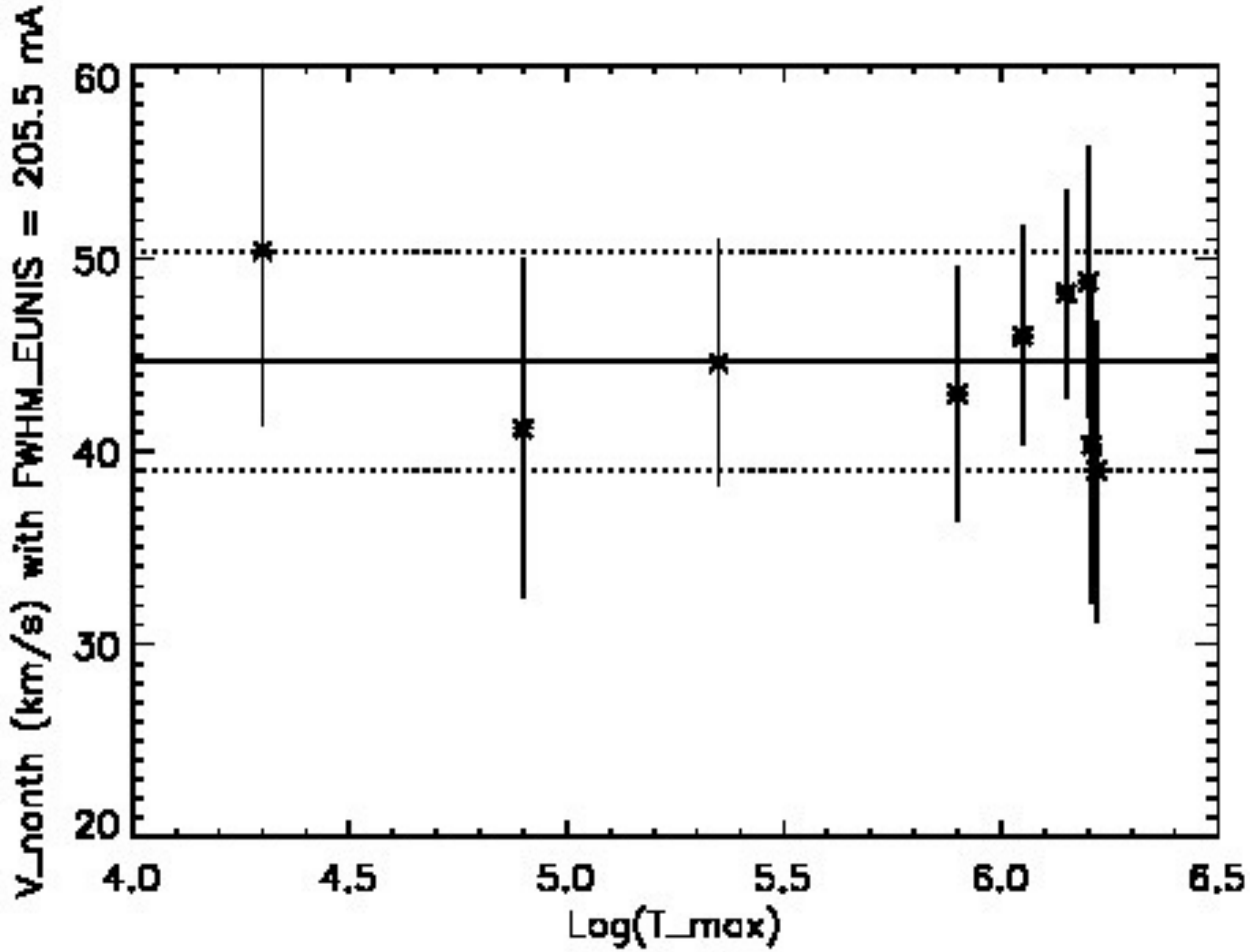
Line	Log (T_{eff})	$FWHM_{therm}$ (mÅ)	$FWHM_{obs}$ (mÅ)	V_{nonth} (km/s)
He I 537.1	4.49	33.80	256.0 +/- 12.8	56.5 +/- 7.9
O III 599.6	4.88	29.57	248.9 +/- 13.0	47.5 +/- 7.4
O V 629.7	5.35	53.35	263.4 +/- 9.7	49.9 +/- 5.5
Ca X 557.7	6.09	69.98	251.2 +/- 5.1	48.1 +/- 5.6
Mg X 609.8	6.22	114.3	274.5 +/- 6.7	47.9 +/- 5.3
Mg X 624.9	6.22	117.1	281.9 +/- 7.0	49.7 +/- 5.0
Si XI 580.9	6.29	109.6	262.9 +/- 9.1	45.0 +/- 7.0
Si XI 604.2	6.29	114.0	264.9 +/- 9.1	43.3 +/- 6.7
Al XI 550.0	6.32	109.6	271.2 +/- 7.6	52.3 +/- 6.2

EUNIS V_{nonth} for Strong, Separate Lines with F_{inst} = 205.5 ± 11.7 mÅ.

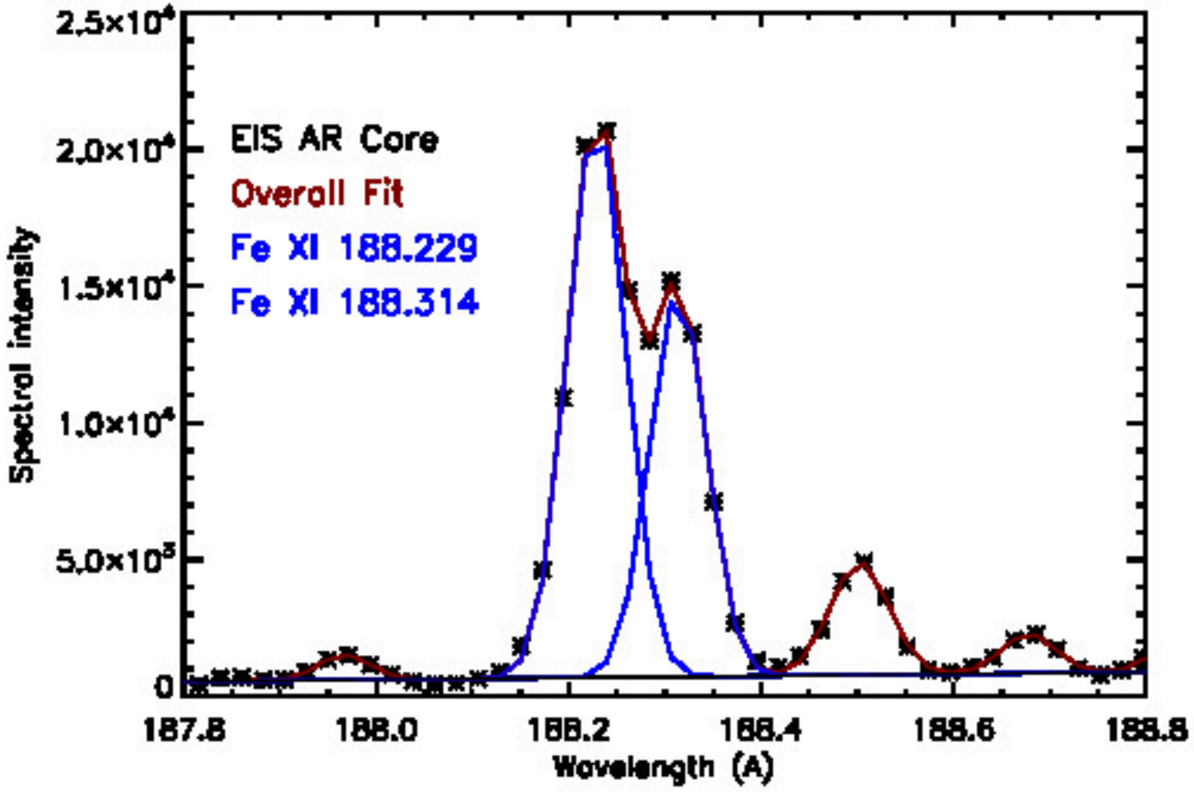
Here, T_{max} is temperature of max ionization fraction, and F_{inst} is based on only He I 584.3 in lab.
Range of measured values is V_{nonth} = 44.7 ± 5.7 km/s; average ± 1σ = 44.6 ± 3.8 km/s.

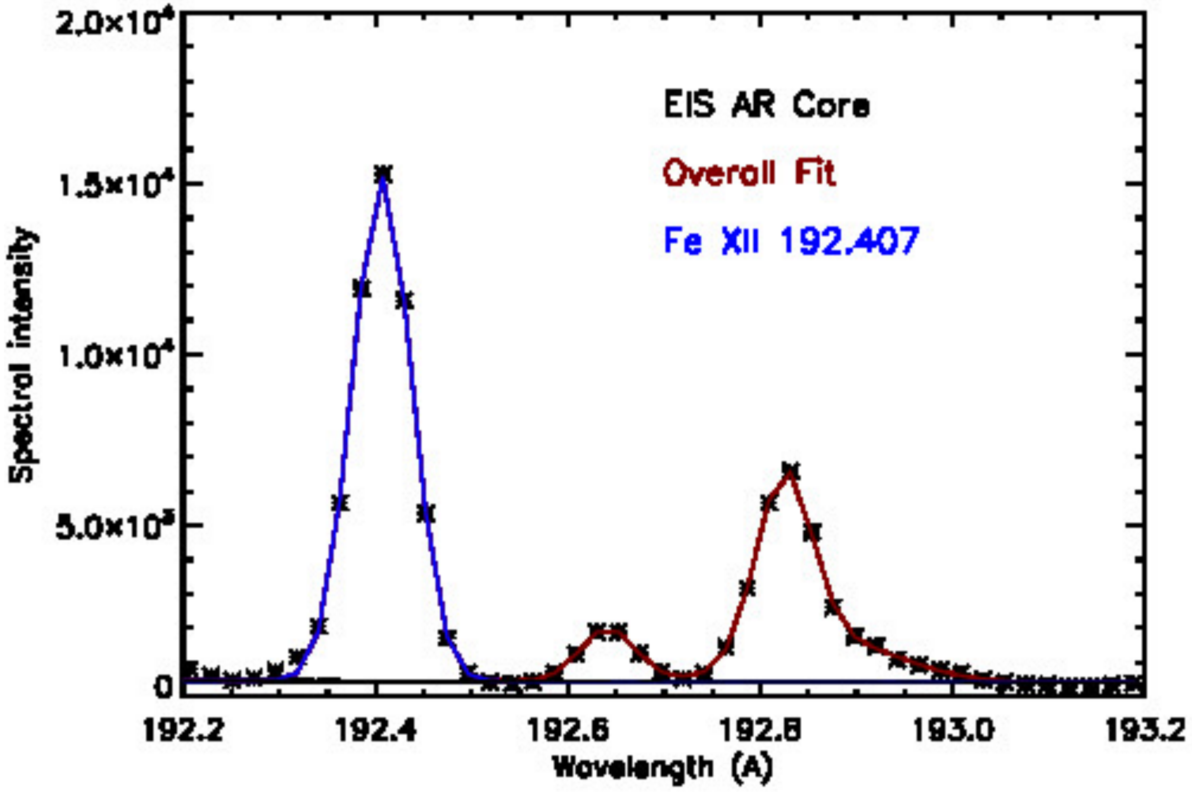
Line	Log (T_{max})	$FWHM_{therm}$ (mÅ)	$FWHM_{obs}$ (mÅ)	V_{nonth} (km/s)
He I 537.1	4.3	27.16	256.0 +/- 12.8	50.4 +/- 9.1
O III 599.6	4.9	30.26	248.9 +/- 13.0	41.2 +/- 8.8
O V 629.7	5.35	53.35	263.4 +/- 9.7	44.6 +/- 6.4
Ca X 557.7	5.9	56.23	251.2 +/- 5.1	43.0 +/- 6.6
Mg X 609.8	6.05	93.84	274.5 +/- 6.7	46.0 +/- 5.7
Mg X 624.9	6.05	96.16	281.9 +/- 7.0	48.2 +/- 5.4
Si XI 580.9	6.21	99.98	262.9 +/- 9.1	40.3 +/- 8.1
Si XI 604.2	6.21	104.0	264.9 +/- 9.1	39.0 +/- 7.8
Al XI 550.0	6.2	95.47	271.2 +/- 7.6	48.8 +/- 7.0

EUNIS V_{nonth} in AR Core: 44.7 ± 5.7 km/s Independent of T_{max}

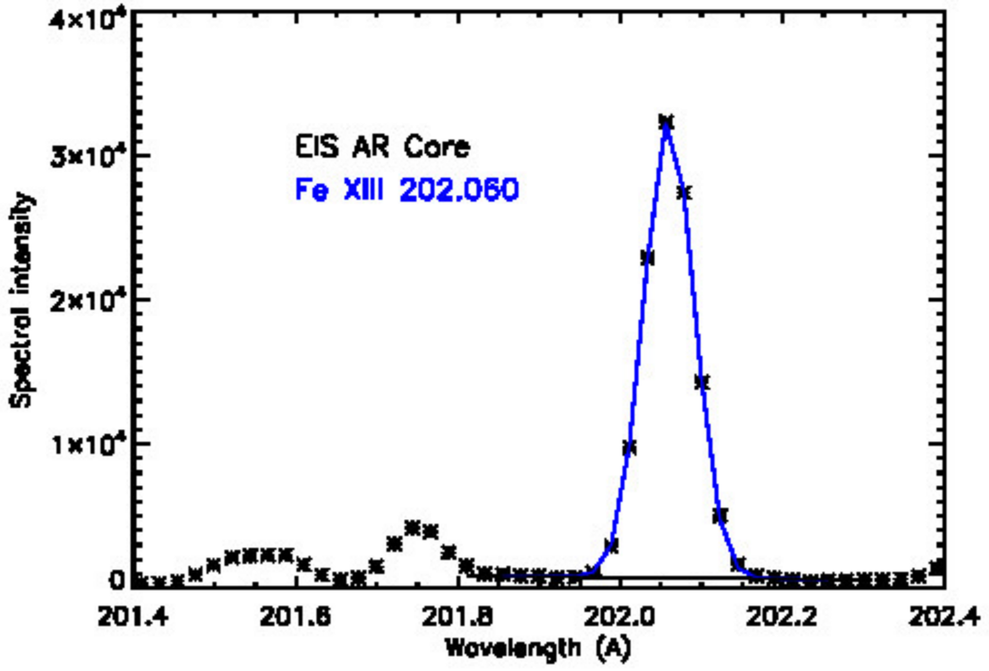


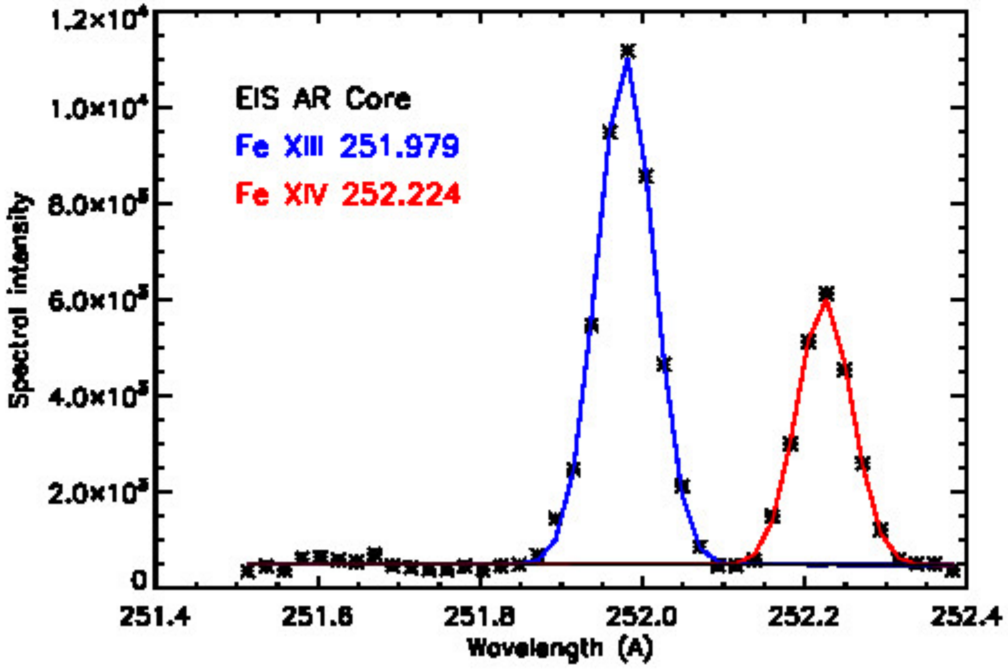
More EIS profiles in Core: Fe XI 188.2, 188.3; Fe XII 192.4



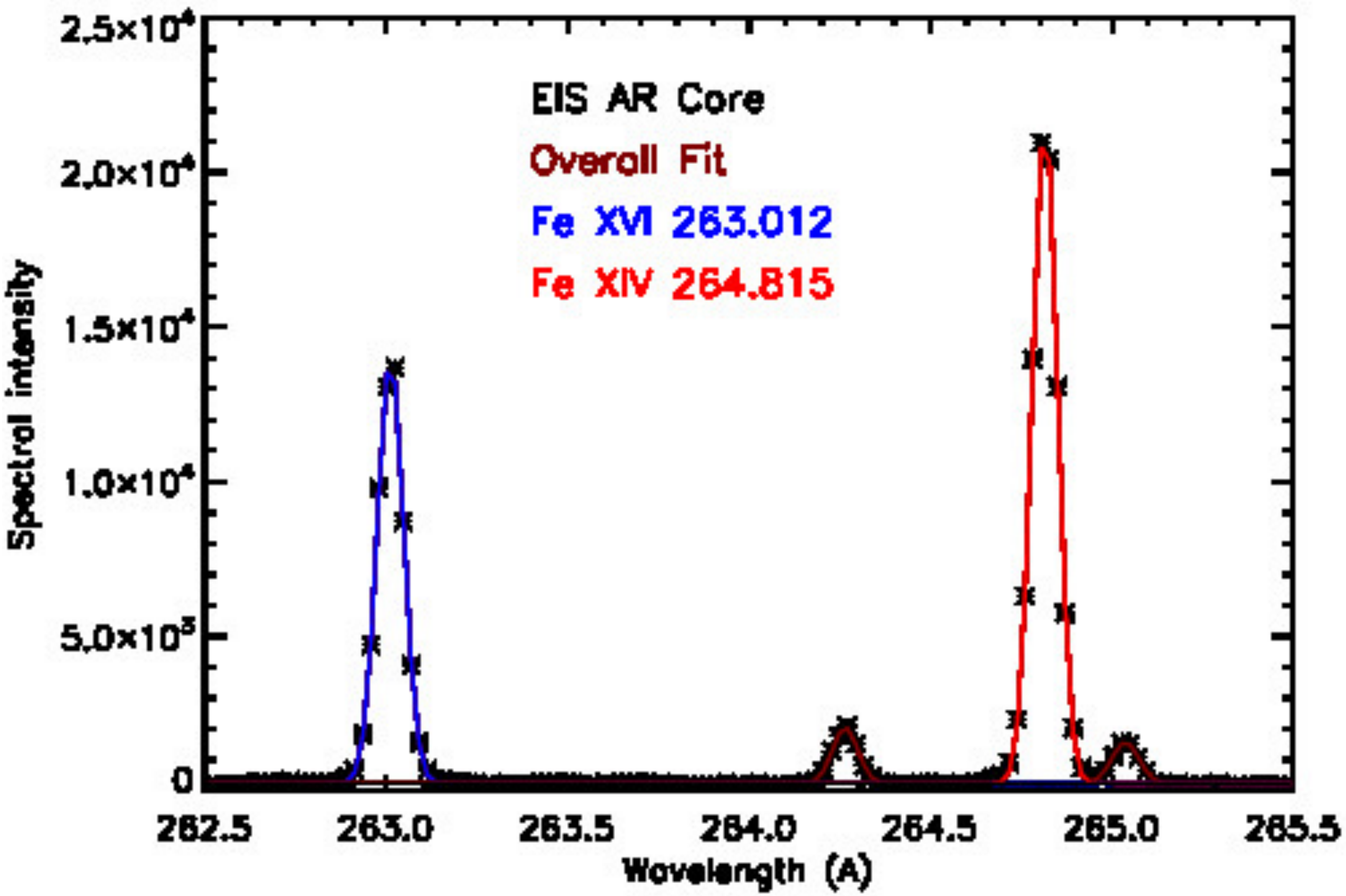


More EIS profiles in Core: Fe XIII 202.0 & Fe XIII 252.0





More EIS profiles in Core: Fe XIV 264.8 with Fe XVI 263.0

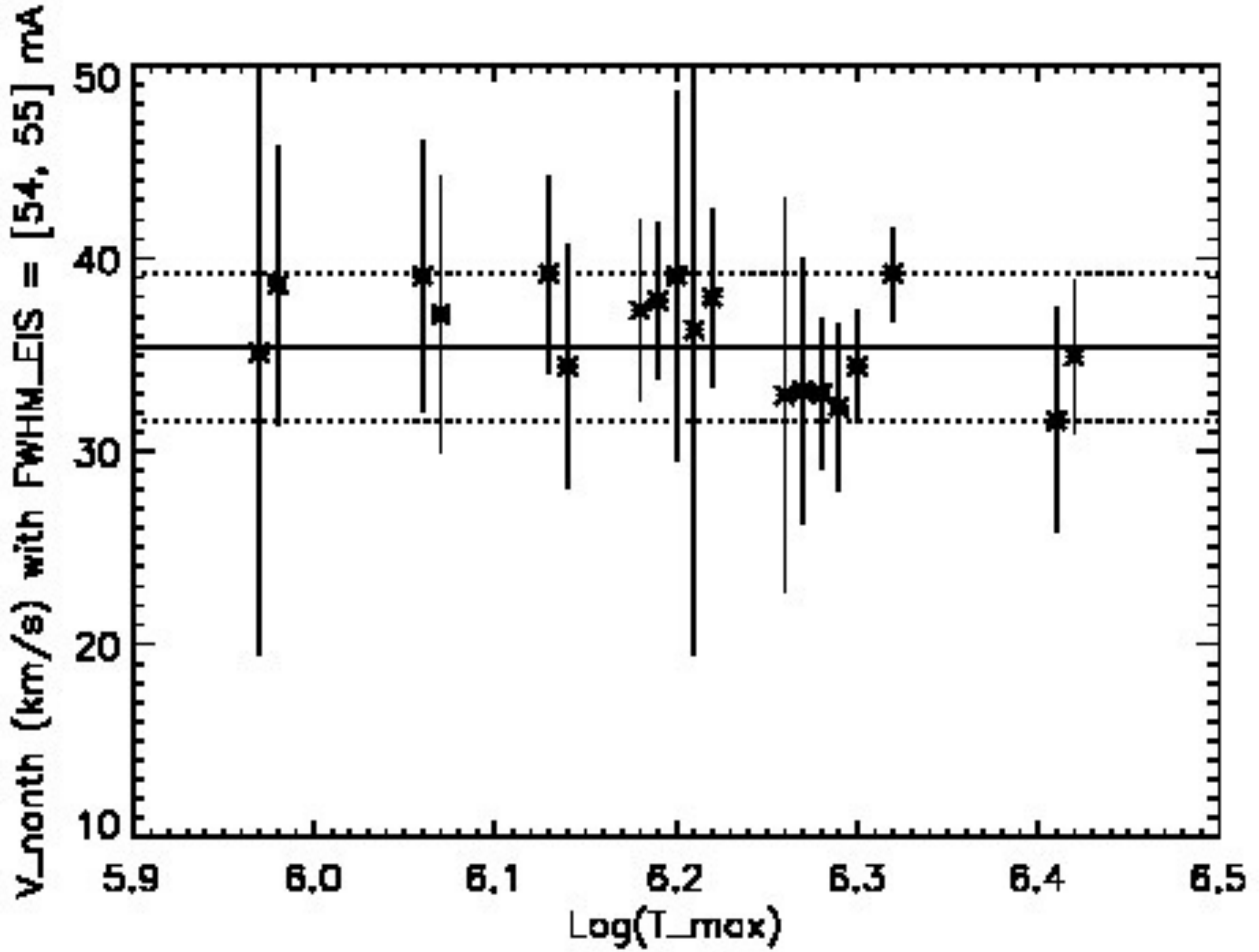


EIS V_{nonth} for Subset of 19 Strong, Separate Lines with F_{inst} = [54, 55] mÅ

Here, T_{max} is temperature of max ionization fraction, and F_{inst} is from Korendyke *et al*. and Brown *et al*.
Range of measured values for all 19 lines is V_{nonth} = 35.4 ± 3.8 km/s; average ± 1σ = 36.0 ± 2.6 km/s.
If use average of fits in individual spatial pixels rather than fits to average core spectrum, get 38.7 ± 6.1, 39.0 ± 4.1.

Line	Log (T_{max})	$FWHM_{therm}$ (mÅ)	$FWHM_{obs}$ (mÅ)	V_{nonth} (km/s)
Fe X 184.5	5.98	17.28	69.15 ± 3.47	38.6 ± 7.2
Fe XI 188.2	6.07	19.55	70.49 ± 3.53	39.1 ± 7.0
Fe XI 188.3	6.07	19.56	69.34 ± 3.43	37.1 ± 7.1
Fe XII 192.4	6.13	21.42	71.62 ± 2.17	39.2 ± 5.1
Fe XIII 202.0	6.20	24.37	72.83 ± 1.35	37.8 ± 4.1
Fe XIII 252.0	6.20	30.41	82.36 ± 3.64	38.0 ± 4.6
Fe XIV 264.8	6.28	35.03	81.31 ± 2.75	33.0 ± 3.9
Fe XV 284.2	6.32	39.37	91.68 ± 1.70	39.2 ± 2.4
Fe XVI 263.0	6.42	40.88	85.42 ± 2.89	34.9 ± 4.0

EIS V_{nonth} in AR Core: 35.4 ± 3.8 km/s Independent of T



V_{nonth} in AR Core With EUNIS and EIS

- Range of EUNIS measurements: 44.7 ± 5.7 km/s.
- Average ± 1-sigma of EUNIS measurements: 44.6 ± 3.8 km/s.
- Range of EIS measurements: 35.4 ± 3.8 km/s.
- Average ± 1-sigma of EIS measurements: 36.0 ± 2.6 km/s.
- Range of EUNIS **and** EIS measurements: 41.0 ± 9.4 km/s.
- Average ± 1-sigma of EUNIS **and** EIS measurements: 38.7 ± 5.0 km/s.
- V_{nonth} is independent of T for $4.3 < \log T < 6.42$.

- If use EIS F_{inst} = 68 ± 3 (Note #7), get range of real values 18.0 ± 12.2 km/s.

EUNIS V_{nonth} for Strong, Separate QS Lines (F_{inst} = 205.5 ± 11.7 mÅ).

Here, T_{max} is temperature of max ionization fraction, and F_{inst} is based on only He I 584.3 in lab.
Range of measured values is V_{nonth} = 45.5 ± 7.1 km/s; average ± 1σ = 42.9 ± 4.8 km/s.

Line	Log (T_{max})	$FWHM_{therm}$ (mÅ)	$FWHM_{obs}$ (mÅ)	V_{nonth} (km/s)
He I 537.1	4.3	27.16	260.0 +/- 12.8	52.6 +/- 8.8
O III 599.6	4.9	30.26	244.0 +/- 13.0	38.4 +/- 9.3
O V 629.7	5.35	53.35	256.0 +/- 9.7	40.9 +/- 6.9
Ca X 557.7	5.9	56.23	250.2 +/- 5.1	42.3 +/- 6.7
Mg X 609.8	6.05	93.84	261.1 +/- 6.7	38.7 +/- 6.7
Mg X 624.9	6.05	96.16	274.7 +/- 7.0	44.6 +/- 5.7
Si XI 580.9	6.21	99.98	-	-
Si XI 604.2	6.21	104.0	-	-
Al XI 550.0	6.2	95.47	-	-

EIS V_{nonth} for Subset of Strong, Separate QS Lines with F_{inst} = [54, 55] mÅ

Here, T_{max} is temperature of max ionization fraction, and F_{inst} is from Korendyke *et al*. and Brown *et al*.
Range of measured values for 5 useful lines is V_{nonth} = 41.6 ± 4.2 km/s; average ± 1σ = 40.9 ± 3.2 km/s.

Line	Log (T_{max})	$FWHM_{therm}$ (mÅ)	$FWHM_{obs}$ (mÅ)	V_{nonth} (km/s)
Fe X 184.5	5.98	17.28	70.38 ± 3.47	40.7 ± 6.9
Fe XI 188.2	6.07	19.55	74.77 ± 3.53	45.8 ± 6.2
Fe XI 188.3	6.07	19.56	69.49 ± 3.43	37.4 ± 7.1
Fe XII 192.4	6.13	21.42	74.09 ± 2.17	43.0 ± 4.7
Fe XIII 202.0	6.20	24.37	72.80 ± 1.35	37.7 ± 4.1
Fe XIII 252.0	6.20	30.41	-	-
Fe XIV 264.8	6.28	35.03	-	-
Fe XV 284.2	6.32	39.37	-	-
Fe XVI 263.0	6.42	40.88	-	-

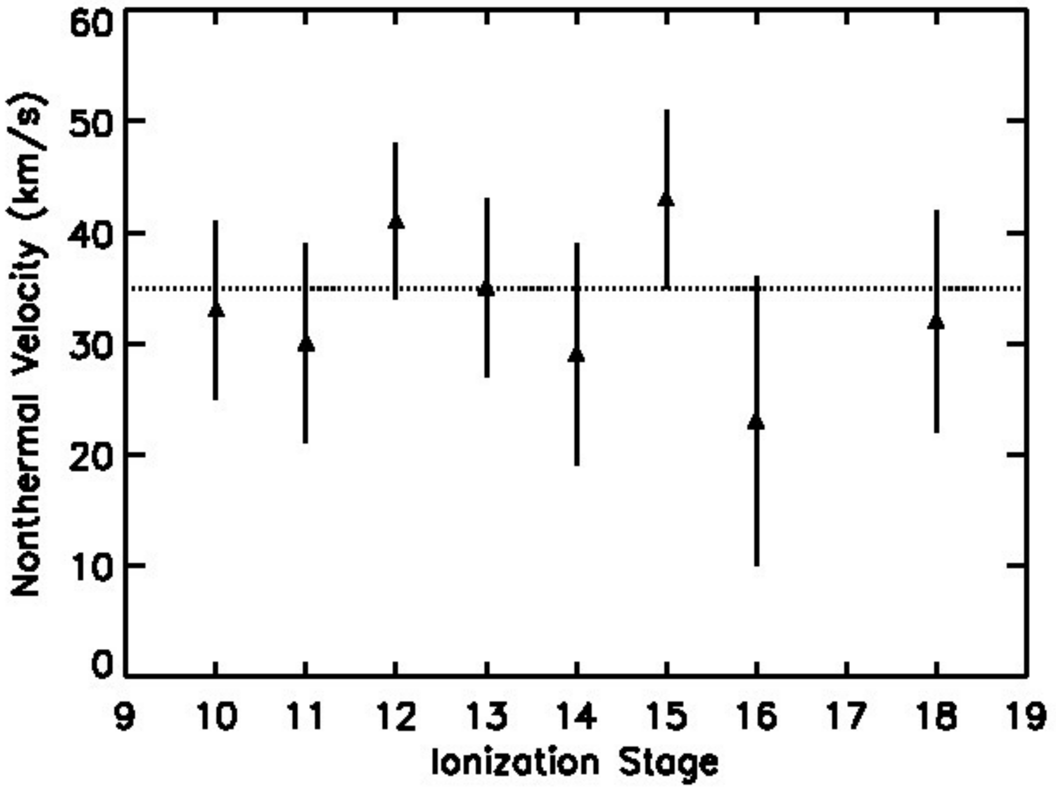
V_{nonth} in QS With EUNIS and EIS

- Range of EUNIS measurements: 45.5 ± 7.1 km/s.
- Average ± 1-sigma of EUNIS measurements: 42.9 ± 4.8 km/s.
- Range of EIS measurements: 41.6 ± 4.2 km/s.
- Average ± 1-sigma of EIS measurements: 40.9 ± 3.2 km/s.
- Range of EUNIS **and** EIS measurements: 45.0 ± 7.6 km/s.
- Average ± 1-sigma of EUNIS **and** EIS measurements: 42.0 ± 4.3 km/s.
- V_{nonth} is independent of T for $4.3 < \log T < 6.2$.

Comparison With Other Measurements

Nonthermal AR Velocities from SERTS-97

F_{inst} = 115.0 ± 1.4 mÅ; all values consistent with 35 km/s (Brosius et al 2000).



Nonthermal AR Velocities from *Hinode*/EIS, *SoHO*/SUMER, HRTS, *SMM*/XRP

- Saba & Strong (1991; XRP AR): V_{nonth} = 42 ± 30, 58 ± 4, 44 ± 4 km/s for O VIII, Ne IX, Mg XI.
- Doyle *et al*. (1997; HRTS QS limb): V_{nonth} = 27 km/s for Fe XII.
- Chae *et al*. (1998; SUMER QS): V_{nonth} = 23 ± 5, 16 ± 7 for Mg X, Fe XII.
- Landi *et al*. (2003; SUMER, above AR at 1.06-1.20 R_{solar}): V_{nonth} = 20-35 km/s independent of T or height for T = 2.6-6.6 MK.
- Brooks & Warren (2016; EIS): V_{nonth} = 17.6 ± 5.3 km/s for 16 loops in 15 ARs for 1.1-3.6 MK; use Young (2011) for F_{inst} . No trend with T or B flux.

Summary and Conclusions

- Lab measurements of F_{inst} are challenging & uncertain, but essential.
- For the EUNIS LW channel we adopt F_{inst} = 205.5 ± 11.7 mÅ; for the EIS SW channel we adopt F_{inst} = 54.0 ± 3.1 mÅ; for the EIS LW channel we adopt F_{inst} = 55.0 ± 3.1 mÅ.
- In AR core, EUNIS & EIS yield V_{nonth} = 41.0 ± 9.4 km/s independent of T for 4.3 < log T < 6.4.
- In QS, EUNIS & EIS yield V_{nonth} = 45.0 ± 7.6 km/s independent of T for 4.3 < log T < 6.2.
- Can these measurements constrain coronal heating mechanisms and/or other processes that occur in solar atmosphere?