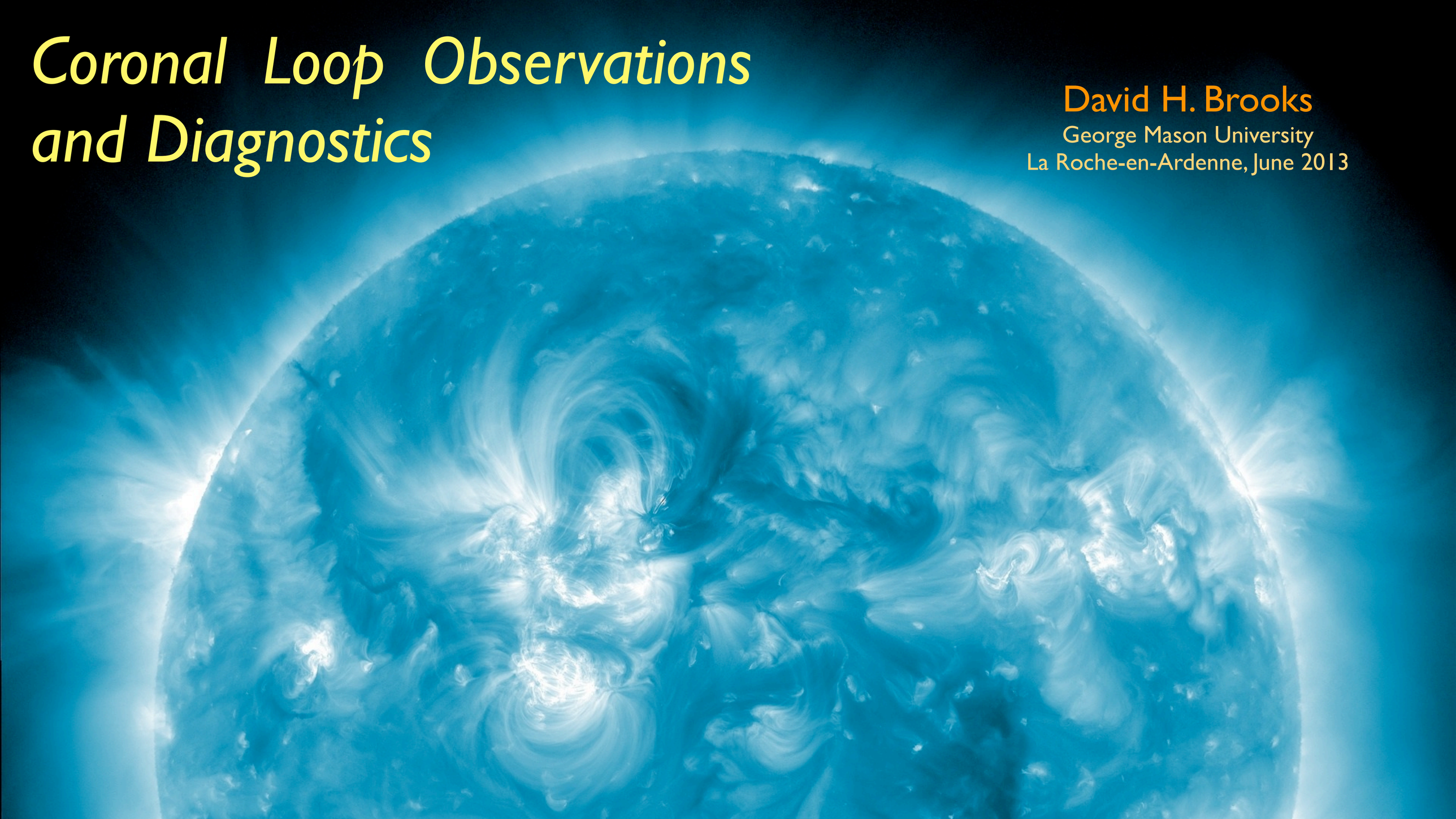
Coronal Loop Observations and Diagnostics

David H. Brooks
George Mason University
La Roche-en-Ardenne, June 2013



Overview

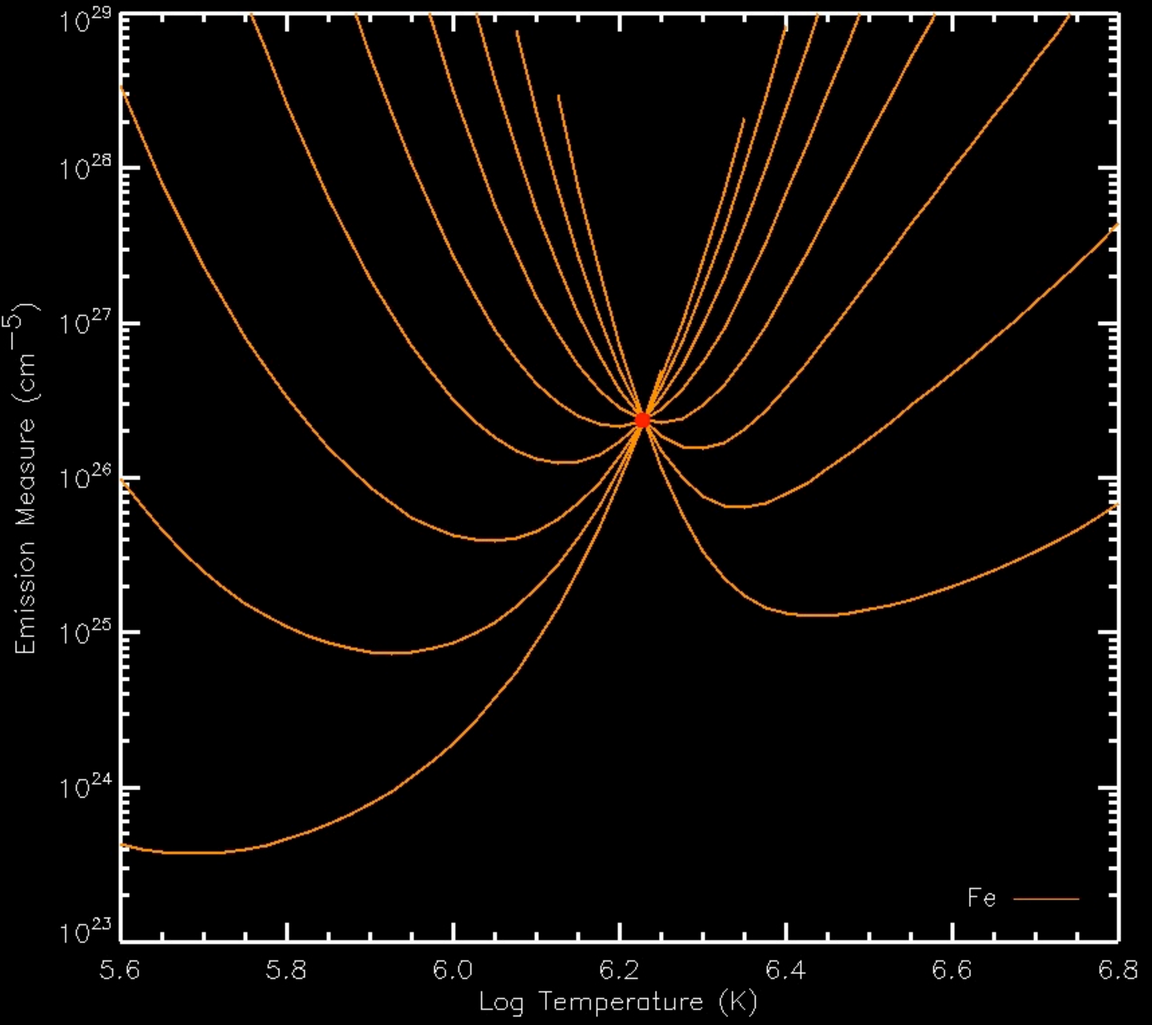
- Differential Emission Measure (DEM)
  - Loops 1: Are coronal loops isothermal or multi-thermal?
  - Why couldn't we decide?
  - Recent developments (Hinode, STEREO, SDO, Hi-C)
  - Can we successfully reach agreement now?

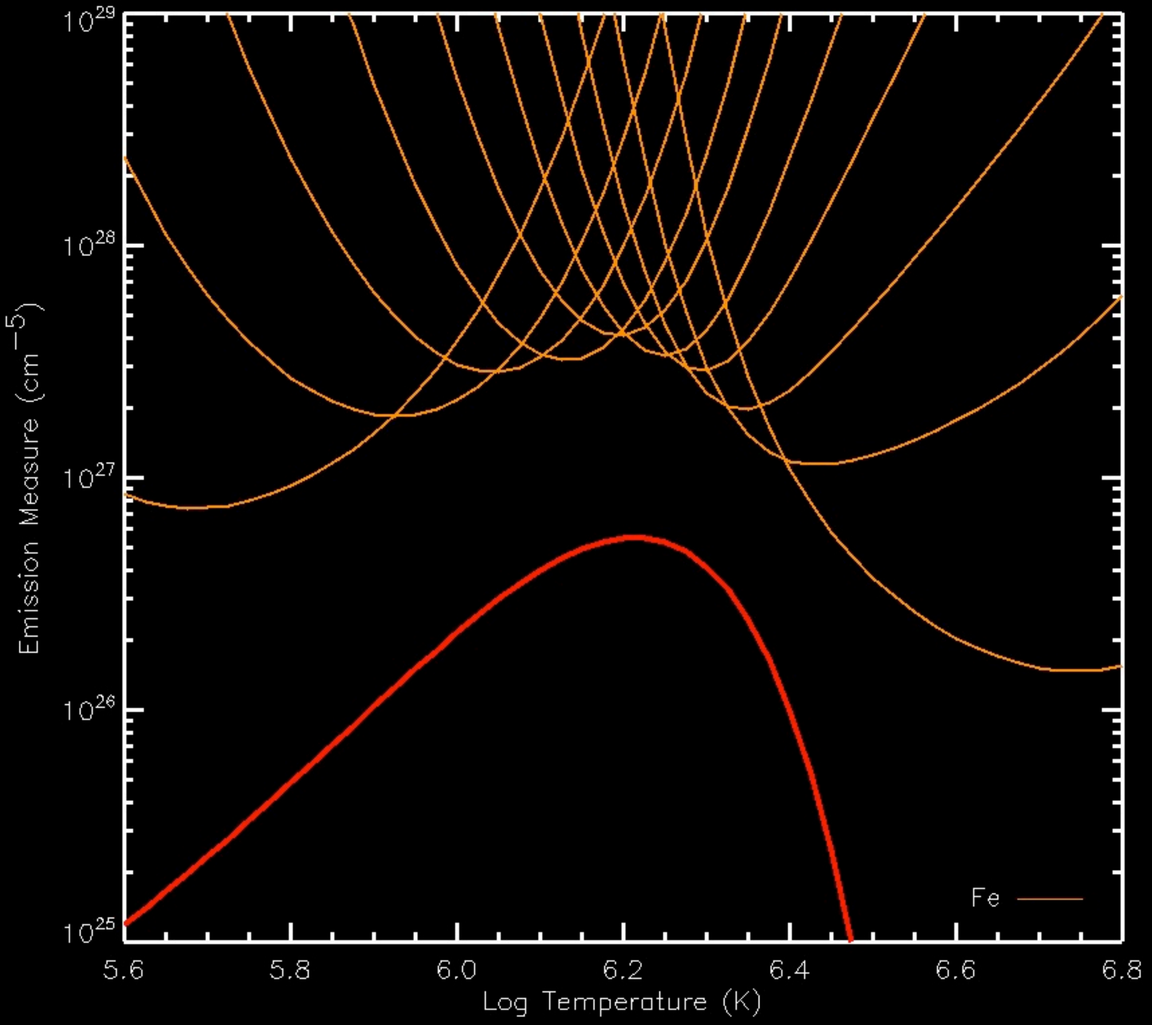
- Filling Factors
  - Loops 1: Are coronal loops monolithic or filamented structures?
  - What are the filling factors of loops? Is the filling factor a useful quantity to know?
  - Other diagnostics of sub-structure?

- Elemental Abundances
  - Why are they important? What can they tell us?
  - Recent results.

Isothermal?

Multi-thermal?

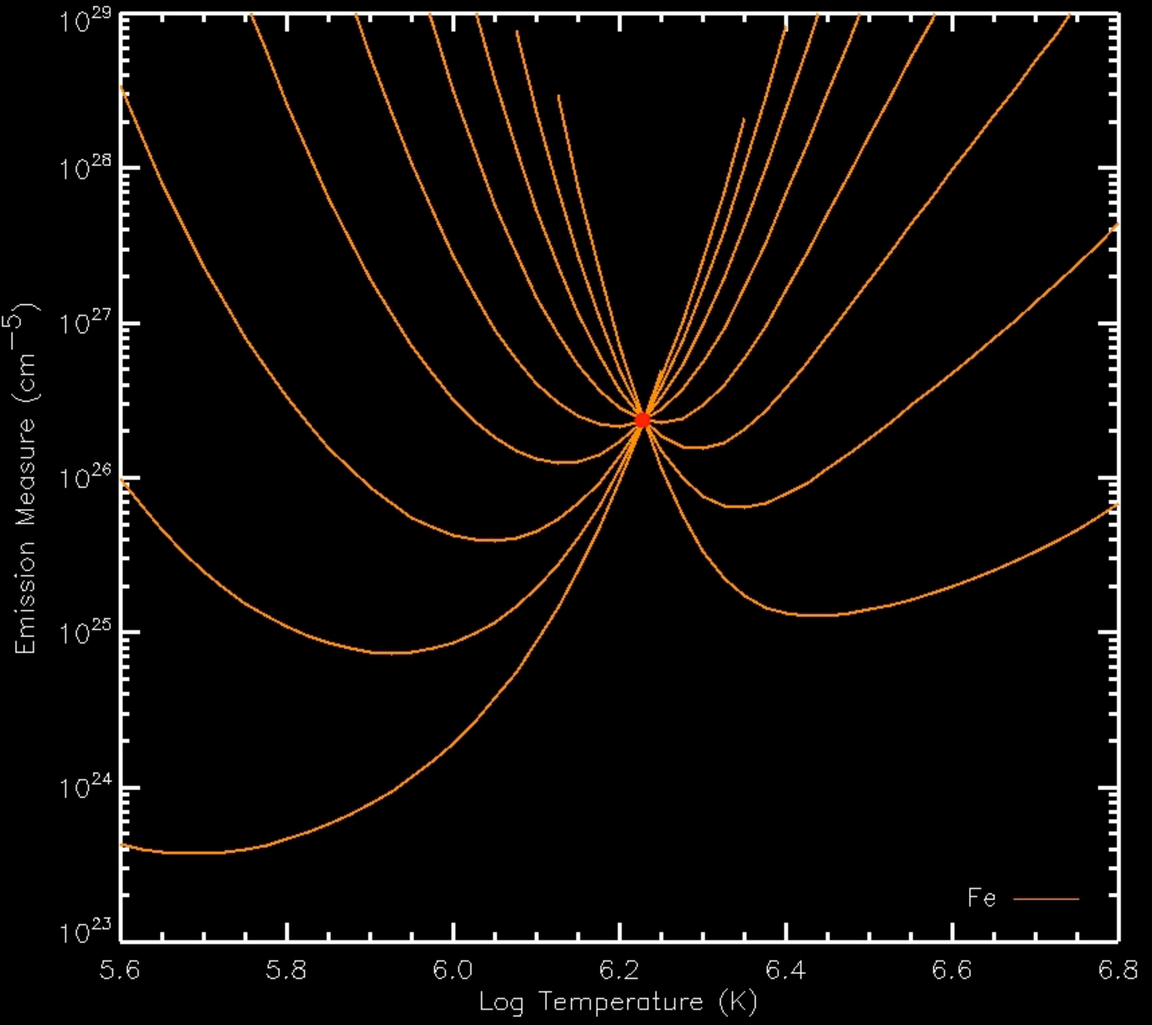


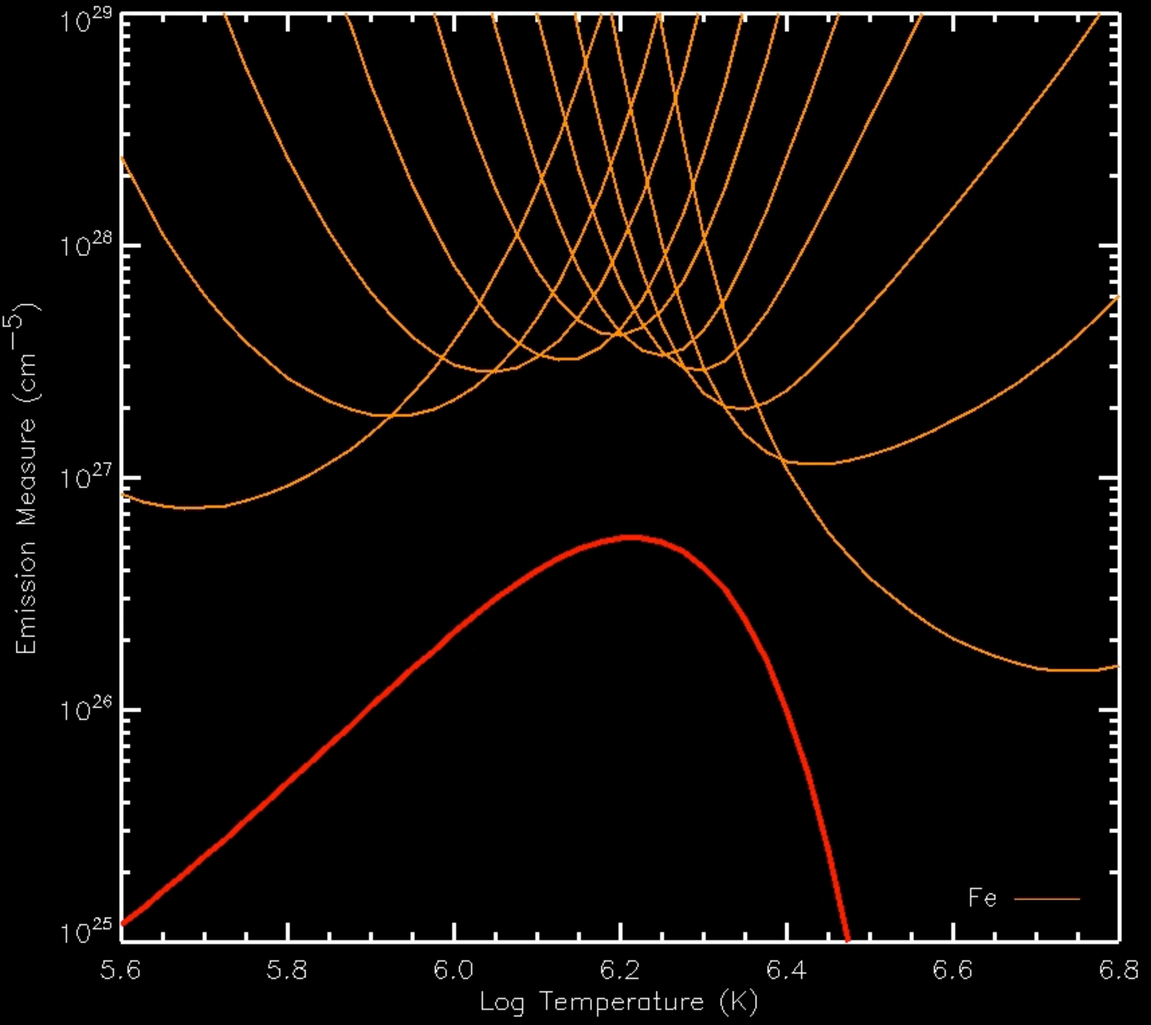


Lenz et al (1999), Chae et al (2002), Martens et al (2002), Testa et al (2002), Del Zanna (2003), Del Zanna & Mason (2003), Warren et al (2008), Tripathi et al (2009)

Isothermal?

Multi-thermal?



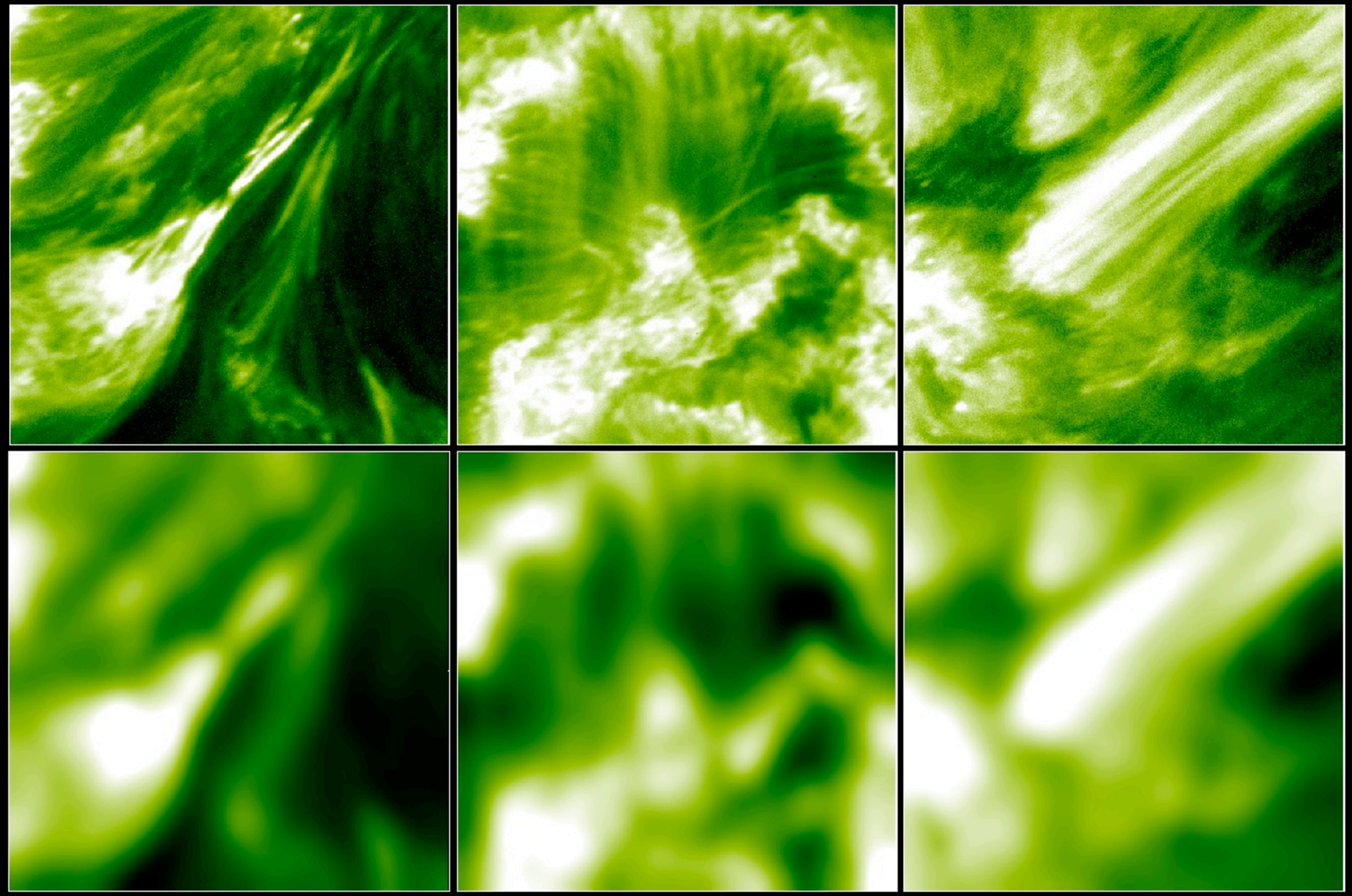


Aschwanden et al (1999, 2000, 2001, 2002, 2005, 2007, 2008, 2011, 2013)
Schmelz et al (2001, 2002, 2003, 2005, 2006, 2007, 2008, 2009, 2010, 2011, 2013)

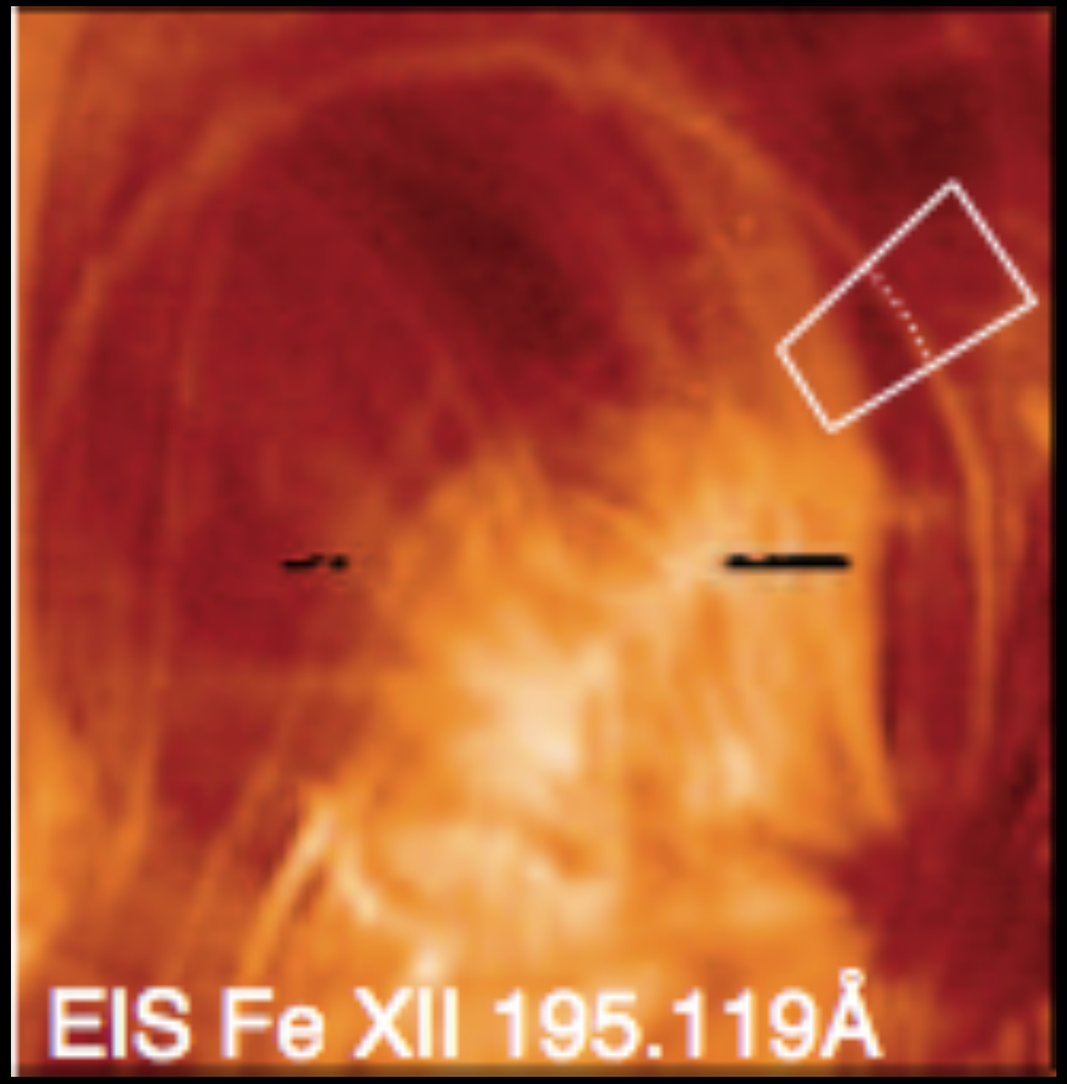
Spectrometer Problem: Spatial Resolution

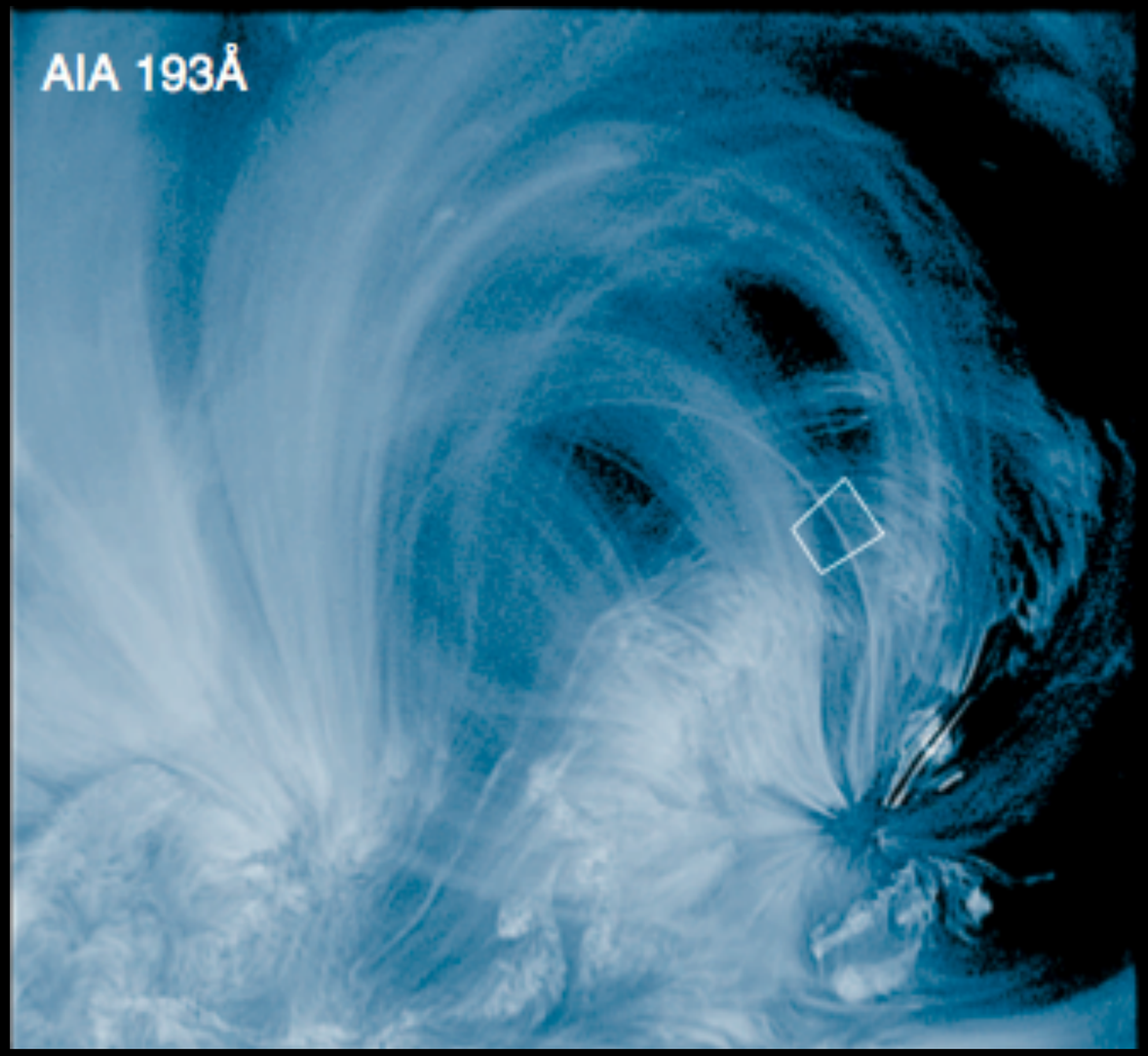
Hi-C

Hi-C convolved with PSF for SOHO/CDS

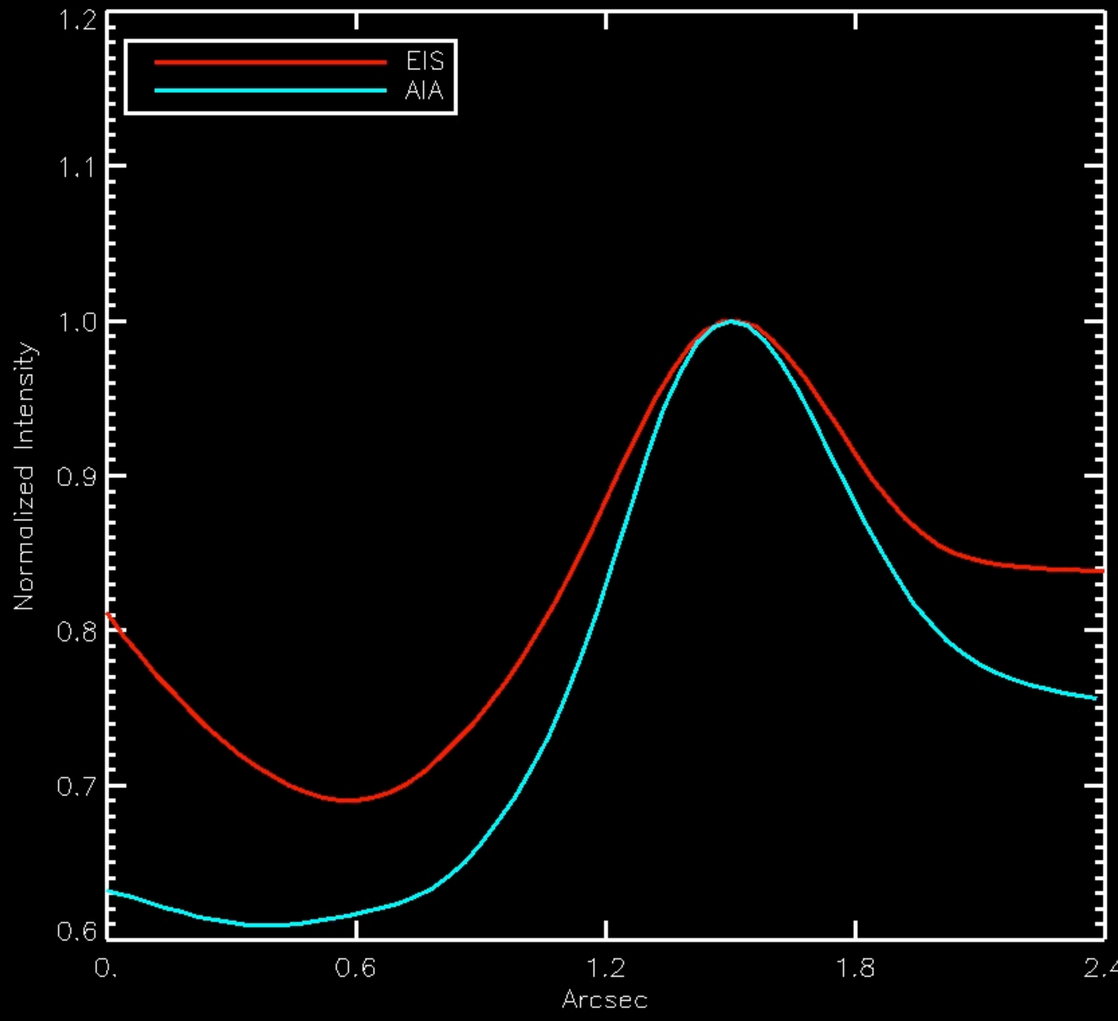


Hinode/EIS v SDO/AIA

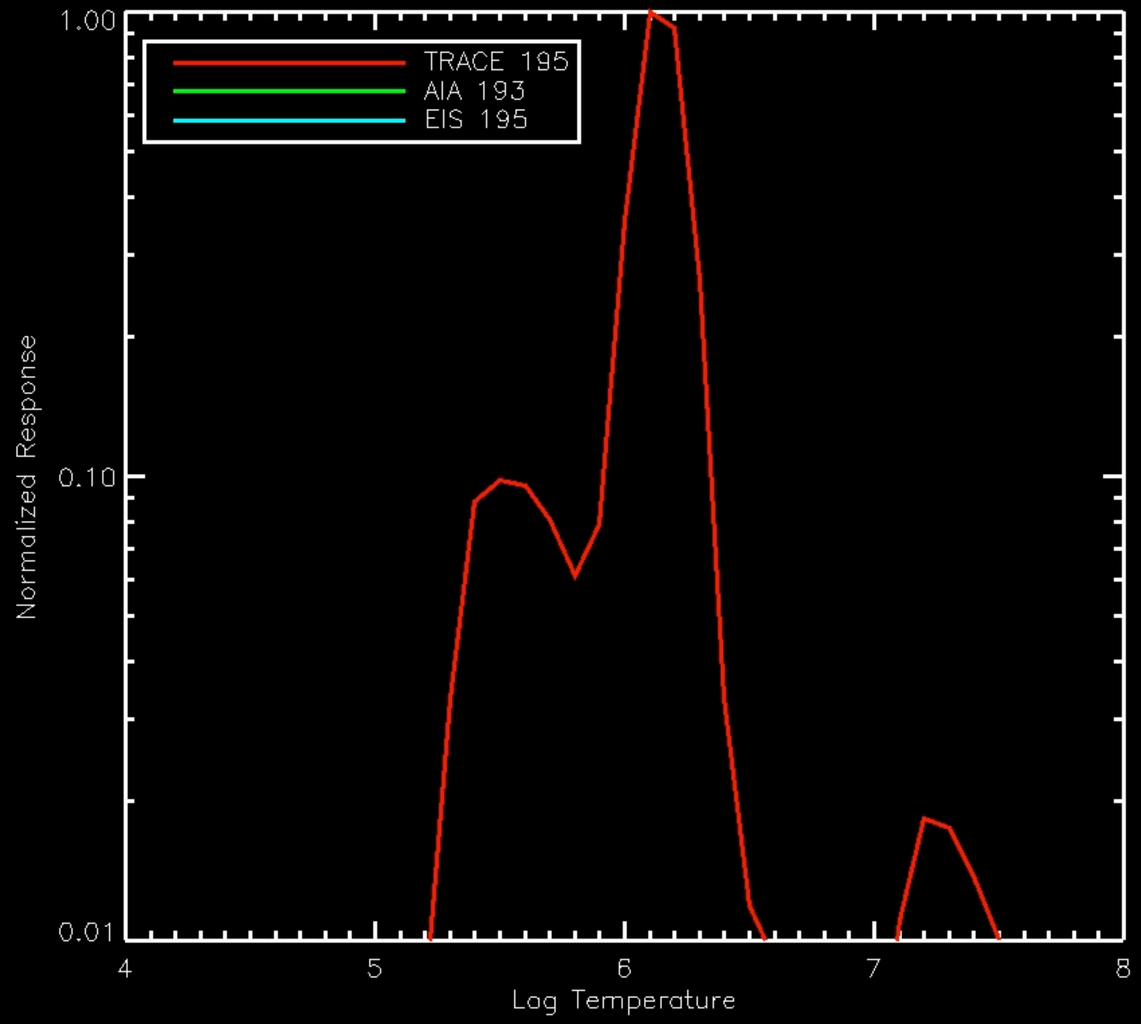


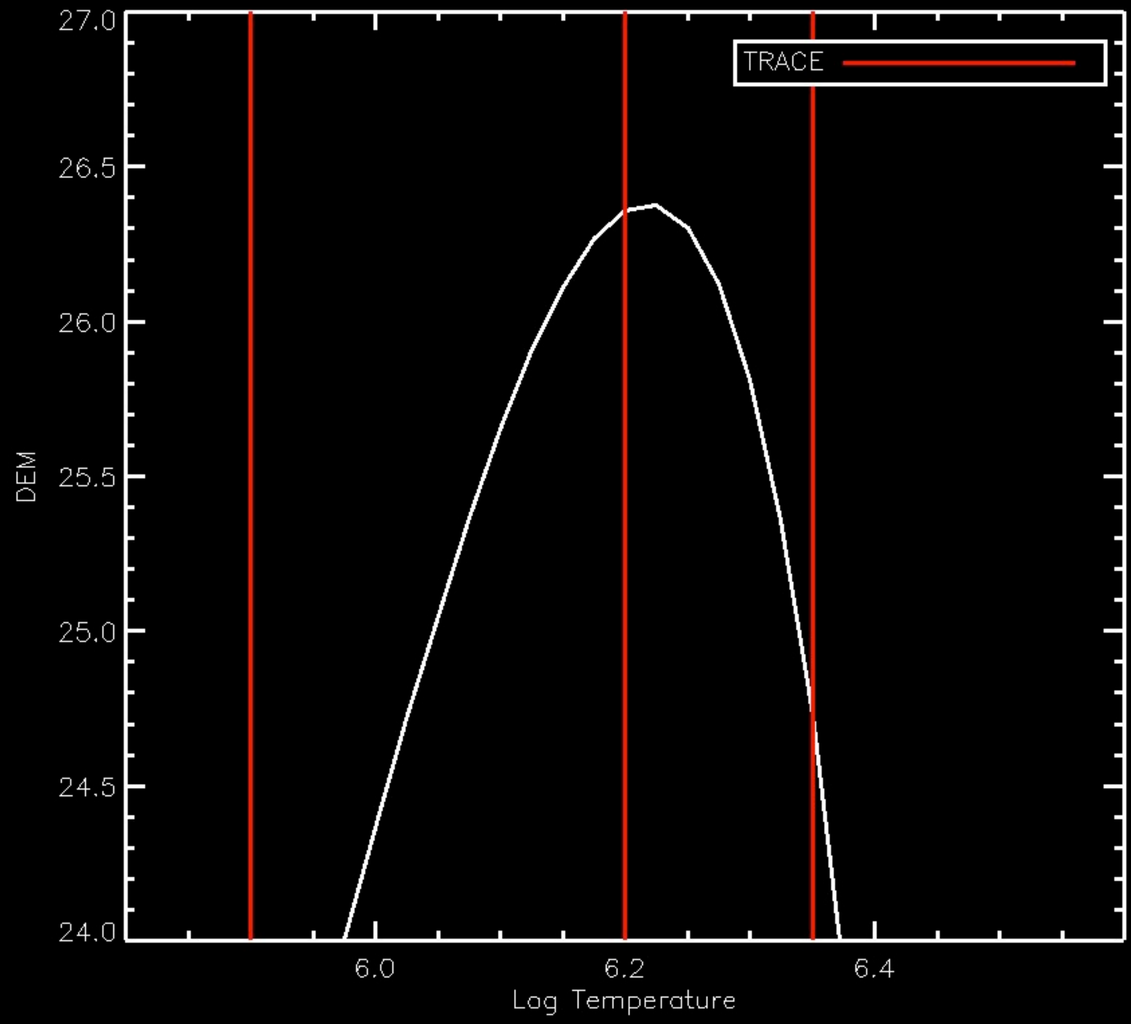


Hinode/EIS v SDO/AIA



Imager Problem: Temperature Resolution





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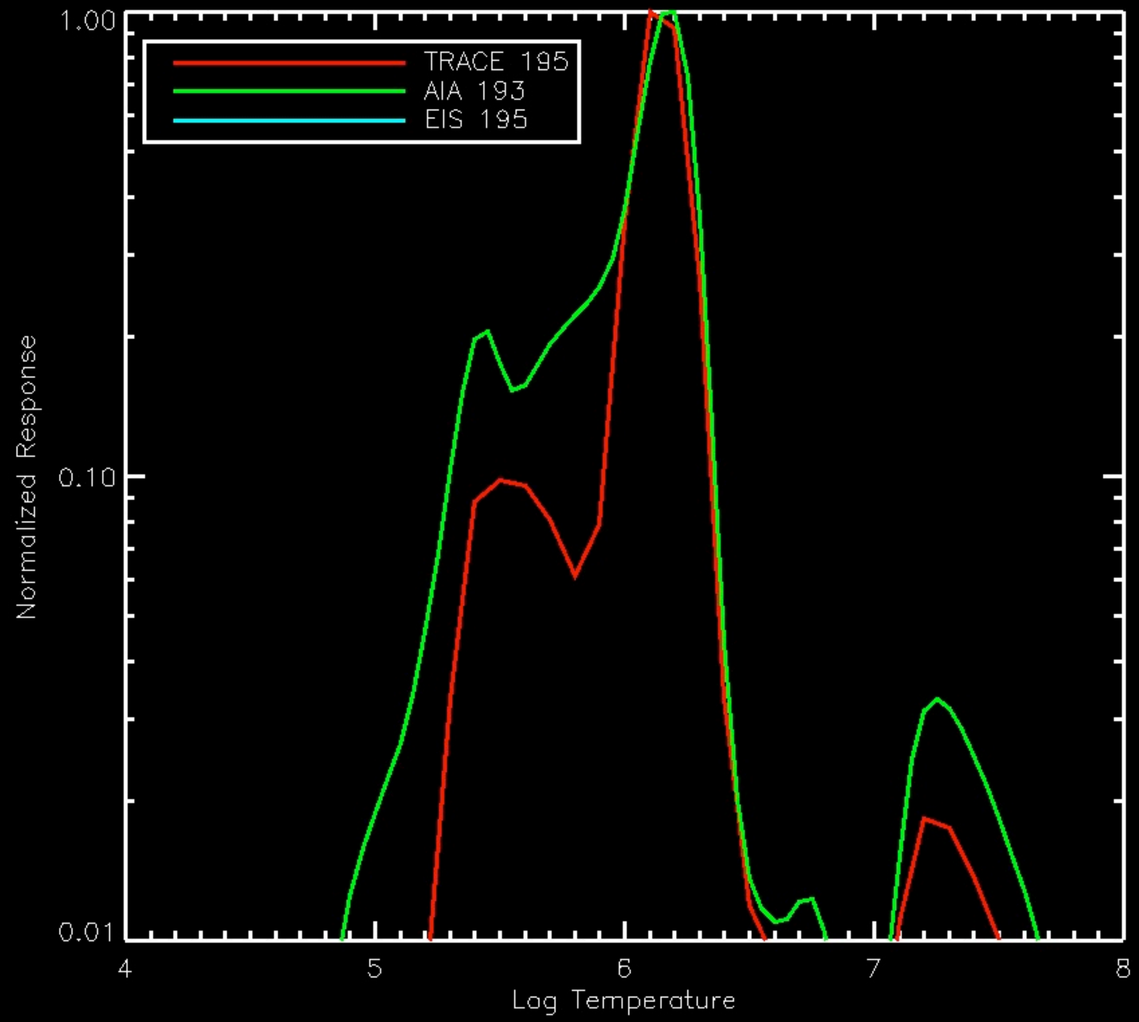
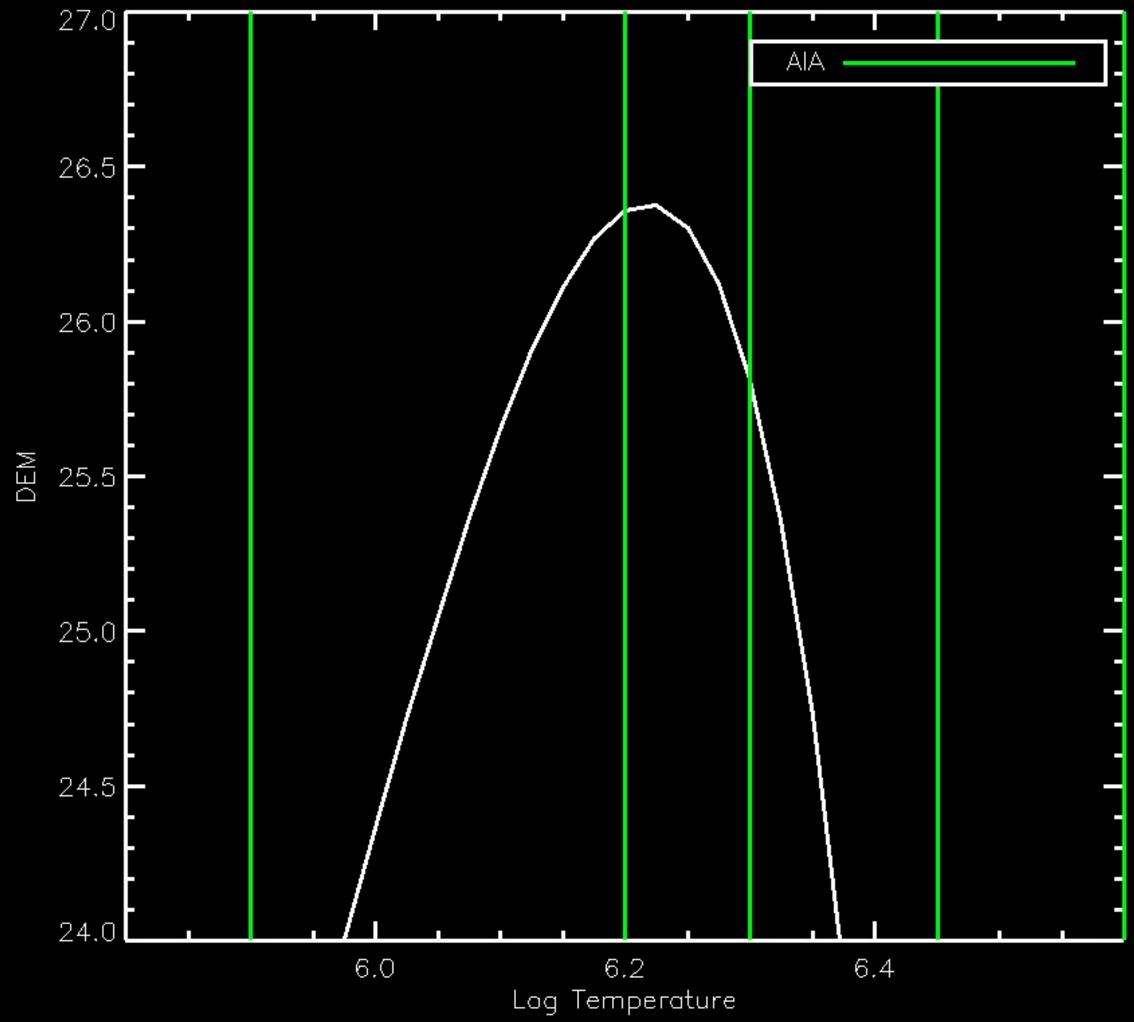
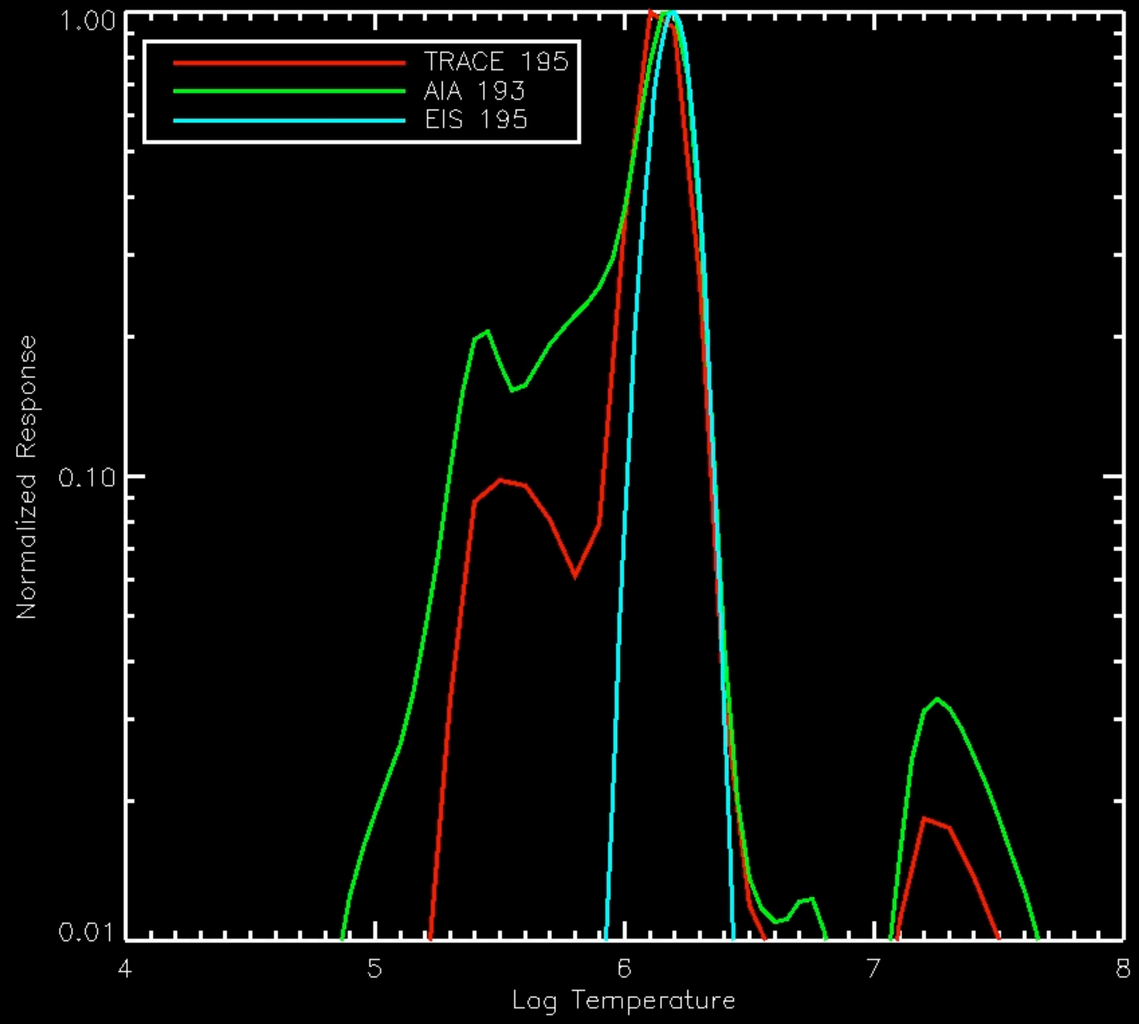
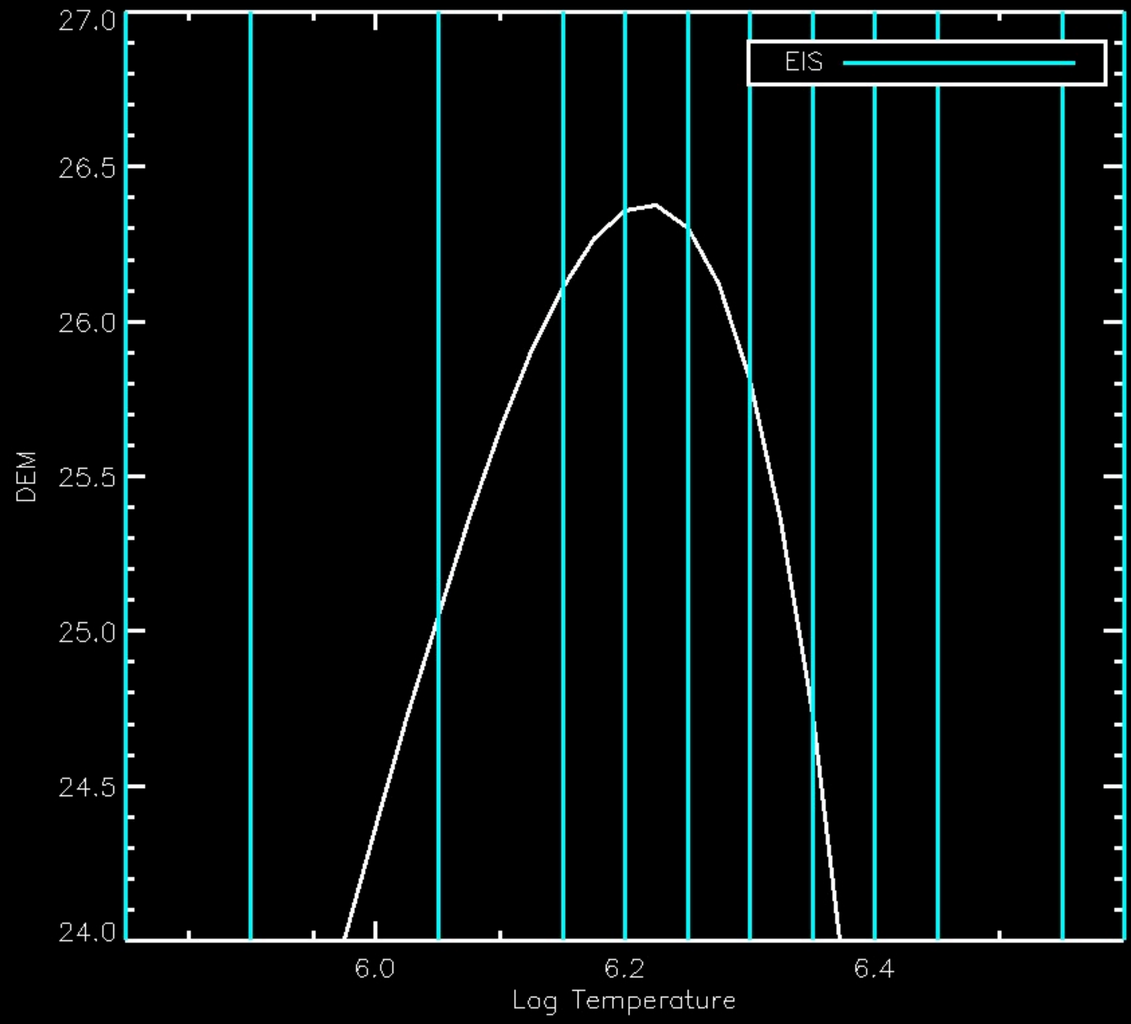


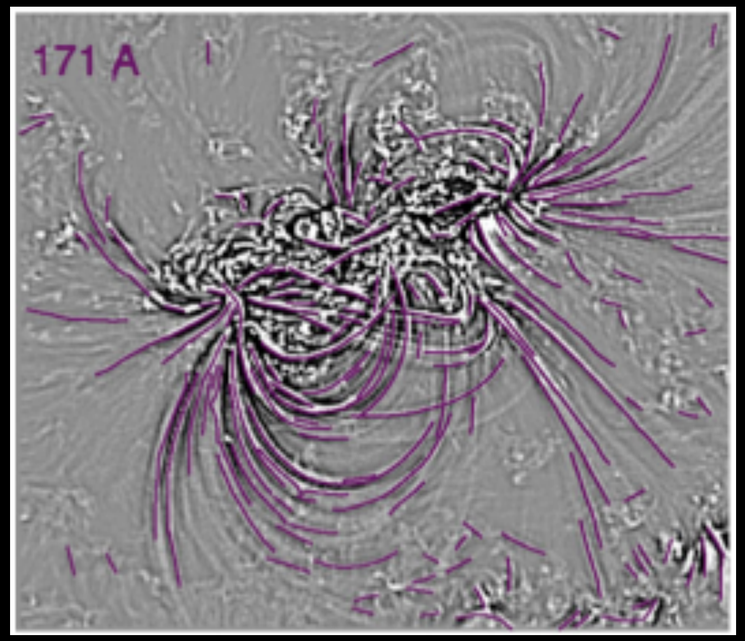


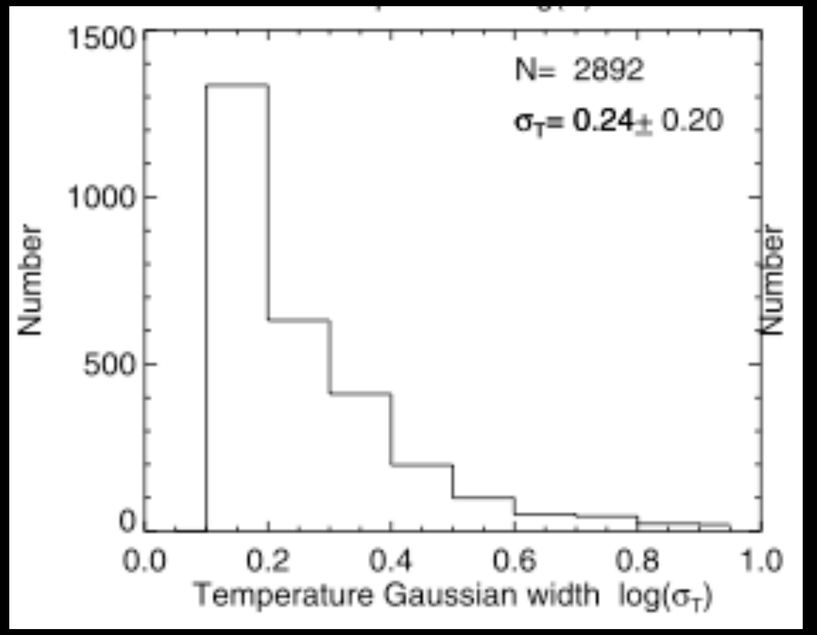
Imager Problem: Temperature Resolution



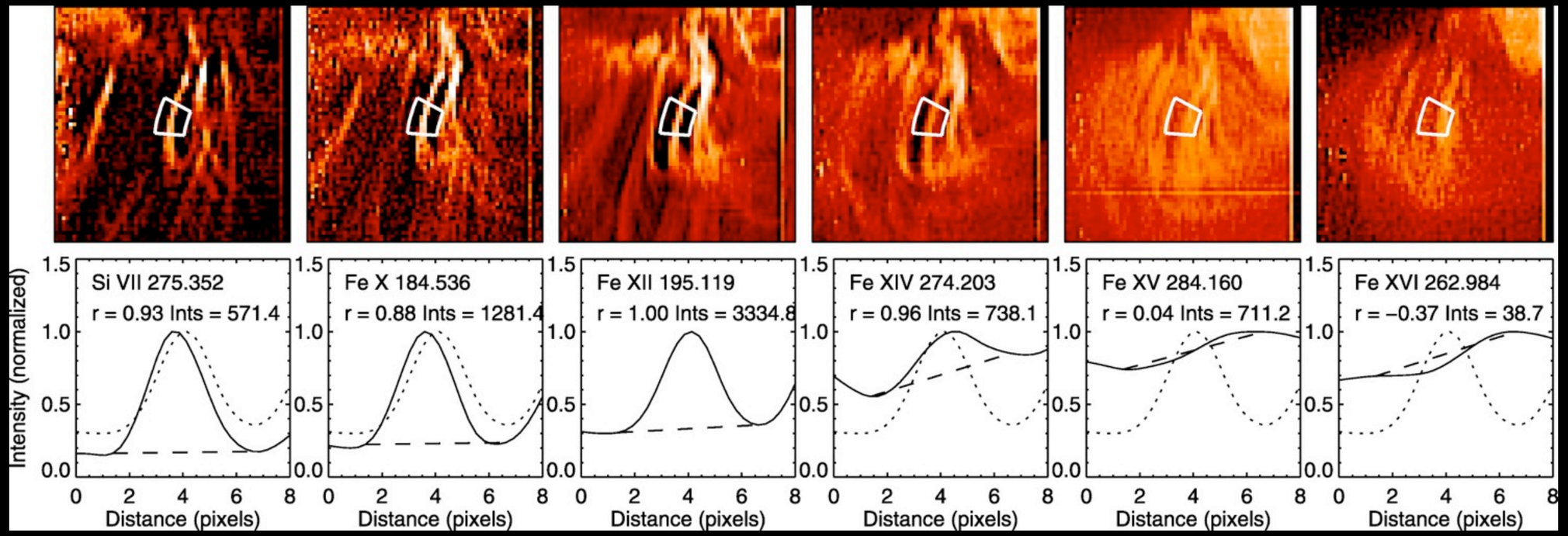


Aschwanden et al (2013):
"We detect 570 loop segments... and corroborate previous TRACE and AIA results on their near isothermality..."





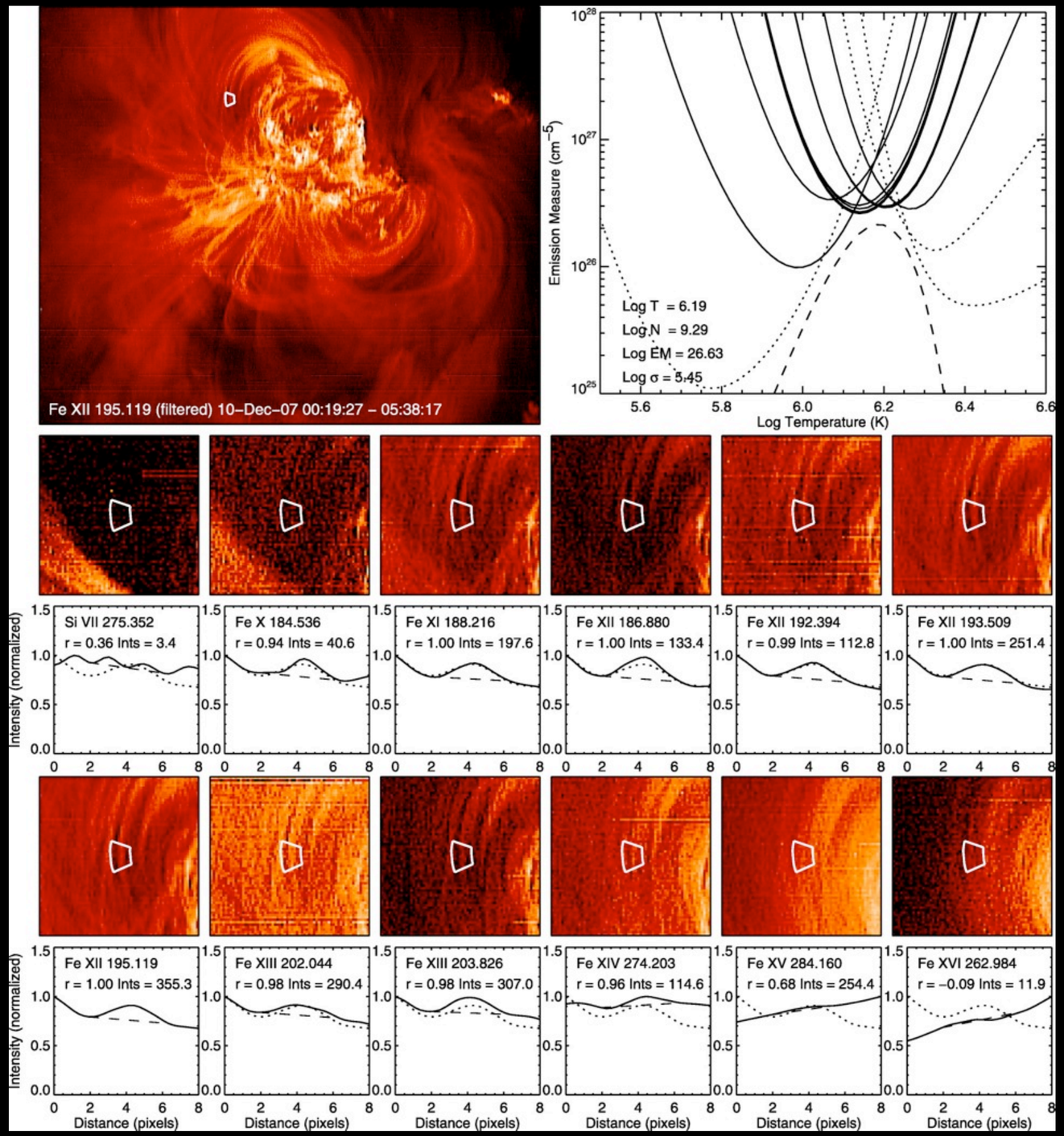
Strong emission
0.6--2.0MK



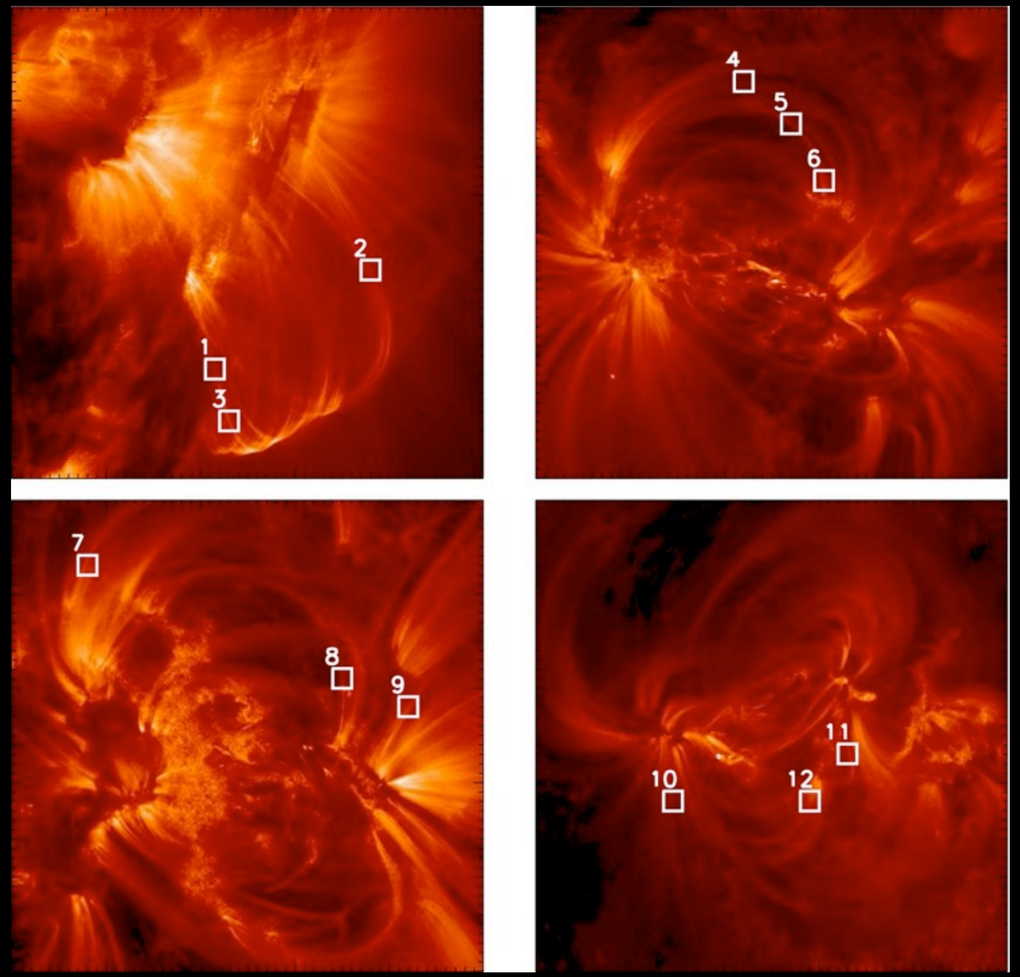
Typical EIS Loop DEM

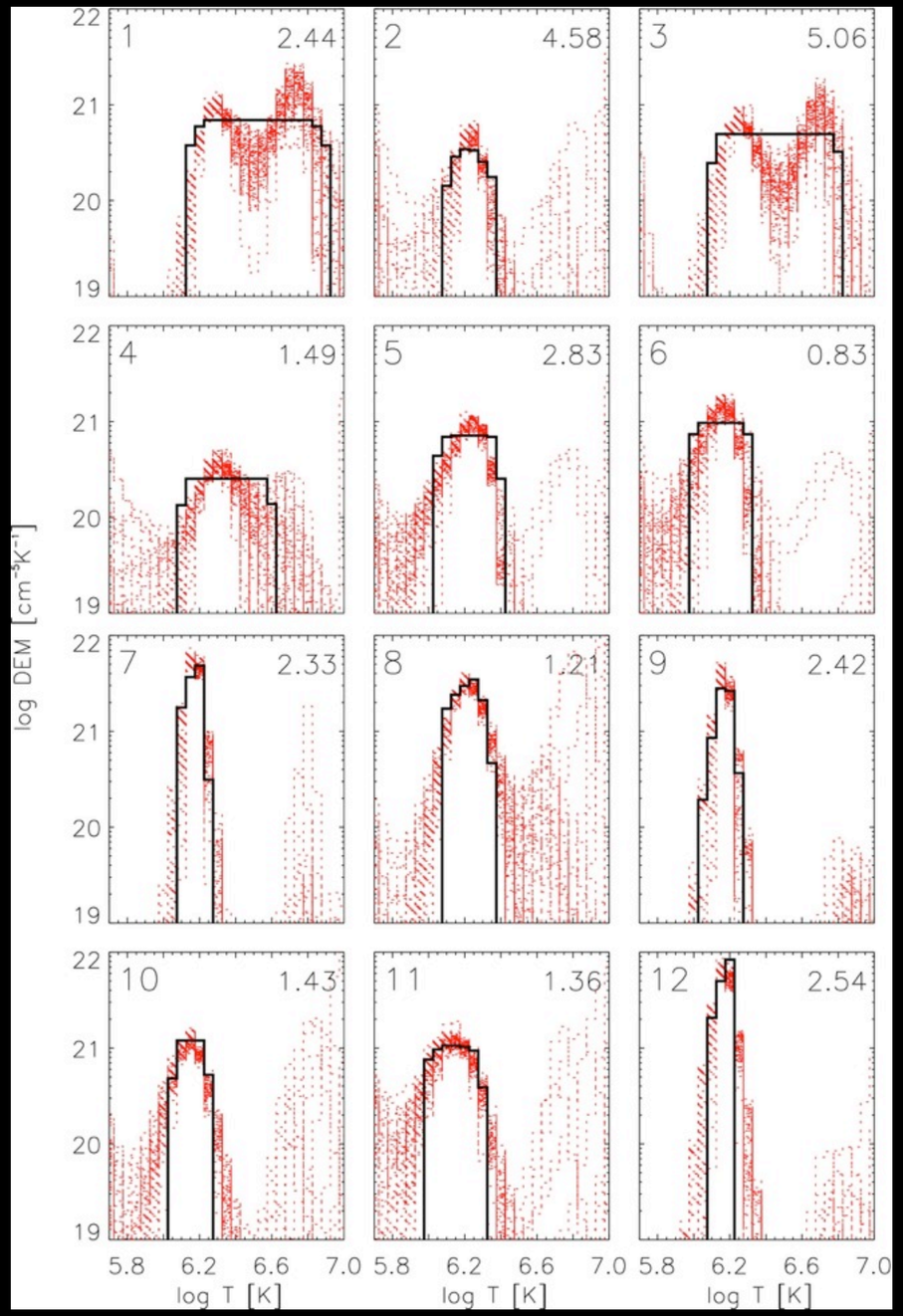
Log Gaussian T width < 5.4

Warren et al (2008)



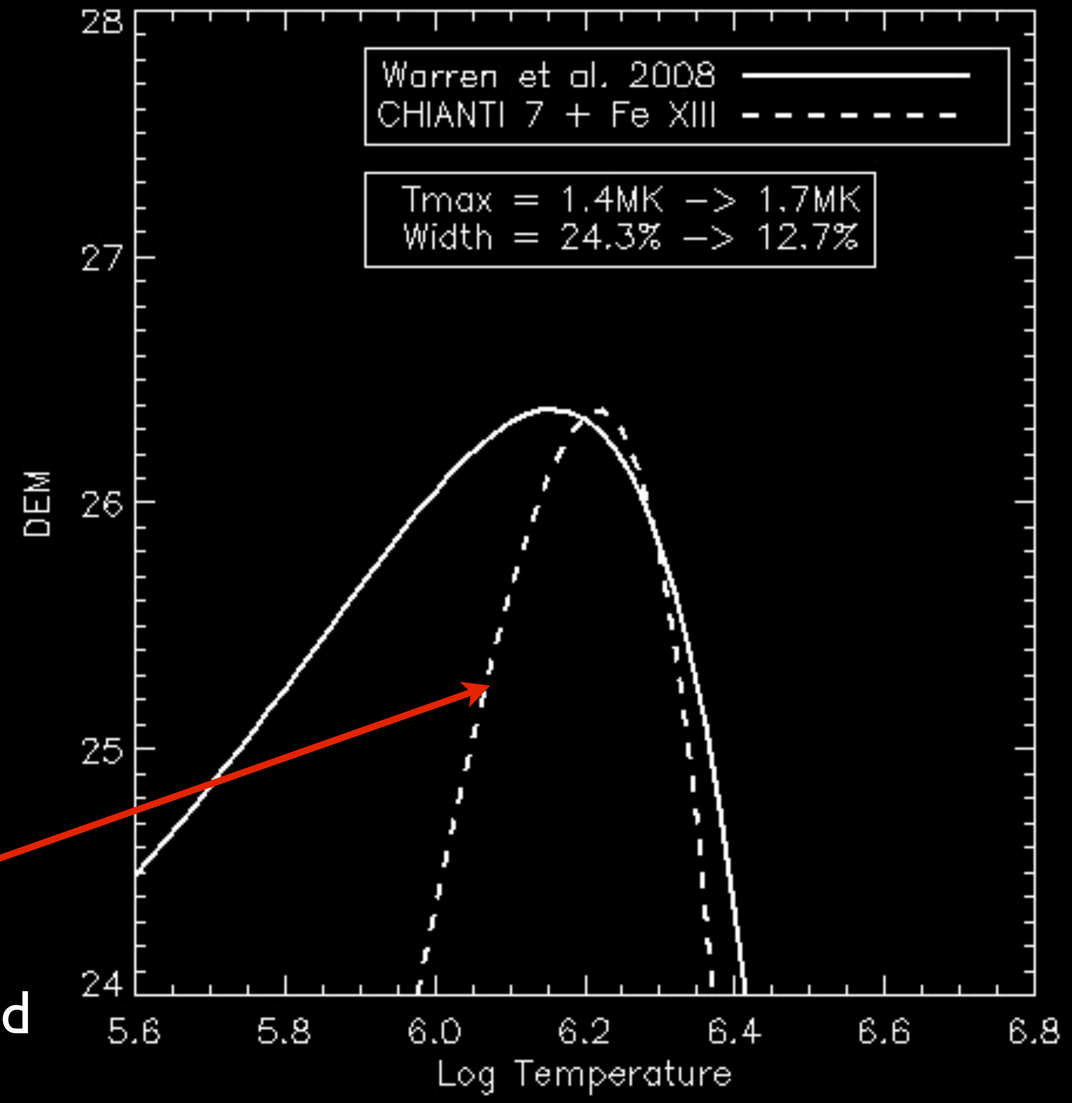
Schmelz et al. (2013a,b):
AIA loops "not consistent with isothermal plasma"
EIS/XRT "most in mid-range between isothermal & broad DEM", "could be explained by cooling?"





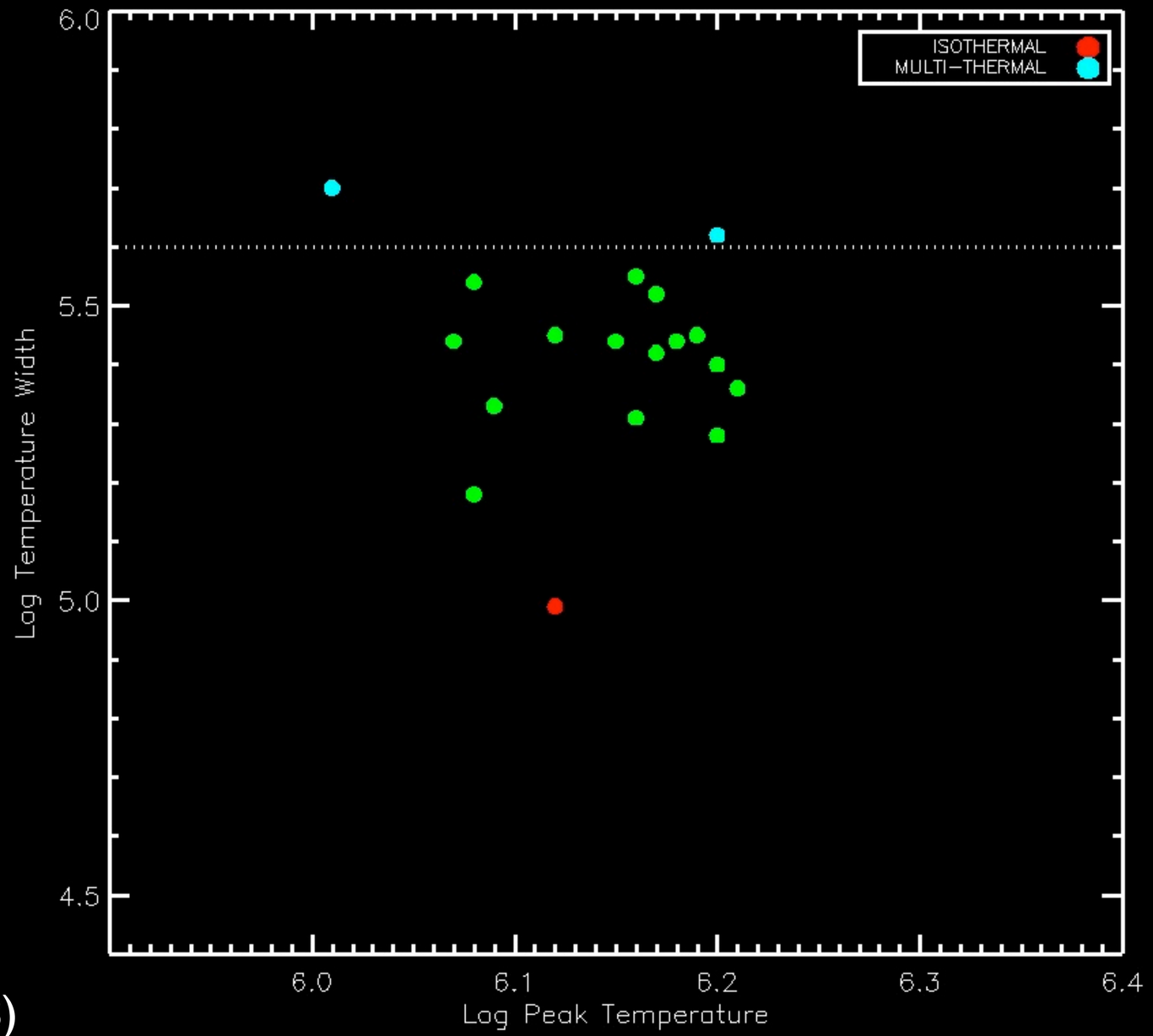
Developments in EIS DEM Analysis

- Ionization Fractions (Dere et al. 2009, Bryans et al. 2009)
- Atomic data for Fe (CHIANTI 7.1, Del Zanna et al. 2008-13).
- Line selection & formation (Brooks et al. 2009, Warren & Brooks 2009).
- Density diagnostics (Young et al. 2009, Watanabe et al. 2009).
- Ca lines constrain high Temperature (Warren et al. 2008).



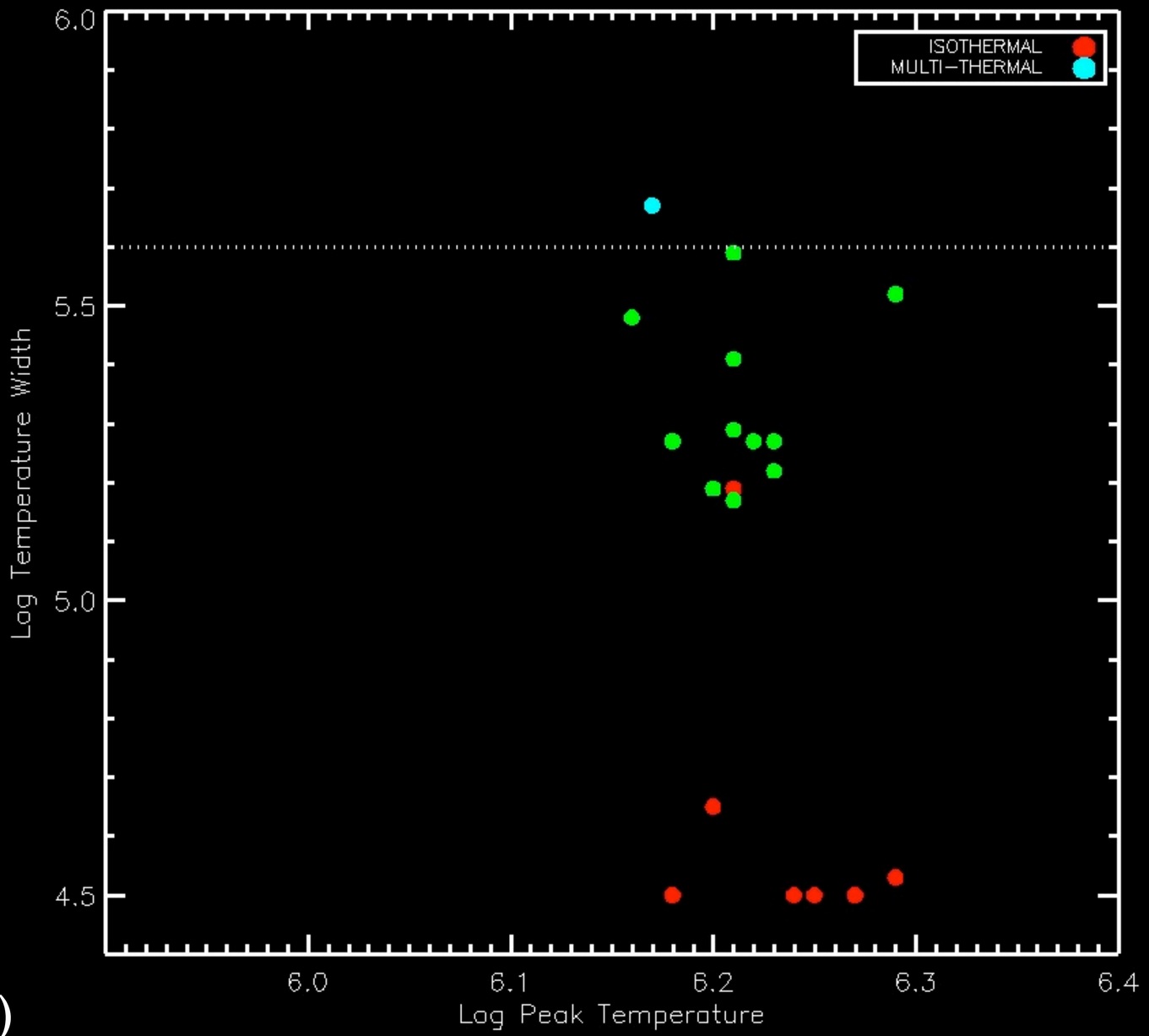
Warm Loop DEM narrower and peaked at higher temperature

Developments in EIS DEM Analysis



Warren et al (2008)

Developments in EIS DEM Analysis

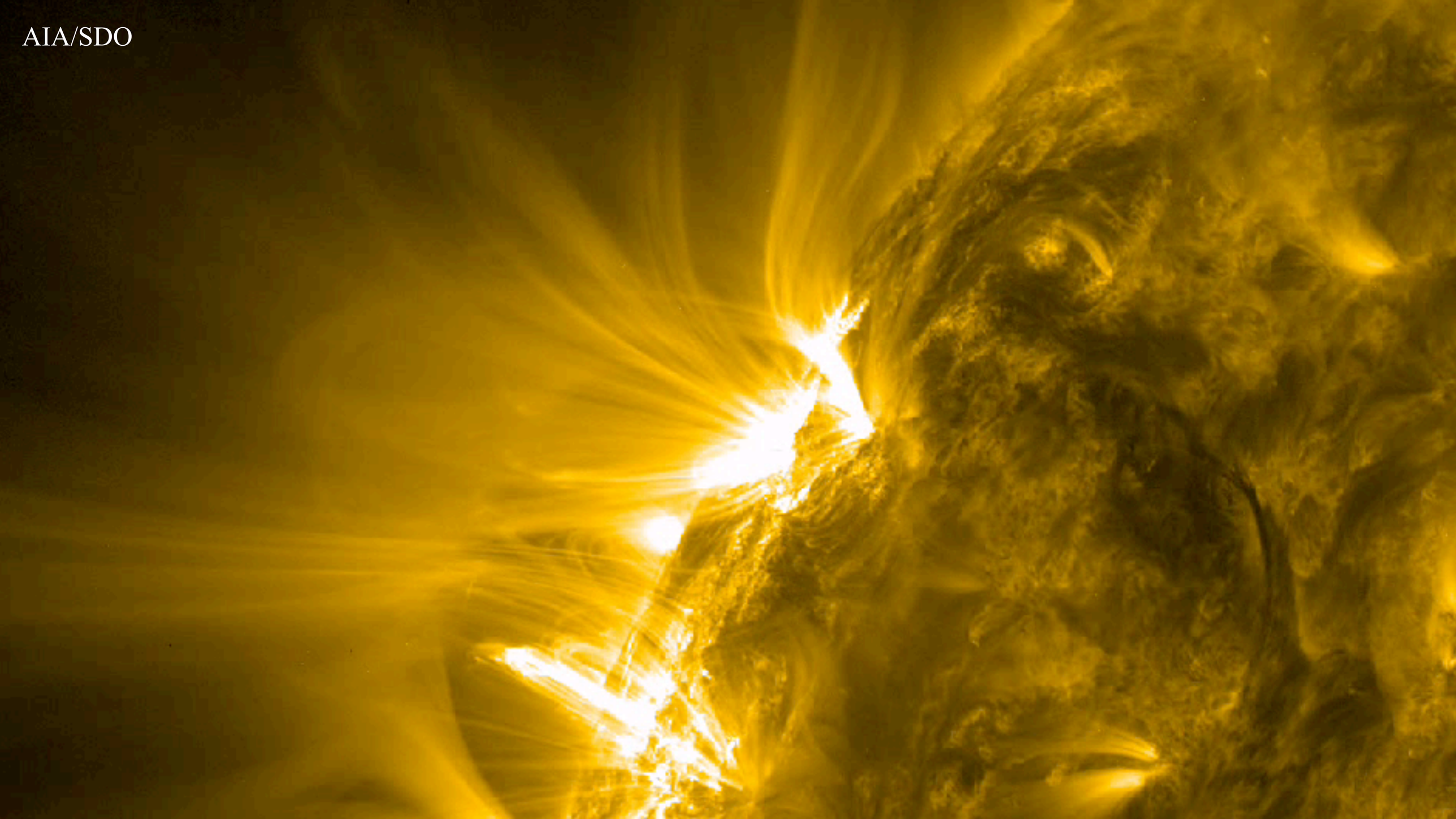


Brooks et al (2012)

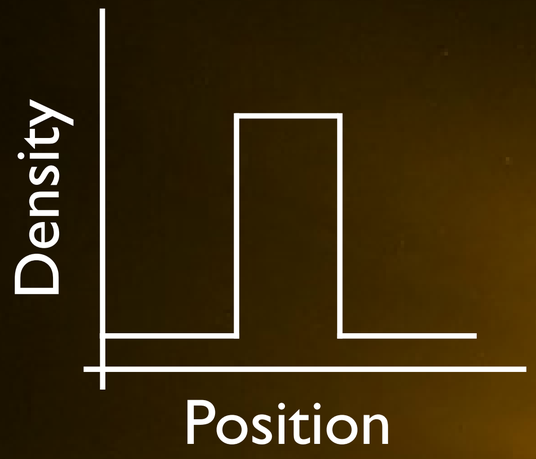
Loop DEM Summary

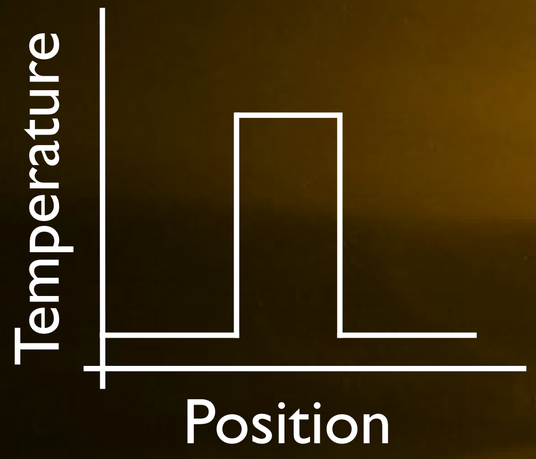
- DEM measurements by spectrometers/imagers have historically been in conflict.
- Observed at 1000km spatial scales, a few loops are broadly multi-thermal and a few are isothermal.
- Recent updates suggest that most warm loops have relatively narrow DEMs, but are not quite isothermal. Do we agree?
- Suggests they are composed of at least a few threads, but are nearly resolved...

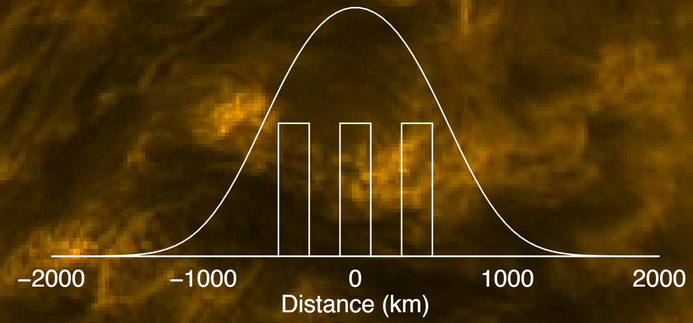
AIA/SDO

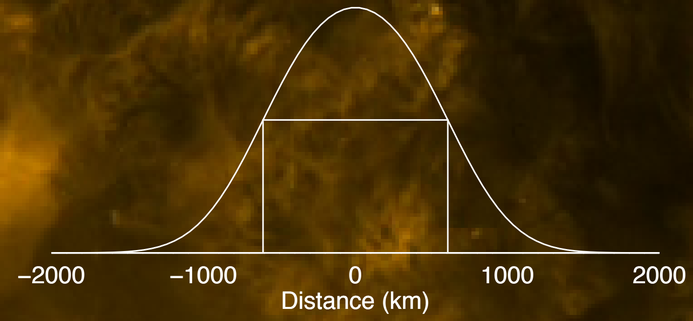

AIA/SDO

AIA/SDO









What size are fundamental loops?

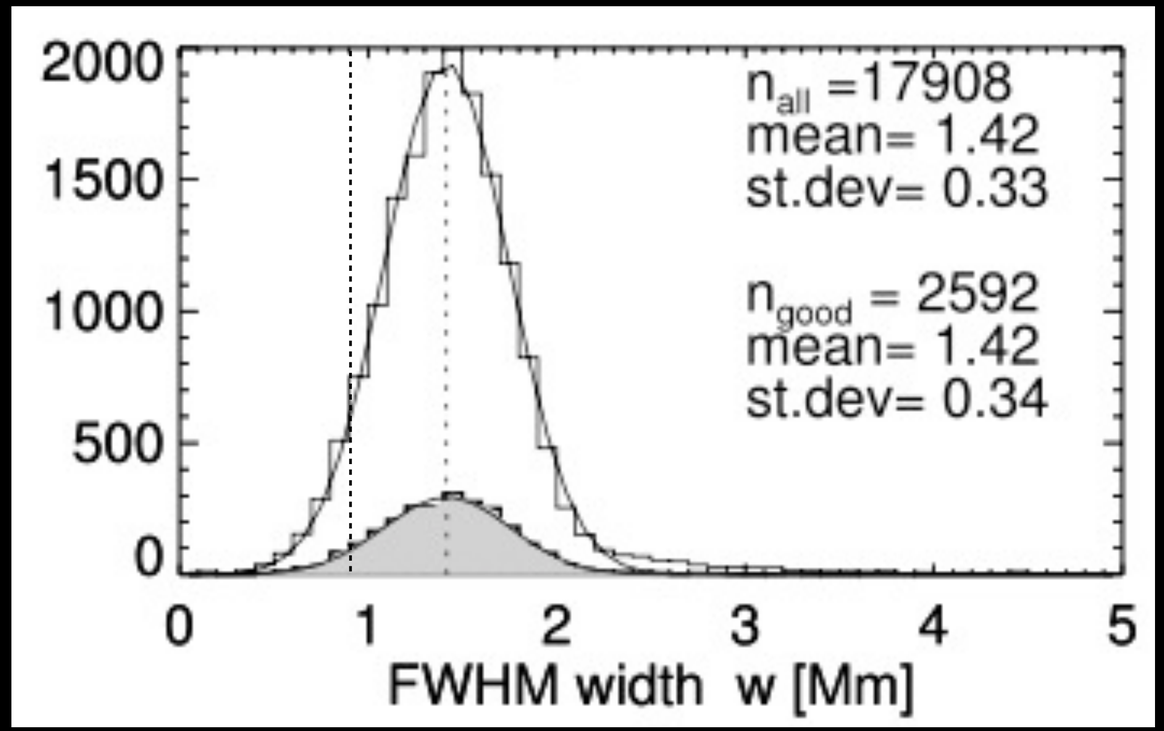
Unknown. Ambiguous.

Background - Imaging

- 18,000 loop segments in TRACE.
- Narrow T distributions (only 3 filters).
- FWHM = 1420 ± 340 km
- TRACE PSF = 900 km

} Resolved!

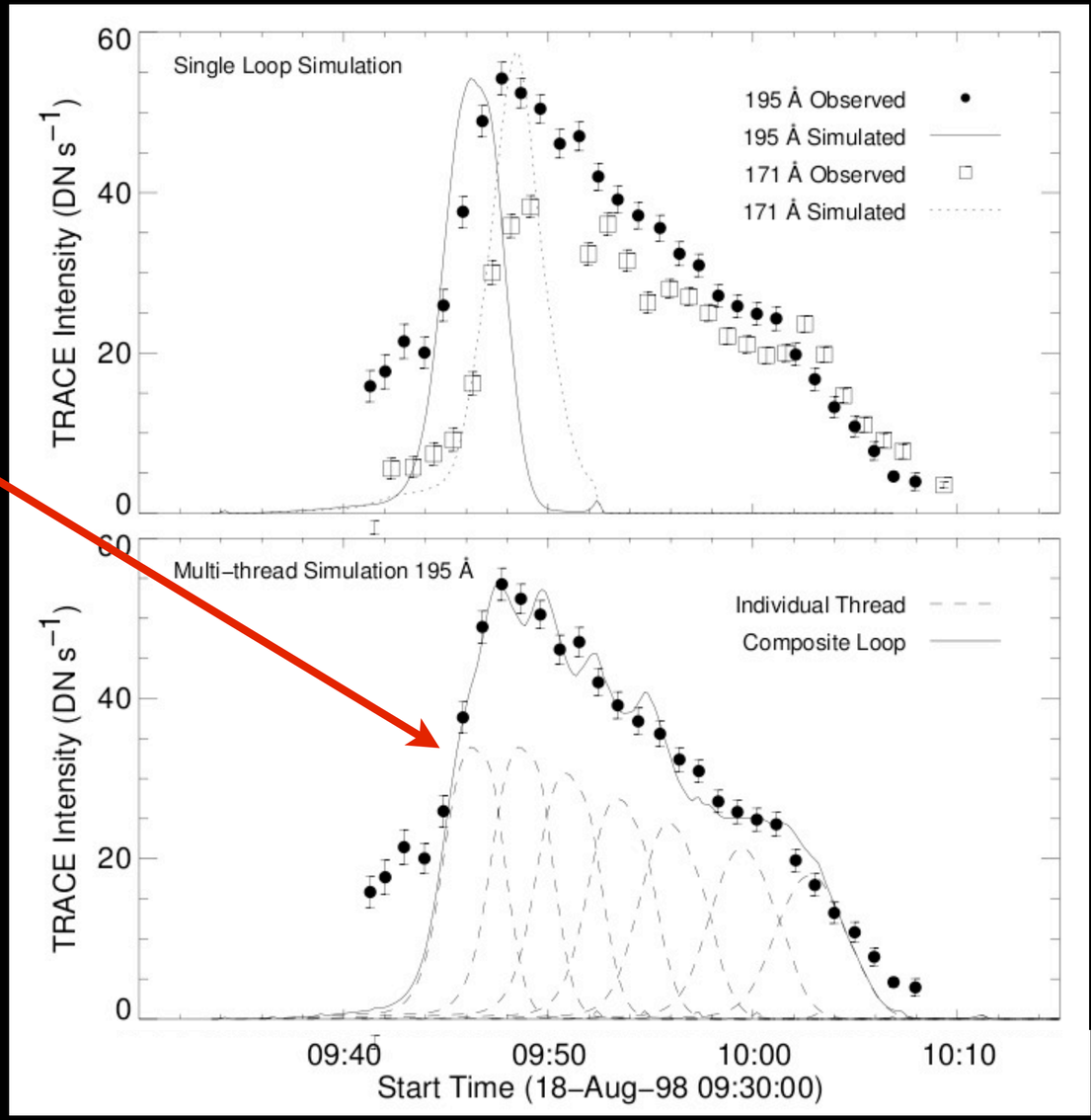
- No density measurements. Volume filled.



Aschwanden & Nightingale (2005)

Background: 1D hydro models

- At least a few threads needed to simulate TRACE light curves.



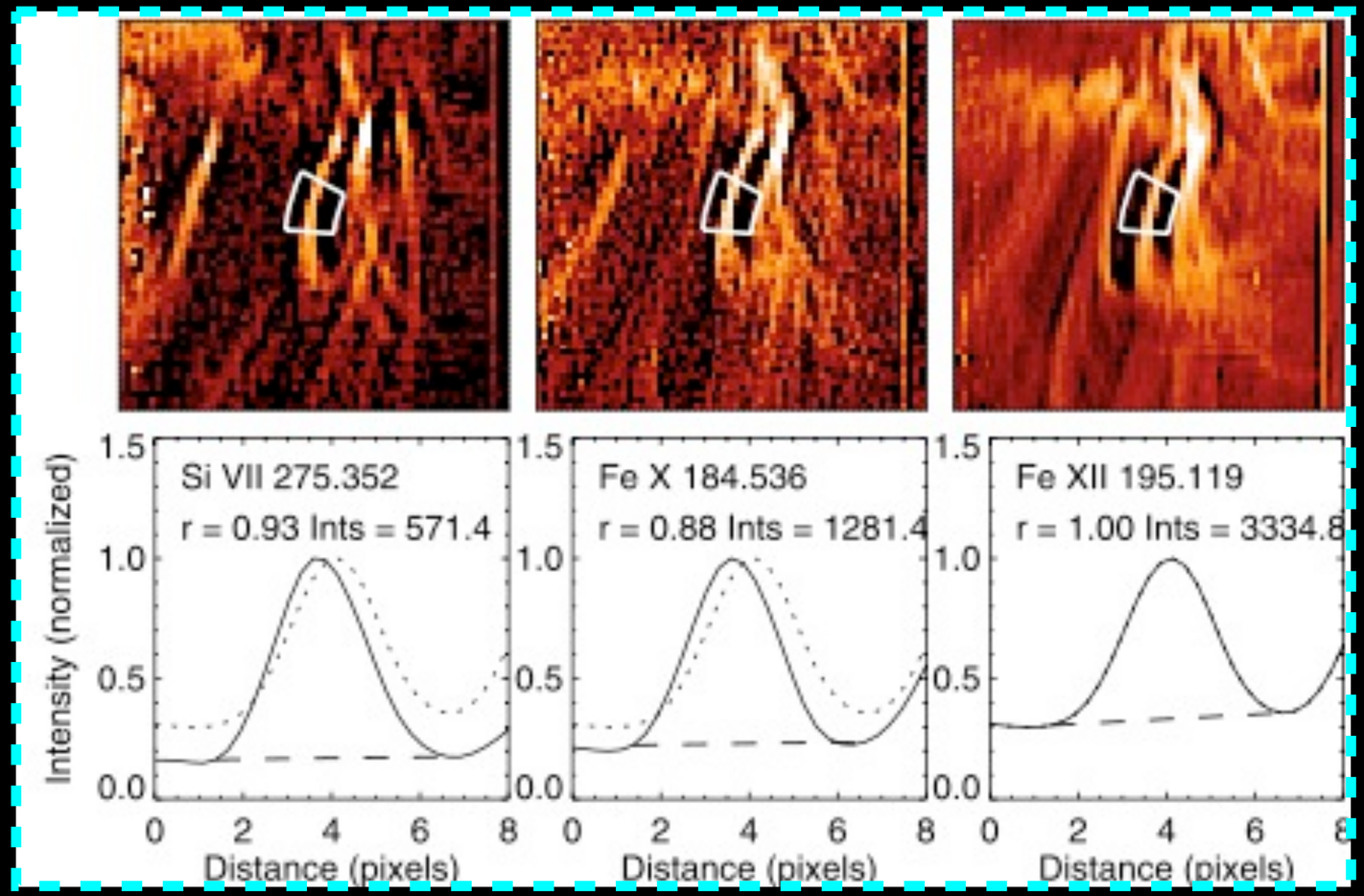
Warren et al. (2003)

Filling Factor Measurements

$$I = G(T,n)n^2\frac{V}{l^2}$$

Atomic Physics

$$I = G(T,n)n^2\frac{fV'}{l^2}$$



Filling Factor Measurements

$$I = G(T,n)n^2\frac{V}{l^2}$$

Atomic Physics

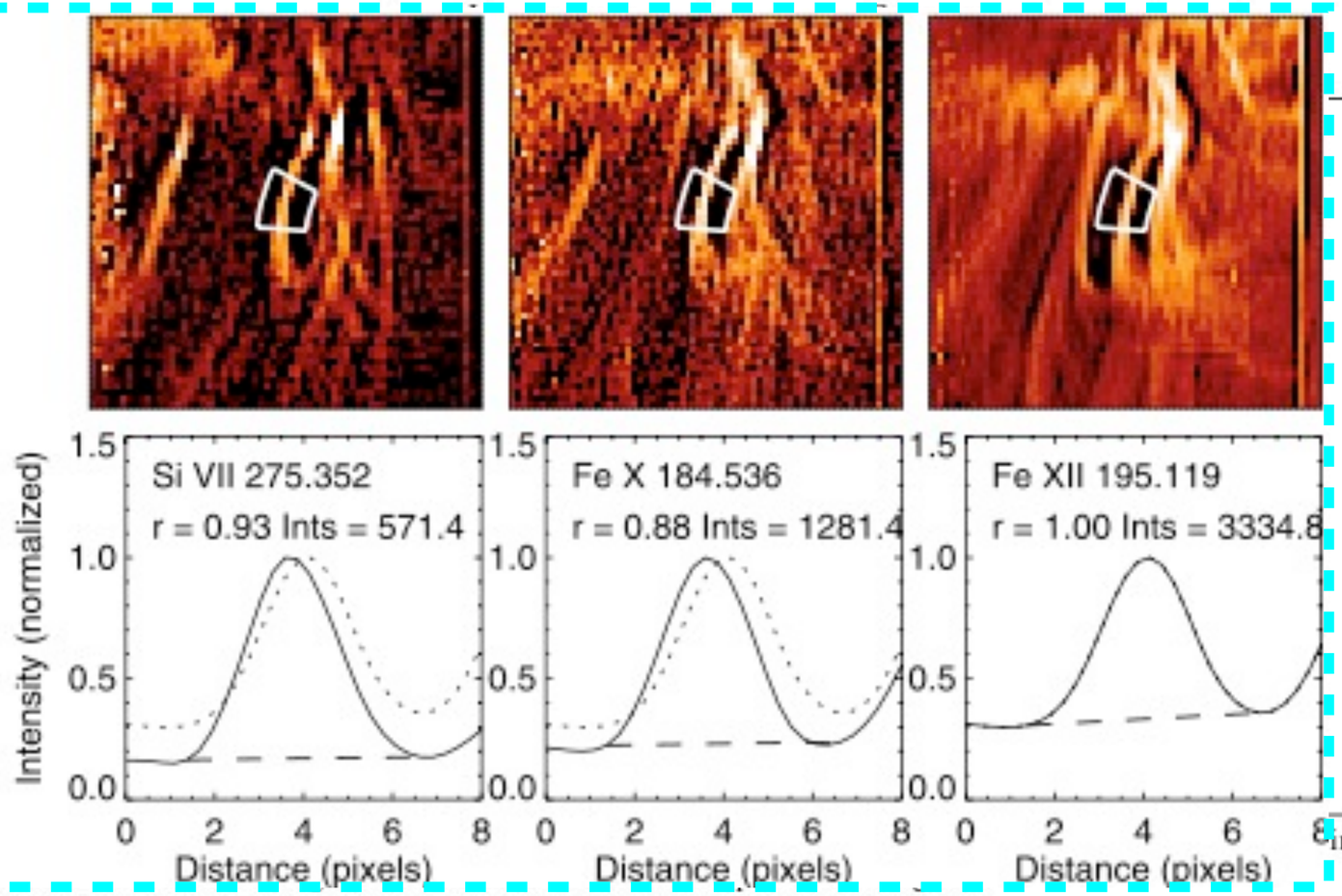
$$I = G(T,n)n^2\frac{fV'}{l^2}$$

TABLE 1

EMISSION MEASURE ANALYSIS OF ACTIVE REGION LOOPS OBSERVED WITH EIS

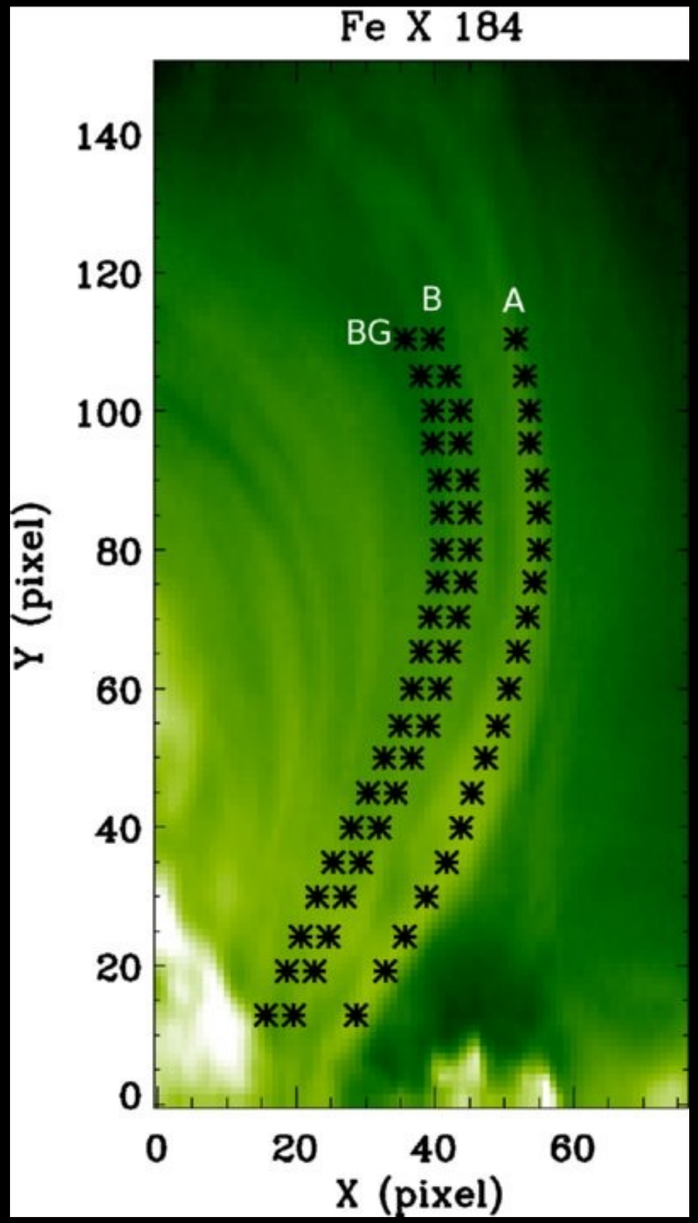
No.	Date	f (%)
1	07 Dec 10	9.1
2	07 Dec 11	2.0
3	07 Dec 11	3.3
4	07 Dec 12	2.6
5	07 Dec 12	19.6
6	07 Dec 12	24.2
7	07 Dec 12	6.8
8	07 Dec 13	12.0
9	07 Dec 13	18.4
10	07 Dec 15	7.0
11	07 Dec 15	2.8
12	07 Dec 15	3.5
13	07 Dec 15	1.3
14	07 Dec 18	0.3
15	07 Dec 18	11.5
16	07 Dec 18	2.1
17	07 Dec 18	1.7
18	07 Dec 10	11.6
19	07 Dec 11	0.6
20	07 Dec 13	3.7

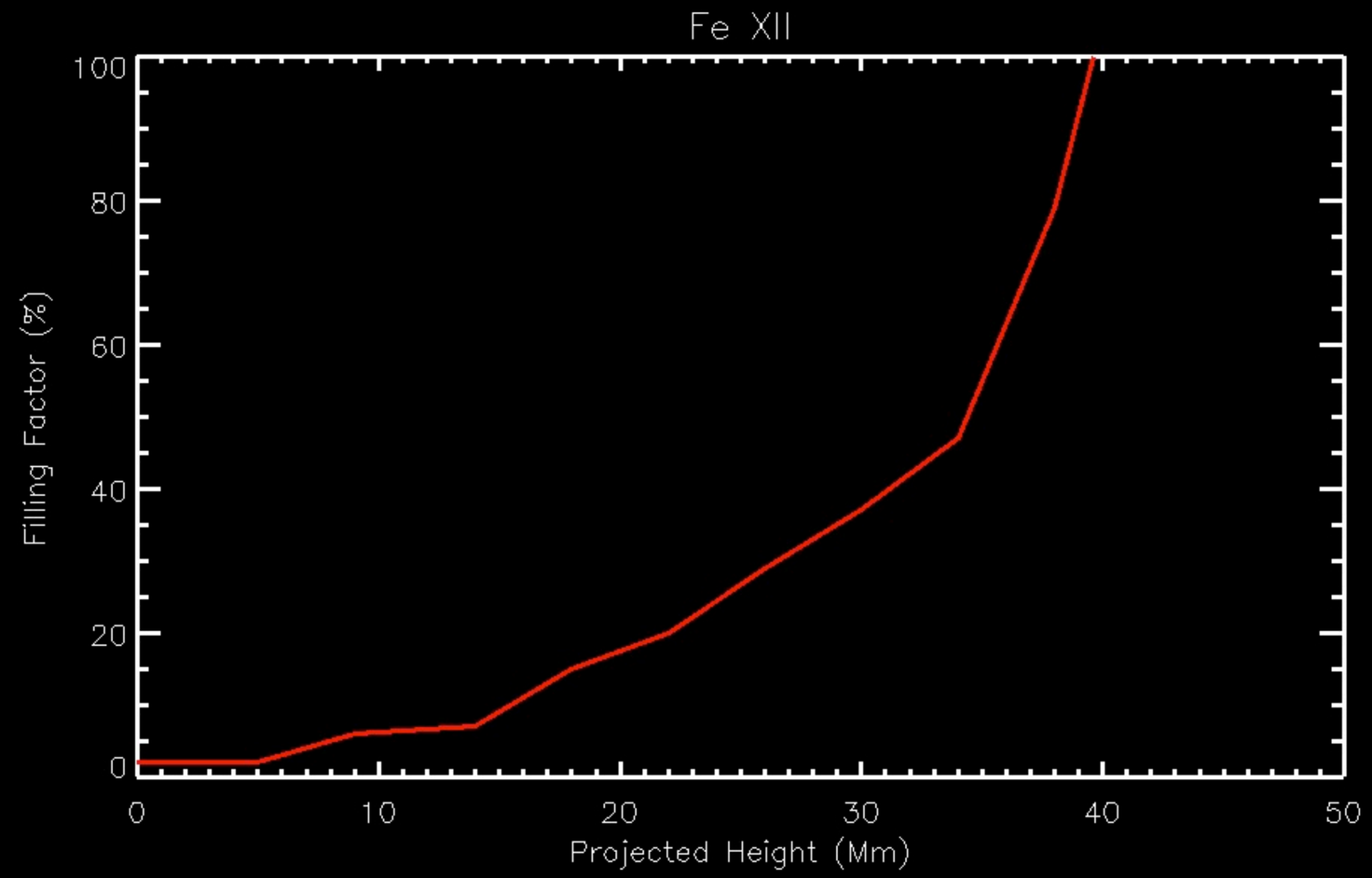
NOTE.—The date a
measured in Fe XII l



Warren et al. (2008)

Filling Factor Measurements





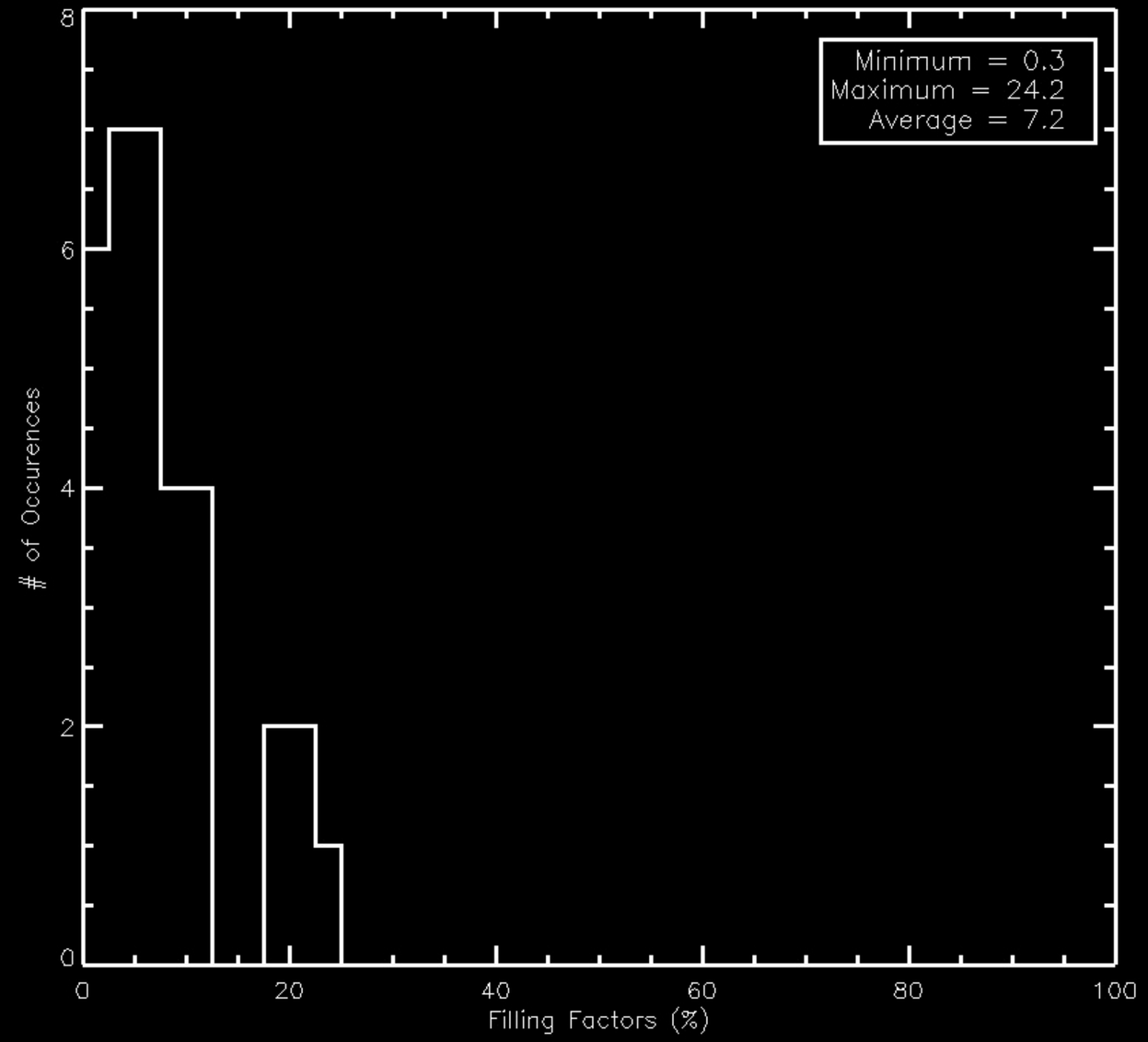
Increases with projected height, 2% to >100%
(Tripathi et al 2009)

Developments in EIS Filling Factor Measurements

20 Loops (Warren et al. 2008)

Filling Factors (f) ~ 10%

f < 25% (20/20)



Developments in EIS Filling Factor Measurements

Update Only!

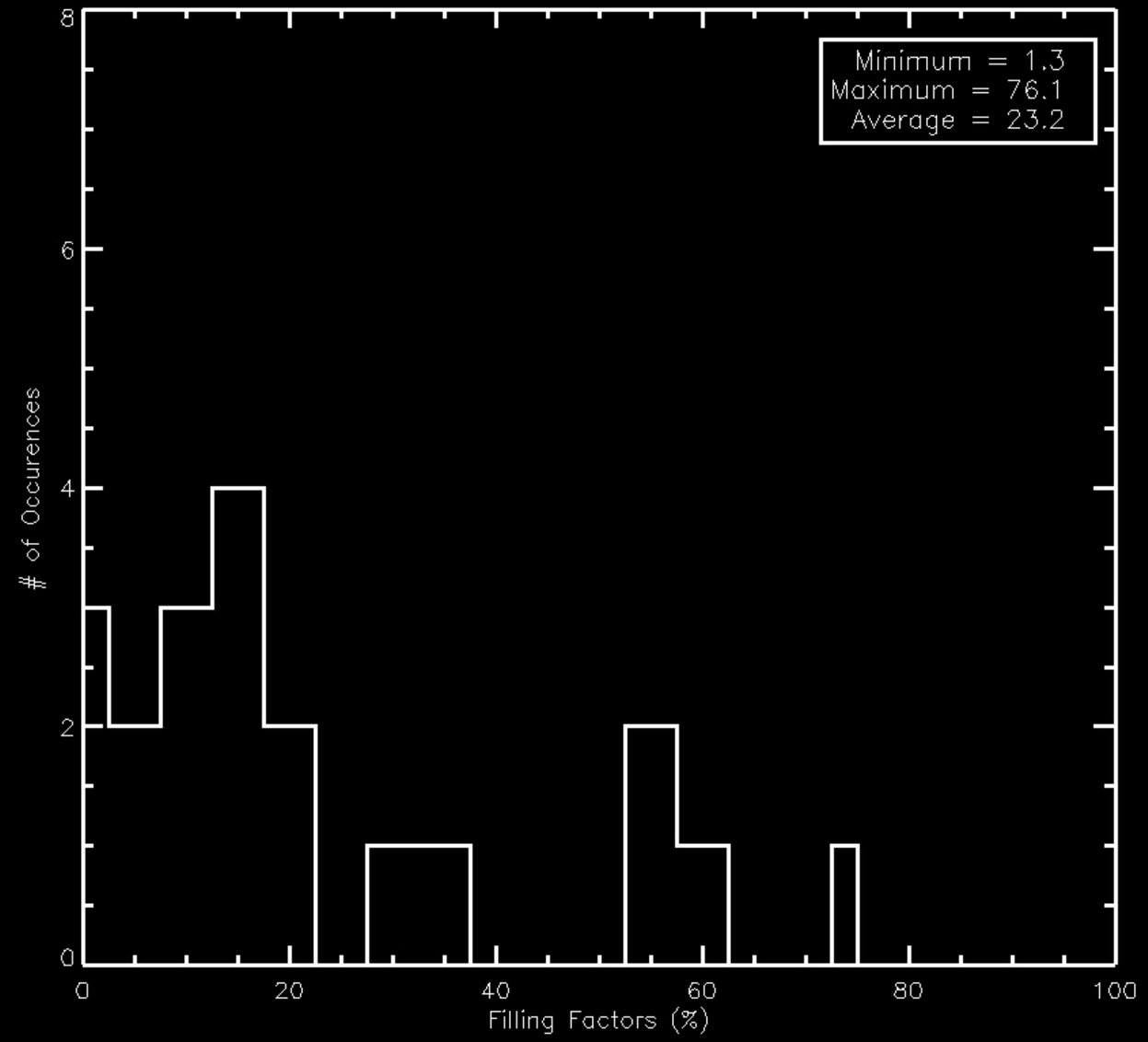
20 Loops (Warren et al. 2008)

Filling Factors (f) ~ 25%

Previous results too small!

f > 25% (6/20)

f ~ 76% (1/20). Nearly Resolved?



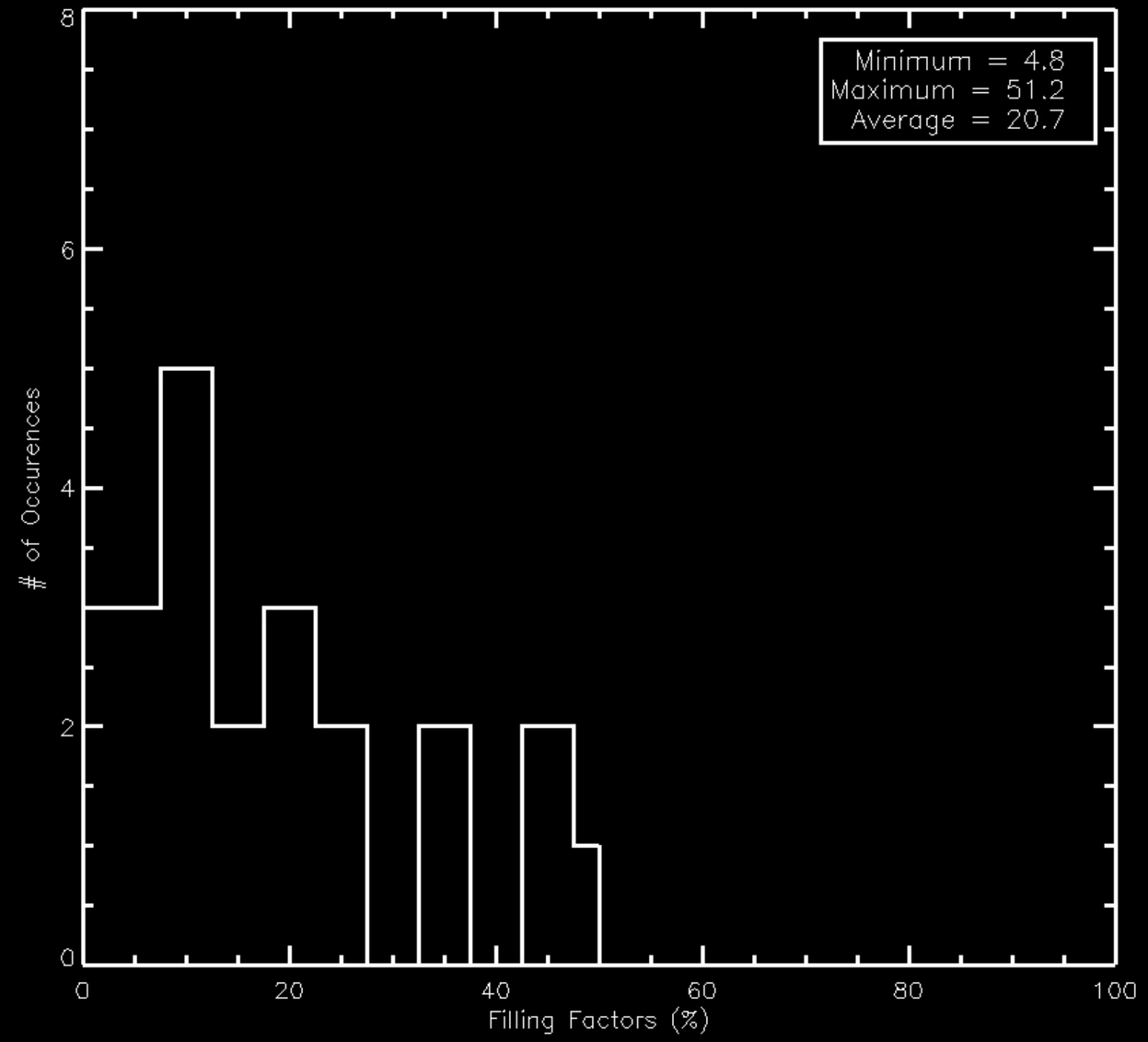
Developments in EIS Filling Factor Measurements

Different Loop Sample

20 Loops (Brooks et al. 2012)

Filling Factors (f) ~ 20%

f > 25% (7/20)



Developments in EIS Filling Factor Measurements

AIA width measurements

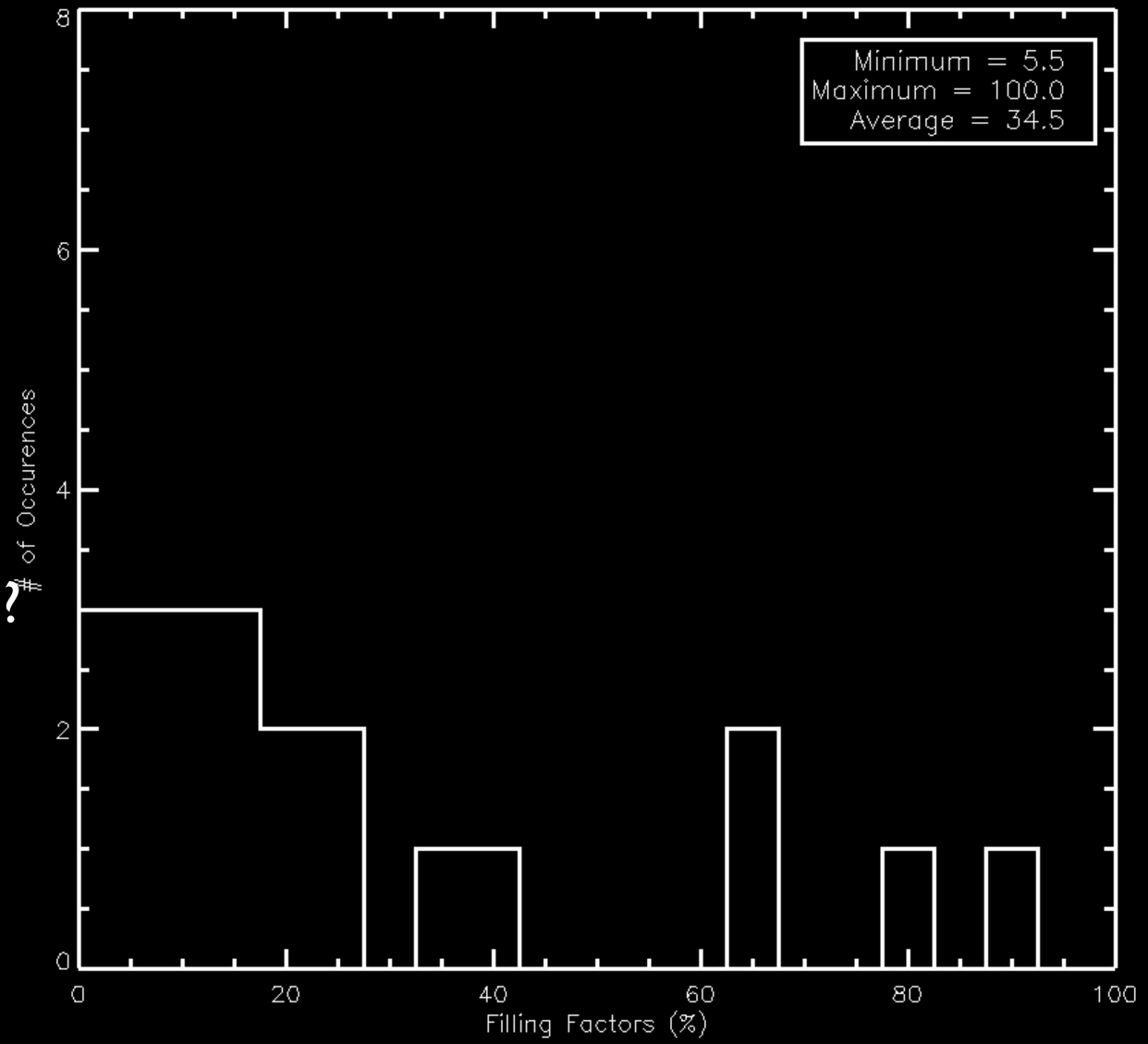
20 Loops (Brooks et al. 2012)

Filling Factors (f) ~ 35%

f > 25% (9/20)

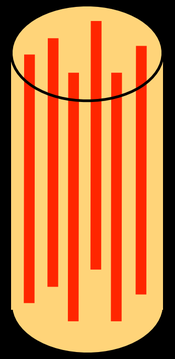
f ~ 65-80% (3/20). Nearly Resolved?

2/20 Resolved?



Estimating the volume of emission: Multi-strand model - known geometry

$$I_{tot} = G(T,n)n^2 \frac{V}{l^2} = \underbrace{G(T,n)n^2}_{\text{Atomic Data}} \frac{N\pi r^2 l}{l^2}$$



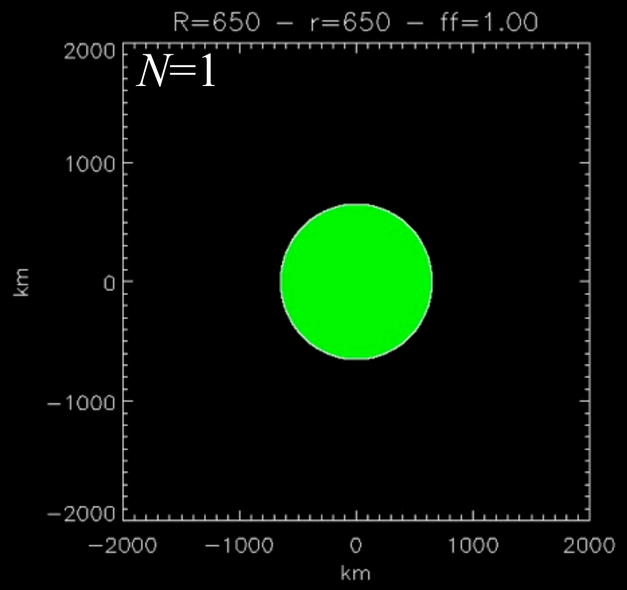
N strands
Radius r
Density n
Temperature T
Envelope R

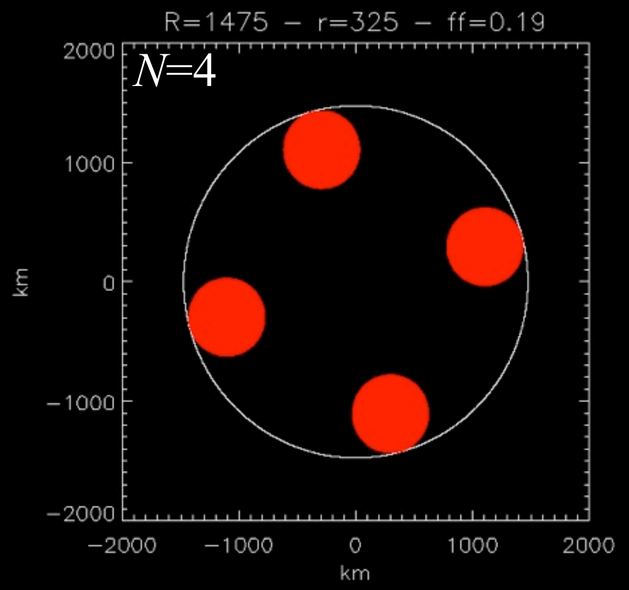
l: pixel length

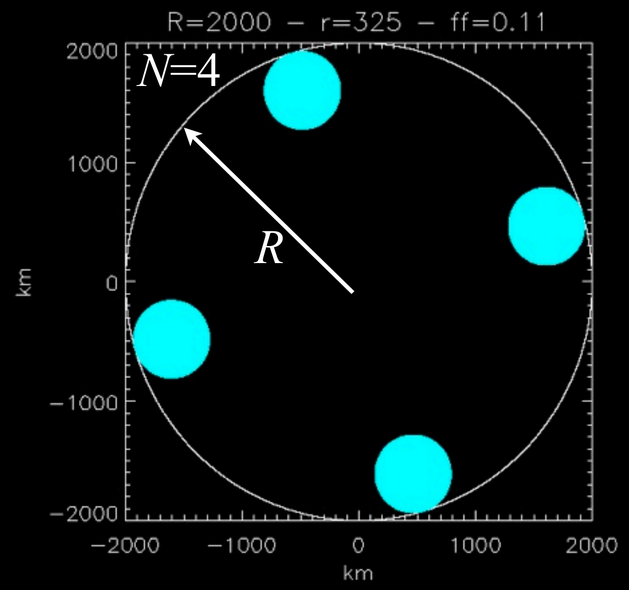
n: density!

$$I_{tot} = ANr^2$$

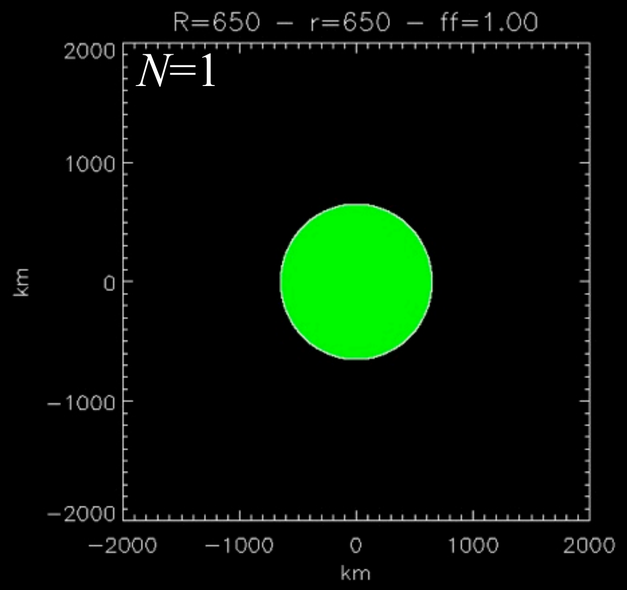
$$I_{tot} = ANr^2$$

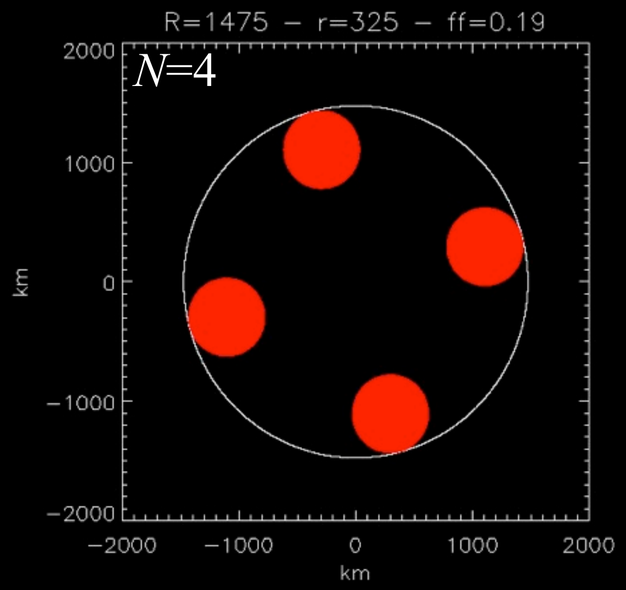

R=650 – r=650 – ff=1.00
N=1
2000
1000
0
−1000
−2000
km
−2000 −1000 0 1000 2000
km

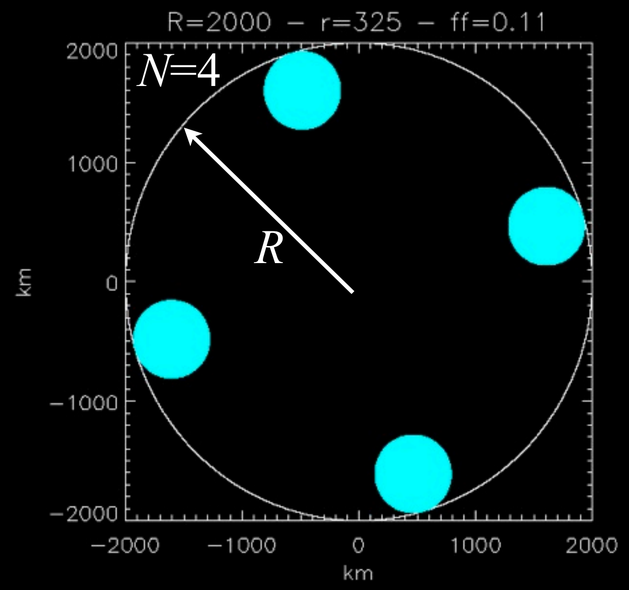

R=1475 – r=325 – ff=0.19
N=4
2000
1000
0
−1000
−2000
km
−2000 −1000 0 1000 2000
km


R=2000 – r=325 – ff=0.11
N=4
R
2000
1000
0
−1000
−2000
km
−2000 −1000 0 1000 2000
km

$$I_{tot} = ANr^2$$

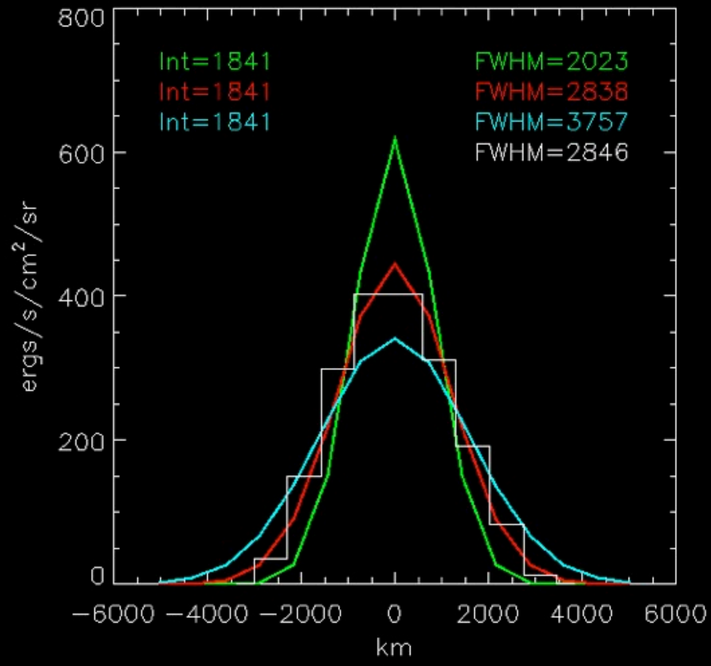




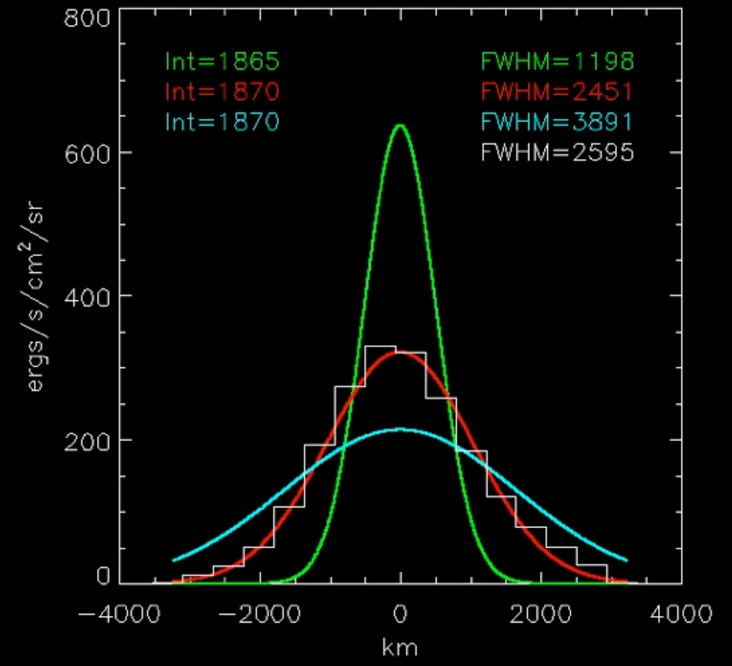


$$I_{obs}(x) = PSF_{inst} * f(r, N, R)$$

EIS/Hinode

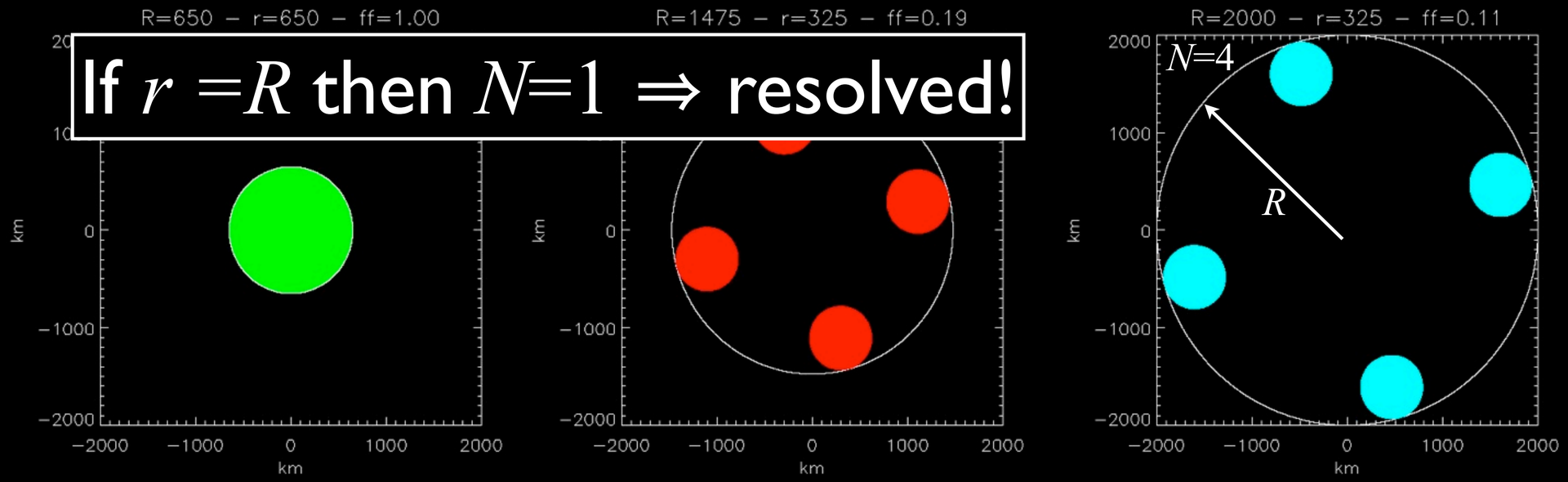


AIA/SDO

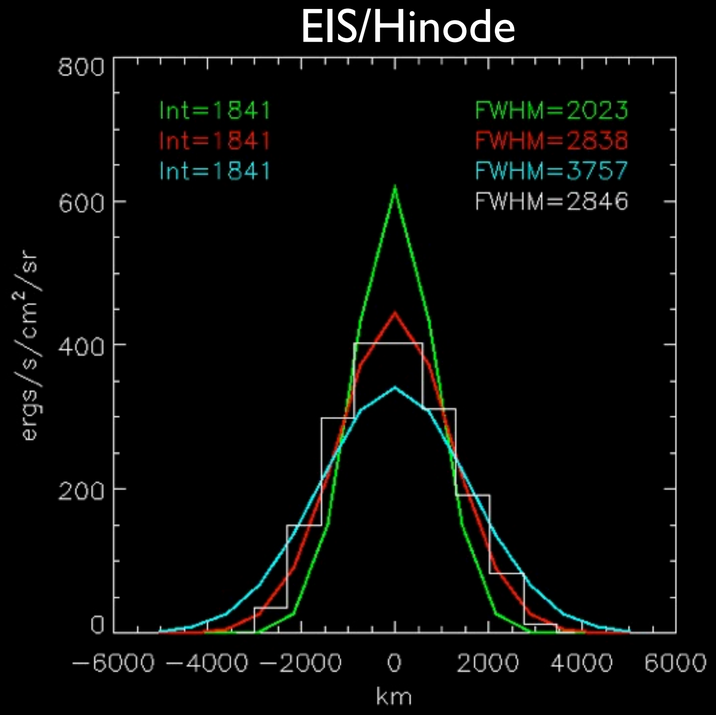


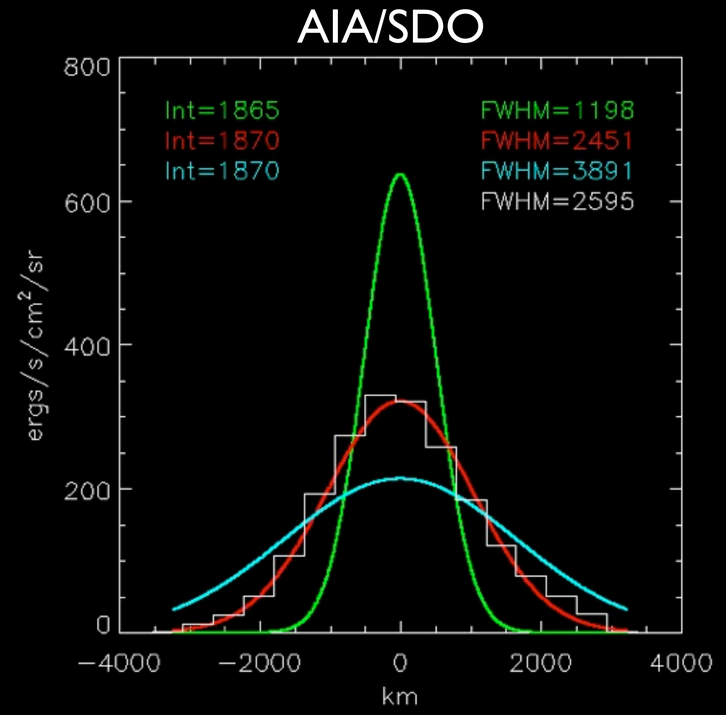
$$I_{tot} = ANr^2$$

If $r = R$ then $N=1 \Rightarrow$ resolved!

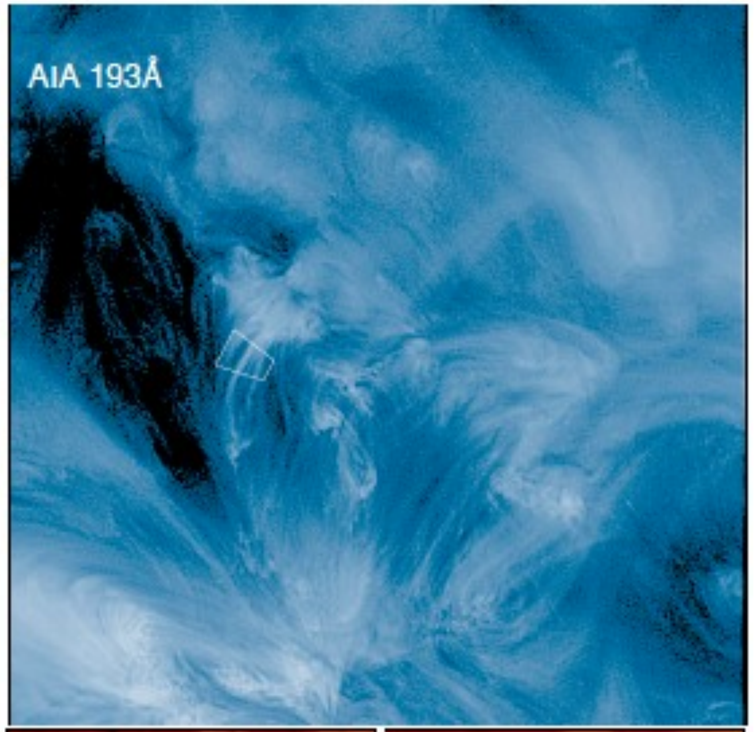


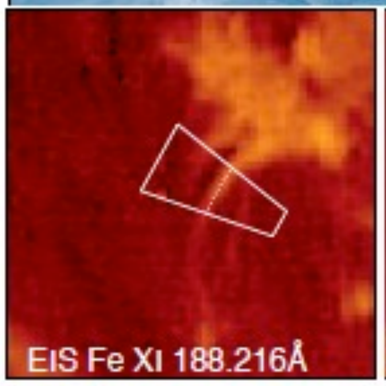
$$I_{obs}(x) = PSF_{inst} * f(r, N, R)$$

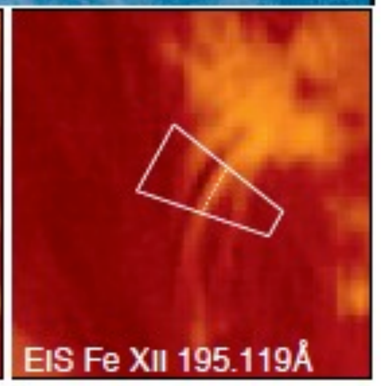


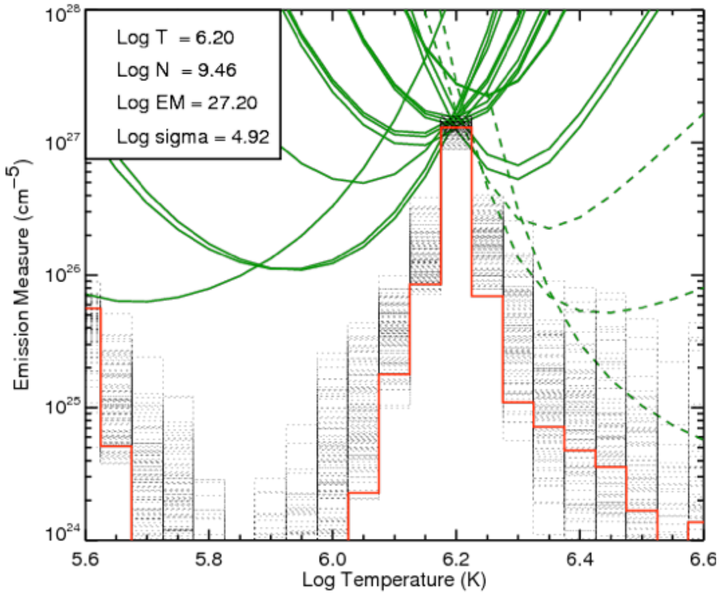


Data analysis - typical case

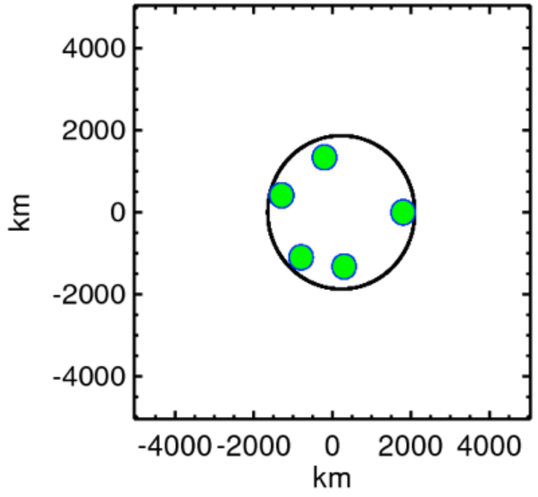


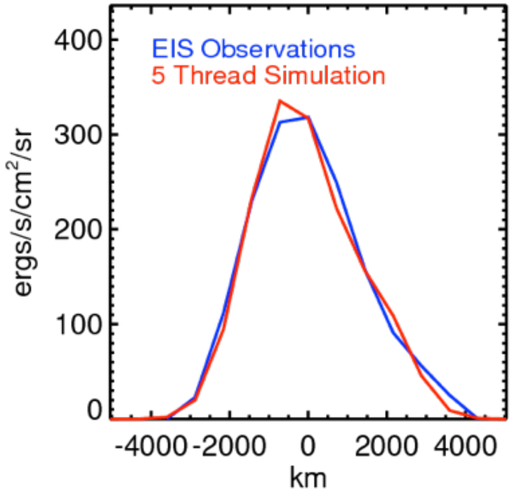


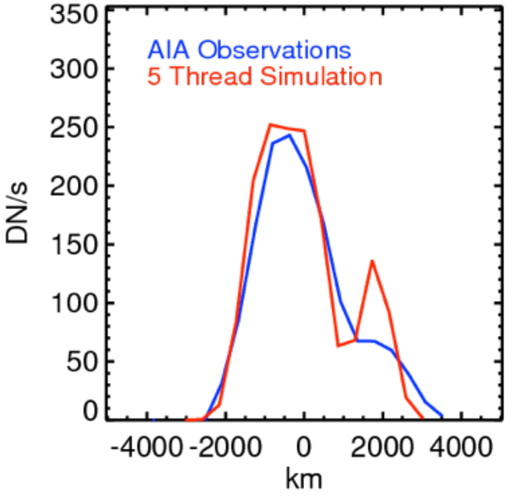




Unresolved loop:
5 strands with 280 km radius
needed to explain
EIS and AIA intensities and widths



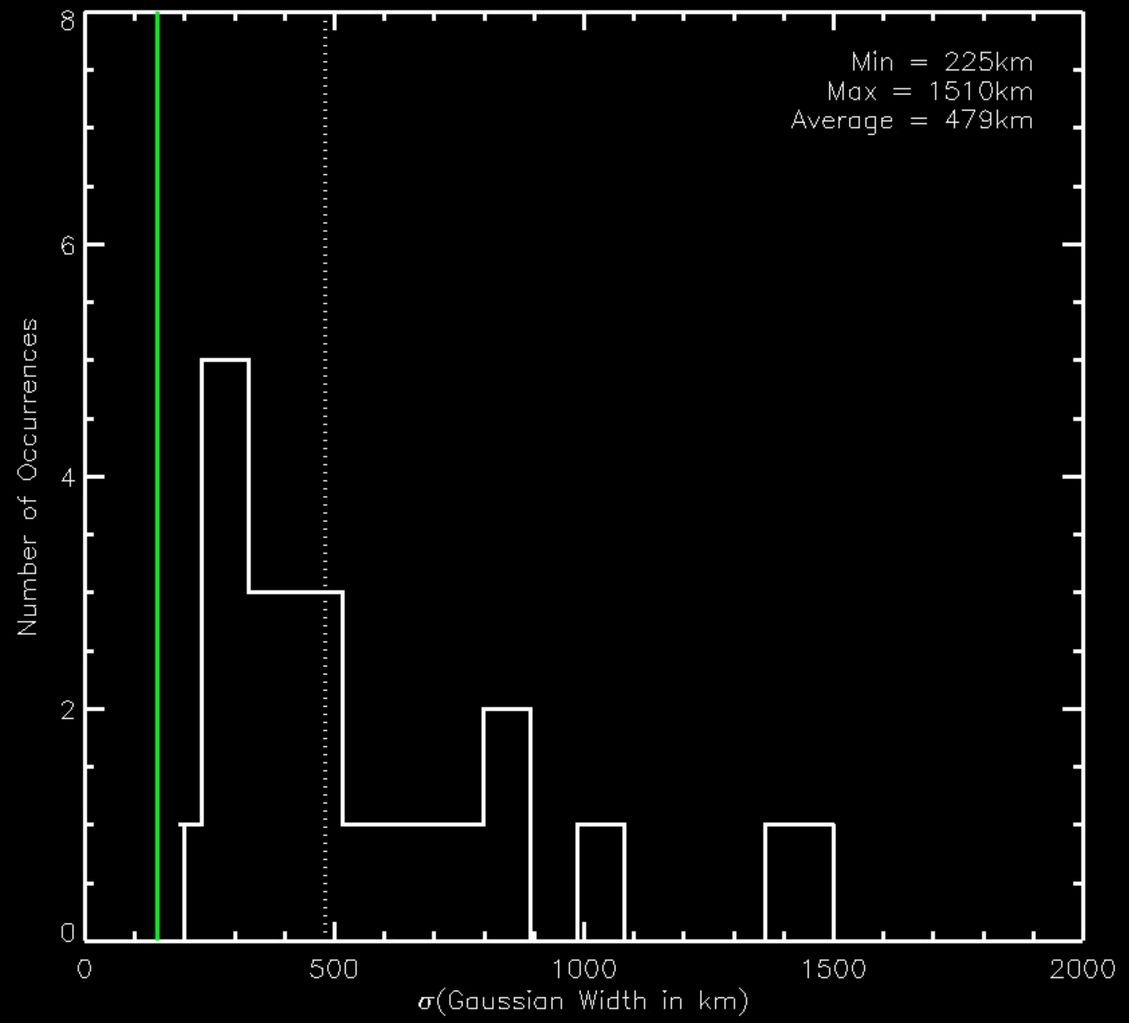




Results

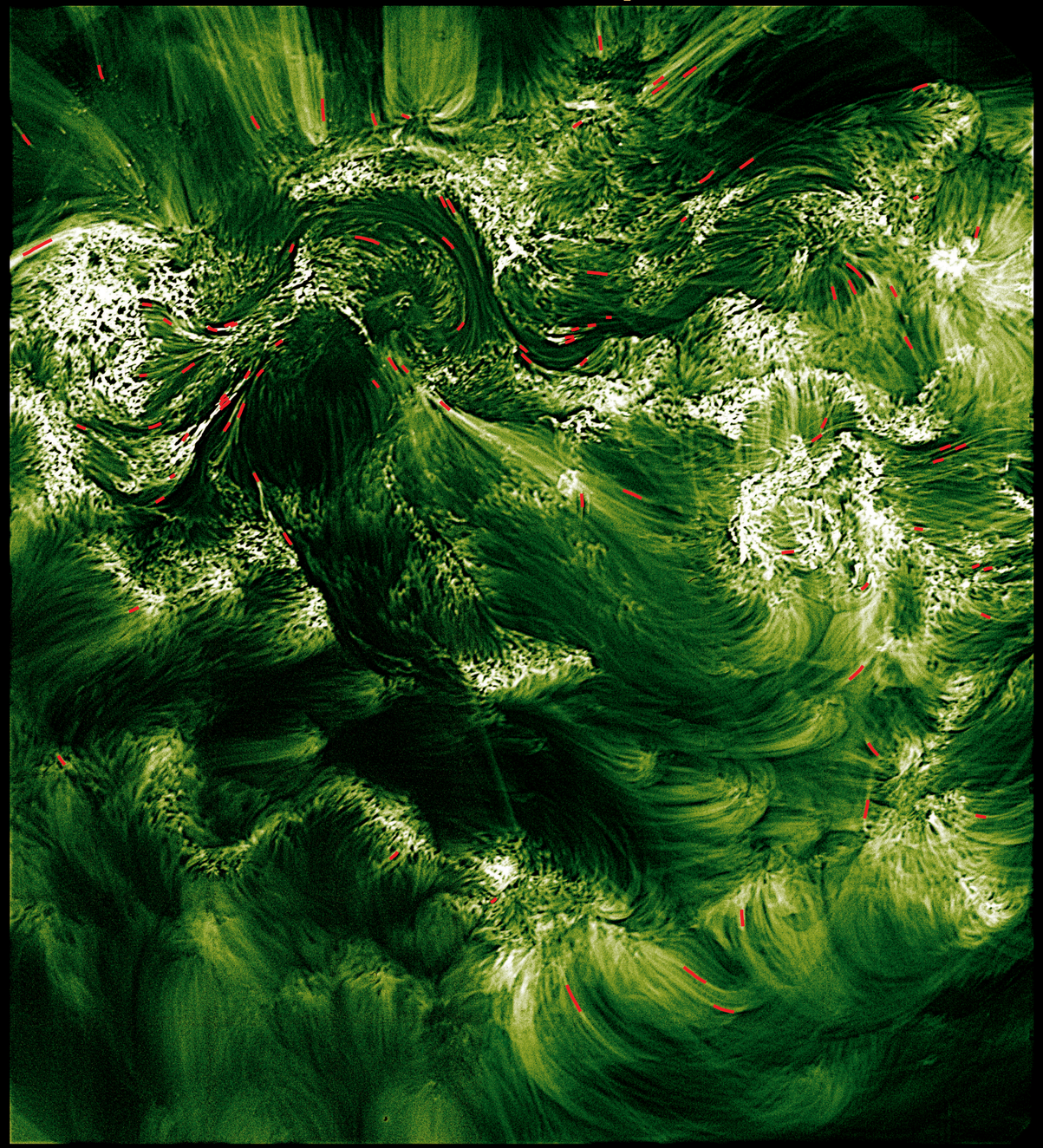
$1 \leq N \leq 8$; Four $N = 1$ loops ; $\mu_{1/2}(r) = 470$ km

Brooks et al (2012)

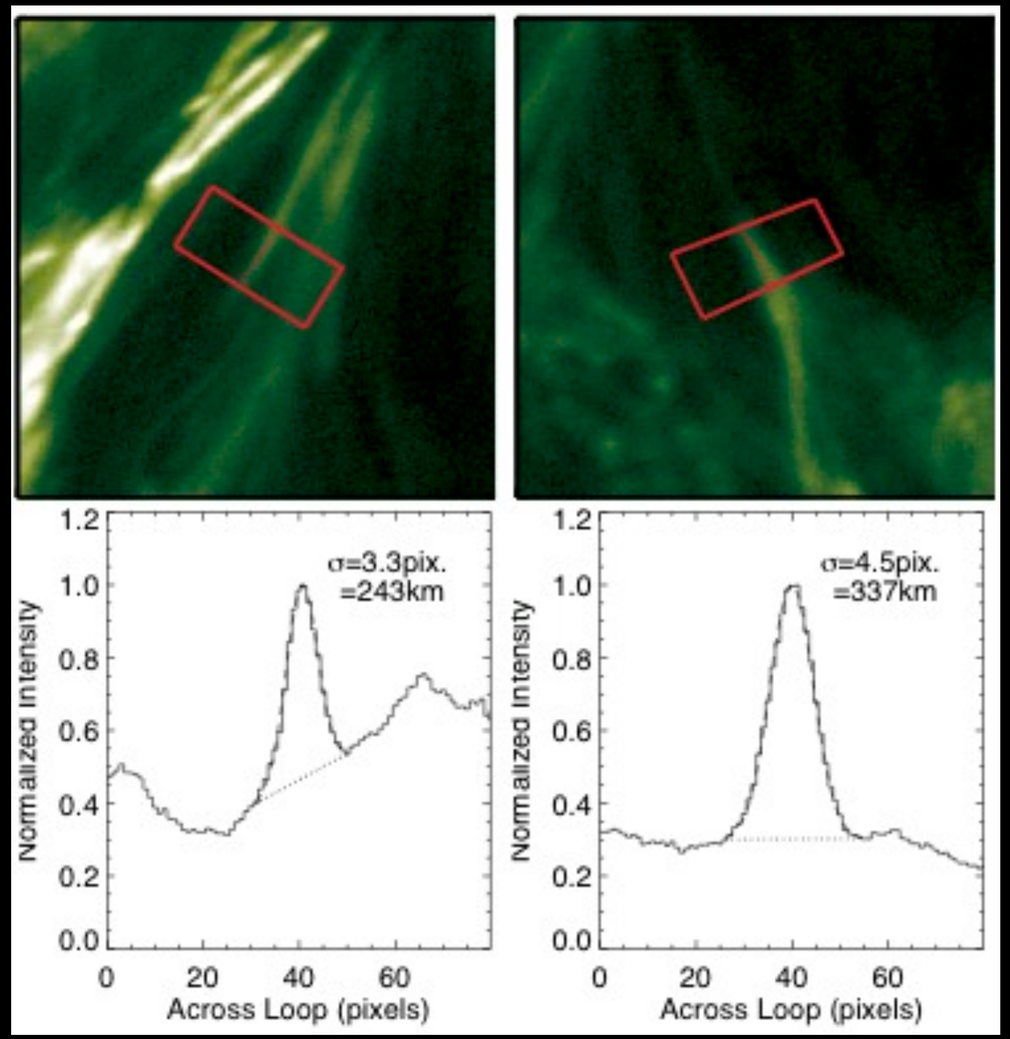


Hundreds! 0.2-0.3” (0.1”/pixel) should resolve all these loops!

Hi-C has 0.1”/pixel



91 Loop Segments

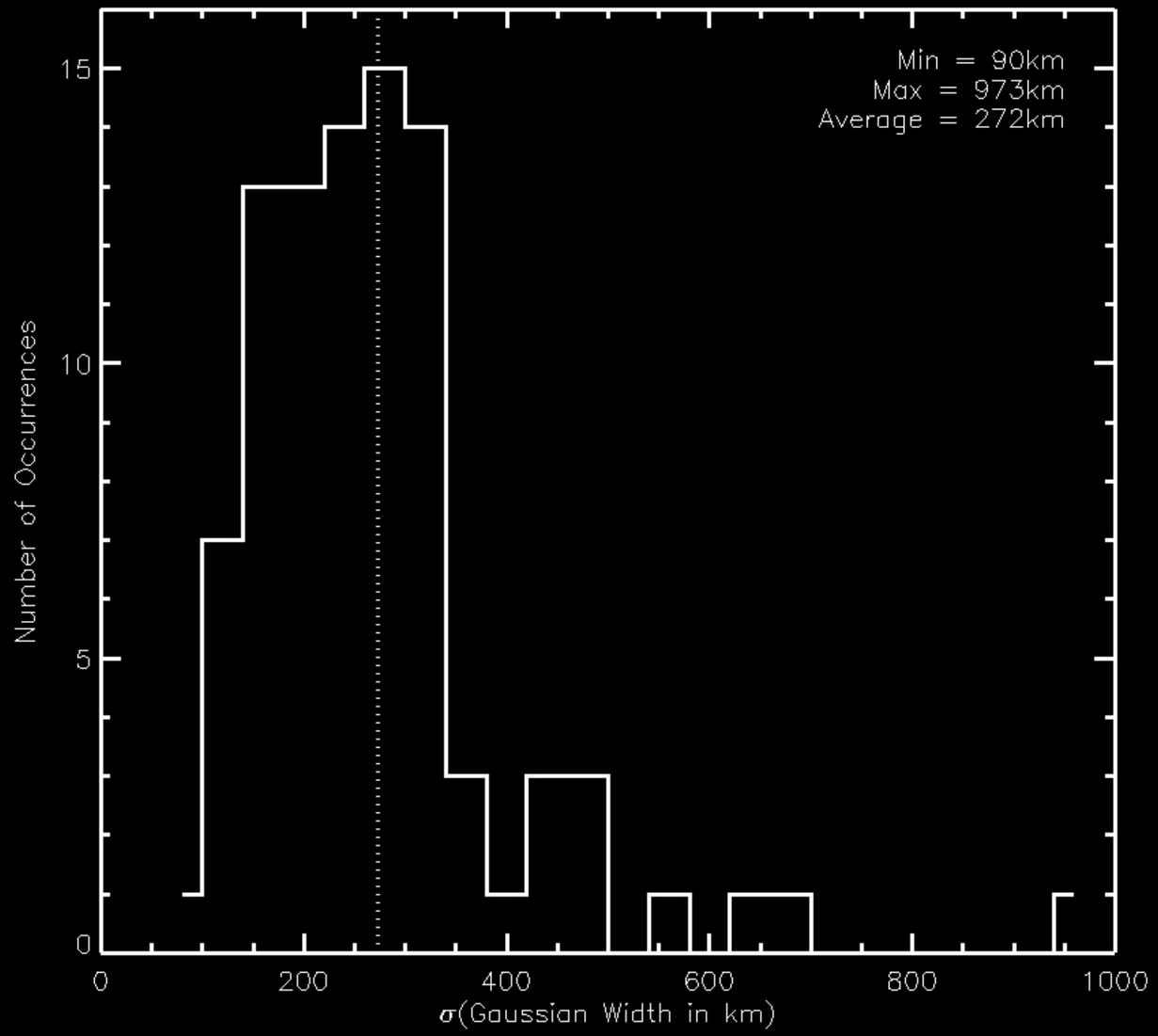


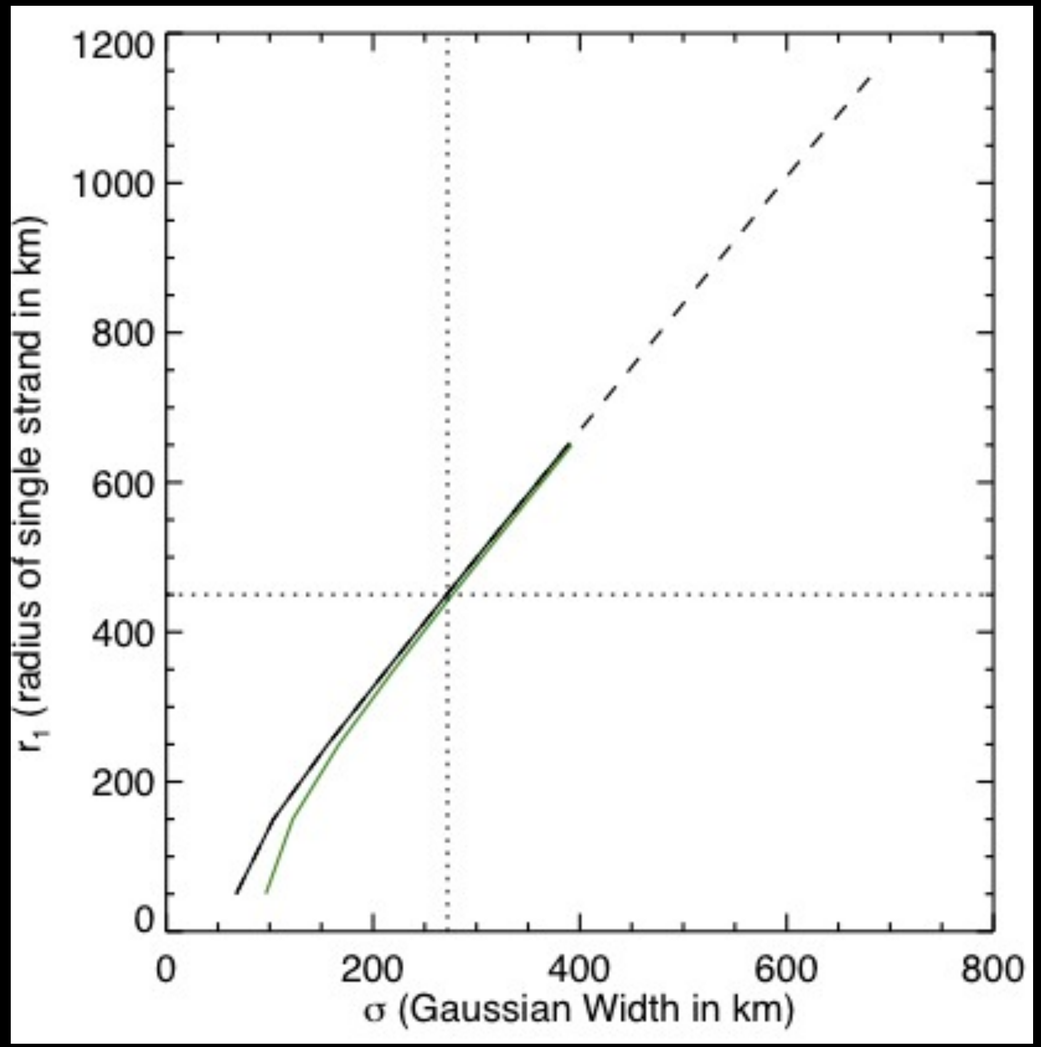
(Brooks et al 2013)

Results:

Average Width = 270km

Loop Radius = 450km

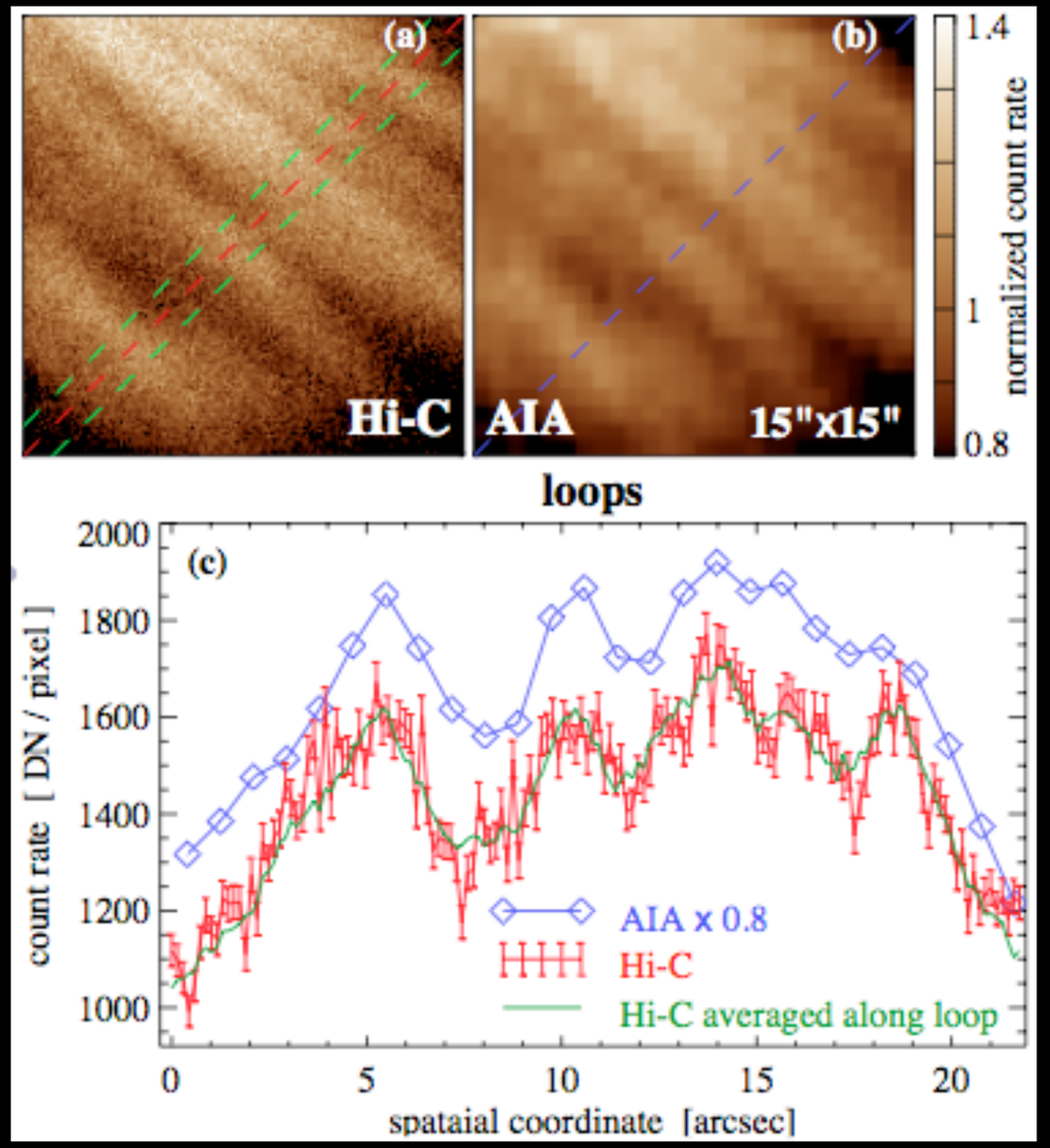




Consistent with EIS (470km average)

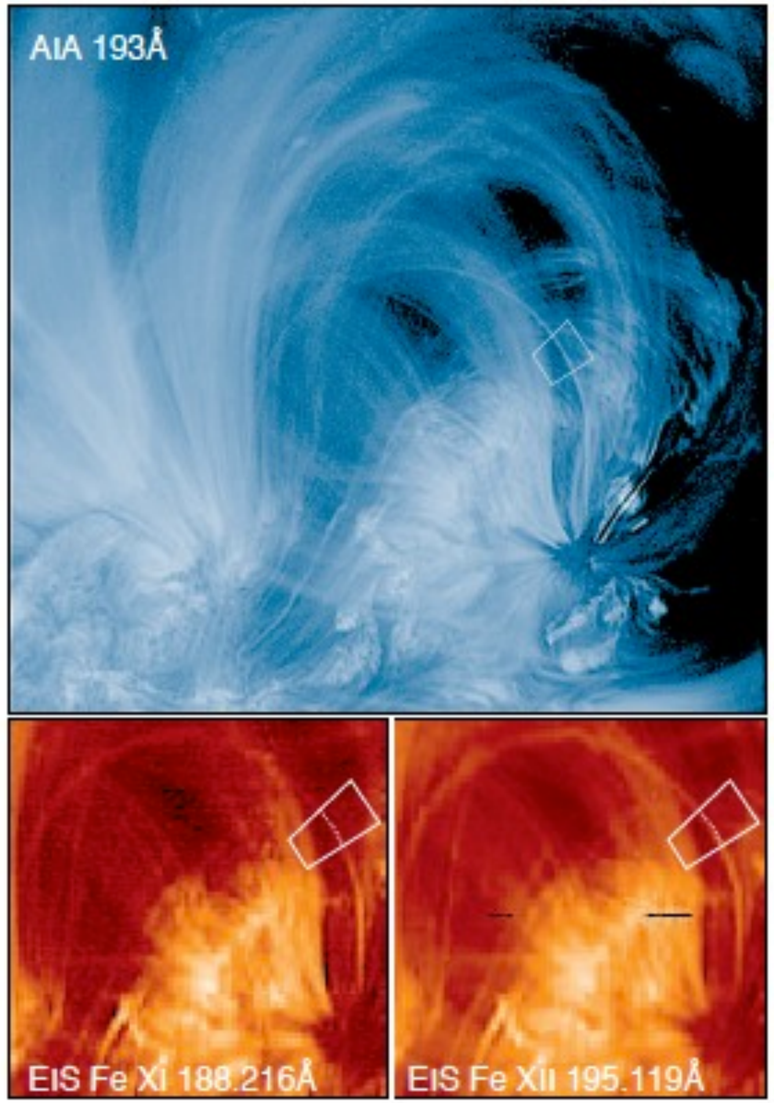
Long loops observed by Hi-C

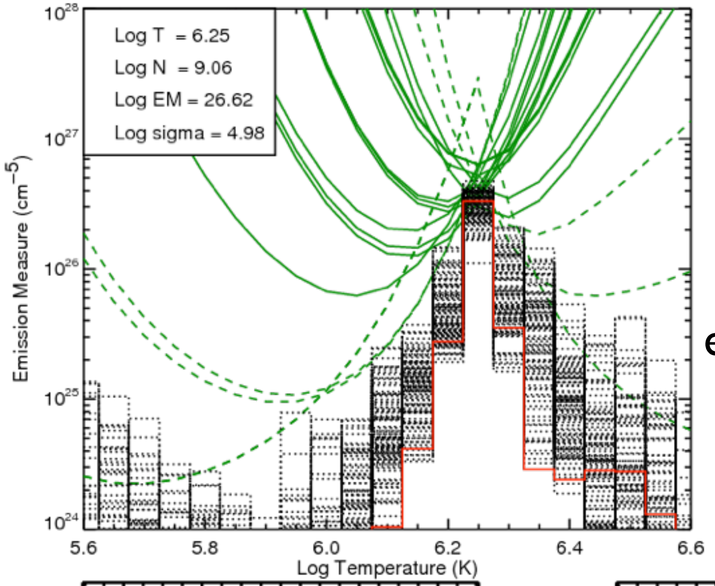
Could be monolithic structures?



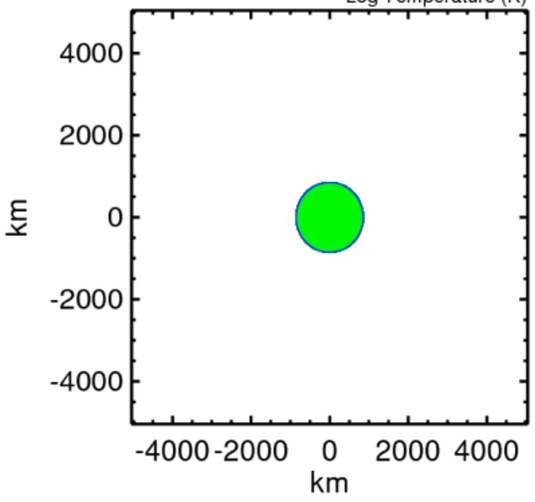
Peter et al (2013)

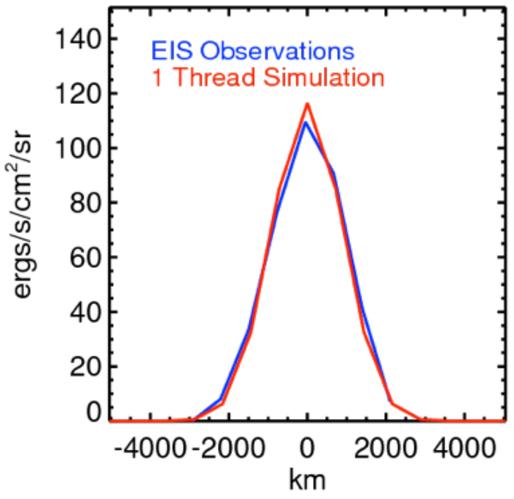
Data analysis - rare case

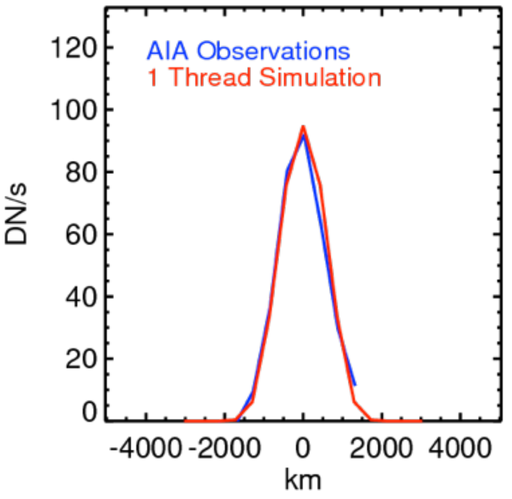




Resolved loop:
1 strand with 830 km radius
explains EIS and AIA intensities and widths

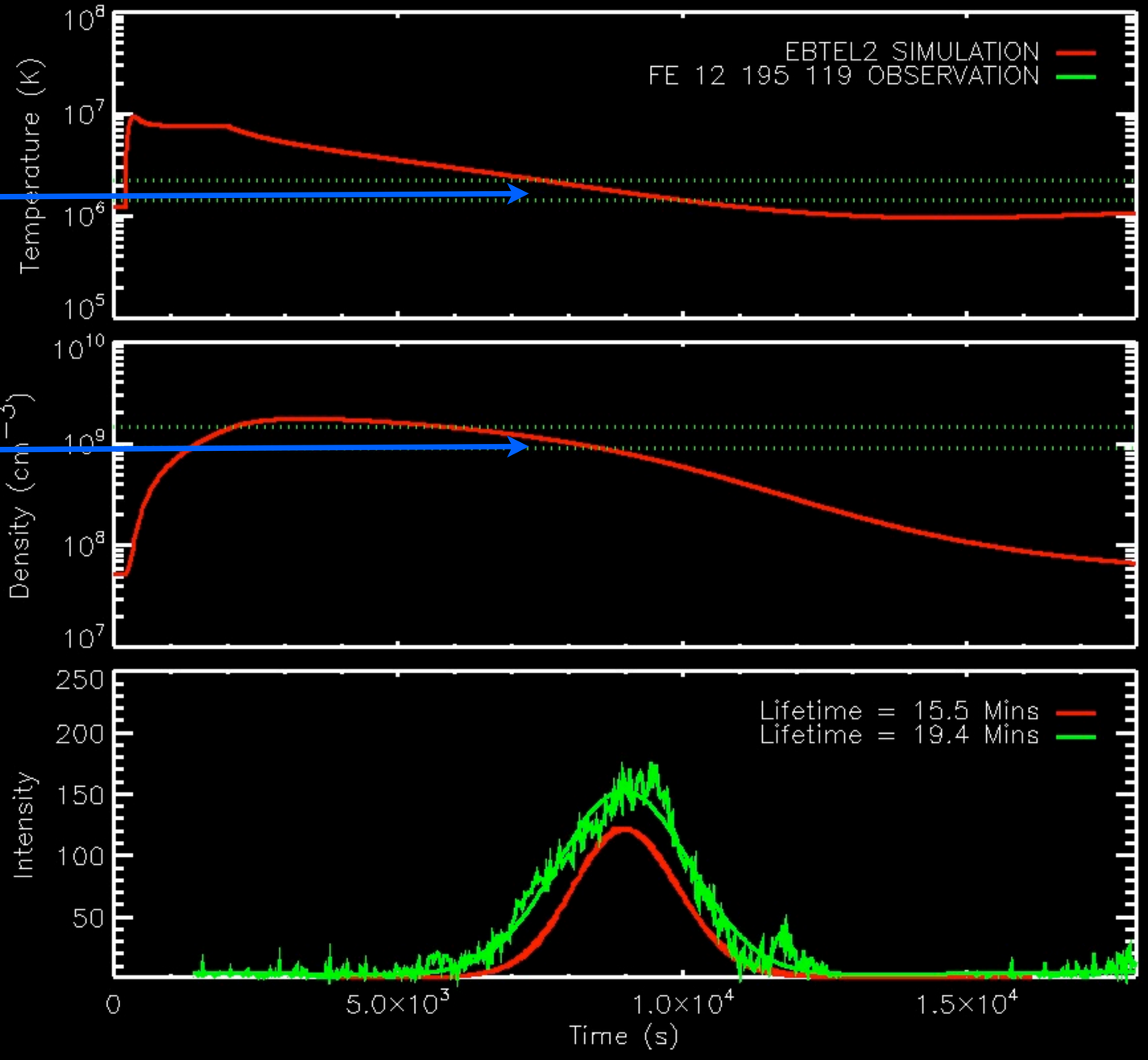






Consistent with single strand cooling time

Observed Temperature, Density, and Lifetime are matched!



Filling Factors Summary

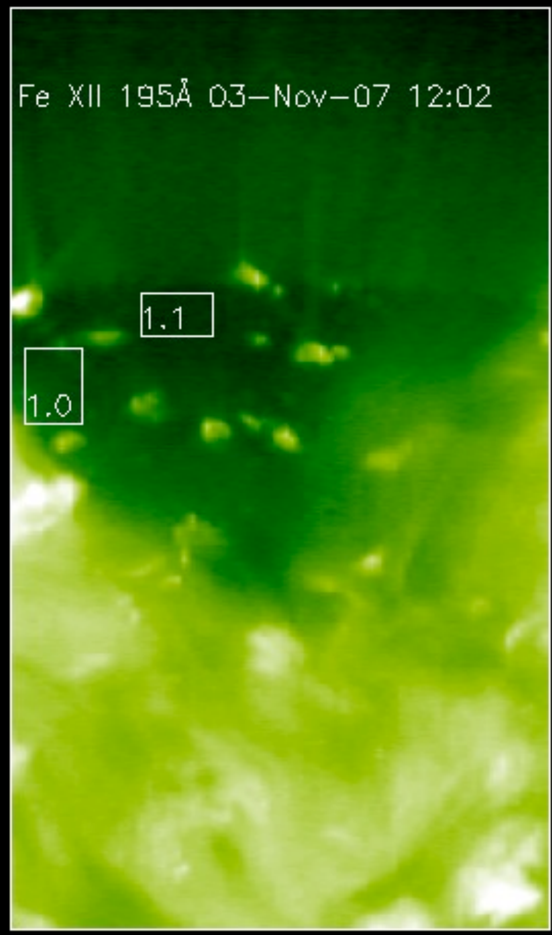
- Measurements have generally suggested sub-structure (loop filling factors 10%).
- Recent updates suggest these numbers are *too small* (should be 25-35%).
- Filling factor is heavily dependent on geometrical assumptions...
- Physical models suggest loops are composed of < 10 strands.
- The biggest (longest?) loops may be resolved by Hinode & AIA.
- Hi-C/Solar-C should resolve all EIS loops.

Abundances: What can they tell us?

- Hinode/EIS has opened a new era of well constrained, high spatial resolution measurements of elemental abundances.

Diagnostic potential investigated by Feldman et al (2009).

Photospheric Abundances in polar CH (Brooks & Warren 2011). Consistent with fast wind.



Abundances: What can they tell us?

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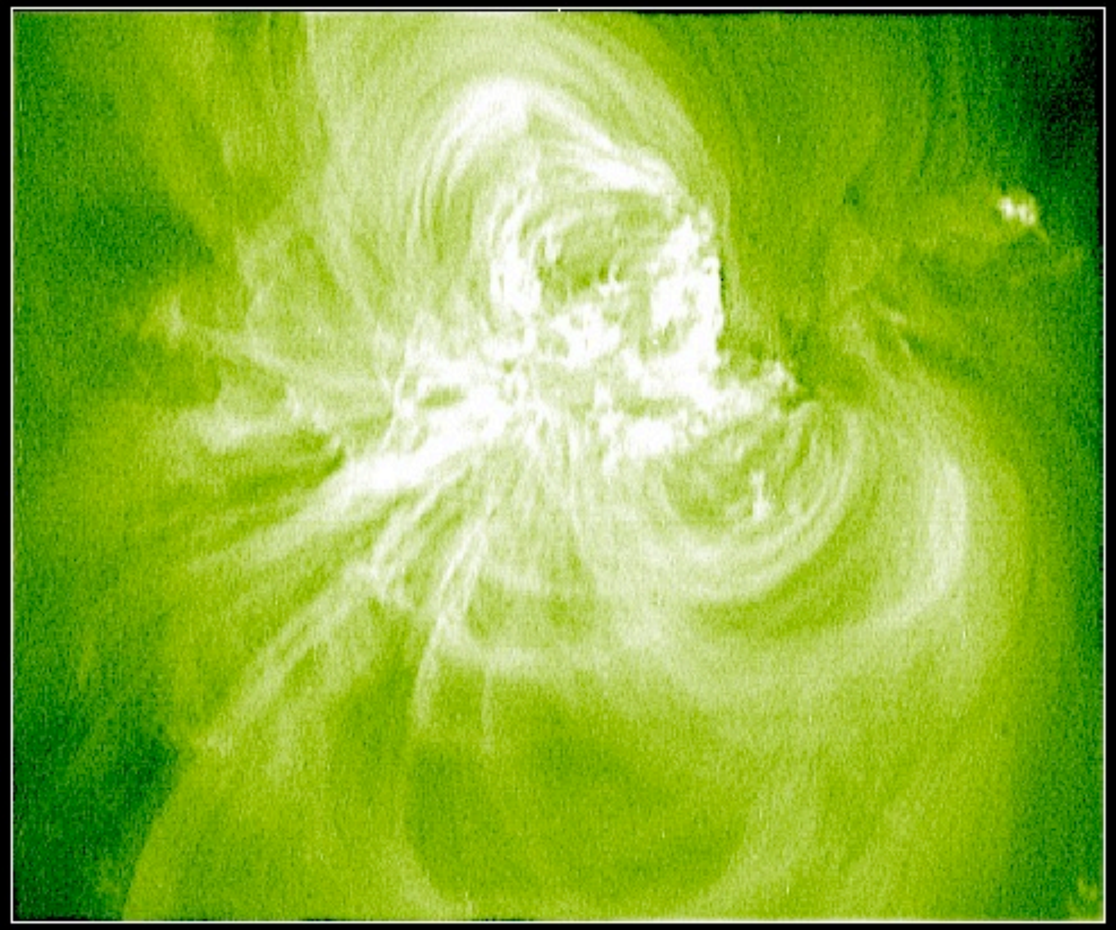
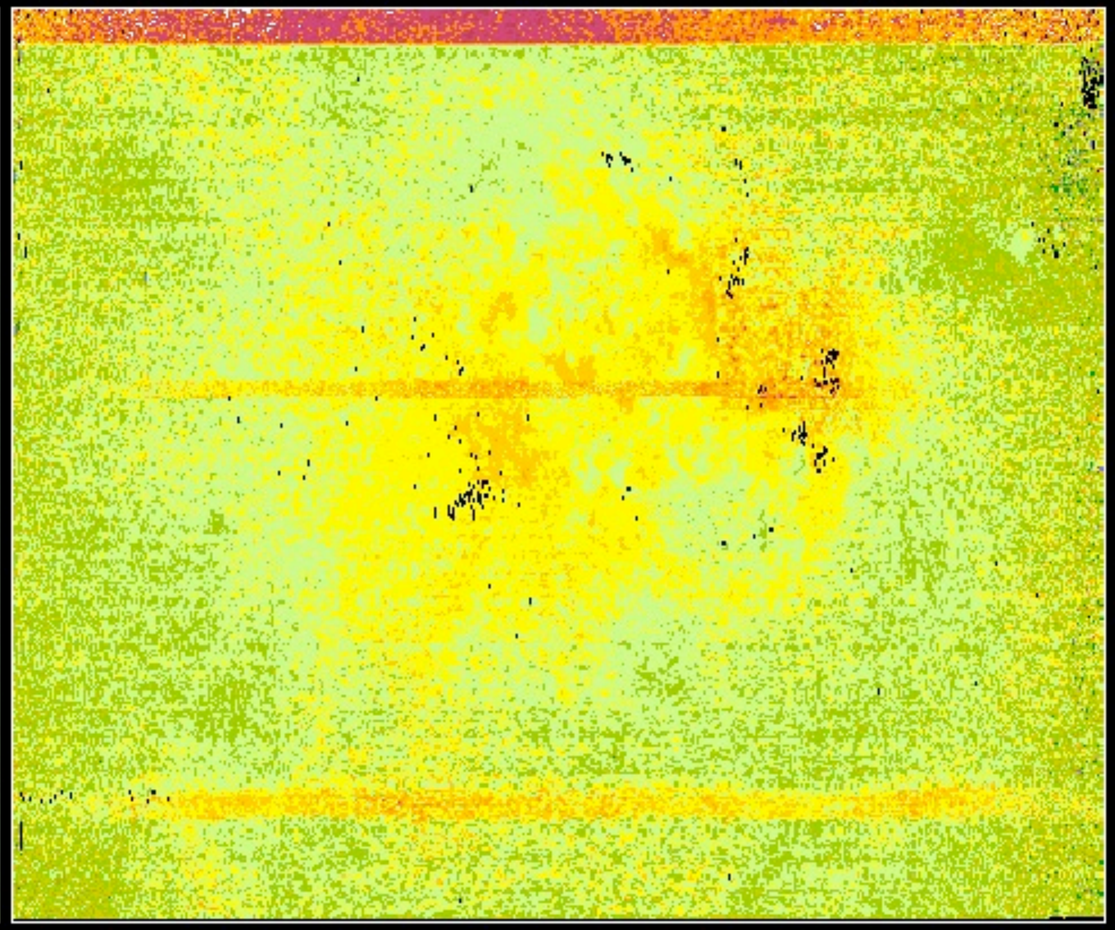


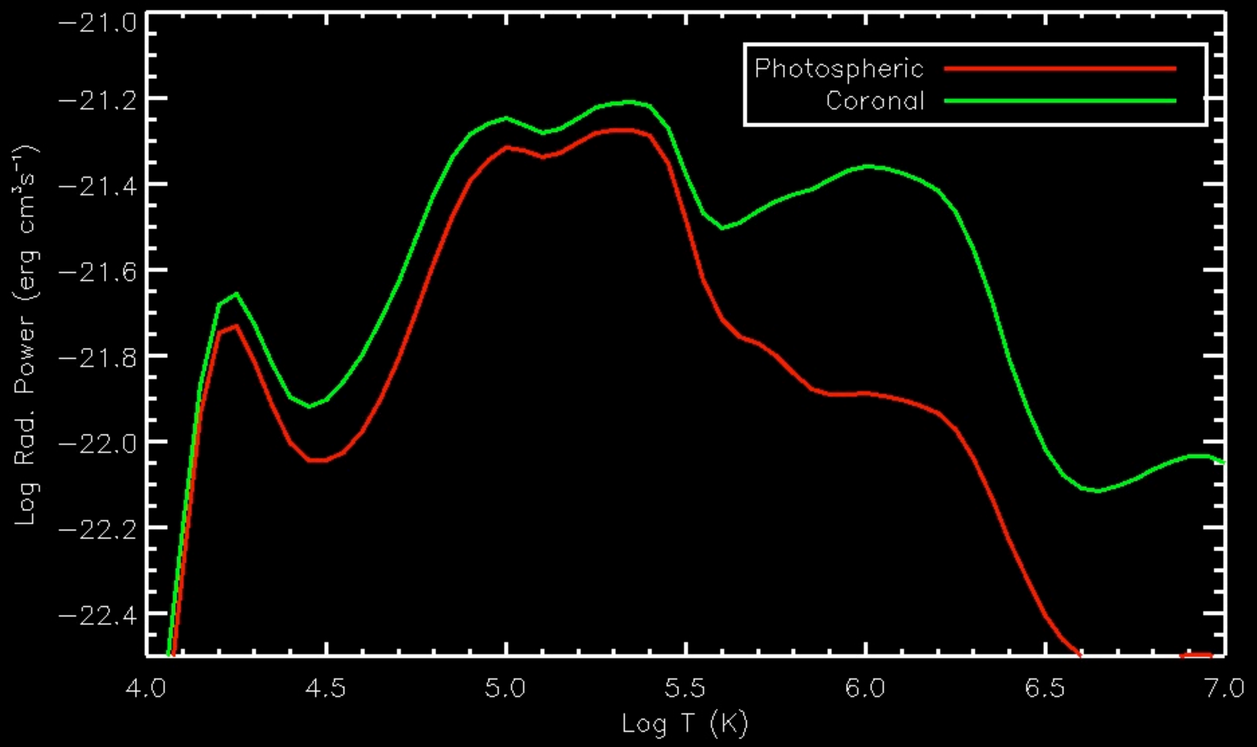
Fe XII Intensity

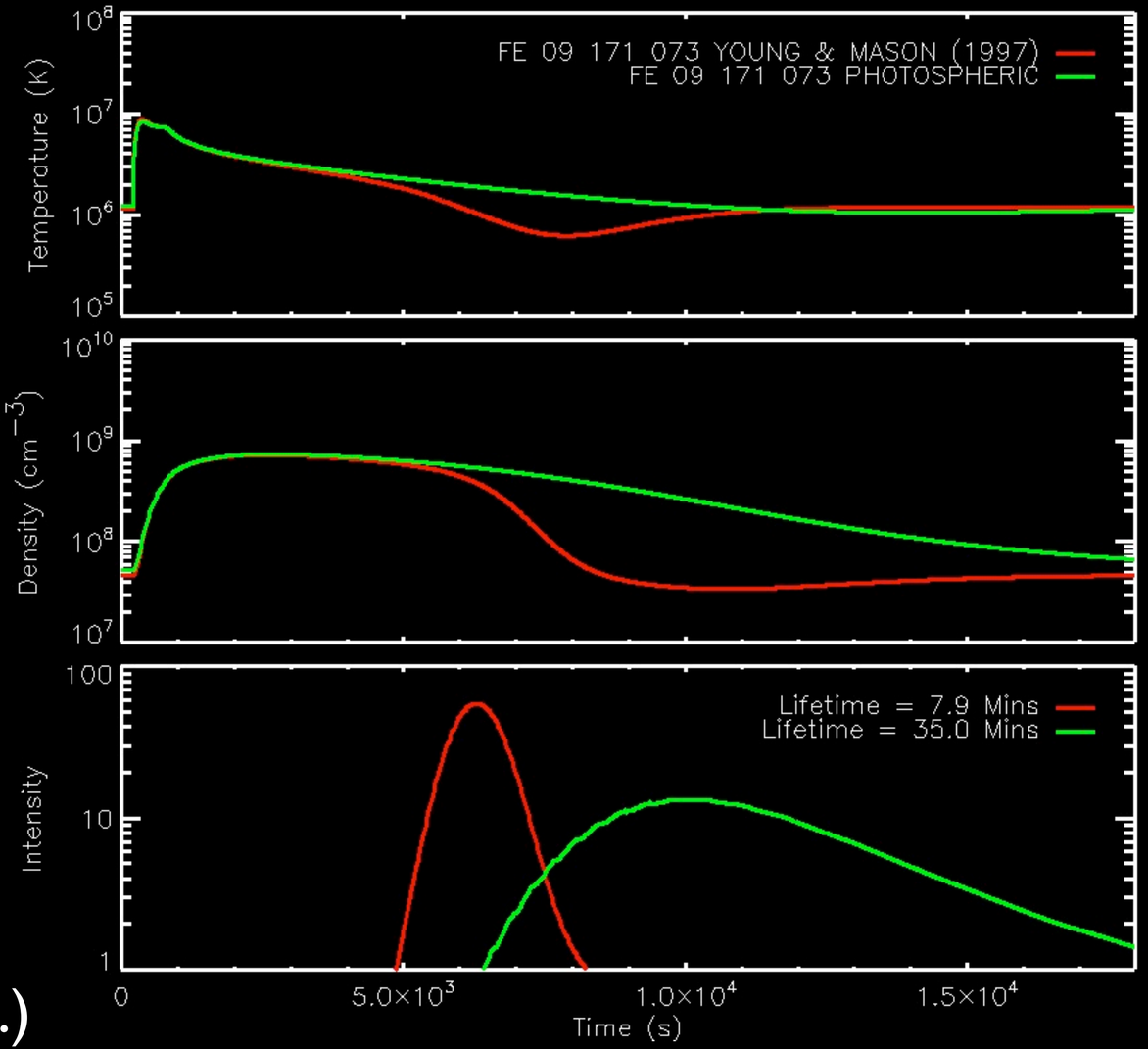


FIP Bias Map

Self Consistent Loop Modeling

EBTEL-2 (Cargill, Bradshaw, Klimchuk 2012)



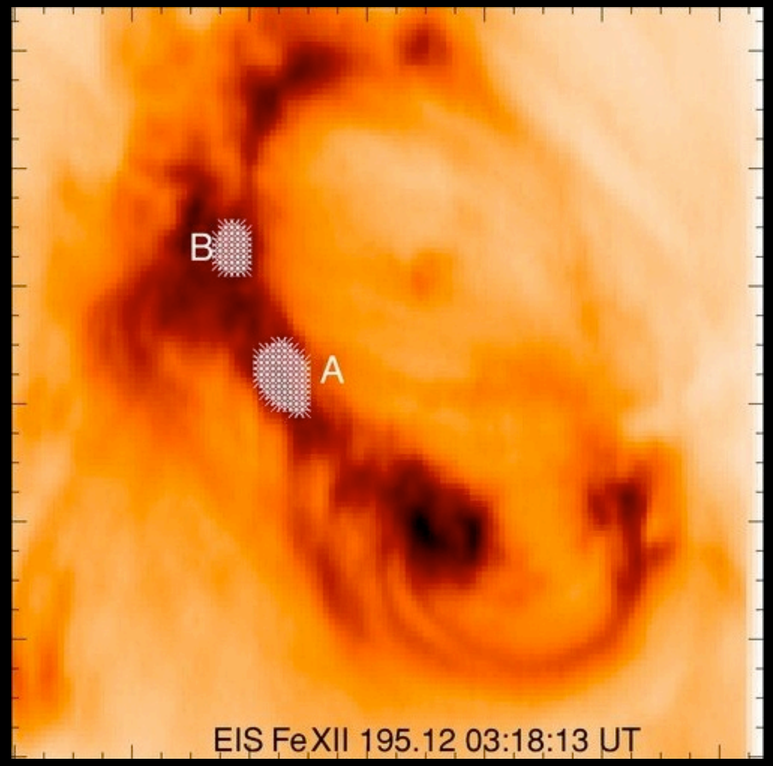


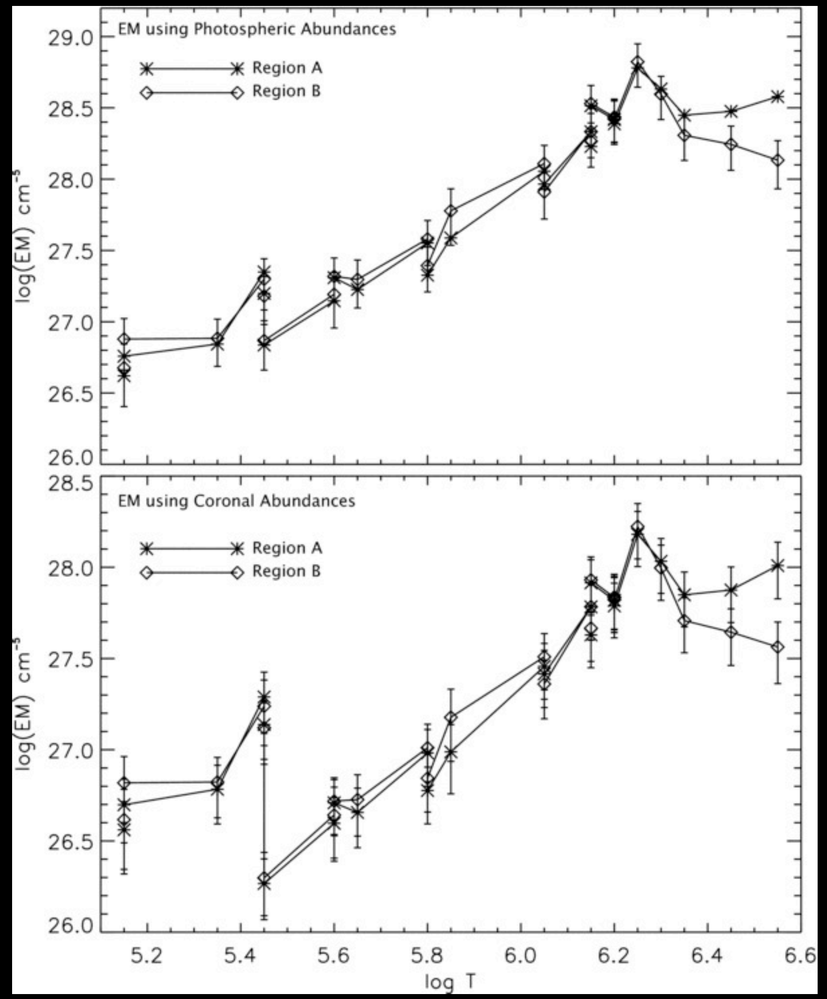
Modeling wih measured properties (L, n, T, abund.)

Loop lifetime extended/shortened by smaller/larger abundances & hence radiative losses.

Measurements in Active Regions

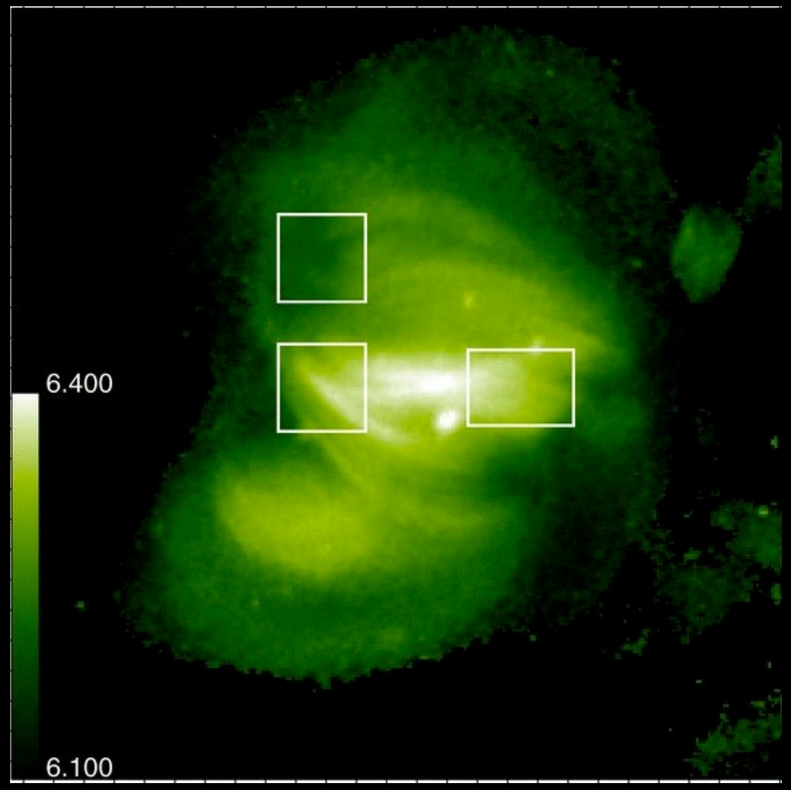
Photospheric abundances in moss (Tripathi et al 2010)

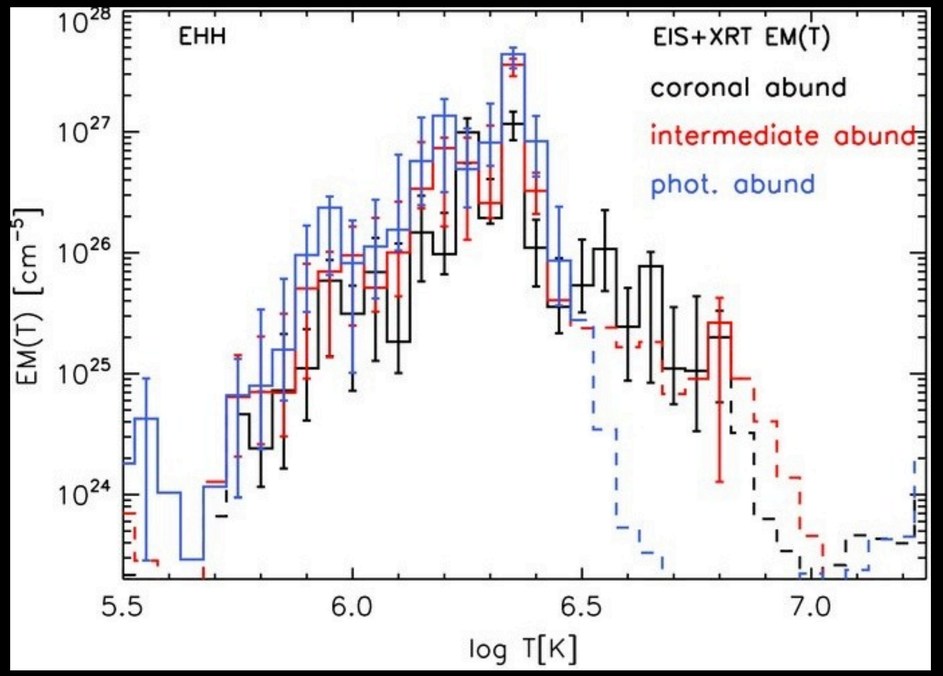




Measurements in Active Regions

Non-flaring AR: photospheric abundances in hot loops? (Testa et al 2011)

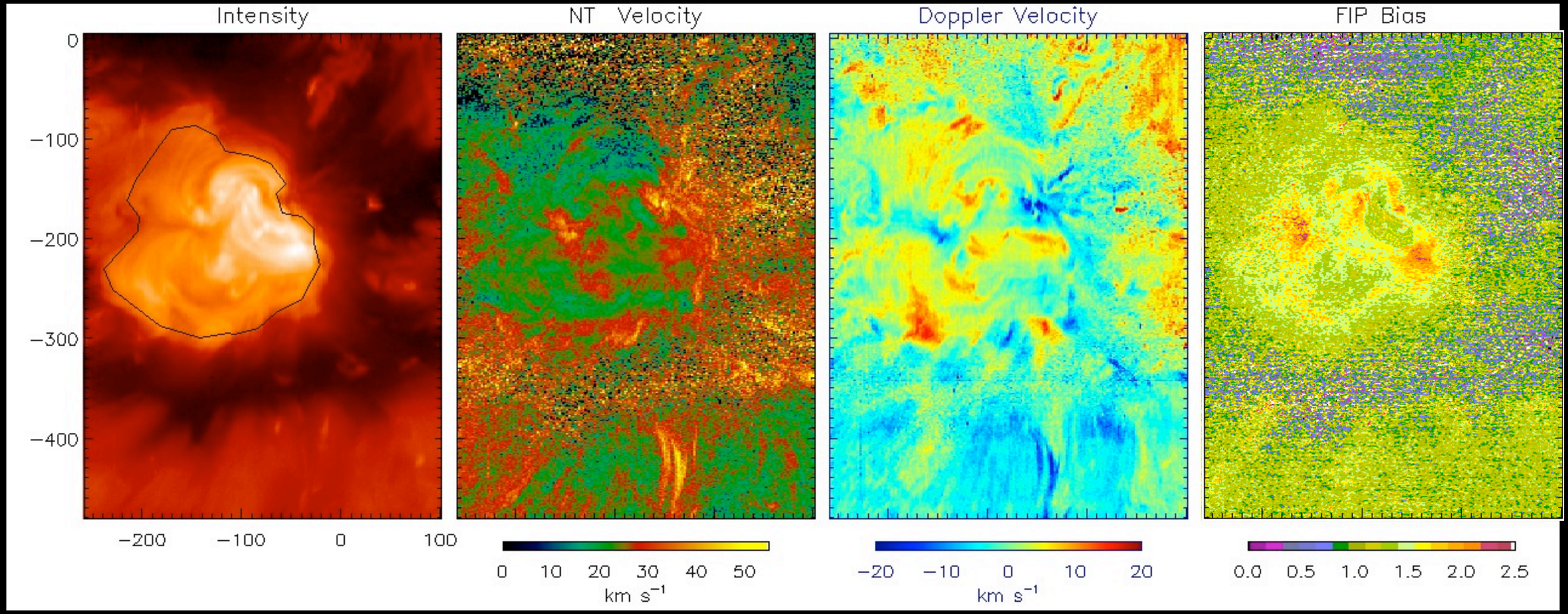




Del Zanna (2012) also found "low" S, Ar, abundances at high T in diffuse AR background

Evidence of Mixing Process/Location of Fractionation

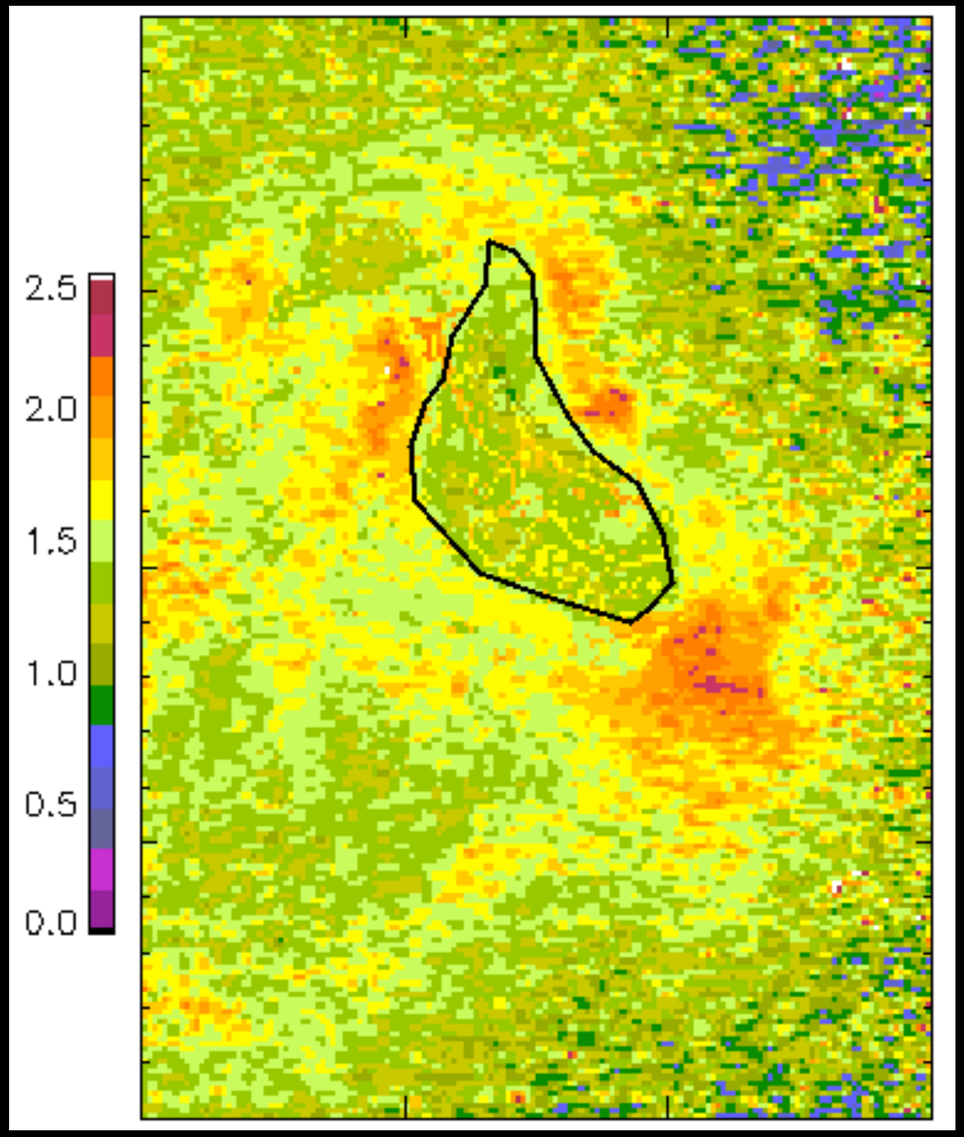
- Baker et al (2013) - Anemone AR emerging in an equatorial coronal hole



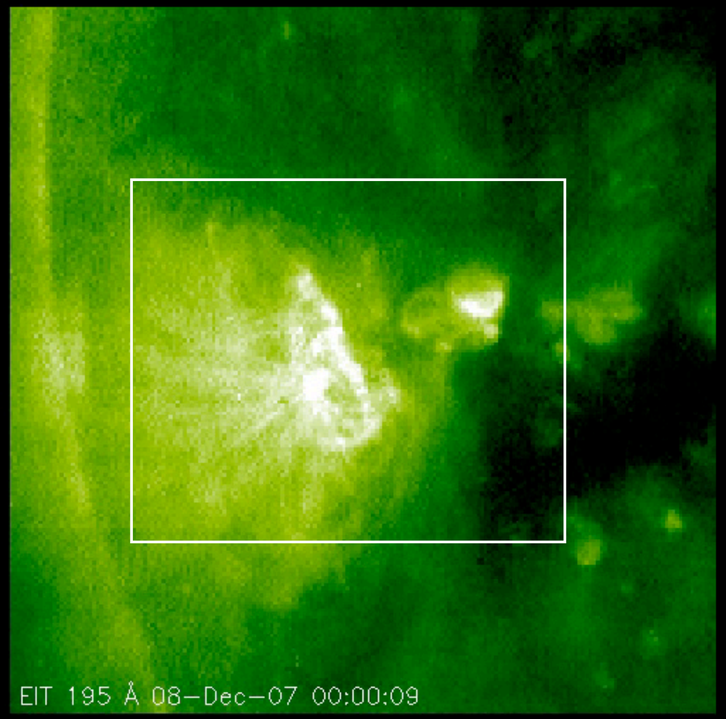
New Evidence of Bald Patch Topology?

Low FIP bias in channel where sigmoid is forming (Baker et al 2013)

If flux rope is forming low down, reconnection at bald patch heats and lifts up photospheric plasma (Green & Kliem 2009)

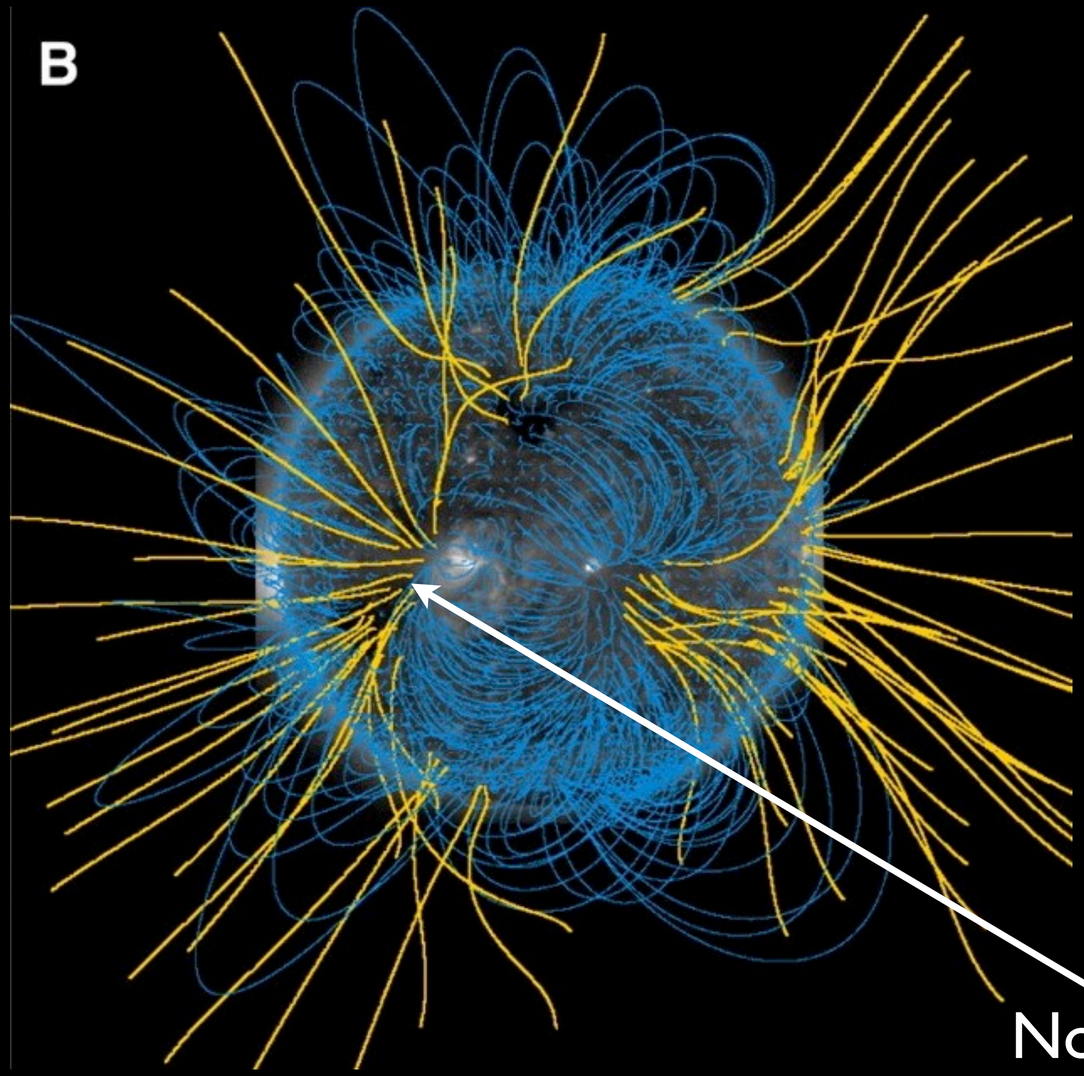


Tracer of Plasma Origin 1. Slow Solar Wind

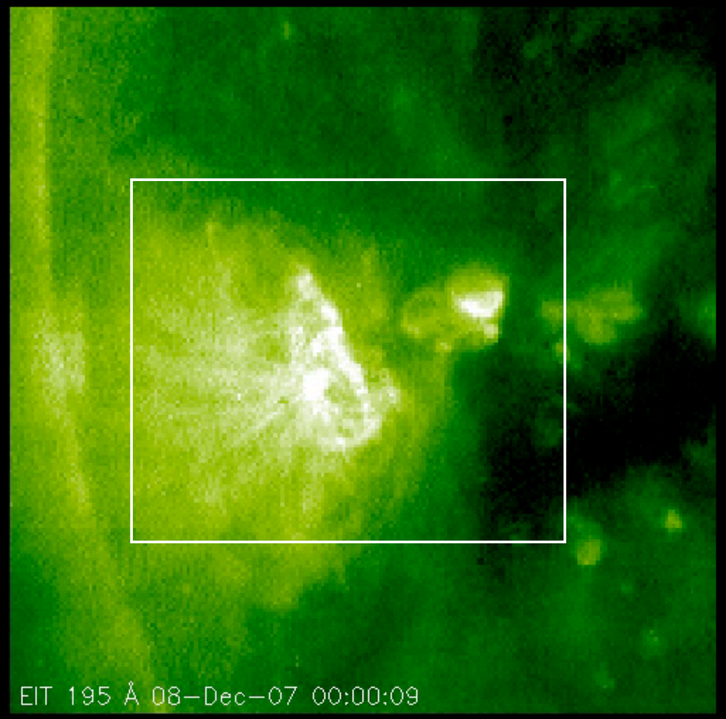


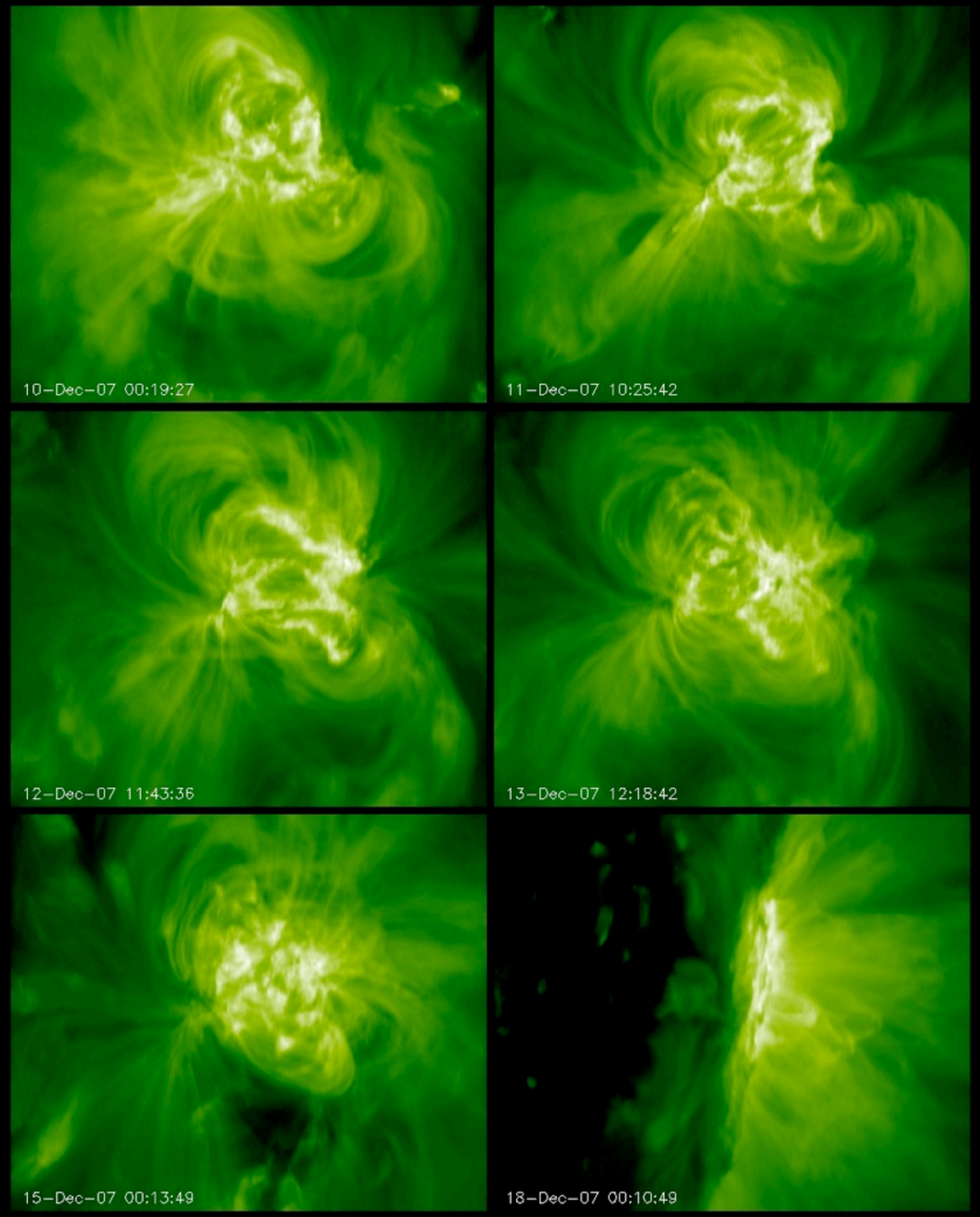
Brooks & Warren (2011)

- EIS "Detailed Map". Dec 8-18, 2007
  - -460″x384″ slit raster
  - -1″ slit, 40s exposures, ~5 hours
  - -Fe VIII - Fe XVI



Not strictly "magnetically closed corona"





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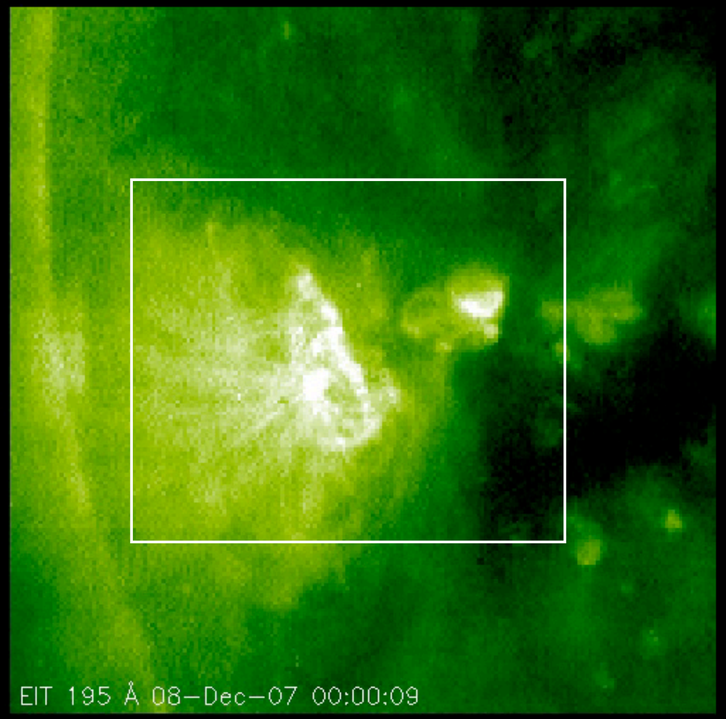

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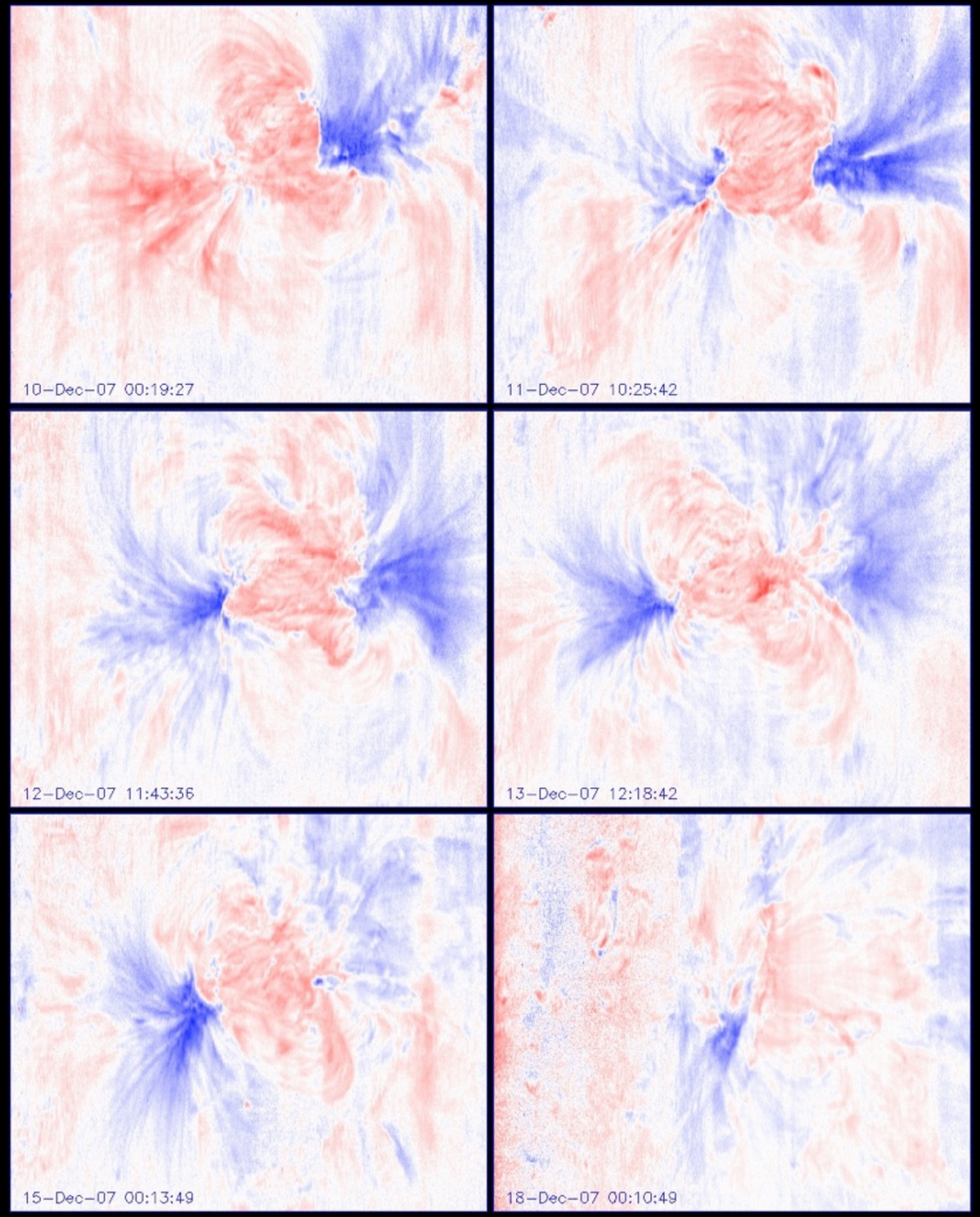


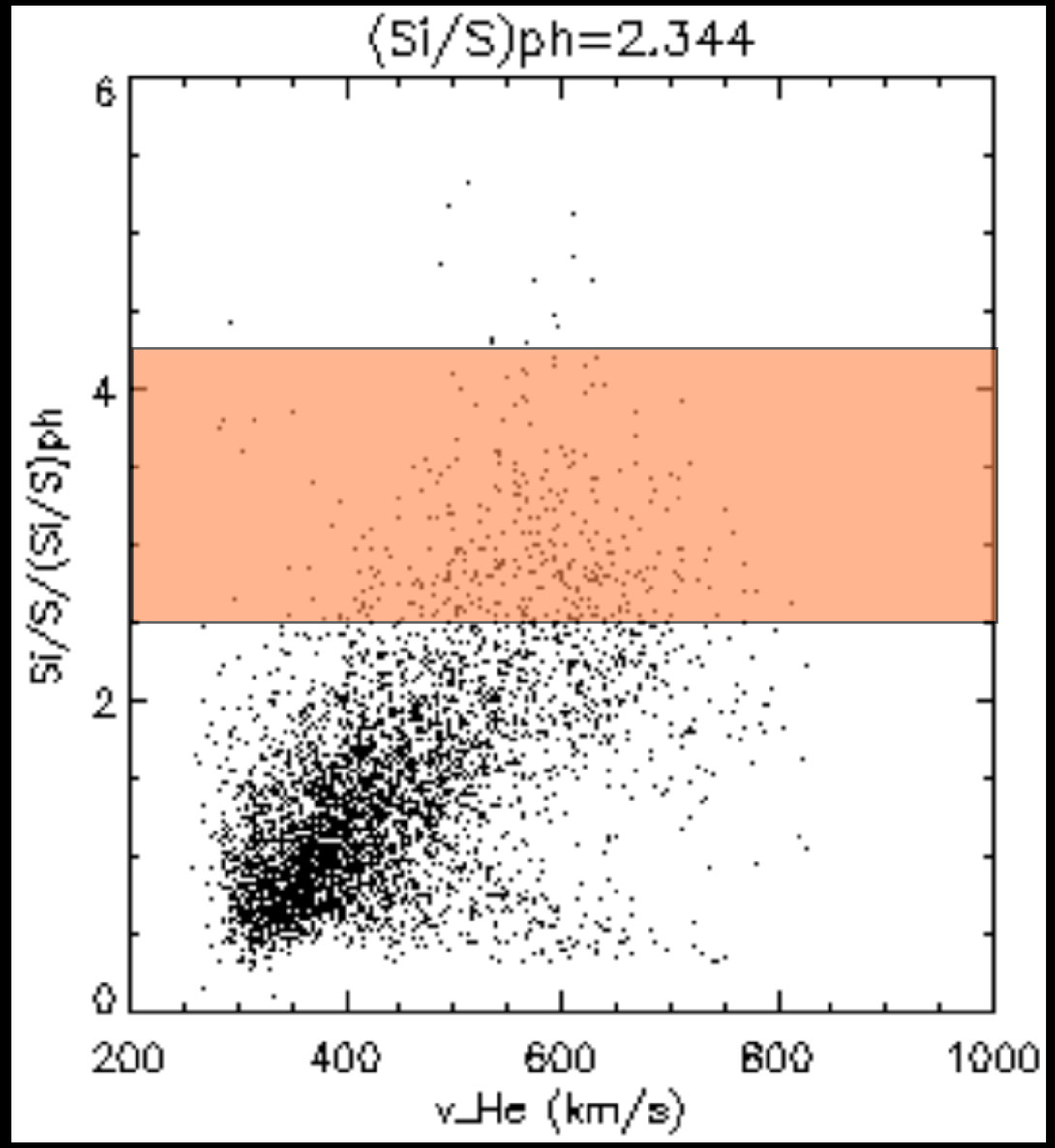
EIS Fe XII 195.119 Å

Composition of Outflows v In-Situ @ Earth

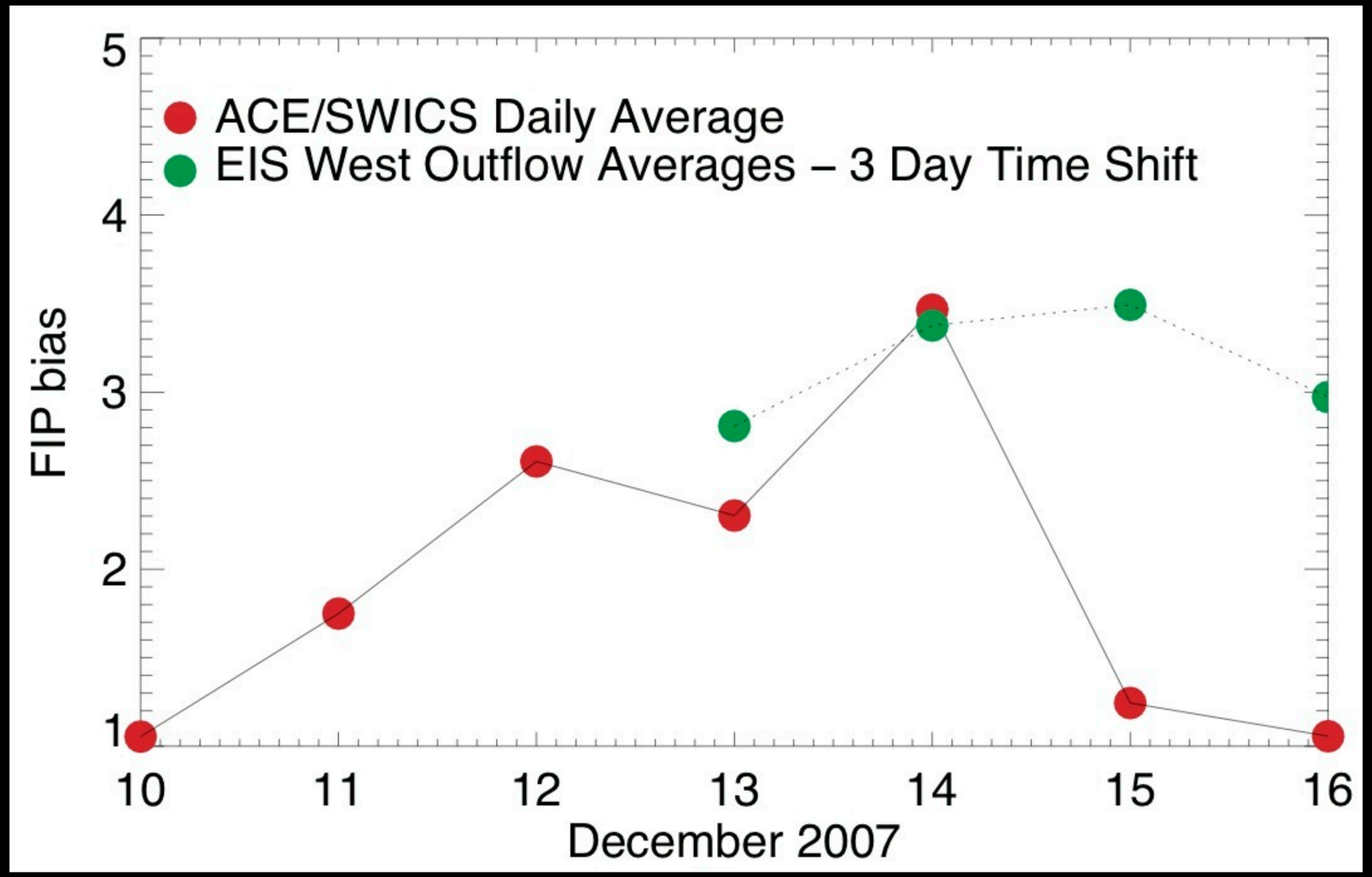
FIP enhancement factor is 3-4.

Consistent with slow wind values (Von Steiger 2000).

Outflows →

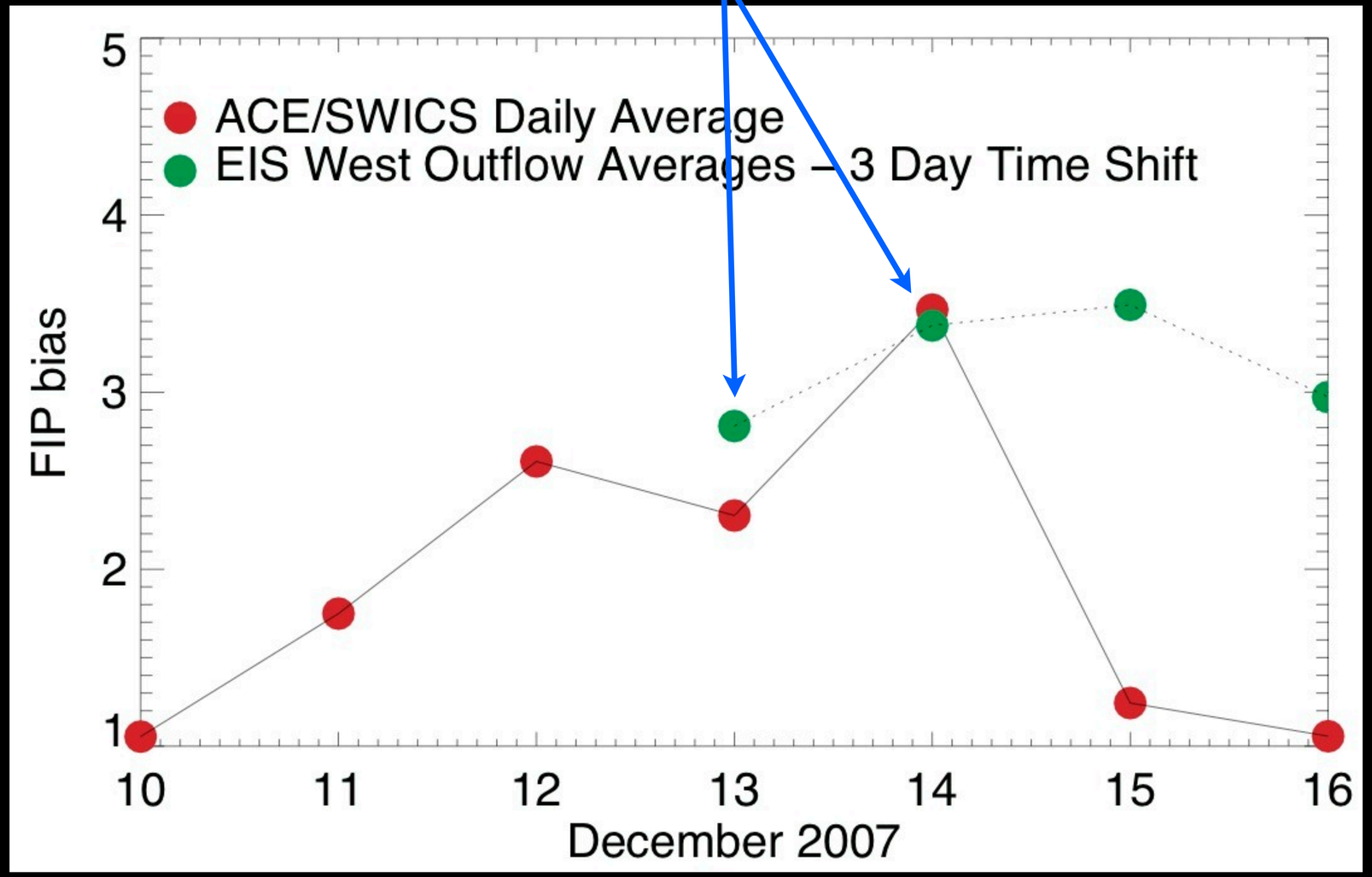


ACE/SWICS 1-day averages
Jan. 1998 - Feb. 2010



Composition of outflow plasma in this region is the same as the slow wind at Earth

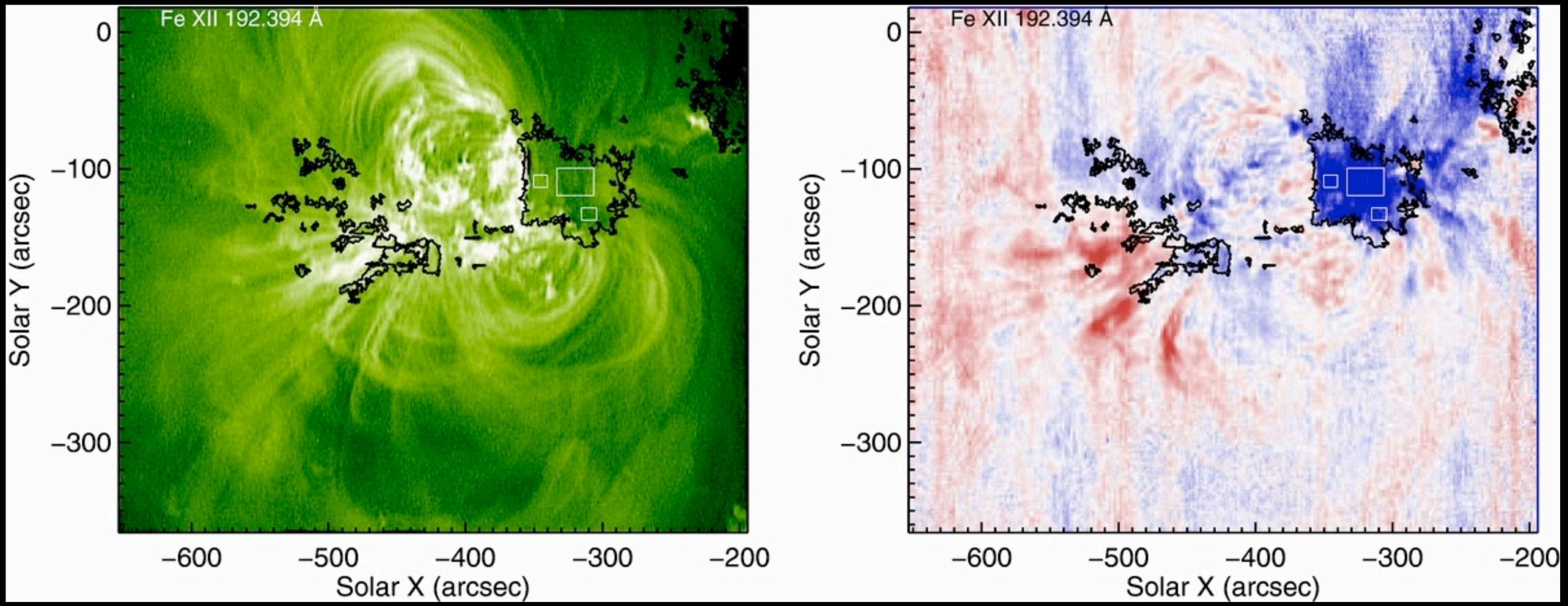
EIS data on Dec. 10-11 within 20% of SWICS on Dec. 13-14.



Composition of outflow plasma in this region is the same as the slow wind at Earth

Tracer of Plasma Origin II. Coronal Line Asymmetries

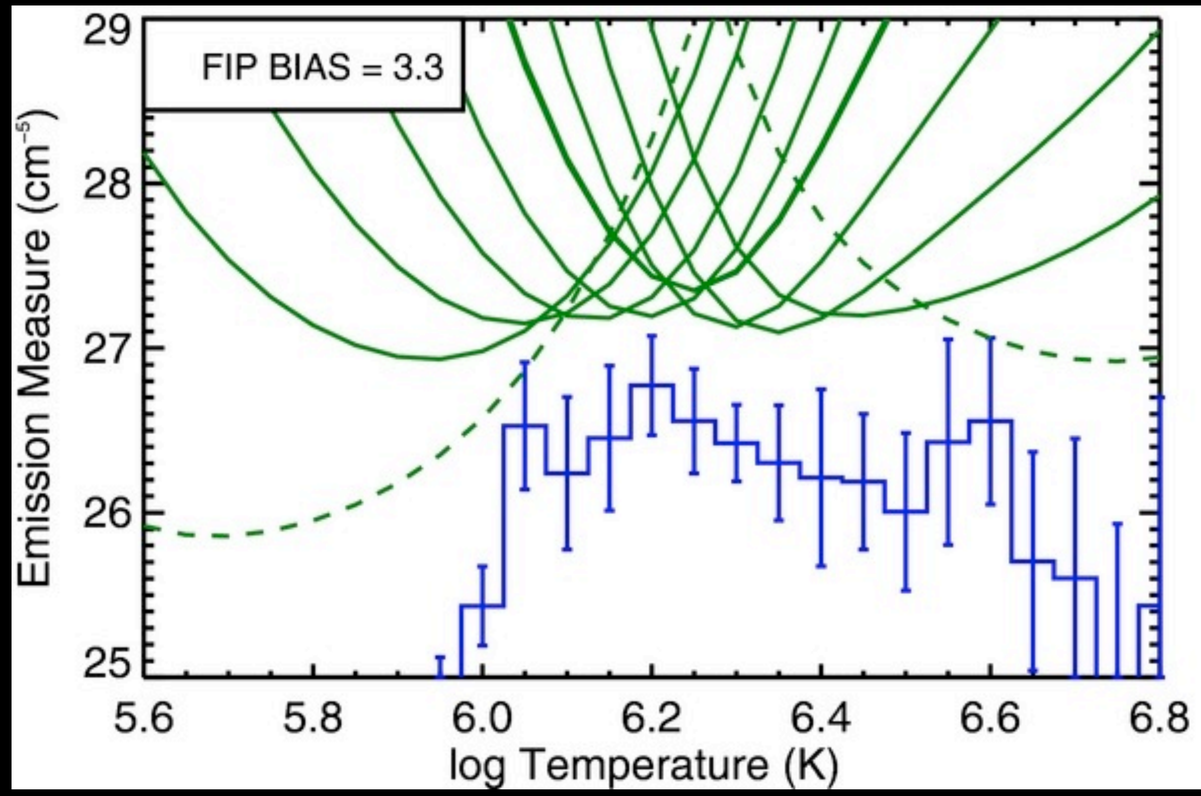
Locations of asymmetric profiles in the same region



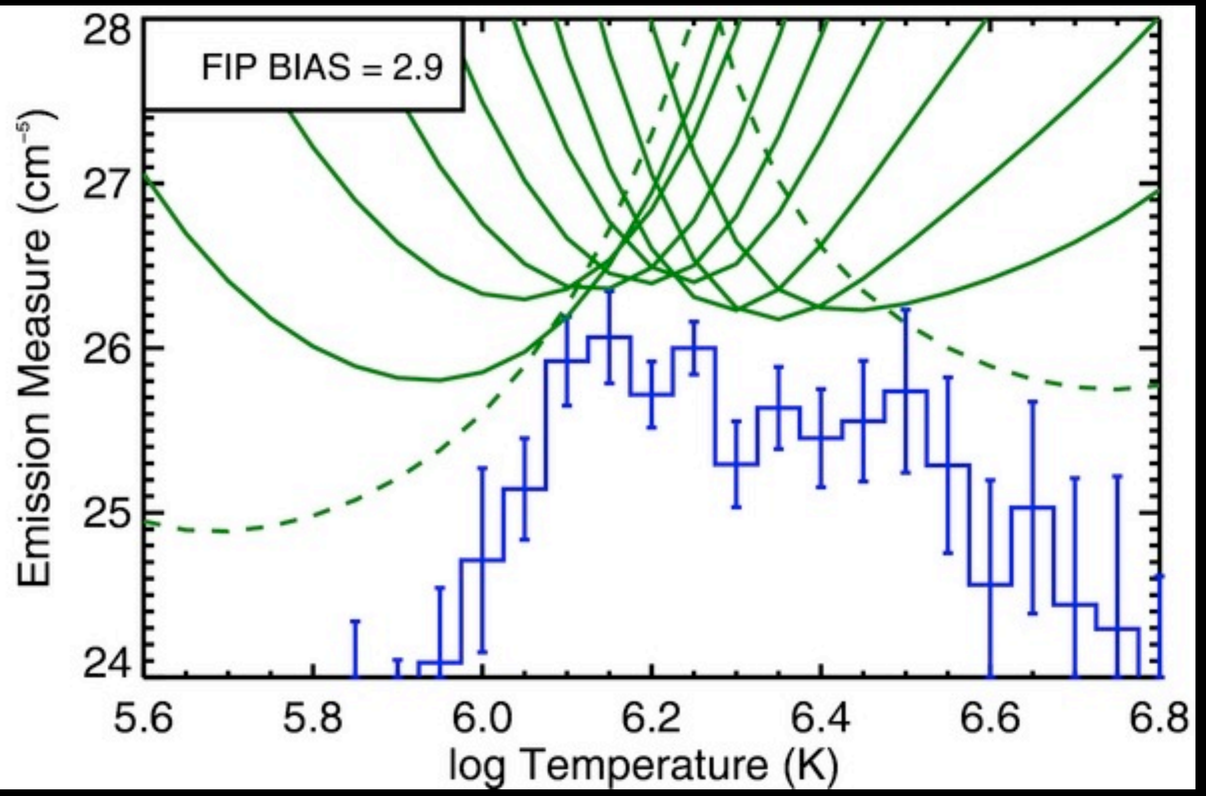
Brooks & Warren (2012)

Tracer of Plasma Origin II. Coronal Line Asymmetries

DEMs for bulk outflow and blue wing are dominated by coronal emission and the FIP bias is similar.



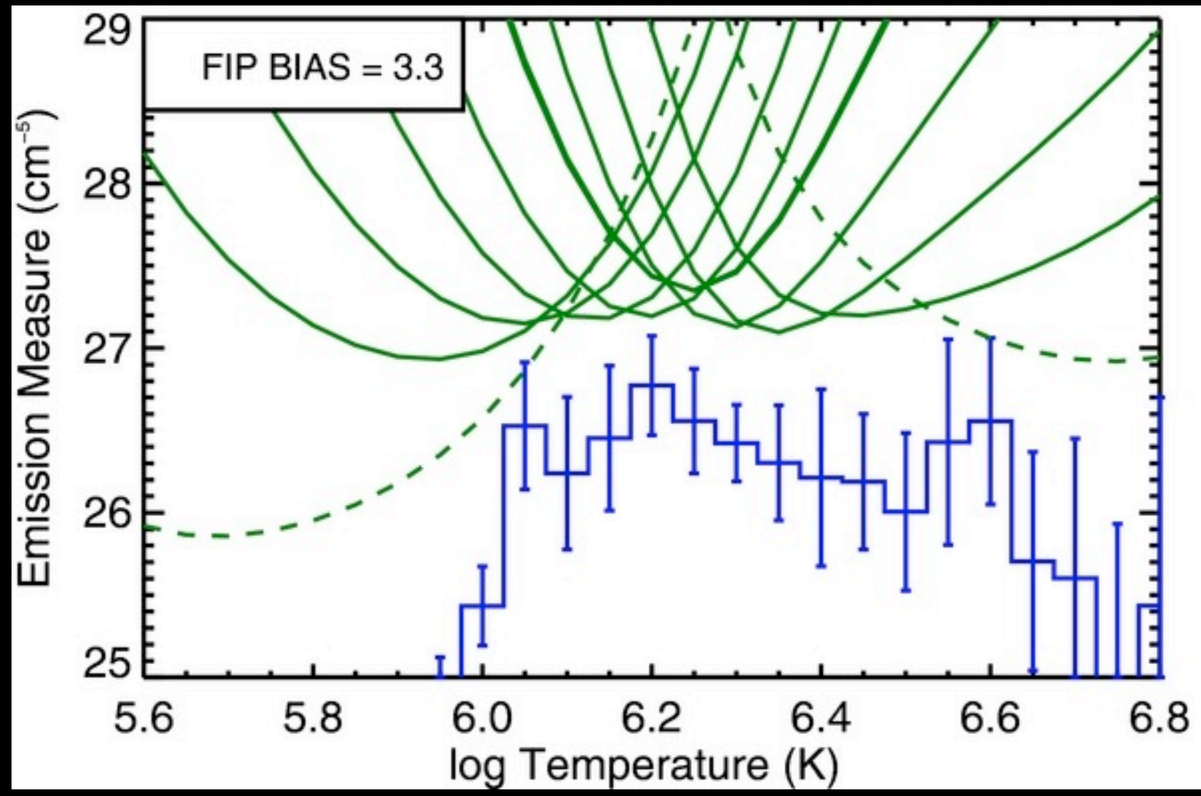
Bulk Outflow



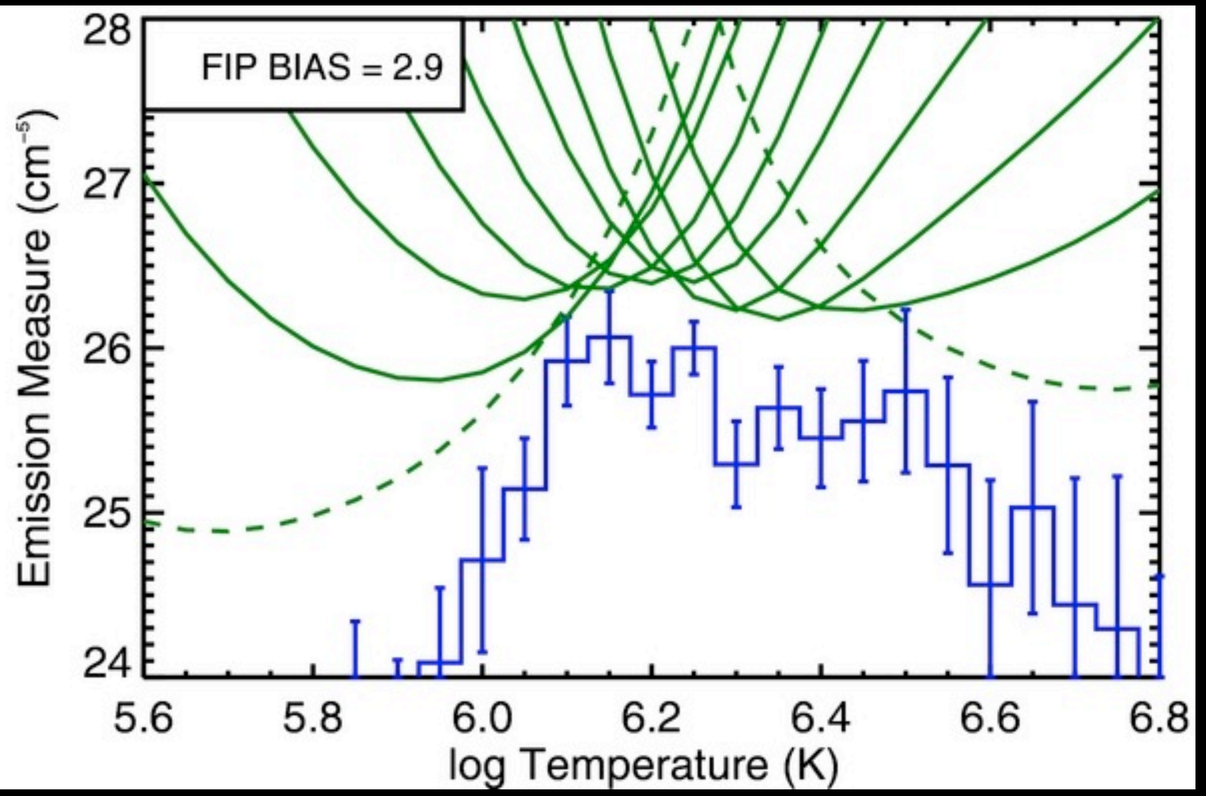
Blue wing

Tracer of Plasma Origin II. Coronal Line Asymmetries

Asymmetries produced by *coronal* plasma. Casts doubt on type II spicule explanation.



Bulk Outflow



Blue wing

Elemental Abundances Summary

- High spatial and spectral resolution measurements can trace loop filling process, magnetic topology, plasma source.
- Self-consistent modeling.
- New observational information. Largely unexplored field...

Conclusions

- Coronal loops observed at 1000km spatial scales are unresolved, multi-stranded, and mildly multi-thermal. “Multi-stranded” means “A few strands”.

- Strands observed at 100km spatial scales are probably resolved monolithic structures and isothermal...

- Heating mechanism should explain coherent evolution of a few threads, on spatial scales of hundreds of km.

- Corona is nearly isothermal over hundreds to thousands of km!

- Abundances are important and useful!

The End