FUV studies of the hot and warm intracluster gas in M87

Mike Anderson
MPA
michevan@mpa-garching.mpg.de

Anderson and Sunyaev (2016)
MNRAS, 459, 2806

Anderson and Sunyaev (2017)
submitted to arXiv next week

Galaxy Clusters 2017
5 July 2017

Outline

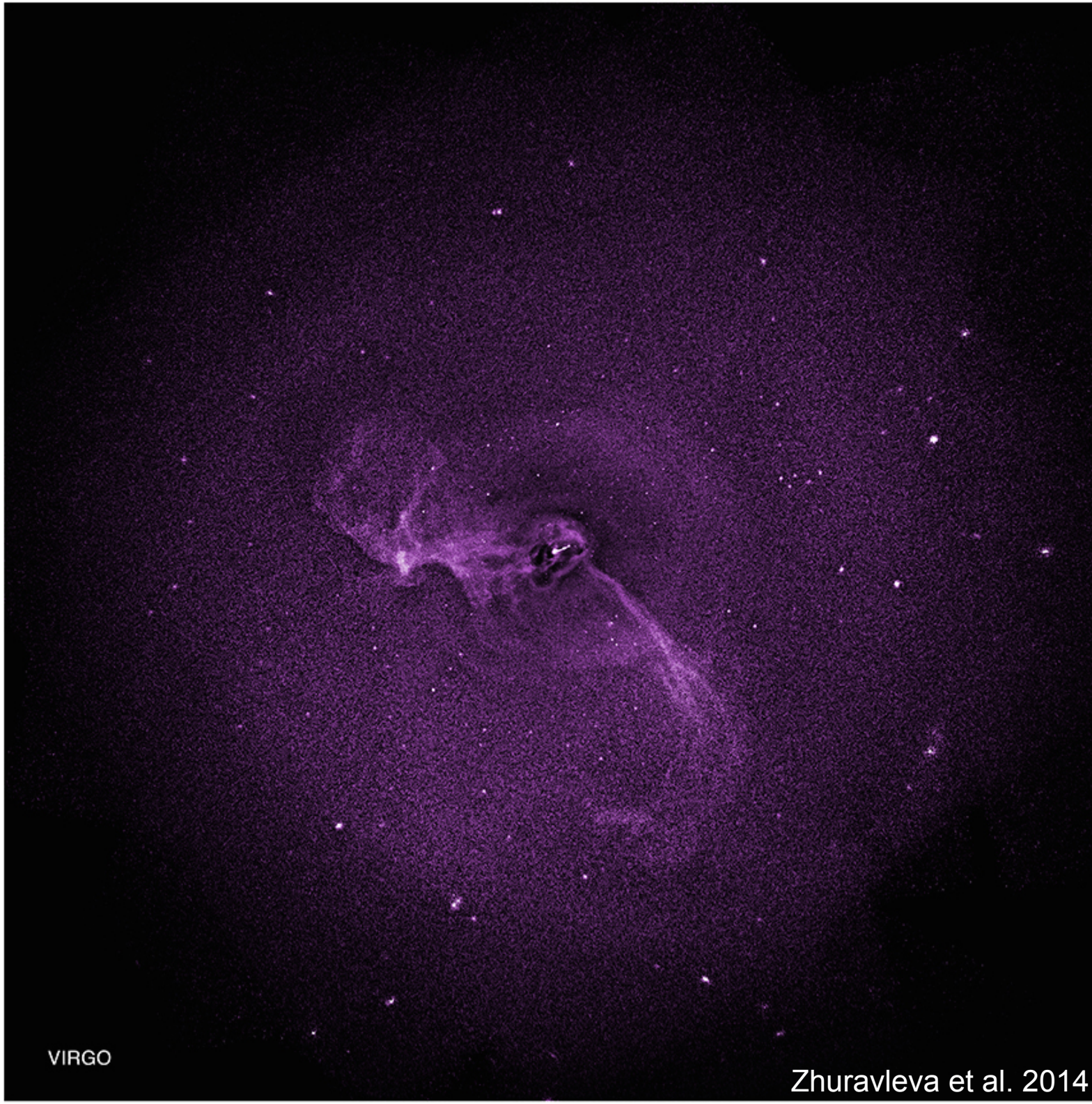
- Review Hα filaments in M87

- Introduce the [Fe XXI] 1354A transition

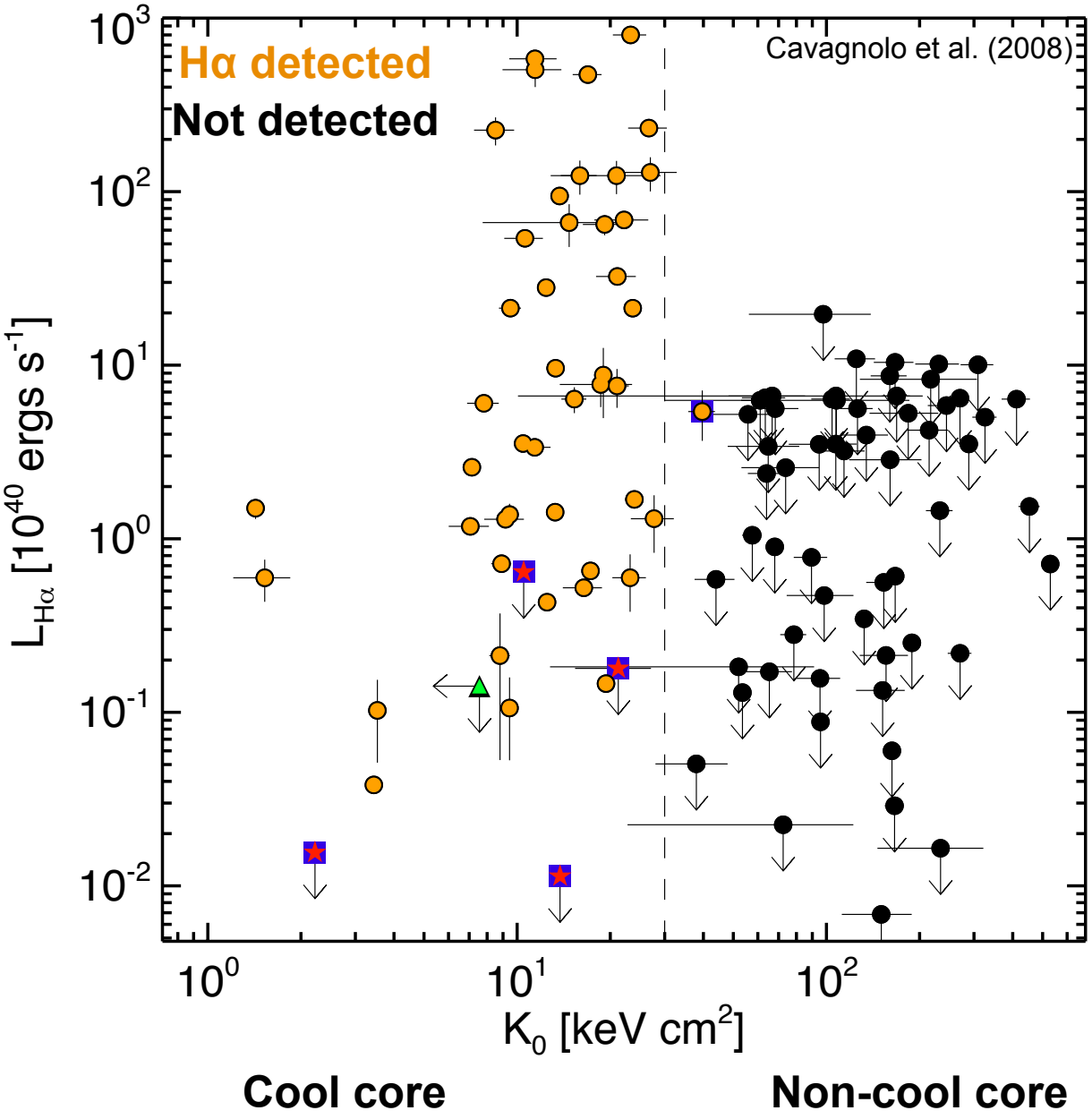
- Present new HST/COS spectra of M87 filament

- Discuss excitation mechanism of FUV and optical line emission

- Physical picture of multiphase M87 ISM



Hα in Galaxy Clusters



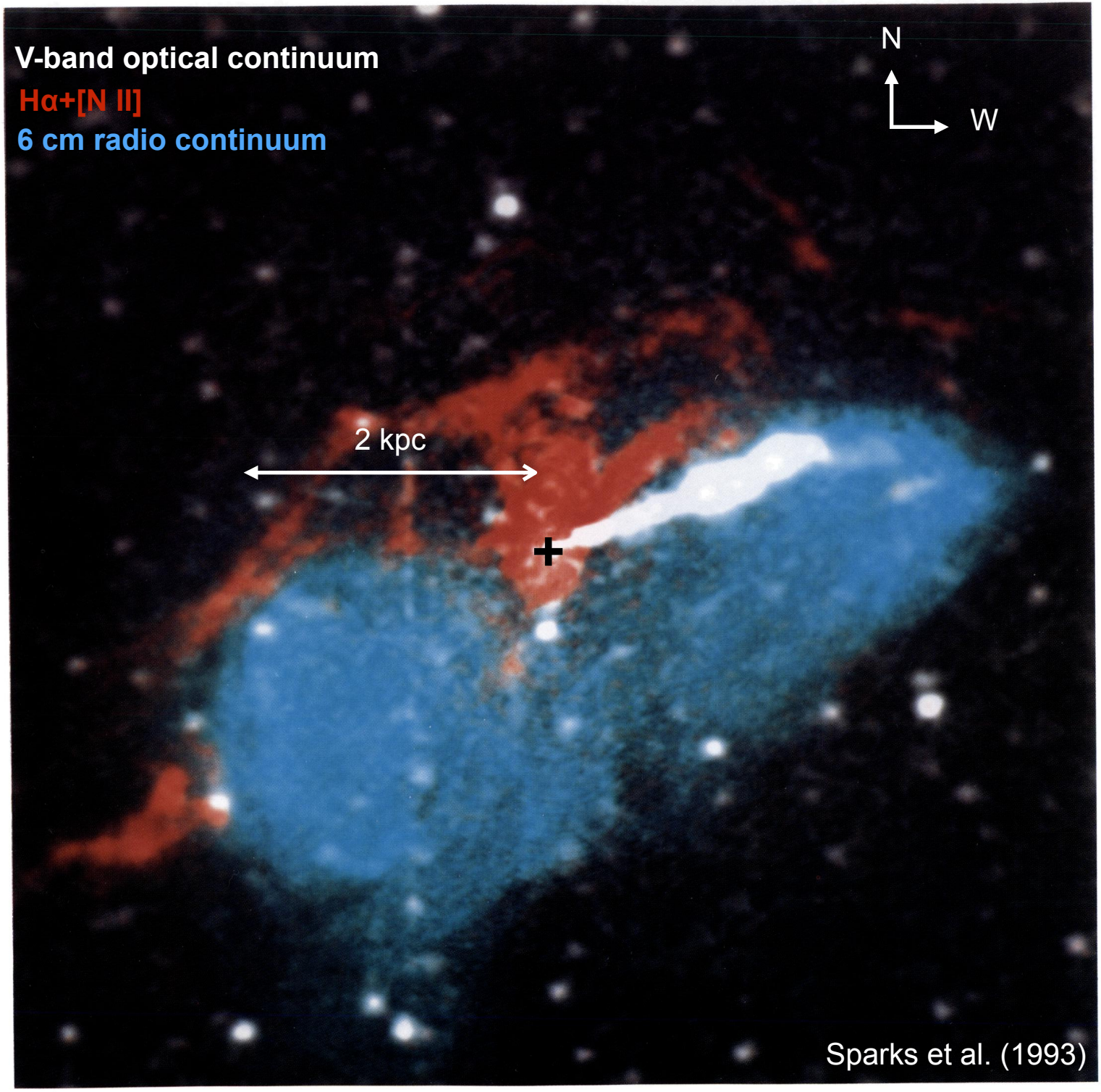
- Hα is associated with ICM cooling

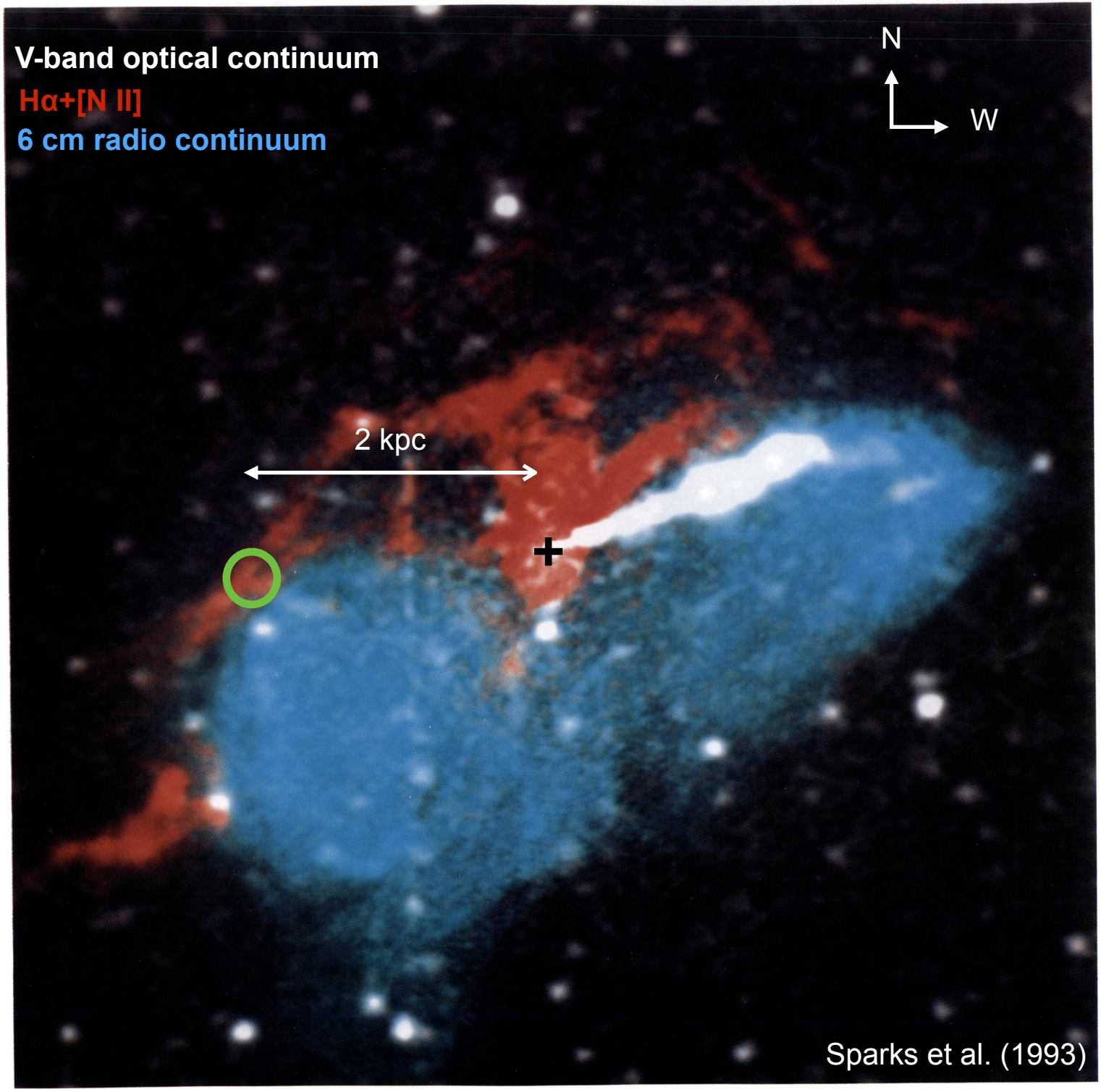
- Usually organized into filamentary structures

- Filaments often, but not always, are actively forming stars

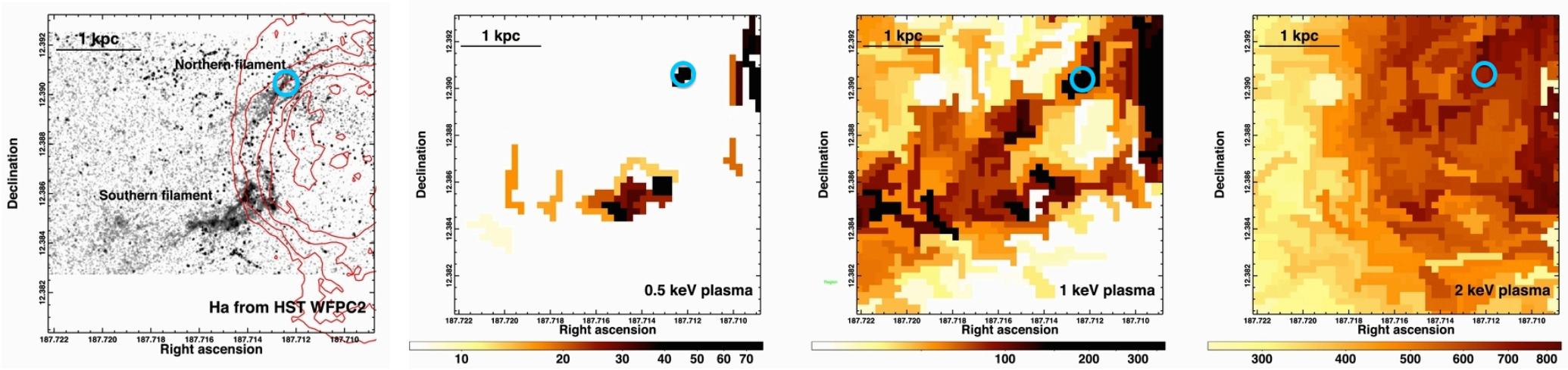
- Cooling is unstable; filaments should grow into cooling flows but this is not observed

- AGN feedback?


V-band optical continuum
Hα+[N II]
6 cm radio continuum
N
W
2 kpc
Sparks et al. (1993)


V-band optical continuum
Hα+[N II]
6 cm radio continuum
N
W
2 kpc
Sparks et al. (1993)

Filamentary Structure in M87

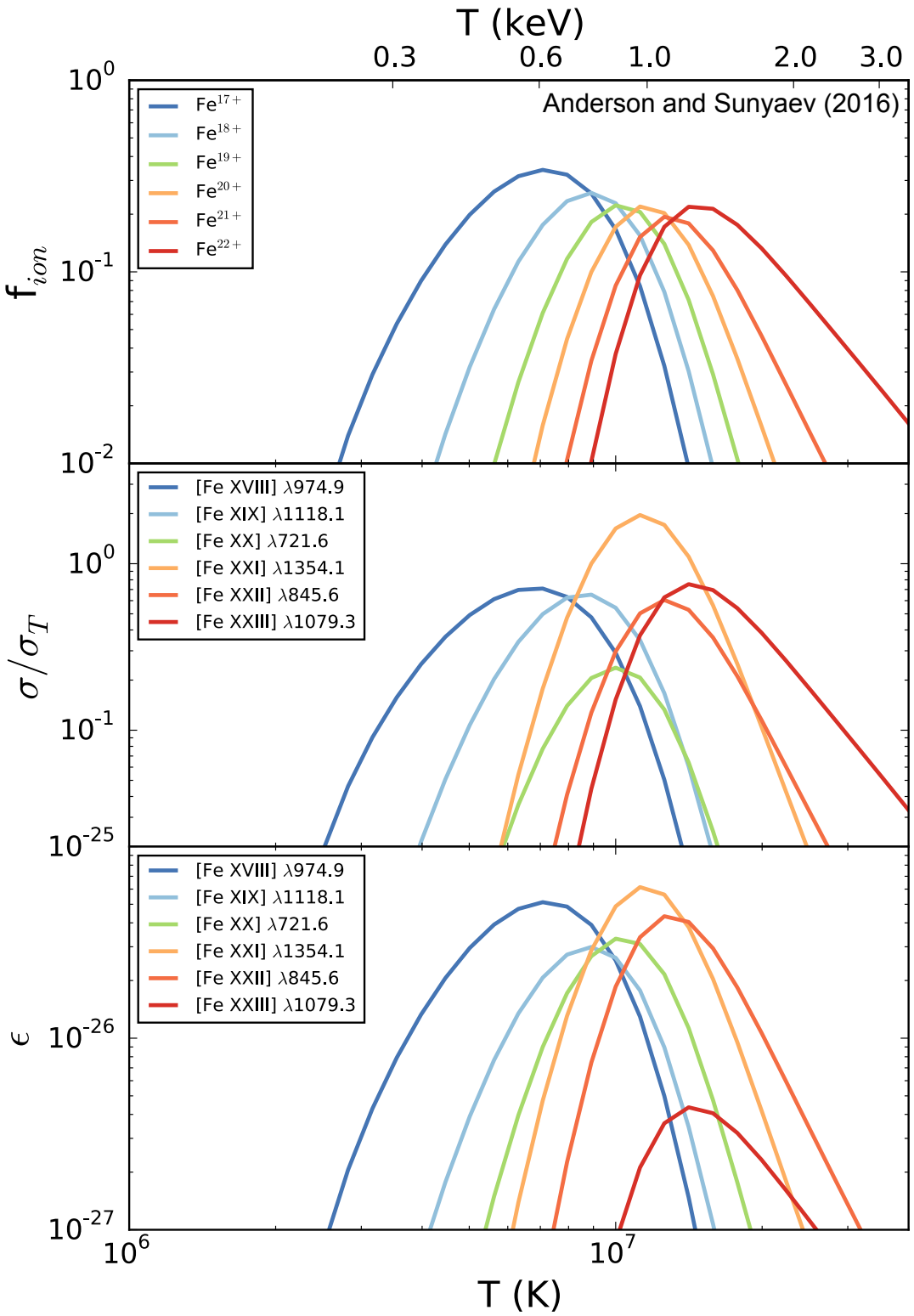


Werner et al. (2013)

- Multiphase (Hα, [C II], C IV, multiphase ICM)

- filaments avoid radio lobes

- filaments contain 1 keV (10^7 K) plasma…



Forbidden Fe lines

- ground-state magnetic dipole transitions

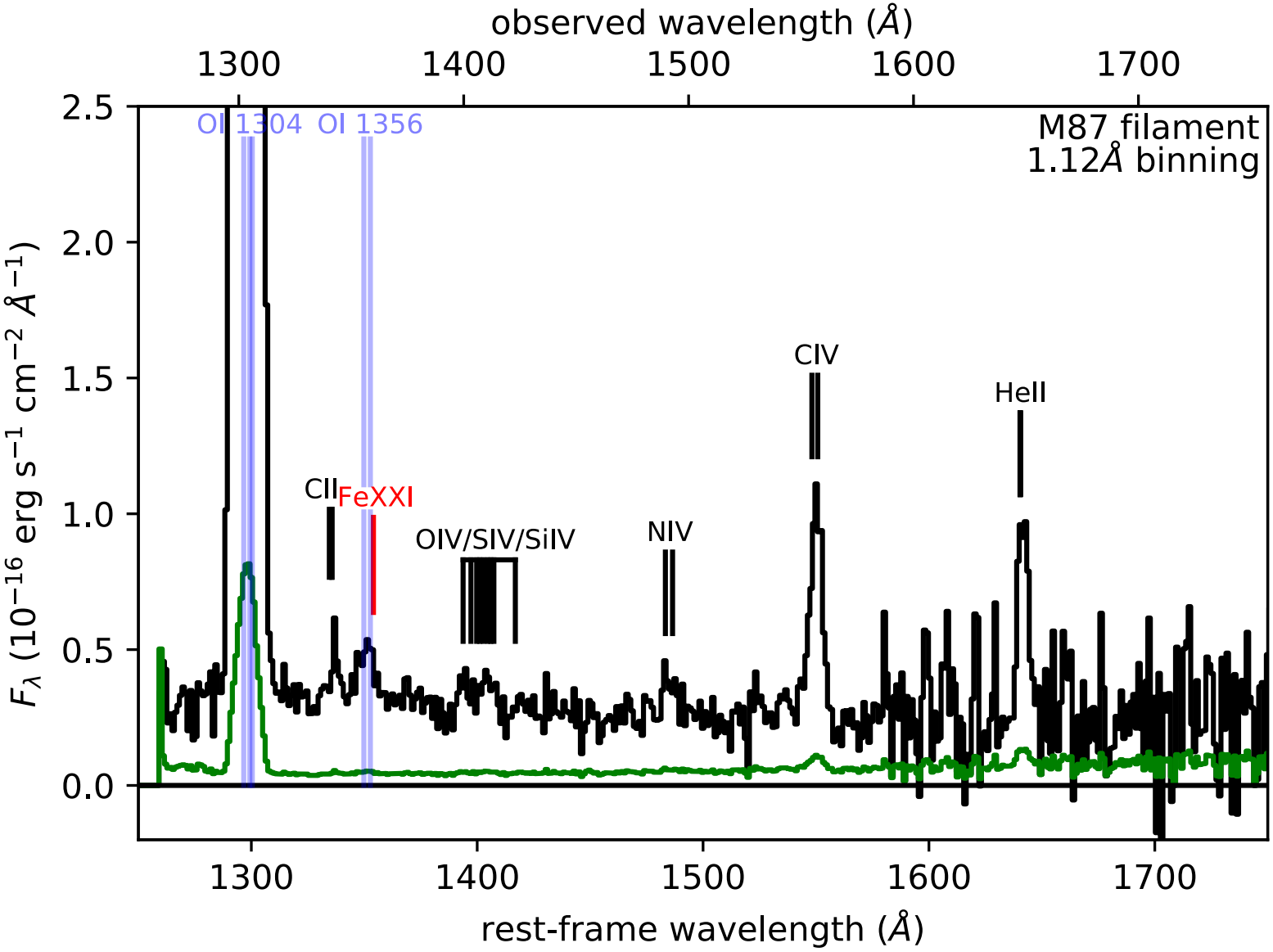
- produced from 10^7 K plasma in CIE

- often seen in Solar flare spectra

- [Fe XXI] 1354A is the strongest

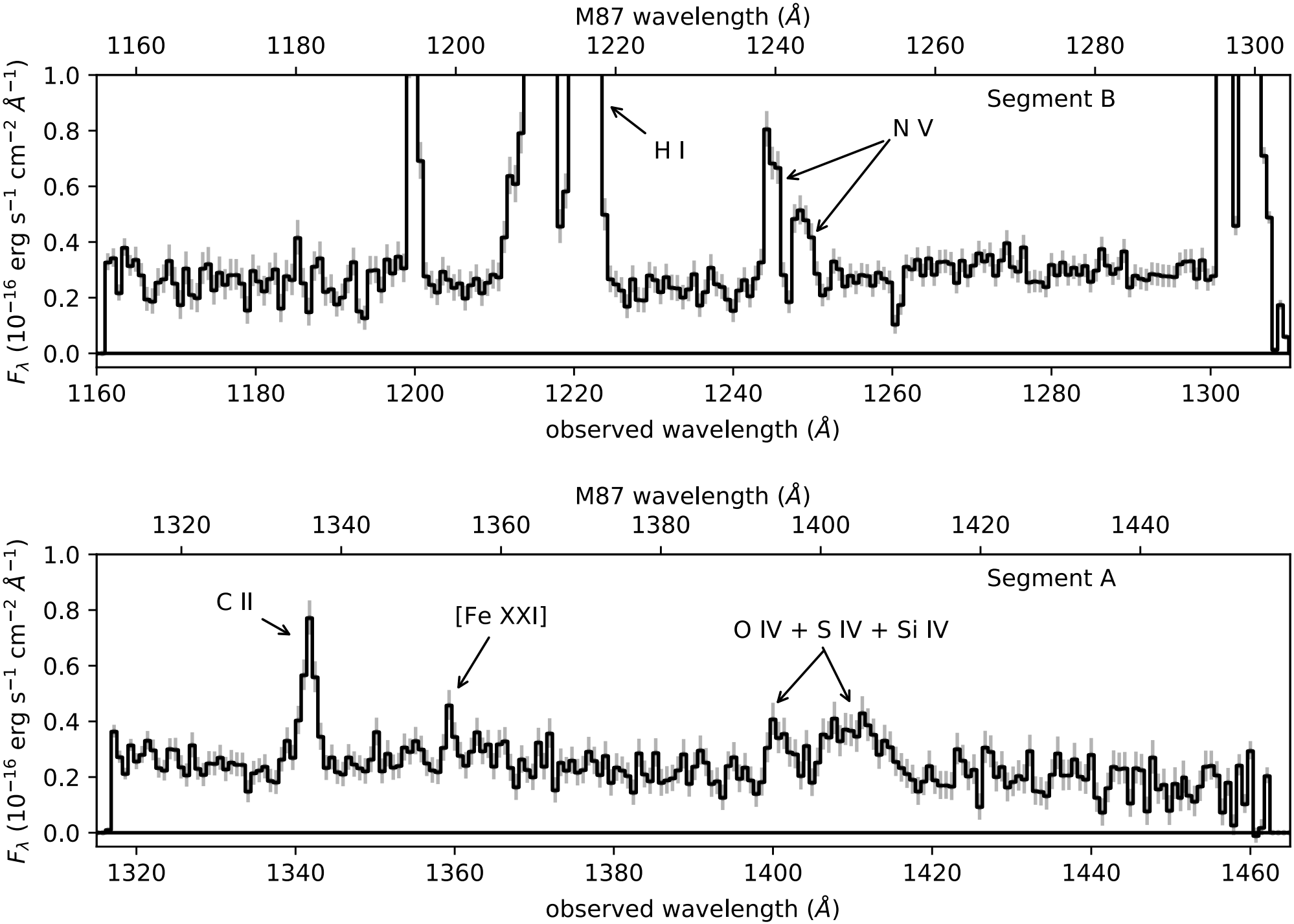
- opens the possibility of measuring ICM kinematics at FUV spectrograph resolution (COS: A~3000 cm^2, $\Delta v \sim 15$ km/s)

Archival HST/COS spectrum of filament



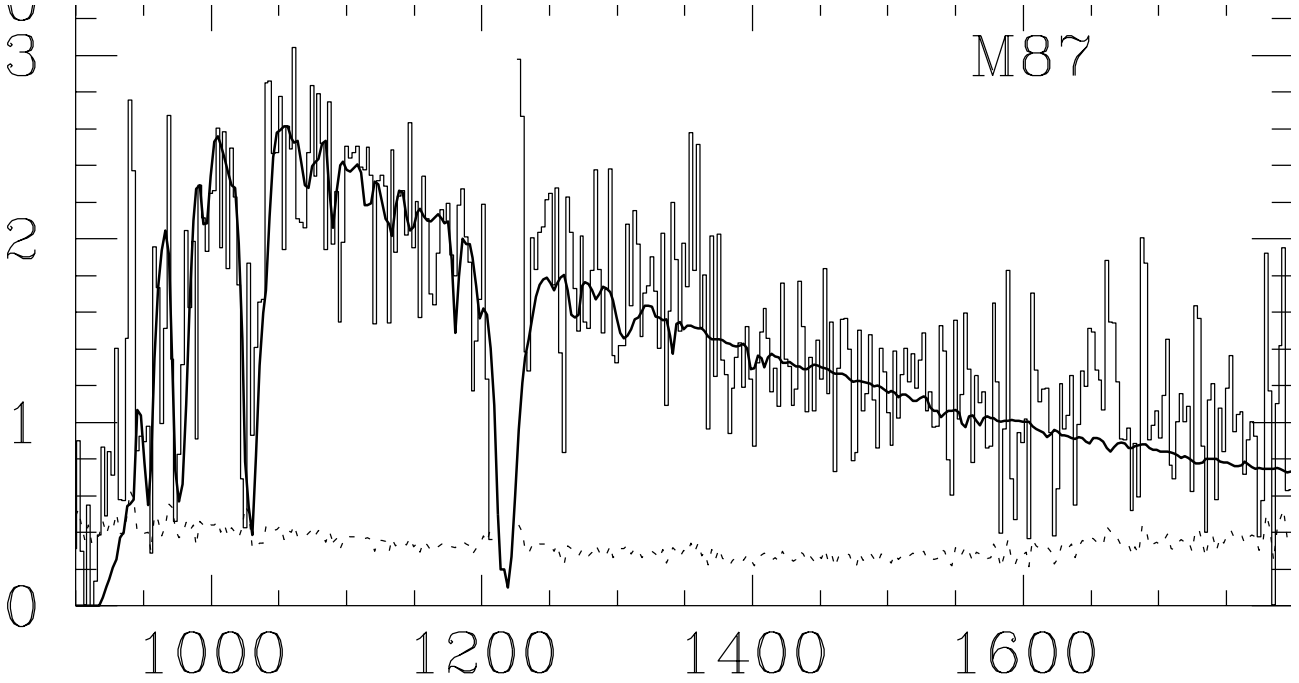
- low-resolution spectrum
- C IV λ1549 and He II λ1640 are clearly detected (Sparks et al. 2012)
- tentative (2.2σ) evidence for [Fe XXI] as well

New HST/COS spectrum of filament



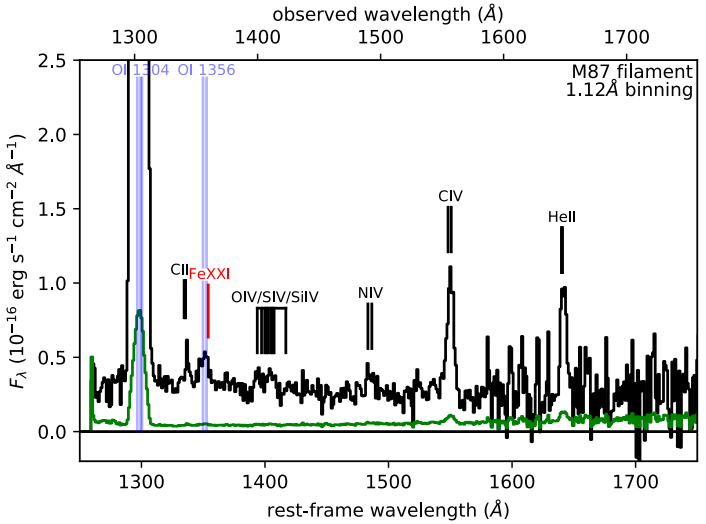
FUV continuum?

Brown et al. (1997)

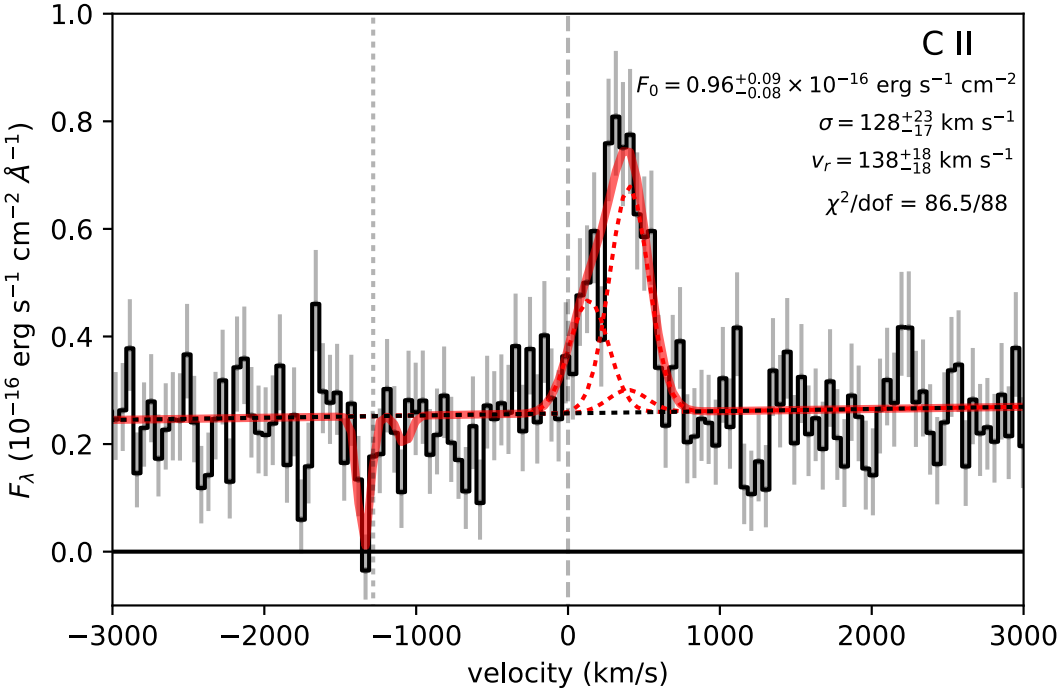


FUV continuum due to “FUV excess” from M87

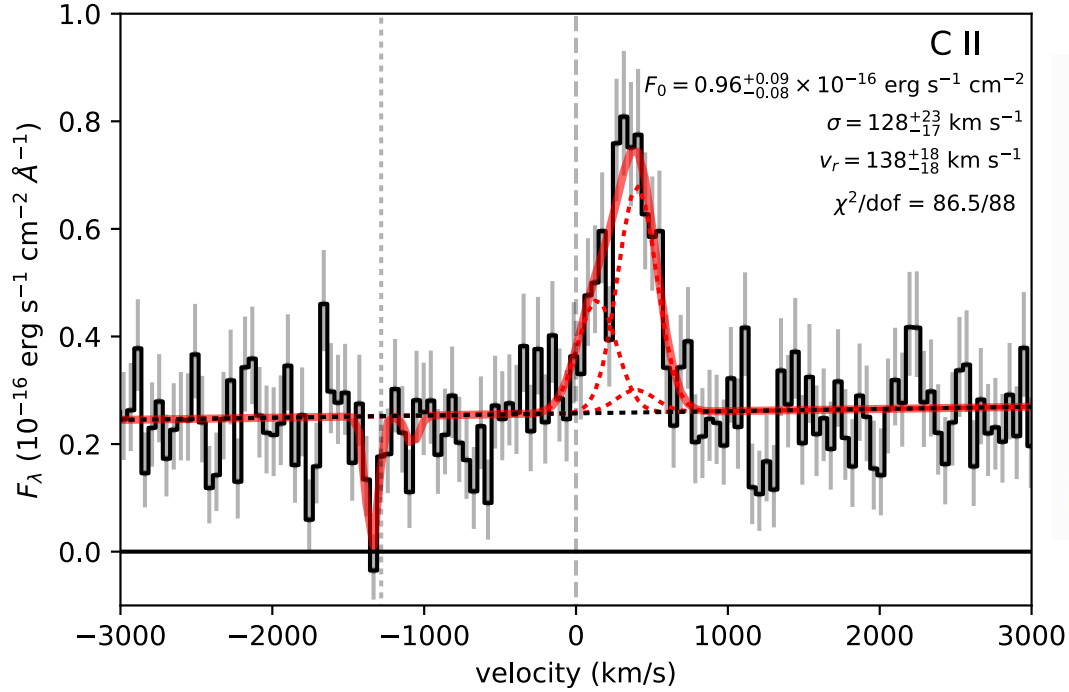
Remains somewhat mysterious, but seems to be produced from evolved low-mass stars



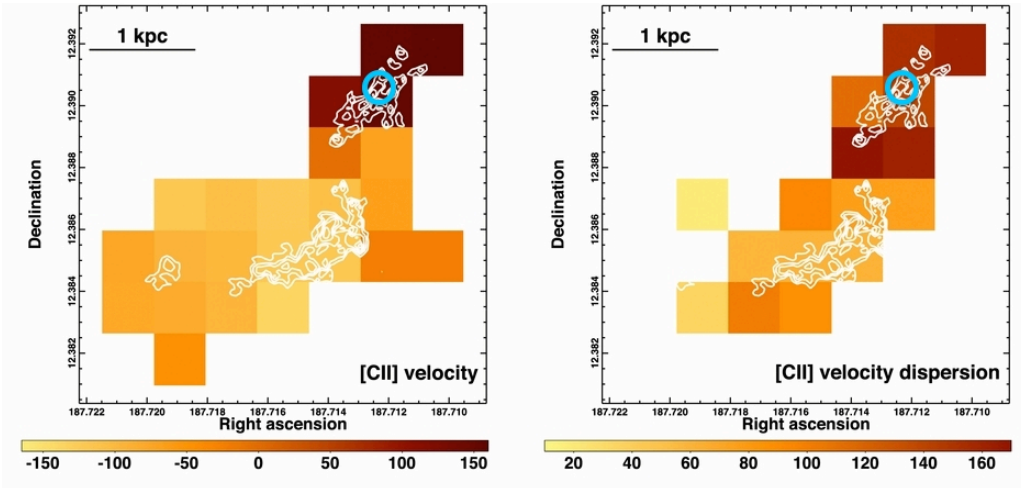
Line fitting: C II 1335 and N V 1238



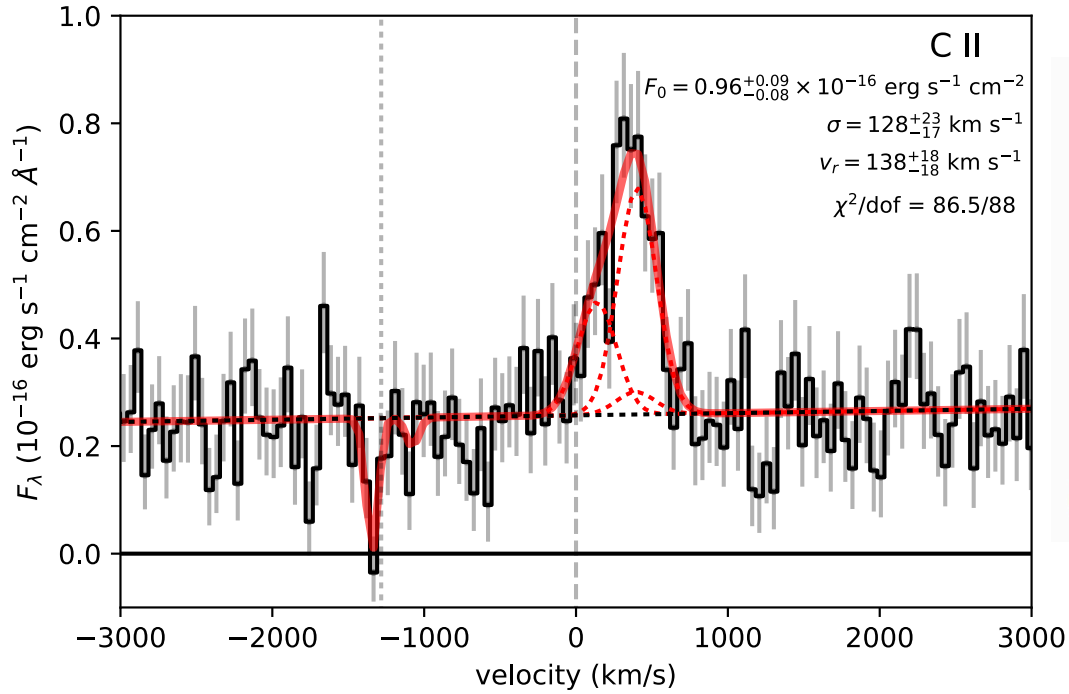
Line fitting: C II 1335 and N V 1238



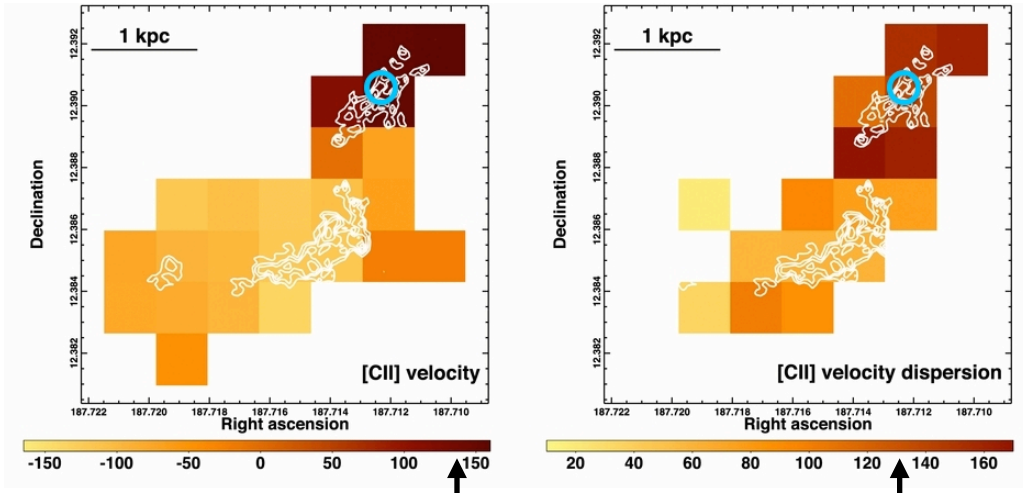
Werner et al. (2013)



Line fitting: C II 1335 and N V 1238



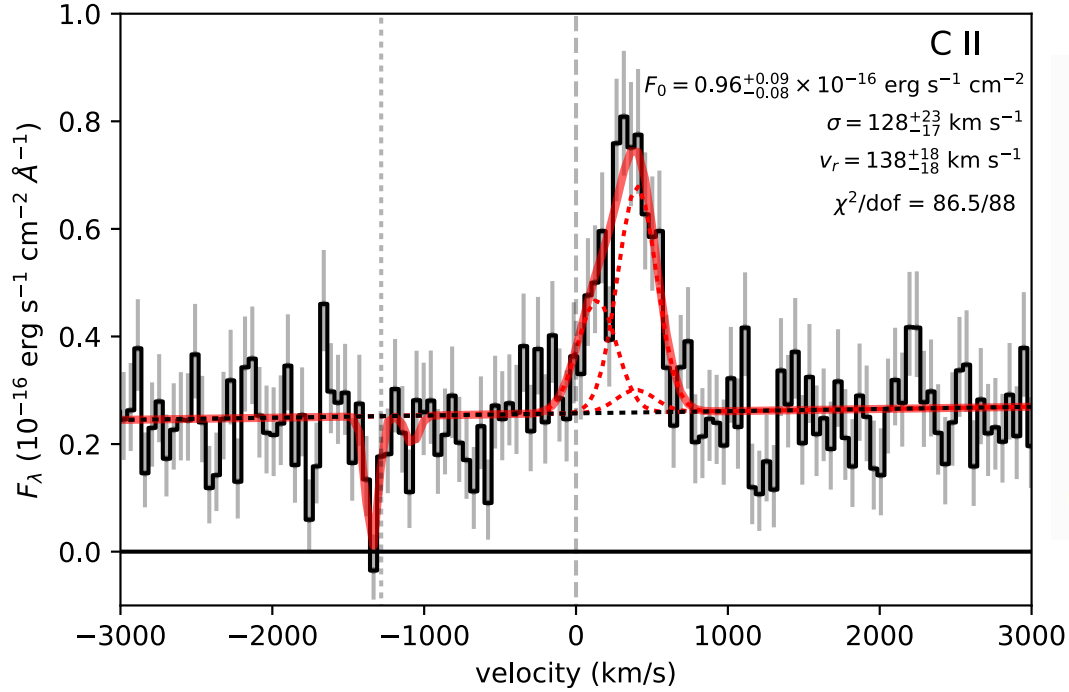
Werner et al. (2013)



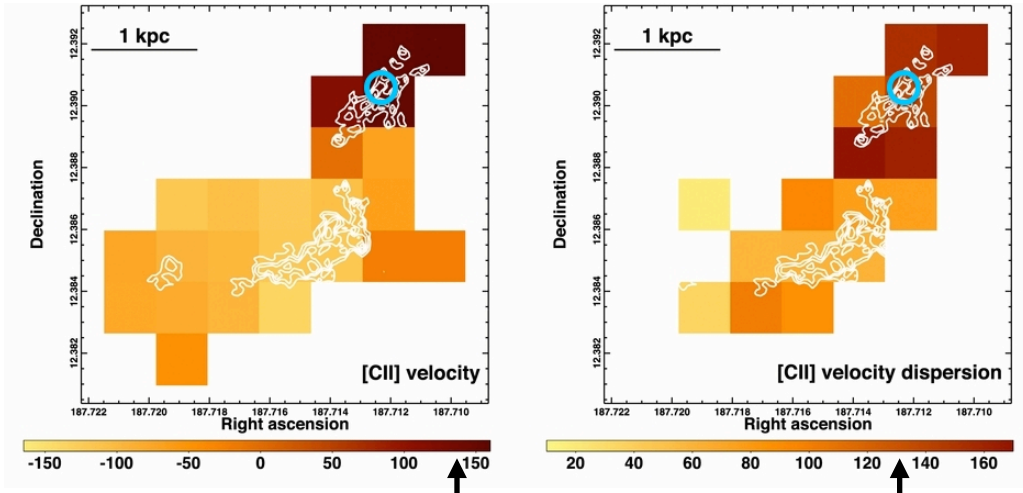
$v_r \approx 140$ km/s

$\sigma \approx 130$ km/s

Line fitting: C II 1335 and N V 1238



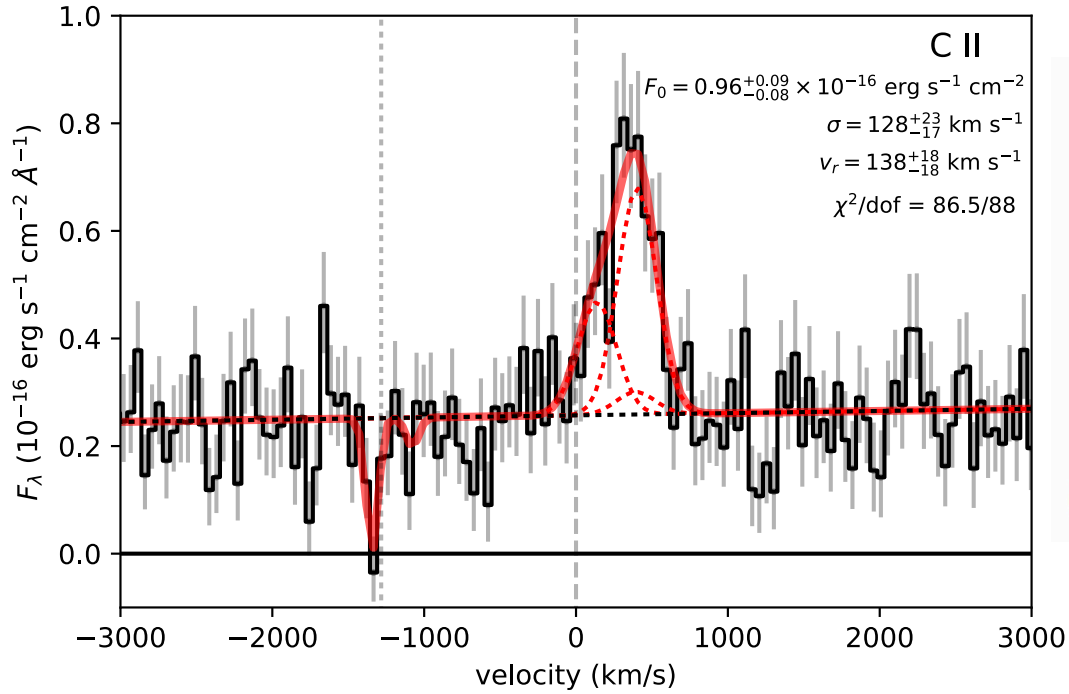
Werner et al. (2013)



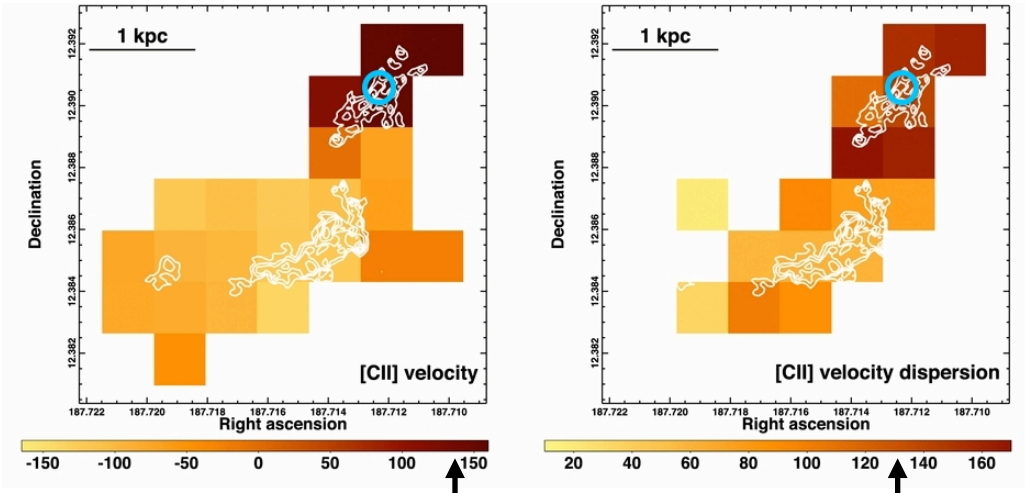
$v_r \approx 140$ km/s $\sigma \approx 130$ km/s

C II λ1335 matches [C II] 158μm
in both v_r and σ

Line fitting: C II 1335 and N V 1238

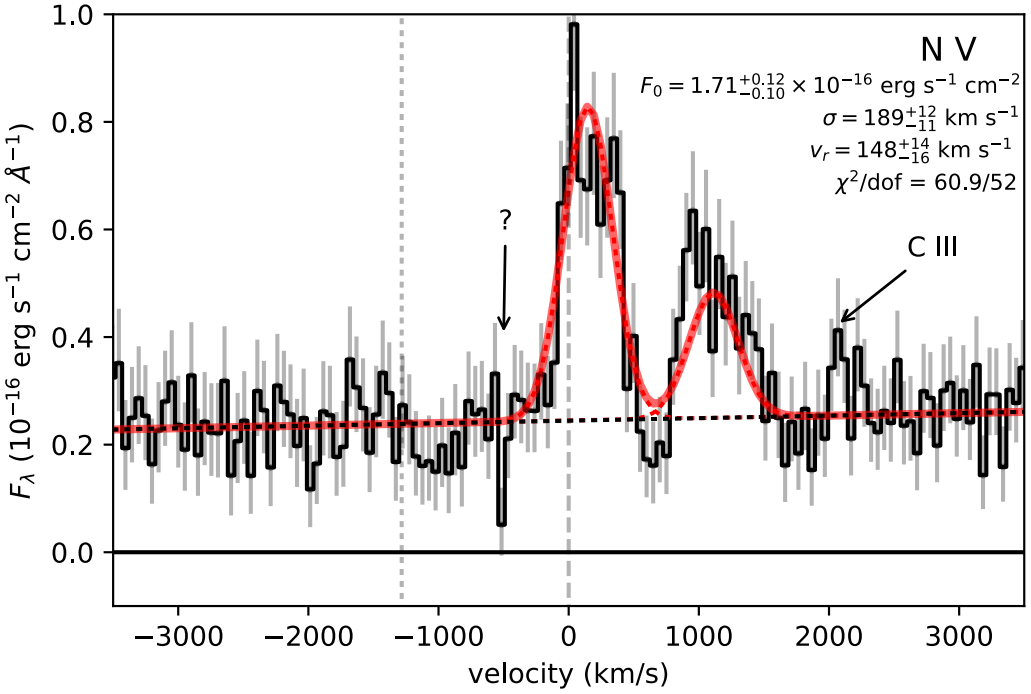


Werner et al. (2013)

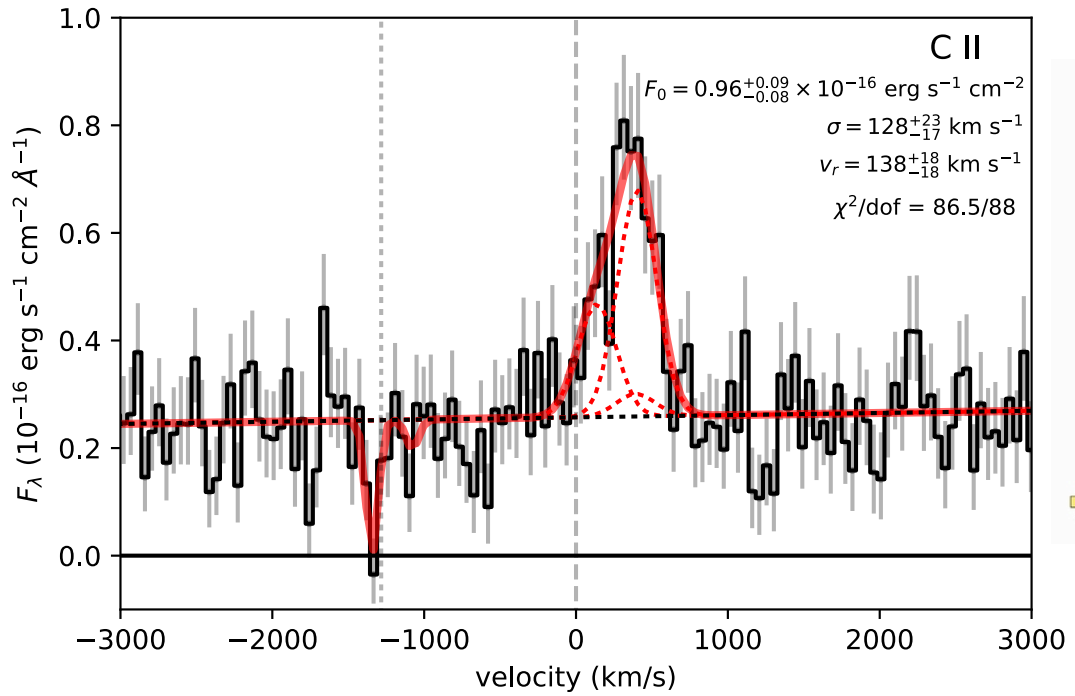


$v_r \approx 140$ km/s $\sigma \approx 130$ km/s

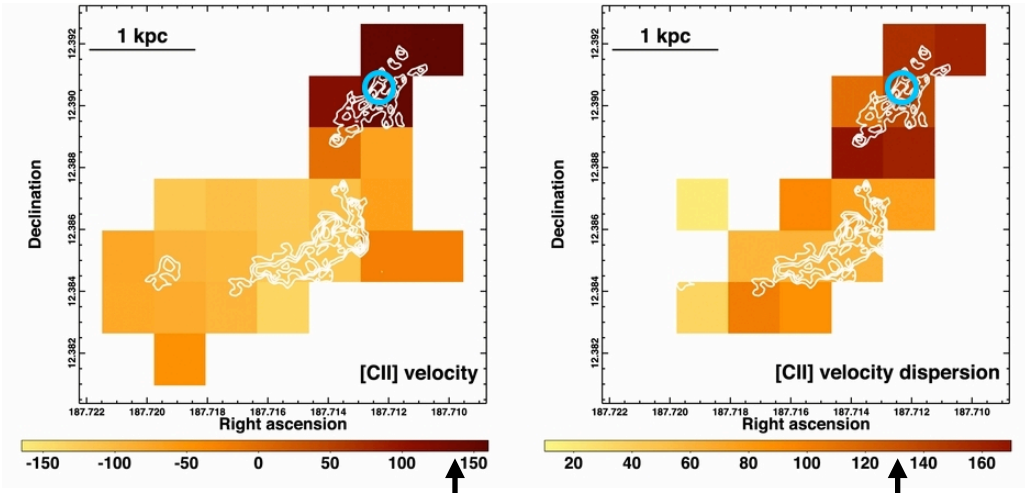
C II λ1335 matches [C II] 158μm in both v_r and σ



Line fitting: C II 1335 and N V 1238



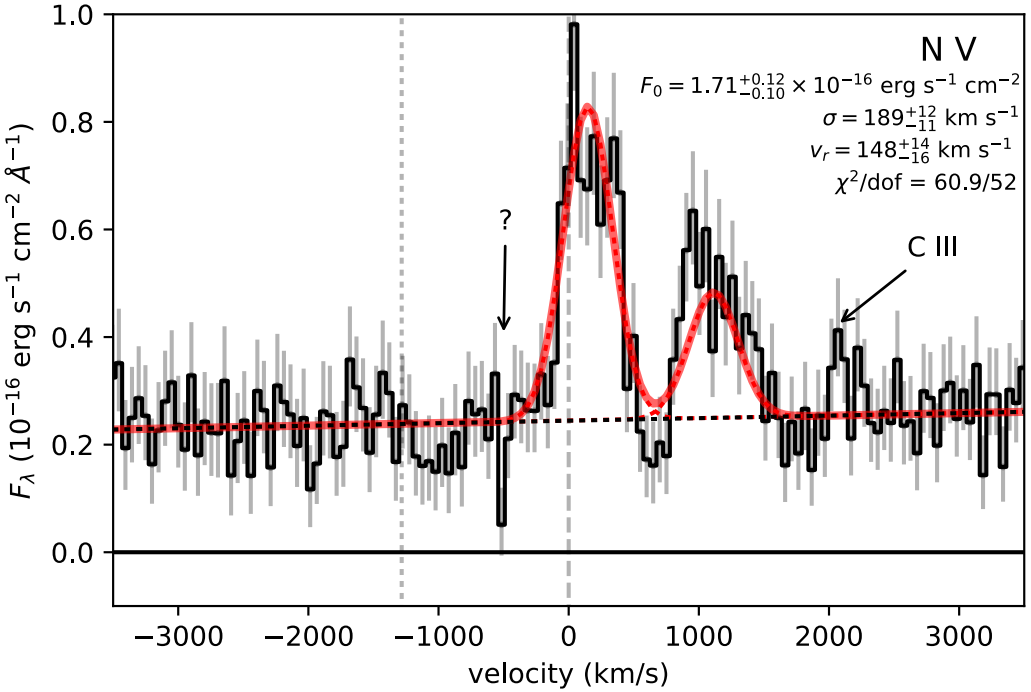
Werner et al. (2013)



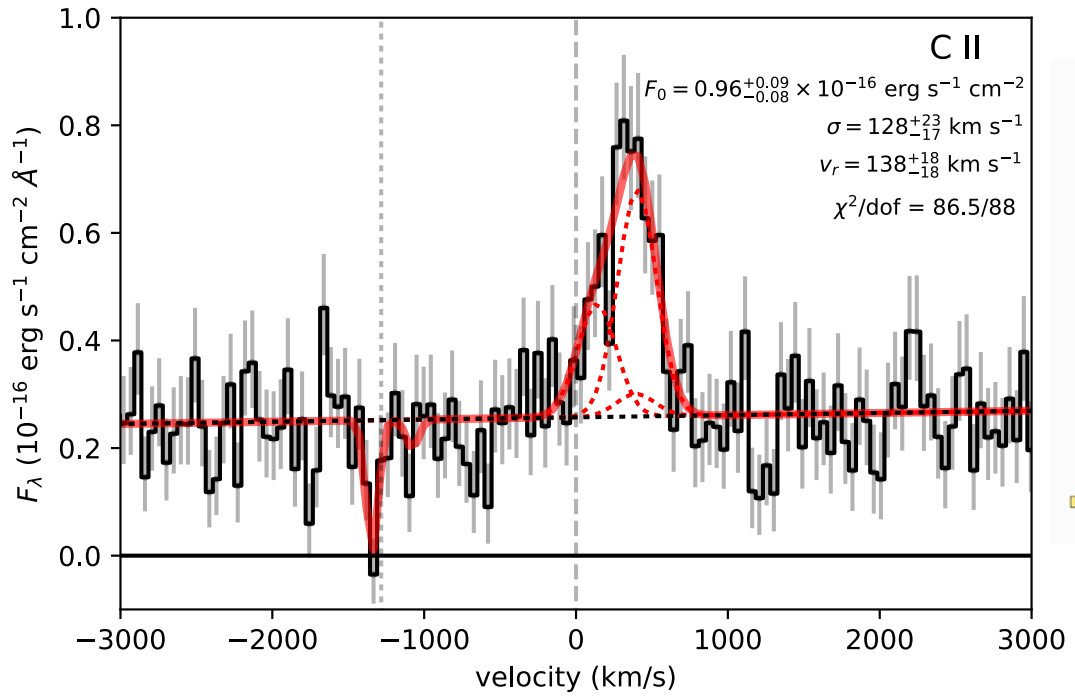
$v_r \approx 140$ km/s $\sigma \approx 130$ km/s

C II λ1335 matches [C II] 158μm in both v_r and σ

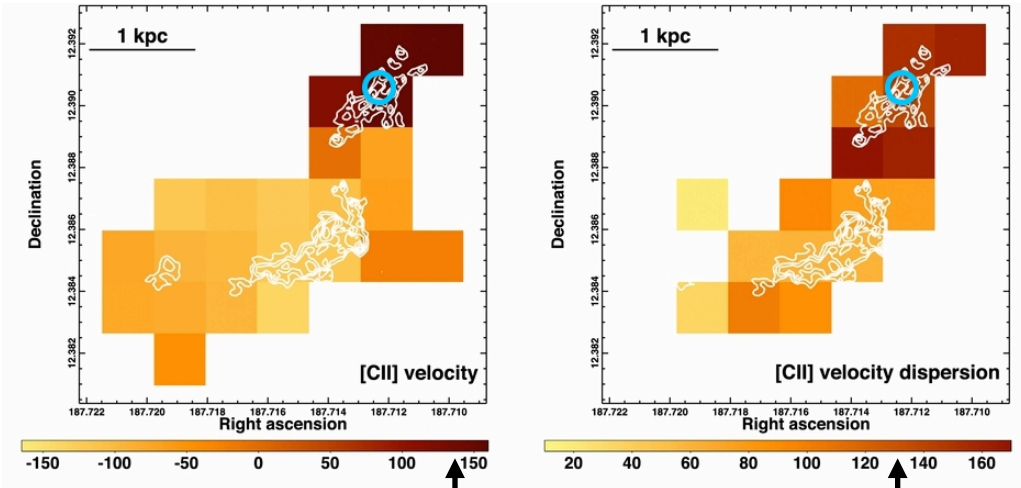
NV is wider and somewhat non-Gaussian but has same as v_r as C II



Line fitting: C II 1335 and N V 1238



Werner et al. (2013)

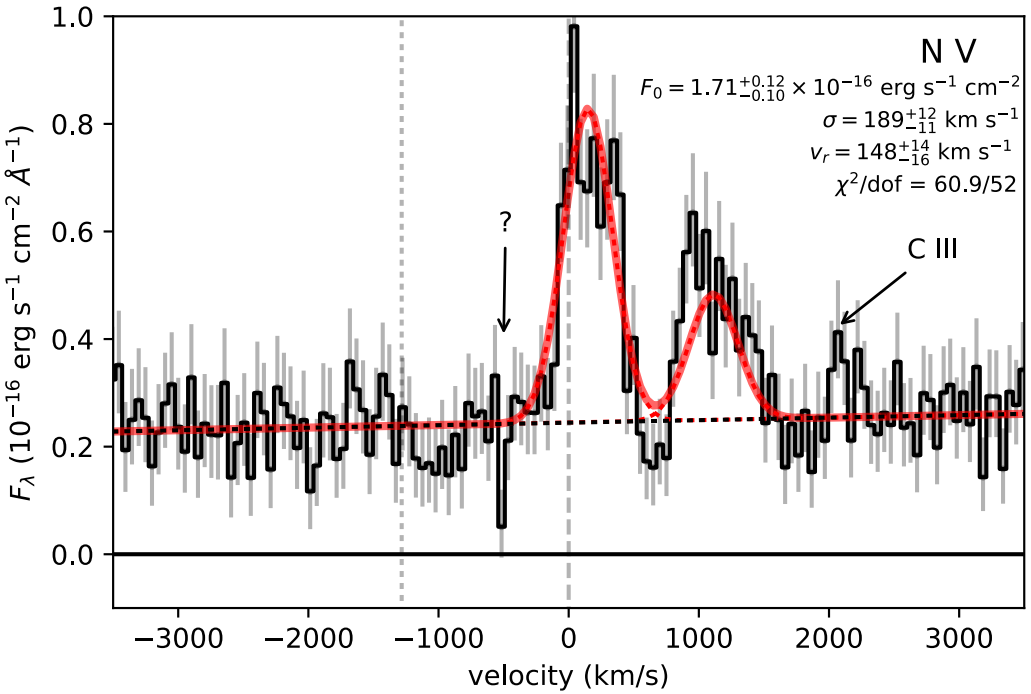


$v_r \approx 140$ km/s $\sigma \approx 130$ km/s

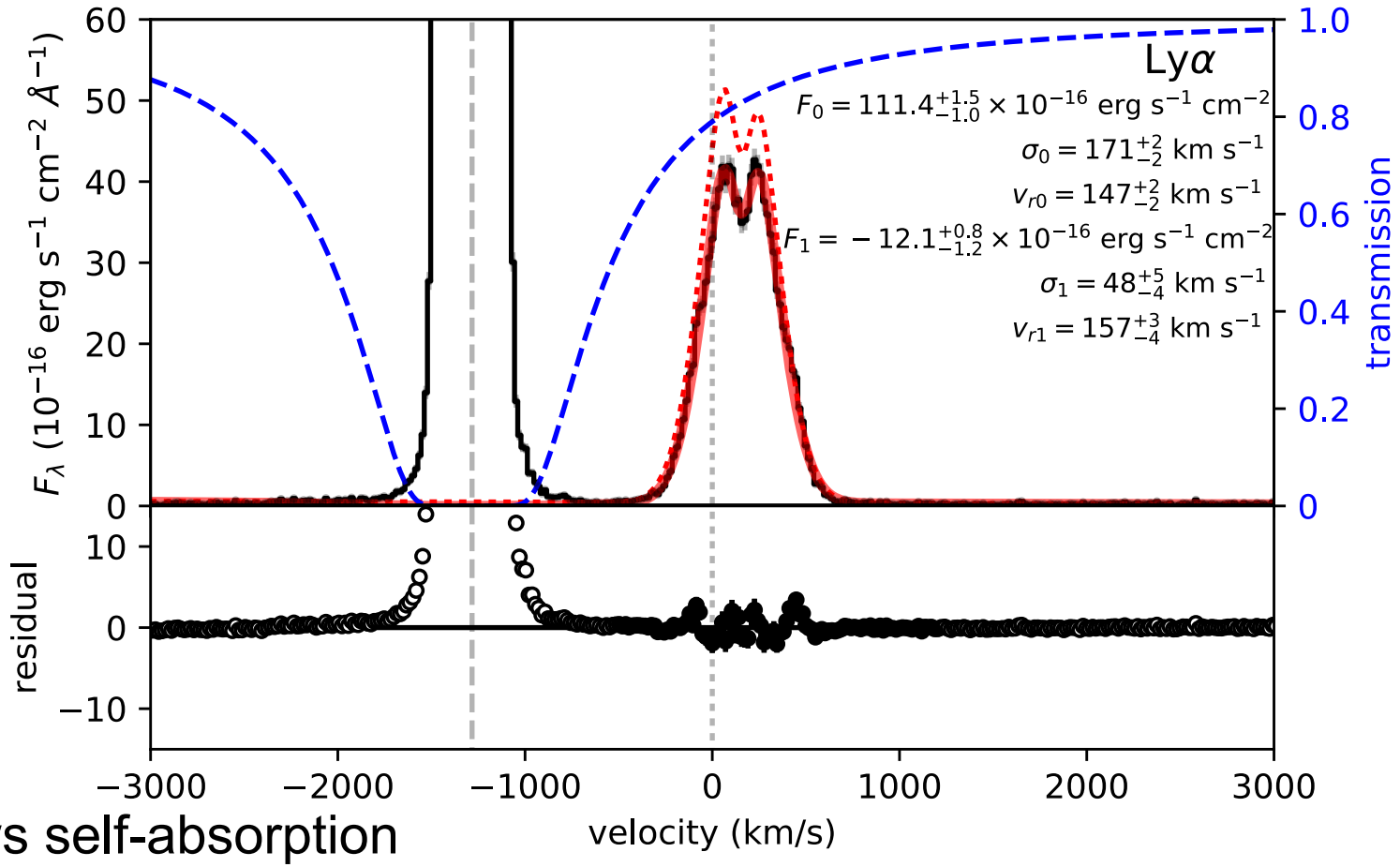
C II λ1335 matches [C II] 158μm in both v_r and σ

NV is wider and somewhat non-Gaussian but has same as v_r as C II

turbulent boundary layer?
or just noise?



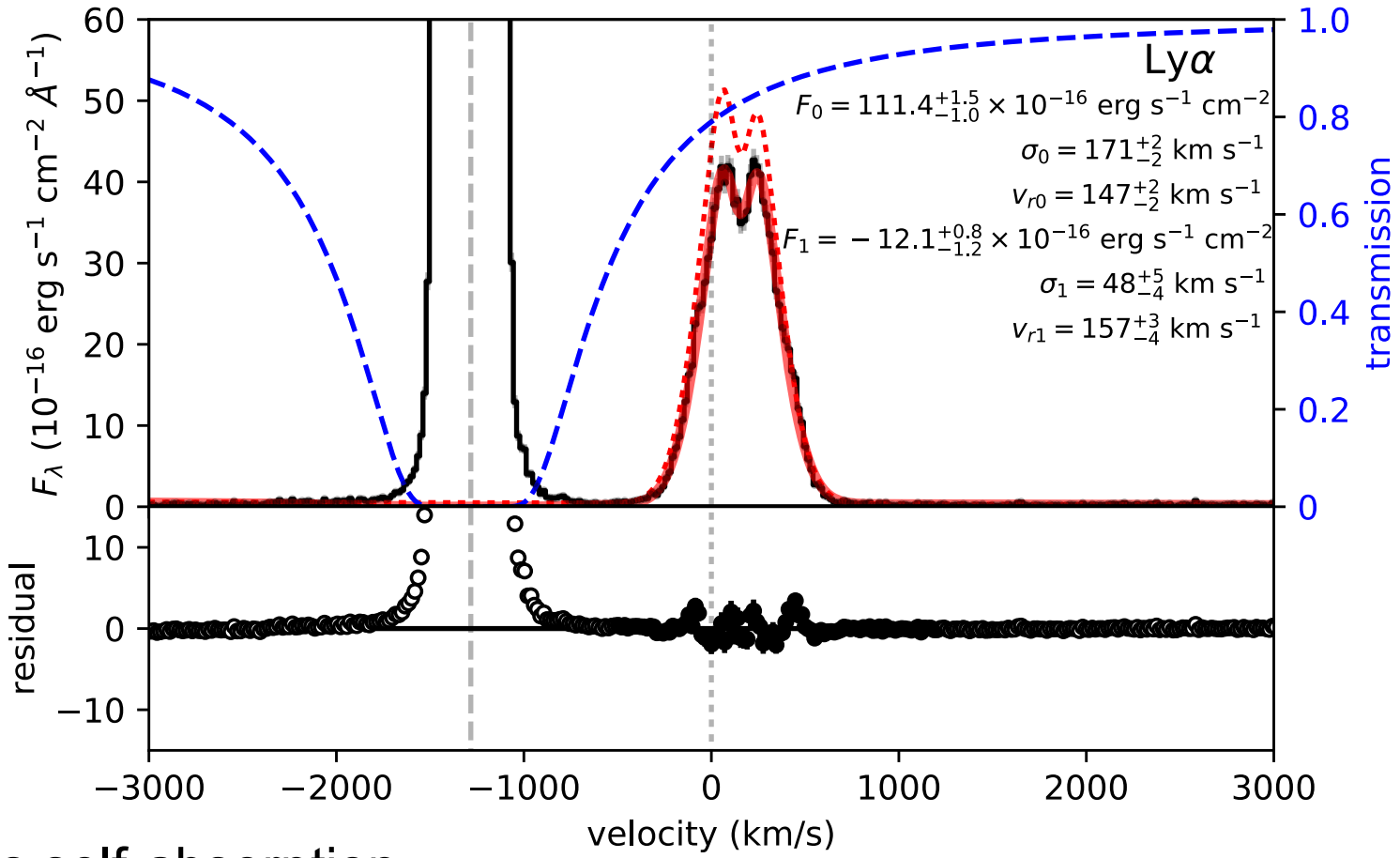
Line fitting: Lyα



Lyα is narrow and shows self-absorption

Red dotted line is corrected for Galactic absorption

Line fitting: Lyα

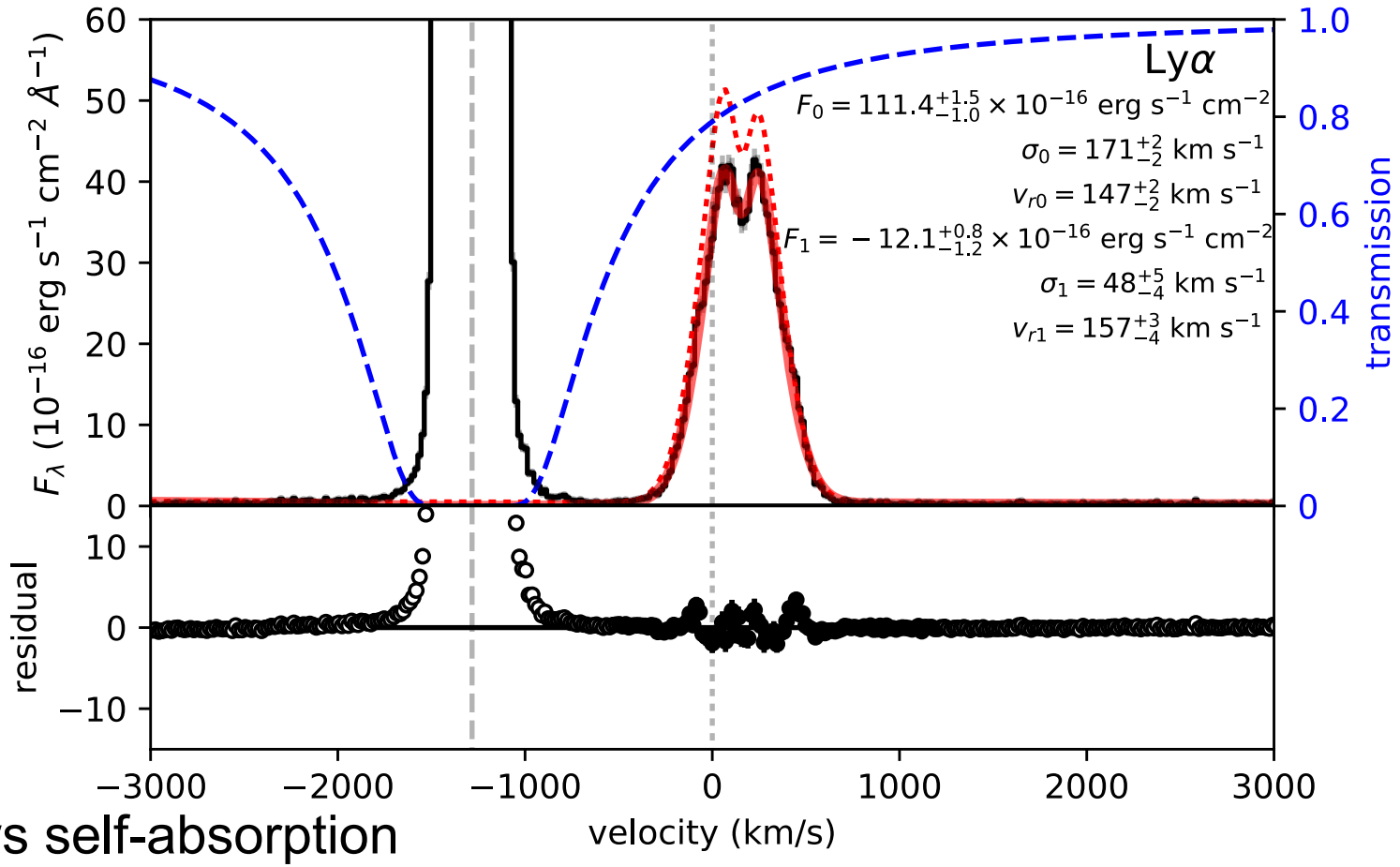


Lyα is narrow and shows self-absorption

Red dotted line is corrected for Galactic absorption

Intrinsic profile is asymmetric -> blueshifted injection velocity in rest frame of filament

Line fitting: Lyα



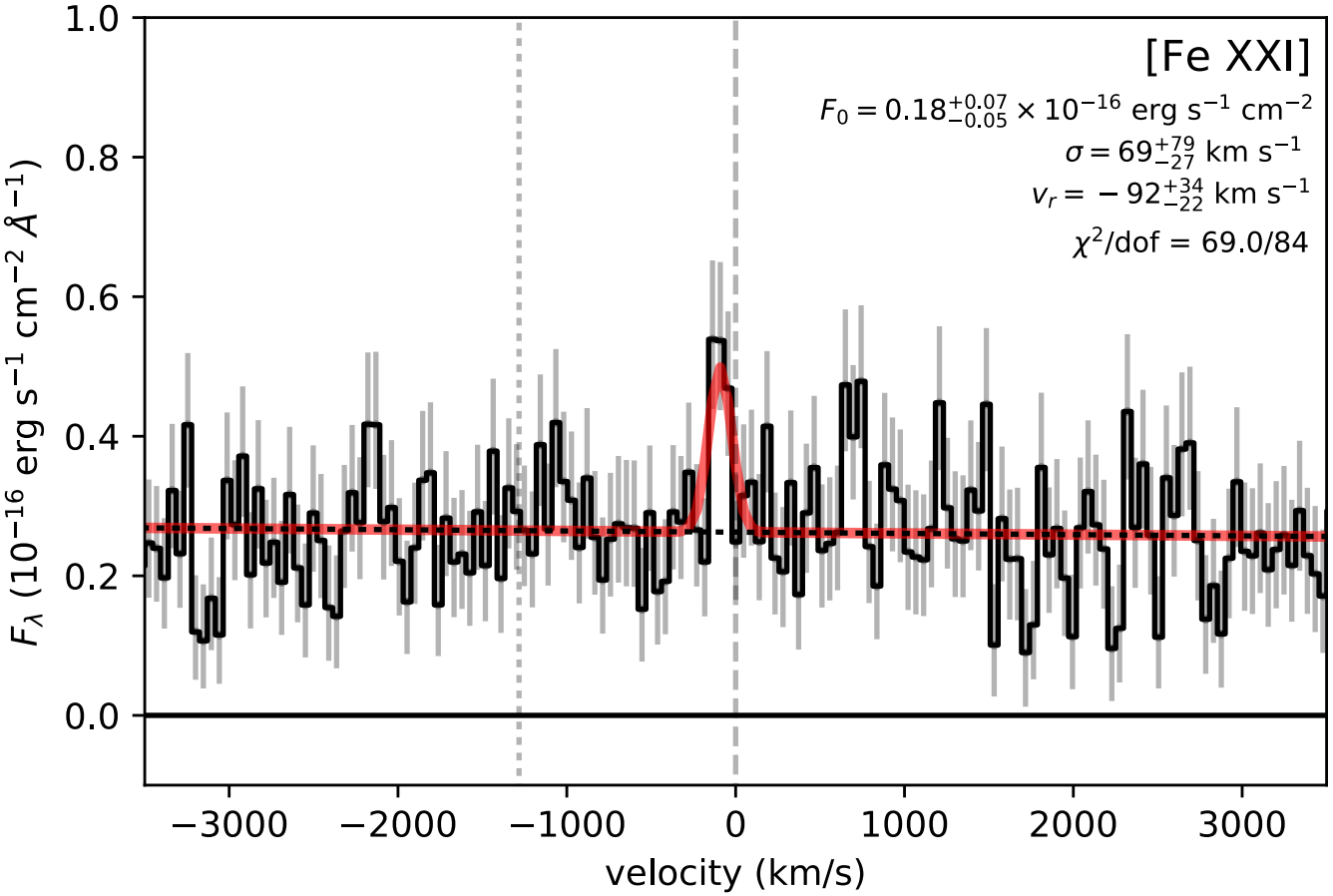
Lyα is narrow and shows self-absorption

Red dotted line is corrected for Galactic absorption

Intrinsic profile is asymmetric -> blueshifted injection velocity in rest frame of filament

Overall Lyα has same v_r as C II and N V, and slightly higher σ due to resonant scattering.

Line fitting: [Fe XXI]

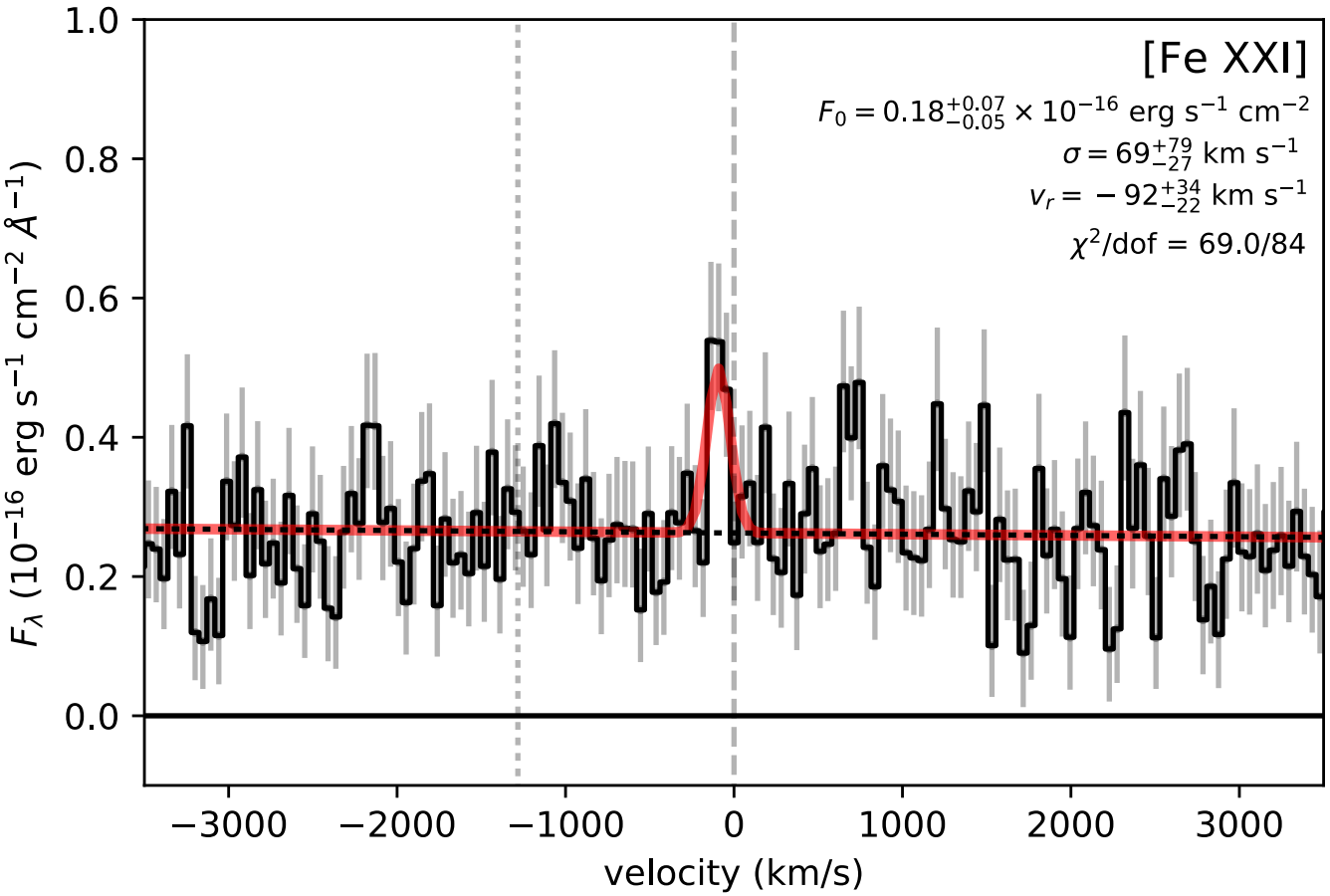


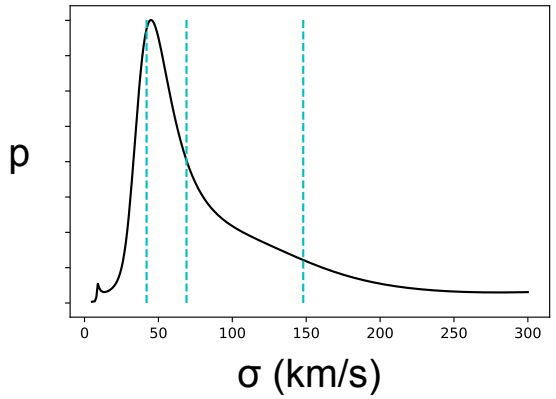
[Fe XXI] is detected at 4.4-5.1σ, depending on the binning

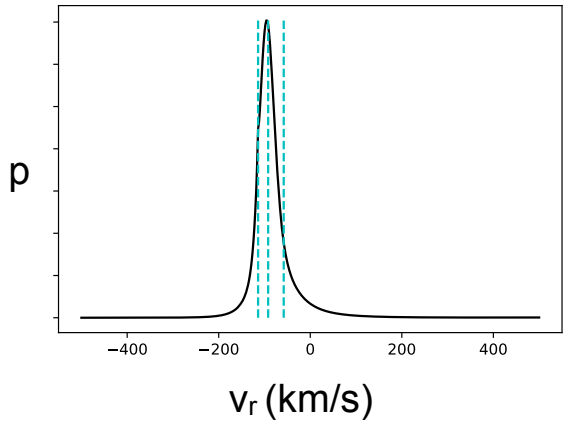
Parameters are roughly consistent with our 2.2σ measurement using archival data, but this measurement is much more precise

Note the blueshift and the narrowness of the line

Line fitting: [Fe XXI]





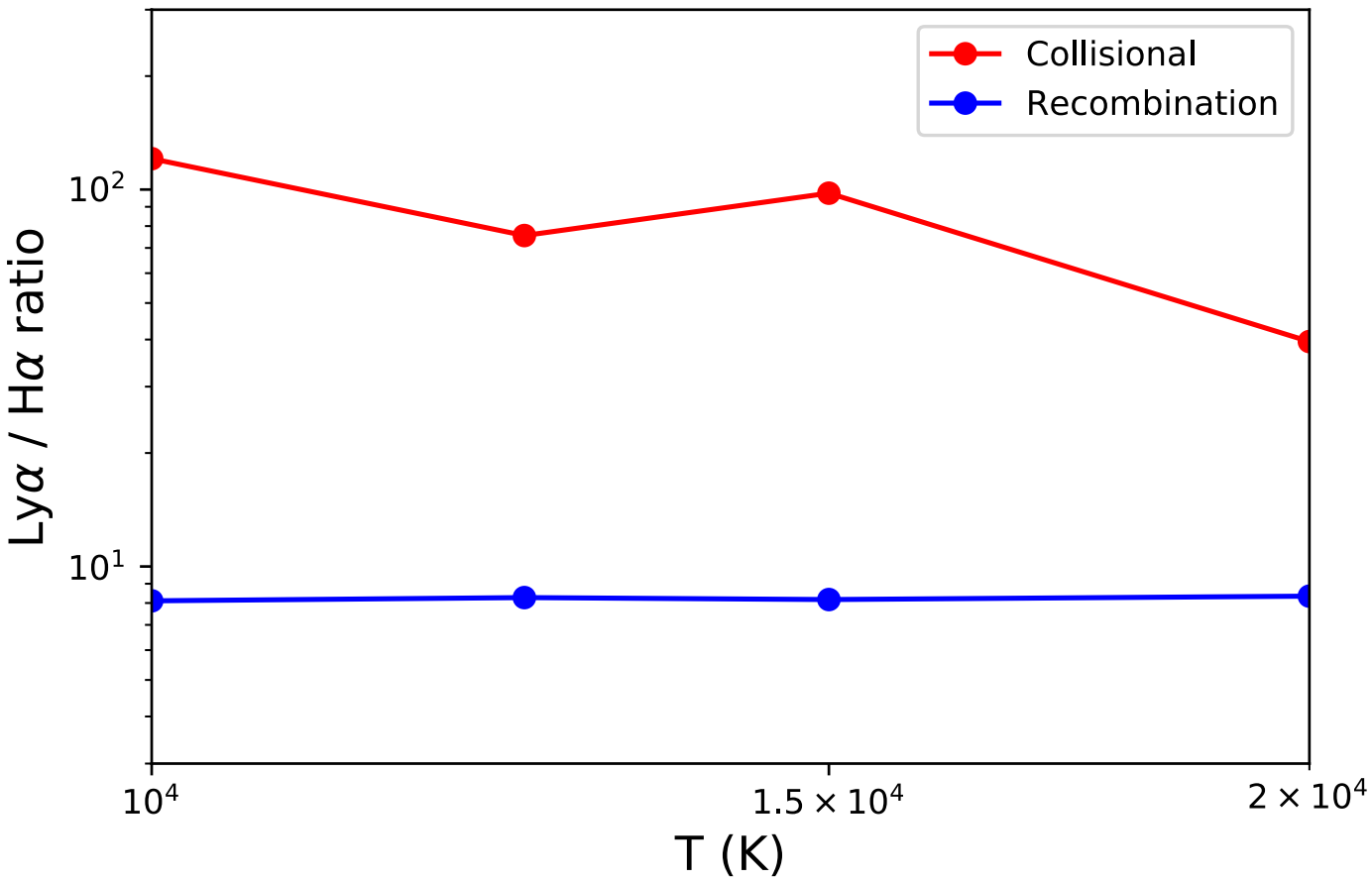


[Fe XXI] is detected at 4.4-5.1σ, depending on the binning

Parameters are roughly consistent with our 2.2σ measurement using archival data, but this measurement is much more precise

Note the blueshift and the narrowness of the line

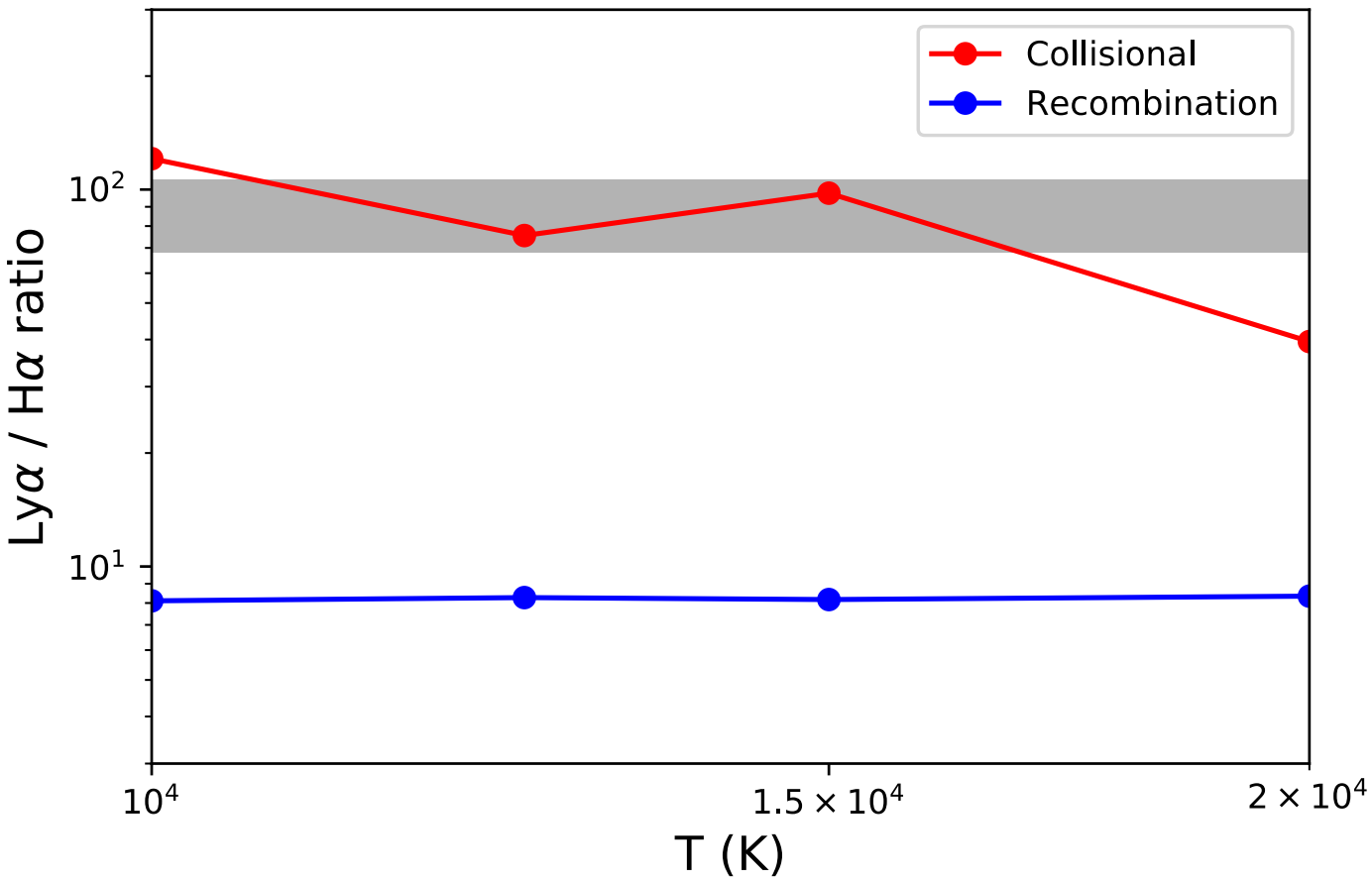
Collisional Excitation or Recombination?



Lyα : Hα is an excellent diagnostic of the excitation mechanism

We have Lyα, and can get Hα from archival HST observations

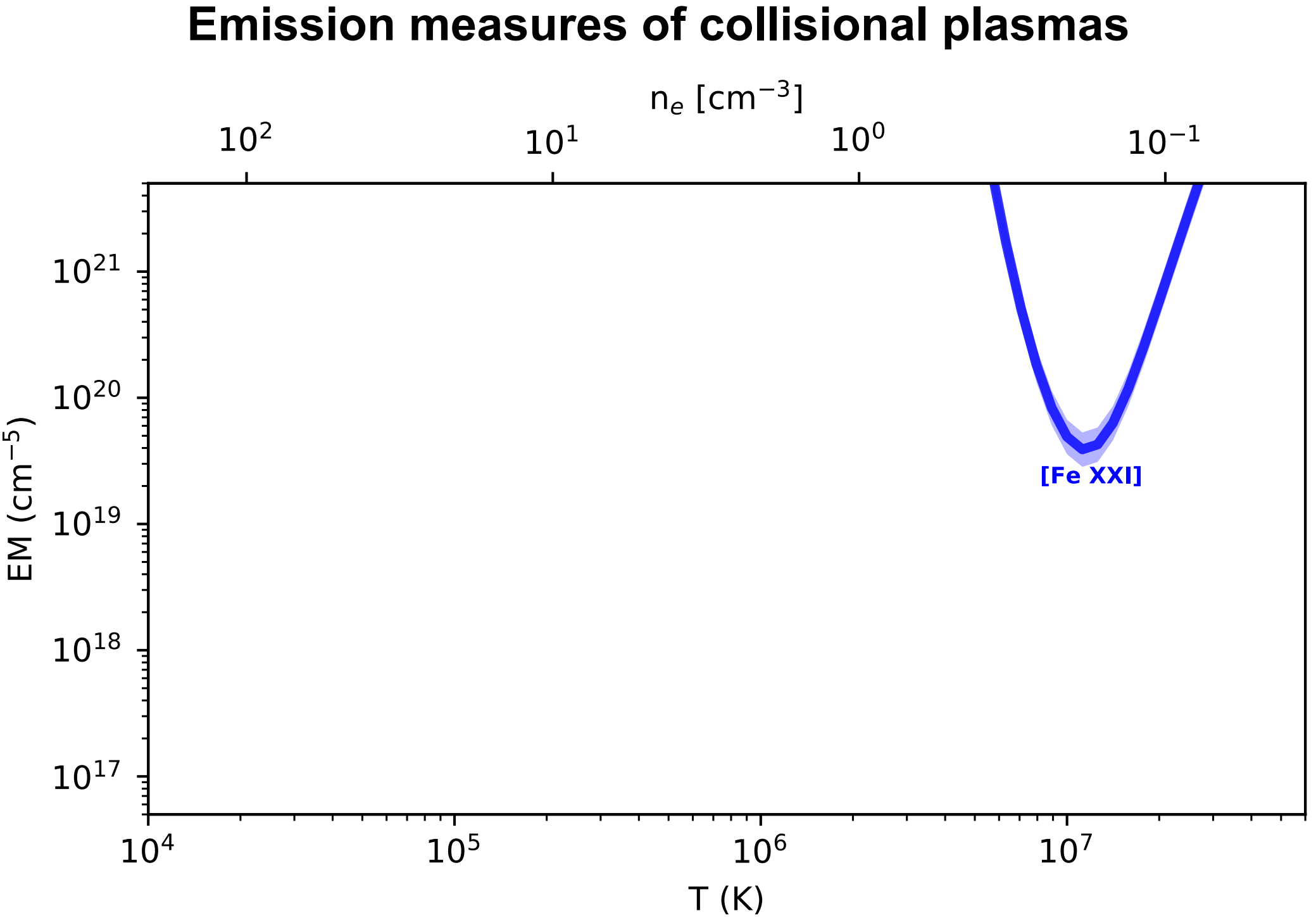
Collisional Excitation or Recombination?

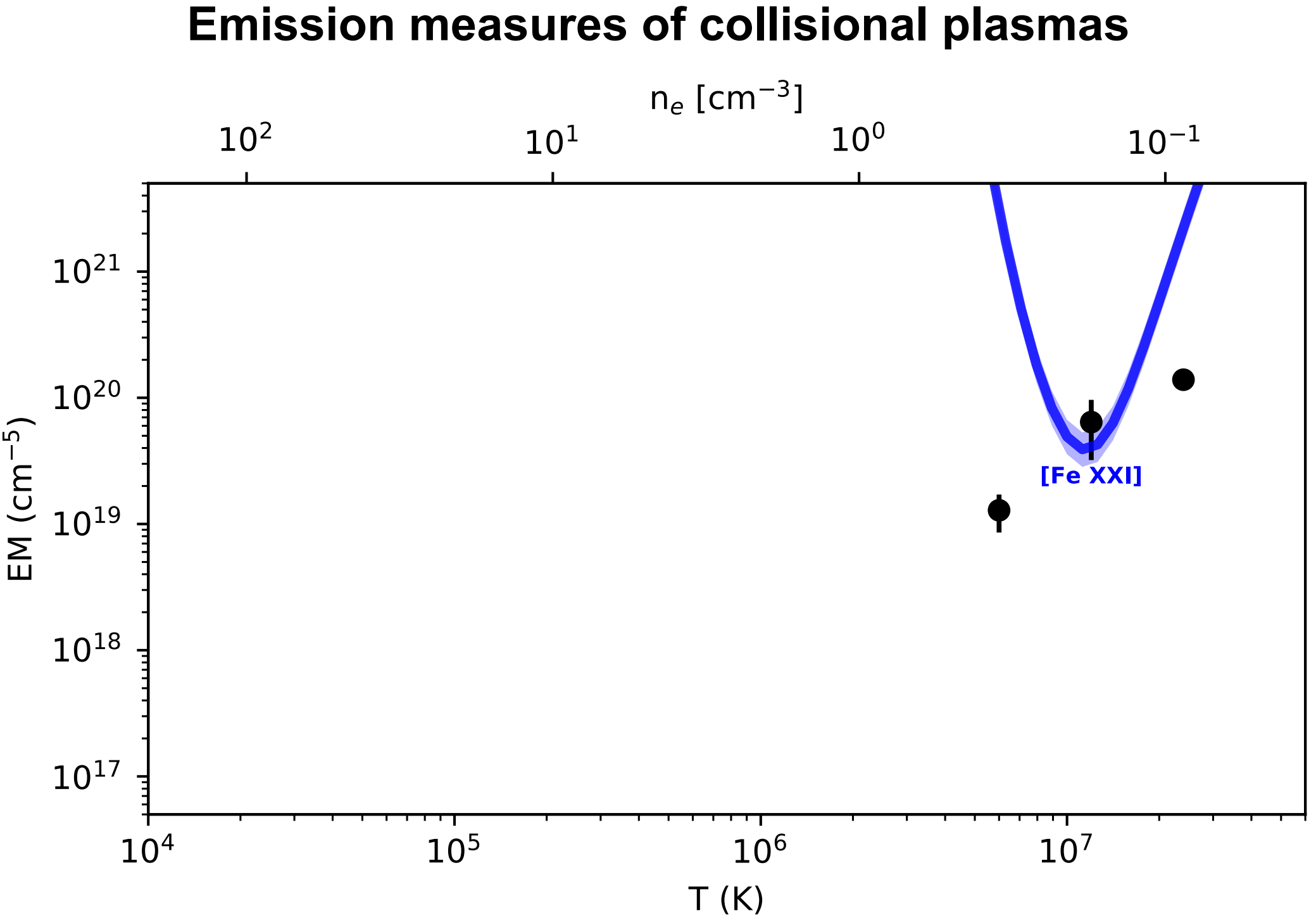


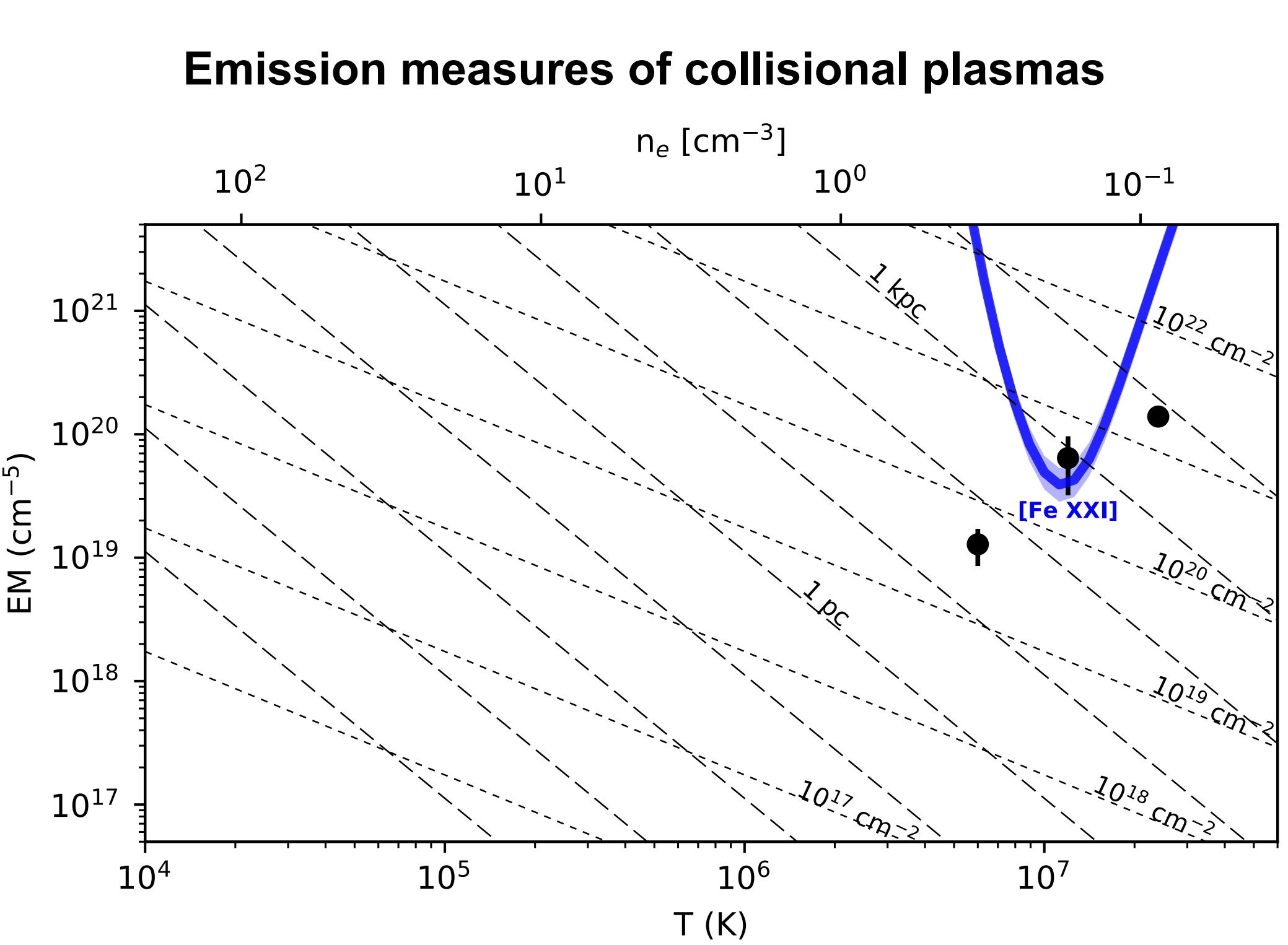
Lyα : Hα is an excellent diagnostic of the excitation mechanism

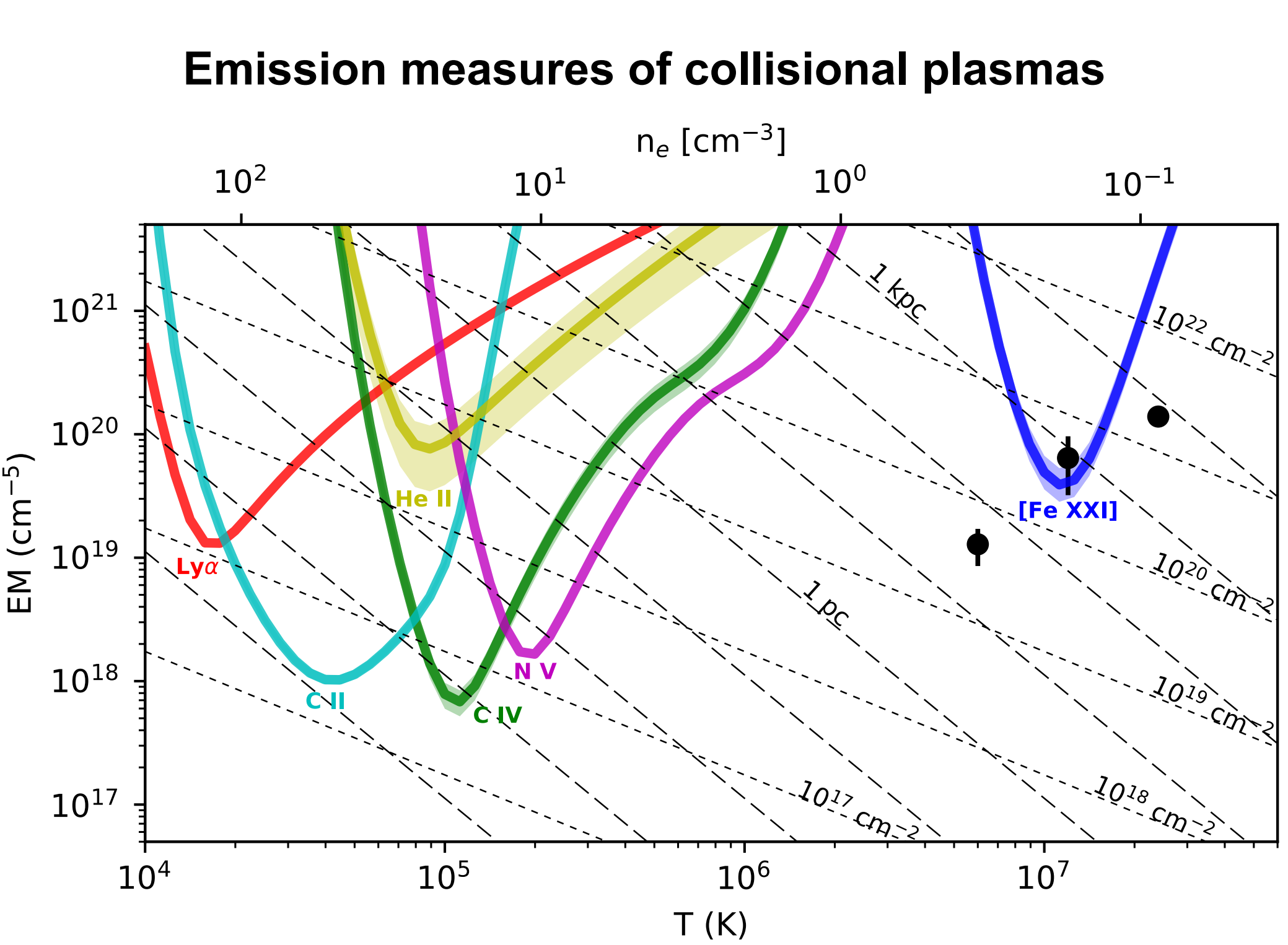
We have Lyα, and can get Hα from archival HST observations

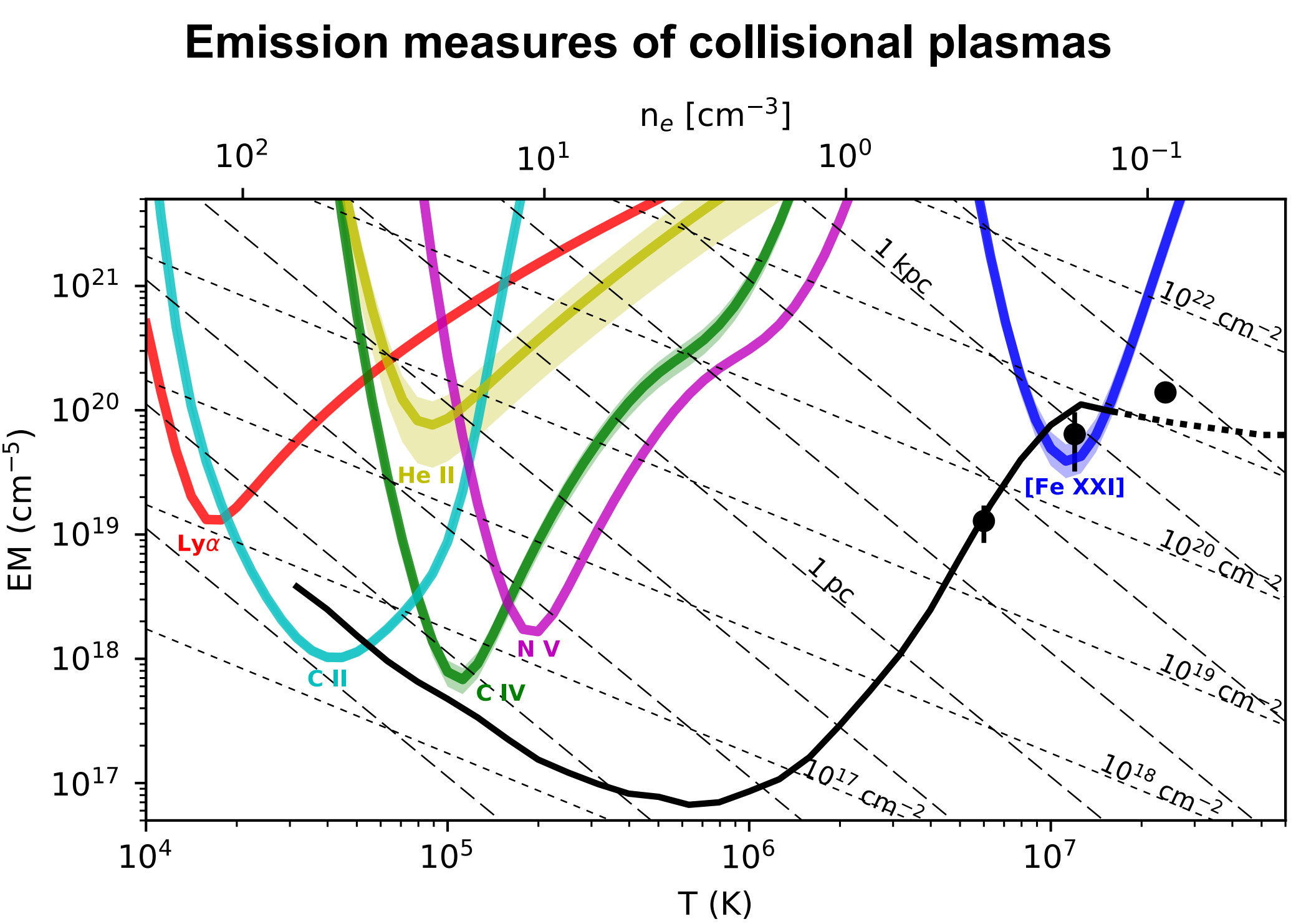
Result: the filament seems to be collisionally excited


Emission measures of collisional plasmas
n_e [cm^{-3}]
10^2
10^1
10^0
10^{-1}
10^{21}
10^{20}
10^{19}
10^{18}
10^{17}
EM (cm^{-5})
[Fe XXI]
10^4
10^5
10^6
10^7
T (K)

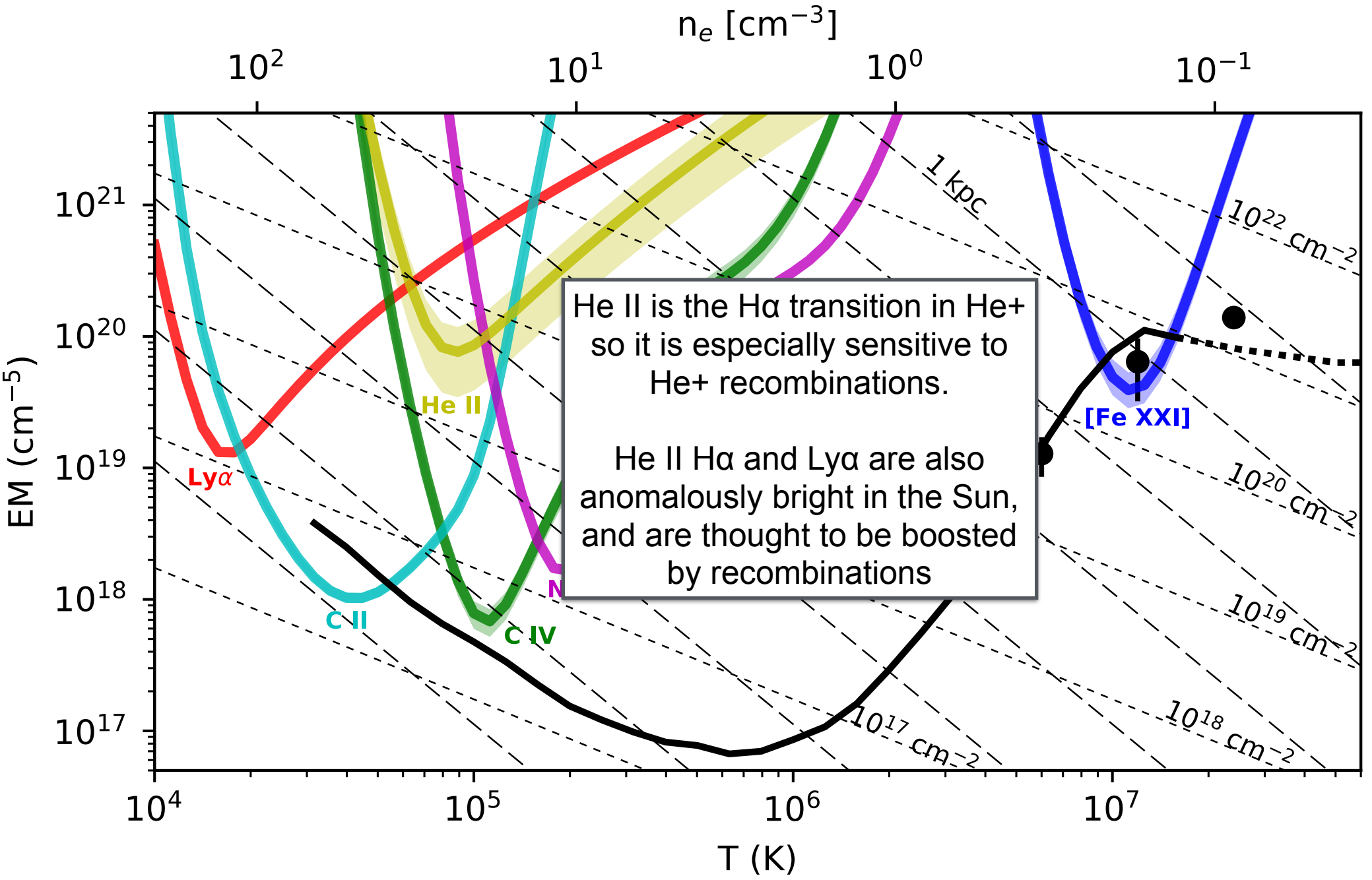

Emission measures of collisional plasmas
n_e [cm^{-3}]
10^2
10^1
10^0
10^{-1}
10^{21}
10^{20}
10^{19}
10^{18}
10^{17}
EM (cm^{-5})
[Fe XXI]
10^4
10^5
10^6
10^7
T (K)

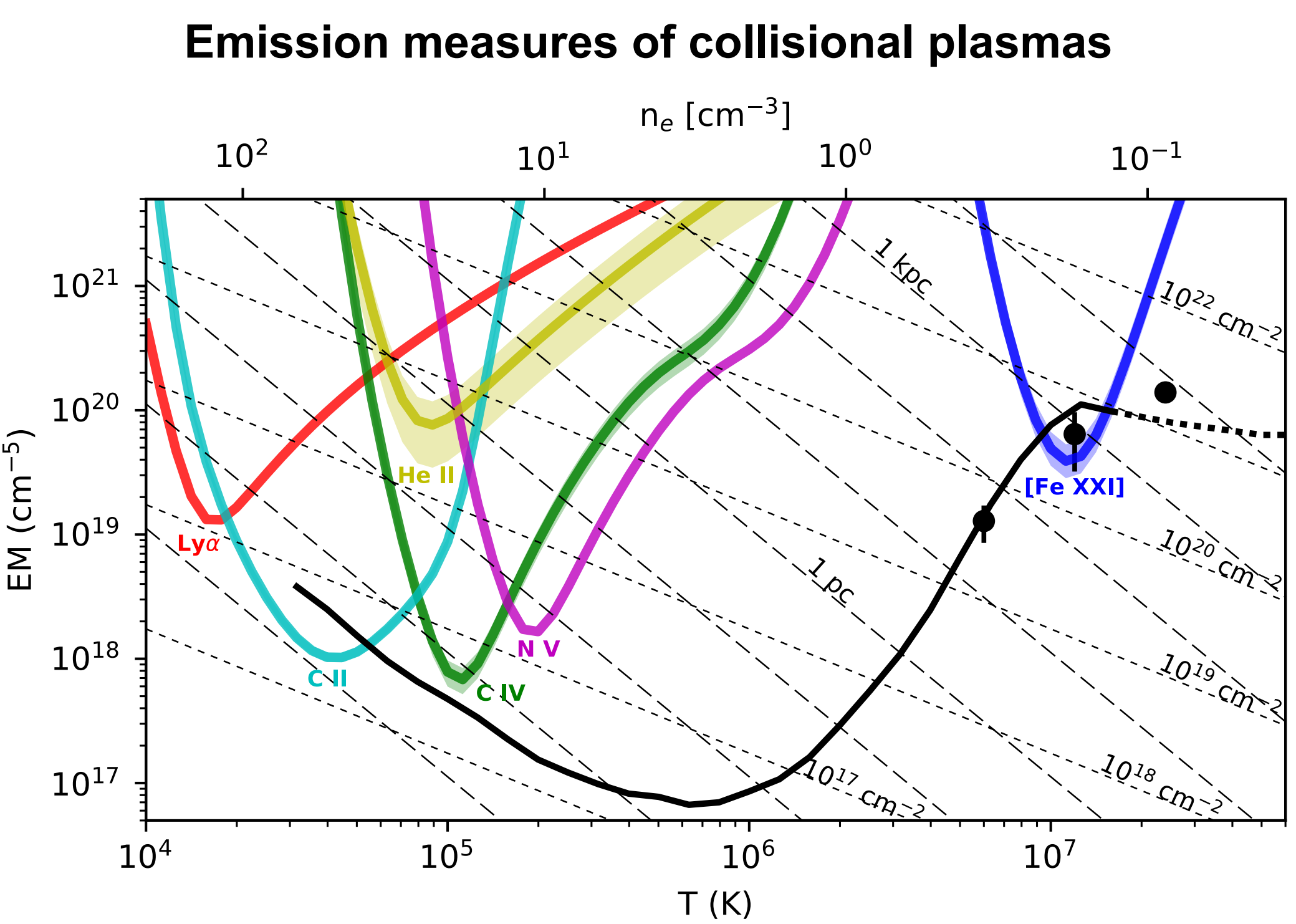

Emission measures of collisional plasmas
n_e [cm^-3]
10^2
10^1
10^0
10^-1
EM (cm^-5)
10^21
10^20
10^19
10^18
10^17
T (K)
10^4
10^5
10^6
10^7
1 kpc
1 pc
10^22 cm^-2
10^20 cm^-2
10^19 cm^-2
10^18 cm^-2
10^17 cm^-2
[Fe XXI]


Emission measures of collisional plasmas
n_e [cm^{-3}]
10^2
10^1
10^0
10^{-1}
EM (cm^{-5})
10^{21}
10^{20}
10^{19}
10^{18}
10^{17}
10^4
10^5
10^6
10^7
T (K)
1 kpc
1 pc
10^{22} cm^{-2}
10^{20} cm^{-2}
10^{19} cm^{-2}
10^{18} cm^{-2}
10^{17} cm^{-2}
Lyα
He II
C II
C IV
N V
[Fe XXI]


Emission measures of collisional plasmas
n_e [cm^{-3}]
10^2
10^1
10^0
10^{-1}
EM (cm^{-5})
10^{21}
10^{20}
10^{19}
10^{18}
10^{17}
10^4
10^5
10^6
10^7
T (K)
1 kpc
1 pc
10^{22} cm^{-2}
10^{20} cm^{-2}
10^{19} cm^{-2}
10^{18} cm^{-2}
10^{17} cm^{-2}
Lyα
He II
C II
C IV
N V
[Fe XXI]

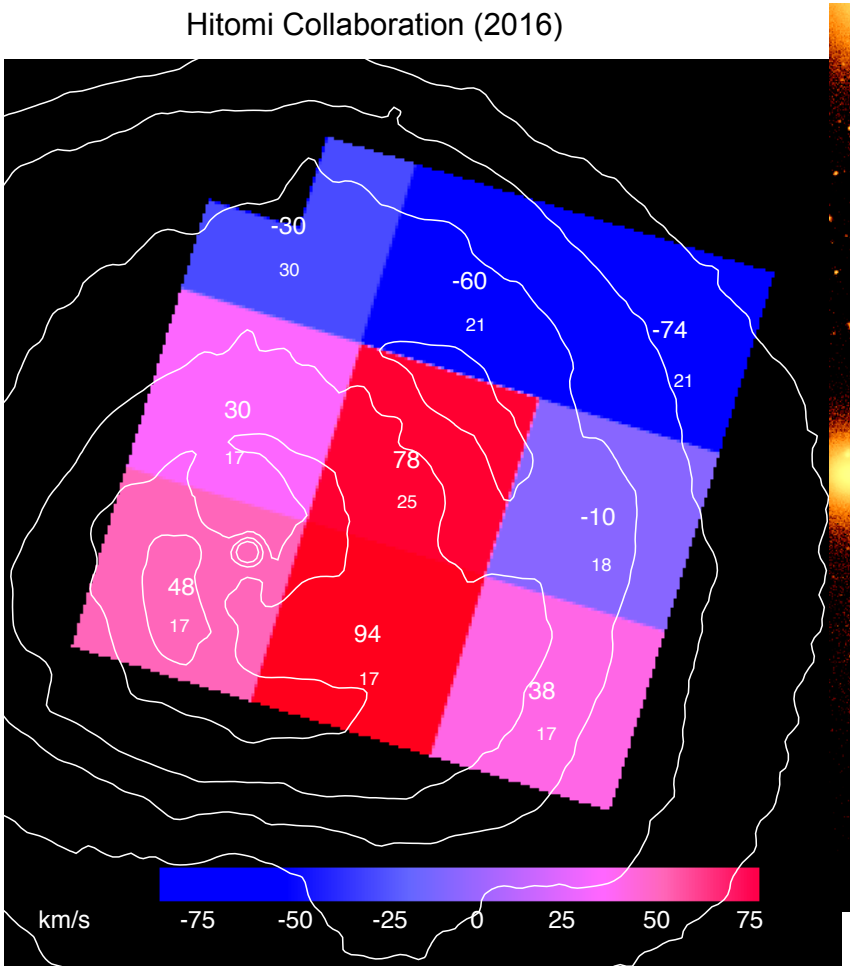
Emission measures of collisional plasmas

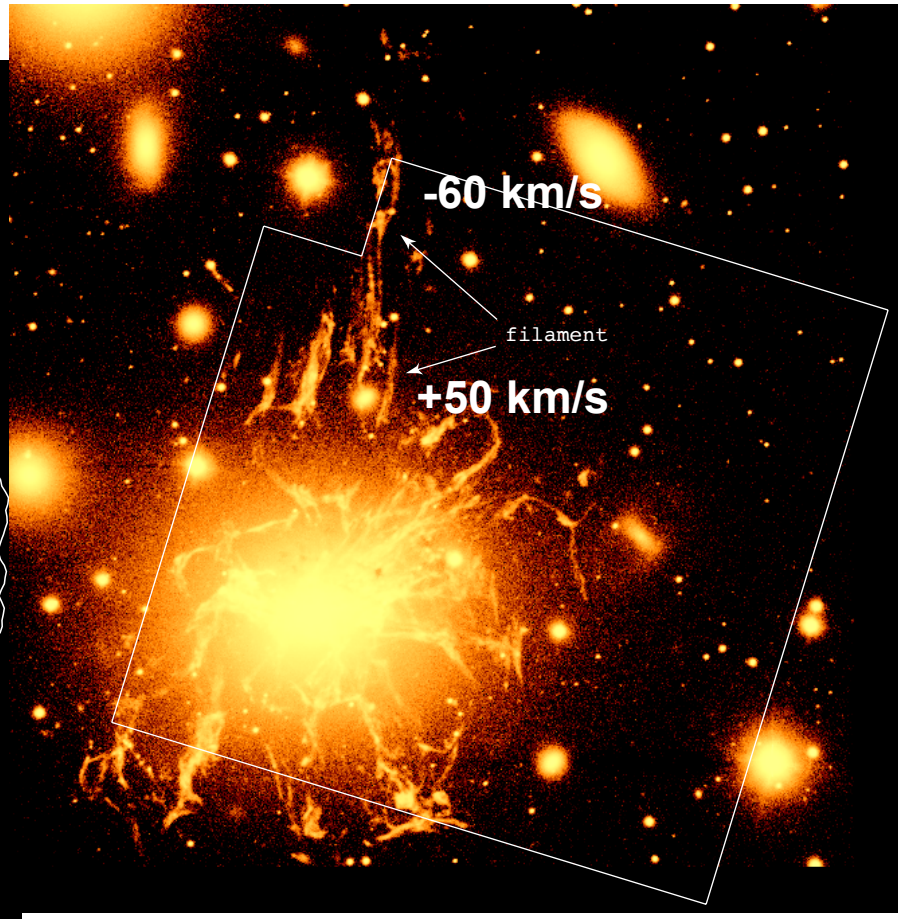


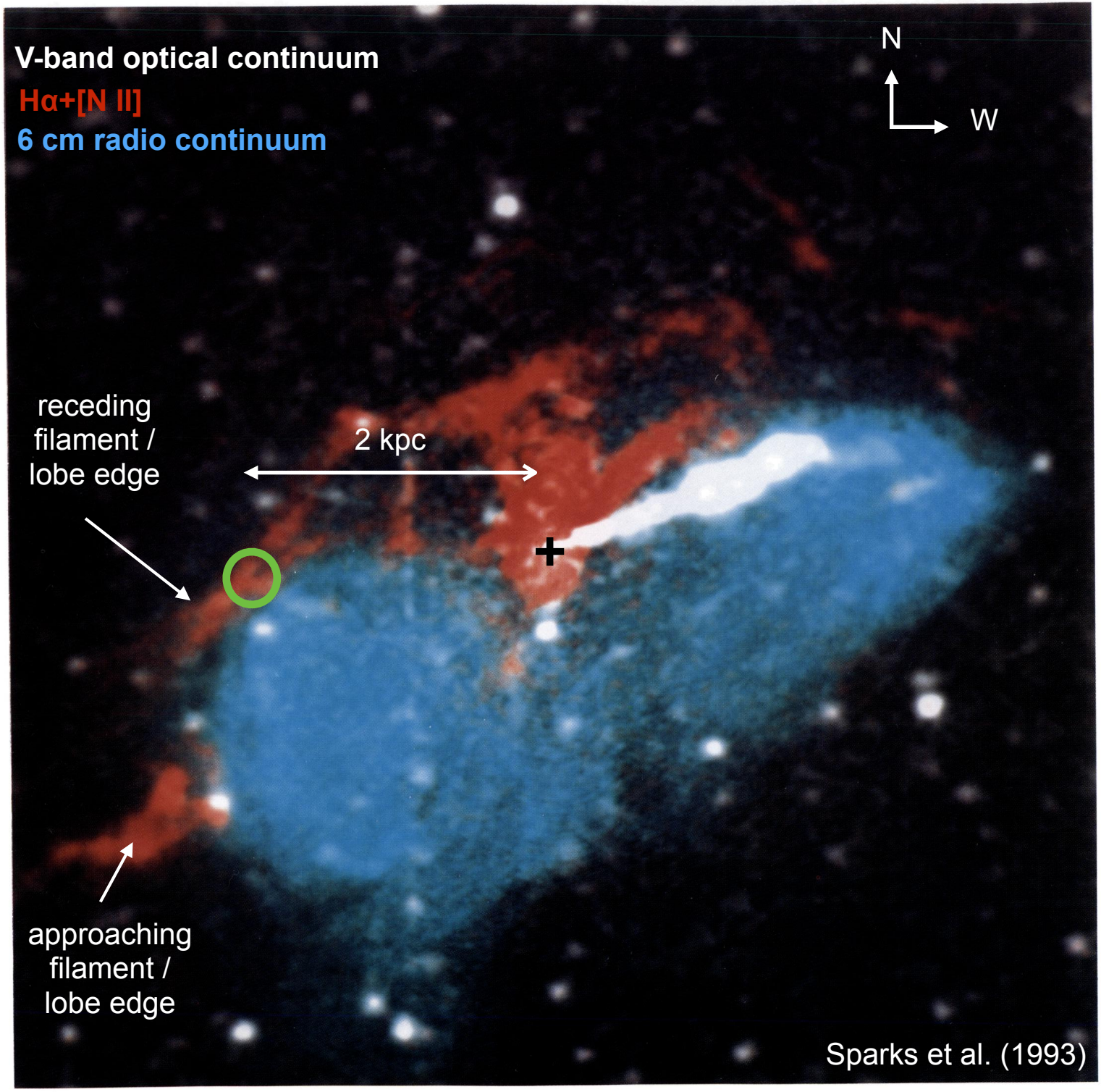

Emission measures of collisional plasmas
n_e [cm^{-3}]
10^2
10^1
10^0
10^{-1}
EM (cm^{-5})
10^{21}
10^{20}
10^{19}
10^{18}
10^{17}
10^4
10^5
10^6
10^7
T (K)
1 kpc
1 pc
10^{22} cm^{-2}
10^{20} cm^{-2}
10^{19} cm^{-2}
10^{18} cm^{-2}
10^{17} cm^{-2}
Lyα
He II
C II
C IV
N V
[Fe XXI]

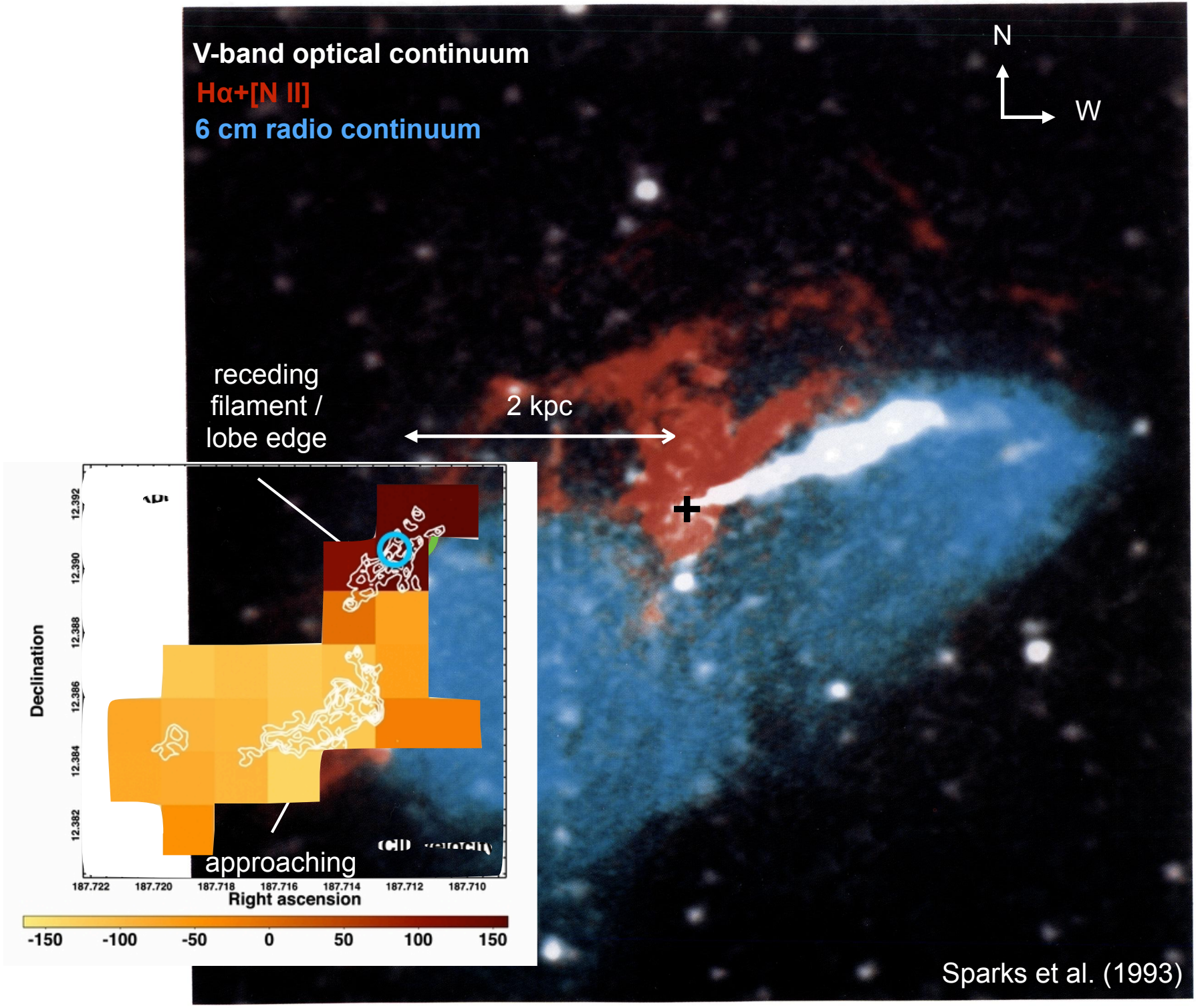
Blueshifted [Fe XXI]?

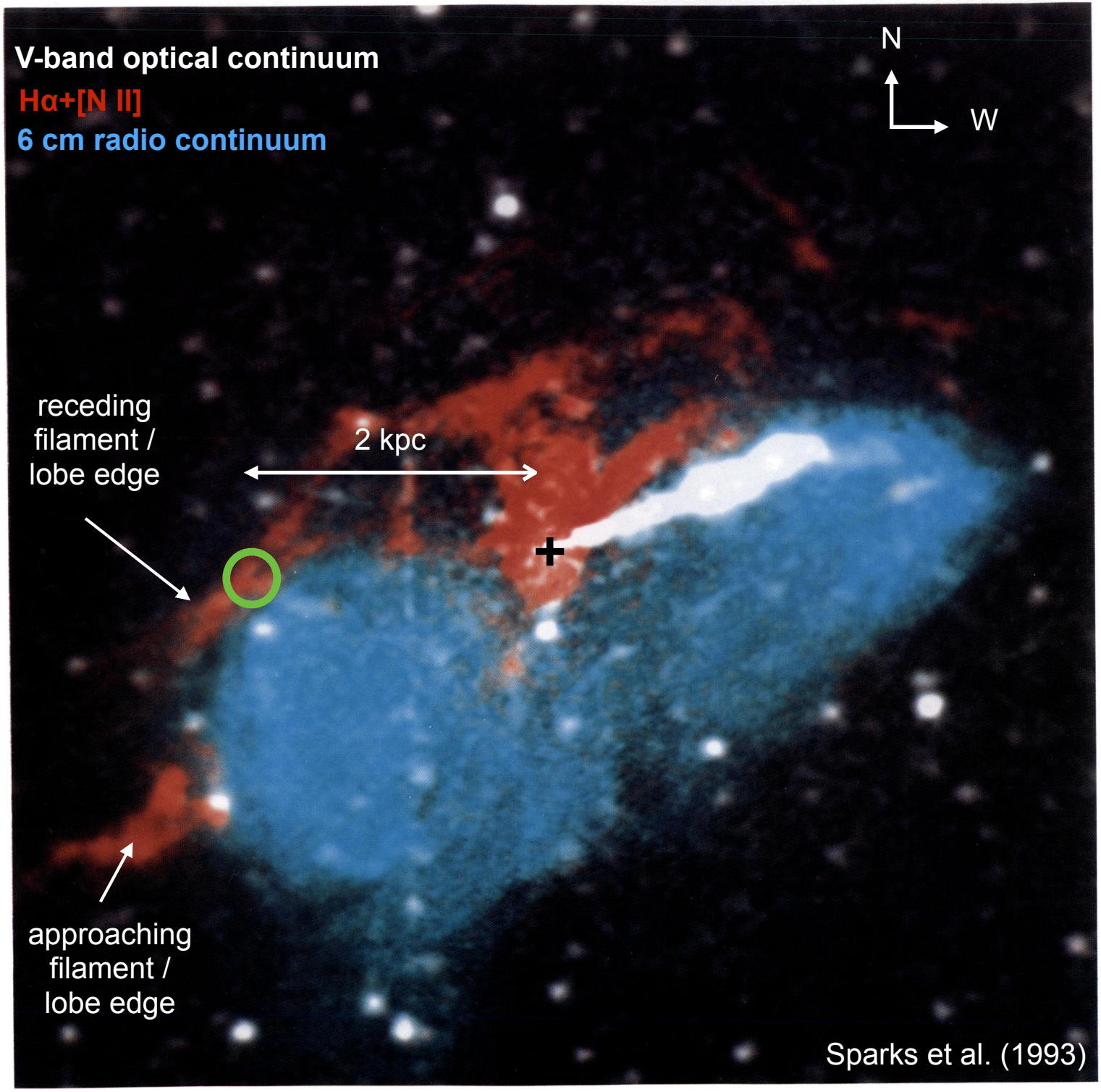
Hitomi Collaboration (2016)

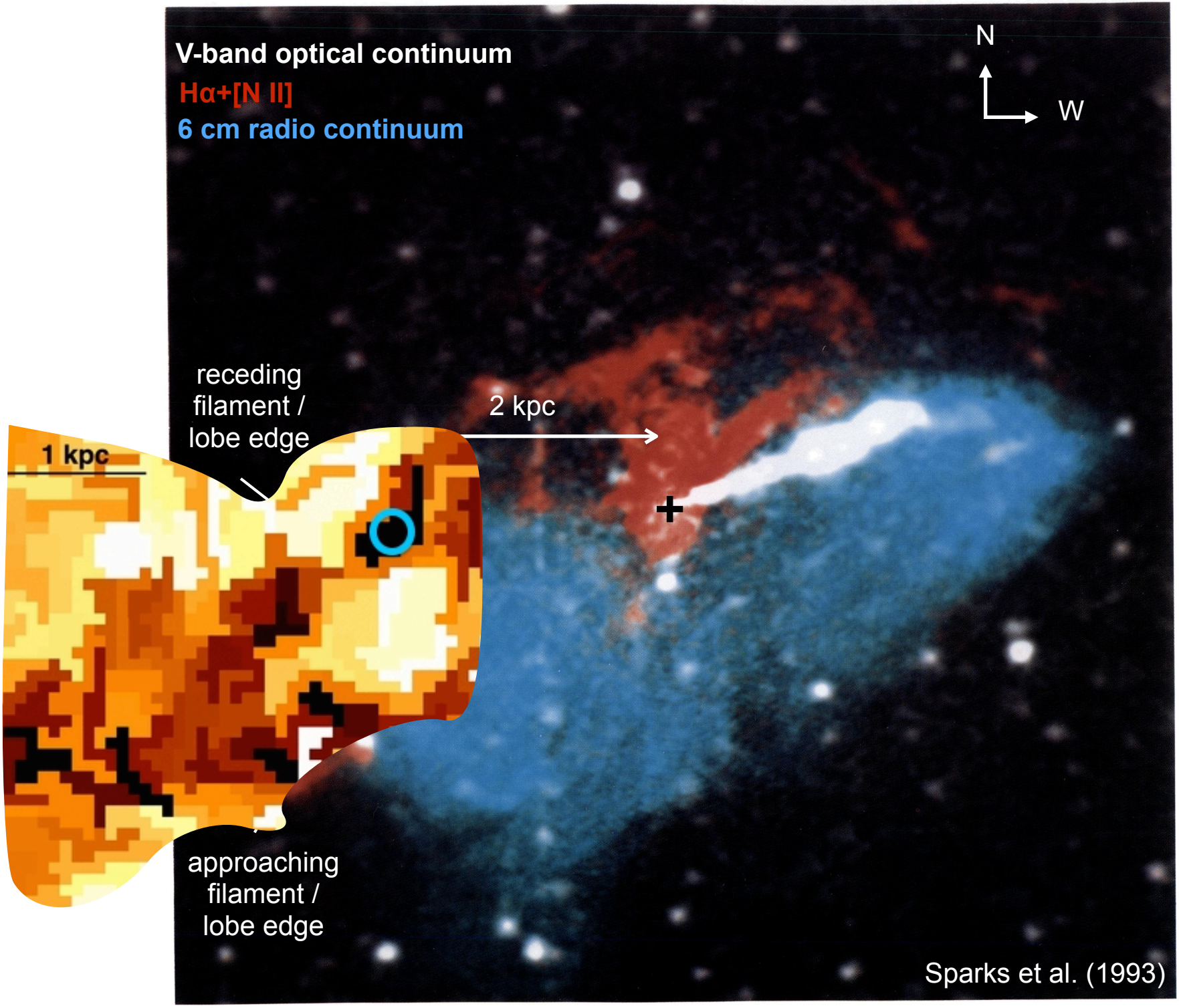


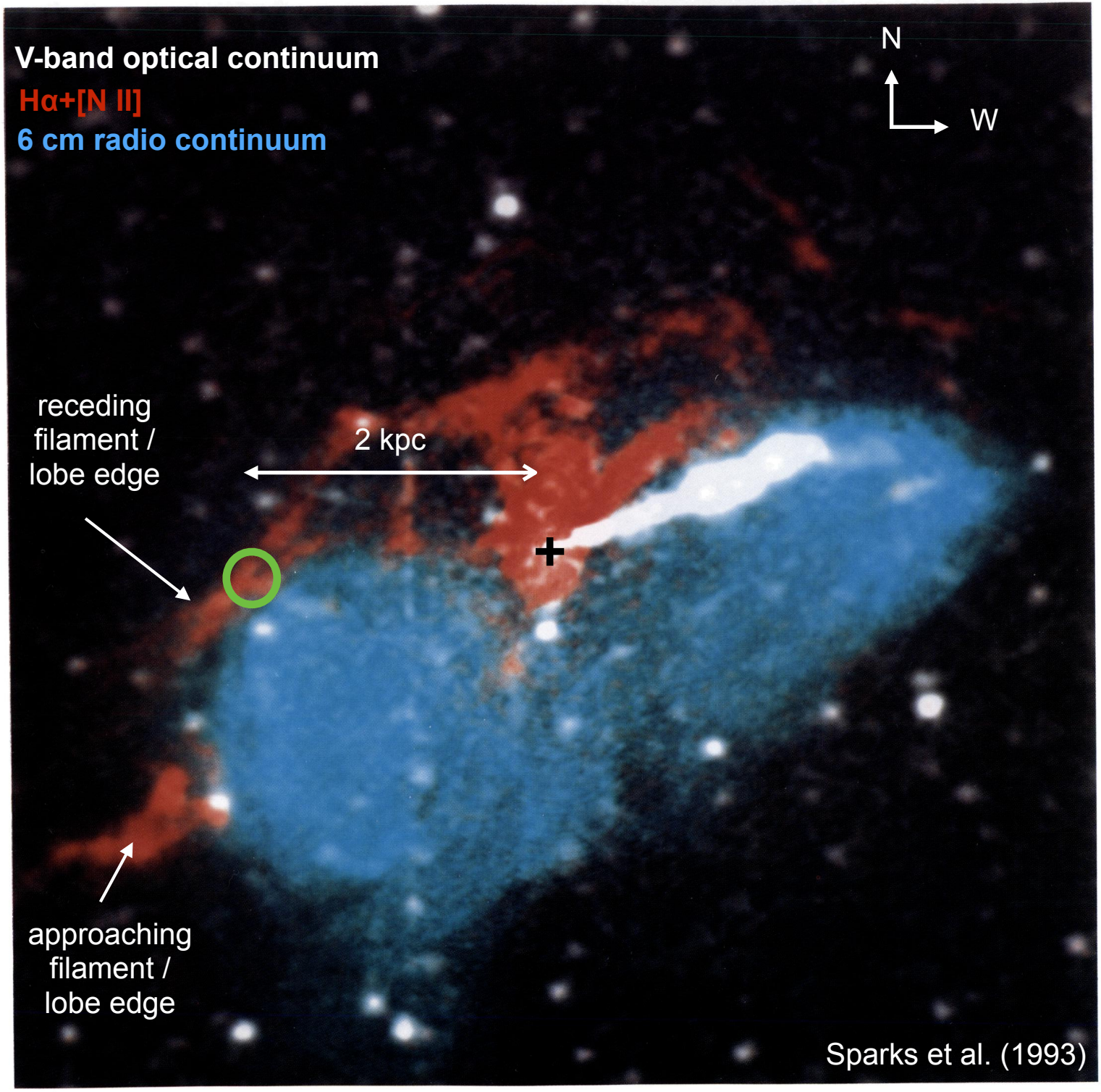



V-band optical continuum
Hα+[N II]
6 cm radio continuum
N
W
receding
filament /
lobe edge
2 kpc
approaching
filament /
lobe edge
Sparks et al. (1993)


V-band optical continuum
Hα+[N II]
6 cm radio continuum
N
W
receding
filament /
lobe edge
2 kpc
approaching
Declination
12.392
12.390
12.388
12.386
12.384
12.382
187.722
187.720
187.718
187.716
187.714
187.712
187.710
Right ascension
-150
-100
-50
0
50
100
150
Sparks et al. (1993)


V-band optical continuum
Hα+[N II]
6 cm radio continuum
N
W
receding
filament /
lobe edge
2 kpc
approaching
filament /
lobe edge
Sparks et al. (1993)


V-band optical continuum
Hα+[N II]
6 cm radio continuum
N
W
receding
filament /
lobe edge
2 kpc
1 kpc
approaching
filament /
lobe edge
Sparks et al. (1993)


V-band optical continuum
Hα+[N II]
6 cm radio continuum
N
W
receding
filament /
lobe edge
2 kpc
approaching
filament /
lobe edge
Sparks et al. (1993)

Conclusions

M87 filament seems to be largely collisionally excited

FUV emission comes from extremely narrow boundary layer

[Fe XXI] is detected from 1 keV ICM at 4.4-5.1σ

1 keV plasma is kinematically decoupled from the filament
(v_r = -92 +34 -22 km/s, σ = 69 +79 -27 km/s)

Only the second direct measurement to date of ICM turbulence

Our HST/COS observations of [Fe XXI] used ~38 ks of observing time
Hitomi observations of Fe XXV used 230 ks of observing time
These techniques are complementary!
But, when 1 keV plasma is present, [Fe XXI] can be very efficient