Hot, warm, and cold gas in a sightline towards a filament in M87

Mike Anderson

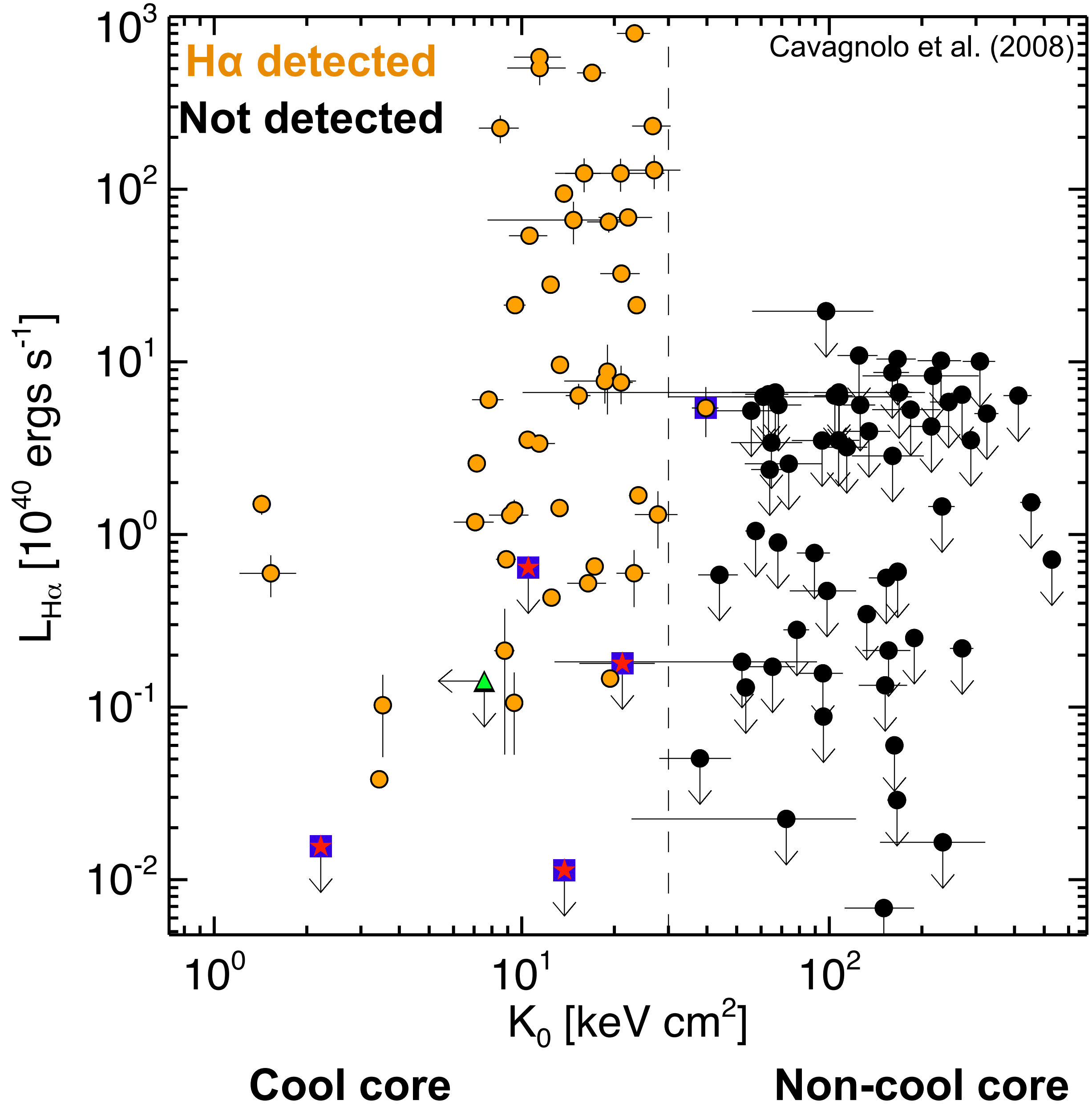
MPA Garching

Anderson and Sunyaev (2016)
MNRAS, 459, 2806

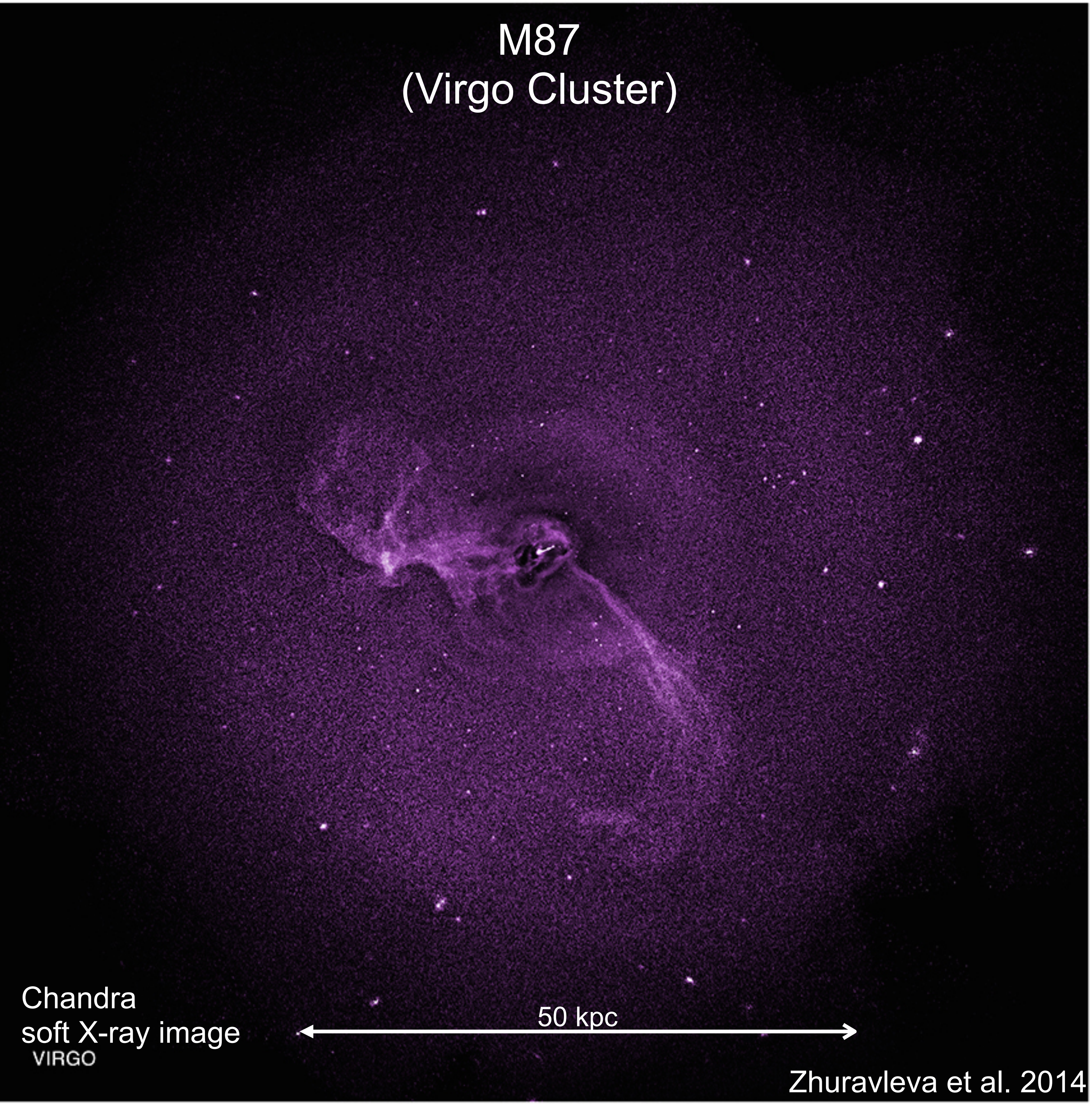
Anderson and Sunyaev (2017)
to be submitted soon

Galaxy Evolution in Groups and Clusters at 'low' Redshift:
Theory and Observations
12 December 2017

Hα and Cool-core Galaxy Clusters



- <u>Hα is associated with ICM cooling</u>
- 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?

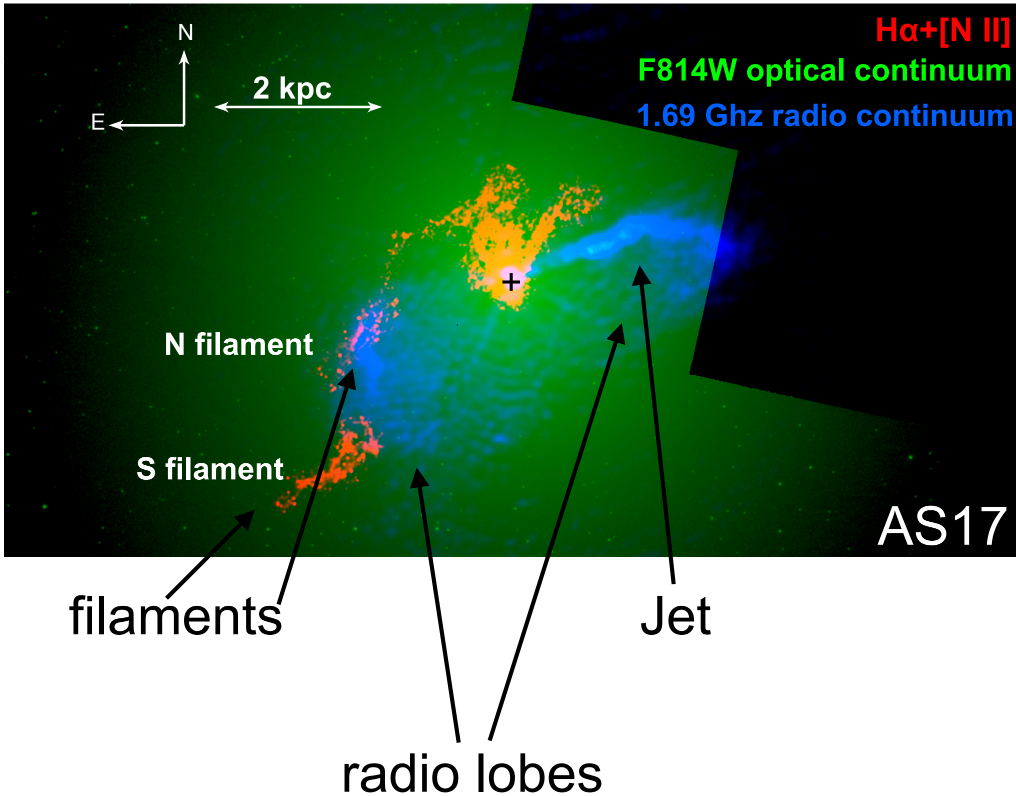


<u>Why M87 / Virgo?</u>

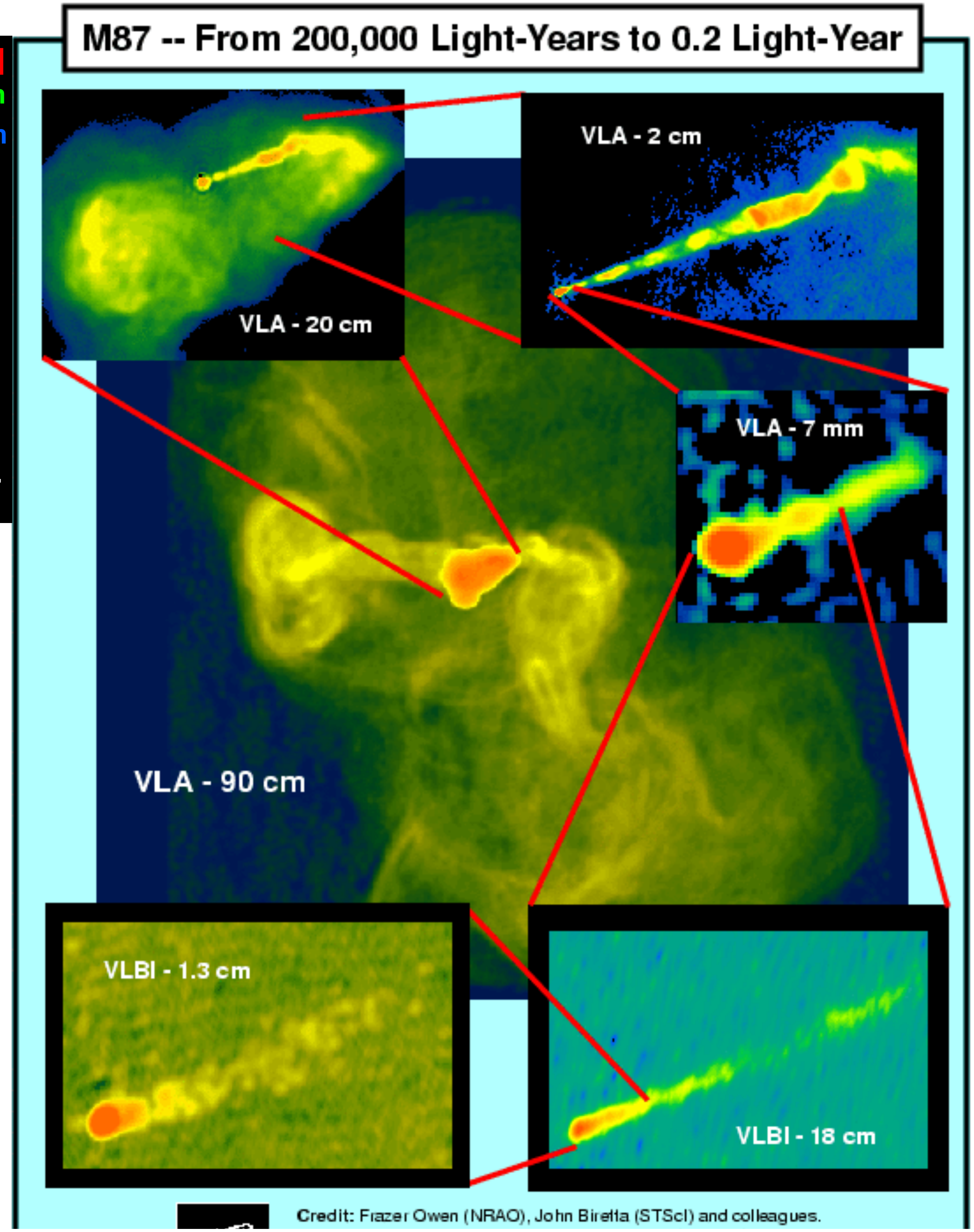
- Virgo is the nearest galaxy cluster (d = 16.7 Mpc) and can be studied at very high resolution
- M87 is already well-studied at nearly every wavelength, so a comprehensive understanding is possible
- **M87 filaments are not forming stars**, unlike Perseus, so we can disentangle the filament phenomenon from star formation

Zooming into M87

Radio + optical



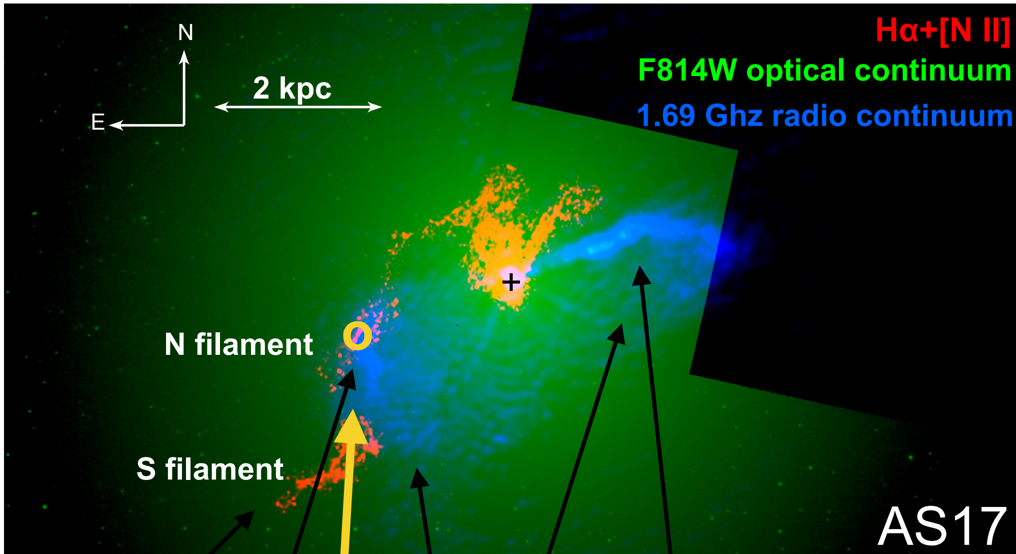
Radio



The filaments avoid radio lobes

Zooming into M87

Radio + optical



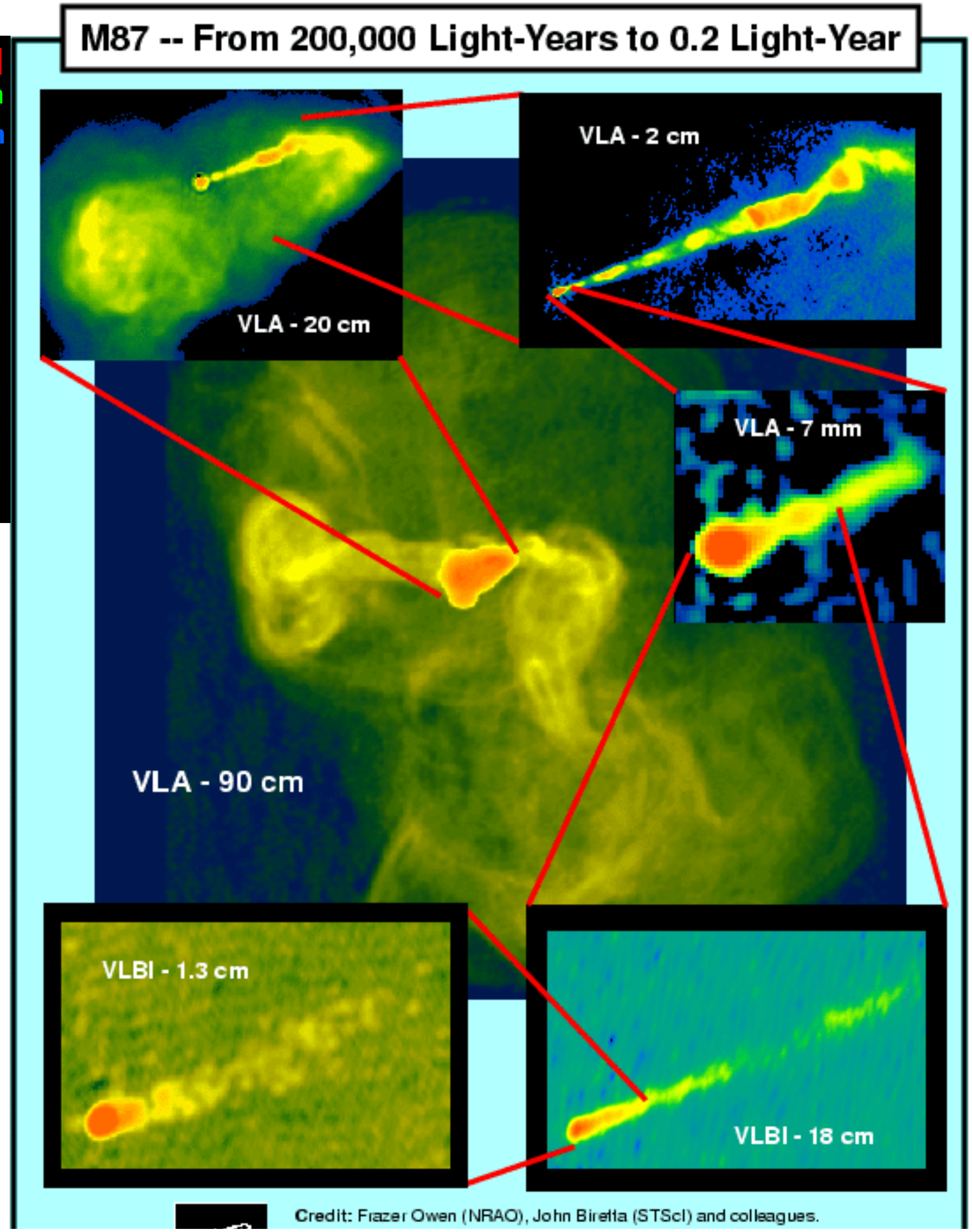
filaments

Jet

radio lobes

We observed the N filament with the COS spectrograph on HST (aperture radius = 100 pc)

Radio

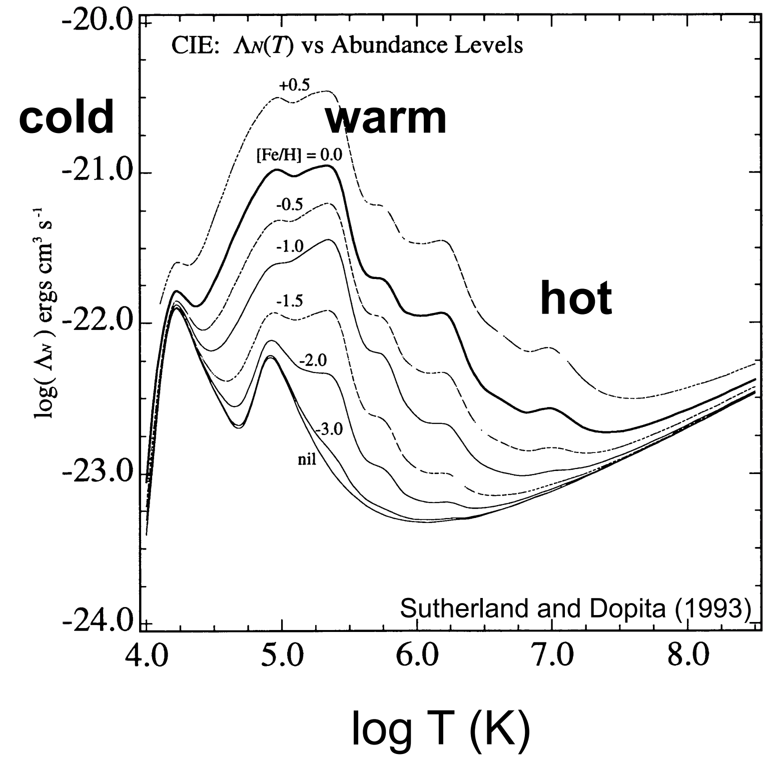


Hot, warm, and cold gas around the N filament in M87

Part 1: hot gas (T ~ 10^7 K; kT ~ 1 keV)

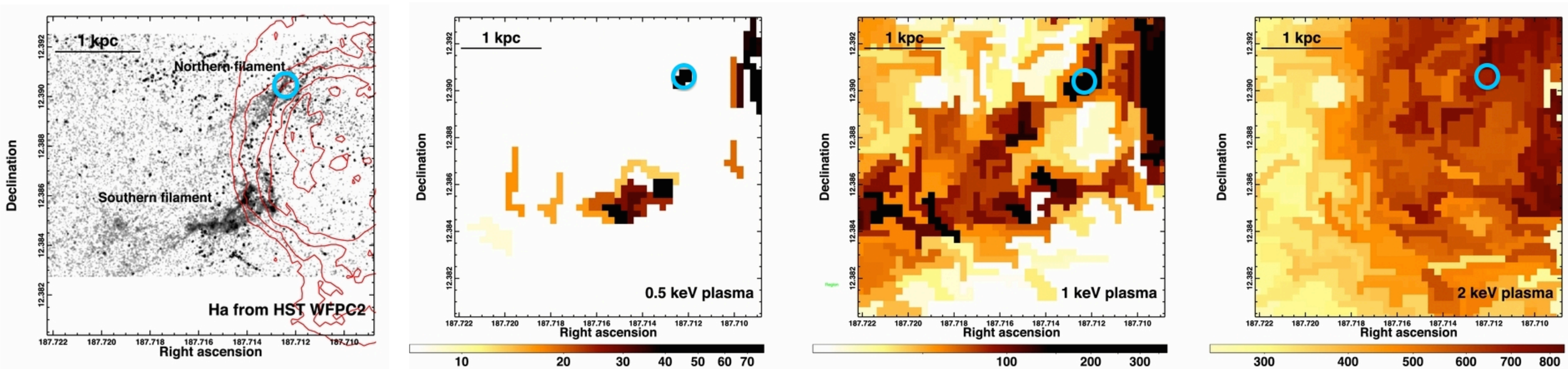
Part 2: warm gas (10^4 K ≲ T ≲ 10^6 K)

Part 3: cold gas (T ≲ 10^3 K)



Part 1: Hot Gas

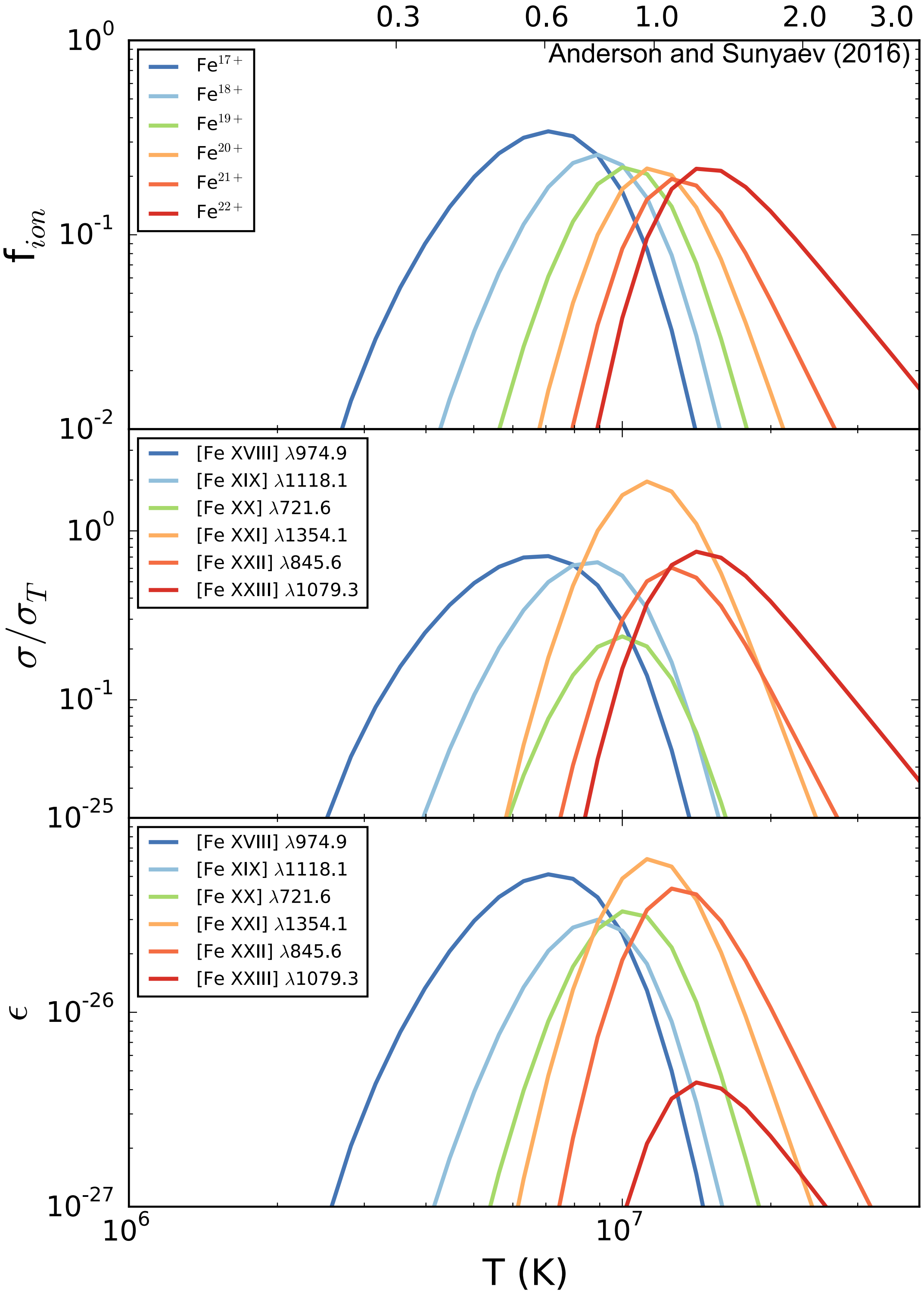
<u>Virgo Intracluster Medium around our sightline</u>



Werner et al. (2013)

- Virgo ICM in the core has kT ~ 2 keV
- ICM is multiphase at locations of filaments
- N filament has significant amounts of 1 keV and 0.5 keV gas

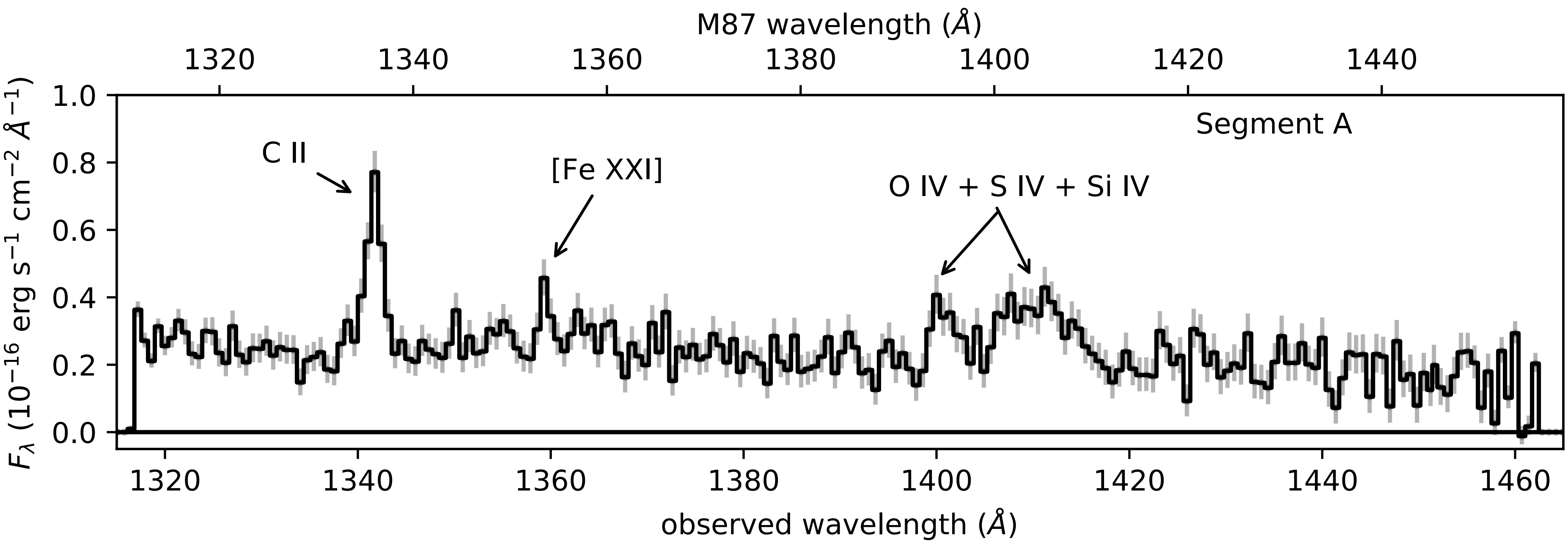
Part 1: Hot Gas



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 hot halo kinematics at FUV spectrograph resolution (COS: A~3000 cm^2, Δv ~ 15 km/s)

Part 1: Hot Gas



- [Fe XXI] is detected! S/N is 4.4 - 5.1 (depending on binning)

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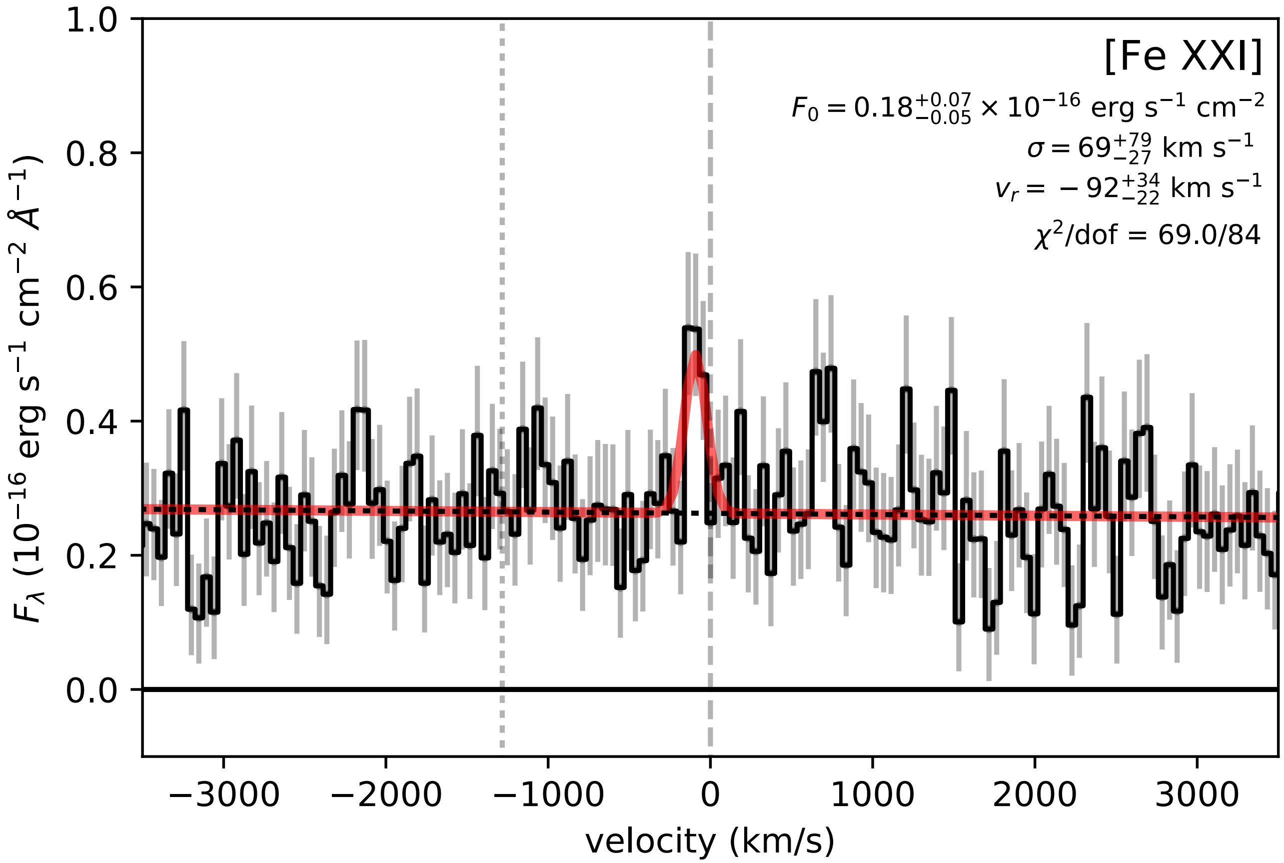
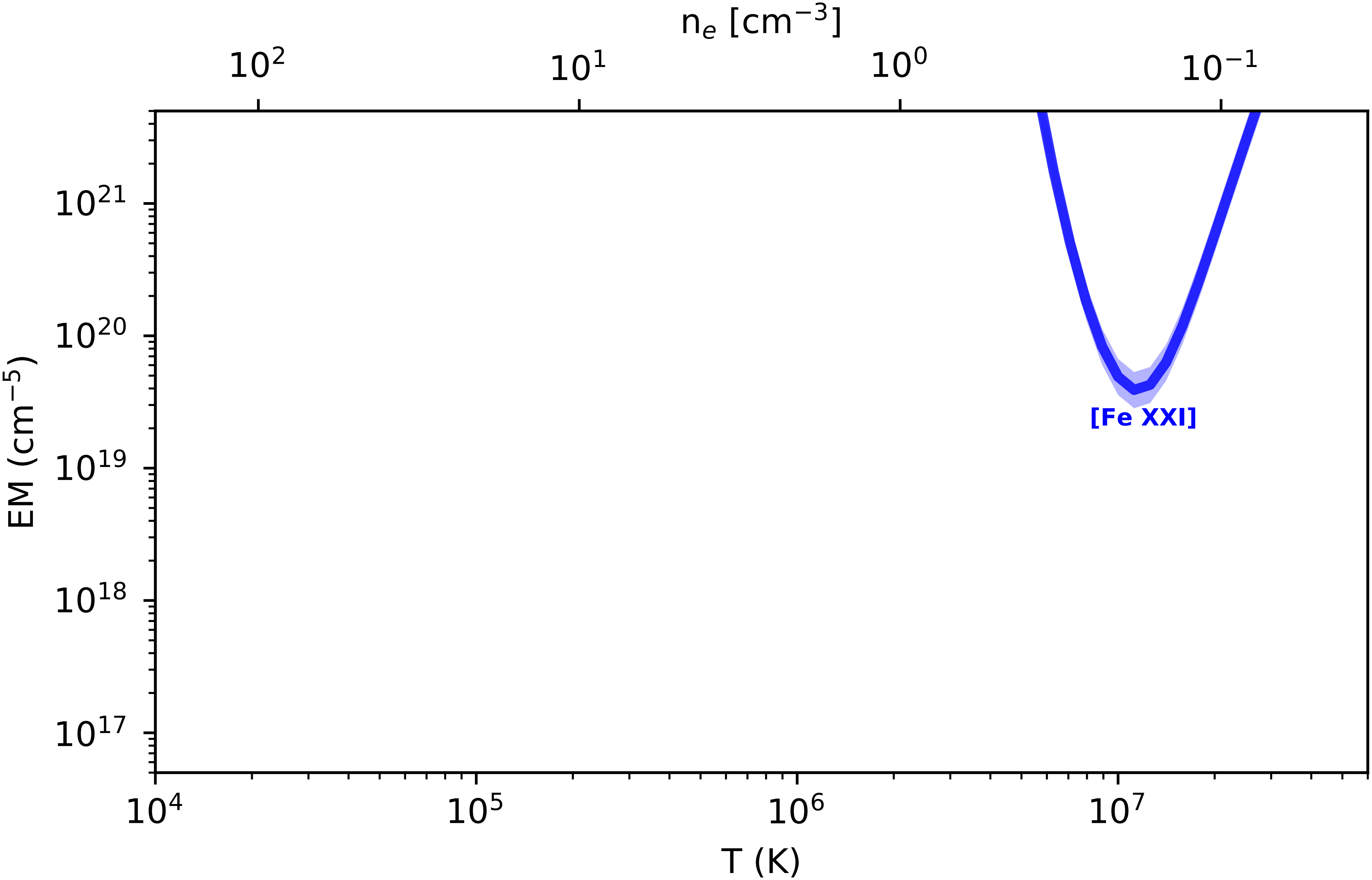


- [Fe XXI] is detected! S/N is 4.4 - 5.1 (depending on binning)
- v_r gives bulk velocity of ICM (blueshifted relative to M87)
- σ_r is an estimate of the 1D turbulence in the ICM
  (turbulent pressure is 2% -1 +11 of the thermal pressure)
- **<u>This is only the second direct measurement of ICM kinematics</u>**
  (after the Hitomi microcalorimeter observations of Perseus)

Part 1: Hot Gas

$$\mathrm{EM} = \frac{4\pi d^2 F}{\epsilon \times A \times Z_{\mathrm{Fe}}}$$

Emission measure analysis



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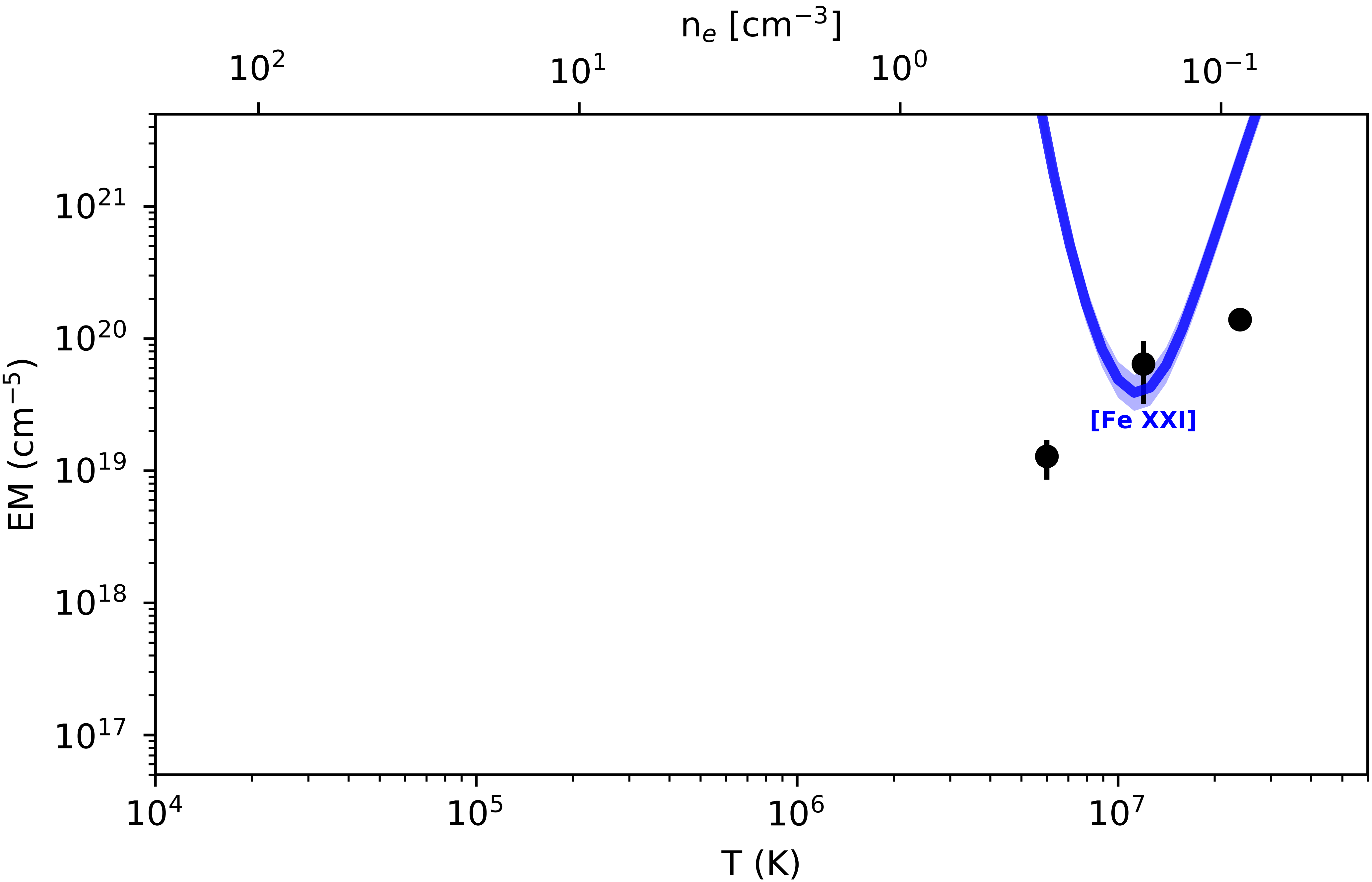
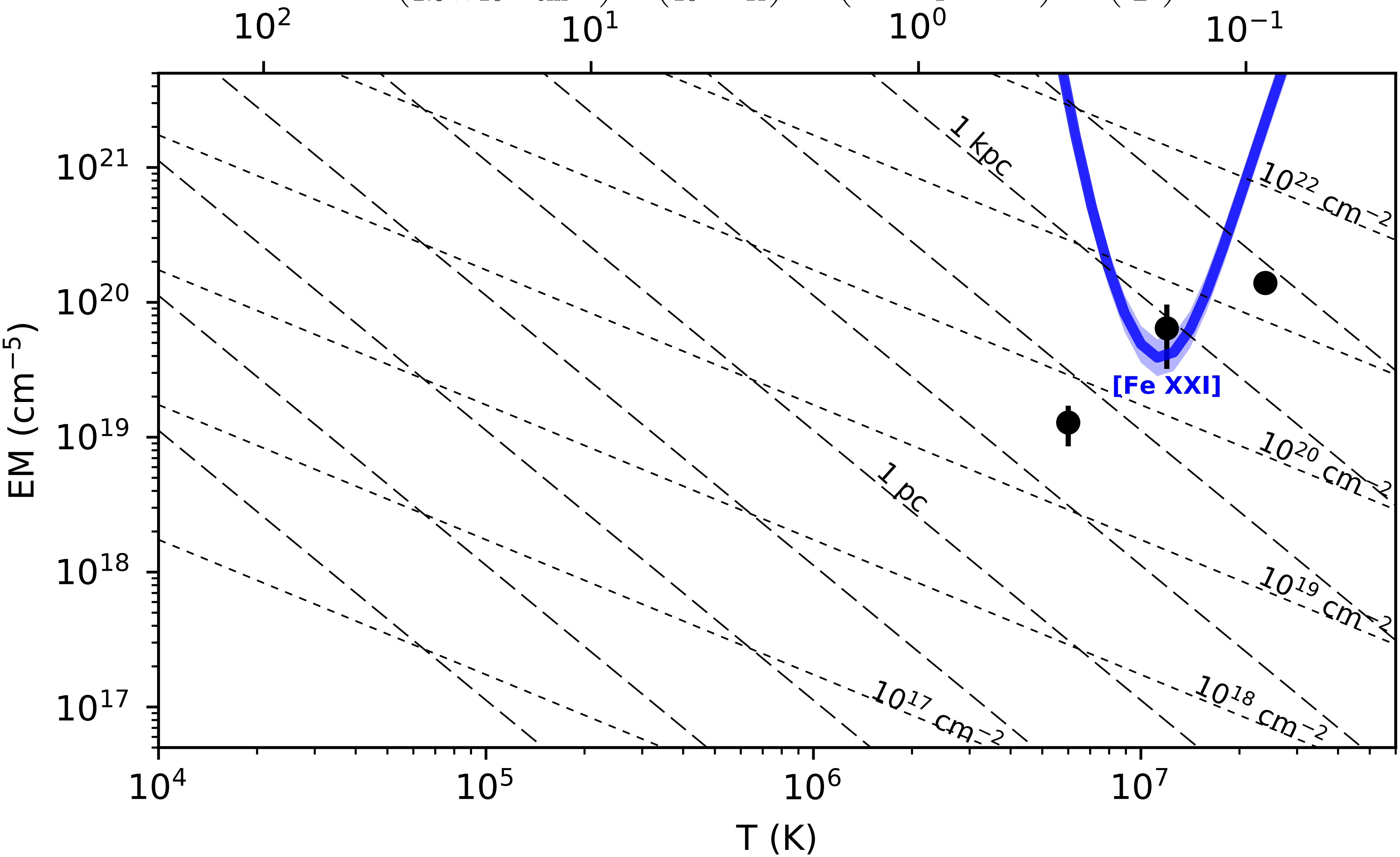


Part 1: Hot Gas

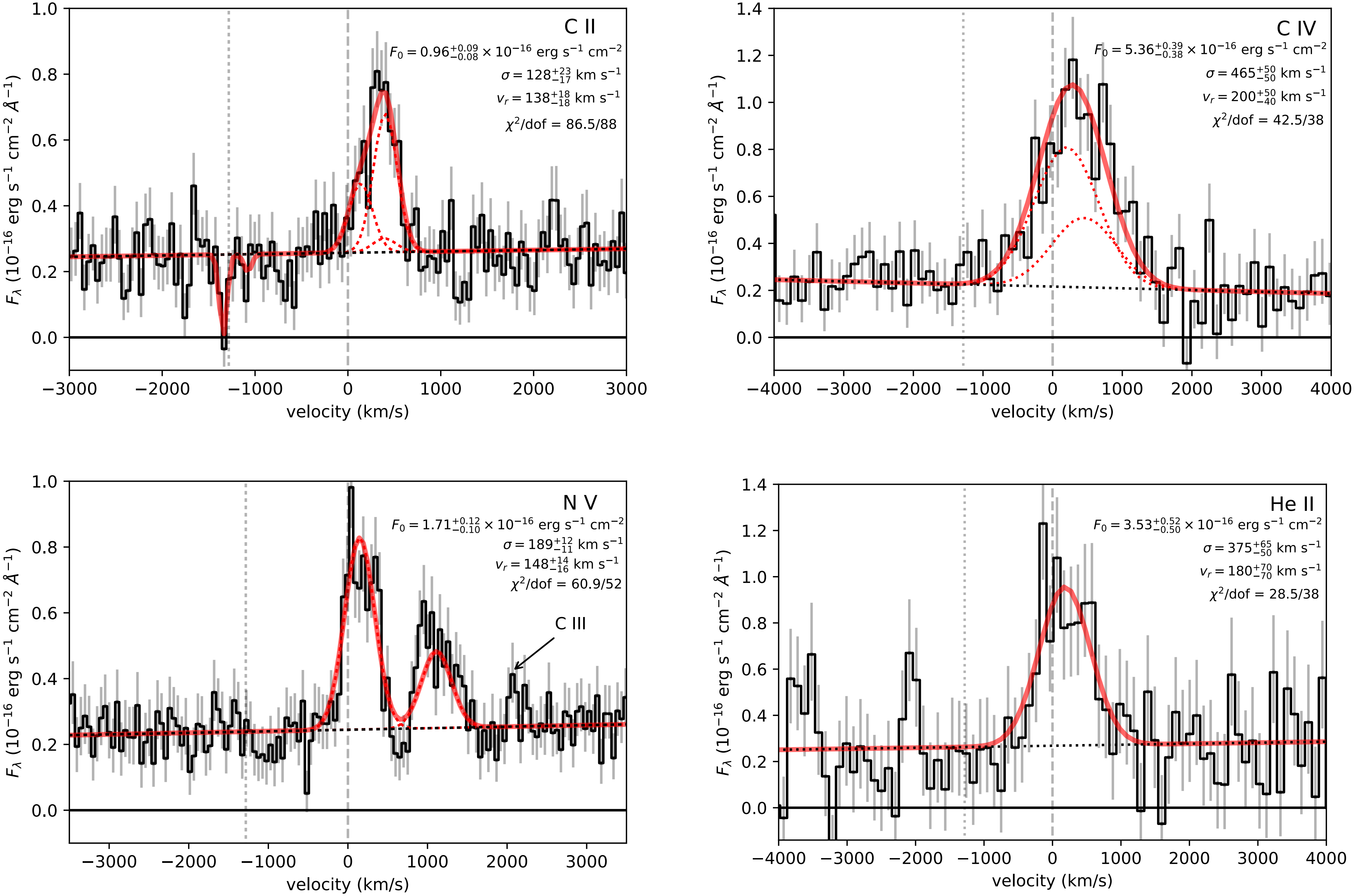
Emission measure analysis

$$l = 3.0\ \mathrm{kpc} \times \left(\frac{\mathrm{EM}}{2.5\times10^{20}\ \mathrm{cm}^{-5}}\right) \times \left(\frac{T}{10^{7.05}\ \mathrm{K}}\right)^2 \times \left(\frac{4\times10^{6}\ \mathrm{cm}^{-3}\ \mathrm{K}}{P}\right)^2 \times \left(\frac{Z_\odot}{Z}\right)$$



Part 2: Warm Gas

Permitted FUV lines



Part 2: Warm Gas

Summary of FUV line models

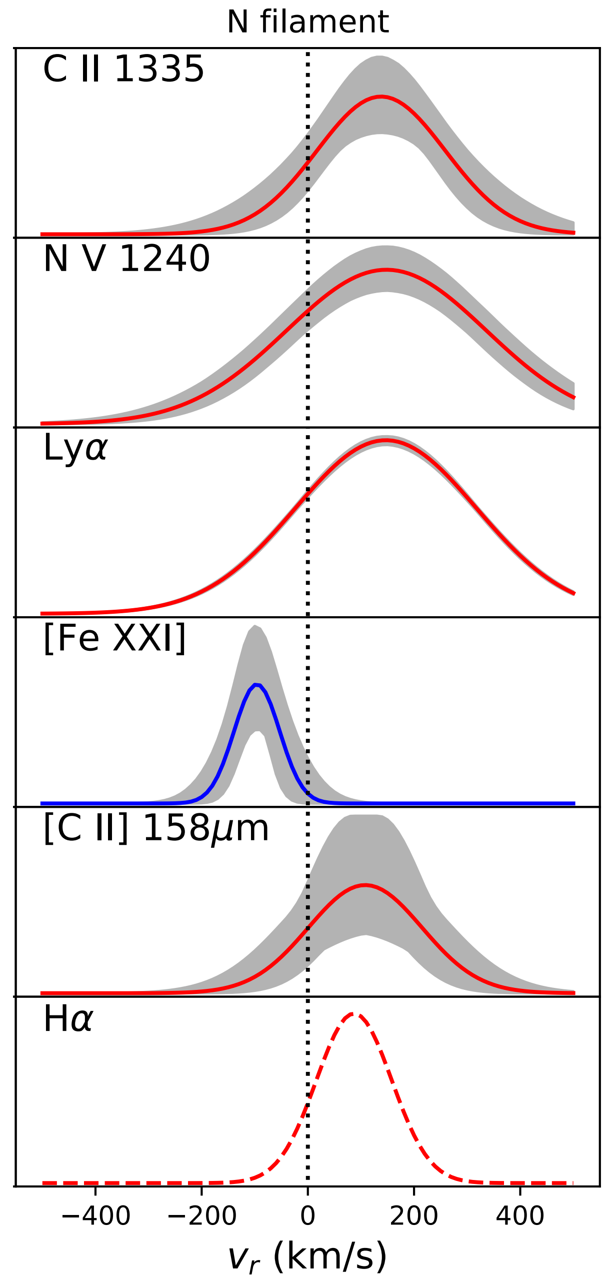
- Permitted FUV lines are all approximately consistent with one another

- they likely all originate from filament

- CIV and He II are also consistent

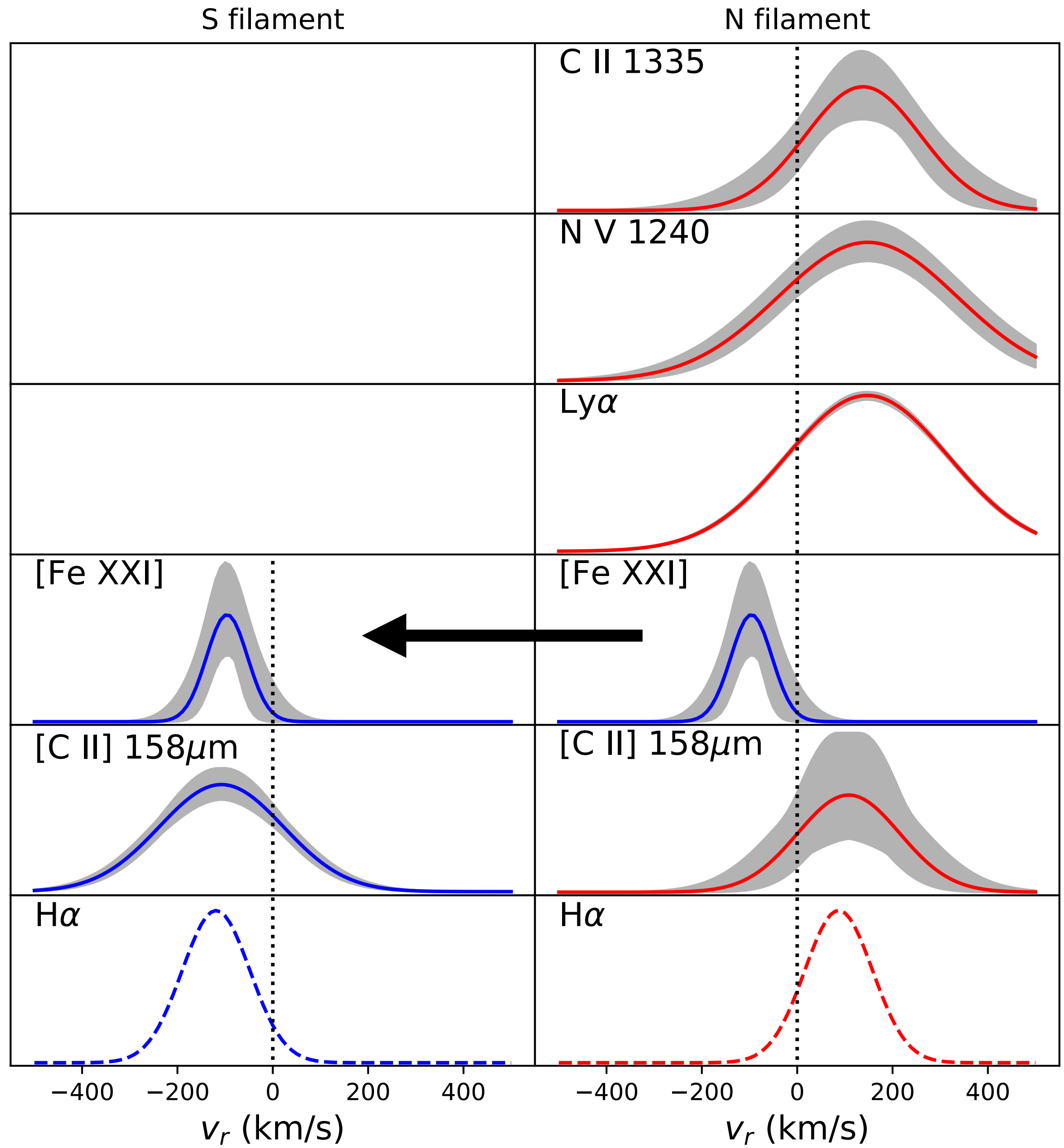
- Ha and a [C II] far-IR line are also consistent and also likely originate from filament

- [Fe XXI] is narrower and blueshifted, unlike the other lines



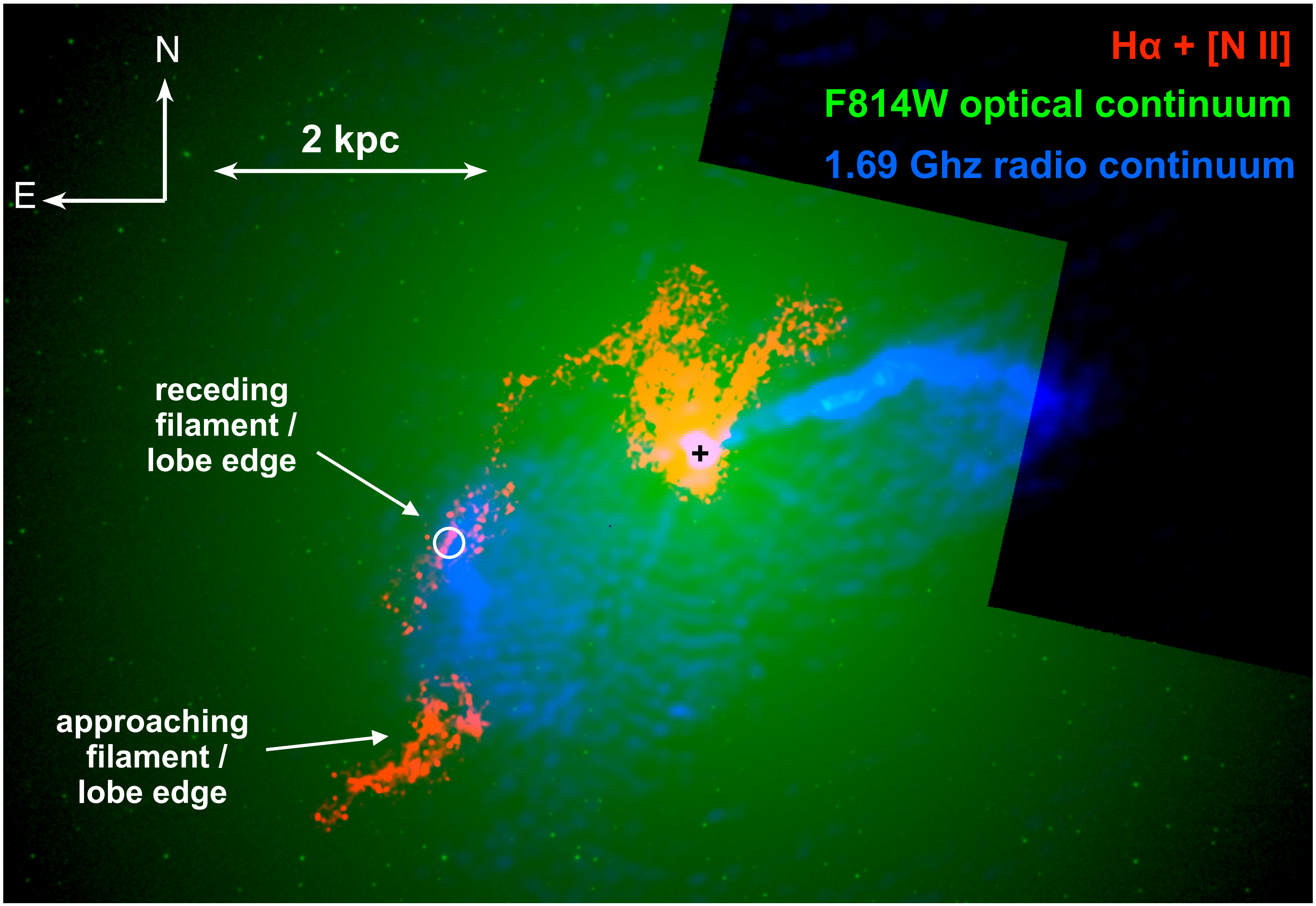
Part 2: Warm Gas

Summary of FUV line models



Part 2: Warm Gas

How to explain [Fe XXI] kinematics?



Part 2: Warm Gas

Note the very short path lengths in the EM analysis

Mass traced by FUV lines is typically just ~ 10/f Msun

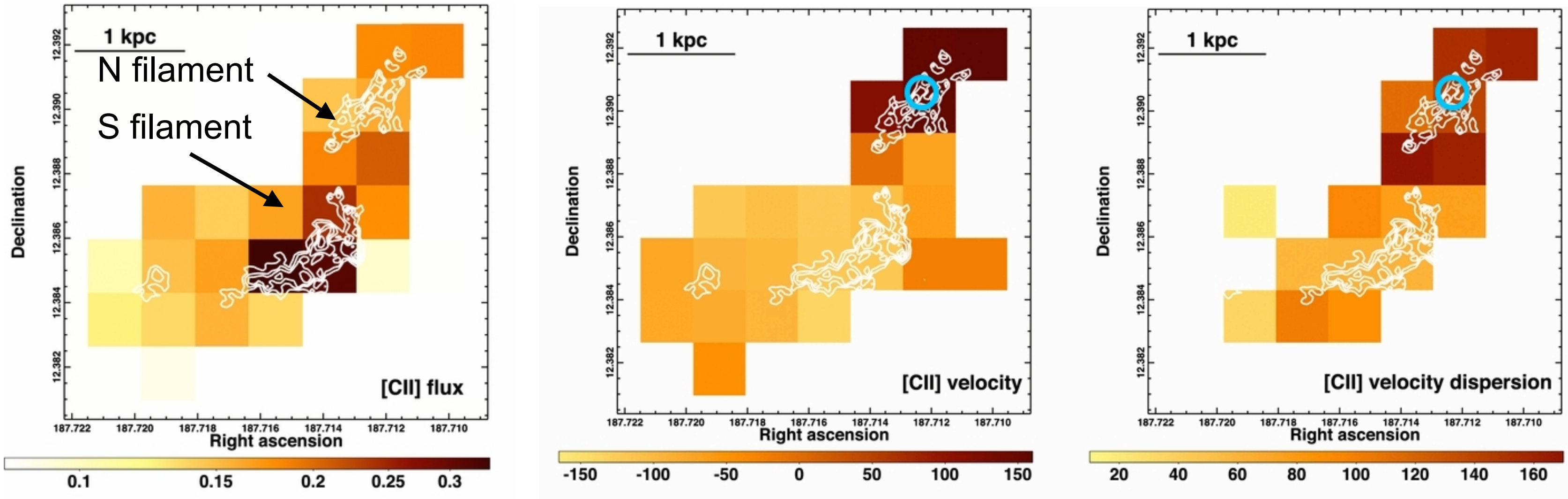
However, the lines are very bright and dominate cooling in the region

Lya luminosity ~4e38 erg/s
(path length *l* < 1 pc)

This line is brighter than L_X for the ICM along the whole sightline!
(path length *l* ~ 10 kpc)

Part 3: Cold Gas

Werner et al. (2013)



Herschel / PACS observations of this field show [C II] 158 μm emission

spatial resolution is poor but it roughly correlates with the filaments

we analyzed the Herschel data and in the N filament we measure:

$v_r = 108 \pm 24$ km/s and $\sigma_r = 107 \pm 20$ km/s

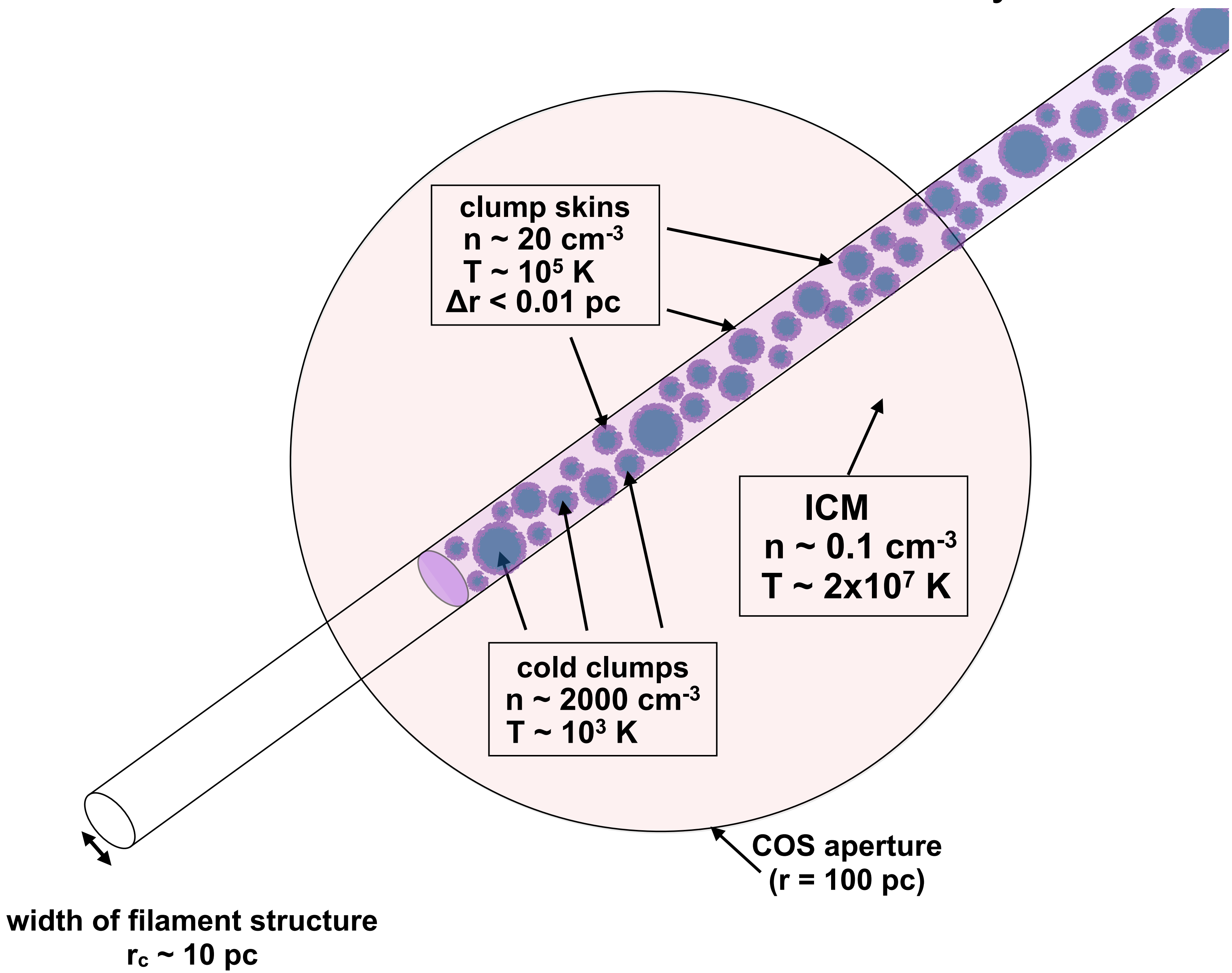
for comparison, using C II 1335A, we measured

$v_r = 138 \pm 18$ km/s and $\sigma_r = 128 +23 -17$ km/s

so both FUV and FIR CII lines have same kinematics

Part 3: Cold Gas

Schematic of Filament Geometry



Conclusions

We detect [Fe XXI] at about 5σ, and use it to measure ICM kinematics
in M87. This is only the second direct measurement for a galaxy cluster

We detect and measure many FUV lines,
which we associate with a narrow shell around the filament
The mass in the warm phase is small (10-100 Msun) but this phase is
very important for overall cooling budget

We associate [C II] 158 μm with the cold core of the filament
Cold phase dominates the mass of filament
Filament must be clumpy and have a low volume filling factor

Many open questions!
- what confines the clumps within the filament? (magnetic fields?)
- are the filaments evaporating or cooling?
- how does the structure of star-forming filaments differ from this filament?