Hot Gas Properties of Starburst-Driven Outflows

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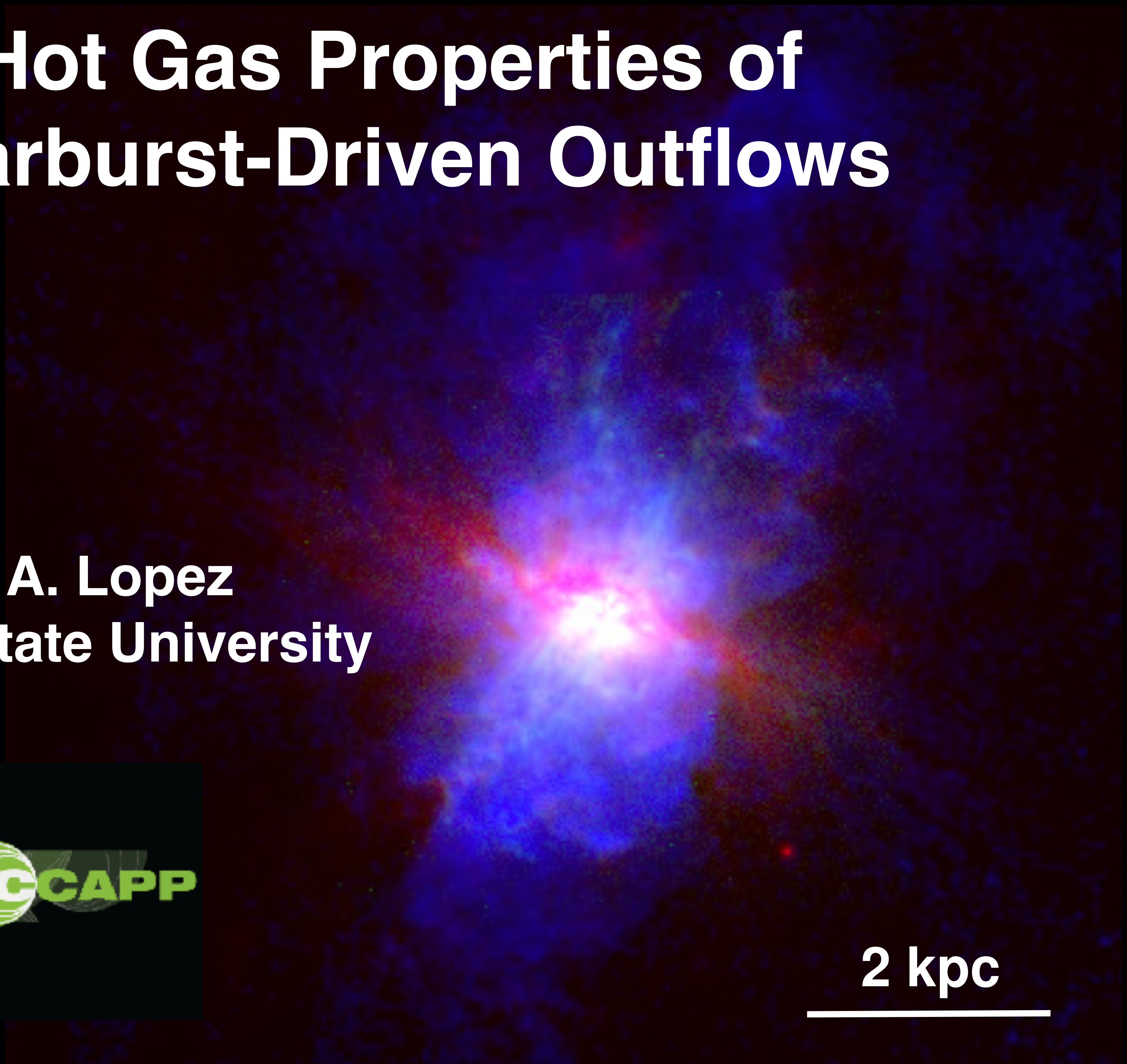

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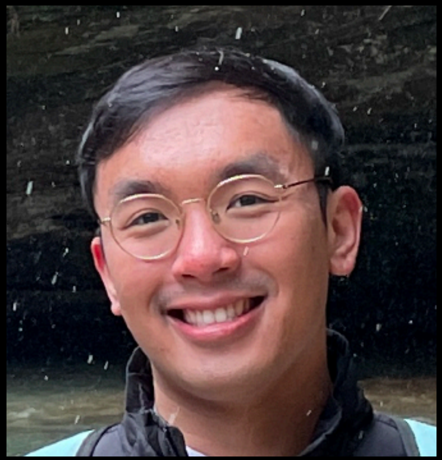
Department of Astronomy
CCAPP

Collaborators

Sebastian Lopez, OSU PhD Student



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Conclusions

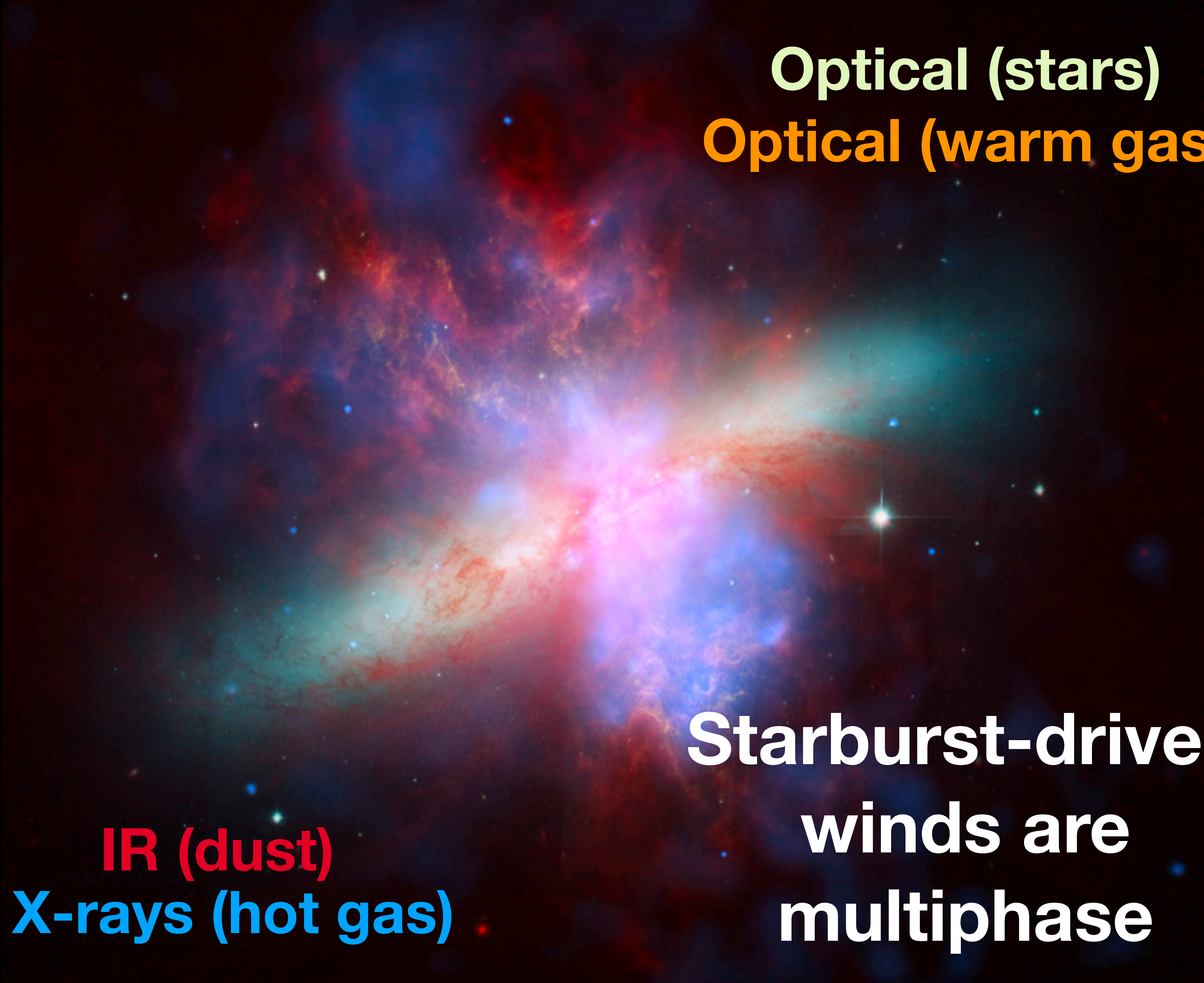
Hot phase of starburst-driven winds carries energy and metals, entrains other phases.

Deep X-ray data enables study of gradients in metallicity, temperature, and density of the hot phase, important to address outstanding questions related to winds.

Metallicity gradients out to a few kpc in M82 and NGC 253 show metal enrichment. Examination of more sources is needed to explore how metal loading depends on host galaxies (e.g., host galaxy stellar masses)

Hot gas temp and density profiles are broader than predicted for a spherical, adiabatic expanding wind. Need a non-spherical wind + mass loading to produce observed profiles.

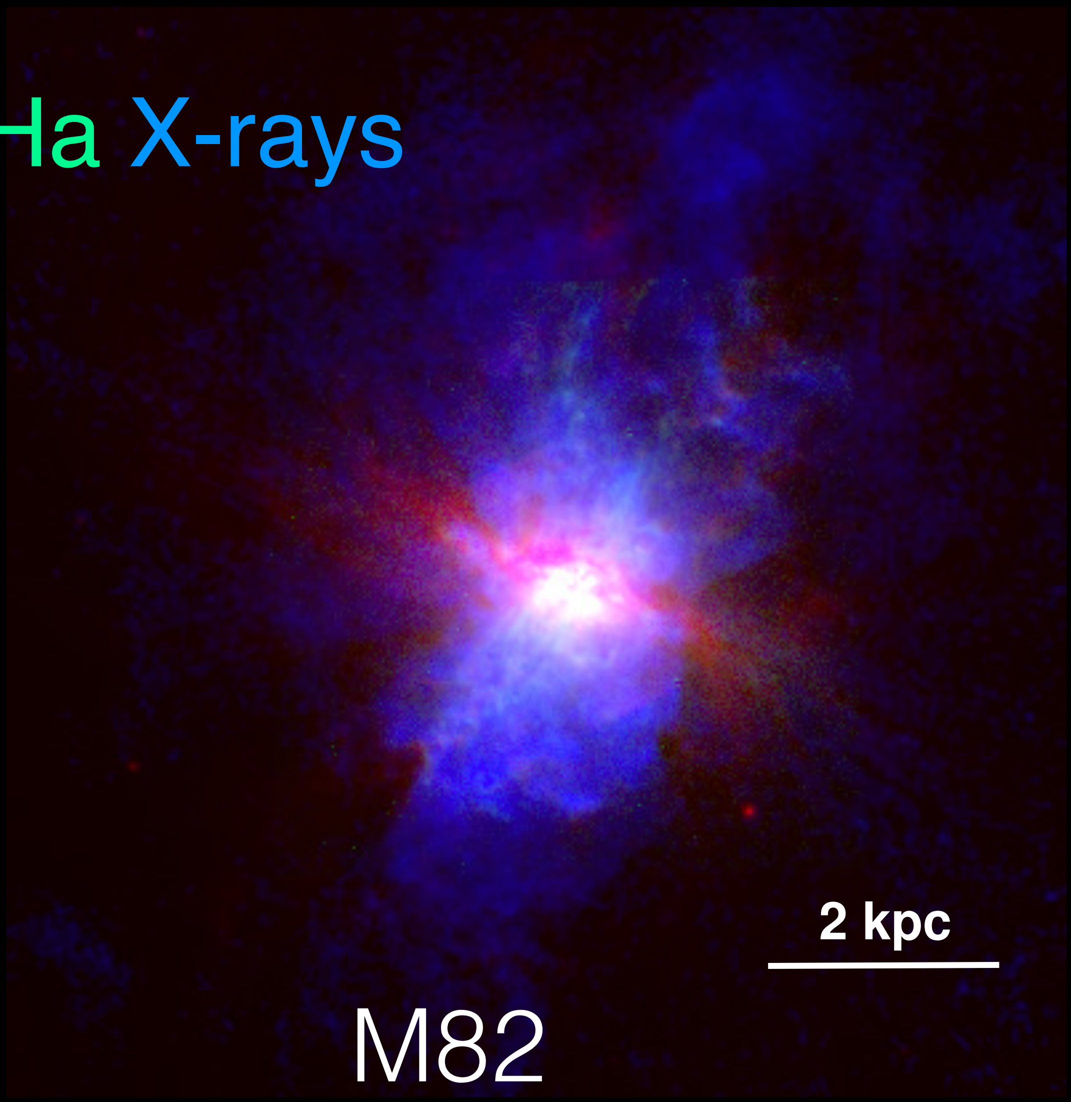
Hot gas velocity measurements + multiphase comparison are important next constraints on starburst-driven outflows.

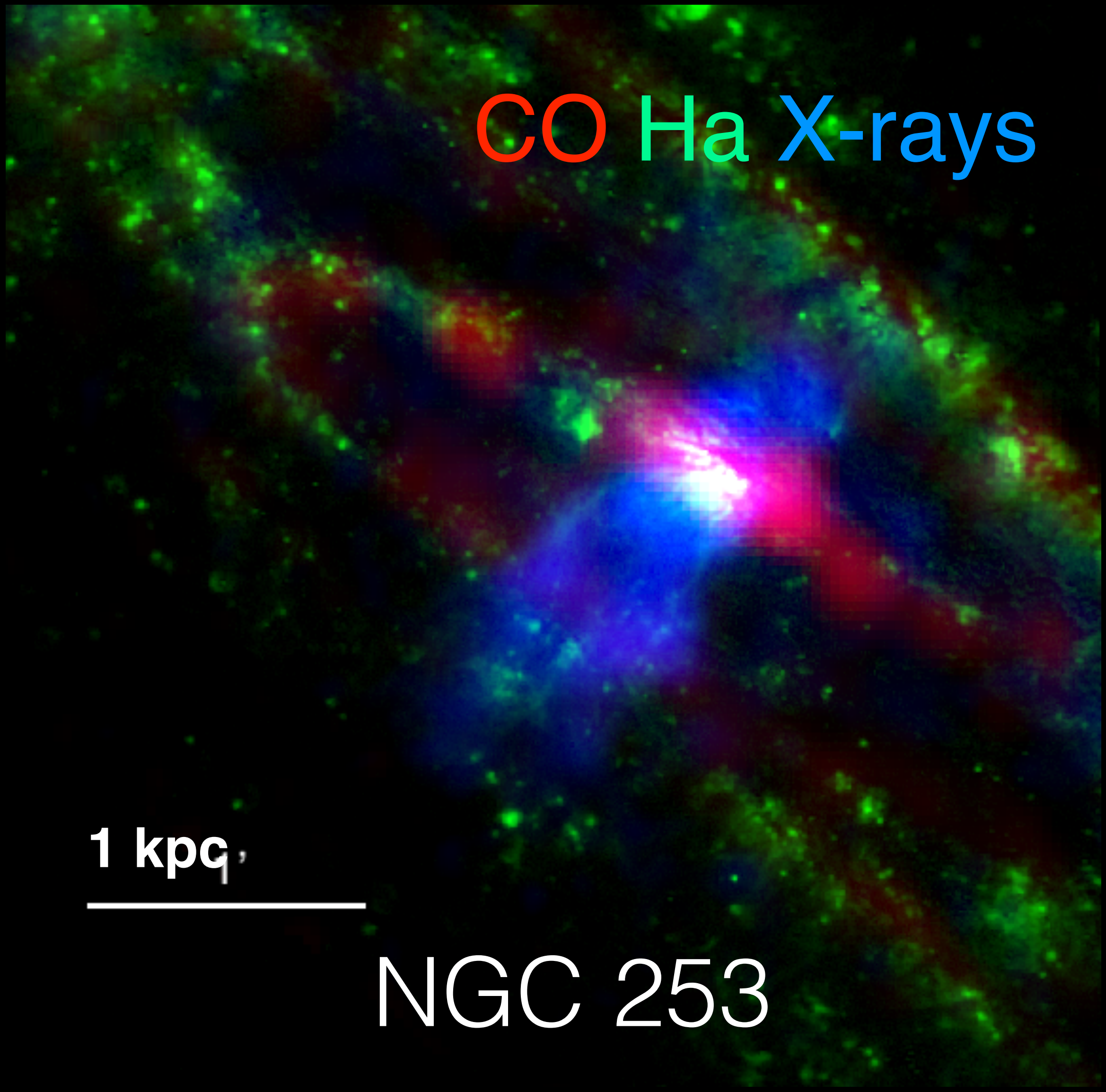

Optical (stars)
Optical (warm gas)
Starburst-driven winds are multiphase
IR (dust)
X-rays (hot gas)

Open Questions

How do hot winds couple to cool clouds? How much mass and metals are launched in each phase? How do these characteristics depend on host galaxy properties?

X-rays are key because they carry most energy & metals





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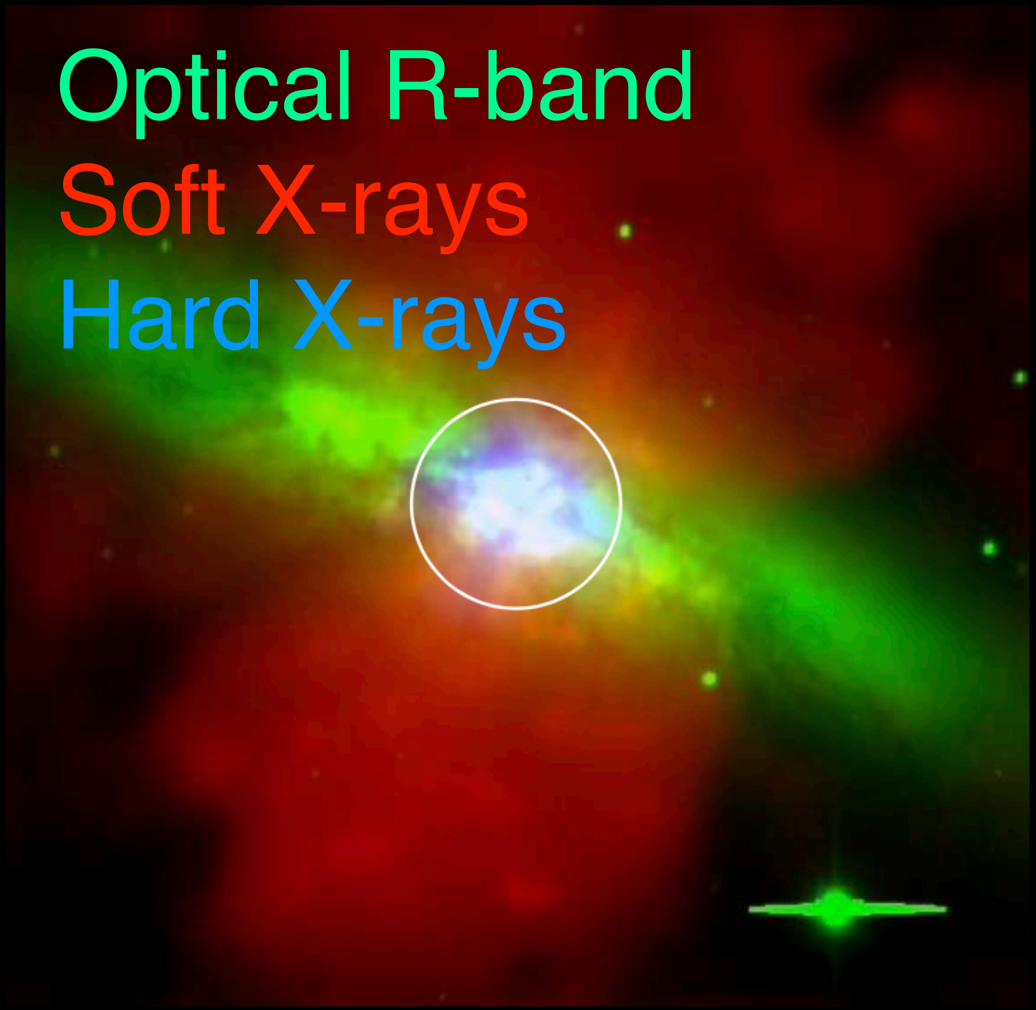
X-ray Studies of Starburst-Driven Outflows

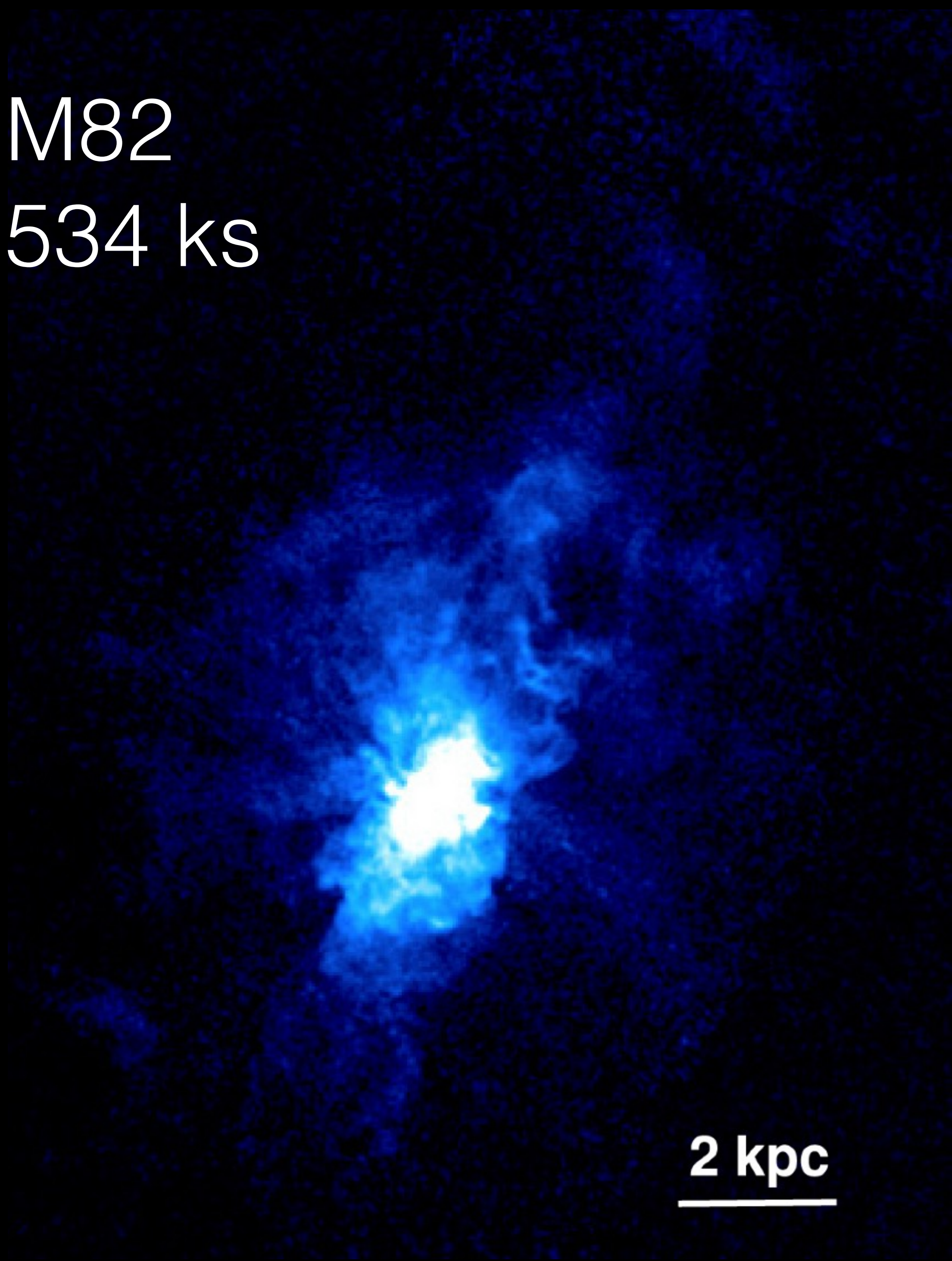


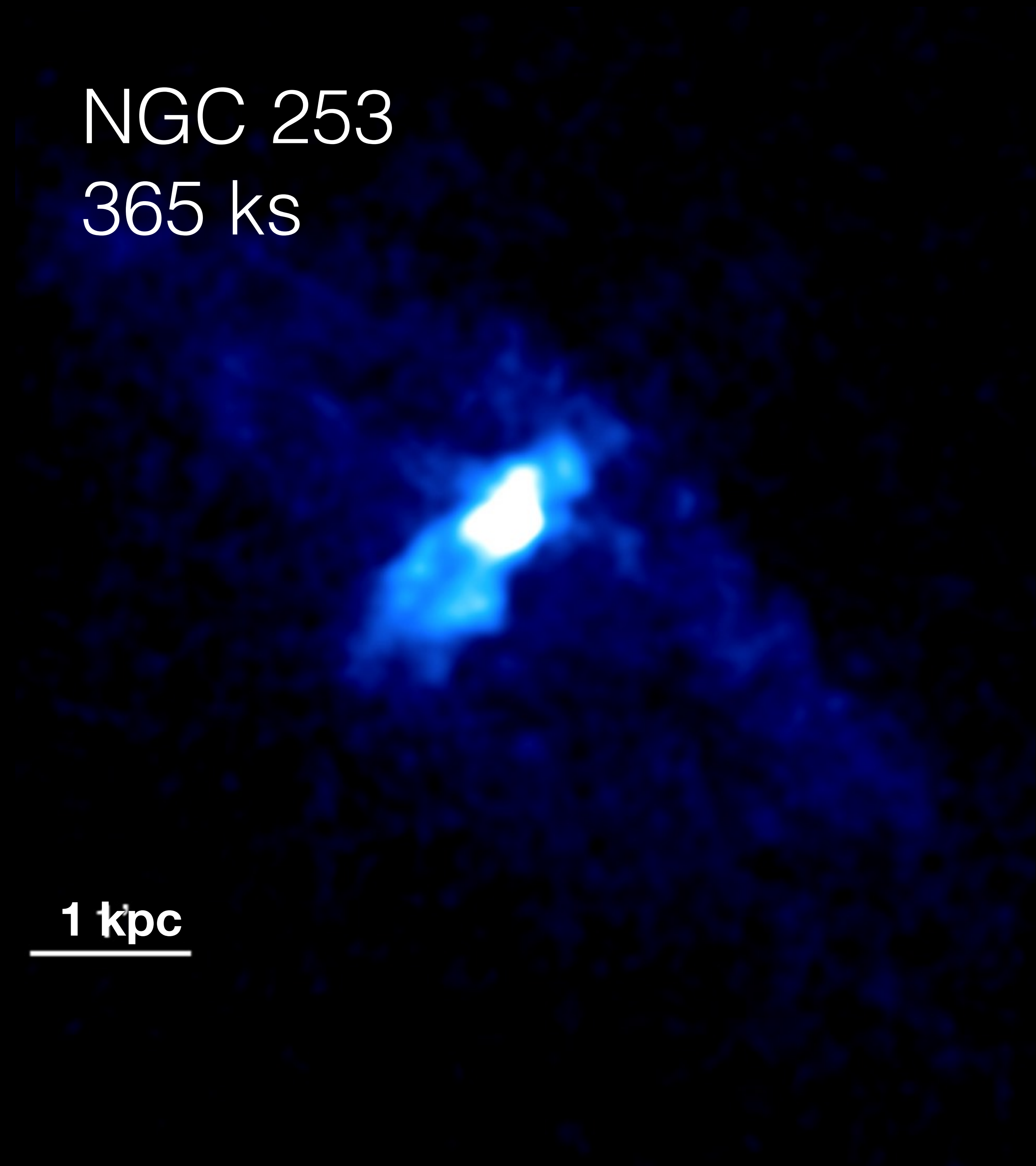
Strickland & Heckman (2007, 2009) analyzed hard X-ray data, focusing on central 500 pc of M82 and found high thermalization efficiency α and mild mass loading β

$$\dot{M}_{\rm hot} = \beta\, \dot{M}_{\rm SFR},$$

$$\dot{E}_{\rm hot} = 3.1 \times 10^{41}\ {\rm ergs\ s^{-1}}\ \alpha\ (\dot{M}_{\rm SFR}/{\rm M_\odot\ yr^{-1}}),$$

X-ray Studies of Starburst-Driven Outflows





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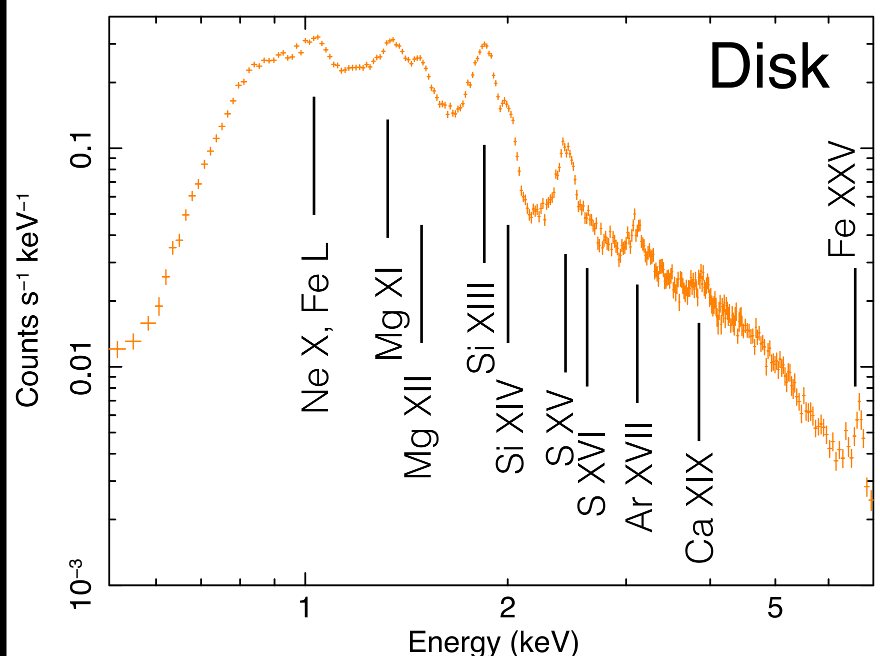
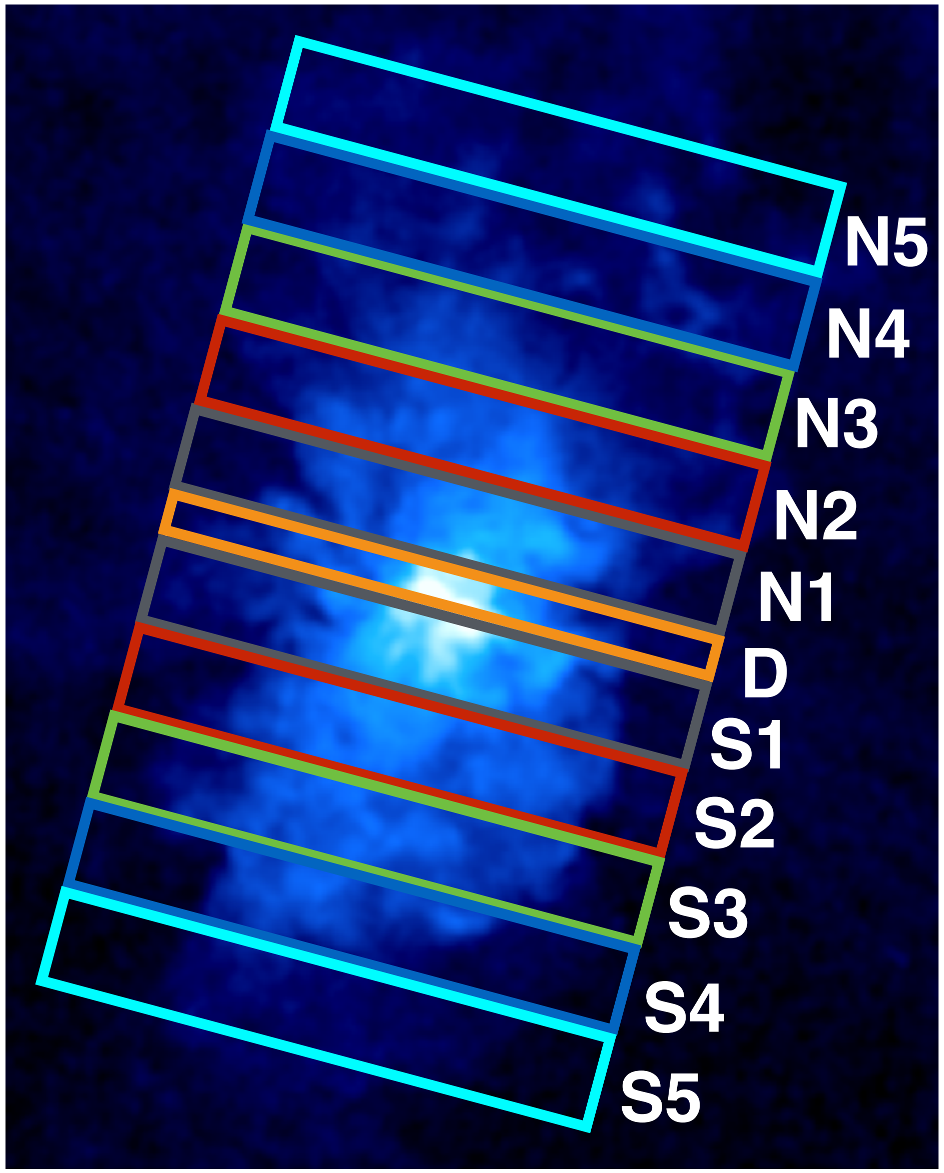
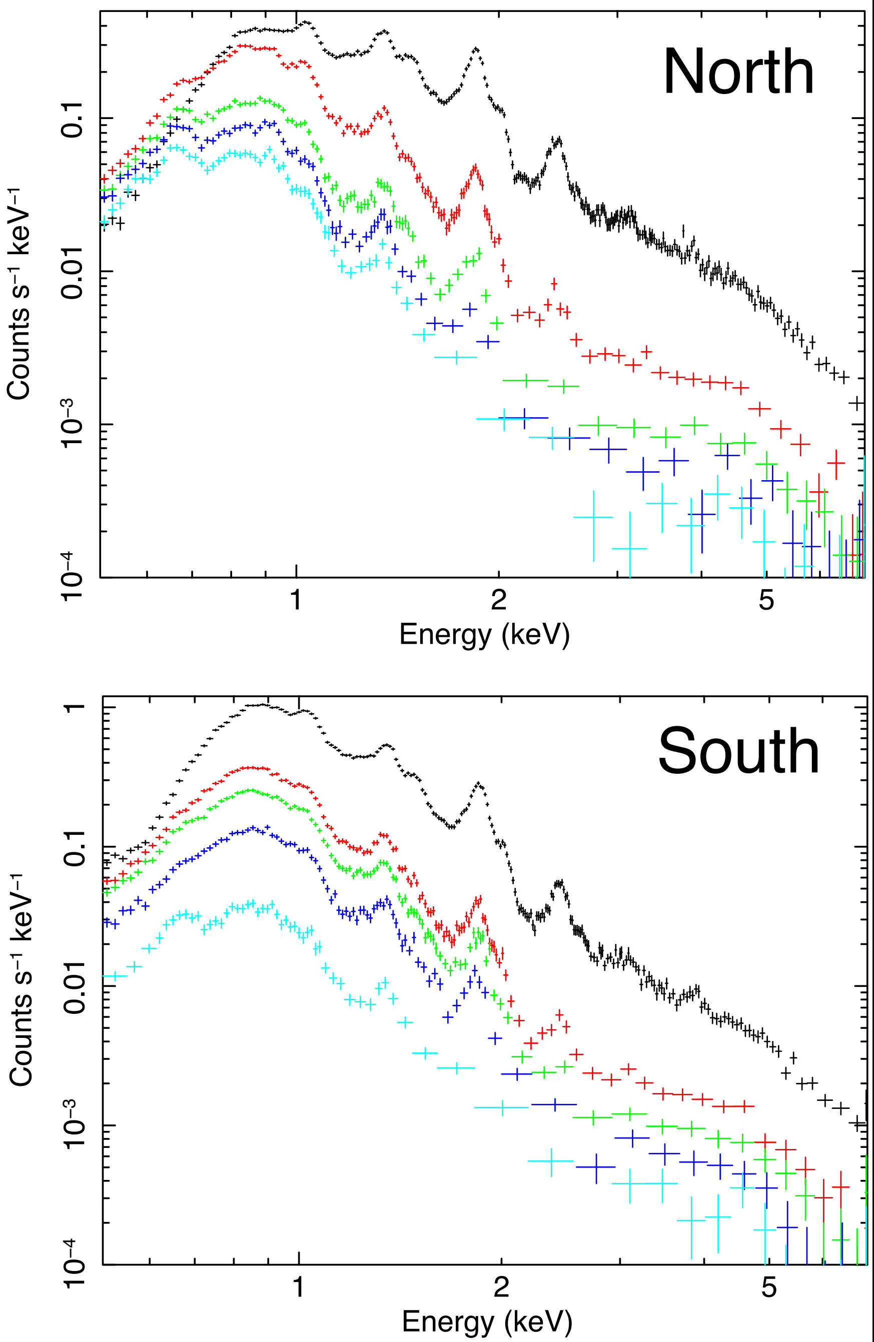
Hot Gas Gradients in Galactic Outflows

Use deep Chandra data to measure gradients in hot gas properties along minor axis of outflows.







Model as absorbed 1-3 thermal plasmas + non-thermal emission + charge exchange

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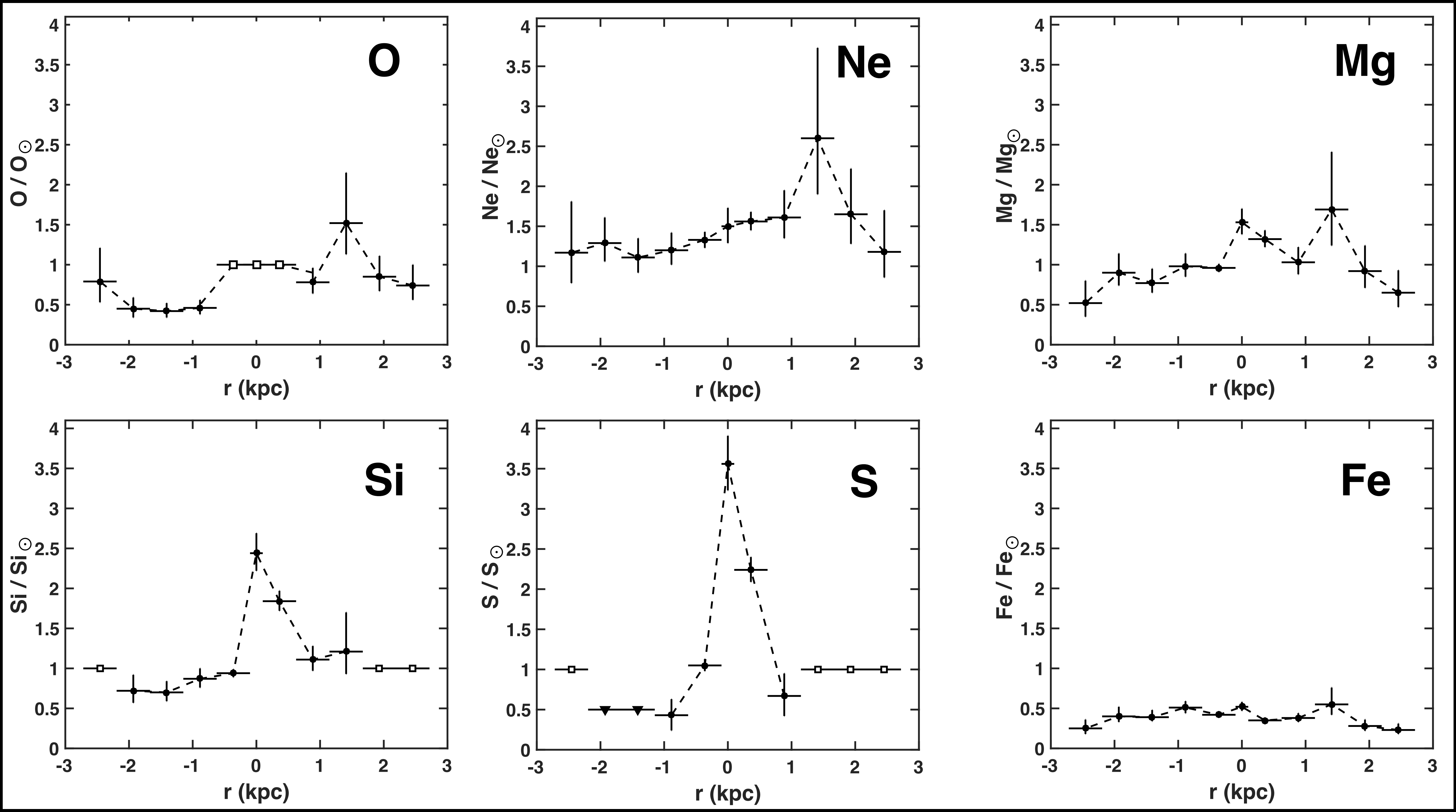
Metallicity Gradients in Outflows



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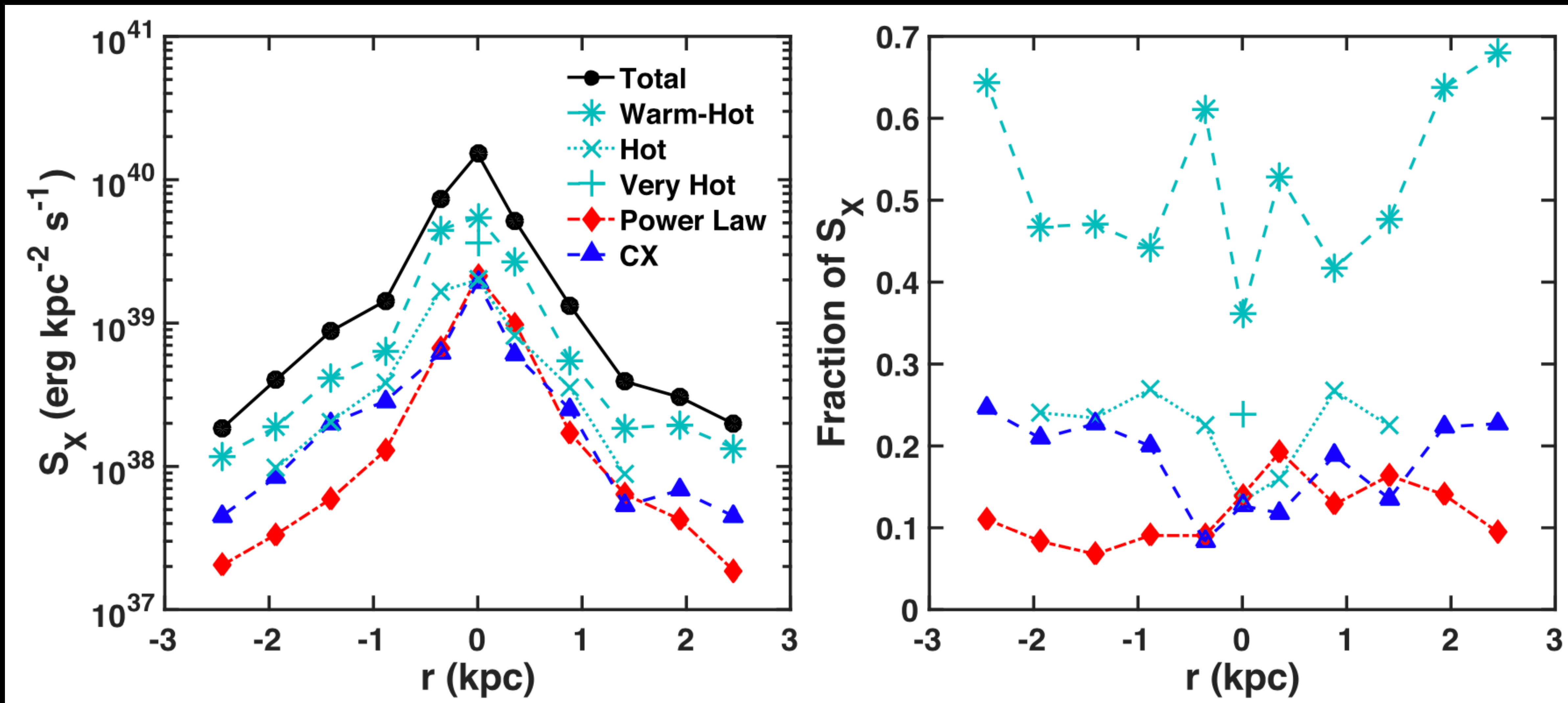
Emission Components Along Outflows



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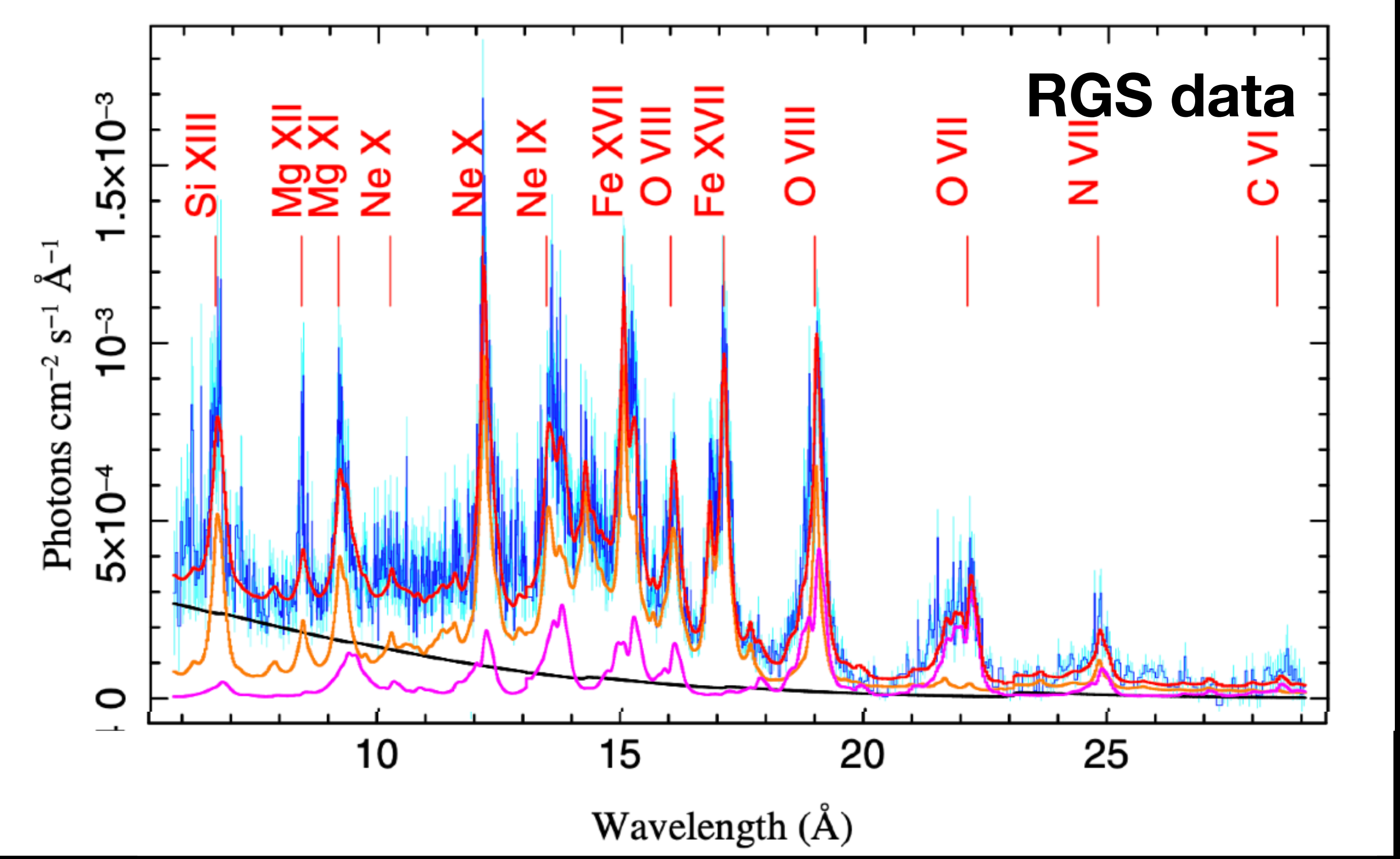
Warm-hot (kT = 0.3-0.7 keV) component dominates, producing 40-70% of emission. Hot component (kT = 0.9-1.7 keV) produces ~20-30%. Hottest component (~7 keV) is only in central region.

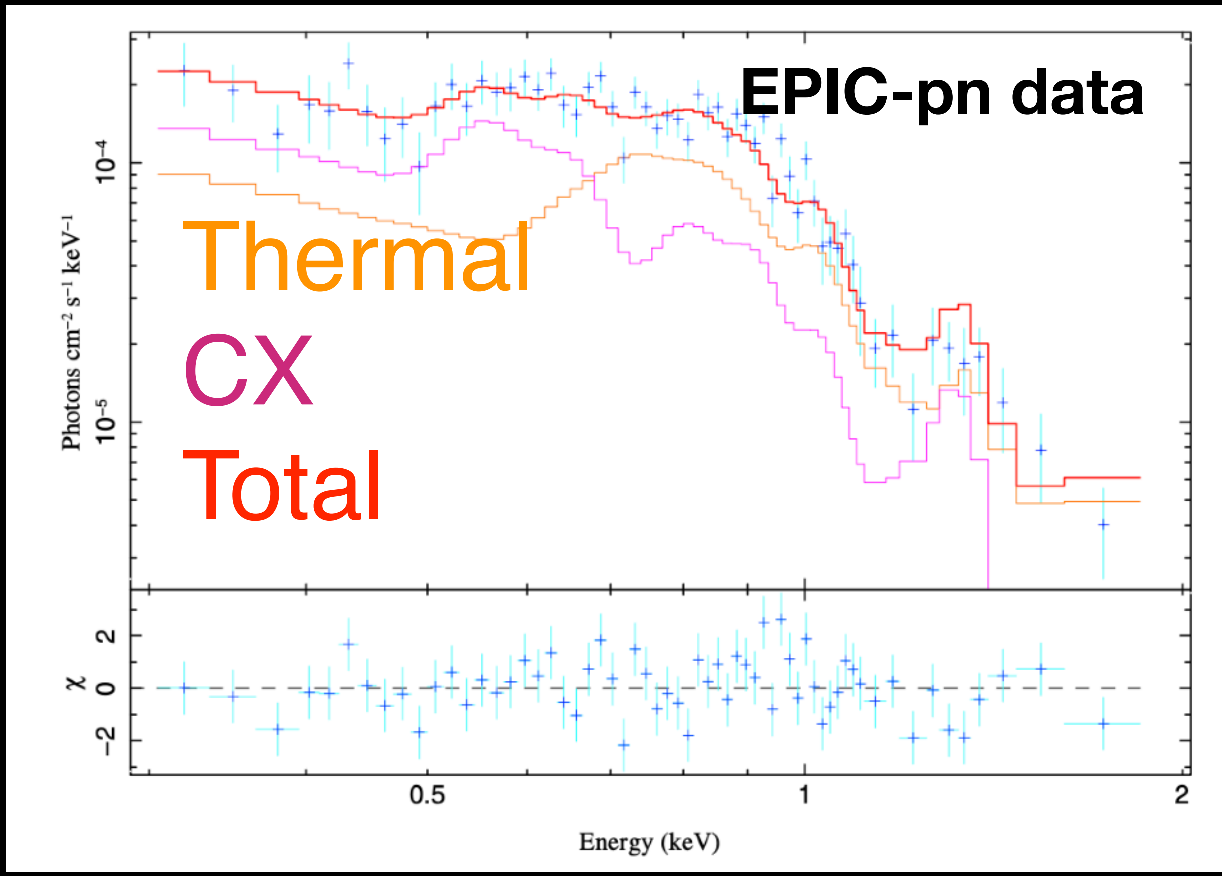
Charge exchange produces 8-25% of emission

Importance of Modeling Charge Exchange

Charge exchange (CX) contributes substantially to the soft X-ray flux of starburst-driven winds.

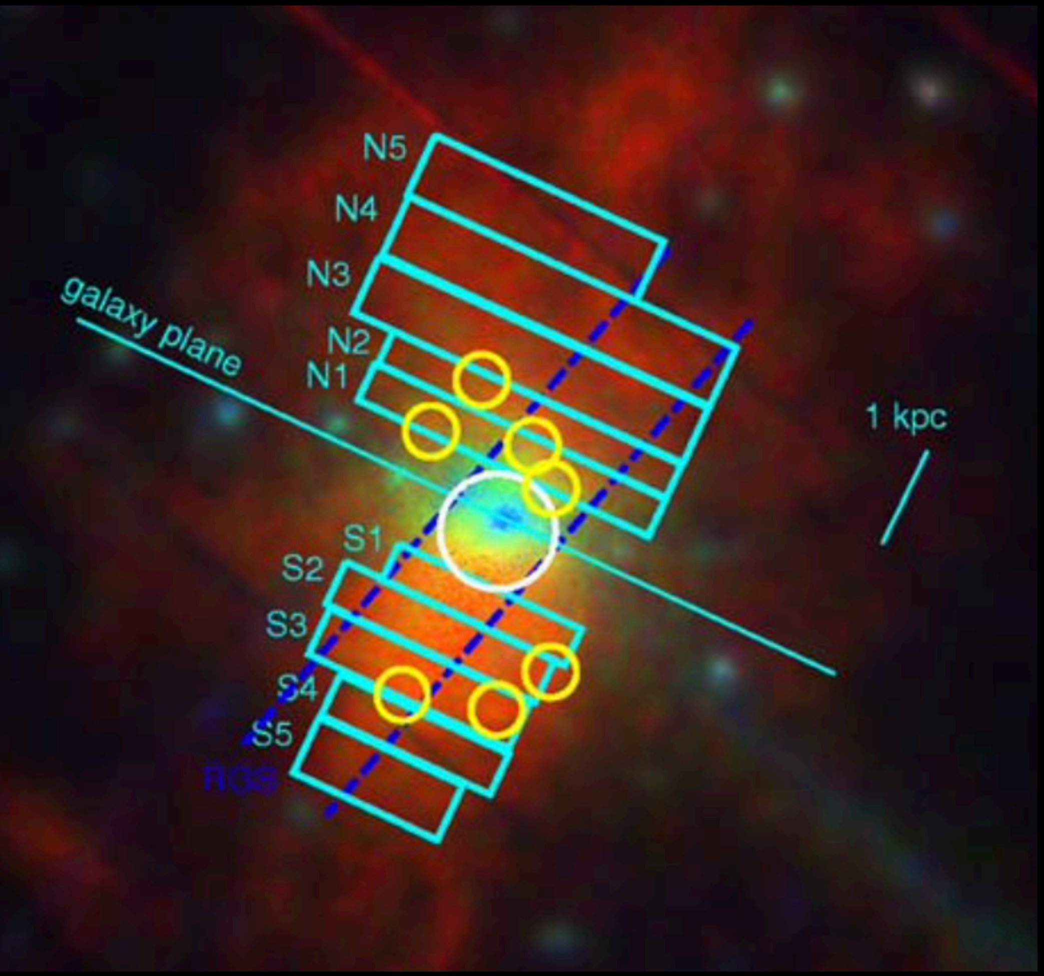
Zhang+14 found that 25% of the 0.4-2 keV flux may be associated with CX. May be evidence of mass loading.





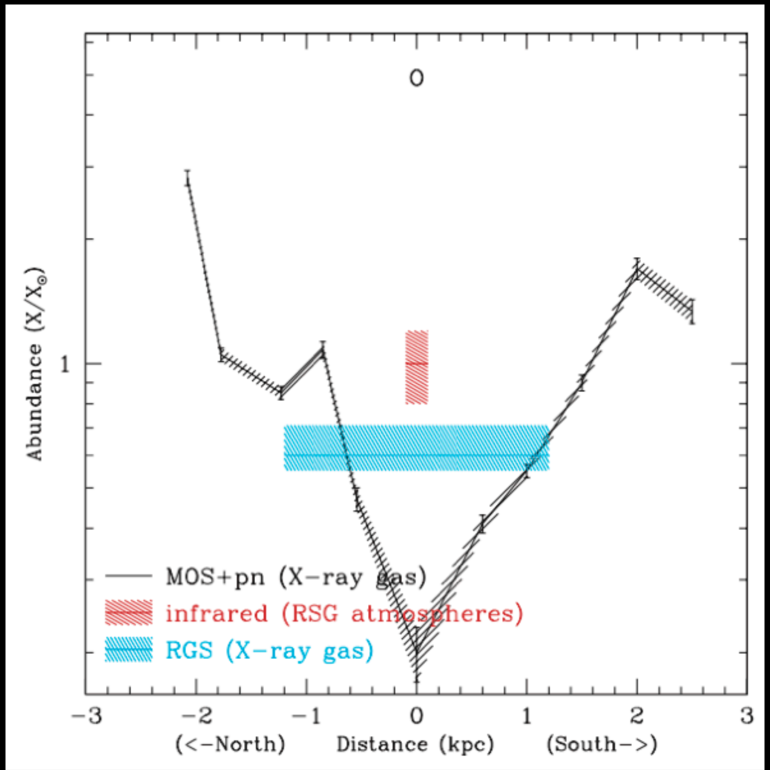
Zhang+14

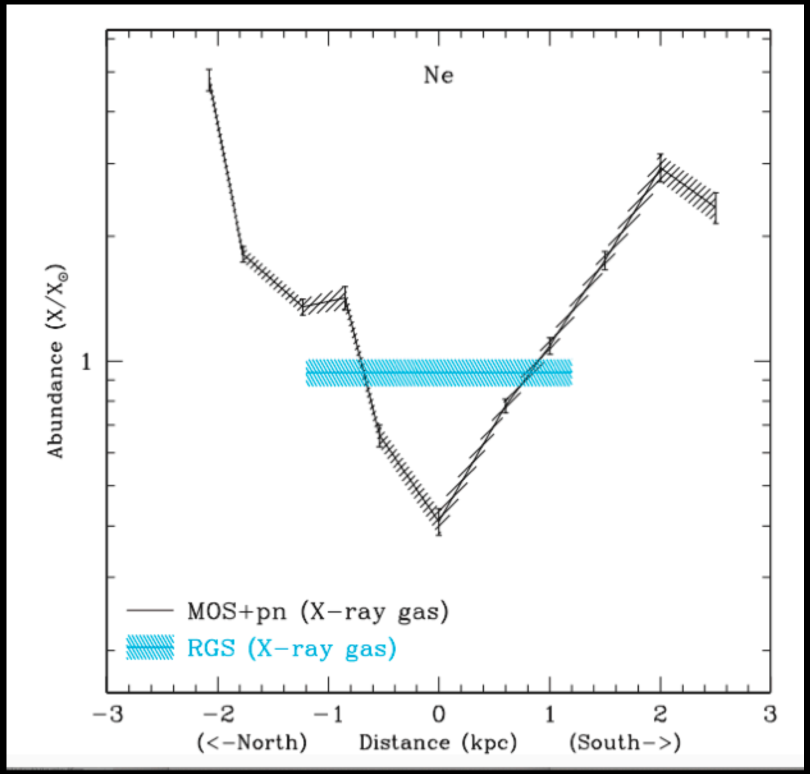
Importance of Modeling Charge Exchange

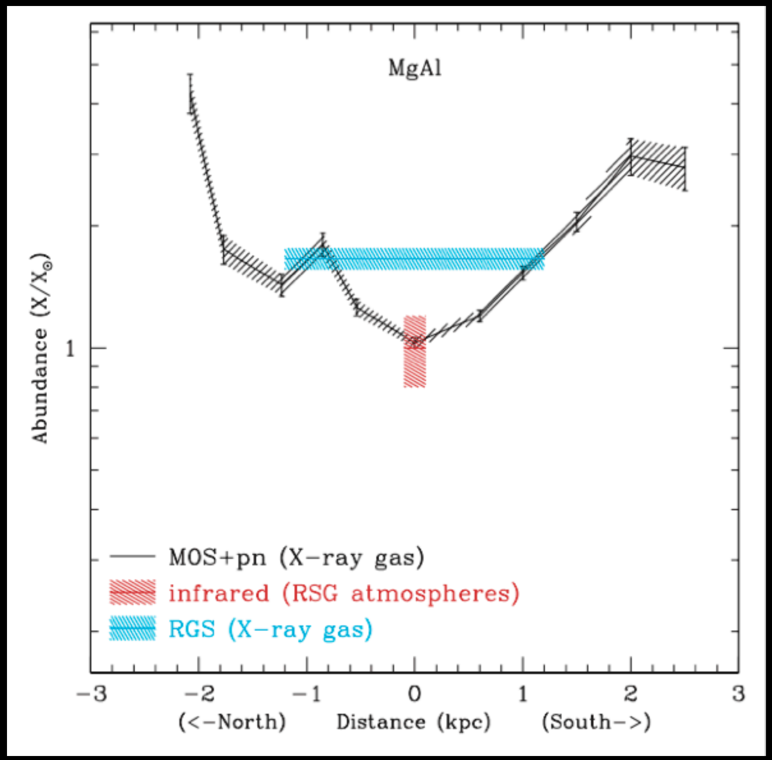


Not accounting for it can lead to inaccurate measurements of metals & temperature.

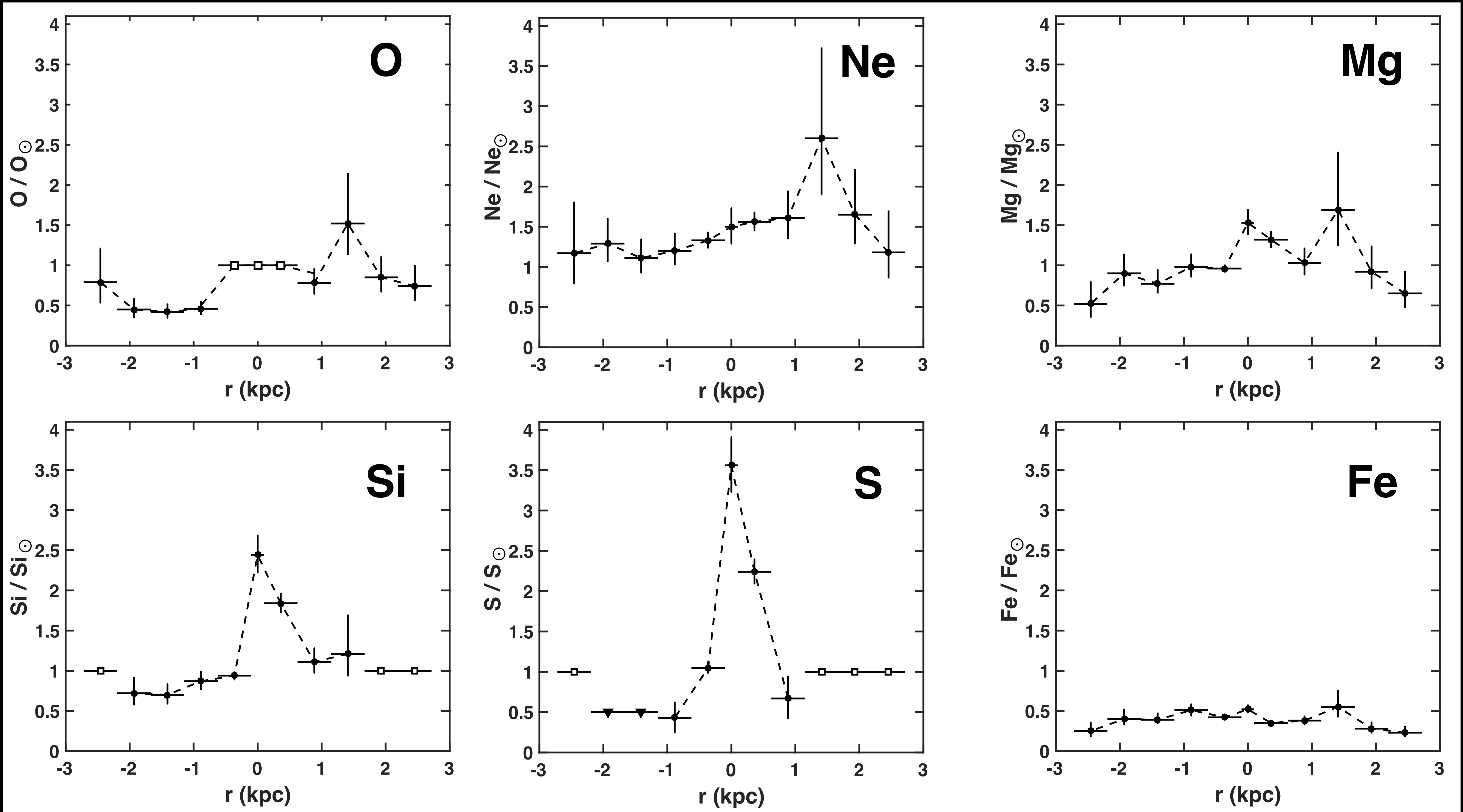
Ranalli+08 analyzed a 73-ks XMM observation and found that alpha elements were enhanced 10x in the outflow relative to the disk — likely because they did not model CX







Metallicity Gradients in Outflows



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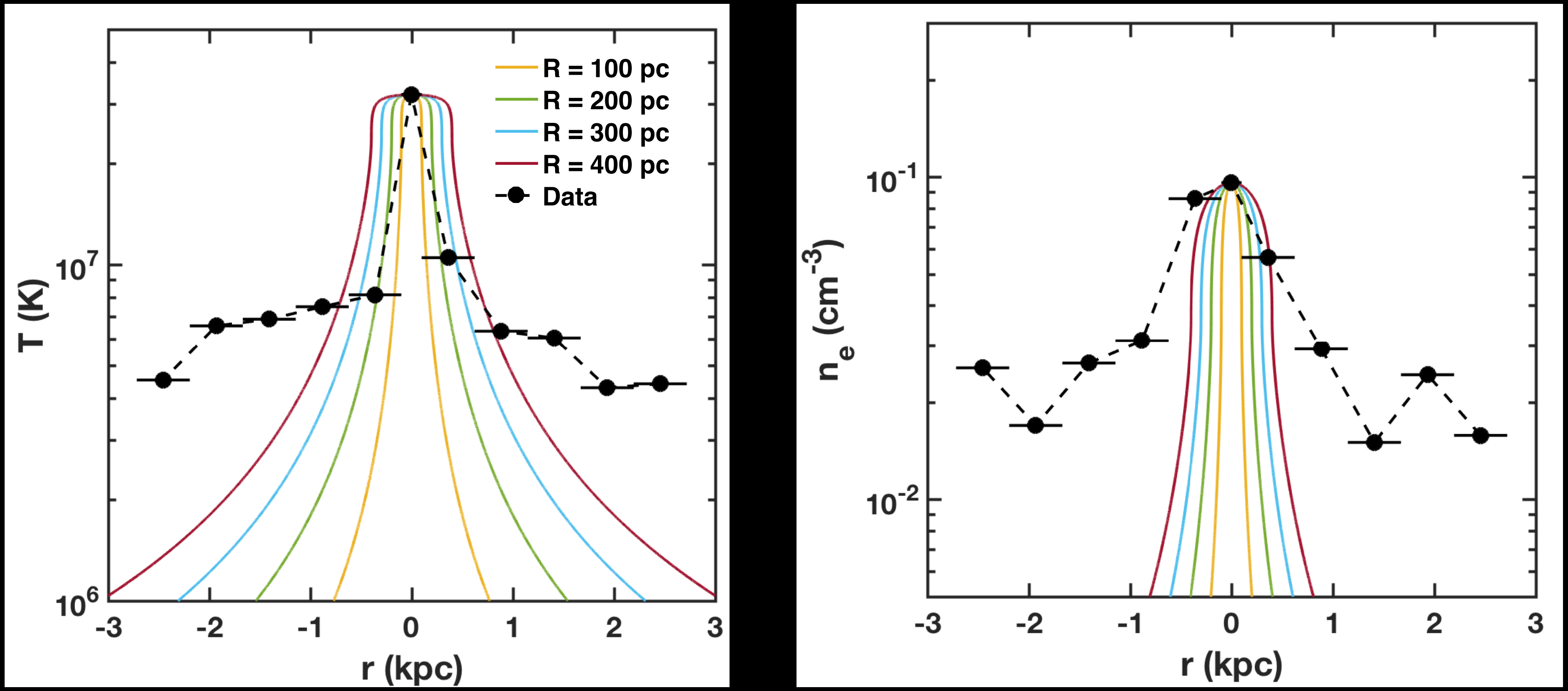
Temperature & Density Profiles: Evidence of Geometry & Mass Loading



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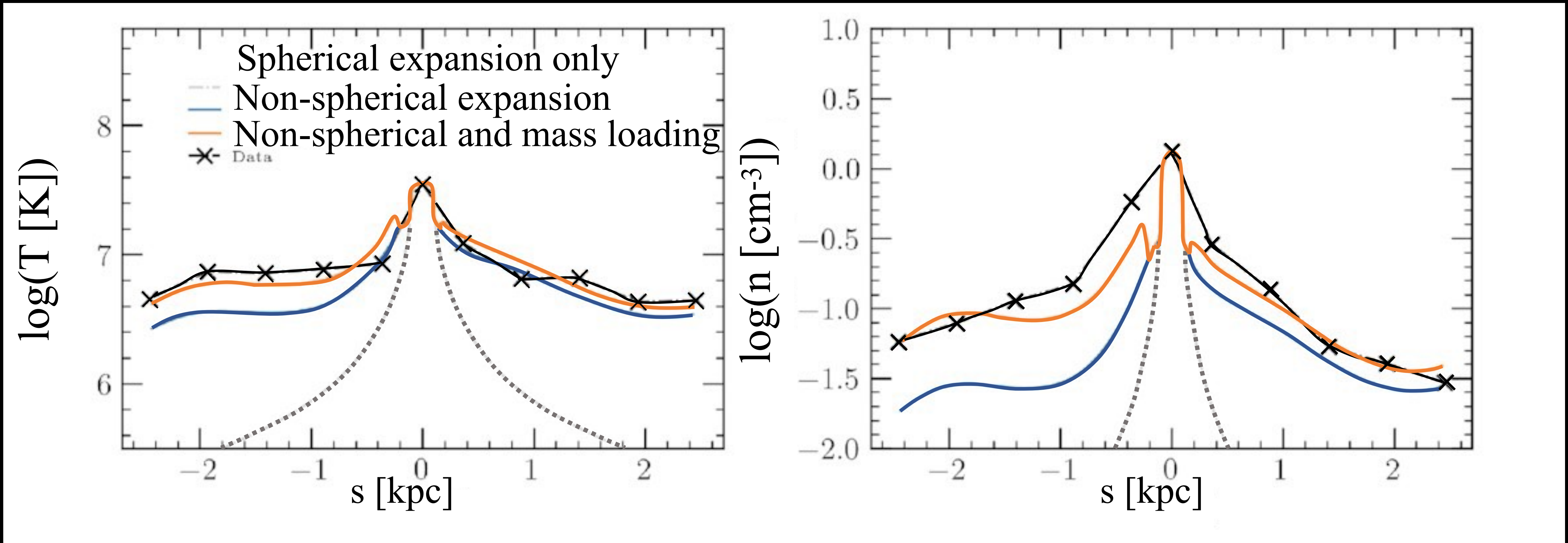
Temperature and density profiles are broader than expected for spherical wind with uniform energy & mass injection that undergoes adiabatic expansion (Chevalier & Clegg 1985)

Temperature & Density Profiles: Evidence of Geometry & Mass Loading

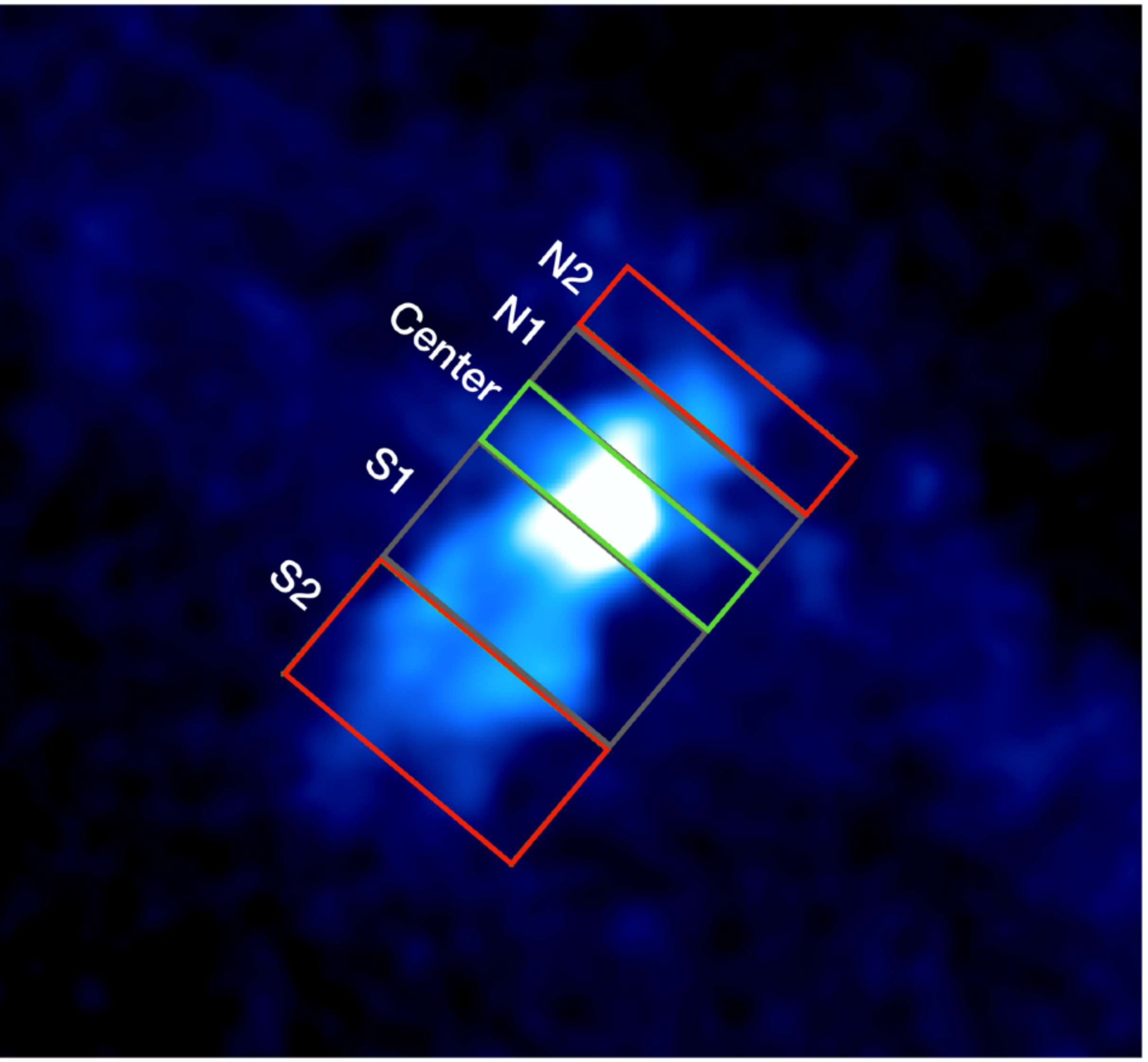


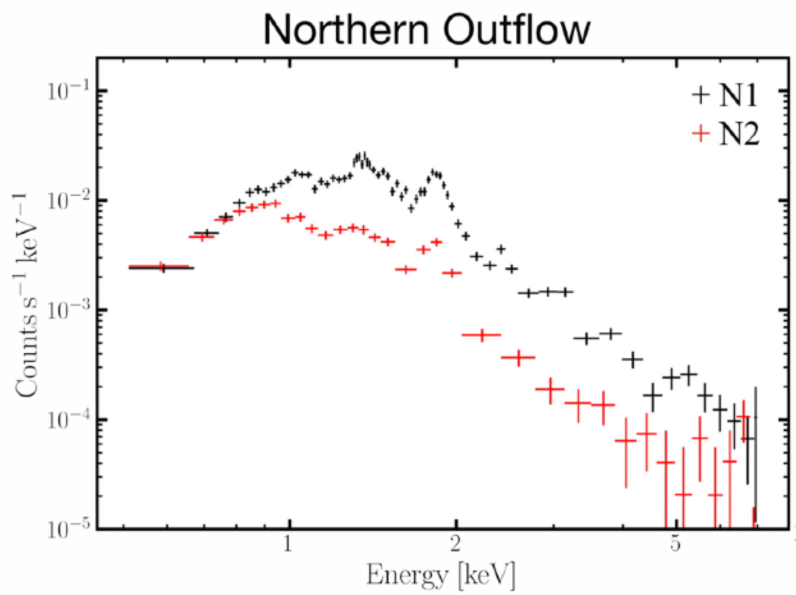
Nguyen & Thompson 2021

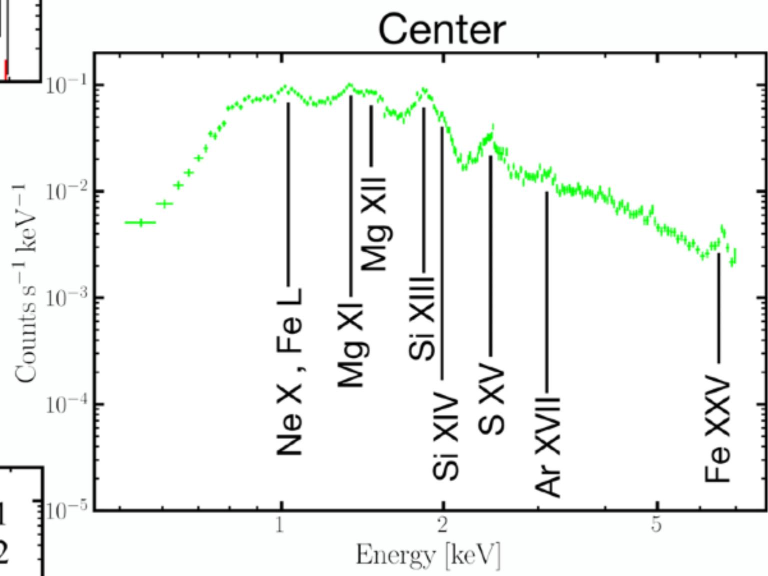
Semi-analytic models by Nguyen & Thompson 2021 and Nguyen+23 showed that non-spherical expansion of the outflow and mass loading more accurately reproduce the profiles.

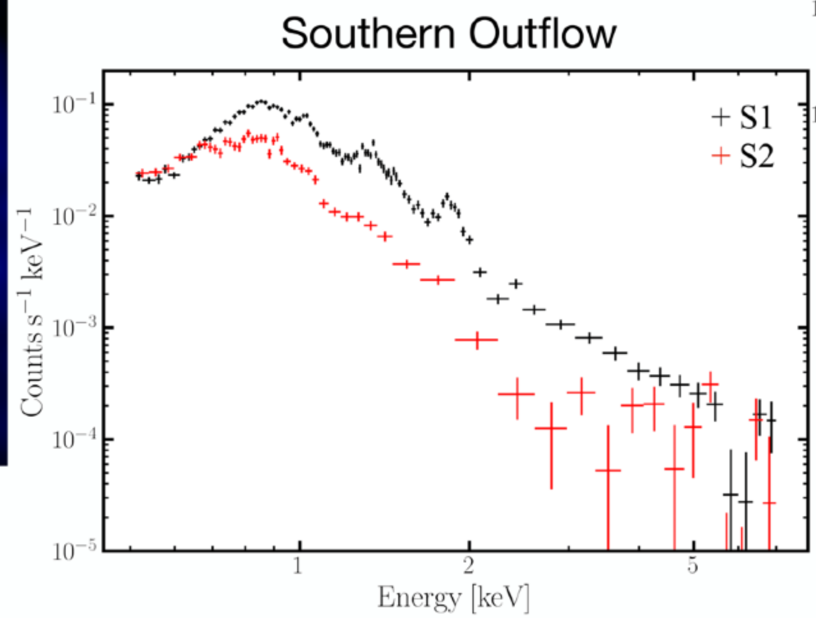
Hot Gas Gradients in Galactic Outflows

NGC 253









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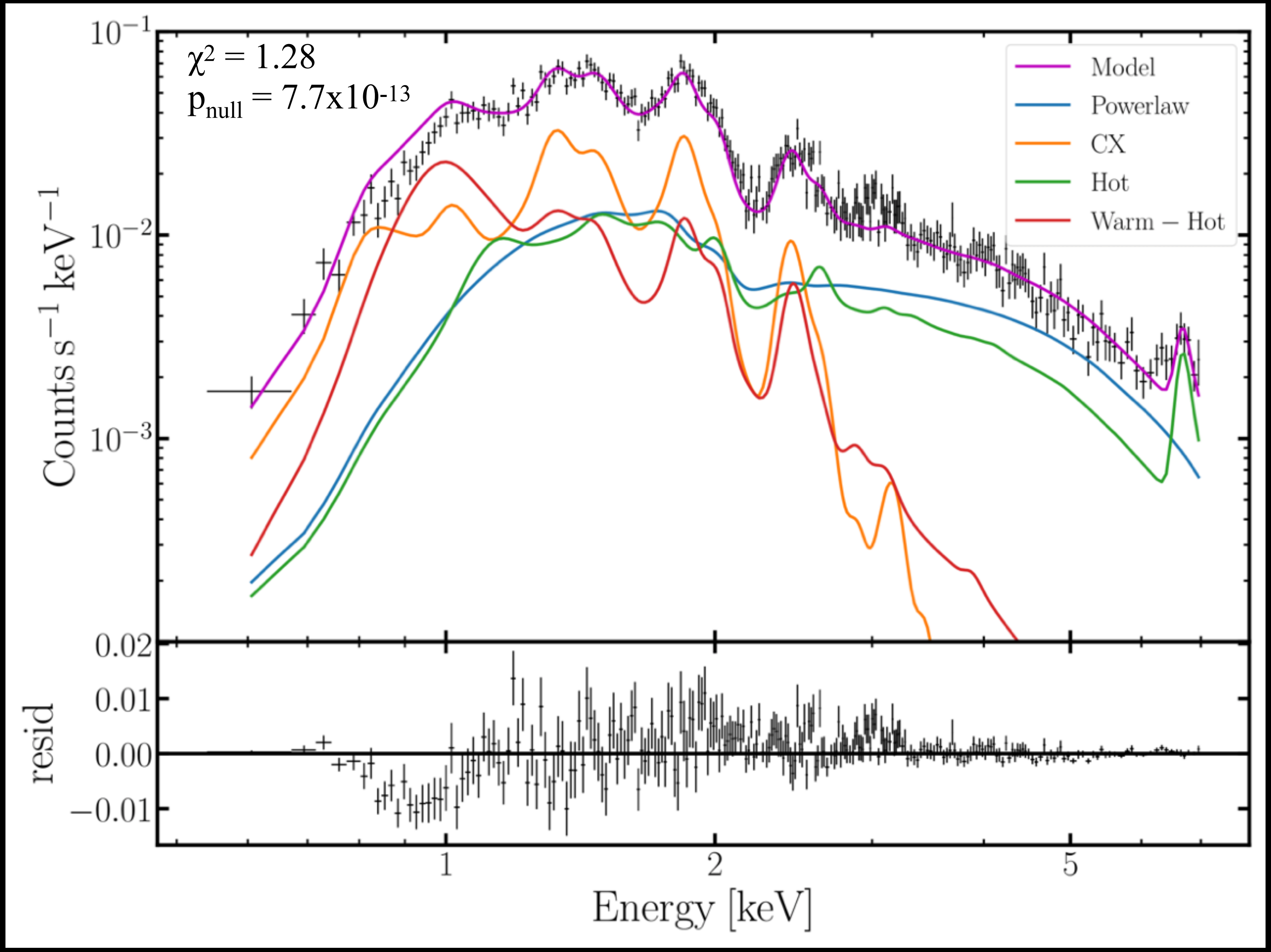
Hot Gas Gradients in Galactic Outflows

Central region had 2 thermal components + power law + CX

CX found in central region and southern outflow but not in northern outflow, perhaps because of high column density there

CX contributes 20-40% to the total emission.

NGC 253 Central Region Spectra



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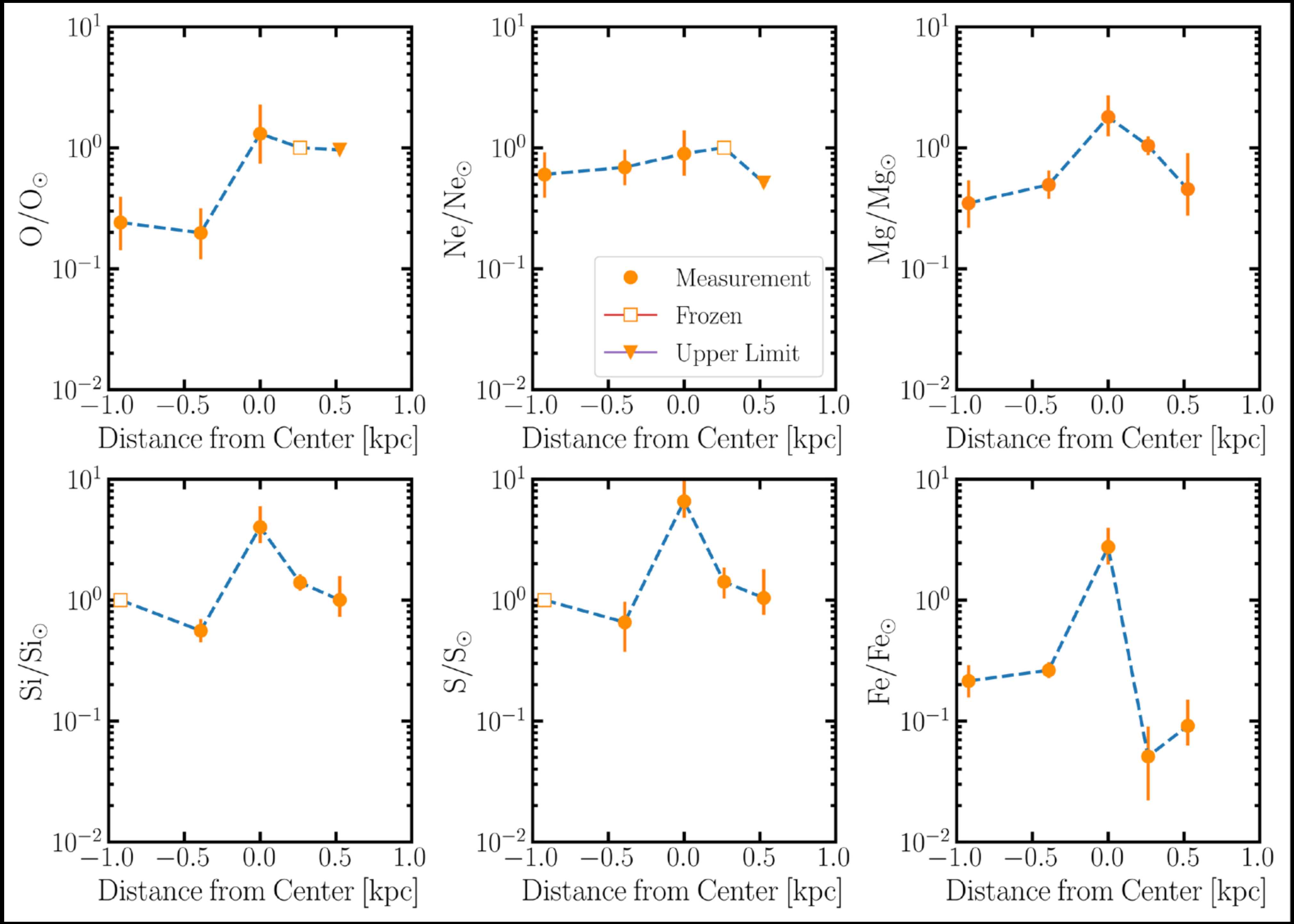
Metallicity Gradients in Outflows



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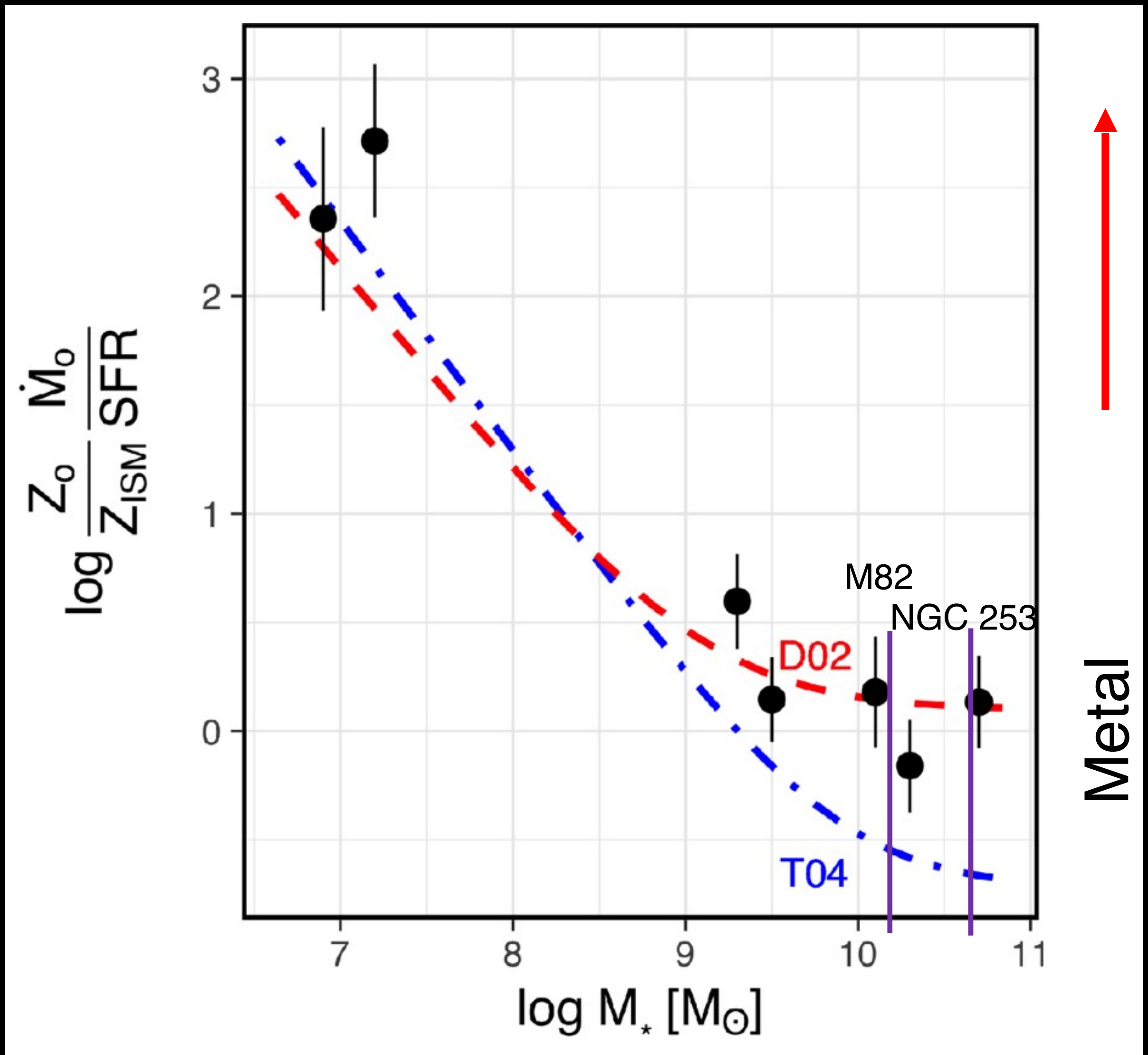
Peak in center, decrease along outflows; contrasts M82 where profiles were more flat (metals getting out more).

Metal Loading vs. Stellar Mass

Why do M82 and NGC 253 have different (hot phase) metallicity profiles?

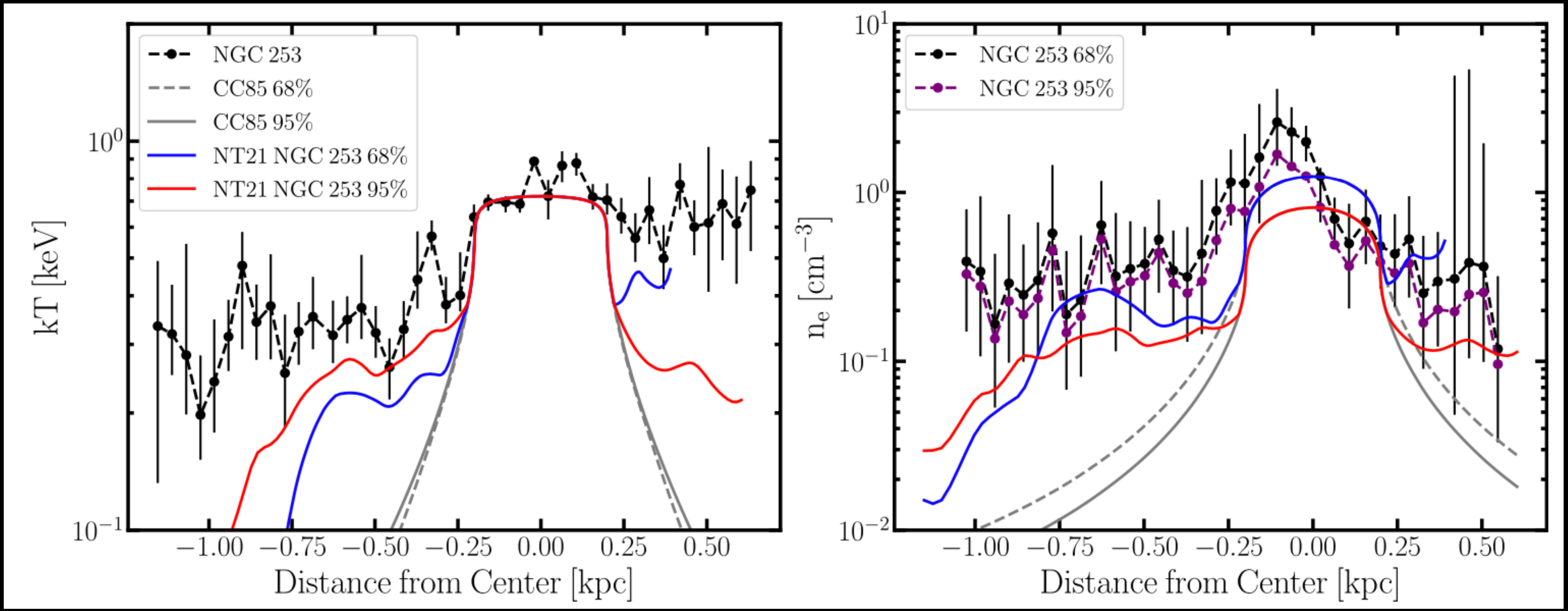
Consider the mass-metallicity relationship (Tremonti+04): Chisholm+18 found that metal loading factor decreases with galaxy stellar mass in the warm phase.

Is the same true for the hot phase?



Chisholm+18

Temperature & Density Profiles: Evidence of Geometry & Mass Loading



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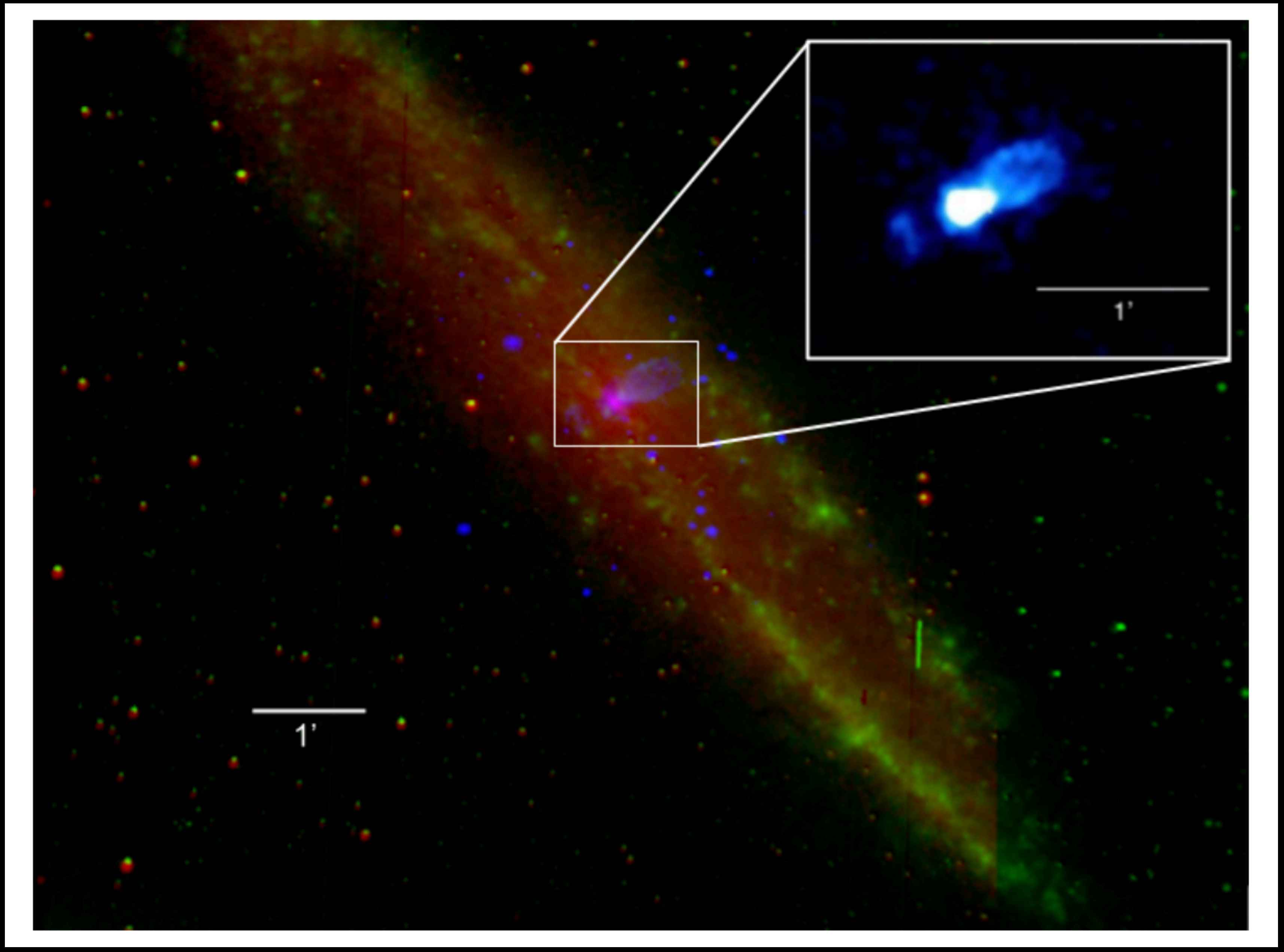
Obtained temperature and density profiles using smaller regions and compared to CC85 and Nguyen & Thompson 21. Again see that non-spherical geometry and mass loading are necessary to account for broad profiles.

Expanding the Sample

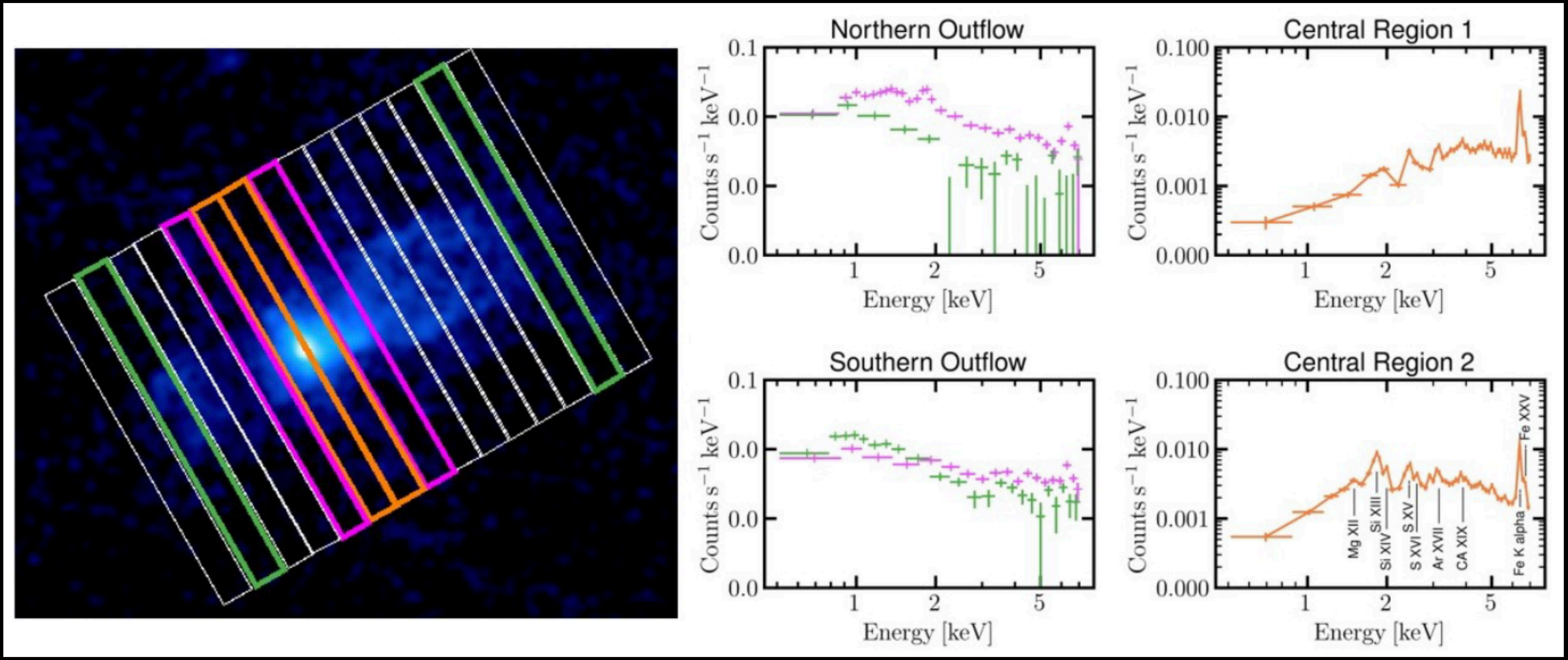
Analyzing ~15 edge-on galaxies with star formation-driven outflows to measure profiles across many sources

Next paper is NGC 4945 (Porraz, S. Lopez, L. Lopez+24)



NGC 4945

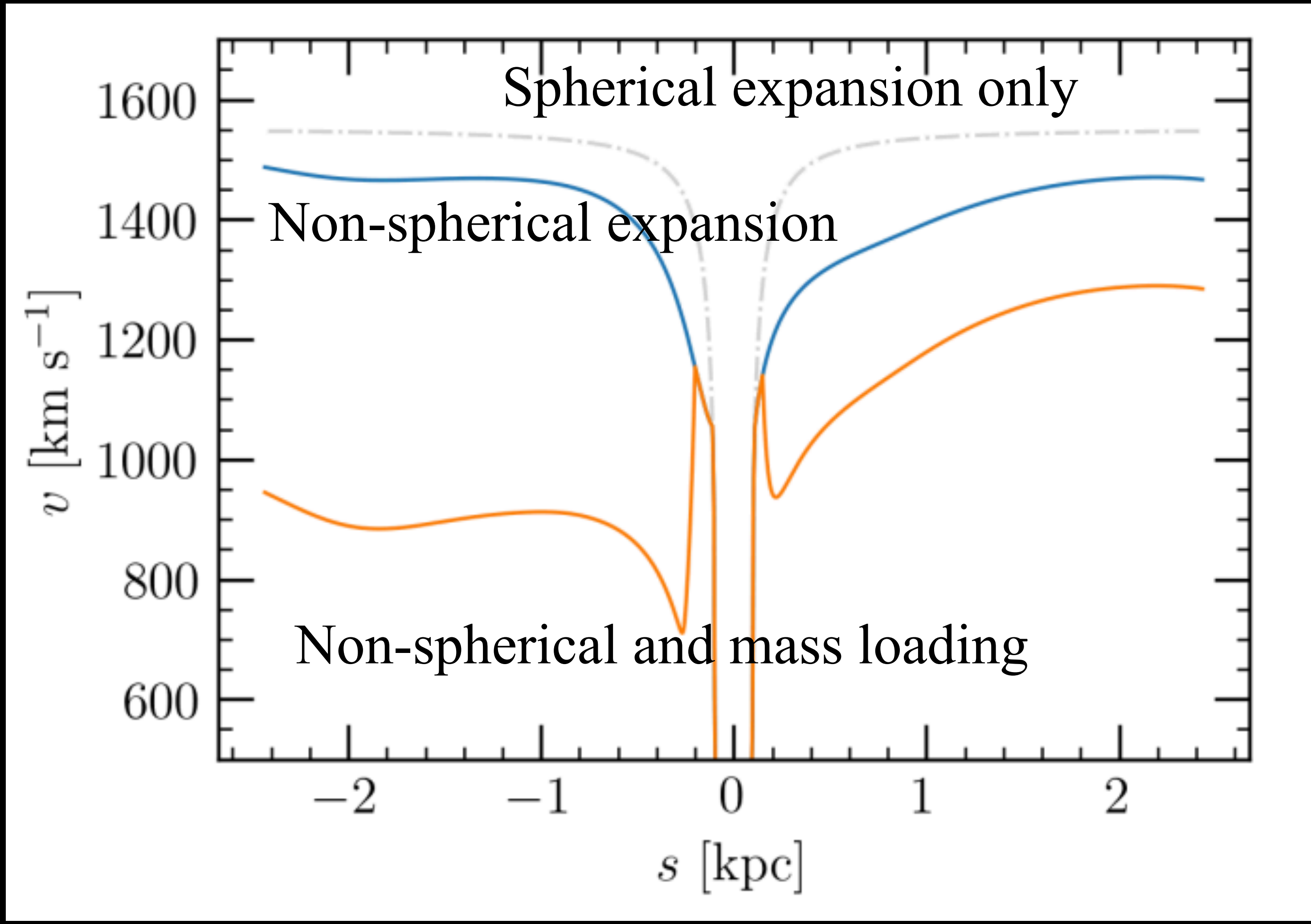
NGC 4945 is complicated because it is a bright Seyfert 2, though it is not energetically dominant (Forbes & Norris 98)



Porraz, S. Lopez, L. Lopez+24

Profiles similar to M82 and NGC 253; CX detected in Northern outflow & contributes 12% to total emission.

Another Observable: Hot Gas Velocity



Nguyen & Thompson 2021

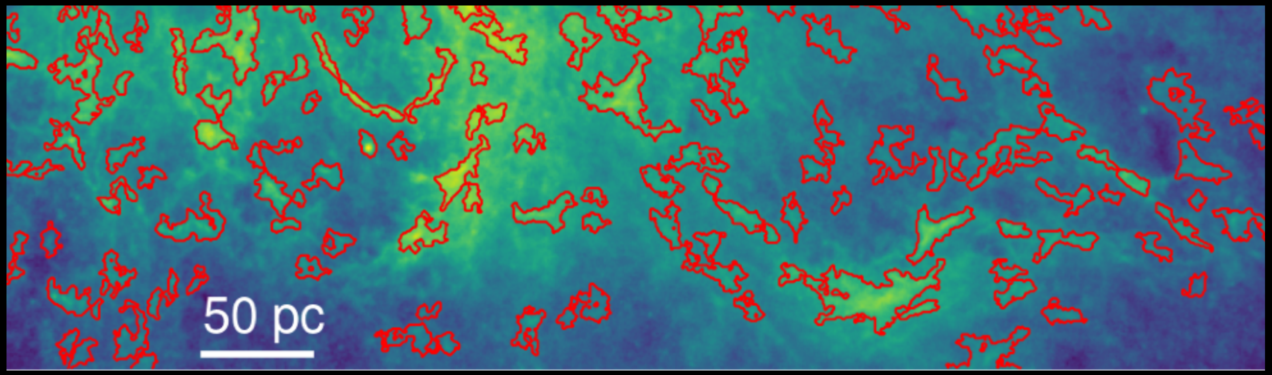
Velocities of the hot phase along the outflow would be immensely helpful to constrain geometry & mass loading

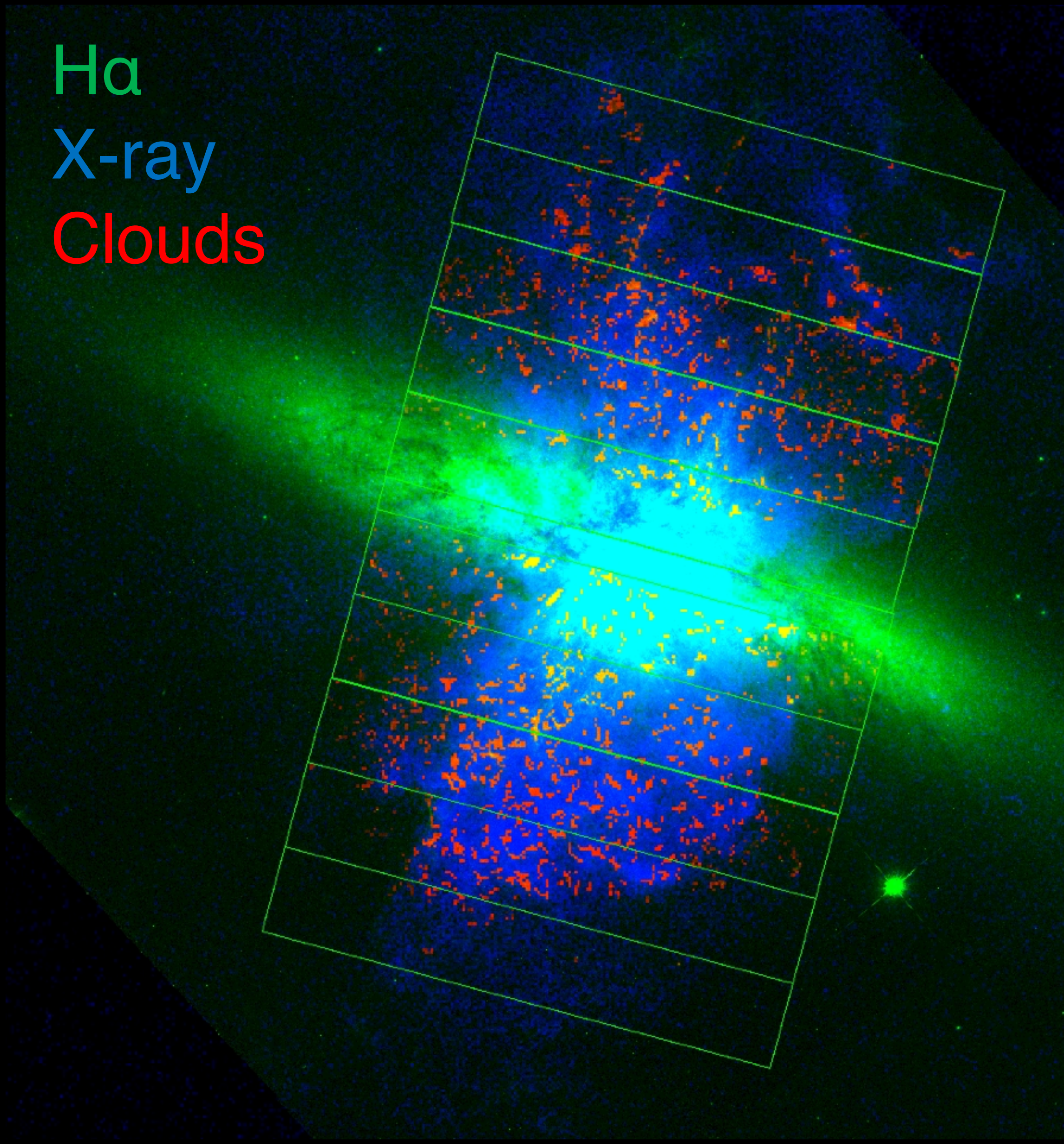
XRISM will give us important first constraints on hot gas velocities along the outflows of starburst galaxies

Ongoing: What is the Origin of Cool Clouds in the Hot Wind?

Does the hot wind fluid cool radiatively, or do entrained cool clouds avoid being destroyed somehow?

To answer, we are testing how to best identify Hα clouds using watershed and dendrogram algorithms, then we are relating their sizes/column densities/morphologies to hot gas properties.





S. Lopez, L. Lopez+24

Conclusions

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