From Simulations to Spectra:

Investigating AGN Wind-Disk Interactions and Asymmetric Galactic Outflows

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Motivation

Asymmetric outflow in NGC7469

- JWST MIRI has revealed a one-sided, high-velocity outflow in the quasar galaxy NGC 7469 (z=0.016) in [Ne V] line (Armus et al. 2023).
- Blue-shifted lines in optical are often interpreted by extinction. But this IR line suggests the asymmetry could be intrinsic.
- Understanding the physical origin of this asymmetry is crucial to interpreting AGN feedback and its impact on host galaxies.

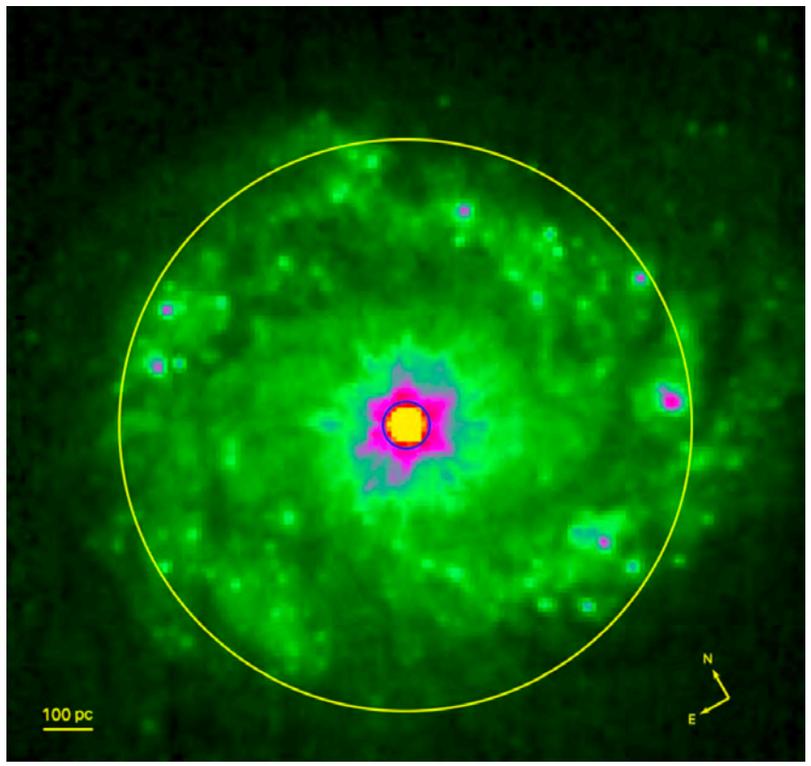
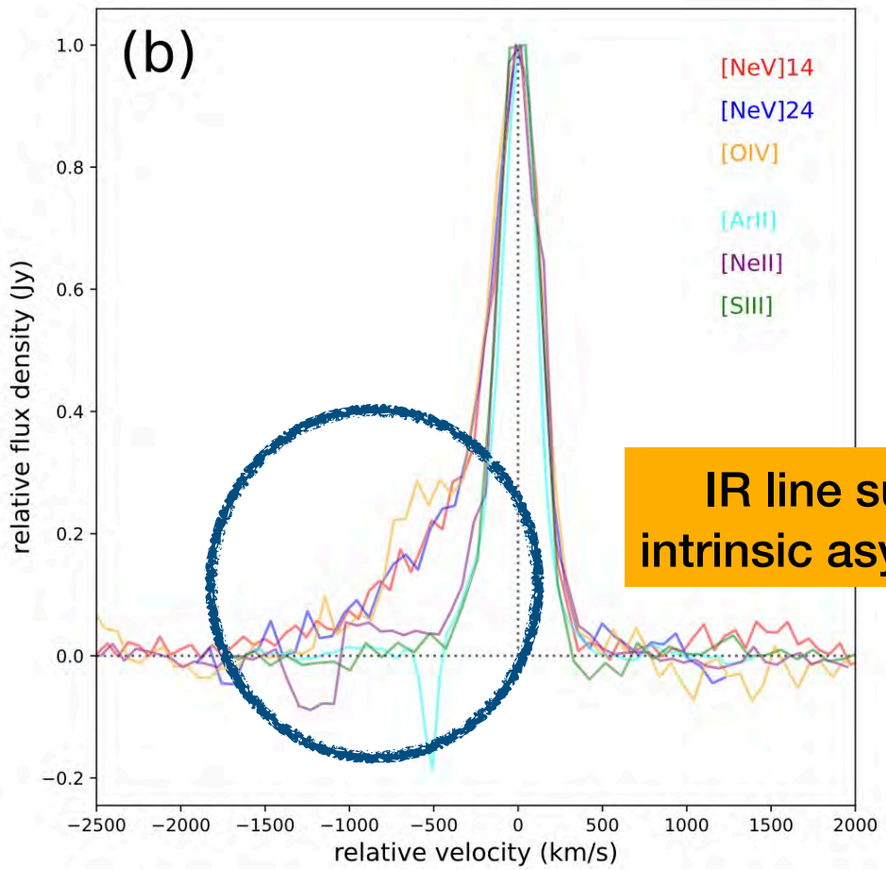


Image of NGC 7469 from NIRCam



IR line suggest intrinsic asymmetry !

MIRI nuclear spectrum with normalized and continuum-subtracted

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Can AGN wind–disk interactions produce asymmetric outflows in simulation?

If so, how do we compare simulation with observations?

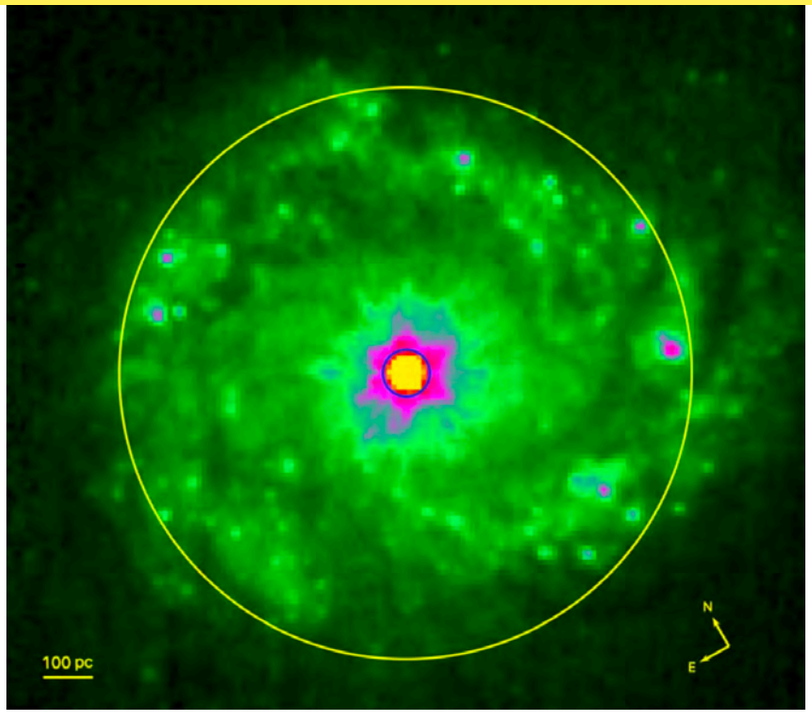
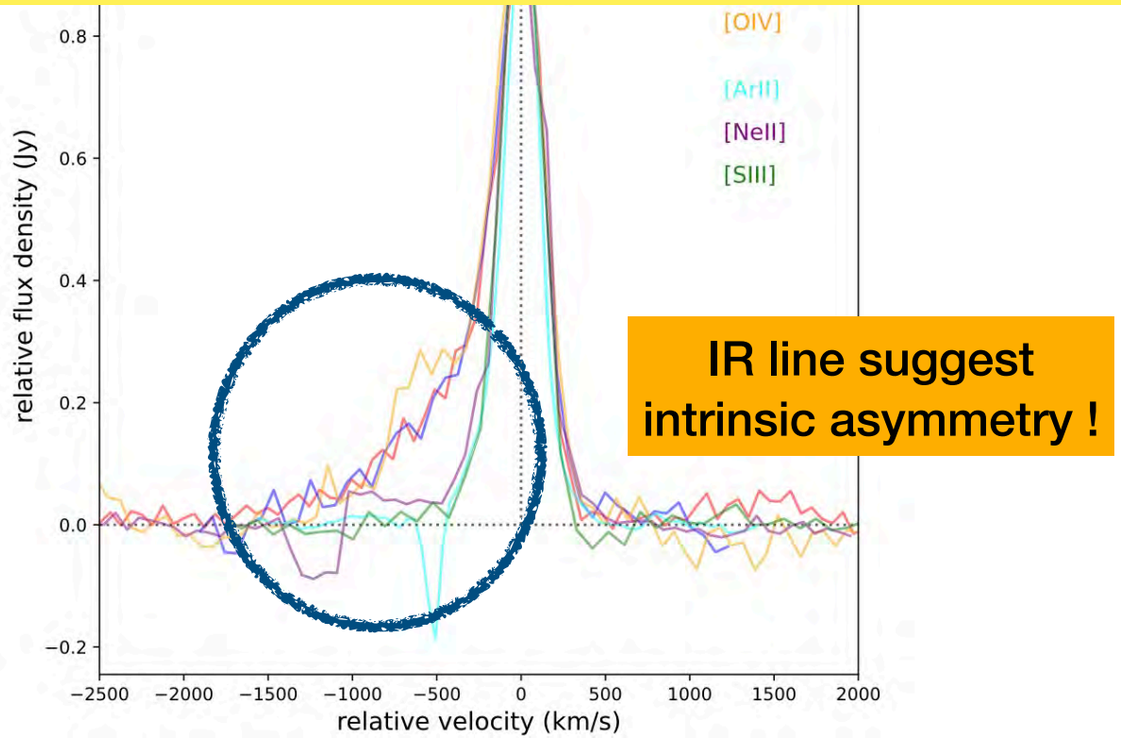


Image of NGC 7469 from NIRCam



MIRI nuclear spectrum with normalized and continuum-subtracted

How do we investigate this from the simulation side?

AGN Wind + Clumpy Disk

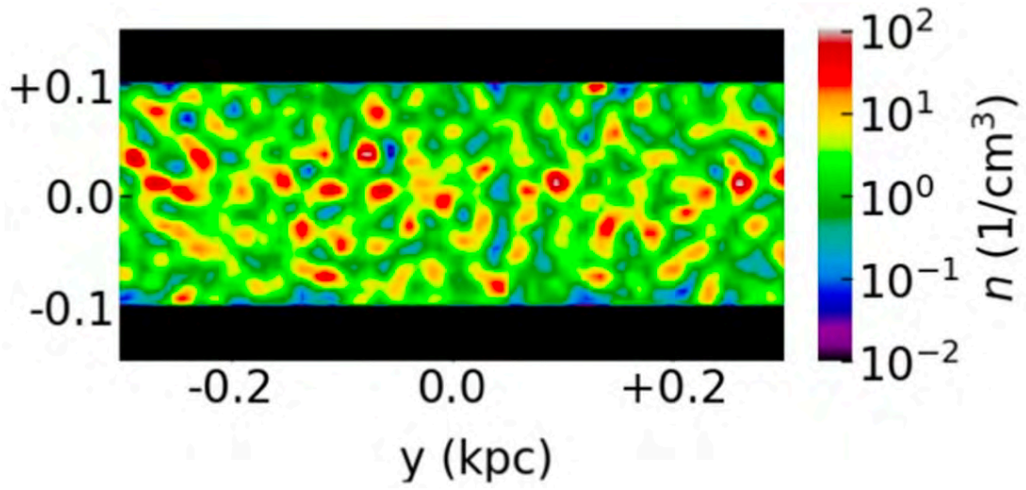
Test if asymmetry outflow form

Generate synthetic spectra

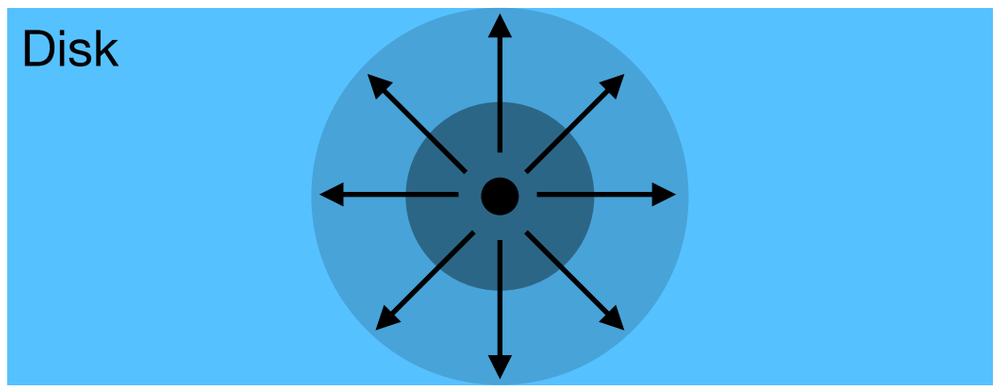
Comparing with JWST observation

Methods: Simulation

- **GAMER-SR**: GPU-accelerated AMR Code, developed by Prof. Hsi-Yu Schive(NTU).
- 3D special relativistic hydrodynamic (SRHD) simulation.
- Box size: 14 x 14 x 28 kpc^3, evolved to 4Myr.
- AGN feedback is modeled by injecting an isotropic, ultra-fast wind from boundary of SMBH, r=4pc following Costa et al. (2020).
- The galaxy disk is modeled as a clumpy, multiphase ISM, with individual clumps ~20 pc, following Tseng et al. (2024).



Number density distribution of the disk.

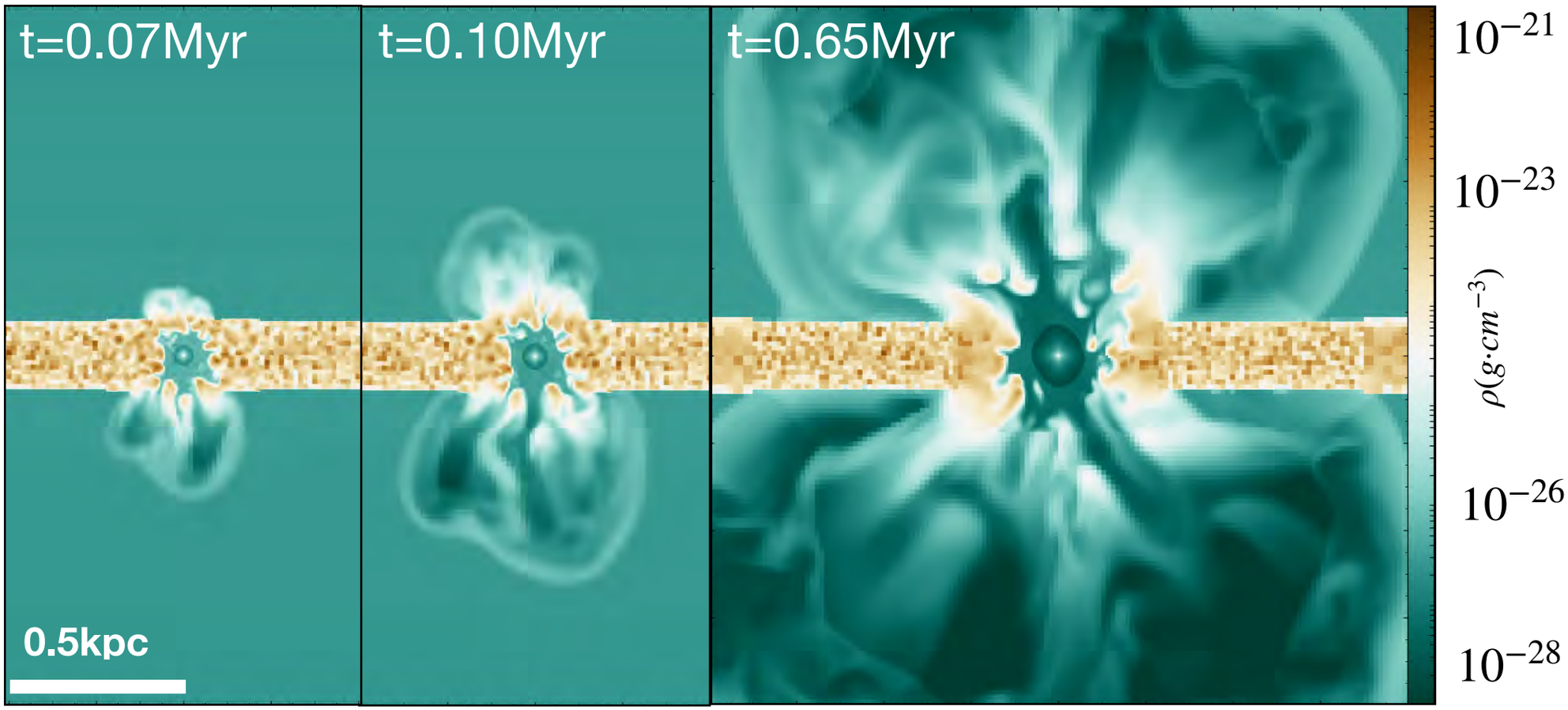


Wind inject from boundary of SMBH, r=4pc

Results

Morphology: Asymmetric bubbles

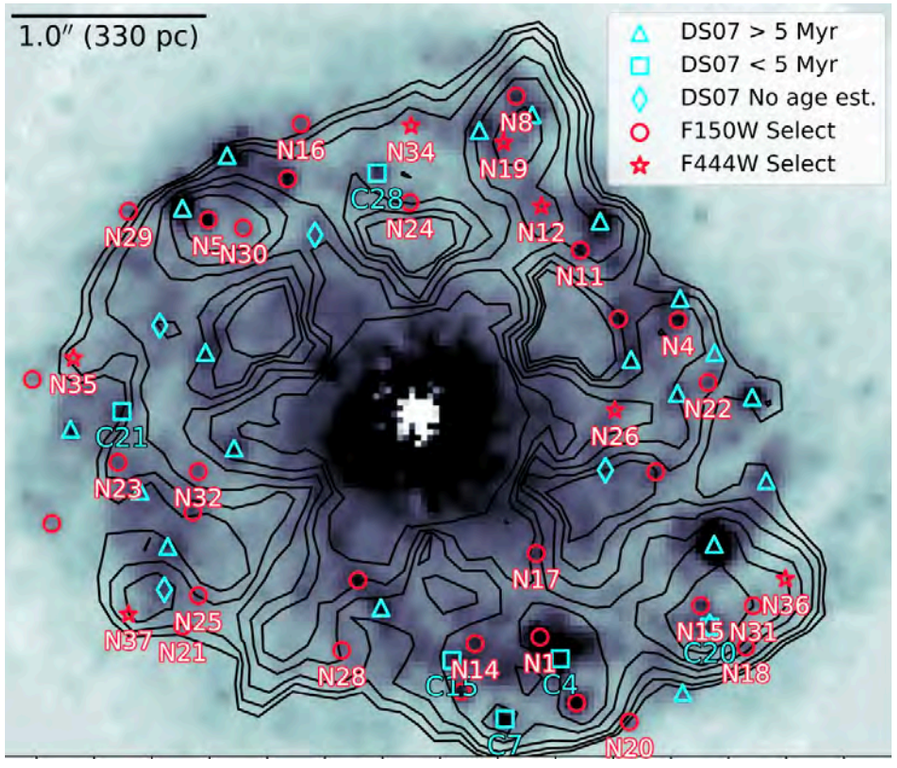
- The early-stage bubble asymmetry formed from interaction between the AGN wind and the anisotropic density distribution in the clumpy disk.
- As the simulation progresses, lobes expand into lower-density regions and asymmetry disappear.



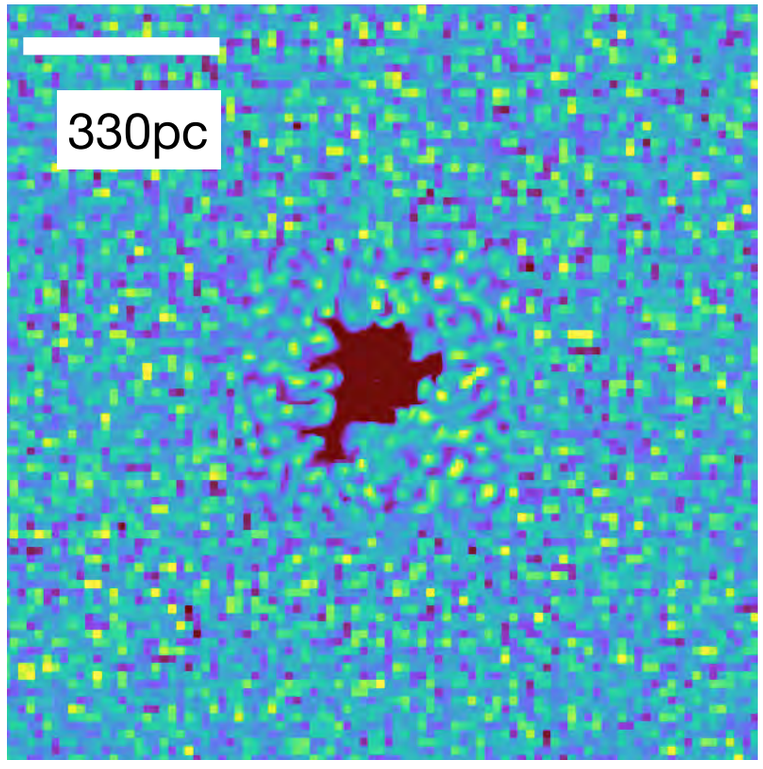
Results

Morphology: Asymmetric bubbles

- NGC 7469 hosts a compact circumnuclear starburst ring (r = 0.5 kpc).
- In the simulation, we saw similar structure in early stages.
- This similarity shows our simulation can match shape seen in NGC 7469.



JWST NIRCam/F150W image of NGC7469

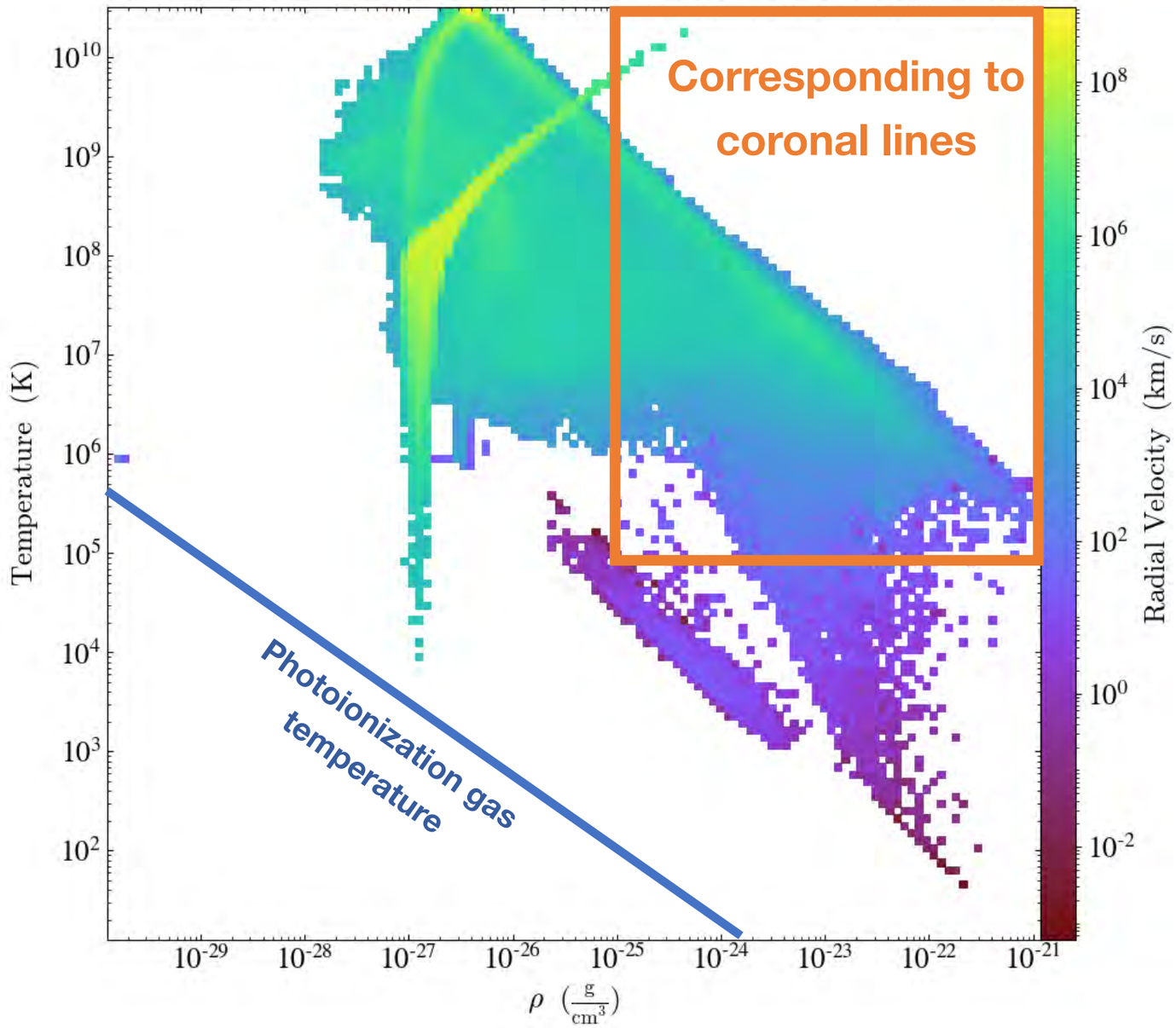


Density slice plot of the galactic center (t=0.1Myr)

Results

Phyiscal Properties: Phase Diagram

- We examine the phase plot to identify which gas phases produce observable emission lines.
- We take $T > 10^5 K, \rho > 10^{-26} g/cm^3$ as the criteria of observable CGM gas from Tumlison et al. (2017).
- Fast, hot gas lies outside typical CGM detection regions, making it difficult to observe in optical.

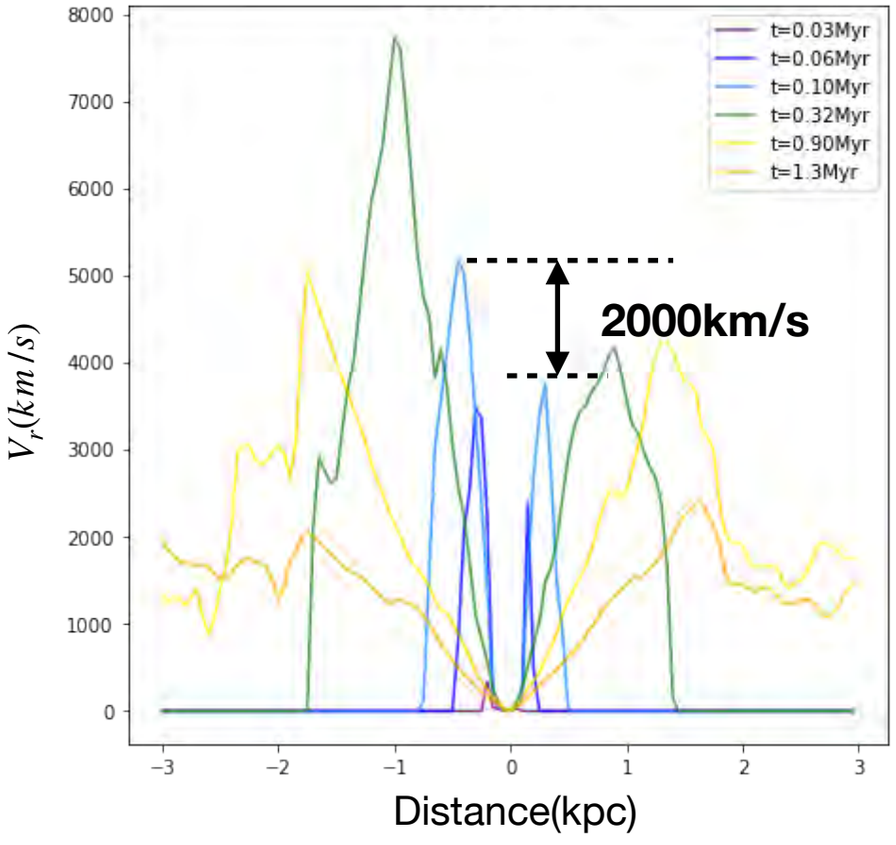


Results

Radial Velocity Profile + Gas Phase Selection

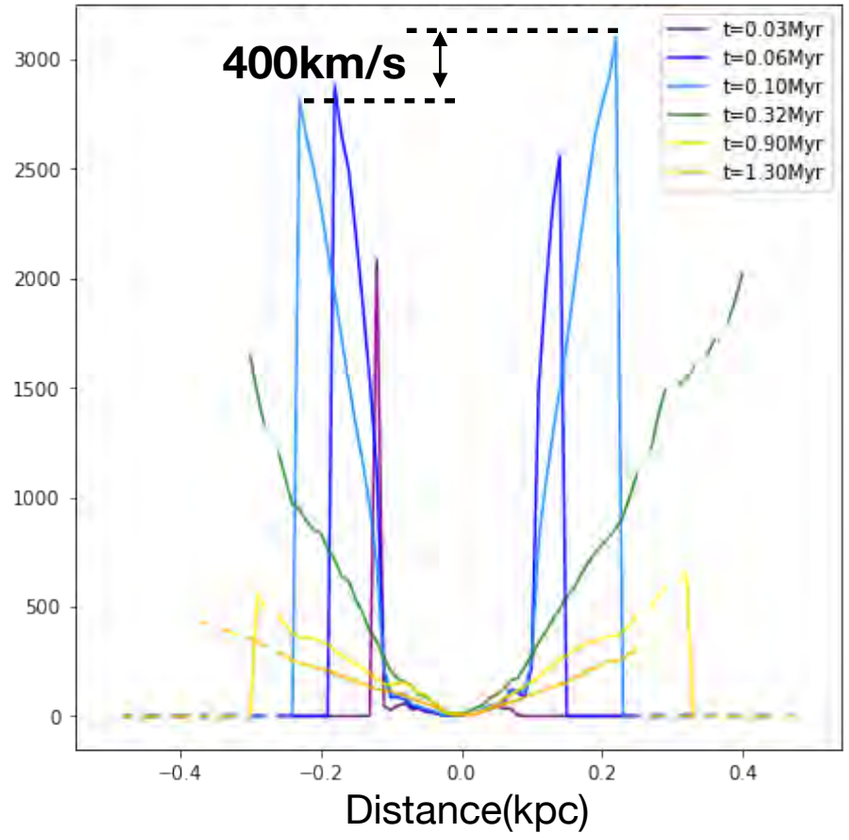
- For low-z quasars, outflow reaches a few thousands km/s, with side-to-side differences up to 1000 km/s.
- The radial velocity profile before selection, asymmetry is obvious and the maximum of radial velocity difference from side-to-side can reach up to 2000km/s
- Asymmetry remains even after selection, indicating the outflow is intrinsic and observable.

Before Selection



Observable gas

After Selection



Synthetic Spectra: TRIDENT

- TRIDENT is a python-based tool for generating synthetic absorption and emission spectra from hydrodynamical simulation data.

- We generates mock spectra by the following steps:

1. Tracing sightlines through simulation outputs

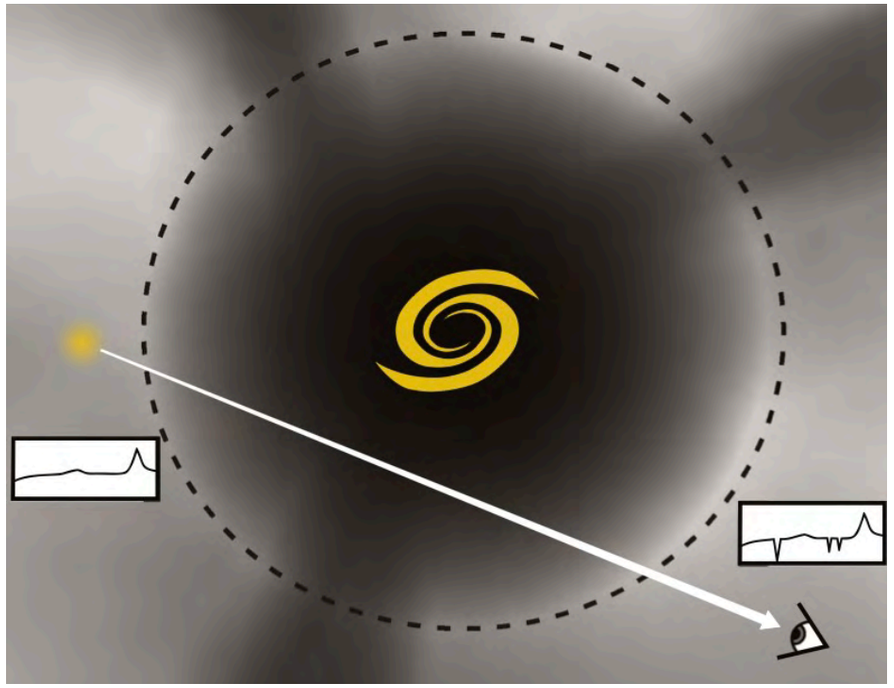
2. Assuming solar metallicity

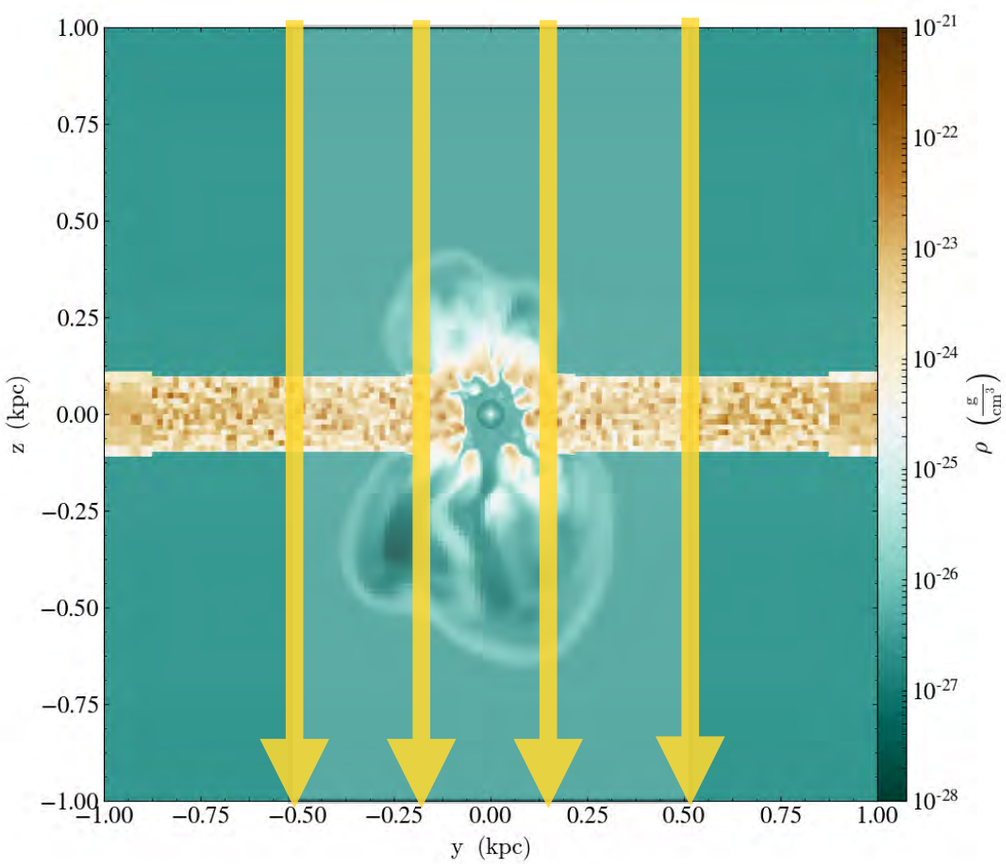
3. Estimate ion abundances: interpolating the density, temperature, and radiation field over a large three-dimensional lookup table

4. Mapping physical structures directly to spectral features.

Sampling within the radius of 0.5kpc

5. Calculate the mean value for the final spectra of the bubbles.



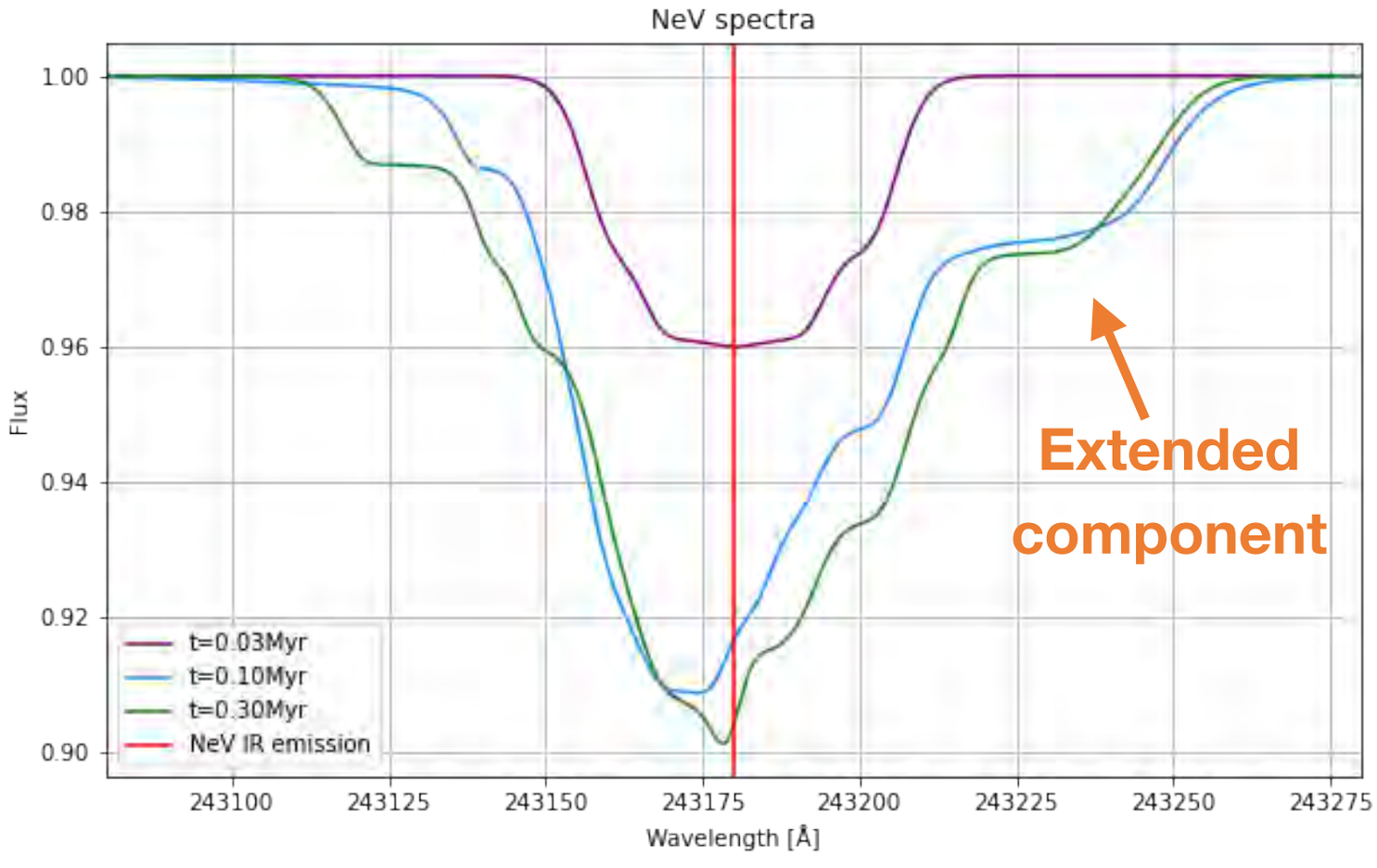


Hummes et al.(2017)

Results

[Ne V] Mock Spectra

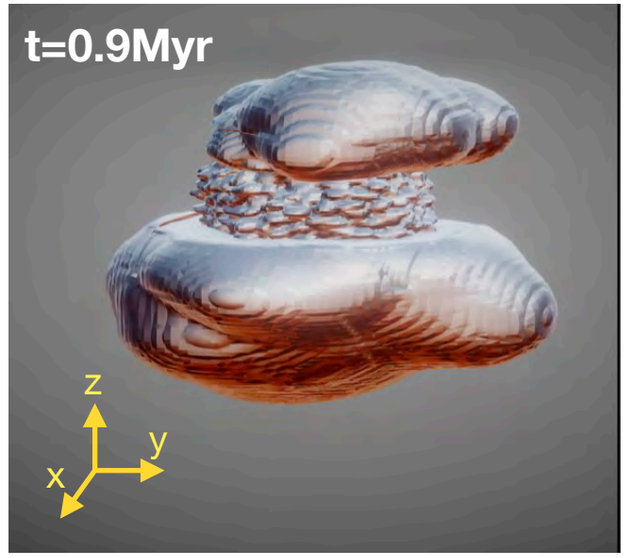
- The measured velocity of the extended component is only ~74 km/s, far below the simulation's intrinsic speeds.
- The mismatch occurs because TRIDENT mainly detects cooler, denser gas.
- Hot, fast outflows are too diffuse to contribute significantly to optical/IR emission.

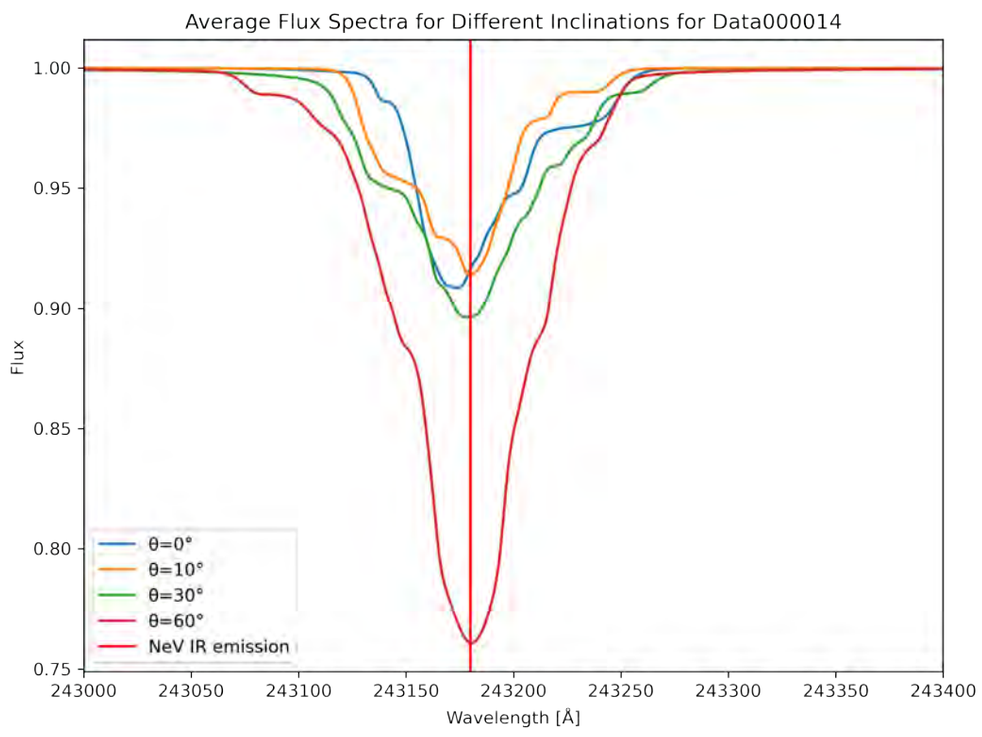


Discussion

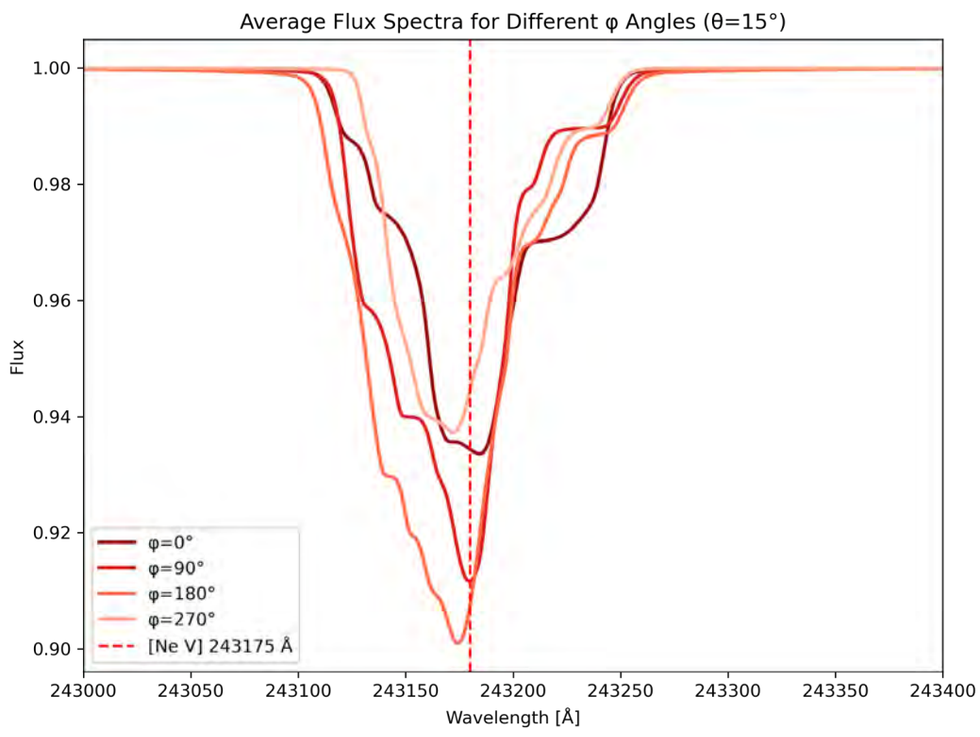
Observability with Different Inclination Angle

- 3D visualization of outflow bubbles (Vrad > 10 km/s) shows a highly irregular structure.
- We calculate spectra with different inclination angle θ, but didn't see a clear trend. Spectral predictions depend on both θ ,ϕ and the geometry of outflow structure.
- Therefore, the maximum observing angle does not vary monotonically and requires considering the full angular dependence.





$\phi = 0, \theta = 0°,10°,30°,60°$



$\phi = 0°,90°,180°,270°, \theta = 15°$

Quantitative Comparison

NGC 7469 vs Simulation

Quantity	NGC7469	Simulation
Eddington Ratio	0.3	0.1
Radius of Ring (kpc)	0.58	0.5
Mass Outflow Rate($M_\odot$/yr)	4	8
Max V_{rad}(km/s)	1700	8000 Intrinsic / 3000 Selected
Max Side-to-side Difference(km/s)	500	4000 Intrinsic / 80 Selected

Summary

- JWST observations of NGC 7469 reveal an intrinsic asymmetric, high-velocity [Ne V] outflow.

- We proposed that AGN wind interacting with a clumpy galactic disk is a plausible mechanism for producing asymmetric outflow.

- We performed 3D SRHD simulations with GAMER-SR to verify this scenario. The results show early-stage asymmetry, both in the outflow morphology and its radial velocity profiles.

- Synthetic spectra from TRIDENT reproduce asymmetry but underpredict velocity due to the dominance of cooler, denser gas.

- The maximum observable angle does not vary monotonically due to the complex 3D outflow structure.