# From Simulation to Spectra:
# Investigating AGN Wind-Disk Interactions and Asymmetric Galactic Outflows

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## Take-Home Messages

- Asymmetric outflows form in our 3D-SRHD simulations when AGN winds interact with a clumpy galactic disk.
- This wind-disk interaction provides a plausible explanation for the intrinsic one-sided outflow observed in NGC 7469 with JWST.
- [NeV] mock spectra show velocity asymmetry but underestimate true speeds due to limited emission from hot, diffuse gas.
- Cooling timescales are much longer than the time of simulation, justifying our decision to neglect radiative cooling.

## Motivations

AGN wind is a candidate for the formation of the Fermi and eROSITA bubbles. We investigate this using simulations and discovered that early asymmetries can arise from interactions between AGN winds and a clumpy galactic disk. Similar asymmetries appear in JWST observations of NGC 7469 (Armus et al. 2023), motivating a closer investigation into the physical mechanisms behind these features.

## Methods

- We perform 3D simulations using the GPU-accelerated special relativistic hydrodynamic (SRHD)-adaptive mesh refinement (AMR) code **GAMER-SR** (Tseng et al. 2021).
- The **galaxy disk** is modeled as a **clumpy, multiphase ISM**, with individual clumps ~20 pc in size.
- AGN feedback is modeled by injecting an **isotropic, ultra-fast wind** at the galactic center, following Costa et al. (2020).
- The simulation runs for a total of **4 Myr**, capturing both early and intermediate stages of bubble evolution.
- To study observability, we generate **synthetic spectra** using **TRIDENT** (Hummels et al. 2017), with resolution similar to HST.

## Results

- Simulations show a **strong asymmetry in bubble formation** during the early stages.
- One lobe expands rapidly, while **the other is slowed by interaction with** dense clumps in **the galactic disk.**
- The peak mass outflow rate reaches 8 $M_\odot$/yr, consistent with values observed in NGC 7469.
- **After selecting gas** with $\rho > 10^{-25}$ g/cm$^3$ and $T > 10^5$ K (coronal-line conditions), the **velocity asymmetry persists.**
- Phase diagrams reveal that the fast, hot gas lies outside standard CGM detection regions (Tumlinson et al. 2017), which may explain why it's difficult to observe in optical/IR.

## Discussion

### Mock Spectra

[NeV] mock spectra from TRIDENT show clear velocity asymmetry, but the measured velocity of the **extended component is only ~74 km/s,** far below the simulation's intrinsic speeds (up to 8000 km/s). This mismatch occurs because TRIDENT detects cooler, denser gas, while the hot, fast outflows are too diffuse to contribute significantly to optical/IR emission. Reducing the disk density could enhance spectral visibility by allowing more high-velocity gas to cool and emit.

### Cooling

Radiative cooling is neglected because cooling timescales exceed the 4 Myr simulation duration. **Hot outflows ($T > 10^7$ K) cool on Gyr timescales**, and even gas at $10^5$–$10^6$ K has a median cooling time of 11 Myr.

**The cooler phase ($T \approx 10^5$ K) cools faster (~100 Myr) but plays a minor role in driving the outflow**. These values confirm that cooling is dynamically negligible, supporting the adiabatic approximation.

| 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 |
| V_max (km/s) | 1700 | 3000 |
| ΔV_max (km/s) | 700 | 80 |

Table. 1 Comparison with NGC 7469. Simulation values of V_max and ΔV_max are measured after coronal-line selection (Fig. 3, right panel), representing the peak outflow speed and the velocity asymmetry between two sides.

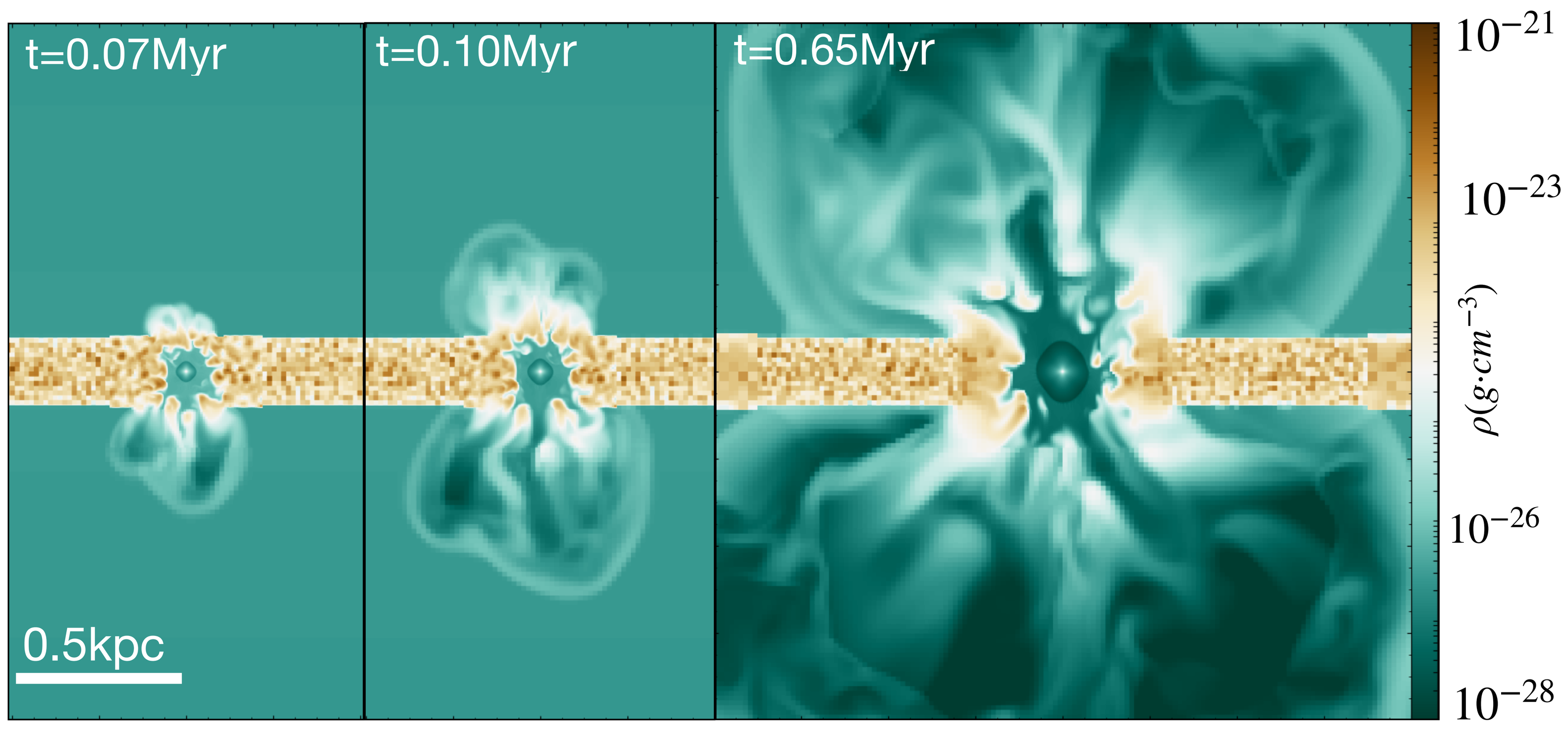


Figure. 1 The slices of density at t=0.06, 0.1, 0.32 My respectively. The asymmetry of the bubbles can be seen in the early stage.

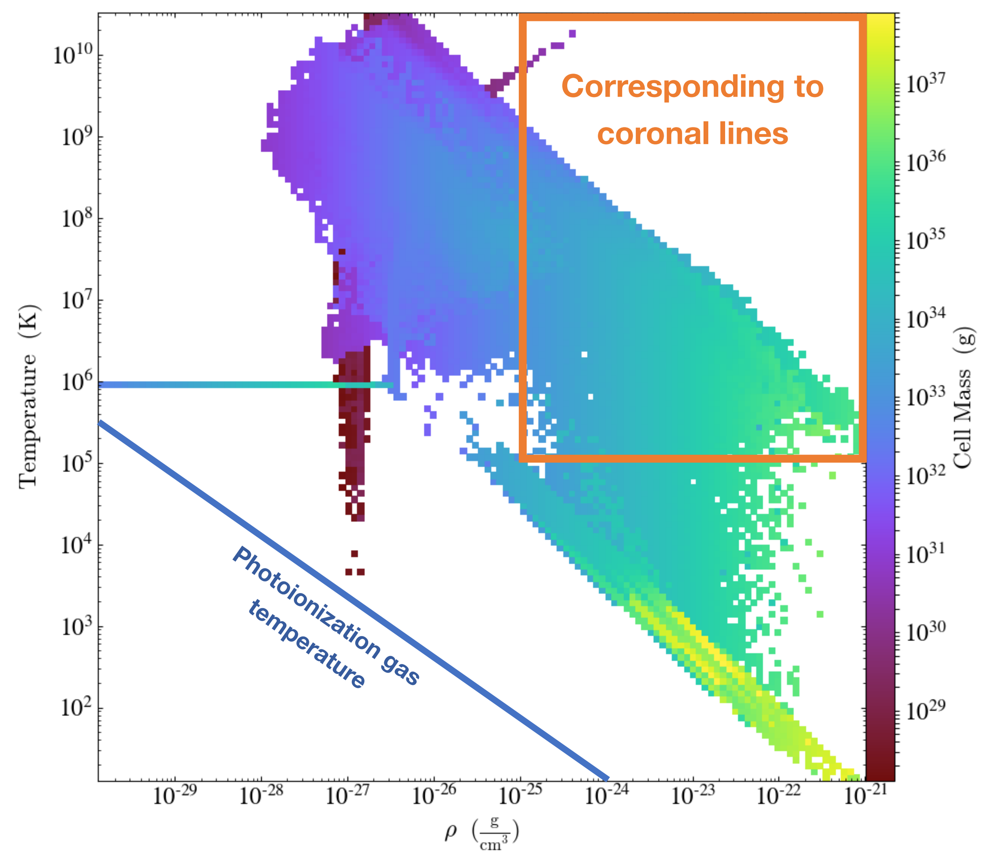


Figure. 2 The phase diagram of the galaxy at t = 0.1 Myr shows the region where gas exhibits properties similar to ionized coronal lines, highlighted by the orange rectangle.

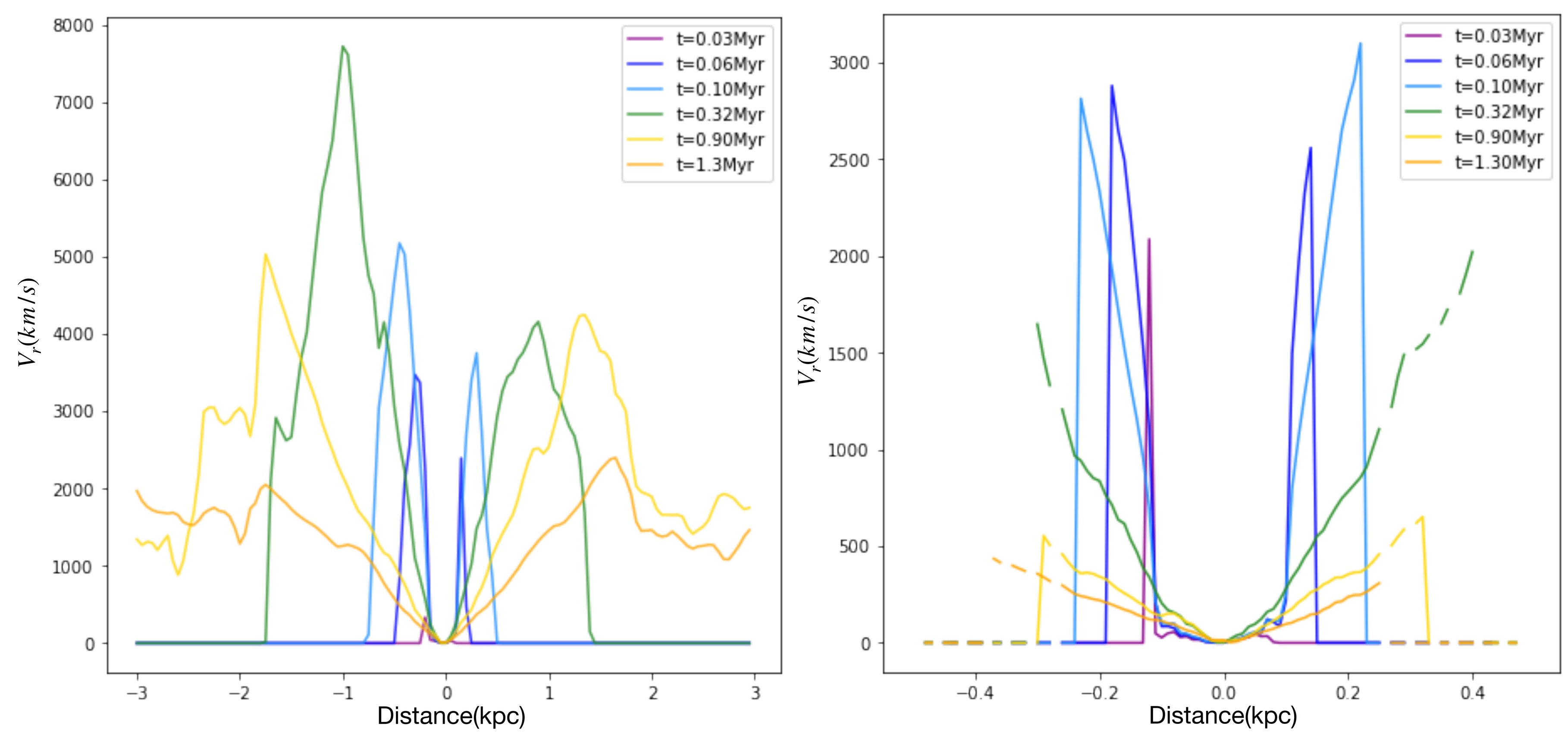


Figure. 3 The profile of radial velocity at different time along z-axis. The left panel is the whole simulation. The right panel is after selection for coronal lines.

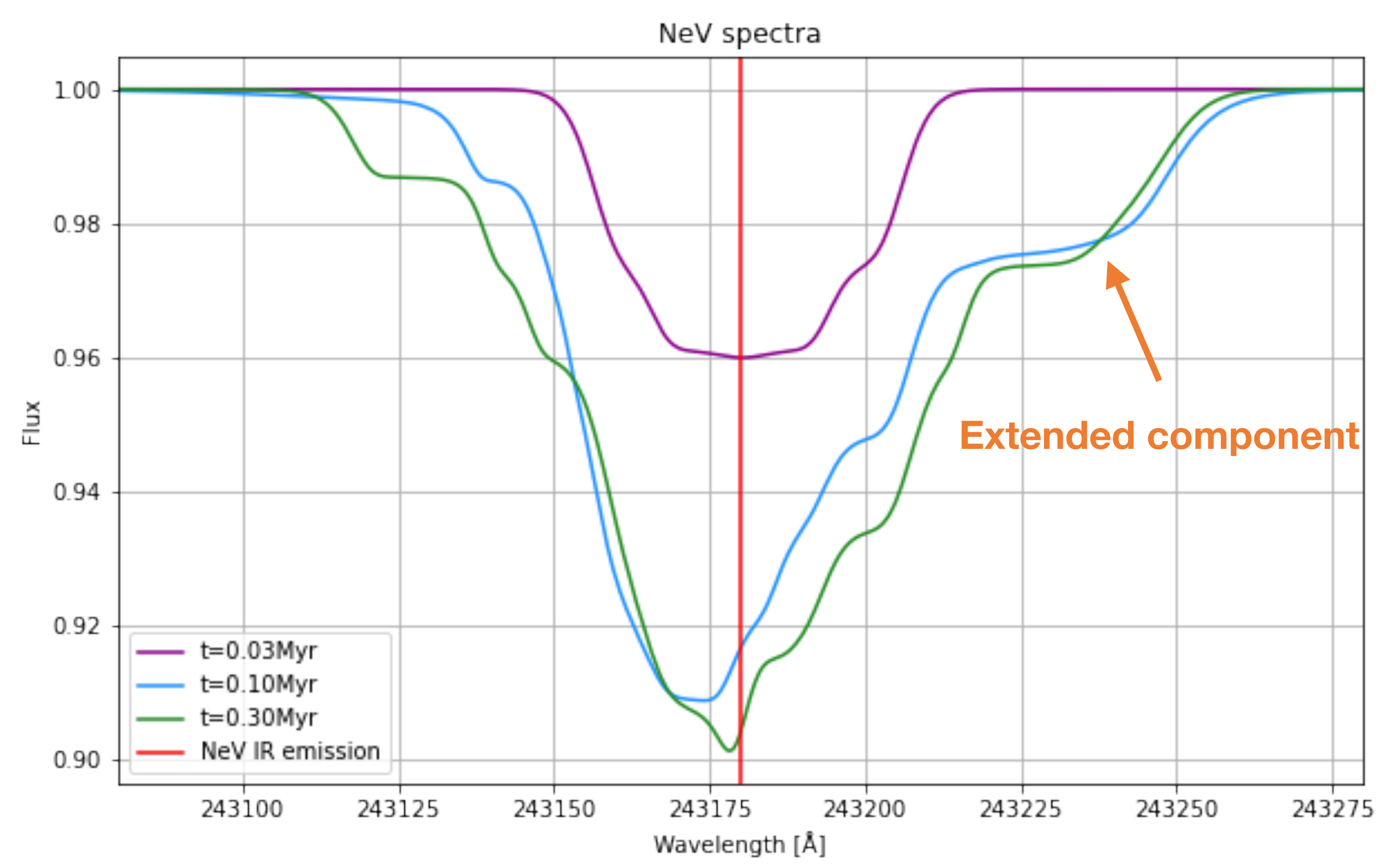


Figure. 4 Mock spectra of the galaxy at t=0.03,0.1, and 0.3 Myr, generated using TRIDENT. At 0.1 and 0.3 Myr, an extended component appears at longer wavelengths. The red vertical line marks the NeV IR emission at 243180Å.

References
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