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

Chiung-Yin Chang[1], Hsiang-Yi Karen Yang[1]

[1] Institute of Astronomy, National Tsing Hua University, Hsinchu, Taiwan

Abstract

We use 3D special relativistic hydrodynamic (SRHD) simulations to study AGN-driven winds in a disk galaxy. Our results reveal an early-stage (t ~ 0.1 Myr) asymmetry in bubble formation, with one bubble reaching velocities up to 2000 km/s while the other remains underdeveloped due to interactions with the clumpy disk. This aligns with JWST observations of NGC 7469, which show a circumnuclear starburst ring and one-sided high-velocity outflows.

To explore observational signatures, we generate mock spectra using TRIDENT, finding that the asymmetry is detectable in the [NeV] line. Phase diagrams suggest that matching observed JWST emission requires the disk density in our simulations to be at least an order of magnitude lower. These findings provide insight into AGN wind-disk interactions and offer a potential explanation for the asymmetric outflows in NGC 7469.

Methods

For these simulations, we utilize the GPU-accelerated SRHD adaptive-mesh-refinement (AMR) code, gamer-sr (Schive et al. 2010, 2018; Tseng et al. 2021). Using **3D SRHD** simulations enables us to simulate the formation of galactic bubbles resulting from relativistic-fluid injections from the Galactic Center (GC).

This work incorporates the **clumpy multiphase interstellar medium disk.** The **largest size of an individual clump** in this model is **approximately 20 pc**.

For AGN feedback, we inject an isotropic, ultra-fast AGN wind at the GC, following Costa et al. (2020).

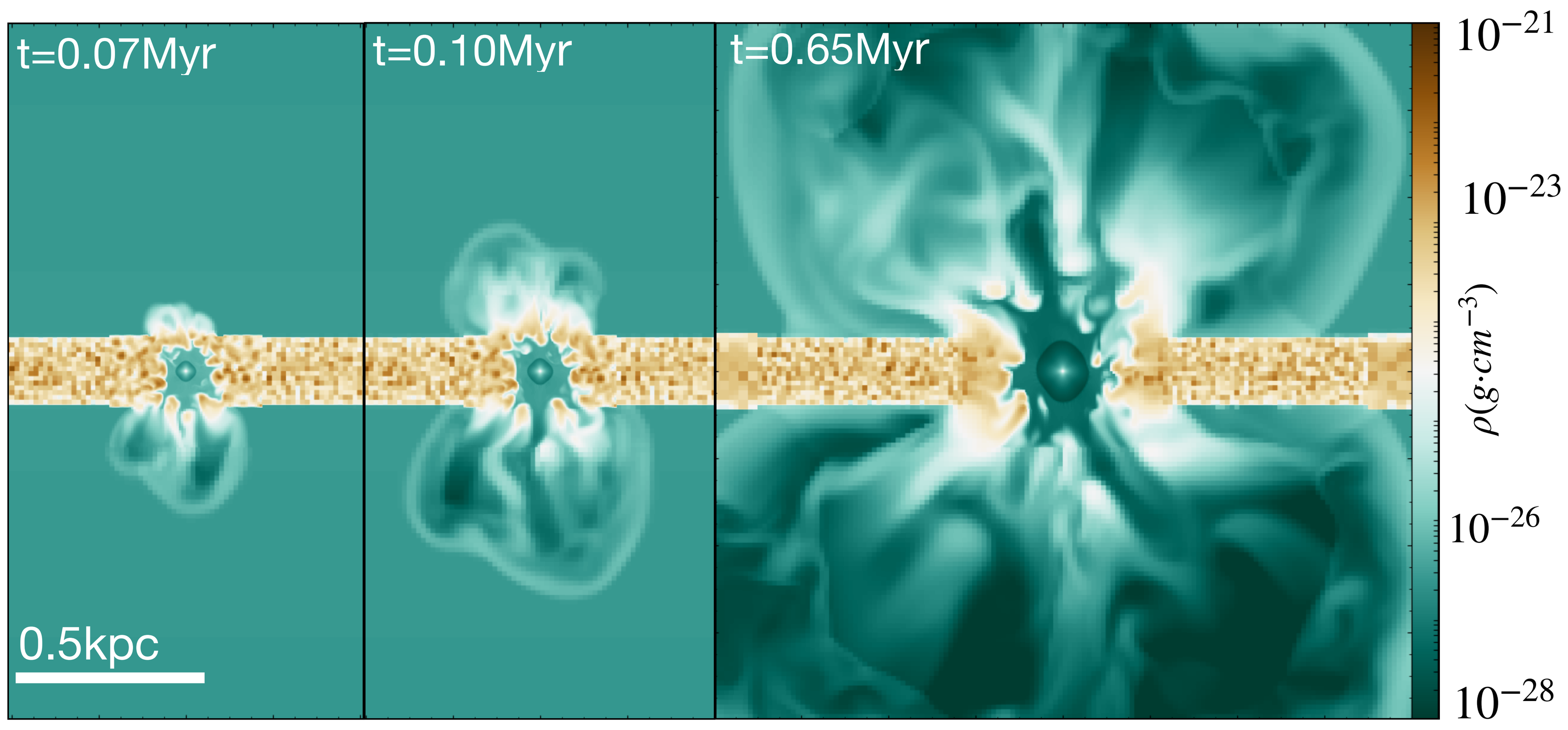

Figure. 1 The slices of density at t=0.06, 0.1, 0.32 My respectively.
The asymmetry of the bubbles can be seen in the early stage (t~0.1Myr)

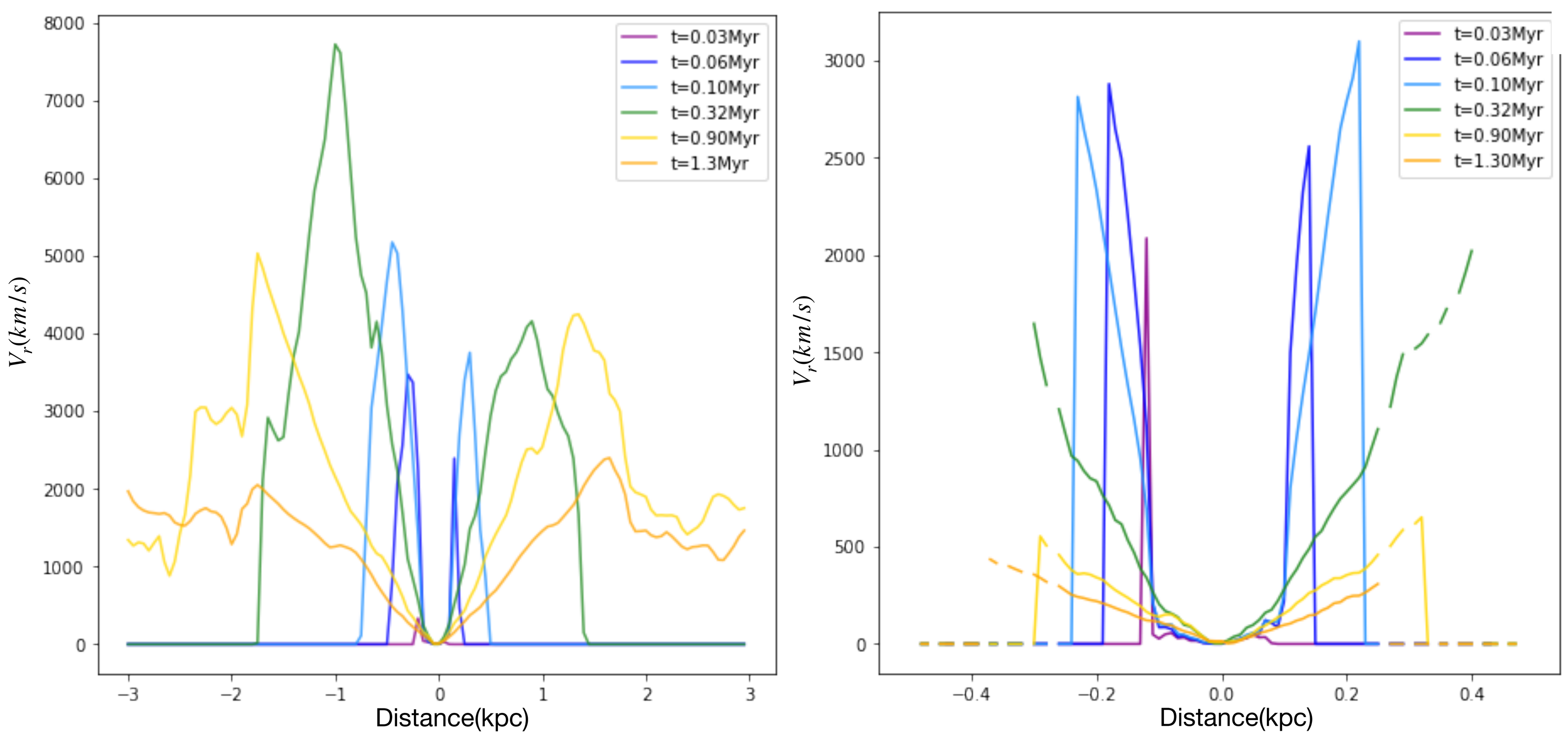

Figure. 2 The profile of radial velocity at different time along z-axis. The left panel is the whole simulation. The right panel is profile.

Results

In our simulation, we observed a distinct **asymmetry in the radial velocity and density during the early stages** of bubble formation (See Figure 1). To align our findings with observational data, we calculated the **mass outflow rate in the outflow region**. Remarkably, at t=0.1 Myr, this rate peaked at 8 solar masses per year.

To confirm its observability of our result, we plotted the phase diagram and select the region where the density is larger than $10^{-25} g\cdot cm^{-3}$ and temperature exceeds than 10^5 K , similar to the properties of ionized coronal lines. The asymmetry in radial velocity persisted after the selection (see Fig. 2).

Our simulation proposes a potential mechanism to explain the one-sided outflow observed in NGC 7469, which we attribute to the interaction between AGN winds and the clumpy galactic disk. This interaction is analyzed in terms of physical parameters (see Table. 1).

Mock Spectra

To evaluate consistency with real data, we use TRIDENT from Hummels et al. (2017) to generate mock spectra. The [NeV] line (Fig. 4) shows an asymmetric profile, indicating varying bubble velocities. After 0.06 Myr, an extended asymmetric component appears, matching the radial velocity distribution after selection. However, the measured velocity is 74 km/s—much lower than expected in our simulation.

Compared to the CGM phase diagram from Tumlinson et al. (2017), our gas is hotter and denser than expected (Fig. 3), likely making fast outflows harder to detect. Reducing disk density by an order of magnitude could improve visibility. While results are broadly consistent, further adjustments to disk parameters may be needed for more realistic spectra.

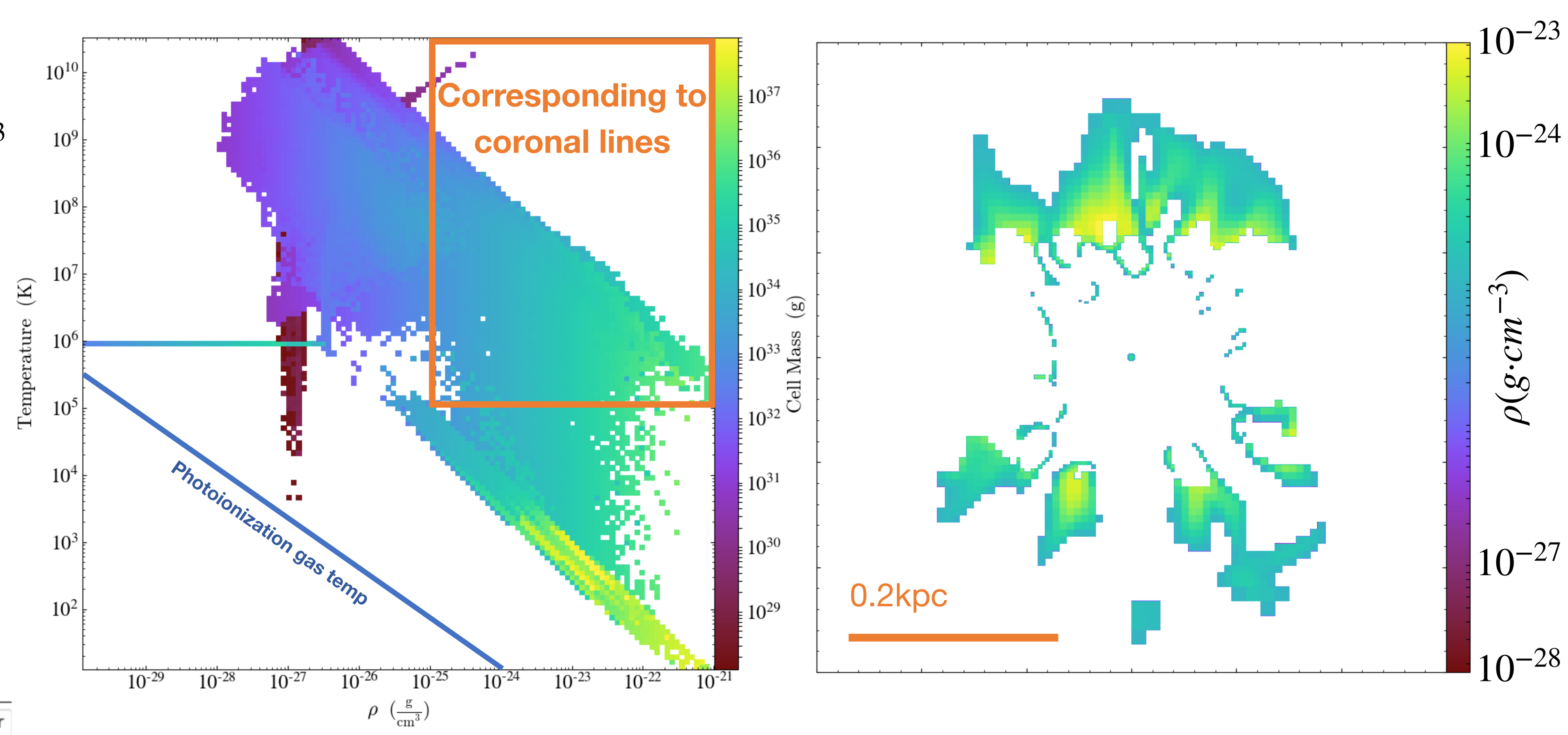

Figure. 3 (Left)The phase diagram of the galaxy at t = 0.32 Myr shows the region where gas exhibits properties similar to ionized coronal lines, highlighted by the orange rectangle. (Right) The density slice of the observable central outflow after density and temperature selection.

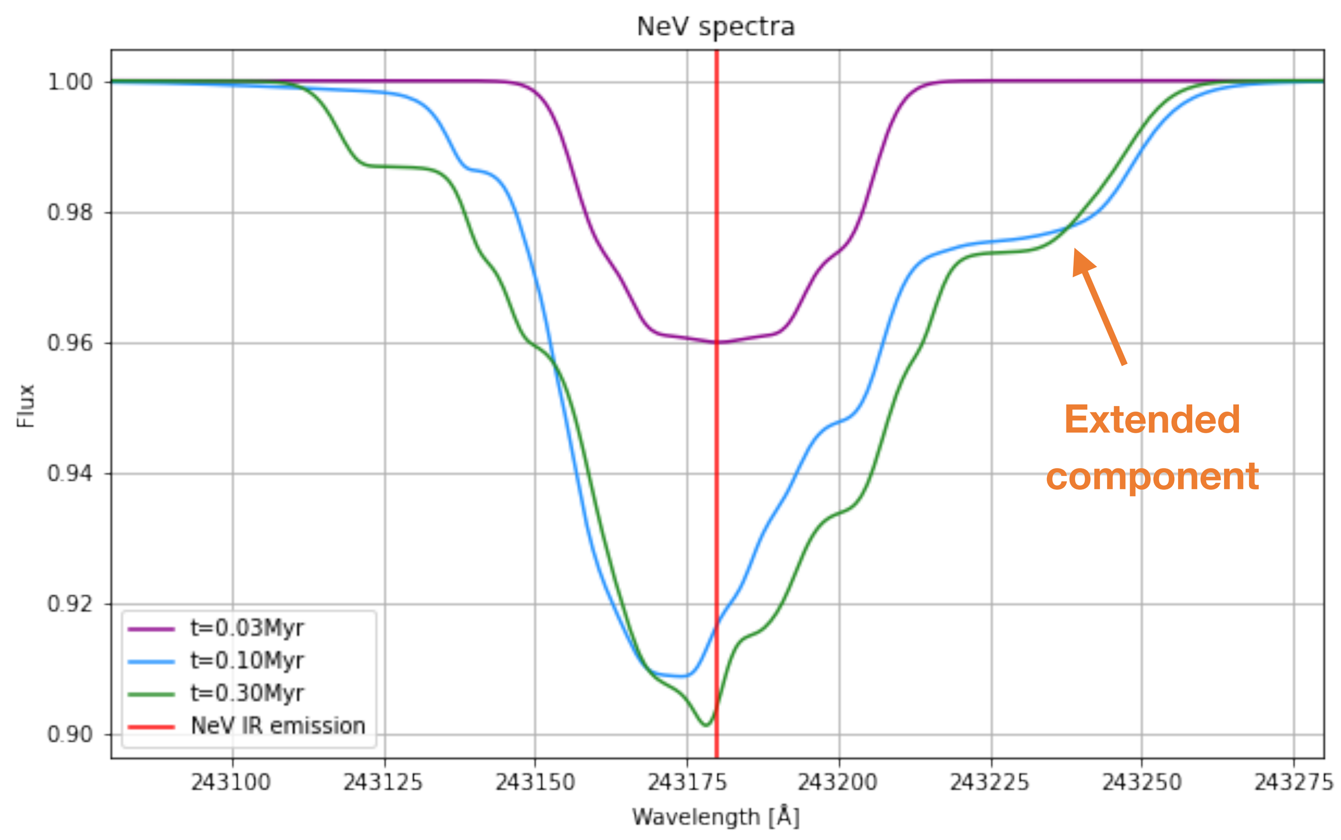

Figure. 4 Mock spectra of the galaxy at t=0.03,0.1, and 0.3 Myr, generated using TRIDENT. At 0.1 and 0.3 Myr, an extended component appears at longer wavelengths.
The red vertical line marks the NeV IR emission at 243180Å

Quantity	NGC7469	Simulation
Eddington Ratio	0.3	0.1
Radius of Ring (kpc)	0.58	0.5
Mass Outflow Rate (Solar mass/yr)	4	8
Δ V_max (km/s)	1700	8000
V_max (km/s)	700	~74(after selection)

Table. 1 The comparison of parameters between NGC7469 and the simulation.

References:
Armus et al. (2023). ApJ, 942(2), L37.
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Tumlinson et al. (2017). Annual Review of A&A 2017
Hummels, C. B. Et al.(2017). ApJ, 847(1), 59.