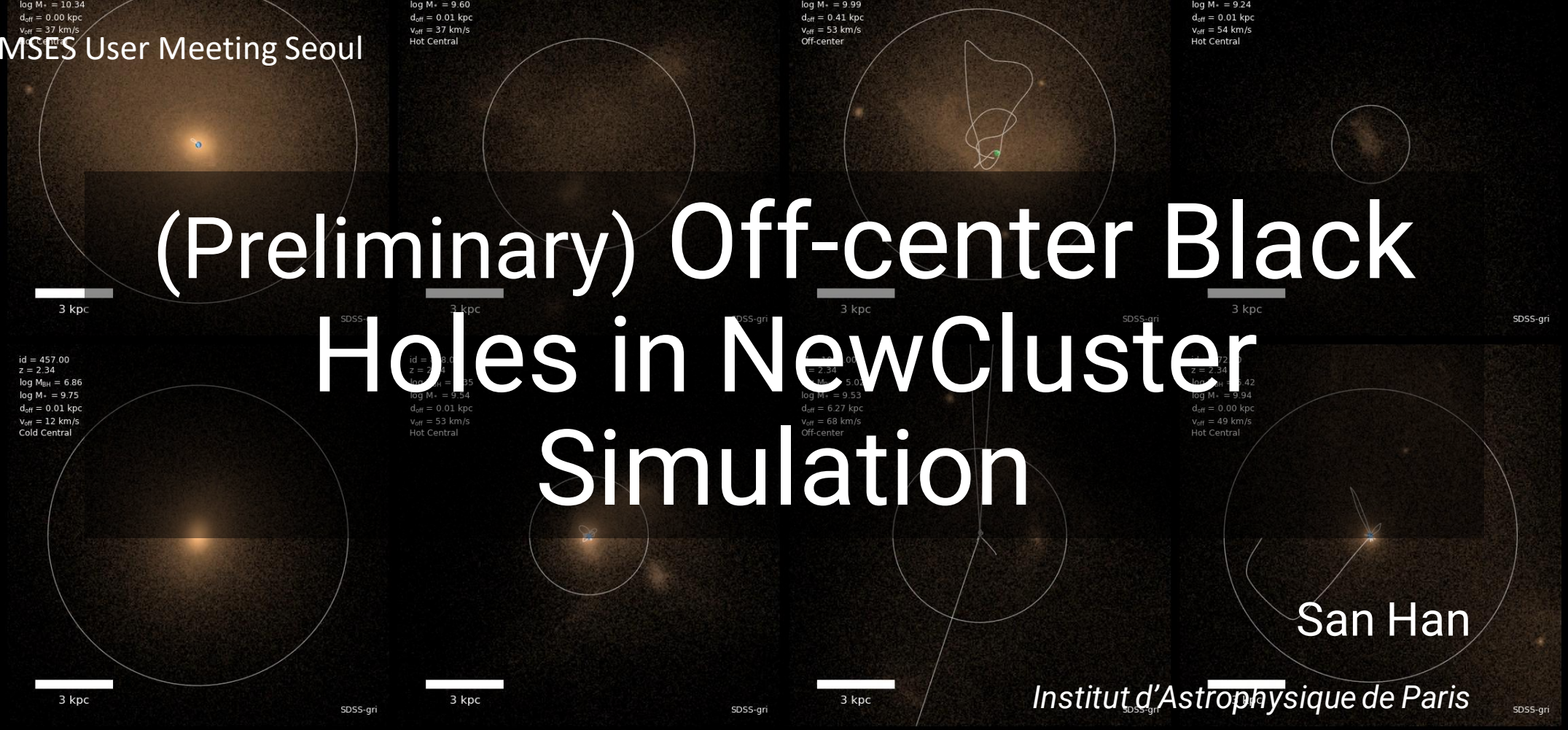


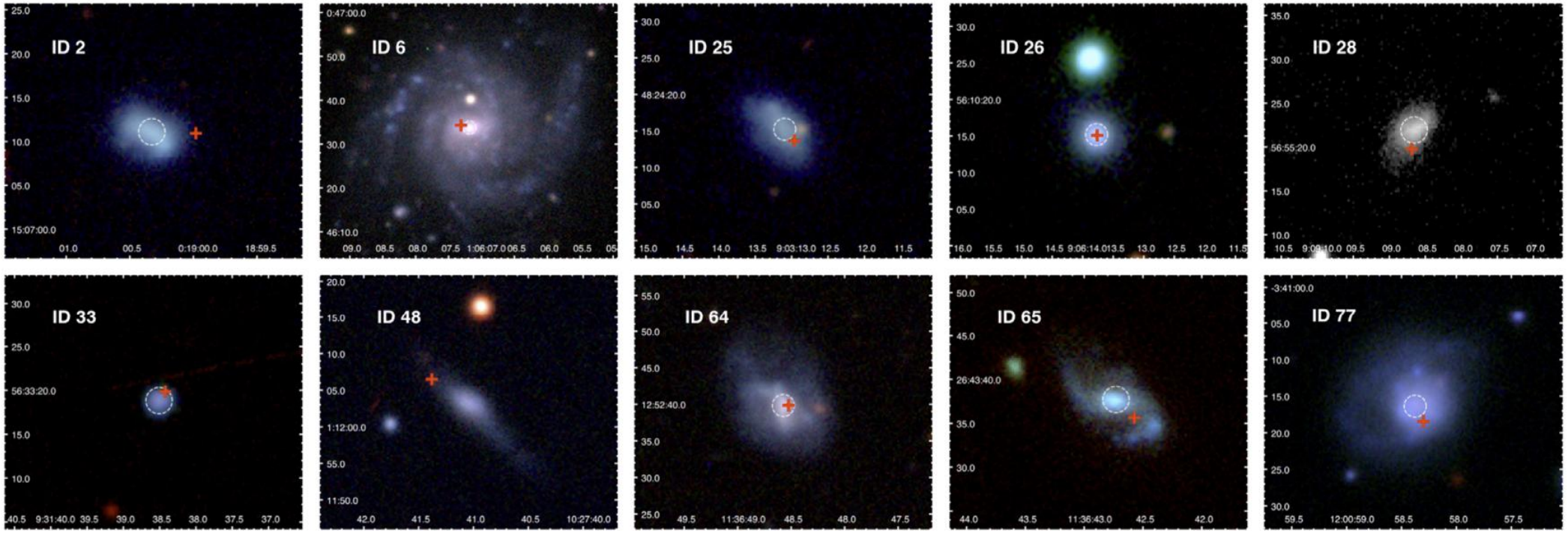
(Preliminary) Off-center Black Holes in NewCluster Simulation

San Han

Institut d'Astrophysique de Paris

+ (NewCluster collaboration)

Observations of Off-center MBHs



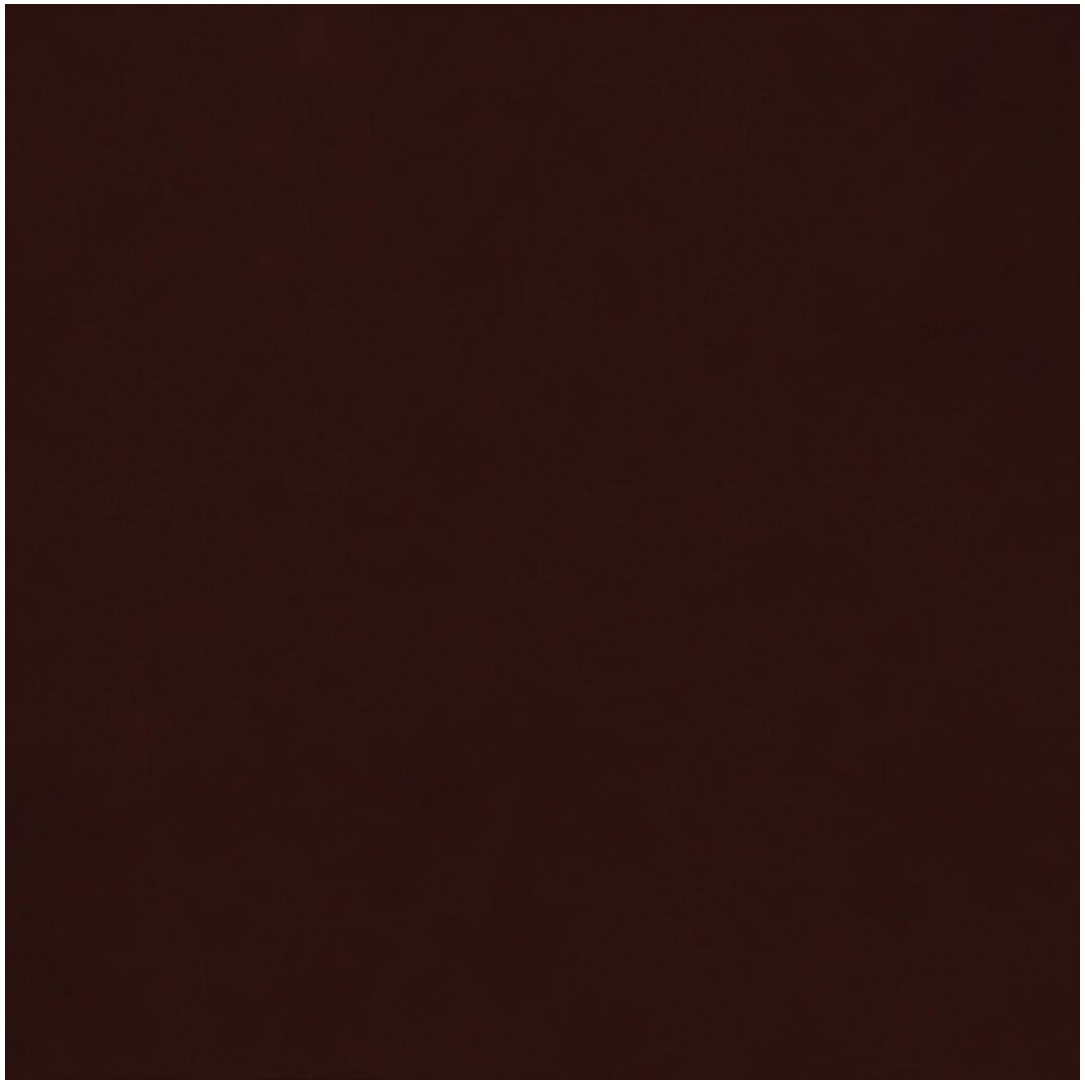
Reines+ 2020

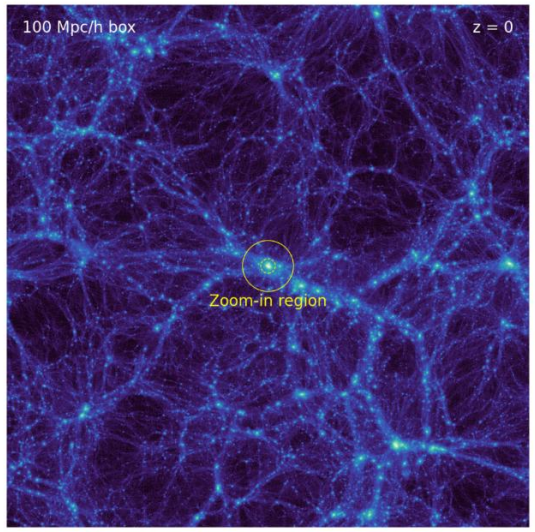
- Radio confirmation of off-center AGN (Reines+ 2020)
- Off-center quasar (Chiaberge+ 2017)
- Off-center tidal disruption events (Yao+ 2025)
- ULXs (HLXs), Globular clusters containing IMBHs…

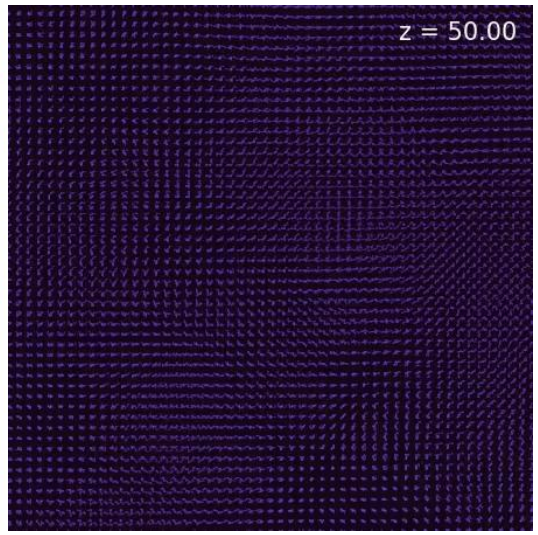
Studies and proposed origins of off-center BHs

- Galaxy mergers (Tremmel+ 2018, Bellovary+ 2021) ☺
  - Central MBH of tidally disrupted galaxy permanently orbit the galaxy
- 3-body dynamical slingshots (Valtonen+ 1994, Hoffman & Loeb 2007) 😐
  - Requires >=triple system of MBH that are close to each other
- Gravitational wave recoil kicks (Komossa+ 2012) ☹
  - Acceleration 100~1000km/s
  - Can produce permanently orphan black hole

NewCluster Simulation







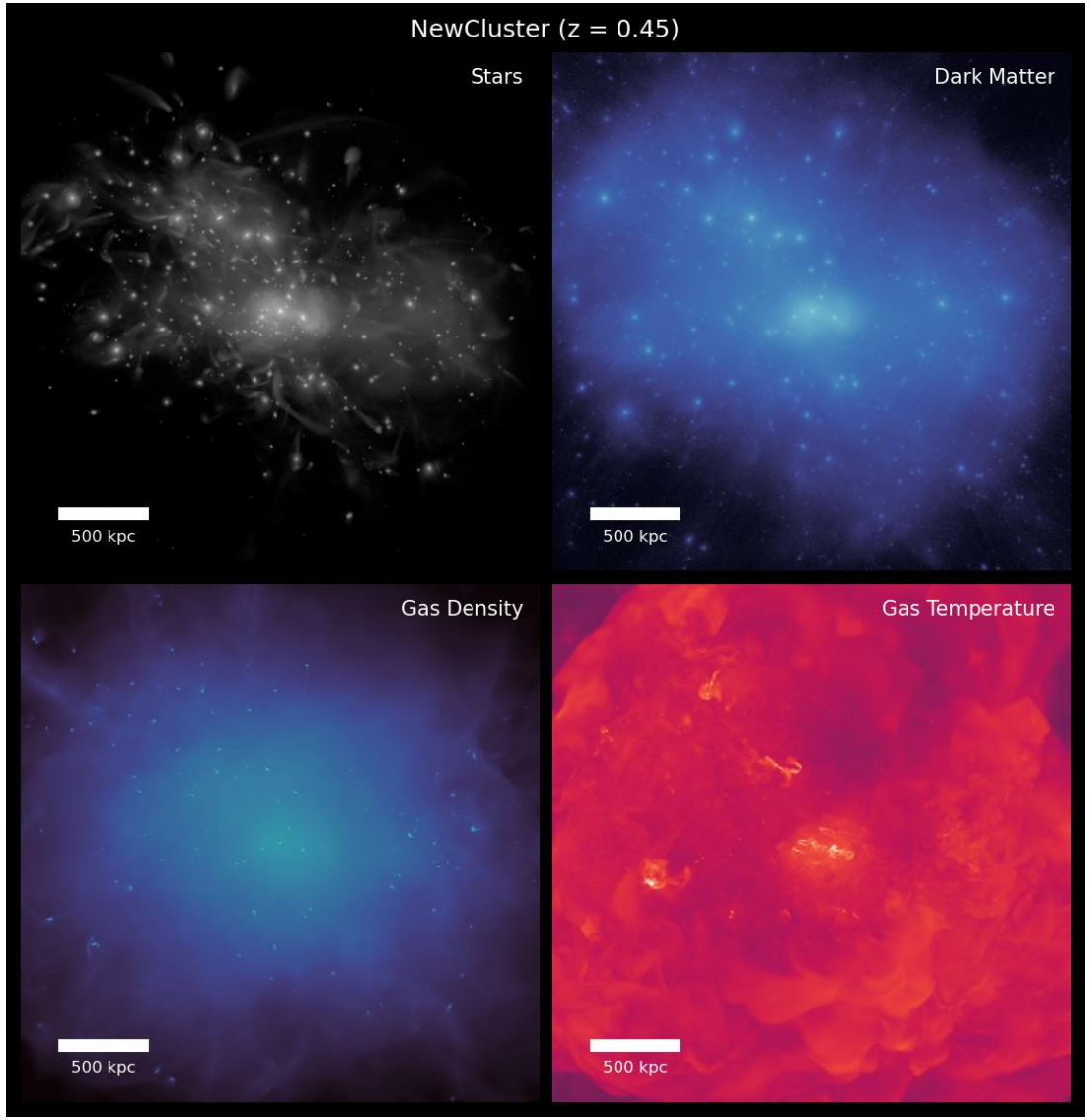
Cosmological hydrodynamic zoom-in simulation selected for target cluster with $M_{vir} \sim 4.7 \times 10^{14} M_{\odot}$ and up to $3.5 R_{vir}$.

Spatial resolution: ~ 70 pc

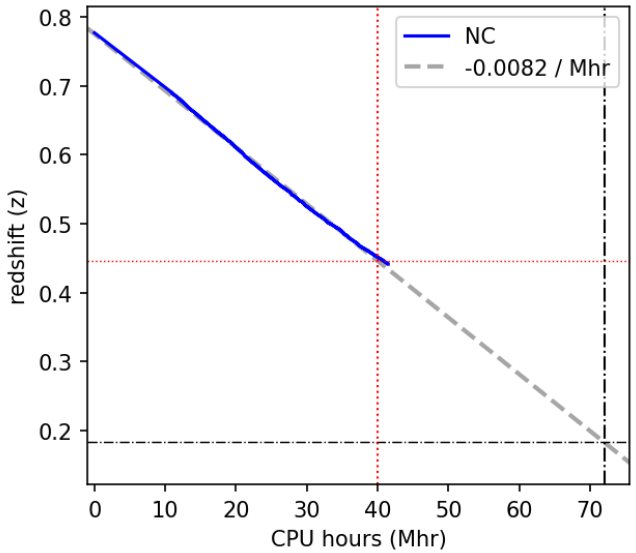
Mass resolution: $2 \times 10^{4} M_{\odot}$ (stars) $1.6 \times 10^{6} M_{\odot}$ (DM)

Astrophysical prescriptions: Gravo-thermo-turbulent SF, SN II, Ia, AGN feedback, 9 chemical species, 4 on-the-fly dust species

NewCluster Run: Current status

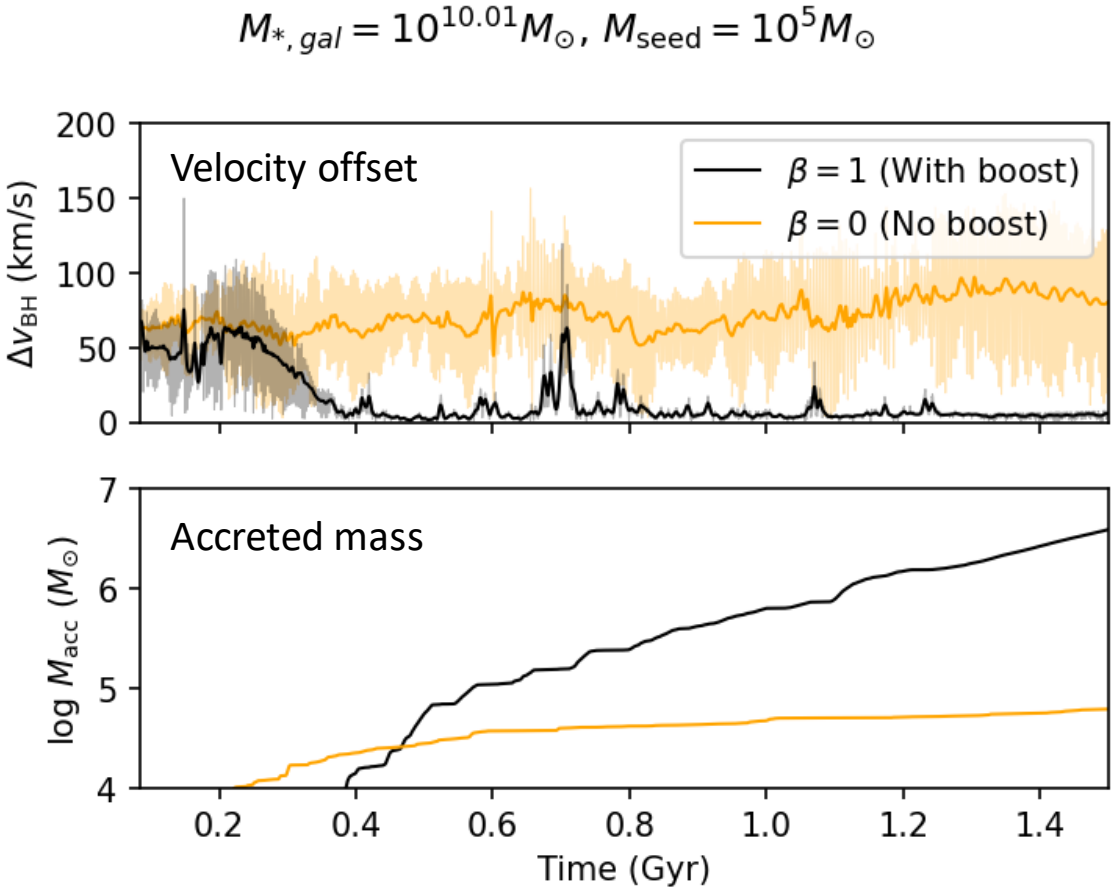


- NC simulation has reached z = 0.45 at April 2026, and planned to reach z = 0.2 at the end of 2026.
- 603 scheduled snapshots in total, all snapshots converted to HDF5 format (300TB -> 90TB)
- Latest snapshot at z=0.45 involves ongoing merger between two clusters
- If you are interested on using, don't hesitate to contact me!

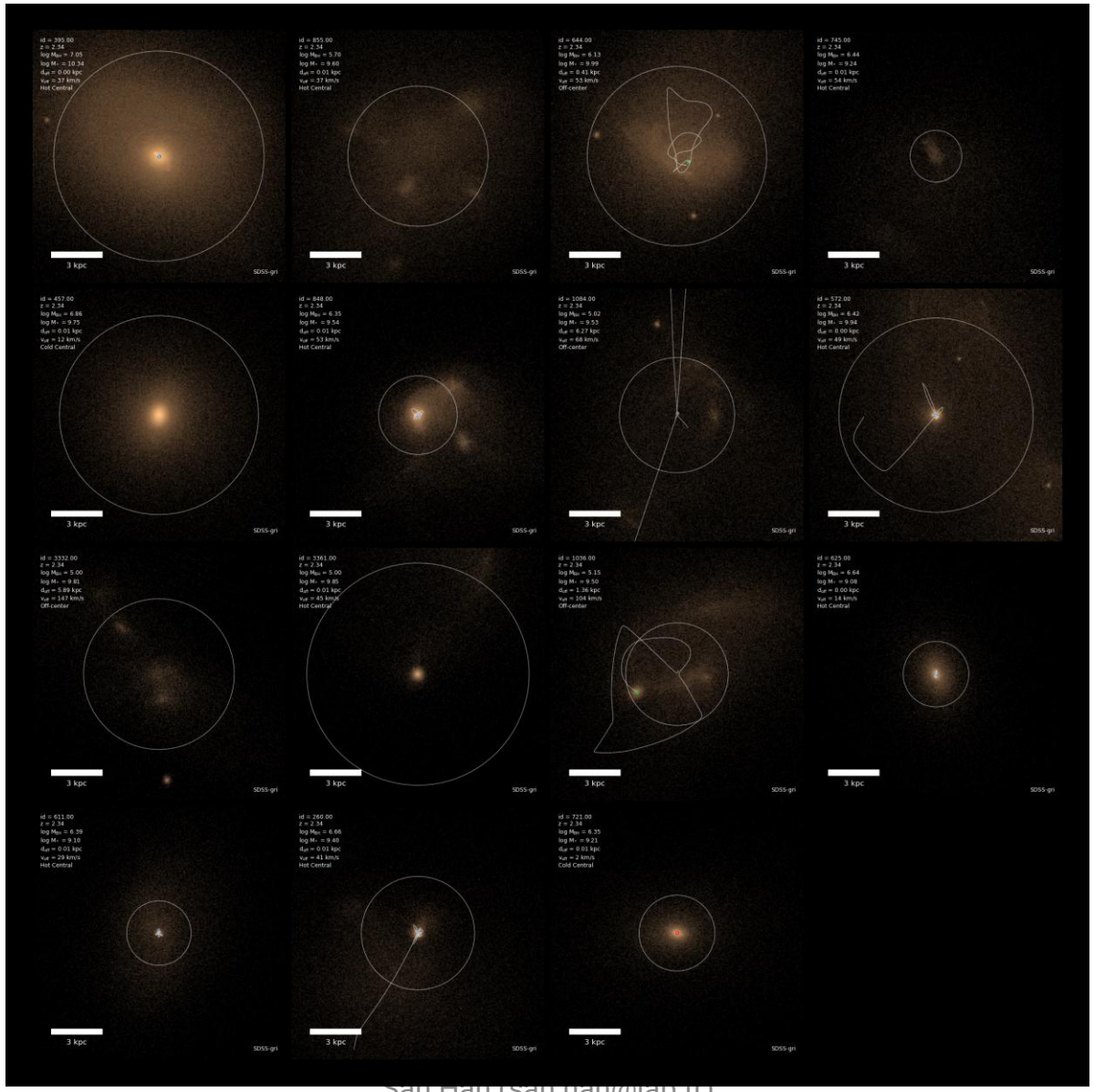


Modeling black holes in NewCluster

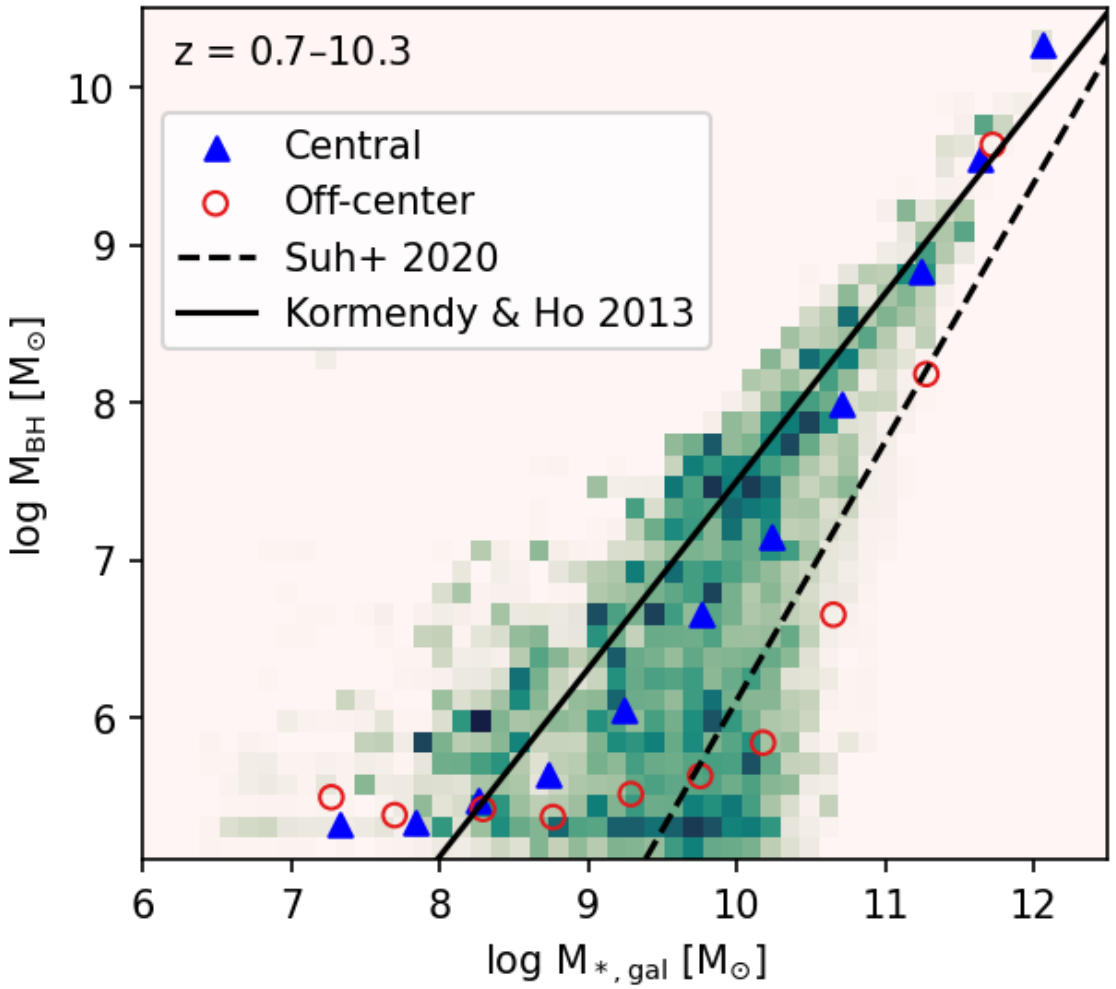
- **Formation**
  - Stellar density (> 2500 H/cc) + velocity dispersion (> 50 km/s)
  - Gas density (> 100 H/cc)
  - Seed mass: $10^5\,M_{sol}$
- **Feedback** – Thermal / Kinetic dual mode feedback depending on Eddington ratio
  - Quasar mode feedback efficiency set to 0.05 (1/3 of NewHorizon)
- **Dynamical friction**
  - From gas (Ostriker 99, Dubois+ 13), without boost
  - DM and stars (Pfisher+ 19), with boost scales with (d/d_{thr}) with density above threshold d_{thr} = 5 H/cc



Examples of Off-center BHs evolution

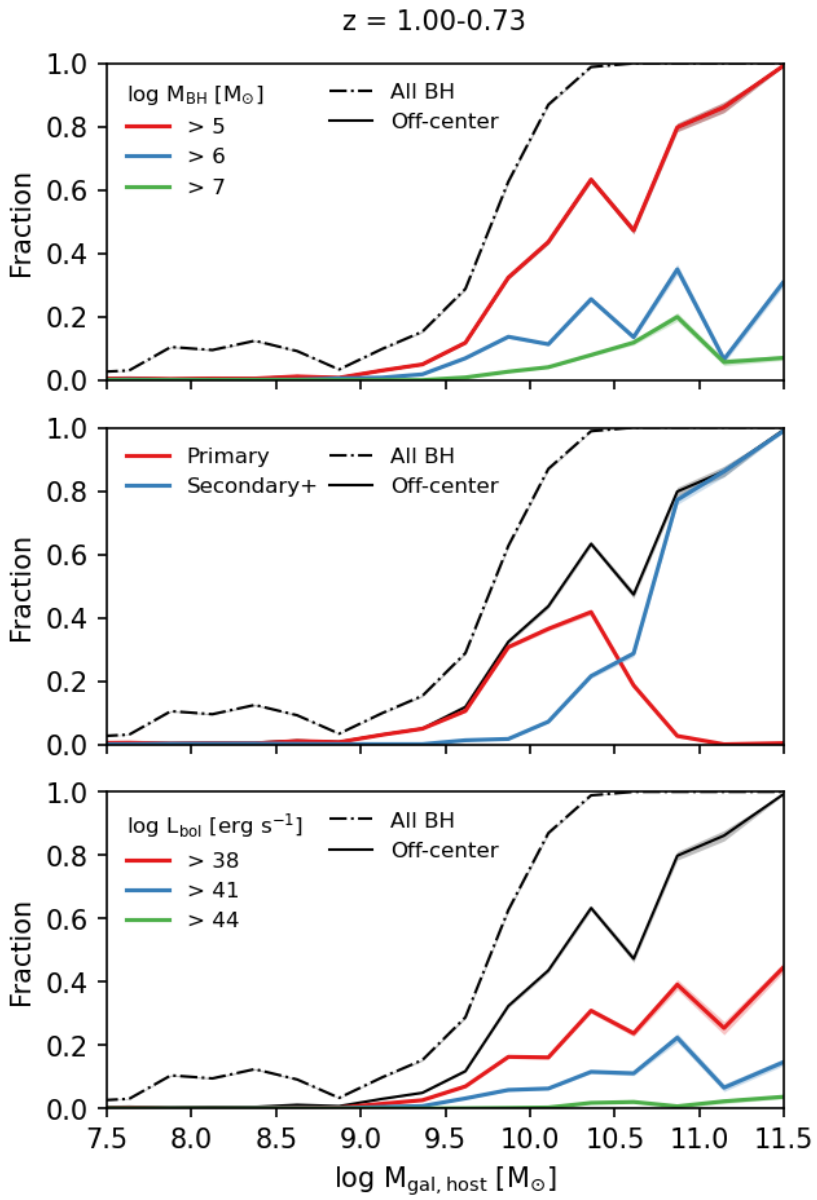


Galaxy-BH matching and off-center detection



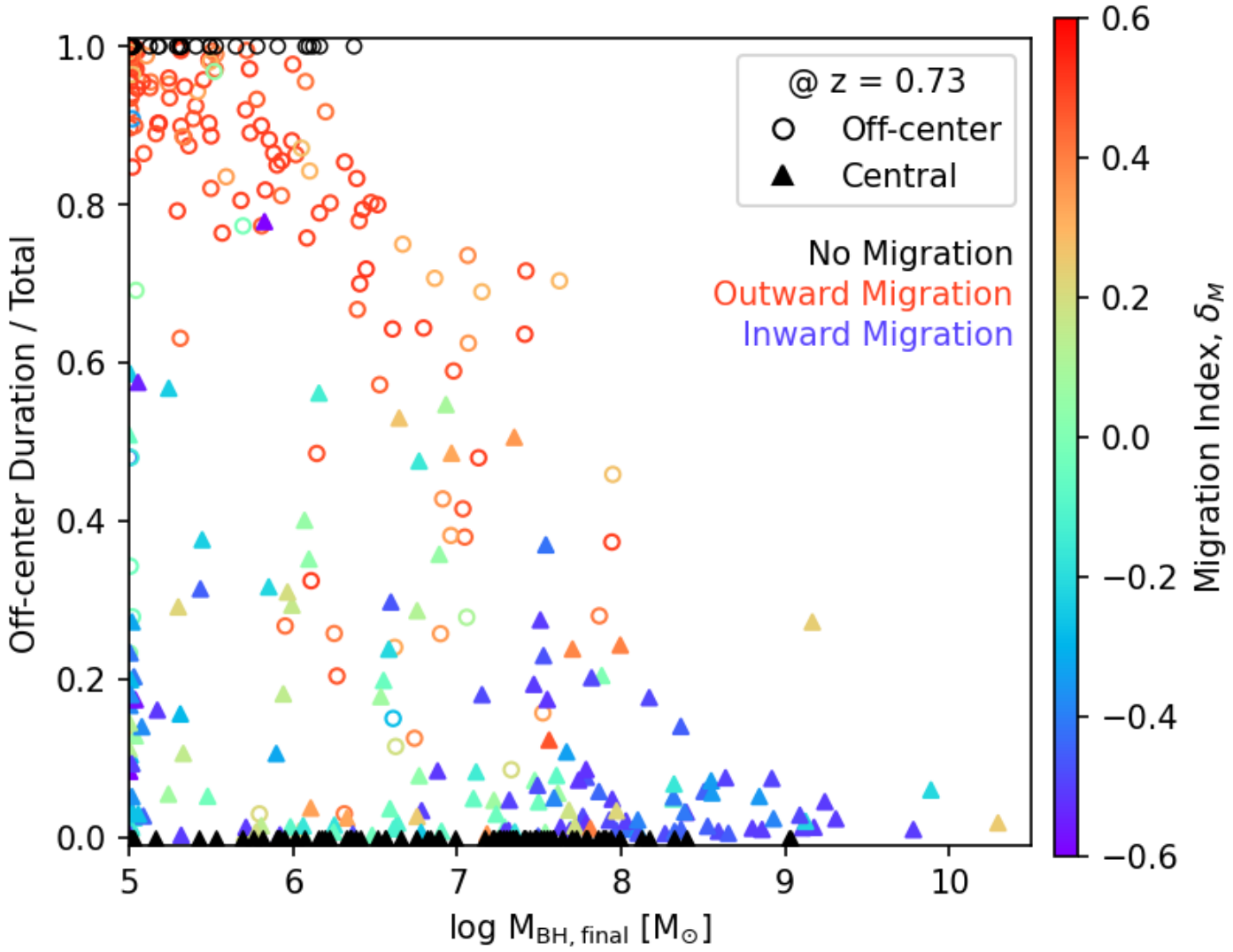
- **Sample:** 429 snapshots from z = 0.73 to z = 10, ~100,000 galaxy snapshots with range of log M_* ⊂ [6-12]
- **Galaxy:** Position-based halo detection with AdaptaHOP, using most massive Substructure Method (MSM).
- **Matching:** Up to 10kpc distance for galaxy-BH matching.
- BHs with spatial offset > 0.1kpc are marked as off-center.

Off-center statistics



- Increasing general probability of having off-center black holes at more massive galaxies.
- Galaxies with off-center primary black holes are most common at intermediate-mass galaxies (~$10^{10\text{-}10.5}$ M_{sol}), reaching up to maximum fraction of ~40% at z~<1.
- Off-center black holes with higher bolometric luminosity remains at lower fraction.

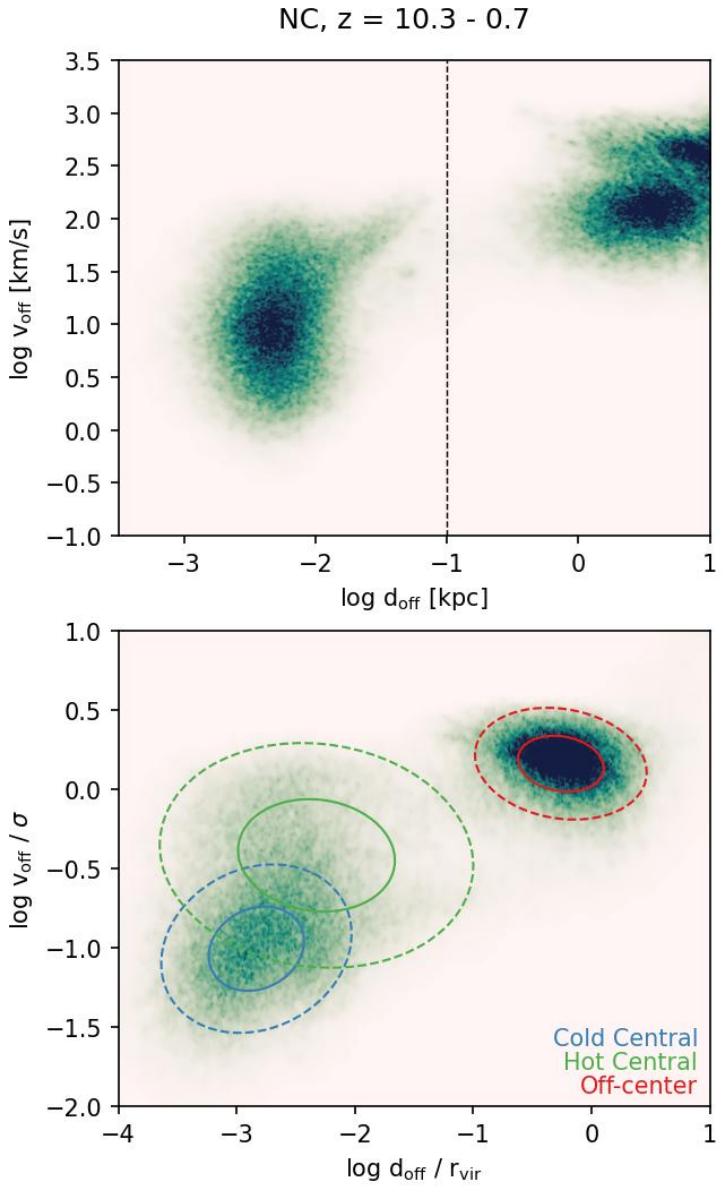
Evolution of off-center black holes



$$\delta_M = \frac{\langle t_{\rm off} \rangle - \langle t_{\rm cen} \rangle}{T_{\rm total}}$$

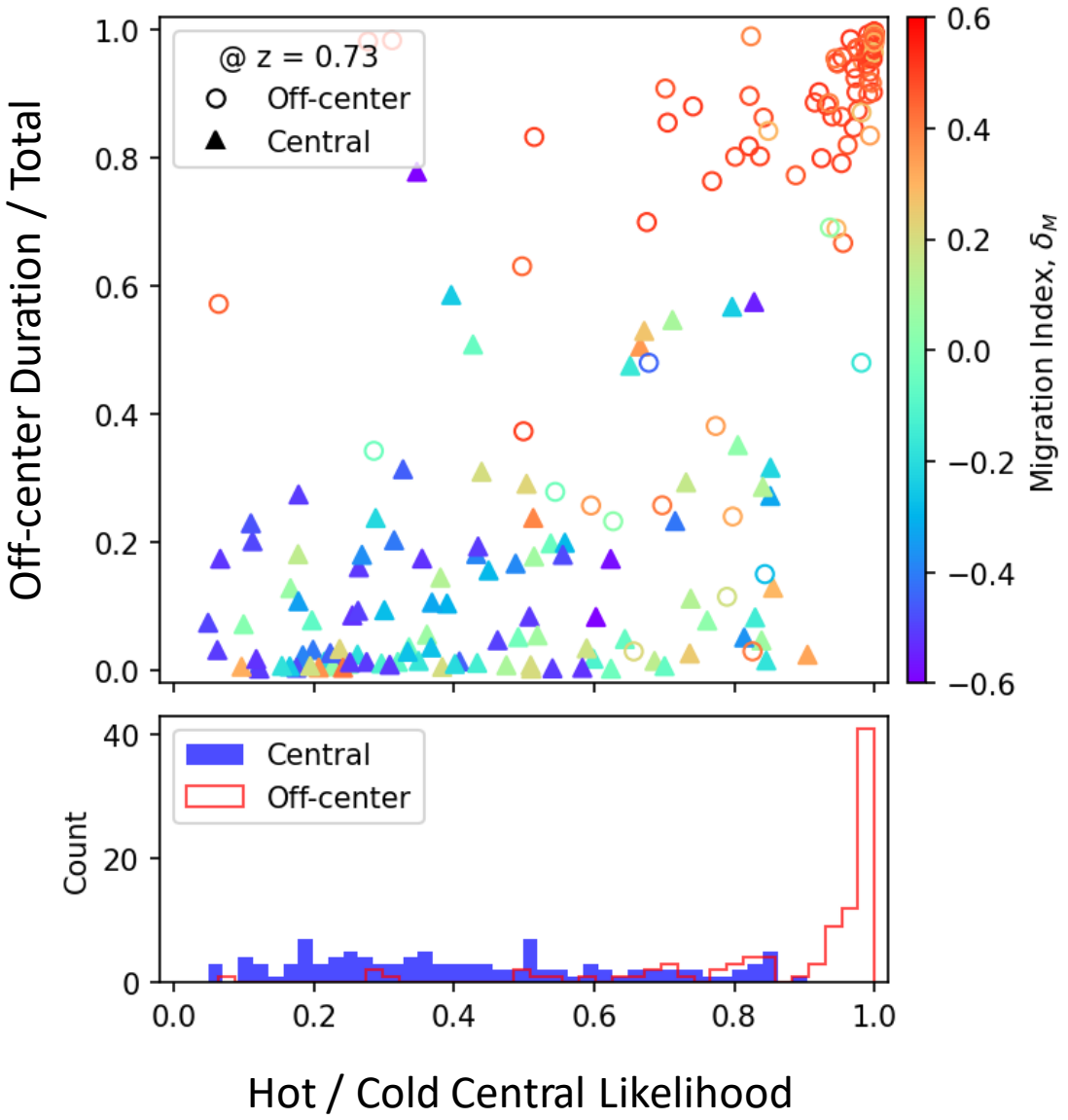
- Massive BH experienced central phase for growing
- Long-lasting off-center black holes (red circles) tend to be formed through outward migration.
- Some central black holes experience early off-center phase (blue triangles) before inward migration.

Two classes of central phase



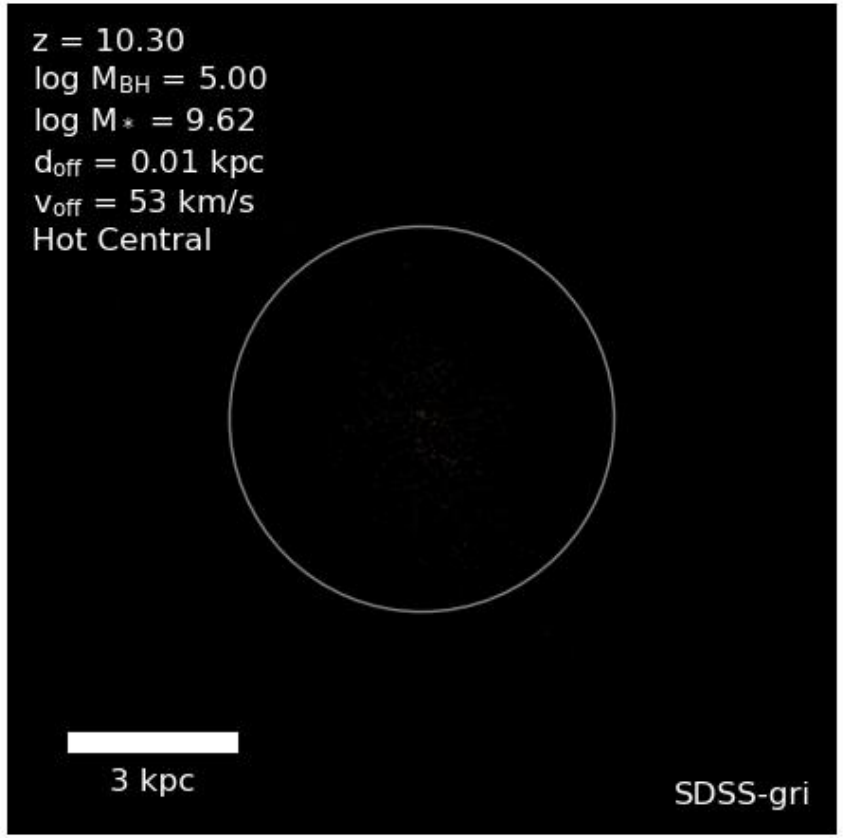
- Clear deviation between central and off-center population
- Central BH population seems to be divided into to 2 different subclasses (centrals that are dynamically “cold” and “hot”)
- Gaussian Mixture Model (+ IsolationForest) is used to compute likelihood of cold and hot central species.

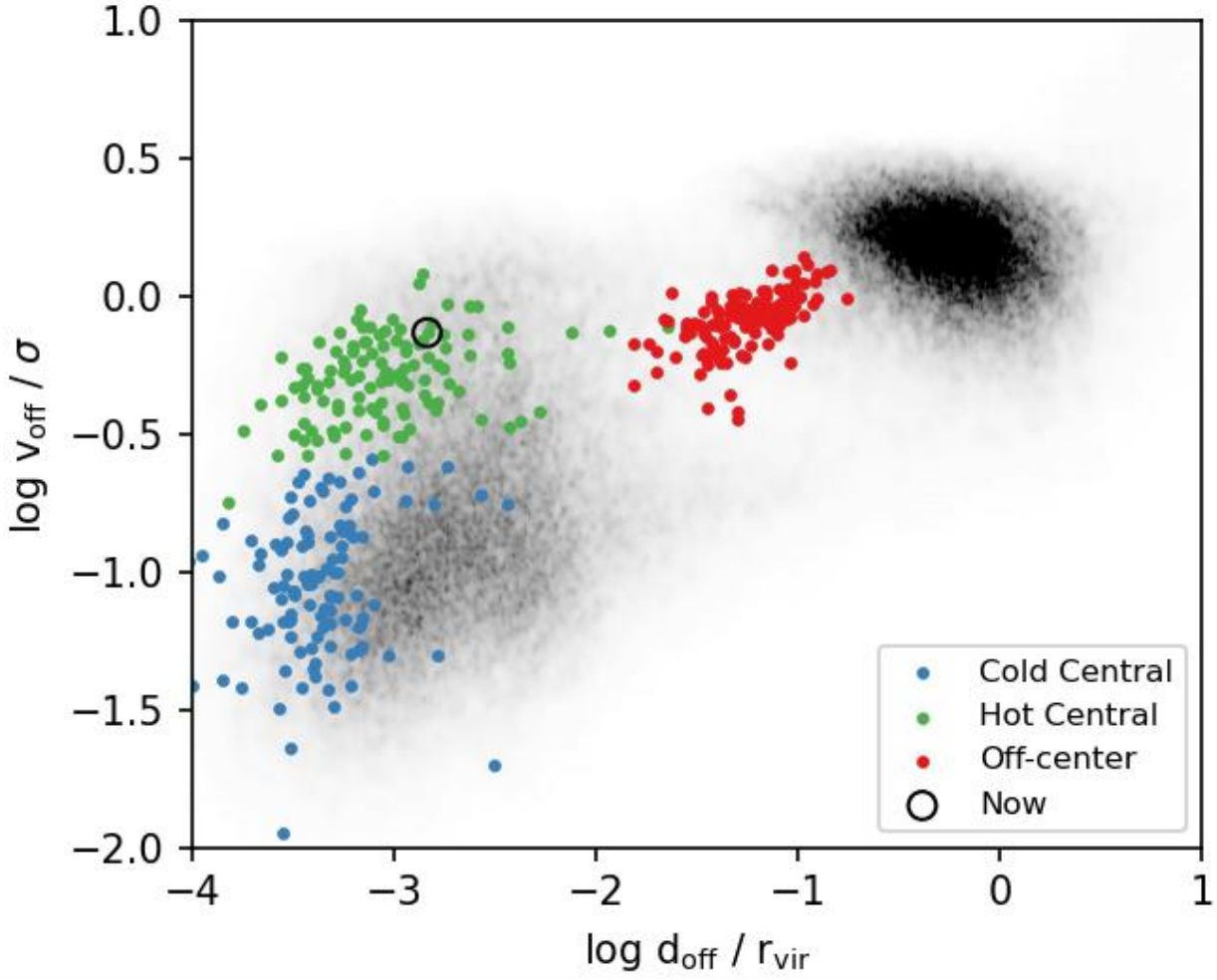
Hot centrals: transitional phase of off-center BHs



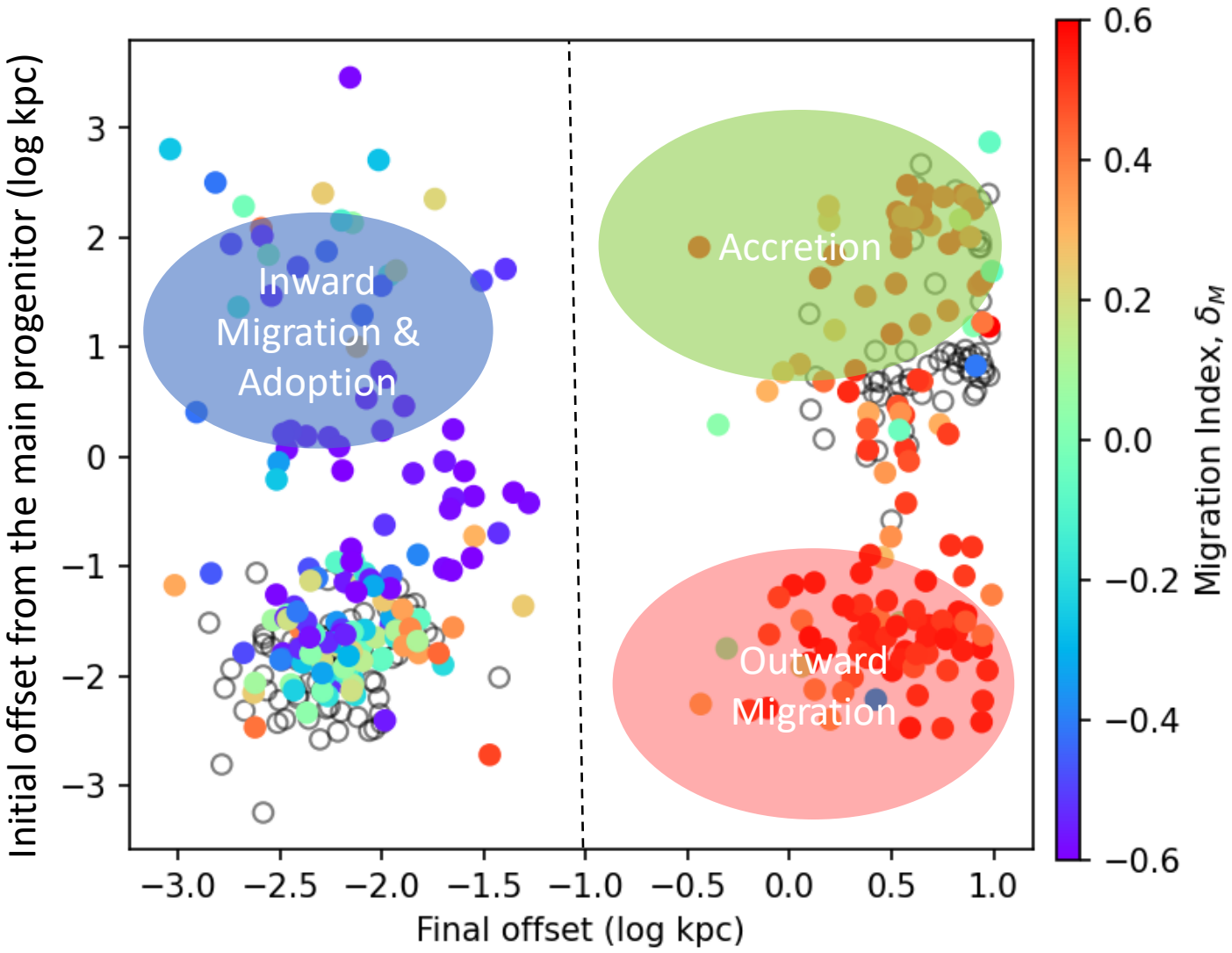
- Off-center BHs mostly experience hot central phase before migrating outward
- Hot centrals represent transitional population with unstable dynamics that would likely to evolve into off-center.

Visualizing Transition to Off-center



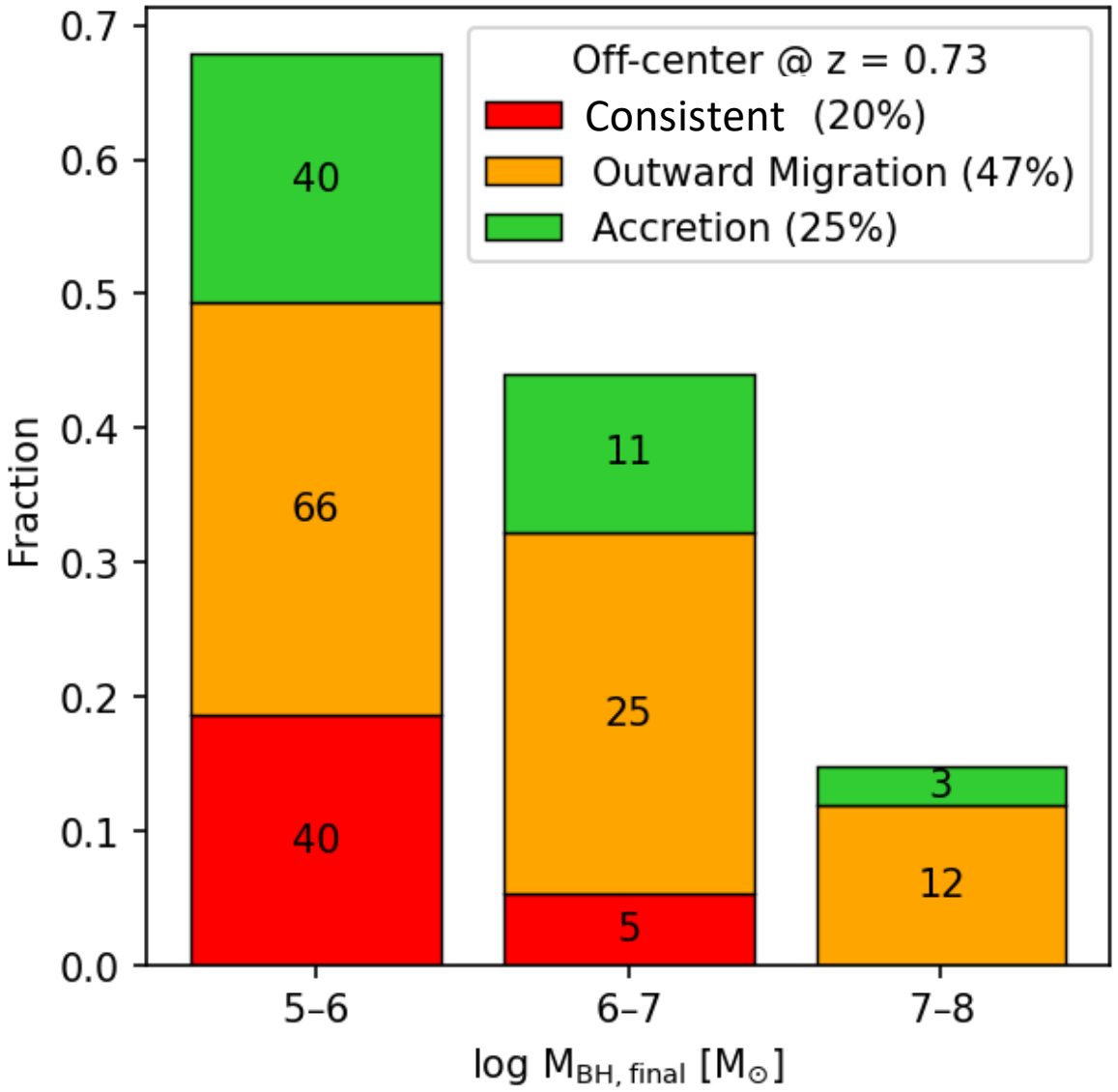


Accretion & Adoption



- There seem to be two distinct origins of off-center population: outward migration and accretion.
- Some central BHs seem to originate from Inward migration and mergers (“adaptation”).

Final statistics of off-center BH origin



- Origins with outward migration account for ~half of the population and become increasingly dominant at higher masses.
- Each of accreted and “consistent” off-centers fills the quarter of the populations.

Summary & Discussion

- NewCluster simulation includes significant population of off-center black holes that can be distinctively identified in the offset distribution.
- Galaxies with primary off-center black holes are most abundant at intermediate masses ($M_* \sim 10^{10\text{-}10.5}\ M_{sol}$).
- There is a secondary population of central BHs with higher velocity offset (Hot centrals), that are likely to be the transitional phase of the BH evolving in to off-center.
- Some fraction off-center BHs were consistently off-center or originated from accretion.
- A new channel for off-center black hole production is outward migration of the central BH, which is the dominant source of massive off-center black holes.
  - Further questions: what triggers migration? is it related to merger, or secular evolution?
  - Is off-center migration related to the properties of galaxies? (e.g., central potential, density configuration)