The Impact of AGN Feedback on Galaxy Formation in Gas-Rich Mergers at z~1-2

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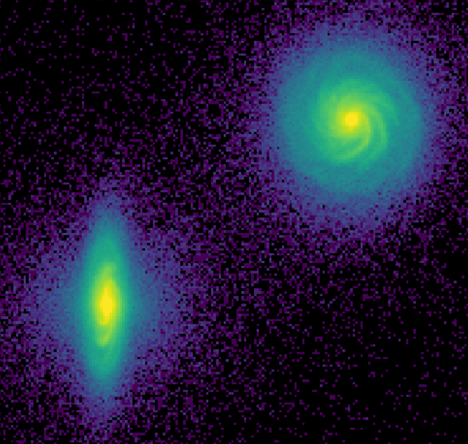
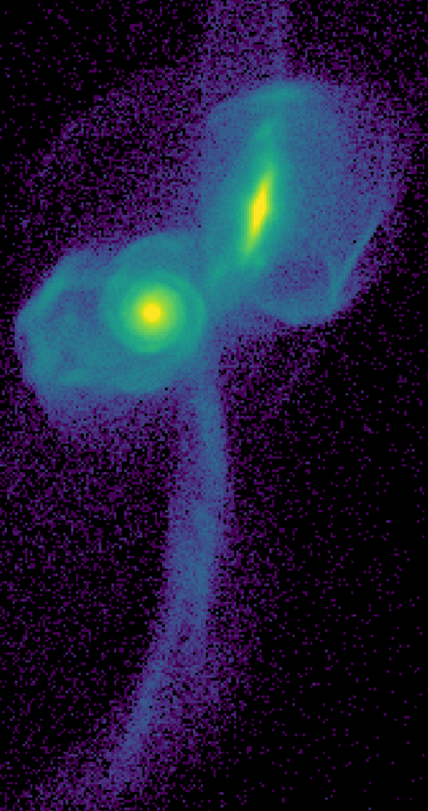


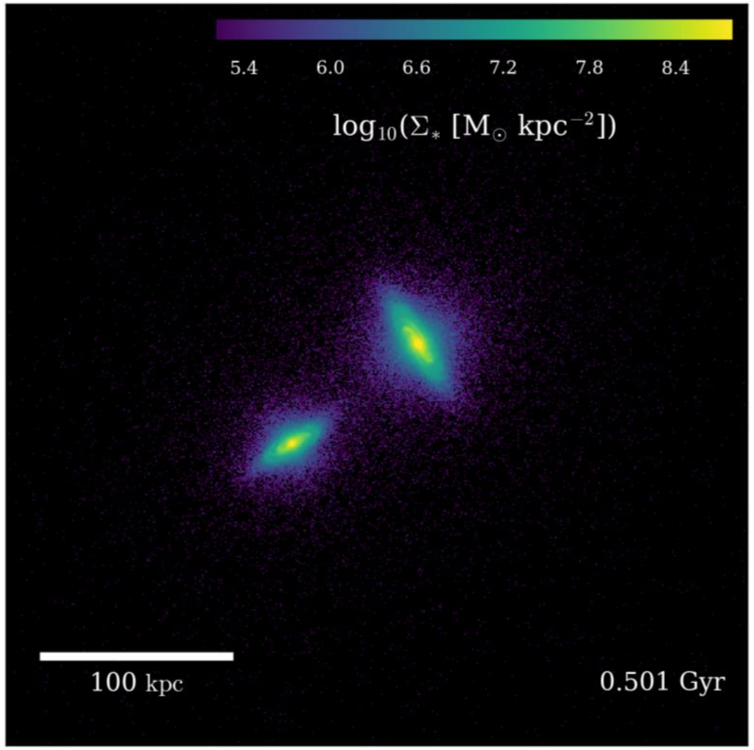


Acronyms: Keep These in Mind...

- BH = Black Hole
  - SMBH = Supermassive Black Hole
- AGN = Active Galactic Nucleus
- SFR = Star Formation Rate
- FB = Feedback

Outline

- Motivation
- Background Theory
- Simulation Codes
- Model Galaxies
- Simulation Results
- Summary



Merger simulation in process

Motivation: Why Bother?

- SMBHs in the cores of most massive galaxies
- Coevolution with host galaxy
  - Mass, velocity dispersion...
- AGNs common in the early Universe
- Galaxies merge frequently
- Peak star formation at z=1-2
  - Age of the Universe ~3.2-5.7 Gyr
  - ~50% of current stellar mass density

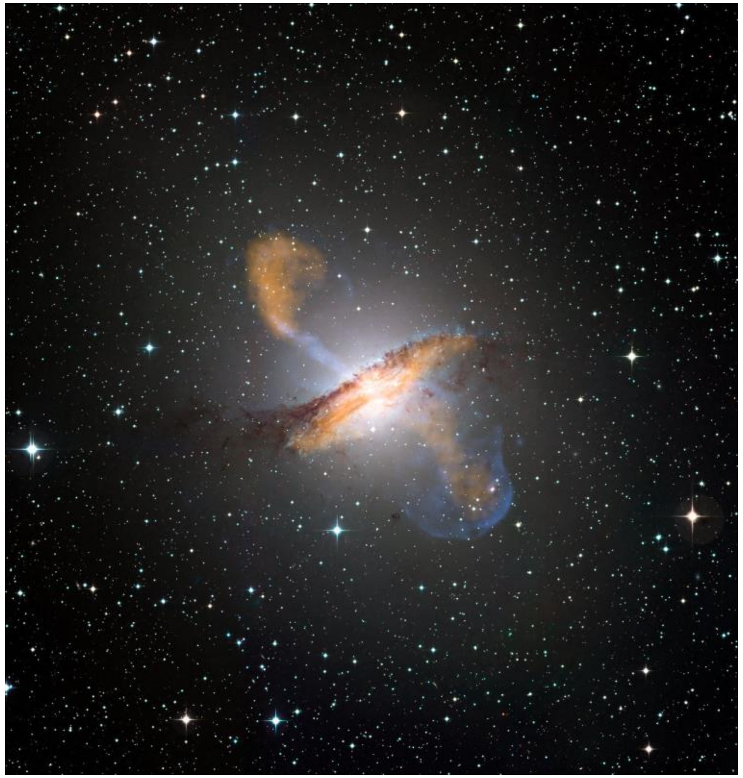
Actual galaxy merger: Antennae Galaxies
(Robert Gendler)

Background Theory

BHs, AGNs, Mergers

AGN and AGN Feedback

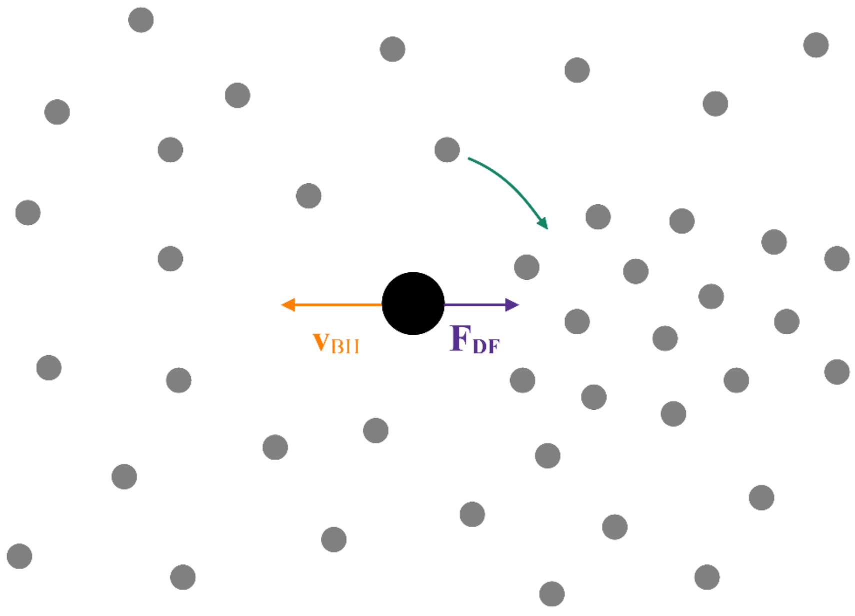
- Highly luminous regions around SMBHs
- SMBH accretes mass from surrounding accretion disk
- AGN Feedback: energy released in accretion heats and disperses gas
    - Critical limit (Eddington limit)



AGN in Centaurus A
(ESO/WFI; MPIfR/ESO/APEX/A.Weiss et al.; NASA/CXC/CfA/R.Kraft et al.)

BH Mergers

- Three phases
  - kpc scale: **dynamical friction**
    - BHs create a ‘wake’ of stars and experience drag
  - pc scale: **3-body scattering**
    - BHs eject stars from the loss cone
  - mpc scale: **gravitational wave emission**
    - Energy loss via GWs
    - Power scales as eccentricity$^{7/2}$



Incredible illustration of dynamical friction

Simulation Codes

N-Body Simulations, GADGET and KETJU

GADGET: Basics

- N-body code with added gas dynamics
- Particles types: stellar, gas, dark matter, BH
  - Gas and stellar particles: 10^5 solar masses
- Limited particle number
  - **Stellar particles, not stars!**
  - Softening
- Stellar feedback
  - Supernovae, stellar wind
- Star formation, gas cooling…

$$\Phi = -\frac{GM}{\sqrt{r^2 + \epsilon^2}}$$

Simplest softening: Plummer potential

$$\Phi(\mathbf{r}) = G\frac{m}{h}W_2\left(\frac{r}{h}\right)$$

Spline kernel softening in GADGET

GADGET: Black Holes

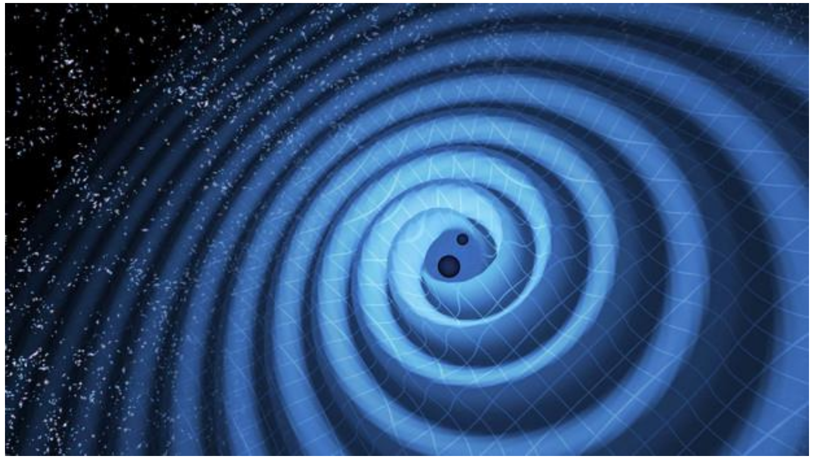
- Close BH-BH and BH-stellar interactions softened
- BH accretion: rate scales as **mass^2**
- AGN feedback
  - Proportional to accretion rate
  - **Thermal**
    - Increase thermal energies of nearby gas particles
    - **Stable, continuous**
  - **Kinetic**
    - Kick nearby gas particles
    - Store energy in reservoir, release once full
    - **Violent, stochastic**

KETJU: Basics

- Extension to GADGET
- Higher-accuracy, **non-softened** dynamics around BHs
  - KETJU region: r=3ϵ=15 pc
- Resolve BH binary phase
  - $E_{kin} + E_{grav} < 0$
  - Down to subparsec scales (GW emission)
  - Post-Newtonian dynamics
  - Merger at separation r_{min}

$$r_{\mathrm{min}} = 6\left(r_{\mathrm{s},i} + r_{\mathrm{s},j}\right) = 6\left(\frac{2GM_{\mathrm{BH},i}}{c^2} + \frac{2GM_{\mathrm{BH},j}}{c^2}\right)$$

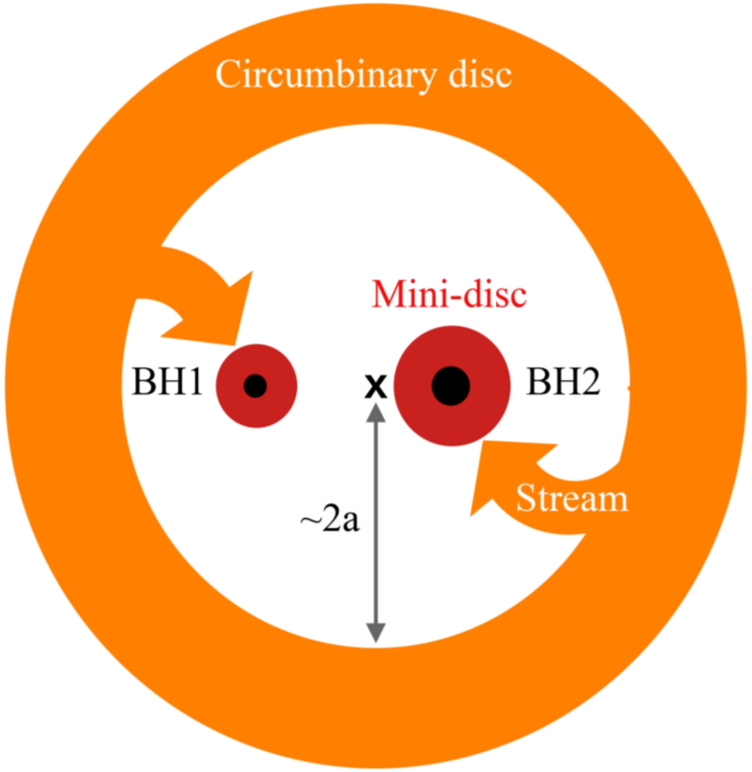
  - ~10^{-5} pc for $M_{BH}=10^7$ solar masses



Your average illustration of gravitational waves
(LIGO / T. Pyle)

KETJU: Black Hole Binary Phase

- Circumbinary disc around both BHs
  - Centered on their center-of-mass
- Gas flows into mini-discs around BHs
- BH binary accretion model
  - Total accretion rate as before
  - Split total rate for primary and secondary BH
    - As a function of mass-ratio
  - Preferential accretion onto the secondary BH
    - Orbits closer to outer disc
    - Mass-ratio evolves towards 1



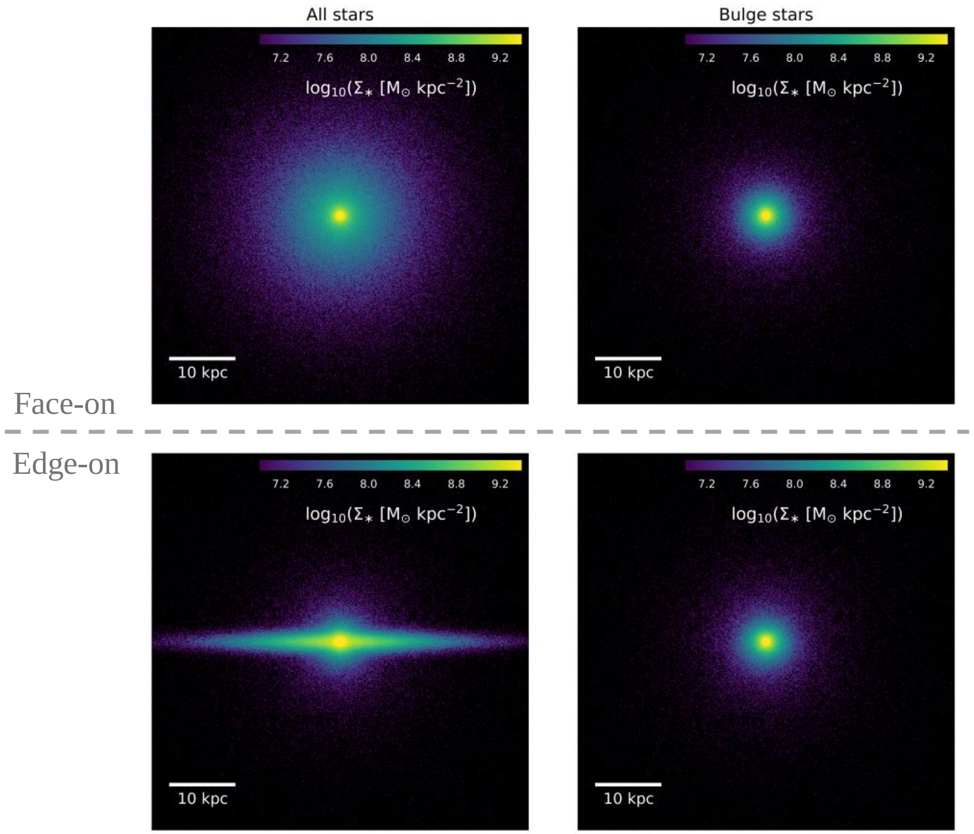
KETJU binary accretion model, x marks the center-of-mass (recreated from Liao et al. 2023)

Model Galaxies

Recipe for Realistic High-Redshift Galaxies

Individual Galaxies: Basics

- Massive, gas-rich spiral galaxies
  - R_{vir}~200 kpc
- z=1 and z=2
  - High gas fractions, low metallicity
  - Rapid star formation
- Components
  - Gaseous and stellar disks
  - Stellar bulge
  - Dark matter halo
  - Central SMBH



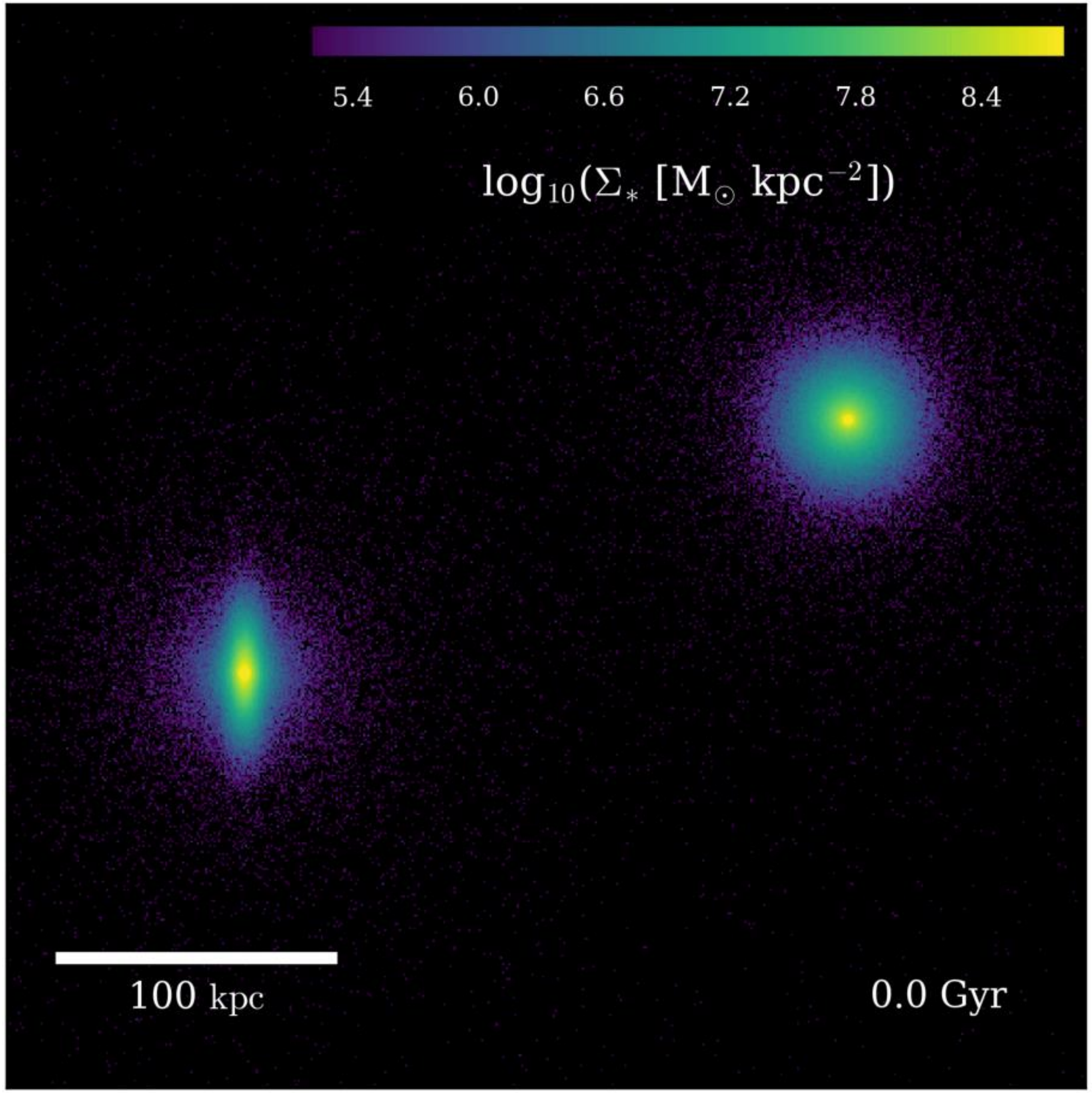
Full galaxy (left panels) and stellar bulge component separated (right panels)

Individual Galaxies: Parameters

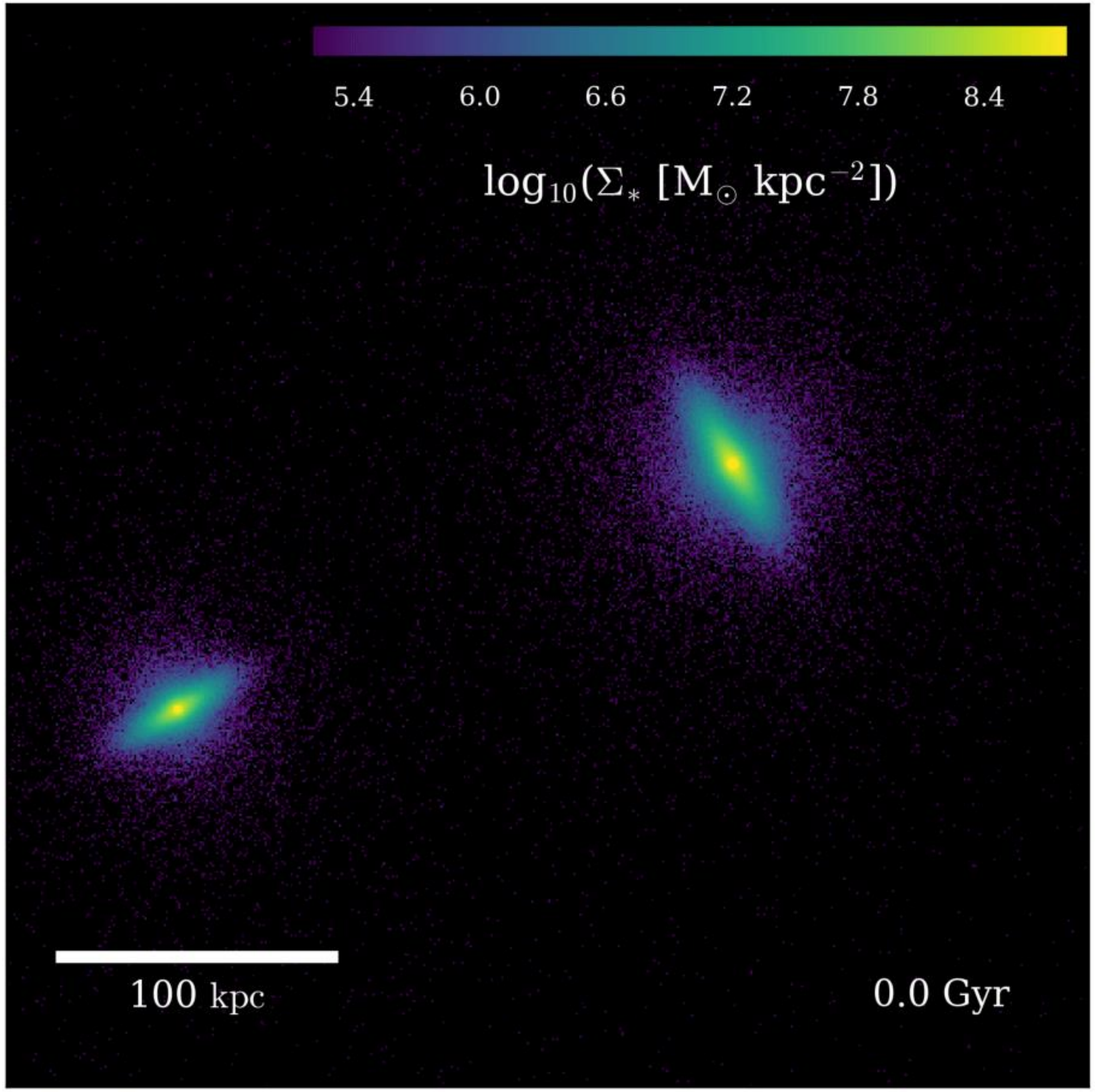
- Key parameters
  - Total mass (~10^{12} solar masses)
  - Disk and bulge mass fractions
  - Gas fraction
    - 40% for z=1, 60% for z=2
  - BH mass (~10^{7} solar masses)
  - Metallicity abundances...

All this work, for what?

GADGET with thermal AGN feedback, mass-ratio 1:1, redshift z=1, orbit G4



KETJU with thermal AGN feedback, mass-ratio 2:1, redshift z=2, orbit G15

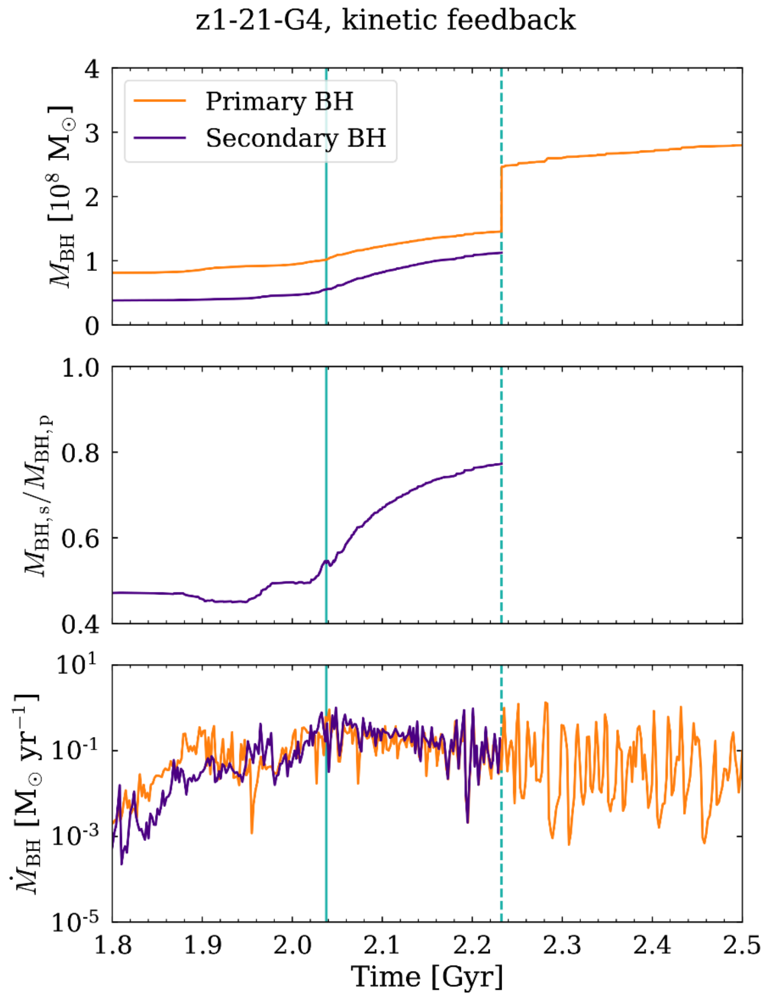


Simulation Results

Selected Highlights and Comparison with Observations

KETJU: BH Growth

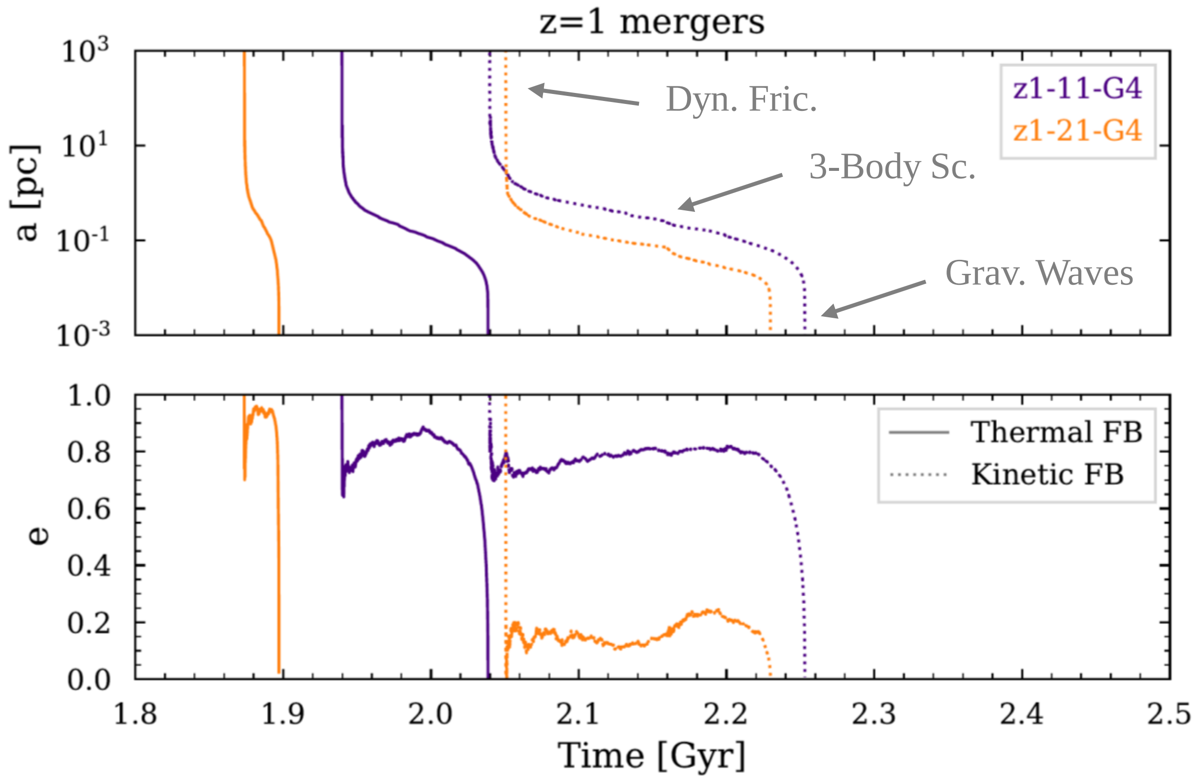
- Simulations as ‘redshift-mass-ratio-orbit’
  - Redshift z=1, mass-ratio 2:1, orbit G4 as z1-21-G4
- Binary phase accretion
  - BH mass-ratio evolves toward 1 throughout binary phase
  - Secondary BH has a higher accretion rate
- High variability due to kinetic feedback



BH masses, BH mass-ratio and accretion rates in z1-21-G4

KETJU: BH Binary Orbital Evolution

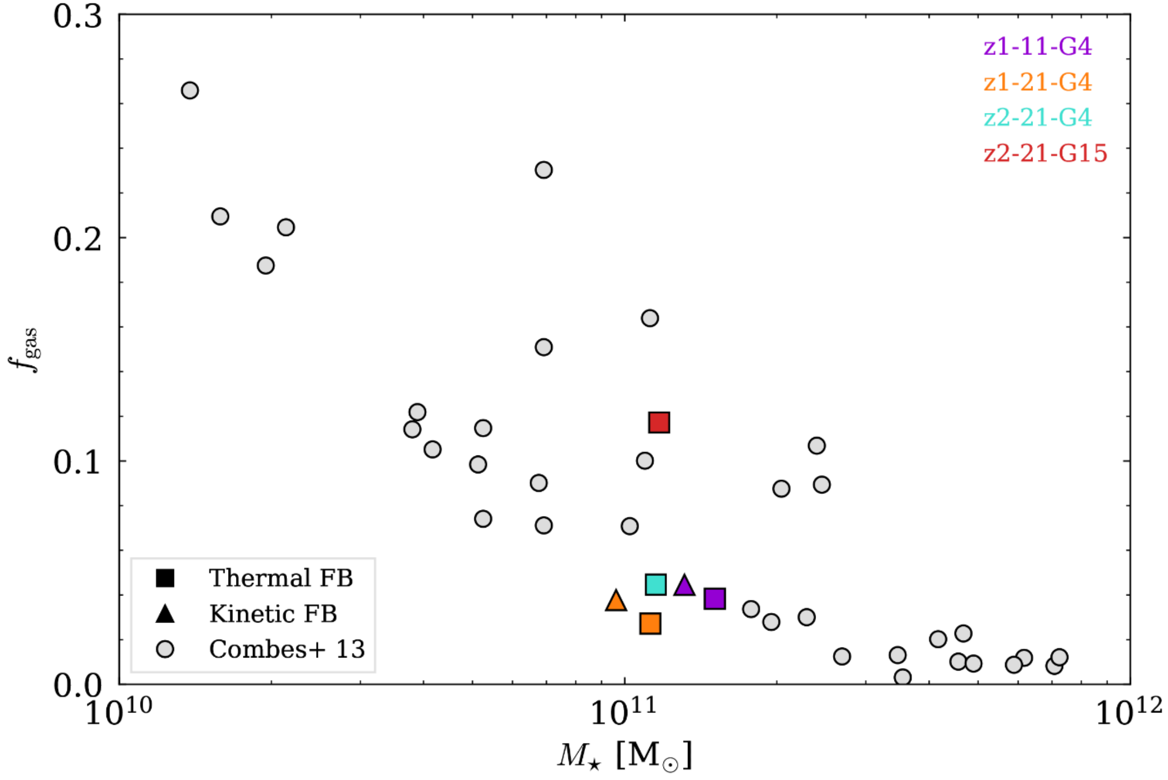
- Semimajor axis a and eccentricity e
- Thermal merges faster than kinetic
  - Kinetic FB removes more gas
- Higher eccentricity = faster merger
  - 3rd merger phase: $e^{7/2}$
  - Exception: z1-21-G4 with kinetic FB
    - Conclusion: 3-body scattering phase (parsec scales) is dominant!



Orbital evolution for the z=1 KETJU BHs: semimajor axis a and eccentricity e

KETJU: Gas Fraction vs. Stellar Mass

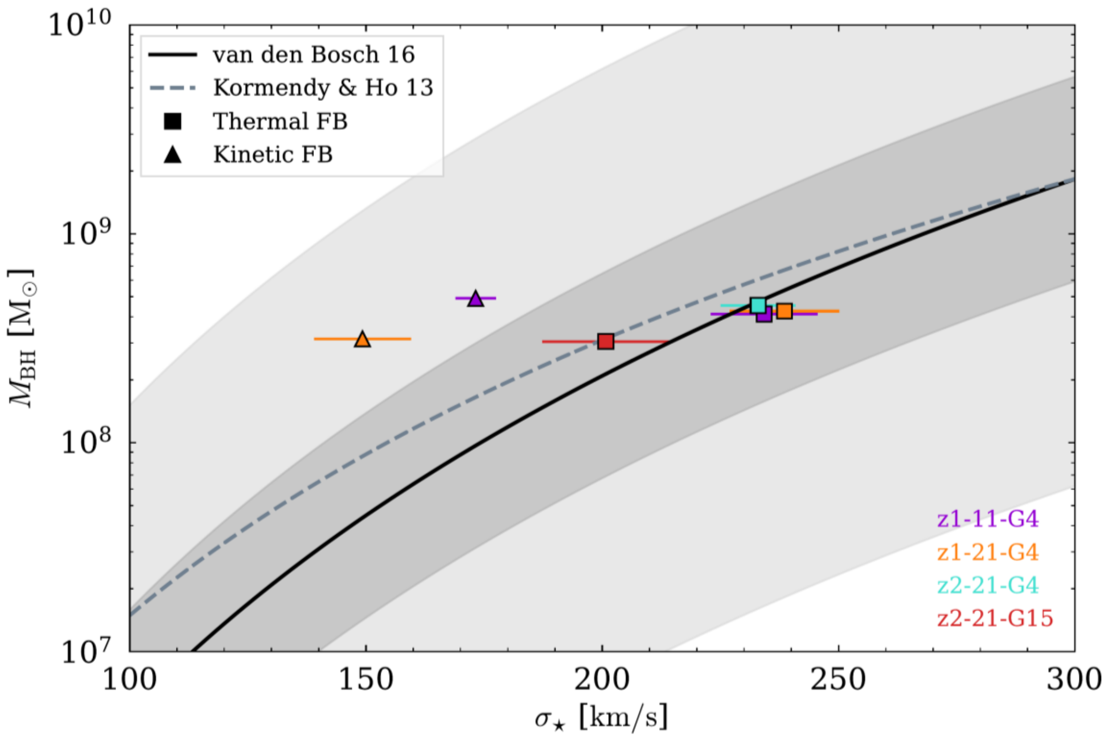
- Gas fraction as a function of stellar mass in the final merger remnants
- Compare with observed ultraluminous infrared galaxies (ULIRGs)
  - Often high SFR in ULIRGs
  - AGNs common in ULIRGs
- Good agreement!



Final gas fraction as a function of stellar mass for the KETJU simulations, gray circles indicate observed ULIRGs

KETJU: BH Mass vs. Velocity Dispersion

- Final BH mass as a function of stellar velocity dispersion
  - Dispersion for 100 random lines-of-sight
- Agreement with observed relations
- Kinetic FB leads to smaller dispersions
  - More gas removed: less stellar particles in the center
  - Thermal FB matches relations better



Final BH mass as a function of central stellar velocity dispersion: KETJU simulations as points, observed relations as curves

Summary

- Galaxy mergers are common in the Universe and important for galaxy evolution
- SMBHs merge in roughly three phases
- AGNs heat and disperse gas via AGN feedback
- High-redshift galaxies are gas-rich and form stars rapidly
- Both thermal and kinetic AGN feedback produce realistic galaxies

Thank you!

Questions?