

Overmassive black holes and little red dots naturally form in simulations

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1.Introduction

- SMBHs exist at <1byr after big-bang
- LRDs at z>4-6 discovered by JWST
 - M_BH exceeds local scaling relation
 - Possible rapidly growing BH in dense, obscured environment during early galaxy assembly
- Several proposed pathways : direct-collapse, PopIII stars => however, not have been reproduced in cosmological simulations
- This cosmological simulation demonstrates:
 - Heavy (1e6Msun) BH seed, by collapse of SM stars, naturally forms in overdense regions exposed to FUV
 - They have LRD-ilke features
 - Rapidly grow into overmassive BH by z~8=> The simulation may offer the abundance and properties of LRDs

2.Rapid Emergence of Overmassive BHs

- Fig 1 : Results of the simulation
 - Gas halo in proto-cluster region illuminated by intense FUV
 - The halo accumulates large gas mass and collapses at z~14
 - Protostars grow rapidly to 5-9e5 Msun
 - Direct collapse to BH of ~1e6Msun (black * in Fig 1a,b)
 - Gravitational potential is unusually deep, results in large amount of surrounding ionized gas, and super-Eddington accretion follows (Fig 1f)
 - Dense and optically thick gas envelope develops
 - Grow to >1e7Msun by z~10
 - Accretion rate drops at z~10, due to gas stripping by encounter with massive neighboring halo
 - Z~8 : BHs settle at the galaxy center, M_BH/M*~0.01, still 10 times larger than local
 - Number density : 1e-4/Mpc^3 <= consistent with that of LRDs observed

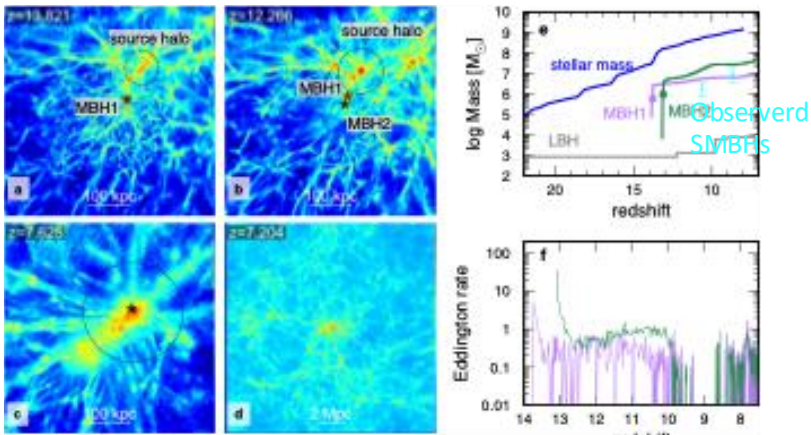


Fig. 1 Formation and evolution of massive seed BHs in the cosmological radiation-hydrodynamic

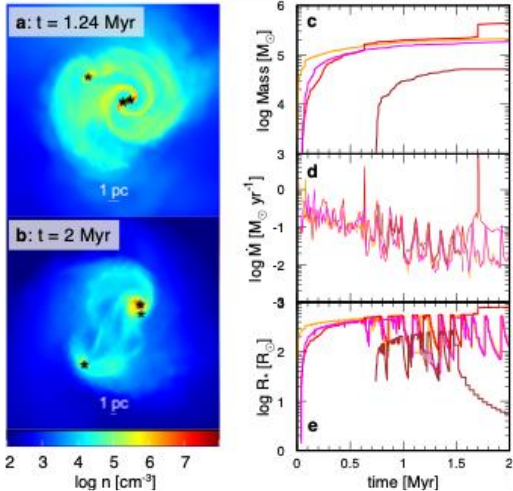


Fig. 3 Formation and evolution of protostars that grow into supermassive stars, which subsequently

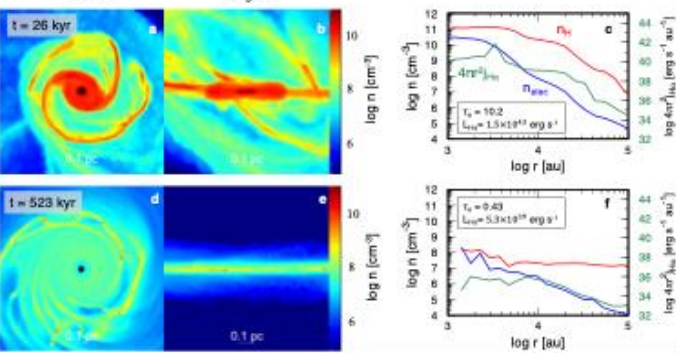


Fig. 4 Formation and evolution of the dense gas disk around MBH2. (a,d) Face-on views of the

What about light-seed BHs (z_form=22, ~800Msun, Pop III remnants) ?
=> Highly inefficient growth (Fig 1e)
• Initial gas supply suppressed by radiative feedback of PopIIIs
• Gas in the host halo quickly photo-evaporates during the seed formation, as gravitational potential is shallow
=> Heavey-seed formation is necessary for formation of SMBH@z>7

3. Proto-supermassive Stellar System

Fig 3: Additional higher-resolution zoom-up simulation of MBH1, to resolve the collapsing event of massive halo
- Hierarchical fragmentation into multiple protostars
- Most massive protostar 4e5Msun after 2Myrs, by accretion of 0.1-1Msun/yr
- Start is at inflated supergiant phase => weak radiative feedback
- Then collapse into BHs, and gas is still tightly bounded around the stars

4. Spectral Signatures of circum-BH disks

- Circum-BH disks naturally reproduce V-shaped continua and Balmer absorptions of LRDs
- Gas density >1e8/cm^3 => enhance n=2 population of H
- High Thomson optical depth => broad Ha emission >1000km/s => no deed for BRLs

Fig 4 : Zoom-in simulation of MBH2

- L_Ha=1.5e43cgs (r<1e4au) : consistent with observations
- Obscured phase ends after few 1e5yrs
 - Dense exists but L_Ha~1e40cgs at 523Kyr
 - Compact BLRs is necessary for further Ha emission
 - Actually, inner region (<100au) may have luminosity of 1e44cgs, and 0.1-1% is expected to emerge in Ha

=> L_Ha=1e41-42 cgs
=> consistent with AGN, natural transition of LRD to AGN

5. Implication for early BH populations

- Heavy seed BH formation is a natural outcome
- BH can rapidly grow to 1e7Msun with direct collapse and S-Eddington accretion =. Resembles “quasistar/BHstar” solution
- Its formation and rapid growth was reproduced in the simulation
- Early universe hosted numerous short-lived rapidly growing MBHs
- Multiple heavy seed can form nearly in a massive halos => BH mergers can be observed with LISA