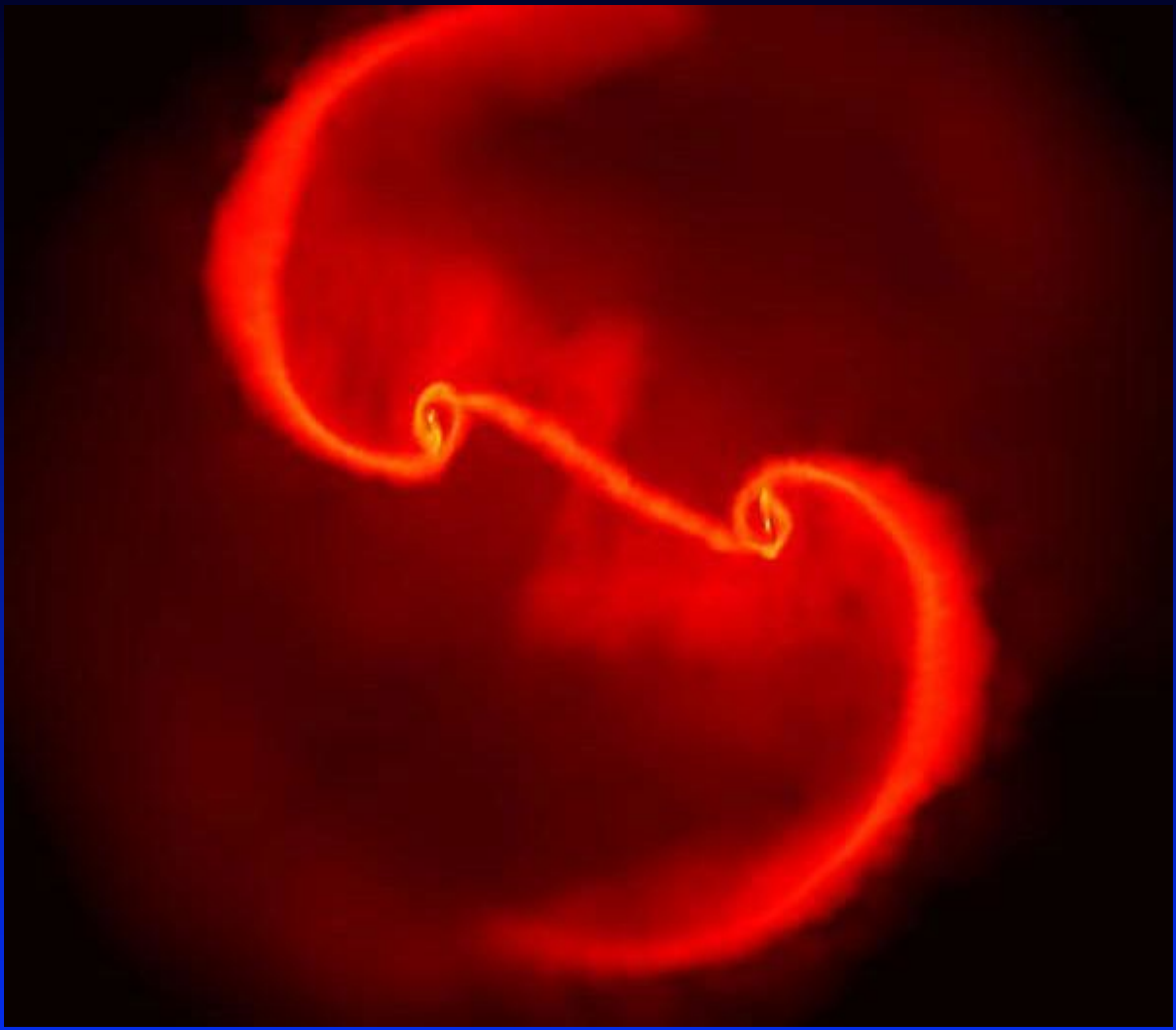

The Origin of Supermassive Black Holes

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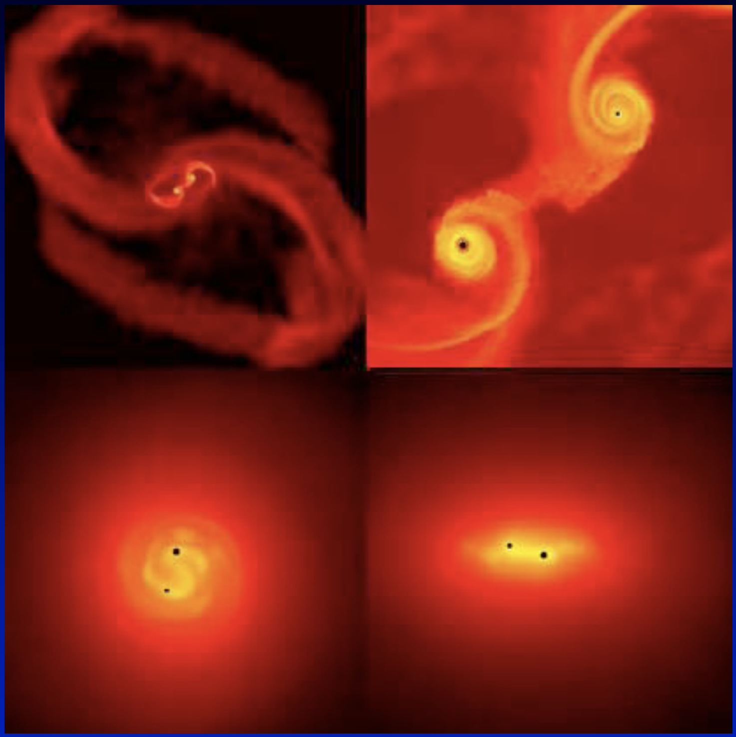
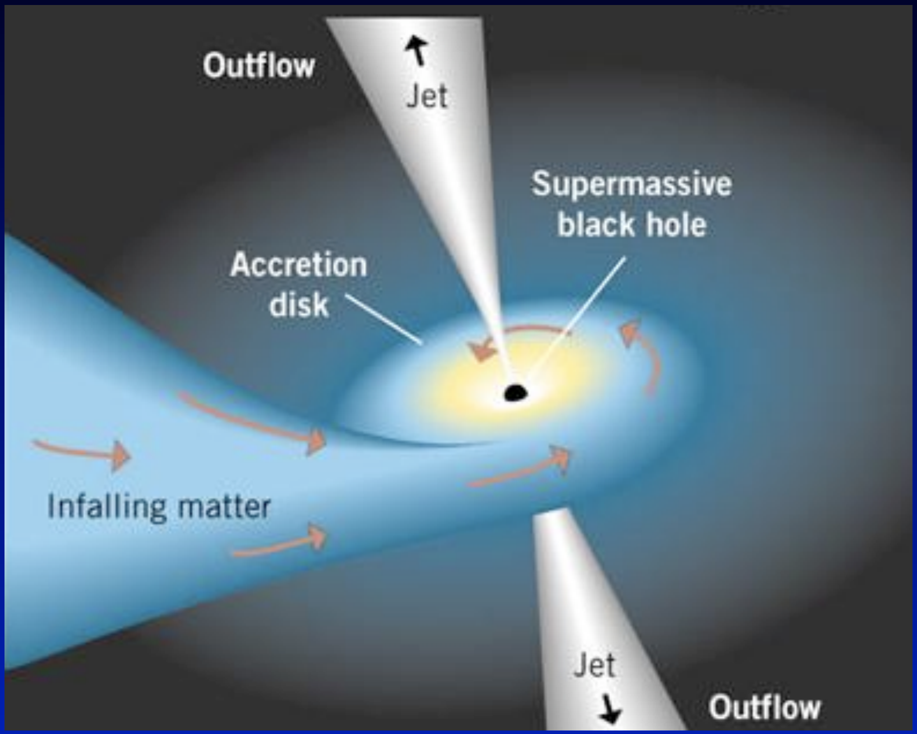


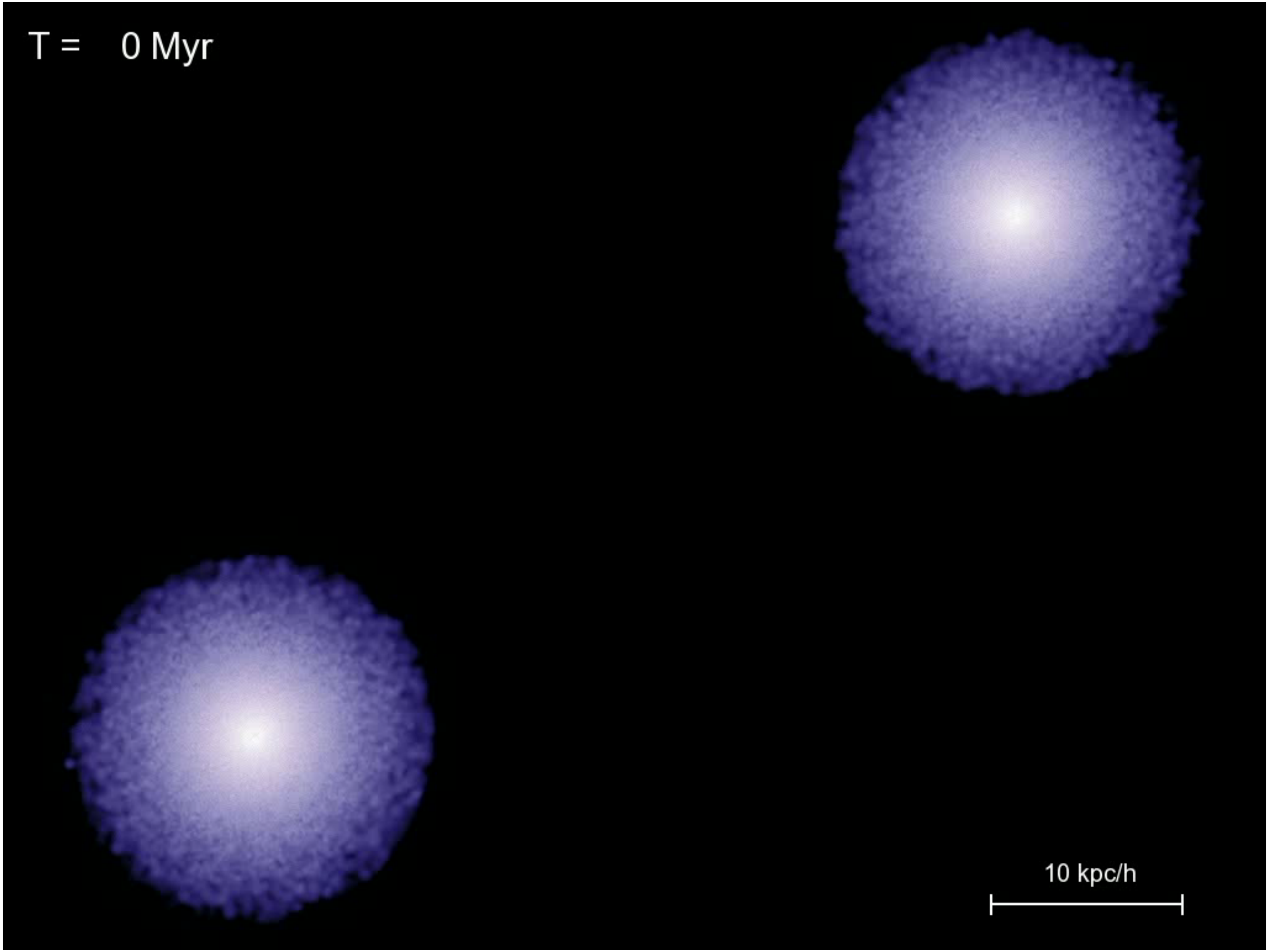
Mergers



Accretion

The SMBH Conundrum

- SDSS quasars of ~ 10^9 Msun have been found at z ~ 6, a Gyr after the Big Bang
- the exponential growth associated with Bondi-Hoyle accretion implies that 100 Msun SMBH seeds can reach 10^9 Msun by z ~ 6, but only if they accrete at the Eddington limit for a Hubble time
- IMBH mergers assemble larger black holes but usually kick the coalesced object from its host halo, and therefore its fuel supply
- radiative feedback during gas infall likely reduces accretion rates to well below the Eddington limit


T = 0 Myr
10 kpc/h

SMBH Seed Candidates

Pop III Star Remnants

Madau & Rees 2001
Volonteri, Haardt & Madau 2003

M_{BH} ~ 50 - 100 Msun or
260 - 500 Msun

e.g. Bromm et al 1999, 2001,
Abel et al 2000, 2002, O'Shea &
Norman 2007

Direct Halo Collapse

M_{BH} ~ 10^3 - 10^5 Msun

H/He line cooling in 10^8 Msun halos:

e.g. Bromm & Loeb 2003,
Lodato & Natarajan 2006,
Regan & Haehnelt 2009a,b
Shang, Bryan & Haiman 2009

"Quasi-stars"

Begelmann, Volonteri & Rees 2006

Stellar Dynamical Processes

Devecci & Volonteri 2009

Direct Halo Collapse Processes

- somehow, through both accretion and mergers a halo reaches 10^8 solar masses without first forming a star
- at this mass, the halo's virial temperature is ~ 10^4 K, sufficient to incite H and He line cooling
- this causes baryons in the halo to collapse into its center, forming a rotationally-supported disk of 10^4 - 10^5 solar masses to (thought to be a fat, extended structure)
- what happens next depends on how efficiently the disk can shed angular momentum and entropy

Collapse of the Disk Via the "Bars Within Bars" Instability

Lodato & Natarjan 2006

- if the disk has zero metallicity and no H_2, it can develop non-axisymmetric dynamical instabilities that efficiently transport angular momentum outward, rapidly feeding a central object

- this object could be a black hole, supermassive star, or a 'quasistar'

“Quasistars” and Supermassive Stars

Begelman, Volonteri & Rees 2006

- the “bars within bars” instability causes mass to rapidly inspiral towards the center of the disk--a supermassive star susceptible to the GR instability may form and directly collapse to a BH

- if the heat generated by central gravitational release is trapped spherically, the disk can puff up and result in spherical accretion

- the gas that pools at the center of this spherical inflow might form a supermassive star with an unusual structure:

  (1) extremely dense pressure-supported core (10 - 20 Msun)
  (2) diffuse radiation-supported outer envelope
  (3) when the central core heats to 5 x 10^8 K it radiates thermal neutrinos, cools catastrophically, and forms a BH
  (4) the BH accretes gas at the Eddington limit of the *mass of the outer envelope*, rapidly growing to 10^3 - 10^4 Msun

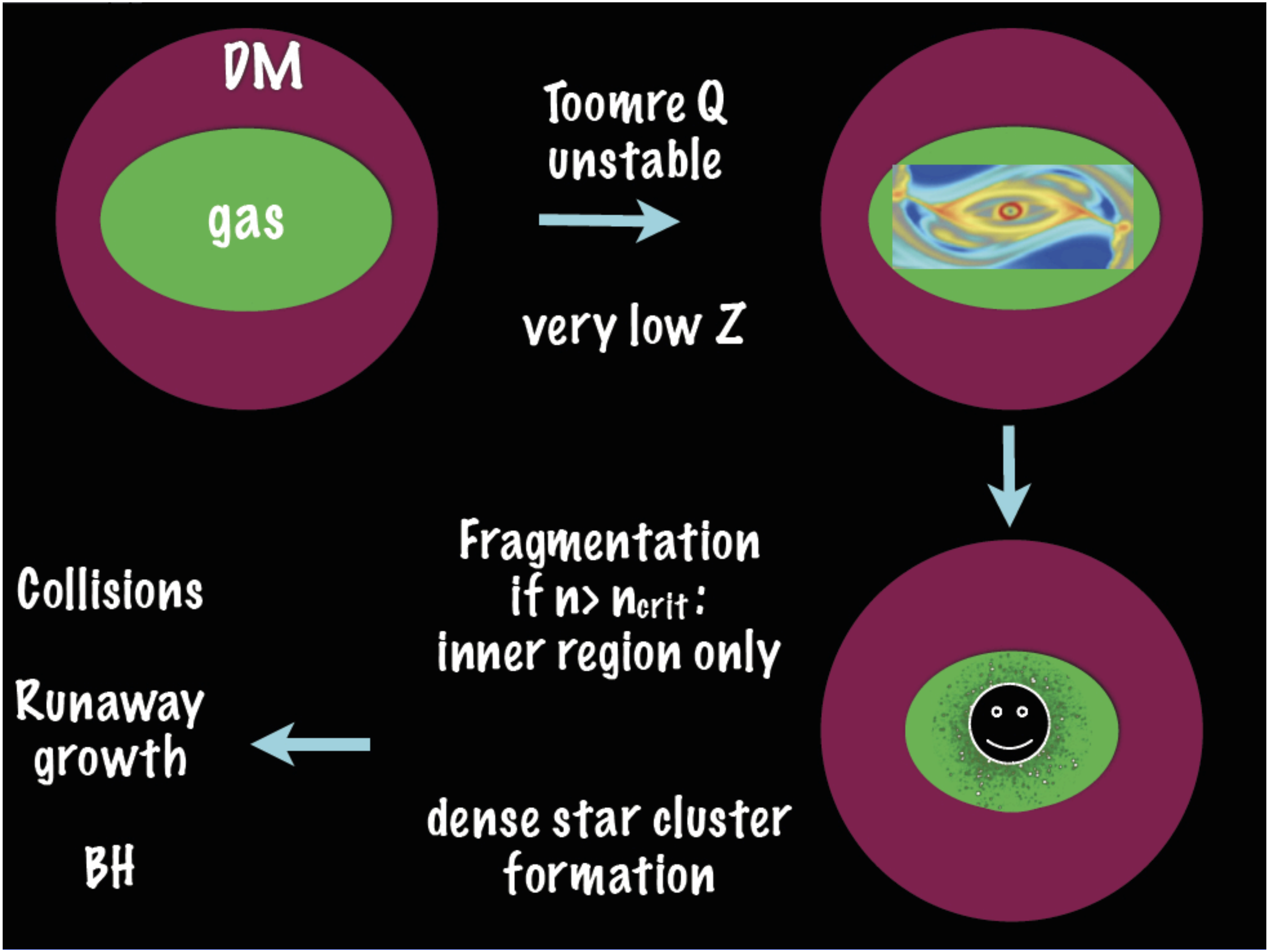
Stellar Dynamics

Devecchi & Volonteri 2009

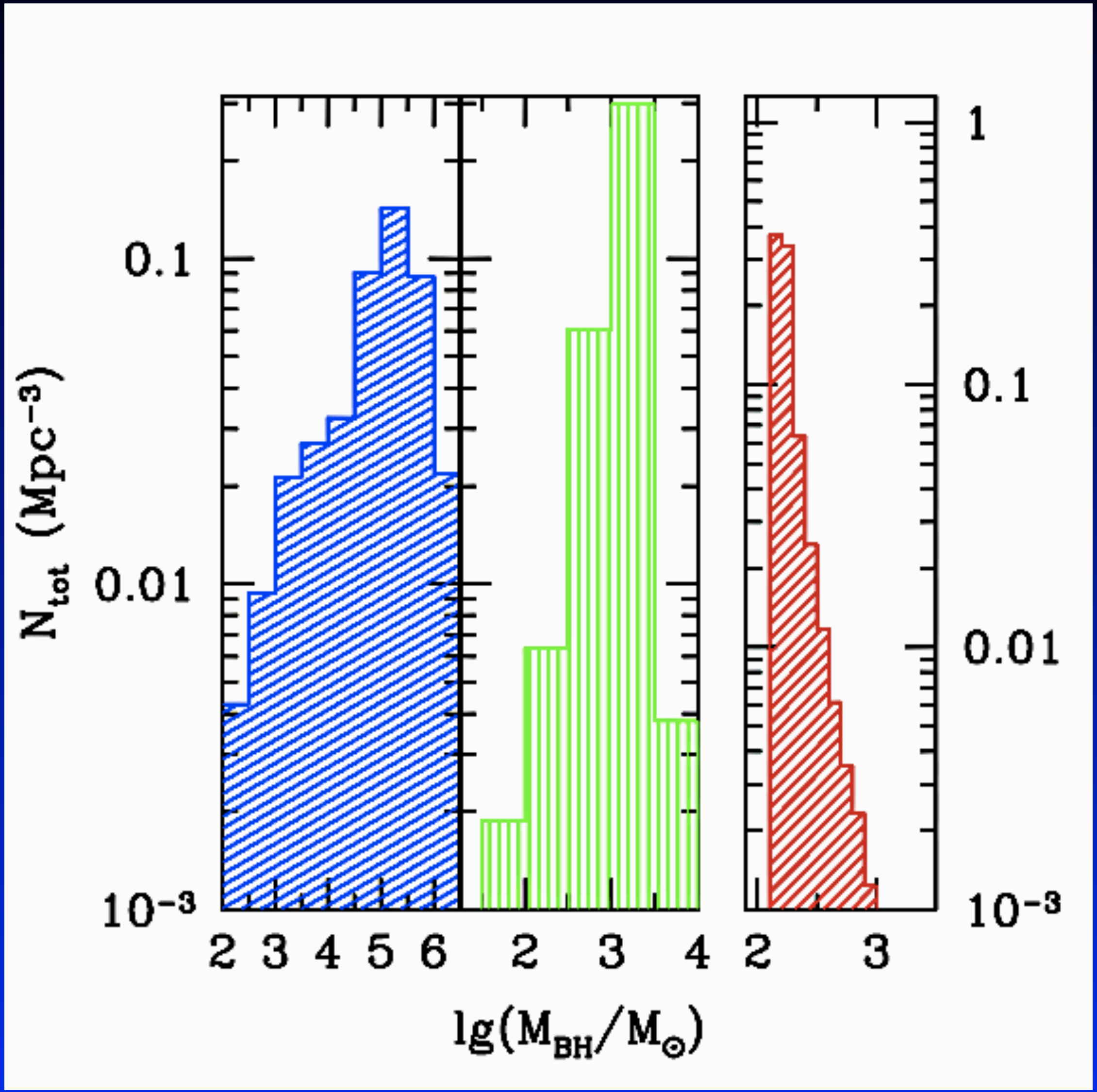
- if the disk is slightly enriched (~ 10^{-5} solar), it may instead develop the Toomre instability and fracture into many stars in the center of the halo

- mass segregation efficiently congregates the more massive stars into the center of the halo on short relaxation times

- this is a *very* dense cluster: frequent stellar collisions ensue and rapidly build up a very massive star that collapses into a 10^4 solar mass BH


DM
gas
Toomre Q unstable
very low Z
Fragmentation if n> ncrit : inner region only
dense star cluster formation
Collisions
Runaway growth
BH

Semianalytical Estimates of the SMBH Seed Mass Function



Numerical Models of Direct Baryon Collapse in 10^8 Solar Mass Halos

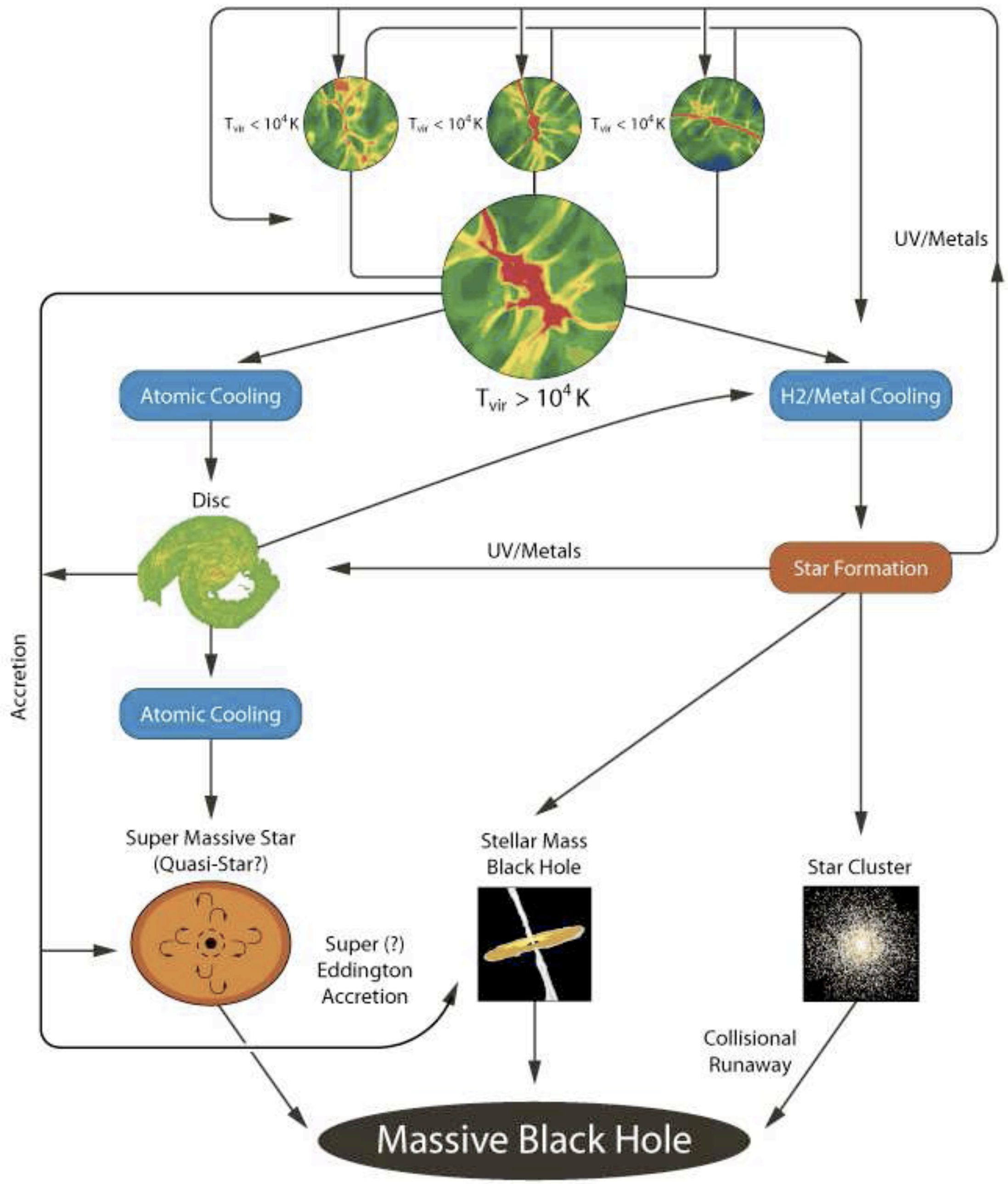
Regan & Haehnelt 2009a,b
Shang, Bryan & Haiman 2009

- from cosmological initial conditions, model the buildup of a 10^8 Msun halo in the absence of H_2 or metals

  (1) simply disable H_2 formation (RH09)
  (2) assume LW backgrounds sufficient to truly suppress all H_2 formation (10^4 - 10^5 J_{21})

- these simulations find the formation of a thick disk; angular momentum is transported out of the disk by mild turbulence (angular momentum segregation)

- they cannot follow the evolution of the disk for dynamical times because high central densities and temperatures yield short Courant times



$T_{vir} < 10^4$ K
$T_{vir} < 10^4$ K
$T_{vir} < 10^4$ K
UV/Metals
$T_{vir} > 10^4$ K
Atomic Cooling
H2/Metal Cooling
Disc
UV/Metals
Star Formation
Accretion
Atomic Cooling
Super Massive Star
(Quasi-Star?)
Super (?)
Eddington
Accretion
Stellar Mass
Black Hole
Star Cluster
Collisional
Runaway
Massive Black Hole

Conclusions

- reductions to accretion efficiency by feedback and mergers indicate that SMBH seeds had to be ‘born big’
- however, direct collapse models all rely on the formation of 10^8 solar-mass halos which have never formed a star in their merger and accretion histories
- this is a truly difficult feat for reasonable values of the LW background at z ~ 15
- primordial SNe in halos not ionized by their progenitors or failed accretion cutoff onto Pop III stars could open additional channels for massive SMBH seeds