Class 20 : Origin of Supermassive BHs

ASTR350 Black Holes (Spring 2022)
Cole Miller

RECAP

- The various faces of supermassive black holes
  - Quasars and Active Galactic Nuclei
  - Relativistic Jets
  - The Quiescent Black Hole at our Galactic Center
  - Tidal Disruption Events

- Wide variety of behaviors *but all connected to supermassive black holes*

This class

- Where do supermassive black holes come from?
  - Evidence that galaxy and SMBH growth are related
    - SMBH affects its host galaxy and vice versa
    - Some extreme examples of massive BHs
  - Evidence that some SMBHs were formed **early in life of universe** ($z>7.5$, $t<700$Myrs from the Big Bang!)
    - Formation in the Big Bang… NO!
  - Need to create a "seed" around which the SMBH grows
  - Possible routes to seed formation
    - Remnants of the first stars
    - Direct collapse of supermassive gas clouds
    - Inefficient accretion from an accretion disk

Supermassive Black Hole Origins

- Stellar mass BHs are born with most of their mass from their natal supernova
  - They grow very little during their short lives (set by the time they have accretion from their normal stellar companion)
- Supermassive BHs (SMBH) grow big from much smaller 'seeds'-
  - nature of seeds not yet clear
  - but probably connected to the evolution of their host galaxy
    - as far as we know all SMBHs are in galaxies with the vast majority lying at the center of the galaxy

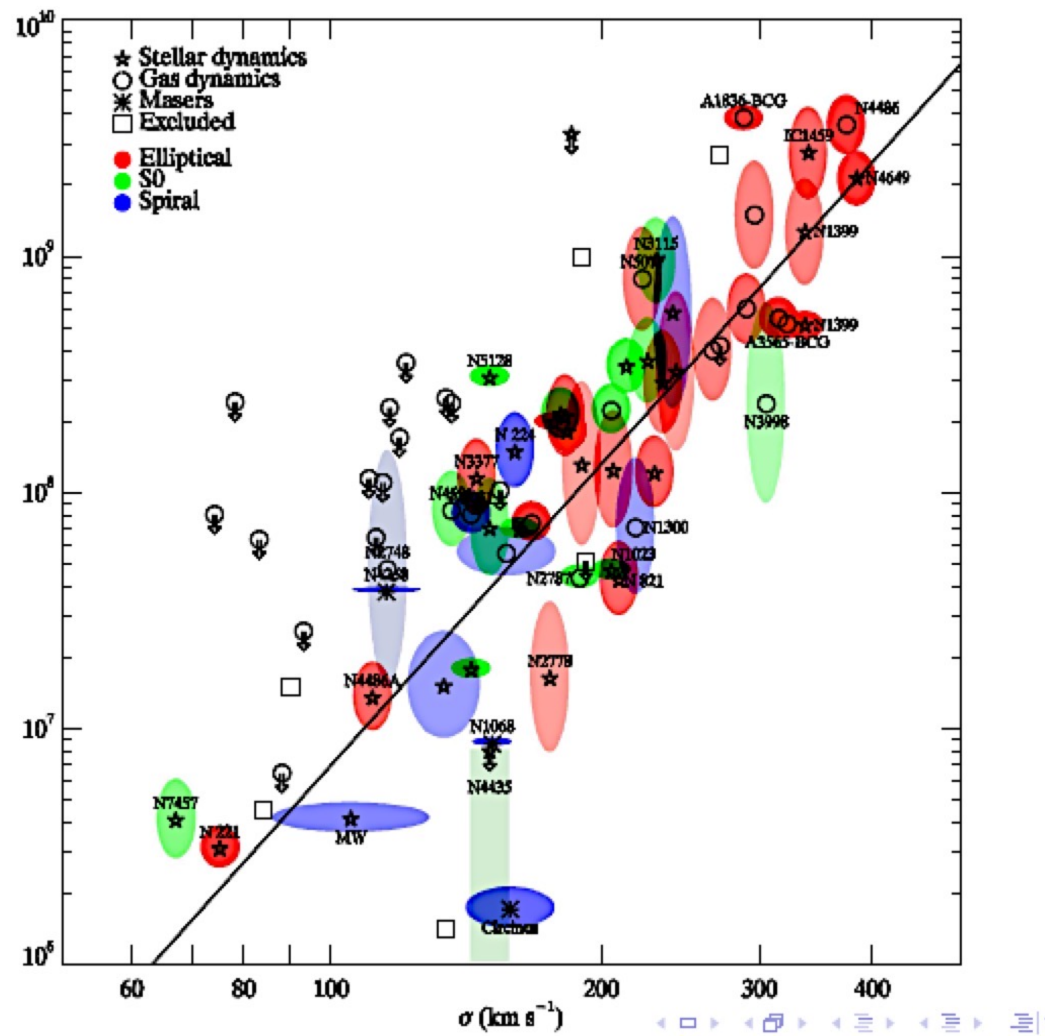
Supermassive Black Hole Origin

- It has been noticed that there is a strong relation between the host galaxy and its SMBH
- 'Every' galactic bulge hosts a supermassive black hole
- Supermassive black holes have cosmological importance…
  - Energy output from black holes growth may be crucial factor in formation/evolution of massive galaxies
  - Galaxy and SMBH growth coupled by powerful feedback processes

Mass of Black Hole Compared to Host Galaxy Property- Sample of non-active galaxies

- Compare mass of black hole with velocity distribution of stars in galaxy
- **BH 'knows' about the galaxy and vice versa**
- Very high detection rate of BHs in 'normal' galaxies- both spheroids and disks
    - only small number of galaxies with interesting upper limits on mass of central black hole (M33).

Mass of black holes



Gultekin 2009 velocity of stars

Hierarchical Formation of Structure

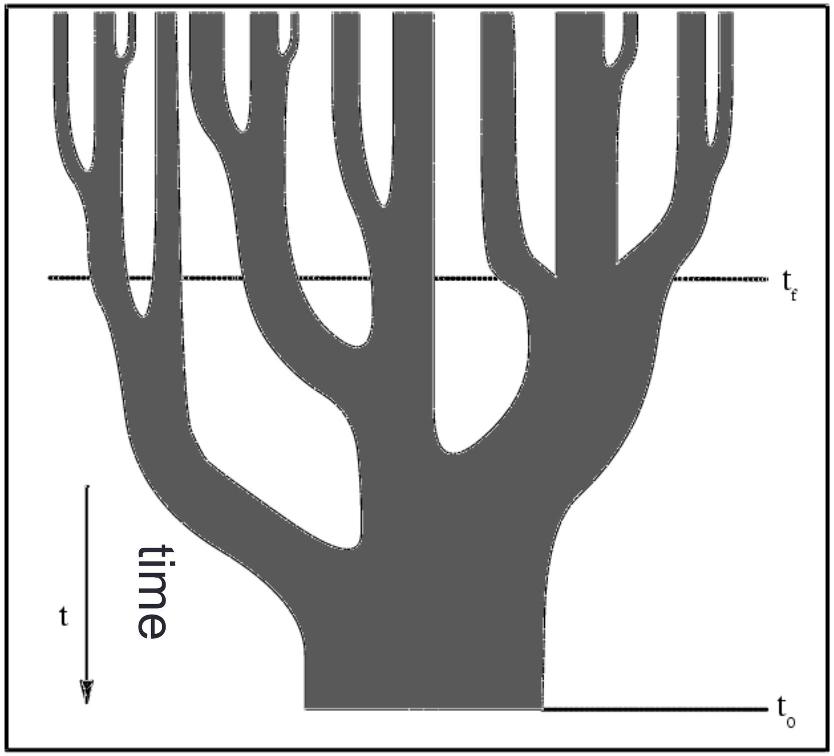
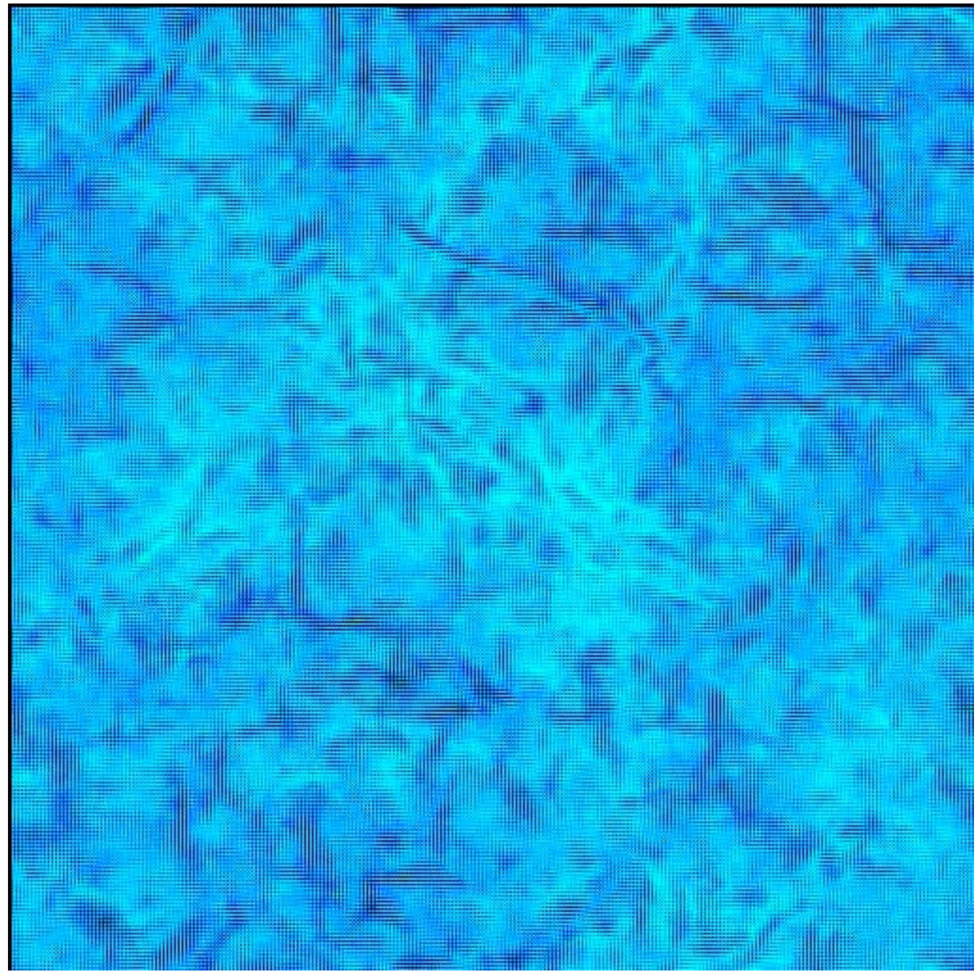


Figure 6. A schematic representation of a "merger tree" depicting the growth of a halo as the result of a series of mergers. Time increases from top to bottom in this figure and the widths of the branches of the tree represent the masses of the individual parent halos. Slicing through the tree horizontally gives the distribution of masses in the parent halos at a given time. The present time t_0 and the formation time t_f are marked by horizontal lines, where the formation time is defined as the time at which a parent halo containing in excess of half of the mass of the final halo was first created.

- A single big galaxy can be traced back to the stage when it was in hundreds of smaller components

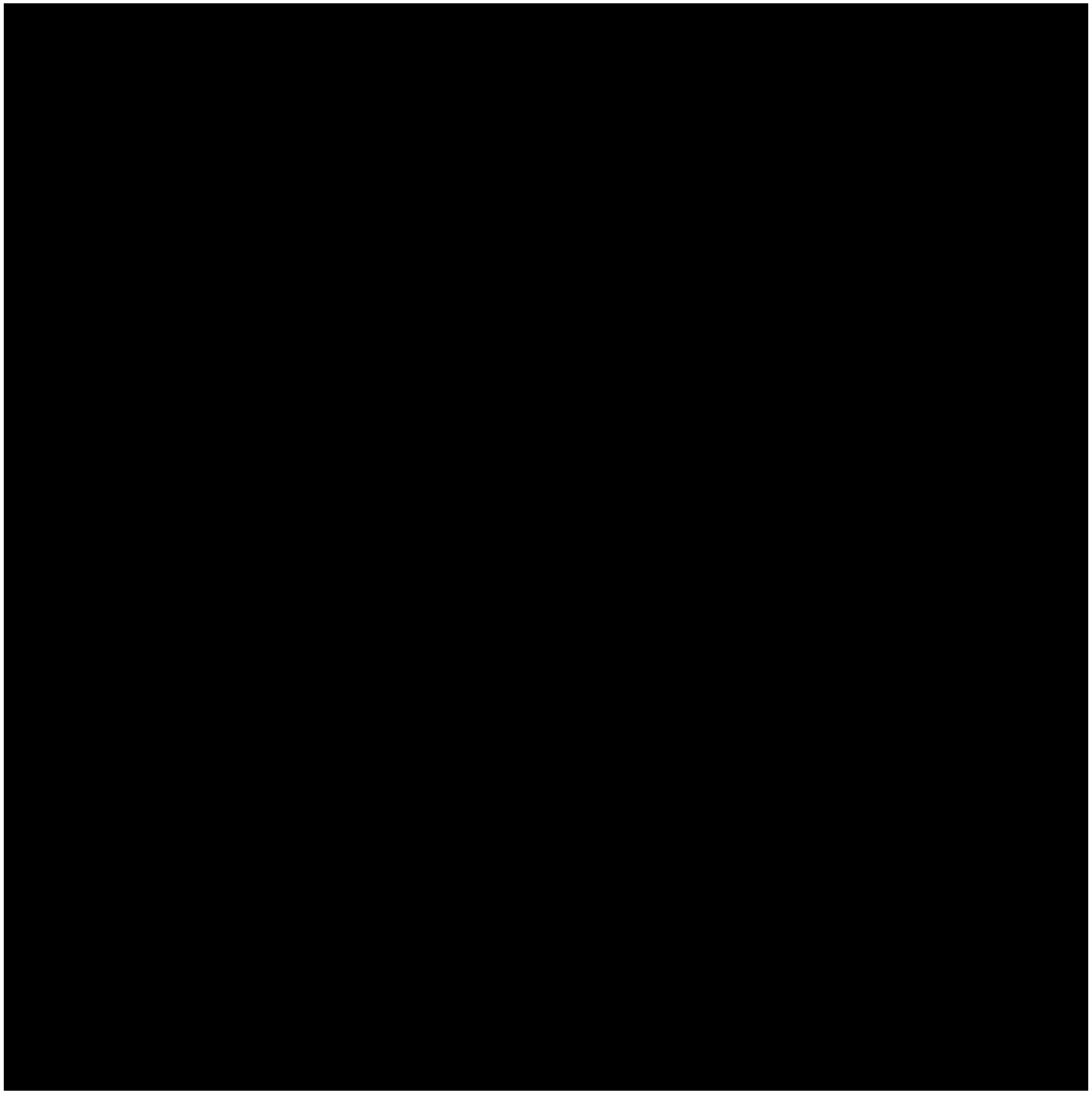


Bode

Simulation of Galaxy Growth

- Notice the large number of mergers
  - galaxies experience multiple mergers during their lifetime.

- If most galaxies host BHs in their center, and a galaxy has been partially made up by multiple mergers, then a black hole merger is likely and can be one of the ways BHs grow.



The Bottom Line..

- Since mass of black holes scales linearly with mass of galaxy one can scale energy required to form a BH with the mass of the galaxy

$$E_{BlackHole} > 30 \times E_{Galaxy}$$

Energy released by growth of Black Hole

Gravitational Binding Energy of Host Galaxy

If the energy is in the right form and available at the right time AGN can have a strong influence on the gas in their galaxy

I : The early appearance of SMBHs

- We see powerful quasars at very large distances and thus long look back times Current record holder is…
  - ULAS J1342+0928 (catchy name!)
  - Redshift z=7.585 (690 Myr after Big Bang)
  - Luminosity L=3x10^{40}W ➔ M>2x10^{9}M$_{sun}$ (Eddington limit argument)

LETTER

doi:10.1038/nature10159

A luminous quasar at a redshift of $z = 7.085$

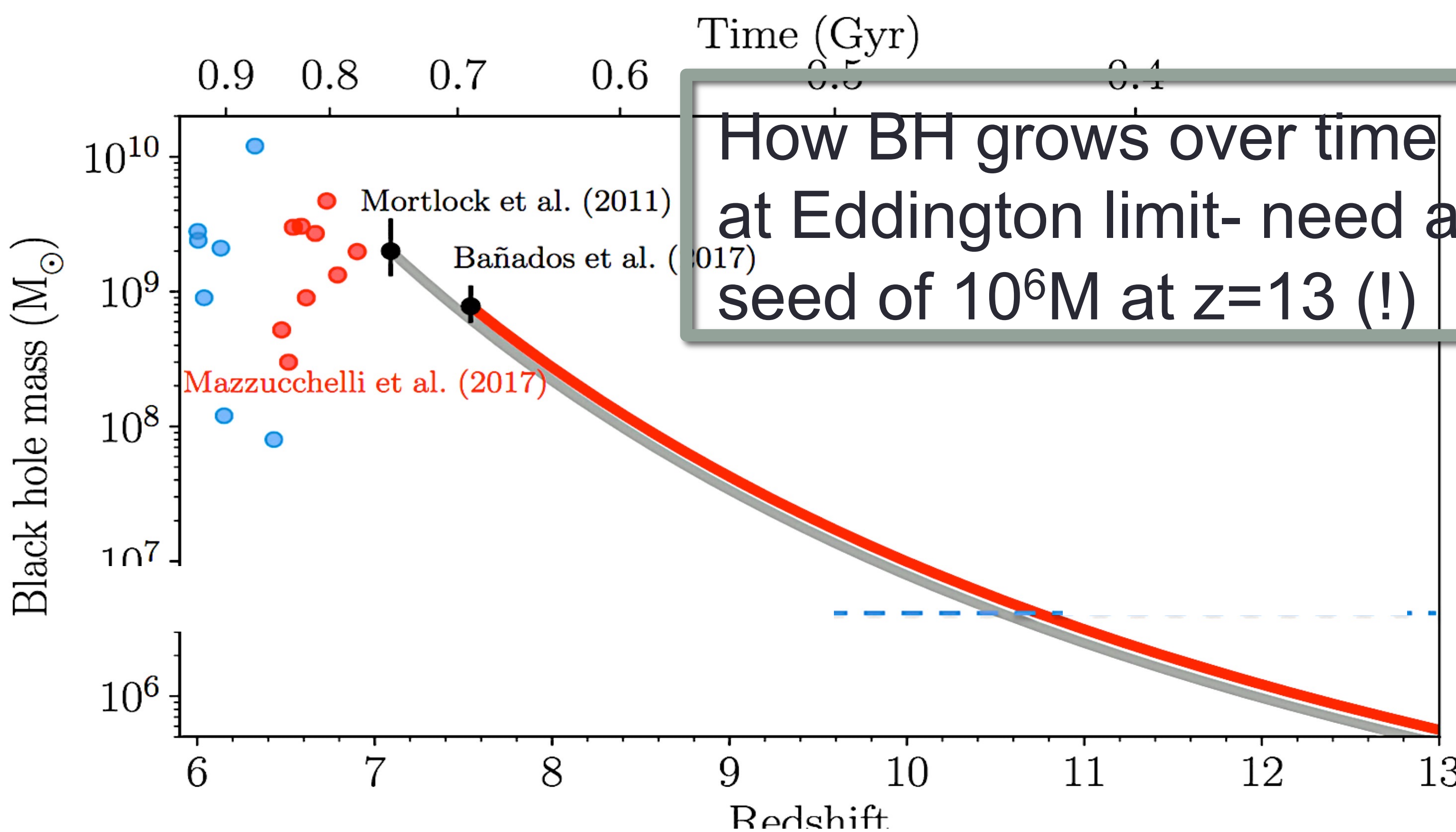
Daniel J. Mortlock[1], Stephen J. Warren[1], Bram P. Venemans[2], Mitesh Patel[1], Paul C. Hewett[3], Richard G. McMahon[3], Chris Simpson[4], Tom Theuns[5,6], Eduardo A. Gonzáles-Solares[3], Andy Adamson[7], Simon Dye[8], Nigel C. Hambly[9], Paul Hirst[10], Mike J. Irwin[3], Ernst Kuiper[11], Andy Lawrence[9] & Huub J. A. Röttgering[11]

The intergalactic medium was not completely reionized until approximately a billion years after the Big Bang, as revealed[1] by observations of quasars with redshifts of less than 6.5. It has been difficult to probe to higher redshifts, however, because quasars have historically been identified[2–4] in optical surveys, which are insensitive to sources at redshifts exceeding 6.5. Here we report observations of a quasar (ULAS J112001.48+064124.3) at a redshift of 7.085, which is 0.77 billion years after the Big Bang. ULAS J1120+0641 has a luminosity of $6.3 \times 10^{13} L_\odot$ and hosts a black hole with a mass of $2 \times 10^{9} M_\odot$ (where $L_\odot$ and $M_\odot$ are the luminosity and mass of the Sun). The measured radius of the ionized near zone around ULAS J1120+0641 is 1.9 megaparsecs, a factor of three smaller than is typical for quasars at redshifts between 6.0 and 6.4. The near-zone transmission profile is consistent with a Lyα damping wing[5], suggesting that the neutral fraction of the intergalactic medium in front of ULAS J1120+0641 exceeded 0.1.

photometry from UKIDSS, the Sloan Digital Sky Survey[7] (SDSS) and follow-up observations on UKIRT and the Liverpool Telescope (listed in Fig. 1) was consistent[8] with a quasar of redshift $z \gtrsim 6.5$. Hence, a spectrum was obtained using the Gemini Multi-Object Spectrograph on the Gemini North Telescope on the night beginning 27 November 2010. The absence of significant emission blueward of a sharp break at $\lambda = 0.98$ µm confirmed ULAS J1120+0641 as a quasar with a preliminary redshift of $z = 7.08$. Assuming a fiducial flat cosmological model[9] (that is, cosmological density parameters $\Omega_m = 0.26$, $\Omega_b = 0.024$, $\Omega_\Lambda = 0.74$ and current value of the Hubble parameter $H_0 = 72$ km s^{-1} Mpc^{-1}), ULAS J1120+0641 is seen as it was 12.9 billion years (Gyr) ago, when the Universe was 0.77 Gyr old. Although three sources have been spectroscopically confirmed to have even higher redshifts, two are faint $J_{AB} \gtrsim 26$ galaxies[10,11] and the other is a γ-ray burst, which has since faded[12]. Indeed, it has not been possible to obtain high signal-to-noise ratio spectroscopy of any sources beyond the most dis-

The Highest Redshift Quasars- The Birth of SMBHs

Recent studies (Banados et al 2018) have detected SMBHs at z~7.5 (690 Myr after Big Bang) with mass $M_{SMBH}=8\times10^8\ M_{sun}$ (highest z accessible from the ground)



How BH grows over time at Eddington limit- need a seed of 10^6M at z=13 (!)

III: SMBHs from the Big Bang?

- Can supermassive black holes form by the exotic processes occurring in the very early Universe ($t<10^{-6}$s)?

- No! A very robust argument…
  - At any time, there is a finite volume of the Universe that is in causal contact ("inside the particle horizon")
  - Hence there is a finite amount of mass that is in causal contact ("mass contained within the particle horizon"). Calculations show that this is:

$$M_H \approx 10^{30}\left(\frac{t}{10^{-6}s}\right)kg$$

  - Hence, impossible to form any object with $M>M_{sun}$ at a time $t<10^{-6}$s after the Big Bang.

III : SMBHs from dark matter accretion?

- OK… so they can't form in the *very* early Universe

- But can SMBHs "condense" out of the dark matter?
  - That way, they can avoid the Eddington limit! (WHY??)
  - Plus there is more dark matter than normal matter.

- No! At least not in our standard view of dark matter...
  - Dark matter only interacts gravitationally
  - So, it is very difficult for a particle of dark matter to lose energy or angular momentum
  - Thus, it is very difficult for large amounts of dark matter to collapse down into compact objects

IV : “Baryonic” routes to SMBHs

- OK… SMBHs can’t form in early Universe or from dark matter collapse
  - They must form from normal matter (aka baryonic matter) doing 'normal' things…
  - Baryonic matter can lose energy and angular momentum, so can be collapsed much more easily than dark matter

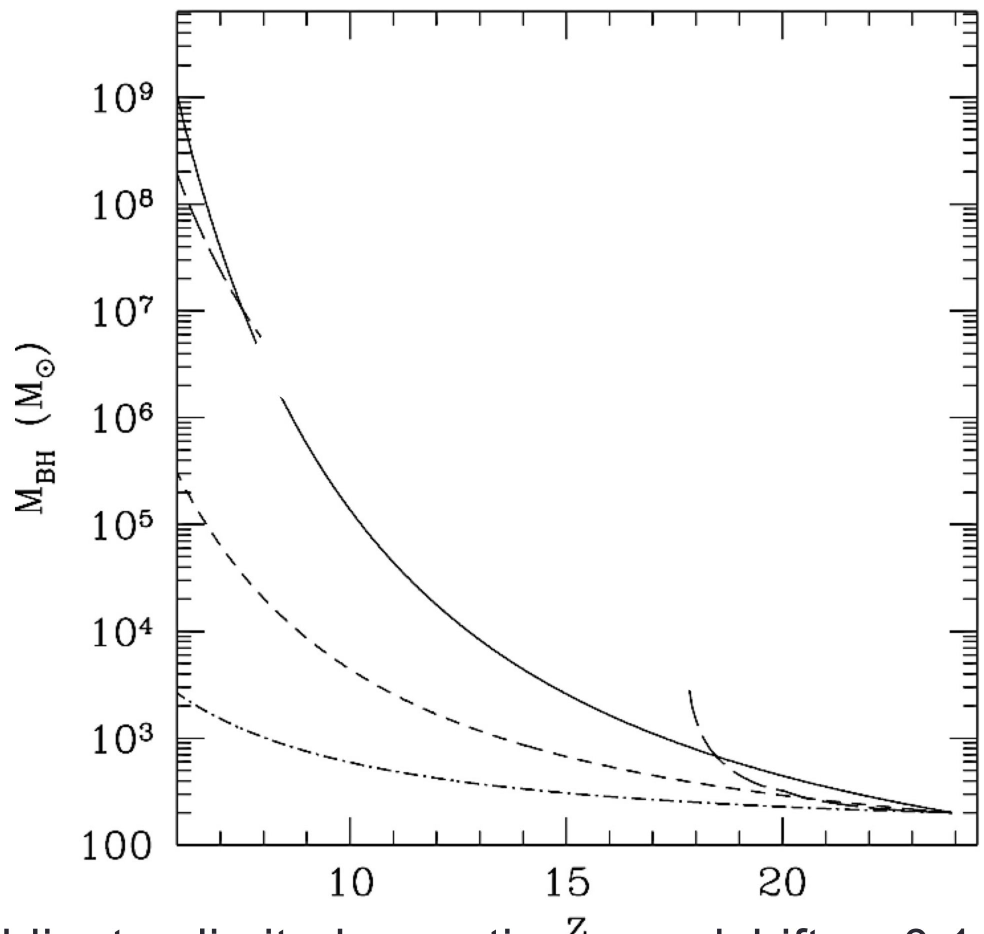
- SMBH formation must be a two step process:
  - Step 1 : Formation of a “seed” black hole
  - Step 2 : Growth of the seed up to large mass

How to Evolve to Massiveness

- The e-folding time (i.e., time to increase by factor of e=2.718...) for growth at the Eddington limit with 10% efficiency is 45Myrs (called Salpeter time)
  Independent of M_{BH}

So to grow from, $10^3 M_\odot$-$10^6 M_\odot$ requires 7 $t_{salpeter}$

and to grow from, $10^3 M_\odot$-$10^9 M_\odot$ requires 14 $t_{salpeter}$, which is about 630 million years



Eddington limited accretion vs redshift: ε= 0.1 (solid line), ε= 0.2 (short dashed line), ε= 0.4 (dot-dashed line).

Is 630 million years large or small?

- Remember that in astronomy, everything needs context!
- We see ~10^9 M_{sun} SMBHs 690 million years after Big Bang
- But it takes 200-300 million years after Big Bang for the first stars, and thus the first stellar-origin black holes, to form
- Added to 630 million years gives >800 million years even at continuous Eddington accretion at 10% efficiency
- So we have a problem!

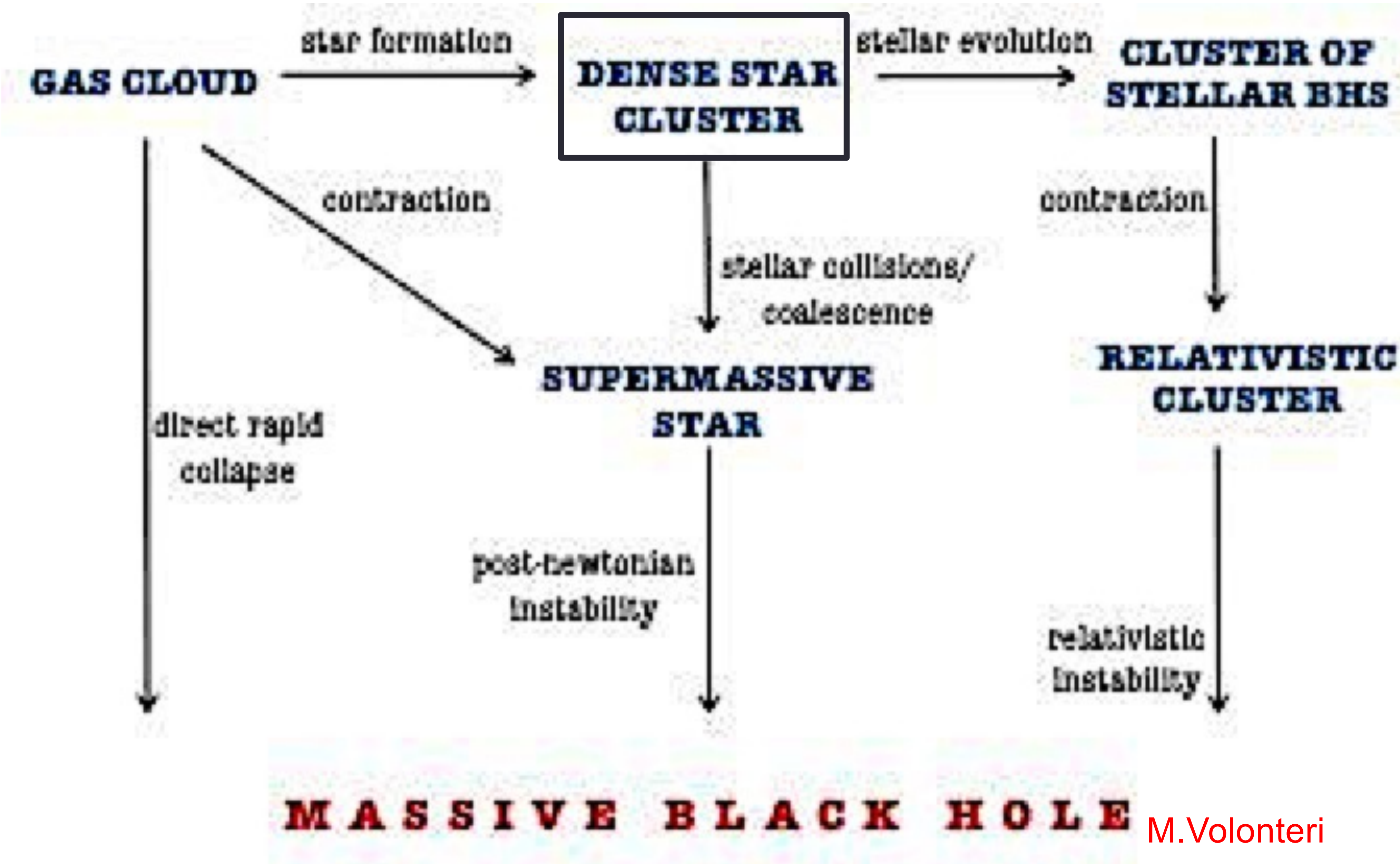
How do we solve the problem?

- Possibility 1: lower the accretion efficiency
- Remember that the limit is the Eddington ***luminosity***, not the accretion rate per se
- At the Eddington luminosity, and accretion efficiency x, the mass accretion rate is $L/(xc^2)$. Thus lower efficiency of radiation production gives higher rate of mass accretion at the Eddington luminosity
- How do we lower accretion efficiency?
- One way is to merge things like black holes; why does that produce very little radiation?
  Dittmann and Miller 2020!
- Another is if the matter flow is so fast that photons are swept (or "advected") into black hole

How do we solve the problem?

- Possibility 2: start with a heavy BH
- Remember, Eddington-limited growth is exponential, which means that increasing mass by a factor of 10^6 takes only twice as long as increasing the mass by a factor of 10^3
- But still, starting at 10^5 M_{sun} to 10^6 M_{sun}, versus 10 M_{sun}, can halve the time to the target 10^9 M_{sun}
- Supermassive stars? Clusters of objects? Let's find out...

Paths to the Creation of a SMBH



M.Volonteri

All Roads Lead to a Black Hole?

Whenever the mass density and total mass are large enough the formation of a black hole MUST happen

No matter what the original form of the baryonic matter (gas, dense cluster of stars etc) a BH forms

However, the routes to the BH can be many and diverse and control the final mass and spin.

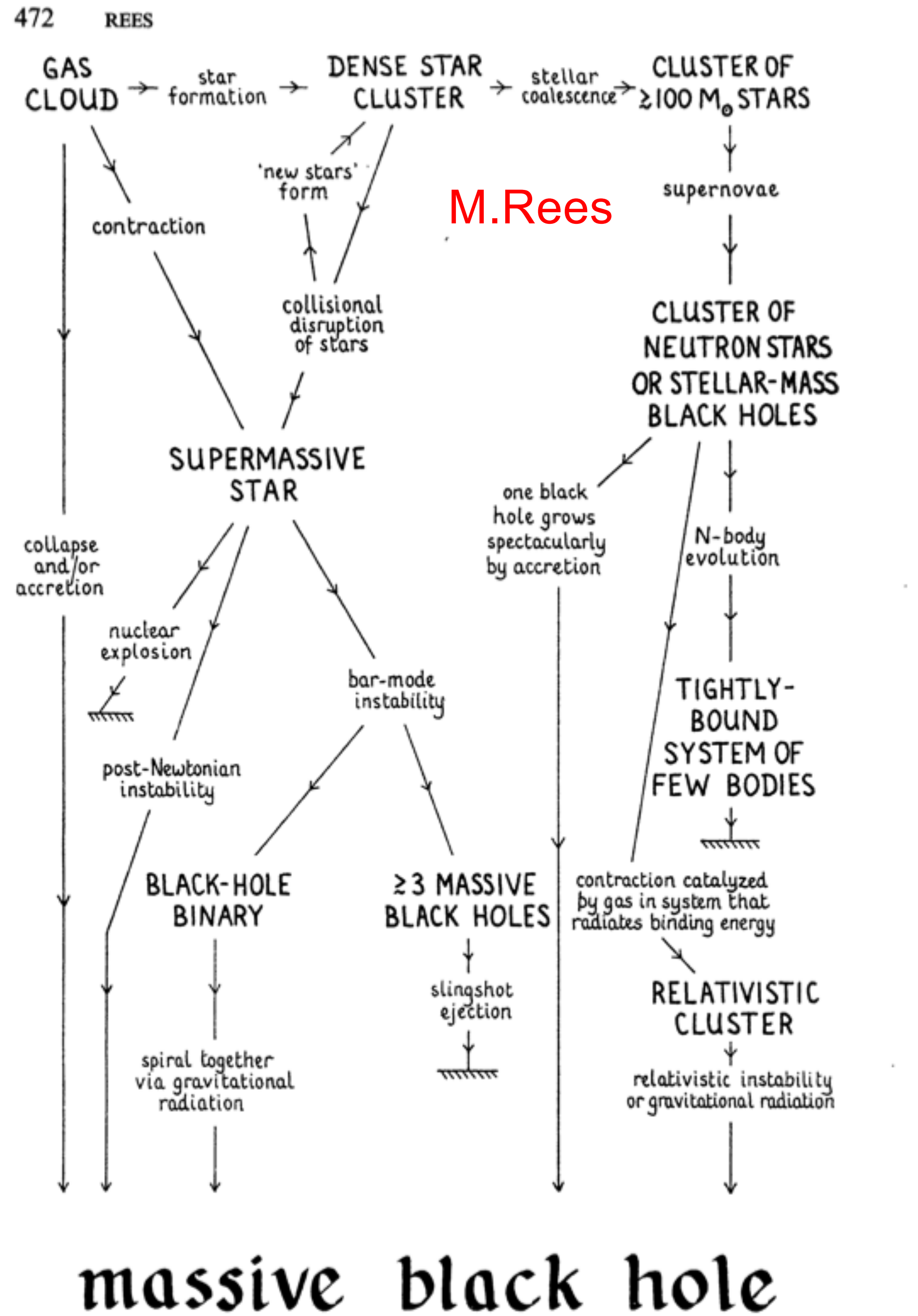


Figure 1 Schematic diagram [reproduced from Rees (106)] showing possible routes for runaway evolution in active galactic nuclei.

Globular Clusters-

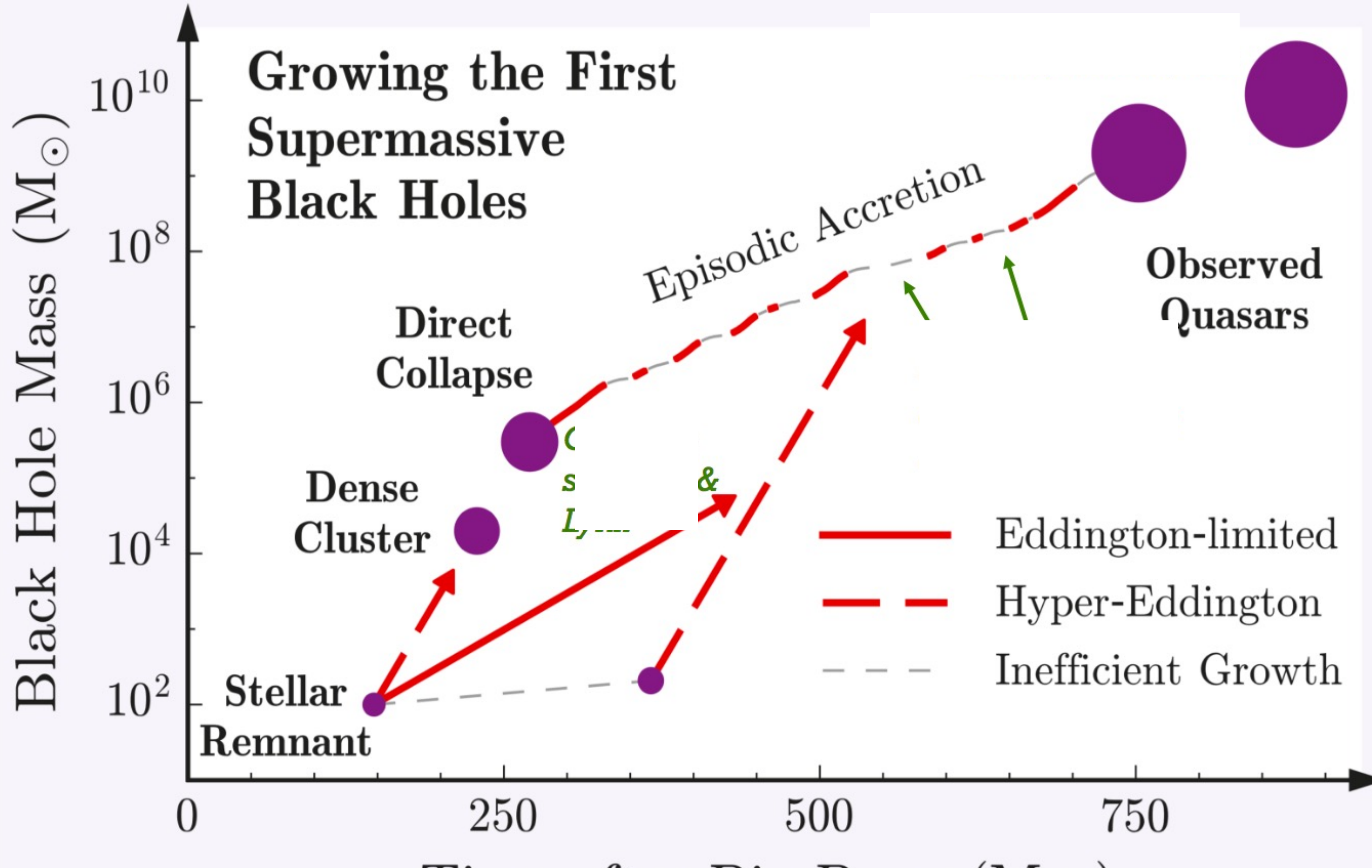
These are common objects around normal galaxies

This massive ball of stars ($M\sim10^6M_\odot$) WILL NOT collapse into a single black hole

BUT it may contain several stellar mass BHs which may merge into a bigger ($1000M_\odot$) one which could become a SMBH seed.

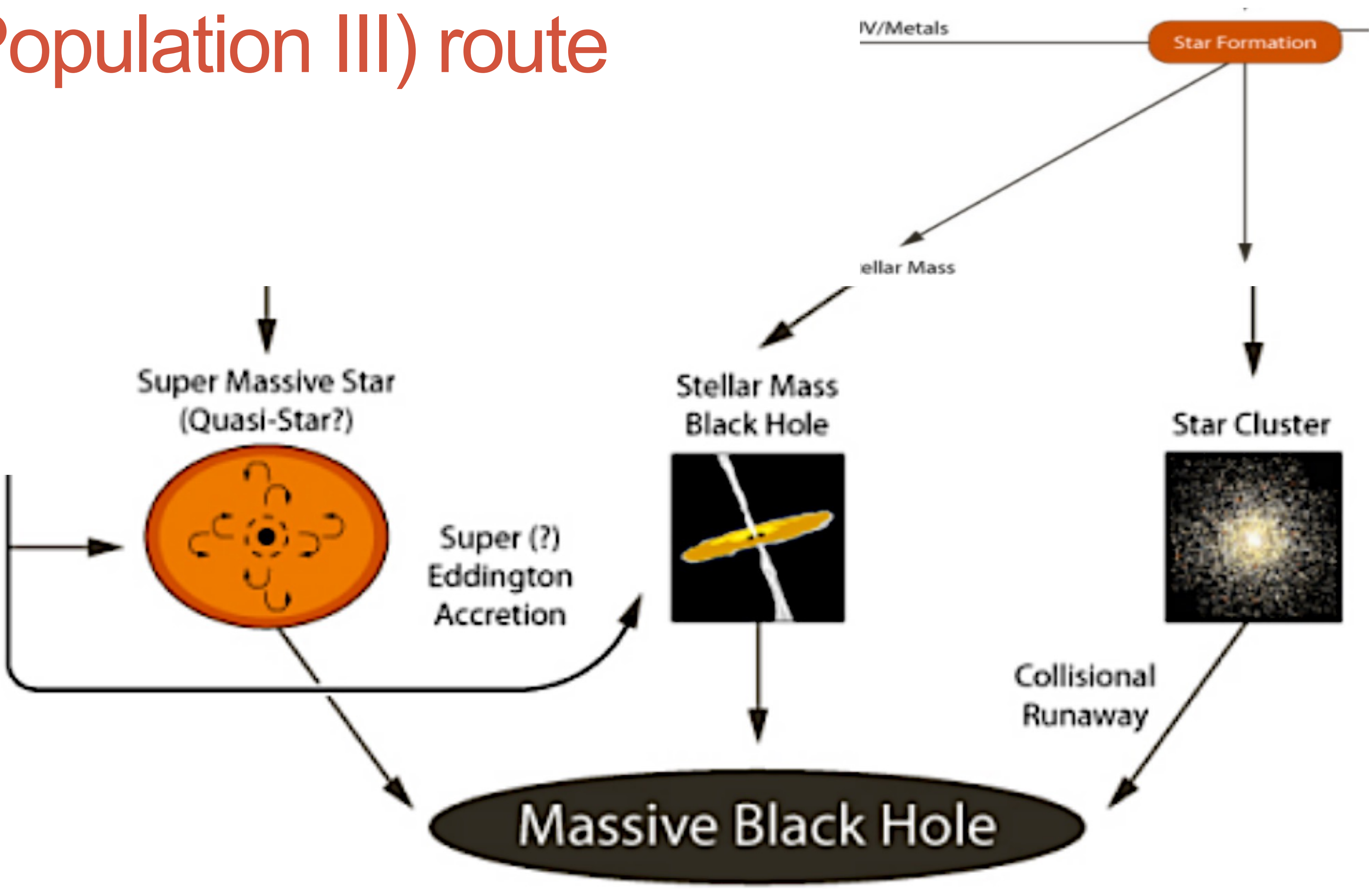
I've done work on this too...

Possible Seeds of First SMBHs



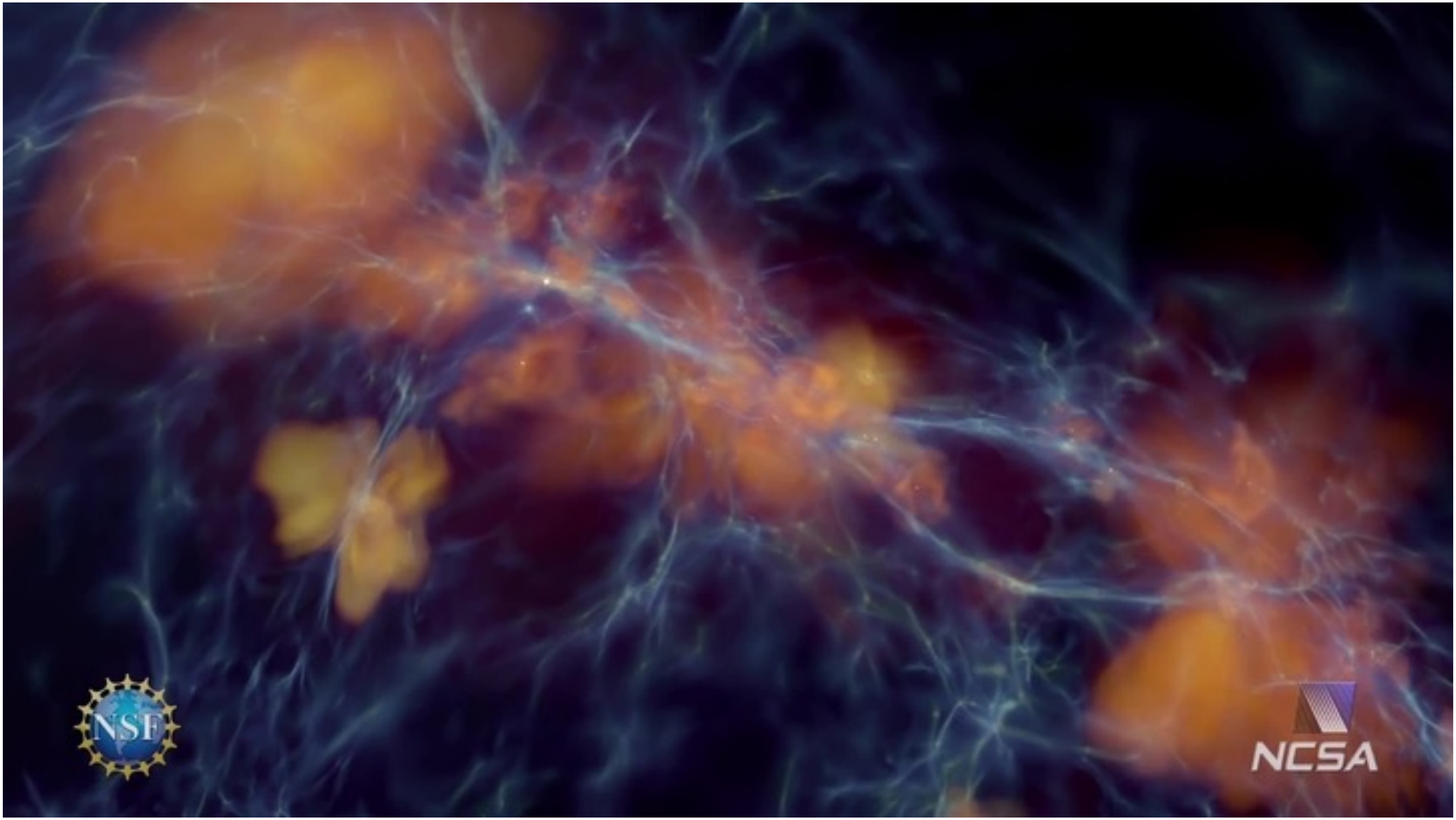
Smith et al. (2017)

How to Get Started -The First Stars (Population III) route



How to Get Started -The First Stars (Population III) route

- the seeds of SMBHs can be associated with the remnants of the first generation of stars, formed out of 'zero metallicity' gas.
  - Form from pristine, unpolluted gas from the Big Bang (H, He, trace Li)
  - Maybe start forming 200-300 million years after BB, z~20-30. The first stars are believed to form at z∼20−30
  - Can get more massive than today's "normal" stars… maybe several hundred solar masses
  - At end of life, massive Pop III stars can undergo direct collapse to black hole without supernova! Can leave a ~100M_{sun} black hole (or maybe even a small cluster of these BHs).
  - These are the seeds that can start accreting…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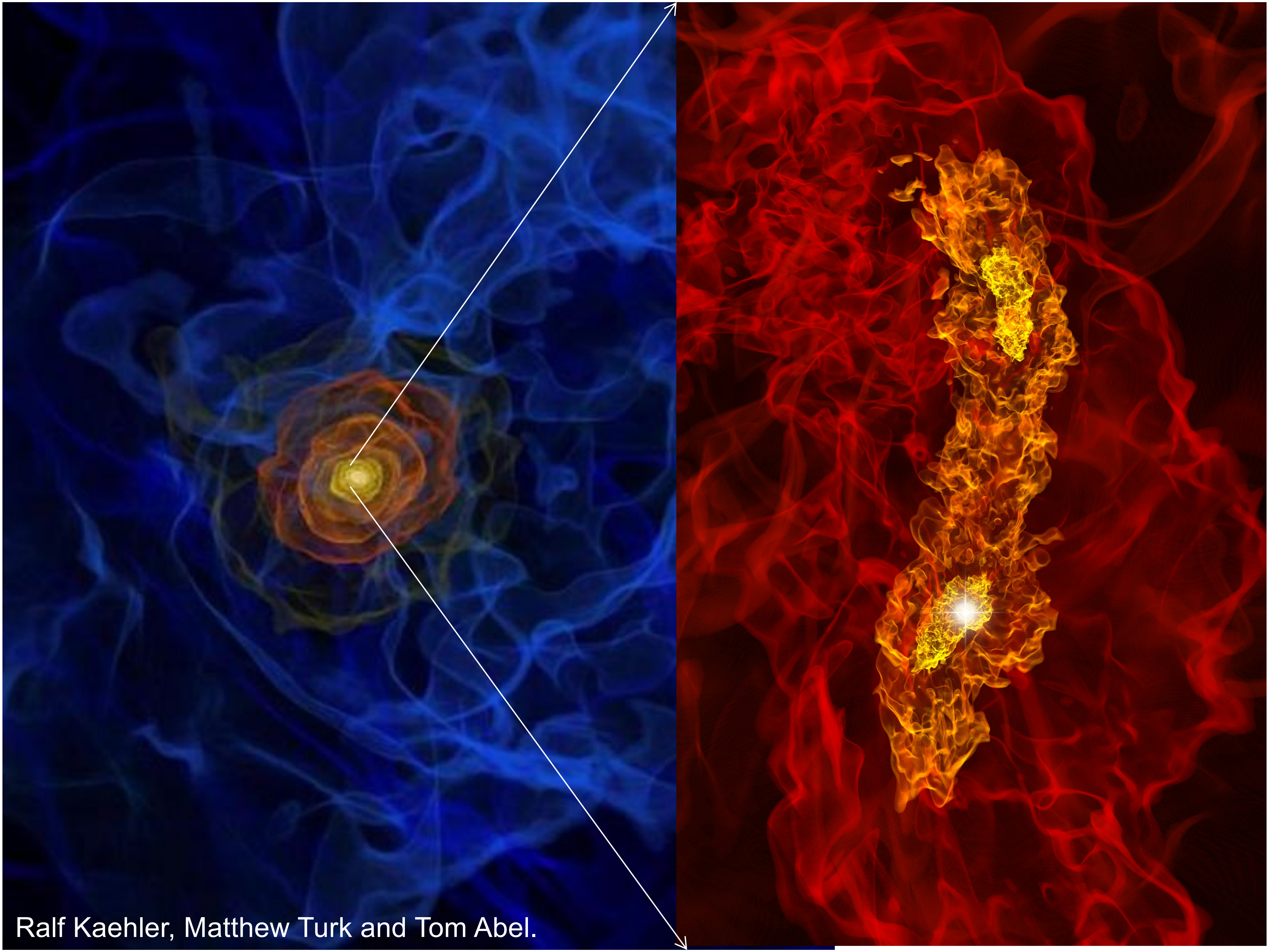
NCSA


Ralf Kaehler, Matthew Turk and Tom Abel.

How to Get Started: Direct collapse route

- Direct formation of a BH from a collapsing gas cloud
- Gas flows in protogalaxy form large central gas cloud
- Cloud gravitationally collapses towards center of galaxy…
  - Tricky issue is explaining why it doesn't fragment to form stars
  - Need to regulate rate that it cools… if it cools too fast, it fragments!
- Center of cloud collapses to $10^4 M_{sun}$ black hole
- Black hole feeds, initially from this same gas cloud and later from the rest of the protogalaxy

- In either scenario, feedback fights growth

- Area of cutting-edge research!

Feedback

- Feedback is the effect of the BH on its host galaxy and vice versa.
- The tremendous energy emitted by the black hole affects its surroundings
- The fuel to grow the black hole comes from its host galaxy
- These are intimately related.

LETTER

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An over-massive black hole in the compact lenticular galaxy NGC 1277

Remco C. E. van den Bosch[1,2], Karl Gebhardt[2], Kayhan Gültekin[3], Glenn van de Ven[1], Arjen van der Wel[1] & Jonelle L. Walsh[2]

Most massive galaxies have supermassive black holes at their centres, and the masses of the black holes are believed to correlate with properties of the host-galaxy bulge component[1]. Several explanations have been proposed for the existence of these locally established empirical relationships, including the non-causal, statistical process of galaxy–galaxy merging[2], direct feedback between the black hole and its host galaxy[3], and galaxy–galaxy merging and the subsequent violent relaxation and dissipation[4]. The empirical scaling relations are therefore important for distinguishing between various theoretical models of galaxy evolution[5,6], and they furthermore form the basis for all black-hole mass measurements at large distances. Observations have shown that the mass of the black hole is typically 0.1 per cent of the mass of the stellar bulge of the galaxy[7,8]. Until now, the galaxy with the largest known fraction of its mass in its central black hole (11 per cent) was the small galaxy NGC 4486B[1,9]. Here we report observations of the stellar kinematics of NGC 1277, which is a compact, lenticular galaxy with a mass of 1.2×10^{11} solar masses. From the data, we determine that the mass of the central black hole is 1.7×10^{10} solar masses, or 59 per cent of its bulge mass. We also show observations of five other compact galaxies that have properties similar to NGC 1277 and therefore may also contain over-massive black holes. It is not yet known if these galaxies represent a tail of a distribution, or if disk-dominated galaxies fail to follow the usual black-hole mass scaling relations[4,10].

galaxies listed in Table 1 contains more than 10 billion solar masses, which is 100 times more than typical galaxies of the same size.

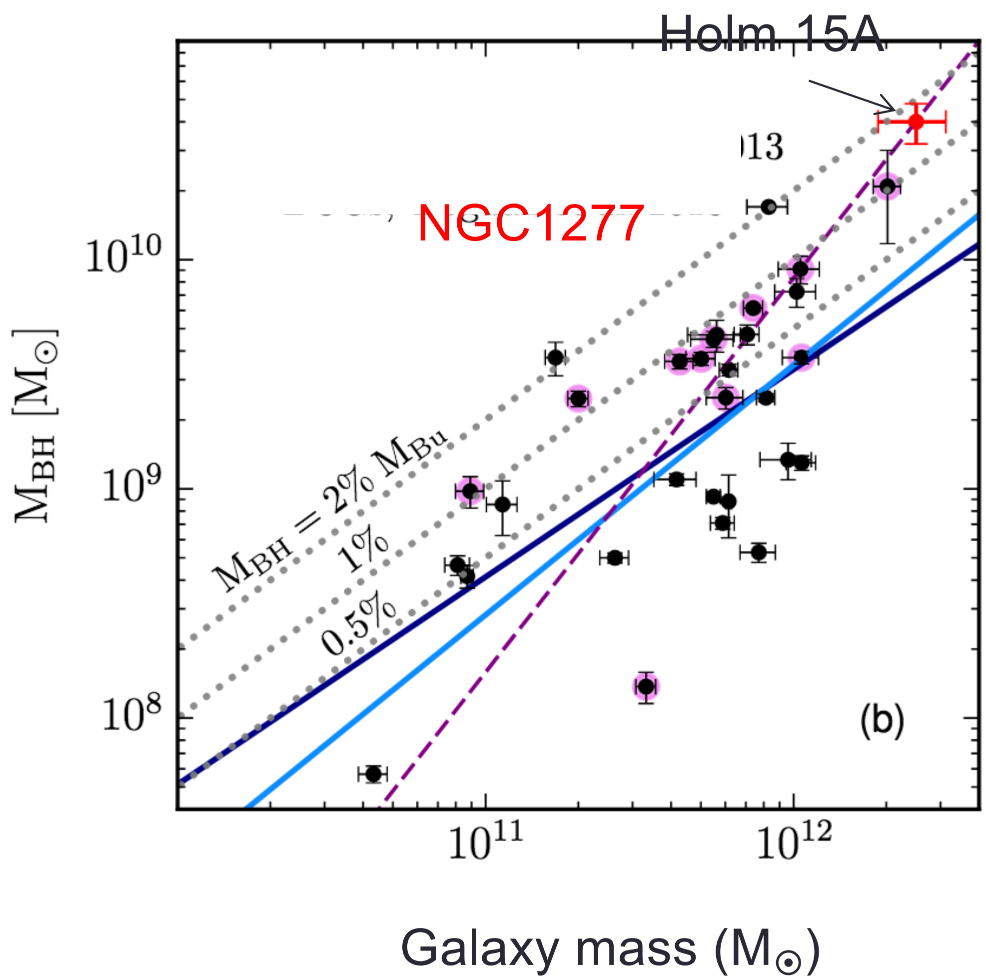
Black-hole masses can be measured directly by fitting self-consistent Schwarzschild models[12] to spatially resolved spectroscopy data and high-resolution imaging. Archival Hubble Space Telescope (HST) imaging is available for one of these six dense galaxies, NGC 1277. On the basis of the HST imaging (Fig. 1) and the stellar kinematics (Fig. 2), we constructed 600,000 orbit-based models using iterative refinement to search parameter space[13,14]. The best-fit model is then found by marginalizing over all parameters: the stellar mass-to-light ratio, the black-hole mass and the mass and concentration of the Navarro–Frenk–White dark halo[15]. The confidence intervals are determined with the goodness-of-fit statistic χ^2. We measure a black-hole mass of $(17 \pm 3) \times 10^9$ solar masses ($M_\odot$) and a total stellar mass of $(1.2 \pm 0.4) \times 10^{11} M_\odot$, with 1-s.d. confidence intervals based on $\Delta\chi^2 = 1$ after marginalizing over the dark-halo parameters (Supplementary Information). The black hole in NGC 1277 is one of the most massive black holes to be dynamically confirmed, and moreover has a mass fraction of 14% of the total stellar mass in the galaxy.

No galaxy with such a large ratio of black-hole mass to stellar mass has previously been seen. Owing to the strong disk-like rotation (Fig. 2) and the lack of an unambiguous bulge in NGC 1277 (Fig. 1), it is unclear where to evaluate its black hole against the relation between black-hole mass and bulge luminosity. The central pseudo-bulge contains 24% of the light (Fig. 1) and the black-hole/bulge mass

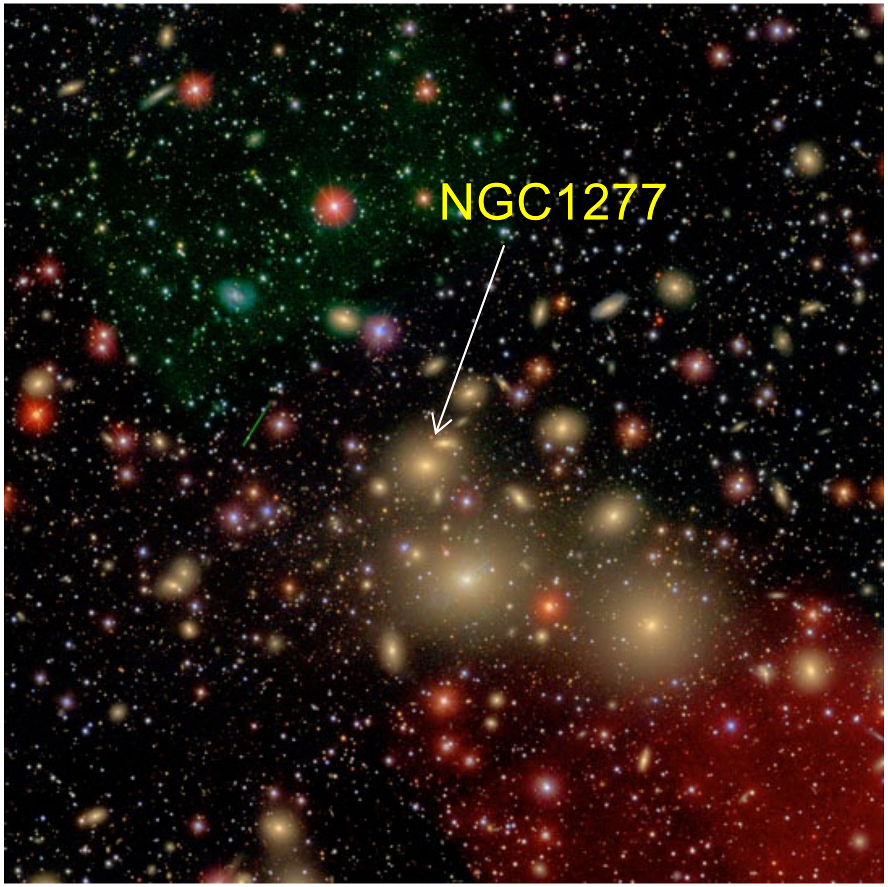
van den Bosch et al. (2012)

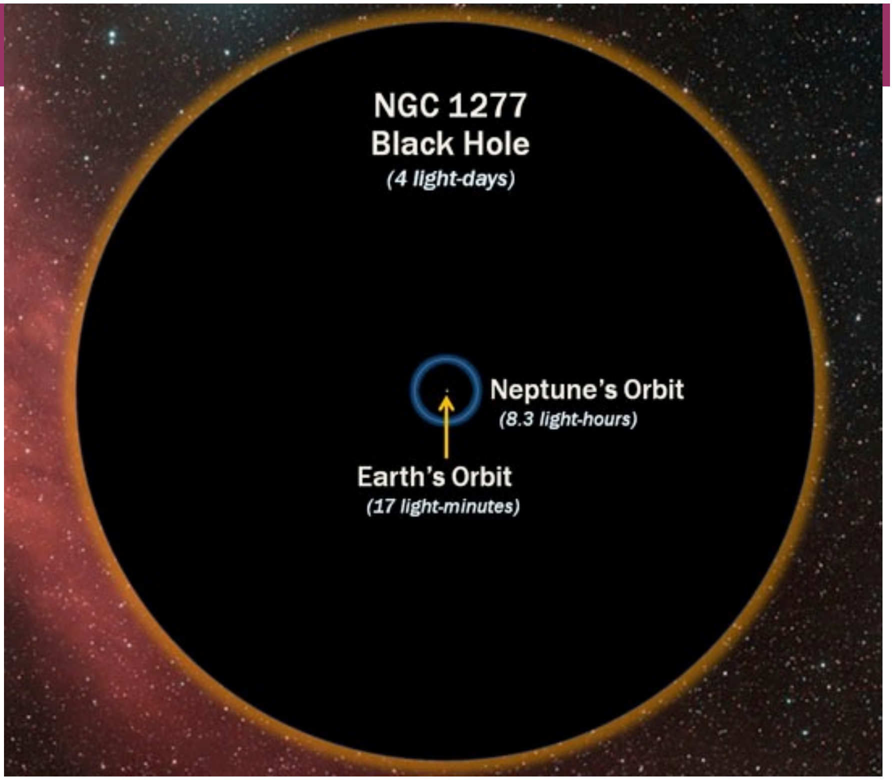
Some of the SMBHs Can get 'Really' Massive

- This graph shows the most massive SMBHs known- reaching up to $4x10^{10}M_\odot$
- The ---lines show the fraction of the galaxy mass of the SMBH (ignore the other lines)
- The previous champion was NGC1277 (next slide)



NGC1277





- Processes to explain BH-galaxy connection
  - Feedback between the black hole and its host galaxy
- Galaxy–galaxy merging and the subsequent black hole merging
- 'Over feeding'

THE FORMATION OF STRUCTURE

- Computer simulations model the growth, then collapse, of inhomogeneities
- Result is a "numerical simulation" of evolution in the Universe

- Simulations:
  - Simulate the evolution of the Universe in a large "box" of space.
  - "Box" is typically large (10s to 100s of Mpc) but small compared to observable Universe (8 Gpc)
  - Start off with "initial conditions" of *nearly* uniform distribution of matter, with small inhomogeneities
- Gravity causes fluctuations to grow: mass condenses into regions that initially had highest density

The complexity of the systems and the physics involved requires numerical simulation

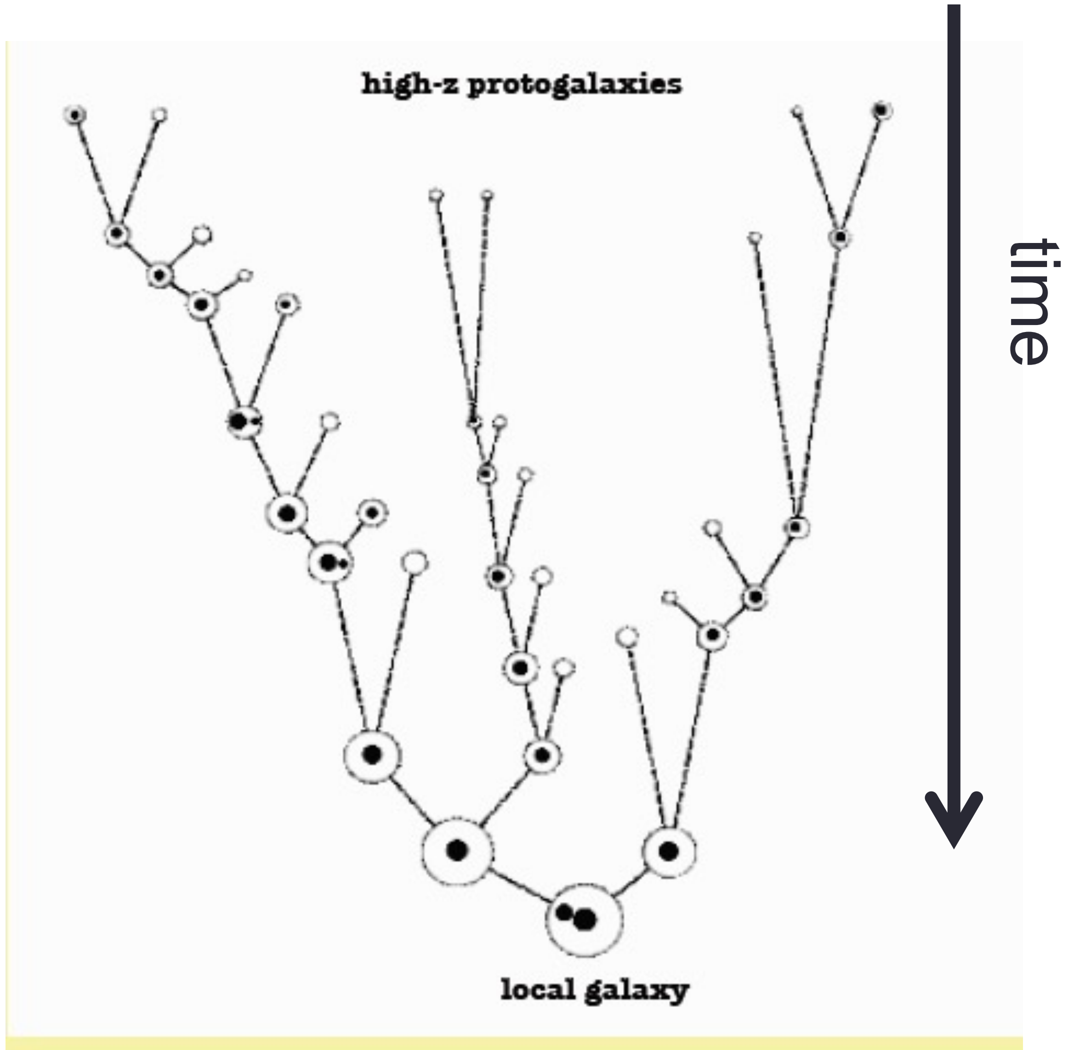
ASSEMBLY AND MERGING HISTORY OF SUPERMASSIVE BLACK HOLES IN HIERARCHICAL MODELS OF GALAXY FORMATION

Volonteri, Haardt, & Madau

- Gravitational instability due to the non-uniform matter distribution caused matter to condense until small regions become gravitationally bound

- The first collapsing objects are small and merge later to form

  more massive systems: BOTTOM-UP/HIERARCHICAL
- Make assumption that these 'small' objects host BHs and that as the galaxies merge the BHs do also
- When they merge they emit gravitational waves

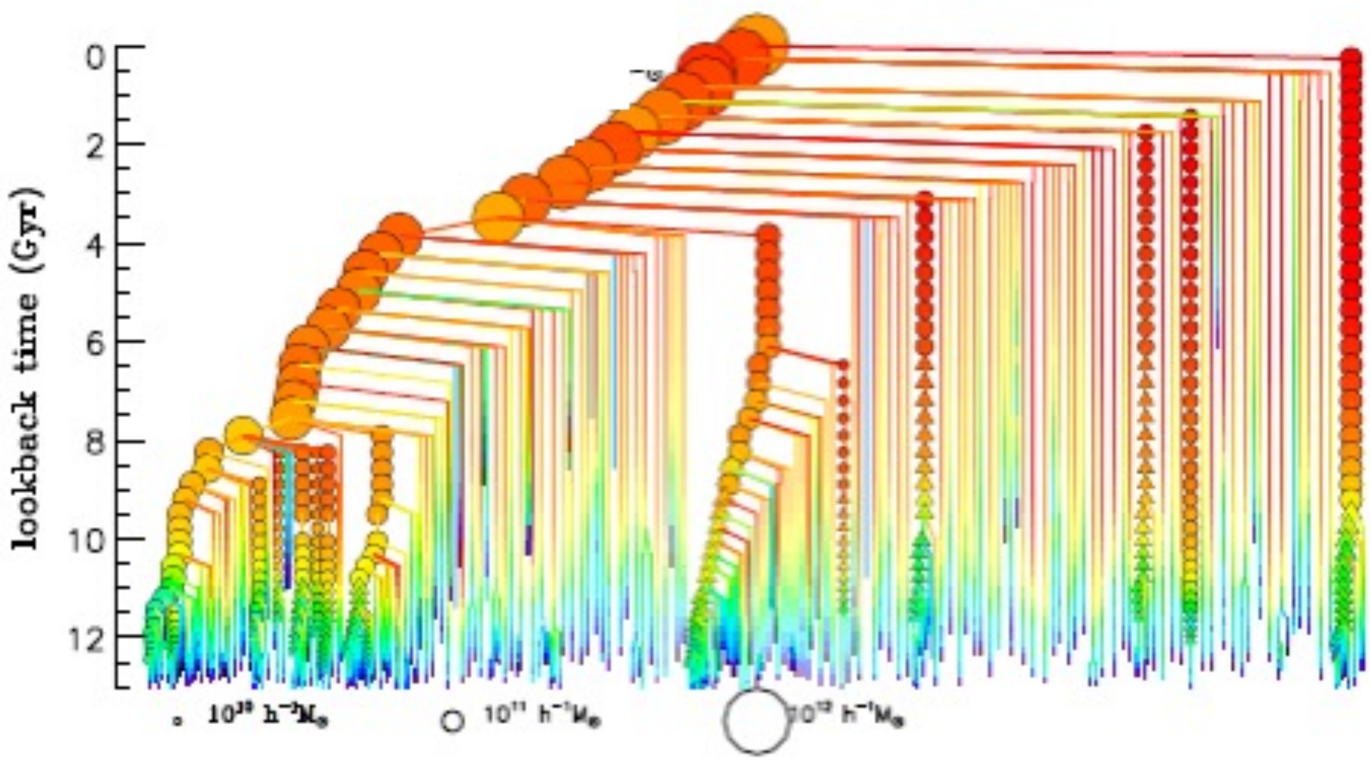


Cold Dark Matter (CDM) theory of structure formation

- small things form first
- merge together over time to form big things
- Expect massive (luminous) BHs to appear later in the universe than smaller mass BHs

Now

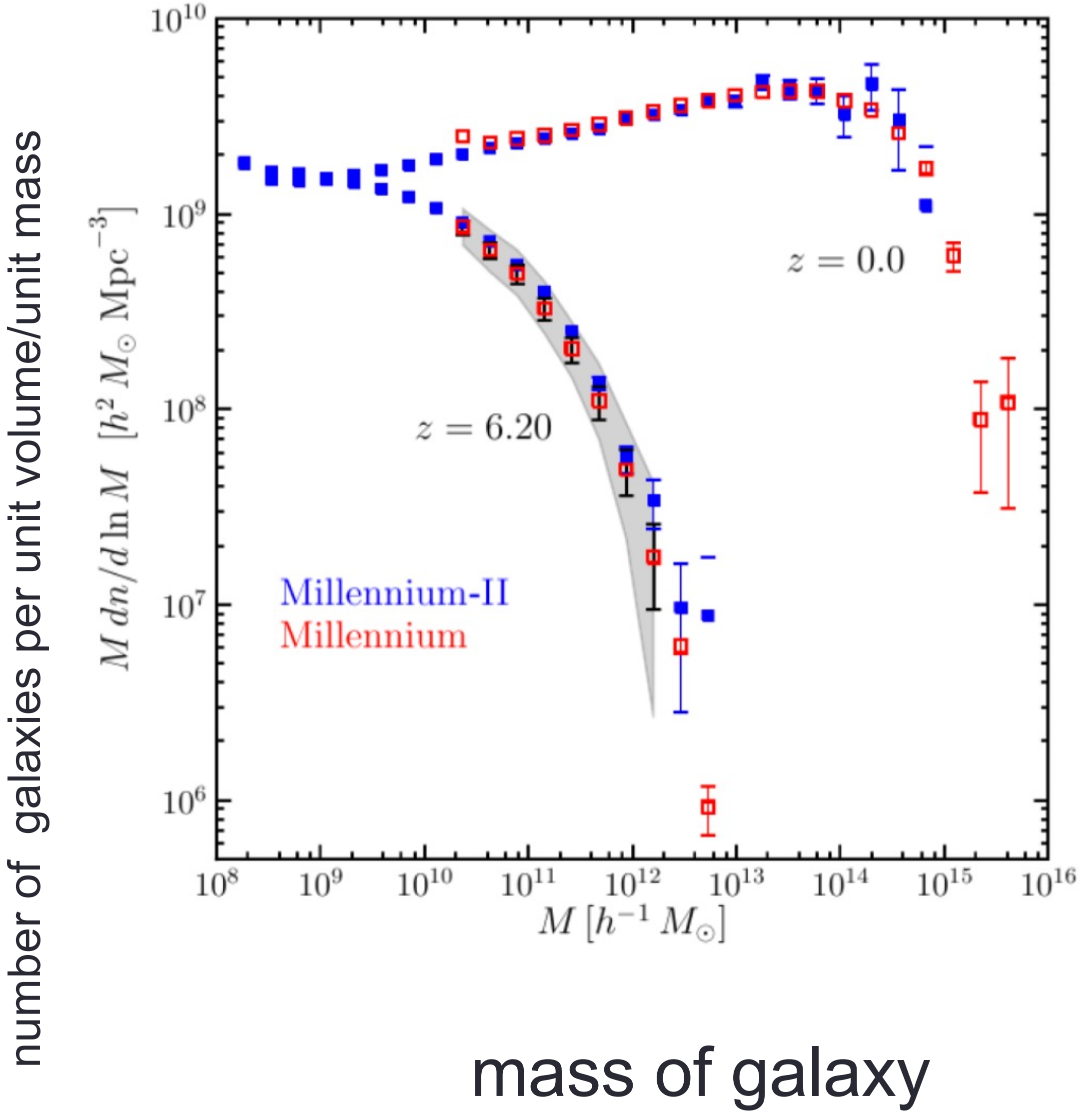
10^{10} yrs ago



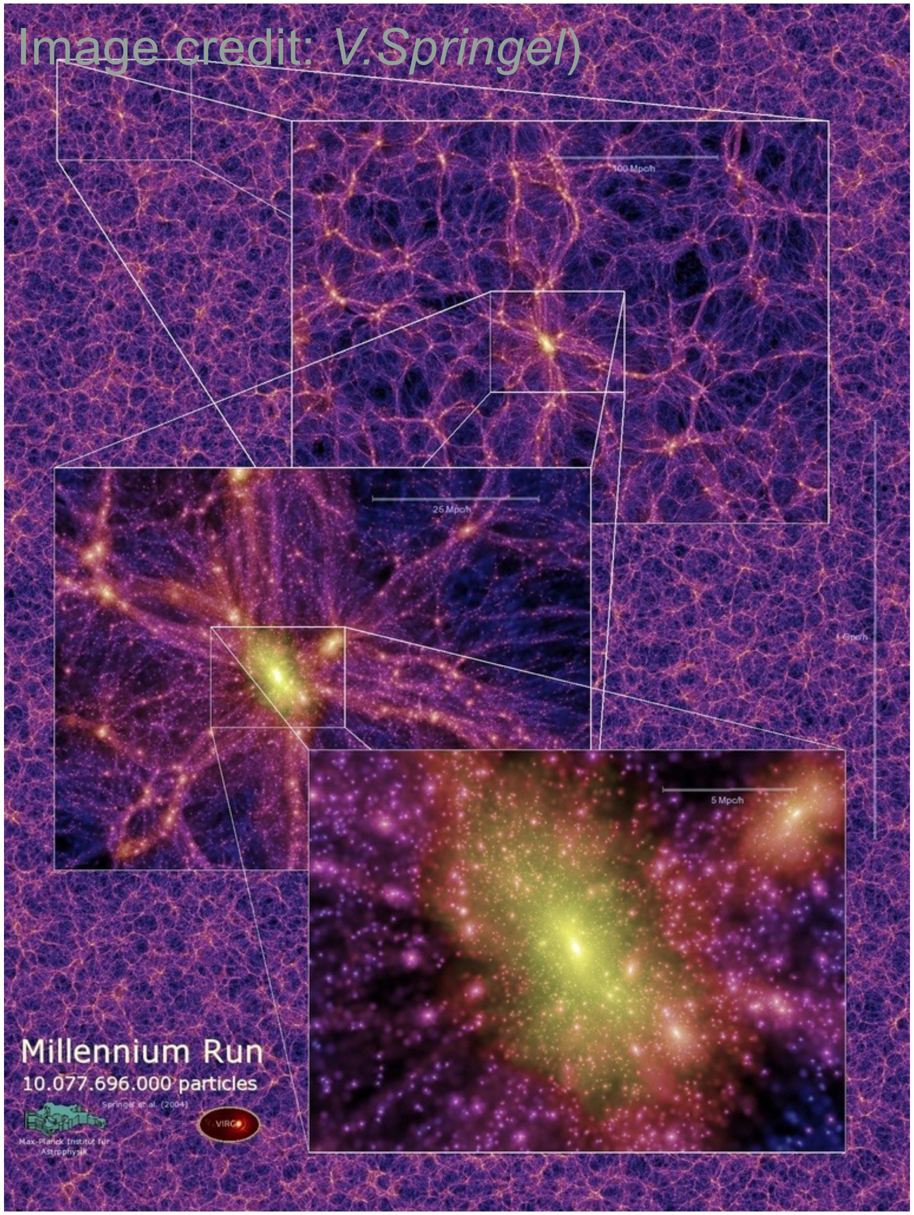
circle size is logarithmically proportional to galaxy mass

Growth of Galaxies

- At high redshift very few massive galaxies
- Number of massive galaxies increases dramatically with time
- Massive galaxies have big black holes



The "Millennium simulation"



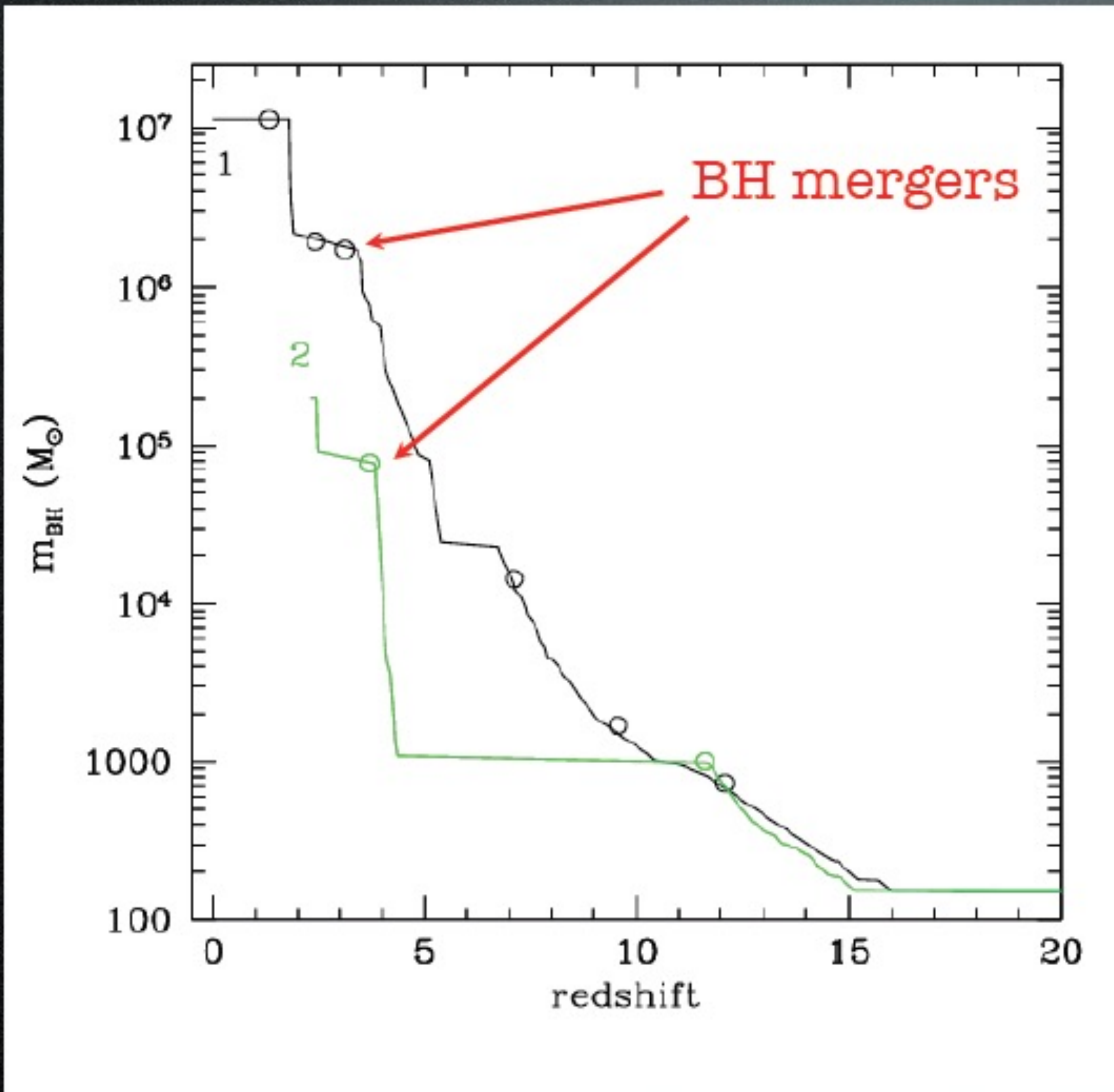
- Follows what becomes 20 million galaxies over 2 billion years
- Volume (2 Glyr)^3
- More than 10^{10} particles
- 25 Terabytes of data produced

- In this picture color corresponds to the logarithm of the density (dark purple low, yellow high)

20Mpc thick slice at z=0 with 4x zoomed regions

Folding in mergers and accretion in a hierarchical model...

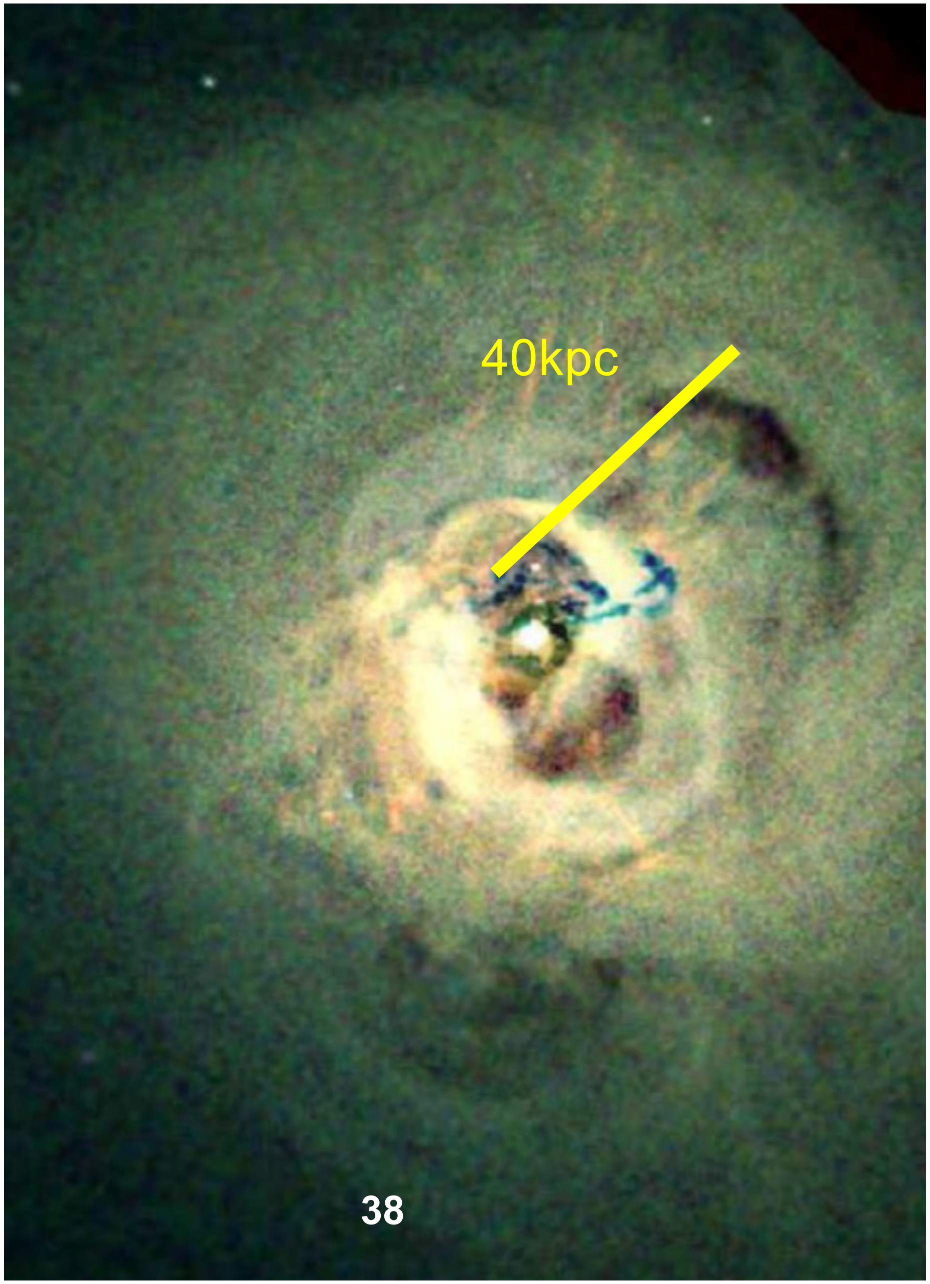
Volonteri 2008



- ✔ MBH mergers are rare events, as they require a merger between two galaxies BOTH with a central MBH
- ✔ not ALL MBHs experience a merger in their lifetime, only ~ 40-50%
- ✔ mass growth dominated by accretion [redacted]

Back Holes Can Influence Galaxies Over Enormous Scales

- X-ray Image of NGC1275- the AGN is pushing gas very far away- huge amount of energy required



Problems with the Formation of Structure/Galaxies

- How did the universe come to look like it does?

- Detailed numerical simulations show that gravity+ hydrodynamics does not produce the universe we see -many things are wrong e.g. galaxies are too big, too bright too blue, form at wrong time, wrong place.

Paradiso Canto 31

- What else is required?
  - FEEDBACK-The influence of objects on the universe (stars and AGN)
  - Stars don't have enough energy
  - So it has to be AGN
    - How?
    - Where?
    - When?
- lots of reasons to believe in feedback

Paradiso Canto 31

How the Observable Universe Came to Be

- **Dark matter** evolution in the universe is now understood
  - **it is not well understood how 'baryonic structures' (galaxies, groups, clusters) form.**
- For models to fit the data additional physics (beyond gravity and hydrodynamics) is required (heating, cooling, mass and metal injection, gas motions etc- this is called feedback)
- AGN seem to be a critical component in this story.... but we do not know
  - How is massive black hole growth and galaxy formation coupled?
  - How do feedback processes couple enormous spatial scales- from Schwarzschild radius to Mpc?
-

Galaxy formation and accretion on supermassive black holes appear to be closely related

Observational evidence suggests a link between BH growth and galaxy formation:

Connection of BH mass to Galaxy mass
Similarity of evolution

Theoretical models often assume that BH growth is self-regulated by **strong** feedback:

- Blow out of gas in the halo once a crtitical M_B is reached
  Silk & Rees (1998), Wyithe & Loeb (2003)

Black holes play an important role in galaxy formation

Springel 2004

Galaxy formation models need to include the growth and feedback of black holes !

Co-evolution of Galaxies and Black Holes

Comparison of
growth of galaxies
(Star formation luminosity density)
vs growth of AGN
(luminosity density)
of AGN (Fiore et al 2018)

At z<4 black hole growth and galaxy growth parallel each other