ORIGIN OF SUPERMASSIVE BLACK HOLES

Lecture 13, Introduction to Black Hole Astrophysics

NTHU, 5/25/2021

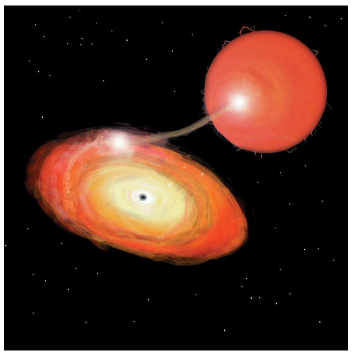
PREVIOUS LECTURE…

- AGN feedback is important for formation and evolution of galaxies, evident from both simulations and observations (e.g., the M-sigma relation)
- Quasar-mode feedback
  - From AGN accreting at high Eddington rate at higher redshifts
  - Operate by expelling gas from galaxies via winds
  - Plausible mechanism for the M-sigma relation
  - Could quench star formation and regulate SMBH growth
- Jet-mode feedback
  - From AGN accreting at lower Eddington rate at lower redshifts
  - Operate by heating surrounding gas by jets
  - Can prevent galaxy clusters from collapsing
  - Can limit the growth of massive galaxies

THIS LECTURE

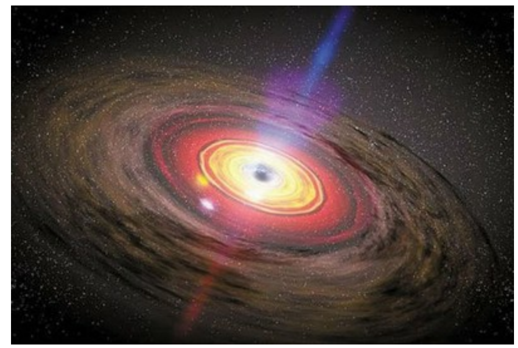
- A problem of SMBH growth – how to form massive quasars in the early universe?
- How to solve the problem – BH "seeds"
- Three scenarios of BH seed formation
- Subsequent growth of SMBHs
- Open questions

BLACK HOLES COME IN TWO FLAVORS



Stellar-mass BHs

- Masses: several to tens of M_{sun}
- Originated from collapses of massive stars
- Distributed within galaxies
- Shine in X-ray when accreting from a companion star – X-ray binary



SMBHs

- Masses: ~10^6-10^{10} M_{sun}
- ***Origin???***
- Located at the center of galaxies
- Shine in optical/UV when accreting materials near the galactic centers -- AGN

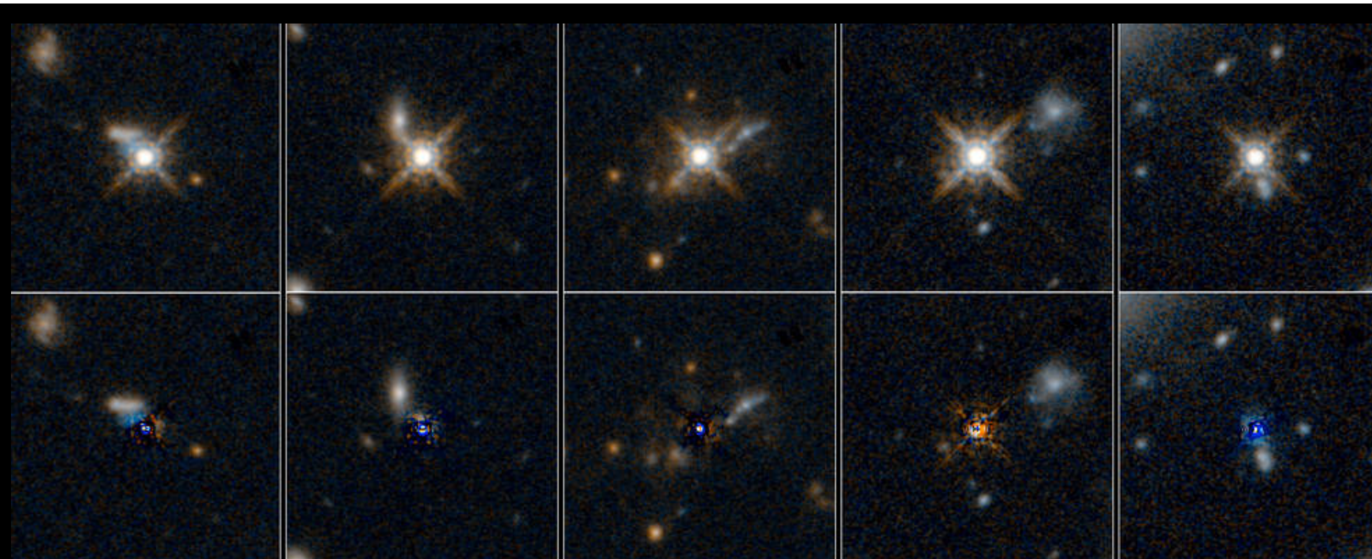
Astronomy and astrophysics [edit]

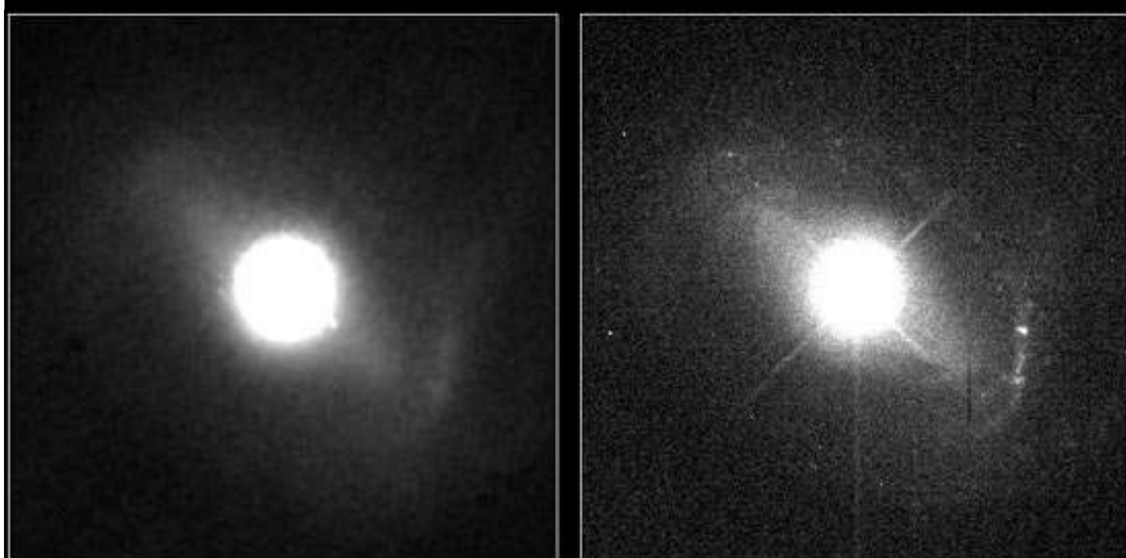
Main article: List of unsolved problems in astronomy

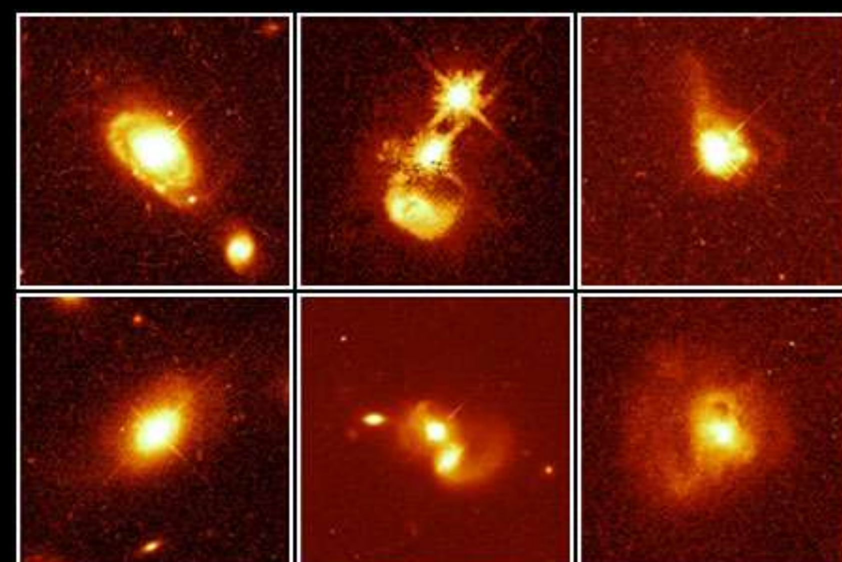
- Supermassive black holes: What is the origin of the M-sigma relation between supermassive black hole mass and galaxy velocity dispersion?[41] How did the most distant quasars grow their supermassive black holes up to 10^{10} solar masses so early in the history of the universe?

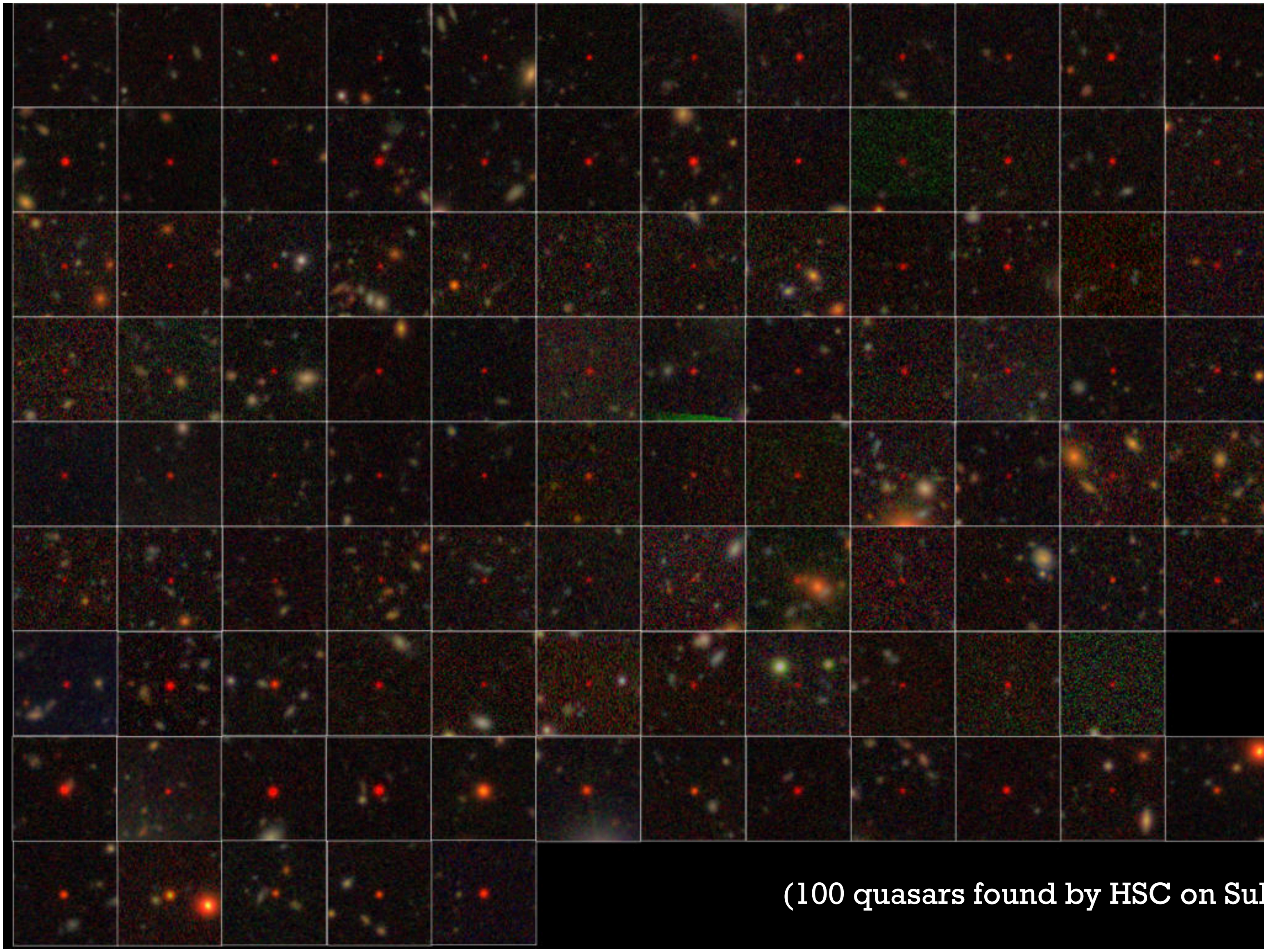
QUASARS

(HST images)





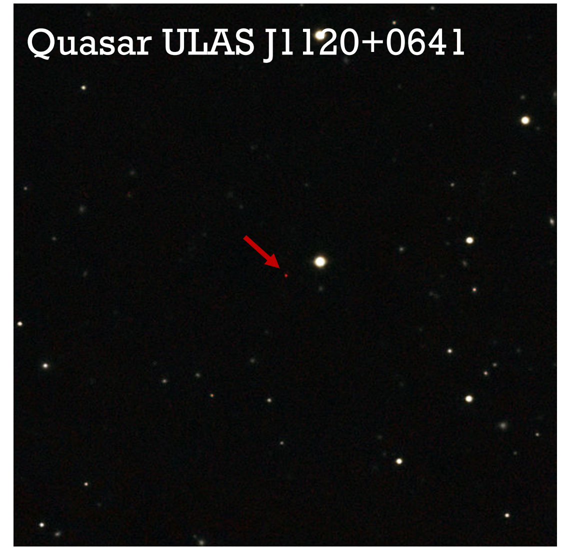




QUASARS

(100 quasars found by HSC on Subaru, 13 billion lyr away)

THE POWERFUL QUASARS IN THE EARLY UNIVERSE



- In 2011, the quasar ULAS J112001.48+064124.3 was discovered
  - Redshift z = 7.085 (***760 Myr*** after Big Bang)
  - Luminosity L = 3×10^{40} W -> ***M >~ 2x10⁹ M_sun***
- The record was broken in 2018 by another quasar ULAS J134208.10+092838.61
  - Redshift z = 7.54 (690 Myr after Big Bang)
  - Luminosity L = 1.5×10^{40} W -> $M \gtrsim 8 \times 10^8 M_{sun}$
- Several tens of quasars with similar masses were found after ~1 Gyr after Big Bang
- These objects are relatively rare; most quasars are found at z~2-3
- But their existence is surprising!!

GROWING EARLY QUASARS

- The maximum rate that BHs can grow is limited by the ***Eddington luminosity***
- Recall that $L_{Edd} \equiv \varepsilon \dot{M}_{Edd} c^2$
- Thus the BH accretion rate is

$$\dot{M}_{BH} = (1-\varepsilon)\dot{M}_{Edd} = 2.2\times10^{-9}\left(\frac{M_{BH}}{M_{sun}}\right)\left(\frac{1-\varepsilon}{\varepsilon}\right) M_{sun} yr^{-1}$$

$$\dot{M}_{BH} = \frac{dM_{BH}}{dt} = AM_{BH}\left(\frac{1-\varepsilon}{\varepsilon}\right), \qquad A = 2.2\times10^{-9} yr^{-1}$$

$$\Rightarrow M_{BH}(t) = M_{BH}(0)e^{\left(\frac{1-\varepsilon}{\varepsilon}\right)\left(\frac{t}{t_{Edd}}\right)}, \quad t_{Edd} = A^{-1} = 450\ Myr$$

GROWING EARLY QUASARS

$$M_{BH}(t) = M_{BH}(0)e^{\left(\frac{1-\varepsilon}{\varepsilon}\right)\left(\frac{t}{t_{Edd}}\right)}, \quad t_{Edd} = A^{-1} = 450\ Myr$$

- Given $\varepsilon = 0.1$, one can show that there is not enough time for a stellar-mass BH with ~10 M_{sun} to grow to ~10^9 M_{sun} within such a short timescale of 600-700 Myr
- Instead, the massive SMBHs in the early universe can be explained if BHs form from initial "***BH seeds***" with ***$M(0) = 10^2 \sim 10^5\ M_{sun}$***
- After seed formation, these early quasars have to grow exponentially at the Eddington rate
- SMBHs are not grown from smbhs, but they have completely different origin!!

FORMATION OF BH SEEDS

- Structures in the universe form from initial density perturbations due to gravitational instabilities
  - "***hierarchical***": small halos merge into larger halos
  - Gravity is mainly dominated by dark matter; baryons/gas follow
  - Dark matter interacts by gravity only; gas can interact/collide/cool
- Important considerations regarding gas within dark matter halos:
  - When gas ***cools*** more quickly, the gas clouds would tend to fragment and form stars rather than a BH
  - Gas cools faster when it has more ***metals*** (anything heavier than H & He)
  - In general, ***~ zero metallicity*** is required to prevent rapid cooling -> only possible in the early universe before supernovae produces metals!
- Three proposed scenarios for BH seed formation depending on the environments:
  - *I.* ***Pop III stars***
  - *II.* ***Collapse of star clusters***
  - *III.* ***Direct collapse of gas clouds***

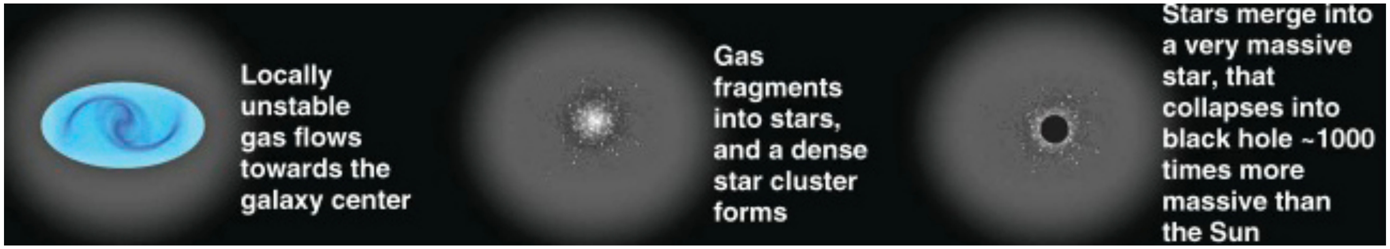
(I) POP III STARS

- ***Pop III star*** = population 3 stars = ***first stars*** formed from unpolluted gas in the early universe before supernovae eject metals into the interstellar medium
  - Types of stars: Pop I (metal-rich), Pop II (metal-poor), Pop III (***metal-free***)
- Occurs in metal-free minihalos at z~20-50
- Key ingredient: without metals, the gas clouds cool very slowly, allowing formation of much more massive stars compared to stars today
- Formation process of the BH seed:

- Predicted mass of BH seeds: ***10^2~10^3 M_{sun} (light seeds)***

(II) COLLAPSE OF STAR CLUSTERS

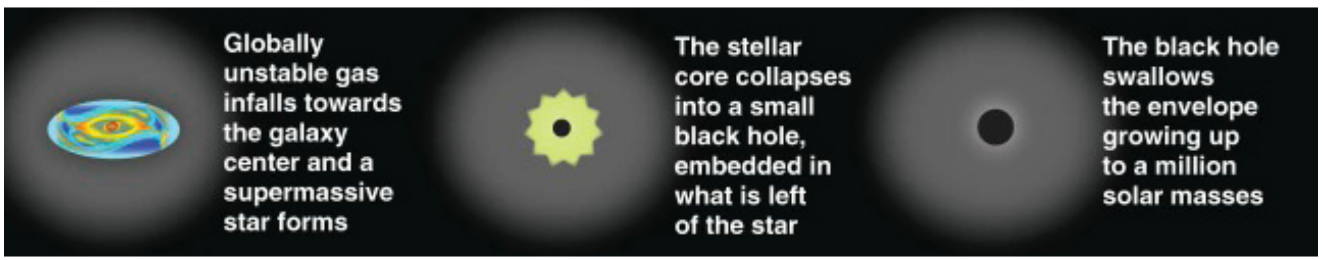
- Occurs in almost metal-free small halos ($T<10^4$K) at z~10-15
- Key ingredient: within this temperature range, cooling is more efficient, which results in the formation of a dense star cluster
- Formation process of the BH seed:



- Predicted mass of BH seeds: ***10^2~10^4 M_{sun} (intermediate seeds)***

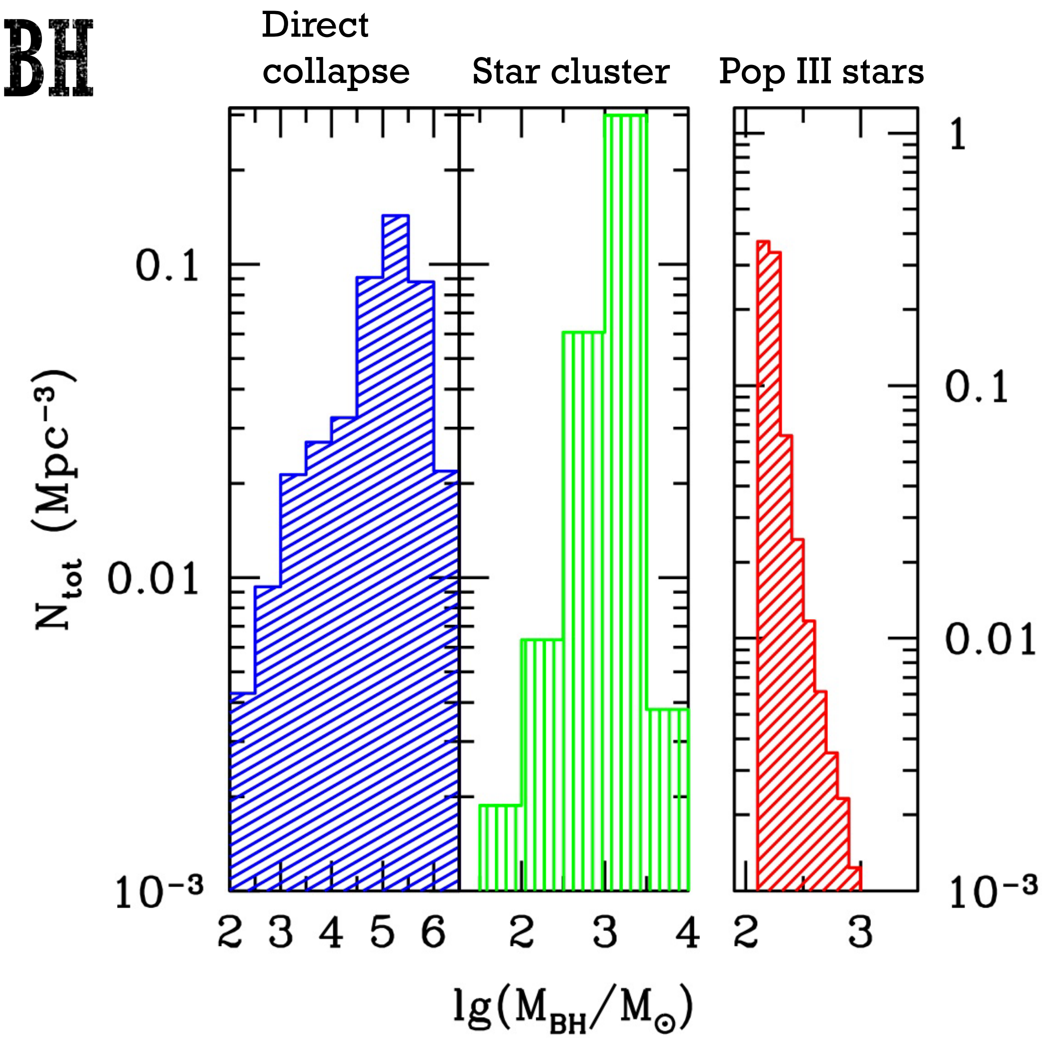
(III) DIRECT COLLAPSE OF GAS CLOUDS

- Occurs in almost metal-free large halos ($T>10^4K$) at $z\sim5-10$
- Key ingredient: gas cooling is suppressed by radiation from nearby stars, which prevents fragmentation and form a supermassive star at the center of the gas cloud
  - These environments are rare since these halos need to be close to stars but not too close to be polluted by metals
- Formation process of the BH seed:



- Predicted mass of BH seeds: ***$10^4\sim10^6$ M_{sun} (heavy seeds)***

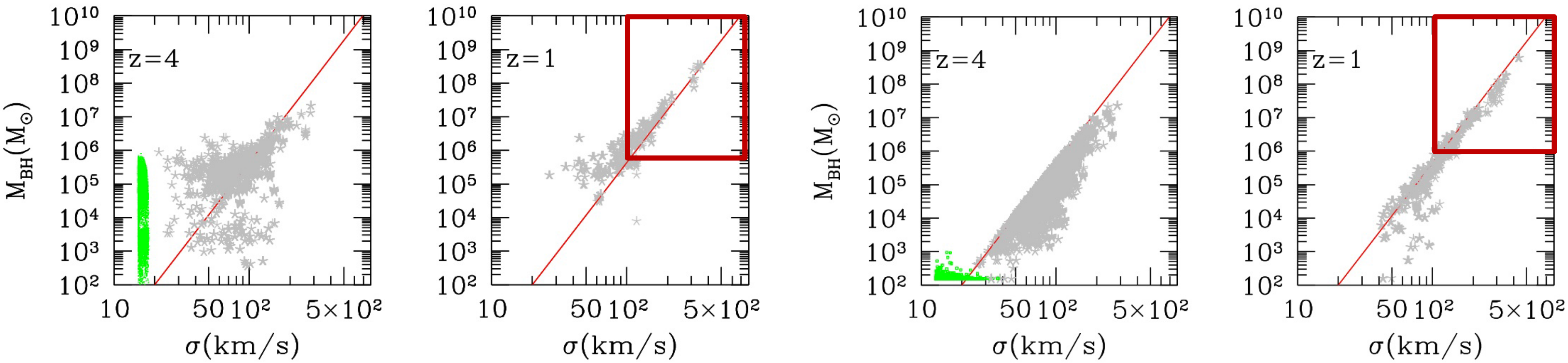
SUMMARY OF BH SEED MASSES



A POSSIBLE WAY TO DISTINGUISH SEEDING MECHANISMS

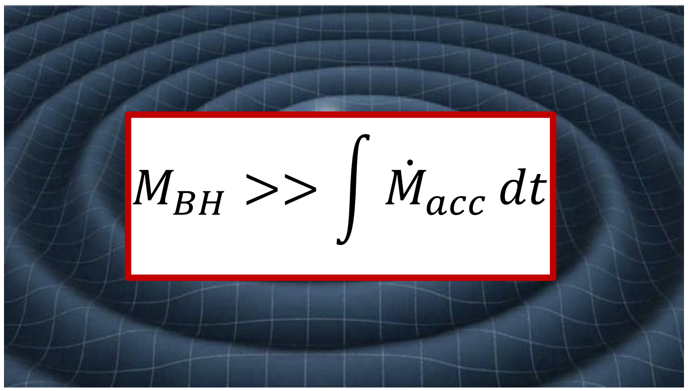
- Different seeding mechanisms predict different evolution on the M-sigma relation
- Important to probe the distribution of ***intermediate-mass BHs (IMBHs, ~10^2-10^5 M_{sun})*** or measure the M-sigma relation at higher redshifts

Direct collapse (heavy seeds) **Pop III stars (light seeds)**



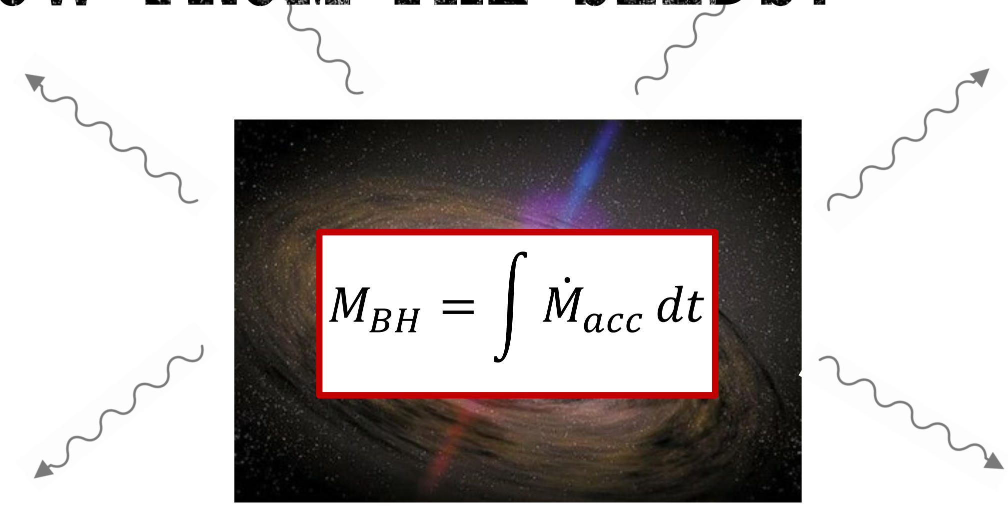
Volonteri & Natarajan (2009)

HOW DO SMBHS GROW FROM THE SEEDS?



$$M_{BH} >> \int \dot{M}_{acc}\, dt$$

By ***BH mergers*** – do SMBHs obtain most of their masses by merging smaller BHs?



$$M_{BH} = \int \dot{M}_{acc}\, dt$$

By ***accretion*** – do SMBHs obtain most of their masses by accreting gas and stars from their surroundings?

THE SOLTAN ARGUMENT

- In 1982, Soltan proposed the idea that, if quasars were powered by accretion onto SMBHs, then such SMBHs must exist in our local universe as ”dead” quasars
- That is, the mass distributions of SMBHs today are the results of the ***accretion*** history inferred from AGN
- If true, the following relationship should hold:

$$\mathcal{E}_{acc}(1+z) = \frac{\varepsilon}{1-\varepsilon}\rho_{BH}c^2$$

Energy density of radiation from accreting SMBHs; measured from observed AGN spectra

Due to redshift of photon energy during cosmic expansion

Density of SMBHs; measured from galaxy distributions & M-sigma relation

IMPLICATIONS OF THE SOLTAN RELATION

- SMBHs obtain most of their masses by ***radiatively efficient accretion*** of gas and stars, instead of by merging with other BHs or radiatively inefficient accretion flows
- SMBHs in normal galaxies today are evolved from luminous AGN at higher redshifts.
  - ~10% of SMBHs are currently actively accreting, i.e., AGN
  - Could it be that only ~10% of the SMBHs are AGN all the time, while the other ~90% SMBHs are quiescent all the time??
  - ***No***: This scenario would produce a population of hyper-massive BHs within a small fraction of galaxies, inconsistent with observational data
  - ***Yes***: Most SMBHs experience AGN activity for ~10% of their lifetime

SOME OPEN QUESTIONS

- Which BH seeding mechanism is supported by the observational data?
- After the BH seeds formed, how can they sustain continuous growth at the Eddington rate, especially under the influence of feedback?
- How likely is it to form early SMBHs by super-Eddington accretion? What conditions are necessary? How much can the mass grow?
- What is the distribution of IMBHs? What are the best ways to observe them? Do they exist in all dwarf galaxies? Do they have similar properties as SMBHs or not?

SUMMARY

- The origin of SMBHs is one of the major unsolved questions in astrophysics
- Existence of billion-M_{sun} quasars at z>6 requires accretion at the Eddington rate of ***BH seeds*** with masses 10^2~10^5 M_{sun}
- Three proposed mechanisms for BH seed formation:
  - ***Pop III stars***: z~20-50, M_{BH} ~ 10^2~10^3 M_{sun} (light seeds)
  - ***Collapse of star clusters***: z~10-15, M_{BH} ~ 10^2~10^4 M_{sun} (intermediate seeds)
  - ***Direct collapse of gas clouds***: z~5-10, M_{BH} ~ 10^4~10^6 M_{sun} (heavy seeds)
- The Soltan argument -- after seed formation, SMBHs grow mainly by ***radiatively efficient accretion*** of gas and stars, instead of merging with other BHs or radiatively inefficient accretion flows

PRESENTATIONS 5/25

- This jet from a monster black hole is so huge it dwarfs our Milky Way galaxy by Zi-Xuan Lin 林姿璇

https://qrgo.page.link/P8zRy

- BH-NS star collisions could finally settle the different measurements over the expansion rate of the universe by Jia-Lun Li 李佳倫

https://qrgo.page.link/NzP3p

- Jia-Ying Zhong 鍾佳穎

https://qrgo.page.link/Zqm9x