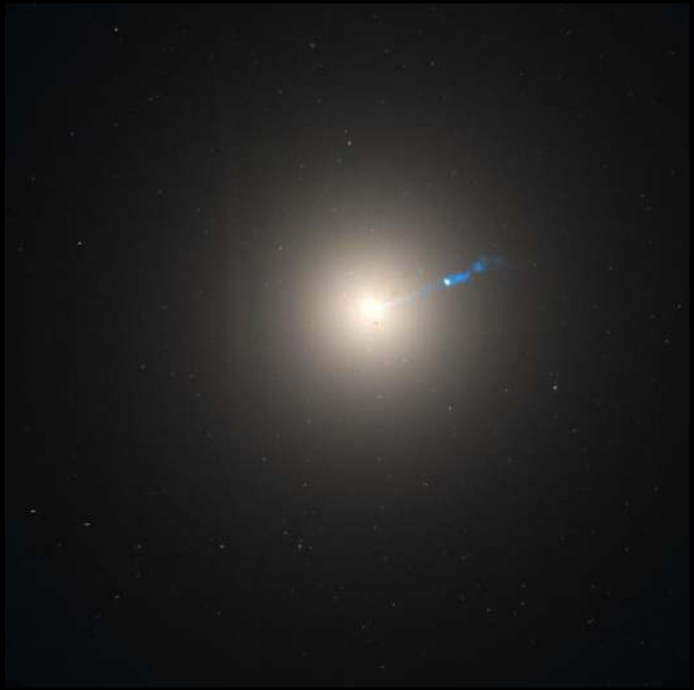
The Assembly of the First Massive Black Holes

(Inayoshi, Visbal, Haiman 2020)

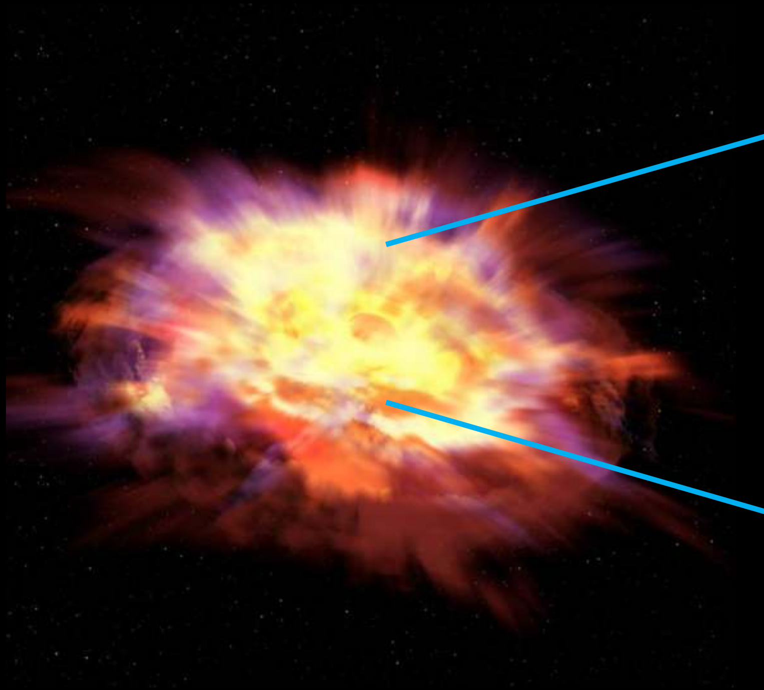
Ryan Hazlett

Credit: NASA/JPL-Caltech

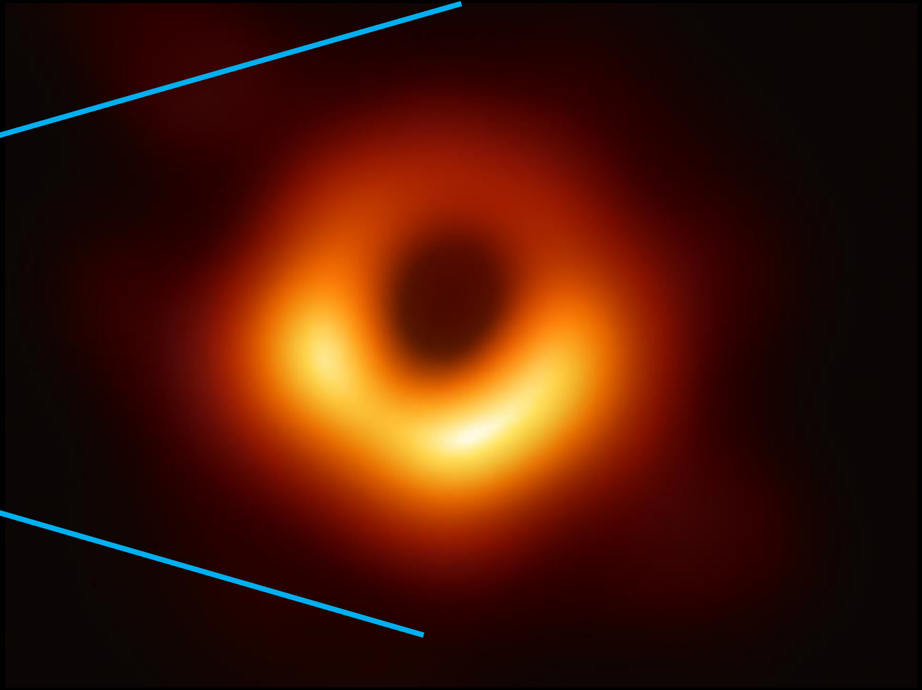
Where are Supermassive Black Holes?



Quasar, Messier 87



Artist’s rendition of an AGN



First image of a SMBH at center of M87

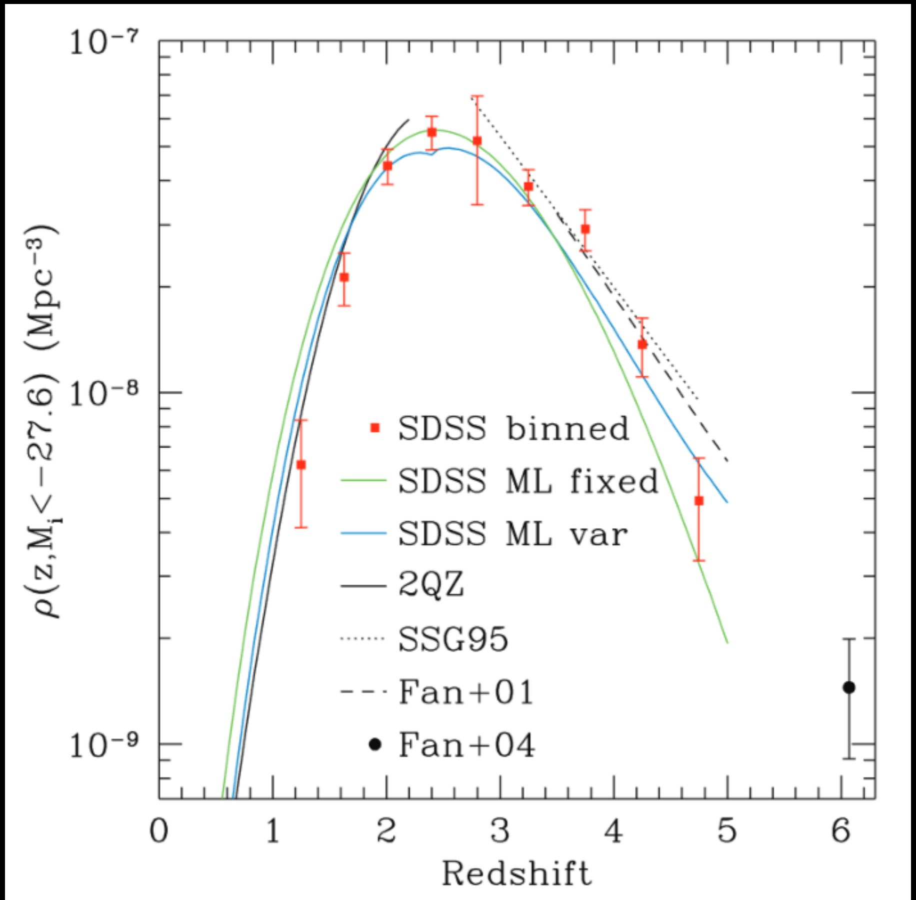
Credit: NASA/HST

Credit: International Gemini Observatory/NOIRLab/NSF/AURA/P

Credit: Event Horizon Telescope collaboration

Why do we care about SMBHs?

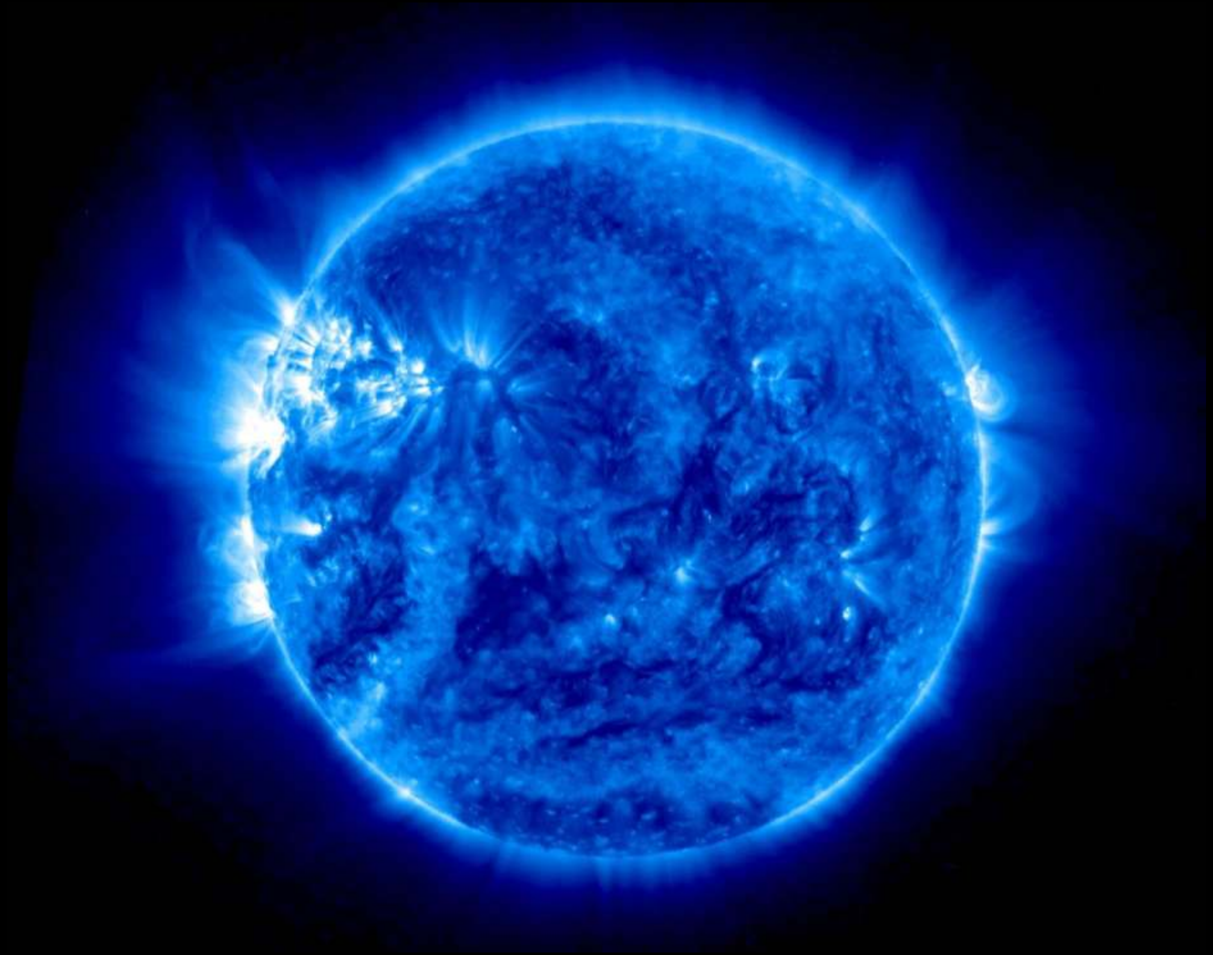
Density of Luminous Quasars



Adopted from Figure 20, Richards et al. (2006a)

How did supermassive black holes like the one in M87 form?

Black Holes from the First Stars



- The first stars were able to grow much larger than stars today.
- What was different in the early universe?

Describing a Star Forming Cloud

$$M_{Jeans} \approx \left(\frac{5kT_{cloud}}{G\mu m_h}\right)^{3/2} \left(\frac{3}{4\pi\rho_0}\right)^{1/2}$$

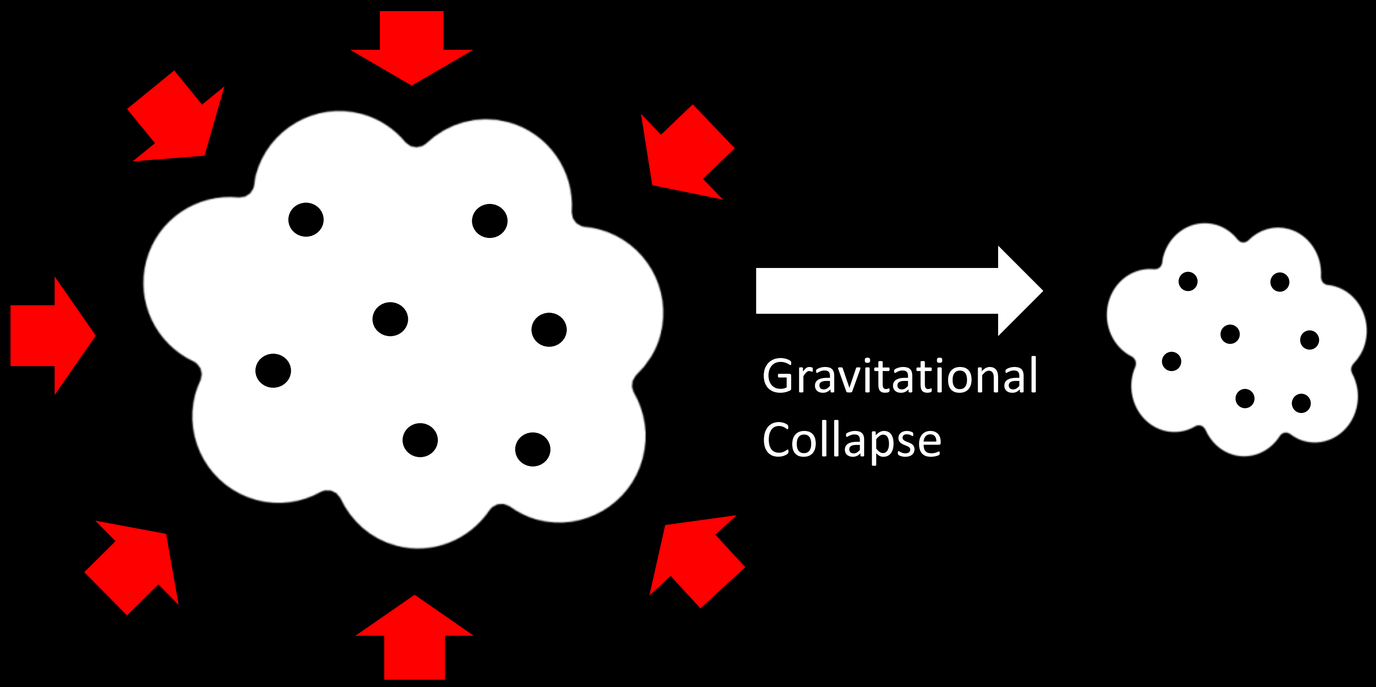
When does the cloud collapse?

If $M_{cloud} > M_{Jeans}$

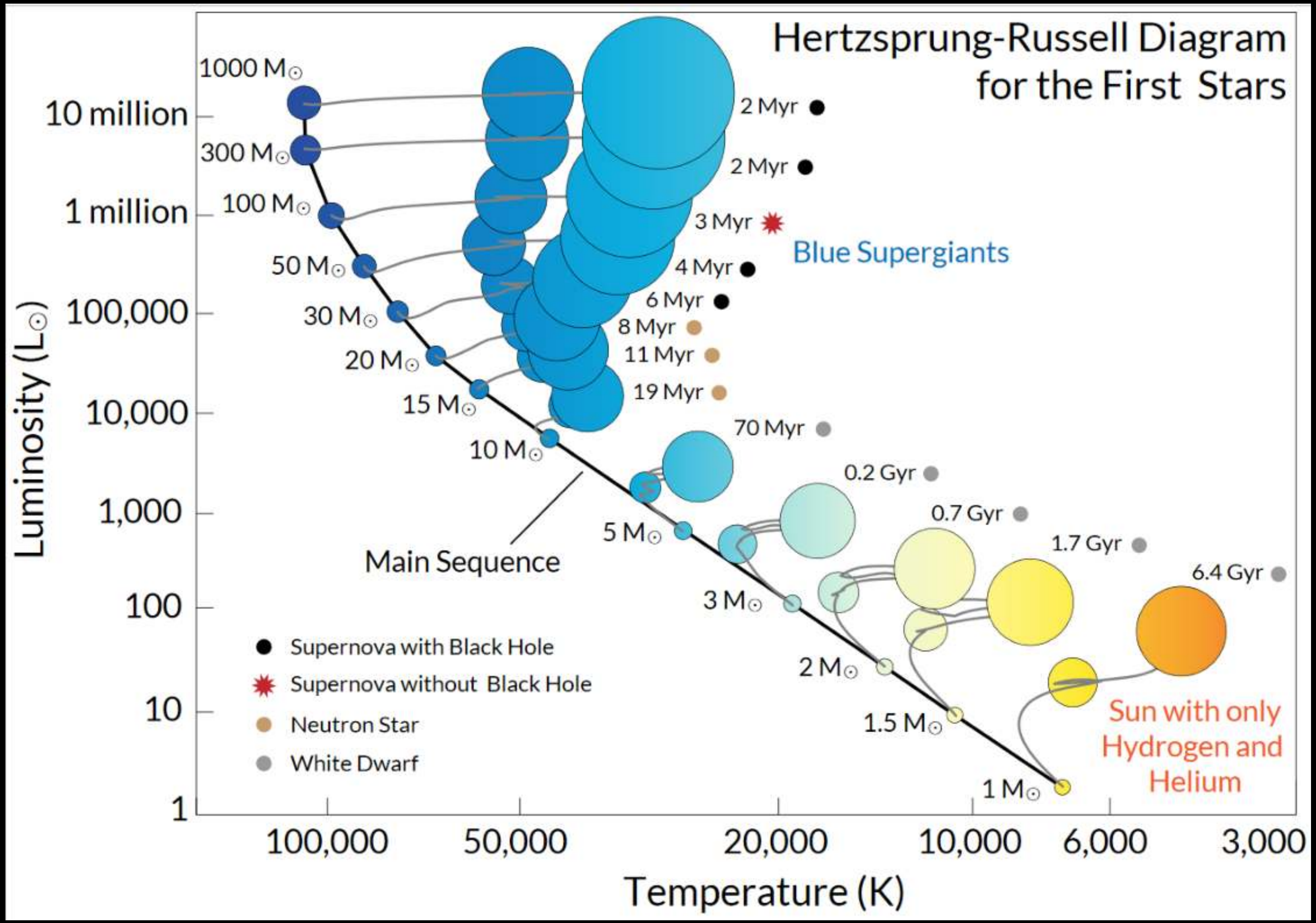
Gravitational energy is larger than internal energy, cloud collapses

What is Different in Early Universe?

$$M_{Jeans} \approx \left(\frac{5kT_{cloud}}{G\mu m_h}\right)^{3/2} \left(\frac{3}{4\pi\rho_0}\right)^{1/2}$$



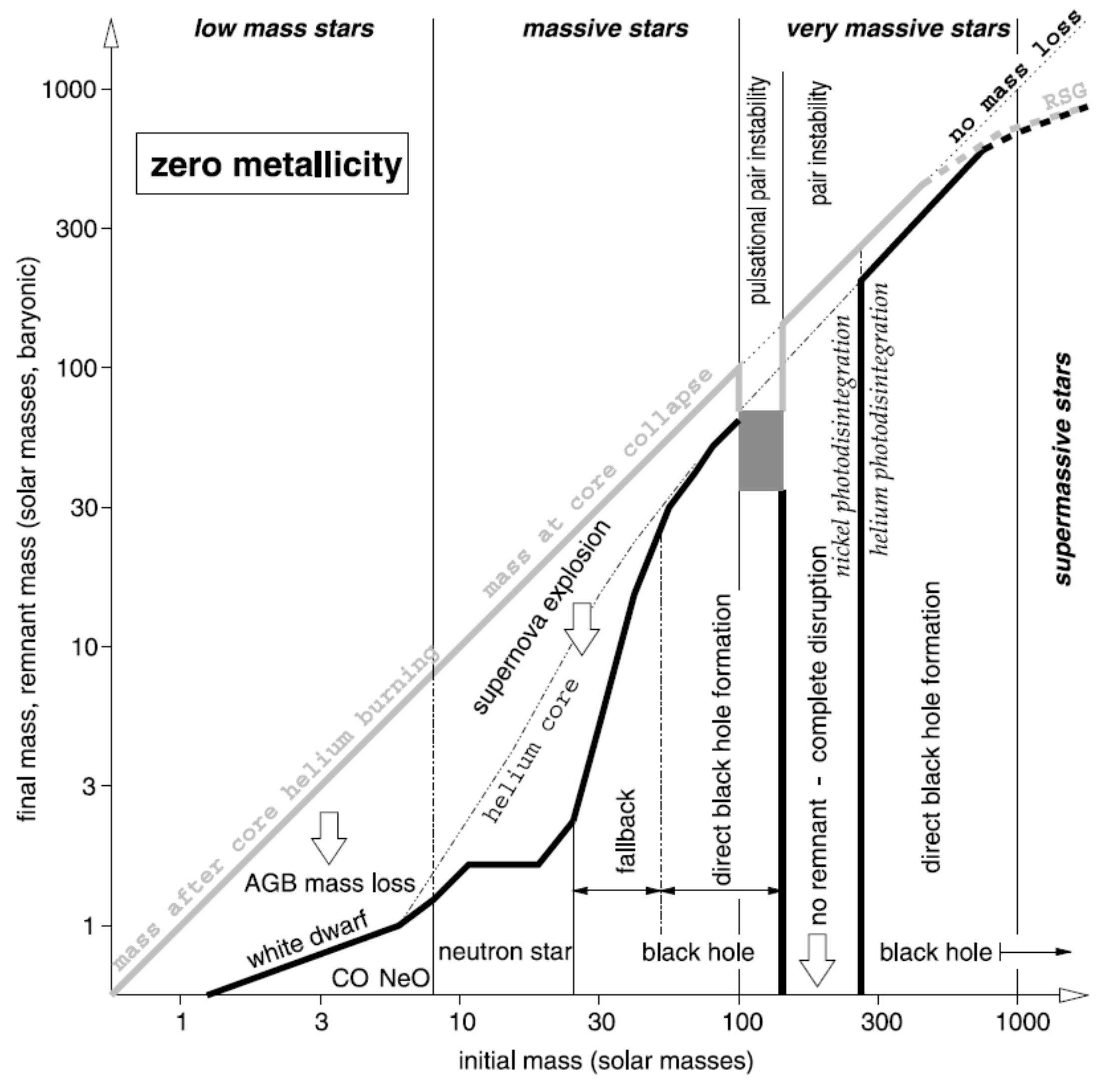
What is different about the First Stars?



Adopted from Windhorst et al. (2018)

- The first stars can become much more massive than stars today.
- IMF for first stars between $10 < M_*/M_\odot < 10^3$
- Mass distribution of first stars is “top-heavy”

How Big were the First Black Holes?



Adopted from Figure 9 Greif (2015)

- Consider first stars between $50 < M_*/M_\odot < 300$
- Models suggest these stars could form black holes of $10 < M_\bullet/M_\odot < 200$

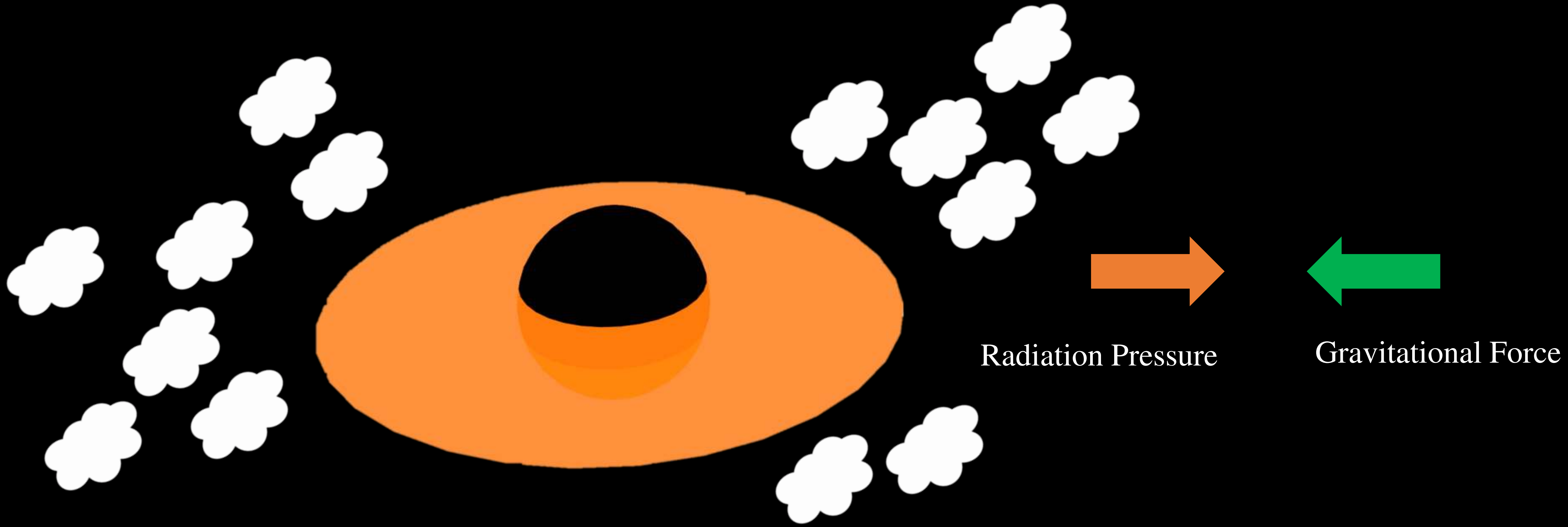
How do the first black holes grow after they form?

Accreting SMBHs observed in Quasars

Artist's rendition of accreting SMBH

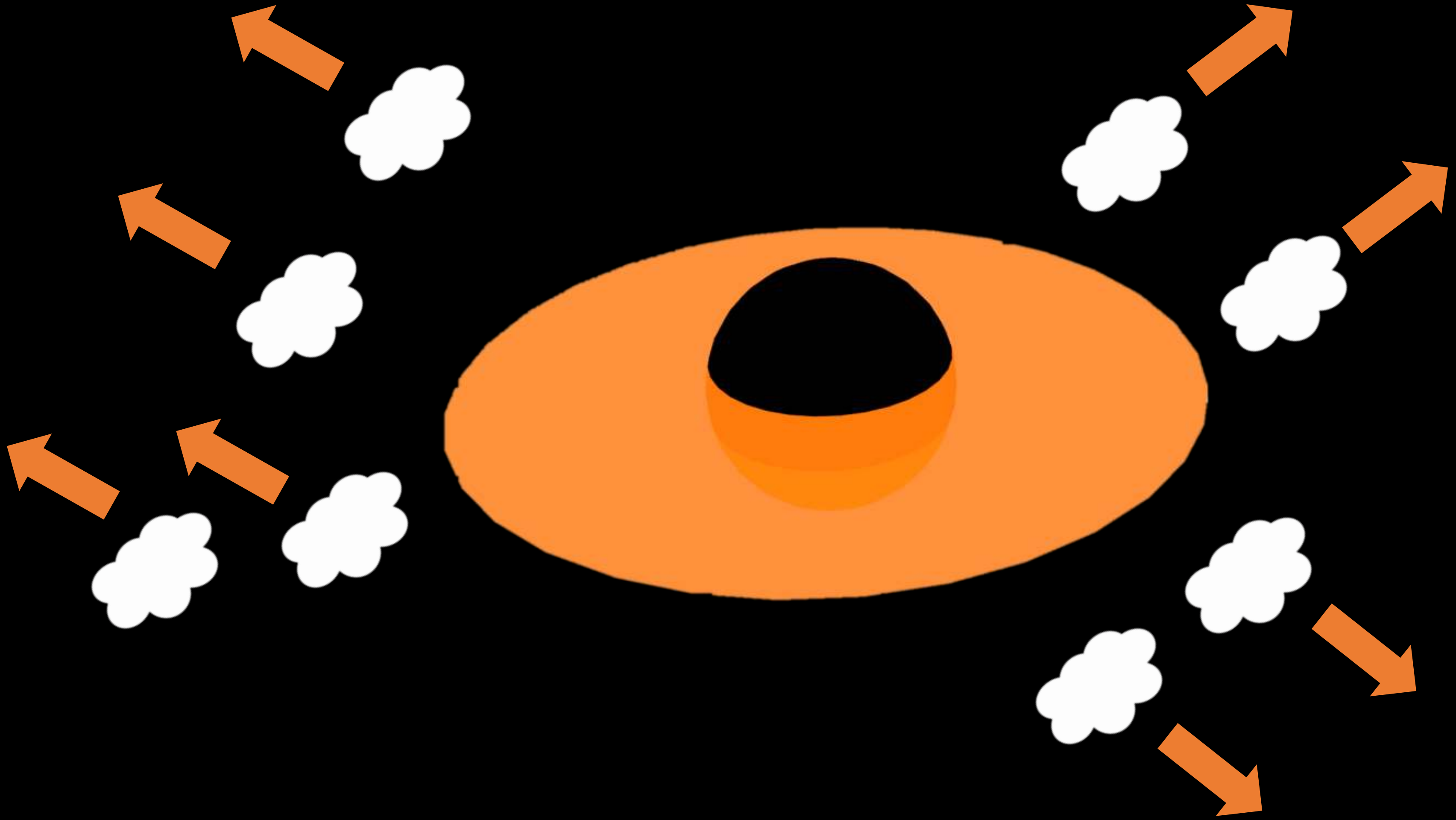
Credit: International Gemini Observatory/NOIRLab/NSF/AURA/P

Accretion at the Eddington Limit



Equilibrium between radiation pressure and gravitational force

Difficult to accrete above Eddington Limit



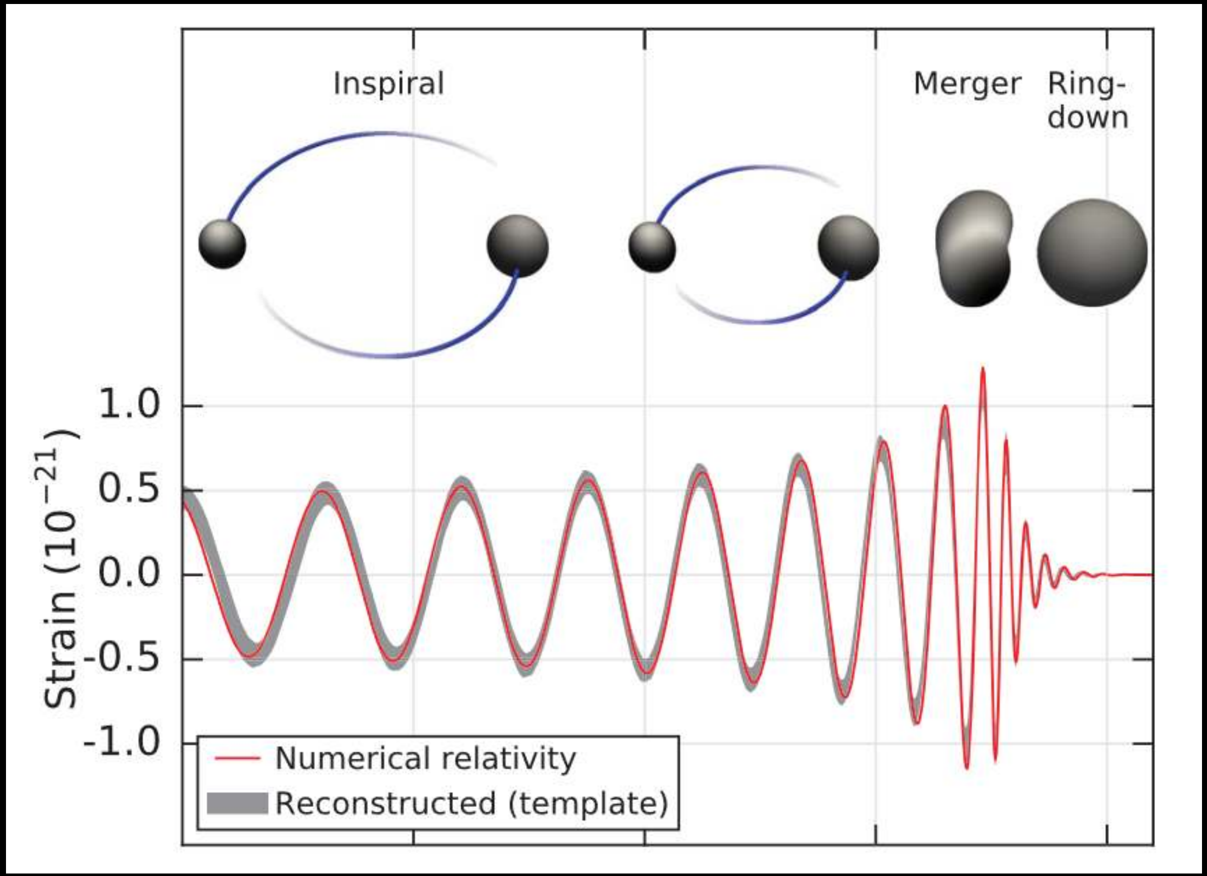
- Accretion results in more radiation from disk
- Not enough matter to overcome radiation pressure
- Infalling matter “blown away”

Possible Problem!

- The first black holes need to grow a lot to reach observed SMBH masses.

- A lot of growth using accretion only.

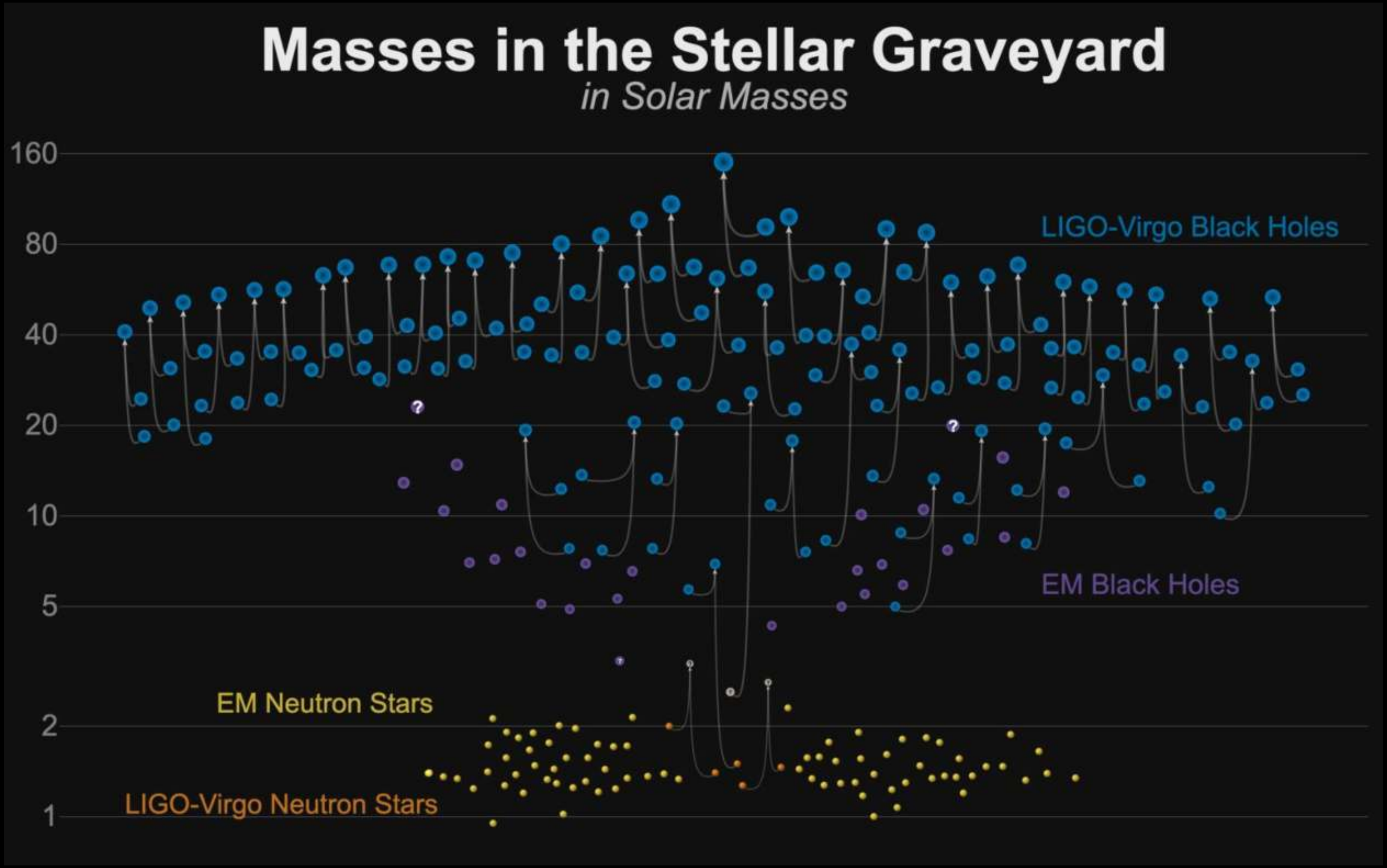
What about Mergers?



Adopted from Figure 2, Abbott et al. (2016)

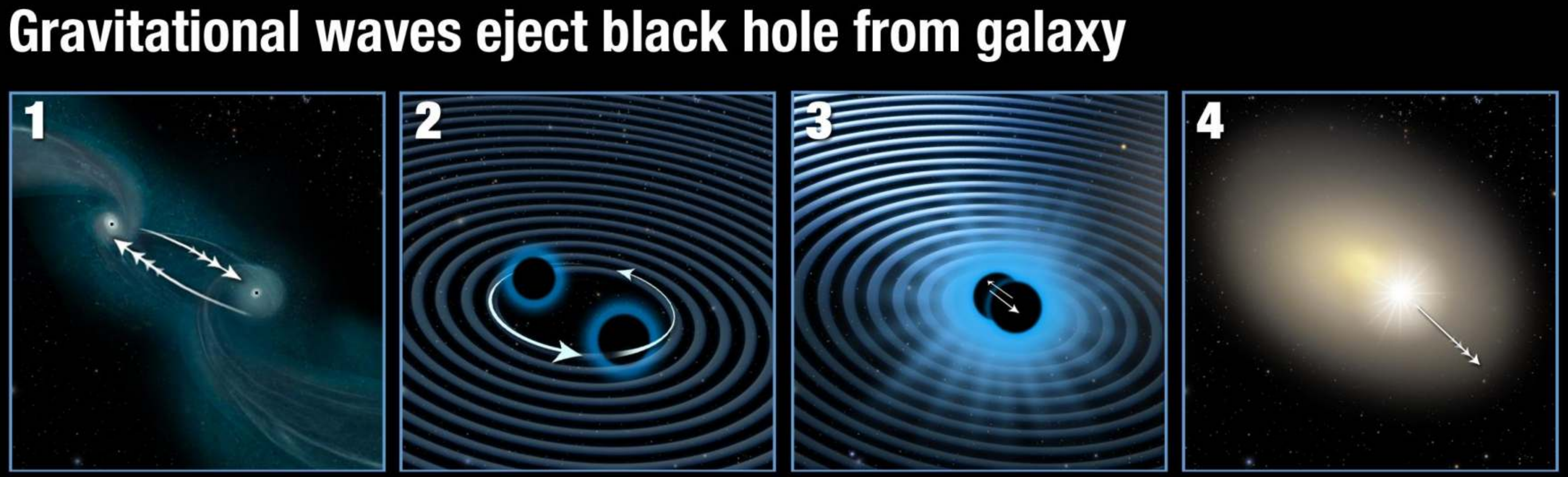
What about Mergers?

$M_\odot$



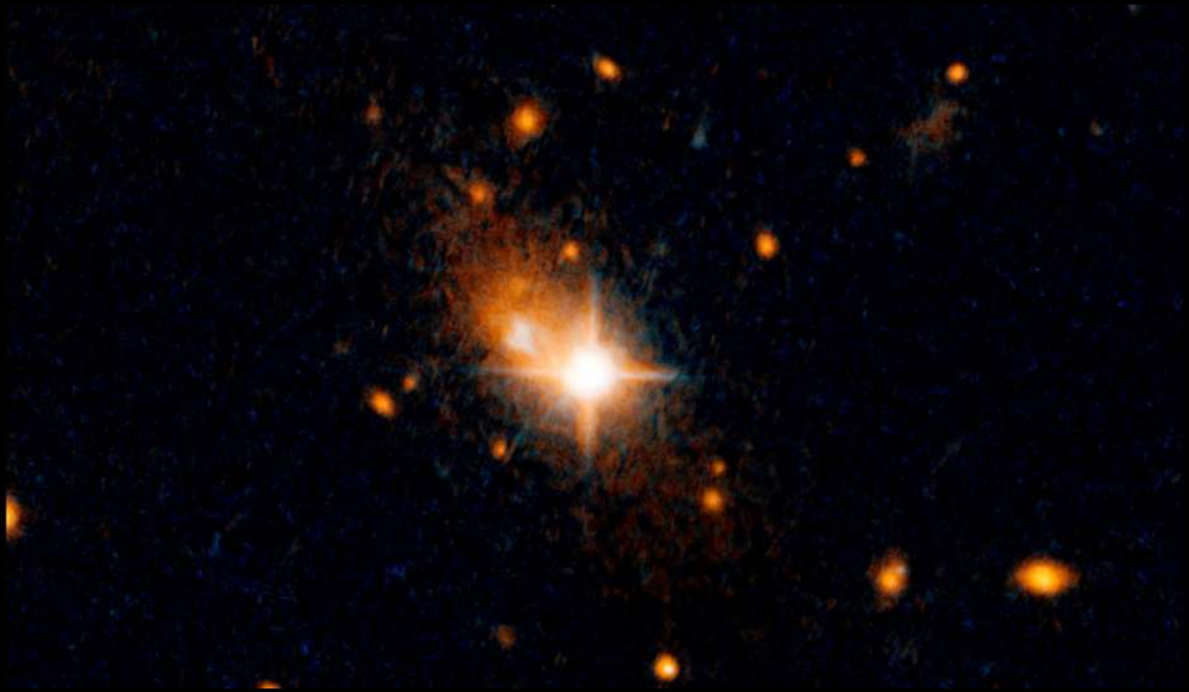
Credit: LIGO-Virgo

Mergers stopping growth?



Credit: NASA, ESA, and A. Feild (STScI)

Mergers stopping growth?

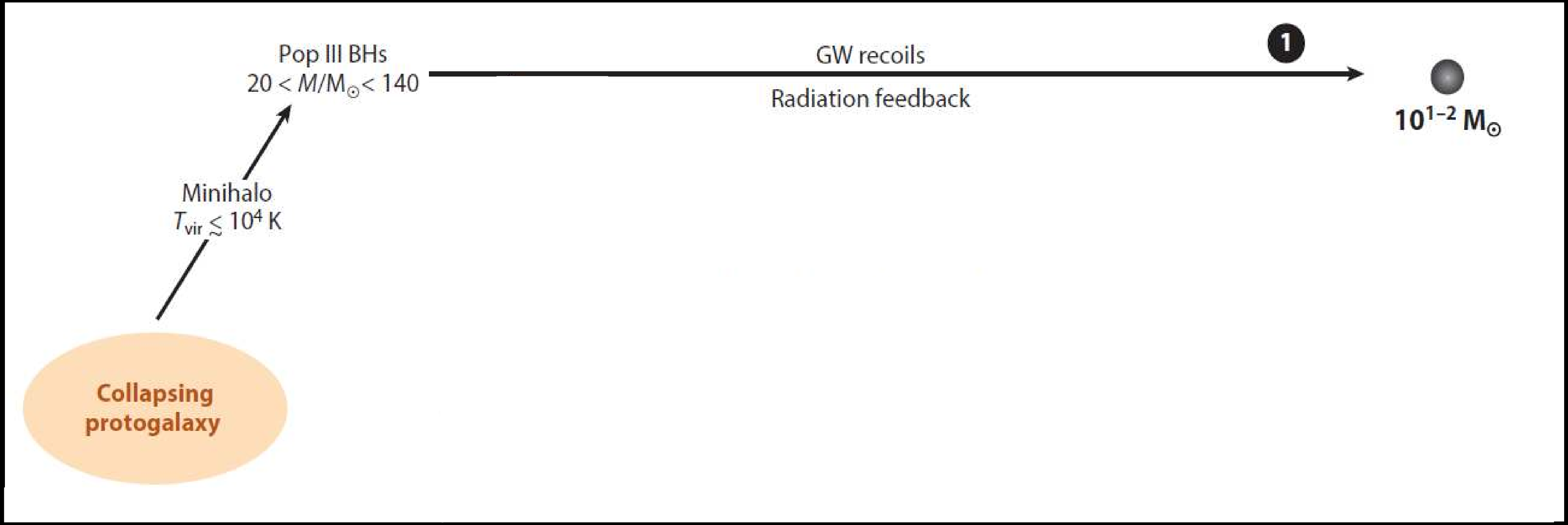


Hubble image of 3C 186 showing a quasar far from its host galaxy's core

- Observational evidence of ejected black holes.
- Typical gravitational recoil velocities may be bigger than 100 km s^{-1}

Credit: NASA, ESA, and M. Chiaberge (STScI and JHU)

Seed of a Supermassive Black Hole

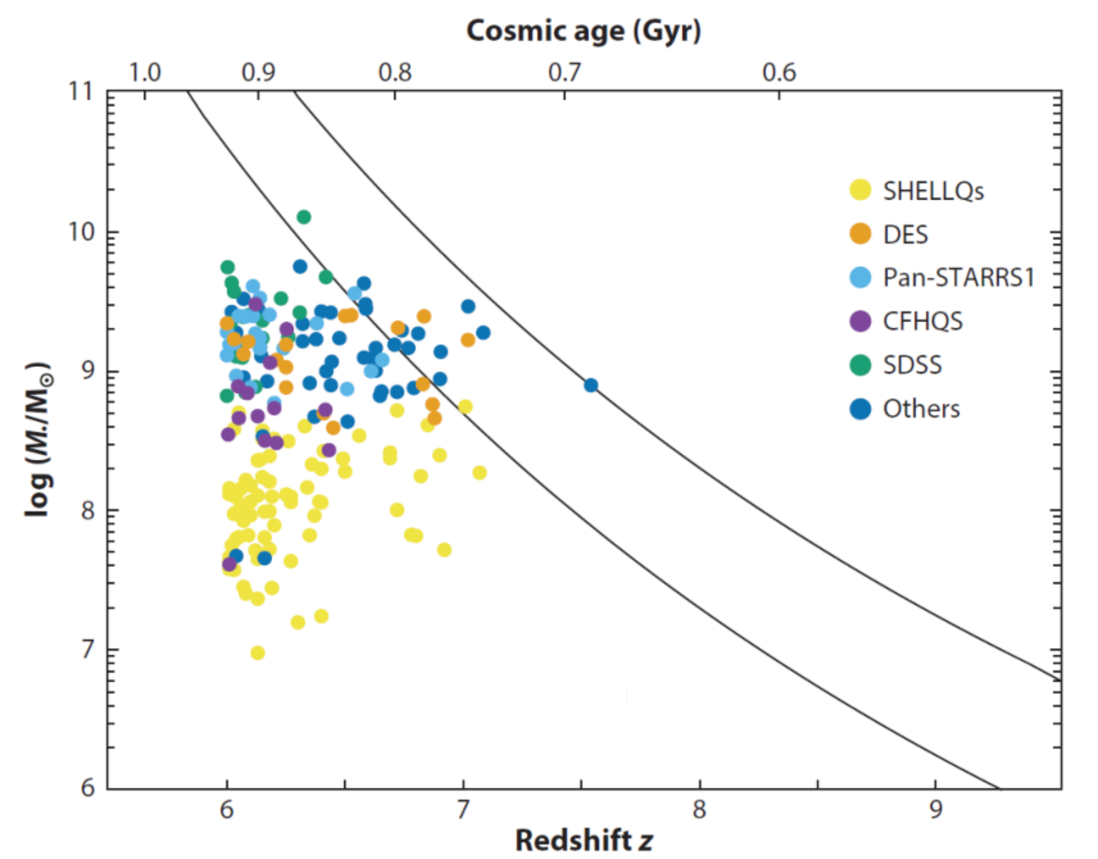


Adopted from Figure 3, Inayoshi, Visbal, Haiman (2020)

- Can this seed black hole explain observed SMBH masses?

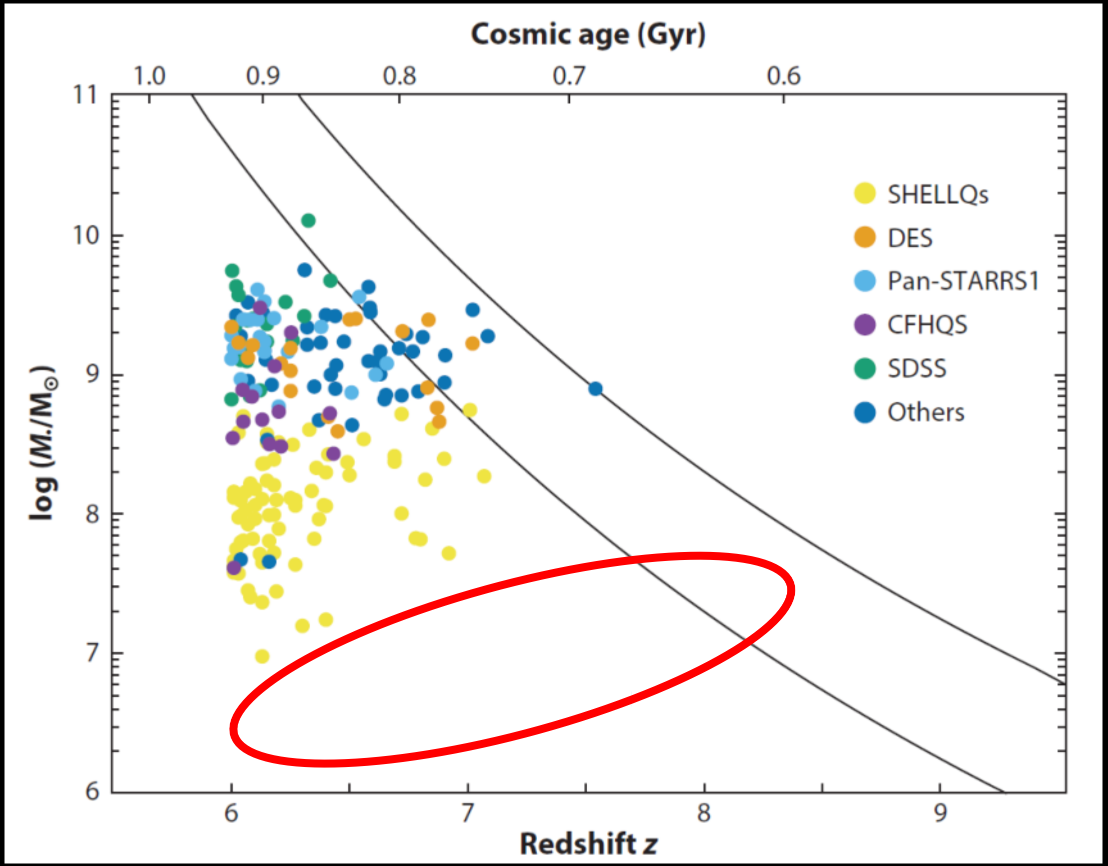
- Let’s look at the earliest SMBHs we can see!

Supermassive black holes in the early universe



Adopted from Figure 1, Inayoshi, Visbal, Haiman (2020)

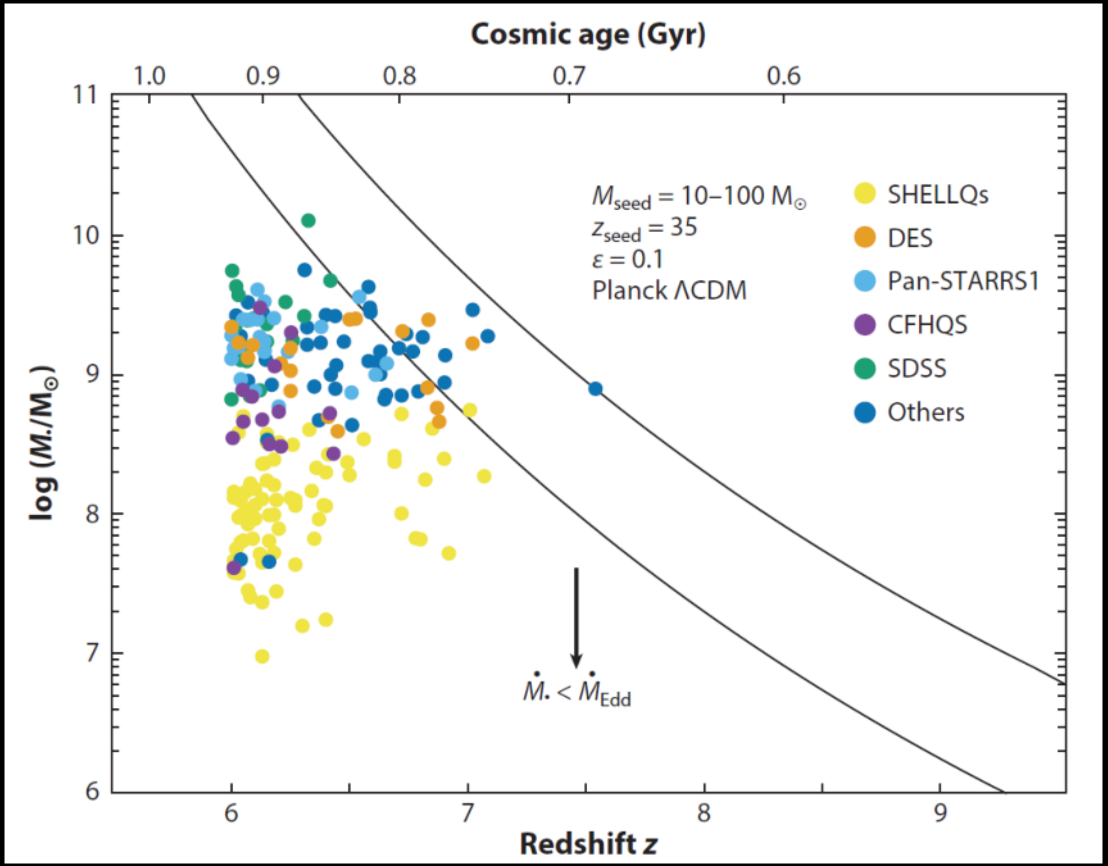
Supermassive black holes in the early universe



Adopted from Figure 1, Inayoshi, Visbal, Haiman (2020)

- Currently unable to observe Quasars at very high redshifts.
- Unable to see quasars with lower mass black holes.

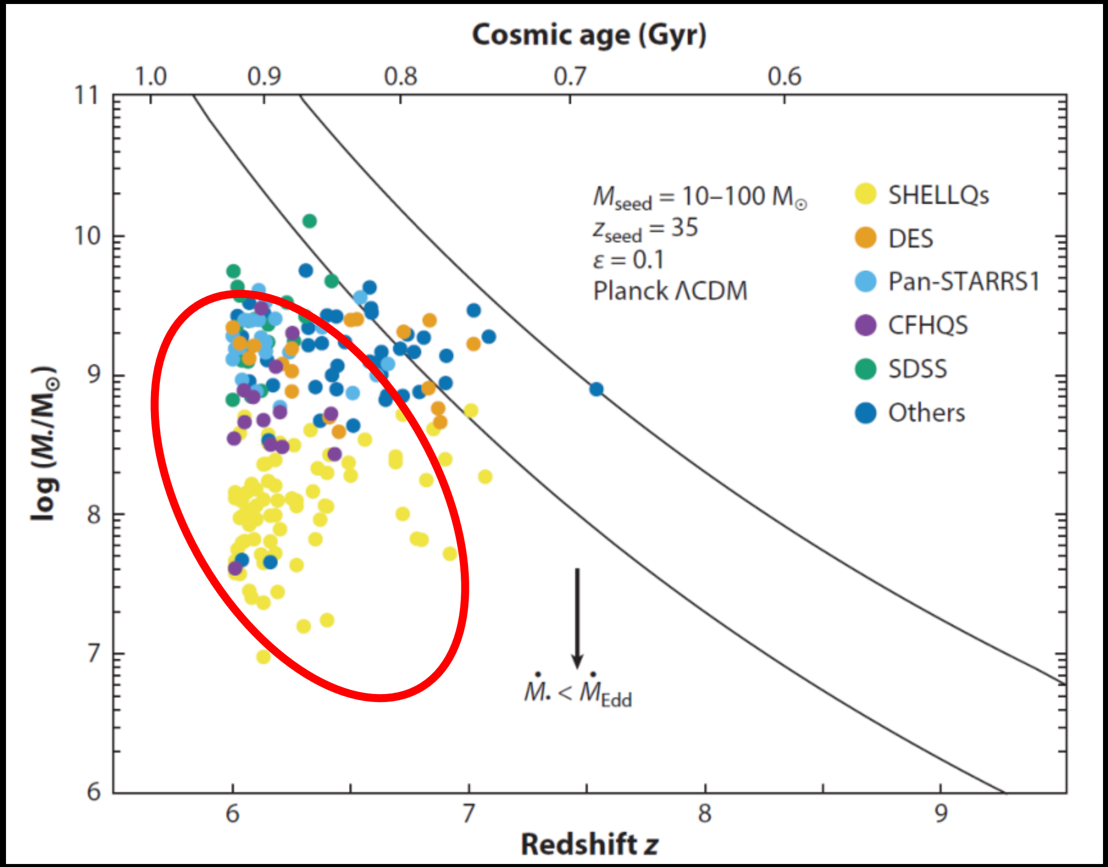
Supermassive black holes in the early universe



Adopted from Figure 1, Inayoshi, Visbal, Haiman (2020)

- Curves are for first black holes growing continuously at the Eddington Rate.

Supermassive black holes in the early universe



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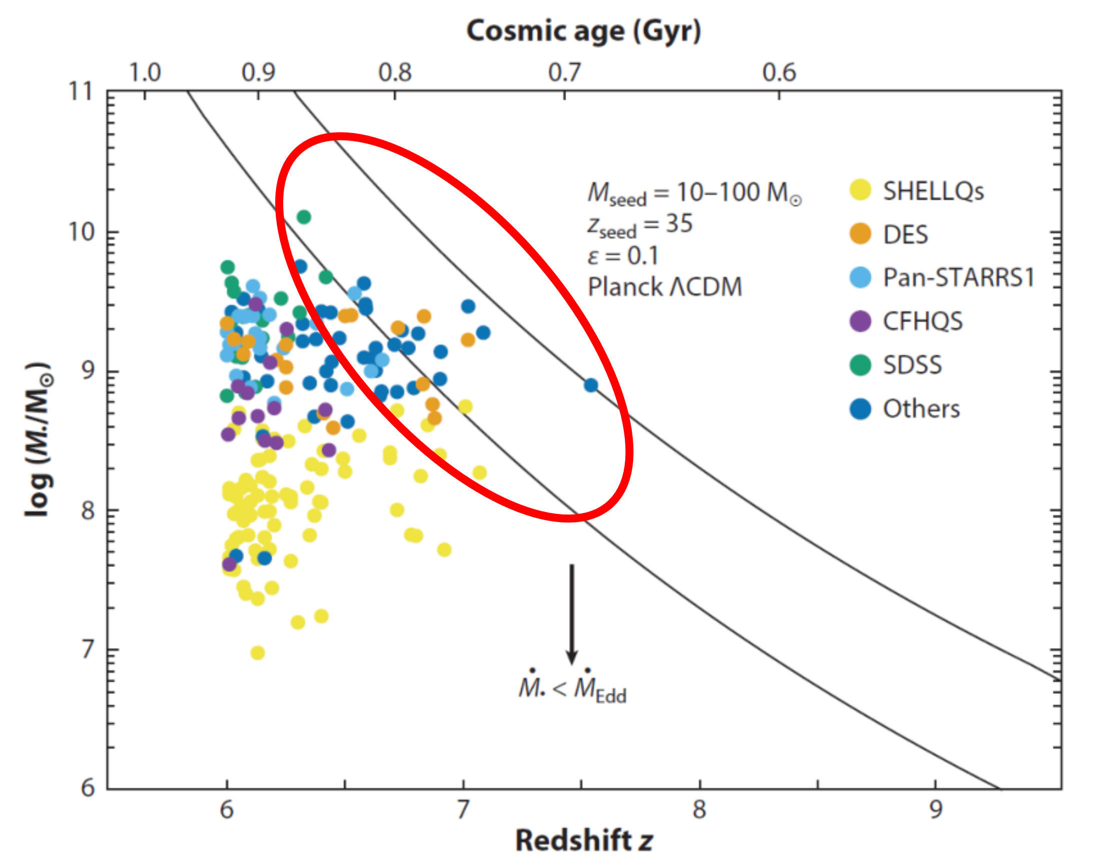
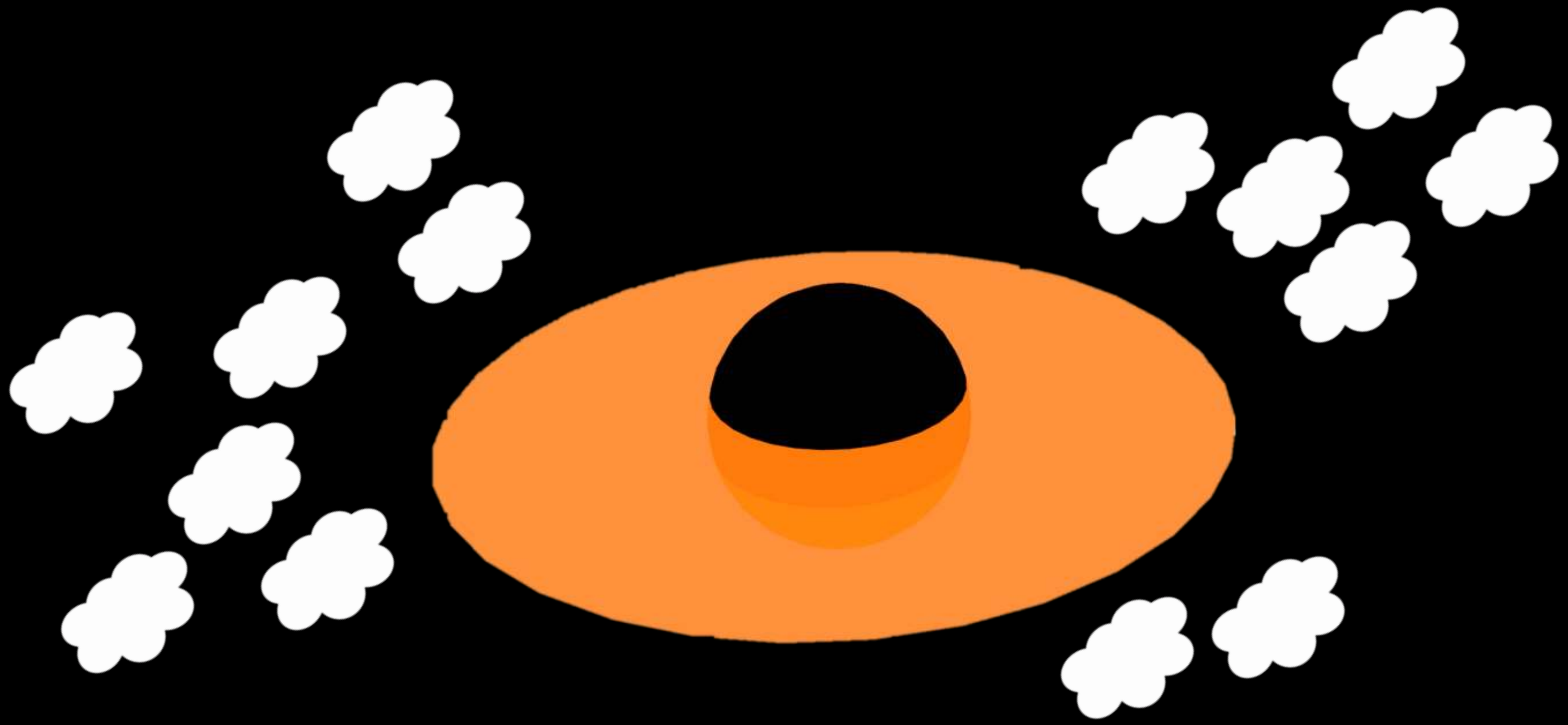
Supermassive black holes in the early universe



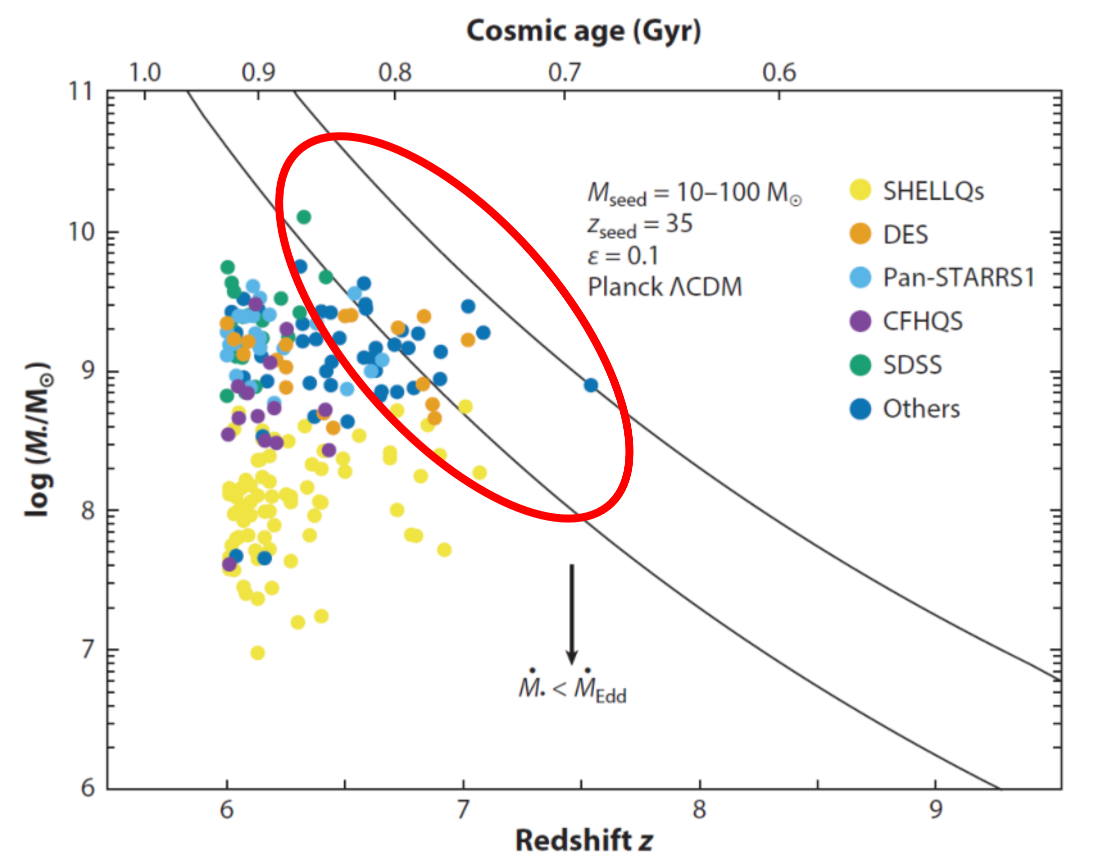
Adopted from Figure 1, Inayoshi, Visbal, Haiman (2020)

A Timescale Problem



- Black hole accretes at the Eddington limit for $\approx$0.8 Gyr
- Has to grow in size around <u>eight orders of magnitude</u>!

Supermassive black holes in the early universe



Adopted from Figure 1, Inayoshi, Visbal, Haiman (2020)

How could black holes in the early universe get so massive?

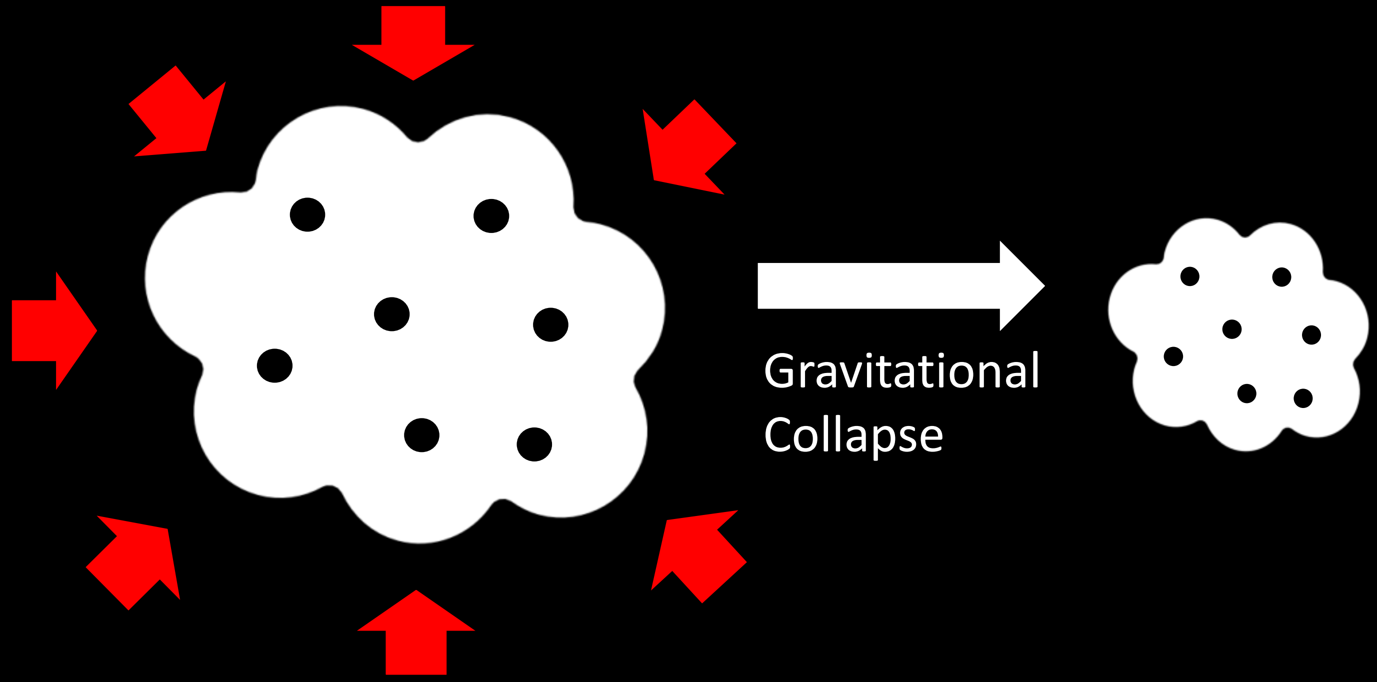
Possible Explanations:

- Increase the growth rate of the first black holes.
- Increase the initial mass of the first black holes.

How can we form a SMBH seed even more massive?

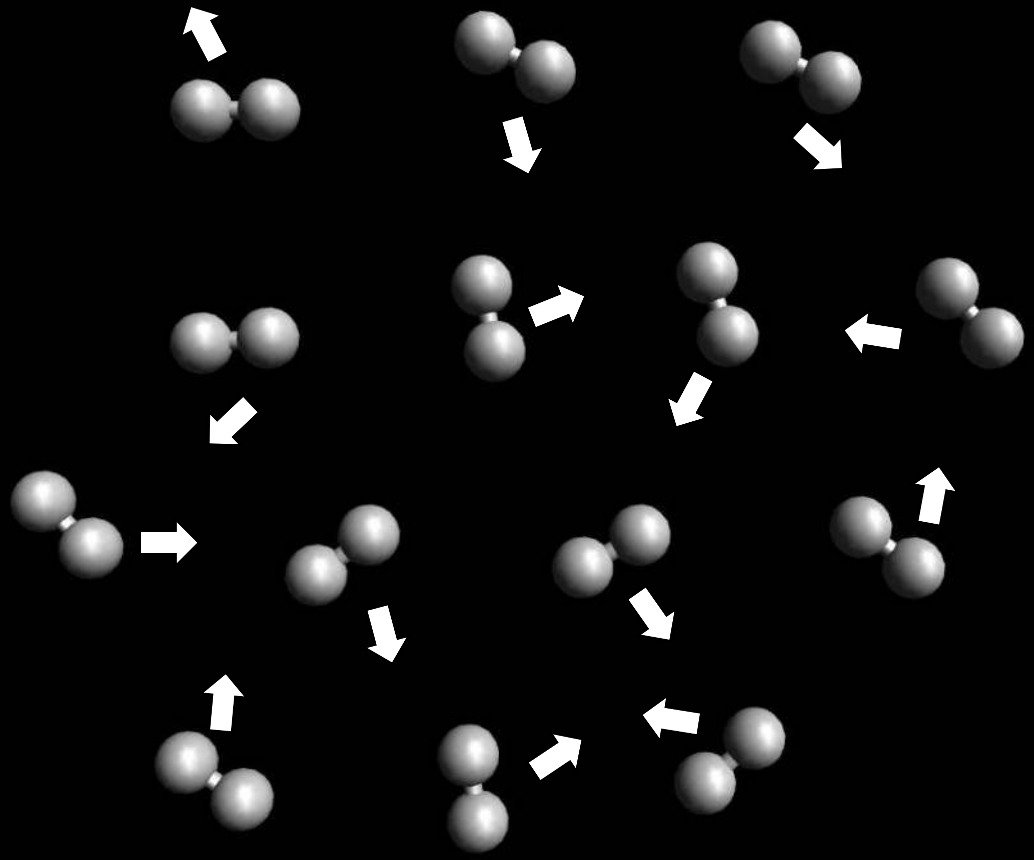
Forming a more massive cloud

$$M_{Jeans} \approx \left(\frac{5kT_{cloud}}{G\mu m_h}\right)^{3/2}\left(\frac{3}{4\pi\rho_0}\right)^{1/2}$$



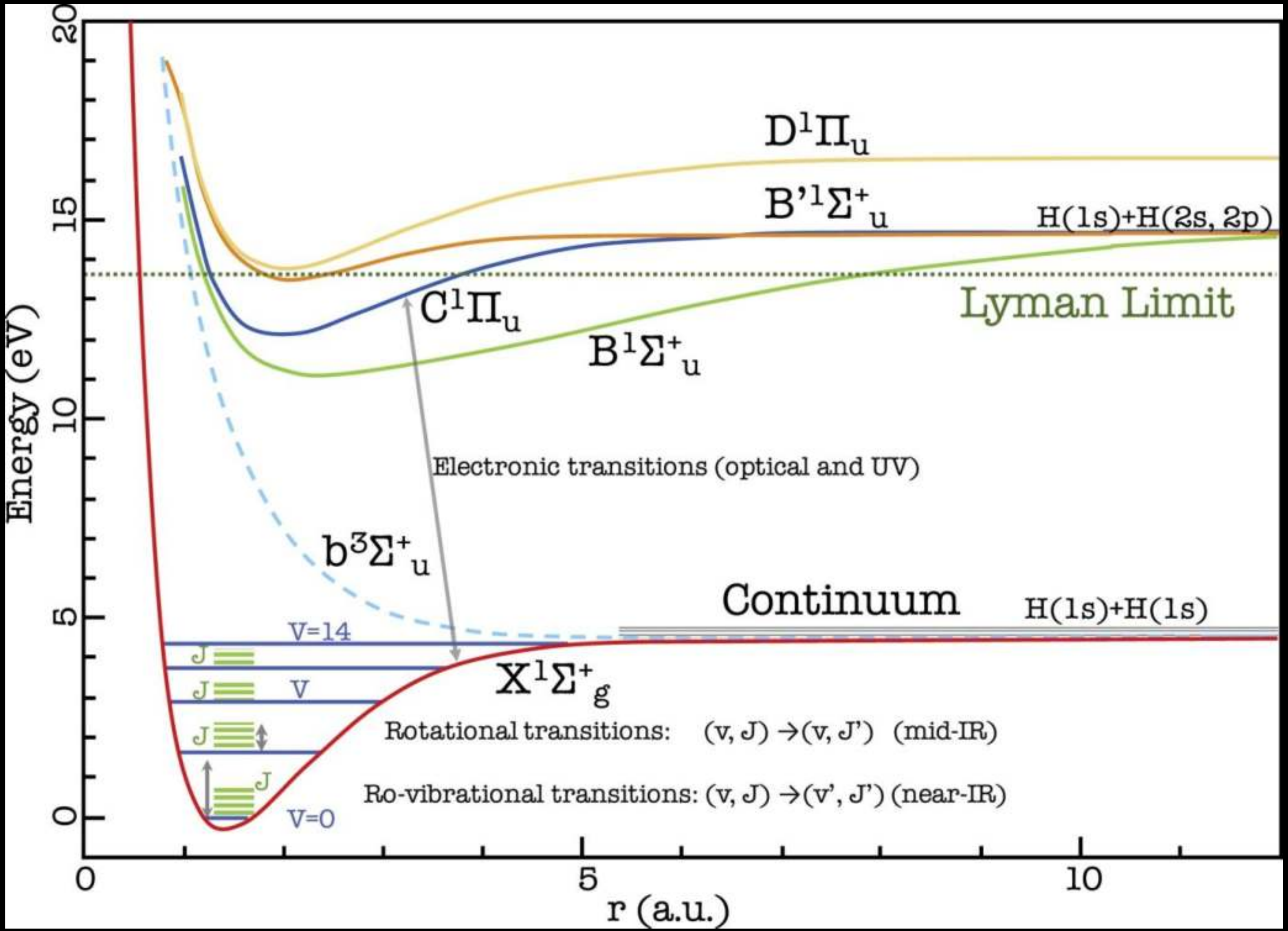
T_{cloud} ⬆

Suppressing Cooling Mechanisms



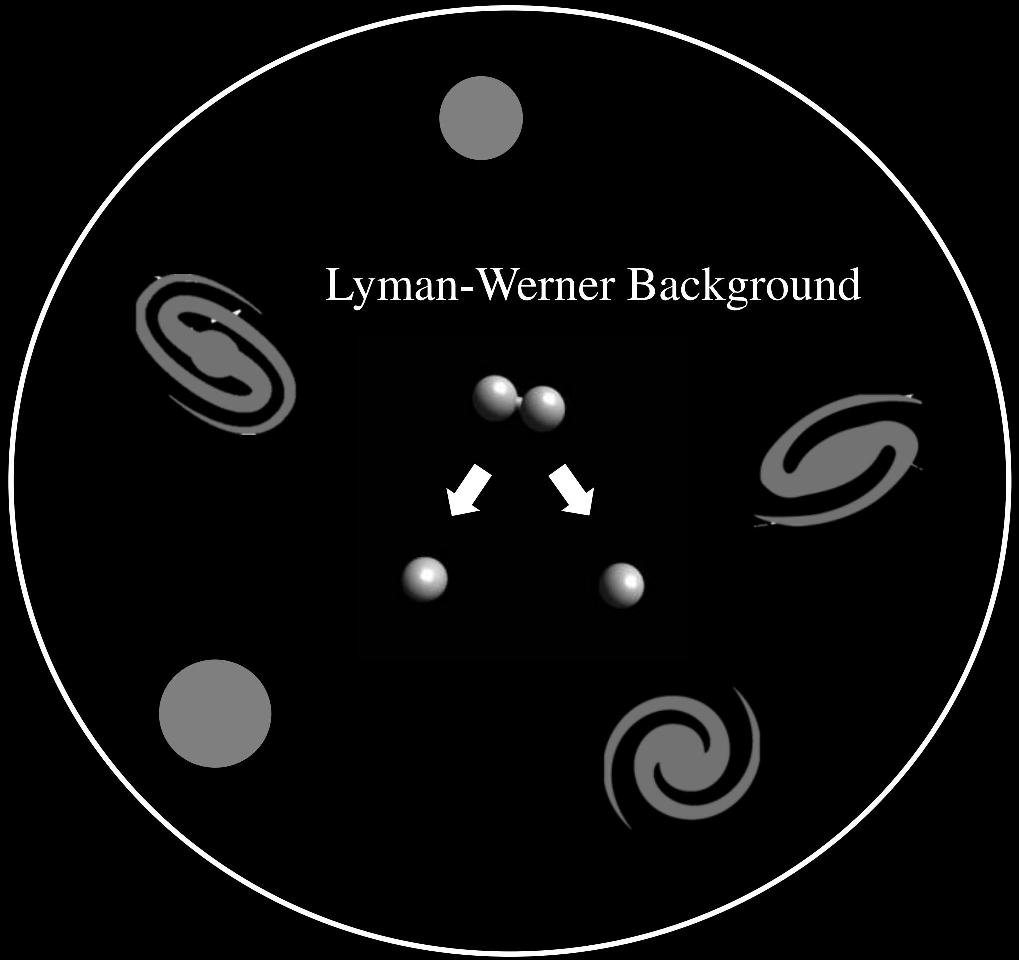
- To get a bigger star
- Remove H_2 as a cooling mechanism!

H_2 Photodissociation



Green is Lyman, Blue is Werner. Adopted from Figure 3, Wakelam et al. (2017)

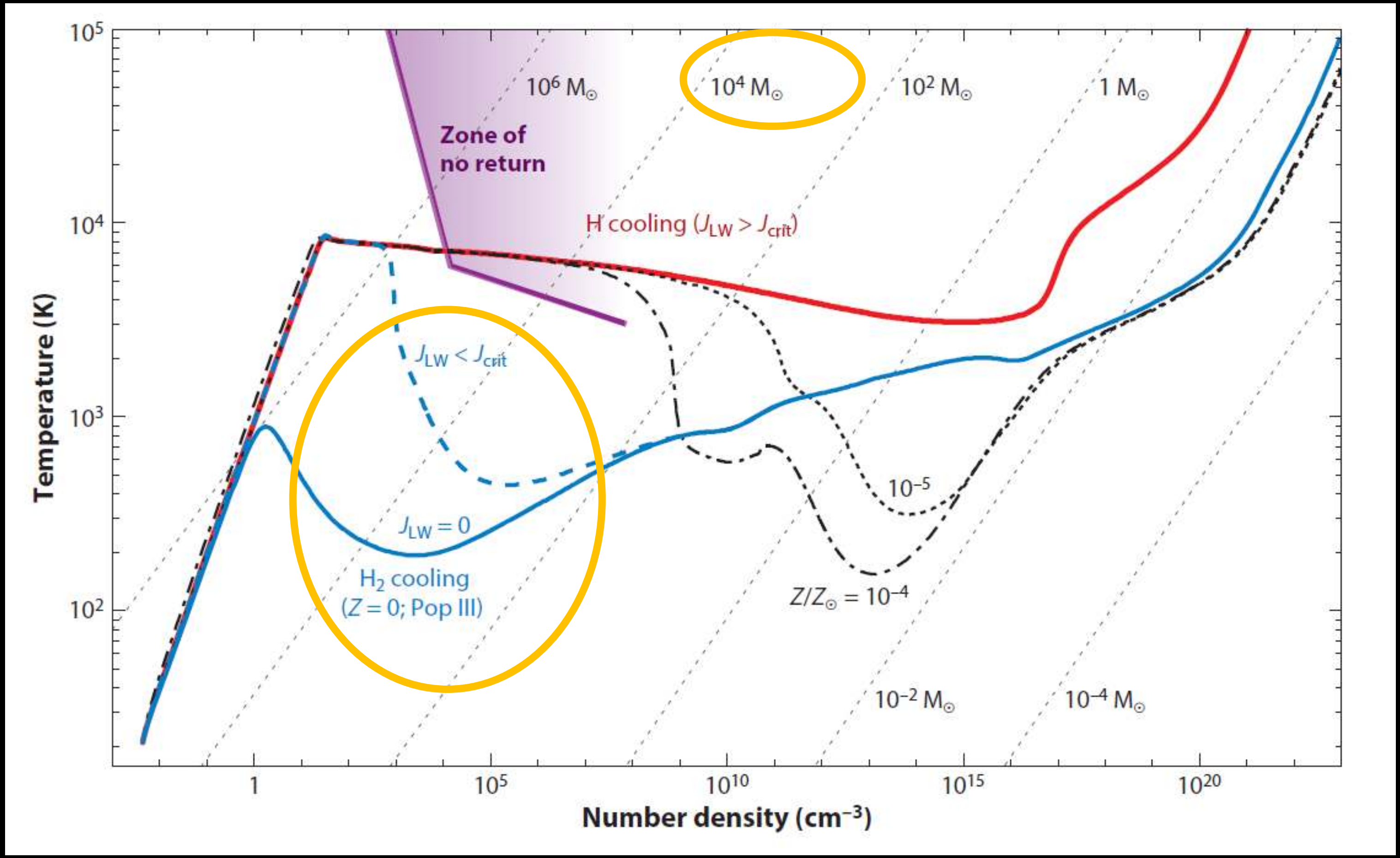
Where do the LW-photons come from?



- How can we create an extremely large cloud that does not fragment?

- Can we create a larger black hole?

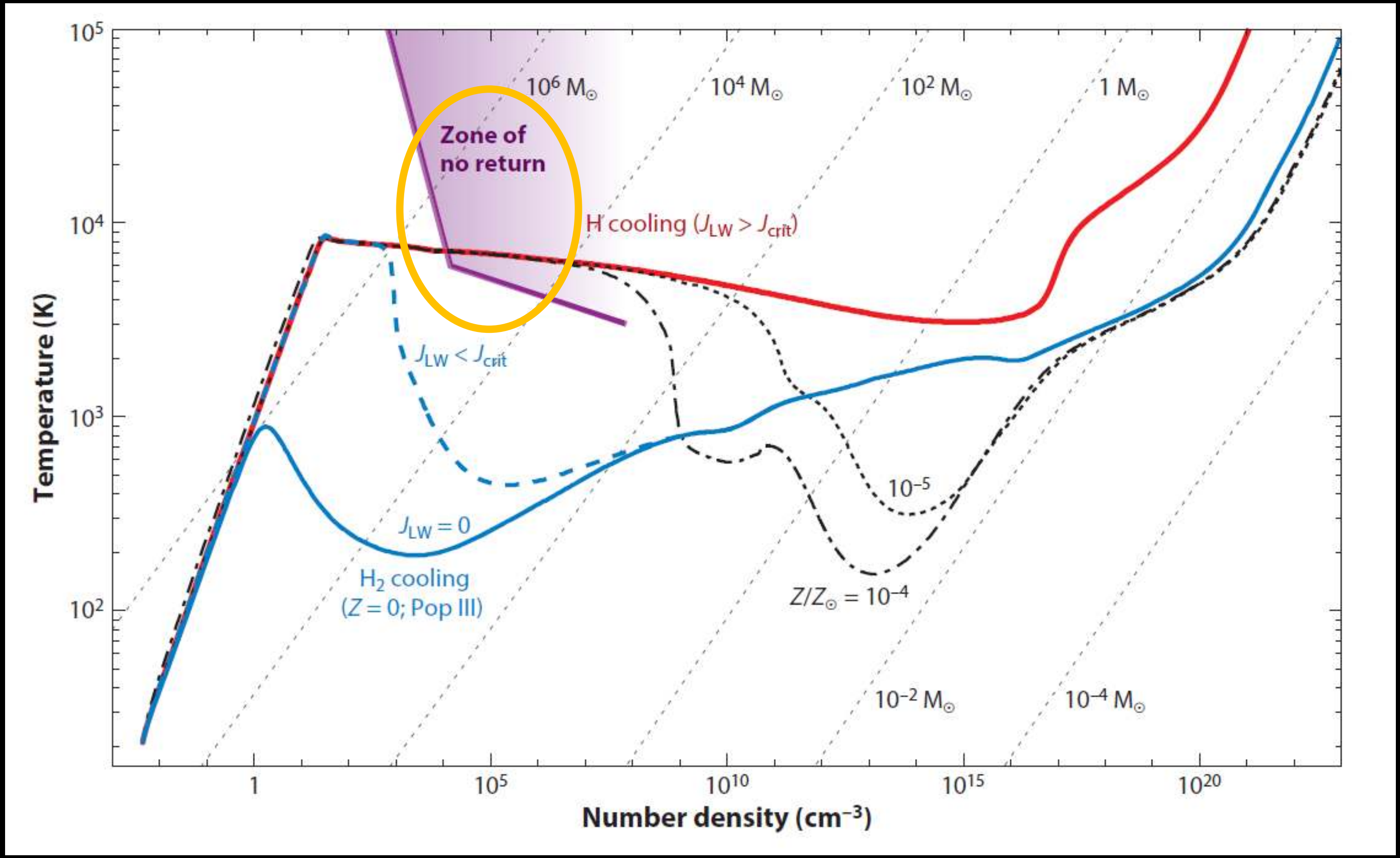
Creating an extremely large gas cloud



Adopted from Figure 7, Inayoshi, Visbal, Haiman (2020)

- Look at blue curves.
- Get Jeans mass for cloud consistent with first stars.

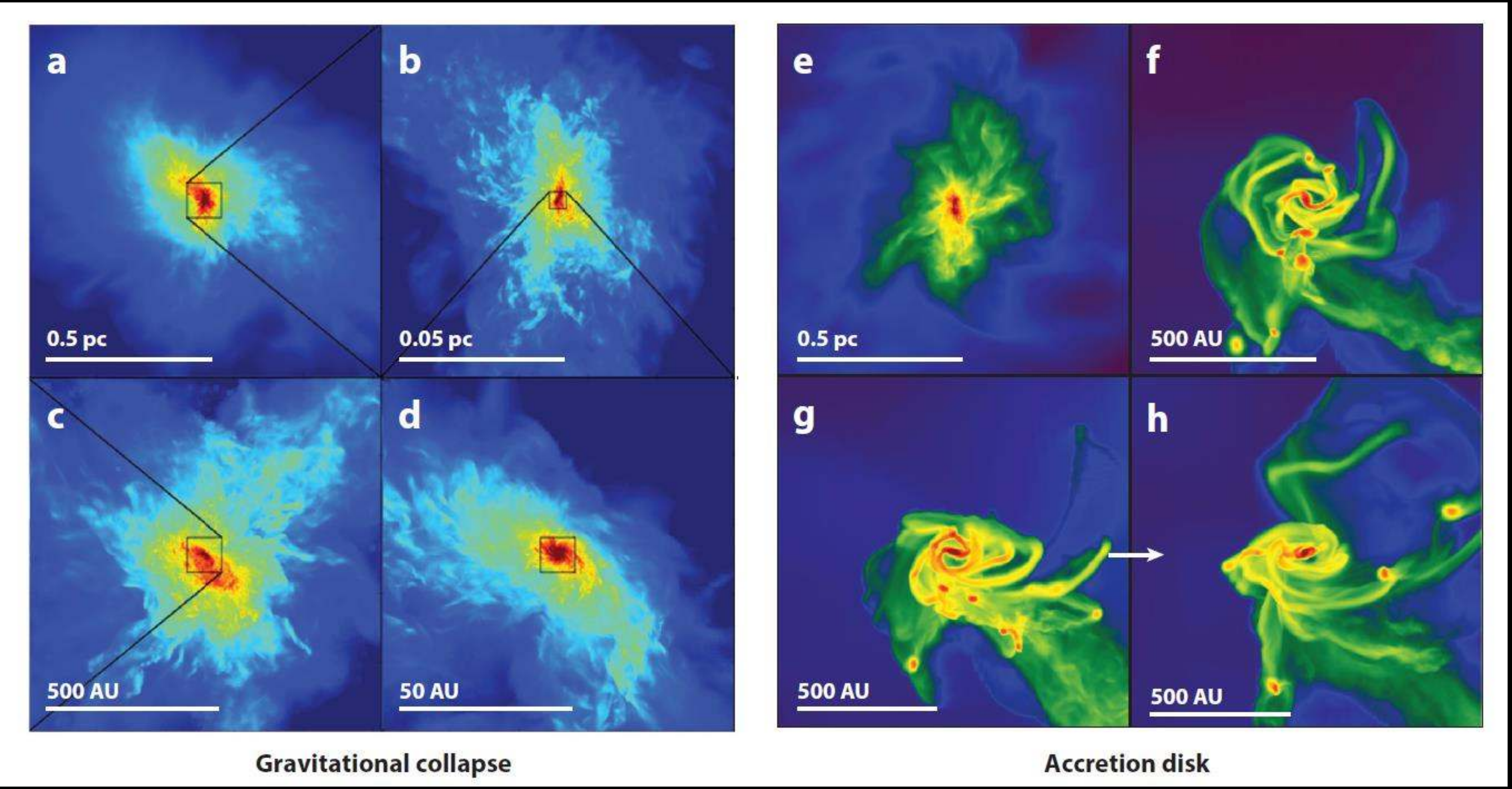
Creating an extremely large gas cloud



Adopted from Omukai et al. (2008)

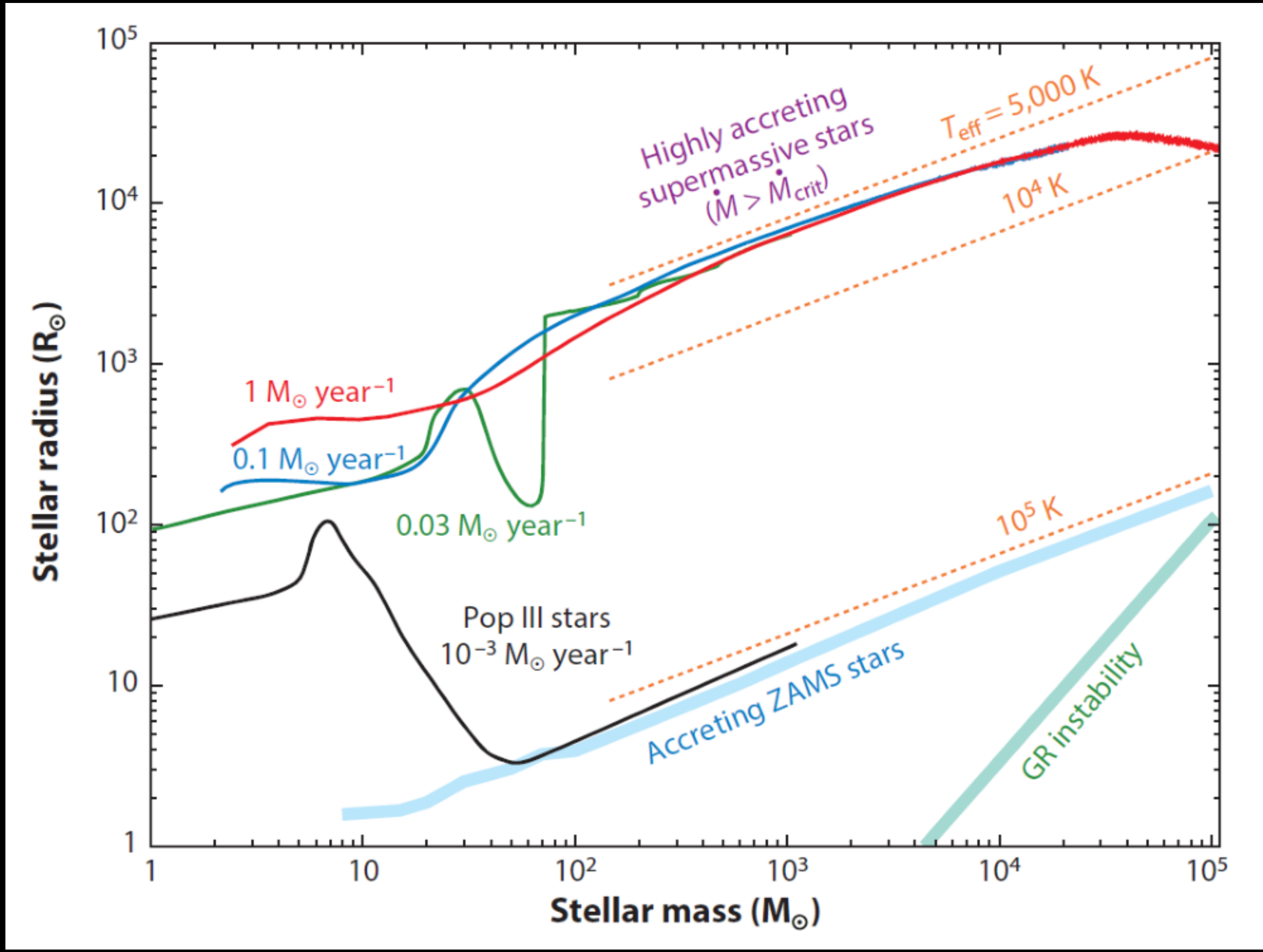
- Look at the red curve.
- Gas enters zone of no return where subsequent H_2 cooling is averted.

A Huge Protostar



Panels a–d adapted from figure 1 of Becerra et al. (2015), and panels *e–h* adapted from figures 7 and 11 of Regan et al. (2014a)

A Supermassive Star!



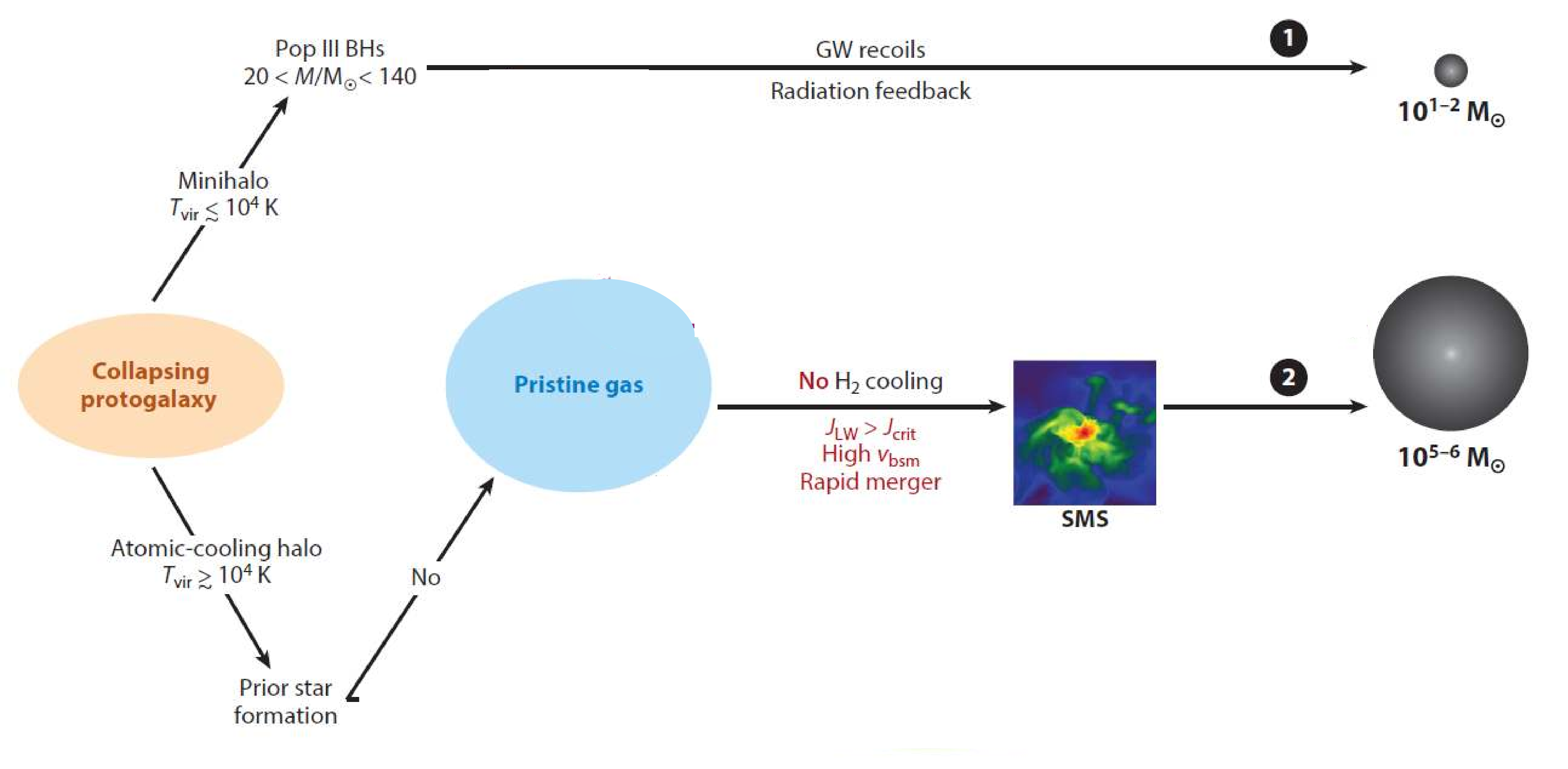
Data taken from Hosokawa et al. (2012, 2013)

- The first stars discussed earlier is black curve.

- If accretion rate is high enough, form a SMS around $10^5\ M_\odot$

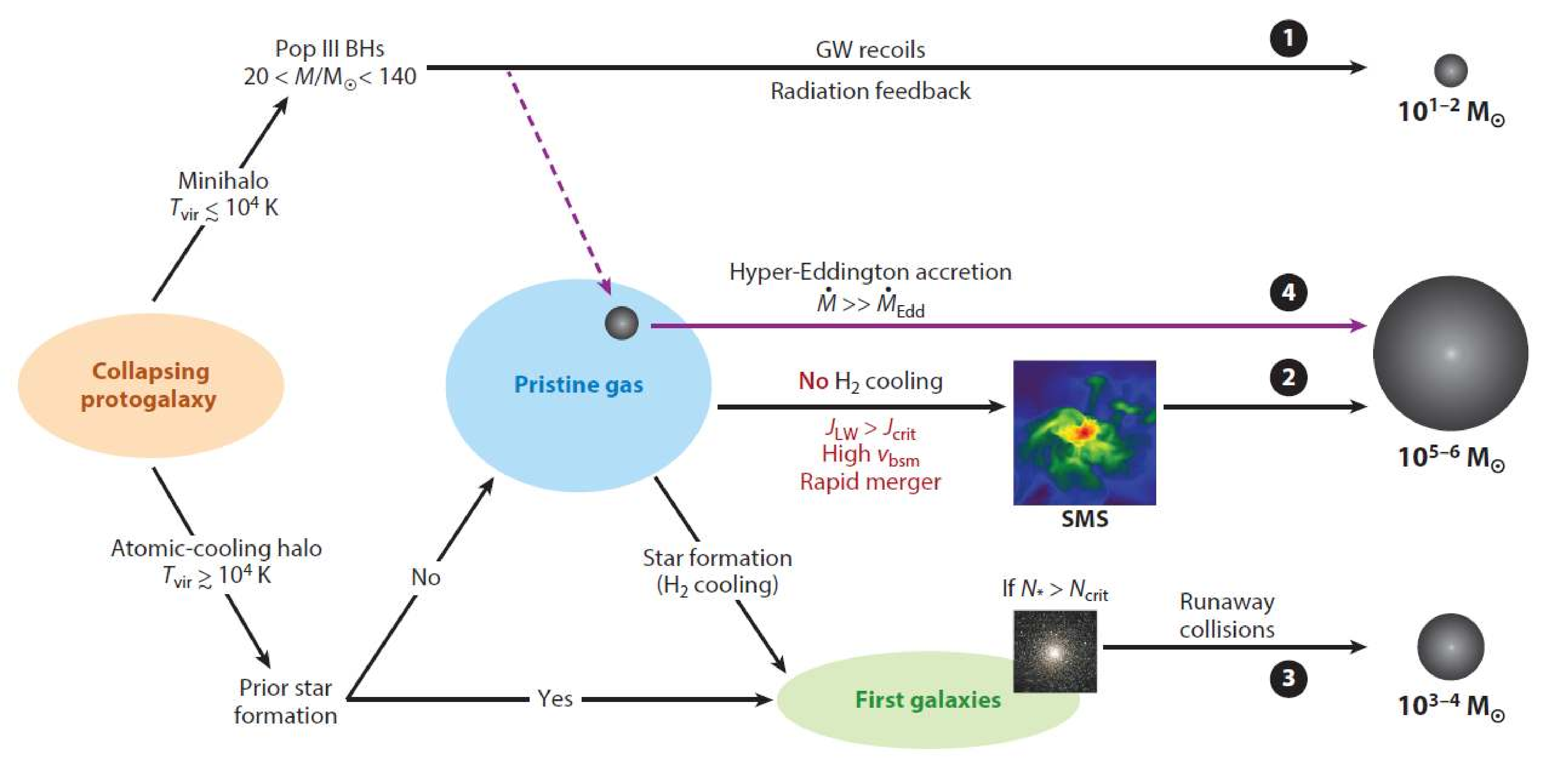
- Collapses into around $10^5\ M_\odot$ SMBH.

Massive Black Holes in Early Universe



Adopted from Figure 3, Inayoshi, Visbal, Haiman (2020)

Massive Black Holes in Early Universe



Adopted from Figure 3, Inayoshi, Visbal, Haiman (2020)

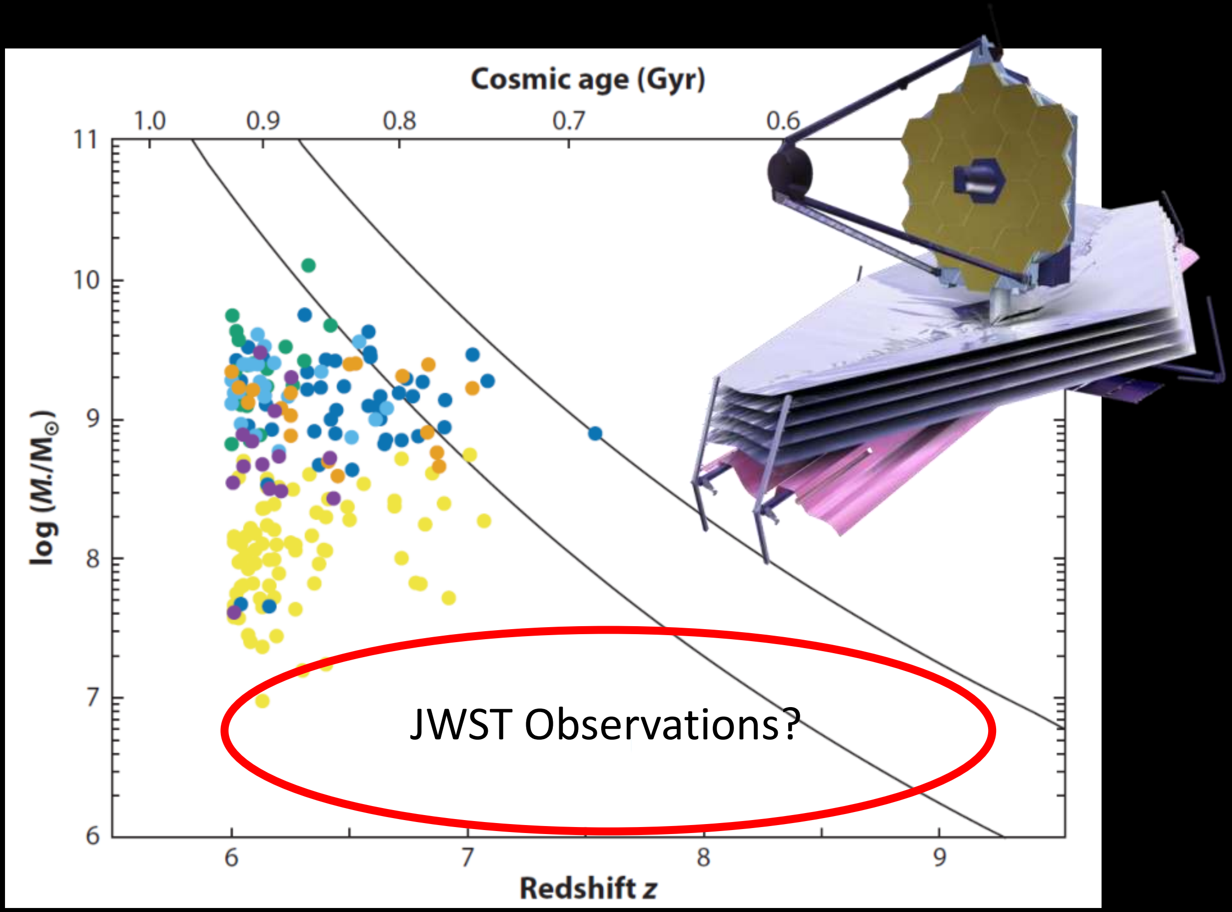
Moving Forward

What observations are needed to analyze the theory?

Moving Forward

- Current observations of SMBHs at $z \approx 6$ unlikely to contain information on SMBH seeding.
- SMBHs have grown many orders of magnitude in mass since then.
- Memory of seed formation and early accretion erased.
- Need to diagnose the IMF of early BHs at their birth and their subsequent growth.

Moving Forward



Adopted from Figure 1, Inayoshi, Visbal, Haiman (2020)

- Find black holes $\sim 10^5\ M_\odot$, at redshifts $z > 10$.

- Should be possible in megasecond exposures with JWST's NIRCam.

Moving Forward

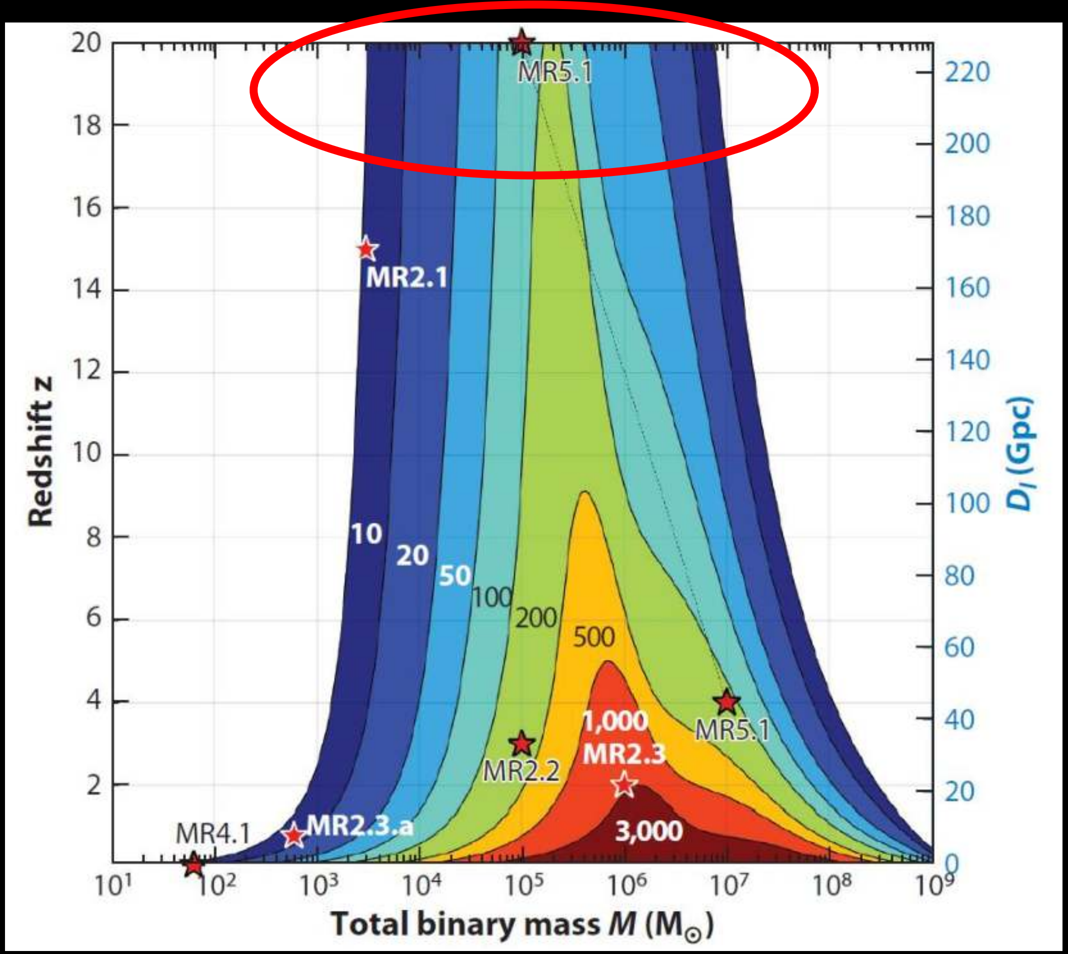


Figure adapted from Amaro-Seoane et al. (2017)

- Detect BH mergers around $10^{4-7}\ M_{\odot}$ out to redshifts beyond $z \approx 20$.

Take away

- Refine the formation theory of the first black holes
- Combine with new observations
- Greatly improve our understanding of the first black holes and SMBHs in the universe today

References

Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2016, Physical Review Letters, 116, 061102, doi:10.1103/PhysRevLett.116.06110

Chiaberge, M., Ely, J. C., Meyer, E. T., et al. 2017, A&A, 600, A57, doi:10.1051/0004-6361/20162952

Greif, T. H. 2015, Computational Astrophysics and Cosmology, 2, 3, doi:10.1186/s40668-014-0006-

Haiman Z., 2004, ApJ, 613, 3, doi:10.1086/422910

Hirano, S., Hosokawa, T., Yoshida, N., et al. 2014, ApJ, 781, 60, doi:10.1088/0004-637X/781/2/60

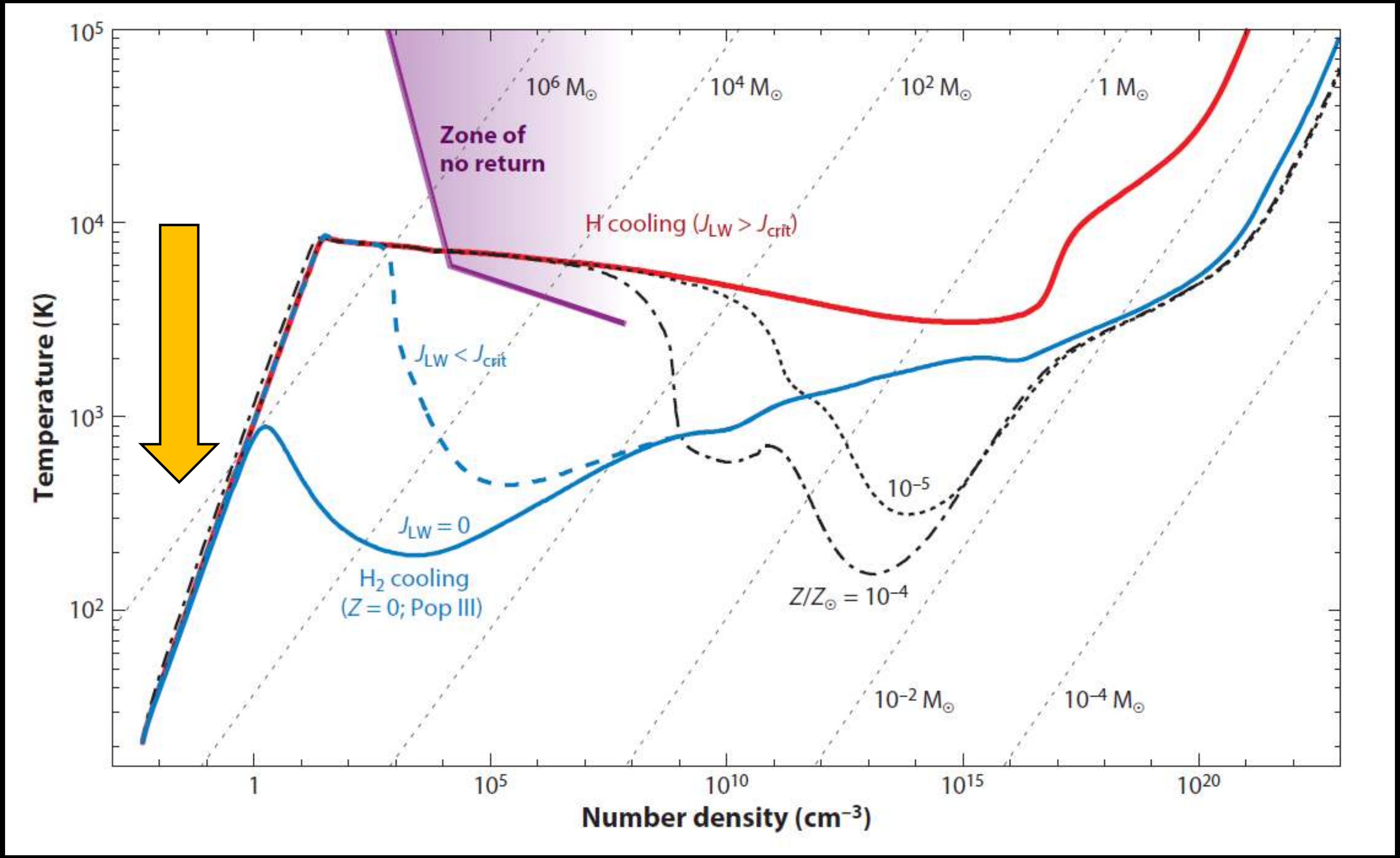
Inayoshi, K., Visbal, E., & Haiman, Z. 2020, ARA&A, 58, 27, doi:10.1146/annurev-astro-120419-014455

Richards, G. T., Strauss, M. A., Fan, X., et al. 2006, AJ, 131, 2766, doi:10.1086/50355

The Event Horizon Telescope Collaboration et al. 2019, ApJL, 875, L1, doi:10.3847/2041-8213/ab0ec7

Windhorst, R. A., Timmes, F. X., Wyithe, J. S. B., et al. 2018, ApJS, 234, 41, doi:10.3847/1538-4365/aaa760

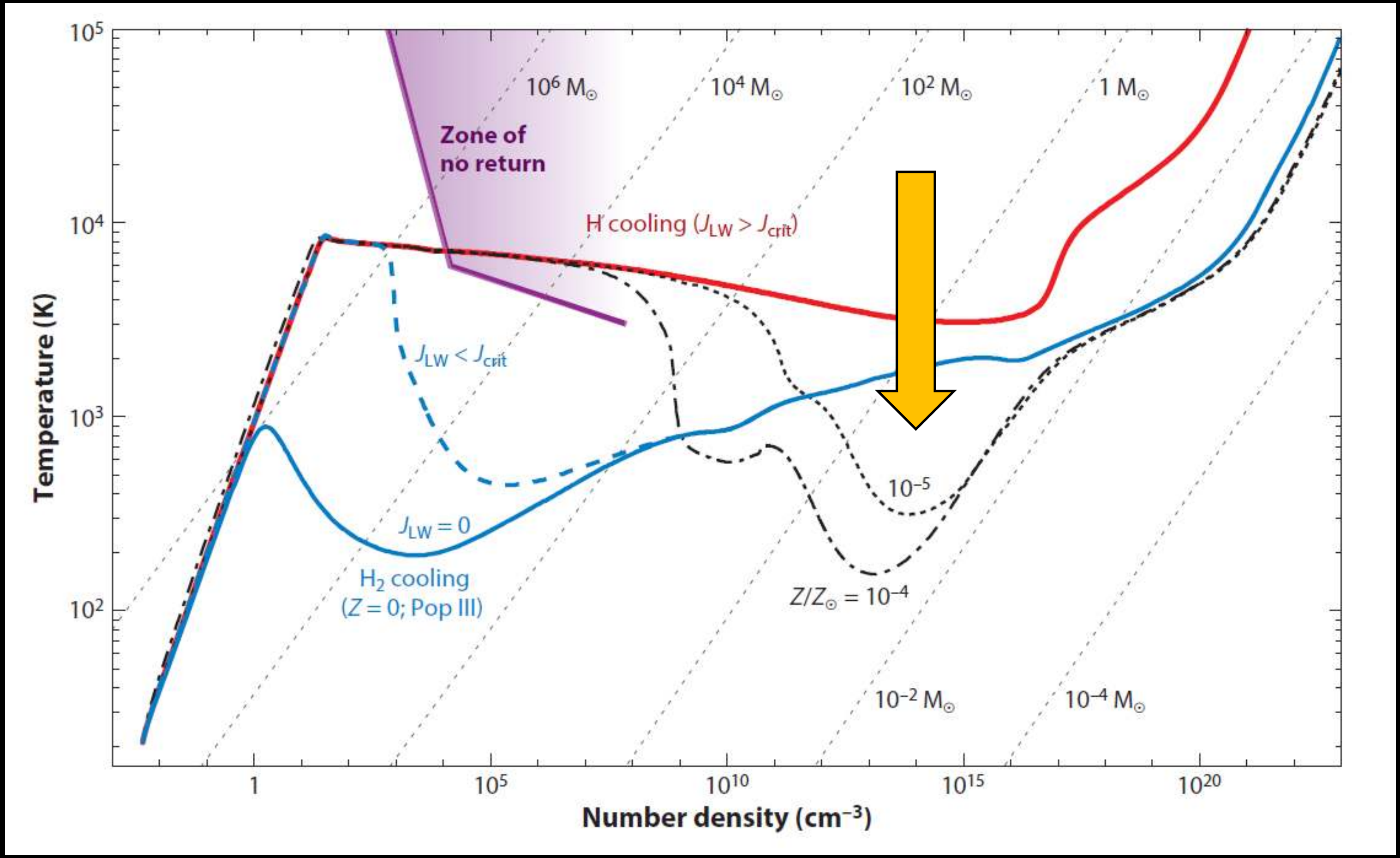
Creating an extremely large gas cloud



Adopted from Omukai et al. (2008)

- Cloud begins to collapse at the bottom-left.
- At the lowest densities cooling is inefficient.
- Gas is heated by compression.

Creating an extremely large gas cloud



Adopted from Omukai et al. (2008)

- Black curves show the evolution of metal- and dust-polluted gas.
- Collapsing gas experiences a rapid temperature drop.