Seeding Supermassive Black Holes with Self-Interacting Dark Matter

A unified scenario with baryons

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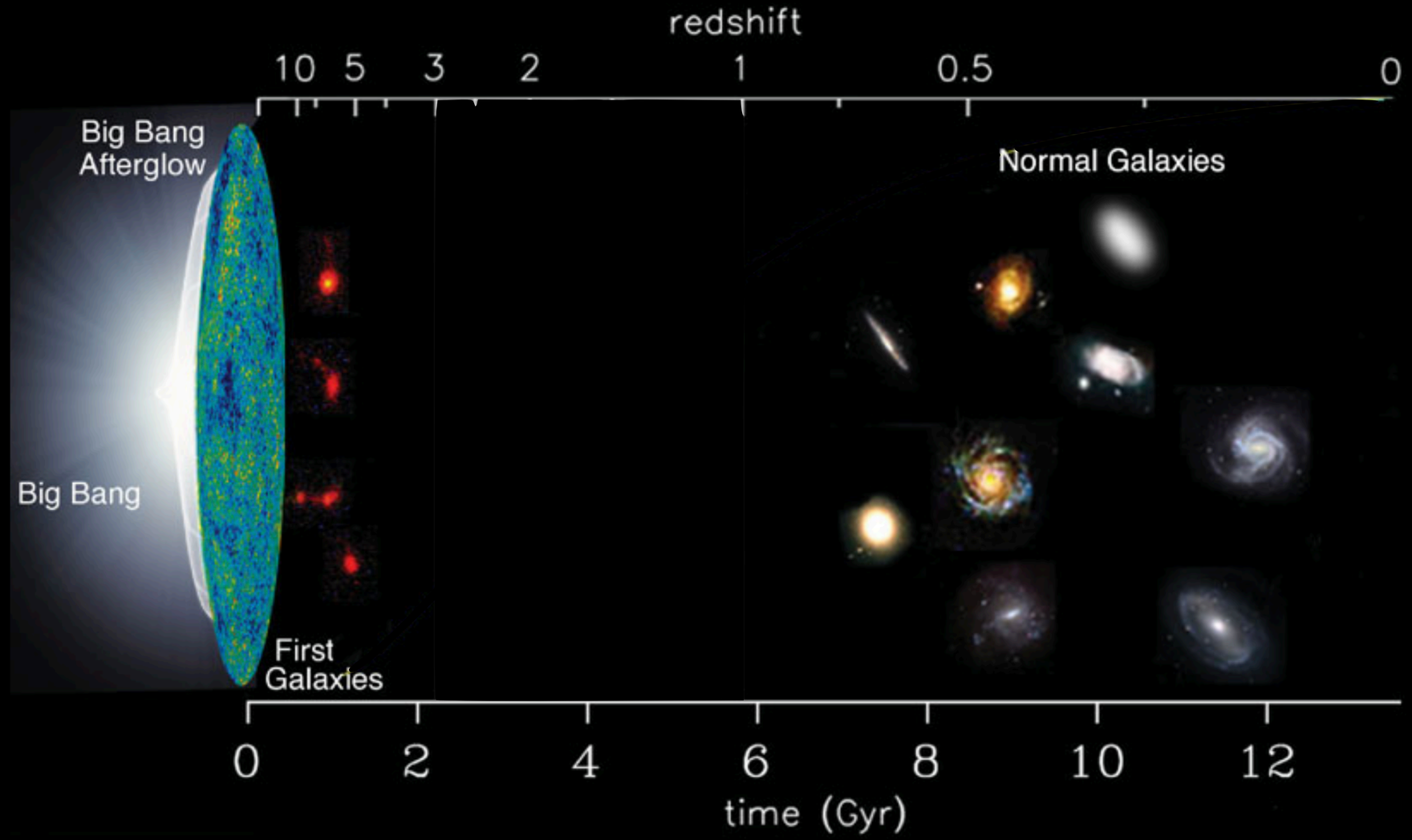
In collaboration with W.-X. Feng and H.-B. Yu, APJL 914 (2021), arXiv: 2108.11967

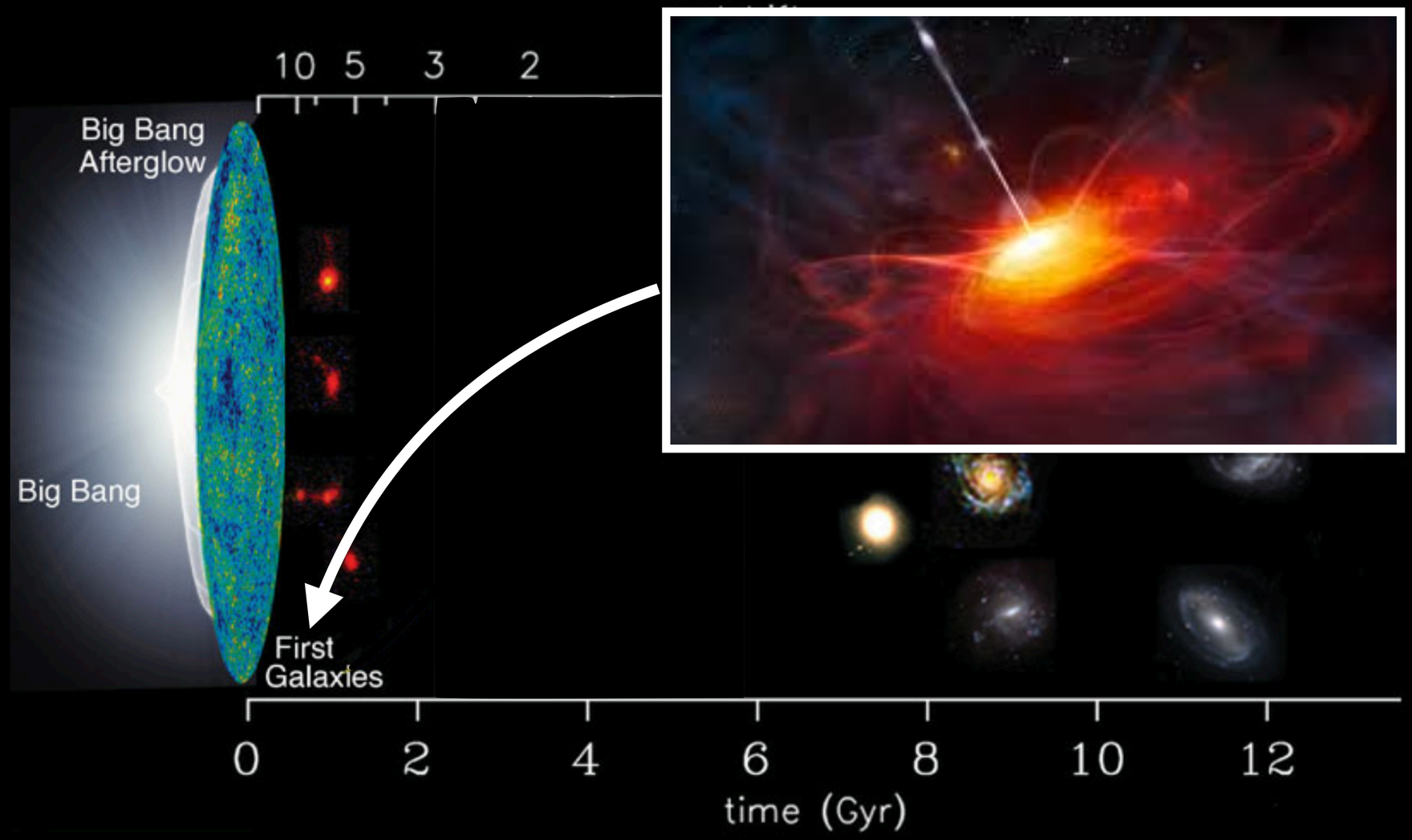
AstroDark 2021, 12/09/2021

The cosmic history



from Labbe ‘09

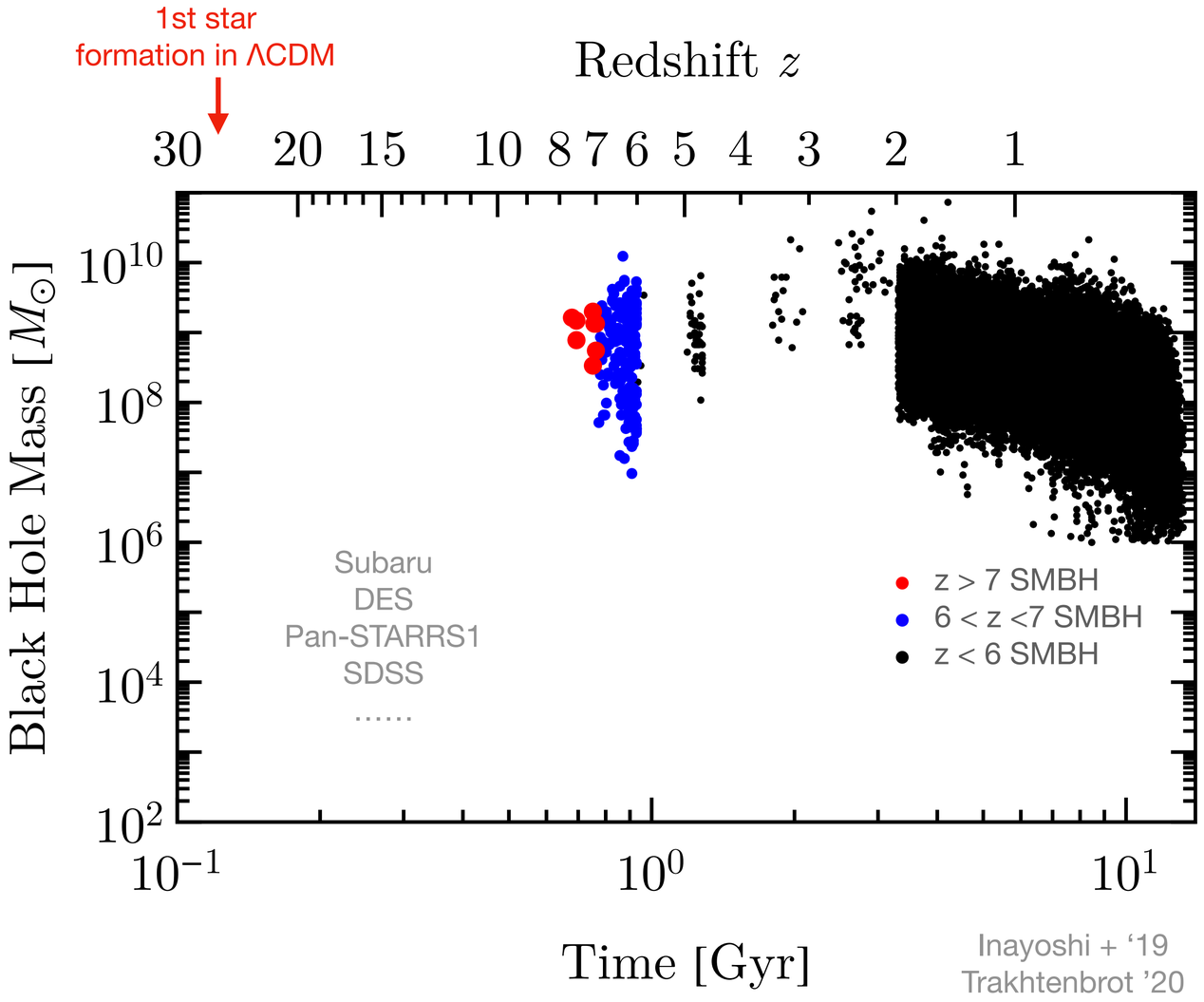
The first supermassive black holes (SMBHs)



from Labbe ‘09

The first supermassive black holes (SMBHs)

- ~200 SMBHs with mass ≥ 10^6 $M_\odot$ at z > 6
- 7 SMBHs with mass ≥ 10^8 $M_\odot$ at z > 7



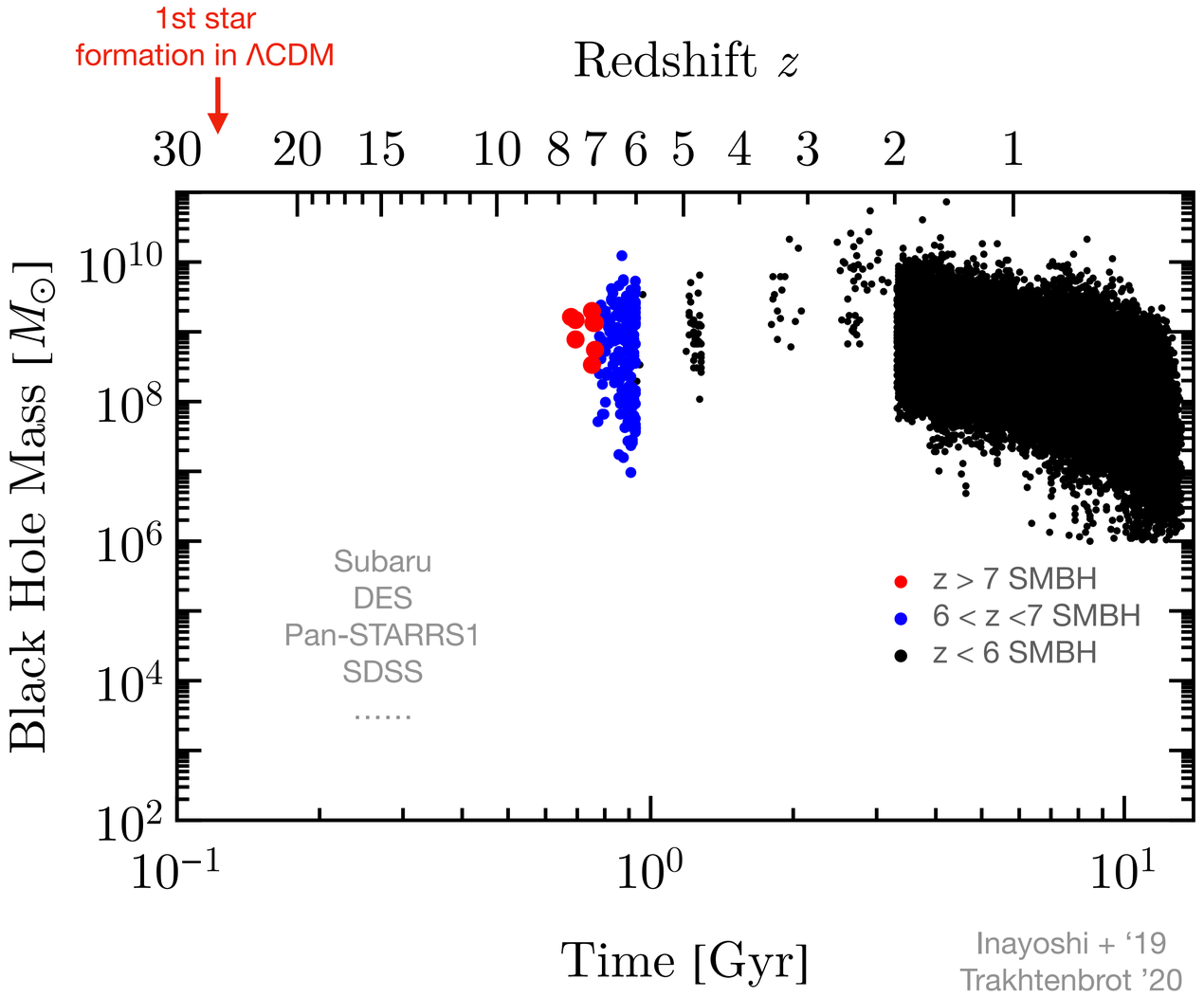
Inayoshi + '19
Trakhtenbrot '20

The growth puzzle

- ~200 SMBHs with mass ≥ $10^6\ M_\odot$ at z > 6
- 7 SMBHs with mass ≥ $10^8\ M_\odot$ at z > 7

How do they form?

🤔



Inayoshi + '19
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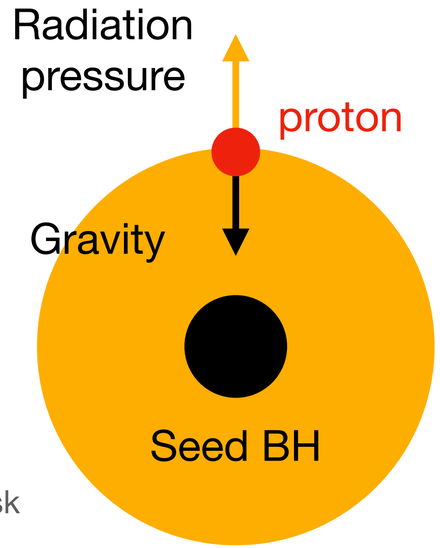
Eddington accretion



top view
of the accretion disk

Elapse time

$$M_{\rm BH} = M_{\rm seed}\exp(\Delta t/\tau)$$

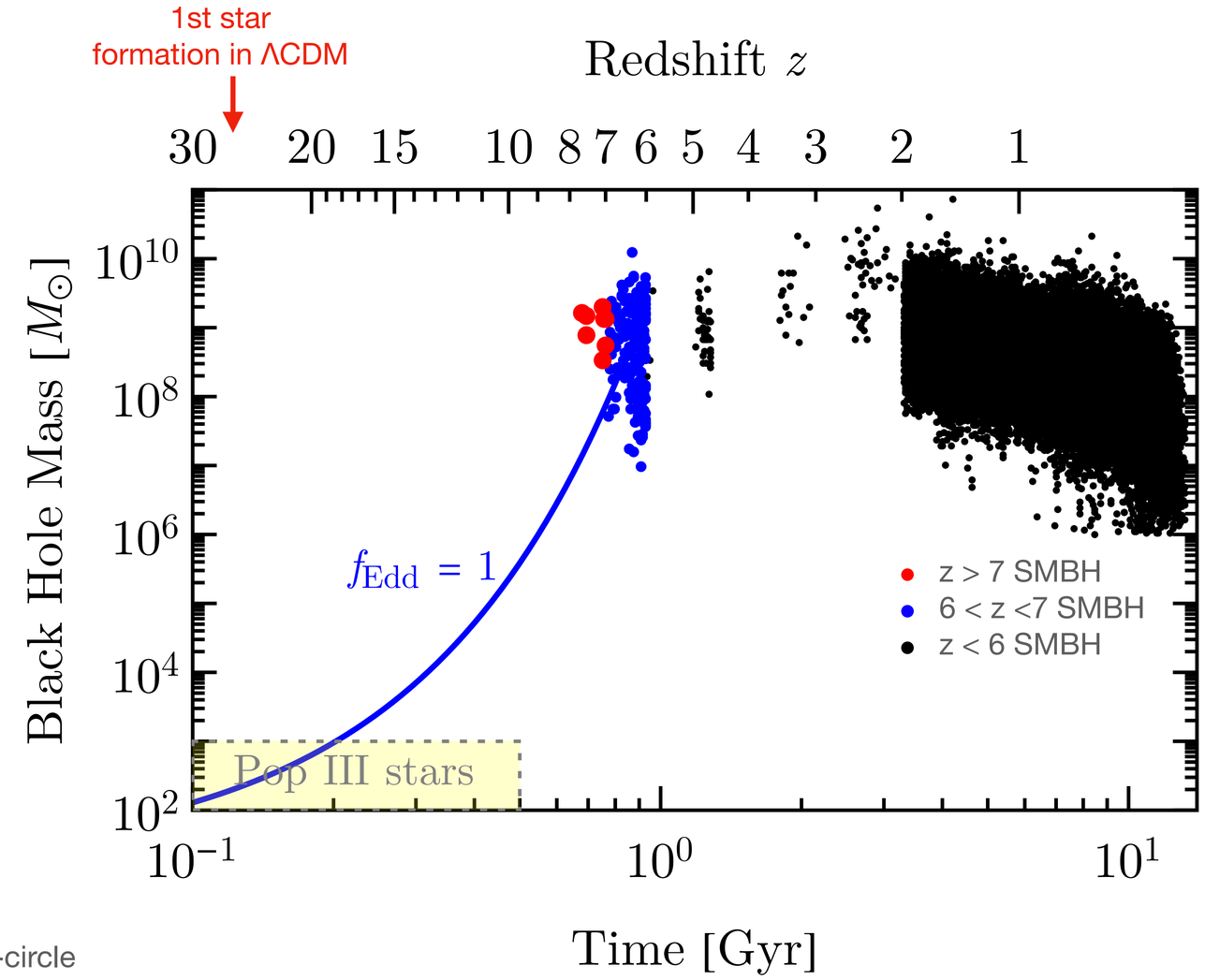
e-folding time

$$\tau = \frac{450\ {\rm Myr}}{f_{\rm Edd}}\frac{\epsilon}{1-\epsilon}$$

$L_{\rm bol}/L_{\rm Edd}$

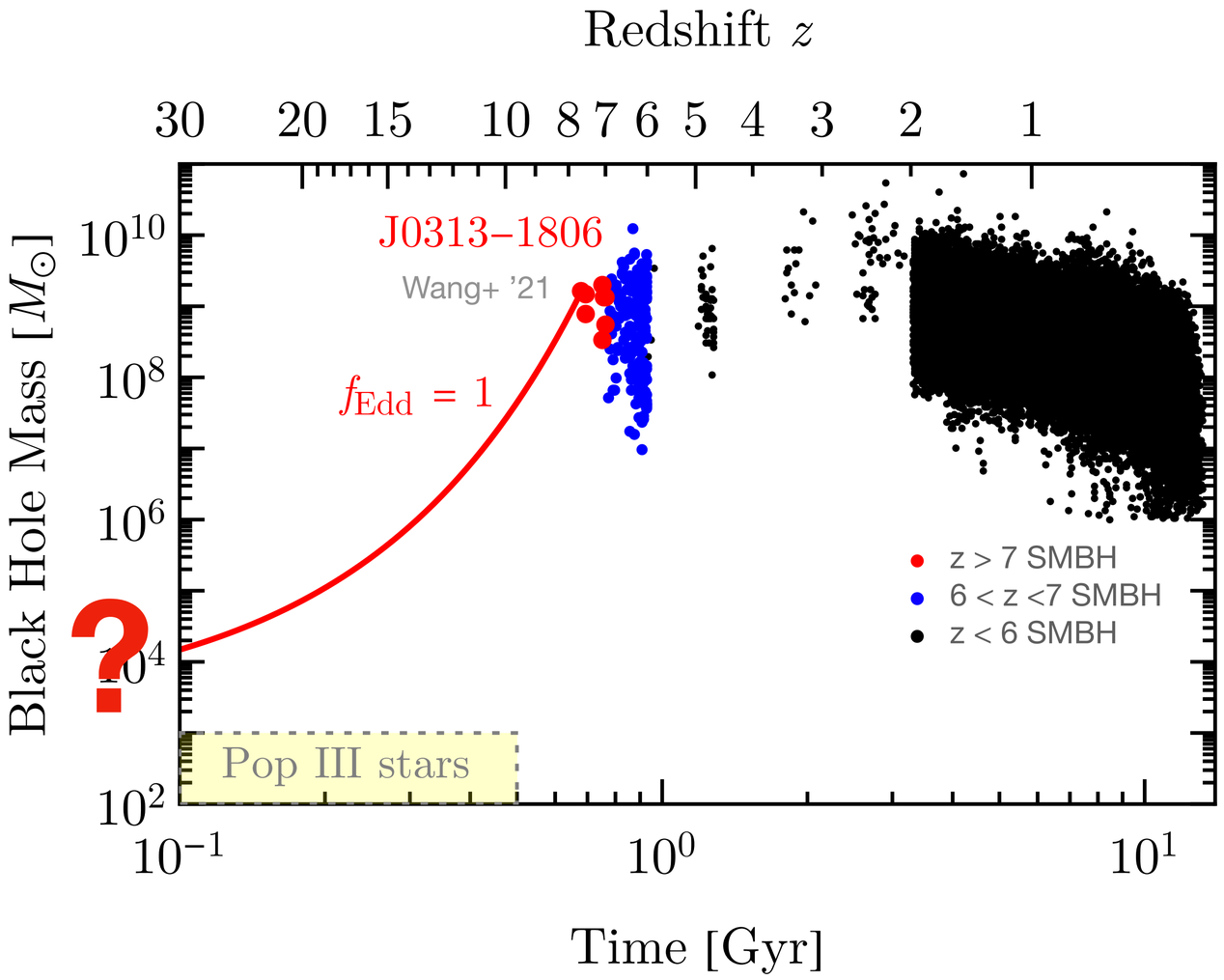
0.1

Assume 100% duty-circle



The growth puzzle

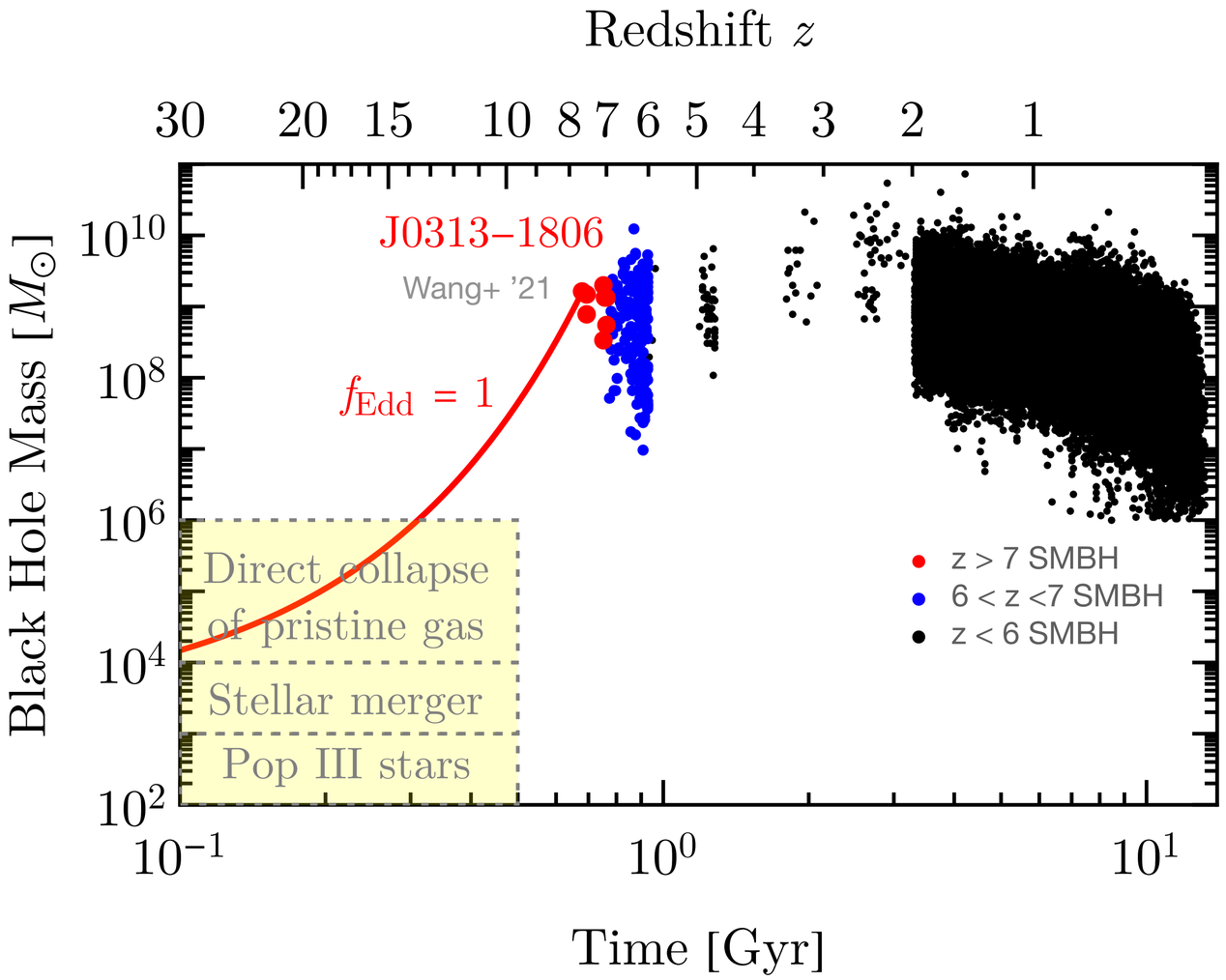
- For z > 7 SMBHs, collapsed Pop III stars are not heavy enough…



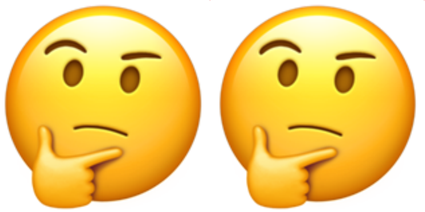
The growth puzzle

- For z > 7 SMBHs, collapsed Pop III stars are not heavy enough.
- One way to solve the puzzle is to form more massive seed BHs
  - The direct collapse of pristine gas …

Omukai ’01, Bromm & Loeb ’03,
Begelman+ ’06, Hosokawa+, ’13
Regan+ ’17, Ardaneh+ ’18, Wise+ ’19…



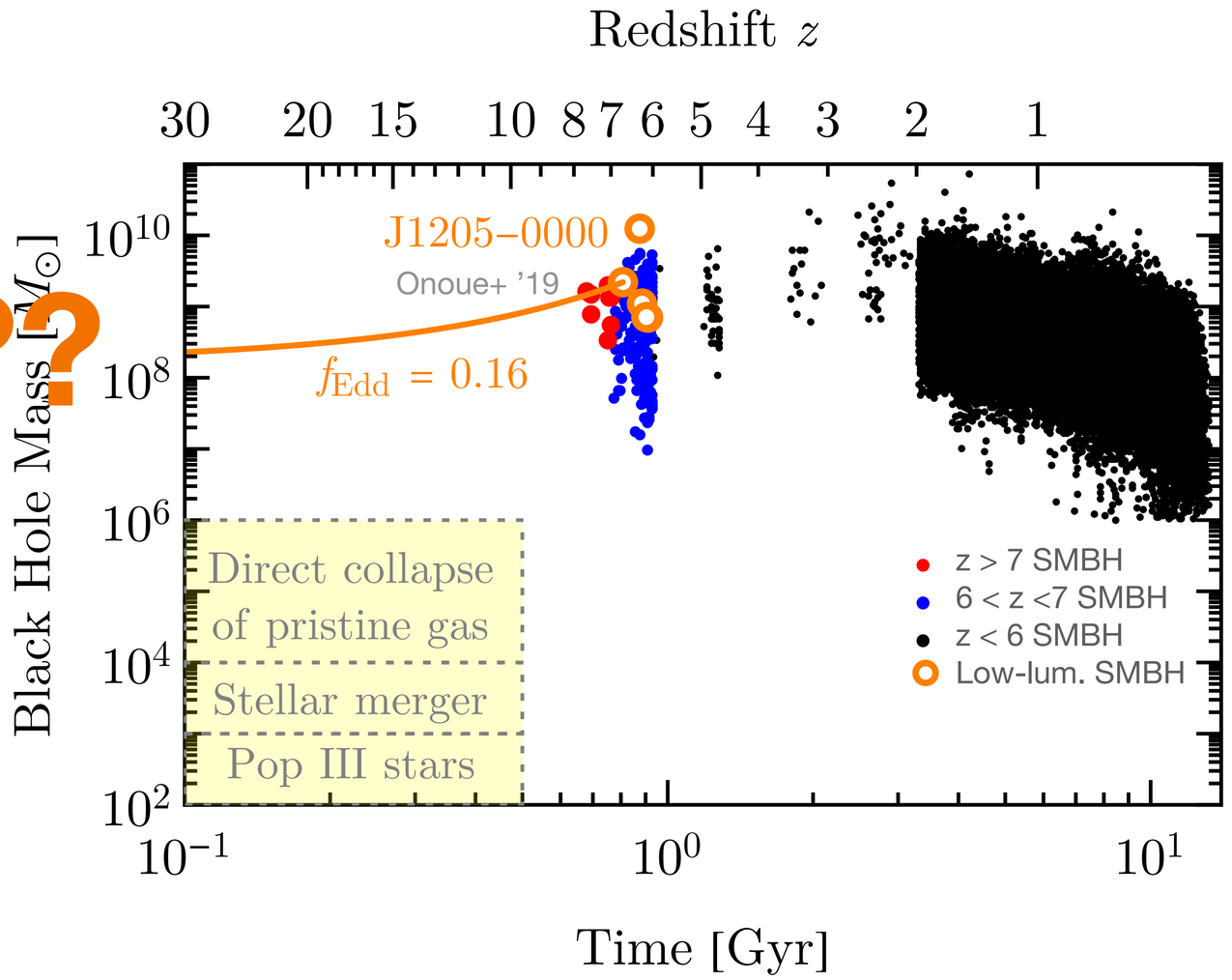
The growth puzzle (ver 2.0)



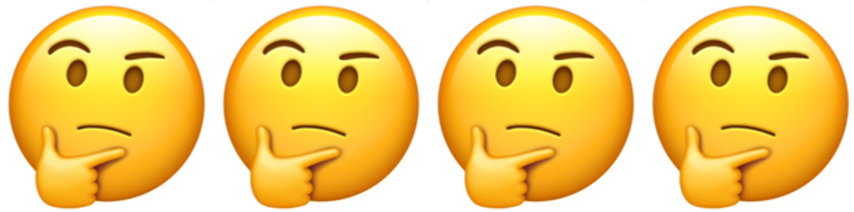
- Among the first SMBHs, there is a population of low-luminosity SMBHs.

Mazzucchelli+ ’17, Shen+ ’19, Onoue+ ’19 [SHELLQs]…

- Accretion process is slow.
- (Maybe there was a fast accretion period.)



The growth puzzle (ver 3.0)

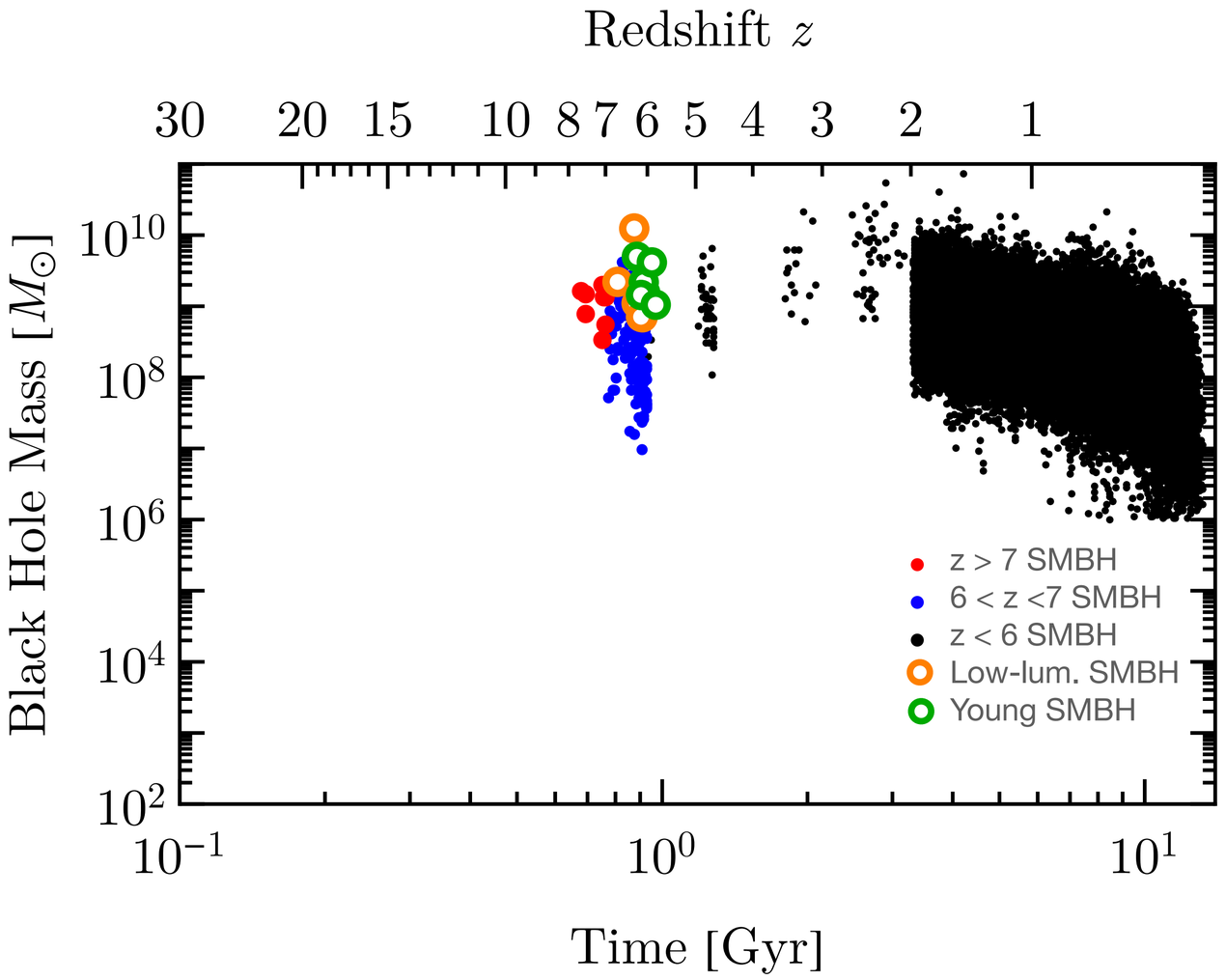


- There is also a population of “young” SMBHs

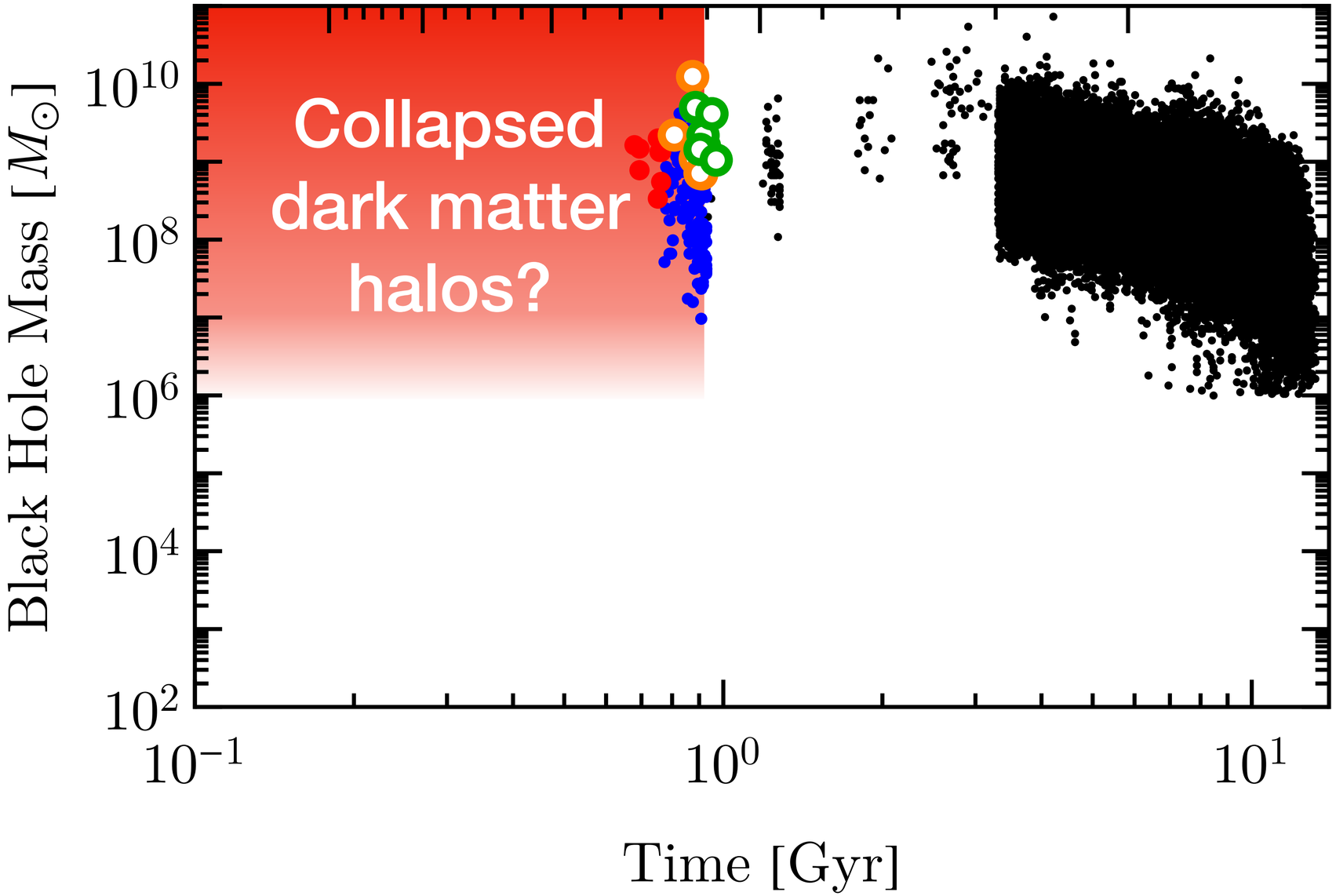
$$\Delta t < 0.1\,\mathrm{Myr}$$

Eilers+ ’18, ‘20
age is measured by the size of proximity zone

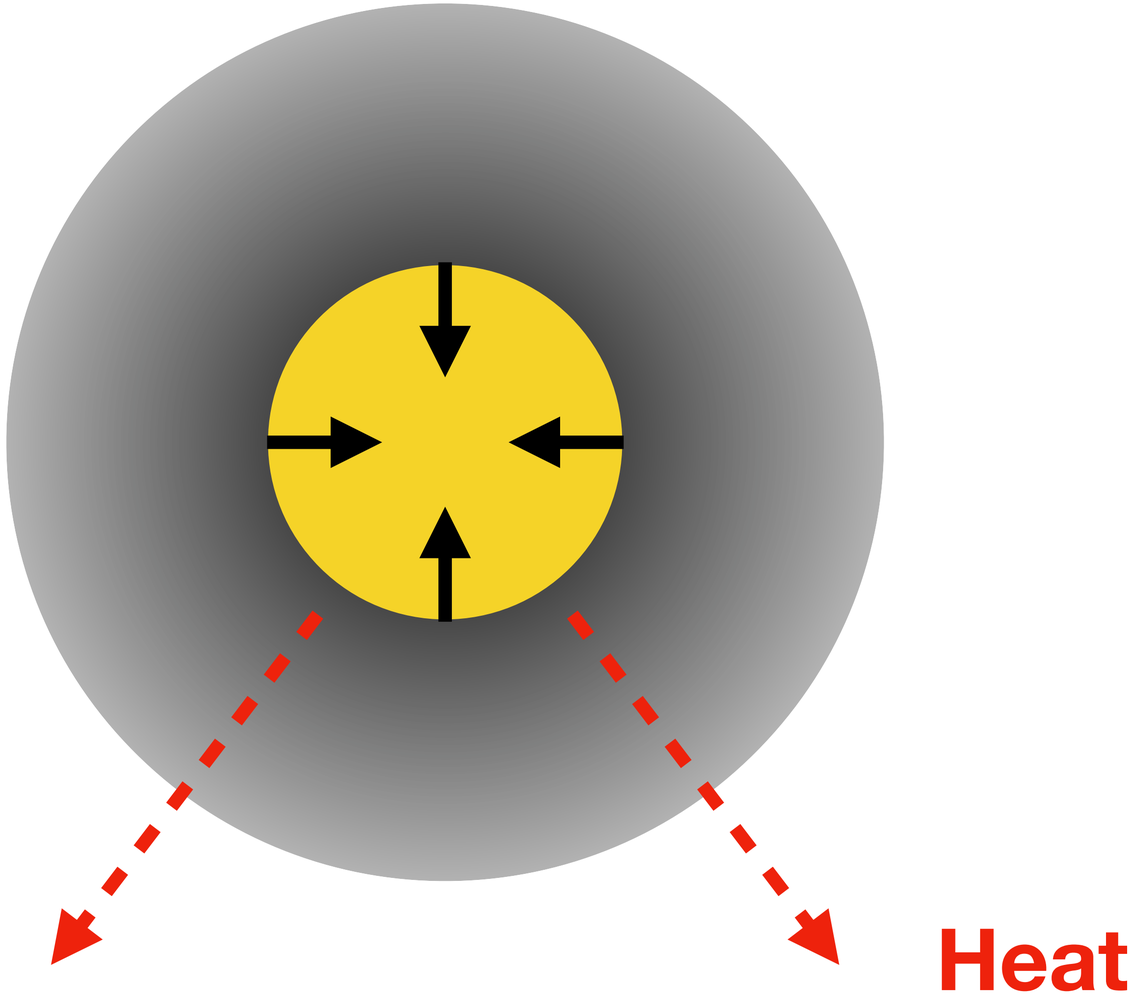
- Accretion period is super short.
- Growth from Eddington accretion is negligible.



Even more massive seeds?



Collapsing a dark matter halo



A dark matter halo

How long does it take for a Galactic-sized halo to collapse?

- Cold collisionless dark matter (CDM) halo

$$t_{\rm coll} \sim 10^{67}\,{\rm Gyr}\,\left(\frac{m}{1\,{\rm GeV}}\right)^{-1}$$

$M_{halo} = 10^{12}\ M_{sun}$
m: dark matter mass

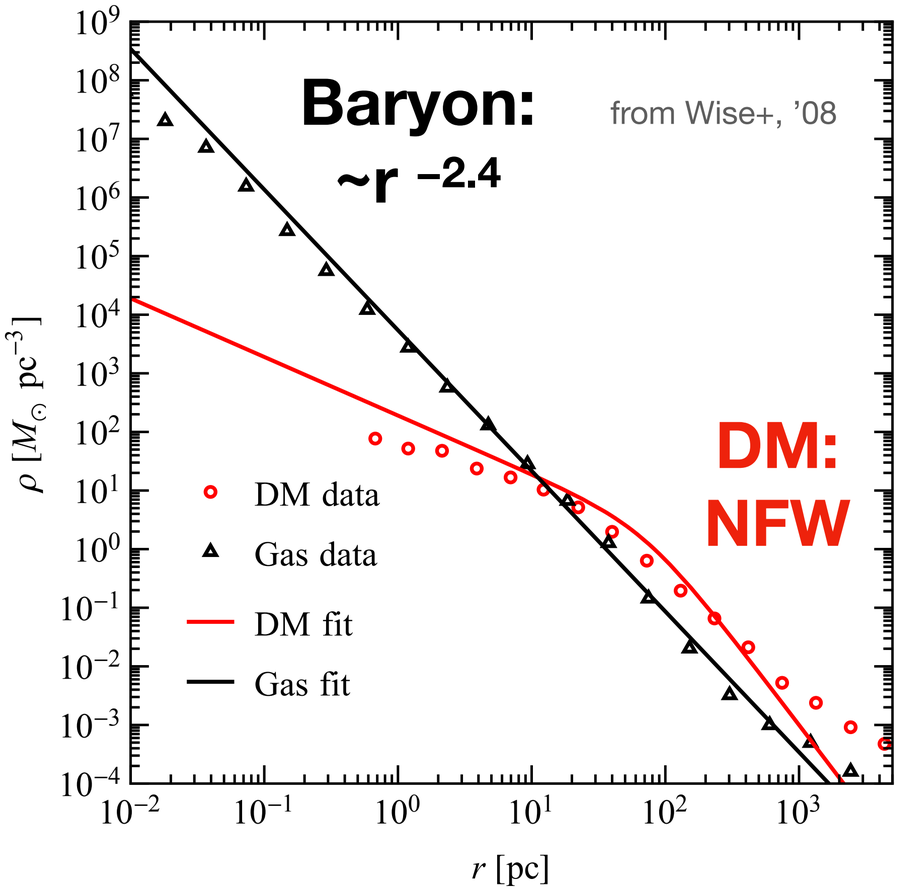
- Self-interacting dark matter (SIDM) halo

$$t_{\rm coll} \sim 10\,{\rm Gyr}\,\left(\frac{\sigma/m}{1\,{\rm cm}^2/{\rm g}}\right)^{-1}$$

$M_{halo} = 10^{12}\ M_{sun}$, c = 3, z = 9
σ: self-interaction cross section
1 cm^2/g ~ n-p cross section strength

Our scenario

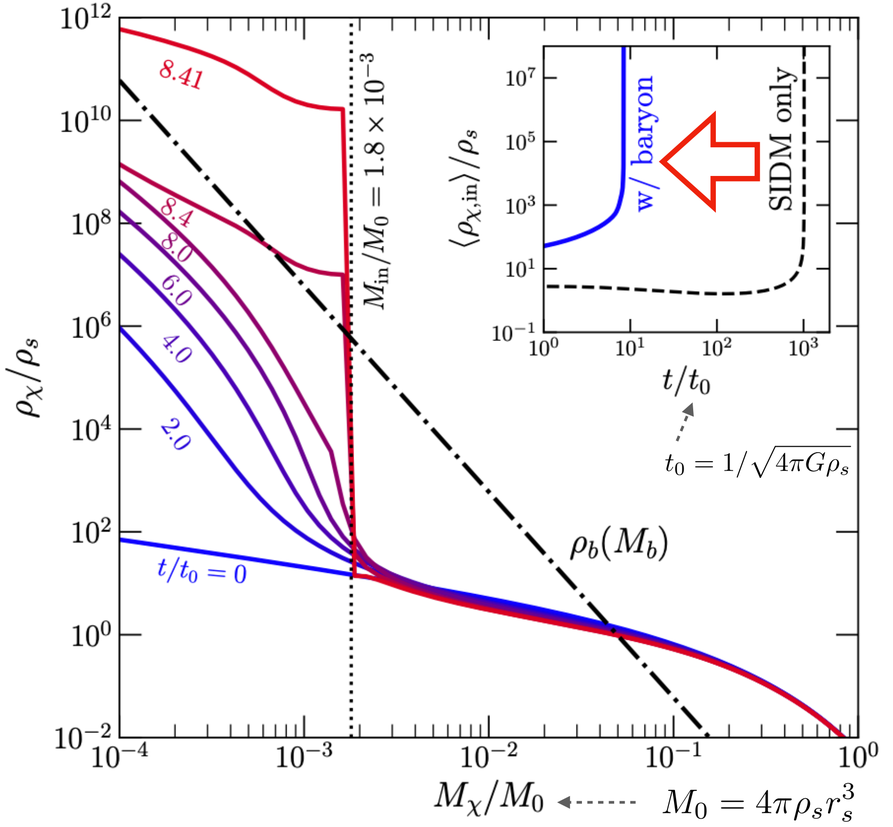
Galactic-sized SIDM halo



Result

- An ultrahigh density region emerges at the halo center.
- The collapse time is ~100 shorter than that from the SIDM-only halo (w/ the same cross section strength).
- Also found if baryons follow a compact Hernquist profile.
- Also found in N-body simulations (Yang & Yu ’21, Sameie+ ’21).

$r_s\rho_s\sigma/m = 0.2$ Collapse process

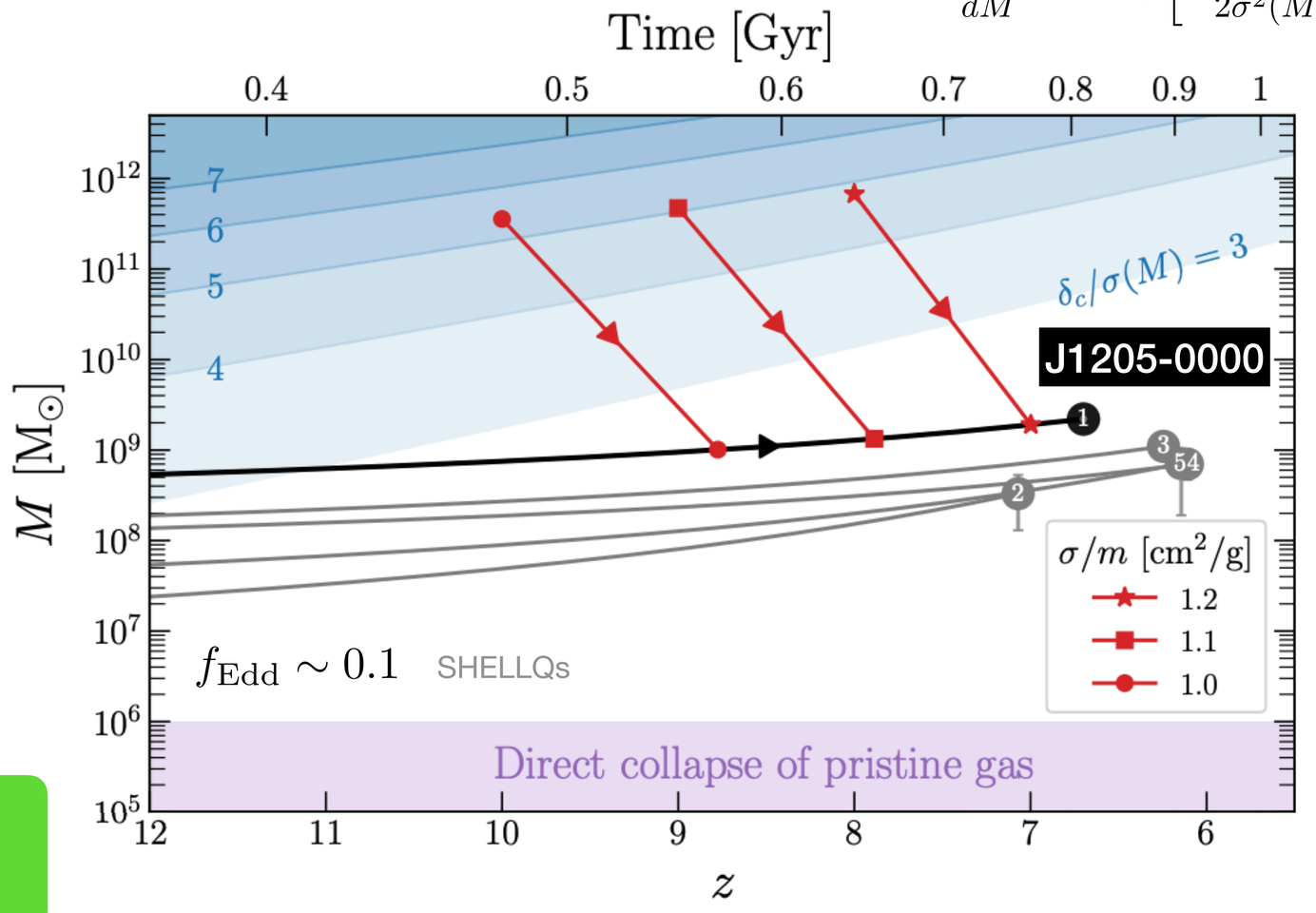


Form low-luminosity SMBHs

- Need galactic-sized DM halos at high redshift (rare in the early Universe).
- Need cross section strength σ/m~ O(1 cm²/g)
- Only need moderate concentration (c~3).

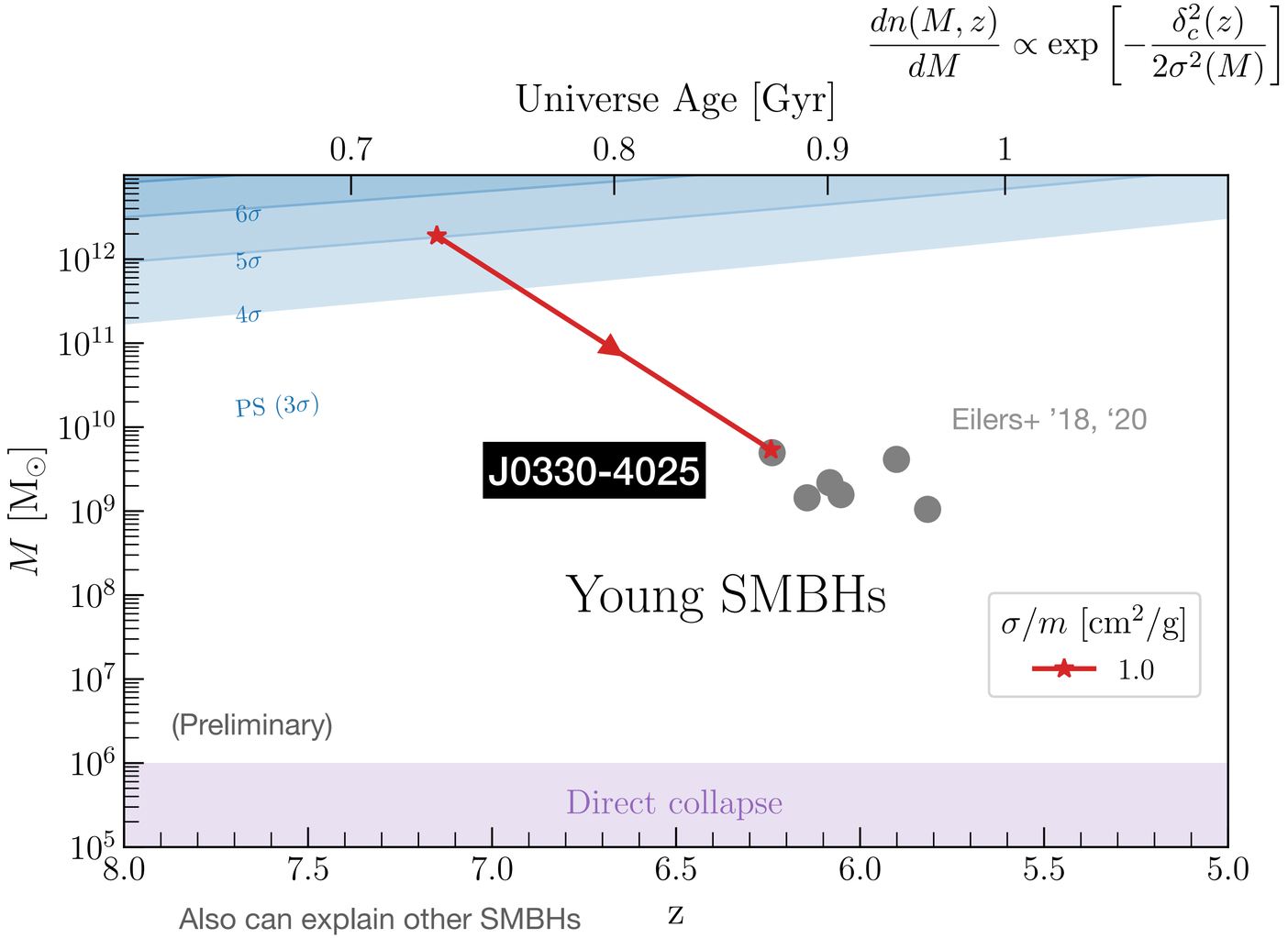
solve the small-scale problems of the CDM paradigm

$$\frac{dn(M,z)}{dM} \propto \exp\left[-\frac{\delta_c^2(z)}{2\sigma^2(M)}\right]$$



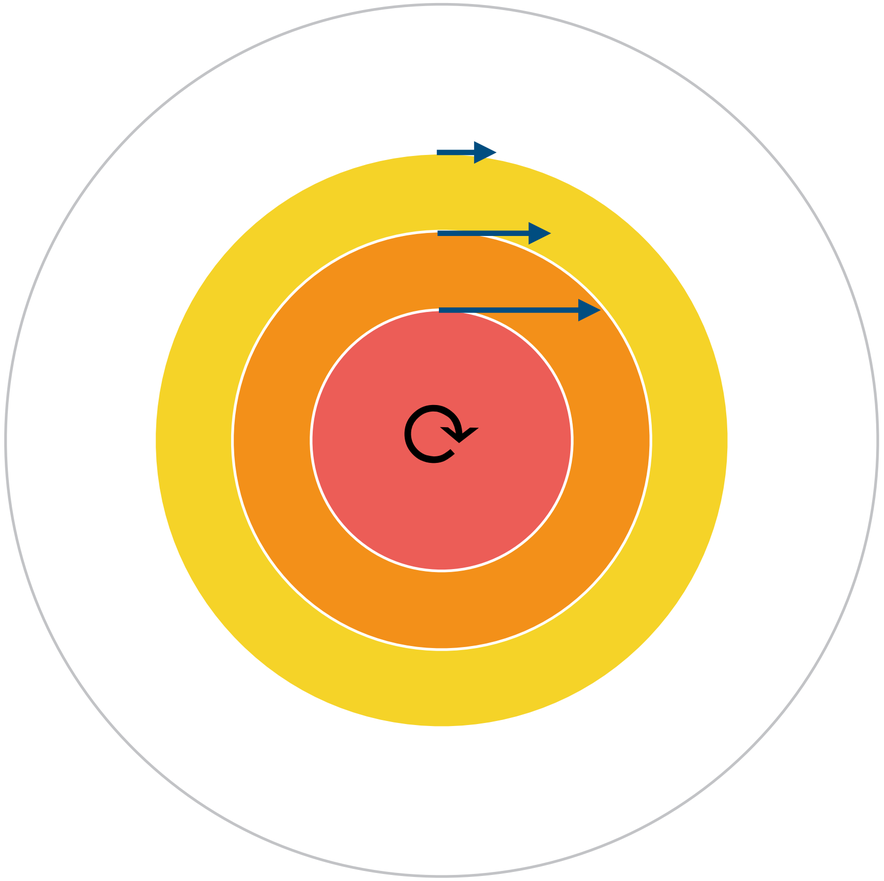
Form young SMBHs

- Need galactic-sized DM halos at high redshift (rare in the early Universe).
- Need cross section strength σ/m~ O(1 cm²/g)
- Only need moderate concentration (c~3).



How to dissipate angular momentum?

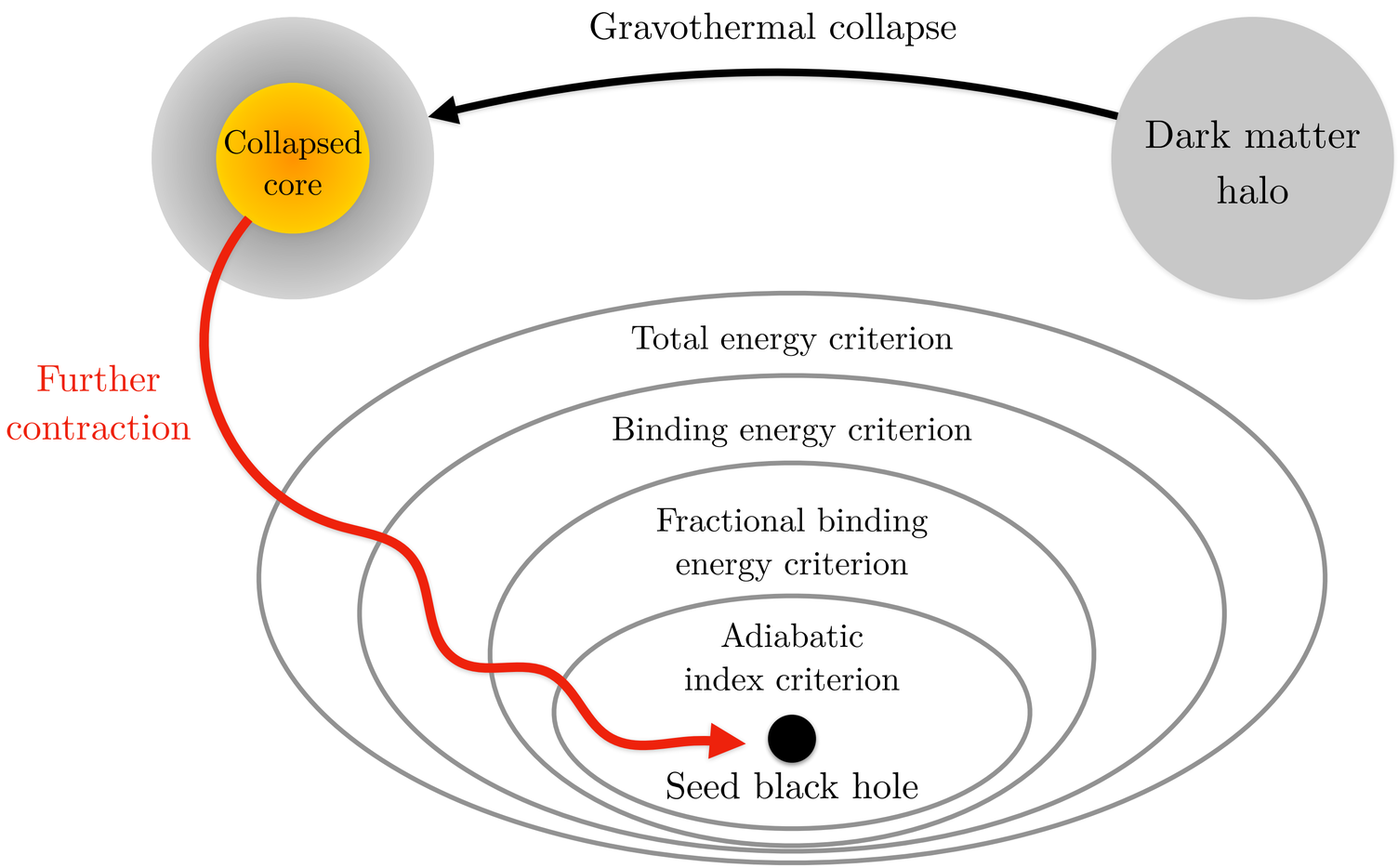
Collisional viscosity



Angular momentum for the central region can be dissipated efficiently by self-interactions.

Collapsed halo = black hole?

The general relativistic instability can be triggered for the collapsed core.



more details can be found in 2108.11967

Summary

- The first SMBHs challenges astrophysics and may require new thinking.
- SIDM + baryon provides a pathway to seed those SMBHs.
- We will learn a lot more about the first SMBHs in the near future, e.g. James Webb Space Telescope, Square Kilometer Array.

Thank you!