Tracing Cosmic Evolution through Dark Matter Phenomena: The Origin of Supermassive Black Holes in JWST Era

Presenter: Saiyang Zhang

4th yr PhD Candidate, Cosmic Frontier Center & Weinberg Institute

Department of Physics, University of Texas at Austin

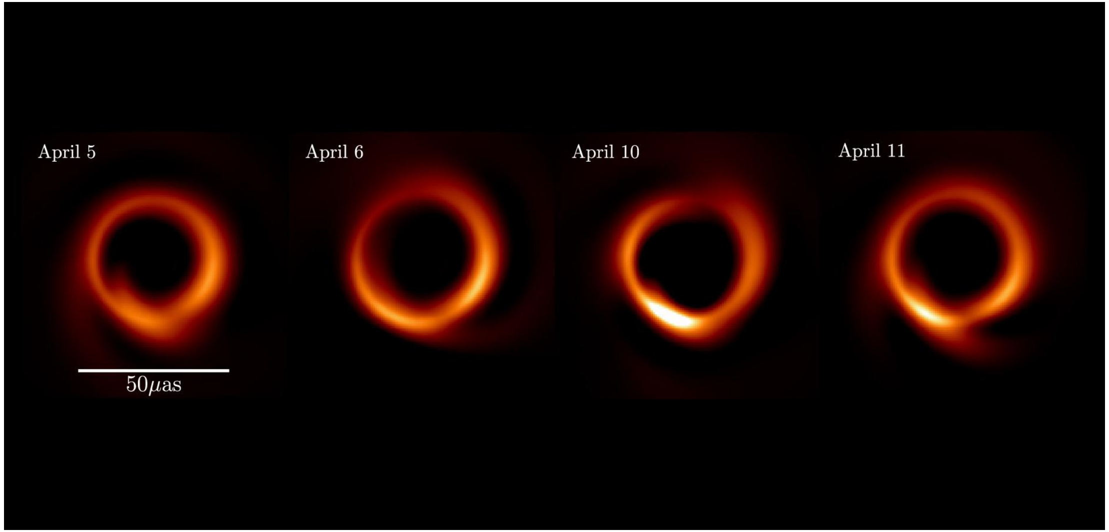
Collaborators: Katherine Freese(UT Austin), Volker Bromm(UT Austin), Cosmin Ilie(Colgate Univ), Boyuan Liu(Cambridge Univ)

Content

- Supermassive Black Holes (SMBHs): an overview
- Results from the latest JWST observations
- Beyond Standard Model physics on SMBH seeding

Supermassive Black Hole (SMBH)

- Mass >10^6 solar mass black holes
- Accrete surrounding material through gravity and form accretion disk
- Produce copious amount of X-ray emission, also a radio source
- Could be observed through emission line broadening (fast moving clouds)



M87, Medeiros et al. (2023) [2304.06079]

Black Hole Growth and Eddington Limit

Balancing the two forces gives:

$$\frac{GMm}{R^2} = \frac{L\kappa m}{4\pi R^2 c}$$

And solving for this luminosity we get:

$$L = \frac{4\pi GMc}{\kappa}$$

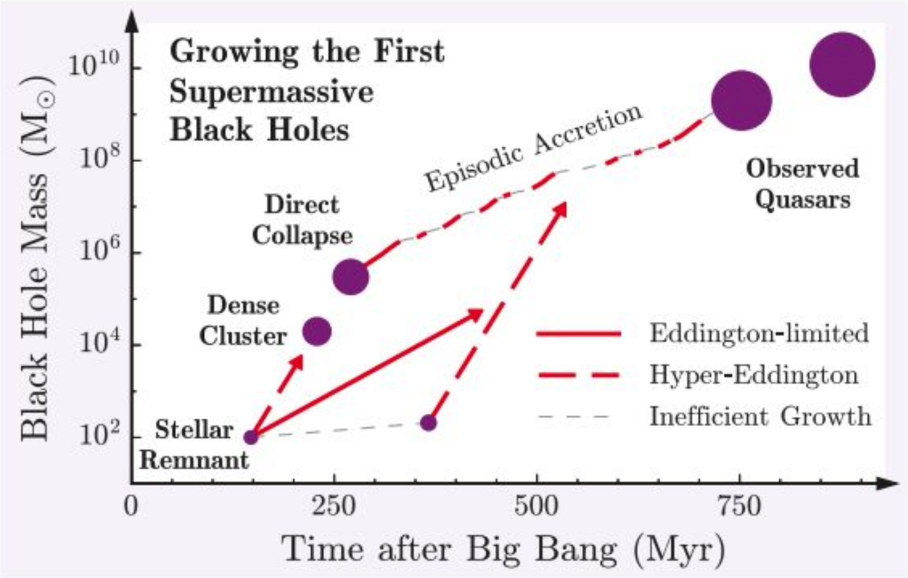
This has a profound implication. If our accreting object radiates at more than the Eddington luminosity, even a glut of "fuel" will be blown away by radiation pressure: we get a natural feedback process with a limiting accretion rate. We derive this by setting the accretion luminosity equal to the Eddington luminosity:

$$\epsilon \dot{M} c^2 = \frac{4\pi GMcm_p}{\sigma_T}$$

From which the limiting *Eddington accretion rate* is:

$$\dot{M}_{Edd} = \frac{4\pi GMm_p}{\epsilon c \sigma_T}$$

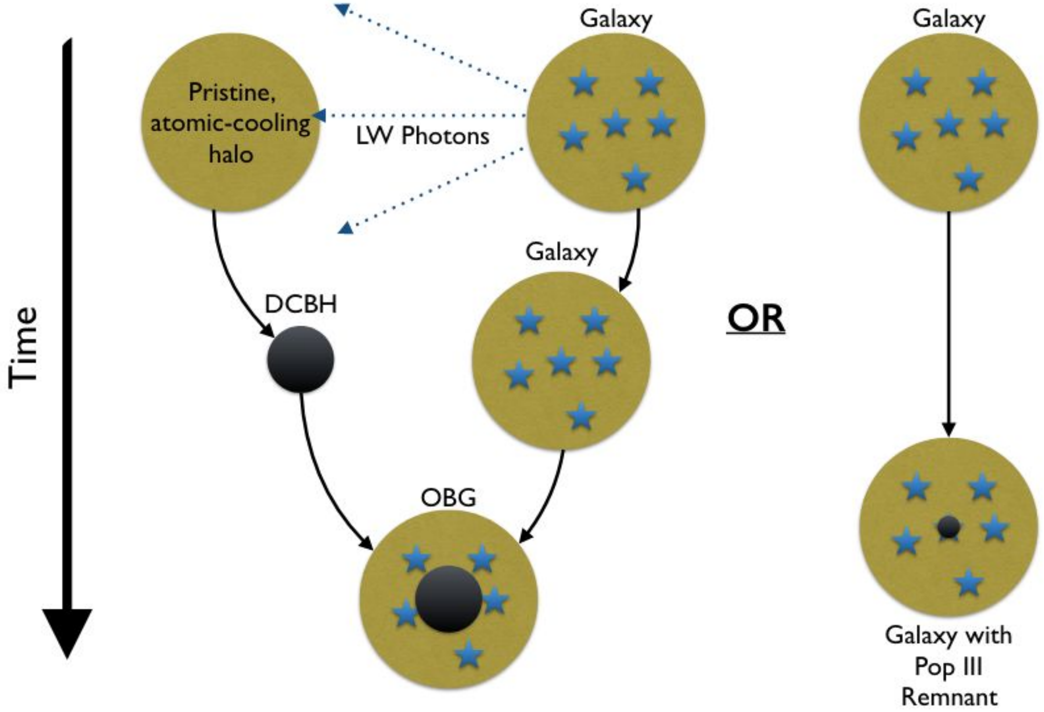
https://www-astro.physics.ox.ac.uk/~garret/teaching/lecture7-2012.pdf



Smith et al. (2017) [1703.03083]

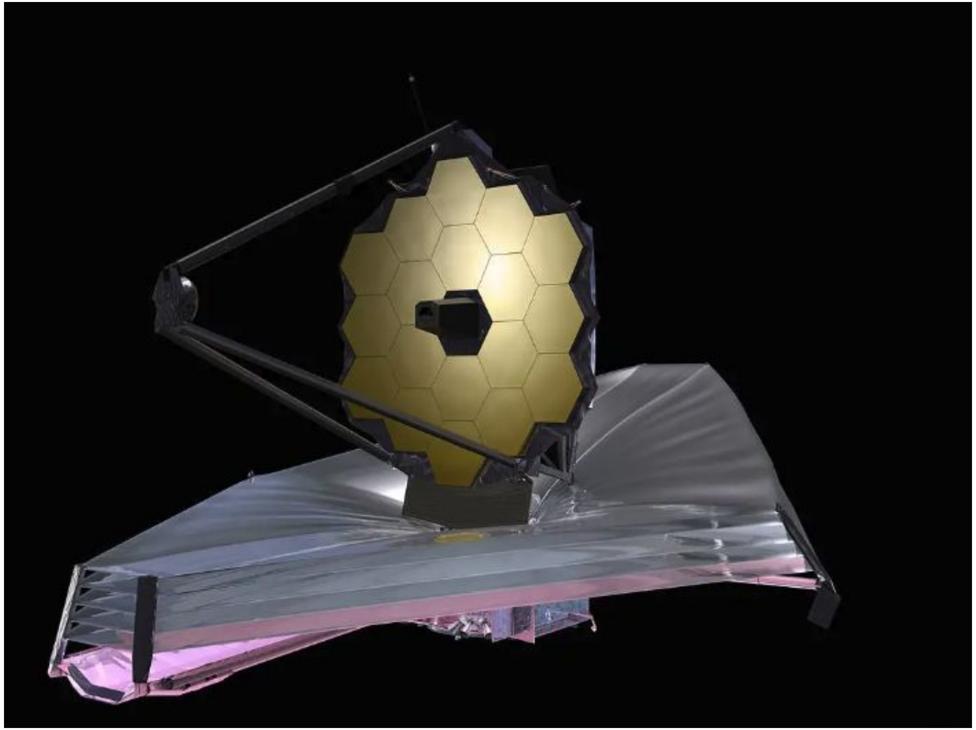
Light Seed vs. Heavy Seed in ΛCDM Model

- Pop III star remnants
- Dense Star Cluster
- Direct Collapse Black Hole (DCBH)

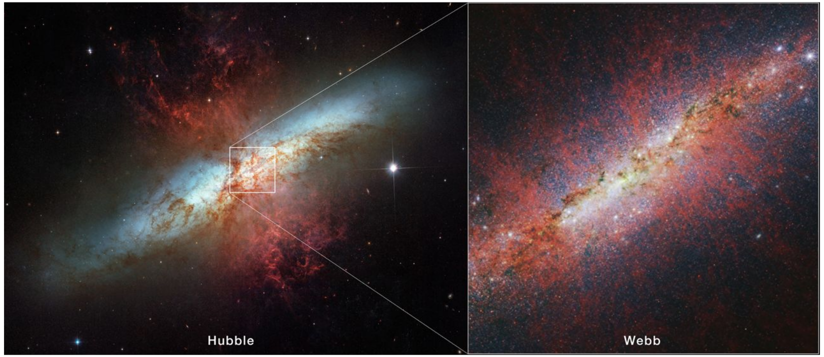


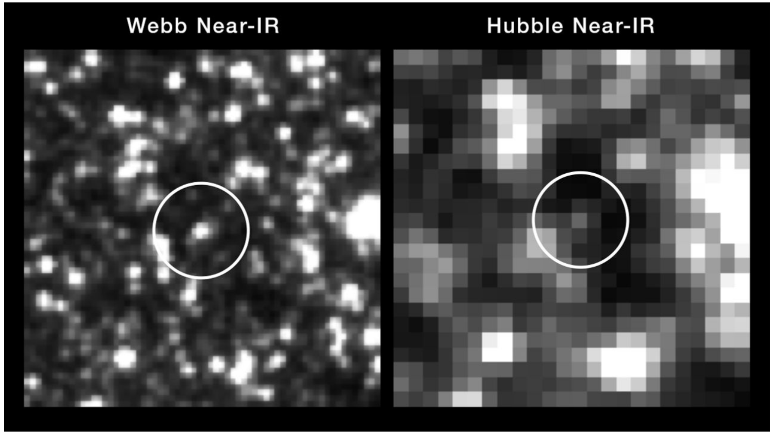
Smith et al. (2019) [1904.12890]

James Webb Space Telescope (JWST)



https://www.nasa.gov/image-article/james-webb-space-telescope-jwst/

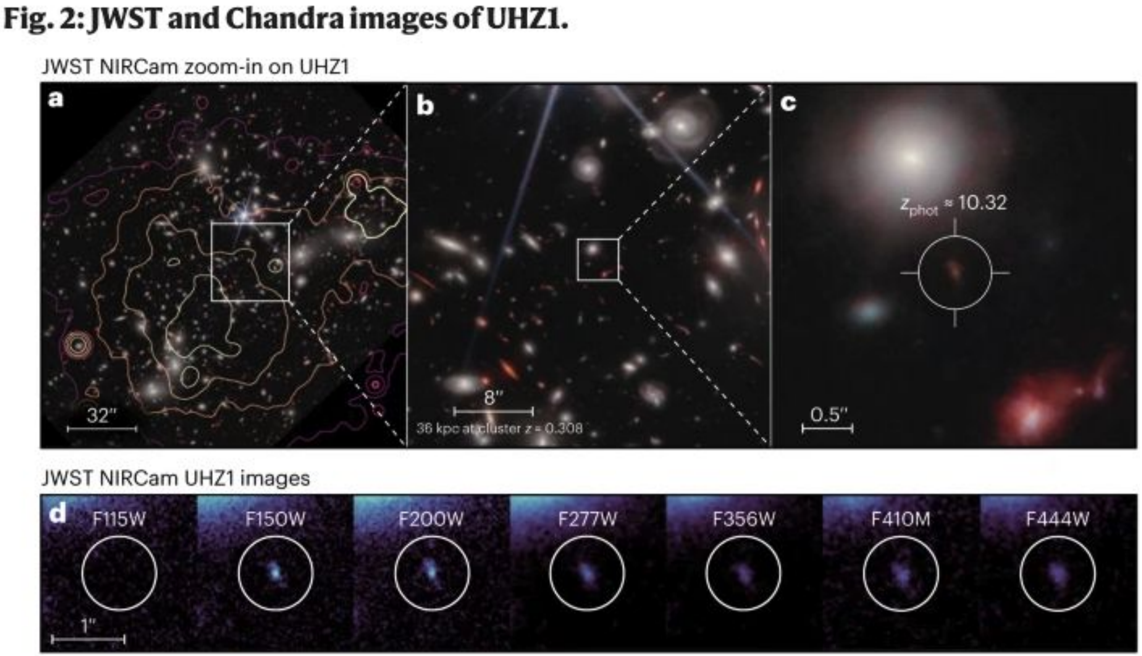


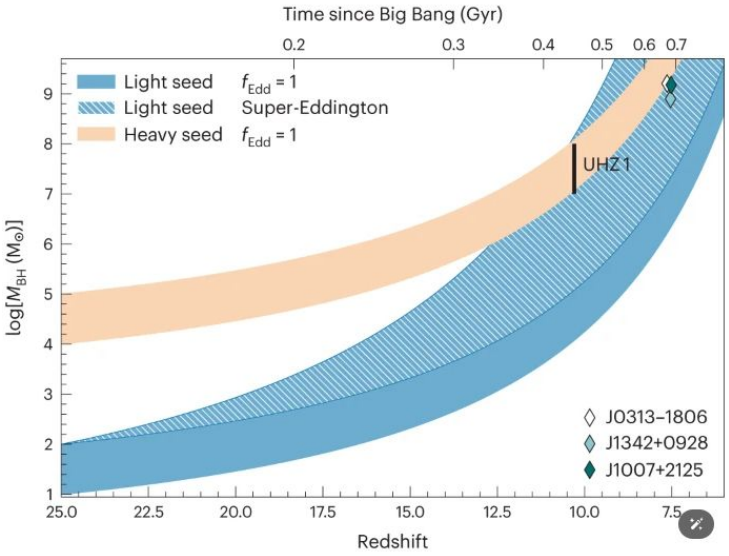


Questions on Cosmology from JWST Discovery

- Stress testing standard universe model (Boylan-Kolchin (2023) [2208.01611])
  - Discovery of too massive galaxies with stellar mass $>10^9$ solar mass at high redshift $z > 10$
  - Challenging current cosmic structure/galaxy formation theory and simulations
  - Need new theory/models to explain, or over-prediction of stellar mass (Wang et al. (2024) [arXiv:2403.02399])
- Early Supermassive Black Hole formation
  - See next page

Some Recent Discoveries from JWST

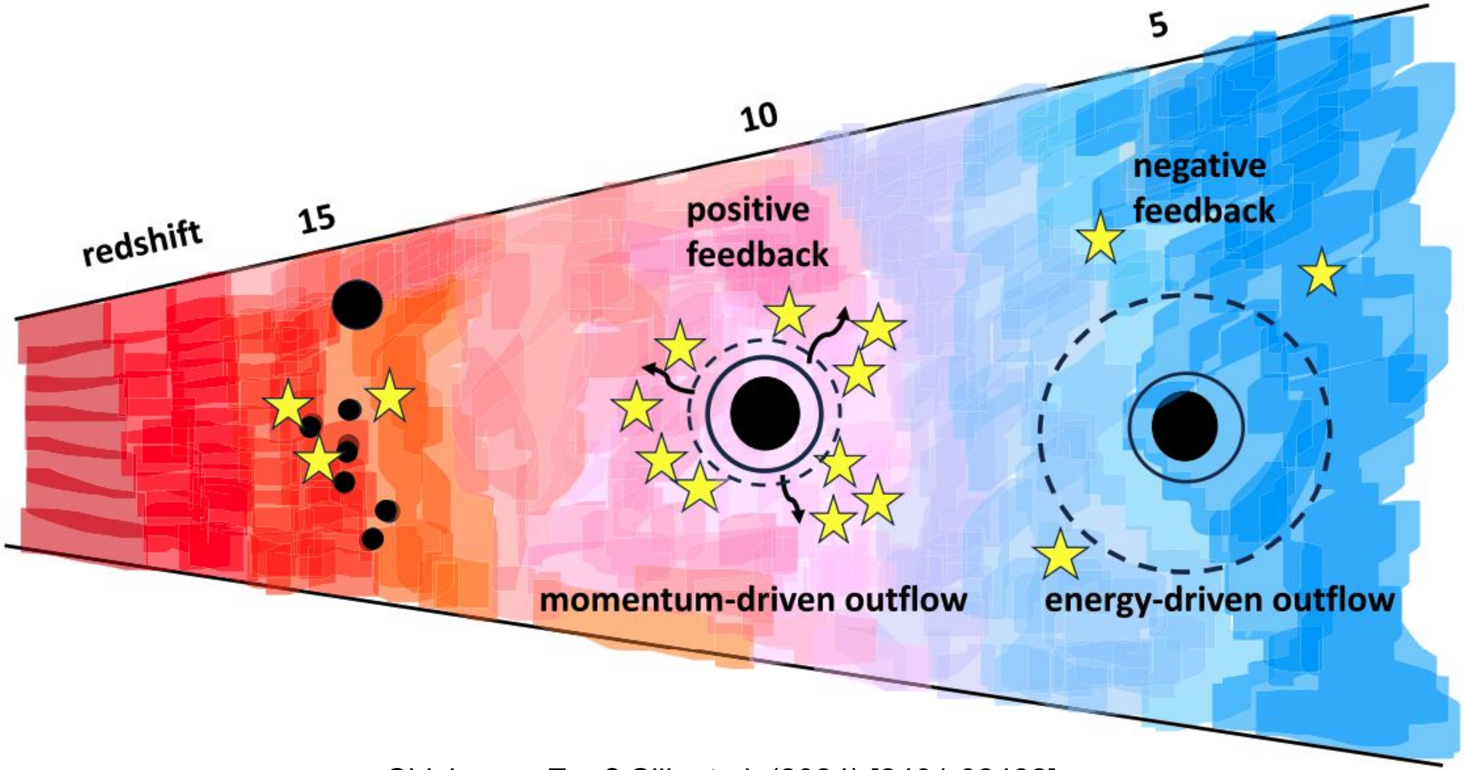




z=10 AGN: UHZ-1

Bodgan et al. (2024) [2305.15458]

Co-evolution of SMBH with Galaxy



Chicken or Egg? Silk et al. (2024) [2401.02482]

Beyond Standard Model Path

- Supermassive Dark Star (WIMP)
- (Massive) Primordial Black Holes (PBH)

About Dark Stars

https://www.sci.news/astronomy/webb-supermassive-dark-stars-12096.html

- Formed in the center of mini-halo
- Powered by DM(WIMPs), no fusion reaction
- Capture DM to refuel
- Can grow supermassive to about ~10^7 solar mass
- Collapse into massive black hole seed after fuel depleted

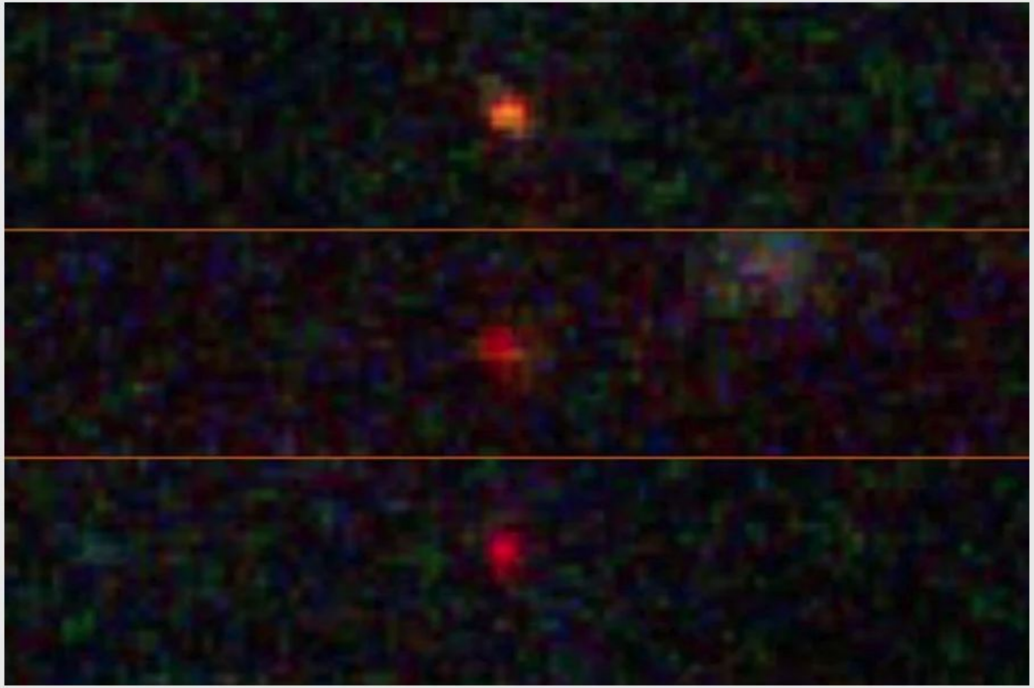
Freese et al. (2008) [0802.1724]

JULY 20, 2023 | 5 MIN READ

JWST Might Have Spotted the First Dark Matter Stars

Stars fueled by the self-annihilation of dark matter might have been spotted for the first time by JWST

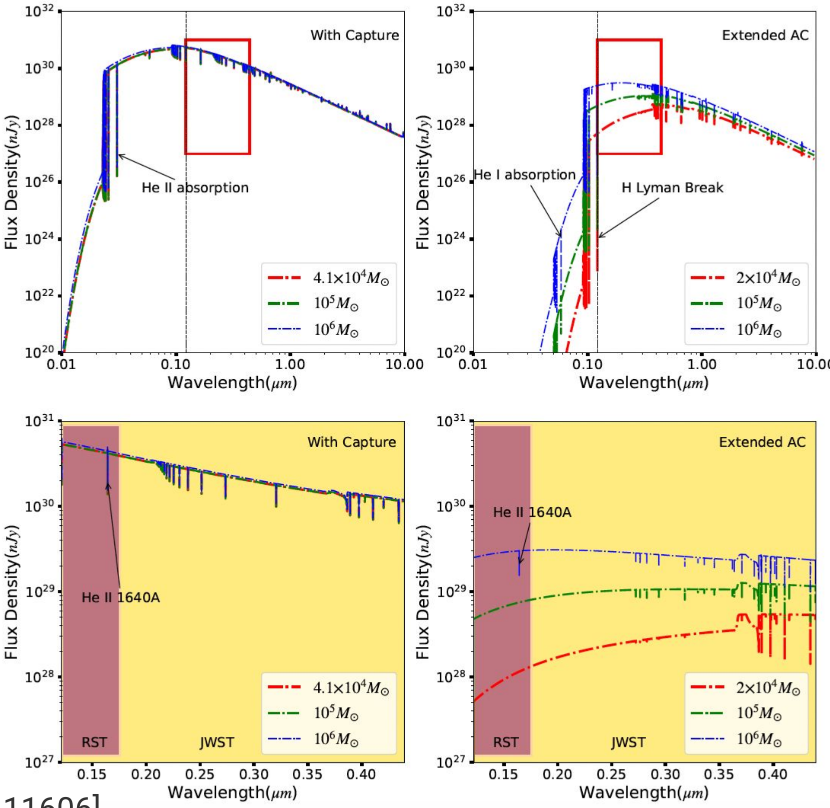
BY STEPHANIE PAPPAS



https://www.scientificamerican.com/article/jwst-might-have-spotted-the-first-dark-matter-stars/

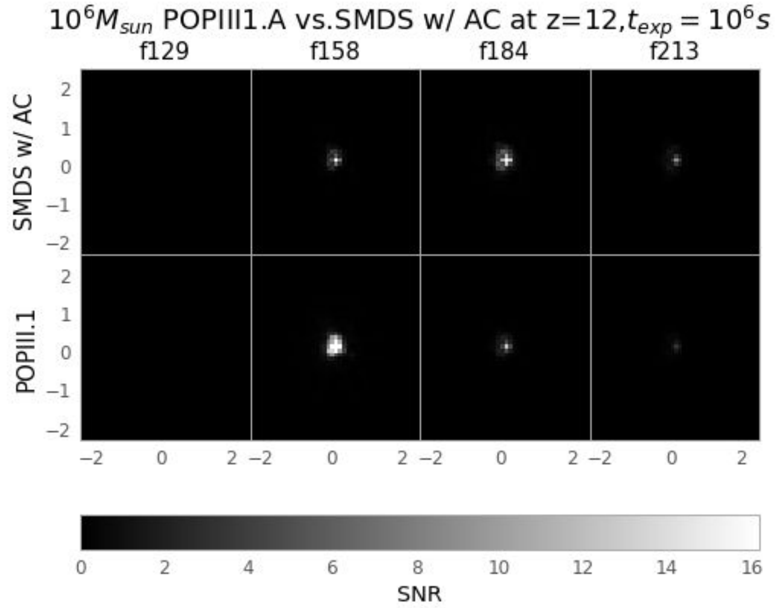
Dark Stars Detectable by Roman Space Telescope (RST)

- RST have similar detection limit as JWST but have much wider field of view
- RST could detect supermassive dark stars up to z~14, and capable of distinguishing them from early galaxies by unique spectral features
- Lensing by foreground object can help us find less massive dark stars

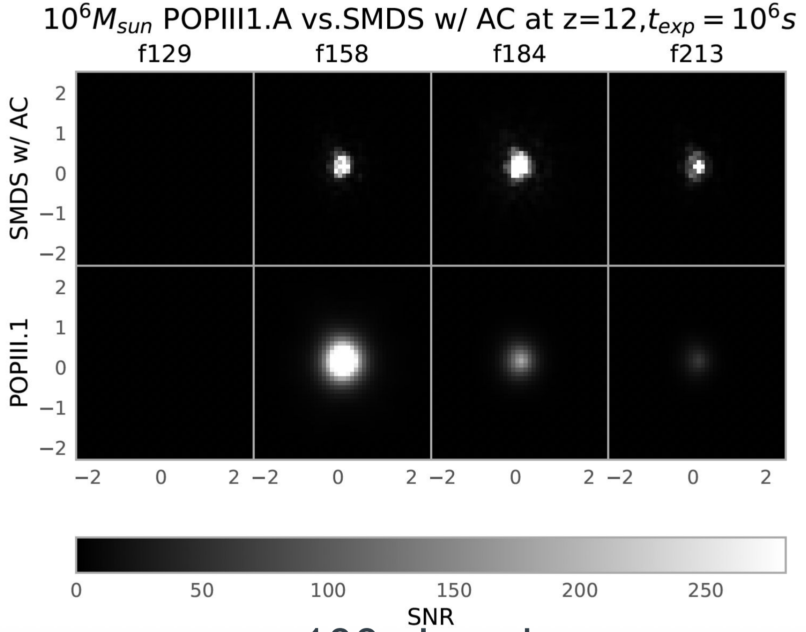


Zhang et al.(2024) [2306.11606]

Dark Stars Detectable by Roman Space Telescope (RST)



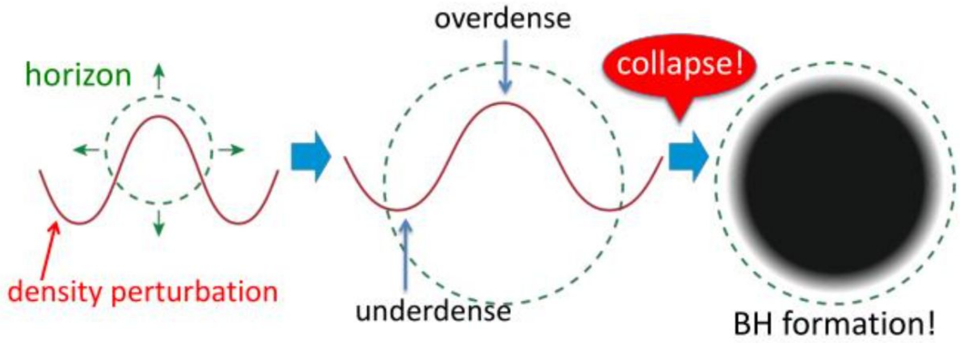
No Lensing



100x Lensing

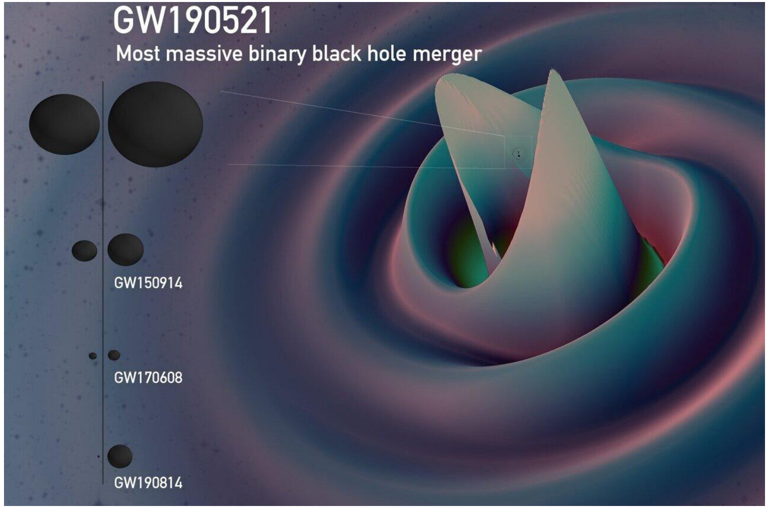
Zhang et al.(2024) [2306.11606]

Primordial Black Holes



Formation

https://en.wikipedia.org/wiki/Primordial_black_hole



Gravitational Wave as a Probe

https://phys.org/news/2021-03-gw190521-event-primordial-black-holes.html

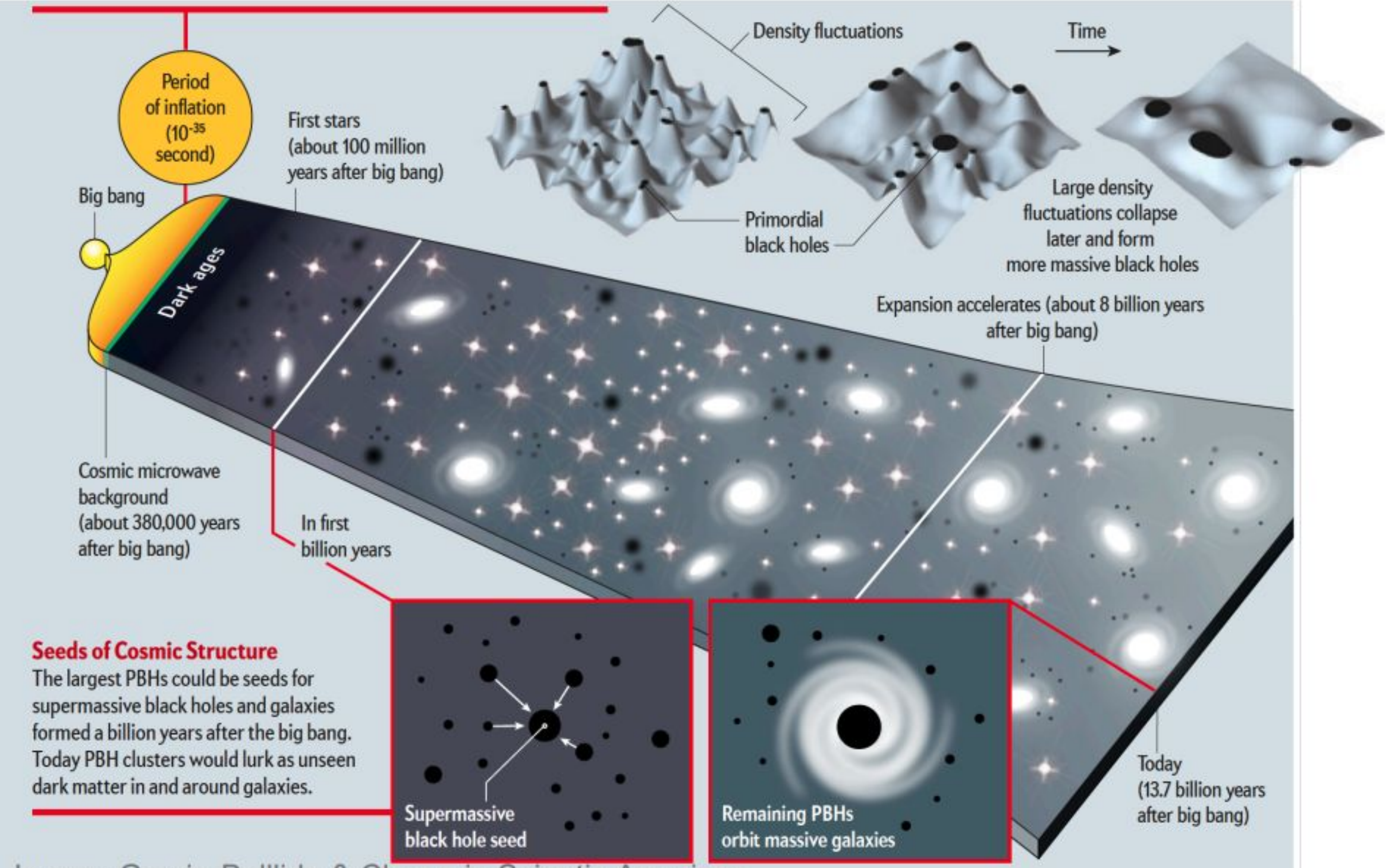
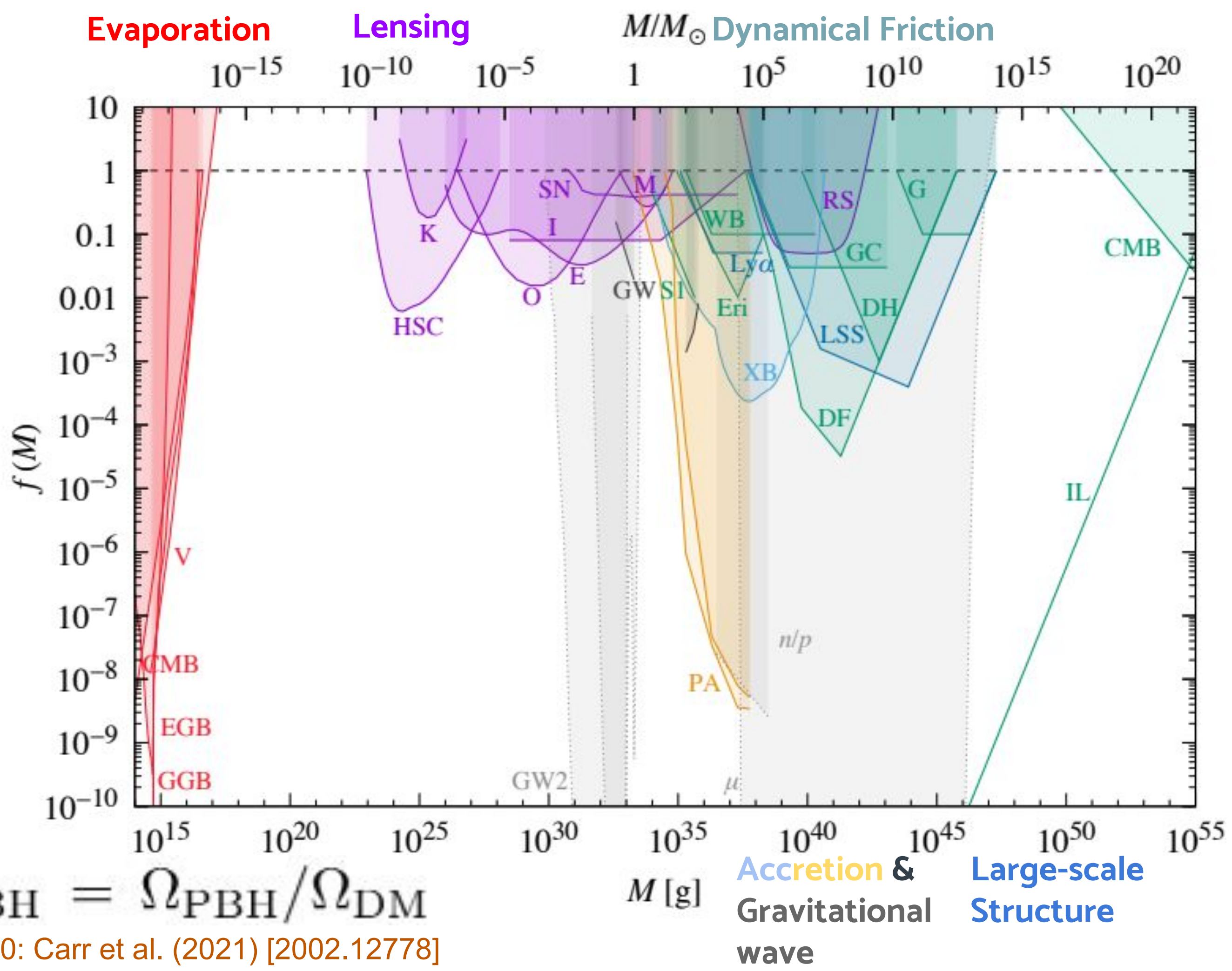


Image: Garcia-Belllido & Clesse in Scientic American

Credit:
https://kspa.soe.ucsc.edu/sites/default/files/Lecture1_PN.pdf

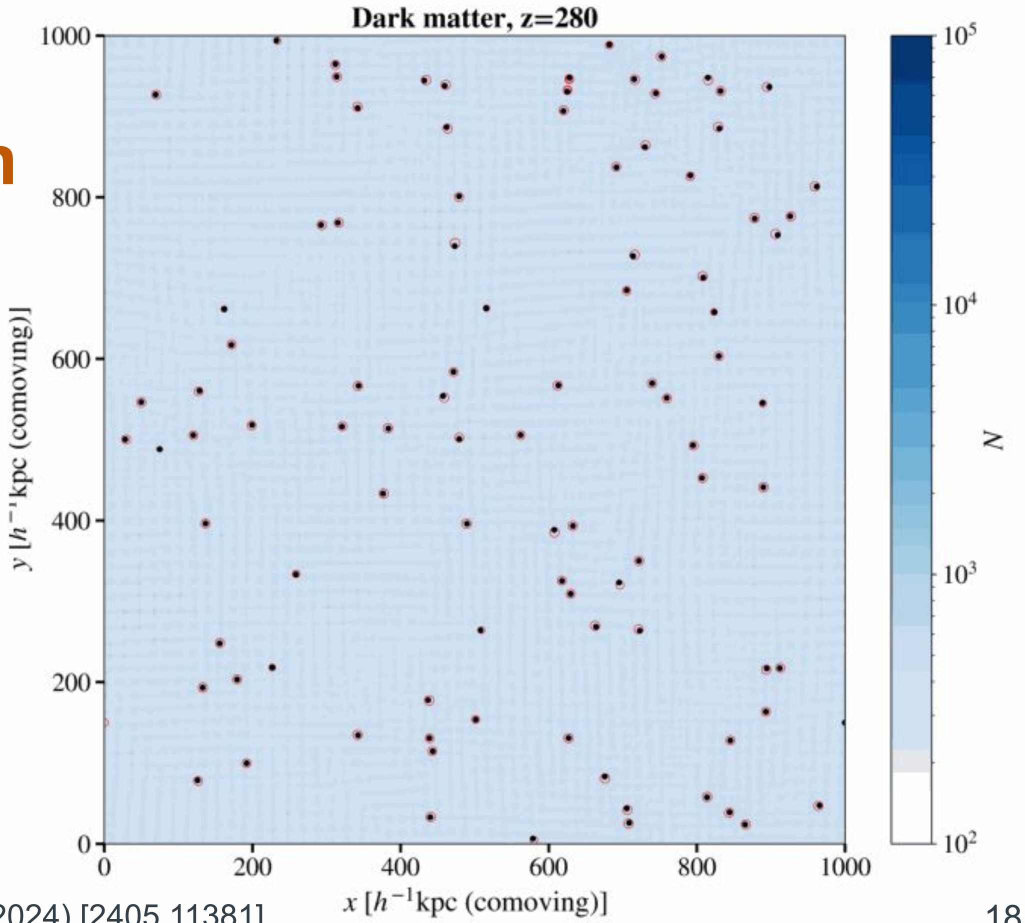


$$f_{\rm PBH} = \Omega_{\rm PBH}/\Omega_{\rm DM}$$

Fig 10: Carr et al. (2021) [2002.12778]

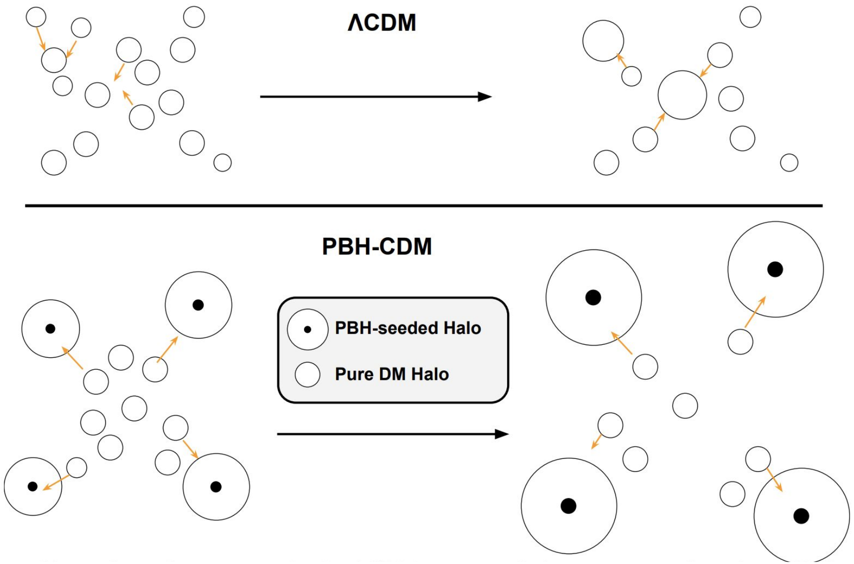
Primordial Black Holes and Structure Formation

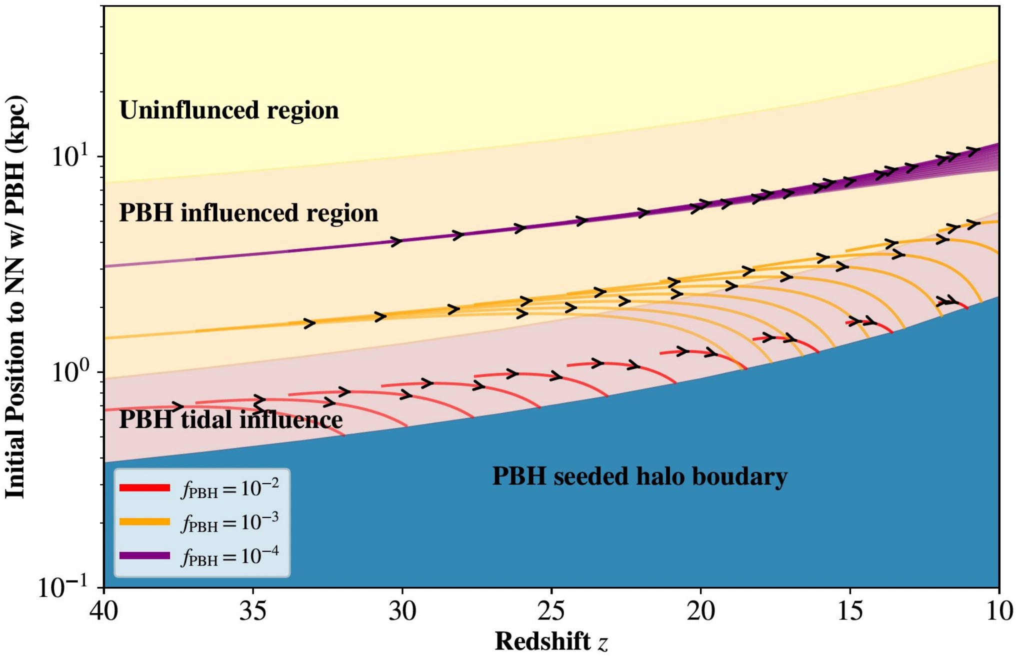
- 10^6 solar mass **Primordial Black Hole** candidate used in this work
- **Primordial Black Holes** will seed the formation of halos surrounding them
- **Primordial Black Hole** seeded halos will engulf newly formed neighboring halos



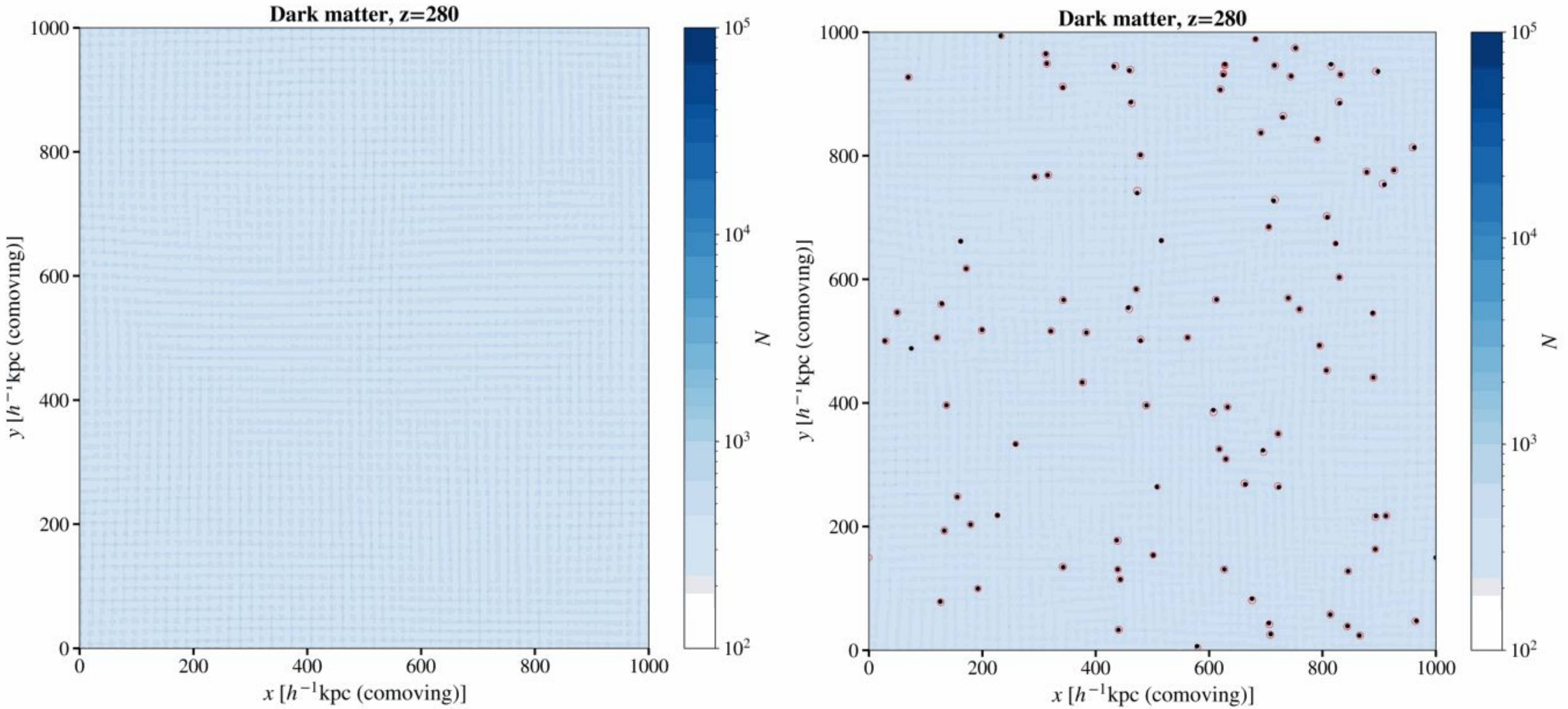
Zhang et al. (2024) [2405.11381]

Halo Dynamics in PBH Universe





Zhang et al. (2024) [2405.11381]



Zhang et al. (2024) [2405.11381]

In the Future

- Run more cosmological simulations with different initial conditions/scales for Primordial Black Holes
- Study how would different Primordial Black Hole candidates influence the formation of the first stars and galaxies
- Find more possible observational features from Dark Stars and Primordial Black Holes
- Data mining from available JWST dataset

Summary

- In the era of deep sky surveys, we are closer to understand the formation of SMBH in early universe
- Early JWST results favor the heavy seed scenario
- Different astrophysical phenomenologies from beyond standard model DM could also form massive seeds to solve the problem involving supermassive black hole formation

Thank you!
Grazie!