銀河・超巨大ブラックホール
共進化過程の理解に向けて

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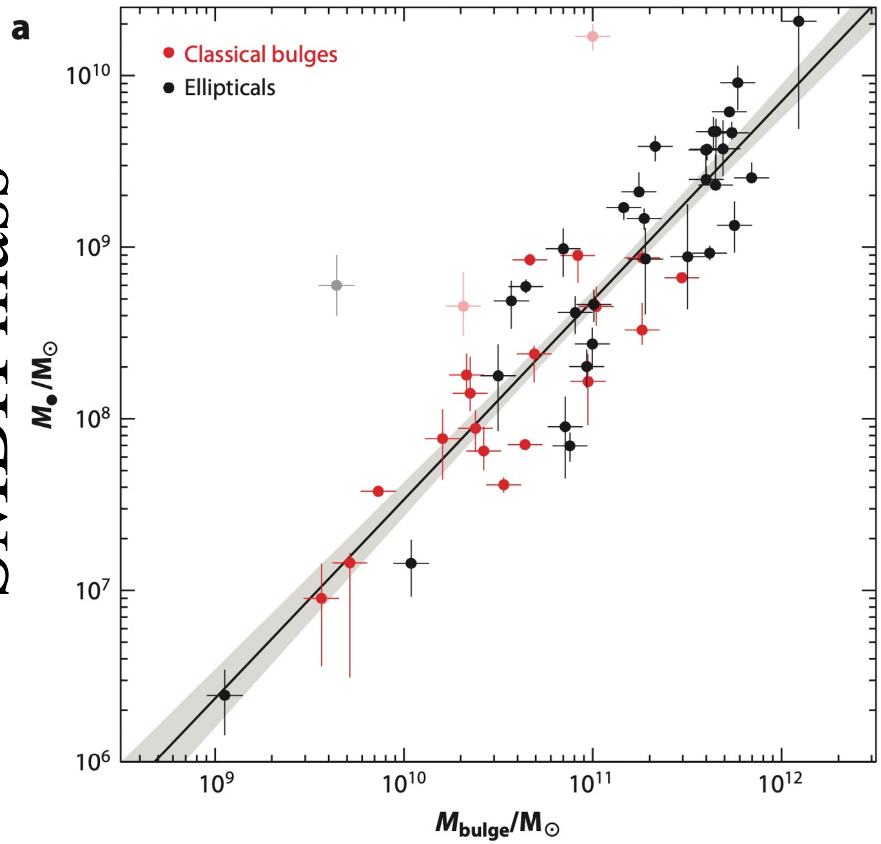
マルチメッセンジャー天文学の展開

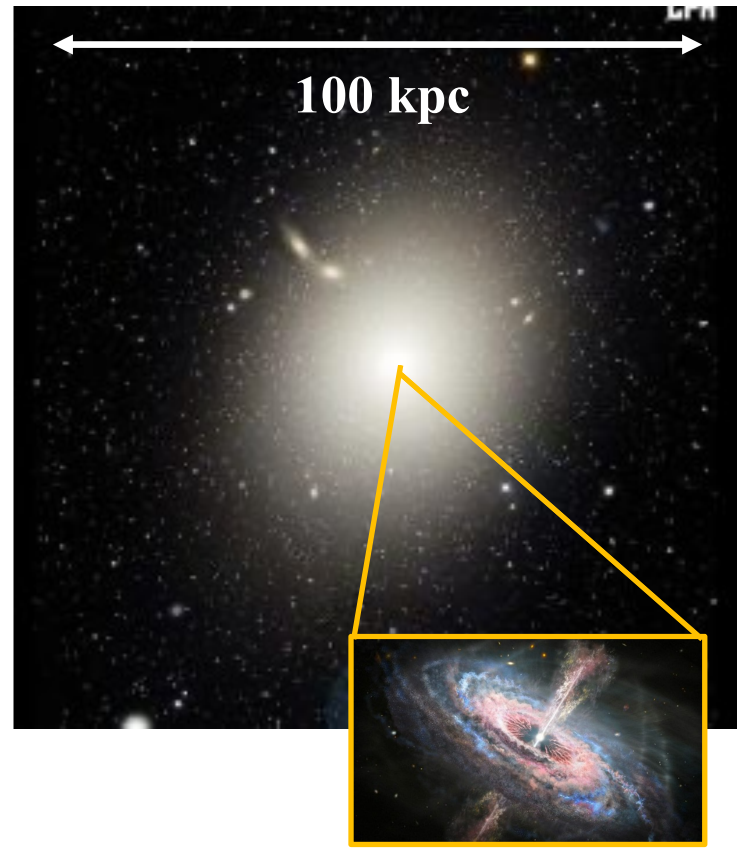
東京大学柏キャンパス, ２０２３年11月2日

Coevolution of galaxies and SMBHs

SMBH mass

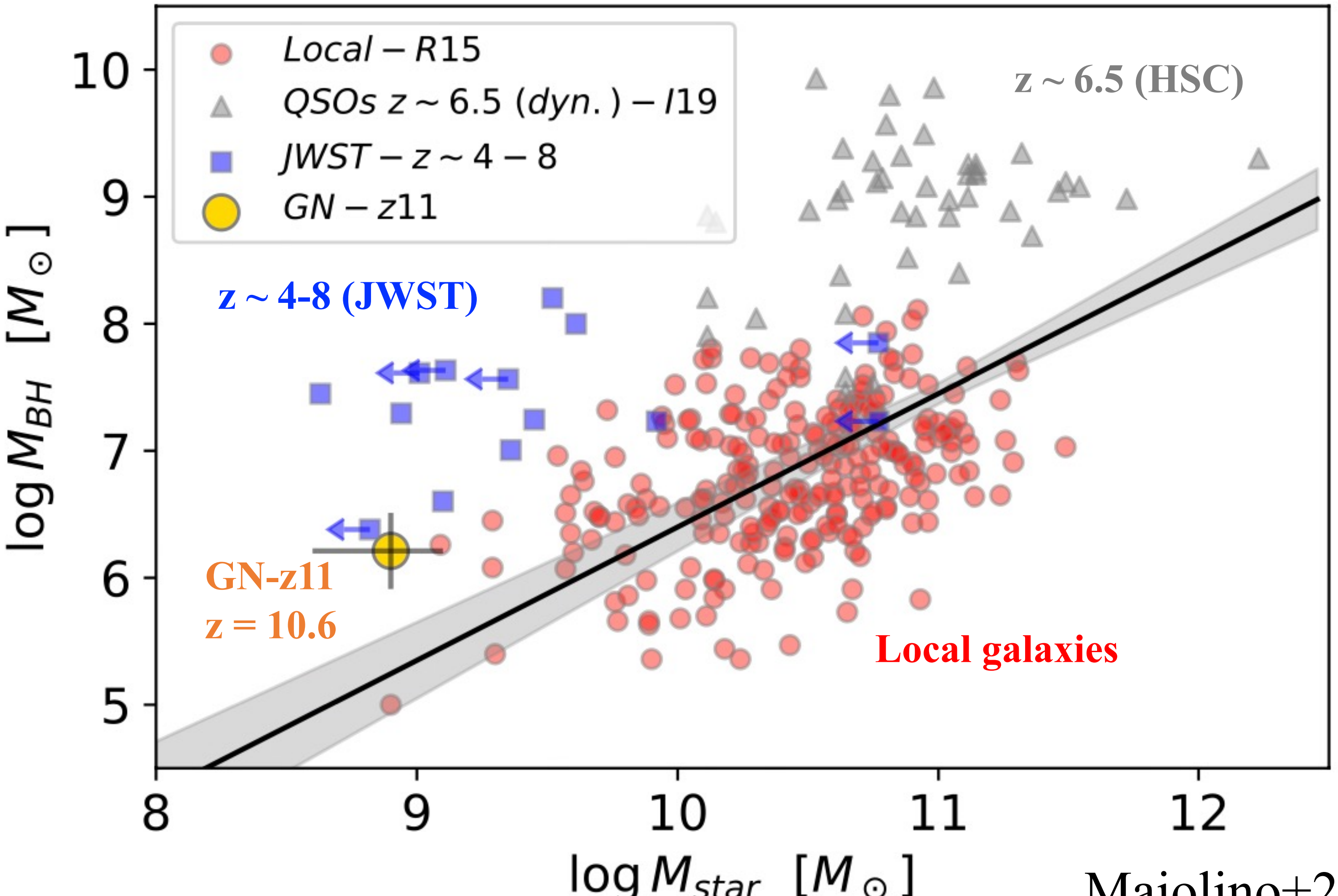


Bulge mass



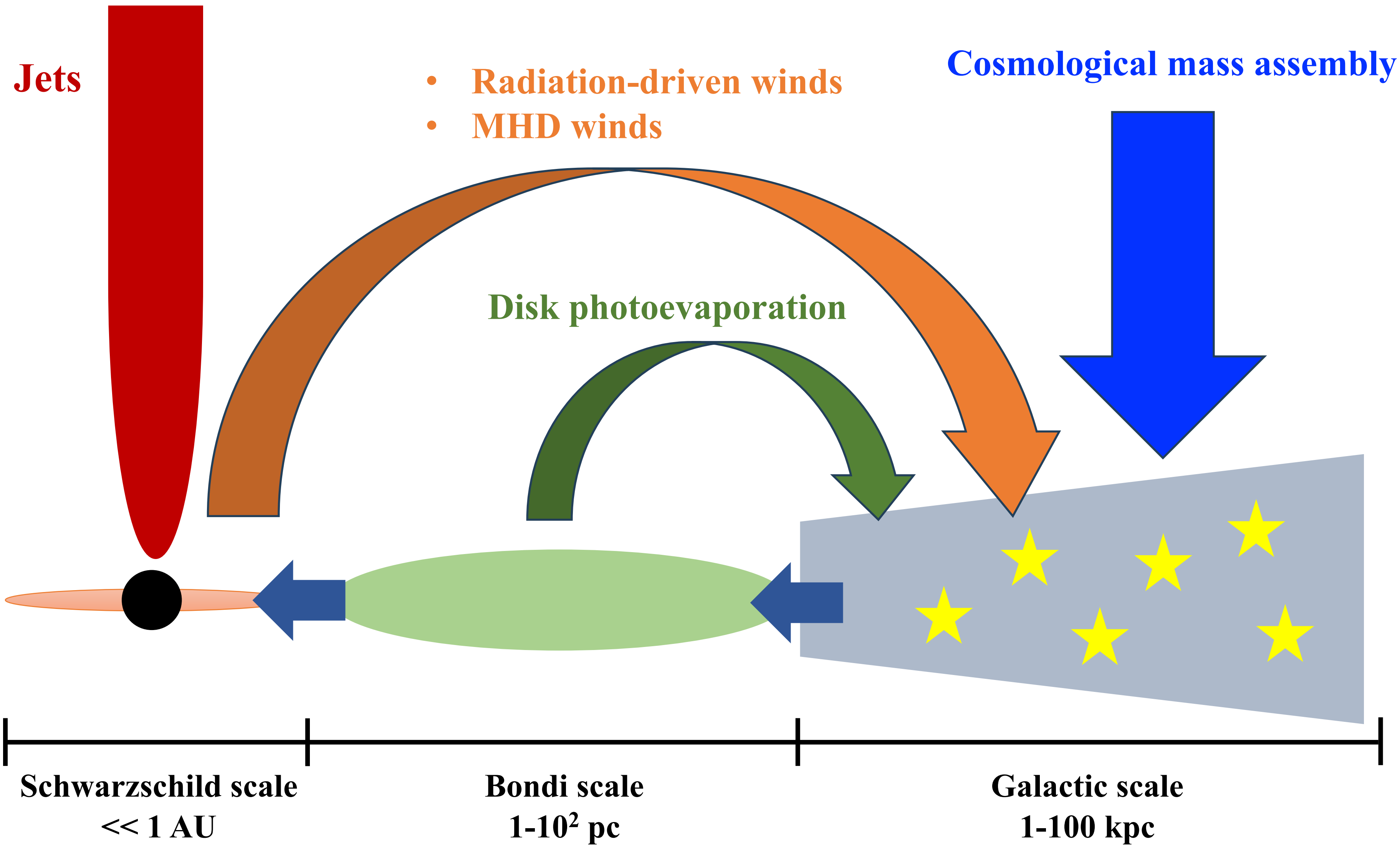
< 1 pc

Overmassive BHs in the early universe



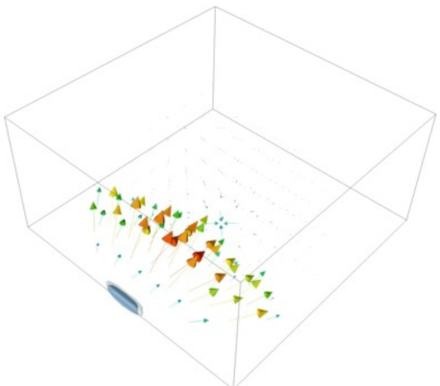
Maiolino+2023

Galactic ecosystem with AGNs

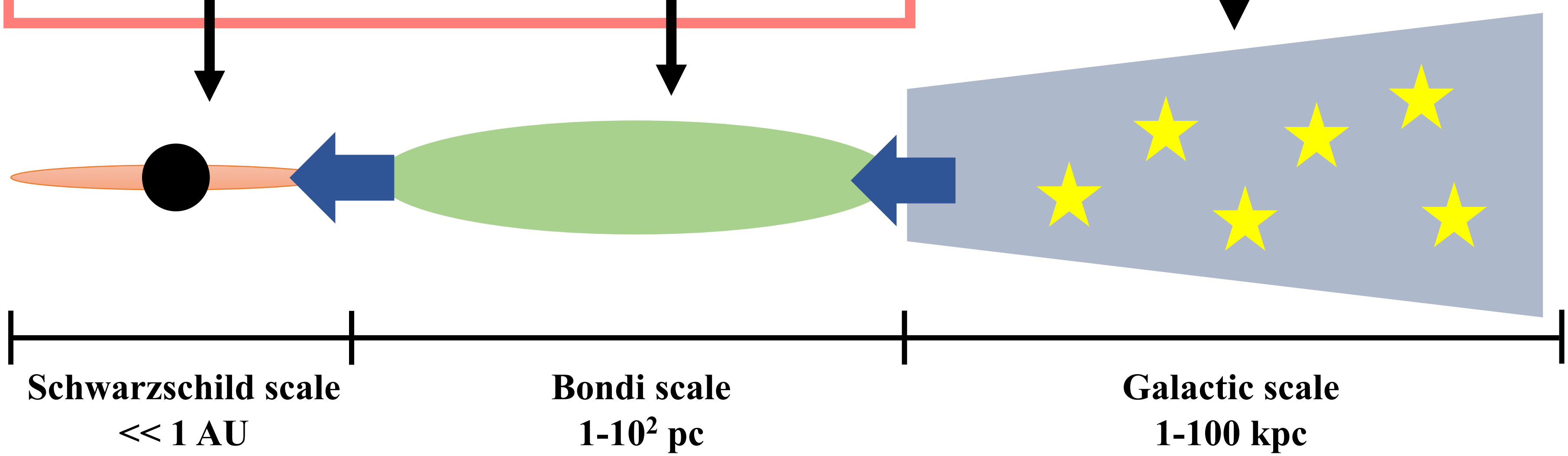


Galactic ecosystem with AGNs

Radiation hydrodynamical simulations
(e.g., DT+2019, 20, 21, 22)



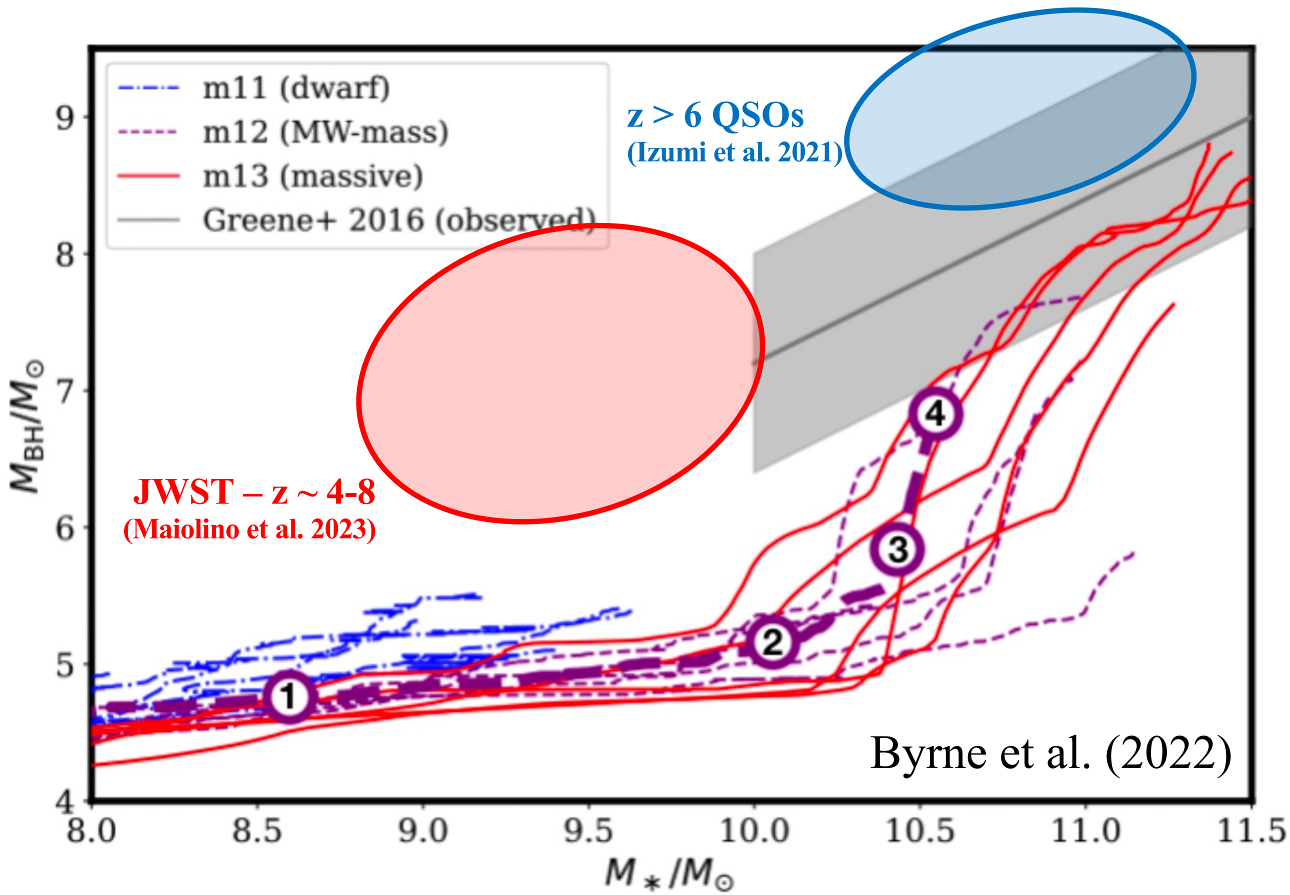
- **Galaxy-scale simulations**
- **Semi-ana. model**
  (e.g., DT in prep.)



SMBH formation in cosmological simulations

- M_{bh}-M_* relation has not been explained yet.
- e.g., Byrne+2022: suppose no AGN feedback

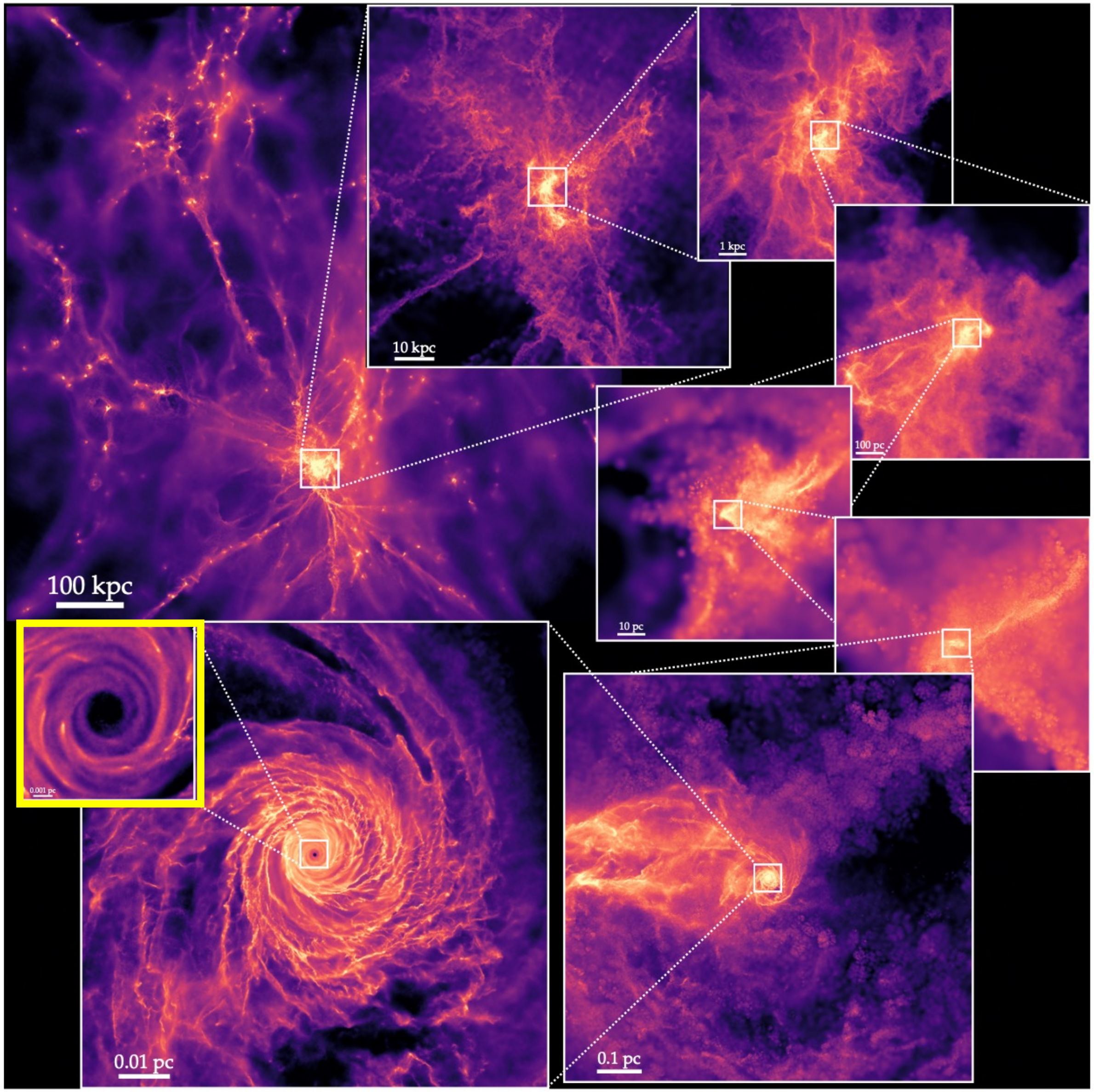
→ **Need to learn more about galactic-scale physics.**



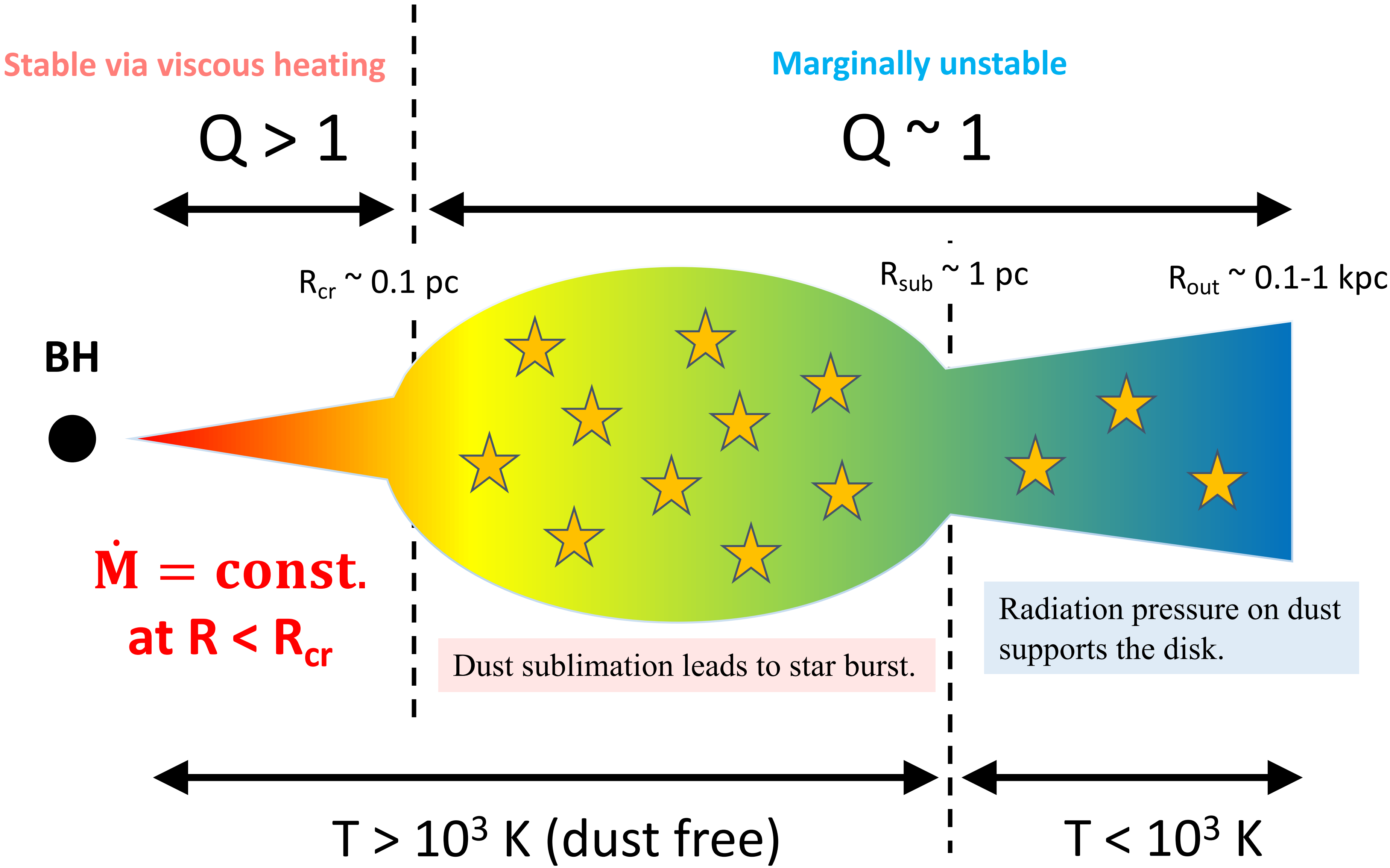
Hopkins et al. (2023)

- First RMHD simulation resolving AGN accretion disks from cosmological initial condition.

$\sim 300\ r_s$



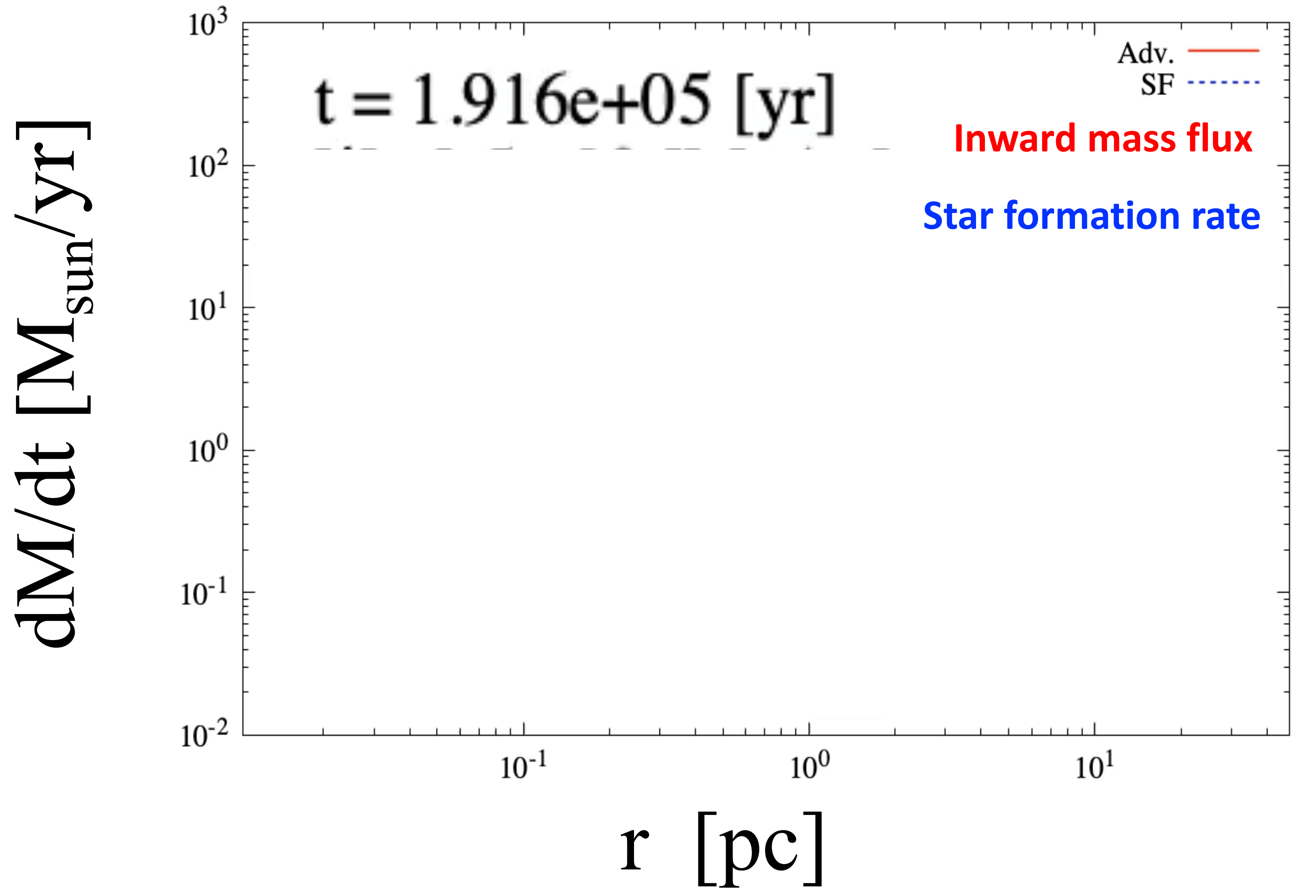
Star formation around the central BH



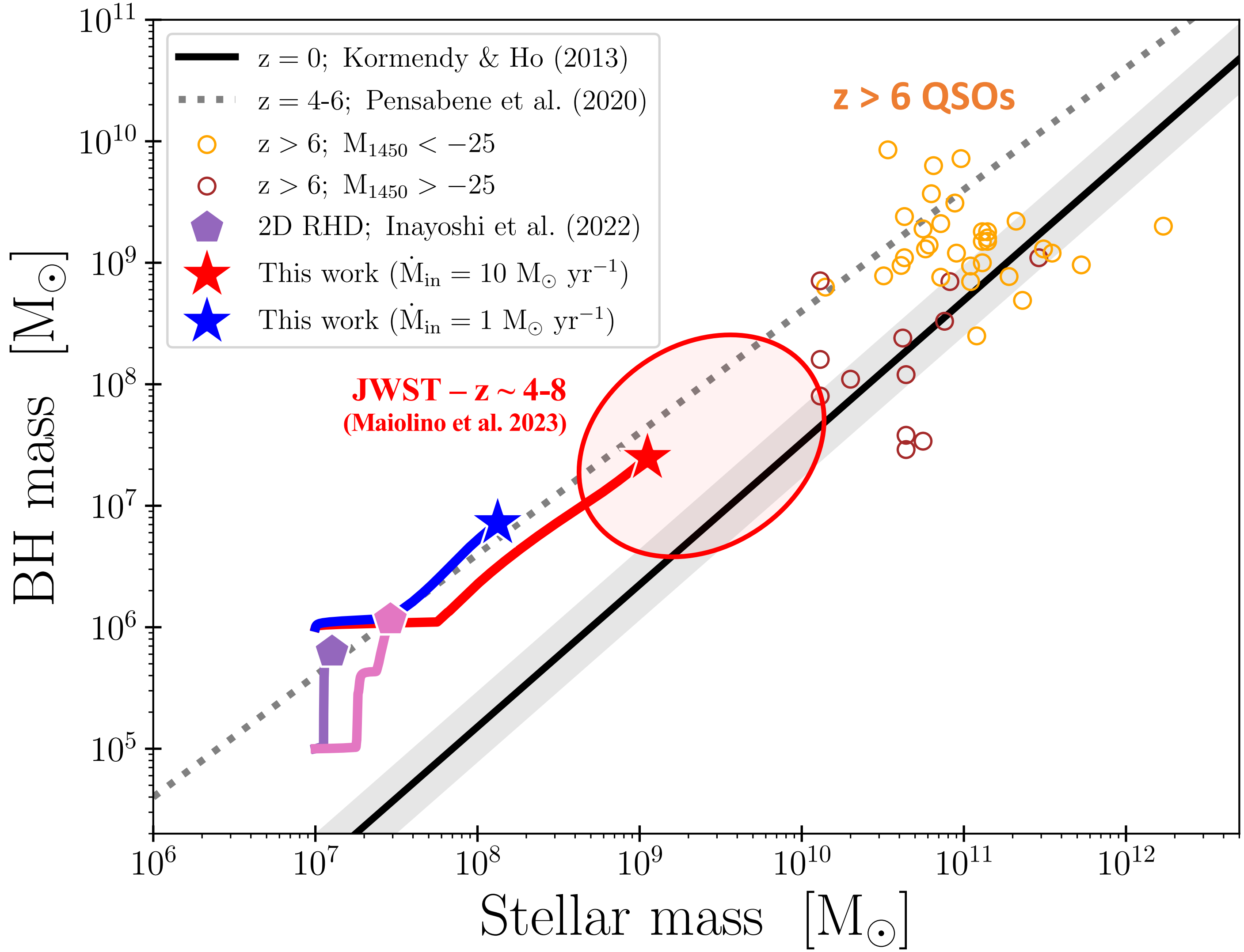
1D non-steady accretion disk model

Suppose BH mass growth in the early universe

- **$M_{BH} = 10^6\ M_{sun}$, $M_{star} = 10^7\ M_{sun}$** (cf. 2D RHD sims. by Inayoshi+2022)
- **$\dot{M} = 10^{-2}\ M_{sun}/yr$ @ t = 0 → $\dot{M} = 10\ M_{sun}/yr$ @ t = 100 Myr**

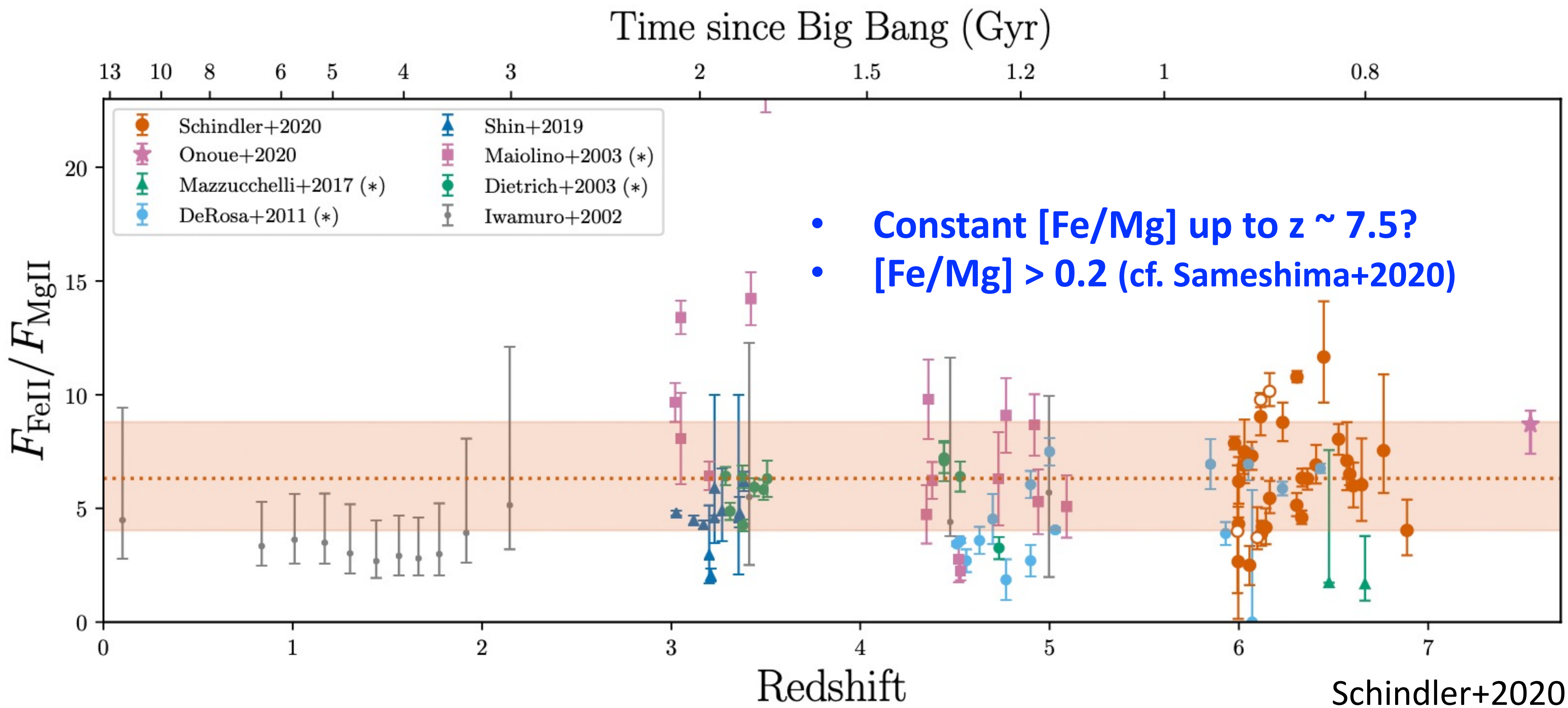


Coevolution of galaxies and SMBHs



Chemical evolution of AGNs

High [Fe/Mg] abundance in high-z QSOs?



- **Constant [Fe/Mg] up to z ~ 7.5?**
- **[Fe/Mg] > 0.2 (cf. Sameshima+2020)**

Schindler+2020

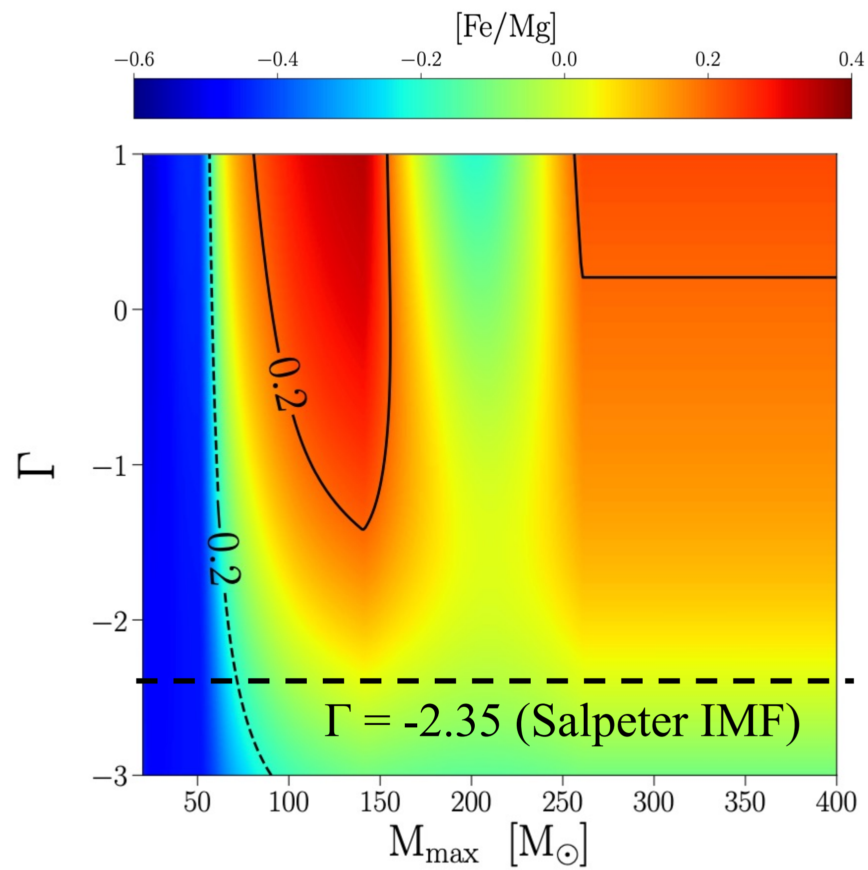
Cannot be explained with Type Ia SN (τ_{delay} ~ 1 Gyr)

Top-heavy IMF around BLRs?

- ✓ Massive core-collapse SNe and PISNe can enrich iron very efficiently.
- ✓ **Top-heavy IMF with Γ > -1 and M_{max} > 100 $M_{\odot}$** is required to explain [Fe/Mg] > 0.2 in BLRs.
- ✓ The top-heavy IMF leads to various transient events in AGNs (DT+2022).
  - ✓ BH mergers ~ 1 Gpc^{-3} yr^{-1} (10% of the local merger rate)
  - ✓ CCSNe ~ 1 Gpc^{-3} yr^{-1}
- ✓ **Transient events in AGN disks would be a good target in Multi-messenger astronomy (e.g., Yan+2022, Tagawa+2023a,b).**

Single power-law IMF

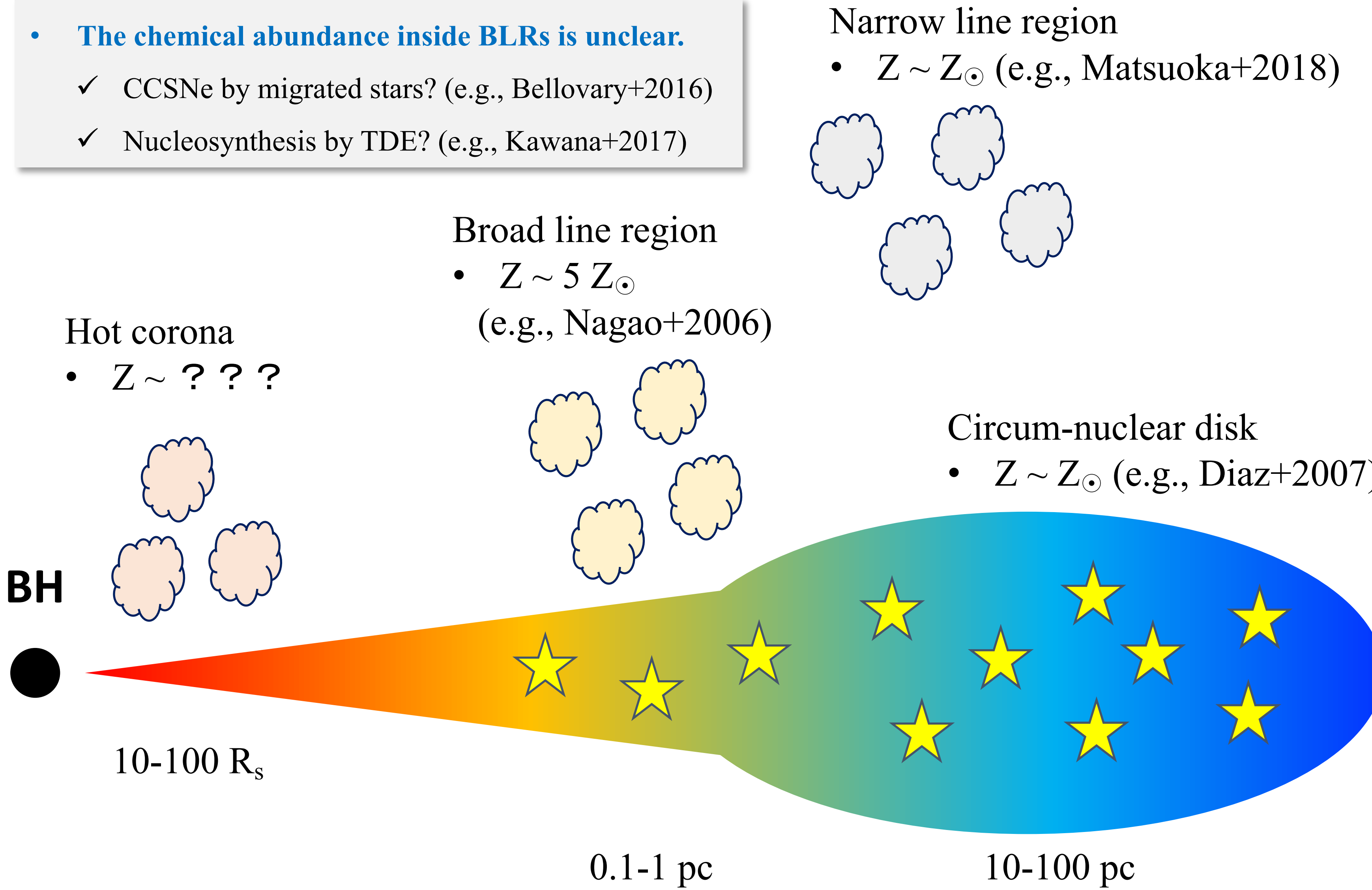
$$\phi \propto m^{\Gamma} \ (0.1\ \mathrm{M}_{\odot} \leq m \leq M_{\mathrm{max}})$$



DT+2022

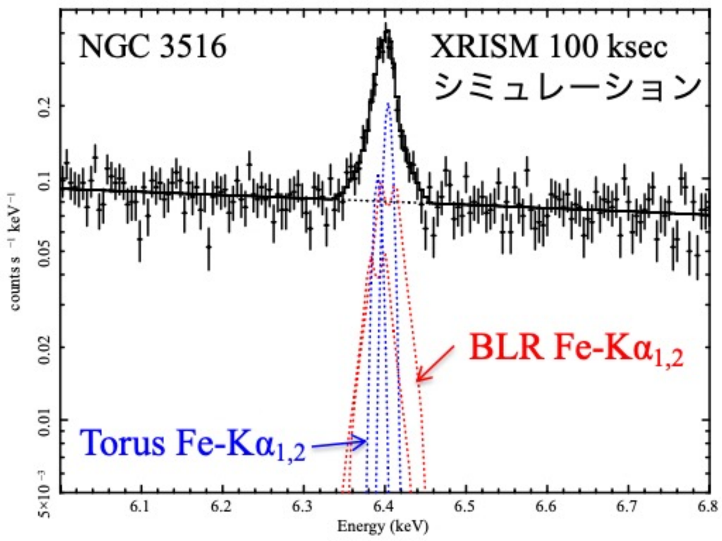
Metallicities in galactic nuclei

- **The chemical abundance inside BLRs is unclear.**
  - ✓ CCSNe by migrated stars? (e.g., Bellovary+2016)
  - ✓ Nucleosynthesis by TDE? (e.g., Kawana+2017)

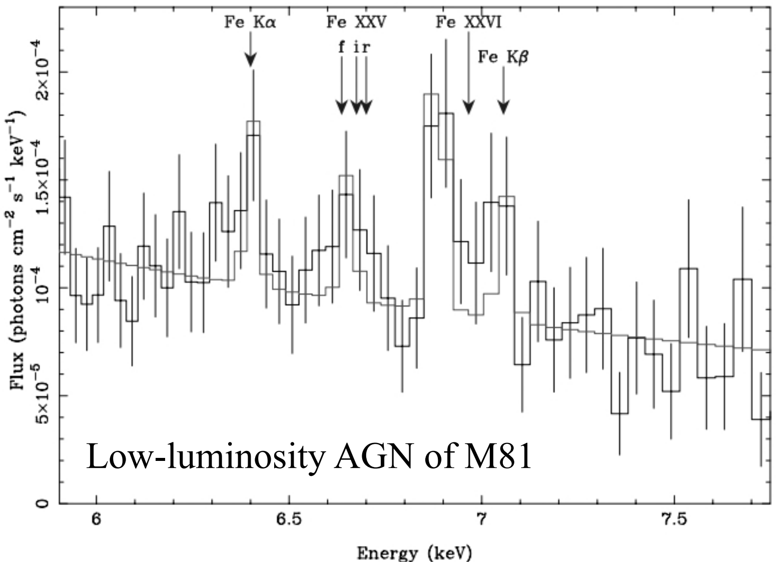


Metallicity measurements from BLRs to hot corona

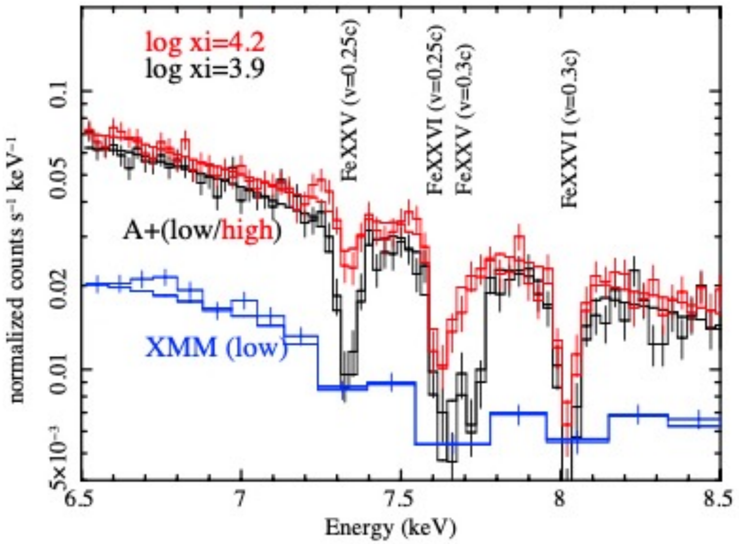
- **XRISM and Athena would be helpful.**
  - ✓ Fe Kα lines from BLR and dusty torus
  - ✓ Absorption line by UFOs from inner acc. disks
  - ✓ Highly ionized iron in hot corona (T ~ 10^7 K)



Kindly provided by H. Noda (Osaka univ.)

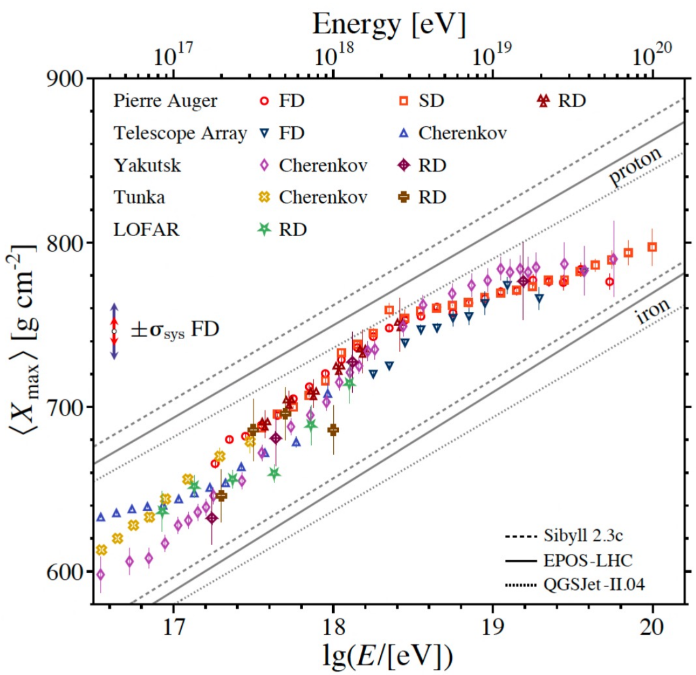


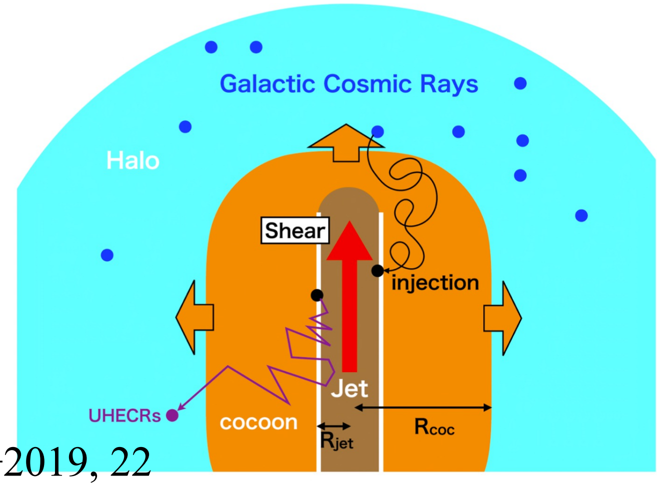
Young et al. (2008)



Cappi et al. (2013)

Chemical composition of UHECR



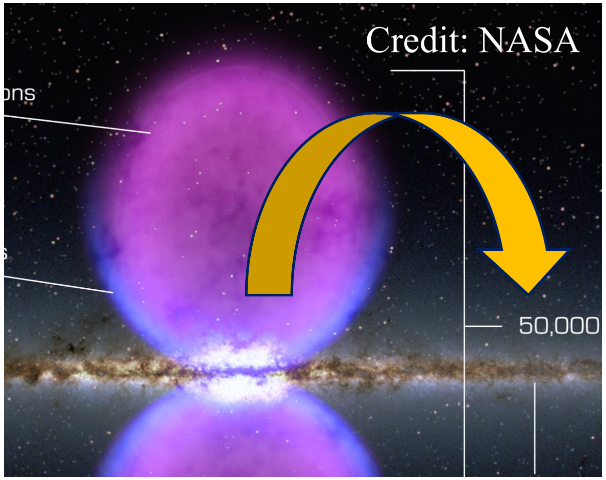


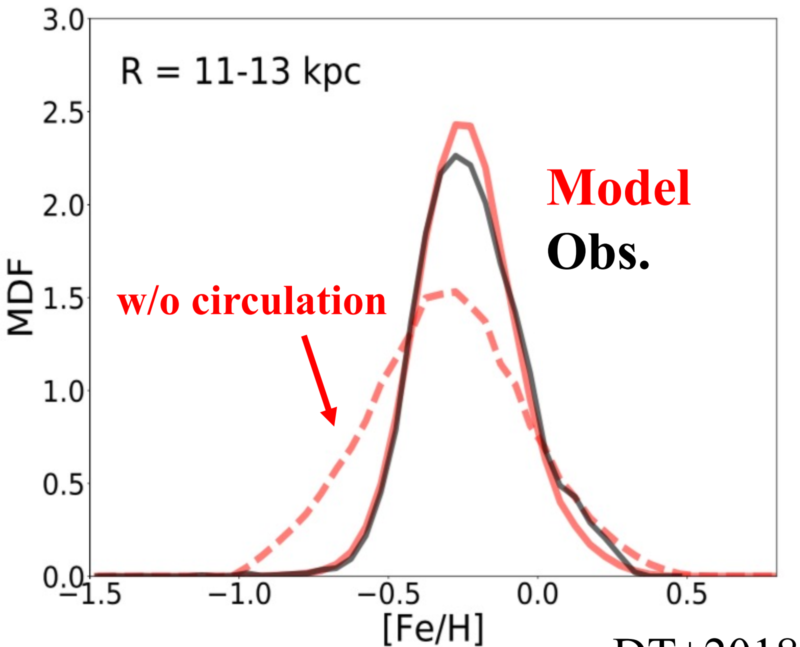
Rieger+2019, 22

- Observations of X_{max} tell us about the composition of UHECRs (Sako-san's talk).
- The composition of UHECR should depend on where they formed.
- The AGN jet scenario assumes seed compositions, e.g., solar-abundance.
- **Observing the chemical abundance of hot corona would reduce an uncertain factor in UHECR production.**

Circulation of metal-enriched gas

- For super-Edd. accretion, over 90% of supplied mass is blown away as outflow (e.g., Nomura+2021, Hu+2021).
- Gas ejected from galactic nuclei can accrete again on the galactic disk（e.g., Bekki et al. 2009）.
- Galactic fountain with metal-enriched gas promotes chemical enrichment of the outer region（e.g., Tsujimoto+2010, Bresolin+2012, DT+2018）.
- **Co-chemical evolution of galaxies and AGNs**

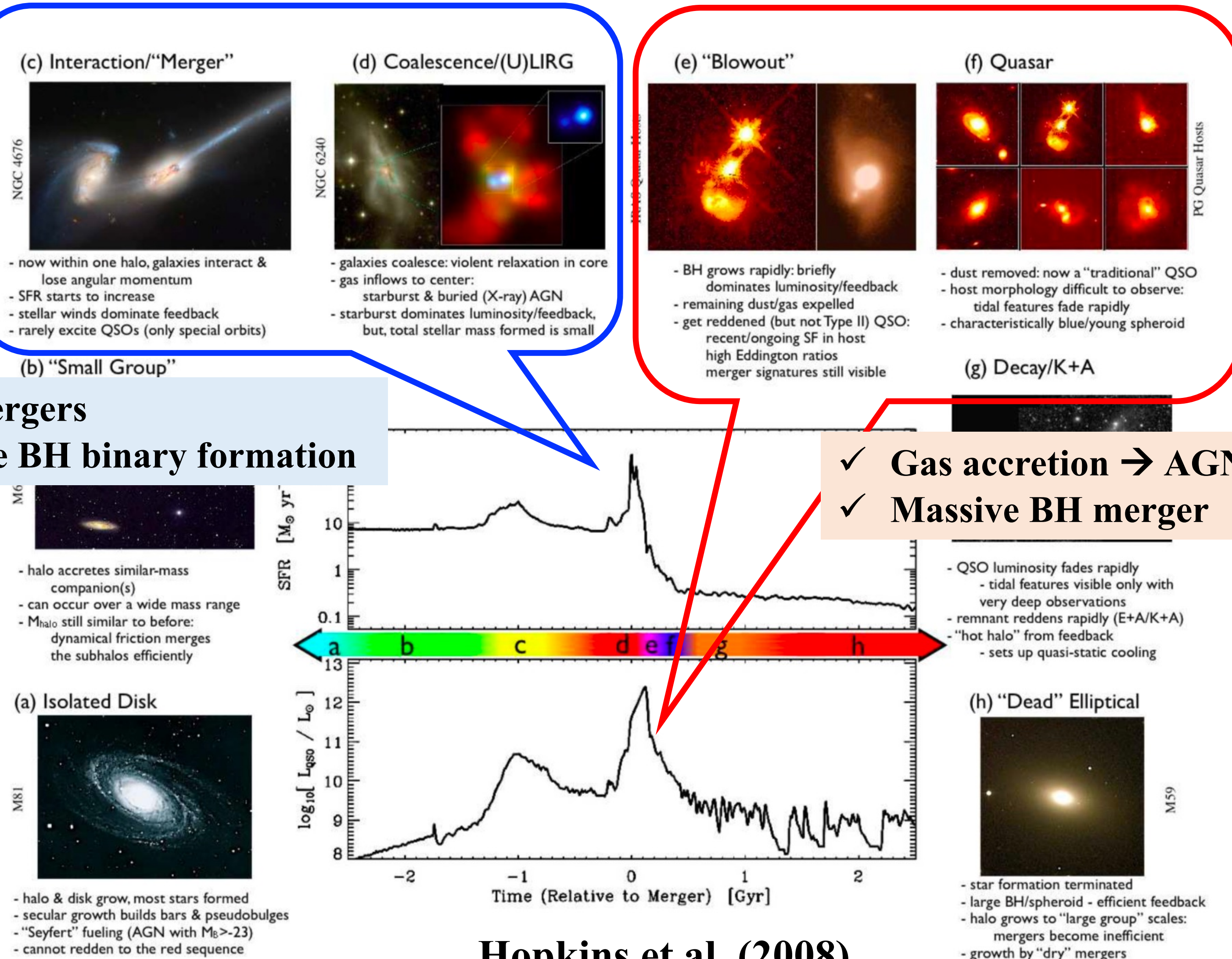




DT+2018

SMBH mergers

Galaxy mergers induce BH growth



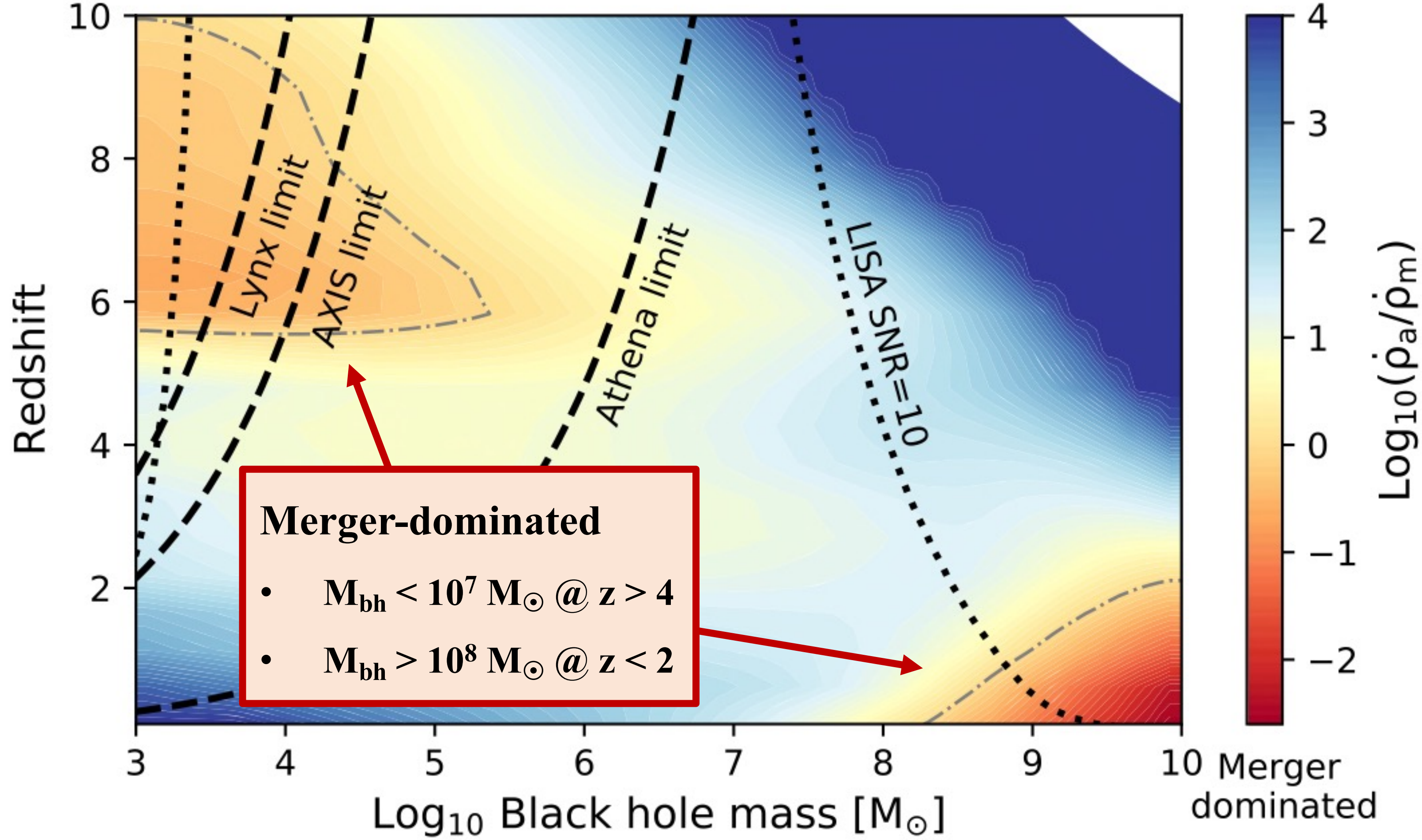
Galaxy mergers
→ Massive BH binary formation

✓ Gas accretion → AGN feedback
✓ Massive BH merger

Hopkins et al. (2008)

Accretion vs. Mergers

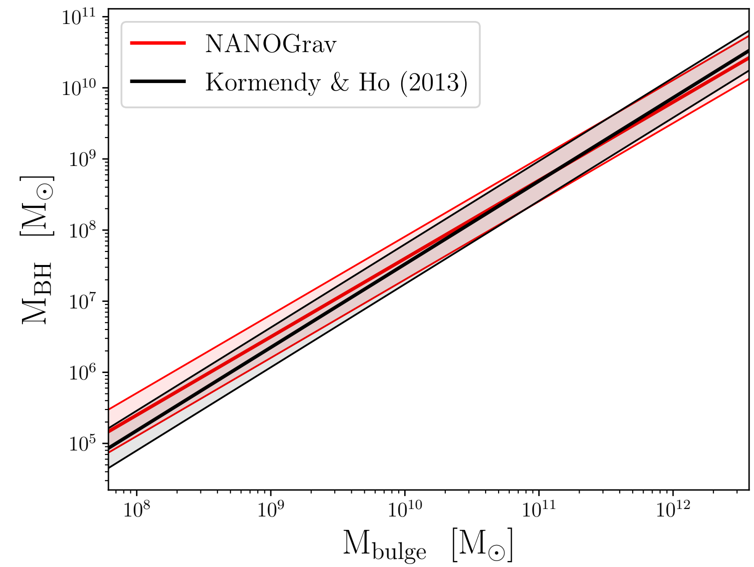
Semi-analytic model (Pacucci+2020)

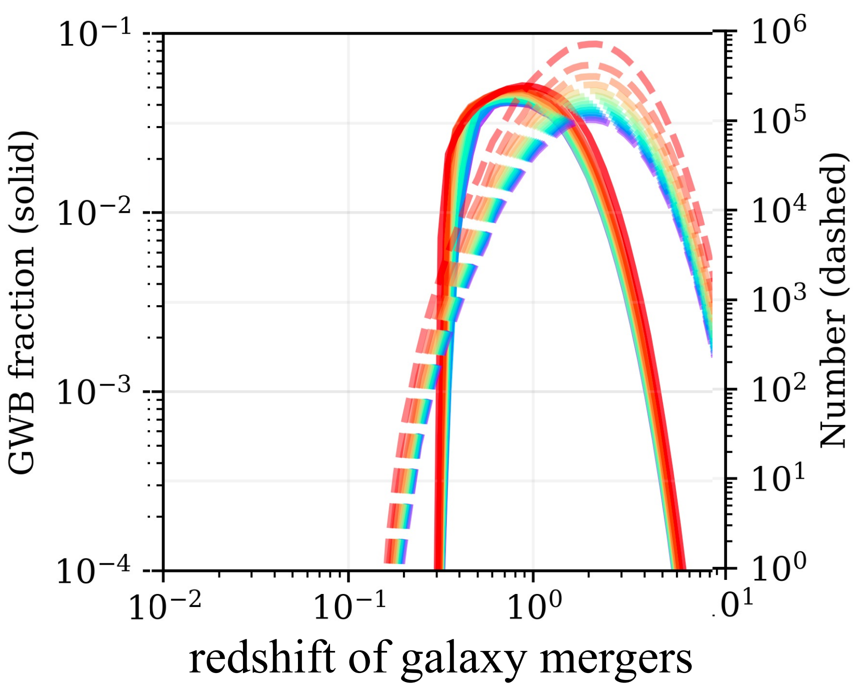


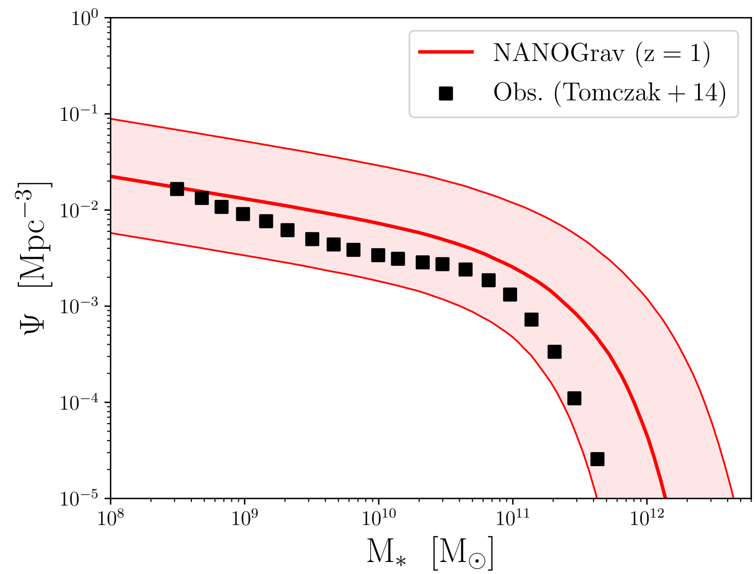
Future GW and X-ray facilities will cover the entire BH mass and redshift ranges.

Gravitational wave background

- **The first detection of GWB was reported this June (e.g., The NANOGrav collaboration, 2023).**
- $A_{GWB} \sim 2.4 \times 10^{-15}$ at $f = 1yr^{-1}$ is somewhat higher than expected, but possible in terms of the cosmic mass density of SMBHs.
- **Mergers of host galaxies happen around z = 1.**





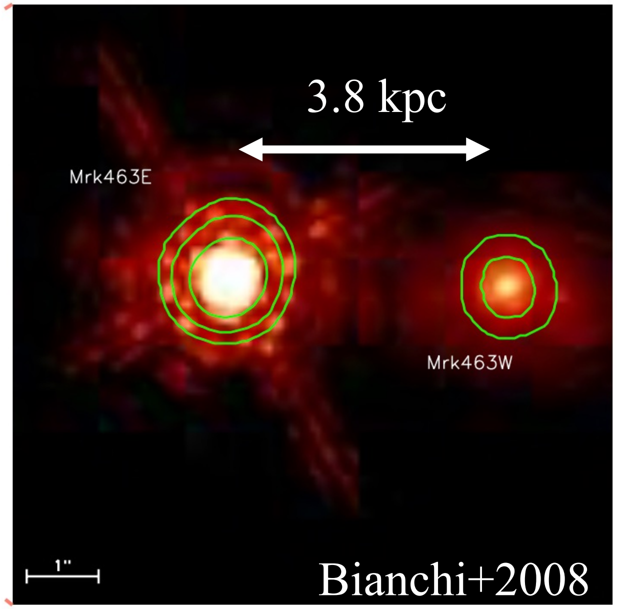


Ultra-Luminous Infrared Galaxies (ULIRGs)

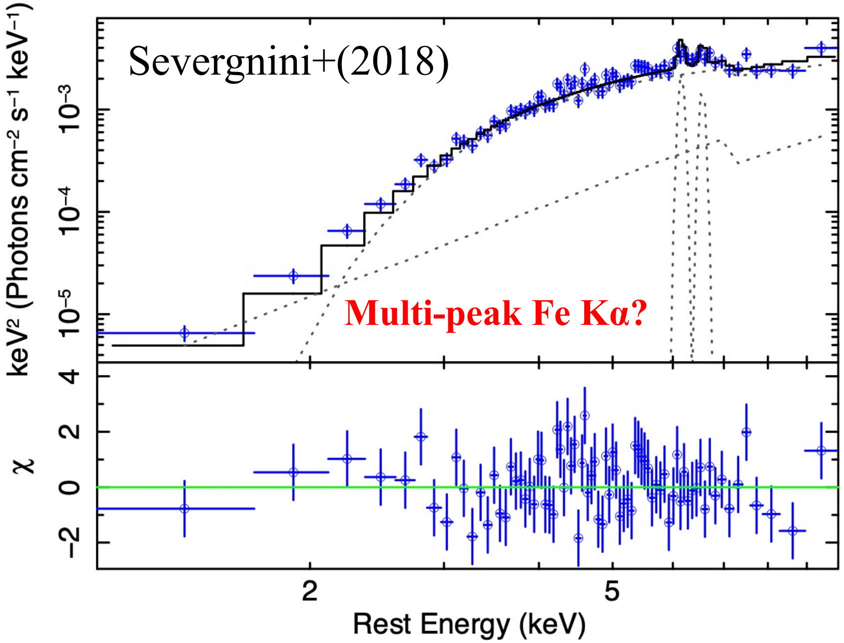
- Starburst galaxies with $L_{IR} > 10^{12} L_{\odot}$
- Promising candidates for merging galaxies
- AGNs are highly dust obscured.
- Dual AGNs have been detected with hard X-rays, but the separation is usually several kpc.

Searching for spatially-unresolved dual AGNs

- **Sub-pc SMBH binaries in ULIRG can contribute to the GWB observed by PTA.**
- Observing multi-peak emission lines in the X-ray band is a possible way.
- **High energy resolution of XRISM and Athena would enable us to detect sub-pc SMBH binaries.**



Swift-BAT observation of a local AGN



Summary

1. Gas accretion on BHs

- The nature of AGN feedback, especially disk photoevaporation, has been actively investigated with multi-dimensional radiation hydrodynamic simulations.
- Modeling the mass transfer mechanism from galactic scale to nuclear scale would be a key to understand coevolution of galaxies and SMBHs.

2. Chemical evolution of AGNs

- Studying galactic-ecosystem in terms of chemical evolution is interesting, and multi-messenger approaches can play an essential role.

3. SMBH mergers

- Galaxy mergers induce starburst and SMBH mergers, so an important phase in co-evolution of galaxies and SMBHs.
- Future observational facilities, like LISA, Athena, and Lynx, will enable us to further understand this phase.