The Origins of Gas Accreted by Supermassive Black Holes:
The Importance of Recycled Gas

"What properties of host galaxies affect black hole growth?"

2023 Survey Science Group Workshop, Jan 16-18th 2023

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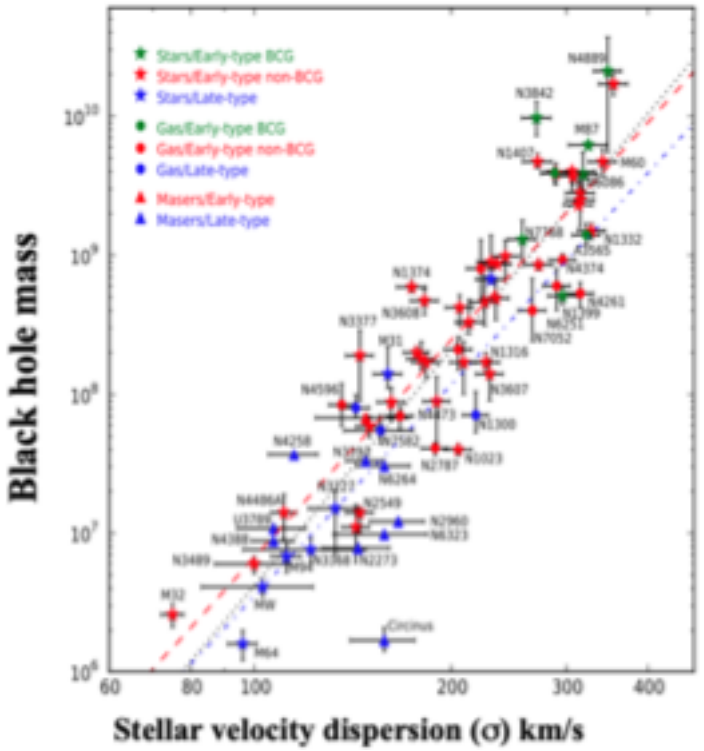
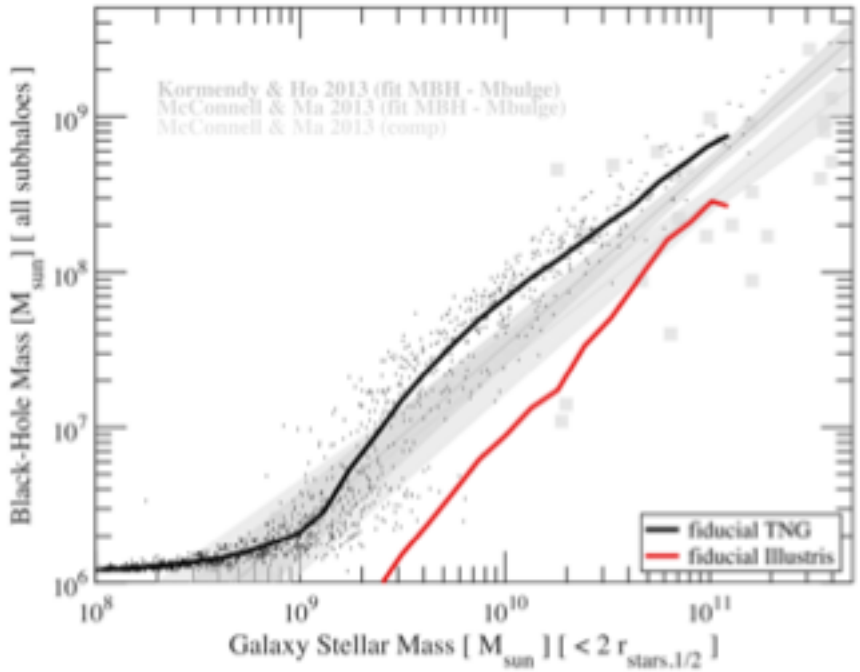
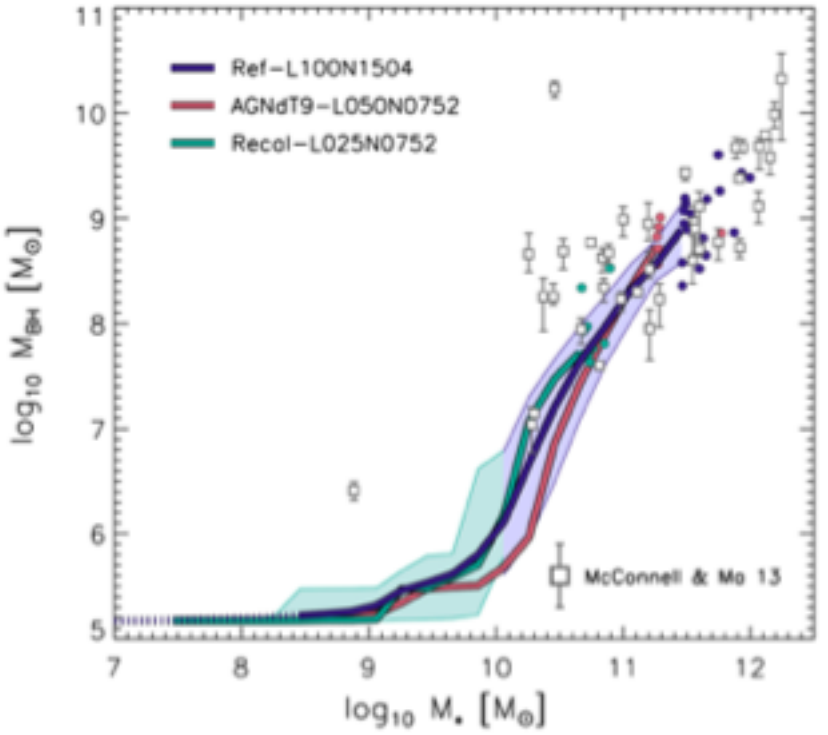
Key question

- **~10^9 M_{sun} supermassive blackholes (monsters) we see today…**







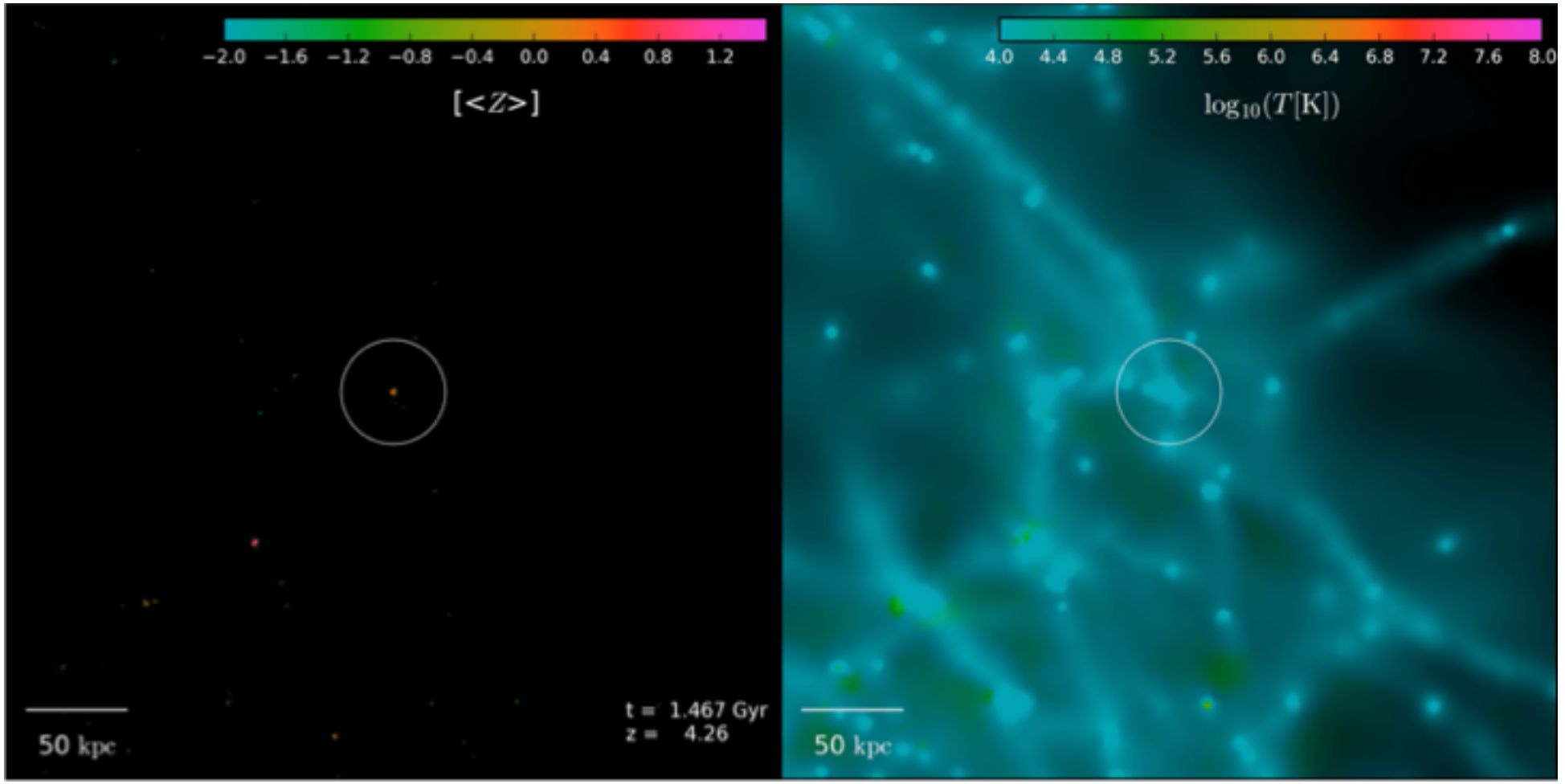
Observation (McConnell&Ma+13) TNG (Pillepich+17) EAGLE (Schaye+15)

- **How does the host galaxy nurture ~10^9 M_{sun} central black holes?**

Zoom-in cosmological hydro simulations

- 10 cosmological zoom-in simulations: 10 central galaxies with z=0 mass
  M_{stel}= $10^{11\text{-}12}$ M_{sun}
  M_{BH}= 1-5 x 10^{9} M_{sun}
  from **Choi+17**
- GADGET-3 SPH simulations
- Feedback from AGN
  Choi+12/14/15

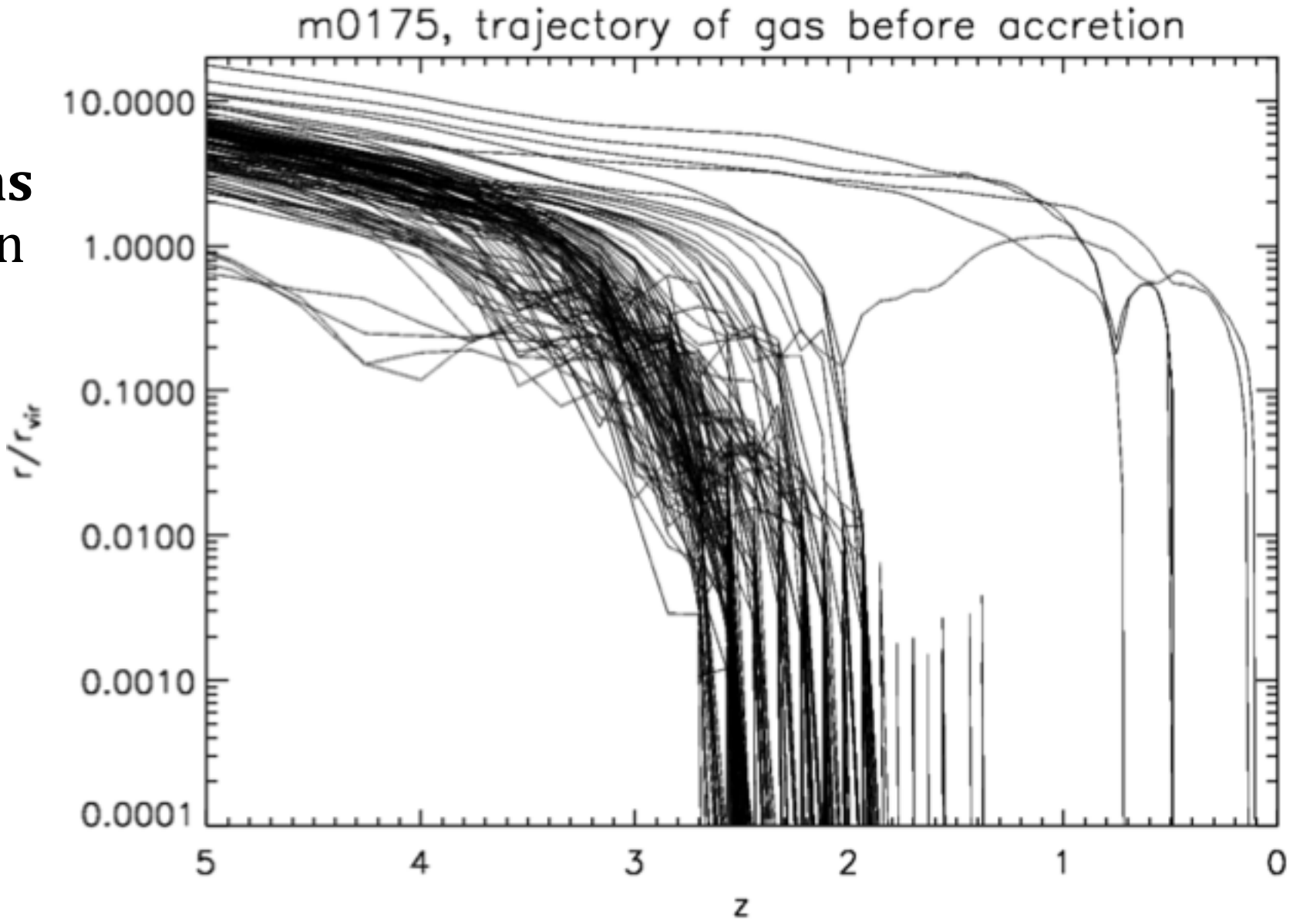
1. Momentum feedback via broad absorption line winds
2. Radiative feedback via photoionization & Compton heating



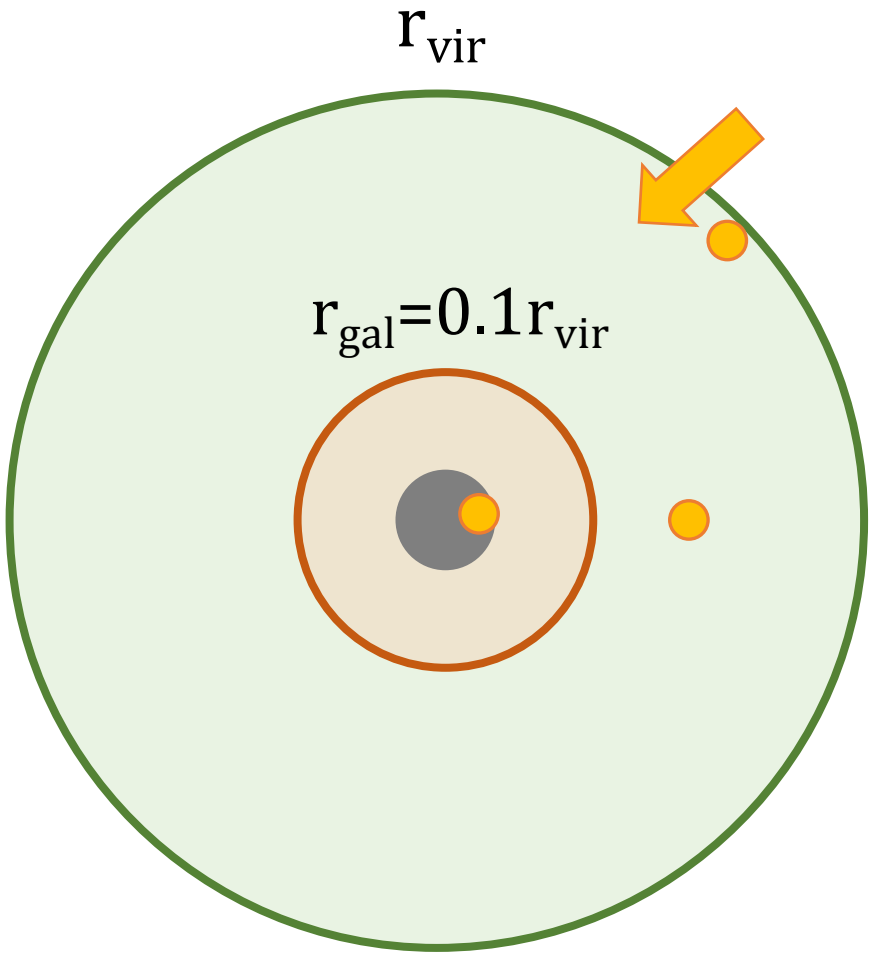
- BH accretion: Bondi-Hoyle-Littleton + Soft Bondi criterion (limits the accretion to the bound gas within the Bondi radius) **Choi+12**
- Feedback from stellar population: SN winds, winds from young massive stars, and AGB winds **Nunez+17**

The trajectory of gas particles

- Methodology: we trace back the evolution of **each gas particle** that is eaten by central BHs in cosmological hydrodynamic simulation.

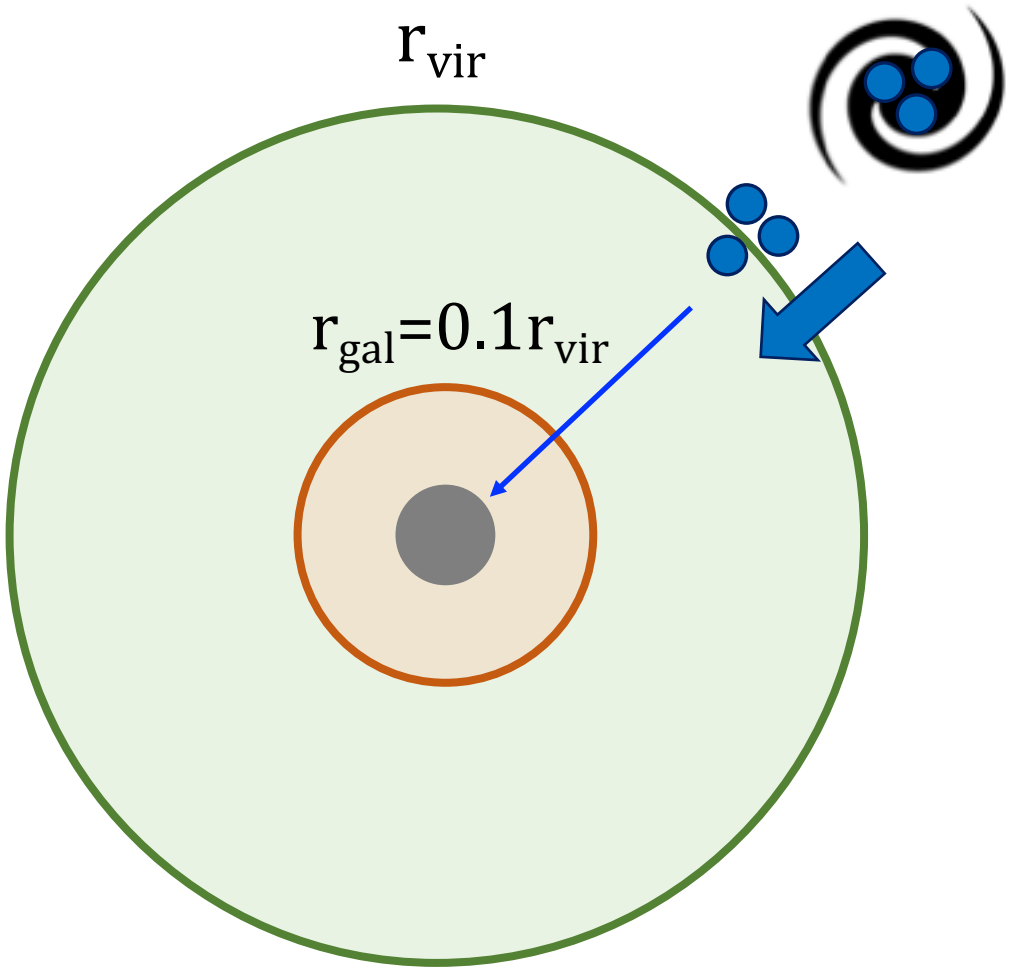


Definition #1. early



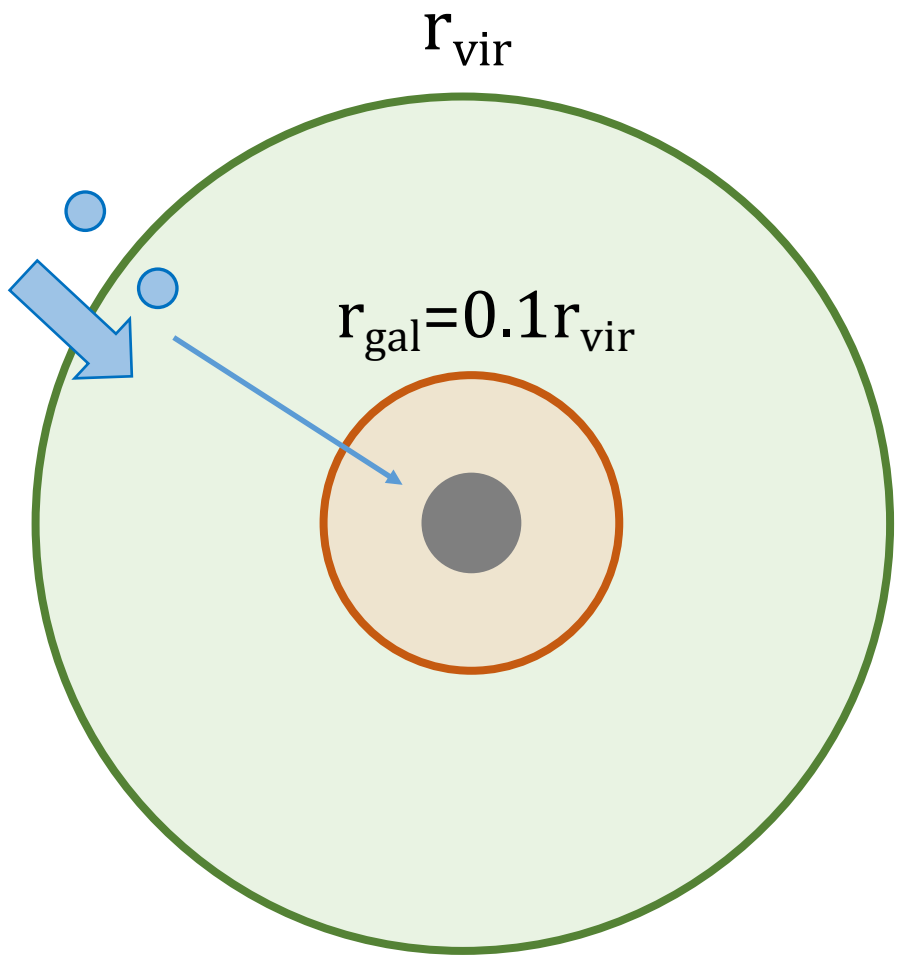
- All gas entered the main halo virial radius **by z=5**.
- All gas eaten by central BHs by **z=5**.

Definition #2. external



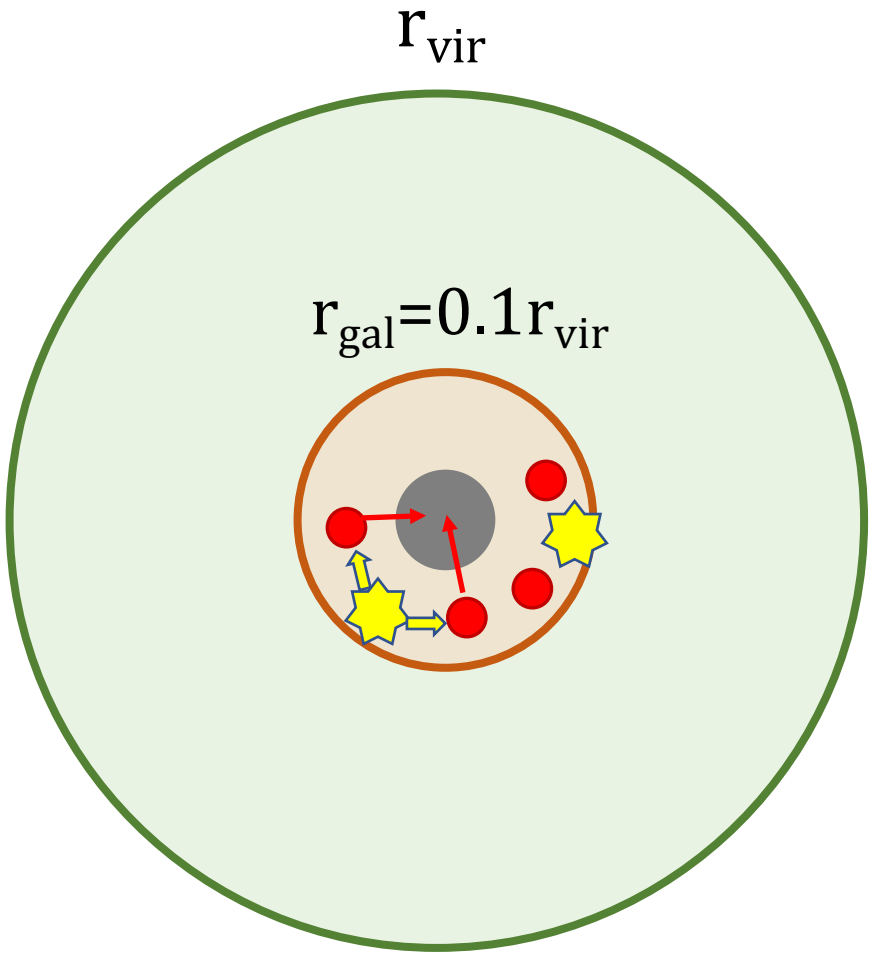
- All gas ever belonged to the other galaxies or subhalos before they entered the main halo after z=5.
- Gas that enters the main along a merging galaxy
- Stripped gas from a merging galaxy

Definition #3. smooth



- Smoothly accreted gas – not ever belonged to any other galaxies, and accreted after z=5.
- Usually enter the main halo along the filamentary gas streams.

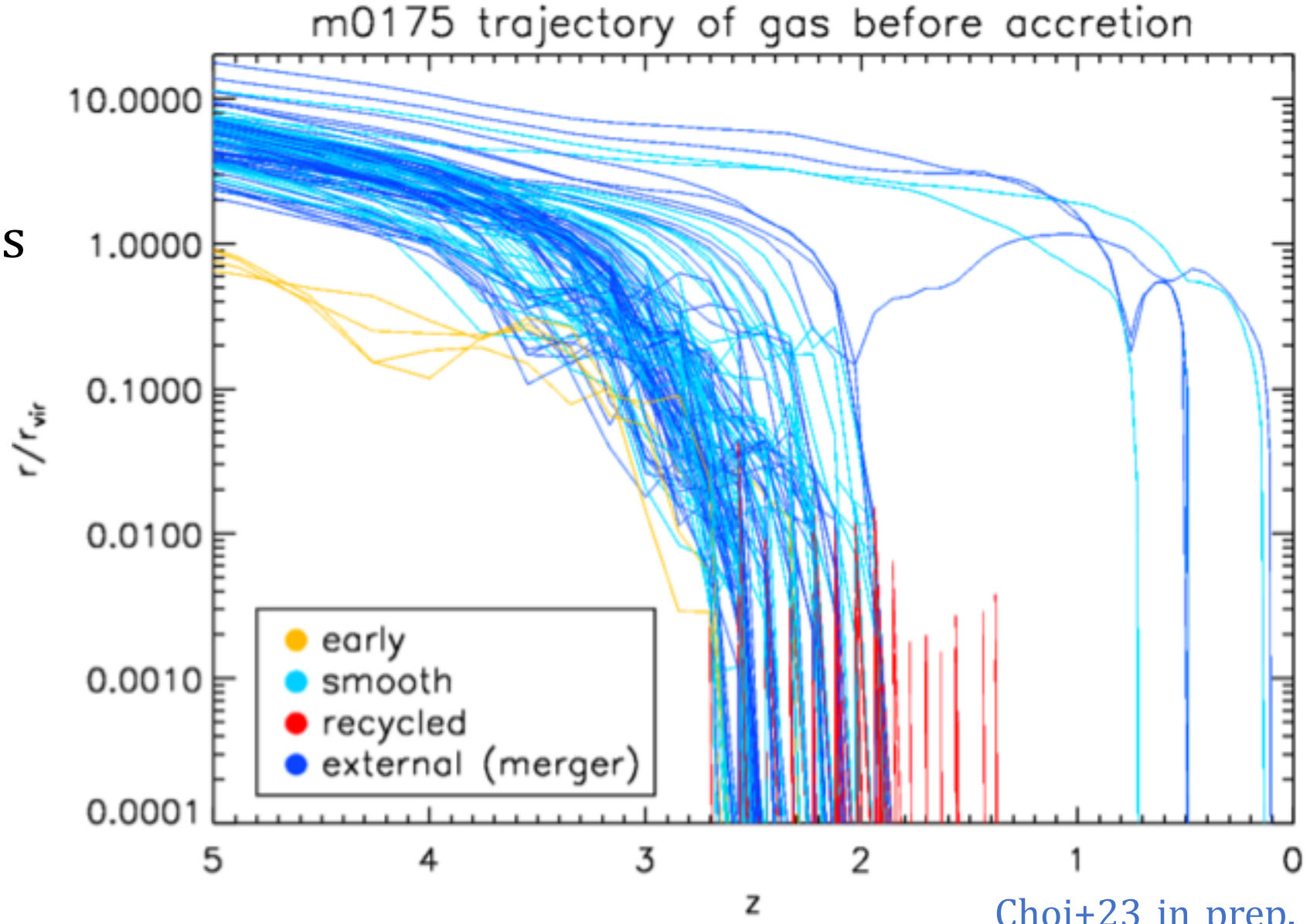
Definition #4. recycled



- **Stellar evolution output**: SN winds, winds from young massive stars, AGB winds.
- With our assumed IMF, ~30 % of initial stellar mass will return to ISM over 14 Gyr evolution.
- We only count for recycled gas produced within 0.1 r_{vir} in this analysis.
- i.e., Recycled gas produced outside of 0.1 r_{vir} (in other galaxies, etc.) is **not** defined as “recycled”.

The trajectory of gas particles

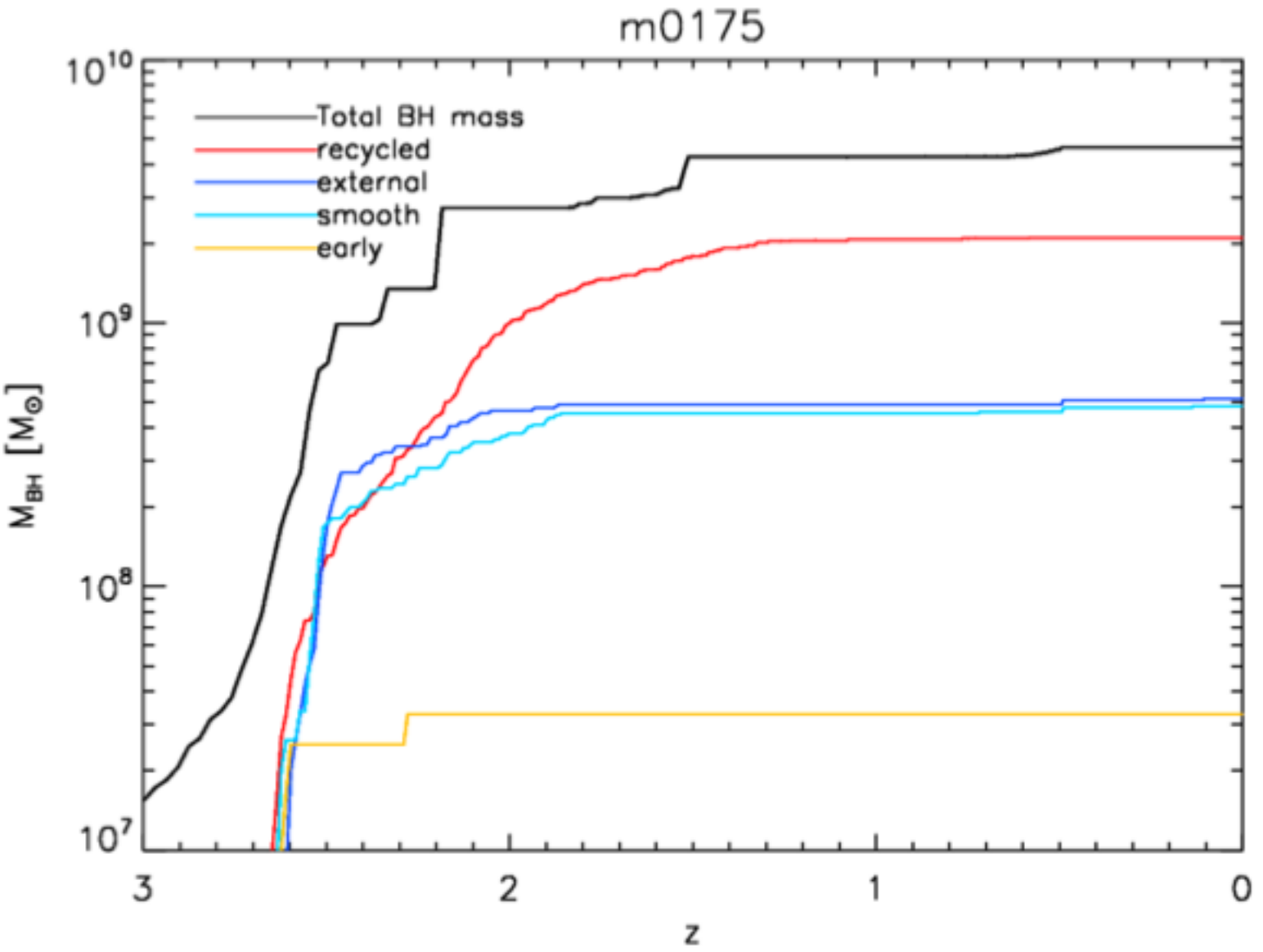
- We trace back the evolution of **each gas particle** that is eaten by central BHs and classify their origin:
  - Early
  - Smooth
  - Recycled
  - External



Choi+23 in prep.

Central black hole mass evolution

- Cumulative mass contribution of ~5e9 M_{sun} SMBH by recycled, external, smooth, and early.
- Recycled gas is the dominant source of fuel for this black hole, especially in the late times.

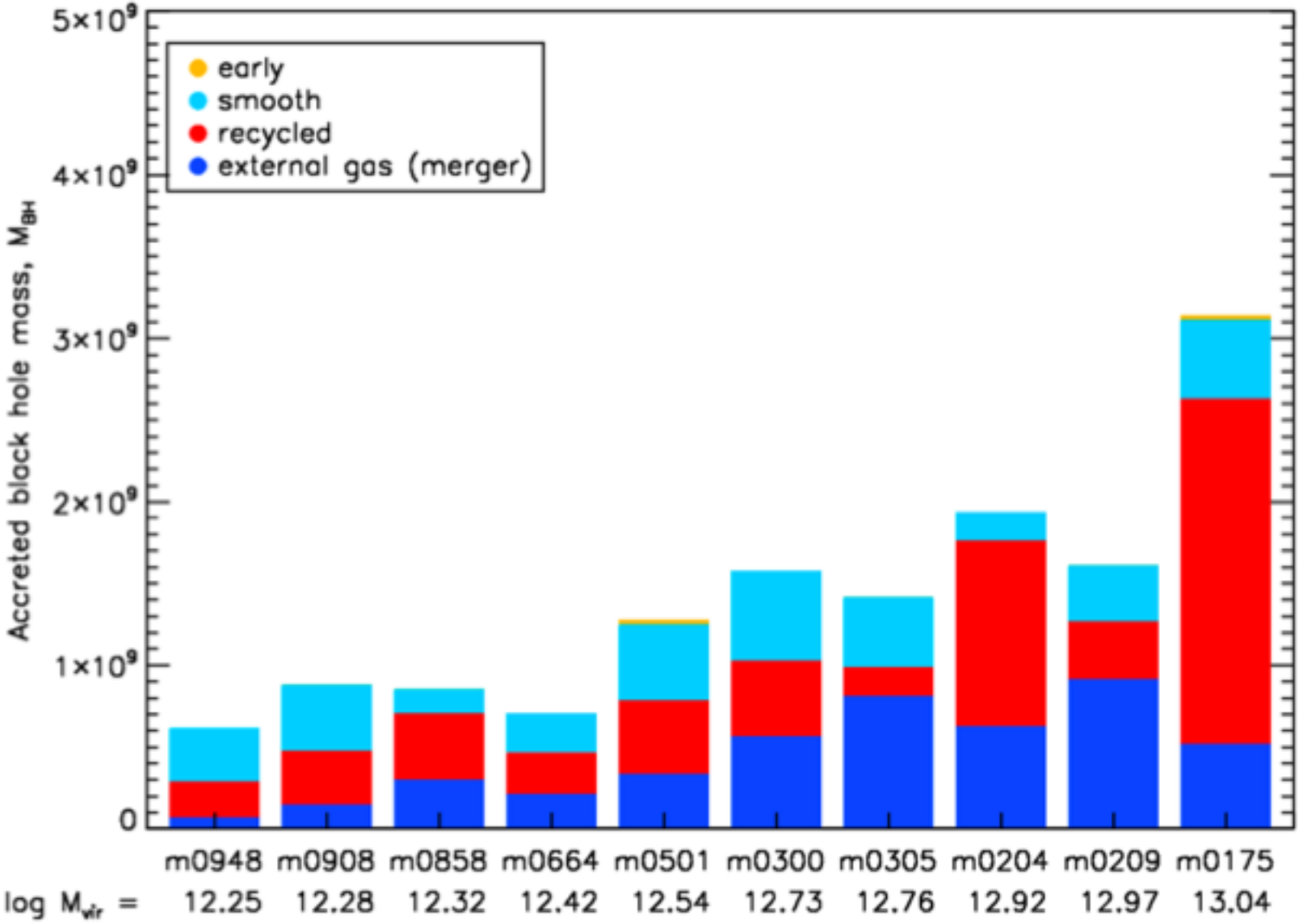


Choi+23 in prep.

Black hole mass budget (bar plot)

Choi+23 in prep.

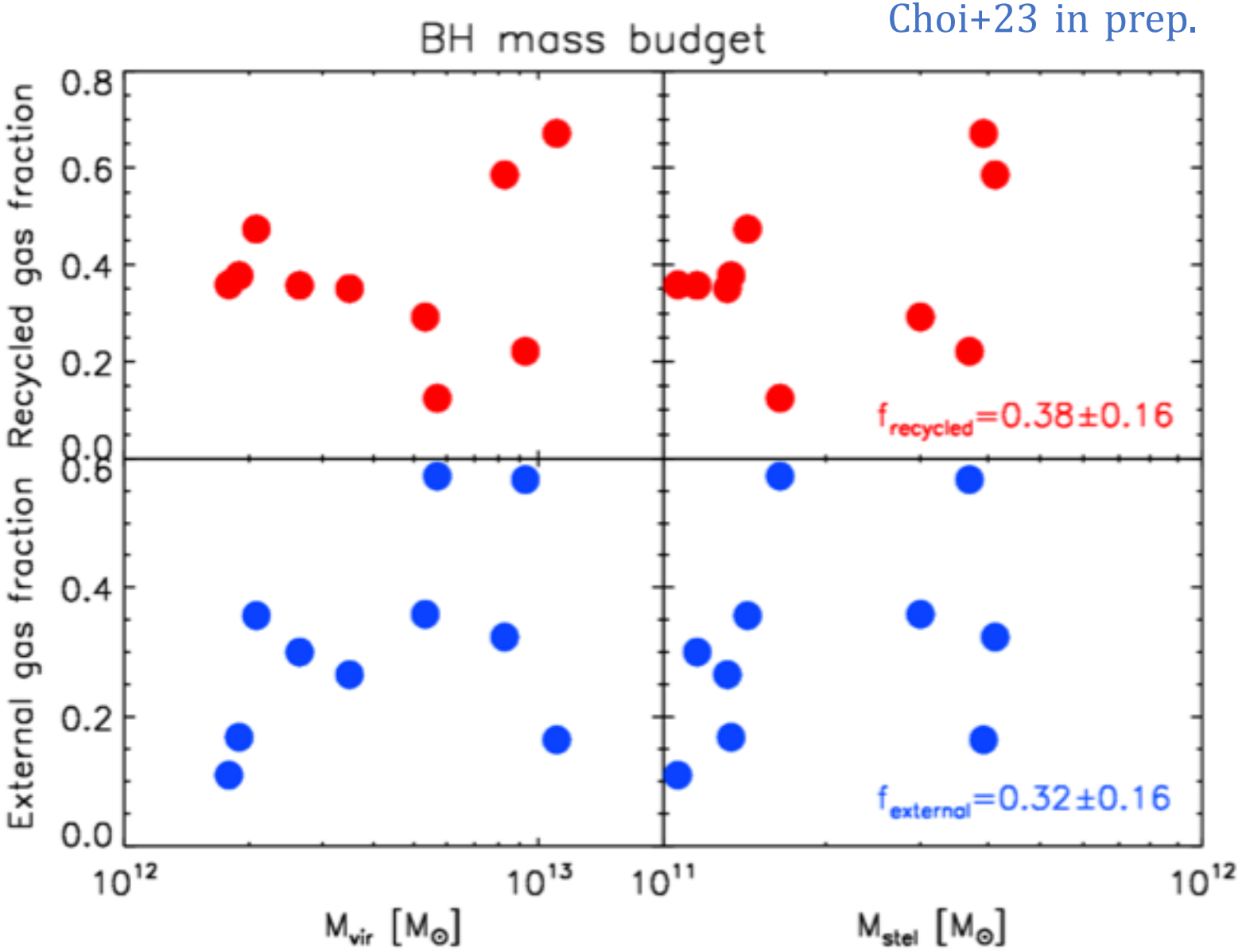
- Analysis for 10 SMBH evolution M_{BH}= 1-5 x 10^9 M_{sun}
- Among accretion mass budget, recycled gas appears to be the dominant fuel for most SMBHs.



Fraction of gas origin for BH accretion

- Recycled gas appears to be the primary source of fuel for SMBHs (~40 %).
- External gas is the secondary source of fuel for SMBHs (~30 %).

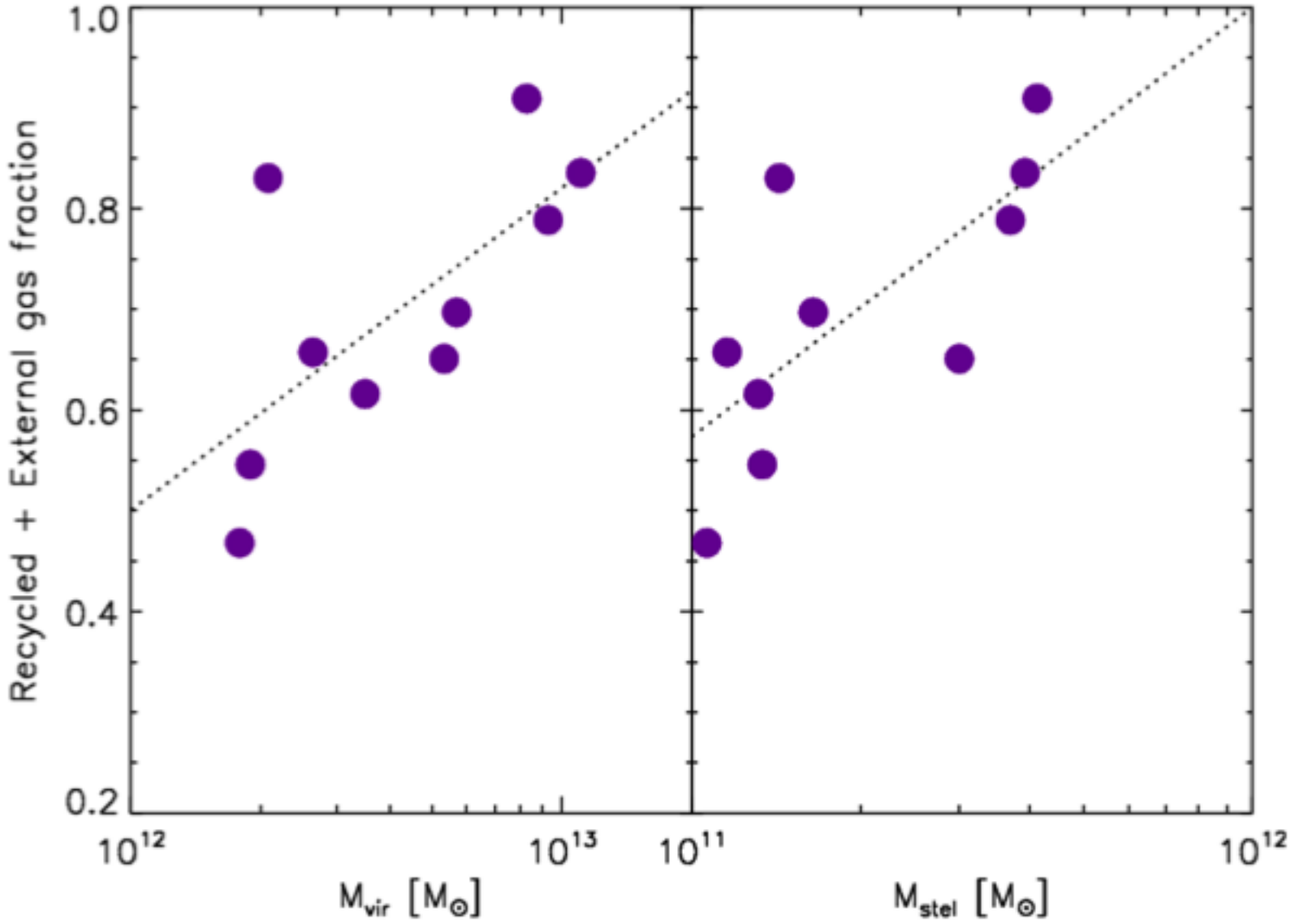
Choi+23 in prep.



Fraction of gas origin for BH accretion

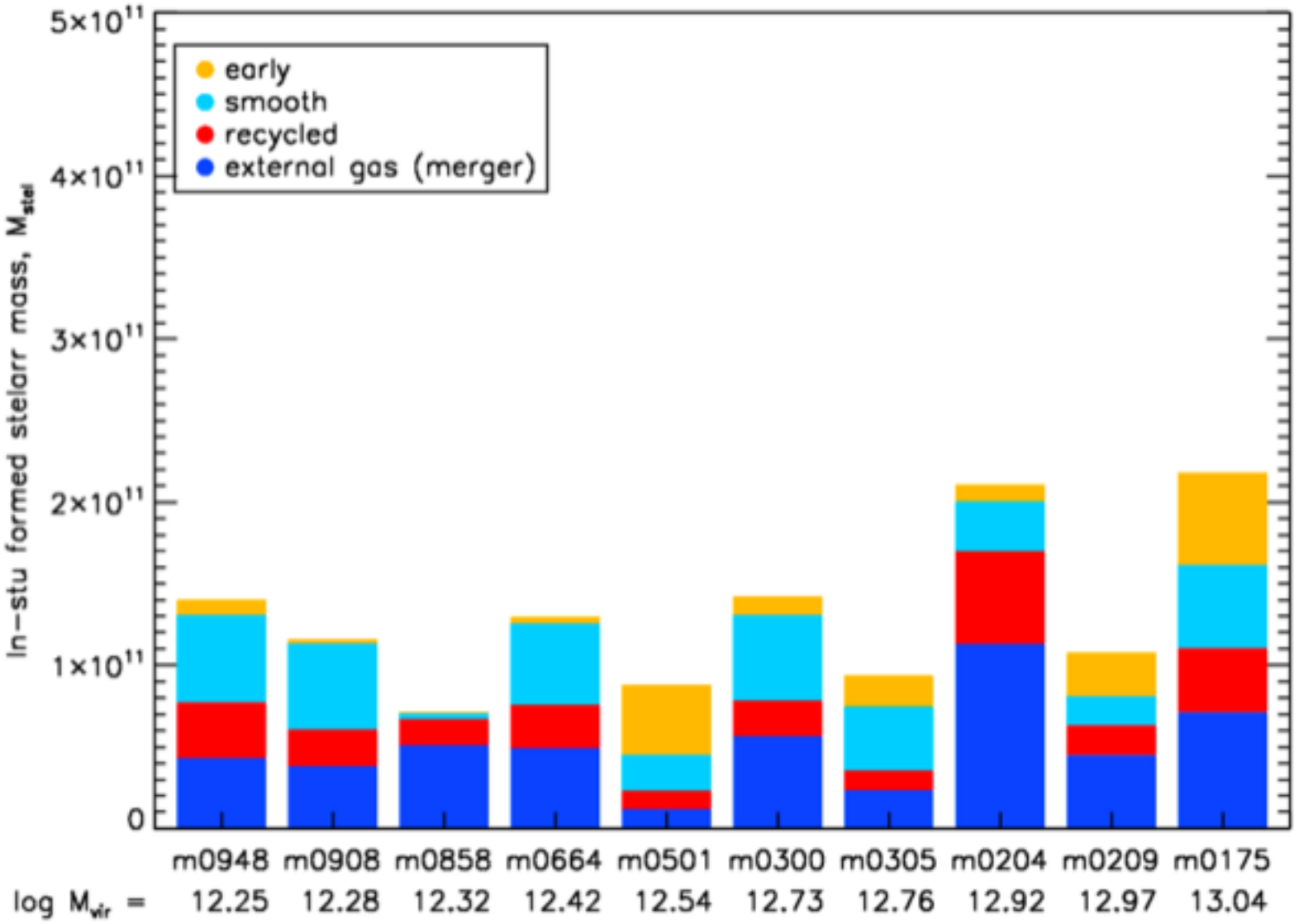
- Recycled gas + external gas appears to form better correlations with galaxy masses (viral/stellar).

Choi+23 in prep.



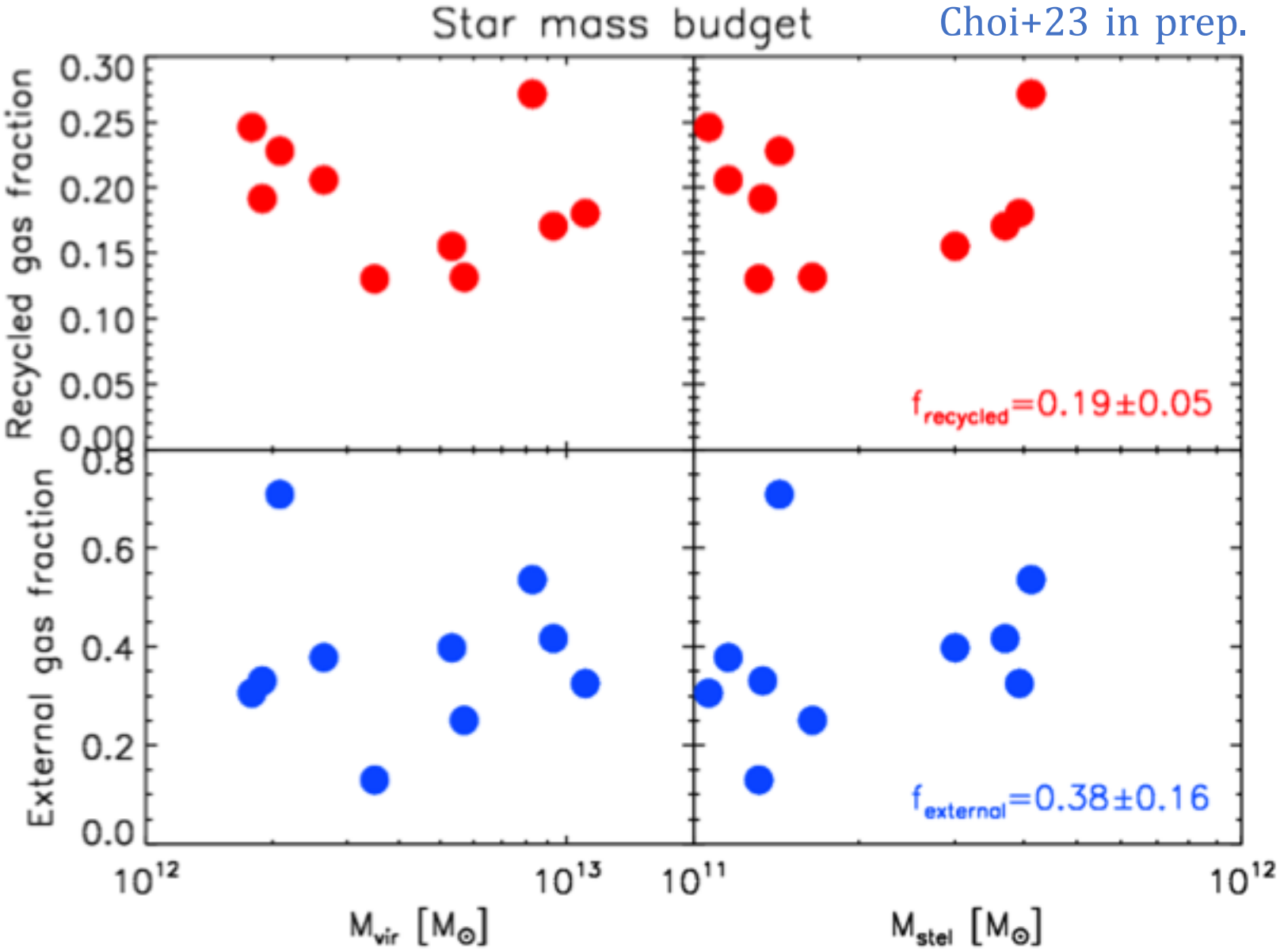
Stellar mass budget (bar plot)

- Is recycled gas the most efficient BH fueling source? Or is it simply the most available gas?
- Same analysis for all stars born within the galaxy.
- External gas is the dominant fuel for star formation in many galaxy cases.
- Higher contribution by early and smooth gas compared to BH feeding.



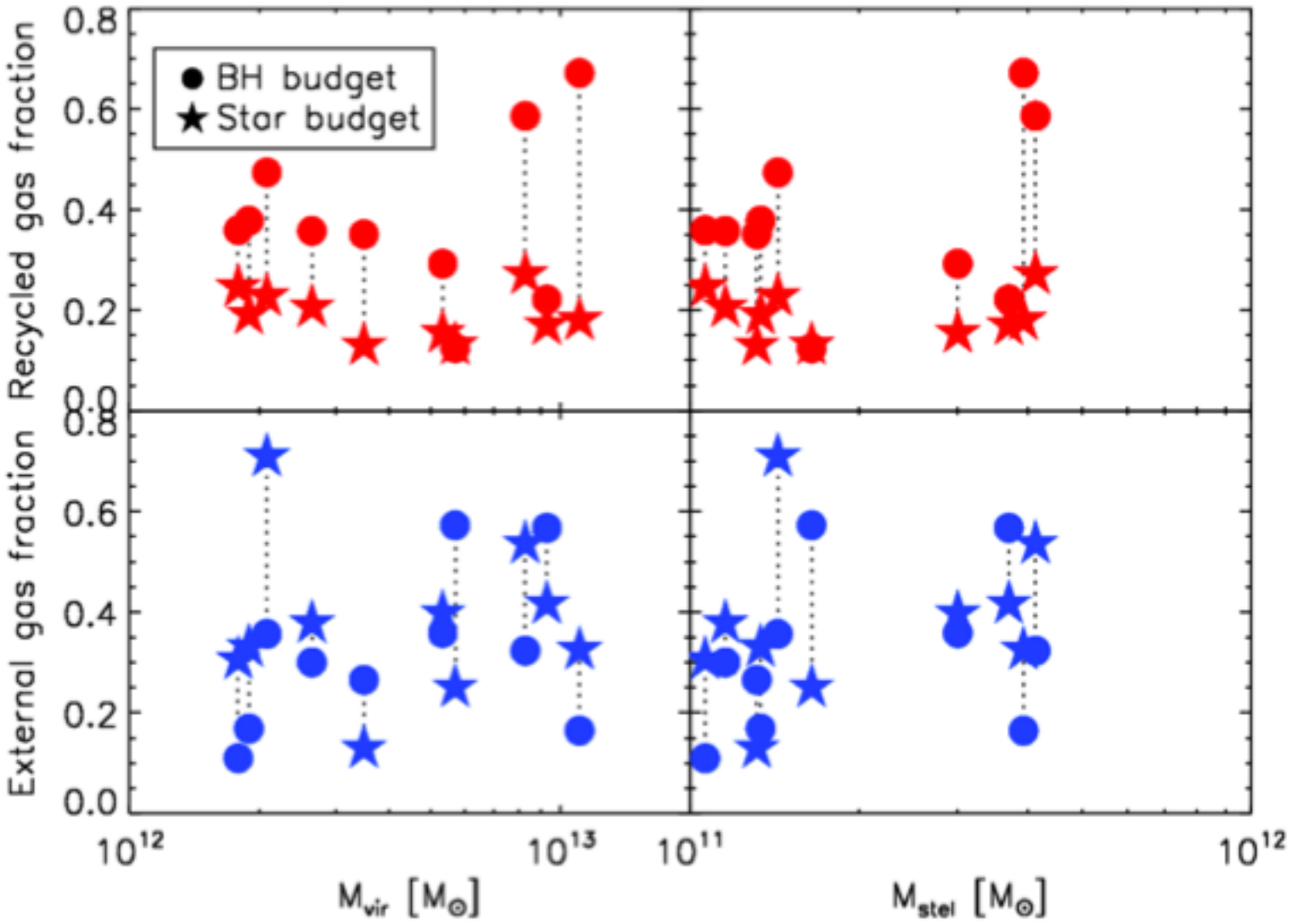
Fraction of gas origin for SF formation

- Much lower fraction of contribution by recycled gas for star formation within the galaxy (~20 %).
- External gas is the primary source of fuel for star formation in most of massive galaxies (~40 %).



Recycled gas fraction is always higher for BH

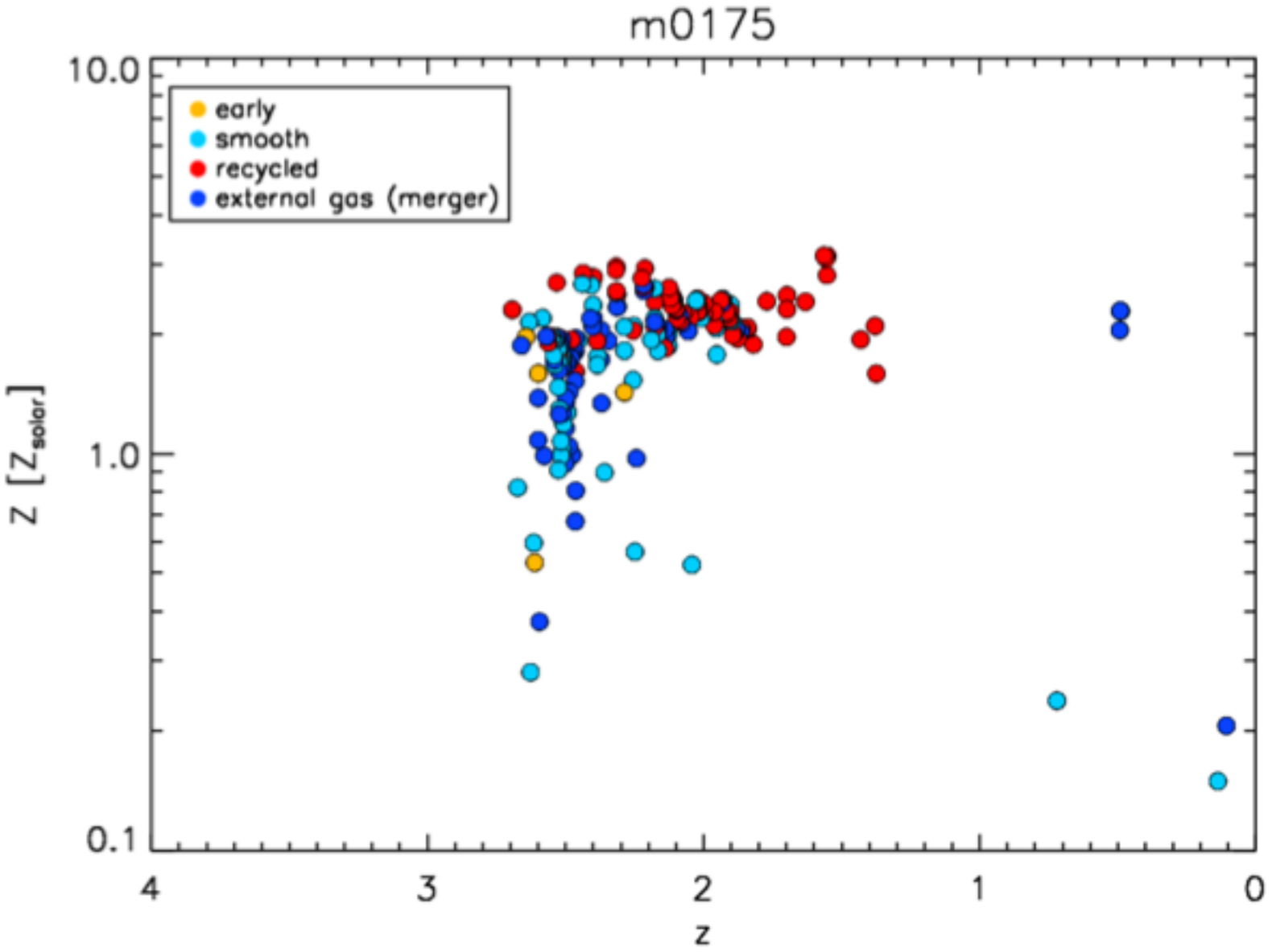
- The recycled gas from dying stars can trigger star formation, but it can more effectively collapse toward the galaxy center to feed the black hole.



Choi+23 in prep.

What we predict for AGN survey..(1)

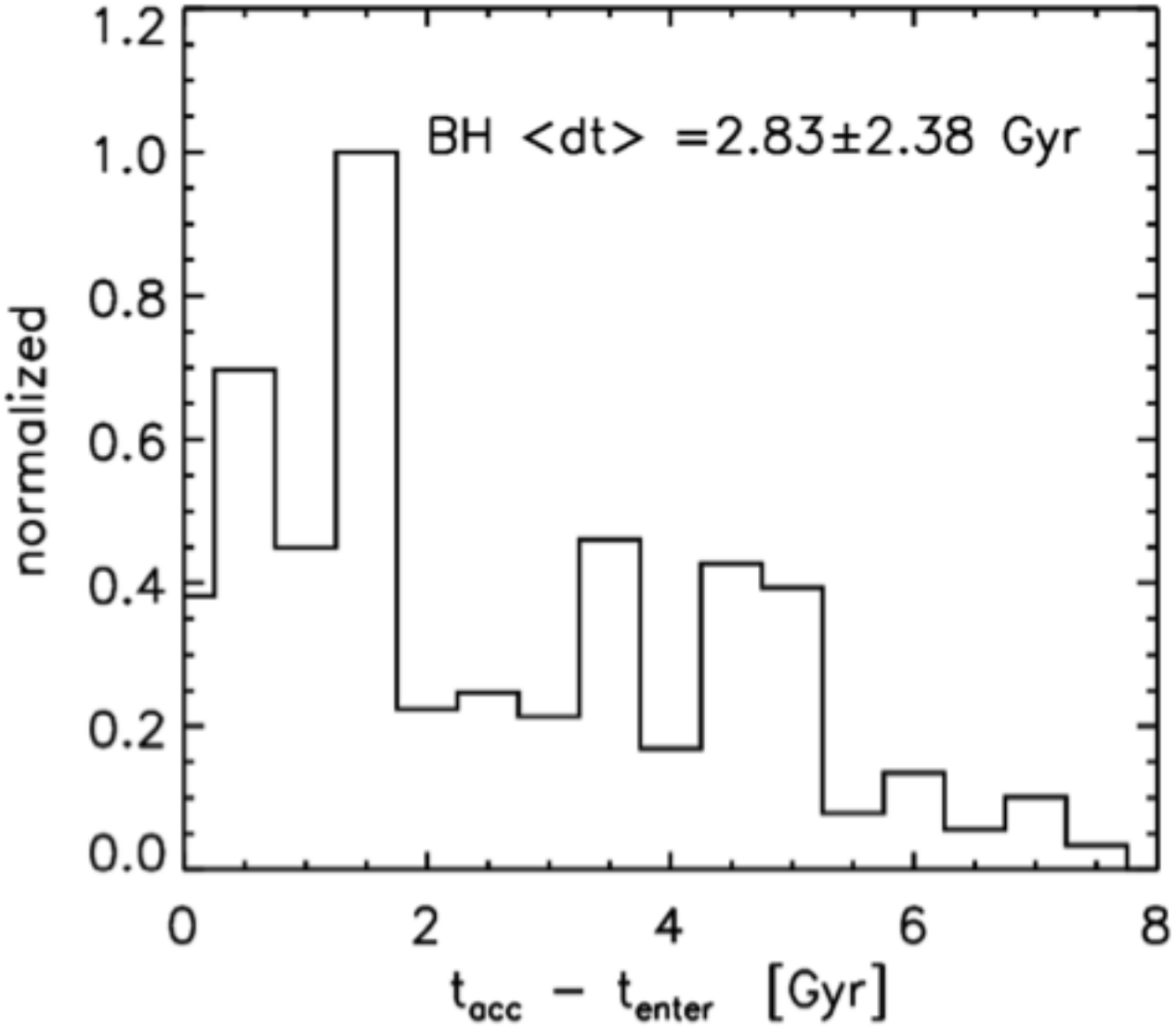
- **High-metallicity gas accretion** from z~3 due to recycled gas contribution.
- Future work: abundance comparison with high-z BLR (Woo, J-H.)
- Element abundance prediction is also possible as we explicitly trace the evolution of 11 species (H, He, C, N, O, Ne, Mg, Si, S, Ca, Fe)



What we predict for AGN survey..(2)

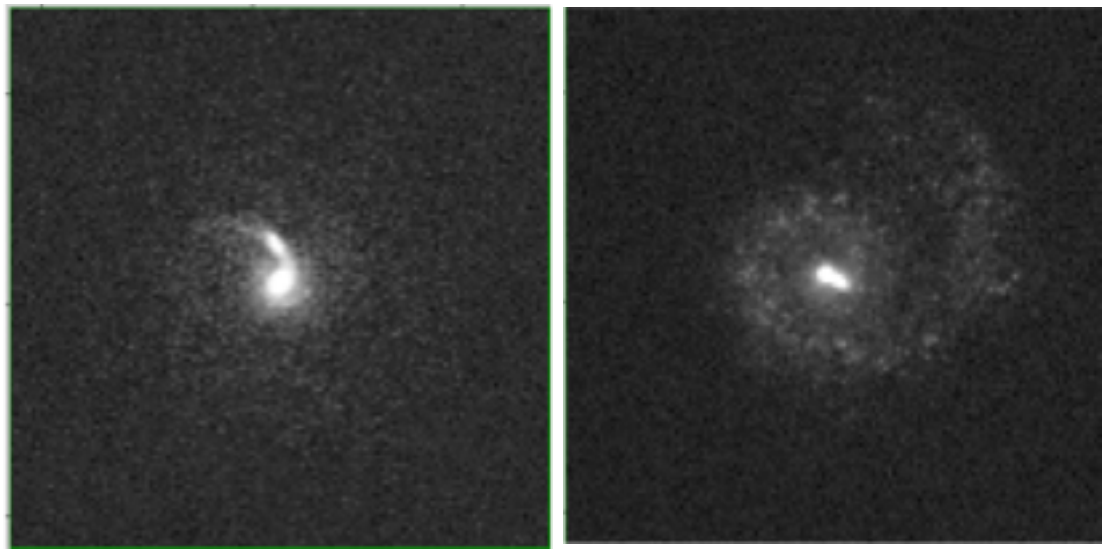
- Very long timescale for external gas to be actually accreted to the BH
- t_{enter}: the moment gas enters the main halo (r_{vir})
- t_{acc}: the moment gas actually accretes to BH
- Possibly the reason **why we do not see a clear AGN-merger connection in AGN survey observations.**

Choi+23 in prep.

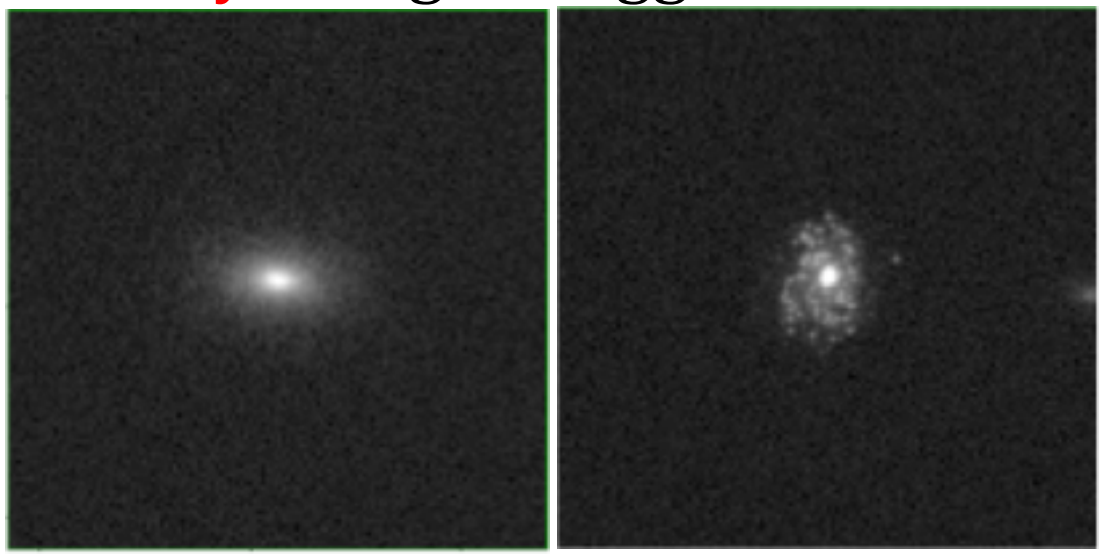


What we predict for AGN survey.. (3)

- Galaxy mock images with external gas triggered AGN



- Galaxy mock images with recycled gas triggered AGN



- Can **machine learning** distinguish AGN with different fueling sources?

Summary

- To study the fueling mechanisms of supermassive black holes (SMBH), we trace the history of gas that central SMBHs (1-5x10^9 M_{sun}) accrete and classify their origin as one of

  early / external / smooth / recycled

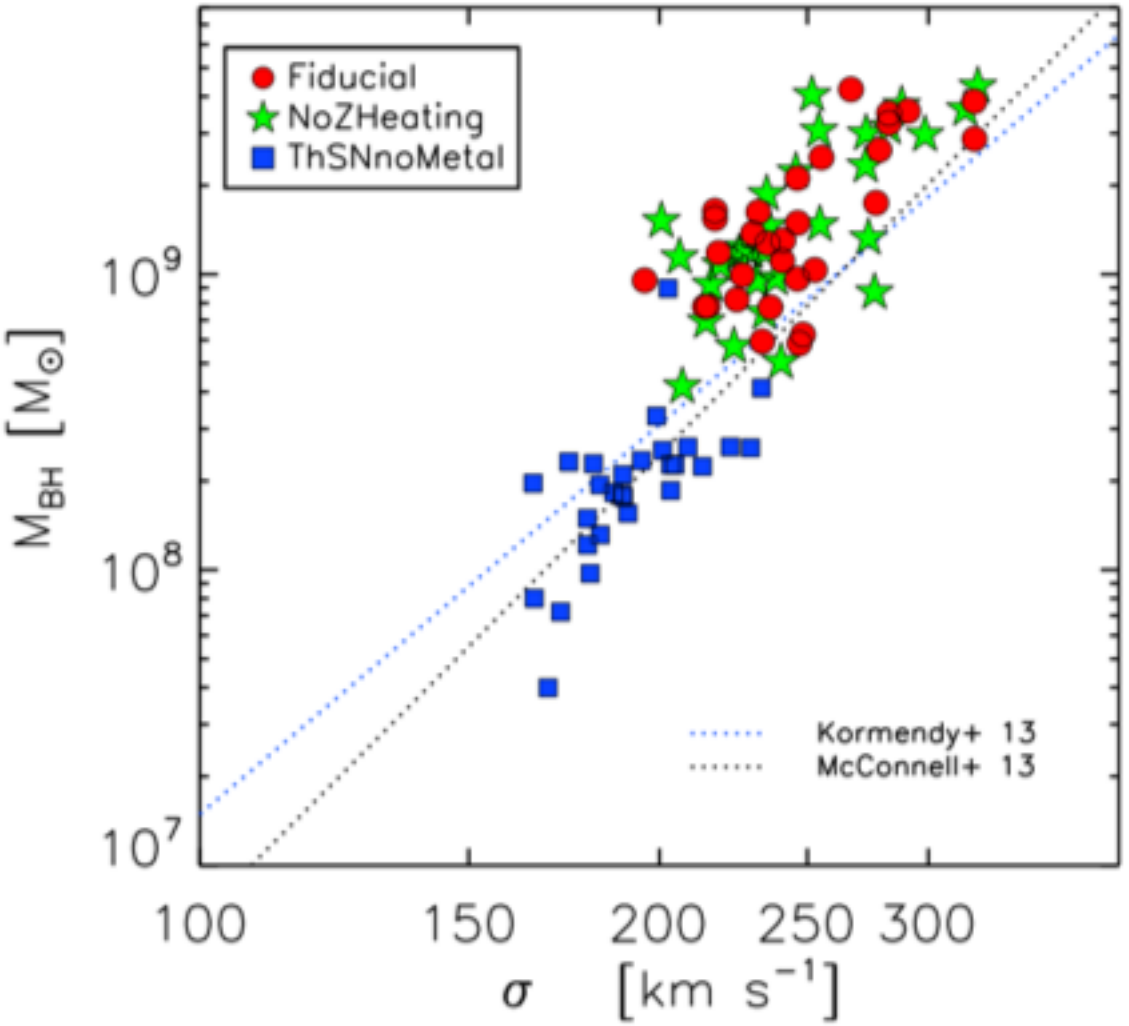
- The recycled gas from dying stars is the most important fuel source for the SMBH.
  - It can easily penetrate to galaxy center, feeding the SMBH.
- SMBHs in the massive halos ($10^{12\text{-}13}$) tend to accrete a higher fraction of merger-accreted gas (external origin) than smooth-accreted gas.
  - Galaxy mergers also play an important role in feeding the SMBH in massive galaxies, but its effect highly depends on the galaxy's merger history.

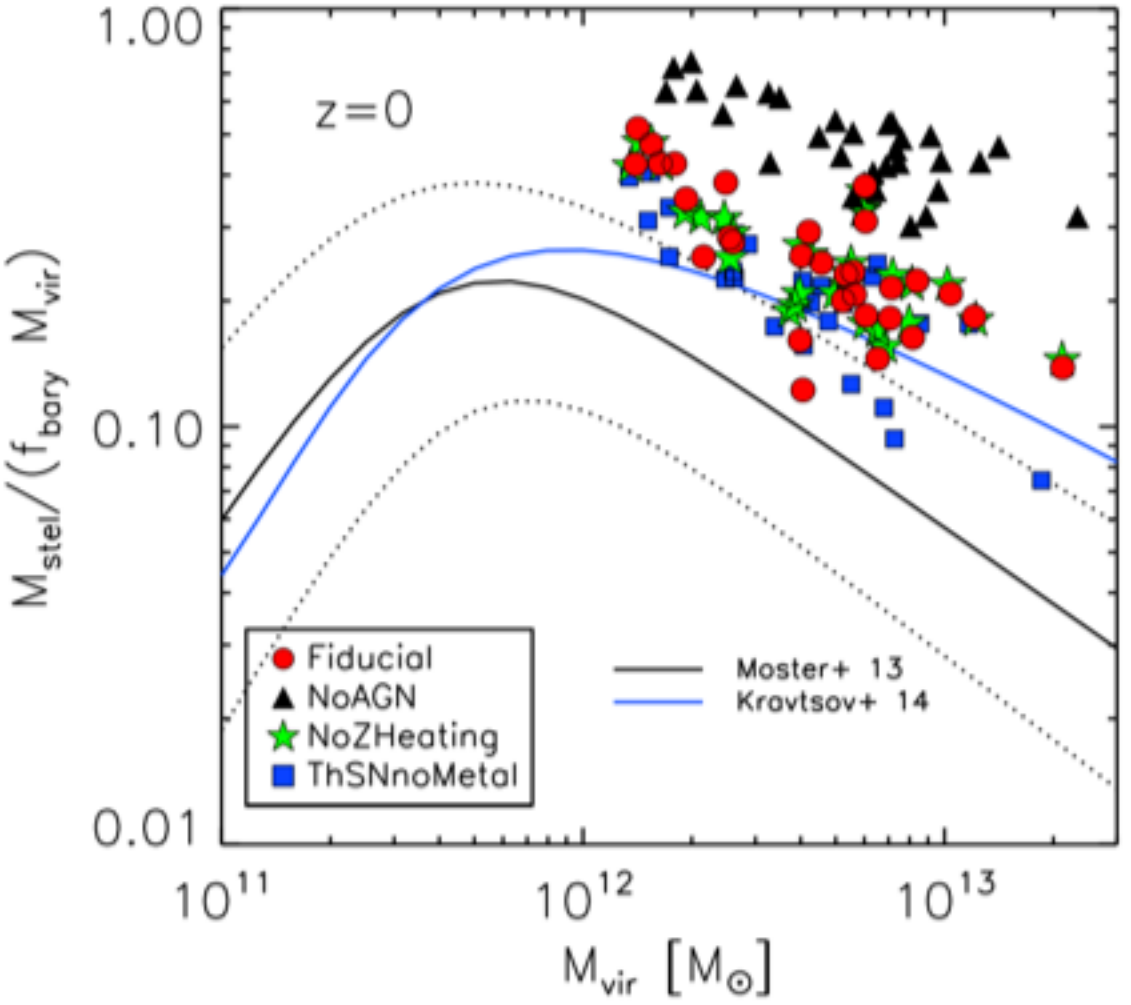
Thank you!

back-up slides ☺

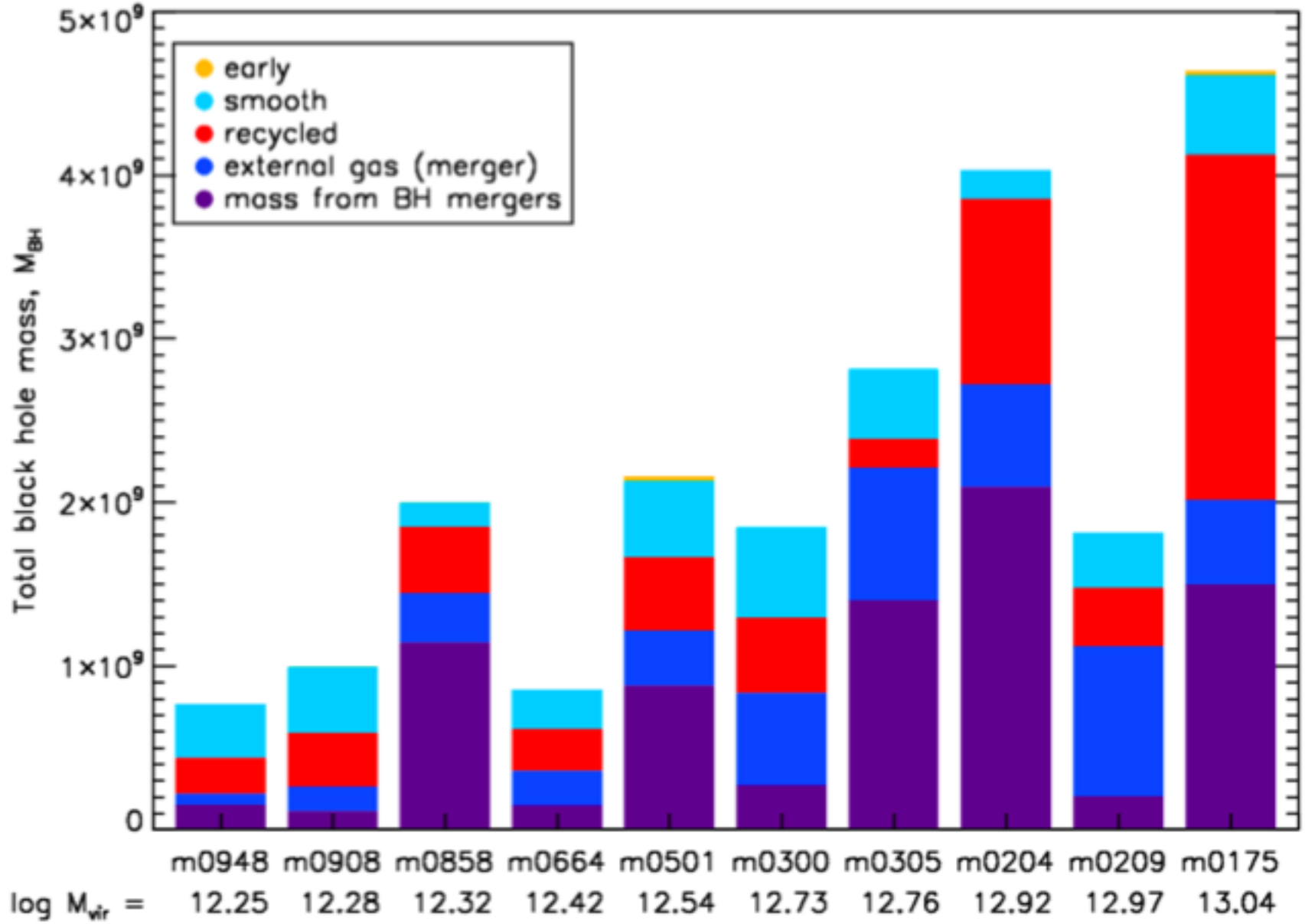
Appendix: M-sigma / Mhalo - Mstel

Choi+17

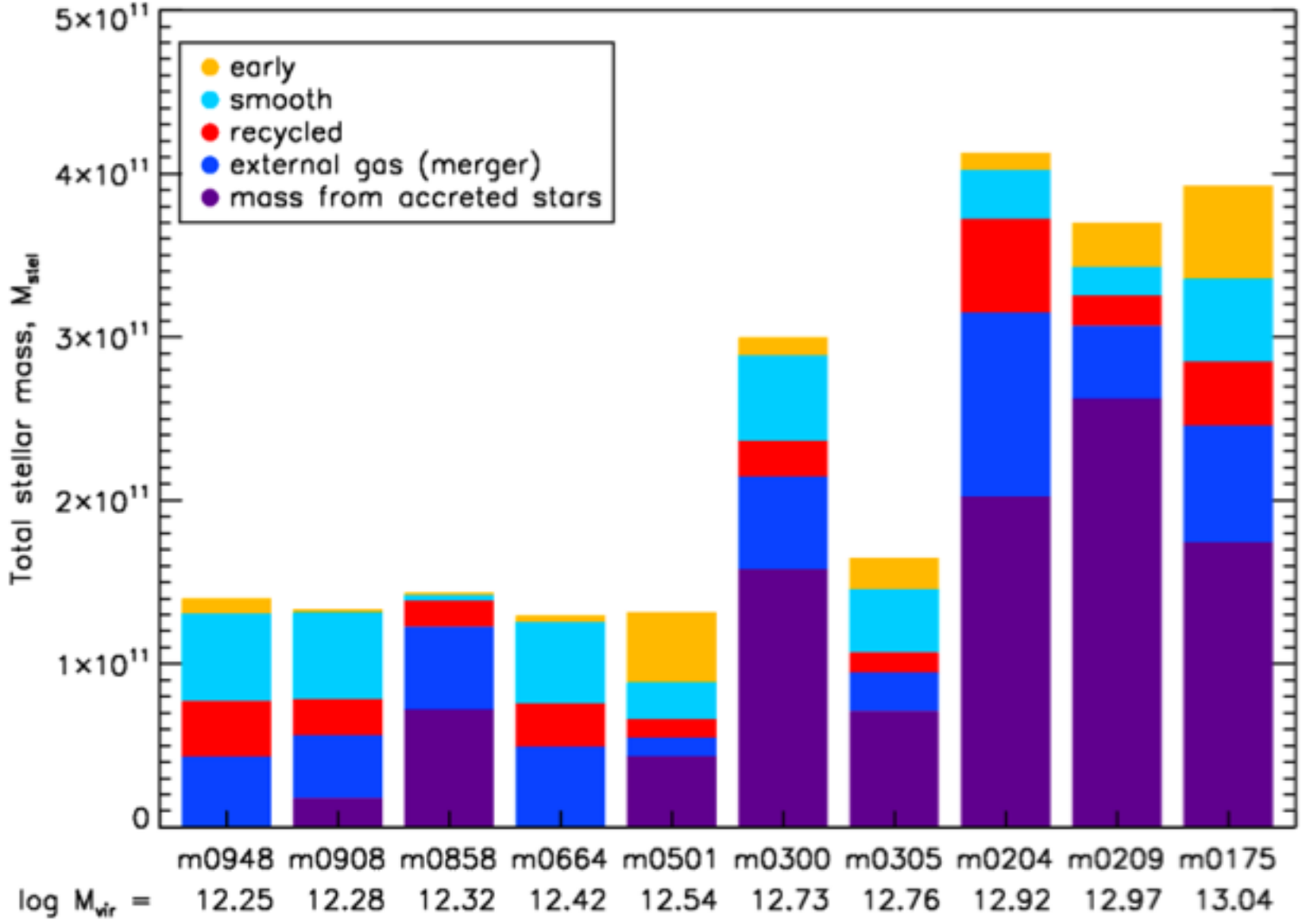




Appendix : BH mass budget (bh mergers)



Appendix : SF mass budget (accreted stars)



Accretion & star formation timescales