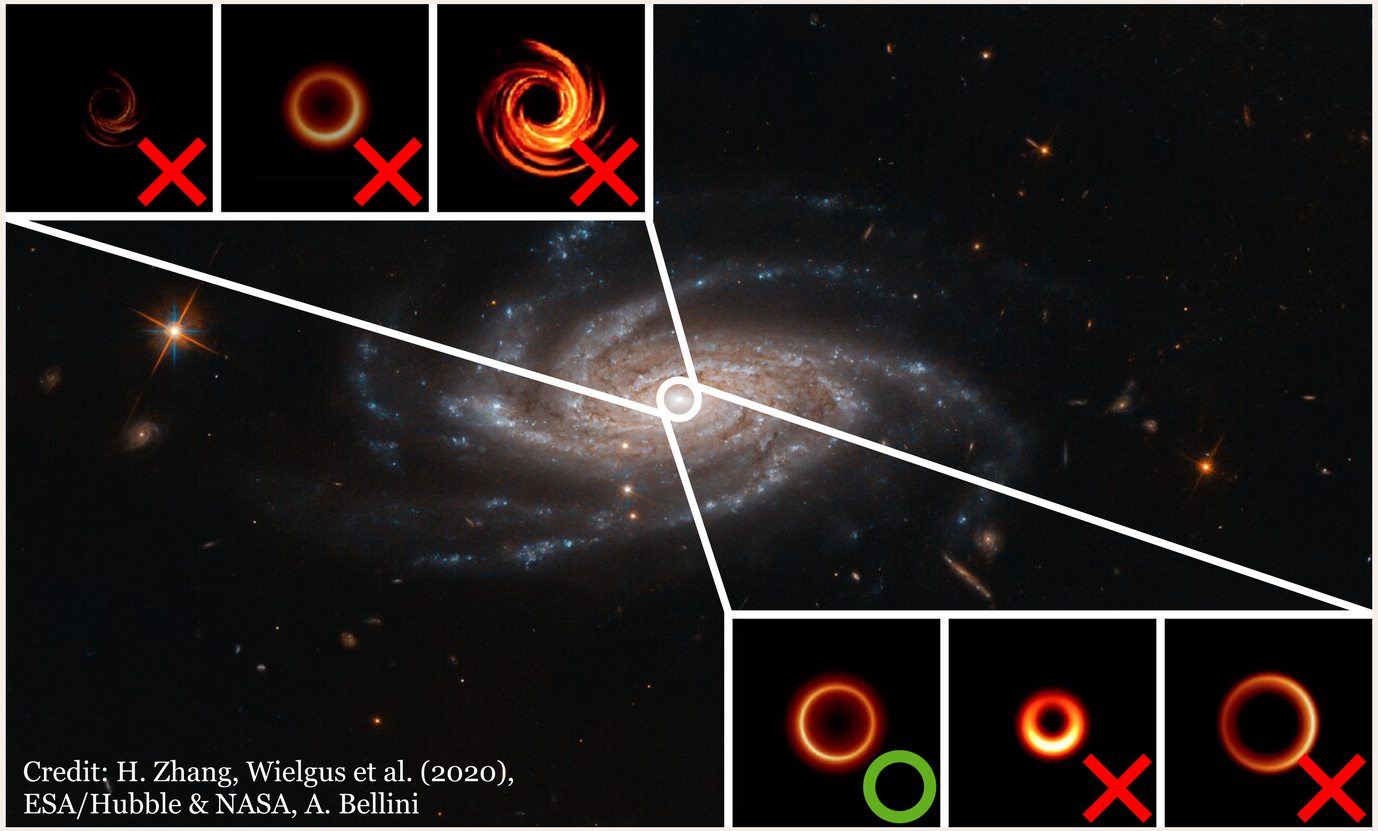
TRINITY: Empirical Dark Matter Halo—Galaxy—Supermassive Black Hole Connection from z = 0 – 10

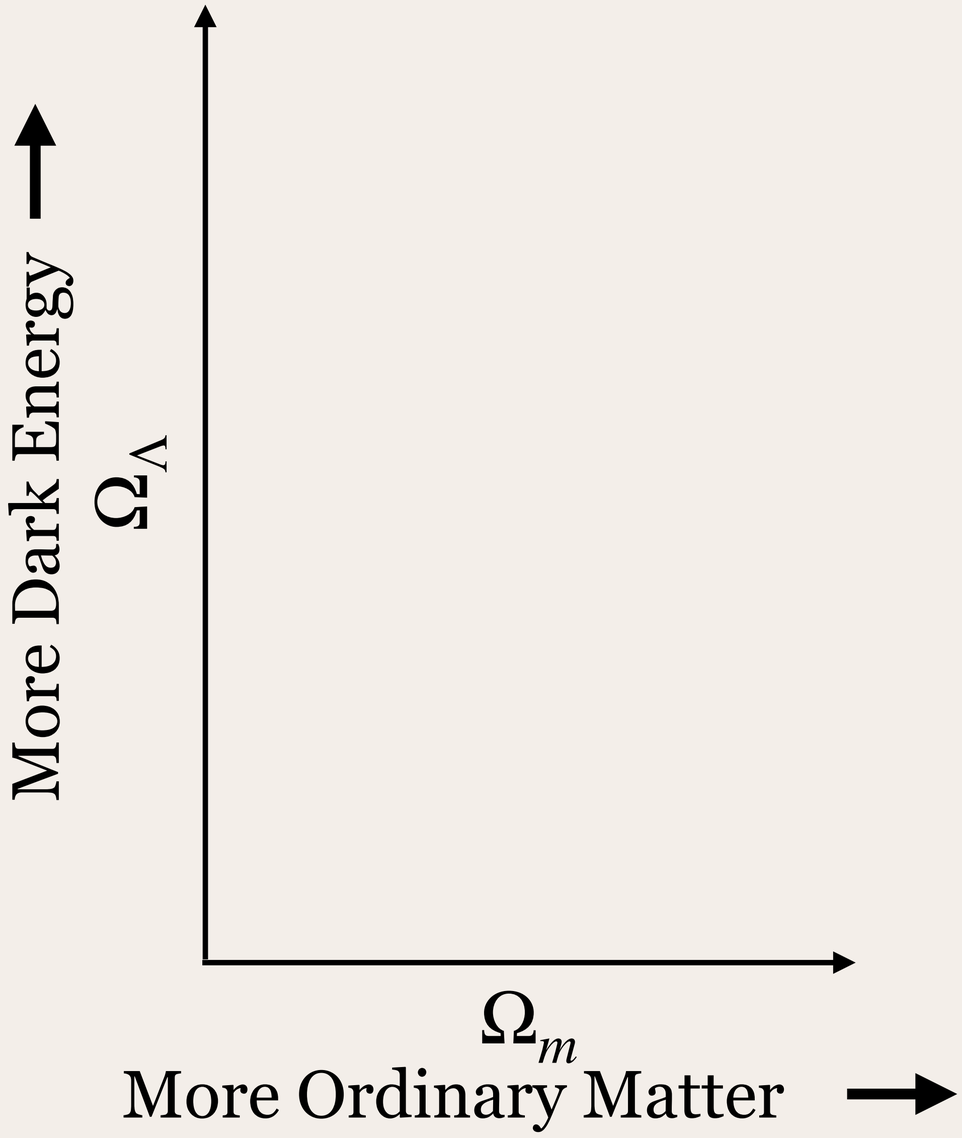


Haowen Zhang (张昊文),

Advisor: Peter Behroozi,

Collaborators: Marta Volonteri, Joseph Silk, Xiaohui Fan, Phil Hopkins, Jinyi Yang, and James Aird

Empirical Models: Physical Latent Spaces



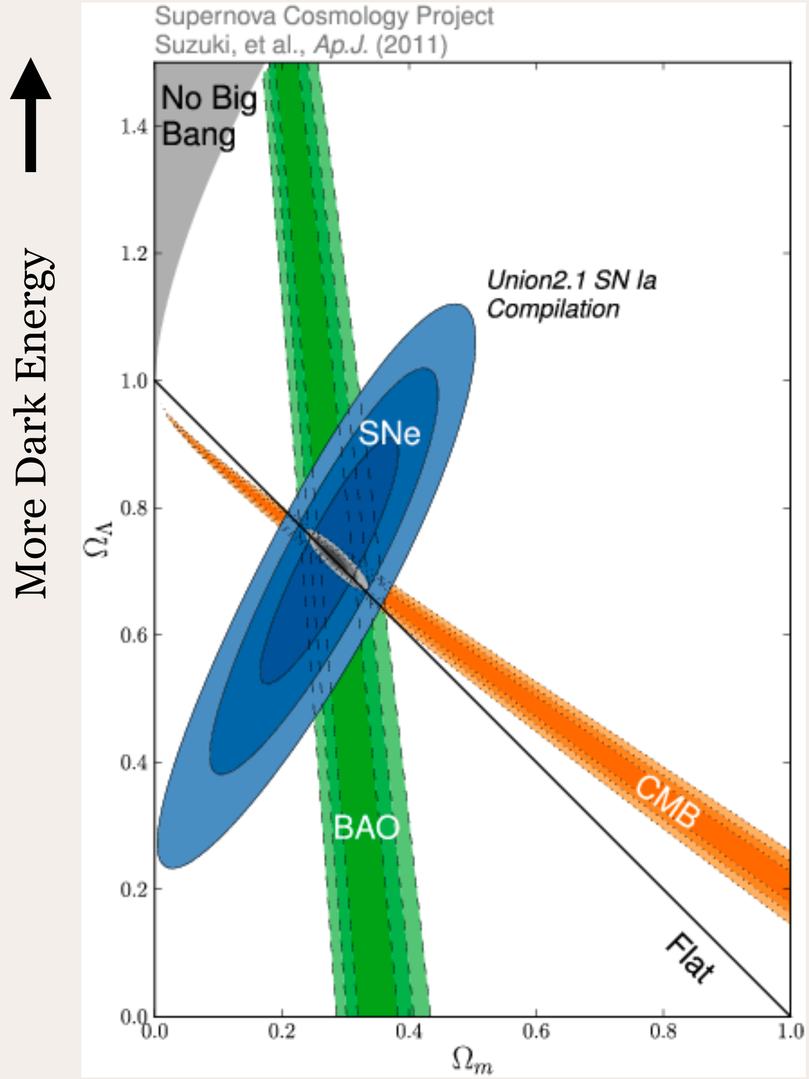
Empirical Models: More Data to Break Degeneracies

More Dark Energy

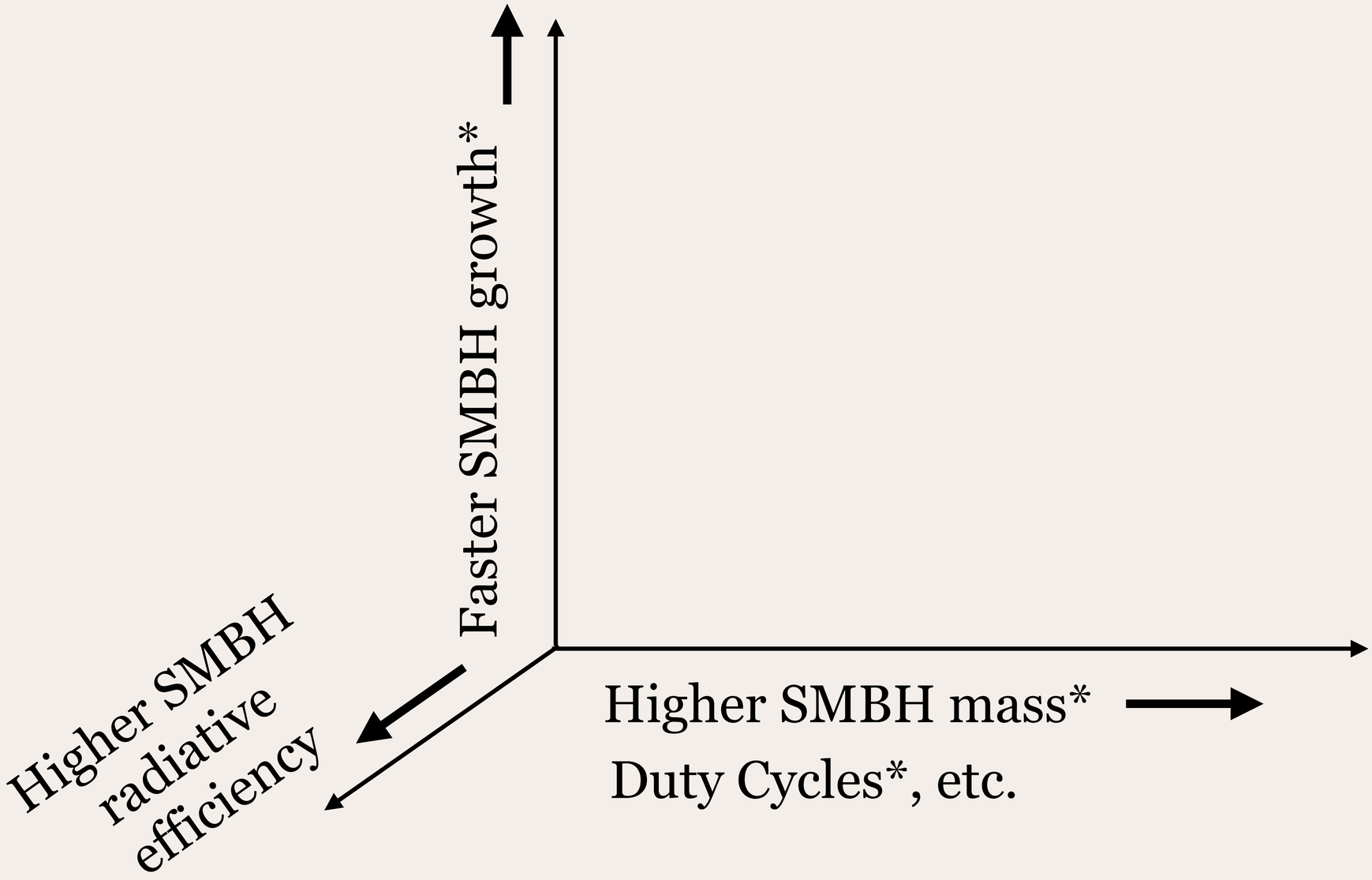
Ω_Λ

Ω_m

More Ordinary Matter



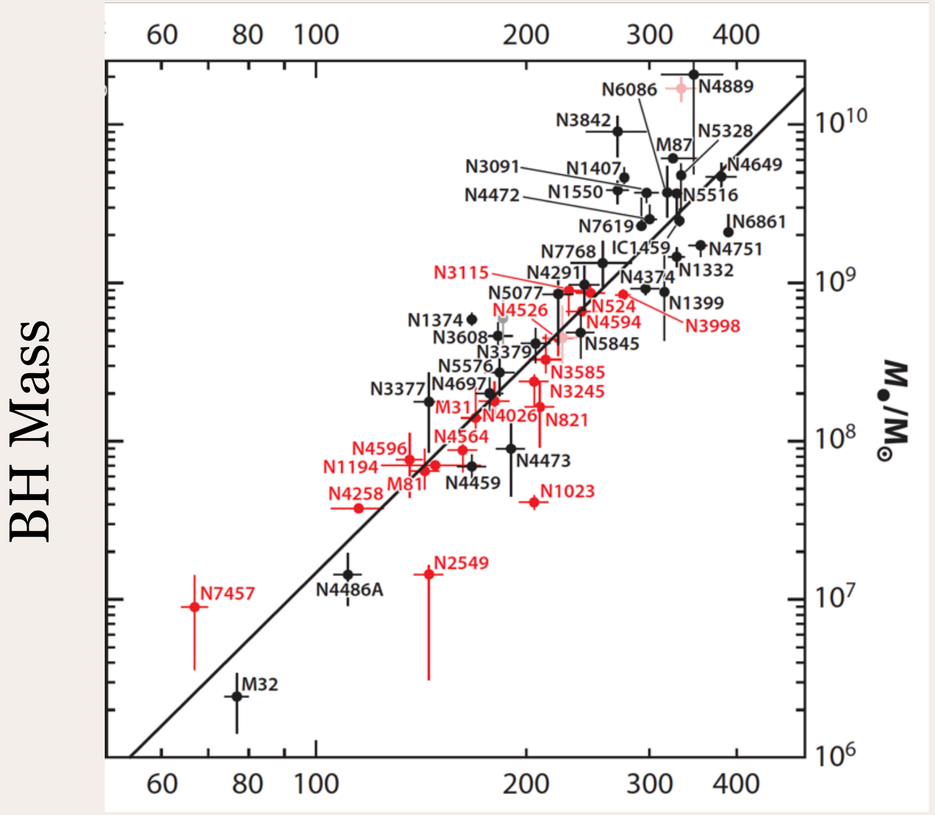
TRINITY: Latent Space For Galaxy—SMBH connection



*All as functions of galaxy mass

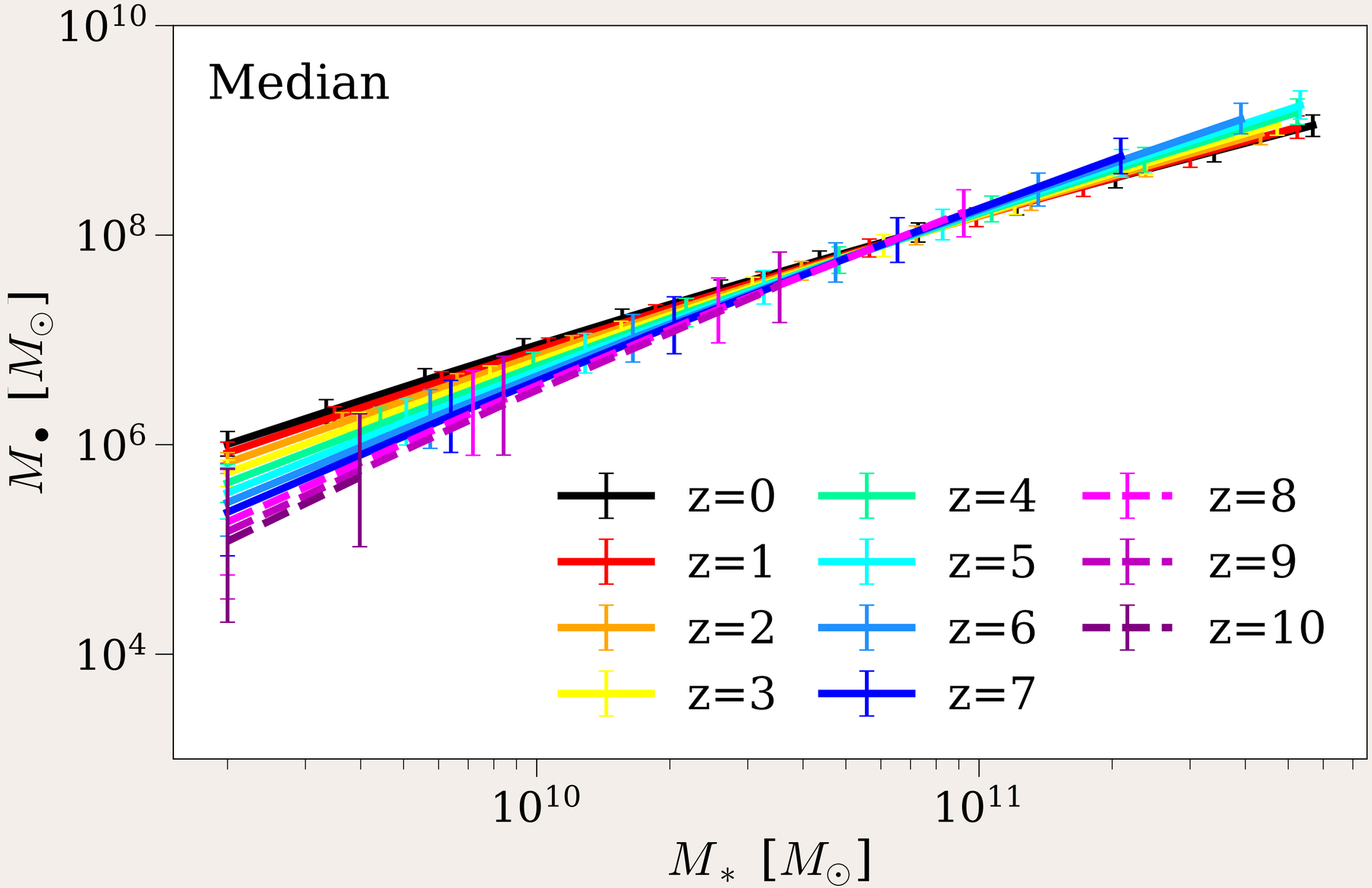
TRINITY: Why This Latent Space?

Local Universe: M-σ Relation

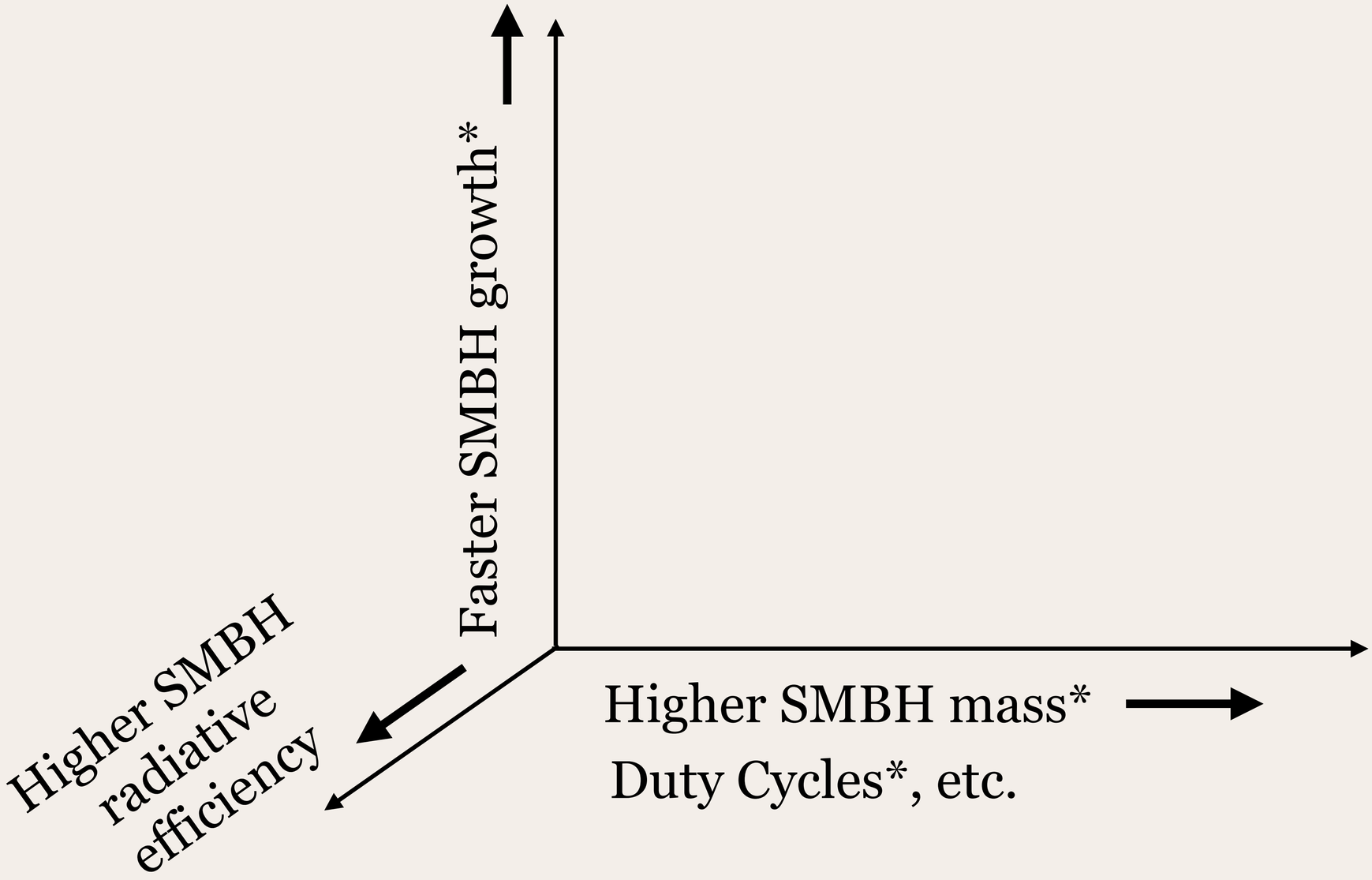


Kormendy & Ho 2013

TRINITY: Why This Latent Space?



TRINITY: Latent Space For Galaxy—SMBH connection



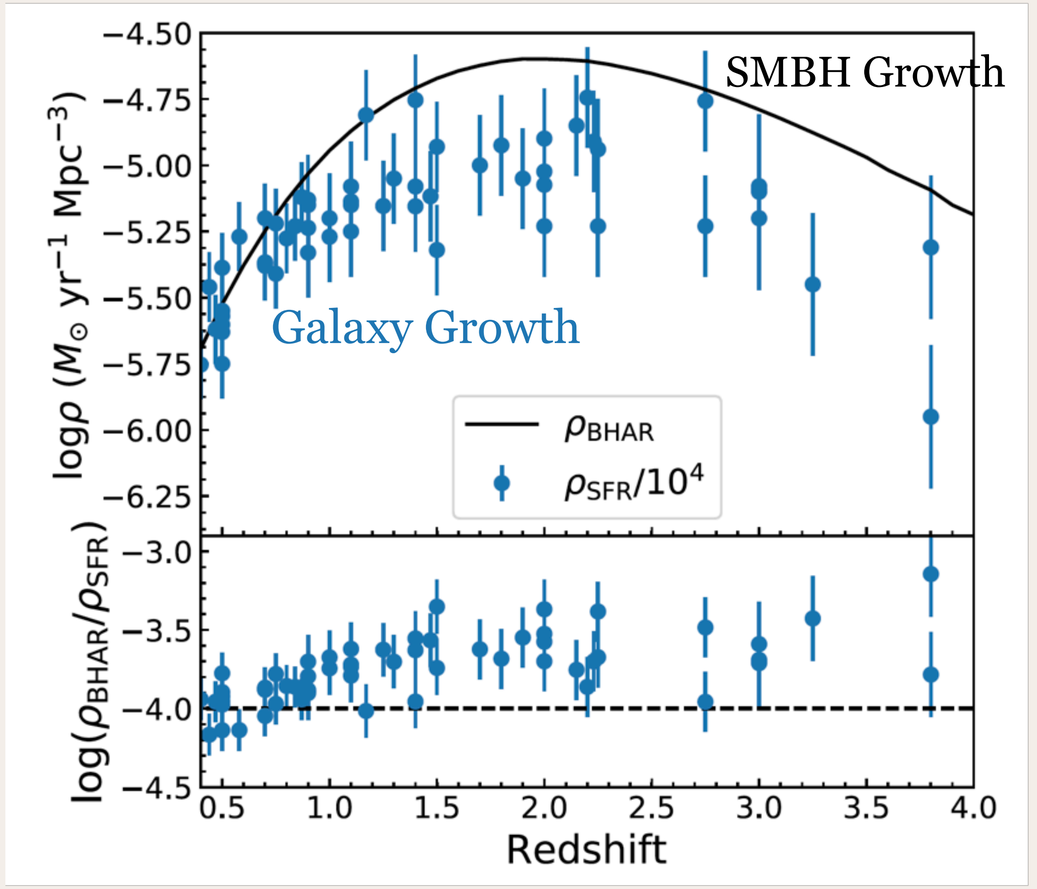
*All as functions of galaxy mass

TRINITY: Why This Latent Space?

z>0: ***Cosmic*** BHAR/SFR Ratio

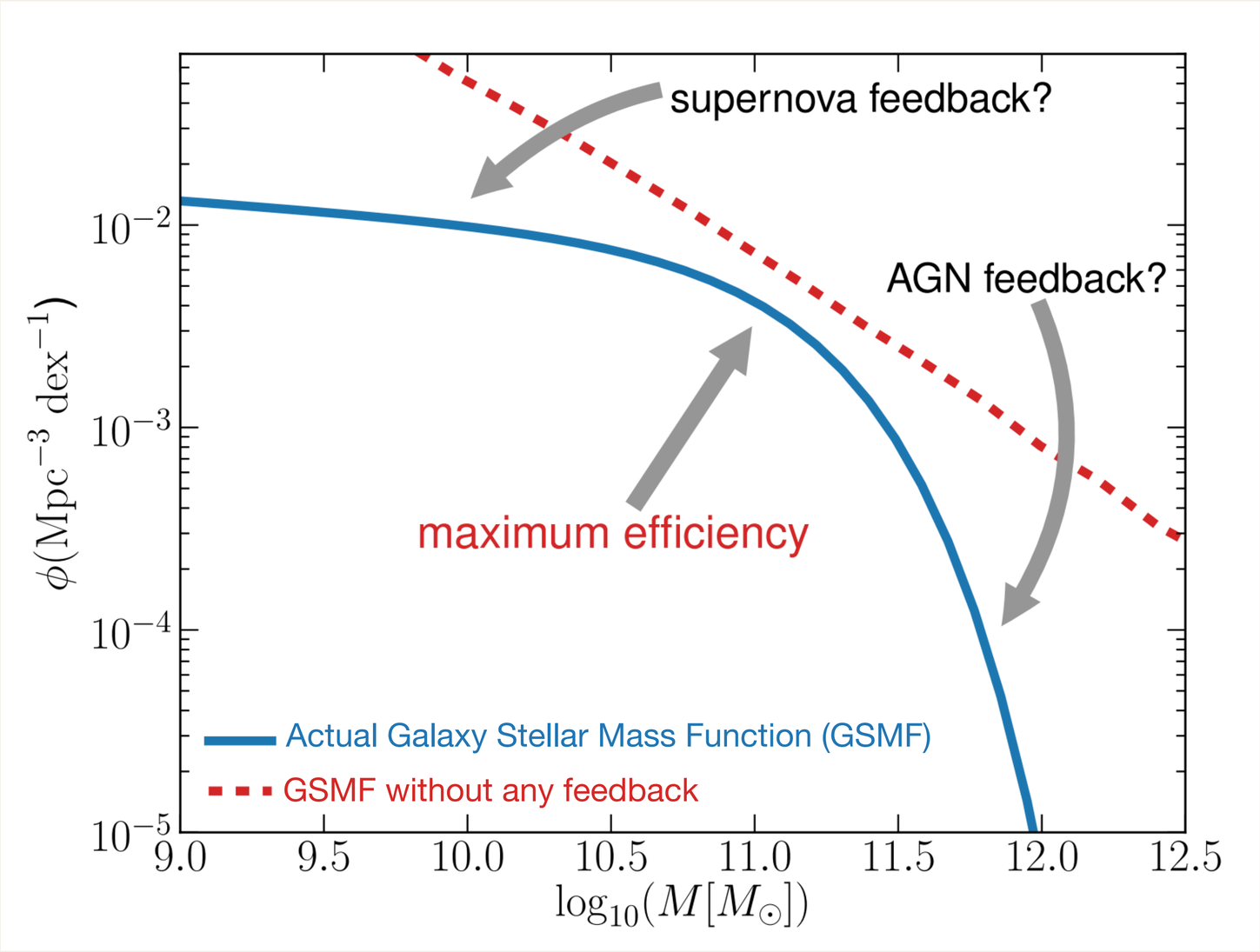
Cosmic Growth Rate

Growth Ratio



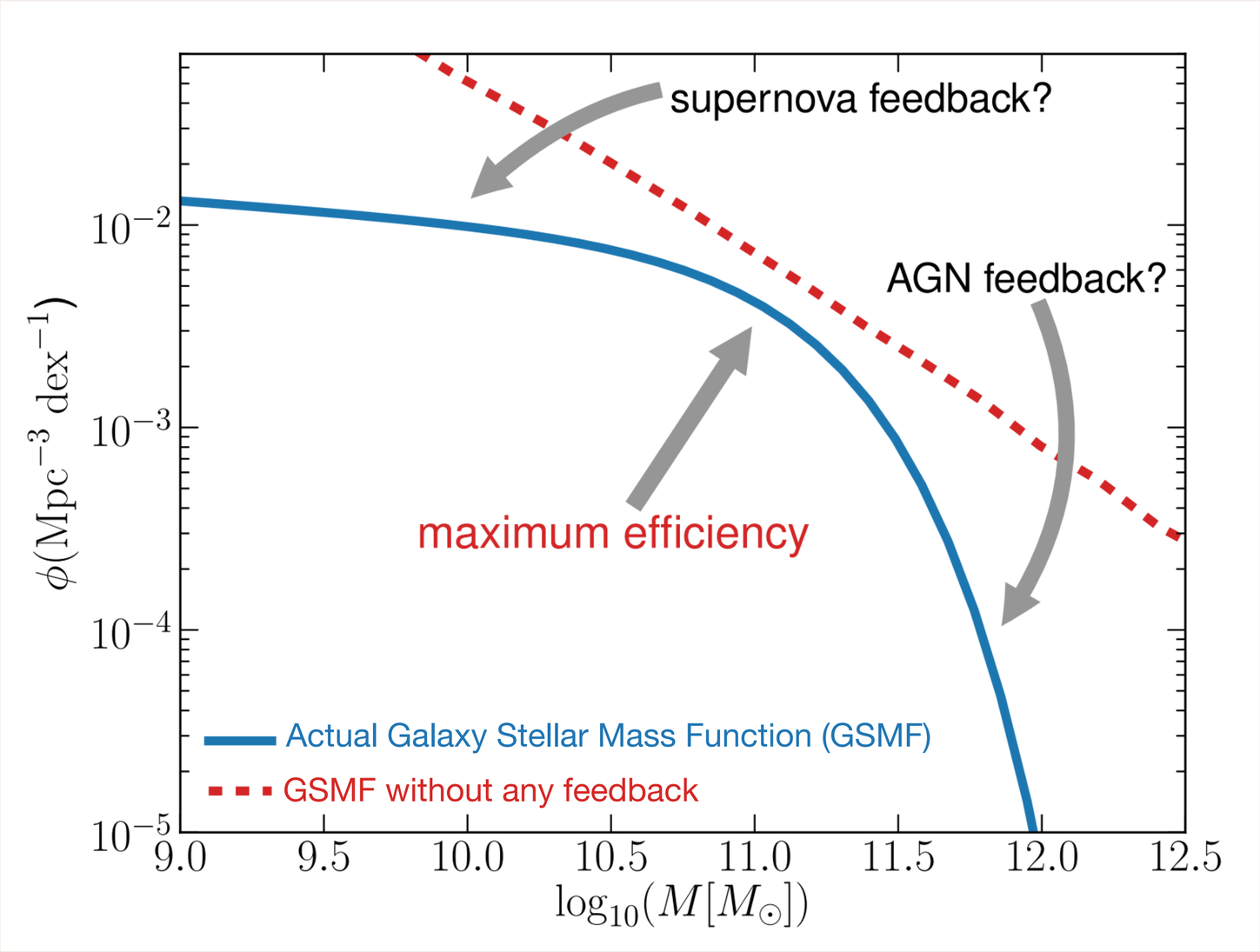
Yang et al. (2017)

TRINITY: Why This Latent Space?



Mutch et al. (2013)

TRINITY: Why This Latent Space?

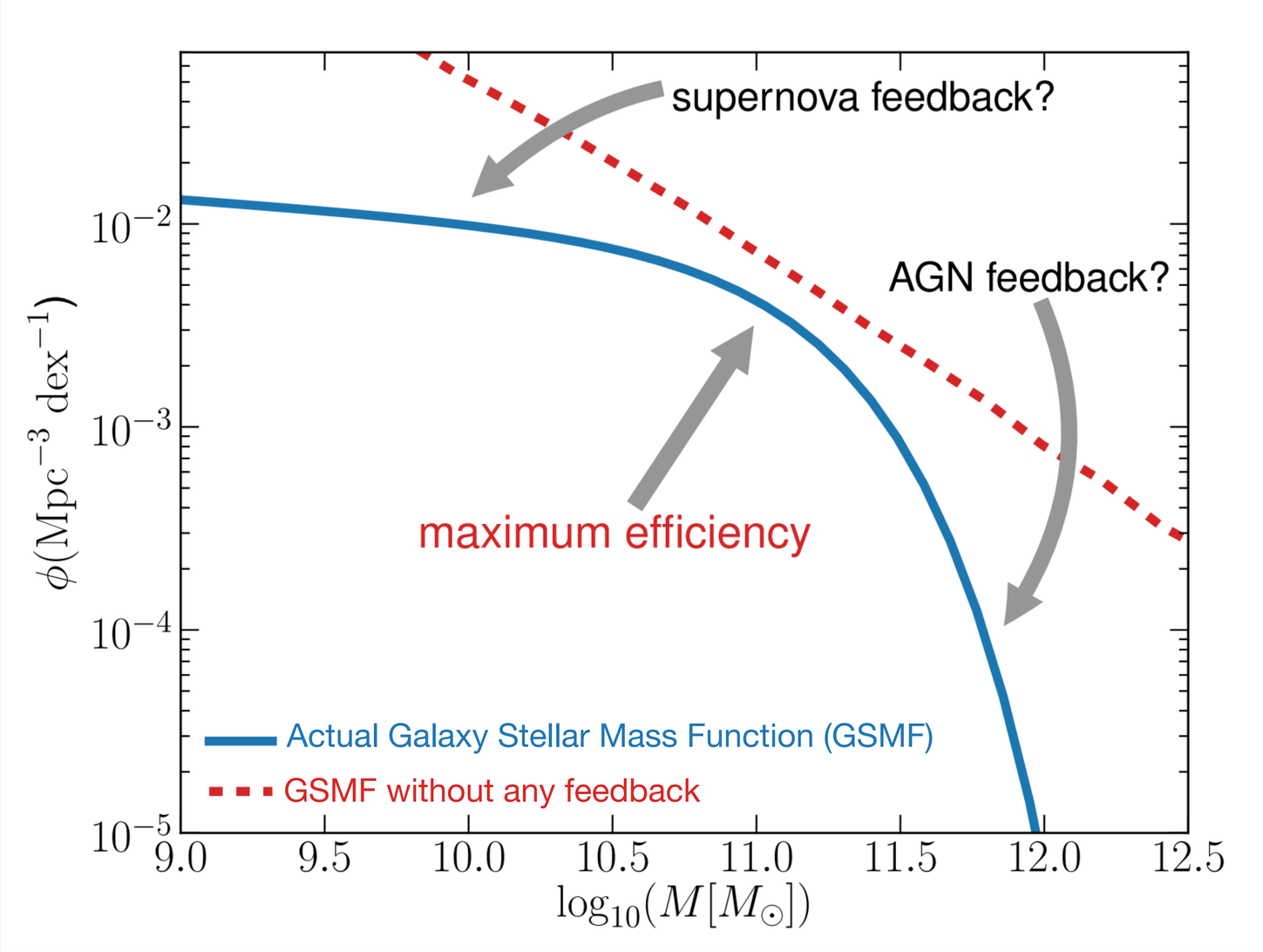


Mutch et al. (2013)

AGN Feedback Mode

$$\sim \eta_{\mathrm{Edd}} \sim \frac{\dot{M}_{\mathrm{BH}}}{M_{\mathrm{BH}}}$$

TRINITY: Why This Latent Space?



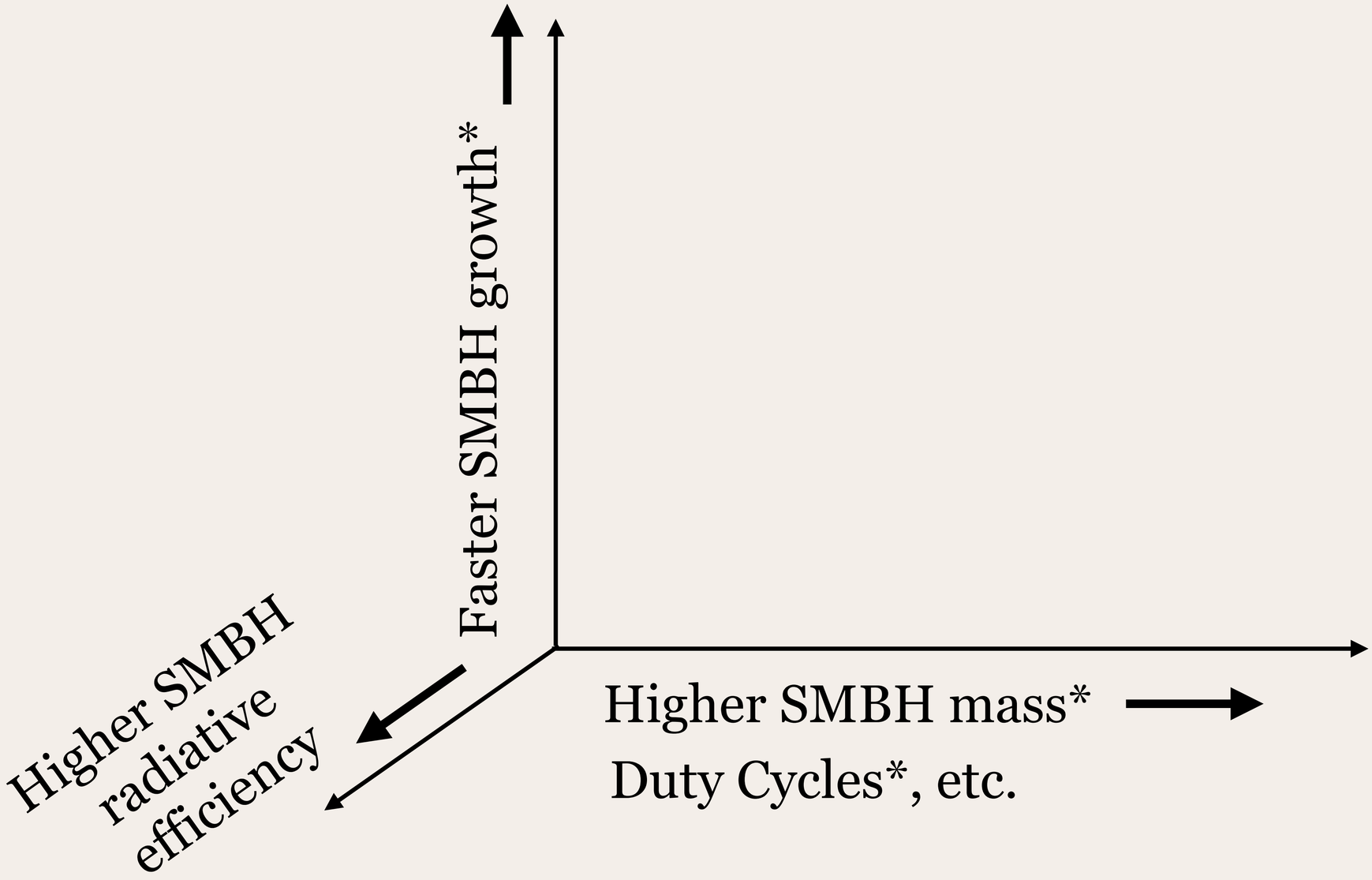
Mutch et al. (2013)

AGN Feedback Mode

$$\sim \eta_{\mathrm{Edd}} \sim \frac{\dot{M}_{\mathrm{BH}}}{M_{\mathrm{BH}}}$$

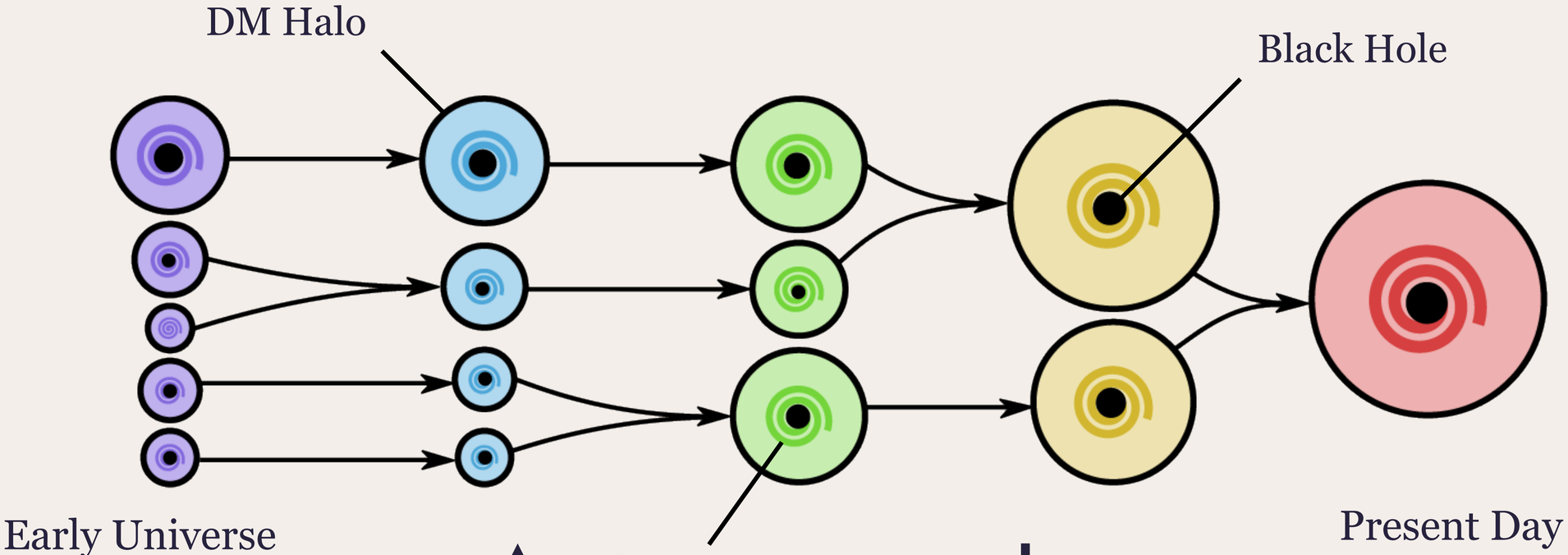
Low η_{Edd} ➡ More kinetic feedback

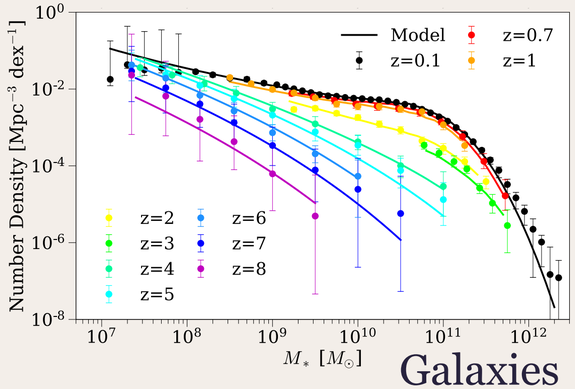
TRINITY: Latent Space For Galaxy—SMBH connection



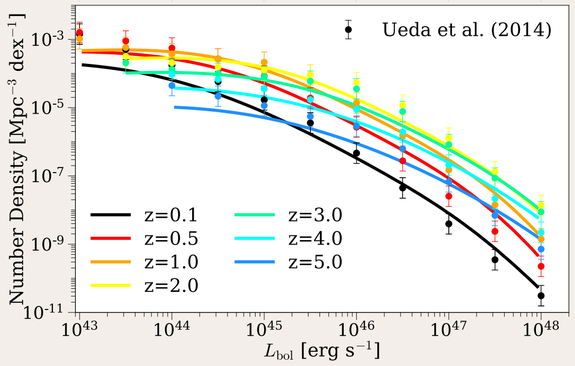
*All as functions of galaxy mass

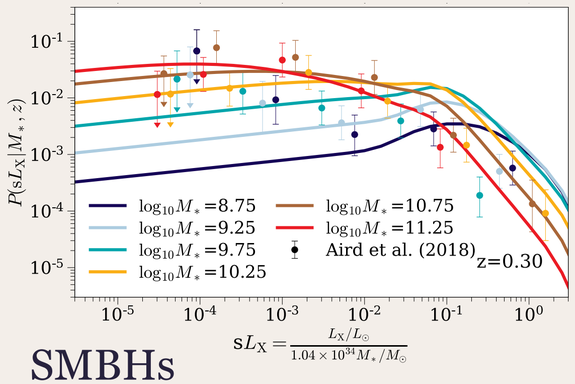
TRINITY: Breaking Degeneracies





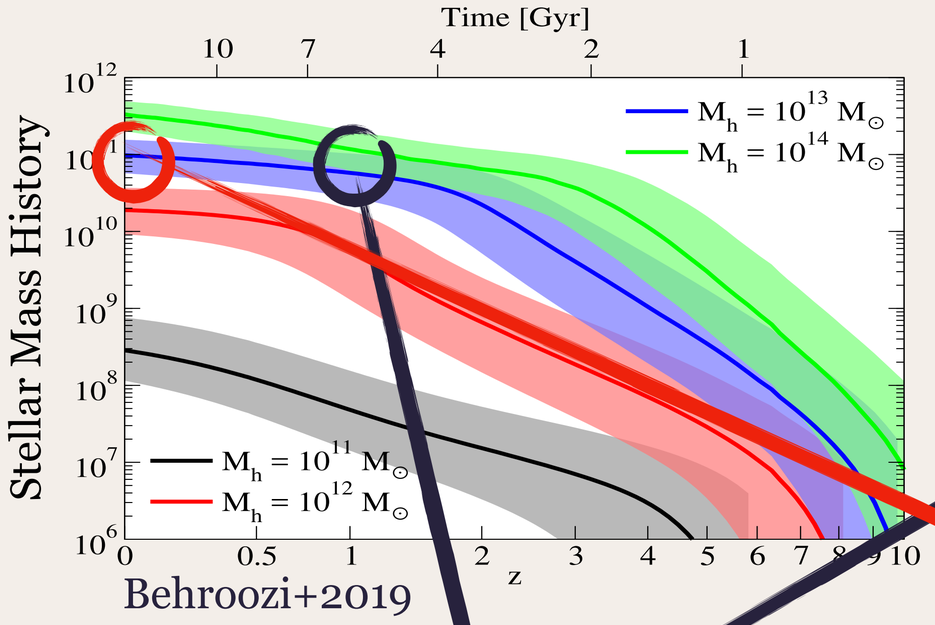
Galaxies

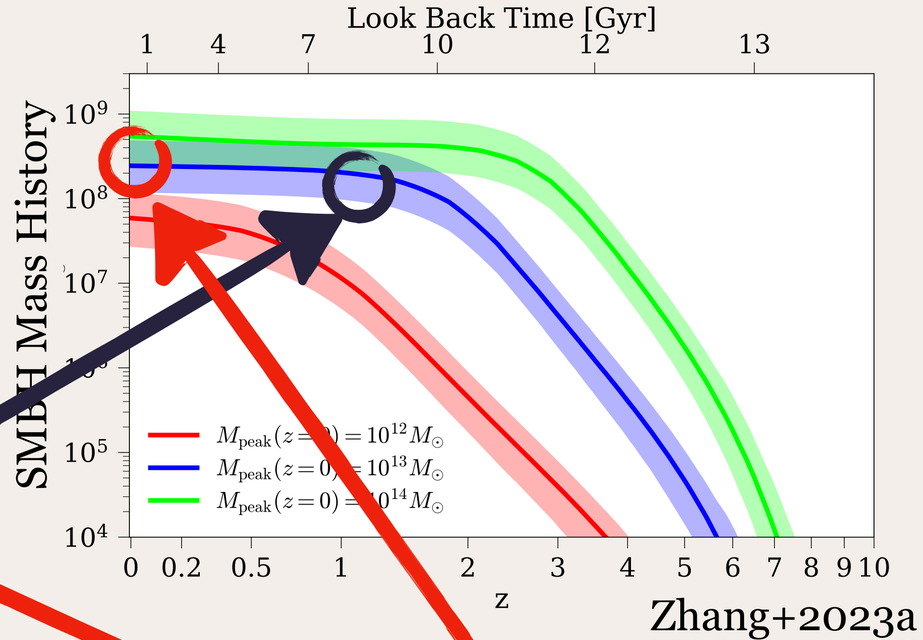


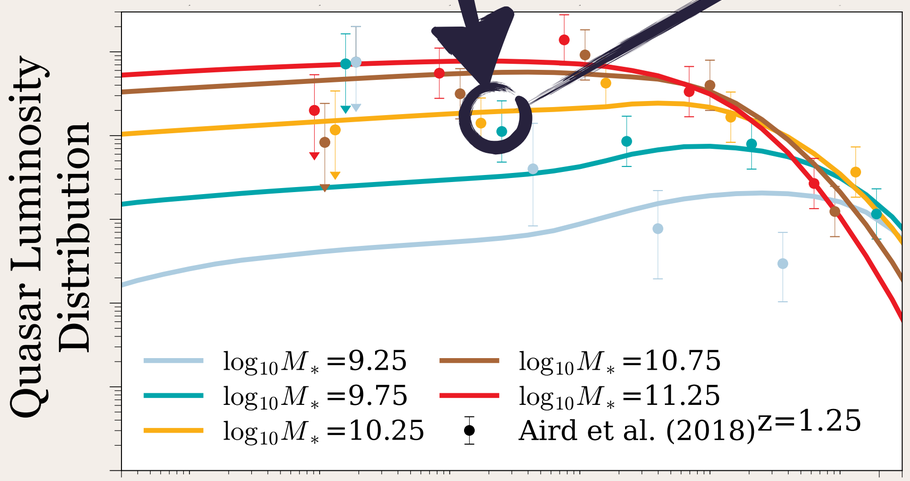


SMBHs

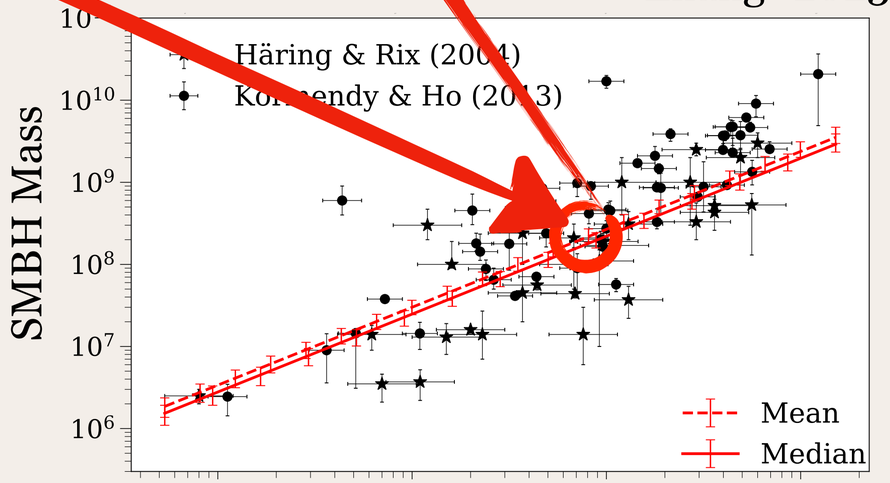
TRINITY: Breaking Degeneracies







z>0 Quasar Luminosity

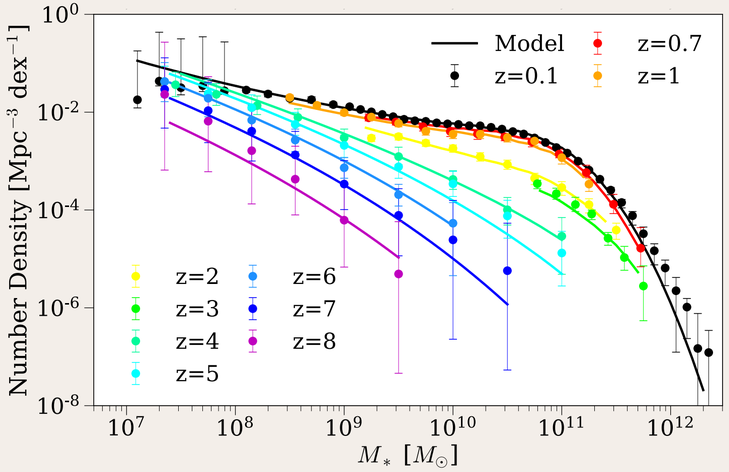


z=0 Galaxy Bulge Mass

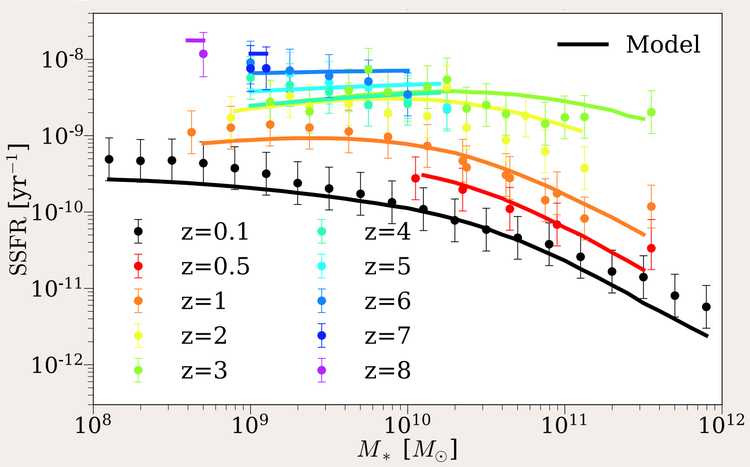
*These are only a small subset of our data constraints

TRINITY: Data Constraints

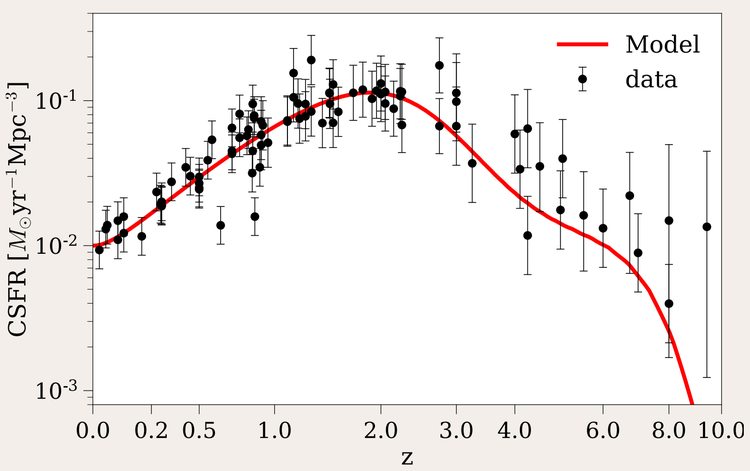
Stellar Mass Functions



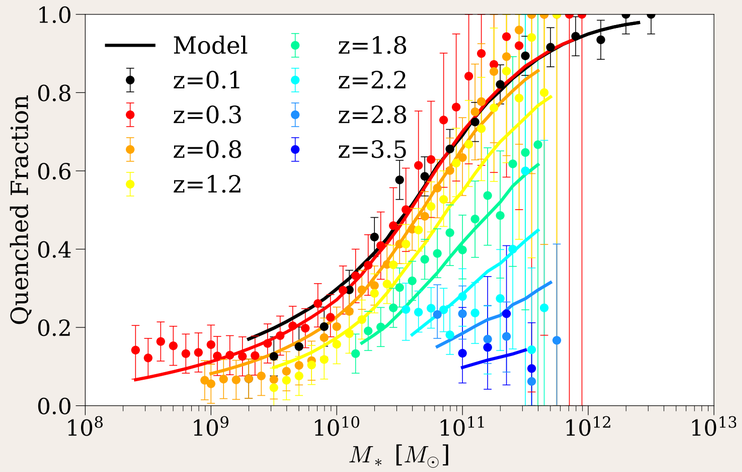
Specific Star Formation Rates



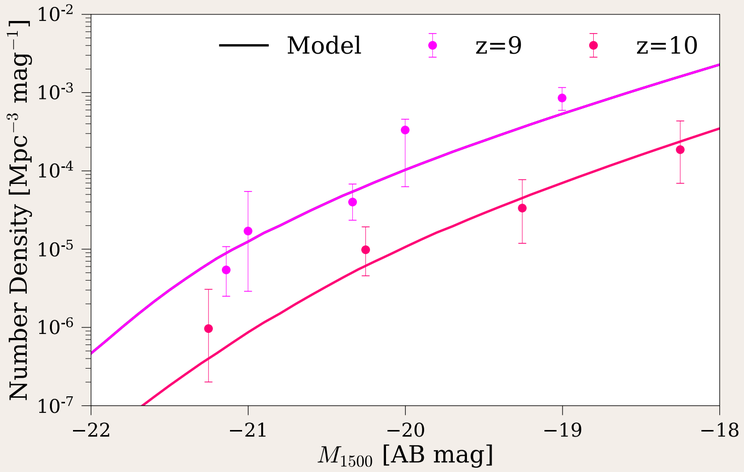
Cosmic Star Formation Rates



Quenched Fractions

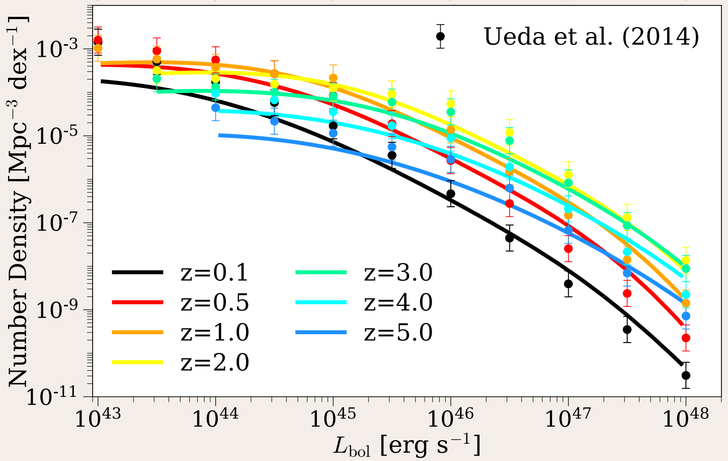


UV Luminosity Functions

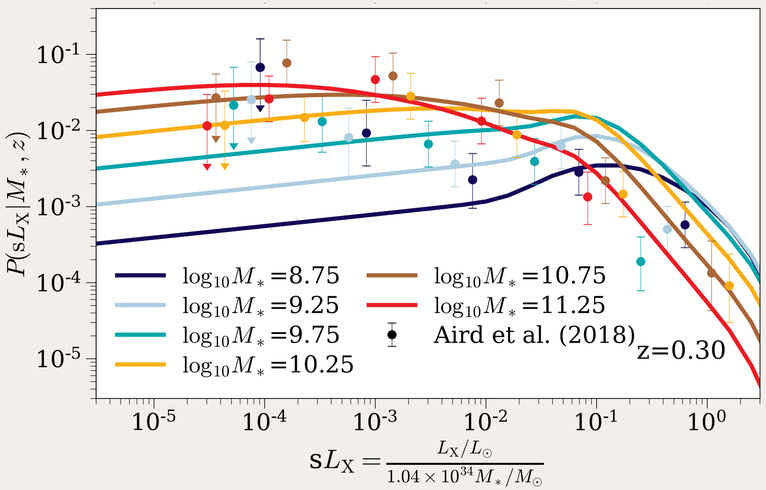


TRINITY: Data Constraints

Quasar Luminosity Functions

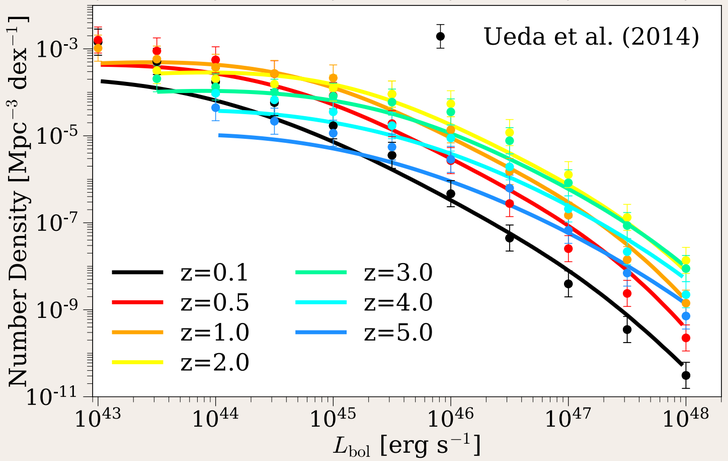


Quasar Probability Distribution Functions (0 < z < 2.5)



TRINITY: Data Constraints

Quasar Luminosity Functions



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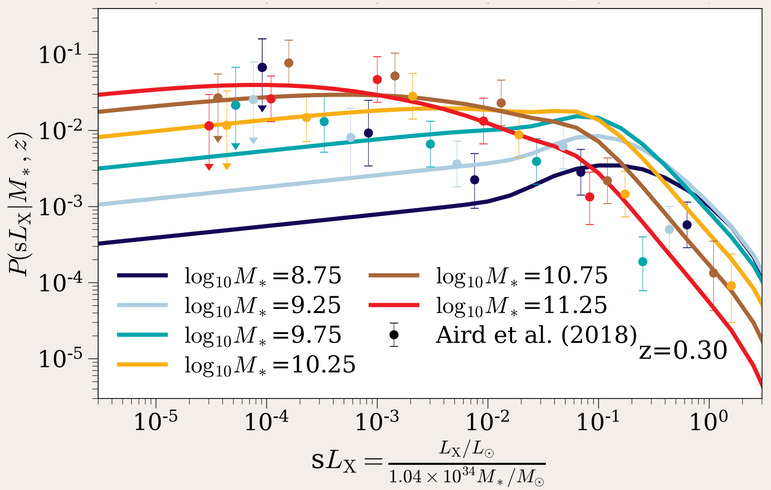
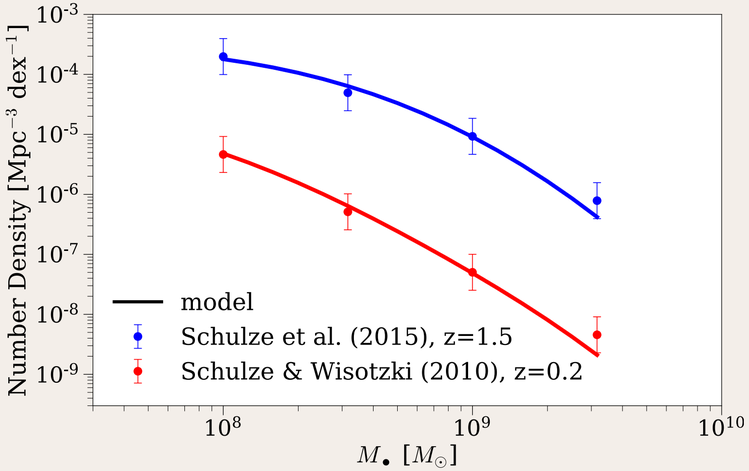
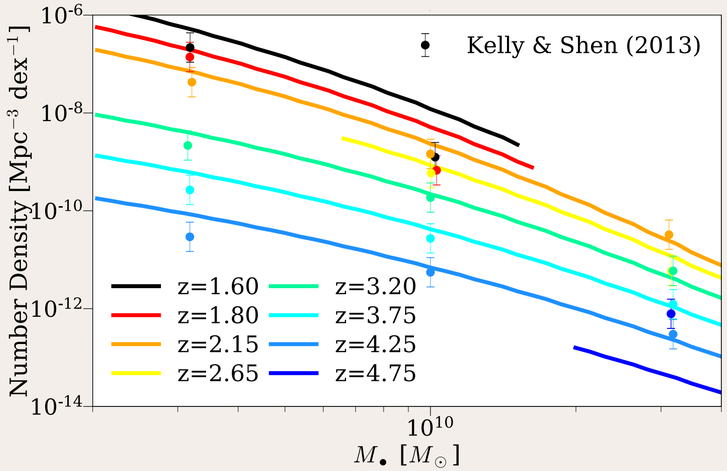


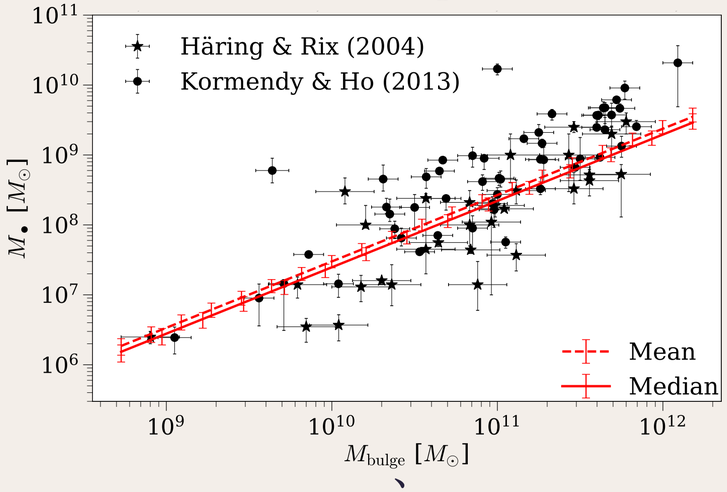
Active Black Hole Mass Functions



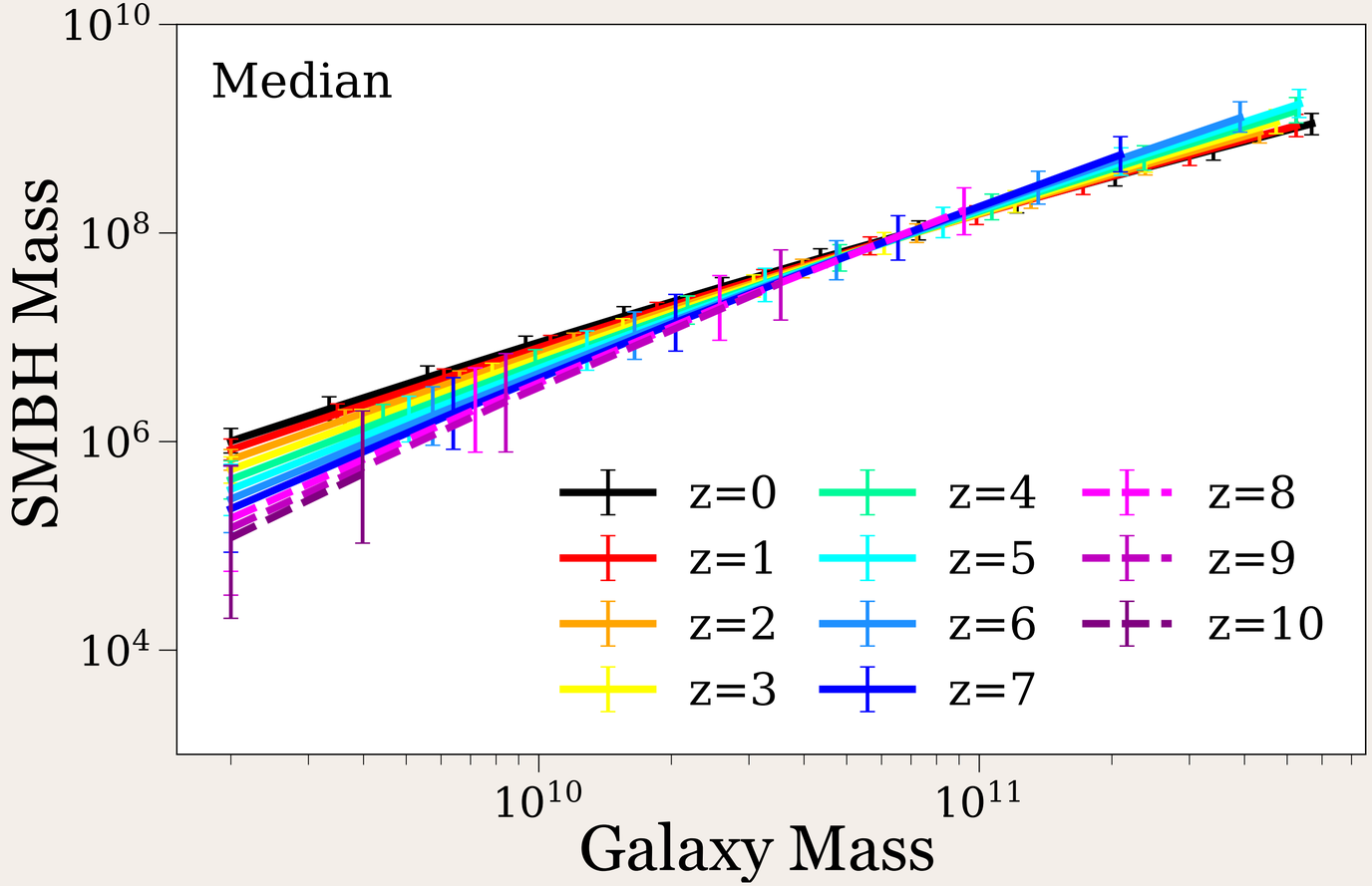
Type I Quasar Black Hole Mass Functions

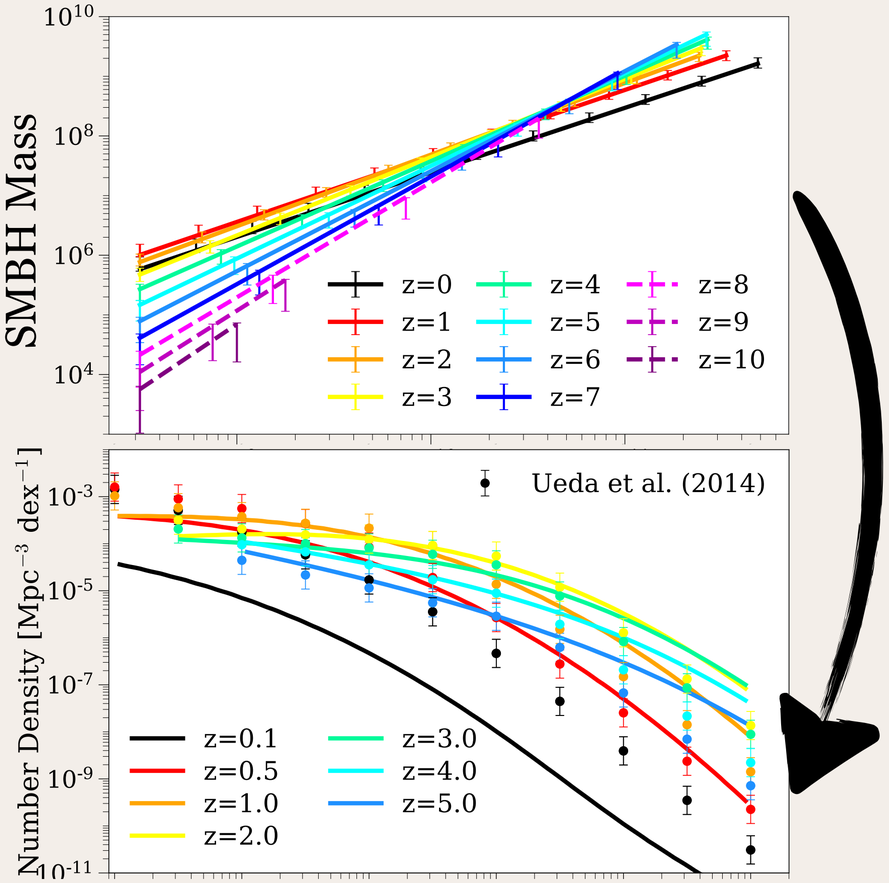


z=0 BH mass—bulge Mass Relation



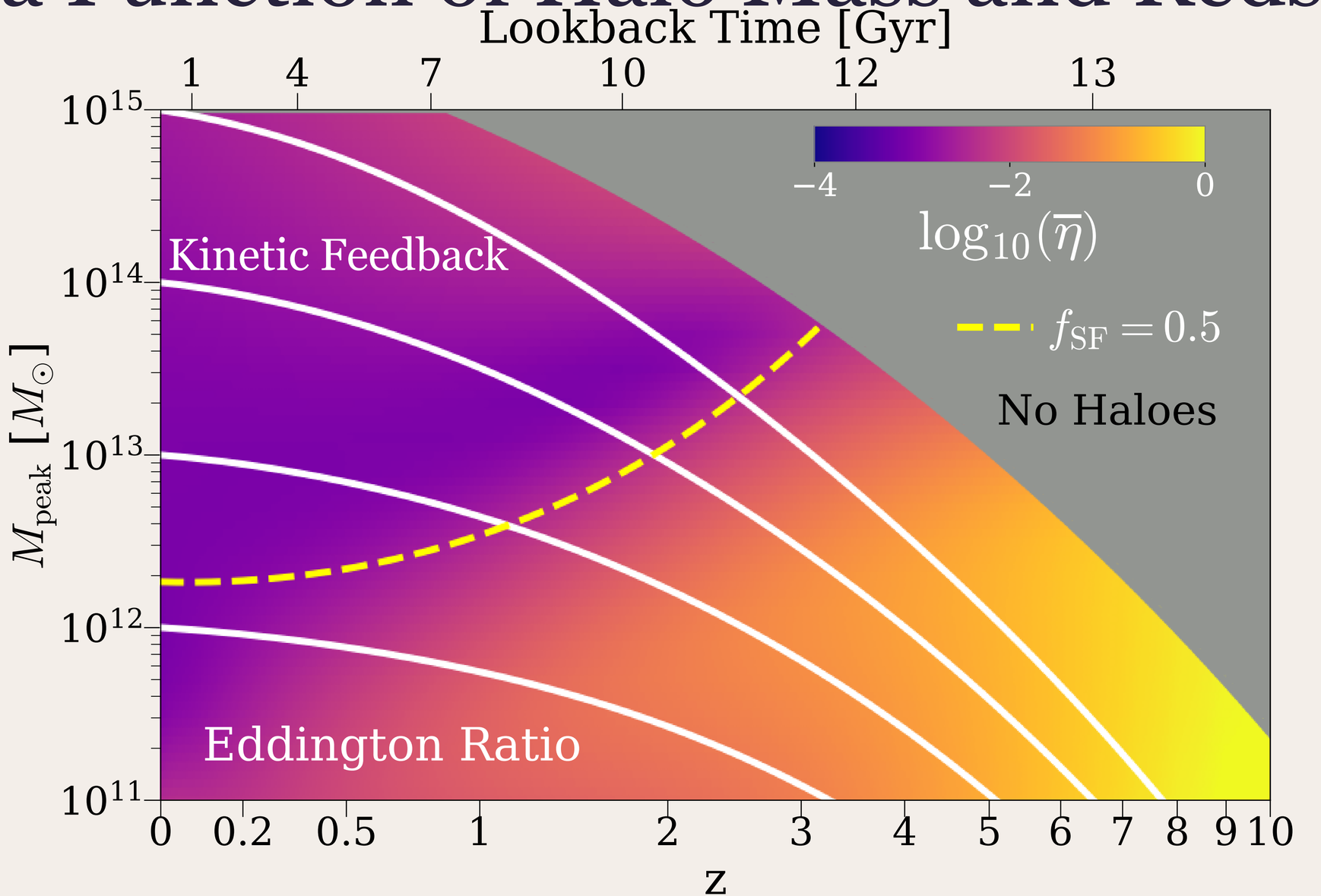
TRINITY Prediction: SMBH Mass—Galaxy Mass Relation





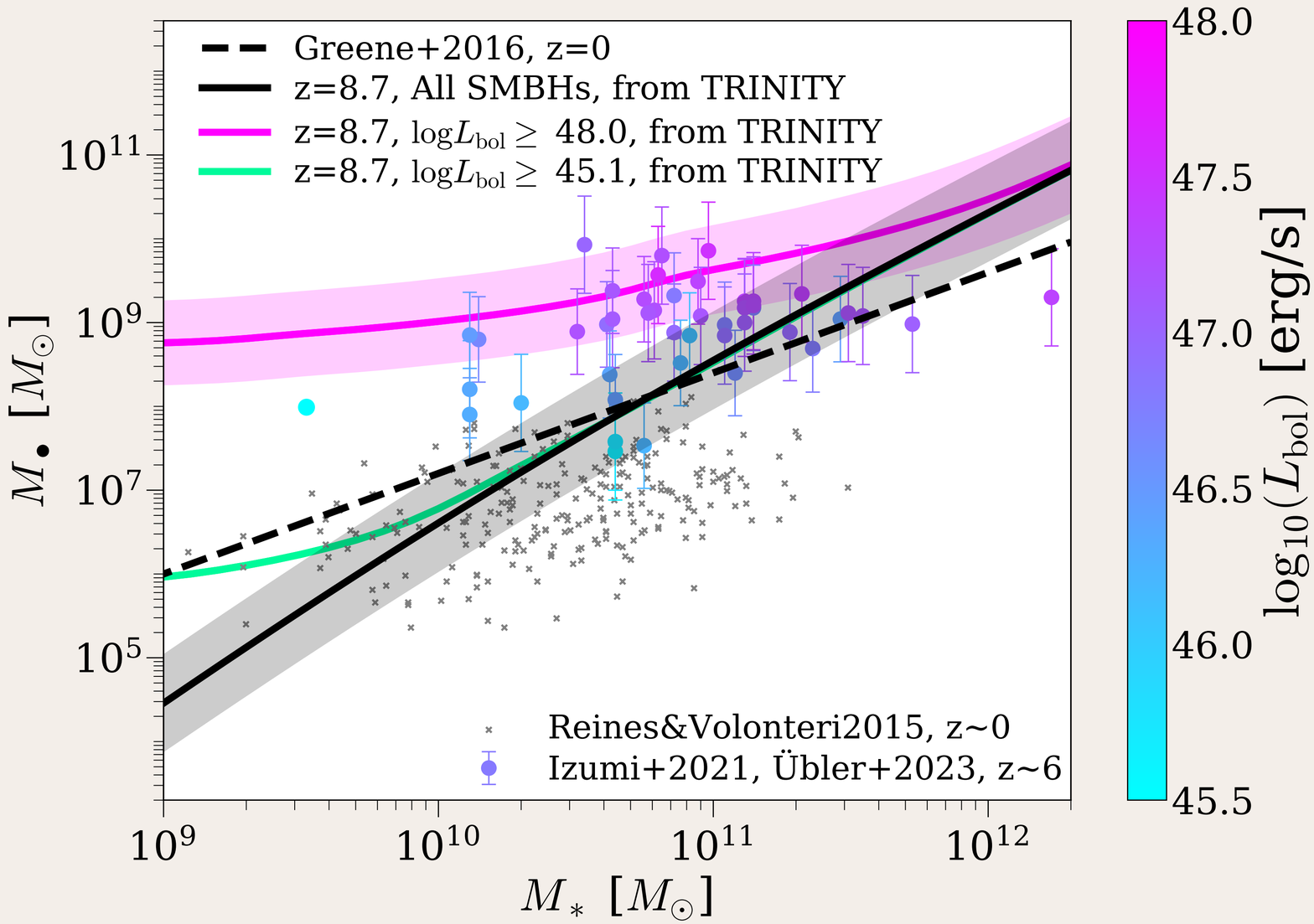
WRONG galaxy—SMBH relations *violate* data constraints, e.g., quasar luminosity functions

TRINITY Prediction: Average Eddington Ratio as a Function of Halo Mass and Redshift

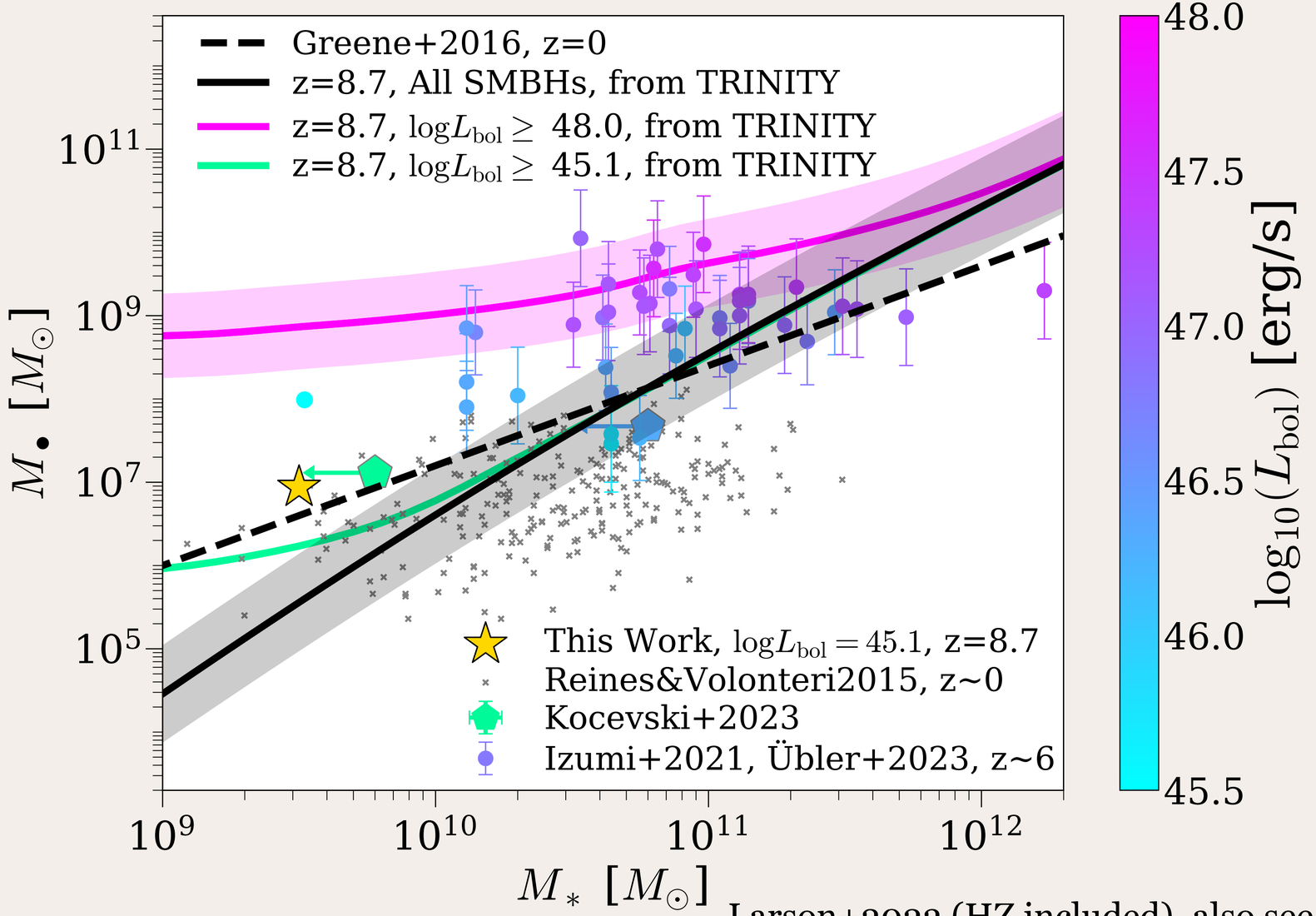


Zhang+2023a

TRINITY: Luminosity-dependent Bias in the $M_\bullet - M_*$ relation for quasars

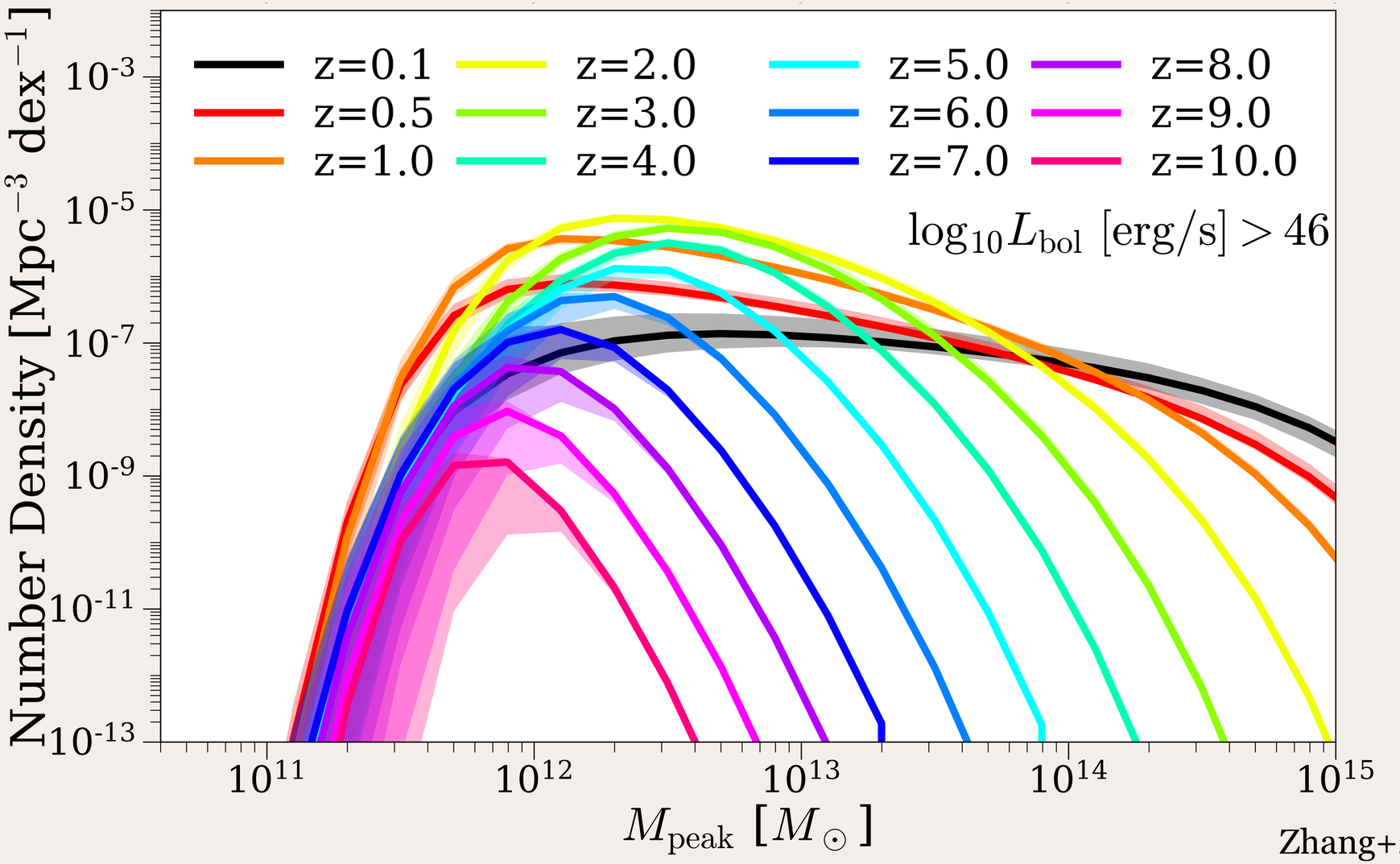


TRINITY: Luminosity-dependent Bias in the $M_\bullet - M_*$ relation for quasars



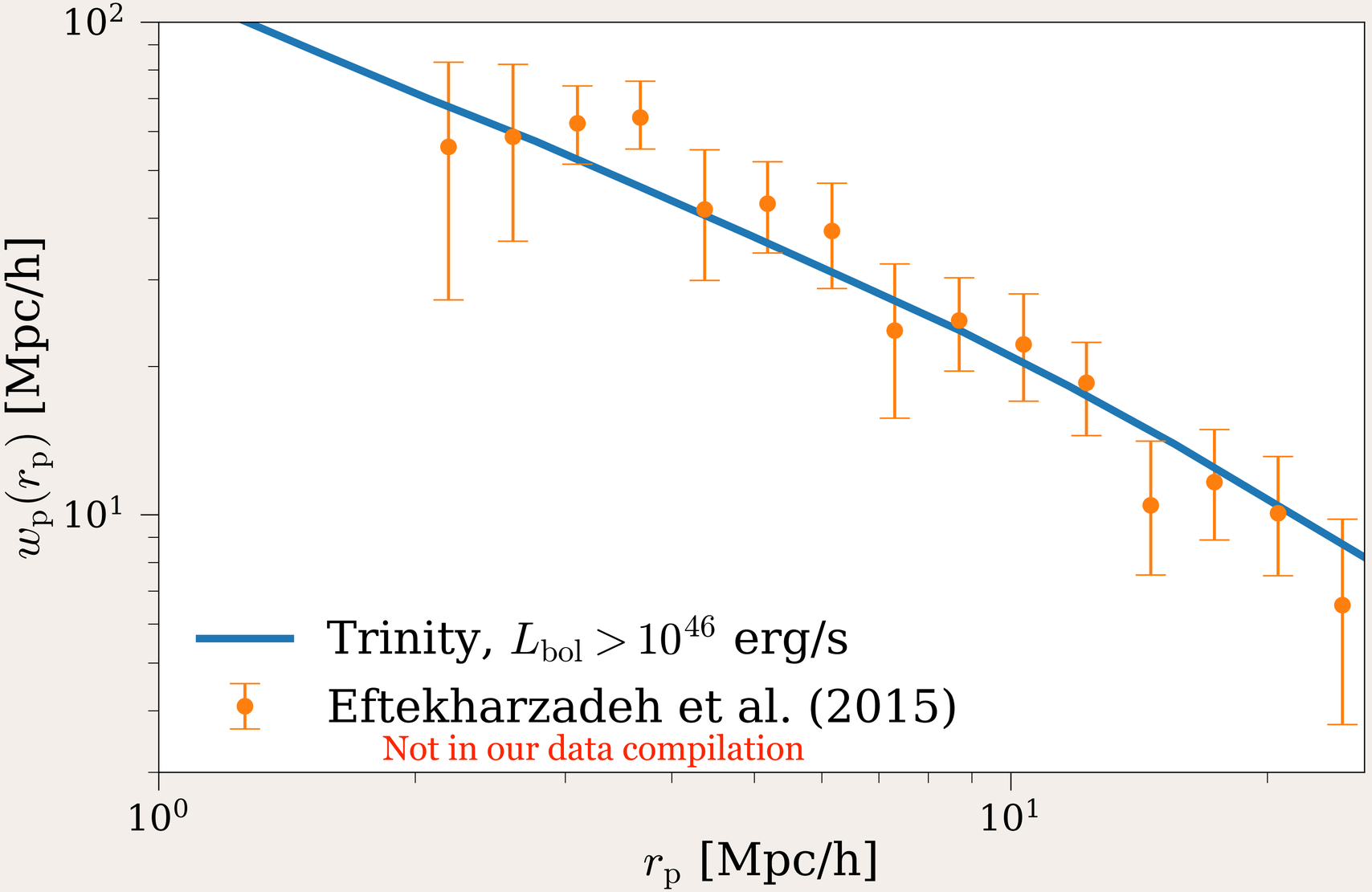
Larson+2023 (HZ included), also see Zhang+2023b, submitted

TRINITY: Quasar Host Halo Mass Functions from $0 < z < 10$



Zhang+2023c, in prep.

TRINITY Prediction: AGN Clustering



Oddisey Knox
(Undergraduate@UofA)

Knox, Zhang & Behroozi 2023 in prep.

Summary

- TRINITY: Flexible, data-driven empirical model connecting halos, galaxies, and SMBHs for z=0-10
- Main Results:
  - SMBH mass—galaxy mass relation from z=0-10: Not much evolution;
  - High-z quasars are biased samples to study the high-z SMBH mass—galaxy mass relation;
  - Quasar host halo mass functions from z=0-10: peak around 10^12 Msun;
- Future Plans: Trinity's predictions on gravitational waves, high-z quasar environments, and tidal disruption events around AGNs