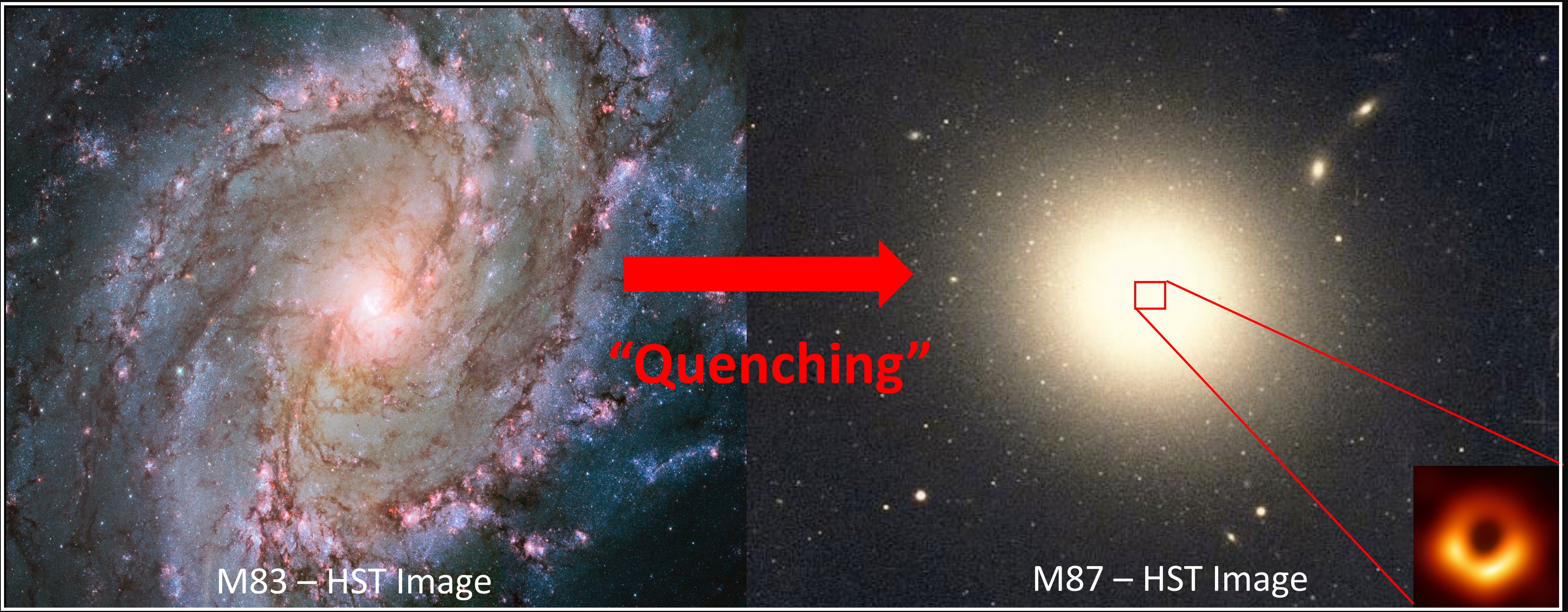
Galaxy Quenching at the High Redshift Frontier:

Evidence for AGN Feedback Quenching Galaxies in the first 1 – 3 Gyrs



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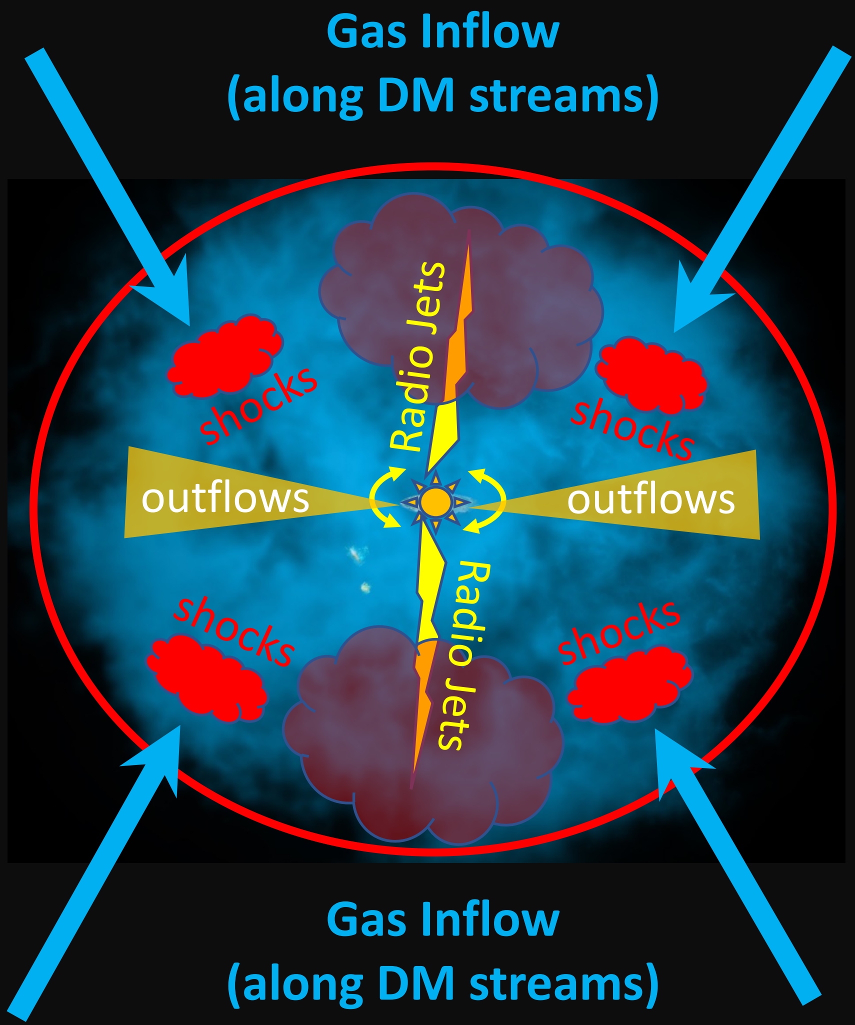
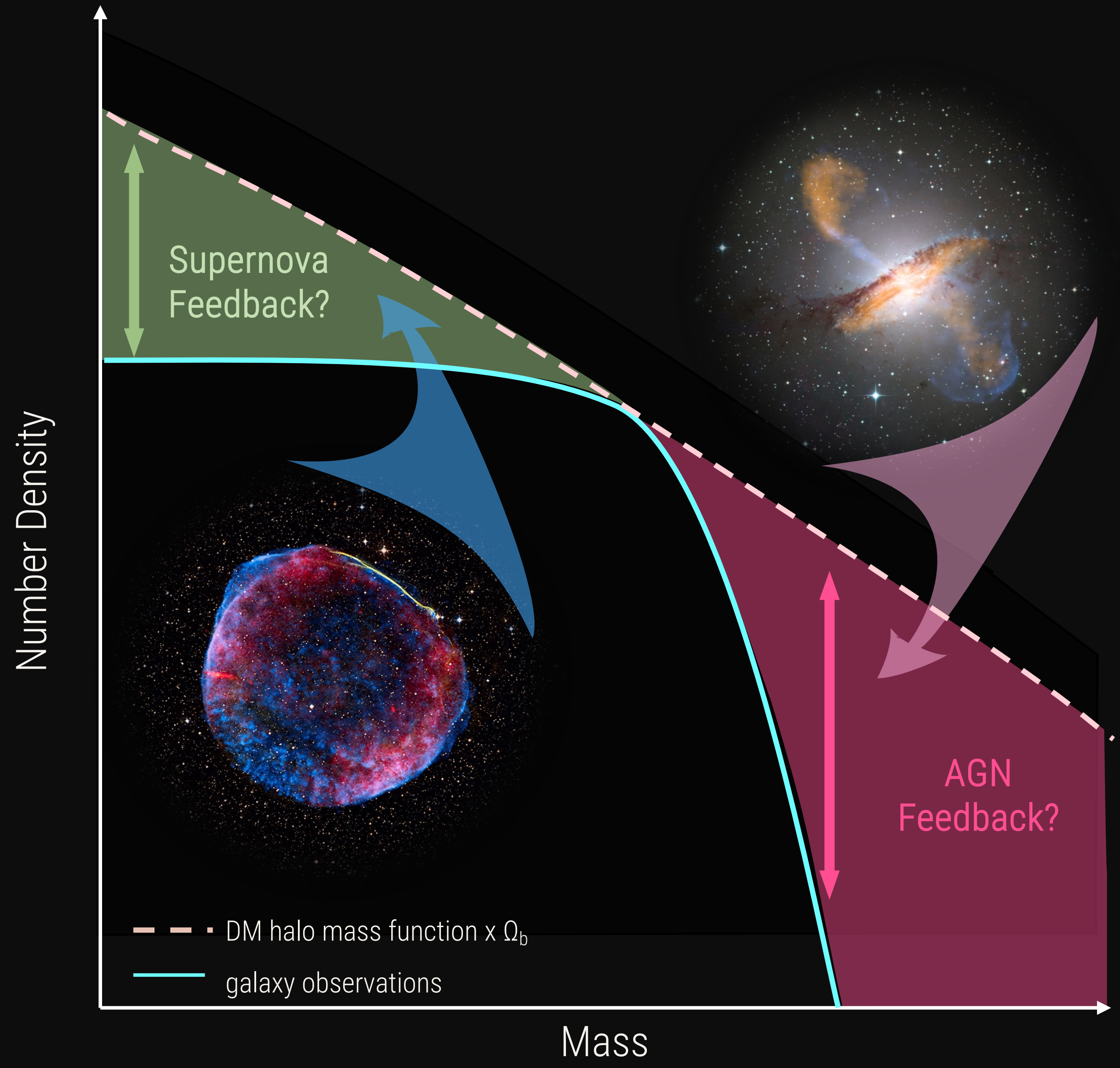
Collaborators: Joanna (Asia) Piotrowska; Paul Goubert; Simcha Brownson; Christopher J. Conselice; Roberto Maiolino; et al.

The Big Theoretical Problem





Only ~5-10% of baryons reside in Stars

Up to ~90% of baryons are in ionized hot (~$10^{7.5}$ K) halo

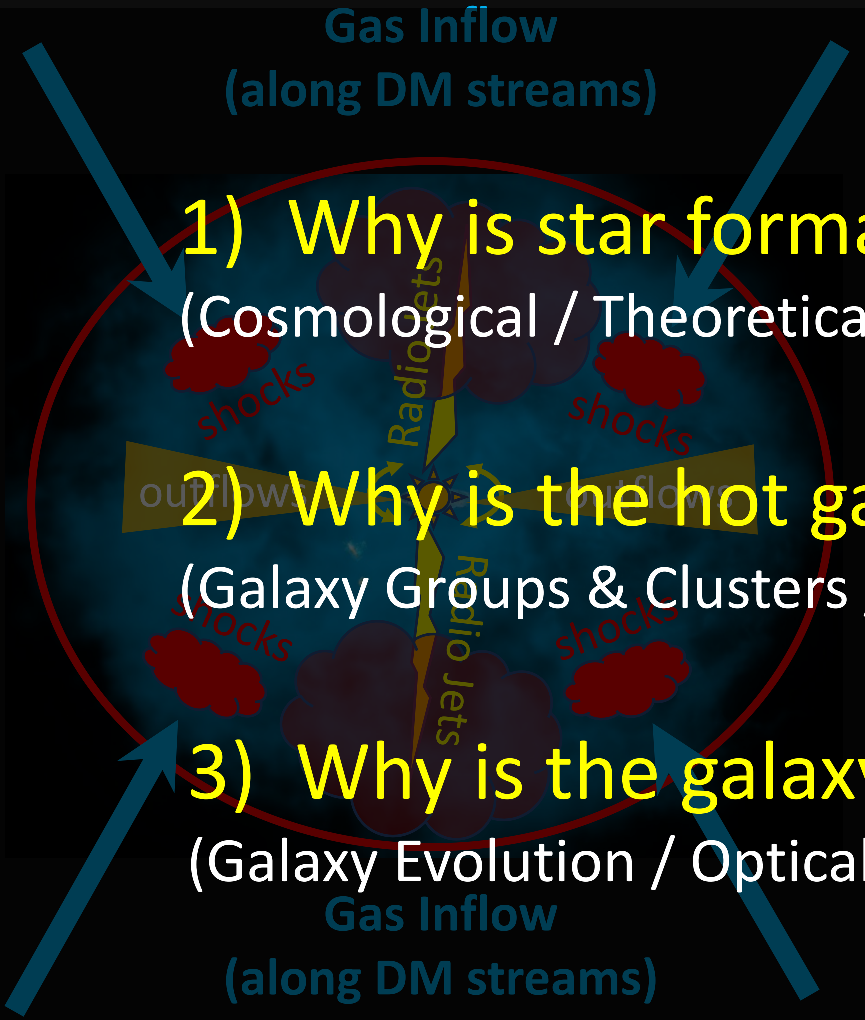
→ How is this system stable for *billions* of years?

The Big Theoretical Problem

1) Why is star formation so inefficient?
(Cosmological / Theoretical Perspective)

2) Why is the hot gas halo stable to cooling & collapse?
(Galaxy Groups & Clusters / X-ray & Radio Perspective)

3) Why is the galaxy population bimodal?
(Galaxy Evolution / Optical – NIR Perspective)



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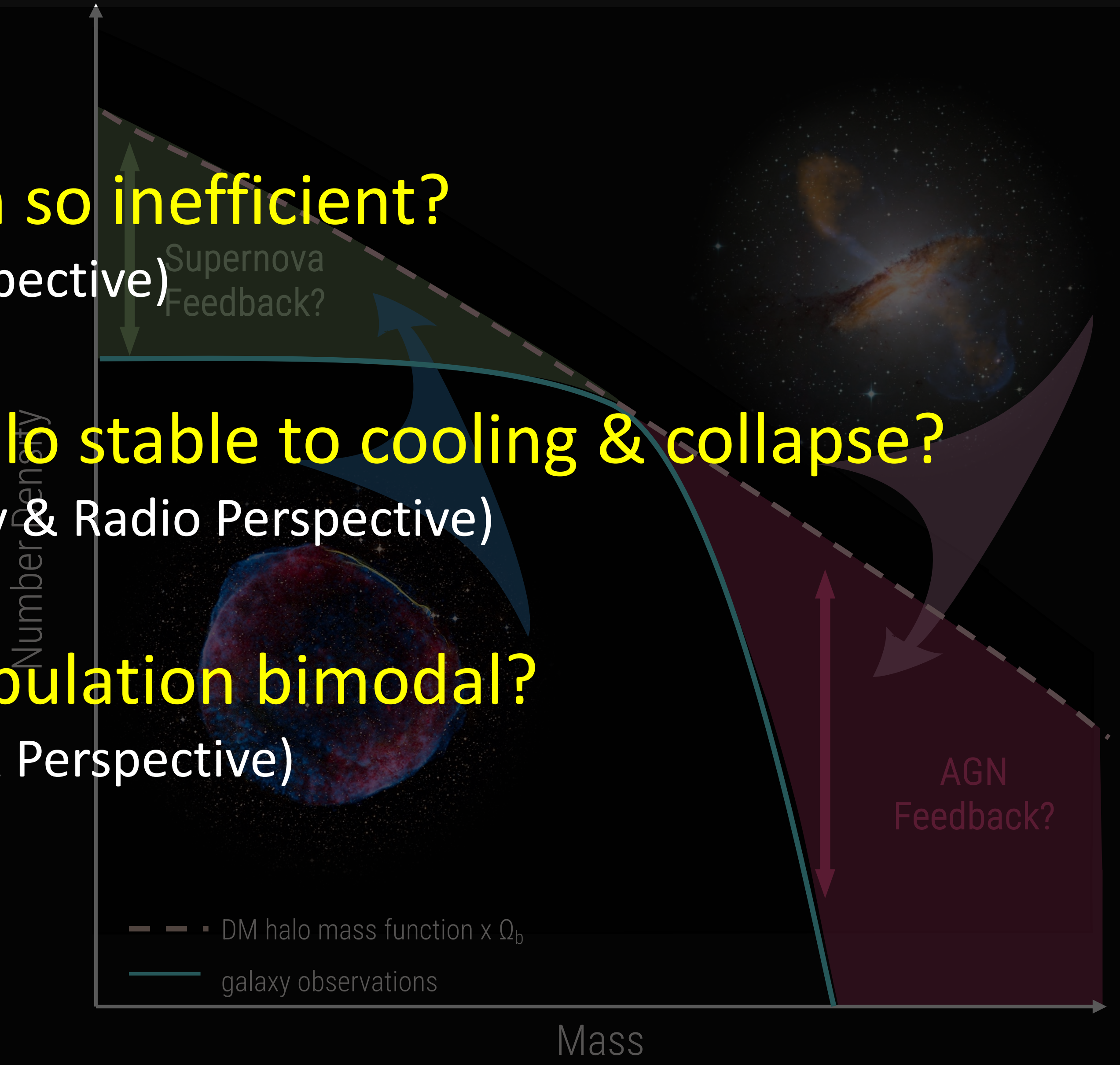
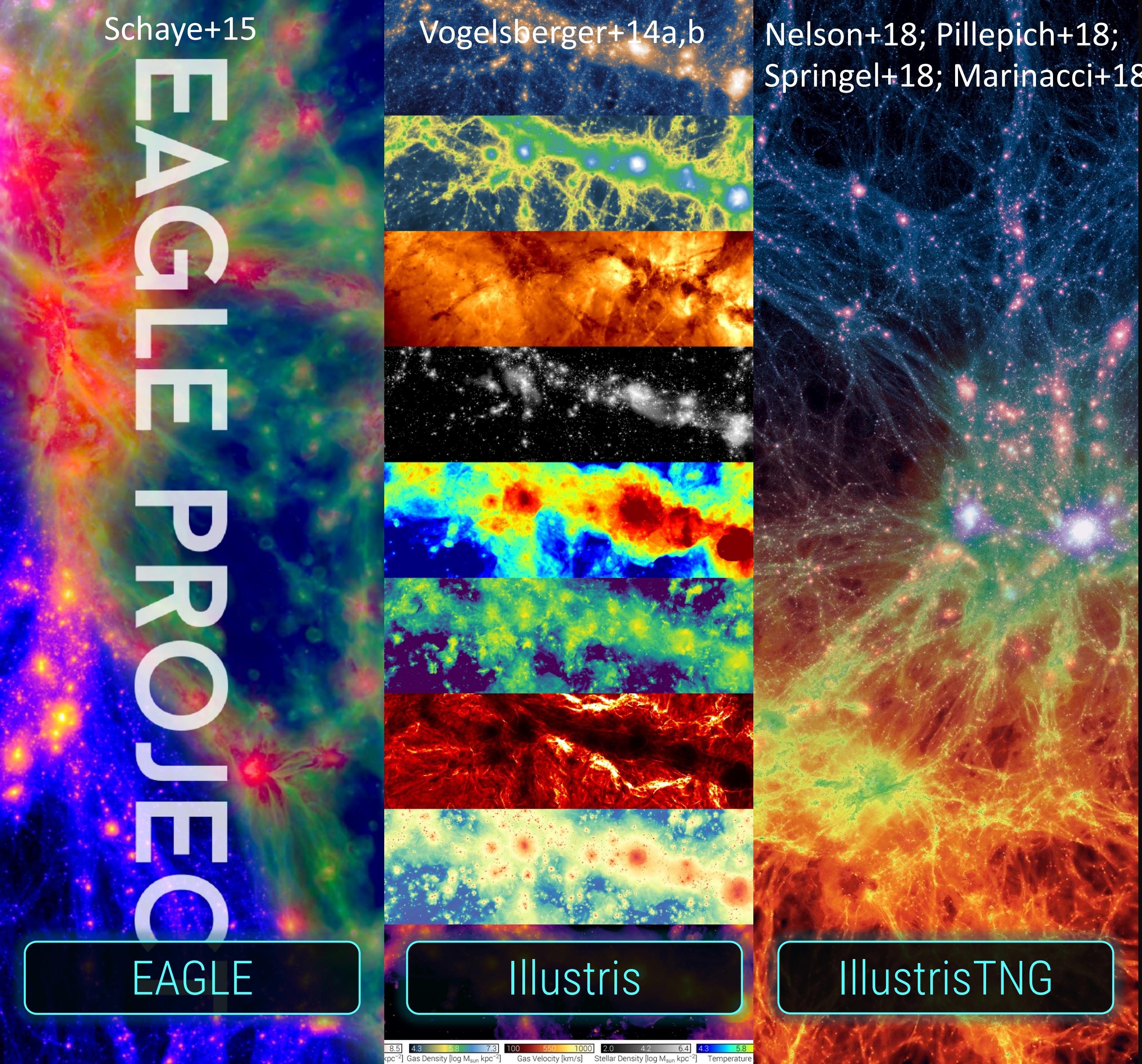
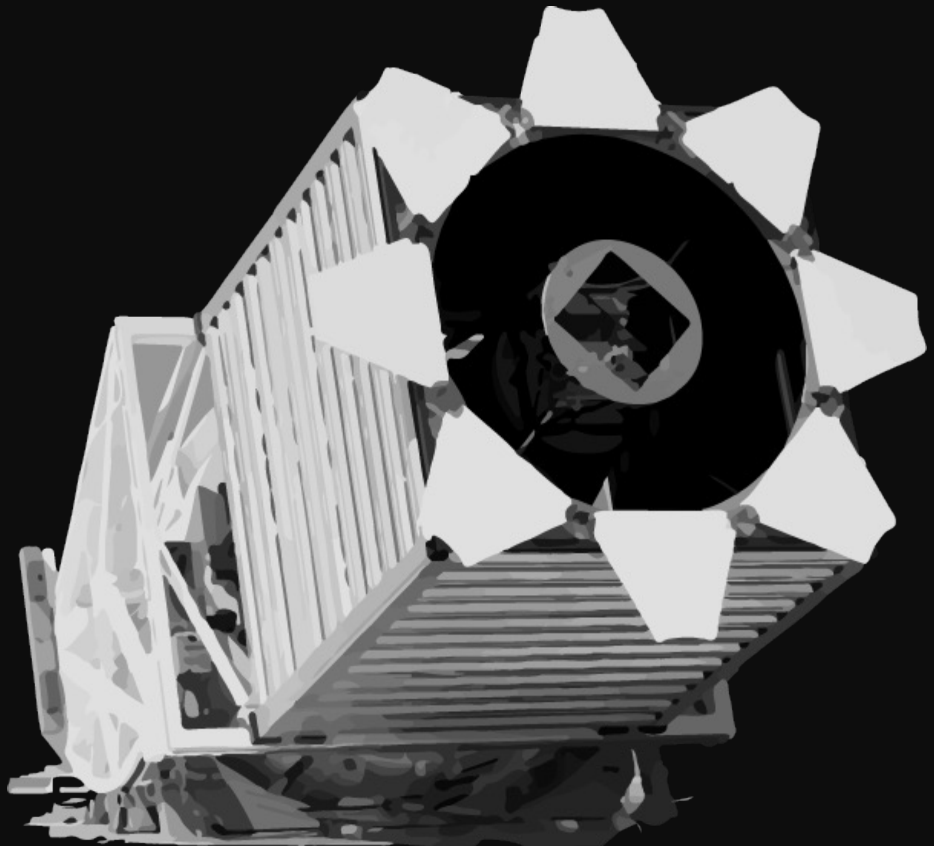
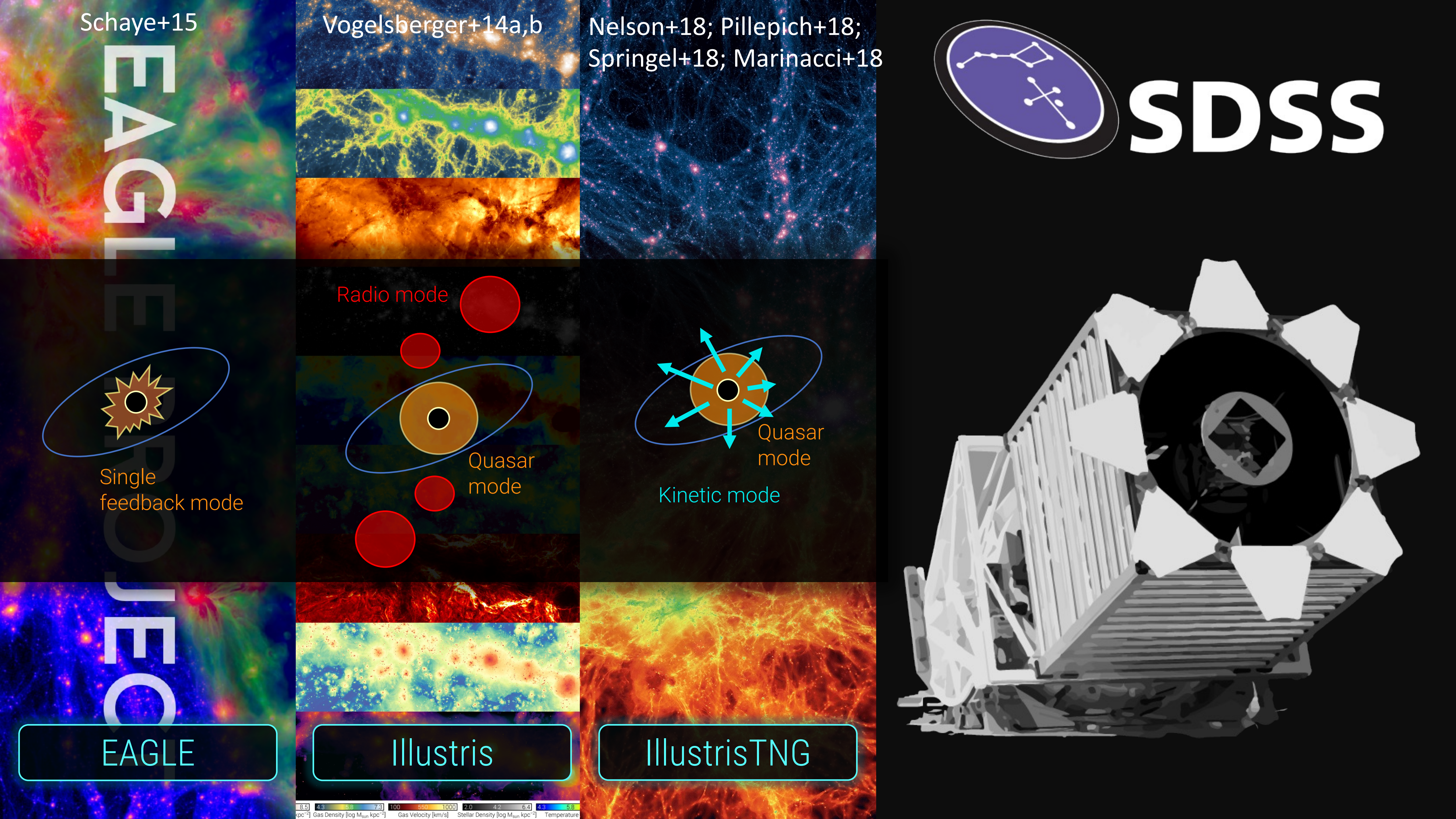



Schaye+15
EAGLE PROJEC
EAGLE
Vogelsberger+14a,b
Illustris
Gas Density [log M$_{sun}$ kpc^{-2}]
Gas Velocity [km/s]
Stellar Density [log M$_{sun}$ kpc^{-2}]
Temperature
Nelson+18; Pillepich+18;
Springel+18; Marinacci+18
IllustrisTNG

SDSS




Schaye+15
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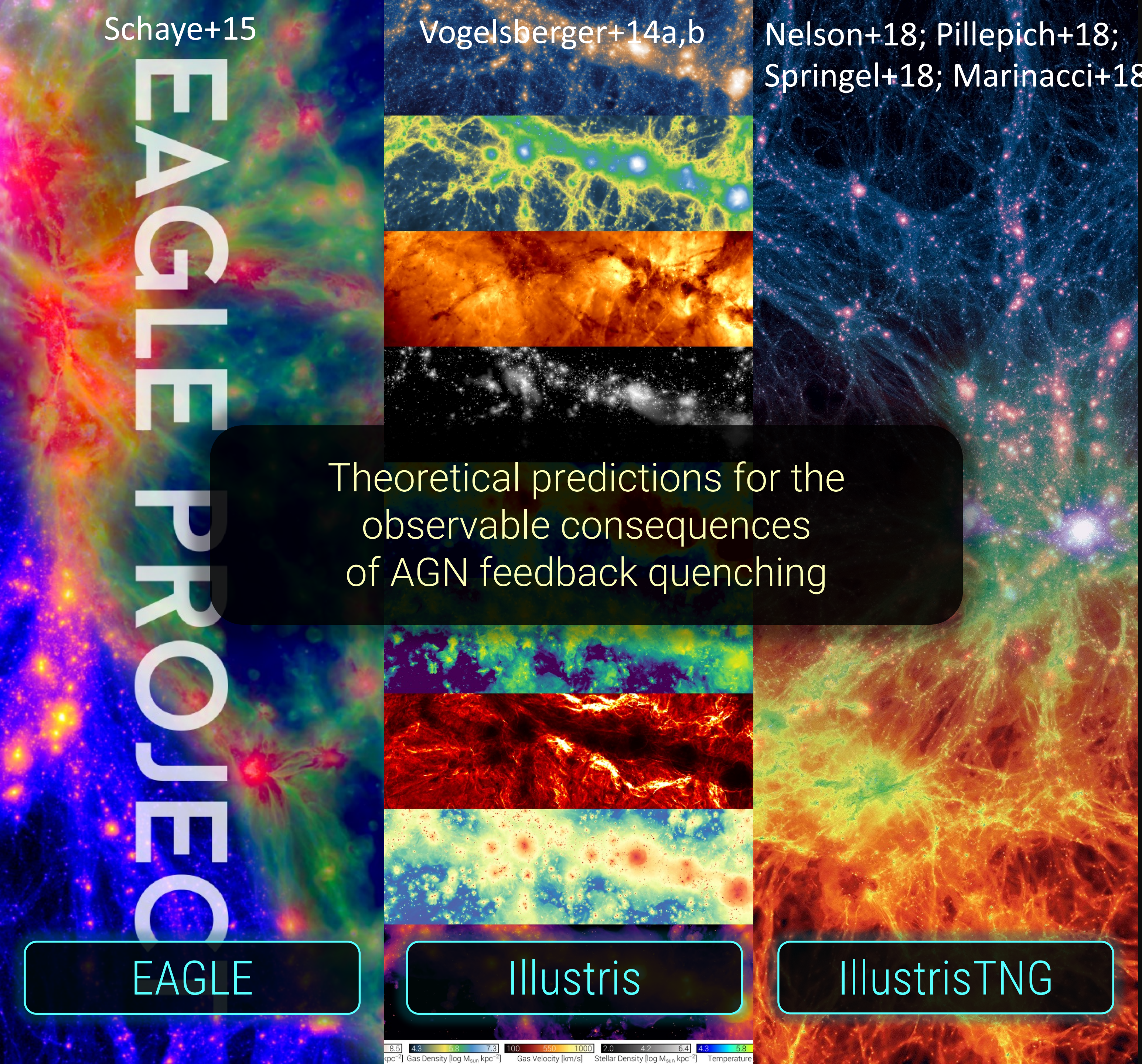
SDSS
Radio mode
Single
feedback mode
Quasar
mode
Quasar
mode
Kinetic mode
EAGLE
Illustris
IllustrisTNG



SDSS

Sloan Digital Sky Survey: ~650k Galaxy Spectra @ z = 0.02 – 0.2 (York+2000; Abazajian+09)

- Stellar masses (Kauffmann+03)
- SFRs (Brinchmann+04)
- Emission line fluxes

MPA-JHU release of spectrum measurements

- Morphological parameters (Simard+11, Mendel+14)
- Halo masses & central/satellite classification (Yang+07 group catalogues)
- Velocity dispersions (Blanton+05)

Energy injected by Supermassive Black Holes ($E_{AGN} \sim M_{BH}$)

Heating by Virial Shocks ($E_{Shocks} \sim M_{Halo}$)

Supernova Explosions ($E_{SN} \sim M_*$)

A Classic ML Classification Problem

M_{Stars}

M_{Halo}

M_{BH}

See Bluck+22

Quenched

Star-forming

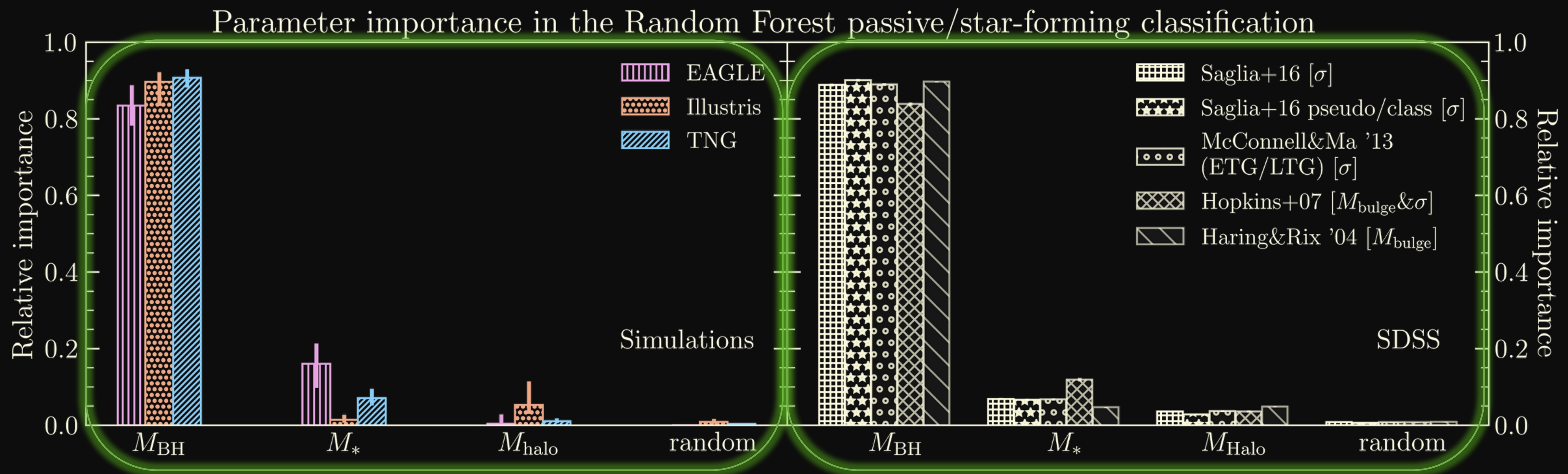
Ranking of Parameter Importance to Quenching

Not a black box!

Stellar Masses:	SED Fitting
Halo Masses:	Abundance Matching
Black Hole Mases:	Dynamics (~100)
	Calibrations (~500k)

$$I_R(k) = \frac{1}{N_{\text{trees}}} \sum_{\text{trees}} \left\{ \frac{\Sigma_{nk} N(n_k) \Delta G(n_k)}{\Sigma_n N(n) \Delta G(n)} \right\}$$

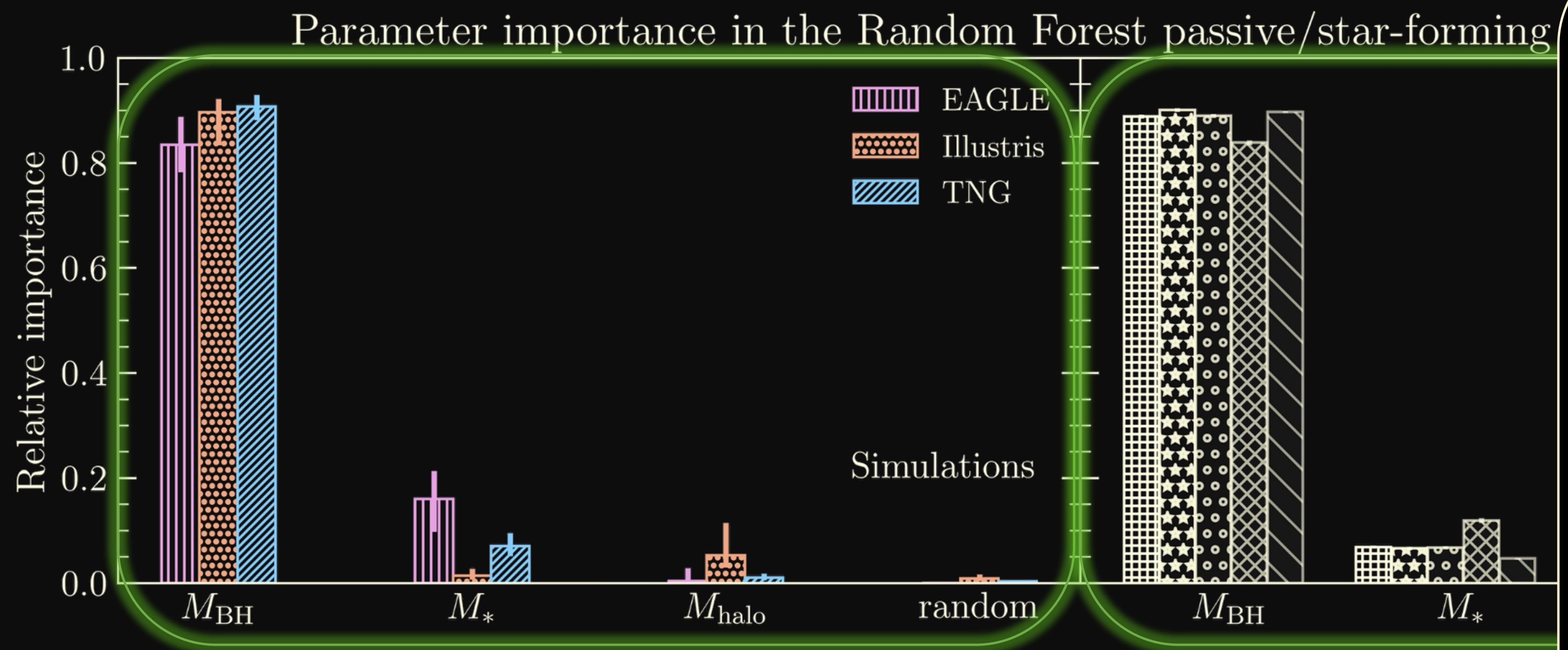
Black Hole Mass is the most important parameter for classifying galaxies into star forming & quenched types

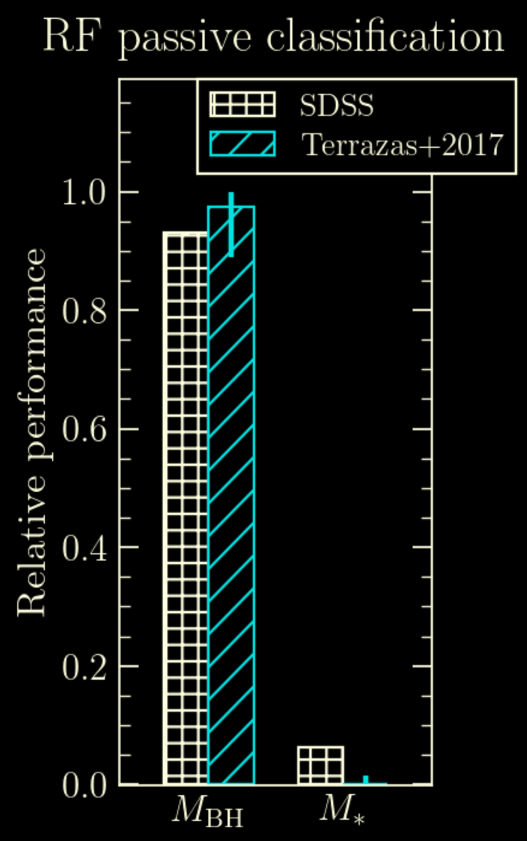


- In simulations this is true regardless of the implemented AGN feedback model
- In observations the result is robust to different choices of M_{BH} calibration

Piotrowska, Bluck+2022
arXiv:2112.07672

Black Hole Mass is the most important parameter for classifying galaxies into star forming & quenched types





Dynamically measured M_{BH} form Terrazas+2017 central galaxy sample

- In simulations this is true regardless of the implemented AGN feedback model
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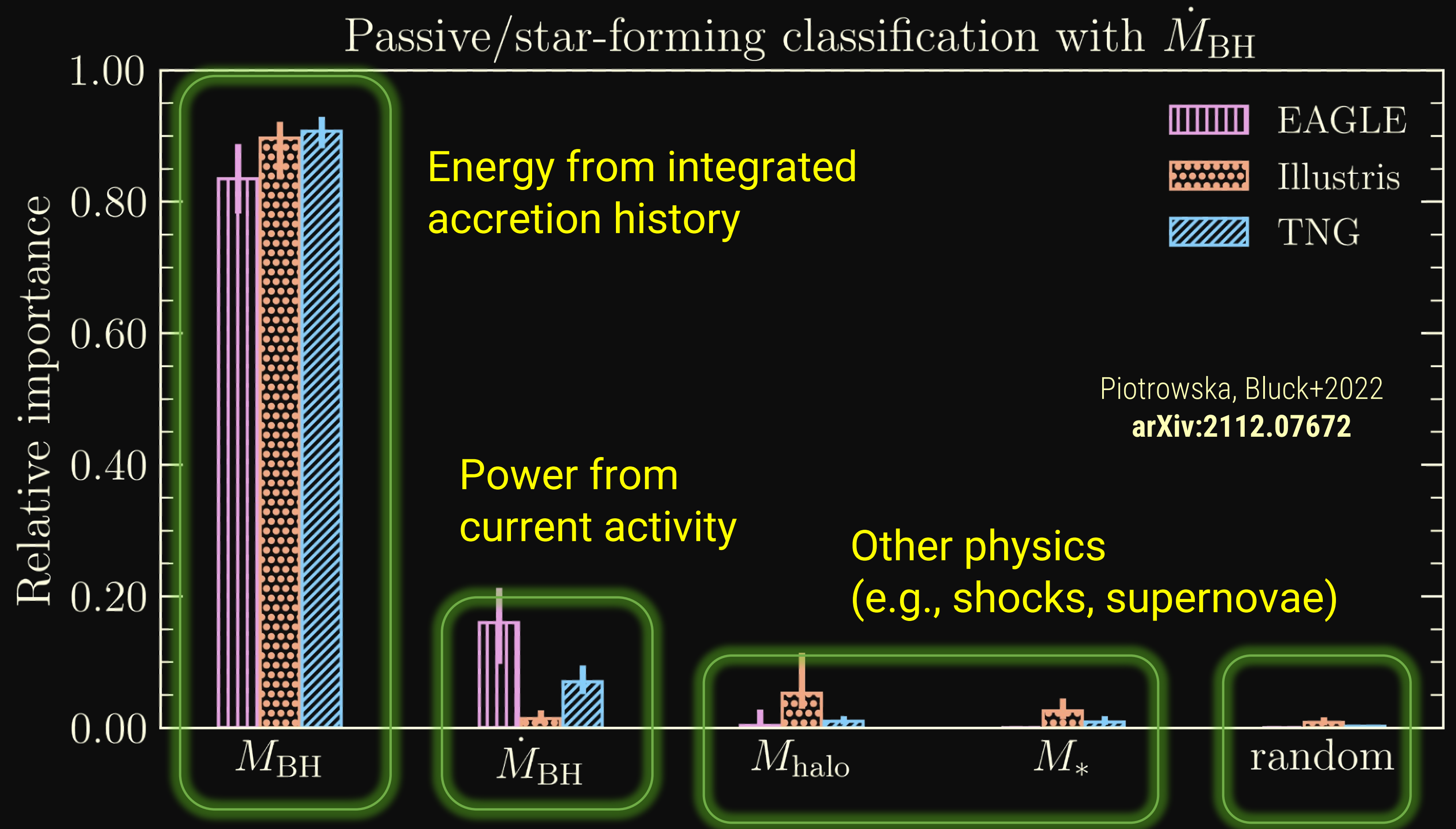
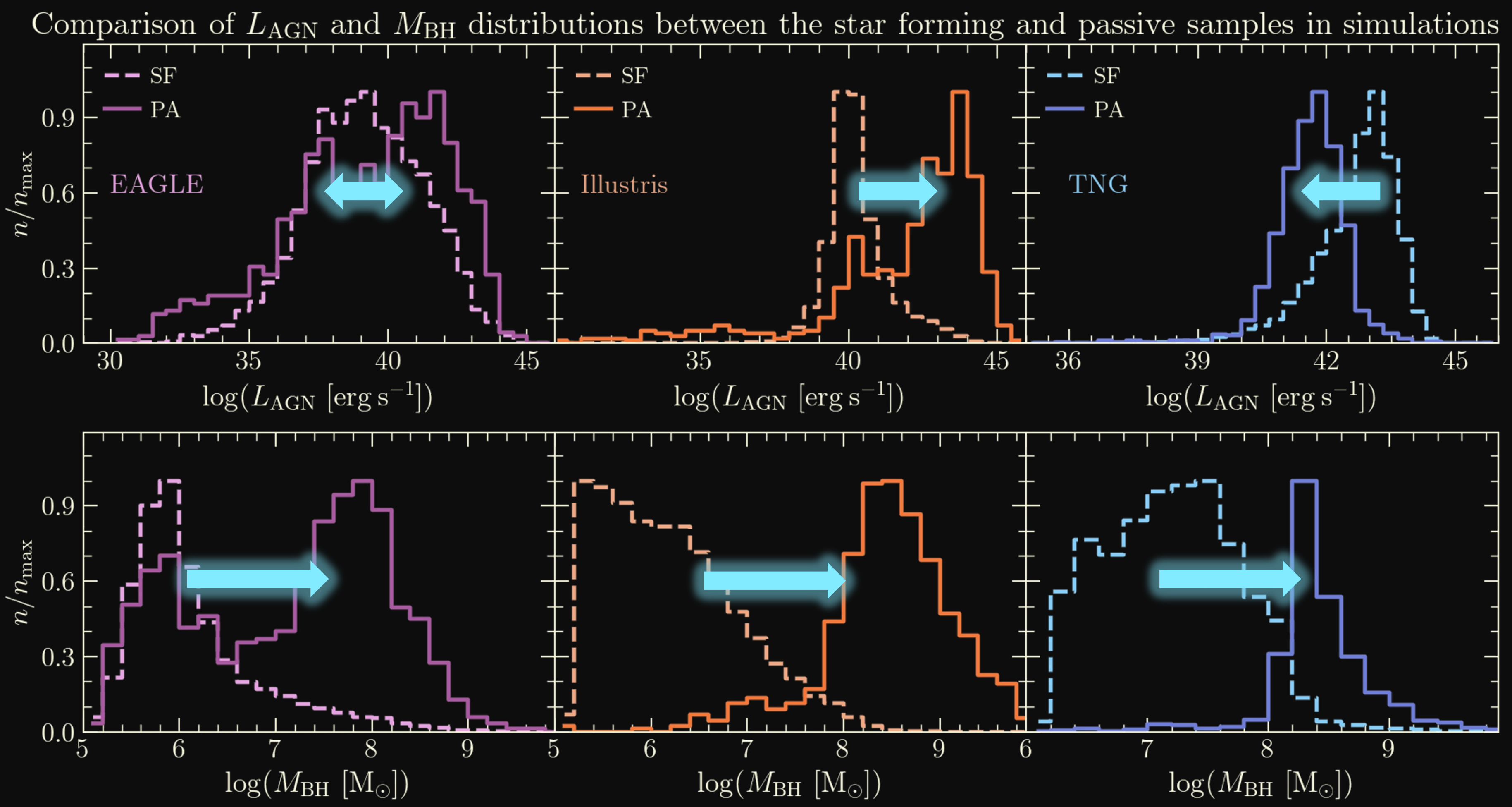
The importance of AGN luminosity is dwarfed by that of supermassive black hole mass



The importance of AGN luminosity is dwarfed by that of supermassive black hole mass

Power:

Energy:



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Entering the Space Age: The High-z Frontier

JWST-CEERS

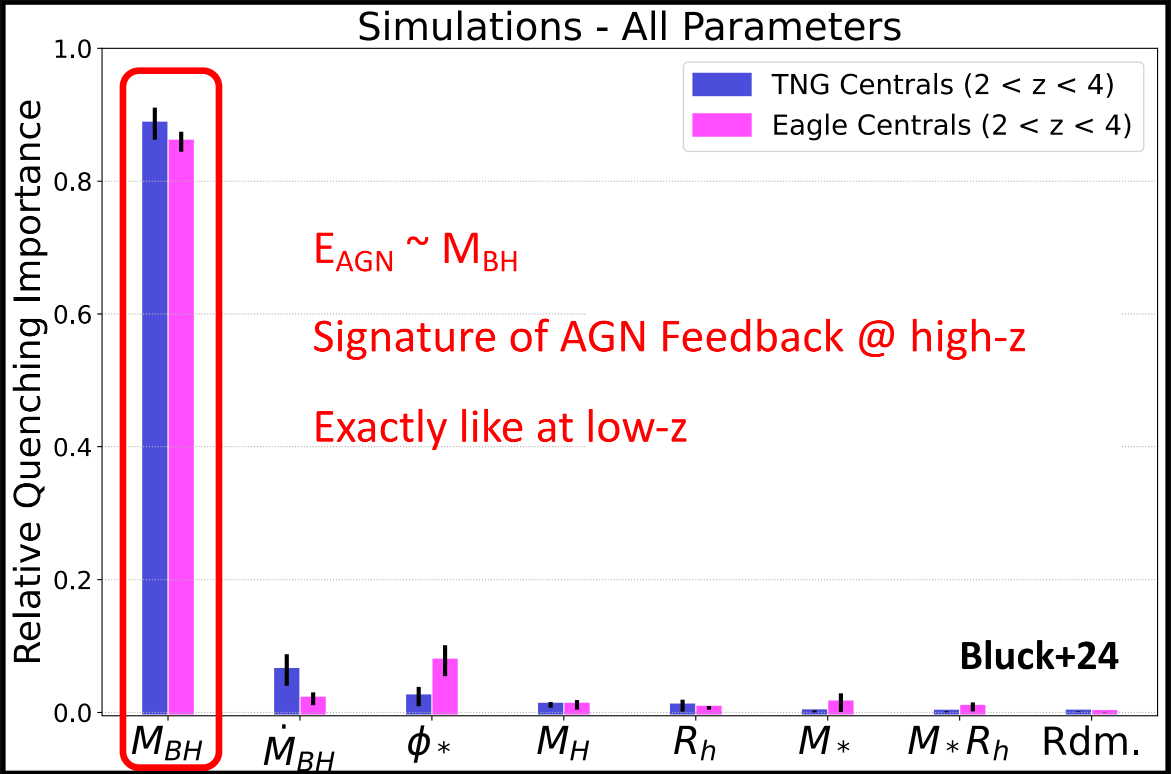
- 100 sq arcmin observations within HST EGS legacy field
- Observations with NIRCam, MIRI, NIRSpec
- This Project: NIRCam Photometry
- Data Papers: Finkelstein+23a,b; Bagley+23; Kartaltepe+23; Kokevski+23; et al.
- Ancillary Data: Duncan+18 (SED fitting); Ormerod+24 (morphologies)

HST-CANDELS

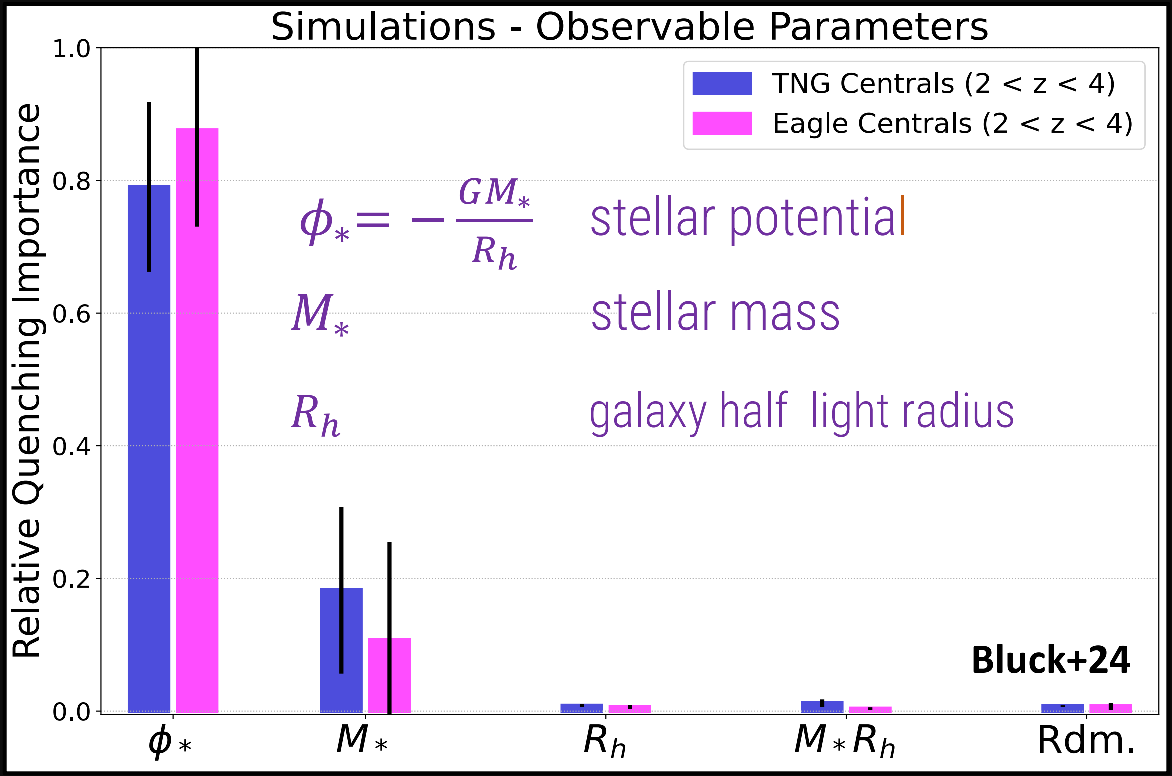
- 720 sq arcmin observations within COSMOS, GOODS, UDS & EGS fields
- Observations with WFC3 & ACS
- This Project: Full Dataset + Follow-up
- Data Papers: Faber+11; Grogin+11; Koekemoer+11; et al.
- Ancillary Data: Dimauro+18 (morphologies & SED fitting)

Star Formation Quenching in JWST-CEERS: Simulations Predictions

Theoretical Perspective



Observational Perspective



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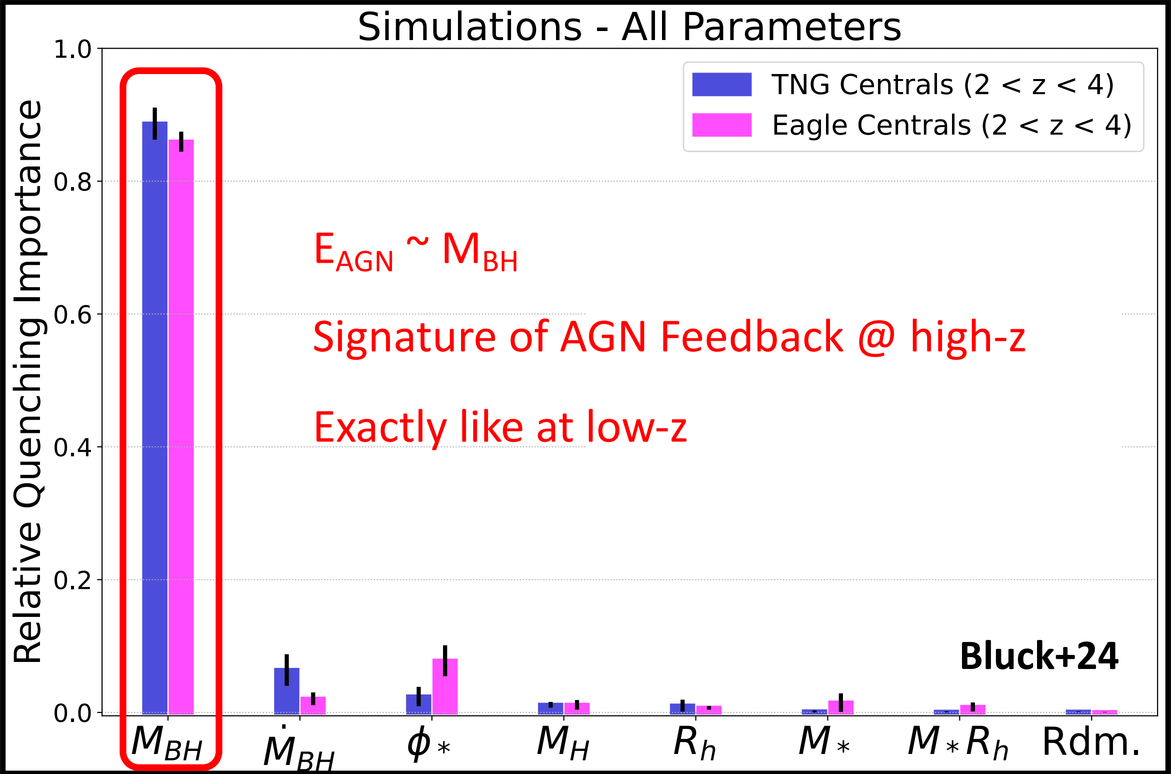
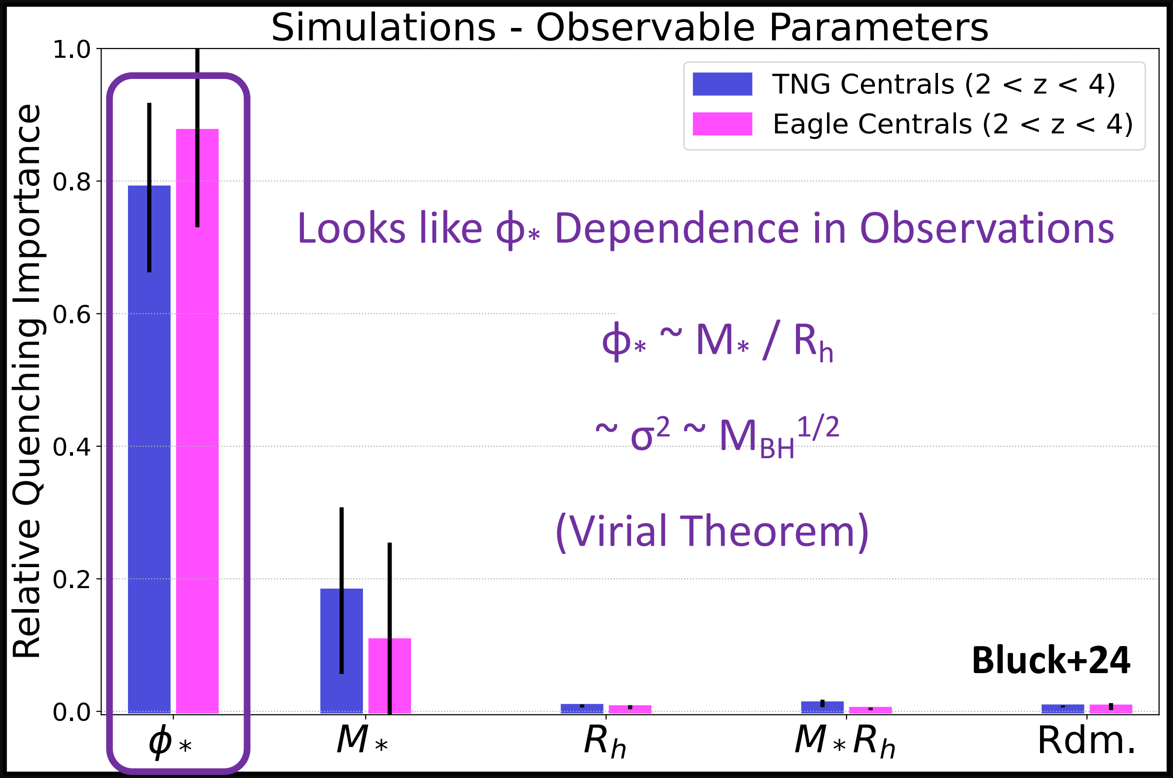


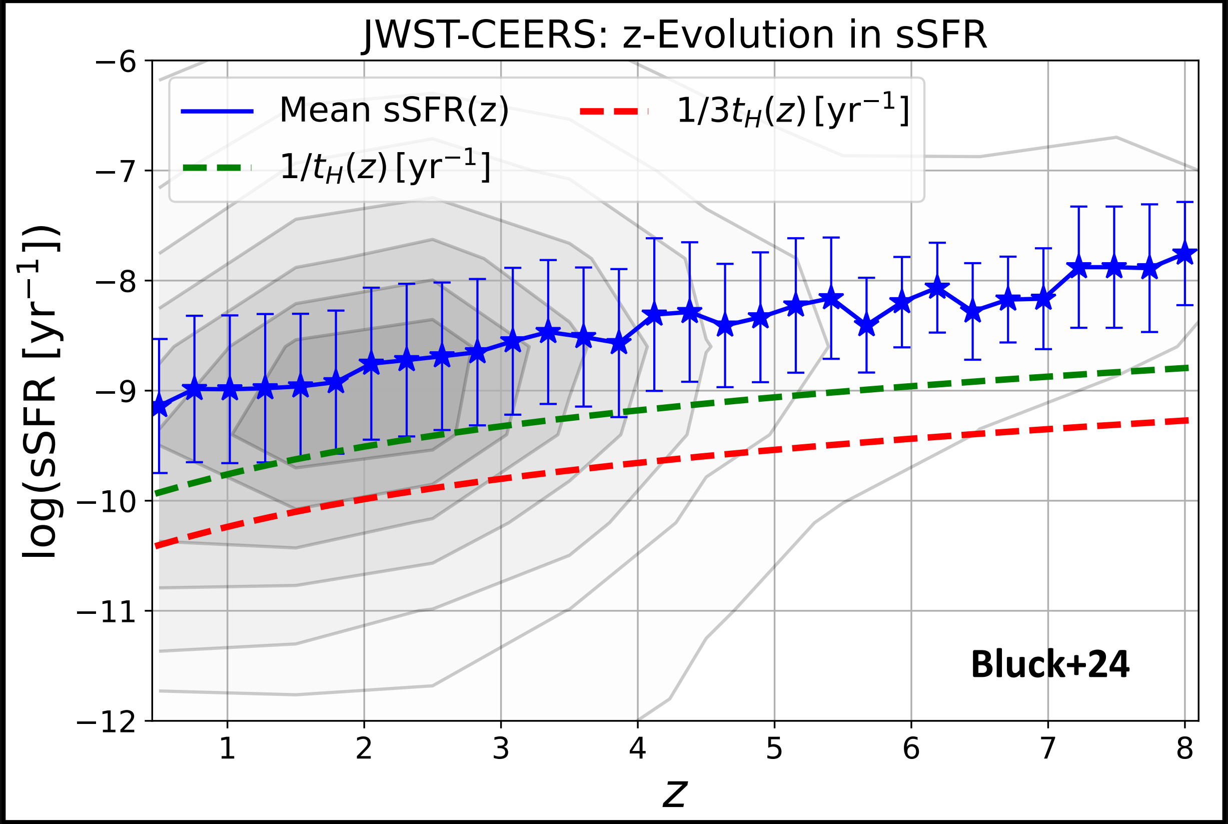
Observational Perspective



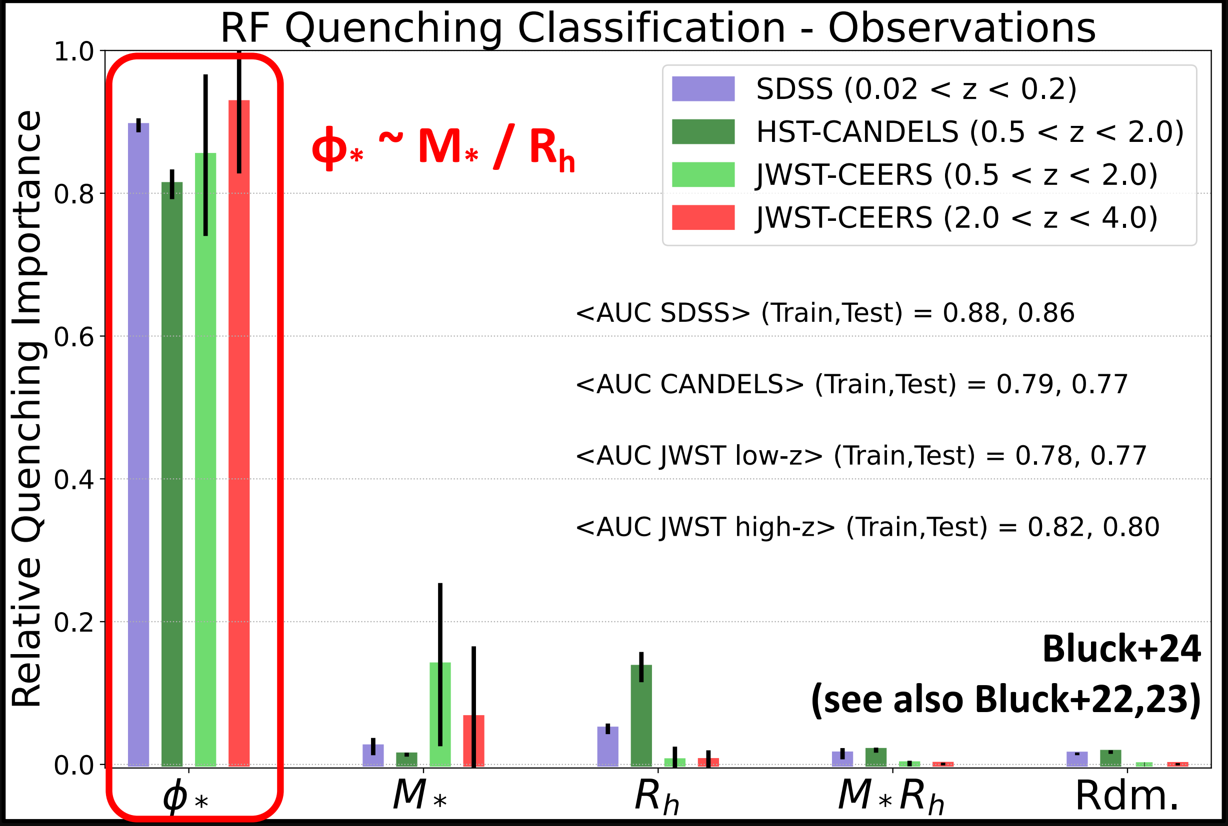
➔ Clear method for testing AGN feedback paradigm @ high-z in extant photometric observations.

Star Formation Quenching in JWST-CEERS: Observational Results

Defining Quiescence



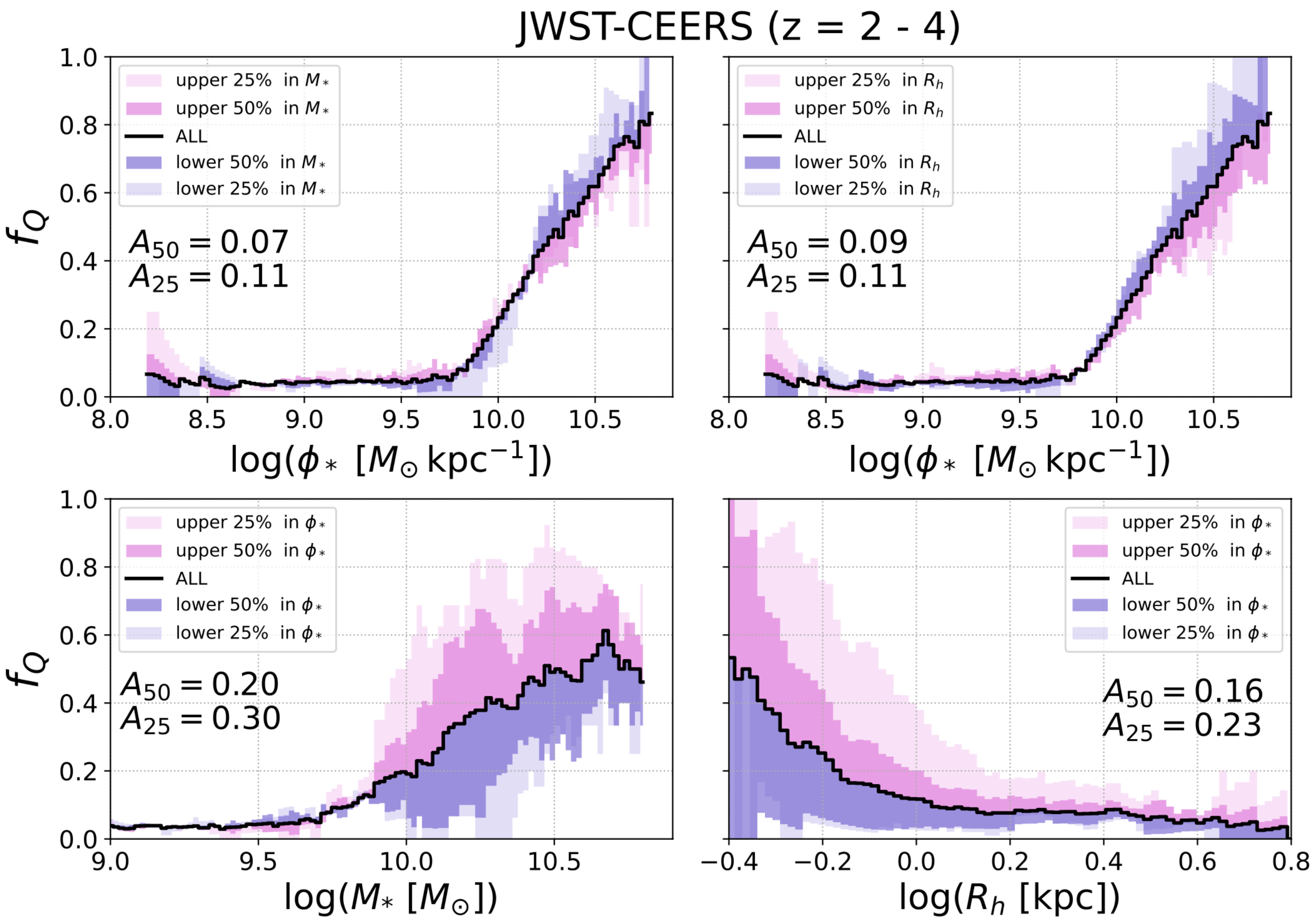
Observational Results



Stable quenching dependence on ϕ_* across 13 Gyrs of Cosmic History

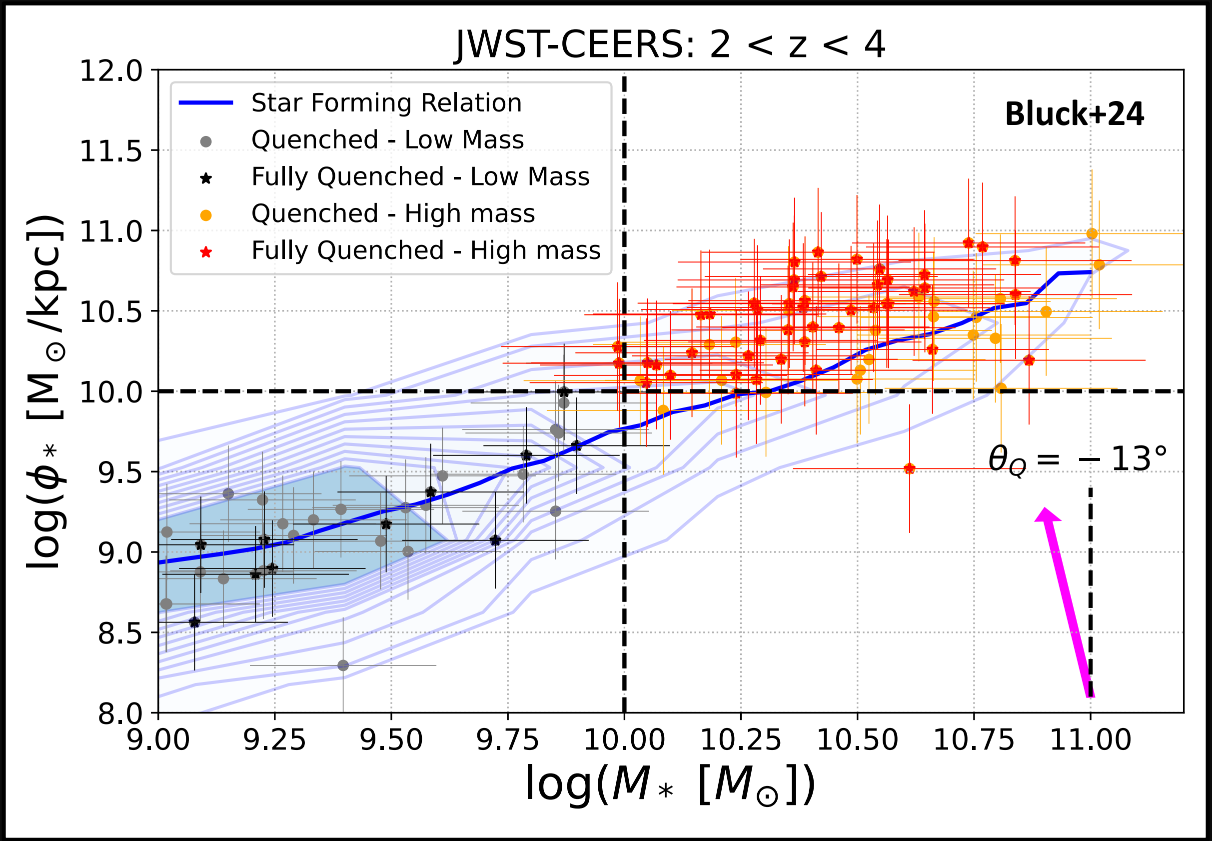
-> Expected result of AGN feedback driven quenching models!

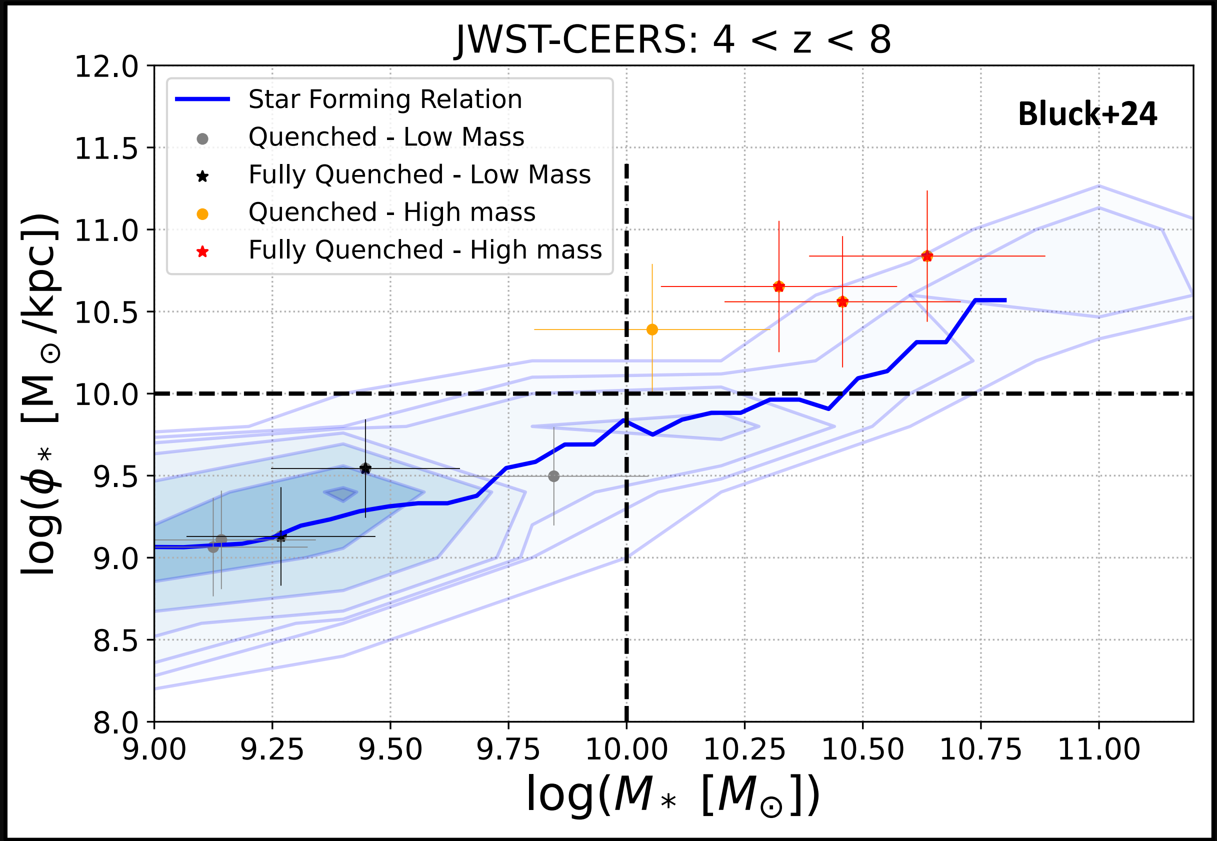
JWST Area Statistics Test @High-z



Bluck+24

Star Formation Quenching in JWST-CEERS: Observational Results



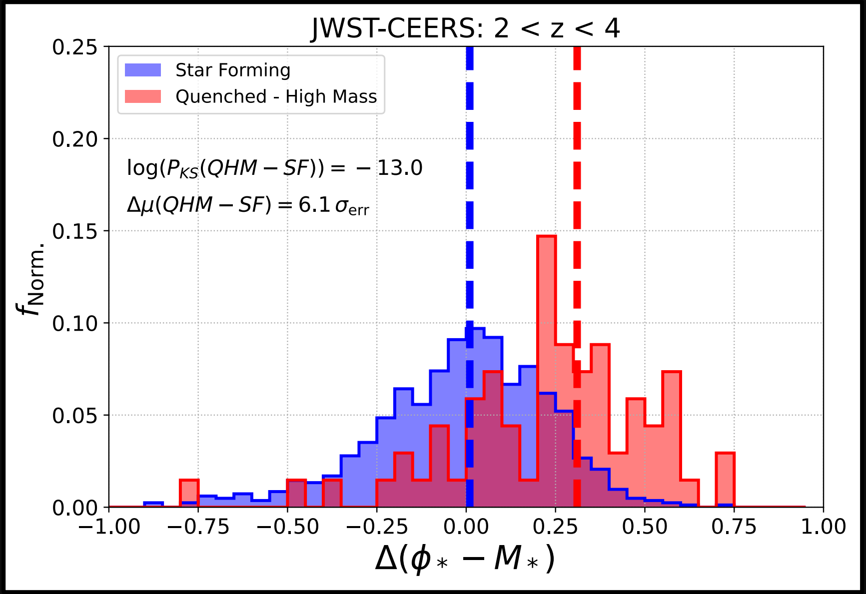


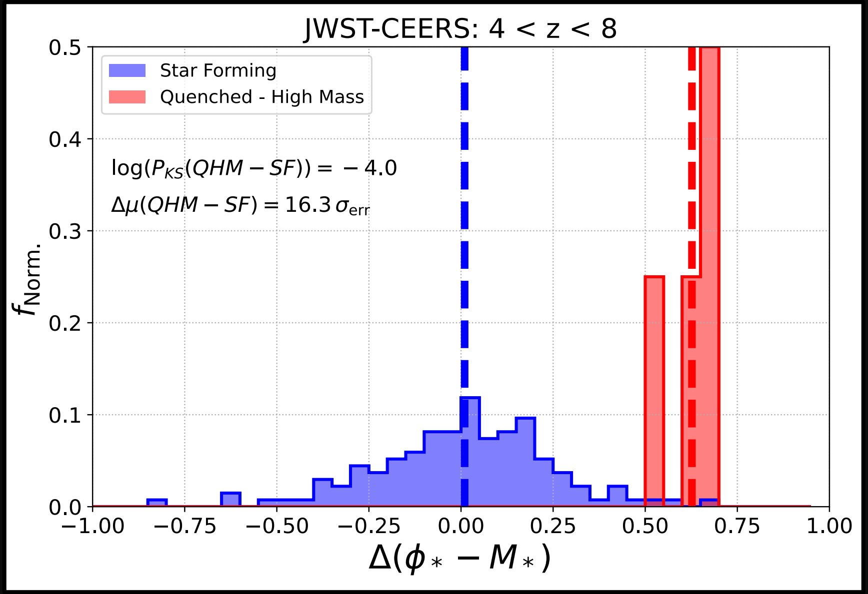
High mass quiescent galaxies have deeper central potentials than star forming galaxies *at a* *fixed stellar mass*

(precisely as predicted in simulations)

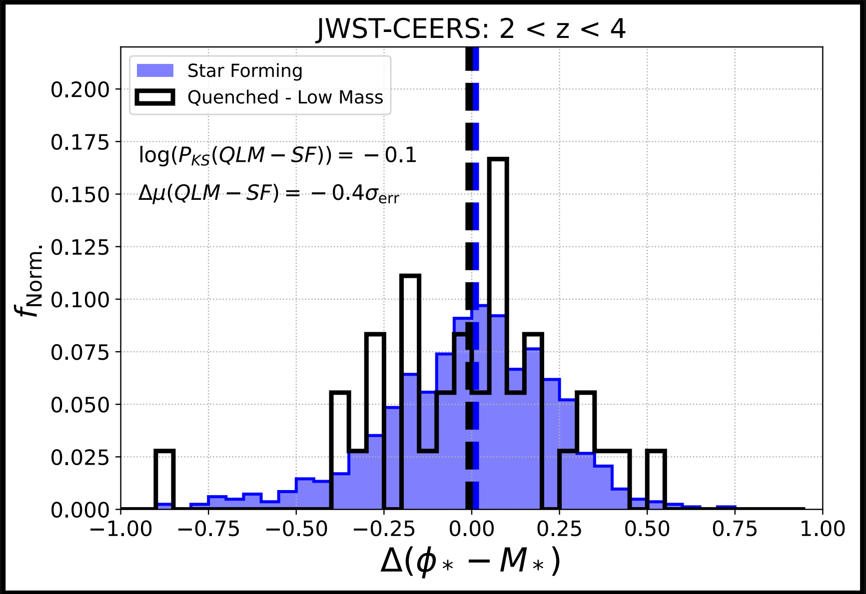
Star Formation Quenching in JWST-CEERS: Observational Results

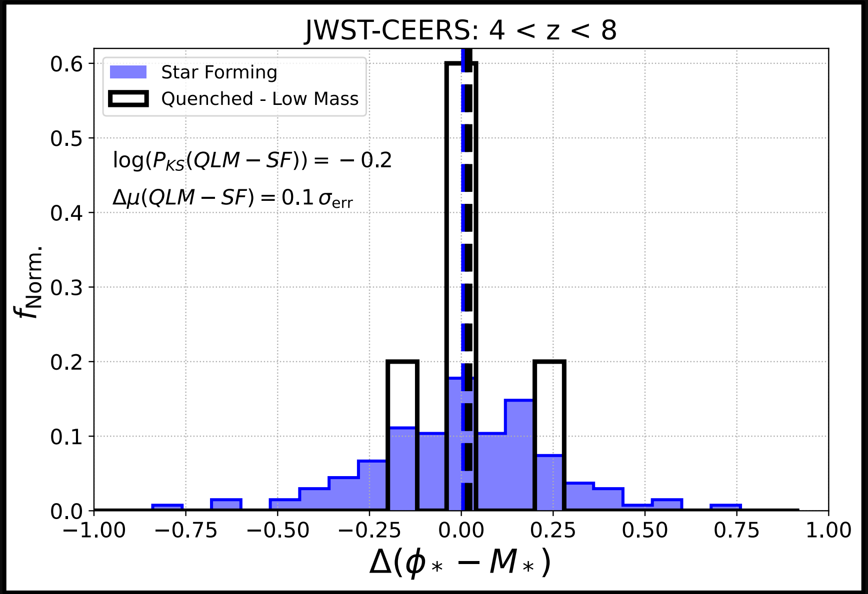
AGN Feedback @ High Mass:





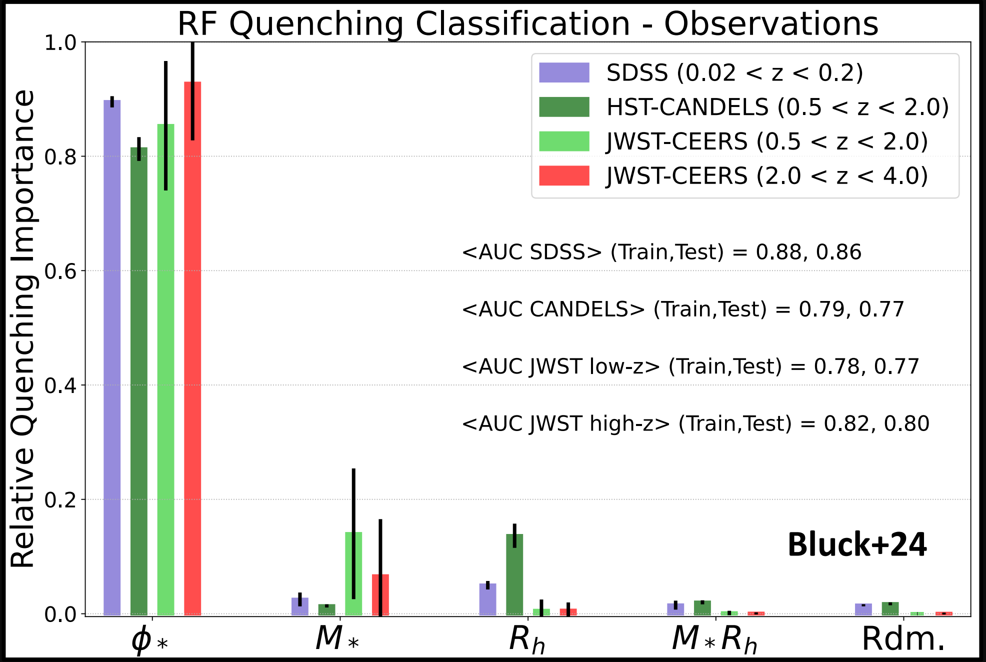
Environment @ Low Mass?:

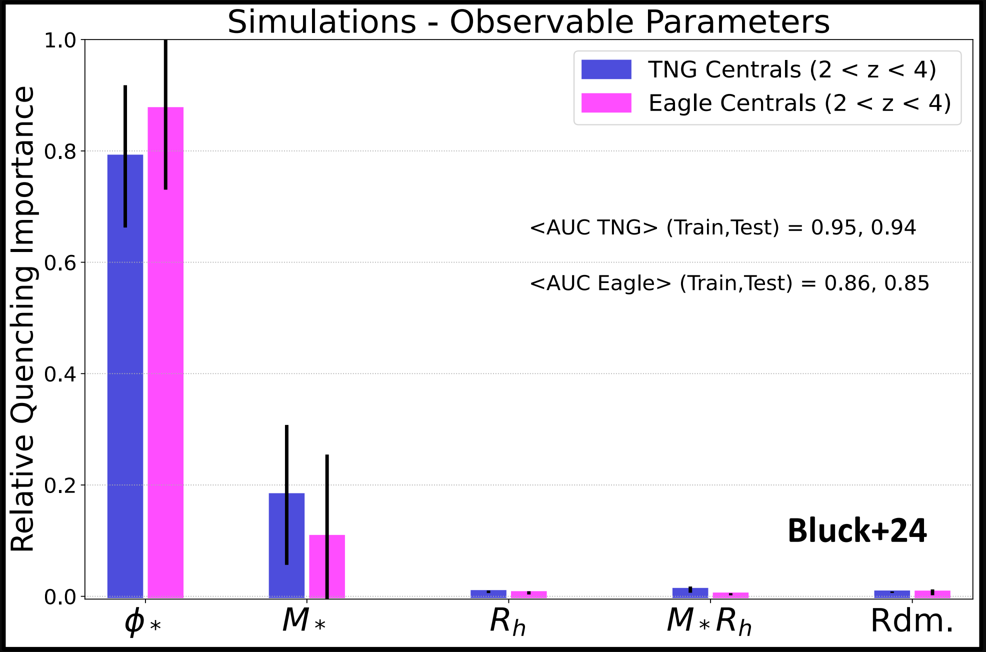




Summary

- ➢ AGN Feedback is predicted by cosmological simulations to quench high mass galaxies across cosmic time.
- ➢ The key observable associated with AGN feedback quenching is black hole mass (M_{BH}) *NOT* AGN luminosity.
- ➢ We find excellent agreement with simulations in z ~ 0 observations with the SDSS (see Piotrowska+22).
- ➢ Simulations predict that in lieu of an M_{BH} measurement, the stellar potential (ϕ_*) should best predict quiescence in photometric data.
- ➢ We confirm this result with HST and JWST observations of galaxies at z = 0.5 – 8 (see Bluck+23,24).
- ➢ Hence, AGN feedback is likely quenching galaxies across the bulk of cosmic history, starting within the first Gyr!





- ❖ **SDSS & Simulations:** Piotrowska, Bluck et al. (2022), MNRAS, 512, 1052
- ❖ **MaNGA Kinematics:** Brownson, Bluck et al. (2022), MNRAS, 511, 1913
- ❖ **Machine Learning:** Bluck et al. (2022), A&A, 659, 160
- ❖ **HST & Simulations:** Bluck et al. (2023), ApJ, 944, 108
- ❖ **JWST & Simulations:** Bluck et al. (2024), ApJ in press, APJ, 961, 163
- ❖ **Environment:** Goubert, Bluck et al. (2024), MNRAS, 528, 4891

Why is Black Hole Mass a Tracer of Energy Input to the System?

And what are the limitations of this approach?

$$E_{AGN} \propto M_{BH}$$

$$= \int \varepsilon L_{AGN}(t)\, dt \qquad = \int \dot{M}_{BH}(t)\, dt$$

$$= \langle \varepsilon \rangle \eta c^2 \int \dot{M}_{acc}(t) dt \qquad = (1-\eta) \int \dot{M}_{acc}(t)\, dt$$

$$+ \Delta M_{BH,\, mergers}$$

$\epsilon_{c(t)} \eta(t)$

- radiative efficiency
- coupling efficiency

M_{BH} growth via accretion

See Bluck+20a for further discussion (arXiv:1911.08857)

End

- aa