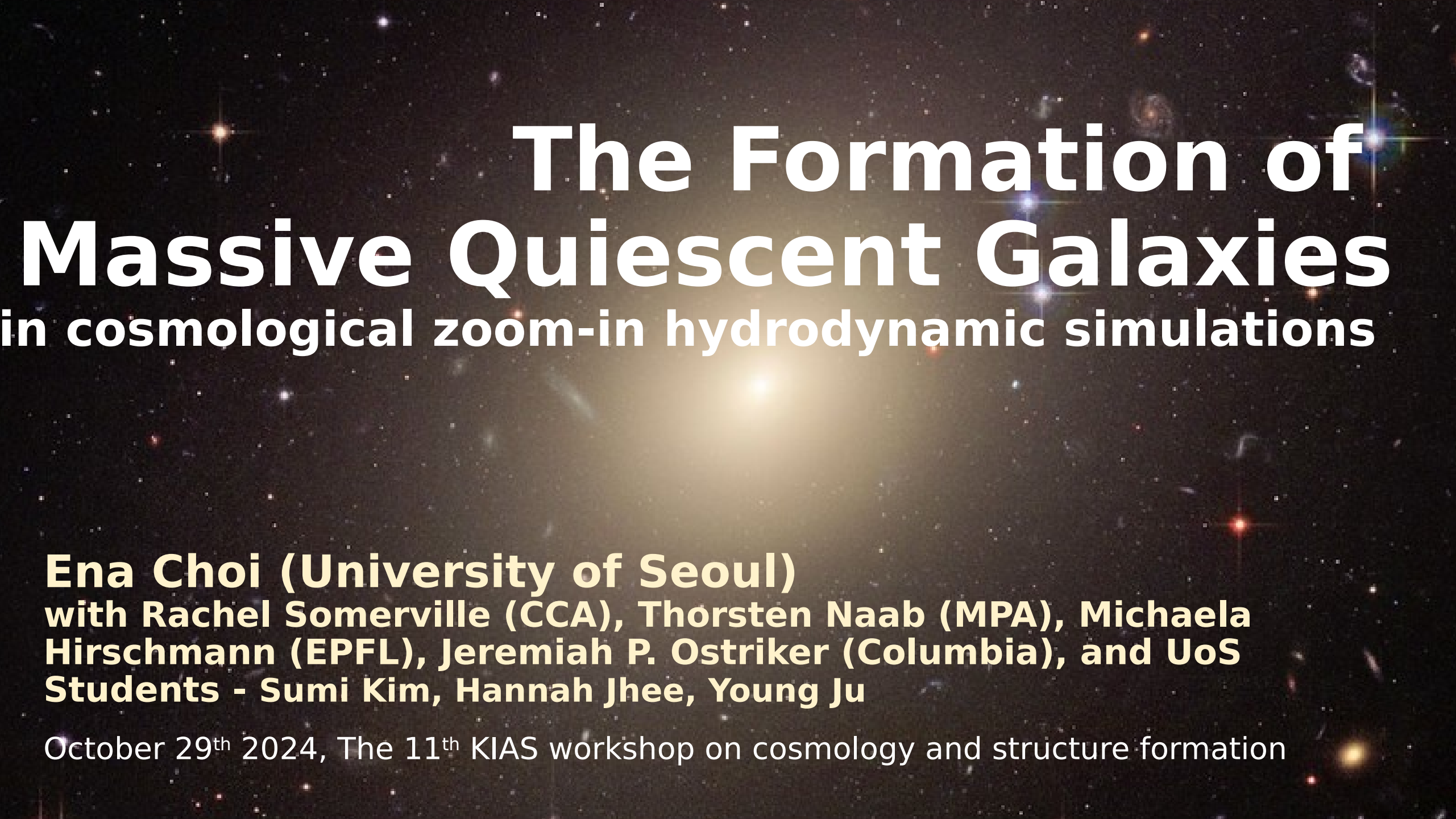
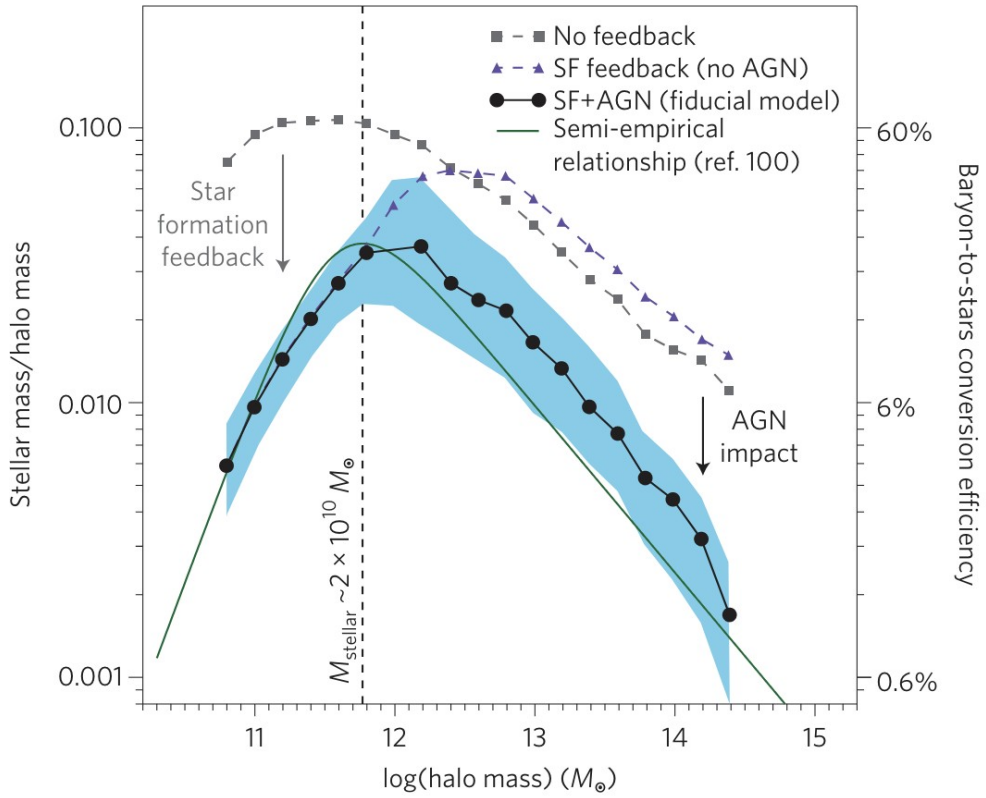


The Formation of Massive Quiescent Galaxies in cosmological zoom-in hydrodynamic simulations

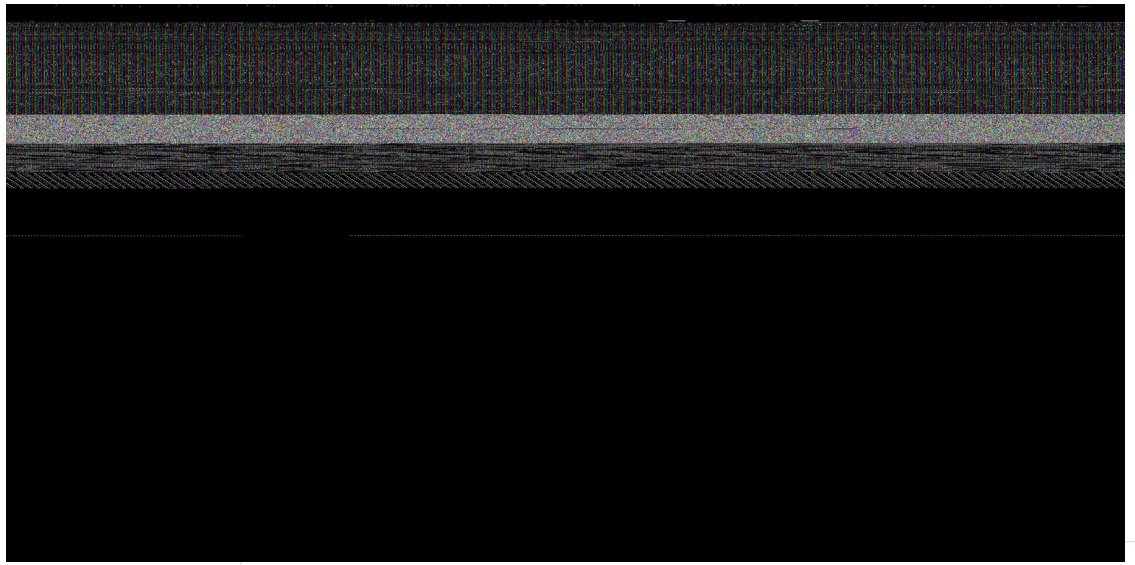
Ena Choi (University of Seoul)
with Rachel Somerville (CCA), Thorsten Naab (MPA), Michaela Hirschmann (EPFL), Jeremiah P. Ostriker (Columbia), and UoS Students - Sumi Kim, Hannah Jhee, Young Ju

October 29th 2024, The 11th KIAS workshop on cosmology and structure formation

AGN feedback is crucial in high-mass ends

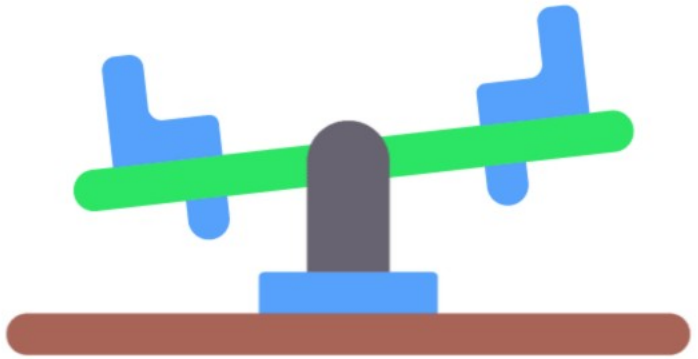


Harrison (2017), sim data from Somerville+08



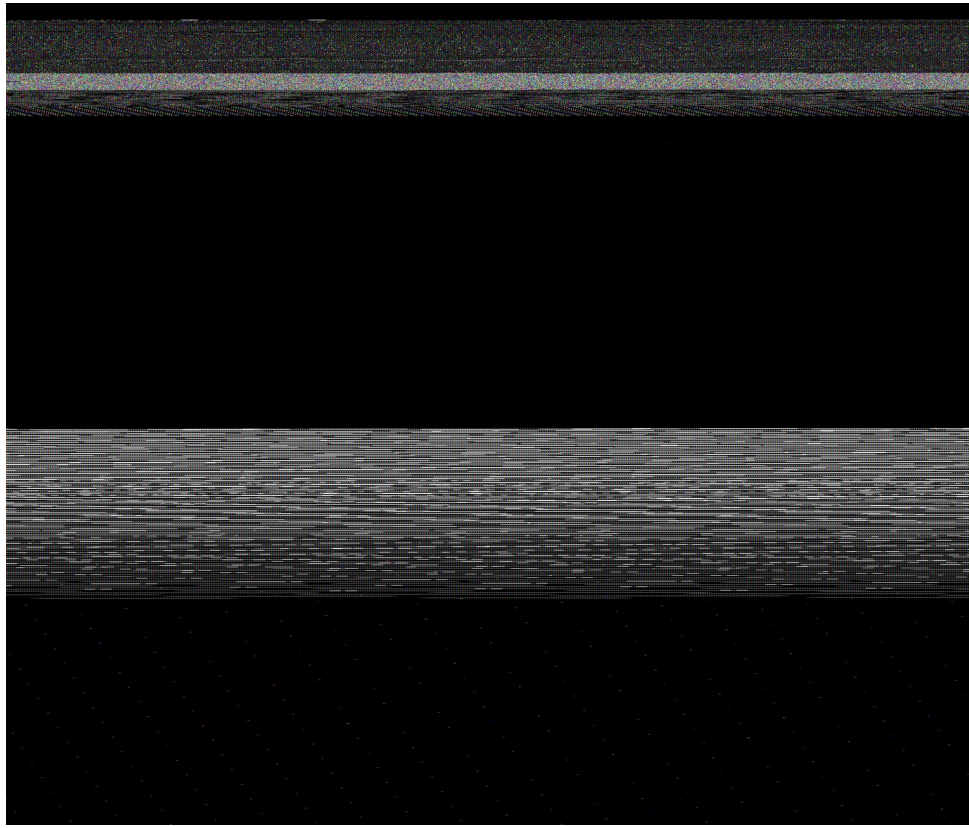
Formation of a single massive galaxy through time in the TNG50 cosmic simulation

- How do we strike the right balance between SN and AGN feedback?



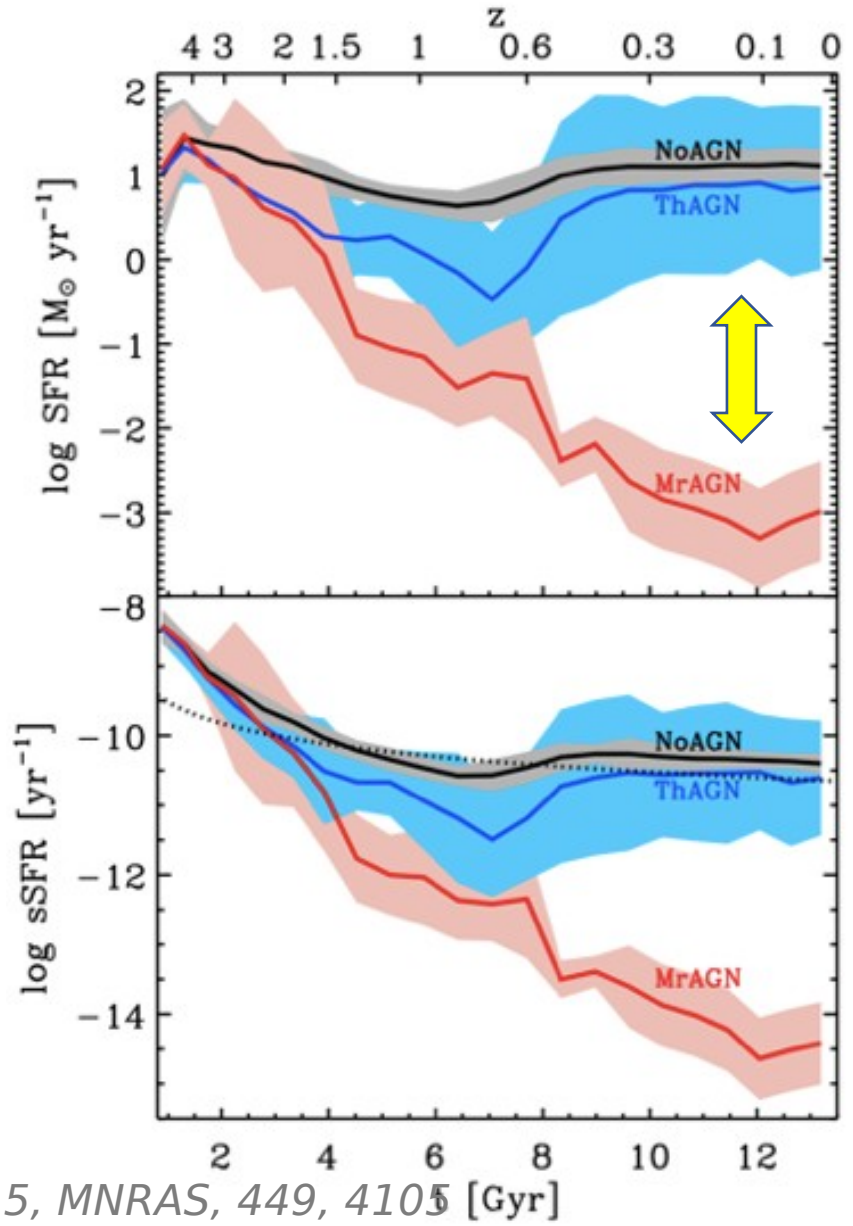
Cosmological zoom-in sim of massive galaxy formation

- GADGET-3 : Modified SPH (SPHGal) Hu+15
- **Momentum feedback from AGN** (1. BAL Winds and 2. Radiative X-ray heating/momentum) Choi+12/14/15
- SN wind feedback, Feedback from massive stars (‘Early’ feedback), AGB winds Núñez+17
- Metal enrichment and metal line cooling Aumer+13 / Modified SPH (SPHGal) Hu+14
- **30 Cosmological zoom-in simulations**: Central galaxies with z=0 mass Mstel=10^{11} - 10^{12} M_{sun} Choi+17



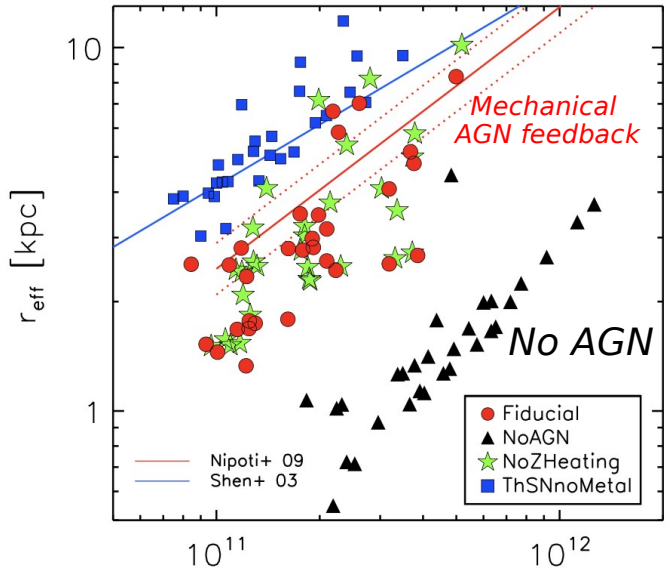
Effect of mechanical AGN feedback on SFR

- ~ 30 zoom-in simulations for
  - 1) **NoAGN**: No AGN and BHs
  - 2) **ThAGN**: Thermal AGN feedback
  - 3) **MrAGN**: Mechanical AGN feedback
- Mechanical feedback effectively quenches the star formation, over much longer timescales compared to the thermal feedback.
- "Red & Dead" elliptical galaxies are reproduced with the mechanical AGN feedback model.



Choi et al. 2015, MNRAS, 449, 4105

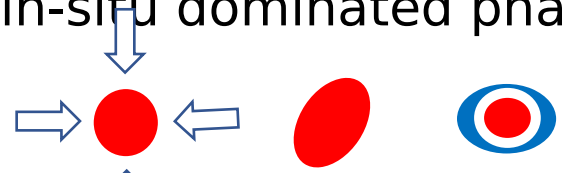
Two-phase formation of elliptical galaxies



Choi et al. 2017

Phase I: Early dissipation phase

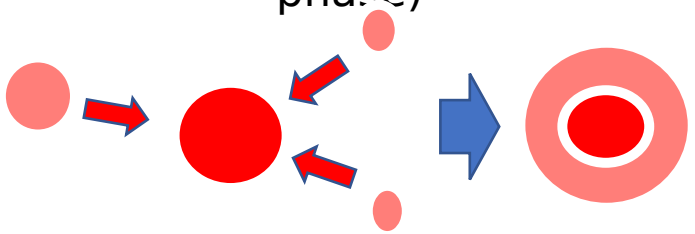
(in-situ dominated phase)



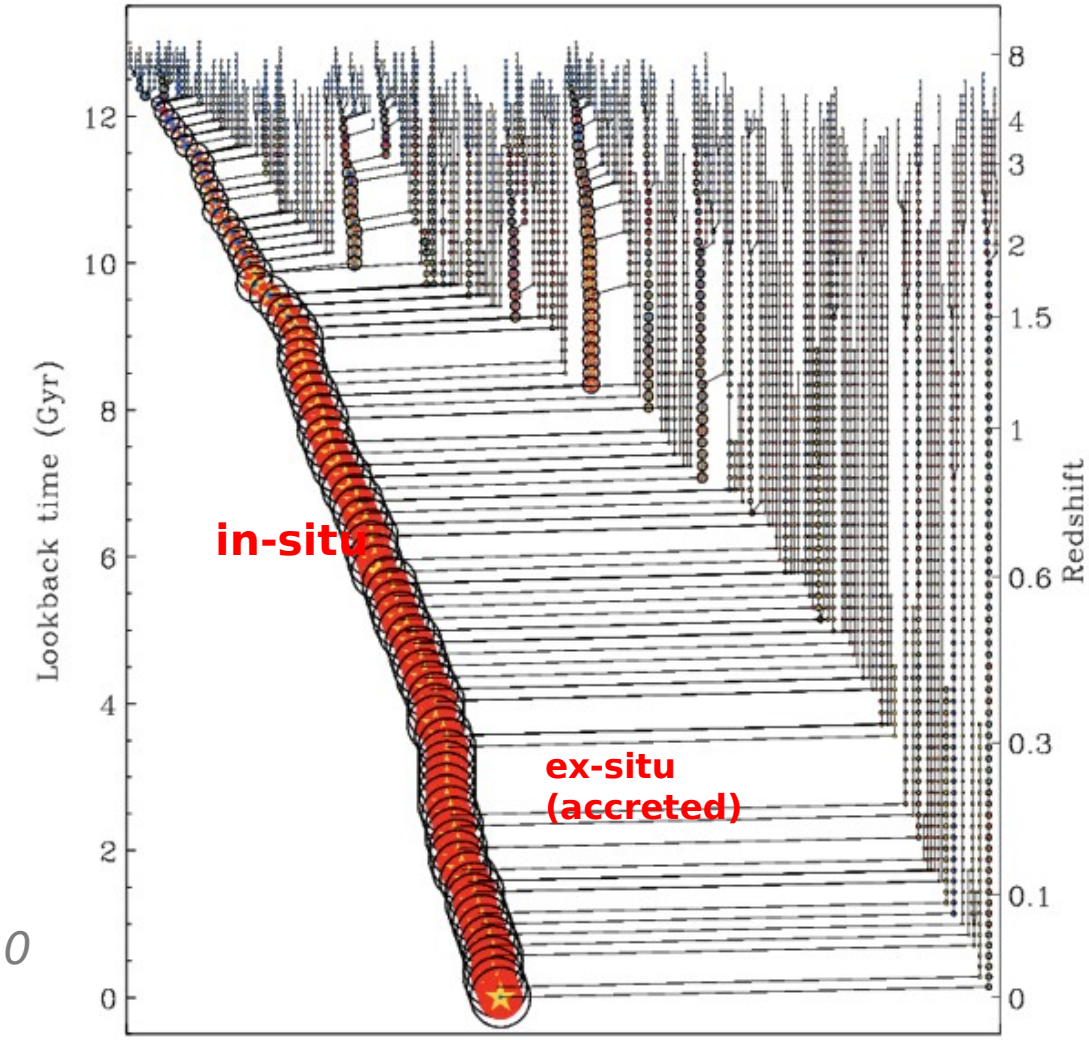
"Compaction"

Phase II: Ex-situ phase

(Minor merger dominated phase)

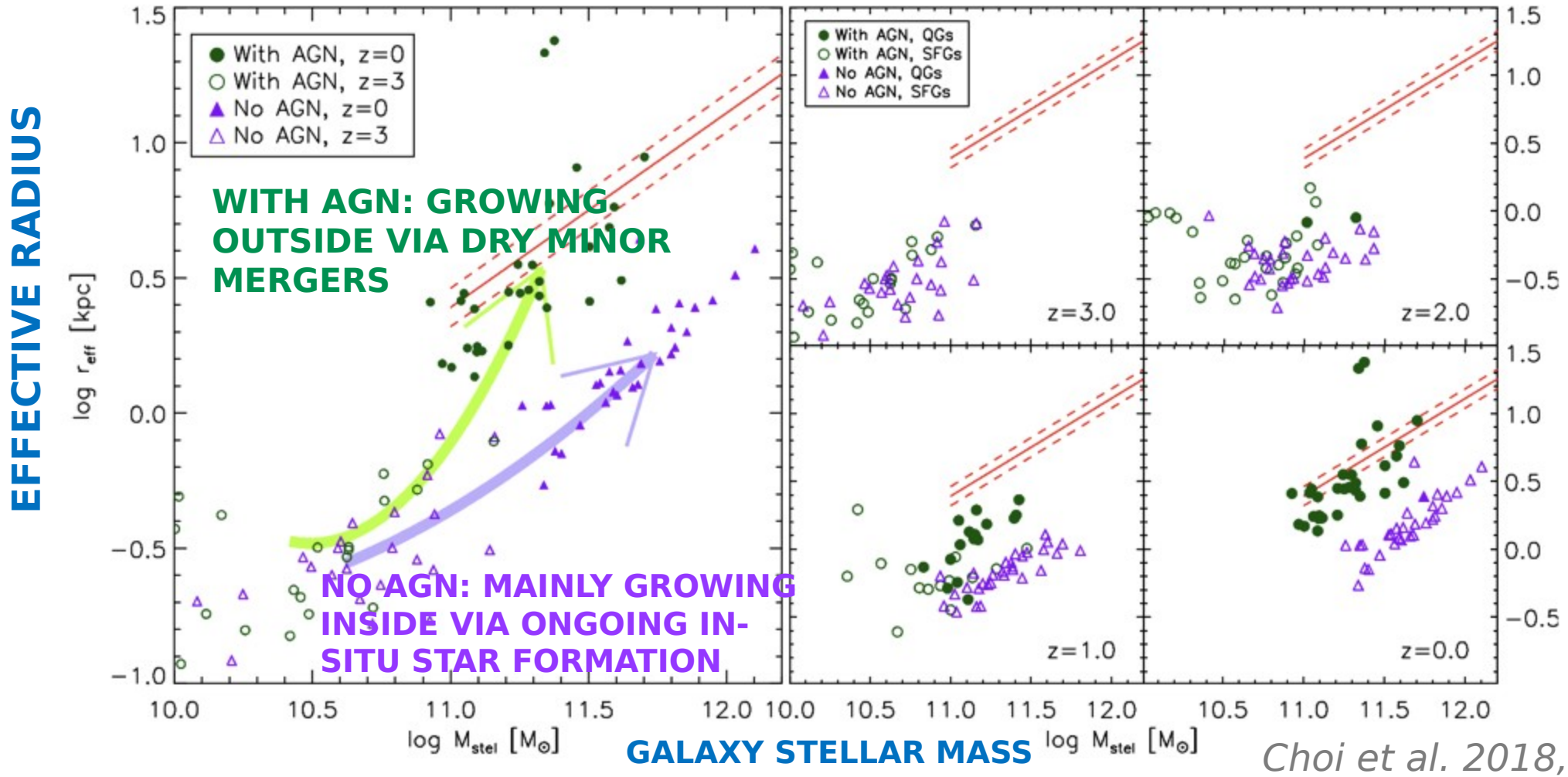


Naab et al. 2009, Oser et al. 2010



Hirschmann et al. 2015

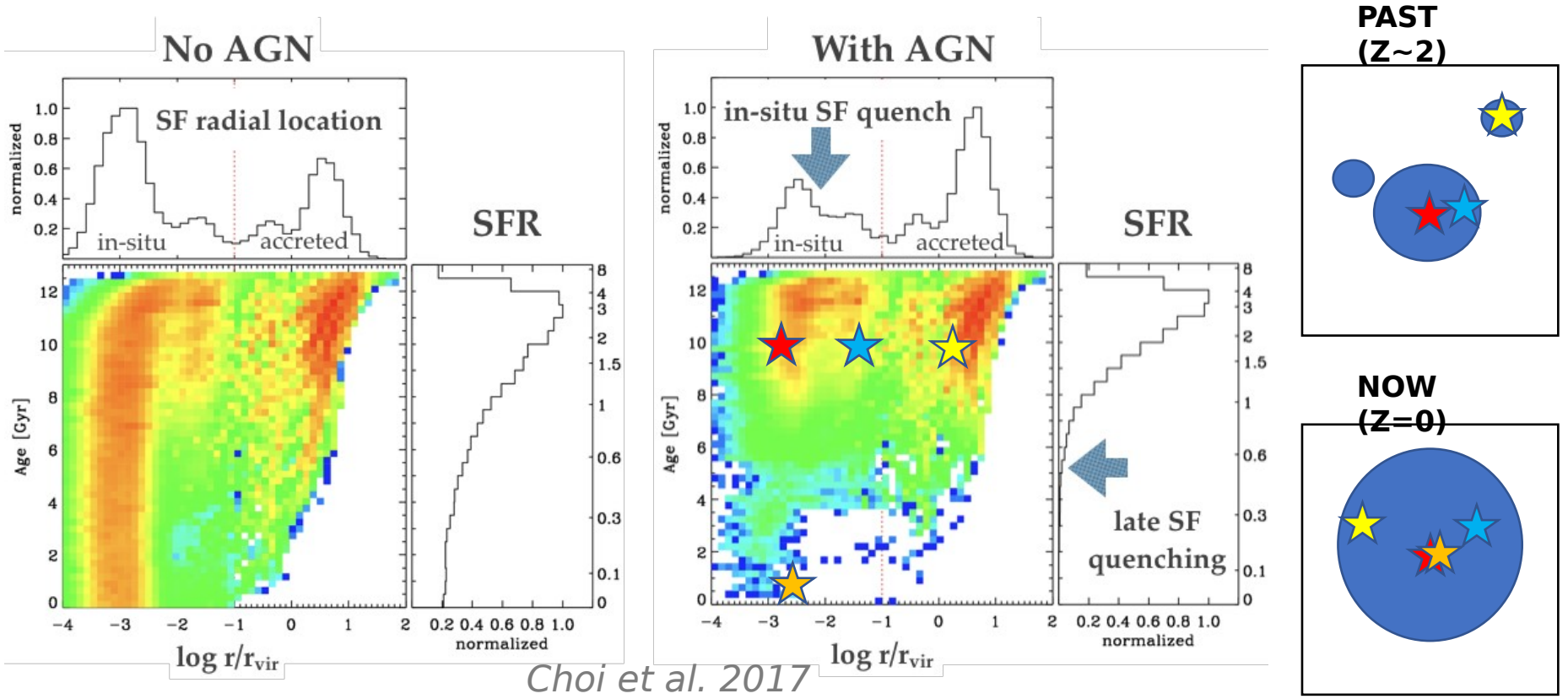
Effect of mechanical AGN feedback on size



Choi et al. 2018, ApJ, 866, 9

- Much steeper evolution in AGN models, after the star formation quenched.
- Overall, galaxy sizes are smaller in noAGN model in all redshift.

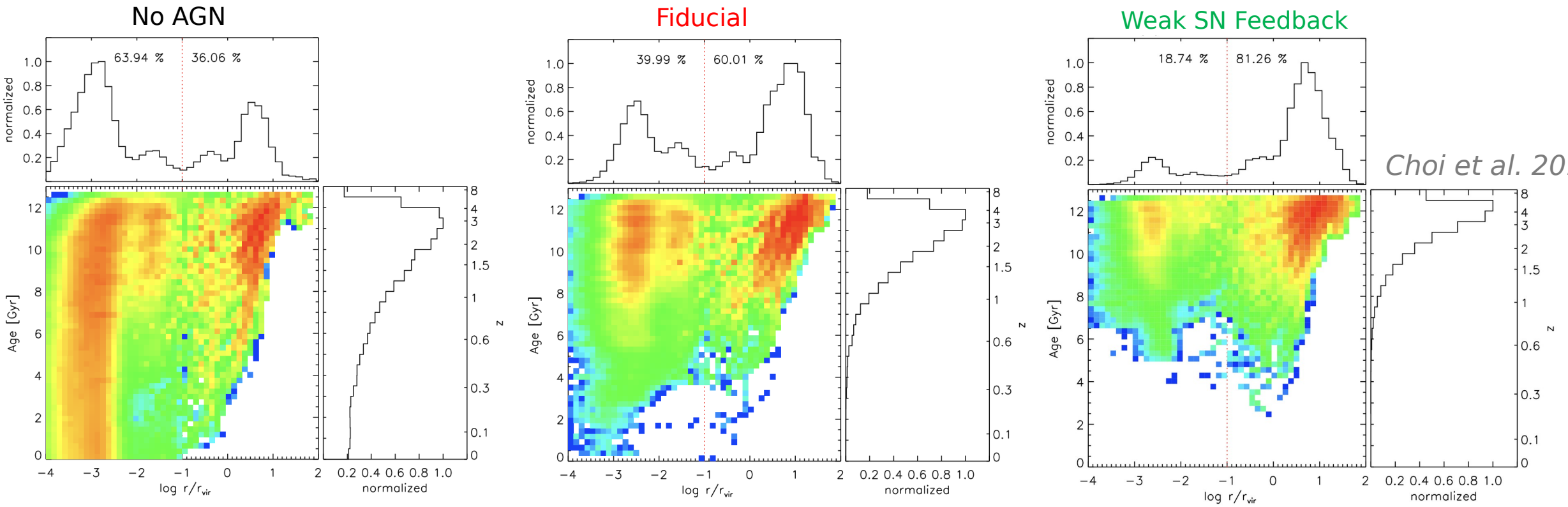
Effect of AGN on the stellar component



Choi et al. 2017

- AGN feedback mainly affects the **Late** and **In-situ** SF: The ratio of in-situ formed to accreted stars is significantly reduced by including AGN feedback.

Effect of SN on the stellar component

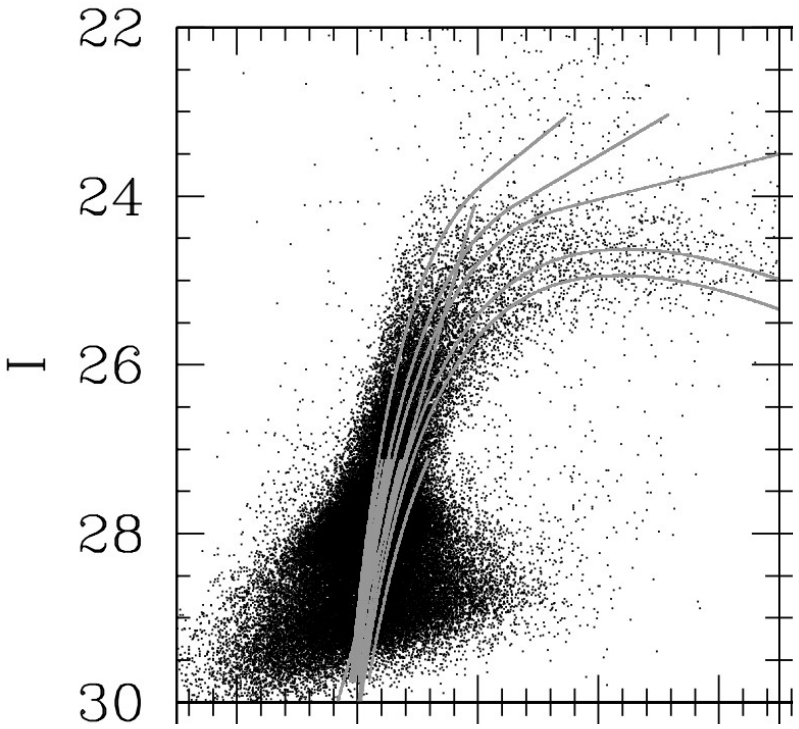


Choi et al. 2017

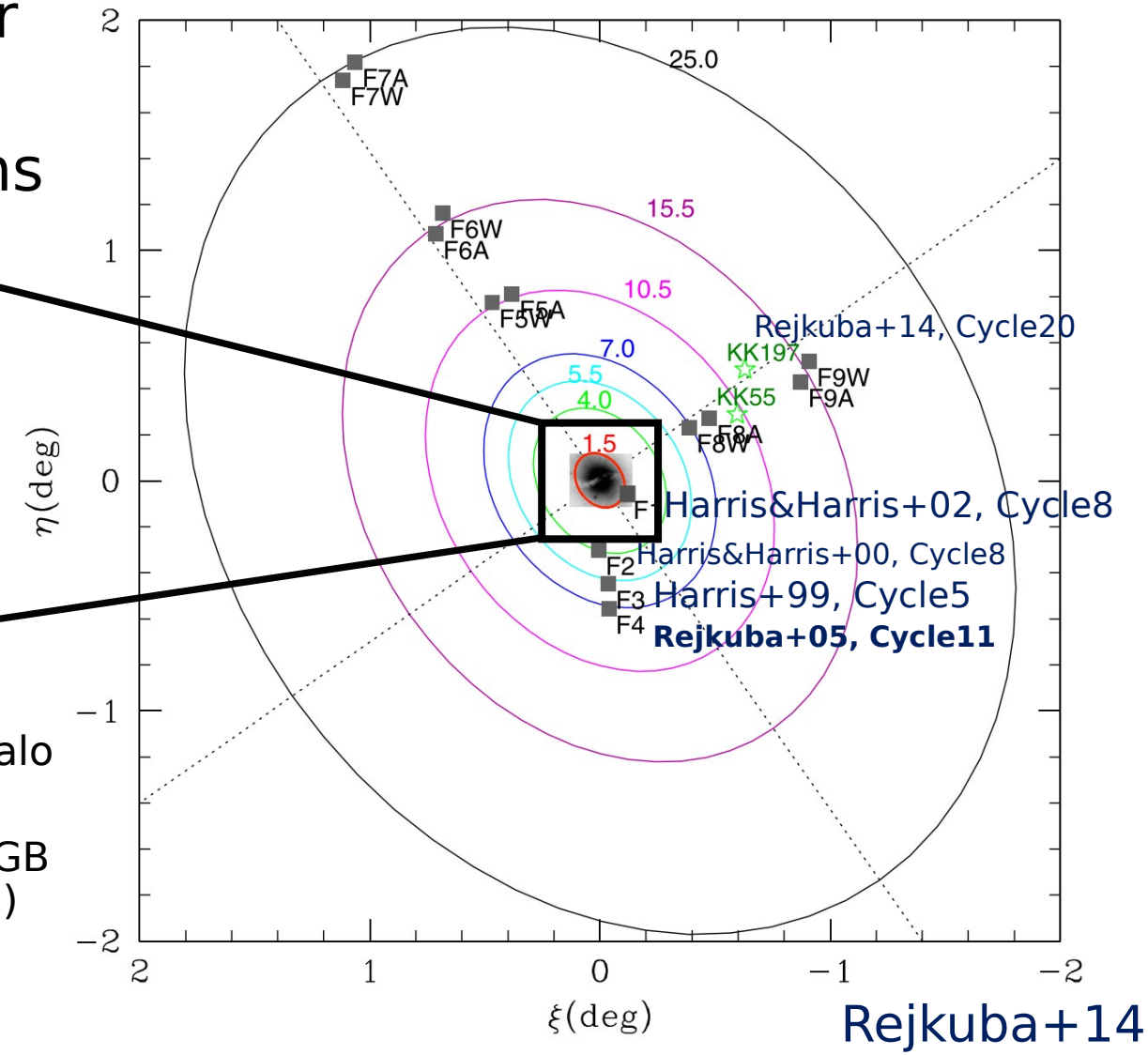
- SN feedback mainly affects the early and ex-situ SF: the ratio of in-situ formed to accreted stars is significantly increased by including strong SN feedback.

HST photometry in NGC 5128 halo fields

- Metallicity information on the outer part of nearby elliptical galaxies
- Distribution of the HST observations in the halo of NGC 5128 ->





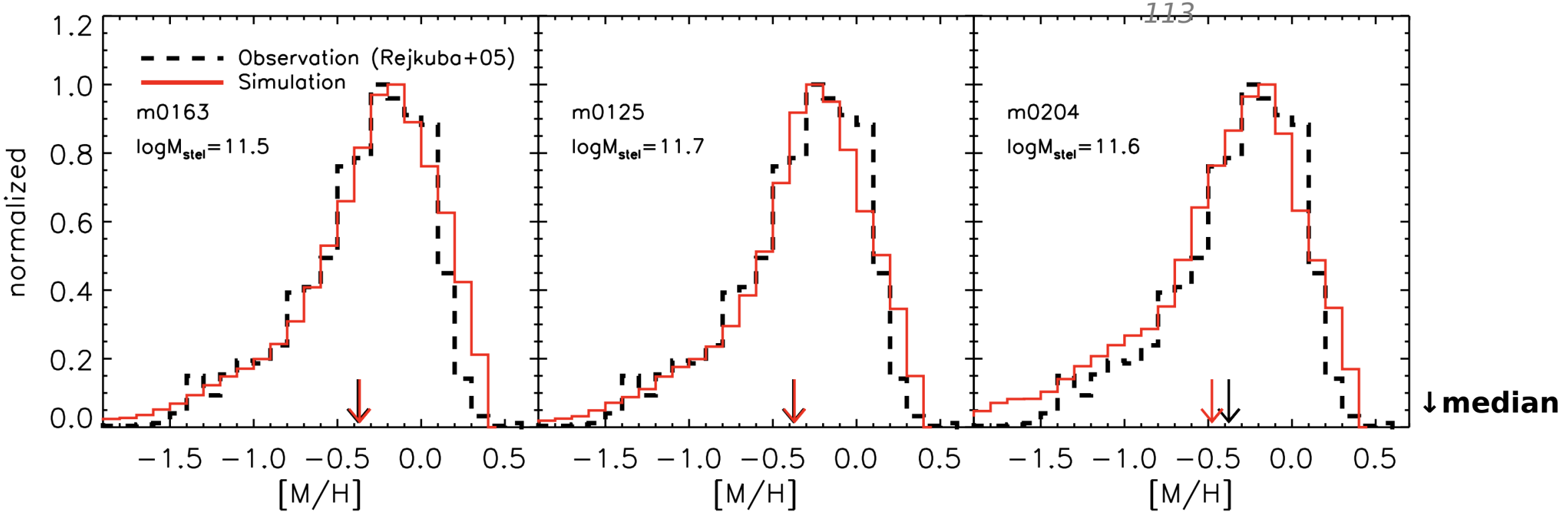


- I vs. (V-I) CMDs of NGC 5128 outer halo at r_{proj} ~ 40 kpc.
- ~3000 resolved RGB stars (Rejkuba+05)
- MDF of RGB stars

Rejkuba+14

The comparison of MDFs (Obs vs. Sims)

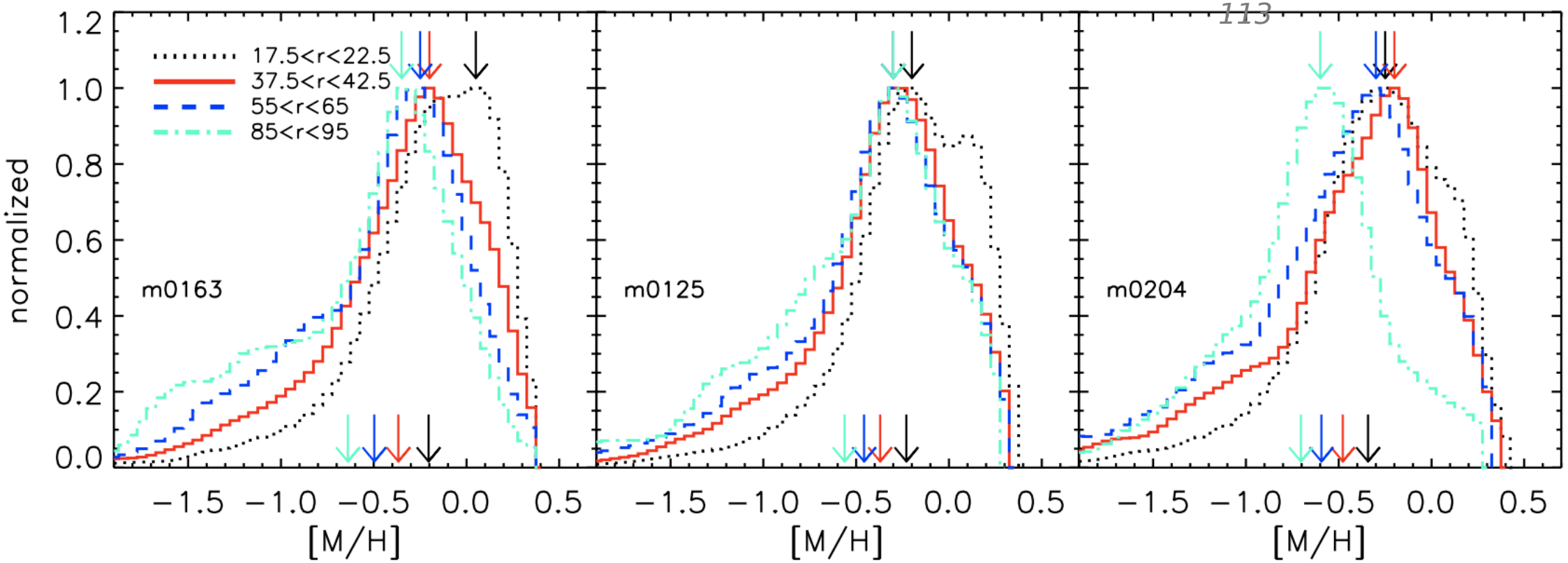
Choi et al. 2022, ApJ, 929, 113



- Simulated MDF: all star particles within 37.5 < r_{proj} < 42.5 kpc
- Observed MDF: r_{proj} ~ 40 kpc outer halo field of NGC 5128

The MDFs for fields at different galactocentric distances

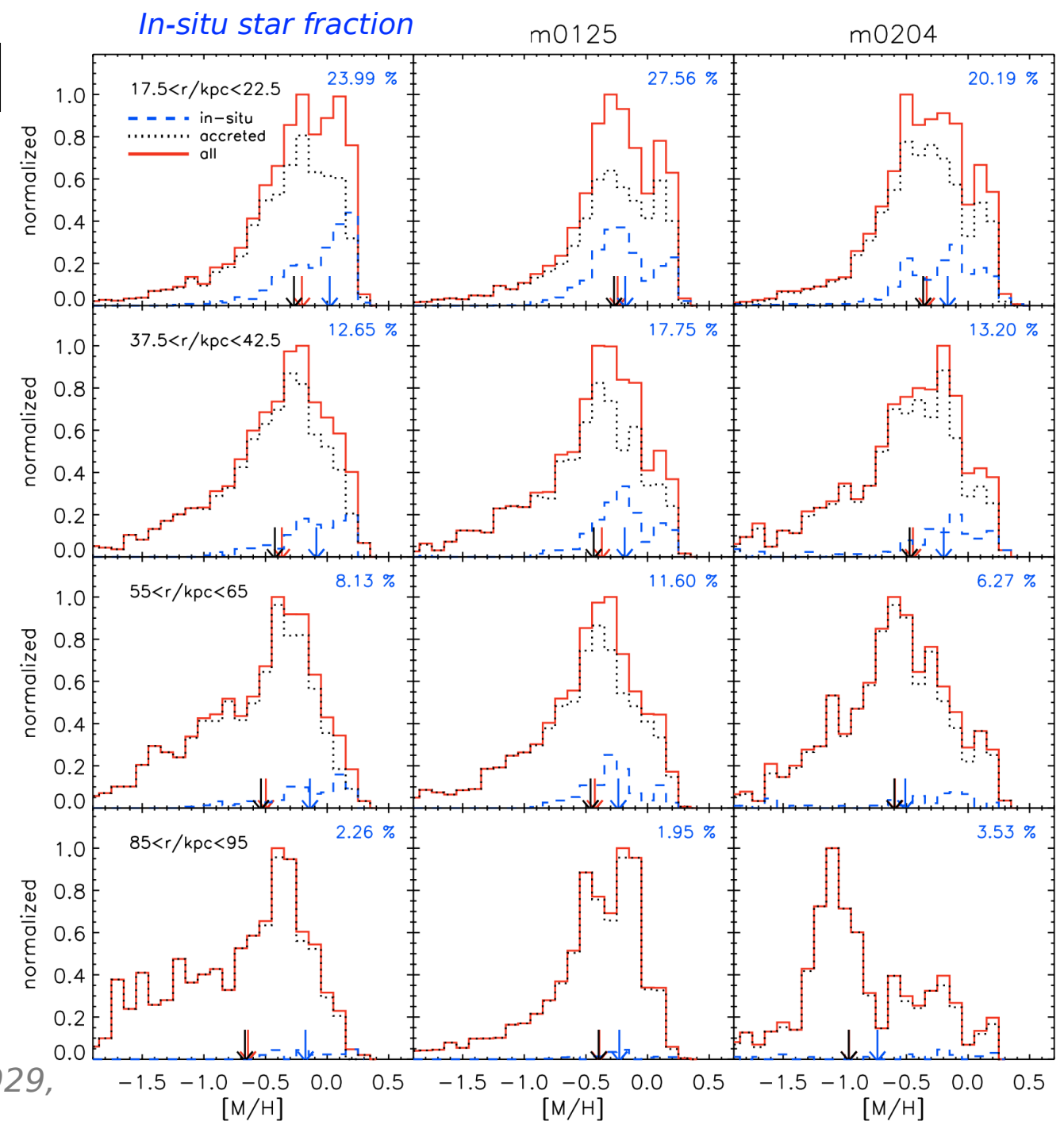
Choi et al. 2022, ApJ, 929, 113



- Simulation predicts that innermost region is more metal-rich on average due to..

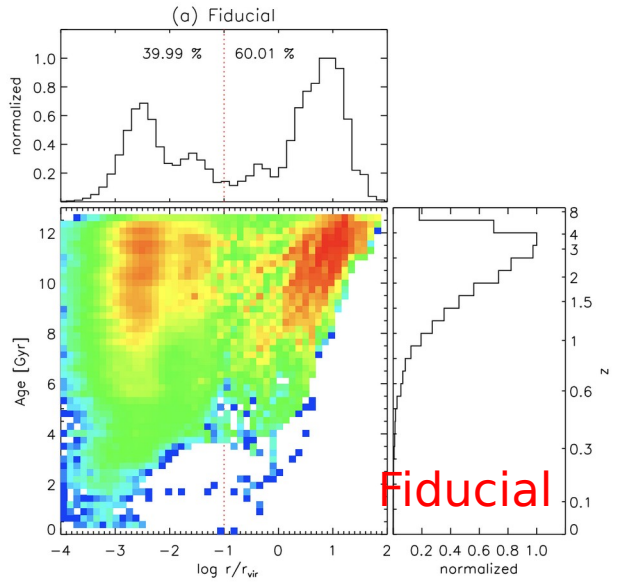
In-situ vs. accreted

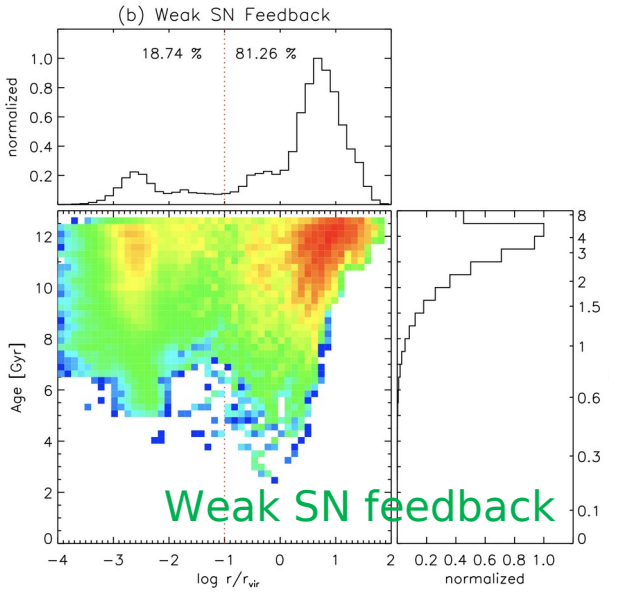
- **….in-situ formed star component.**
- MDF of all stars (red solid line),MDF of in-situ formed stars (blue dashed) and MDF of those formed outside the galaxy and are accreted later on (black dotted).
- **Inner halos tend to have more contribution of in-situ stars.**
- Sometimes distinct metal rich sub-population (by in-situ stars) is shown in MDF for inner regions.
- Outer halo fields (~90 kpc) are dominated by accreted stars.

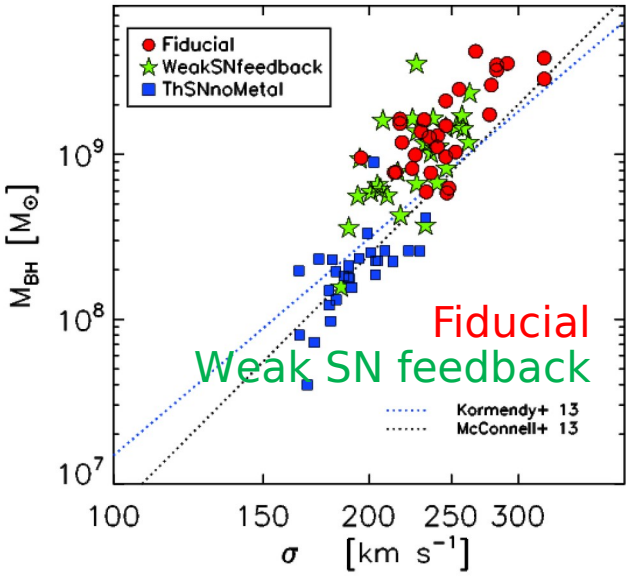


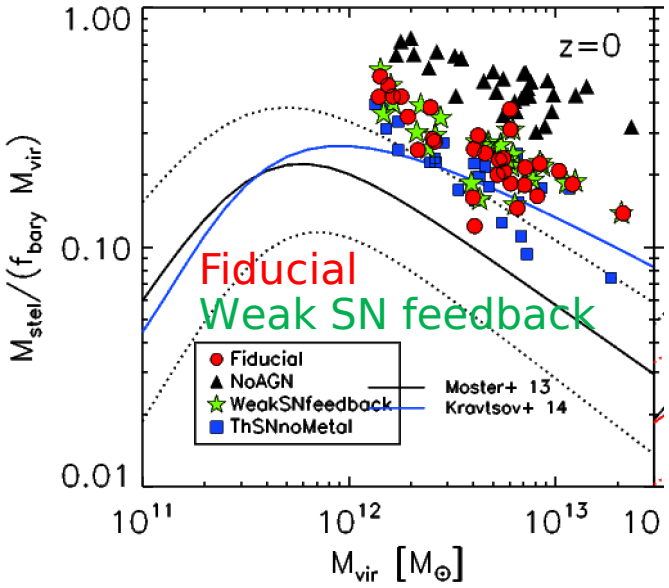
Choi et al. 2022, ApJ, 929, 113

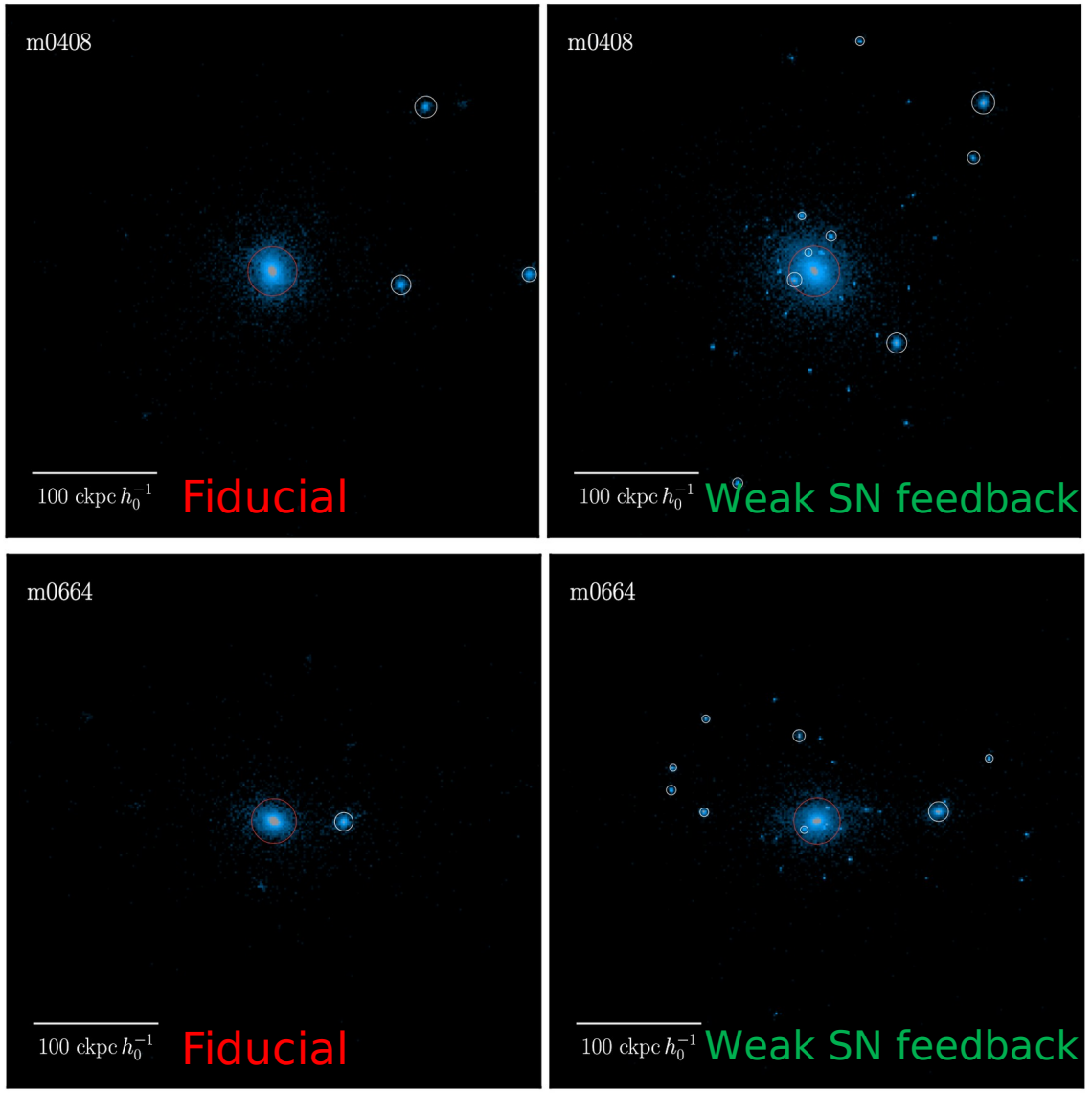
Satellite distribution (Fiducial vs. weakSN)









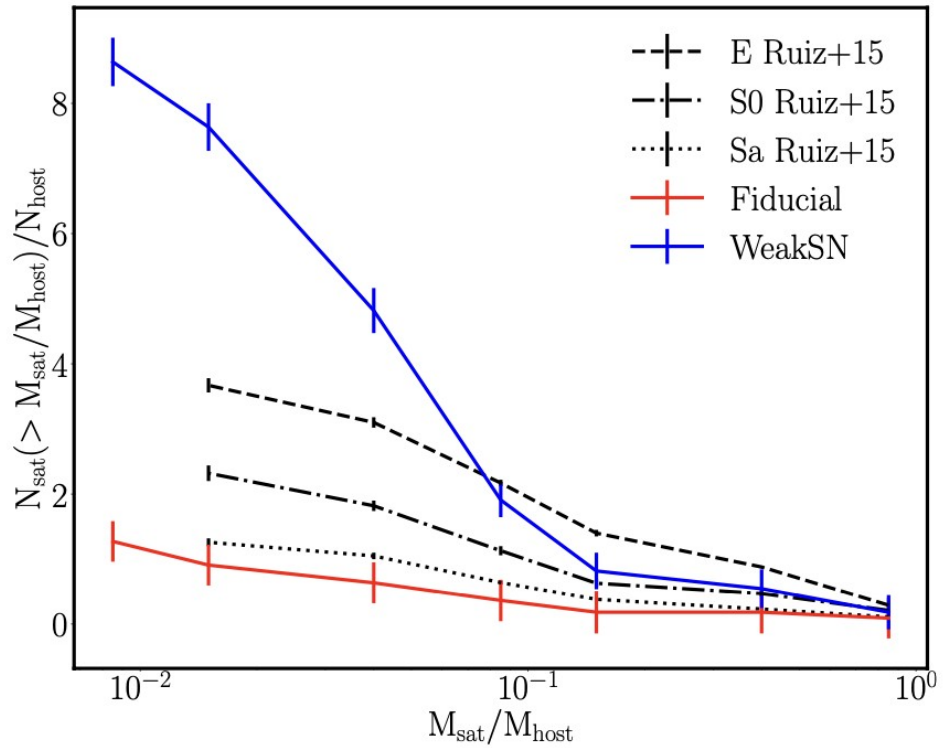


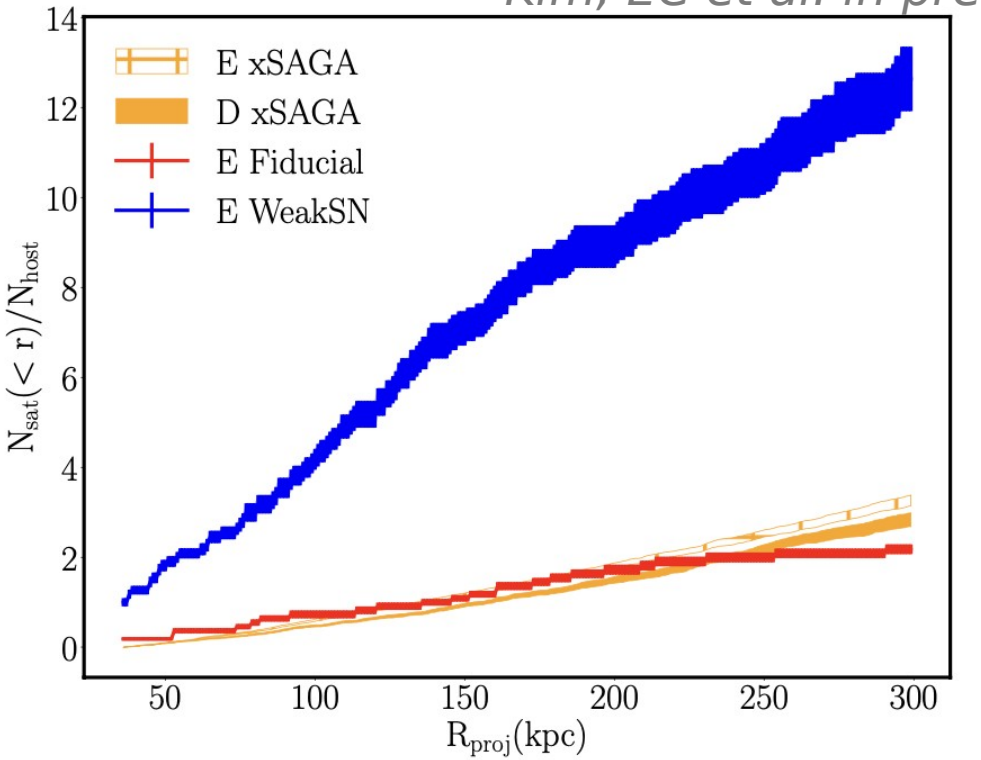
Kim, EC et al. in prep

Satellite distribution comparison with obs.

- Satellite mass and radial distirbution (comparison with SDSS & SAGA survey)

Kim, EC et al. in prep

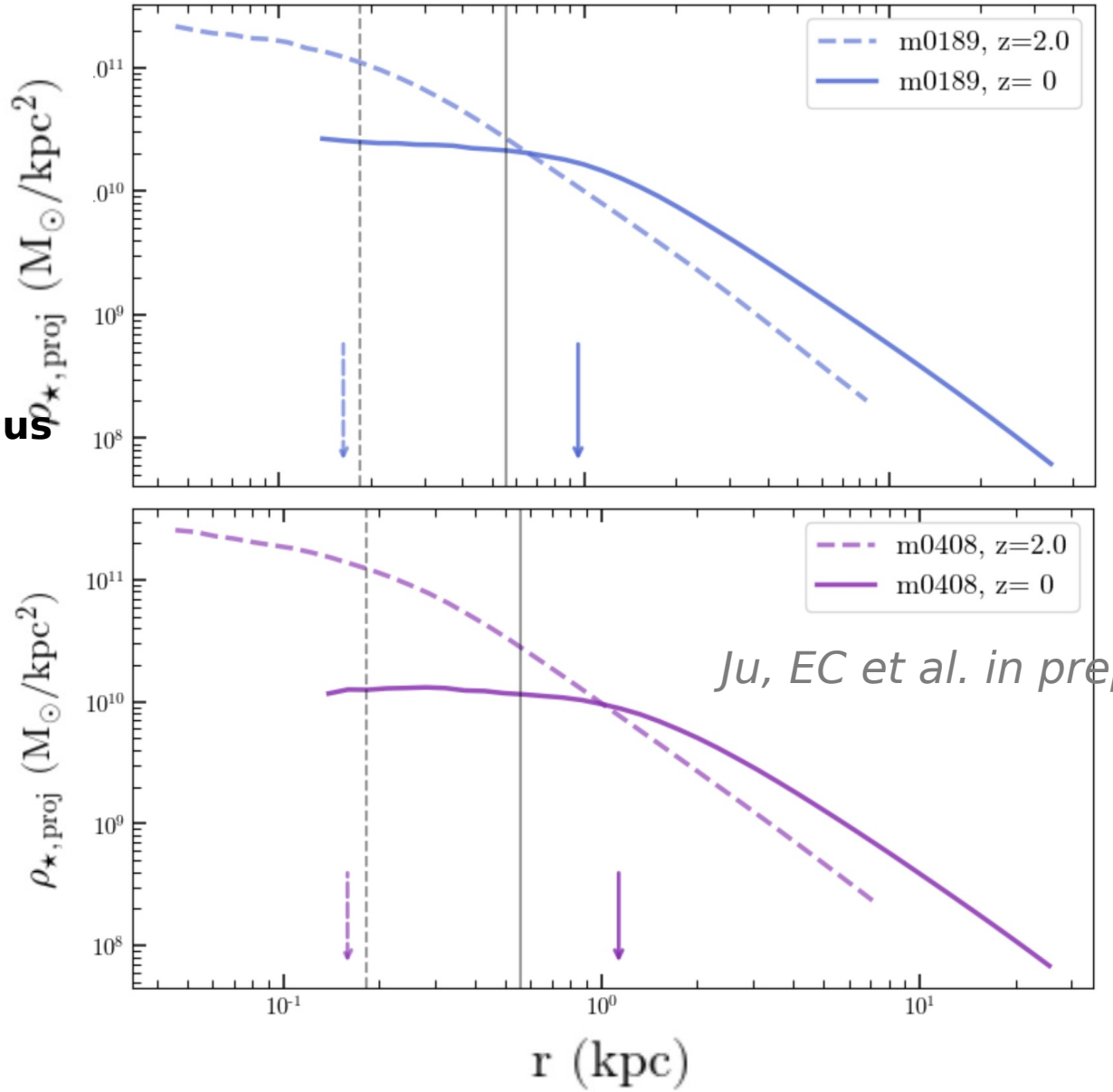




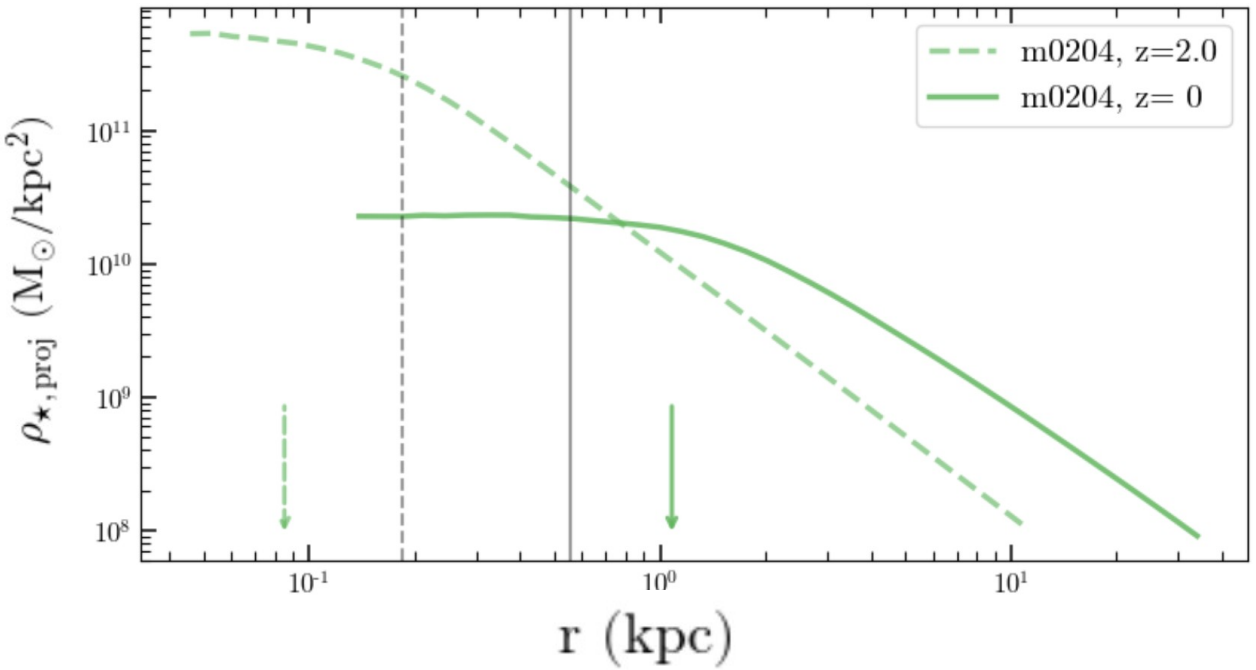
- The Weak SN feedback model overproduces satellite galaxies relative to the observations
- The Fiducial model better aligns with the data, although it seems to underproduce satellites.

Core formation of massive galaxies

- Projected stellar density radial profile
- Flat slope core at z=0 in many simulated galaxies



↓core radius

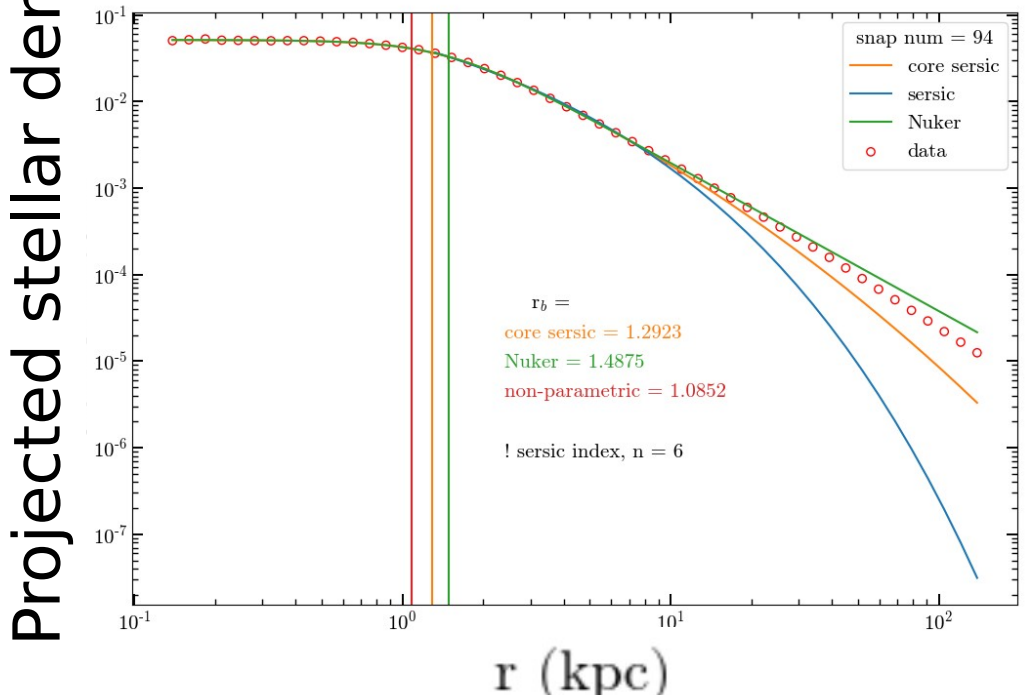


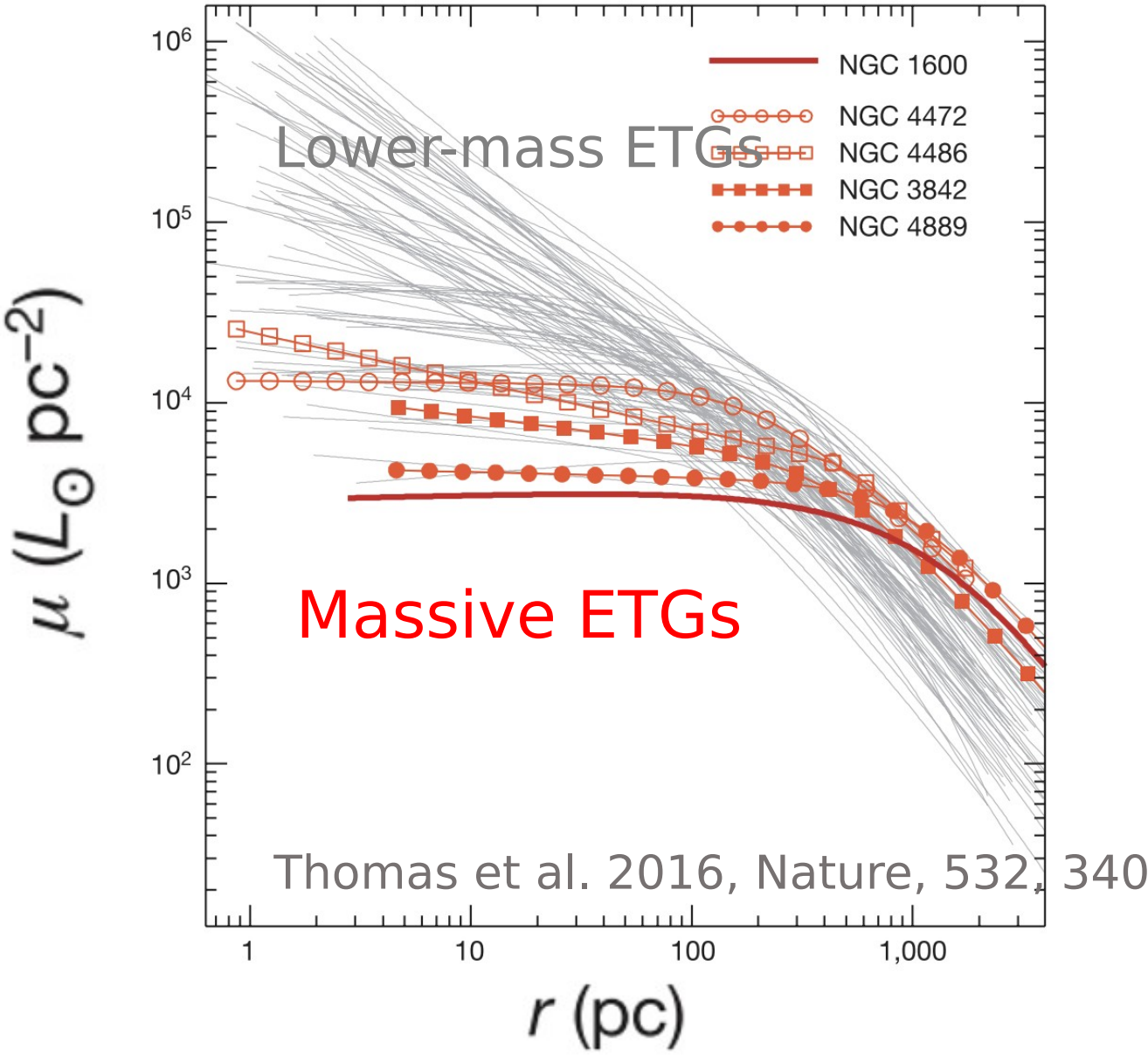
Ju, EC et al. in prep

Core radius fitting & core radius evolution

- Core-Sersic profile – outer power law replaced with a Sersic function.

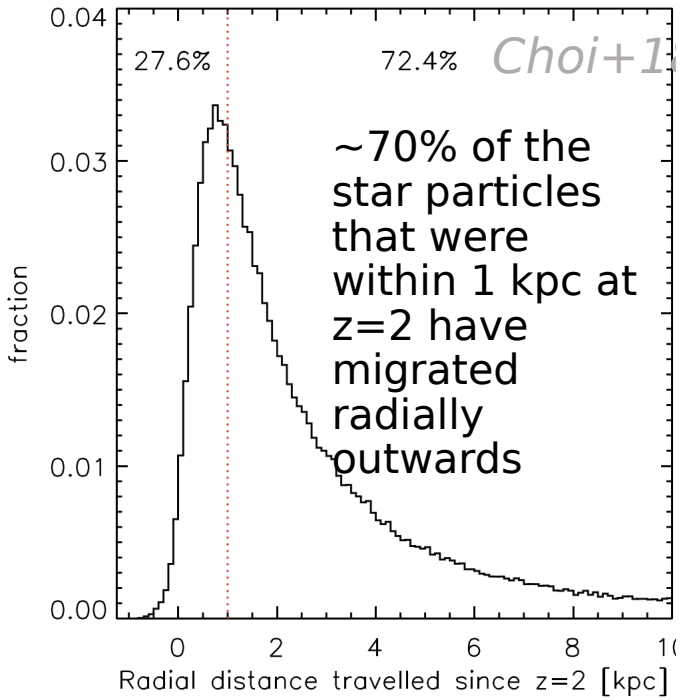
$$\mu(r) = \mu' \left[1 + \left(\frac{r_b}{r}\right)^{\alpha}\right]^{\gamma/\alpha} e^{-b\left[\frac{(r^{\alpha} + r_b^{\alpha})}{r_e^{\alpha}}\right]^{1/(\alpha n)}}$$

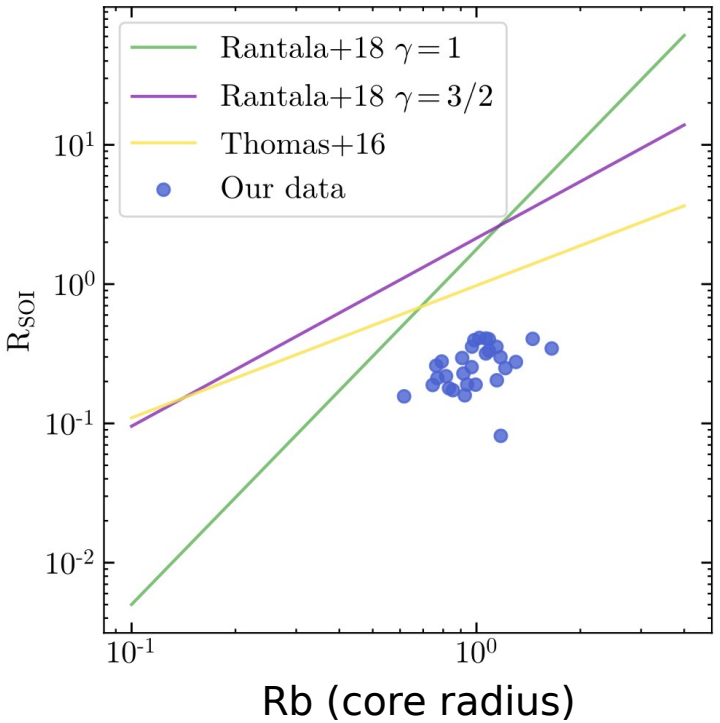


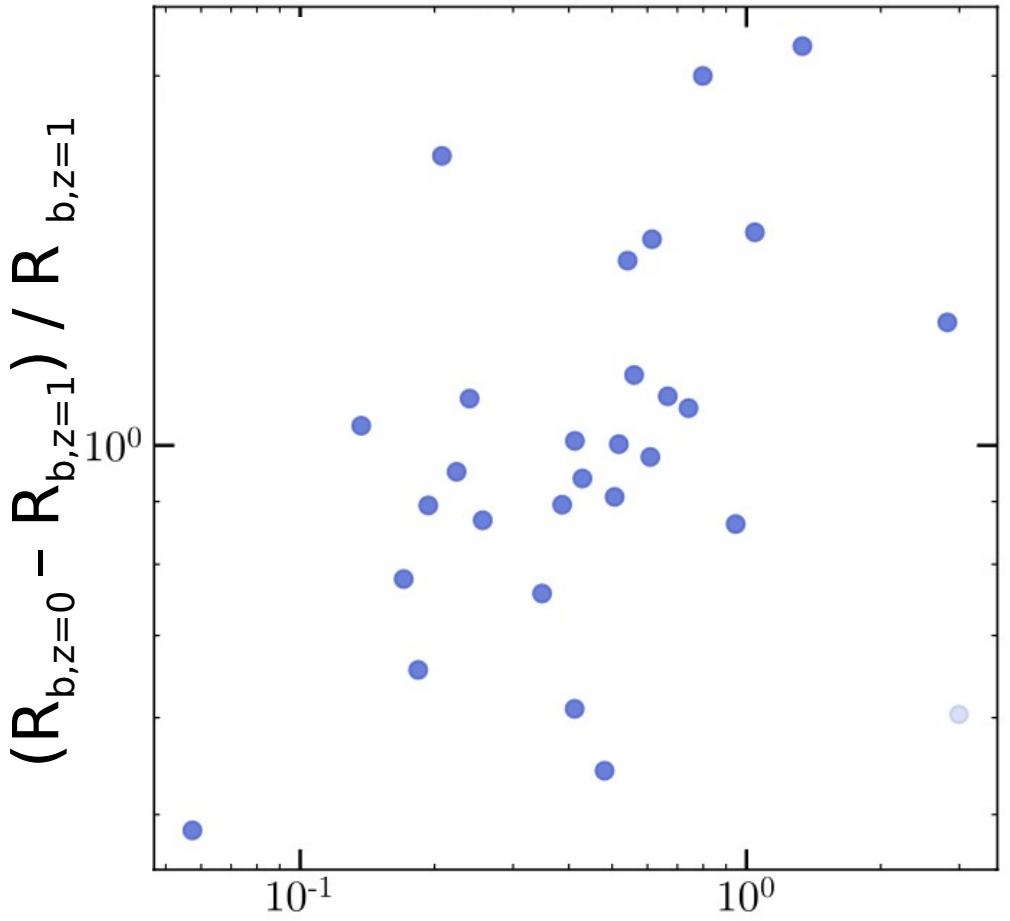


Core formation in response to AGN outflows?

- Correlation between core radius increment vs. cumulative outflowing wind mass.
- Puff-up of central stellar distribution by AGN-driven







Ju, EC et al. in prep

Summary

- The ‘stellar origin’ offers a way to assess the balance between SN and AGN feedback in massive galaxy formation.
- Further feedback balance validation can be achieved by comparing the metallicity of the outer regions of nearby massive galaxies with observations.
- SN feedback (or small-scale feedbacks) can also be tested using satellite distributions.
- Massive galaxy core formation provides another probe to fine-tune AGN feedback models.


JWST NIRcam image of the Carina Nebula (NGC 3324)
Thank you!