Forming diverse galaxies across cosmic time

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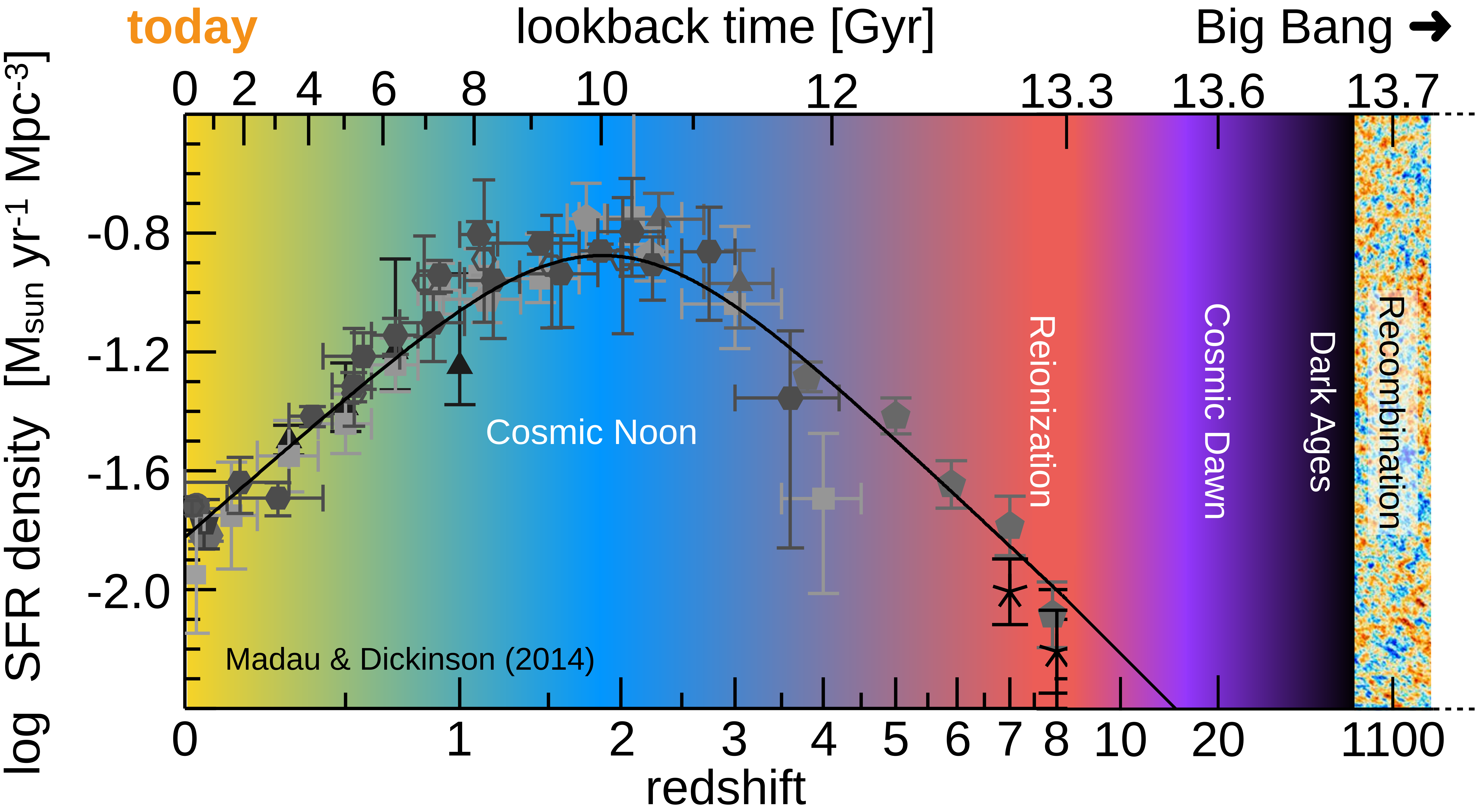
Hubble Ultra Deep Field

2004 HUDF: NASA, ESA, S. Beckwith, M. Stiavelli, A. Koekemoer, R. Thompson, and the STScI HUDF Team
2009 HUDF: NASA, ESA, G. Illingworth, R. Bouwens, and the HUDF09 Team
2012 HUDF: NASA, ESA, R. Ellis, R. McLure, J. Dunlop, B. Robertson, A. Koekemoer, and the HUDF12 Team;
2012 XDF: NASA, ESA, G. Illingworth, D. Magee, P. Oesch, R. Bouwens, and the HUDF09 Team;
2014 HUDF / UV-UDF Credit: NASA, ESA, H. Teplitz, M. Rafelski, A. Koekemoer, R. Windhorst, and Z. Levay

adapted from NAOJ

Key science questions



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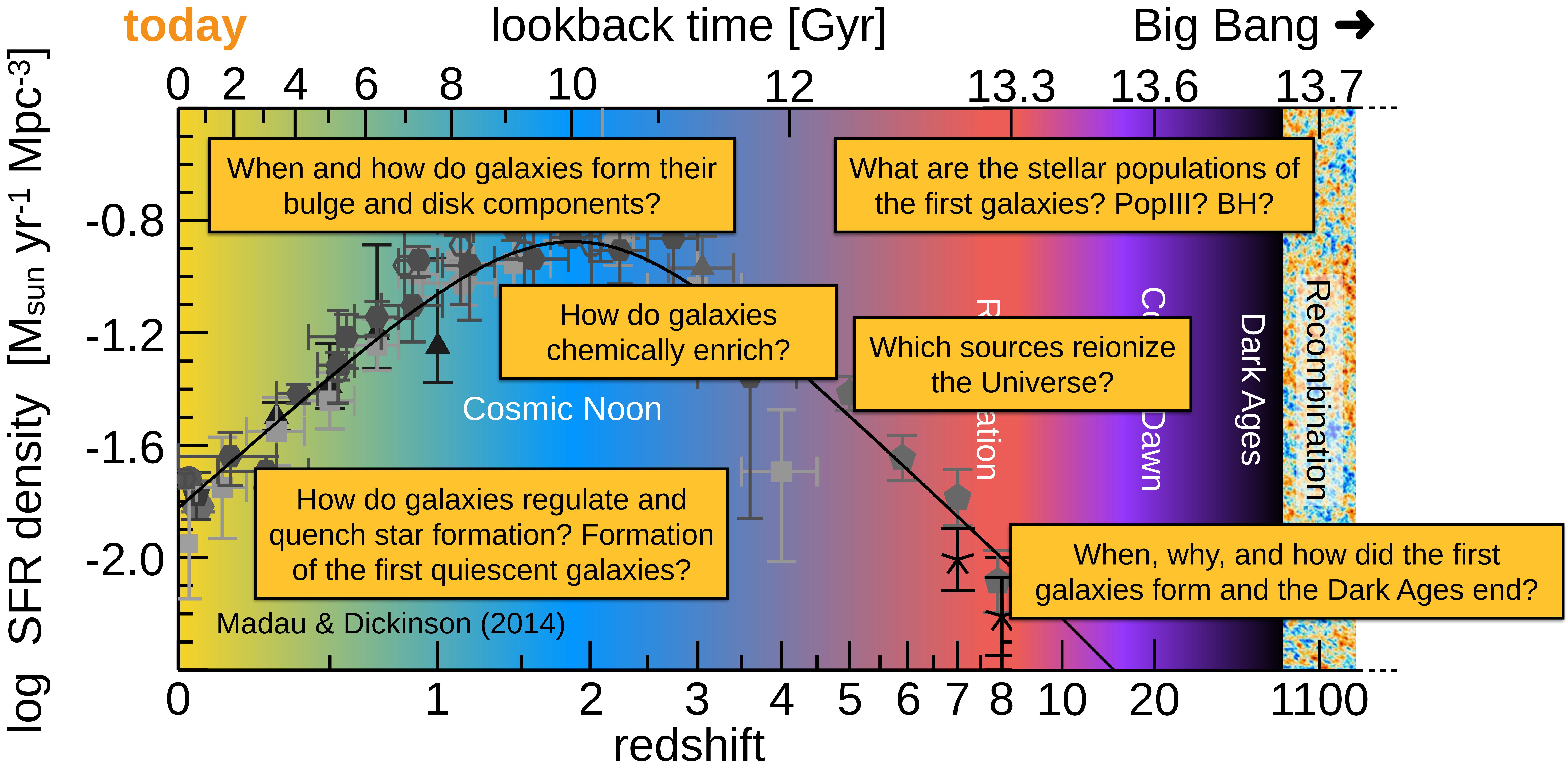


cosmic web (~Gpc)
125 Mpc/h
1 pc = 3 ly = 3x10^16 m


cosmic web (~Gpc)
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dark matter halos (~Mpc)
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cosmic web (~Gpc)
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galaxies (~kpc)
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cosmic web (~Gpc)
125 Mpc/h
star formation (~pc)
dark matter halos (~Mpc)
galaxies (~kpc)
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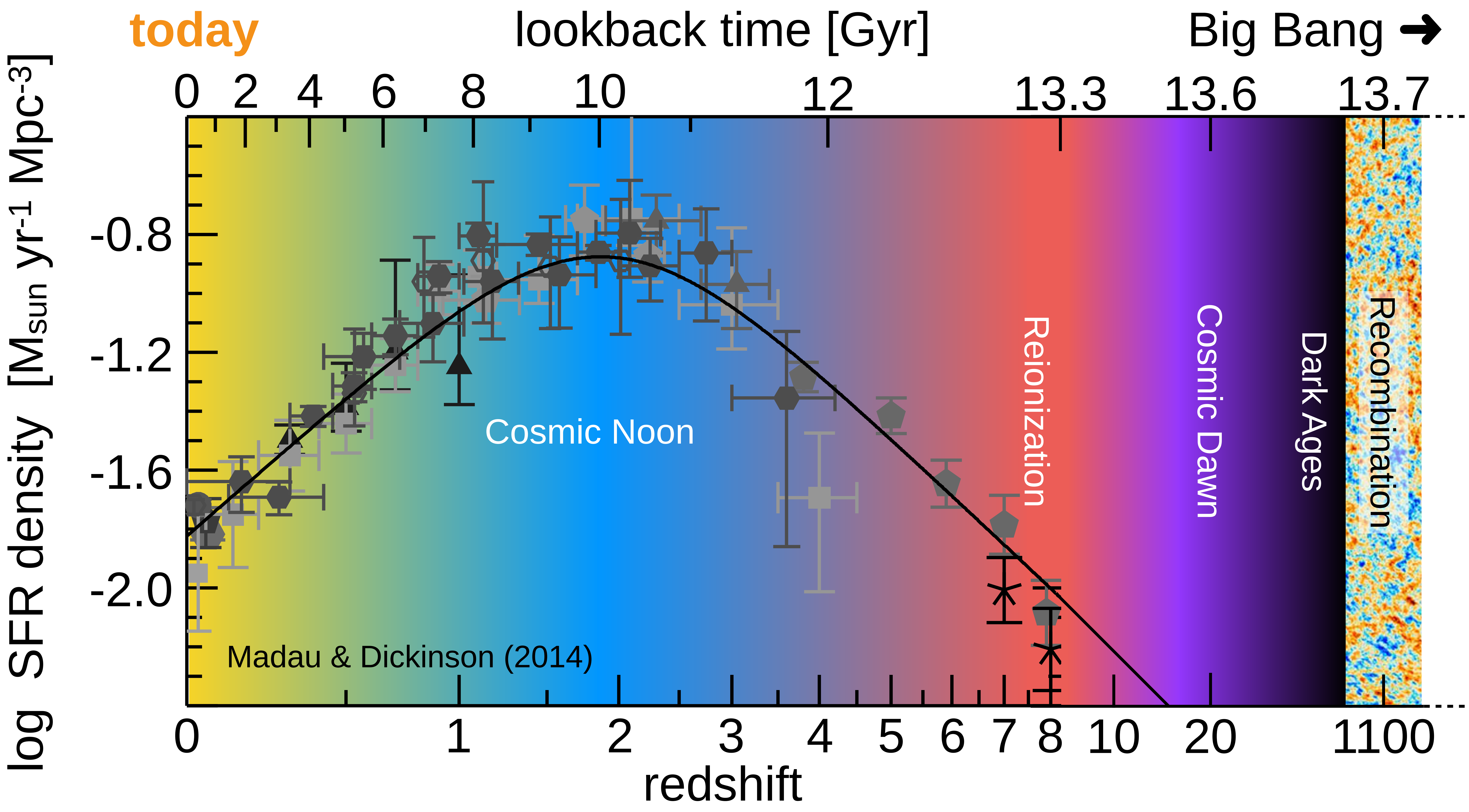
cosmic web (~Gpc)
125 Mpc/h
star formation (~pc)
dark matter halos (~Mpc)
galaxies (~kpc)
black holes (0.01pc)
1 pc = 3 ly = 3x10^16 m


cosmic web (~Gpc)
125 Mpc/h
formation and diffusion of cosmic rays
formation of stars molecular clouds
gas flow & cooling
supernova explosions
magnetic fields
stellar winds
interstellar medium
star formation (~pc)
black hole activity
radiation fields
black hole growth
dark matter halos (~Mpc)
galaxies (~kpc)
black holes (0.01pc)
1 pc = 3 ly = 3x10^16 m

Recent progress



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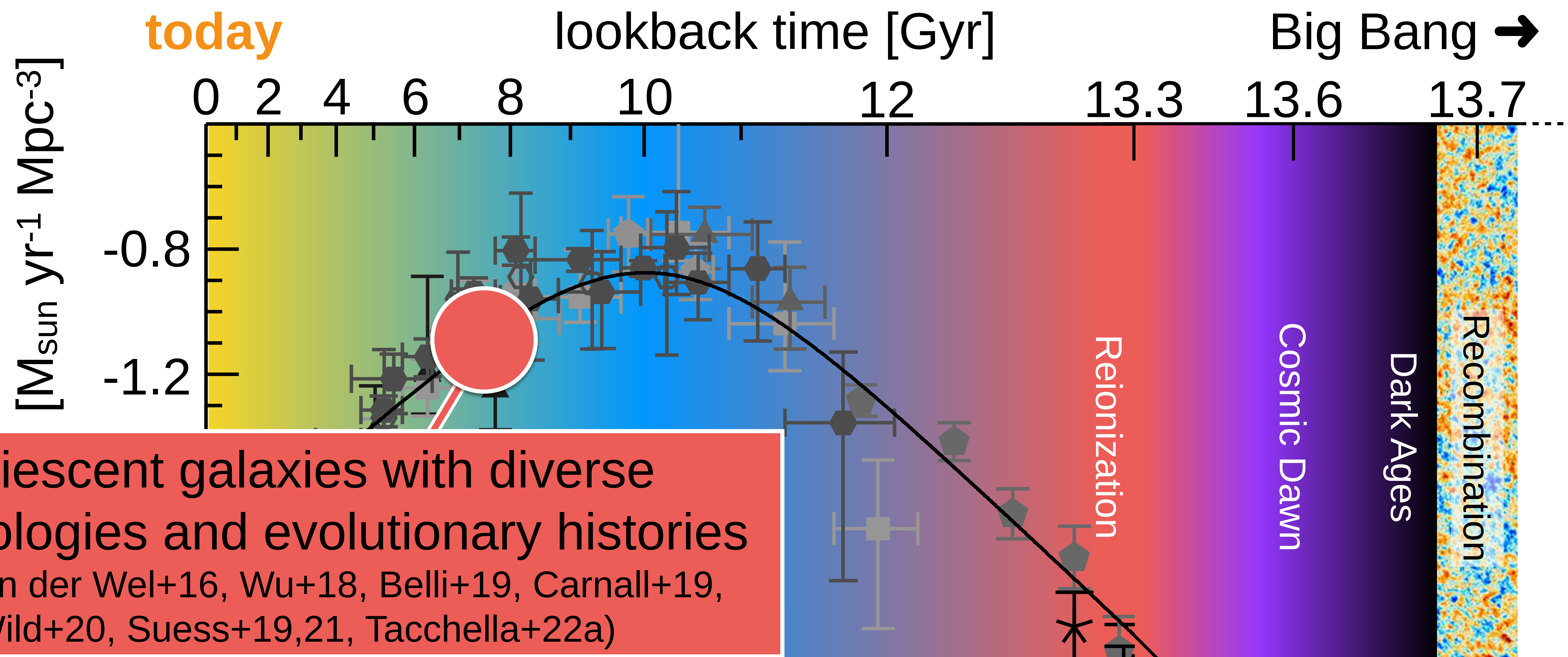
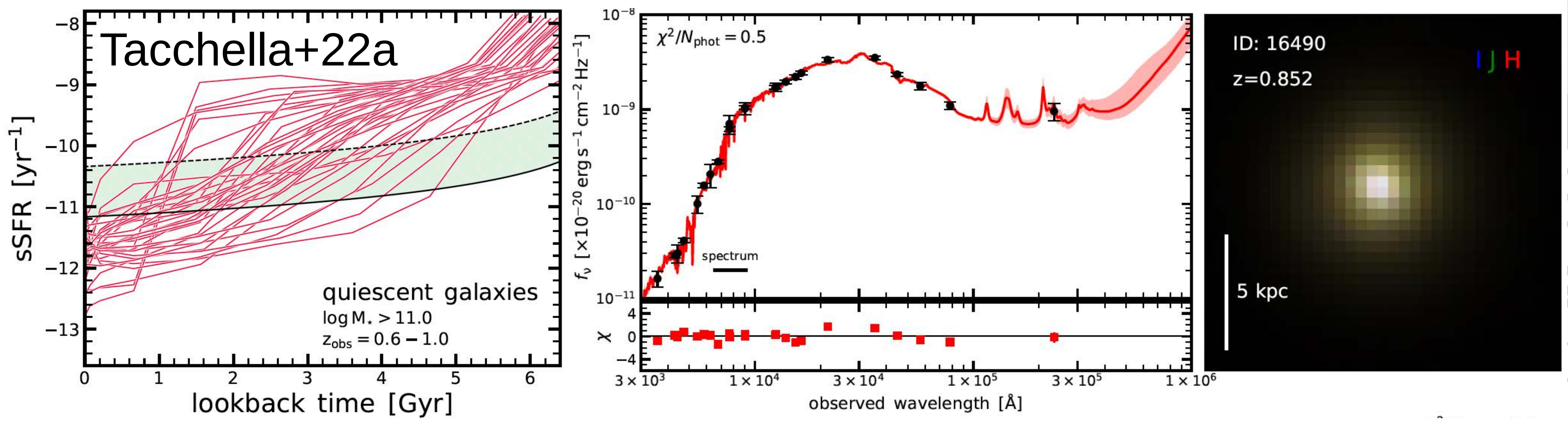


Quiescent galaxies with diverse morphologies and evolutionary histories
(e.g., van der Wel+16, Wu+18, Belli+19, Carnall+19, Wild+20, Suess+19,21, Tacchella+22a)



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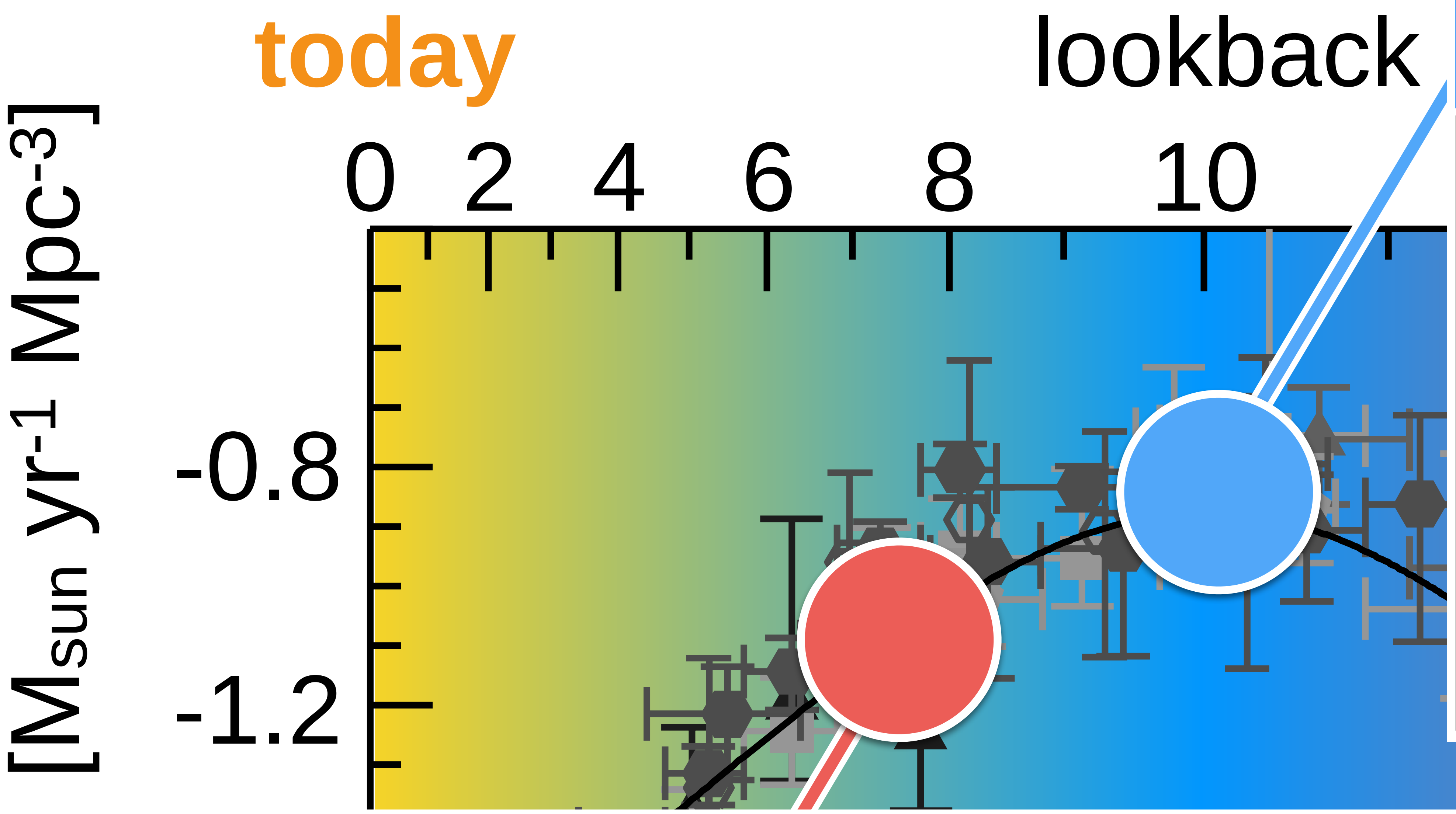
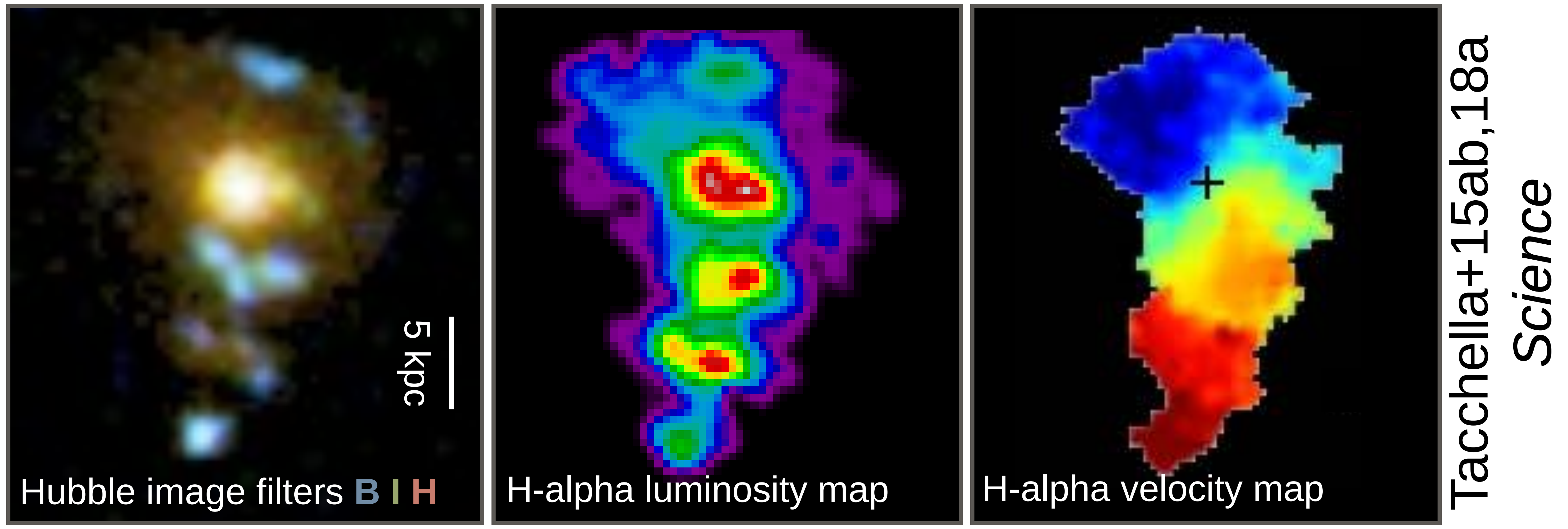
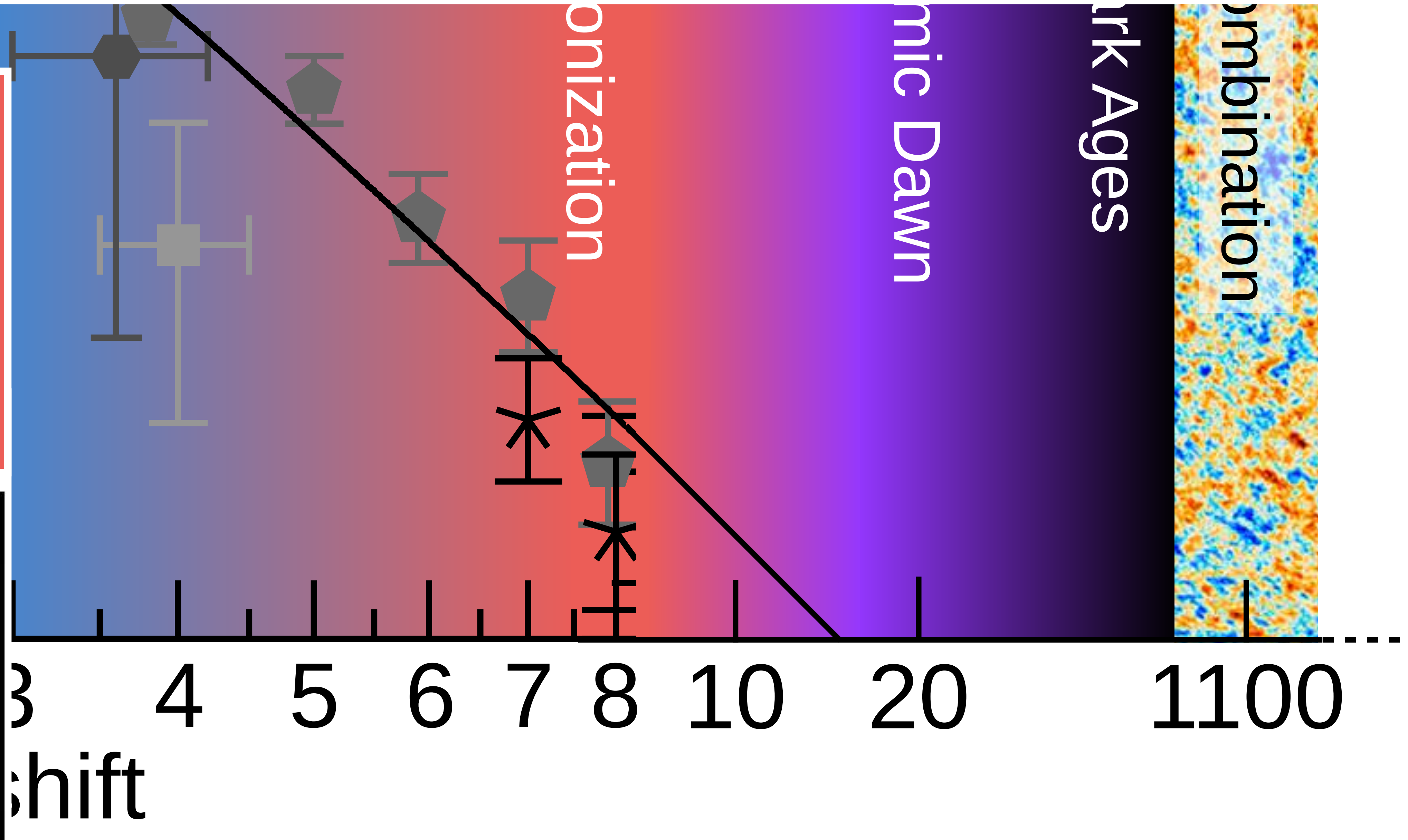


Star-forming galaxies with mature bulges and thick star-forming disks
(e.g., van Dokkum+10, Lang+14, Tacchella+15ab,18 Wisnioski+15, Förster Schreiber & Wuyts 2020)





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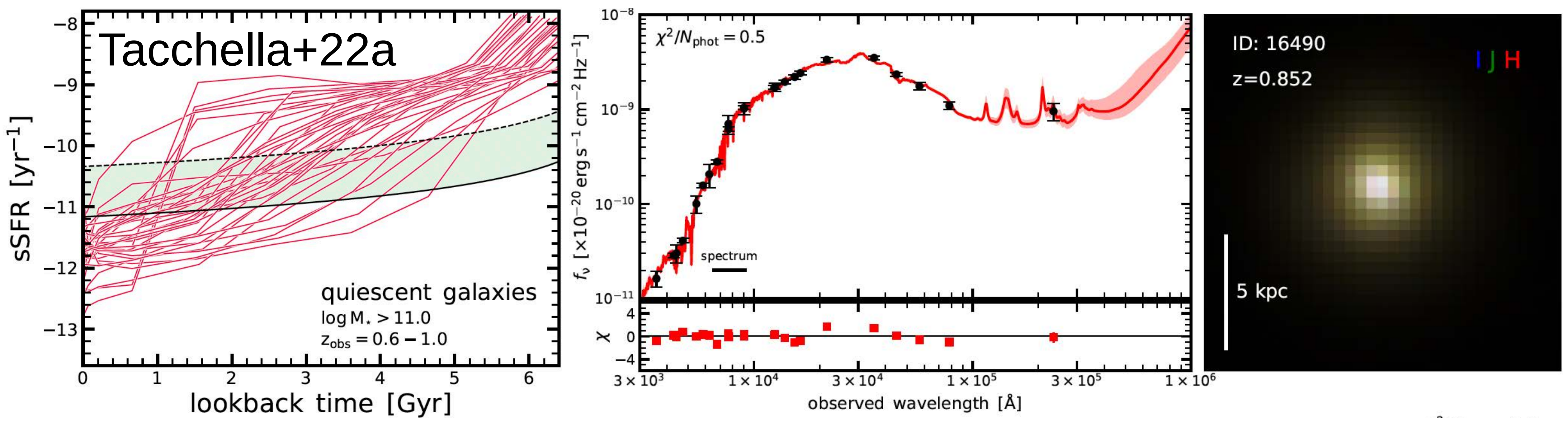

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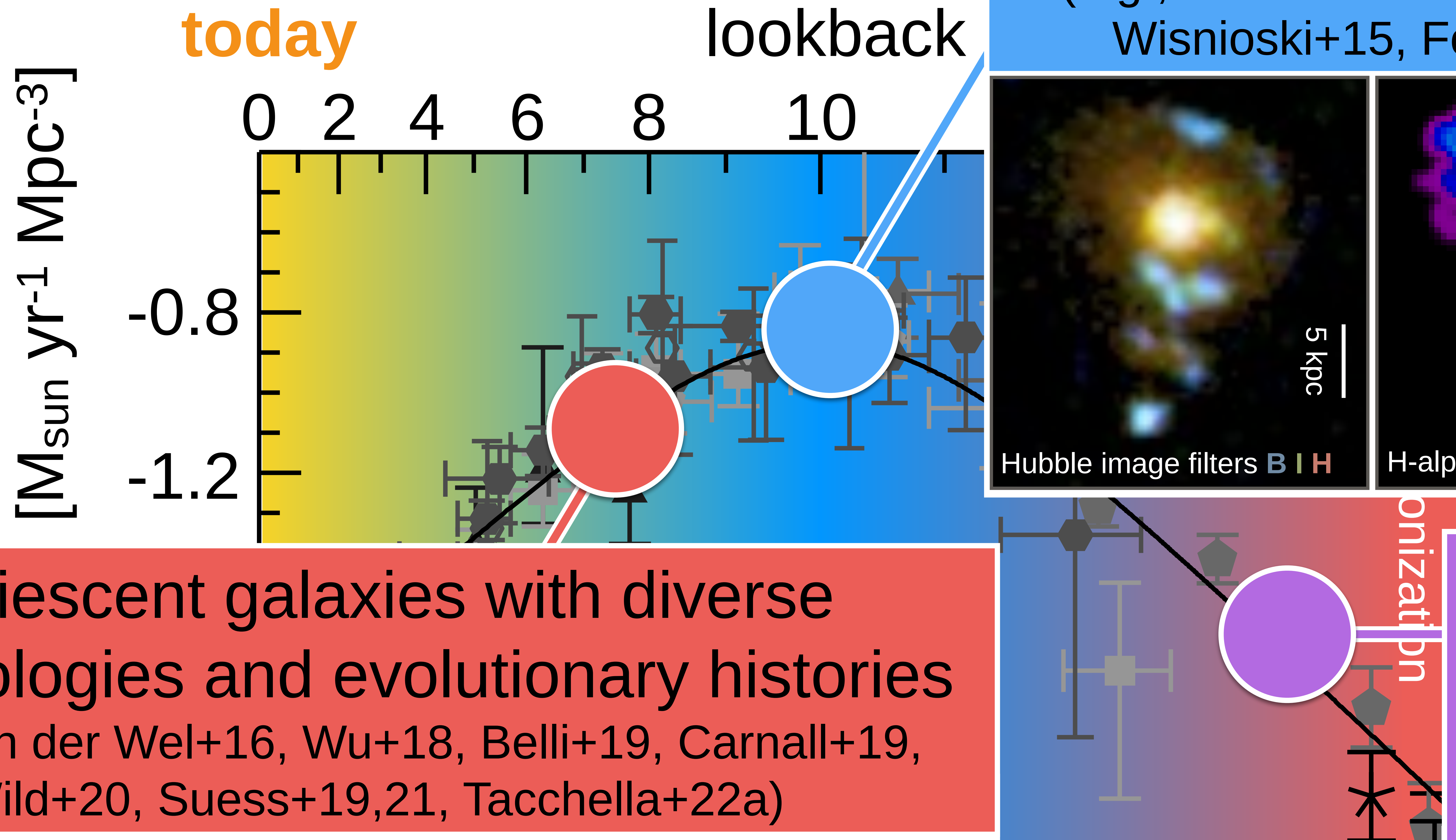

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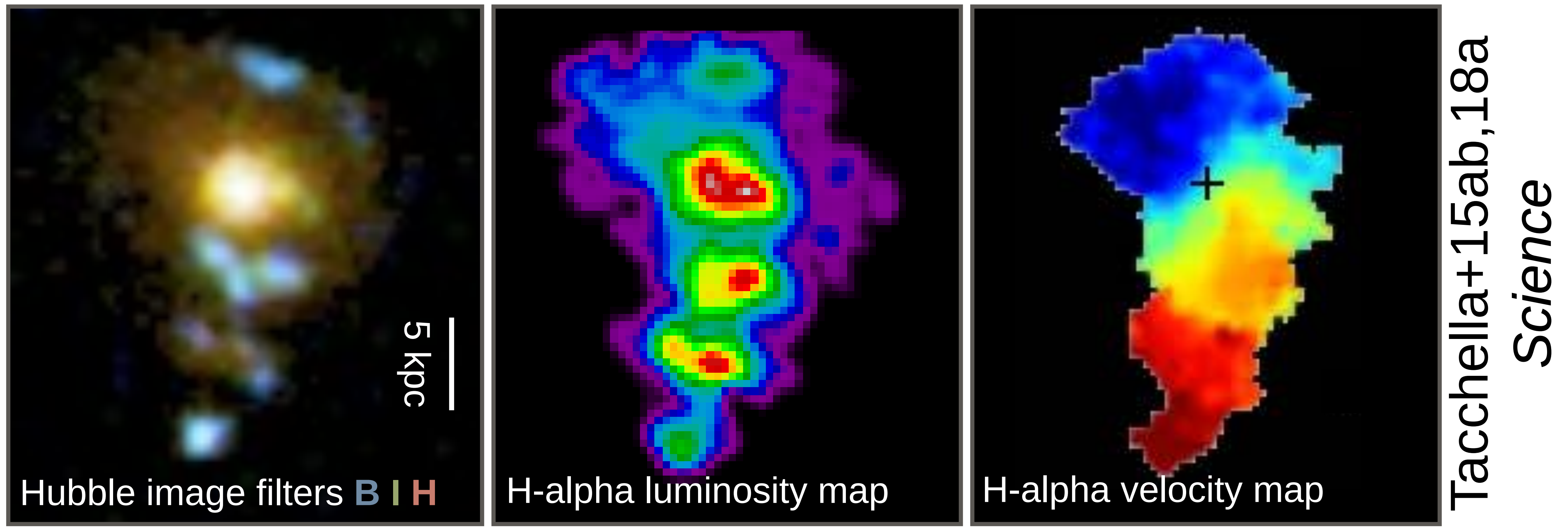

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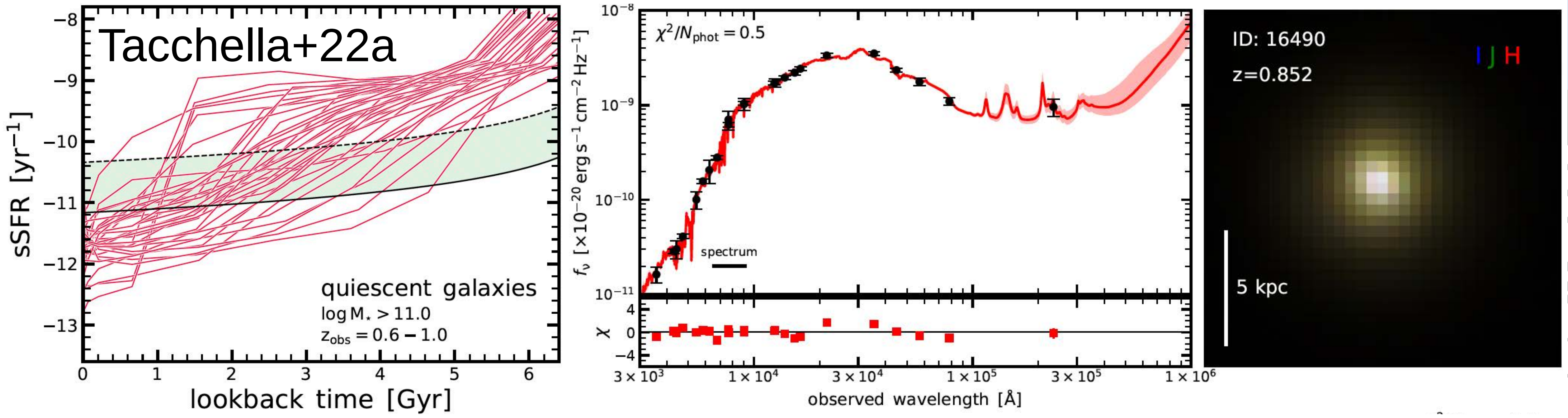
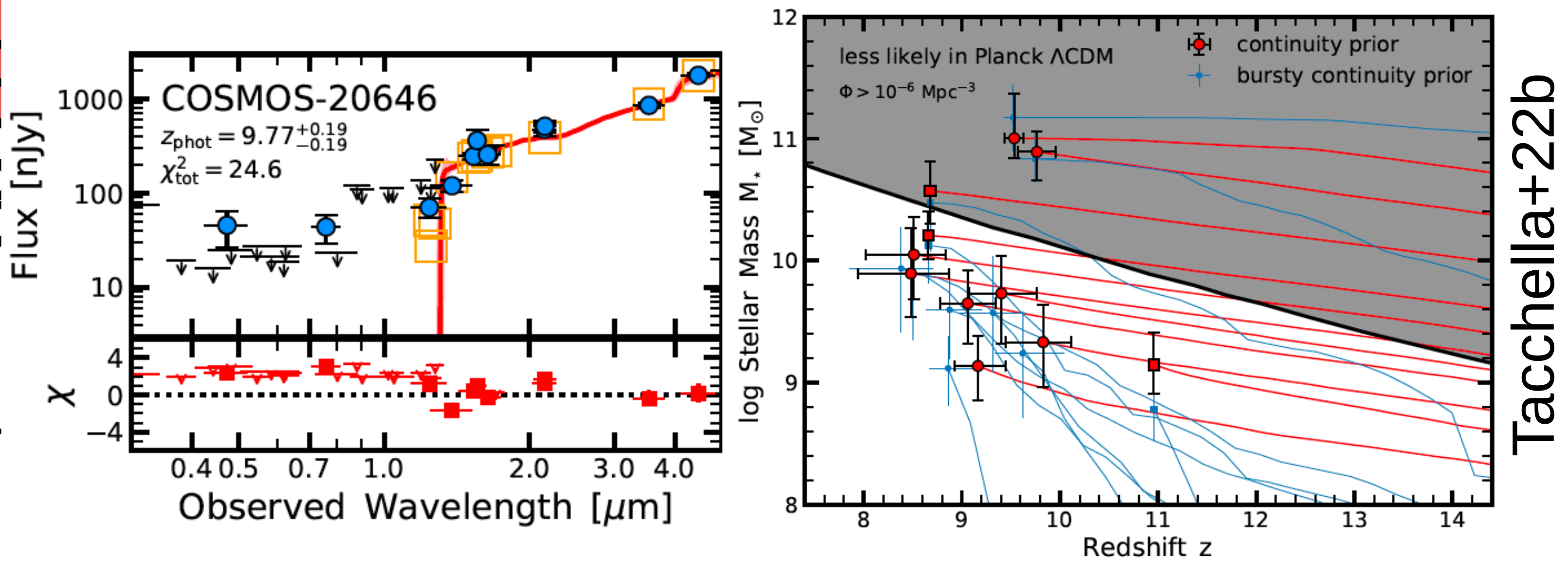


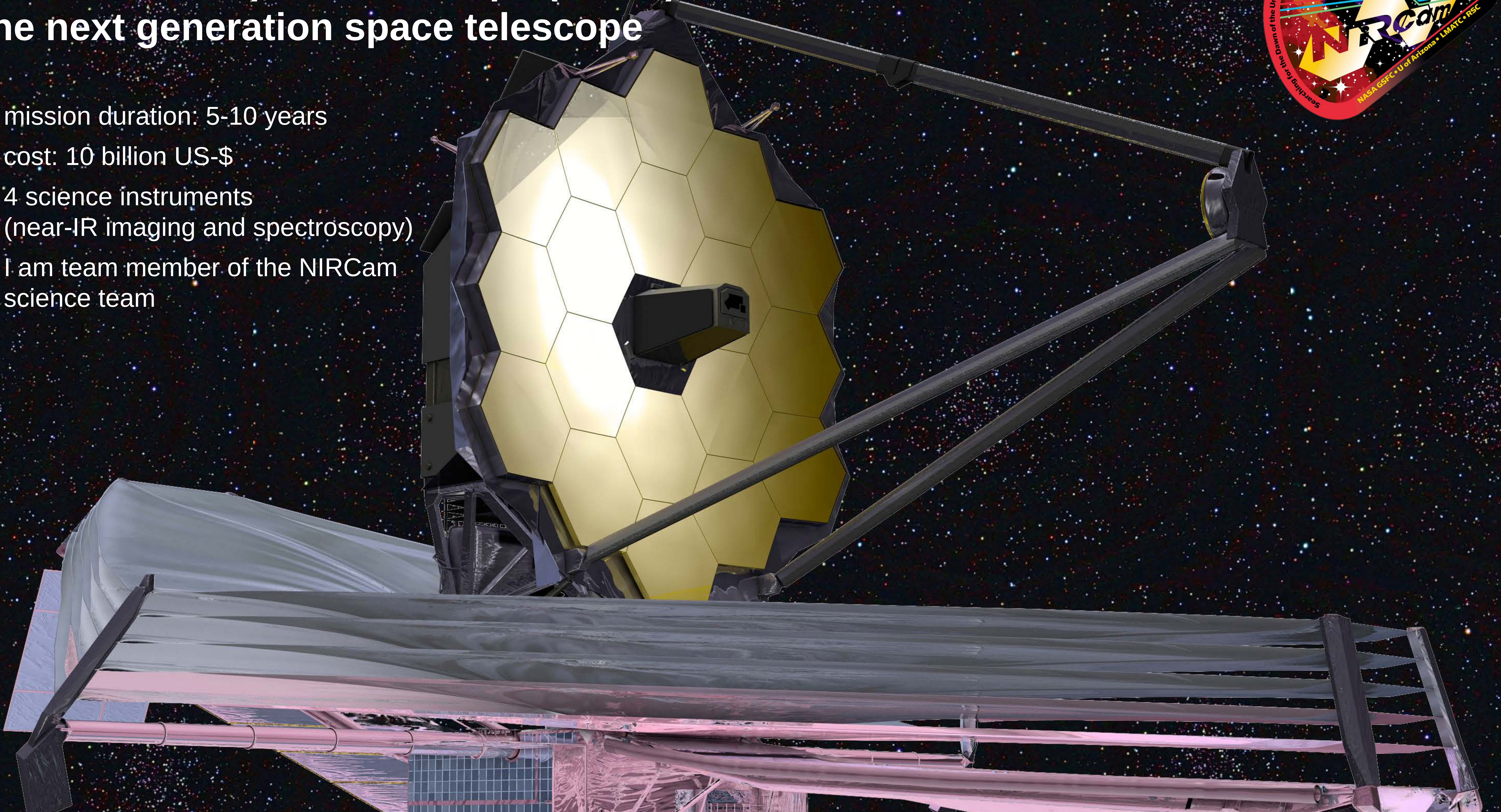
Detection and characterisation (stellar, gas and dust content) of young galaxies at z=6-12

(e.g., Oesch+16, Hashimoto+18, Bouwens+21, Laporte+17,21, Roberts-Borsani+20, Tacchella+22b)



James Webb Space Telescope (JWST)
the next generation space telescope

- mission duration: 5-10 years
- cost: 10 billion US-$
- 4 science instruments
  (near-IR imaging and spectroscopy)
- I am team member of the NIRCam
  science team



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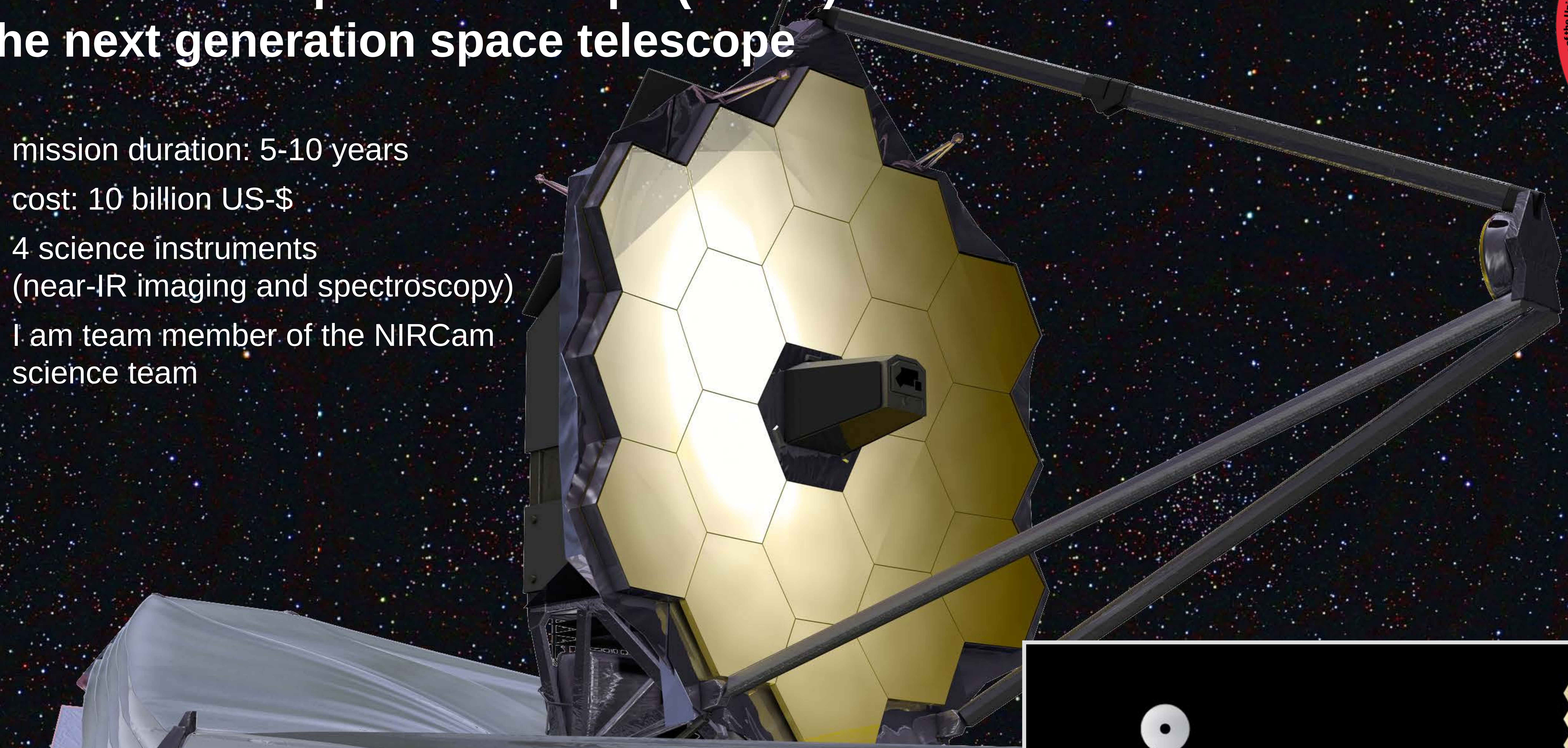
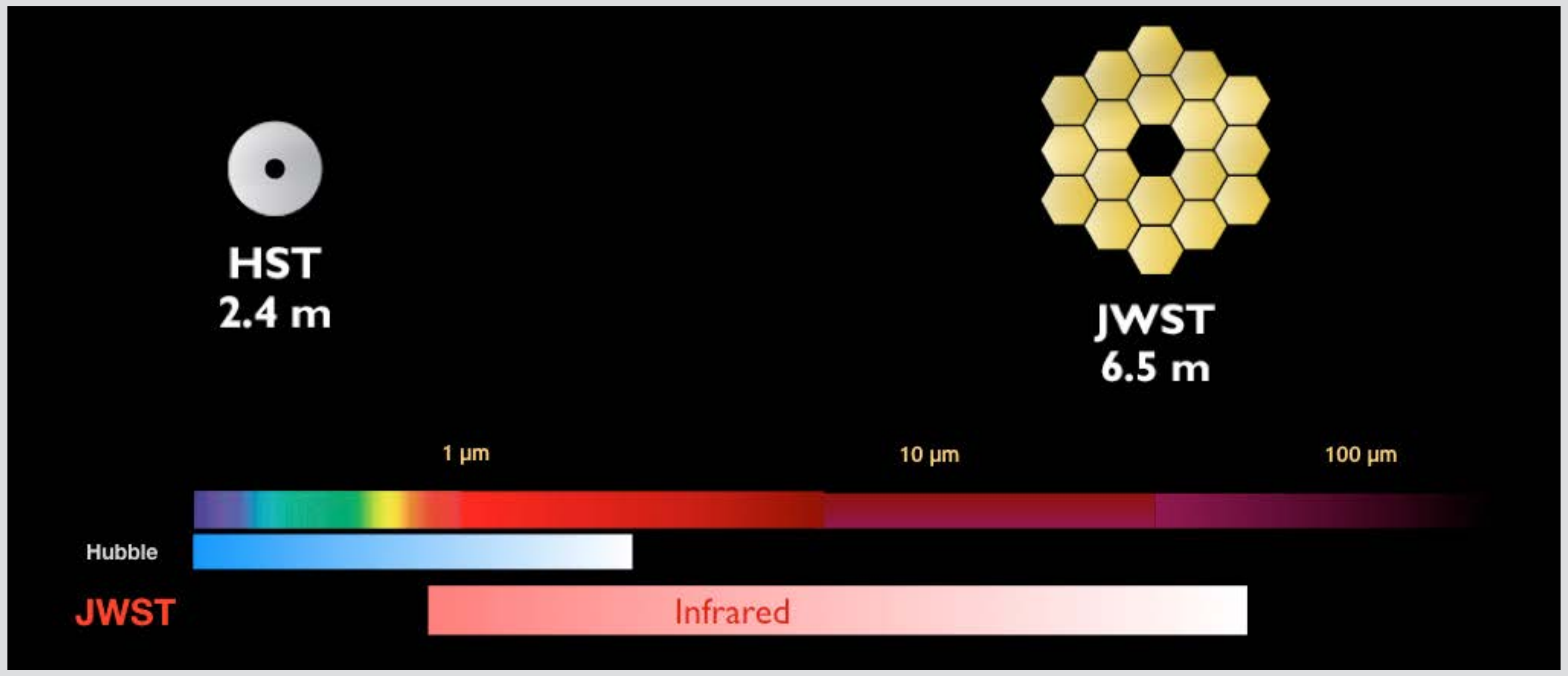
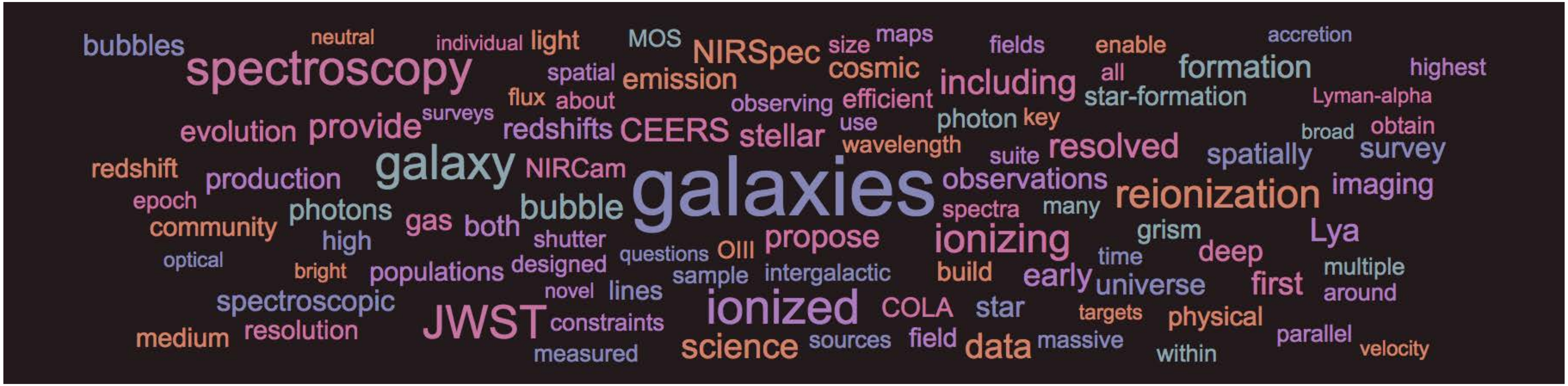




JWST Programmes

- **JWST Advanced Deep Extragalactic Survey (JADES)**
- **The Cosmic Evolution Early Release Science (CEERS) Survey**
- **UDF medium band survey: Using H-alpha emission to reconstruct Ly-alpha escape during the Epoch of Reionization (co-PI Tacchella)**
- Preventing the Slit-Loss Catastrophe Using Flexible, Spatially Resolved Galaxy Models
- Where Cosmic Dawn Breaks First: Mapping the Primordial Overdensity Powering a z~9 Ionized Bubble
- A Pathfinder for JWST Spectroscopy: Deep High Spectral Resolution Maps of Galaxies over 1
- Anatomy of an ionized bubble at z=6.6: Which galaxies reionized the Universe?
- The Stellar and Gas Content of Galaxies at Cosmic Noon



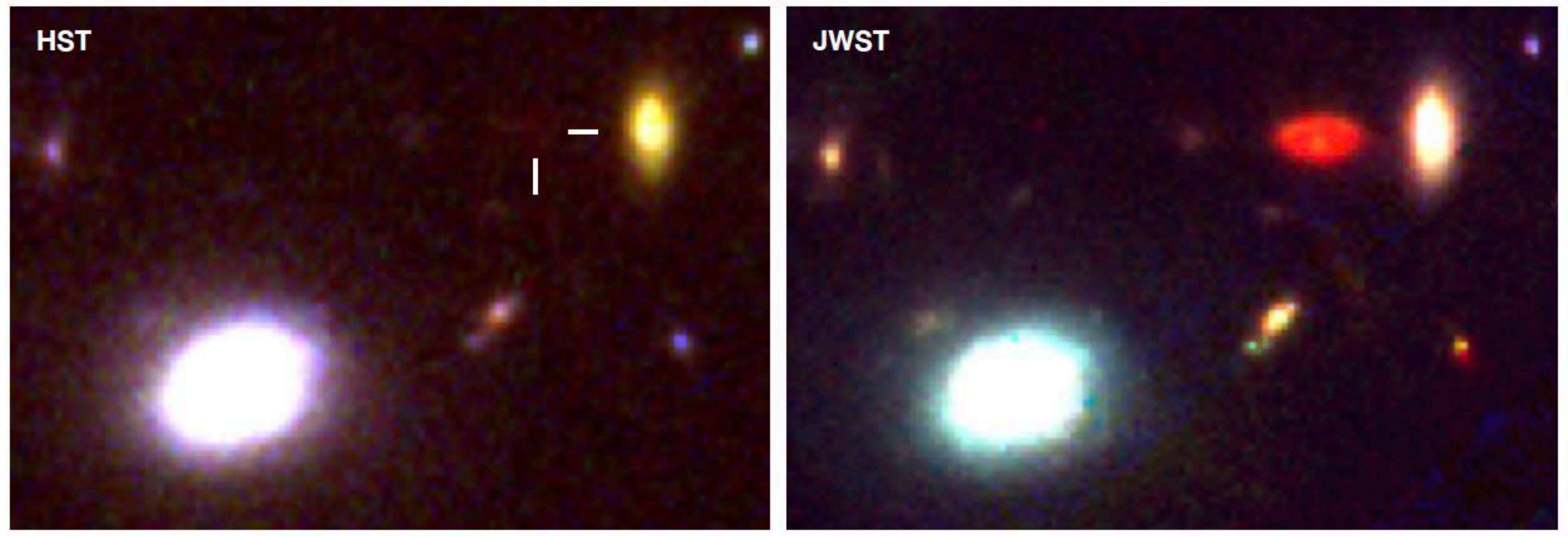
JADES: Overview

- The Extragalactic Theme of NIRCam and NIRSpec is largely centralised onto one monolithic, collaborative programme
  ➜ **JWST Advanced Deep Extragalactic Survey (JADES).**
- Deep imaging and spectroscopy of GOODS-S and GOODS-N, using ~800+800 hrs of pure+parallel in Cycle 1 and 2
  ➜ **Foundation of early universe science for 2020s.**
- Images and spectra of unparalleled depth of thousands of galaxies at z=2-10 with NIRSpec follow-up in the same cycle.
- Full joint collaboration between NIRCam and NIRSpec, plus a small admixture of MIRI-US.

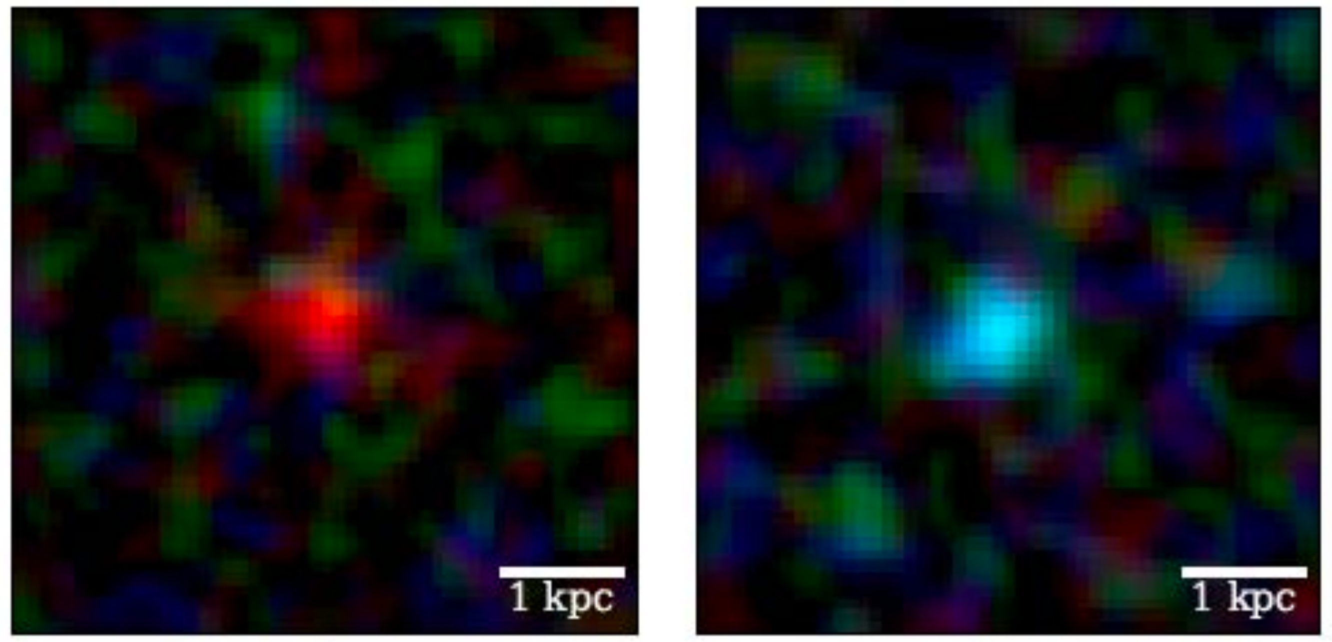
F090W
F200W
F444W

JWST First Results

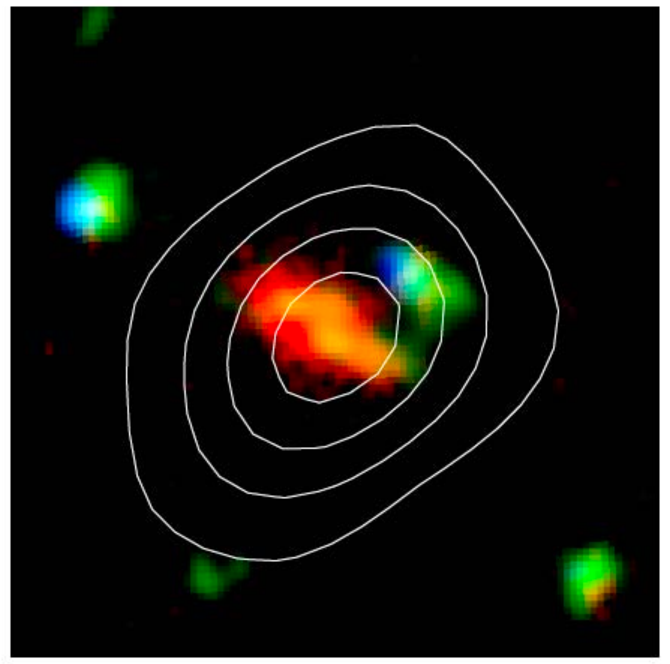
Nelson (incl. ST) et al. (2022):
JWST reveals a population of ultra-red, flattened disk galaxies at 2<z<6 previously missed by HST

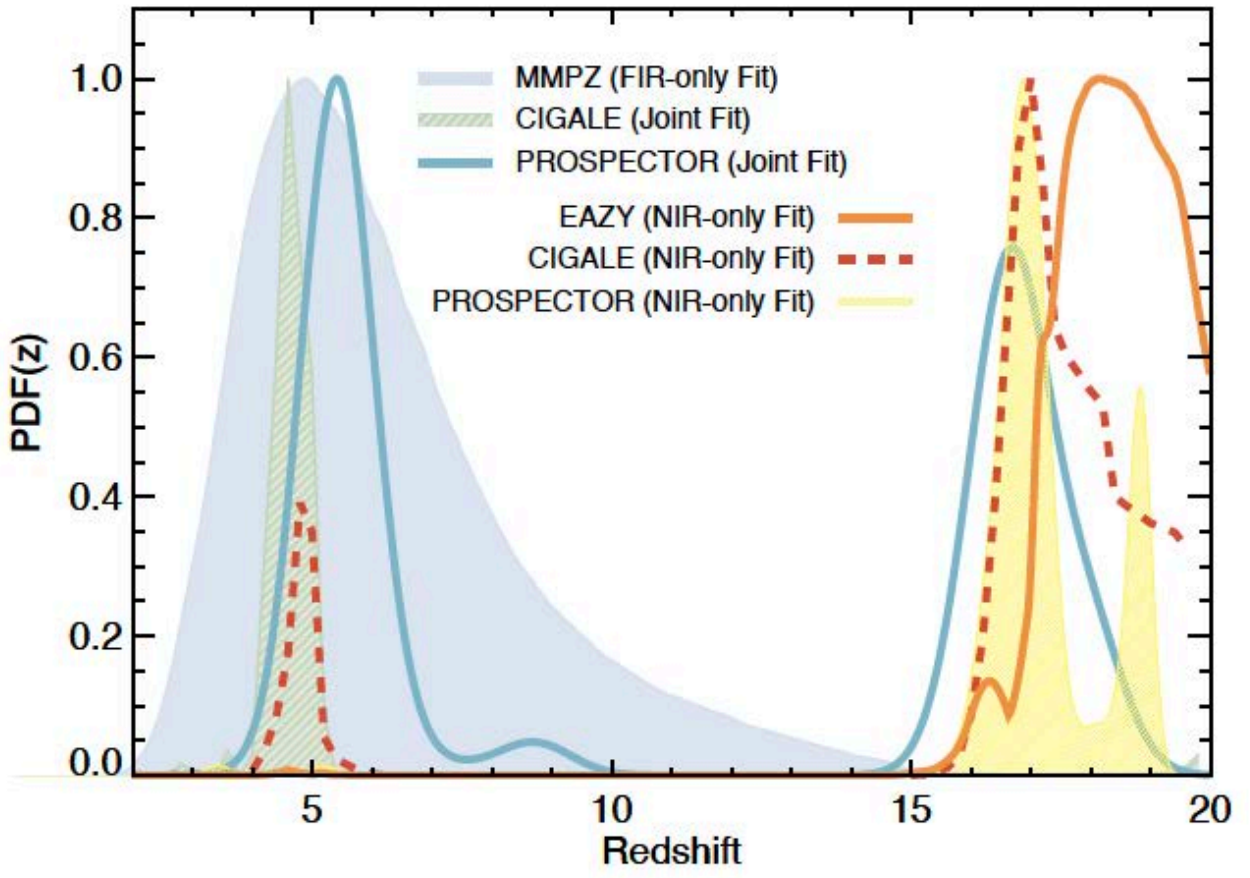


Finkelstein (incl. ST) et al. (2022):
A Long Time Ago in a Galaxy Far, Far Away: A Candidate z~11 Galaxy in Early JWST CEERS Imaging

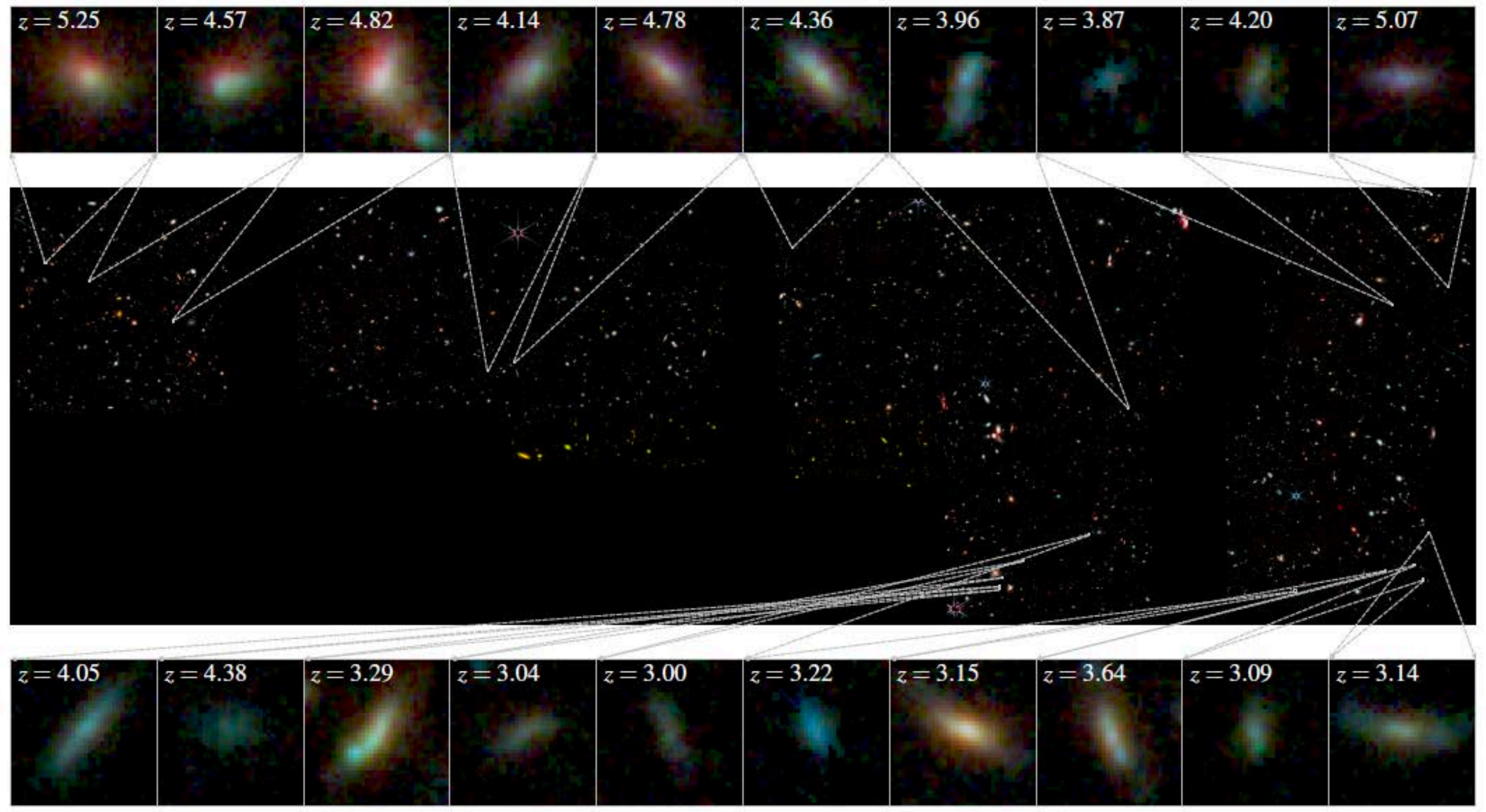


Zavala (incl. ST) et al. (2022):
A dusty starburst masquerading as an ultra-high redshift galaxy in JWST CEERS observations

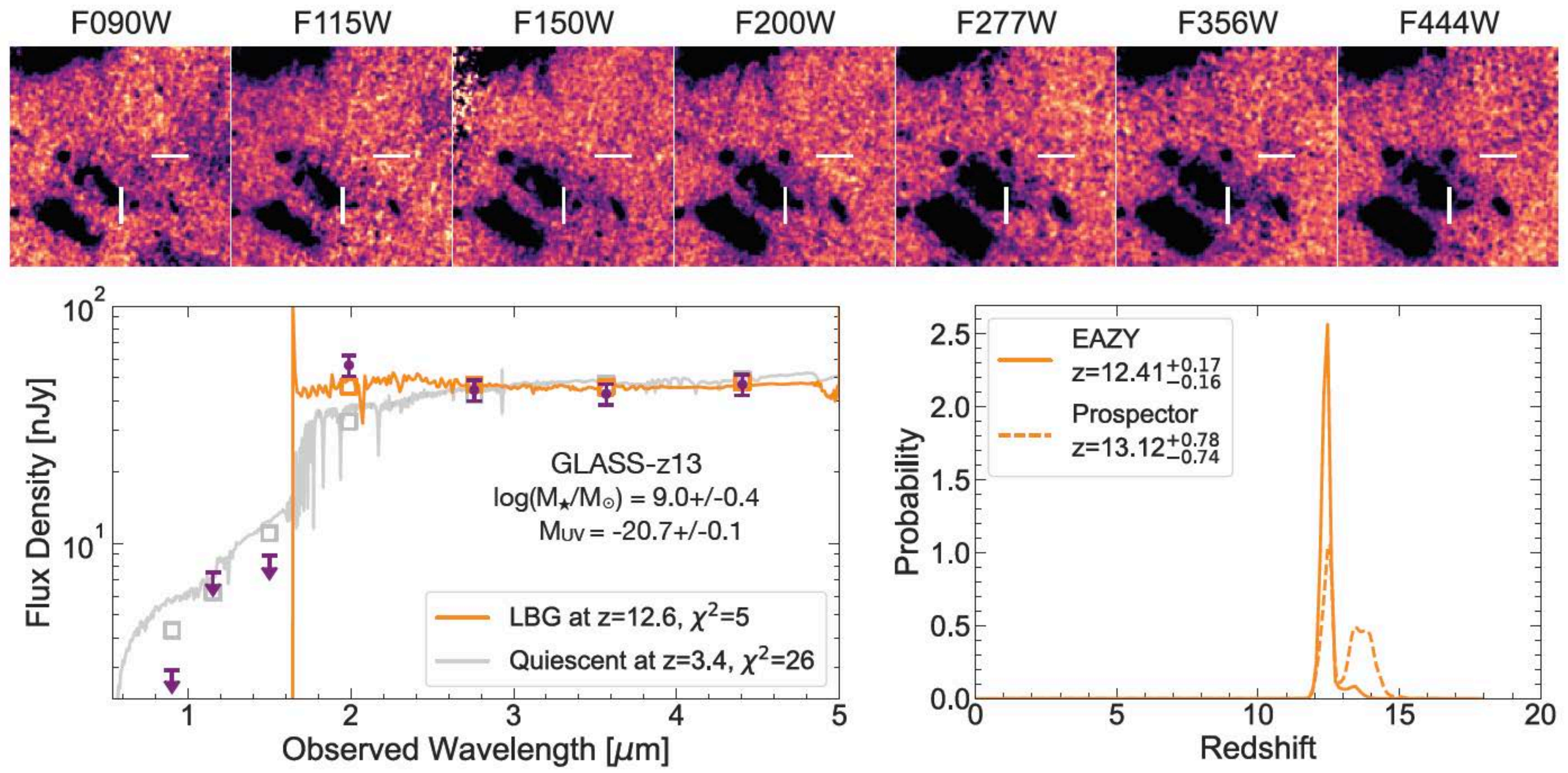




Robertson, Tacchella, et al. (2022):
Morpheus Reveals Distant Disk Galaxy Morphologies with JWST: The First AI/ML Analysis of JWST Images

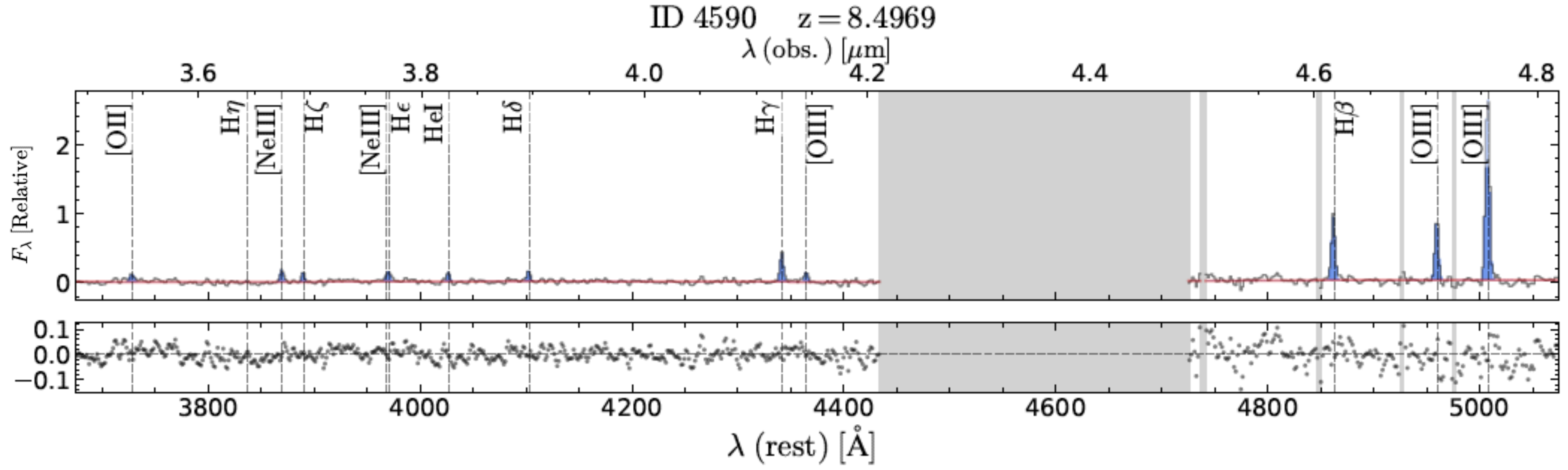


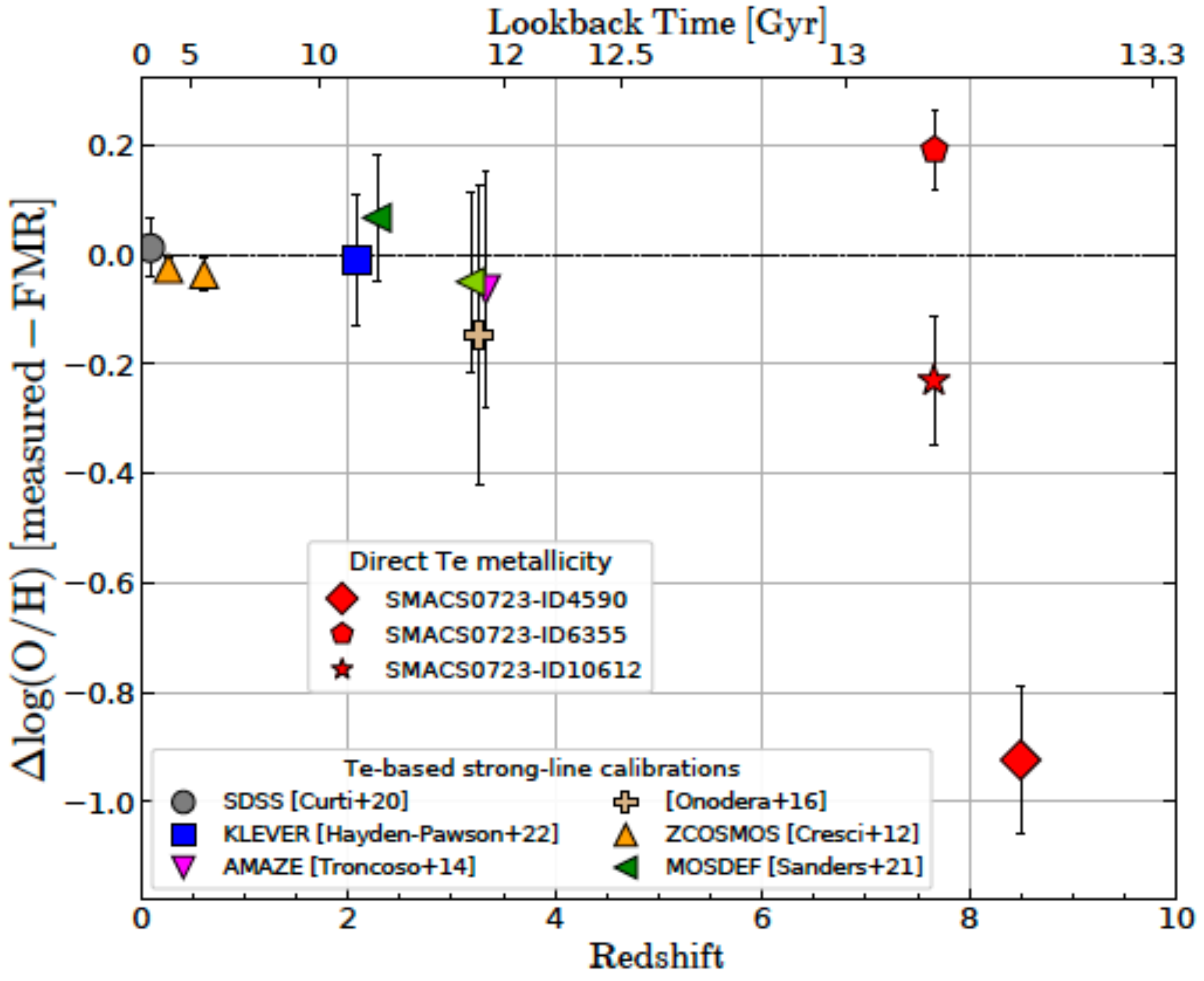
Naidu (incl. ST) et al. (2022):
Two Remarkably Luminous Galaxy Candidates at z=11–13 Revealed by JWST



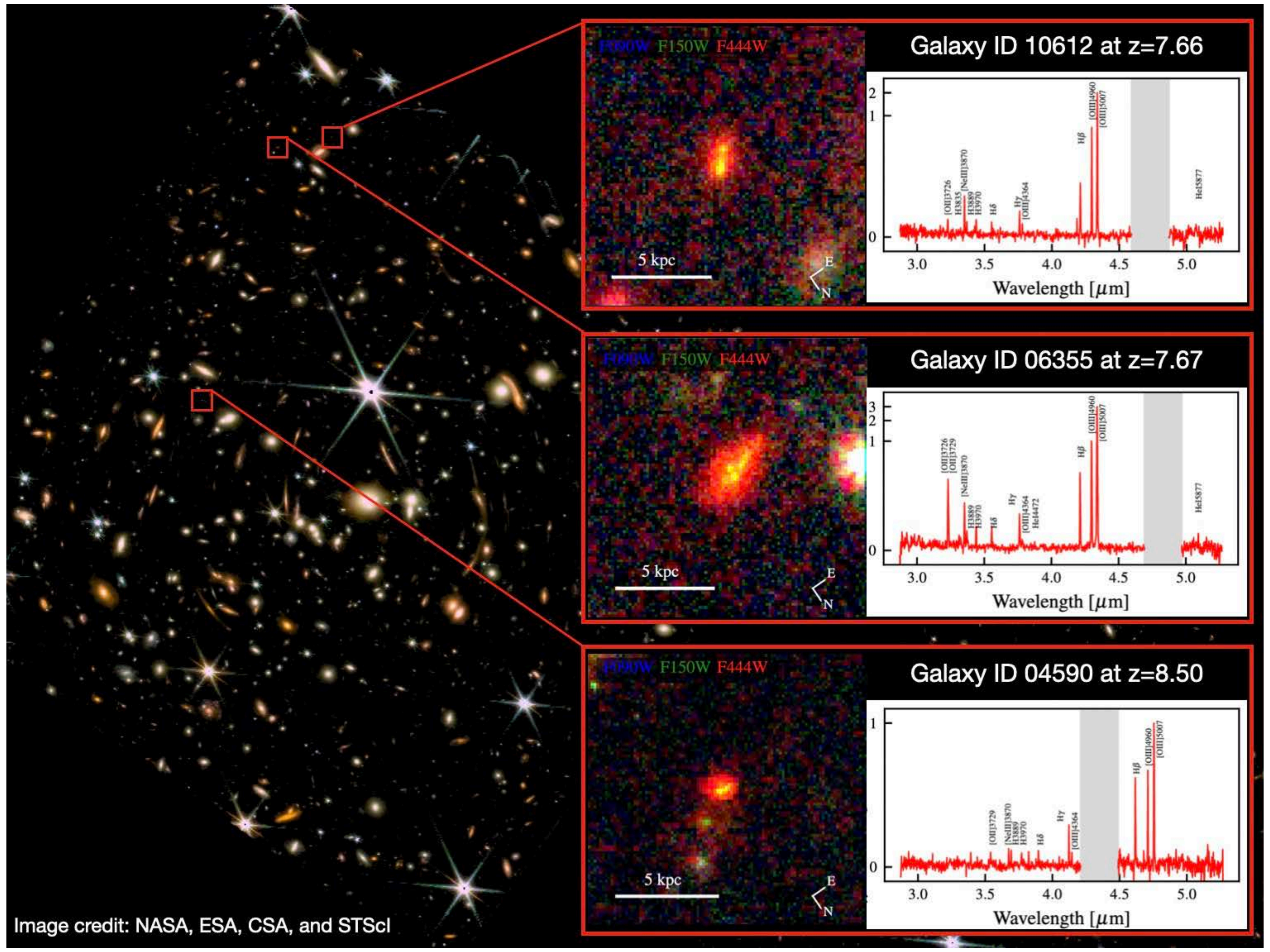
JWST First Results

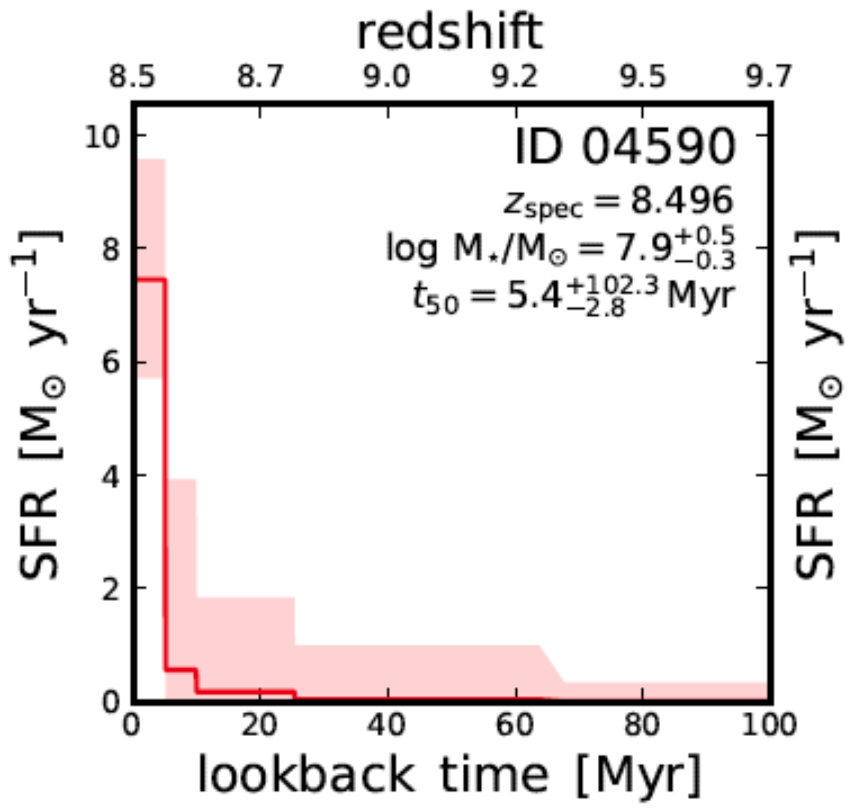
Curti (incl. ST) et al. (2022):
The chemical enrichment in the early Universe as probed by JWST via direct metallicity measurements at z~8

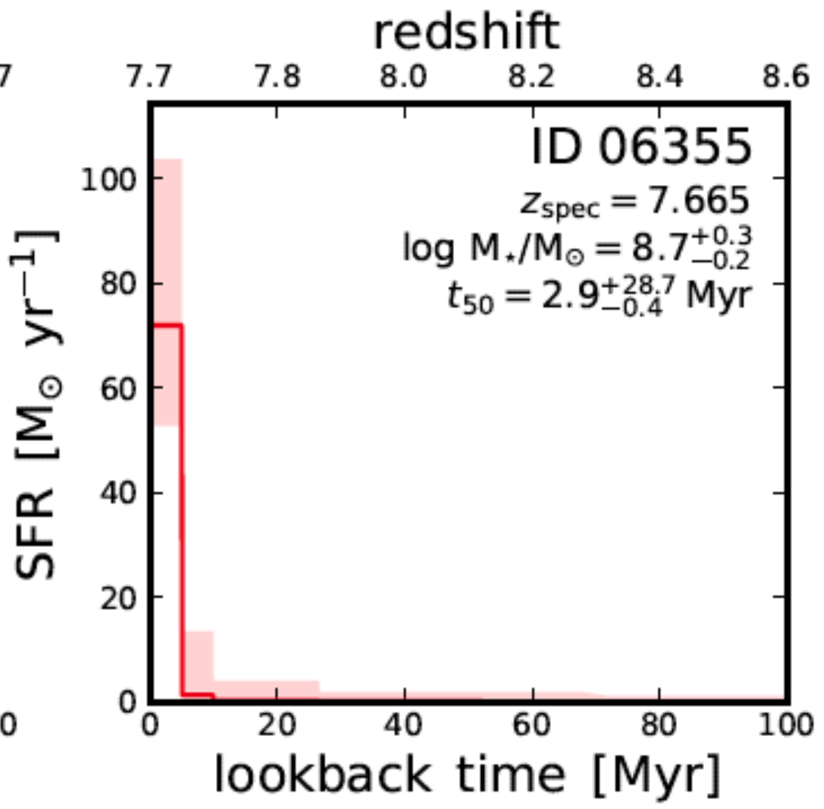


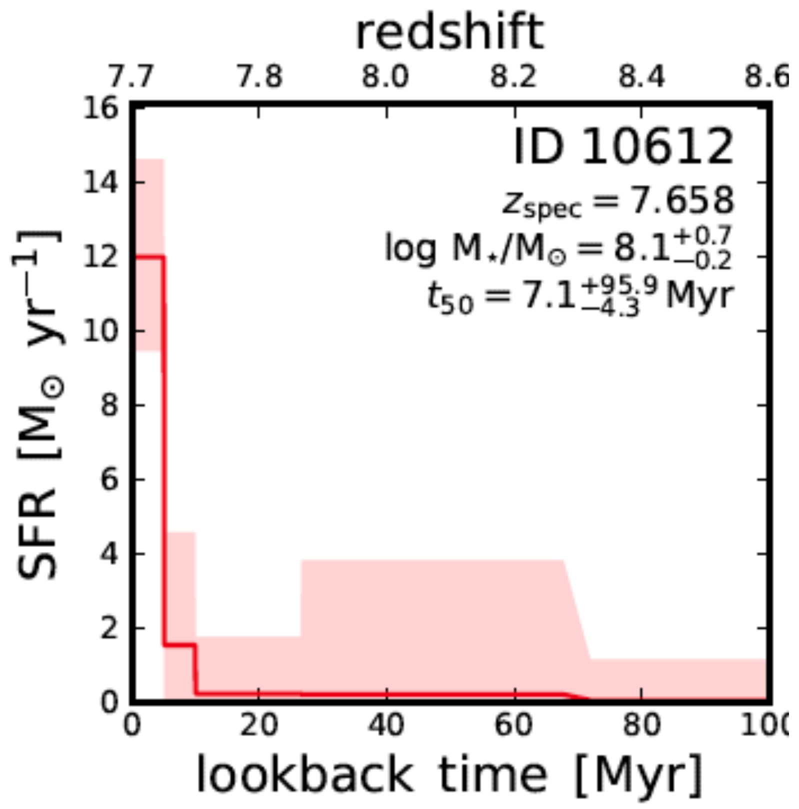


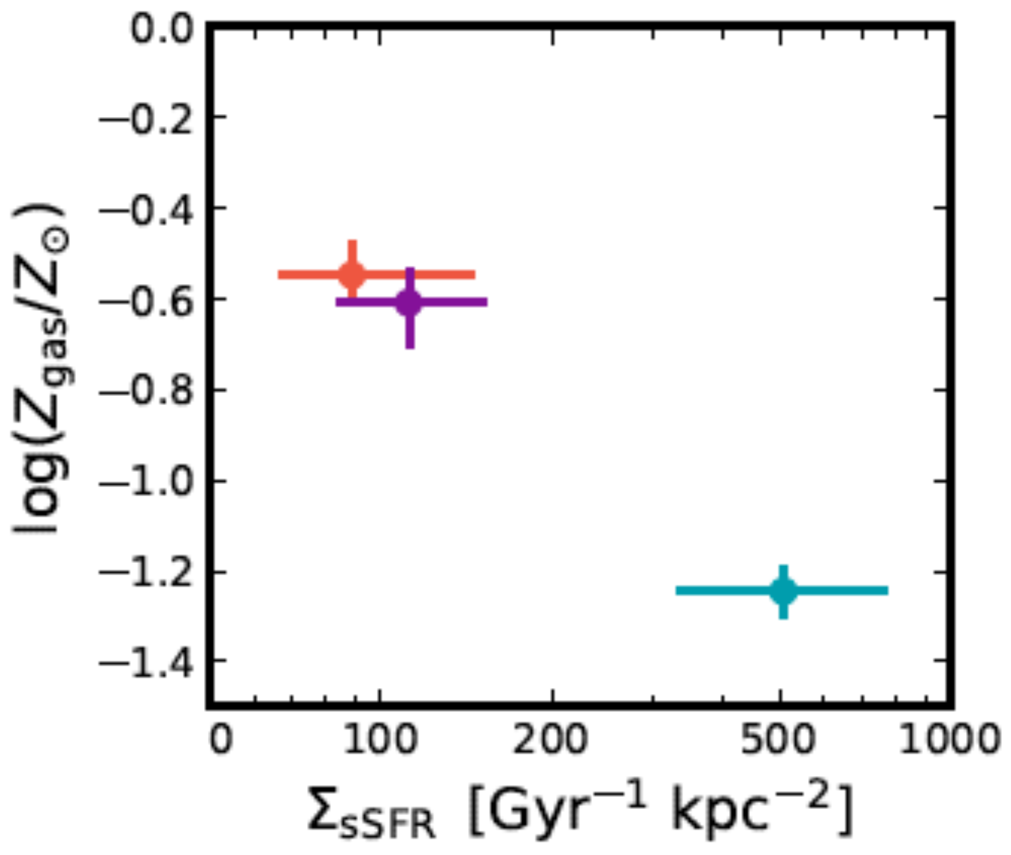
Tacchella et al. (2022d):
Interstellar medium and stellar populations of young galaxies with rising star formation and evolving gas reservoirs











Comparison Theory — Observations

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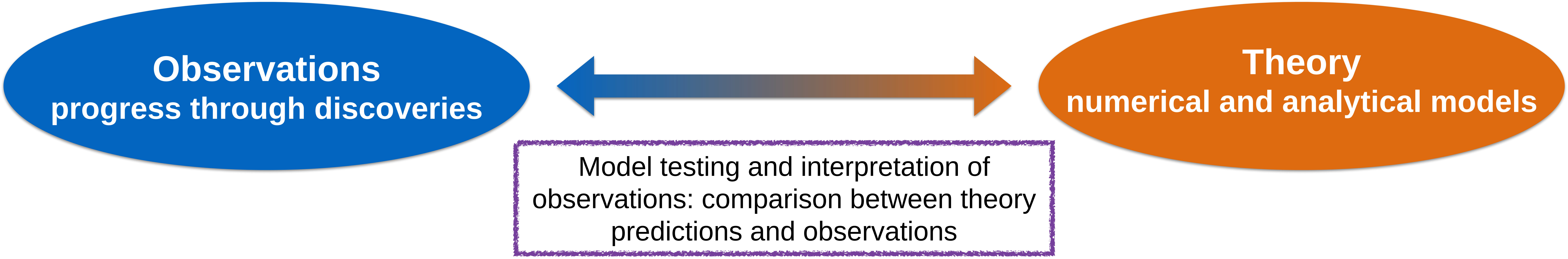

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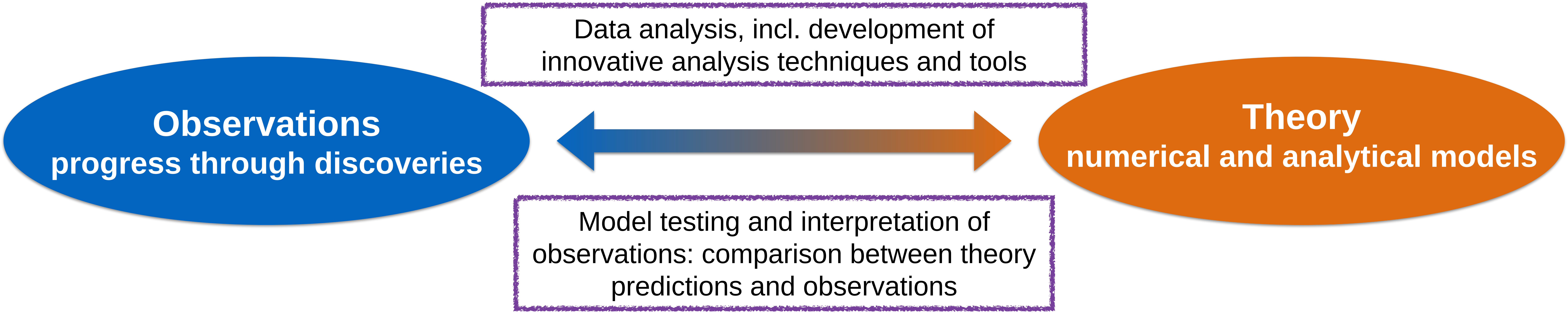


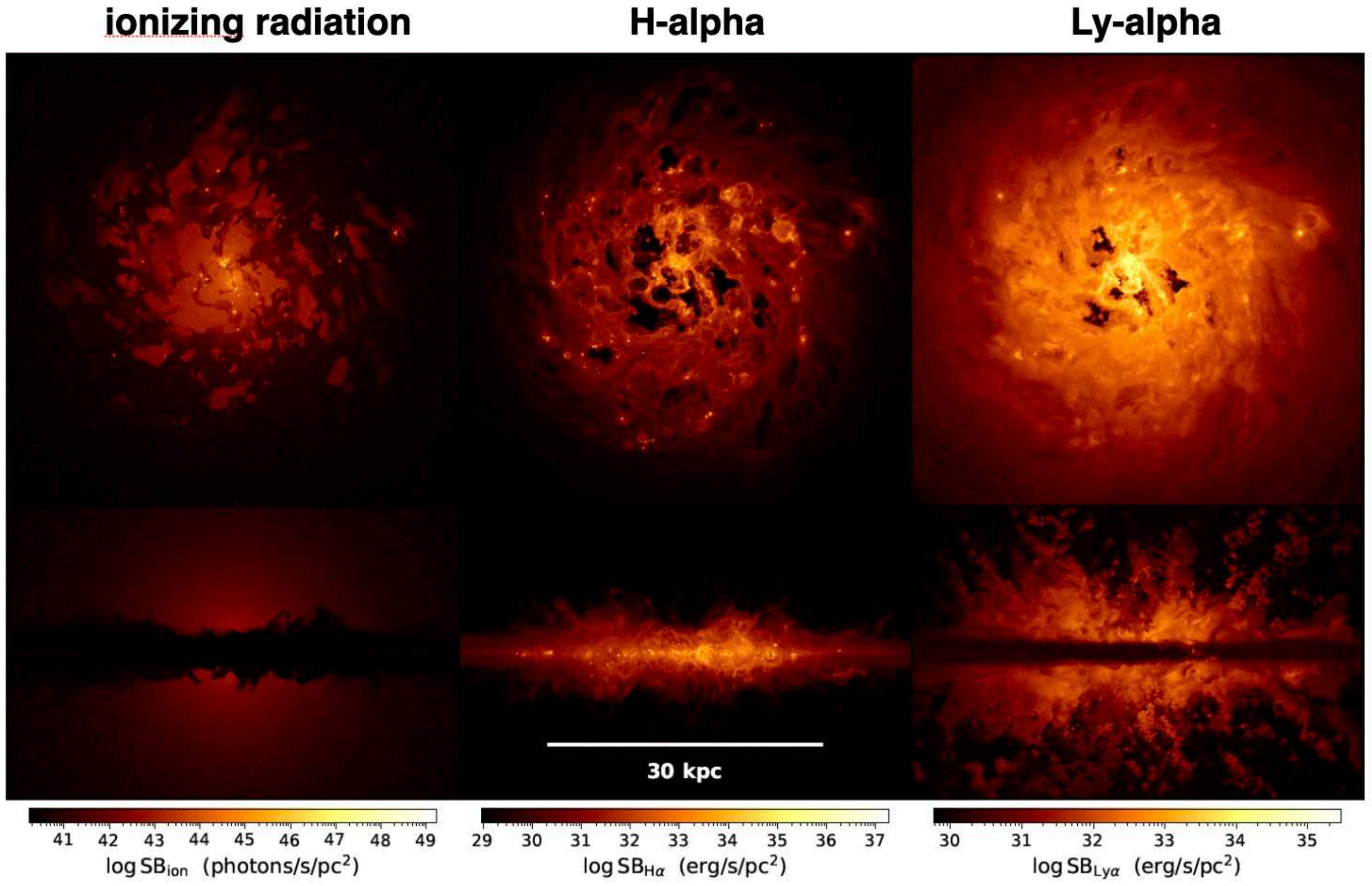
Comparison Theory — Observations

Data analysis, incl. development of innovative analysis techniques and tools

Observations
progress through discoveries

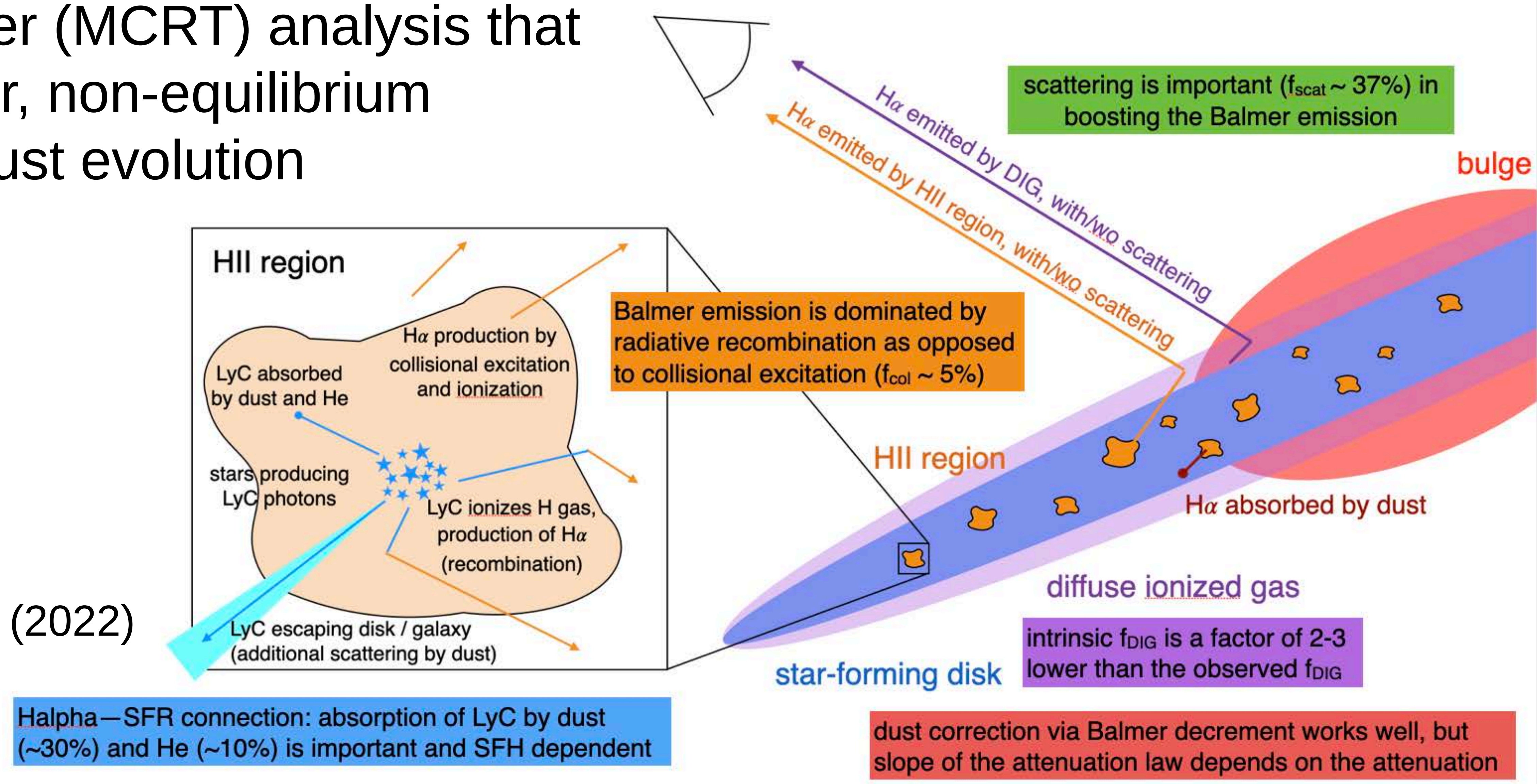
Theory
numerical and analytical models

Model testing and interpretation of observations: comparison between theory predictions and observations



detailed radiative transfer (MCRT) analysis that include radiative transfer, non-equilibrium thermochemistry, and dust evolution

Smith, Kannan, Tacchella et al. (2022)
Tacchella et al. (2022c)



Credits:
IMAGE: NASA, ESA, CSA, STScI

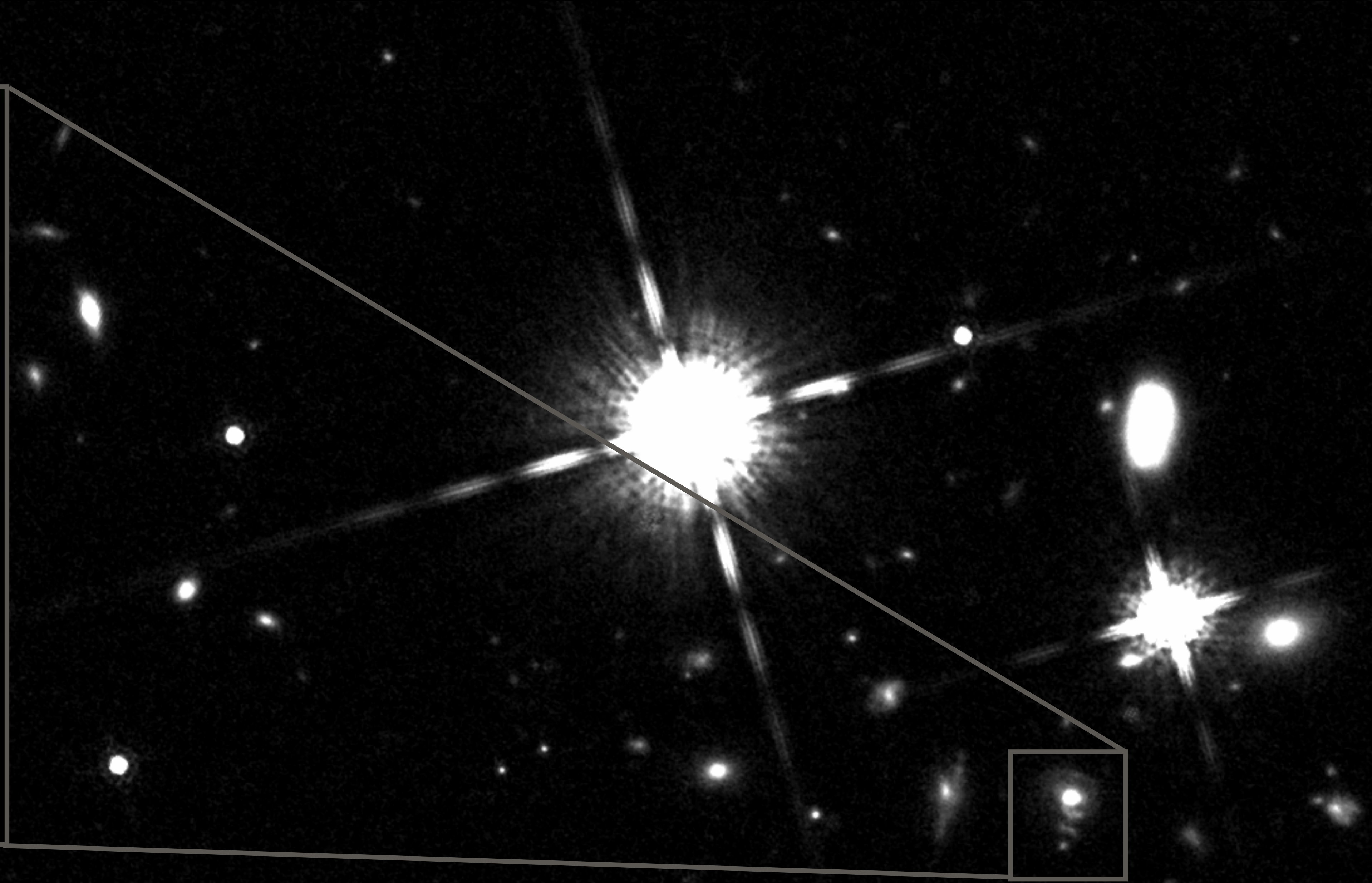
Extra Slides

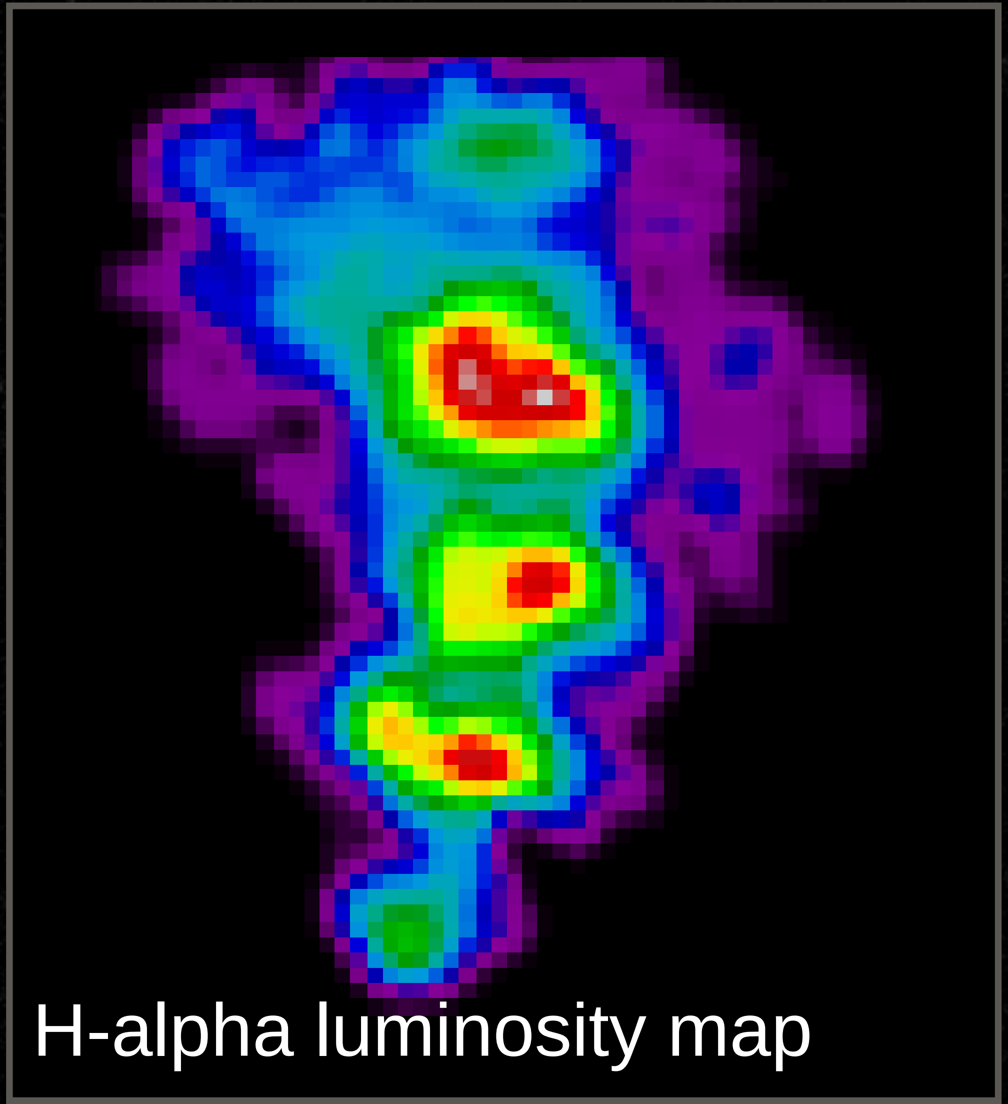
Evidence for mature bulges 3 billion years after the Big Bang

Using the largest adaptive optics (AO) spatially-resolved spectroscopic survey, we discovered mature bulges in young galaxies

Tacchella+ *Science* (2015b); Tacchella+ (2018)

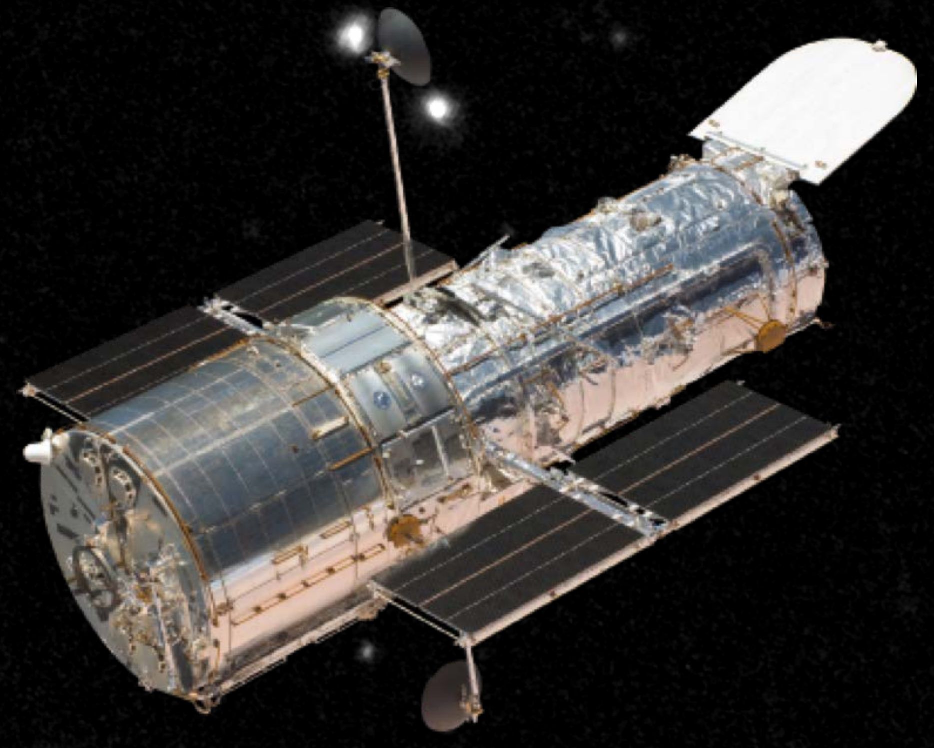
Hubble image filters B I H



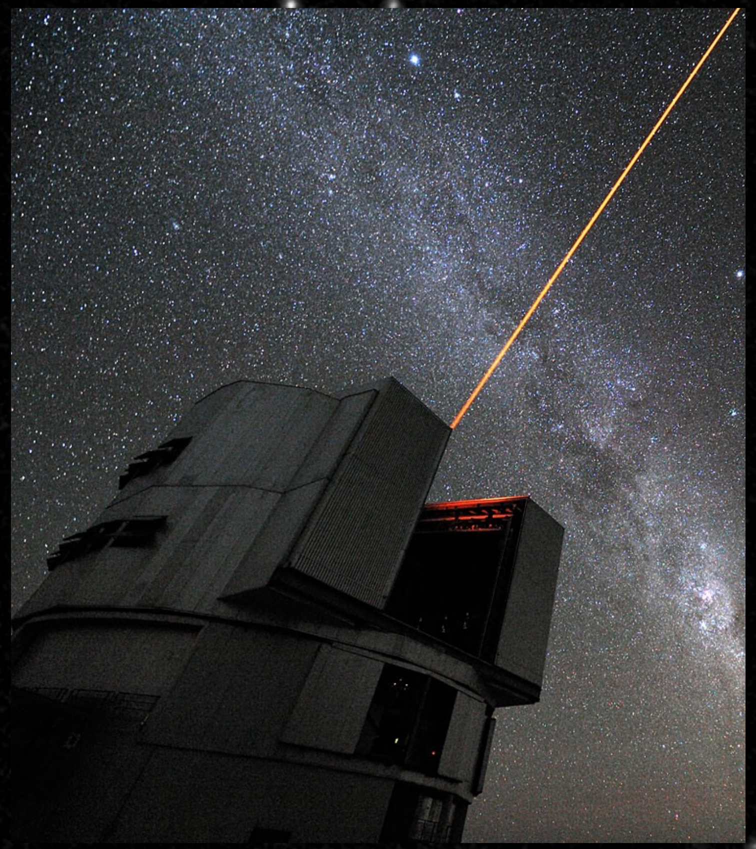


H-alpha luminosity map

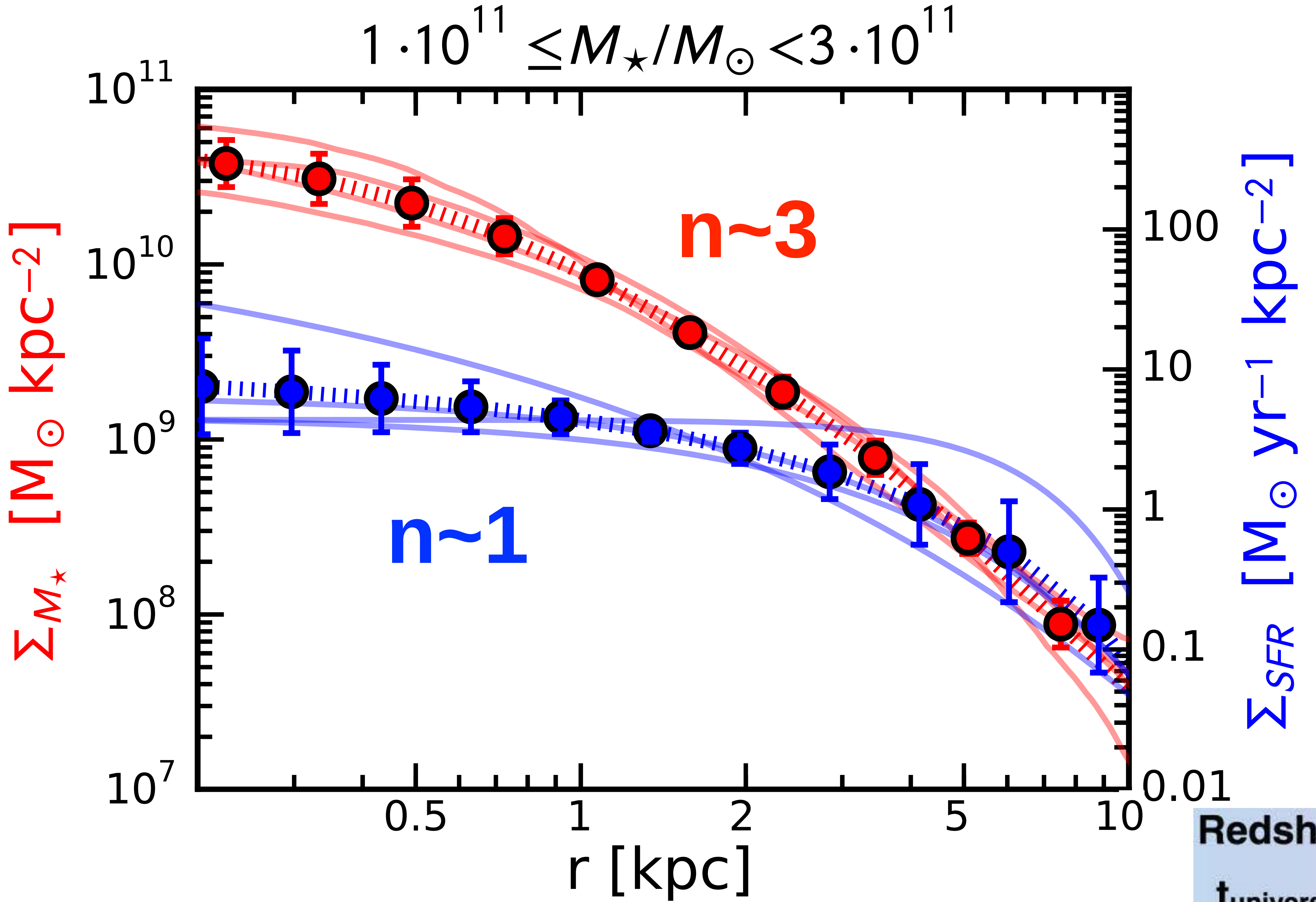
H-alpha velocity map



Tacchella+ (2015a)

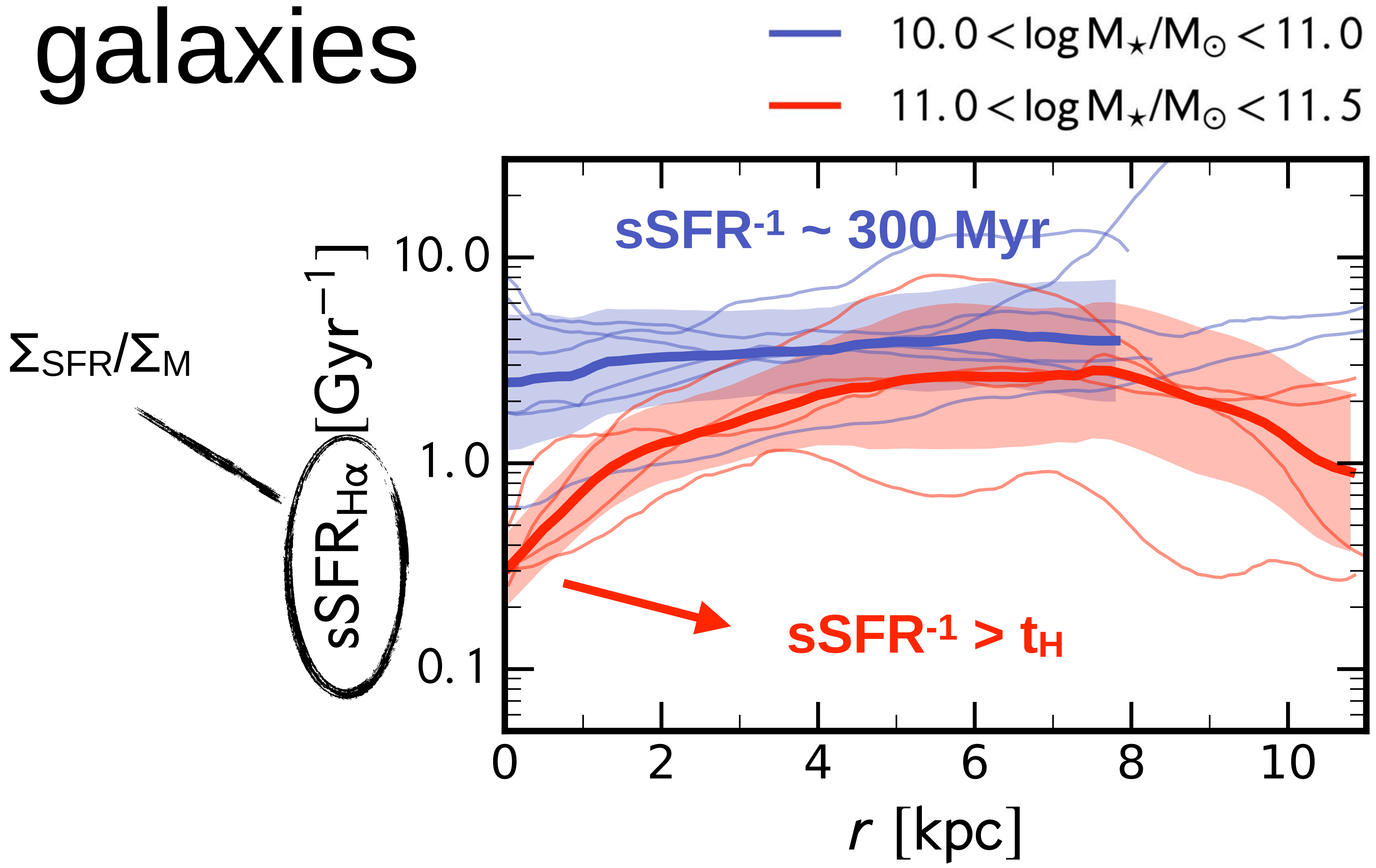


Distribution of star formation in young galaxies

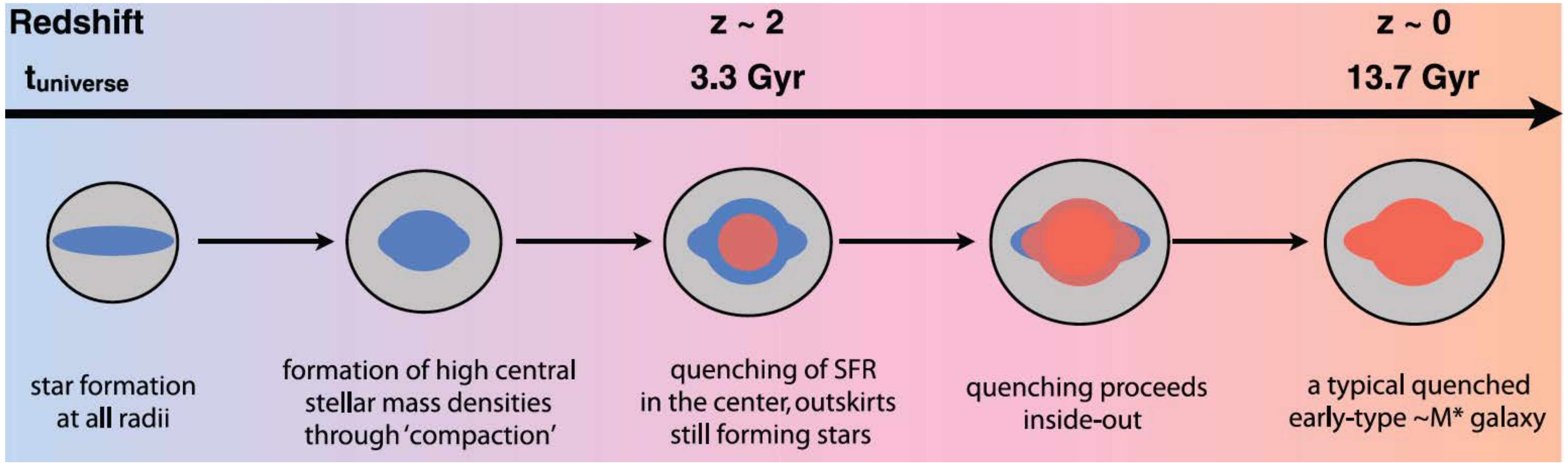


Tacchella+ *Science* (2015b)
Tacchella+ (2018)

Discovery:
Galaxies cease their star formation in their cores first!
➜ inside-out quenching

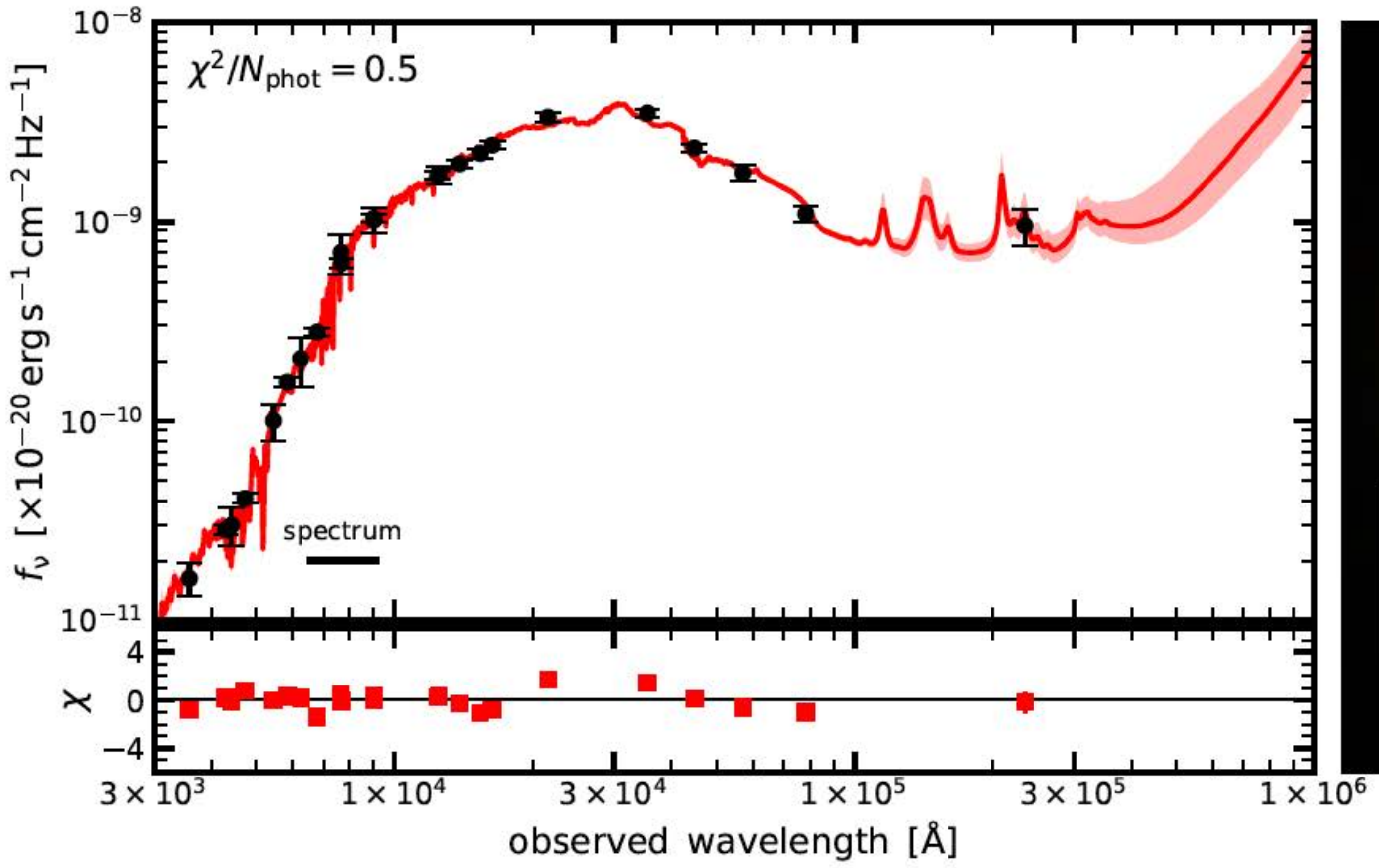


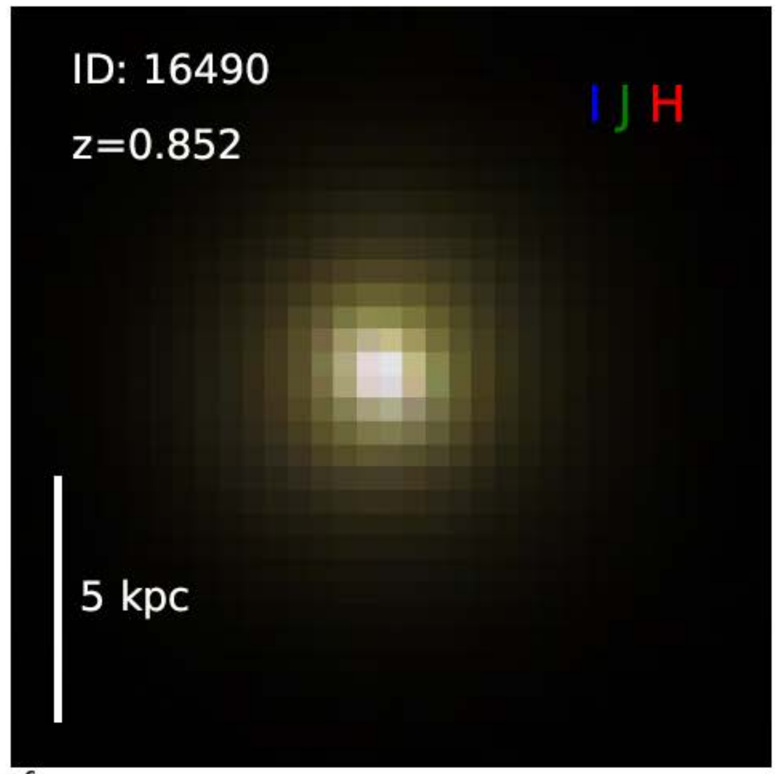
similar results at lower redshifts:
Nelson+ (2016), Ellison+ (2018), Morselli+ (2019)

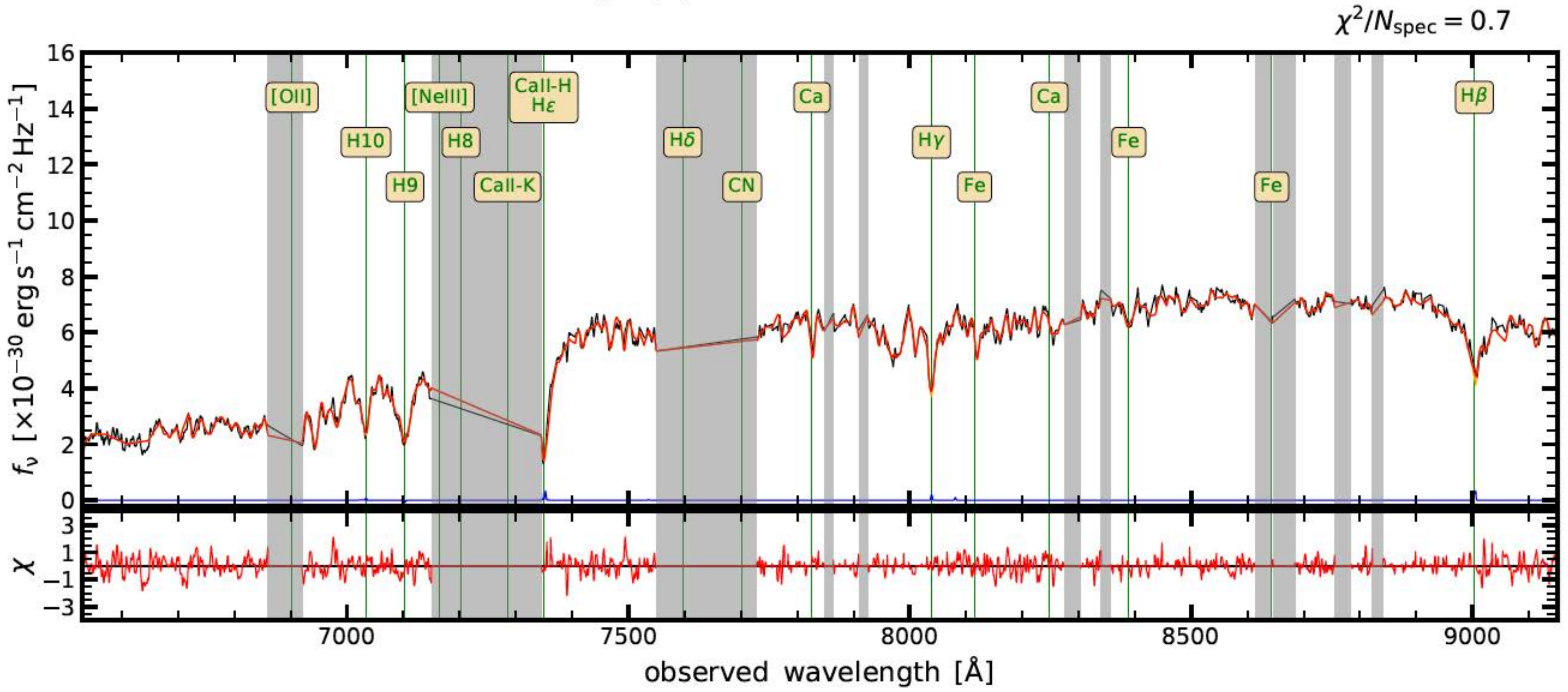


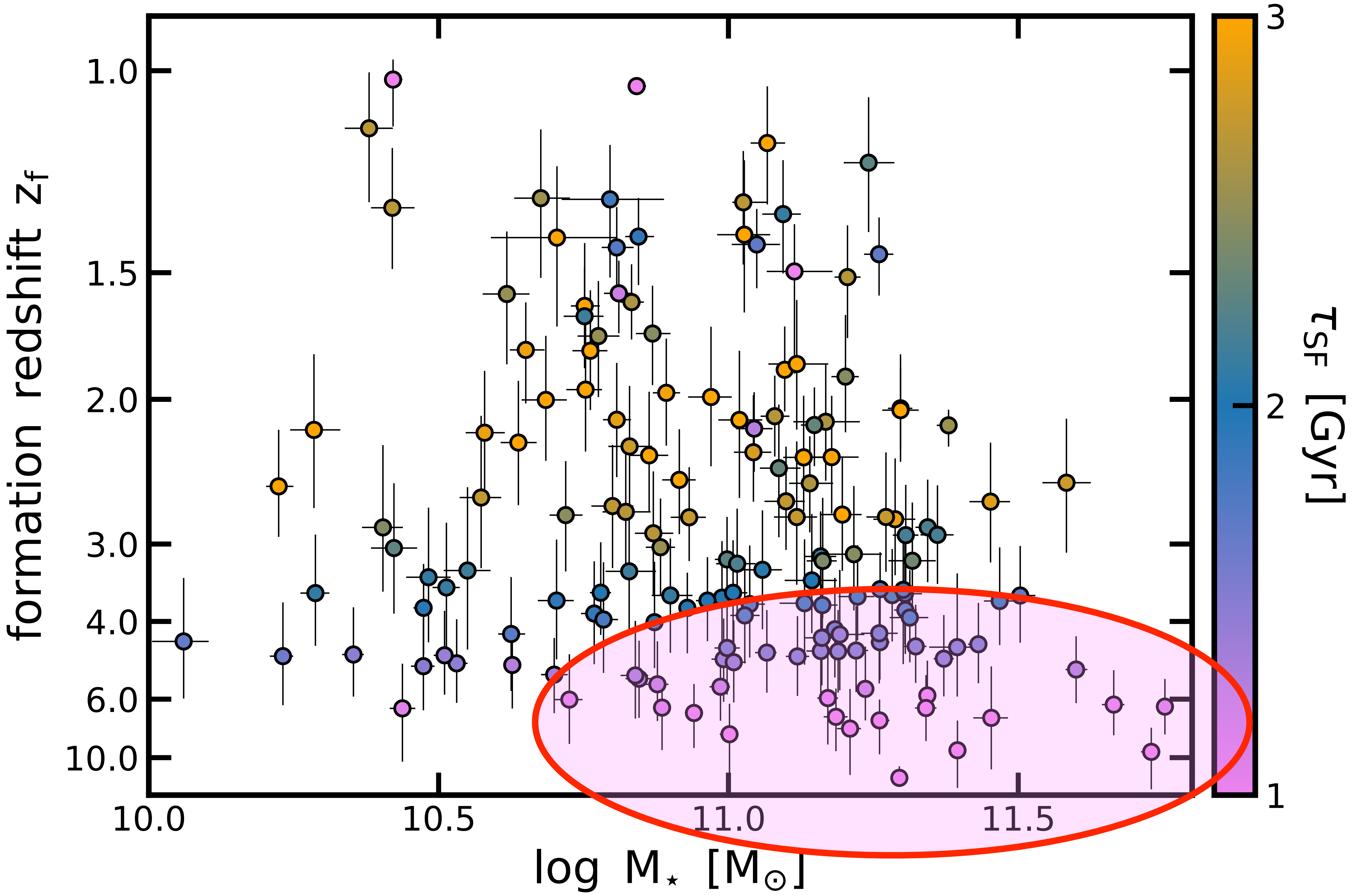
Galaxy Archaeology: Decoding the Light

Using the Keck observatory, we obtained deep spectroscopy to constrain the stellar ages of the stars in galaxies at redshift z~1









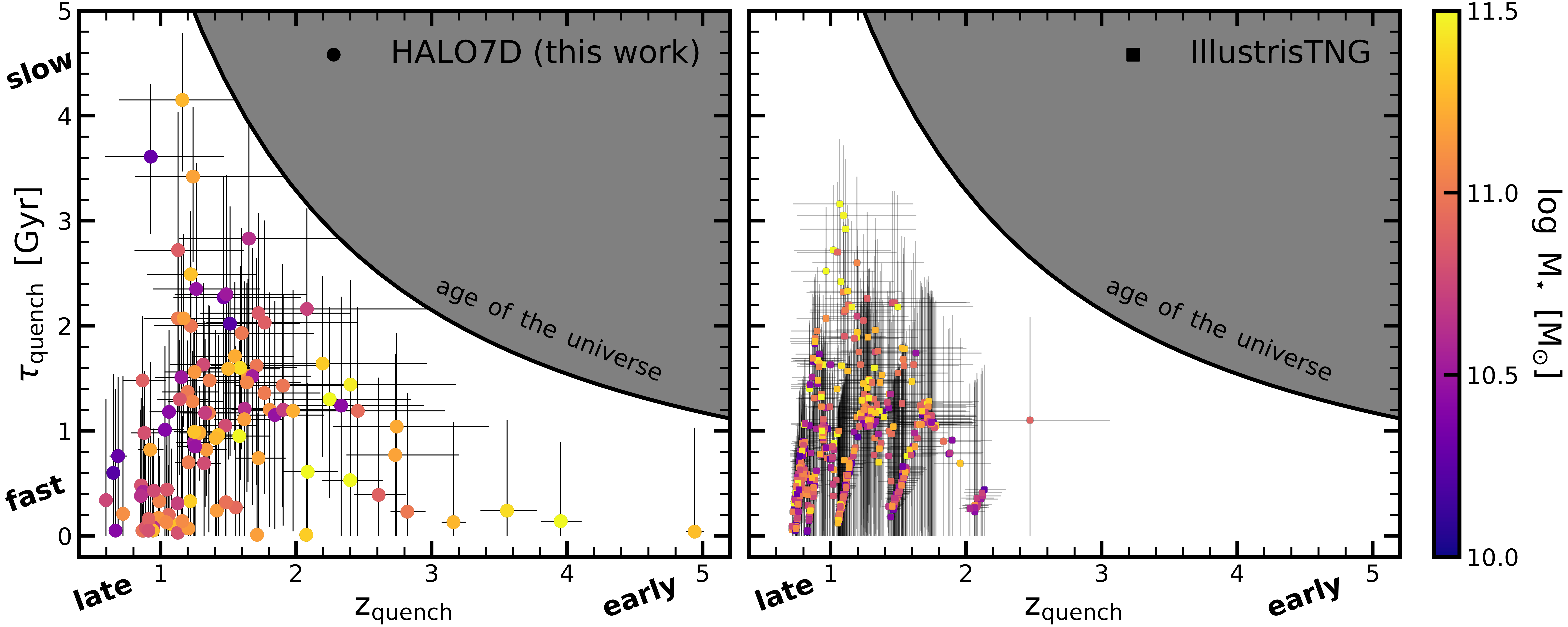
We find that the most massive galaxies have ages that are consistent with formation redshift of z~10.

Quenching timescales

large diversity of quenching timescale and quenching epochs

➜ consistent with other studies showing fast and slow quenching paths (i.e., Wu+18, Belli+19, Suess+20)

➜ combination of internal and external quenching mechanism (black hole + dark matter halo?)



Forcepho: New Photometry Tool

https://forcepho.readthedocs.io/en/latest/

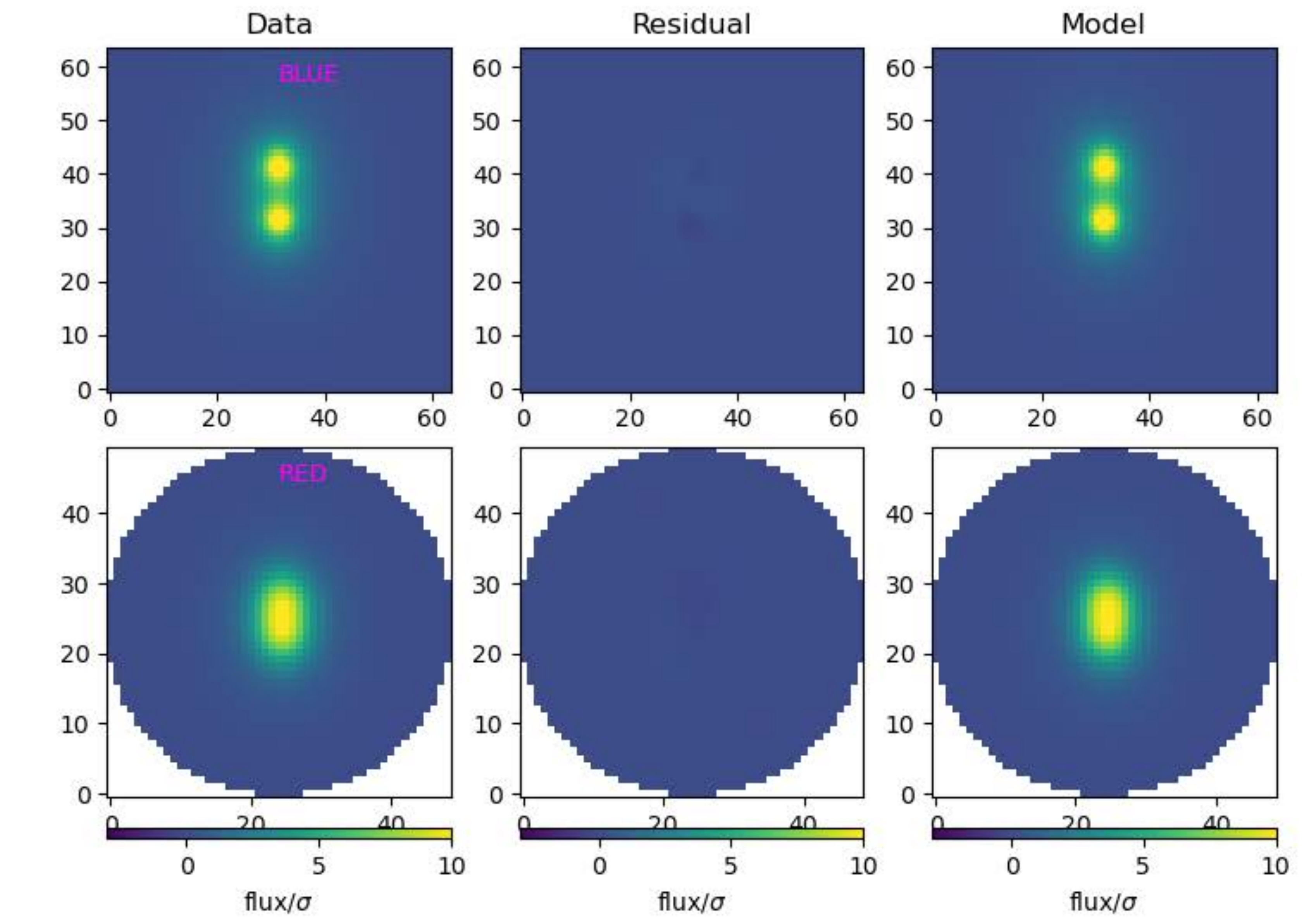
- development lead: Ben Johnson (Harvard)
- code to infer the fluxes and shapes of galaxies from astronomical images
- modelling the appearance of multiple sources in multiple bands simultaneously
- it approximates both the PSF and the intrinsic galaxy shape (Sersic profiles) as mixtures of Gaussians
- runs on CPUs and GPUs

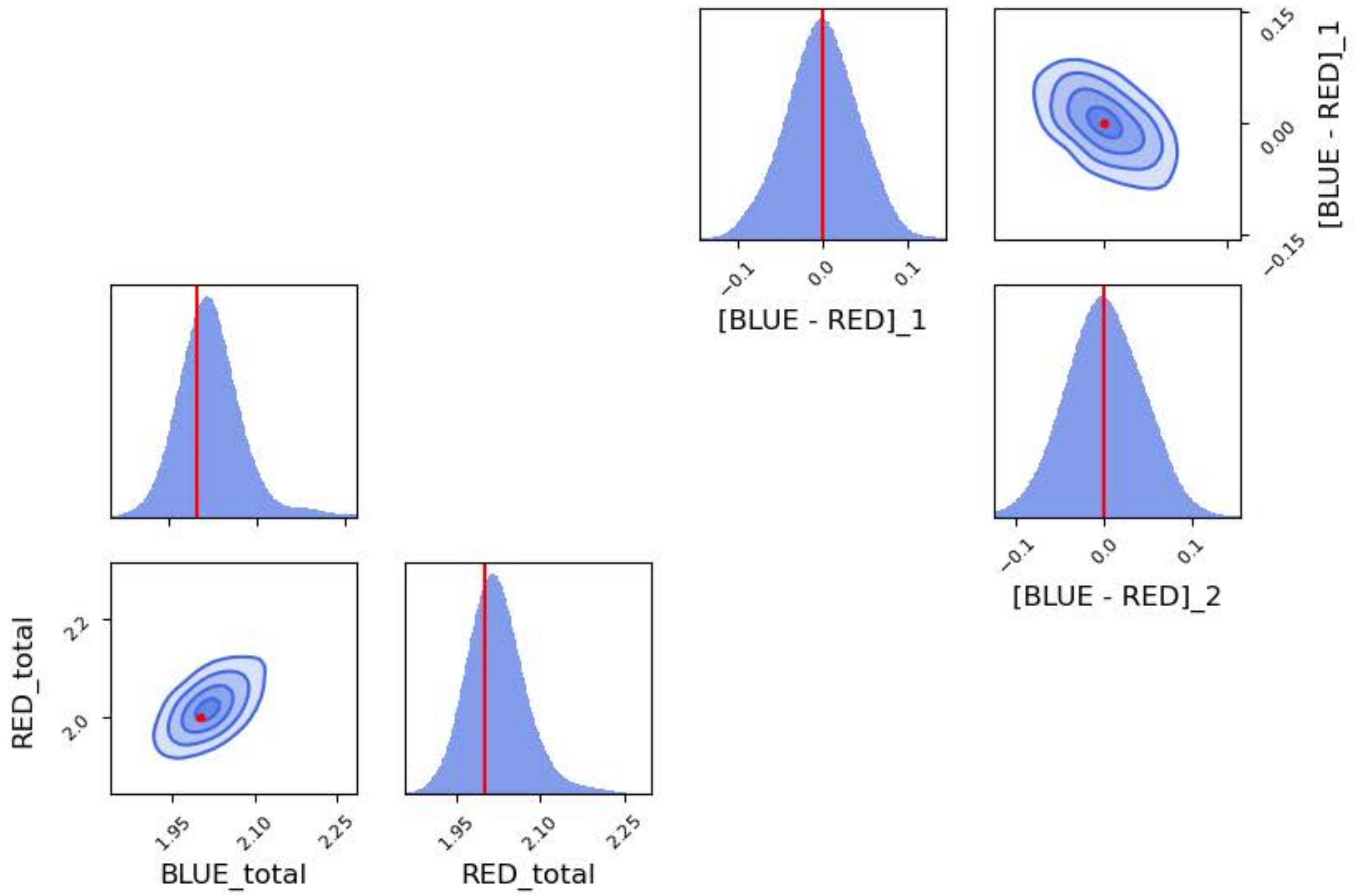
Input

- flux calibrated images, uncertainties, and masks
- WCS information
- PSFs — Gaussian mixture approximations must be computed.
- Input detection list / peak catalog

Output

- Chain catalog: posterior samples for flux and shape parameters for every source
- Summary catalog: Posterior percentiles and (multivariate) Gaussianized uncertainties for every object
- Residuals mosaic images

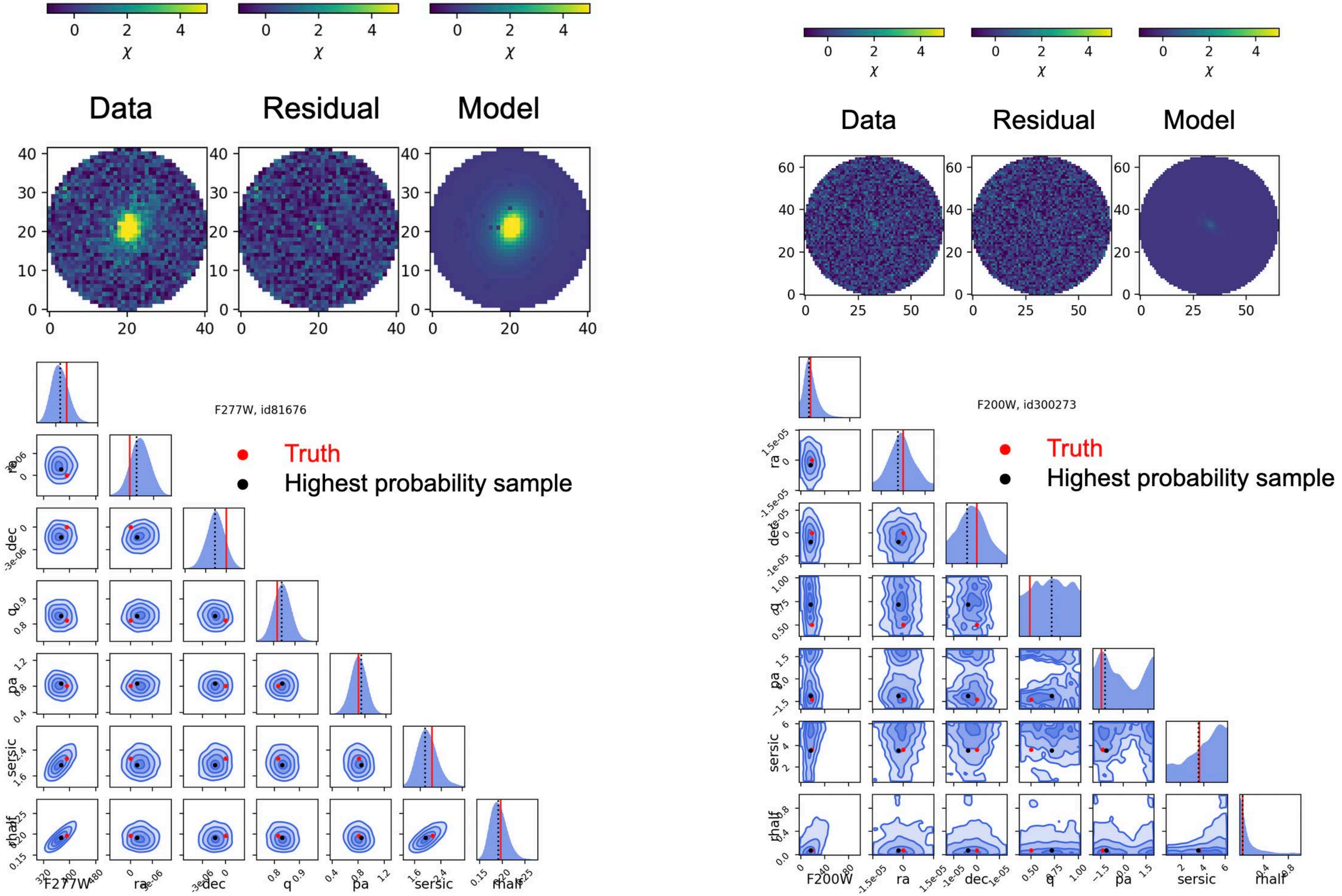




Forcepho: New Photometry Tool

https://forcepho.readthedocs.io/en/latest/

- tests on JADES simulated images:
  individual slope images instead of the mosaic because PSF is better characterised and the uncertainties are not correlated.



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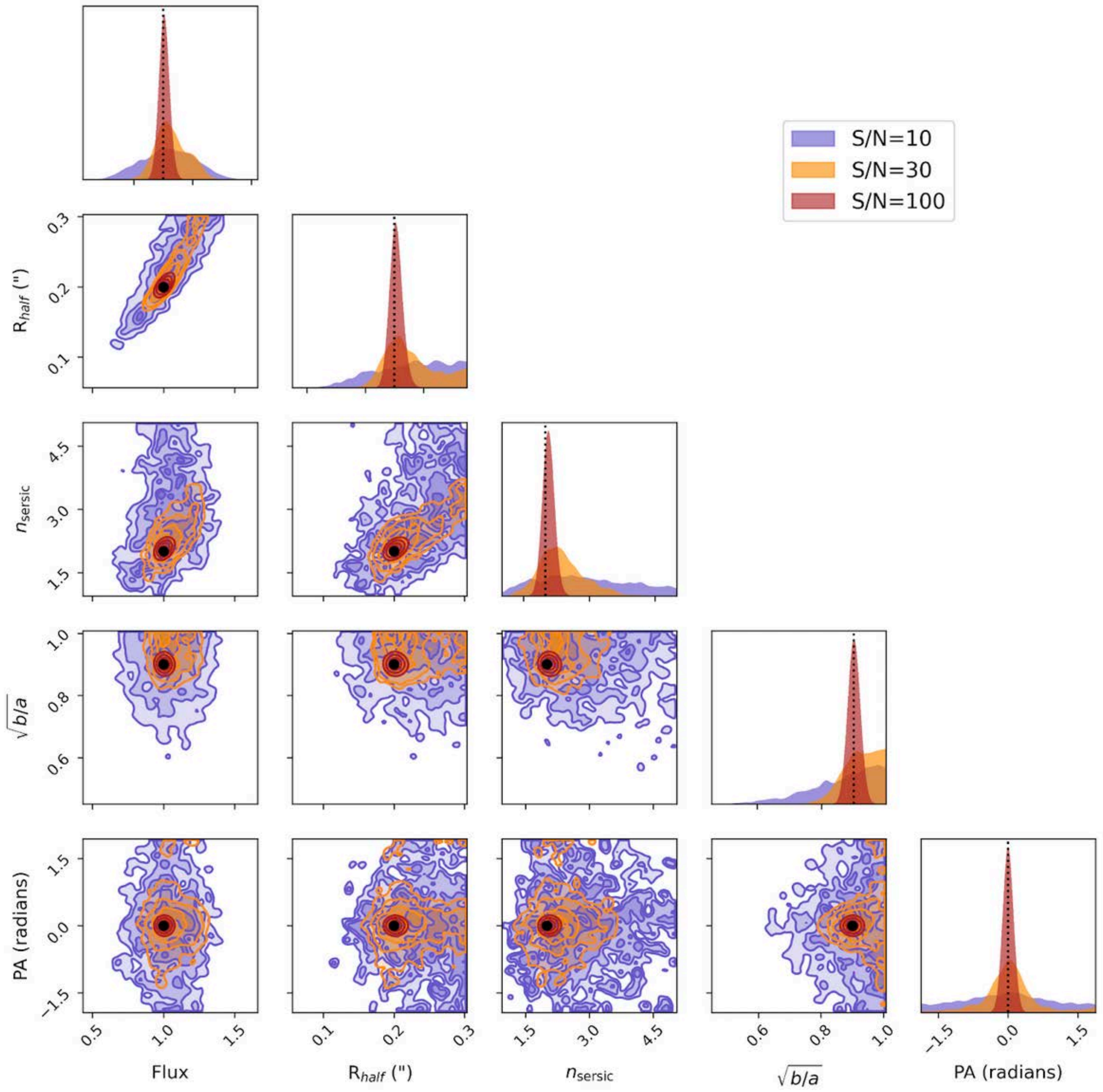
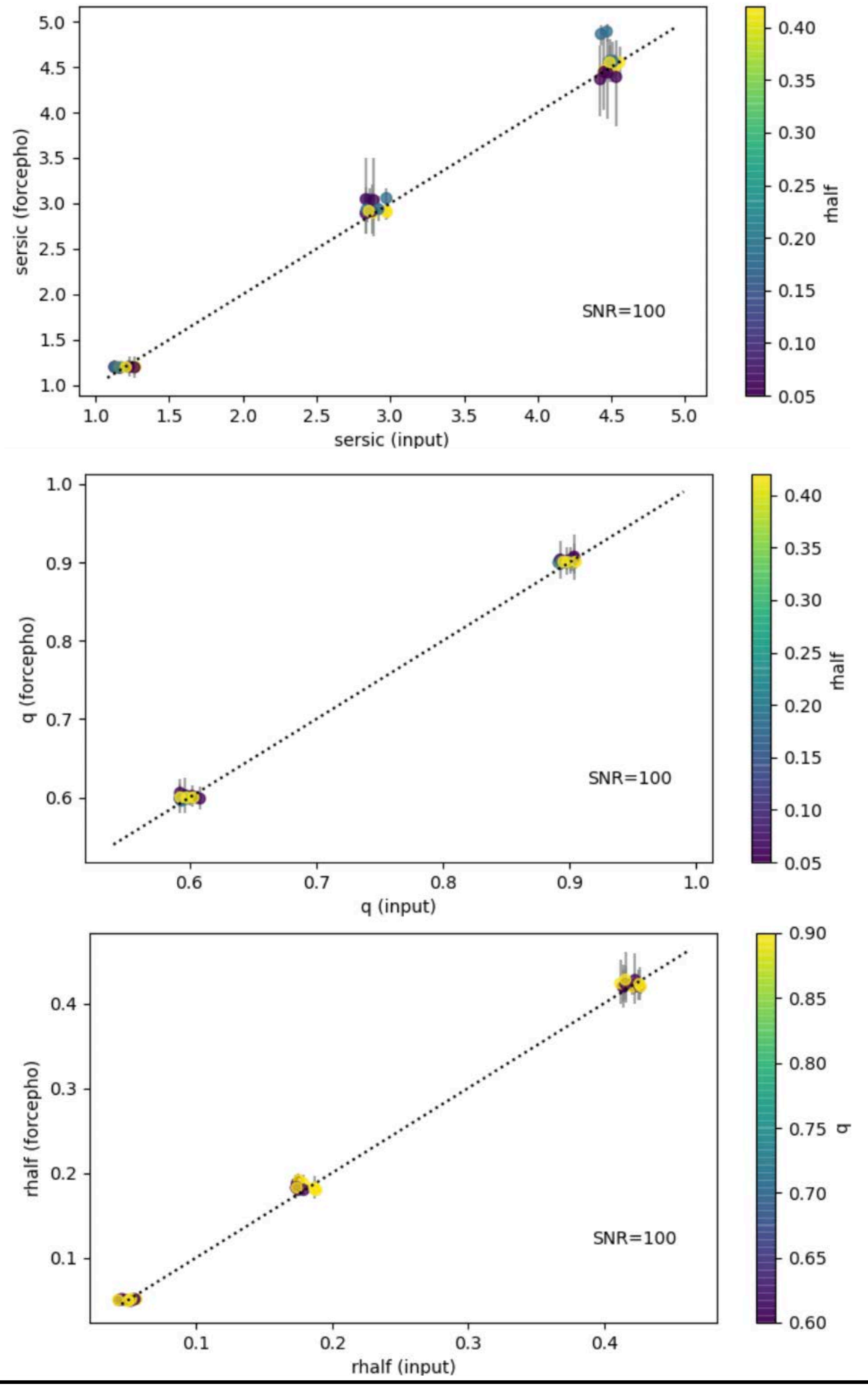
- tests on GALSIM images:
  with Gaussian PSF and JWST PSF





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- tests on JADES simulated images:
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- tests on GALSIM images:
  with Gaussian PSF and JWST PSF
- tests on HST images… and soon on JWST!

HST UDF F435W