Studying Galaxy Evolution with Spectroscopic Surveys: What We Have Learned and an Eye Toward the Future

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A REVIEW ON GALAXY EVOLUTION

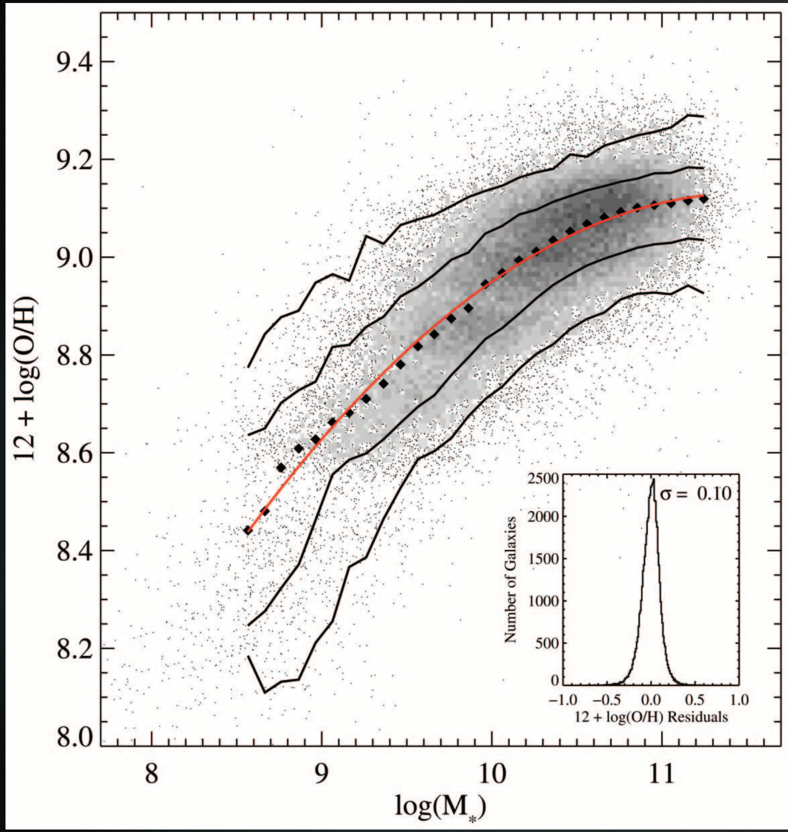
FROM GALAXIES TO COSMOLOGY WITH DEEP SPECTROSCOPIC SURVEYS

A TRIBUTE TO OLIVIER LE FÈVRE

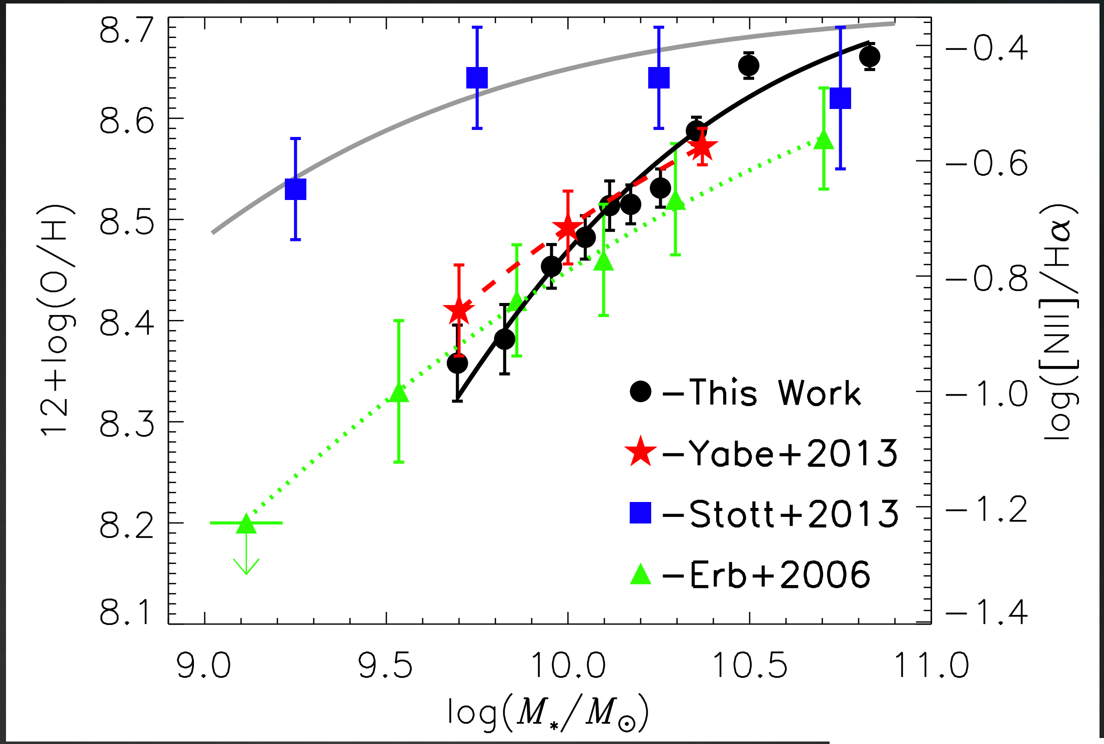
Spectroscopic Surveys From Low-z to High-z

- SDSS revolutionized our understanding of galaxies in the nearby universe
  - Surveys like MaNGA continue to!
- High-z optical surveys have gotten larger and pushed to higher and higher z
  - CFRS, VVDS, DEEP2, zCOSMOS, VIPERS, VUDS, ….
- Near-IR Surveys have taken us the next step
  - MOSDEF, KBSS, FMOS-COSMOS, 3D-HST, …..
  - KMOS-3D

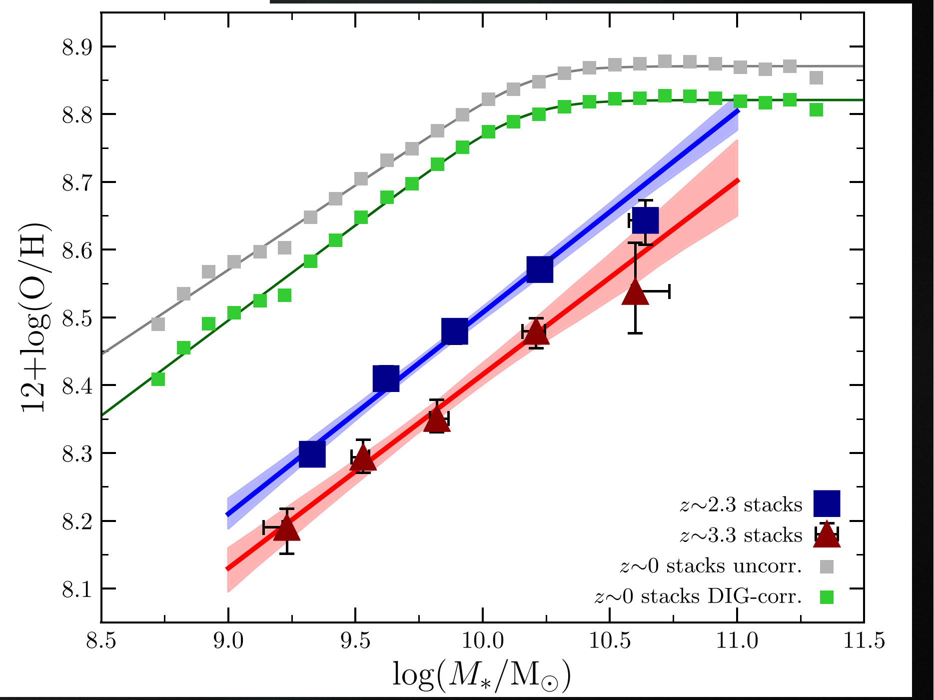
Metallicity



Tremonti et al. 2004, z<0.1, SDSS



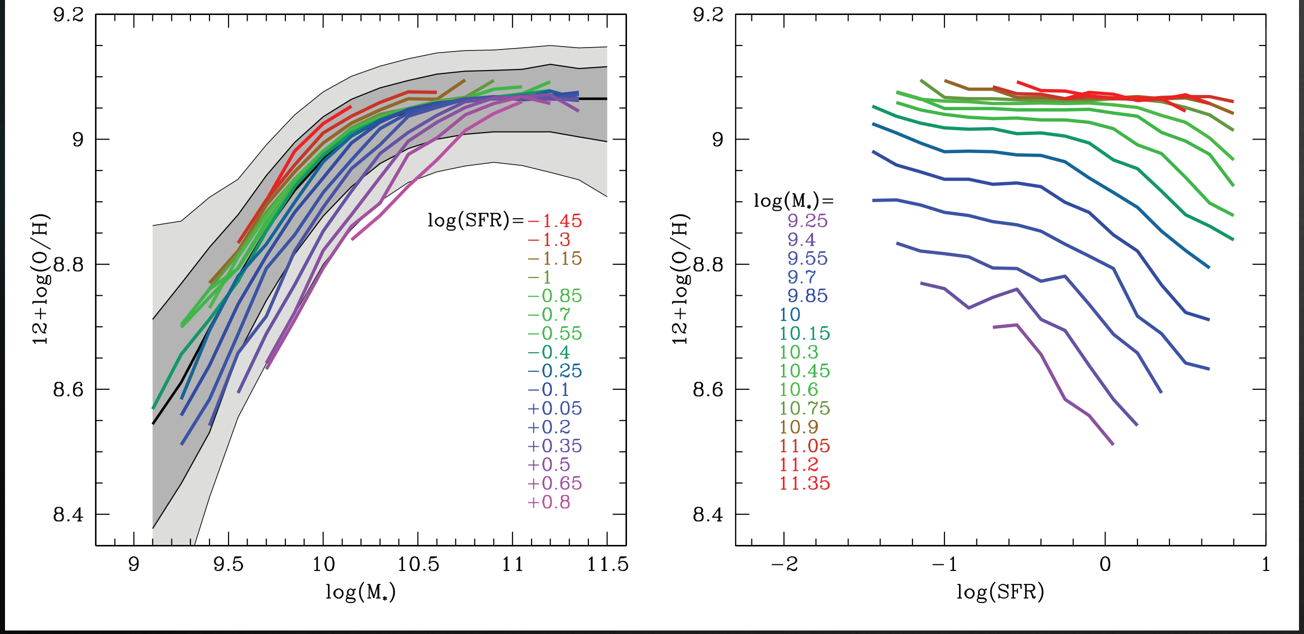
Zahid et al. (incl. Kartaltepe) 2014, z~1.6, FMOS-COSMOS

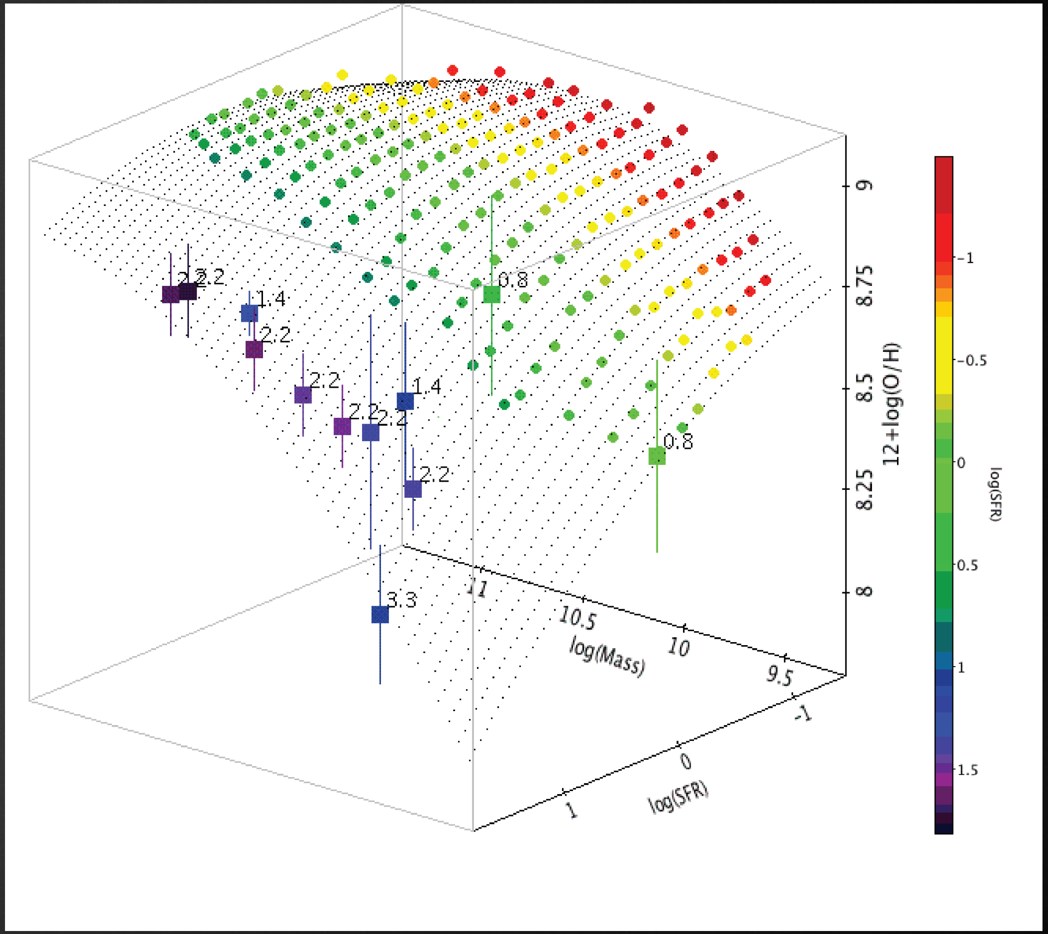


Sanders et al. 2021, z=2-3, MOSDEF

The Fundamental Metallicity Relation

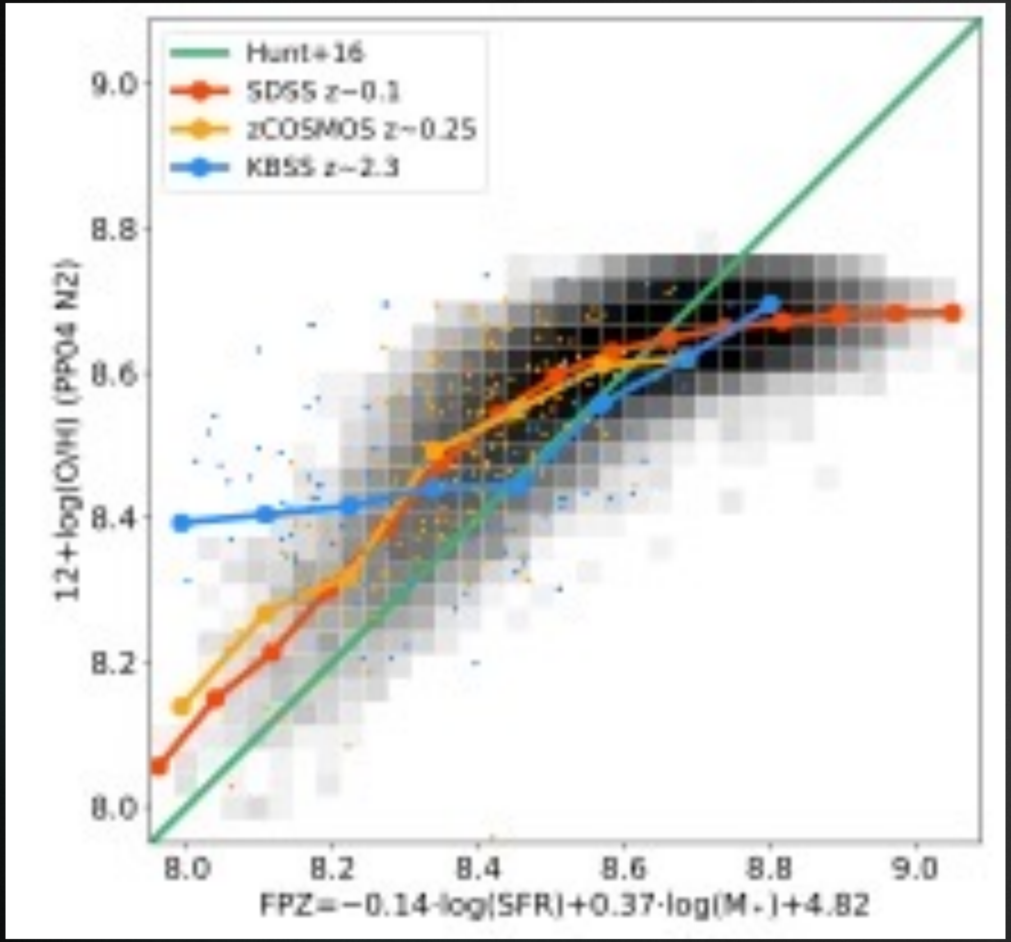
- z = 0 from SDSS
- z > 0.5, various sources from literature
- See talk by Francesco Pistis

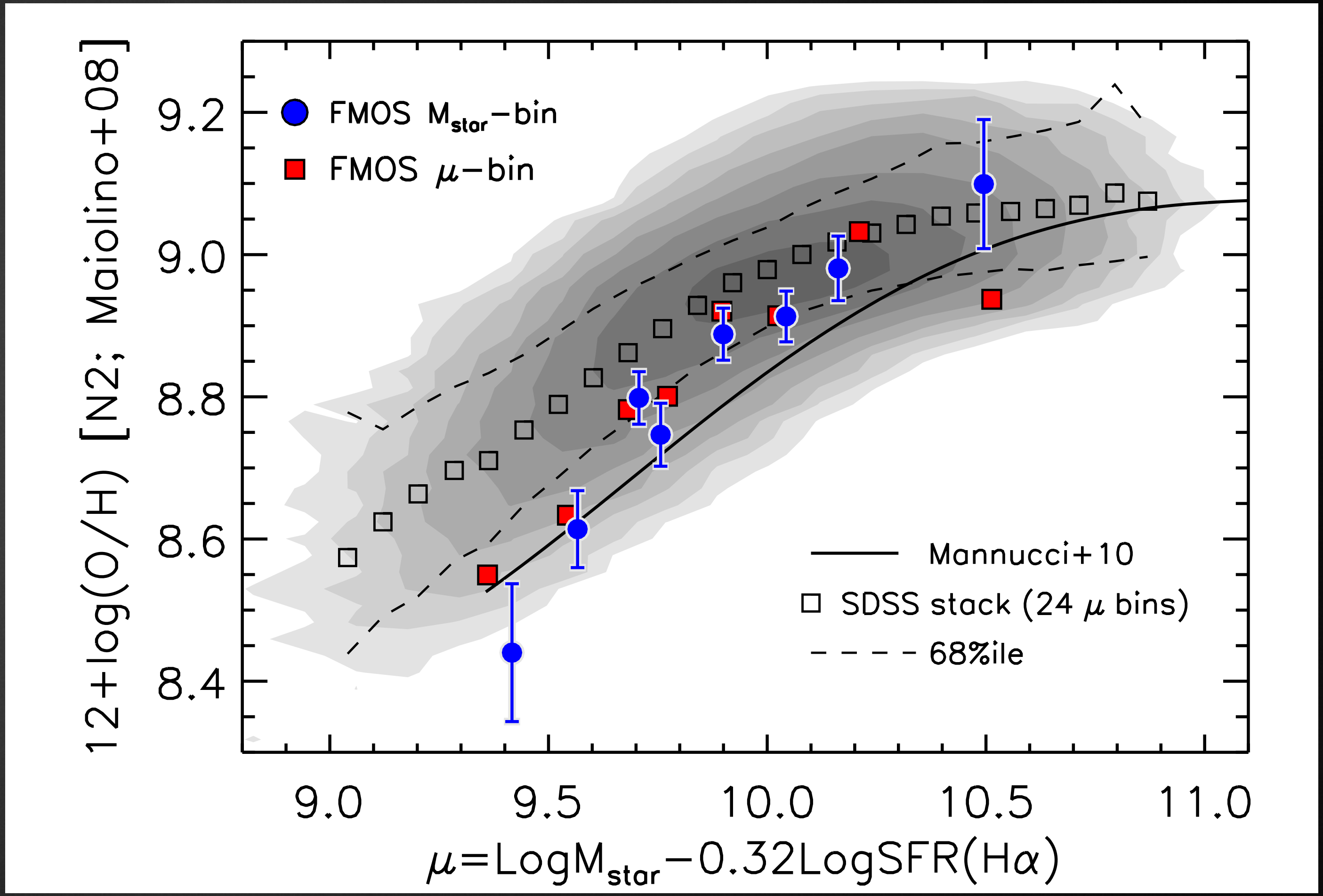




Mannucci et al. 2010

Evolution of the FMR?





Cresci et al. 2019
See also, Wuyts et al. 2012, Henry et al. 2013

Kashino et al. (incl. Kartaltepe) 2017
See also Zahid et al. 2014, Grasshorn-Gebhardt 2016

Galaxy Merger Rates

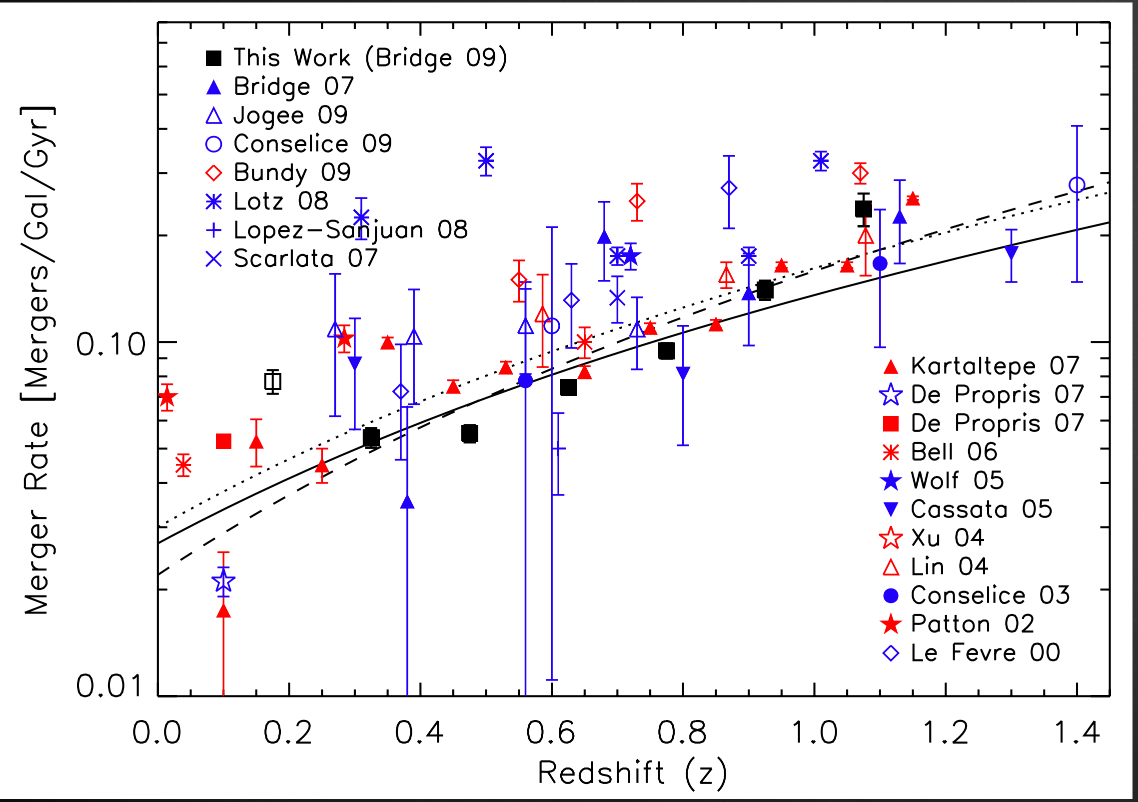
Hubble Space Telescope imaging of the CFRS and LDSS redshift surveys – IV. Influence of mergers in the evolution of faint field galaxies from $z \sim 1$

O. Le Fèvre,[1★] R. Abraham,[2] S. J. Lilly,[3] R. S. Ellis,[2] J. Brinchmann,[2] D. Schade,[6] L. Tresse,[1,4] M. Colless,[5] D. Crampton,[6] K. Glazebrook,[7] F. Hammer[8] and T. Broadhurst[9]

- Spectroscopically identified galaxy pairs and mergers

EVOLUTION OF THE GALAXY MERGER RATE

- How common were mergers in the past compared to today?



Bridge et al. 2010

?

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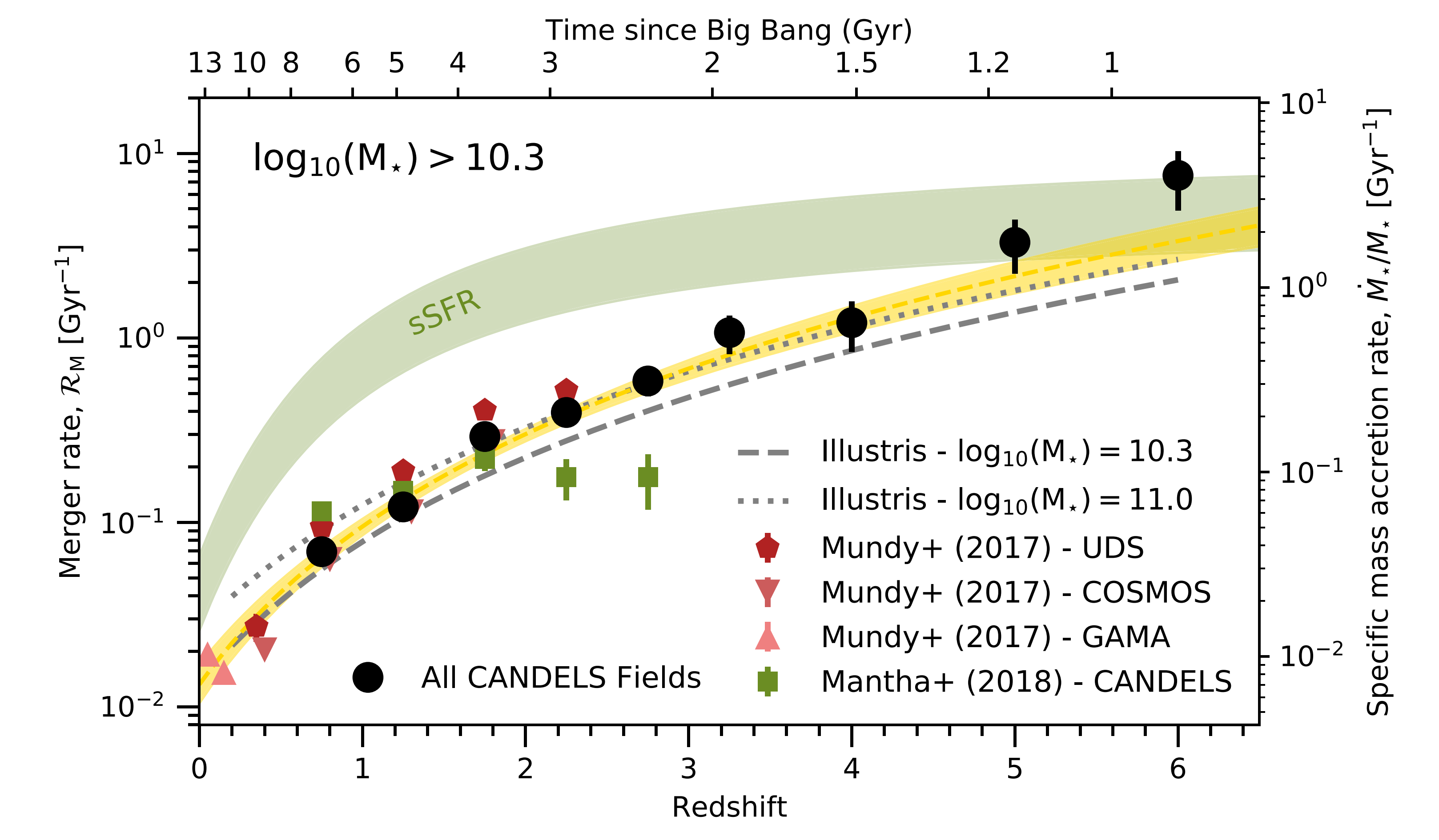
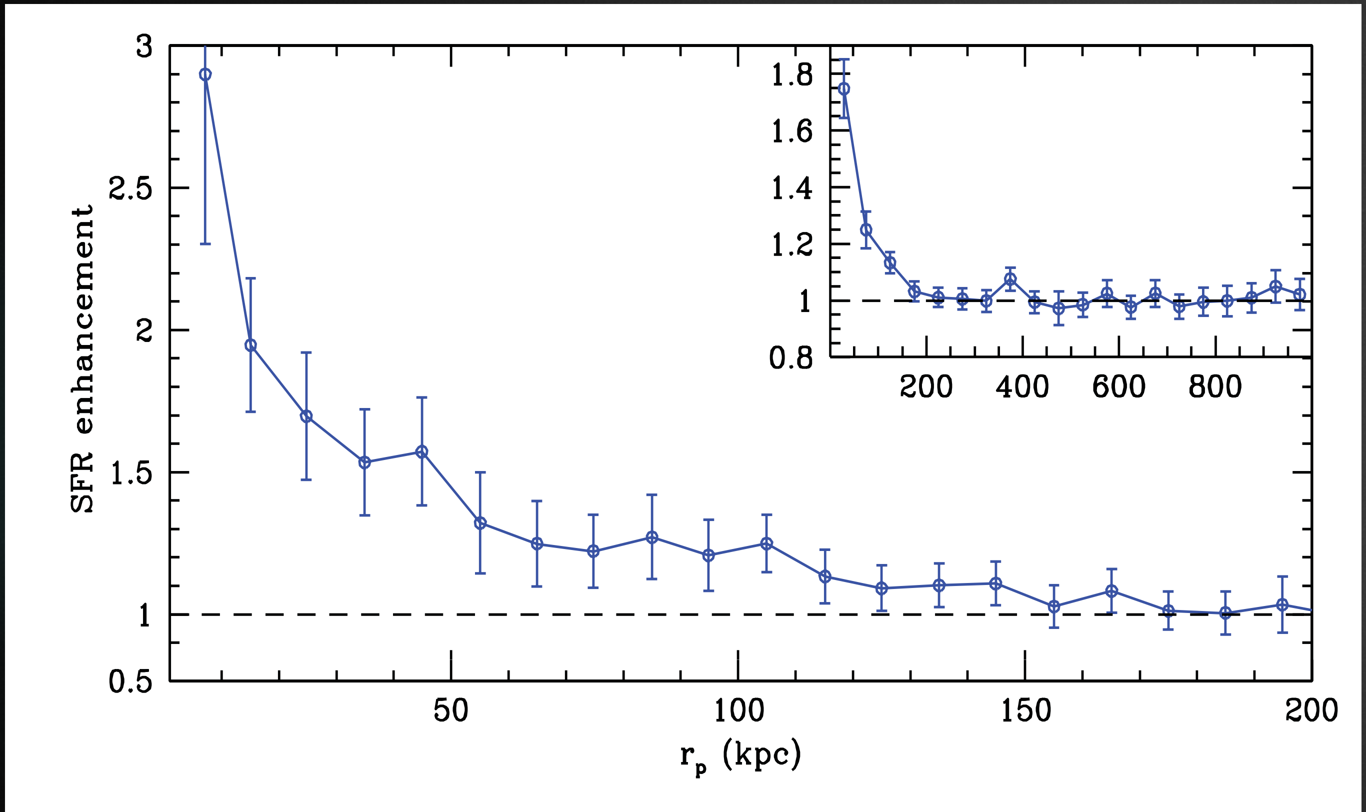
EVOLUTION OF THE GALAXY MERGER RATE

- How common were mergers in the past compared to today?

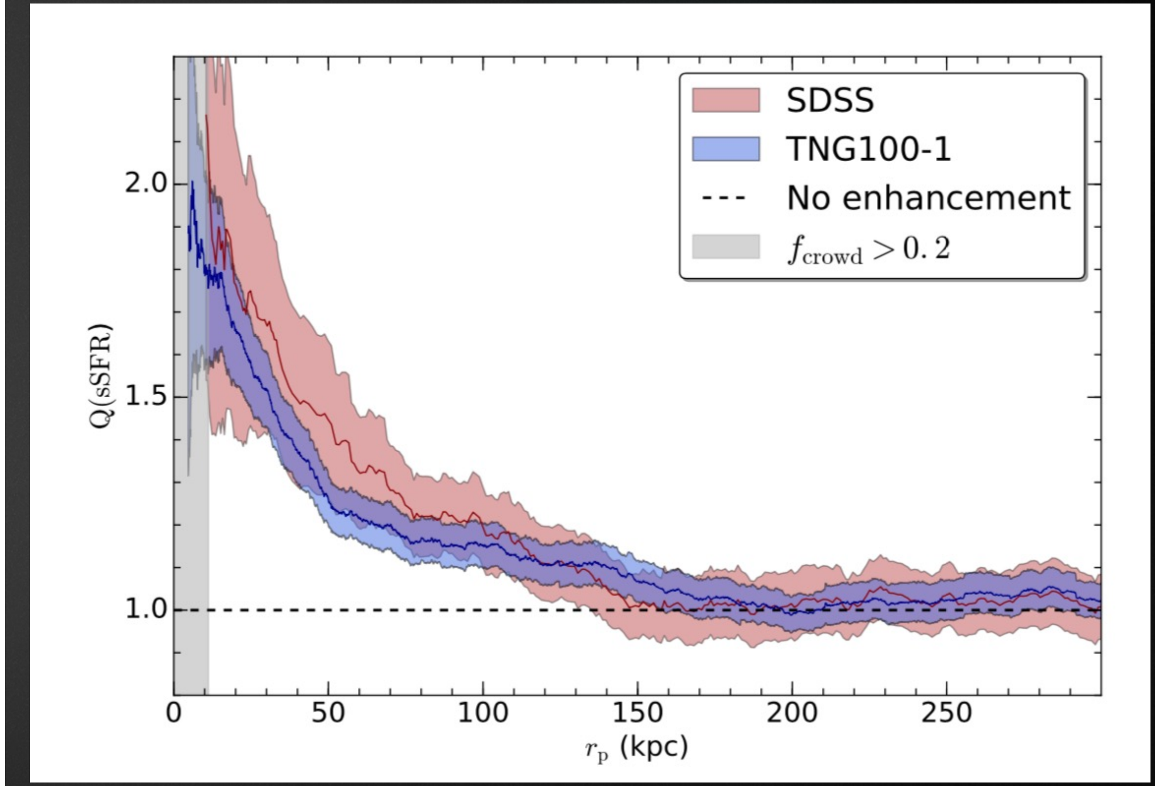


Duncan et al. (incl. Kartaltepe) 2019
See also, Ferreira et al. 2000

Star Formation Enhancement in Nearby Galaxy Pairs



Patton et al. (2013)

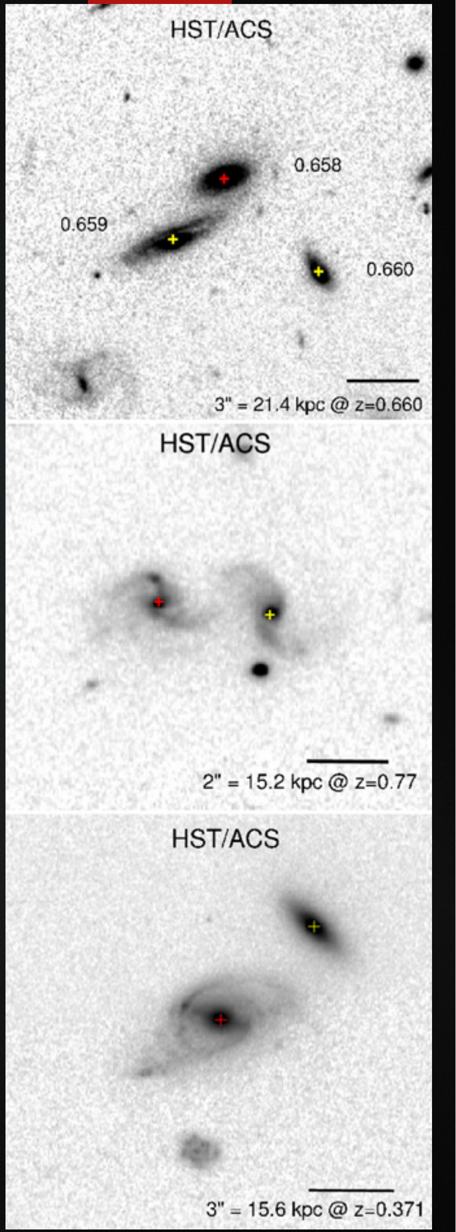


Patton et al. (2020)

Increasing Numbers of Spectroscopically Confirmed Pairs at High-z

- **de Ravel et al. 2009:** 314 major pairs at $0.15 < z < 1.0$
- **Silverman et al. 2011**: 562 major and minor pairs at $0.25 < z < 1.05$
- **Tasca et al. 2014**: 12 major pairs at $2 < z < 4$
- **Ventou et al. 2017**: 113 major and minor pairs at $0.2 < z < 6$
- **Shah et al. 2020**: 1300 major pairs at $0.5 < z < 3.0$
- **Dai et al. 2021**: 416 major and minor pairs at $0.2 < z < 1.6$
- + more from ALMA surveys!

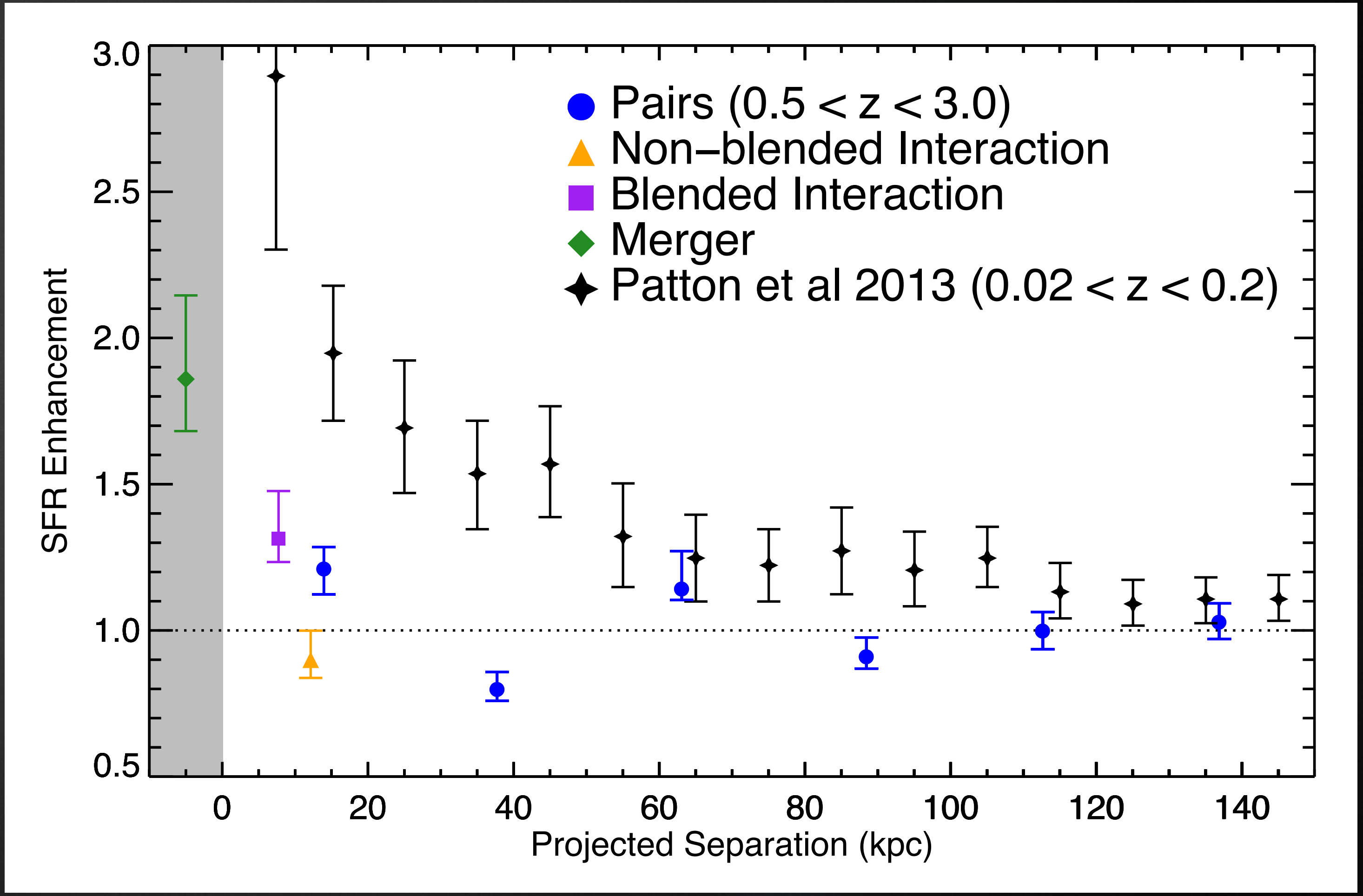
- Overall, still very small numbers at $z > 2$…



Silverman et al. 2011

Star Formation Enhancement in Distant Galaxy Pairs

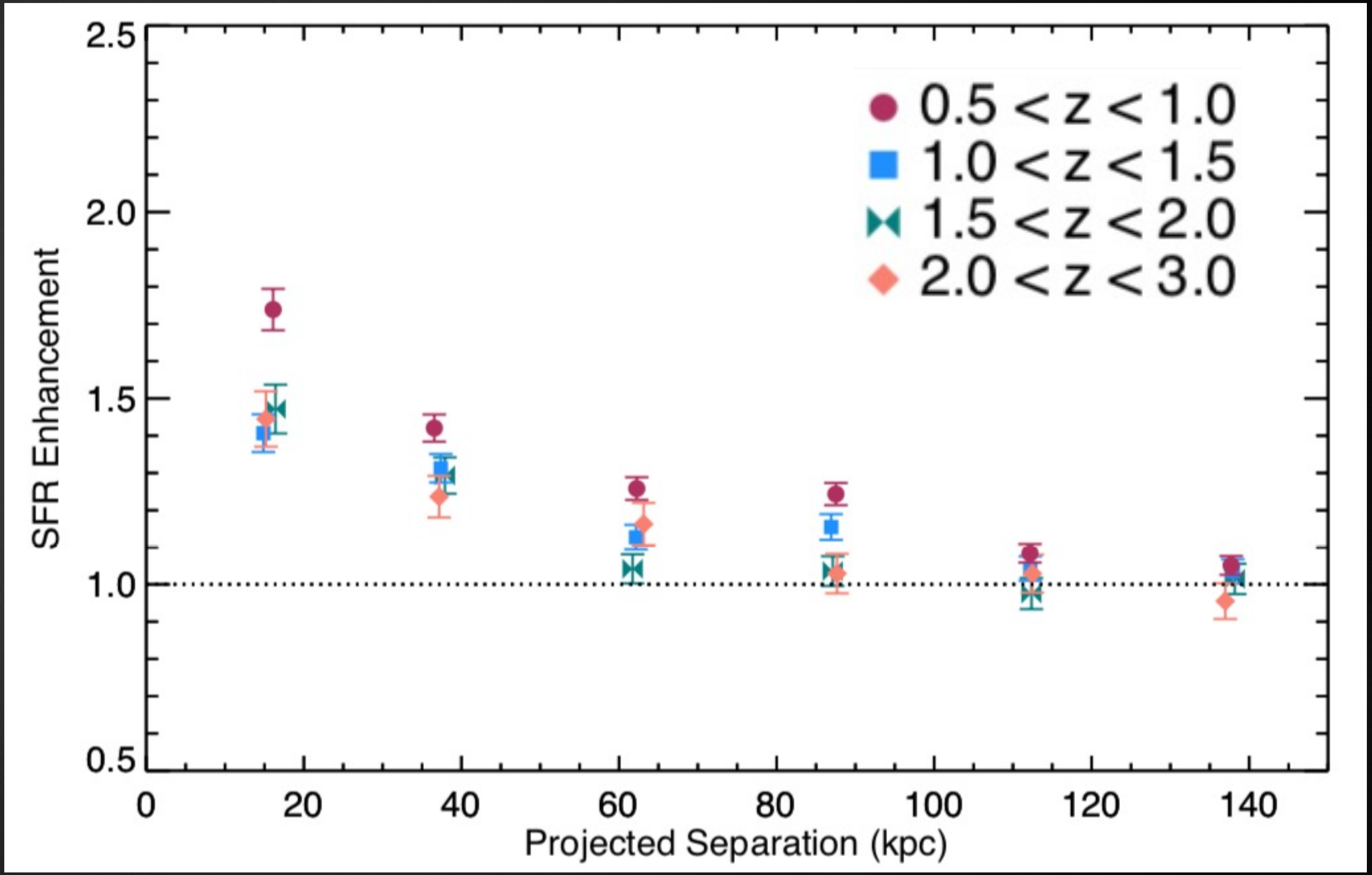
- ~1300 spectroscopically identified major merger pairs in COSMOS and CANDELS ($0.5 < z < 3$)
- ~300 visually identified mergers and close interactions
- SFR in pairs/mergers relative to that of a matched control sample



Shah, Kartaltepe, et al., 2022, submitted

SFR Enhancement in IllustrisTNG Pairs

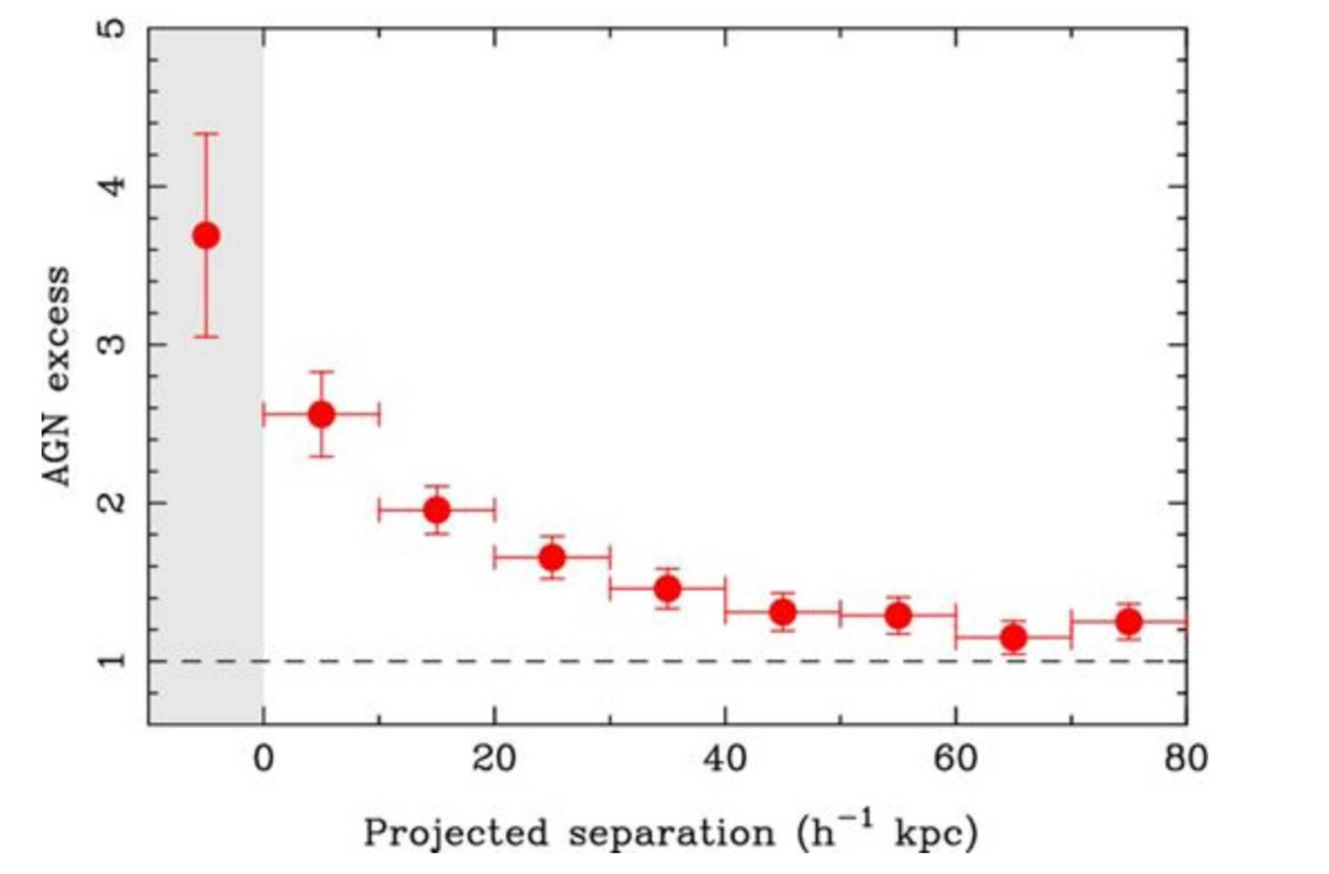
- Selected the same way as observed pairs
- See only slight decrease in enhancement with redshift



Shah, Kartaltepe, et al., in prep

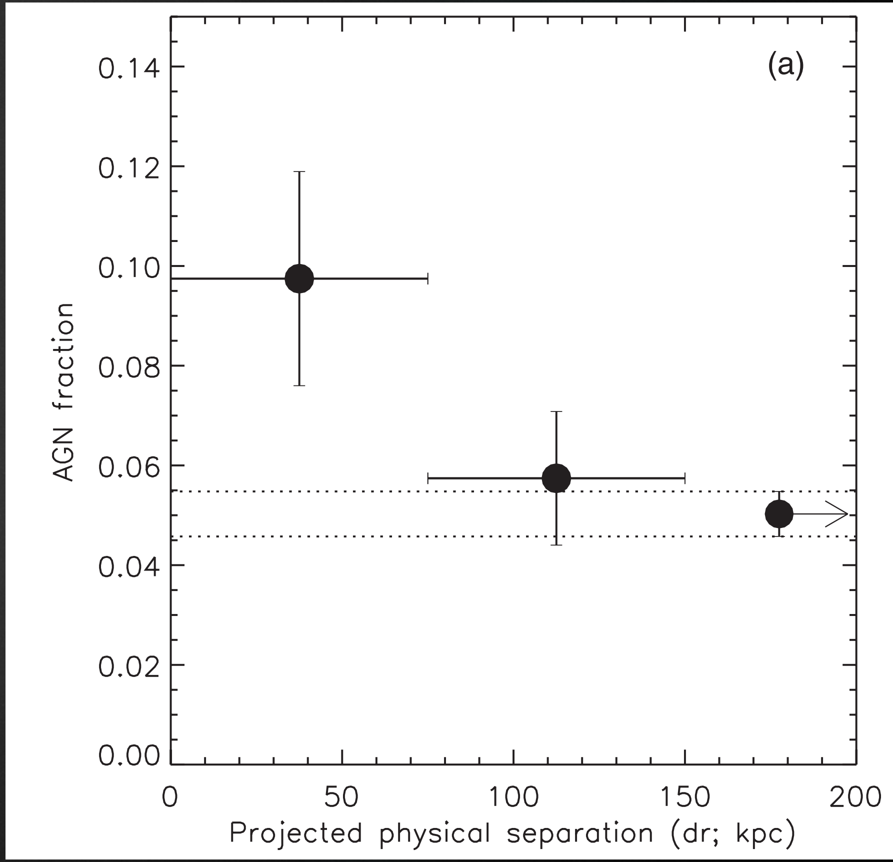
AGN Enhancement in Nearby Galaxy Pairs

SDSS Pairs (0.01 < z < 0.2)



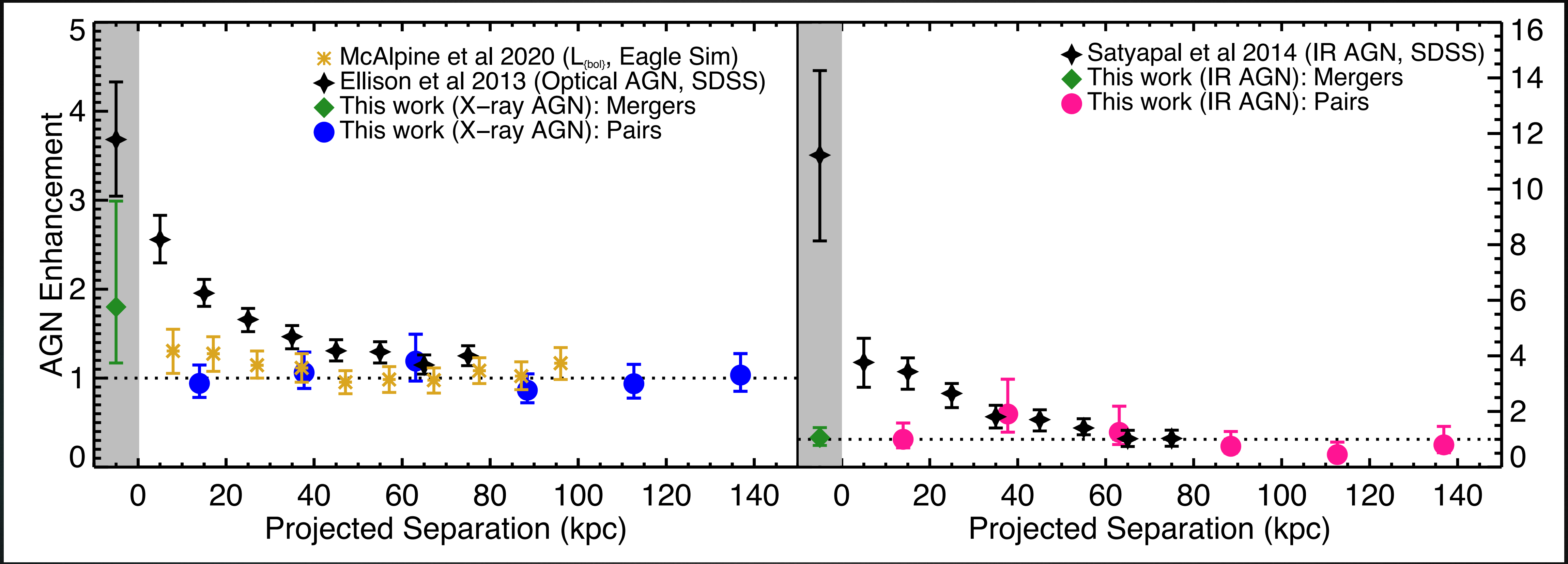
Ellison et al. (2013)

zCOSMOS Pairs (0.25 < z < 1.05)



Silverman et al. (2011)

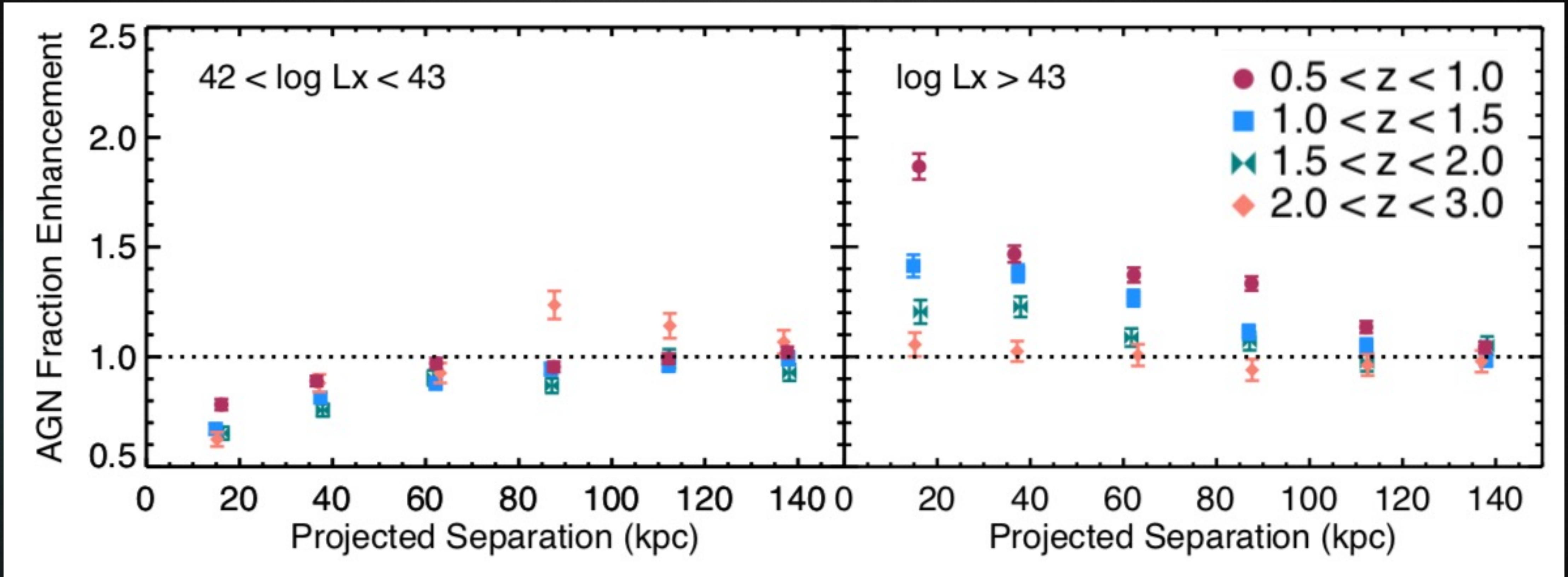
AGN Enhancement at Higher z?



Shah, Kartaltepe, et al., 2020

- ~1300 major merger pairs in COSMOS and CANDELS (0.5 < z < 3)
- AGN fraction in pairs relative to that of a matched control sample

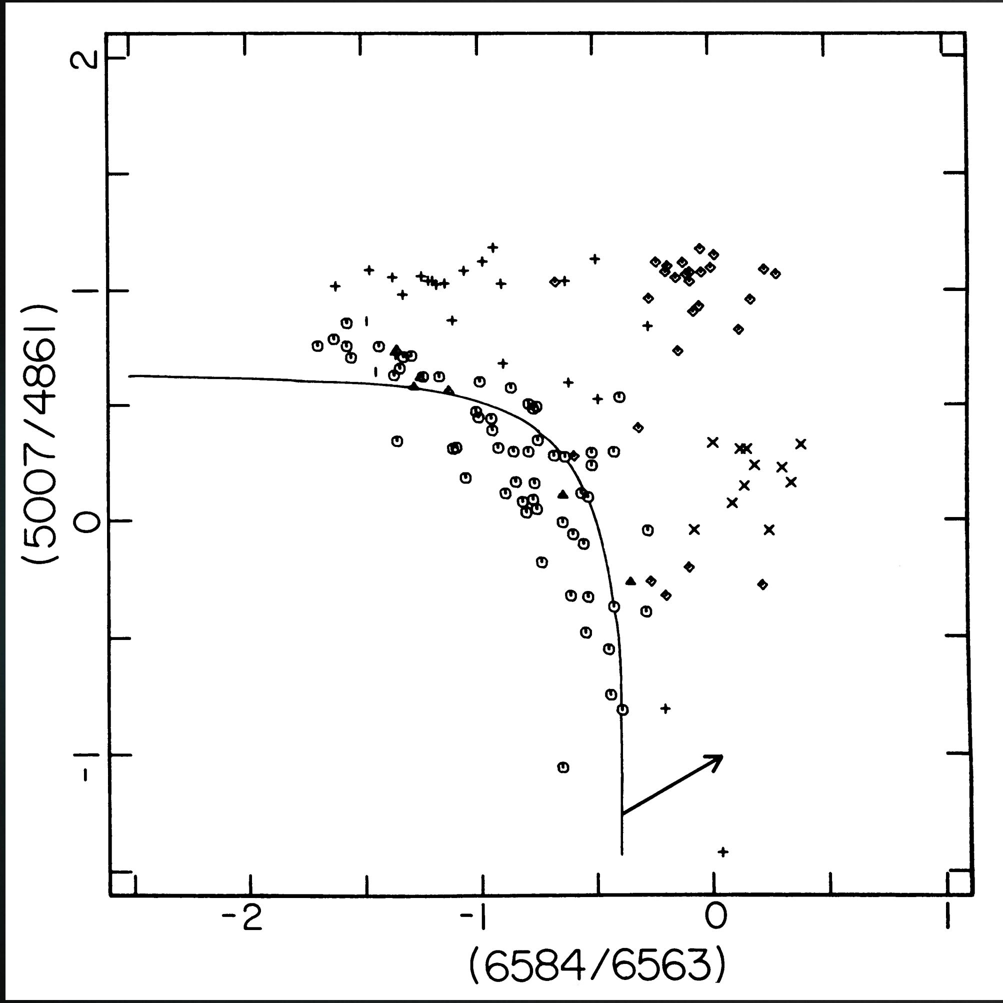
“X-Ray” AGN Enhancement in IllustrisTNG



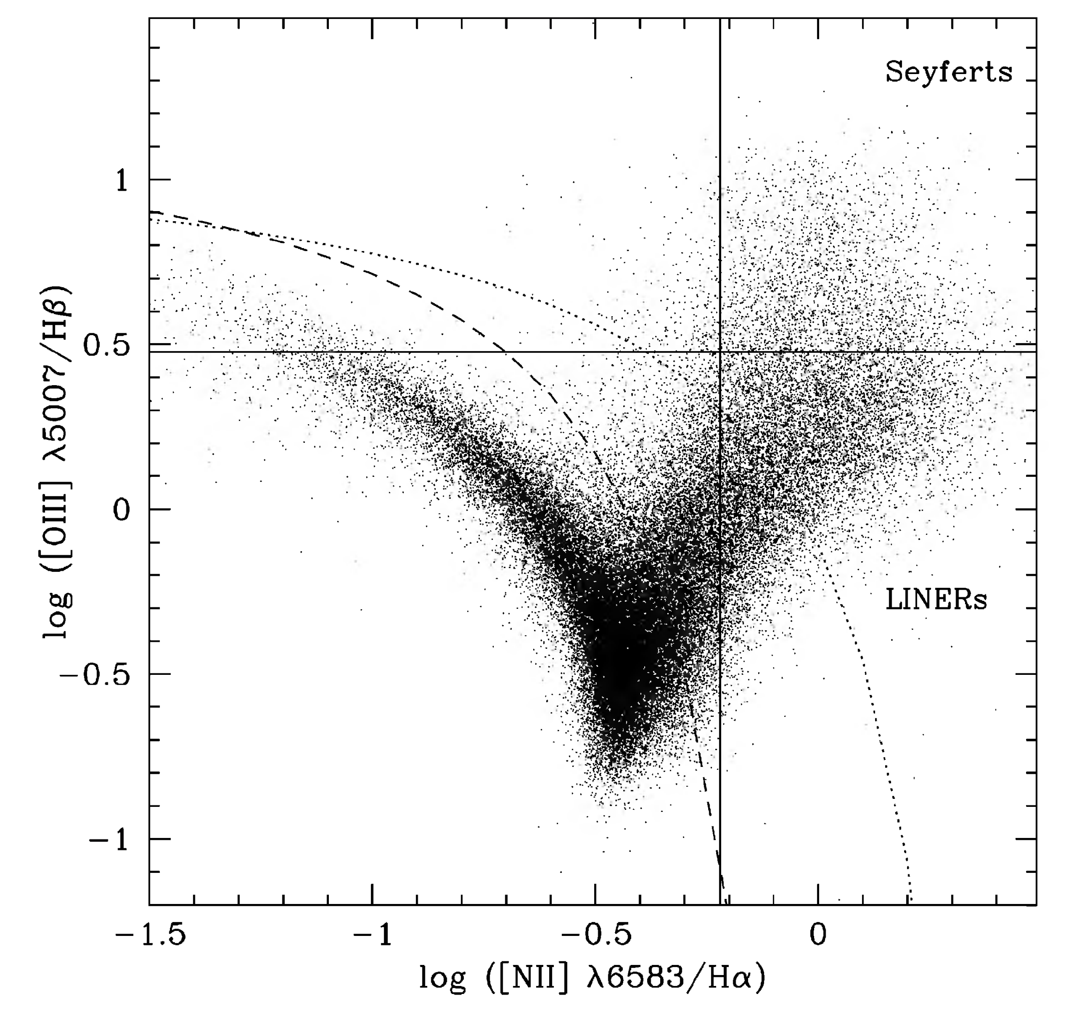
Shah, Kartaltepe, et al., in prep

- Lx estimated using BH accretion rate from IllustrisTNG

AGN Selection via BPT

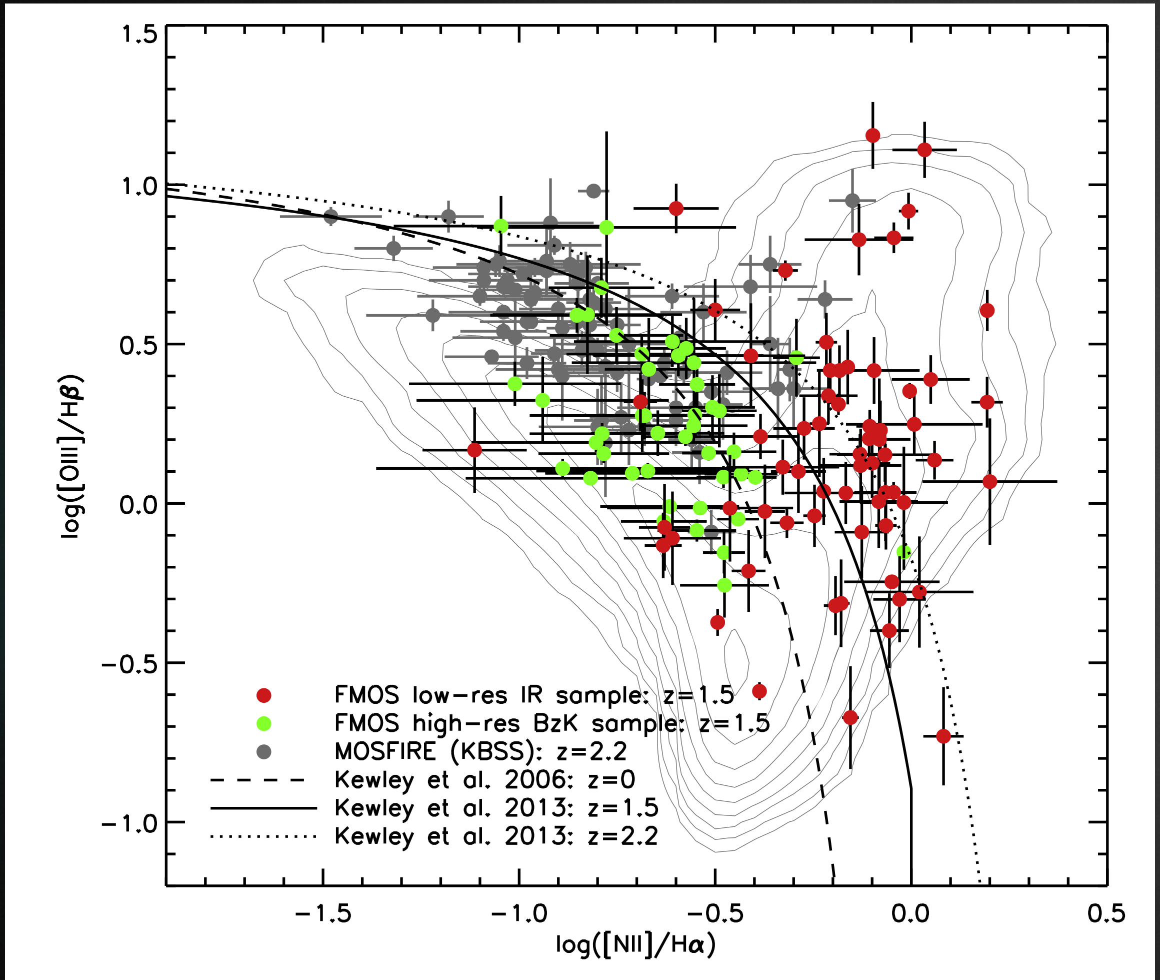


Baldwin, Philips, & Terlevich 1981

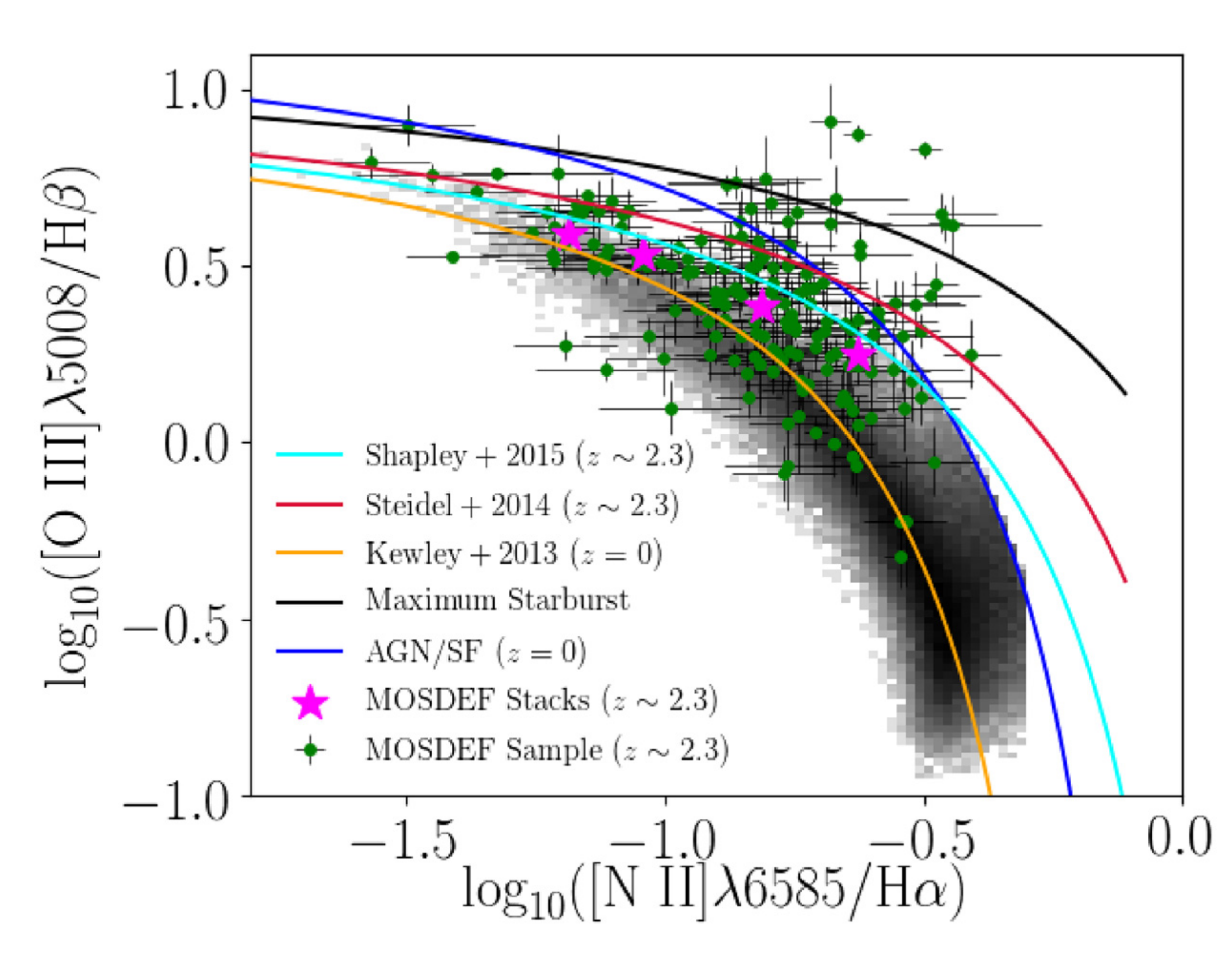


Kauffmann et al. 2003

BPT at High-z



Kartaltepe et al. 2015, z~1.5

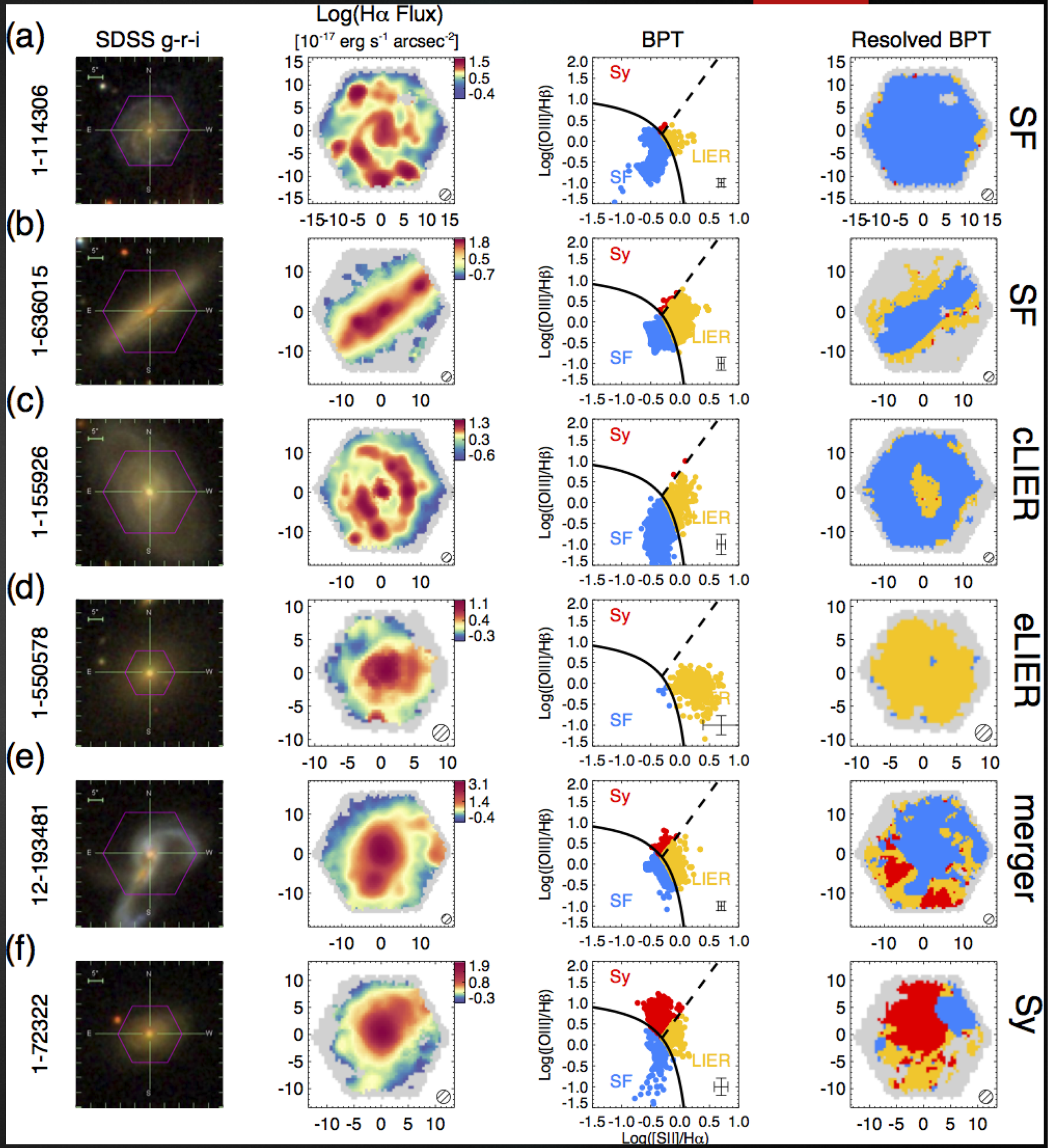


Runco et al. 2021, z~2.3

Resolved Spectroscopy with IFUs

- With resolved spectroscopy, one can:

- Isolate nuclear and specific star forming regions
- Identify low luminosity AGN
- Study the impact of shocks
- Study the properties of outflows
- Look at metallicity gradients
- Probe detailed kinematics

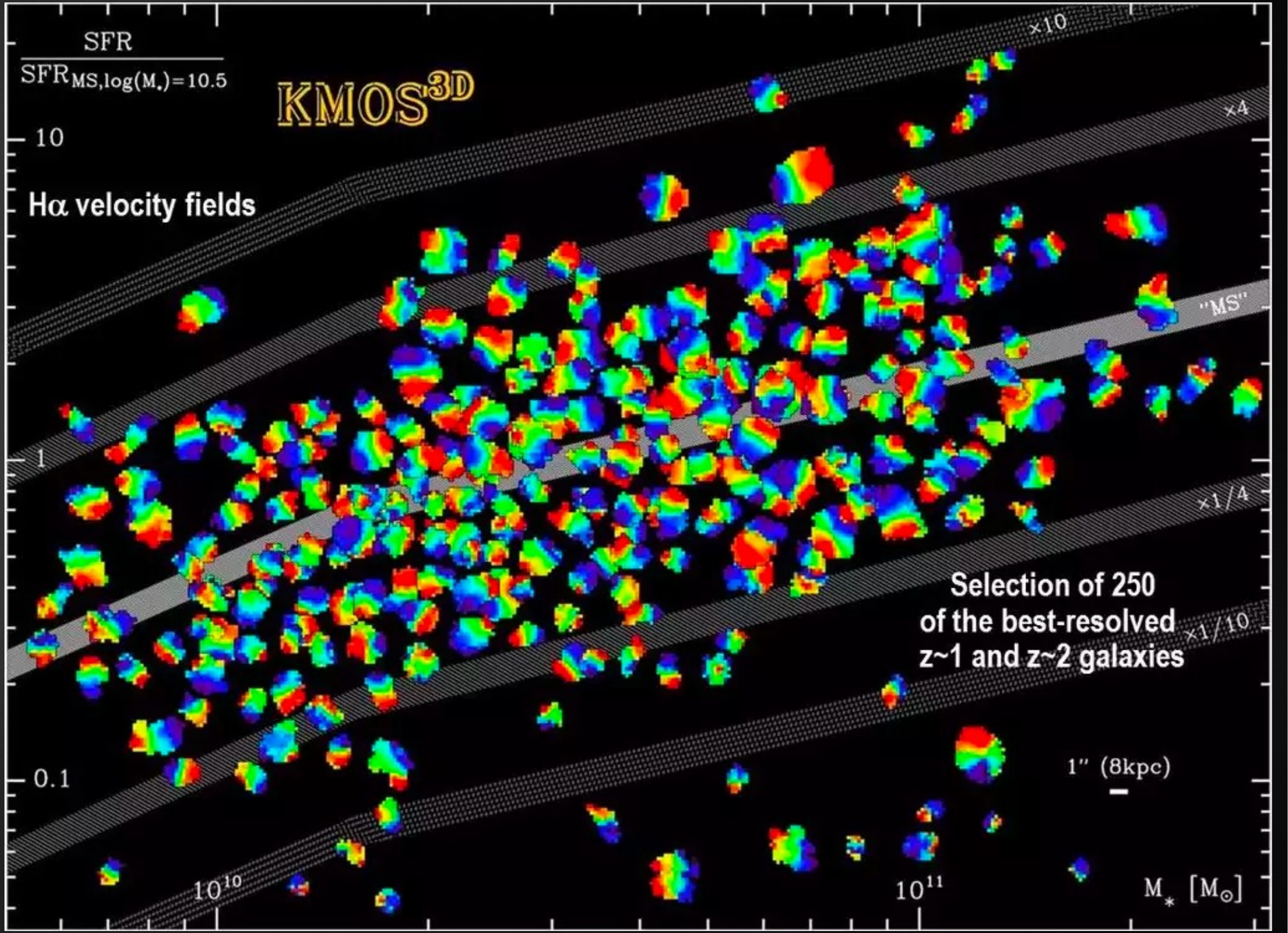


Belfiore et al. 2016

We've Only Seen the Tip of the Iceberg at High-z

https://www.mpe.mpg.de/ir/KMOS3D

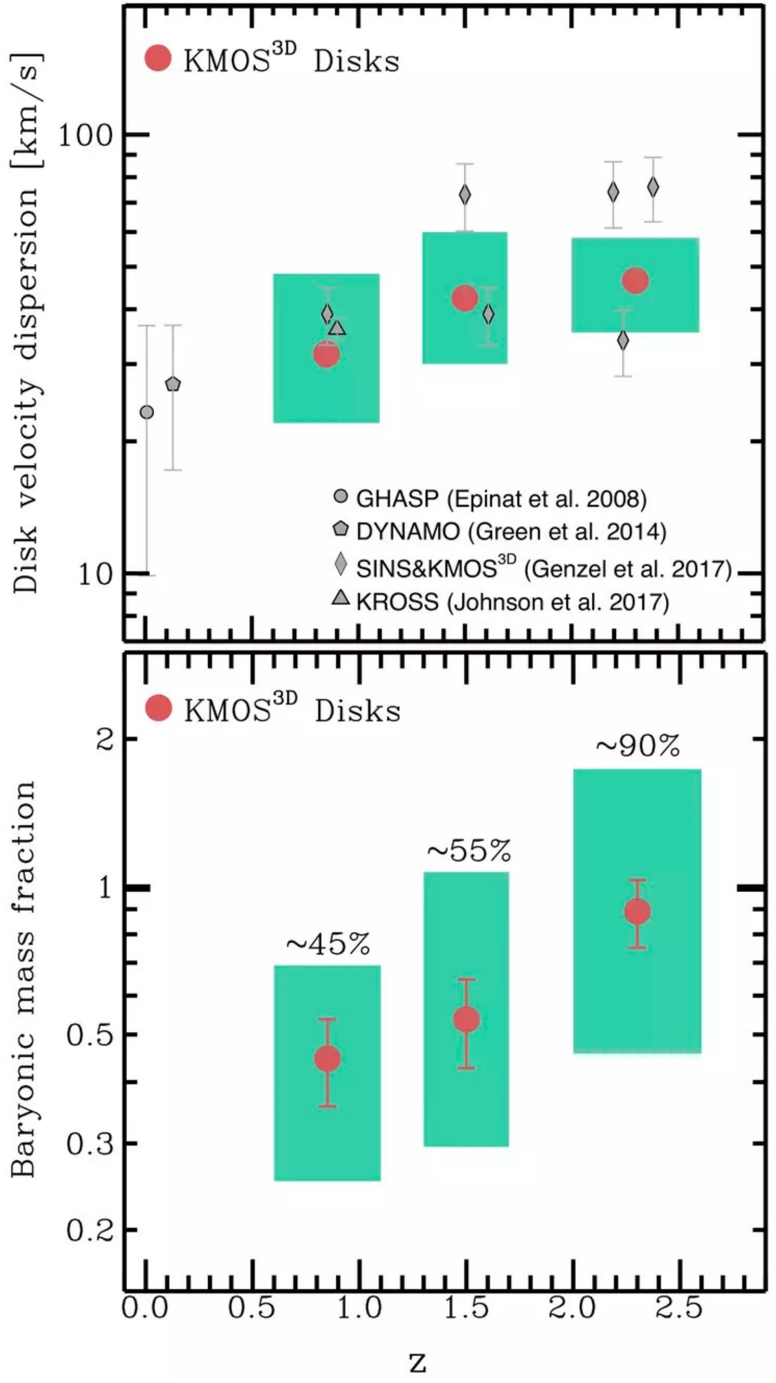
- KMOS-3D: NIR IFU spectroscopy of 700 galaxies at 0.7 < z < 2.7
- Hα velocity fields of 250 z~1 and 2 galaxies, relative to the star forming main sequence

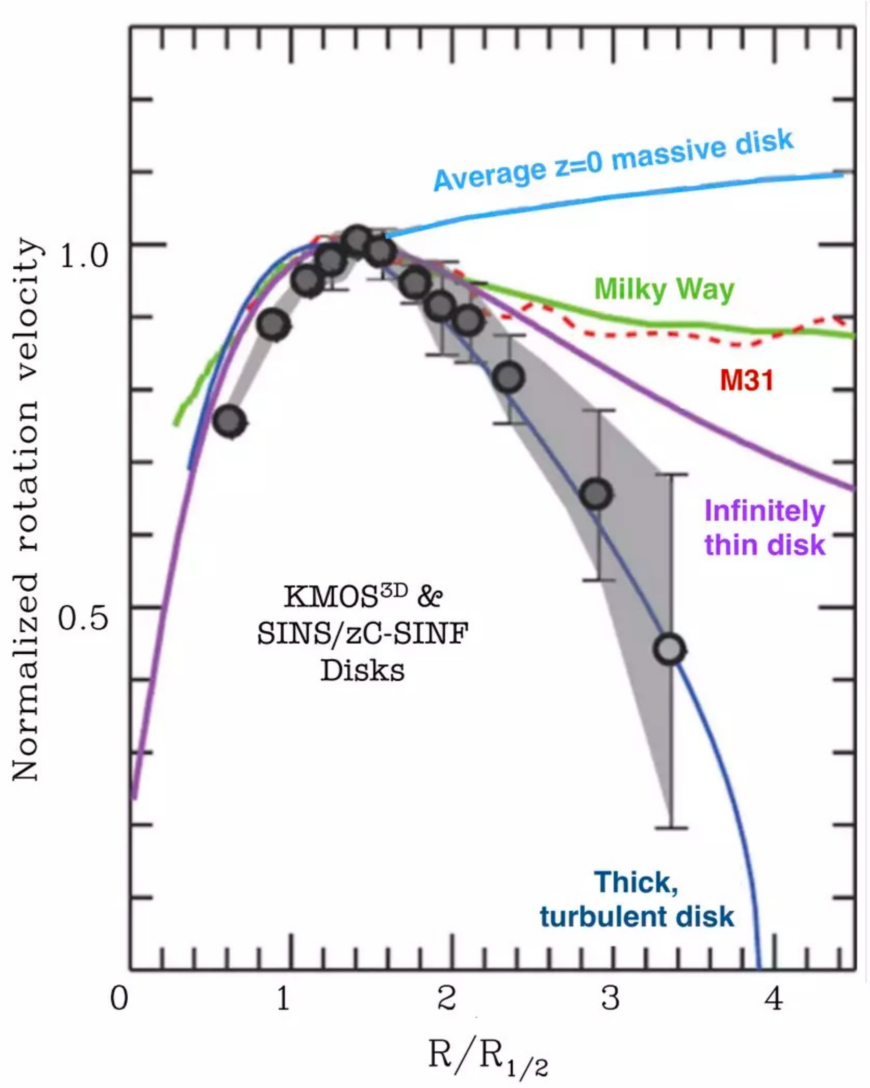


Wisnioski et al. 2015, 2019

KMOS-3D

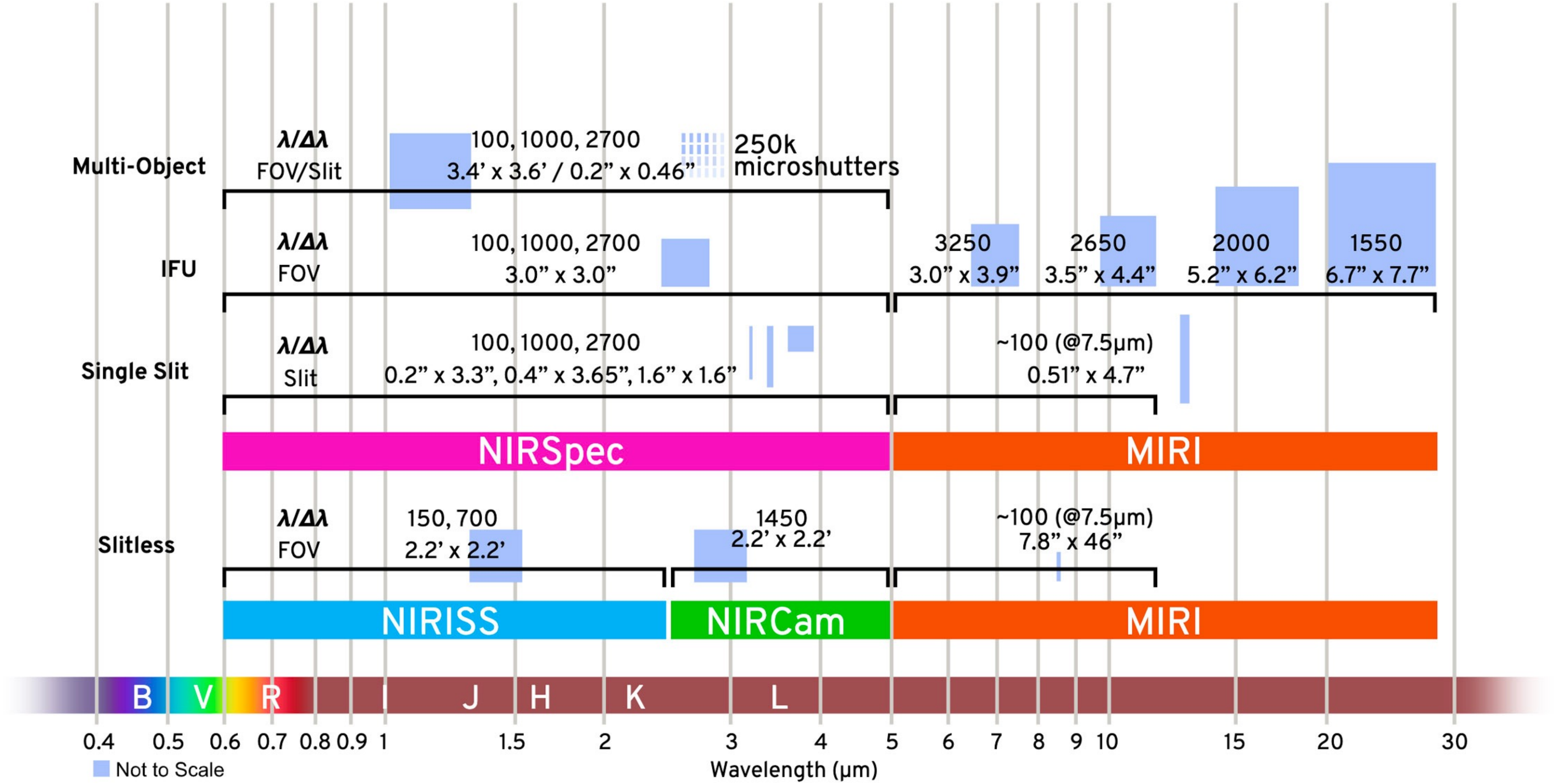
- Rotation curves of high-z disks suggest an evolution in the dark matter content of galaxies





Genzel et al. 2017, 2020
Lang et al. 2017
Price et al. 2021

JWST Spectroscopic Modes

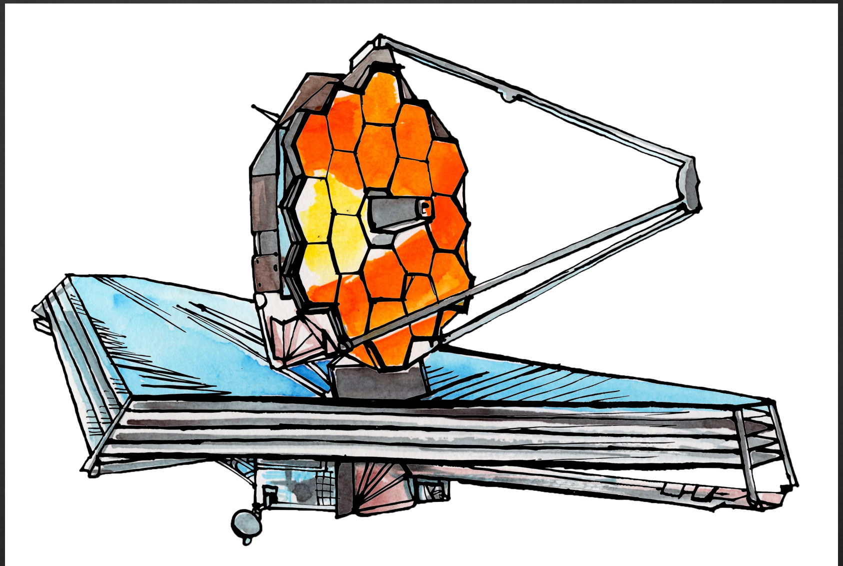


JWST Possibilities

Metallicity measurements using strong lines, weak lines, and direct calibration

Strong lines detectable out to high-z

MIR AGN Diagnostics



Resolved stellar kinematics

ISM conditions in the early universe: Evolution of the ionization parameter and ionizing photon production, gas density/pressure

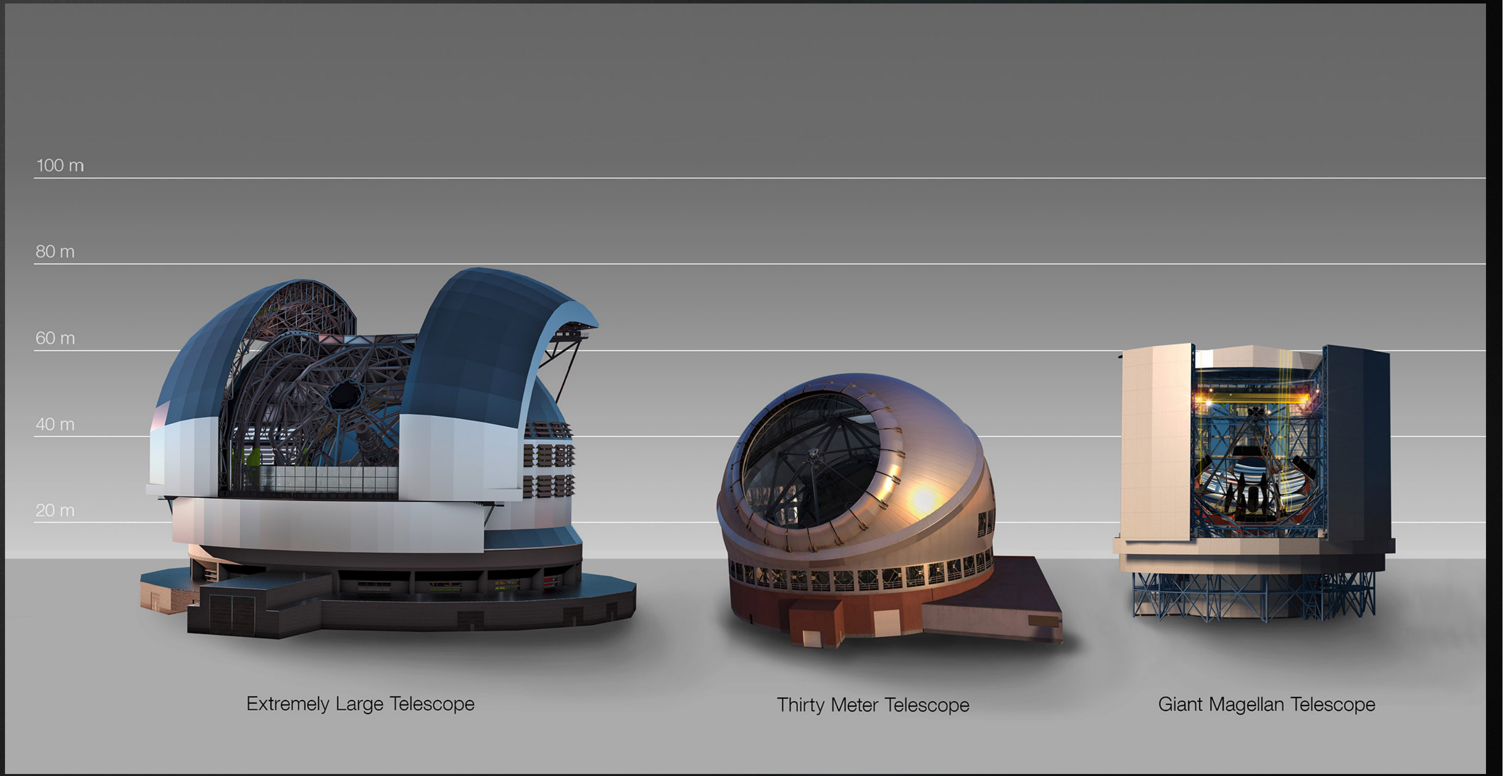
Redshifts for large numbers of faint/low mass/ high-z galaxies (including pairs!)

Your Favorite Topic Here!

The 30-m Class ELTs

- IFUs+AO (multiplexed?) will enable ‘MaNGA’ at high-z!
  - Resolved metallicities
  - Resolved stellar kinematics for faint galaxies

- Next-Generation NIR MOS
  - Measure redshifts,
    metallicities,
    ISM conditions, AGN
    diagnostics, etc.
    for large samples of
    galaxies



Summary

- Large optical and NIR spectroscopic surveys have enabled tremendous progress in our understanding of galaxy evolution
  - MZR and FMR well-established, evolution of FMR debated
  - Merger rate better constrained to moderate z, larger samples needed at higher z
  - Possibly evolving role of interactions in fueling star formation and AGN activity but larger samples of spectroscopically confirmed pairs at z>2 are needed
  - AGN and ISM diagnostics out to cosmic noon
- IFU surveys at low-z (MaNGA, CALIFA, SAMI) enable detailed studies of physical processes in galaxies
  - High-z surveys like KMOS-3D are beginning to scratch the surveys
- Larger, fainter, and higher-z samples are needed to address many open questions
  - Will be possible with JWST, ELTs, and surveys with PFS, MOONS, Euclid, Roman, etc.