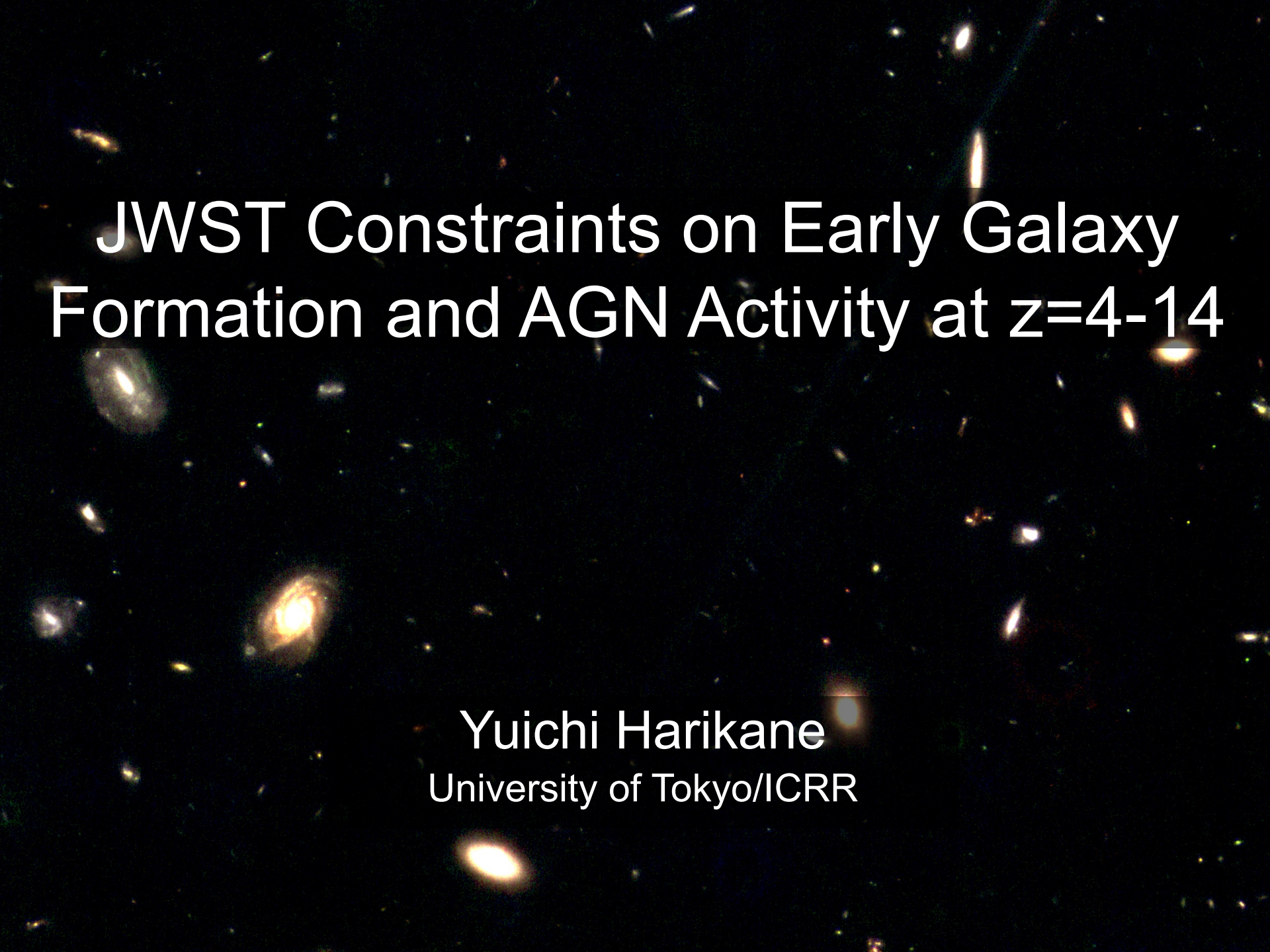
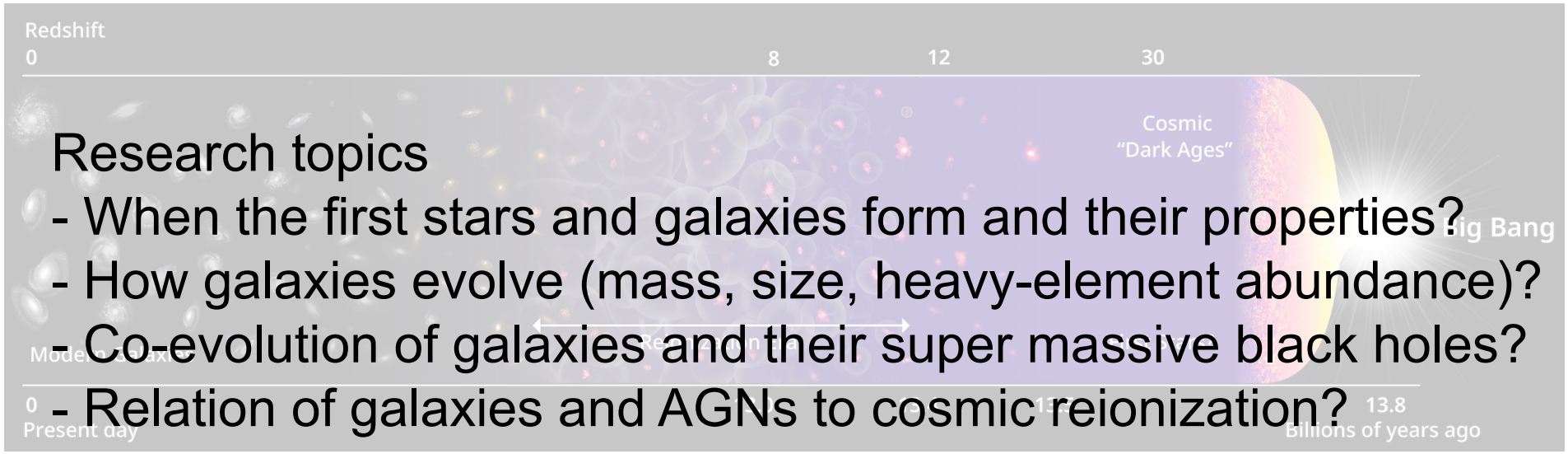


JWST Constraints on Early Galaxy Formation and AGN Activity at z=4-14

Yuichi Harikane
University of Tokyo/ICRR

Goal of Galaxy Formation Study

- Understanding how galaxies form and evolve in the 13.8 billion-year cosmic history



Research topics
- When the first stars and galaxies form and their properties?
- How galaxies evolve (mass, size, heavy-element abundance)?
- Co-evolution of galaxies and their super massive black holes?
- Relation of galaxies and AGNs to cosmic reionization?

Harikane et al.

Present day ← Big Bang

Milky way galaxy

Andromeda galaxy

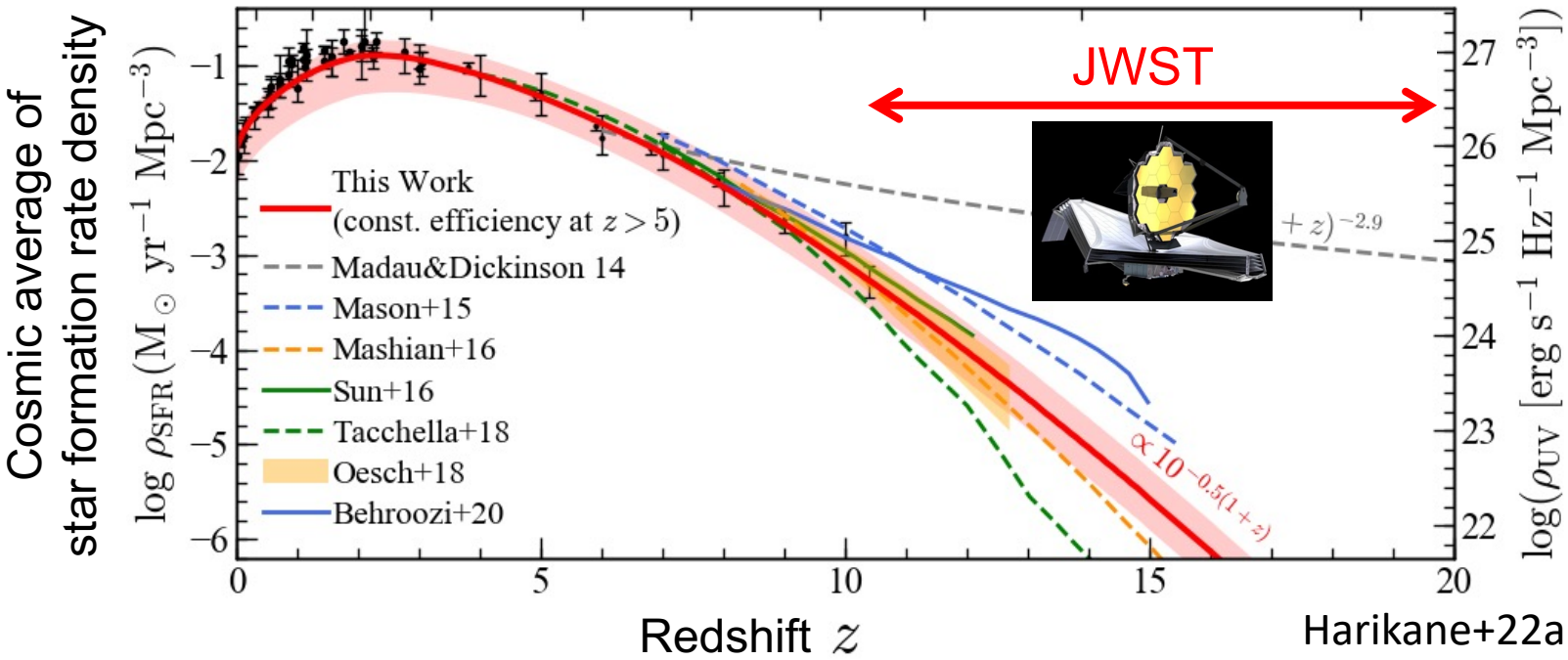
High redshift galaxies

First stars?

First galaxies?

Results/Predictions Before JWST

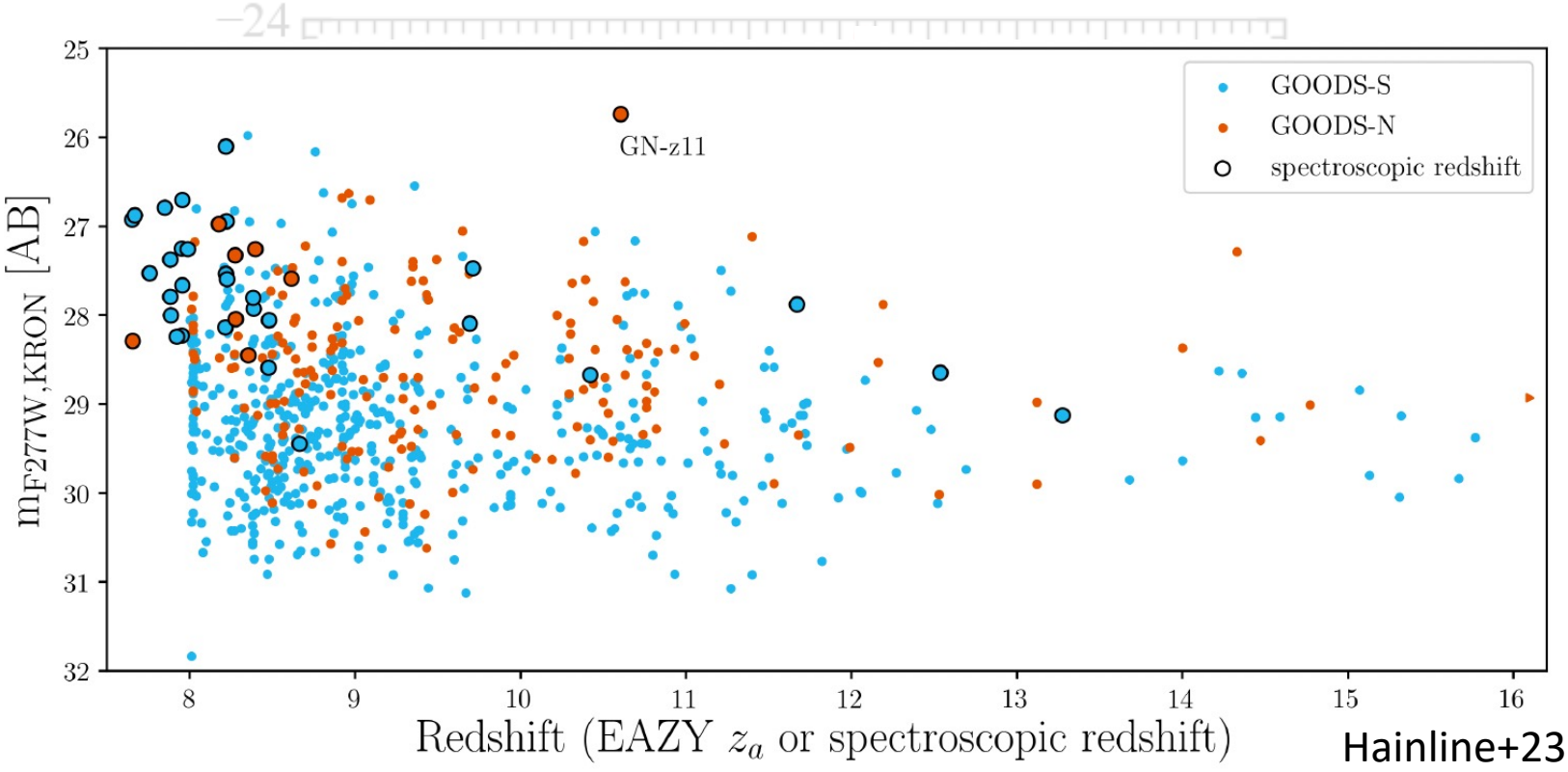
- Cosmic star formation rate density at z~0-10
  - Results from Hubble Space Telescope
- Constant star formation efficiency (SFR/(dM_h/dt)) model
  - Reproducing evolution at z=0-10, $10^{-0.5(1+z)}$ at z>10



See e.g., Bouché+10,Madau+14,Bouwens+15,Finkelstein+15,Mason+15,Tacchella+18,Oesch+18,Tacconi+20…

JWST High Redshift Galaxy Candidates

- >20 galaxies at z~9-16 from the first datasets
  - Current: >700 galaxies at z>8 from JADES GTO

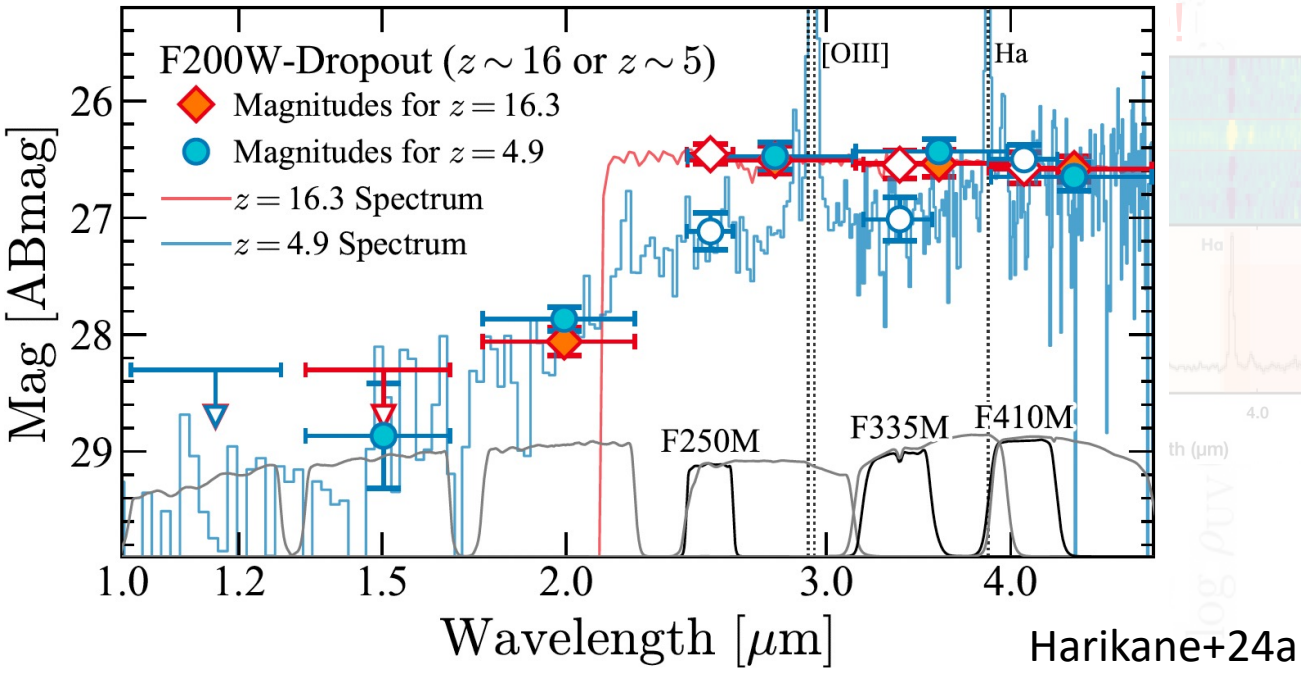


Hainline+23

See also, Naidu+22, Castellano+22, Finkelstein+22,23ab, Donnan+23ab, Bouwens+23ab, Perez-Gonzalez+23, Franco+23, Atek+22,23, Adams+22,23, McLeod+24, Austin+23, Casey+23, Morishita+23ab, …

JWST Observations

- Higher SFR density at z>10 based on photo-z
- Contamination? e.g., z~16 candidate → z=4.9



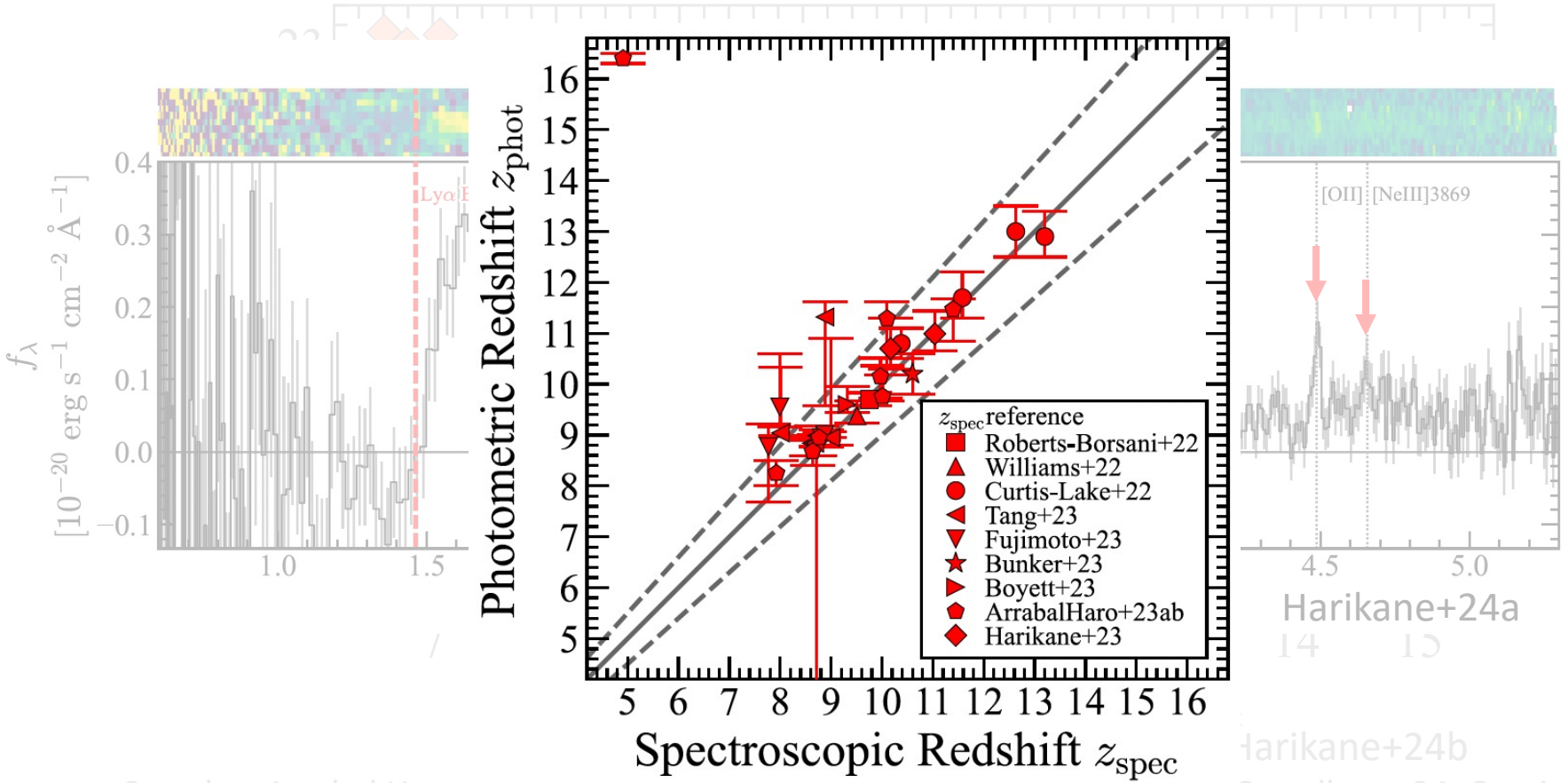
Harikane+24a

Arrabal Haro+23

Harikane+23a,24a

JWST Spec-z Sample

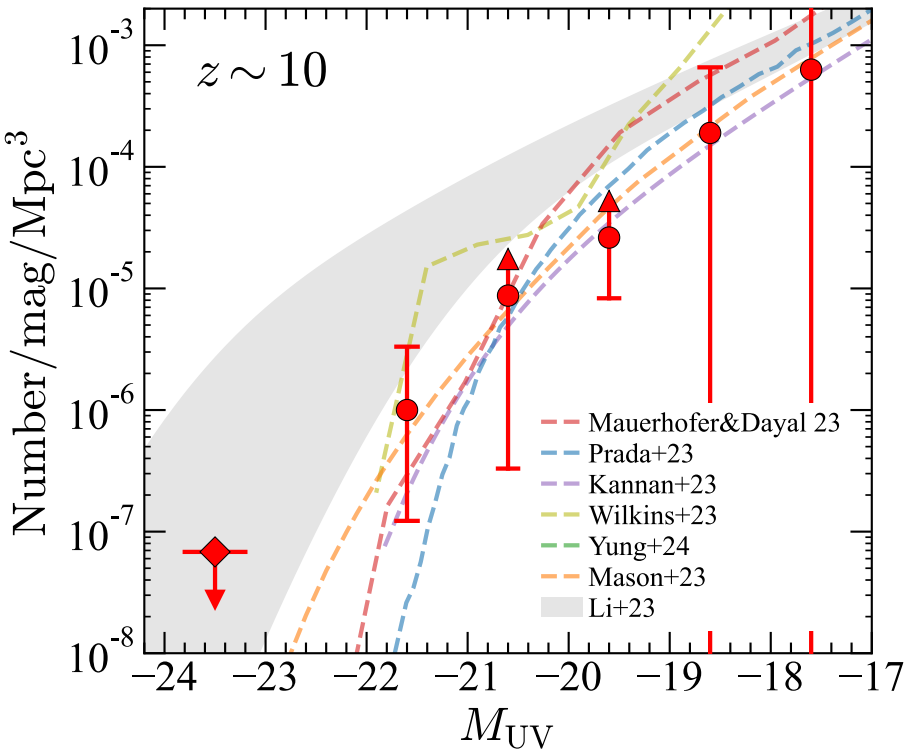
- ~20 galaxies at z_{spec}>10 confirmed w/ NIRSpec
  - z_{phot} agrees well with z_{spec} except for a few sources

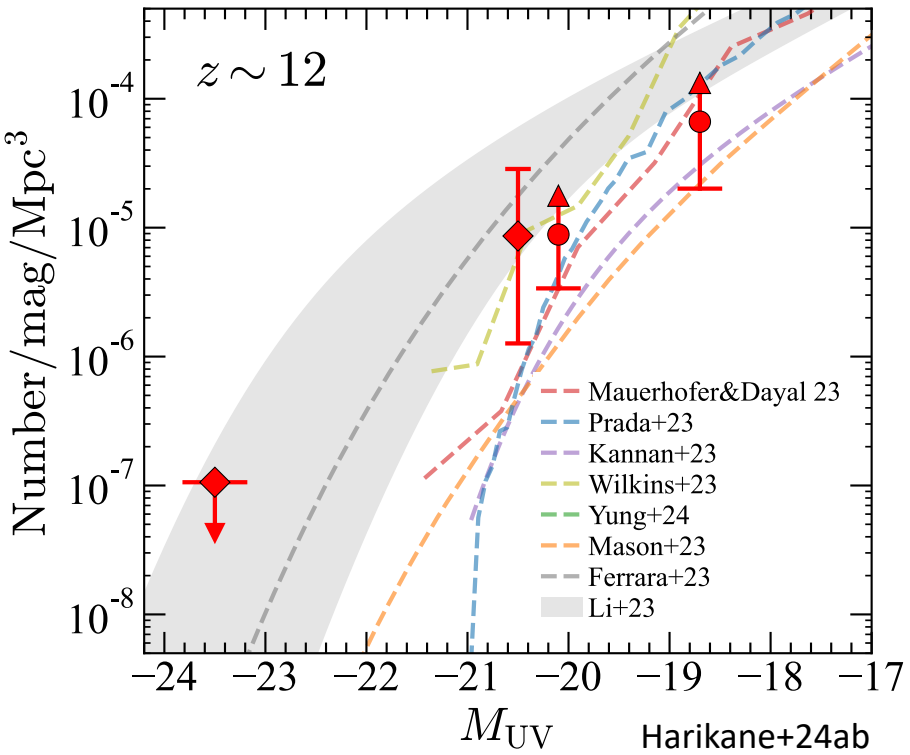


See also, Arrabal Haro+23ab, Curtis-Lake+23, Wang+23, Fujimoto+23ab, Castellano+24, Carniani+24...

Spec-z UV Luminosity Function

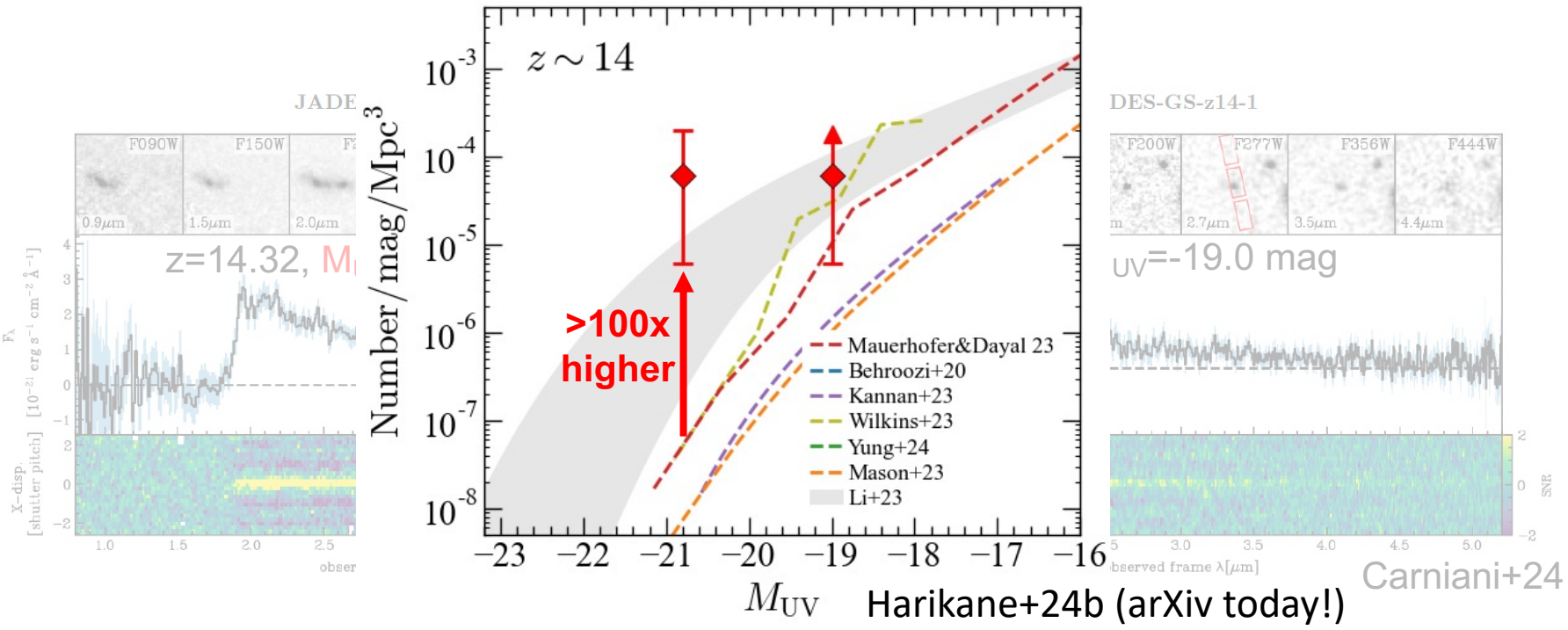
- Free from low-z contamination
  - Consistent with photo-z results
  - Some models underestimate at z~12 & M_{UV}<-20 mag





Recent Confirmation of z=14 Galaxies

- Two galaxies at z_{spec}=14 found in 9 arcmin^2 data
  - >100x higher number density than theoretical models
  - Really high density? Cosmic variance? (but included in the error…)

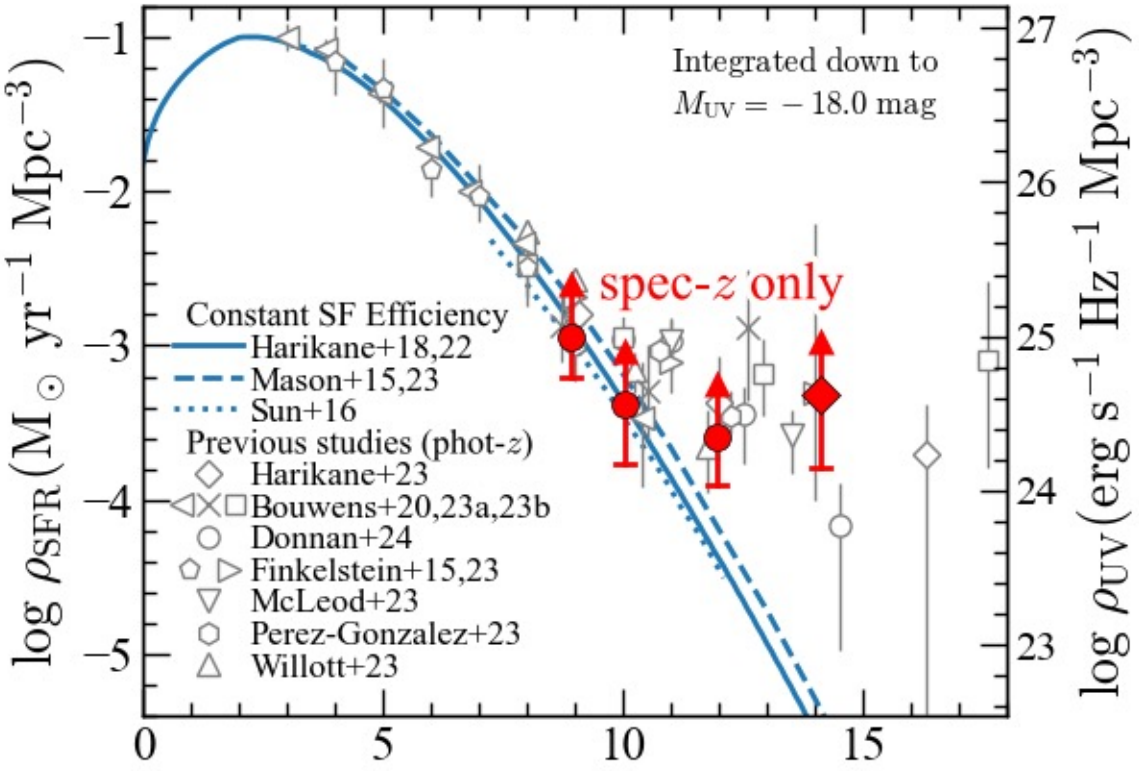


Spec-z Cosmic SFR Density at z=9-14

- UV→SFR: $SFR(M_\odot\ \mathrm{yr}^{-1}) = \mathcal{K}_{\mathrm{UV}} L_{\mathrm{UV}}(\mathrm{erg\ s}^{-1}\ \mathrm{Hz}^{-1})$

$$\mathcal{K}_{\mathrm{UV}} = 1.15 \times 10^{-28}\ M_\odot\,\mathrm{yr}^{-1}/(\mathrm{erg\ s}^{-1}\mathrm{Hz}^{-1})$$

- Tension with constant efficiency models at z>10



Harikane+24ab, see also Bouwens+23

Physical Interpretations

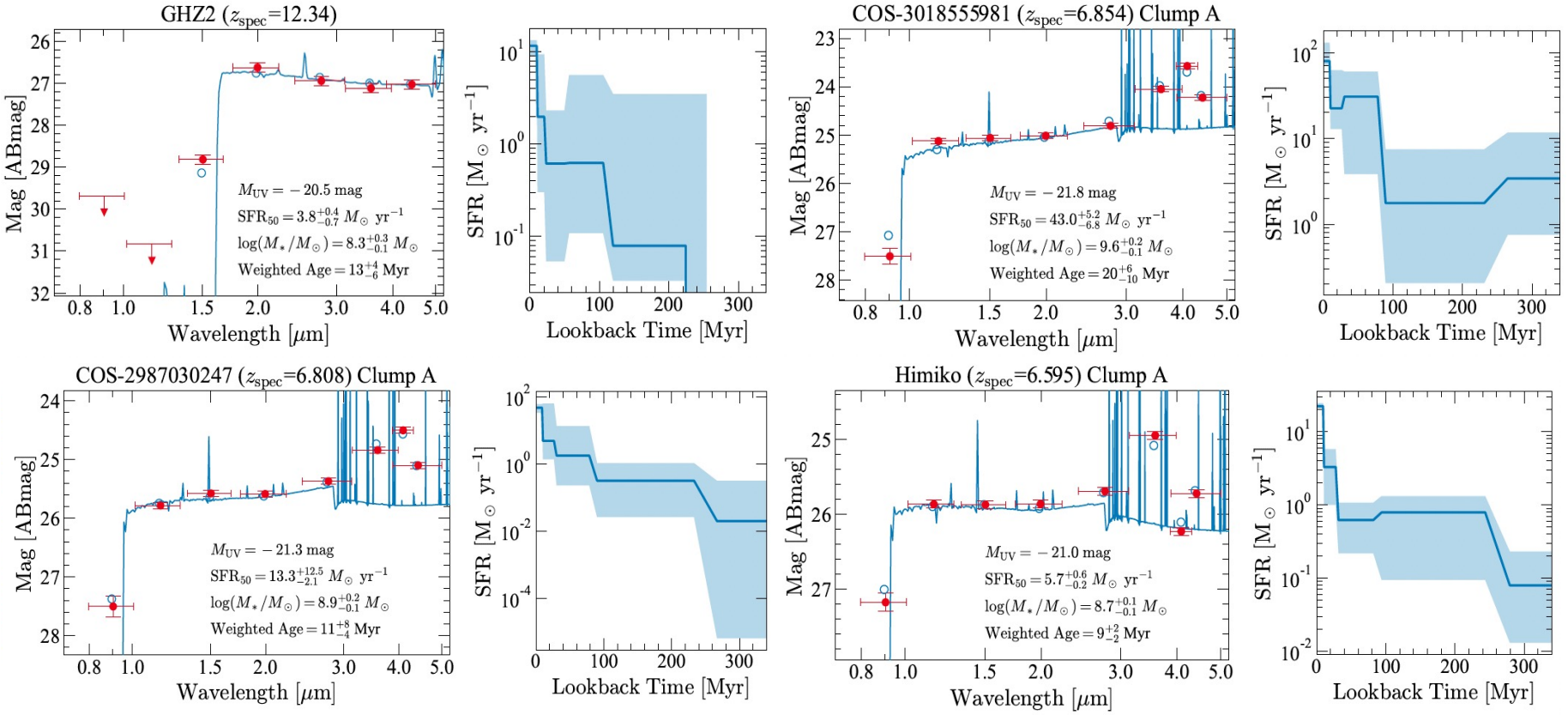
Why are we finding more galaxies at z>10 than models?

Models: calibrated at z=0-10. Different galaxy formation physics at z>10?

1. **High star formation efficiency**, e.g., by feedback free starburst (Dekel+23), compact star formation (Fukushima+22, Ono+23)
2. **Top-heavy initial mass function** (lower K_{UV}, possibly w/ Pop-III, e.g., Chon+22, Cameron+23, see also Rasmussen Cueto+23, Anne's talk)
3. **Radiation driven outflow** (Ferrara+22,23)
4. **Bursty star formation** (e.g., Mason+23, Shen+23, Sun+23ab, see also Pallottini+23, discussed in next slide)
5. **Cosmology** (e.g., Menci+23, Parashari+23, Hirano+23)
6. **AGN activity** (e.g., Hedge+24)

Star Formation Histories

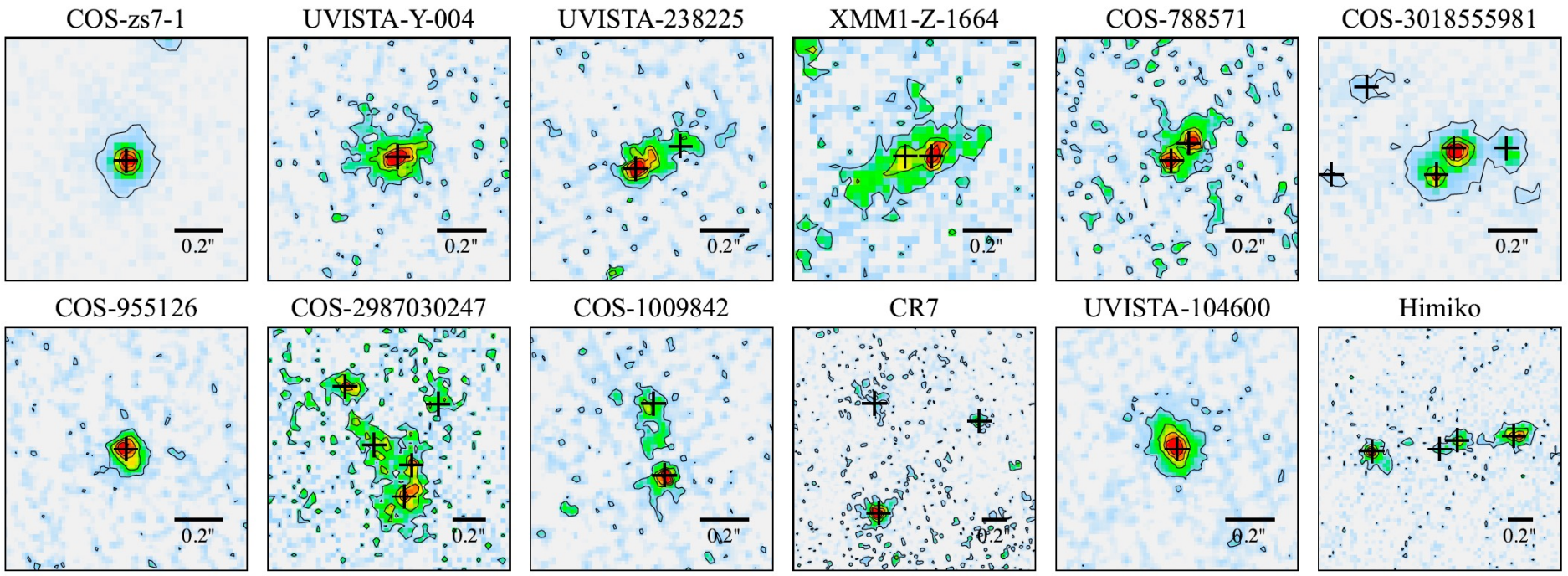
- Bright gals at z~7-12: bursty star formation histories
  - Starbursts boosting the UV luminosity of these galaxies



Harikane+24b, See also e.g., Endsley+23

Clumpy Morphologies at z~7

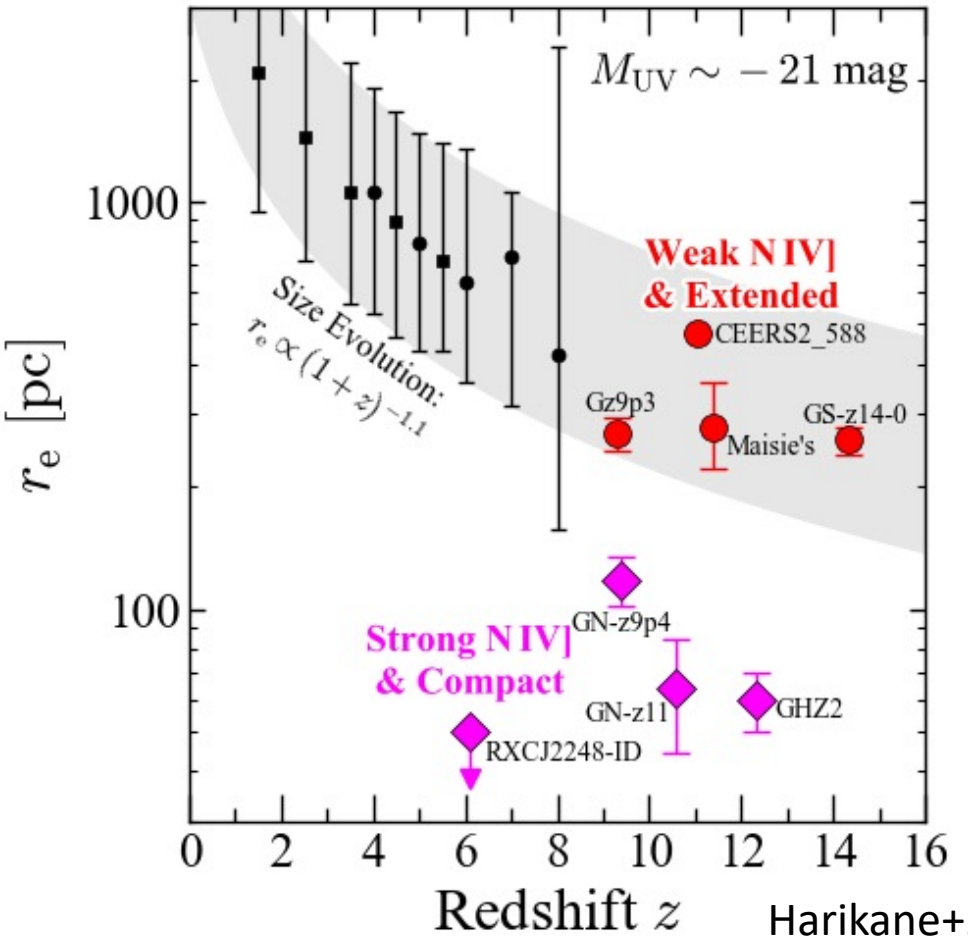
- 70% of bright galaxies at z_{spec}~7 show clumpy morphologies w/ multiple components
  - Recent starburst induced by mergers?



Harikane+24b

Galaxies at z>10: Compact or Extended

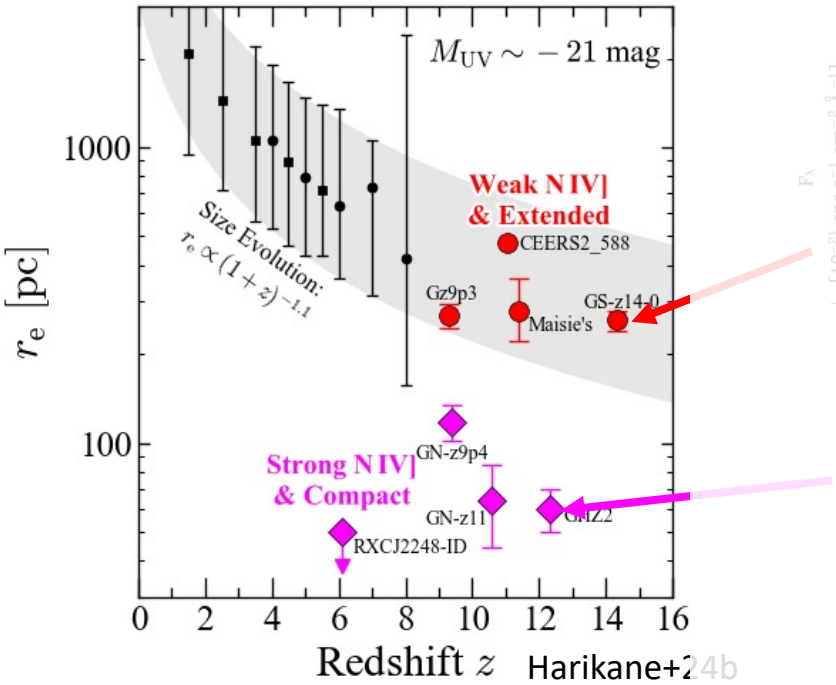
- Two types of bright (M_{UV}<-20 mag) galaxies at z>10
  - Extende
  - Compa

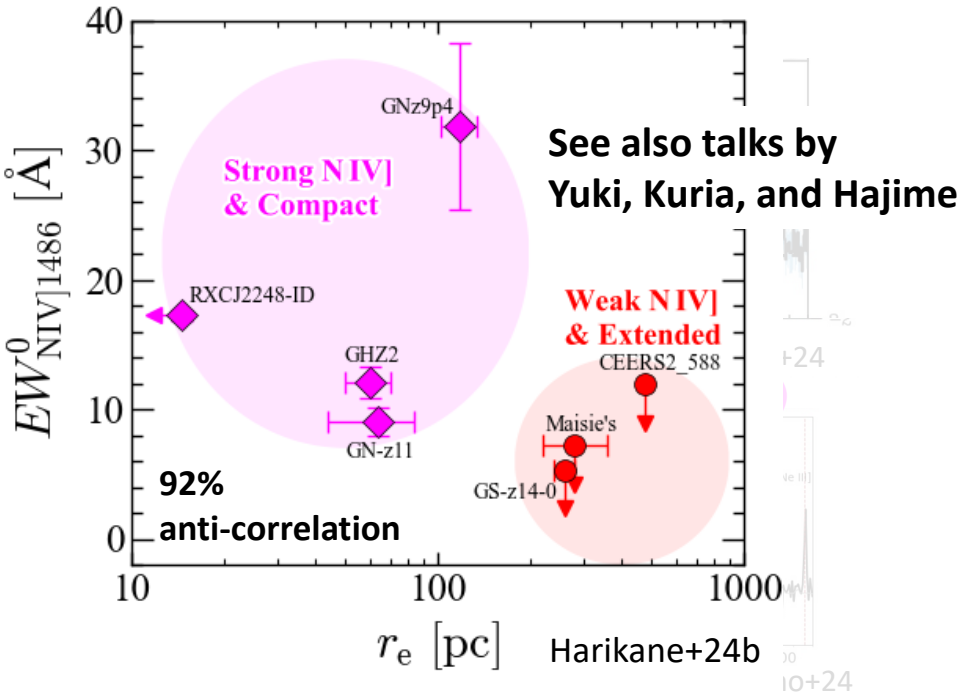


Harikane+24b (arXiv today!)

Galaxies at z>10: Compact or Extended

- Two types of bright (M_{UV}<-20 mag) galaxies at z>10
  - Extended galaxies wo/ strong emission lines
    → merger-induced starburst?
  - Compact galaxies w/ high ionization emission lines
    → compact SF (enhancing N production) or AGN?

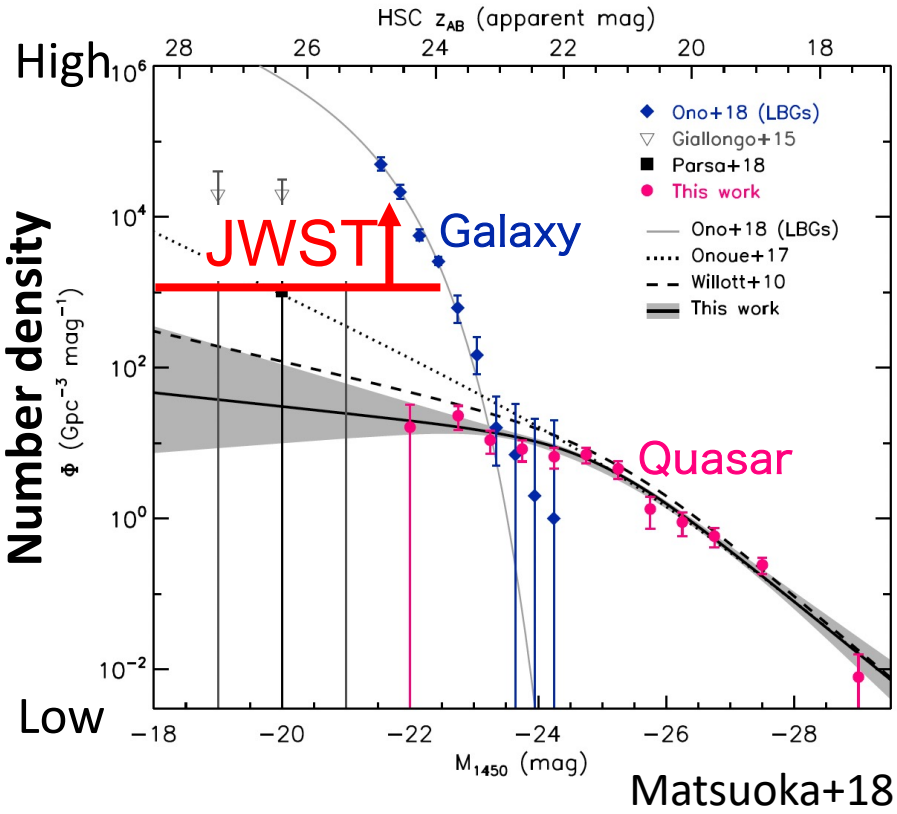




See also talks by Yuki, Kuria, and Hajime

How About AGNs?

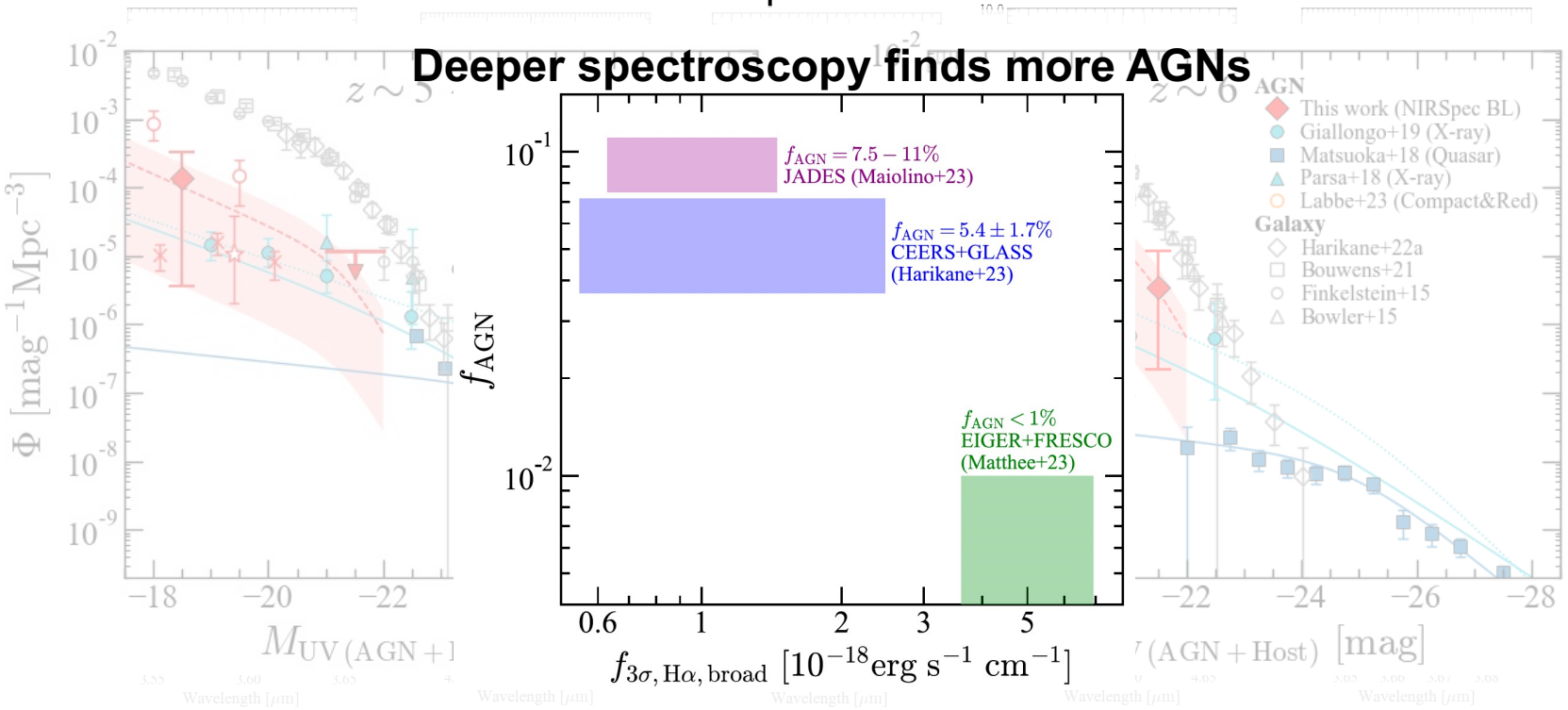
- Before JWST: quasars at z~4-7 w/ M_{BH}~10^9 M_{sun}
- Quasar luminosity function at z~4-7
  - Flat slope at faint end → N<0.2 obj. expected in JWST



Many AGNs at z>4!

See also Jorryt's talk

- 10 AGNs at z=4-7 (from NIRSpec/MSA; Nakajima+23)
  - Broad Ha (FWHM~1000-6000 km/s), narrow [OIII] (<1000 km/s)
  - From 185 galaxies at z_{spec}>3.5, ~5% (~1-2% at z~0, Stern+12)

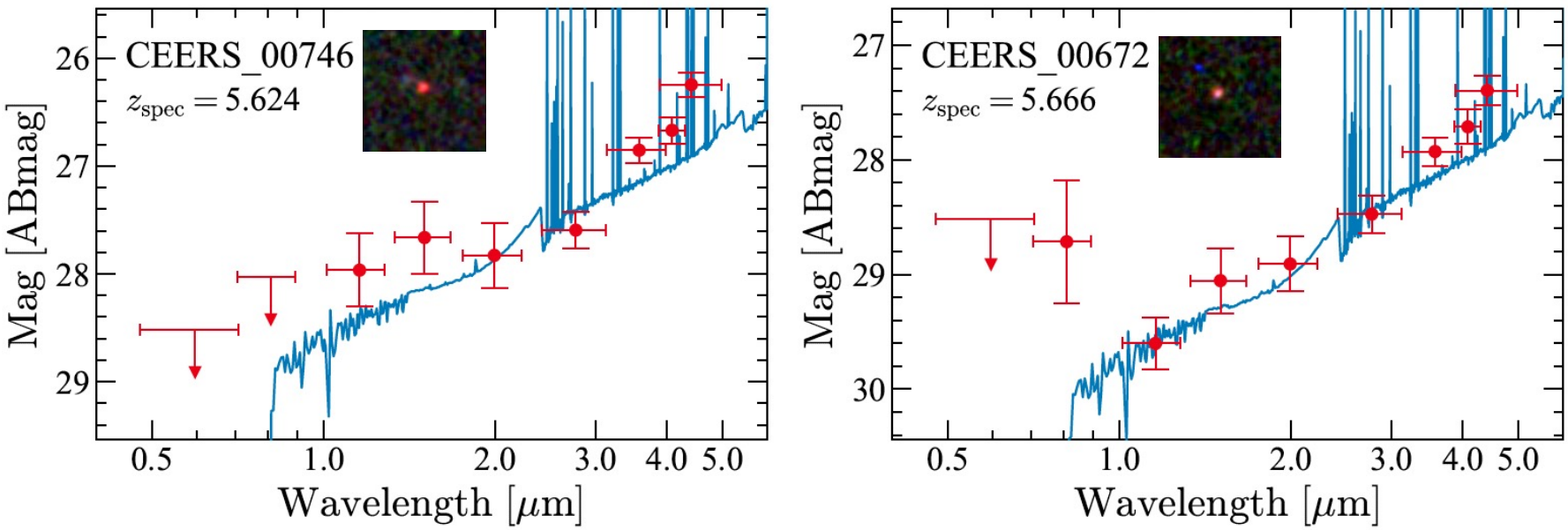


Harikane+23b

see also e.g., Kocevski+23, Ubler+23, Larson+23, Maiolino+23ab, Matthee+23, Labbe+23, Kokrev+23,24, Greene+23

Many AGNs at z>4!

- 7/10 show extended morphologies
  - Dominated by host galaxies, Seyfert galaxies at z>4
  - Contribution of AGNs (compact emission) to rest-UV: 50%
  - Two red&compact AGNs (Av>3, little red dots)

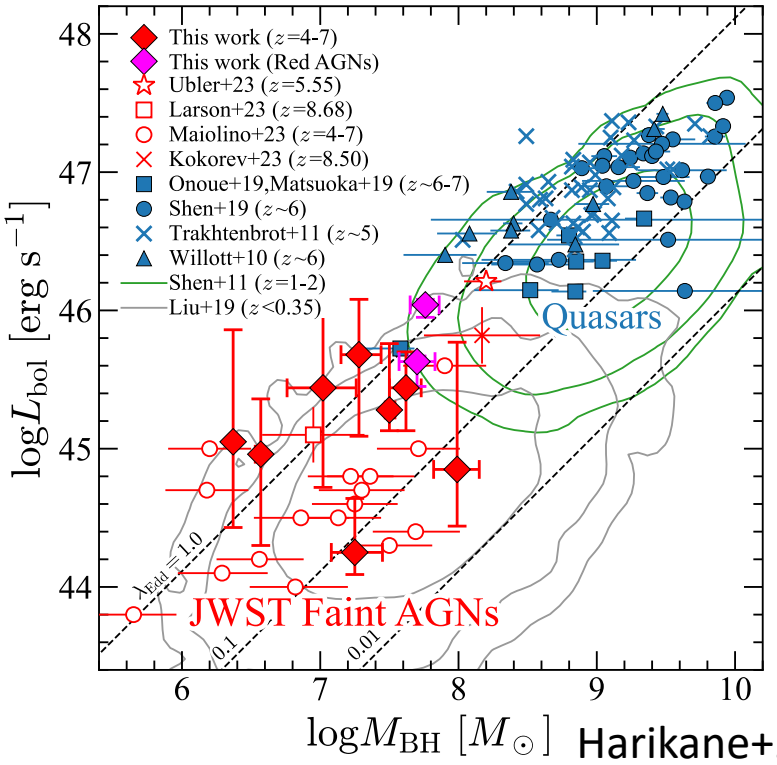


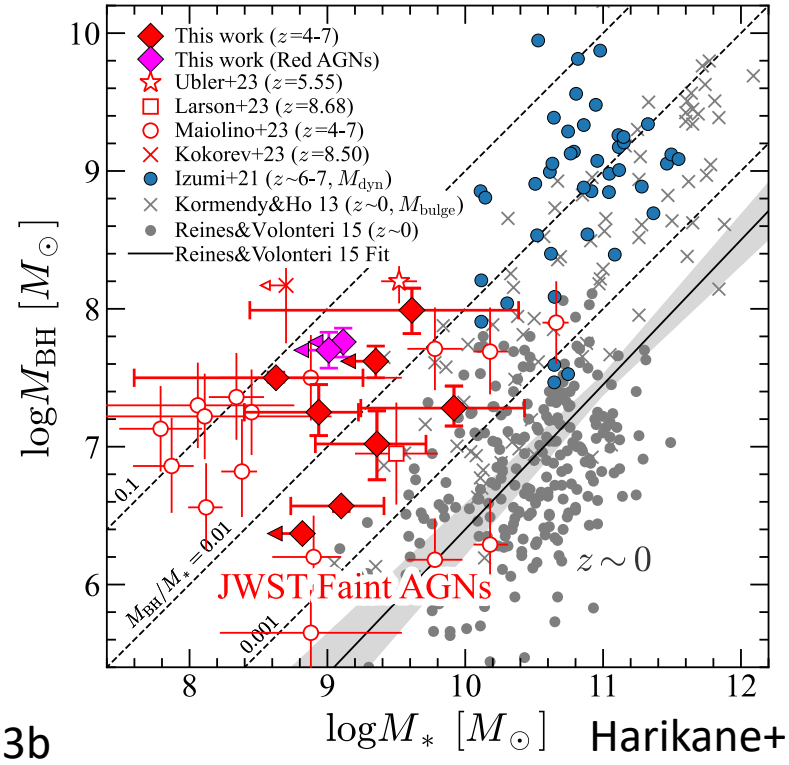
Harikane+23b

see also e.g., Kocevski+23, Ubler+23, Larson+23, Maiolino+23ab, Matthee+23, Labbe+23, Kokrev+23,24, Greene+23

Many AGNs at z>4!

- M_{BH}~10^6-10^8 M_{sun}, 100x smaller than quasars
  - Significantly higher M_{BH} than z~0 M_{BH}-M_* relation

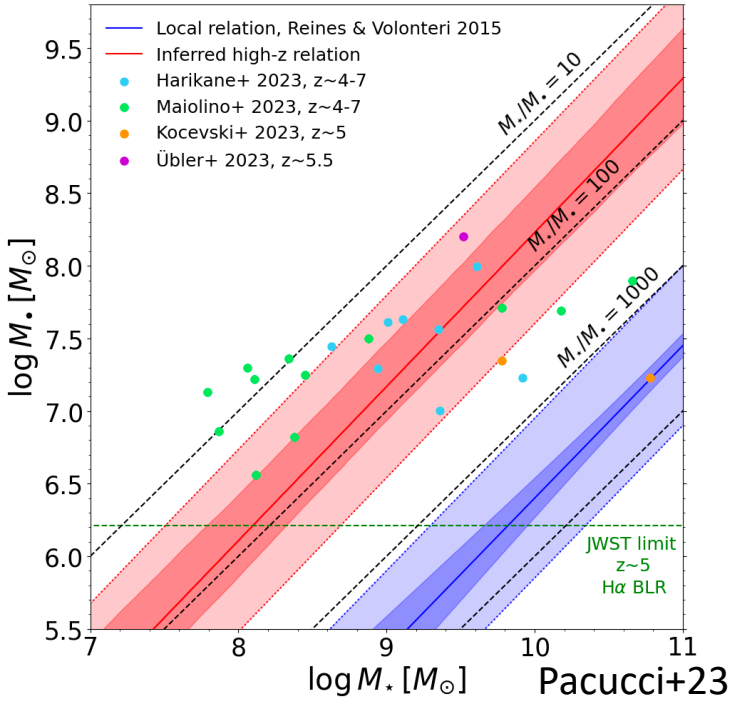


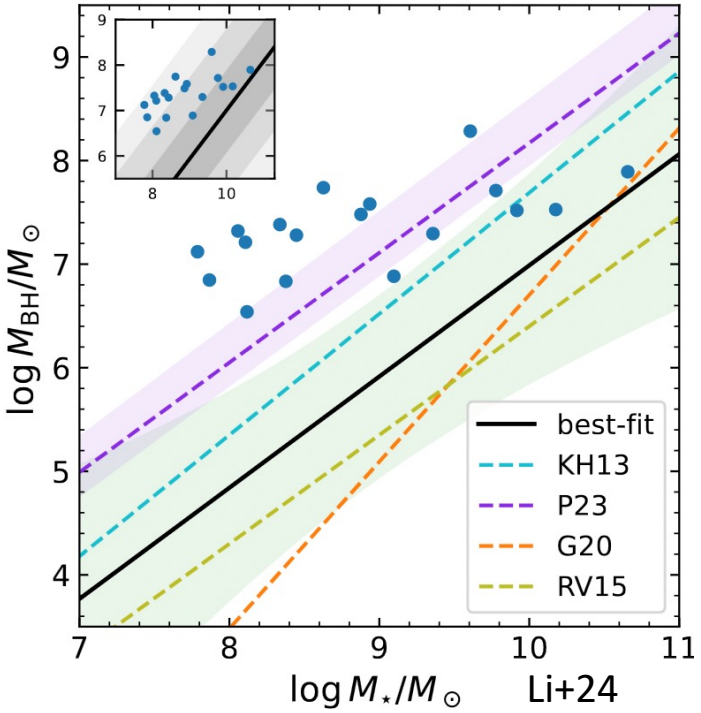


see also e.g., Kocevski+23, Ubler+23, Larson+23, Maiolino+23ab, Matthee+23, Labbe+23, Kokrev+23,24, Greene+23

Is Intrinsic Relation Really Overmassive?

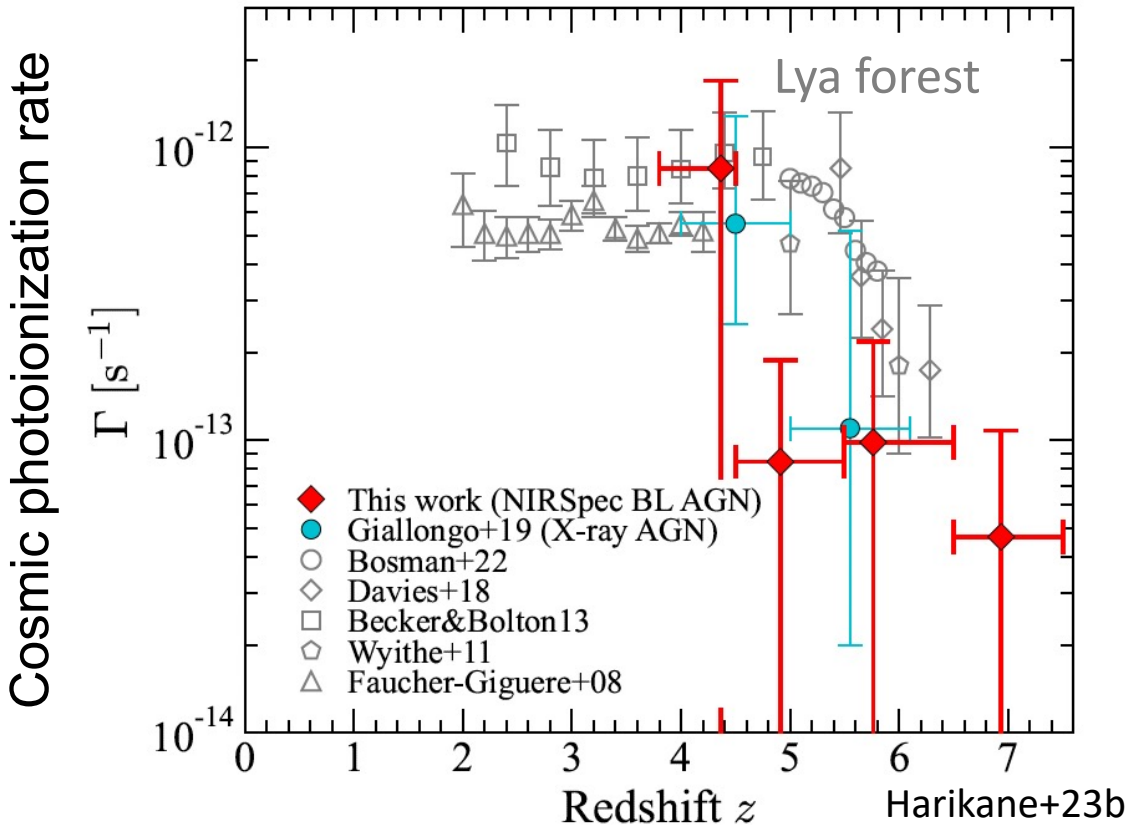
- Observational selection bias should be considered
  - Pacucci+23: Intrinsic relation is overmassive compared to local relation
  - Li+24: consistent with the local relation





Contribution to Reionization

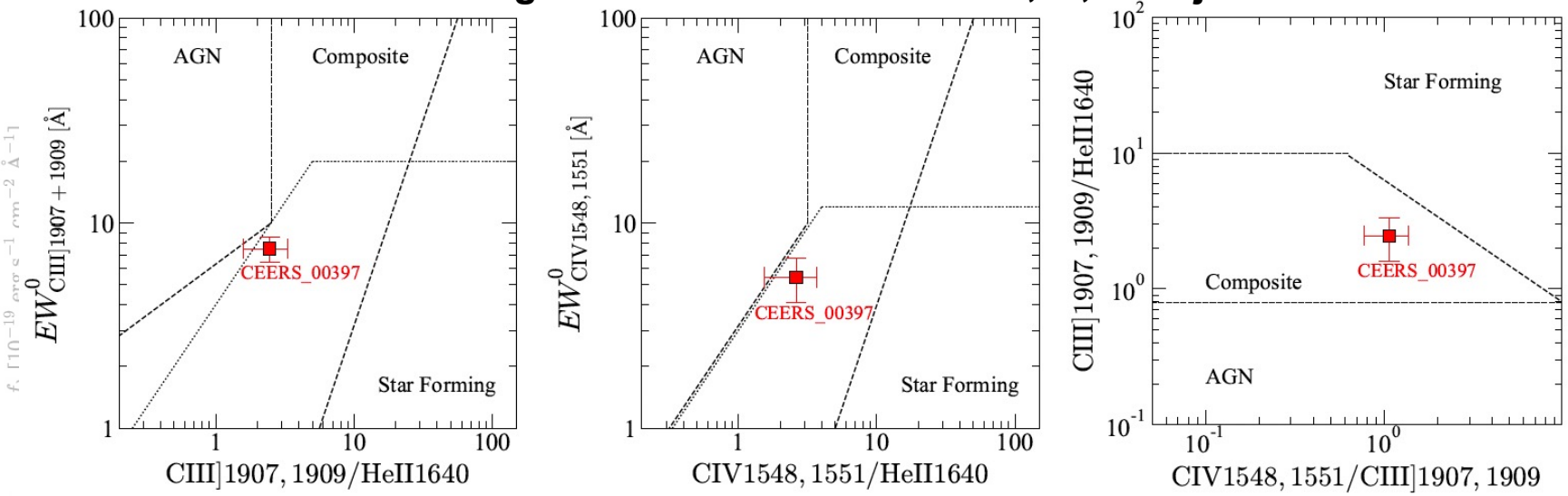
- Contribution from AGNs is up to ~50% at z~6
  - w/ large uncertainty (from escape fraction assumption)



BPT Diagram

- Classical optical BPT diagram does not work
  - Due to low metallicity
- Rest-frame UV diagram may work

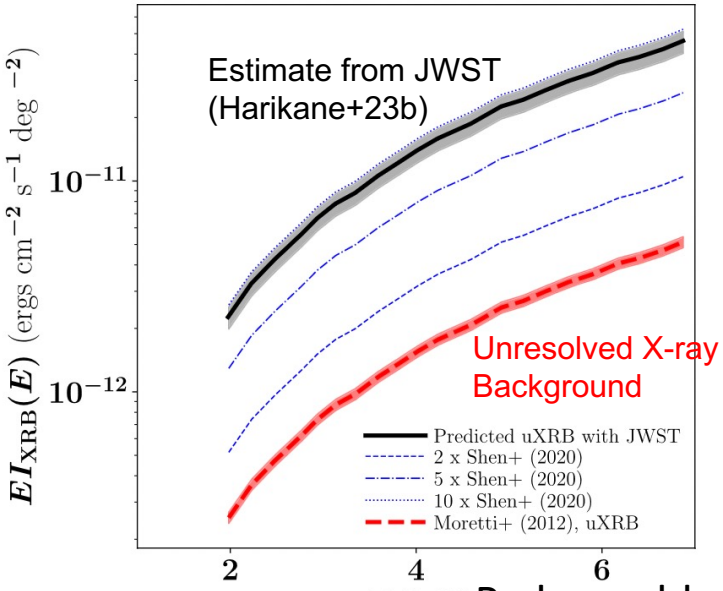
Rest-UV diagrams from Hirschmann+19,23, Nakajima+18



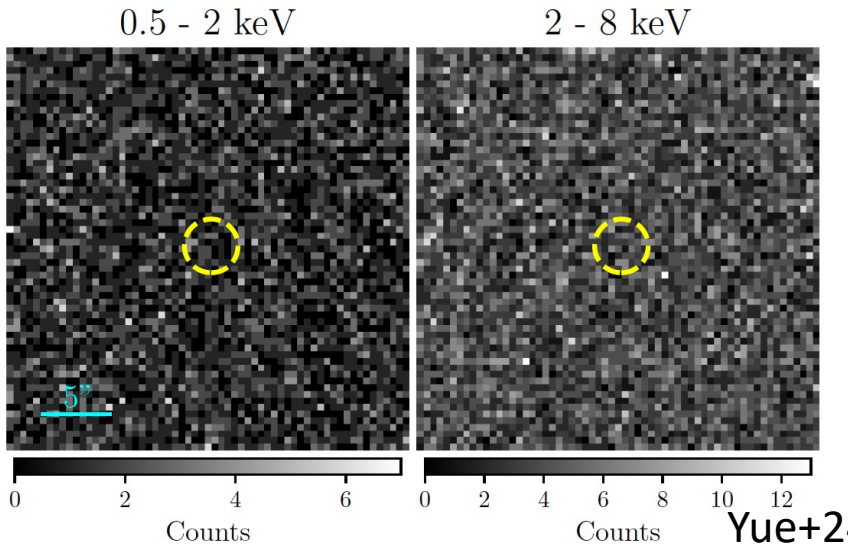
Harikane+23b

Are They Really AGNs?

- JWST broad-line detected AGNs are weak in X-ray
  - Comparison w/ X-ray background (Padmanabhan&Loeb 23)
  - Stacking/individual analysis (Yue+24, Ananna+24, Maiolino+24)
- Special AGNs (Compton-thick and intrinsically faint in X-ray)
- or low-metallicity outflow? (but Z<0.01 Z_{sun} needed)



Padmanabhan&Loeb 23

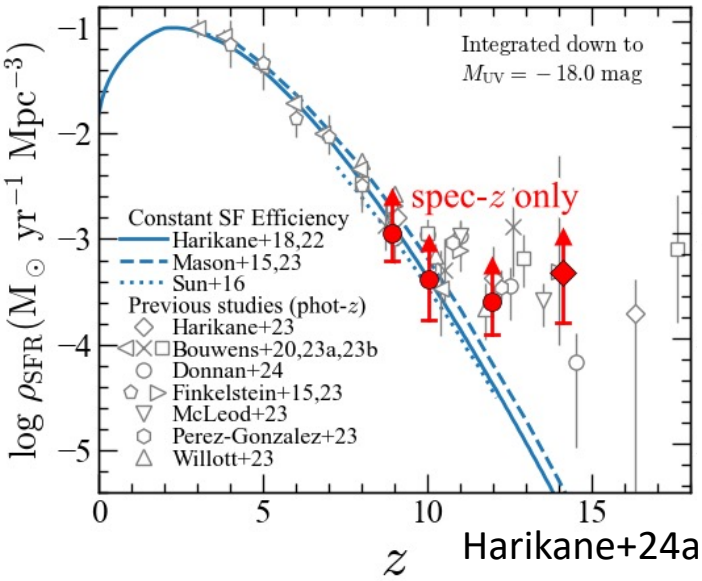


Yue+24

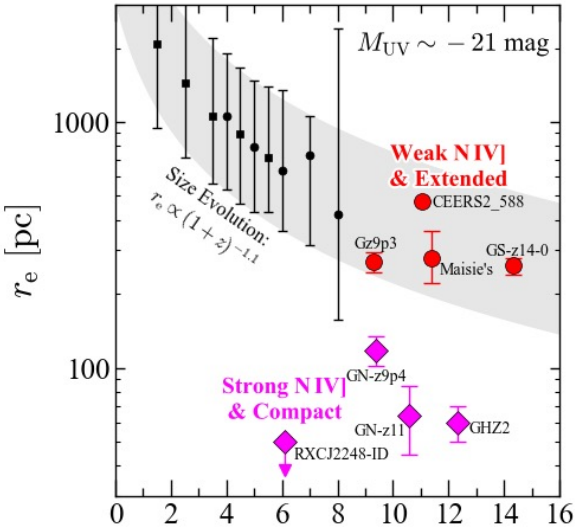
See also Ananna+24, Maiolino+24

Summary

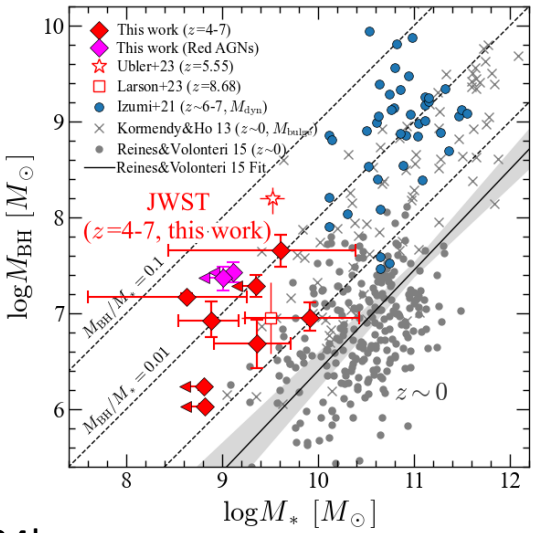
- JWST spec and phot studies of high-z galaxies
  - Large number of z>10 galaxies, more than theoretical model predictions. Excess in SFR densities at z~12-14.
  - Merger-induced starbursts in z~7 bright galaxies?
  - Two types of bright galaxies at z>10 (compact, extended)
  - 10 broad-line AGNs at z=4-7 with M_{BH}~10^6-10^8 M_{sun}



Harikane+24ab



Harikane+24b (arxiv today!)



Harikane+23b