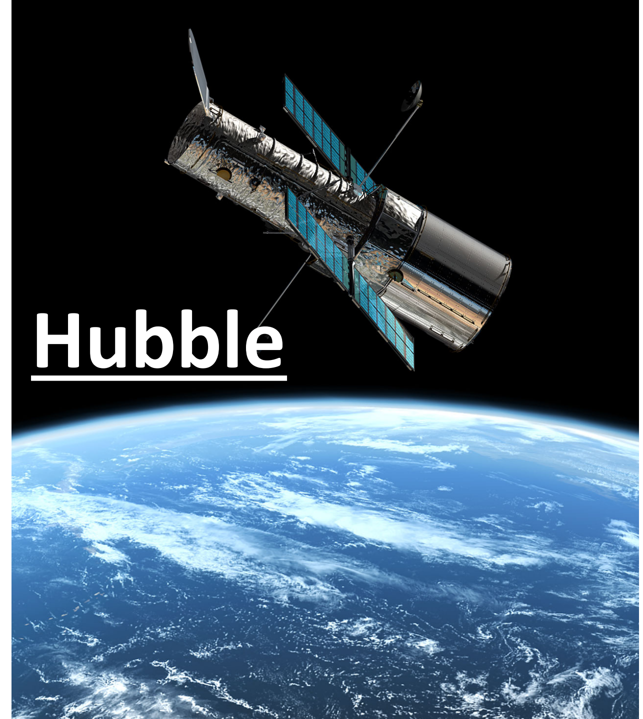
An Overview of Our Research Activities

Yuichi Harikane
Observational Cosmology Group

Our Members in FY2023

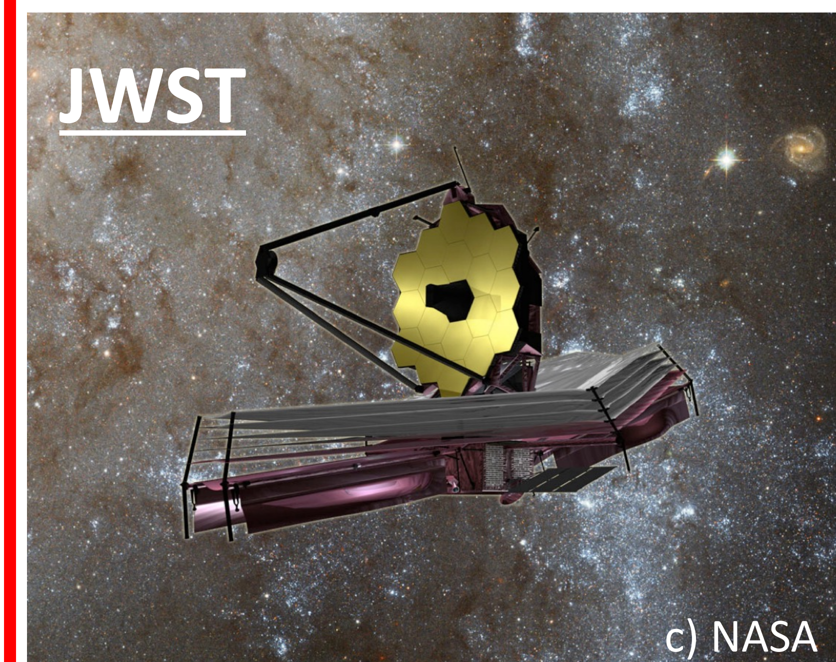
- Total of 15 members including 10 students
- Conducting wide variety of researches on observational cosmology/galaxy formation

c) NAOJ



c) ESA

c) NAOJ

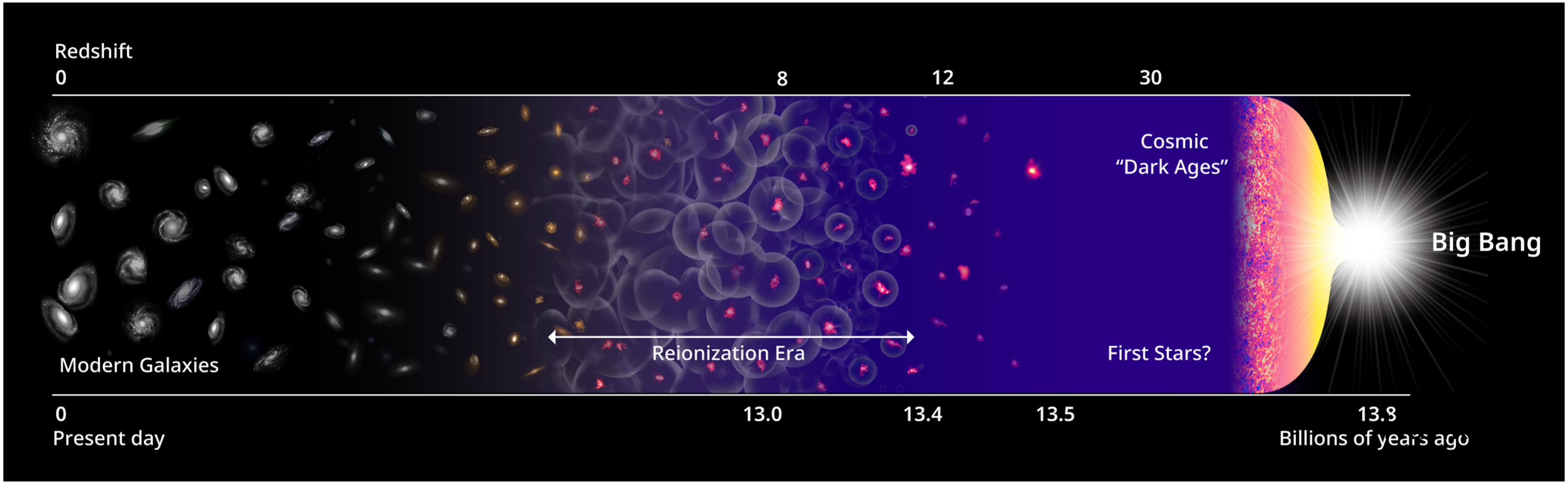


JWST Papers from Our Group

- **Y. Harikane et al. 2023a** “A Comprehensive Study of Galaxies at z 9-16 Found in the Early JWST Data: Ultraviolet Luminosity Functions and Cosmic Star Formation History at the Pre-reionization Epoch”
- **Y. Ono et al. 2023** “Morphologies of Galaxies at $z \gtrsim 9$ Uncovered by JWST/NIRCam Imaging: Cosmic Size Evolution and an Identification of an Extremely Compact Bright Galaxy at z 12”
- **Y. Isobe et al. 2023a** “Redshift Evolution of the Electron Density in the ISM at $z \sim 0-9$ Uncovered with JWST/NIRSpec Spectra and Line-Spread Function Determinations”
- **Y. Harikane et al. 2023b** “JWST/NIRSpec First Census of Broad-Line AGNs at z=4-7: Detection of 10 Faint AGNs with M_BH~10^6-10^7 M_sun and Their Host Galaxy Properties”
- **Y. Harikane et al. 2023c** “Pure Spectroscopic Constraints on UV Luminosity Functions and Cosmic Star Formation History From 25 Galaxies at zspec=8.61−13.20 Confirmed with JWST/NIRSpec”
- **H. Umeda et al. 2023** “JWST Measurements of Neutral Hydrogen Fractions and Ionized Bubble Sizes at z=7−12 Obtained with Lyα Damping Wing Absorptions in 26 Bright Continuum Galaxies”
- **Y. Zhang et al. 2023** “Statistics for Galaxy Outflows at $z \sim 6-9$ with Imaging and Spectroscopic Signatures Identified with JWST/NIRCam and NIRSpec Data”
- **Y. Isobe et al. 2023b** “JWST Identification of Extremely Low C/N Galaxies with $[N/O] \gtrsim 0.5$ at $z \sim 6-10$ Evidencing the Early CNO-Cycle Enrichment and a Connection with Globular Cluster Formation”

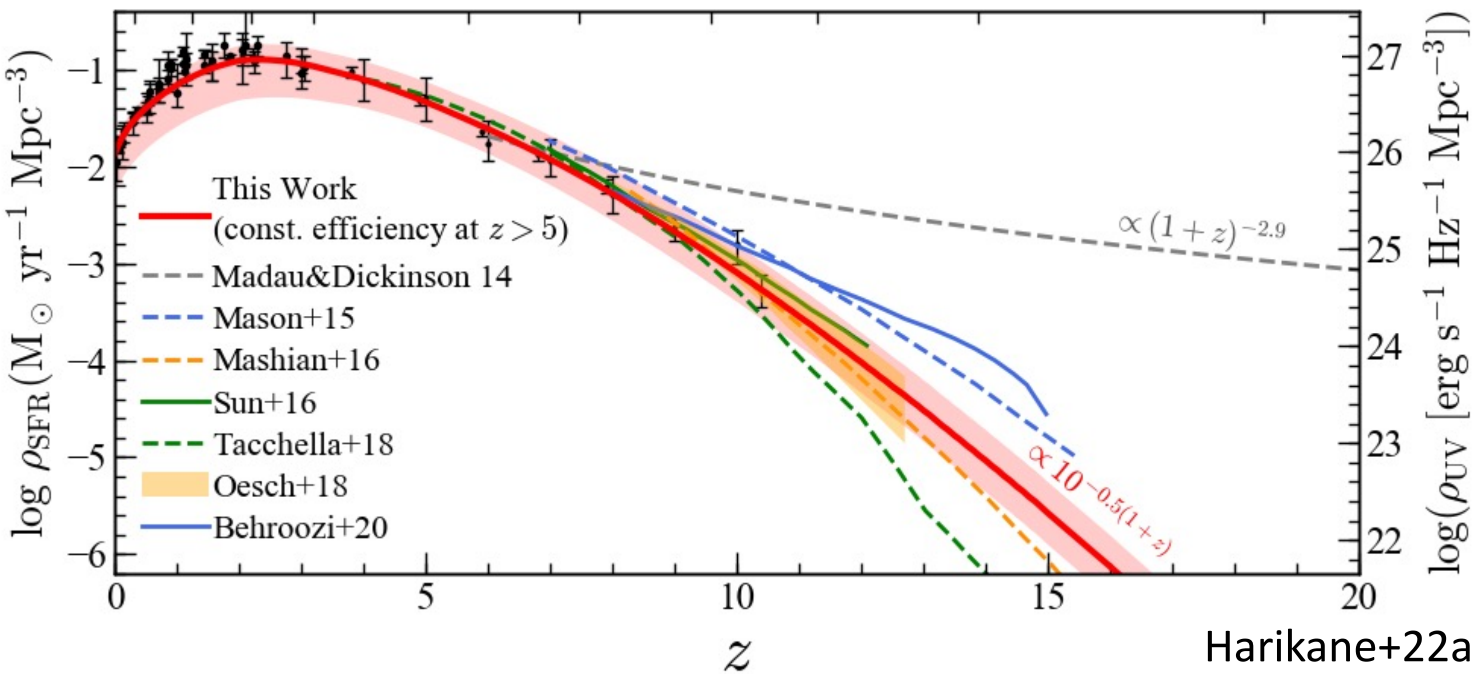
Observing Early Universe at z>4

- Key to understand several important processes
  - First galaxy formation/galaxy evolution
  - Star formation at high redshifts (star formation efficiency, IMF)
  - Galaxy-AGN relation
  - Interstellar medium (ISM) properties (metallicity, density)



Cosmic Star Formation Rate Density

- SFR density evolution at z~0-10
  - HST results (e.g., Bouwens+15, Finkelstein+15)
- Constant star formation efficiency model (SFR/(dM_h/dt))
  - Reproducing evolution at z=0-10, $10^{-0.5(1+z)}$ at z>10



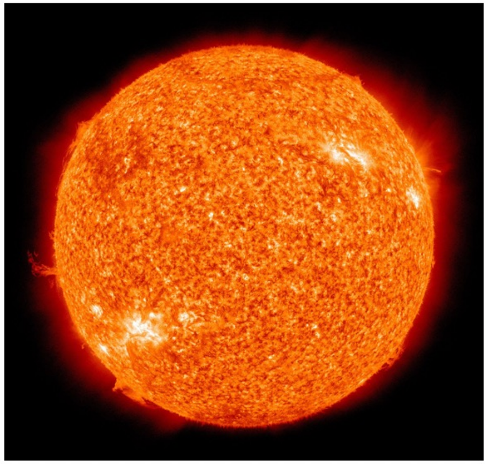
Harikane+22a

See also e.g., Madau+14, Bouwens+15,20, Mason+15, Tacchella+18,…

Distance Galaxies are…

- Faint: 25-30 magnitudes, $\times 10^{10}$ fainter than Sirius
- Red: due to redshift $\lambda_{obs}=(1+z) \times \lambda_{int}$
  - Hubble space telescope: up to 1.6um (z~11)
- Need a large infrared telescope → JWST

Sun -27 mag

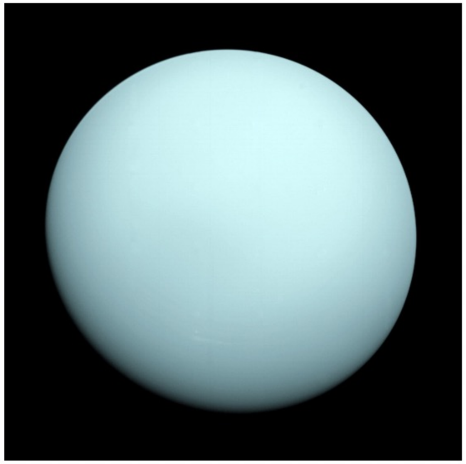


(NASA)

Sirius -1 mag

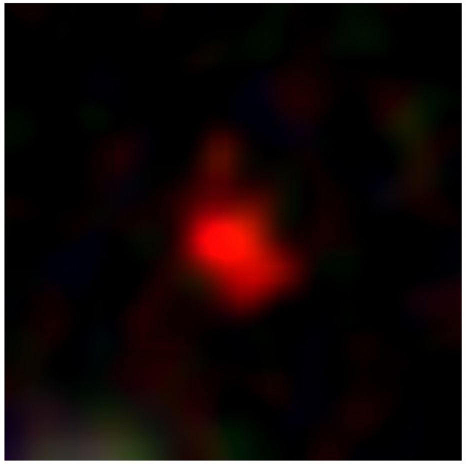
(STScI)

Uranus 6 mag



(NASA)

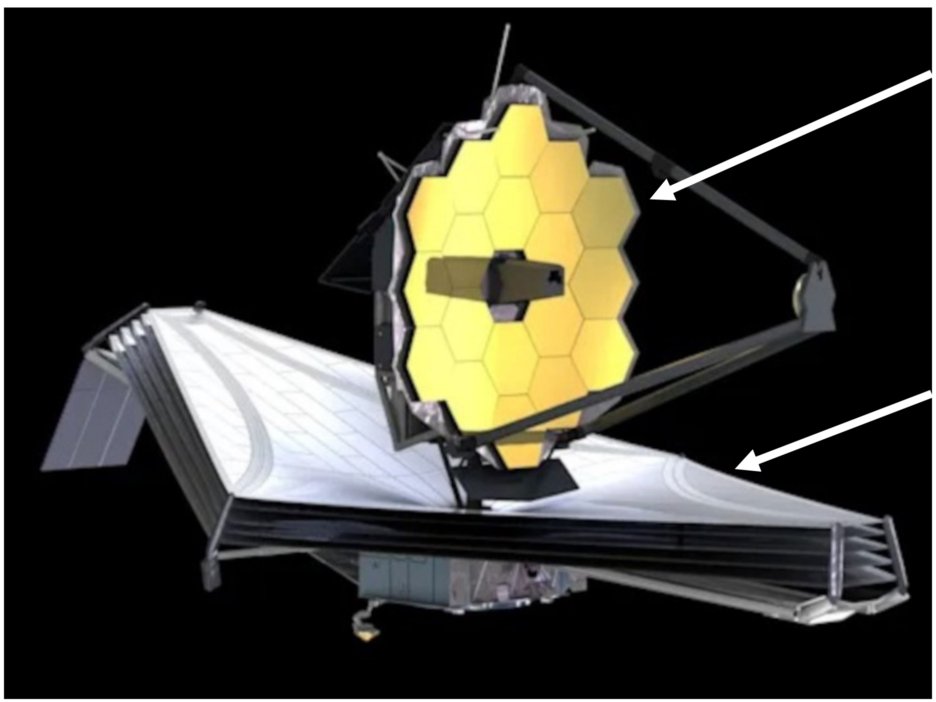
Distant galaxy 25 mag



(Harikane et al.)

James Webb Space Telescope (JWST)

- Infrared telescope with 6.5m-diameter mirror
  - Hubble: 2.4m
  - Launch on 2021 Dec. 25th, first data on 2022 July 12th



Main mirror (6.5m-diameter)
Combination of 18 segment mirrors
Gold-coated

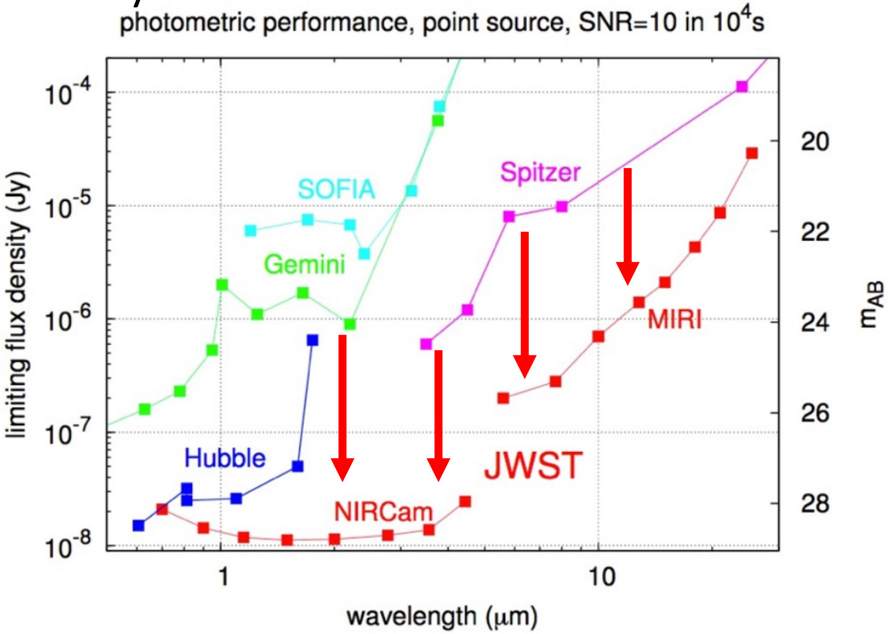
Sun-shield
Keeping 40 K by shielding sunlight

NASA

Comparison with Other Telescopes

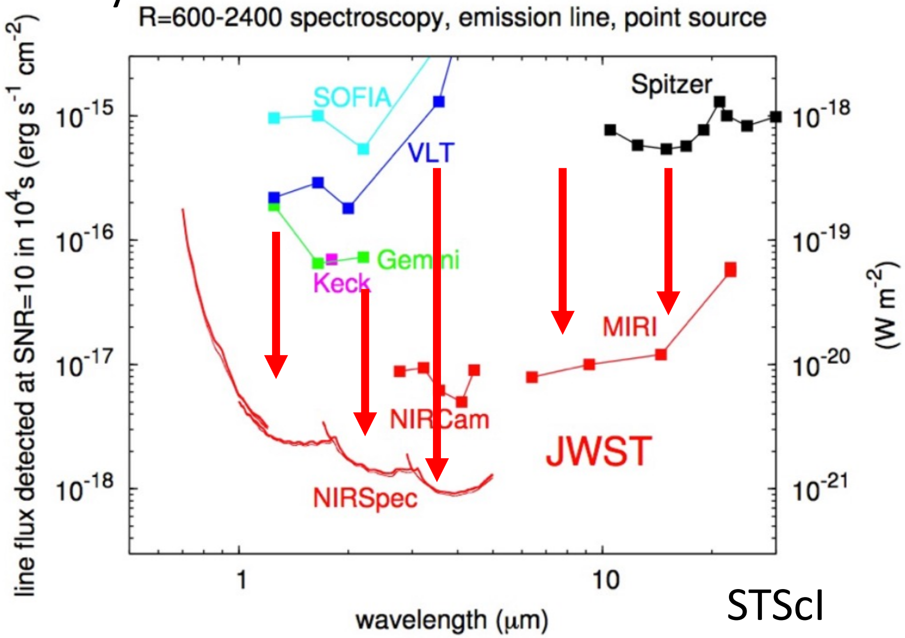
- Sensitivity improved by x10-1000 at infrared

Imaging



Wavelength [μm]

Spectroscopy



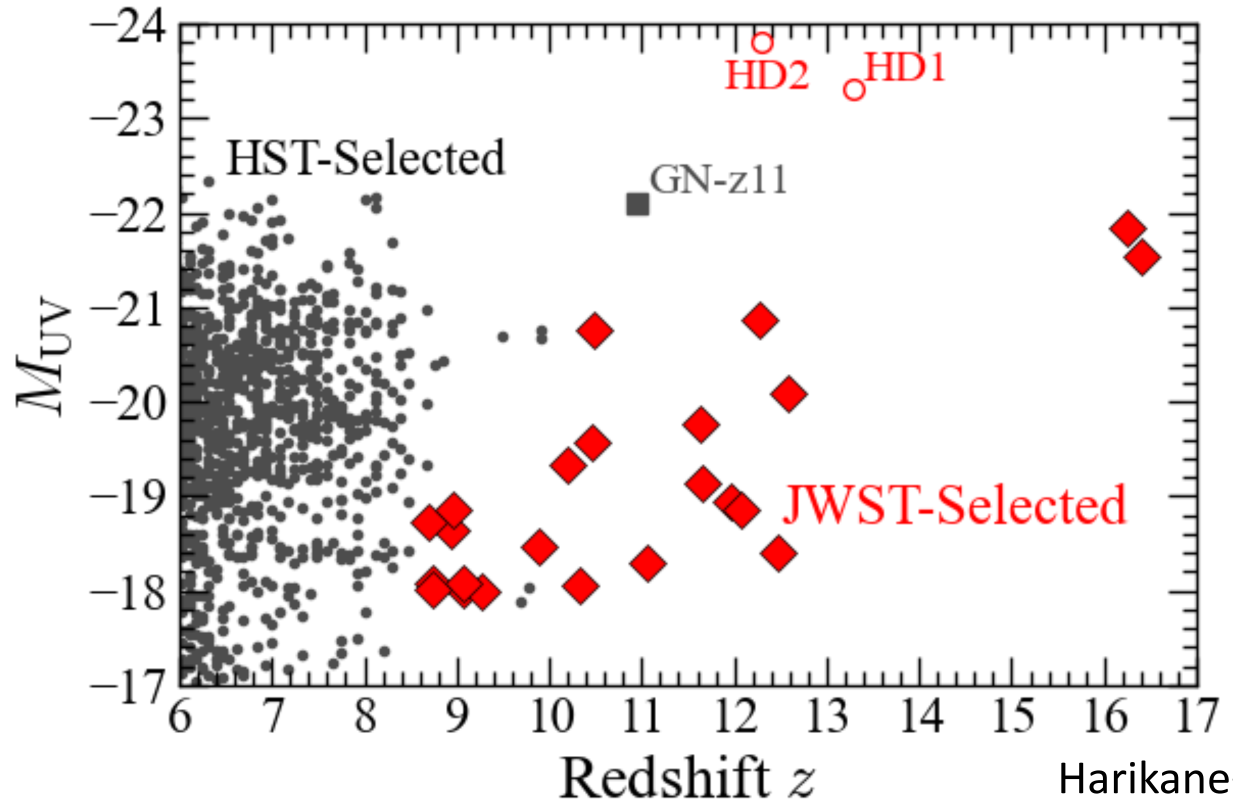
STScI

Wavelength [μm]

https://www.stsci.edu/jwst/about-jwst/history/historical-sensitivity-estimates

JWST Galaxy Sample at z~9-16

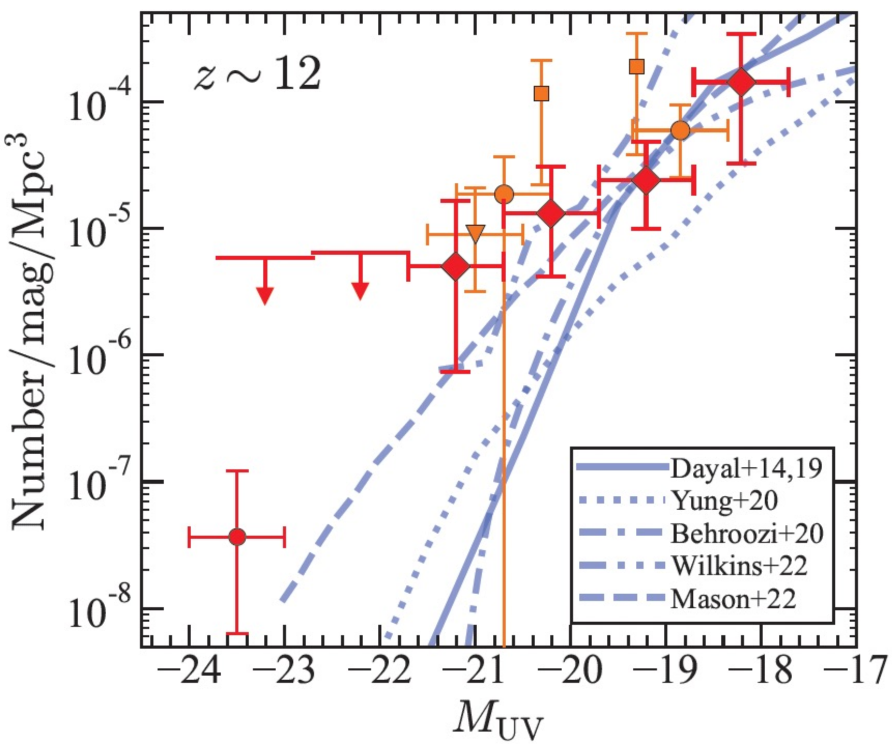
- A total of 23 galaxy candidates at z~9-16
  - 90 arcmin^2 from ERO+ERS NIRCam images
  - Lyman break color selection + photo-z

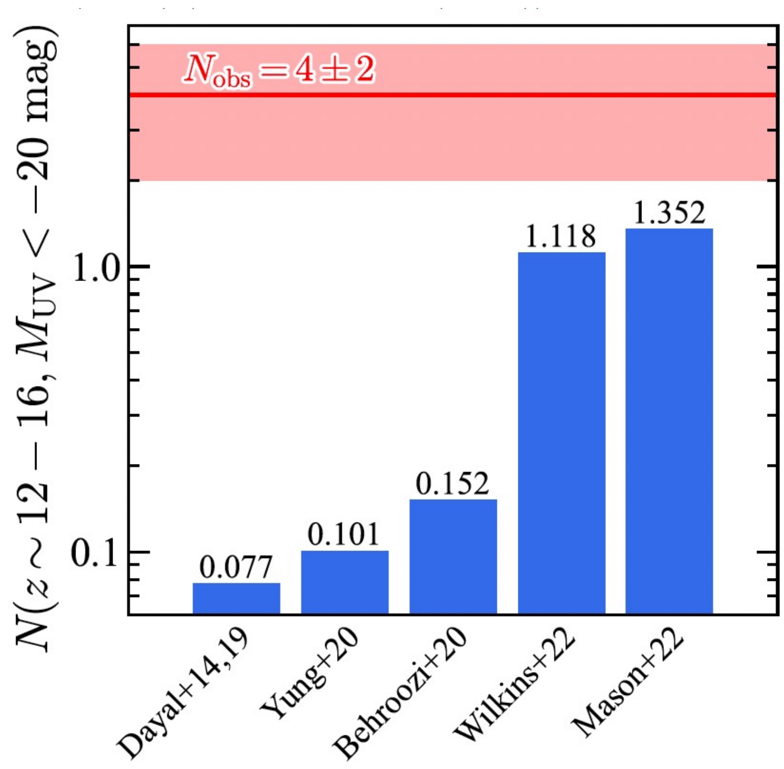


Harikane+23a

Comparison with Models

- Surprisingly larger number of galaxies than models
  - Tension between models and observations

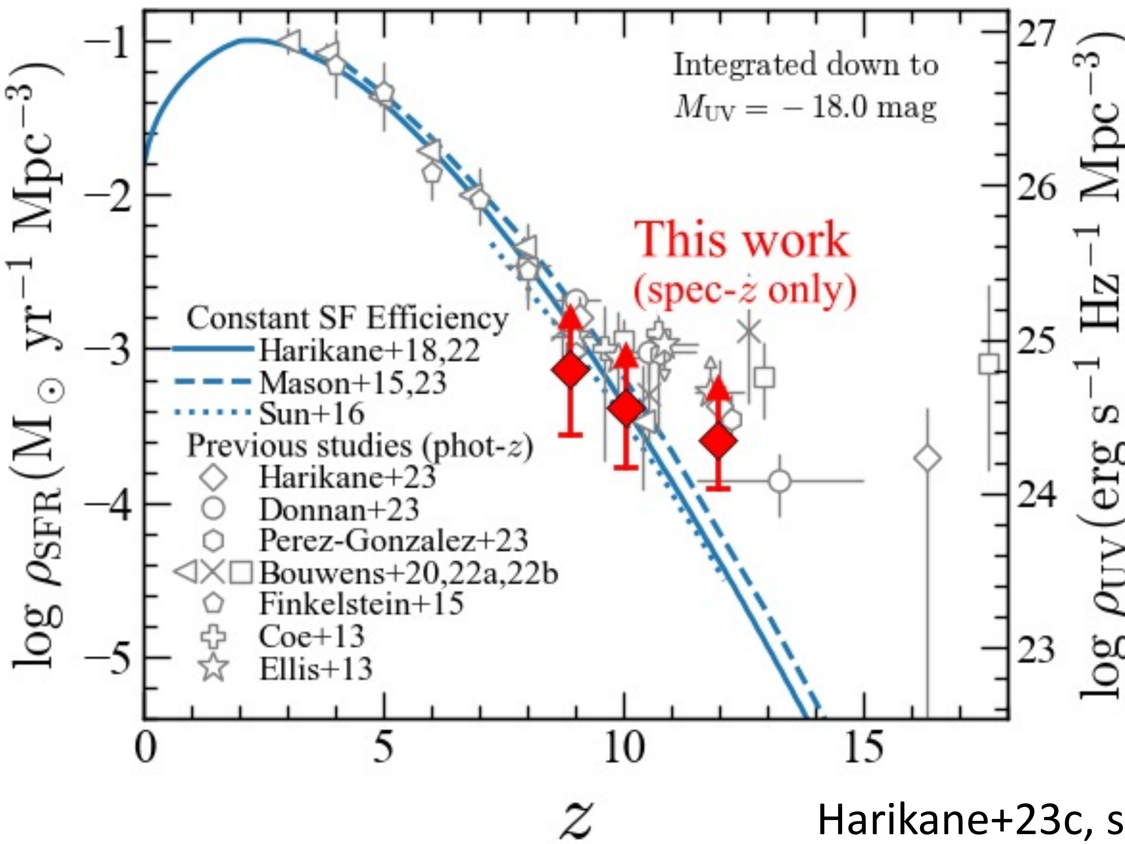




Harikane+23a

Spec-z Cosmic SFR Density at z=9-12

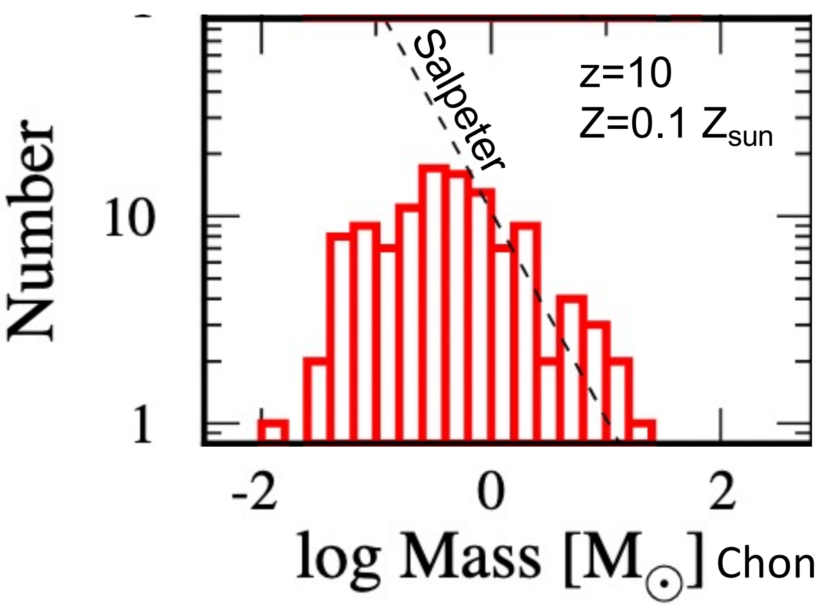
- UV→SFR: $SFR(M_\odot \text{ yr}^{-1}) = \mathcal{K}_{\rm UV} L_{\rm UV}(\text{erg s}^{-1} \text{ Hz}^{-1})$,
  $\mathcal{K}_{\rm UV} = 1.15 \times 10^{-28} \; M_\odot \, \text{yr}^{-1}/(\text{erg s}^{-1}\text{Hz}^{-1})$
- Tension with constant efficiency models at z>10



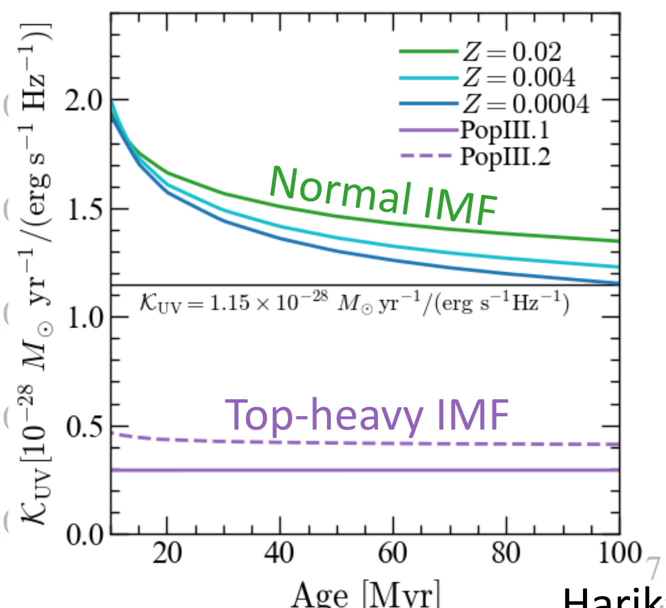
Harikane+23c, see also Bouwens+22

Physical Interpretations

- Why high SFR density at z>10?
  1. High efficiency (>5%) at pre-EoR (e.g., Fukushima+22)
  2. Many AGN populations? (discussed later)
  3. A top-heavy IMF w/ CMB and/or low-Z (Pop III?)



Chon+22

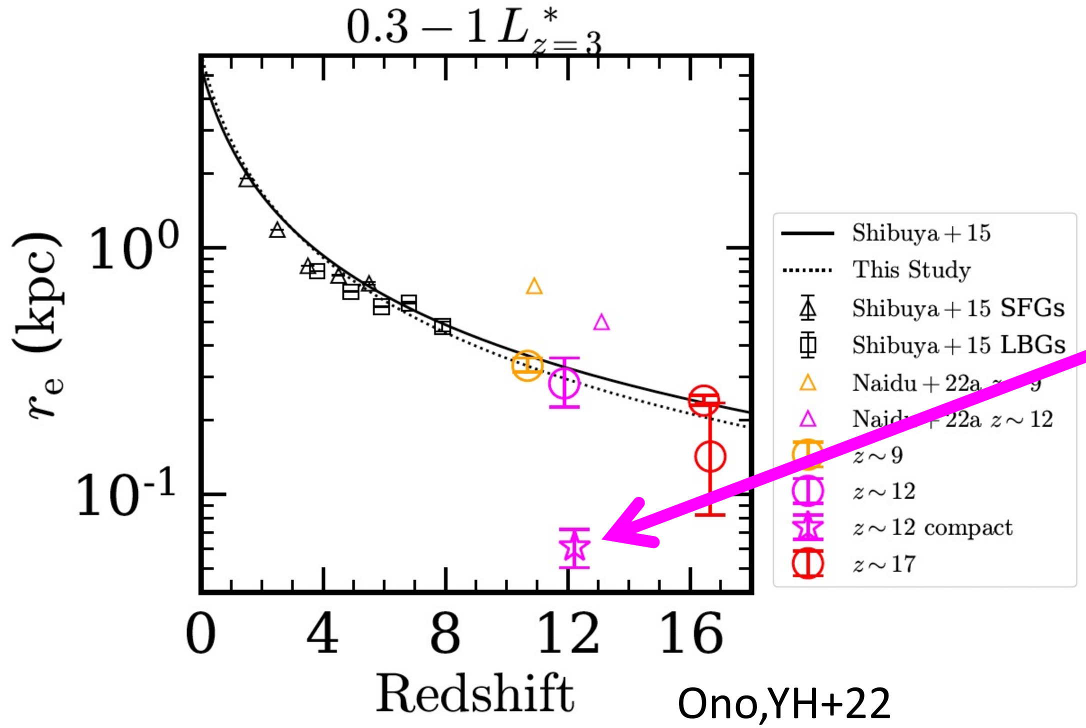


Harikane+23a

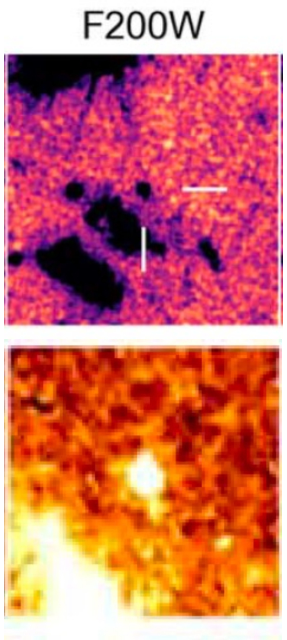
See also Inayoshi,YH+22, Lovell,Harrison,YH+22

Size of z>10 Galaxies

- R_e=200-300 pc w/ Sersic index=1-1.5 (disk)
  - Consistent w/ size evolution at z=9-16 w/ $(1+z)^{-1.2}$
- GL-z12-1 is very compact (r_e=60 pc)
  - Why this galaxy is so compact?



Ono,YH+22

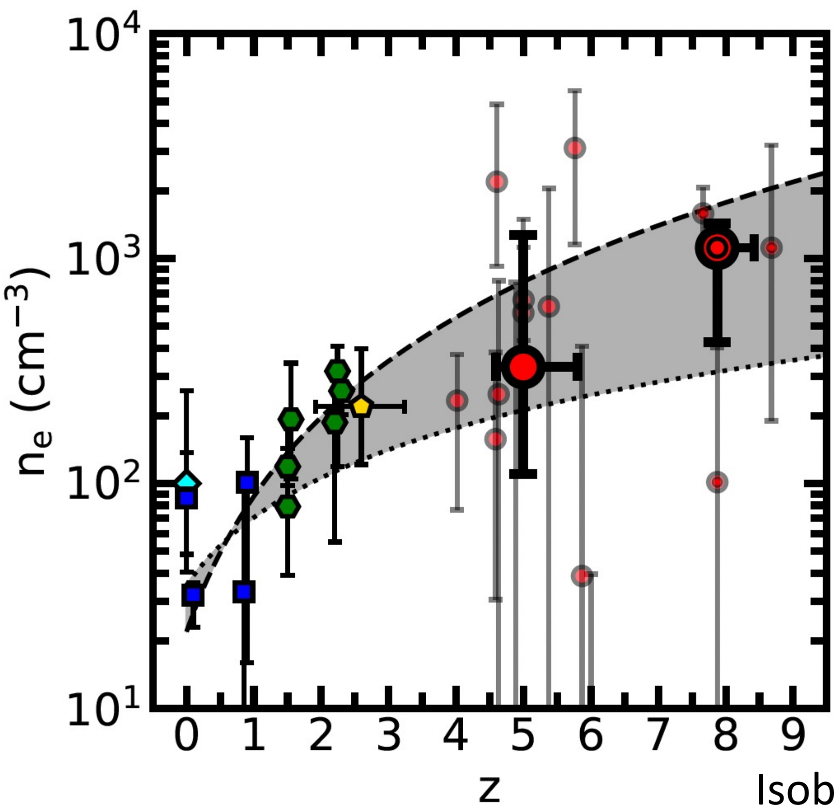


Naidu+22

Castellano+22

High ISM Density in High-z Galaxies

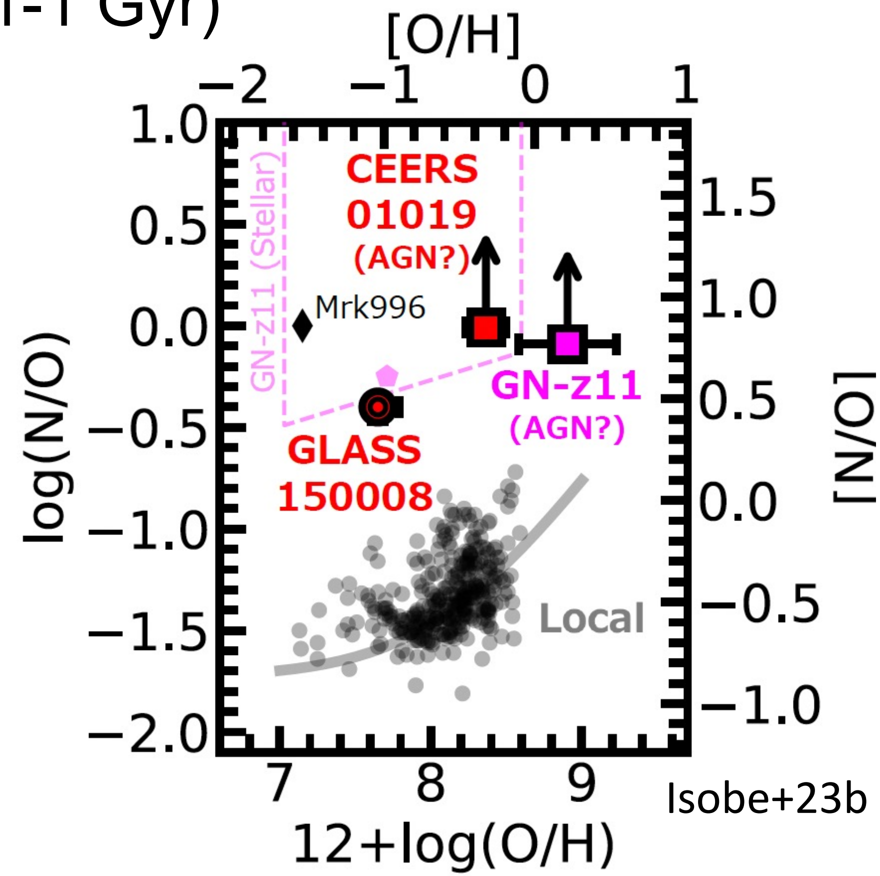
- Electron density n_e~300-1000 cm^{-3} at z~4-9
  - Significantly higher than z~0 galaxies (10-100 cm^{-3})
  - Why? Related to size evolution of galaxies?



Isobe+23a

High Nitrogen Abundance Ratio at z~6-11

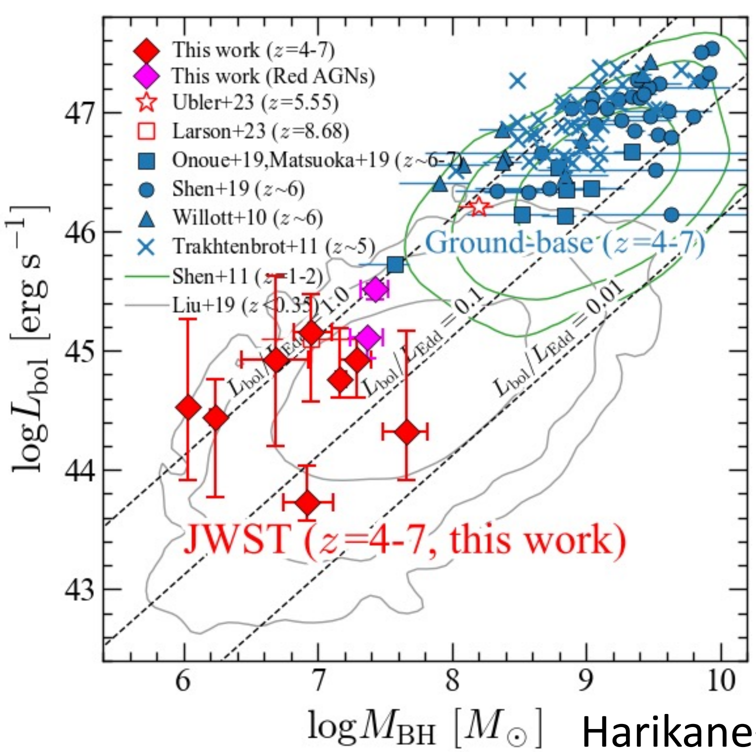
- Extremely high N/O abundance ratios in bright galaxies at z~6-11
  - Nitrogen: IaSNe+AGB (0.1-1 Gyr)
  - Oxygen: CCSNe (10 Myr)
- Interpretations
  - CNO cycle materials
  - Super-massive stars
  - Wolf-Rayet stars
  - Tidal disruption
  - Runaway stellar collision



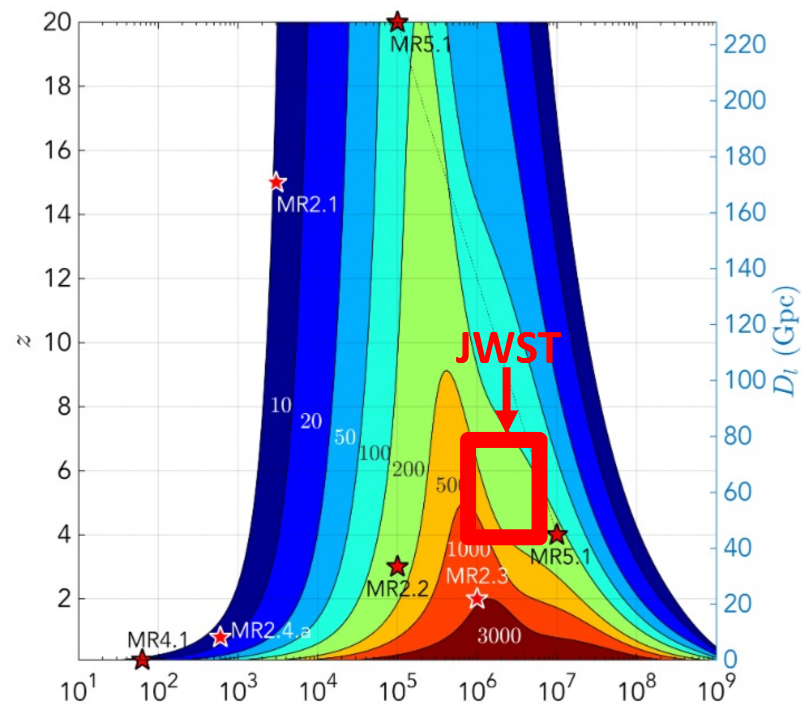
Isobe+23b

Many AGNs at z>4!

- M_{BH}~10^6-10^7 M_{sun} higher than z~0 M_*-M_{BH} relation
  - Significantly lower M_{BH} than quasars at z>4
  - BH-BH binary of these BHs can be detected with LISA?



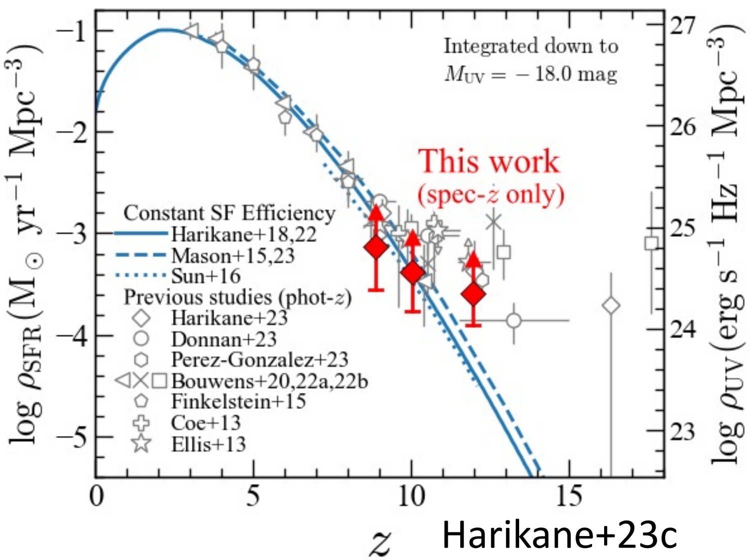
Harikane+23b



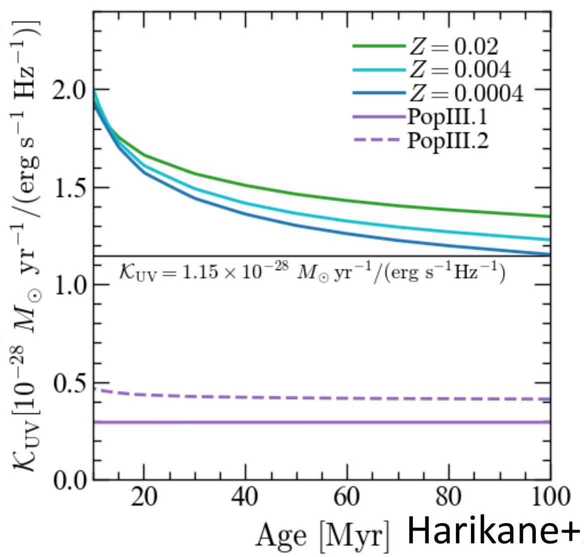
Amaro-Seoane+17

Summary

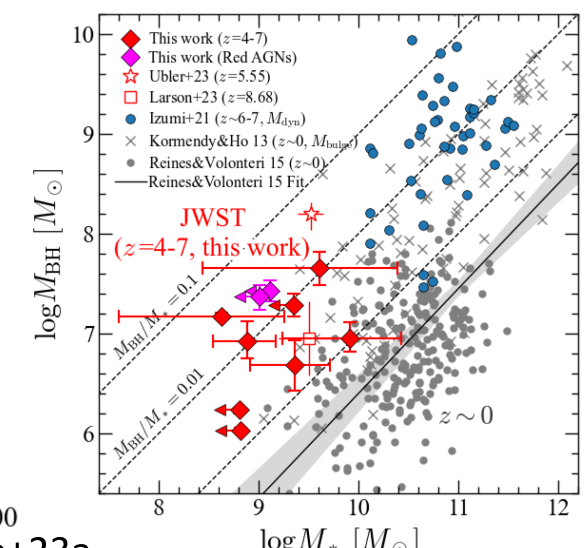
- JWST spec and phot studies of z=9-16 galaxies
  - Large number of z>10 galaxies, more than theoretical model predictions
  - Excess in SFR densities at z>10, high SF efficiency, AGN, or top-heavy IMF at high-z?
  - 10 broad-line AGNs at z=4-7 with M_{BH}~10^6-10^7 M_{sun}



Harikane+23c



Harikane+23a



Harikane+23b