



JWST Observations of Supermassive Black Holes in the Early Universe

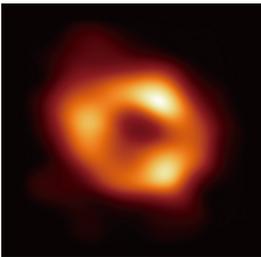
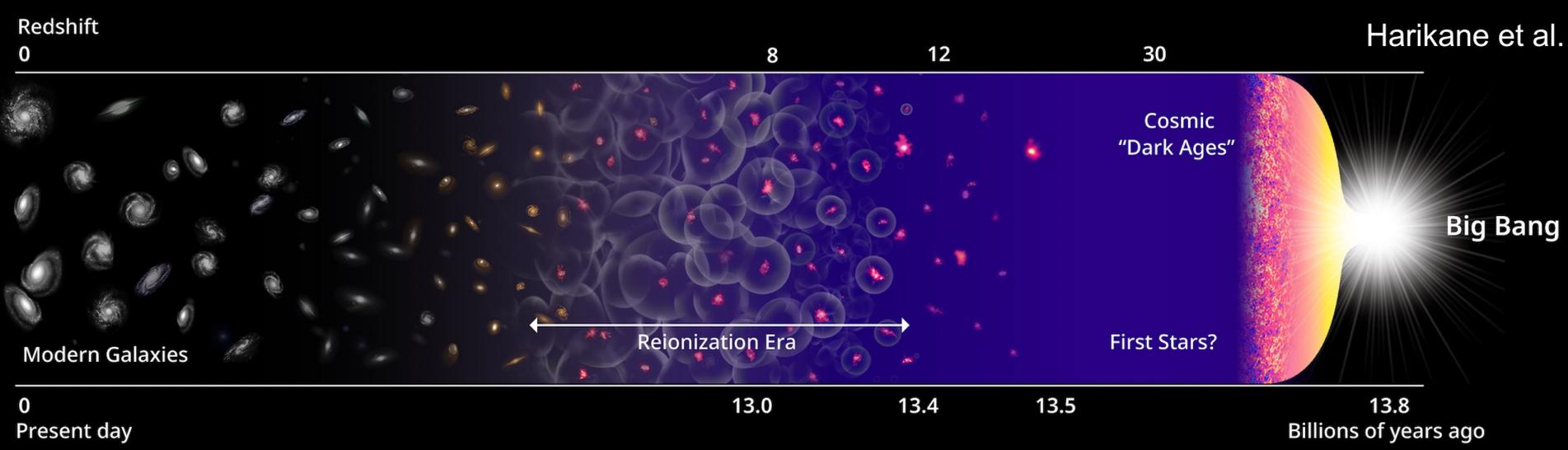
See Kohei's talk for theoretical perspective.

Yuichi Harikane (University of Tokyo)

JWST First Image of a galaxy cluster, SMACS0723,
released in July 2022 (NASA)

Formation of Supermassive Black Holes

Harikane et al.



EHT Collaboration

Present-day

Observations at high-z needed

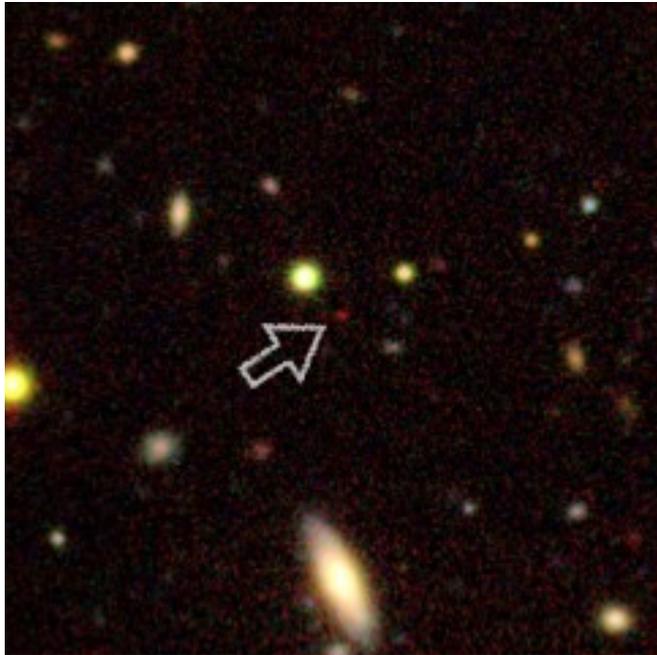
← ? Seed black holes

? When and how did the seed form?

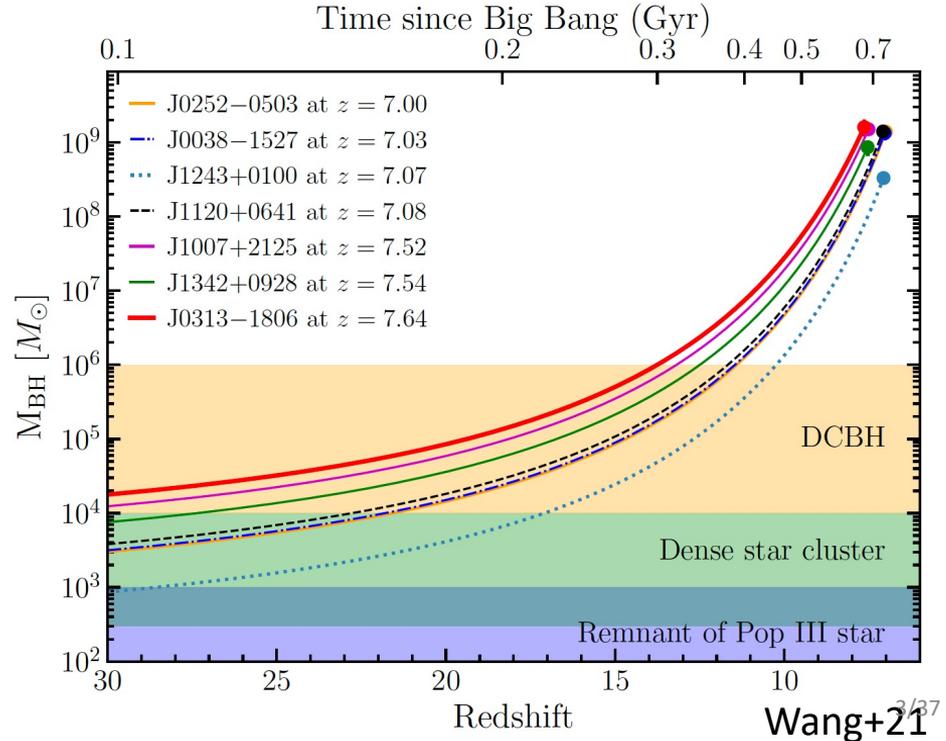
How did they grow? (slow? fast?)

High Redshift AGNs Before JWST

- Quasar: bright AGNs with massive BHs, up to at $z \sim 7.6$, but rare.

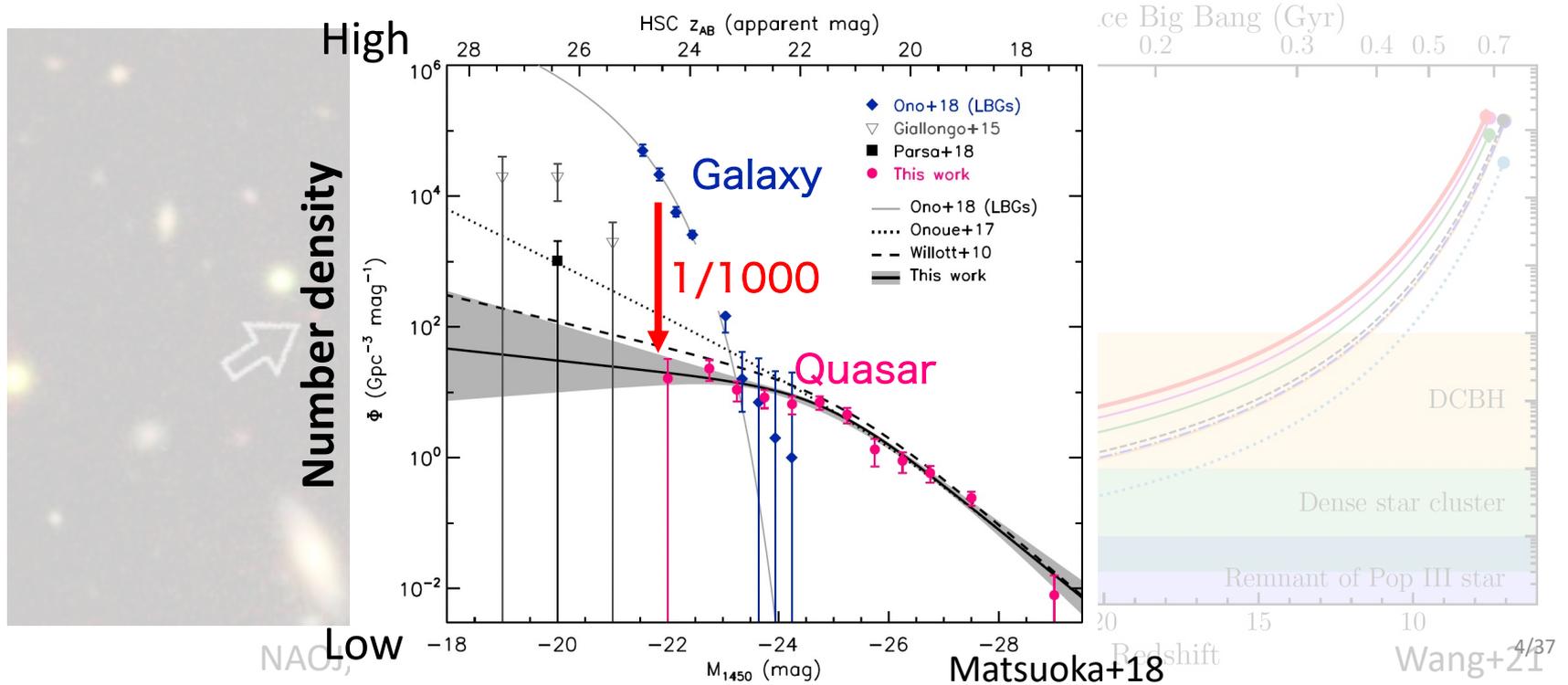


NAOJ, Matsuoka et al.



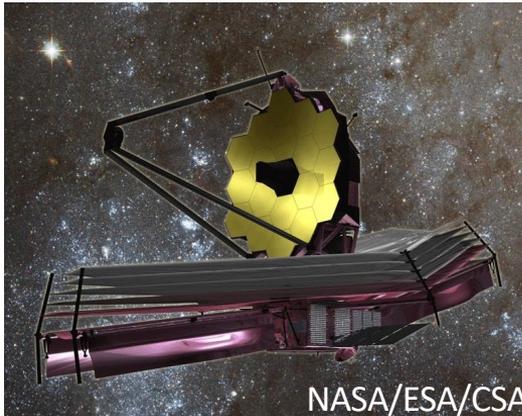
High Redshift AGNs Before JWST

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James Webb Space Telescope (JWST)

- A large infrared space telescope w/ 6.5m mirror
- The most expensive telescope ever built
 - 1 billion USD (Hubble Space Telescope: 0.2 billion USD)
 - Launch: Dec. 25th 2021, first data release: July 12th 2022
 - Original launch date: 2007, but delayed many times. Waiting for 14 years...



NASA/ESA/CSA

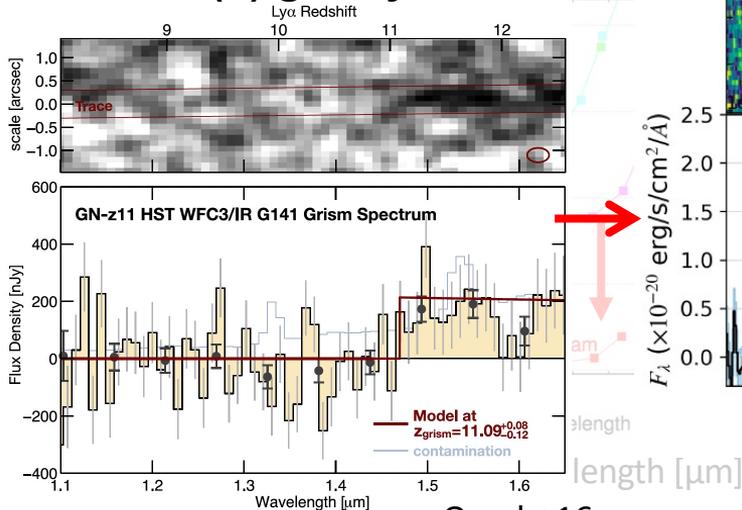


First image release at the White House (NASA)

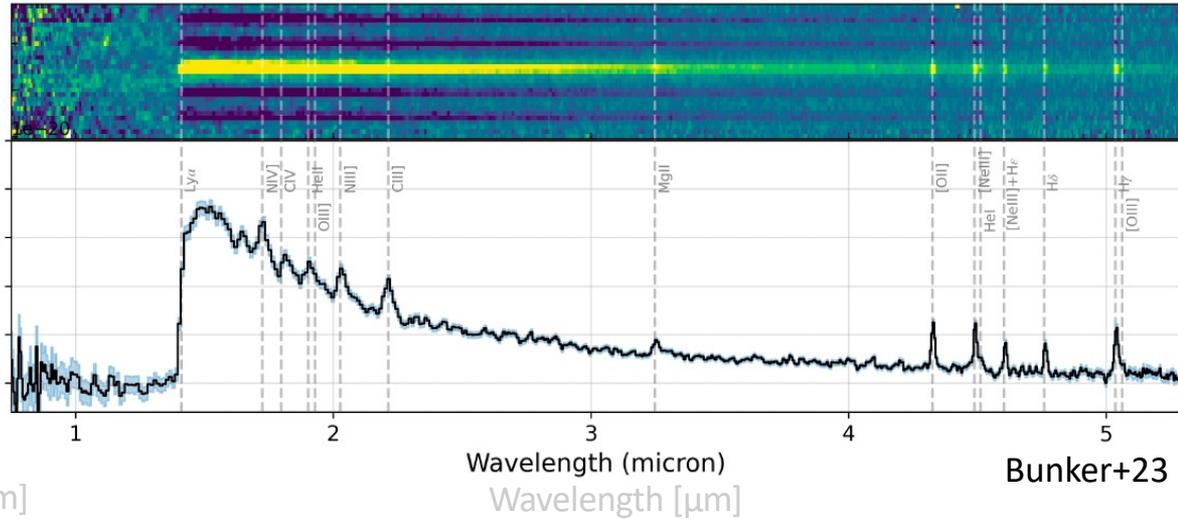
JWST's Sensitivity

- Sensitivity improved by x10-1000 at infrared
- Efficiently observe faint high redshift galaxies

HST ~11 hour spectrum of $z \sim 11$ galaxy GN-z11

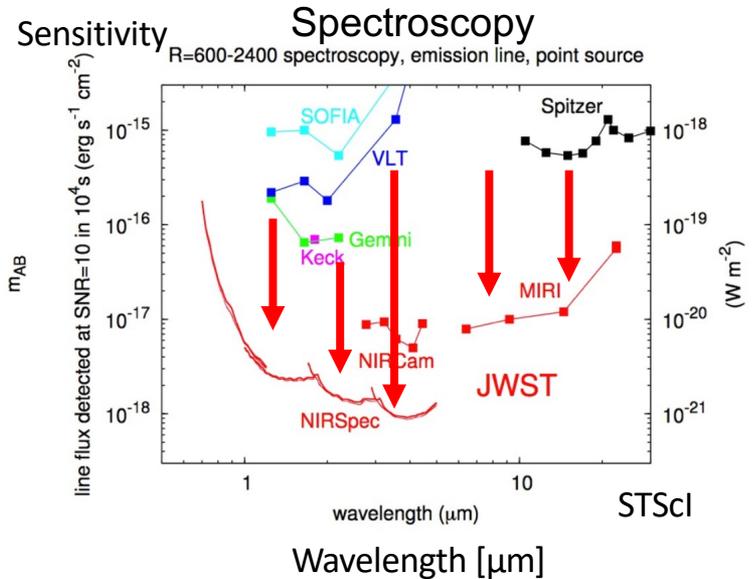
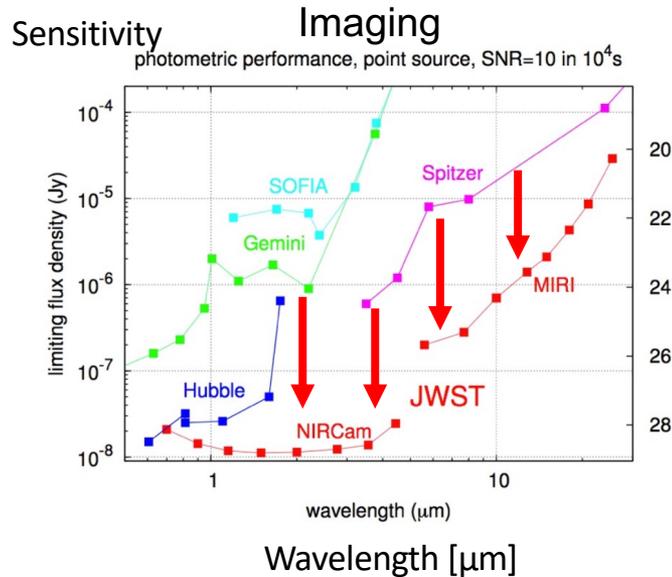


JWST/NIRSpec ~7 hour spectrum of the same galaxy



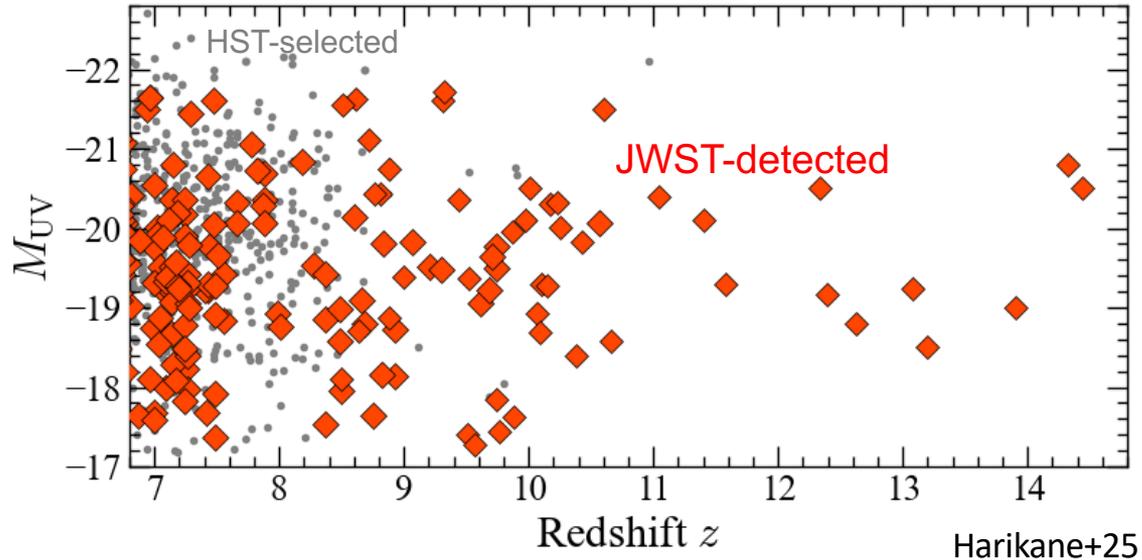
JWST's Sensitivity

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High Redshift Galaxies Found by JWST

- With its ~ 3 year operation, the JWST has discovered a large number of **galaxies** up to $z \sim 14$



* Red diamonds are spectroscopically confirmed galaxies. There are many more galaxies awaiting for confirmation.

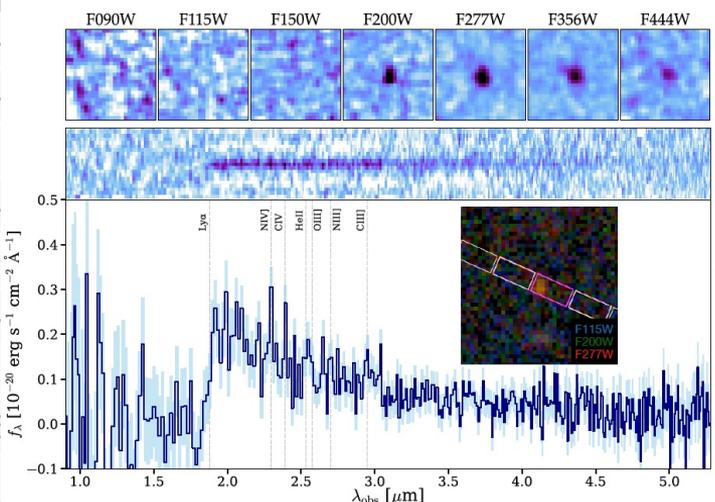
List of the Highest- z_{spec} Galaxies

Before JWST

	Name	Redshift	Feature	Reference
1	GN-z11	10.96	Lyman break, line?	Oesch+16, Jiang+20
2	MACS1149-JD1	9.11	[OIII], Ly α ?	Hashimoto+18
3	EGSY8p7	8.68	Ly α	Zitrin+15

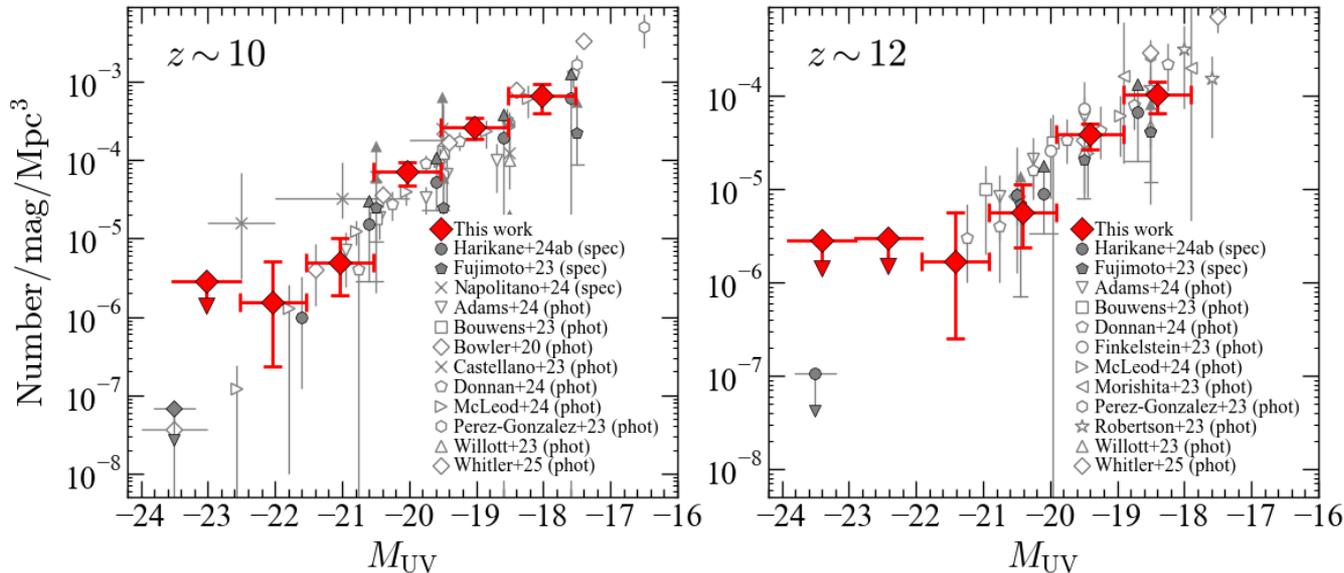


After JWST

	Name	Redshift	Feature	Reference
1	MoM-z14	14.44	Lyman break, CIV? NIV?	Naidu+25
2	JADES-GS-z14-			Carniani+24
3	JADES-GS-z14-			Carniani+24
4	PAN-z14-1			Donnan+26
5	JADES-GS-z13-			Curtis-Lake+23
6	UNCOVER-z13			Wang+23
7	JADES-GS-z12-			Curtis-Lake+23
8	UNCOVER-z12			Wang+23
9	CAPERS-EGS-			Roberts-Borsani+25
10	GHZ2			Naidu+25
...				Castellano+24

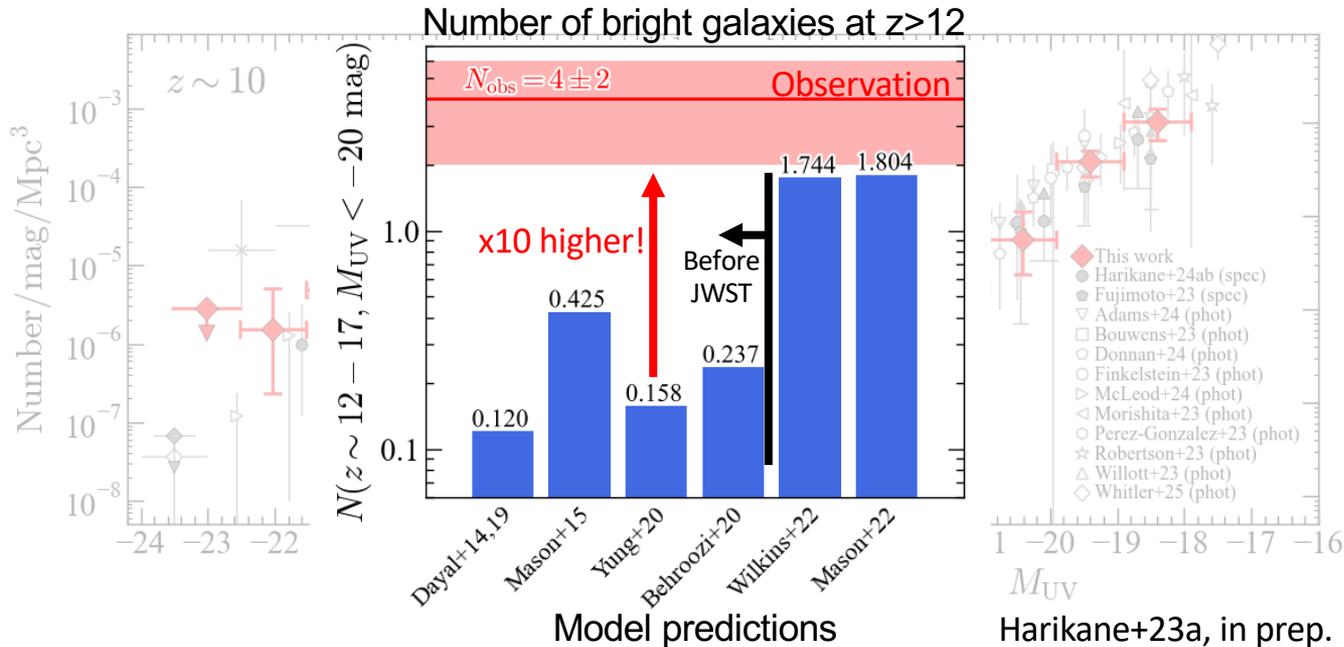
UV Luminosity Function

- Density of galaxies as a function of UV luminosity
 - Number of bright galaxies discovered by JWST is surprisingly higher than model predictions before JWST



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Why We See the Tension in Obs. vs Models?

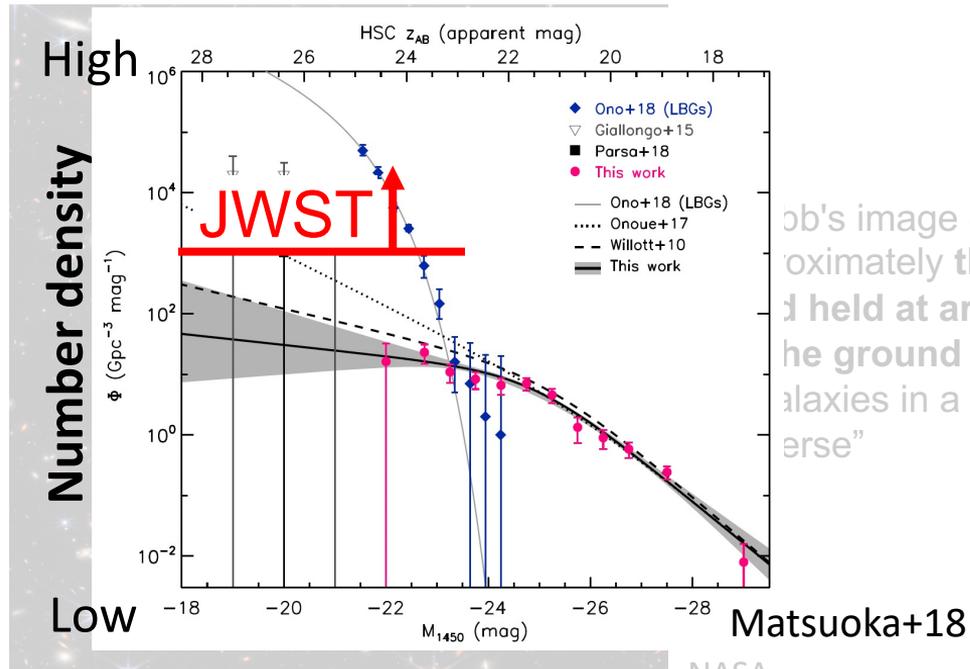
Models: calibrated at $z=0-10$. Different galaxy formation physics at $z>10$?

1. **High star formation efficiency**, e.g., by feedback free starburst (Dekel+23), compact starburst (Fukushima+22, Ono+23)
2. **Top-heavy initial mass function** (e.g., Chon+22, Cameron+23, see also Rasmussen Cueto+23)
3. **Radiation driven outflow** (Ferrara+22,23)
4. **Bursty star formation** (e.g., Mason+23, Shen+23, Sun+23ab, Donnan+25, Kokorev+25, Mitsuhashi+26, see also Pallottini+23)
5. **Cosmology** (e.g., Menci+23, Parashari+23, Hirano+23, Shen+24)
6. **AGN activity** (e.g., Hedge+24)

See discussions in Harikane+23a,24,25a

How About AGNs? They are rare...

- JWST First Image: Galaxy Cluster SMACS0723
 - A small field of view ($2 \times 2 \text{ arcmin}^2$) → difficult to find rare objects (e.g., quasars)



“This image covers a patch of sky approximately the size of a grain of dust held at arm's length by someone on the ground – and reveals thousands of galaxies in a tiny sliver of vast universe”

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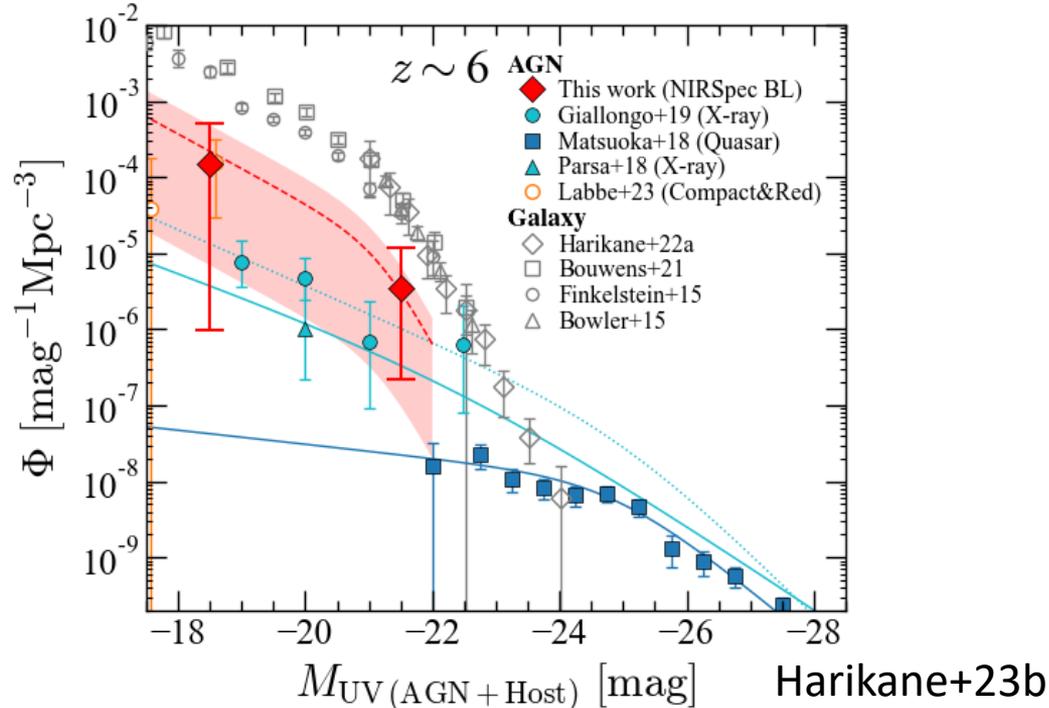
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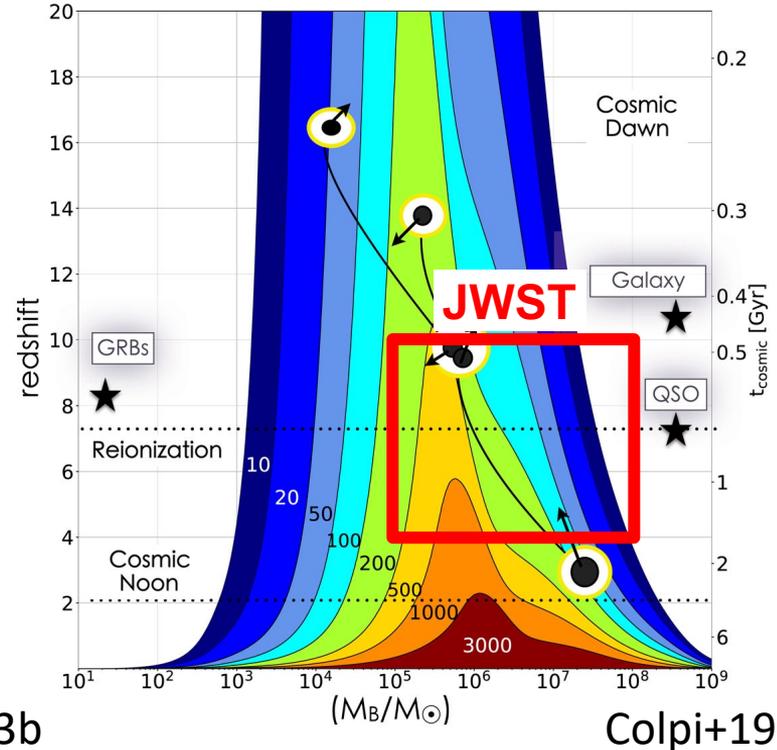
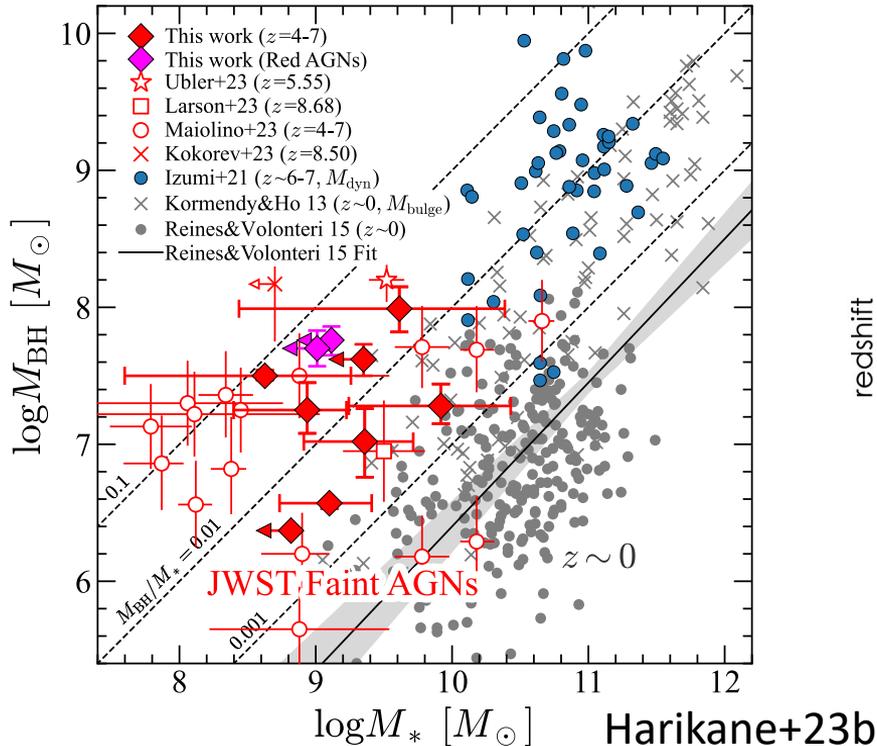
Surprisingly Large Number of AGNs at $z > 4$

- Number densities of JWST-discovered faint AGNs are larger than extrapolation of QSO luminosity functions



Are Their Black Holes Overmassive?

- $M_{\text{BH}} \sim 10^5 - 10^8 M_{\text{sun}}$, smaller than QSOs, in the LISA parameter range



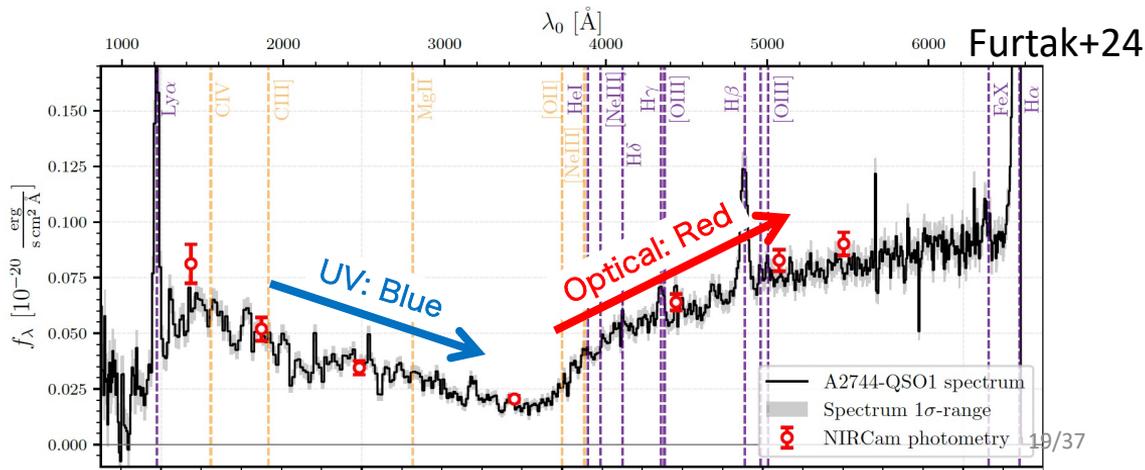
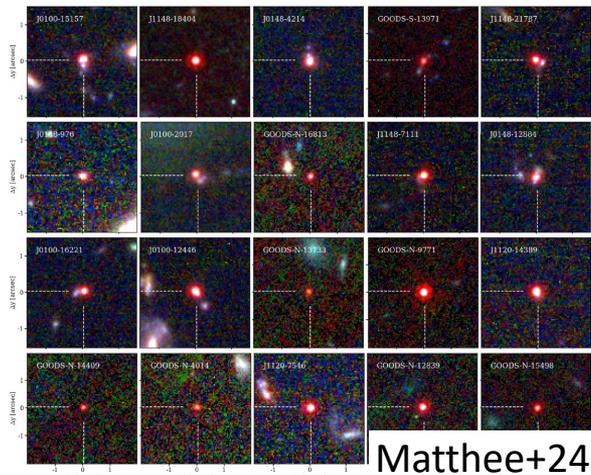
Images of JWST-Discovered Faint AGNs

- Host galaxies detected in most of them → Type-1 Seyfert
 - Two compact and red AGNs = little red dots



What are Little Red Dots (LRDs)?

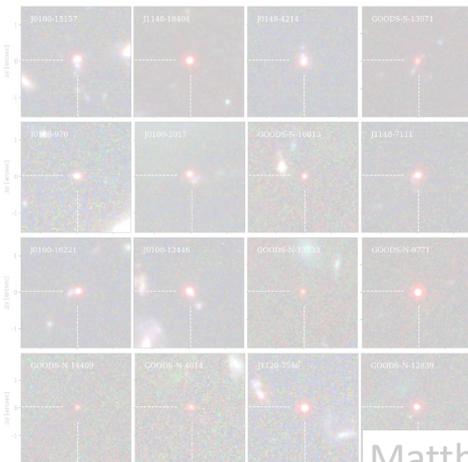
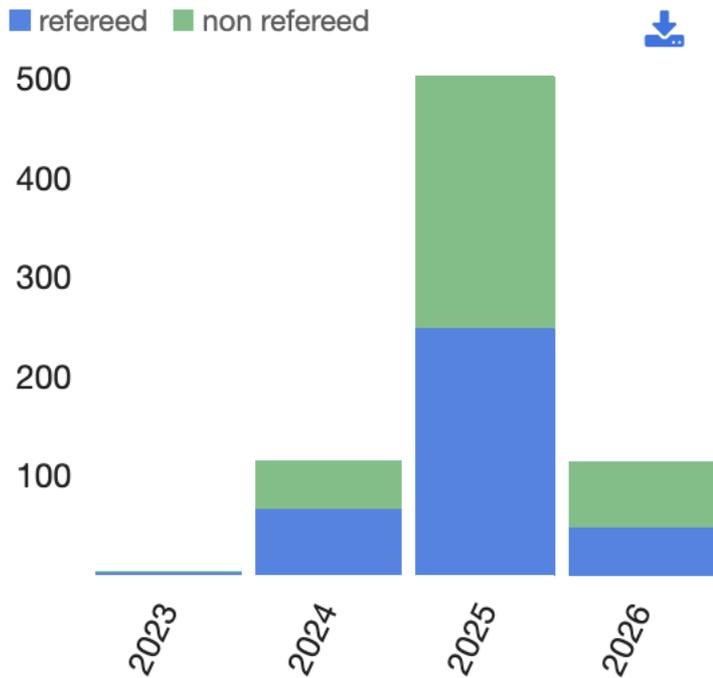
- 10-20% of JWST faint AGNs: red and compact “little red dots (LRDs)”
 - Possibly new population (new category of AGNs)
 - N~100 spec-z confirmed, N>500 photometrically identified.
- Definition of LRDs
 1. V-shape SED, 2. compact, 3. broad Hydrogen Balmer line



What are Little Red Dots (LRDs)?

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 1. V-shape SED, ...

Number of papers discussing little red dots

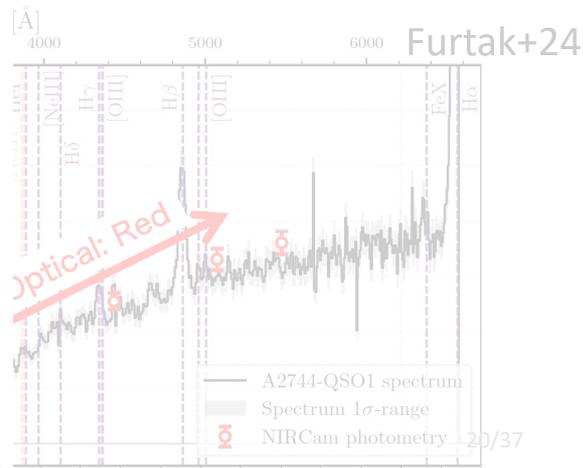


Mattheucci+24



identified.

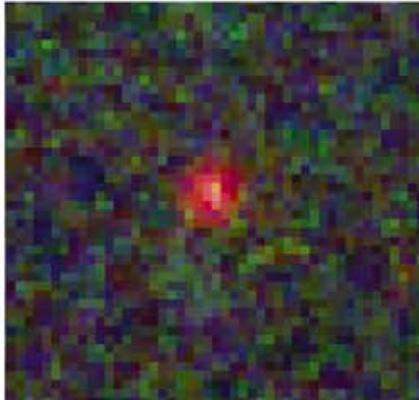
mer line



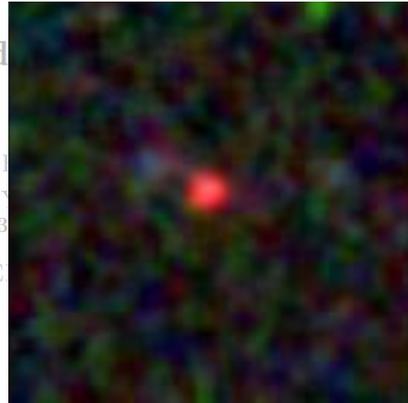
Name of “Little Red Dots”

- Matthee+24 used “little red dots” in its paper title
- Harikane+23, Kocevski+23 discussed red and compact AGNs (LRDs)
- Labbe+23 photometric identification of too massive galaxies (→LRDs)

Kocevski+23

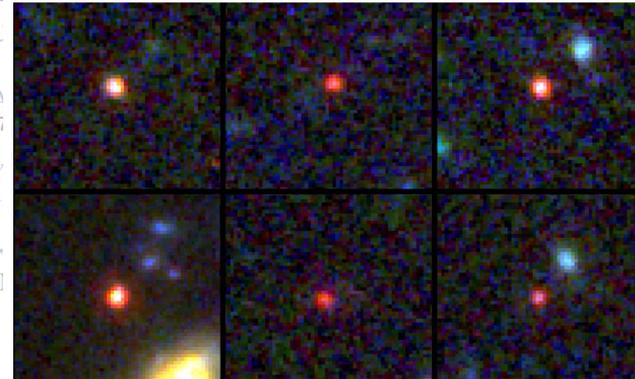


Harikane+23b



James Webb telescope detects evidence of ancient ‘universe breaker’ galaxies

Huge systems appear to be far larger than was presumed possible so early after big bang, say scientists



The six candidate galaxies, based on observations by Nasa's James Webb space telescope. Photograph: Nasa/Reuters

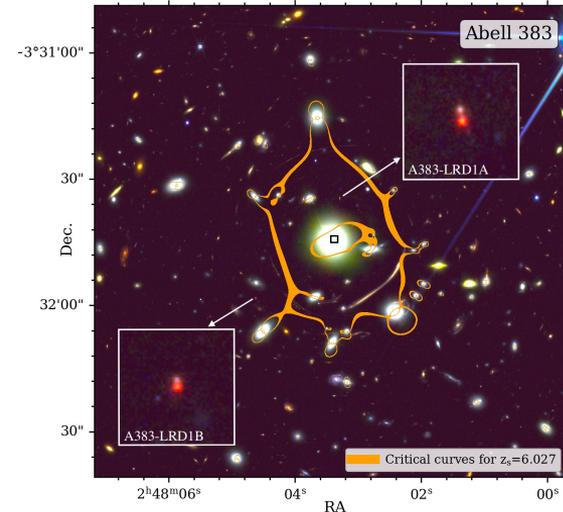
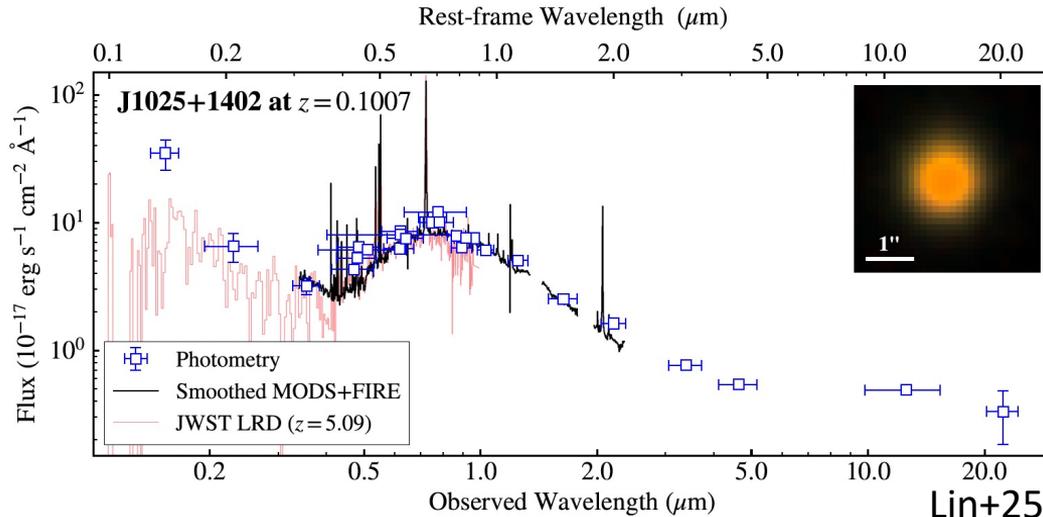
and FRESCO

EILERS,²
KENZIE,¹
DI,¹¹
MASEDA,¹⁵
Labbe+23²⁰

Web news in
The Guardian

Re-Discoveries of Little Red Dots

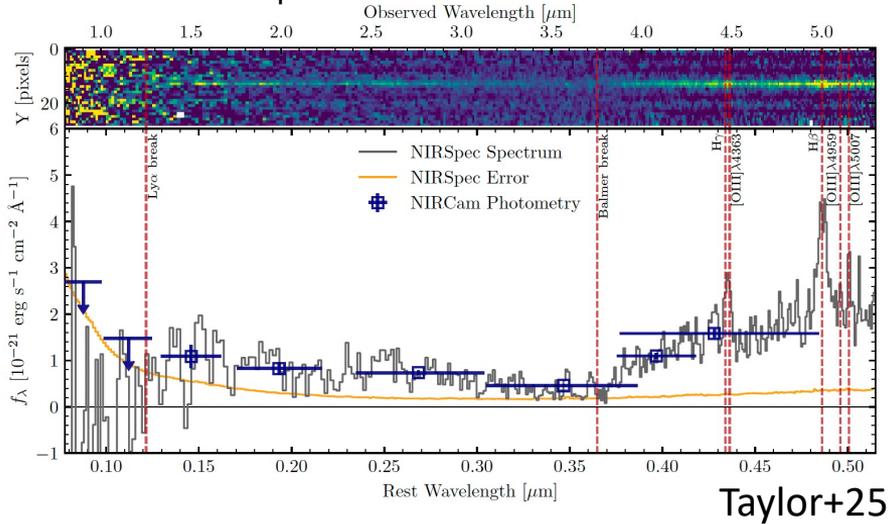
- $z=0$: previously-known metal-poor galaxies (Izotov+08) are LRDs
 - Strange broad $H\alpha$ lines were reported, but we didn't know what they are...
- $z=6$: a previously-known strong Ly α emitting galaxy is an LRD
 - Red optical emission w/ Spitzer is reported



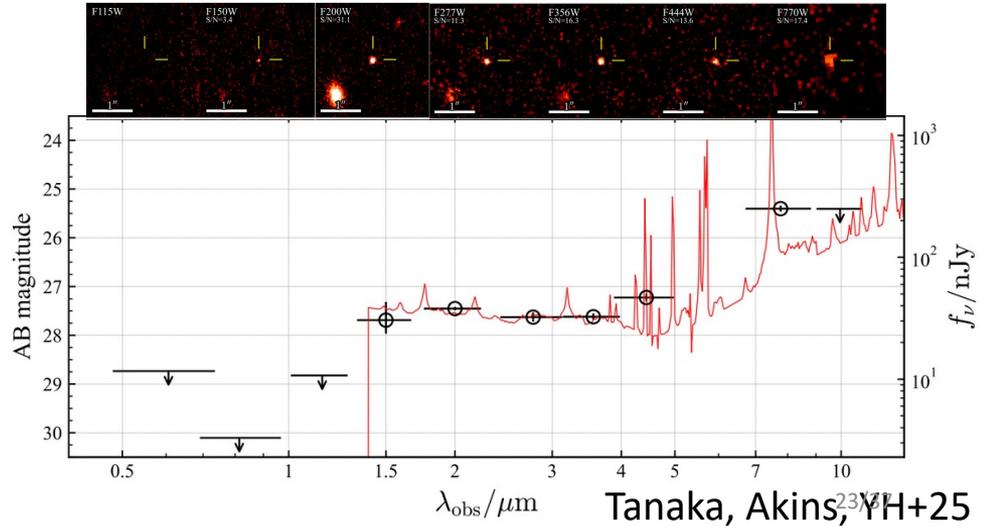
LRD is more Common at Higher Redshifts

- LRDs at $z=9-10$ are recently identified
 - LRD fraction among galaxies increasing towards higher redshifts
 - First episode of supermassive black hole growth? (Inayoshi 25)

$z_{\text{spec}}=9.3$ LRD spectrum

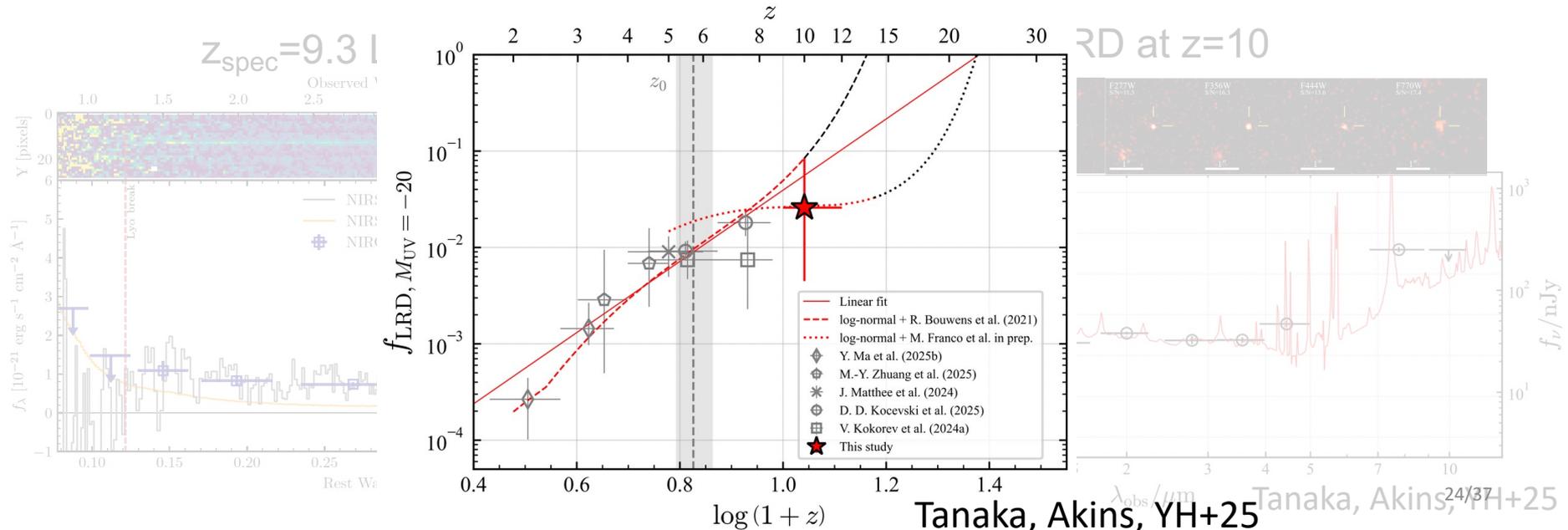


LRD at $z=10$



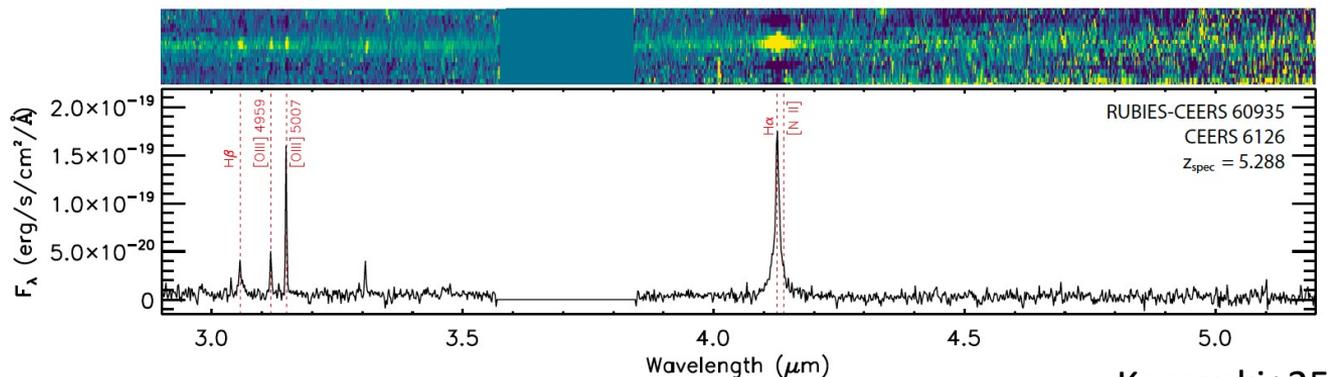
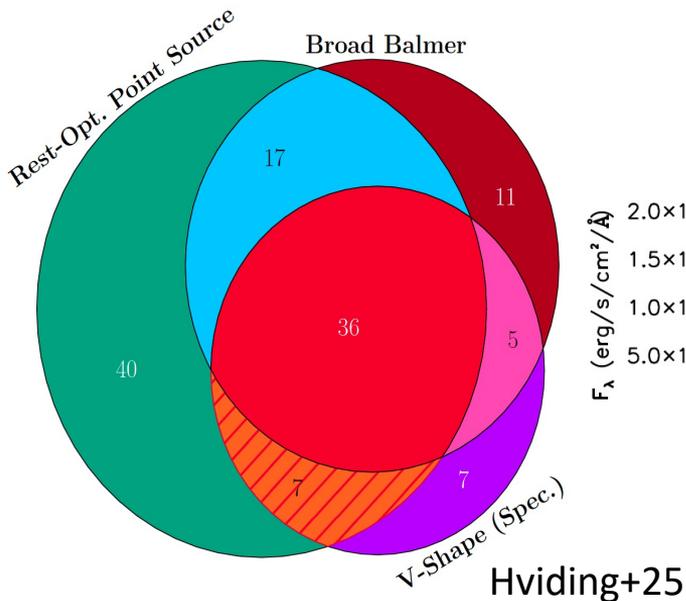
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Are Little Red Dots AGNs?

- Probably yes!
- 80% of V-shaped compact objects show broad H α lines similar to local type-1 AGNs

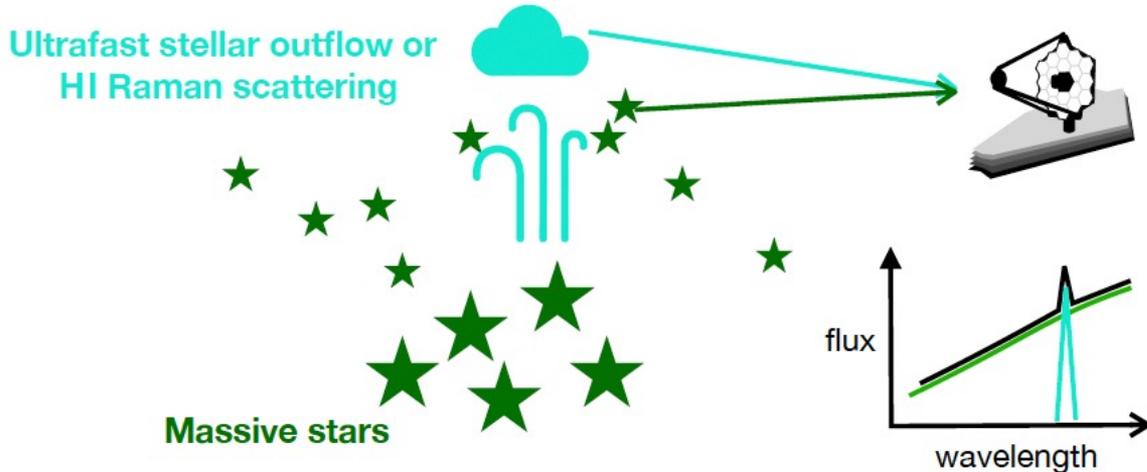


Kocevski+25

Non-AGN Scenario is Difficult...

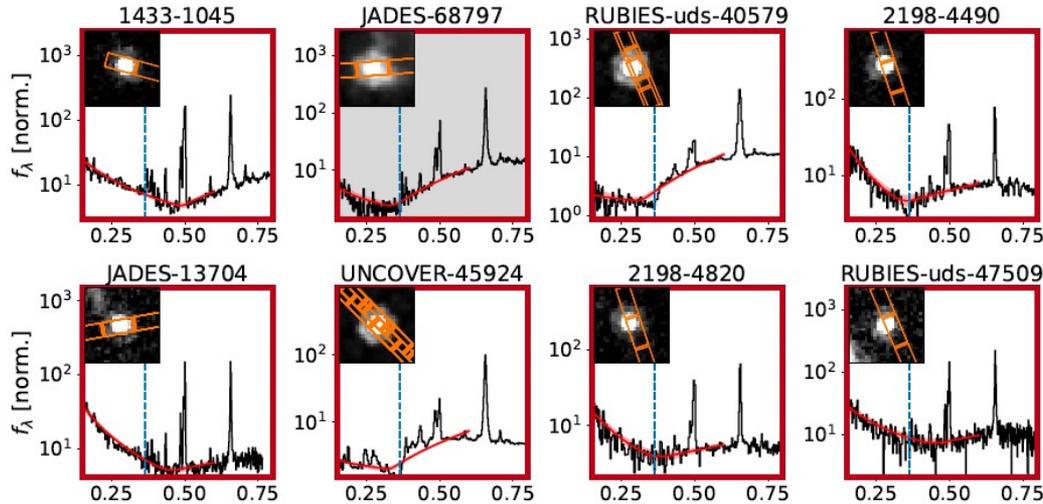
- Need to explain broad (>1000 km/s) H α lines while narrow [OIII] lines
 - Collisional deexcitation is not effective in galaxies' ISM densities
 - Ultrafast pristine gas outflow? No such examples in other galaxies

(d) stellar continuum + non-AGN broad H α

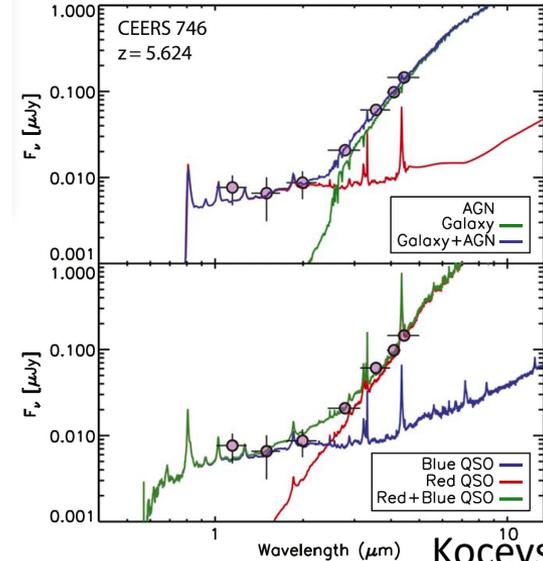


Puzzling Property 1: V-Shaped SED

- Most of LRDs show the break of the V-shape around $\sim 4000 \text{ \AA}$
- What is the origin of blue UV and red optical emission?
 - Galaxy+AGN? AGN+galaxy? AGN+AGN? AGN+scattered photons?



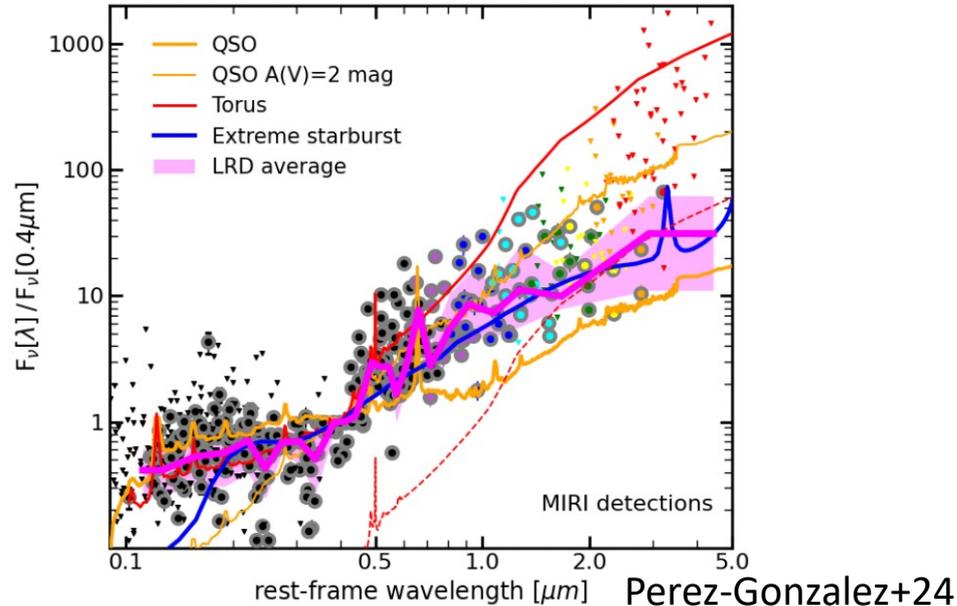
Setton+24



Kocevski+23b

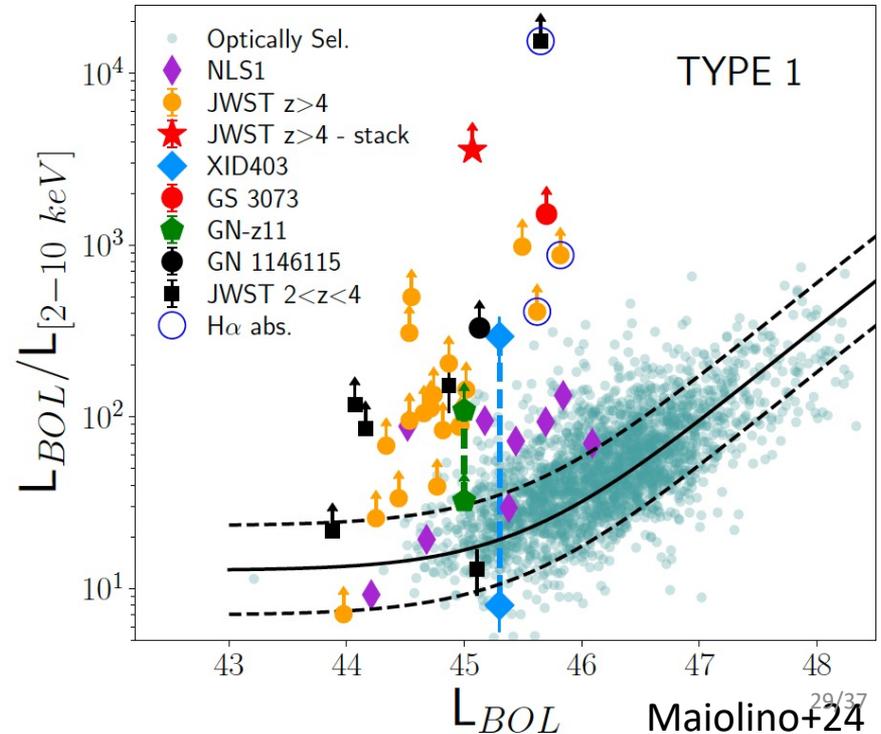
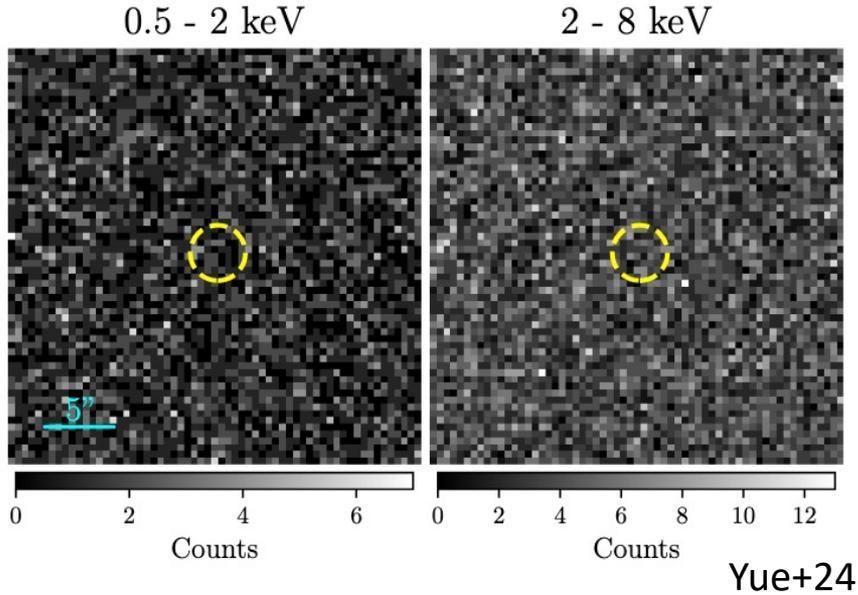
Puzzling Property 2: Weak Dust Emission

- Red optical continuum and high Ha/H β ratios \rightarrow dusty AGNs?
- No hot dust or cold dust detected in JWST/MIRI and ALMA
 - Weak/no torus. Bolometric correction for normal AGNs cannot be used.



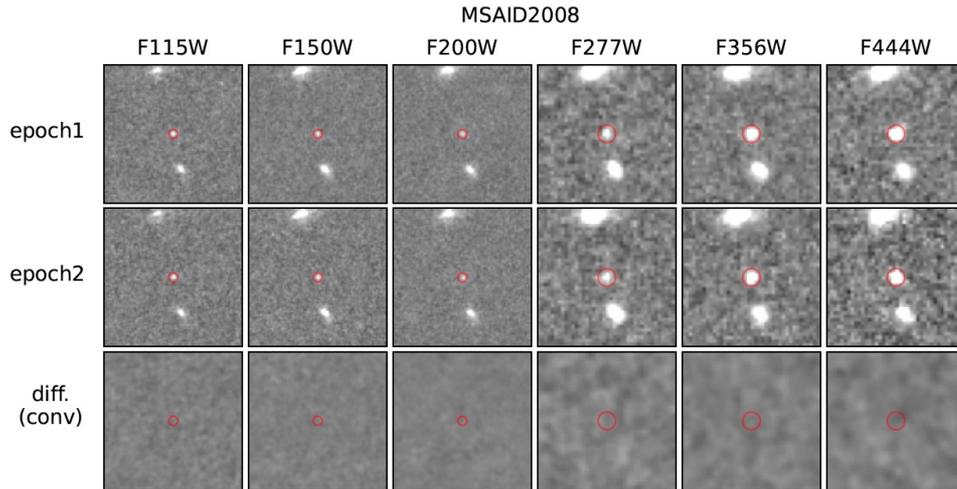
Puzzling Property 3: Weak X-ray

- Type-1 AGNs usually bright in X-ray, but LRDs are very faint...

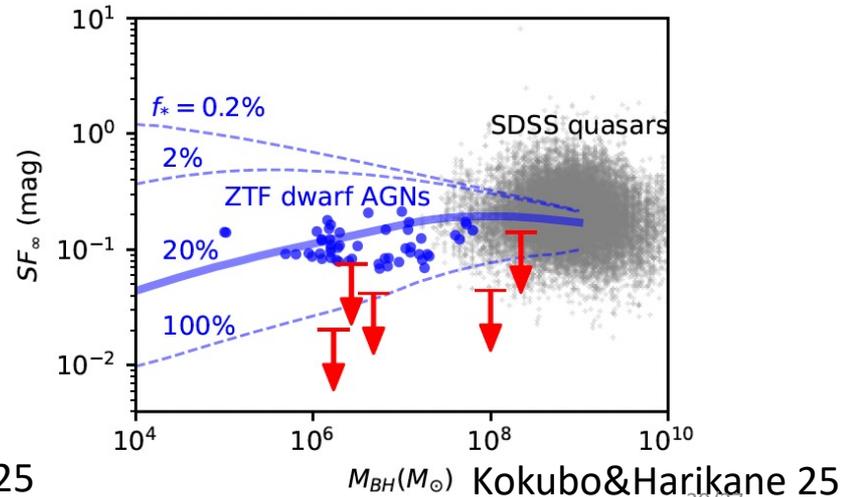


Puzzling Property 4: Weak Variability

- Type-1 AGN usually show variability in ~ 50 day scale
- No variability detected in LRDs in 2-yr JWST data (~ 100 days in rest-frame)
 - Report of $>$ year-scale variability in lensed LRDs (discussed later)

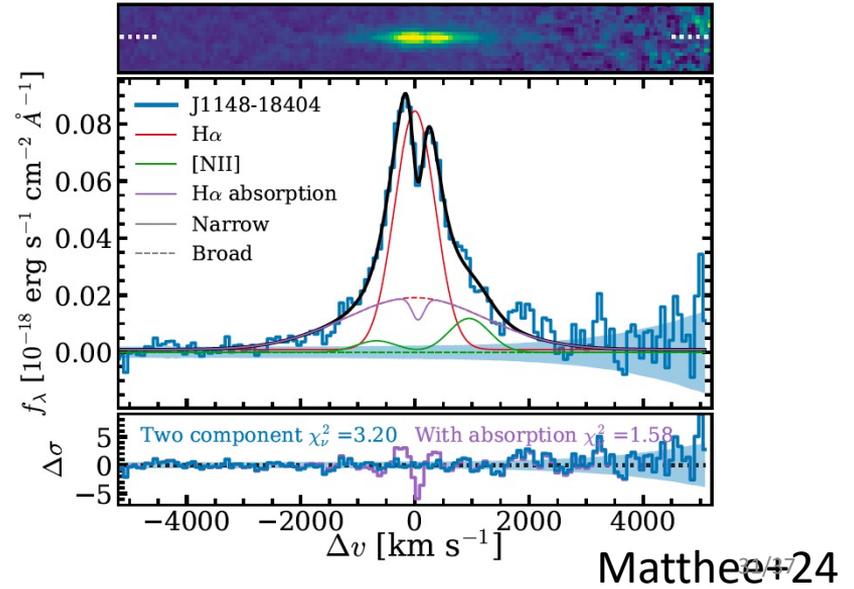
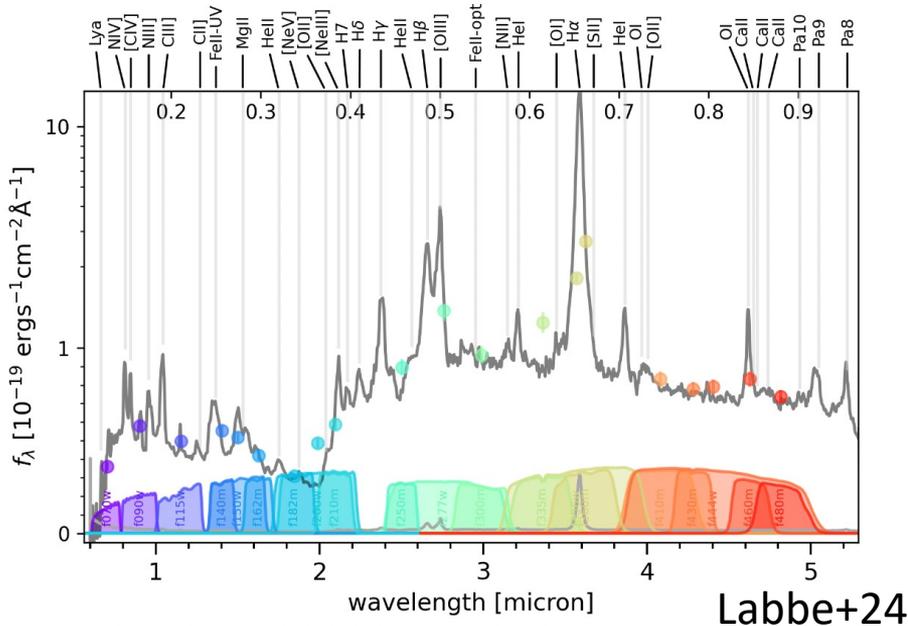


Kokubo&Harikane 25



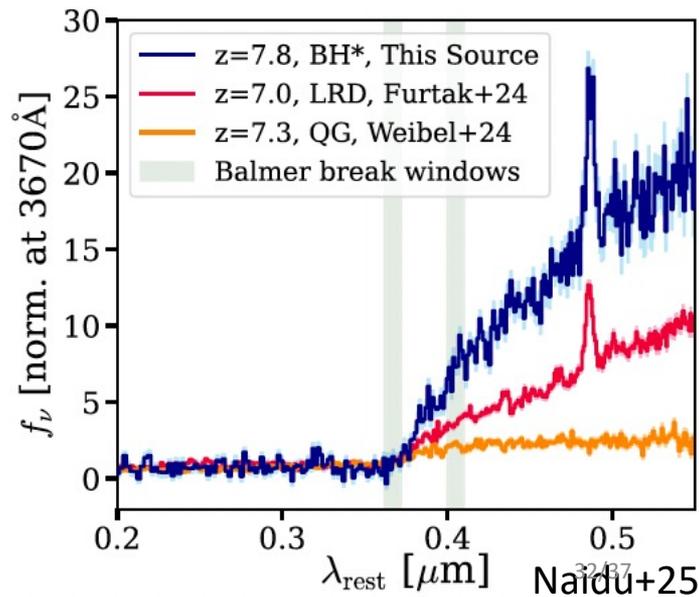
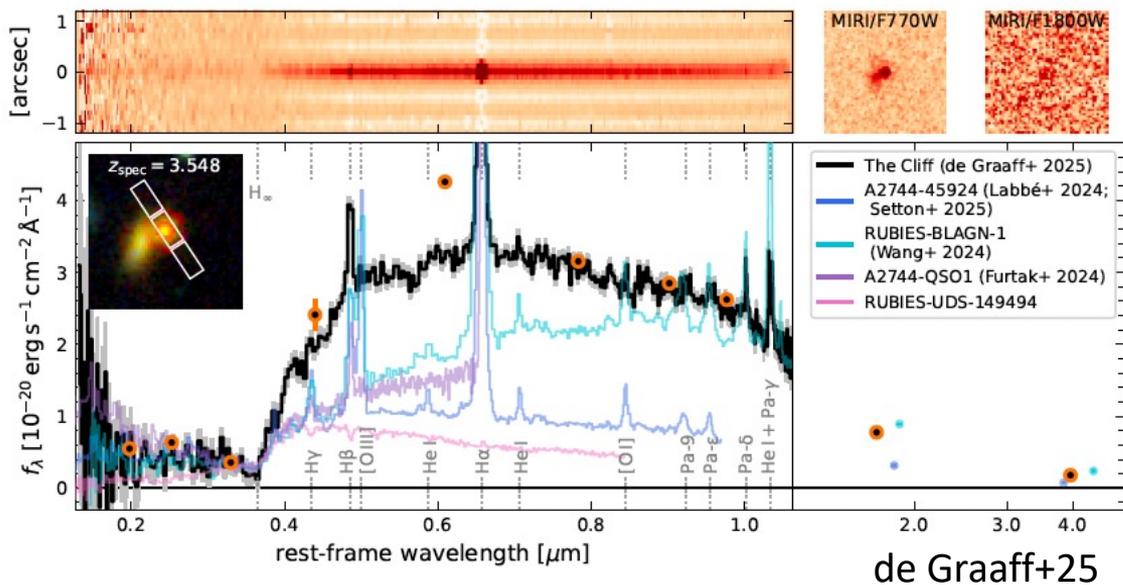
Puzzling Property 5: Balmer Break/Absorption

- Some LRDs show Balmer breaks and/or Balmer absorption lines
 - Quasars showing Balmer absorption are very rare.
 - Similar to old stellar populations. Optical continuum = stars? Too massive?



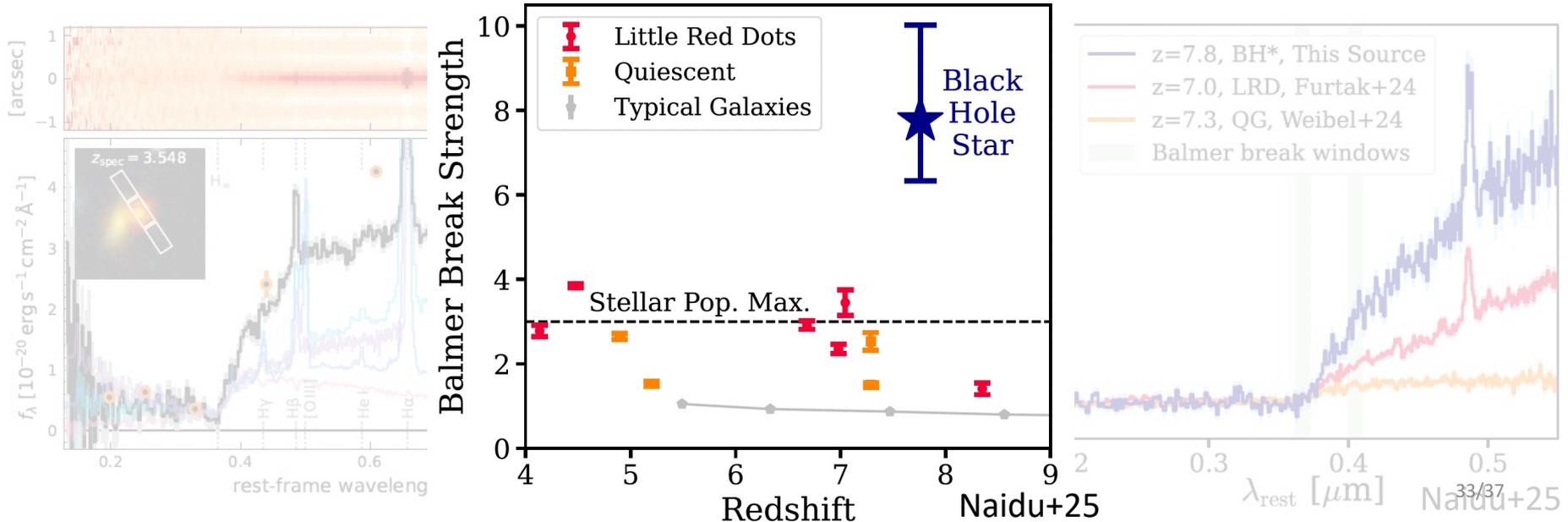
What is the True Nature of LRDs?

- Many strange properties: V-shape, weak dust, X-ray, variability,...
- Discoveries of LRDs with too strong Balmer break
 - Optical continuum is not stellar origin!



What is the True Nature of LRDs?

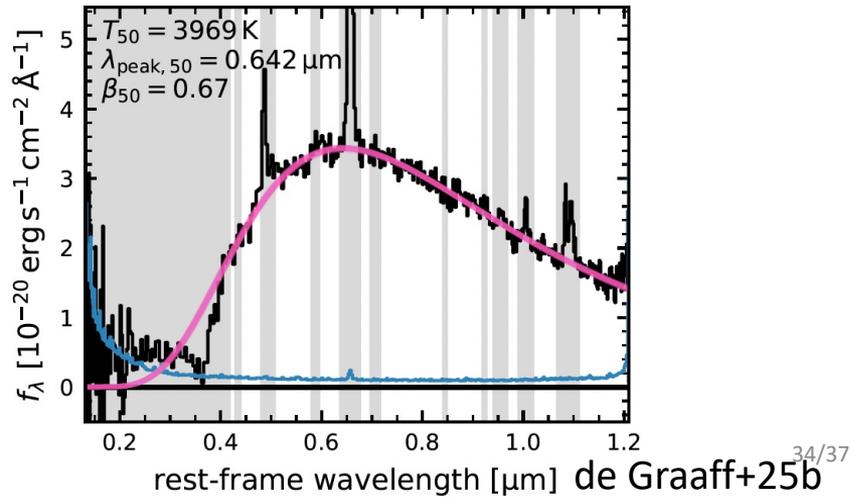
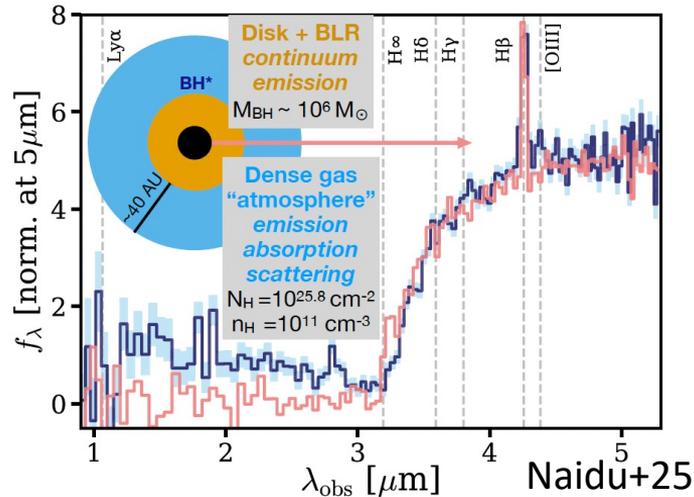
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Black-Hole Star (BH*)/Black Hole Envelope Model

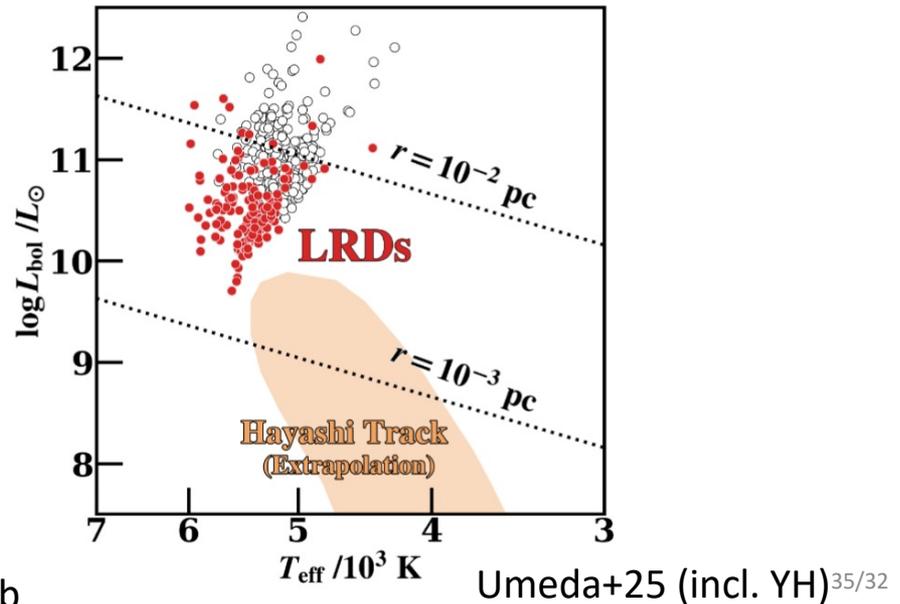
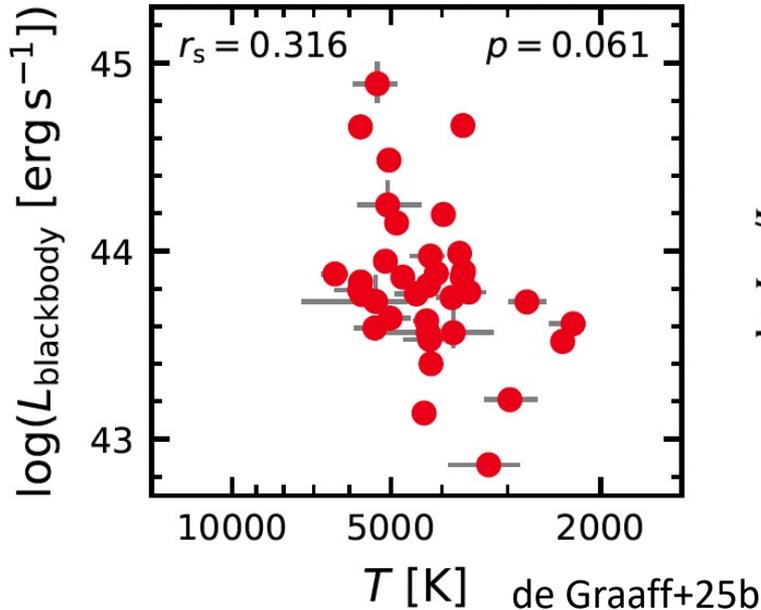
See Kohei's talk

- Supermassive black holes surrounded by dense gas
 - Red optical continuum: single black body emission from dense gas
 - Balmer break & absorption lines: absorption by dense gas (many n=2 hydrogen)
 - Blue UV continuum: from host galaxies?
 - Consistent with LRDs' puzzling properties: weak in dust, X-ray, variability



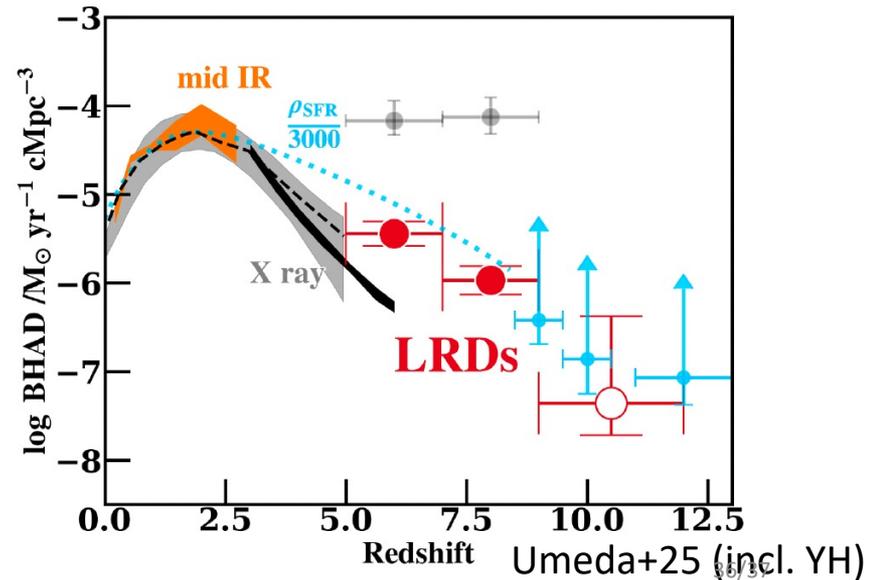
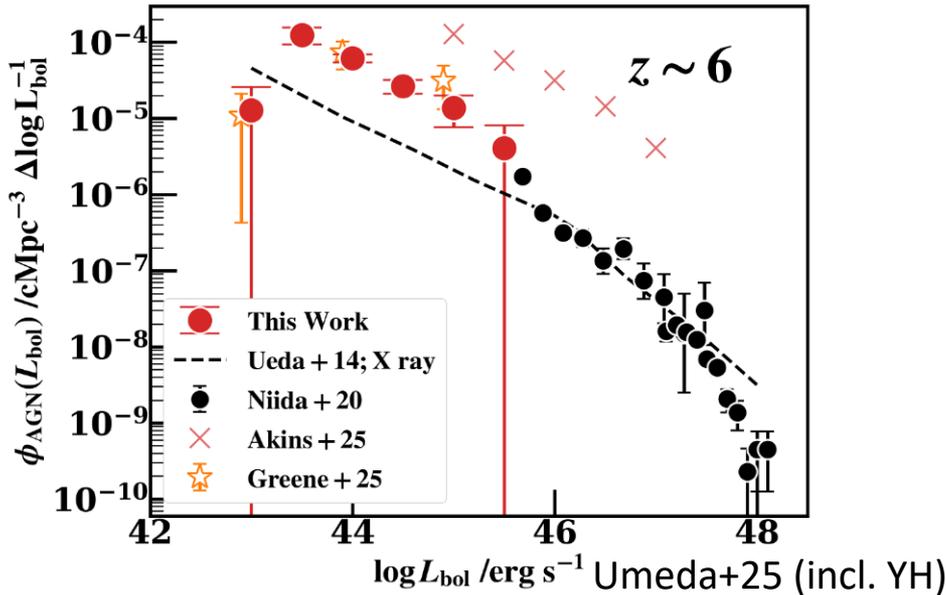
HR-Diagram of Little Red Dots

- Modified black body fit
 - Well fitted with single black bodies, but different temperatures (~ 3000 - 7000 K)
 - Size: 0.01 - 0.001 pc



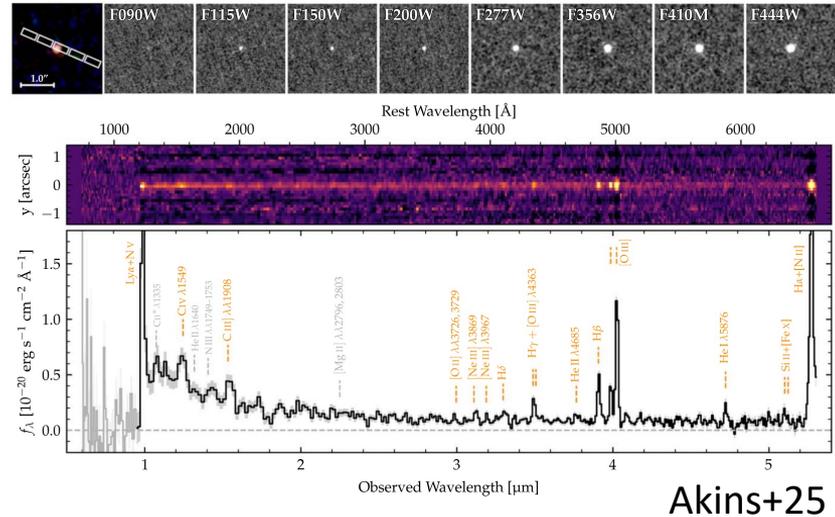
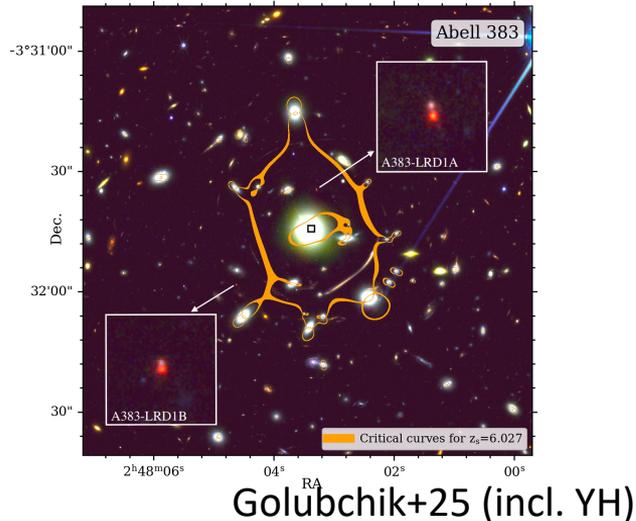
Statistics with BH*/Envelope Model

- Total luminosity (bolometric luminosity) can be estimated
- Bolometric luminosity functions and BH accretion rate densities
 - Significantly smaller than previous estimates assuming typical AGN SEDs



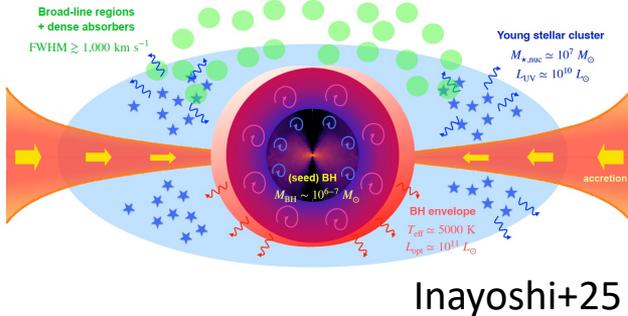
Host Galaxies of Little Red Dots

- ~40% of LRDs: extended UV emission and/or blue companions
- UV emission probably from host galaxies
 - AGN-like high-ionization line in some LRDs. Some contributions from AGNs?
- Narrow [OIII] lines are very weak → metal-poor? (Maiolino+25)

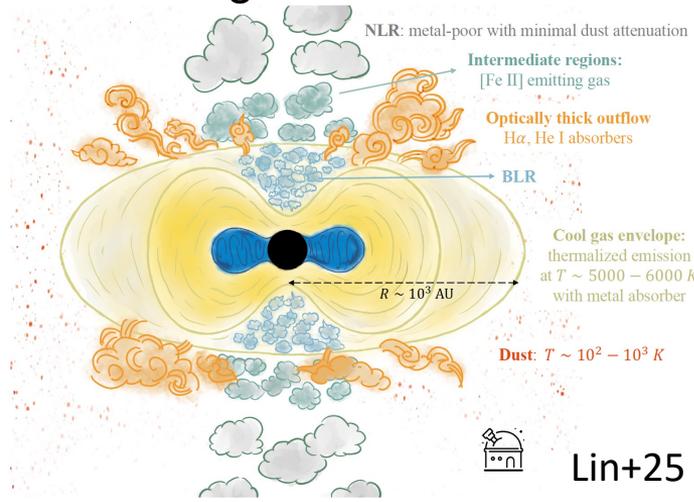


Mystery 1: Structure of BH*/Envelope

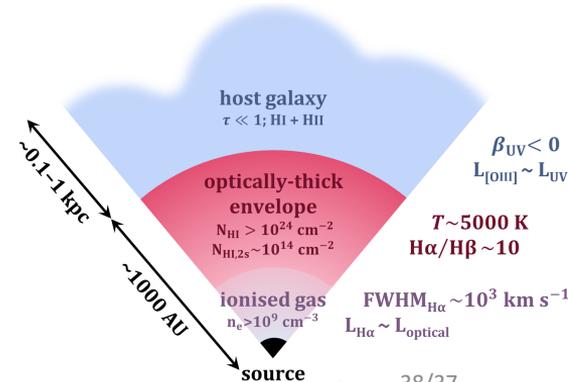
- Where is the broad line region? Outside or inside of the envelope?
 - In partly ionized core? Related to absorption line depth?
- Covering fraction? Almost unity?
 - Most of V-shaped LRDs show broad lines (type-1)
 - How to explain the AGN-like high-ionization emission line in UV?



Inayoshi+25



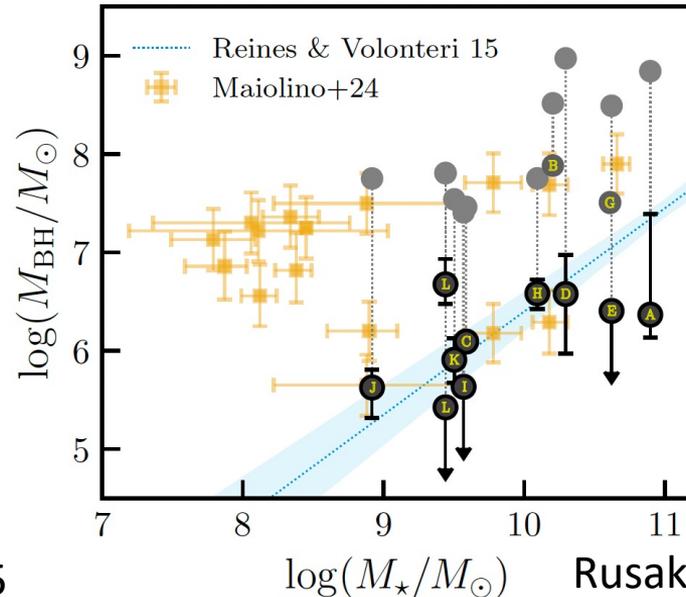
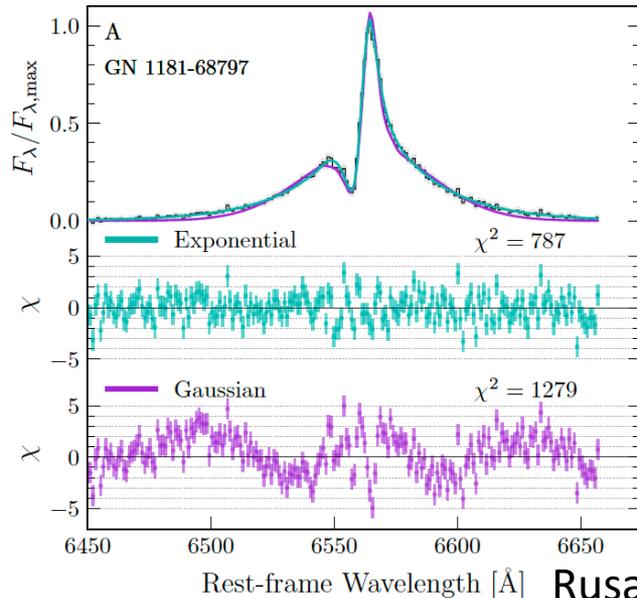
Lin+25



de Graff+25

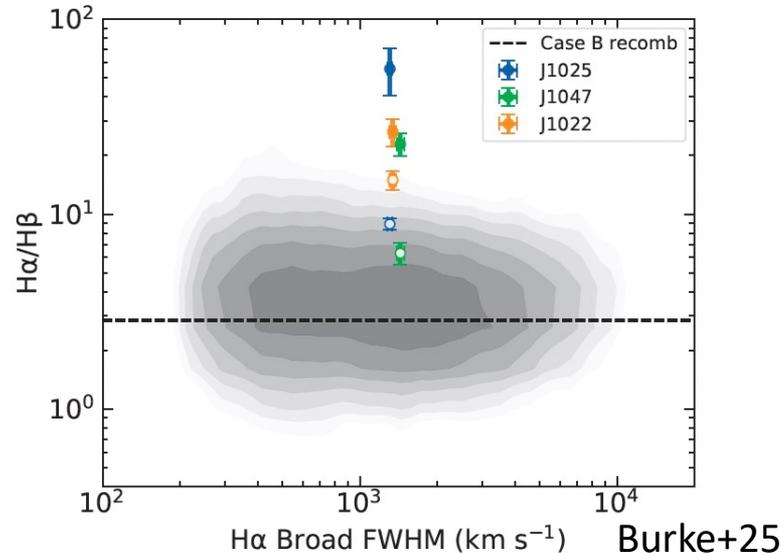
Mystery 3: Black Hole Masses

- Broad lines can be fitted with exponential profile rather than Gaussian
 - Significant electron scattering broadening the H α lines (see also Sneppen+26)
 - Black hole masses were overestimated?



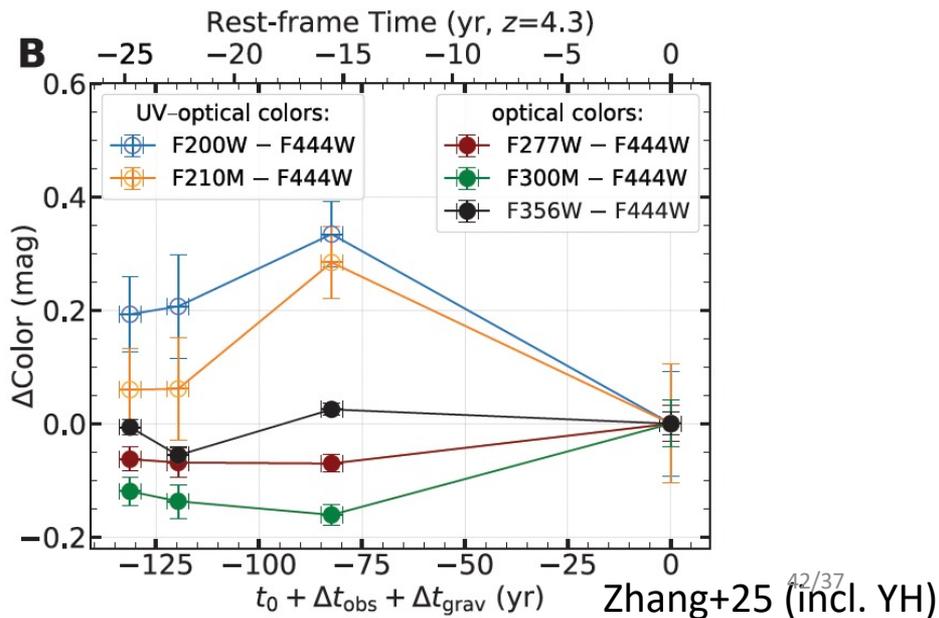
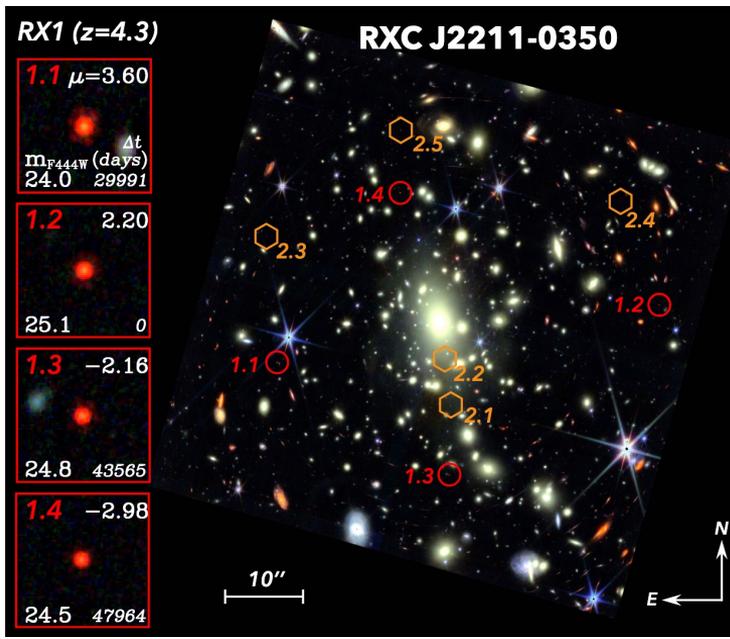
Mystery 4: Too High Ha/H β Ratio

- High Ha/H β ratios usually due to dust, but no dust detections in LRDs
 - Collisional excitation of H α ?
 - Collisional de-excitation of H β ?
 - Resonant scattering with H β \rightarrow H α + Pa α



Mystery 5: Origin of Time Variability

- Some reports of >2-20 yr scale variability in color or equivalent width
 - What is its origin? AGN activity from accretion? Pulsation?
 - If Cepheid-like pulsation exists, can we use LRDs as a standard candle?

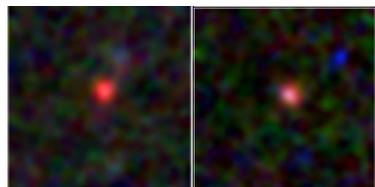


Future Prospects

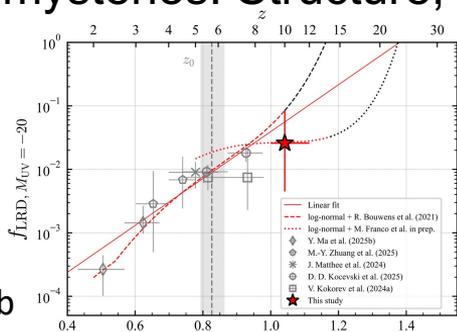
- Toward the true nature of little red dots
 - Studies of emission/absorption lines → internal structures of BH*/envelope
 - Time-domain analysis, with help from gravitational lensing, may give us hints
- Toward the origin of the supermassive black holes
 - Search for LRDs at higher- z . JWST/MIRI observations of $z > 10$ galaxies are key
 - Large systematic uncertainty in current black hole mass estimates of LRDs

Summary

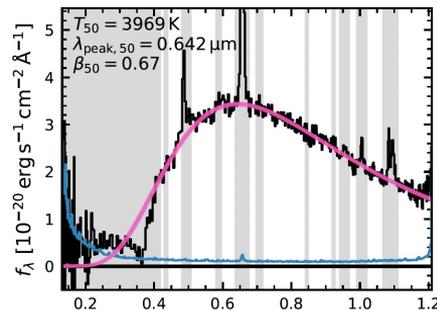
- JWST is identifying many high-redshift faint AGNs than we expected
- Little red dots (LRDs): new populations of AGNs discovered by JWST
 - V-shaped SEDs, compact morphologies, and broad hydrogen Balmer lines
 - LRD fraction increases towards higher redshifts
 - Unlike normal AGNs, LRDs are weak in X-ray, dust, and variability
 - LRDs' puzzling properties can be (partly) explained by BH*/envelope models
 - Still many mysteries! Structure, absorption velocities, black hole masses,...



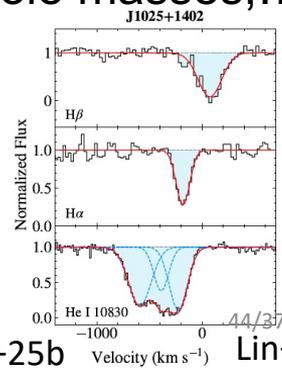
Harikane+23b



Tanaka, Akins, YH+25



de Graaff+25b



Lin+25