高エネルギー宇宙物理学研究会2025 招待講演

JWSTの最新成果レビュー
Little Red Dotsを中心に

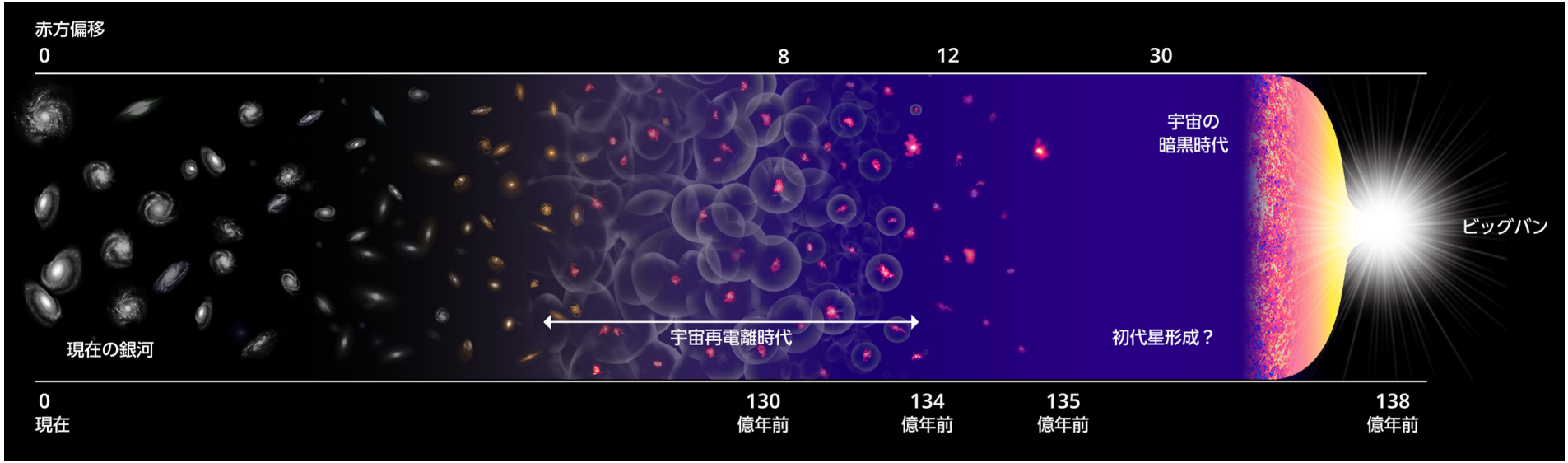
播金優一（東京大学宇宙線研究所）

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

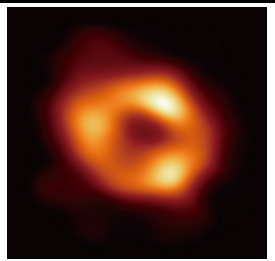
本日の内容

- バックグラウンド: 巨大ブラックホール形成
- JWSTによるAGN観測
- Little Red Dotsとその性質
- Little Red Dots研究の今後の課題

巨大ブラックホール形成



Harikane et al.



EHT Collaboration

現在の宇宙

？種ブラックホール

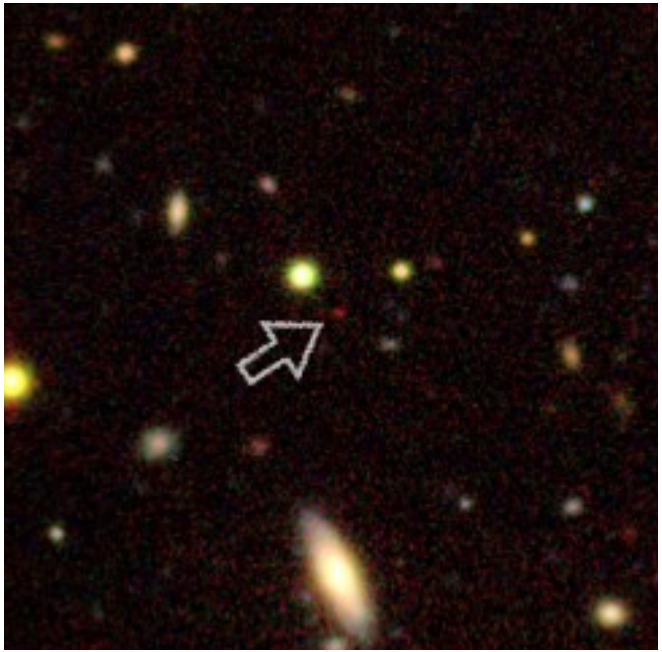
いつ種が生まれたのか？
どのような種が生まれたのか？

？

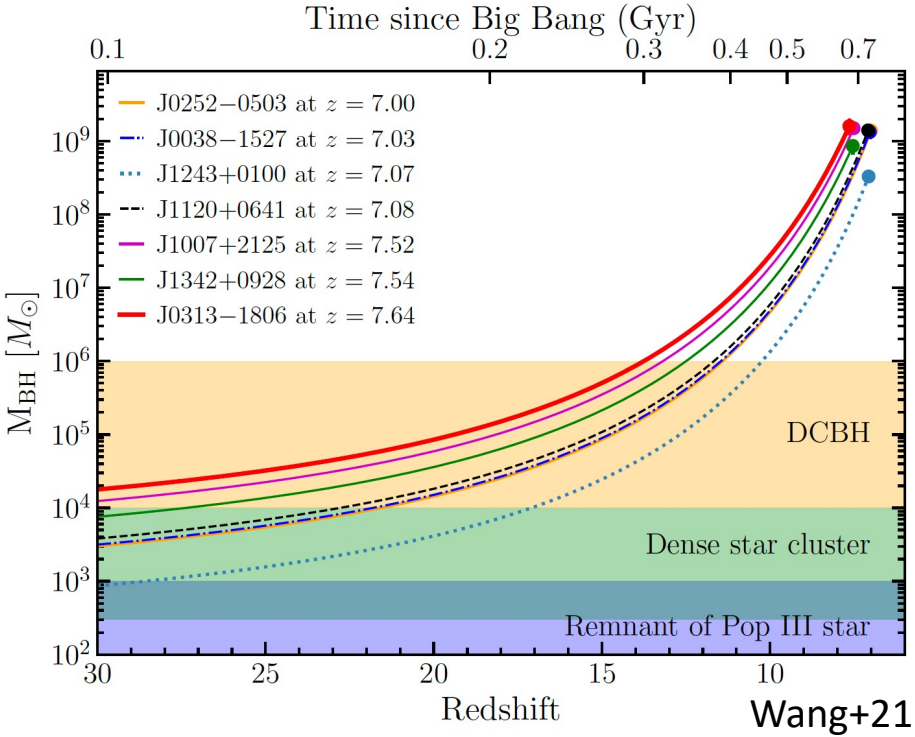
どう成長したのか？

High Redshift AGNs Before JWST

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



NAOJ, Matsuoka et al.



Wang+21

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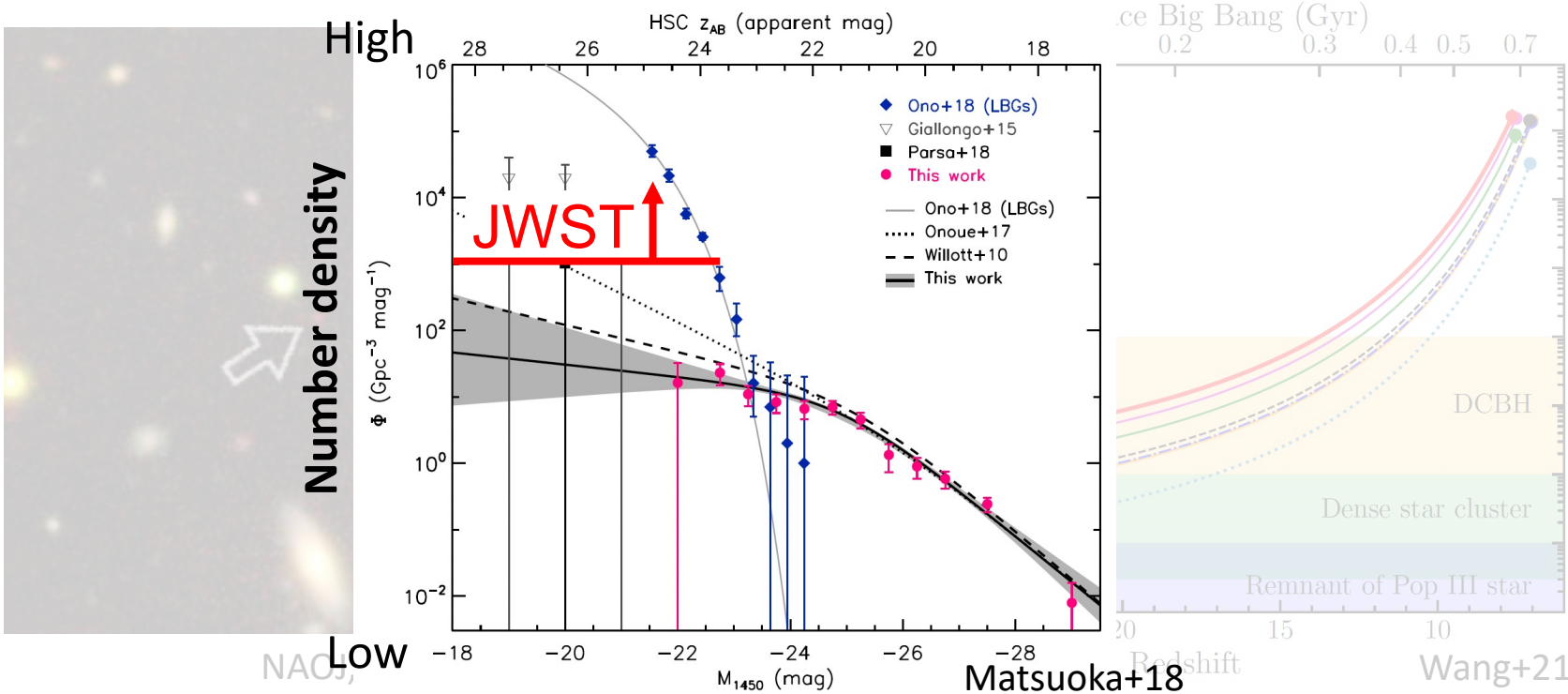
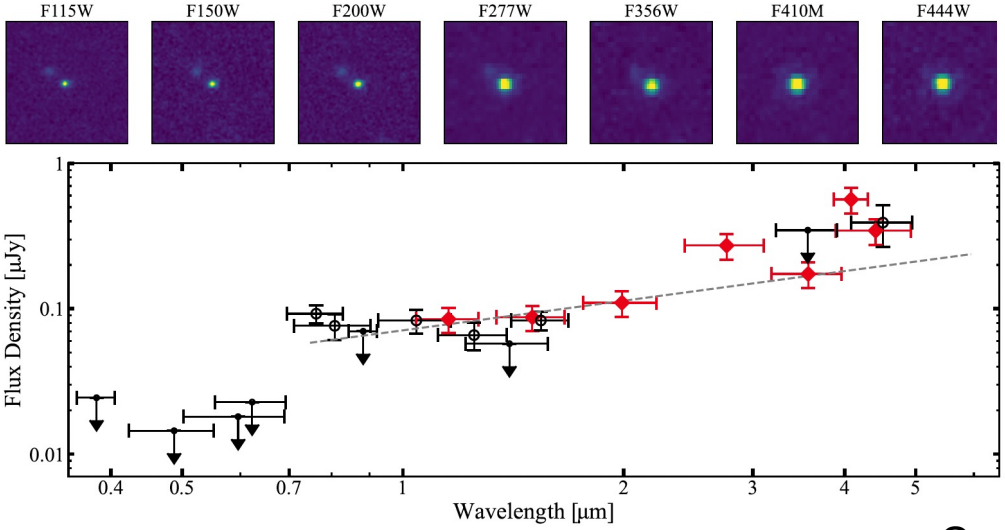
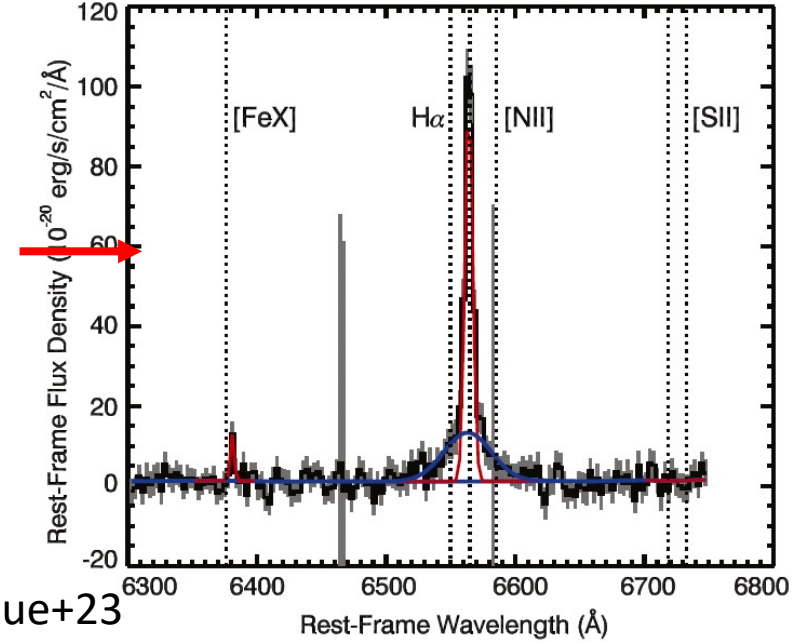


High Redshift AGNs in the JWST Era

- JWST first year: several faint broad-line AGNs discovered
  - Broad (>1000 km/s) Hα lines, narrow (<500 km/s) [OIII] lines



Onoue+23



Kocevski+23

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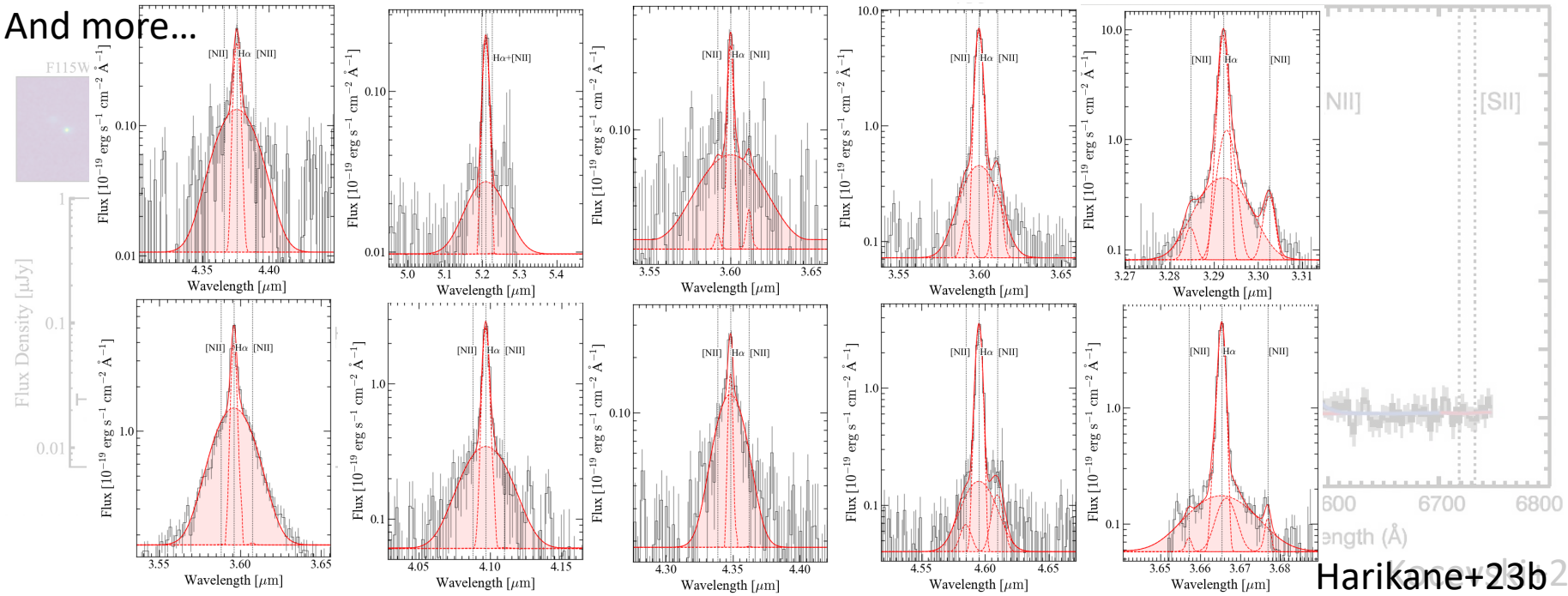

Harikane+23b

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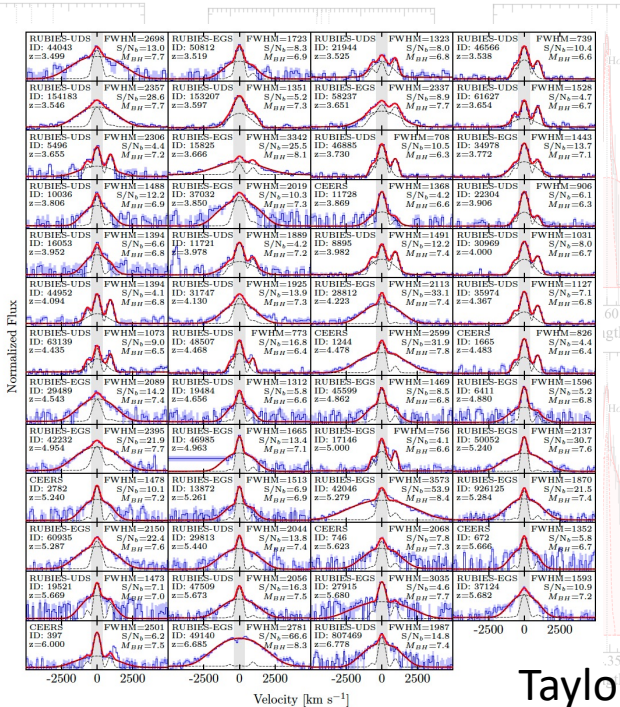
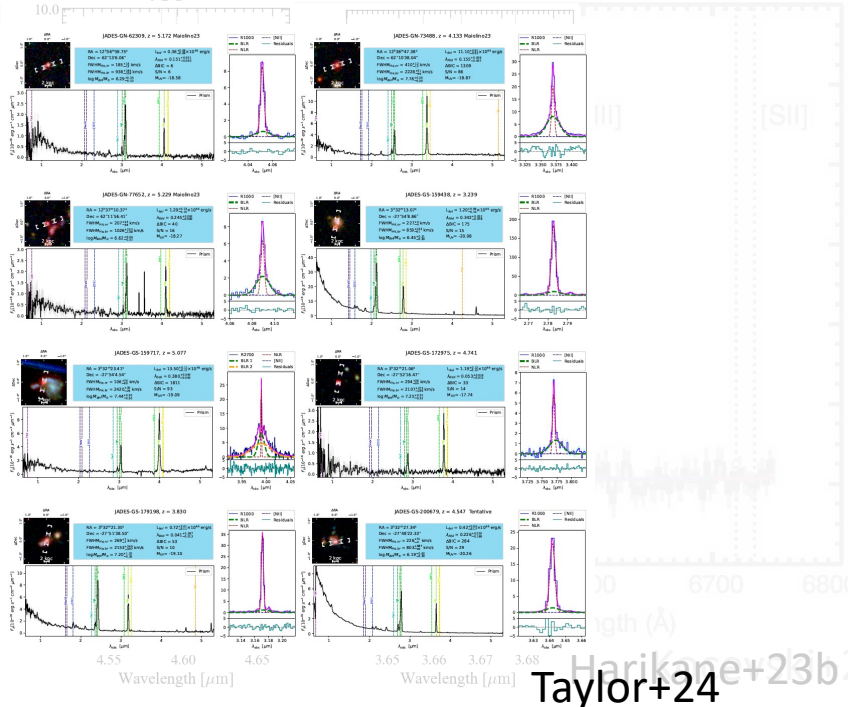


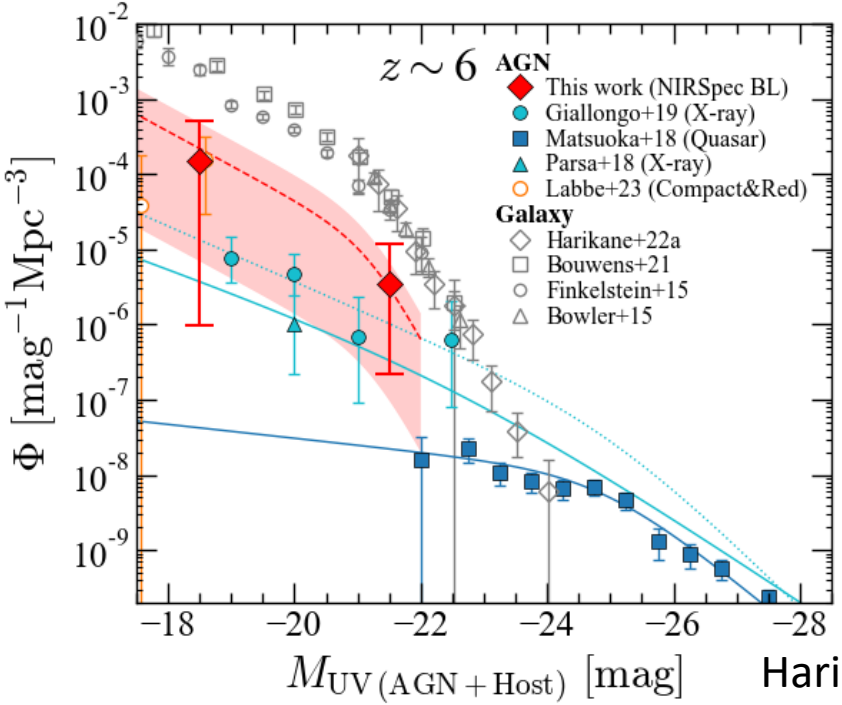
Taylor+24



Taylor+24

Surprisingly Large Number of AGNs at z>4

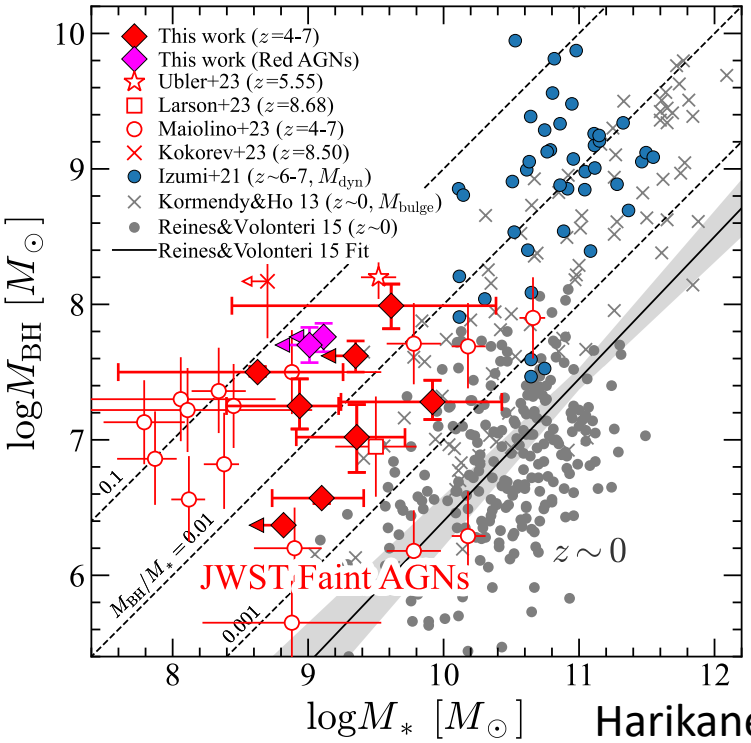
- Number densities of JWST-discovered faint AGNs are larger than extrapolation of QSO luminosity functions



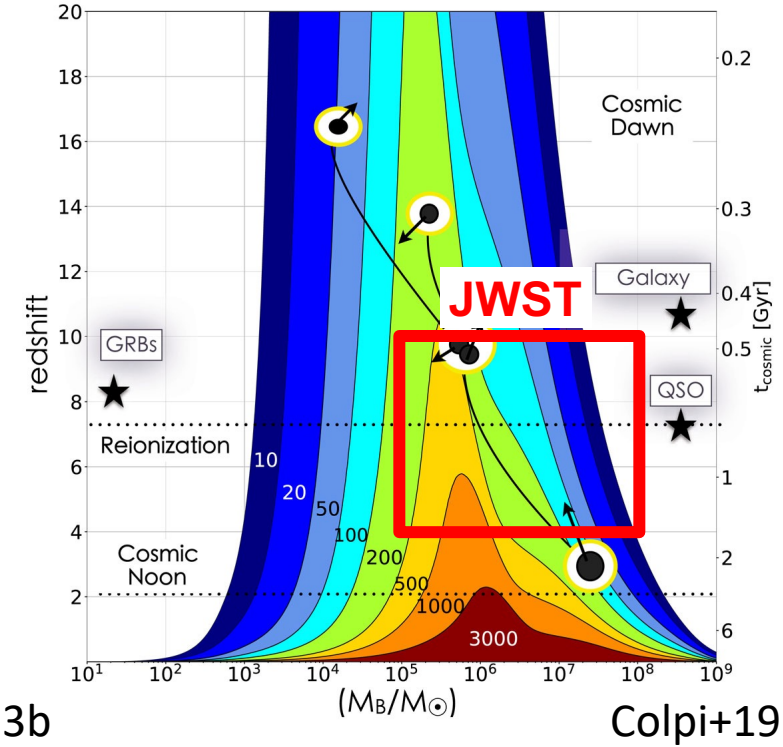
Harikane+23b

Are Their Black Holes Overmassive?

- M_{BH}~10^5-10^8 M_{sun}, smaller than QSOs, in the LISA parameter range



Harikane+23b



Colpi+19

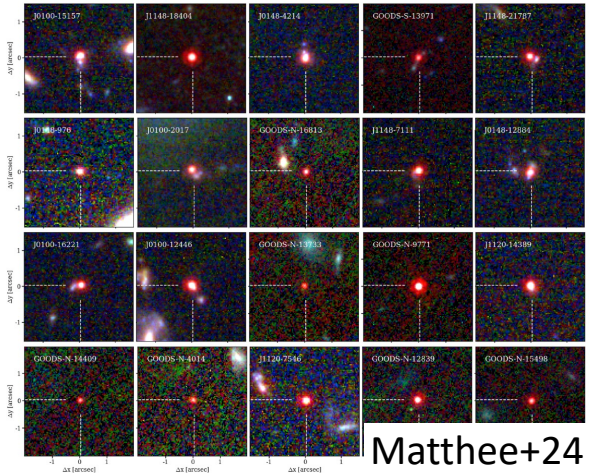
Images of JWST-Discovered Faint AGNs

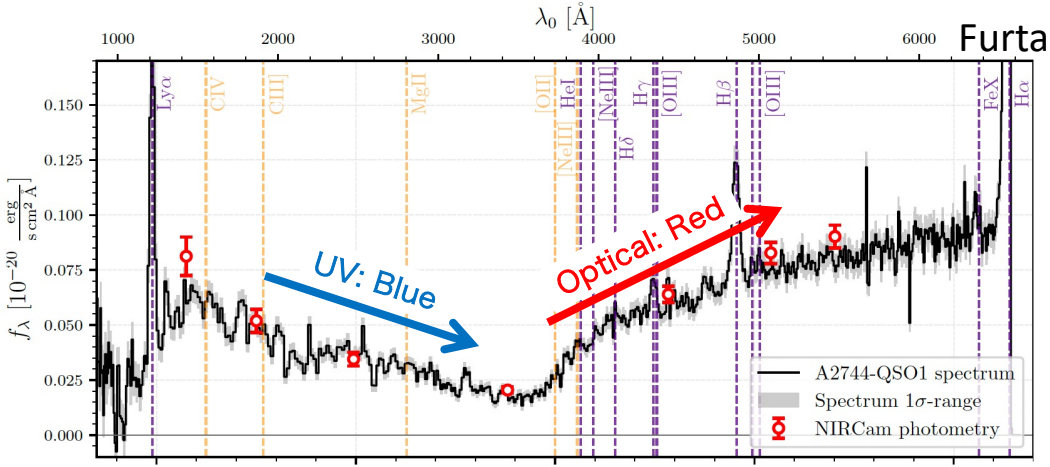
- Host galaxies detected in most of them → Type-1 Seyfert
  - Two compact and red AGNs = little red dots

Harikane+23b

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 (most important), 2. compact, 3. broad Hydrogen Balmer line





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- 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)

Little Red Dots: an abundant population of faint AGN at $z \sim 5$ revealed by the EIGER and FRESCO JWST surveys

Jorryt Matthee,[1,*] Rohan P. Naidu,[2,†] Gabriel Brammer,[3] John Chisholm,[4] Anna-Christina Eilers,[2] Andy Goulding,[5] Jenny Greene,[5] Daichi Kashino,[6,7] Ivo Labbe,[8] Simon J. Lilly,[1] Ruari Mackenzie,[1] Pascal A. Oesch,[9,3] Andrea Weibel,[9] Stijn Wuyts,[10] Mengyuan Xiao,[9] Rongmon Bordoloi,[11] Rychard Bouwens,[12] Pieter van Dokkum,[13] Garth Illingworth,[14] Ivan Kramarenko,[9] Michael V. Maseda,[15] Charlotte Mason,[3,16] Romain A. Meyer,[17,9] Erica J. Nelson,[18] Naveen A. Reddy,[19] Irene Shivaei,[20] Robert A. Simcoe,[2] and Minghao Yue[2]

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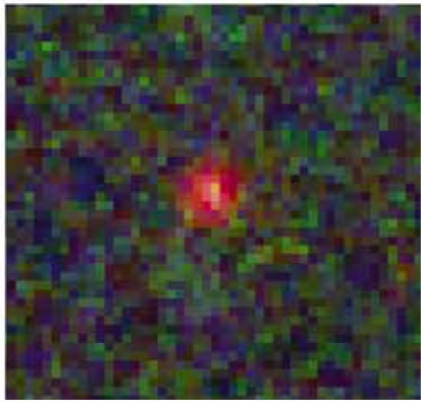
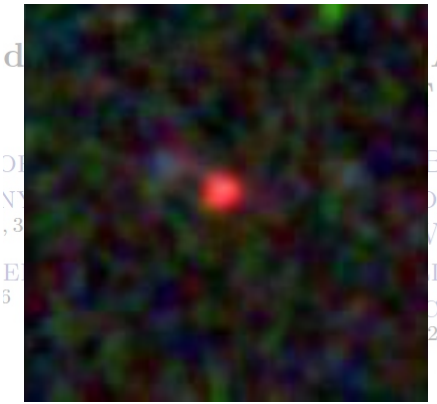
Kocevski+23

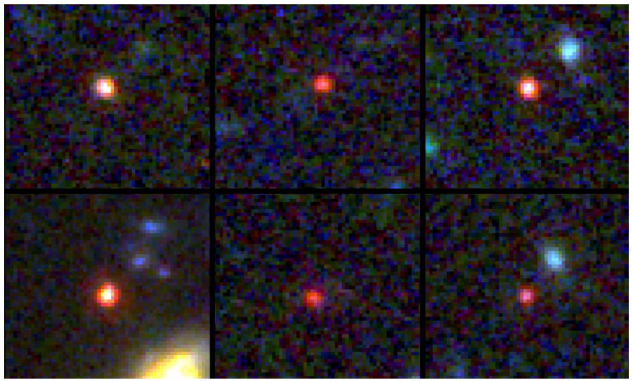


Harikane+23b



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



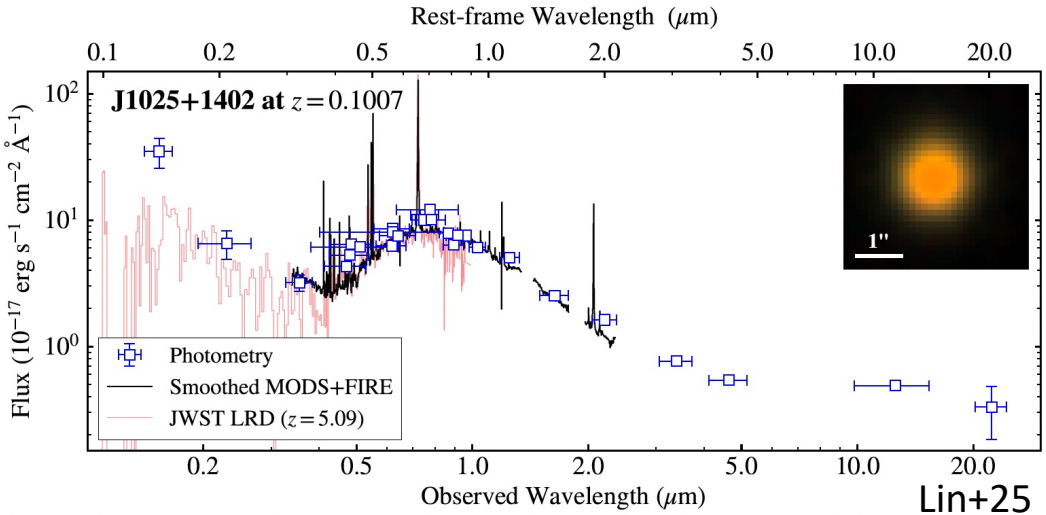
The six candidate galaxies, based on observations by Nasa's James Webb space telescope. Photograph: Nasa/Reuters

Labbe+23

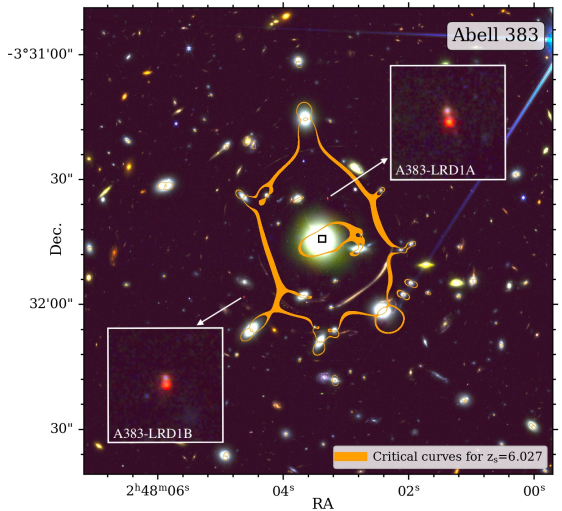
Web news in The Guardian

Re-Discoveries of Little Red Dots

- z=0: previously-known metal-poor galaxies are LRDs
  - Strange broad Hα lines are reported
- z=6: a previously-known strong Lya emitting galaxy is an LRD
  - Red optical emission w/ Spitzer is reported



Lin+25

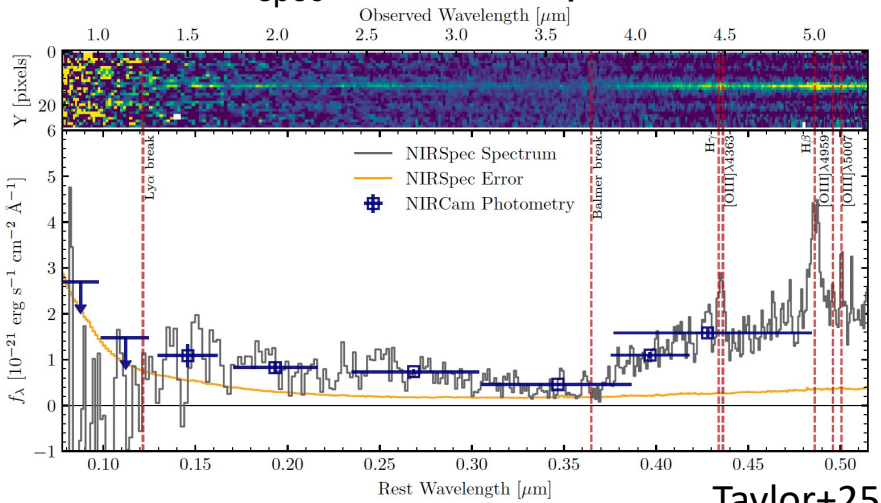


Golubchik+25 (incl. YH)

LRD is more Common at Higher Redshifts

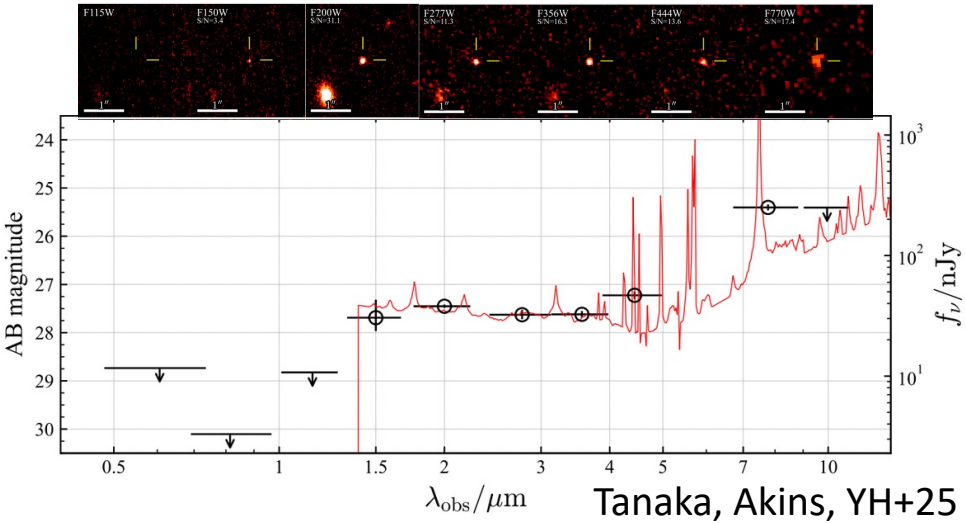
- LRDs at z=9-10 are recently identified
  - LRD fraction among galaxies increasing towards higher redshifts
  - First episode of supermassive black hole growth? (Inayoshi 25)

z_{spec}=9.3 LRD spectrum



Taylor+25

LRD at z=10



Tanaka, Akins, YH+25

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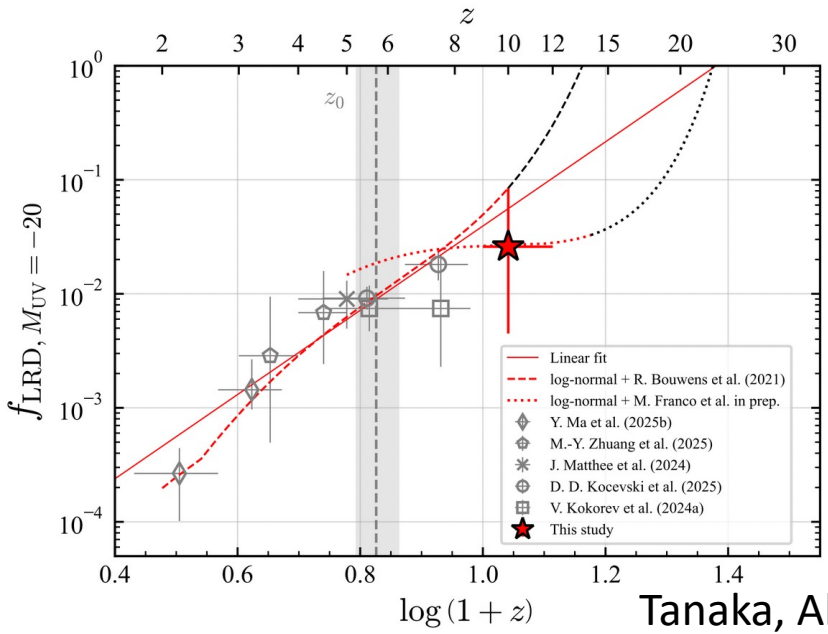
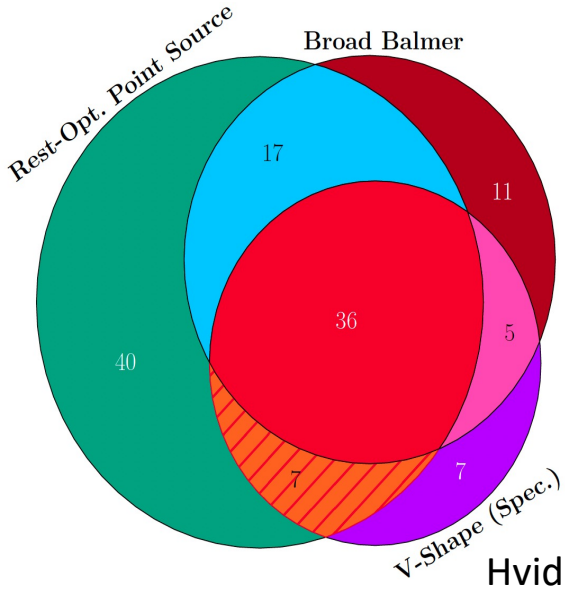


Tanaka, Akins, YH+25

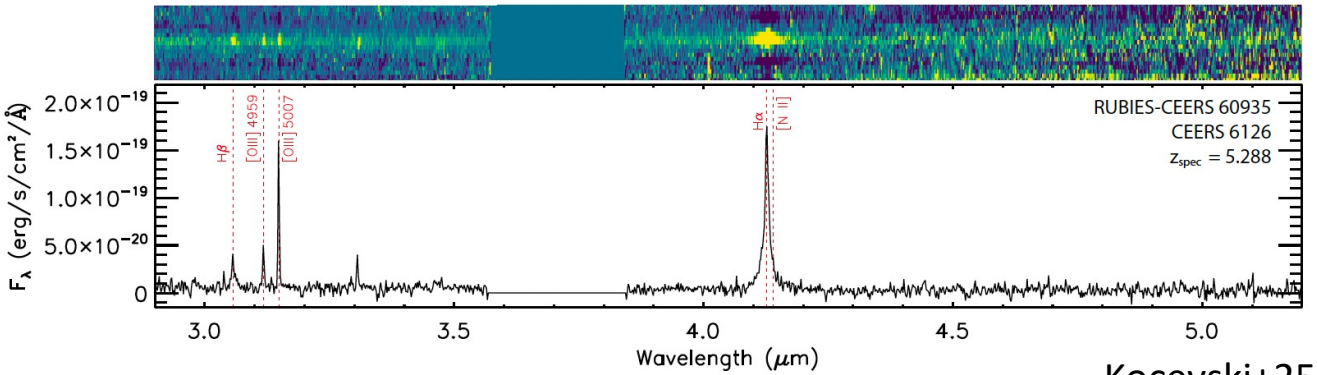
Tanaka, Akins, YH+25

Are Little Red Dots AGNs?

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



Hviding+25



Kocevski+25

Non-AGN Scenario is Difficult…

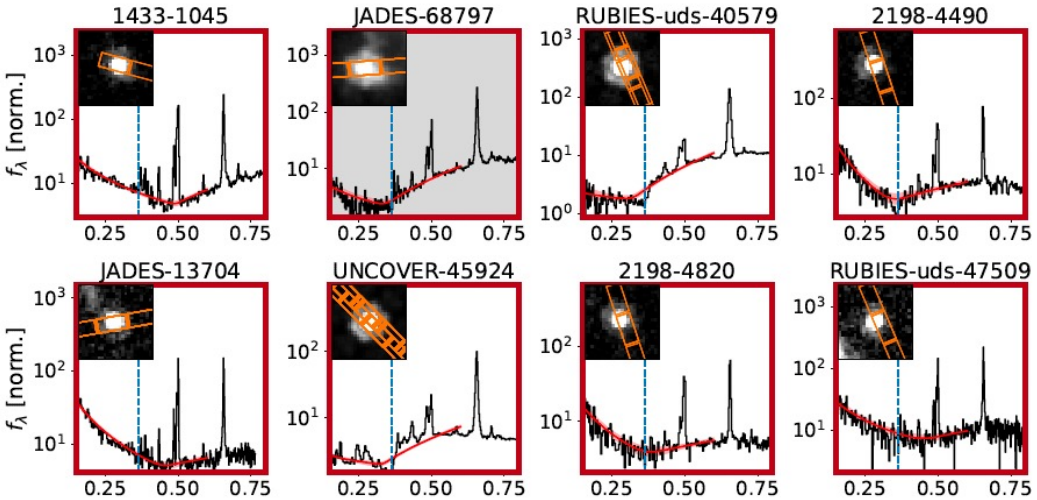
- Need to explain broad (>1000 km/s) Ha lines while narrow [OIII] lines
  - Collisional deexcitation is not effective in galaxies' ISM densities
  - Ultrafast pristine gas outflow? No such examples in other galaxies

(d) stellar continuum + non-AGN broad Hα

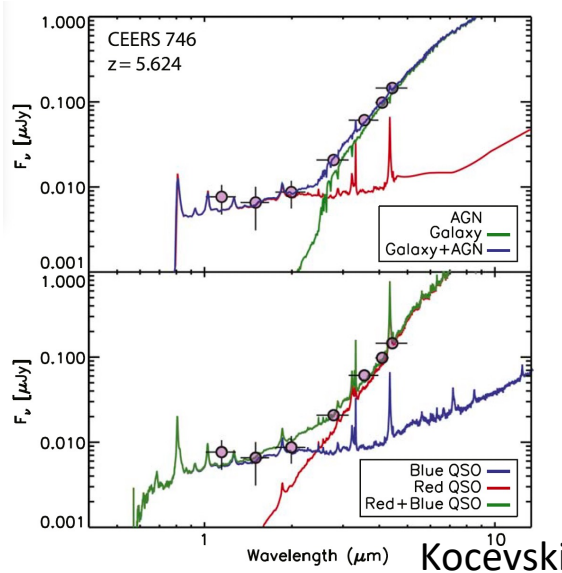
Kokubo&Harikane 25

Puzzling Property 1: V-Shaped SED

- Most of LRDs show the break of the V-shape around ~4000 A
- What is the origin of blue UV and red optical emission?
  - Galaxy+AGN? AGN+galaxy? AGN+AGN? AGN+scattered photons?



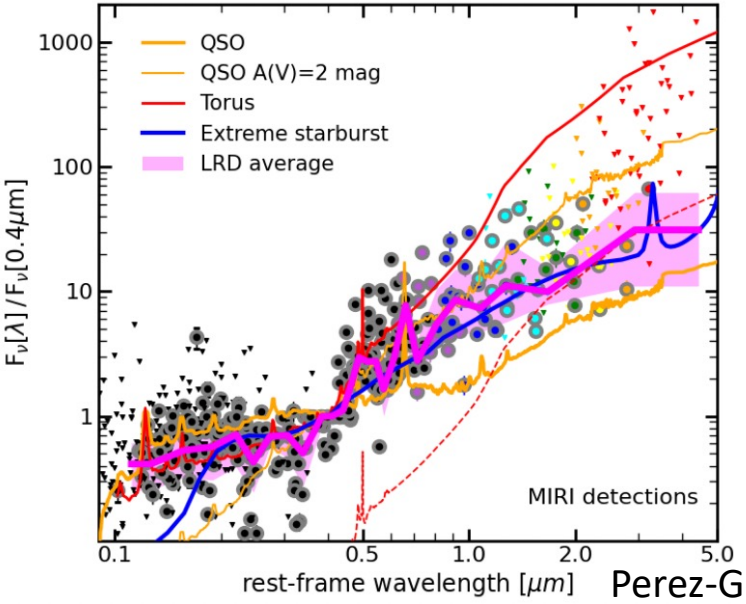
Setton+24



Kocevski+23b

Puzzling Property 2: Weak Dust Emission

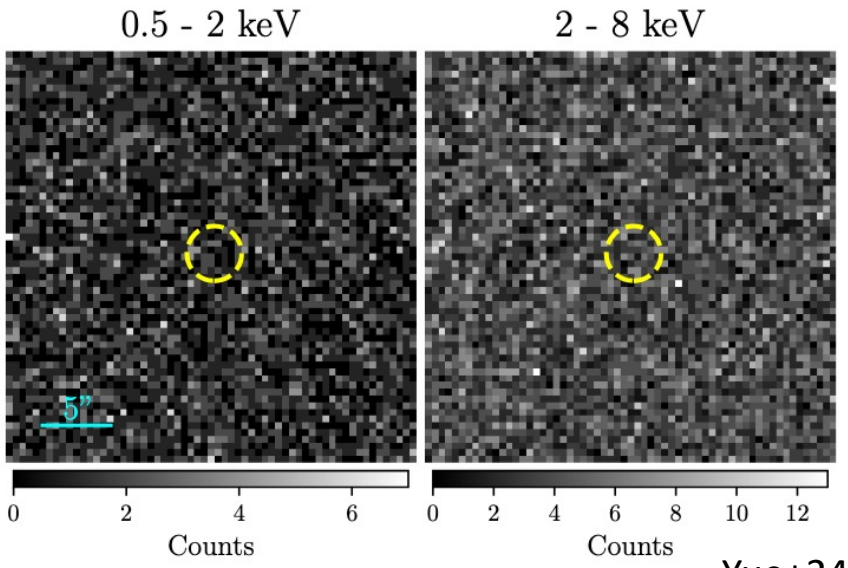
- Red optical continuum and high Ha/Hb ratios → dusty AGNs?
- No hot dust or cold dust detected in JWST/MIRI and ALMA
  - Bolometric correction for normal AGNs cannot be used



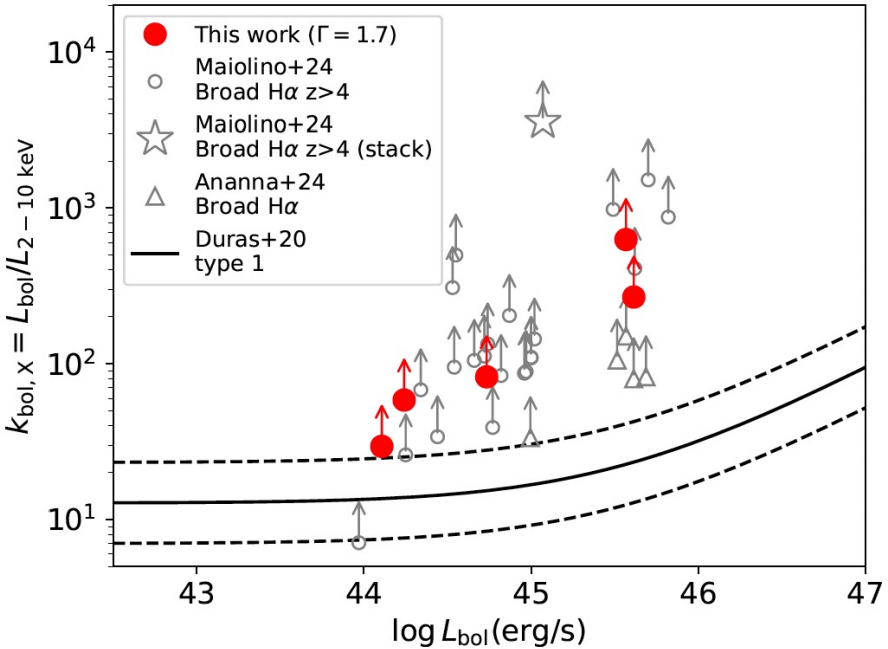
Perez-Gonzalez+24

Puzzling Property 3: Weak X-ray

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



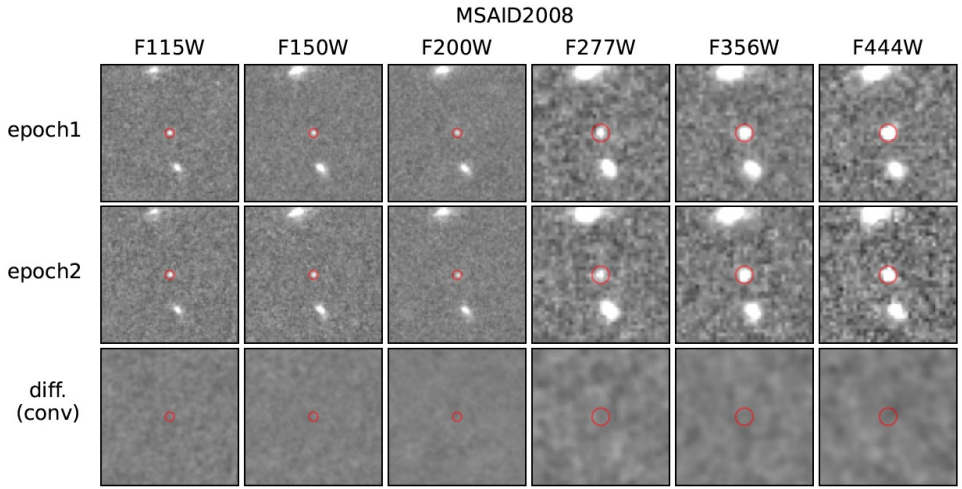
Yue+24



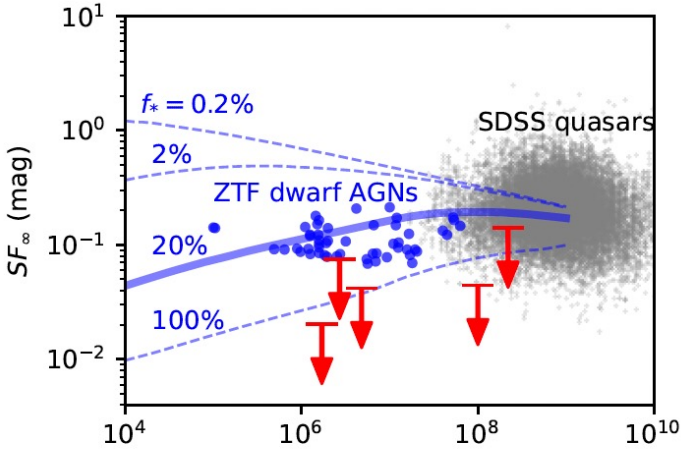
Kokubo&Harikane 25

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 (see also arXiv next week!)



Kokubo&Harikane 25



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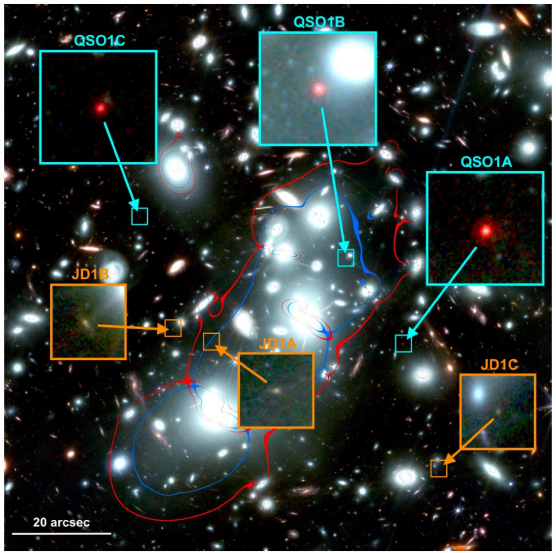
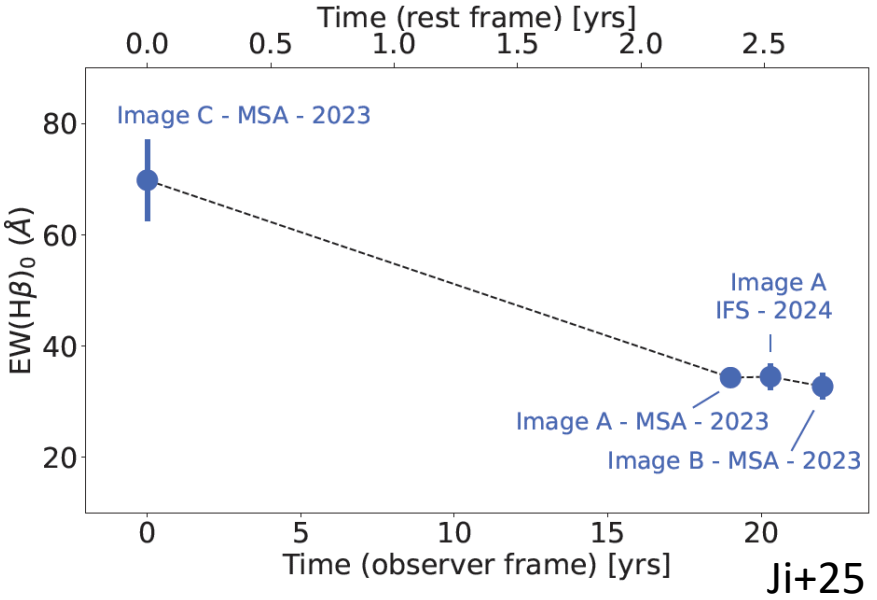


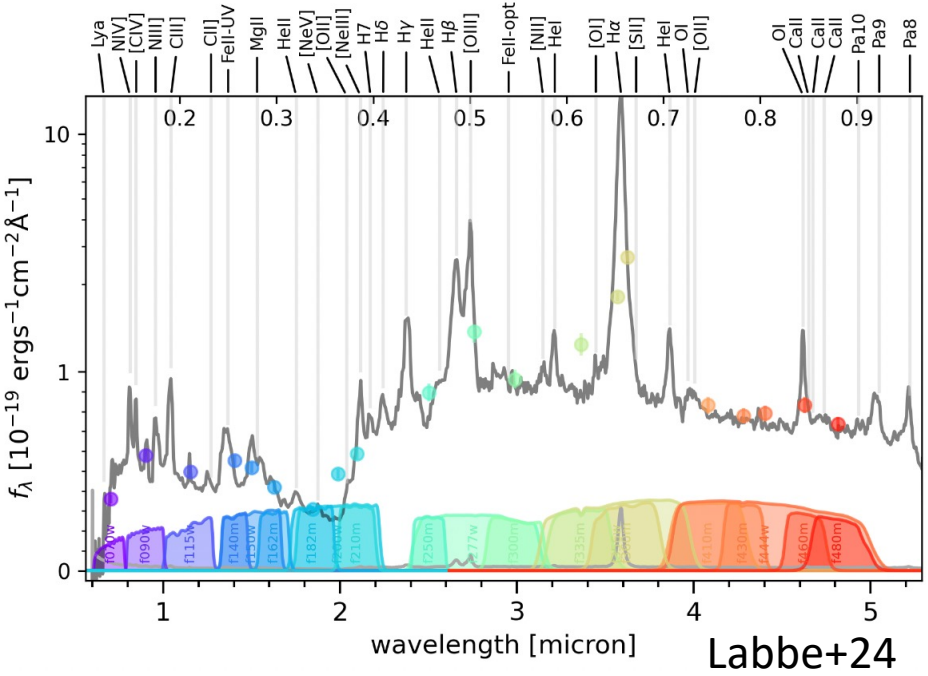
Furtak+23



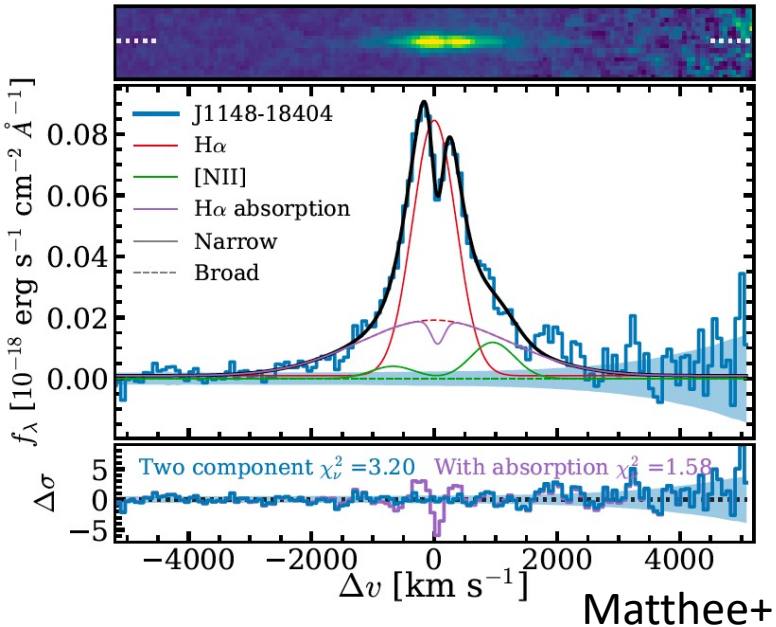
Ji+25

Puzzling Property 5: Balmer Break/Absorption

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



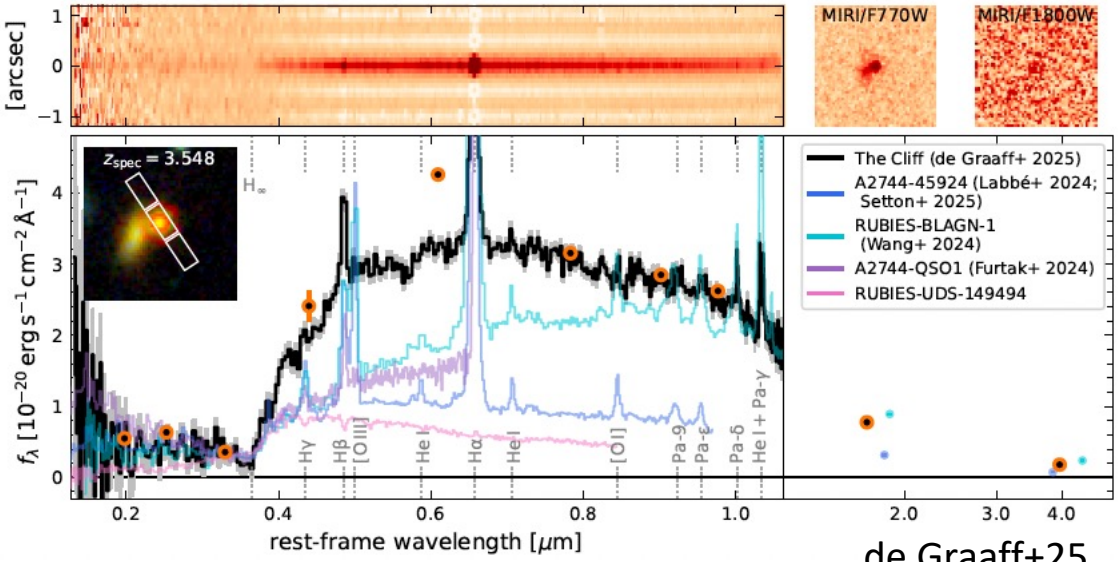
Labbe+24



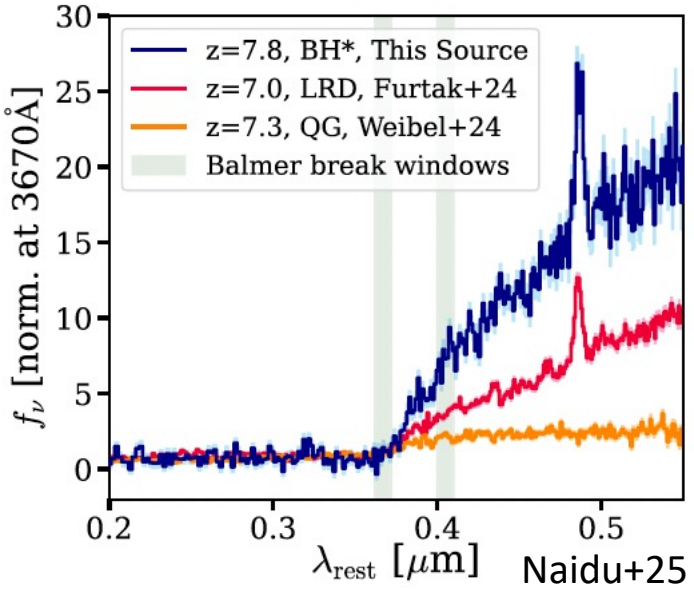
Matthee+24

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!



de Graaff+25



Naidu+25

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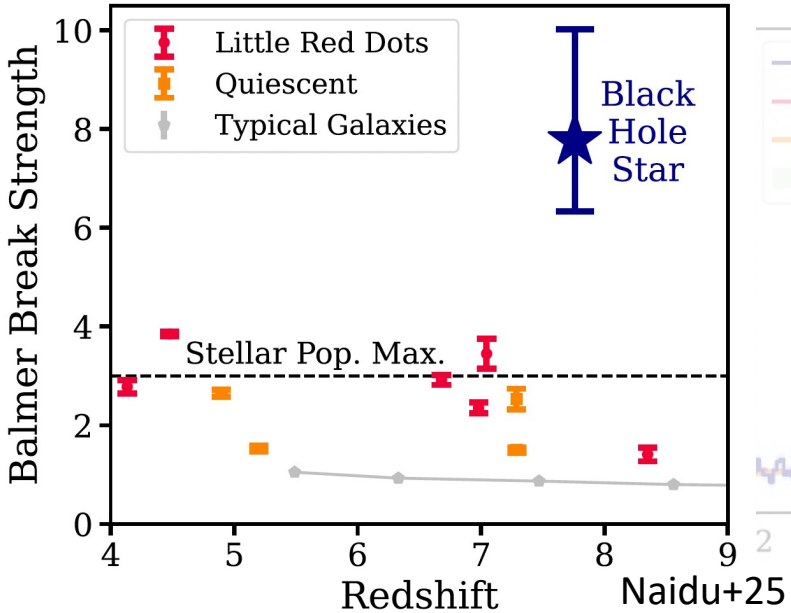
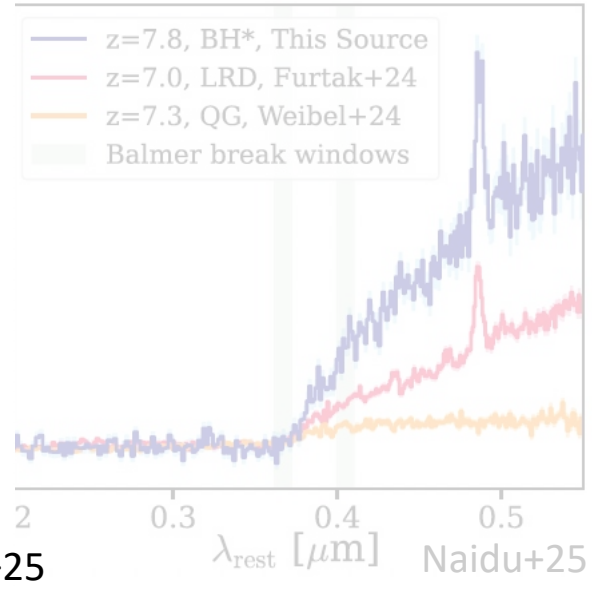
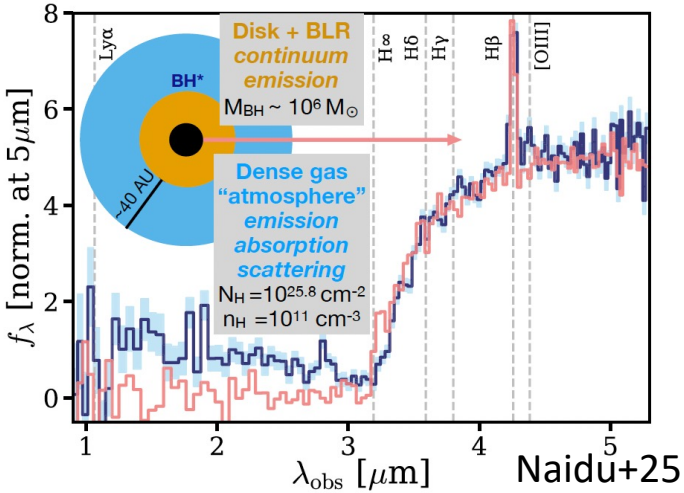




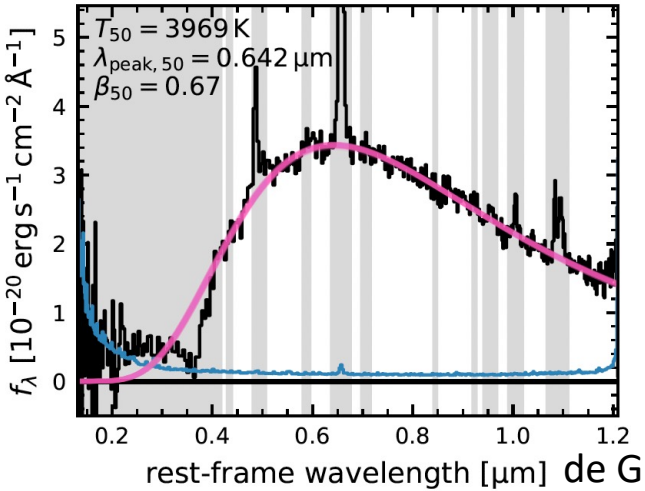
Black-Hole Star (BH*)/Black Hole Envelope Model

木戸さん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, variabilitiy



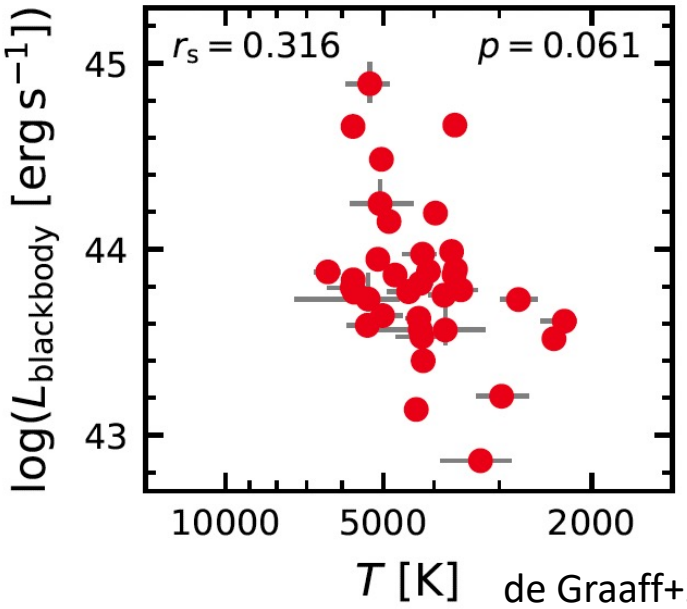
Naidu+25



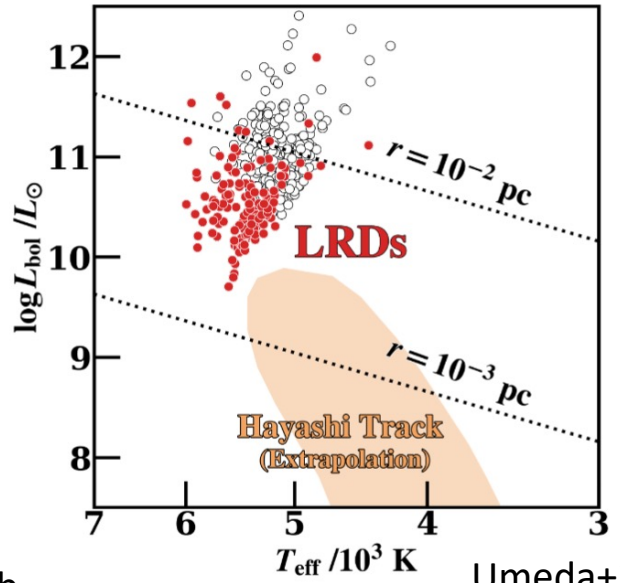
de Graaff+25b

HR-Diagram of Little Red Dots

- Modified black body fit
  - Well fitted with single black bodies, but different temperatures
  - Size: 0.01-0.001 pc



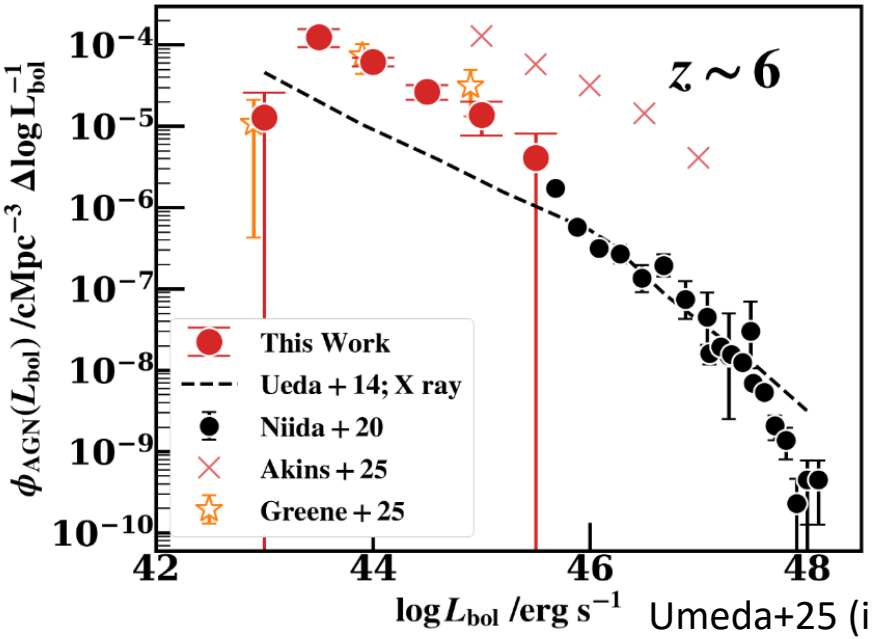
de Graaff+25b



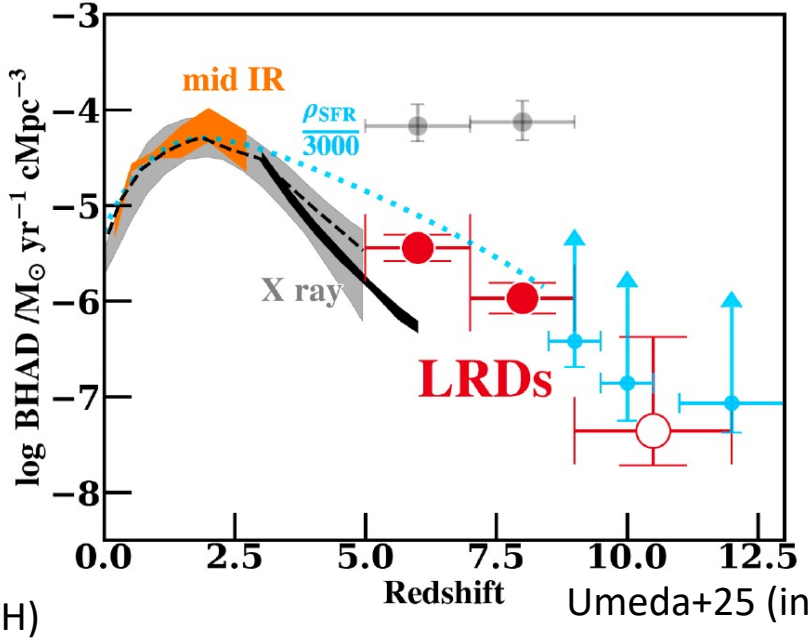
Umeda+25 (incl. YH)

Statistics with BH*/Envelope Model

- Total luminosity (bolometric luminosity) can be estimated
- Bolometric luminosity functions and BH accretion rate densities



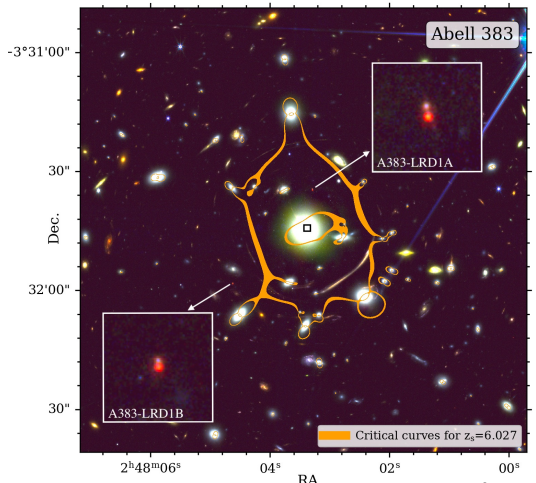
Umeda+25 (incl. YH)



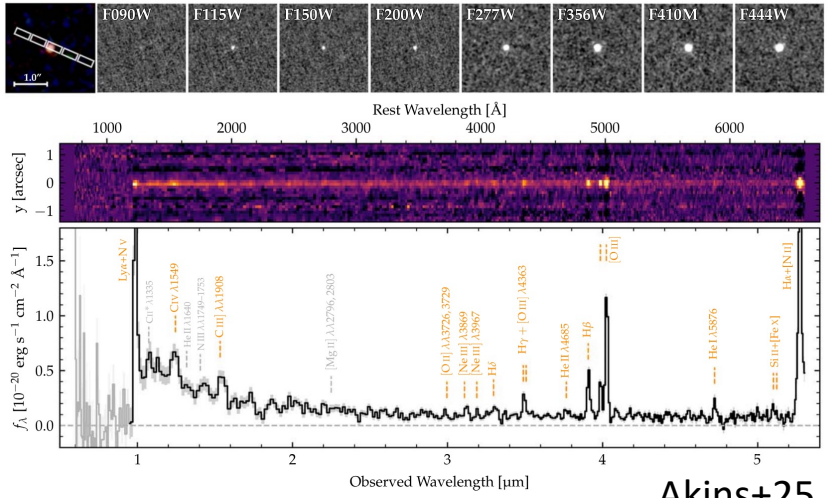
Umeda+25 (incl. YH)

Host Galaxies of Little Red Dots

- Some 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)



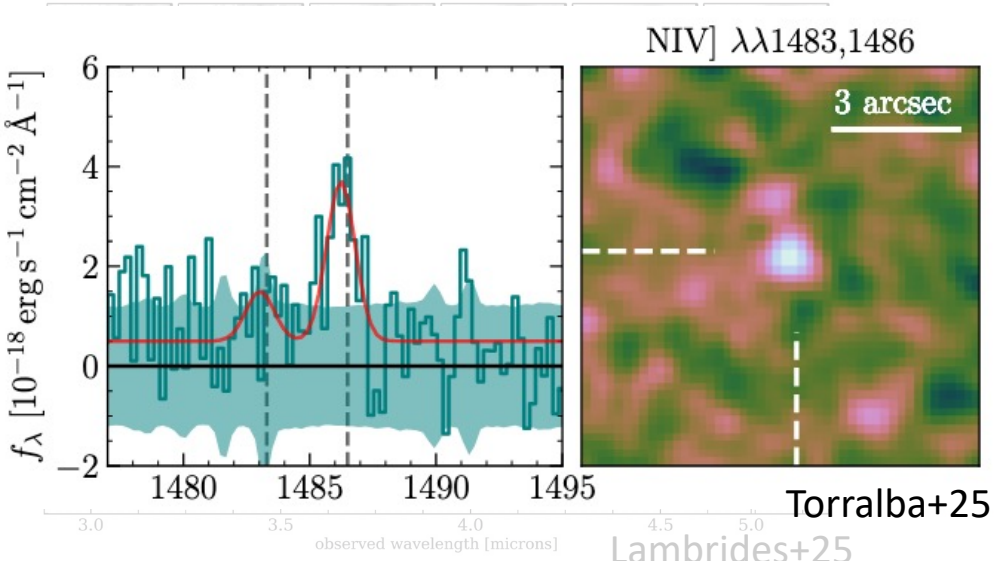
Golubchik+25 (incl. YH)



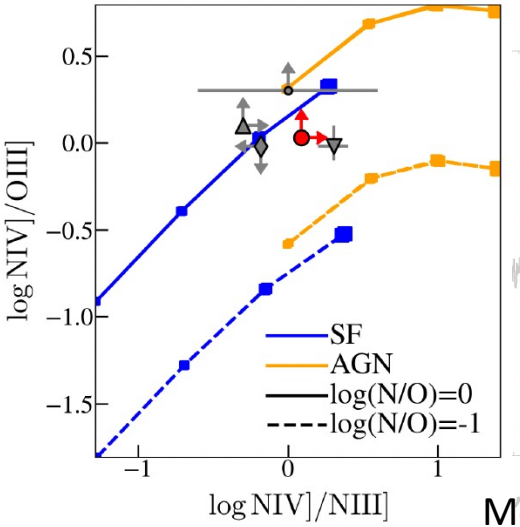
Akins+25

Emission Line Properties

- Narrow iron emission lines are reported in some LRDs
  - QSOs also show iron emission lines but they are broad
- Some LRDs show strong NIV] emission → nitrogen rich



Torralba+25



Morishita+25

Lambrides+25

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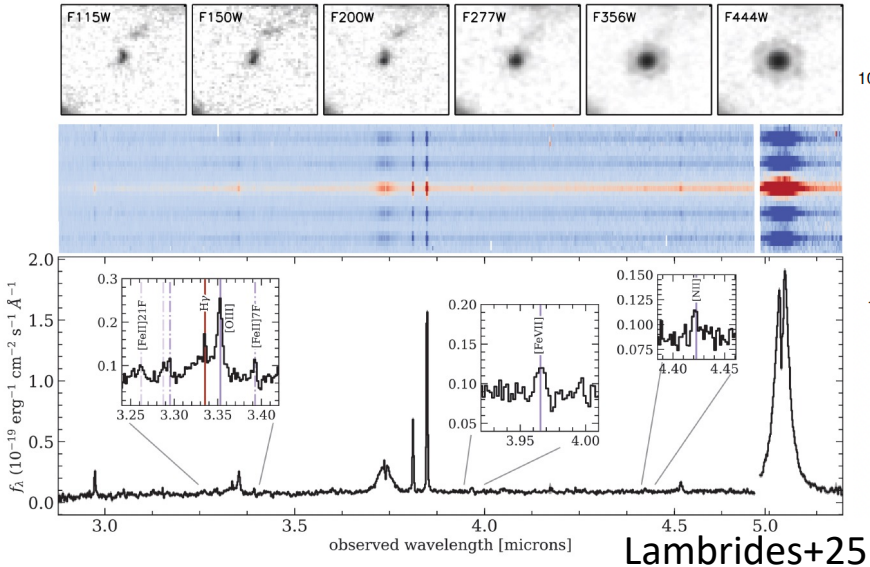
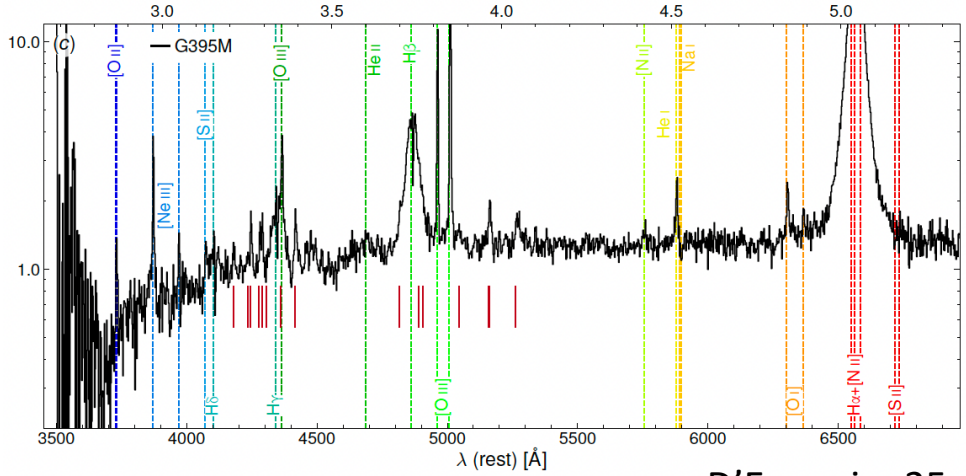


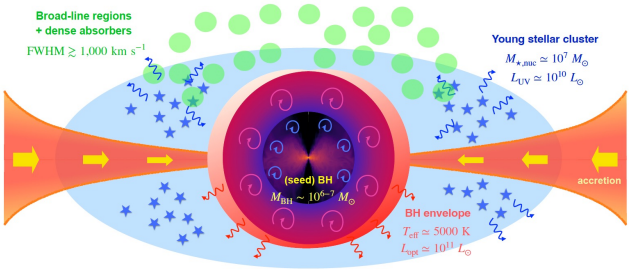
Lambrides+25



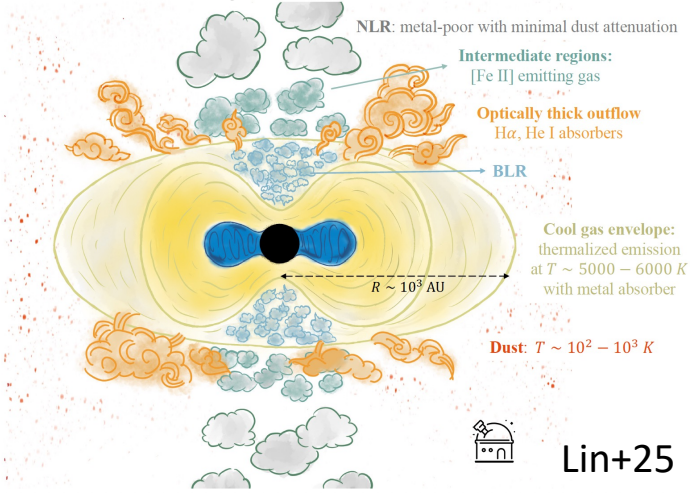
D'Eugenio+25

Mystery 1: Structure of BH*/Envelope

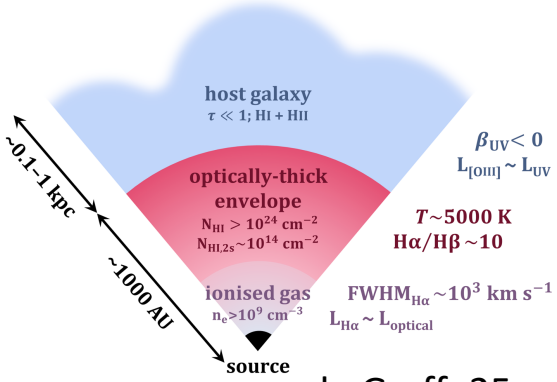
- Where is the broad line region? Outside or inside of the envelope?
  - In partly ionized core? Related to absorption line depth?
- Covering fraction? Almost unity?
  - Most of V-shaped LRDs show broad lines (type-1)
  - How to explain the AGN-like high-ionization emission line in UV?



Inayoshi+25



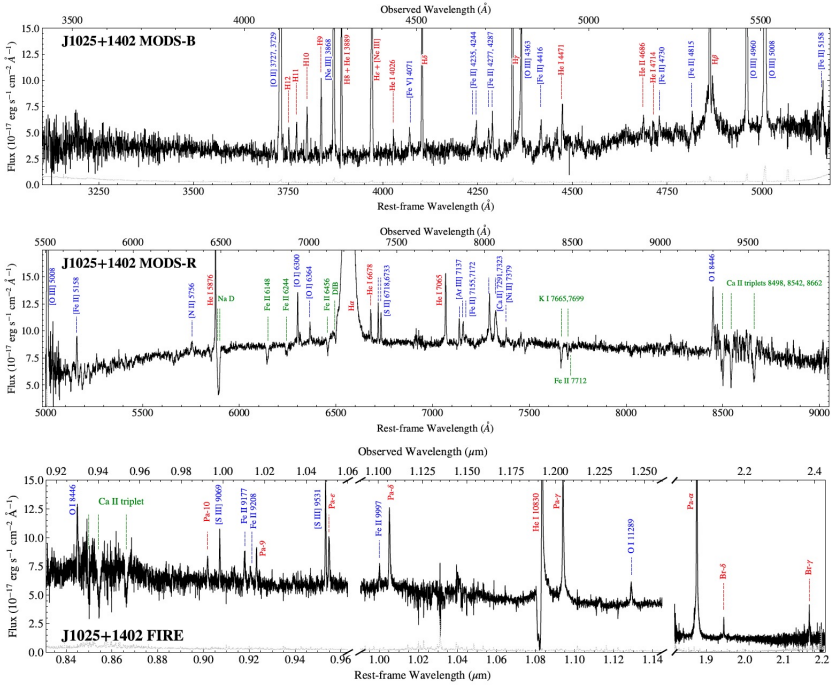
Lin+25

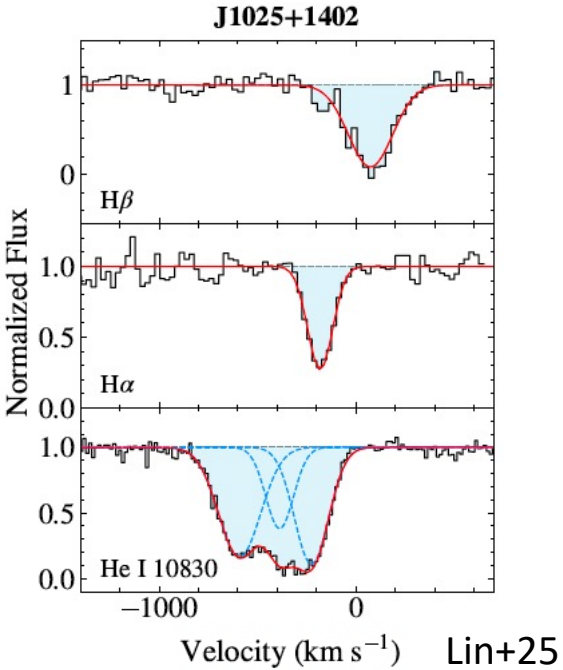


de Graff+25

Mystery 2: Inconsistent Absorption Line Velocities

- Some LRDs show absorption lines in both Hα and Hβ, but their velocities are different with ~100 km/s order. Steep velocity gradient?

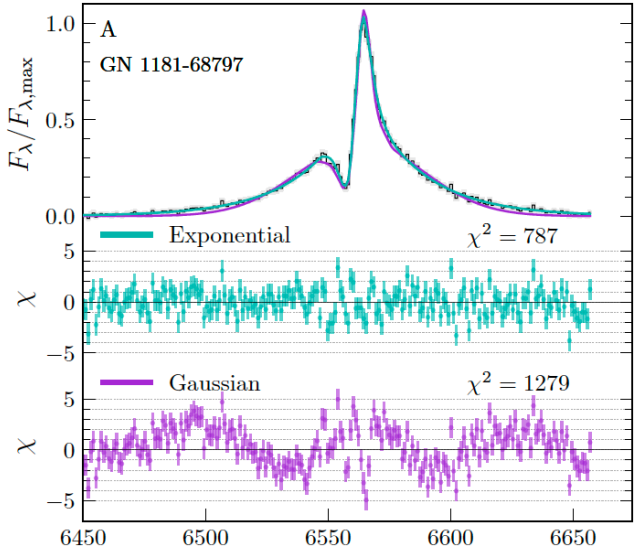




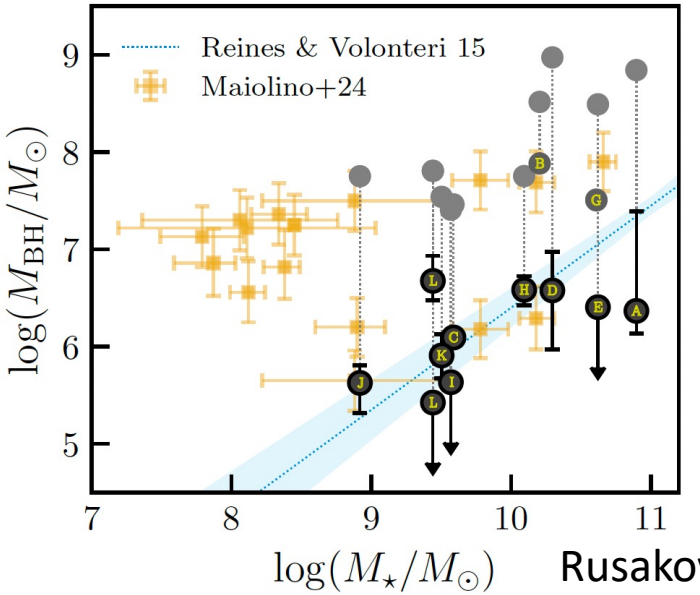
Lin+25

Mystery 3: Black Hole Masses

- Broad lines can be fitted with exponential profile rather than Gaussian
  - Significant electron scattering broadening the Hα lines
  - Black hole masses were overestimated?



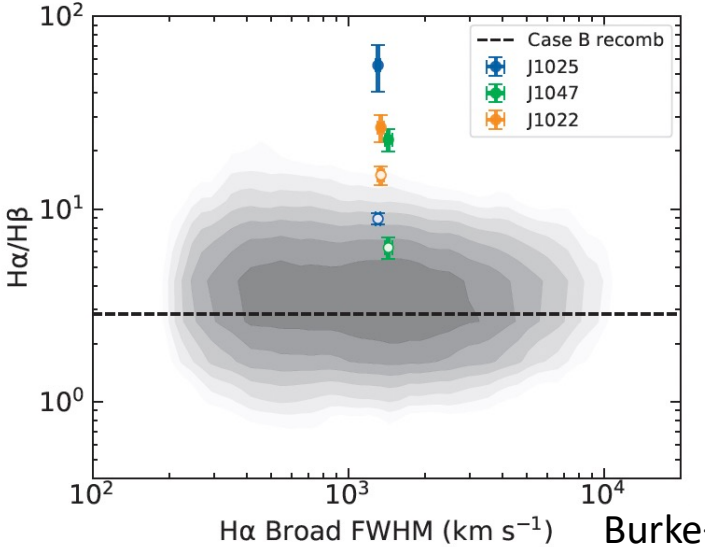
Rusakov+25



Rusakov+25

Mystery 4: Too High Ha/Hb Ratio

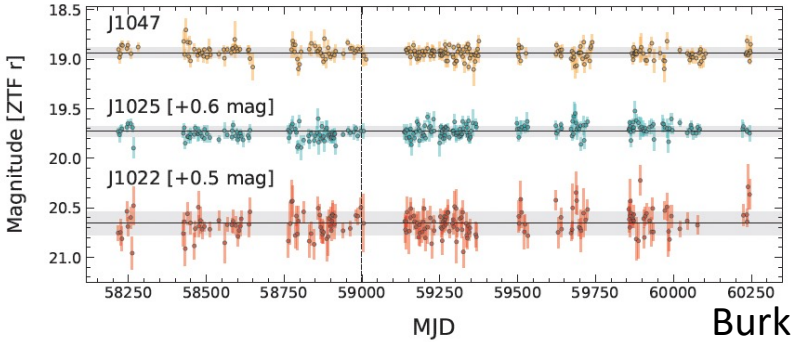
- High Ha/Hb ratios usually due to dust, but no dust detections in LRDs
  - Collisional excitation of Hα?
  - Collational de-excitation of Hβ?
  - Resonant scattering with Hβ → Hα + Paα



Burke+25

Mystery 5: Origin of Time Variability

- Report of year-scale variability in equivalent width
  - Not sure whether broad line or continuum is variable
  - Why no ~50 day-scale variability? (seen in normal AGNs)
  - No variability in 5-year data reported in z~0 LRDs, inconsistent?
- What is the origin of variability?
  - AGN activity from accretion? Pulsation?
  - If Cepheid-like pulsation exists, can we use LRDs as a standard candle?



Burke+25

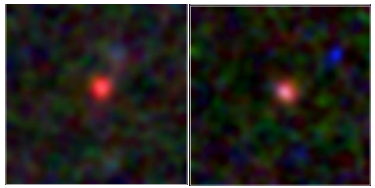
Future Prospects

- Toward the true nature of LRDs
  - Detailed studies of emission/absorption lines may reveal internal structures of BH*/envelope of LRDs
  - Time-domain analysis, with help from gravitational lensing, may give us hints

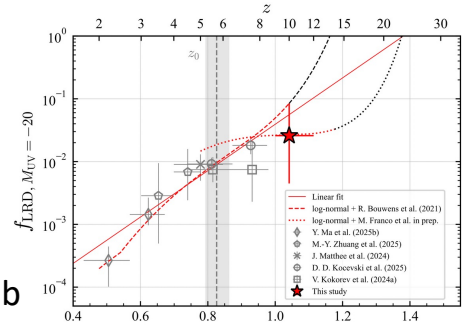
- Toward the origin of the supermassive black holes
  - Search for LRDs at higher redshifts
  - JWST/MIRI observations of z>10 galaxies are key
  - Large systematic uncertainty in current black hole mass estimates of LRDs

Summary

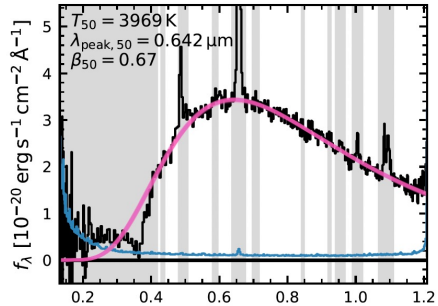
- Little red dots (LRDs): new populations of AGNs discovered by JWST
  - V-shaped SEDs, compact morphologies, and broad hydrogen Balmer lines
  - LRD fraction increases towards higher redshifts
  - Unlike normal AGNs, LRDs are weak in X-ray, dust, and variability
  - LRDs' puzzling properties can be (partly) explained by BH*/envelope models
  - Some LRDs show strong iron or nitrogen emission lines
  - Still many mysteries! Structure, absorption velocities, black hole masses,…



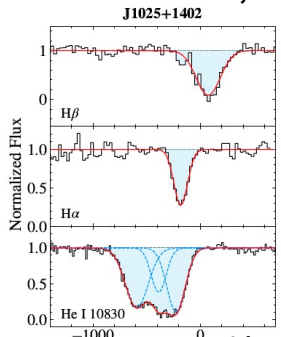
Harikane+23b



Tanaka, Akins, YH+25



de Graaff+25b



Lin+25