

The background of the slide is a deep space image showing a complex network of galaxy filaments and clusters. The filaments are primarily blue and purple, with some reddish-brown areas, set against a dark, star-filled background. The overall appearance is that of a large-scale cosmic structure, possibly a galaxy cluster or a filament of the cosmic web.

The Emergence of the First Massive Black Holes

Kohei Inayoshi

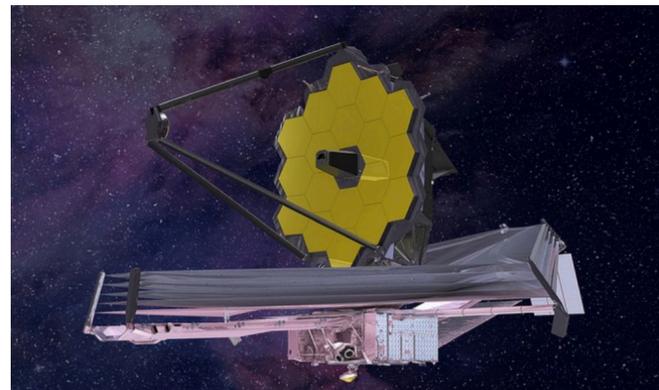
**Peking University
Kavli Institute for Astronomy & Astrophysics**

YKIS2026a @YITP

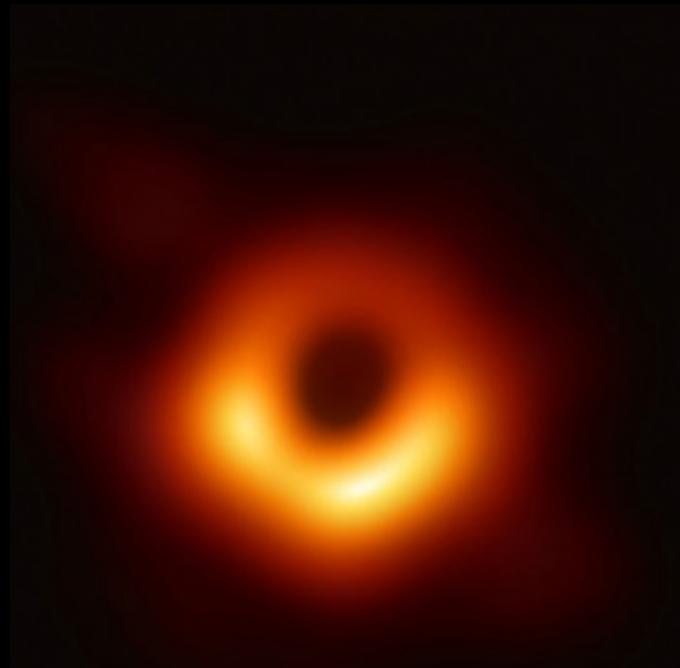
Outline

1. Overviews
2. A new AGN population, LRDs
3. LRDs = Gas-enshrouded AGNs
4. Future perspectives

1. Overviews



Supermassive Black Holes (SMBH)

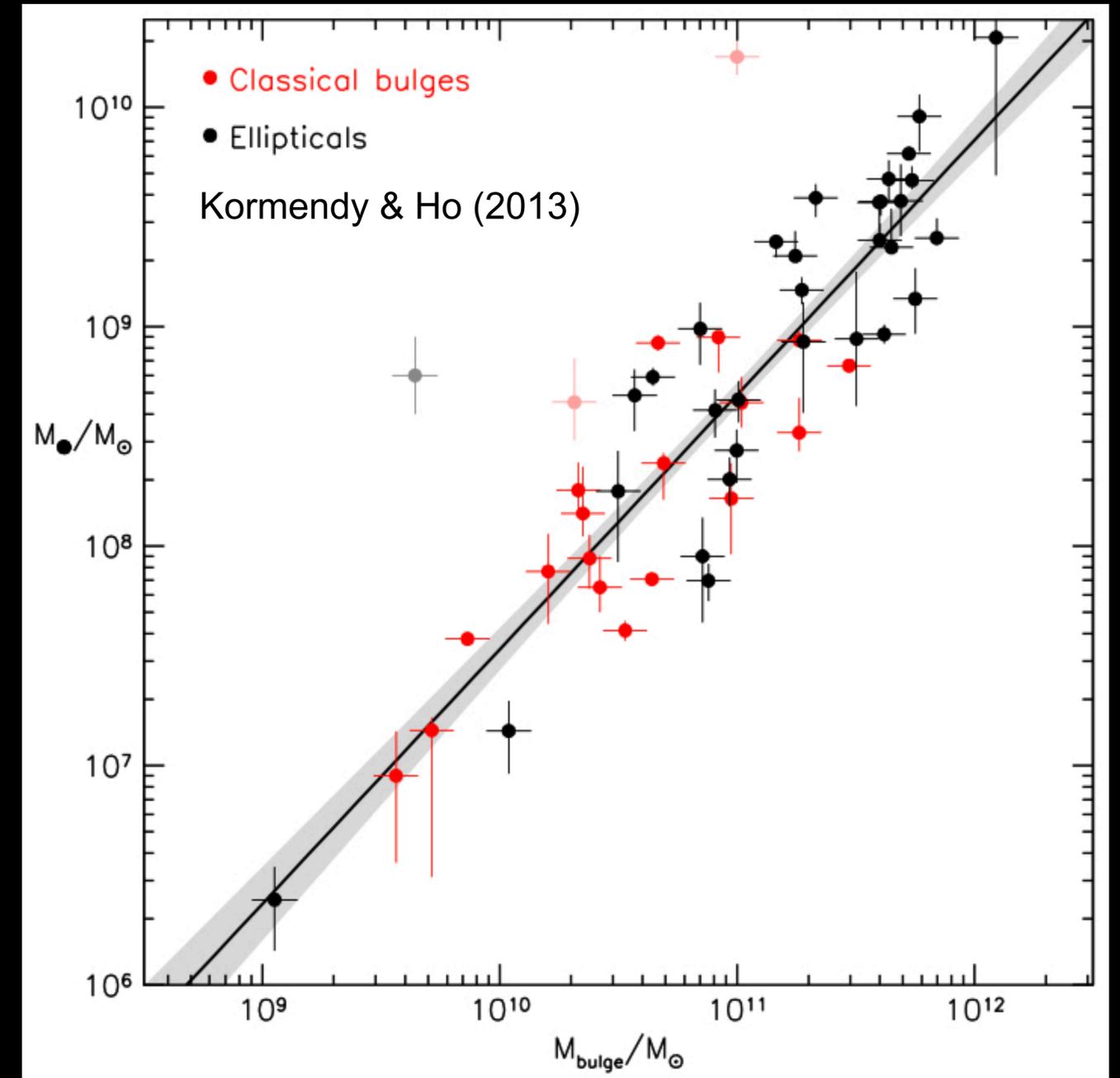


https://en.wikipedia.org/wiki/Messier_87



artist's illustration [ESA/Hubble, L. Calçada (ESO)]

Black Hole mass



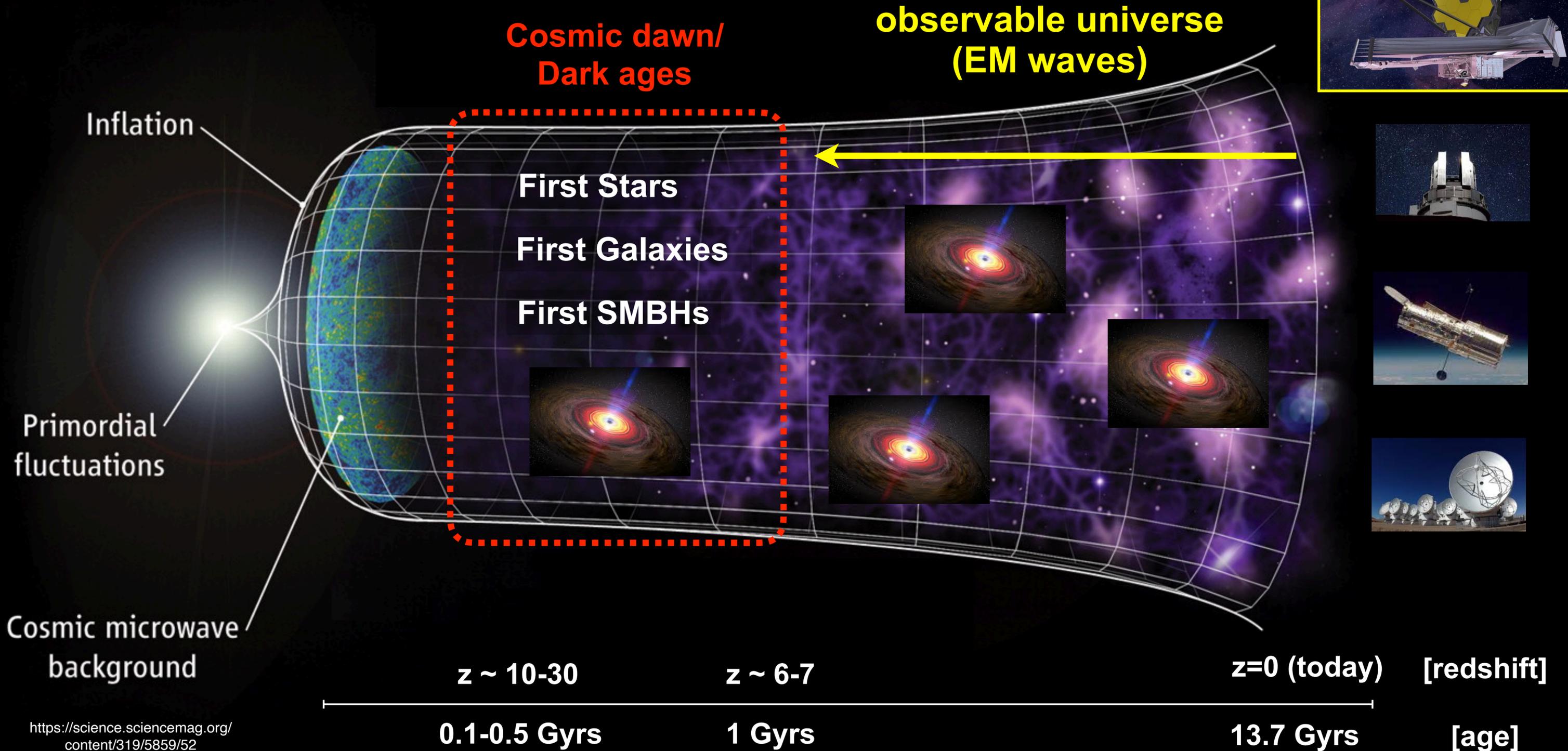
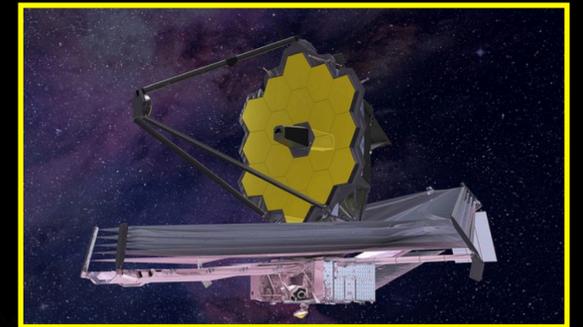
Galaxy mass

Key questions:

- 1) What is the origin of SMBHs?
- 2) How did BHs and galaxies interact?
- 3) Cosmological coevolution & high-z?

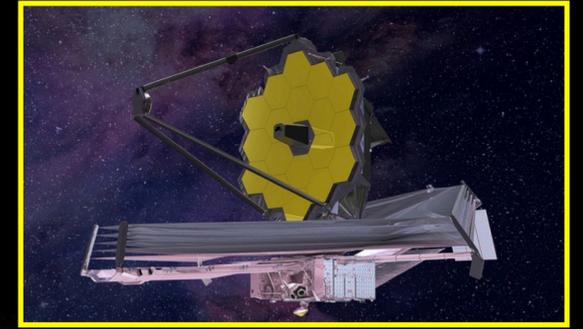
History of the Universe

JWST

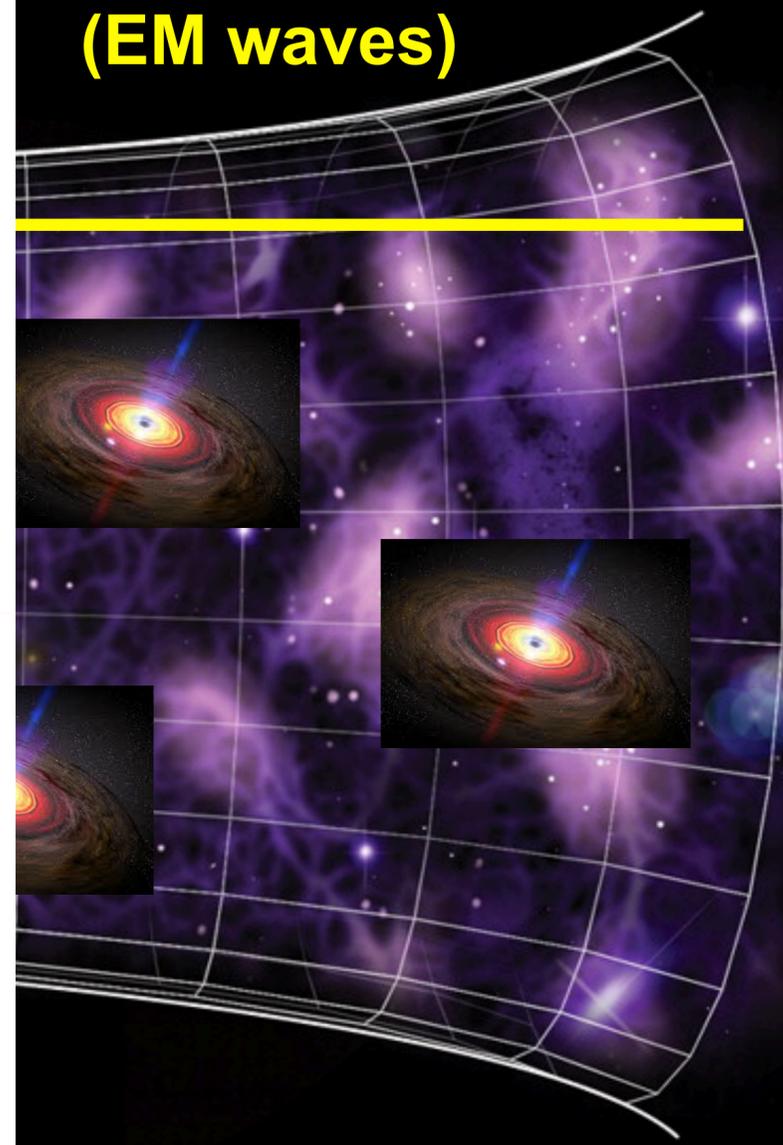
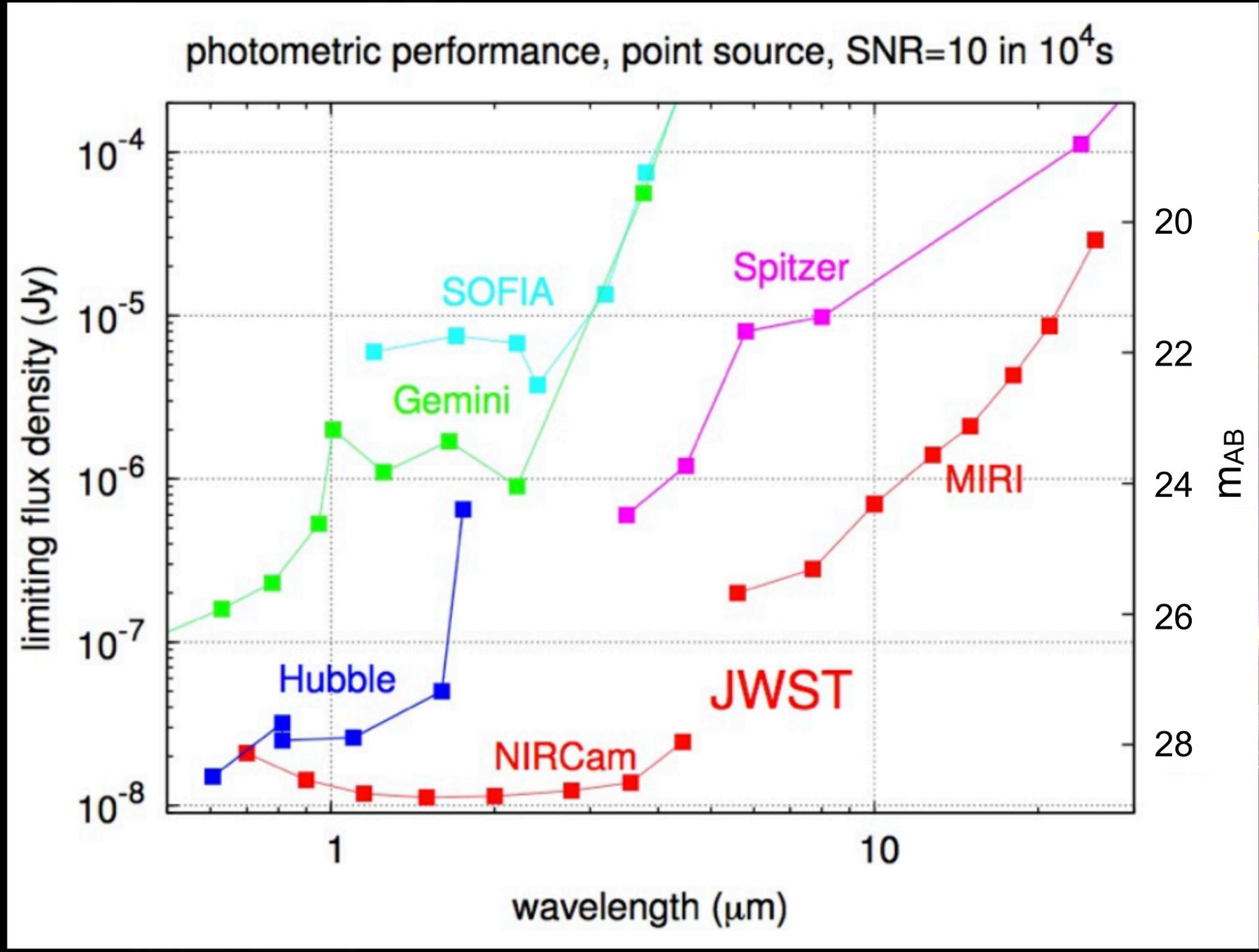


History of the Universe

JWST



**servable universe
(EM waves)**



z=0 (today)

[redshift]

13.7 Gyrs

[age]

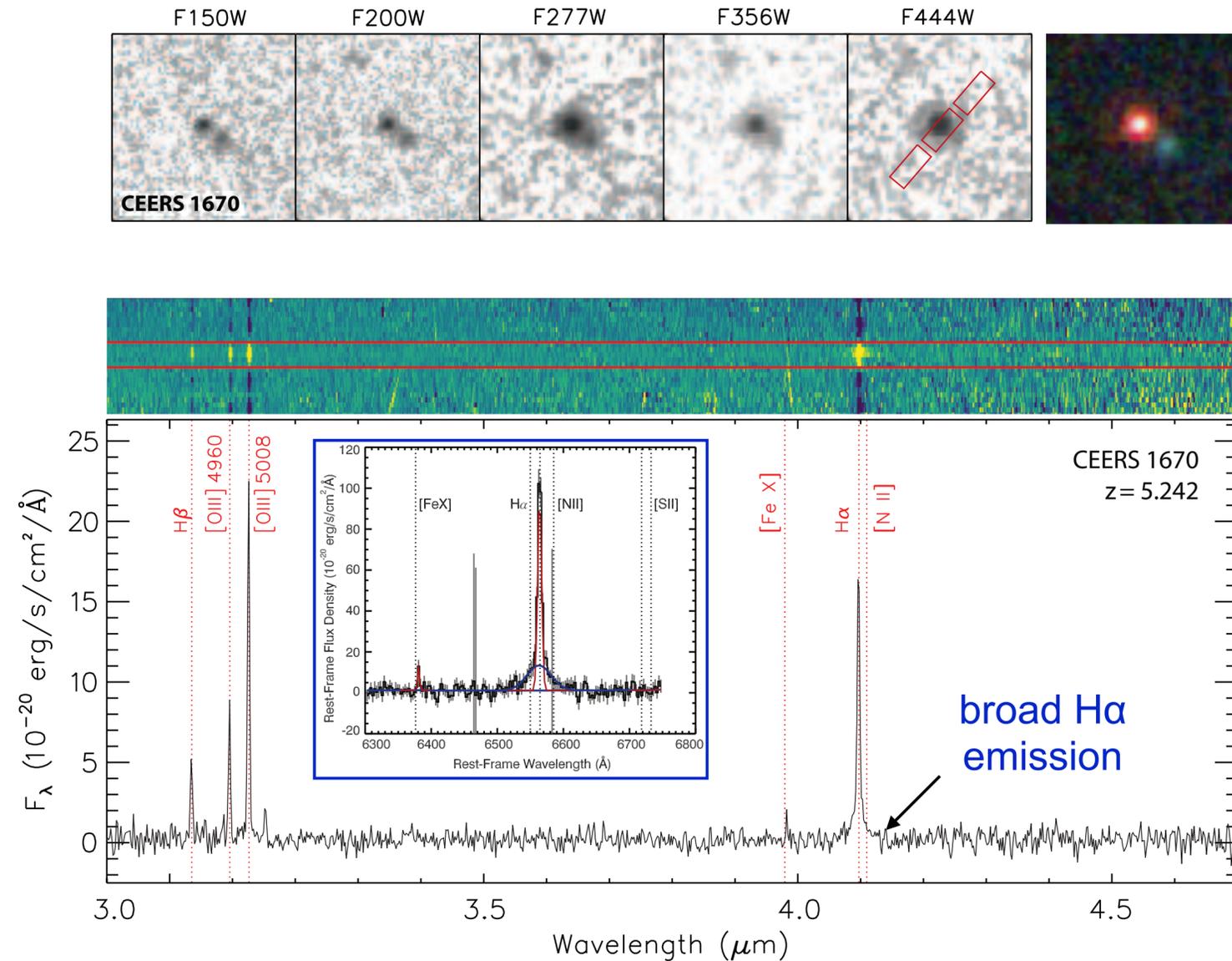
0.1-0.5 Gyrs

1 Gyrs

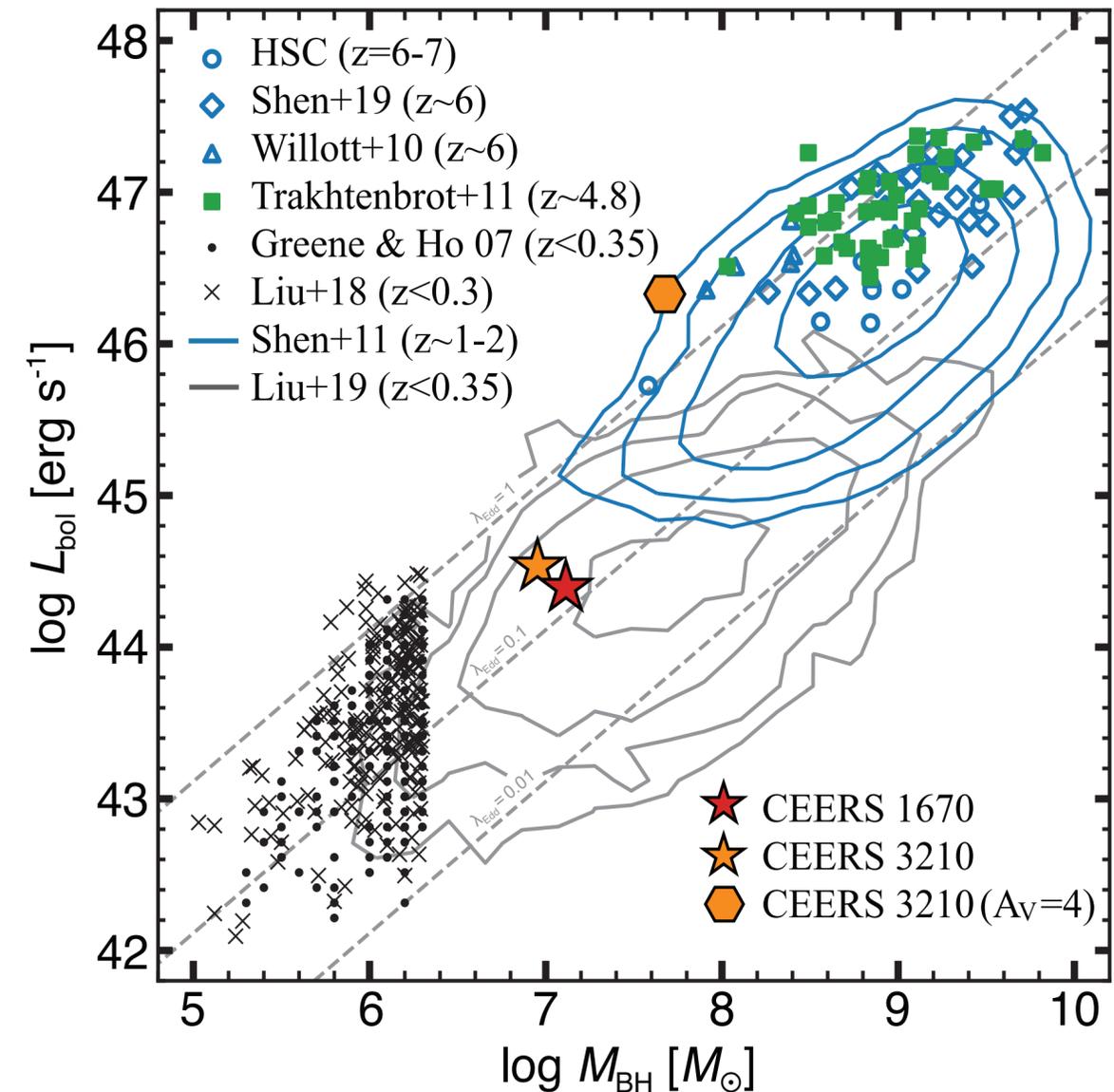
<https://science.sciencemag.org/content/319/5859/52>

Hidden little monsters uncovered by JWST

- A Candidate for the Least-massive Black Hole in the First 1.1 Billion Years of the Universe
- Hidden Little Monsters: Spectroscopic Identification of Low-Mass, Broad-Line AGN at $z > 5$ with CEERS



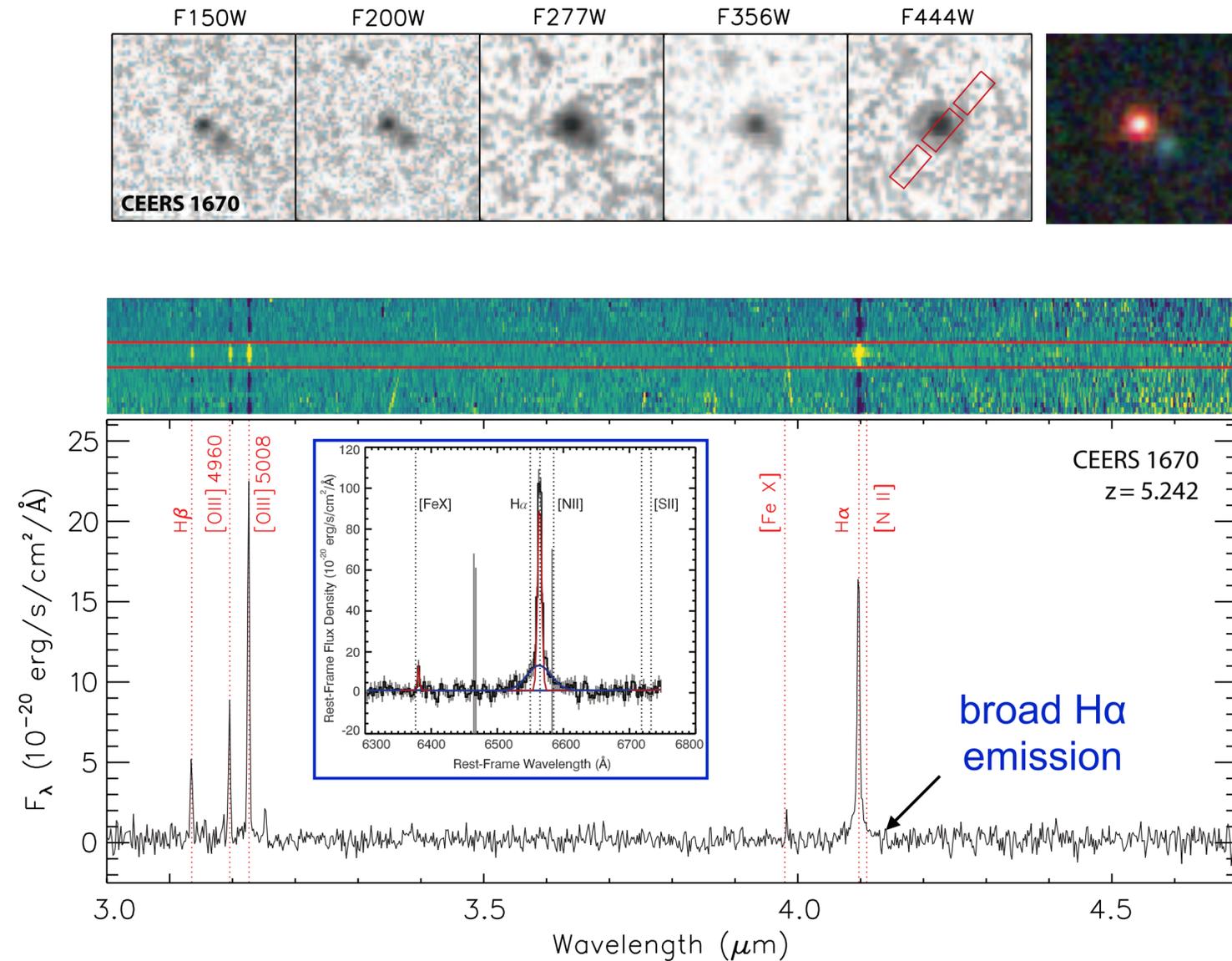
Onoue, KI, Ding+ 2023, Kocevski, Onoue, KI+ 2023



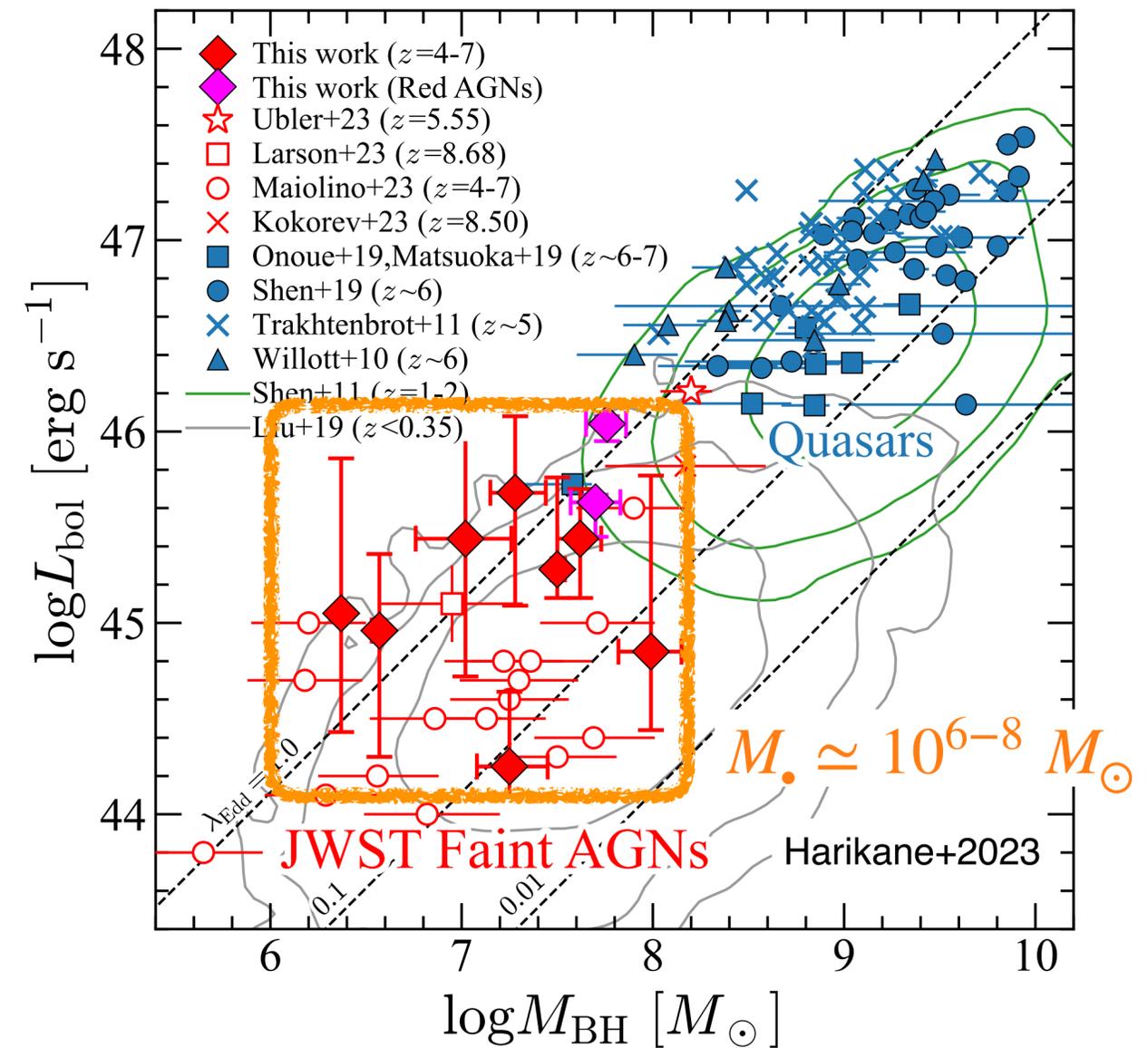
See also Übler+2023, Maiolino+2024, Matthee+2024, Greene+2024

Hidden little monsters uncovered by JWST

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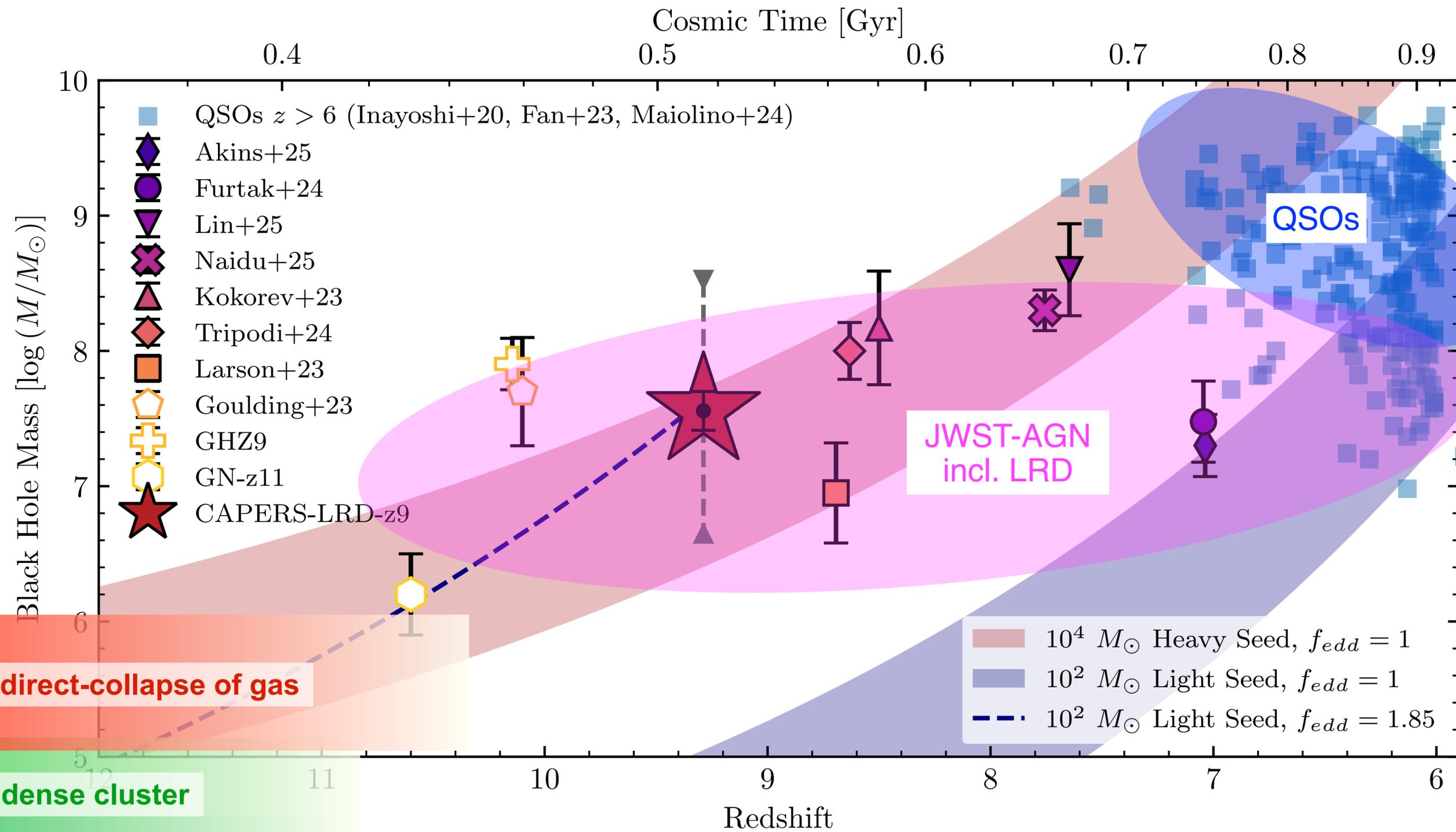


Onoue, KI, Ding+ 2023, Kocevski, Onoue, KI+ 2023



See also Übler+2023, Maiolino+2024, Matthee+2024, Greene+2024

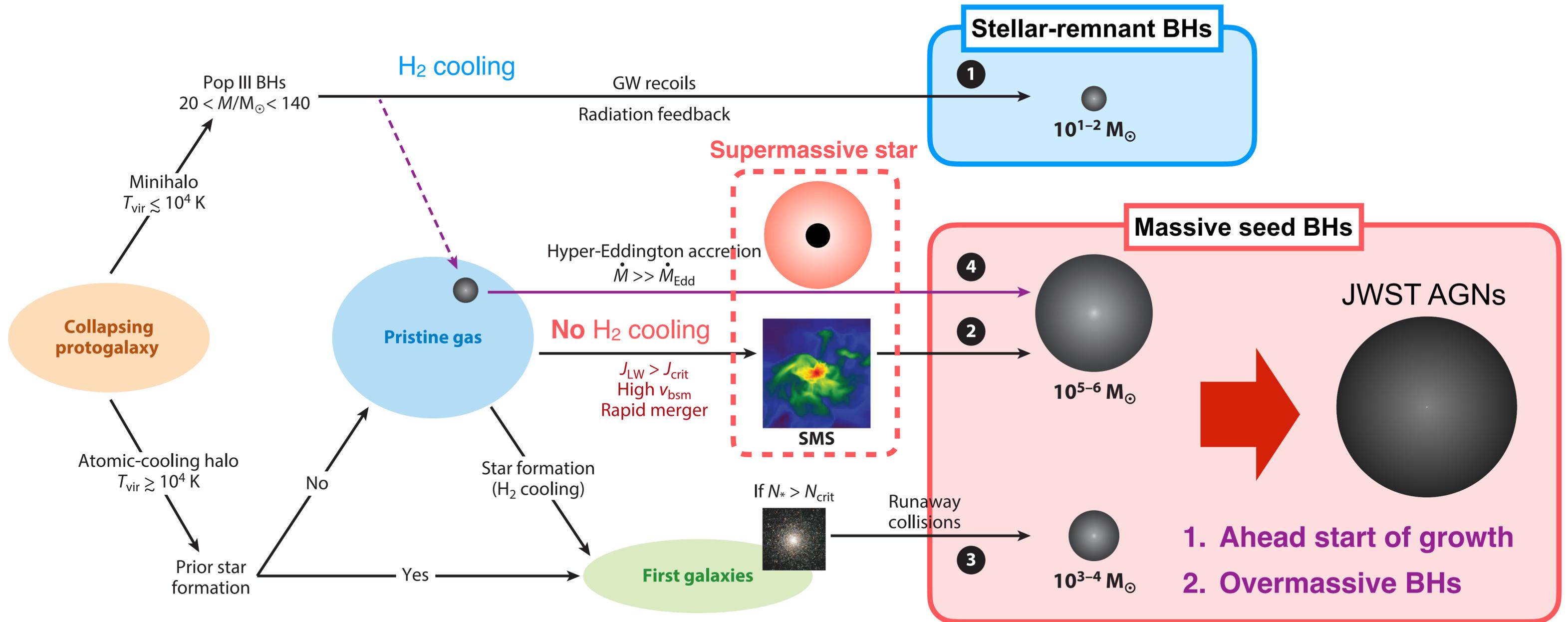
High-z SMBH population



Taylor+2025b

Formation channels of early BHs

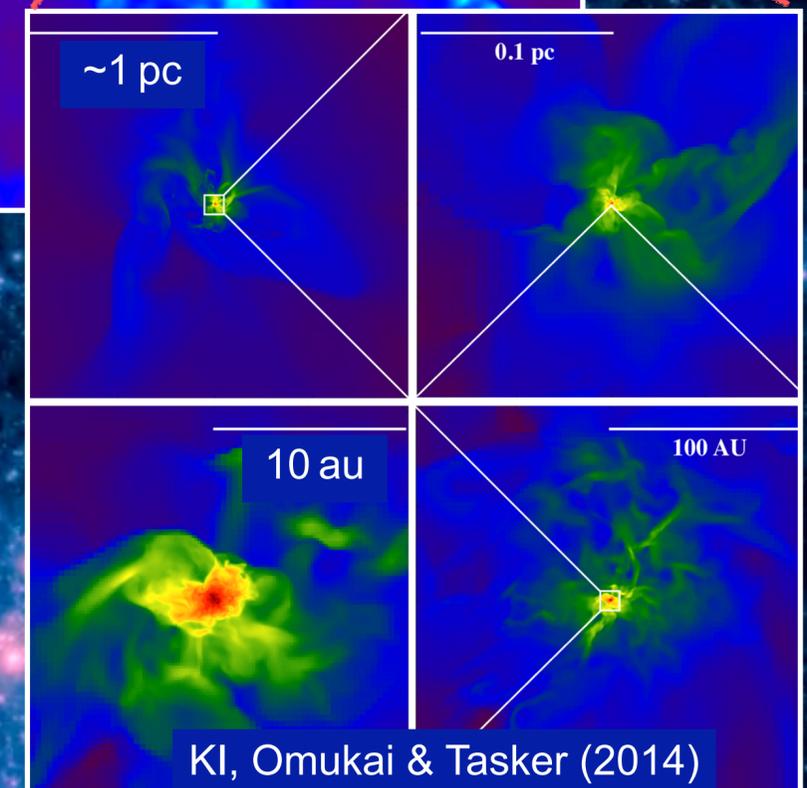
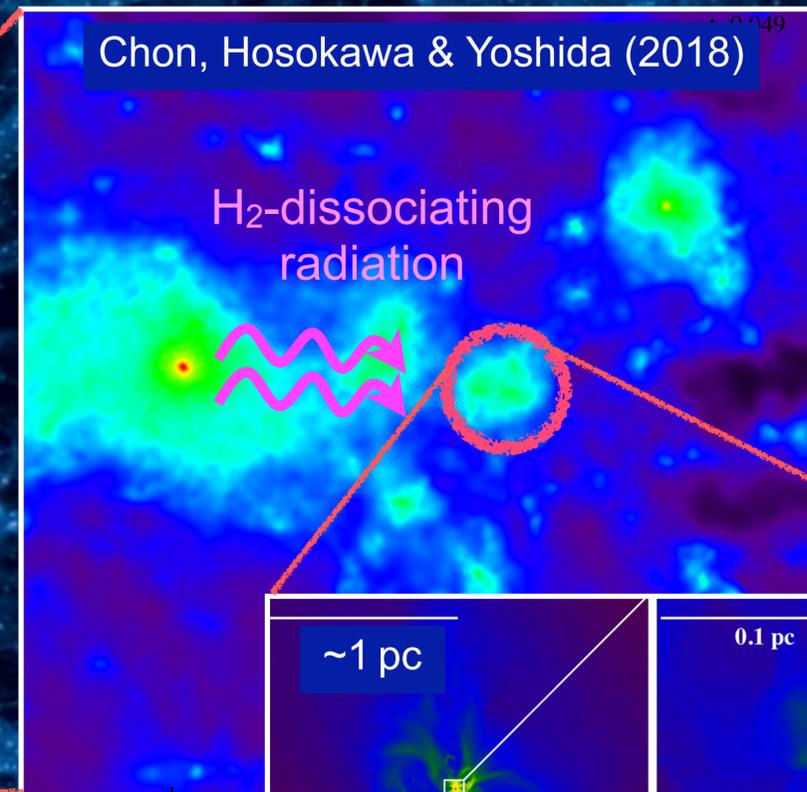
Various masses of seed BHs depending on SF environments (the “up-to-date” Rees diagram)



Seed BH mass function @high-z

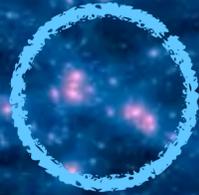
Progenitors of quasar hosts
overdense ($>4\sigma$) rare regions
stronger UV & more mergers
(W.Li et al. 2021, Lupi et al. 2021)

Typical protogalaxies
common ($\sim 2\sigma$) regions
(Ahn et al. 2009, Dijkstra et al. 2008, 2014)

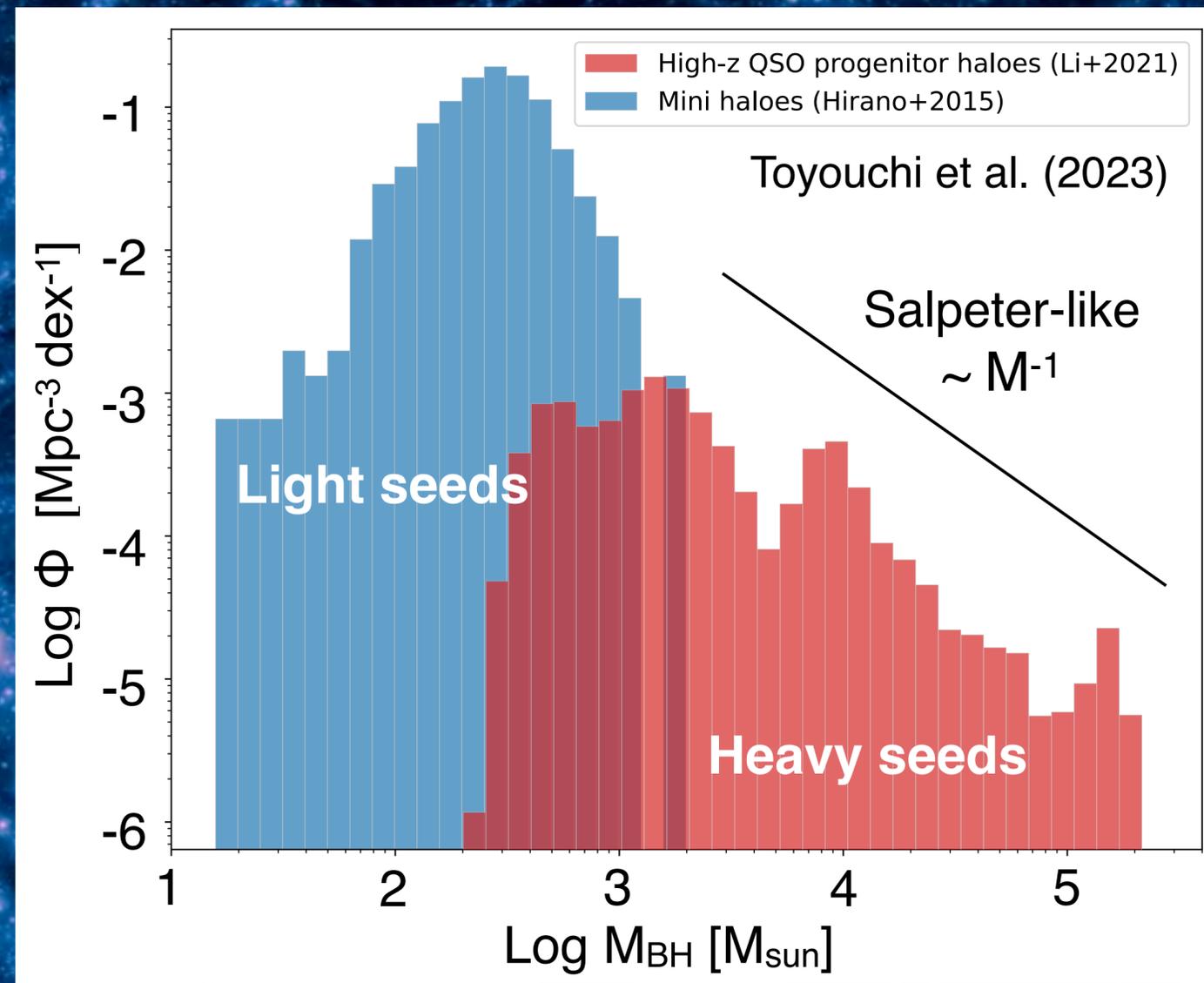


Seed BH mass function @high-z

Progenitors of quasar hosts
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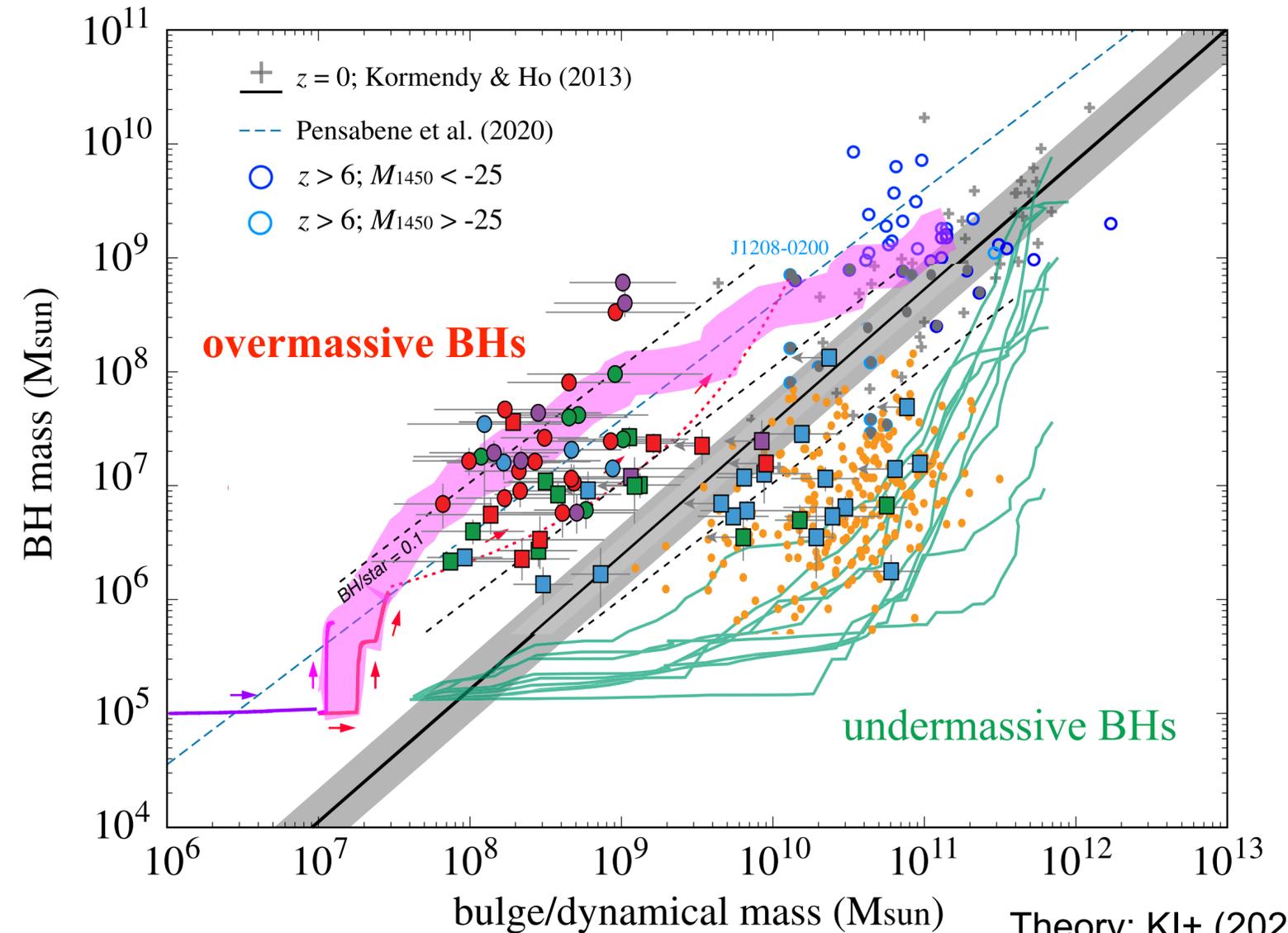
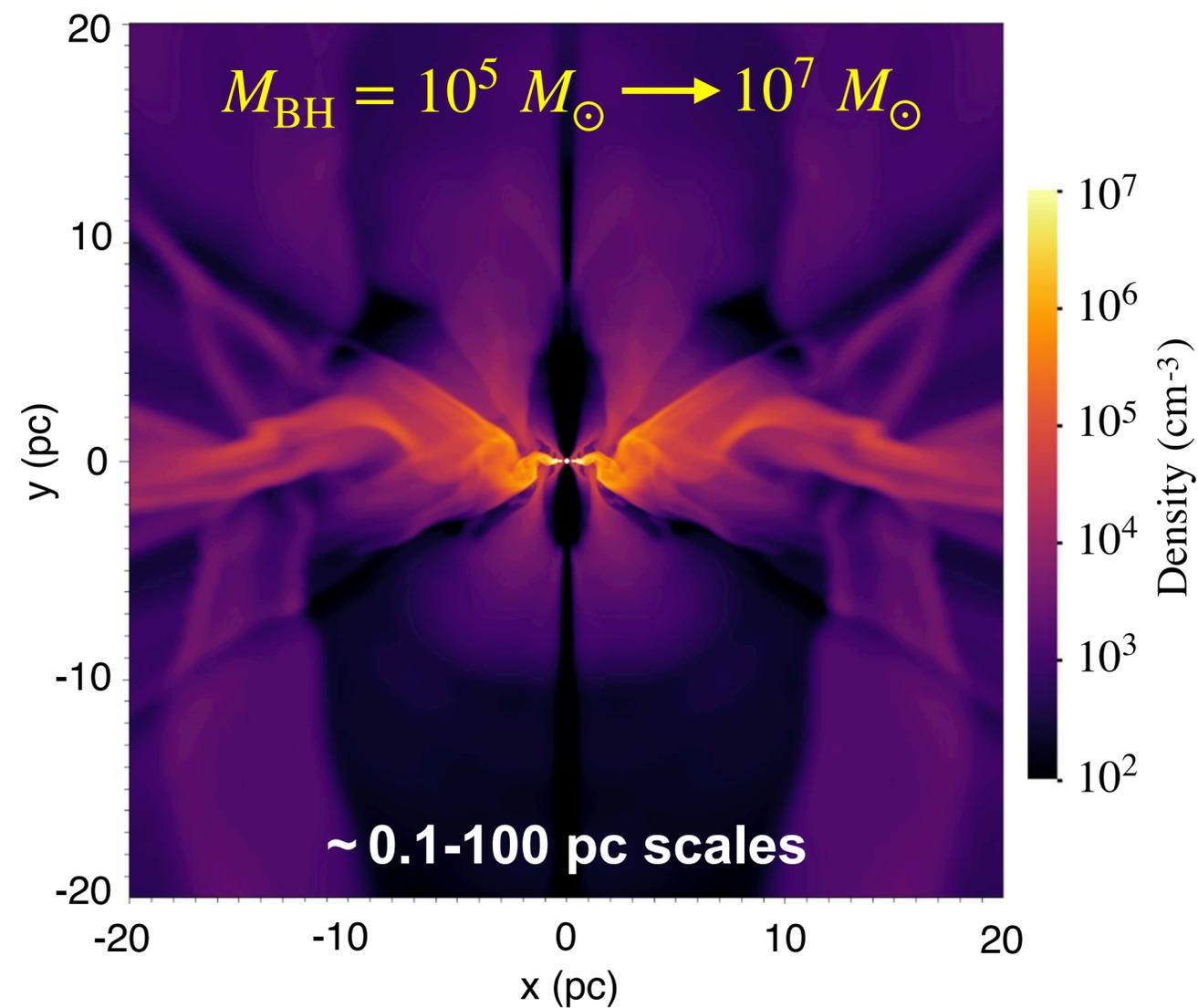
Typical protogalaxies
common ($\sim 2\sigma$) regions
(Ahn et al. 2009, Dijkstra et al. 2008, 2014)



Overmassive BH via rapid growth

Rapid BH growth in **dense environments after their seeding**

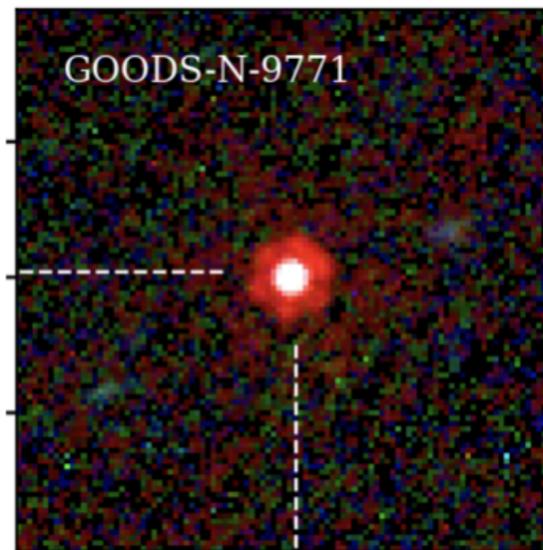
(KI, Haiman & Ostriker 2016, Pacucci+2016, Lupi+2016, Takeo+2020, Shi+2023, Sassano+2023, Massonneau+2023)



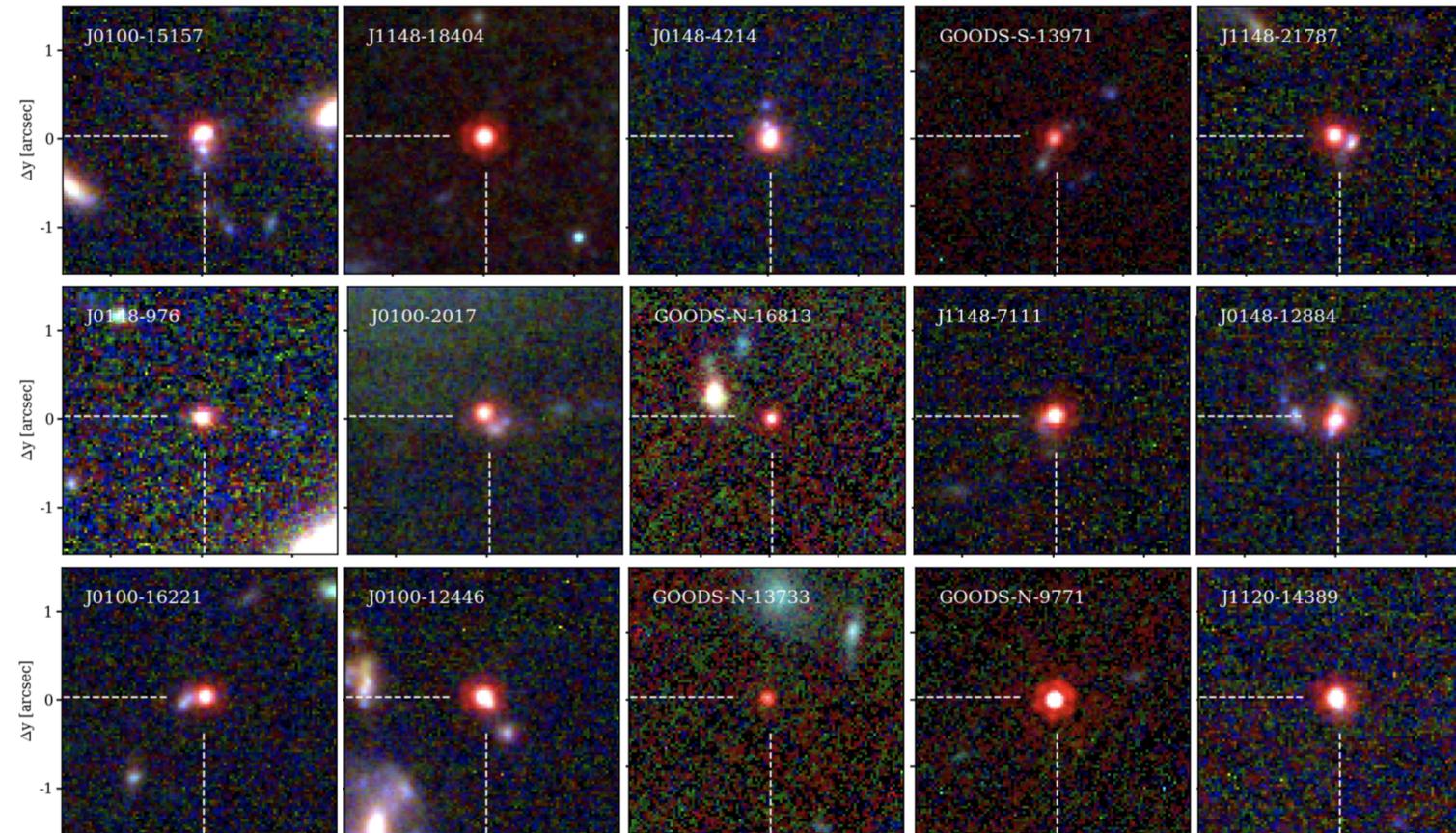
Theory: KI+ (2022a)
Data: Jones+ (2025)

Transient **hyper-Eddington** episodes drive overmassive BHs

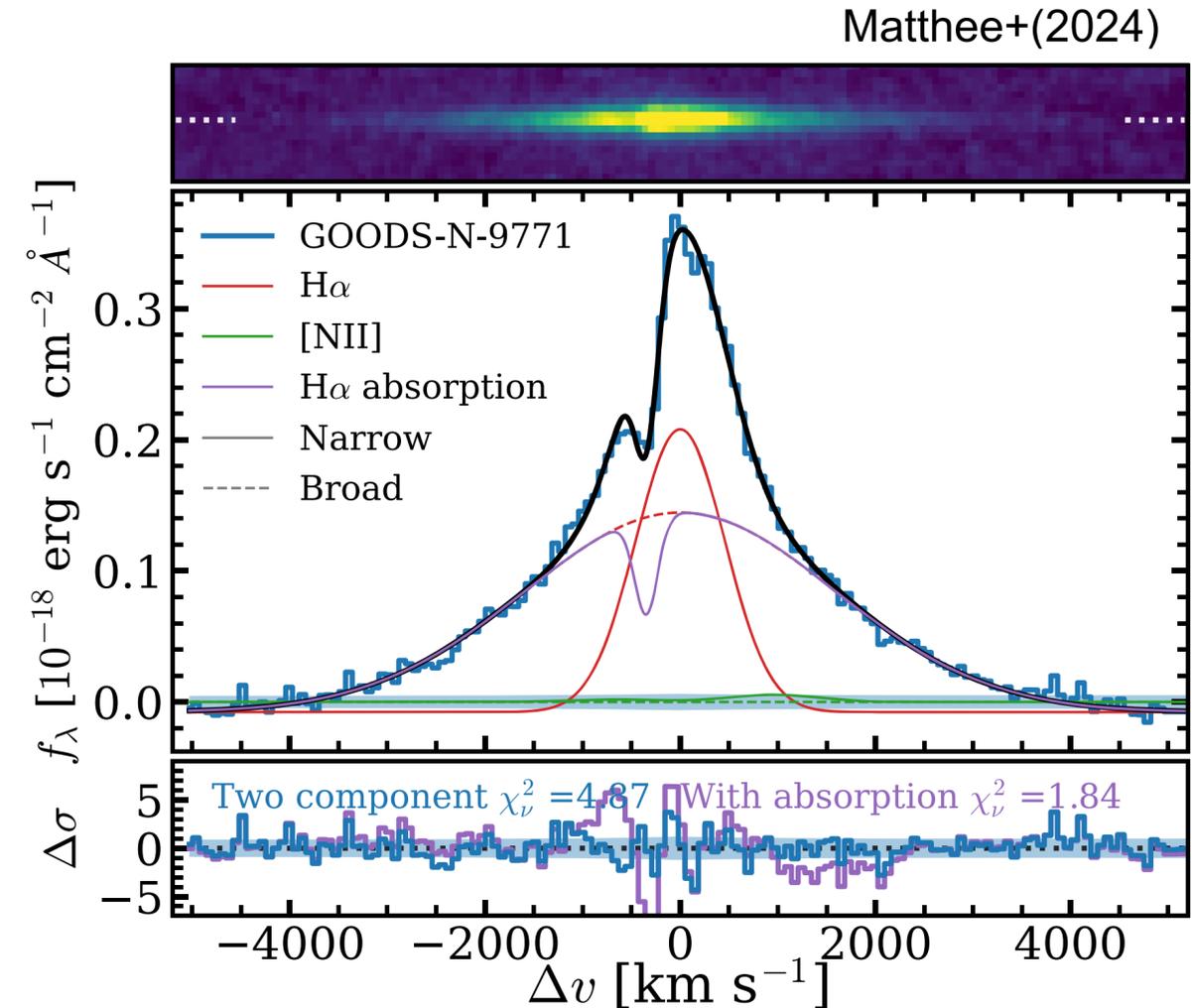
2. A new AGN population “Little Red Dots”



Little Red Dots (LRDs)



- Very compact & red sources (in JWST NIRC2)
- High redshift, abundant but transient populations
- **Broad-component** of Balmer lines (H α /H β)
- Common Balmer **absorption** (>20% of JWST AGN)



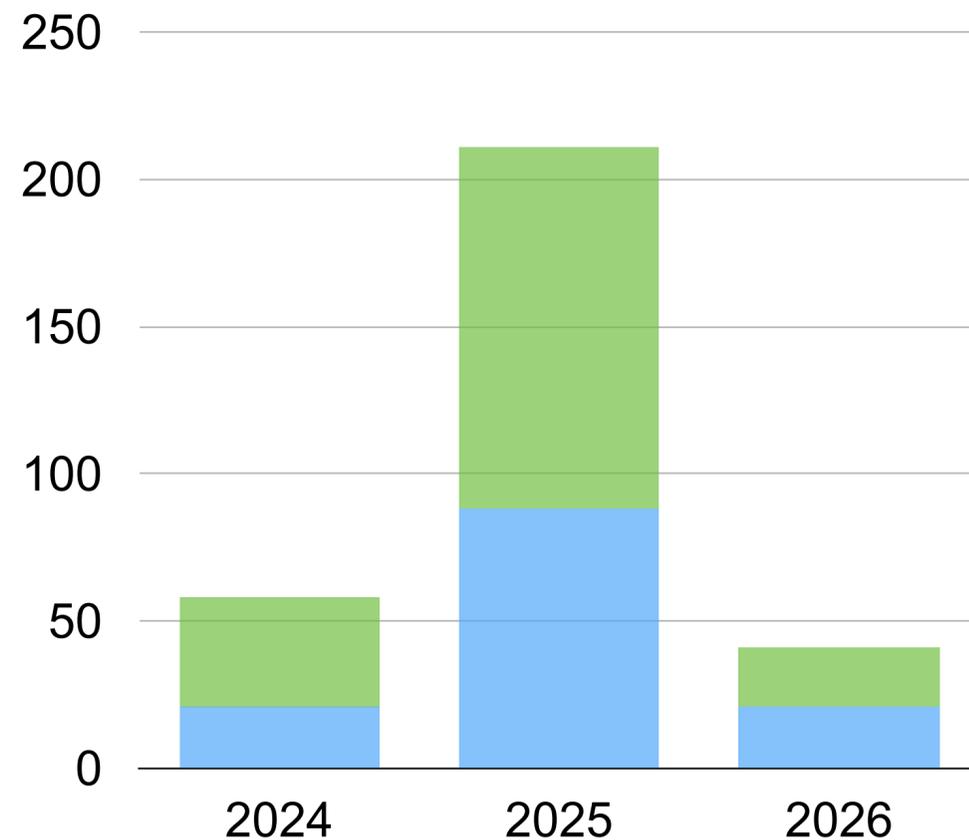
Kocevski+23,24, Labbe+24,25, Furtak+23, Noborigushi+23, Harikane+23, Maiolino+23, Barro+24, Killi+24, Greene+24, B.Wang+24a,b, Kokorev+24, Akins+24, Baggen+24, Casey+24, X.Lin+24,25a,b, Setton+24,25, Taylor+25a,b, Y.Ma+25a,b, Kokubo & Harikane 24, X.Ji+25, Z.Zhang+25, C.Chen+25a,b

many more others! sorry, if your studies are missed here.

Extremely popular objects...

~240 papers/yr (2025-26)

~1 paper per arXiv day



- An extremely overheated topic
- hard to follow all relevant papers

1. [arXiv:2512.13957](#) [pdf, ps, other] [astro-ph.GA](#)

From ASTRID to BRAHMA -- The role of overmassive black holes in little red dots in cosmological simulations

Authors: Patrick LaChance, Aklant Kumar Bhowmick, Rupert A. C. Croft, Tiziana Di Matteo, Yihao Zhou, Fabio Pacucci, Laura Blecha, Paul Torrey, Yueying Ni, Nianyi Chen, Simeon Bird

Submitted 15 December, 2025; originally announced December 2025.

Comments: 13 pages, 7 figures

2. [arXiv:2512.05180](#) [pdf, ps, other] [astro-ph.GA](#)

Little red dot variability over a century reveals black hole envelope via a giant Einstein cross

Authors: Zijian Zhang, Mingyu Li, Masamune Oguri, Xiaojing Lin, Kohei Inayoshi, Catherine Cerny, Dan Coe, Jose M. Diego, Seiji Fujimoto, Linhua Jiang, Guillaume Mahler, Jorjy Matthee, Rohan P. Naidu, Keren Sharon, Yue Shen, Adi Zitrin, Abdurro'uf, Hollis Akins, Joseph F. V. Allingham, Ricardo Amorín, Yoshihisa Asada, Hakim Atek, Franz E. Bauer, Maruša Bradač, Larry D. Bradley, et al. (57 additional authors not shown)

Submitted 4 December, 2025; originally announced December 2025.

Comments: 59 pages, 13 figures, 3 tables, submitted to a peer-reviewed journal; comments are welcome

3. [arXiv:2512.05097](#) [pdf, ps, other] [astro-ph.GA](#)

Highly-ionized gas in lensed $z = 6.027$ Little Red Dot seen through [OIII] $88\mu\text{m}$ with ALMA

Authors: Kirsten K. Knudsen, Johan Richard, Mathilde Jauzac, Tom J. L. C. Bakx, Thiago S. Goncalves, Eiichi Egami, Kiana Kade, Rahul Rana, Laura Sommovigo, Flora Stanley, Daniel P. Stark

Submitted 4 December, 2025; originally announced December 2025.

Comments: Submitted to A&A

4. [arXiv:2512.04208](#) [pdf, ps, other] [astro-ph.GA](#)

A Black-Hole Envelope Interpretation for Cosmological Demographics of Little Red Dots

A Critical Evaluation of the Physical Nature of the Little Red Dots

KOHEI INAYOSHI ¹ AND LUIS C. HO ^{1,2}

¹*Kavli Institute for Astronomy and Astrophysics, Peking University, Beijing 100871, China*

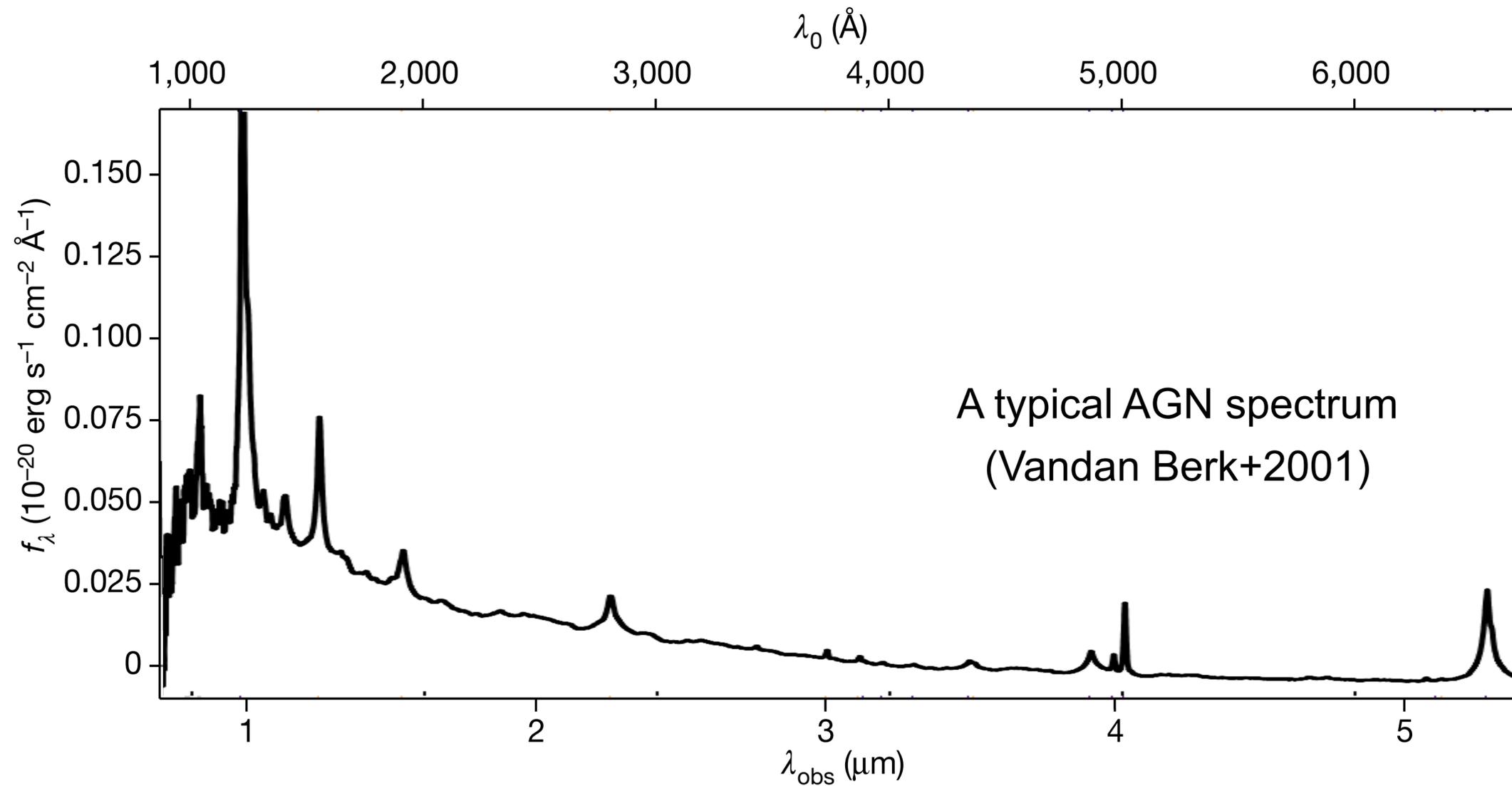
²*Department of Astronomy, School of Physics, Peking University, Beijing 100871, China*

ABSTRACT

Little Red Dots (LRDs) are a newly identified class of active galactic nuclei (AGNs) uncovered by JWST deep surveys. Their enigmatic properties challenge the canonical AGN paradigm and have stimulated numerous ideas on the early formation and growth mechanisms of massive black holes (BHs). In this review, we summarize how early BHs can shape the characteristic features of LRDs, how their nuclear environments differ from those of normal AGNs, and how future observations can distinguish between competing scenarios (AGN or stellar origins). Our main conclusions are as follows:

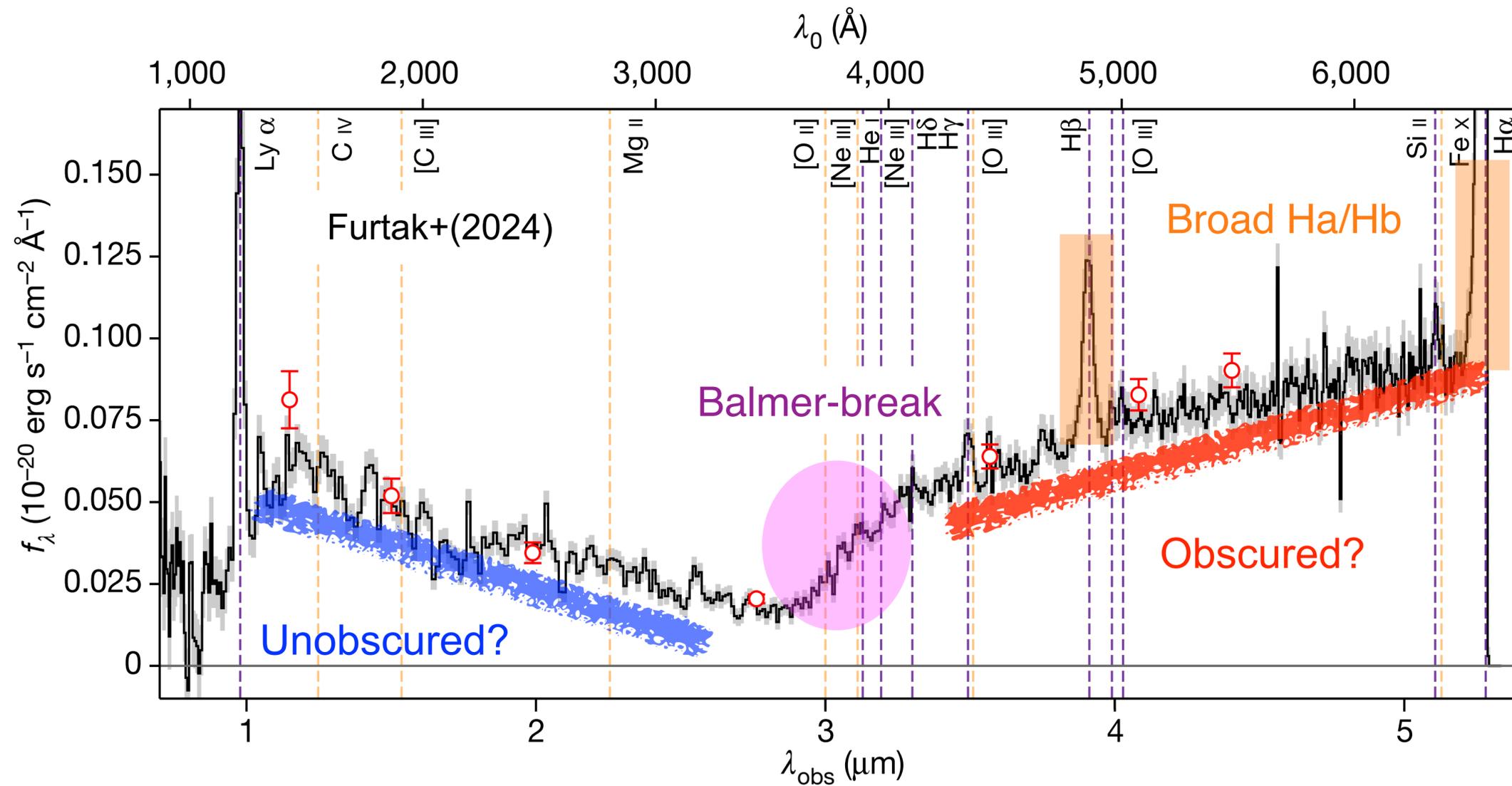
The first LRD review paper

Characteristic v-shape SEDs



- Two-component scenario (e.g., **unobscured galaxy** + **obscured AGN**)
- **Balmer-break** like feature observed in some LRDs

Characteristic v-shape SEDs

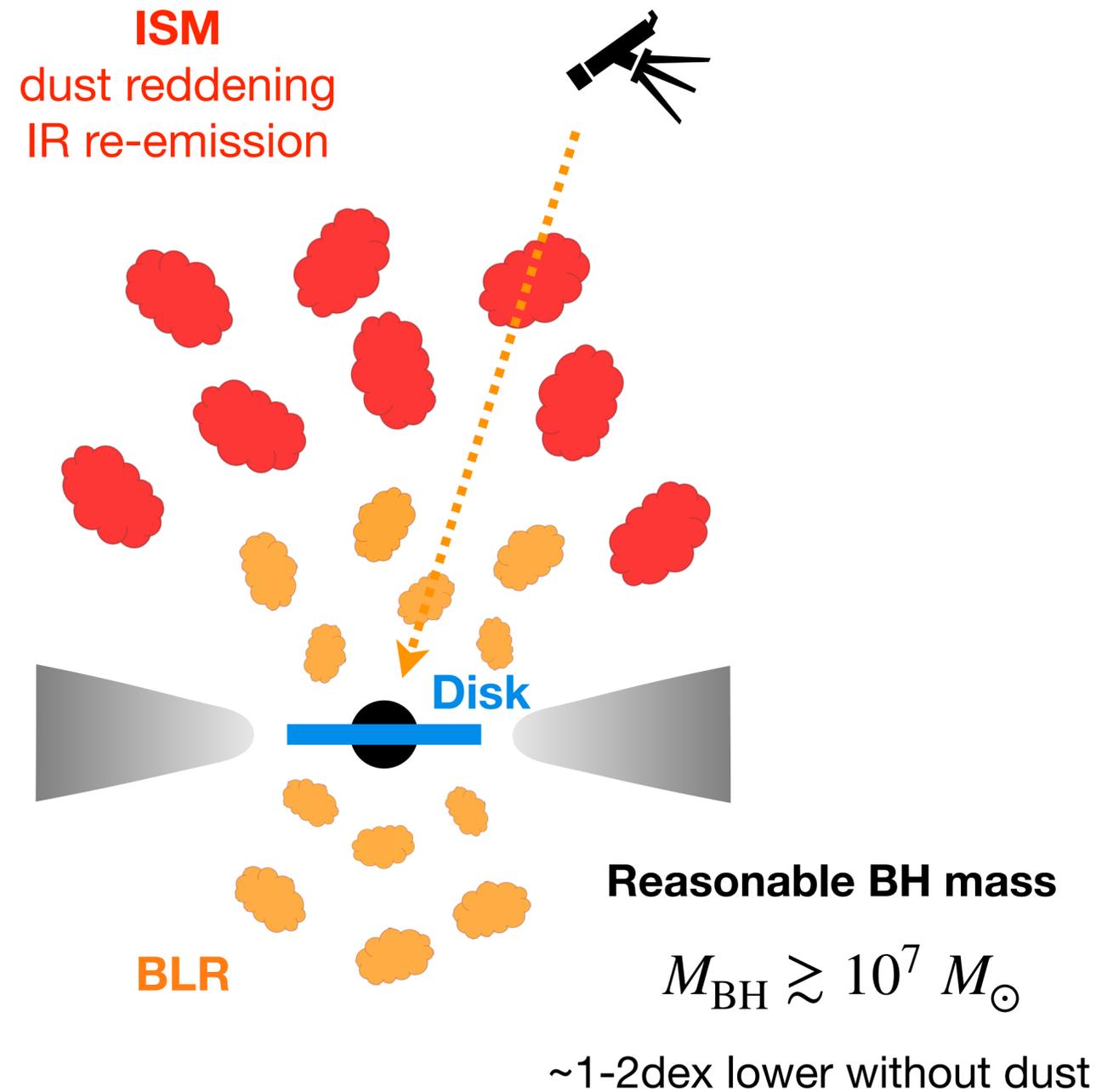


- Two-component scenario (e.g., **unobscured galaxy** + **obscured AGN**)
- **Balmer-break** like feature observed in some LRDs

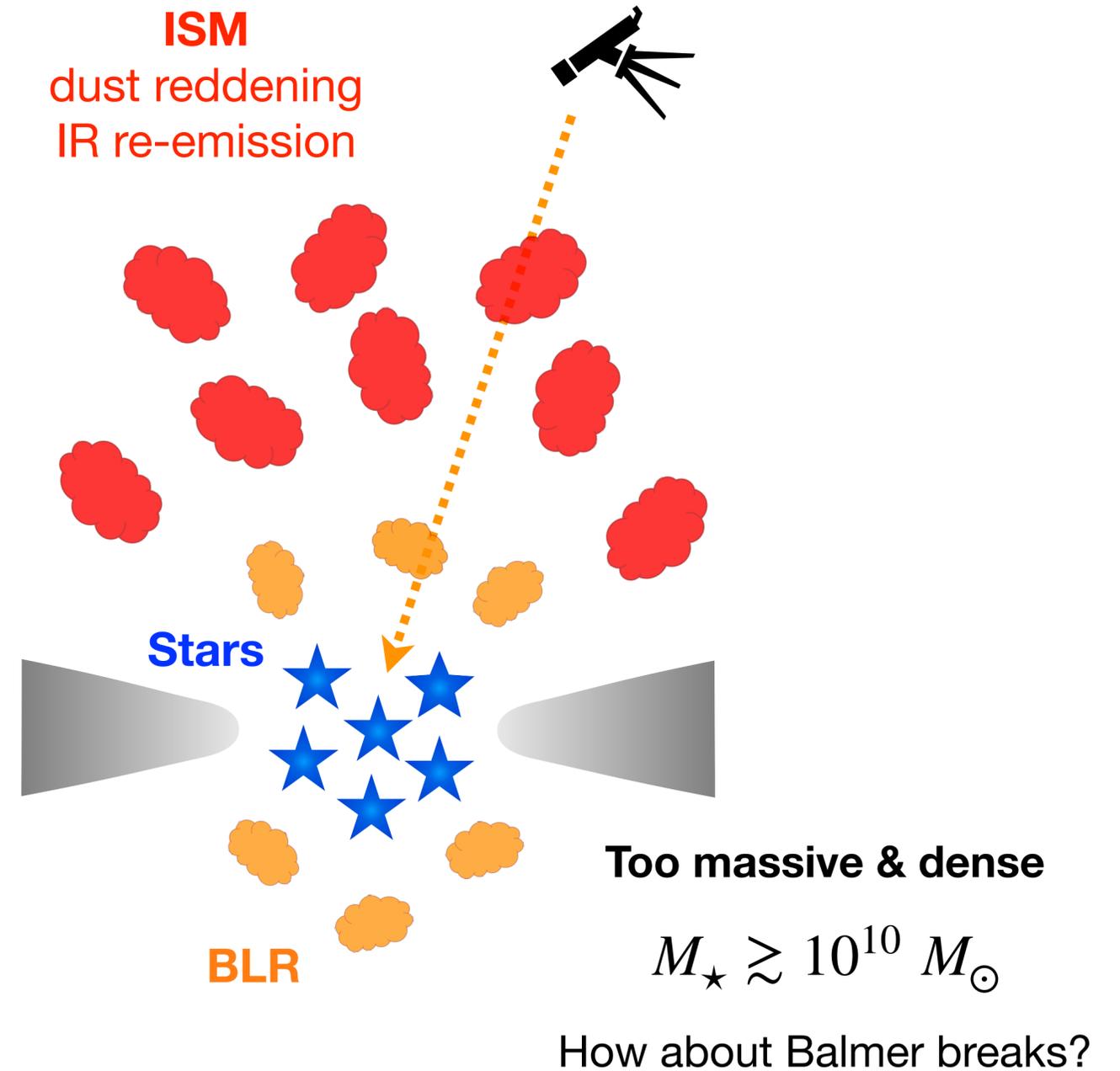
LRD origins: $L_{\text{bol}} \sim 10^{44}$ erg/s

Recall ~1960s'
quasar discovery time
e.g., Lynden-Bell (1969)

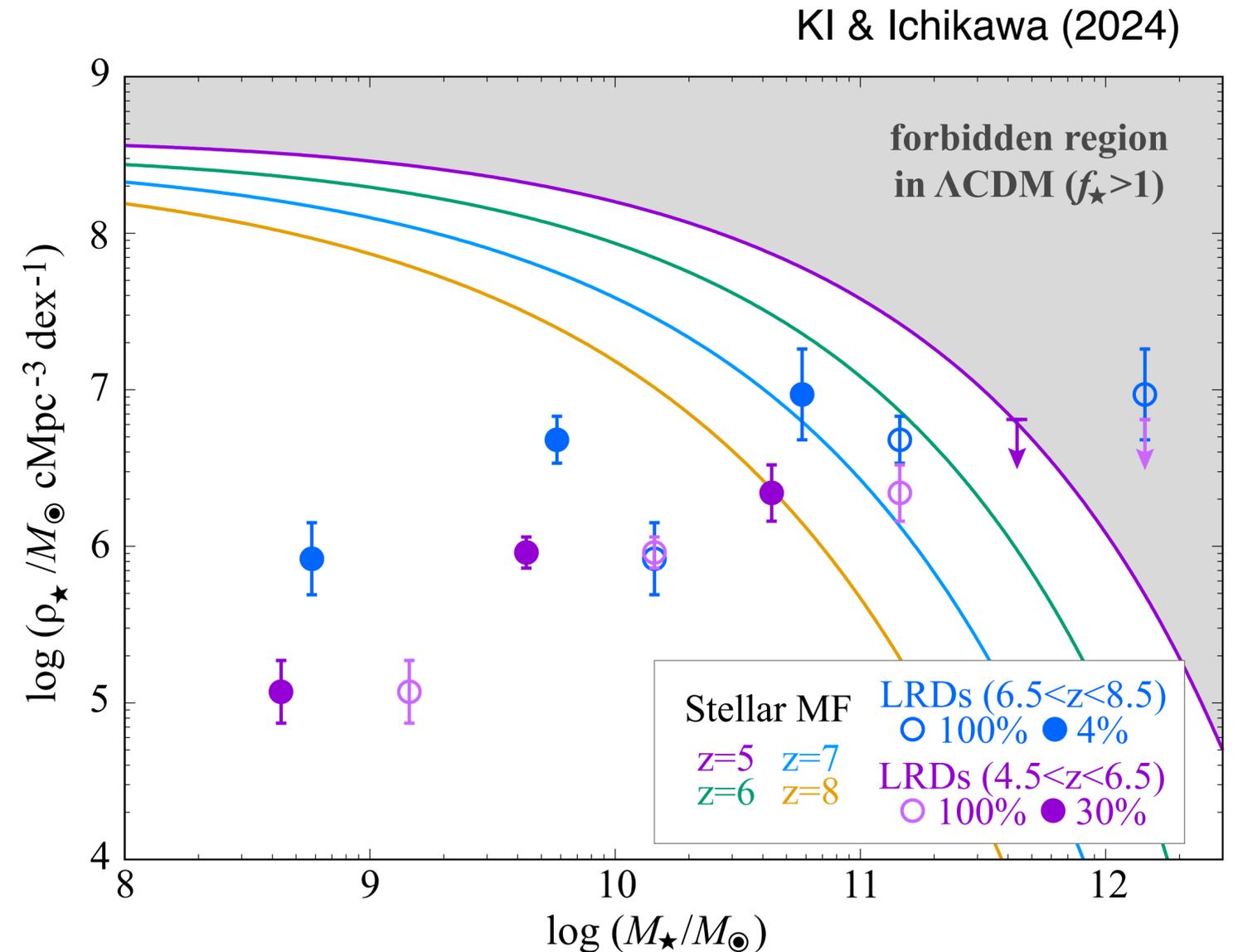
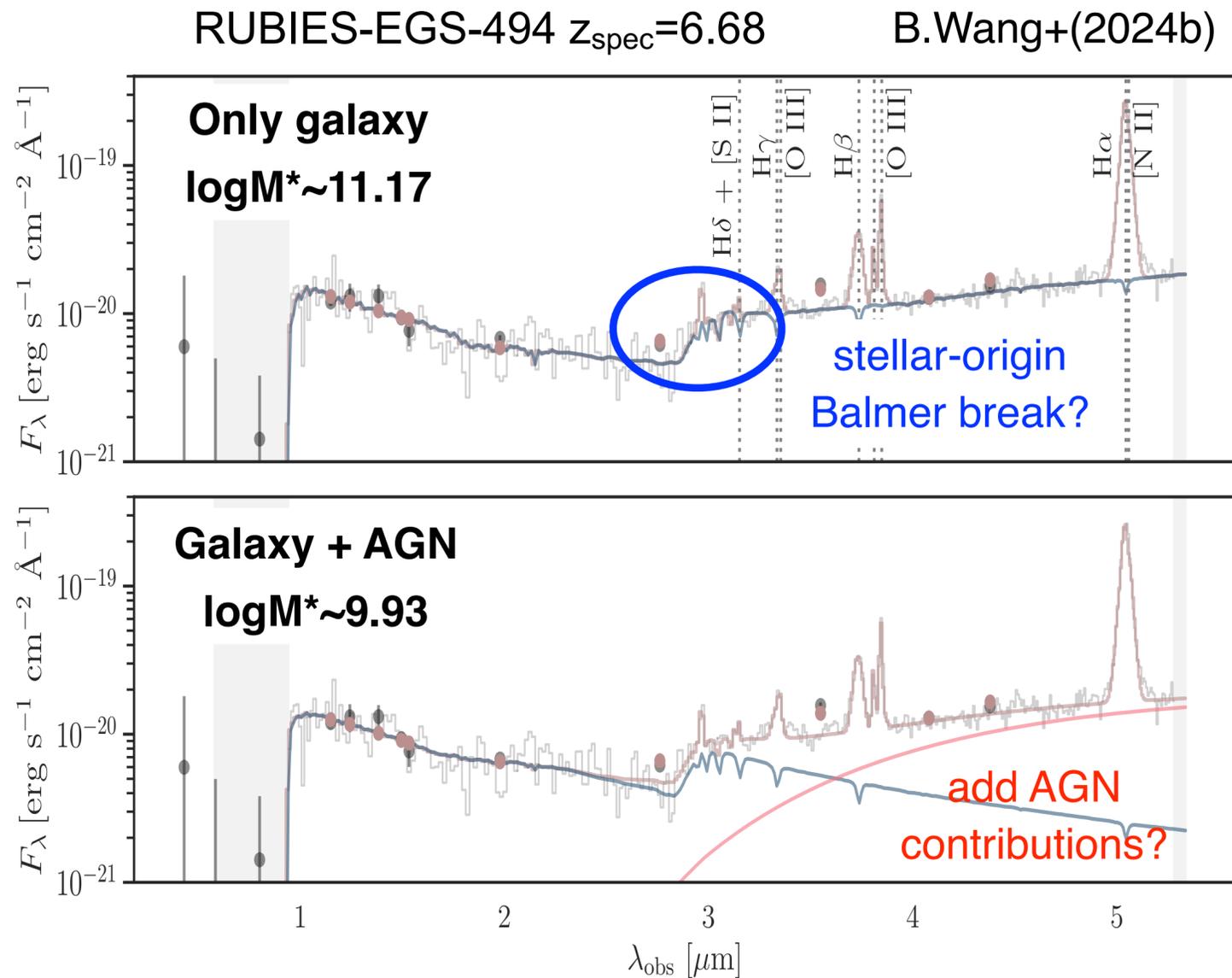
Gravitational energy (accretion)



Nuclear energy (stars)

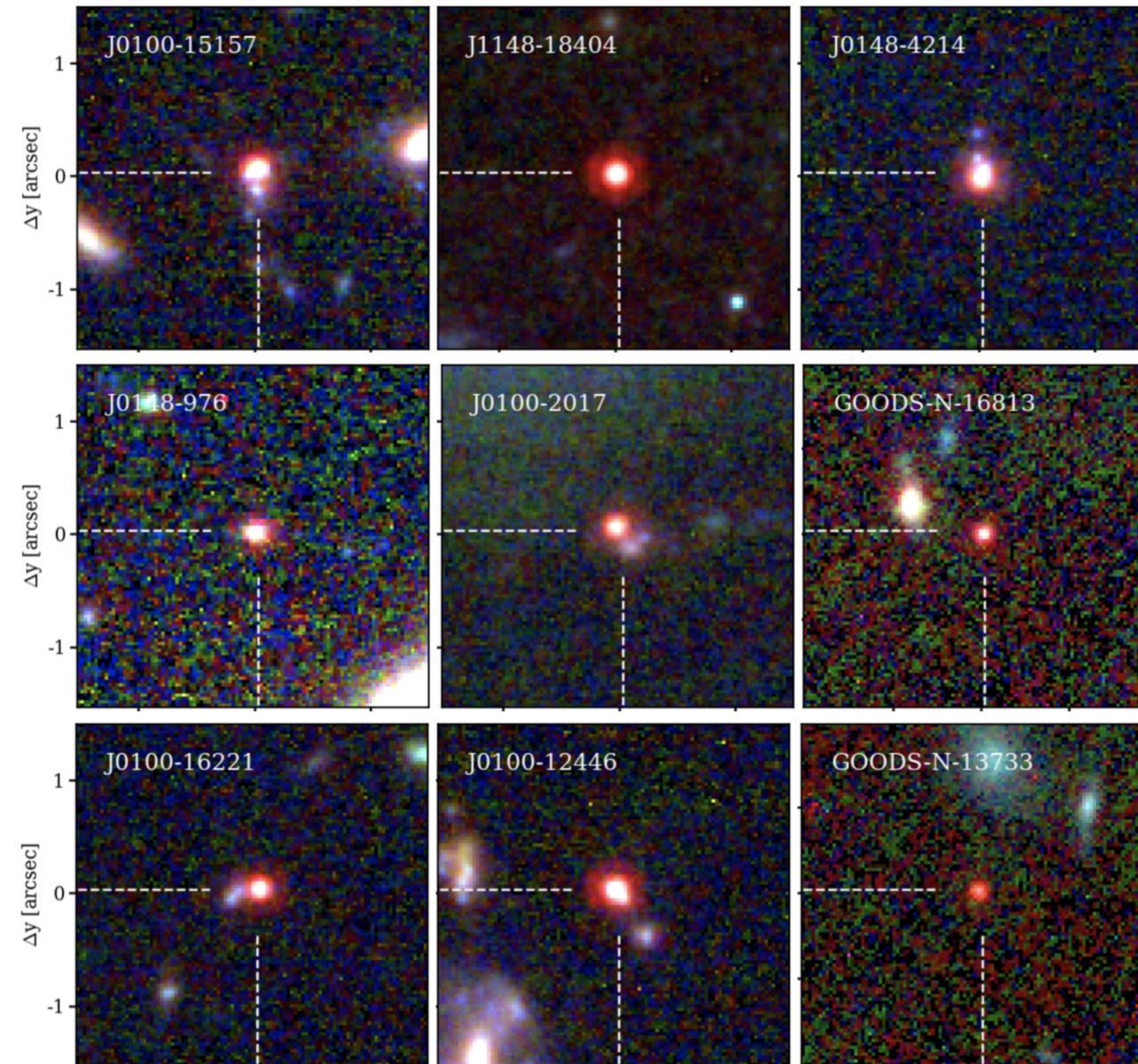


Balmer break: stellar? or AGN?

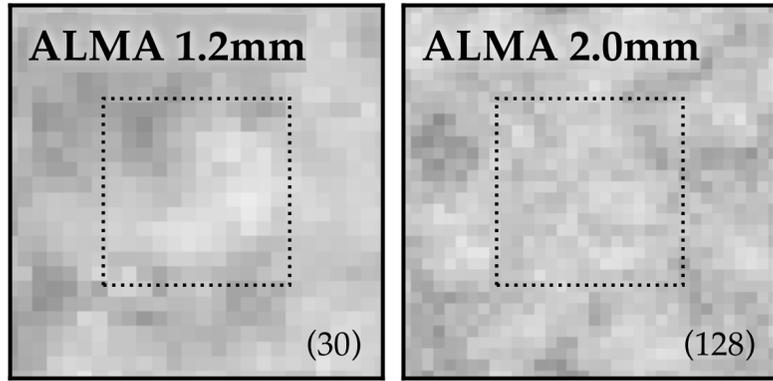


- Stellar-origins of red continua requiring MW-like galaxies at $z > 6$
- Extremely high stellar density and a tension to ΛCDM ($\Omega_b > \Omega_{\text{star}}$)

Spectral characteristics of LRDs

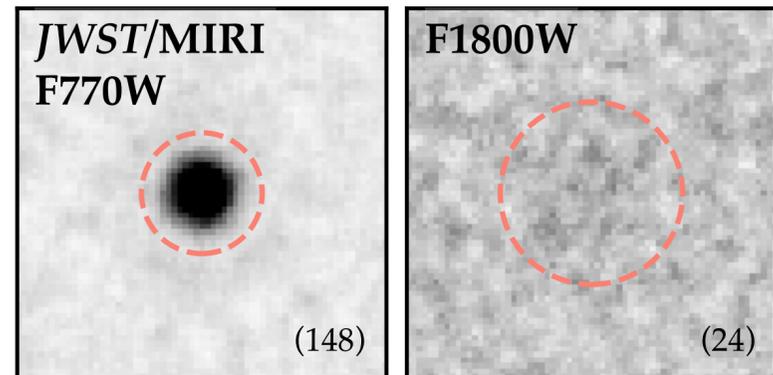


Spectral characteristics of LRDs



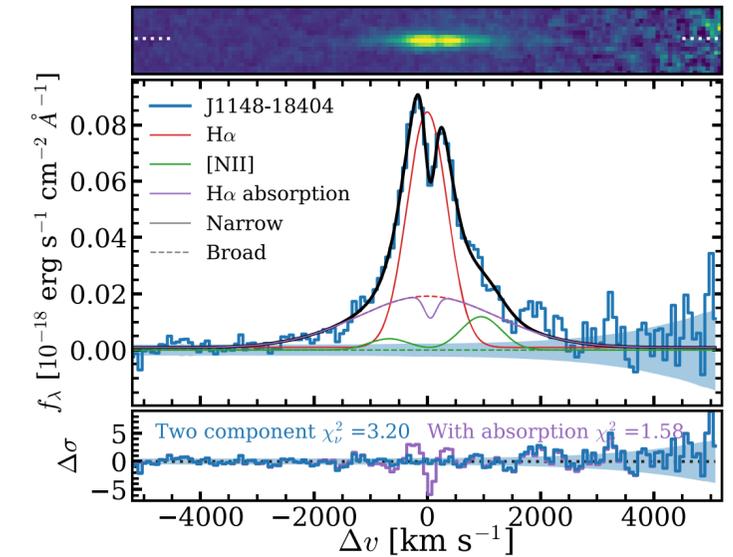
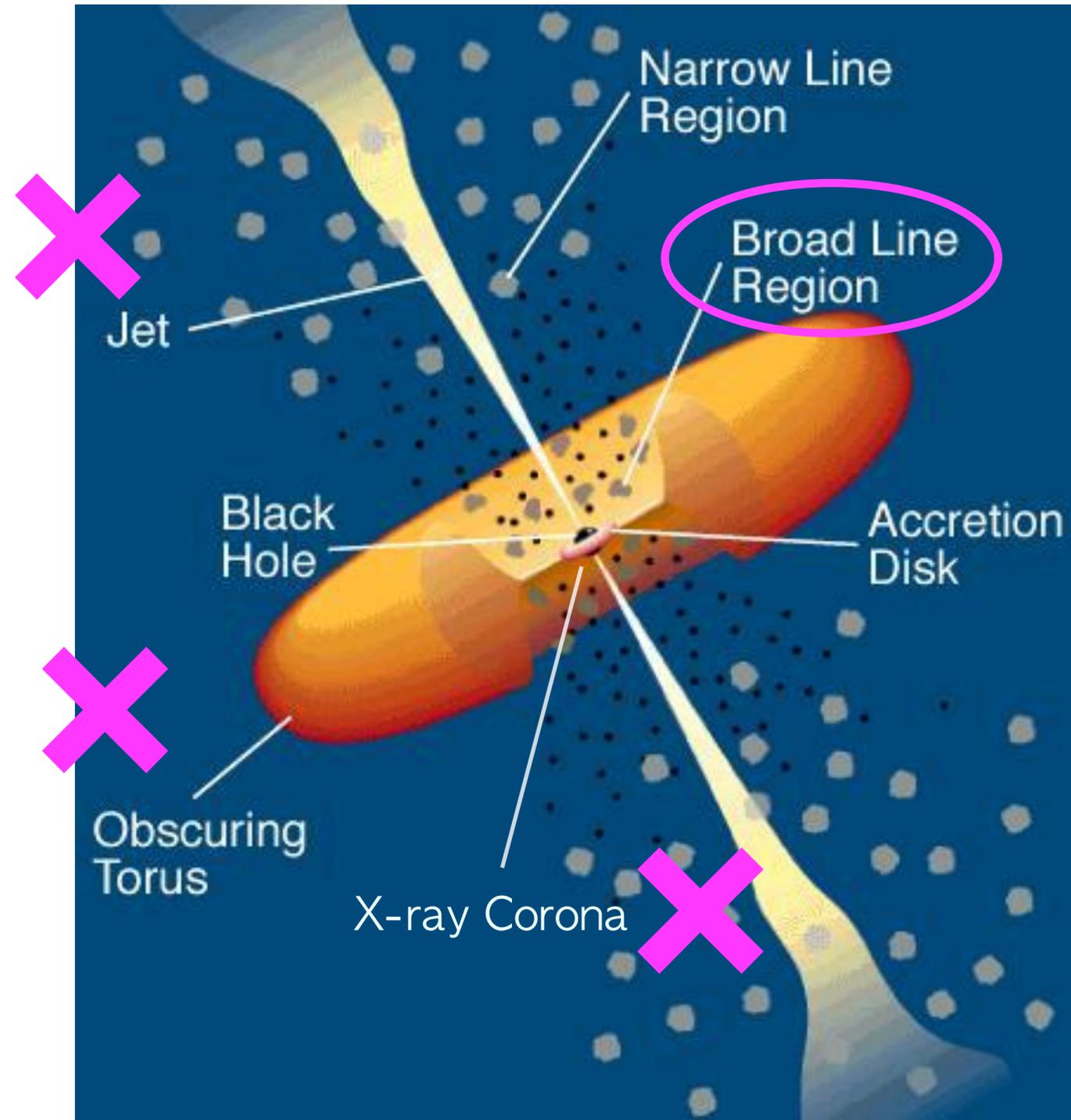
ALMA/VLA/MeerKat non-detection (no cold dust/jets?)

(Labbe+23, Akins+24, Mazzolari+24; Gludemans+KI 25)



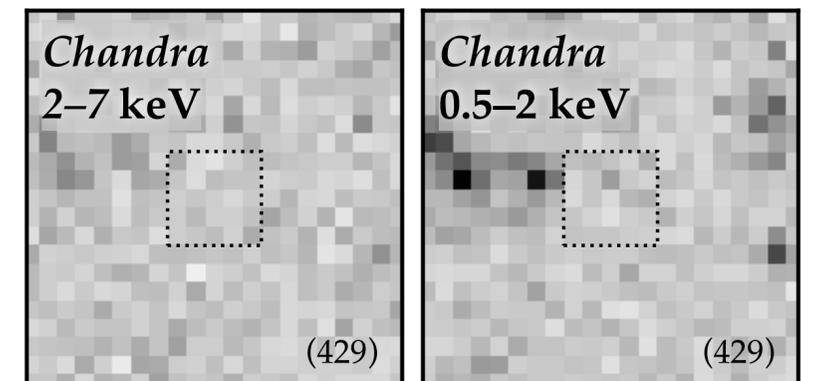
NIR faint (no hot dust)

(Akins+24, Williams+24, Perez-Gonzalez+24)



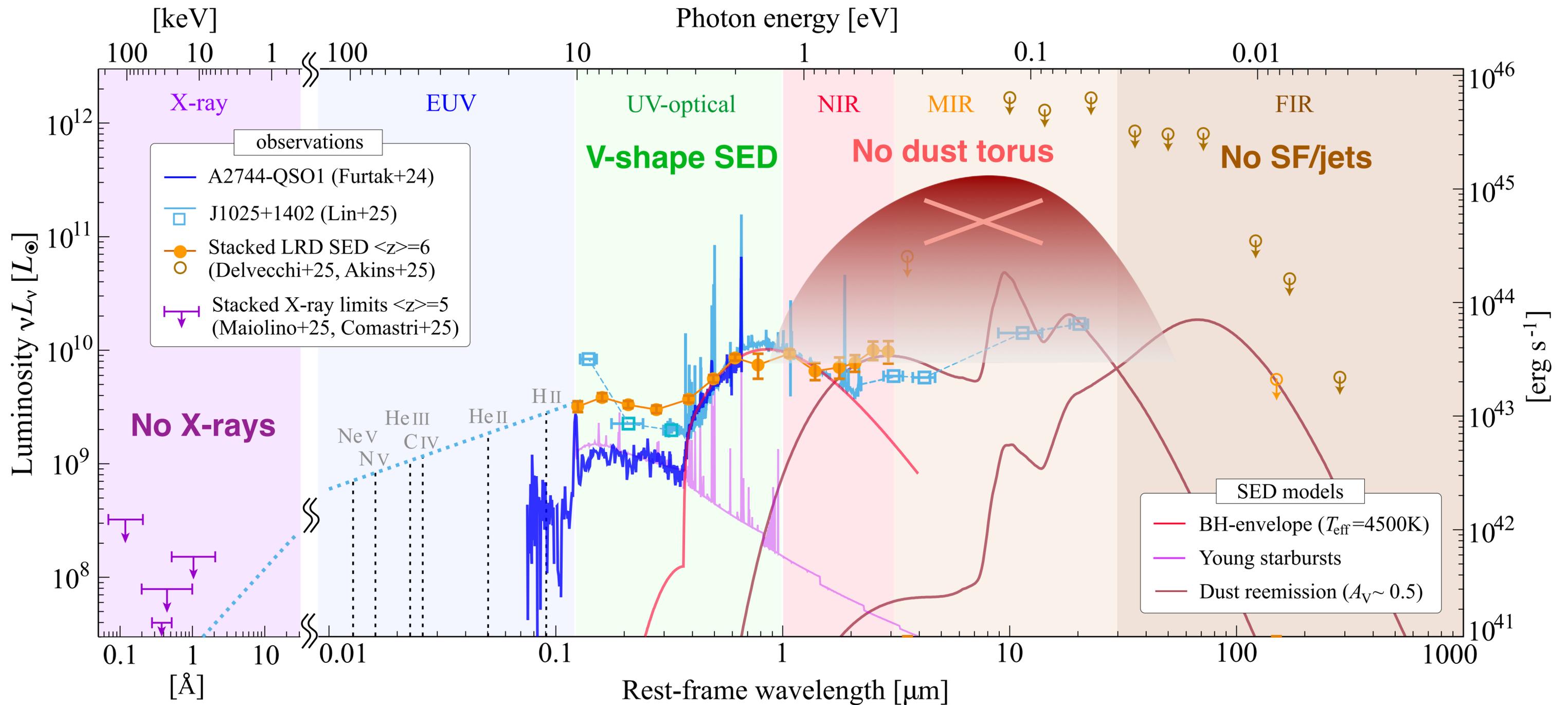
Prominent Balmer absorption

(Matthee+24, Lin+24, B.Wang+25, X.Ji+25, D'Eugenio+25, Kocevski+25)



X-ray non-detection
(Yue+24, Maiolino+24, Ananna+24)

Spectral characteristics of LRDs



3. LRDs = Gas-enshrouded AGNs

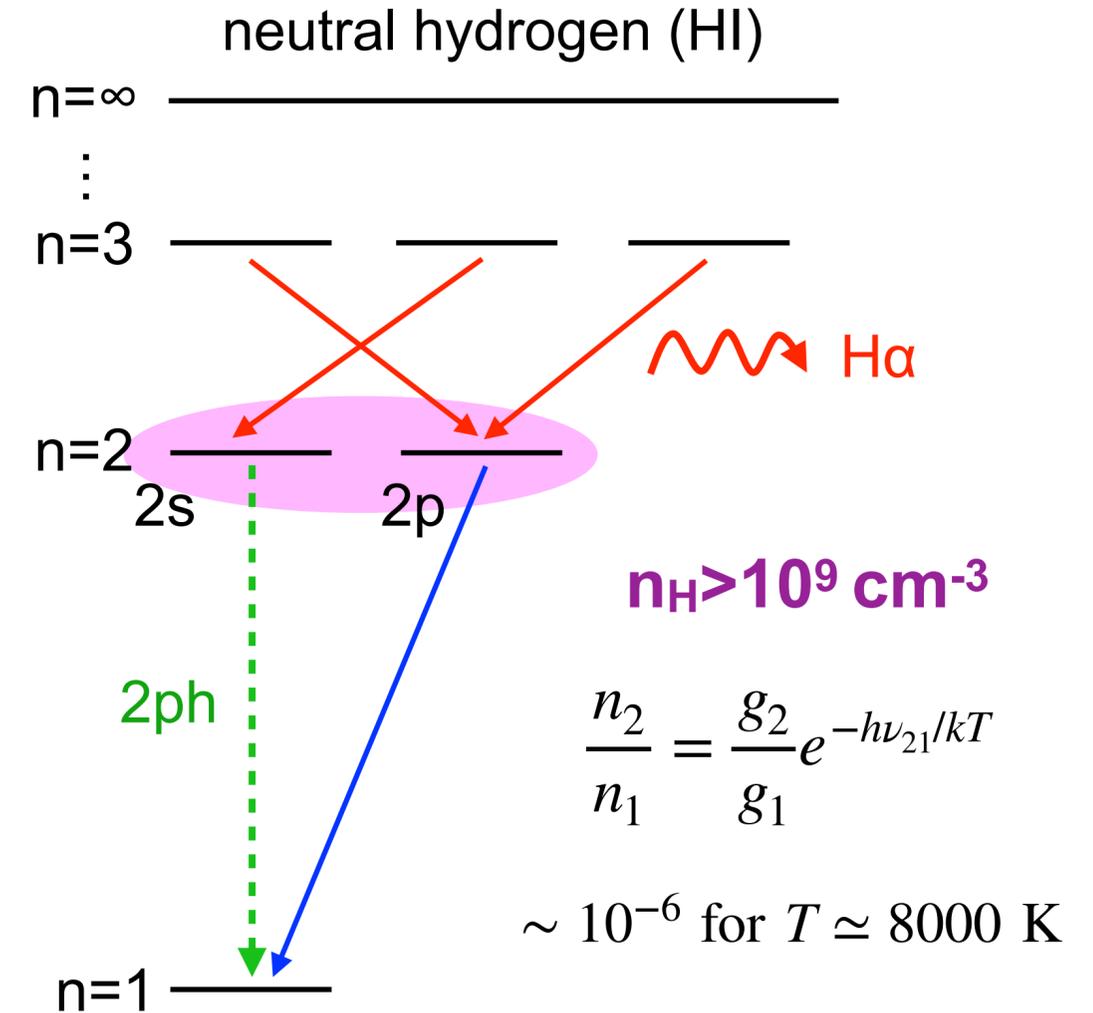
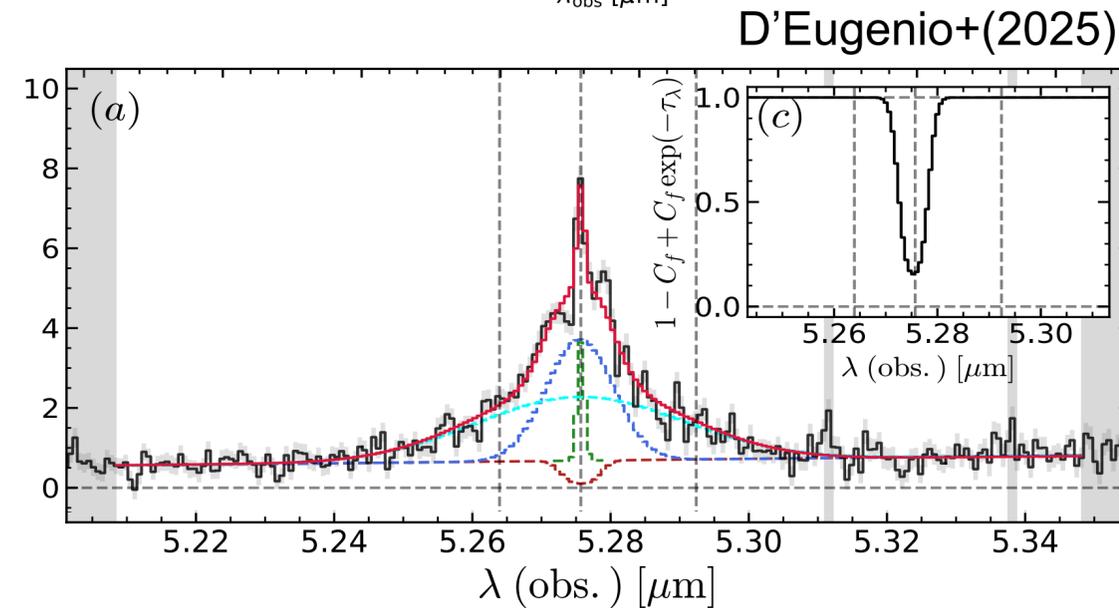
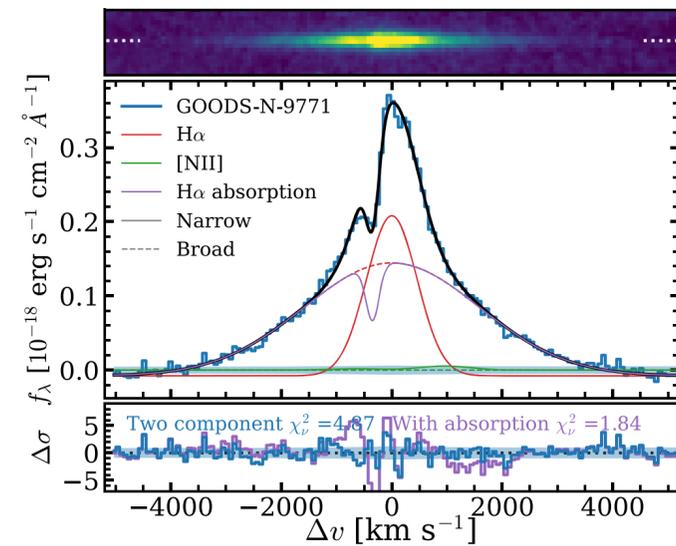
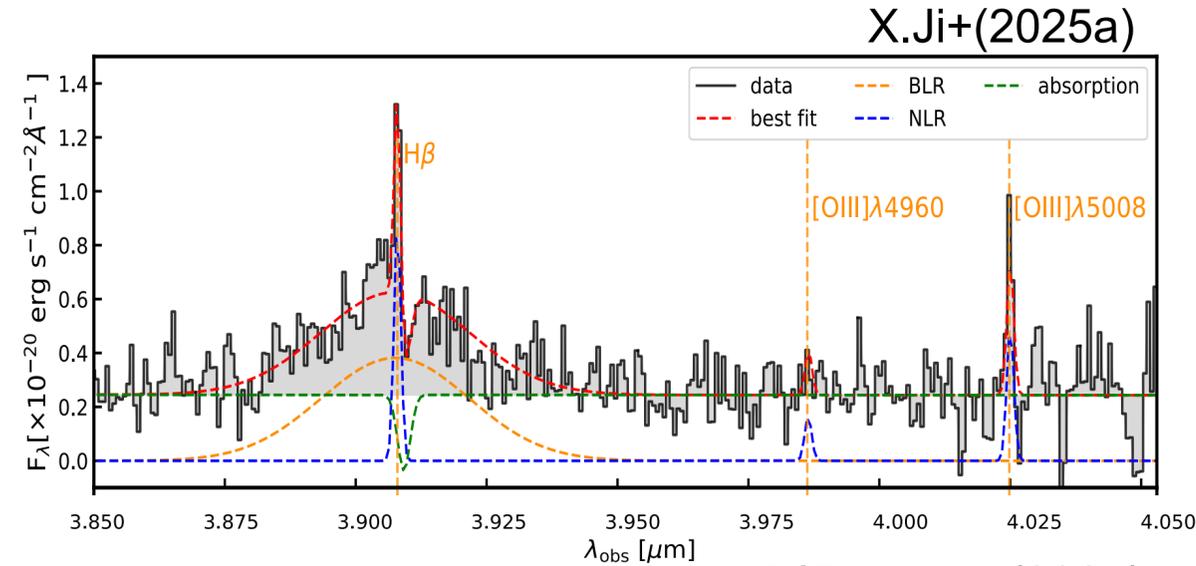
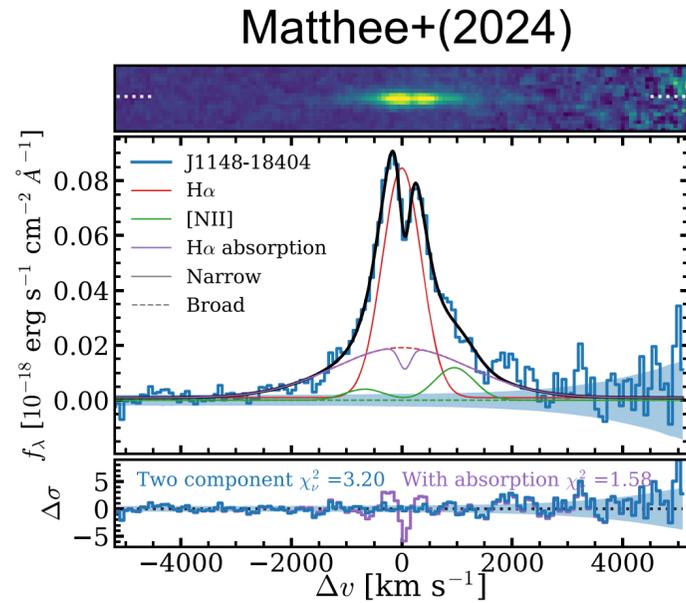


An illustration by Chat-GPT

Two big problems in 2024-2025

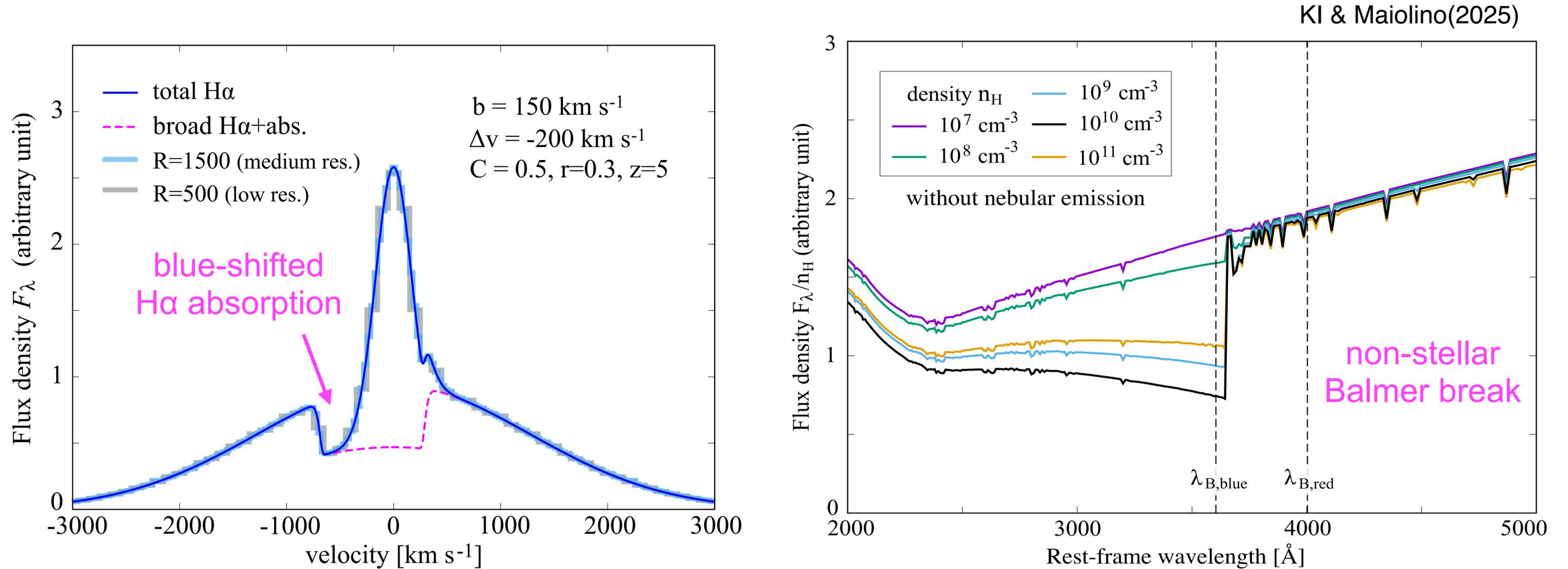
- **What is the main power source of LRDs? Stellar or AGN origin?**
 - Broad-emission lines support the AGN origin (compact massive object), but **Balmer break** features might not be produced by AGNs
- **What makes LRDs red without dust?**
 - If dust is responsible to red optical continua, AGN heated dust re-emits into NIR, but JWST MIRI observations report **the absence of hot dust emission**
 - LRDs are possibly metal-poor systems (see also lacks of metal lines, [OIII])

Balmer absorption on BLAGNs



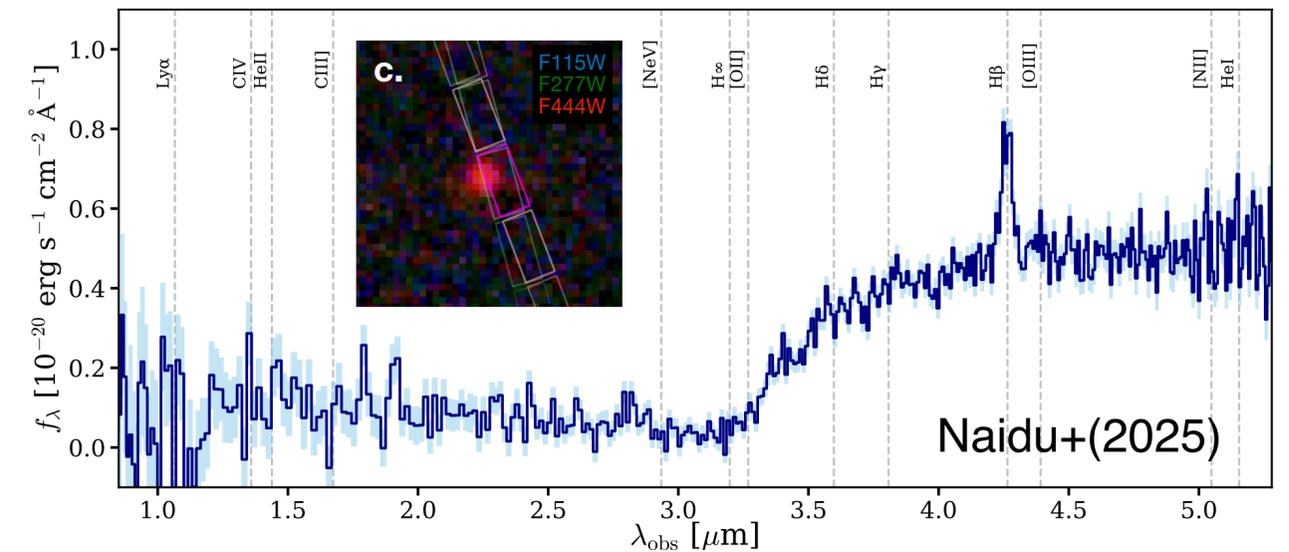
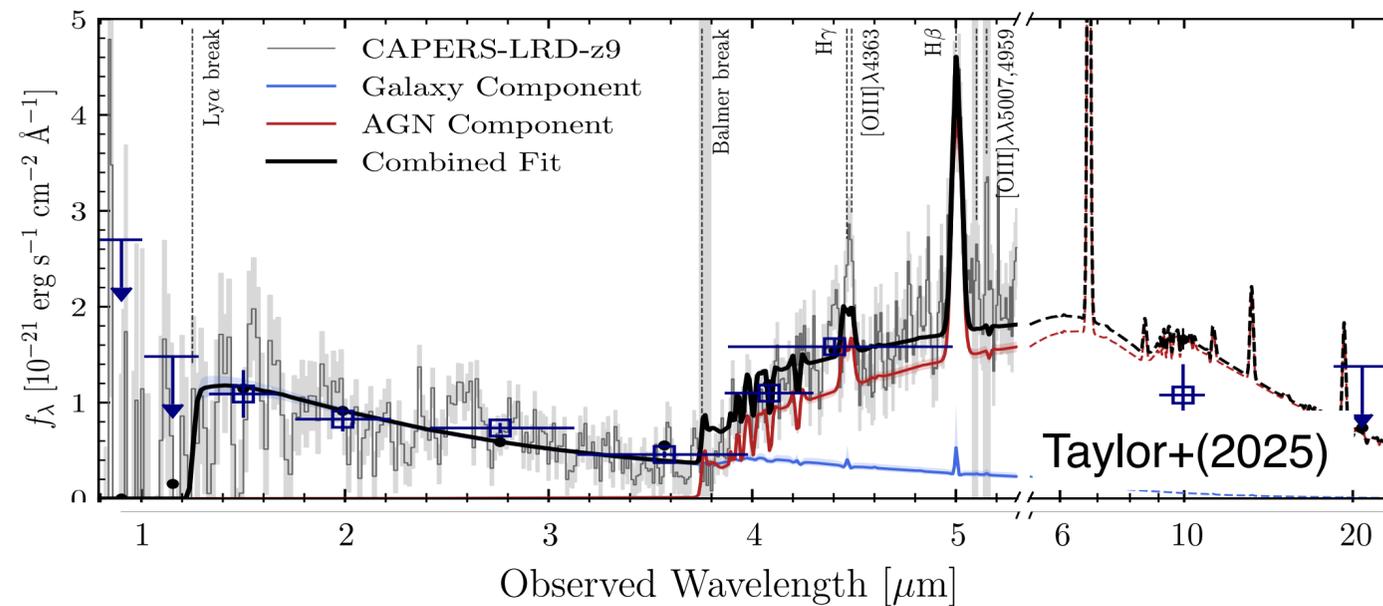
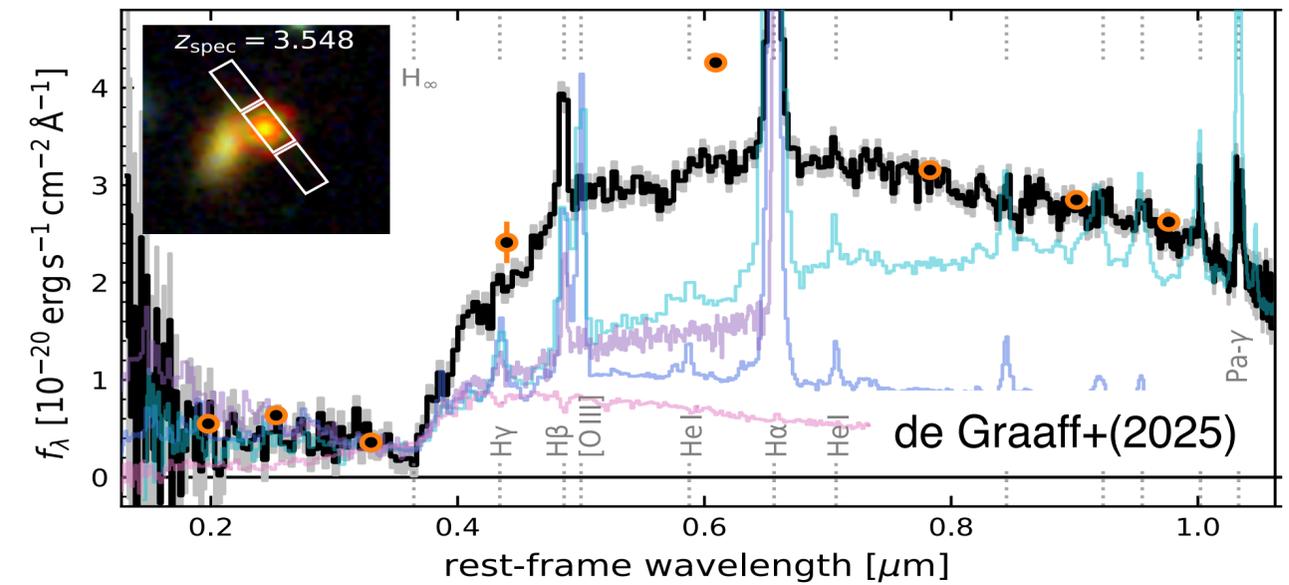
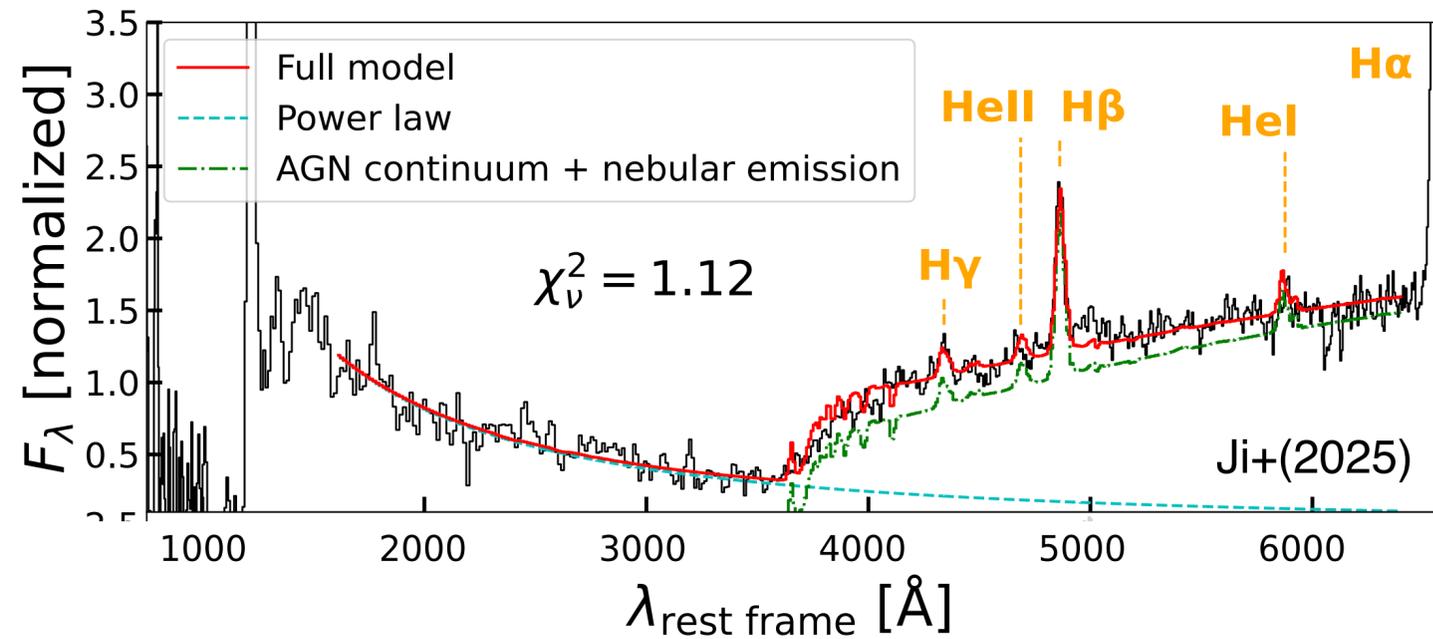
- Absorption on broad Balmer & HeI emission lines; $EW_{\text{abs}} \sim O(10) \text{ \AA}$
- BLRs embedded by **dense gas** with a high covering fraction

Balmer break on pure AGN spectra



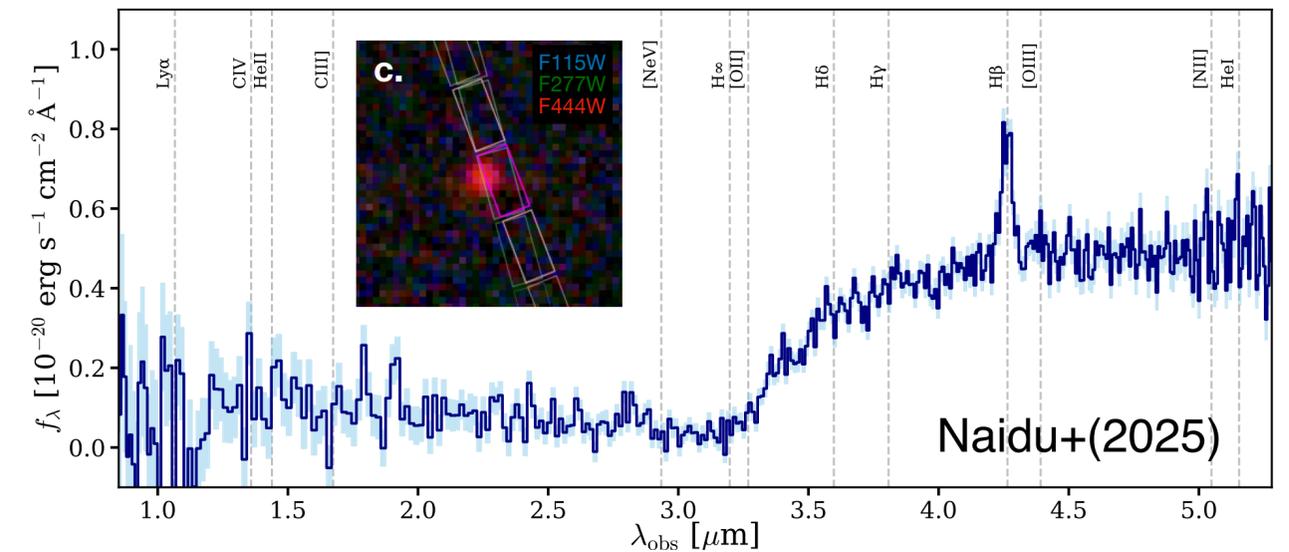
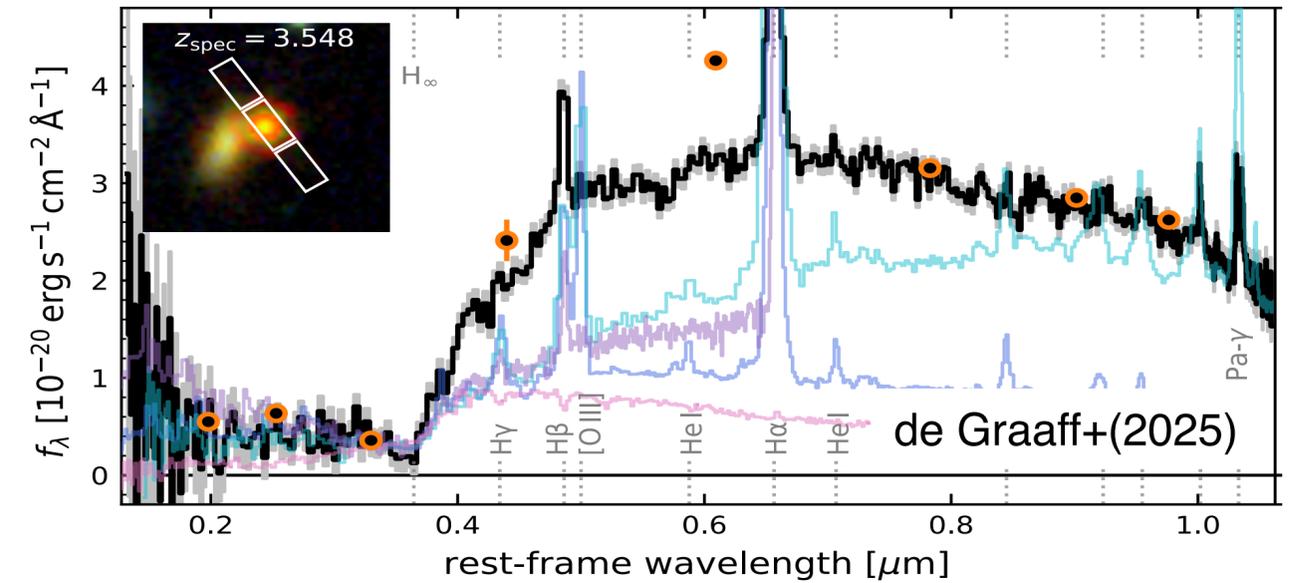
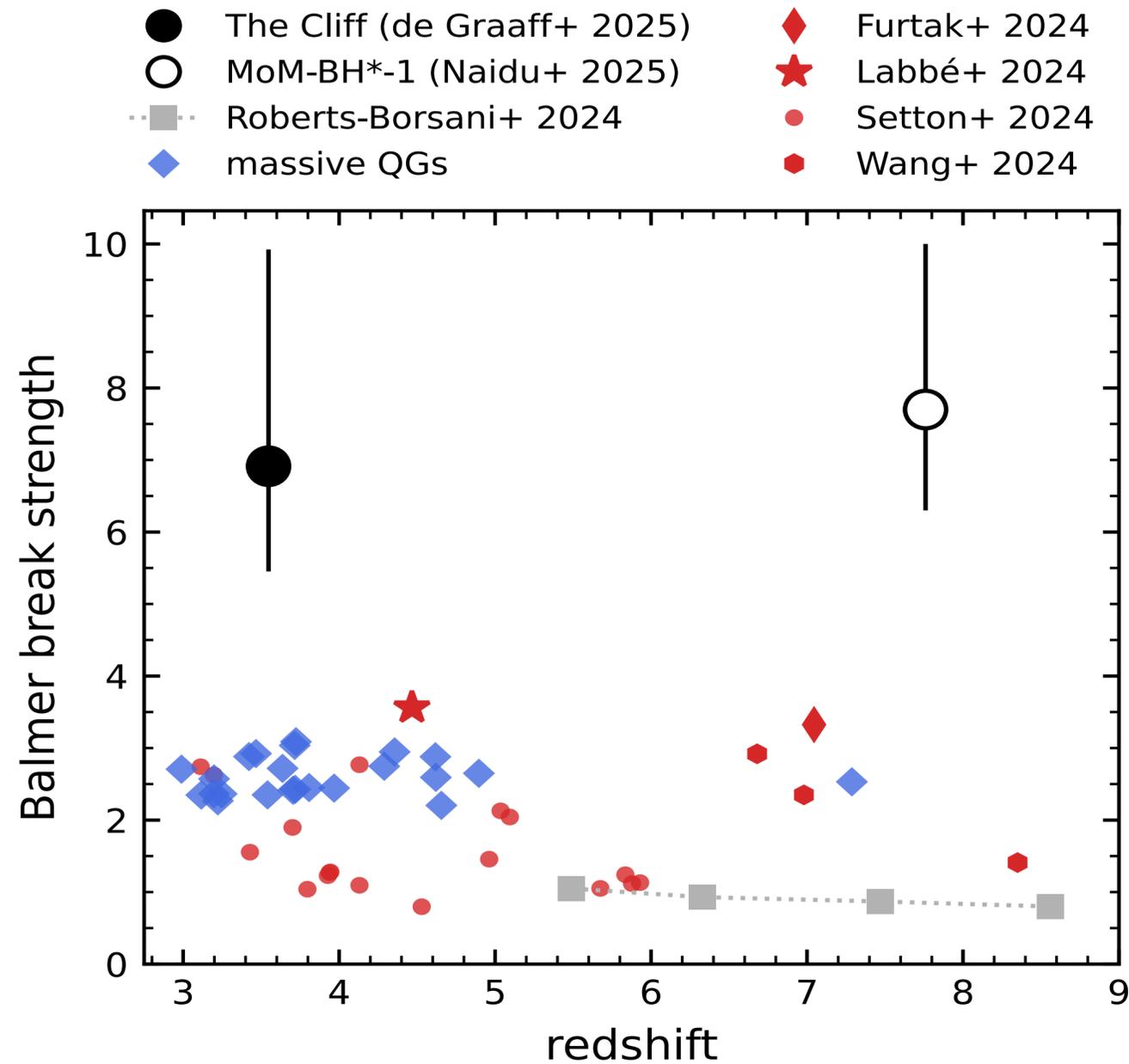
- Balmer break & absorption imprinted by gas absorbers with **the same conditions**
- A potential correlation with **super-Eddington outflows** ($\sim 3-10 \dot{M}_{Edd}$)

LRD with both Balmer breaks + absorption



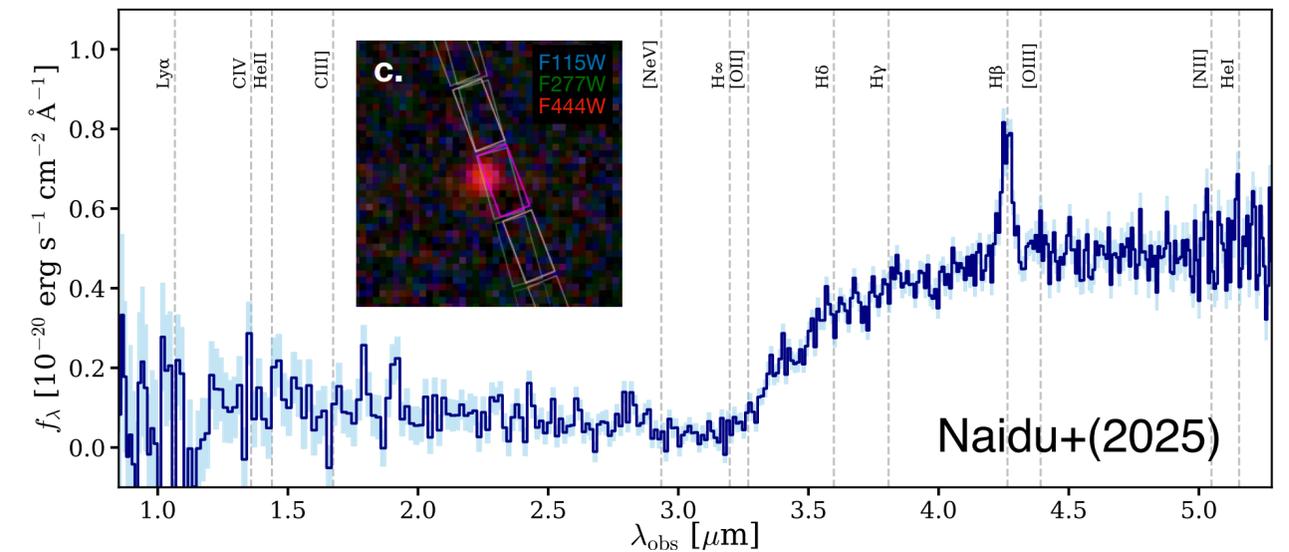
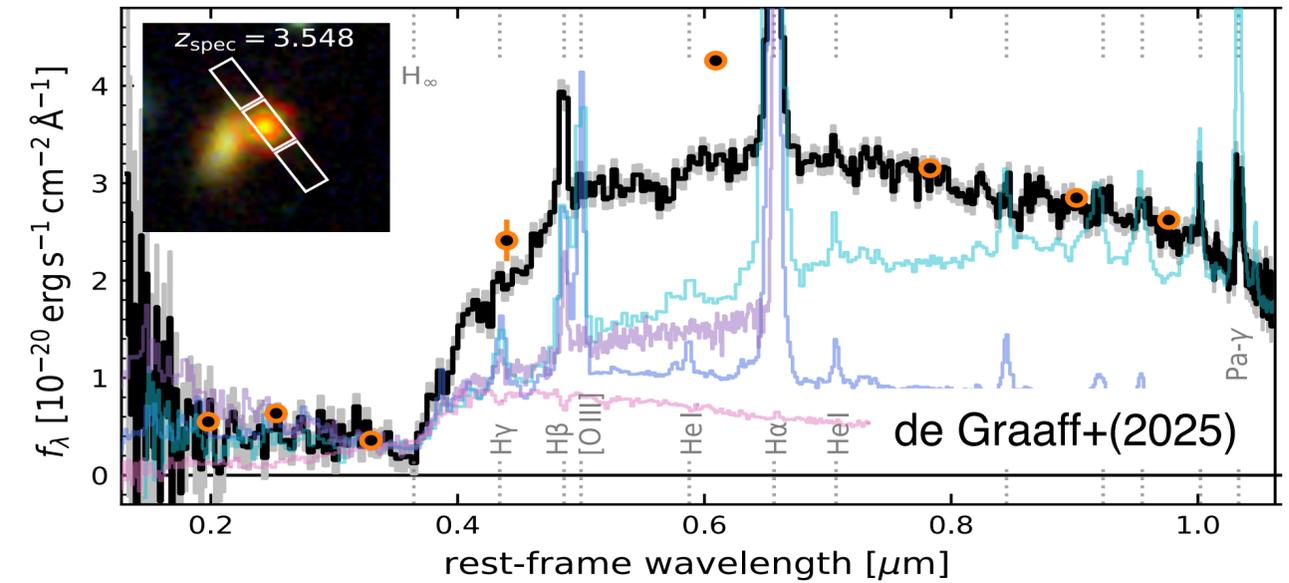
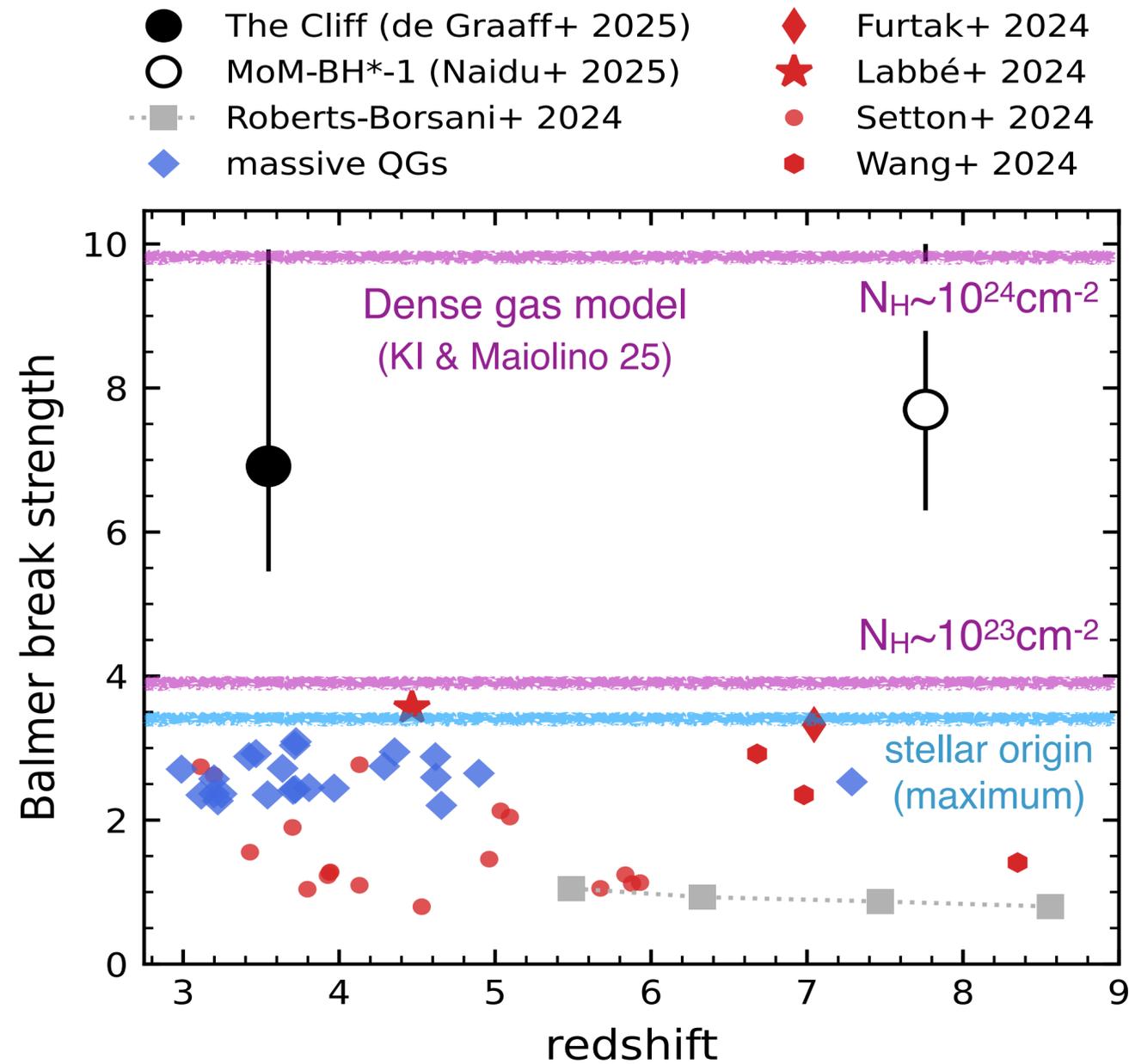
- LRDs with prominent **Balmer breaks too deep** to be stellar origins

LRD with both Balmer breaks + absorption



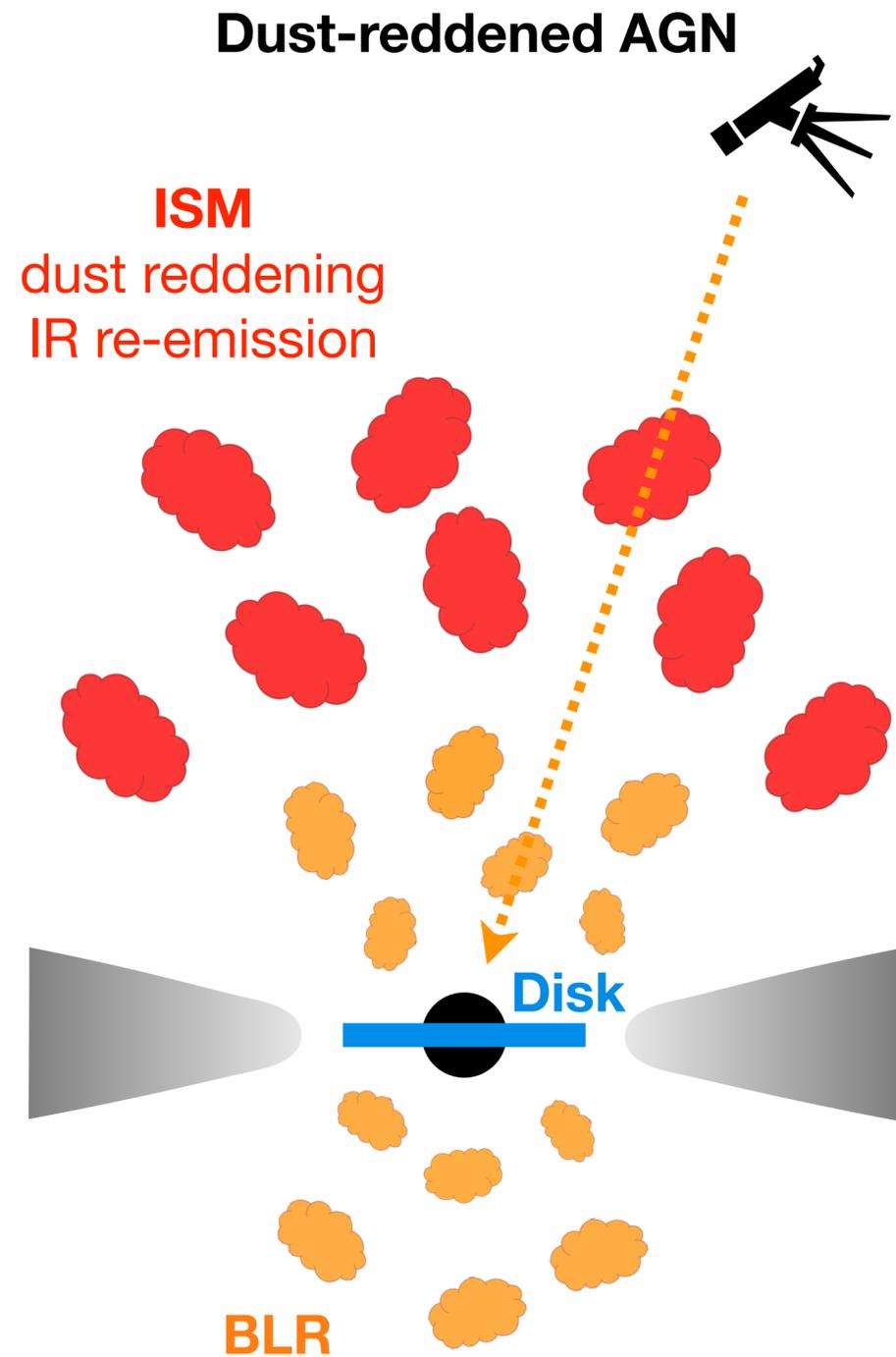
- LRDs with prominent **Balmer breaks too deep** to be stellar origins

LRD with both Balmer breaks + absorption



- LRDs with prominent **Balmer breaks too deep** to be stellar origins

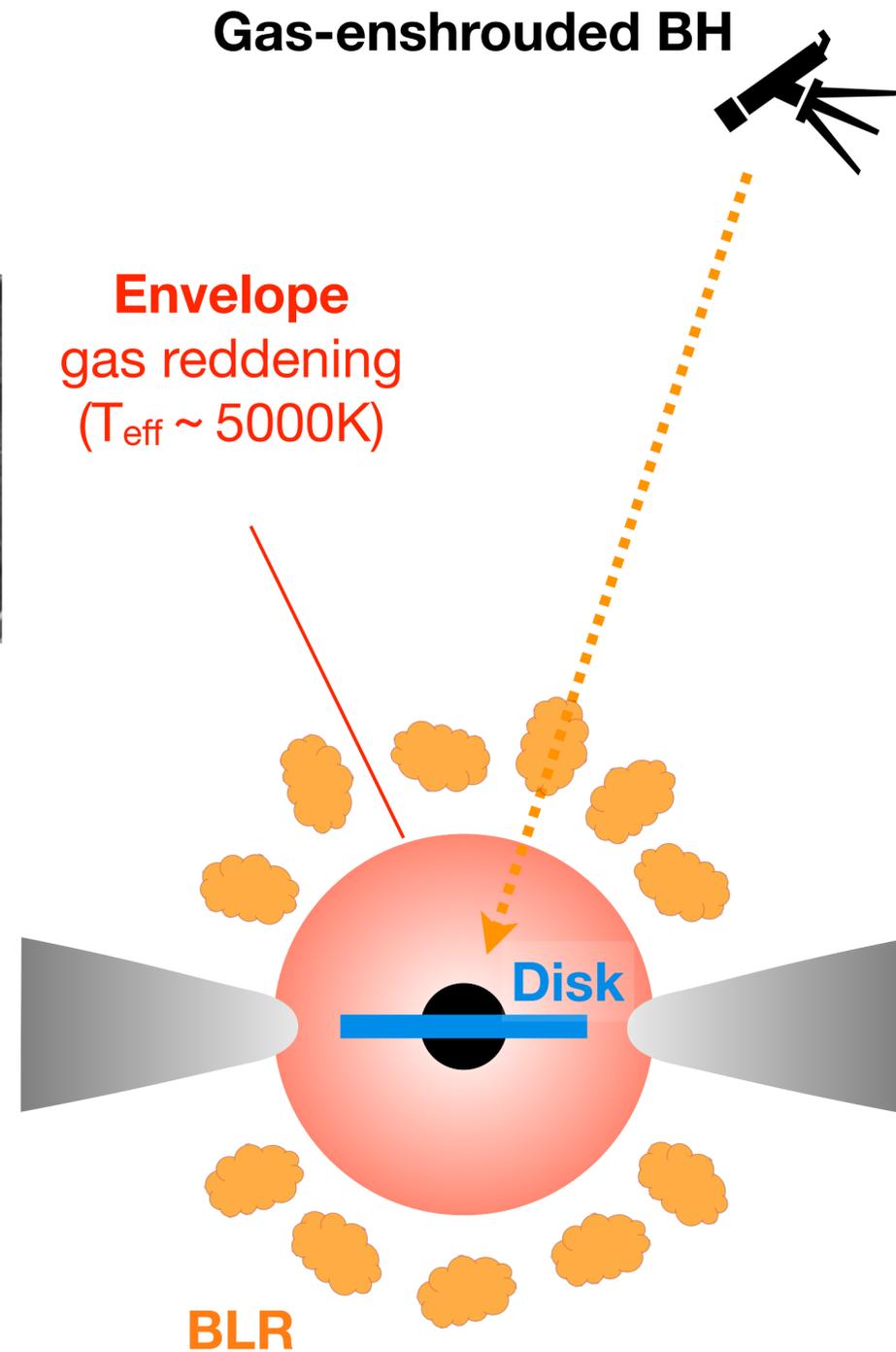
BH + accreting envelope



- LRD spectral characteristics
 - No hot dust (weak NIR emission in MIRI)
 - Dense nucleus (Balmer absorption & break)

BH + accreting envelope

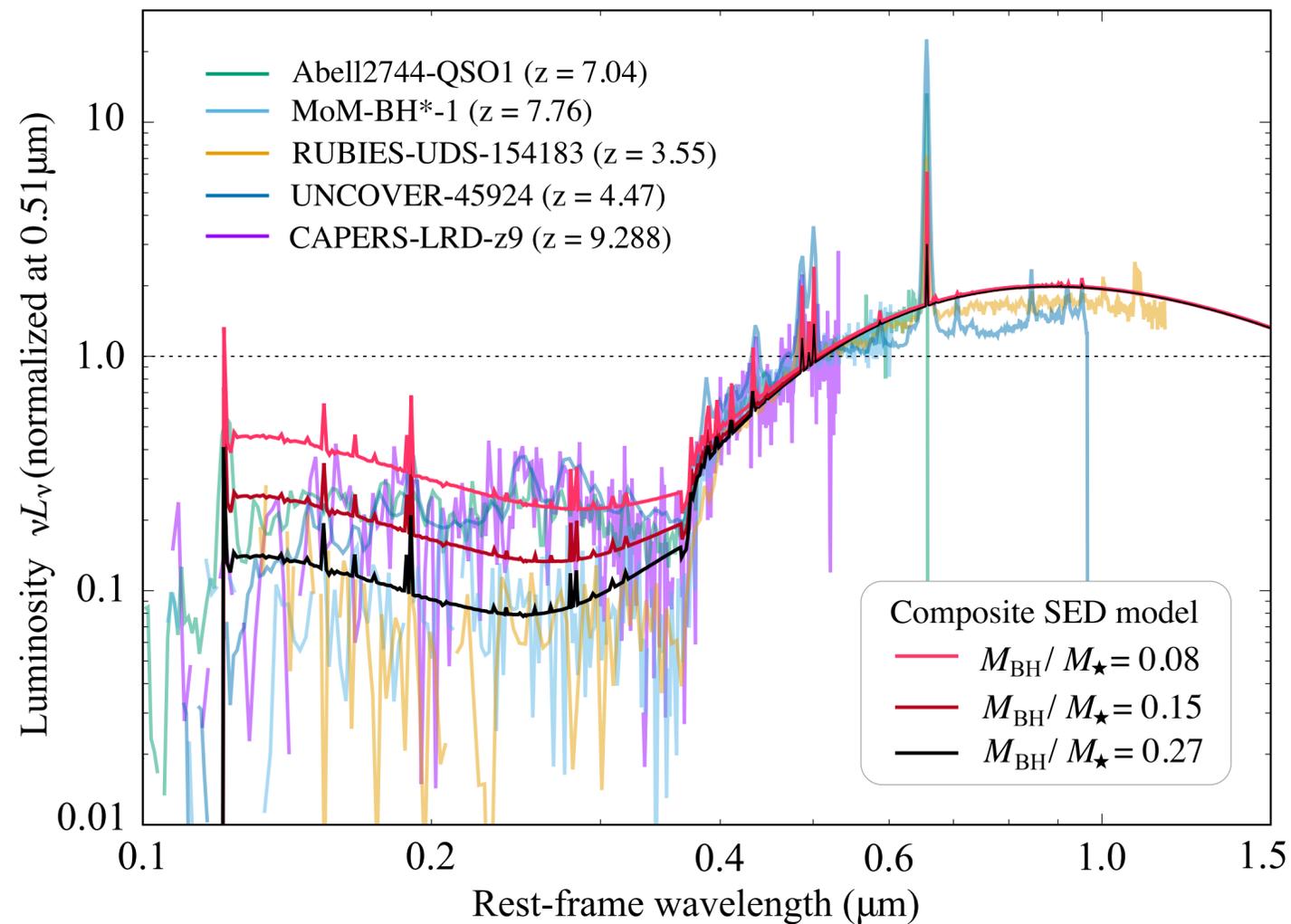
C.Hayashi



- LRD spectral characteristics
 - No hot dust (weak NIR emission in MIRI)
 - Dense nucleus (Balmer absorption & break)
- **Optically-thick absorbers** (or envelope/cocoon)
 - Theory: KI+25, Kido+25, H.Liu+25, Begelman & Dexter 25
 - Observation: Rusakov+25, X.Lin+25, Naidu+25, deGraaff+25, Sneppen+26
 - **$T_{\text{eff}} \sim 5000 \text{ K}$** due to H- ion opacity (Hayashi track)
(Hayashi 1961; Stahler, Palla & Salpeter 1986)
 - Red optical continuum spectra (the Wien law)
 - Weak infrared continuum spectra (the Rayleigh-Jeans law)

BH + accreting envelope

KI, Murase & Kashiyama (2026)



See also Kido+25, deGraaff+25

- LRD spectral characteristics

- No hot dust (weak NIR emission in MIRI)
- Dense nucleus (Balmer absorption & break)

- **Optically-thick absorbers** (or envelope/cocoon)

Theory: KI+25, Kido+25, H.Liu+25, Begelman & Dexter 25

Observation: Rusakov+25, X.Lin+25, Naidu+25, deGraaff+25, Sneppen+26

- **$T_{\text{eff}} \sim 5000 \text{ K}$** due to H- ion opacity (Hayashi track)

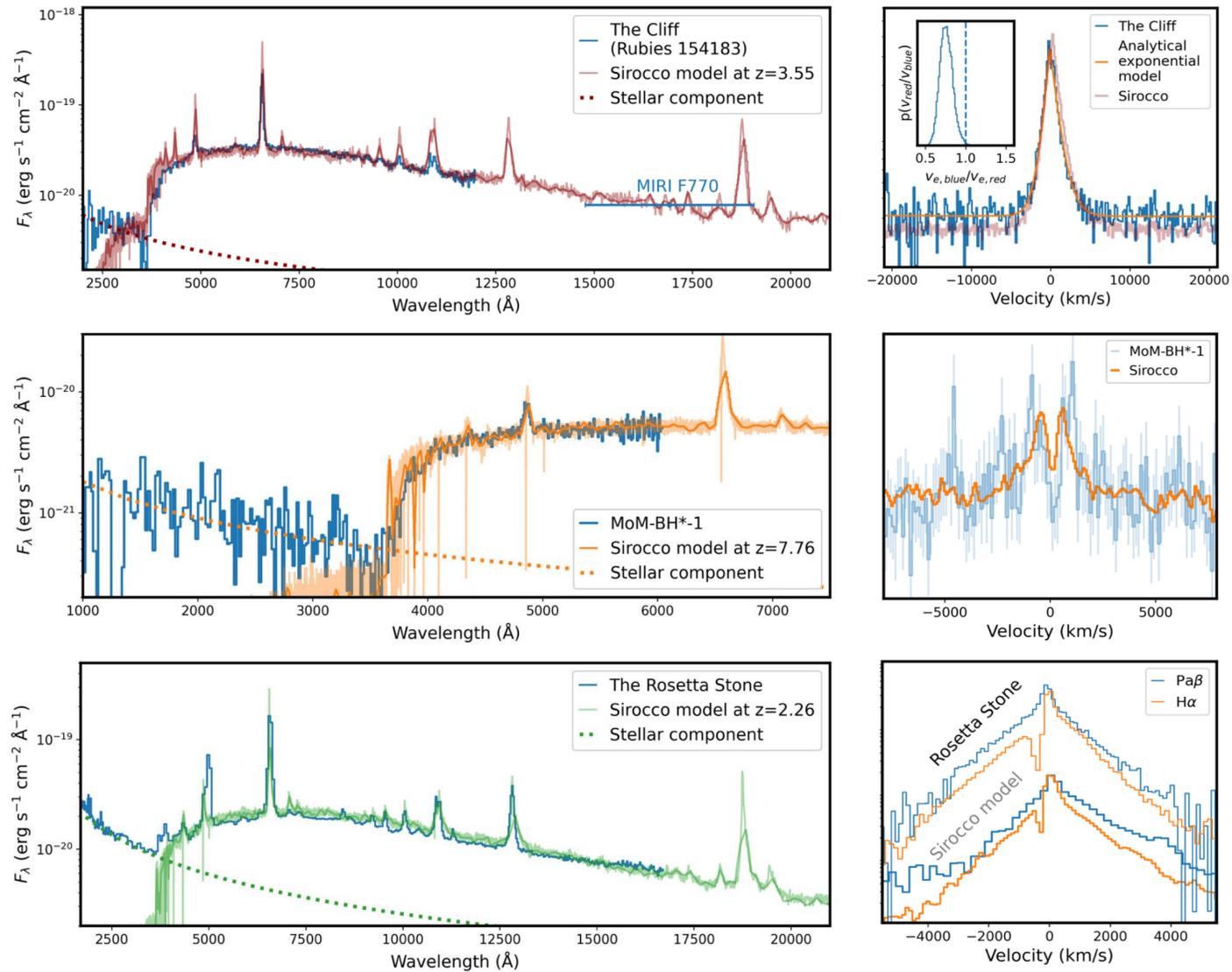
(Hayashi 1961; Stahler, Palla & Salpeter 1986)

- Red optical continuum spectra (the Wien law)

- Weak infrared continuum spectra (the Rayleigh-Jeans law)

BH + accreting envelope

With radiation transfer calculations



Sneppen+ (2026)

- LRD spectral characteristics

- No hot dust (weak NIR emission in MIRI)
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- **Optically-thick absorbers** (or envelope/cocoon)

Theory: KI+25, Kido+25, H.Liu+25, Begelman & Dexter 25

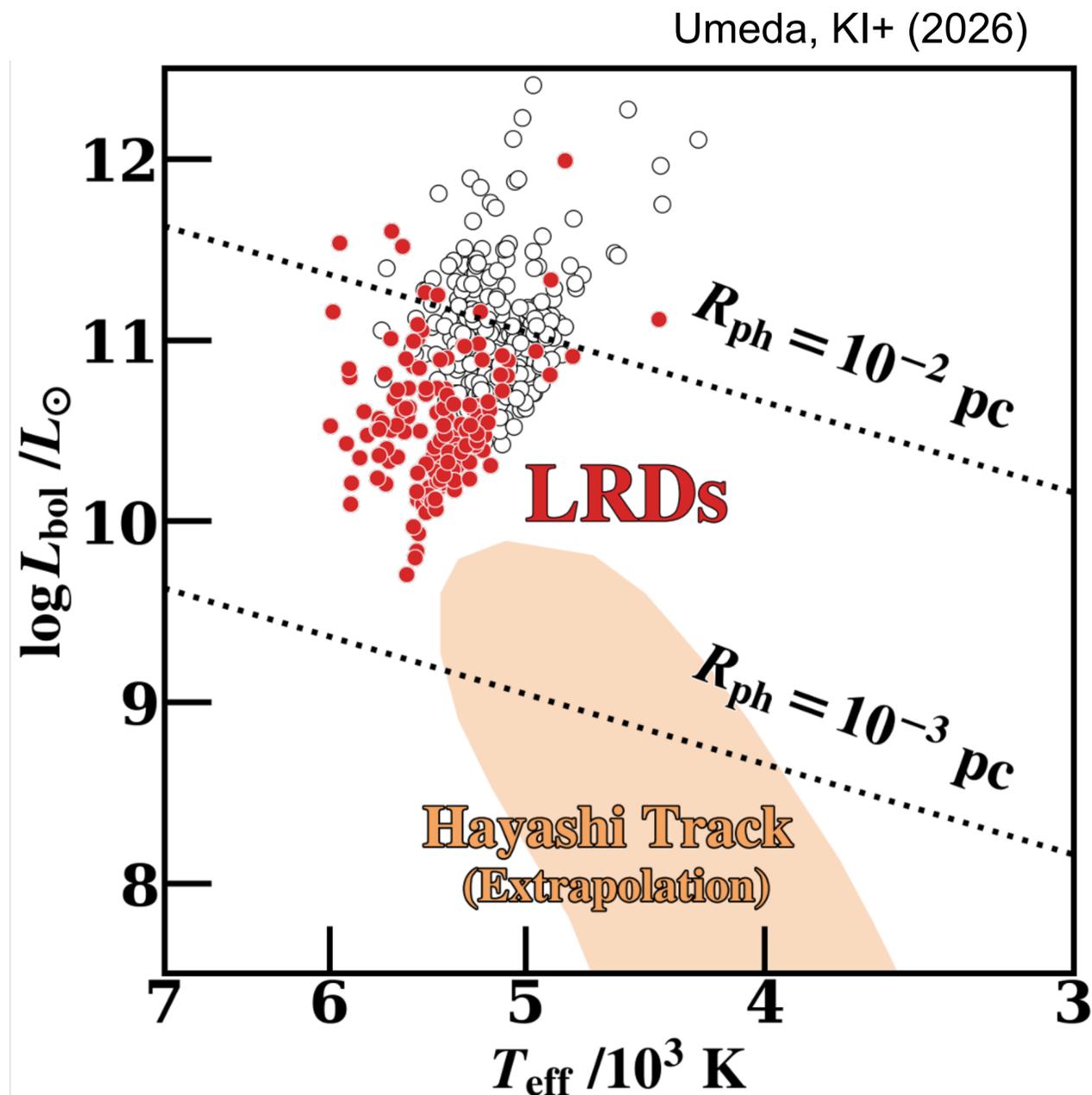
Observation: Rusakov+25, X.Lin+25, Naidu+25, deGraaff+25, Sneppen+26

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 - Red optical continuum spectra (the Wien law)
 - Weak infrared continuum spectra (the Rayleigh-Jeans law)

Two big problems in 2024-2025

- What is the main power source of LRDs? Stellar or AGN origin?
- What makes LRDs red without dust?

A. **Gas-enshrouded AGNs** (or BH envelope, BH*, etc)

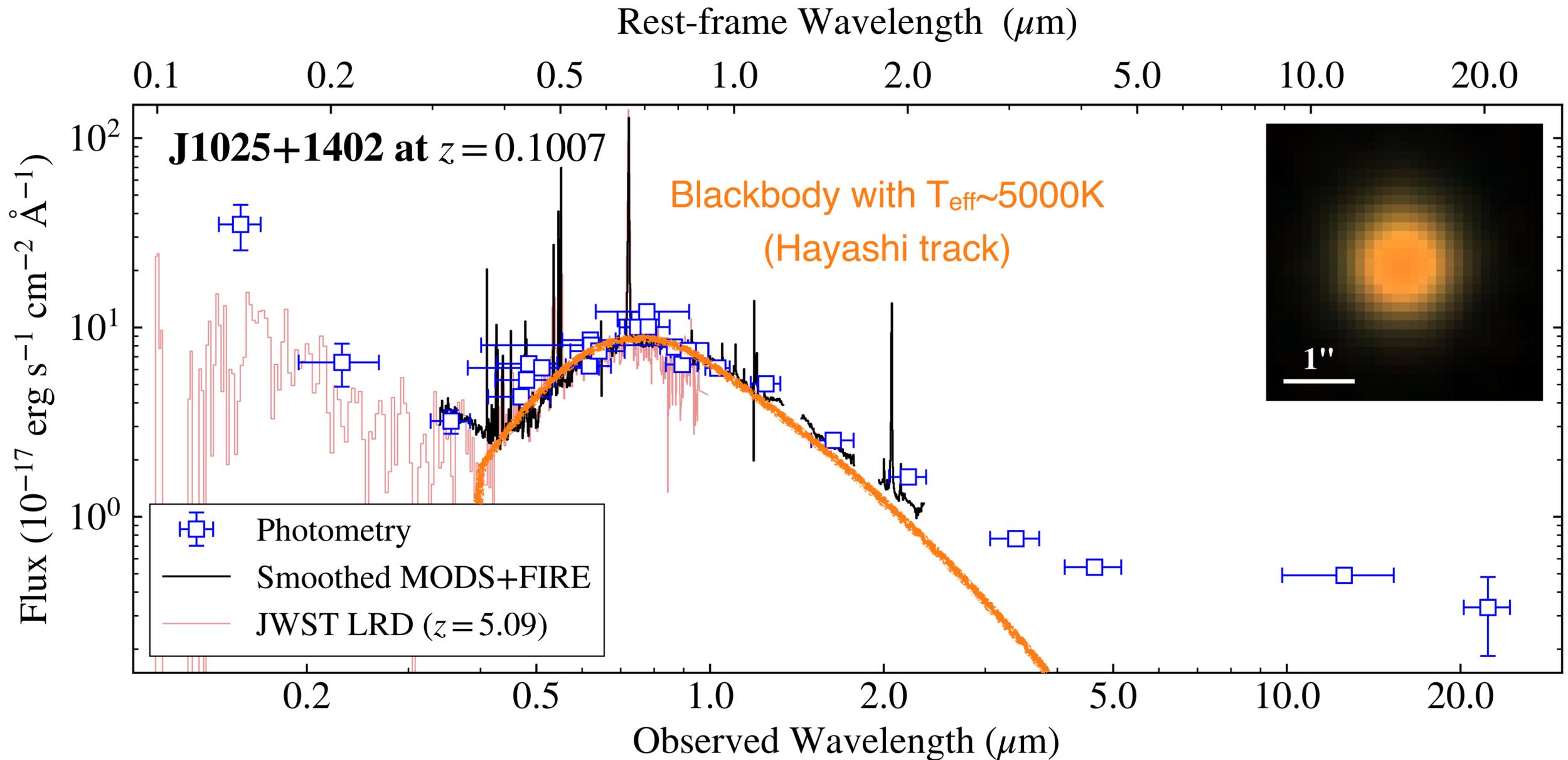
A self-consistent explanation of (i) **Balmer break and absorption**, and (ii) **red optical and weak infrared continua** of LRDs

4. Future perspectives

(with some open discussion)



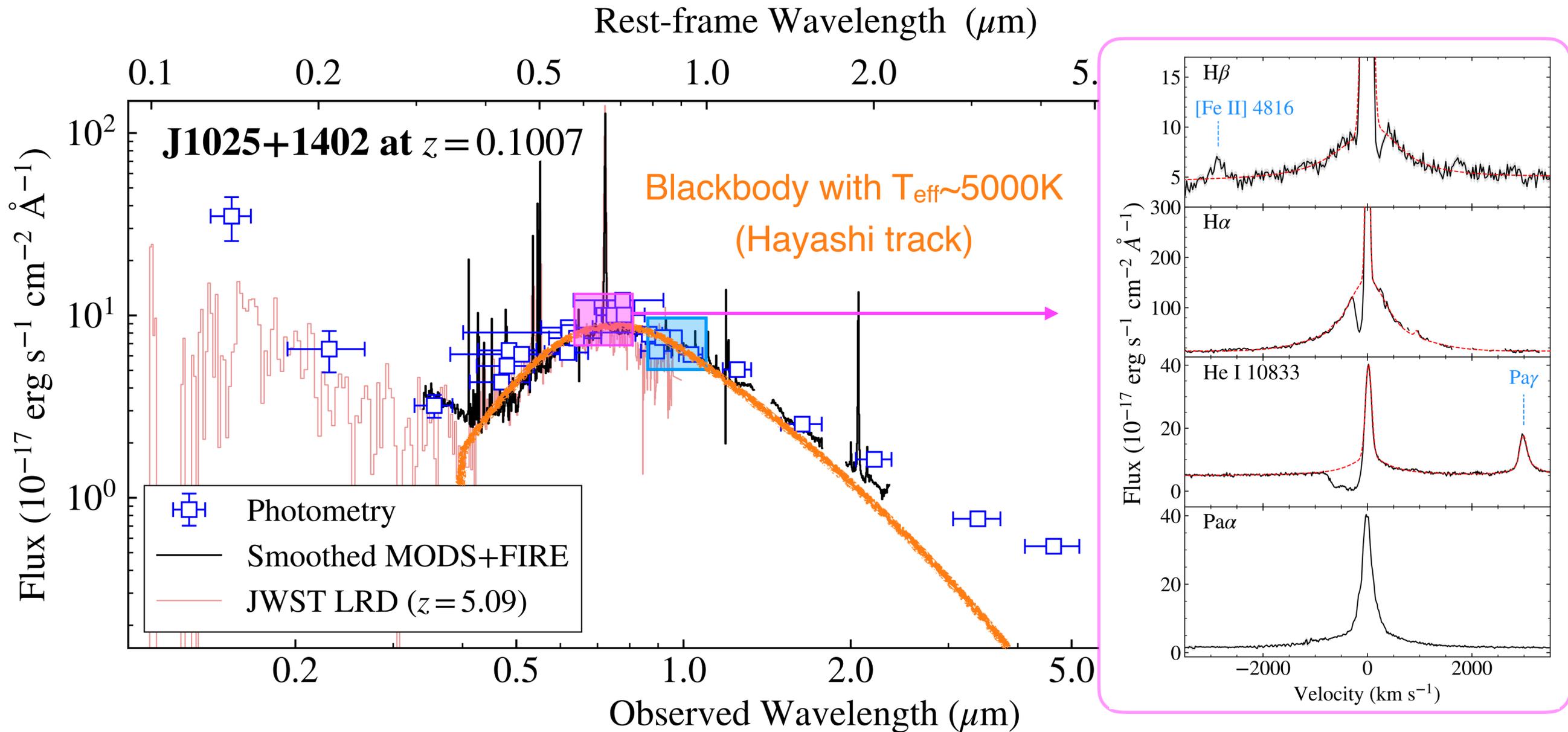
Low-z objects with LRD characteristics



X.Lin et al. + KI (2025)
see also X.Ji et al. (2025b)

- BLAGN with a V- and Λ -shaped SED ($T_{\text{eff}} = 5000\text{K}$)
- Absorption features seen in **stellar atmospheres**

Low-z objects with LRD characteristics

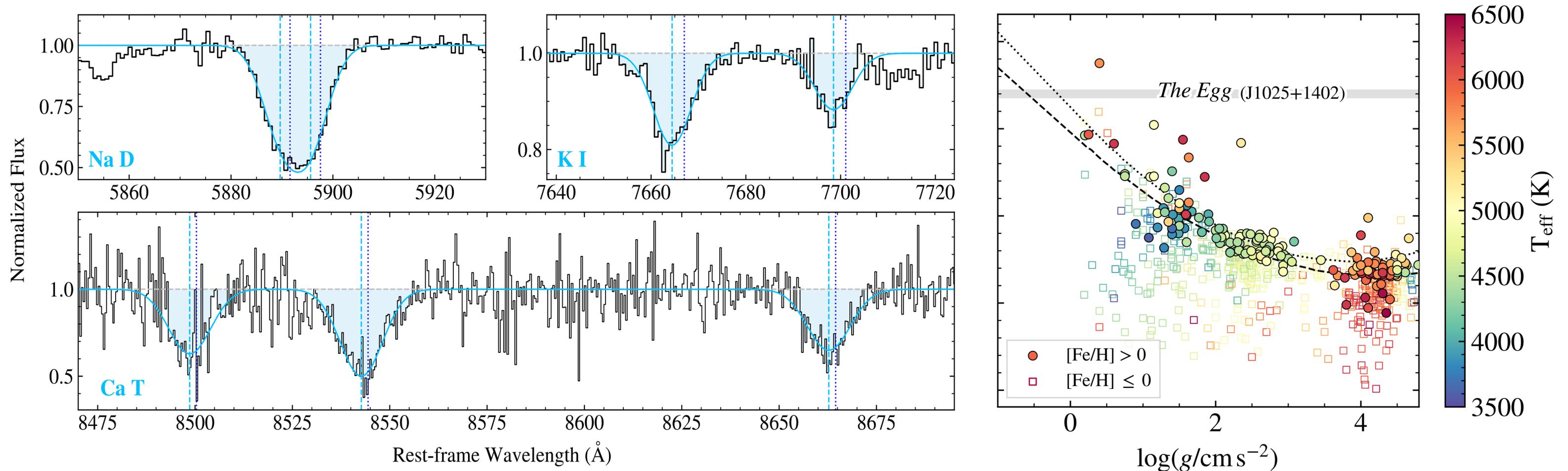


X.Lin et al. + KI (2025)
see also X.Ji et al. (2025b)

- BLAGN with a V- and Λ -shaped SED ($T_{\text{eff}} = 5000\text{K}$)
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Cooled dense atmospheres?

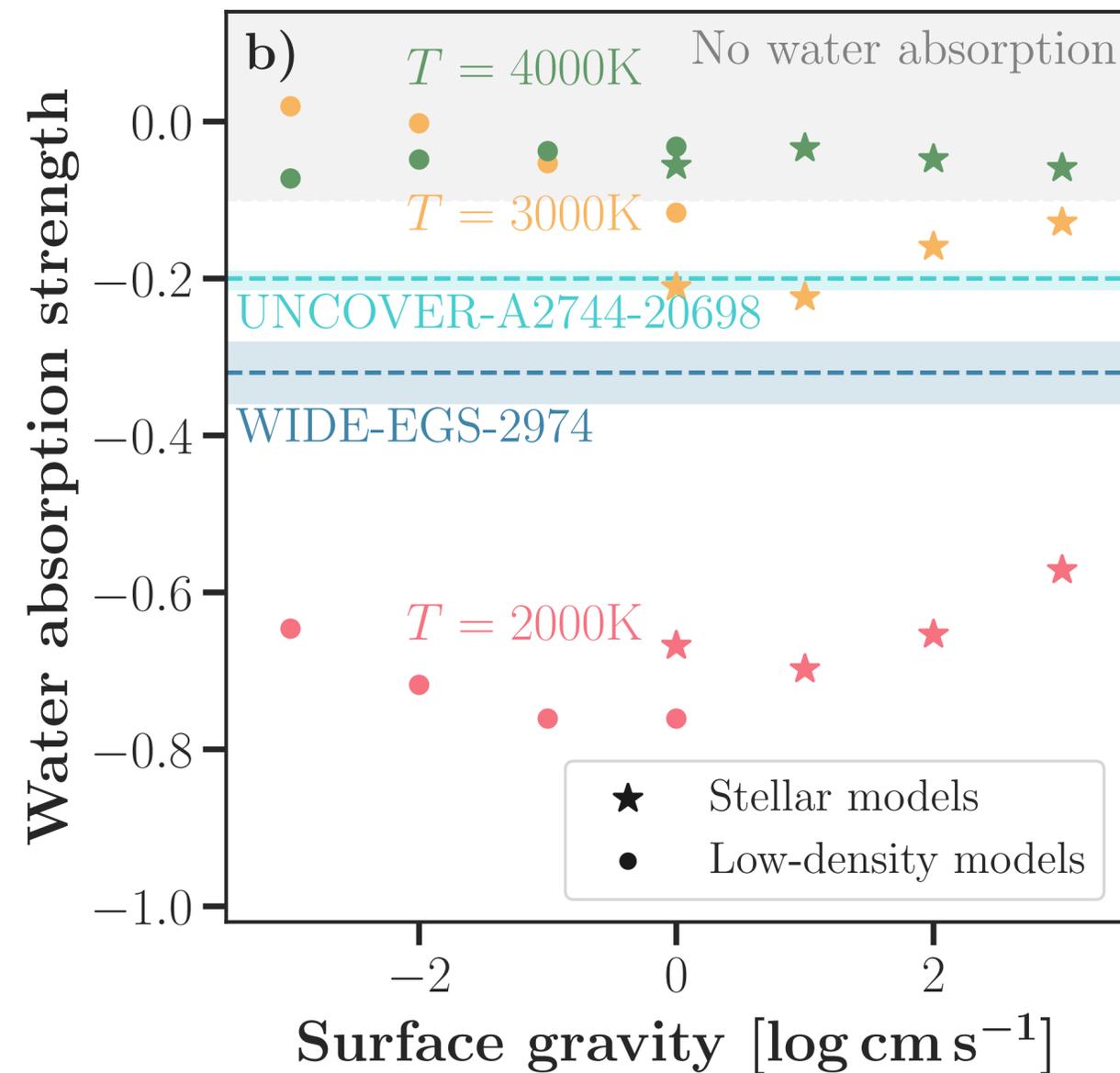
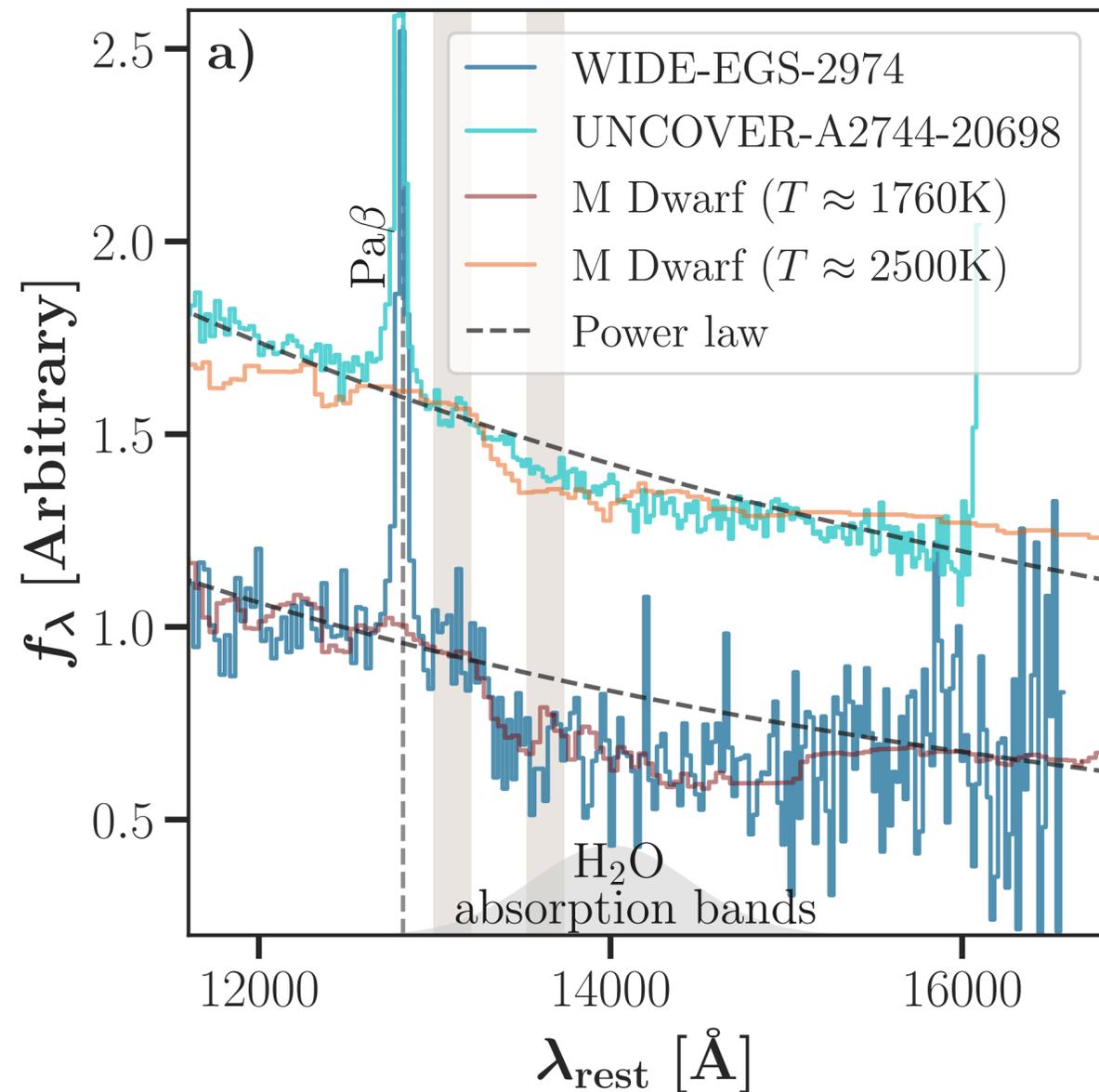
Low-ionization metal absorptions (Na D, K I, Ca T, Ti I, etc)



X.Lin et al. + KI (2025)
see also X.Ji et al. (2025b)

- BLAGN with a V- and Λ -shaped SED ($T_{\text{eff}} = 5000\text{K}$)
- Absorption features seen in **stellar atmospheres**

Cooled dense atmospheres?

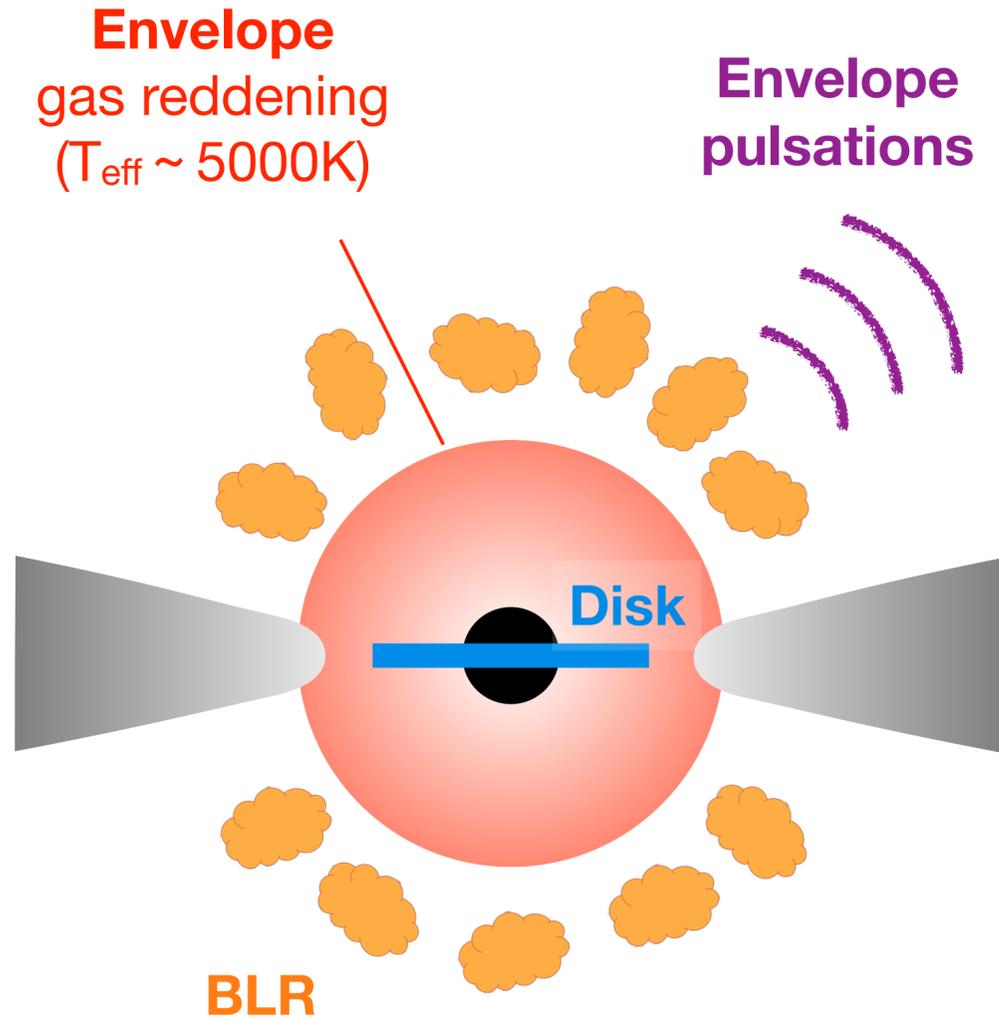


B. Wang+(2026)

- BLAGN with a V- and Λ -shaped SED ($T_{\text{eff}} = 5000\text{K}$)
- Absorption features seen in **stellar atmospheres**

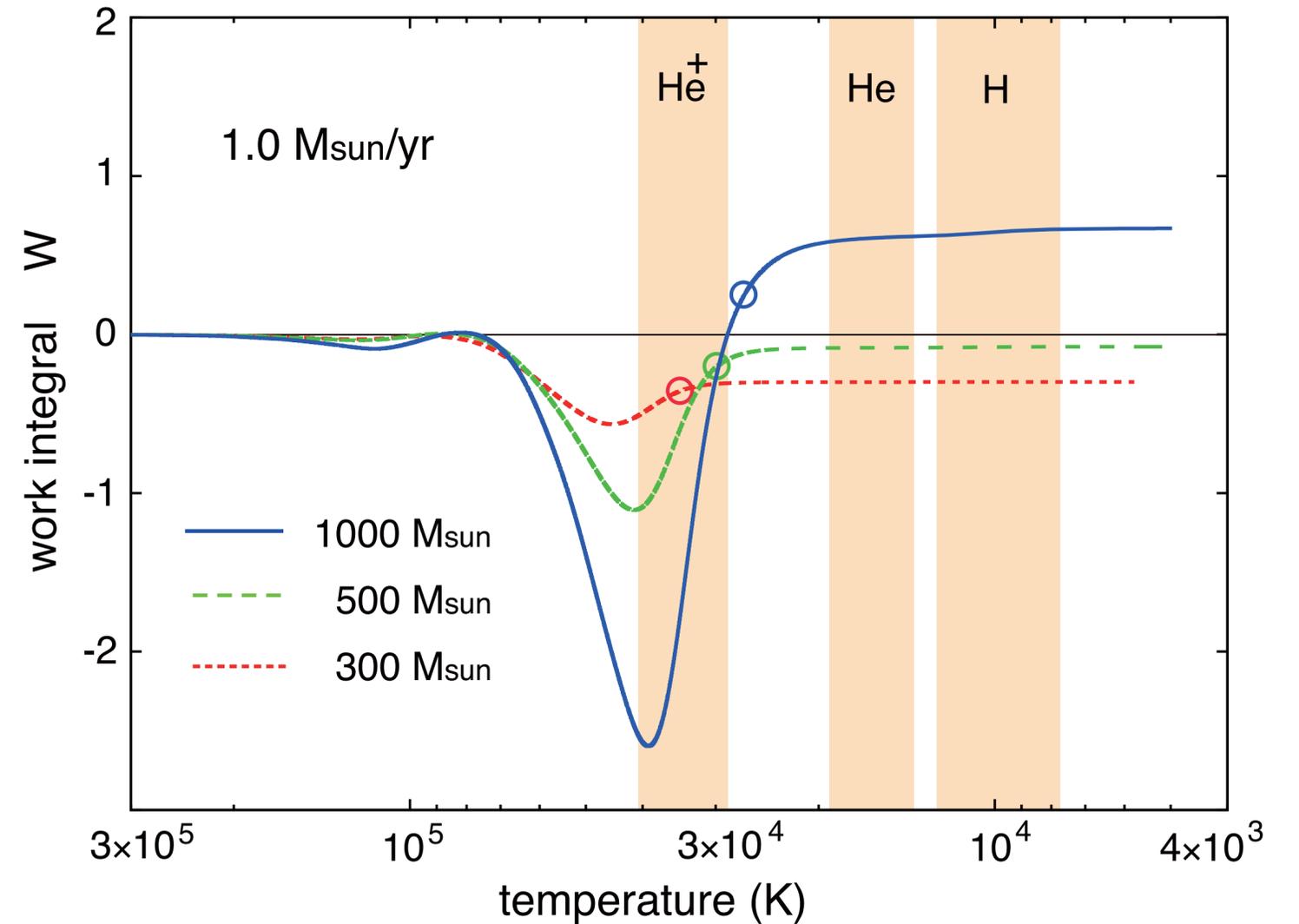
LRD variability — envelope pulsations?

Gas-enshrouded BH



$$P \simeq 17.3 \text{ yr} \left(\frac{L}{10^{11} L_{\odot}} \right)^{1/4} \left(\frac{T_{\text{eff}}}{5000 \text{ K}} \right)^{-3}$$

k-mechanism in an supermassive star's envelope



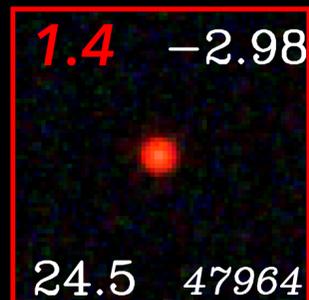
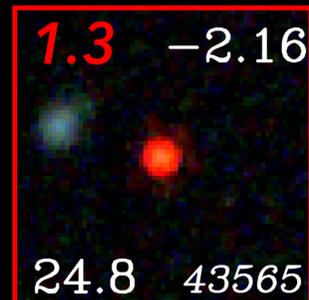
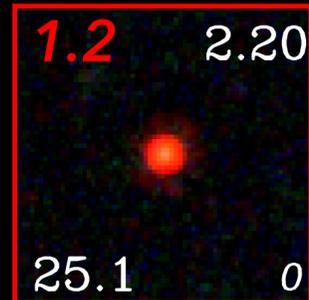
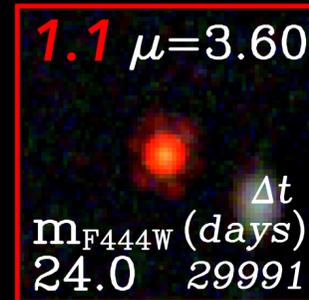
KI, Hosokawa & Omukai (2013)

Agreement with the “**first-overtone**” pulsation mode

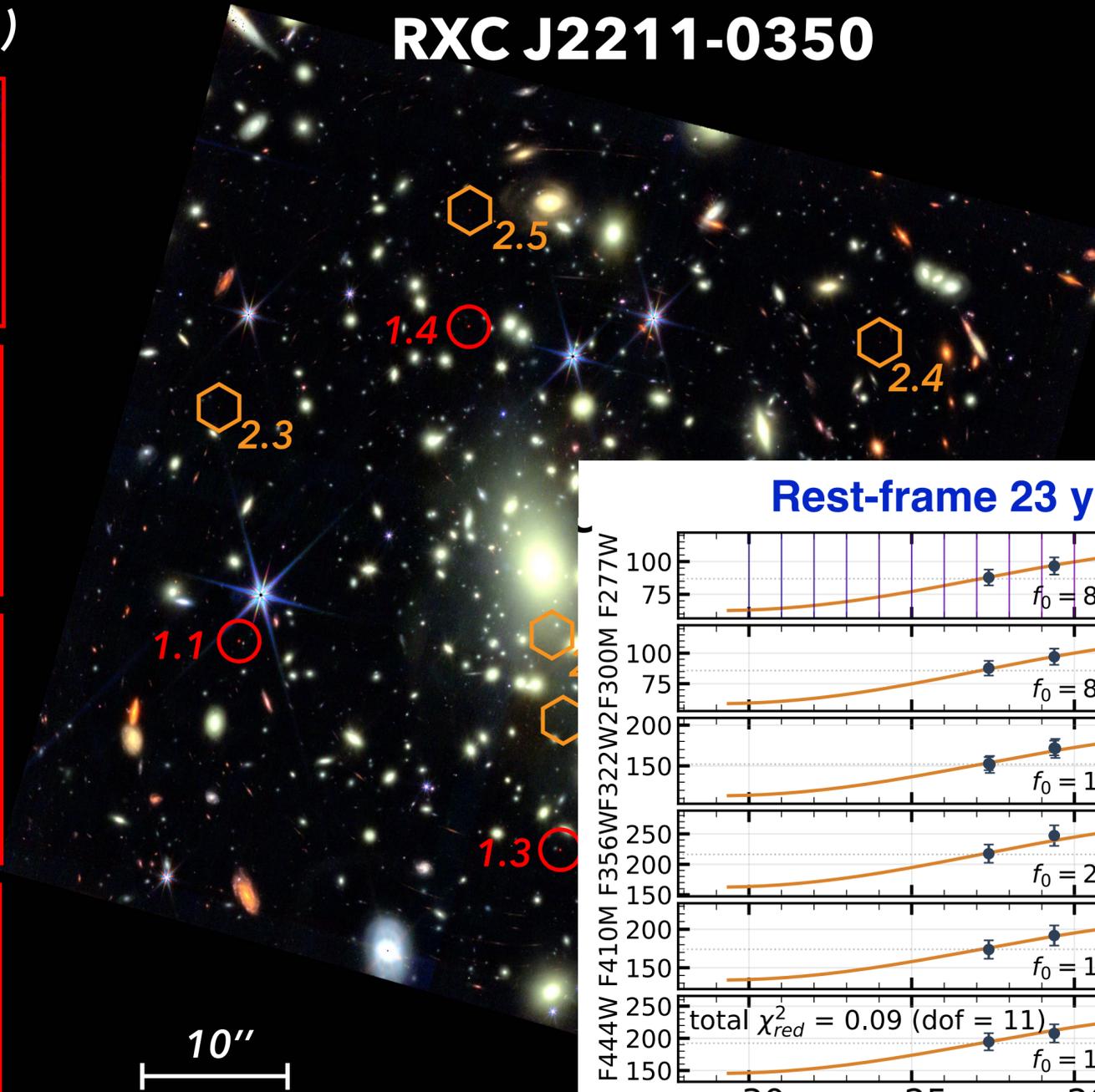
See also Cantiello+ (2025) for a quasi-star

Quadruply imaged LRD with ~ 100 yr variability

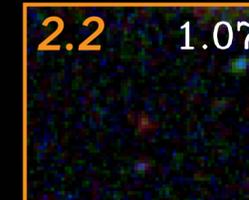
RX1 ($z=4.3$)



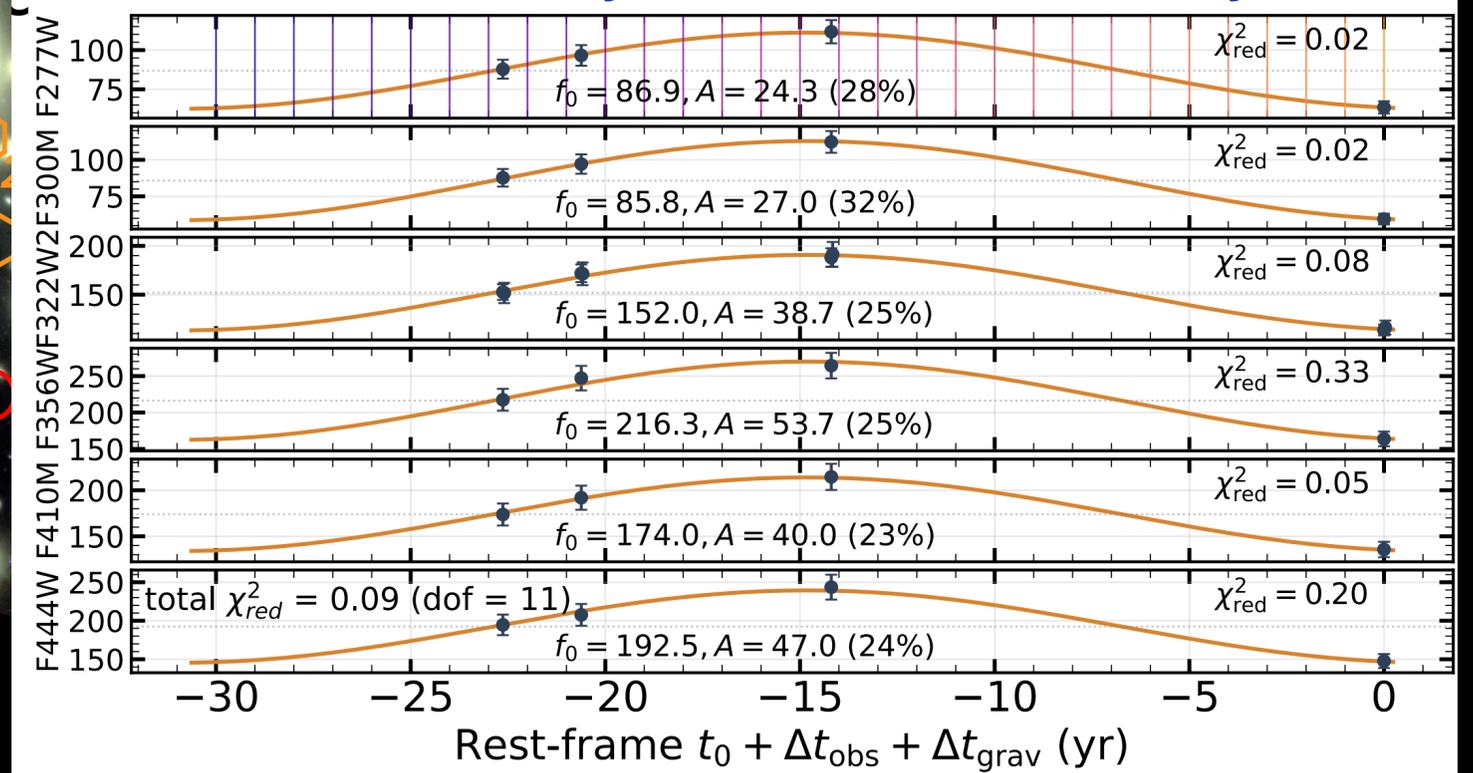
RXC J2211-0350



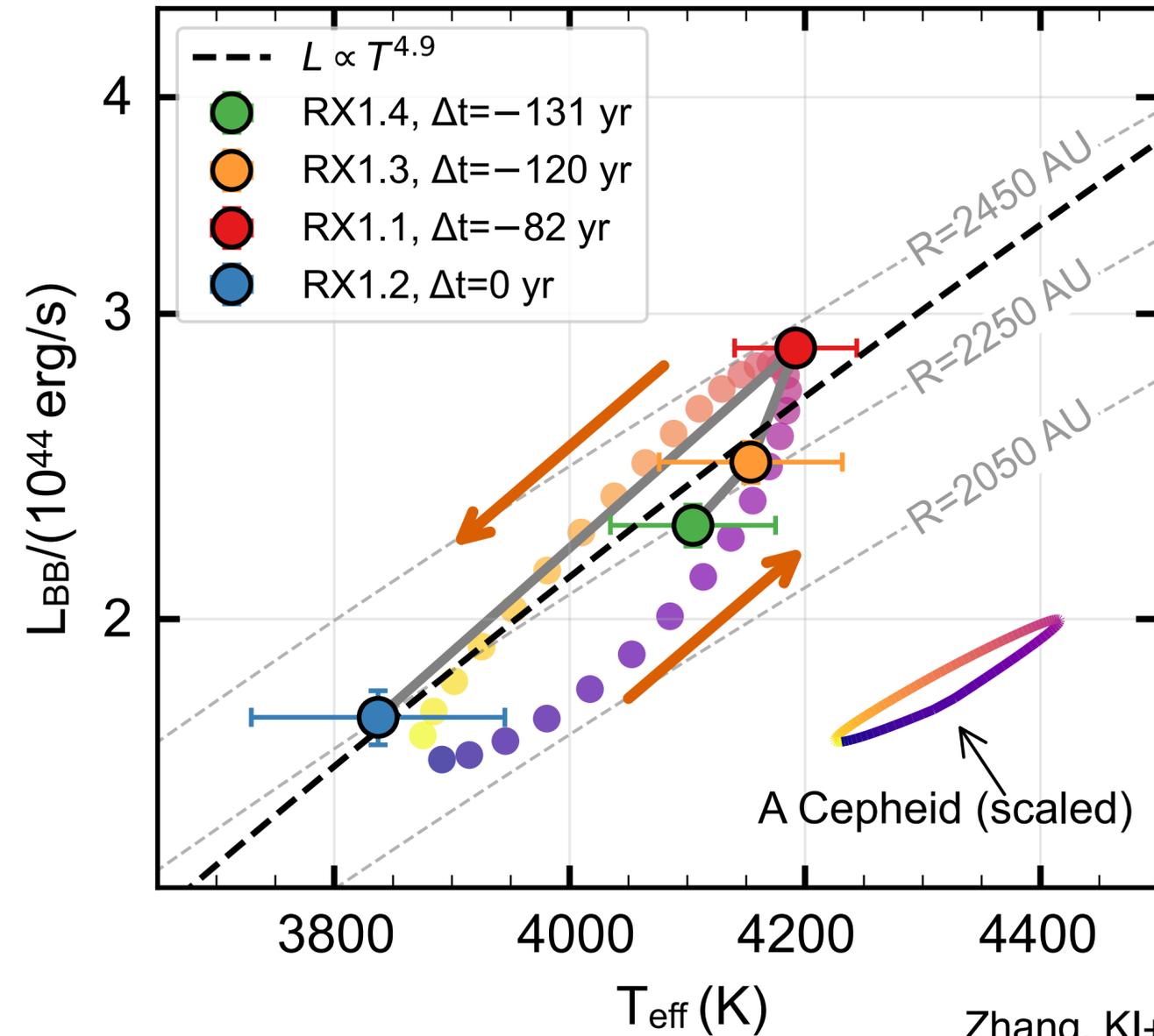
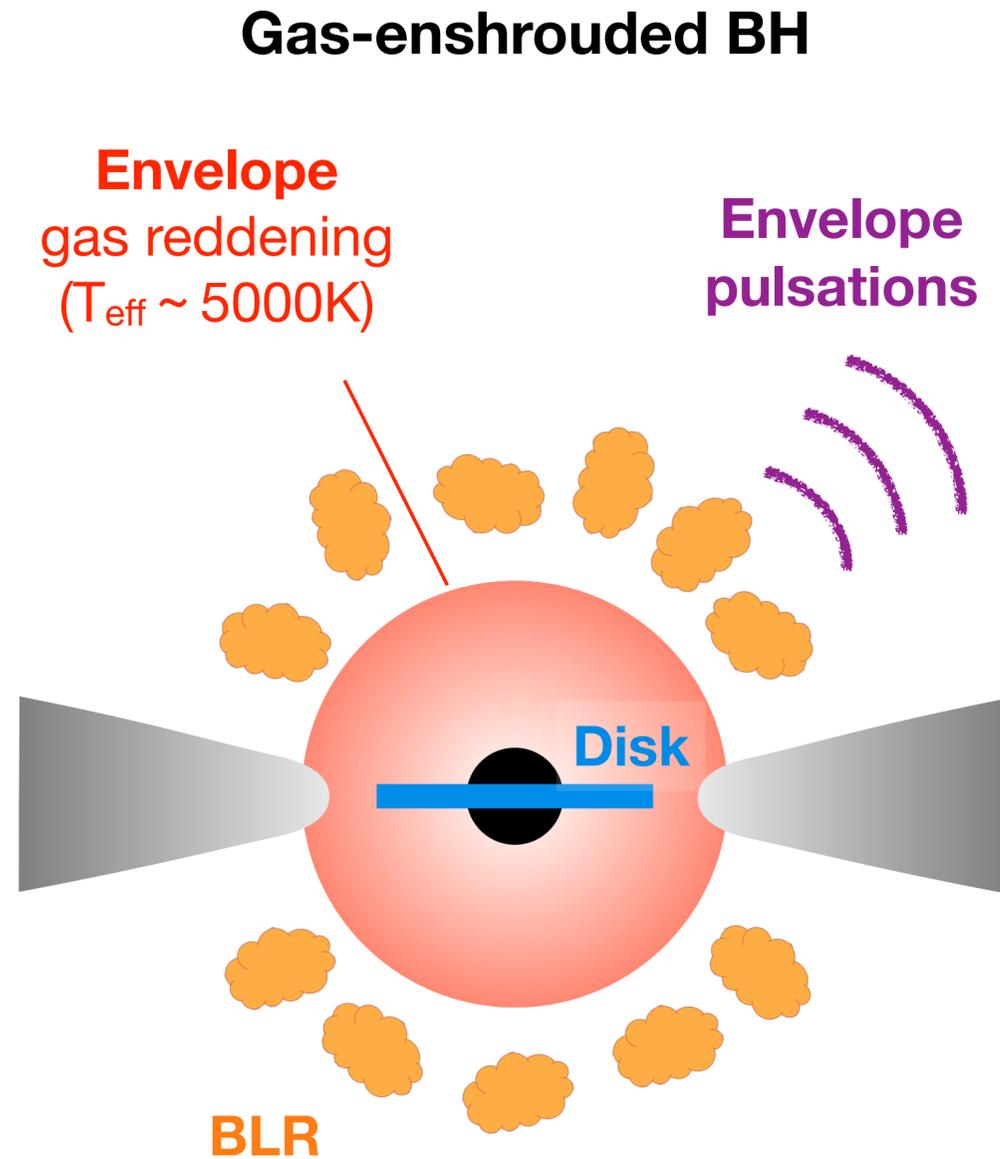
RX2 ($z=4.3$)



Rest-frame 23 yr; Observer's frame 140 yr

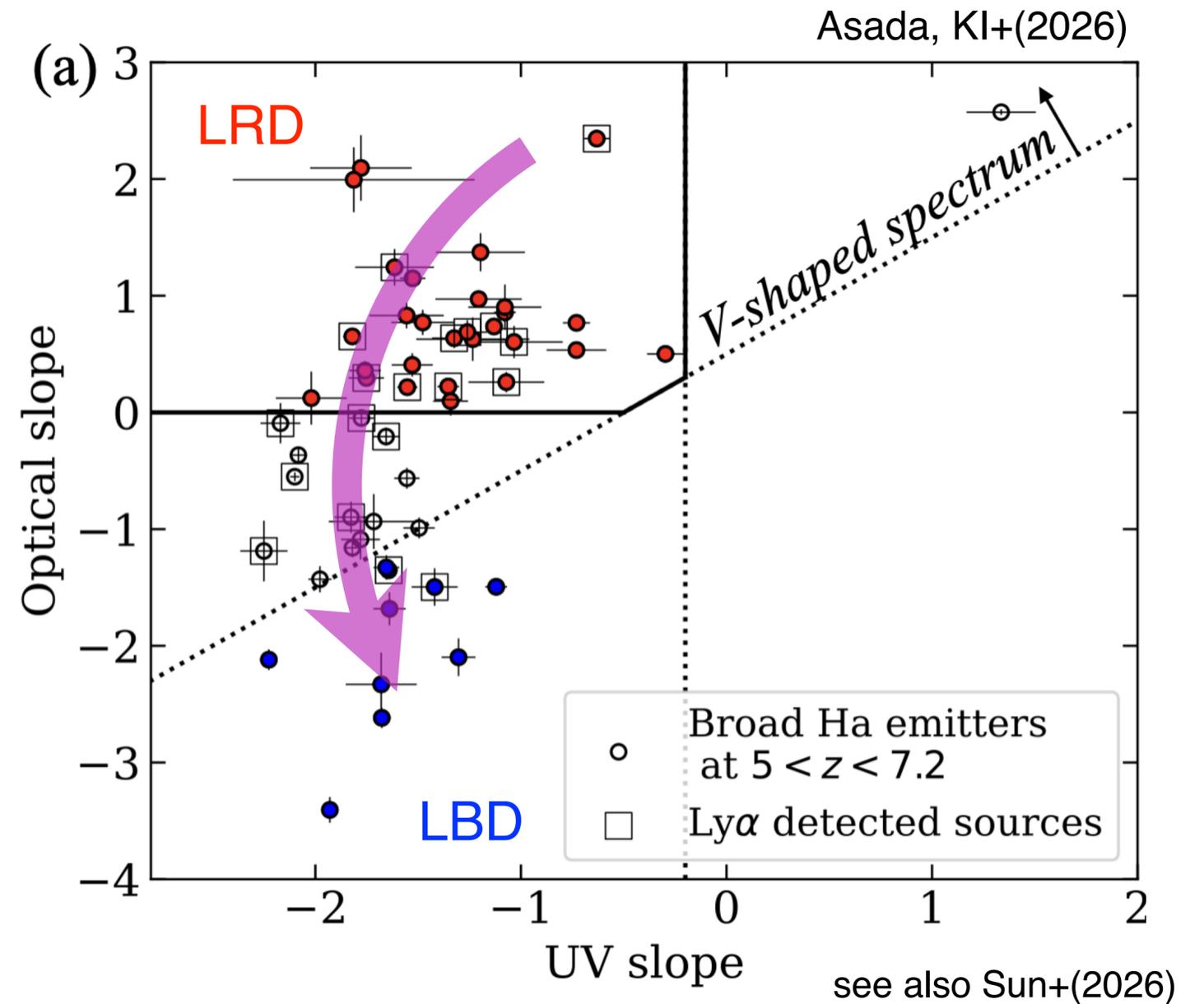
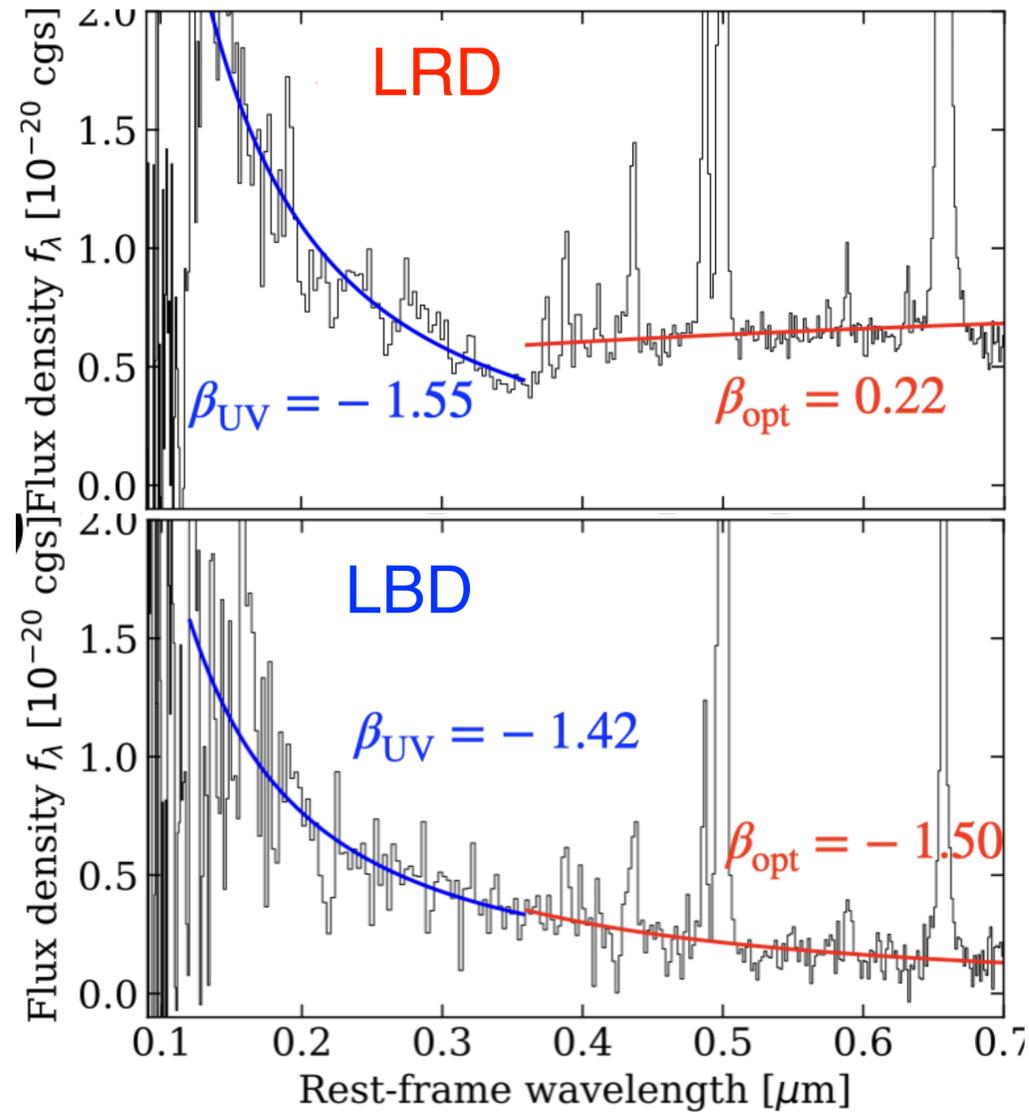
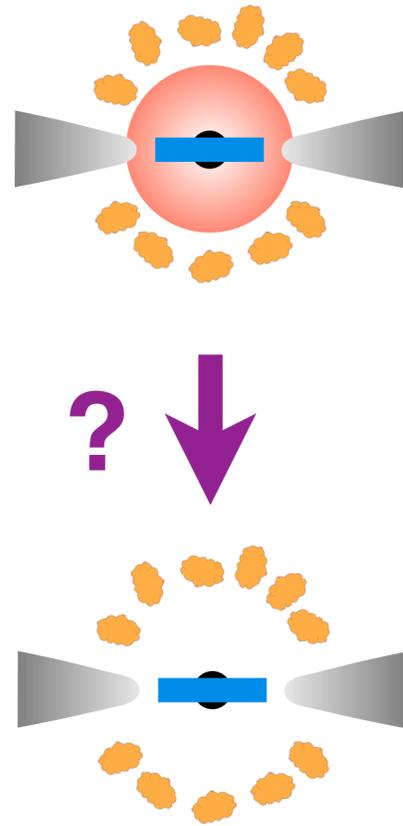


LRD variability — envelope pulsations?



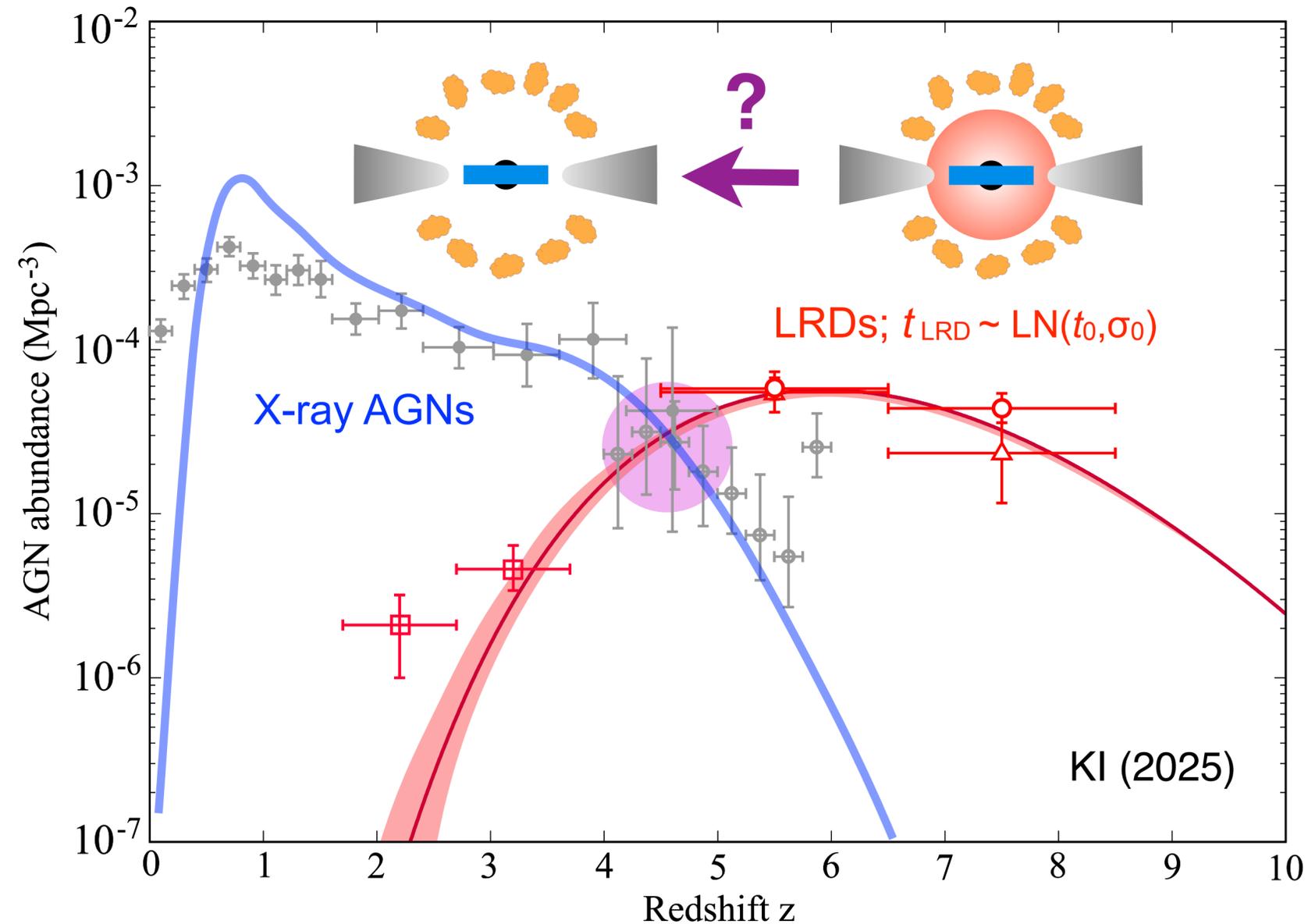
- **Cepheid-like pulsation driven variability** with a ~ 10 -yr-long period

Emergence of LRD populations



A transition from **LRDs** to normal AGNs (**LBDs**) in the later epochs

Transient behavior of LRD populations

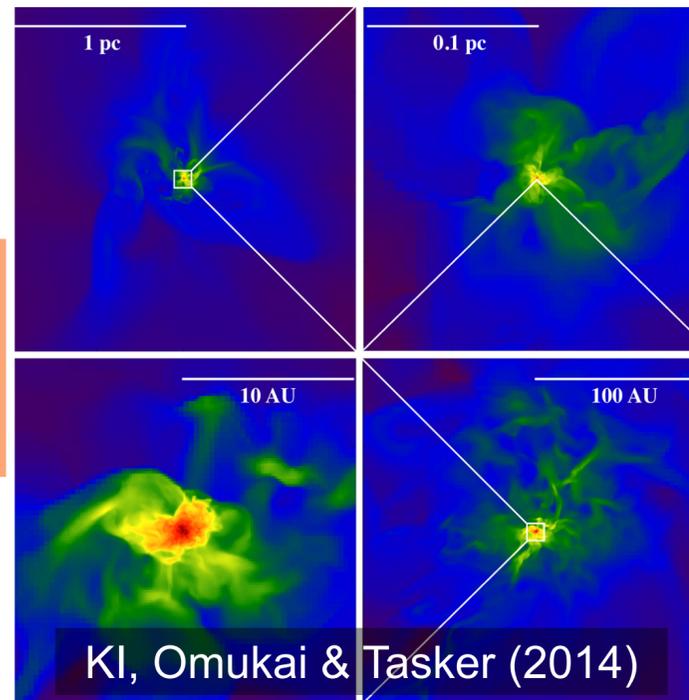


see also
Kocevski+(2025)
Y.Ma+(2025)
Tanaka+(2025)
M.Zhuang+(2025)

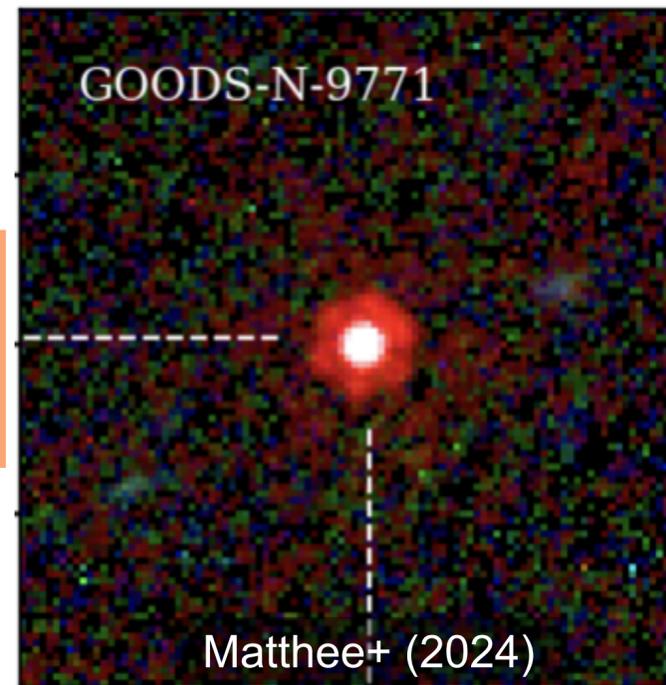
A transition from **LRDs** to normal AGNs (**LBDs**) in the later epochs through envelope feeding and SN/AGN feedback (?)

A missing link between seeds and QSOs

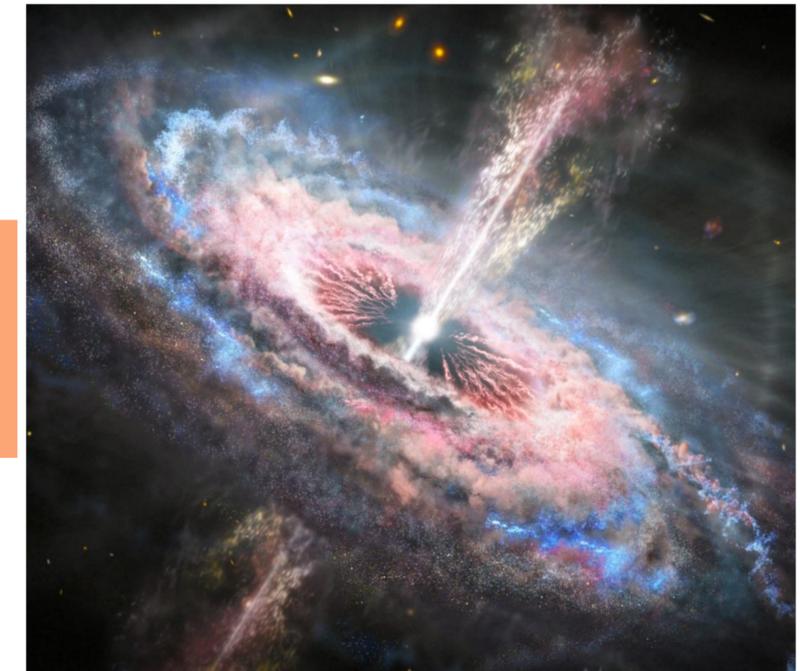
Seed BH formation
($z > 10-20$)



LRD phases
($Z \sim 4-8$)



AGNs
($z < 4-6$)



- First accretion episodes of seed BHs = **LRDs**
- LRD's spectral characteristics related to **dense gas**
- Disappearance LRD's features in later episodes (dust, X-rays, hosts)

Summary

What are Little Red Dots (LRDs)?

- A newly type of BLAGNs with v-shape UV-optical SED, and weak IR, X-rays, radio emission

(Some) Theoretical interpretations

- Heavy BH seeds form in overdense regions and can growth via transient super-Eddington accretion
- Gas-enshrouded AGNs explain co-existence of Balmer absorption and beak, and other key LRD's properties

Welcome to LRD business!

similar to quasar discovery in 1960s



An illustration by Chat-GPT