

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 effect is a sense of vast cosmic scale and dynamic activity.

Little Red Dots as the Very First Activity of Black Hole Growth

Kohei Inayoshi

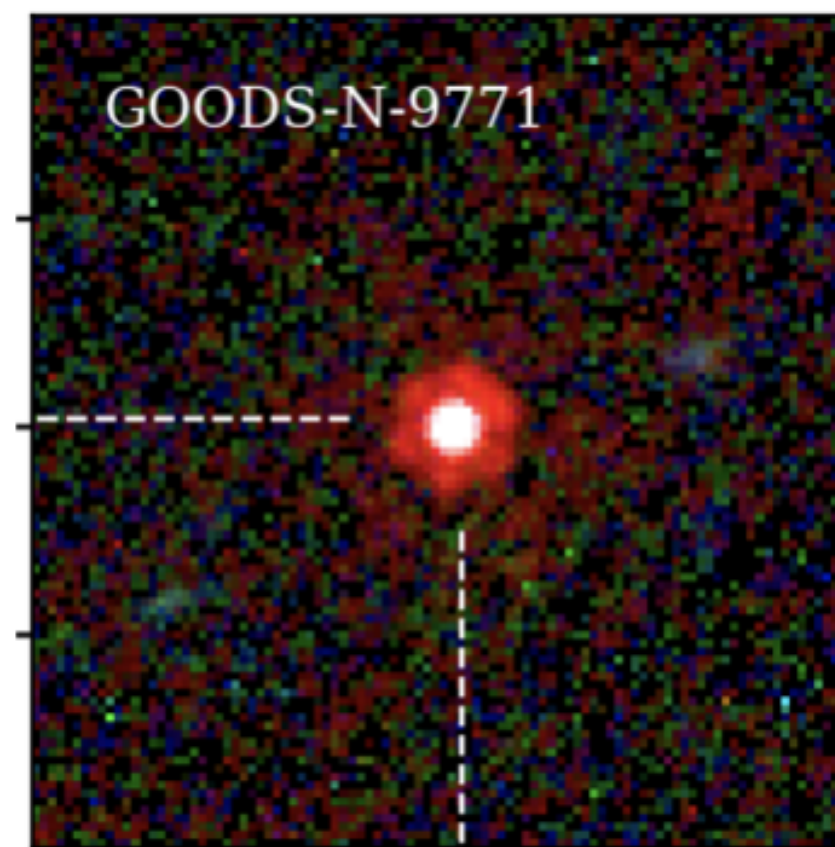
**Peking University
Kavli Institute for Astronomy & Astrophysics**

August 6st, 2025 @YITP

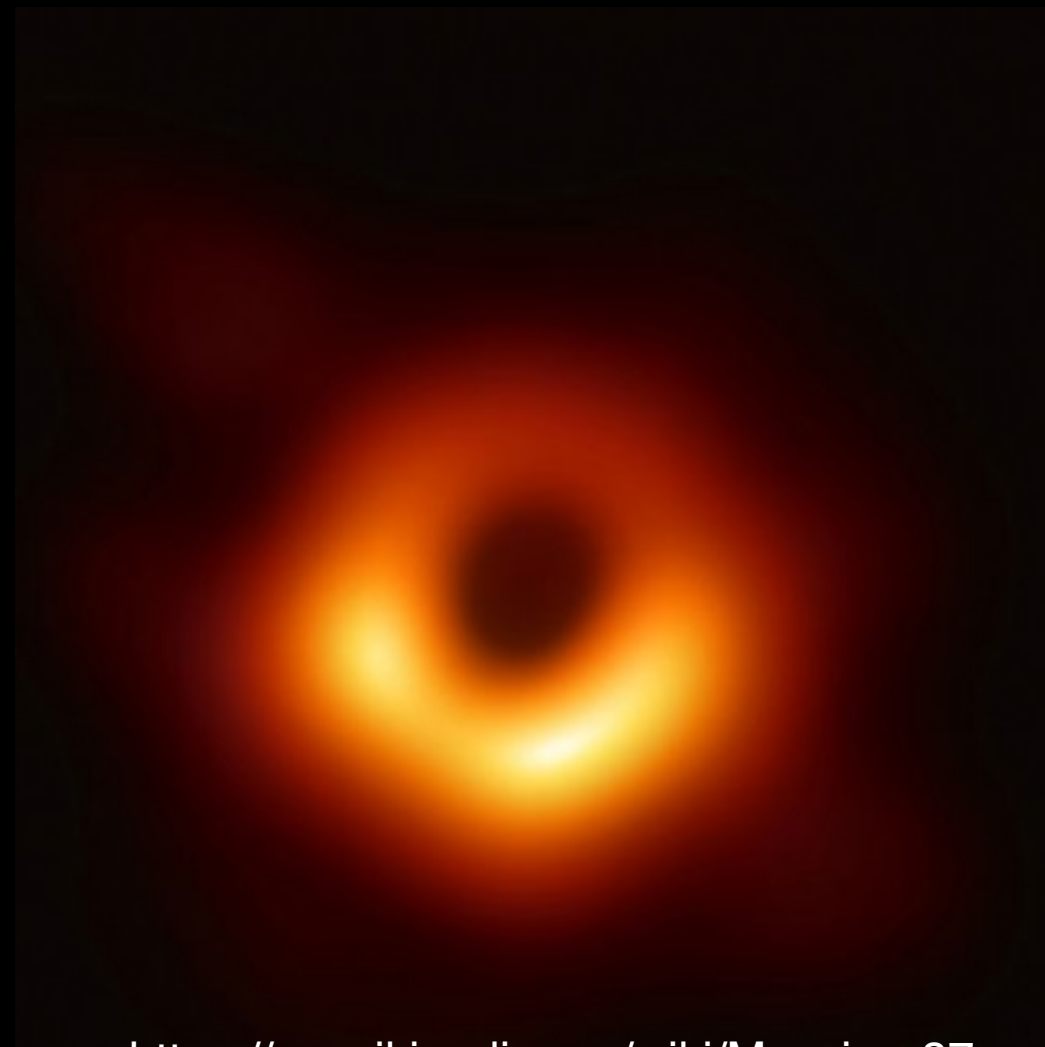
Outline

1. Observational overviews
2. A new AGN population, LRDs
super-Eddington, Balmer, dust...
3. New hypothesis:
LRDs = Very first BH growth phases

1. Observational overviews



Supermassive Black Holes (SMBH)

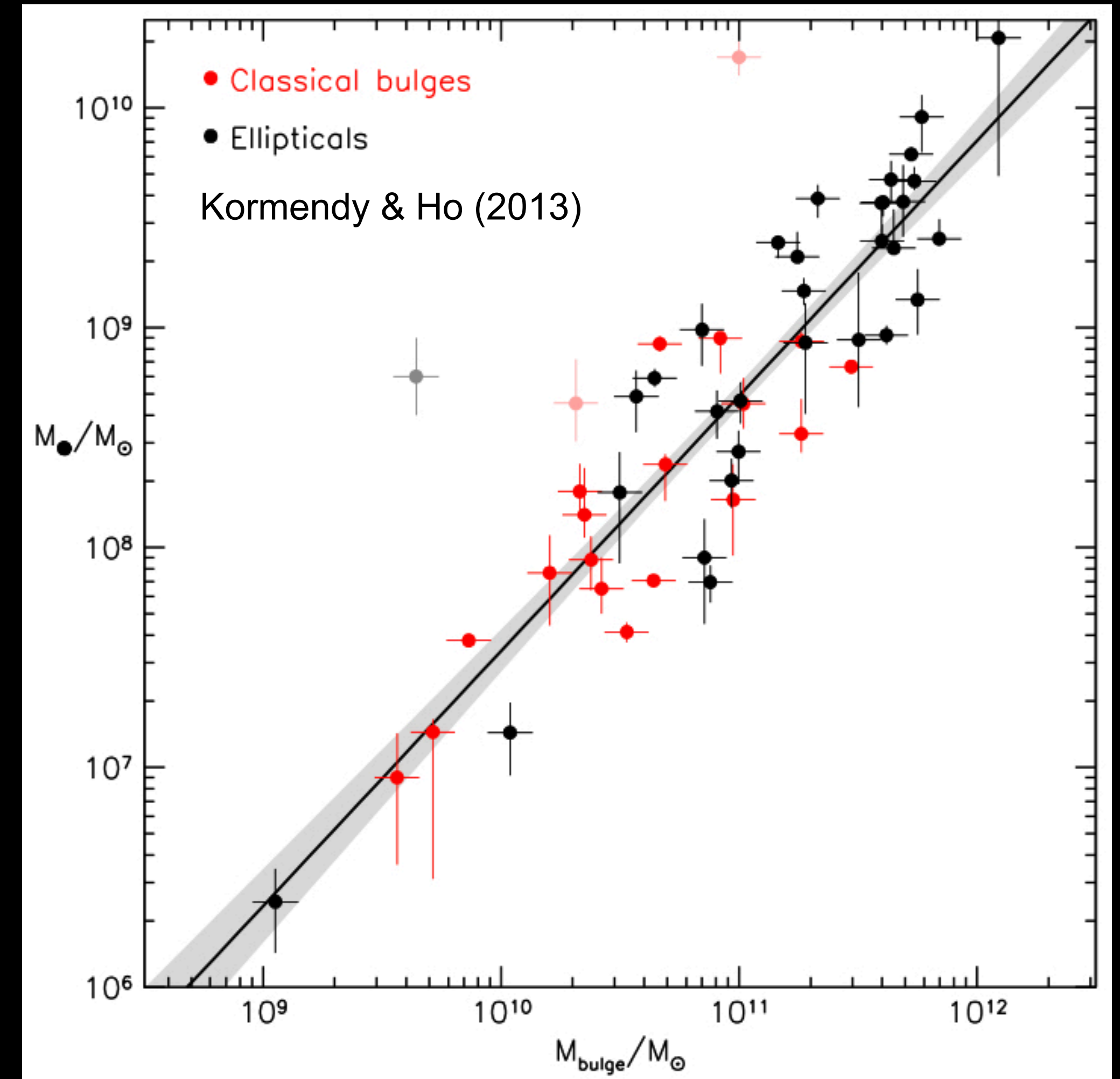


https://en.wikipedia.org/wiki/Messier_87



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

Black Hole mass



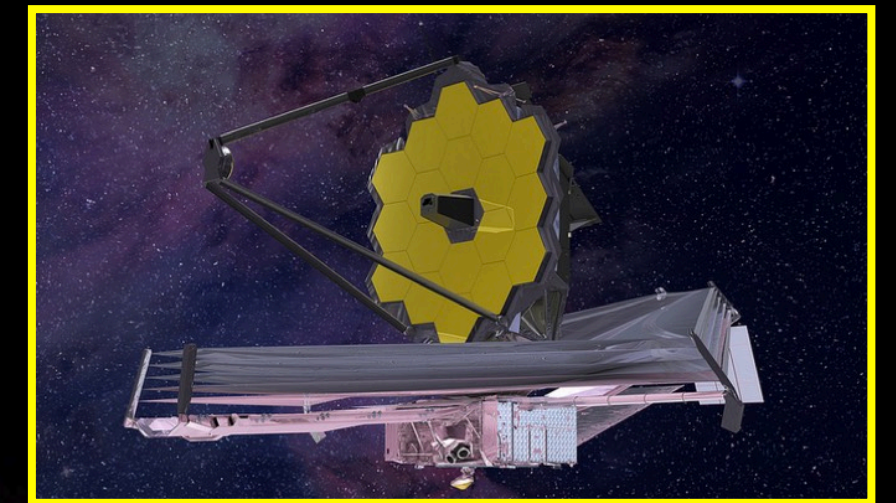
Galaxy mass

Key questions:

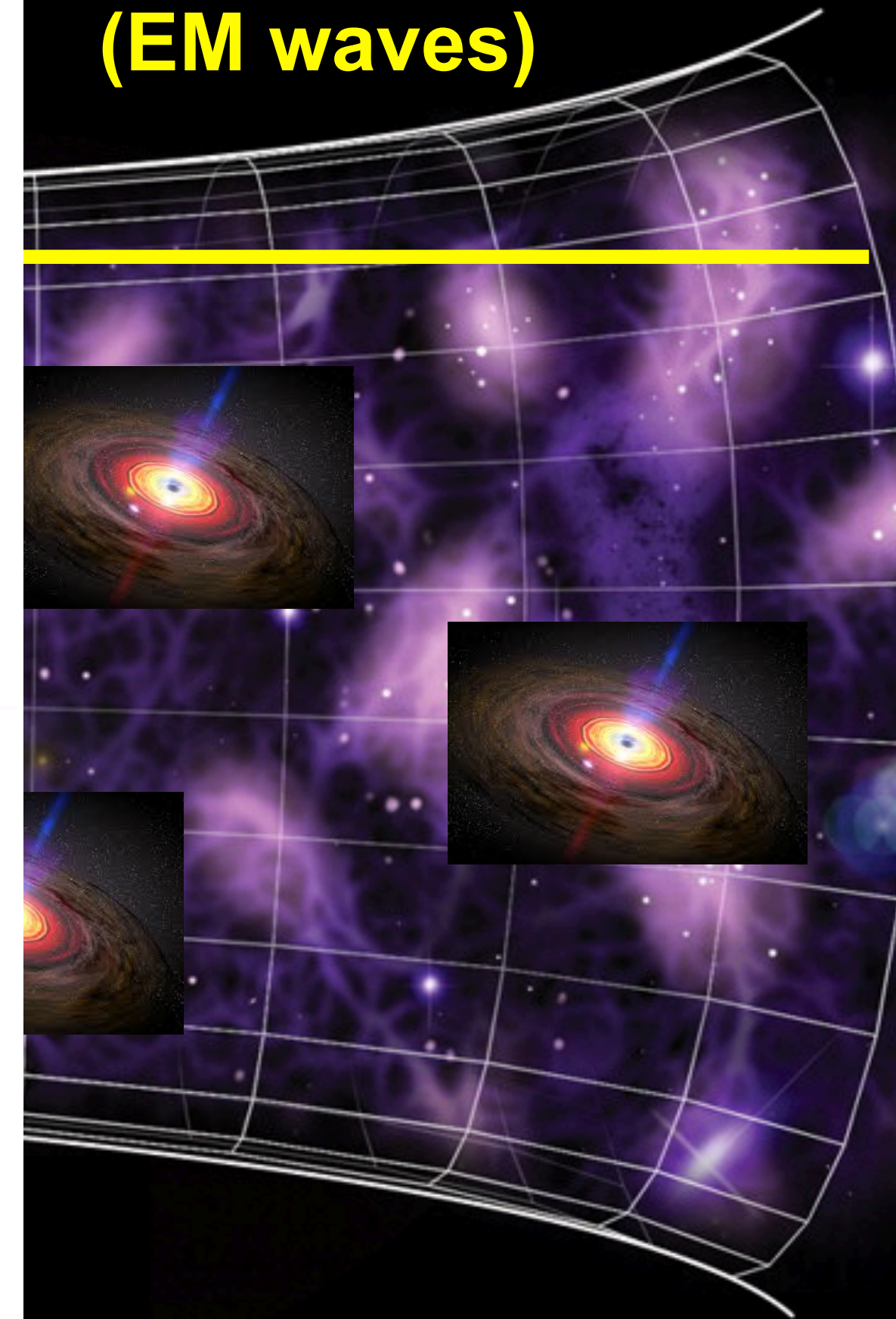
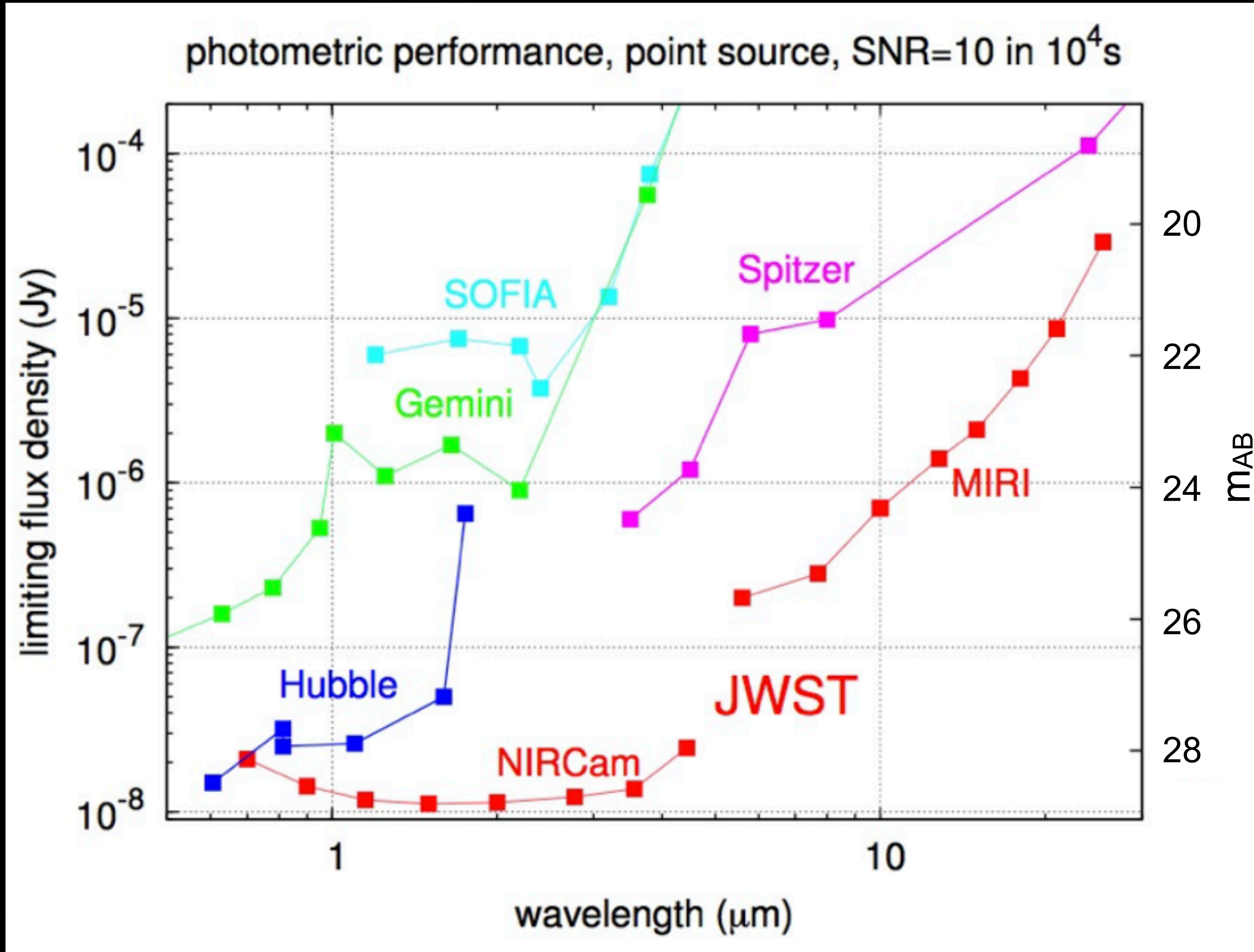
- 1) What is the origin of SMBHs?
- 2) How did BHs and galaxies interact?
- 3) Cosmological coevolution & high-z?

History of the Universe

JWST



**observable universe
(EM waves)**



z=0 (today)

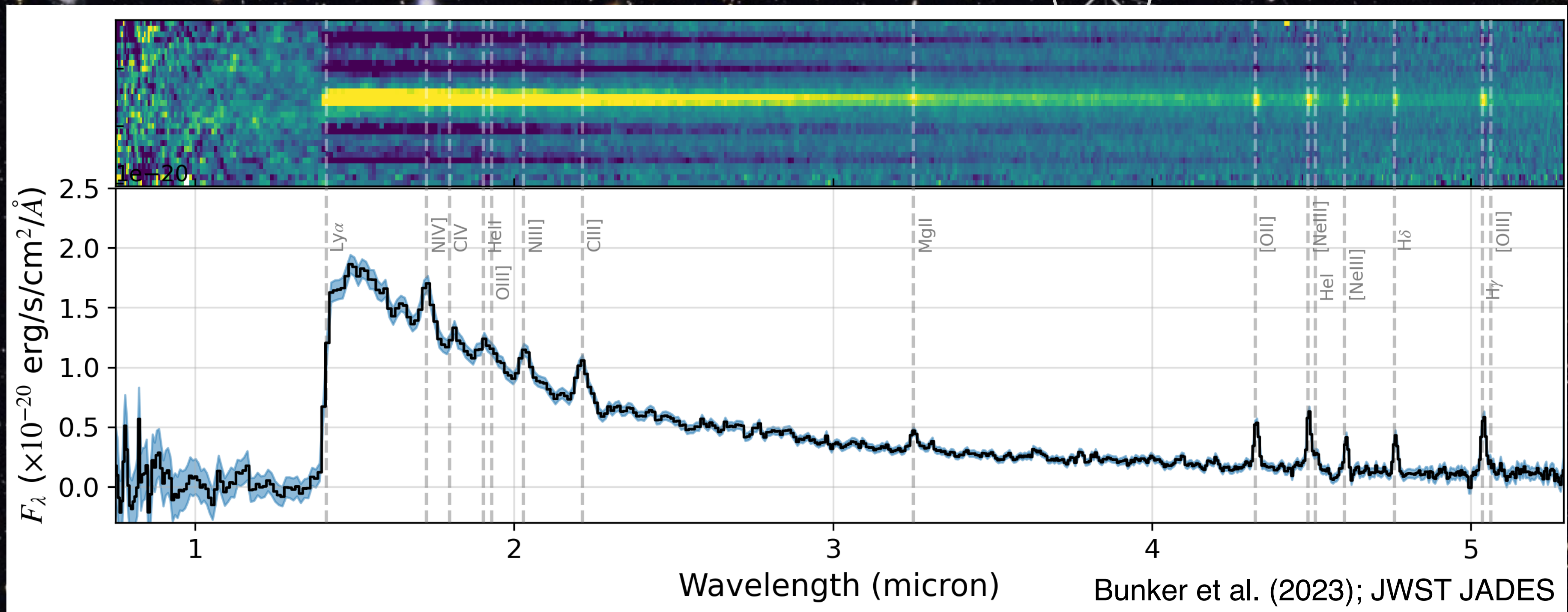
[redshift]

13.7 Gyrs

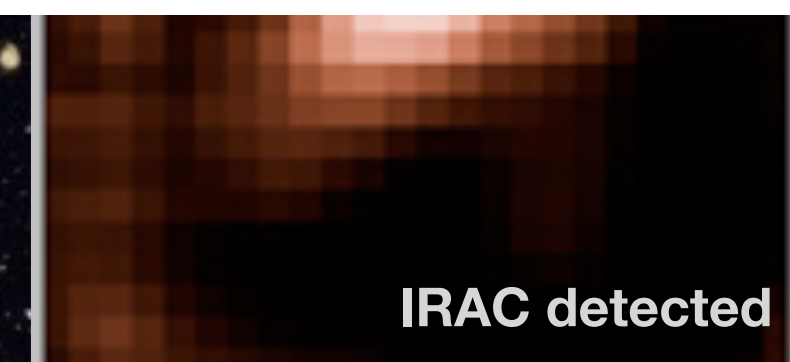
[age]

JWST capabilities for high-z sources

GN-z10-1
 $H_{160}=25.95$
 $z_{\text{phot}} = 10.2 \pm 0.4$

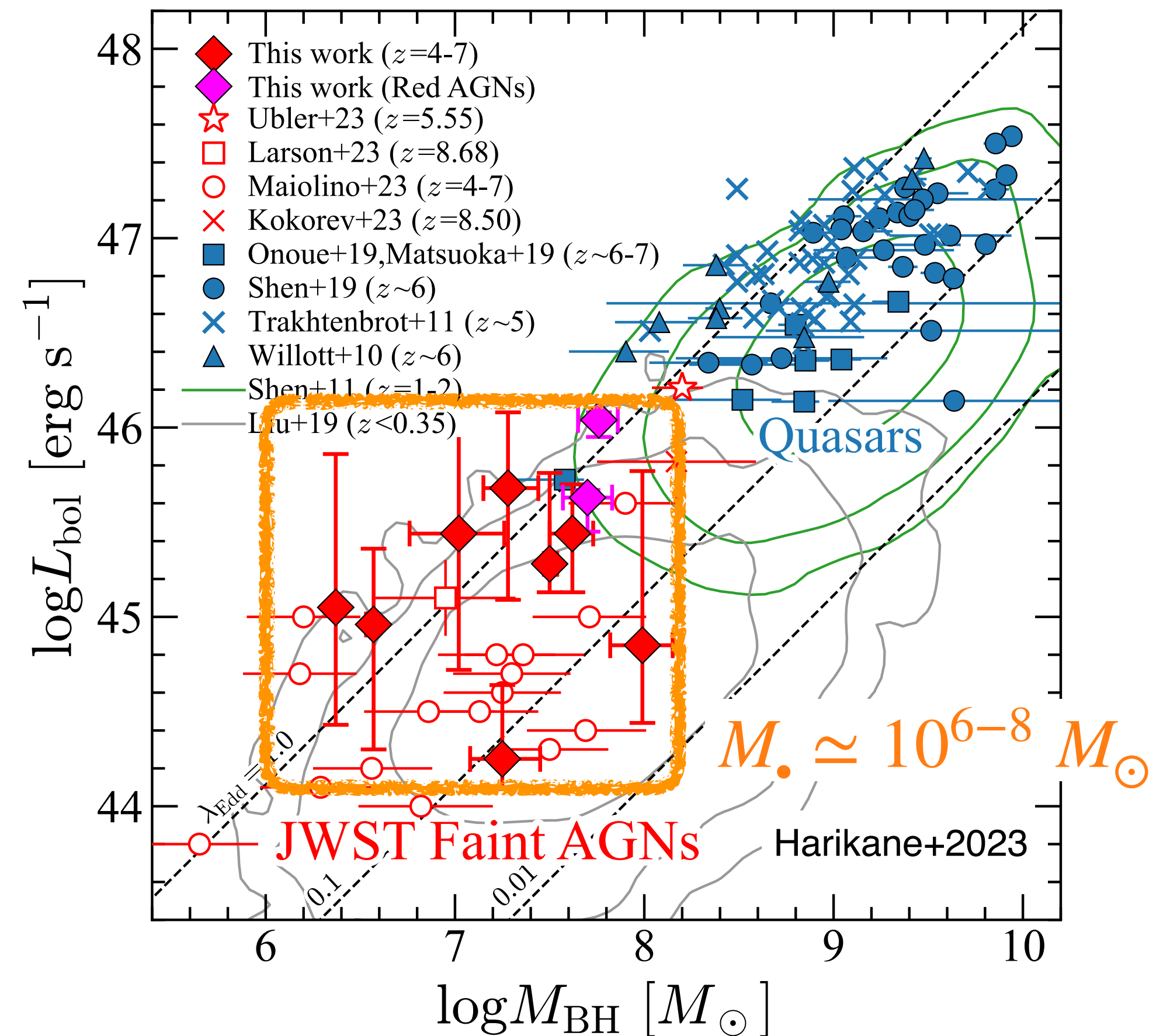
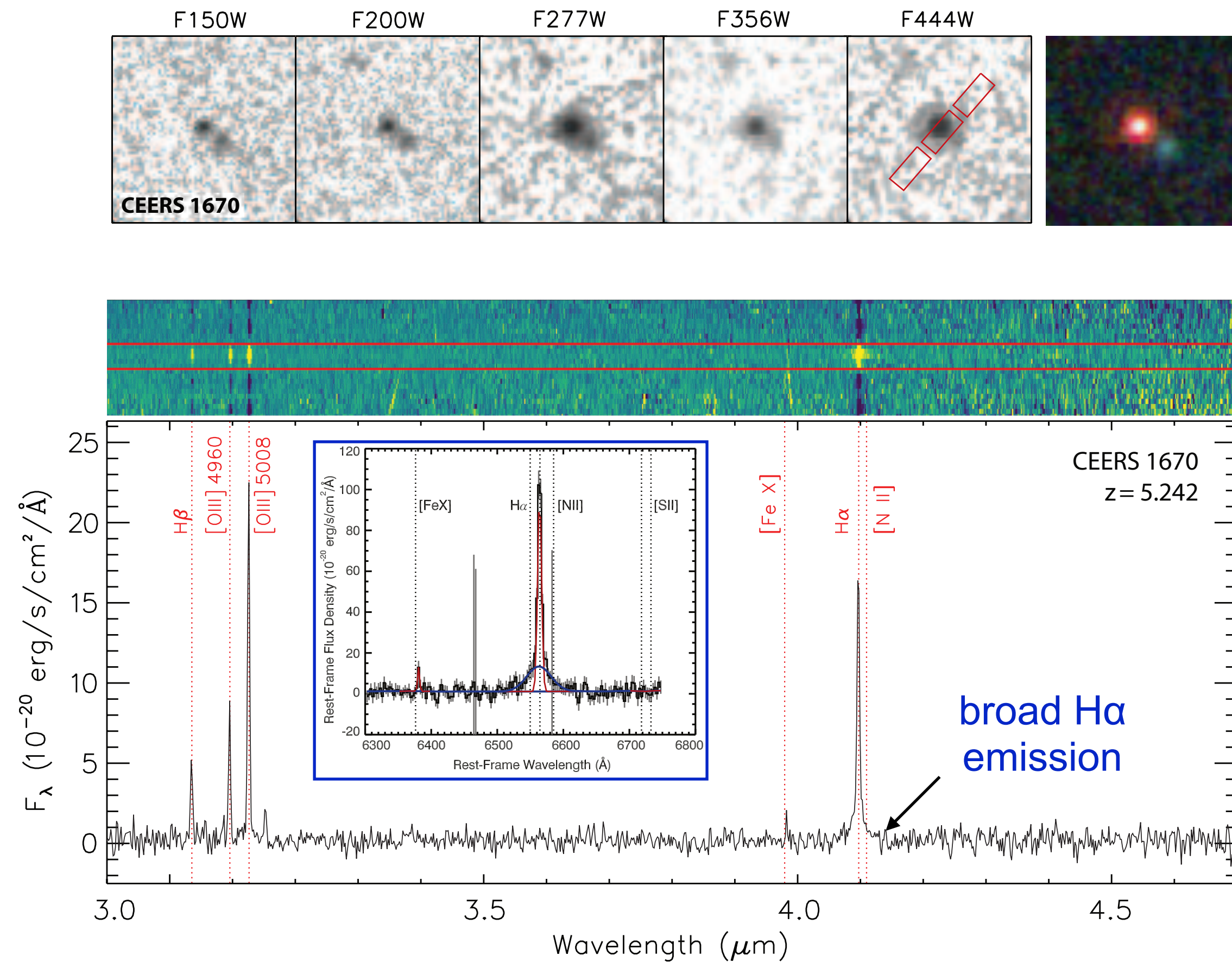


very bright $z \sim 10$ sample from Oesch+14 is
within reach of the WFC3/IR grism

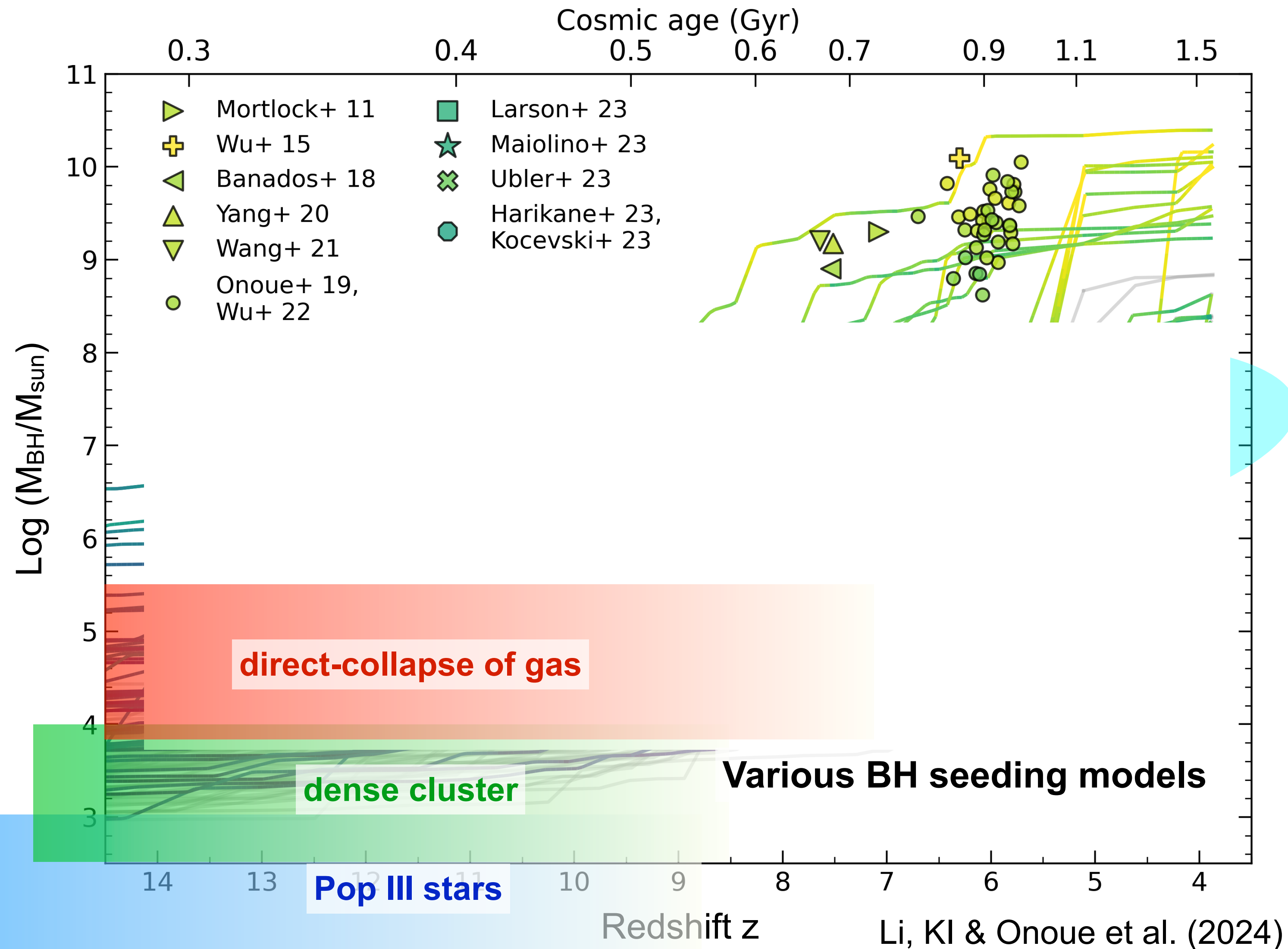


Hidden little monsters uncovered by JWST

- 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

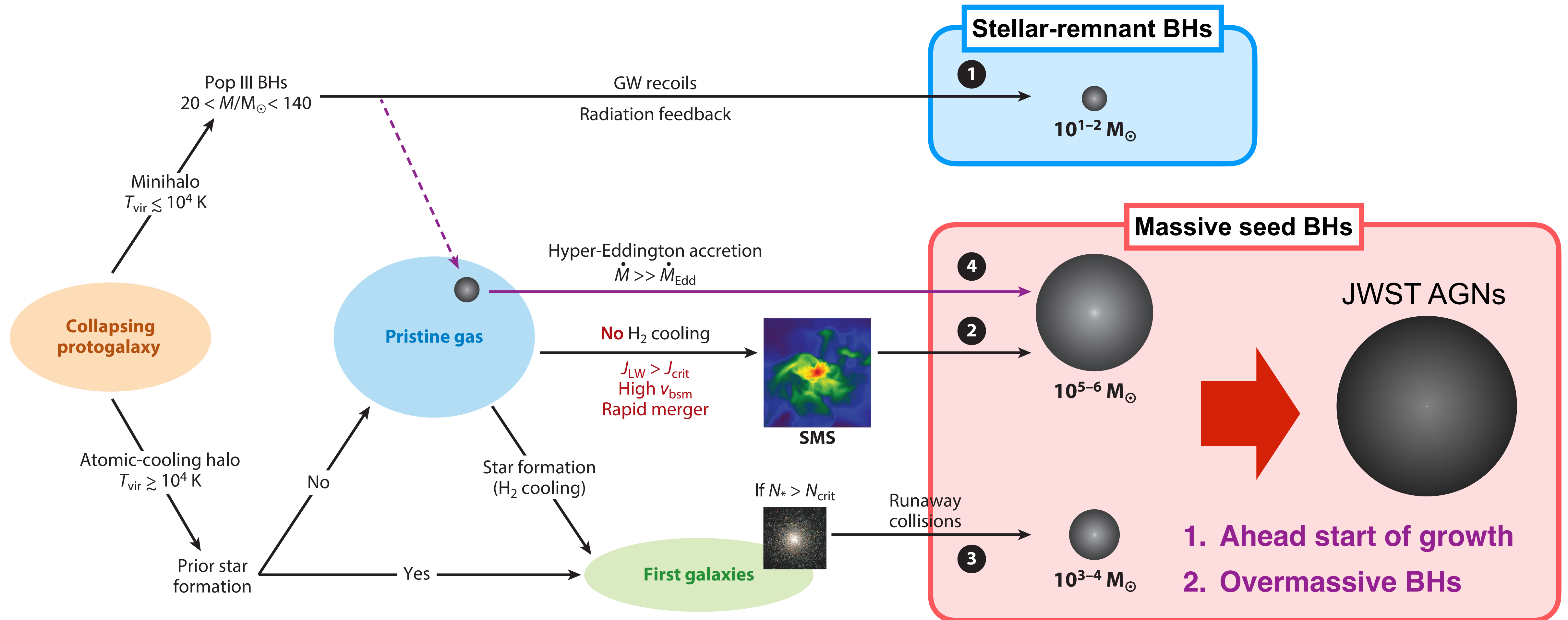


High-z SMBH population

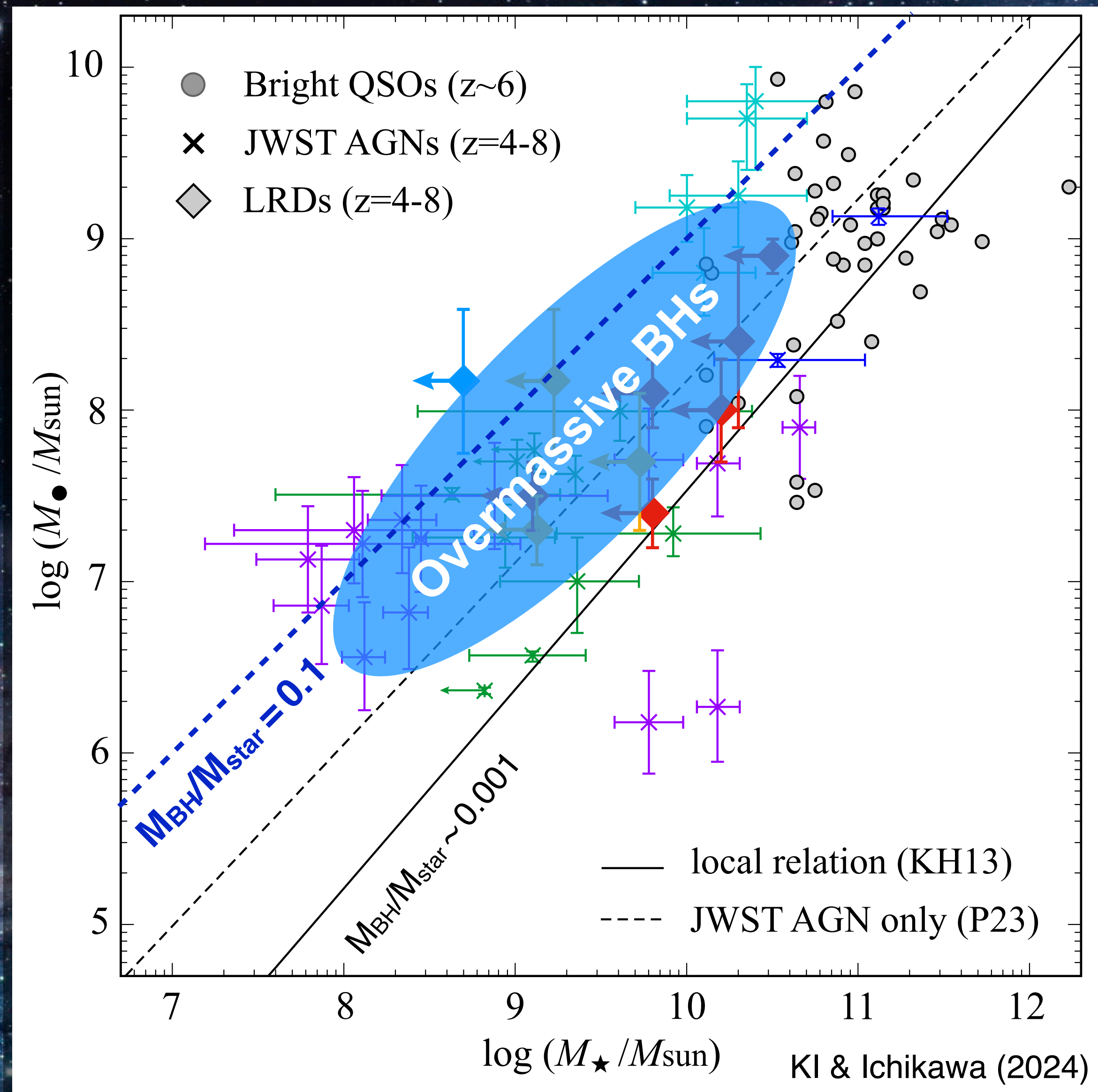


Formation channels of early BHs

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



Early BH-galaxy coevolution



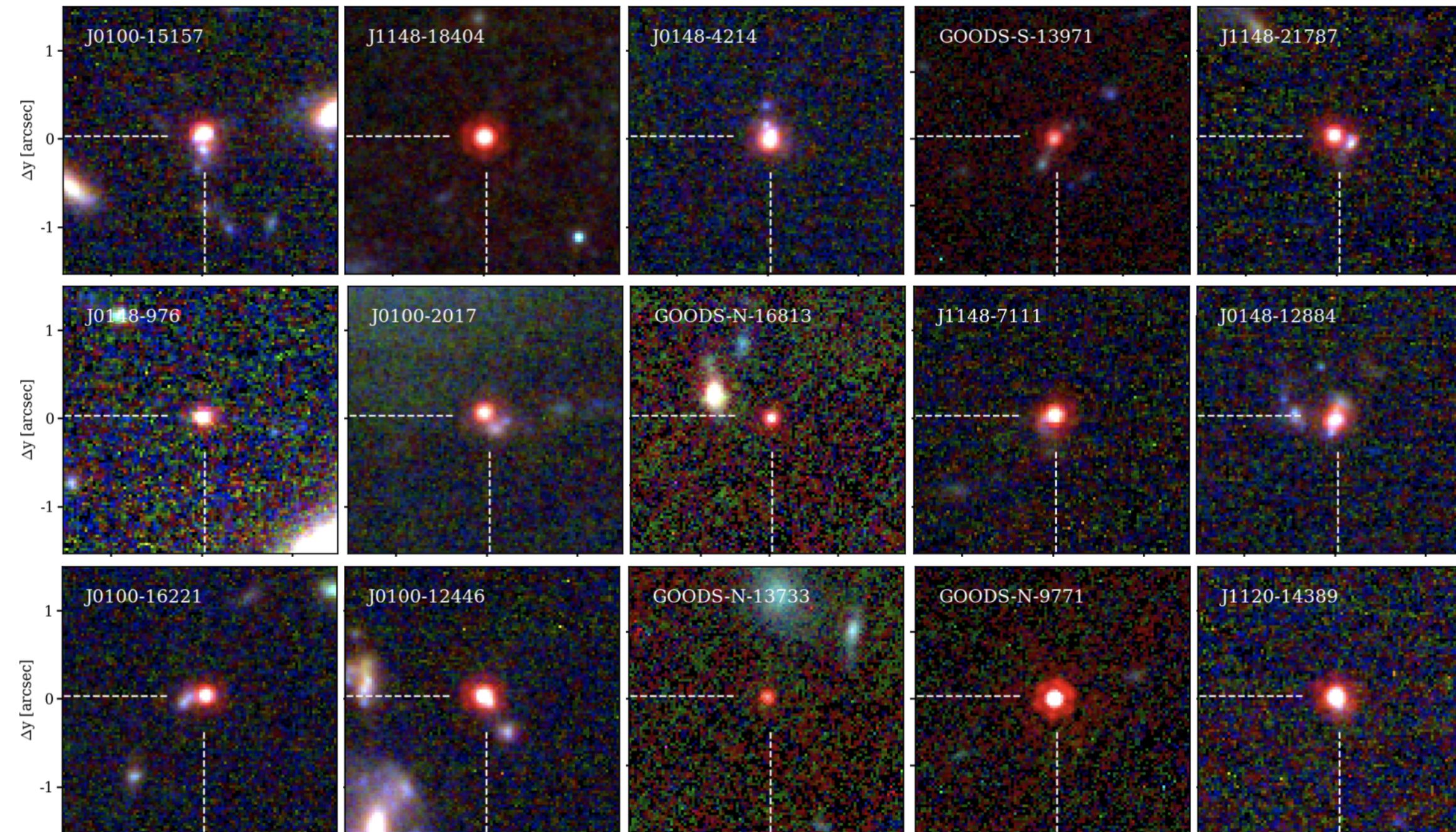
JWST AGNs data from
Kocevski+23, Larson+ 23,
Harikane+ 23, Übler+ 23,
Ding+ 23, Maiolino+ 24a,b,
Marshall+ 23, Yue+ 23

2. A new AGN population, LRDs super-Eddington, Balmer, dust...

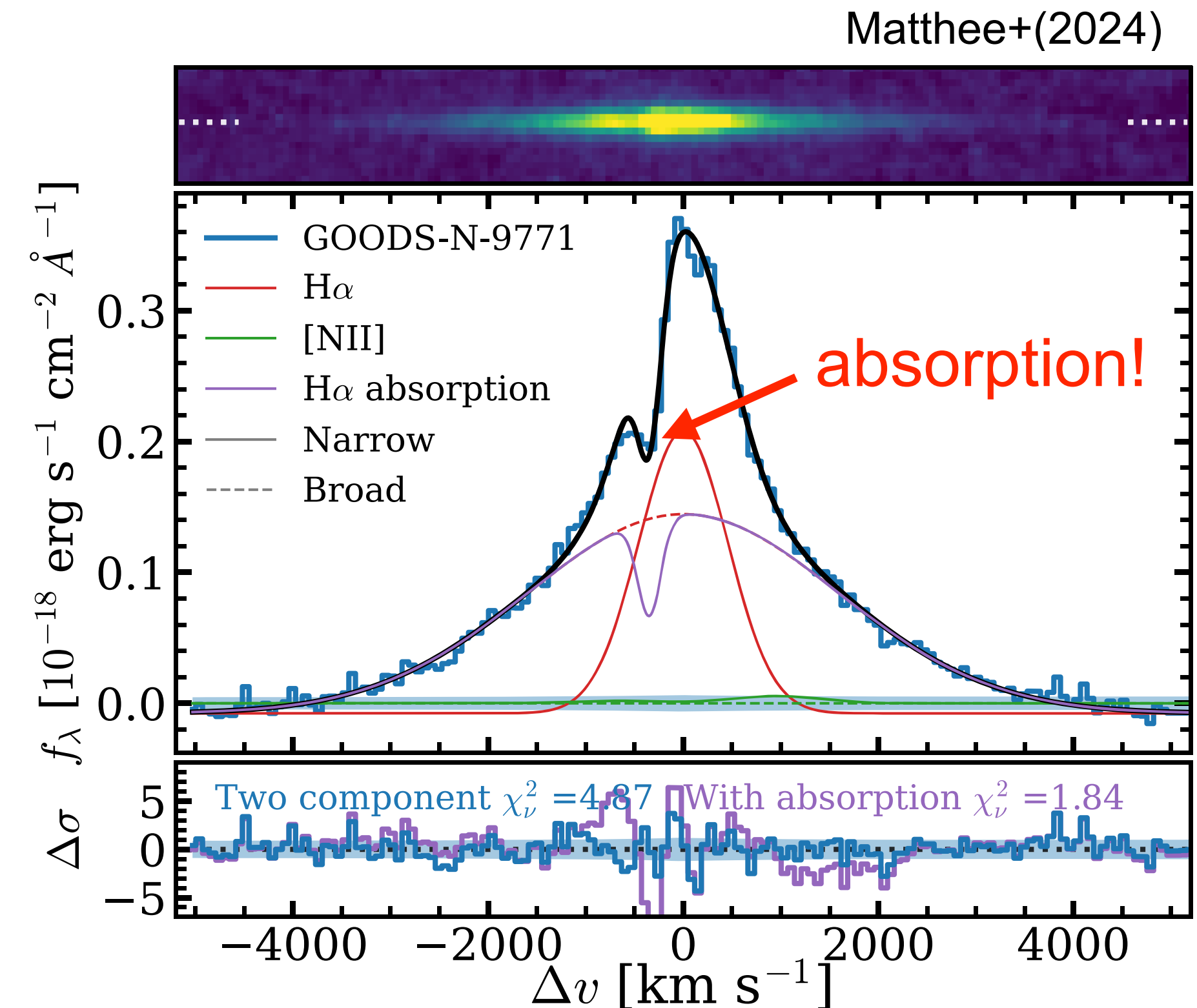


小久保さんのトーク

Little Red Dots (LRDs)



- Very compact & red sources (in JWST NIRCам)
- High redshift, abundant population ($\sim 100 \cdot n_{\text{QSO}}$)
- **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.

LRD energetics

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

Total radiative luminosity:

$$L = 4\pi \underline{d_L^2} F_{\text{obs}} \cdot 10^{0.4 \underline{A_V - 3}} \gtrsim 10^{11 + 0.4 \cdot \underline{A_V - 3}} L_\odot$$

cosmological
distance ($z \sim 4-7$)

reddening correction
($A_V \sim 3$ mag)



An illustration by Chat-GPT

Nuclear energy?

Dusty galaxies: $M_\star \gtrsim 10^{11} M_\odot$

Gravitational energy?

Dusty AGNs: $M_{\text{BH}} \gtrsim 10^7 M_\odot$

Mass

too massive in Λ CDM

reasonable mass ($\sim 100 \cdot M_{\text{seed}}$)

Size

too dense ($R_e < 100$ pc)

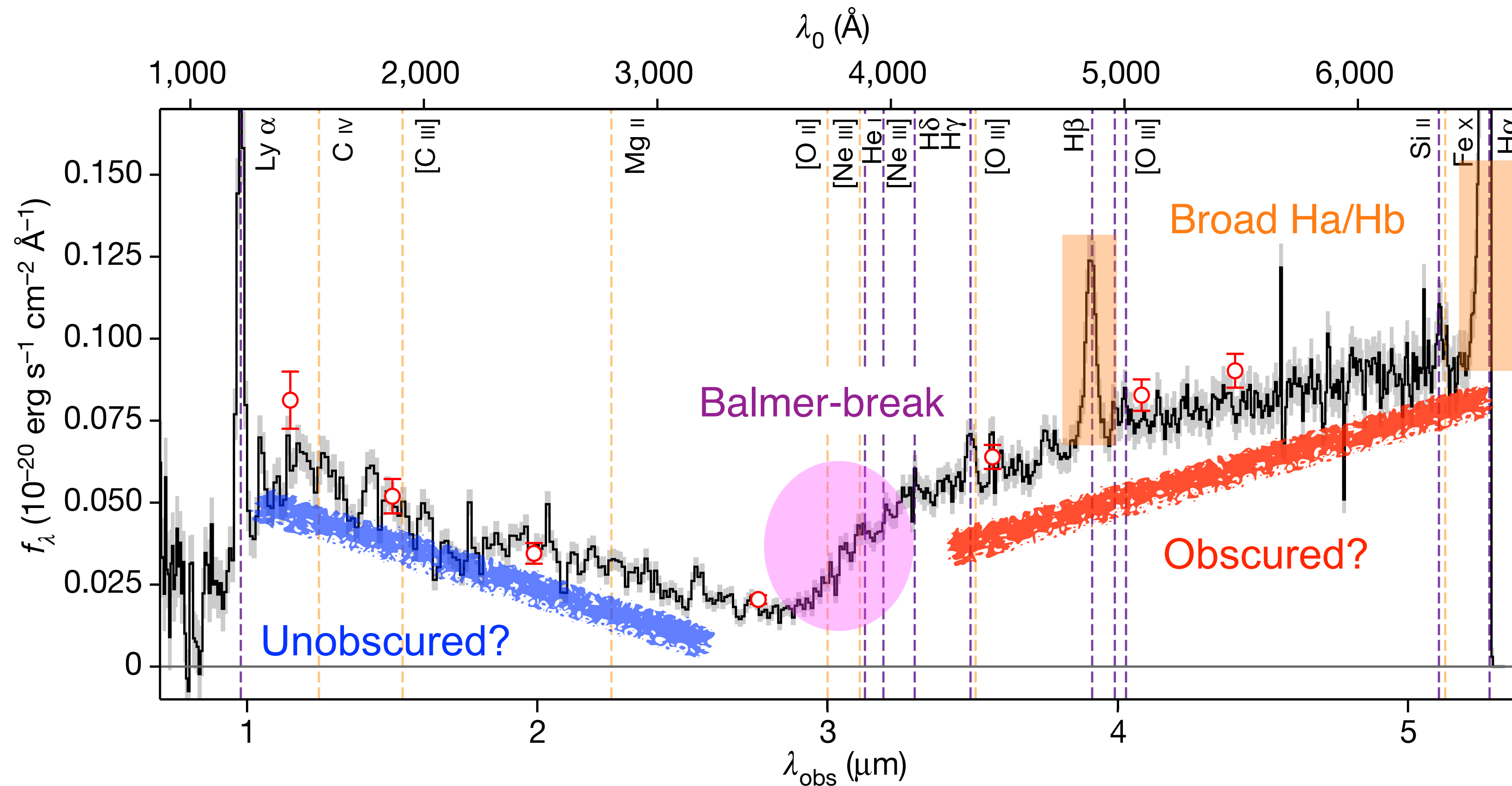
compact dense ($R_e \sim 0.01$ pc)

Time

no way to create variability

$T_{\text{var}} \sim \text{a few months} \cdot (1+z)$

Characteristic v-shape SEDs

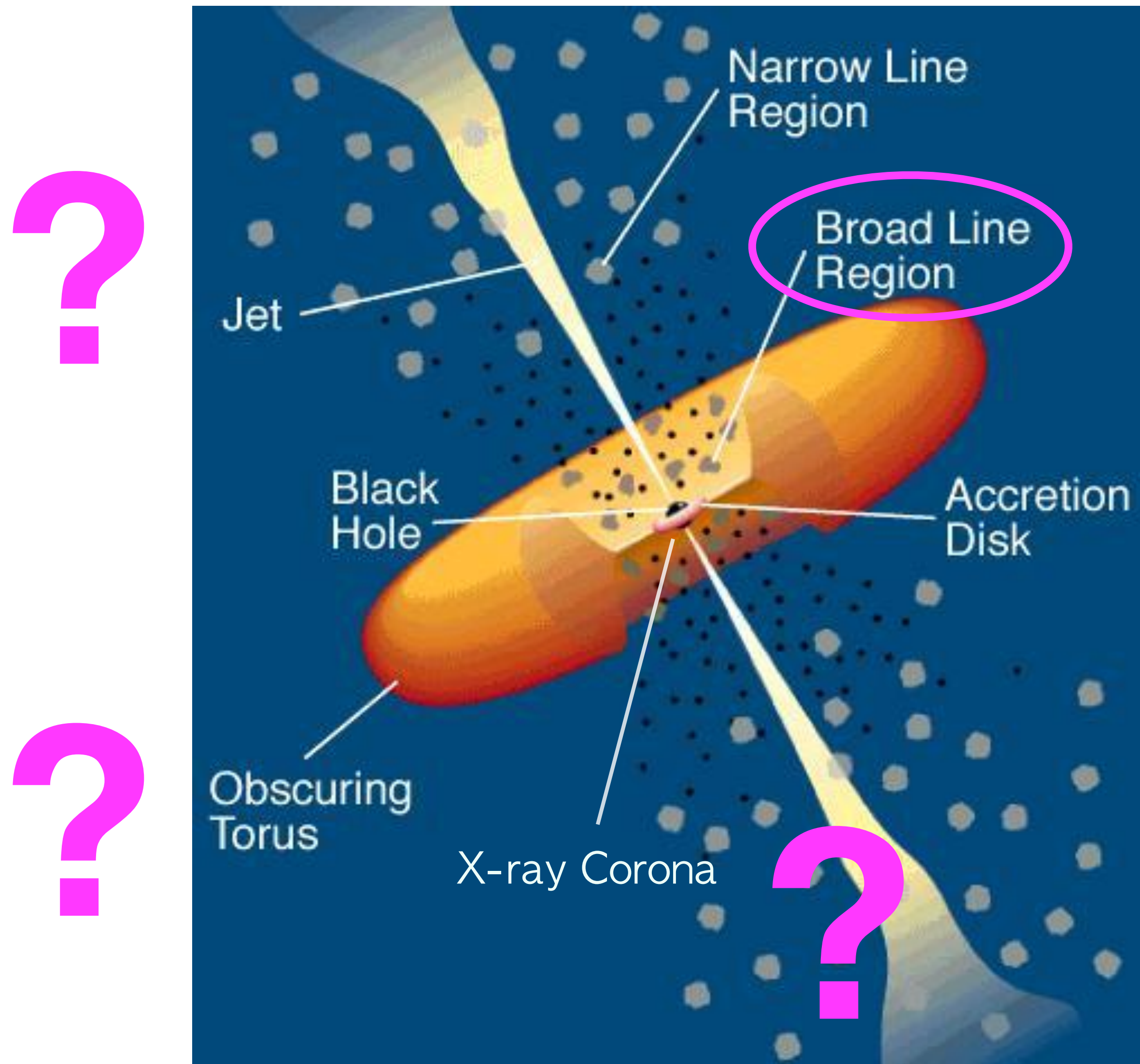


Furtak+(2024.2025)
X.Ji+(2025)
D'Eugenio+(2025)

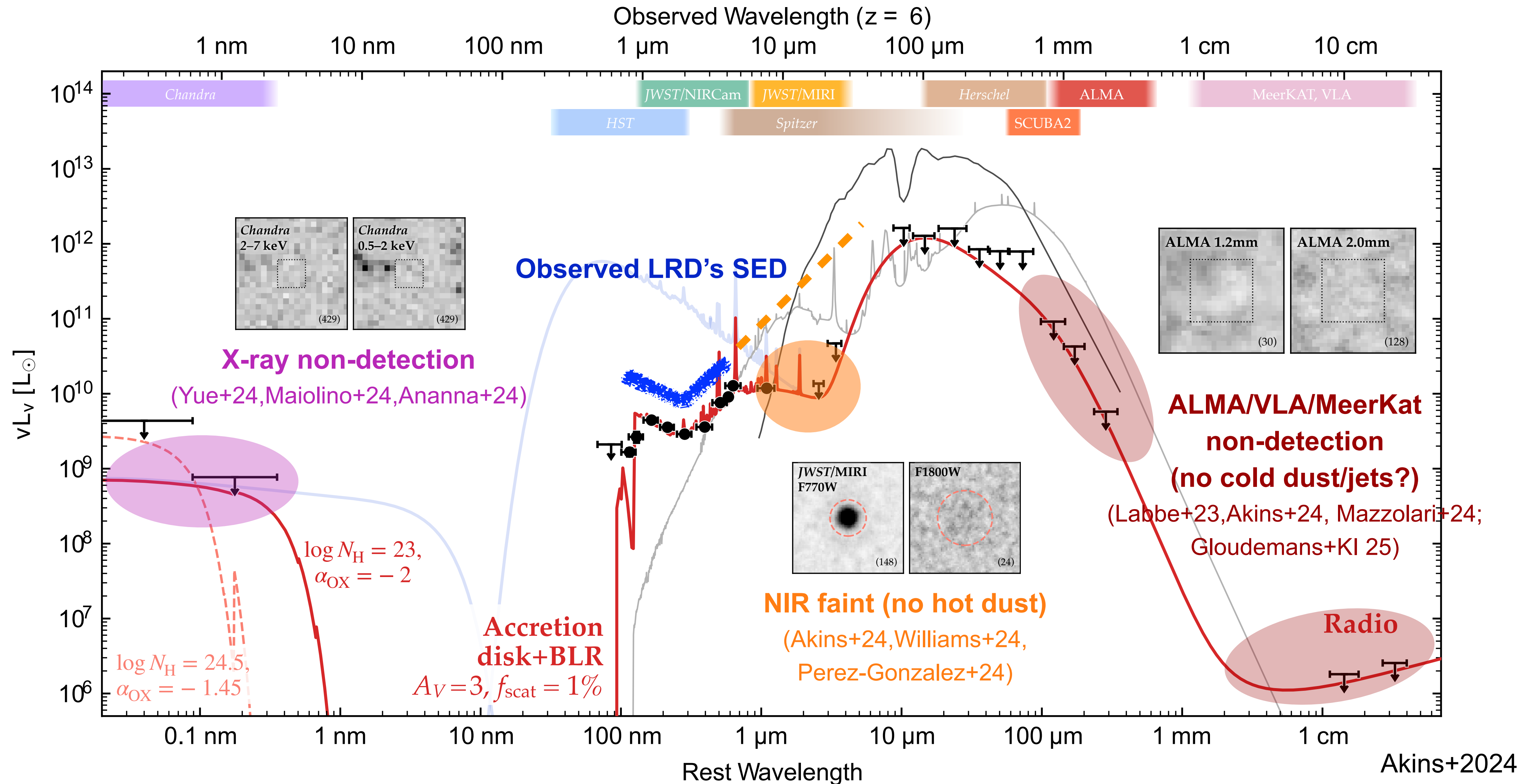
- Two-component scenario (e.g., **unobscured galaxy** + **obscured AGN**)
- Balmer-break like feature observed in some LRDs

can be stellar origins, but in some cases too strong to be explained by stellar origins
(Naidu+2025; Rusakov+2025; de Graaff+2025)

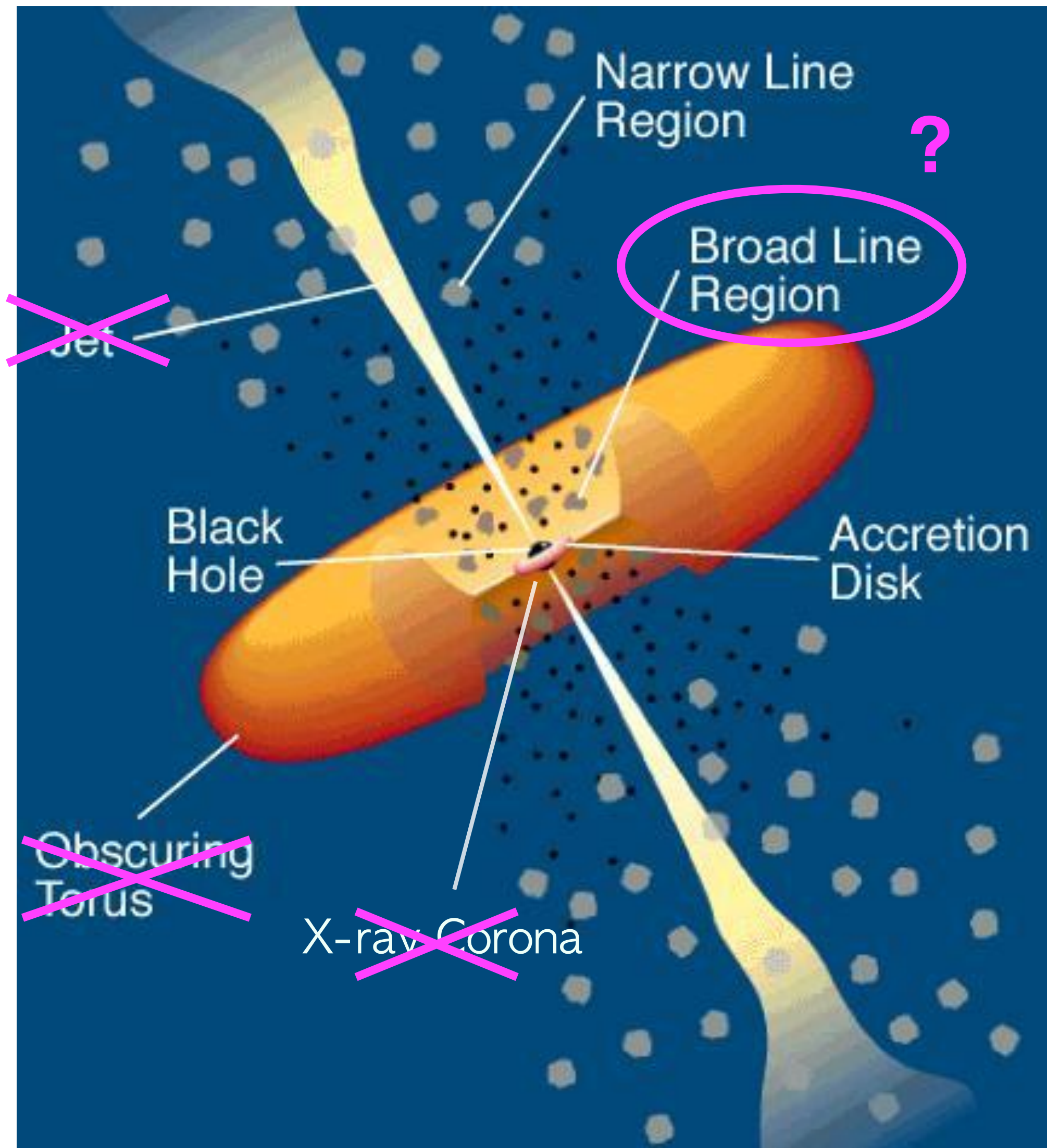
Other AGN signatures?



Other wavelengths... faint or no detection

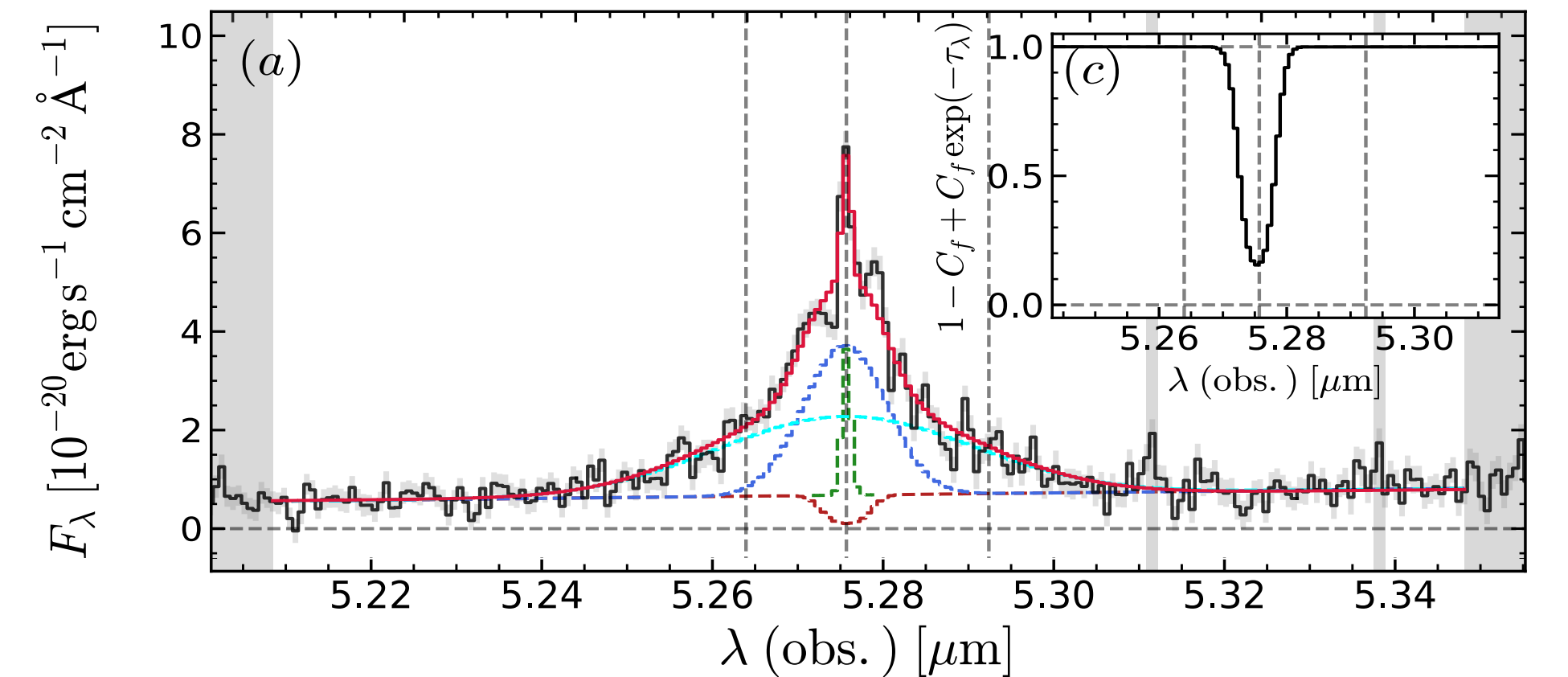
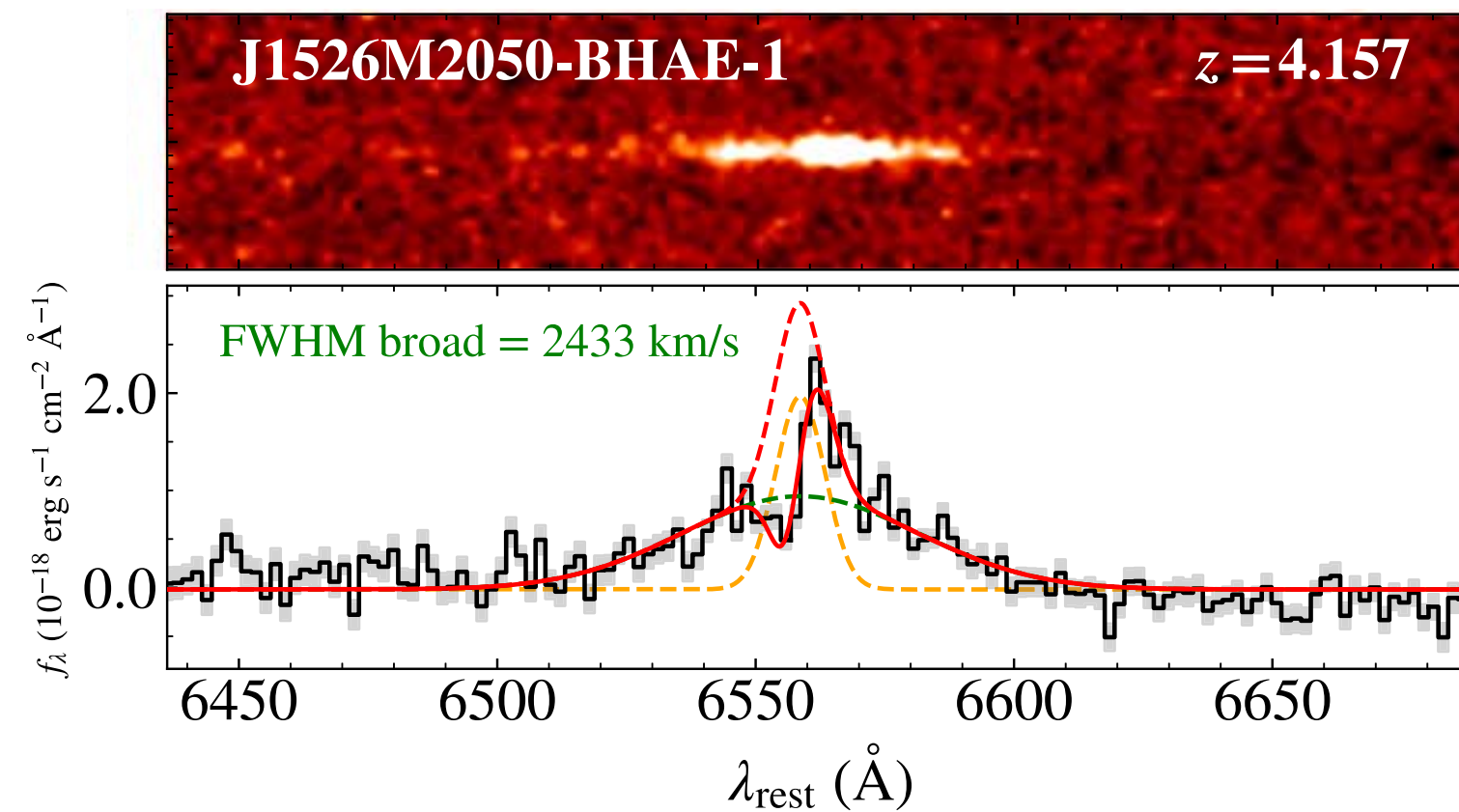
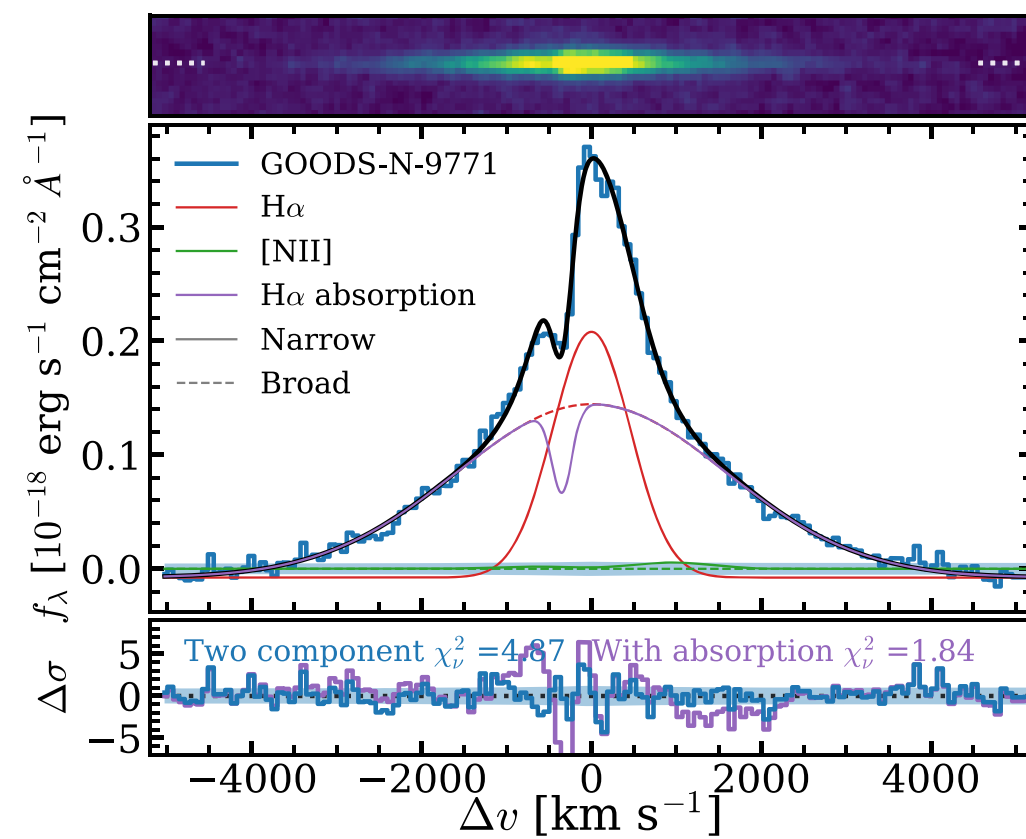
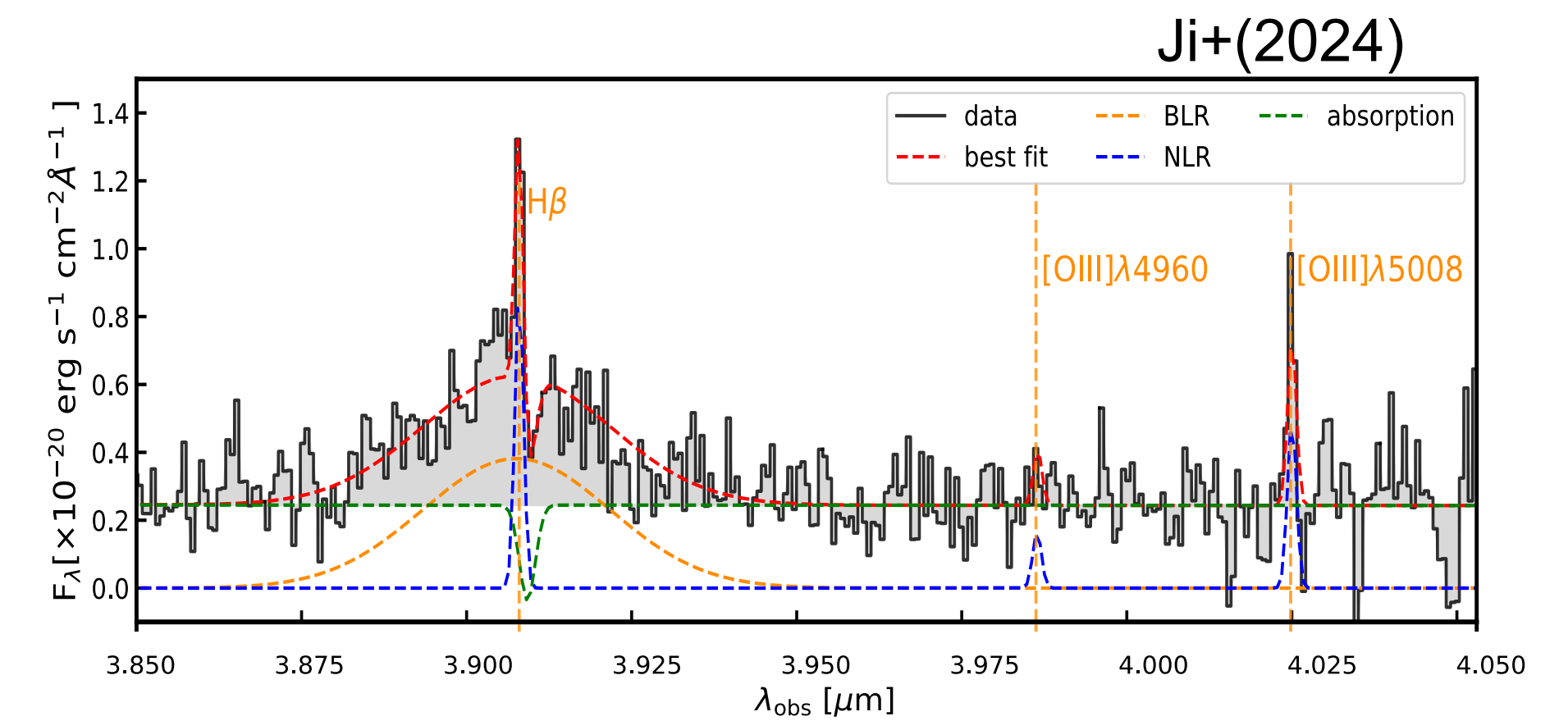
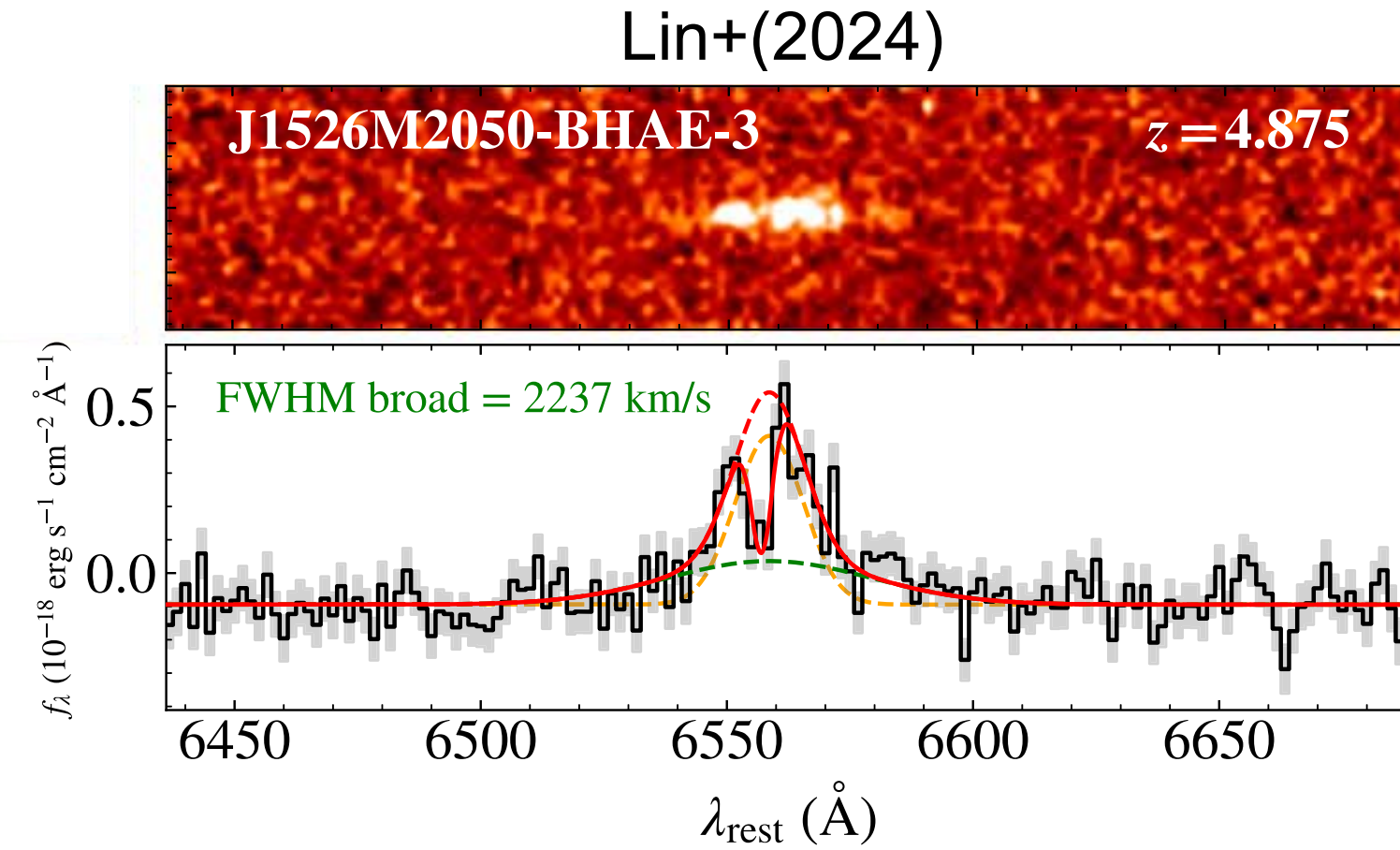
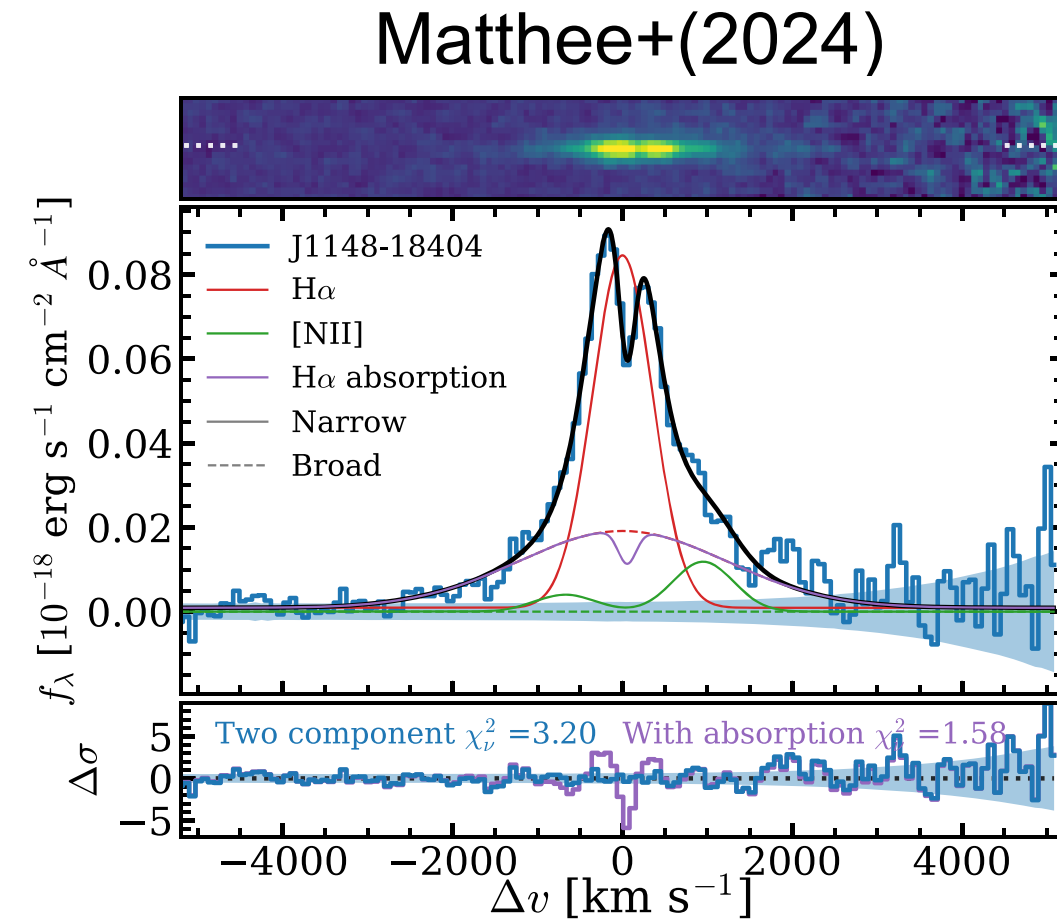


Something missed/different at high-z?



- **Weak** hot coronae (X-rays)
 - **Super-Eddington** accretion (Slim disks)?
(Maiolino+24, Madau & Haardt 24, **KI, Kimura & Noda 25**)
Acknowledge the YITP conference “Exploring Extreme Transients 2024”
- **Weak** relativistic jets (radio)
 - Efficient jet dissipation? **BH + envelopes** (Kido+25)
- **Weak** hot dust emission (NIR)
 - Extended dusty flows? Warm dust? (Z.Li+25, Casey+24)
 - No dusts or **moderate attenuation**? (K.Chen+25)
- **Absorption features** on broad-line emission
 - **Dense gas absorbers** with a high covering factor
(Matthee+24, Juodžbalis+24, Lin+24, KI & Maiolino 25, X. Ji +25)

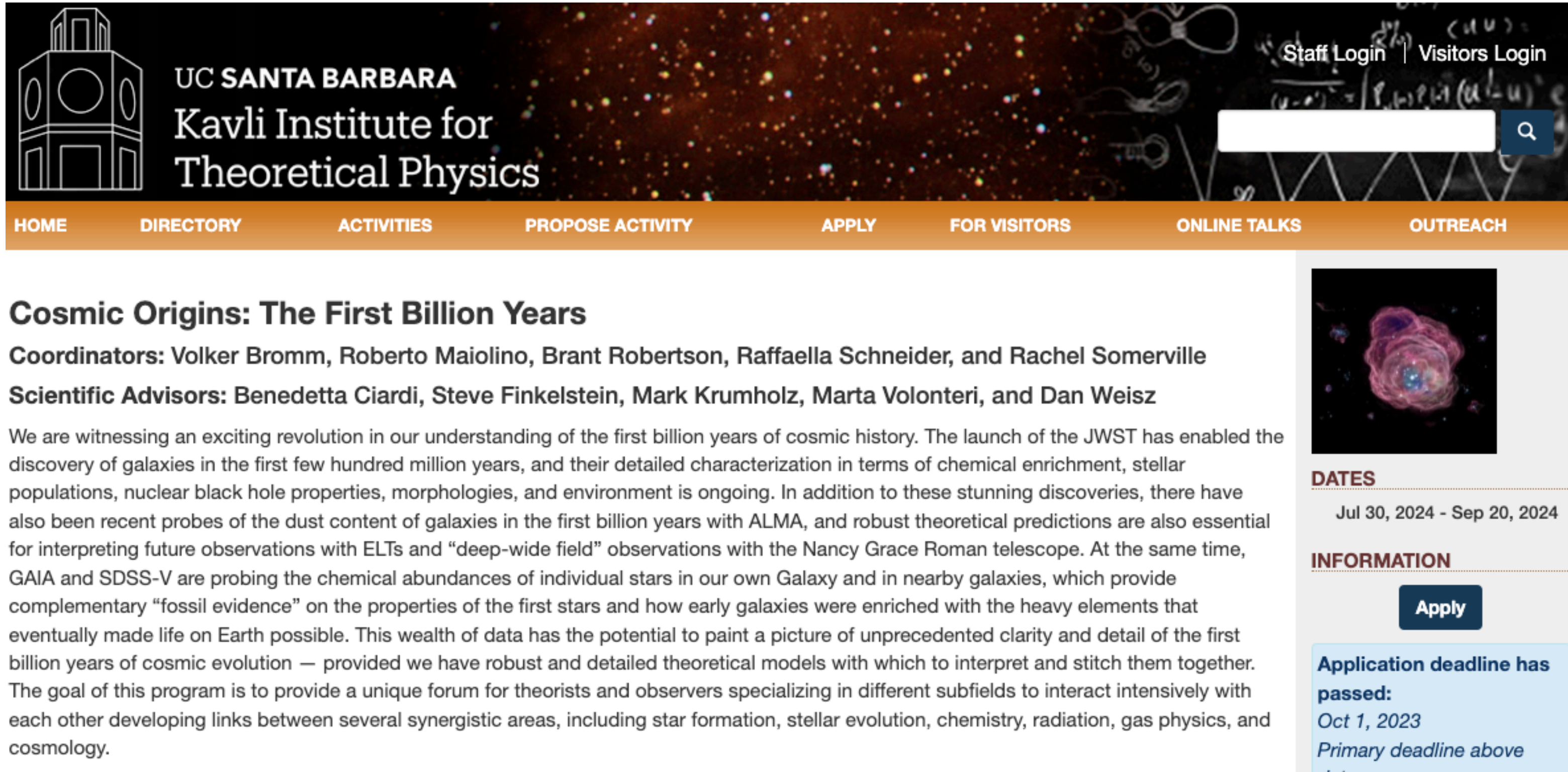
Balmer absorption on BLAGNs



D'Eugenio+(2025)

- Absorption on broad Balmer & HeI emission lines; $\text{EW}_{\text{abs}} \sim \text{O}(10) \text{Å}$
- BLRs embedded by **dense gas** (high covering factor ~ 1)

Good work $\propto$ Good meals



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HOME DIRECTORY ACTIVITIES PROPOSE ACTIVITY APPLY FOR VISITORS ONLINE TALKS OUTREACH

Cosmic Origins: The First Billion Years

Coordinators: Volker Bromm, Roberto Maiolino, Brant Robertson, Raffaella Schneider, and Rachel Somerville
Scientific Advisors: Benedetta Ciardi, Steve Finkelstein, Mark Krumholz, Marta Volonteri, and Dan Weisz

We are witnessing an exciting revolution in our understanding of the first billion years of cosmic history. The launch of the JWST has enabled the discovery of galaxies in the first few hundred million years, and their detailed characterization in terms of chemical enrichment, stellar populations, nuclear black hole properties, morphologies, and environment is ongoing. In addition to these stunning discoveries, there have also been recent probes of the dust content of galaxies in the first billion years with ALMA, and robust theoretical predictions are also essential for interpreting future observations with ELTs and “deep-wide field” observations with the Nancy Grace Roman telescope. At the same time, GAIA and SDSS-V are probing the chemical abundances of individual stars in our own Galaxy and in nearby galaxies, which provide complementary “fossil evidence” on the properties of the first stars and how early galaxies were enriched with the heavy elements that eventually made life on Earth possible. This wealth of data has the potential to paint a picture of unprecedented clarity and detail of the first billion years of cosmic evolution — provided we have robust and detailed theoretical models with which to interpret and stitch them together. The goal of this program is to provide a unique forum for theorists and observers specializing in different subfields to interact intensively with each other developing links between several synergistic areas, including star formation, stellar evolution, chemistry, radiation, gas physics, and cosmology.

DATES
Jul 30, 2024 - Sep 20, 2024

INFORMATION
[Apply](#)

Application deadline has passed:
Oct 1, 2023
Primary deadline above

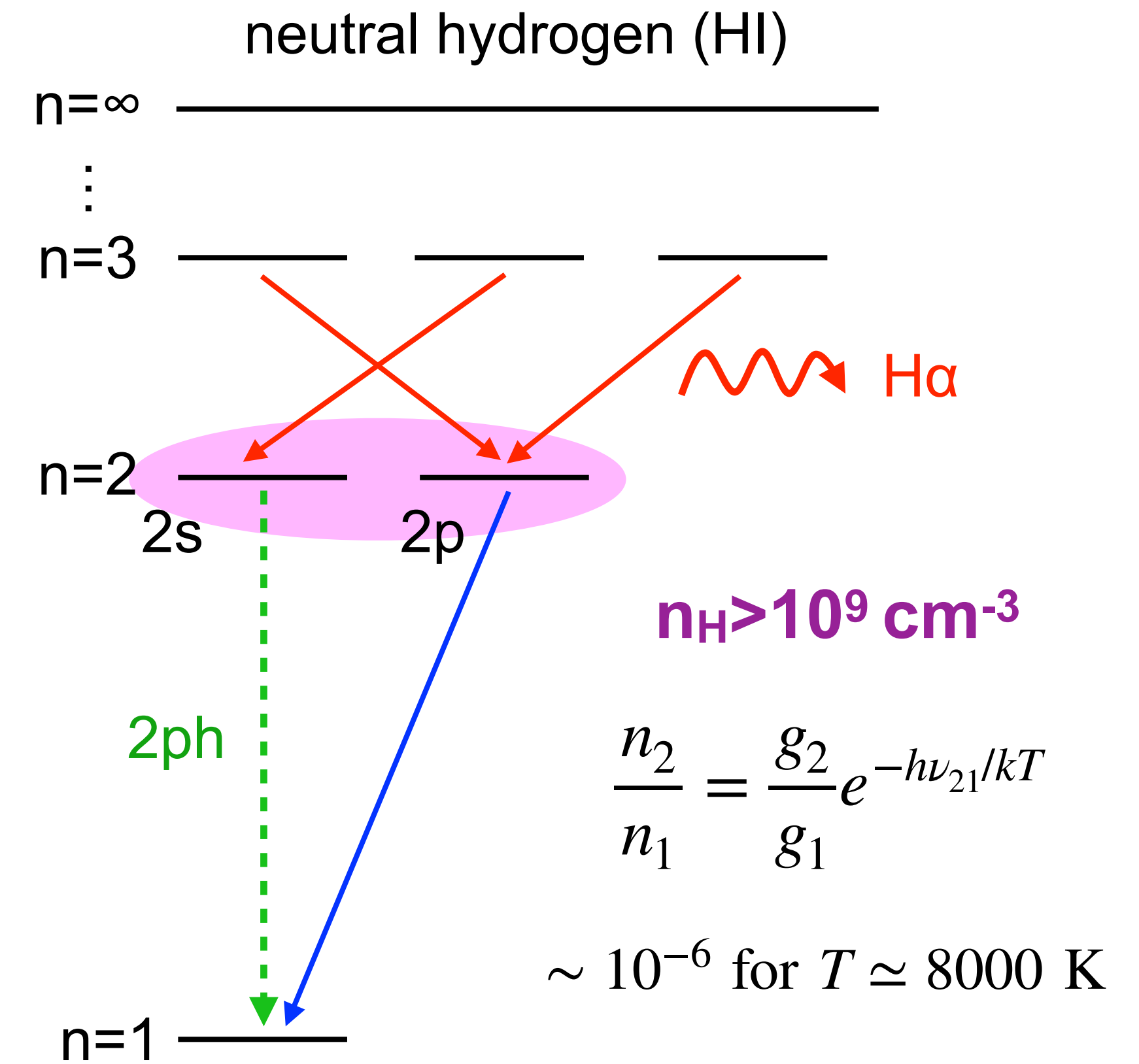
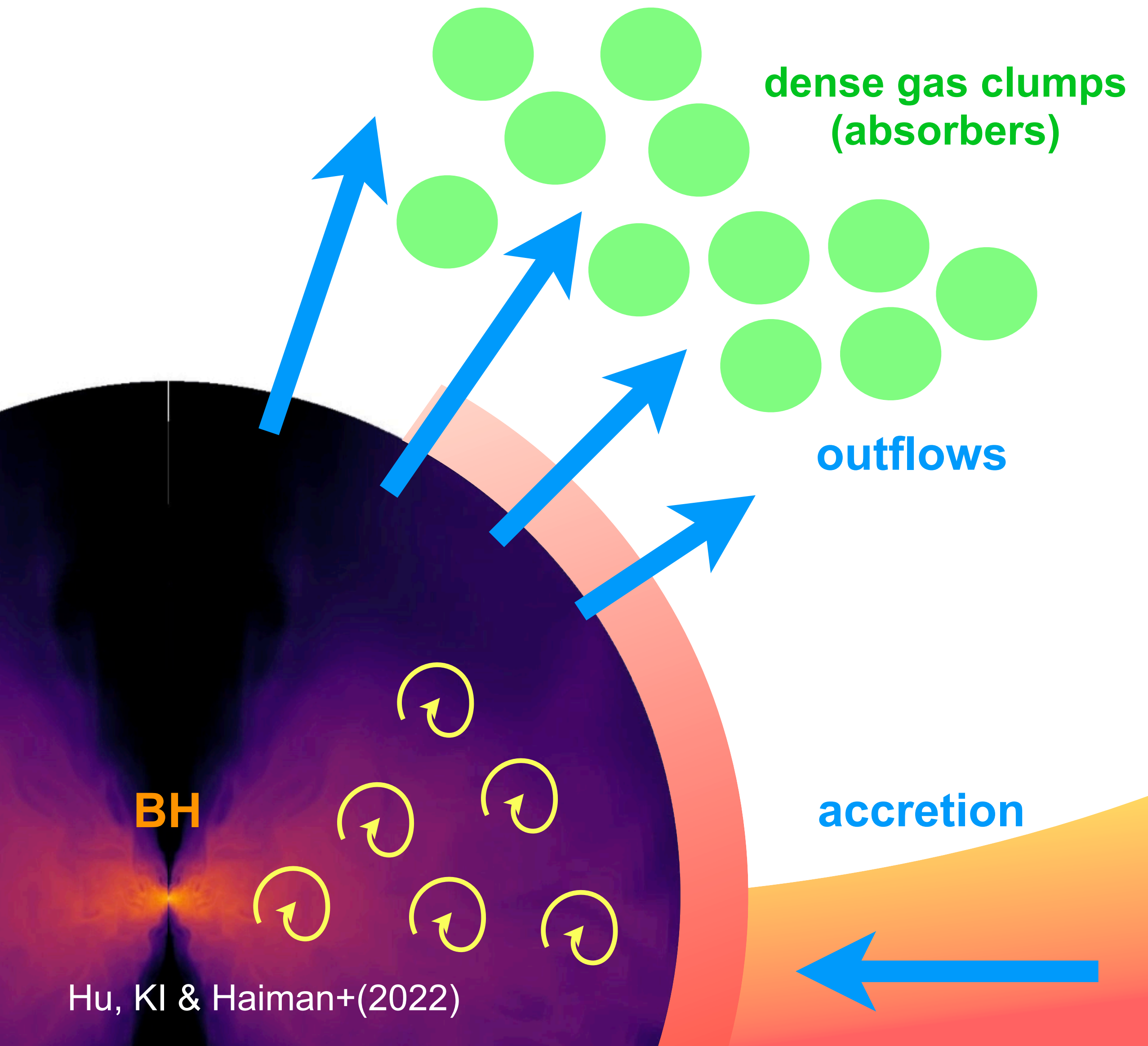
KITP workshop: Cosmic Origins
very serious discussion with Roberto Maiolino



New collaborations will be expected through this YITP workshop

(飲み会にも期待)

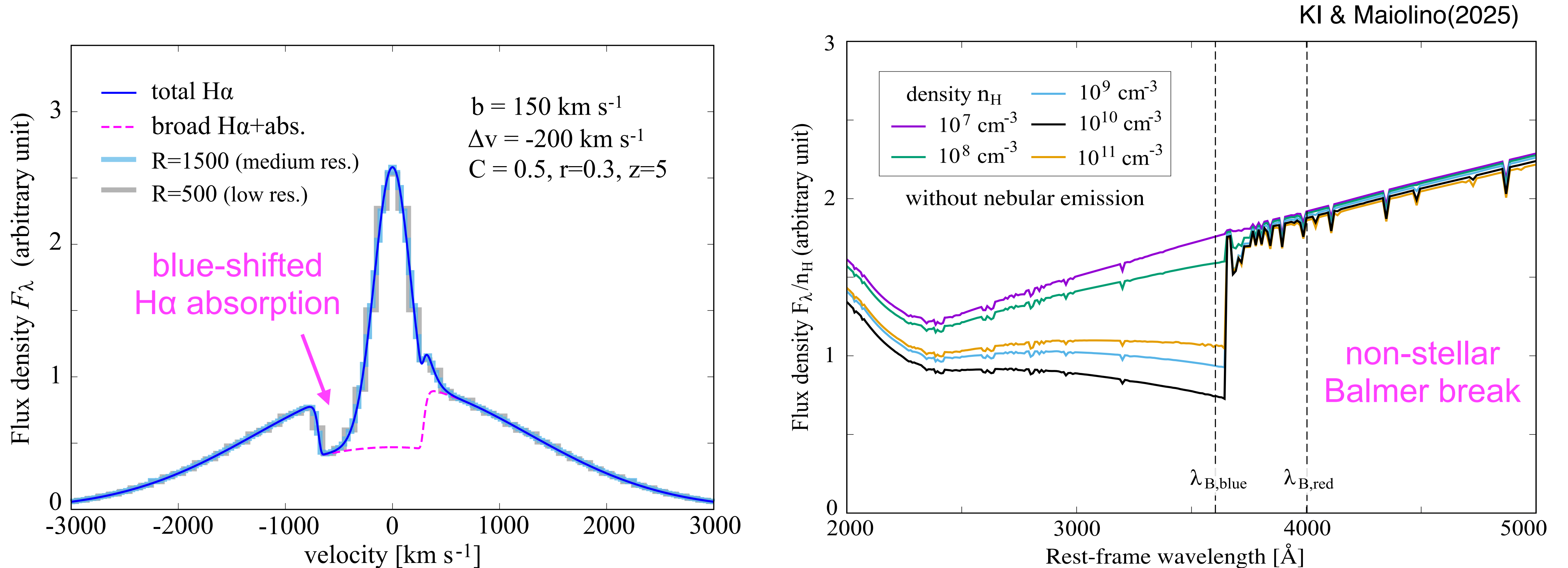
Balmer break on pure AGN spectra



Collisional excitation the $n=2$ state, imprinting **Balmer absorption & break** on AGN spectra

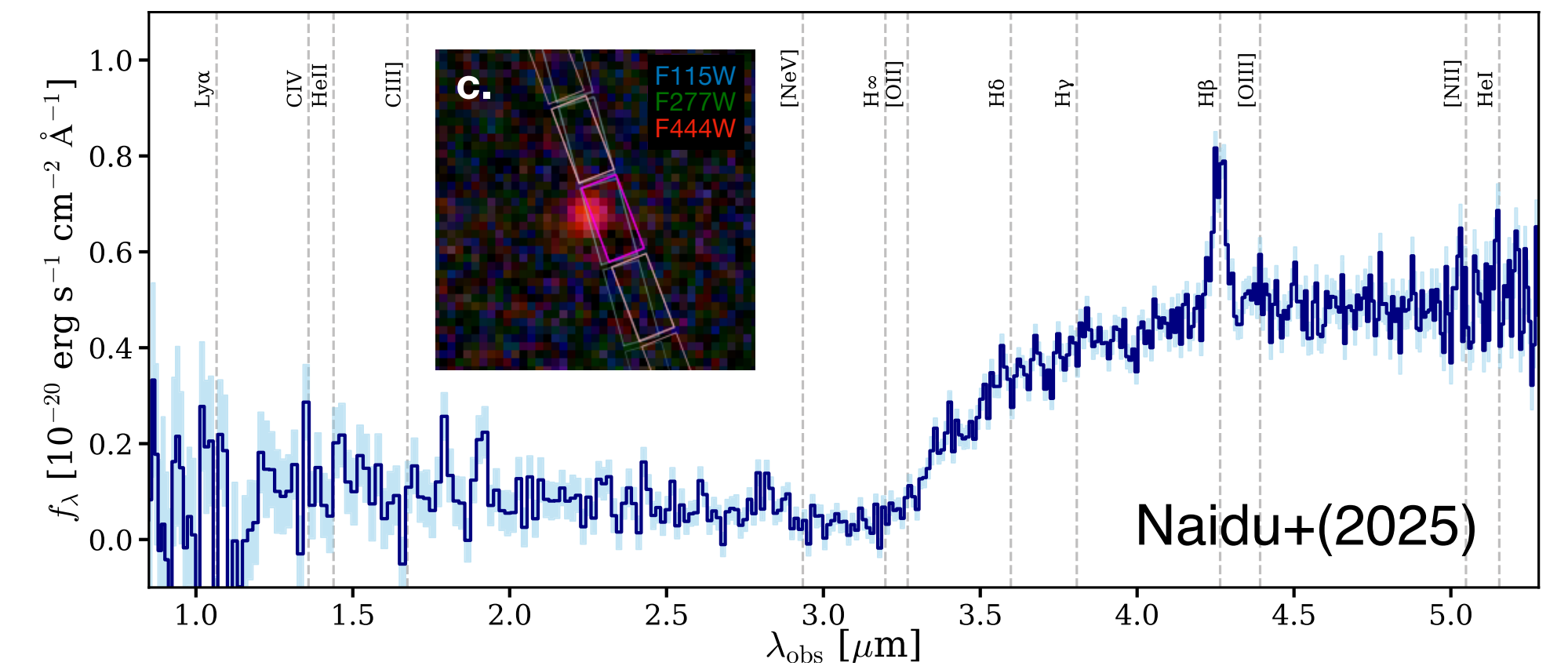
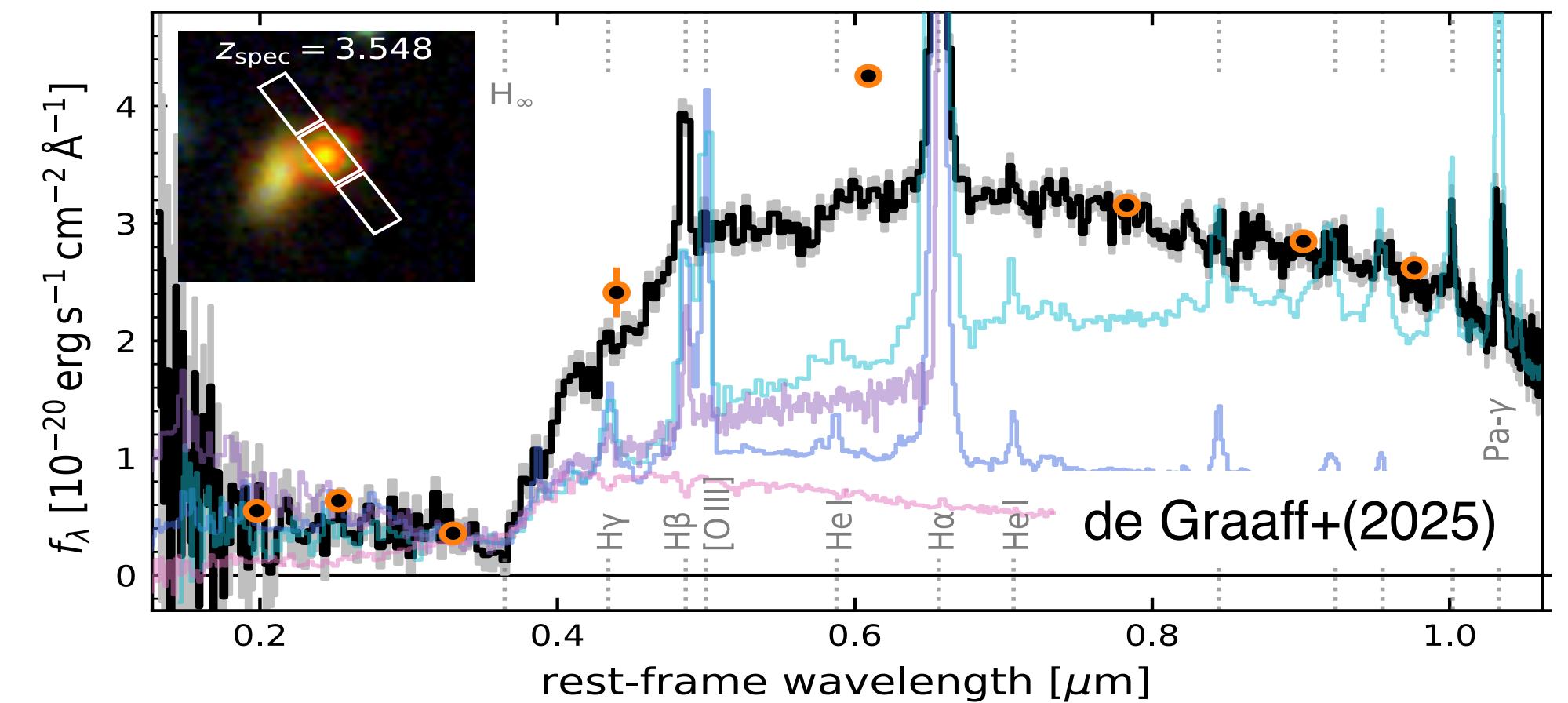
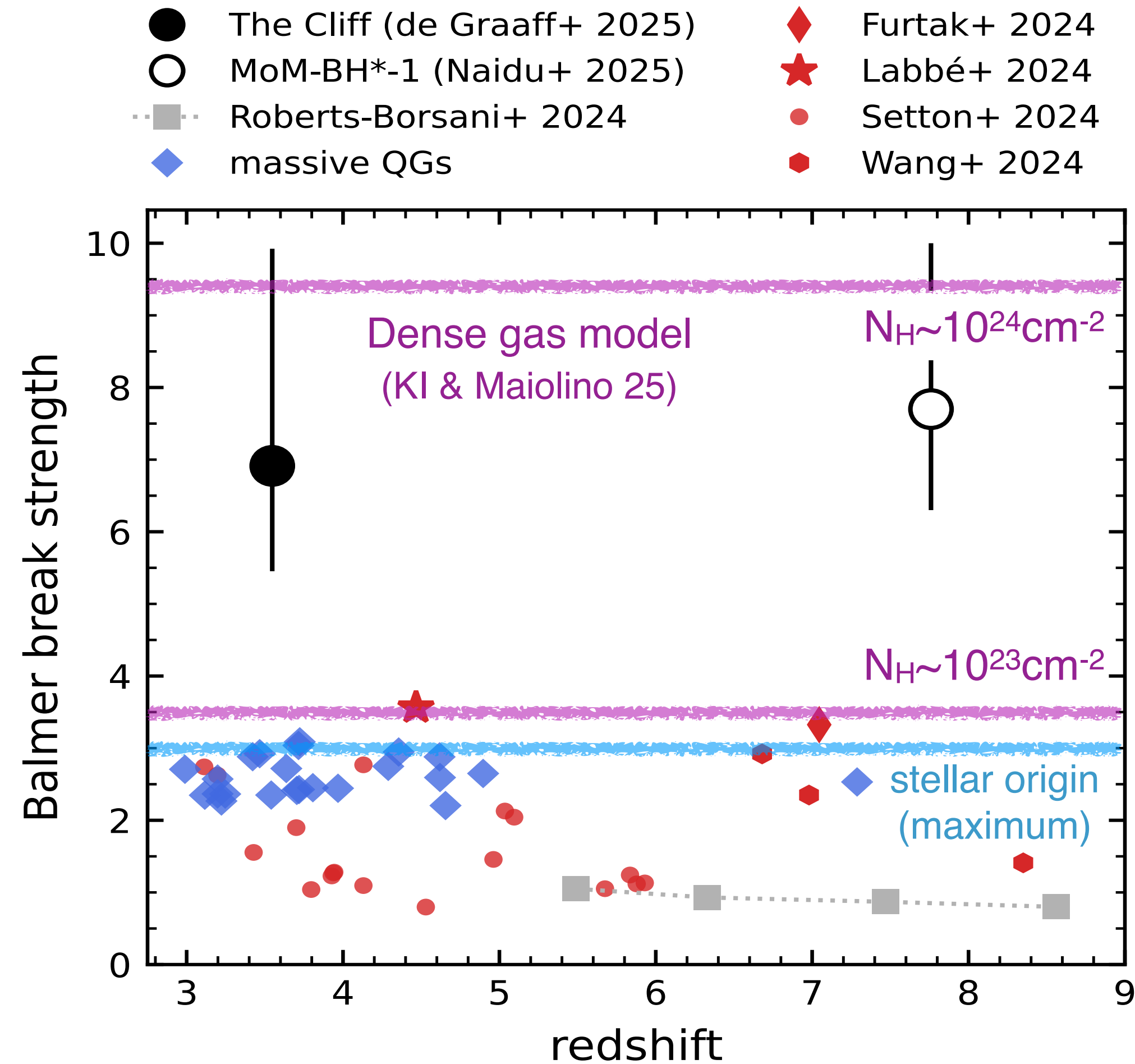
See also Juodžbalis+24, Ji+24, Dai+25, D'Eugenio+(2025)

Balmer break on pure AGN spectra



- Balmer break & absorption features due to dense gas in AGNs
- A potential correlation with **super-Eddington** outflows ($\sim 3-10 \dot{M}_{\text{Edd}}$)

LRD with both Balmer breaks + absorption



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

Looking back on the last Kyoto conference



August 5th, 2024 @Kyoto

Q. Are LRDs explained by supermassive stars or their explosions?

A. Well, maybe no. Because the model seems very ad hoc and doesn't account for the blue UV spectra...

⋮

Two weeks later @UCSB

Well, LRDs are likely AGNs embedded in dense gas, which imprints Balmer absorption & break on their spectra

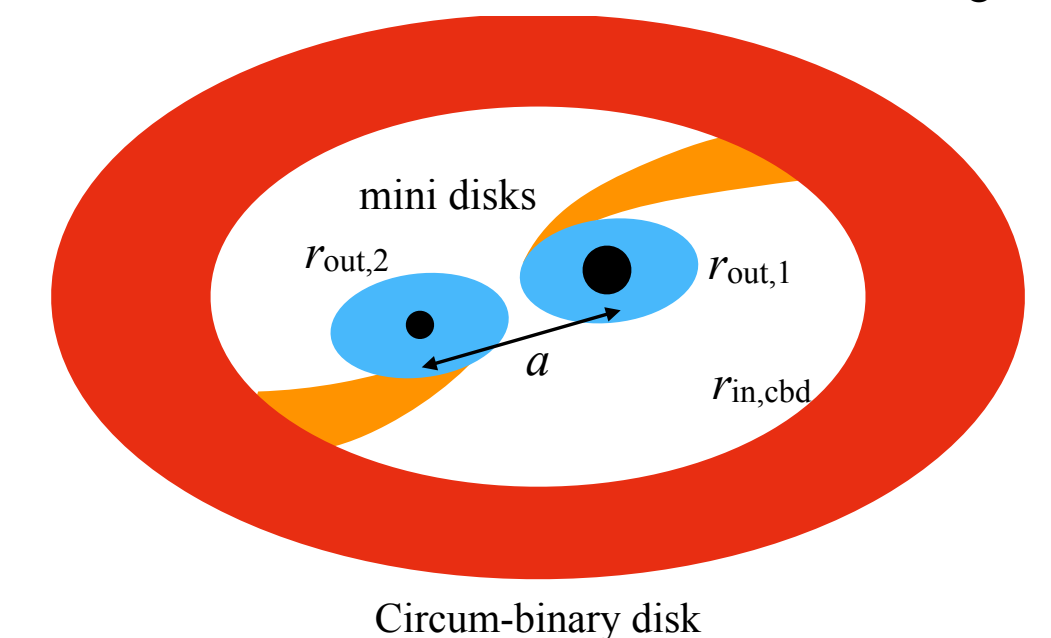
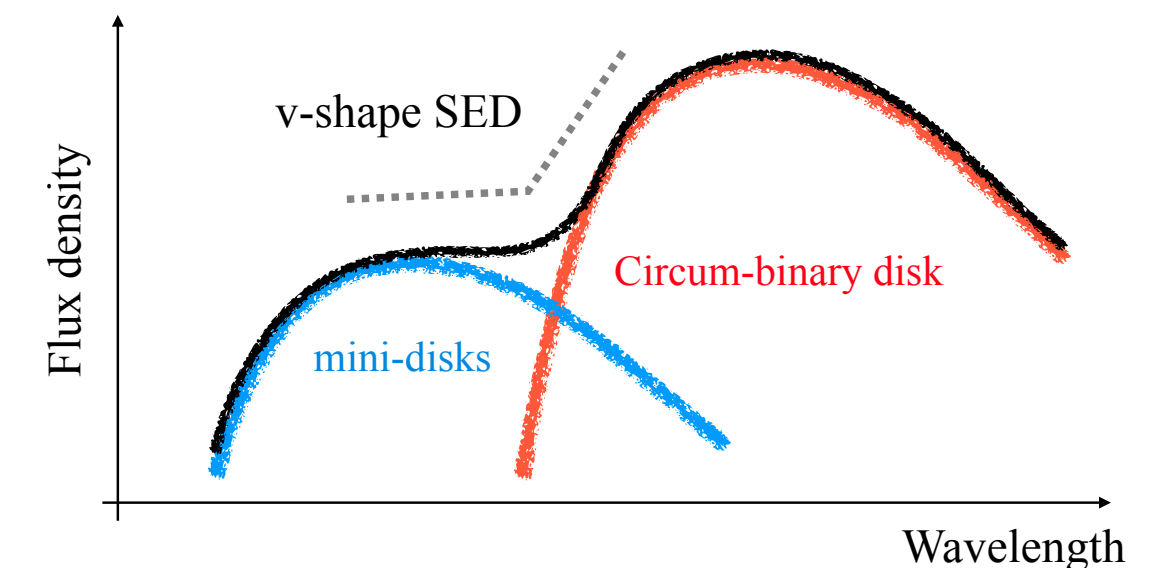
⋮

Another a few months later

Well, LRD's IR spectra look like a blackbody with $T \sim 5000\text{K}$...

Hayashi line? Circum-binary disks? BH+envelope?

Kido+(2025)



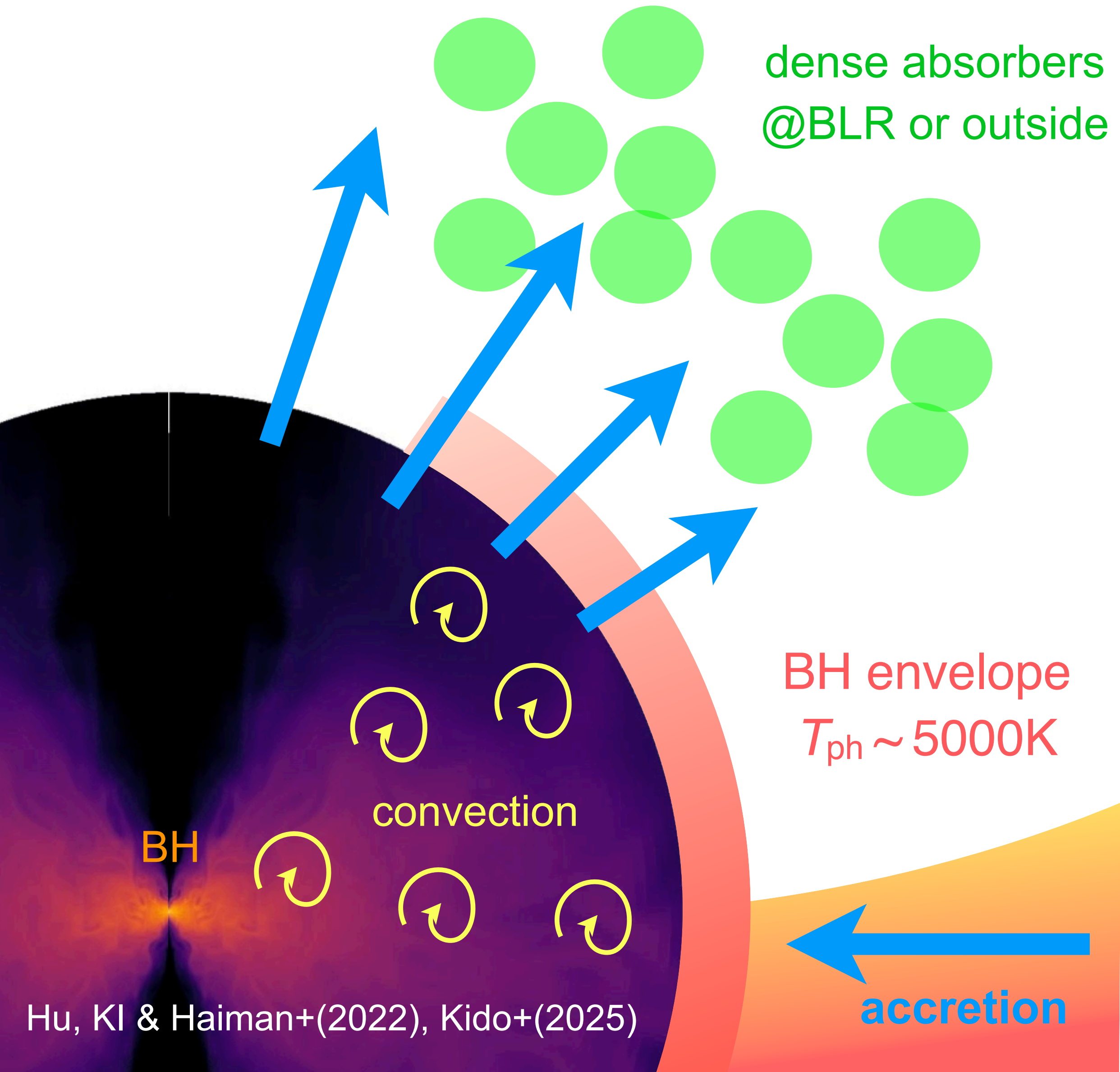
KI, Shangguan, Chen & Ho. (2025)

柴田さん
紫綬褒章おめでとうございます。



井岡さん
林忠四郎賞おめでとうございます。

BH + accreting envelope



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

Kido+25, Liu+25, Begelman & Dexter 25

also Begelman+08,10, Hosokawa+13, KI, Haiman & Ostriker +16

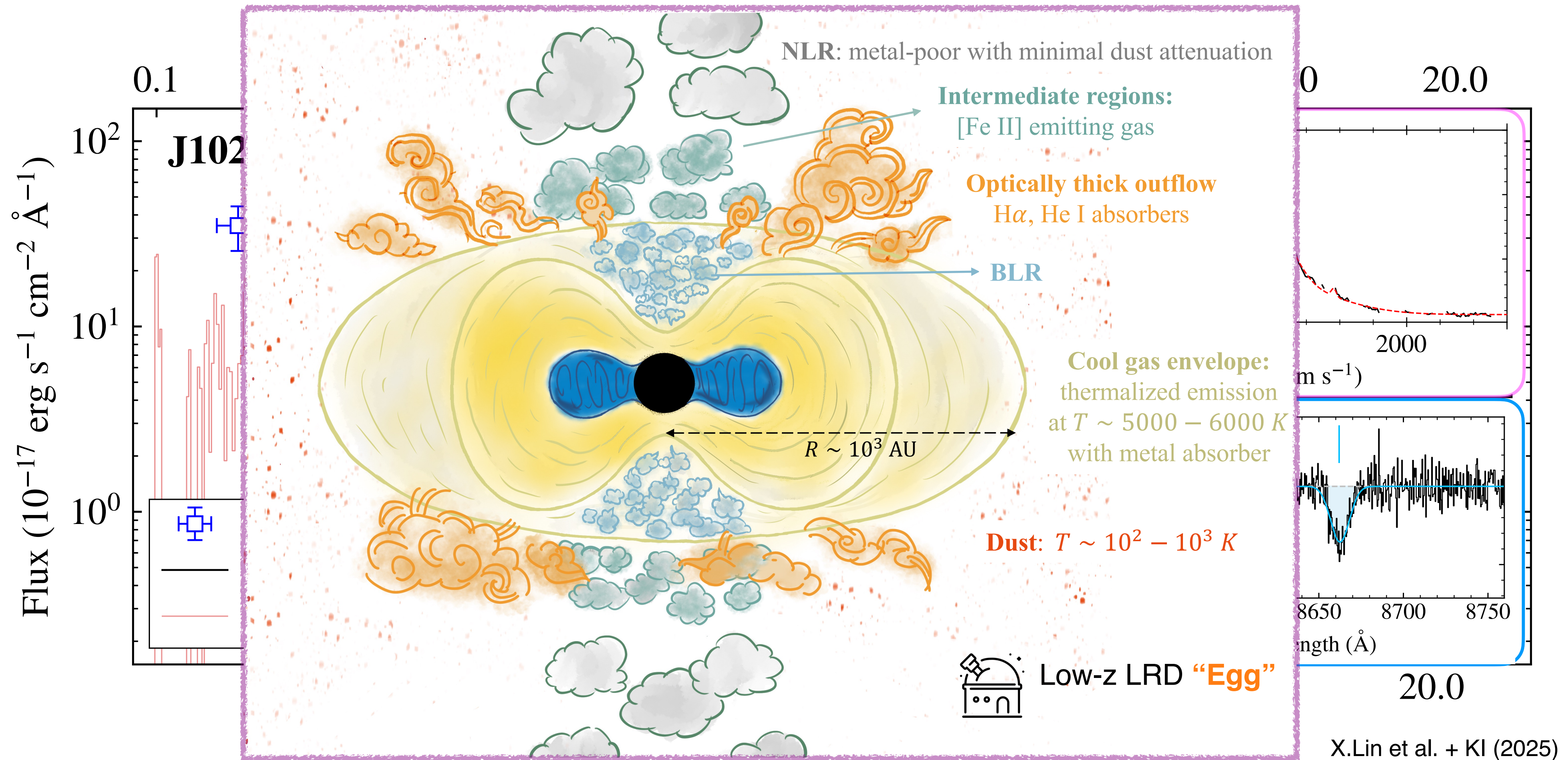
- A high covering factor & high column density
- $T_{\text{eff}} \sim 5000\text{ K}$ due to H- ion opacity (Hayashi track)
- Red optical continuum emission (the Wien tail of BB)
- No dust requirements

$$L_{\text{Edd}} = 4\pi\sigma R_{\text{ph}}^2 T_{\text{eff}}^4$$

$$g = \frac{GM}{R_{\text{ph}}^2} = \frac{\kappa\sigma T_{\text{eff}}^4}{c} \simeq 0.36 T_{\text{eff},5000}^4$$

similar to red supergiants

Low-z objects with LRD characteristics

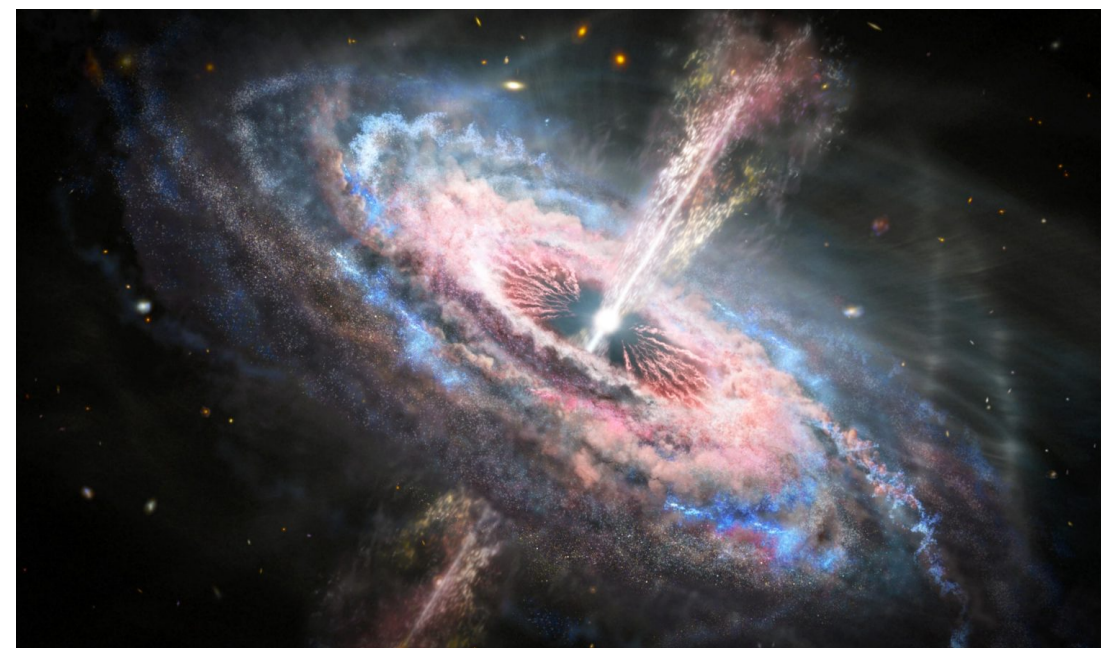


- A compact, broad-line AGN with a V- and Λ -shaped SED and unique absorption features

Too strong to be stellar origin...

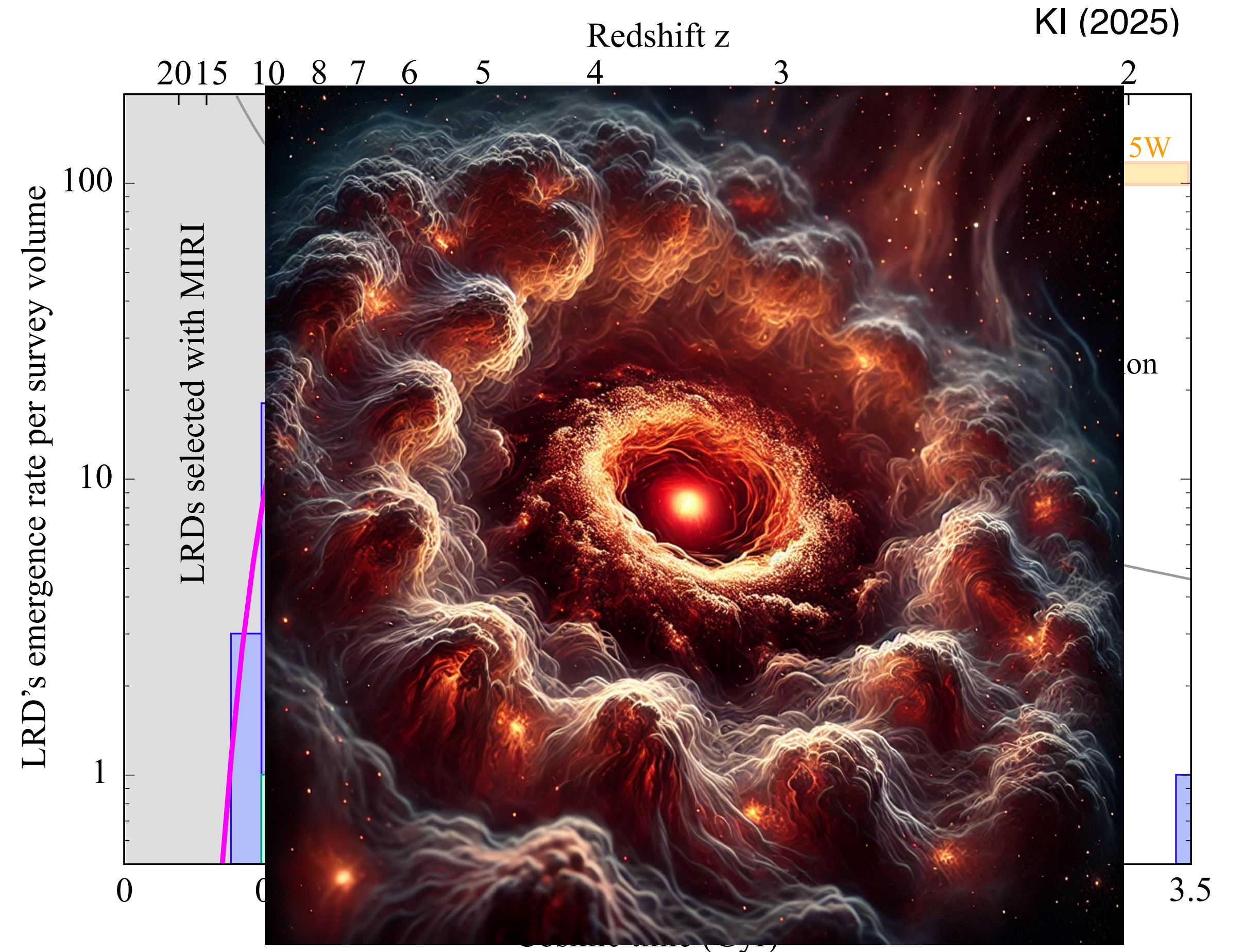
3. New hypothesis:

LRDs = Very first BH growth phases



Key features of the LRD population

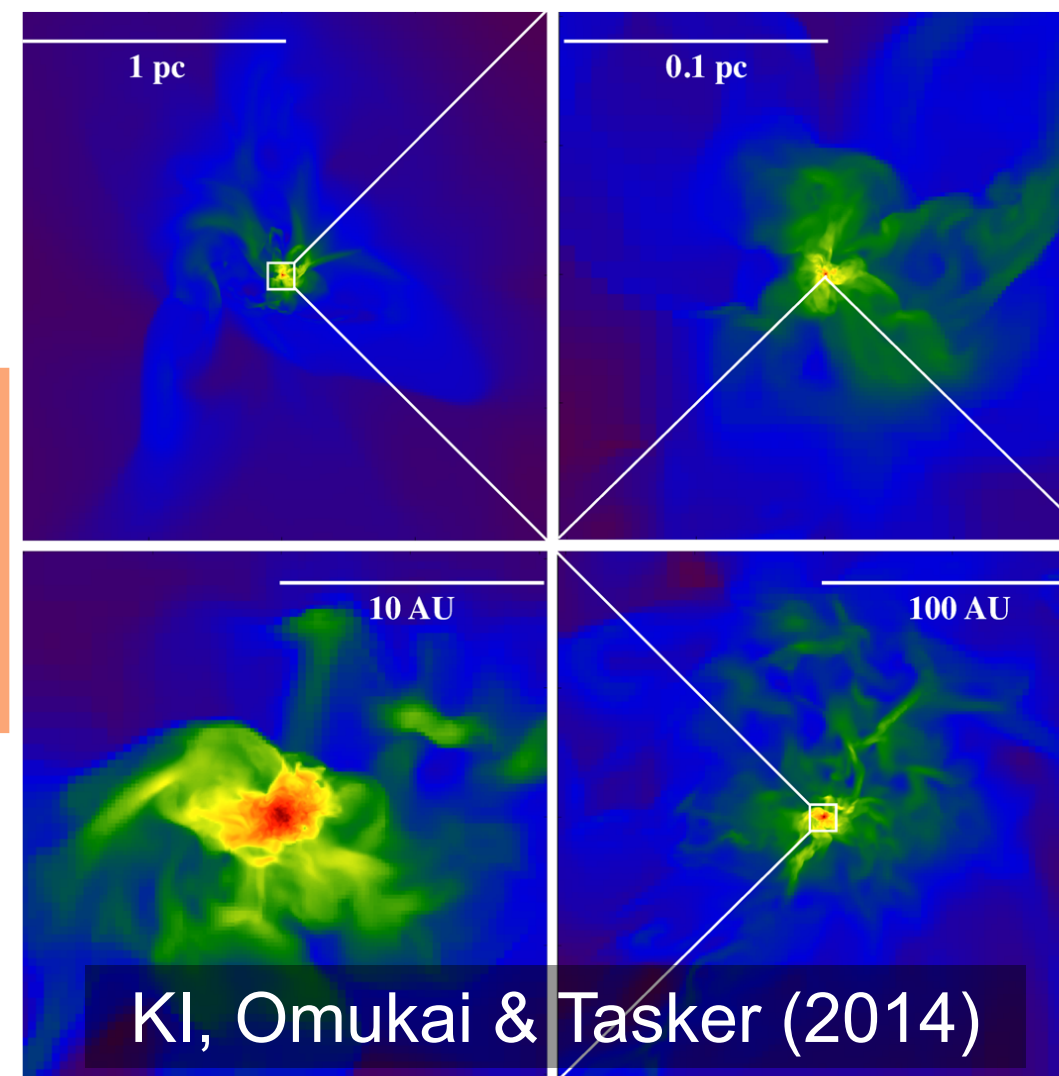
- Broad-line AGNs: $M_{\text{BH}} \sim 10^{6-7} M_{\odot}$
- Spectra distinct from normal AGNs
 - dense gas environments
 - poor (or no) dust grains
 - no signatures of host galaxies
- Cosmic abundance evolution
 - emergence at high-z & decline to low-z
 - transient-like occurrence: $t_{\text{LRD}} \sim \text{LN}(t_0, \sigma_0)$



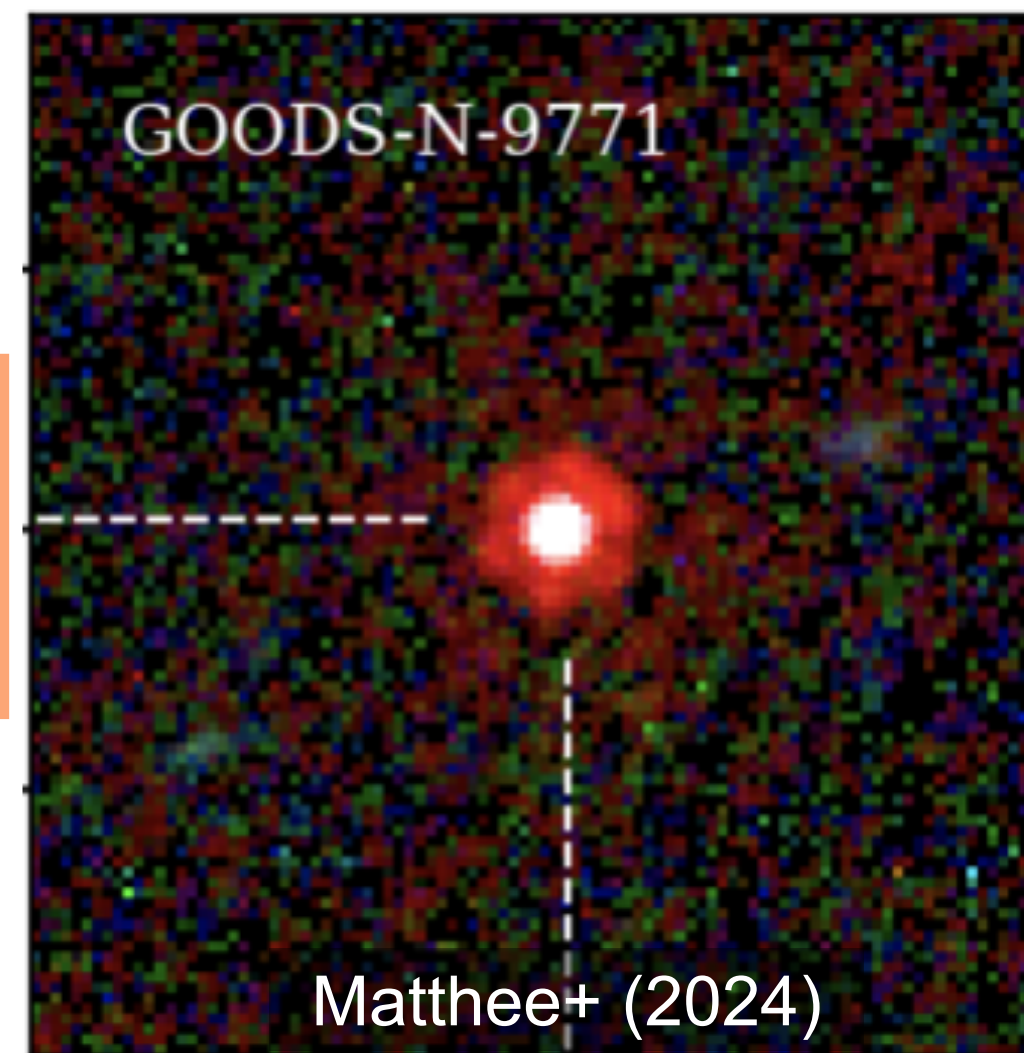
$$\frac{dN}{dt} = \frac{N_0}{\sqrt{2\pi}\sigma_0 t} \exp \left[-\frac{\{\ln(t/t_0)\}^2}{2\sigma_0^2} \right] \quad \begin{array}{l} t_0 \simeq 850 \text{ Myr} \\ \sigma_0 \simeq 0.3 \end{array}$$

A simple hypothesis for the LRD origin

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



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

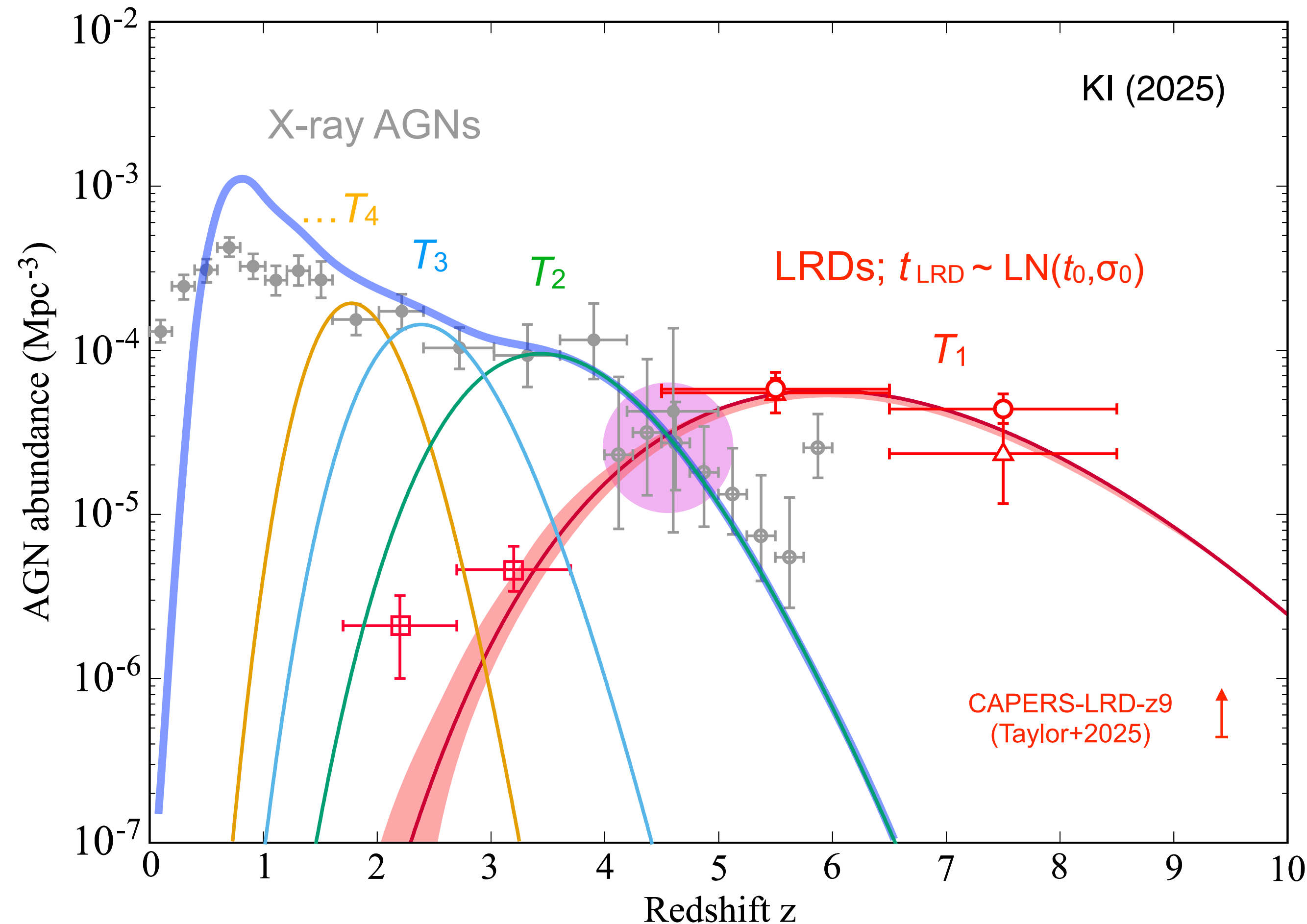


Typical AGNs
($z < 4-6$)



- First accretion episodes of seed BHs in dense gas = **LRDs**
- Individual AGN episodes are triggered following the same LN distribution
- LRD's characteristics disappear in later episodes (e.g., dust, X-rays, hosts)

Emergence of LRD populations



normal AGNs =
 $n(\geq 2)$ -th episodes

$$T_n = \sum_{i=1}^n t_i$$

the sum of log-N variables

$$t_i \sim \text{LN}(t_0, \sigma_0)$$

A transition from early BH accretion in dense & dust-poor environments to normal (X-ray) AGNs in the later epochs at $z < 4-5$

Summary



An illustration by Chat-GPT

What are Little Red Dots (LRDs)?

- A newly type of BLAGNs, with v-shape UV-optical SED, weak IR, X-rays, radio emission
- Transient-like origins with log-normal t-distribution

(Some) Theoretical interpretations

- Dense gas around BHs (super-Eddington): co-existence of Balmer absorption and beak:
- Moderate (or no) dust attenuation: solution for ALMA non-detection, faint MIRI, and no obvious host galaxies

Thank you!