Little Red Dots: A Key Building Block of the Massive BH Population at Cosmic Dawn

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August 5th, 2024 @Transient 2024, YITP


Tenure Associate Prof. (2024.8.1~)
Thank you all for your continuous supports
in the past 15 years, especially to Kyoto colleagues

Outline

1. Overviews of JWST observations
2. Little red dots — AGNs hypothesis
3. Applications — BH growth, spin, TDEs

1. Overview of JWST observations

Supermassive Black Holes (SMBH)

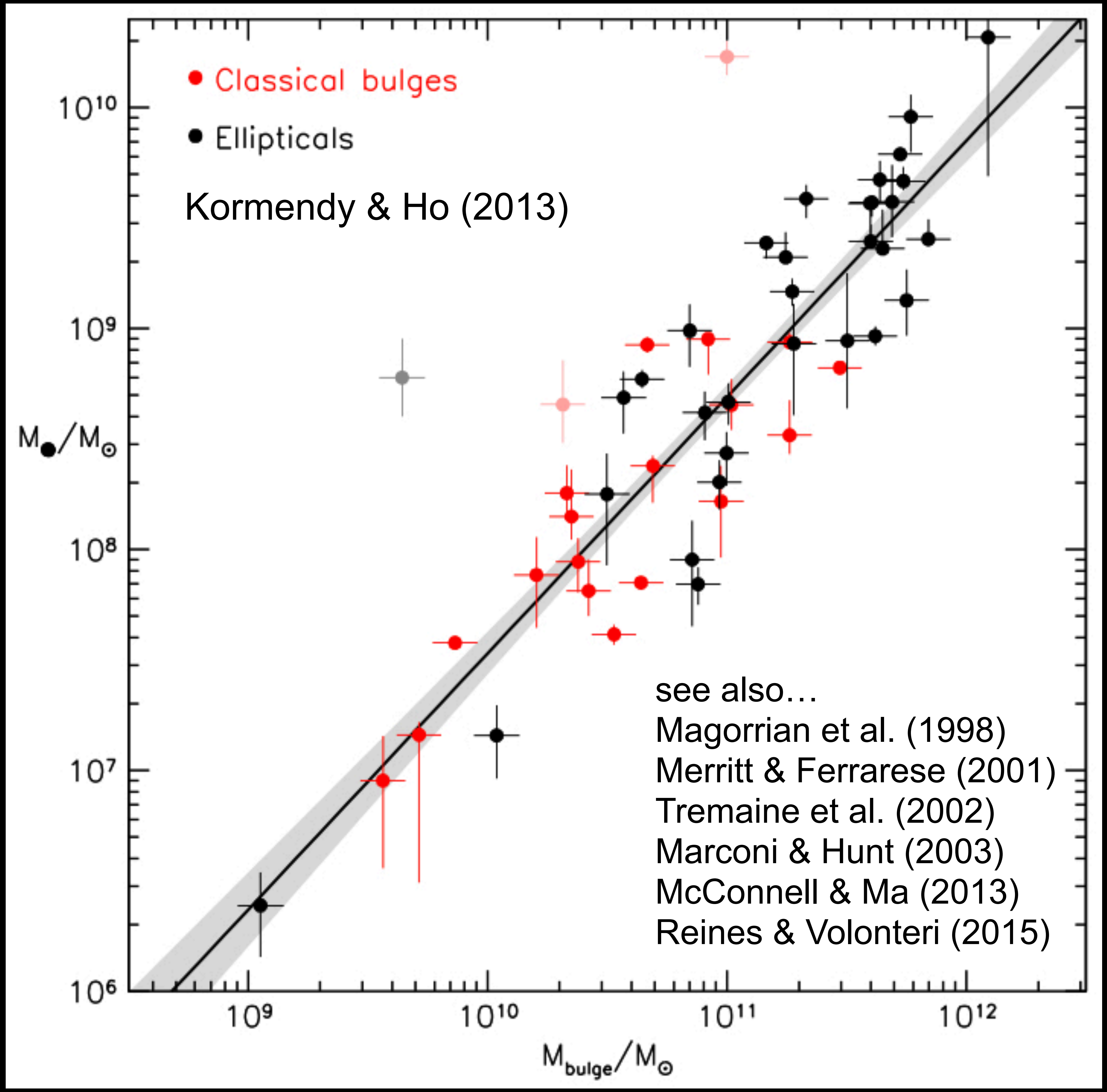
https://en.wikipedia.org/wiki/Messier_87

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

Key questions:

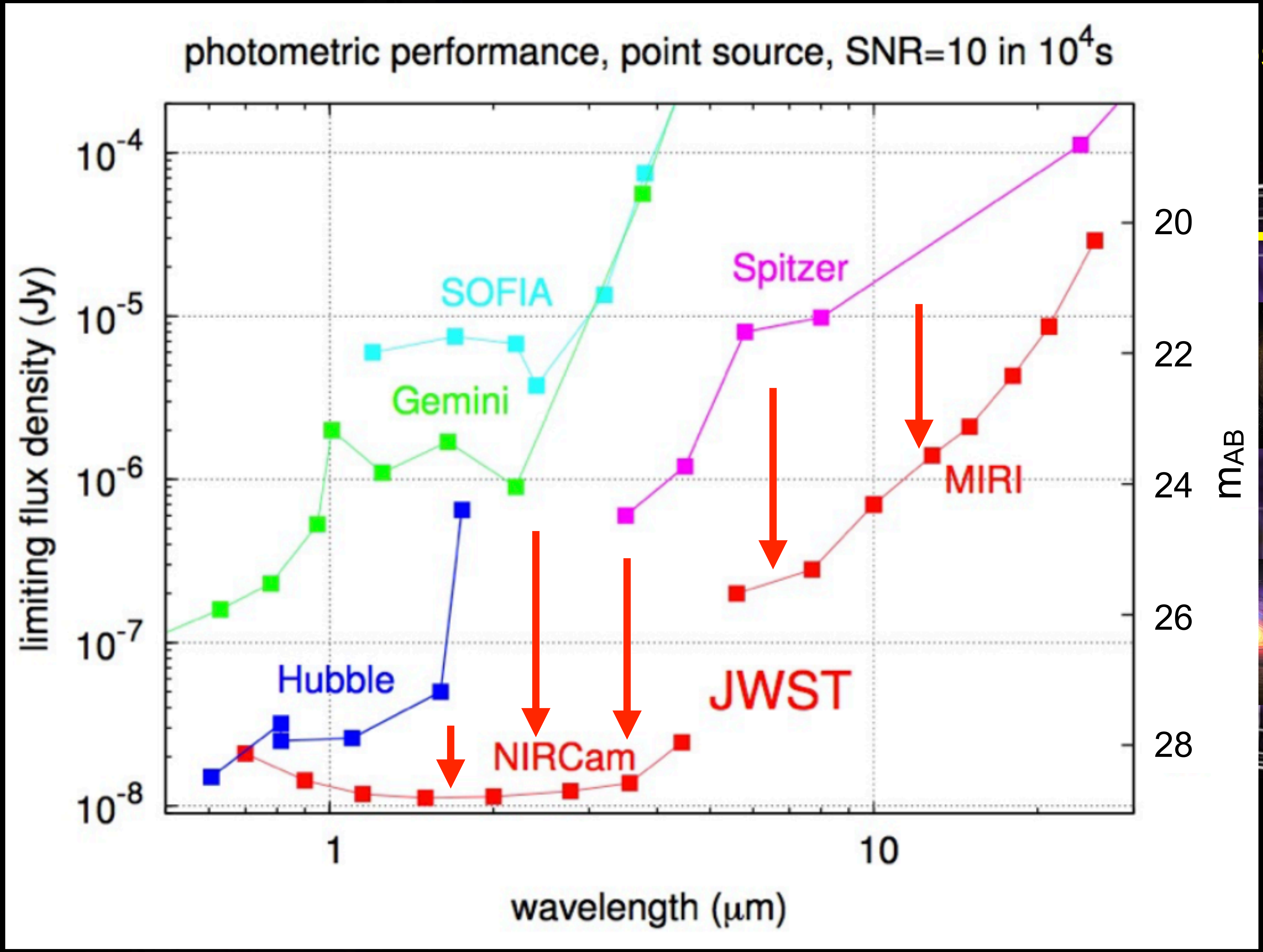
1) What is the origin of SMBHs?
2) How did BHs and galaxies interact?
3) Cosmological coevolution & high-z?

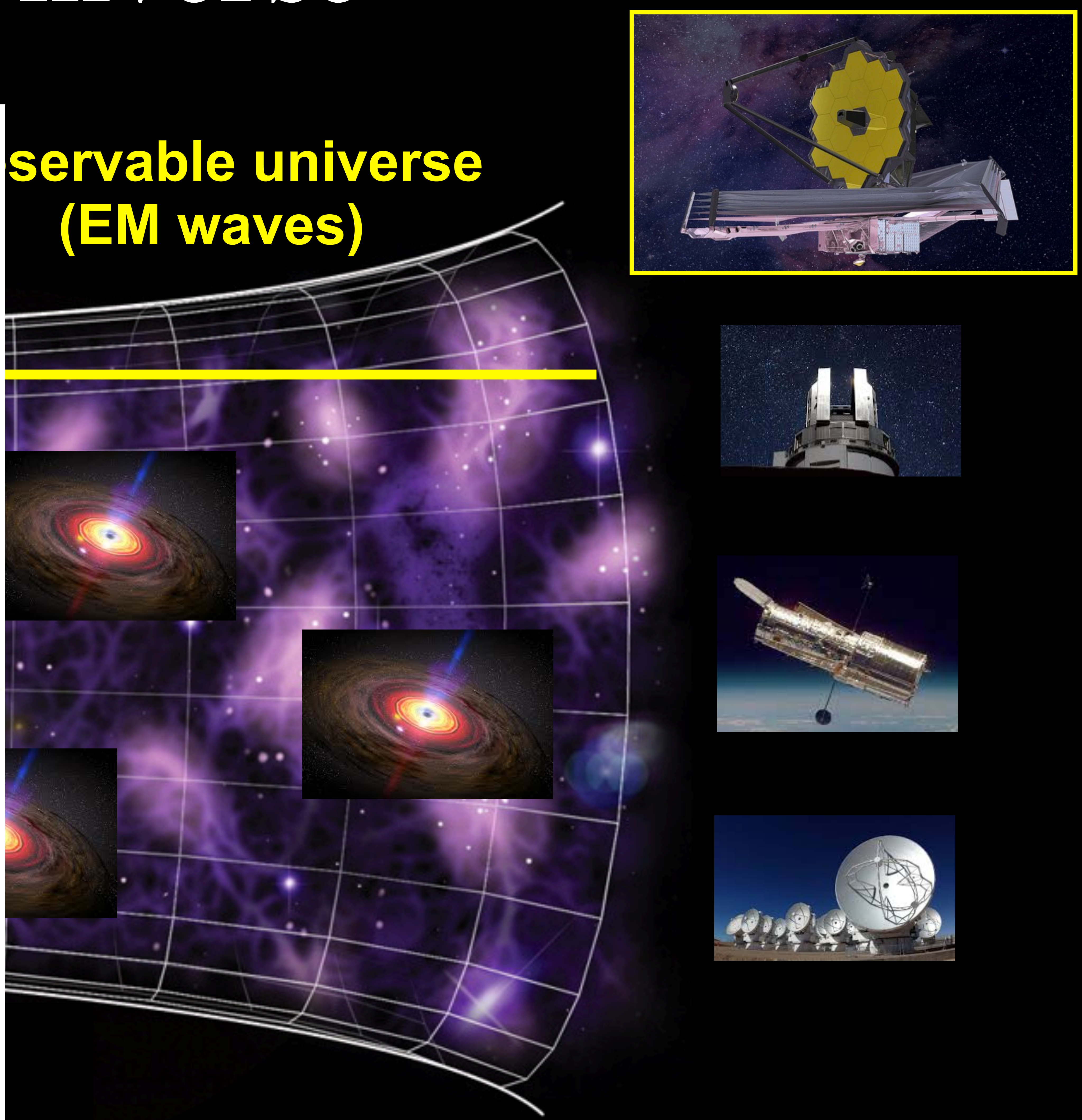
Black Hole mass



Galaxy mass

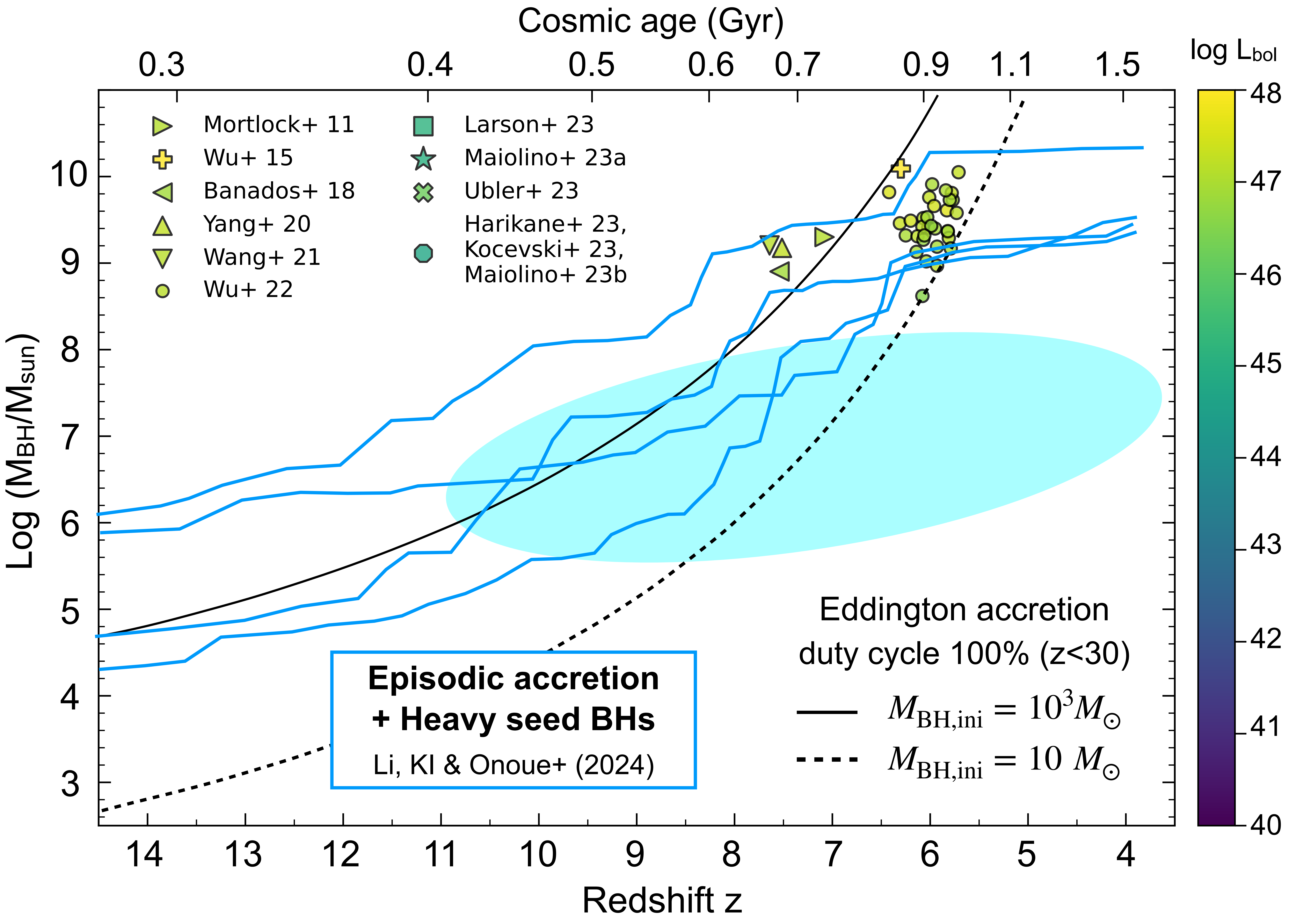
History of the Universe

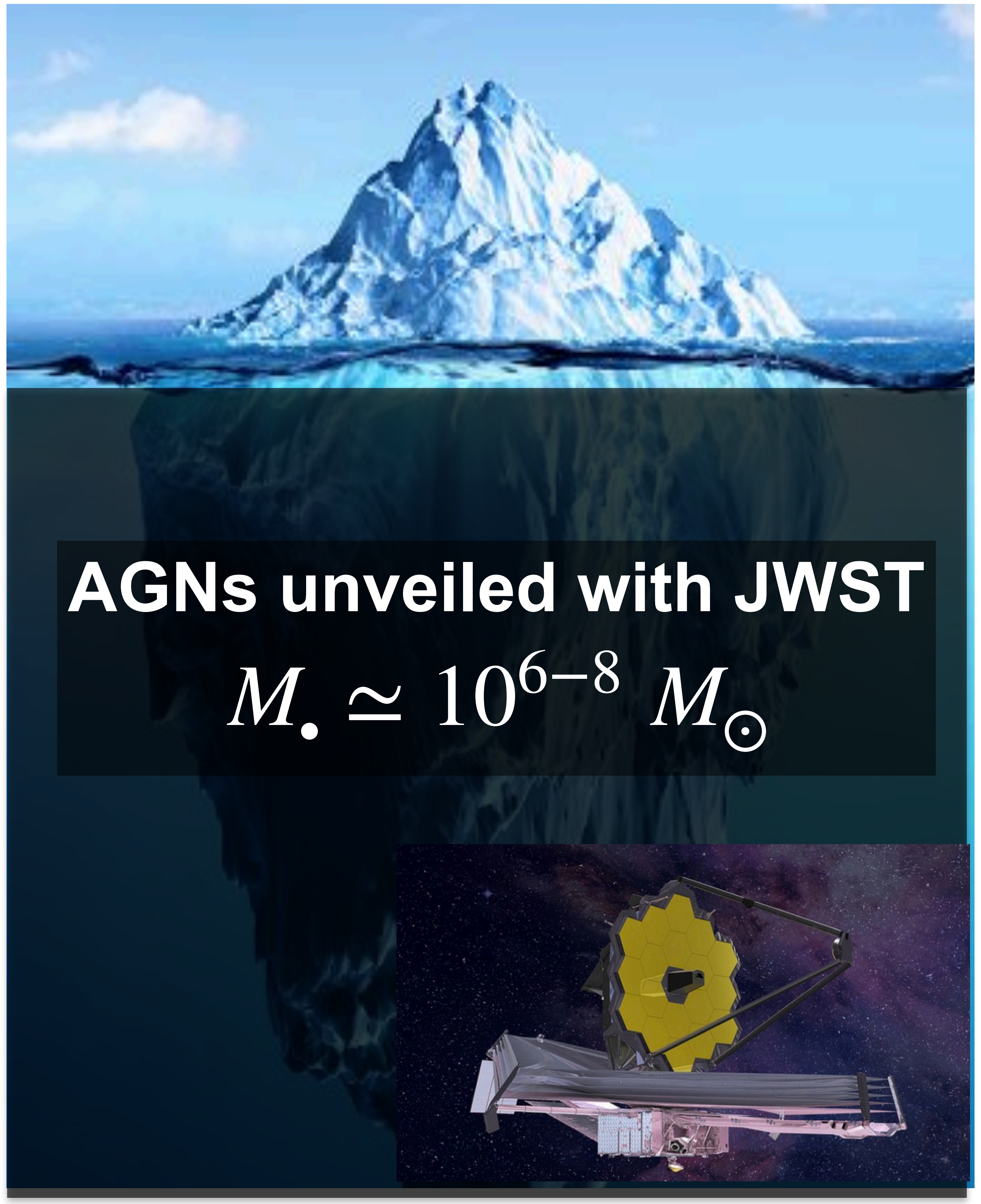




https://science.sciencemag.org/content/319/5859/52

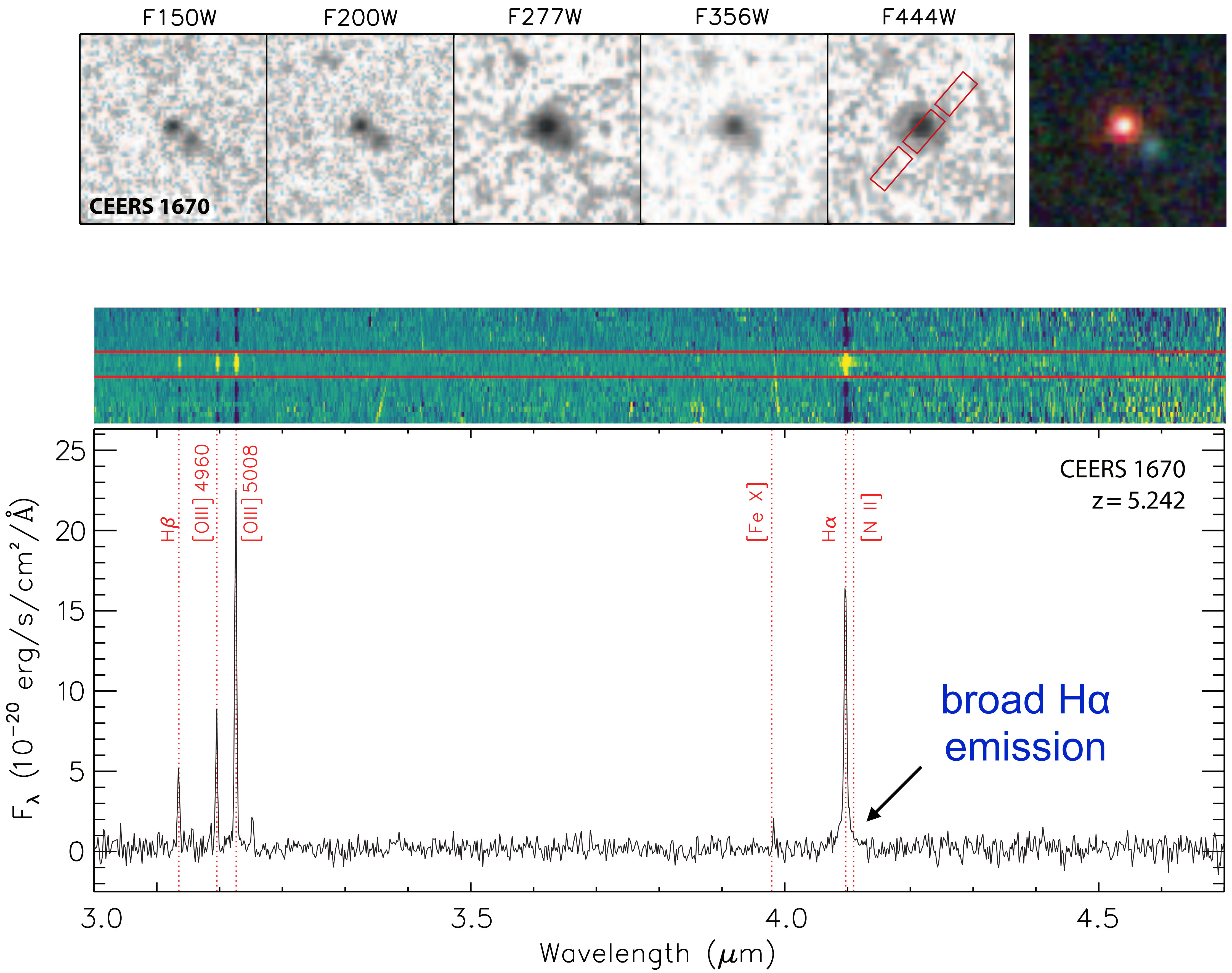
High-z SMBH population

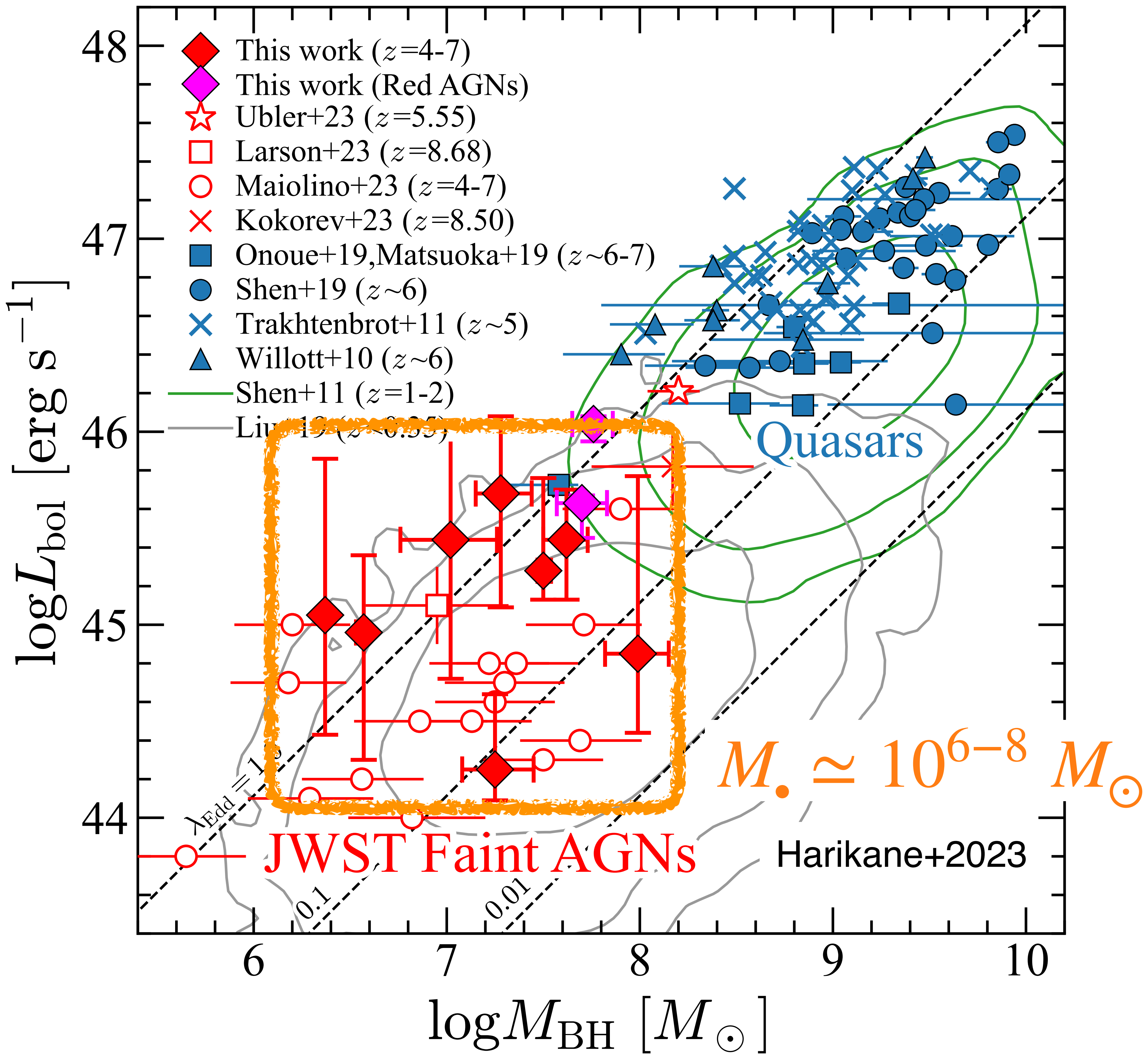




Hidden little monsters uncovered by JWST

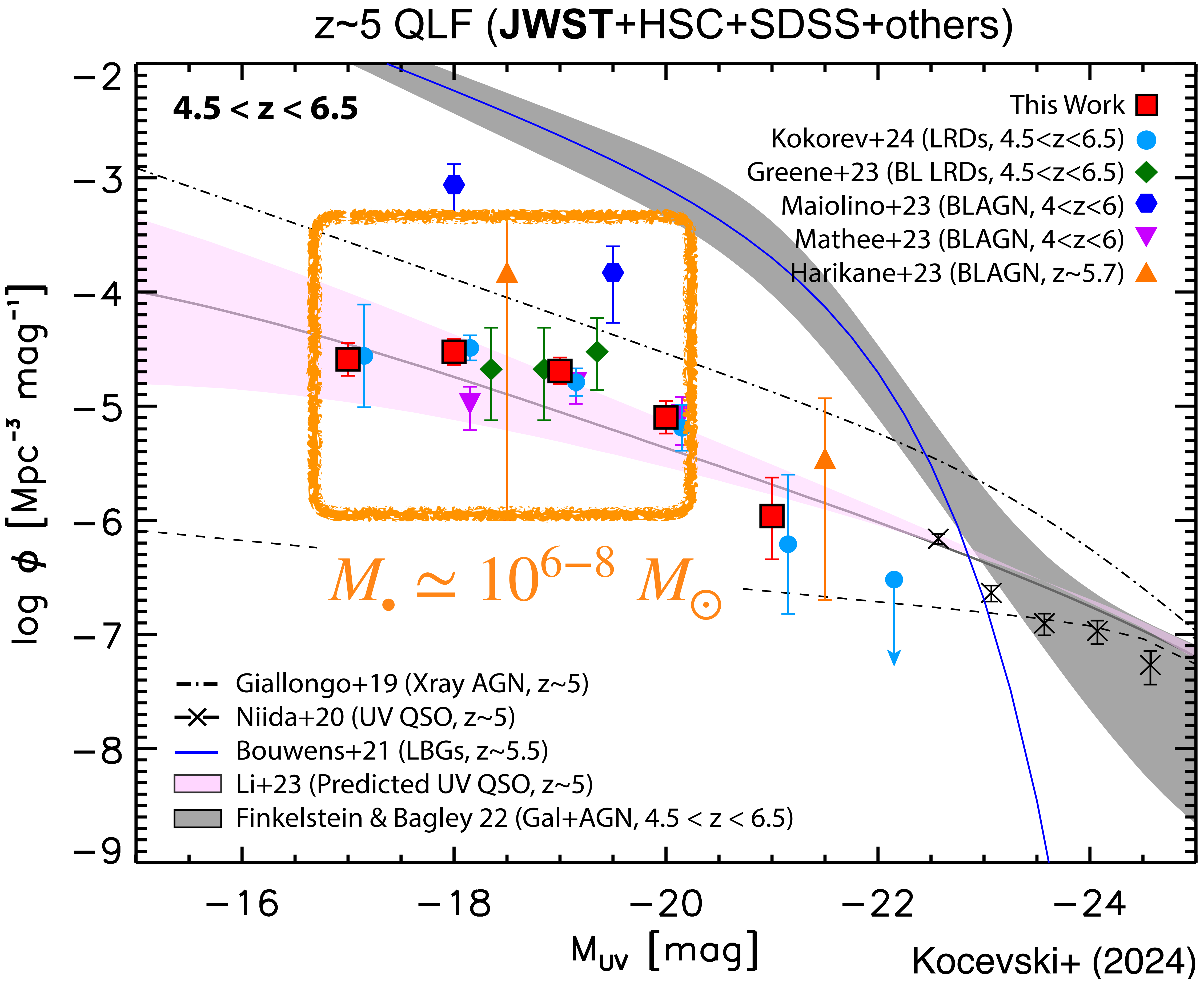
- **A Candidate for the Least-massive Black Hole in the First 1.1 Billion Years of the Universe**
- **Hidden Little Monsters: Spectroscopic Identification of Low-Mass, Broad-Line AGN at $z > 5$ with CEERS**





Onoue, KI, Ding+ (2023), Kocevski, Onoue, KI+ (2023)

Abundant fainter AGNs



Star-forming galaxies

$\Phi \sim 10^{-3} - 10^{-2}\ \mathrm{Mpc^{-3}\ mag^{-1}}$

e.g., Finkelstein+15, Bouwens+21,Harikane+22

JWST broad-line AGNs

$\Phi \sim 10^{-5} - 10^{-4}\ \mathrm{Mpc^{-3}\ mag^{-1}}$

e.g., Onoue+23, Kocevski+23, Harikane+23, Maiolino+23, Matthee+24, Greene+24, Kokorev+24

Bright QSOs (ground-based surveys)

$\Phi \lesssim 10^{-8} - 10^{-7}\ \mathrm{Mpc^{-3}\ mag^{-1}}$

Jiang+18, Matsuoka+18, McGreer+18, Niida+20

Abundant & low-luminosity AGNs (**low-mass BHs**) detected with JWST

Early BH-galaxy coevolution

- **Overmassive BHs** relative to the local relation

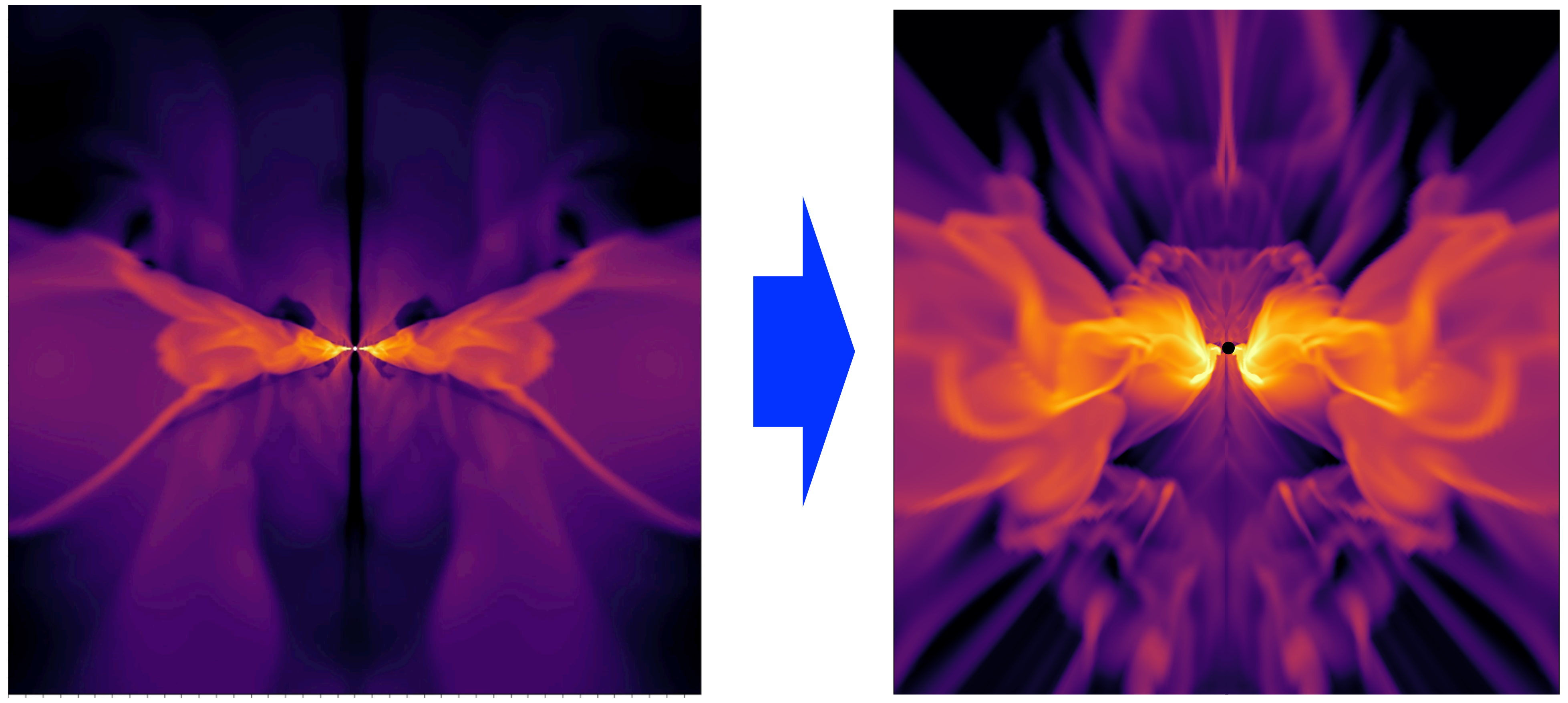
  Intrinsically overmassive or just biased distribution?

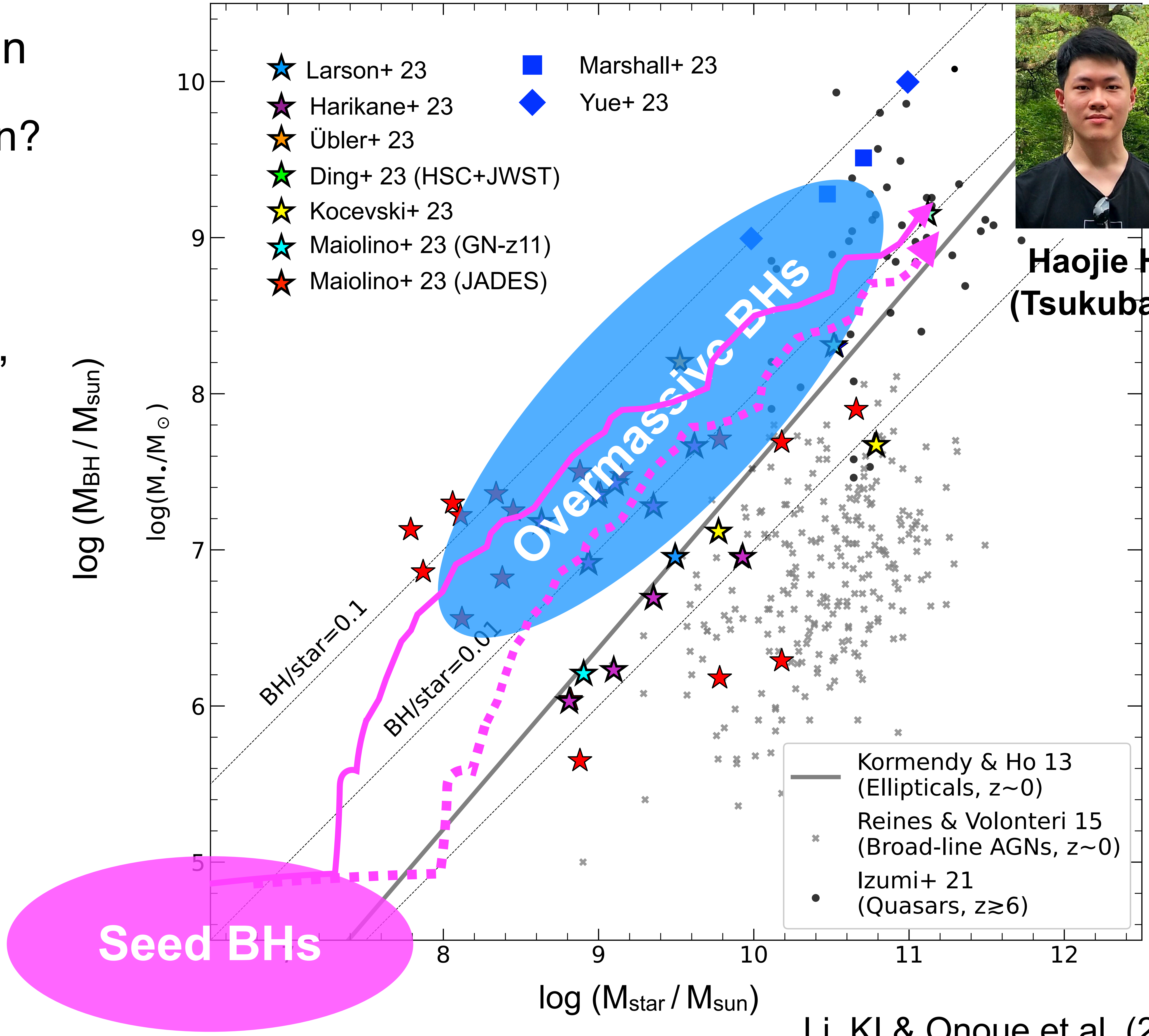
  (Pacucci+23, Li, Silverman & Shen +24, Kormendy & Ho 2013)

- Transient **super-Eddington** accretion of BHs, which are also detectable with JWST

  RHD simulations (KI+22a,b; **Hu+22a,b**)

  Semi-analytical models (Scoggins+23; Schneider+23)





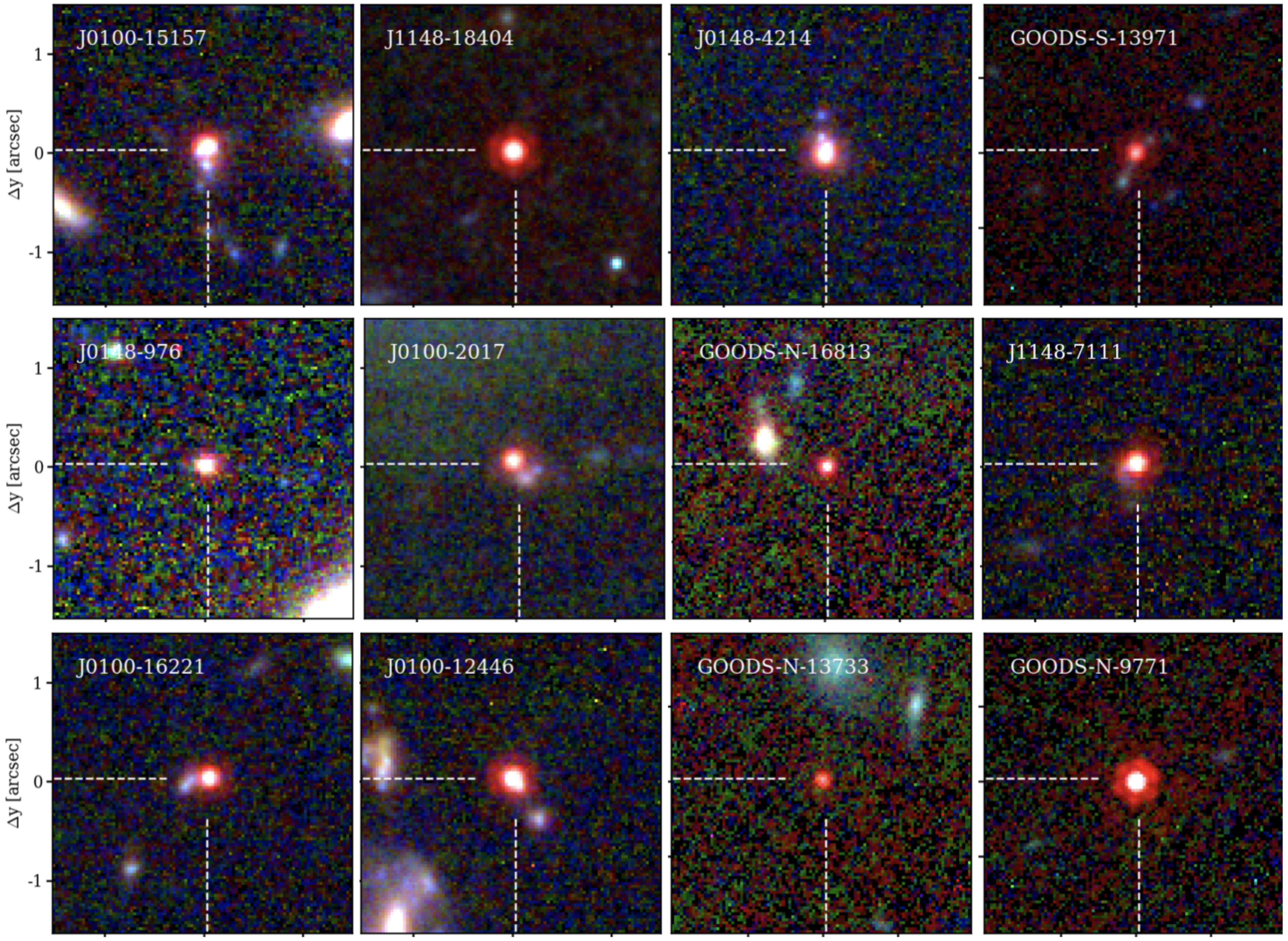
Haojie Hu (Tsukuba U)

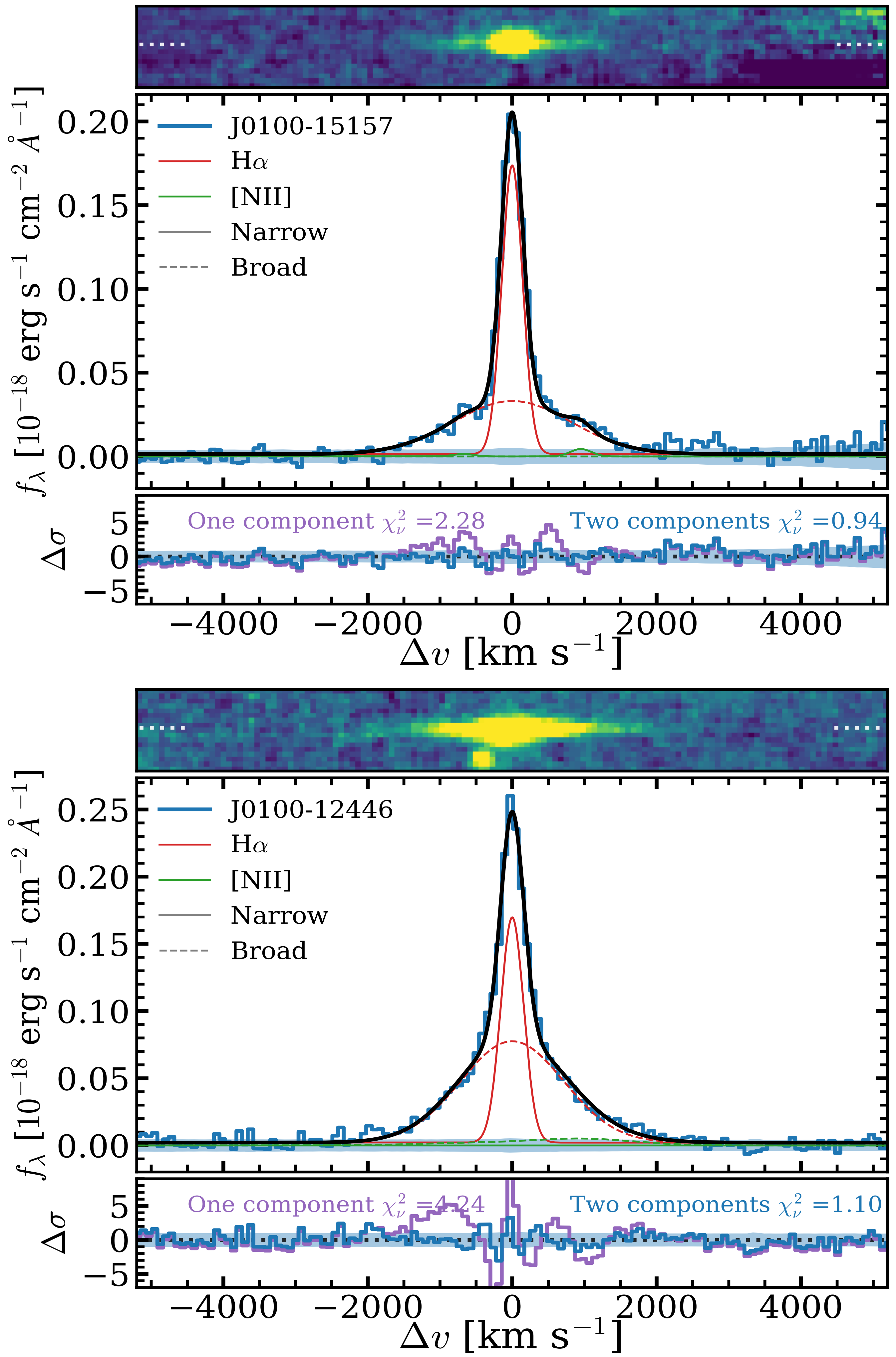
Li, KI & Onoue et al. (2024)

2-1. Little Red Dots
(observations)

NOTE: they seem a new population at high-z sources. We haven't reached a conclusion.
Thus, I might talk about some chaos…

Little Red Dots

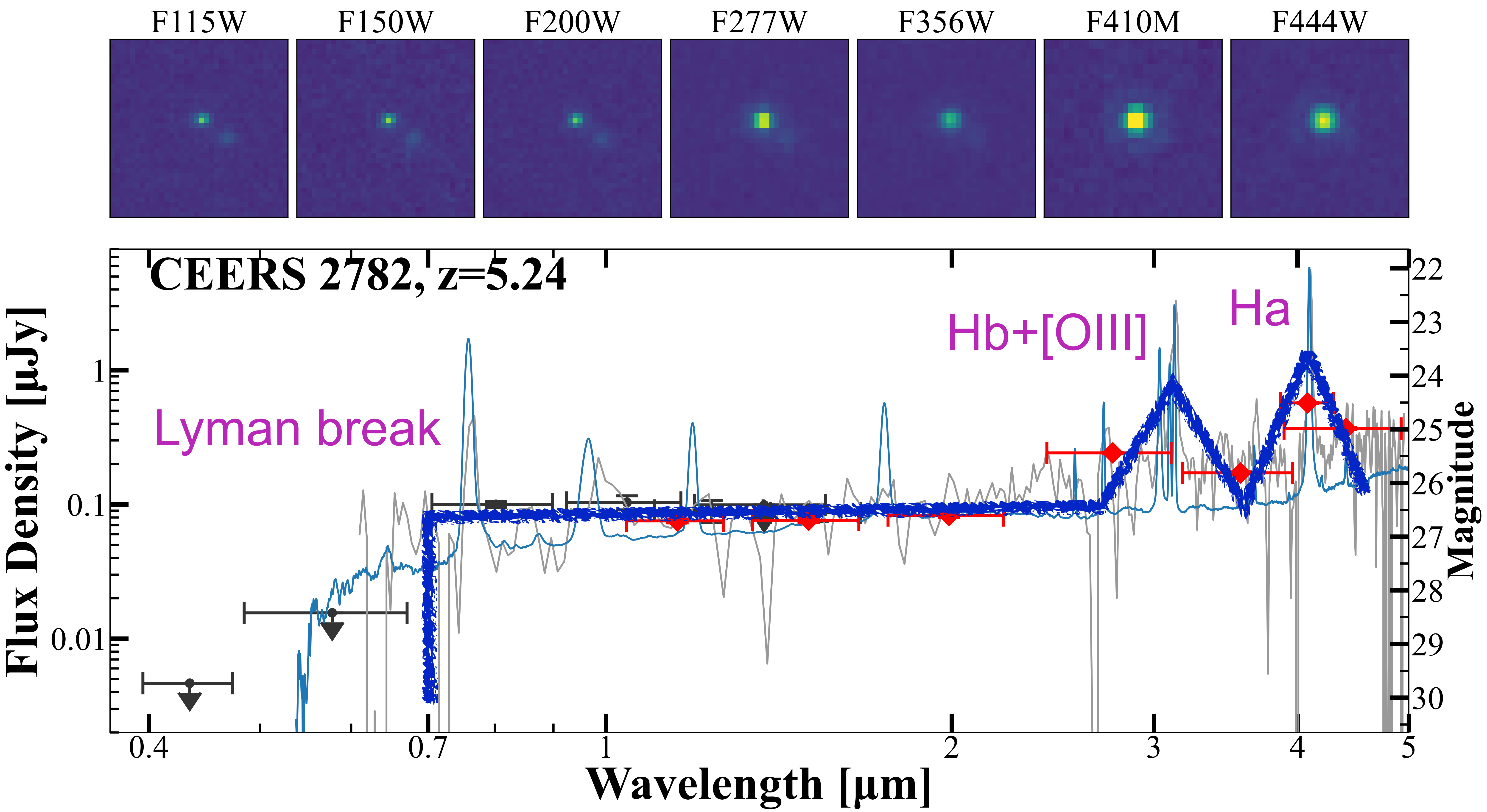




- Very compact & red sources (in JWST NIRCam)
- **Broad-component** of Balmer lines (Ha/Hb)

e.g., Kocevski+23,24, Labbe+24, Greene+24, Kokorev+24,

Normal (unobscured) AGNs seen by JWST

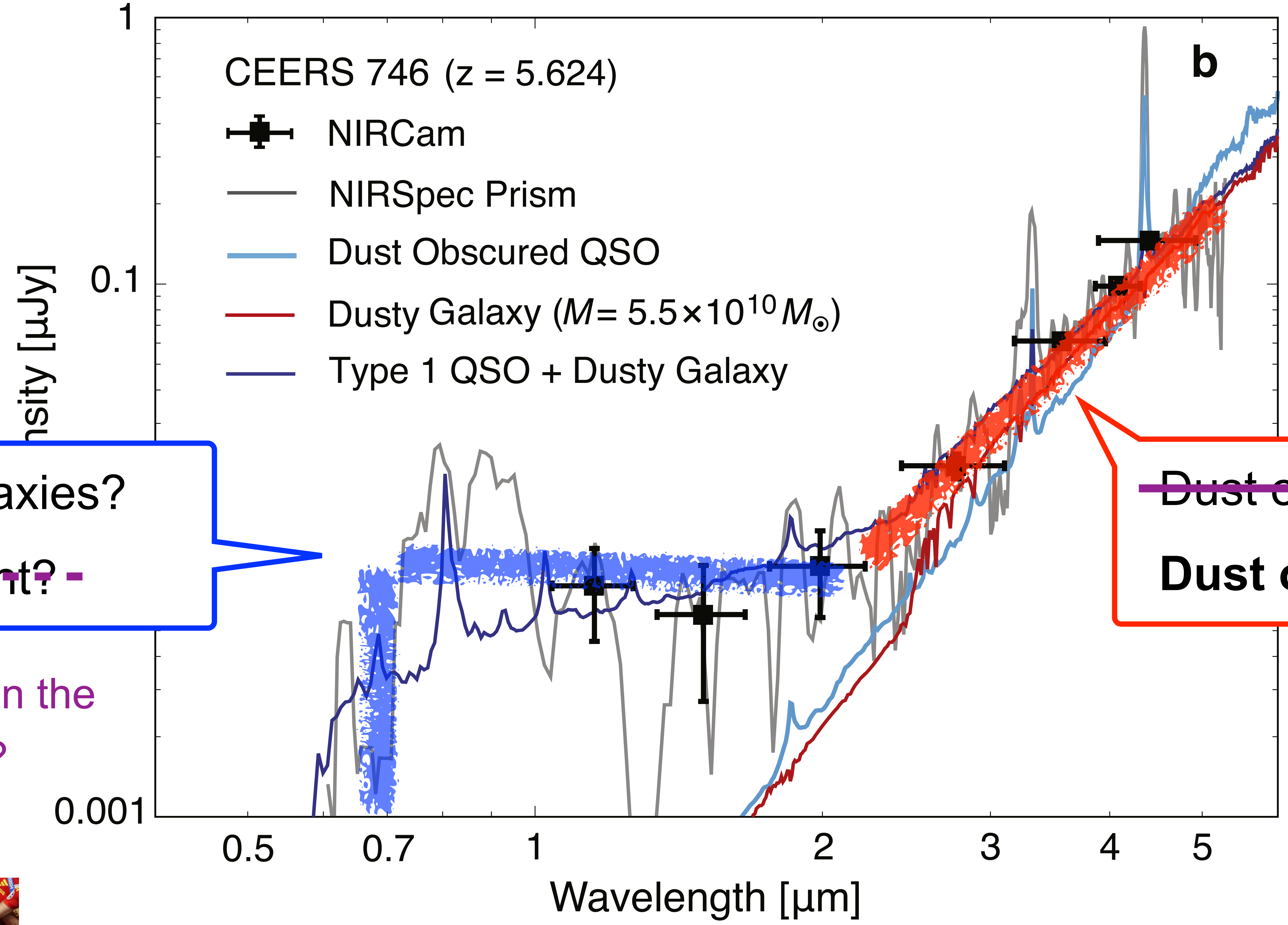


Onoue+23, Kocevski+23, Guo+24 in prep

- Very compact (unless galaxy light dominates)
- **Flat SED** in F_ν (NIRCam) + **broad** Balmer lines (NIRSpec)

Characteristic v-shape SEDs

Kocevski et al. (2023)



Unobscured galaxies?

~~Scatted AGN light?~~

~~Dust obscured galaxies?~~

Dust obscured AGNs?

huge stellar mass (~$10^{11}M_{sun}$) in compact scales (<100pc)…

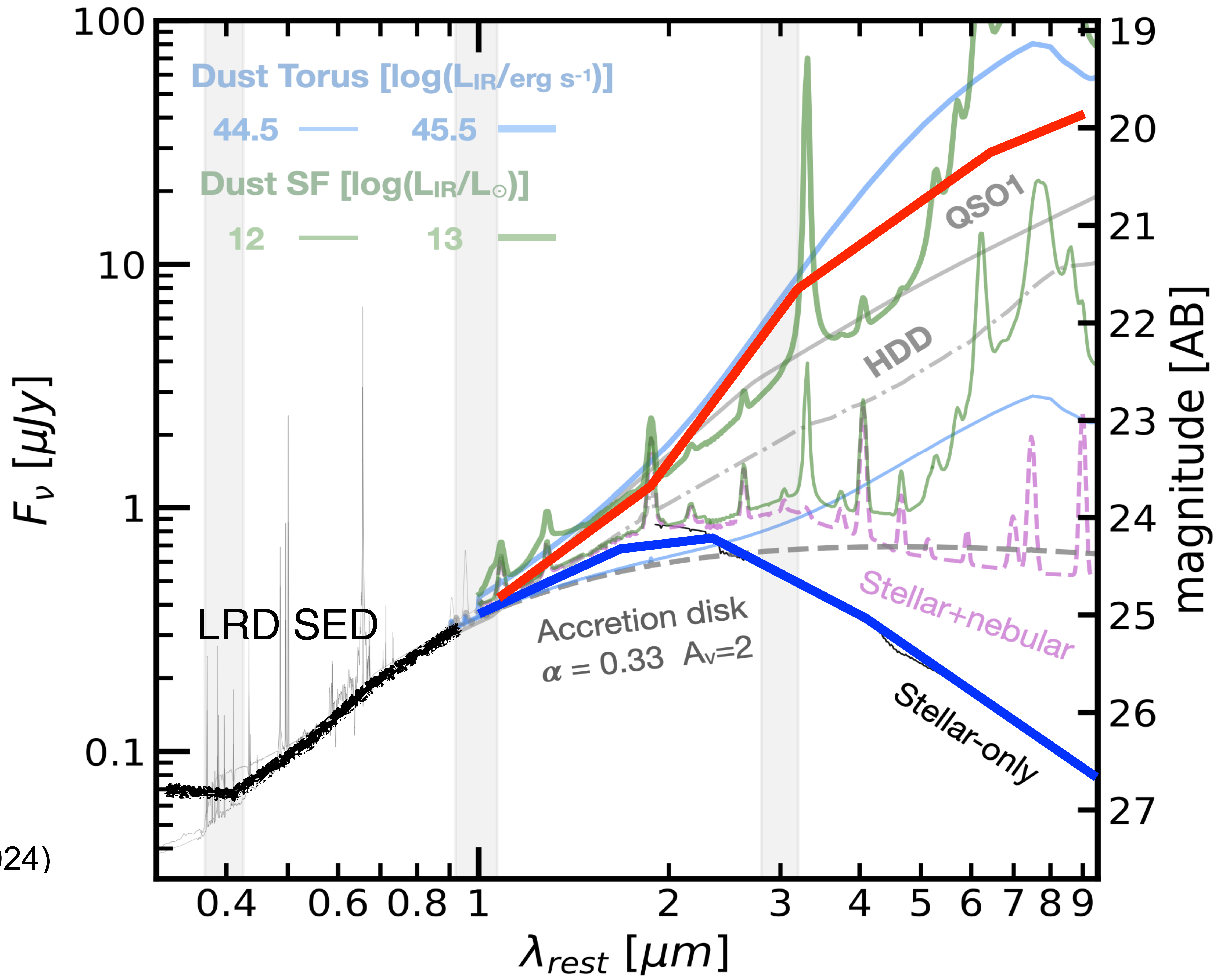
can coincident events explain the uniformity of v-shape SEDs?

If it's an AGN, L_{bol} ~ 10^{46} erg/s

Two components!!

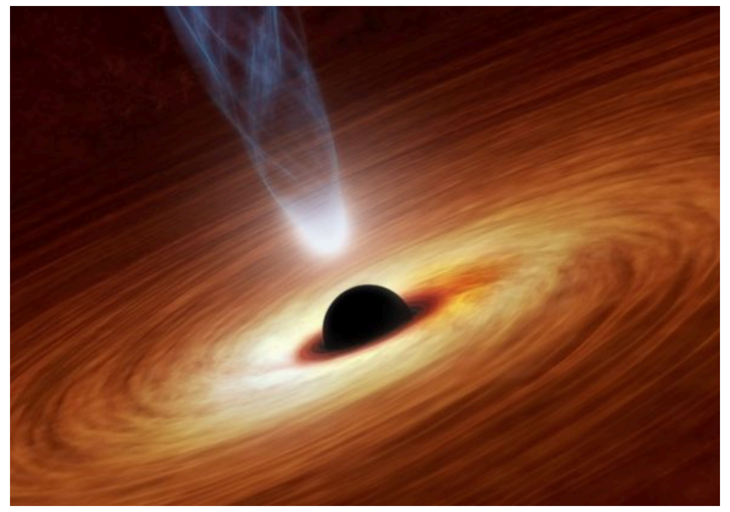
really? simpler is better…

LRD's SED at near IR



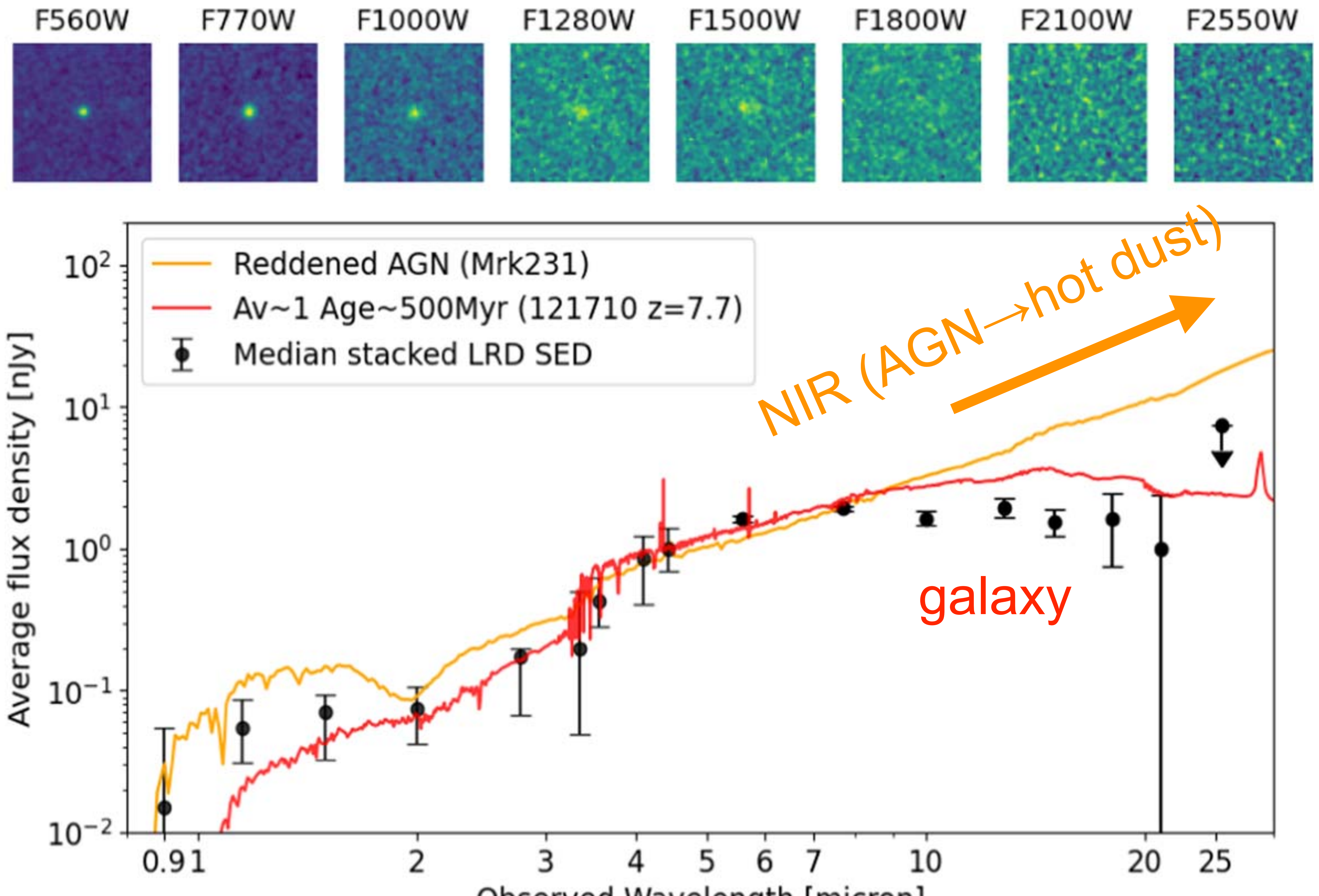
Pérez-González+ (2024)

Obscured AGNs
(hot dust)

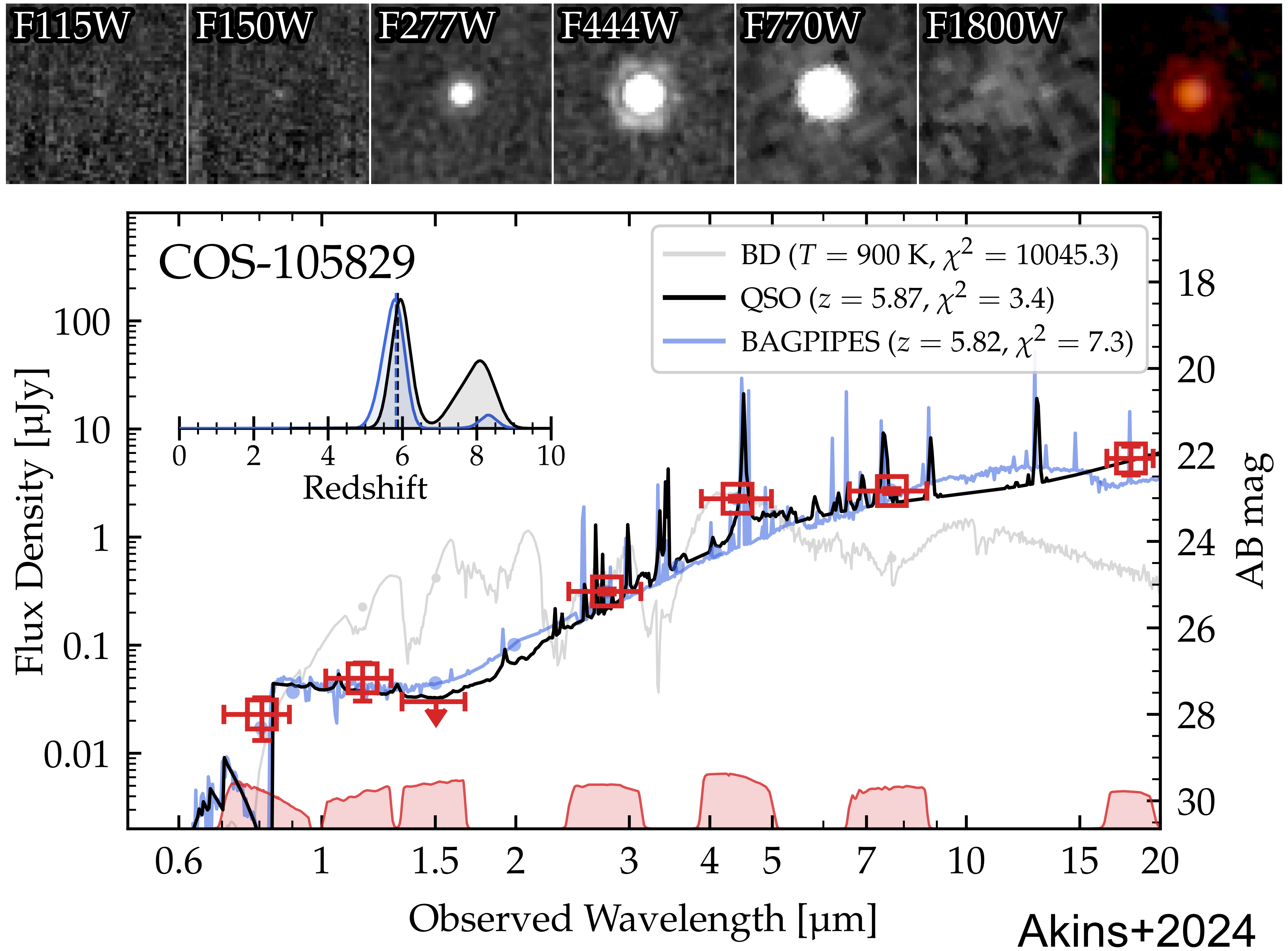


Obscured galaxy

LRD's SED at near IR



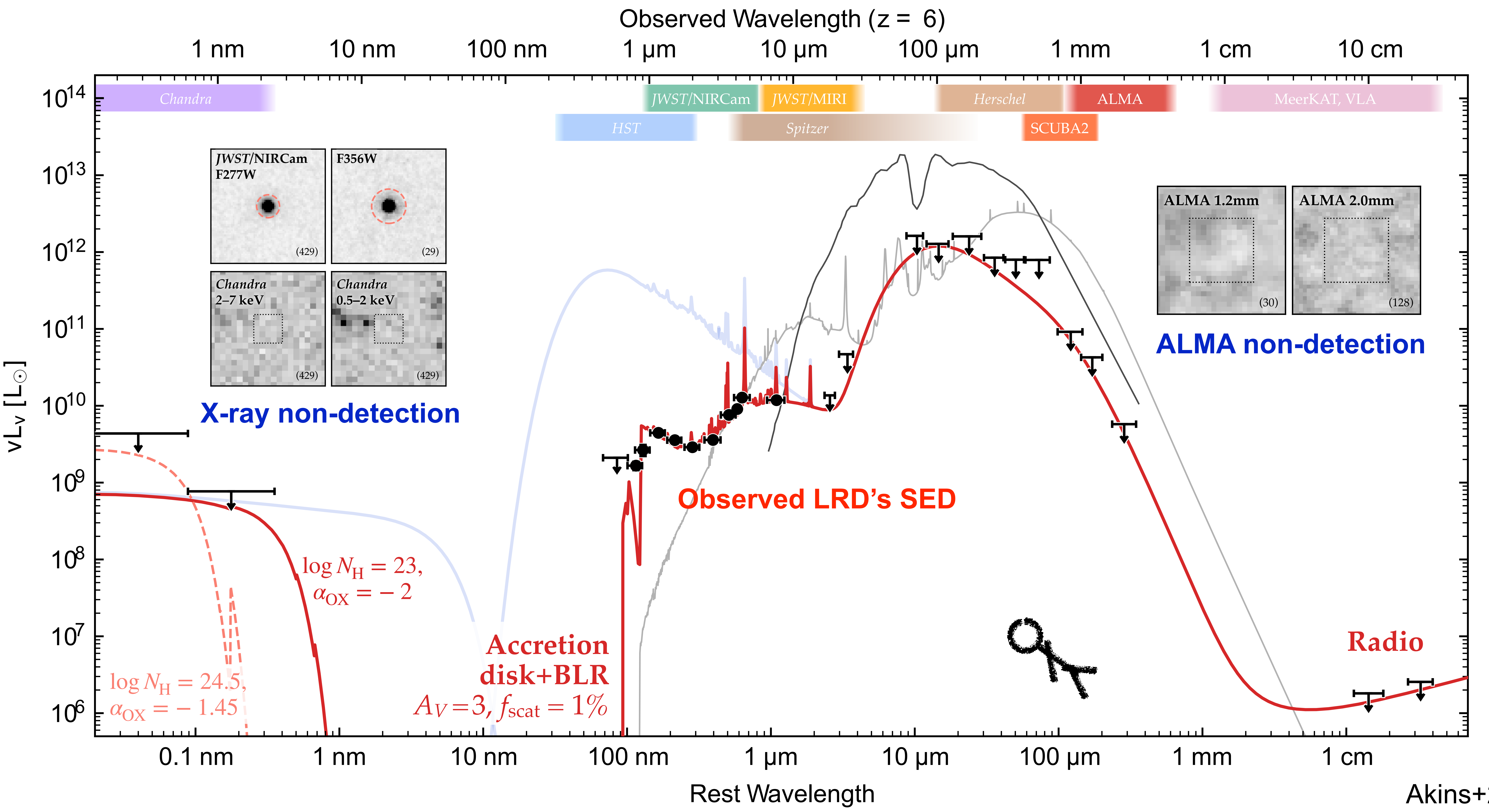
Williams+2024



Akins+2024

- JWST MIRI data disfavors AGN models for optical continuum
- No hot dust heated by AGNs (otherwise, very red in NIR)

A short summary of observations



Akins+2024

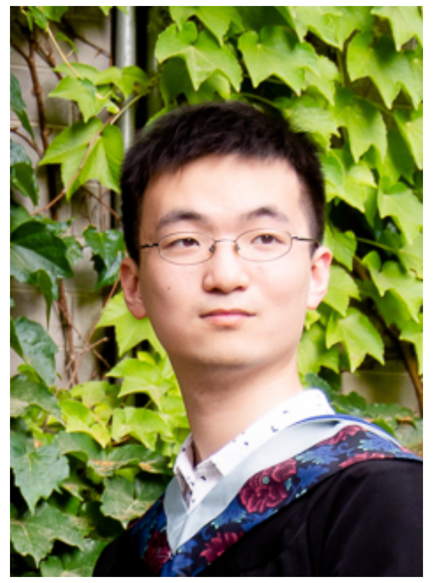
A short summary of observations

	AGN hypothesis		Galaxy hypothesis	
Image	○	Compact	△	No robust host detection*
Broad-line emission	○	The best explanation	×	Stellar origin (WRs/SNe)?
Red optical	○	Dust-reddened AGN	×	dust-reddened galaxy (require too massive galaxy)
Blue UV	×	Unknown (the host galaxy?)	×	Unknown
Faint NIR	△	No hot dust heated by AGN?	○	Consistent
X-ray weak	×	Unknown (super-Edd?)	○	Consistent
ALMA no detection	○	No problem	△	No cold dust heated by star bursts?

2-2. Little Red Dots
(SED model)

Solutions for UV/NIR parts of LRD’s SED

Li, KI, Chen, Ichikawa & Ho (2024)
arXiv:2407.10760



Extinction laws in dense systems

- Heavier extinction from optical to UV

  - SMC / Calzetti's laws (everyone uses)

  - ISM extinction laws (see text book)

- **Gray extinction** at UV ranges (<3000A)

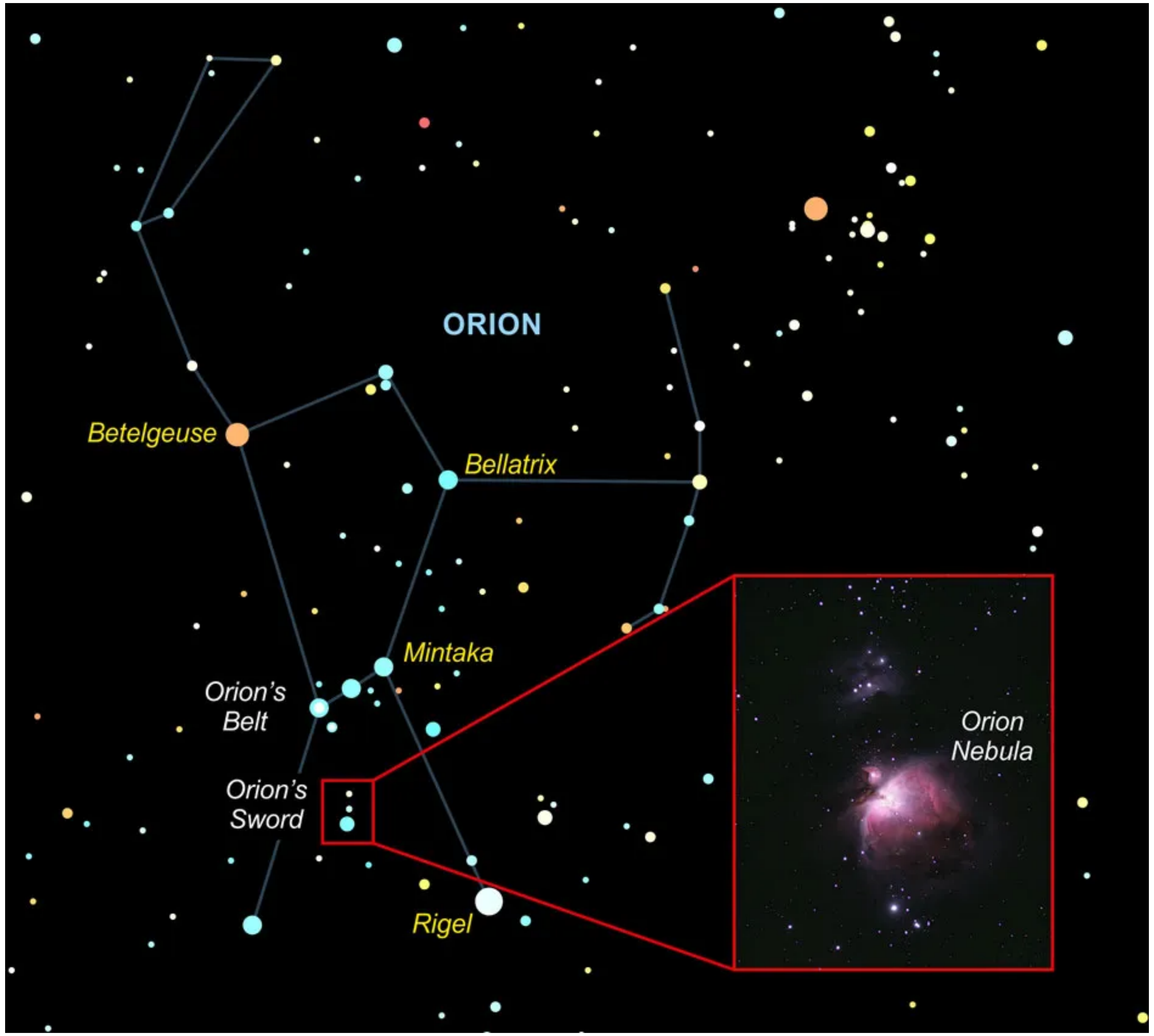
  due to the deficit of small-size grains;

  $a < \lambda/2\pi \sim 0.06\ \mu\mathrm{m}$

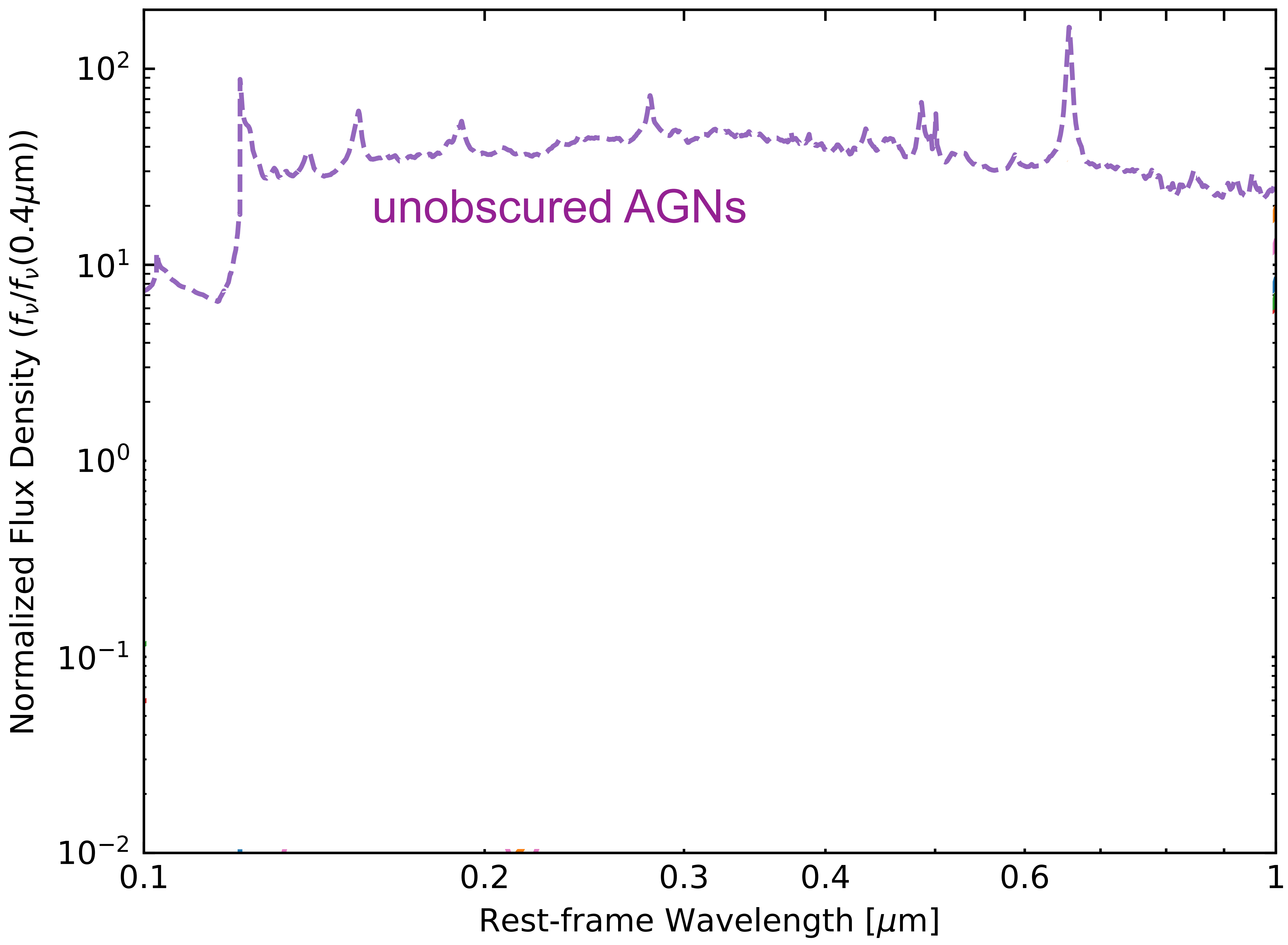
  - Orion Nebula (everyone knows)

  - Composite AGN spectra

  - High-z galaxies (6<z<13)

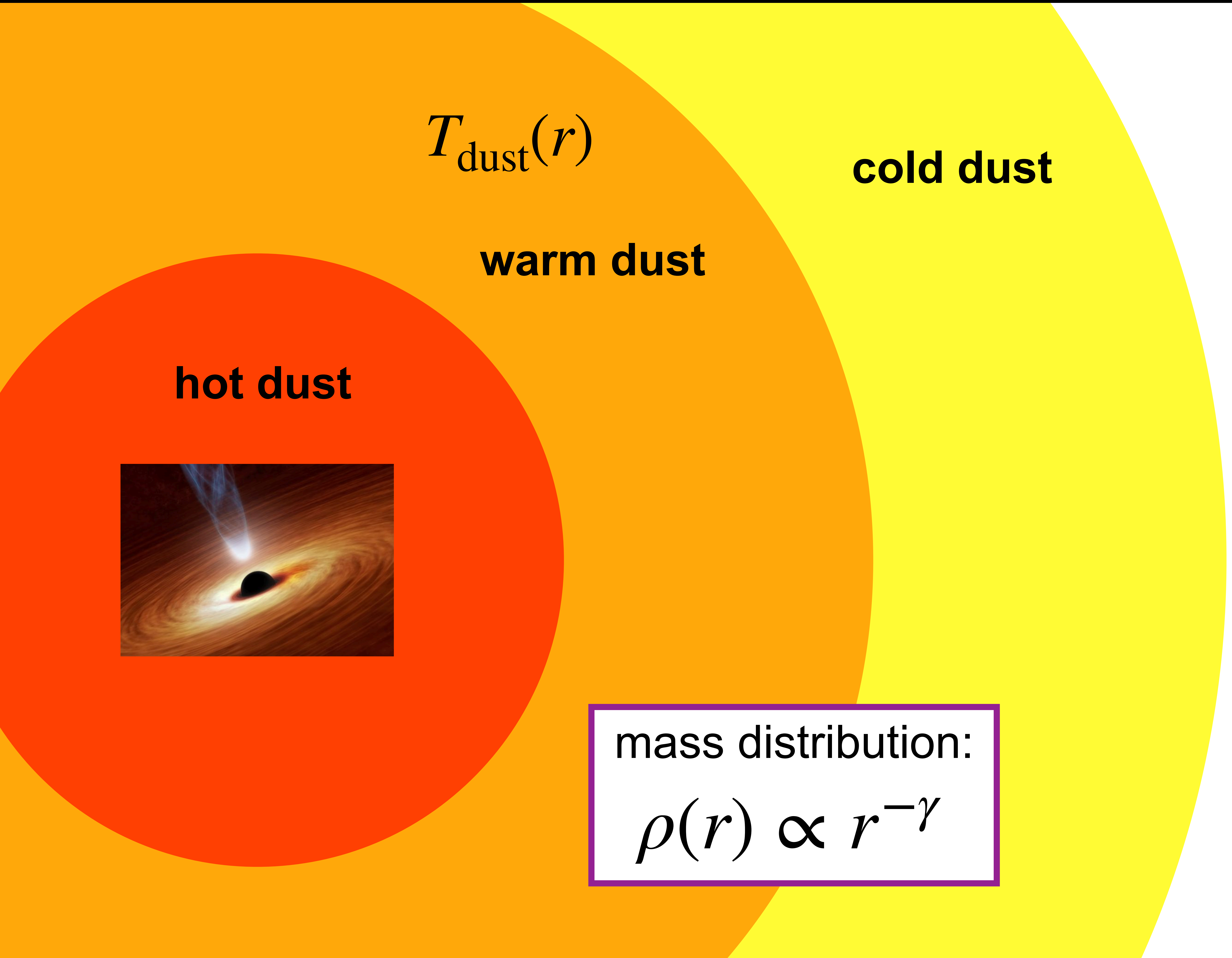


AGN SED + Extinction



Gray extinction maintains the v-shaped SED of LRDs

Re-emitted IR energy



- Torus model $\gamma > 1$

  centrally concentrated density

  IR emission from **hot** dust

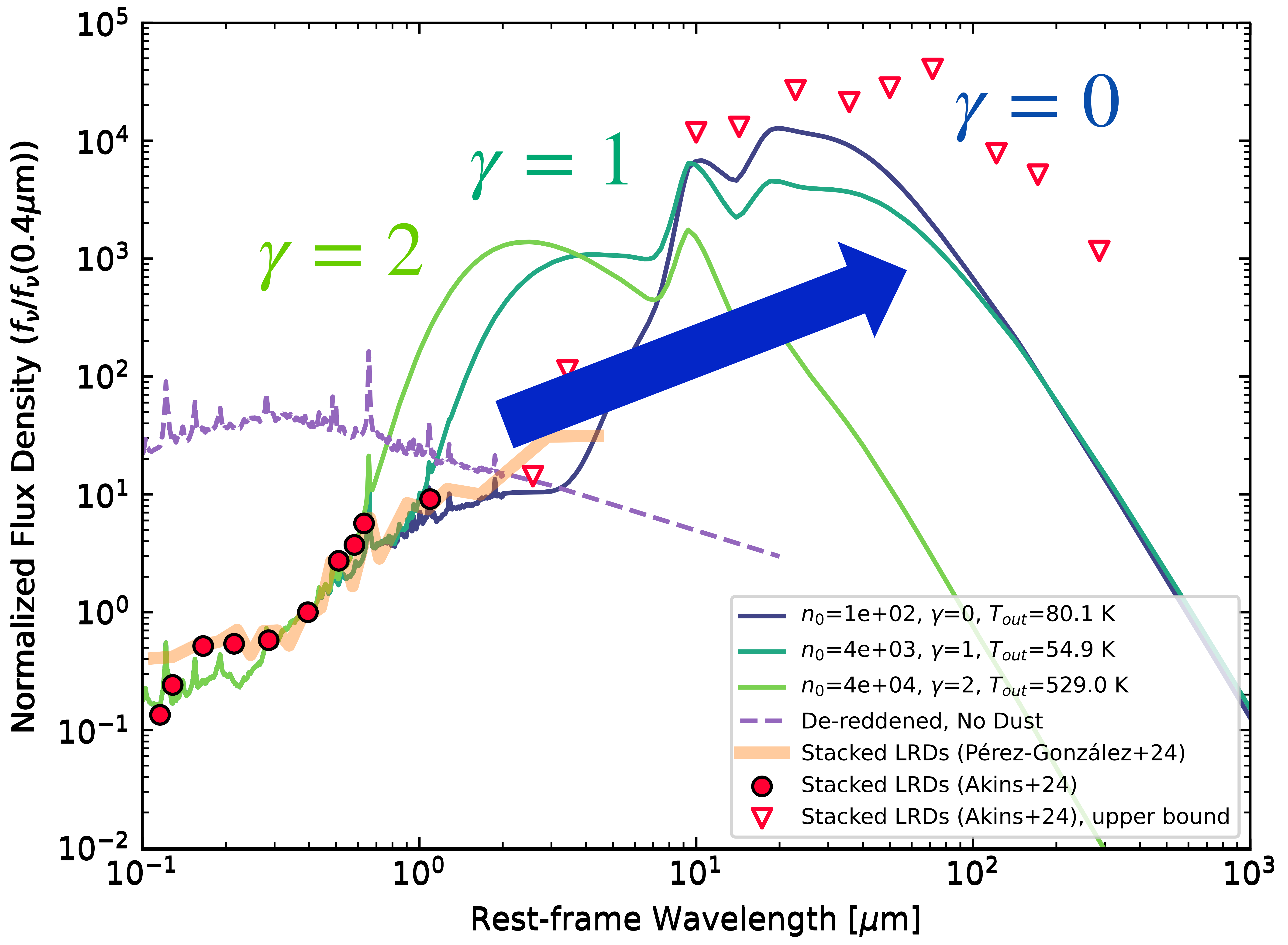
- Our model $0 < \gamma < 1$

  less concentrated density

  IR emission from relatively **cooler** dust

see also e.g.,
Barvainis (1987),
Hönig & Kishimoto (2017)

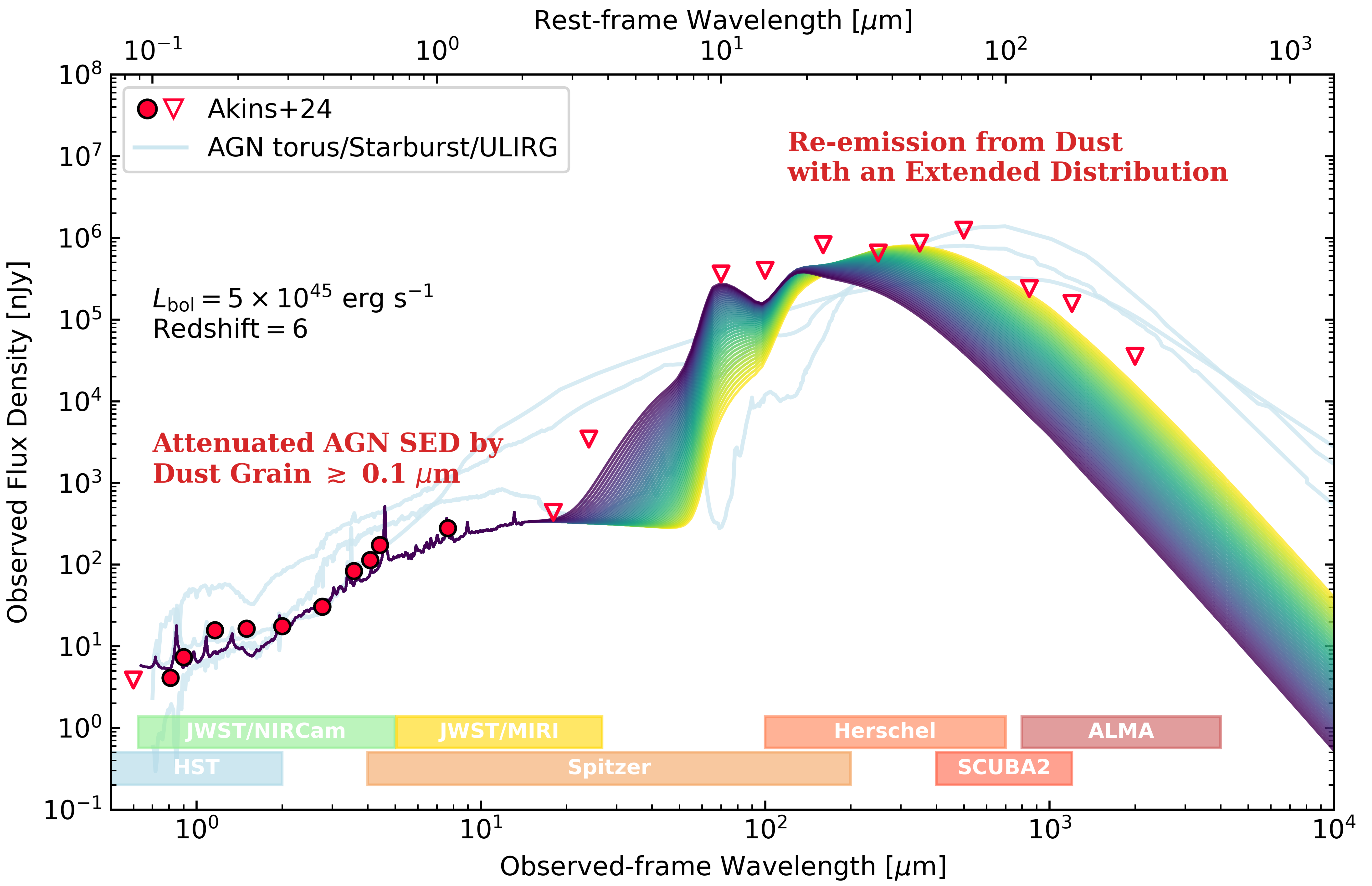
IR SED depending on density gradients



Li, KI, Chen+ 2024

Energy transfer from NIR to MIR with **extended** dust distribution

Multi-wavelength SED of LRDs (only AGN)

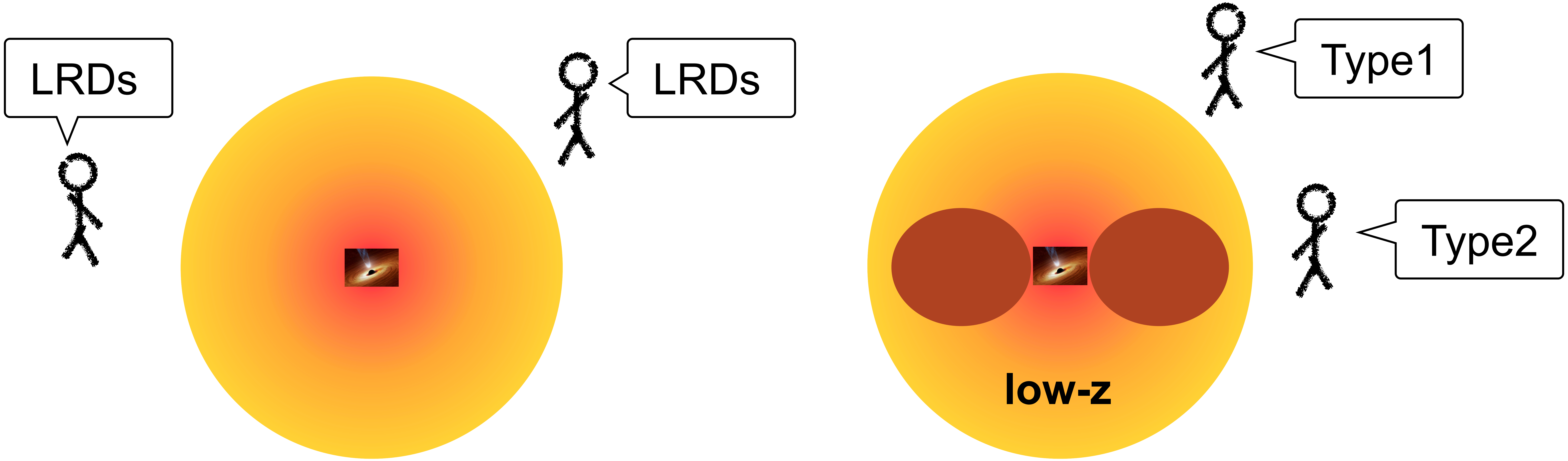


Li, KI, Chen+ 2024

New AGN unified model

- **Classical unified model:**
  Clear classification of low-z AGNs (type 1 vs 2), depending on the viewing angle due to the presence of dense dusty tori

- **Intermediate stage (LRDs):**
  Dynamically unsettled & extended gas/dust at higher redshifts, with a higher covering factor of BLRs



3-1. Applications

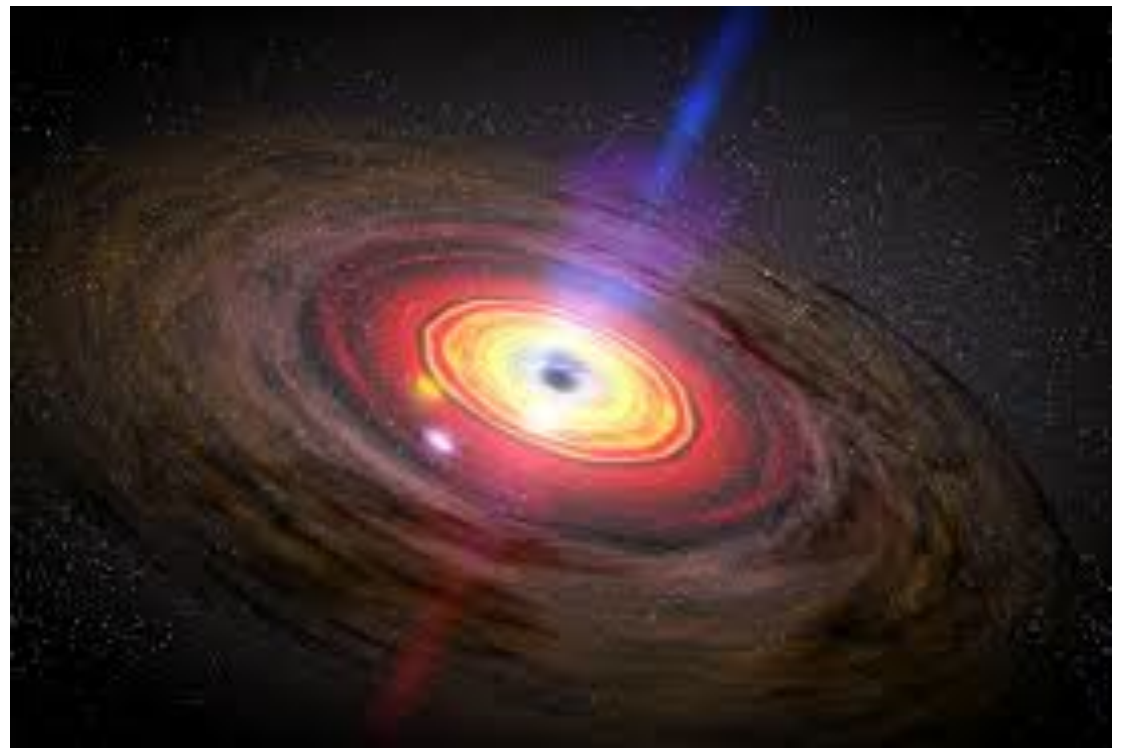
Sołtan-Paczyński argument (BH growth & spin)

KI & Ichikawa (2024)
arXiv:2402.14706

Soltan argument for QSOs

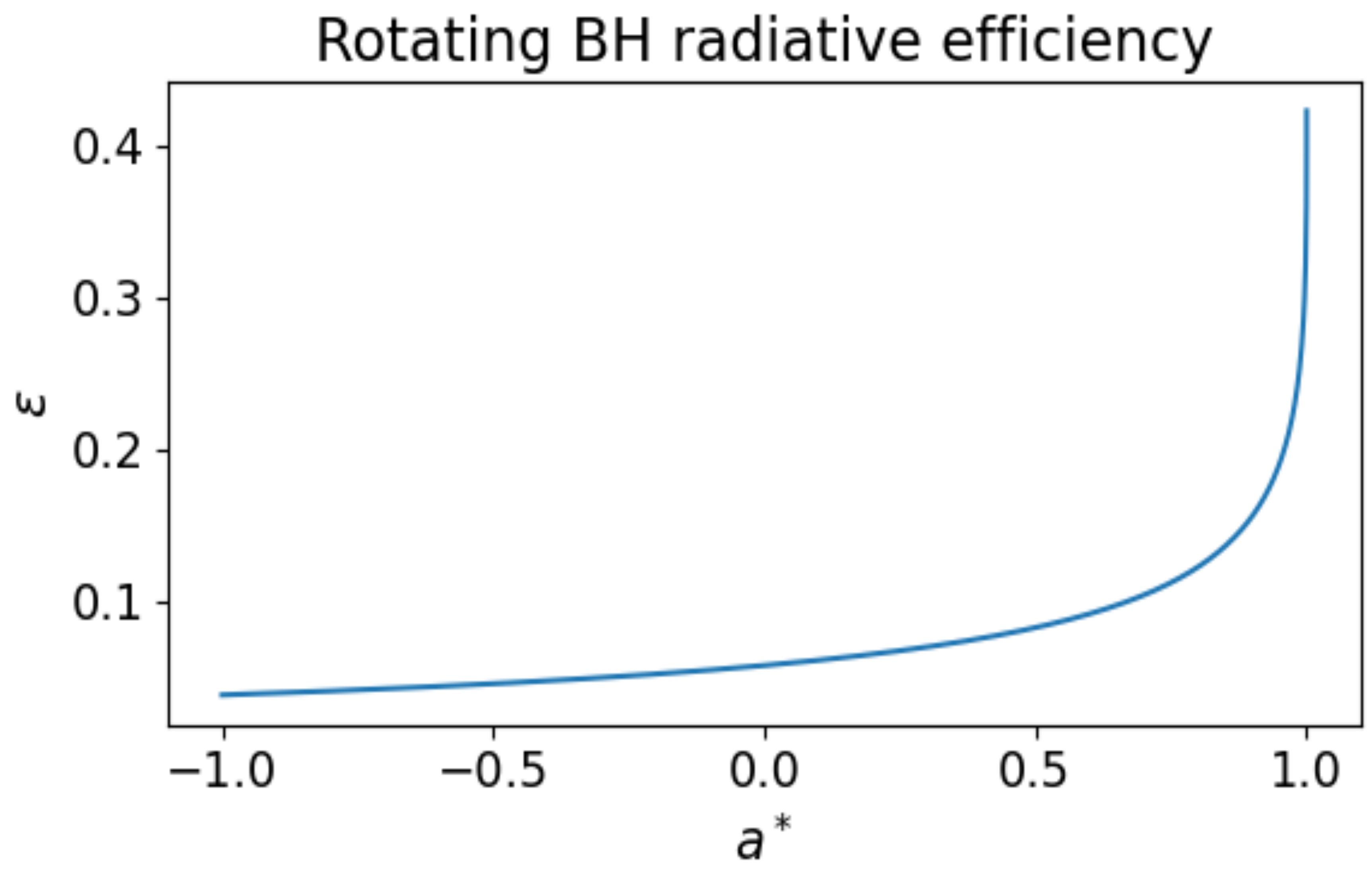
- Mass conservation law in accreting/illuminating BHs

Soltan 1982, Yu & Tremaine 2002



$$M_{\rm BH}(z) = M_{\rm BH}(z_s) + \Delta M_{\rm BH}$$

$$\Delta M_{\rm BH} = \int \dot{M}_{\rm BH}\, dt = \int \frac{1-\epsilon}{\epsilon} \cdot \frac{L}{c^2}\, dt$$



ϵ : radiative efficiency ~ 10%
(disk model, BH spin)
theoretical max ~ 42%

Soltan argument for QSOs

- Mass conservation law in accreting/illuminating BHs

Soltan 1982, Yu & Tremaine 2002

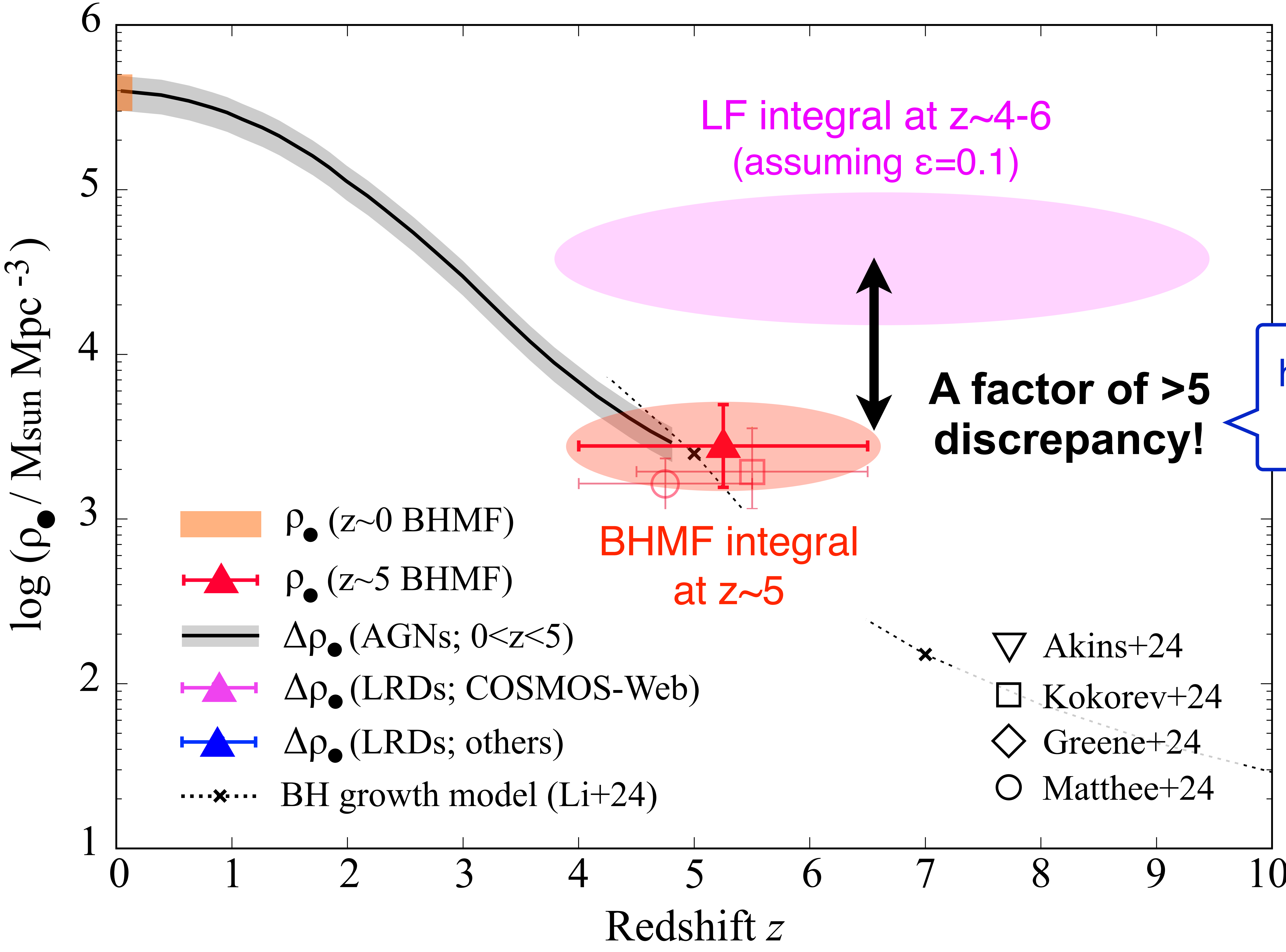
$$\rho_{\rm BH}(z) = \rho_{\rm BH}(z_{\rm s}) + \int \frac{1-\epsilon}{\epsilon} \cdot \frac{\mathscr{L}}{c^2} \frac{dt}{dz} dz$$

$$\simeq \rho_{\rm BH}(z_{\rm s}) + \frac{1-\bar{\epsilon}}{\bar{\epsilon} c^2} \int_{z_s}^{z} dz \frac{dt}{dz} \int_{L_{\rm min}}^{L_{\rm max}} L \frac{d\Phi_{\rm L}(z)}{d\log L} d\log L$$

Mass density of local relic BHs = Mass accreted onto BHs over time

➡ radiatively efficient accretion with moderate spins $\quad \bar{\epsilon} \sim 0.1 \quad (a_\bullet \sim 0.7)$

Soltan argument for the earliest BHs



high radiative efficiency
(rapid BH spins)

KI & Ichikawa 24

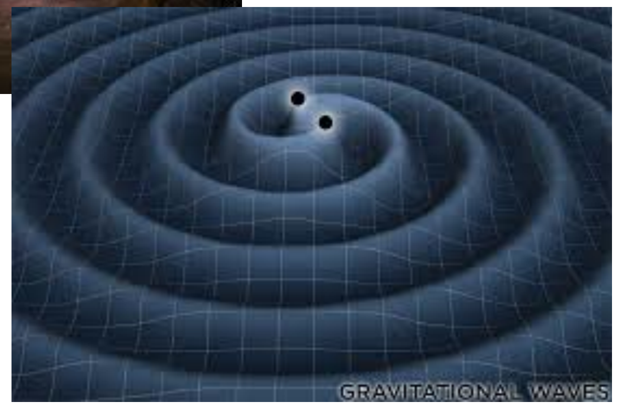
Birth of rapidly spinning BHs at cosmic dawn

Radiative efficiency of **>30%** & rapid BH spins of **a>0.99**

Survey	Redshift	$\log_{10}\Delta\rho_\bullet$	p-value			
		$\epsilon_{\rm rad}=0.1$	$\epsilon_{\rm rad}=0.1$	$\epsilon_{\rm rad}=0.2$	$\epsilon_{\rm rad}=0.3$	$\epsilon_{\rm rad}=0.42$
		$a_\bullet \simeq 0.674$	$a_\bullet \simeq 0.674$	$a_\bullet \simeq 0.960$	$a_\bullet \simeq 0.996$	$a_\bullet \simeq 1.00$
COSMOS-Web	$5<z<9$	$4.82^{+0.29}_{-0.19}$	0.00204	0.00569	0.0132	0.0350
Other surveys	$4.5<z<8.5$	$4.48^{+0.24}_{-0.22}$	0.00291	0.0115	0.0378	0.151

KI & Ichikawa 24

- Radio jets (BZ mechanisms) from early BHs
- Prolonged disk accretion vs. chaotic accretion
- **GW waveform modulation** by BH spins in their coalescences



3-2. Applications

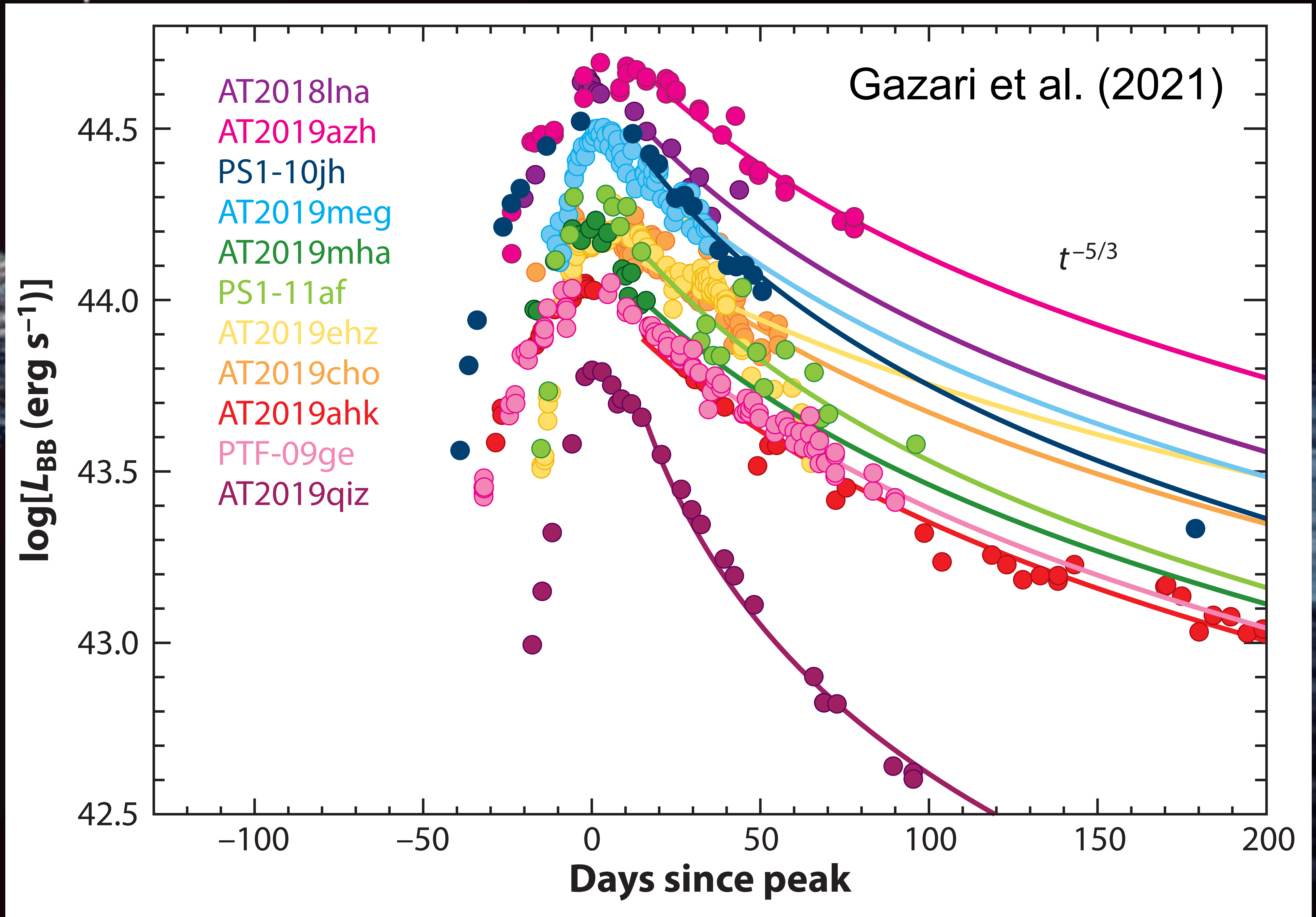
TDEs from LRDs

KI, Kashiyama, Li, Harikane, Ichikawa & Onoue (2024)

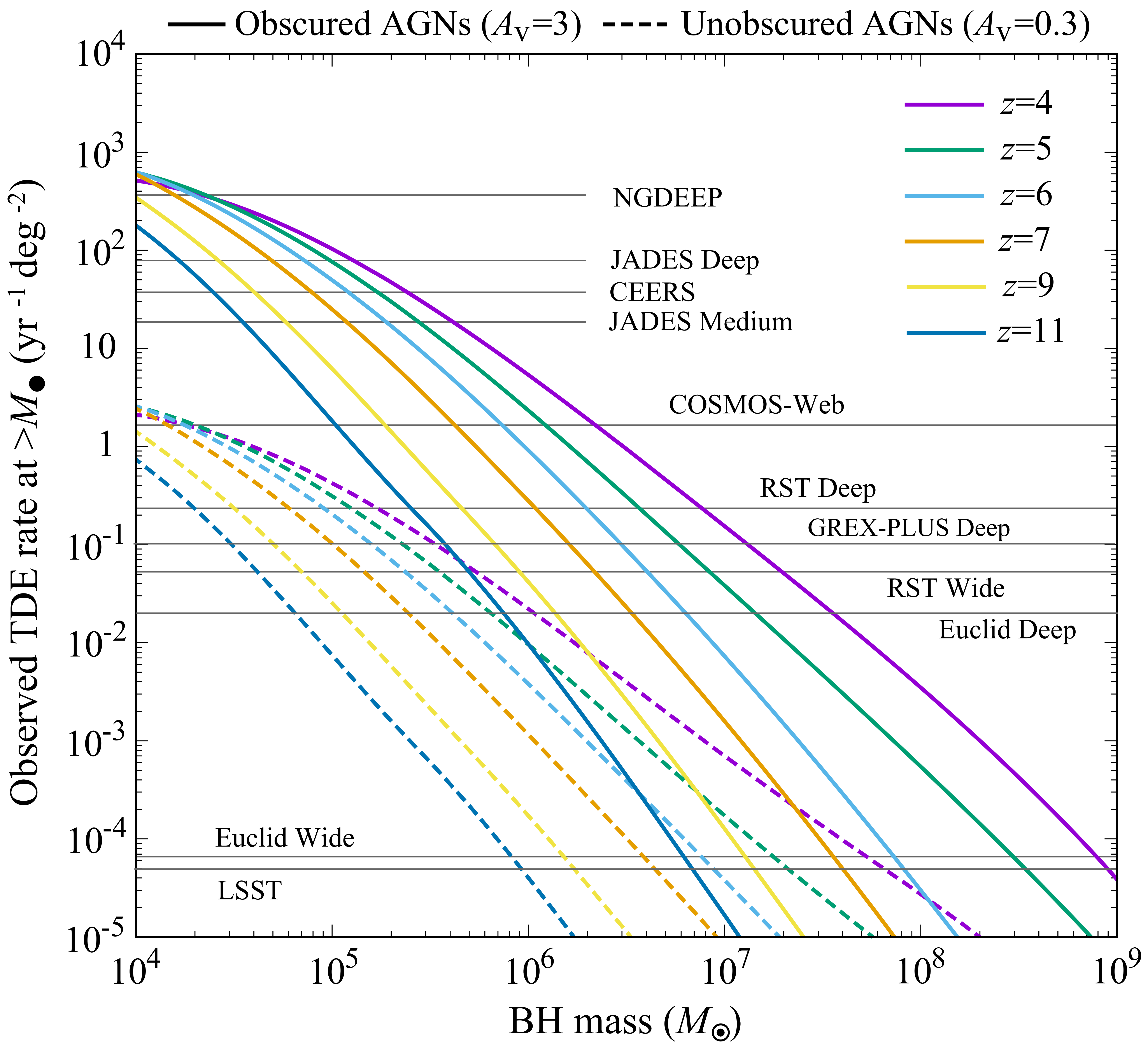
High-z TDEs from JWST AGNs

Rapid BHs spins allow

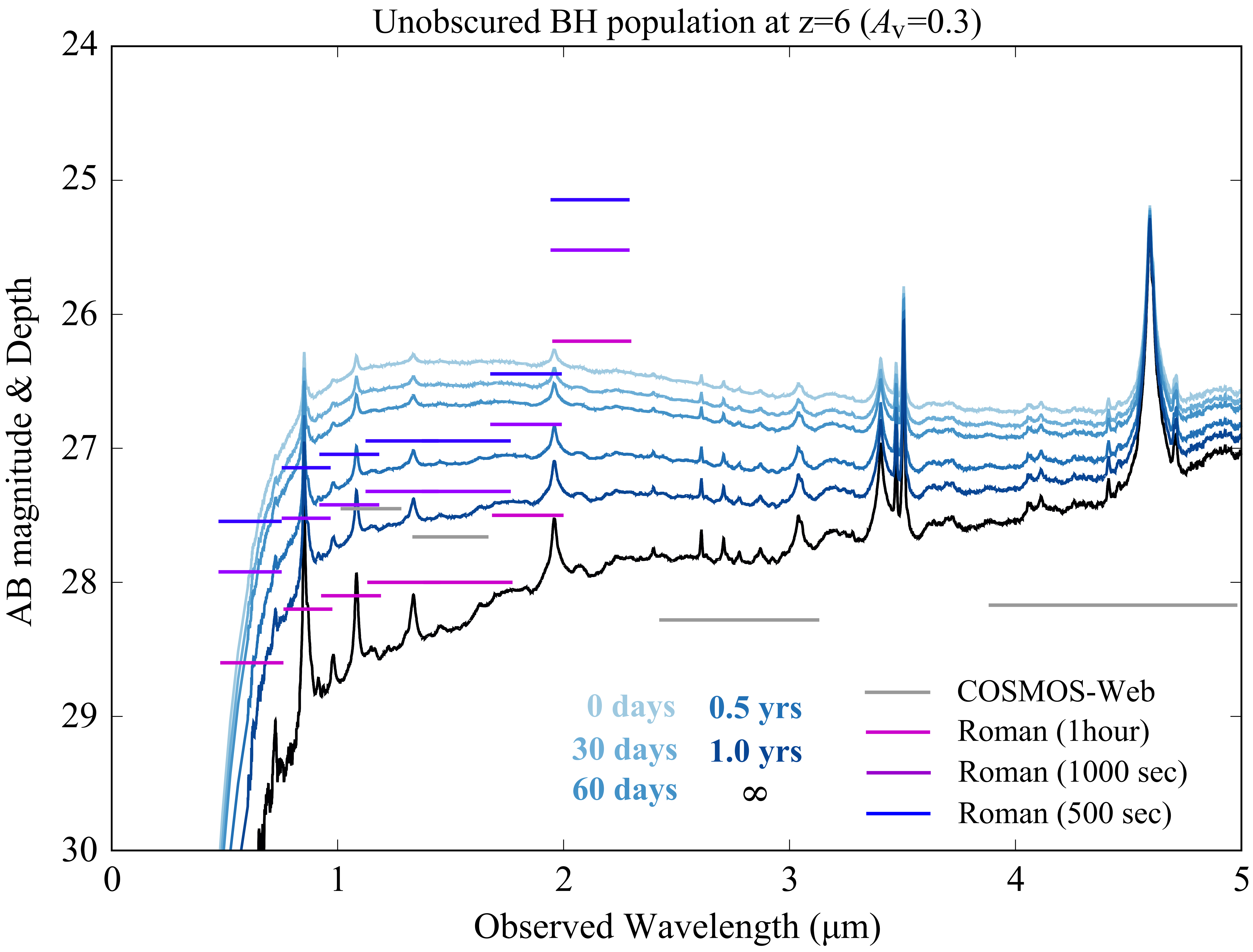
1. TDEs by $M > 10^8 M_{sun}$
2. Brighter jets,
3. …



TDE rate vs. BHMF shape



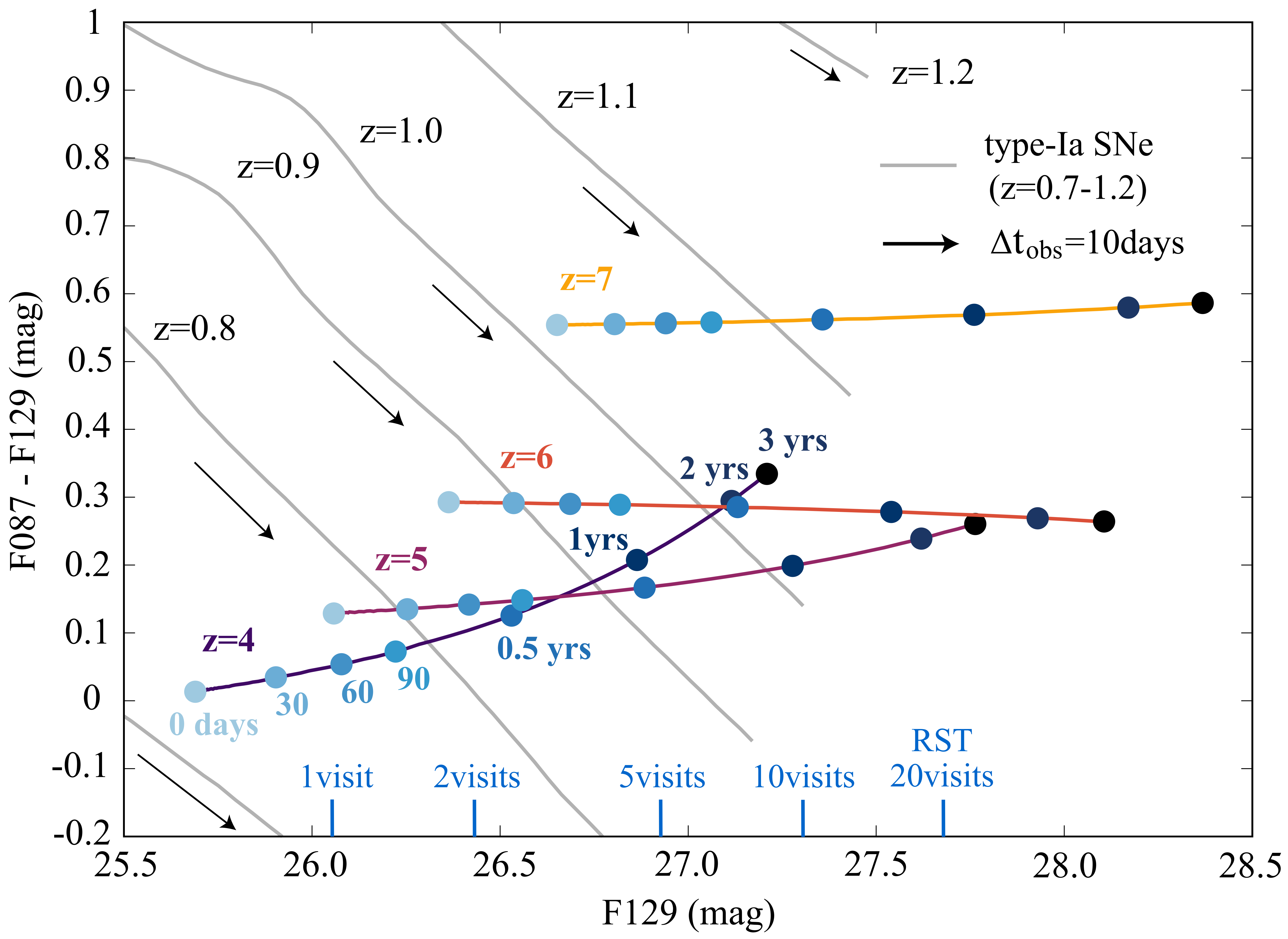
SED evolution of high-z TDEs



SED model
=
composite SED of
low-z quasars
+
TDE (Black body)
PS1-10jh

KI+ (2024)

Color-magnitude diagram for high-z TDEs

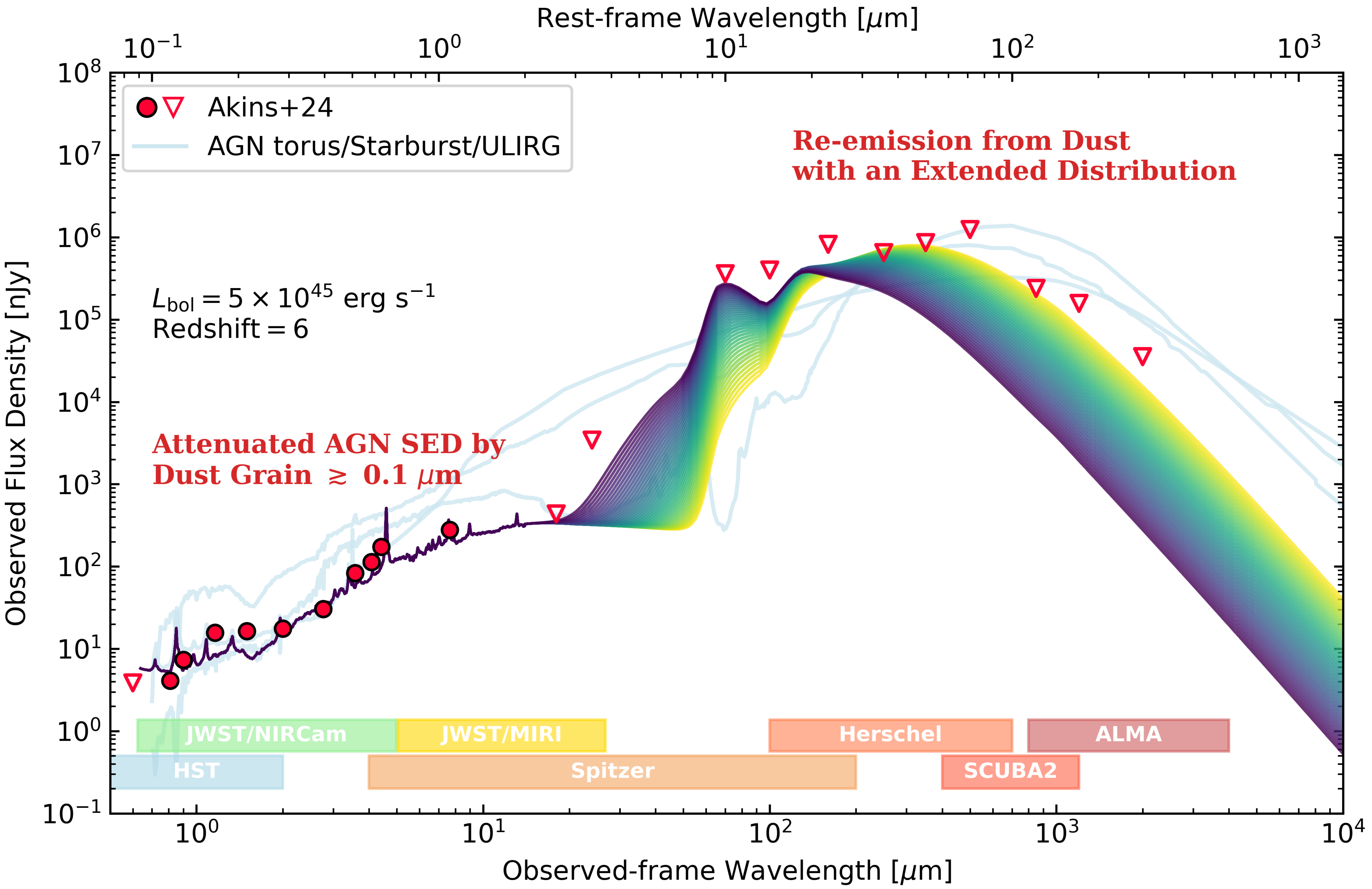


Exp. Time / Visit
= 160 sec

KI+ (2024)

Questions?


GOODS-S-13971


Rest-frame Wavelength [μm]
Observed Flux Density [nJy]
Observed-frame Wavelength [μm]
Akins+24
AGN torus/Starburst/ULIRG
Re-emission from Dust
with an Extended Distribution
$L_{bol} = 5 \times 10^{45}$ erg s^{-1}
Redshift = 6
Attenuated AGN SED by
Dust Grain $\gtrsim$ 0.1 μm
JWST/NIRCam
JWST/MIRI
Herschel
ALMA
HST
Spitzer
SCUBA2