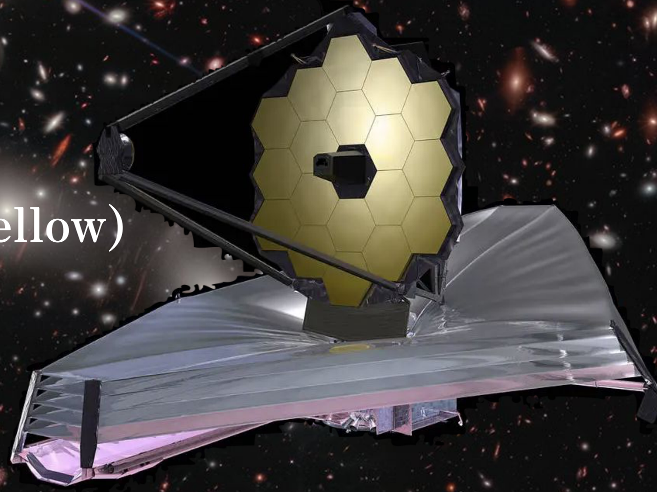
AGNの時間領域天文学

(*JWST*/NIRCam時間軸データを用いた broad-line galaxiesの光度変動探査)

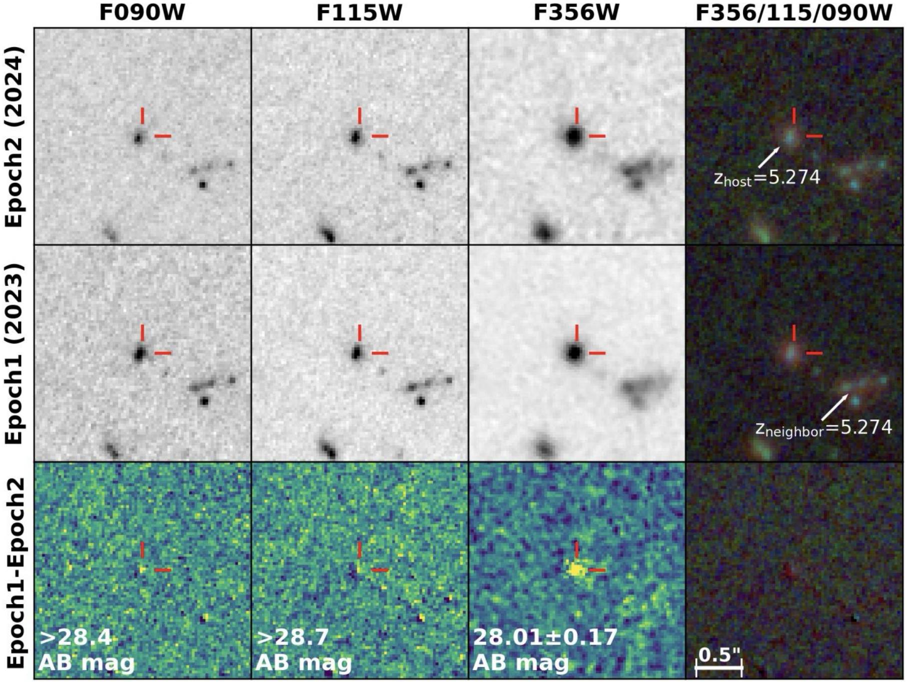
(Kokubo & Harikane, arXiv:2407.04777)



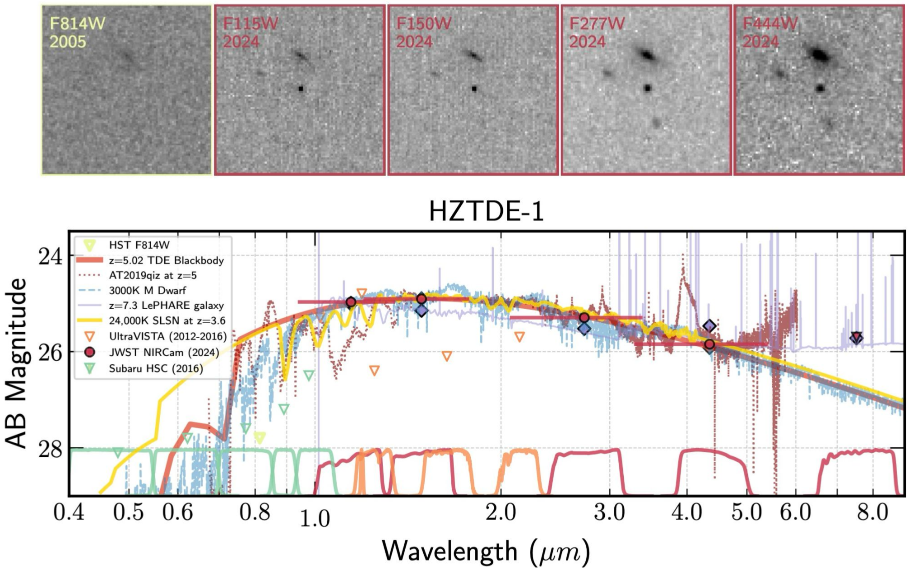
Mitsuru Kokubo (NAOJ fellow)

EET25 Kyoto, Aug 6

JWST as a discoverer of high-z transients/variables



A supernova at z = 5.274 in GOODS-N



TDE? at z = 5.02 in COSMOS

(*JWST*/NIRCam data; DeCoursey+25; Karmen+25)

Content

- Introduction to *Active Galactic Nuclei* (AGN) ：AGNの定義
- AGN surveys, and *JWST*'s surprising findings
- Broad-line AGN candidates discovered by *JWST*
  … are they really AGNs?
  - *Chandra* X-ray
  - *JWST*/NIRCam variability
- Summary and future prospects

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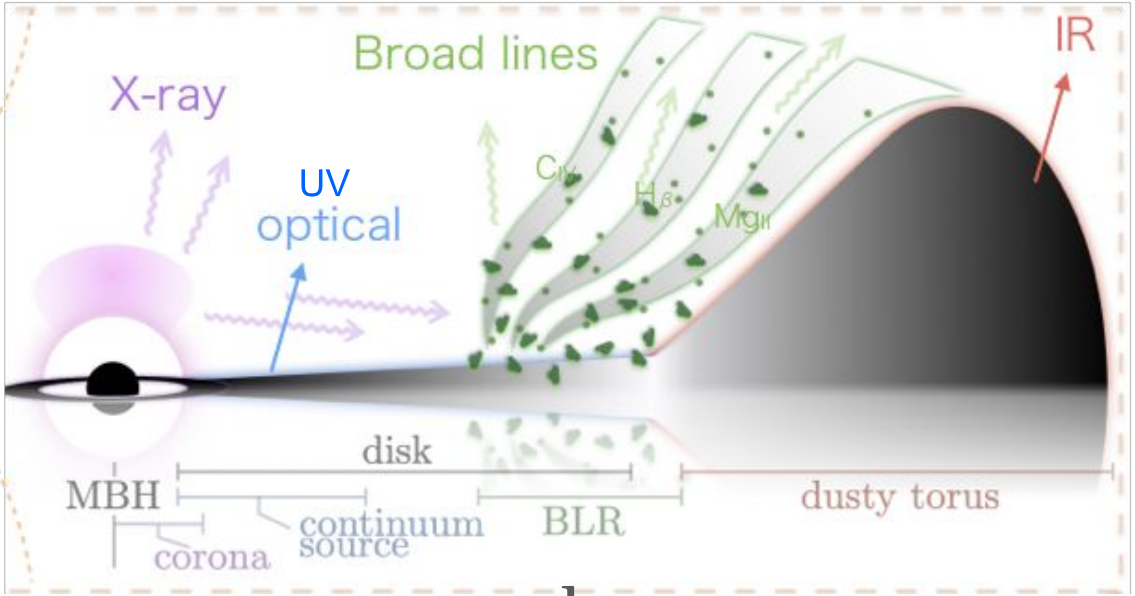
AGN = SMBH accretion system

(remember Noda-san's talk)

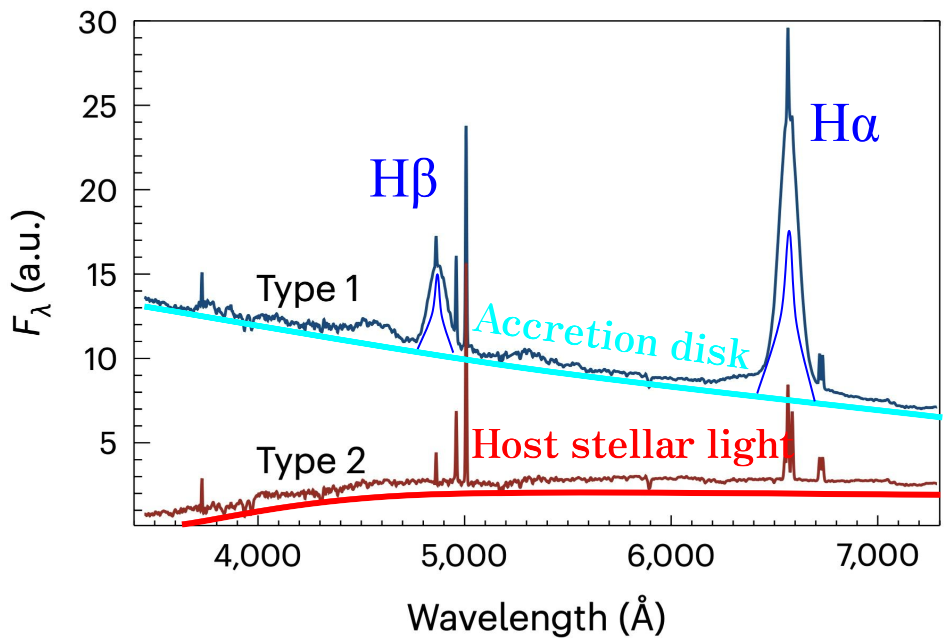


~ pc scale

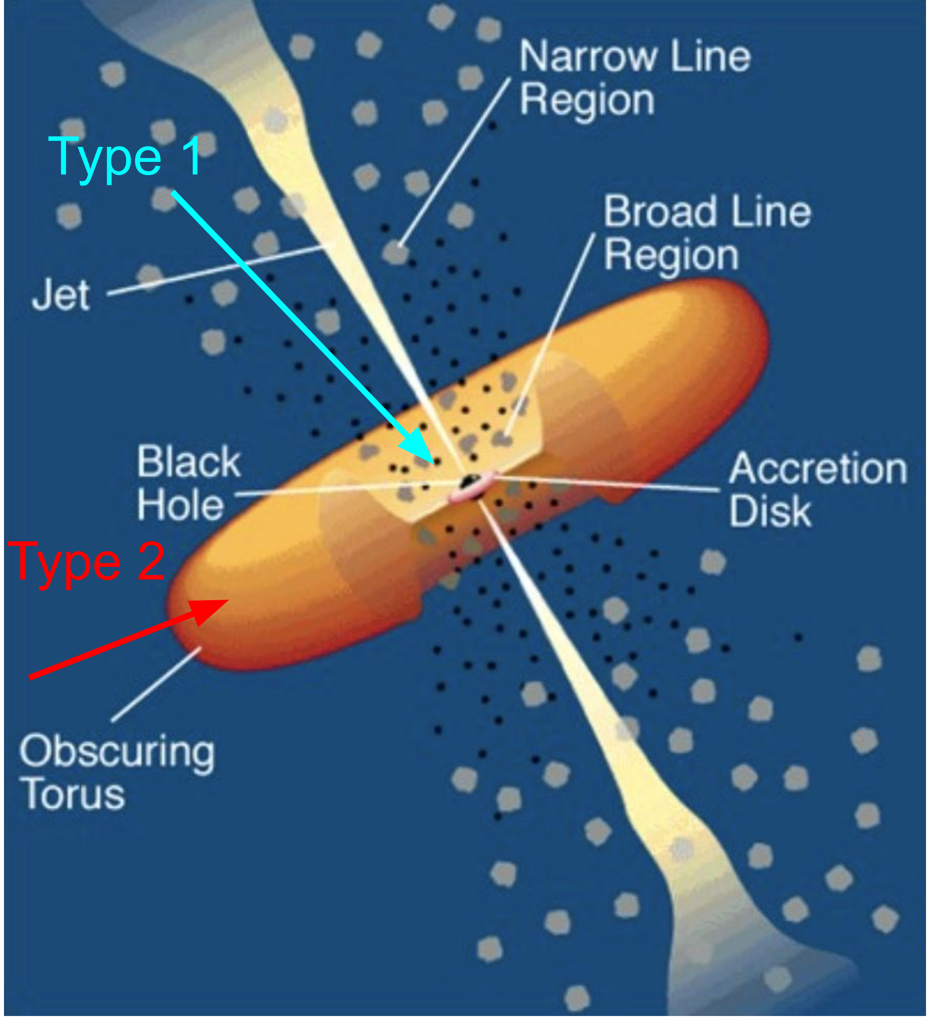
BH sphere of influence: $\theta_{\rm infl} \approx 0.01'' \left(\dfrac{D}{100\,{\rm Mpc}}\right)^{-1} \left(\dfrac{M_{\rm BH}}{10^7\,M_\odot}\right)$ < TMT resolution

Broad line

Ricci & Trakhtenbrot 2023

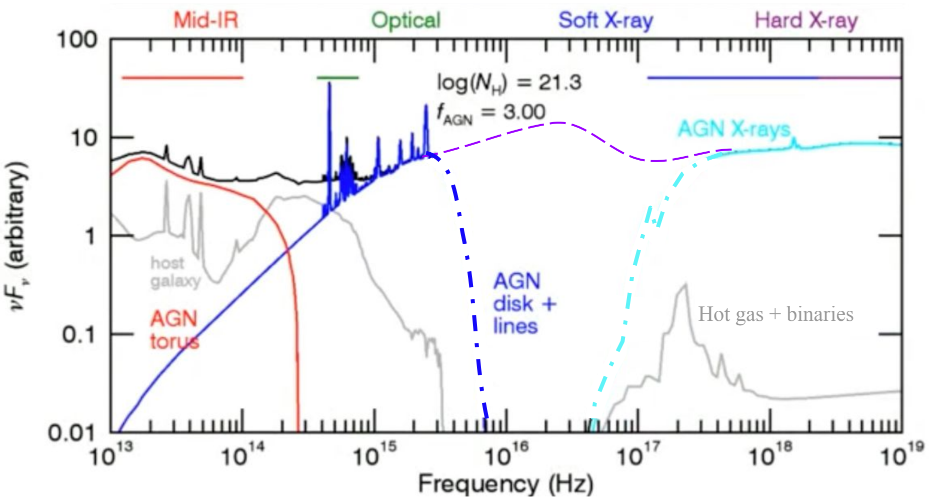


Broad lines (σ > 1000 km s^{-1}) imply the presence of the (active) SMBH

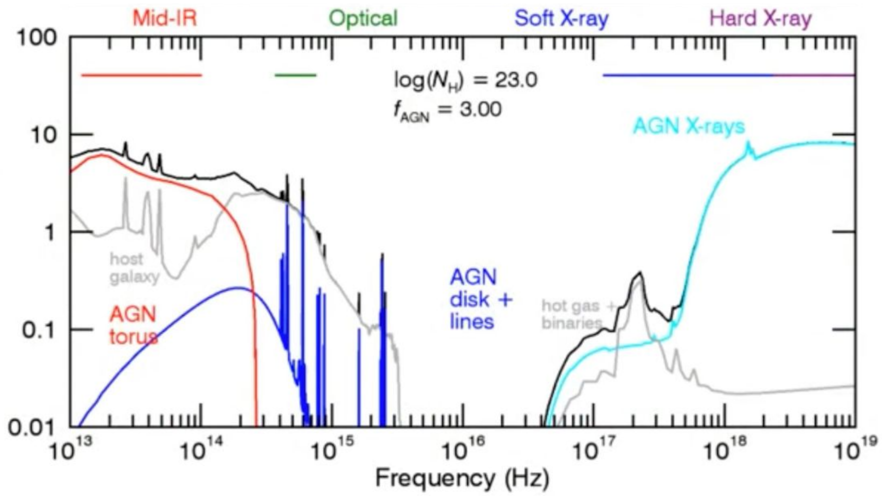


AGN unification model; Urry and Padovani (1995)

Type 1 (unobscured) AGN



Type 2 (obscured) AGN

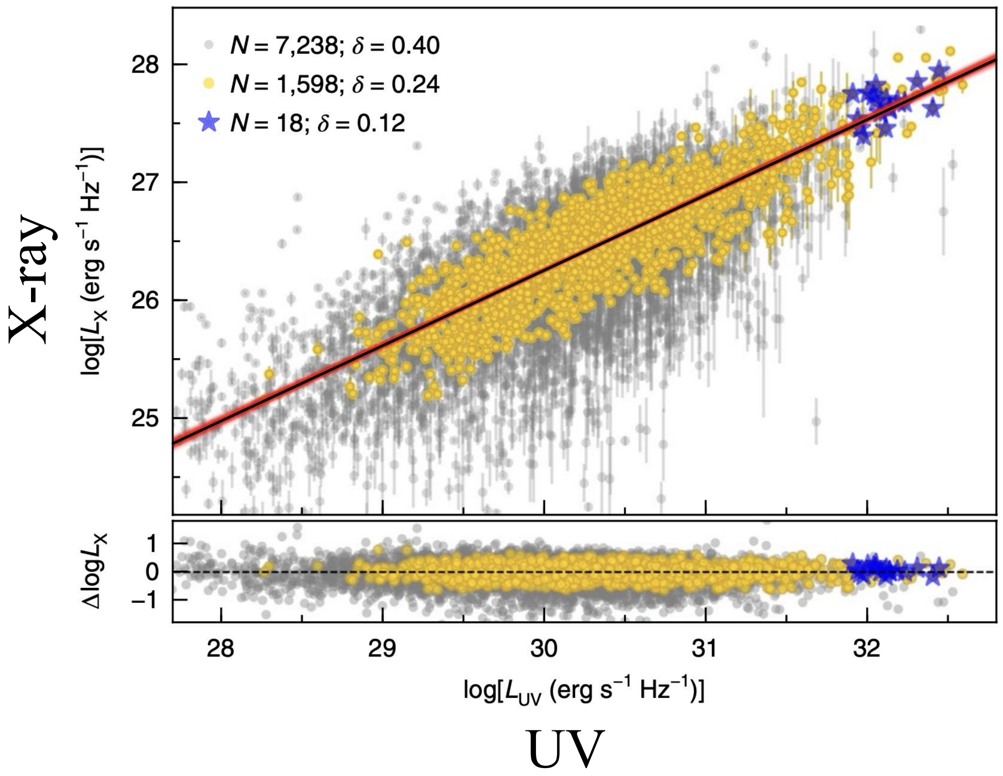


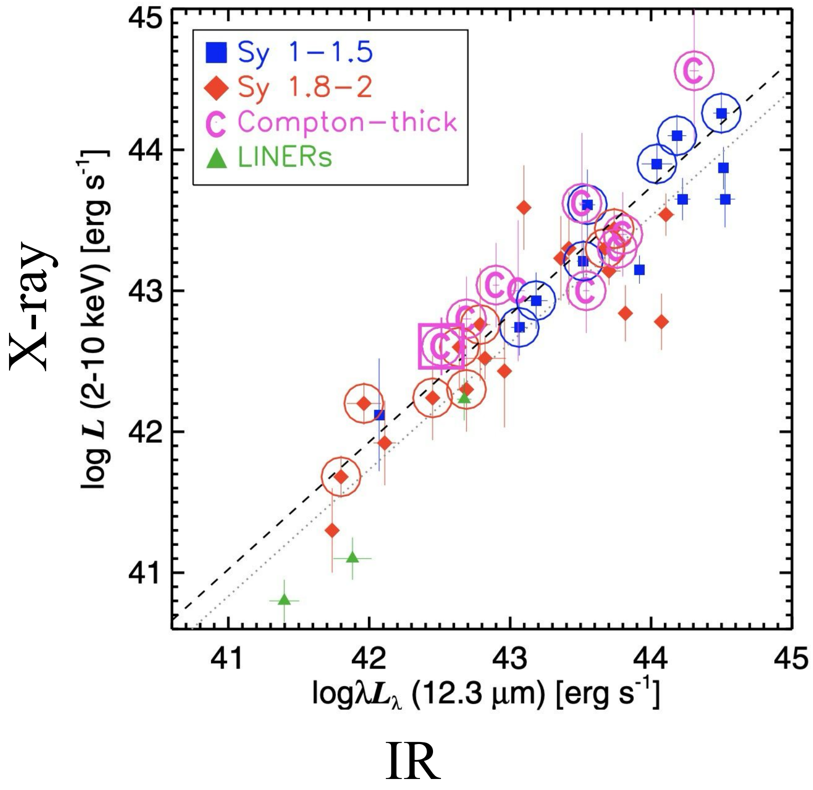
Reddening/extinction (dust)

Photoelectric absorption (gas + dust)

Hickox & Alexander (2018)

Multiband luminosity scaling ($\propto M_{\rm BH}$, Eddington ratio)



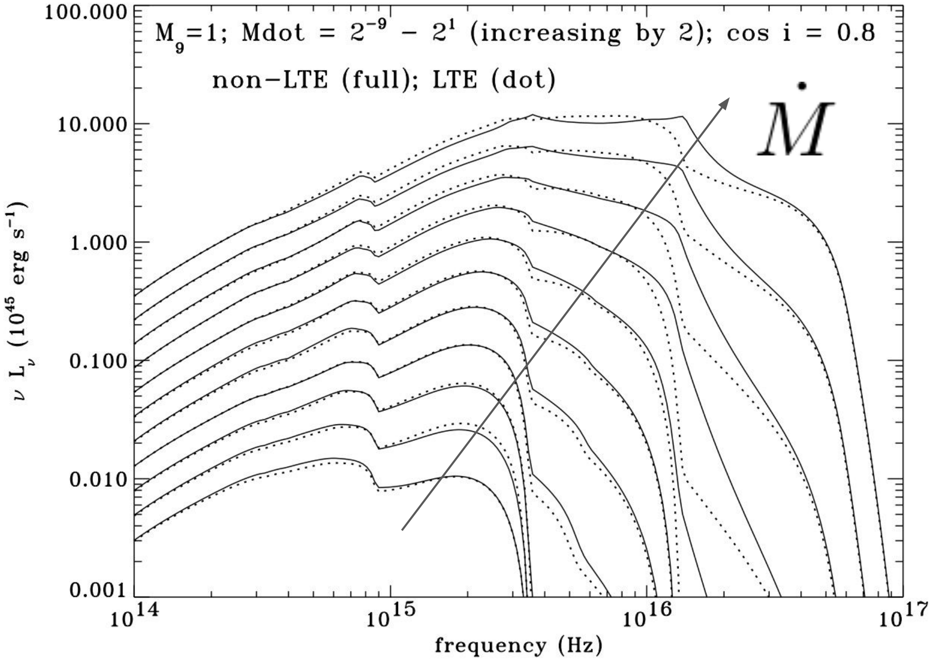


Risaliti & Lusso 2019

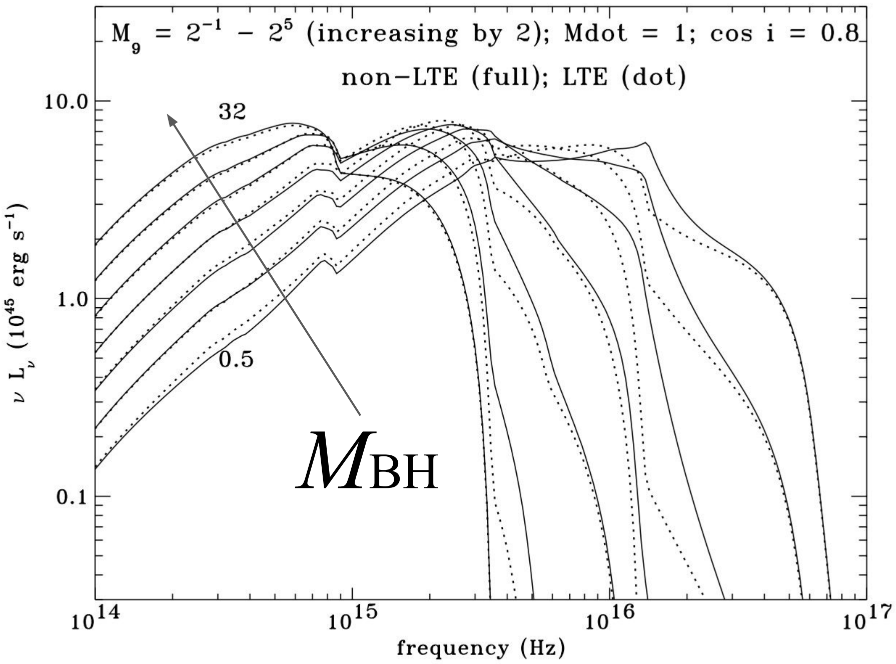
Gandhi+2009

Multiband luminosity scaling ($\propto M_{\rm BH}$, Eddington ratio)

increasing Eddington ratio



increasing Black hole mass



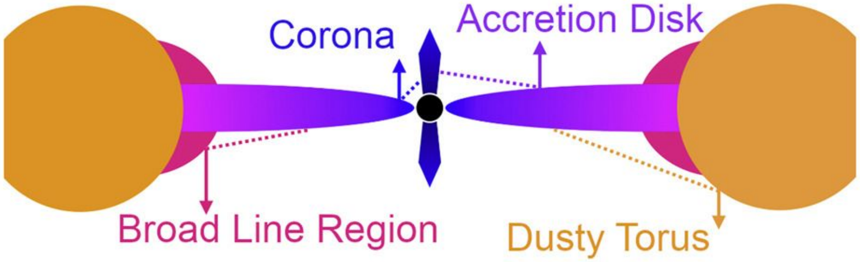
Hydrogen-Helium Page & Thorne Disks (Hubeny+00)

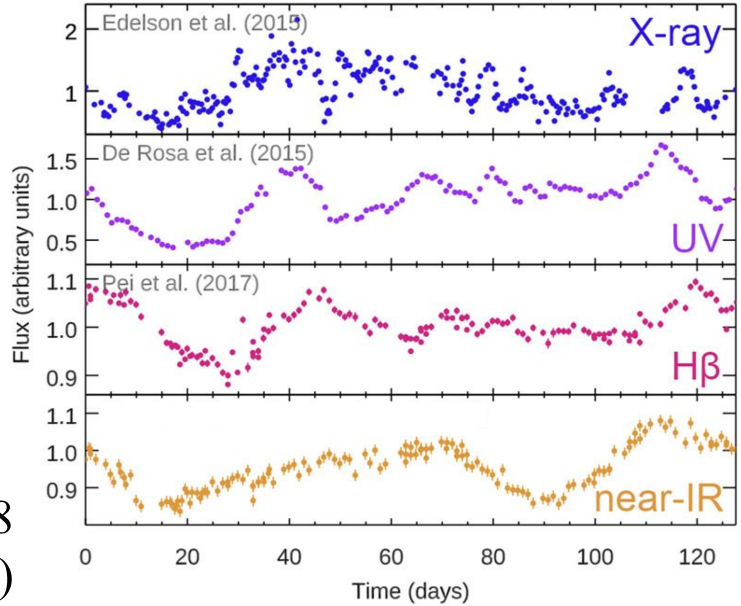
AGN variability

AGNs ubiquitously show
stochastic disk emission variability

- Amplitude ~ 0.1 mag
- $\tau_{\rm d} = 44.6 \text{ days} \left(\frac{M_{\rm BH}}{10^7 \ M_\odot} \right)^{0.38}$

(e.g., Macleod+12, Burke+23, MK+24)





Light curves of NGC5548
(Cackett+21)

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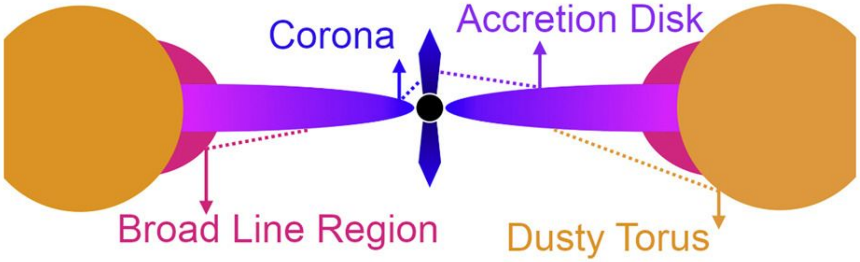
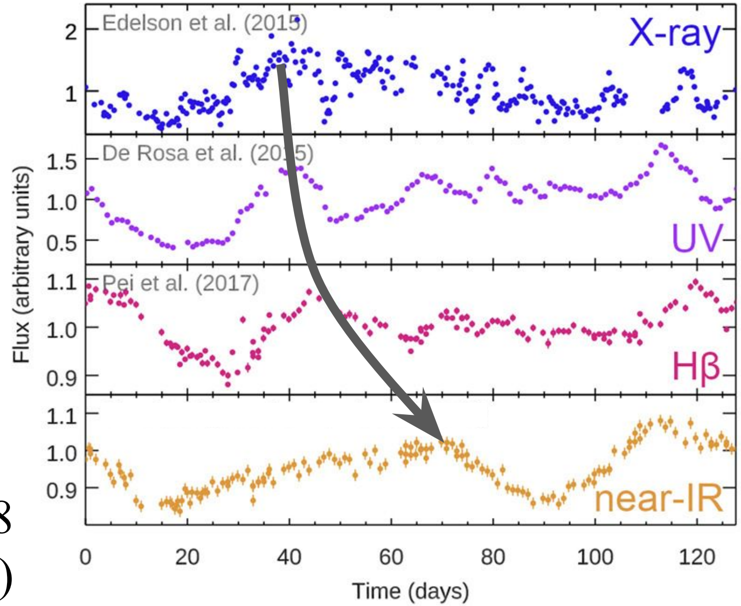
Temporal lag → light crossing time





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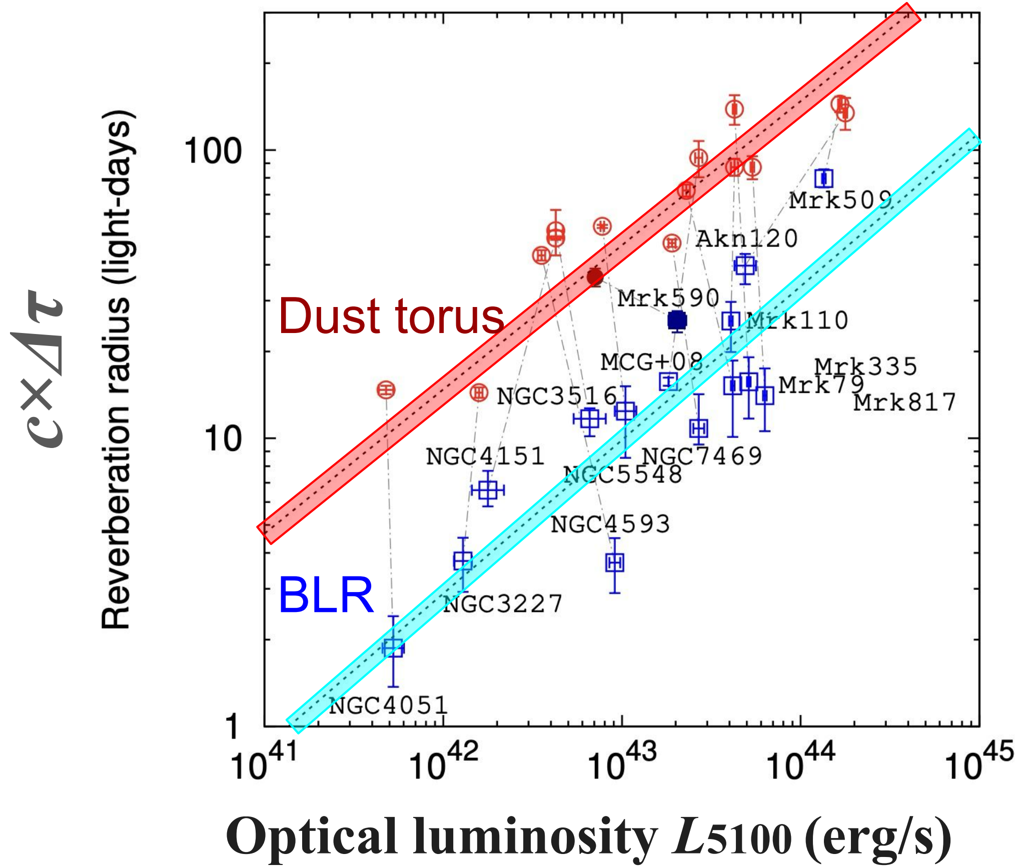
Reverberation mapping (RM): luminosity − size scaling

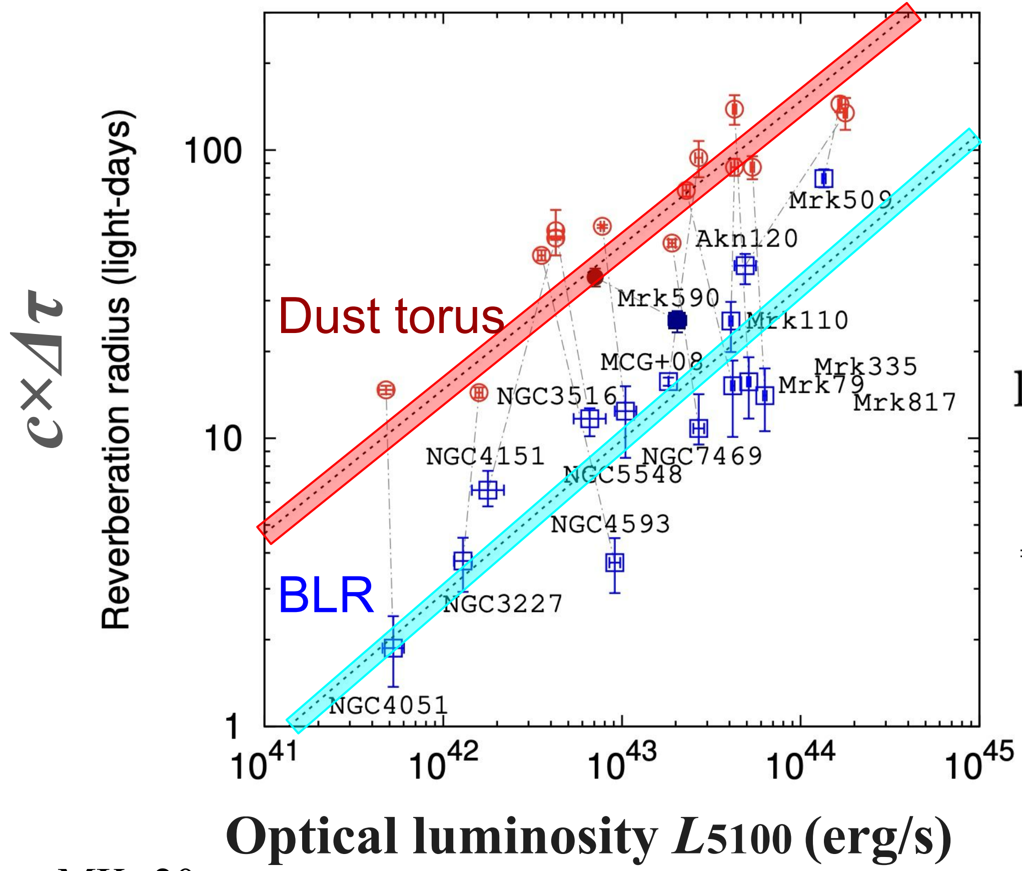


$R \propto (L_{5100Å})^{0.5}$

$$\left(N_{\mathrm{ion}\atop\mathrm{irradiation}} \propto \frac{L_{\mathrm{ion}}}{4\pi R^2} \propto \frac{L_{\mathrm{optical}}}{4\pi R^2} \right)$$

see MK+20

Reverberation mapping (RM): luminosity − size scaling



$R \propto (L_{5100\text{Å}})^{0.5}$

線幅

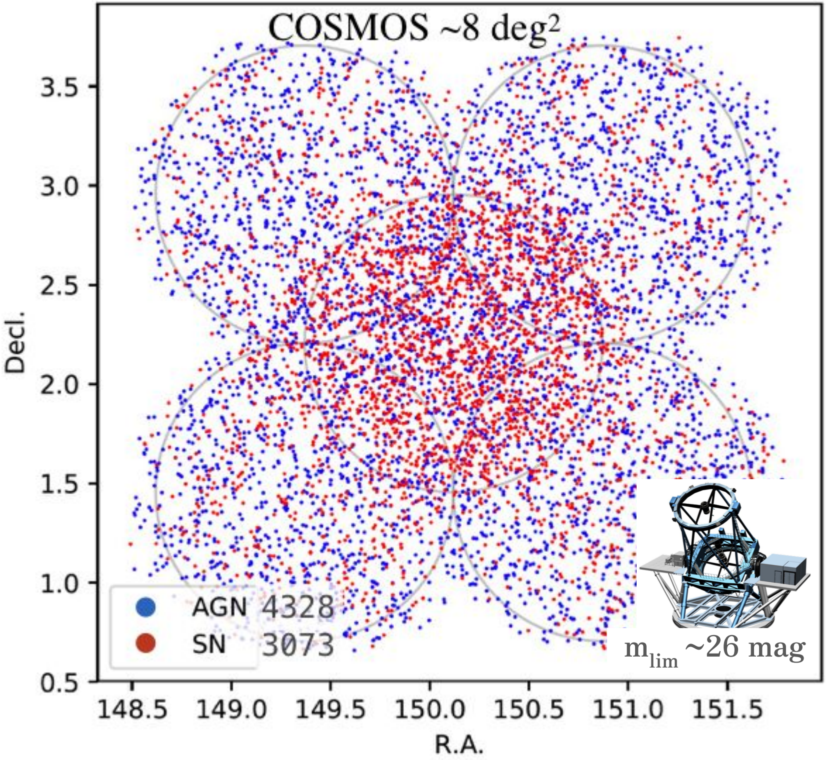
$$\log\ M_{\rm BH}(\mathrm{H}\beta) = \log\ \frac{f\ R\Delta V^2}{G}$$

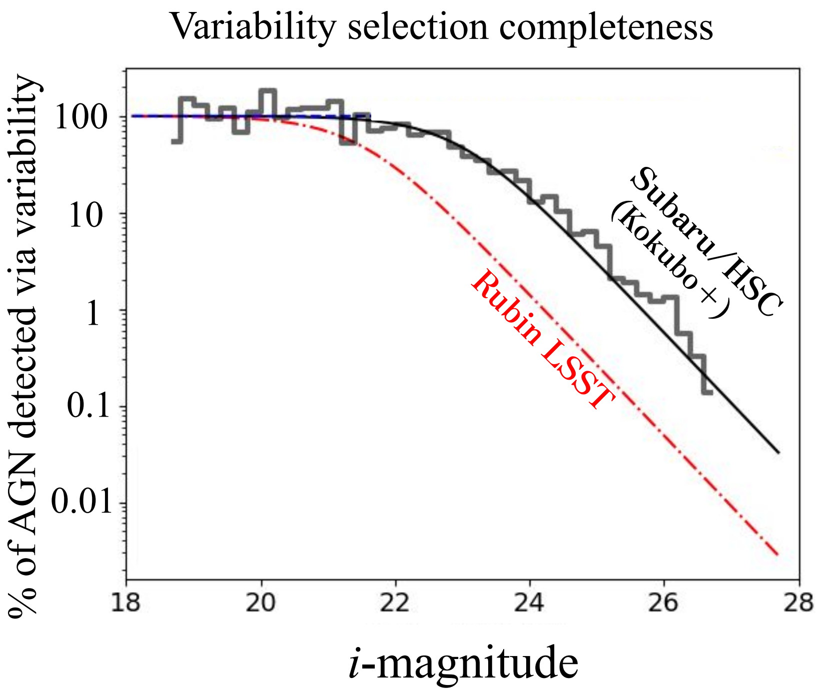
$$= \log\left[\left(\frac{\mathrm{FWHM(H}\beta)}{1000\ \mathrm{km\ s^{-1}}}\right)^2 \left(\frac{\lambda L_\lambda(5100\ \text{Å})}{10^{44}\mathrm{erg\ s^{-1}}}\right)^{0.50}\right] + (6.91 \pm 0.02)$$

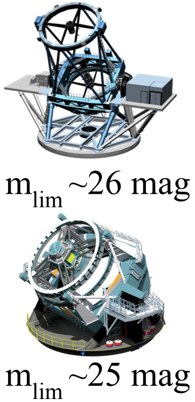
calibrated by
nearby AGNs/galaxies
(e.g., Vestergaard & Peterson 06)

see MK+20

AGN variability as a tool for AGN identification







HSC results: Kimura, MK+20, Hoshi, MK+24, MK+25 in prep.

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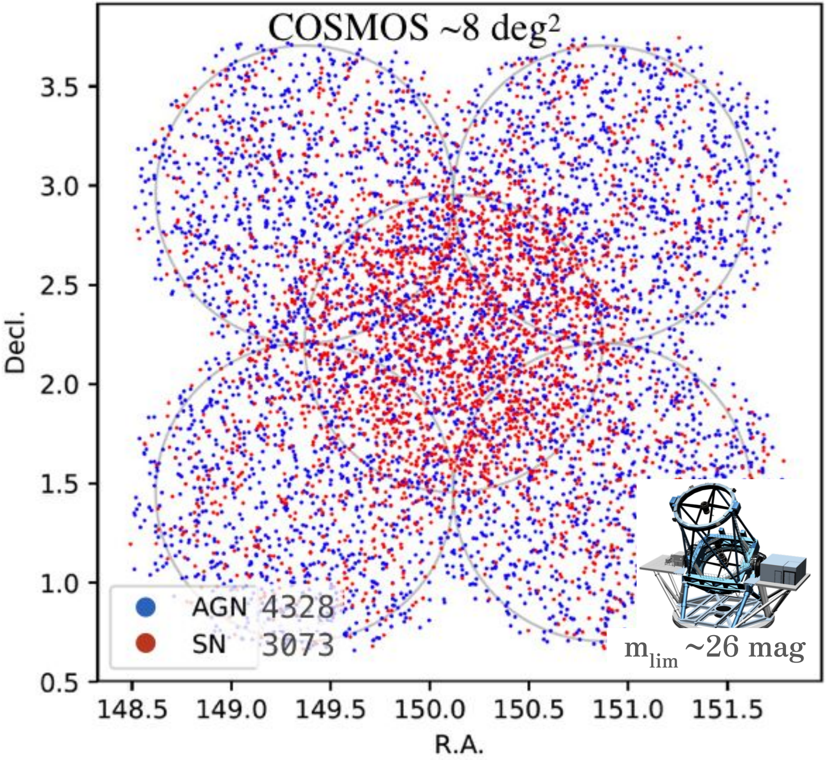

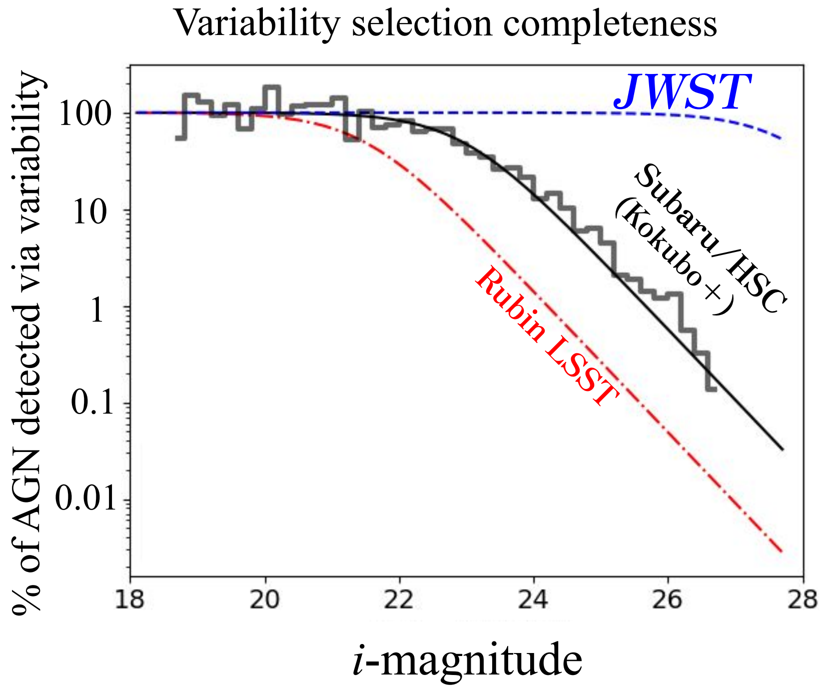

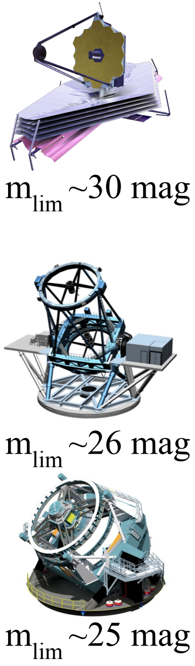

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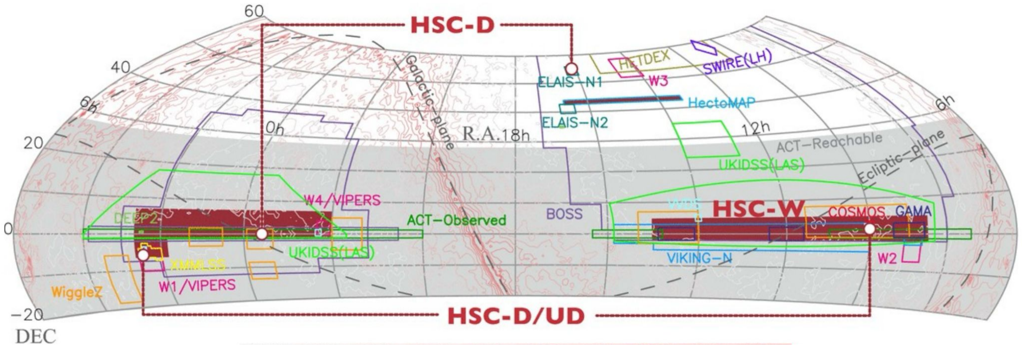
Wide-field galaxy/AGN surveys
– pre-*JWST*

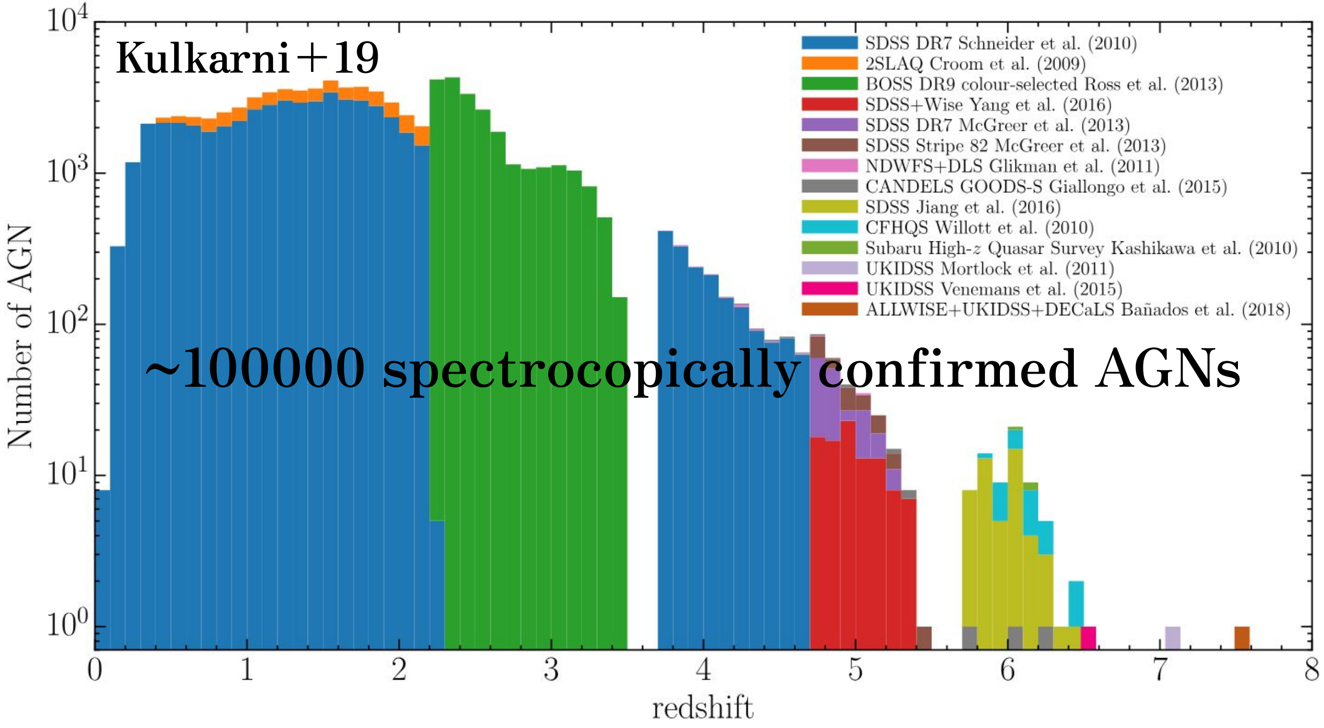


Wide-field (optical) imaging
- morphological and color **selection of targets**

Follow-up spectroscopy
- classification
- BH mass, Eddington ratio, …

Volume density of "luminous" AGNs ~ 100 [cGpc^{-3}] → ~ 10 deg^{-2} over all z
(< 21 mag)

AGN surveys
– pre-*JWST*



AGN surveys
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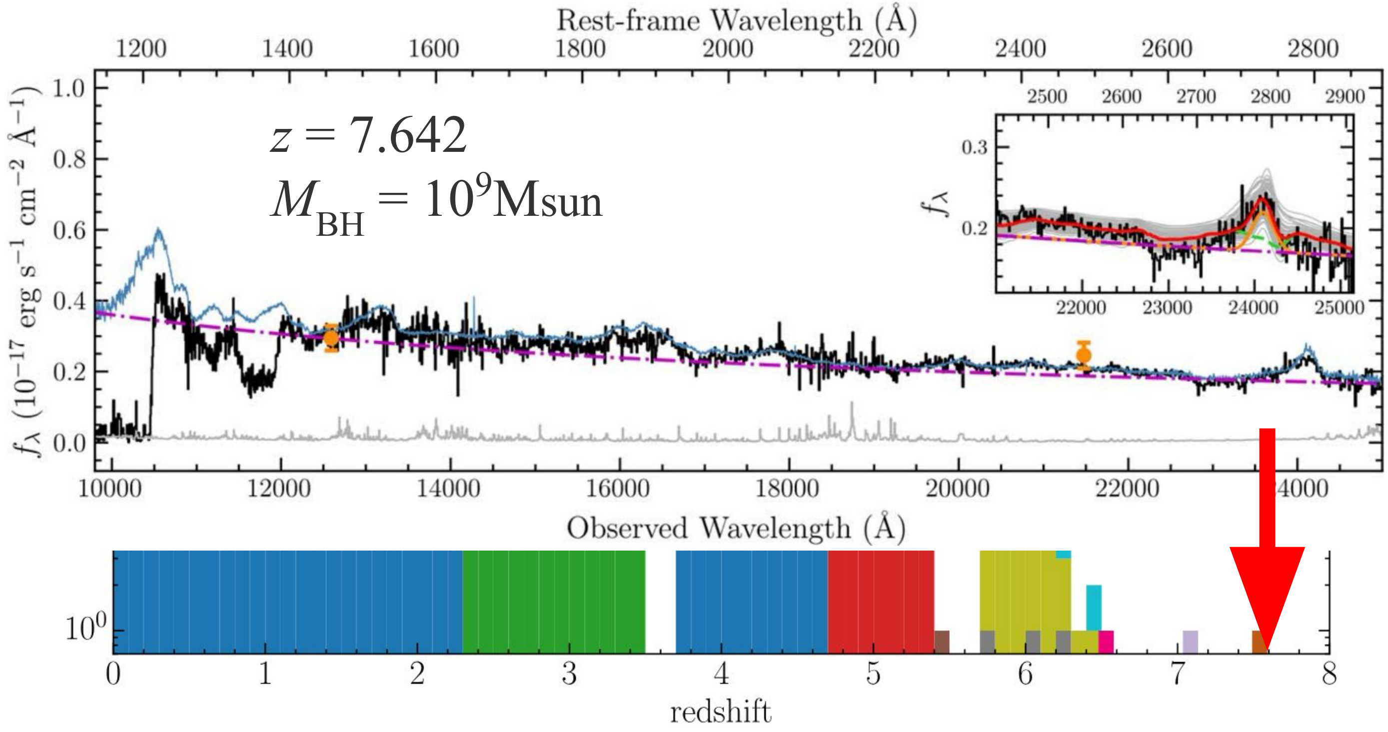
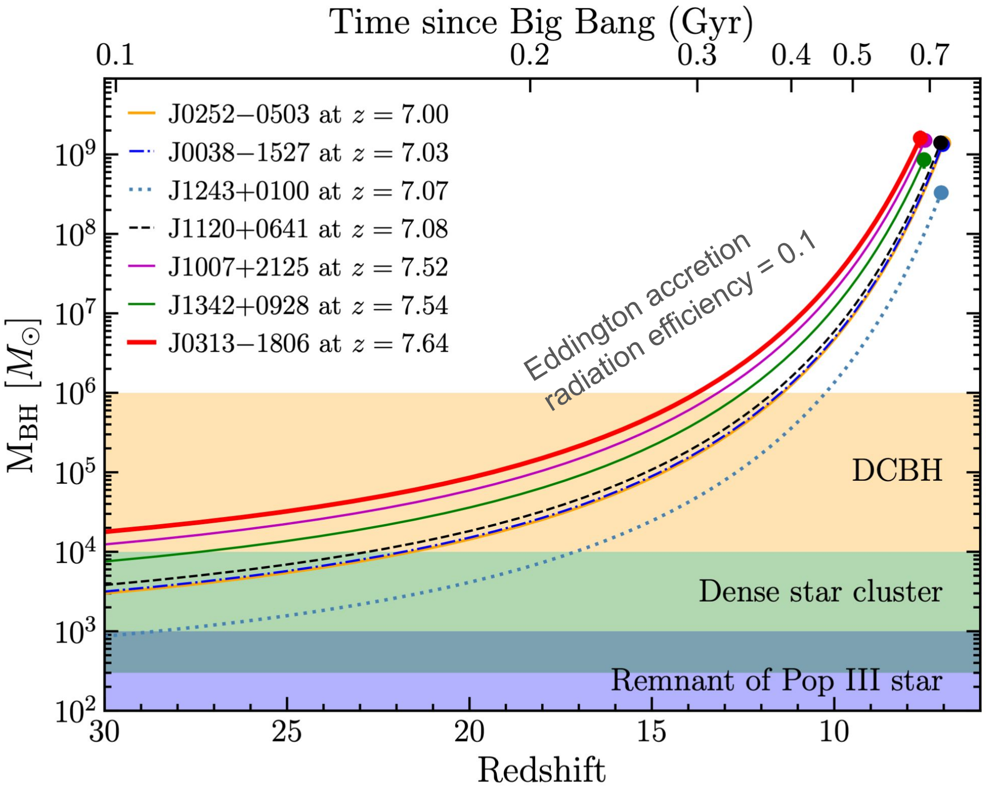
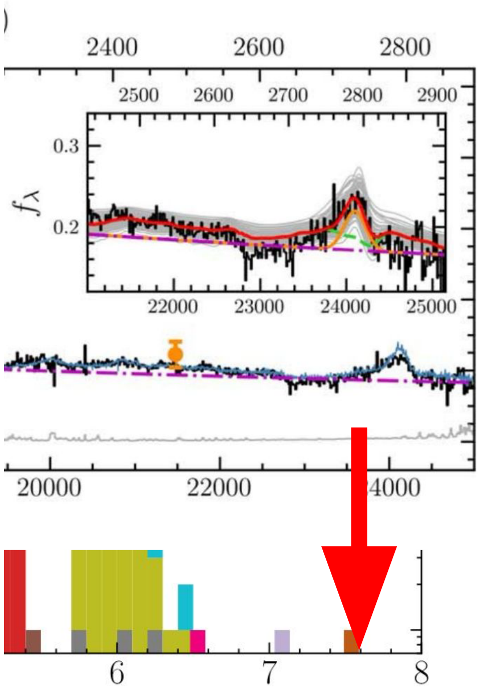


Wang+21

AGN surveys
– pre-*JWST*





Wang+21

AGN luminosity function: pre-*JWST*

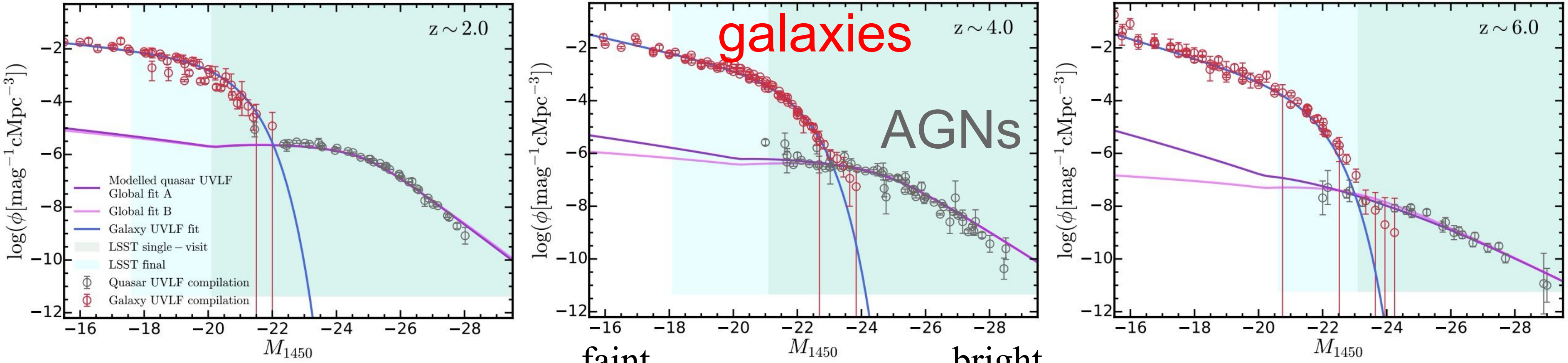
Luminosity

10^{42} 10^{43} 10^{44} 10^{45} 10^{46} erg/s

Shen+20

galaxies

AGNs



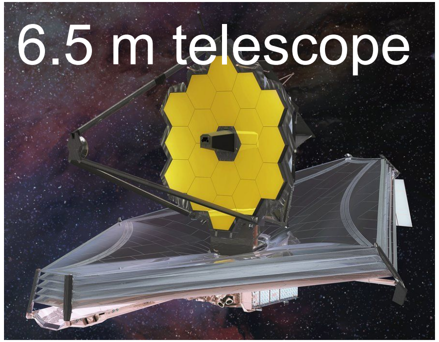
faint

bright

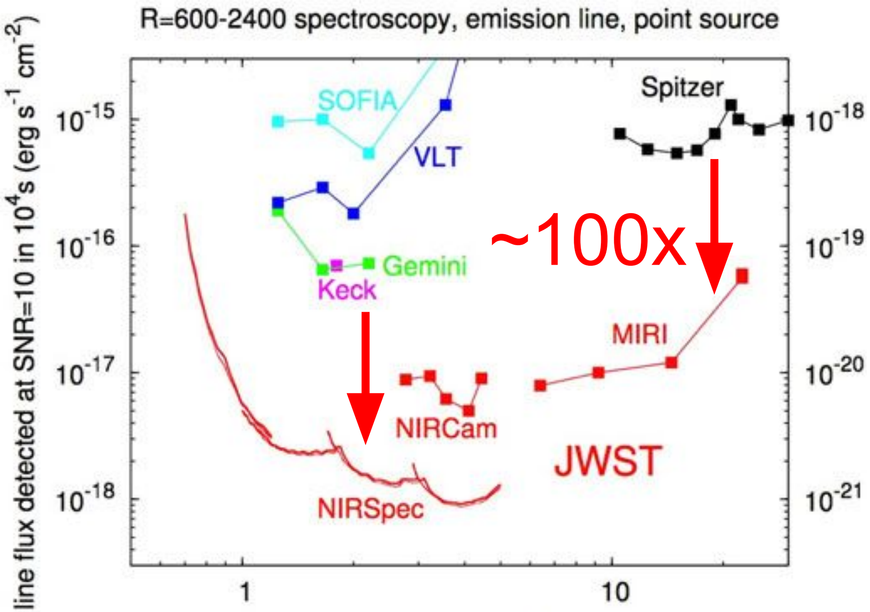
M_{1450}: absolute magnitude at λ_{rest} = 1450Å

JWST era (2022-)

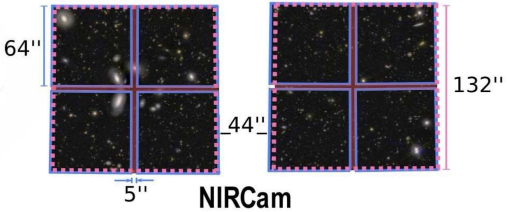
Ultradeep, but tiny field of view

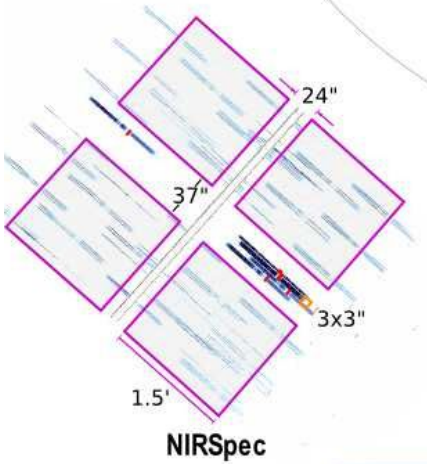


Spectroscopic sensitivity



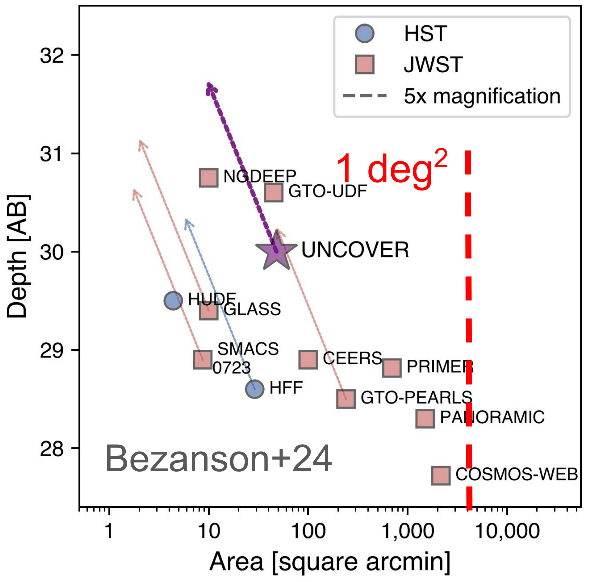
Observing wavelength (µm)

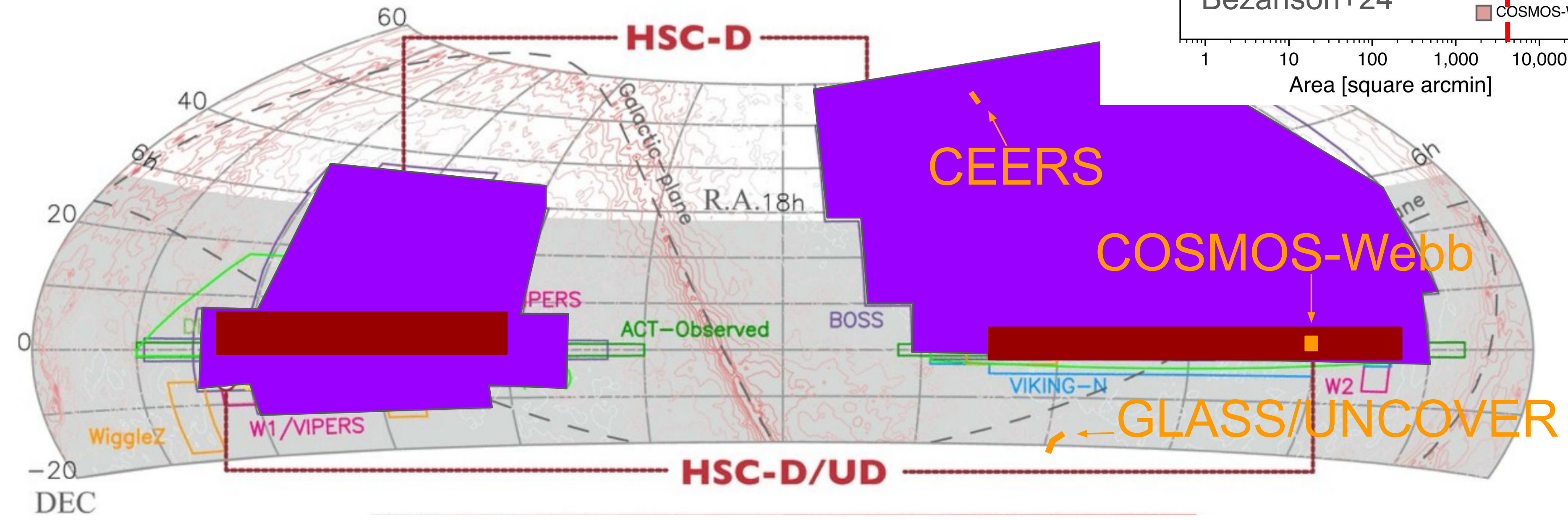




JWST era (2022-)

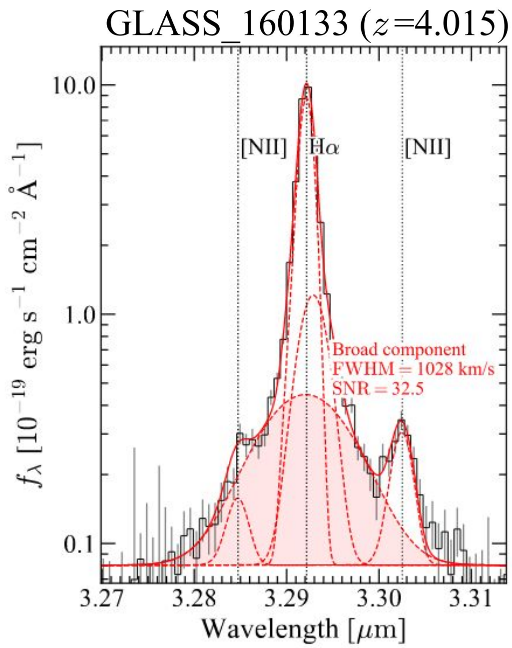
Ultradeep, but tiny field of view
→ “we won’t discover many AGNs with *JWST*”

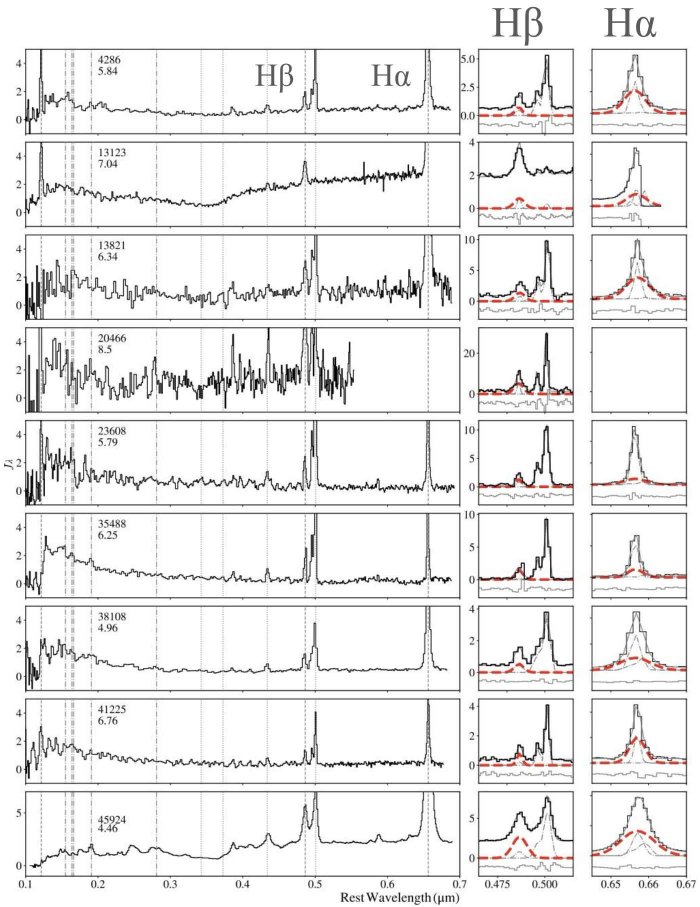




Discovery of abundant “broad (>1000km/s) Hα emitters” at $z>4$

Harikane+23



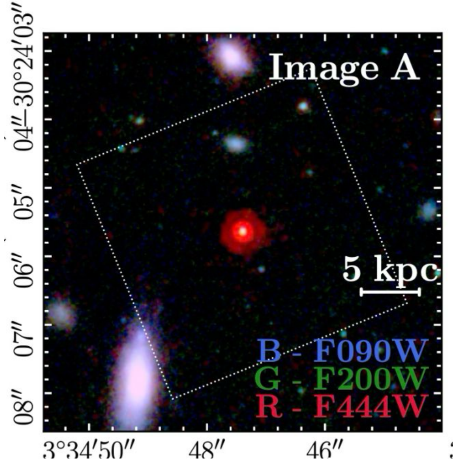


Greene+24

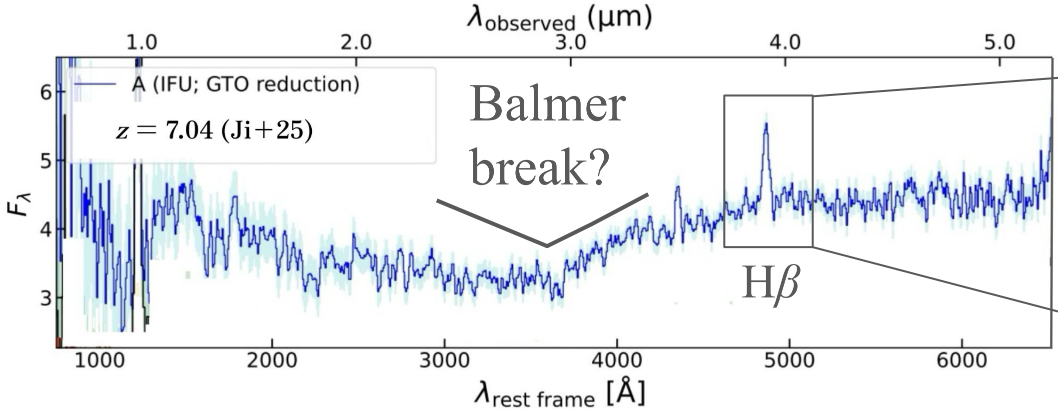
10 Broad-Line AGN candidates at z = 4 - 7
in ~0.01 deg^2 areas

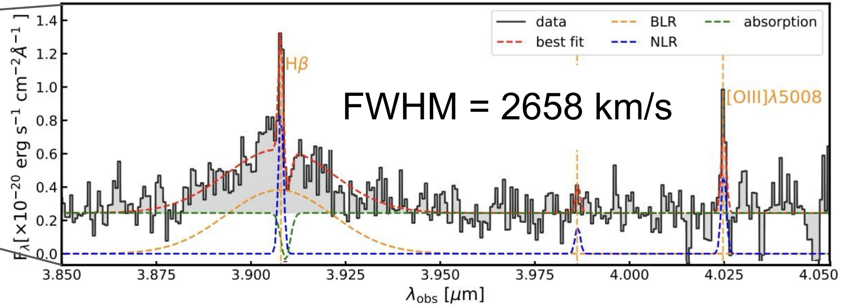
Another surprise: weird *v*-shape SED → "Little Red Dots (LRDs)"

(see Inayoshi-san's talk)

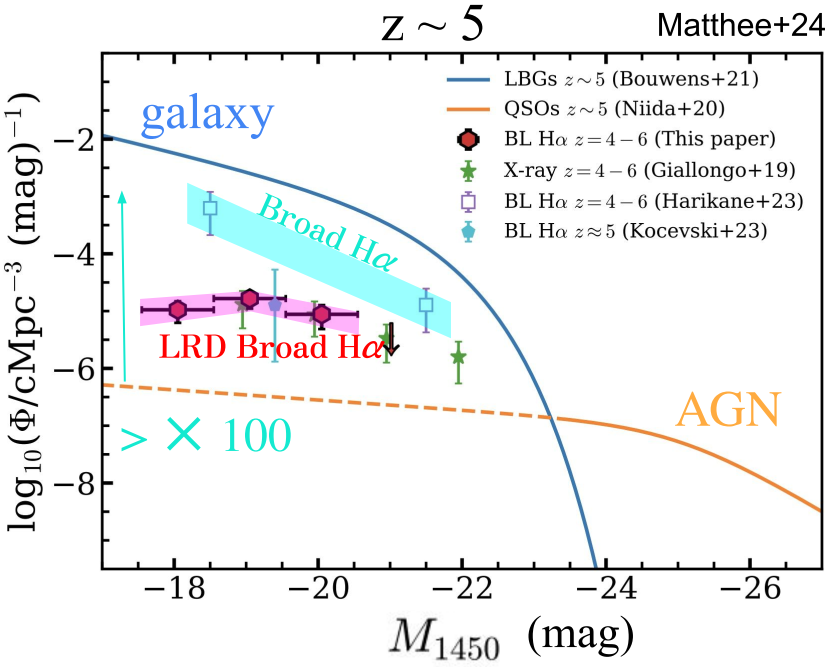


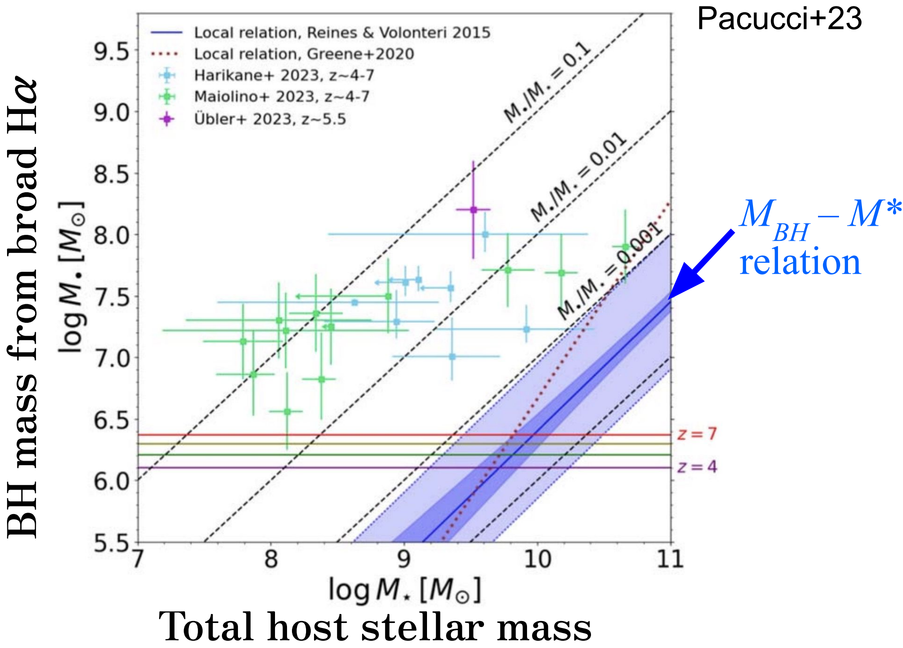
- ~20% of the broad Hα emitters have ***v*-shape** SED (e.g., Ji+25)
  → optically red, UV blue
- Deep dip commonly at ~3600Å
  → Balmer break
- No local analog at z < 4 known





Too many & over-massive for AGN





indicating unexpectedly high spatial density of rapidly-growing AGNs … ?

Are the *JWST* broad Hα emitters really AGNs?

- Only AGN indicator so far is the broad Hα and/or Hβ

FWHM ~ 1000 km/s Balmer lines could be due to:

- High velocity dispersion in ultracompact galaxies (Baggen+24)
- Luminous Blue Variables (SN IIn, ...) (Yue+24, Maiolino+24)
- Electron/Rayleigh/Raman scattering processes (MK 24, Rusakov+25)

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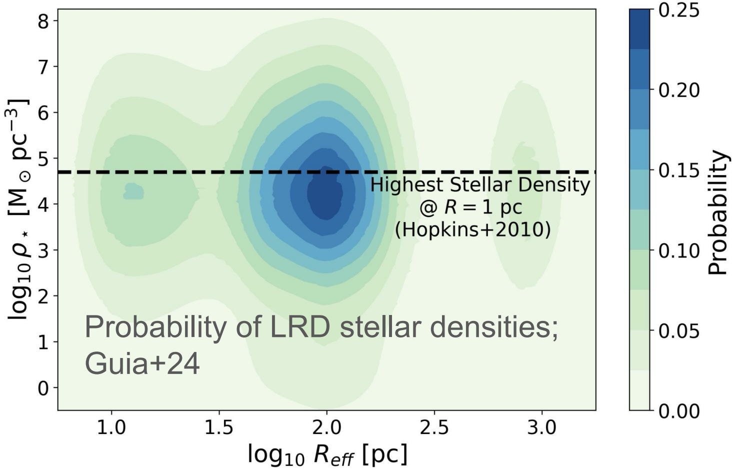

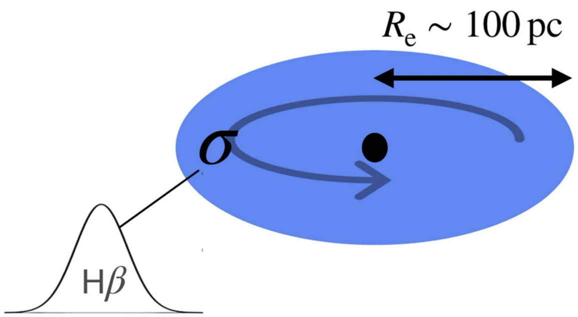

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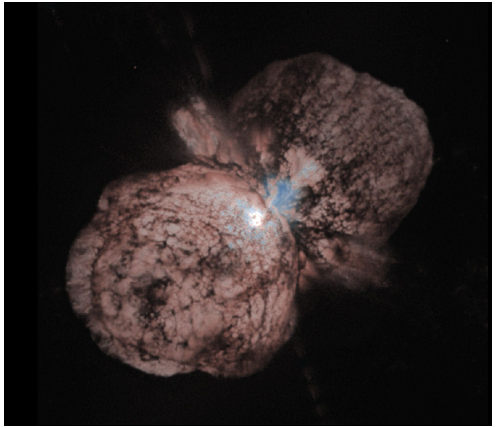
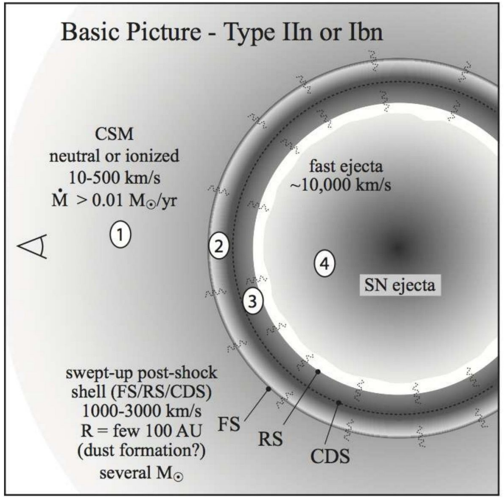




Smith 17

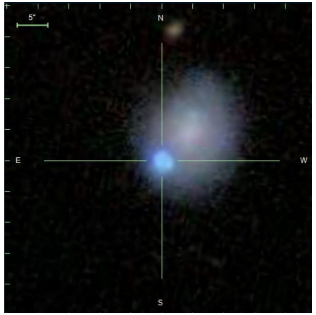
Ejecta/outflow – CSM

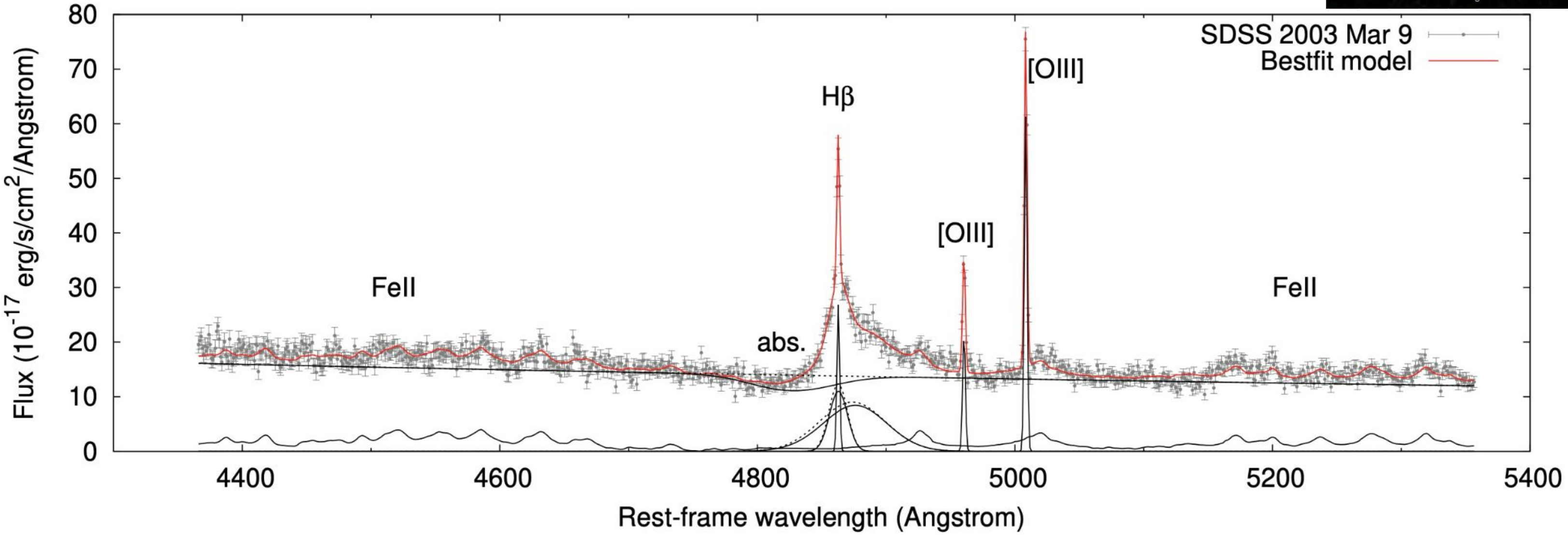
→ Cool Dense Shell

~ AGN BLR

Pseudo AGNs : broad-lined compact objects

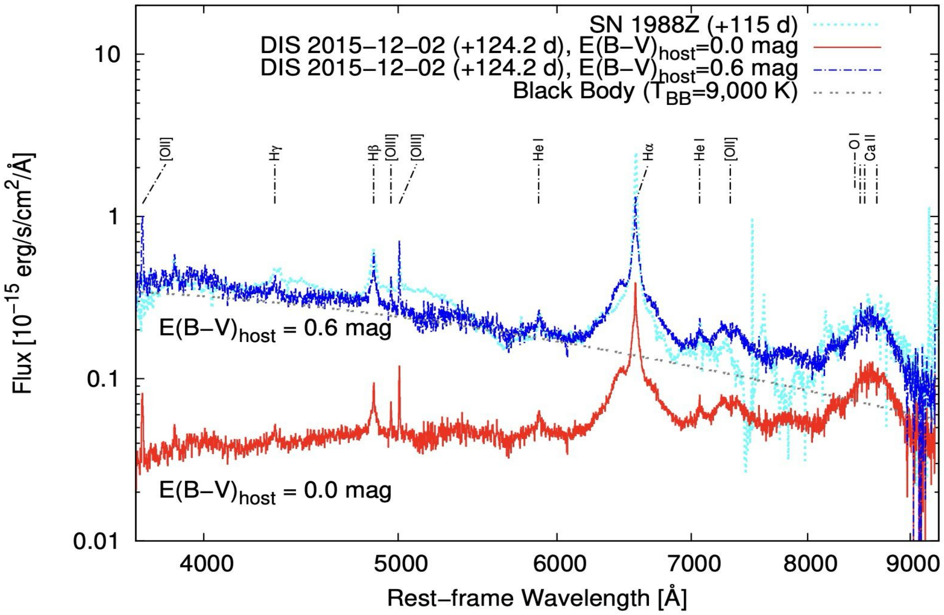
- LBV SDSS1133 (z=0.0079) MK 22
- $L_{\mathrm{H}\alpha} \sim 10^{39}$ erg/s, luminous for >50 yrs

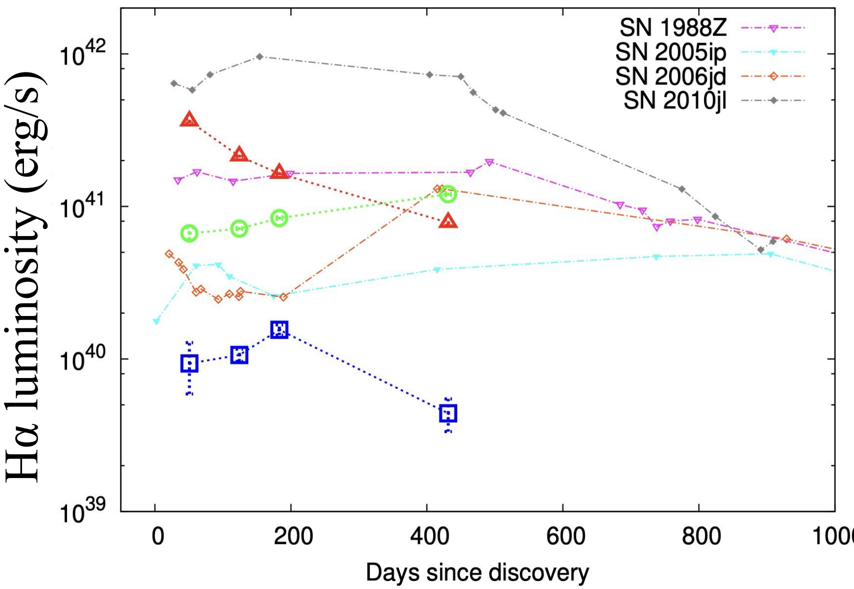




Pseudo AGNs : broad-lined compact objects

- **SN IIn KISS15s** MK+19
- $L_{\mathrm{H}\alpha} \sim 10^{42}$ **erg/s, luminous for > 3 yrs**





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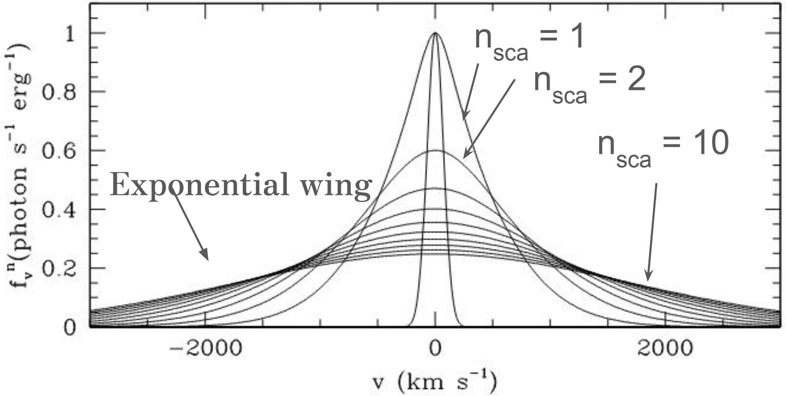
Broad emission lines from (multiple) scattering

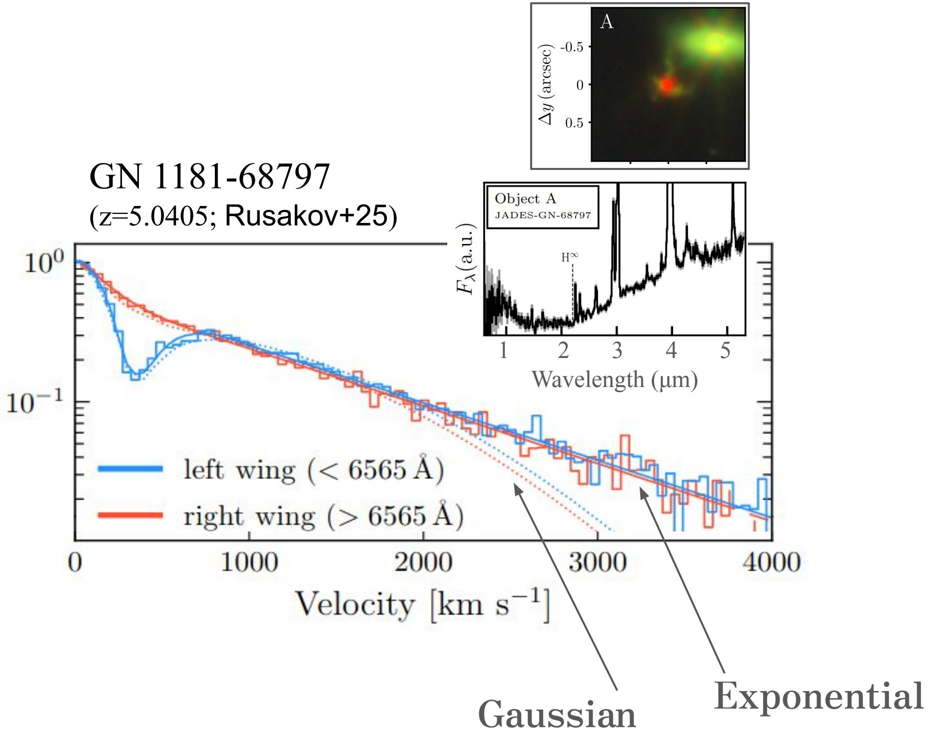
Electron scattering

Laor 06



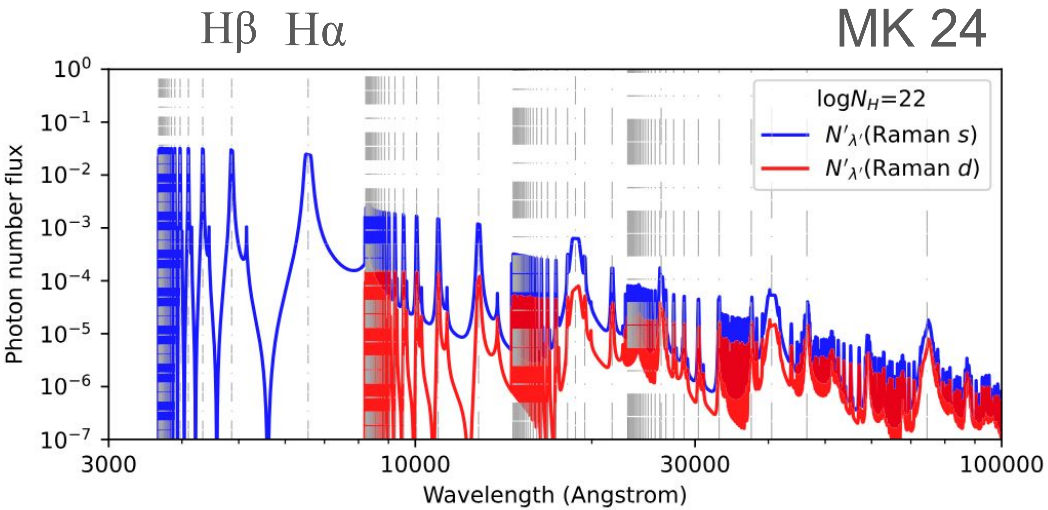
Broadening of narrow lines due to Te=10000K electron scattering

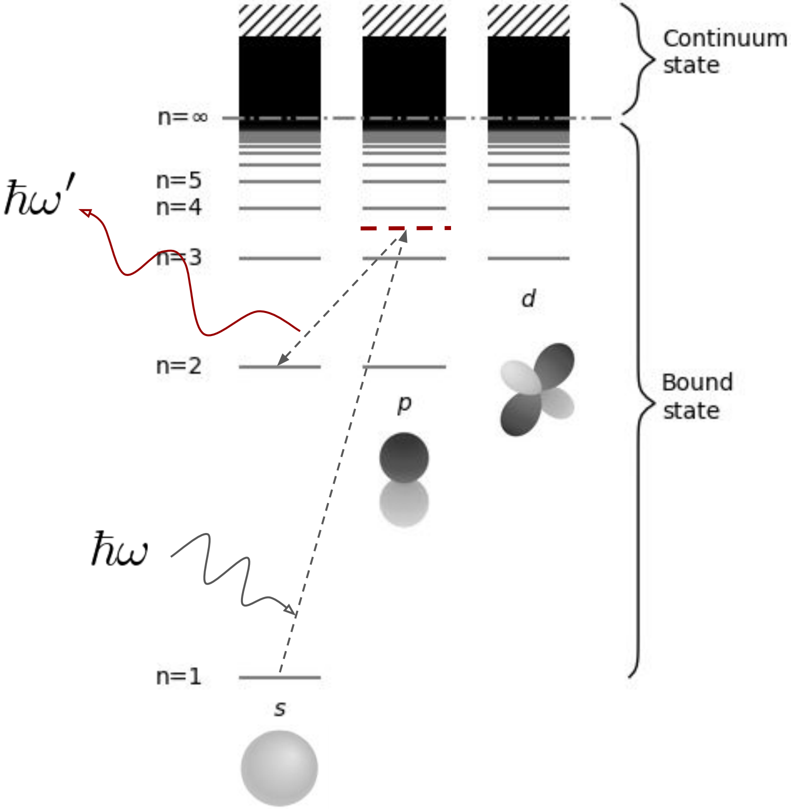
GN 1181-68797
(z=5.0405; Rusakov+25)



Broad emission lines from (multiple) scattering

Hydrogen Rayleigh/Raman scattering





Pseudo-broad line due to
neutral hydrogen Raman scattering

Are the *JWST* broad Hα emitters really AGNs?

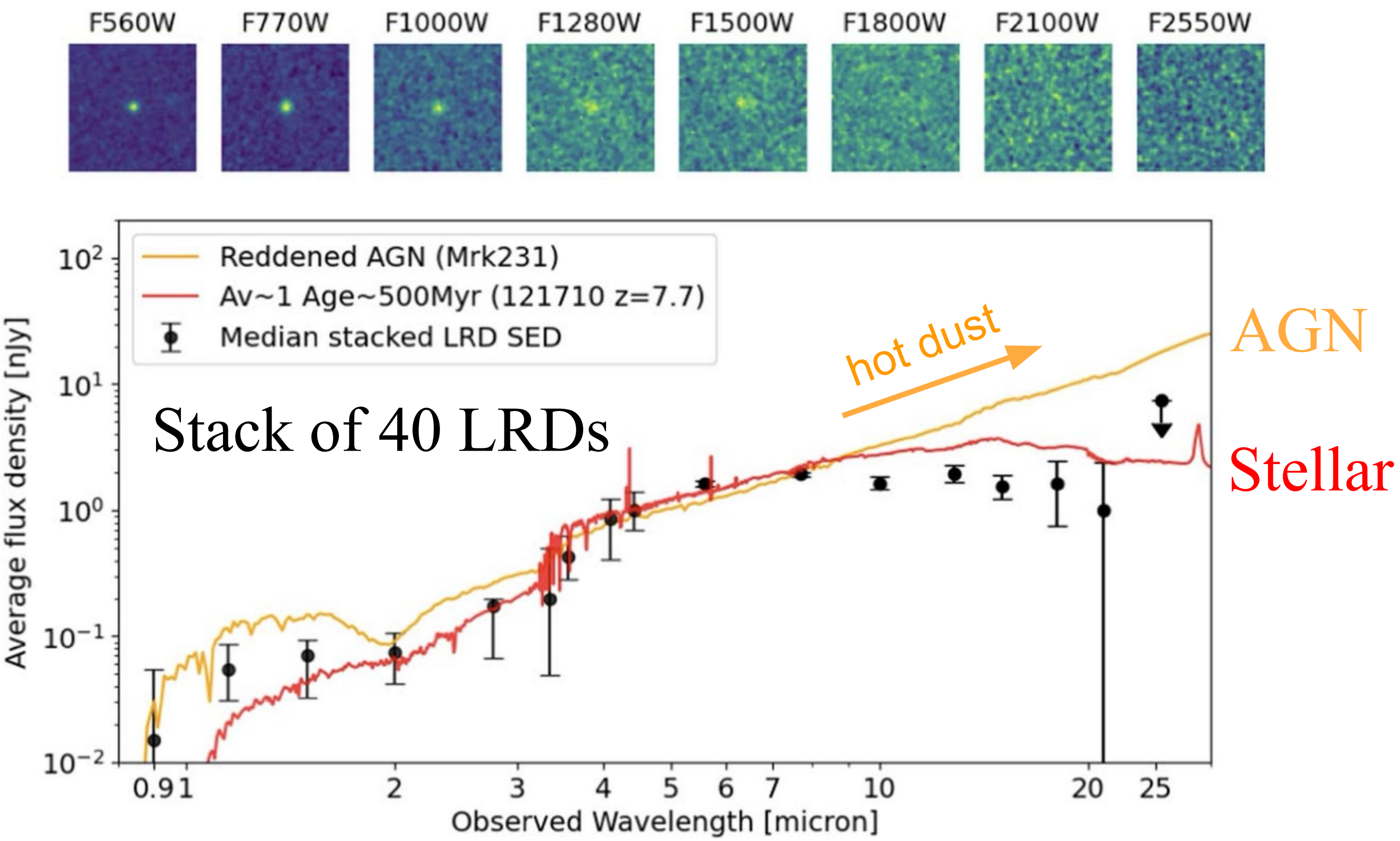
- Only AGN indicator so far is the broad Hα and/or Hβ

  FWHM ~ 1000 km/s Balmer lines could be due to:

  - High velocity dispersion in ultracompact galaxies (Baggen+24)
  - Luminous Blue Variables (SN IIn, …) (Yue+24, Maiolino+24)
  - Electron/Rayleigh/Raman scattering processes (MK 24, Rusakov+25)

- How about other AGN indicators?

  - Hot dusty torus emission: MIRI non-detection (Akins+24, Perez-Gonzalez+24)
  - X-ray: broad Hα emitters are likely to be X-ray faint (Annanna+24, Yue+24, Maiolino+24)
  - AGN rest-frame UV-optical variability


F560W
F770W
F1000W
F1280W
F1500W
F1800W
F2100W
F2550W
Reddened AGN (Mrk231)
Av~1 Age~500Myr (121710 z=7.7)
Median stacked LRD SED
Stack of 40 LRDs
hot dust
AGN
Stellar
Average flux density [nJy]
Observed Wavelength [micron]

Williams+24

Are the *JWST* broad Hα emitters really AGNs?

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← **MK & Harikane 24**

Content

- ❑ Introduction to *Active Galactic Nuclei* (AGN)

- ❑ AGN surveys, and *JWST*'s surprising findings

- ❑ Broad-line AGN candidates discovered by *JWST*
  … are they really AGNs?

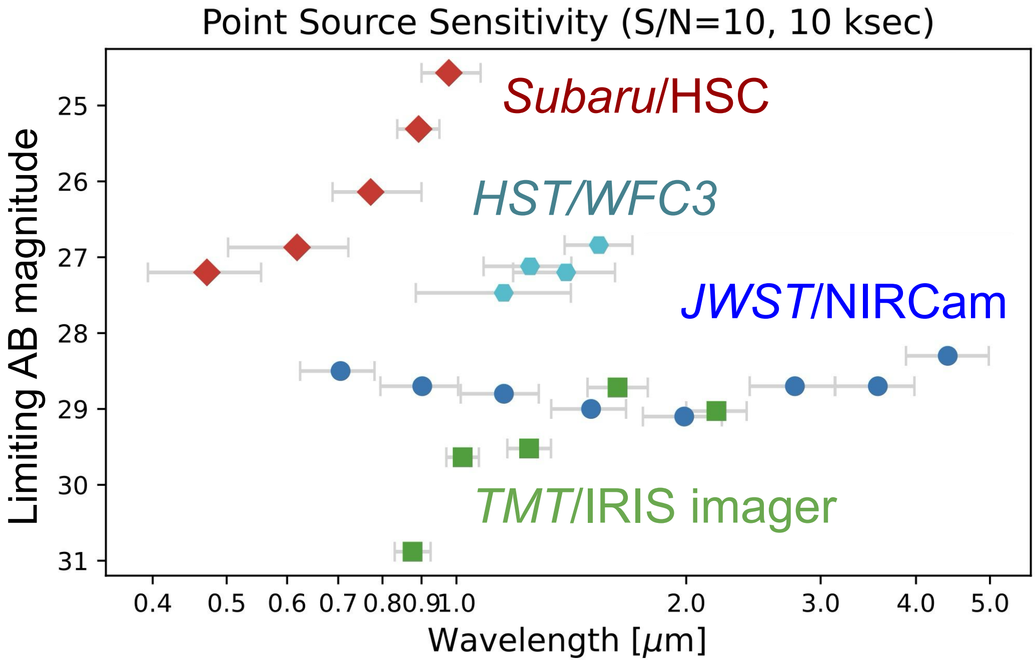
  - ❑ *Chandra* X-ray
  - ❑ *JWST*/NIRCam variability

(MK & Harikane 24)

Variability detection requires ultradeep imaging

- NIRSpec broad Hα emitters : ~ 26 mag
- AGN variability amplitude : ~ 0.1 mag

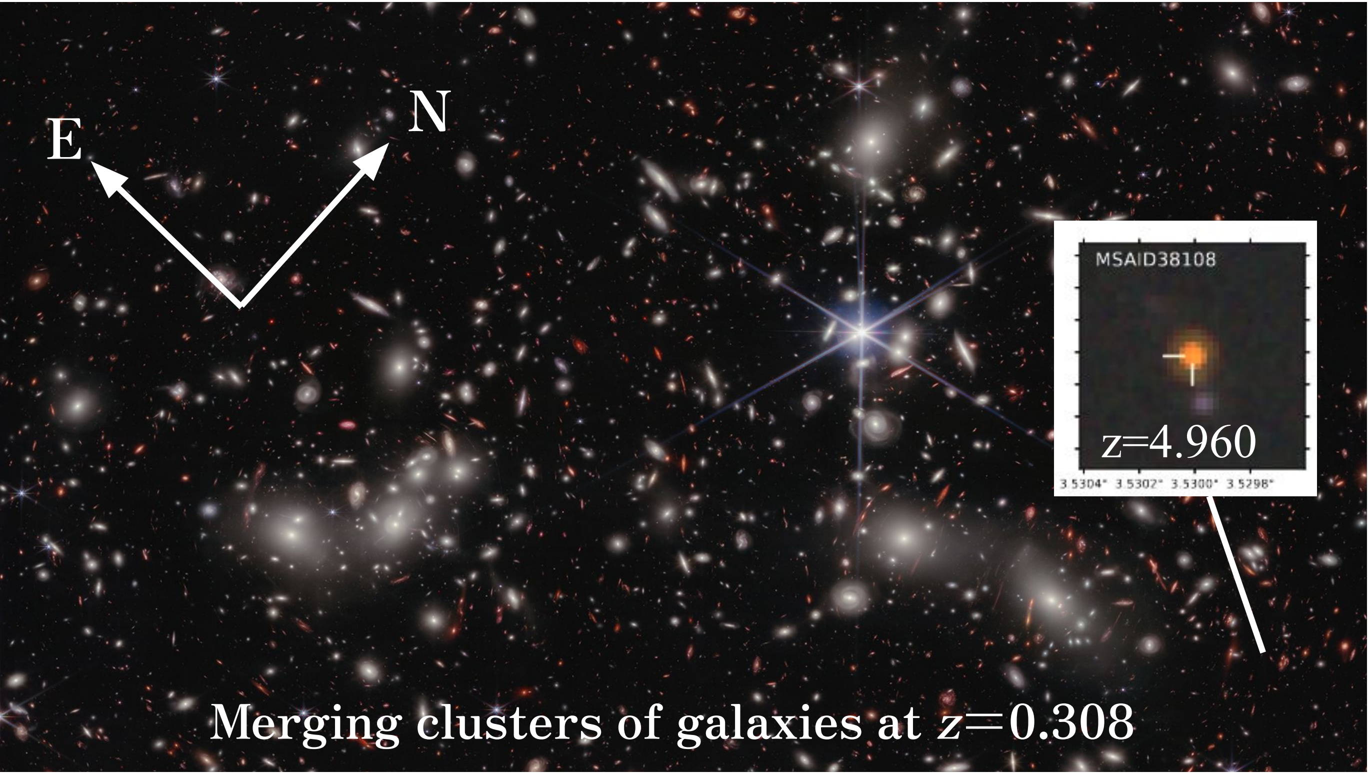
→ ~ 28.5mag imaging depth is necessary



Only feasible with *JWST*/NIRCam
(until the era of 30-m-class telescopes)

JWST/NIRCam multi-epoch imaging for broad Hα emitters

in the Abell2744 region



One of the first release data from *JWST*
- UNCOVER
- GLASS

Many (parallel) imagings afterwards
→ variability analysis

Archival *Chandra* data

JWST/NIRCam multi-epoch imaging for broad Hα emitters

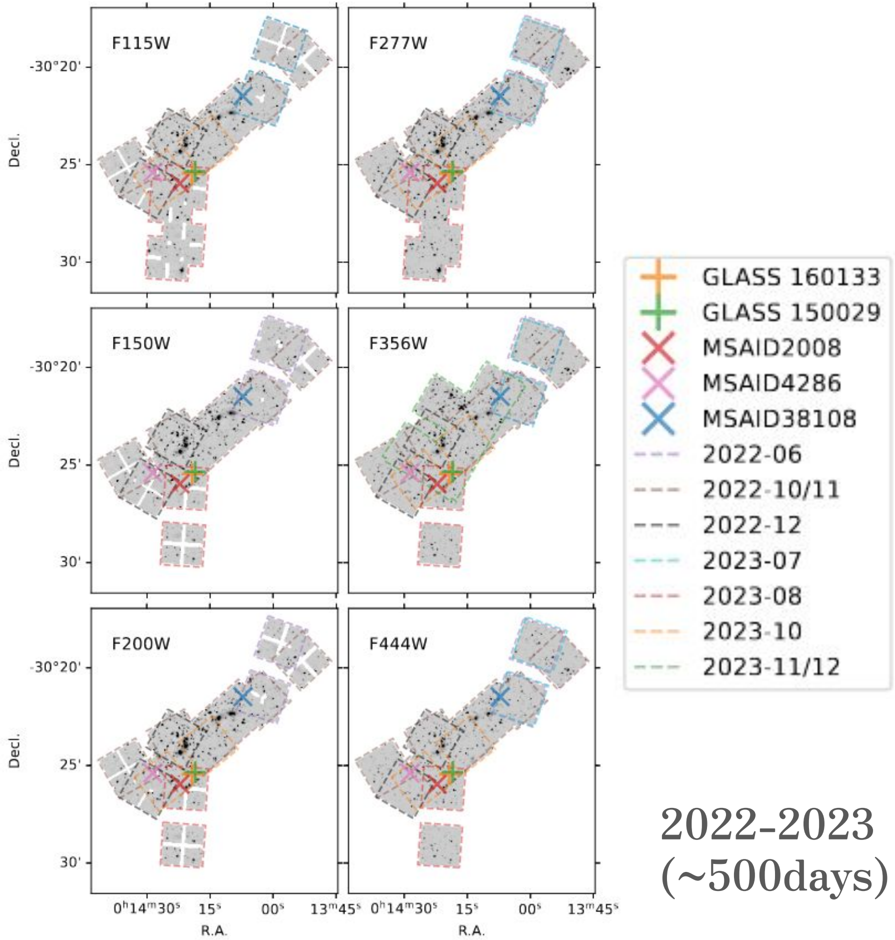
in the Abell2744 region

NIRSpec broad Hα emitters:
Greene+24 : 12 LRDs
Harikane+23 : 2 non-LRDs

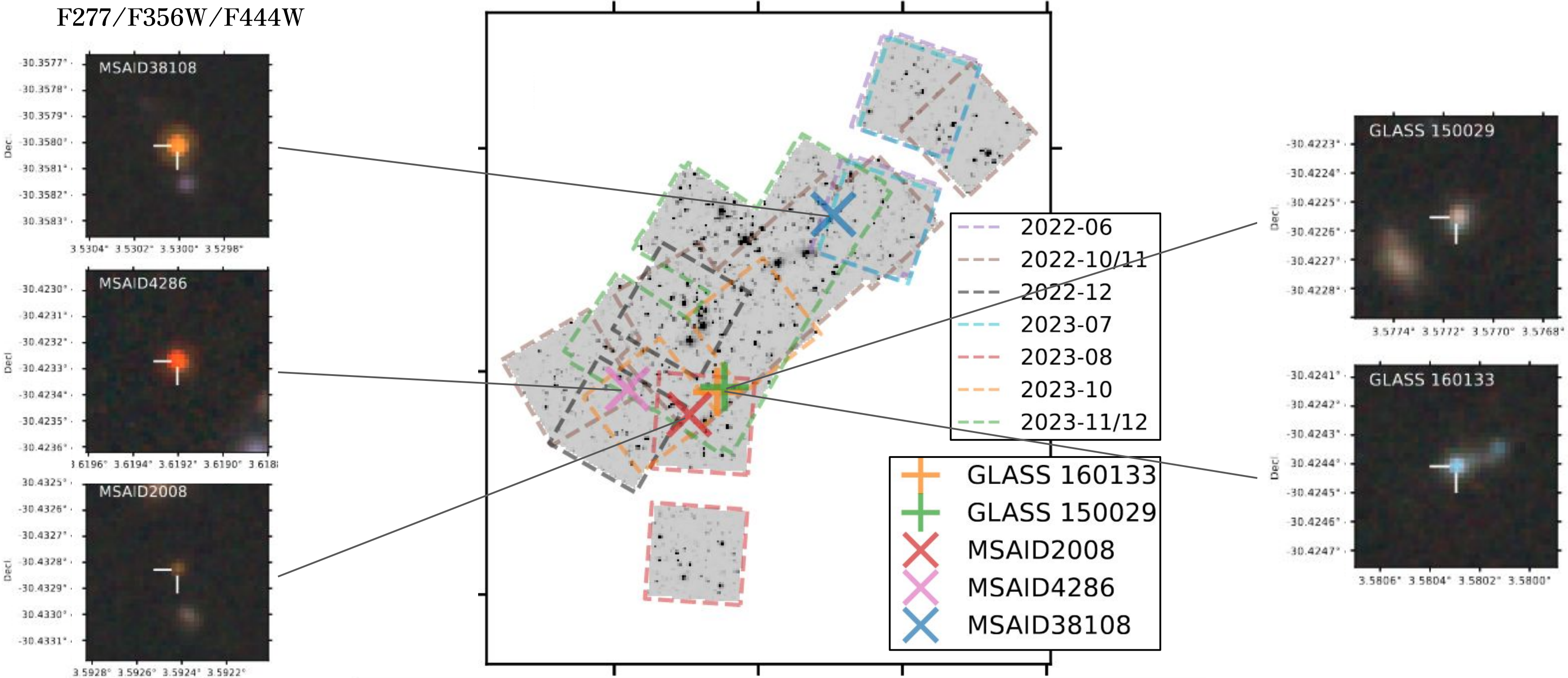
×

Multi-epoch & multi-band:
6 wide-bands F115W ~ F444W
(1.1μm – 4.4μm)

→ 5 objects (3 LRDs, 2 non-LRDs)



2022-2023
(~500days)

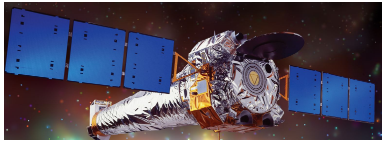


LRDs

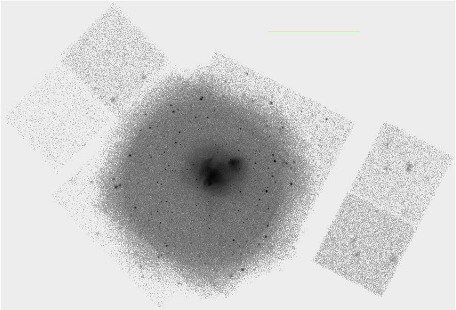
non-LRDs

Name	$z_{\rm spec}$	μ	$L_{\rm H\alpha,broad}$ (10^{42} erg s^{-1})	FWHM$_{\rm H\alpha,broad}$ (km s^{-1})	$M_{\rm BH}$ ($10^7\ M_\odot$)
GLASS 160133	4.015	1.680	$0.67^{+0.06}_{-0.06}$	1028^{+19}_{-13}	0.17
GLASS 150029	4.583	1.676	$0.47^{+0.04}_{-0.03}$	1429^{+10}_{-67}	0.27
MSAID2008	6.740	1.691	$2.5^{+0.5}_{-0.5}$	1200^{+430}_{-430}	0.48
MSAID4286	5.840	1.615	23^{+1}_{-1}	2900^{+1040}_{-1040}	10
MSAID38108	4.960	1.588	26^{+1}_{-1}	4100^{+1980}_{-1980}	22

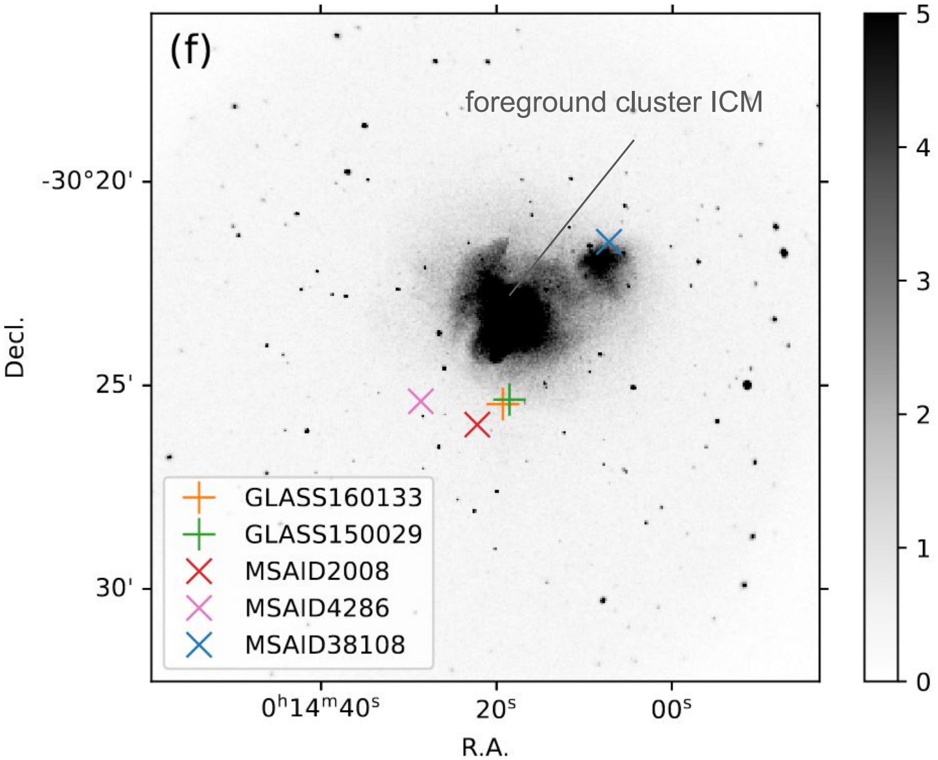
Ultra-deep *Chandra* X-ray



2.2 Msec Coadd from unpublished *Chandra* archival data

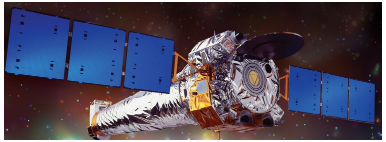


2.2 Msec (~25 days) exposure



(＊Observed: 0.5-7 keV ⇨ rest-frame: 3 - 42 keV for z=5)

Ultra-deep *Chandra* X-ray non-detection



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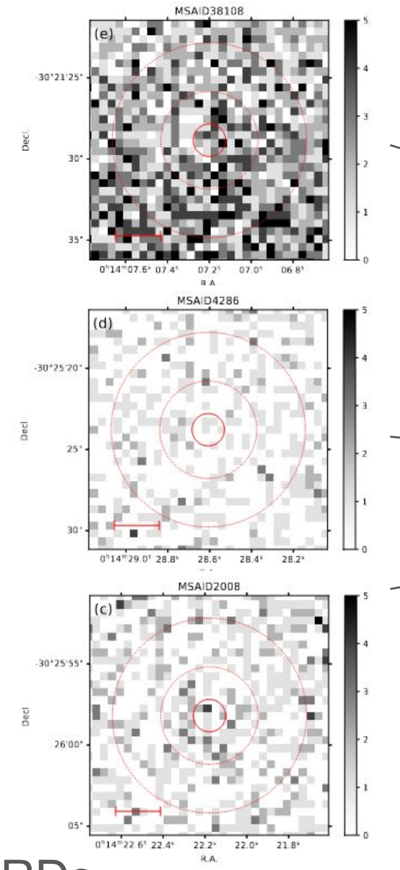

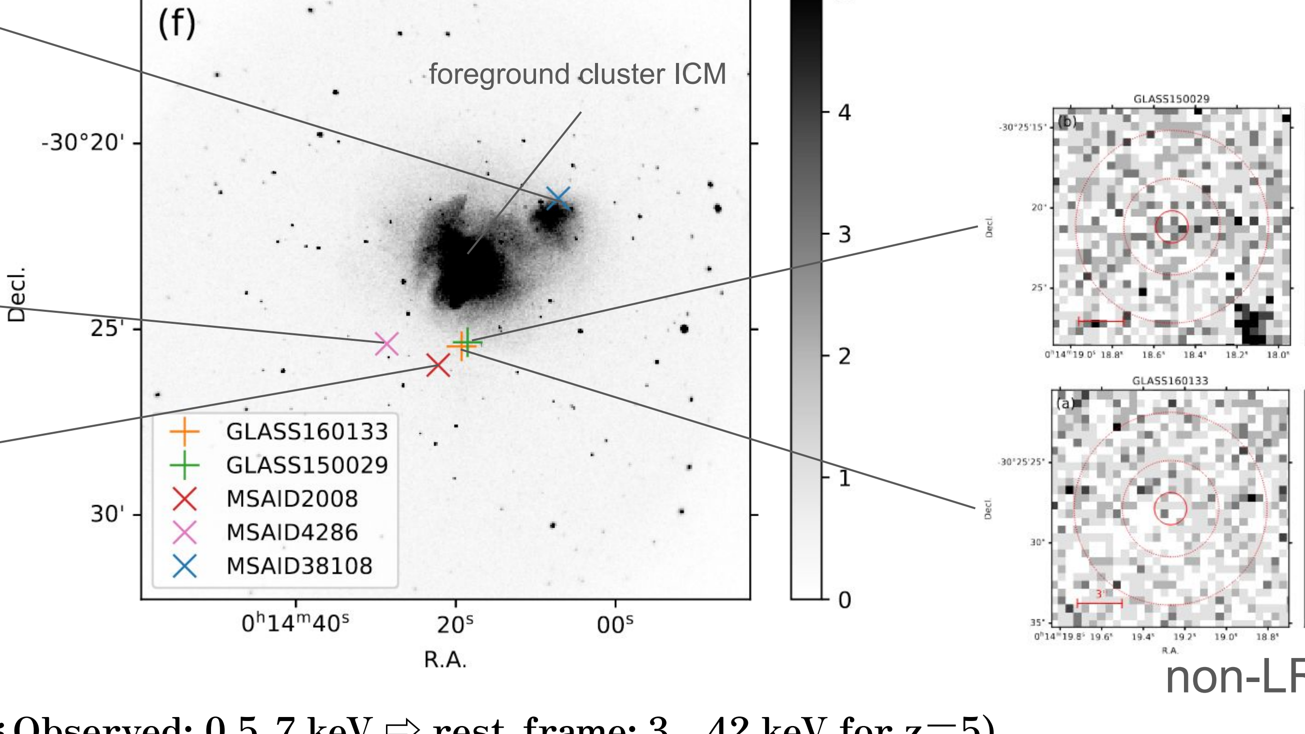

LRDs

non-LRDs

(*Observed: 0.5-7 keV ⇨ rest-frame: 3 - 42 keV for z=5)

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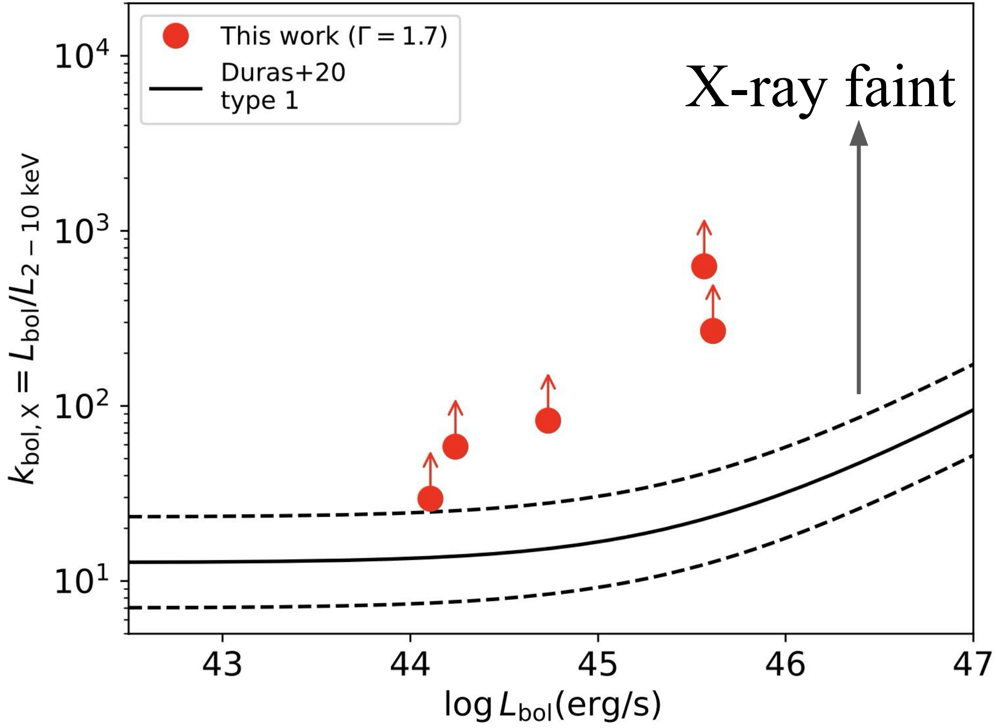
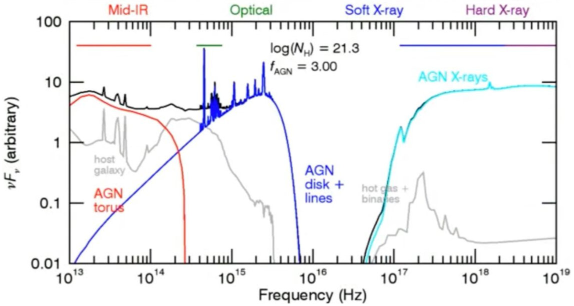
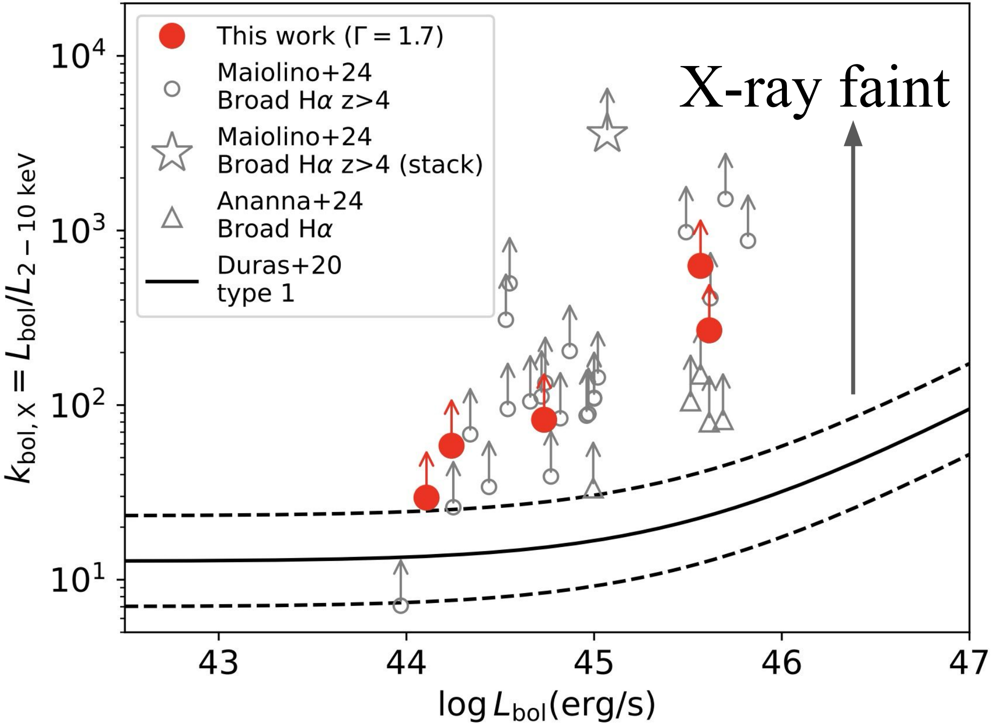


typical AGN (±1σ)



→ Unlikely to be "normal" AGN

Ultra-deep *Chandra* X-ray non-detection



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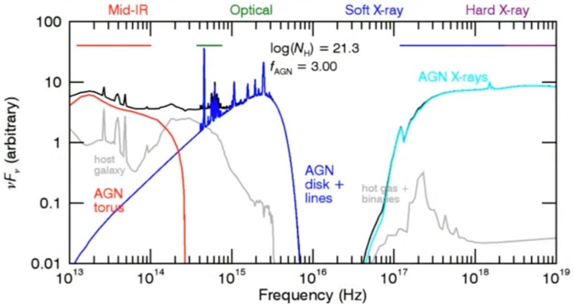

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Variability search

Name	$z_{\rm spec}$	μ	$L_{\rm H\alpha,broad}$ (10^{42} erg s^{-1})	FWHM$_{\rm H\alpha,broad}$ (km s^{-1})	$M_{\rm BH}$ ($10^7\ M_\odot$)
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($M_{\rm BH}$ from Broad Hα line width & luminosity)

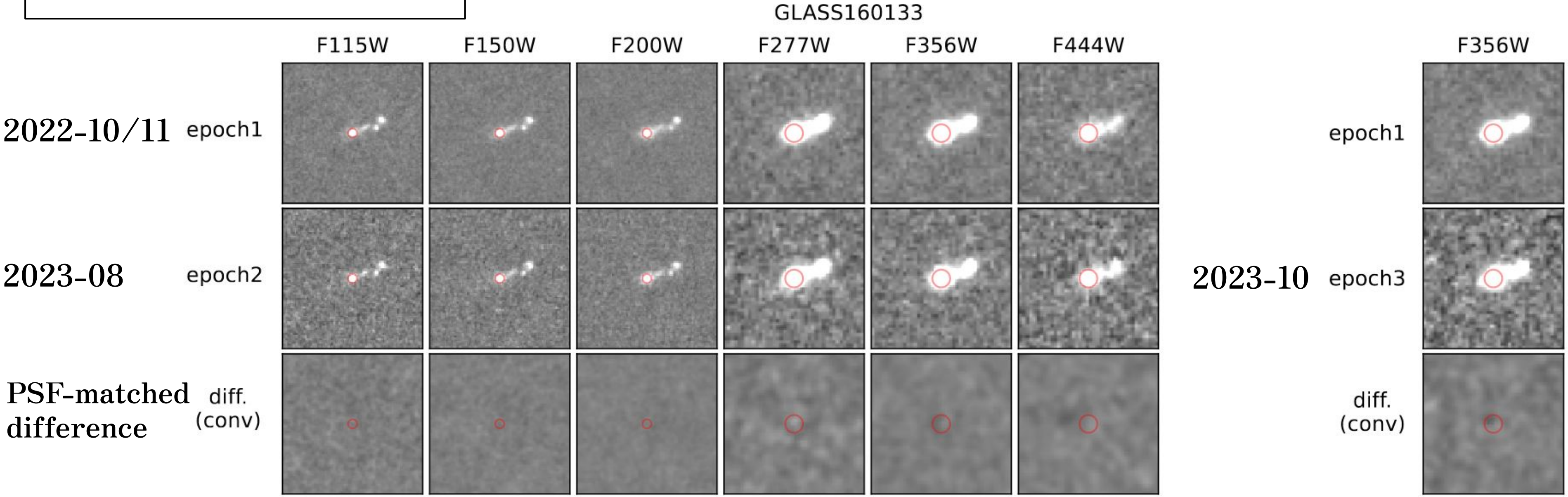
Empirical AGN variability time scale (Burke+23):

$$\tau_{\rm d} = 44.6 \text{ days} \left(\frac{M_{\rm BH}}{10^7\ M_\odot}\right)^{0.38}$$

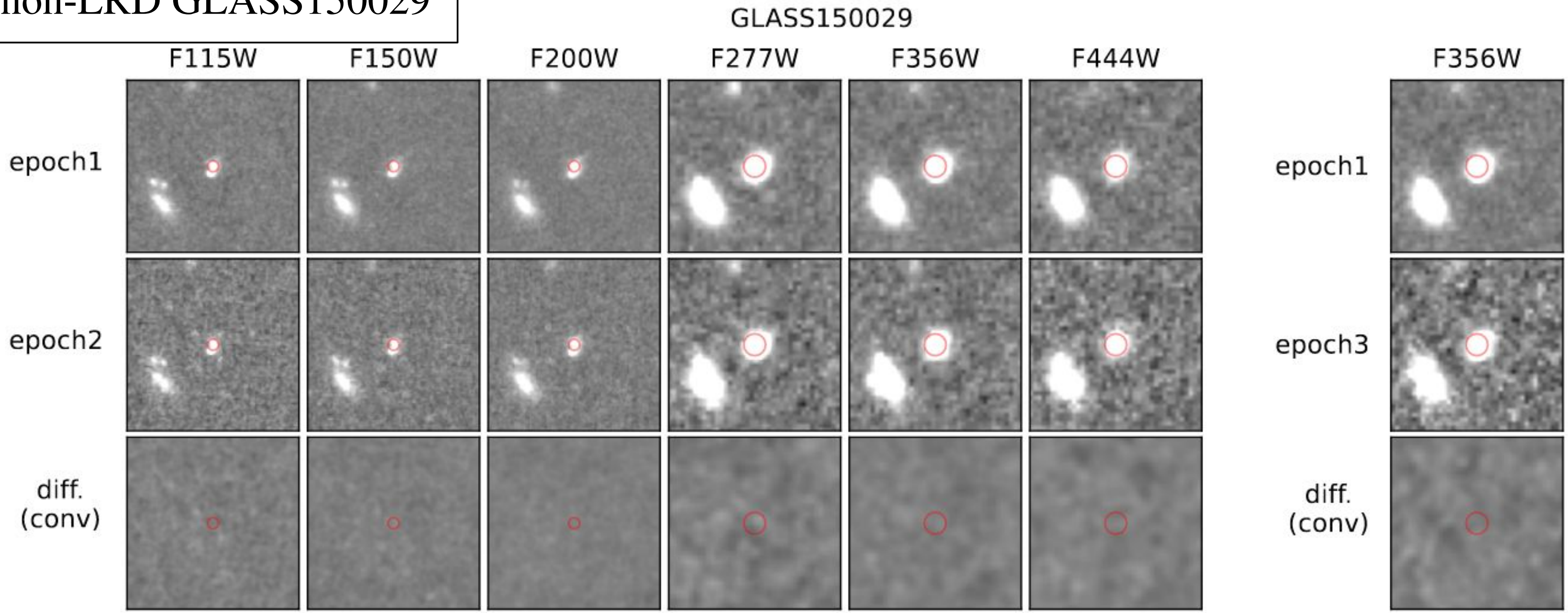
If the broad Hα emitters are z~5 AGNs, $t_{\rm obs}$ ~ 1~2 years of the *JWST* multi-epoch data ($m_{\rm lim}$~ 30 mag) are sufficient to detect the AGN variability

Results: variability search

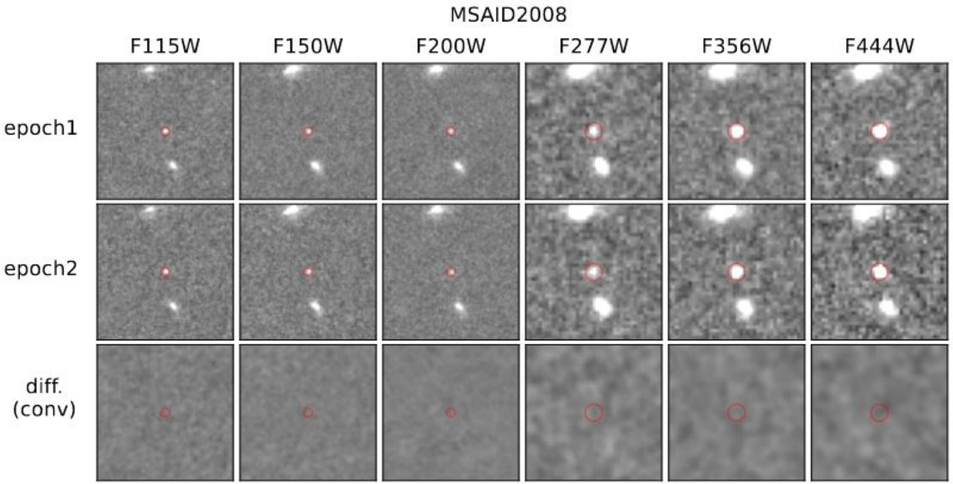
non-LRD GLASS160133

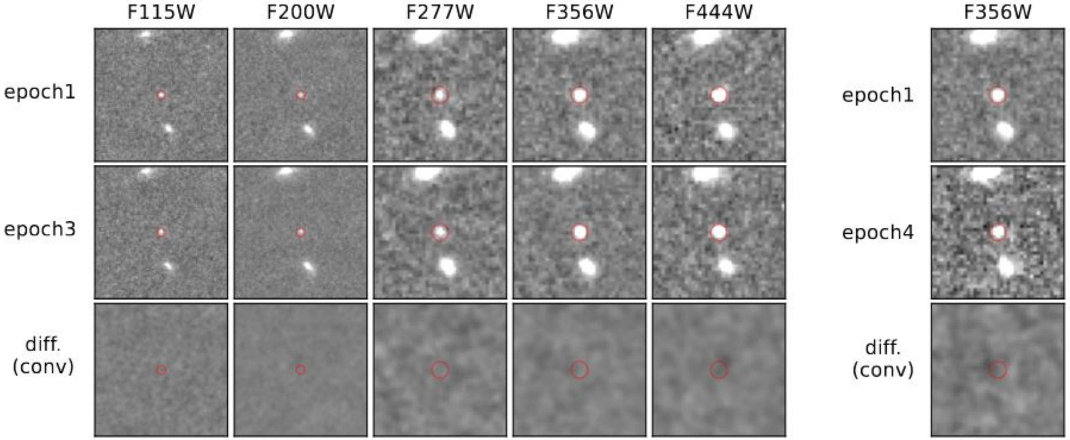


No variability over the rest-frame time ~ 360 days/(1+z) ~ 70days (z=4.015) non-LRD GLASS150029

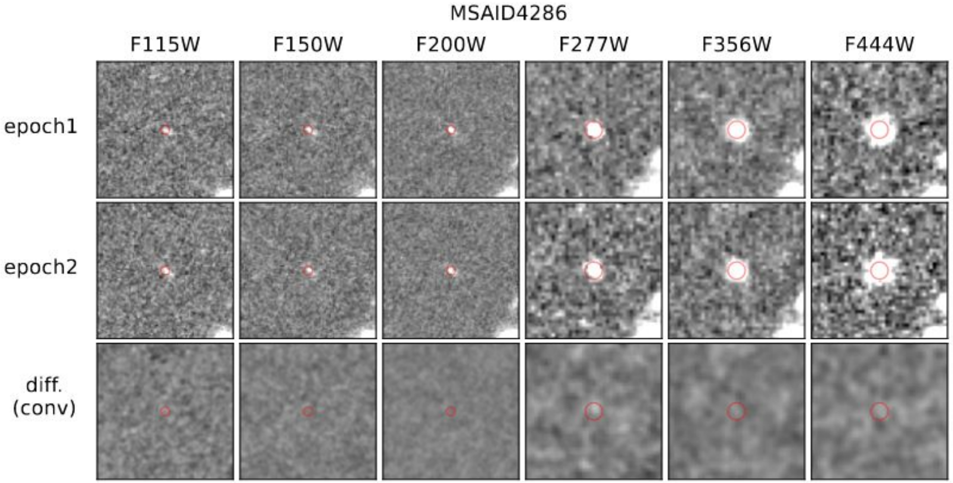


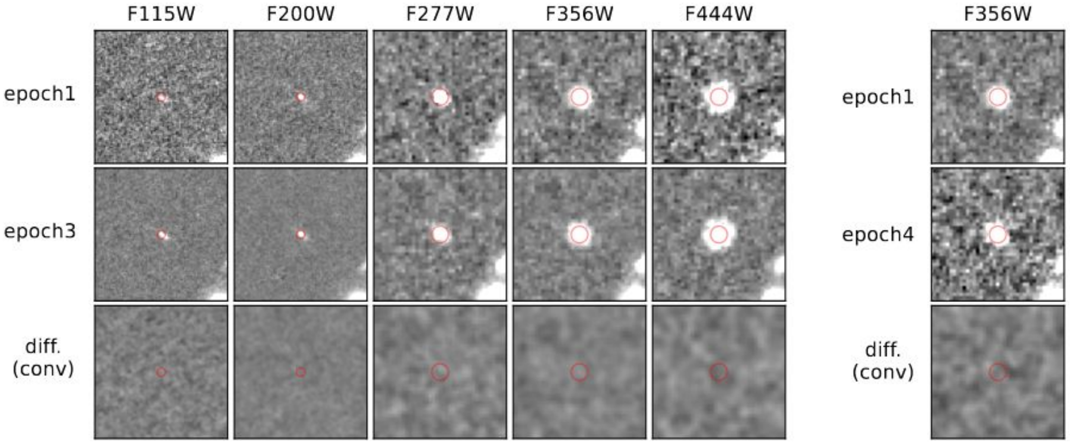
LRD MSAID2008



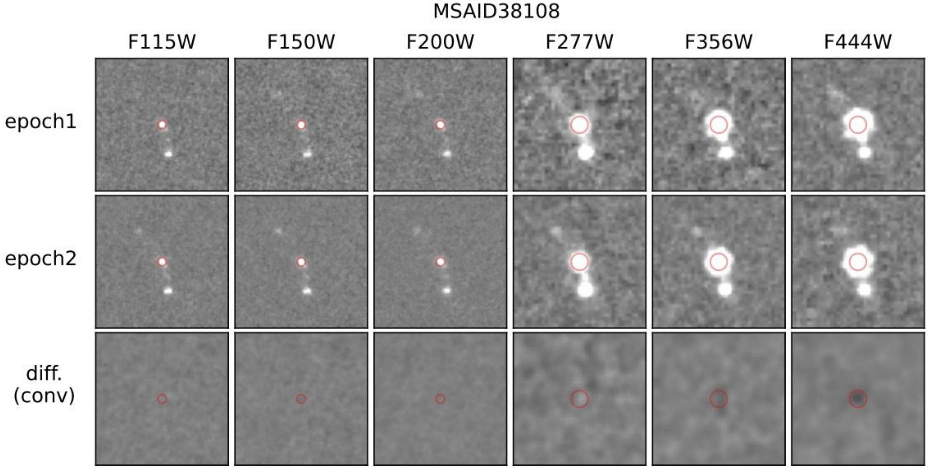


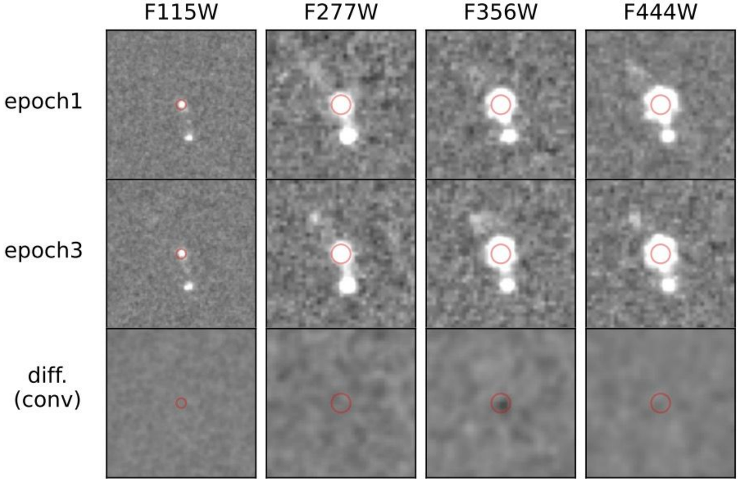
LRD MSAID4286

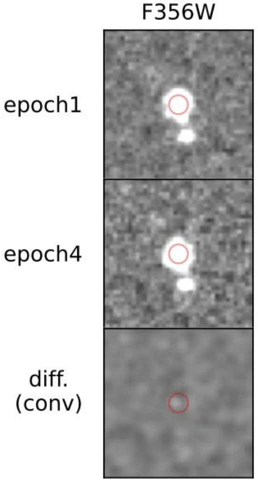




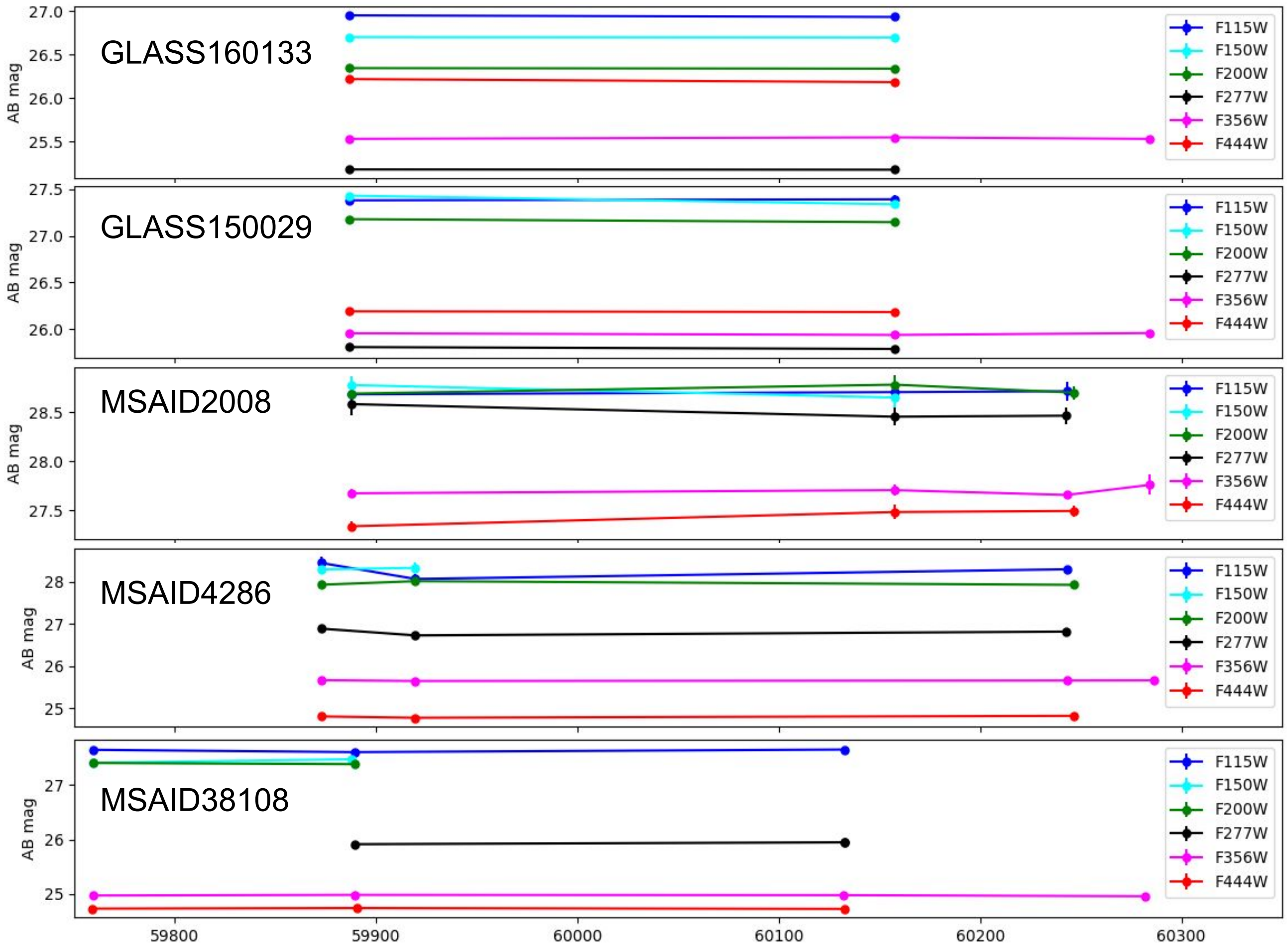
LRD MSAID38108







Lightcurves



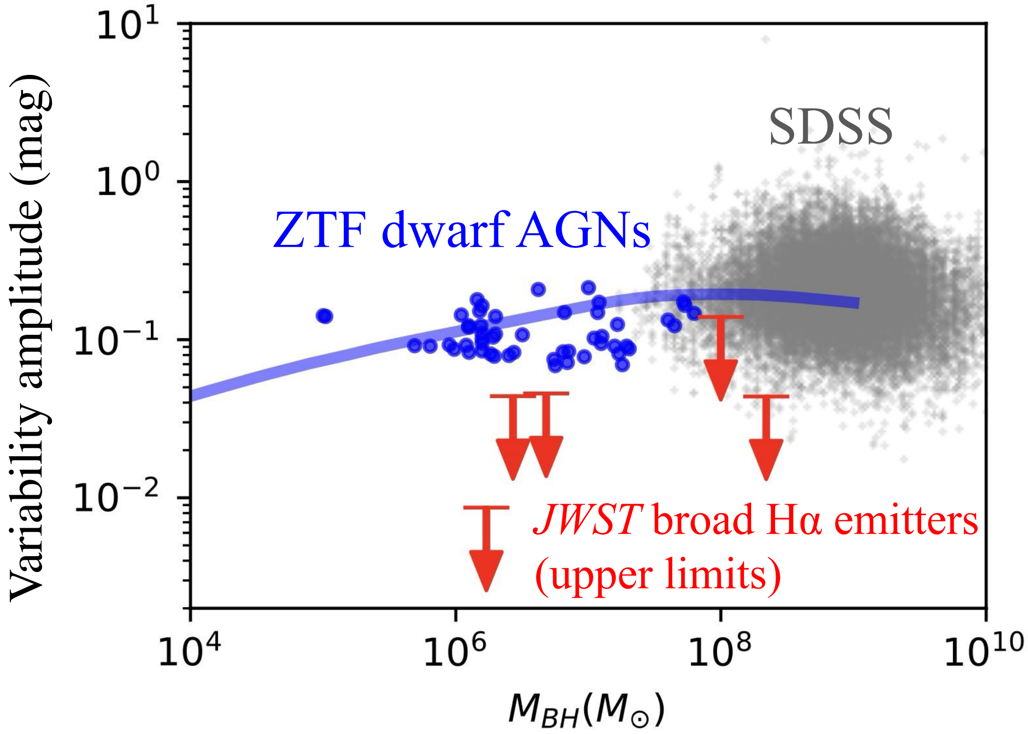
Modified Julian Dates

S/N > 3 variability is not detected over t_{obs} ~ 500 days

Comparisons with the variability of known AGNs

Much less variable than known AGNs

→ Unlikely to be "Normal" AGN

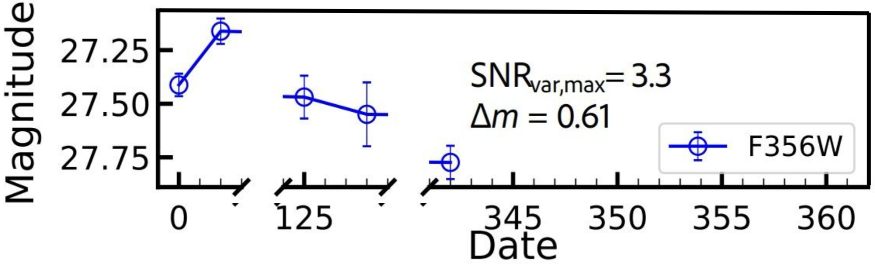


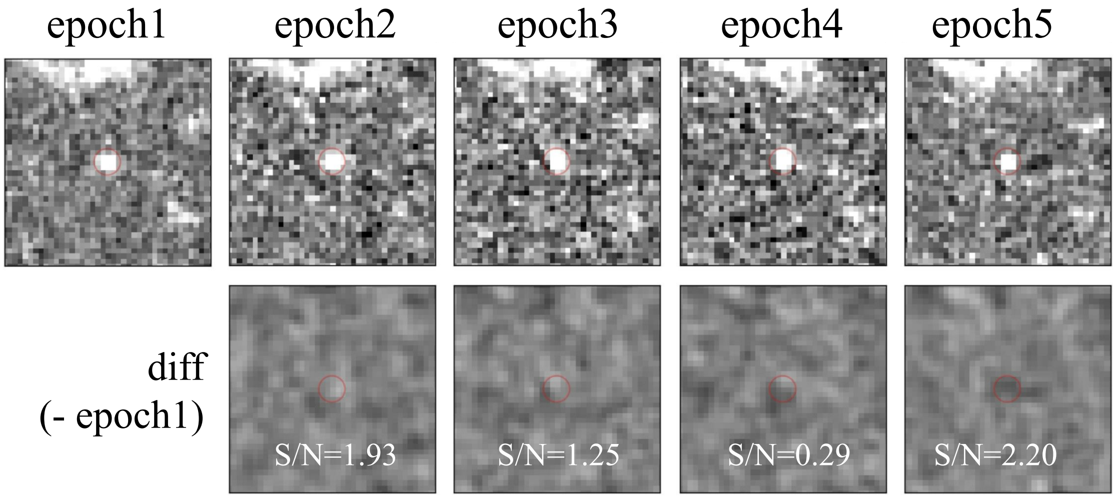
Extension to larger (but sparsely sampled) datasets

- Zhang et al. (2025) claim
  8 LRDs out of 314 LRDs (~2.5%)
  show **~3σ** variability

  However…
  my own re-analysis **fails** to reproduce their variability detection in these 8 LRDs

COS-593, Zhang+25





COS-593
F356W

MK in prep.

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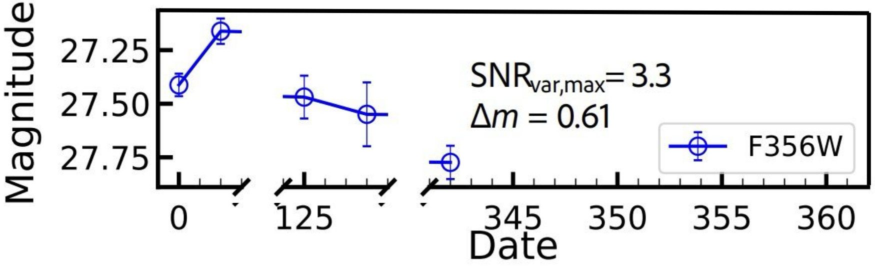
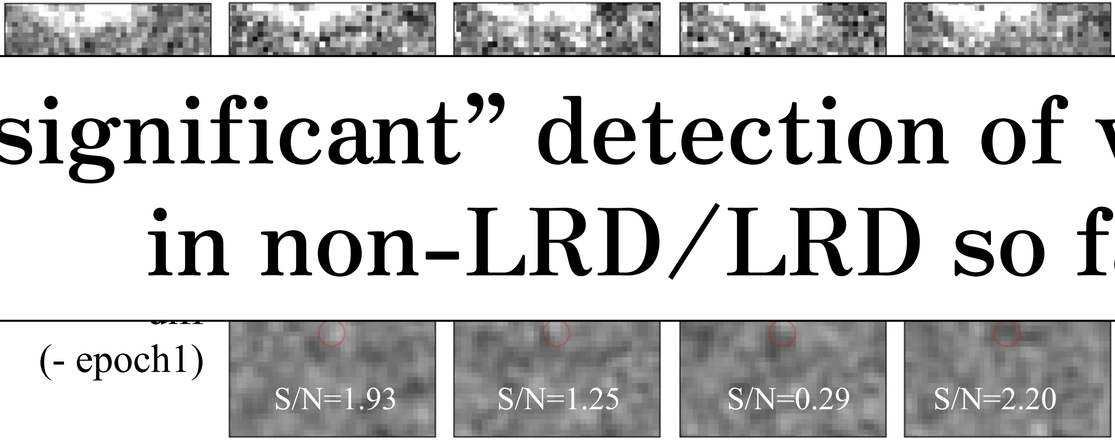


epoch1 epoch2 epoch3 epoch4 epoch5



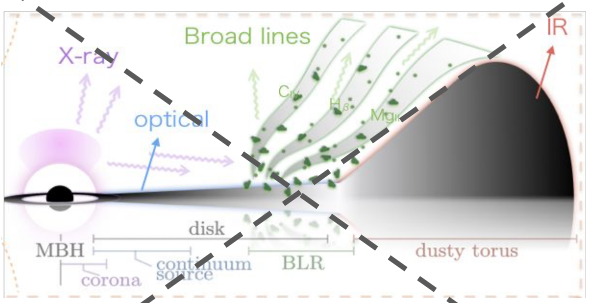
(- epoch1)

No “significant” detection of variability in non-LRD/LRD so far

MK in prep.

Summary

- (一般的には)時間軸天文学データはAGN探査に極めて有用
- *JWST*で発見されたBroad Hα emitters populationは **LRD, non-LRDs** どちらも
  - No dust torus IR
  - No X-ray
  - **No UV-optical variability**



$$\log M_{\rm BH} = \log \frac{f\, R \Delta V^2}{G}$$

つまり我々がよく知っているAGNの定義を満たさない

→ High-z ($z > 4$)(e.g., Kochevski+24)にのみ**大量**に存在する新種天体である.
その物理は... see Inayoshi-san's talk