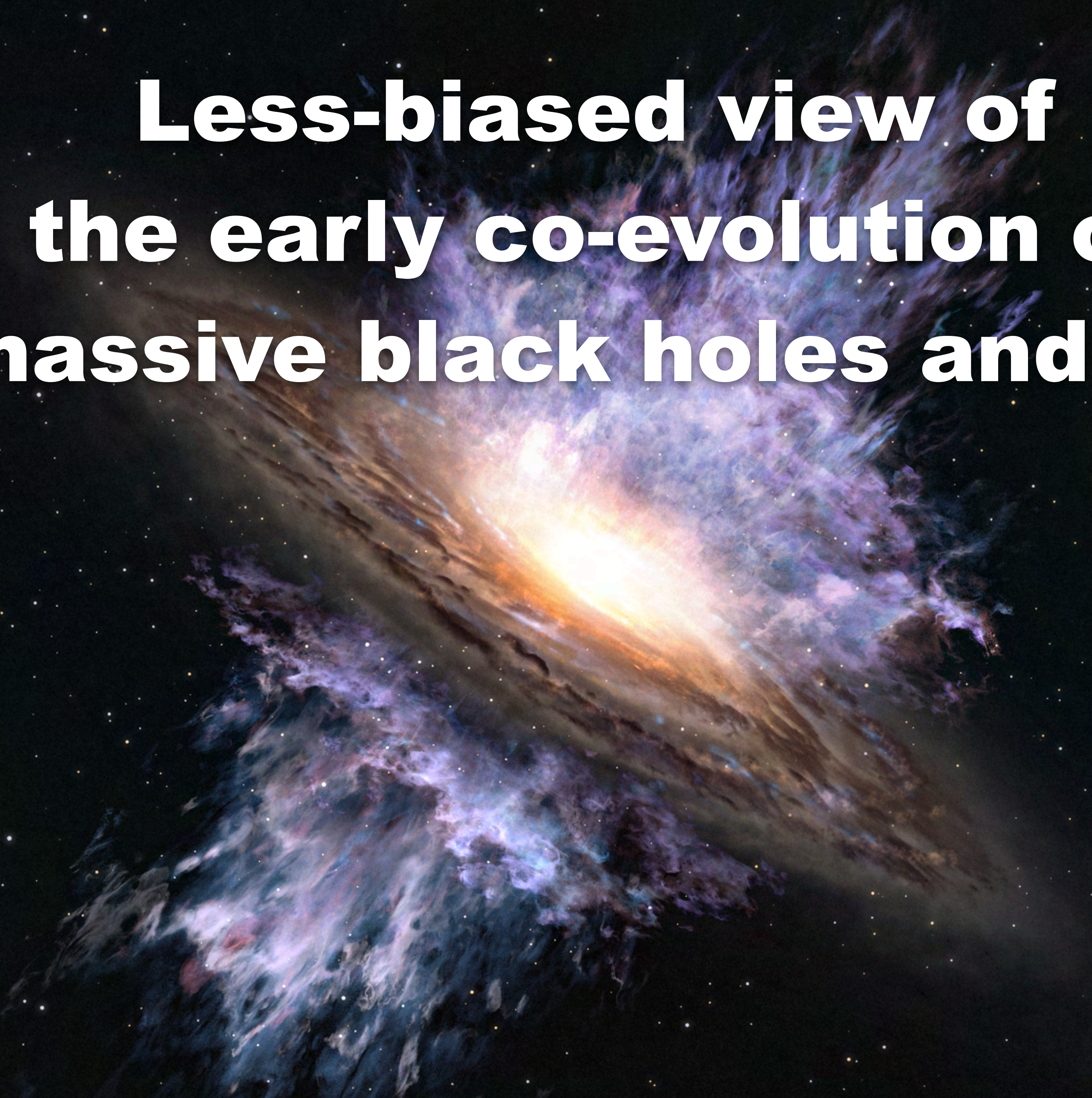
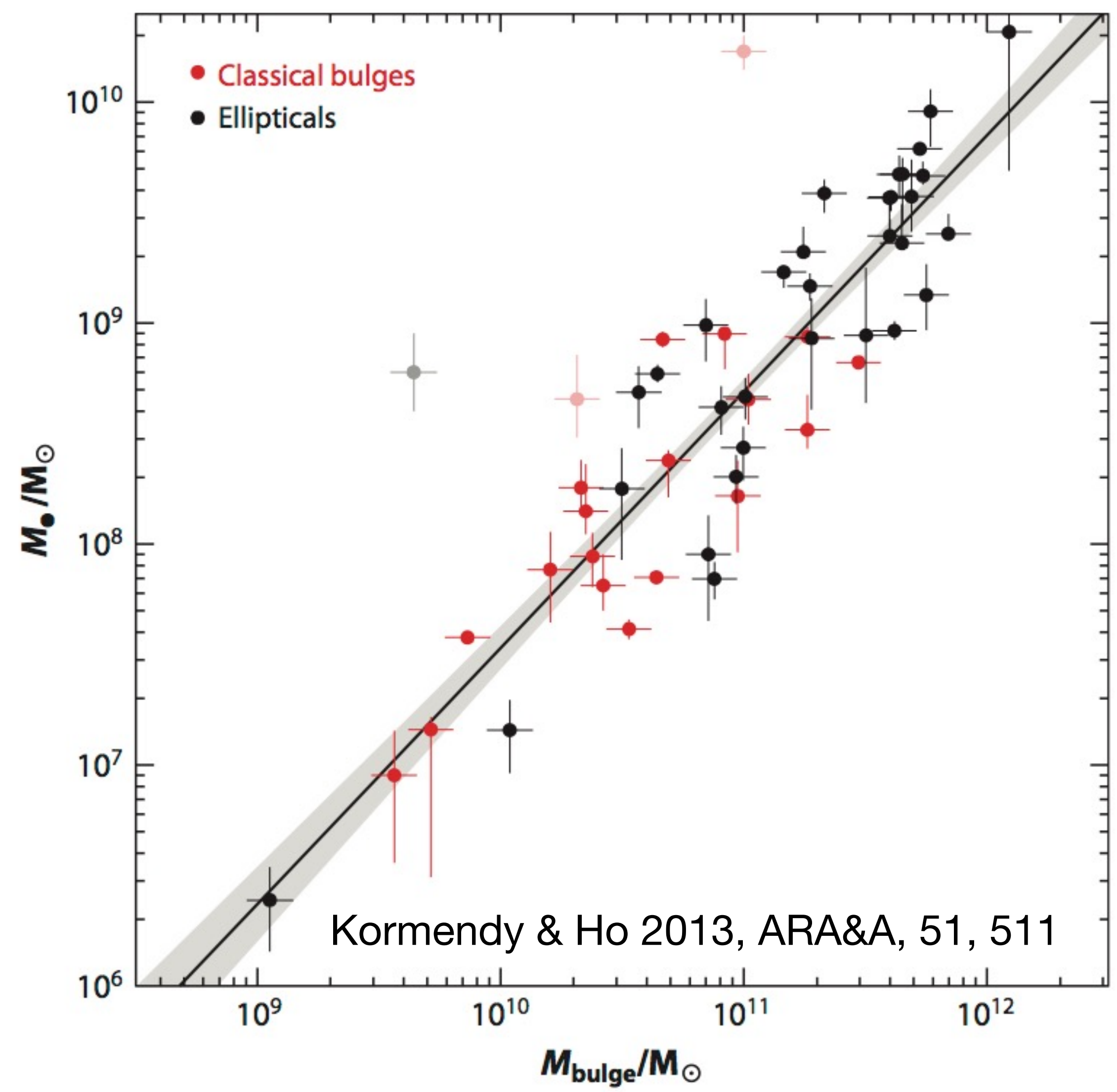
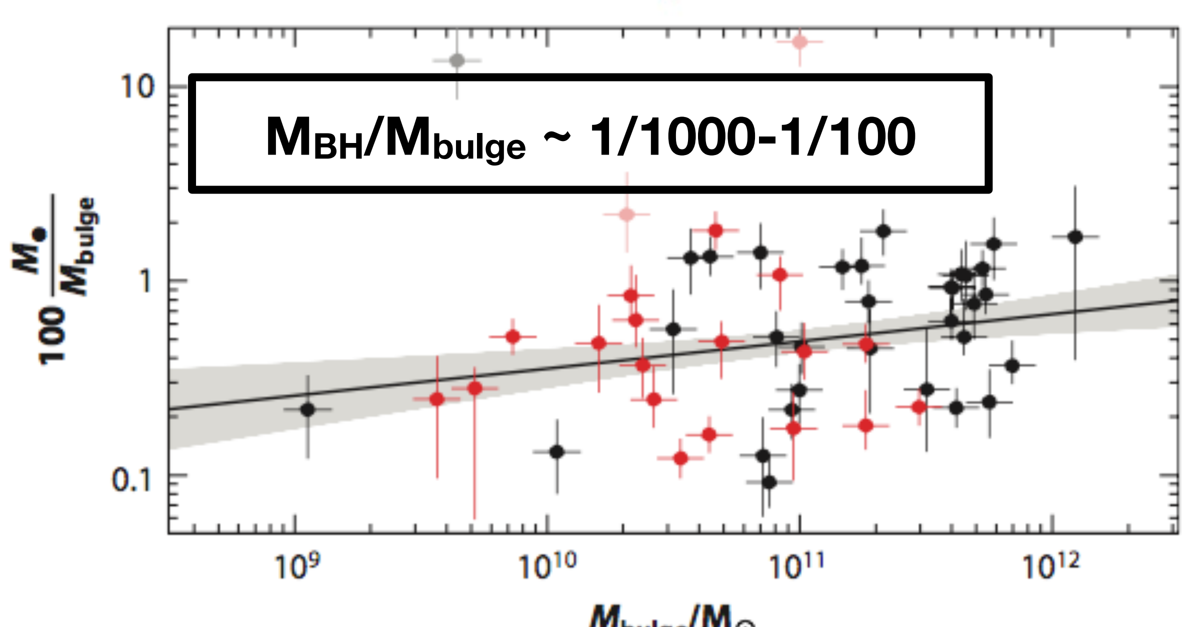
Less-biased view of the early co-evolution of supermassive black holes and galaxies



Takuma Izumi (NAOJ/SOKENDAI)
+ SHELLQs collaboration

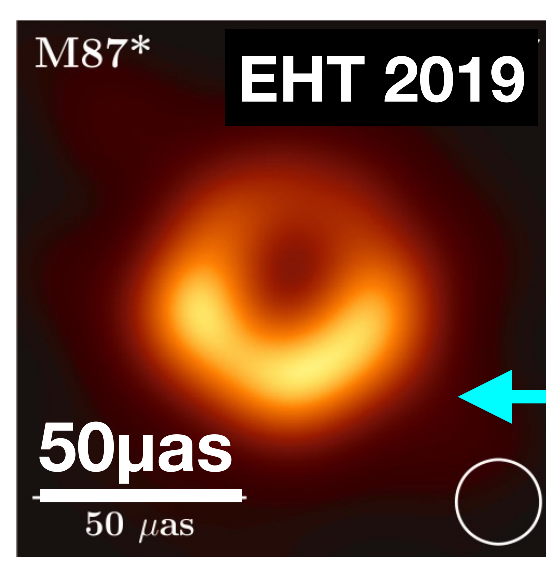
Co-evolution of SMBHs and Host Galaxies?

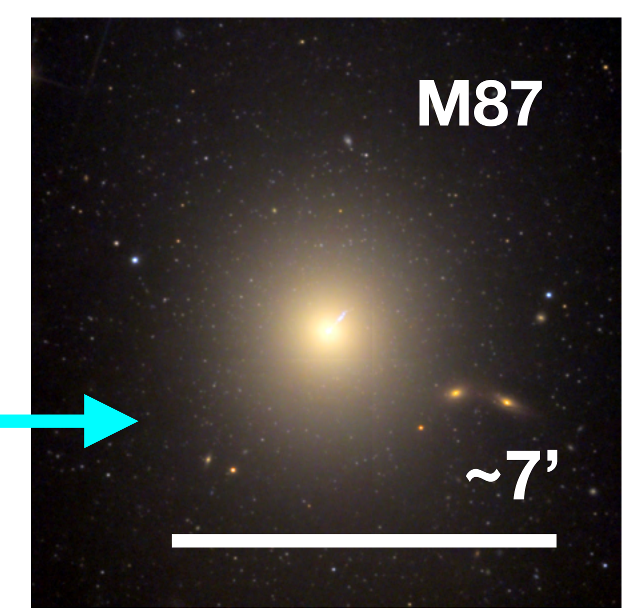


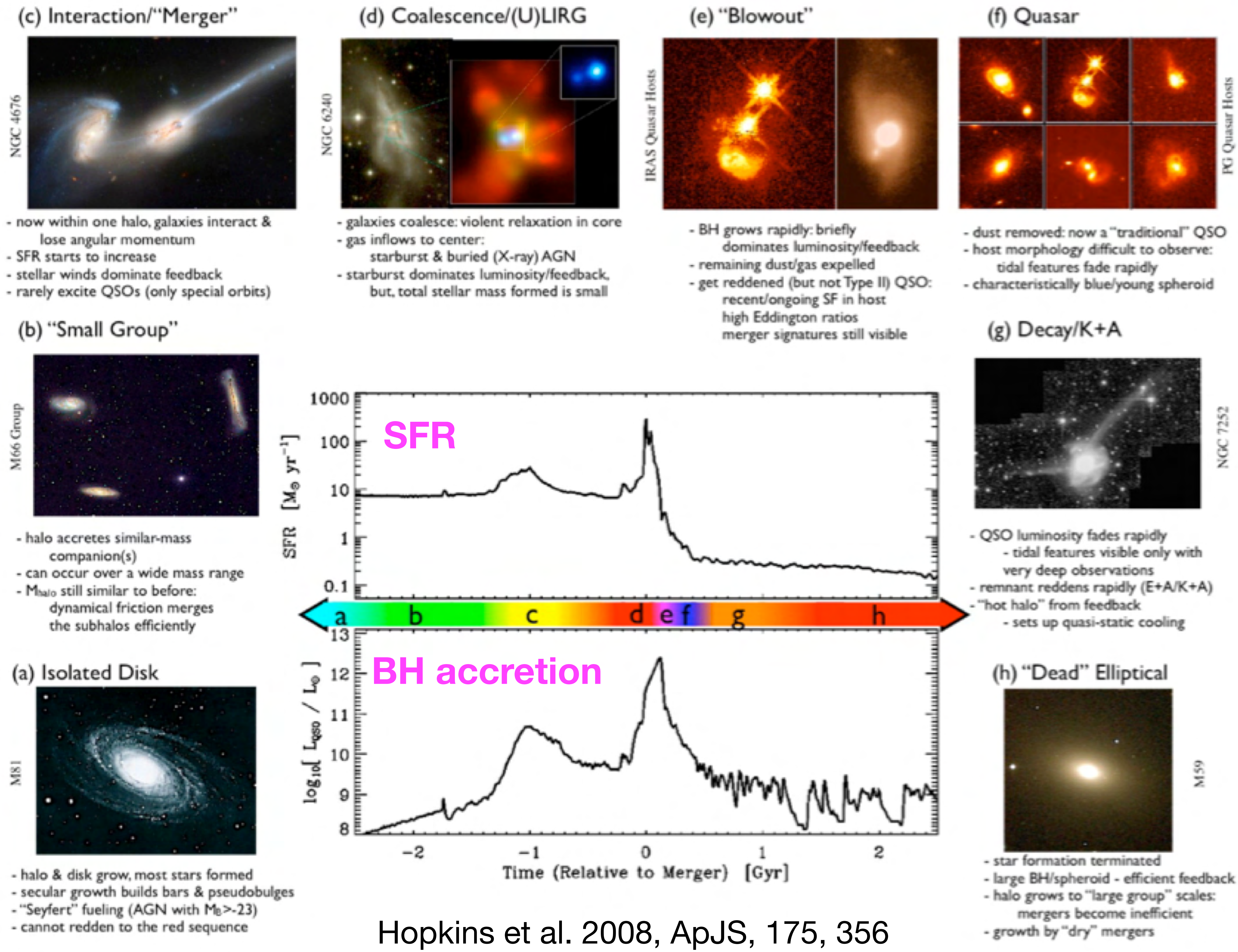


- M_{BH} is tightly correlated with M_{bulge} and σ_* → ***Co-evolution(?)***
- *Why do they know each other* despite their orders of magnitude difference in spatial scale…?
- ***When, where, and how the relation has arisen?***

Trace (i) SMBH growth and (ii) galaxy growth over the cosmic time

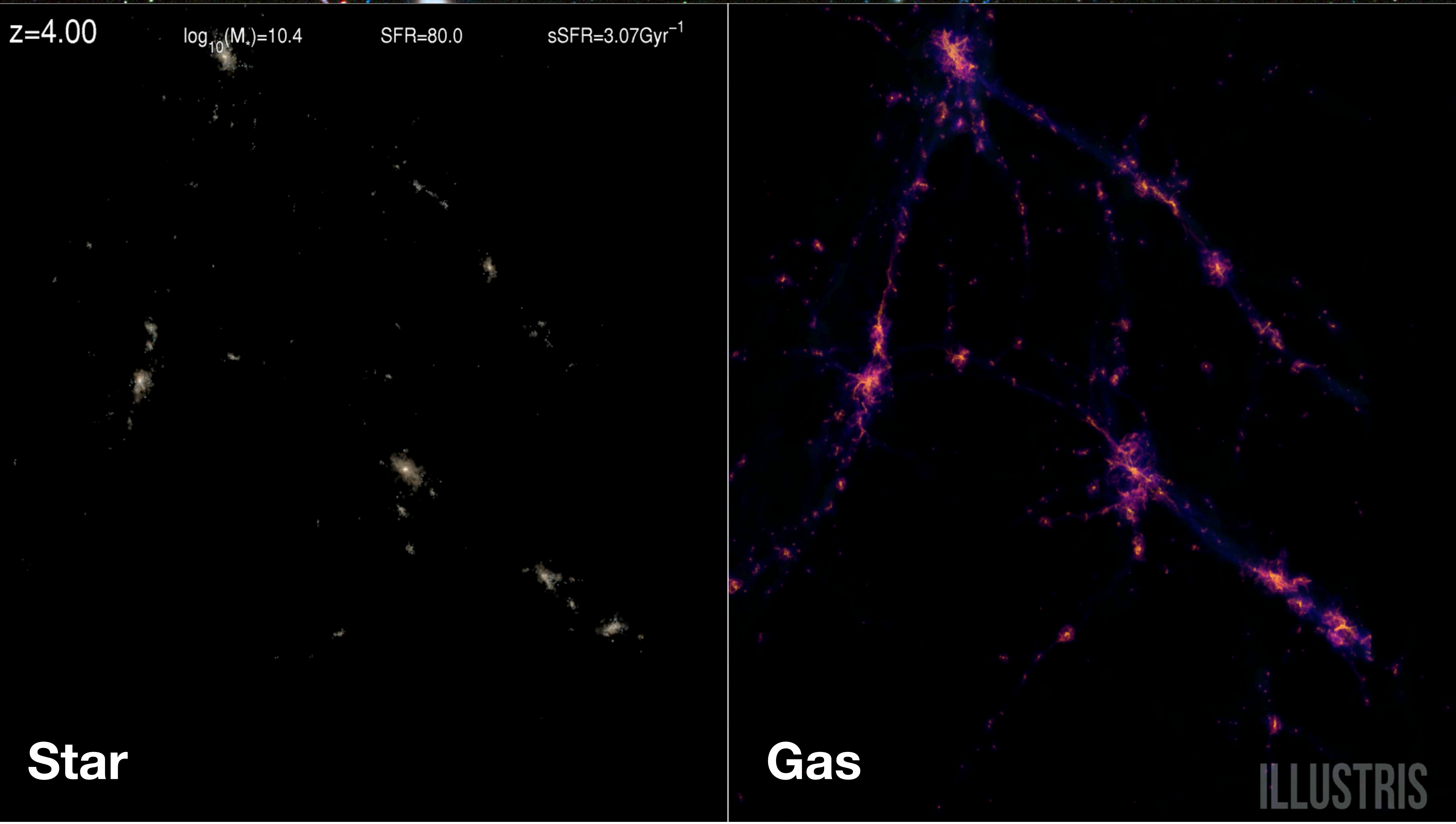






Hopkins et al. 2008, ApJS, 175, 356

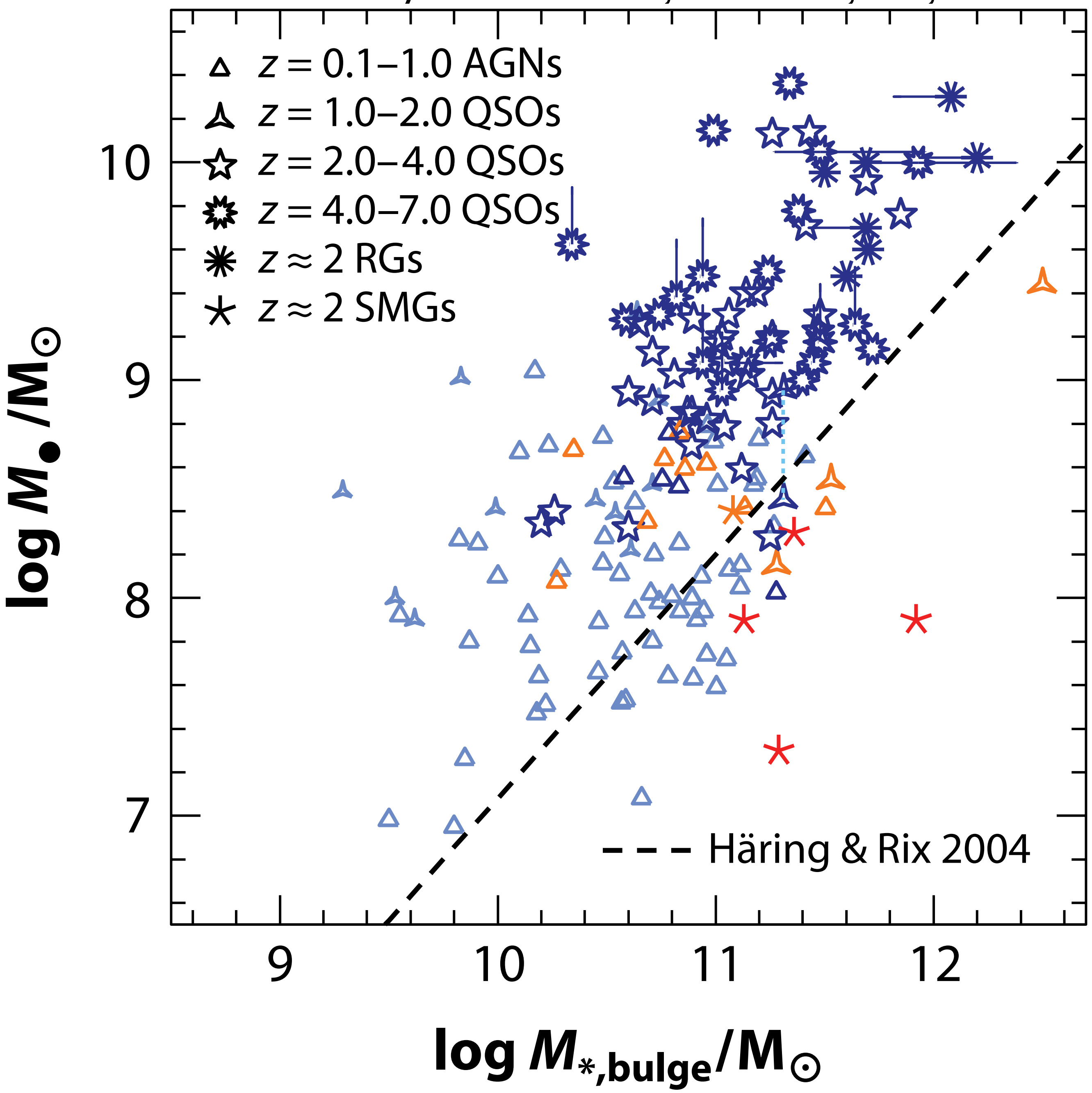
Galaxy mergers and outflows at high-z



Repeated many times, then have grown significantly.

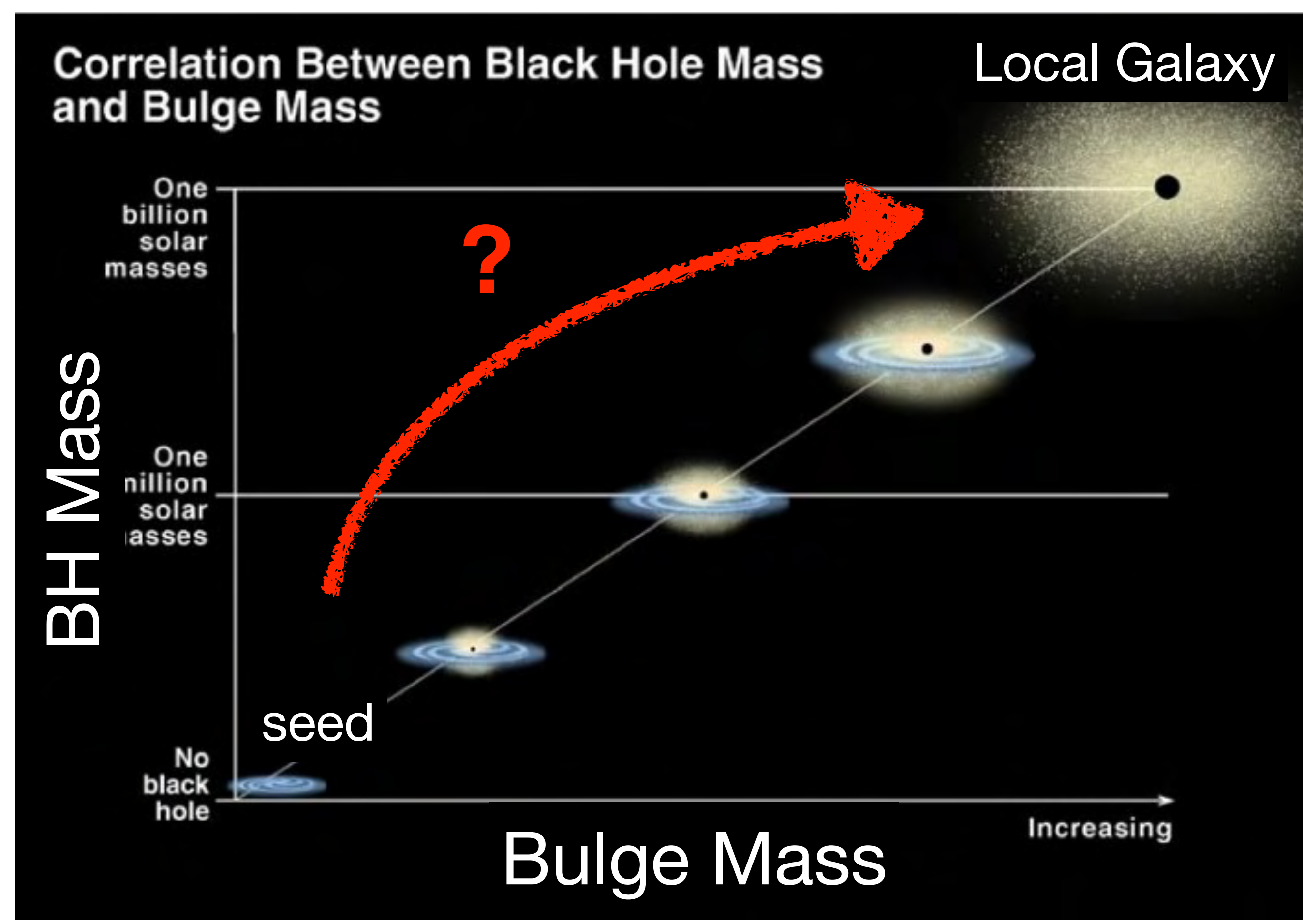
Previous Observations at High-z

Kormendy & Ho 2013, ARA&A, 51, 511

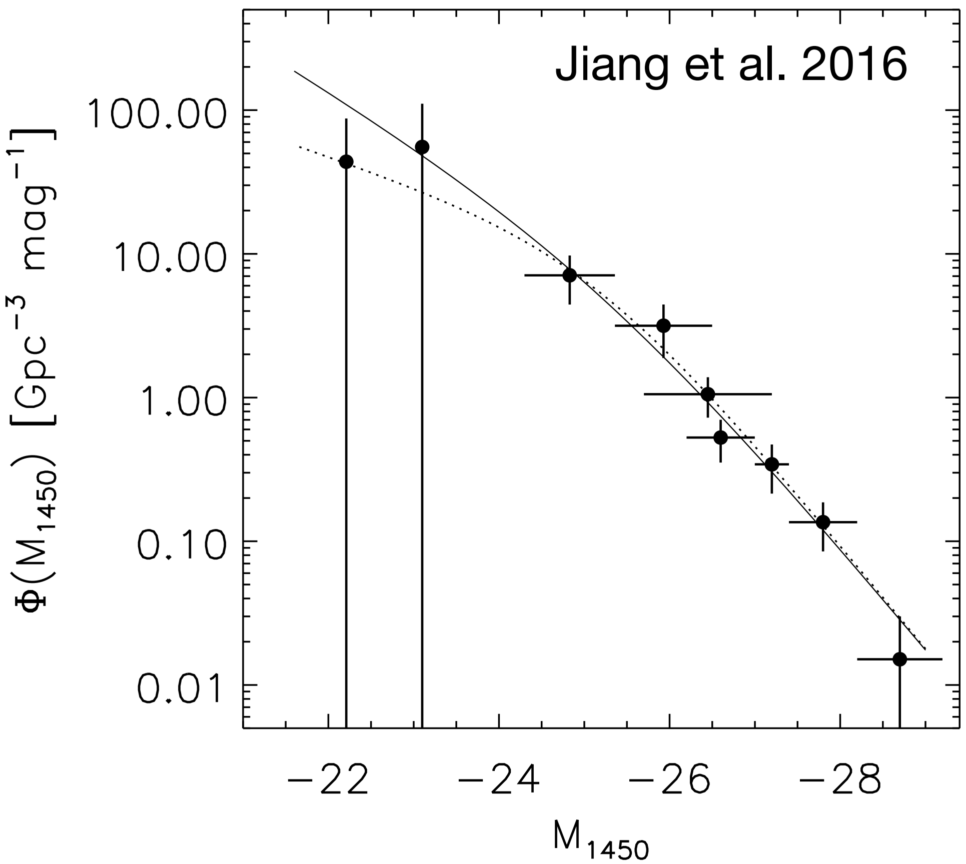


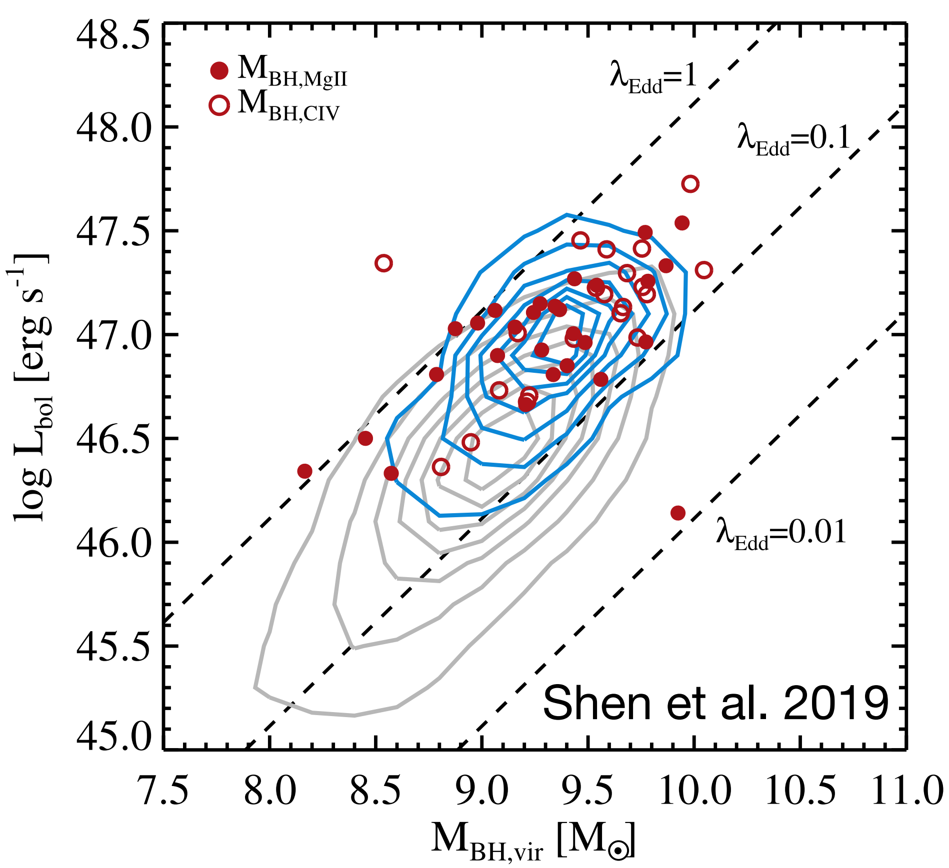
M_{dyn}~M_{star} is usually assumed (until JWST's operation)

- M_{BH} of optically-luminous high-z quasars (e.g., SDSS) are over-massive.
- SMBHs have grown significantly earlier than their host galaxies…?

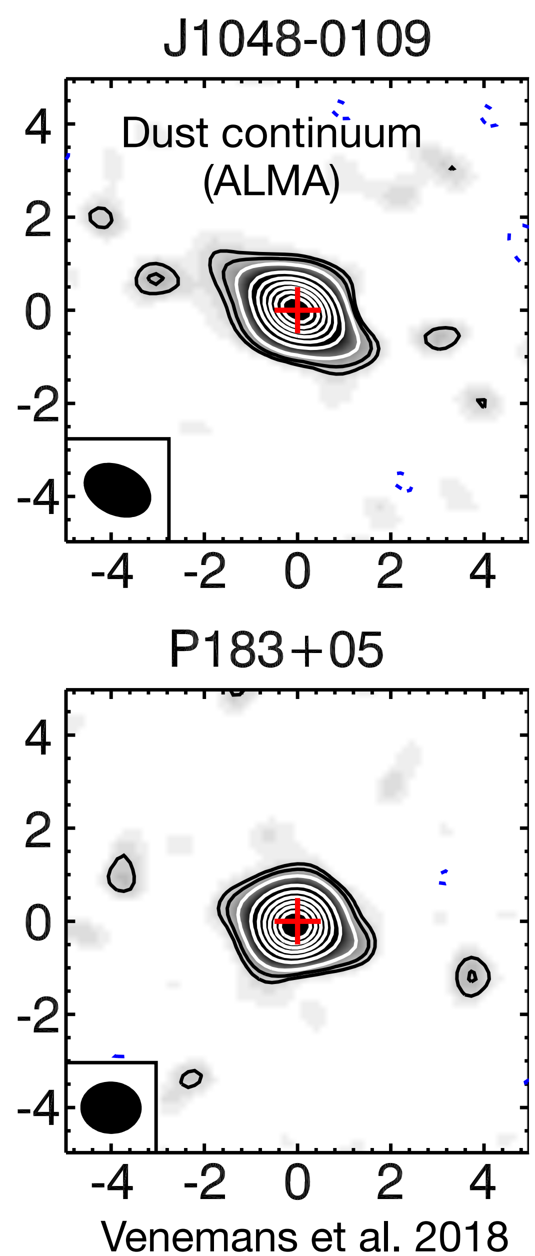


However…

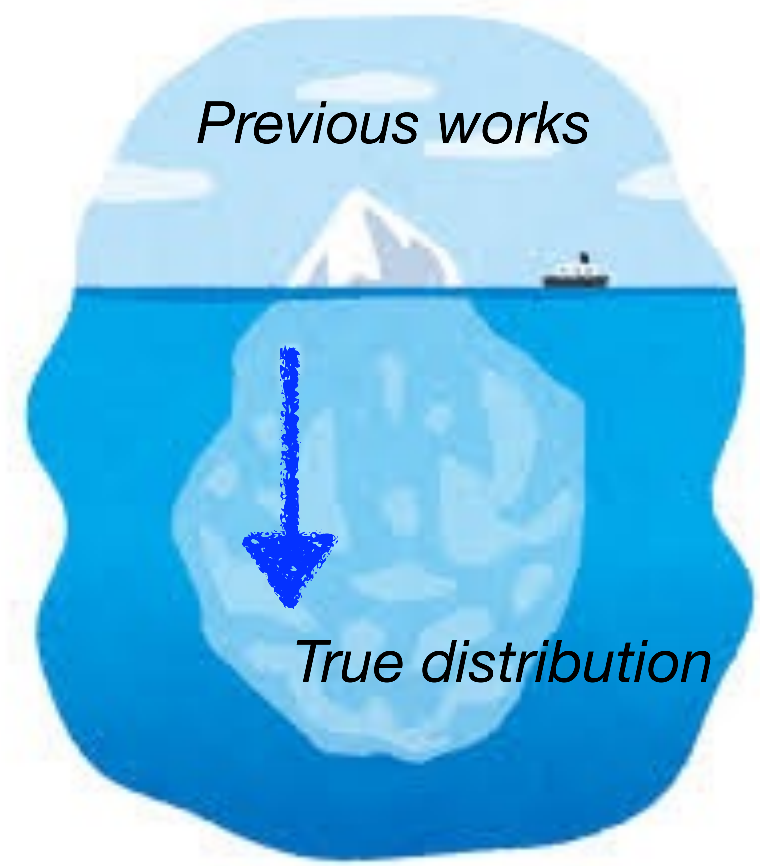




- There has been a selection bias preferring luminous (~massive) quasars!
- They are typically hosted by active starburst galaxies.

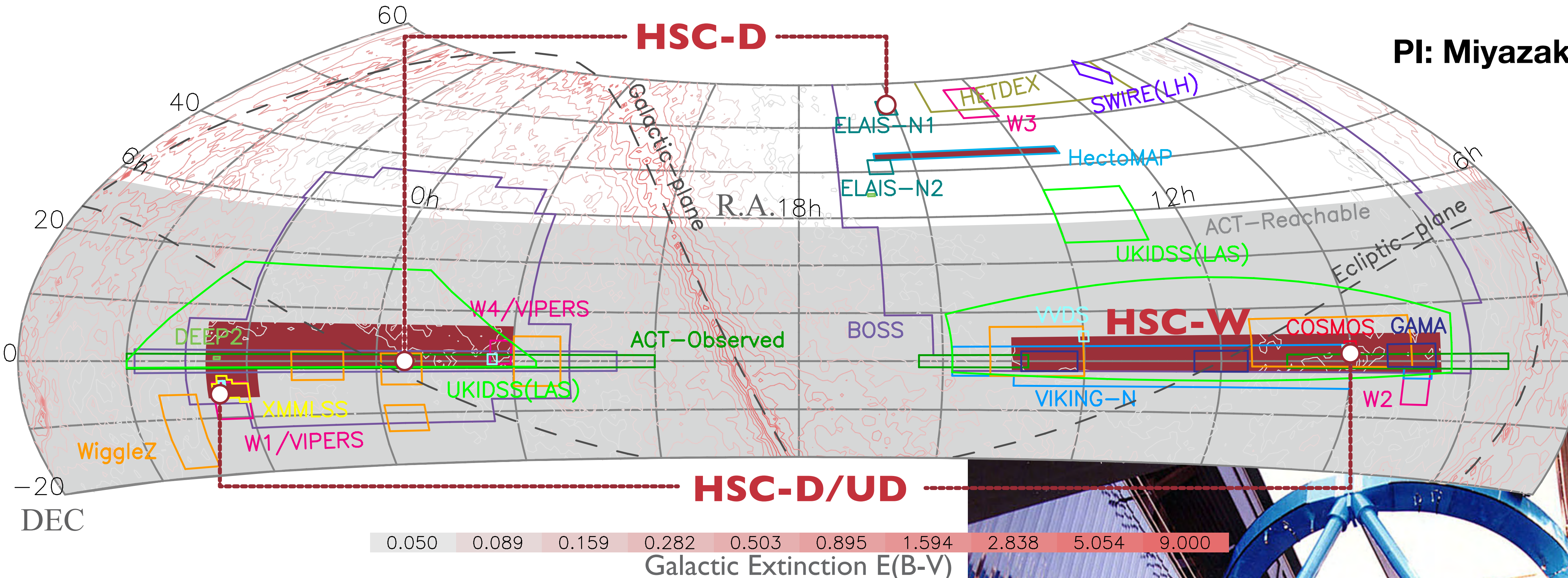


Our understanding has been biased toward extreme objects.

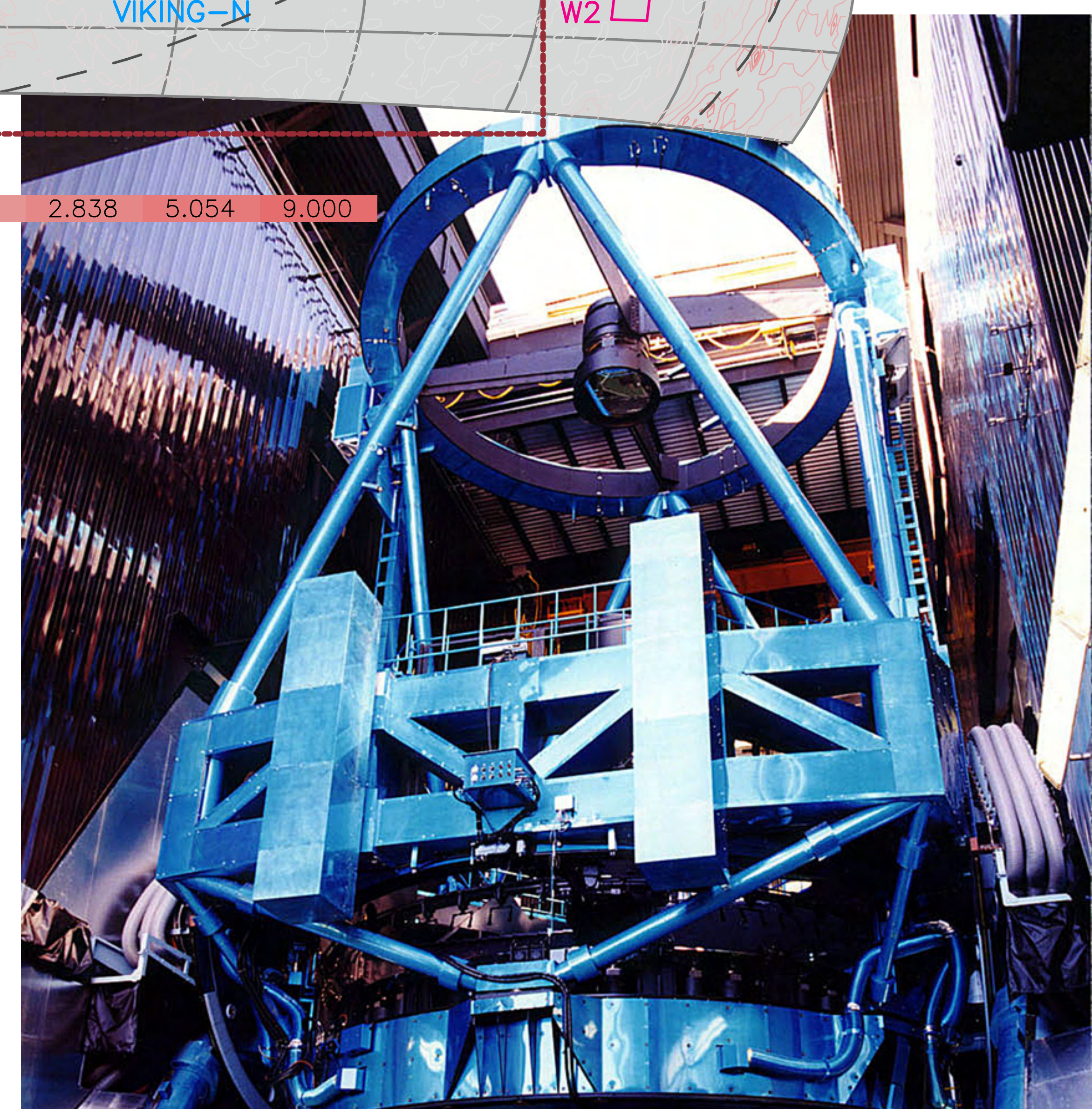


Strategic Survey with the Subaru/HSC

PI: Miyazaki (NAOJ)

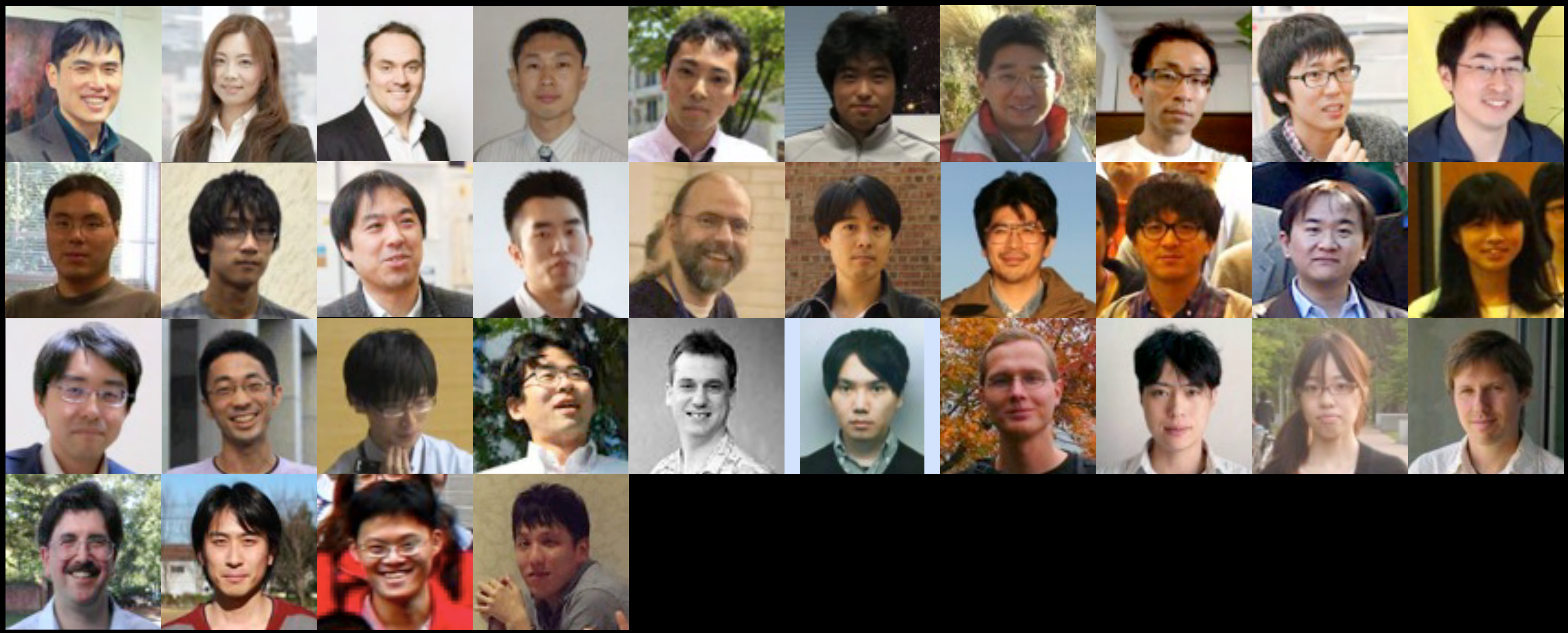


- Subaru Hyper Suprime-Cam (**HSC**)
- First **<u>1000 deg² class</u>** survey (300 nights) with an 8m class telescope
- ***g,r,i,z,y*** bands
- Wide/Deep/Ultra-deep layers
- **<u>>~2 mag deeper</u>** than previous surveys (e.g., r_{AB} < 27.1 mag in the Deep 27 deg² layer)



SHELLQs

Subaru High-z Exploration of Low-Luminosity Quasars



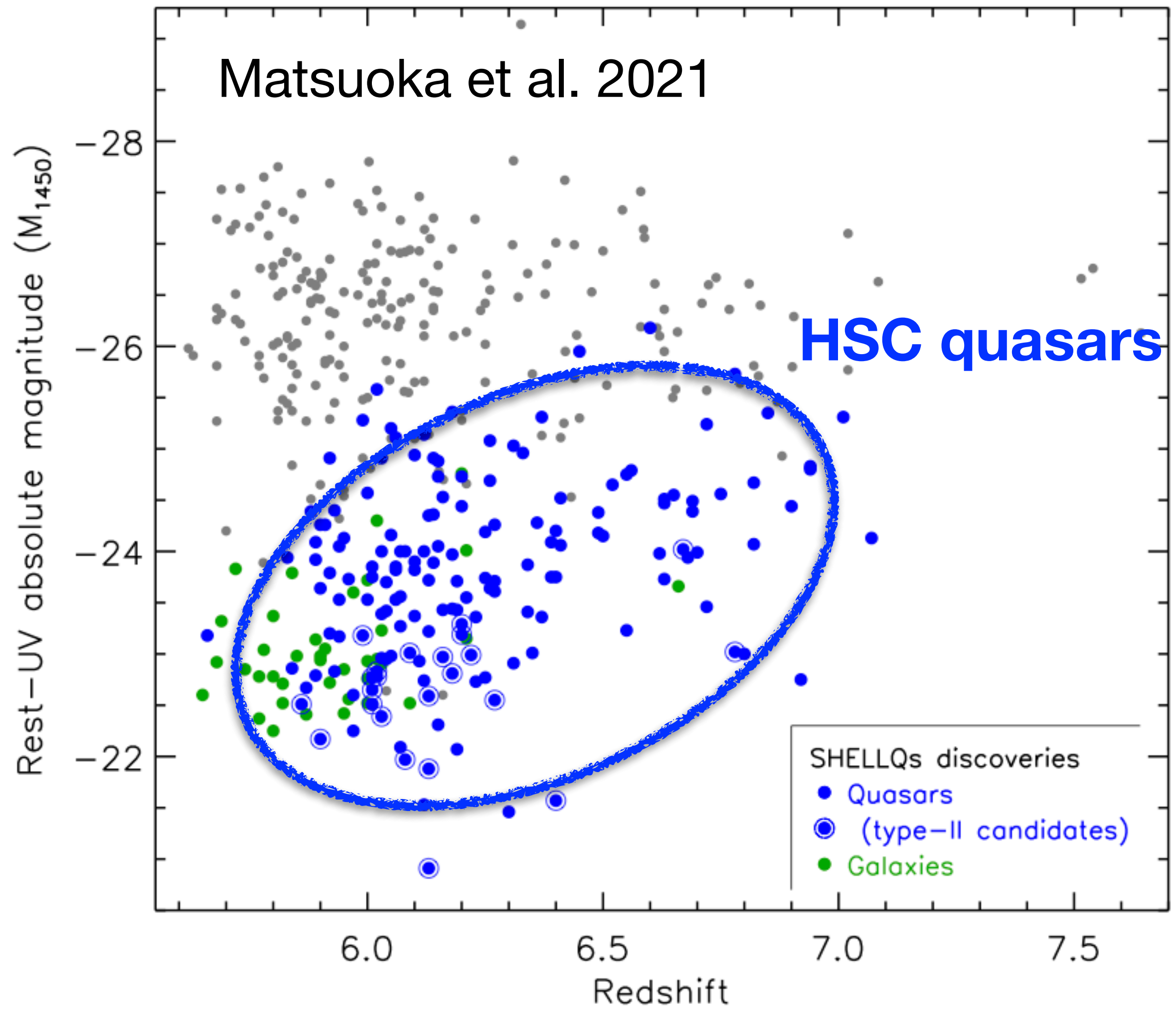
Members

Y. Matsuoka[1] (PI)

M. Akiyama[2], N. Asami[3], S. Foucaud, T. Goto[4], Y. Harikane[5], H. Ikeda[1], M. Imanishi[1], K. Iwasawa[6], T. Izumi[5], N. Kashikawa[1] T. Kawaguchi[7], S. Kikuta[1], K. Kohno[5], C.-H. Lee[1], R. H. Lupton[9], T. Minezaki[5], T. Morokuma[5], T. Nagao[8], M. Niida[8], M. Oguri[5], Y. Ono[5], M. Onoue[1], M. Ouchi[5], P. Price[9], H. Sameshima[10], A. Schulze[5], T. Shibuya[5], H. Shirakata[11], J. D. Silverman[5], M. A. Strauss[9], M. Tanaka[1], J. Tang[12], Y. Toba[8]

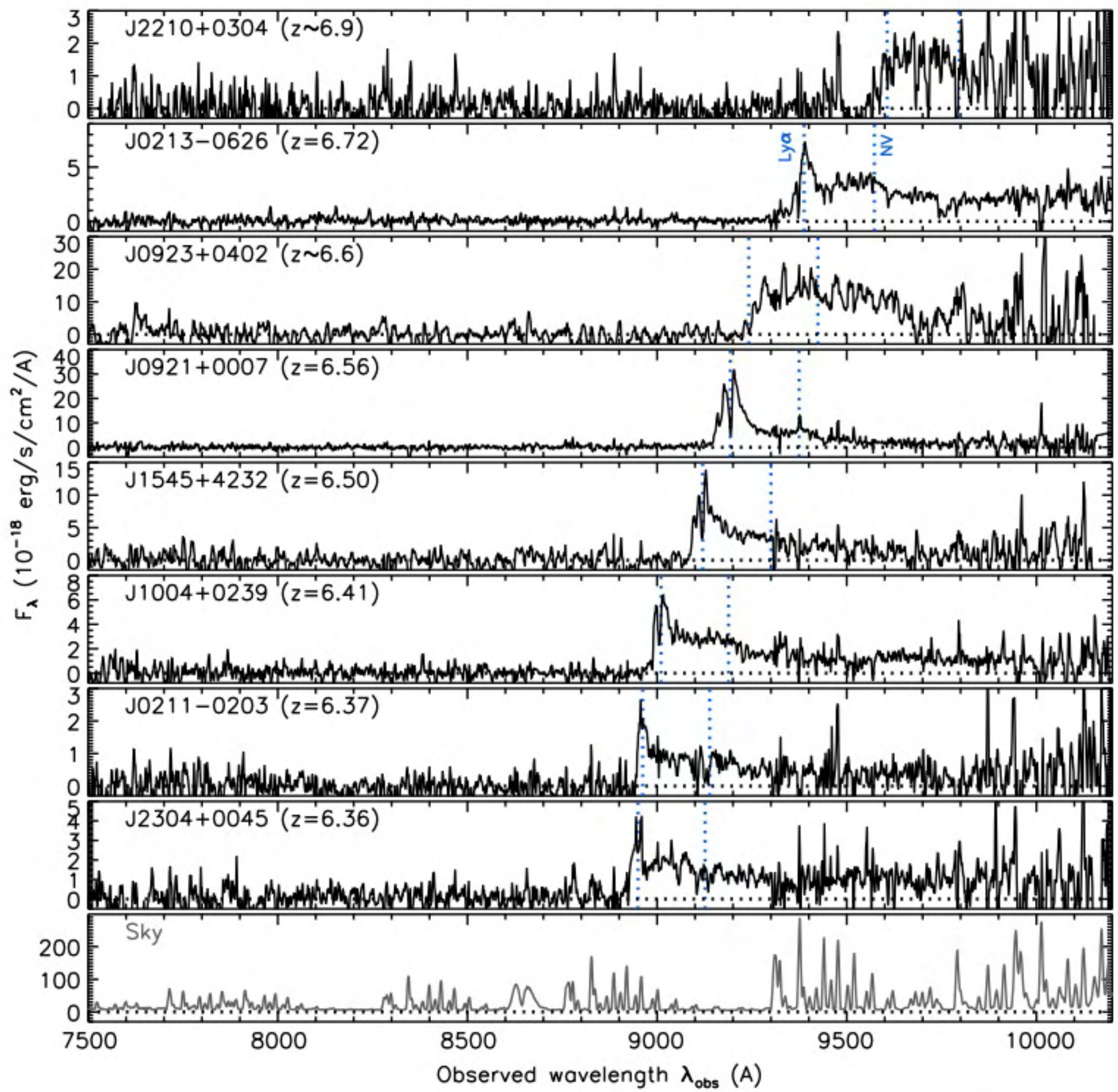
[1]NAOJ, [2]Tohoku, [3]JPSE, [4]Tsinghua, [5]Tokyo, [6]Barcelona, [7]Sapporo Medical, [8]Ehime, [9]Princeton, [10]Kyoto Sangyo, [11]Hokkaido, [12]ASIAA

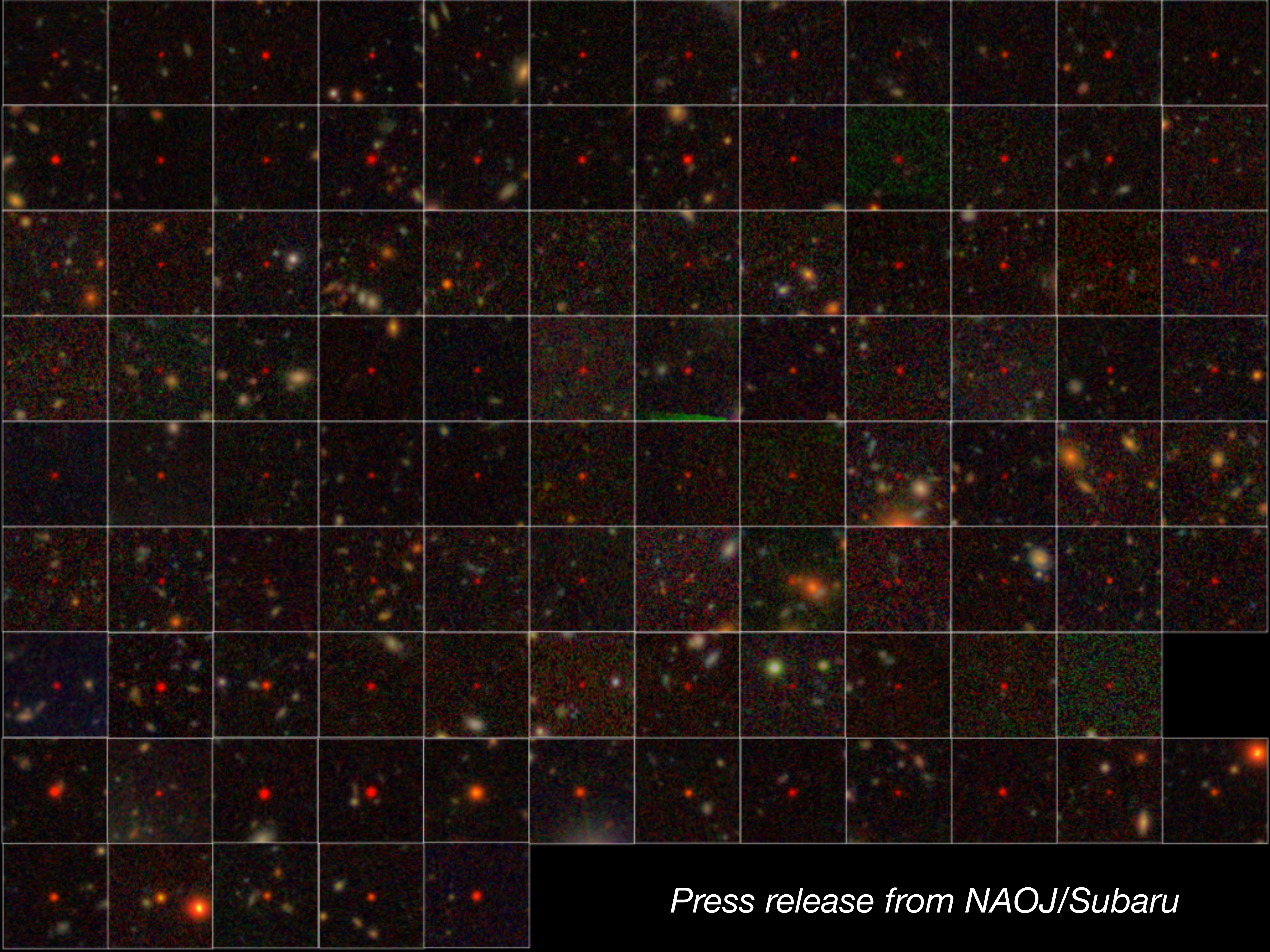
Quasar Discovery

- Bayesian-based photometric selection + spec. follow-up with Subaru and GTC.
- Many z > 6 quasars are being found!! (now <u>**162**</u>)
- They are actually **much fainter** than previously-known quasars

e.g., Matsuoka et al. 2016, 2018a,b, 2019a,b, 2021

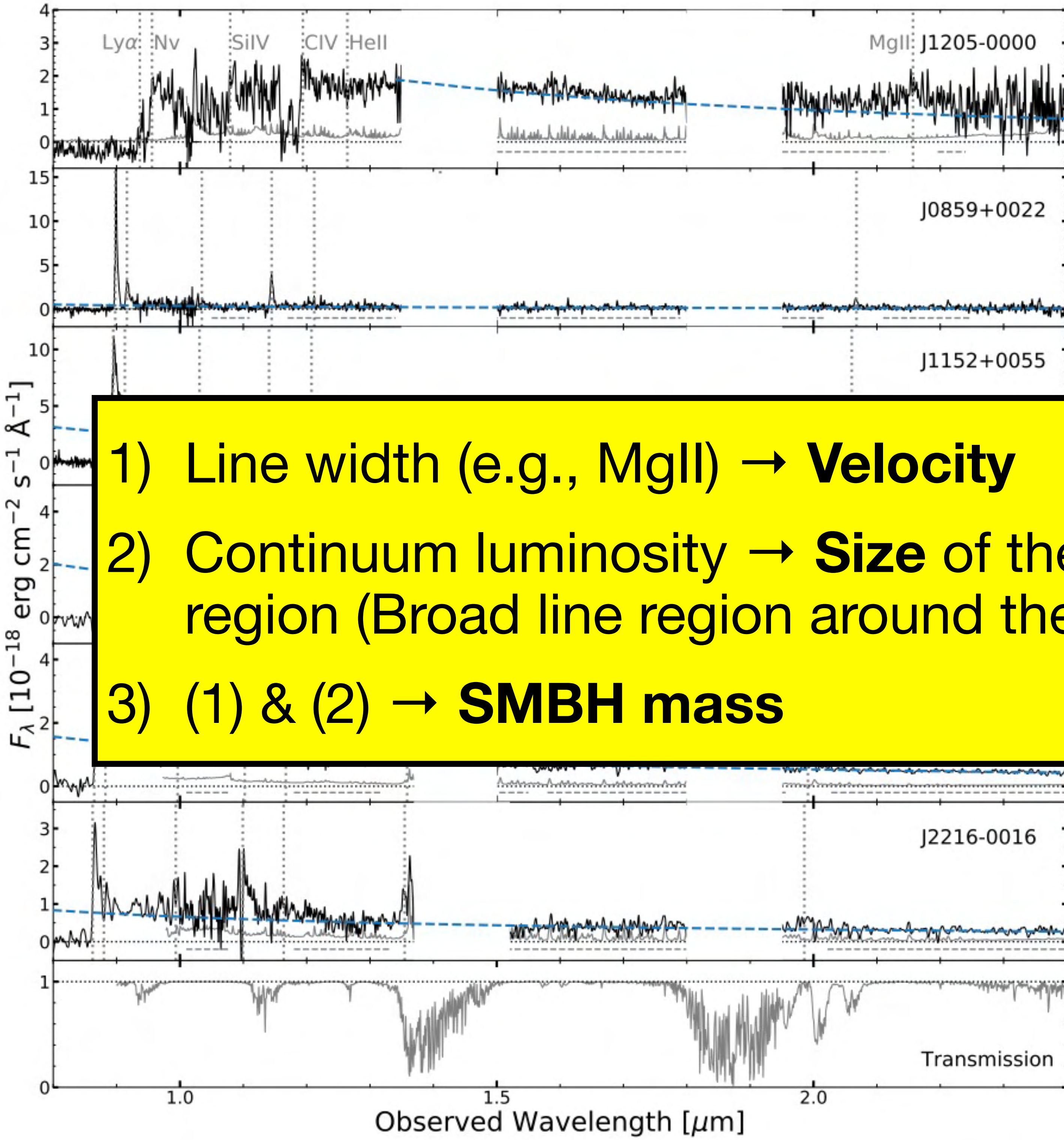




Press release from NAOJ/Subaru

NIR Spectroscopy → M_{BH} Measurement

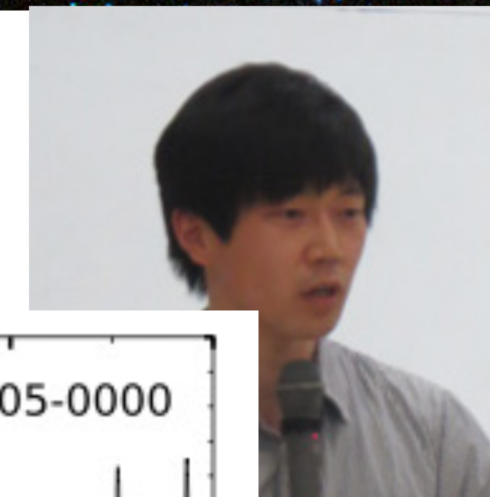
Onoue et al. 2019

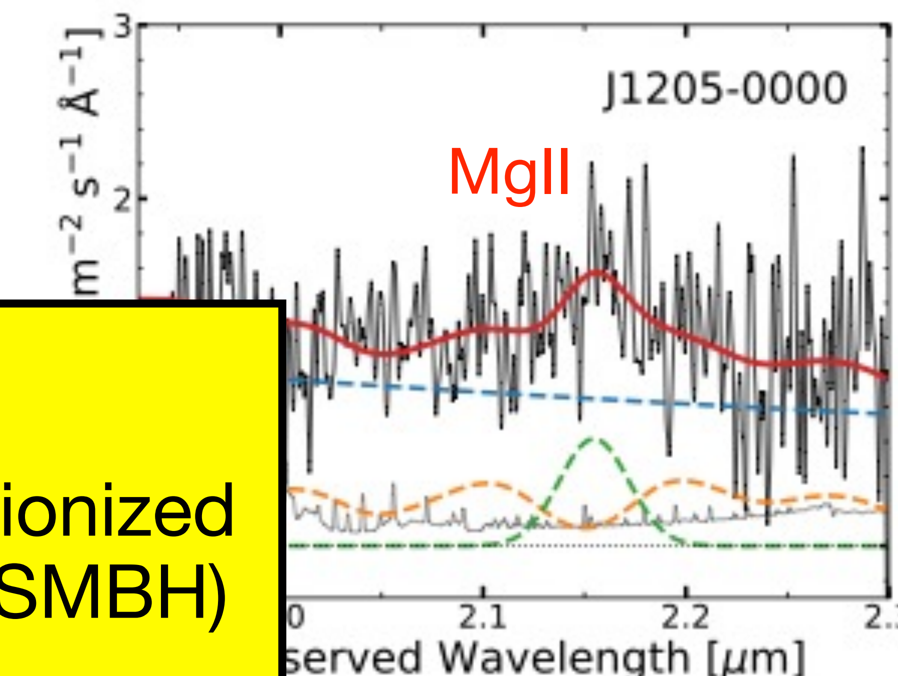


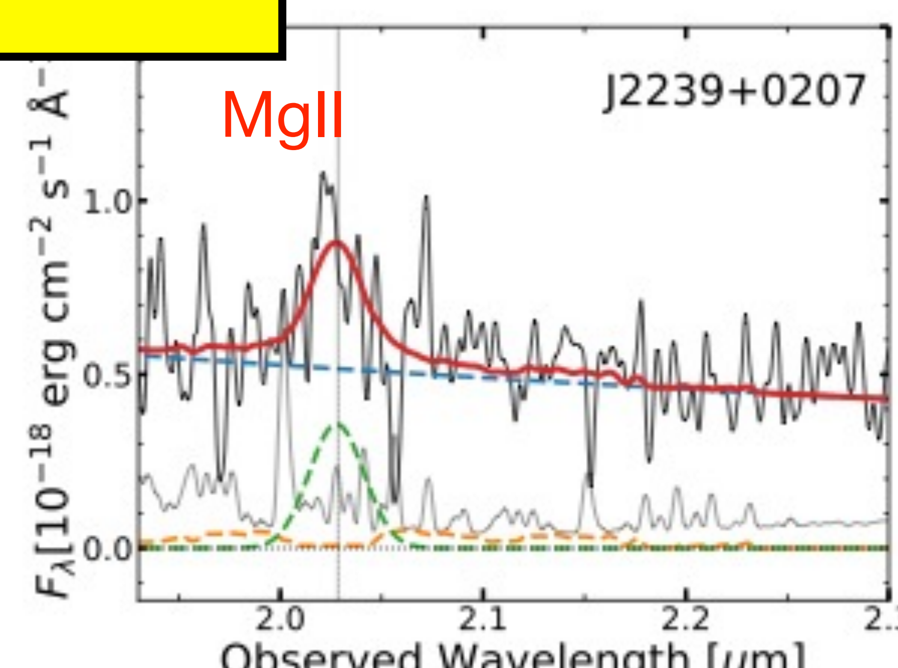
1) Line width (e.g., MgII) → **Velocity**
2) Continuum luminosity → **Size** of the ionized region (Broad line region around the SMBH)
3) (1) & (2) → **SMBH mass**

X-Shooter + GNIRS spectra

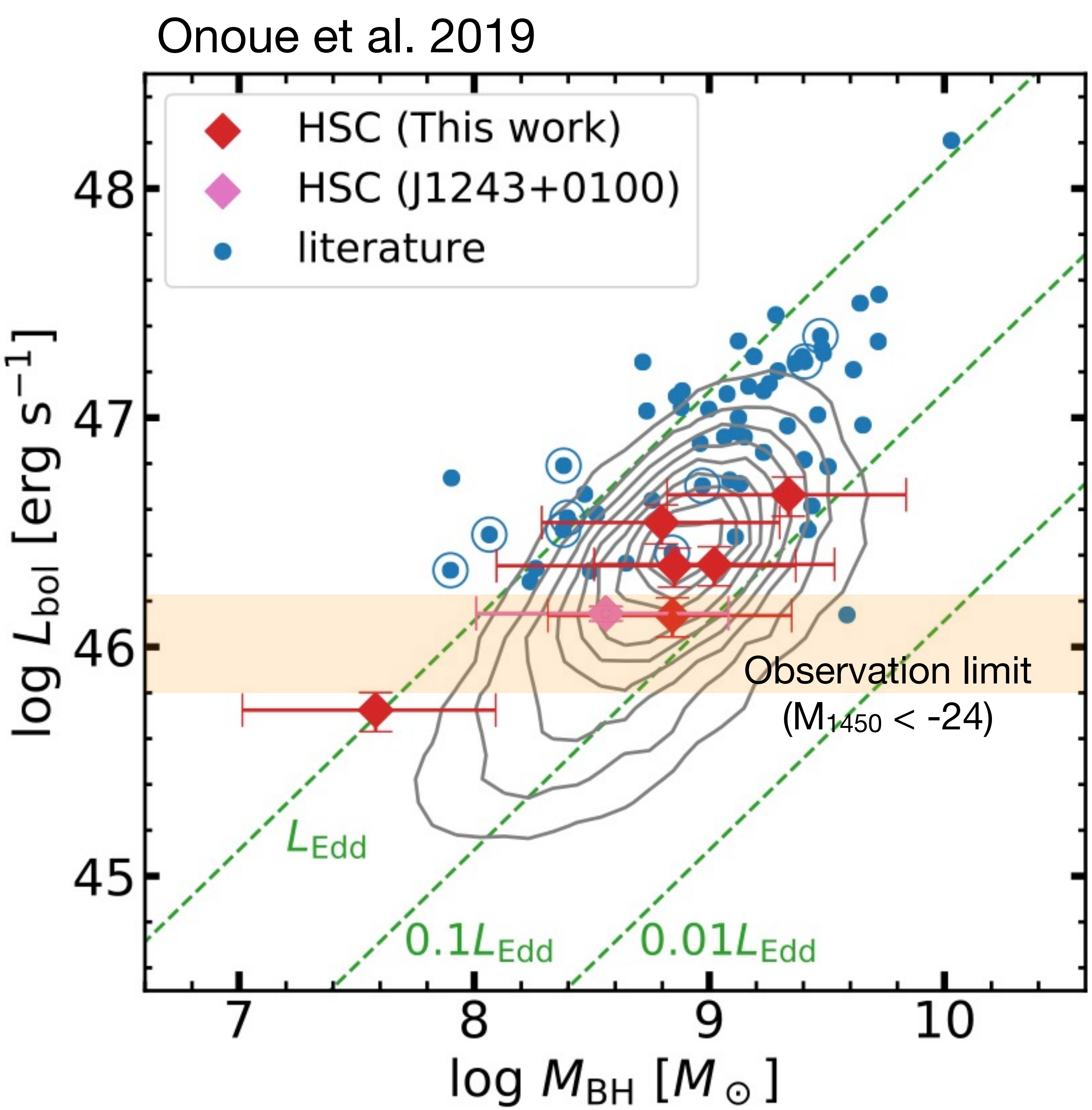
NIR follow-up is being led by **M.Onoue**@KIAA

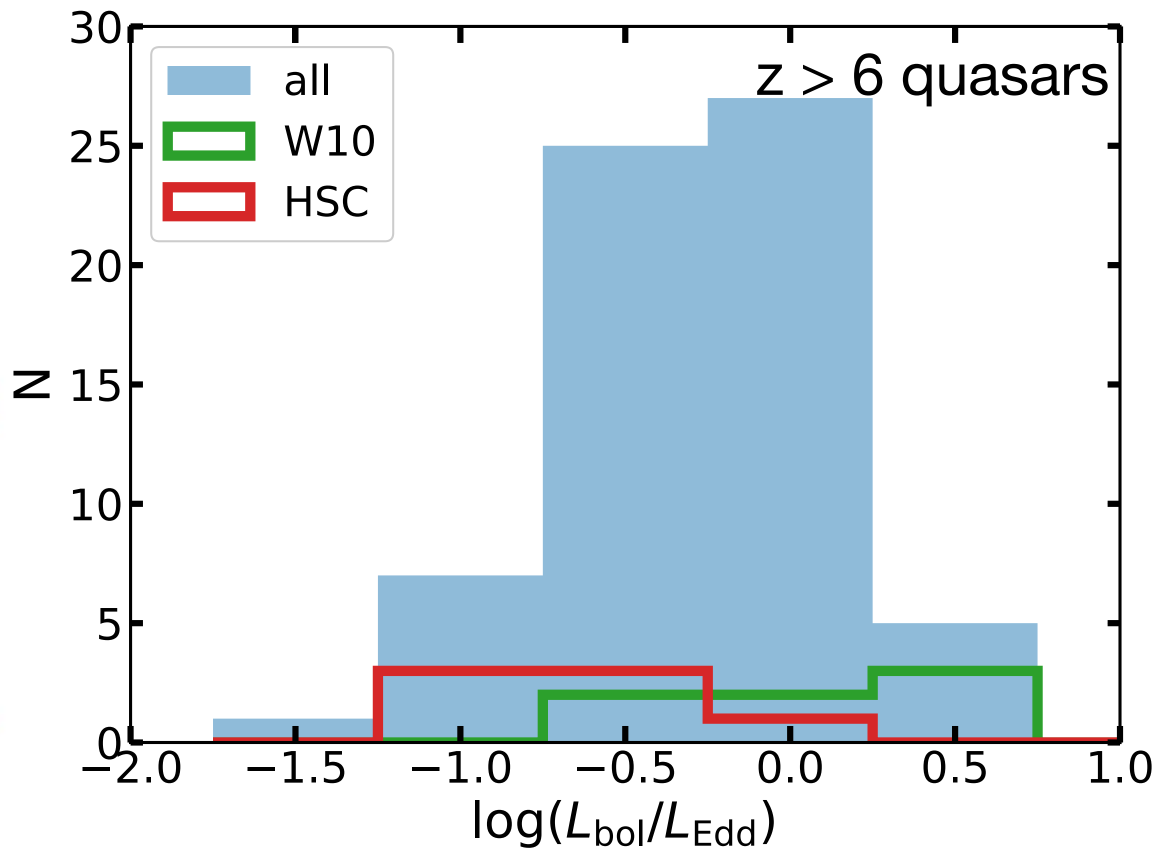






NIR Spectroscopy → M_{BH} Measurement



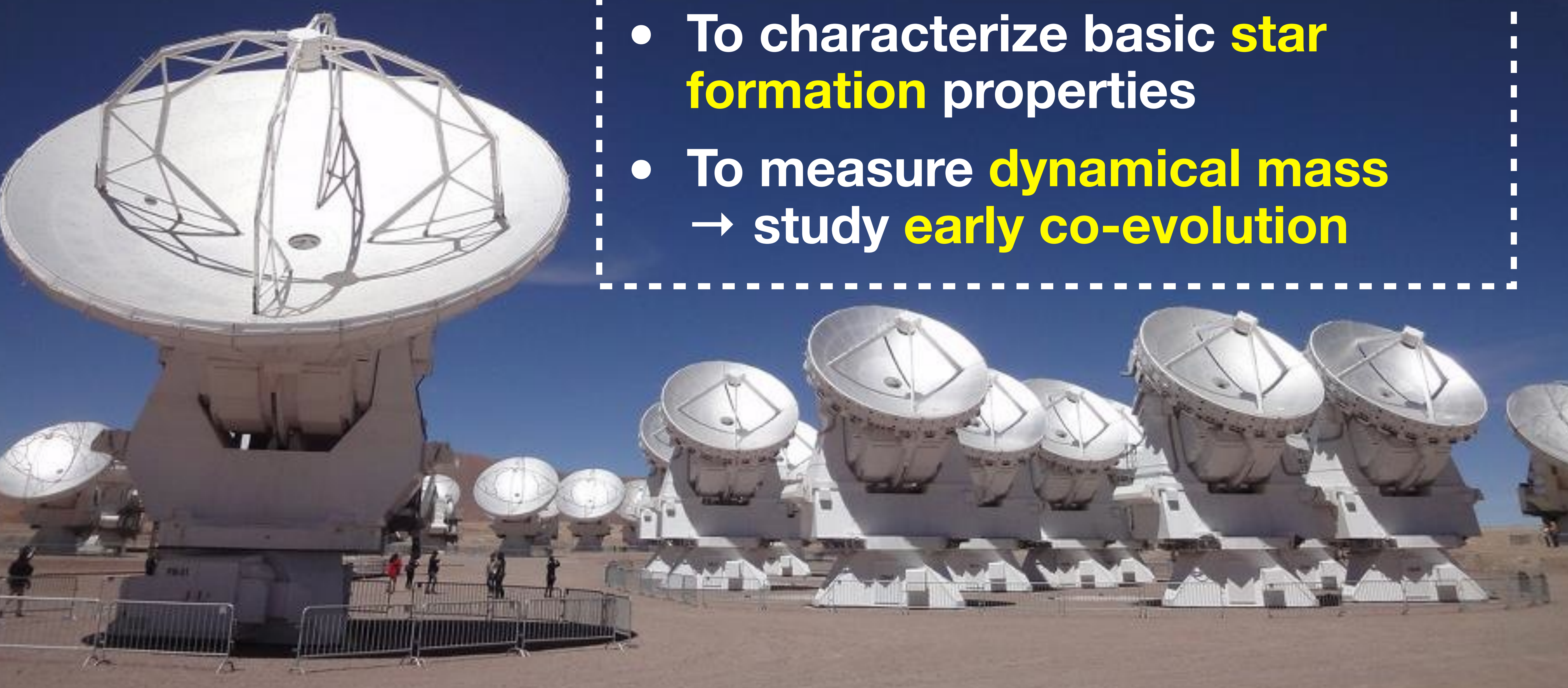


- There is a wide spread in M_{BH} among the HSC quasars → M_{BH} ~1e8–9 M_{sun}
- Corresponding Eddington ratio λ_{Edd} ~0.1–1
- Low-luminosity quasars = Low-mass active BHs + High-mass less-active BHs

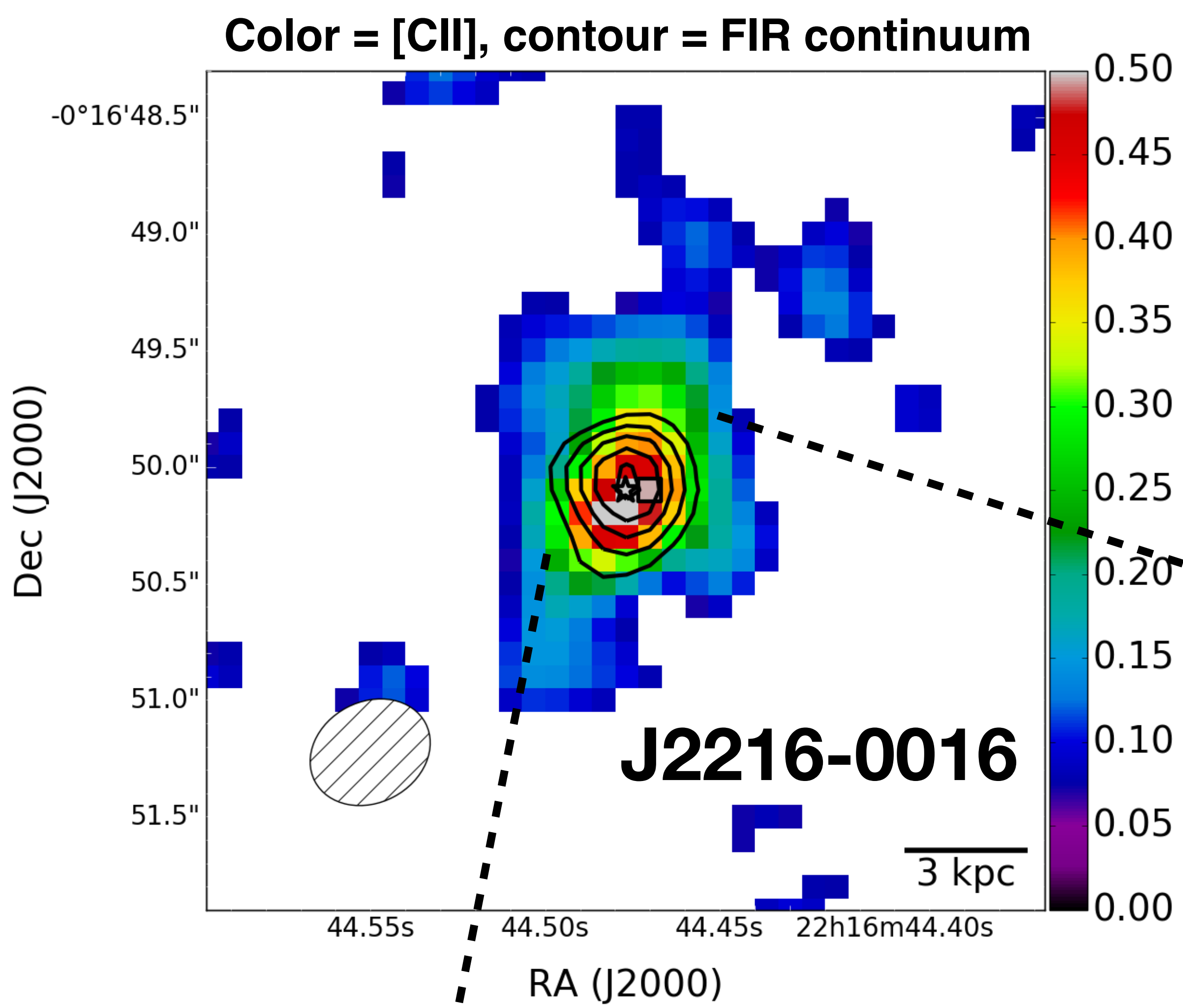
Submm follow-up with ALMA

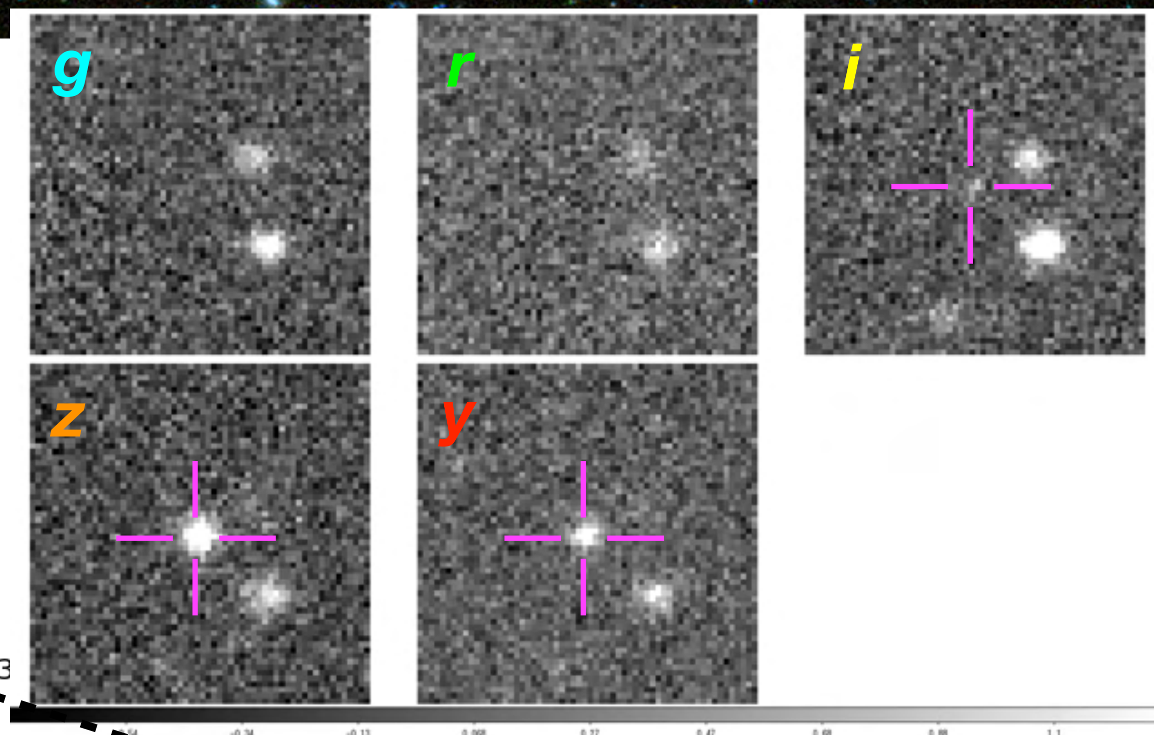
- [CII] + underlying continuum emission
- θ ~ 0.5” ~ 3 kpc
- Cycles 4 + 5 + 7 (total <u>19 quasars</u>)

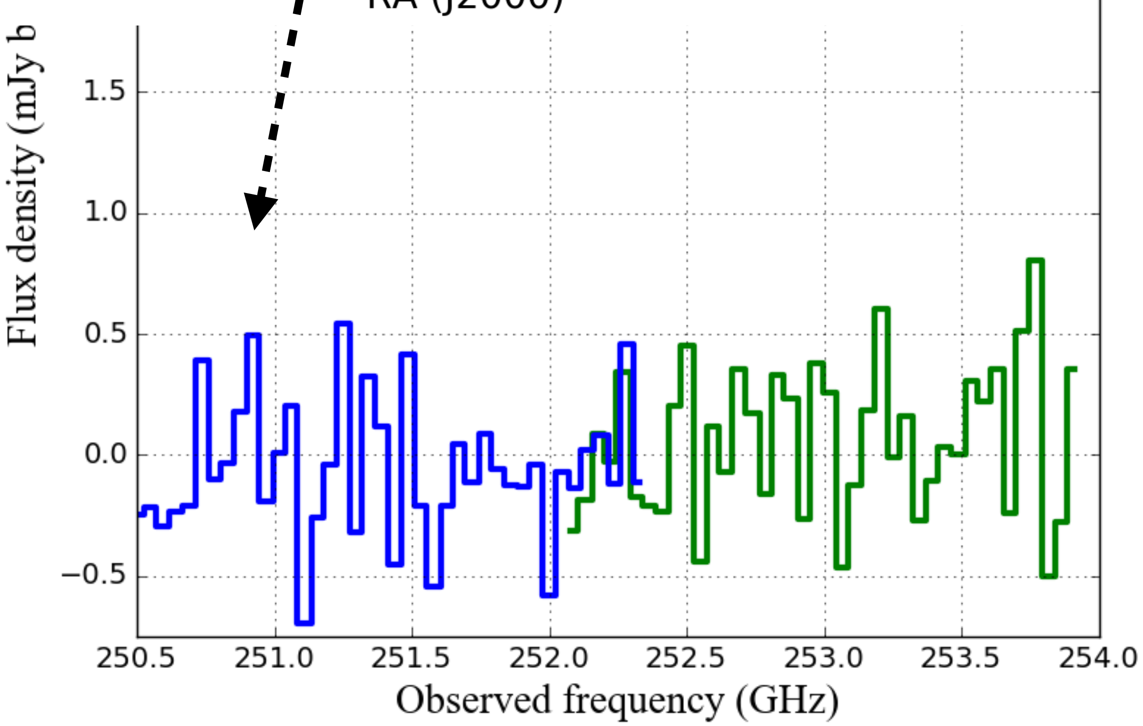
- To characterize basic **star formation** properties
- To measure **dynamical mass** → study **early co-evolution**

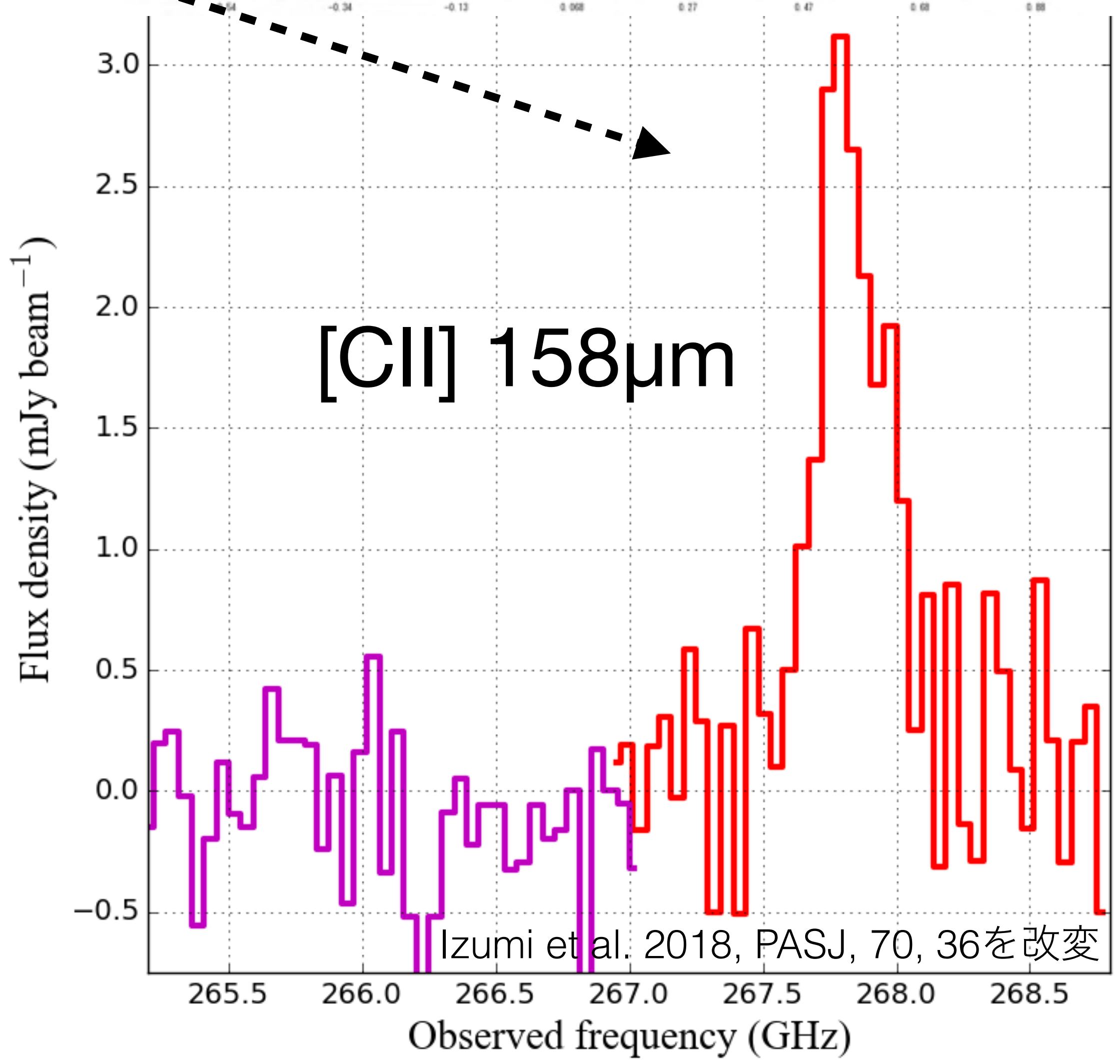


Example: J2216-0016







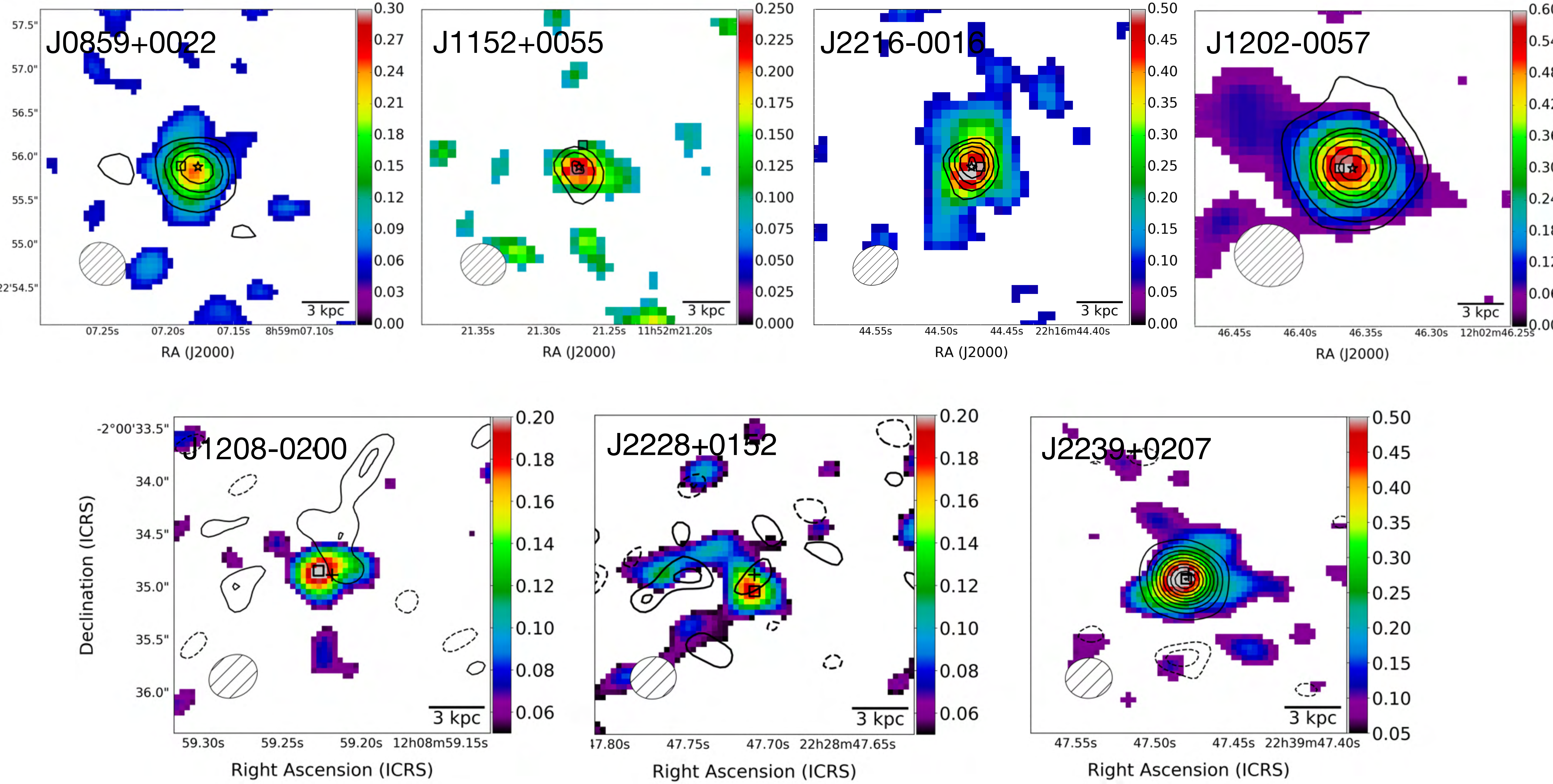


Izumi et al. 2018, PASJ, 70, 36を改変

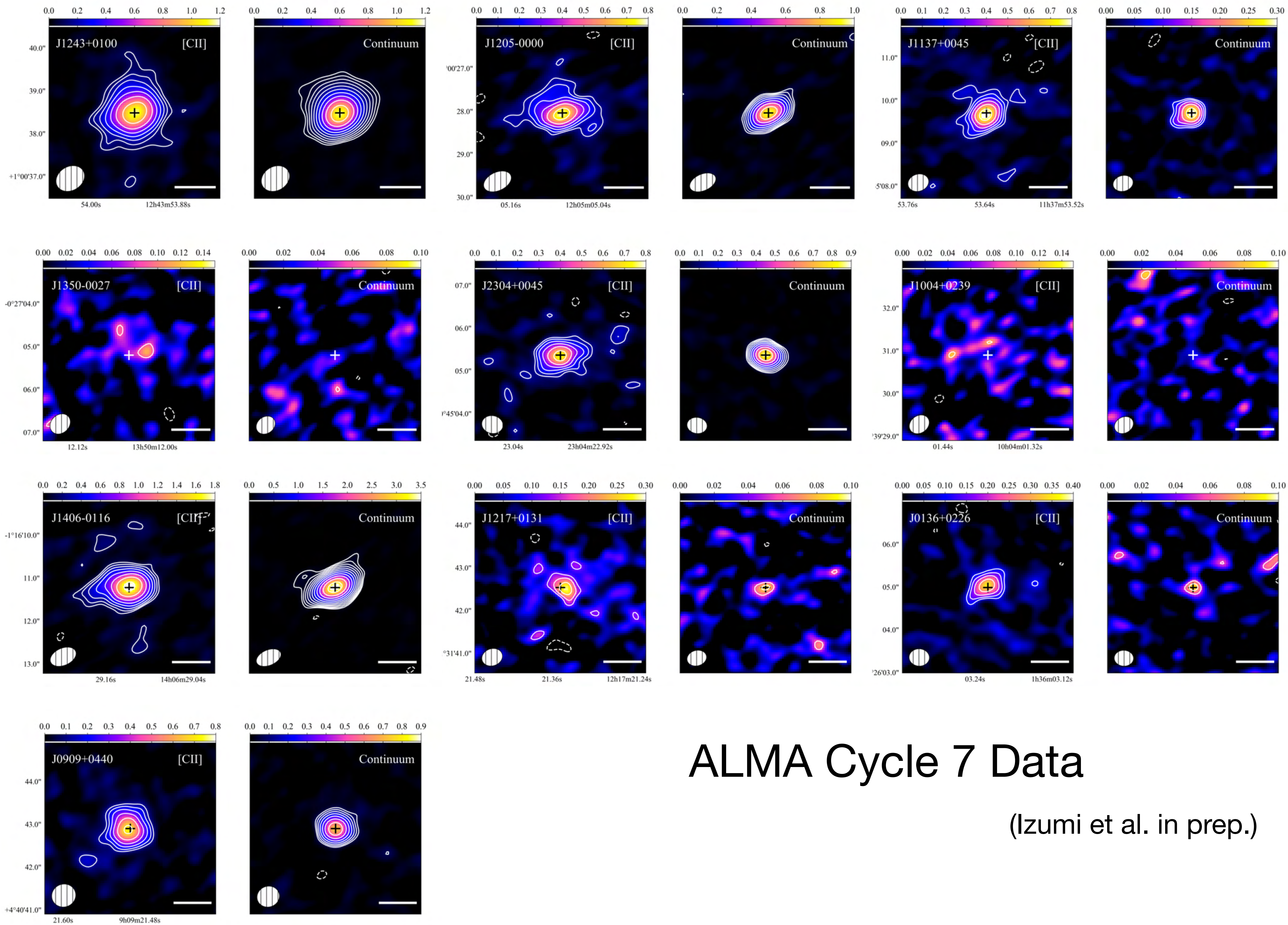
Gallery (Cycle 4 + 5)

Color = [CII] 158 μm
Contour = FIR continuum

(color: Jy/beam km/s unit)



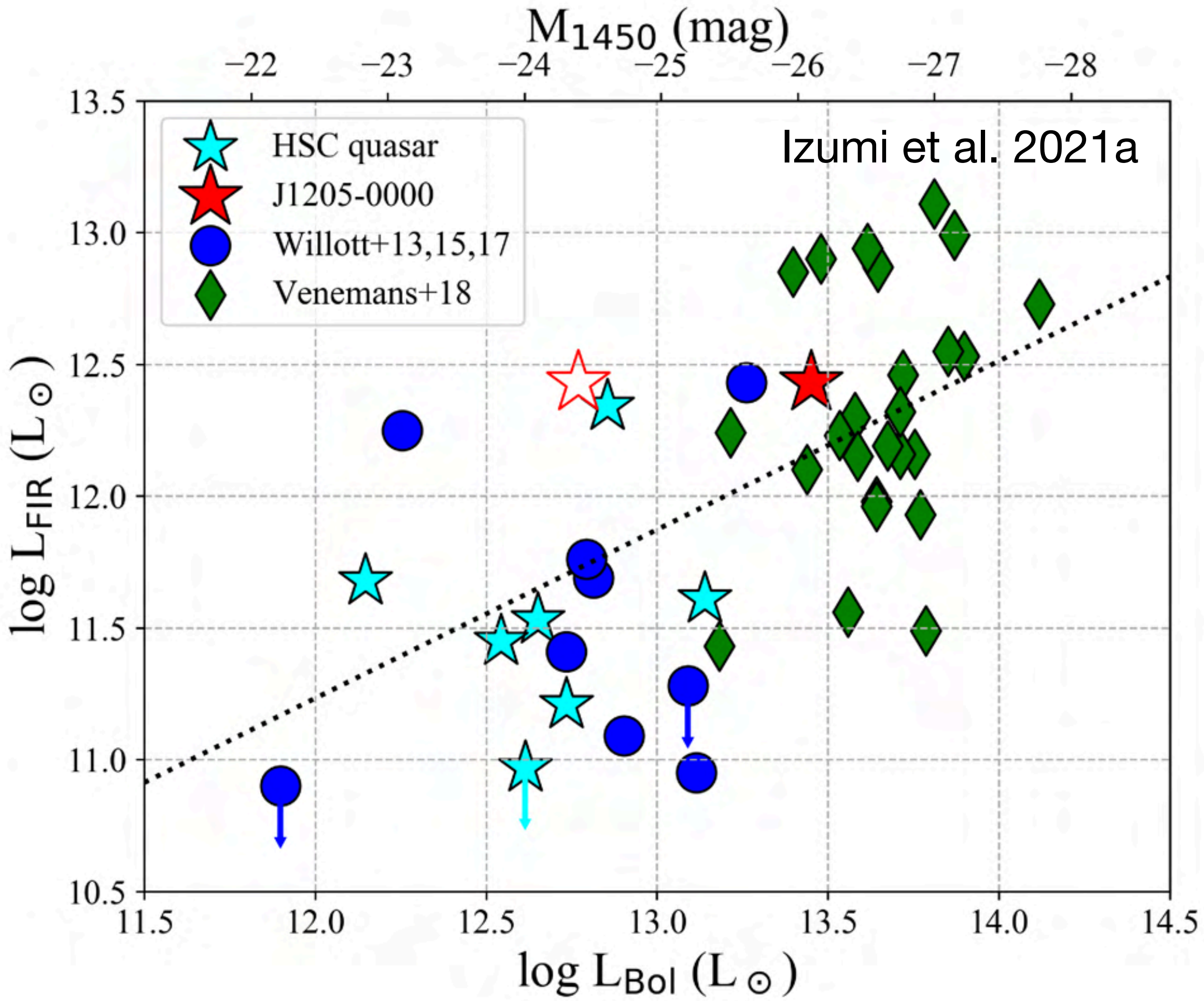
Fortunately, we have successfully detected [CII] emission so far…!

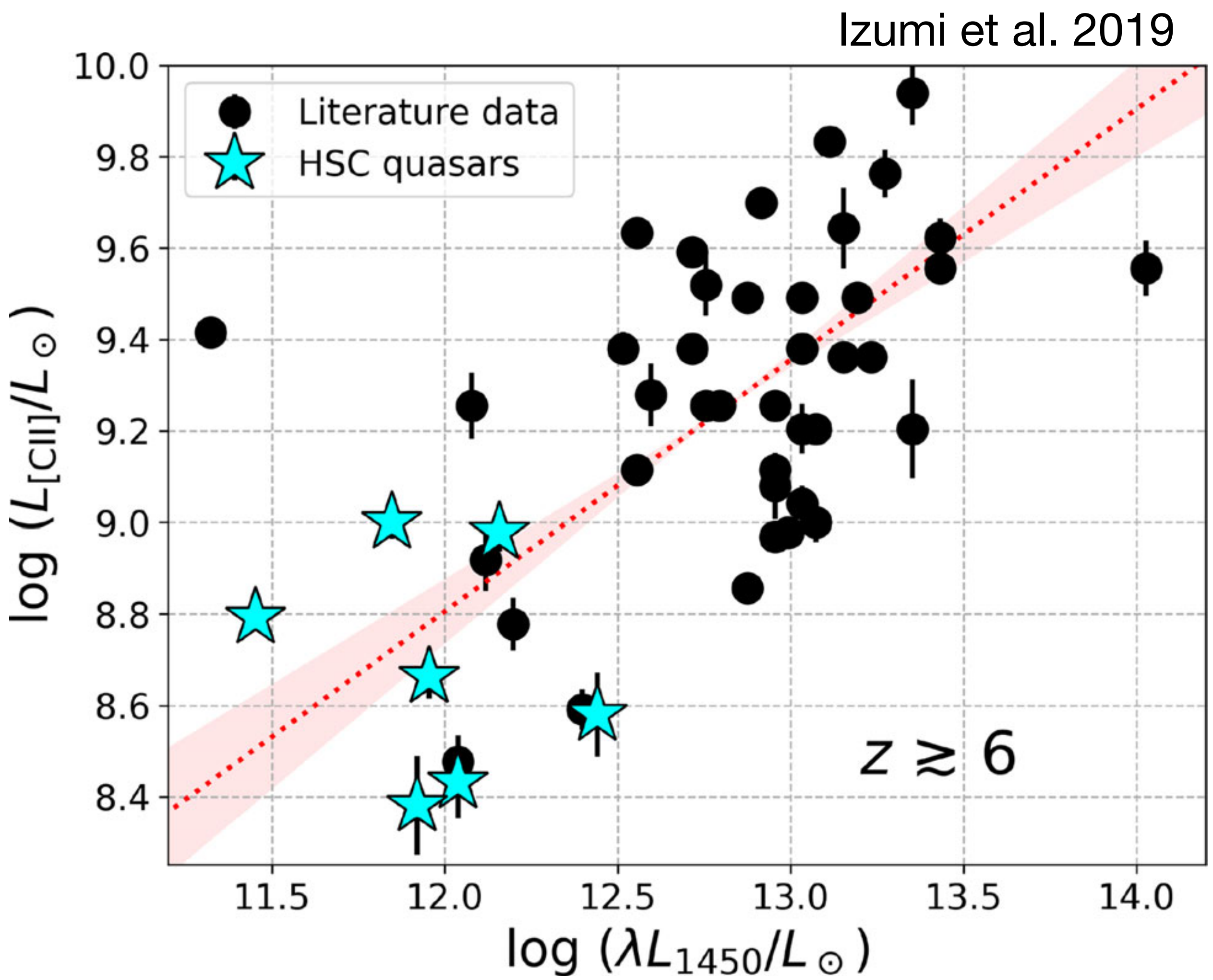


ALMA Cycle 7 Data

(Izumi et al. in prep.)

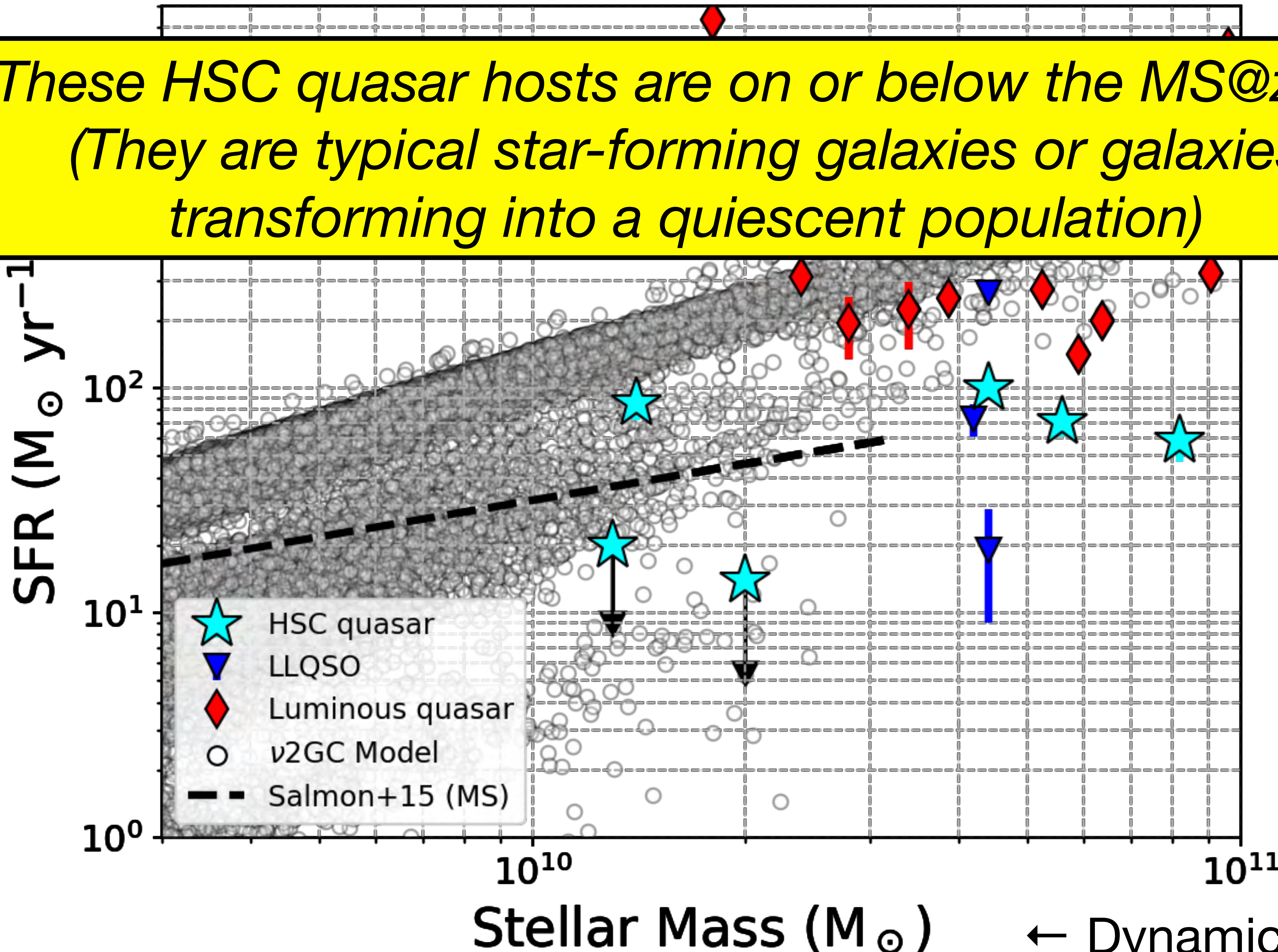
"LIRG"-class Star Formation





- LIRG-class moderate SFR (~several ×10 M_{sun}/yr) in most cases
  c.f., SFR ~ 100-1000 M_{sun}/yr in optically-luminous quasars
- SMBH growth and Host galaxy growth are (quasi-?)synchronized.
  → "*differential*" form of co-evolution

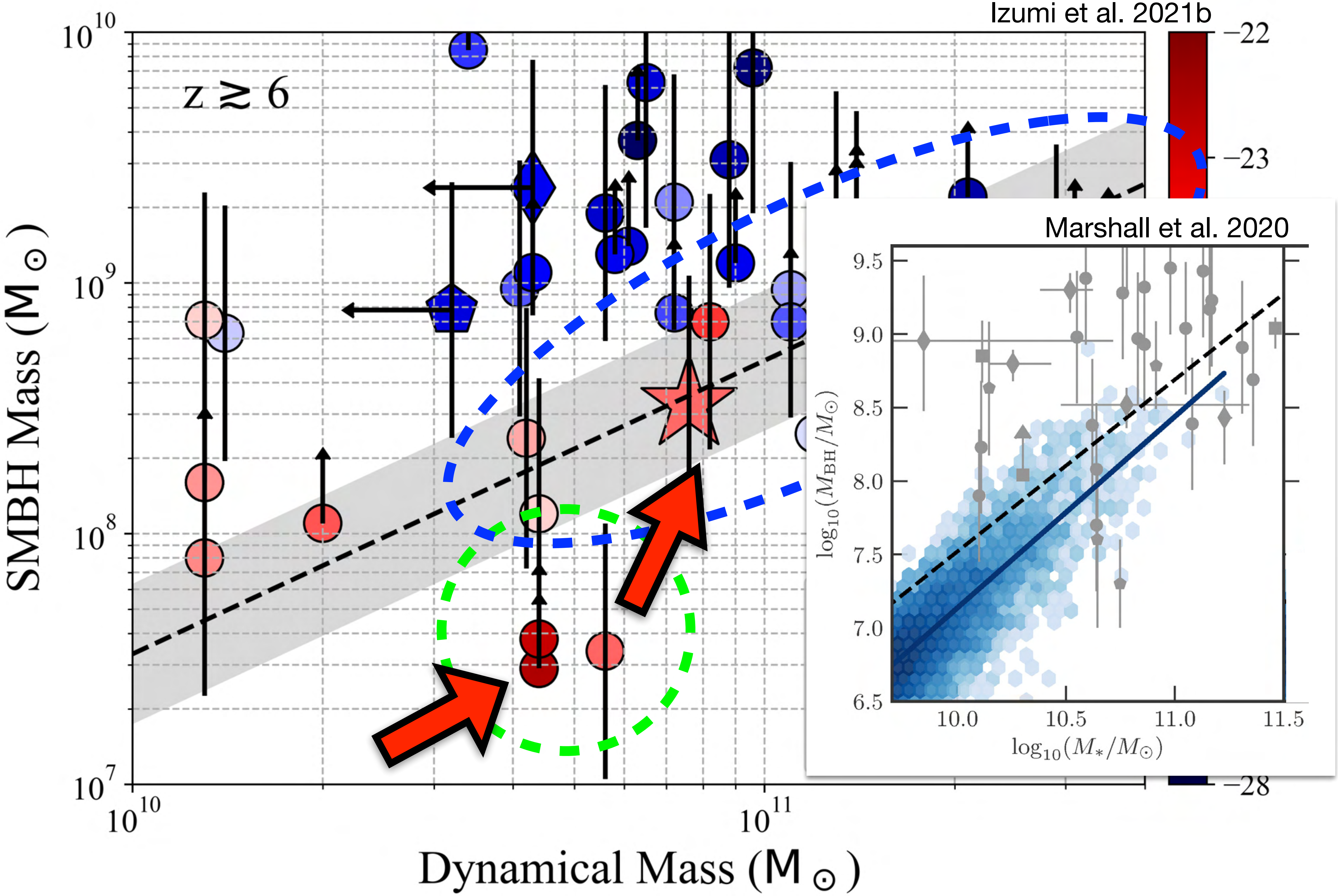
Levels of Star Formation



These HSC quasar hosts are on or below the MS@z~6:
(They are typical star-forming galaxies or galaxies transforming into a quiescent population)

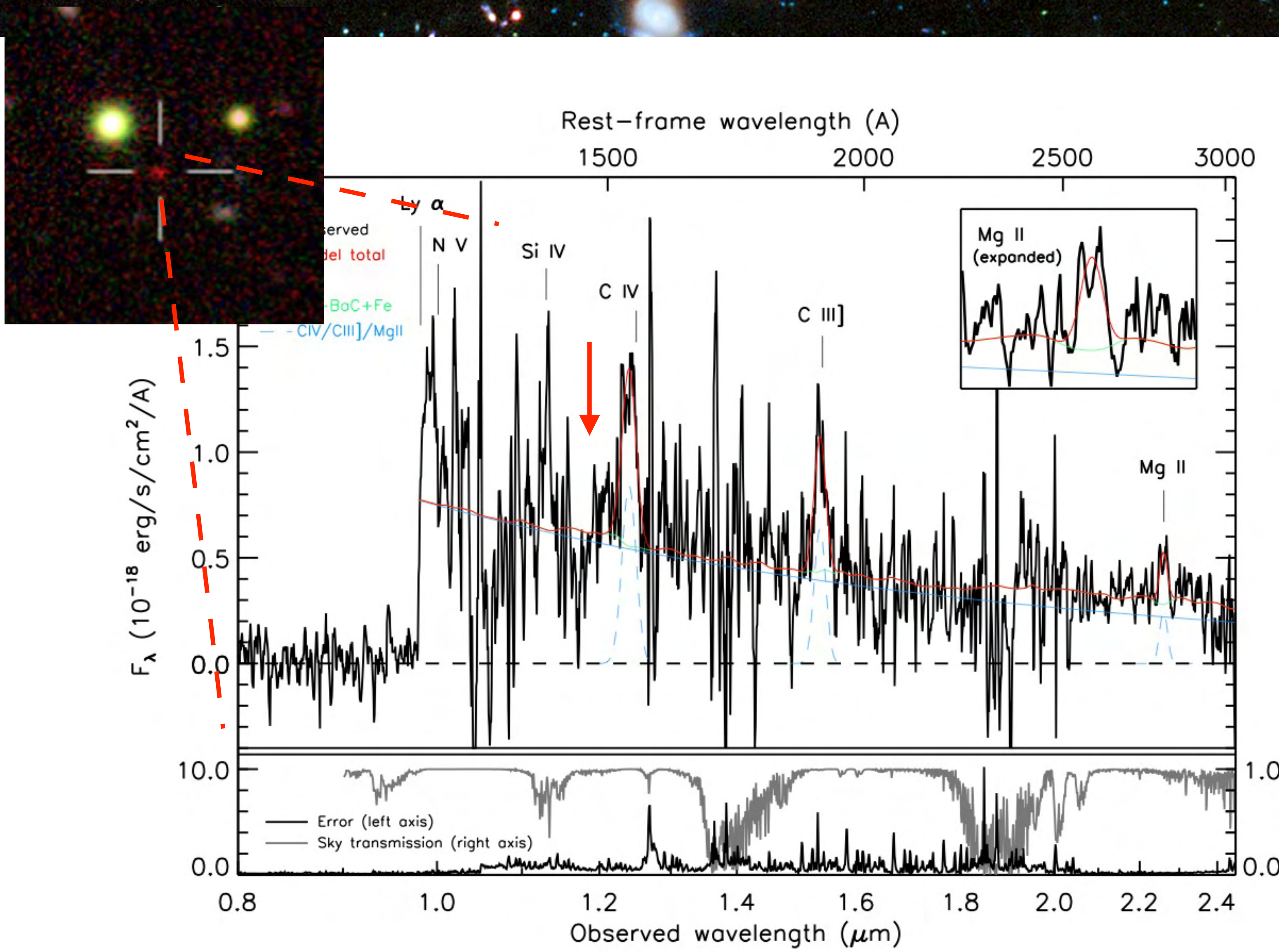
← Dynamical mass

Early co-evolution relation at z ~6–7 ?

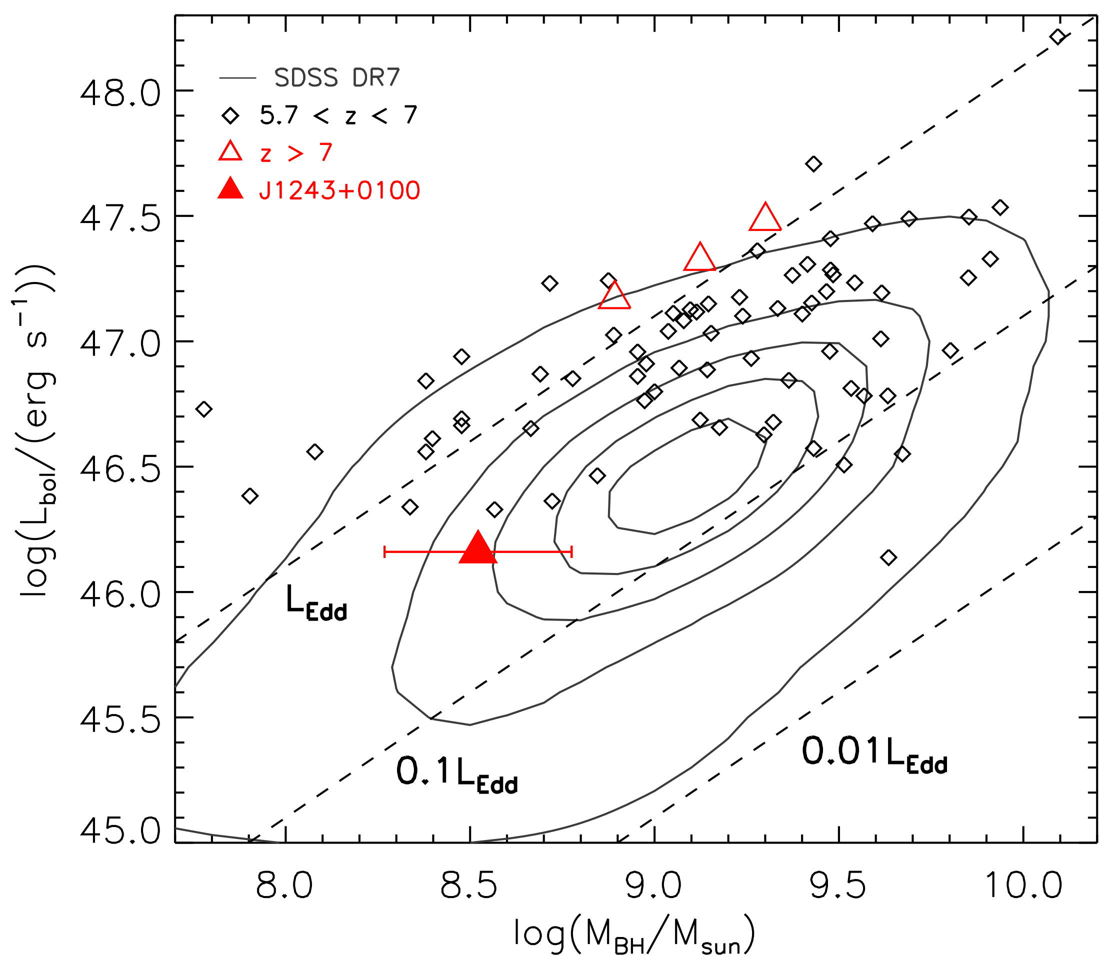



J1243+0100
z = 7.07

J1243+0100: The Highest-z Low-luminosity Quasar

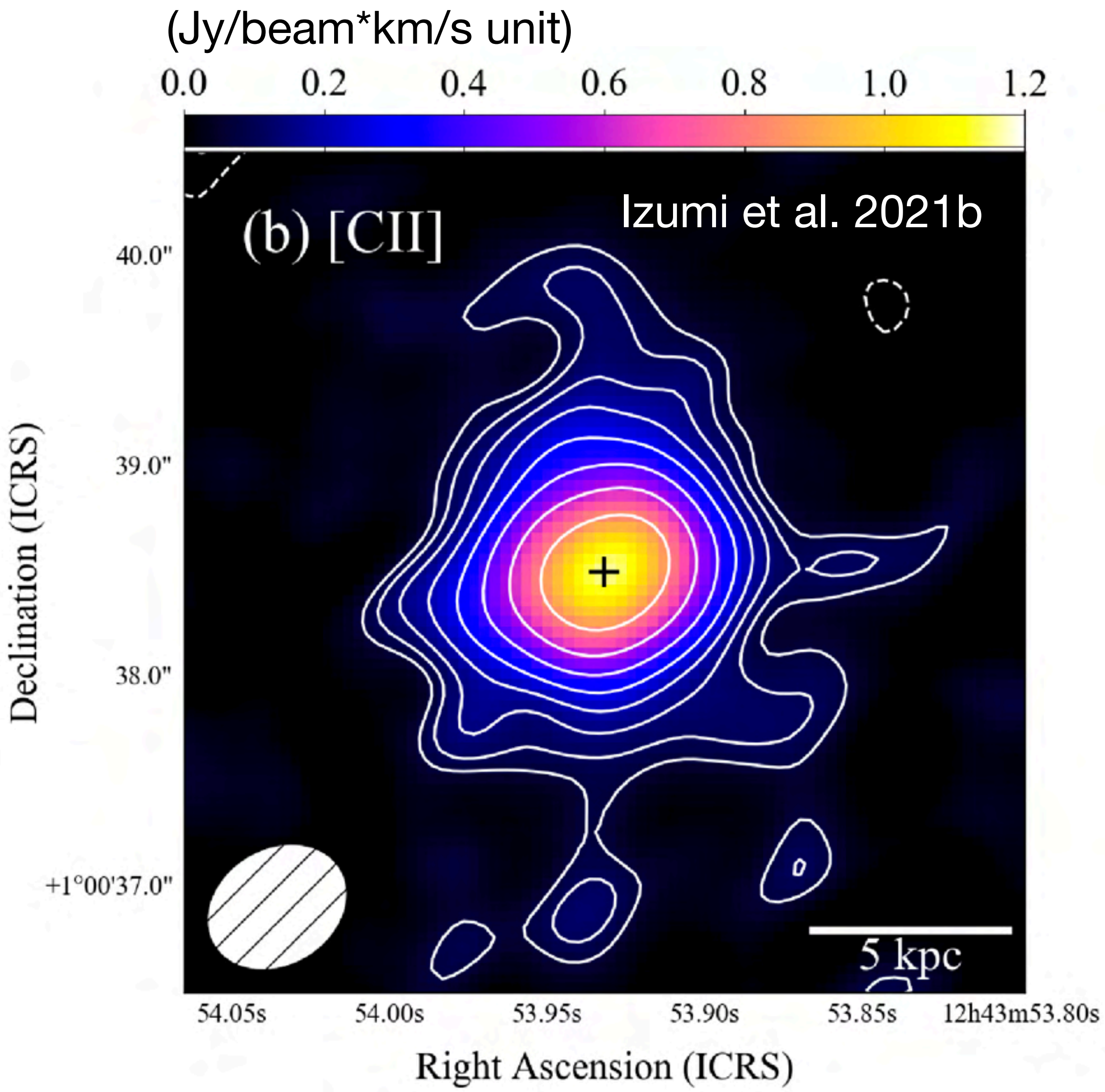


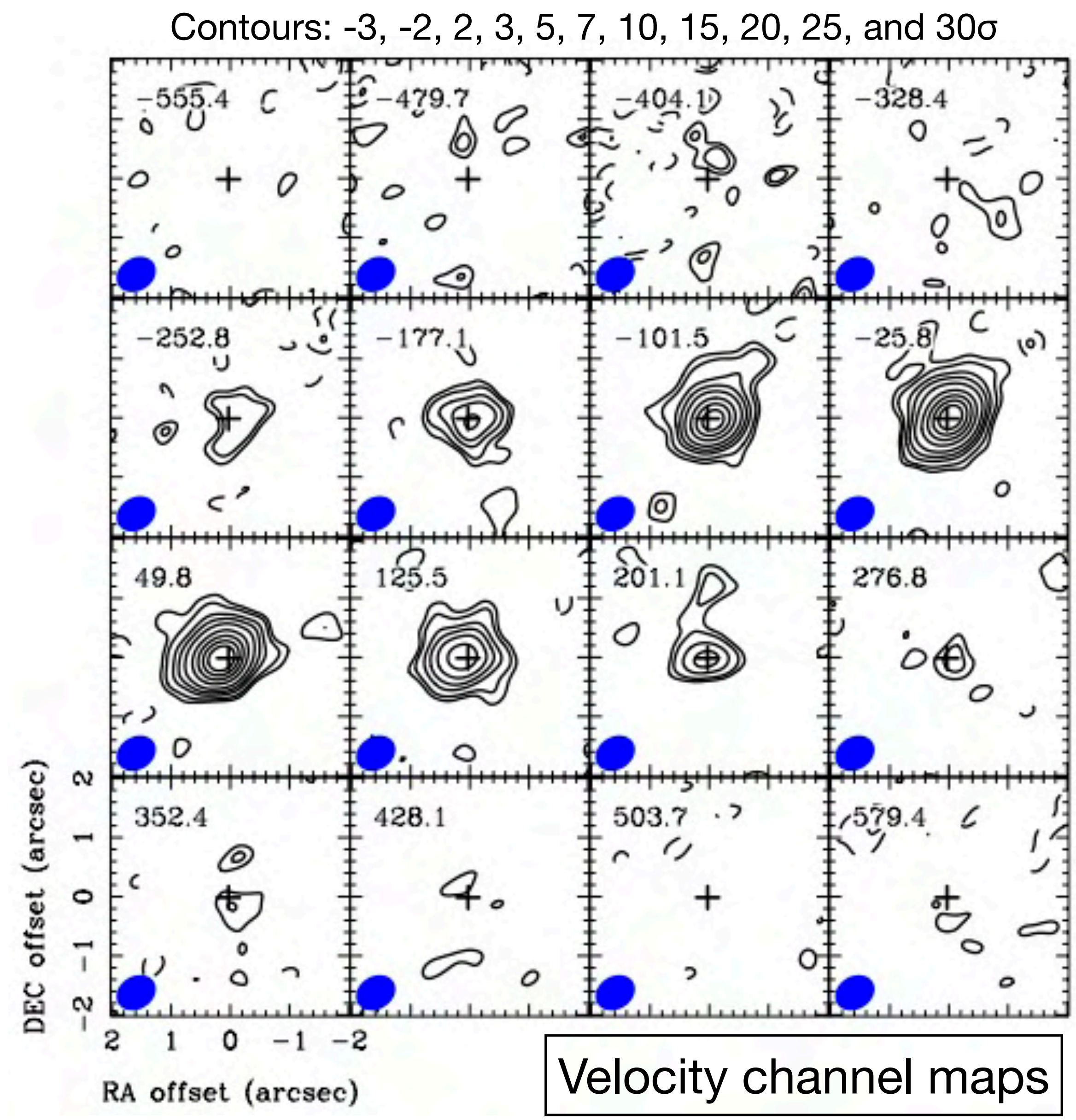
Matsuoka et al. 2019



- Only one low-luminosity quasar ($M_{1450} > -25$ mag) known at $z > 7$ ($z_{MgII} = 7.07$).
- $L_{Bol} = 1.4 \times 10^{46}$ erg/s (~10% of the other $z > 7$ quasars!)
- $M_{BH} = 3.3 \times 10^{8}$ M_{sun} → Eddington ratio = 0.3
- With a CIV broad absorption line → Fast (~2400 km/s) nuclear outflow
  → An intriguing target to study host-galaxy scale feedback.

[CII] 158μm Line Emission

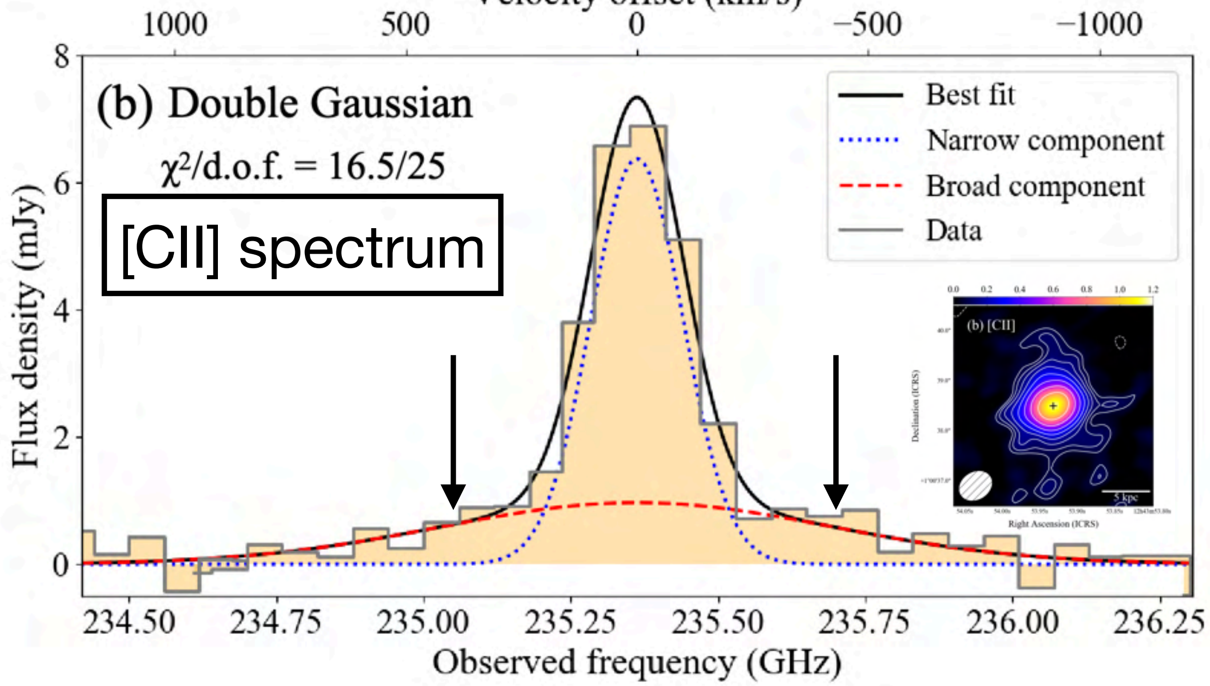


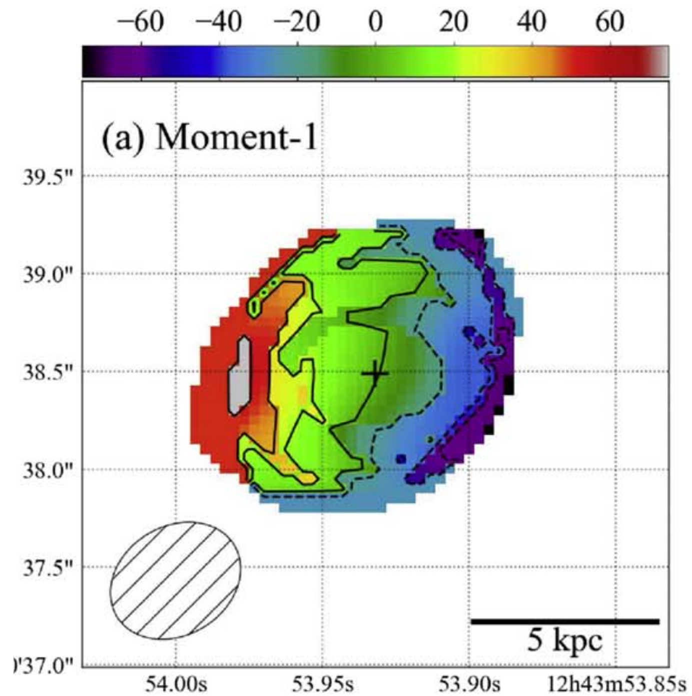


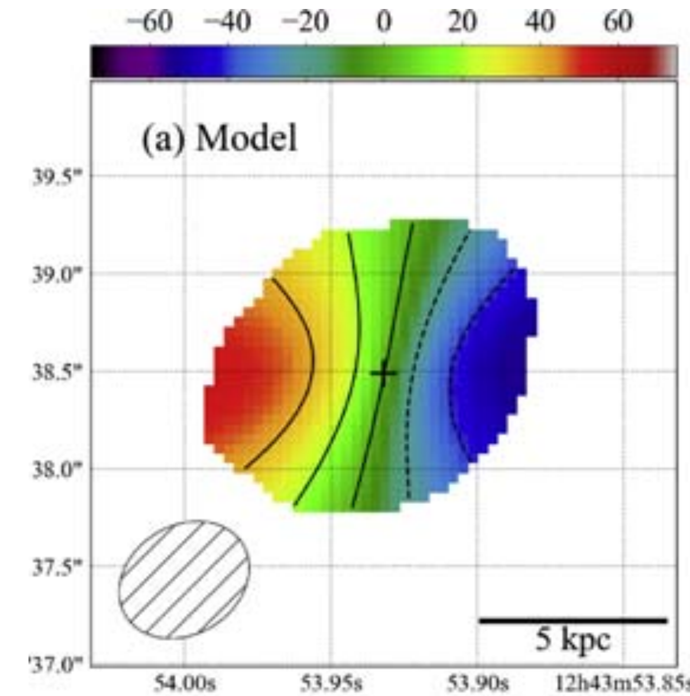
- [CII] is also extended. But the bulk emission comes from the central 1” region.
- Image-plane 2D Gaussian fit: FWHM = 3.6 × 3.5 kpc^2.
  → Close to the face-on view (if the intrinsic gas distribution is circular).
- [CII]-based SFR = 165 M_{sun}/yr.

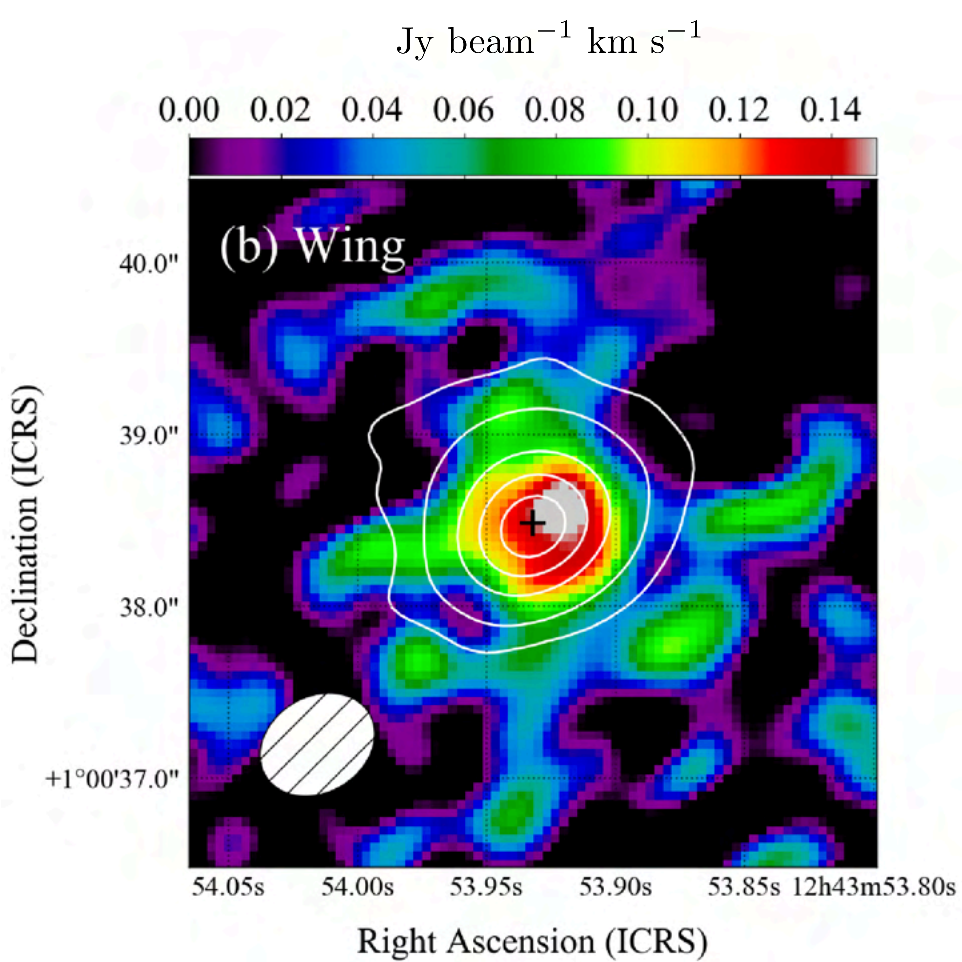
Very Broad [CII] Line Spectrum!

Izumi et al. 2021b









- Very broad symmetric wing (FWHM ~1000 km/s).
- Very compact size of the wing (3σ upper limit FWHM < 0.52" = 2.7 kpc), which is even inside the host.
- Global dynamics = Rotation (no merger)
- All of these support that this broad wing is due to a **fast outflow** (>450 M_{sun}/yr).
  → Total outflow rate (incl. mol) **> 1400 M_{sun}/yr** ??
- **Quasar-driven**…? (∵Narrow [CII]-based $SFR_{[CII]}$ = 165 M_{sun}/yr)

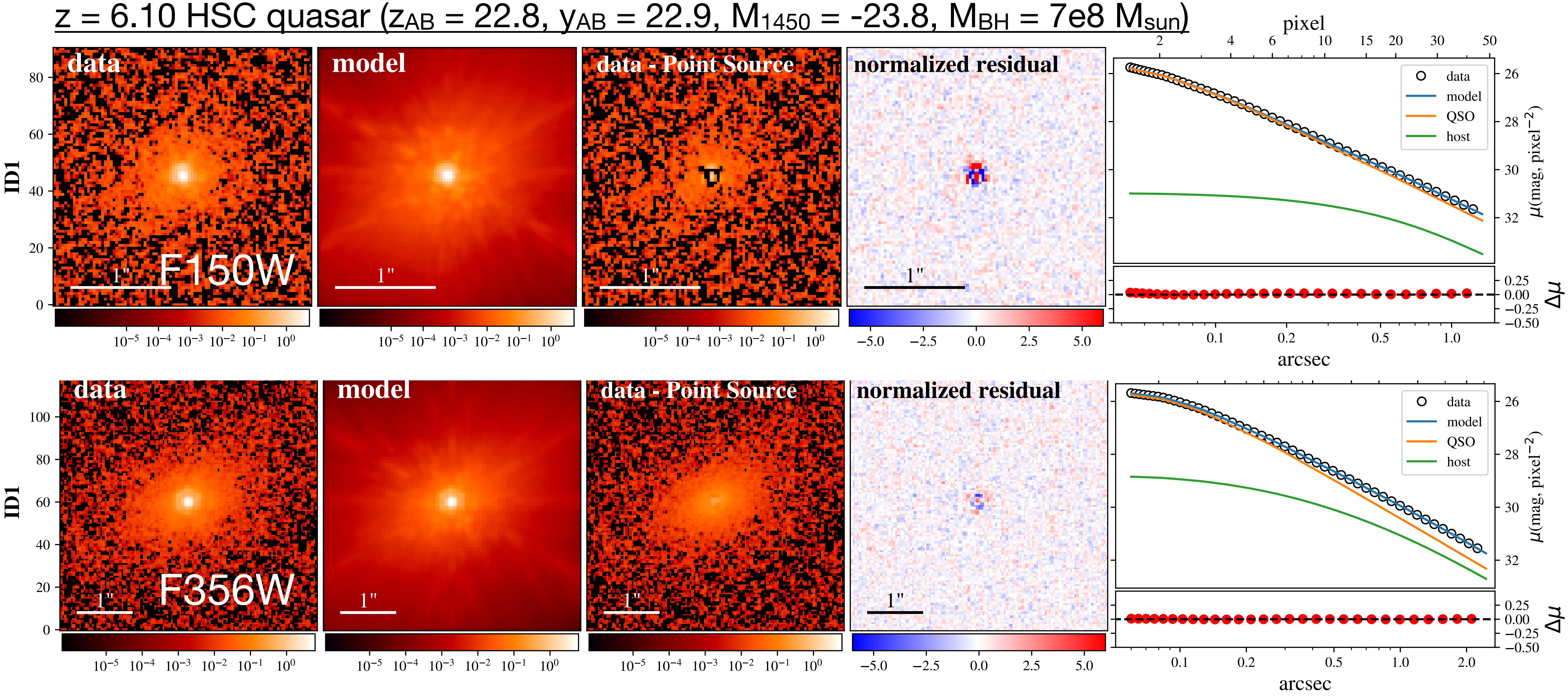
Press release from NAOJ

JWST Observation

- As HSC quasars are relatively “faint”, we have a good chance to directly see their host galaxies with JWST.
  → JWST Cycle 1 program, **approved**!
  (PI: M.Onoue, co-PI: Y. Matsuoka, J. Silverman, X. Ding, T. Izumi)

NIRCam simulations

z = 6.10 HSC quasar (z_{AB} = 22.8, y_{AB} = 22.9, M_{1450} = -23.8, M_{BH} = 7e8 M_{sun})



Summary: Synergy of Subaru and ALMA

- ✦ Our low-luminosity (more general) quasar survey is on-going by using the Subaru Hyper Suprime-Cam (HSC) → now >160 quasars at $z > 6$.

- ✦ NIR follow-up to measure M_{BH} is also on-going.

- ✦ Mostly LIRG-like FIR properties (L_{FIR}, $L_{[CII]}$).
  - SFR ~ several × 10 M_{sun}/yr
  → Clear contrasts to those of the previously discovered quasars (ULIRG/SMG-class star formation)

- ✦ The HSC quasars are typically on or below the MS at $z \sim 6$
  → Transition phase to quiescent galaxies?

- ✦ **The co-evolution relation may have already arisen at z ~ 6–7…!?**
  → Quite rapid mechanism of galaxy evolution will be required.

- ✦ Fast [CII] outflow (neutral outflow rate > 450 M_{sun}/yr) is identified in J1243+0100, indicating the early quasar feedback to the host.
  → Subaru × ALMA is good to study early feedback??

- ✦ Further observations incl. JWST are planned.