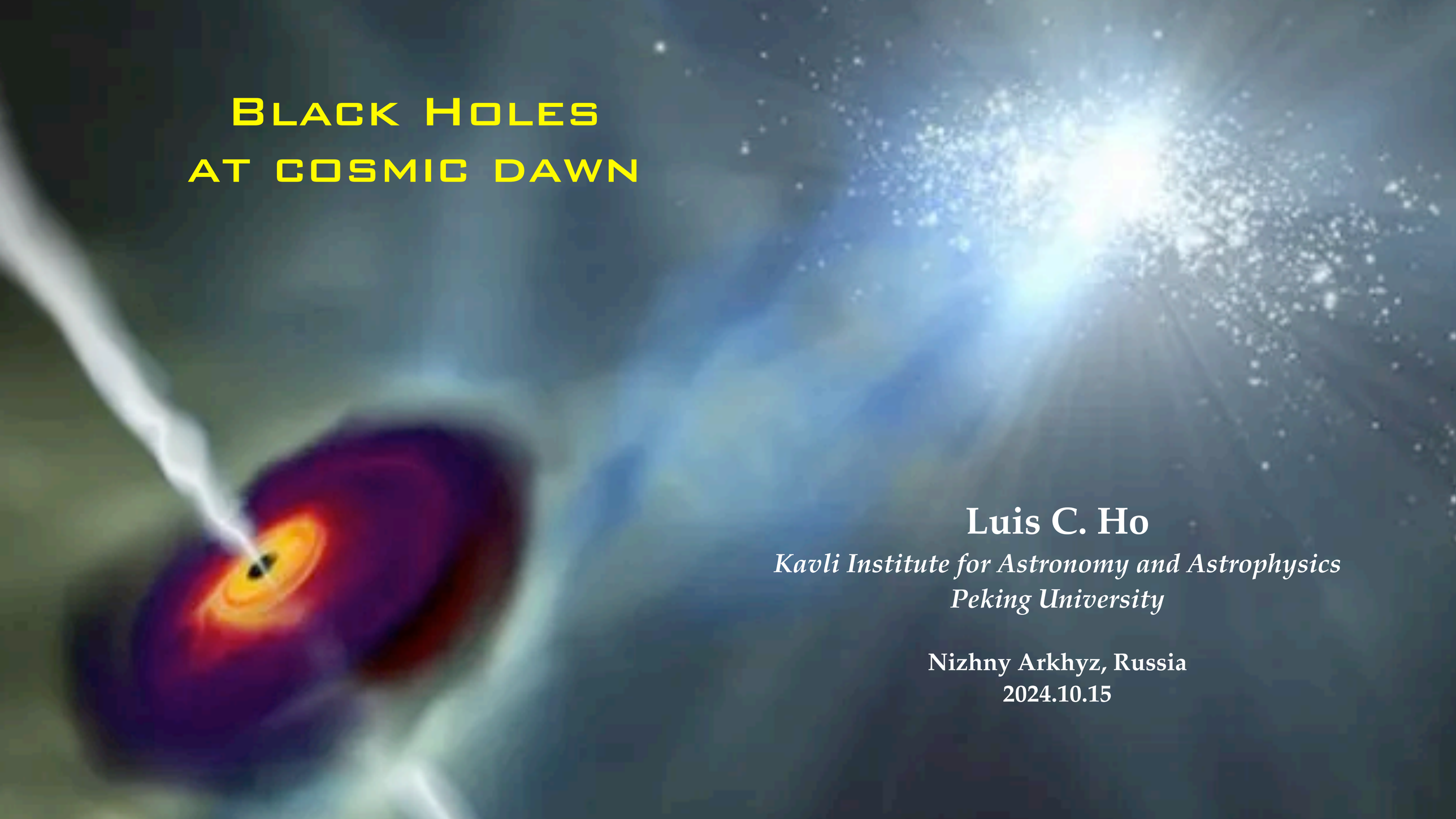


Black Holes at cosmic dawn

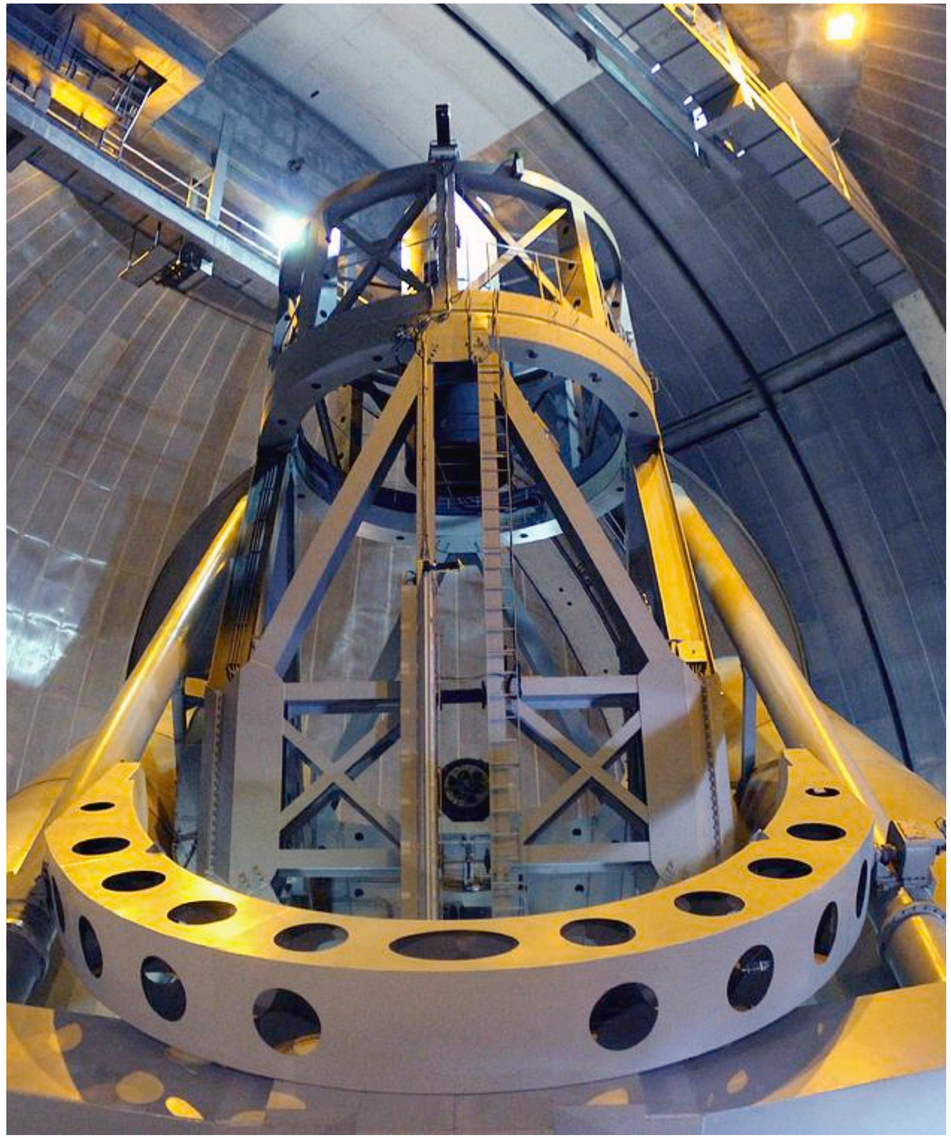
Luis C. Ho

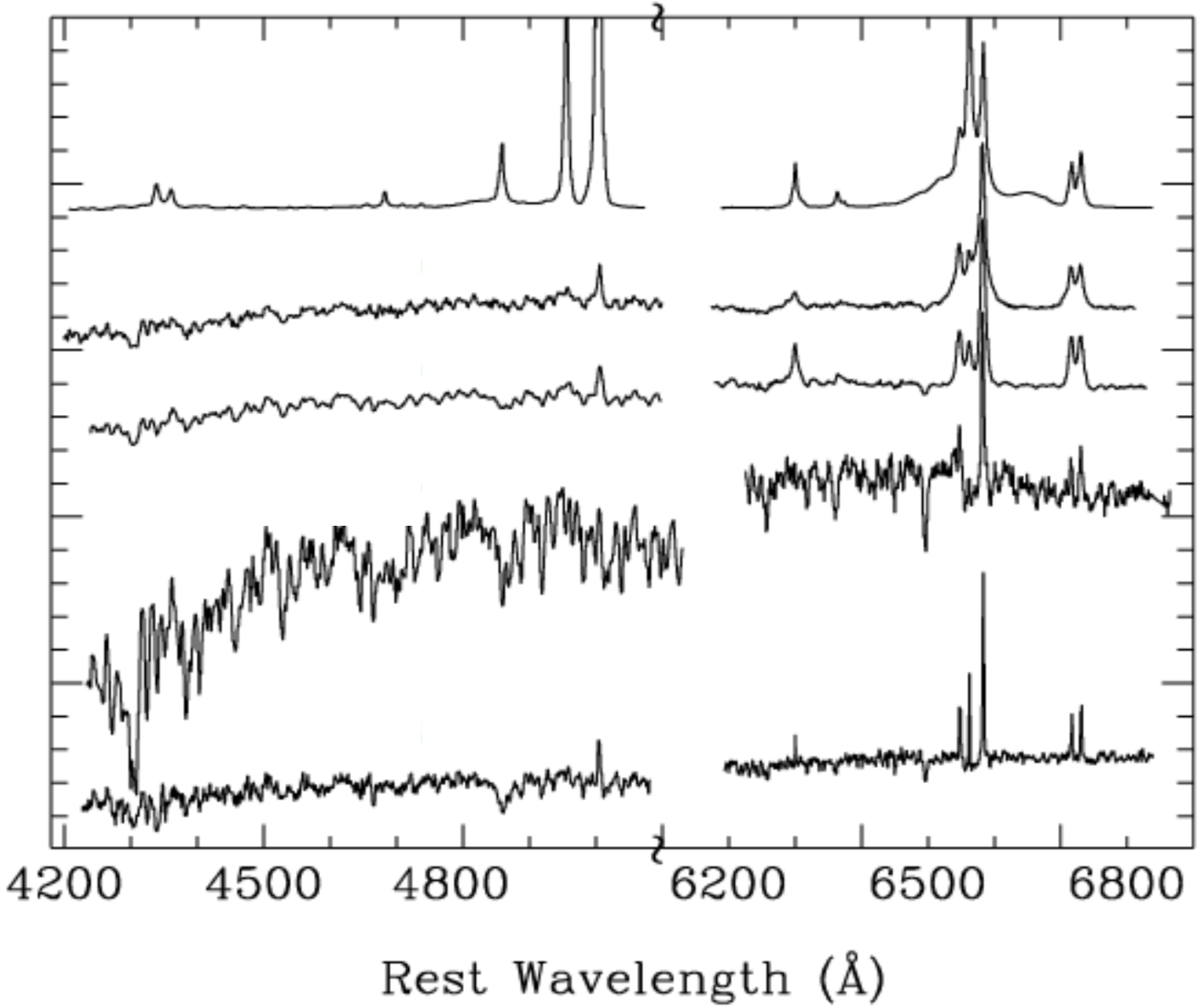
Kavli Institute for Astronomy and Astrophysics
Peking University

Nizhny Arkhyz, Russia
2024.10.15

Palomar Spectroscopic Survey of Nearby Galaxies

Ho, Filippenko & Sargent (1993-2009)





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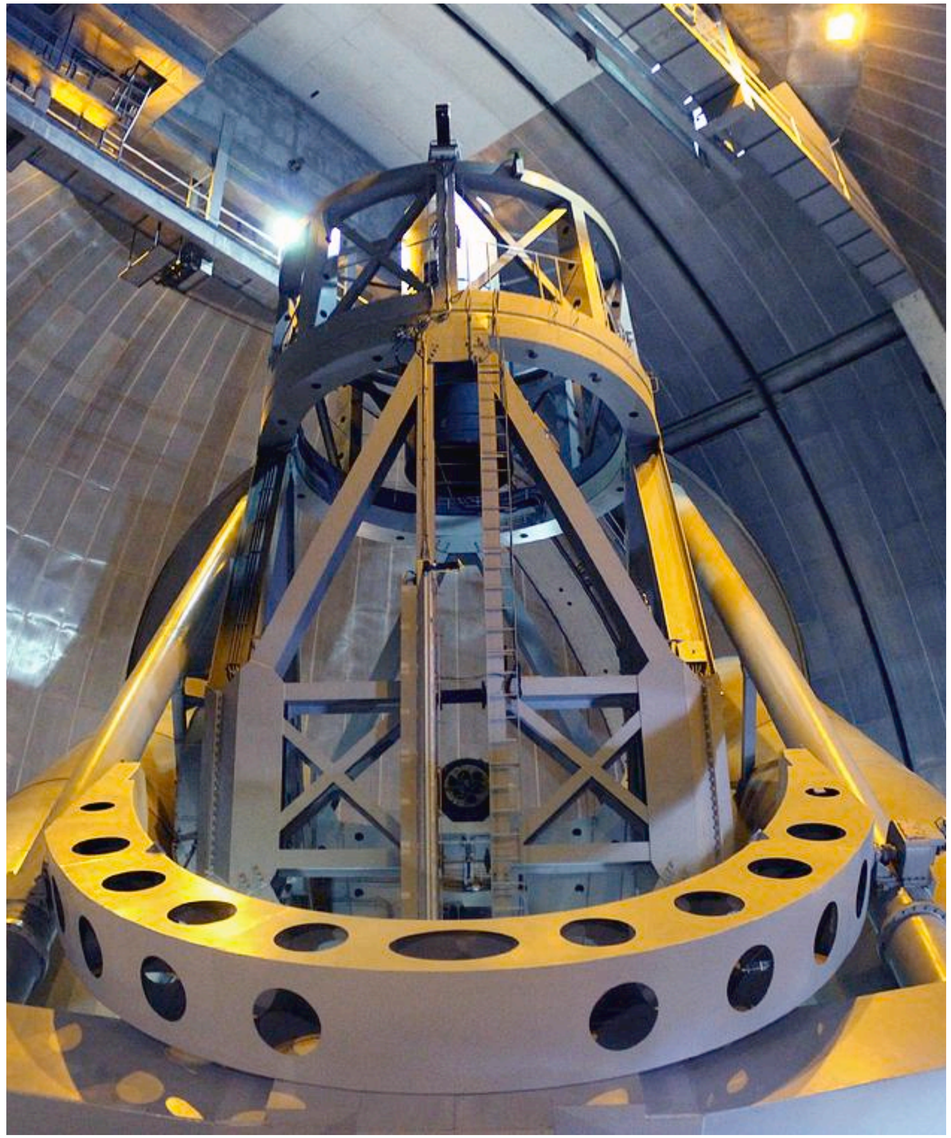
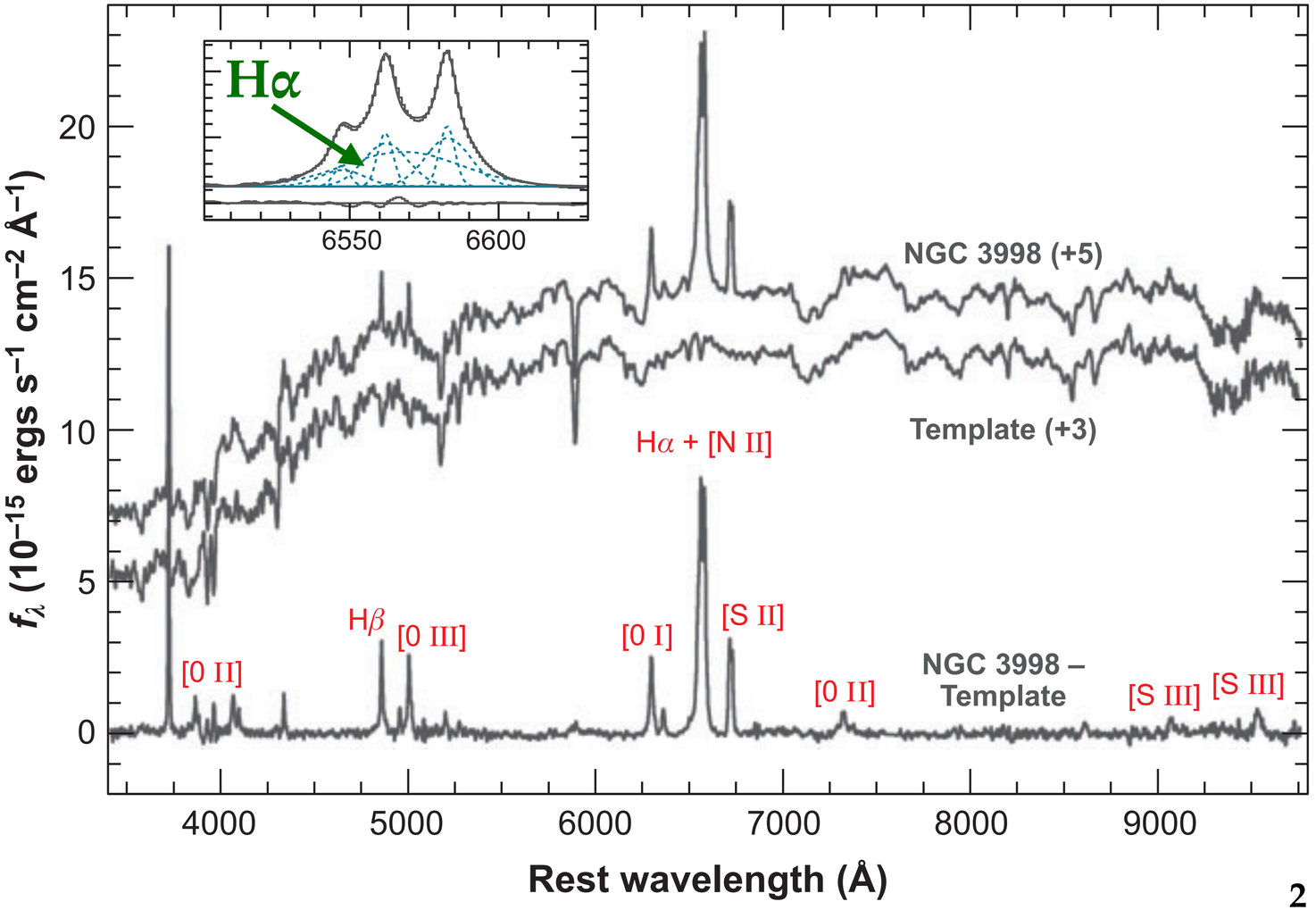


Detection of Broad Hα Emission



Palomar Spectroscopic Survey of Nearby Galaxies

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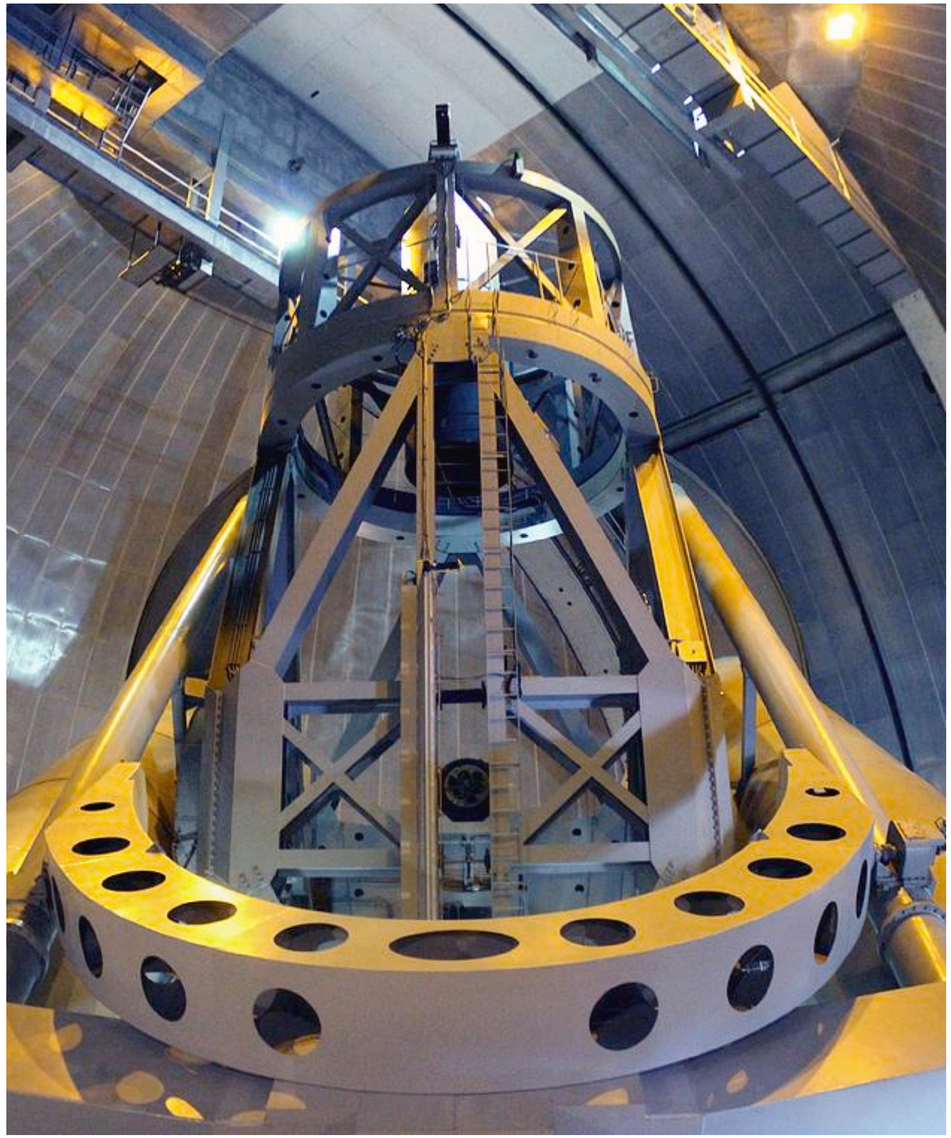
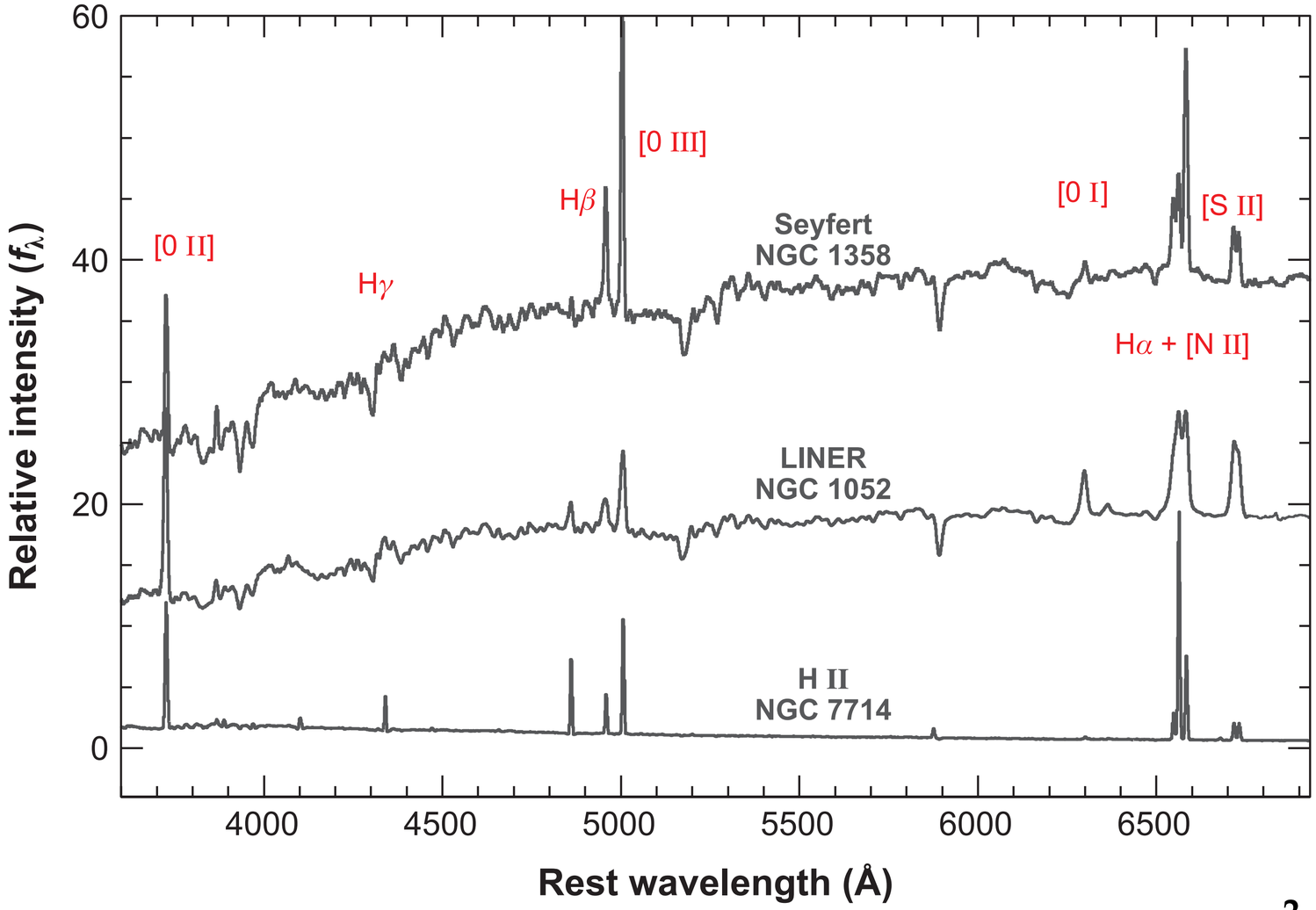
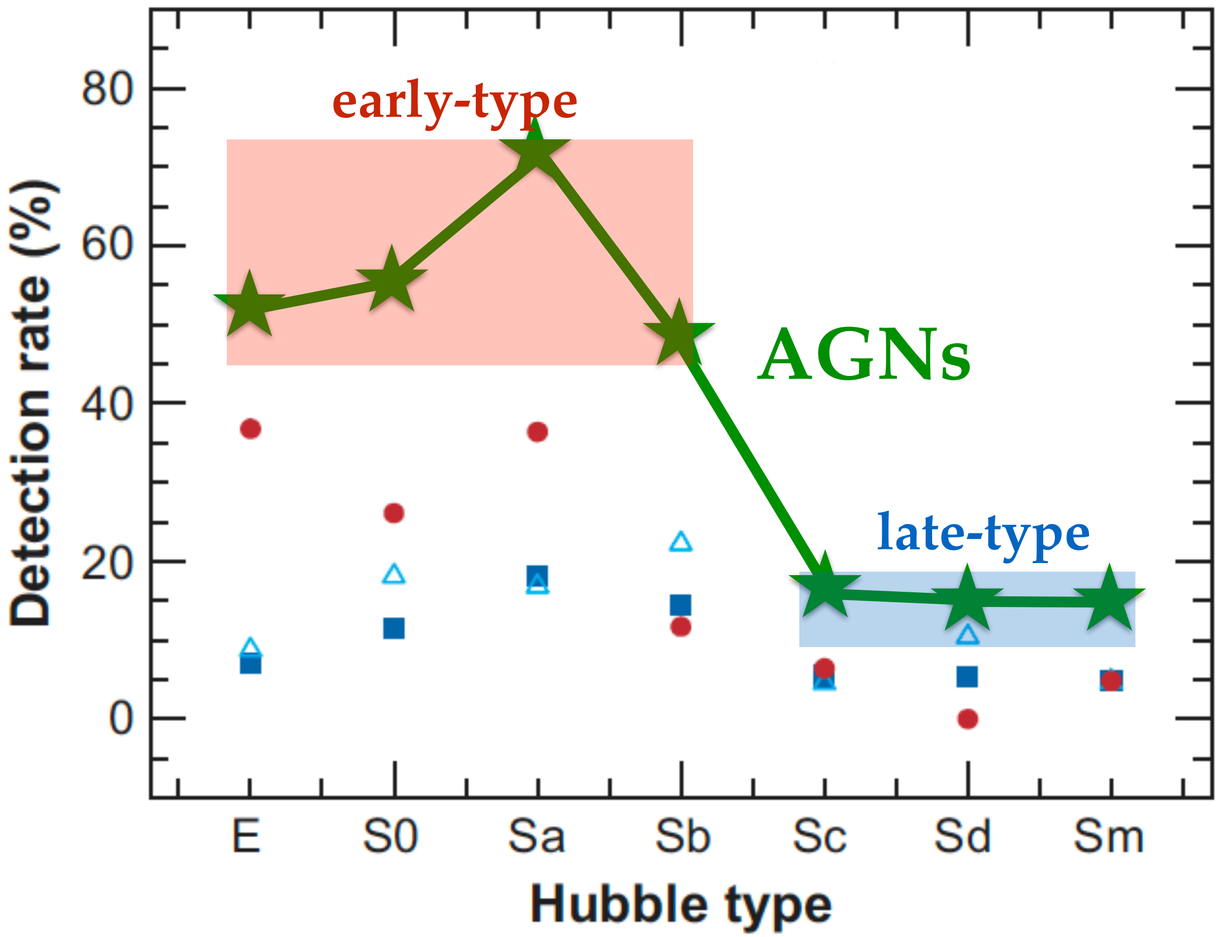


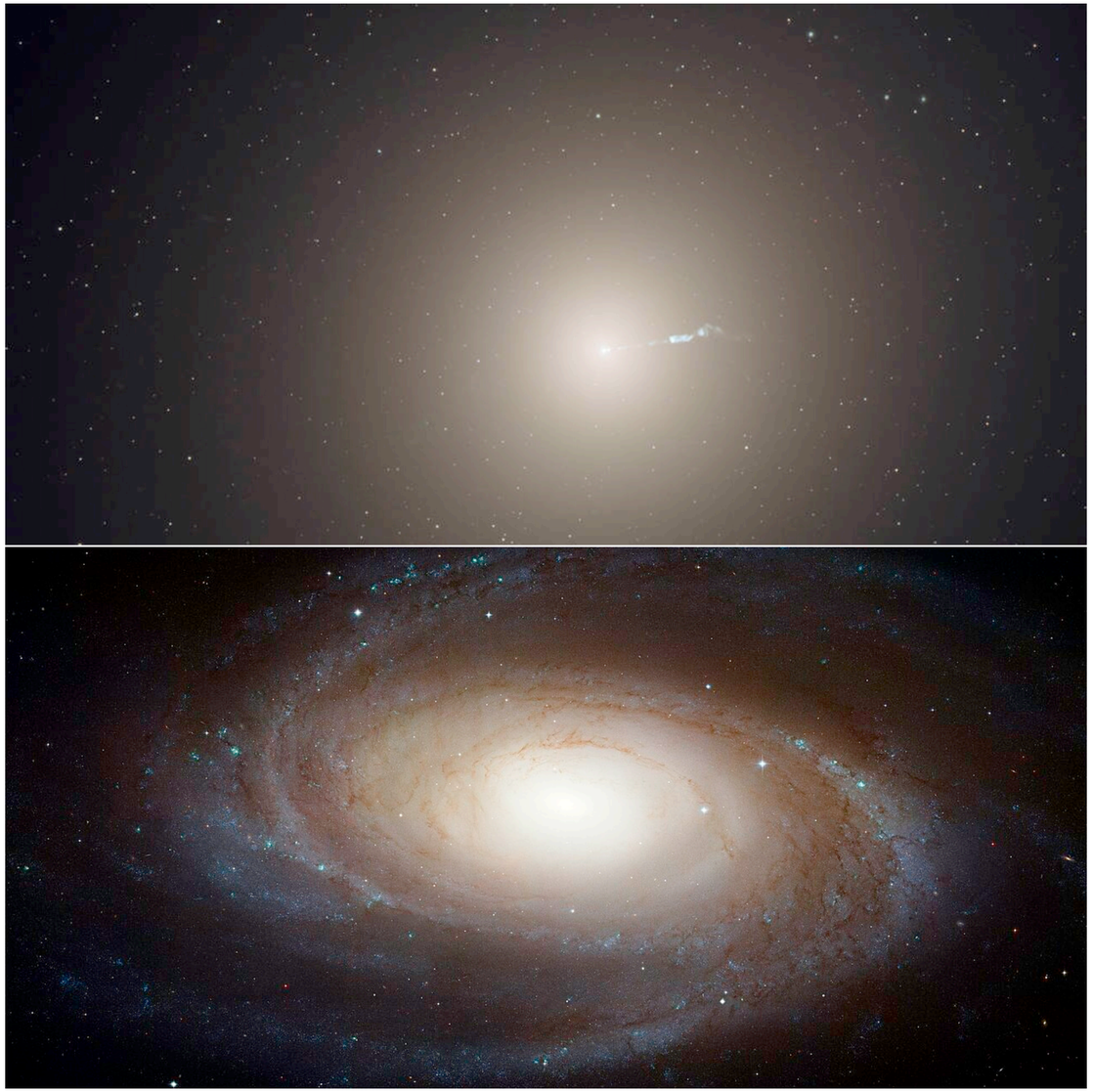
Detection of Narrow Emission Lines



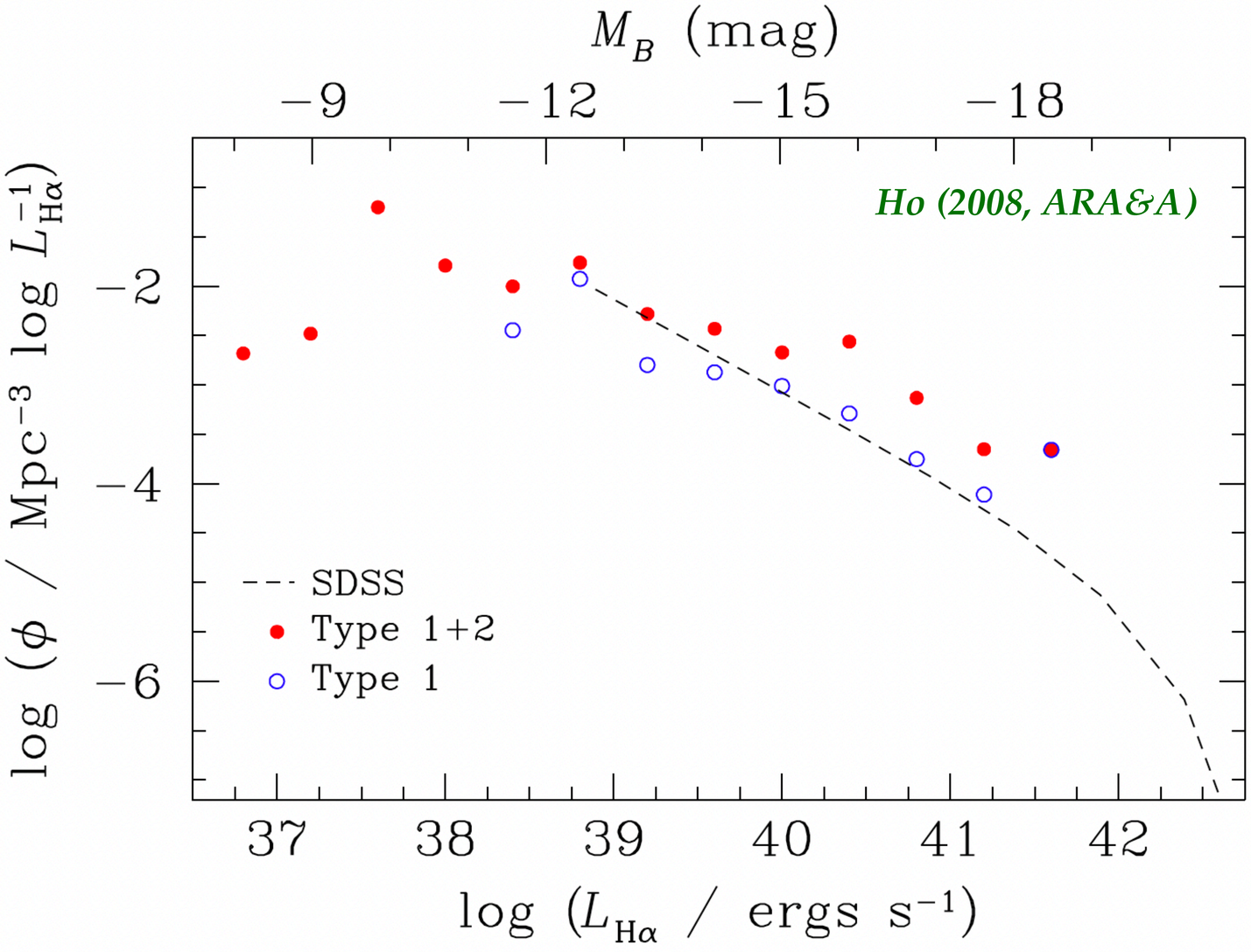
Local Census of AGNs

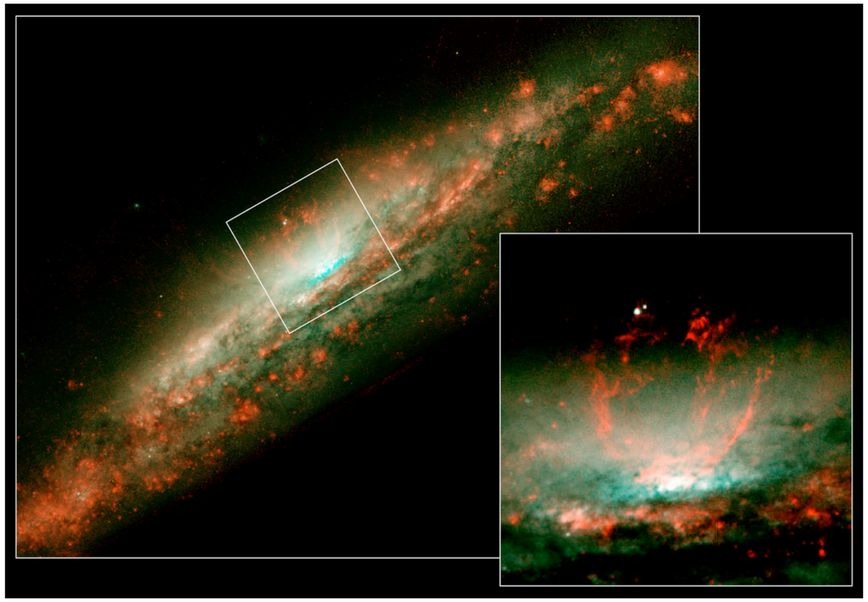
Ho (2008, ARA&A)



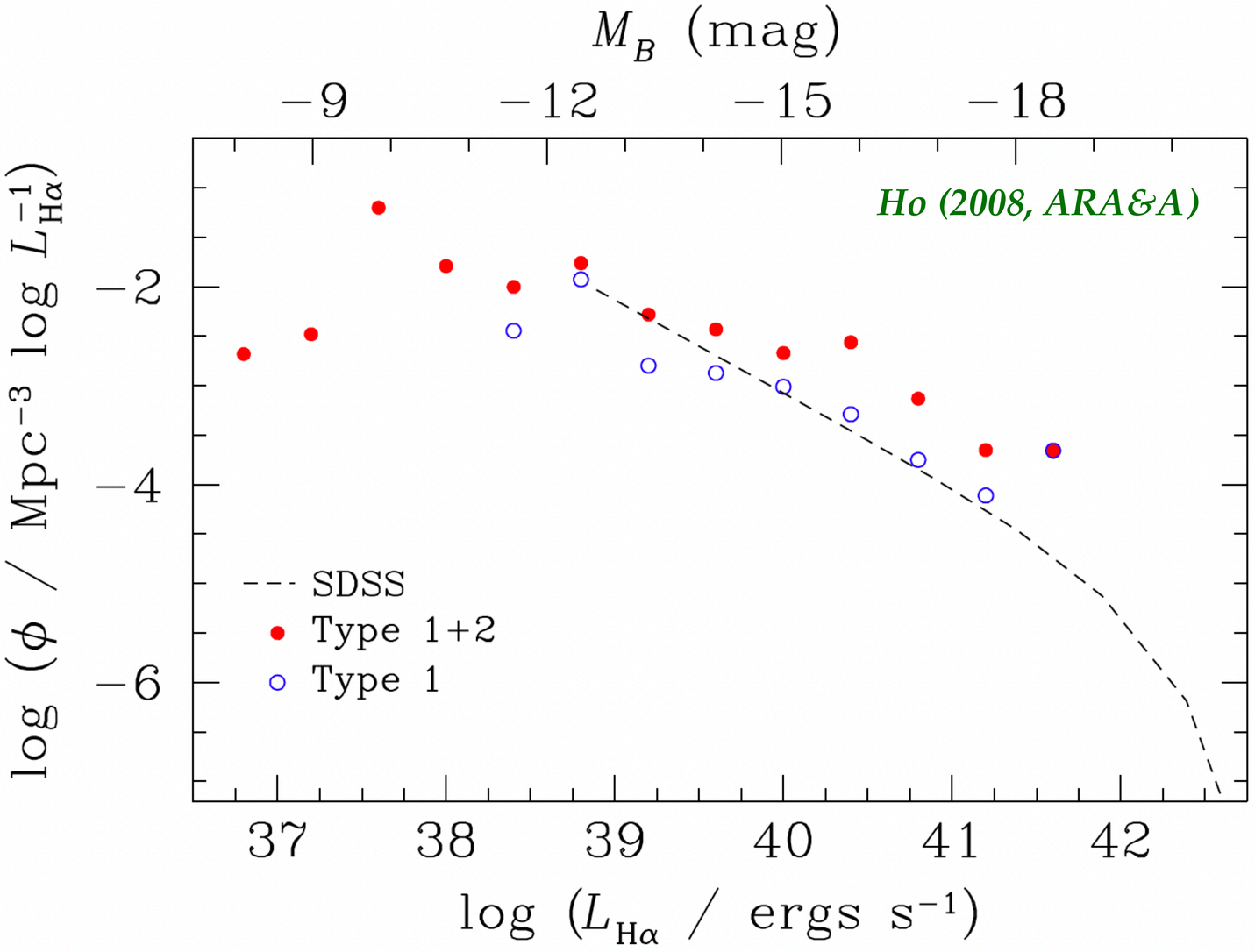


- AGNs 50%–75% in E–Sbc
- Consistent with BHs in 100% bulges





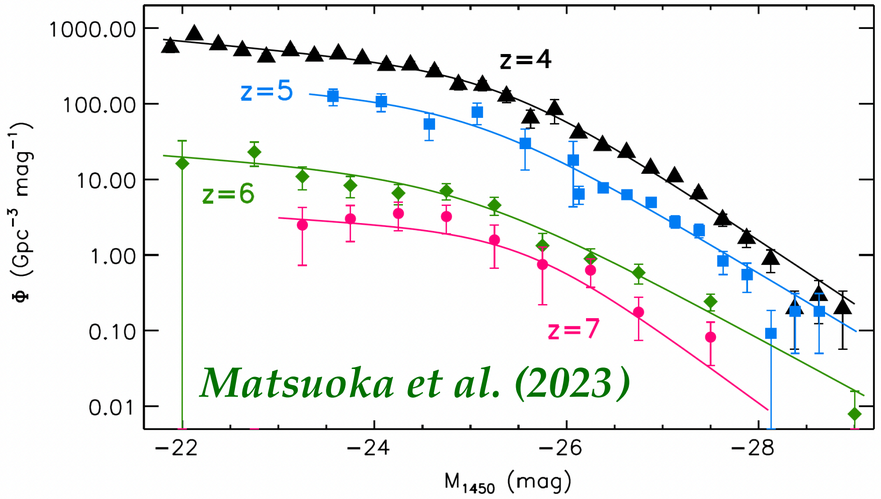
Most central black holes in local galaxies are quiescent or only weakly active



M_B (mag)

−23 −30

QSOs



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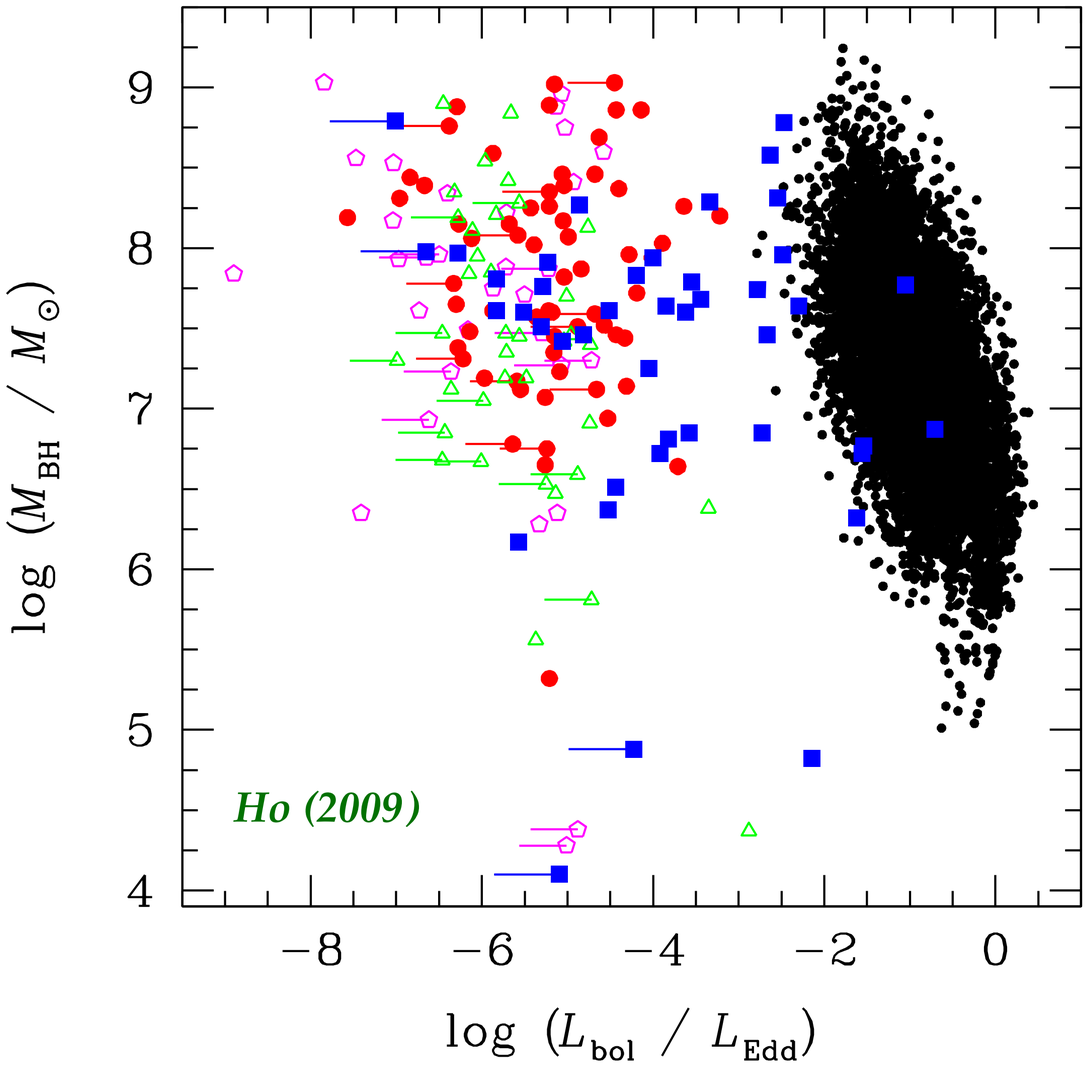
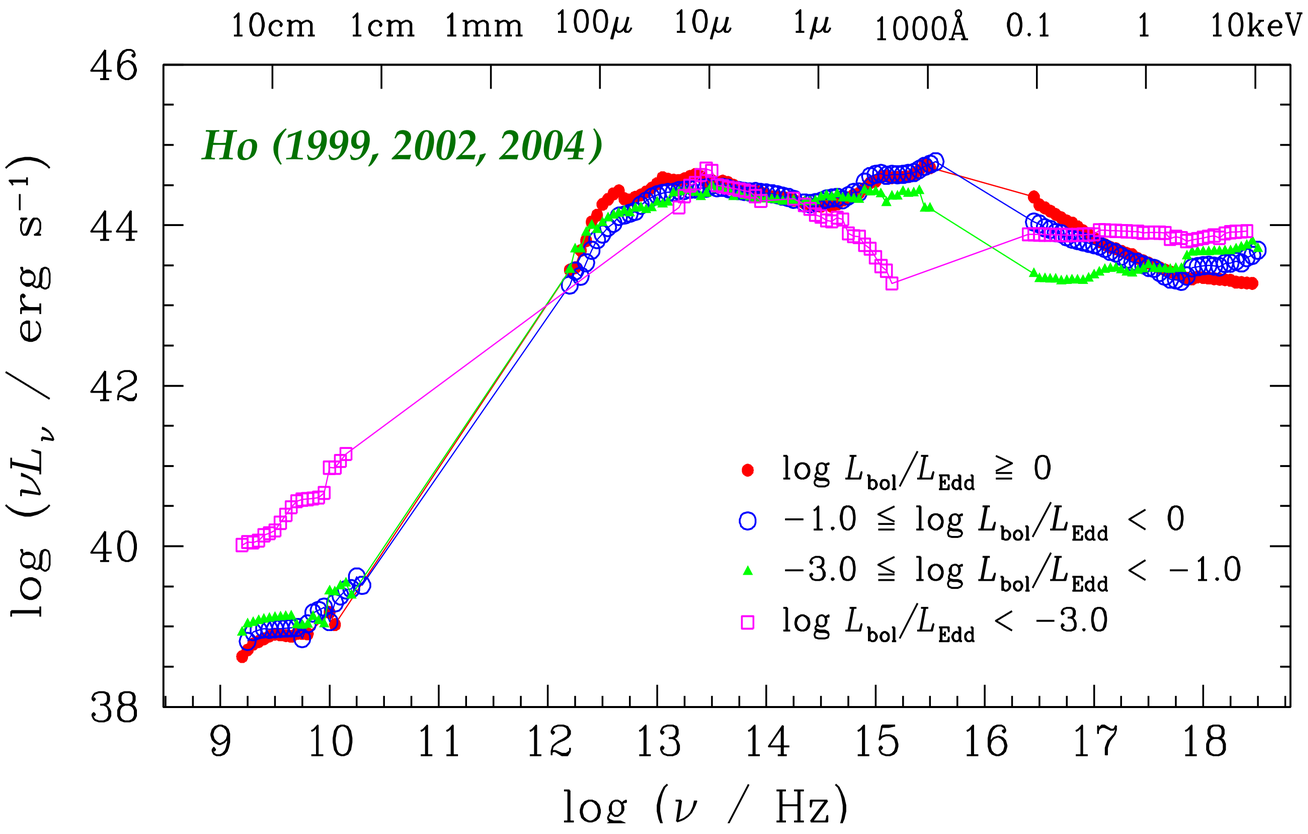
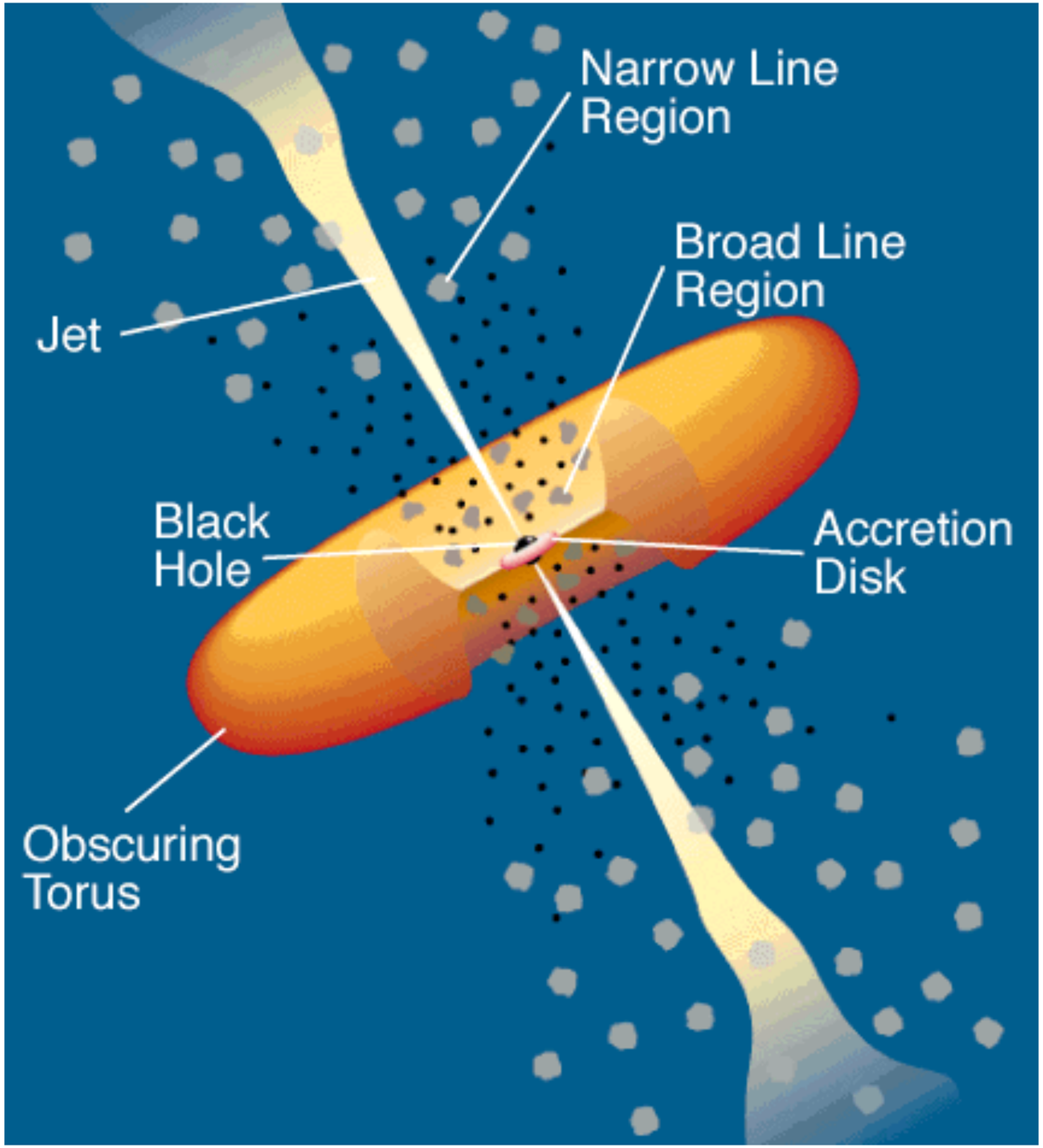




Accretion rates are highly sub-Eddington, with $L_{bol}/L_{Edd} \ll 1$

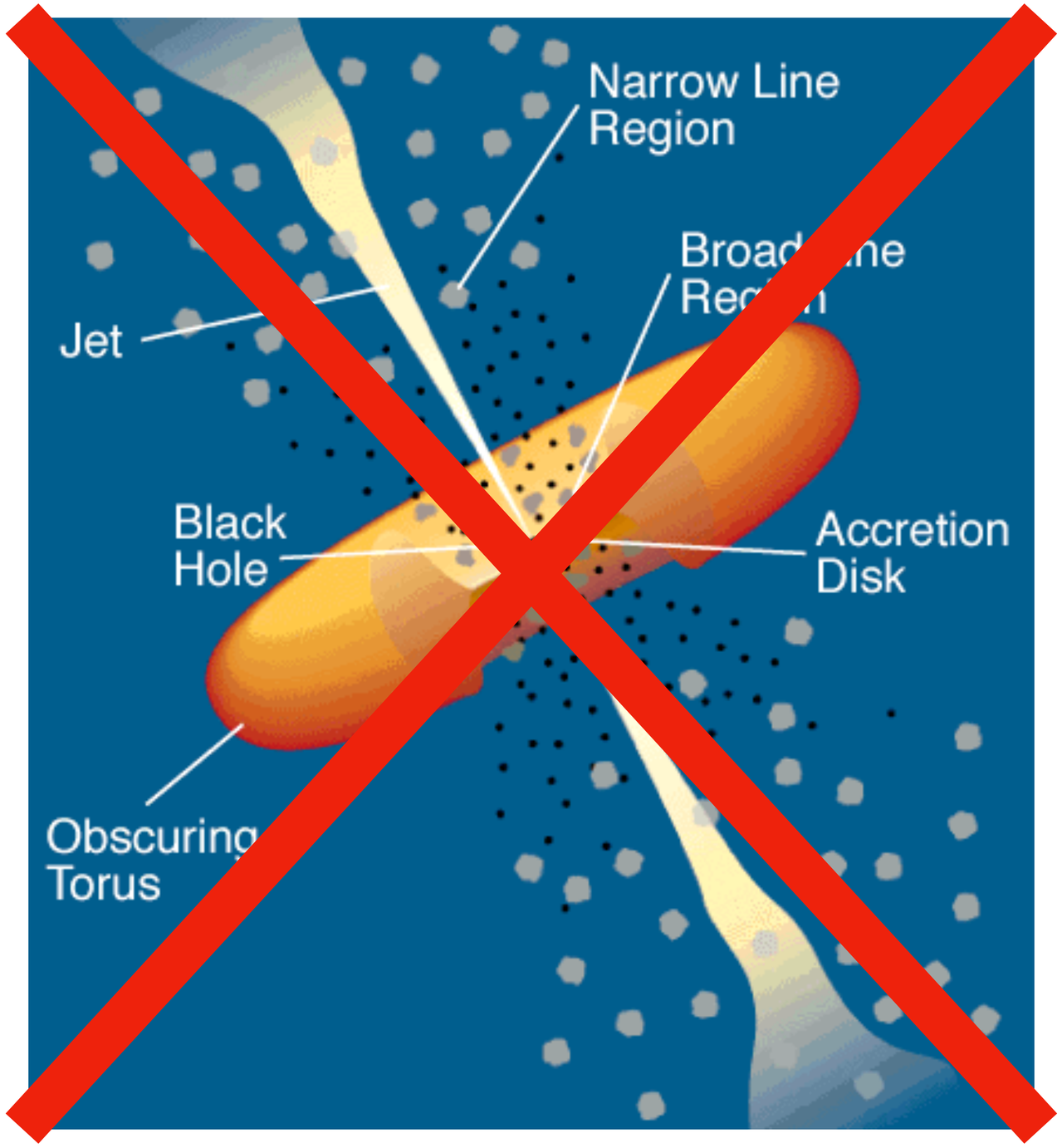
Nonstandard SED, new accretion and ejection physics



Standard Model for AGNs

Rees (1984), Antonucci (1993), Urry & Padovani (1995)

- **Supermassive black hole**
- **Optically thick, geometrically thin, radiatively efficient accretion disk**
- **Dusty, obscuring torus**
- **Highly collimated, relativistic jet**



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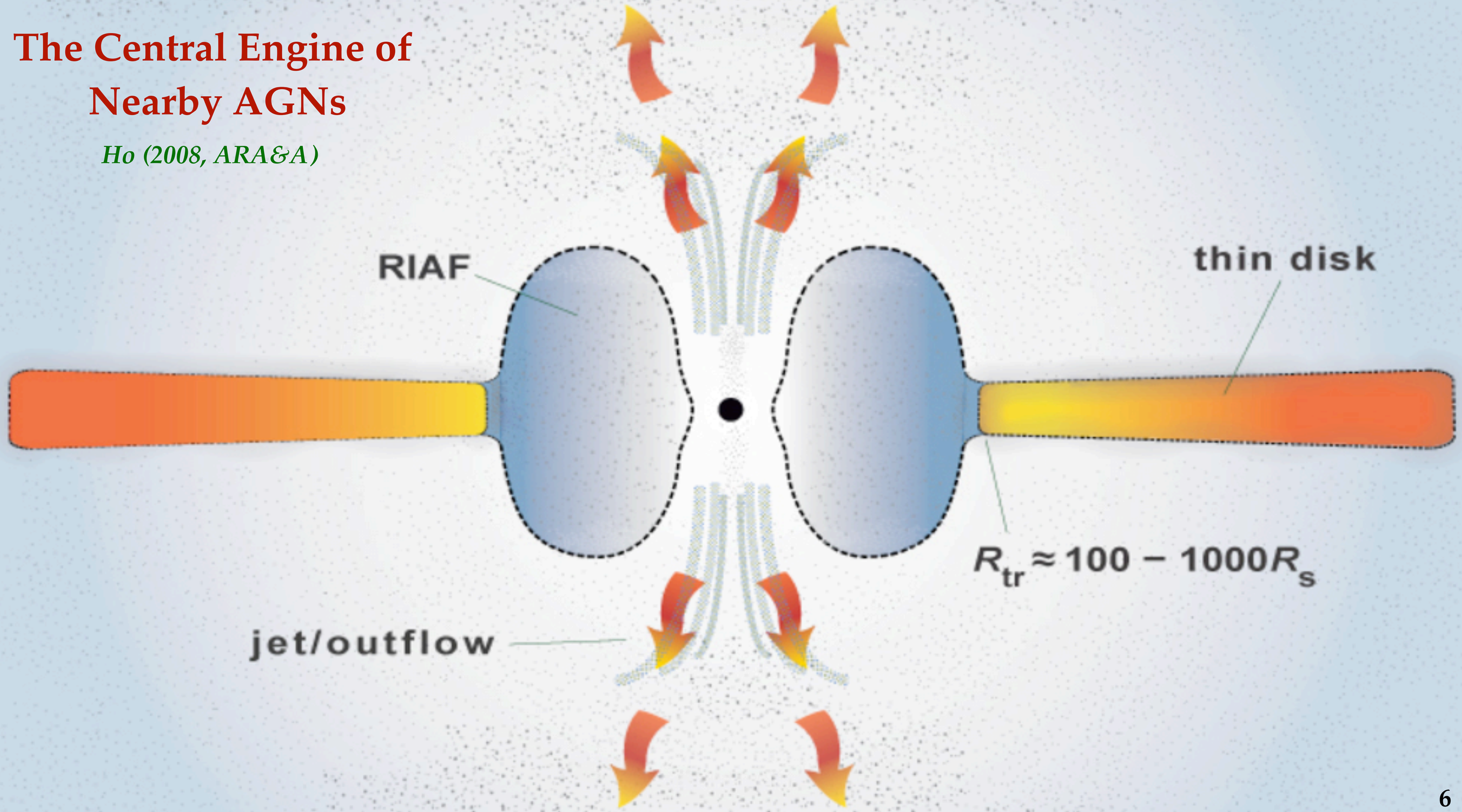
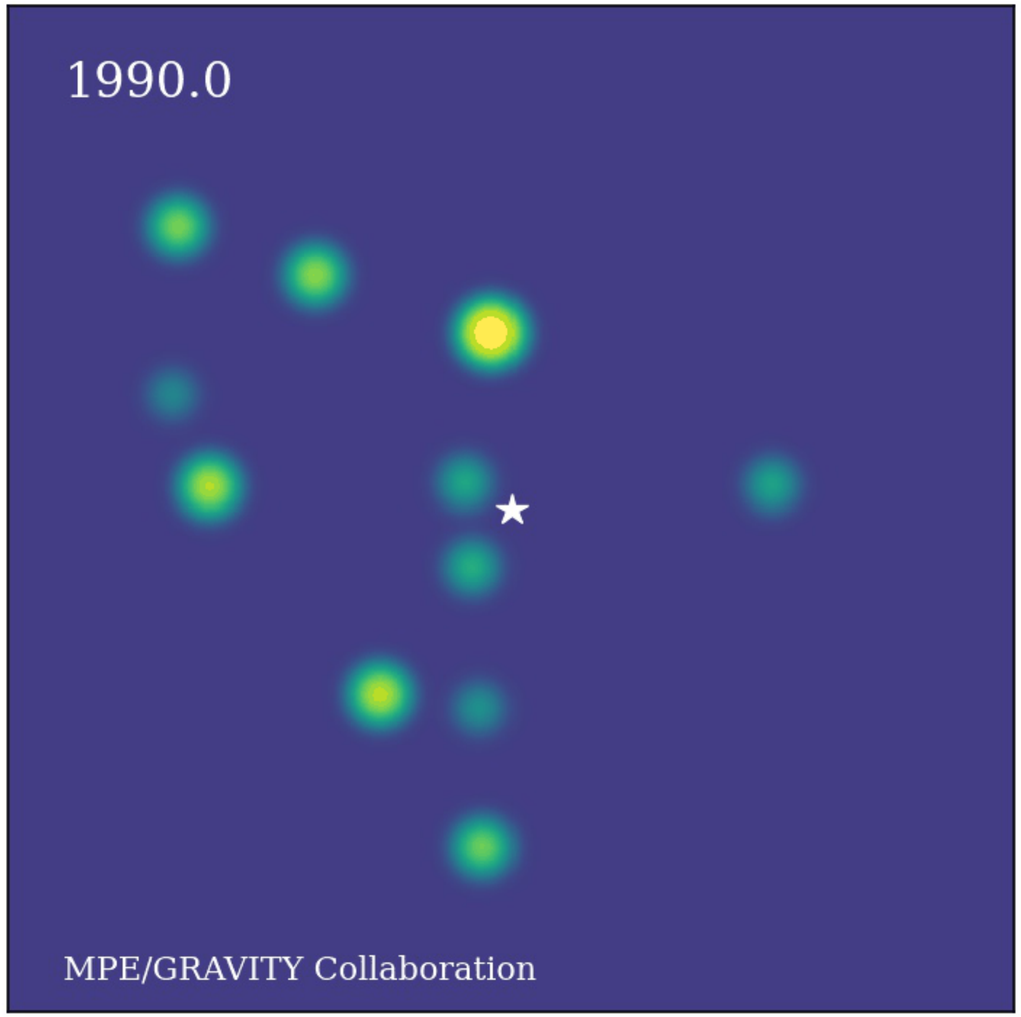
The Central Engine of Nearby AGNs

Ho (2008, ARA&A)

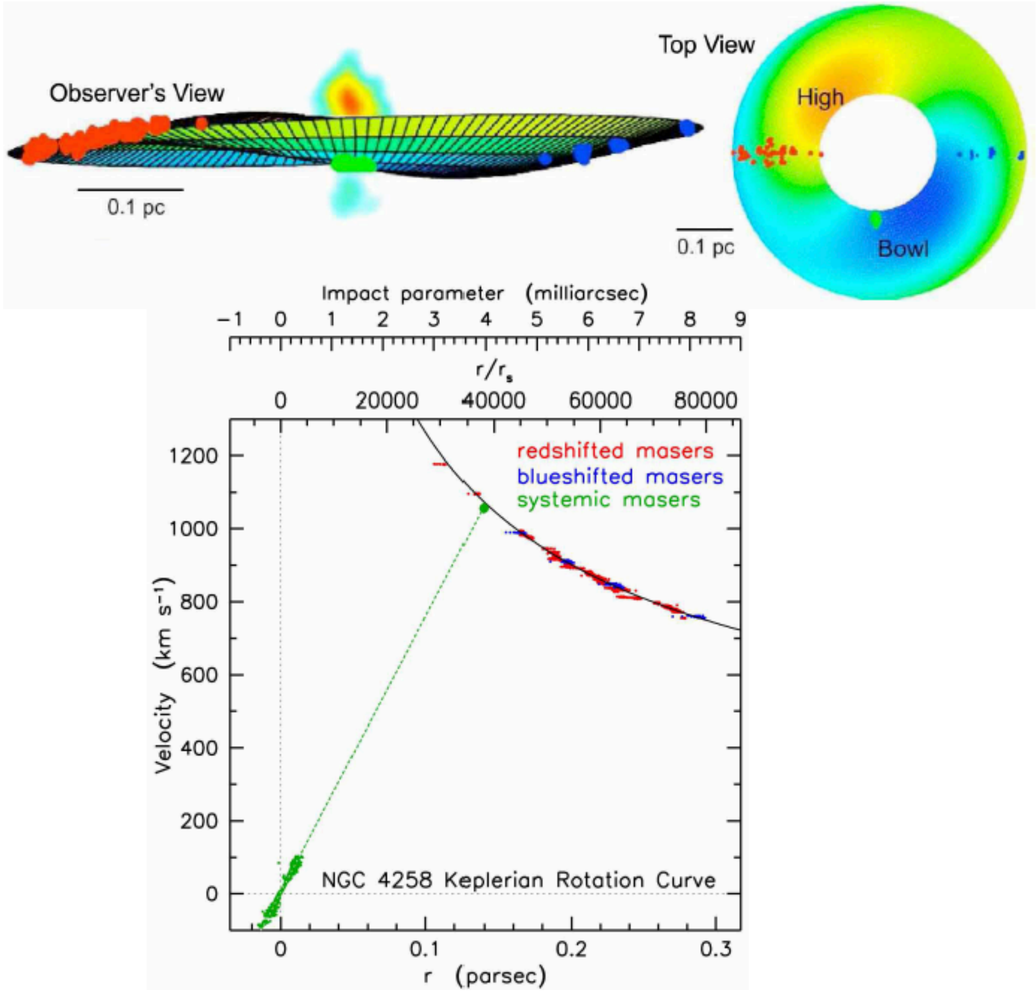


Dynamical Evidence for Supermassive Black Holes



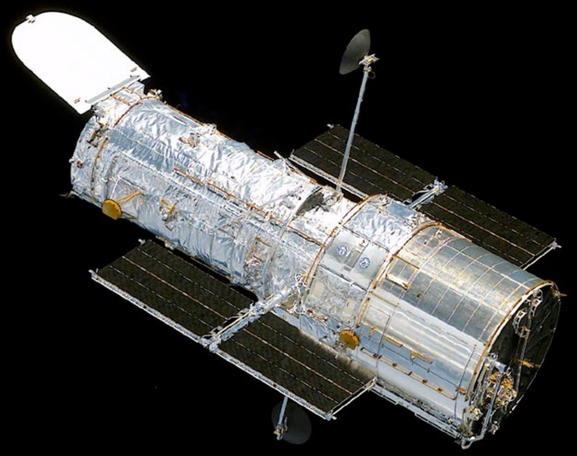
Galactic Center

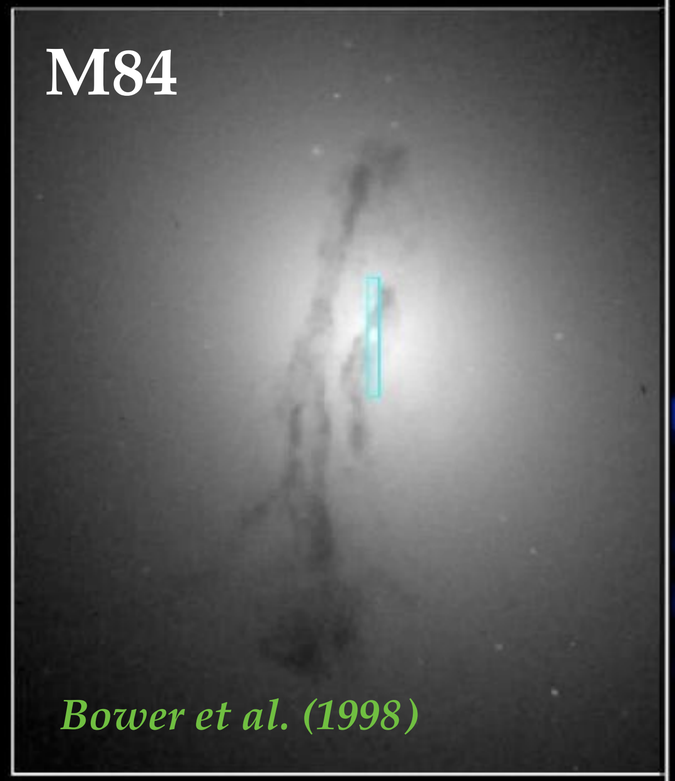
Ghez et al. (2008), Gillessen et al. (2009, 2017)

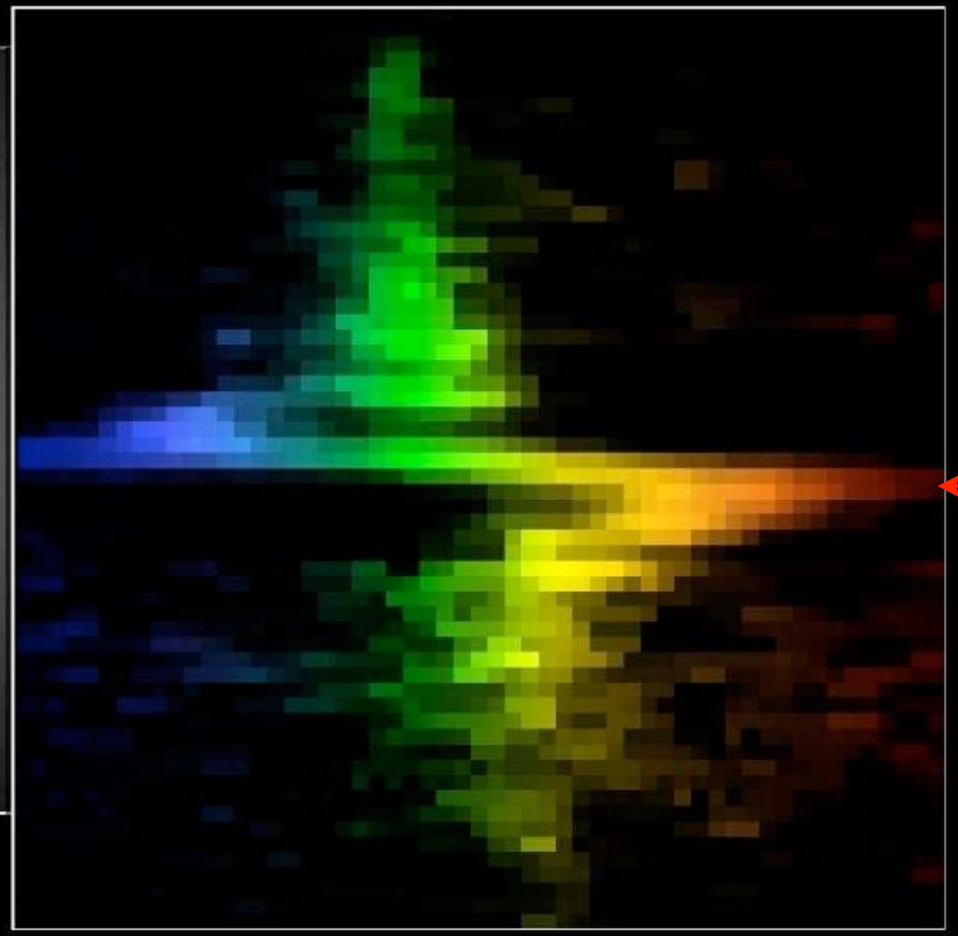


Megamasers in NGC 4258

Miyoshi et al. (1995)

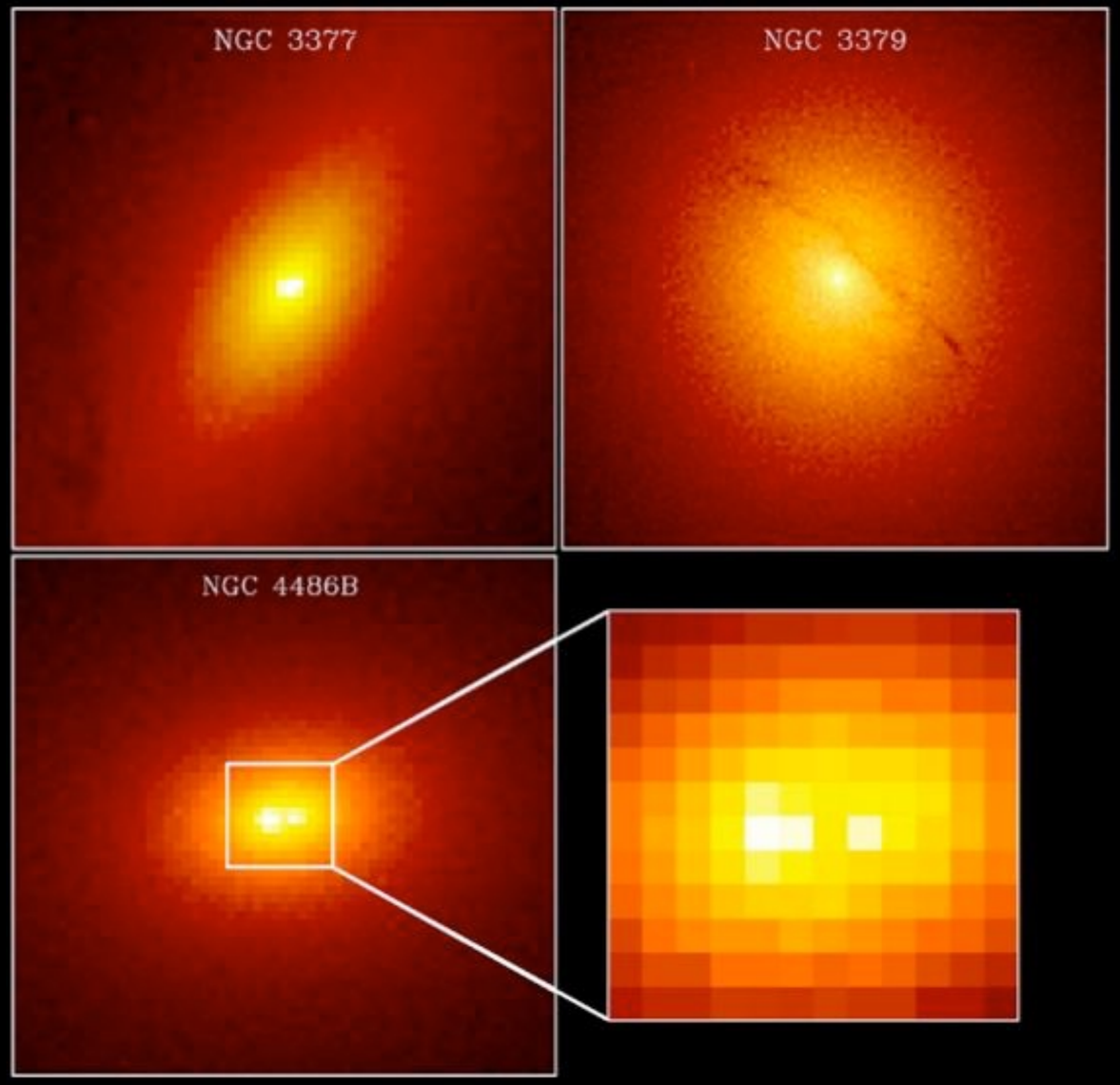


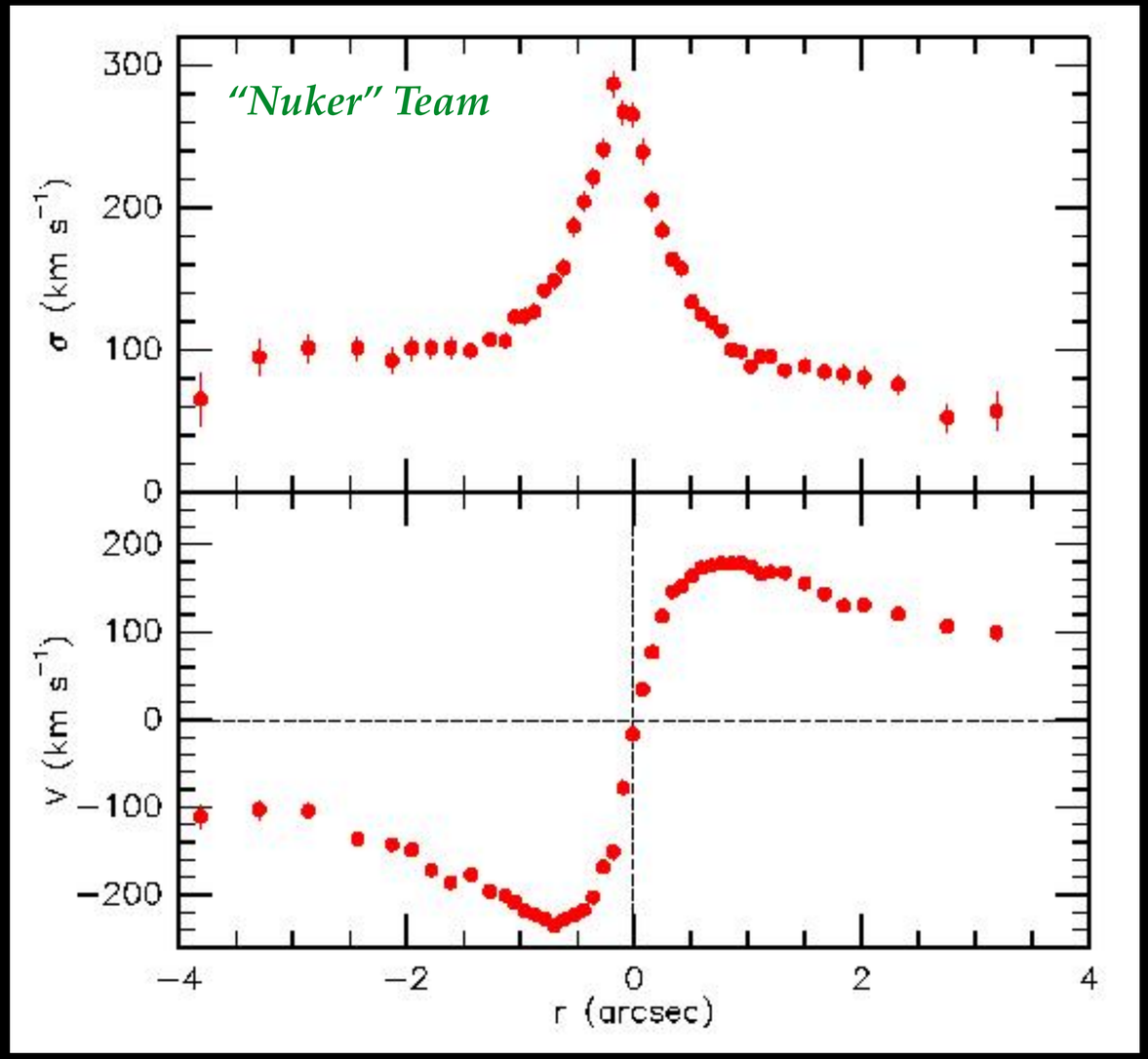


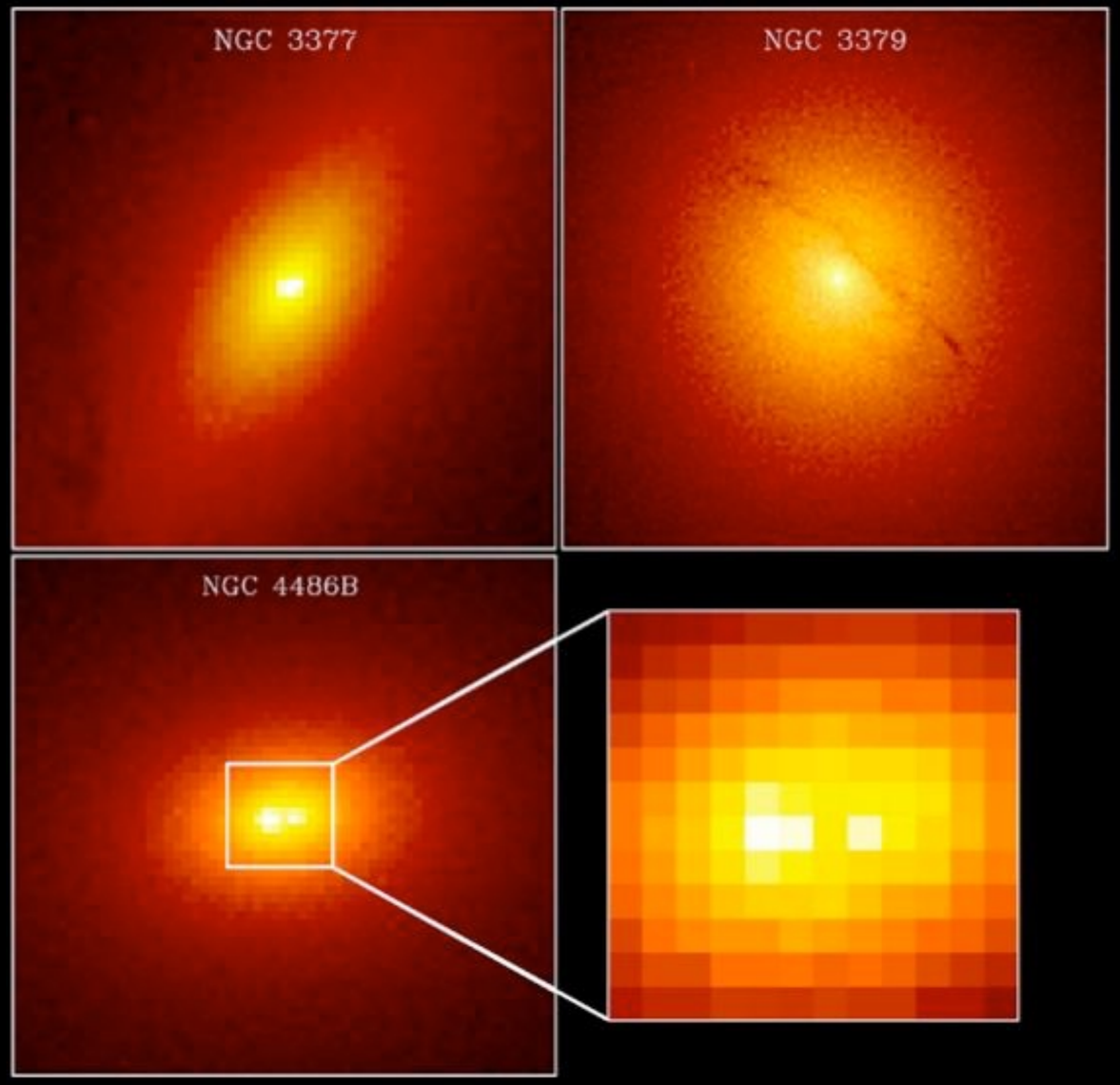


distance from the center

approaching **speed of gas clouds** receding


NGC 3377
NGC 3379
NGC 4486B

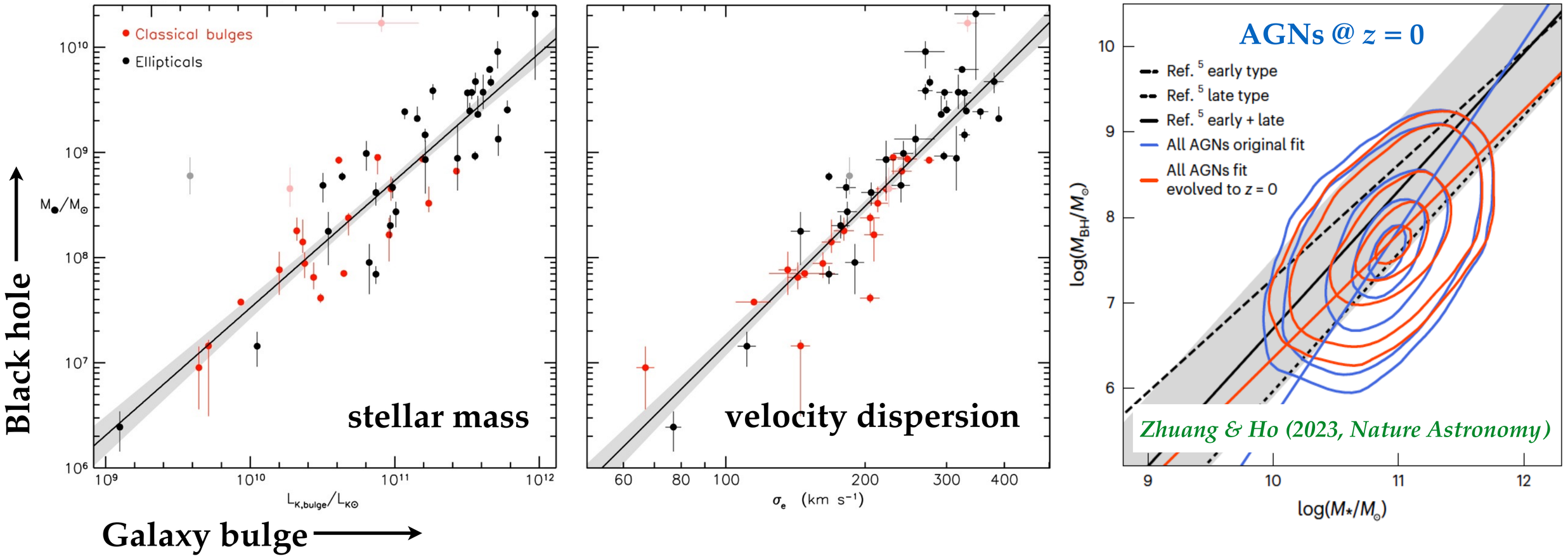

"Nuker" Team
σ (km s⁻¹)
300
200
100
0
V (km s⁻¹)
200
100
0
−100
−200
−4
−2
0
2
4
r (arcsec)



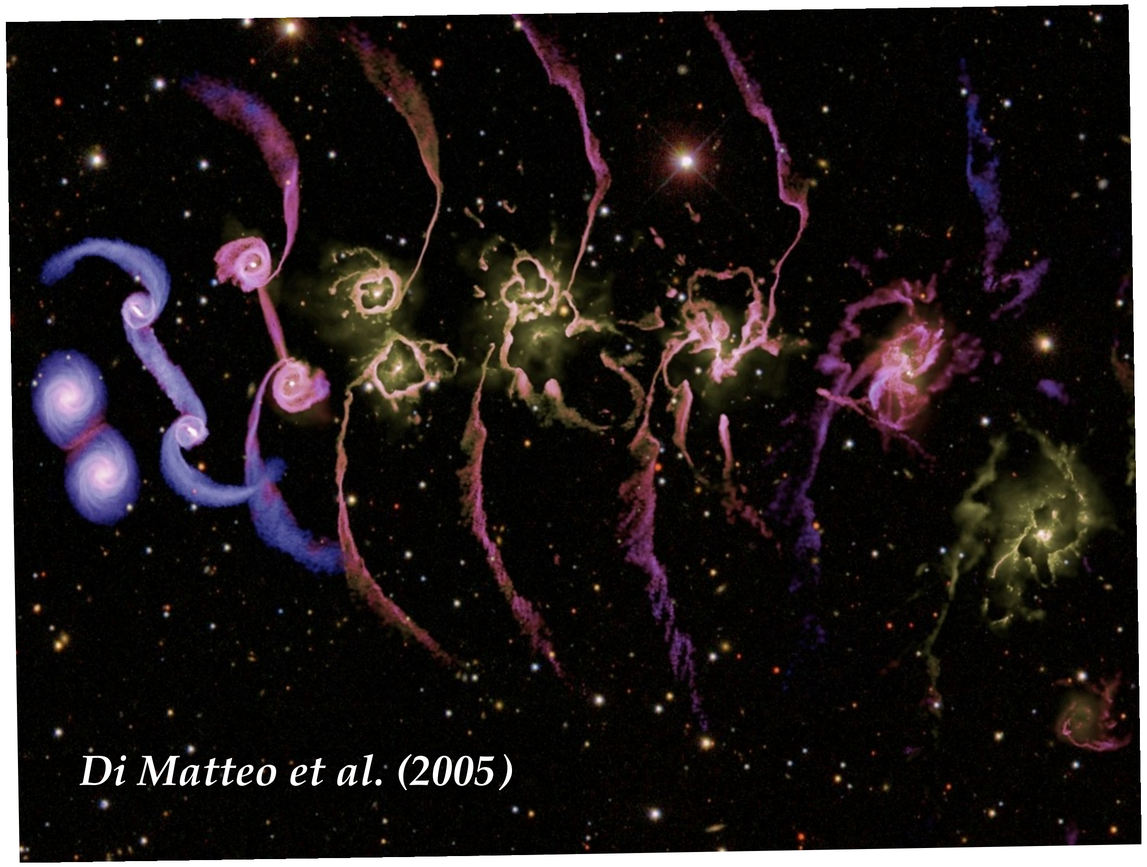
Every bulge has a black hole!

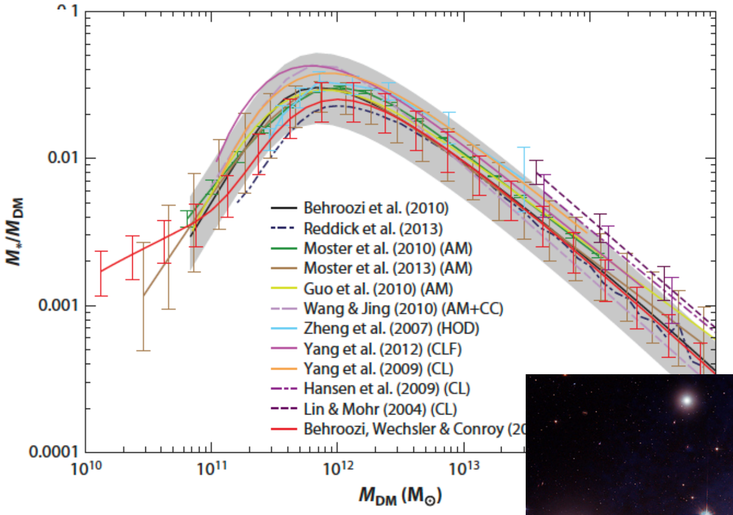
Black Hole – Host Galaxy Scaling Relations

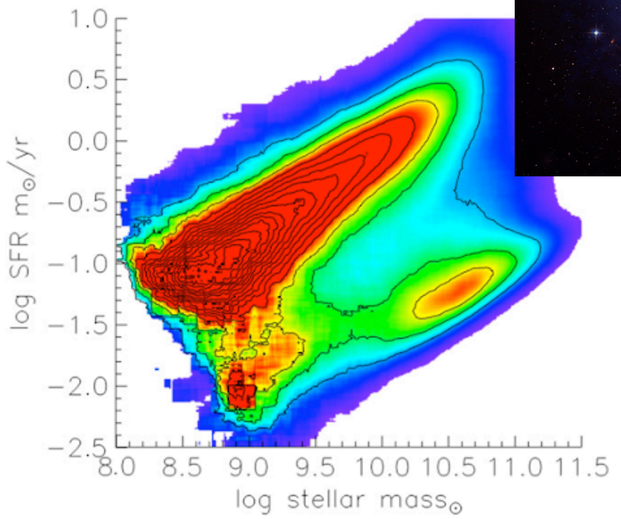
Magorrian+(1998); Gebhardt+(2000); Ferrarese & Merritt (2000); Kormendy & Ho (2013, ARA&A)

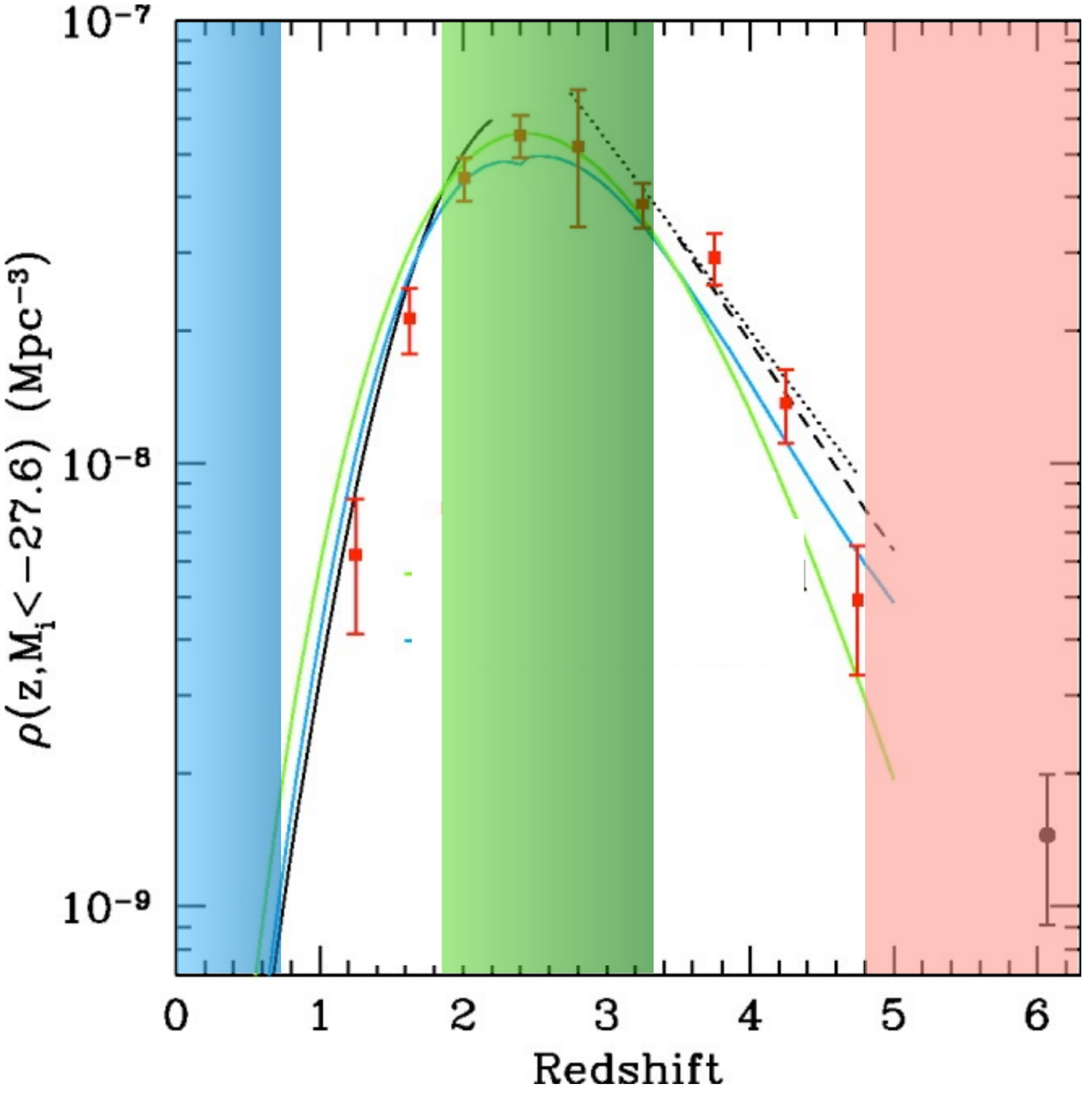


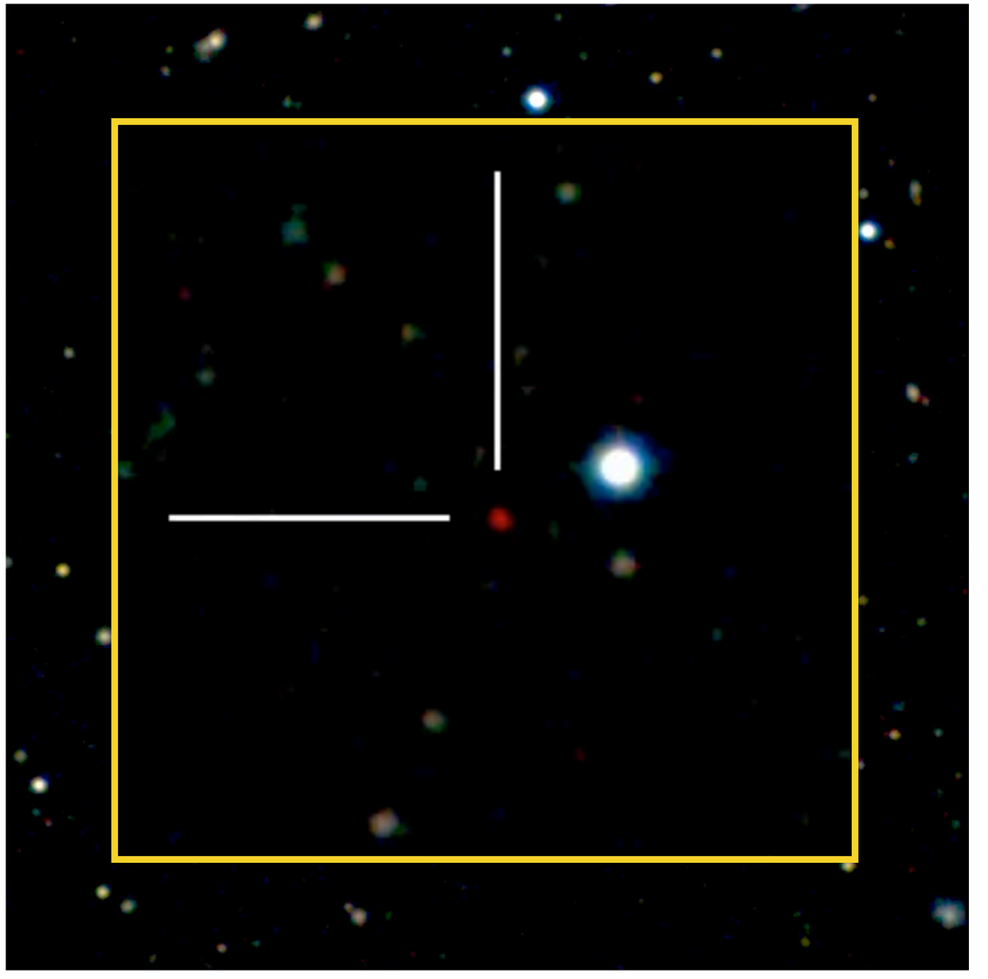
BH-galaxy Coevolution
AGN Feedback

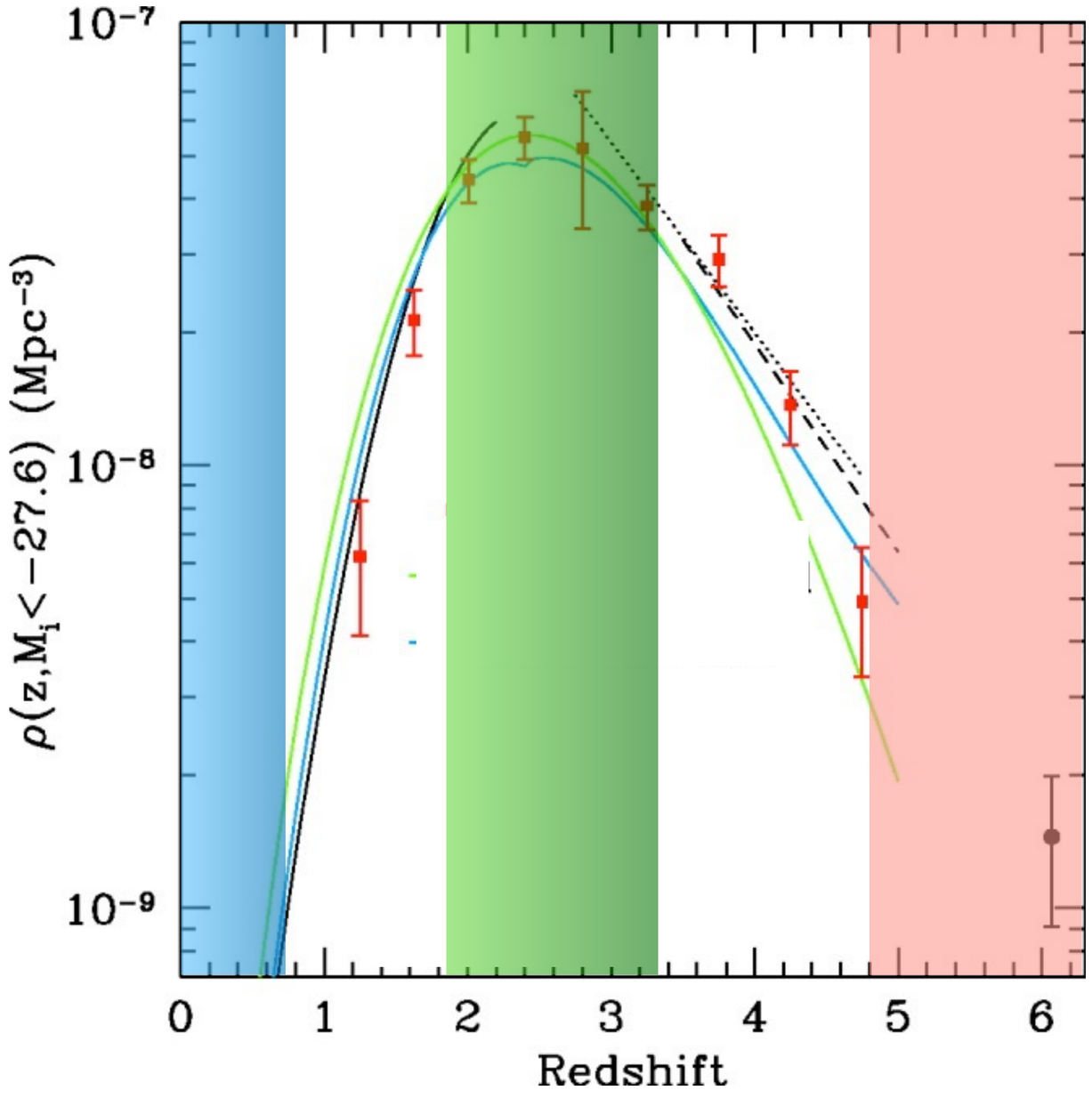


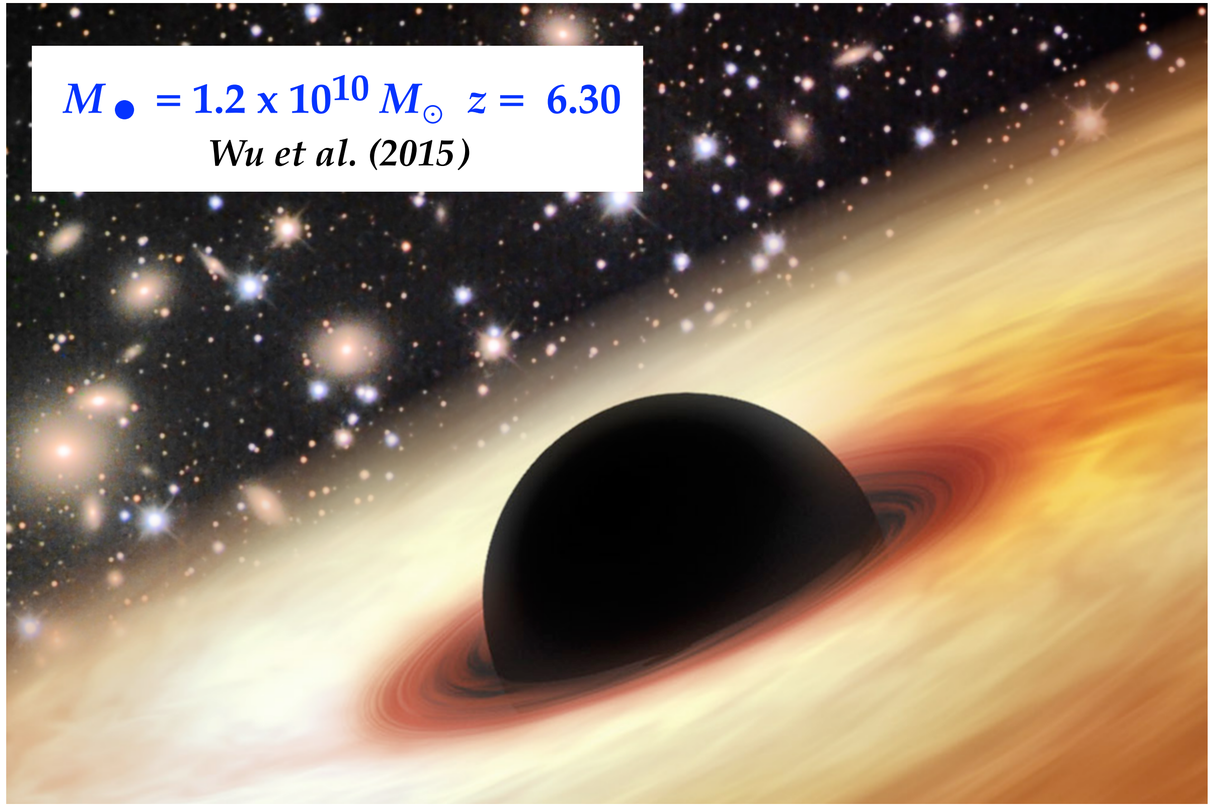


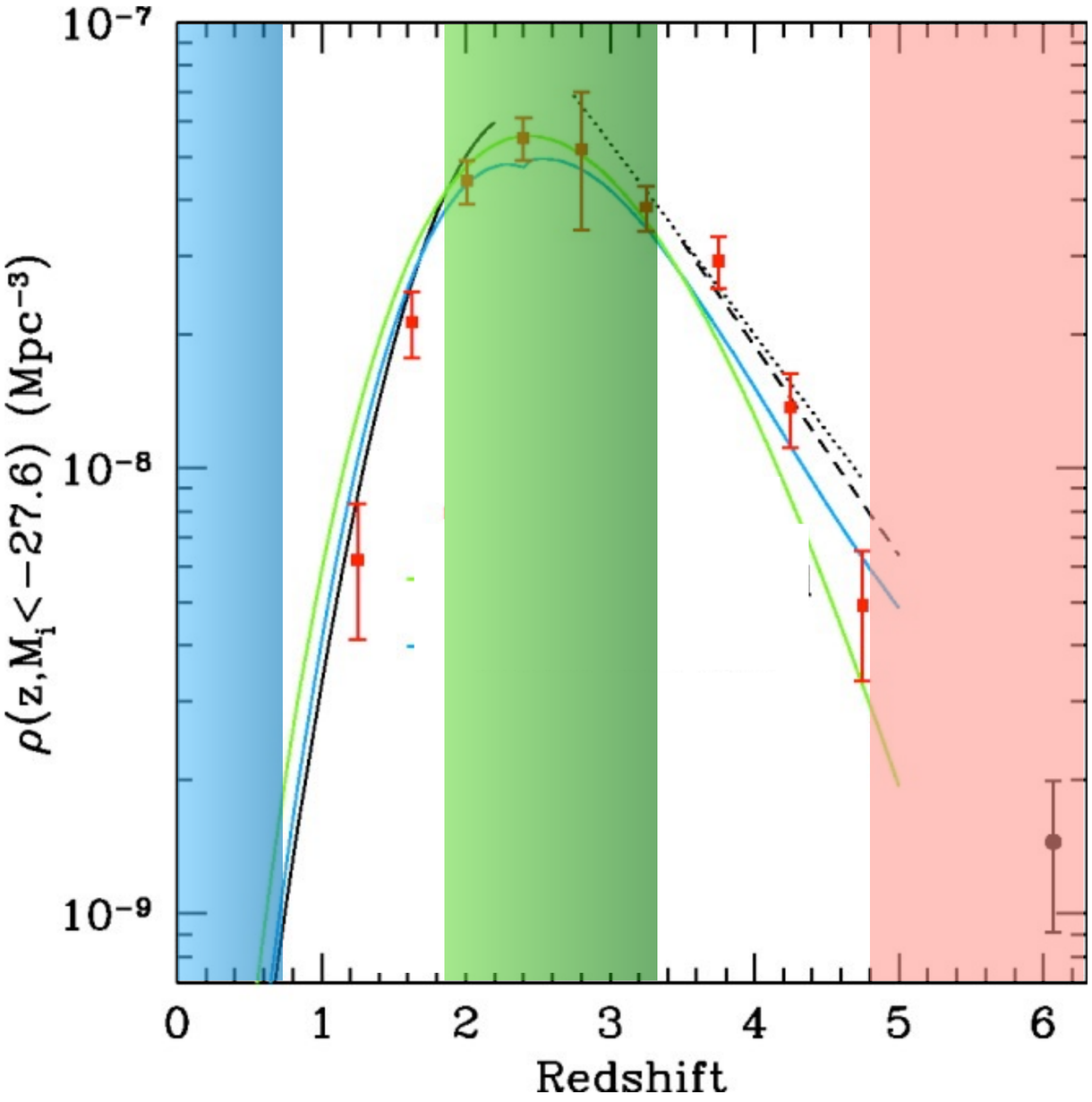


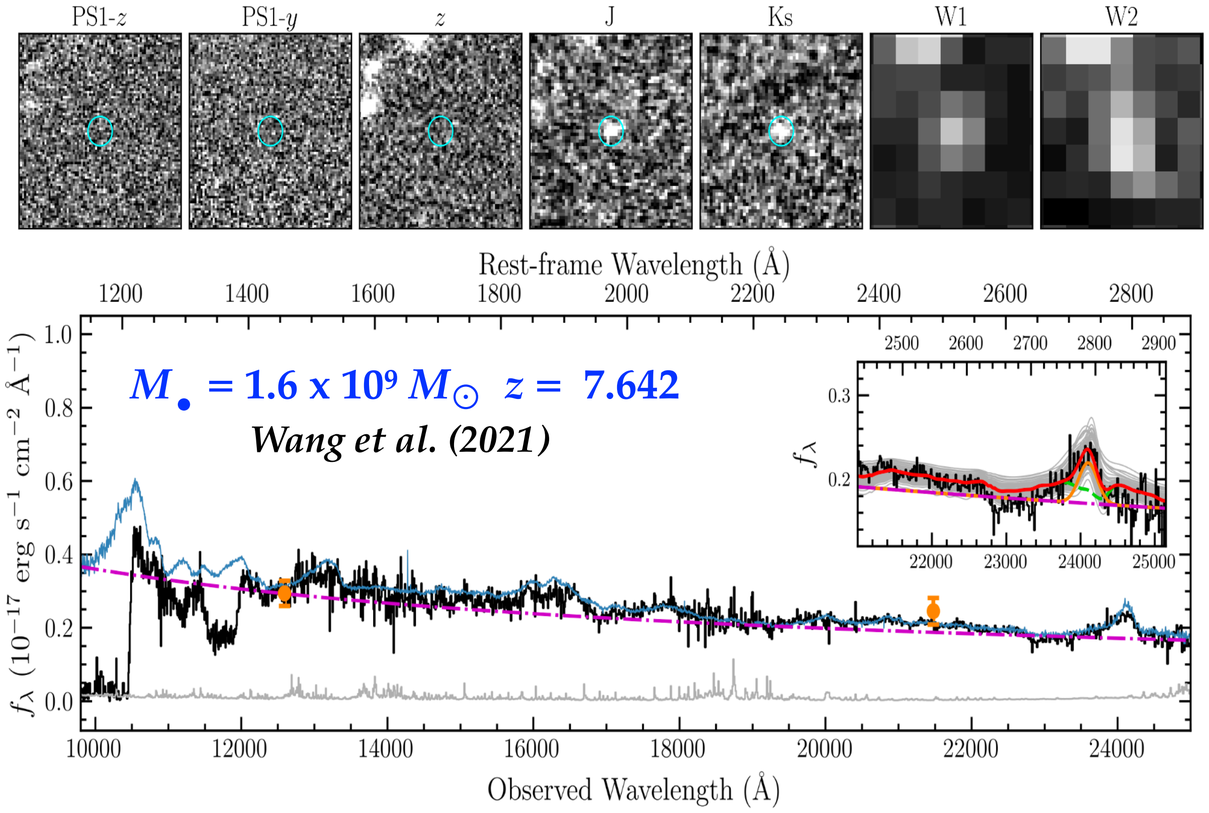

10^{-7}
10^{-8}
10^{-9}
$\rho(z, M_i < -27.6)$ (Mpc^{-3})
0
1
2
3
4
5
6
Redshift

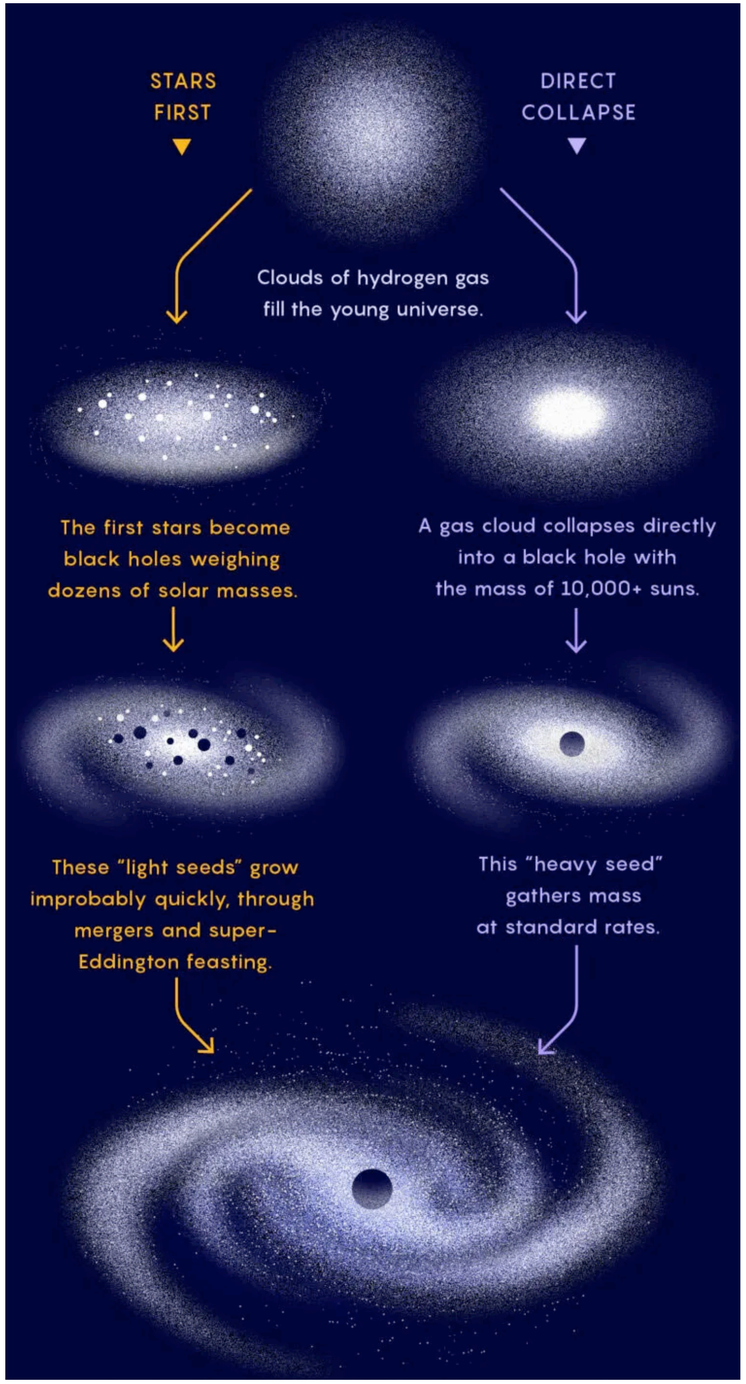



10^{-7}
10^{-8}
10^{-9}
$\rho(z,M_i<-27.6)$ (Mpc^{-3})
0
1
2
3
4
5
6
Redshift


$M_\bullet = 1.2 \times 10^{10} M_\odot$ $z = 6.30$
Wu et al. (2015)


10^{-7}
10^{-8}
10^{-9}
$\rho(z, M_i < -27.6)$ (Mpc^{-3})
0
1
2
3
4
5
6
Redshift

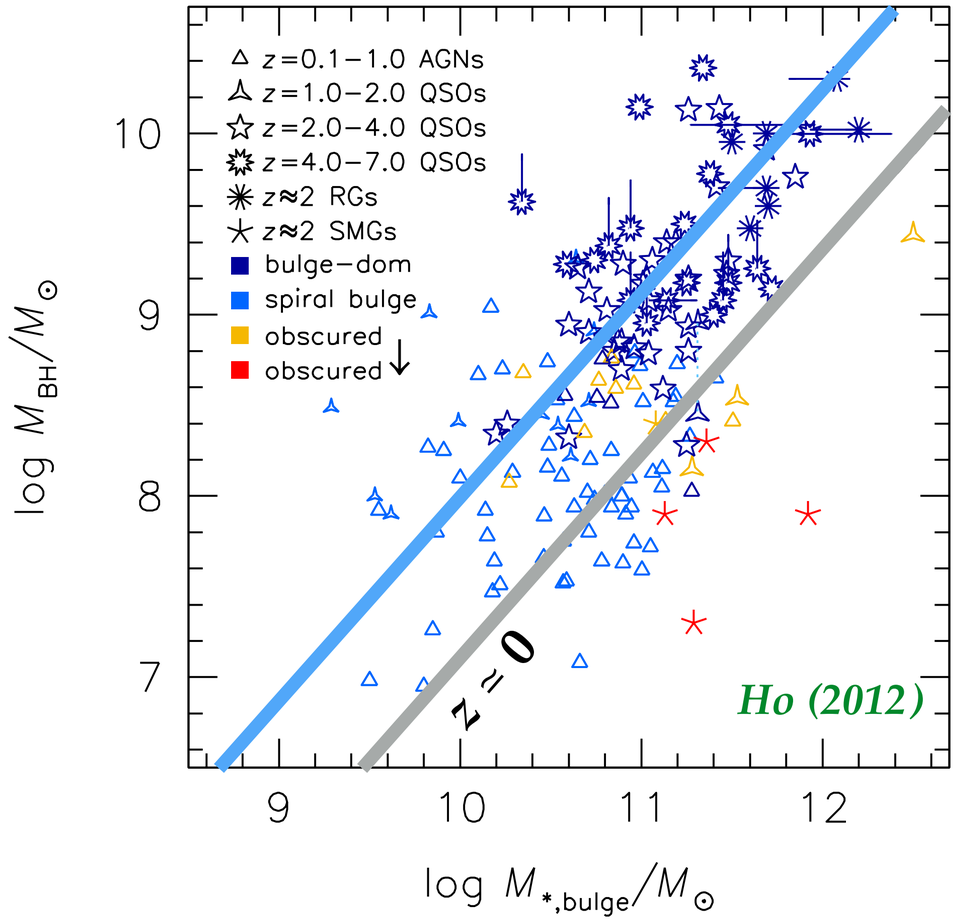

PS1-z
PS1-y
z
J
Ks
W1
W2
Rest-frame Wavelength (Å)
1200
1400
1600
1800
2000
2200
2400
2600
2800
$M_\bullet = 1.6 \times 10^9\, M_\odot$ $z = 7.642$
Wang et al. (2021)
f_λ (10^{-17} erg s^{-1} cm^{-2} Å^{-1})
1.0
0.8
0.6
0.4
0.2
0.0
10000
12000
14000
16000
18000
20000
22000
24000
Observed Wavelength (Å)
2500
2600
2700
2800
2900
0.3
0.2
f_λ
22000
23000
24000
25000



GROWING THE FIRST SUPERMASSIVE BLACK HOLES

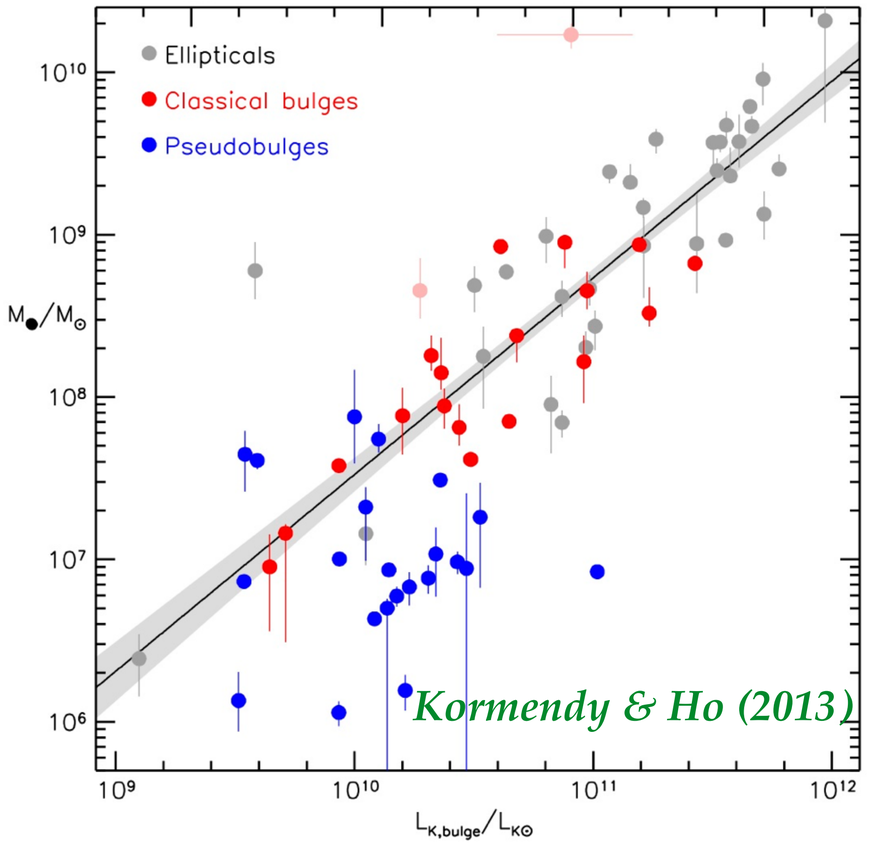
When and how were BH-galaxy scaling relations established? How did they evolved?

$z \simeq 2-7$



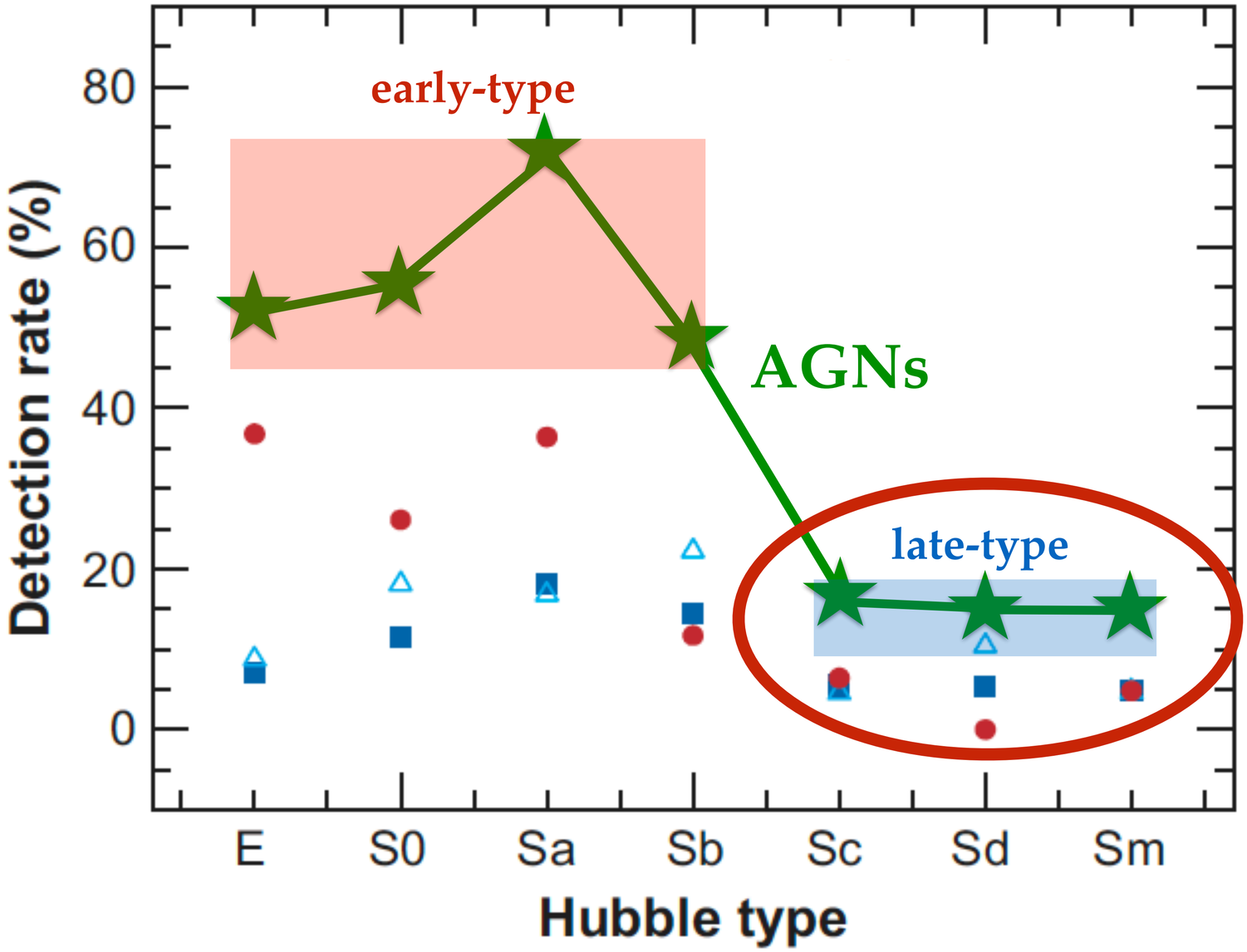
?

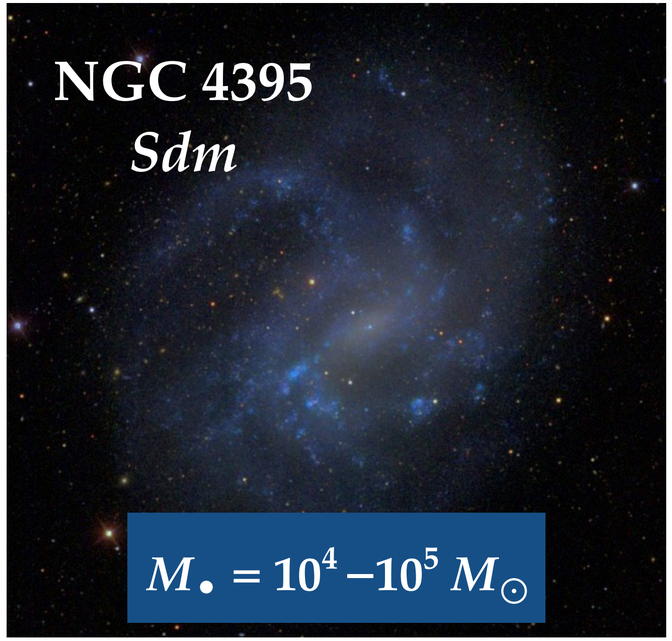
$z \simeq 0$

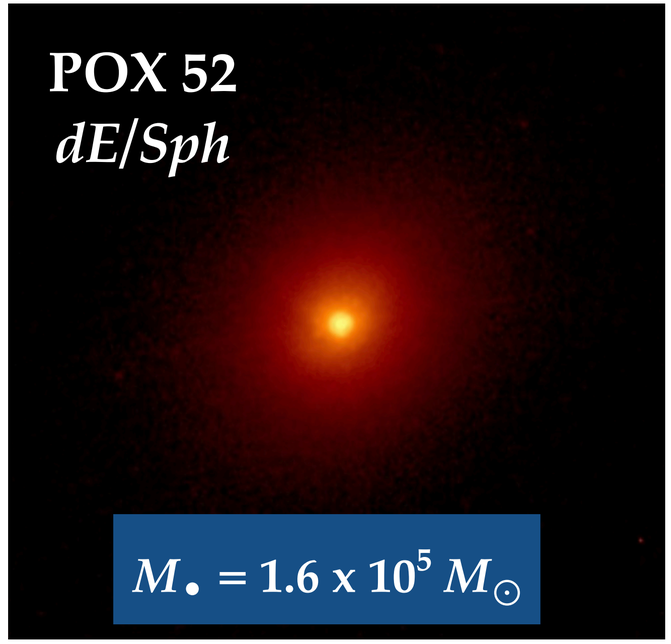


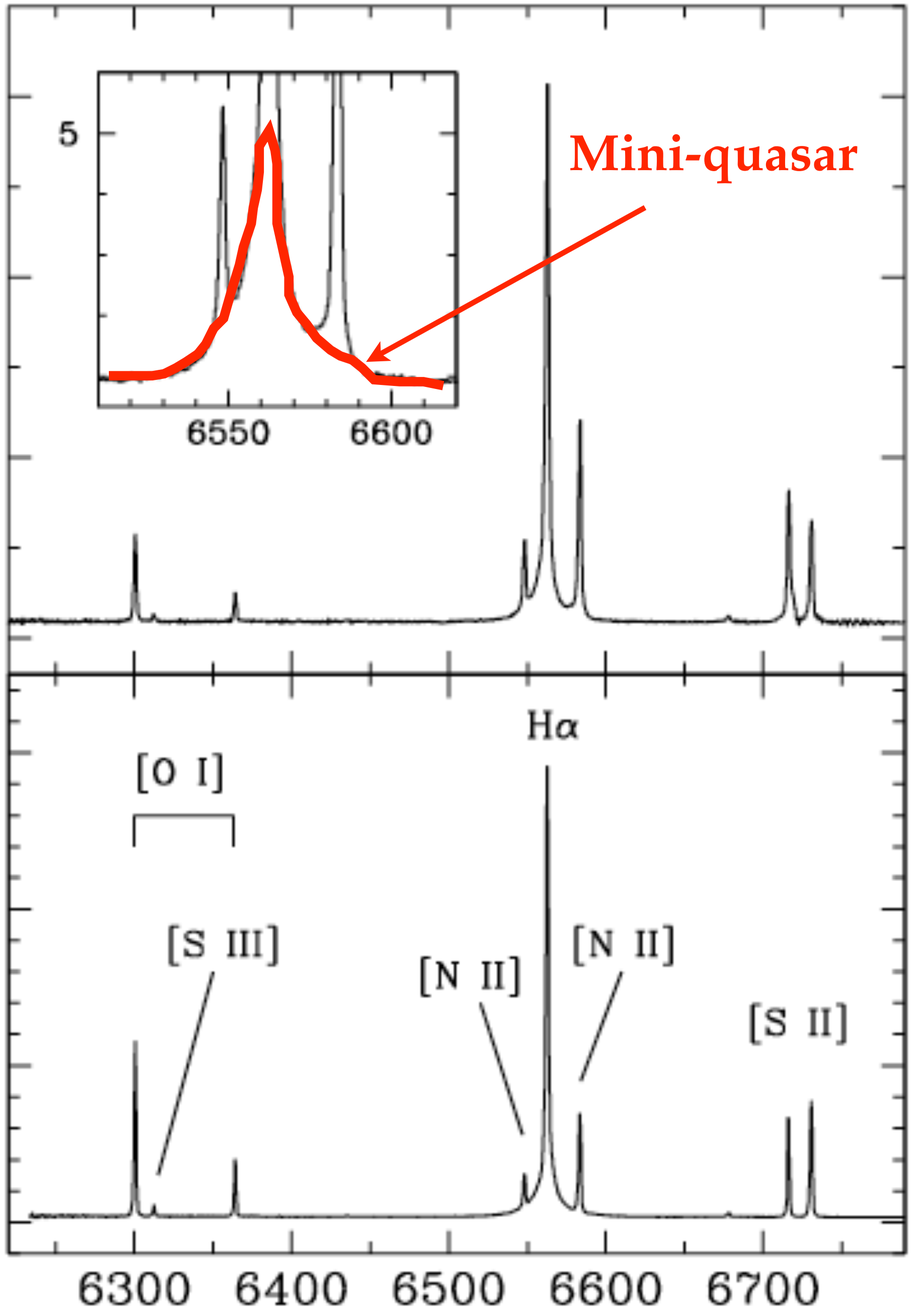
Palomar Spectroscopic Survey of Nearby Galaxies

Ho, Filippenko & Sargent (1993-2009), Ho (2008, ARA&A)

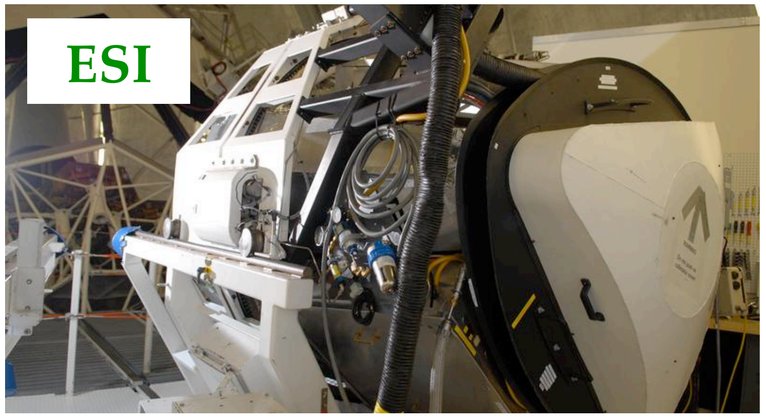




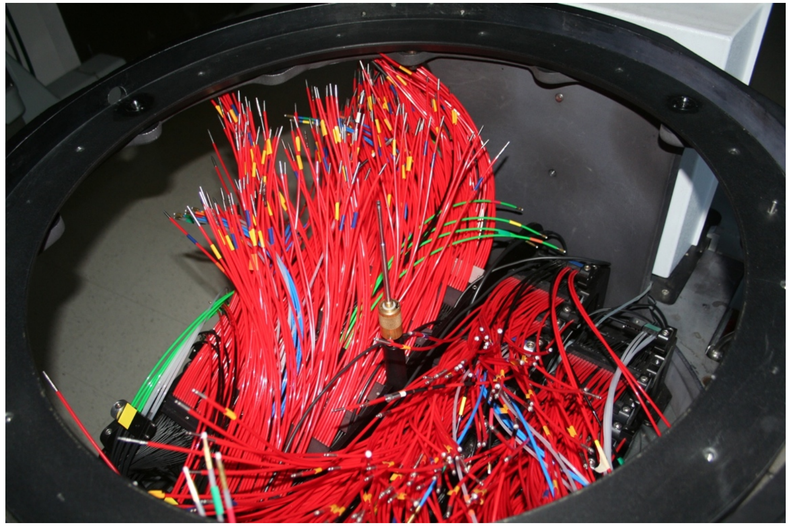




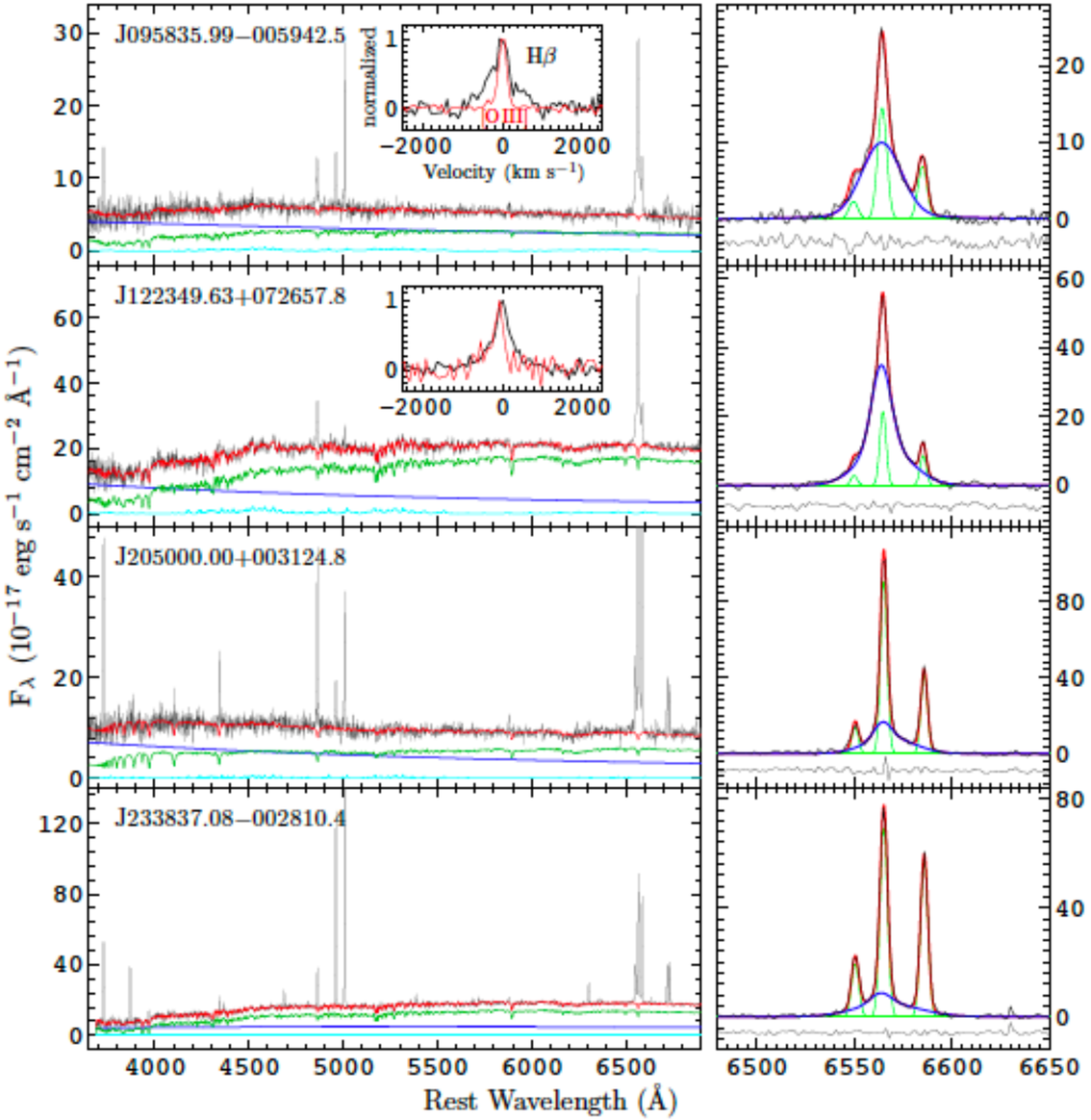
Filippenko, Ho & Sargent (1993)
Filippenko & Ho (2003)

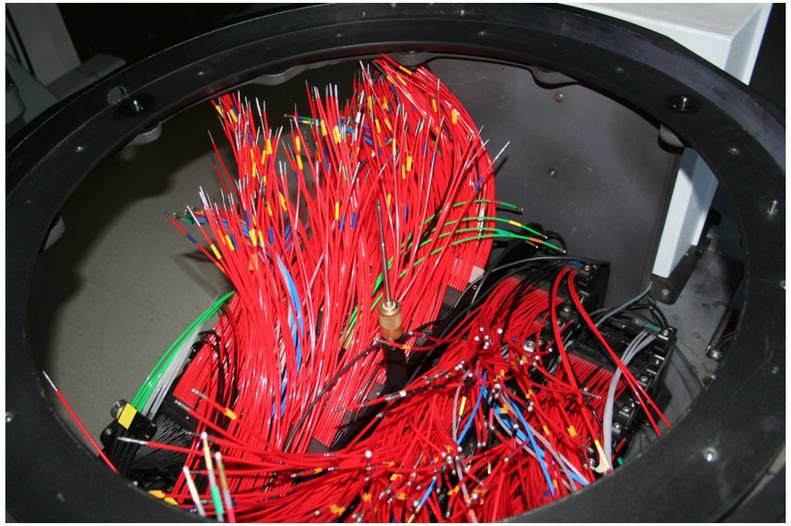


Barth, Ho et al. (2004)

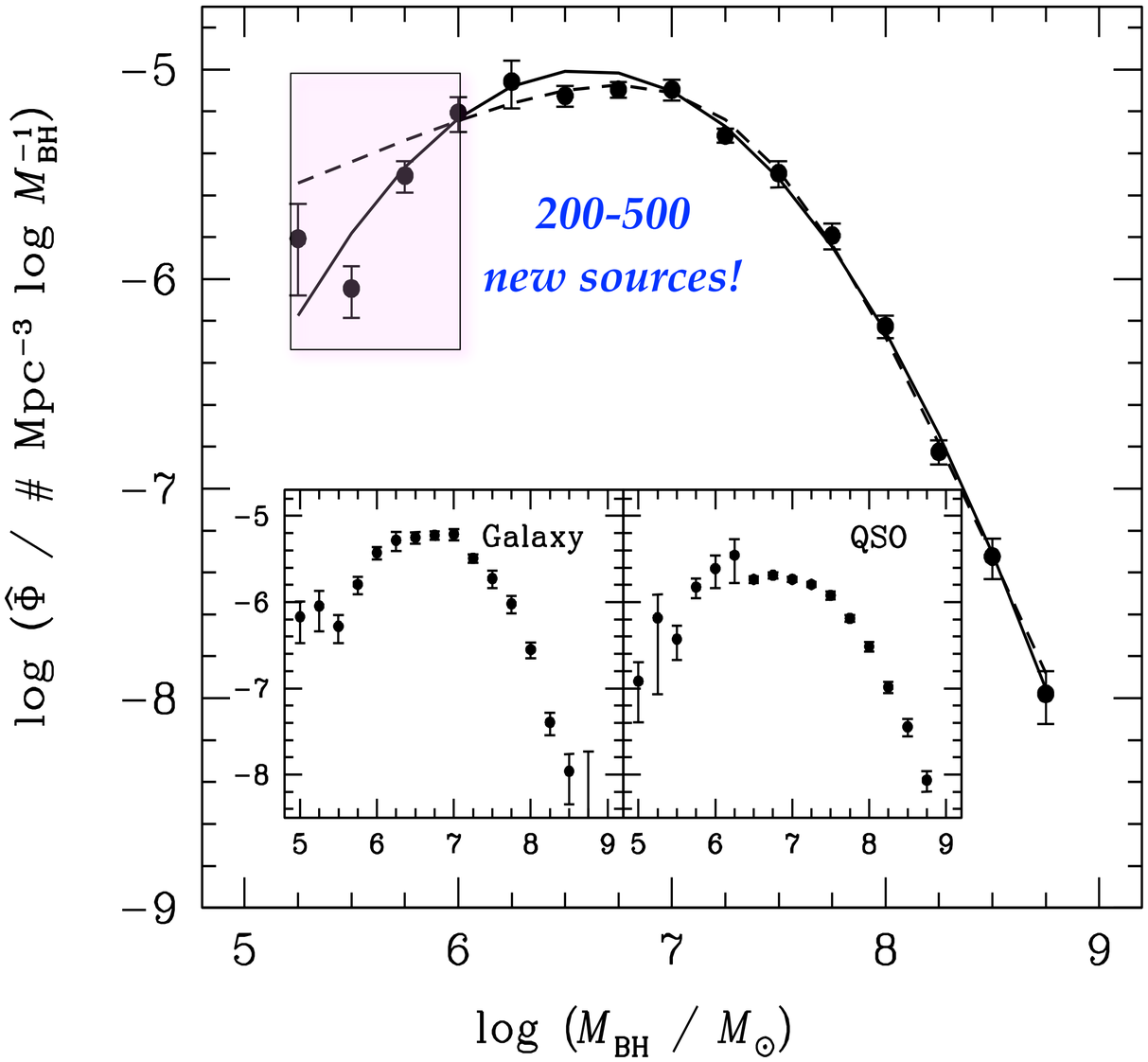


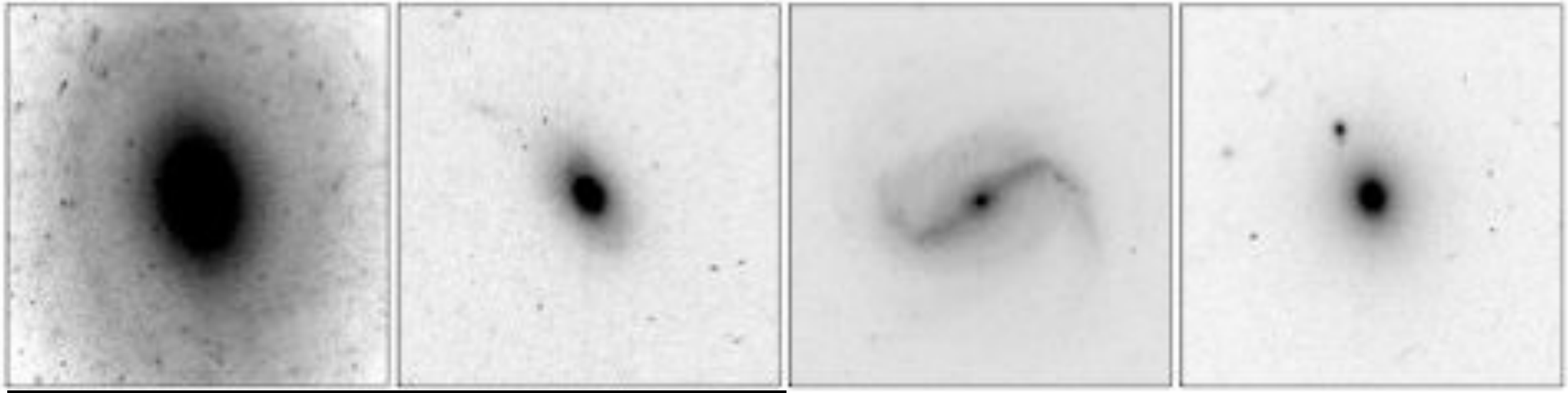
Dong, Ho, Yuan et al. (2012)





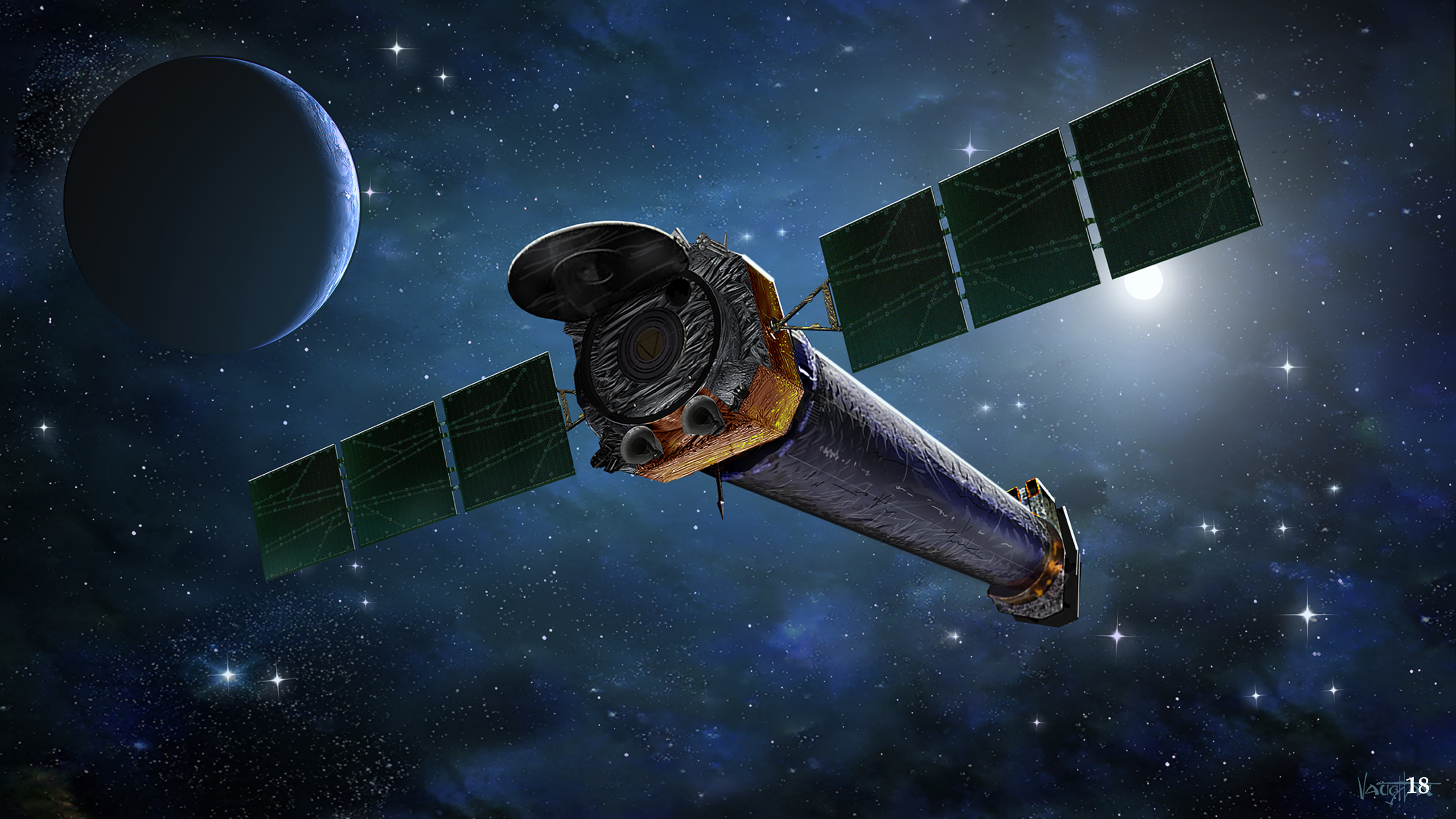
Greene & Ho (2004, 2007a, 2007b)





Under-developed galaxies hosting under-developed, "intermediate-mass" black holes

Greene, Ho & Barth (2008)
Jiang, Greene & Ho (2011a, 2011b)

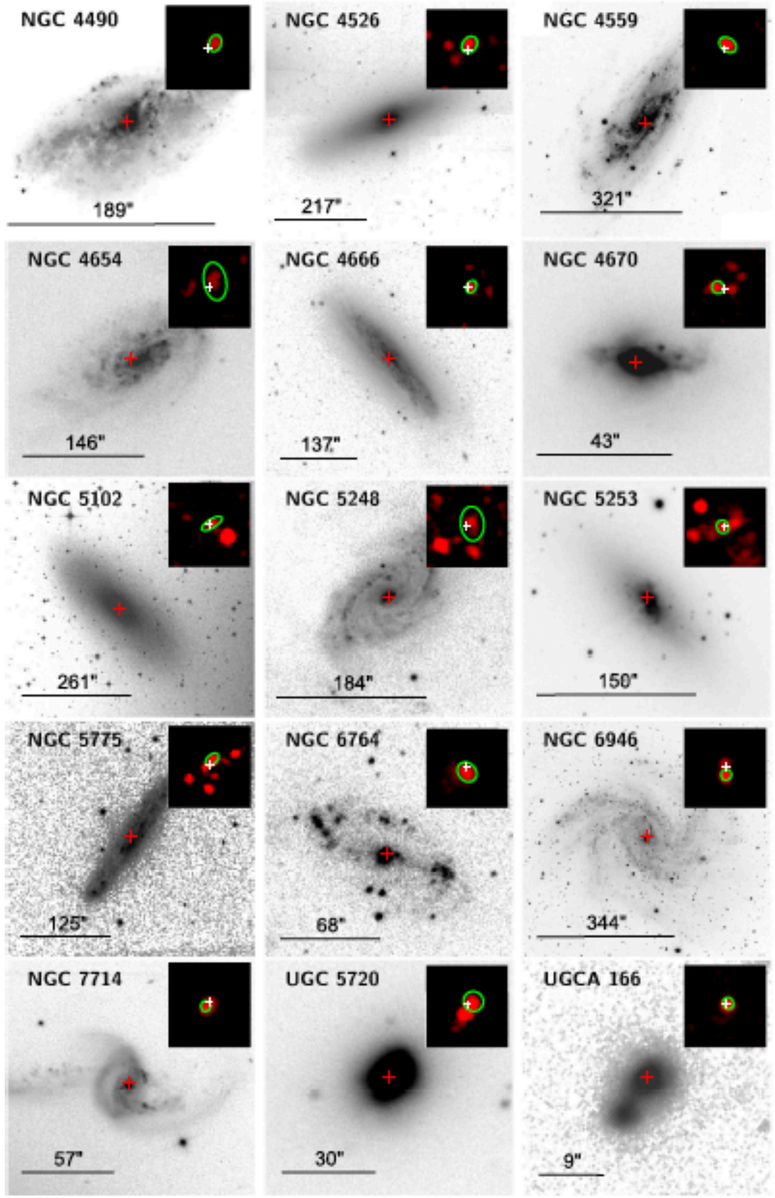


Optical

X-rays

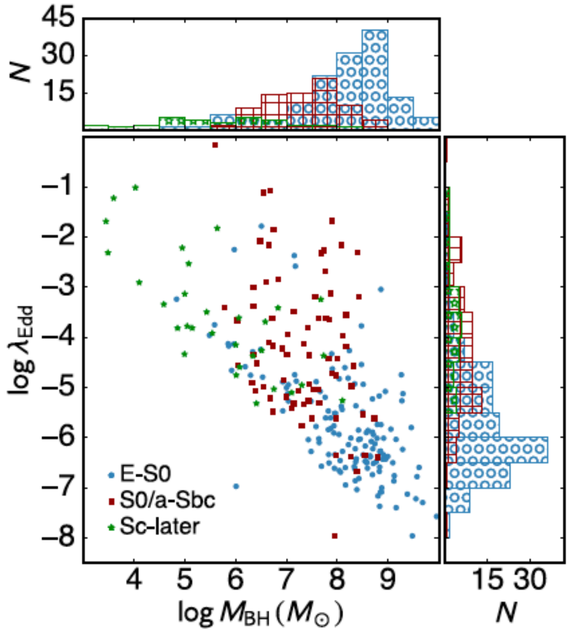
Searching for Intermediate-mass Black Holes with X-rays

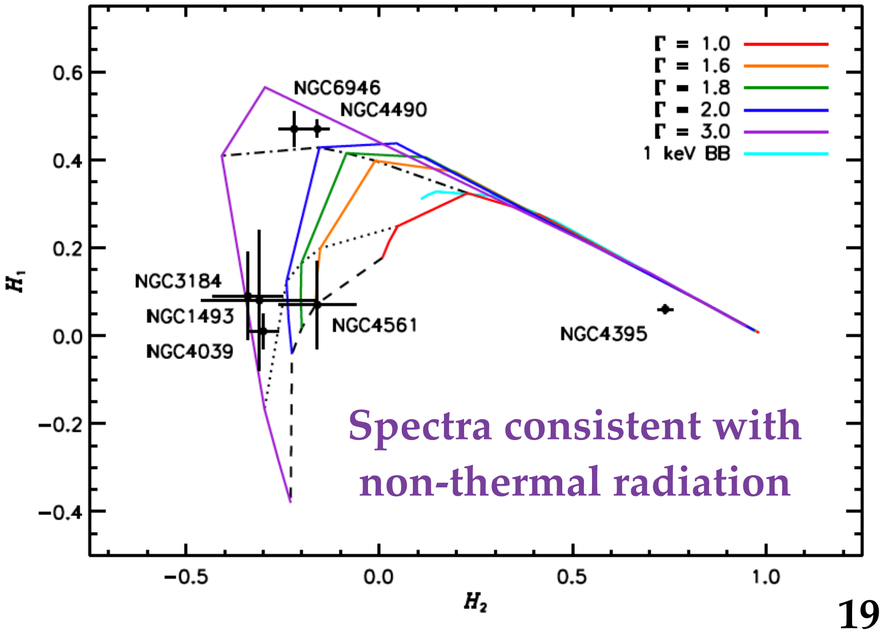
Desroches & Ho (2009); She, Ho & Feng (2017a, 2017b); Bi, Feng, & Ho (2021)



Chandra Survey of Nearby Galaxies

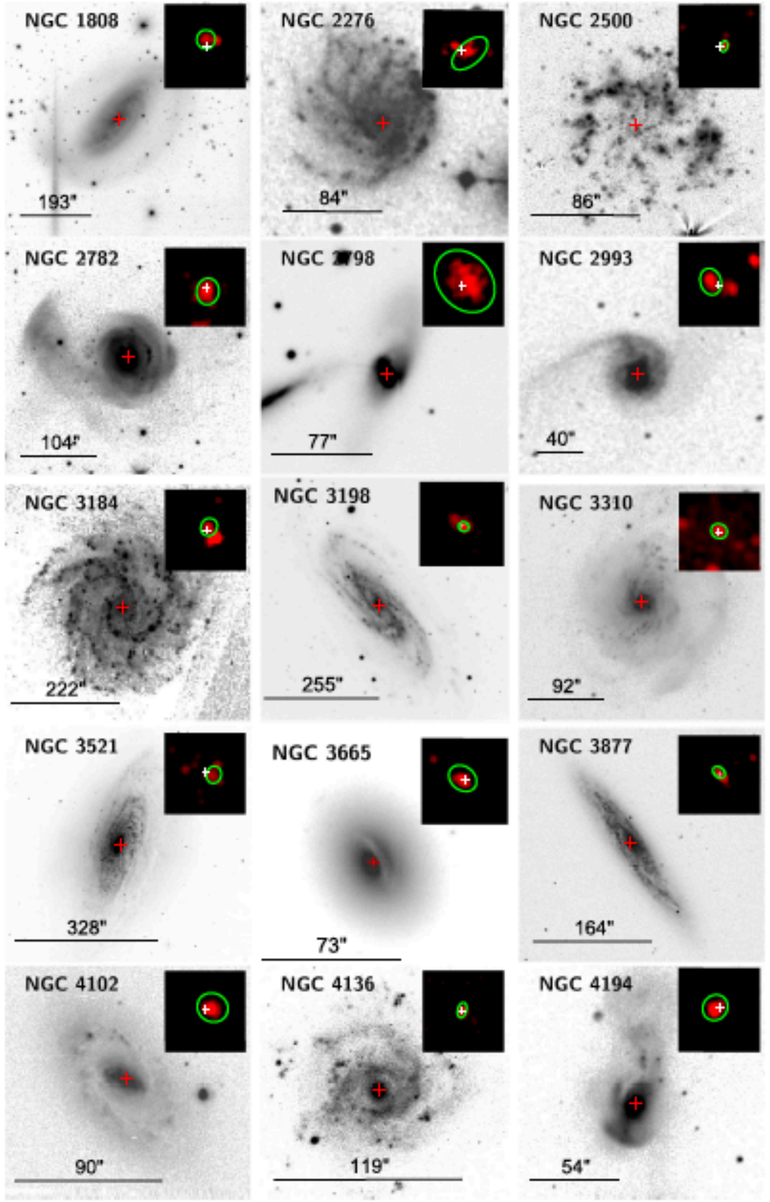
- Sample: 1962 galaxies < 150 Mpc
- 782 active galaxies
- Detection rate in late-type galaxies 28%, much larger than optical detection rate
- Some classified as star-forming galaxies
- Low Eddington ratios





Searching for Intermediate-mass Black Holes with X-rays

Desroches & Ho (2009); She, Ho & Feng (2017a, 2017b); Bi, Feng, & Ho (2021)



Chandra Survey of Nearby Galaxies

- Sample: 1962 galaxies < 150 Mpc
- 782 active galaxies
- Detection rate in late-type galaxies 28%, much larger than optical detection rate
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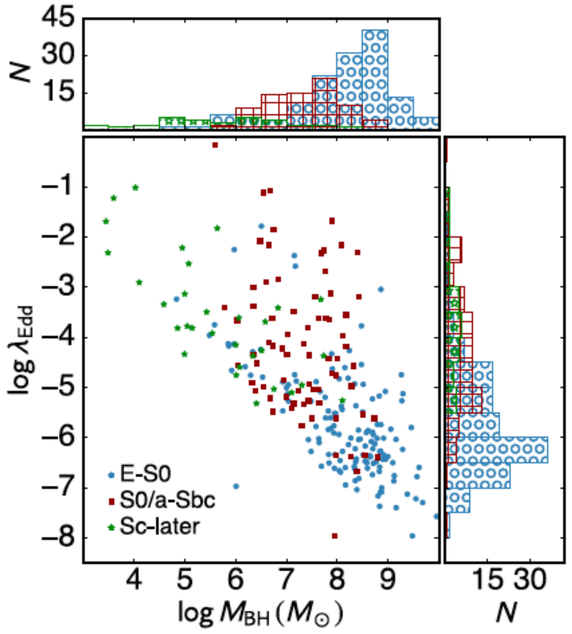
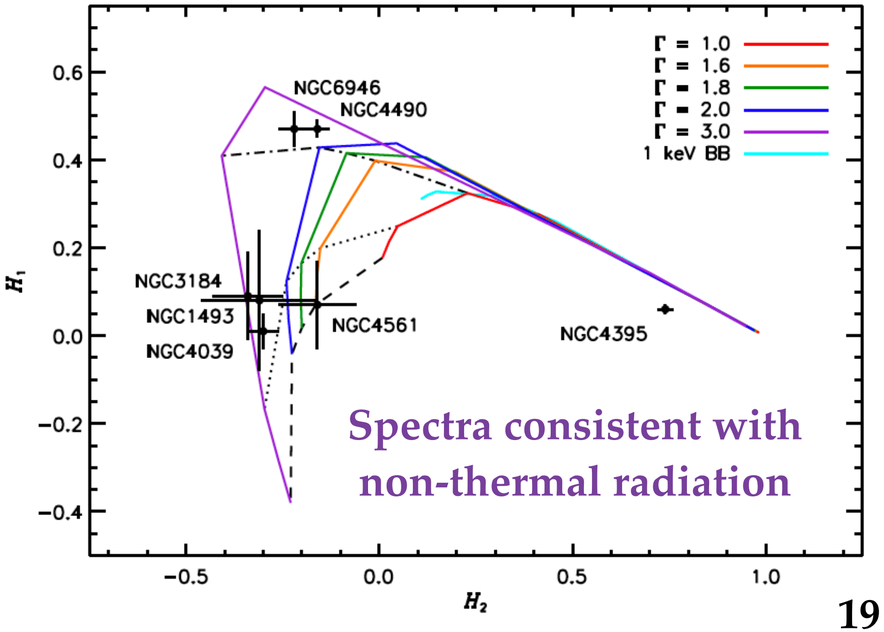
- Low Eddington ratios





Spectra consistent with non-thermal radiation

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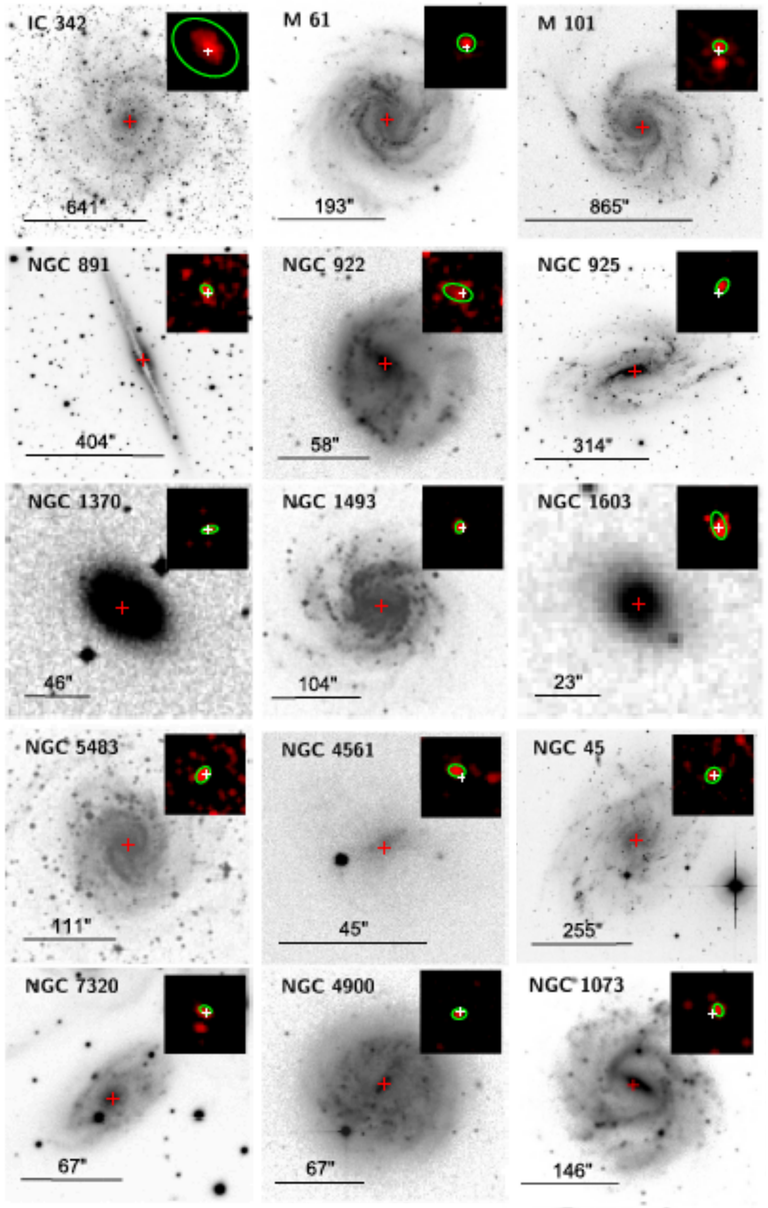

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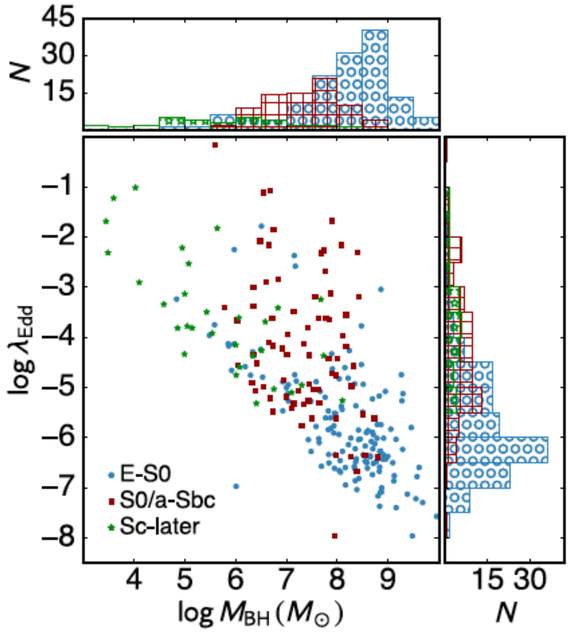
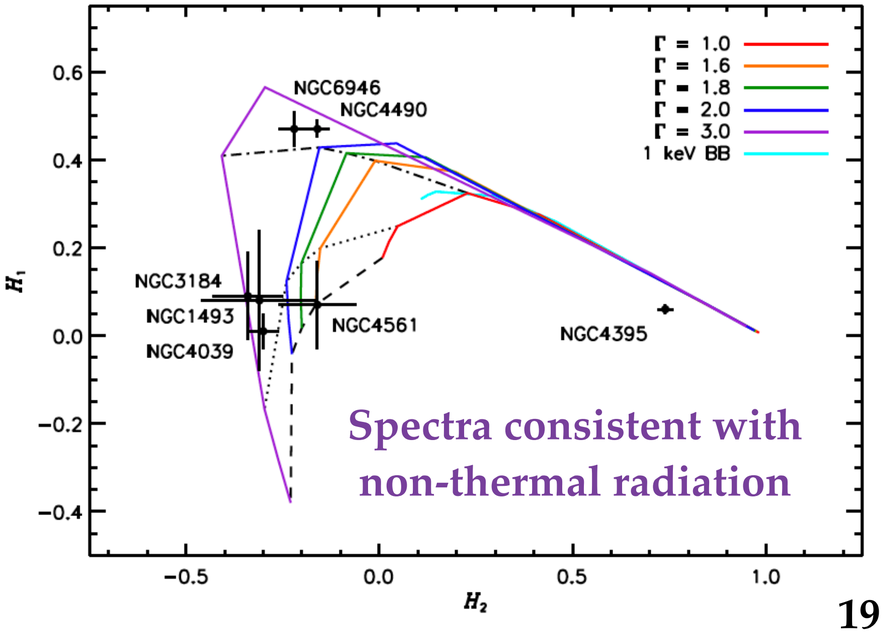
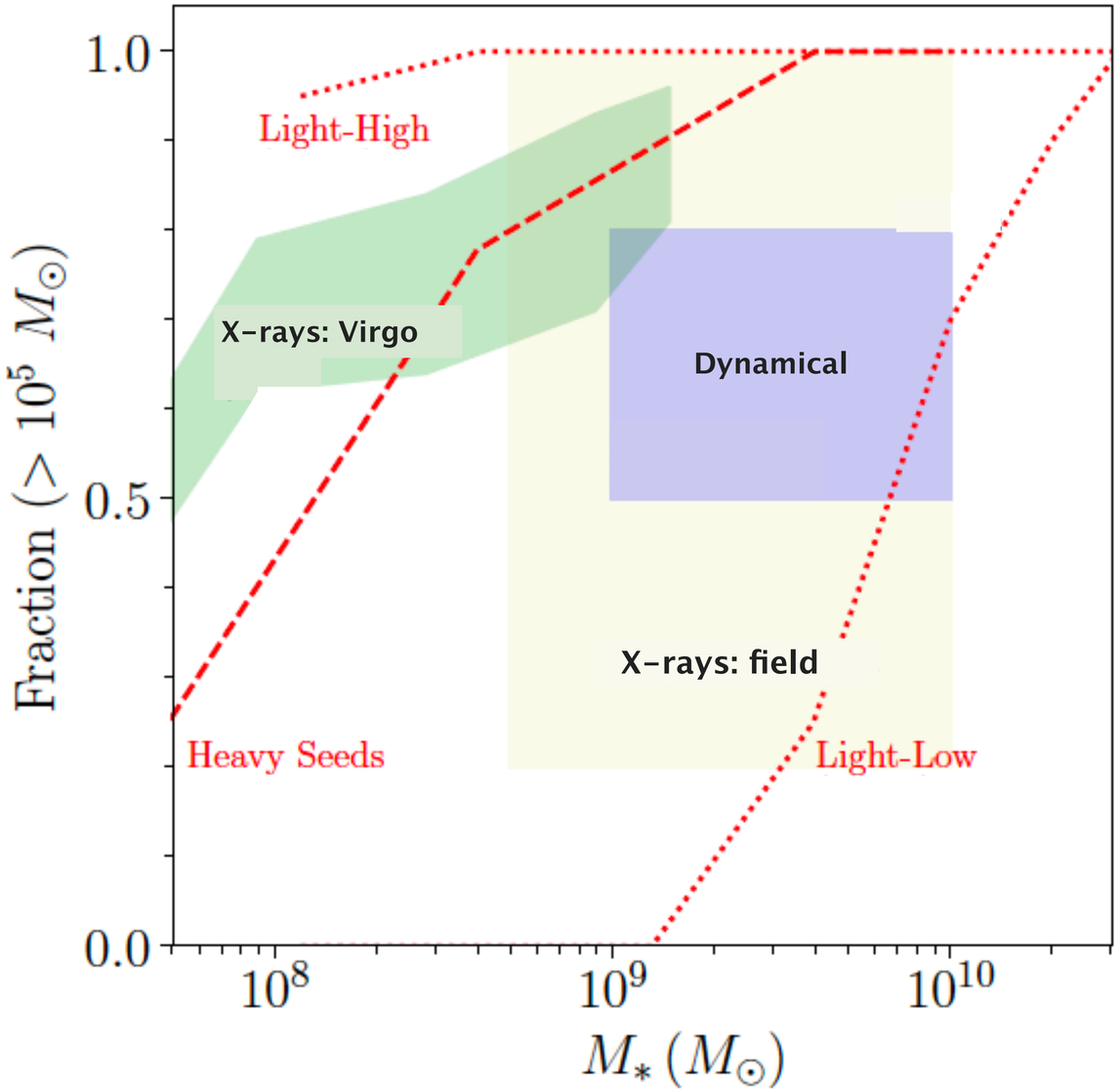




Spectra consistent with non-thermal radiation

Demographics of Intermediate-mass Black Holes

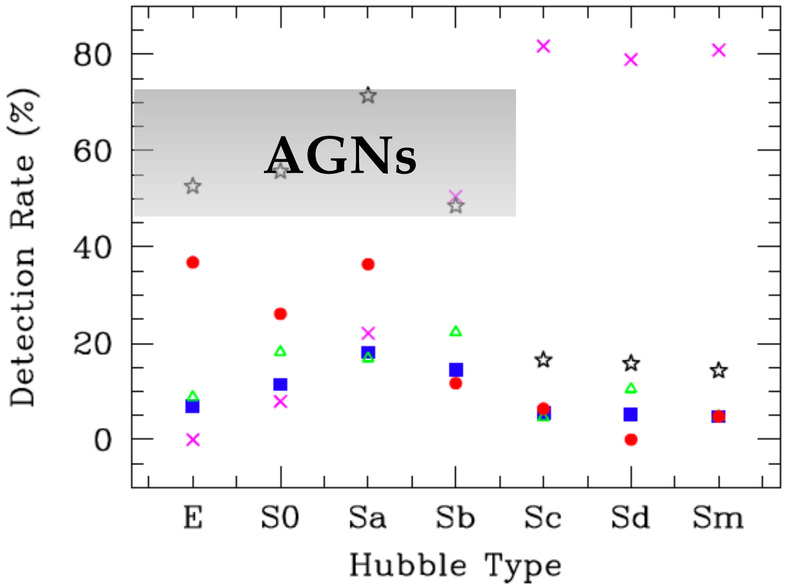
Greene, Strader & Ho (2020, ARA&A)



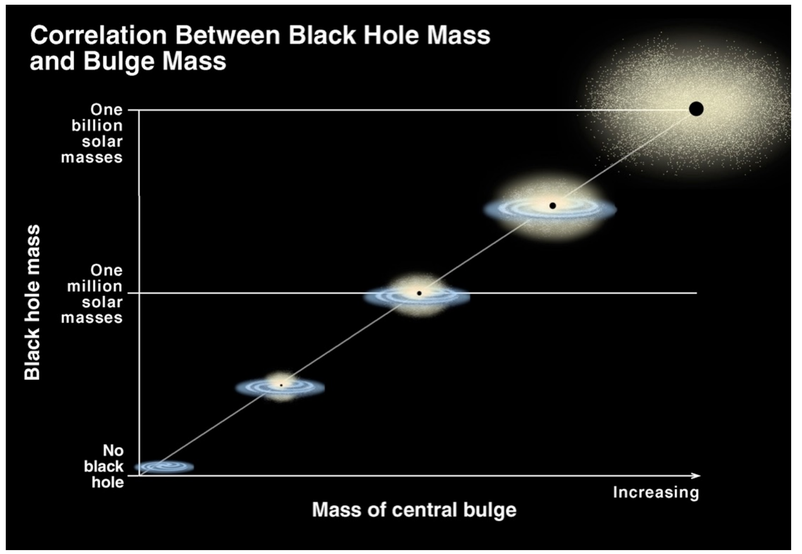
- $M_\bullet \approx 10^5 - 10^6\ M_\odot$
- $M_* \approx 10^8 - 10^{10}\ M_\odot$
- **Occupation fraction of IMBHs ≳ 50%**
- **Consistent with theory:**
  - **"Light seeds" (population III stars)**
  - **"Heavy seeds" (direct collapse)**
- **Dependent on accretion and merging history of seeds**

Demographics of Central Black Holes @ $z = 0$

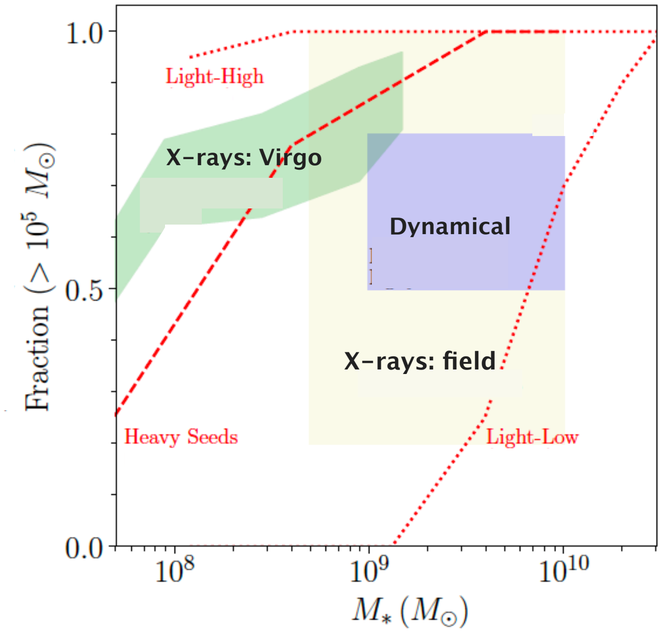
- In bulge galaxies, AGN detection rate ~70%: lower limit on BH occupation fraction.
- In $M_* > 10^{10}\,M_\odot$ galaxies, occupation fraction ~100% for SMBHs with $M_\bullet \approx 10^6 - 10^{10}\,M_\odot$.
- In $M_* < 10^{10}\,M_\odot$ galaxies, occupation fraction $\gtrsim 50\%$ for IMBHs with $M_\bullet \approx 10^4 - 10^6\,M_\odot$.



Ho (2008, ARA&A)



Kormendy & Ho (2013, ARA&A)



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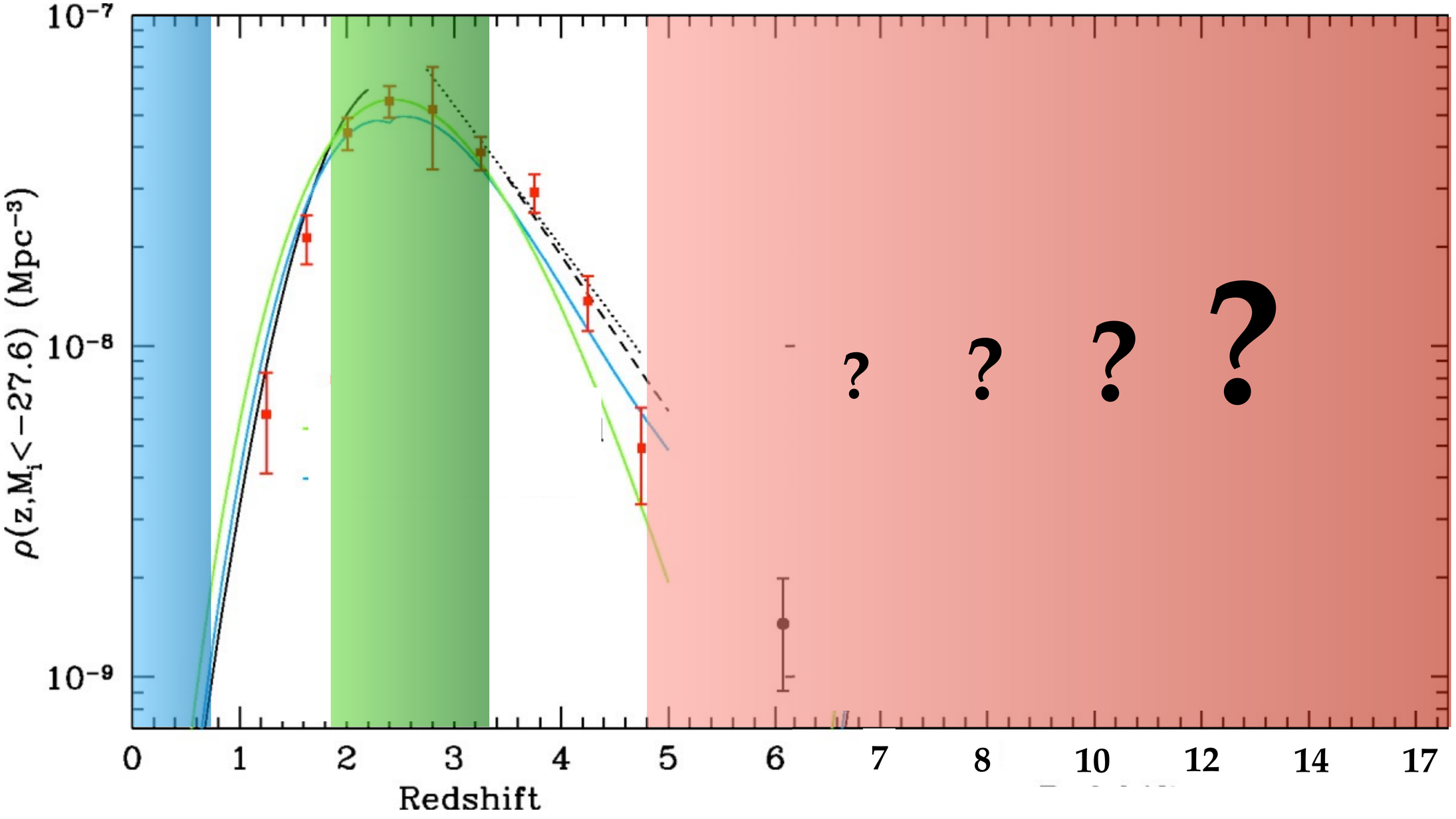
10^{-7}
10^{-8}
10^{-9}
$\rho(z, M_i < -27.6)$ (Mpc^{-3})
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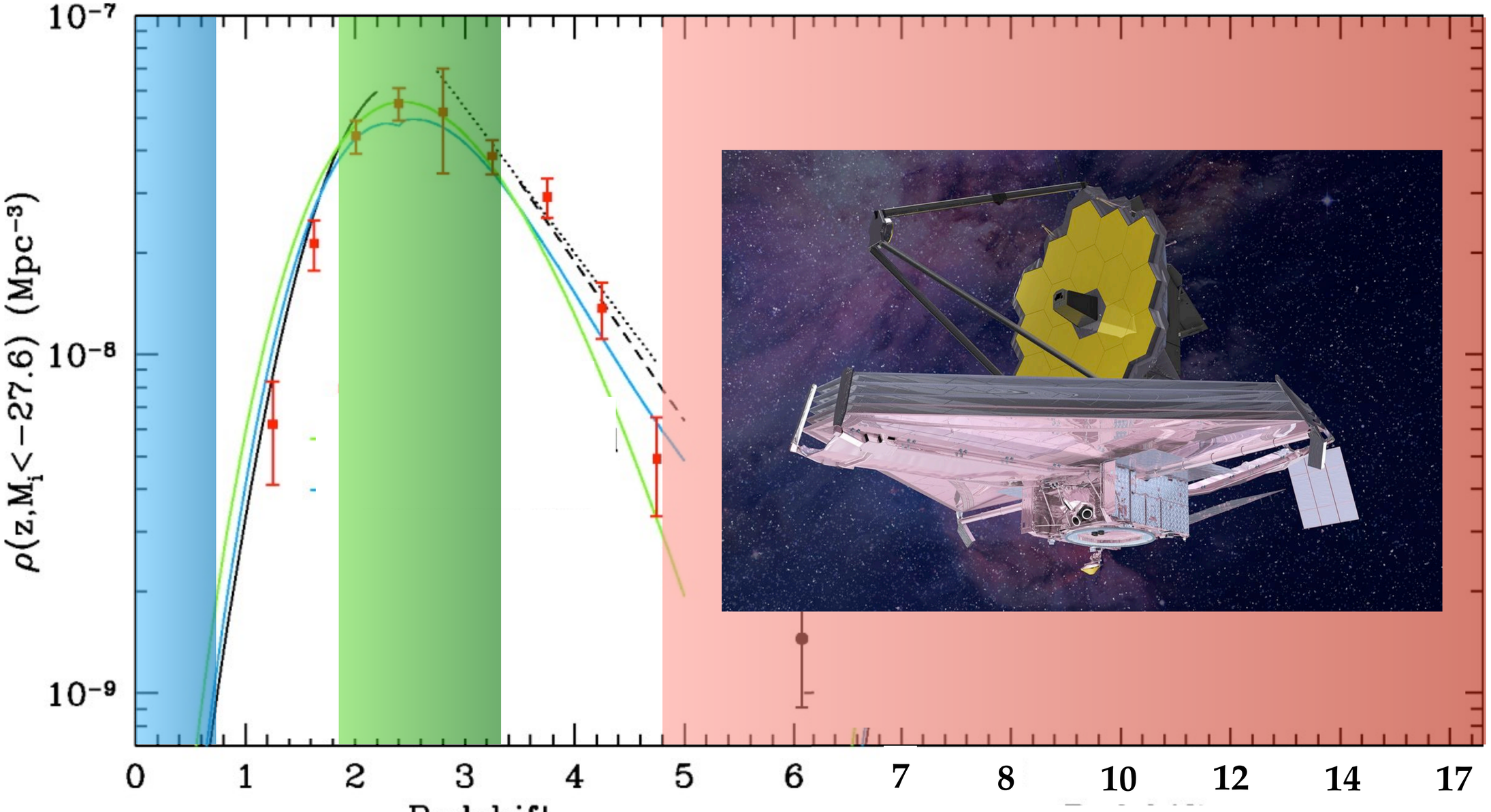
Redshift
? ? ? ?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The Age of Discovery with the James Webb Space Telescope: Excavating the Spectral Signatures of the First Massive Black Holes

Tracing the rise of supermassive black holes:

A panchromatic search for faint, unobscured quasars at $z \gtrsim 6$ with COSMOS-Web and other surveys

A CEERS Discovery of an Accreting Supermassive Black Hole 570 Myr after the Big Bang: Identifying a Progenitor of Massive $z > 6$ Quasars

A supermassive black hole in the early universe growing in the shadows

EPOCHS VII: discovery of high-redshift ($6.5 < z < 12$) AGN candidates in JWST ERO and PEARLS data

UNCOVER: A NIRSpec Identification of a Broad-line AGN at $z = 8.50$

Article https://doi.org/10.1038/s41550-023-02111-9

Evidence for heavy-seed origin of early supermassive black holes from a $z \approx 10$ X-ray quasar

UNCOVER spectroscopy confirms a surprising ubiquity of AGN in red galaxies at $z > 5$

Hidden Little Monsters: Spectroscopic Identification of Low-Mass, Broad-Line AGN at $z > 5$ with CEERS

JADES. The diverse population of infant Black Holes at 4<z<11: merging, tiny, poor, but mighty

CEERS Key Paper. VI. JWST/MIRI Uncovers a Large Population of Obscured AGN at High Redshifts

A Candidate for the Least-massive Black Hole in the First 1.1 Billion Years of the Universe

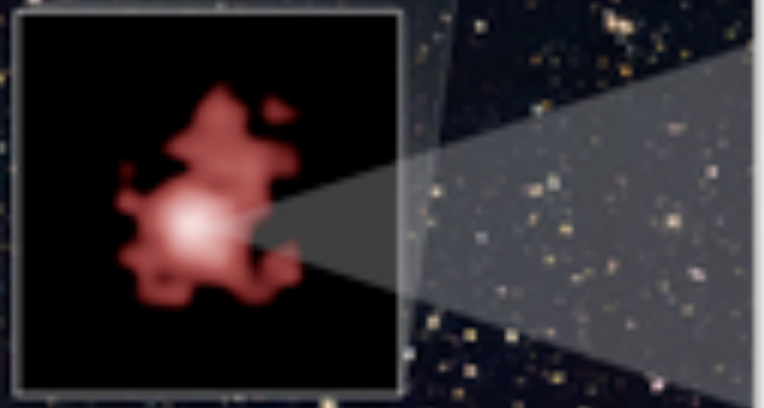
Extremely Red and Compact Object at $z_{phot} \simeq 7.6$ Triply Imaged by A2744

Star Formation and AGN Activity 500 Myr after the Big Bang: Insights from JWST

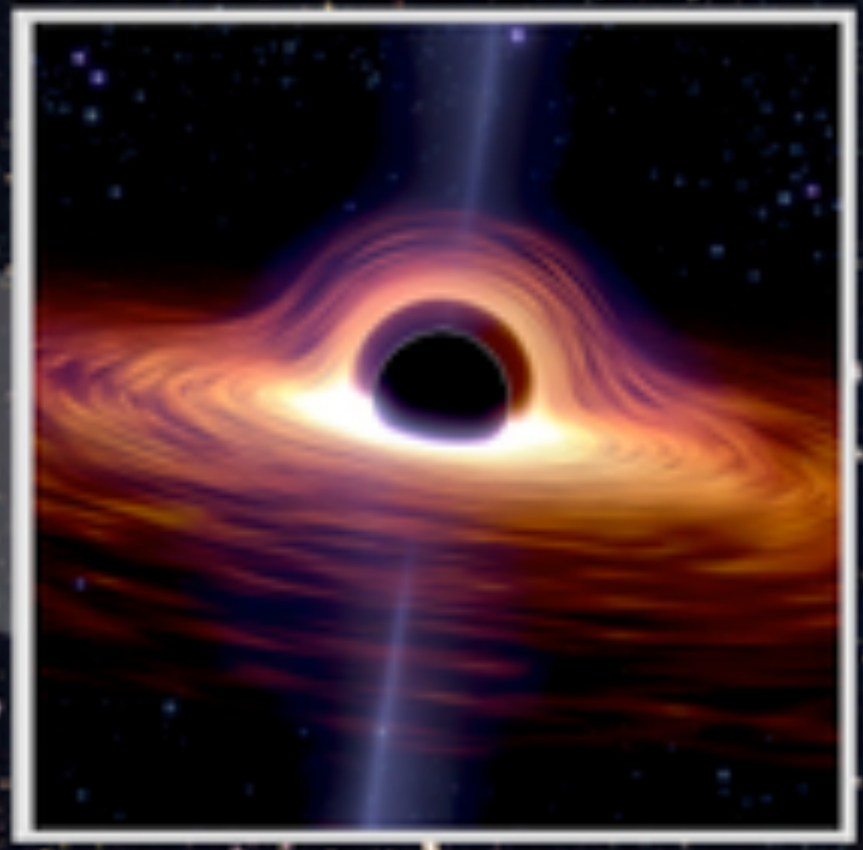
Article

A massive quiescent galaxy at redshift 4.658

Extremely red galaxies at $z = 5 - 9$ with MIRI and NIRSpec: dusty galaxies or obscured AGNs?



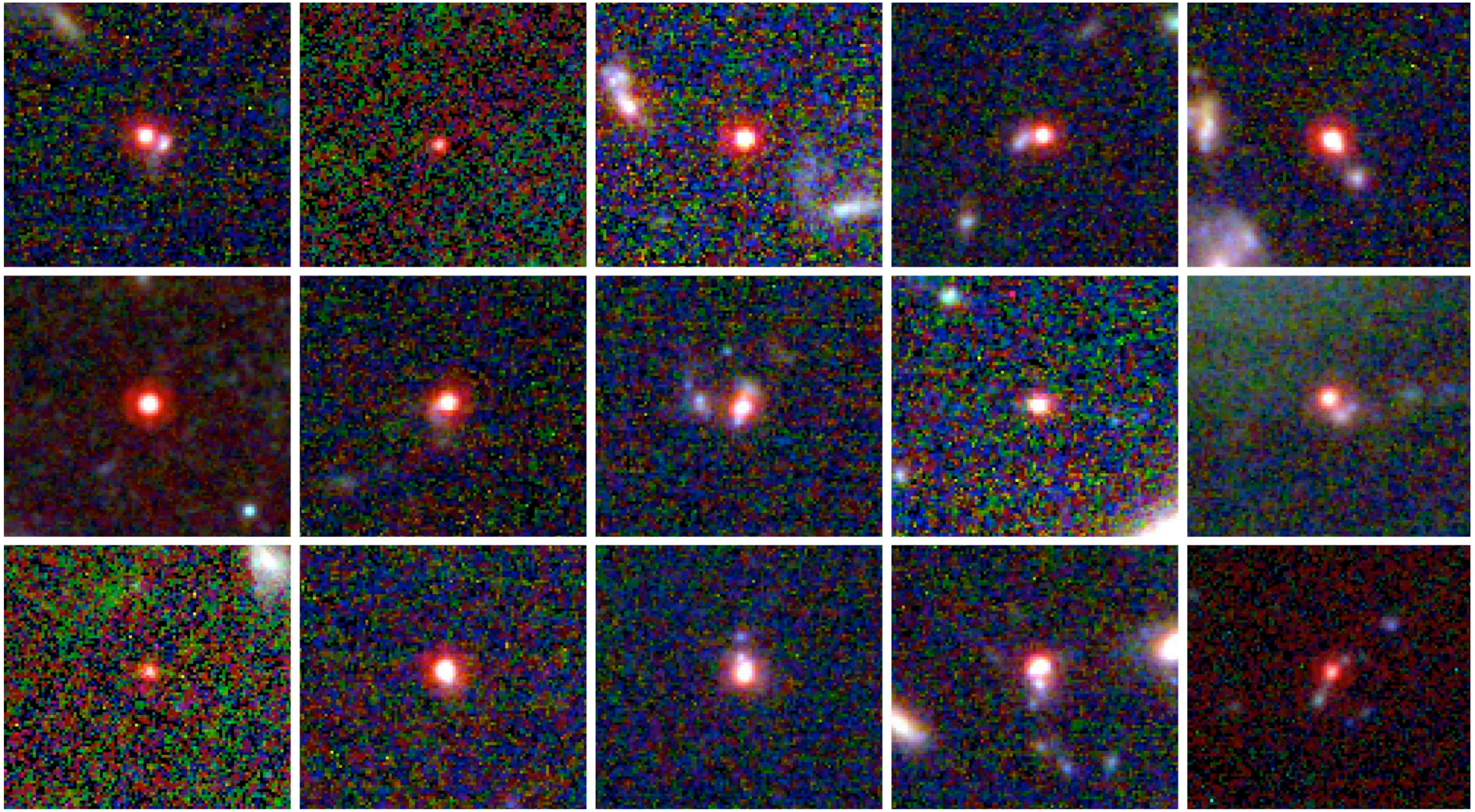
Discovery of
“little red dots”



Progenitors of
quasars

Discovery of the "Little Red Dots"

Kovceski et al. (2023), Harikane et al. (2023), Greene et al. (2024), Matthee et al. (2024), and many others



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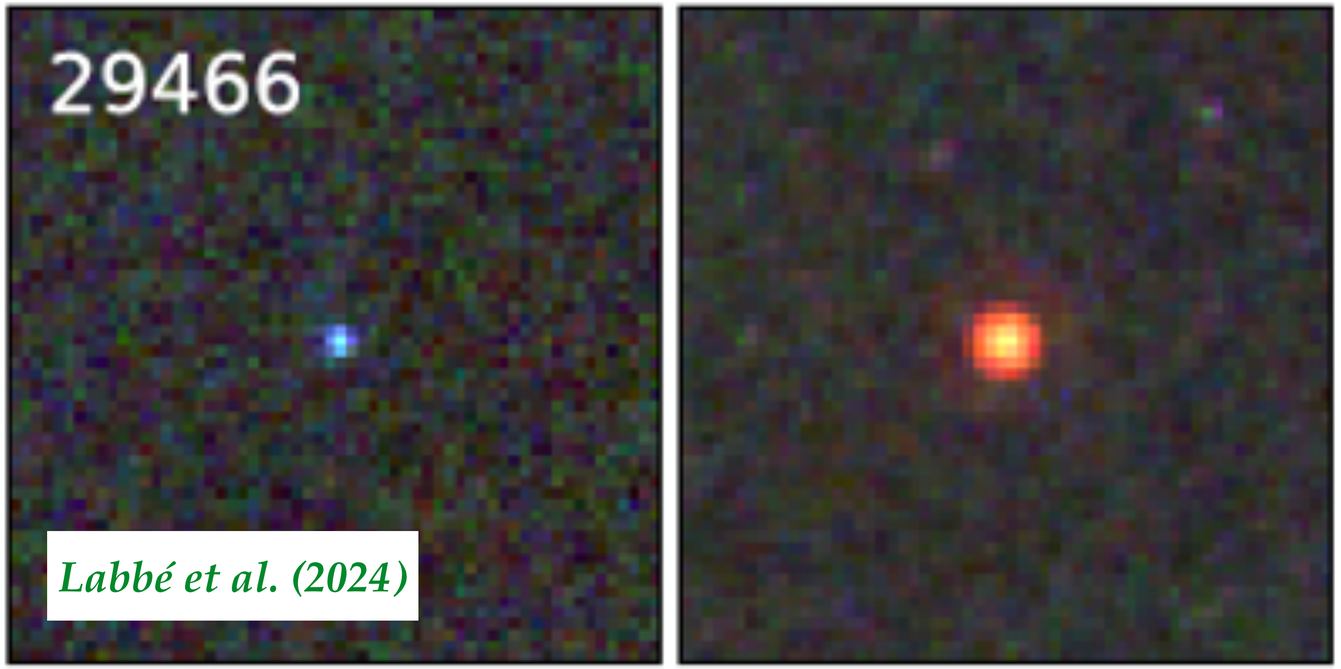
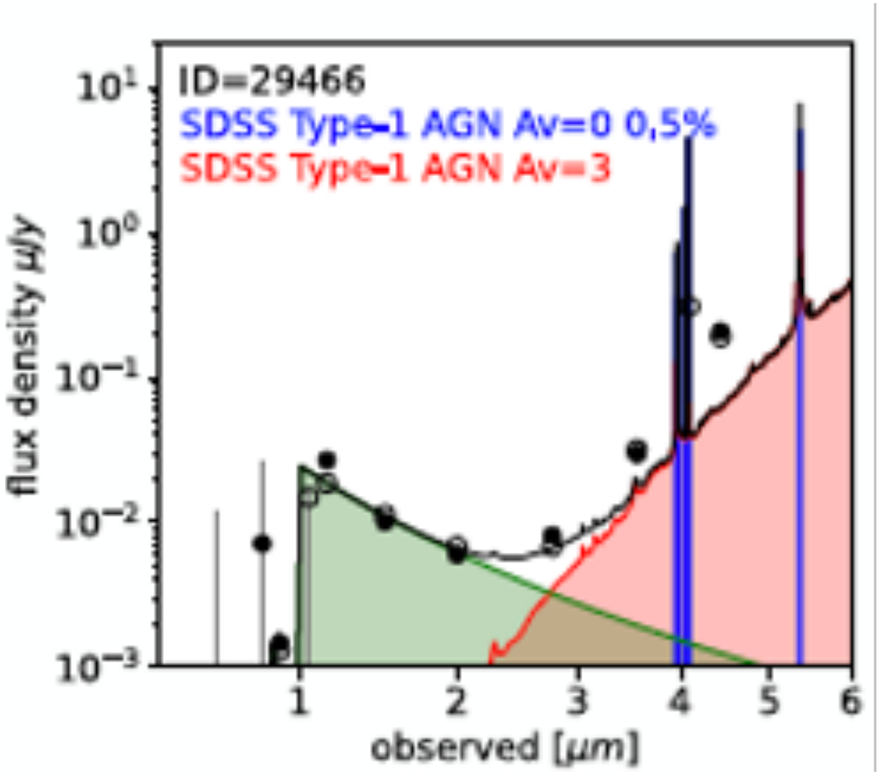


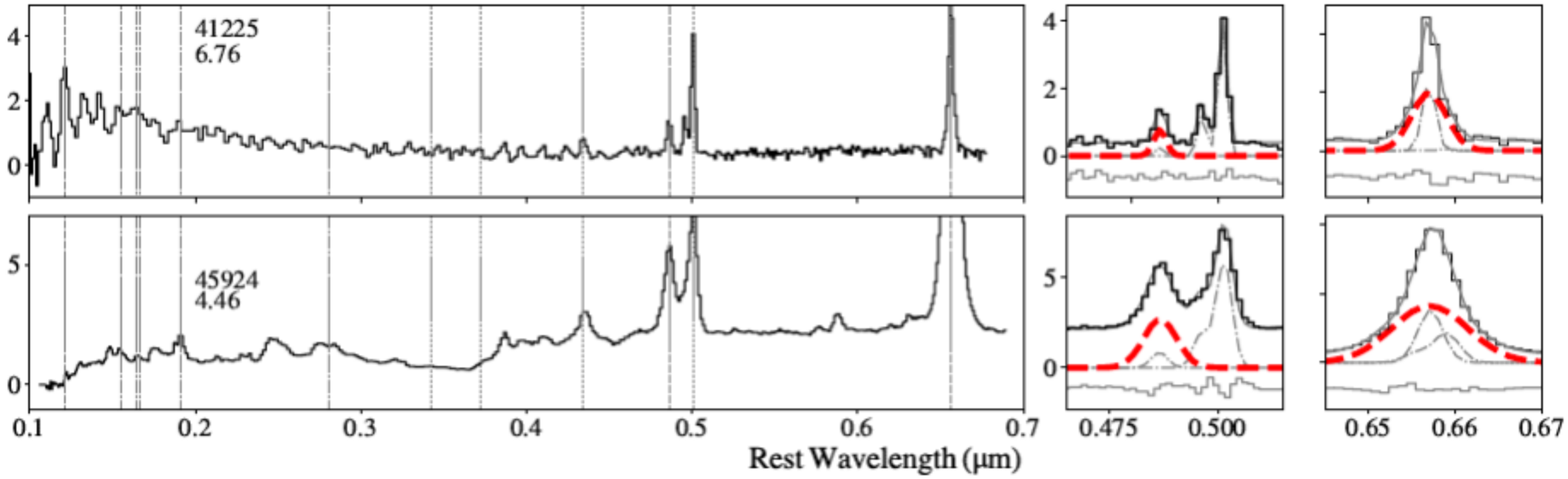


- Extremely compact, point-like
- Upper limits on size: $R_e \lesssim 50$ pc
- Often no sign of any underlying galaxy

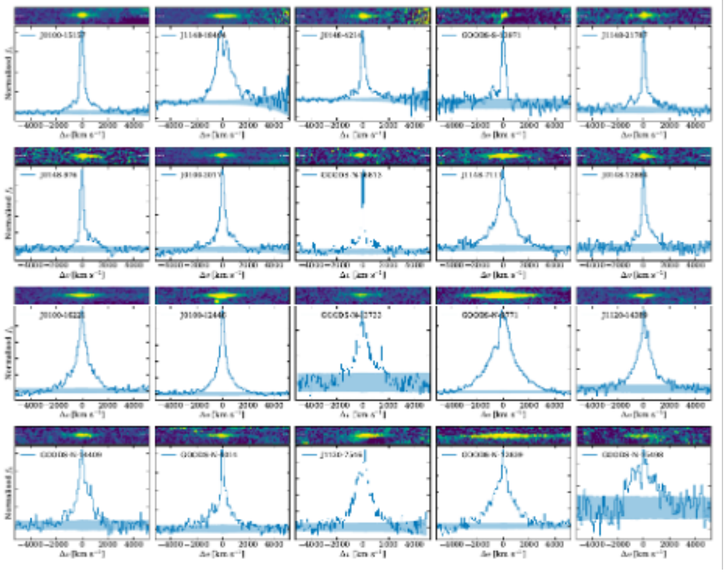
- Peculiar V-shaped spectral energy distribution
- Interpreted as obscured AGN in optical + scattered light in the ultraviolet
- Intrinsically X-ray weak?

"Little Red Dots" are the progenitors of quasars

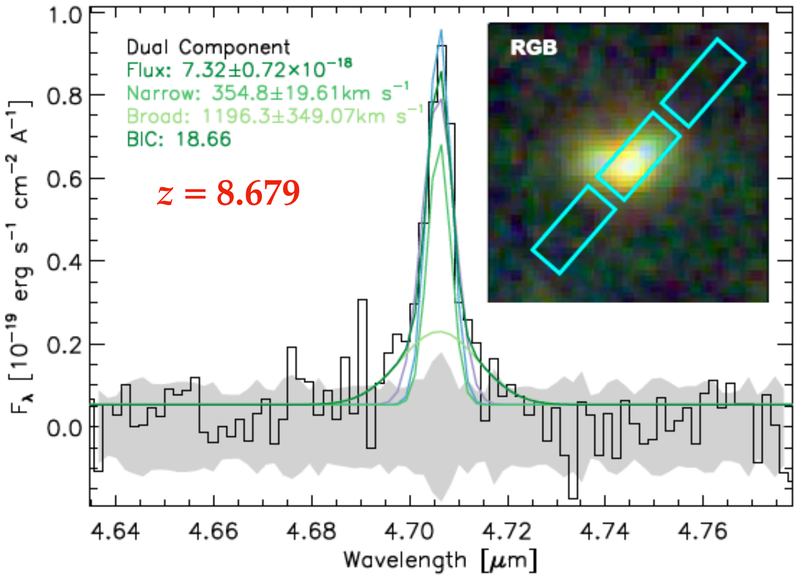
Greene et al. (2024)



Matthee et al. (2024)



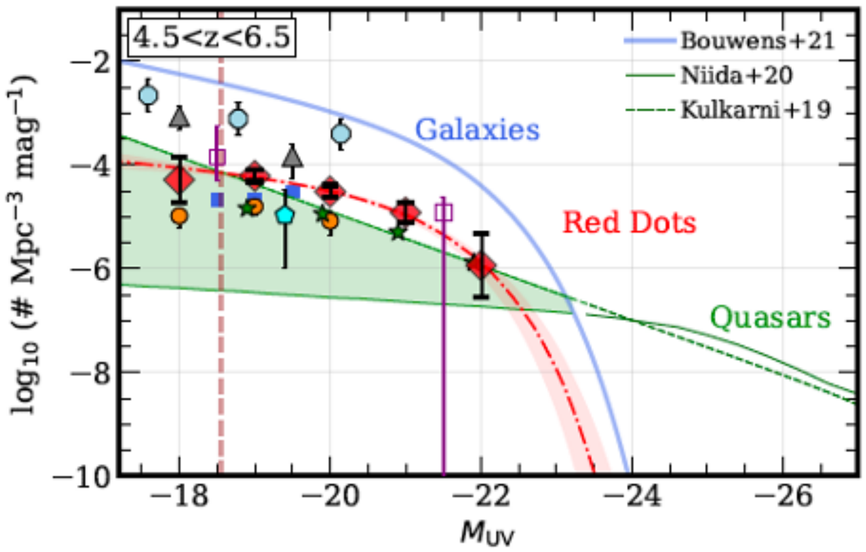
Larson et al. (2023)

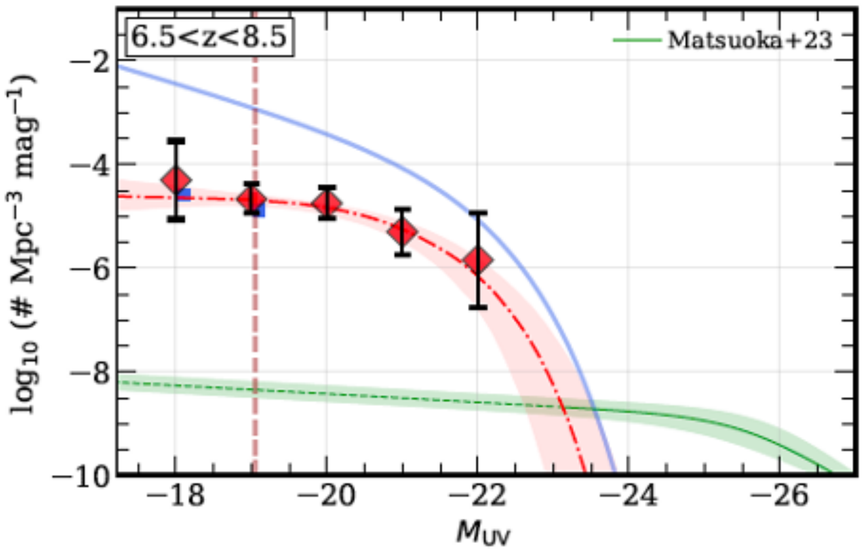


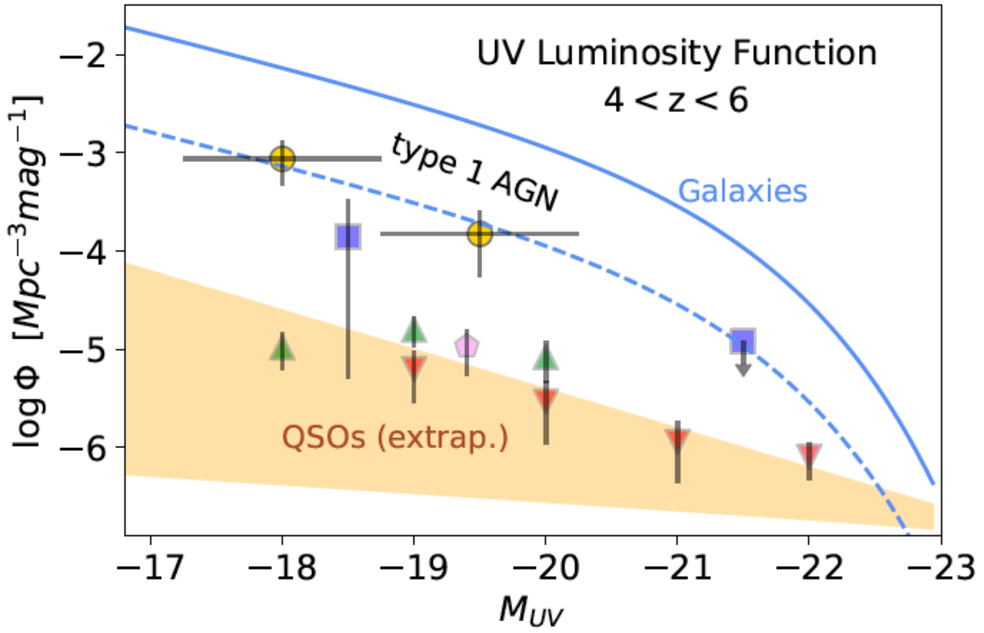
- **Hα FWHM ≈ 1000–5000 km s^{-1}**
- **$M_\bullet \approx 10^6 - 10^8\, M_\odot$**
- **$L_{\rm bol}/L_{\rm Edd} \approx 0.1–1$**
- **Low gas-phase metallicities**

“Little Red Dots” are very abundant

Kocevski et al. (2024), Kokorev et al. (2024), Maiolino et al. (2024)

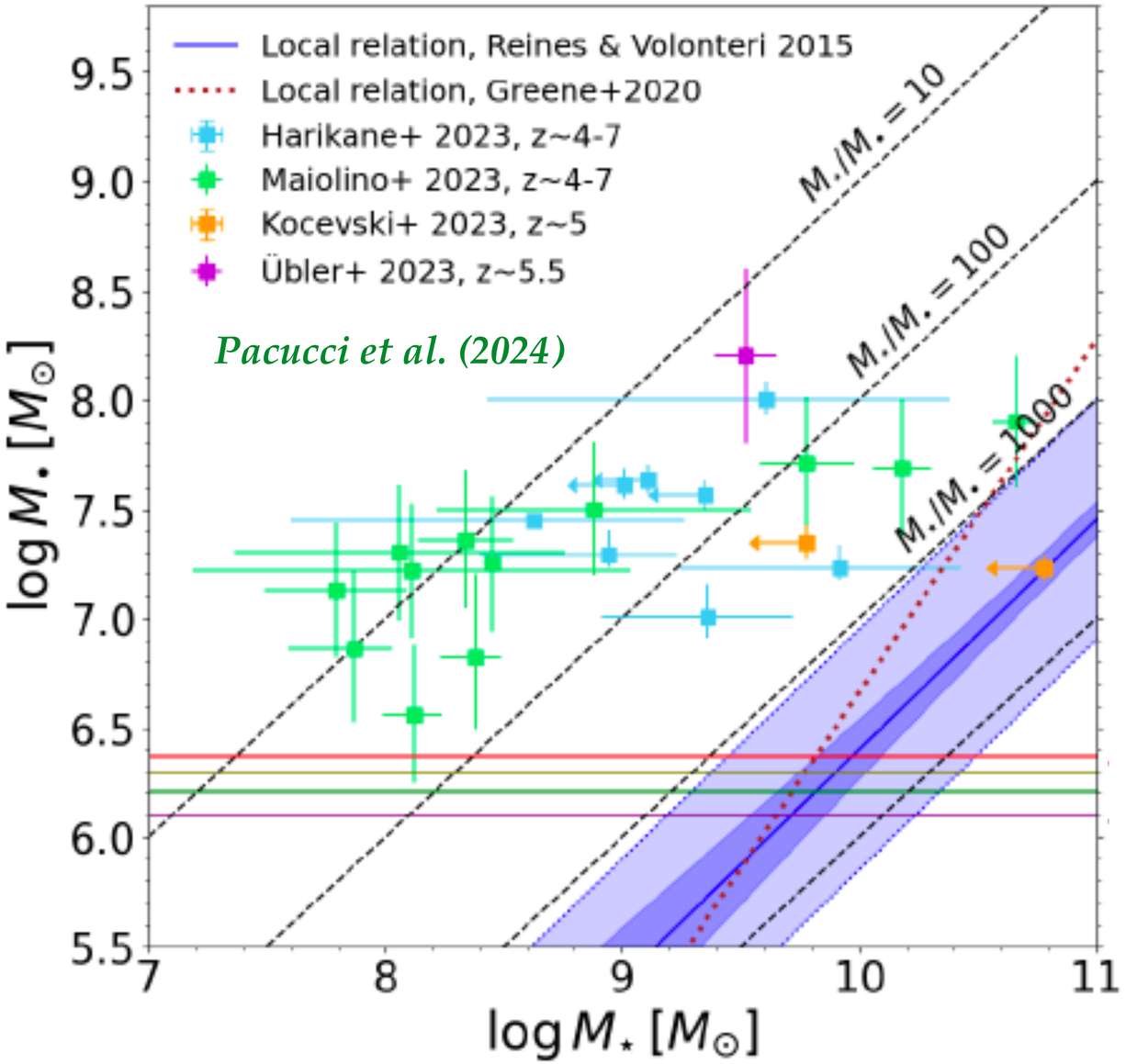


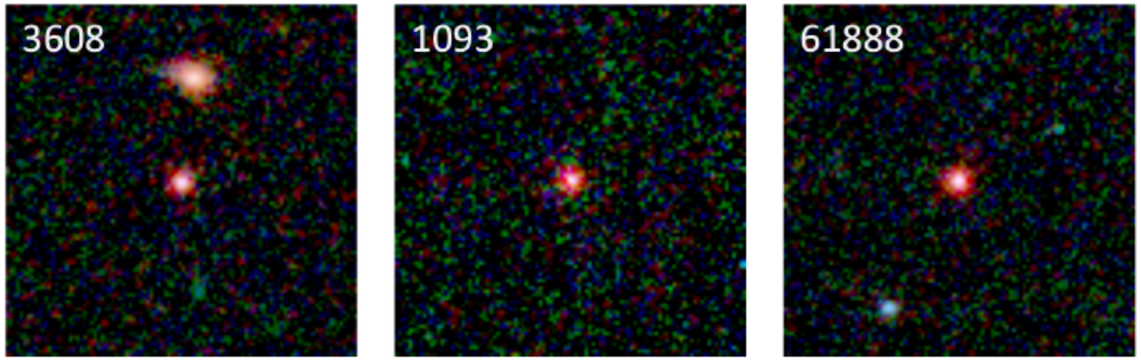




- **Space density 100 times higher than extrapolated luminosity function of UV-selected quasars**
- **Abundance ~10% of the general galaxy population**
- **Expected: since occupation fraction of BHs @ $z = 0 \gg 50\%$, (almost) every young galaxy should have a seed BH**

"Little Red Dots" have overmassive black holes





- $M_\bullet/M_*$ higher than $z = 0$ by factor ~10–100
- Black hole formed faster or earlier than the stars in the host galaxy
- Serious consequences for coevolution and the AGN feedback paradigm

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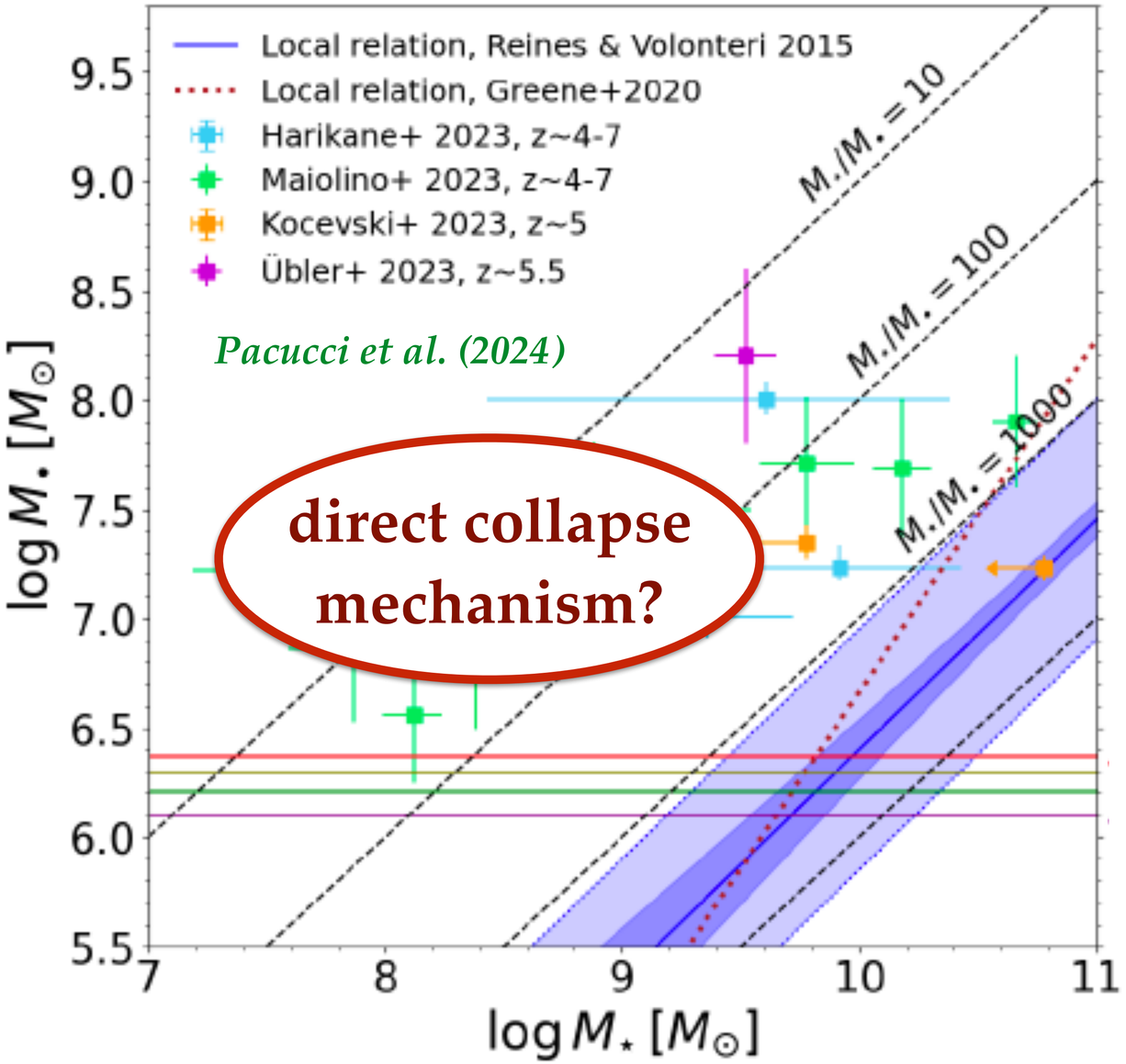

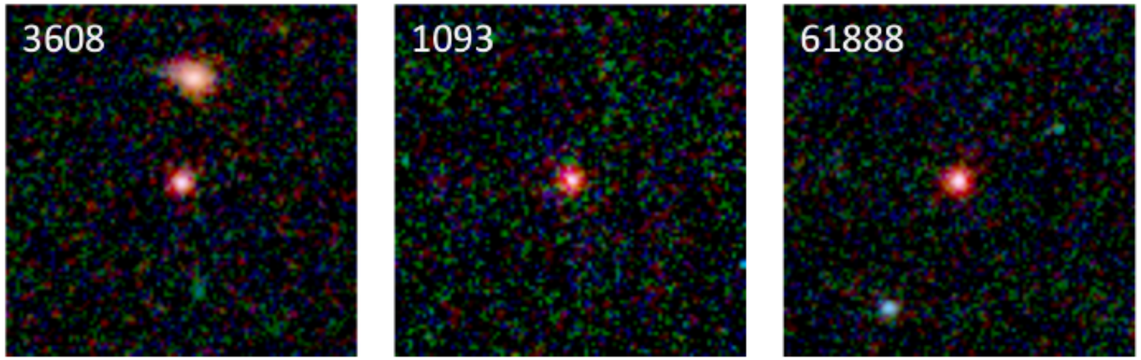

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- Serious consequences for coevolution and the AGN feedback paradigm

- Overmassive black holes may be expected from direct collapse mechanism

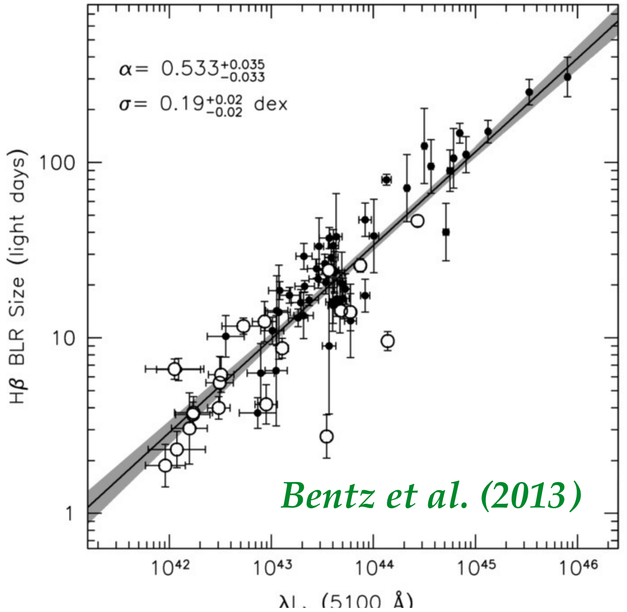
Some caveats… black hole masses likely overestimated

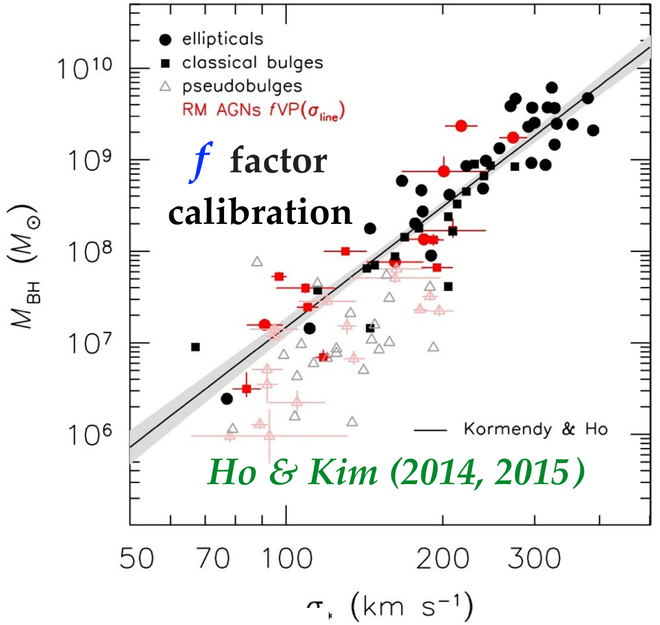
$M_{\rm virial} = f\,RV^2/G$

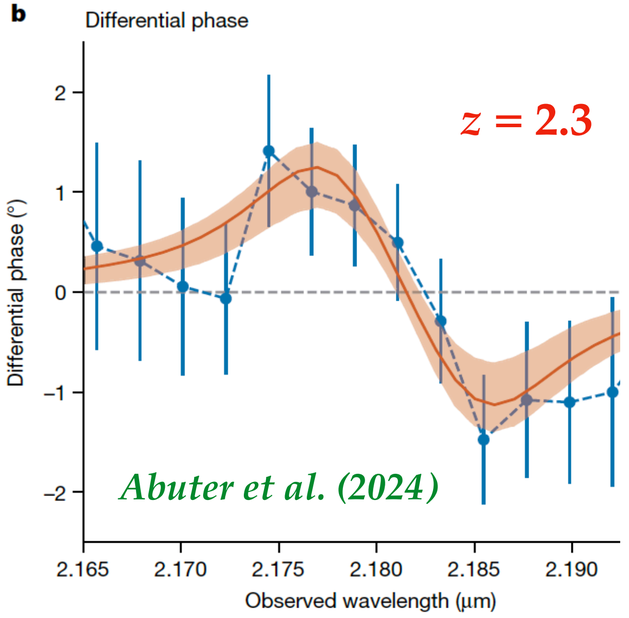
f virial factor

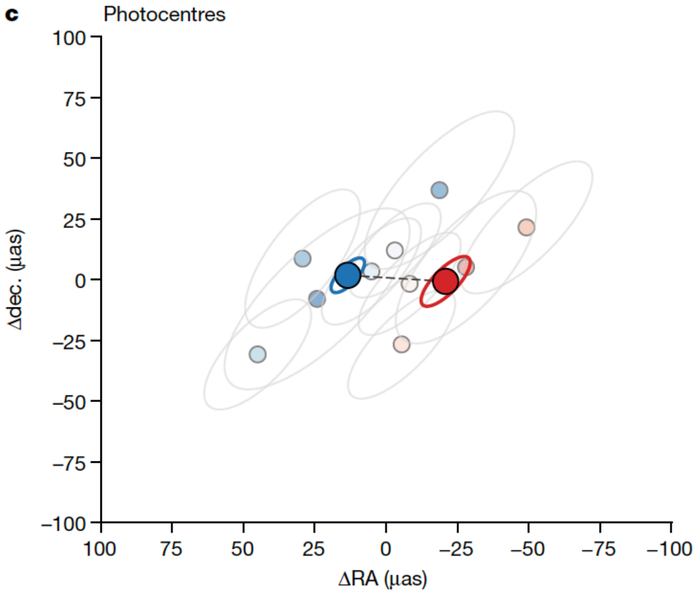
R BLR radius

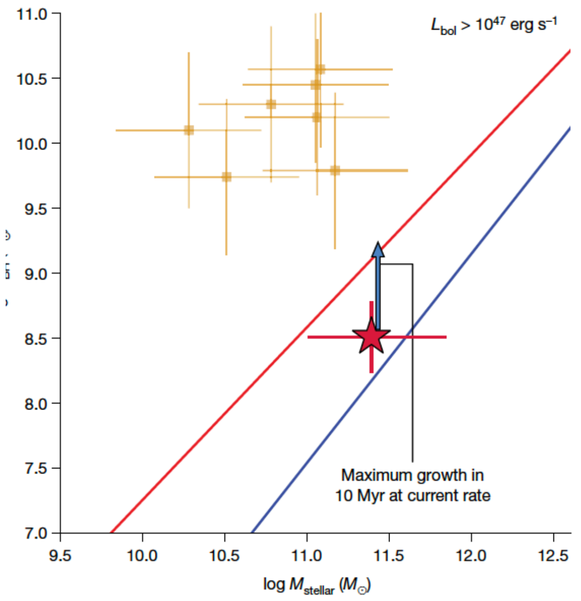
V BLR velocity dispersion







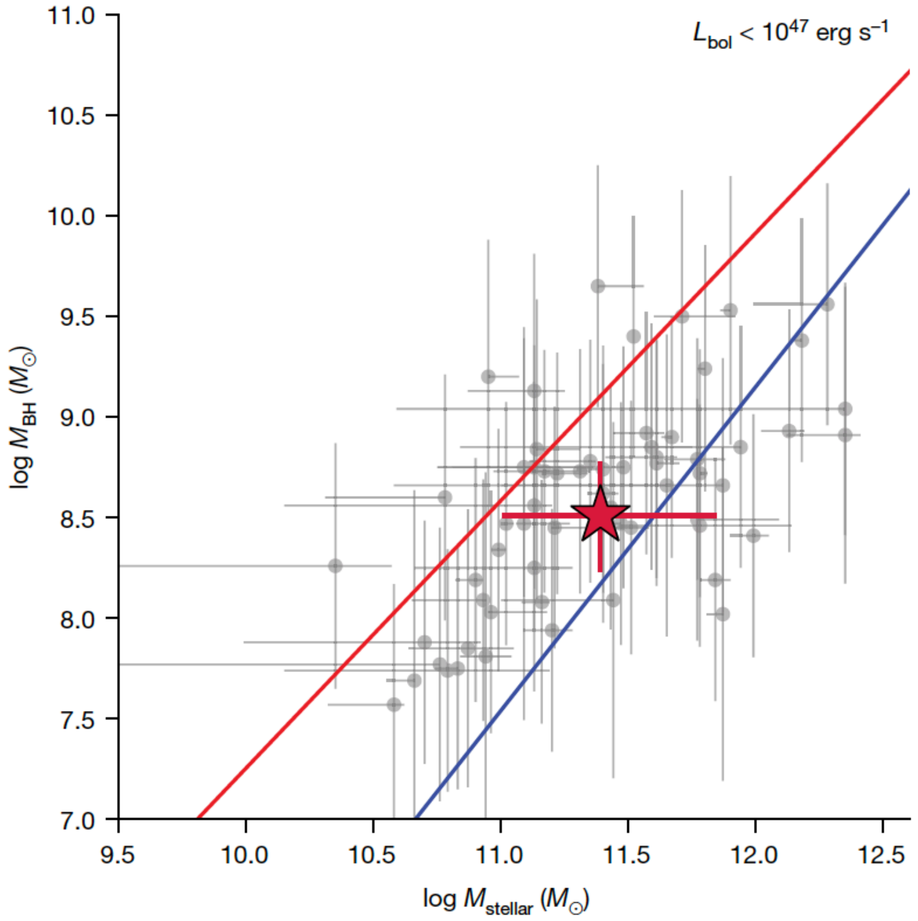




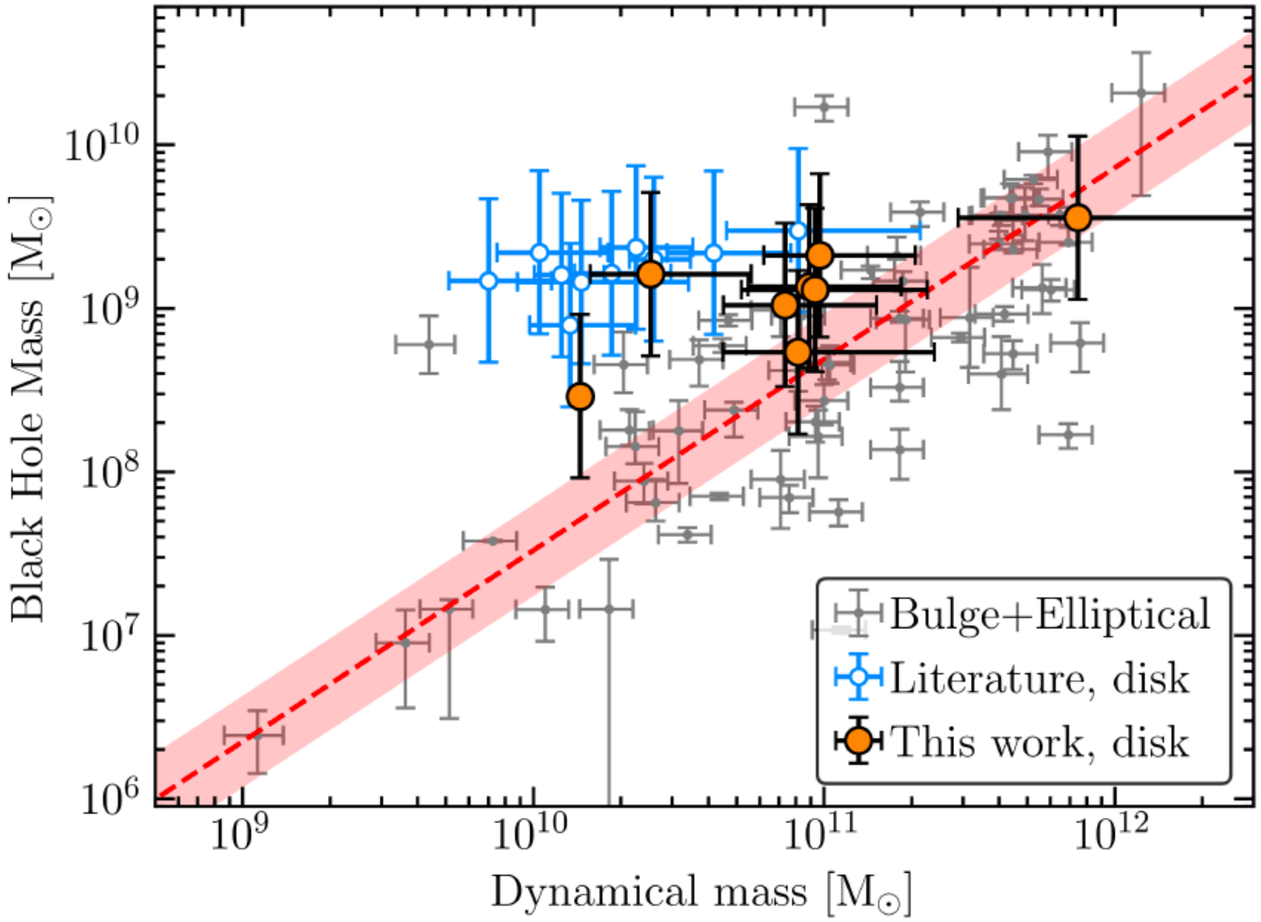
GRAVITY+ measurement of *BH mass: factor of a few lower than single-epoch estimate!*

Caveats: host galaxy (stellar, dynamical) masses very uncertain

Abuter et al. (2024)



F. Wang et al. (2024)



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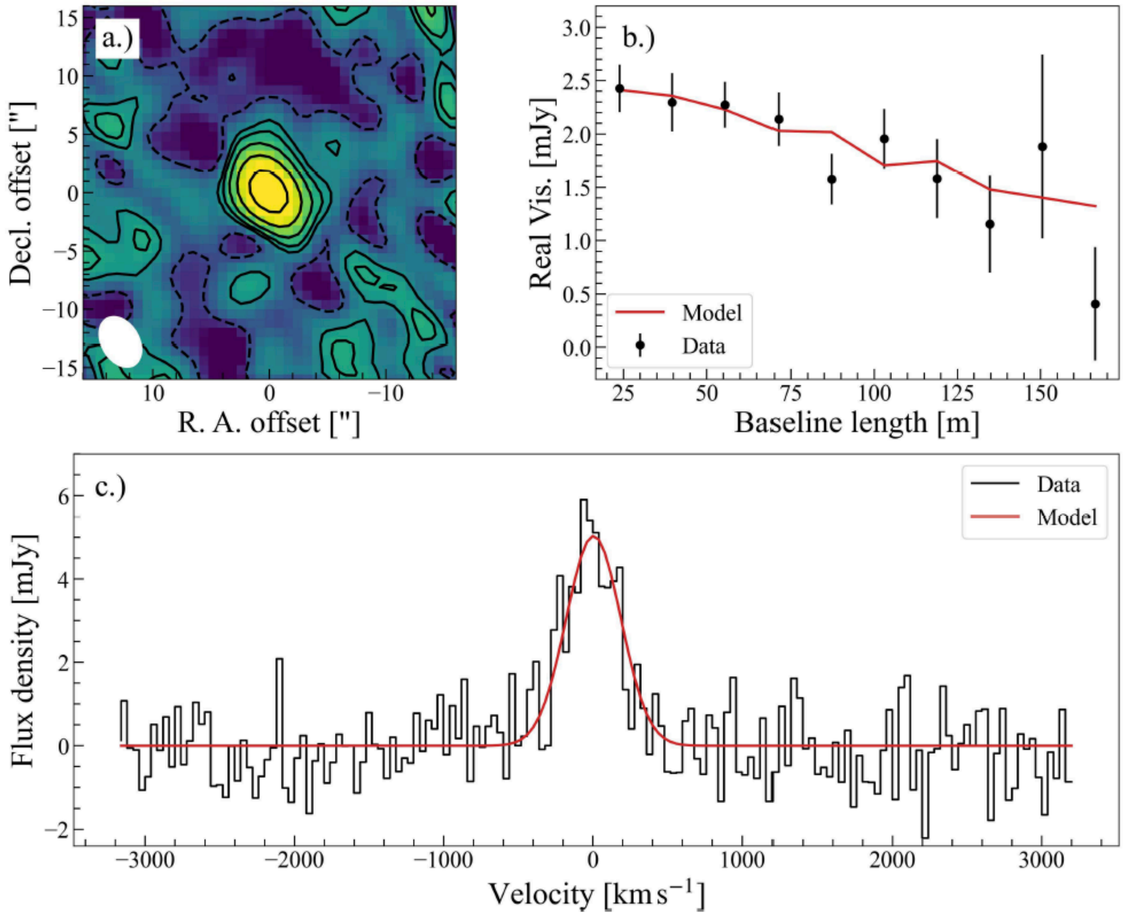

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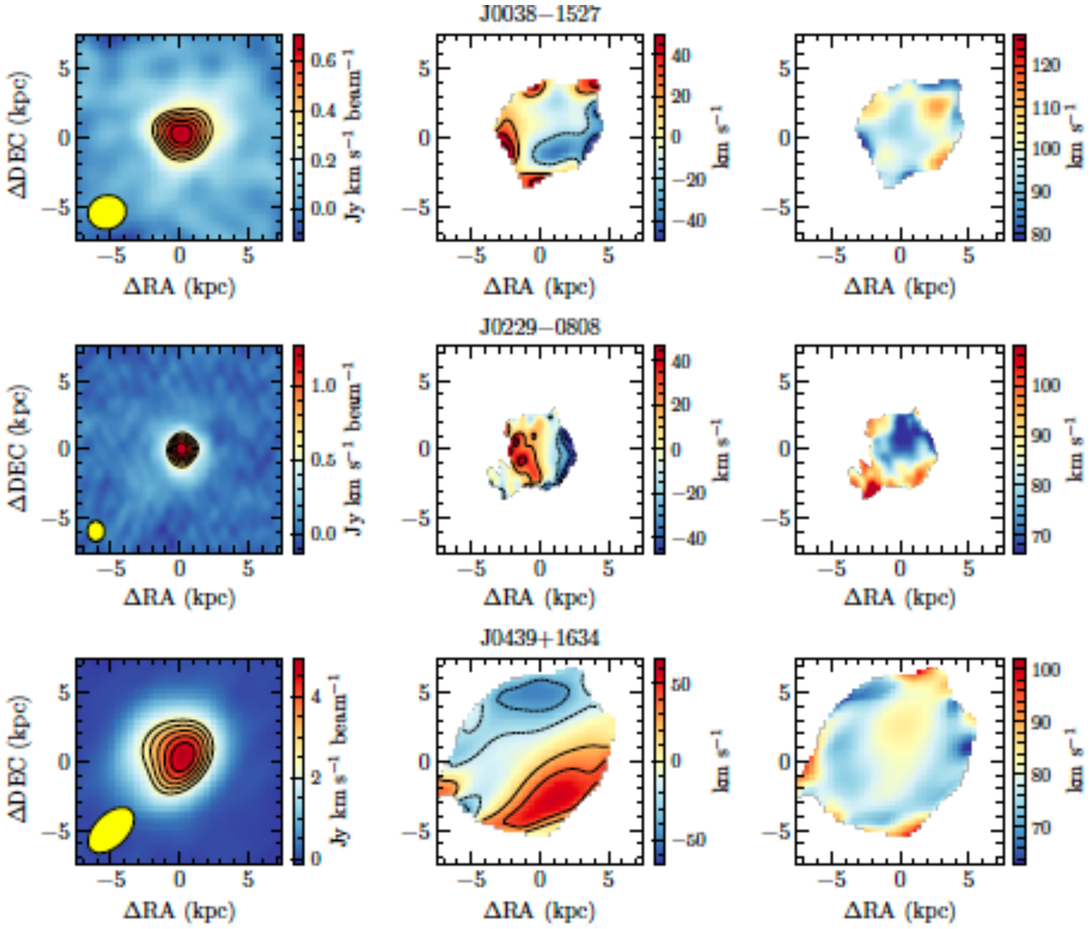
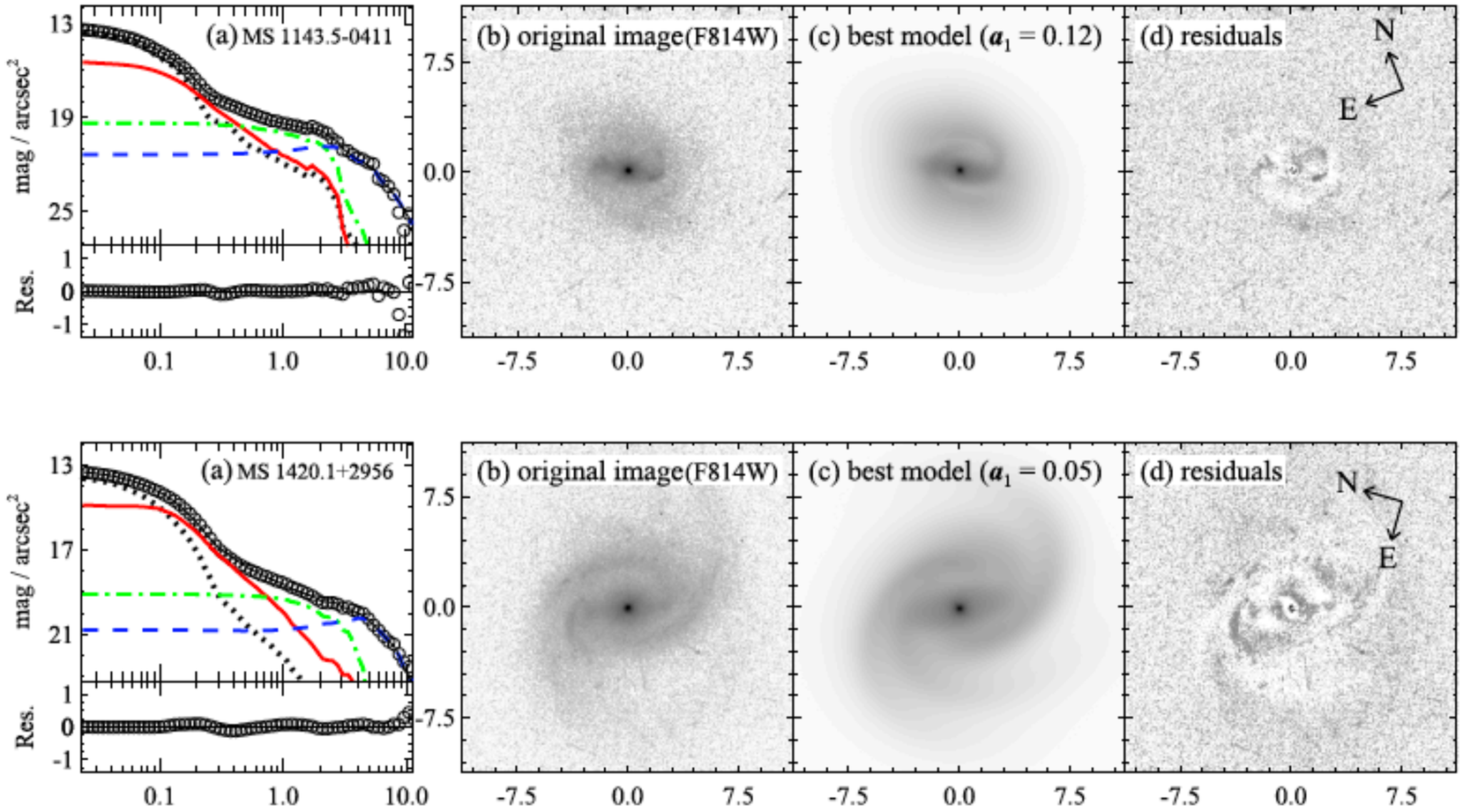


Some caveats… host galaxy (stellar, dynamical) masses very uncertain

The Astrophysical Journal Supplement Series, 232:21 (30pp), 2017 October

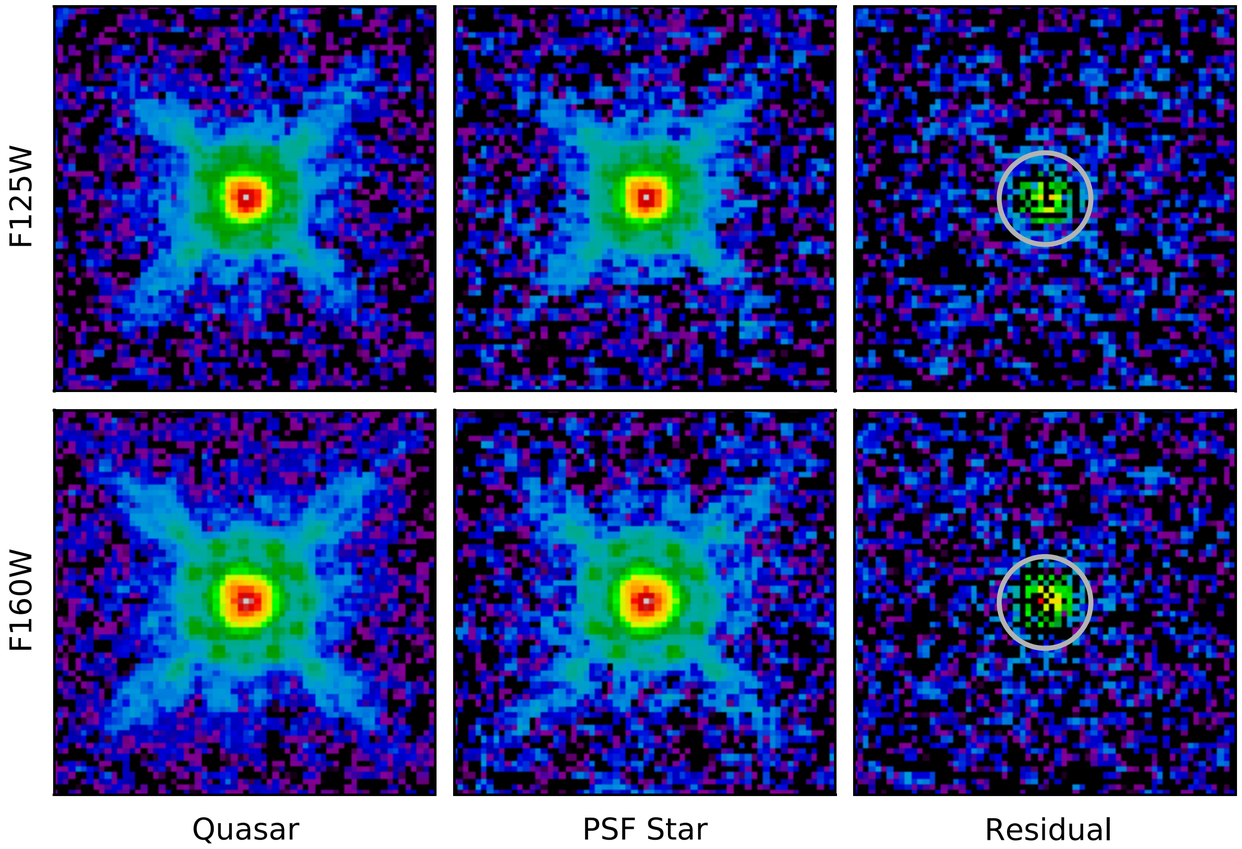
Stellar Photometric Structures of the Host Galaxies of Nearby Type 1 Active Galactic Nuclei*

Minjin Kim[1,2], Luis C. Ho[3,4], Chien Y. Peng[5], Aaron J. Barth[6], and Myungshin Im[7]

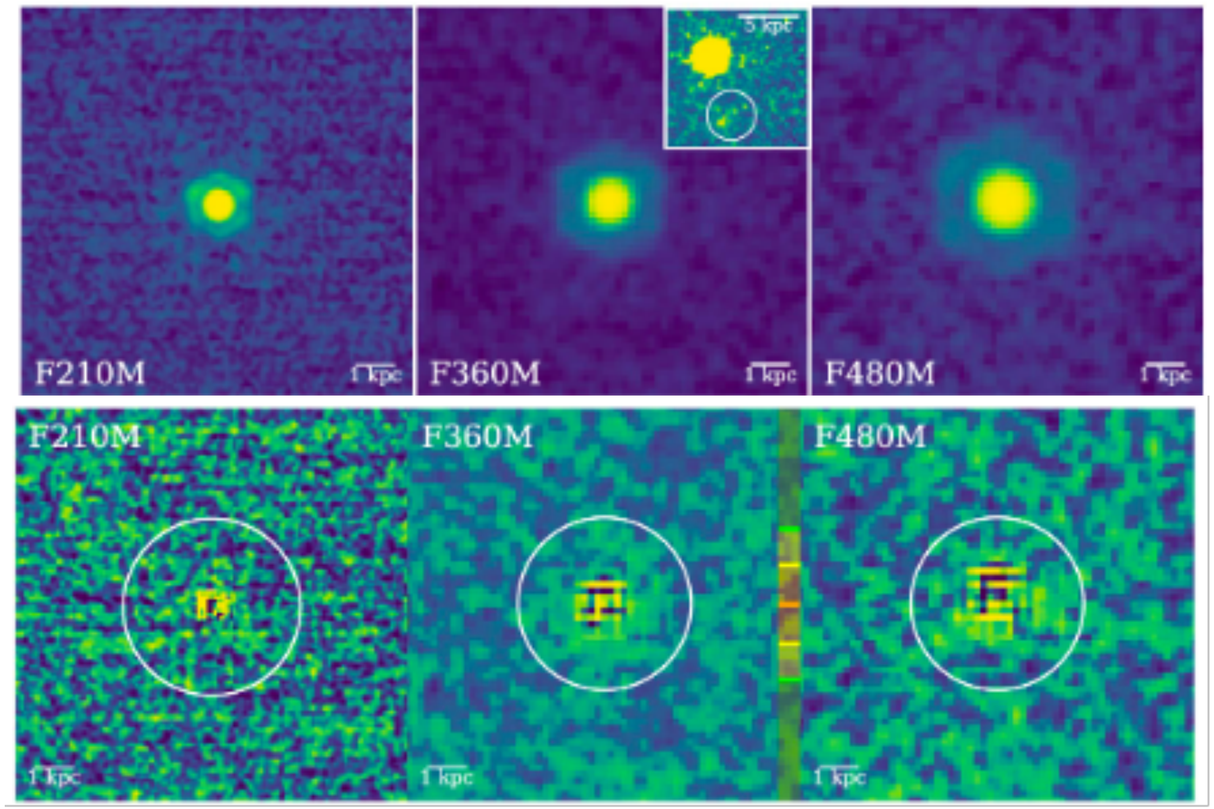


Some caveats… host galaxy (stellar, dynamical) masses very uncertain

HST: $z = 6.42$ *Mechtley et al. (2012)*

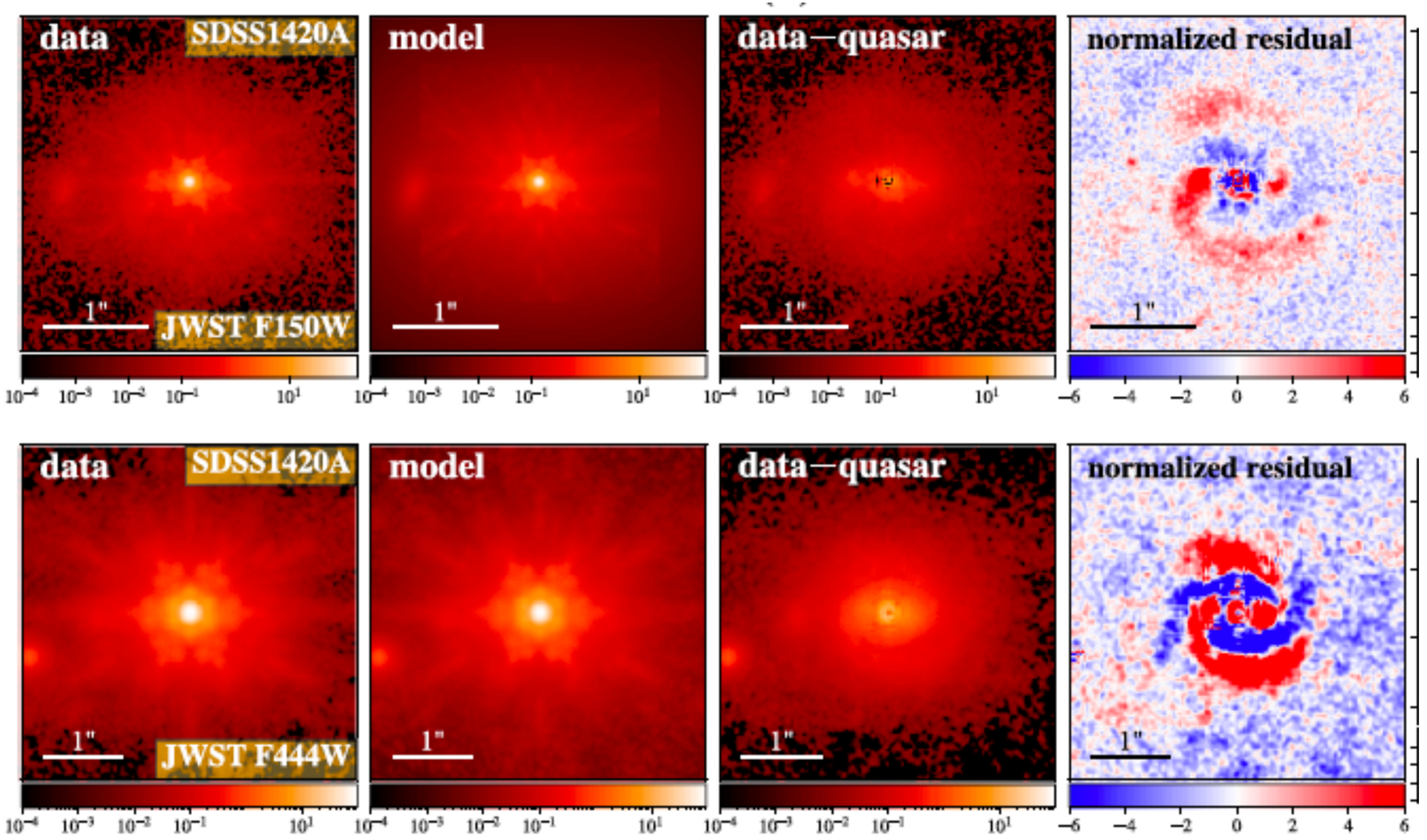


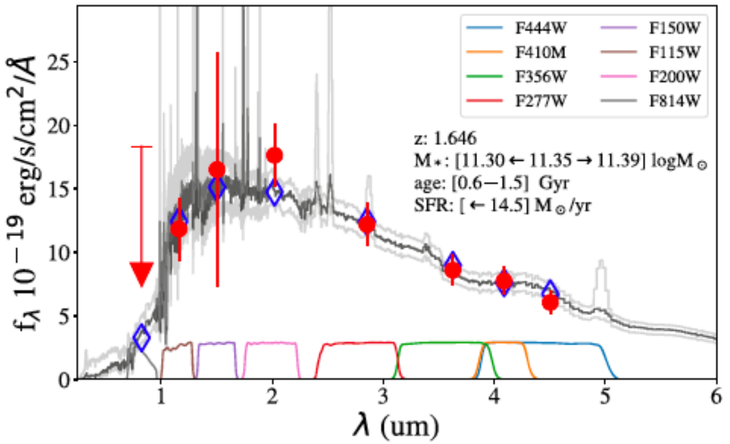
JWST: $z = 6.25$ *Stone et al. (2023)*

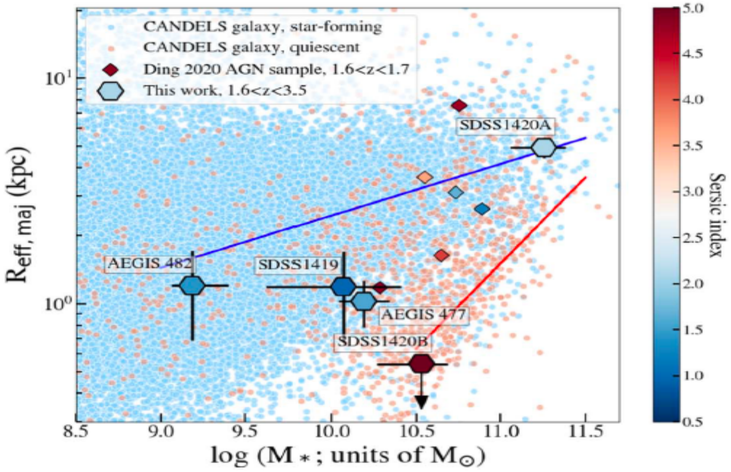


Caveats: host galaxy (stellar, dynamical) masses very uncertain

Ding et al. (2022)

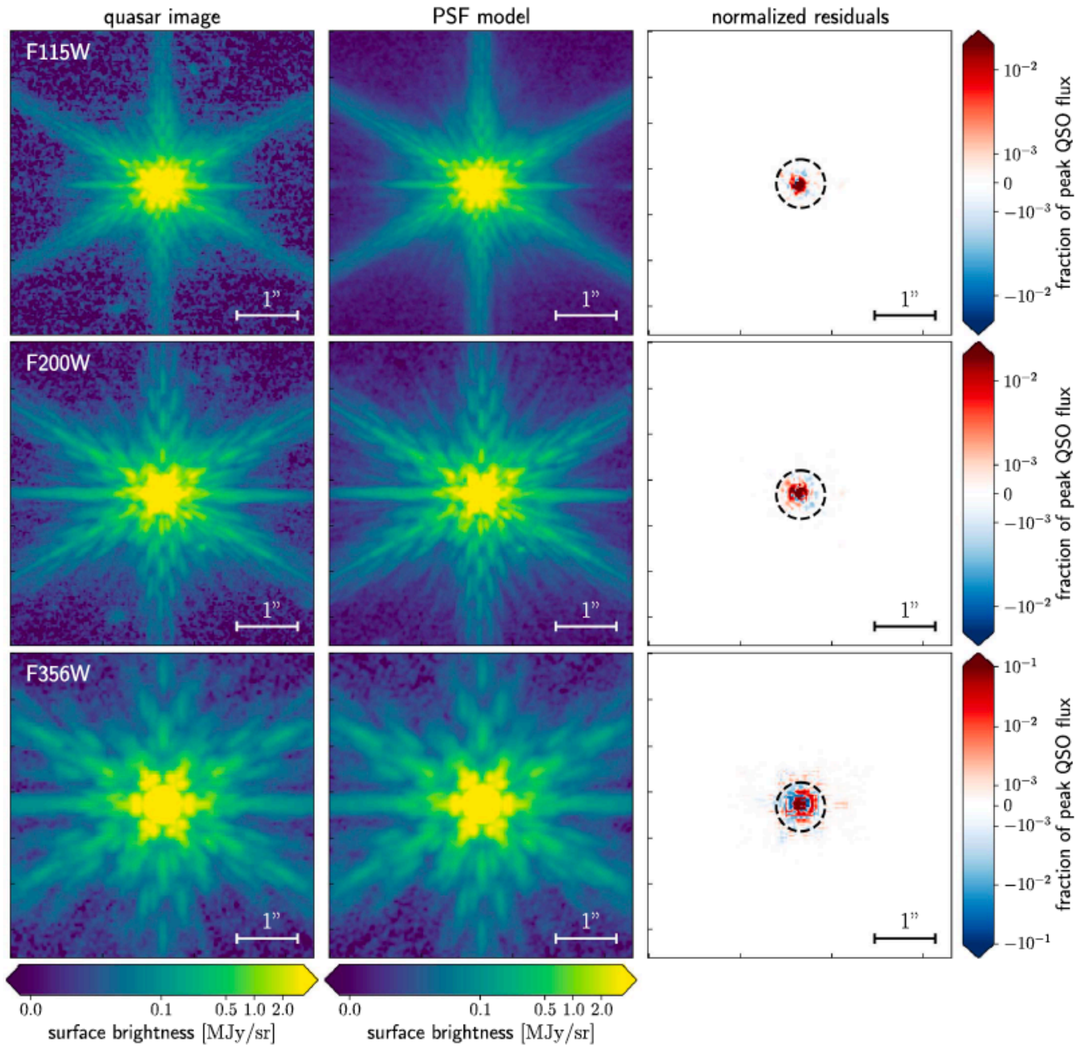




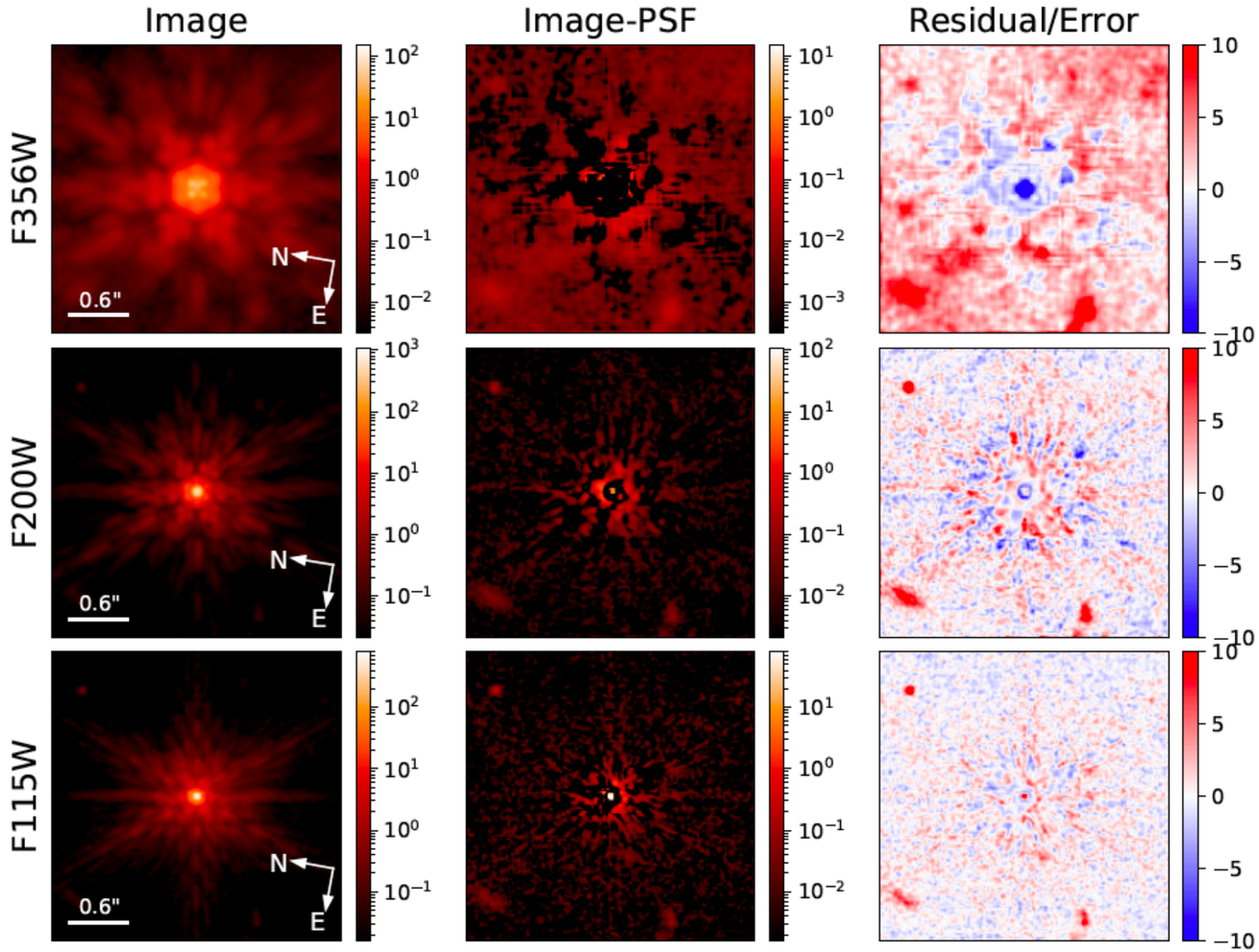


Caveats: host galaxy (stellar, dynamical) masses very uncertain

J0100+2802: *Eilers et al. (2023)*

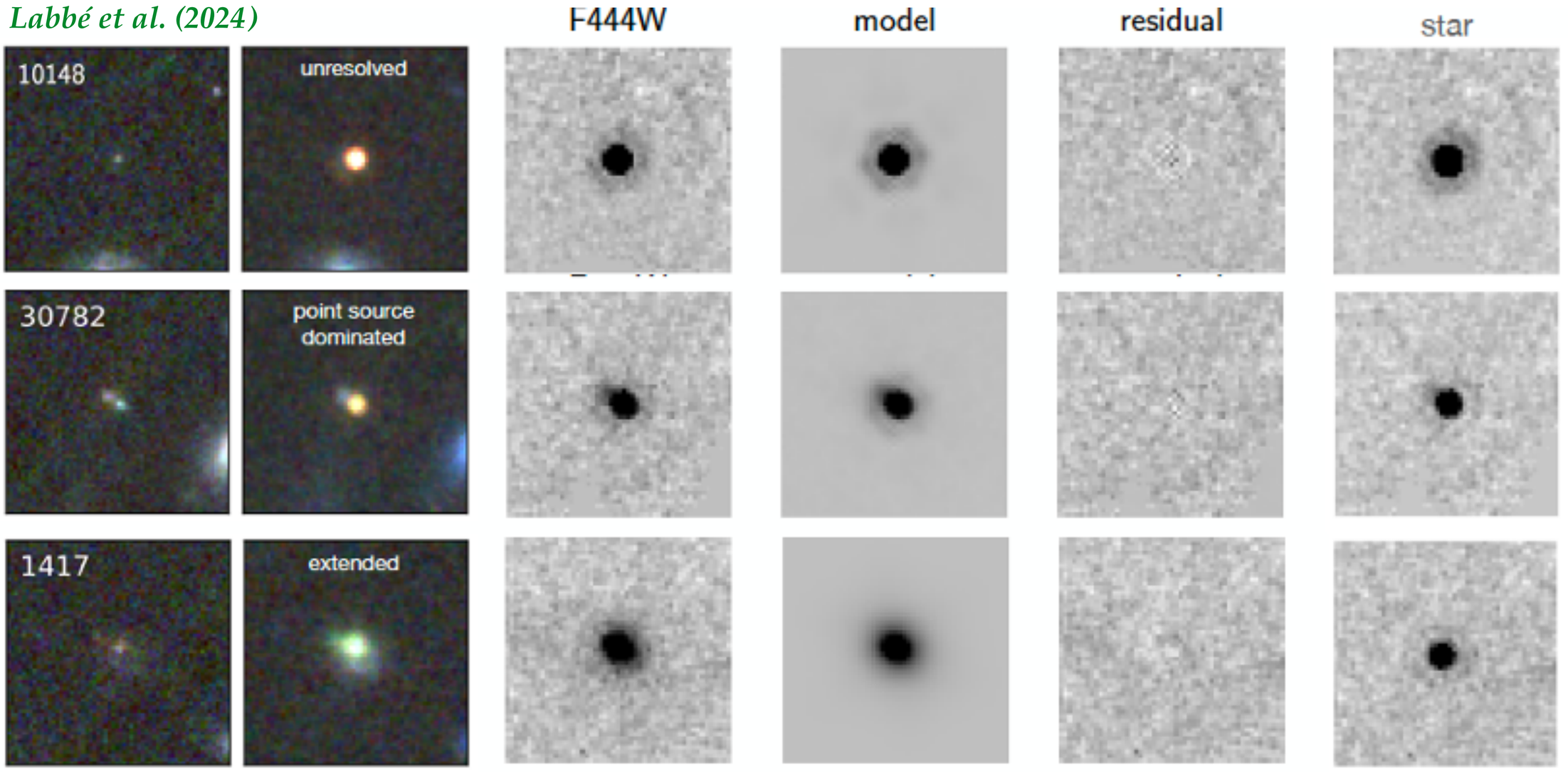


J1148+5251: *Yue et al. (2024)*



Caveats: host galaxy (stellar, dynamical) masses very uncertain

Labbé et al. (2024)

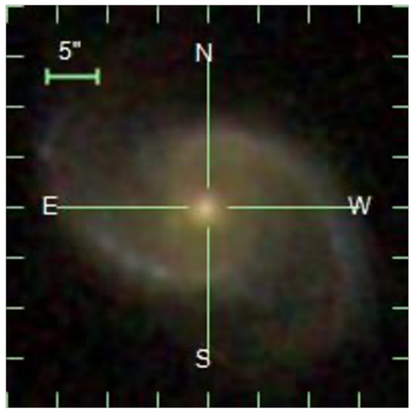


Improvements in Host Galaxy Measurements

Ruancun Li, PhD thesis; Li & Ho (2024)

GALFITS

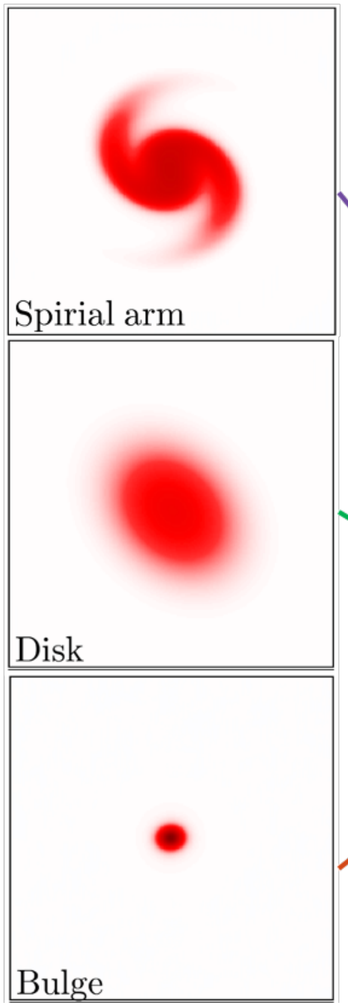
Input multi-band images

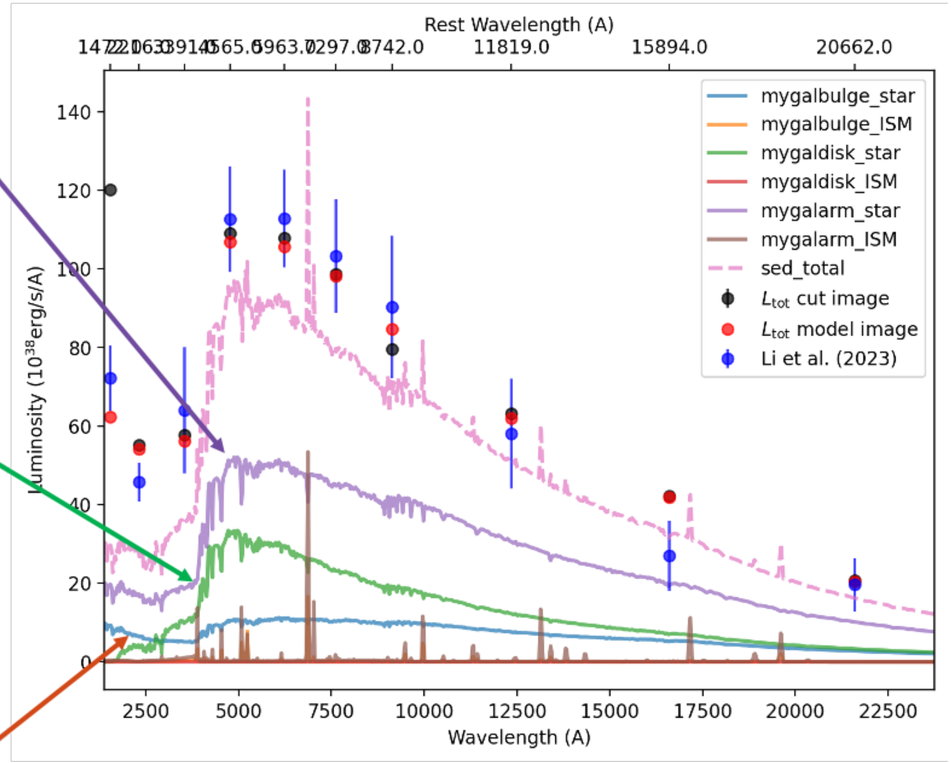


SDSS J0059-0012
Star-forming galaxy

GALFITS

Decomposition





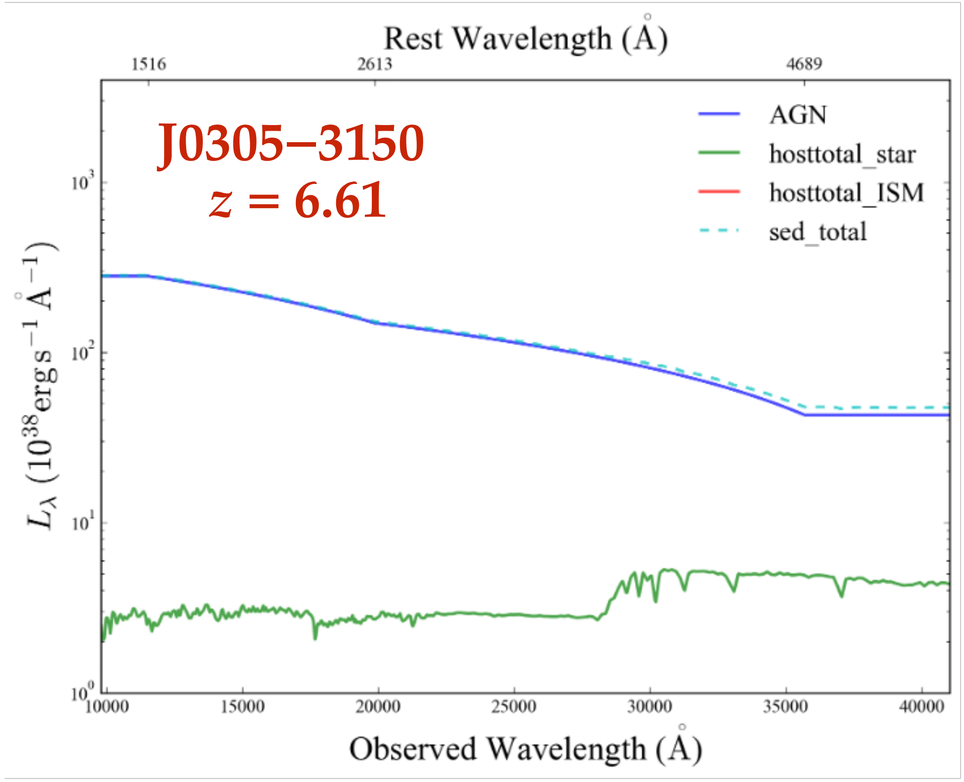
Improvements in Host Galaxy Measurements: Quasars

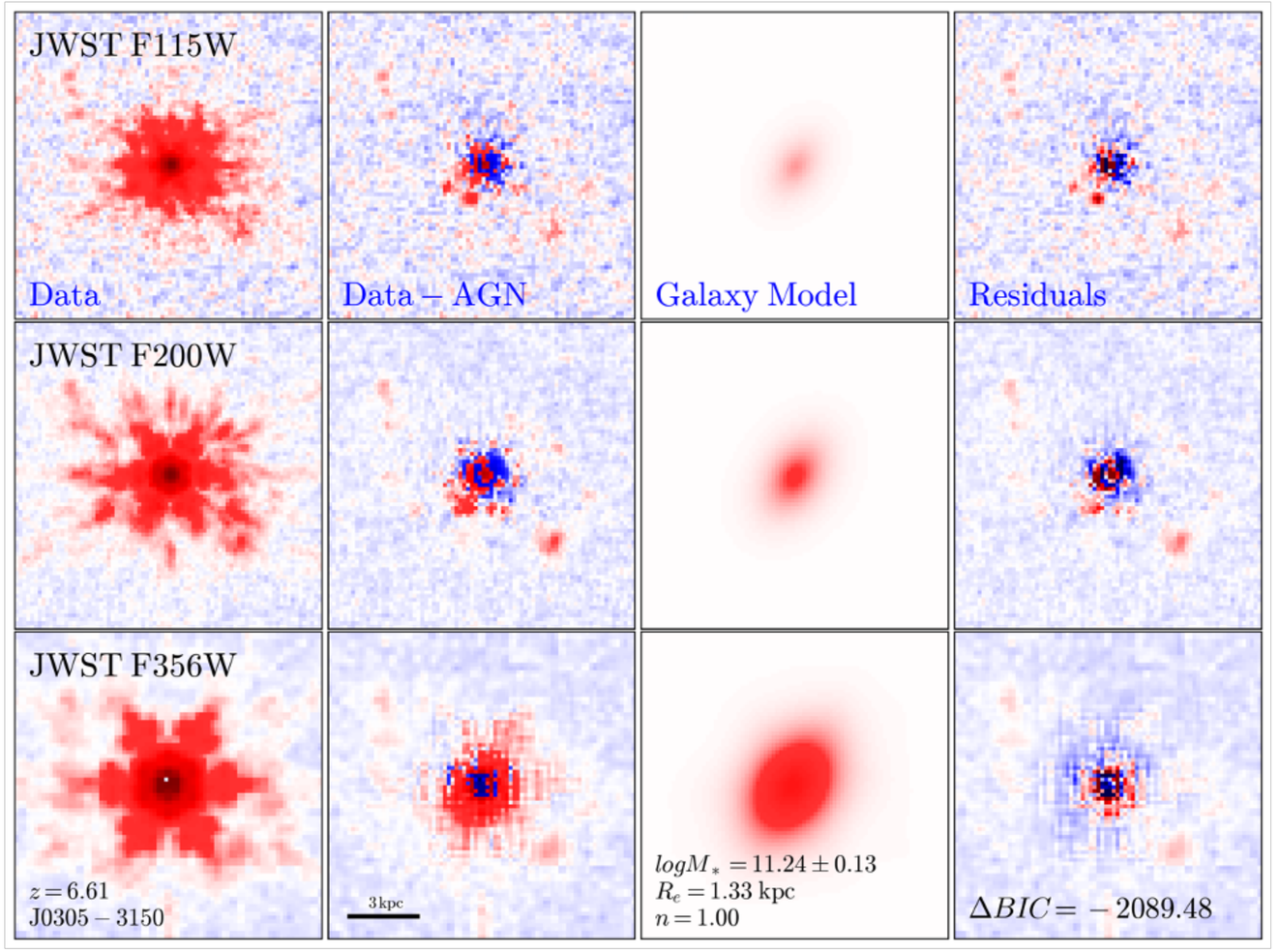
Li, Ho, Chen (2024)

For ASPIRE/EIGER quasars

$\log L_{5100} \geq 45$

Yang et al. (2023), Eilers et al. (2023)



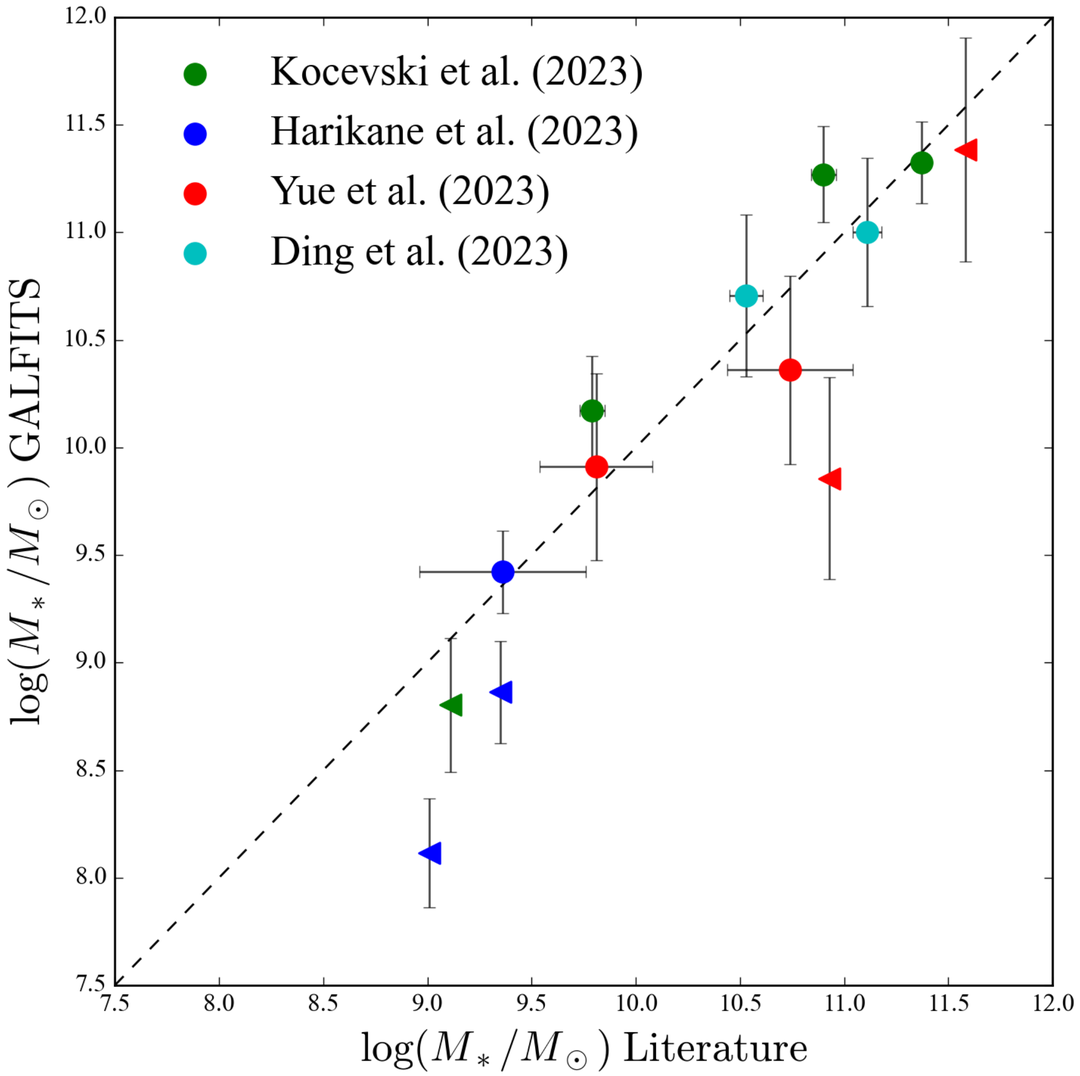


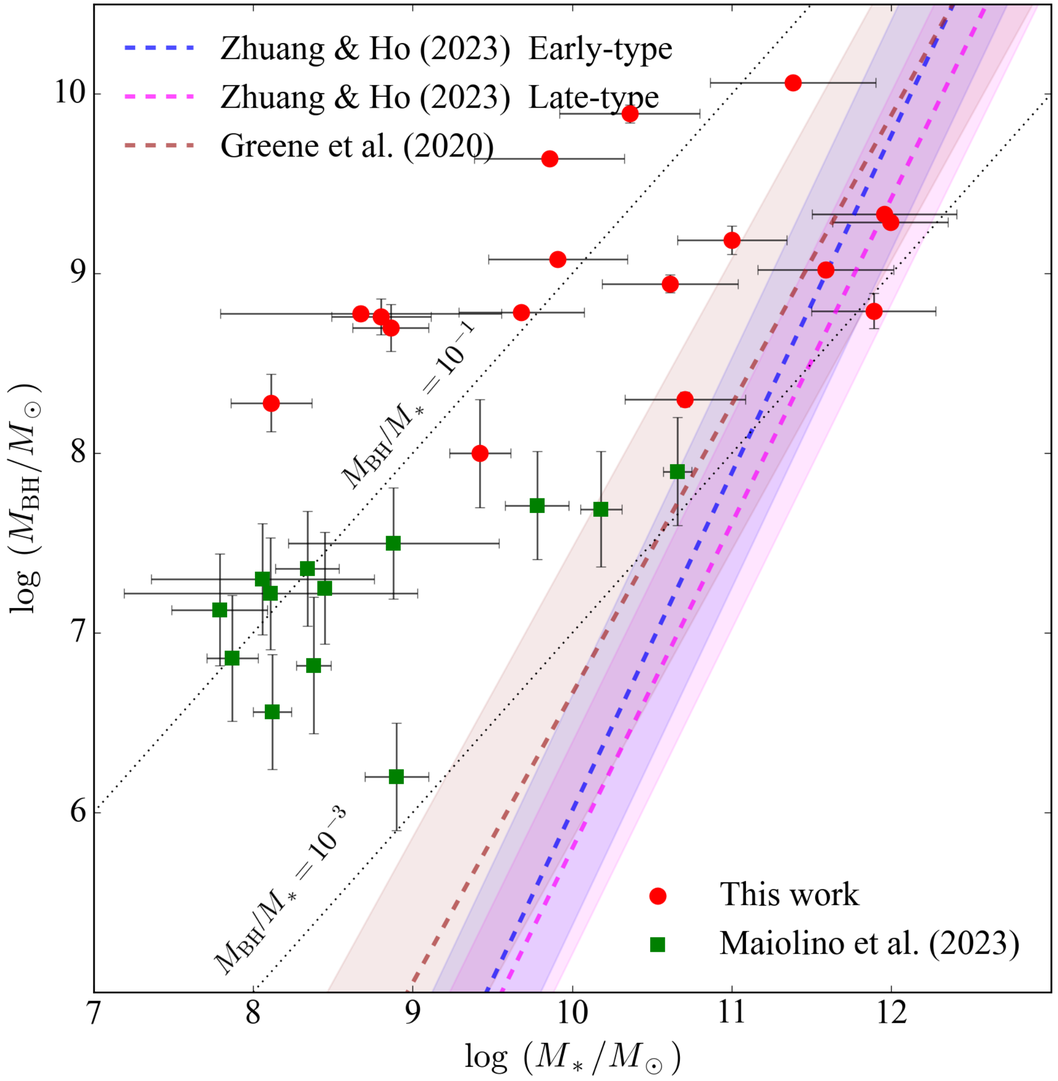
$$\mathrm{BIC} = k\ln(n) - 2\ln(\widehat{L}).$$

Detection: $\Delta BIC = BIC_{p+s} - BIC_p < 0$

Improvements in Host Galaxy Measurements: Quasars

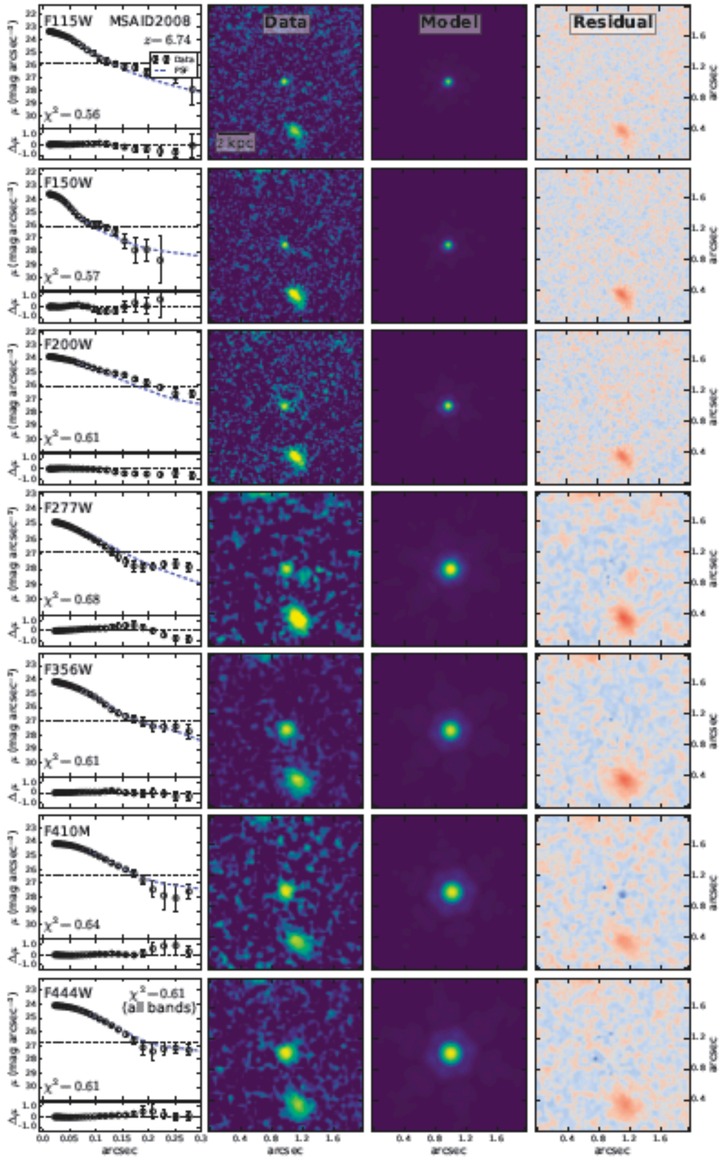
Li, Ho, Chen (2024)

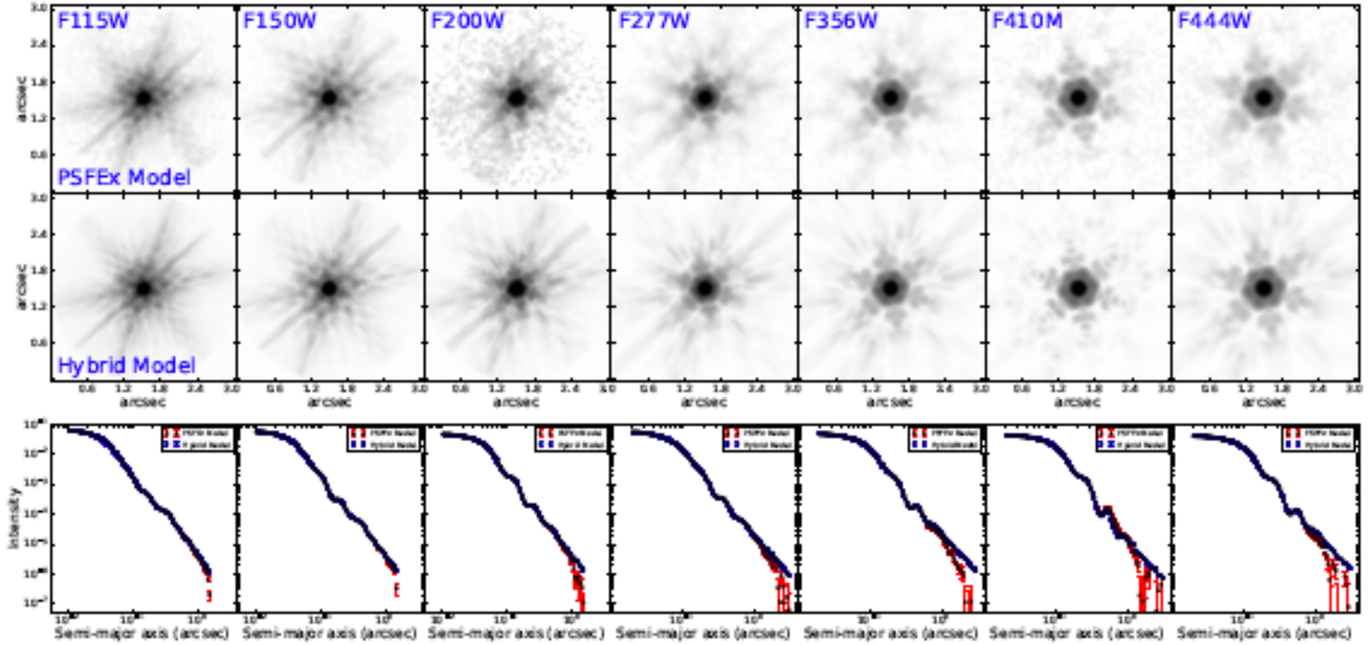




Improvements in Host Galaxy Measurements: Little Red Dots

Chen, Ho, Li & Zhuang (2024)

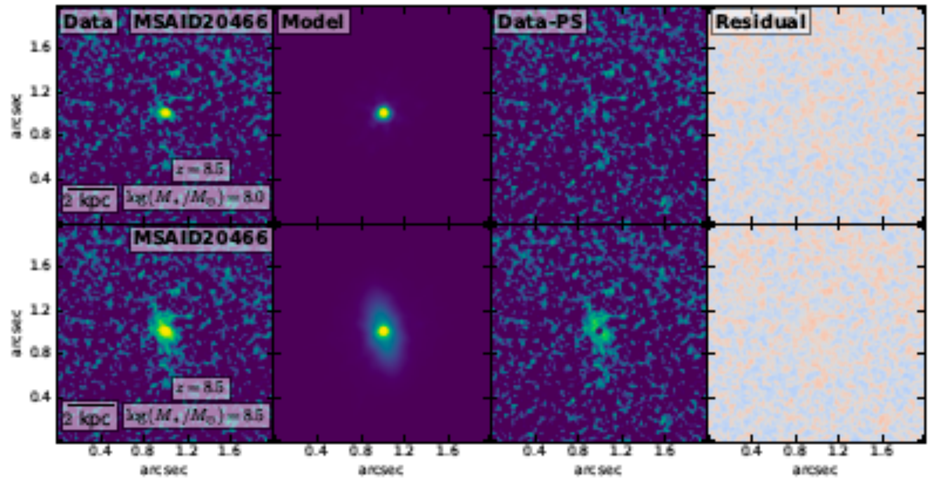


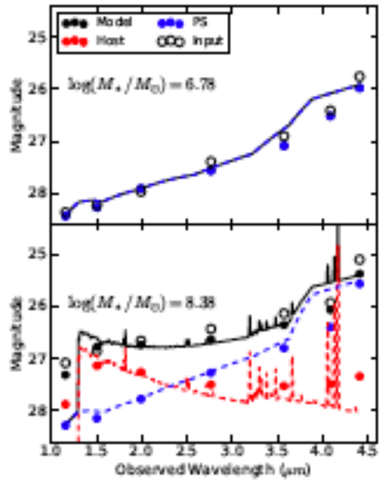


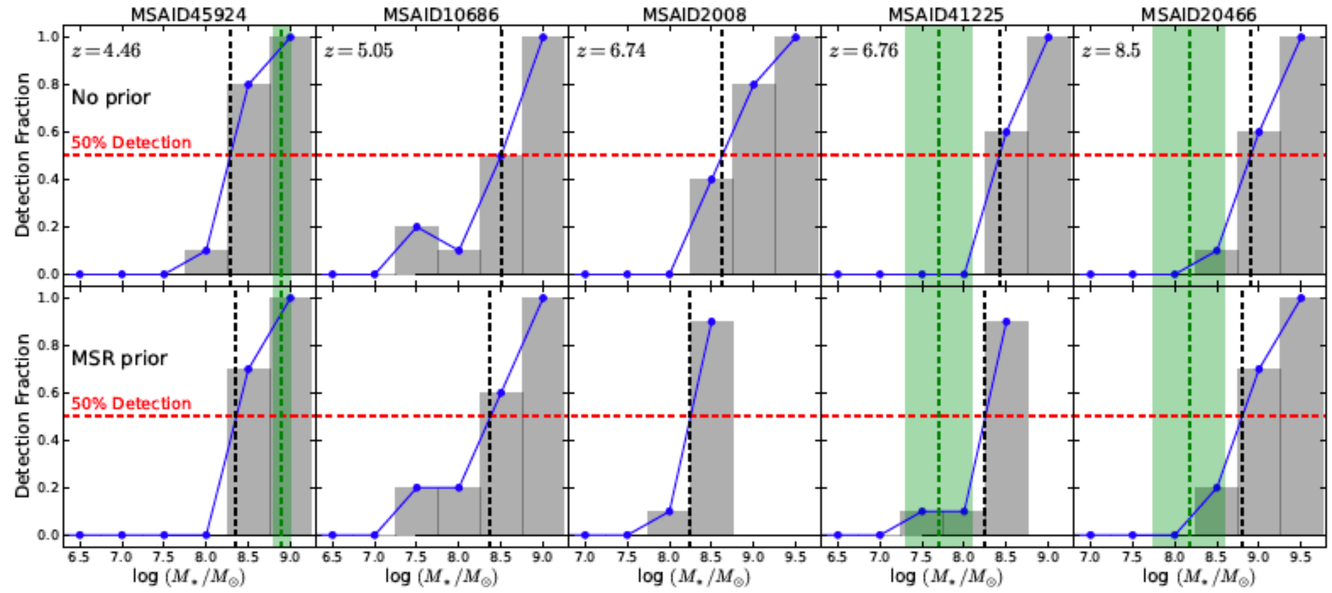
- **Simultaneous fitting of 7 NIRCam bands with GALFITS constrained by physical priors**
- **Accurate, new hybrid PSFs**

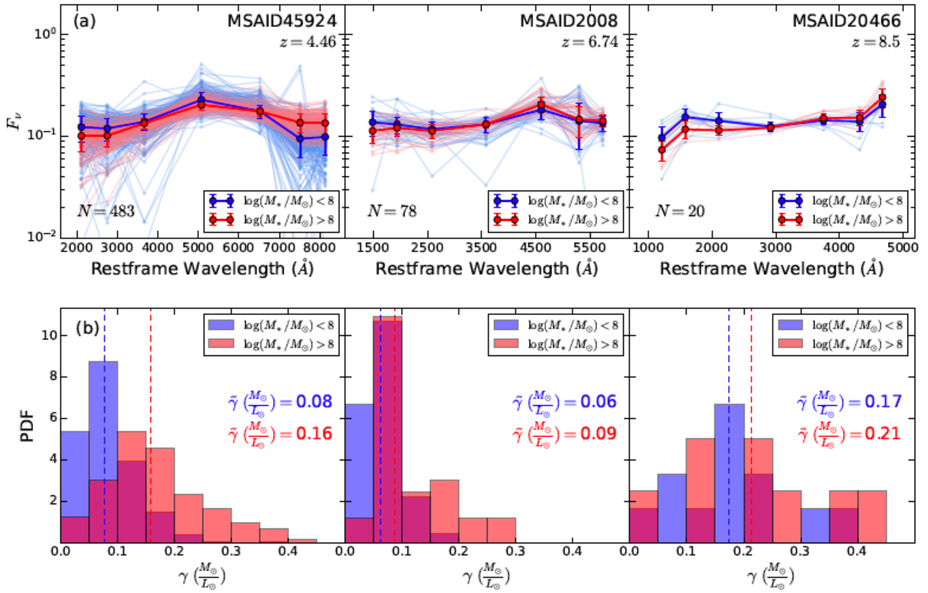
Improvements in Host Galaxy Measurements: Little Red Dots

Chen, Ho, Li & Zhuang (2024)





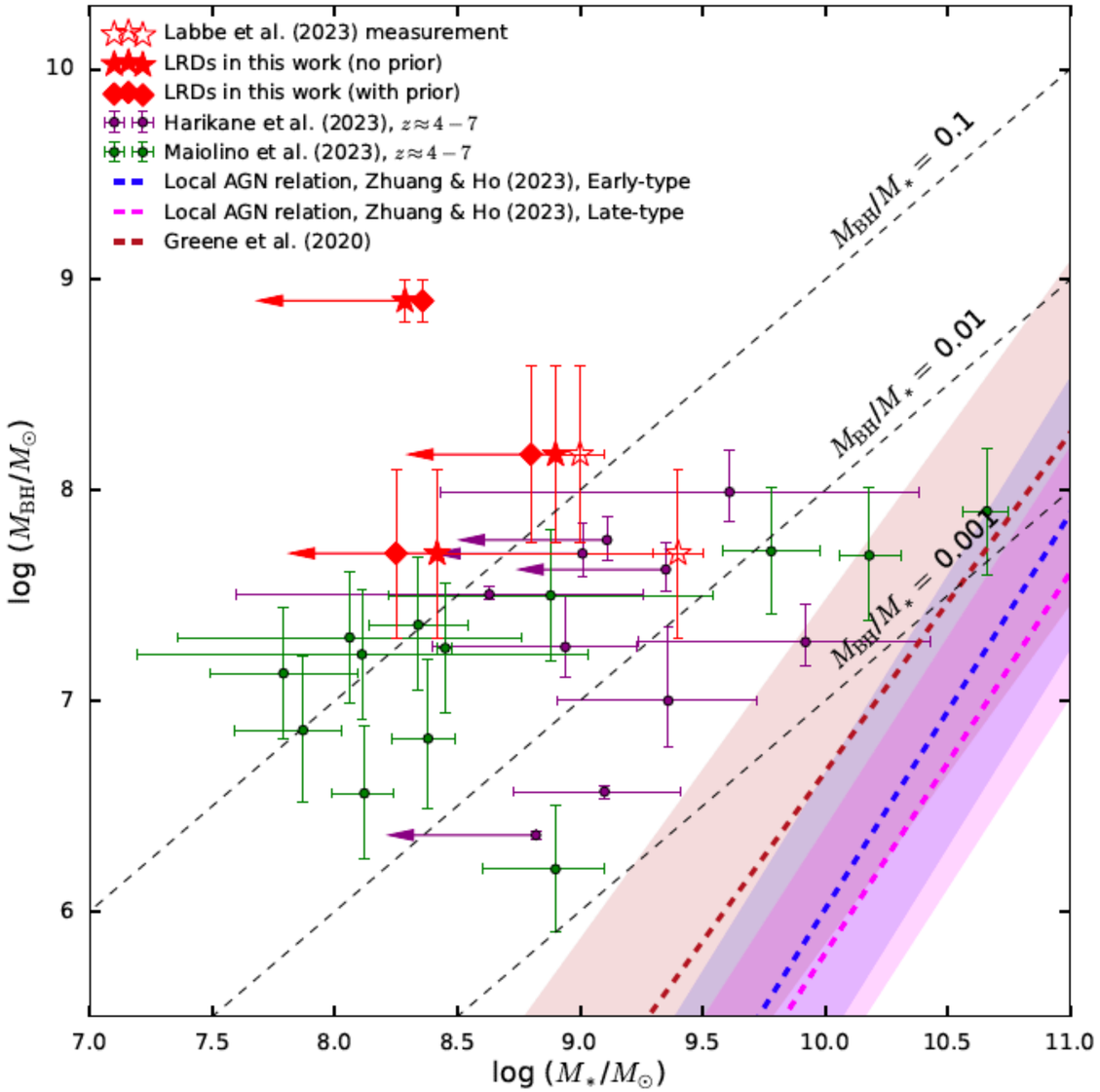




- No host emission detected
- Stringent upper limits placed on the stellar masses of the host galaxies
- Detailed, realistic mock simulations

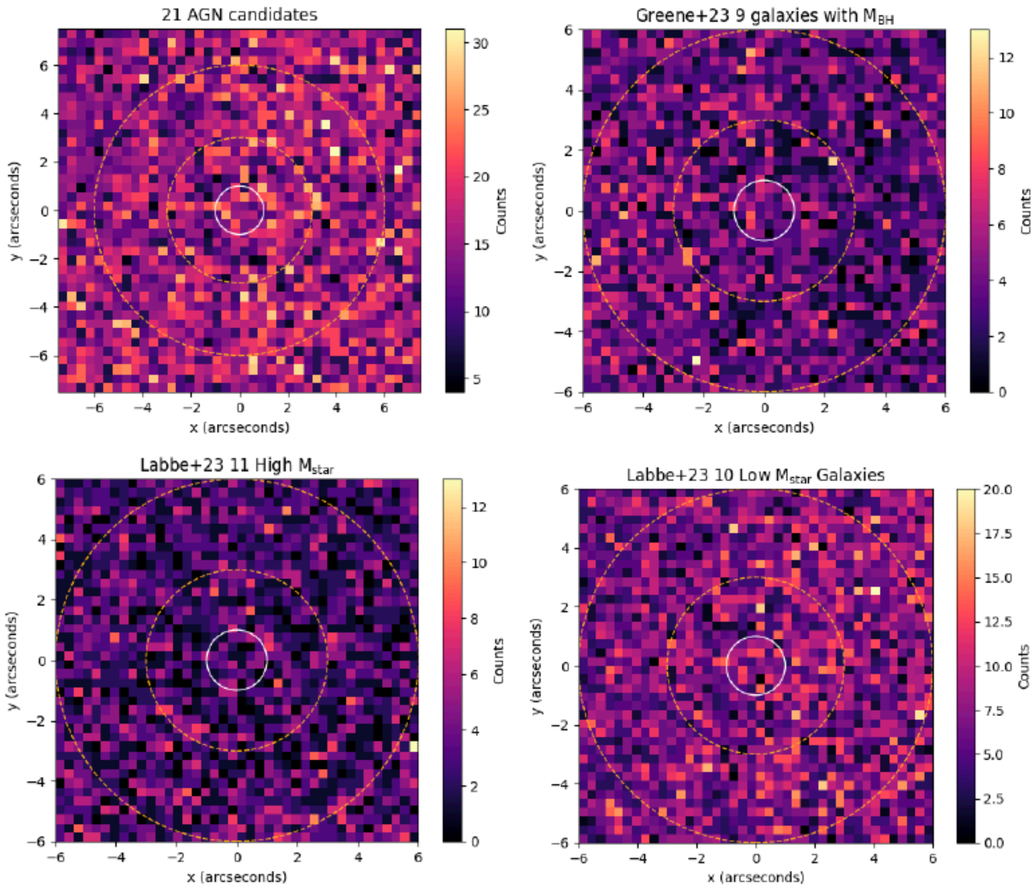
Improvements in Host Galaxy Measurements: Little Red Dots

Chen, Ho, Li & Zhuang (2024)

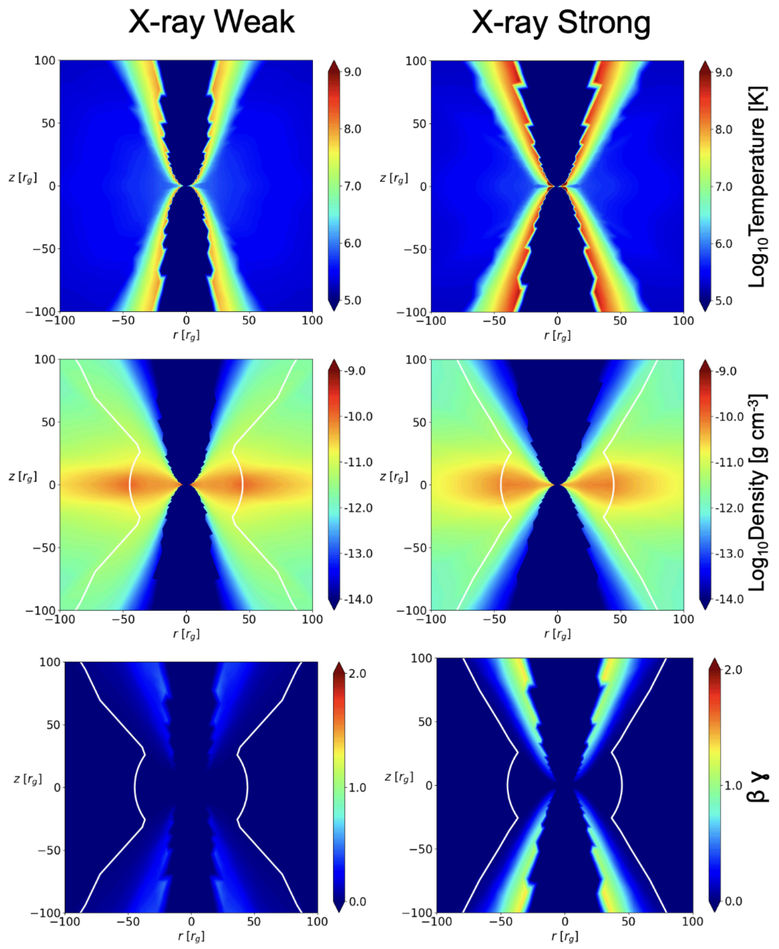


Are LRDs truly AGNs?

No X-rays



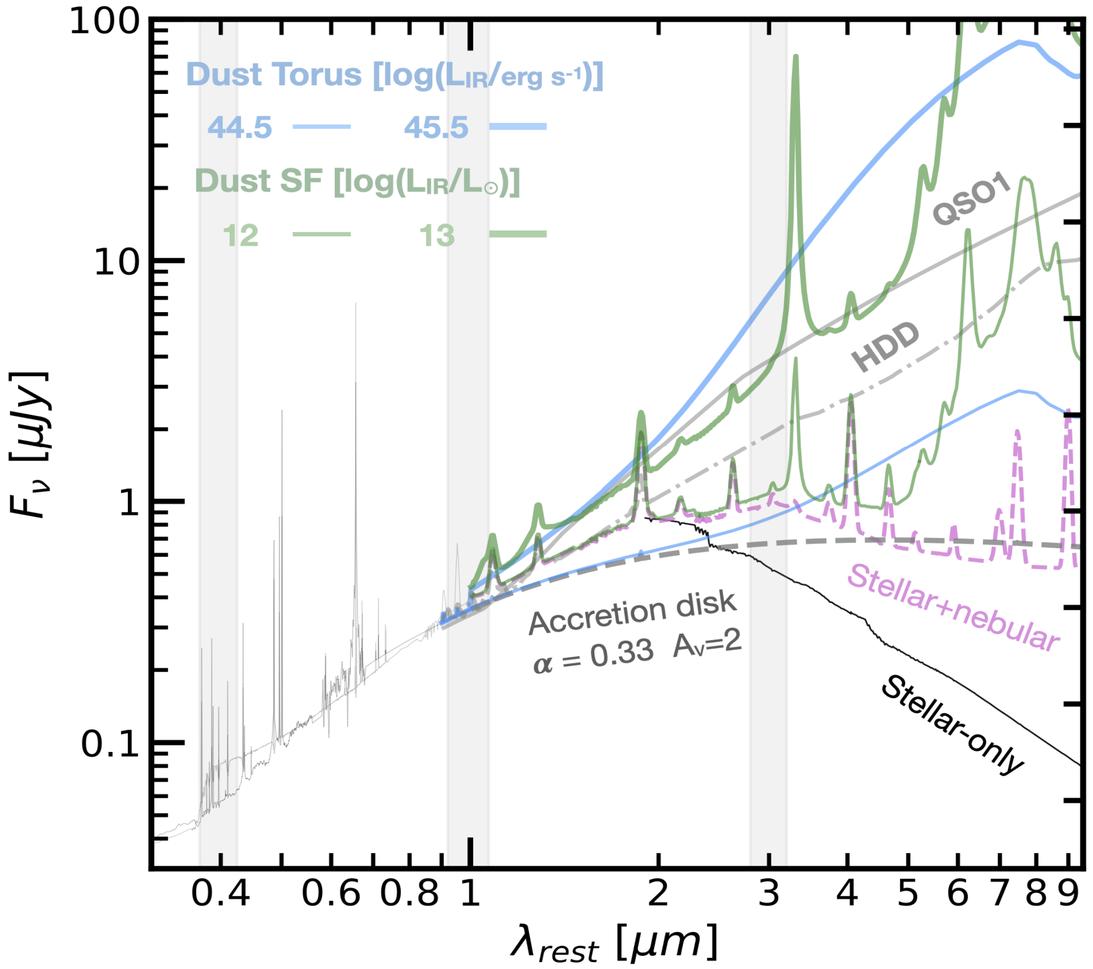
Ananna et al. (2024), Maiolino et al. (2024)



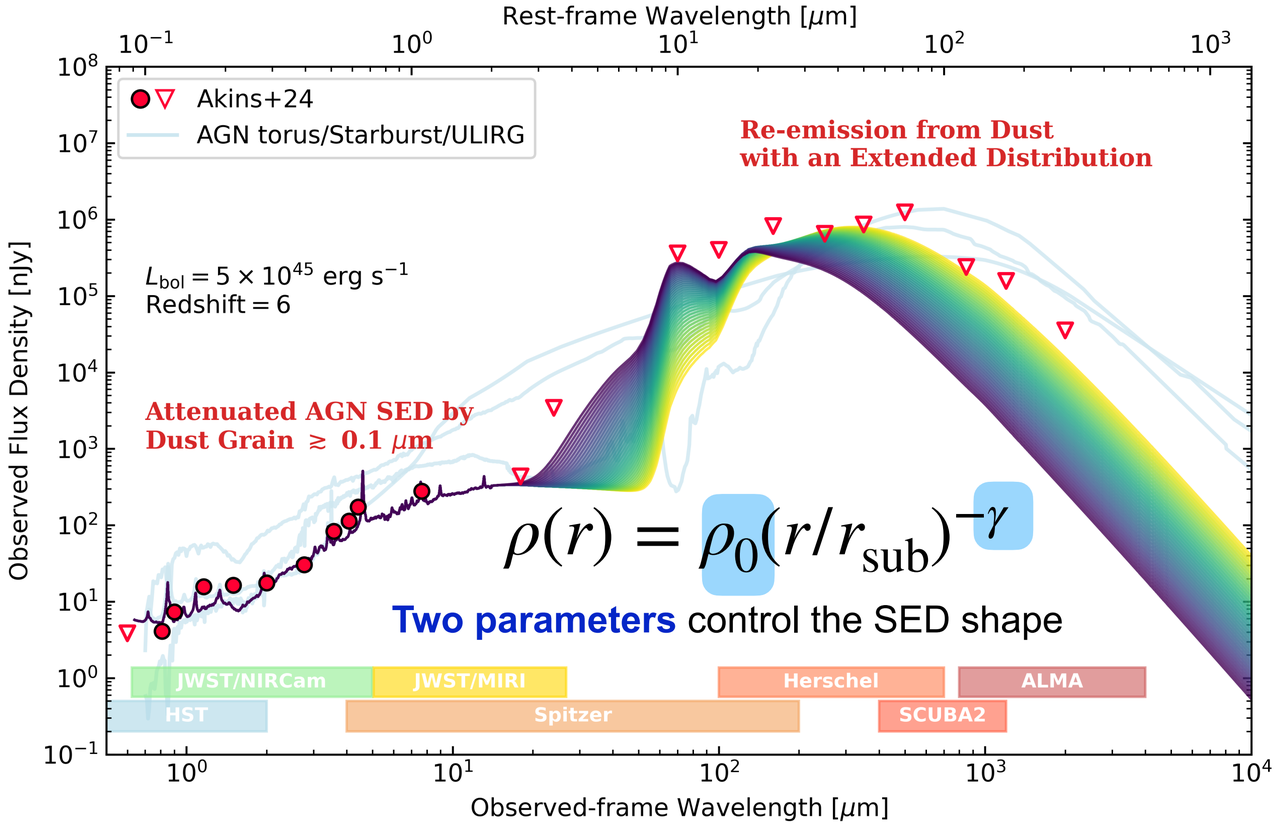
Pacucci & Narayan (2024), Madau & Haardt (2024)

Are LRDs truly AGNs?

No torus



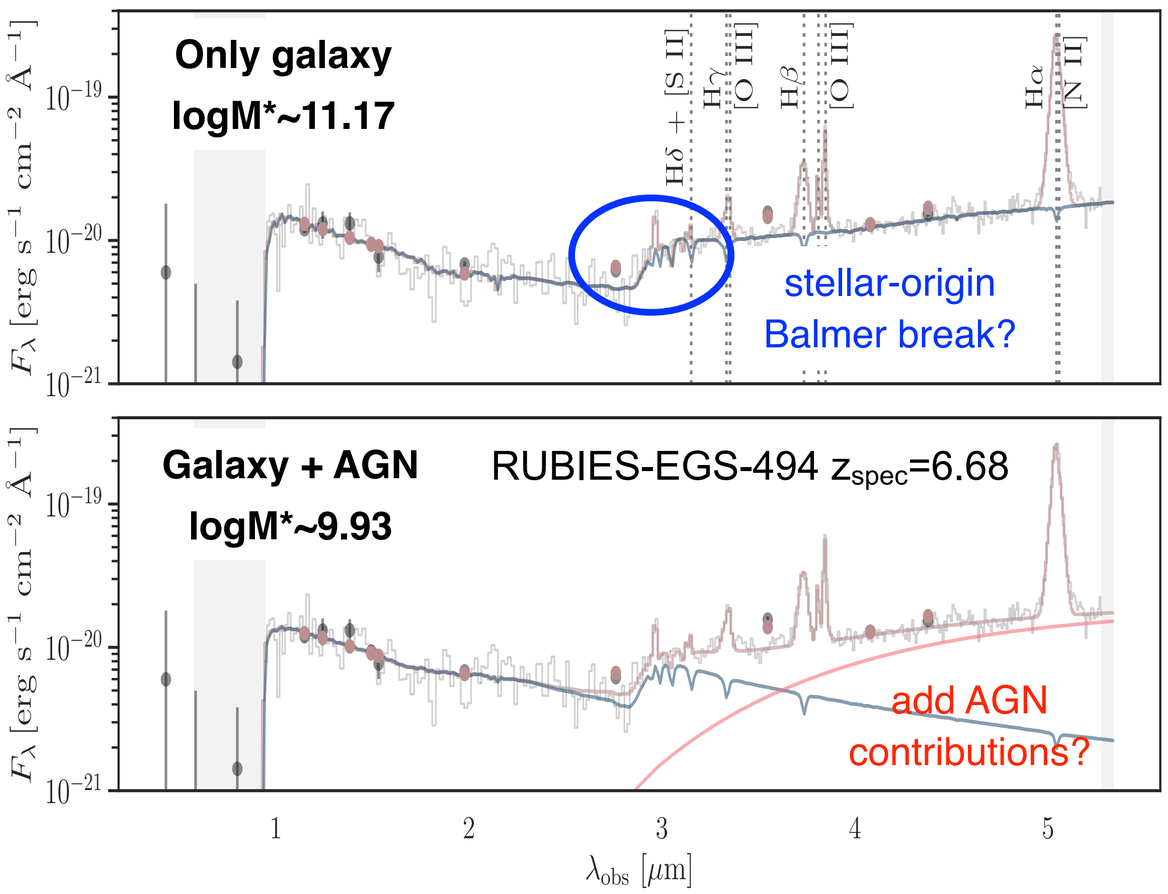
Pérez-González et al. (2024)



Li, Inayoshi, Chen, Ichikawa & Ho (2024)

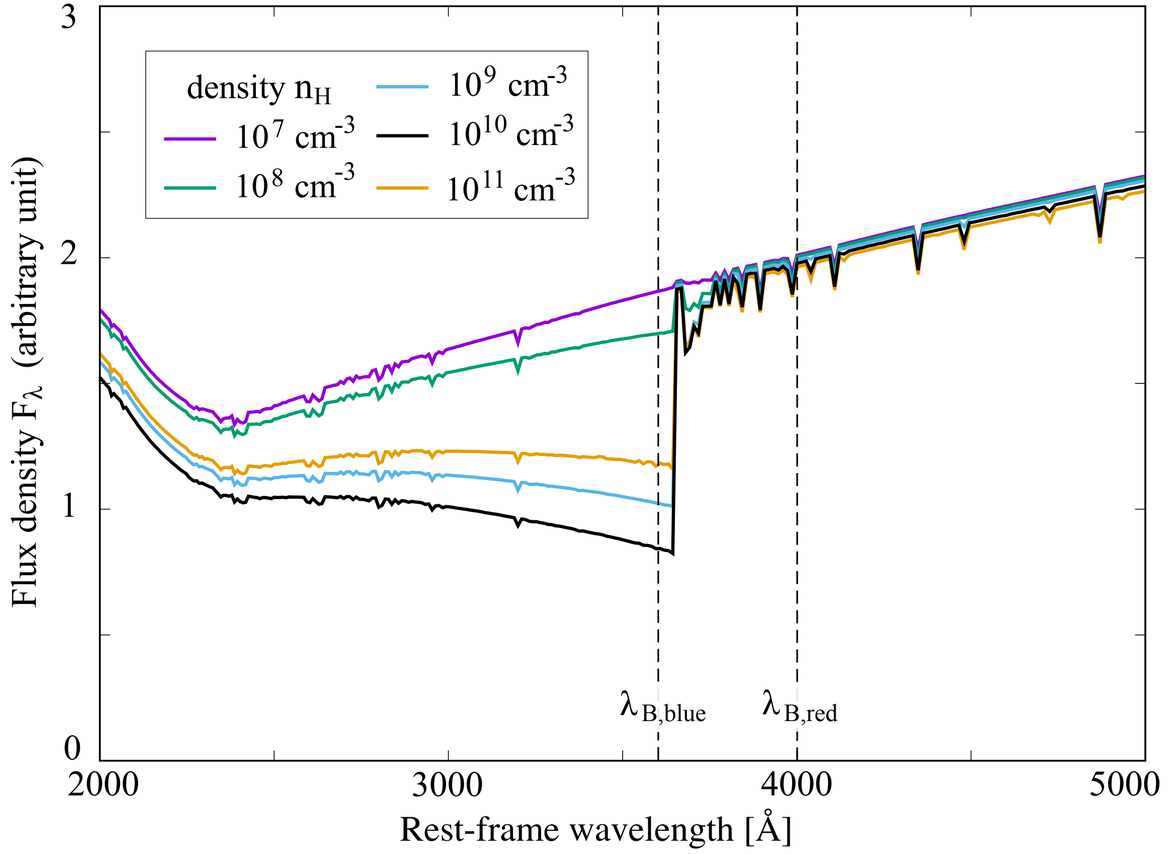
Are LRDs truly AGNs?

Balmer break



Wang et al. (2024)

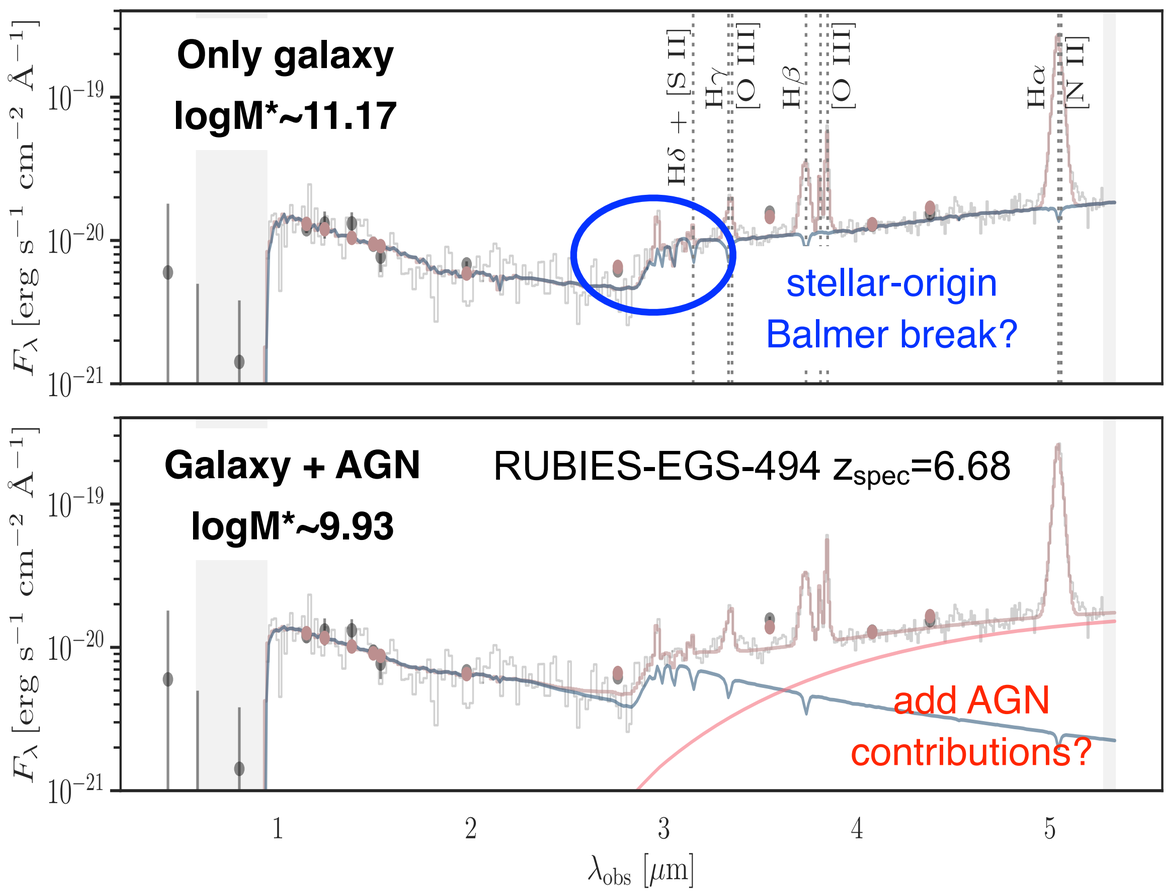
Can arise from dense gas in AGNs!



Inayoshi & Maiolino (2024)

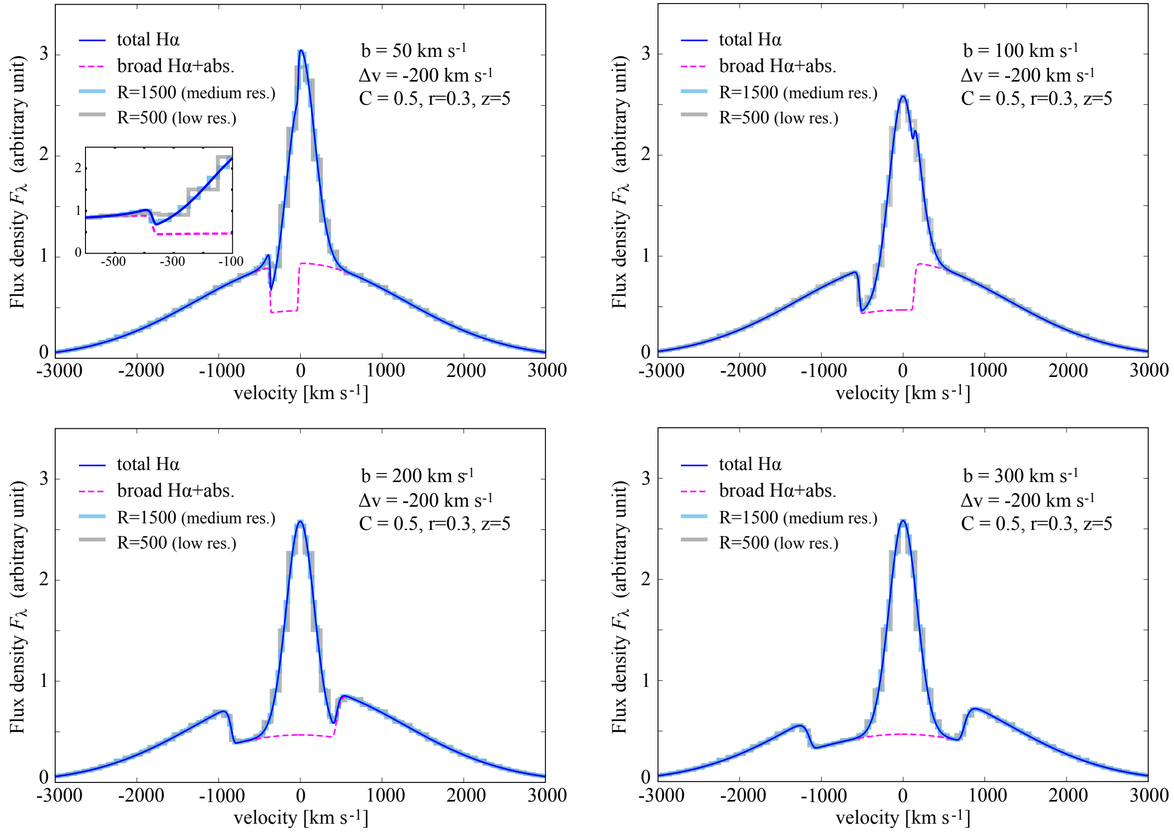
Are LRDs truly AGNs?

Balmer break



Wang et al. (2024)

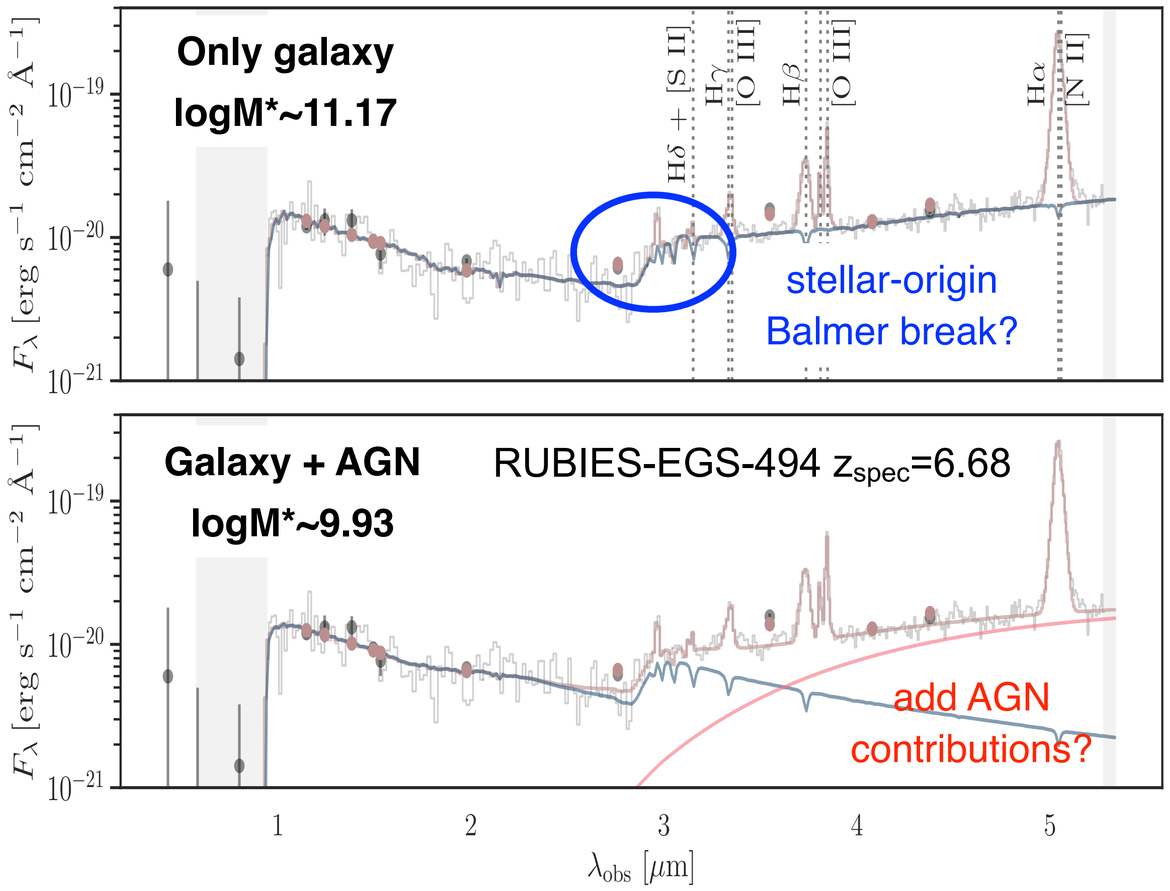
Balmer absorption



Inayoshi & Maiolino (2024)

Are LRDs truly AGNs?

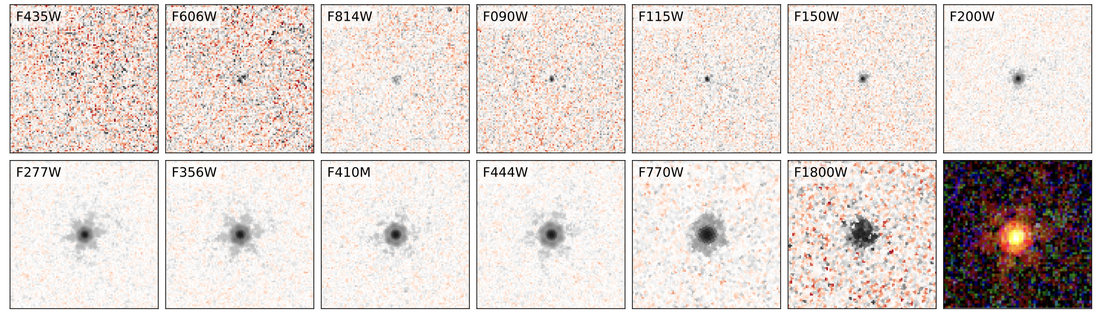
Balmer break

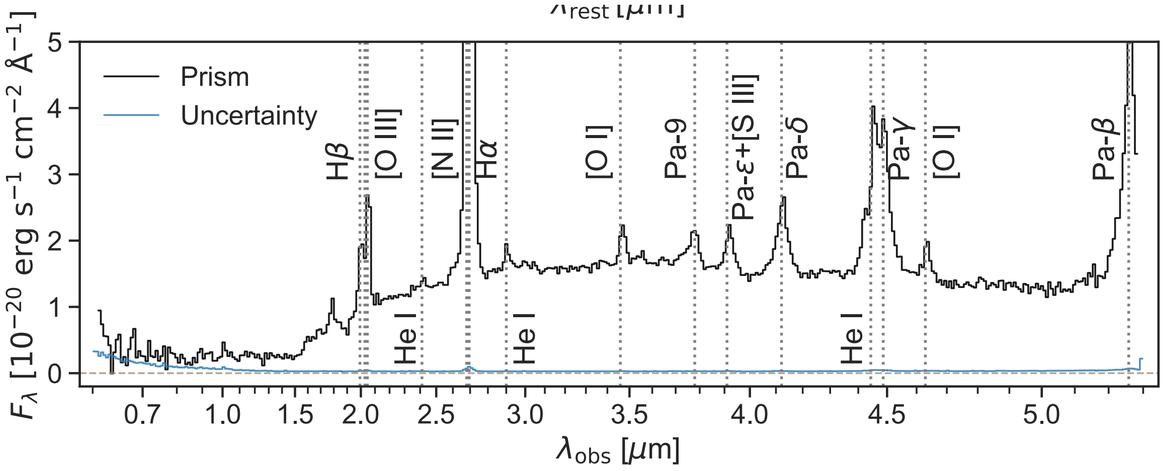


Wang et al. (2024)

Enhanced Hα, O I and lines

RUBIES-BLAGN-1 , an AGN at z = 3.1 (Wang et al. 2024a)



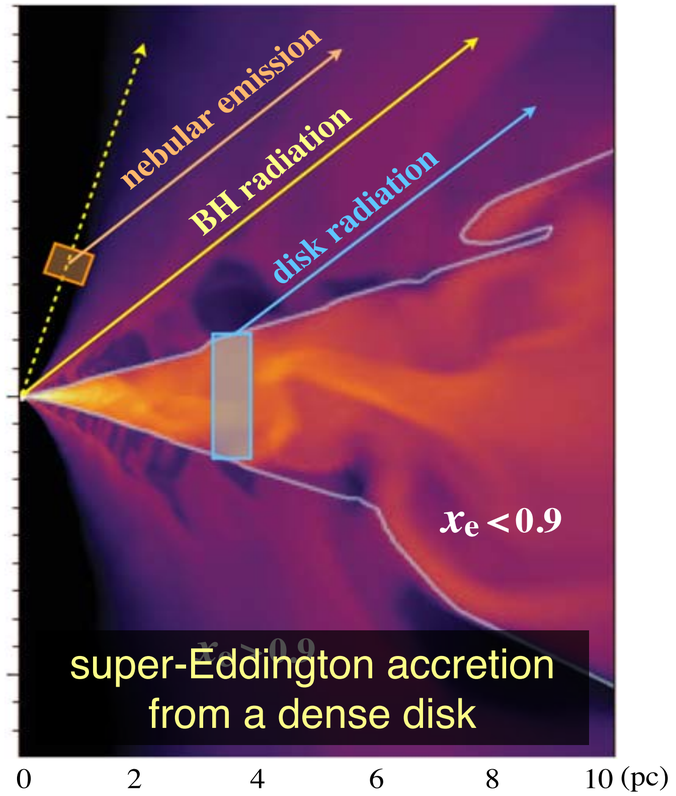


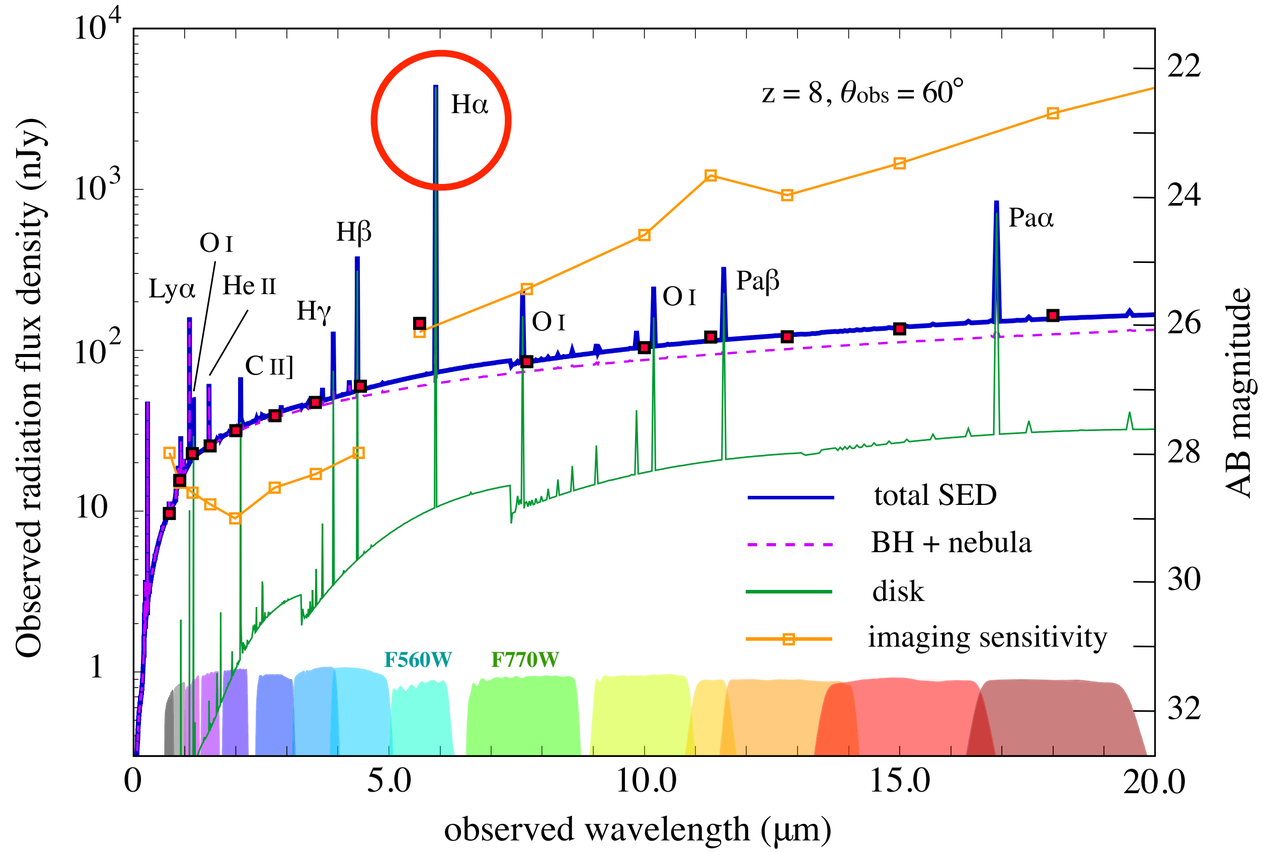
Inayoshi & Maiolino (2024)

Spectra of growing seed BHs

Inayoshi, Onoue, Sugahara, Inoue & Ho (2022)

RHD simulations + CLOUDY





- Strong Balmer lines (e.g., **$EW_{H\alpha}$ = 1300 Å**, $EW_{H\beta}$ = 100 Å, v~200km/s)
- Emission lines of O I due to Lyβ fluorescence ($EW_{OI1304} \gtrsim 10$ Å)

Summary

- Discovery of central black holes as a fundamental constituent of galaxies.
- Black holes coevolve with galaxies. Black hole accretion and feedback are key ingredients to galaxy formation and evolution.
- In $M_* > 10^{10}\,M_\odot$ galaxies, occupation fraction ~100% for SMBHs $M_\bullet \approx 10^6 - 10^{10}\,M_\odot$.
- In $M_* < 10^{10}\,M_\odot$ galaxies, occupation fraction $\gtrsim 50\%$ for IMBHs with $M_\bullet \approx 10^4 - 10^6\,M_\odot$.
- Quasars have $M_\bullet \approx 10^9 - 10^{10}\,M_\odot$ when Universe was < 1 Gyr old.
- JWST discovery of numerous $z \approx 5 - 11$ galaxies with $M_\bullet \approx 10^6 - 10^8\,M_\odot$.
- Important new constraints on formation mechanism of SMBHs, cosmic reionization, and gravitational waves astrophysics.

References

Ho (2008, ARA&A): *Nuclear Activity in Nearby Galaxies*

Kormendy & Ho (2013, ARA&A): *Coevolution of Supermassive Black Holes and Galaxies*

Greene, Strader & Ho (2020, ARA&A): *Intermediate-mass Black Holes*

Dozens of papers on JWST results on AGNs and galaxies