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Exotic Quasars in the Early Universe

Bradford Snios[1], Aneta Siemiginowska[1], Małgosia Sobolewska[1], C. C. Cheung[2], Vinay Kashyap[1], Giulia Migliori[3,4], Daniel A. Schwartz[1], Łukasz Stawarz[5], Diana M. Worrall[6]

[1]Center for Astrophysics | Harvard & Smithsonian, Cambridge, MA 02138, USA
[2]Space Science Division, Naval Research Laboratory, Washington, DC 20375, USA
[3]Department of Physics and Astronomy, University of Bologna, Bologna, Italy
[4]INAF–Institute of Radio Astronomy, Bologna, Bologna, Italy
[5]Astronomical Observatory of the Jagiellonian University, Kraków, Poland
[6]H. H. Wills Physics Laboratory, University of Bristol, Bristol, UK

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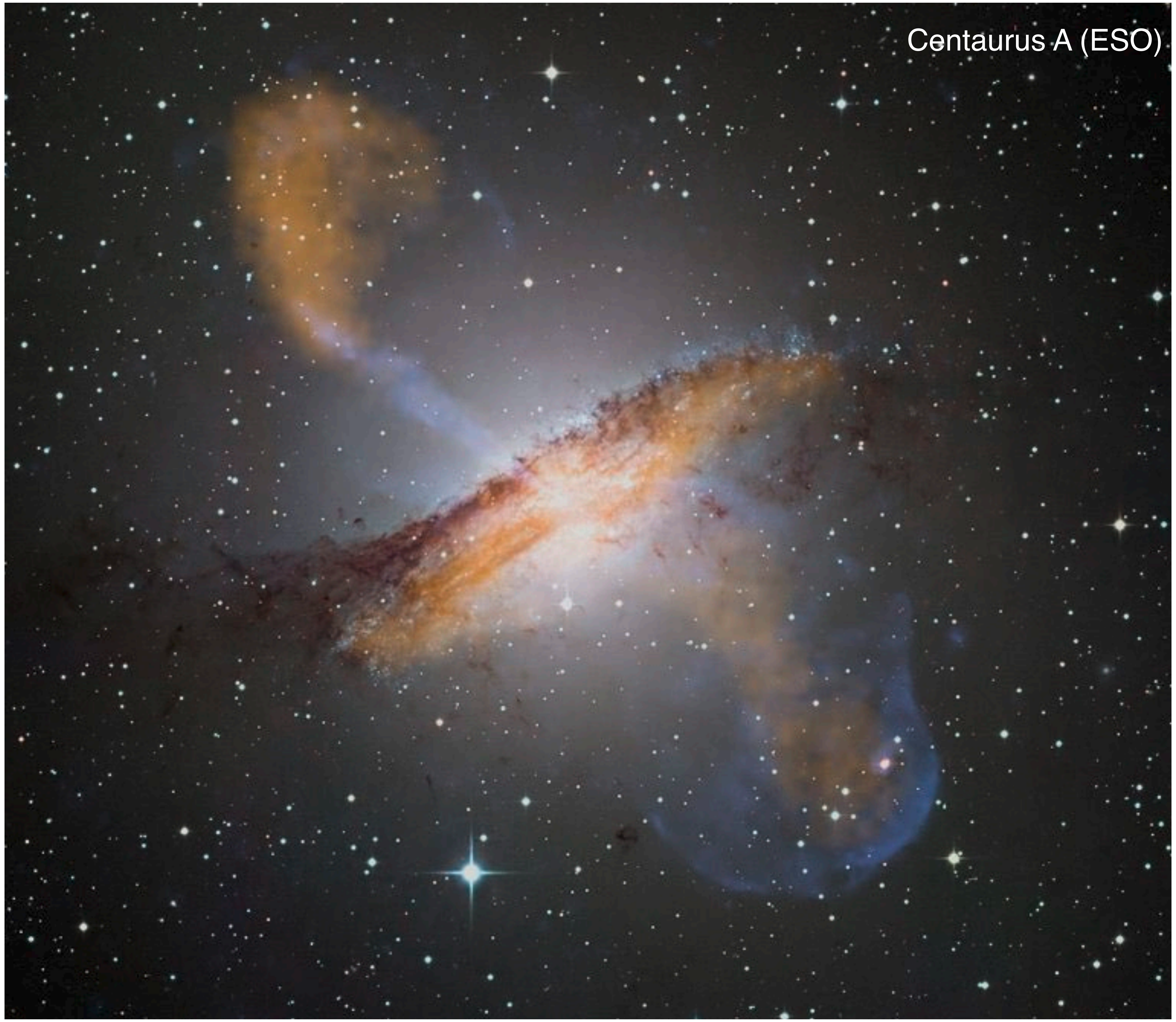
bsnios@cfa.harvard.edu

Quasars

- Quasar is an extremely luminous active galactic nucleus (AGN), that generally contains a supermassive black hole (SMBH)
- Quasars represent the most-massive and most-energetic SMBHs in the Universe
  - Observed over a broad redshift range
- Presence of quasars in early Universe (high-redshift) place constraints on the SMBH formation rates [Volonteri 2012]

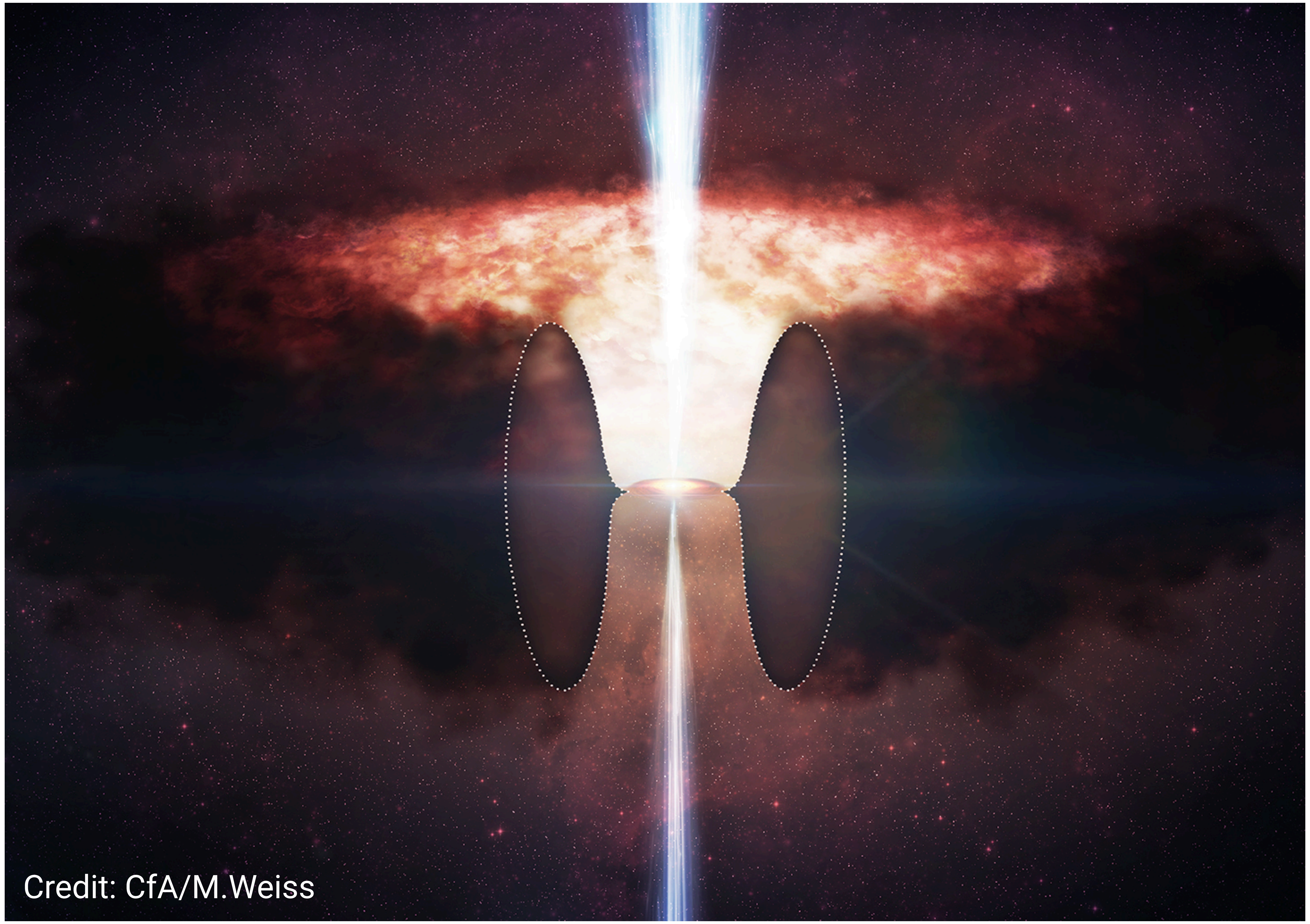


Quasar Formation in the Early Universe

- Formation of quasars in early Universe requires accretion phases where SMBH is significantly obscured by dust/gas
- Obscuration densities can exceed Compton-thick (CT) levels
  - Column density exceeds Compton scattering optical depth

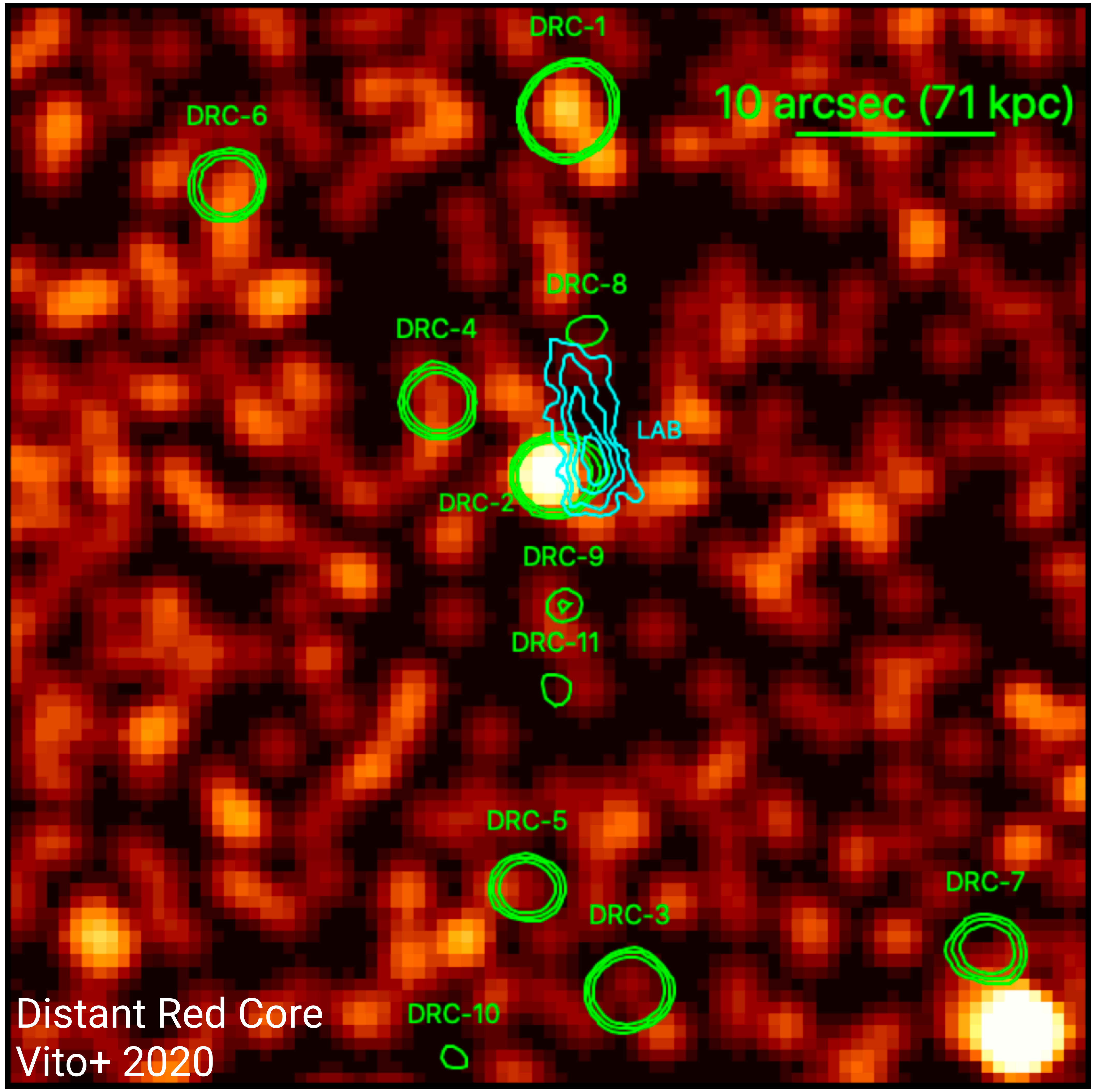
$$n_{\mathrm{H}} \geq 10^{24}\,\mathrm{cm}^{-2}$$

- Majority of high-redshift quasars predicted to be Compton-thick (CT)

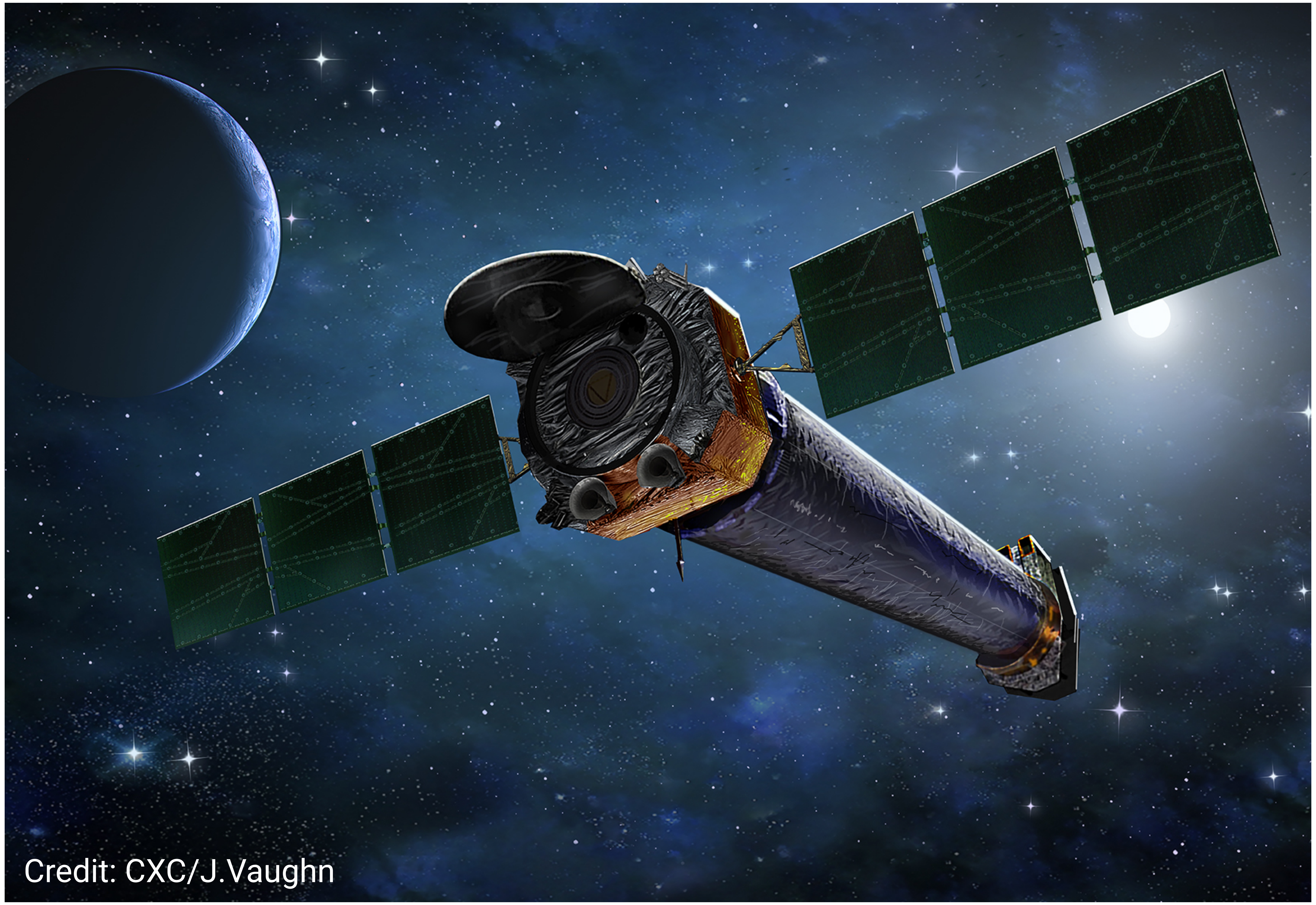


Missing Quasar Population

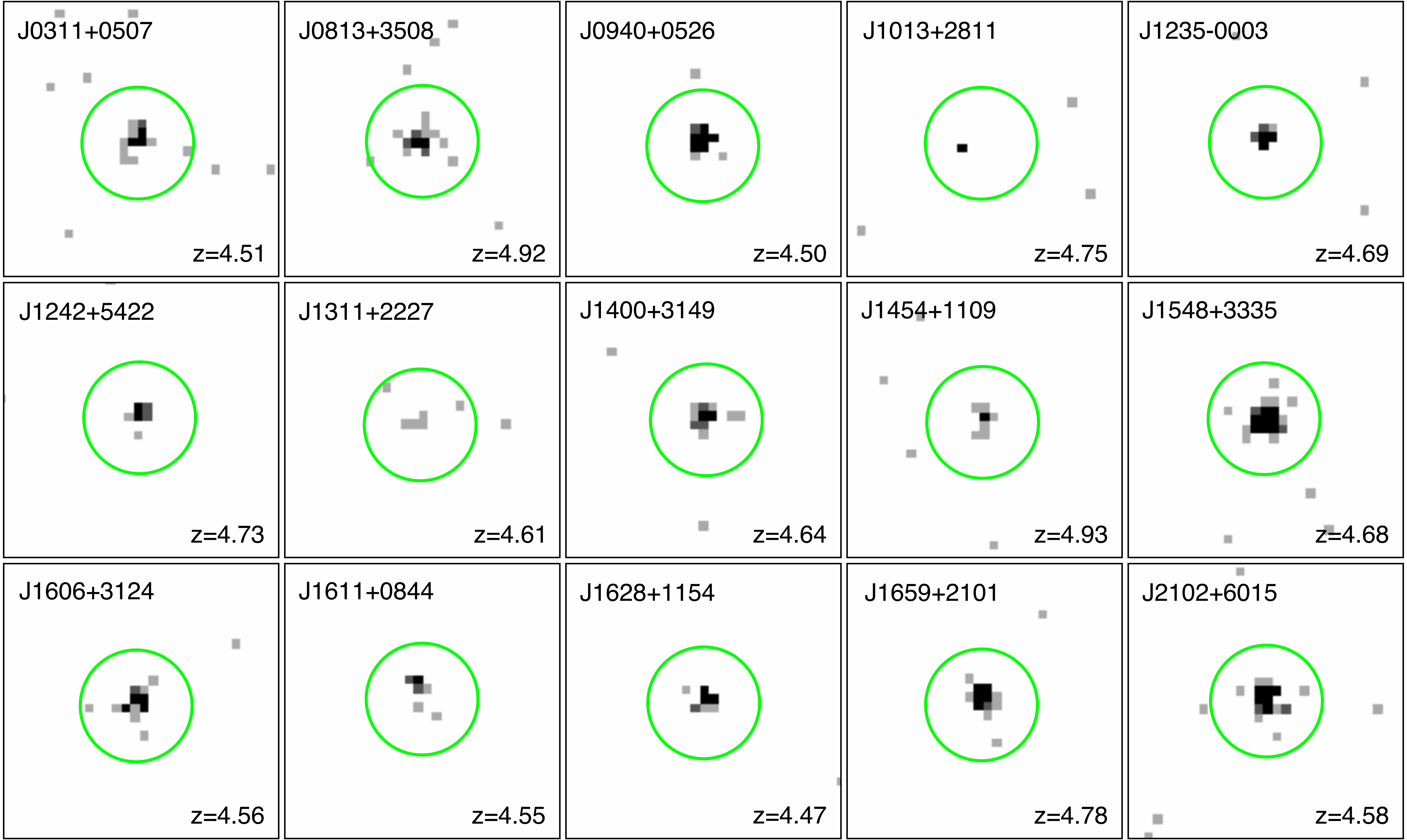
- Despite prediction, high-redshift **CT quasar population remains largely undetected**
  - Only 3 known CT quasars in early Universe ($z > 4$)
- Lack of detection may be attributable to selection biases for quasars that rely on UV observations, which is absorbed
- Alternatively, quasar formation models assuming invalid initial condition in the early Universe
- Characterization of high-redshift quasar population required to answers such questions



High-Redshift Quasar X-Ray Survey

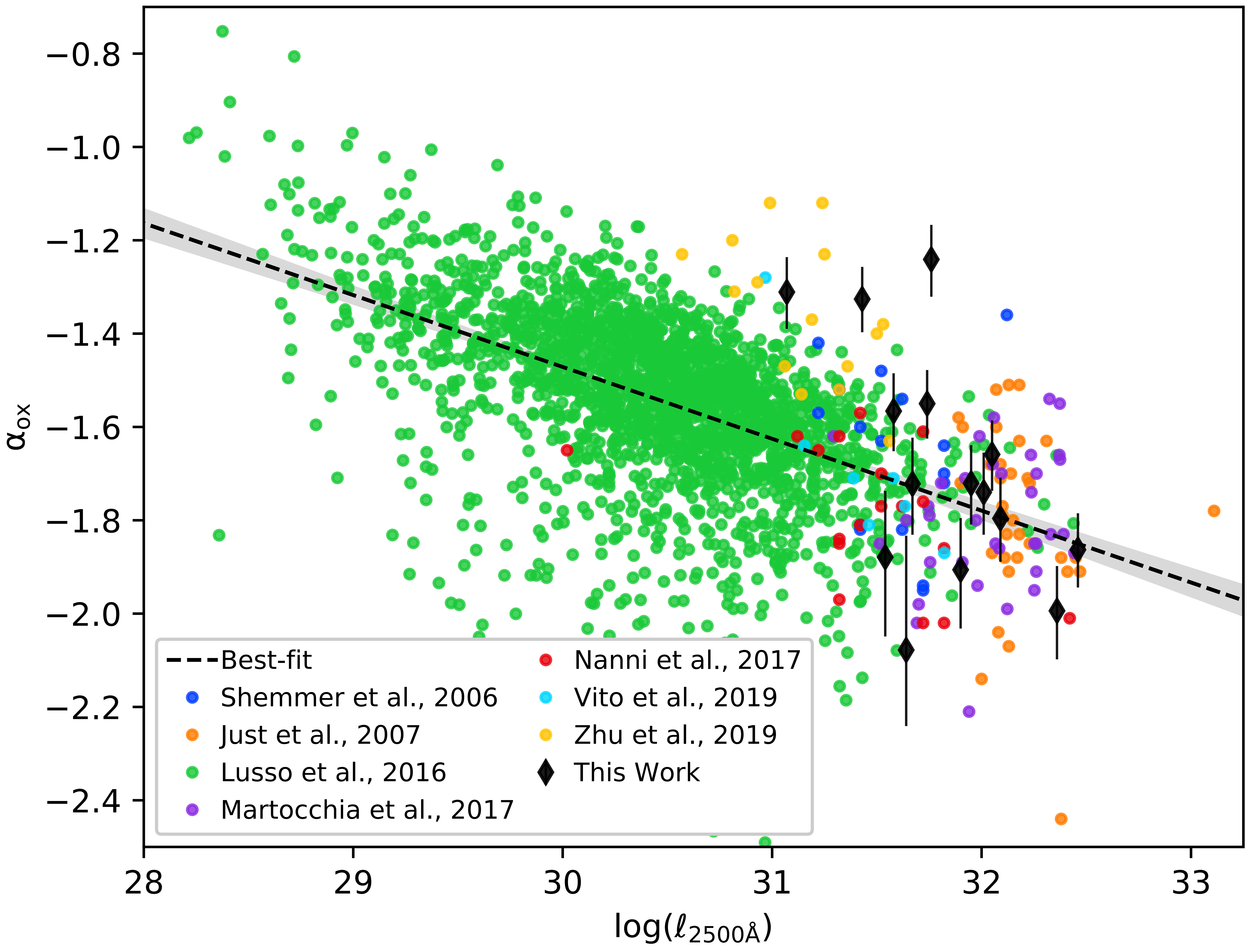


- X-rays not obscured by dust & debris
  - Uniquely capable of detecting CT sources
- Used Chandra X-ray Observatory to survey X-rays from sample of quasars
- Targets selected from compact radio quasar catalog at $z > 4.5$
  - Prioritized sources with steep or peaked at MHz, which indicates young radio sources



J0311+0507
z=4.51
J0813+3508
z=4.92
J0940+0526
z=4.50
J1013+2811
z=4.75
J1235-0003
z=4.69
J1242+5422
z=4.73
J1311+2227
z=4.61
J1400+3149
z=4.64
J1454+1109
z=4.93
J1548+3335
z=4.68
J1606+3124
z=4.56
J1611+0844
z=4.55
J1628+1154
z=4.47
J1659+2101
z=4.78
J2102+6015
z=4.58

Optical–X-ray Properties

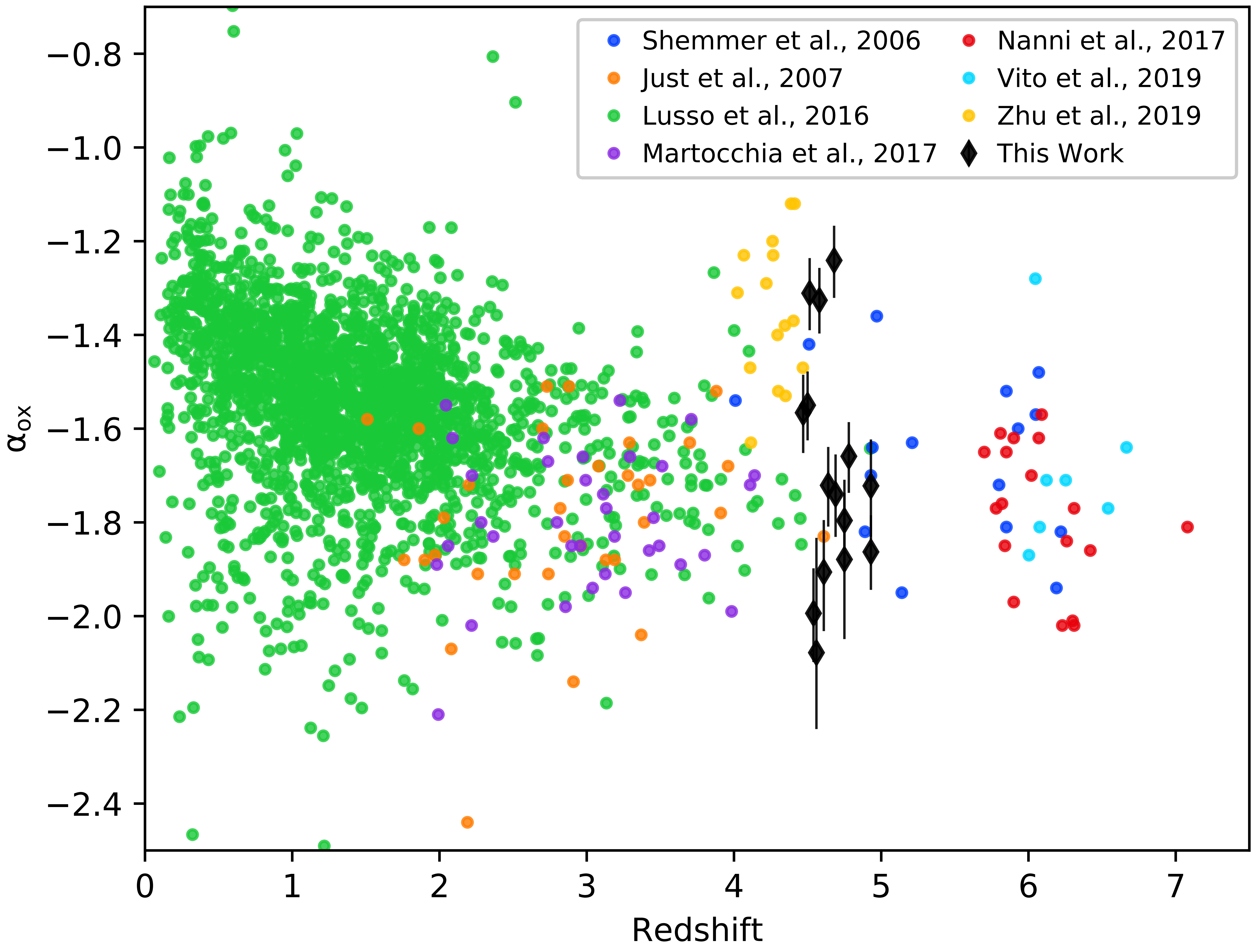


- Calculated optical−X-ray power-law spectral index $\alpha_{\rm ox}$ for all sources in sample
- Compared $\alpha_{\rm ox}$–optical relationship of sample with X-ray bright quasars across redshift

$$\alpha_{\rm ox} = (-0.154 \pm 0.005)\log(\ell_{2500\text{Å}}) + (3.2 \pm 0.2)$$

- Agrees with independent measurements [Nanni+ 2017]

Optical–X-ray Properties (II)



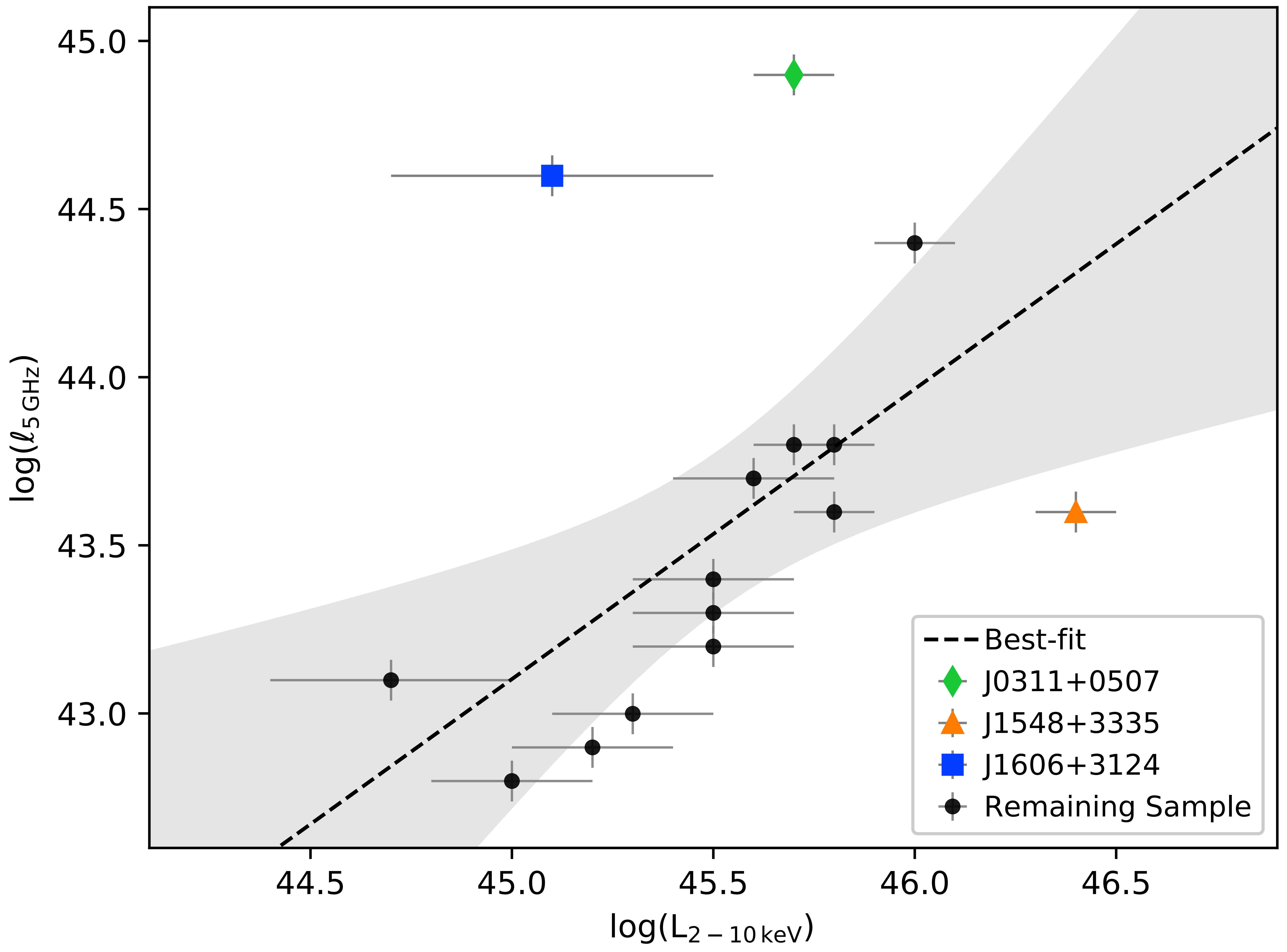
- Assessed quasar population for redshift dependence
- No trend observed in population
- Consistent with results from Vito+ 2019
- Further sampling of quasars at $z > 4$ required to conclusively determine evolution of optical—X-ray relationship

Radio–X-ray Properties

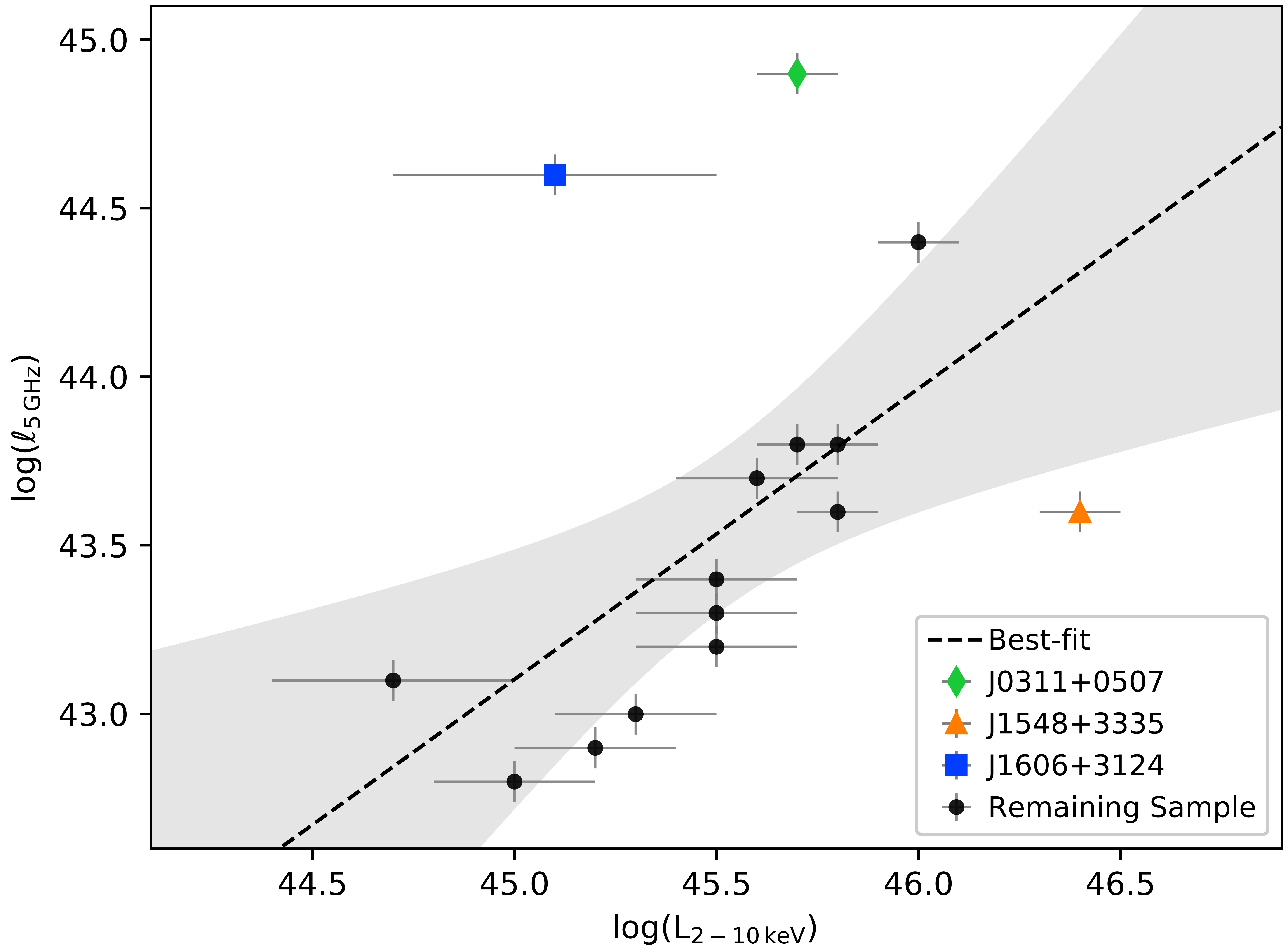
- Measured rest-frame radio and X-ray luminosities, examined for trend in sample
- Akin to fundamental plane [Merloni+2003], assuming similar SMBH masses for sample

$$\log(L_{5\,\mathrm{GHz}}) = (0.9 \pm 0.6)\log(L_{2-10\,\mathrm{keV}}) + (4 \pm 26)$$

- Radio—X-ray relationship observed in data, with three notable outliers
- Follow-up X-ray observations scheduled/completed for each outlier

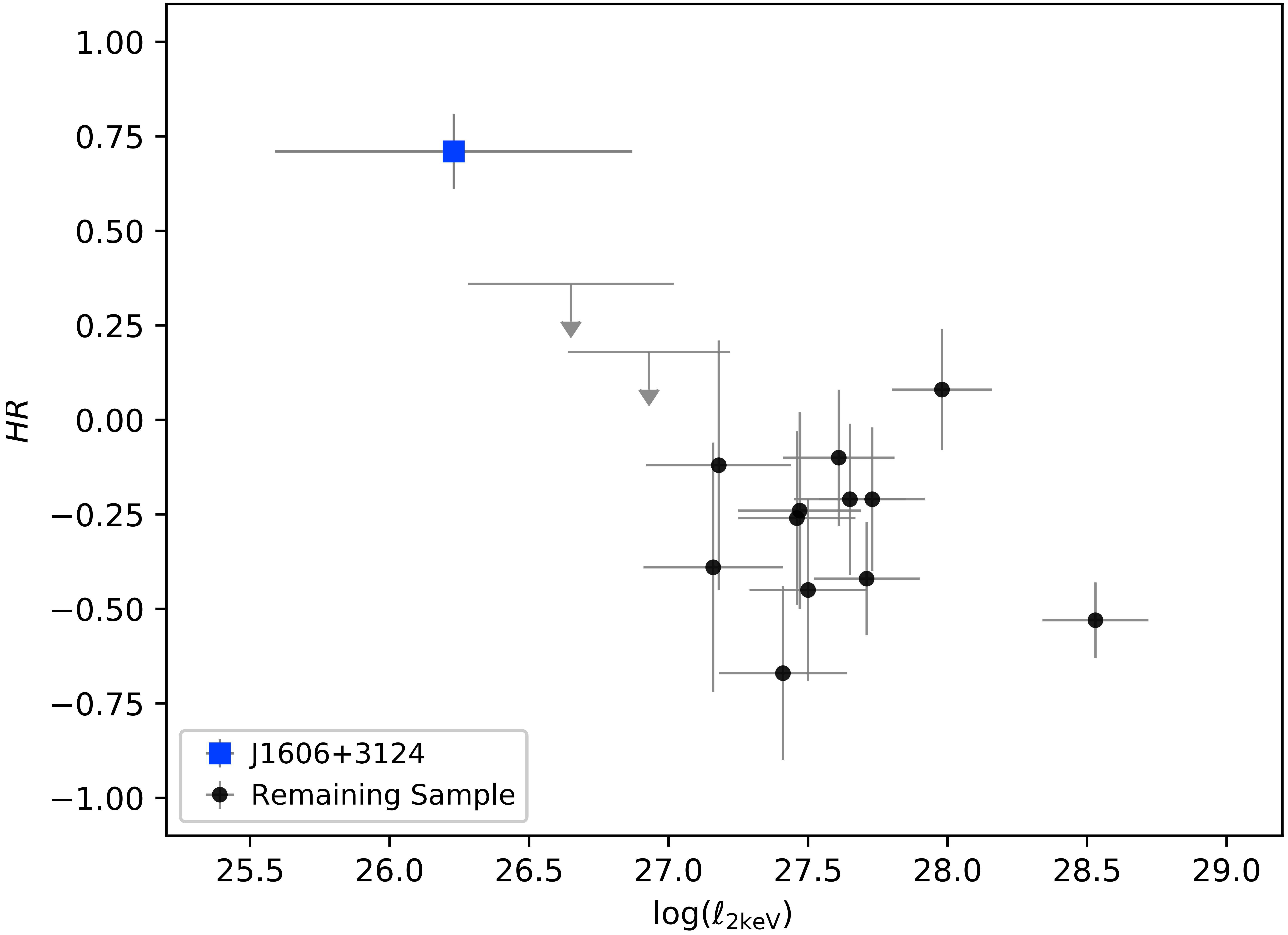


J1606+3124



- Quasar J1606+3124 significant outlier from sample
- X-ray luminosity significantly less than other quasars at comparable radio luminosity

J1606+3124



- Quasar J1606+3124 significant outlier from sample
- X-ray luminosity significantly less than other quasars at comparable radio luminosity
- Hardness ratio of J1606+3124 also significantly higher than remaining sample
- Suggests notable attenuation of soft X-ray flux (< 2 keV)

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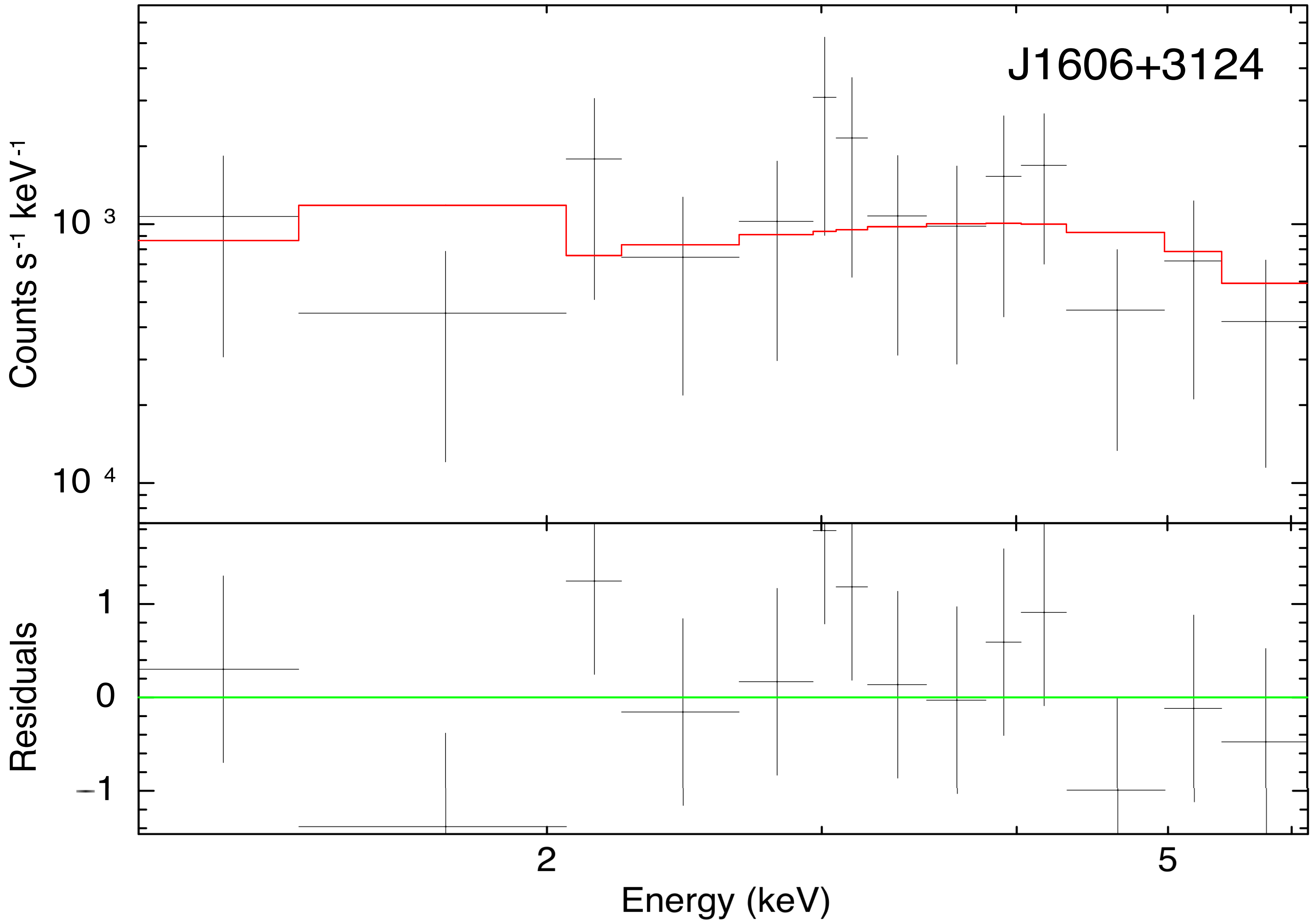
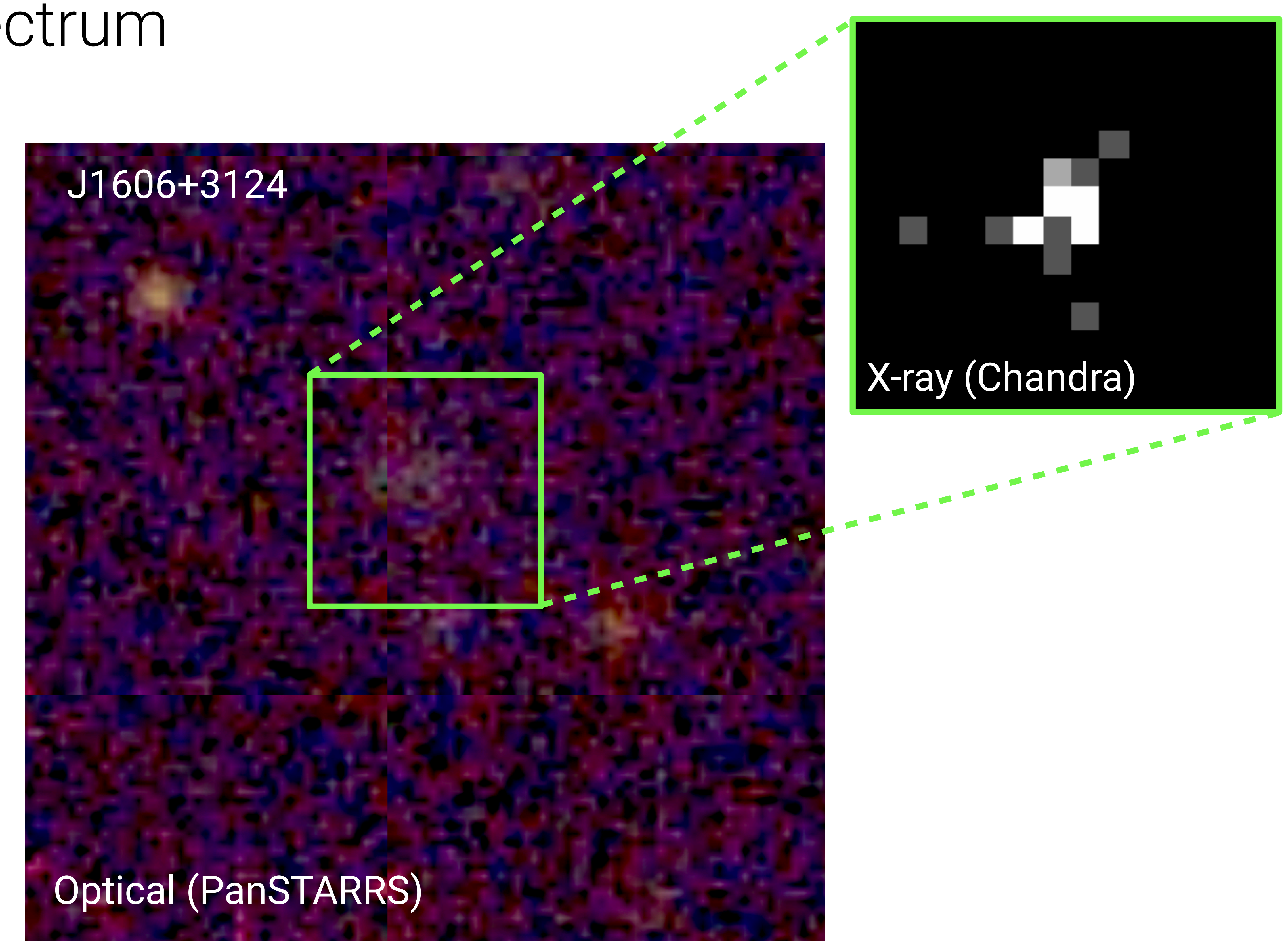
Discovery of Obscured Quasar J1606+3124

- J1606+3124 demonstrates significant attenuation in optical and UV
- Measured intrinsic column density with X-ray spectrum

$$N_H = (1.4 \pm 0.4) \times 10^{24}\,\mathrm{cm}^{-2}$$

- 4th candidate CT quasar at high-redshift





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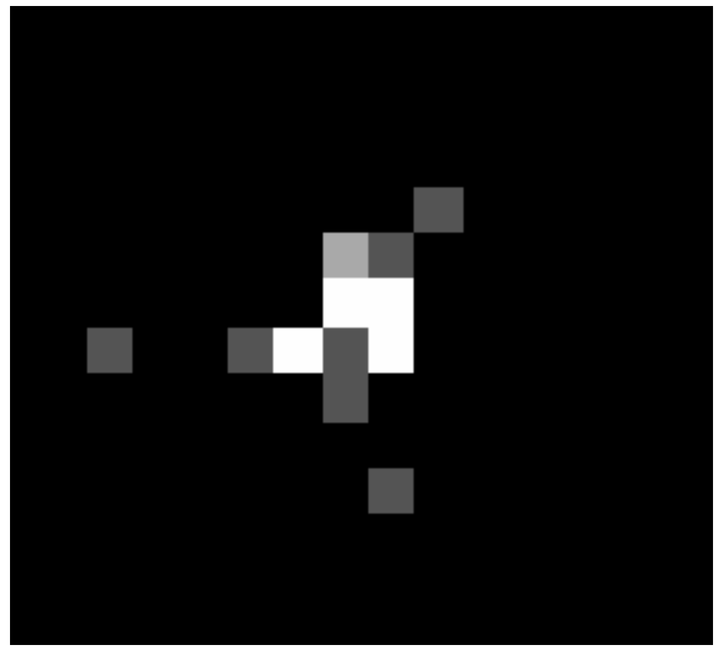
J1606 + 3124: Brightest CT Quasar

- Rest-frame luminosity:

$$L_{2-10\,\mathrm{keV}} = (1.1 \pm 0.5) \times 10^{45}\,\mathrm{erg\,s^{-1}}$$

- 10-10,000 times brighter than other high-redshift, CT quasars
- Indicates presence of high-luminosity, obscured quasars in early Universe
  - Challenges current SMBH formation models



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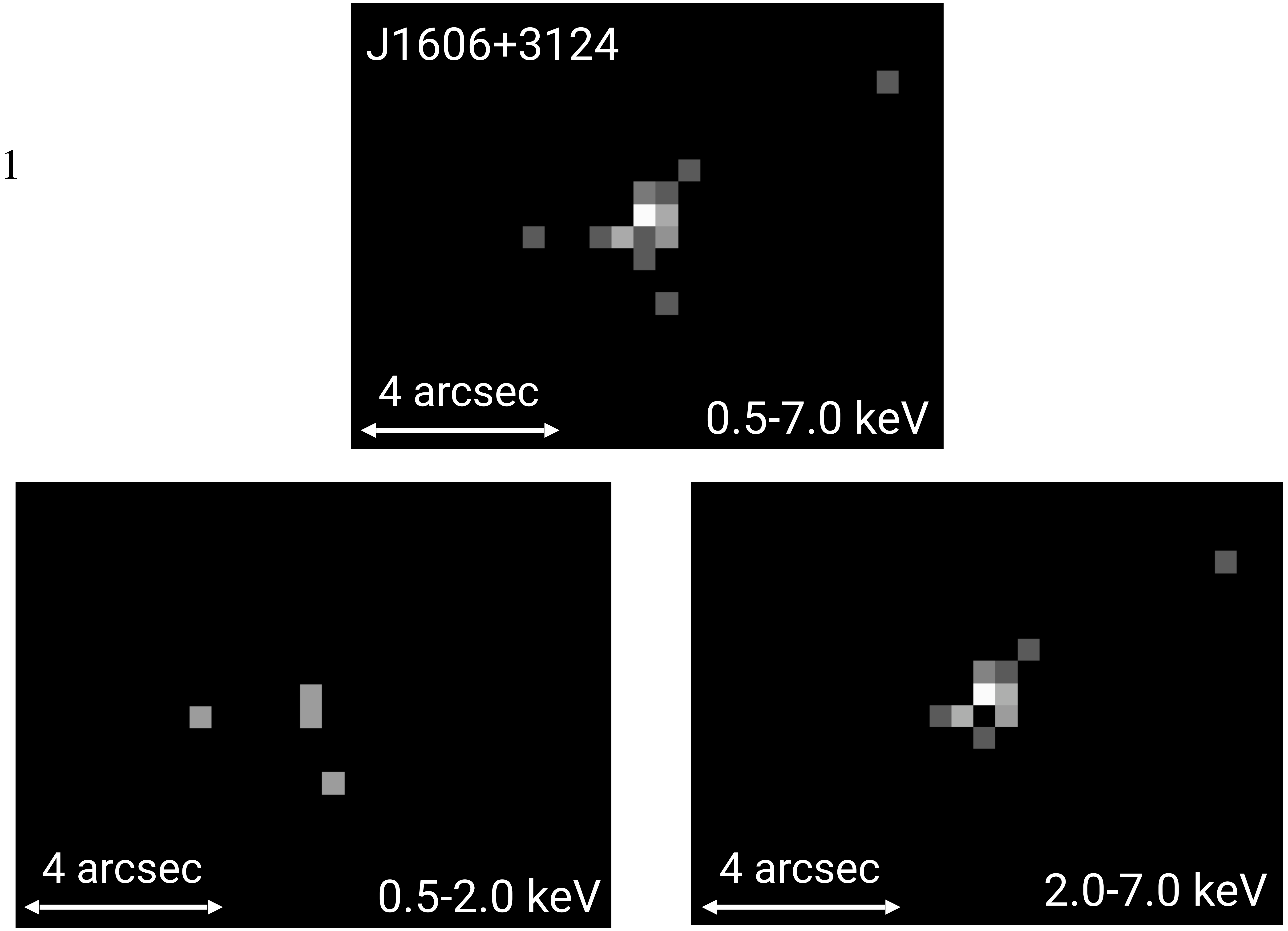

Summary

- Analyzed Chandra X-ray observations of 15 young radio quasars at $4.5 < z < 5.0$
- Optical—X-ray power-law spectral index found consistent with independent estimates
- Radio—X-ray luminosity relationship observed in sample; three outliers detected
- Radio-bright quasar J1606+3124 ($z = 4.56$) determined to be Compton-thick candidate using X-rays observations
  - 4th quasar of this classification identified
  - Follow-up XMM observation scheduled for 2021

For further details, see Snios et al. 2020, ApJ, 899, 127