UNIVERSITÀ DEGLI STUDI FIRENZE

Lighting up a new Standard Candle: calibration of AGNs

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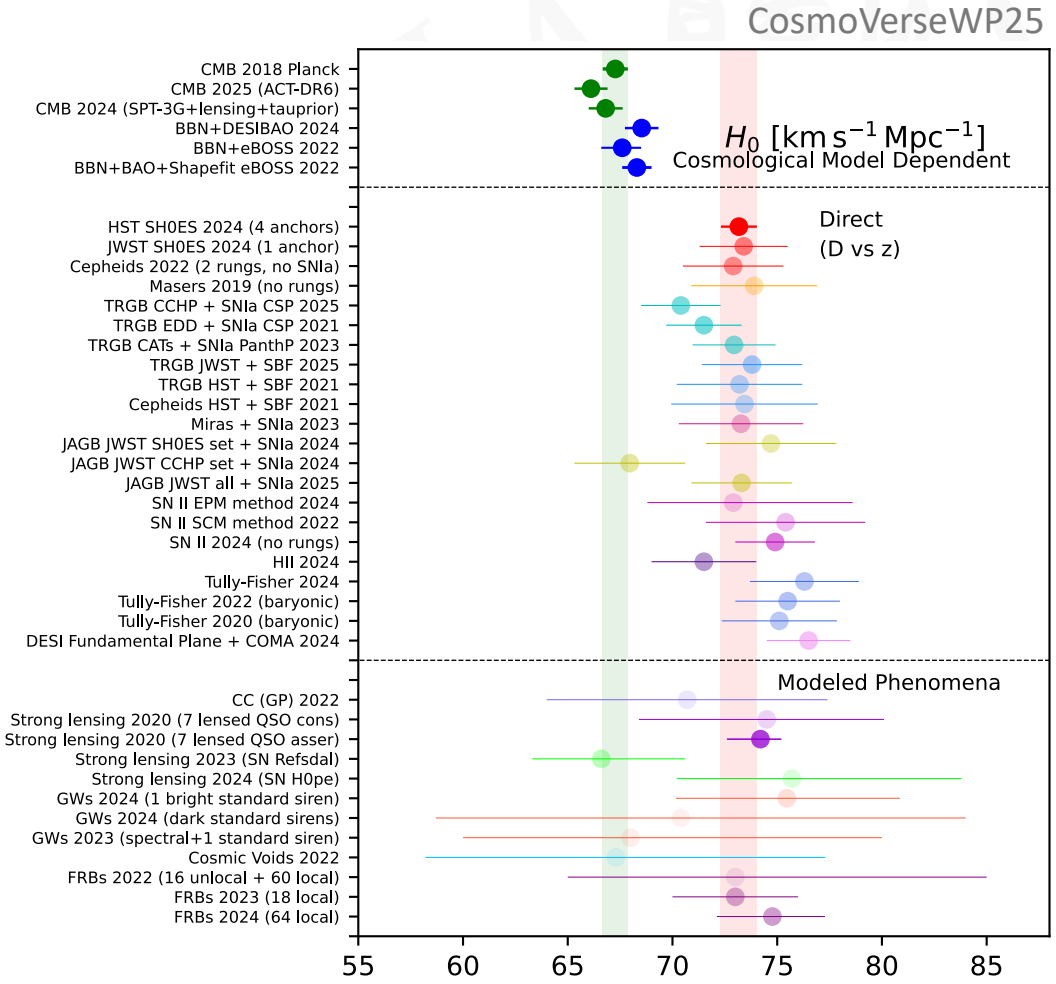
Universe Evolution: Hubble Tension

- "Early" Universe $H_0 = 67.4 \pm 0.5$ km/s/Mpc inferred from CMB (in ΛCDM)
- "Late" Universe $H_0 = 73 \pm 1$ km/s/Mpc based on SN Ia

➡ 5σ tension confirmed by many other independent probes

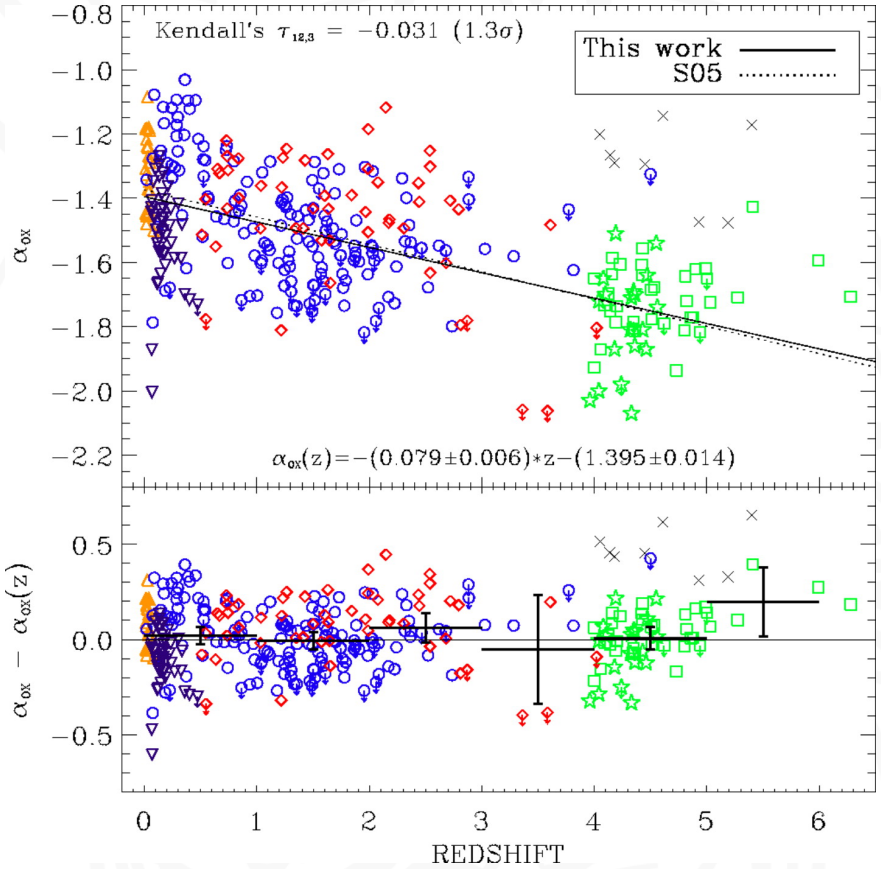


Active Galactic Nuclei as a Cosmological Tool

- ✦ Universal engine mechanism with phenomena that do not evolve with redshift:
  - empirical correlations between properties
  - reverberation mapping
  - super-Eddington accretion, etc.
- ✦ Observed up to z ~ 12

➡ Can be used as a cosmological tool if standartization applied

Steffen+06



UV to X-ray Relation in Quasars

Non-linear relation between the UV and X-ray:

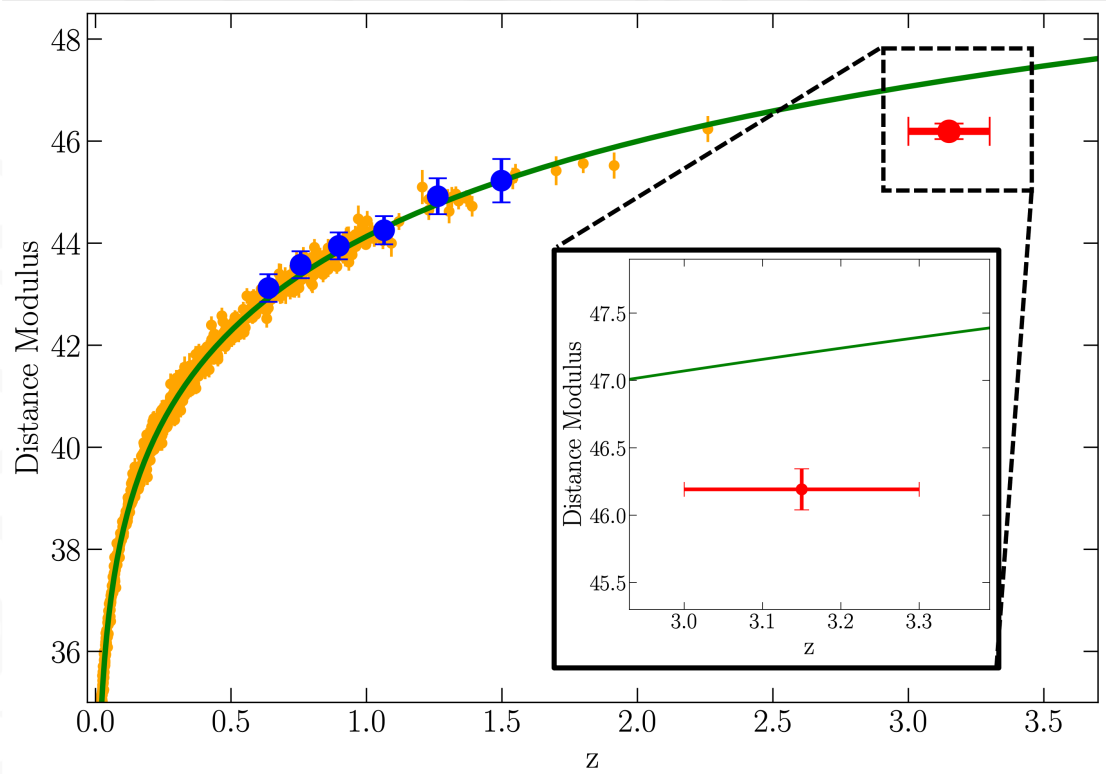
$$\log F_{\rm X} = \gamma \log F_{\rm UV} + 2\,(\gamma - 1) \log D_L + \beta'$$

- suitable for cosmology (e.g., Lusso+20)

➡ Remaining dispersion

➡ Poorly understood physics

Sacchi+22



Accretion Disk Winds from Active Galactic Nuclei

AGN-driven outflows - potential driver of the UV to X-ray relation dispersion

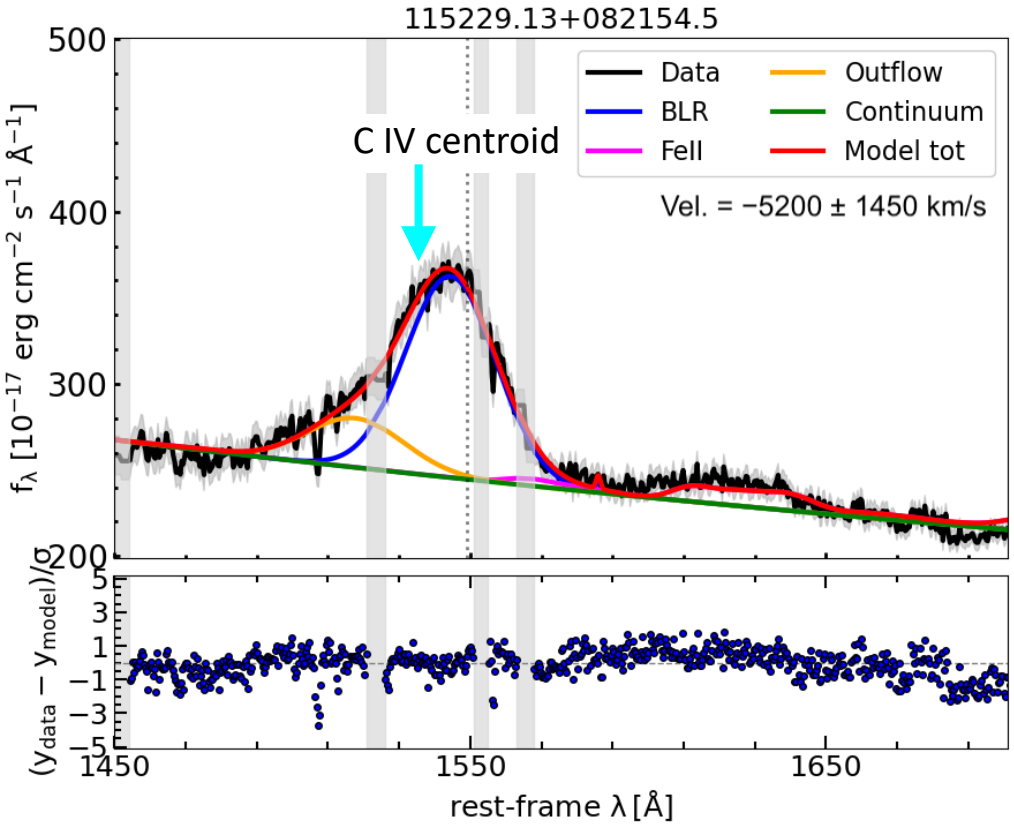
Existence of powerful outflows:

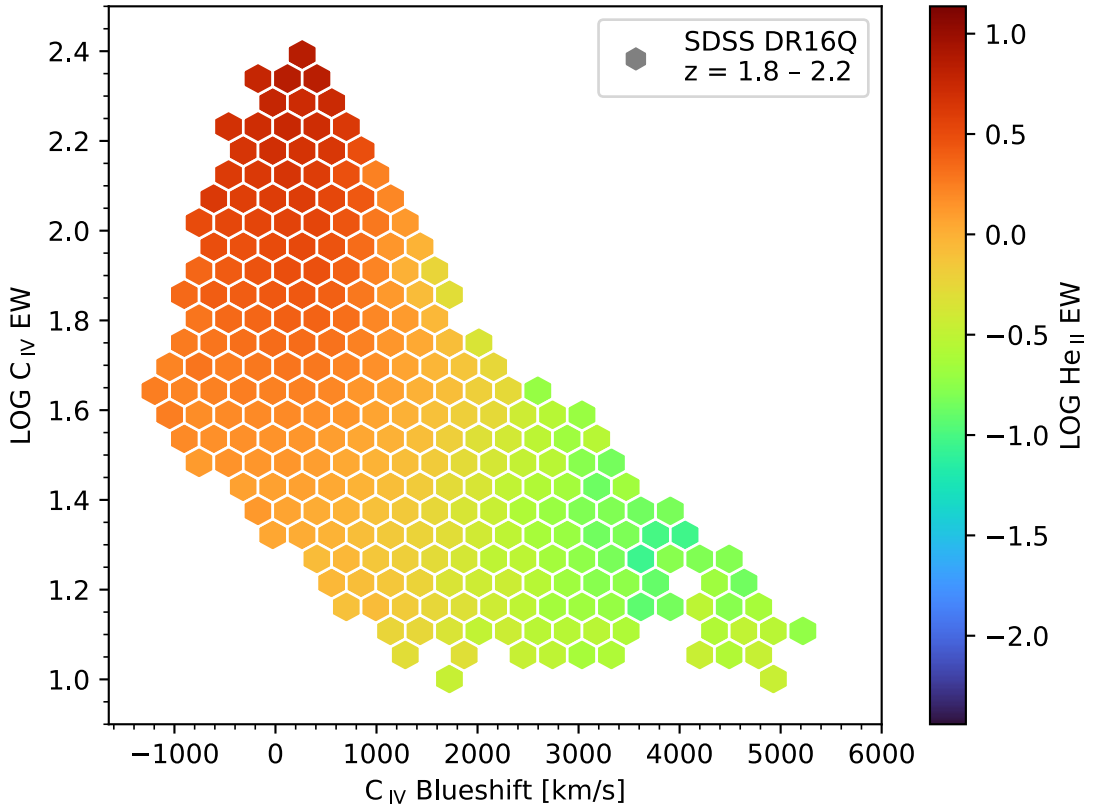
- theoretical models and numerical simulations (e.g., King+Pounds03; Takeuchi+13)
- blue-shifted broad absorption lines (BAL) in ~ 20% of QSOs (e.g., Gibson+09)
- blue-shifted ultra-fast outflows (UFO) in ~ 30-40% of QSOs (e.g., Gofford+13)

➡ Shielding of X-ray emission is required for effective launching of outflows

➡ General relations between UV, X-ray and strength of outflows remain unclear

C IV Emission Line as a Tracer of Outflows



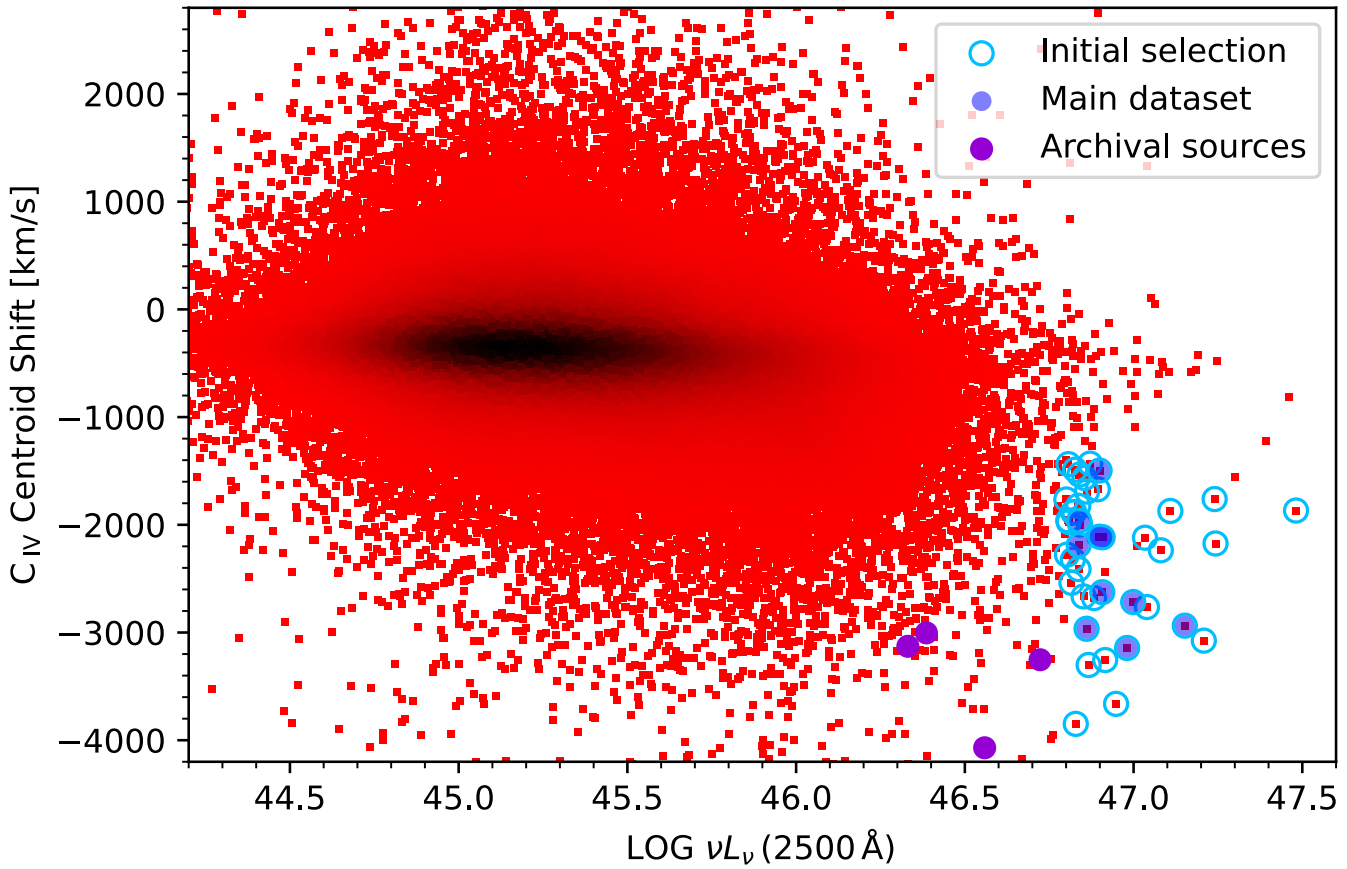


Sample Selection: Targeted Observations

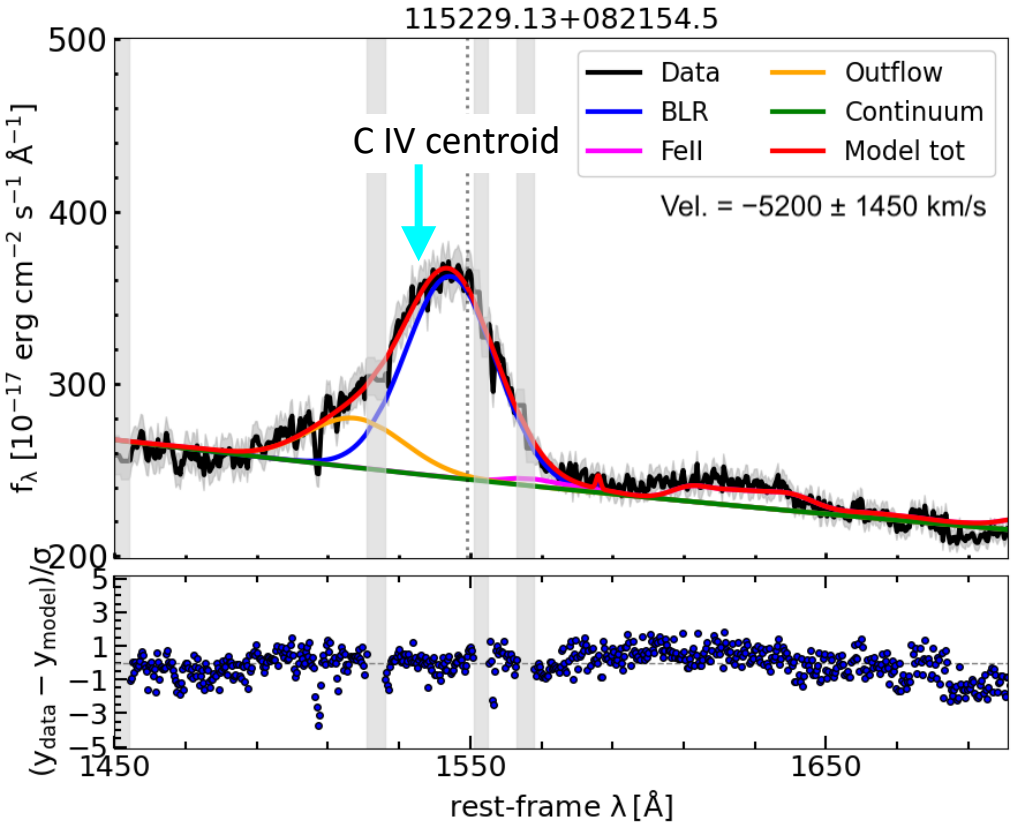
- ✦ SDSS DR16Q (Wu+Shen22)
- $z = 1.8 - 2.2$
- CIV blueshift $> 1{,}400$ km/s
- log $(\nu L_\nu / \mathrm{erg\ s^{-1}}) > 46.8$

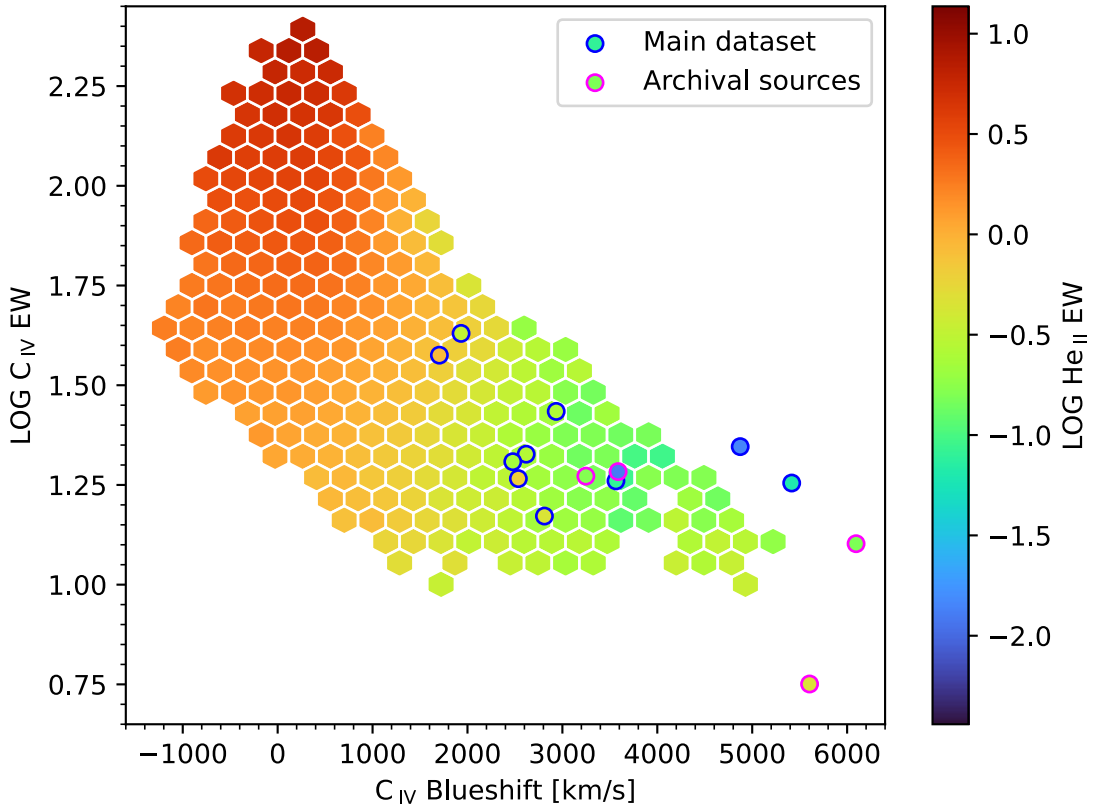
Further down-selection:

- C IV line modeling with multiple components



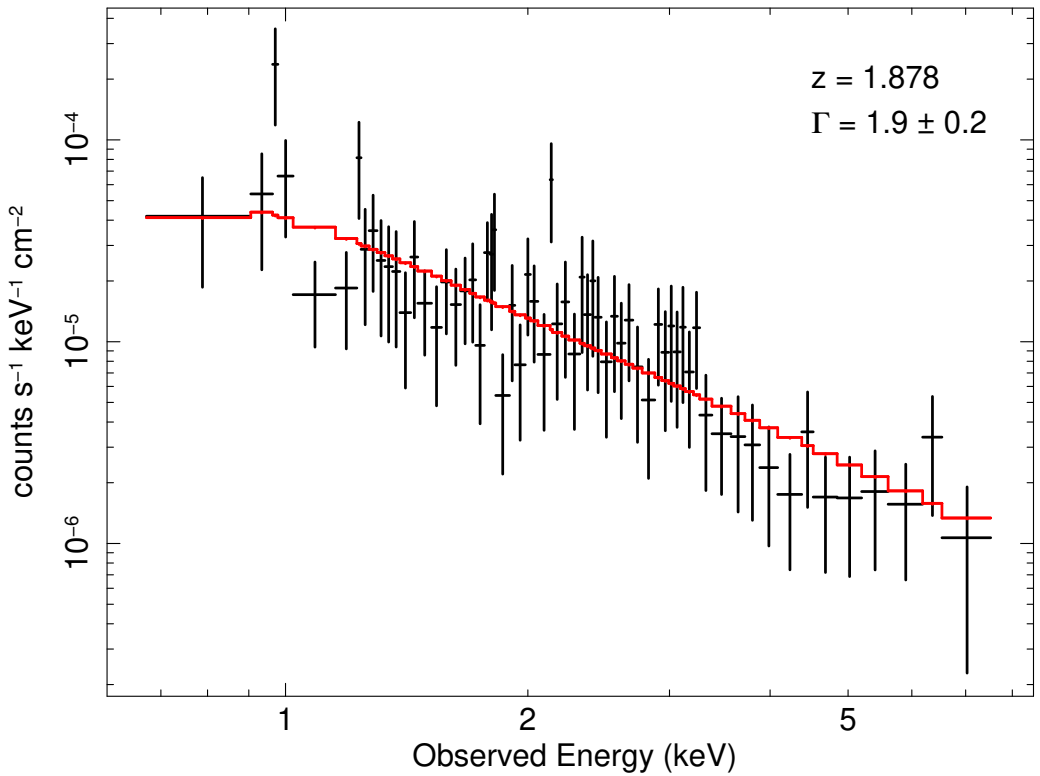
Sample Selection: Targeted Observations



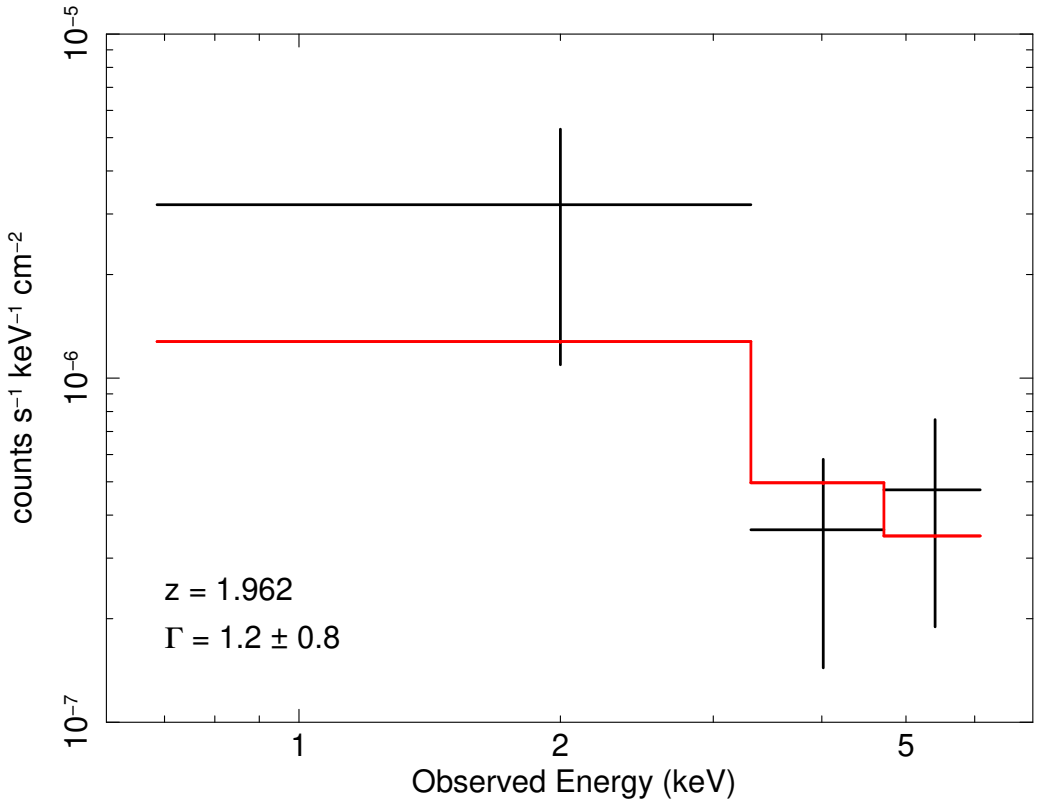


Fitting Observed *Chandra* Spectra

090924.01+000211.0



111800.50+195853.4

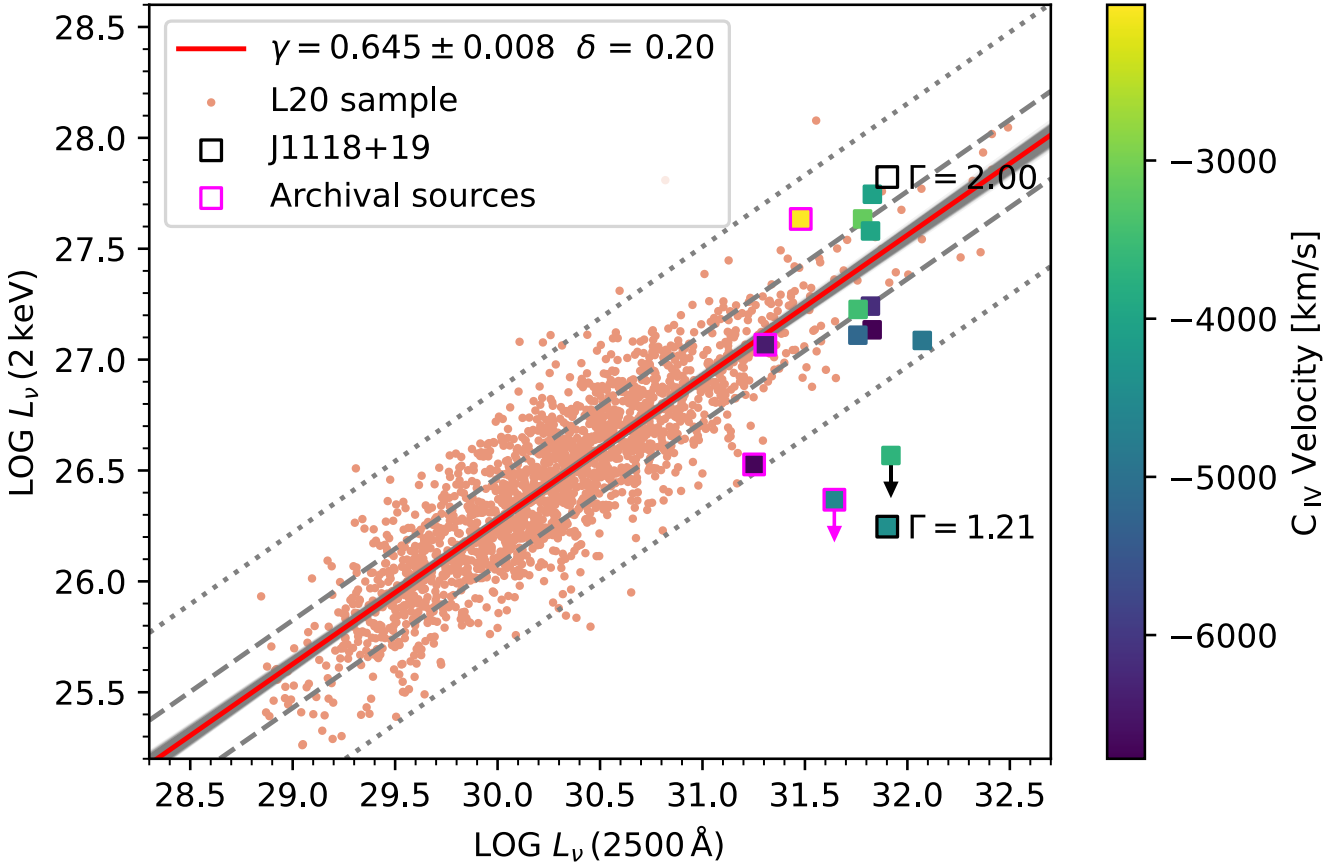


UV to X-ray Relation

Fraction of X-ray 'weak' QSOs:

- only 2 out of 10 / 3 out of 14

➡ In agreement with expectations on average



Connecting X-rays and Outflows: Summary

Sample of extremely luminous radio-quiet non-BAL QSOs with strong outflows:

- ➡ ***No*** significant evidence of correlation
  between excessively low X-ray flux level and presence of strong winds
- ➡ $\sim 2\sigma$ confidence level *hint* for correlation with the presence of outflows > 3000 km/s

- ➡ ***Not yet applicable for selection of cosmological sample***

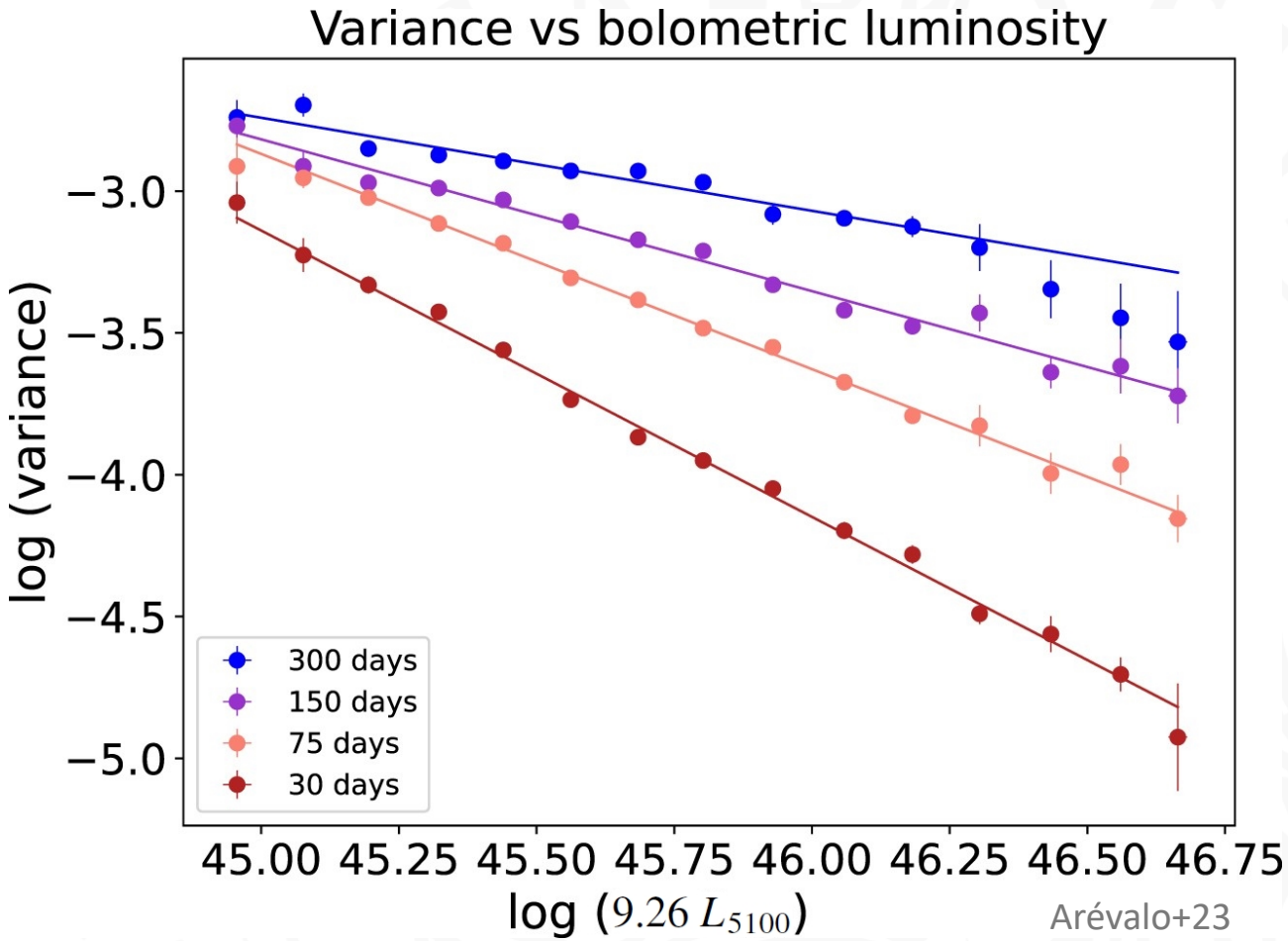
UV-to-Optical Rest-frame Variability in Quasars

Anti-correlation of variability parameters with fundamental quasar properties:

- ✦ characteristic timescale
- ✦ asymptotic amplitude

- Eddington ratio
- BH mass
- rest-frame emitted wavelength

➡ ***Possibility to reduce dispersion***



Sample Selection: Light Curves

✦ ZTF Zubercal DR20 (Drake+25) light curves with at least 30 epochs in *g*, *r*, or *i* band

✦ Damped Harmonic Oscillator Light Curve Modelling with EzTaoX (Yu+25)
Identification of Bad Fits (following Yu+22):

- timescales longer than the span of the light curve
- timescales shorter than one-half the minimum separation between any two observations
- daily observing cadence with a stronger signal than intrinsic timescales

➡ Parent sample: **7679 -> 7145 -> 5855 quasars**

➡ L20 Cosmological sample (Lusso+20): **2148 -> 2044 -> 1701 quasars**

➡ Core of New Cosmological sample: **2057 -> 1950 -> 1619 quasars**

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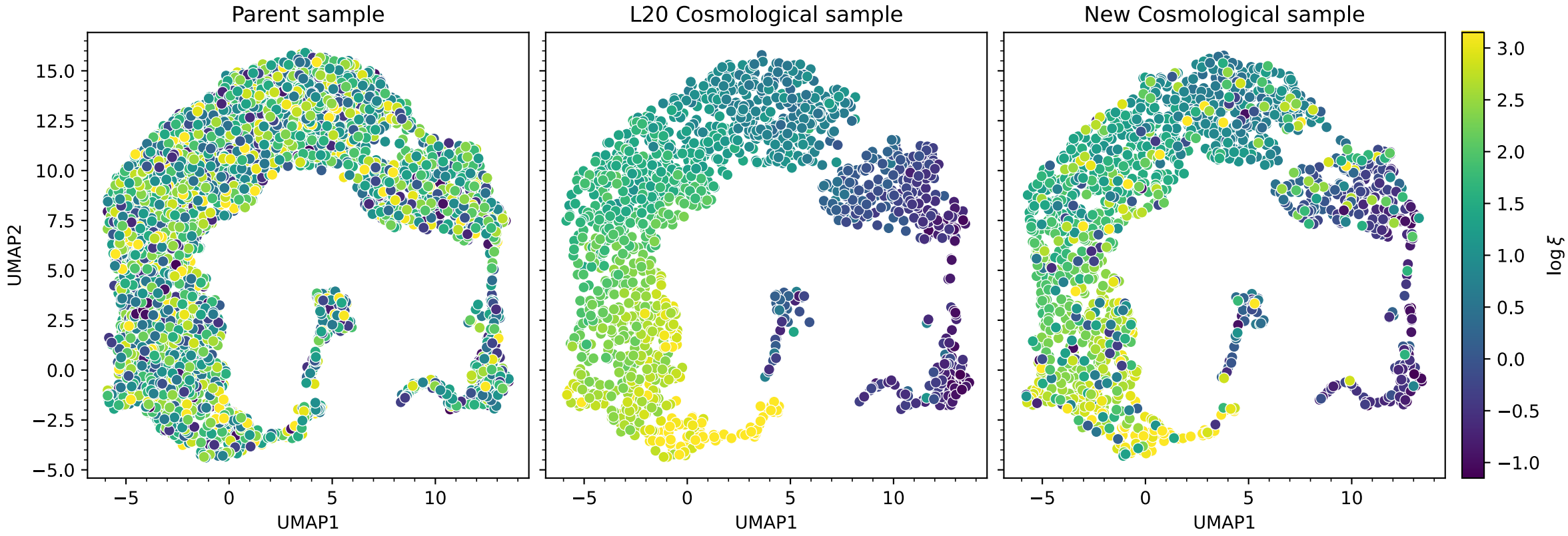
Dimension Reduction with UMAP

Dimension reduction analysis parameters: $L_{\rm UV}$, $L_{\rm X}$, Γ, $M_{\rm BH}$, $\lambda_{\rm Edd}$, $\alpha_{\rm OX}$, $\Delta\alpha_{\rm OX}$, ξ, ω_0, σ_ϵ, $\tau_{\rm perturb}$



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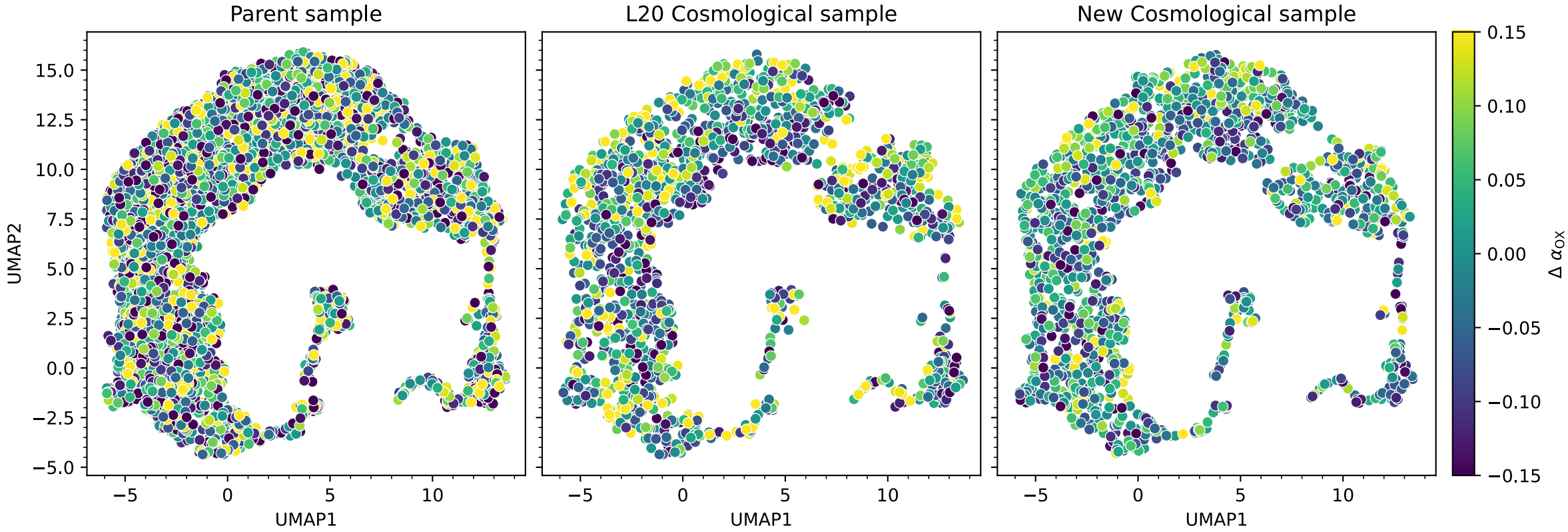


Simultaneous X-ray and UV Variability in Quasars

Standard UV to X-ray relation offers only entangled view of AGN central engine:

✦ $\log L_{\rm X} \sim \log(\lambda_{\rm Edd} M_{\rm BH})$

Multiple spectroscopic observations of the same sources:

- $M_{\rm BH}$ remains constant

➡ Relation between $L_{\rm X}$ and $\lambda_{\rm Edd}$ directly

➡ Insights about corona-disc interplay

➡ ***Possibility to reduce dispersion***

Sample Selection: Simultaneous Observations

✦ SDSS DR16Q (Wu+Shen22) + XMM-Newton 4XMM-DR14 (Webb+20)

Selection filters:

- dust extinction and host-galaxy contamination / gas absorption / bias towards high fluxes

✦ XMM-OM Serendipitous UV Source Survey Catalogue: SUSS6.2 (Page+23)

Selection filters:

- simultaneous X-ray and UV observations
- OM filters above Lyman limit
- at least 3 epochs of simultaneous observations, with at least 1 having multiple OM filters

➡ Resulting sample: **7679 -> 2057 -> 869 -> 115 -> 21 quasars**

Estimating UV Flux for Individual Epochs

Epochs with >2 OM filters:

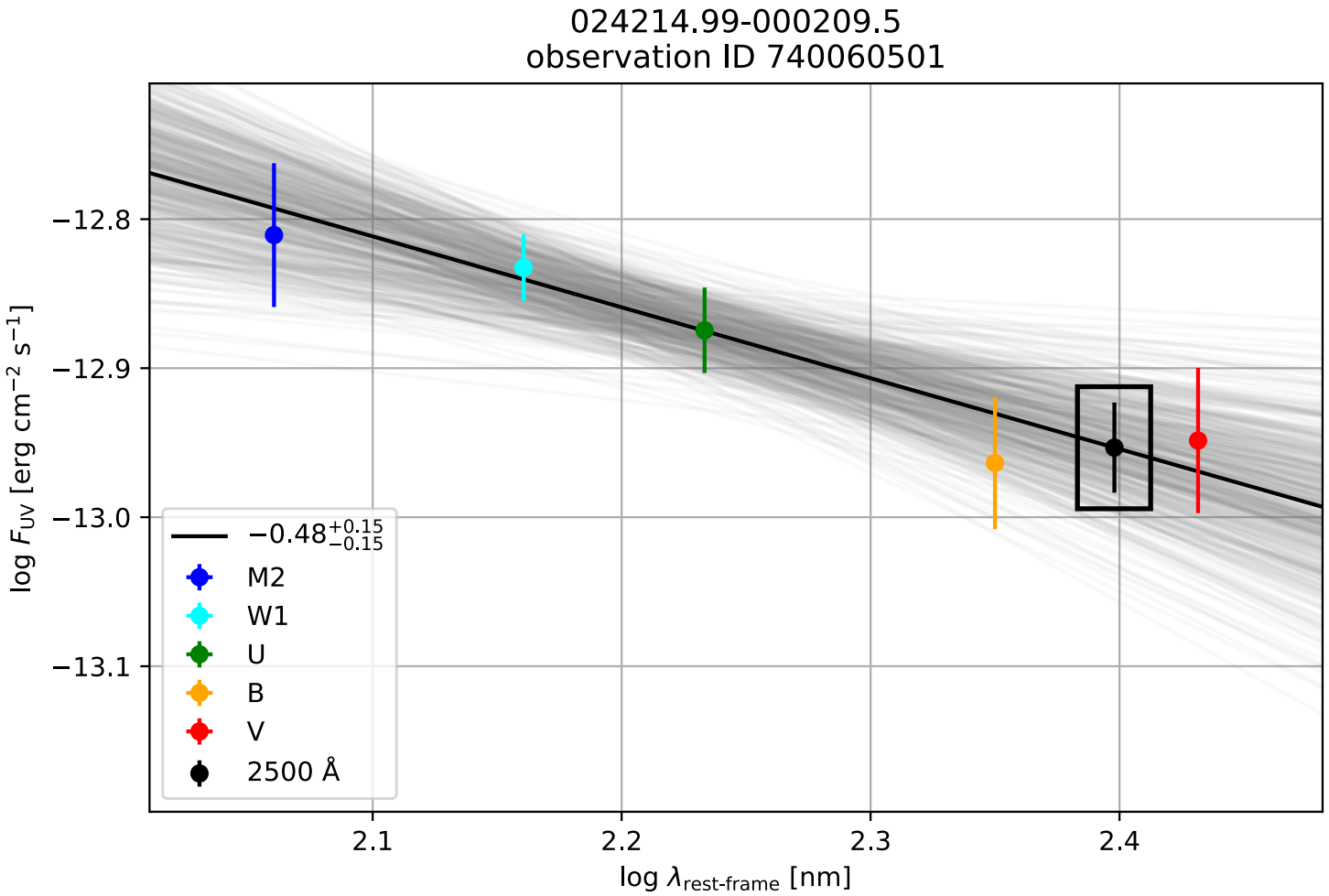
- Markov chain Monte Carlo ensemble sampler

Epochs with 2 OM filters:

- analytical calculation

Epochs with 1 OM filter:

- extrapolation with mean slope



Fitting UV to X-ray Relation for Individual Sources

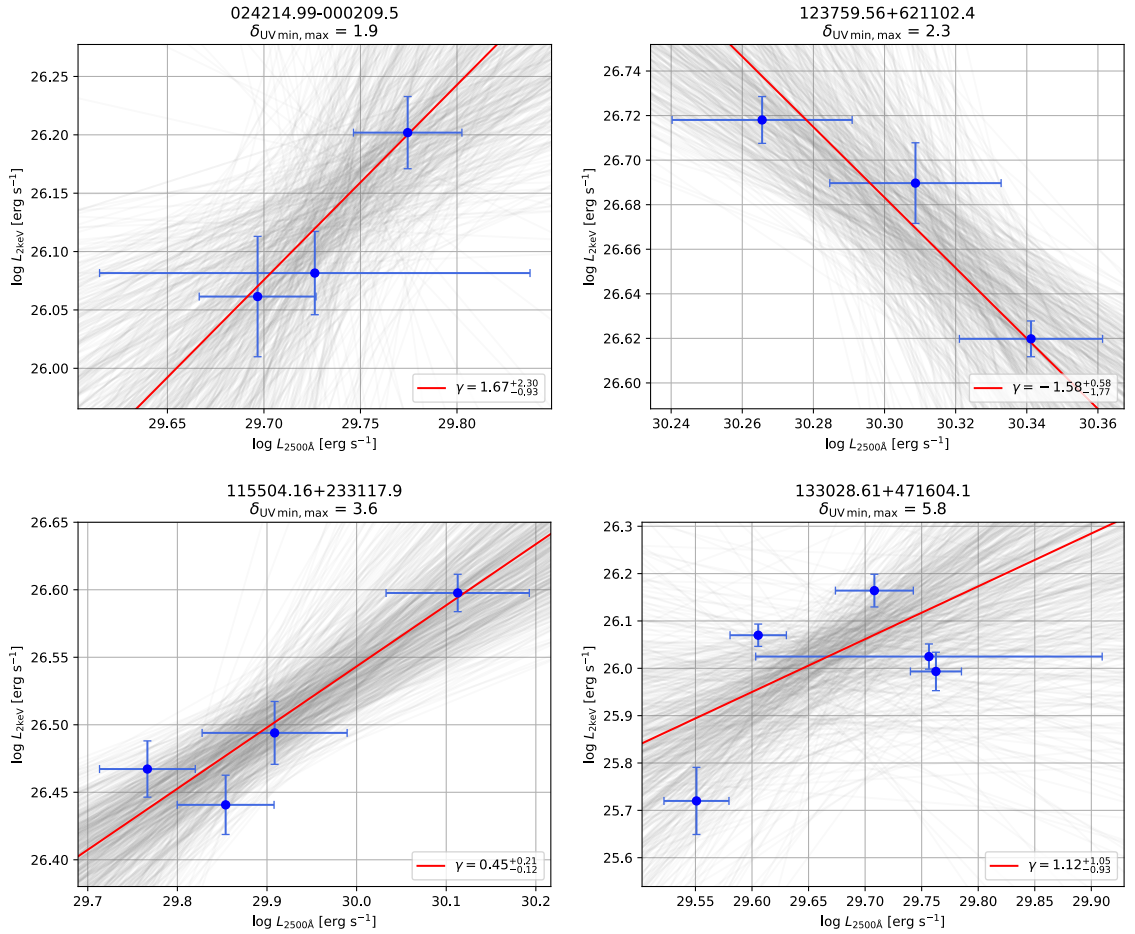
Final selection filter:

- significant UV variability

➡ **4 quasars**

➡ With L_{UV} as a proxy for λ_{Edd}

median slope $\gamma = 0.76^{+0.46}_{-0.45}$



Variability in Quasars: Summary

Effects of UV-to-optical rest-frame variability on UV to X-ray relation:

➡ ***No strong variation in*** $\Delta\alpha_{\rm OX}$ ***as a function of DHO parameters***

Effects of simultaneous X-ray and UV variability on UV to X-ray relation:

➡ Positive correlation between $L_{\rm X}$ and $\lambda_{\rm Edd}$

with $< 1\sigma$ confidence level *hint* for diverging from standard $L_{\rm X} - L_{\rm UV}$ and linear relations

➡ ***Larger sample is required***

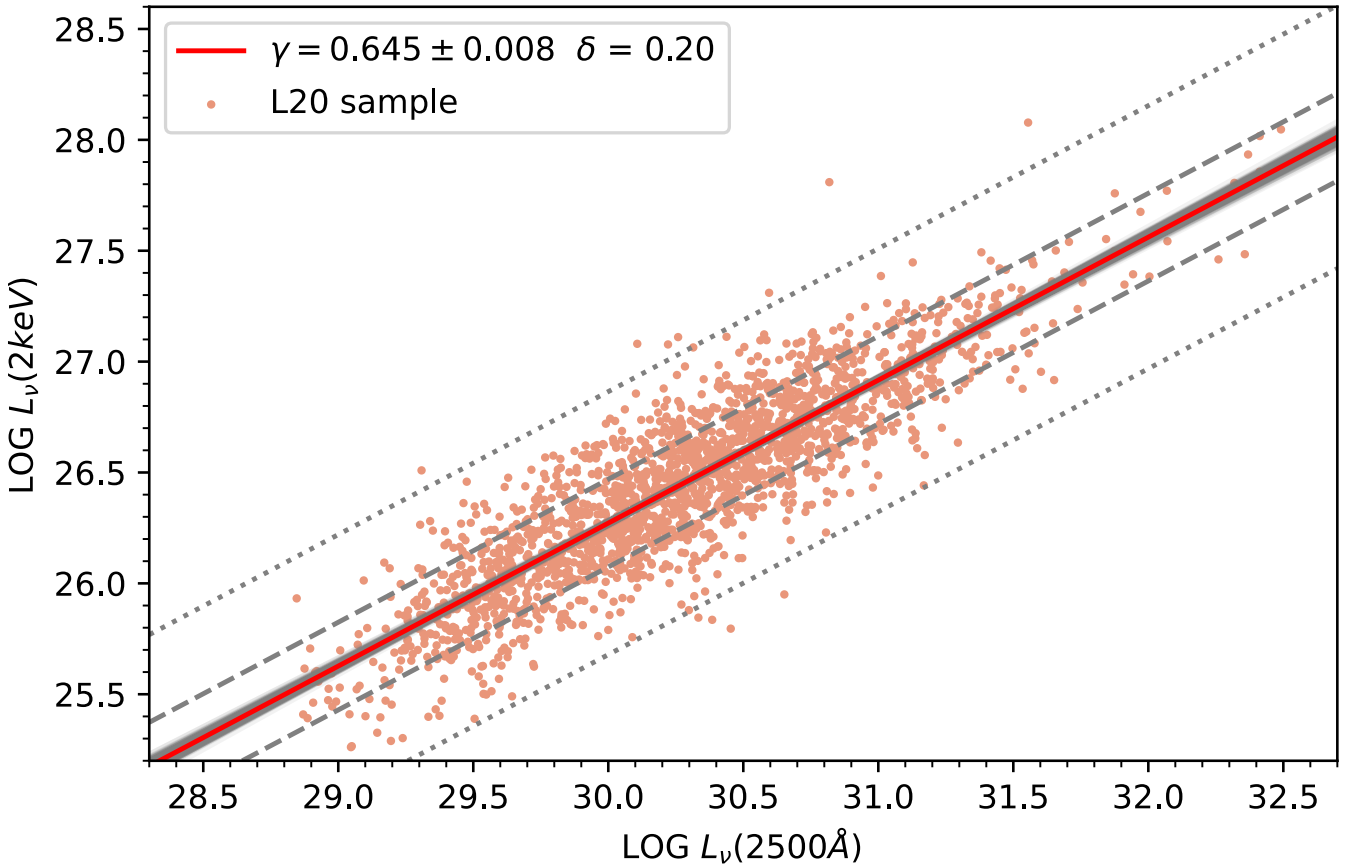
Cosmological Sample of "Normal" Quasars

L20 sample (Lusso+20):

- optically blue
- unobscured

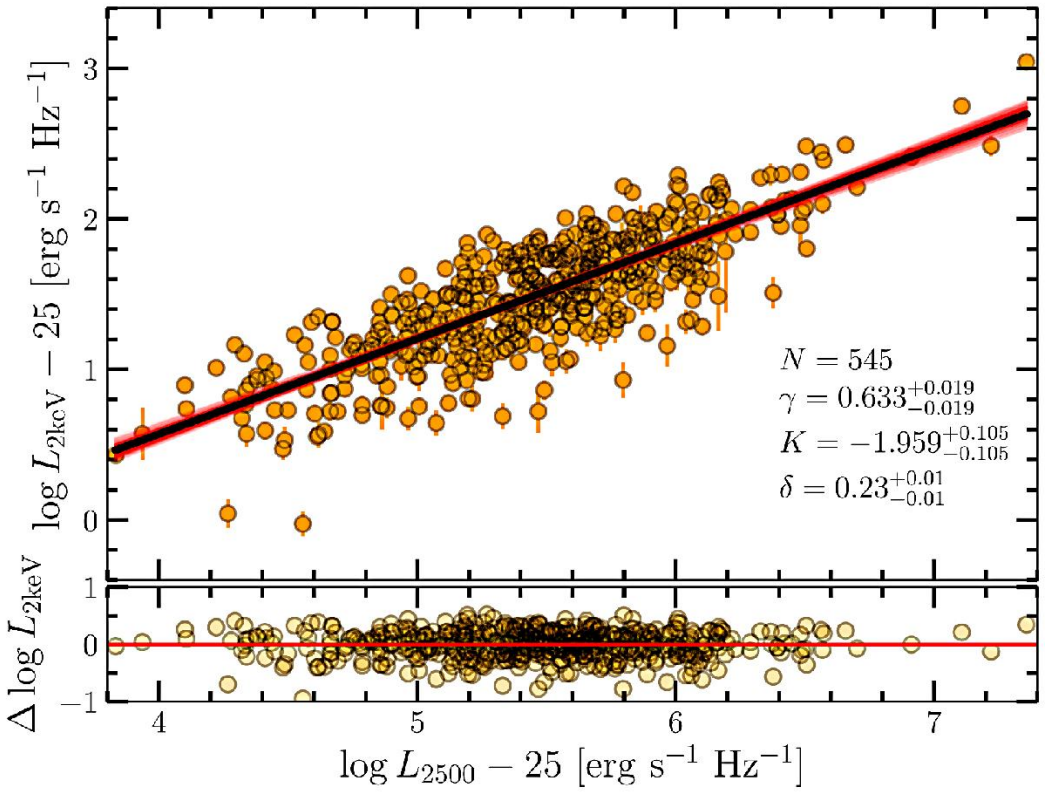
Non-linear UV to X-ray relation:

- $\log L_{\rm X} = \gamma \log L_{\rm UV} + \beta$
- $\alpha_{\rm OX} = 0.3838 \log(L_{2\,\rm keV}/L_{2500\,\text{Å}})$

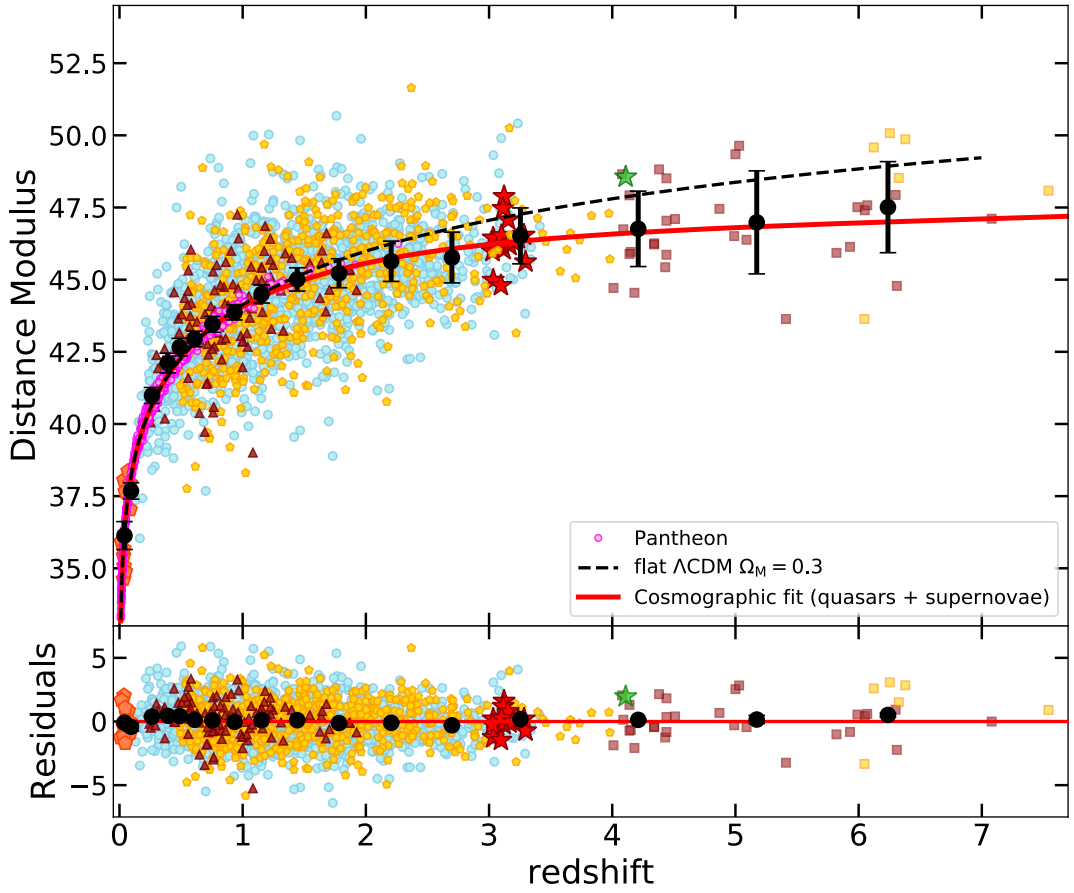


Remaining Dispersion

Lusso+Risaliti17



Lusso+20



Poorly Understood Physics

Accretion disc

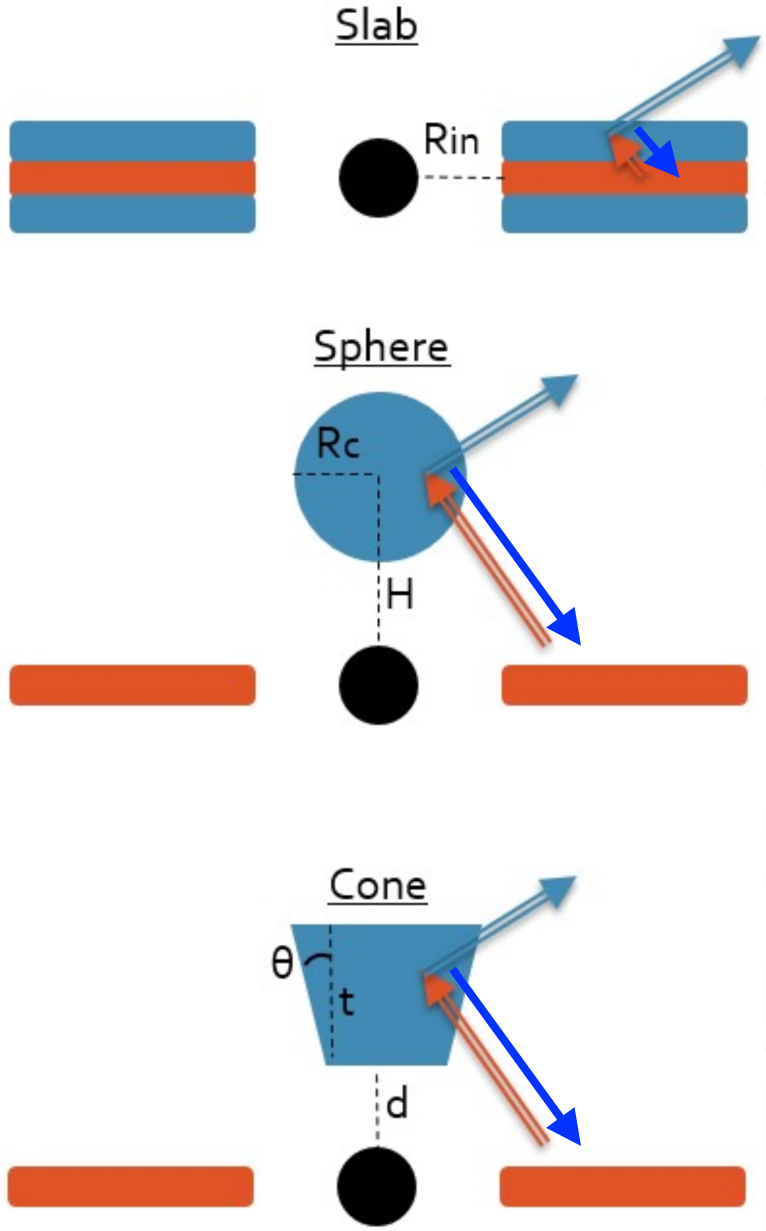
- flow structure and dynamics

X-ray corona

- geometry and location

Corona - disk interplay

- illumination and heating
- processing and reprocessing

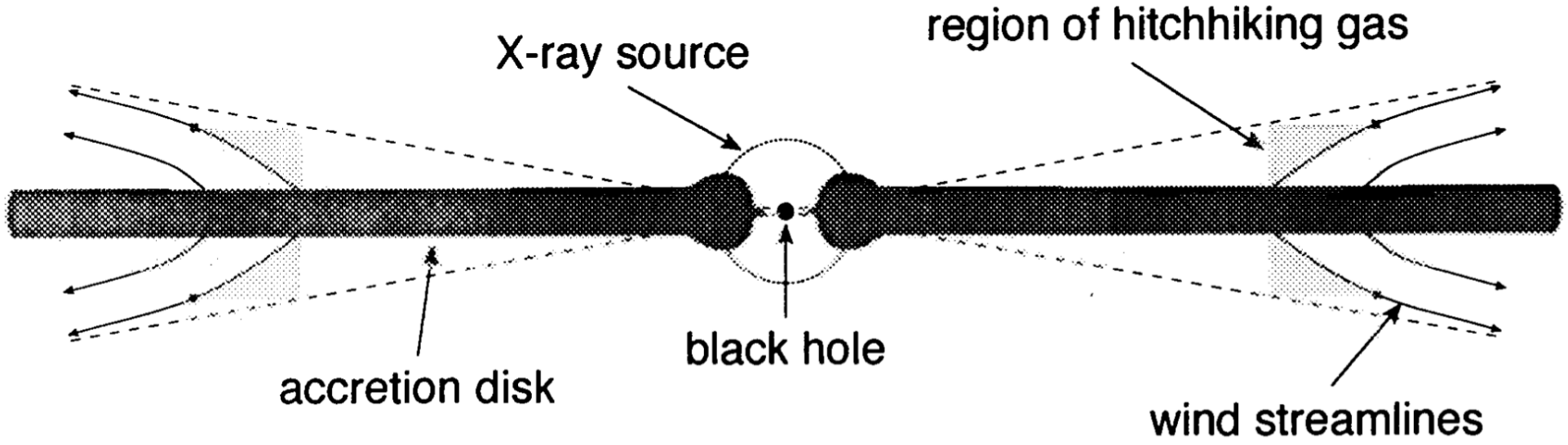


Ursini+22

X-ray Weakness and Outflows in BAL QSOs

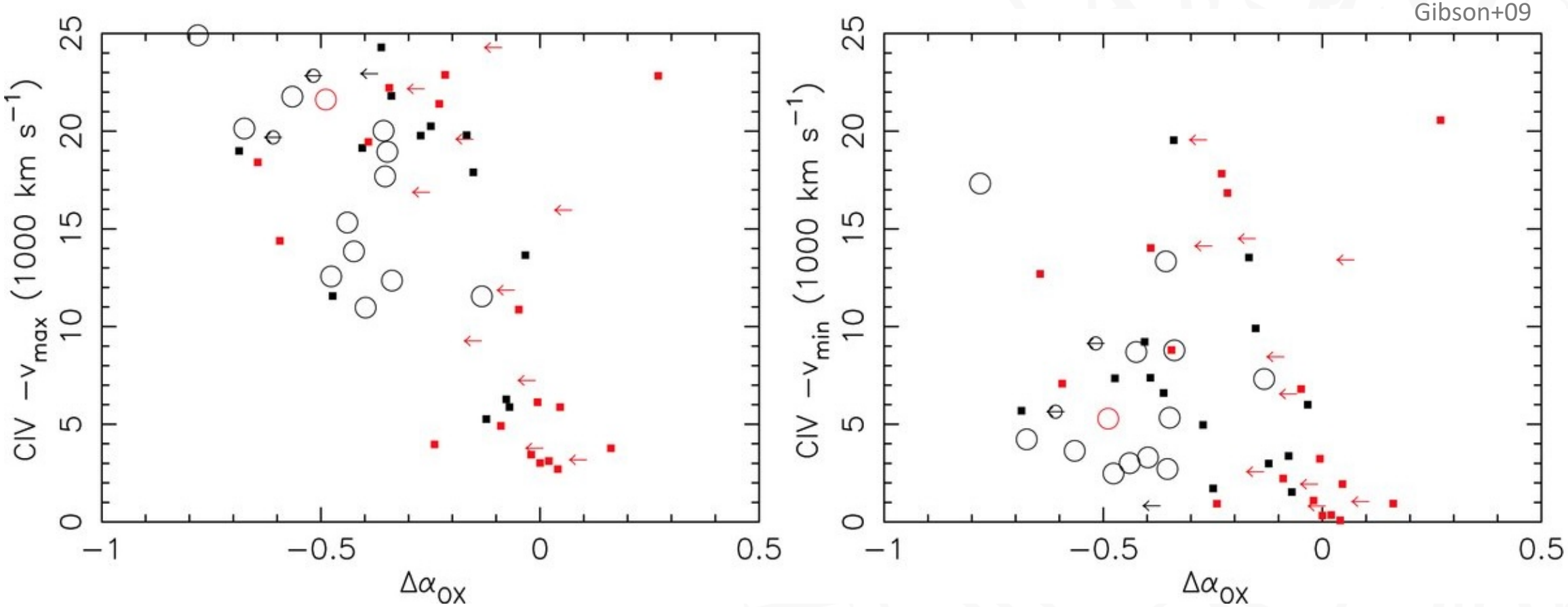
Intrinsic X-ray weakness (absorber) as a prerequisite for winds (e.g., Murray+95):

- shielding BAL outflow from over-ionisation
- enabling efficient line-driven radiative acceleration



X-ray Weakness and Outflows in BAL QSOs

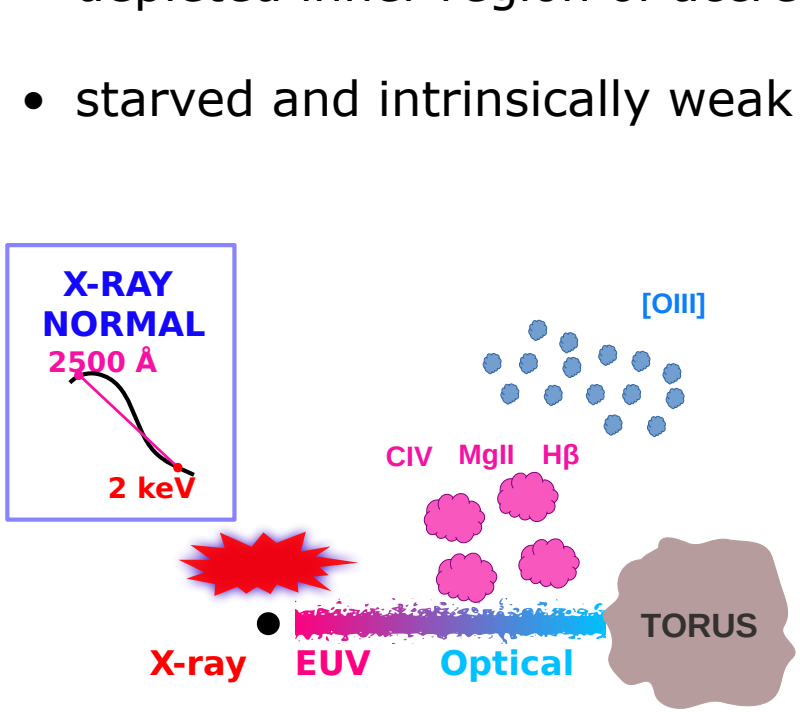
Gibson+09

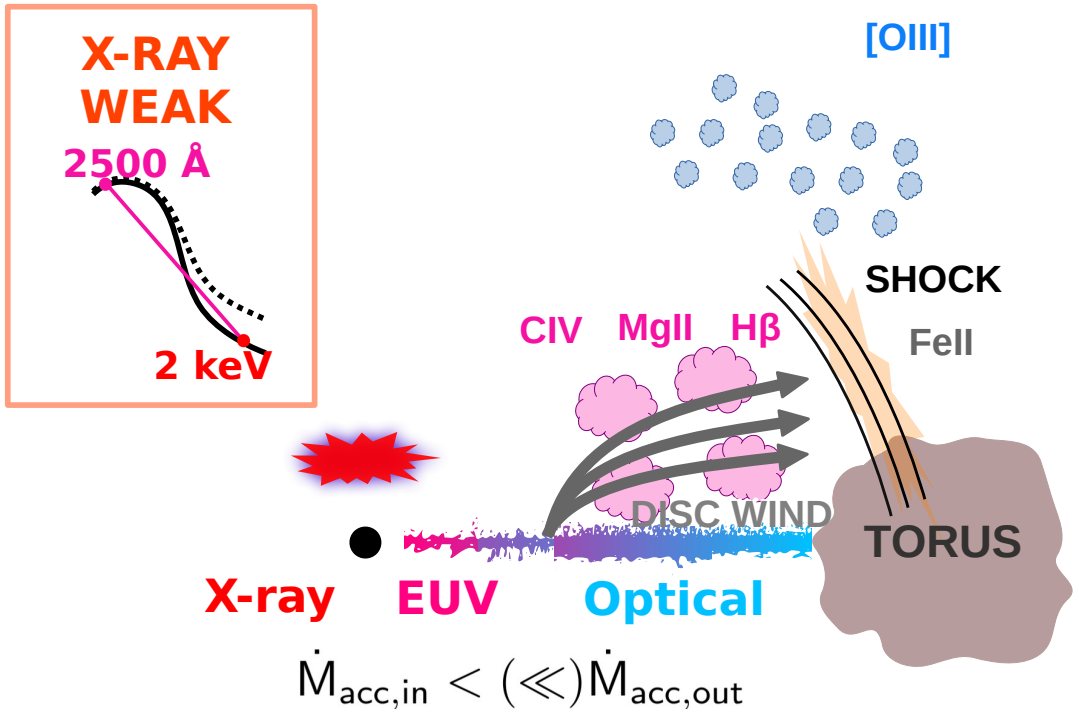


X-ray Weakness and Outflows in non-BAL QSOs

Intrinsic X-ray weakness as a consequence of winds (Lusso+21, Trefoloni+23):

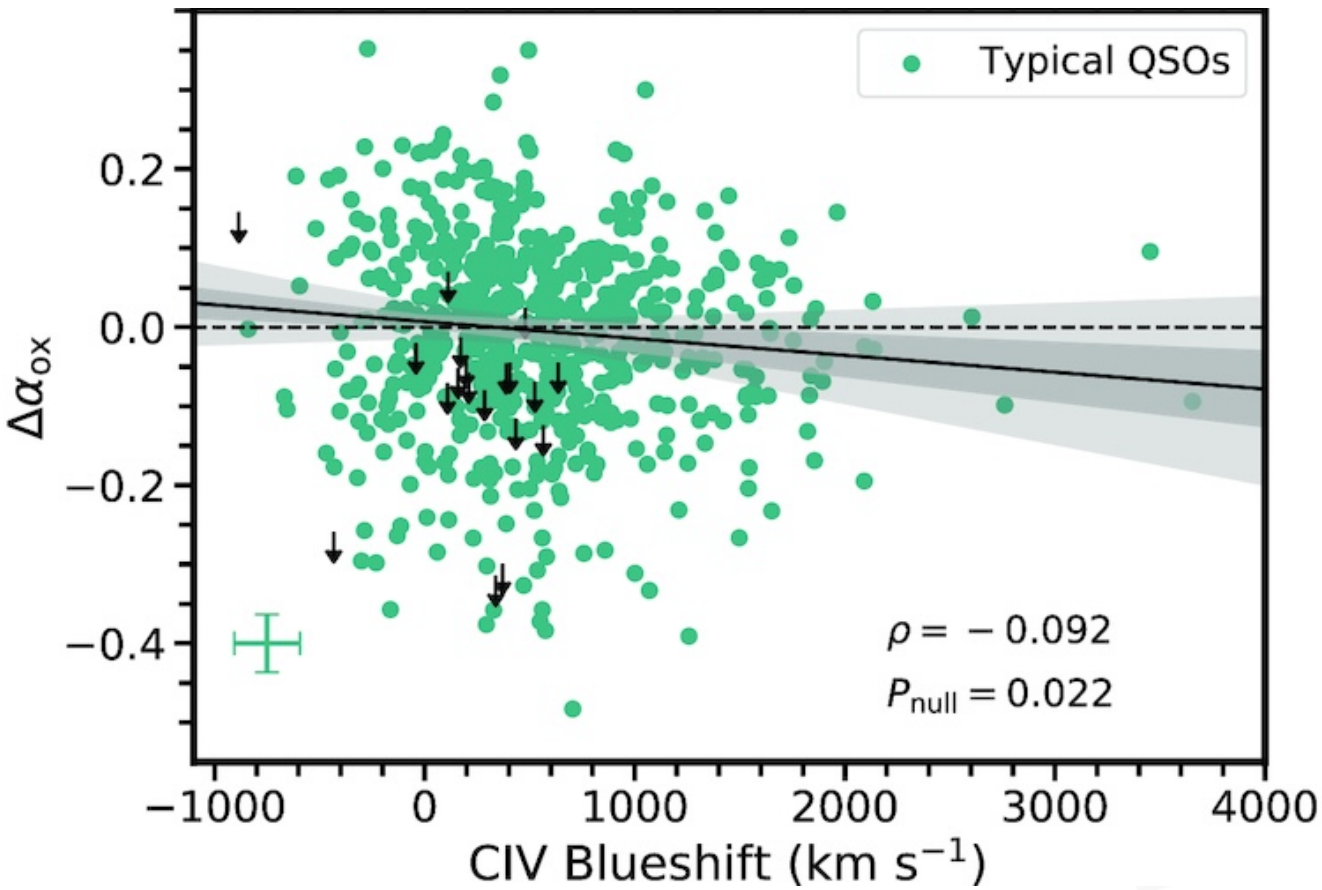
- depleted inner region of accretion disc
- starved and intrinsically weak corona



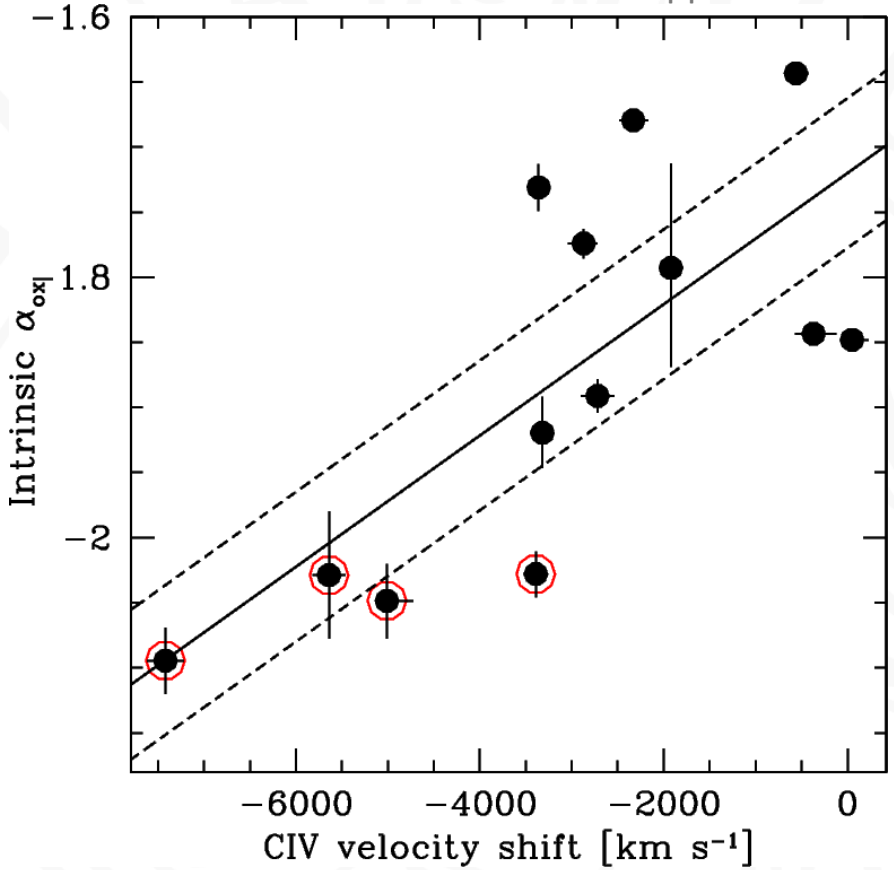


X-ray Weakness and Outflows in non-BAL QSOs

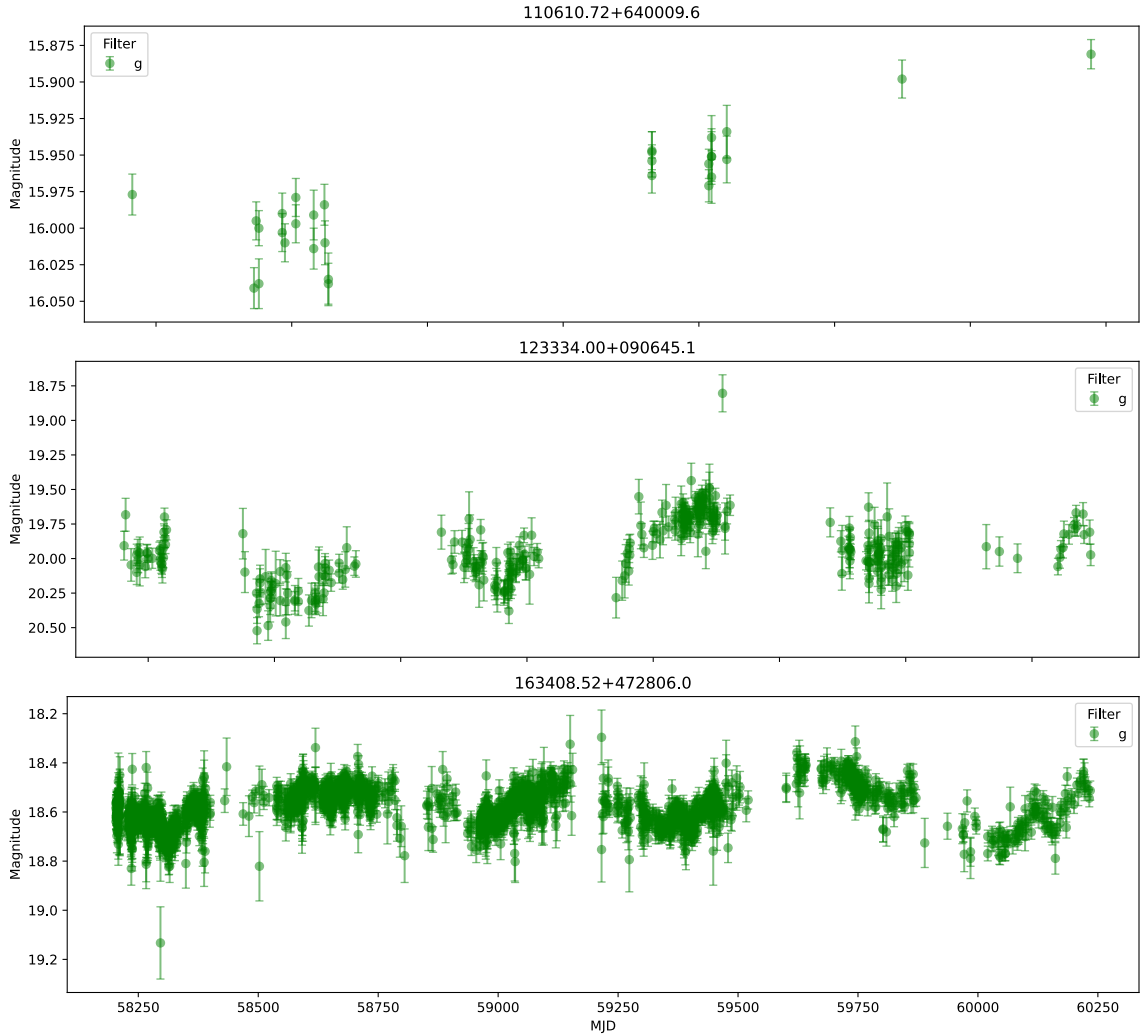
Timlin+20



Zappacosta+20



Sample Selection: Light Curves



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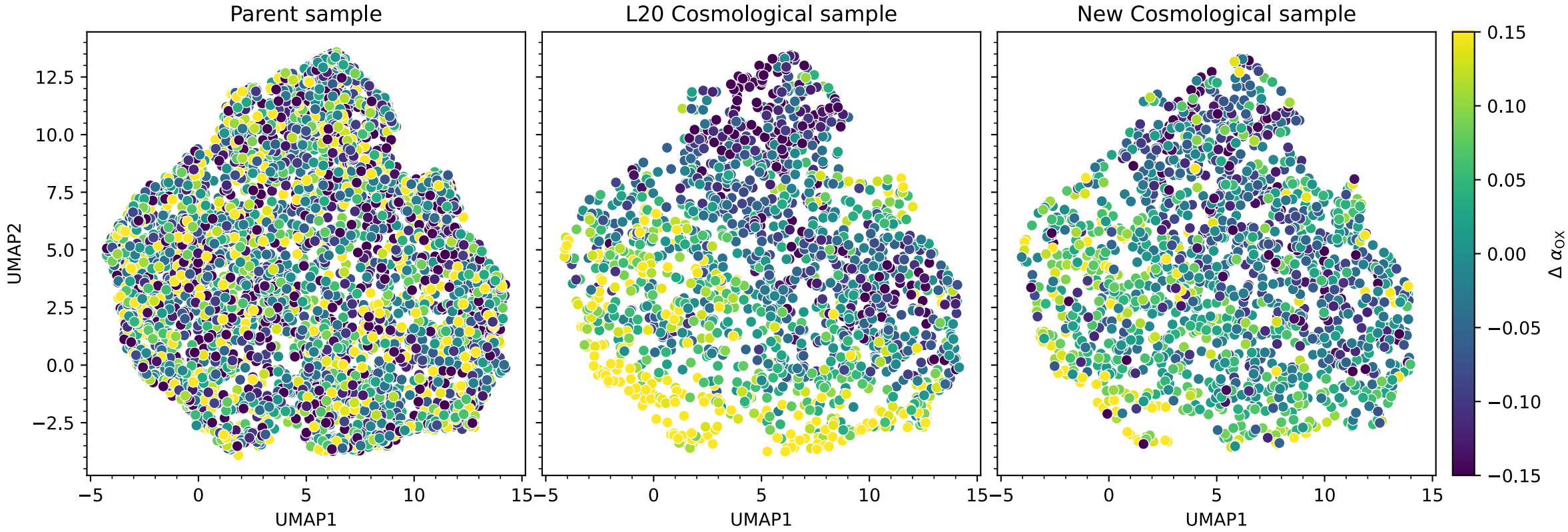

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