Advancements in AGN, Galaxy Cluster and IGM Research

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On the Nature of Weak Emission Line Quasars

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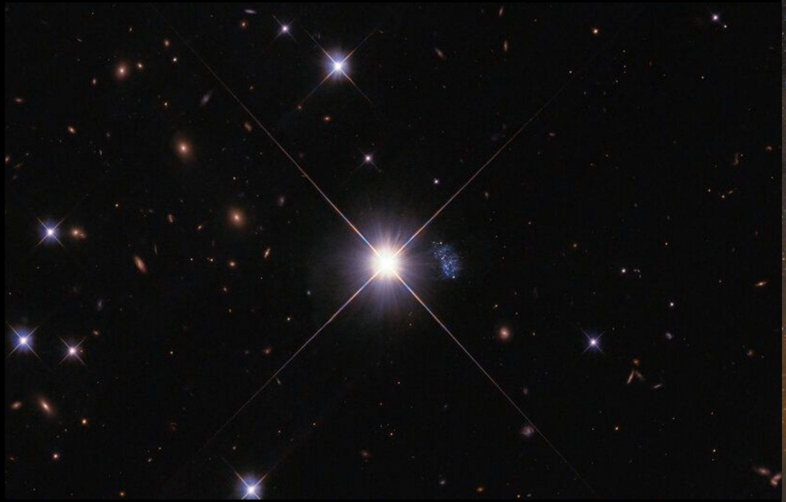
CONTENTS

How do we Identify Astronomical objects

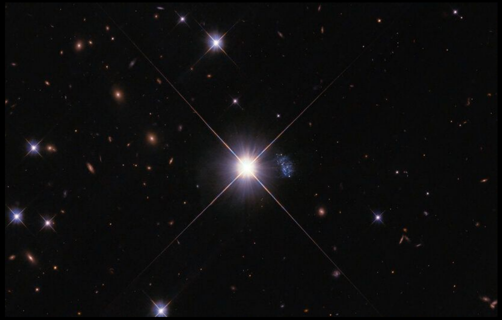
- Image

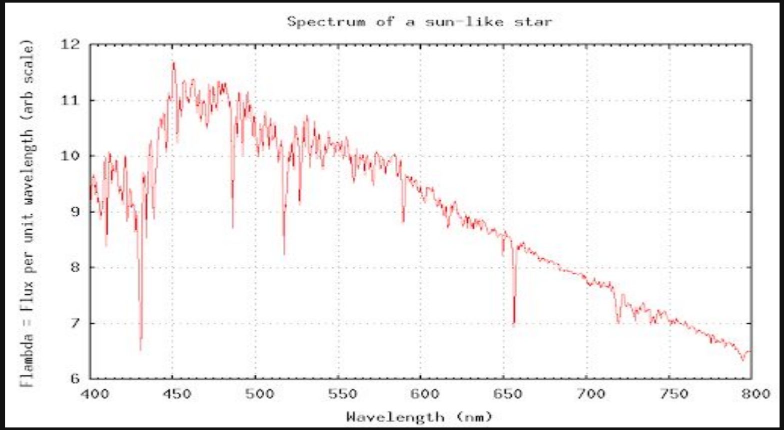


Credit: J. C. Munoz/ESO

How do we Identify Astronomical objects

- **Spectrum**





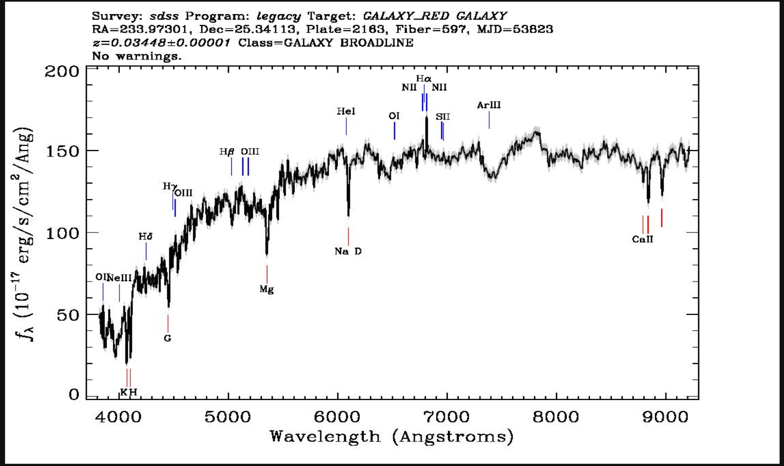
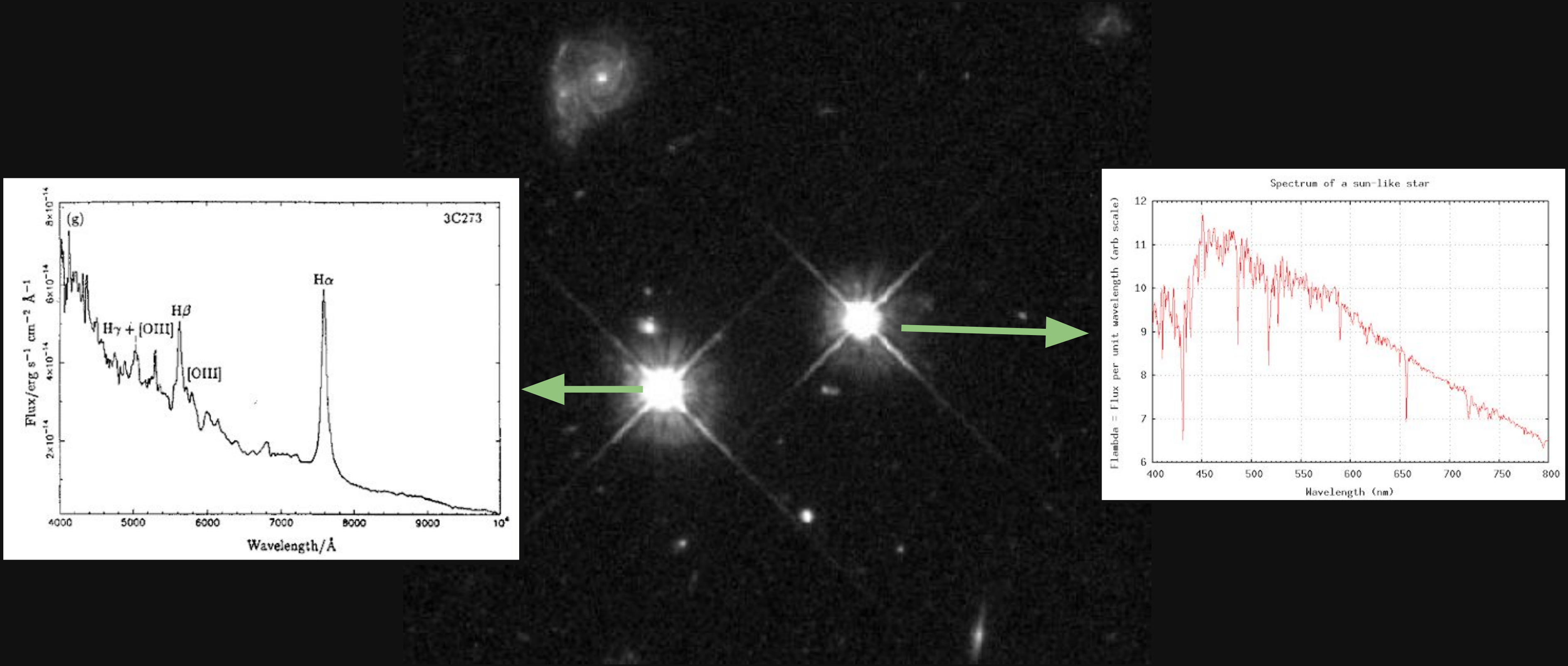
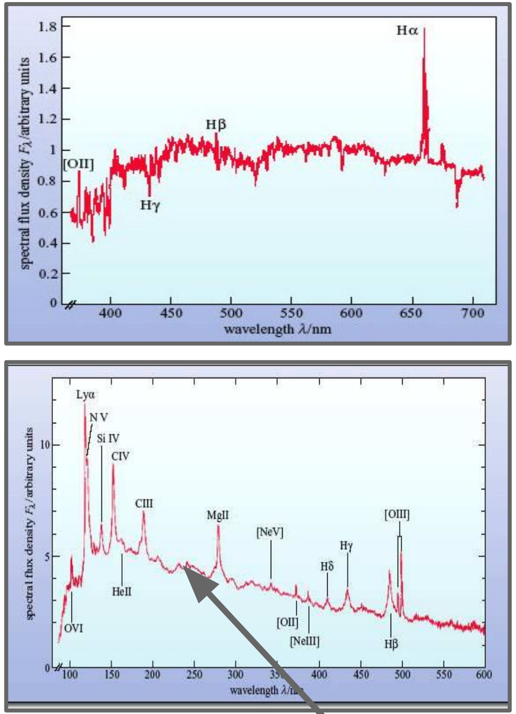


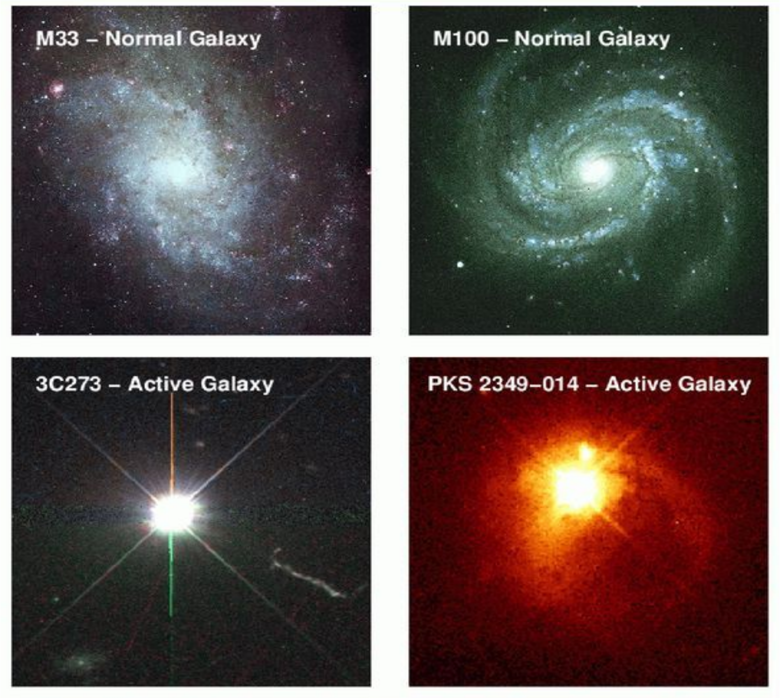
Image Credit: Sky at night magazine



[Image credit: C. Steidel (Caltech) & NASA]

Active Galactic Nuclei(AGN)



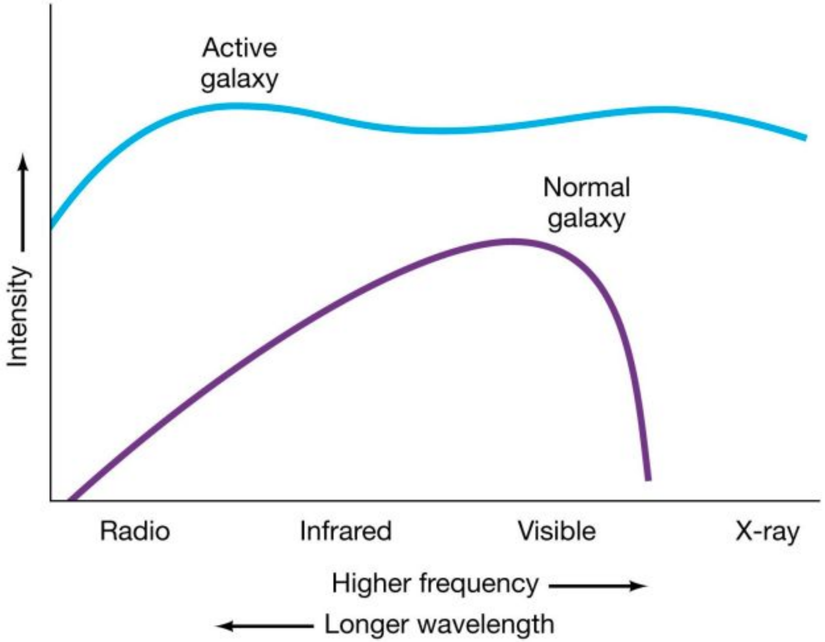


[Image credit: C. Steidel (Caltech) & NASA]

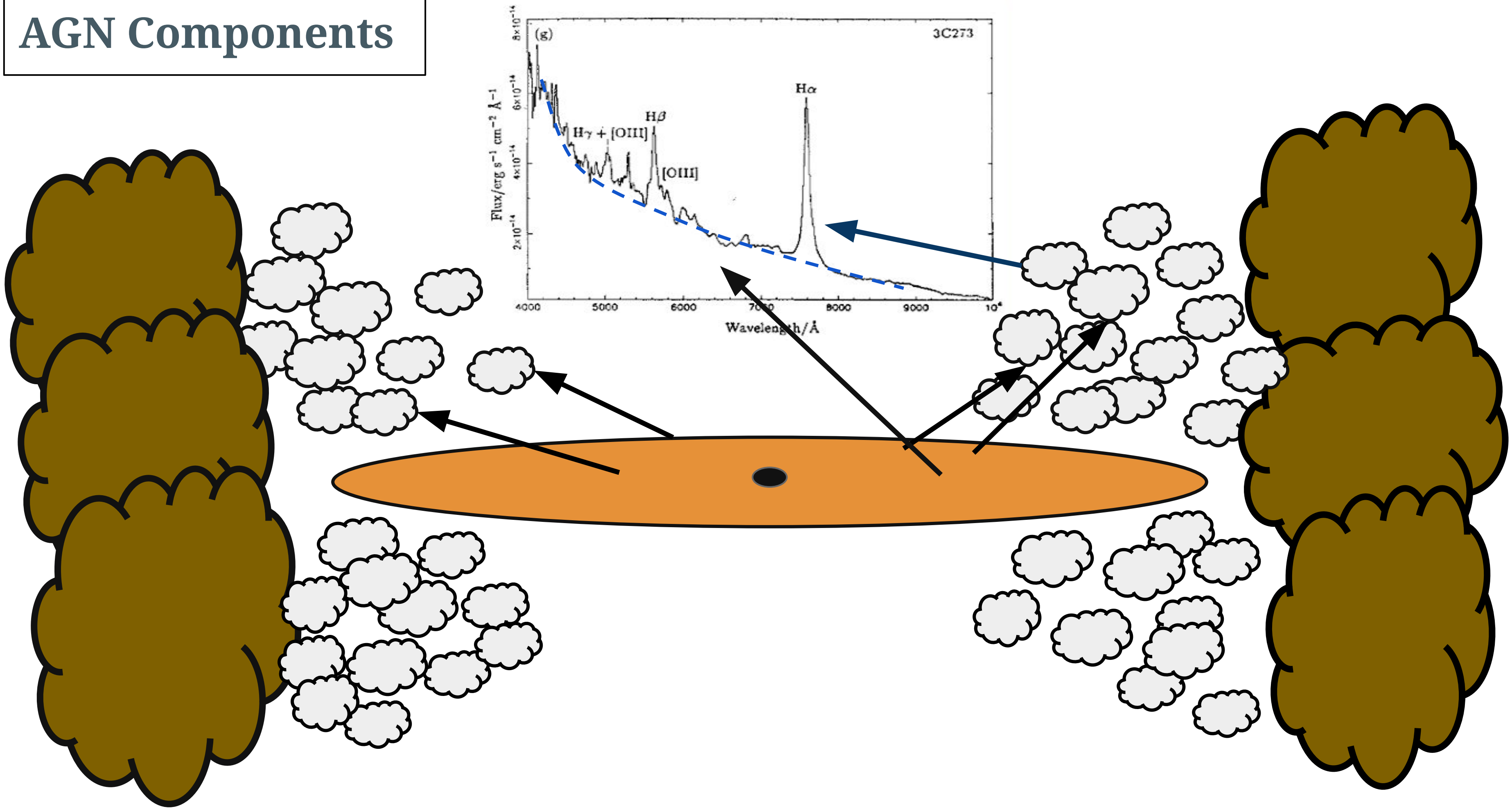
- ★ AGN Spectrum shows power law behaviour unlike star or normal galaxy.
- ★ AGN Spectrum shows broad emission lines > 1000 km/s unlike normal galaxy with line width < 1000 km/s

Introduction

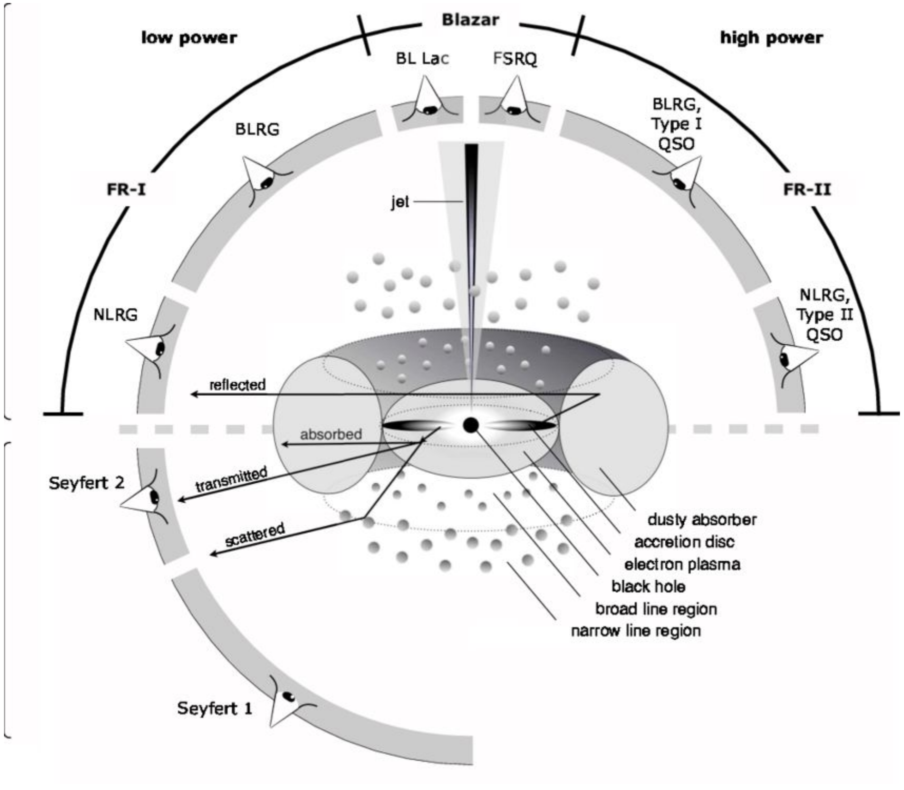
Active galactic nuclei (AGNs) are galaxies whose nuclei are highly luminous, with spectra showing broad emission lines covering a wide range of ionization.



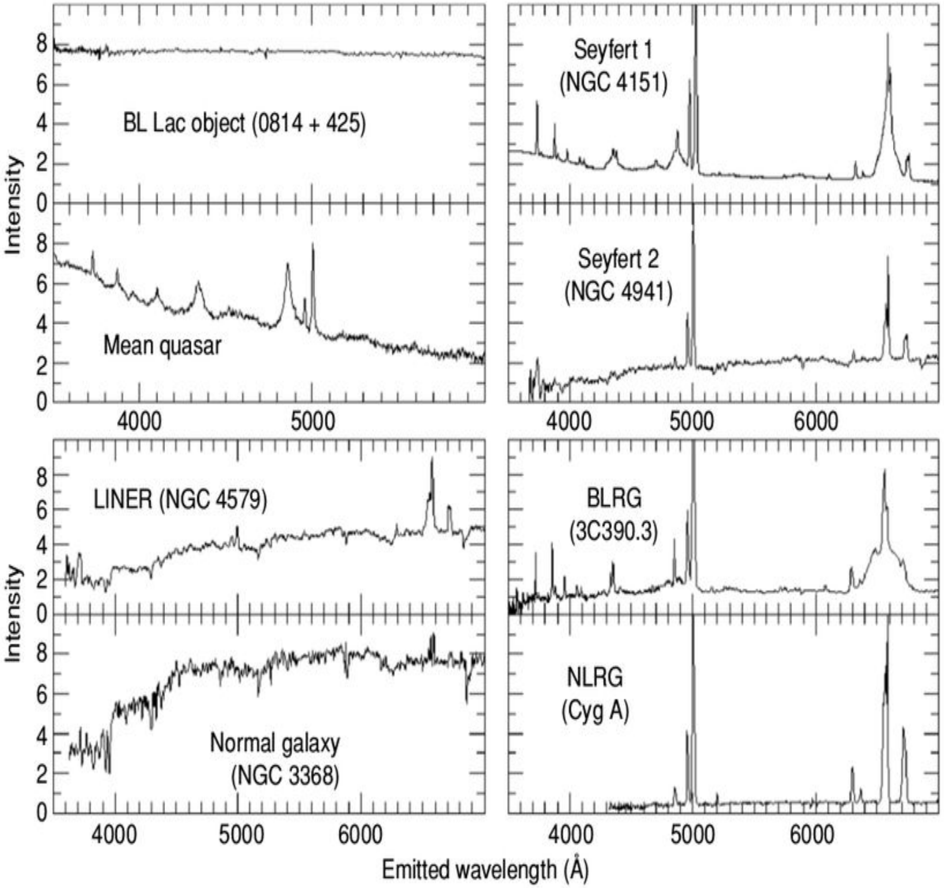
AGN Components



AGN Unification Scheme



[Image credit: Beckman and Shrader 2013]

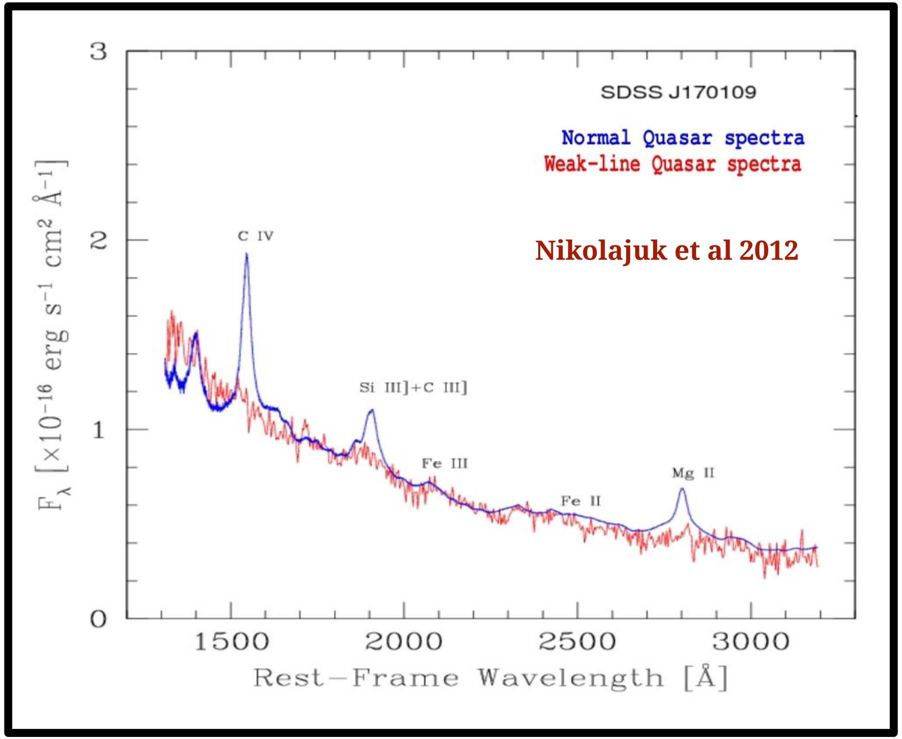


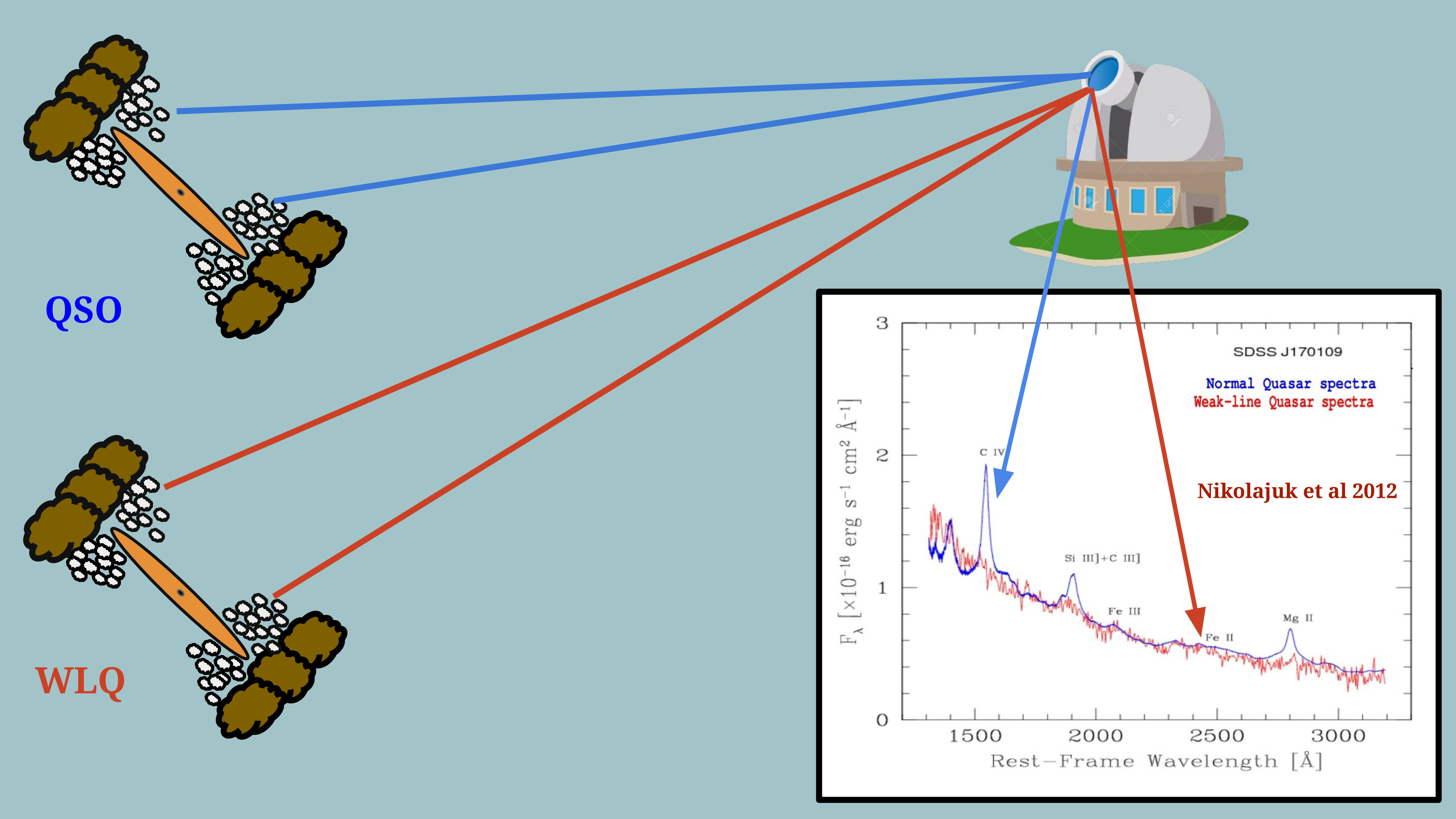
Puzzle of WLQs

- Emission Lines (both broad and narrow) are either absent or very weak [**Shemmeer et al 2009,Plotkin et al 2010**].

- Power law slope is similar to normal Quasars suggest Type 1 QSOs.

- Radio Quiet nature and low polarization suggests they are different as comparison to Blazar.

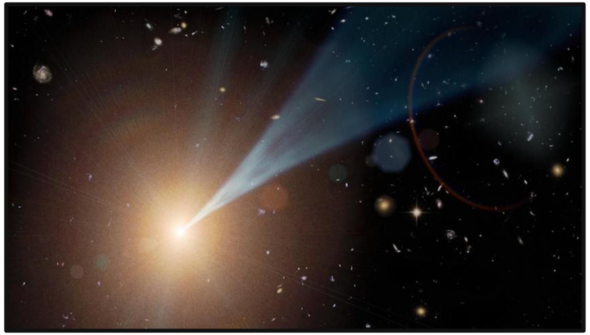




QSO
WLQ
SDSS J170109
Normal Quasar spectra
Weak-line Quasar spectra
Nikolajuk et al 2012
C IV
Si III]+C III]
Fe III
Fe II
Mg II
F_λ [$\times10^{-16}$ erg s^{-1} cm^2 Å^{-1}]
Rest−Frame Wavelength [Å]
0
1
2
3
1500
2000
2500
3000

Possible Mechanism Behind Weak Lines in WLQs

Continuum Boosting



Continuum boosting in WLQ is not favoured as weak line quasars, in contrast to BL-Lacs, are radio quiet objects, shows no variability or strong polarization and show detection of hot thermal dust emission in the infrared.(e.g., Diamond-Stanic et al (2009), Chand et al (2014), Kumar et al (2018))

Possible Mechanism Behind Weak Lines in WLQs

Soft Ionizing Continuum

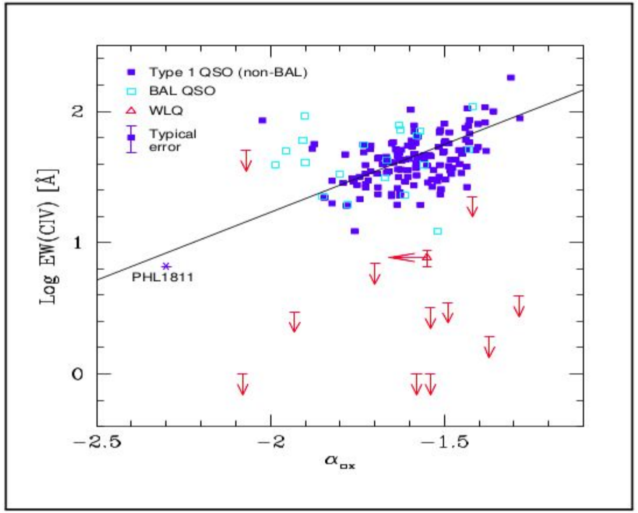
Weak emission lines in WLQs may be the consequence of a very soft ionizing continuum and of a relative deficiency of high energy UV/X-ray photons.

Possible models for Soft ionizing continuum:

1) Cold Accretion Disk e.g. Laor & Davis 2011;
2) Super-eddington accretion e.g. Leighly et al. 2007a,b
3) Shielding Gas model e.g. Wu et al 2011; Luo et al 2015,Ni et al 2018

Soft ionisation continuum is not favoured for the weak emission lines as UV/Soft-X-ray SED of WLQs is similar to those of Normal quasar (e.g.,Nikolajuk,Walter (2012)) .

Possible Mechanism Behind Weak Lines in WLQs



(Nikolajuk et al 2012)

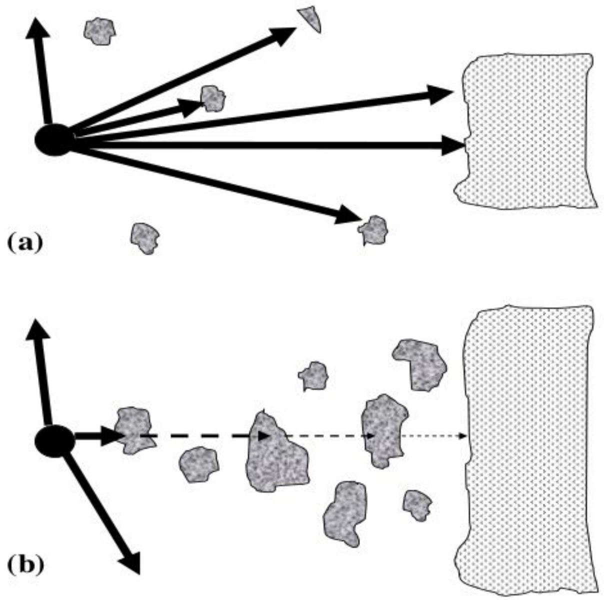
Low BLR Covering Factor

The intensity of an emission line depends on flux of ionizing continuum, L_{ionize} and on the BLR covering factor (e.g.,Ferland 2004 and Nikolajuk,Walter (2012))

$$logEW(line) \approx const_1 + log\frac{\Omega}{4\pi} + \frac{\alpha_{ox}}{const_2}$$

From above graph : The gas covering factor in WLQ i.e Ω_{WLQ} is smaller than QSOs at least by the factor of more than 10 (e.g. Nikolajuk et al 2012).

Small BLR AGN also have Smaller Dusty Torus



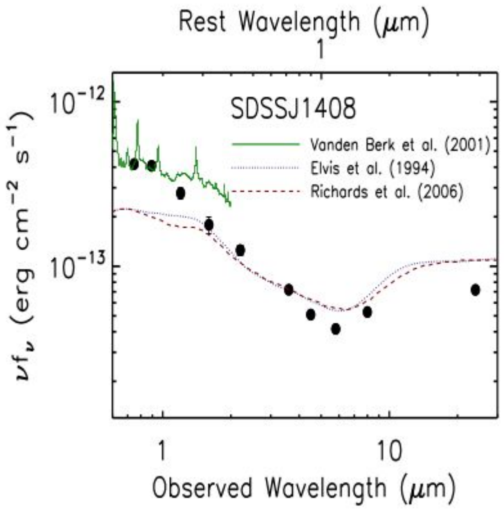
[Image credit Gaskell, Klimek, & Nazarova (2007)]

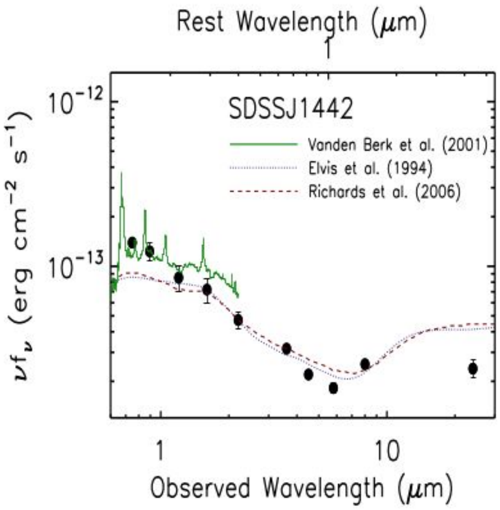
In the equatorial plane the BLR clouds provide shield for Torus, so smaller BLR in WLQ causes an evaporation of dust in the Torus and leads to reduction in the IR emissivity which leads to smaller Dusty Torus eg. Gaskell et. al 2009.

- ❖ Underdeveloped BLR ⇒ smaller covering factor of the dusty torus
- ❖ observational consequences in the infrared (IR) band,
  - ➢ reduction of its IR emissivity in comparison to the normal QSOs
- ❖ **This form the main motive based upon SED fitting using SDSS/WISE.**

Low BLR Covering Factor signature: IR/NIR

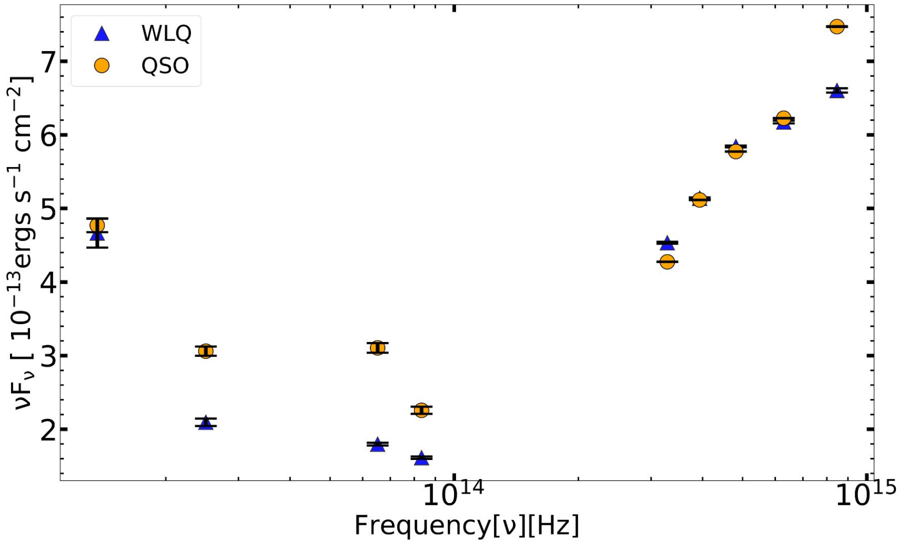
Diamond-Stanic et al 2009, found smaller IR (24μm) flux for two WLQs (out of total 4) by **30-40 %,** implying smaller dusty torus and hence smaller BLR.



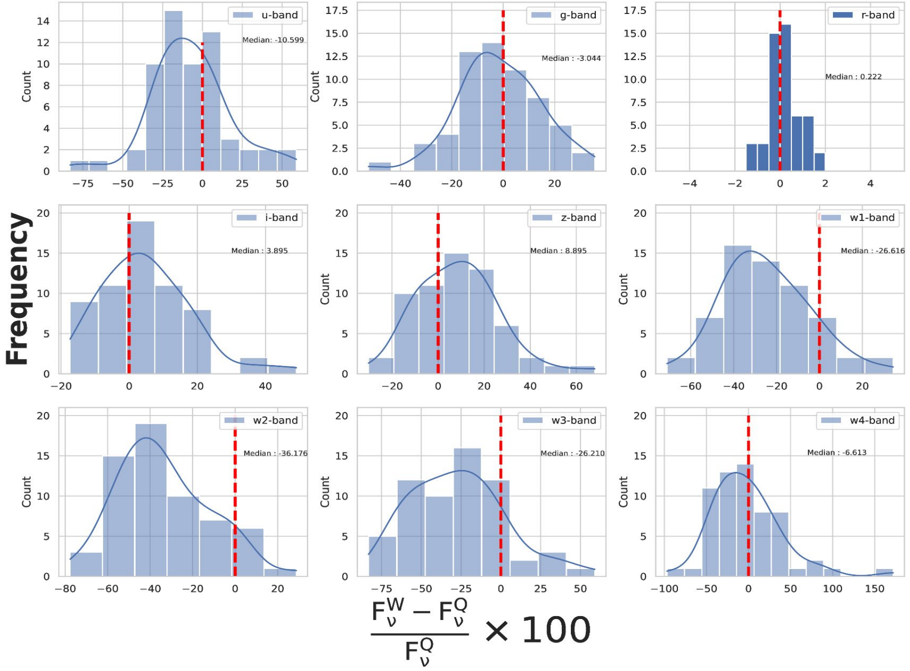


Diamond-Stanic et al (2009)

Flux distribution of WLQ and Normal QSO Sample



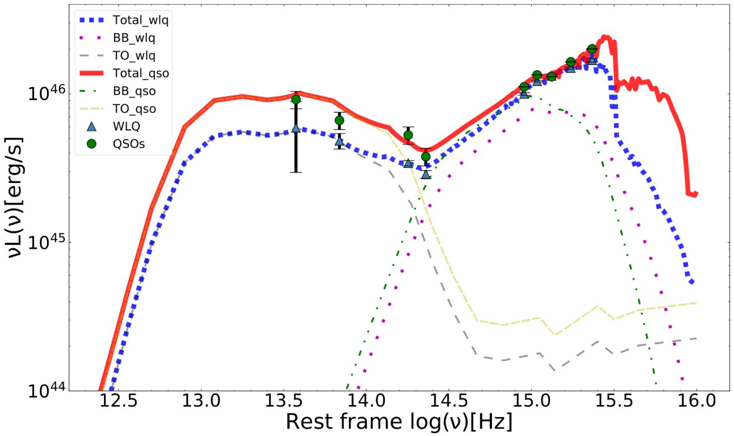
[Median Observed Flux]



The quantification of this difference (in observed frame) requires proper decomposition of SED (in rest frame) into its individual emission components.

SED fit of WLQs & control sample of QSOs

From AGNfitter we have compared the SED of our WLQs sample and the control sample of Normal QSOs.



By Kumar et al.(2023)

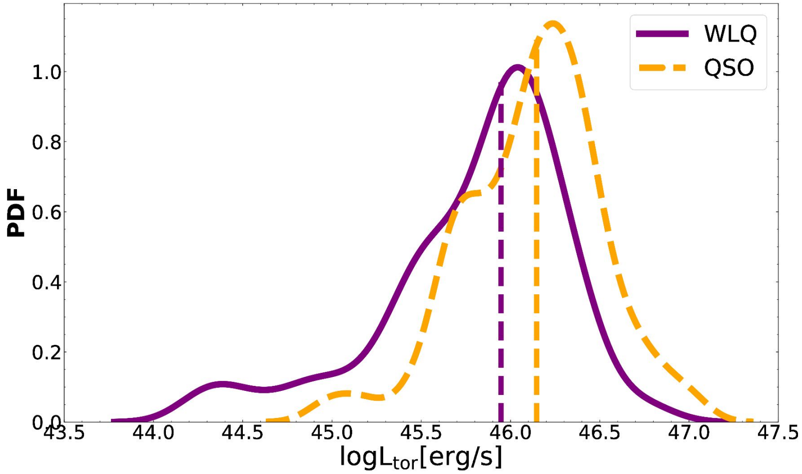
Table 5. The median value of the important parameters of our SED model fit based on 61 WLQs and using their corresponding composite of their control sample of normal QSOs.

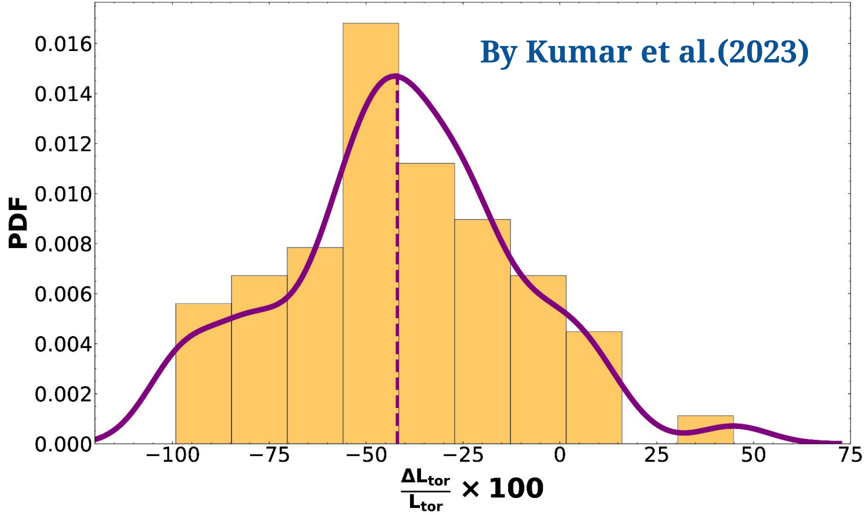
Parameter*	WLQ	σ_{wlq}	QSO	σ_{qso}	%deviation $\left[\frac{WLQ-QSO}{QSO} \times 100\right]$
SB	1.99 ± 0.22	1.68	1.84 ± 0.23	1.78	5.93 ± 19.17
BB	2.49 ± 0.01	0.11	2.62 ± 0.001	0.003	-2.15 ± 0.52
GA	4.29 ± 0.05	0.39	3.52 ± 0.004	0.03	23.01 ± 1.44
TO	2.35 ± 0.03	0.24	2.57 ± 0.01	0.05	-8.59 ± 1.20
EBV_bb	0.06 ± 0.01	0.08	0.10 ± 0.01	0.02	-6.27 ± 15.47
EBV_gal	0.20 ± 0.01	0.09	-0.034 ± 0.004	0.03	-138.38 ± 130.06
Ldered(0.1−1 μm)	14.09 ± 0.42	3.32	19.12 ± 0.02	0.15	-11.81 ± 1.81
Lga(0.1−1 μm)	5.16 ± 0.15	1.17	6.28 ± 0.01	0.06	-5.75 ± 7.37
Ltor(1−30 μm)	8.85 ± 0.51	4.002	13.99 ± 0.29	2.32	-41.69 ± 1.59

*__SB, BB, GA, TO__ refers to normalization parameters of "starbusrt", "big blue bump", "galaxy" and "torus" component respectively.
*__EBV_bb, EBV_gal__ refers to the reddening parameters of "big blue bump" and "galaxy" component respectively.
*__Ldered, Lga, Ltor__ refers to the luminosity of "deredened big blue bump", "galaxy" and "torus" component respectively.
in unit of 10^{45}erg/s.

Relative variation of Torus luminosity :

(L_w-L_q)/L_q

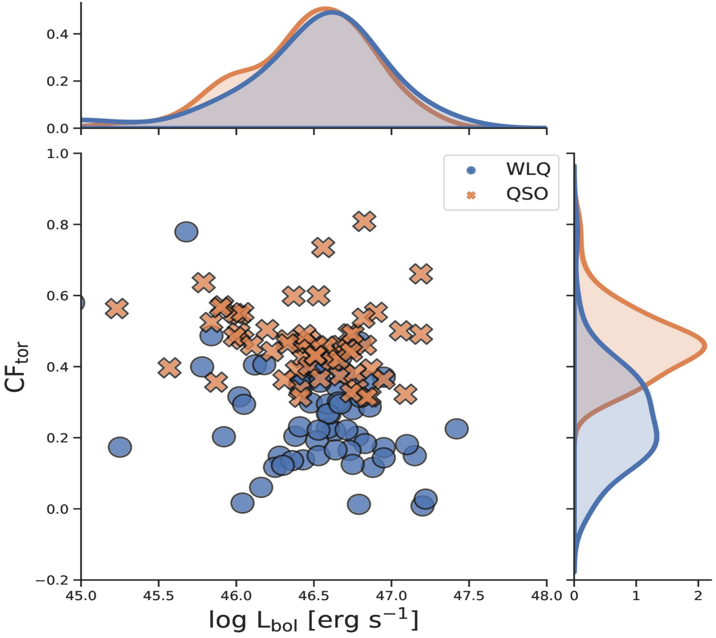


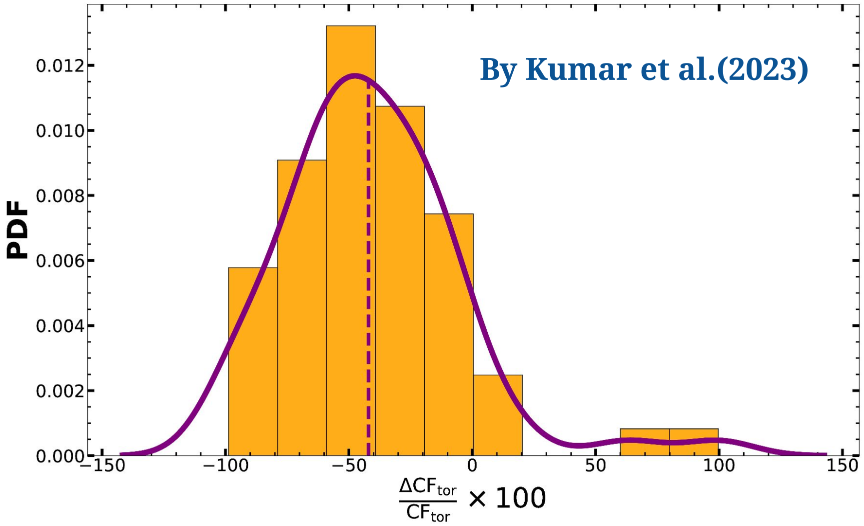


The distribution of L_torus in WLQs and normal QSOs differ significantly with K-S test based p-null of 0.02.

The median percentage deviation ΔLtor/Ltor is found to be −42±2%.

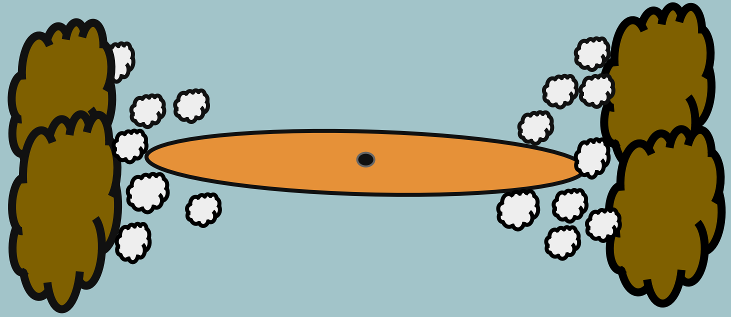
Relative variation of covering factor: CF_tor = L_





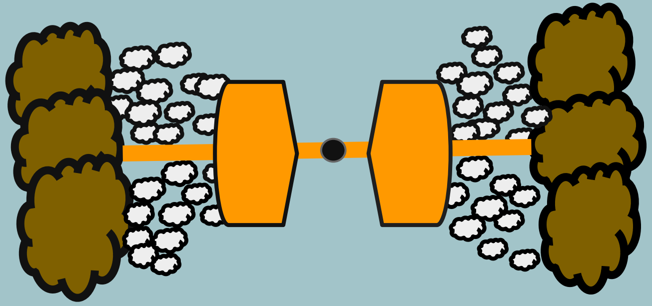
CF_tor distribution differ significantly with k-s test p_null = 4.27×10^{-14}.

The median percentage deviation **ΔCF_tor/CF_tor** is found to be −42±4%.



Underdeveloped BLR Model

- Small BLR covering factor
- Small BLR => Small Torus Covering factor
- Supported by e.g. Diamond-Stanic et al (2009) & Nikolajuk et al 2012



Shielding Gas Model

- High Eddington Ratio
- Low X-ray flux
- Low UV Contribution
- Not supported by observation (e.g.,Nikolajuk,Walter (2012)
- Only able to explain x-ray weak WLQs

Our analysis and result support the scenario in which WLQs have underdeveloped torus and BLR and they belong to early evolutionary phase of QSOs.

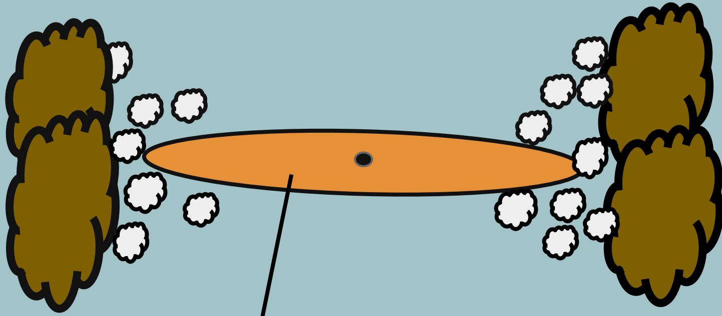
Scenario of Accretion Disk

Follow Up Work to Constrain Accretion Disk

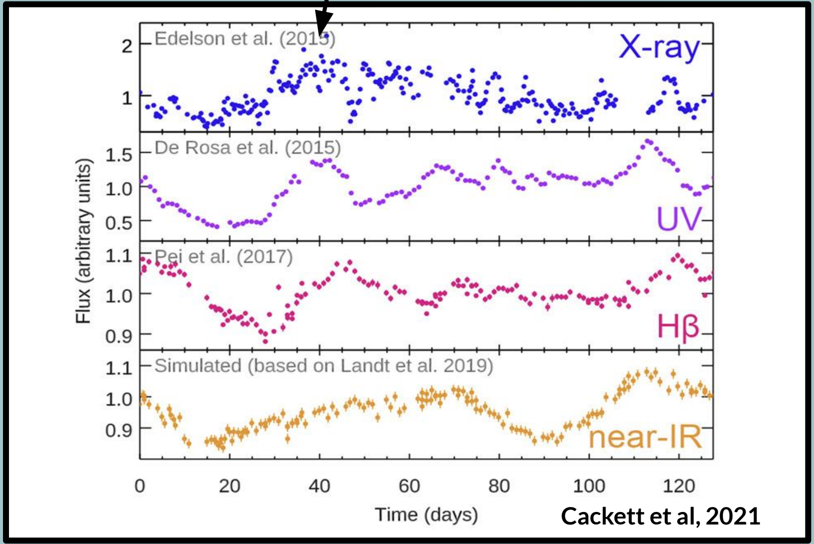
- In our previous work we put constrain over the BLR region and suggest that the **BLR region is underdeveloped** .

- In further analysis we try to constrain the scenario of accretion disk in WLQs using its **variability study**.

- We constrained various parameters that are used to constrain variability e.g **Variability amplitude, Structure Function and Color Variability**.



Underdeveloped BLR Model



Variability Study

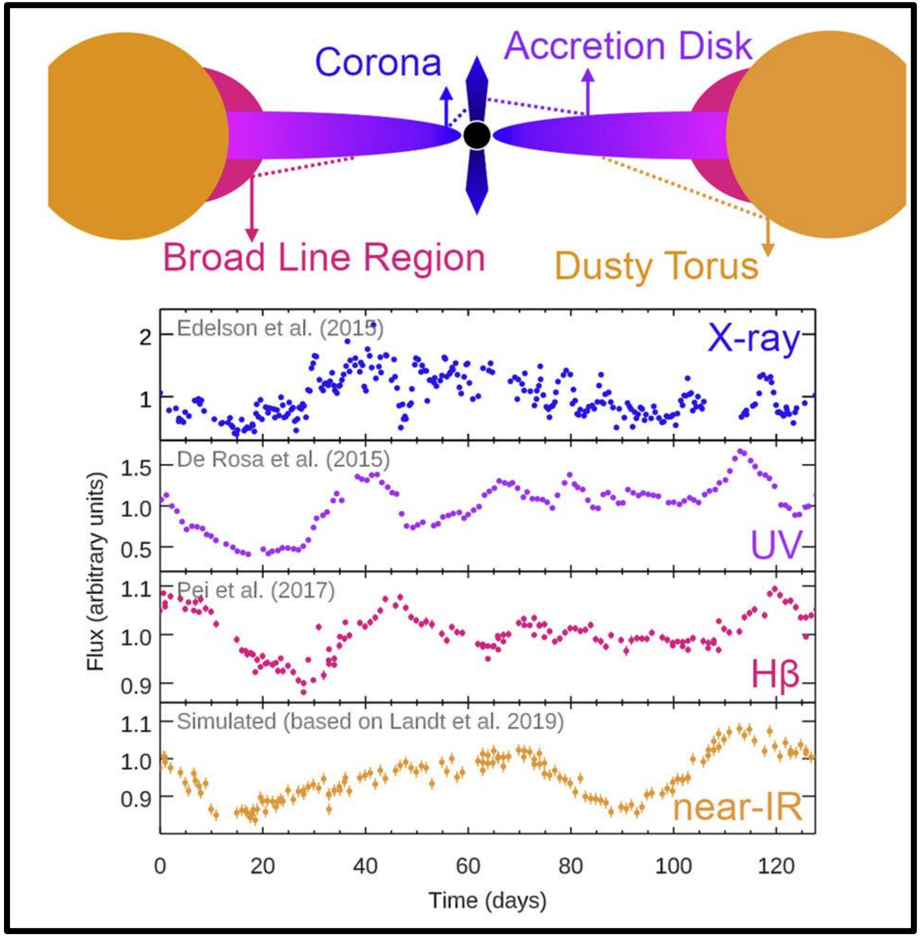
A distinguishing feature:

Variable at all time scales in all wavelengths.

Stochastic in Nature - some sources quasi periodic variability

Correlated variability in different wavelengths - used to map the innermost regions

Various models to describe the AGN variability- Damped Random Walk (DRW) most popular



Cackett et al, 2021

ZWICKY TRANSIENT FACILITY

Sample :

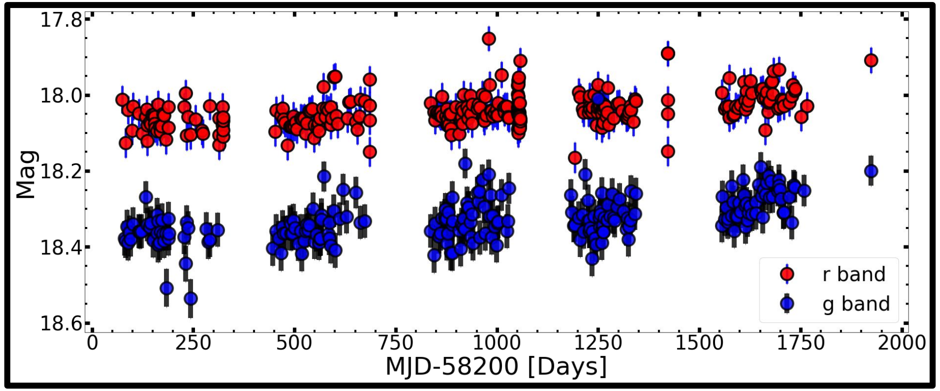
- **We have 95 WLQs sources**
- **We have 782 QSO sources (SDSS DR16)**
  Tolerance: $\Delta z<0.01$ & Δr-band<0.6
- **We have 846 Bl Lac and 999 FSRQ from (Roma-BZCAT catalogue 2015)**

Good cadence for upto 5 years (2018-2023) very unique!

An all sky survey covering wide range of AGN population.

Parameters Constraining Variability

- **Variability Amplitude**
- **Structure Function**
- **Color Variability**

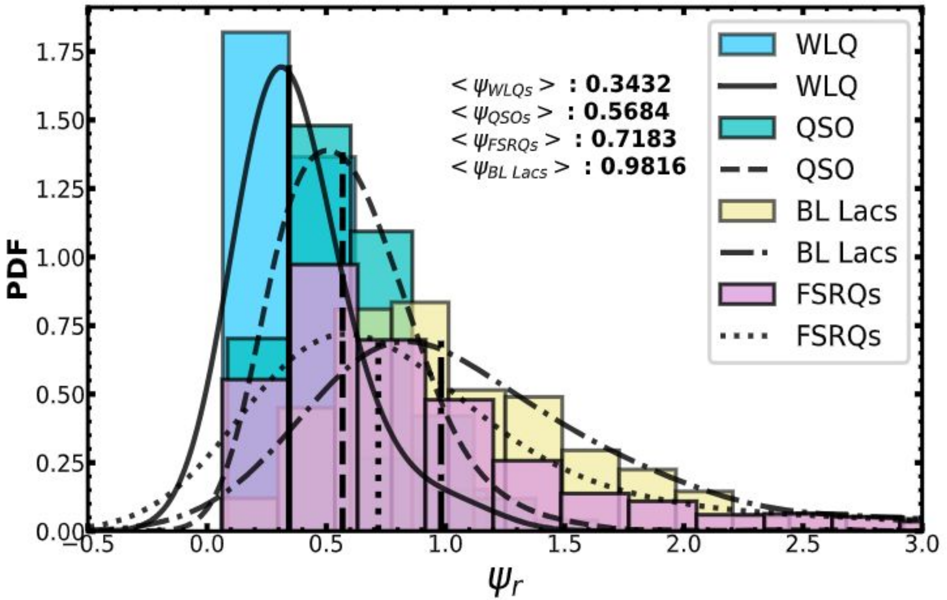


Variability Analysis of WLQs

Variability Amplitude

We first compare the brightness variation in the WLQ, QSO, Bl-Lac and FSRQ. For this we used frequently used quantities.

$$\psi(r) = \sqrt{(A_{max} - A_{min})^2 - 2\sigma^2}$$



where $\sigma^2 = \langle \sigma_i^2 \rangle$, with A_{max} and A_{min} being the maximum and minimum amplitude in the light curve and σ_i^2 being the uncertainty in the i^{th} data point.

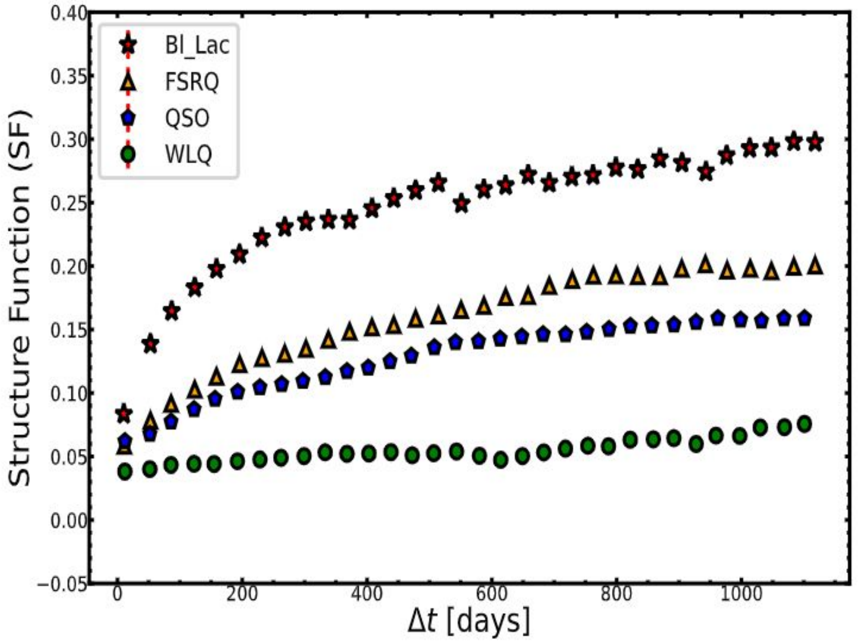
Our results suggests that the Variability amplitude of WLQ is small as comparison to Bl-Lac and normal Quasar with median value of variability amplitude of 0.34.

Variability Analysis of WLQs

Structure Function

$$SF(\Delta t) = \sqrt{\frac{\pi}{2}\langle|m(t+\Delta t) - m(t)|\rangle^2 - \langle\sigma_n^2\rangle}$$

This function is built from the **ZTF light curves** of the sample of sources and is basically a **measure of the ensemble root mean square** (rms) magnitude difference as a function of the **time lag** between different visits, where measurements are typically grouped together into bins.



From Structure Function (SF) analysis, we found that the WLQs do not belong to the Blazar class in terms of variability, but are close to normal QSOs.

Color Variability [r-g vs r]

- The **color variability** of quasars is thought to be caused by **fluctuations** in the accretion disk.
- The gas in the disk is heated by the friction of the rotating material, and this heat is released in the form of electromagnetic radiation.
- The fluctuations in the accretion disk can be caused by a number of factors, including
  - Infall of new material onto the disk
  - Turbulence of the gas and dust in the disk
  - Magnetic fields in the disk (**MHD**)

When these fluctuations occur, they can cause the brightness of the quasar to change, and they can also cause the spectrum of the quasar to change.

Trend in color variability

- **BWB : Blue When Bright**
- **RWB: Redder When Brighter**
- **No Trend**

Color Variability

Sample :

- 94 WLQs
- 782 Normal QSOs

Condition: g and r band data within 2.4 Hr.

Out of 94 WLQs: 39 showed BWB trend, whereas 4 showed RWB trend,

(No strong trend in rest of the targets**)**

For 782 QSOs: 470 showed BWB trend whereas 43 shows RWB,

(No strong trend in rest of the targets**).**

S.No	Source Name	z	L_{bol}	Trend	Variability Amplitude Ψ_r
1	J001444-000018	1.55	46.95	BWB	0.31
2	J001514-103043	1.17	46.28	BWB	0.64
3	J001741-105613	1.80	46.65	BWB	0.59
4	J080040+391700	1.77	47.13	RWB	0.30
5	J142601+243245	2.11	46.75	RWB	0.89
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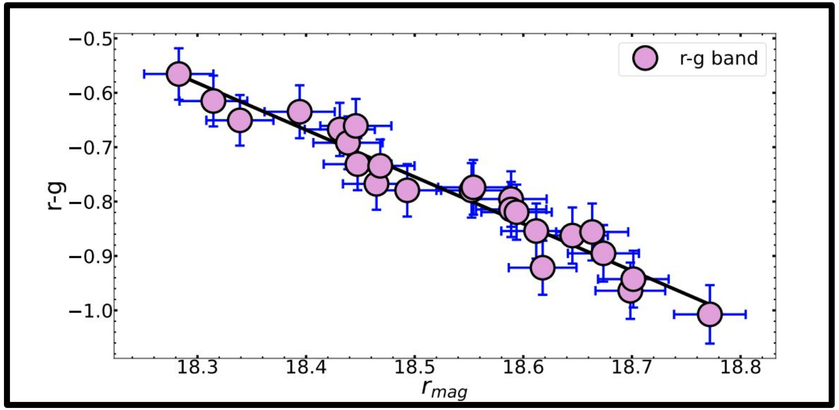
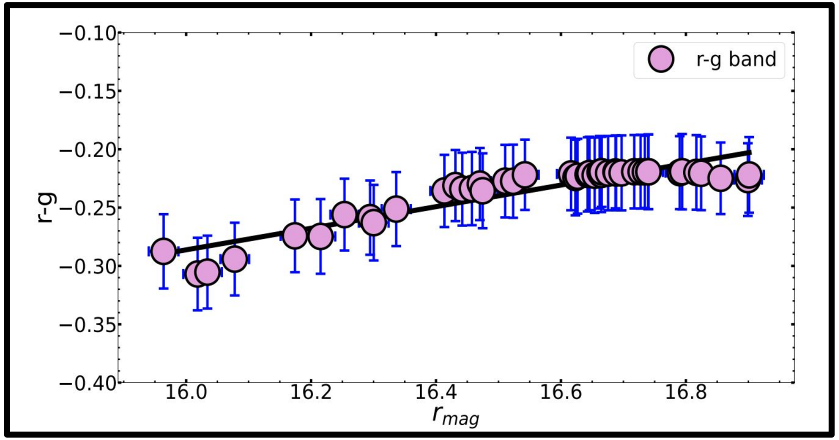
Color Variability



The **BWB trend** is thought to be caused by **fluctuations** that **occur in the inner regions** of the accretion disk. These fluctuations cause the **temperature of the inner regions** of the disk to **increase**, and this causes the emission from the inner regions to **shift towards shorter wavelengths**. As a result, the overall spectrum of the quasar becomes bluer.



The **RWB** trend is thought to be caused by fluctuations that occur in the **outer regions of the accretion disk**. These fluctuations cause the **temperature of the outer regions** of the disk to **decrease**, and this causes the emission from the **outer regions to shift towards longer wavelengths**. As a result, the overall spectrum of the quasar becomes redder.

Variability Amplitude vs Eddington Ratio

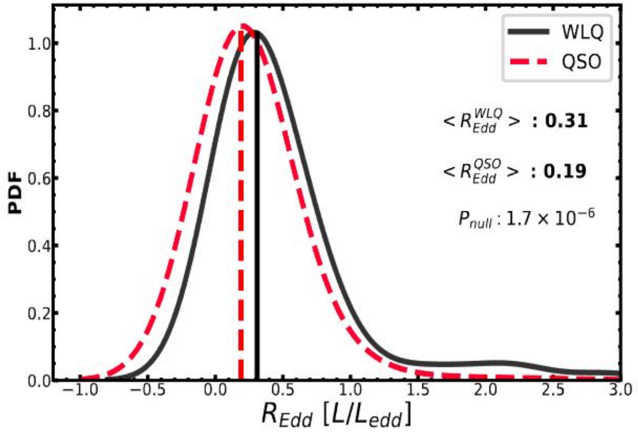
Our results suggests the **anti-correlation** of the **variability amplitude** and **Eddington ratio** as shown in figure, consistent with previous studies as :

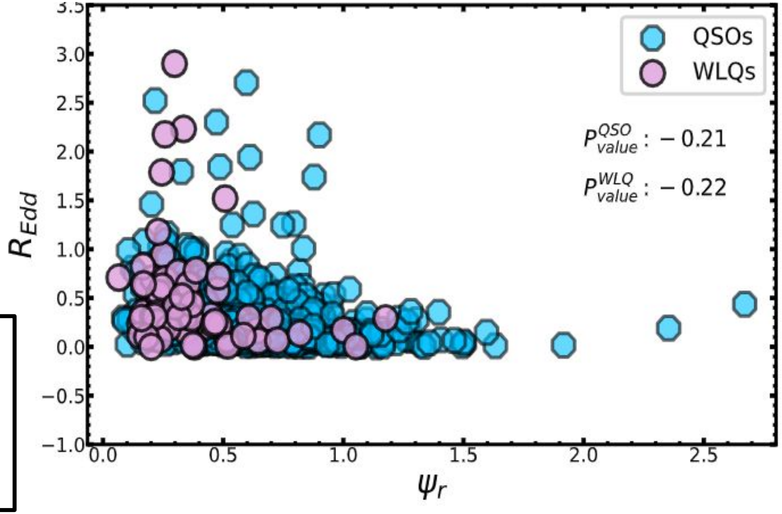
$$R_{Edd} = \frac{L_{Bol}}{L_{Edd}}$$

$$\Rightarrow \psi_r \propto \frac{1}{L_{Bol}}$$

(Wilhite et.al 2008, Zuo et.al 2014)

$$\Rightarrow \psi_r \propto \frac{1}{R^2_{Edd}}$$





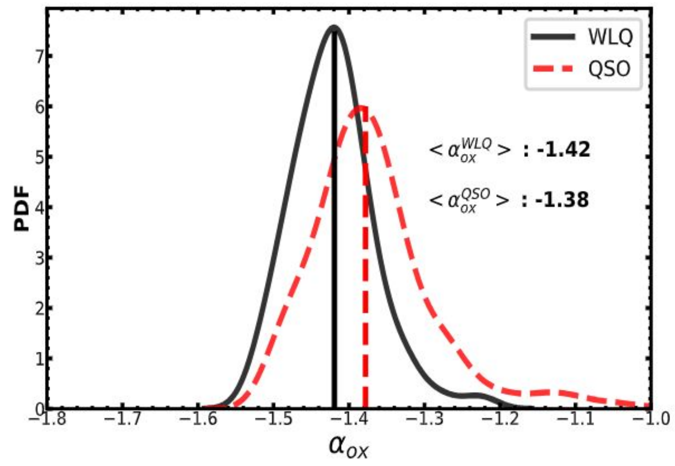
Our results are consistent with the previously well established anti-correlation of variability amplitude and the eddington ratio.

X-ray Parameters

X-ray to Optical Luminosity

$$\alpha_{ox} = -0.14 \times log(L_{2500\mathring{A}}) + 2.64$$

By Steffen et al.(2006)



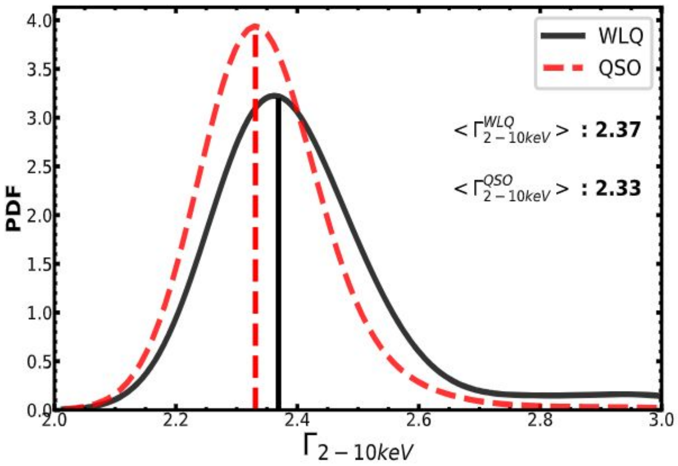
Where

$$L_{2500\mathring{A}} = L_{3000\mathring{A}} \times \left(\frac{\lambda_{2500}}{\lambda_{3000}}\right)^{\alpha}$$

X-ray Photon Index

$$\Gamma_{2-10keV} = 0.32 \times R_{Edd} + 2.27$$

By Brightman et al.(2013)

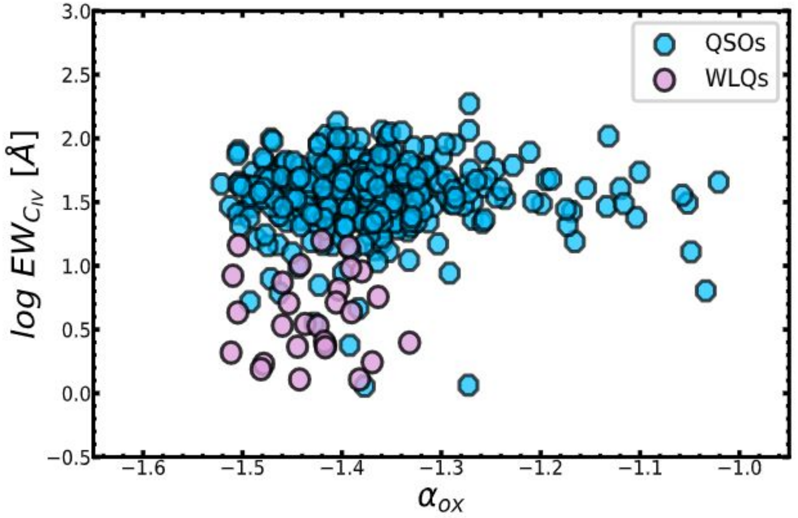


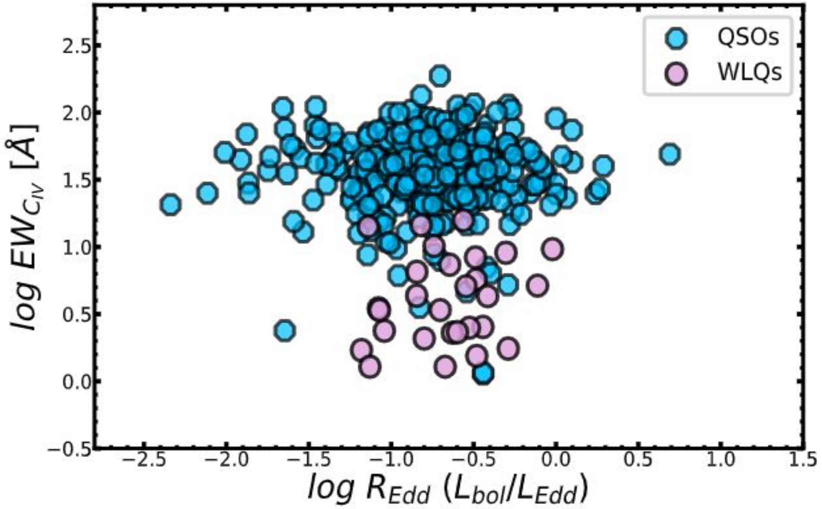
Dependence of EW over Covering Factor

$$log\, EW(line) \approx const_1 + log\frac{\Omega}{4\pi} + \frac{\alpha_{ox}}{const_2}$$

By Nikolajuk et al.(2013)

The median value of alpha_ox for WLQs and normal QSOs are similar which suggests that the smaller value of the WLQs can be explained with **lower covering factor.**





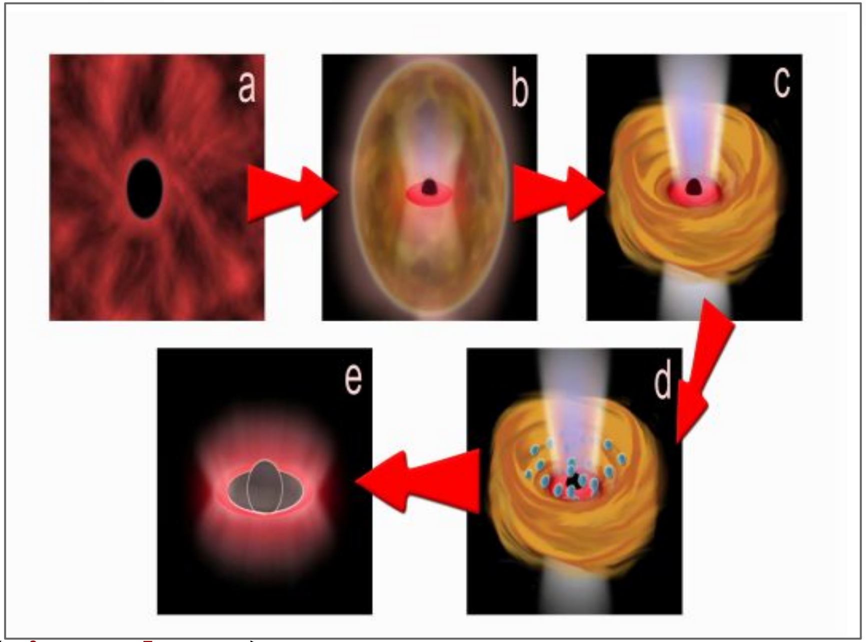
Conclusion

- **A Variability amplitude, Structure–Function and Color Variability analysis of photometric light curves presented here suggests that the mechanism driving optical variability in RQ-WLQs is similar to that operating in QSOs and different from that of blazars.**

- **These findings are consistent with the common view that the central engine in RQ-WLQs, as a population, is akin to that operating in normal QSOs and the primary differences between them might be related to differences in the BLR.**

Conclusion

WLQs, may be a phase of AGN evolution: An illustration



(Liu et al 2011)

WLQ might be in Stage (C)

Evolution stages are:

a) Fast growth of seed black hole.

b) Black hole and disk embedded in dust ball.

c) An-isotropic radiation blow up of dust and hence torus formation.

d) Normal AGN phase with broad line region.

e) AGN phase without fuel.

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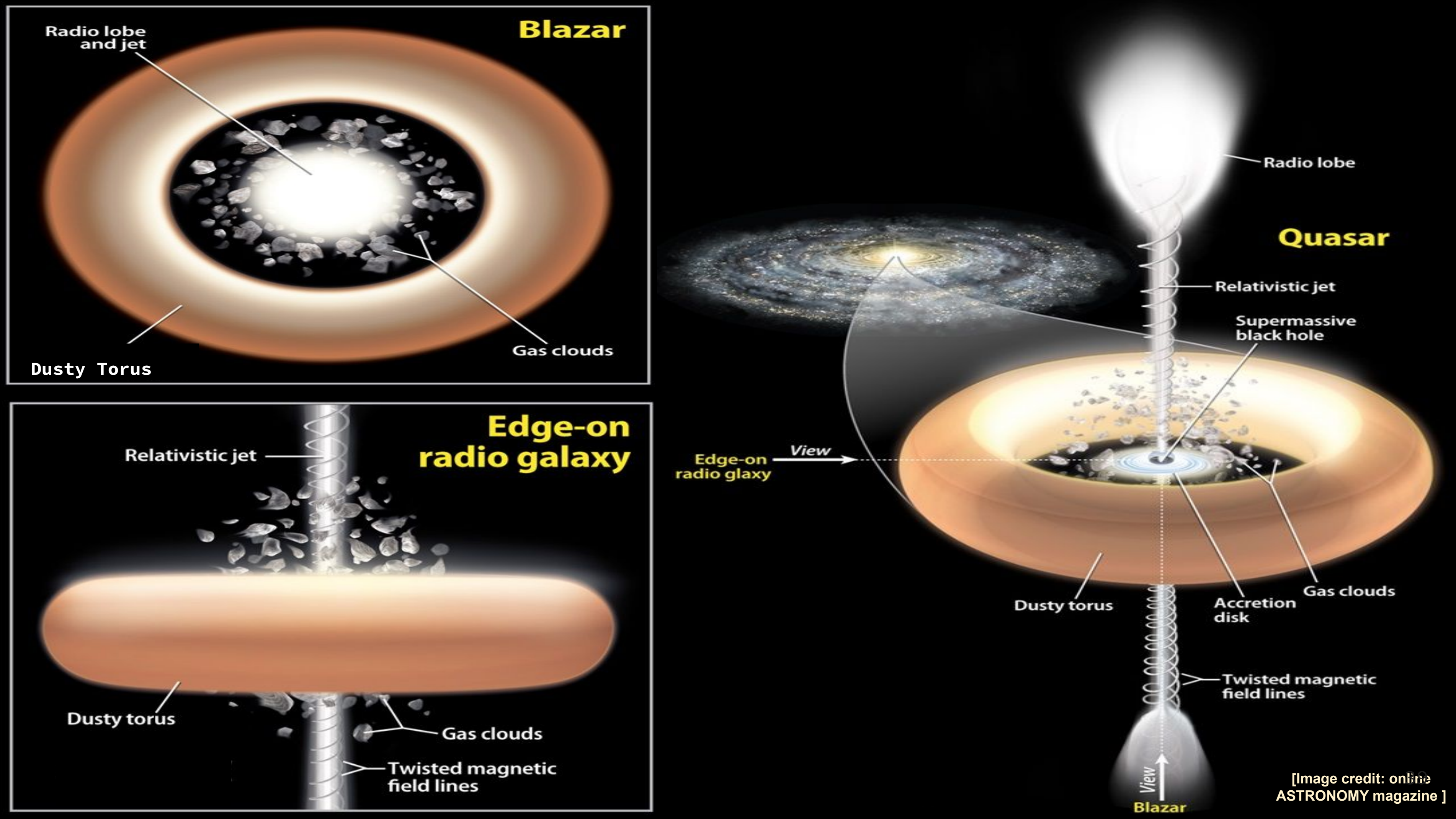
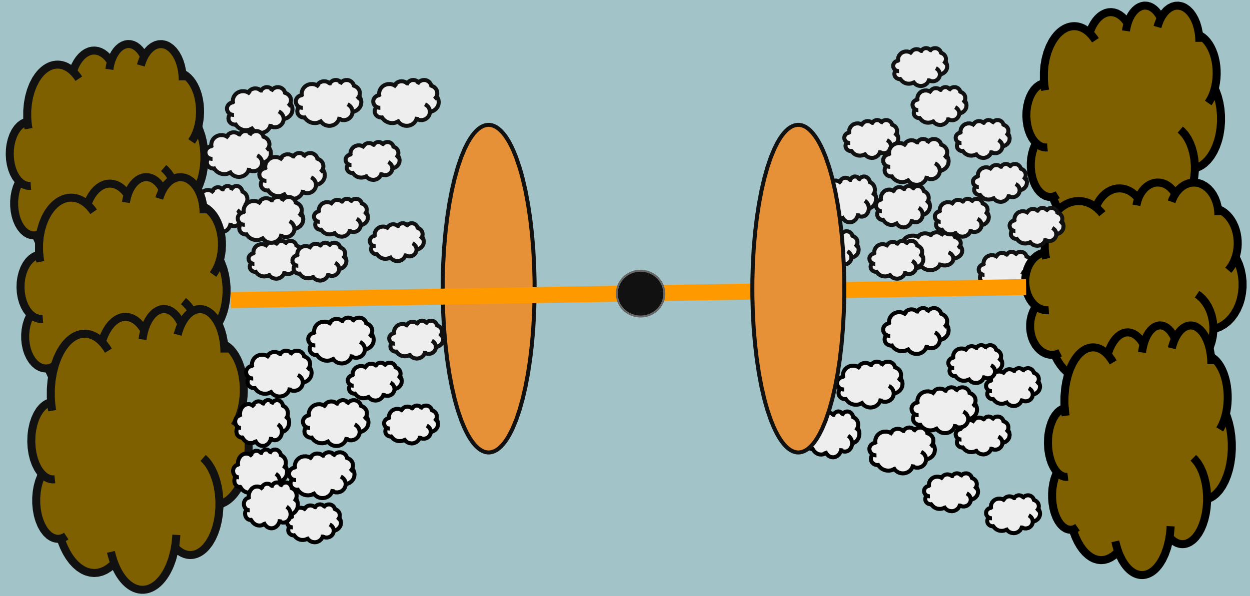
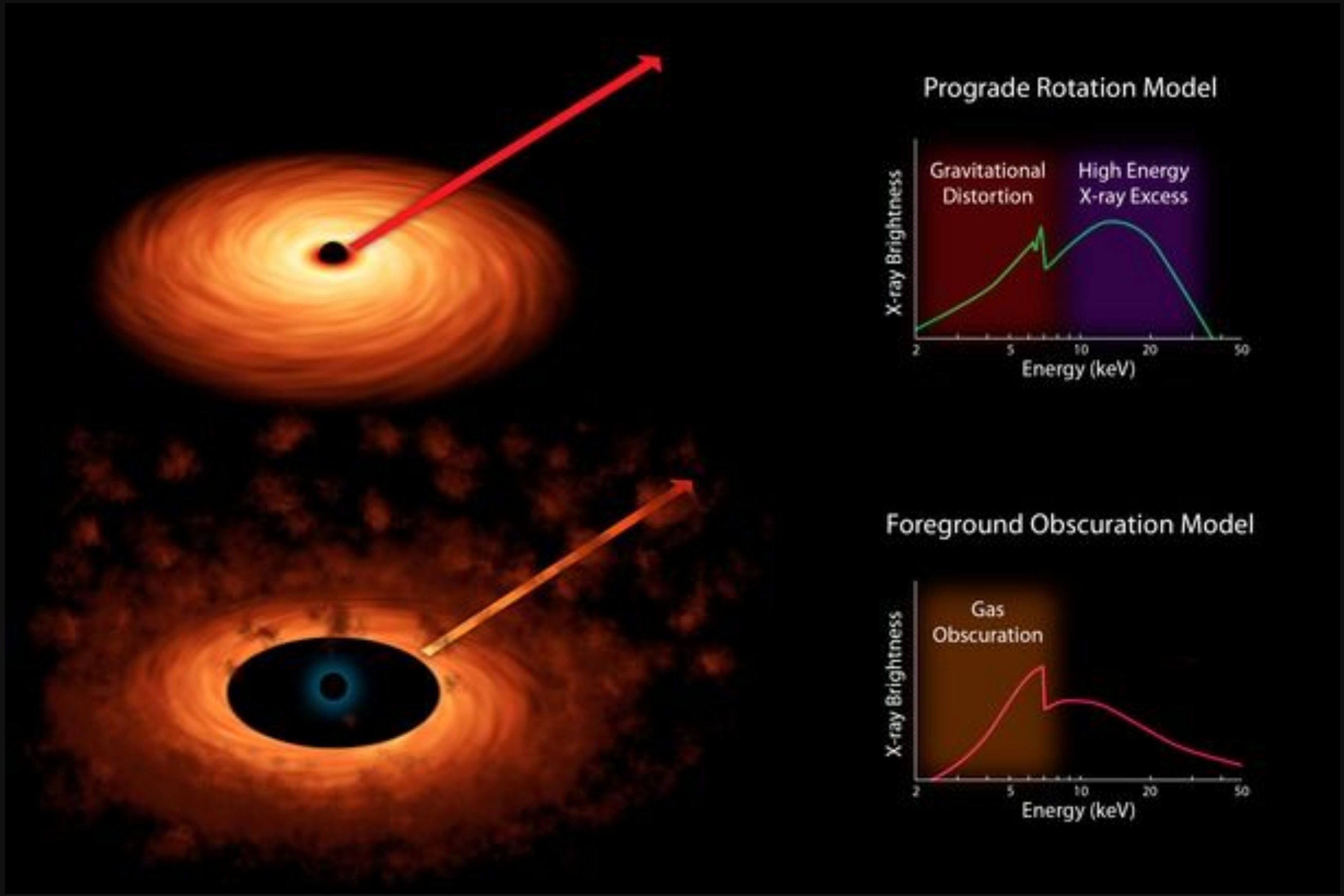
THANK YOU



[Image credit: online ASTRONOMY magazine]




Prograde Rotation Model
Gravitational Distortion
High Energy X-ray Excess
X-ray Brightness
2
5
10
20
50
Energy (keV)
Foreground Obscuration Model
Gas Obscuration
X-ray Brightness
2
5
10
20
50
Energy (keV)