Test the accretion disk theory with color variations in quasars

Junxian Wang
University of Science and Technology of China

Collaborated with:
Yuhan Sun， Xiaoyang Chen, Zhenyi Cai (USTC
and Zhenya Zheng (PUC)

Outline

- The standard thin accretion disk in quasars

  Success and Challenges

- The color variation pattern in quasars

  Bluer when Brighter

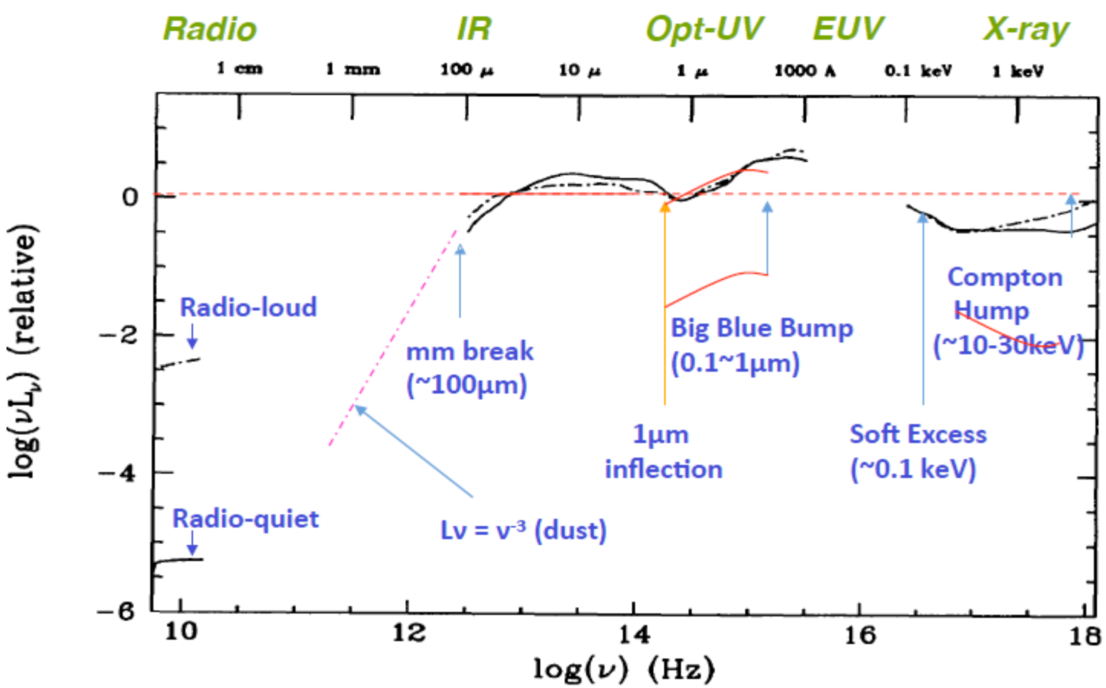
- The color variation is timescale dependent

  The nature of the "Bluer when Brighter" pattern

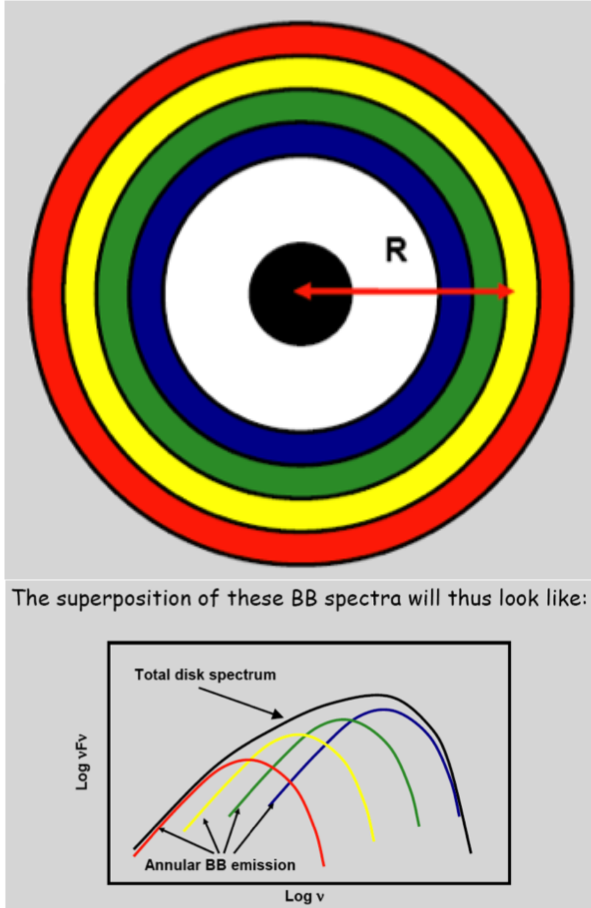
  A new tool to probe the accretion disk

Quasar SED and Accretion Disk Emission

$$T(r)=6\times10^{5}\left(\frac{\dot{M}}{M_{E}}\right)^{1/4}M_{8}^{-1/4}\left(\frac{r}{R_{S}}\right)^{-3/4}K$$



Elvis et al., 1994, ApJS, 95, 1

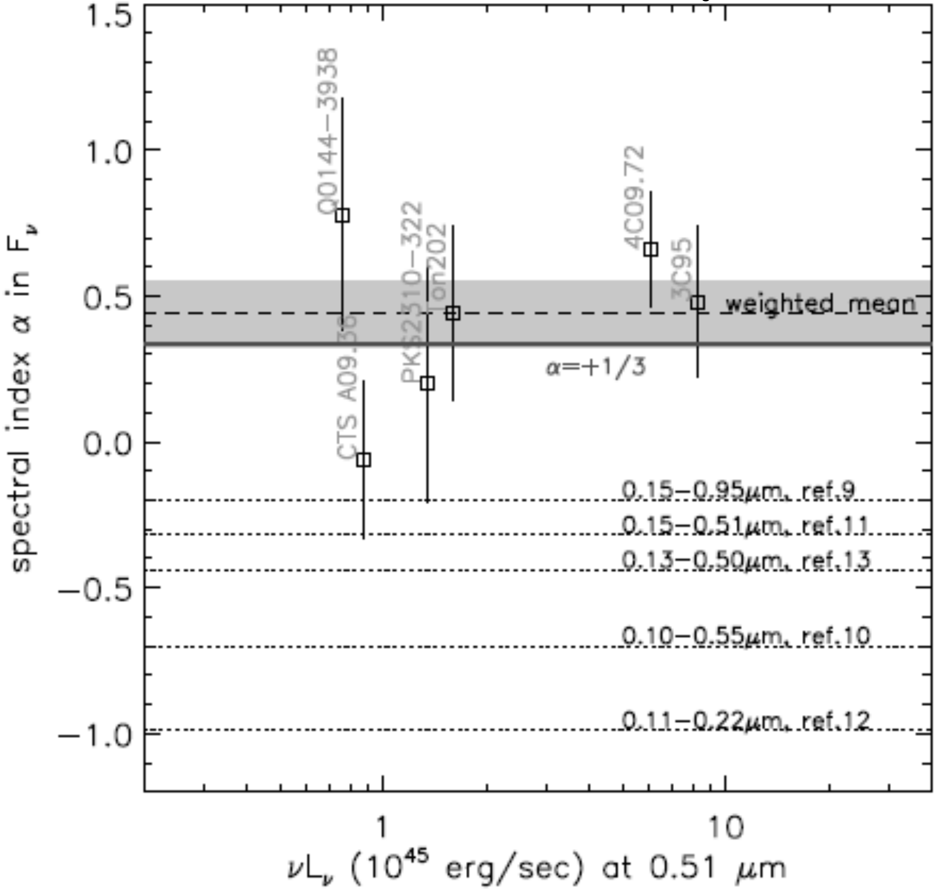


Optical/UV emission (big blue bump) → multi color emission from the accretion disk

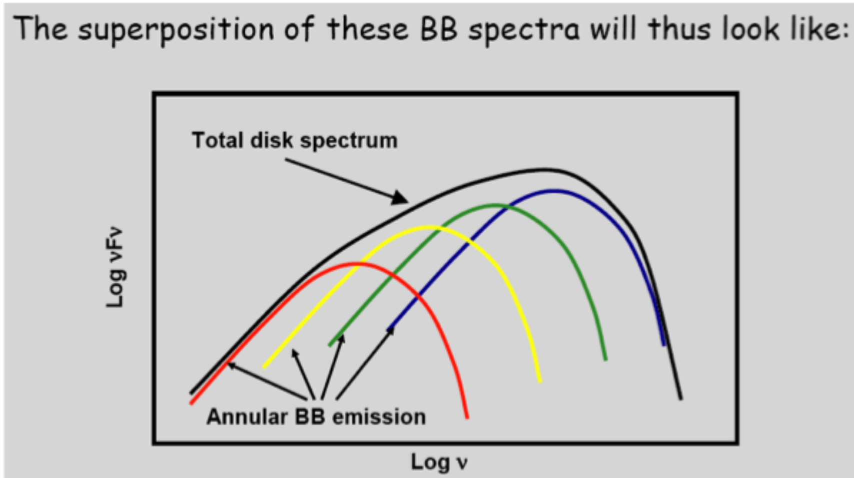
The accretion disk is spatially unresolvable!

Success

The observed optical/IR continuum slope



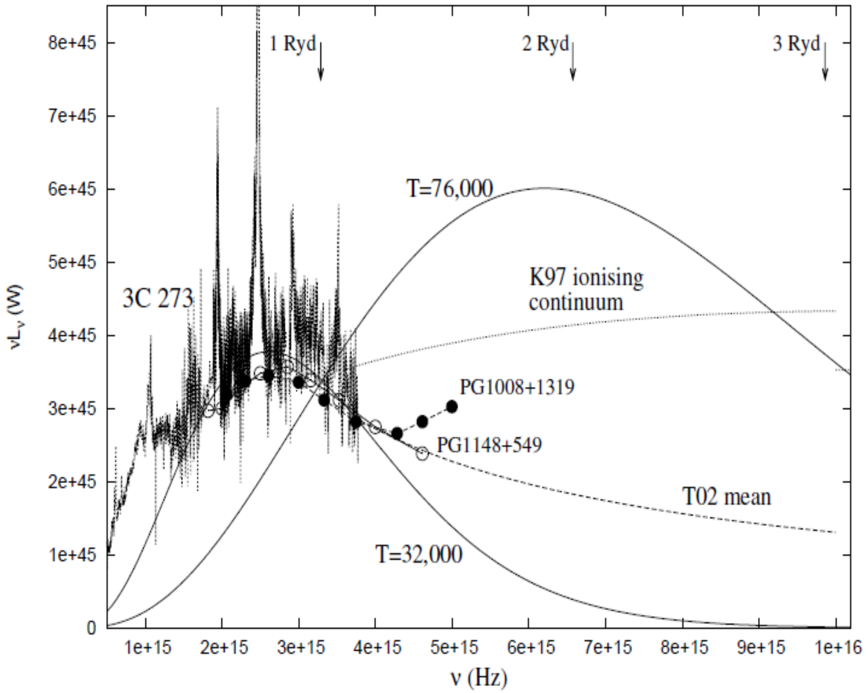
Kishimoto et al. 2008, Nature



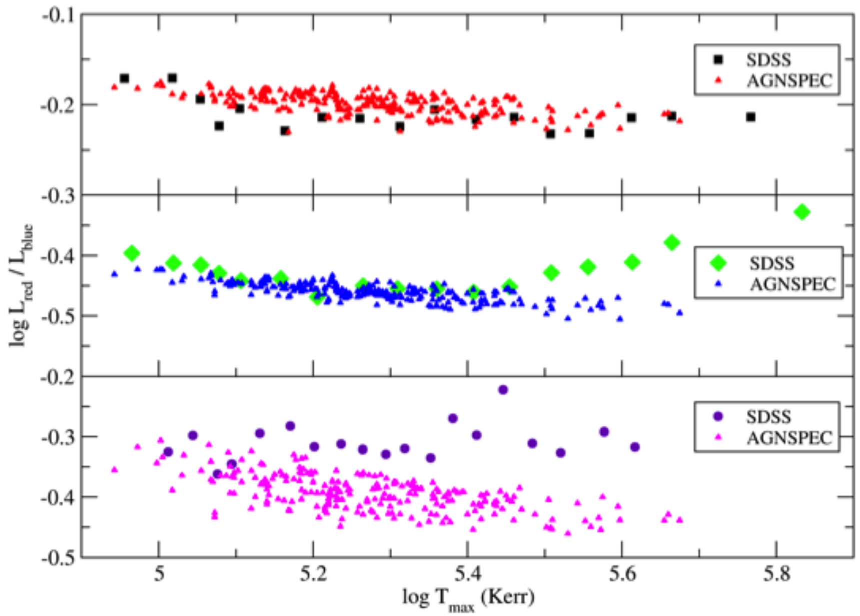
$$L_\nu \propto \nu^{1/3}$$

(intermediate wavelengths)

Challenges to Accretion Disk Theory

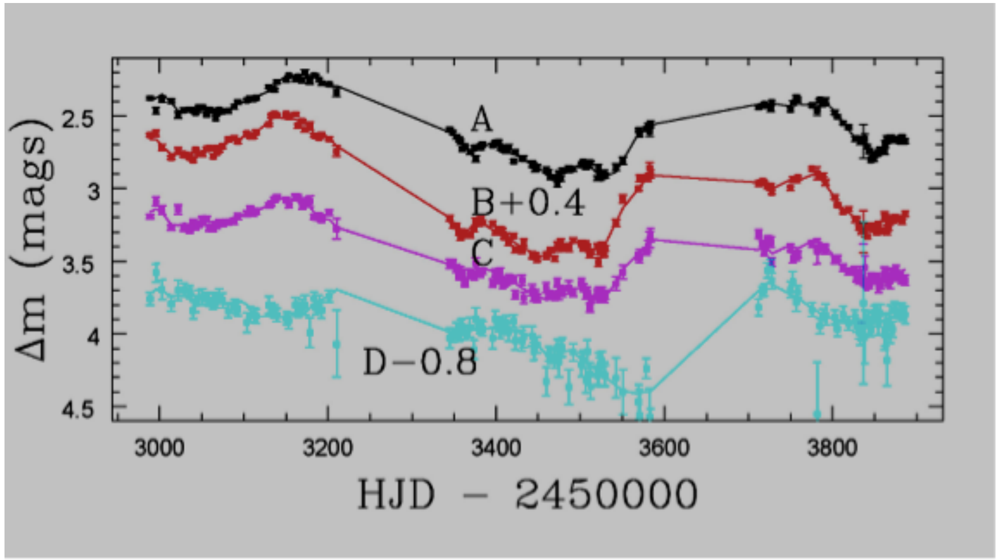


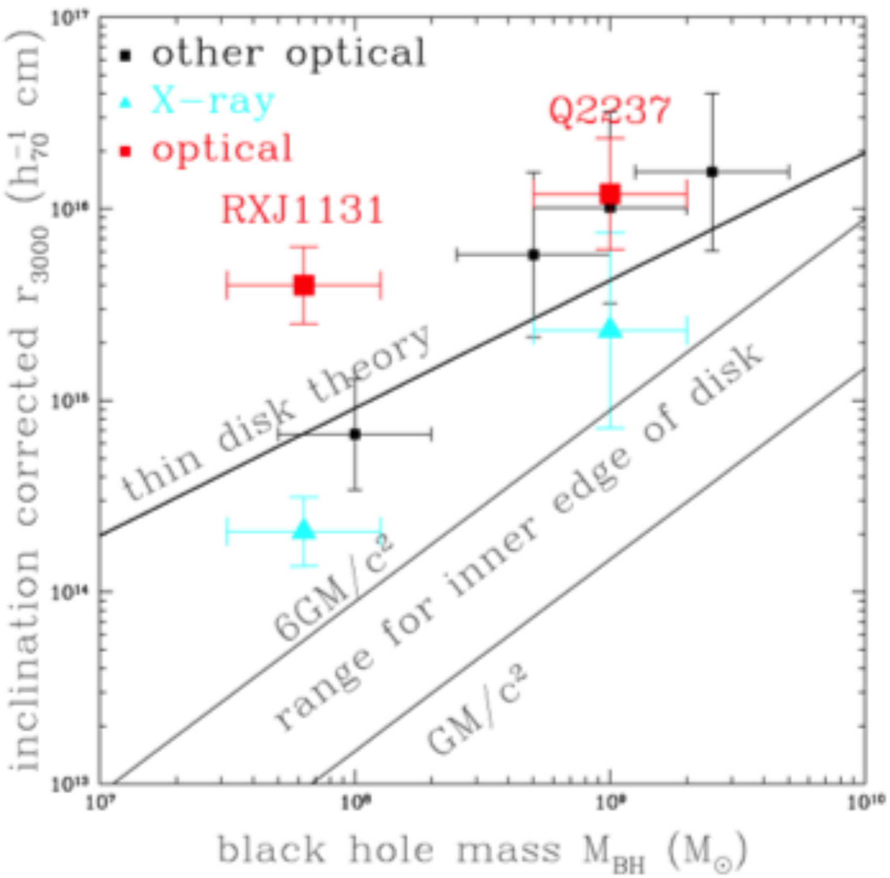
Accretion disks appear too cool comparing with models
e.g. Lawrence 2011
Dust?
Outflow alters the SED? Slone & Netzer (2012)



The color of quasars are expected to rely on black hole mass and accretion rate, but observations did not show the trend, e.g. Bonning et al. 2007

Challenge to Accretion Disk Theory: Accretion disk size in quasars measured through micro-lensing observations





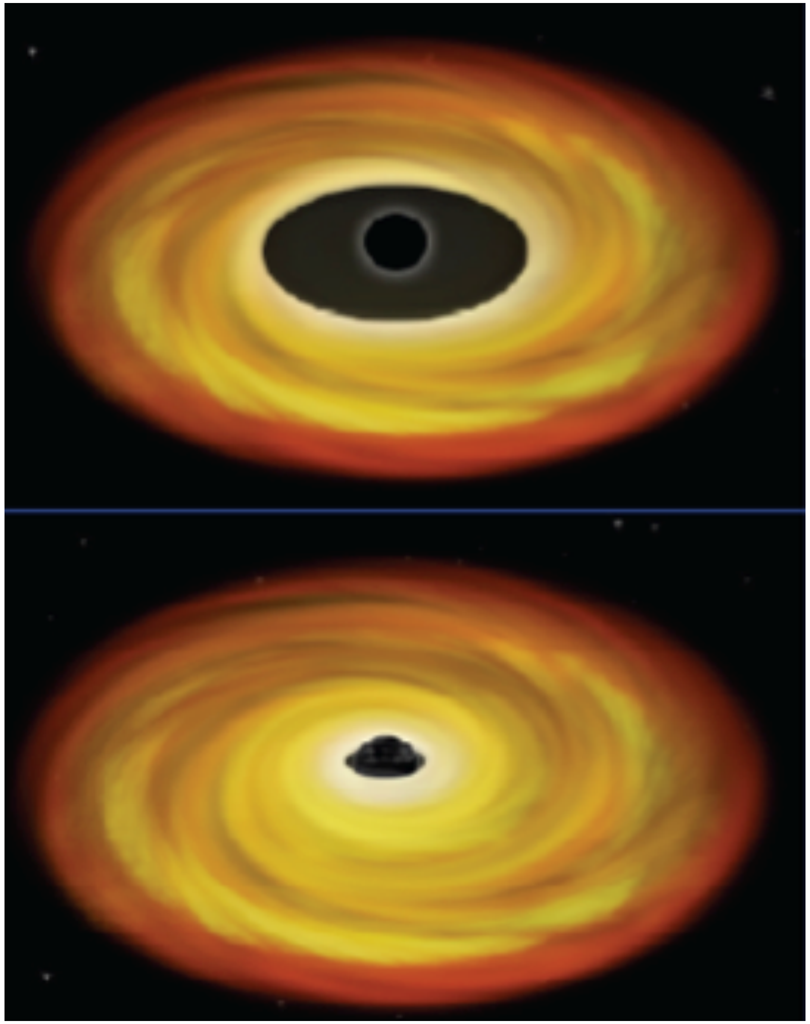
Larger by a factor of ~ 4 comparing with theory

e.g. Dai et al. 2010, Morgan et al. 2010

Also see Xinyu Dai's talk

Comparing with stellar mass black hole

Thin disk model works nicely for stellar mass black holes. People can measure BH spin (e.g. Zhang et al. 1997)



For SMBHs? (not yet, but see Capellupo‘s talk)

Variations Might be useful clues

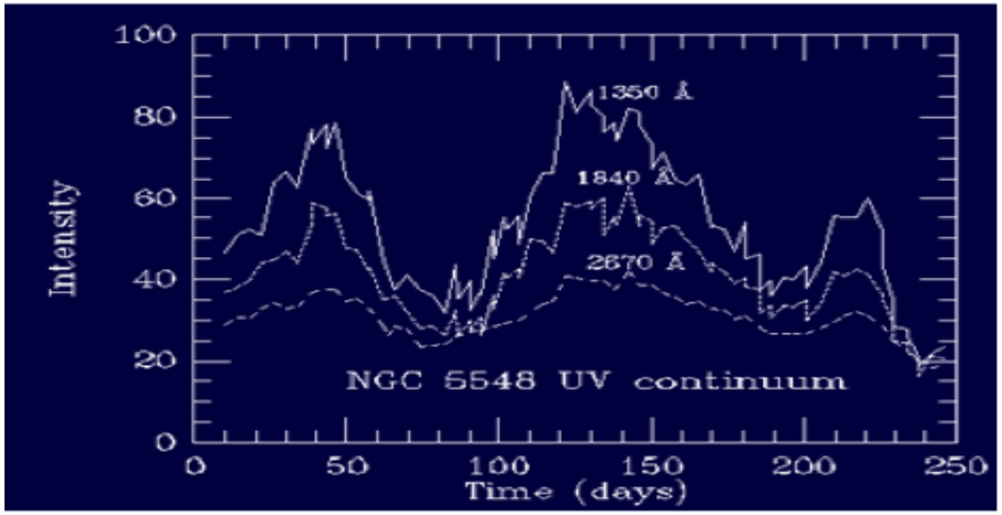
Quasar Variations in optical/UV: fluctuations in AD emission;

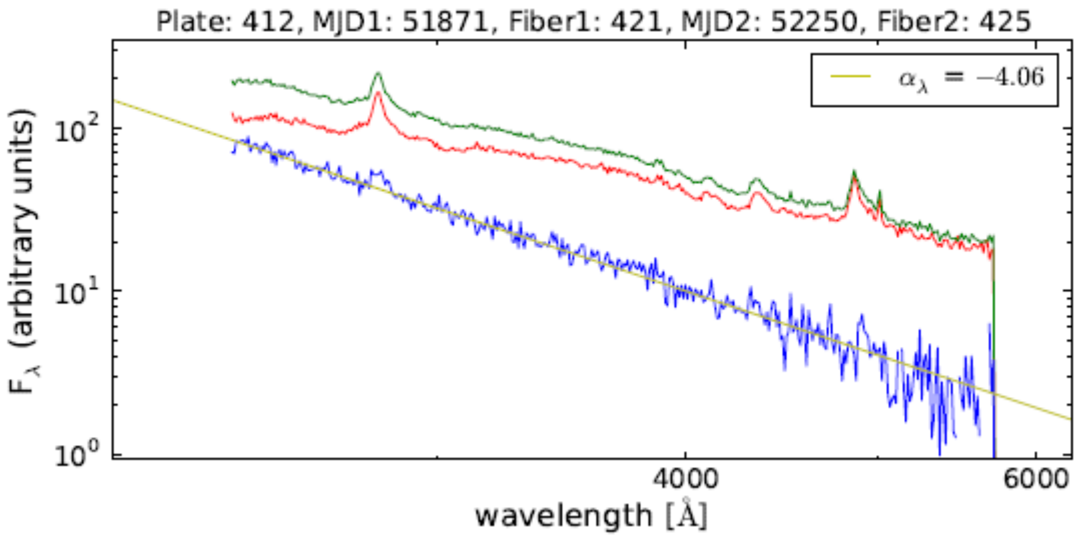
The High/Soft states of X-ray binaries are quite stable at corresponding timescales

Unknown accretion disk physics?
The origin of the variation?

Optical/UV Variations ~ days to years. Important to reverberation mapping studies, and AGN selections.

Color variability: Bluer when Brighter





Simultaneous variations in different bands +

Stronger variation at shorter wavelength

→bluer when brighter

Directly seen in multi-epoch spectra and imaging, e.g. Ruan et al. 2014

See also Giveon et al. 1999; Wilhite et al. 2005; Sakata et al. 2011; Schmidt et al. 2012, Wamsteker et al. 1990; Webb & Malkan 2000, Li SL& Cao XW 2008, Zuo WW et al. 2012, Gu MF & Li SL 2013 , Zhang XG 2013 and more

Possible explanations to the "Bluer when Brighter" pattern

- Contamination from the host galaxy/other none variable redder component

Hawkins 2003, Paltani & Walter 1996, Choloniewski 1981; Winkler et al. 1992; Winkler 1997; Pozo Nu˜nez et al. 2013; Woo et al. 2007; Walsh et al. 2009; Sakata et al. 2010, 2011 and ......

- Changes in global accretion rate

Pereyra et al. 2006; Li & Cao 2008; Sakata et al. 2011; Zuo et al. 2012; Gu & Li 2013, and ......

- Disk instability/thermal fluctuation?

Ruan et al. 2014

Contaminations from host galaxy?

- Radiation from the host galaxy is much redder
- Quasar emission is intrinsically bluer
- Variable bluer emission (with unchanged color) plus constant redder emission → bluer when brighter
- If yes,
- →variation emission = quasar intrinsic emission
- →constant emission = host galaxy
- Such technique has been explored since 1981
- Contrary observational results

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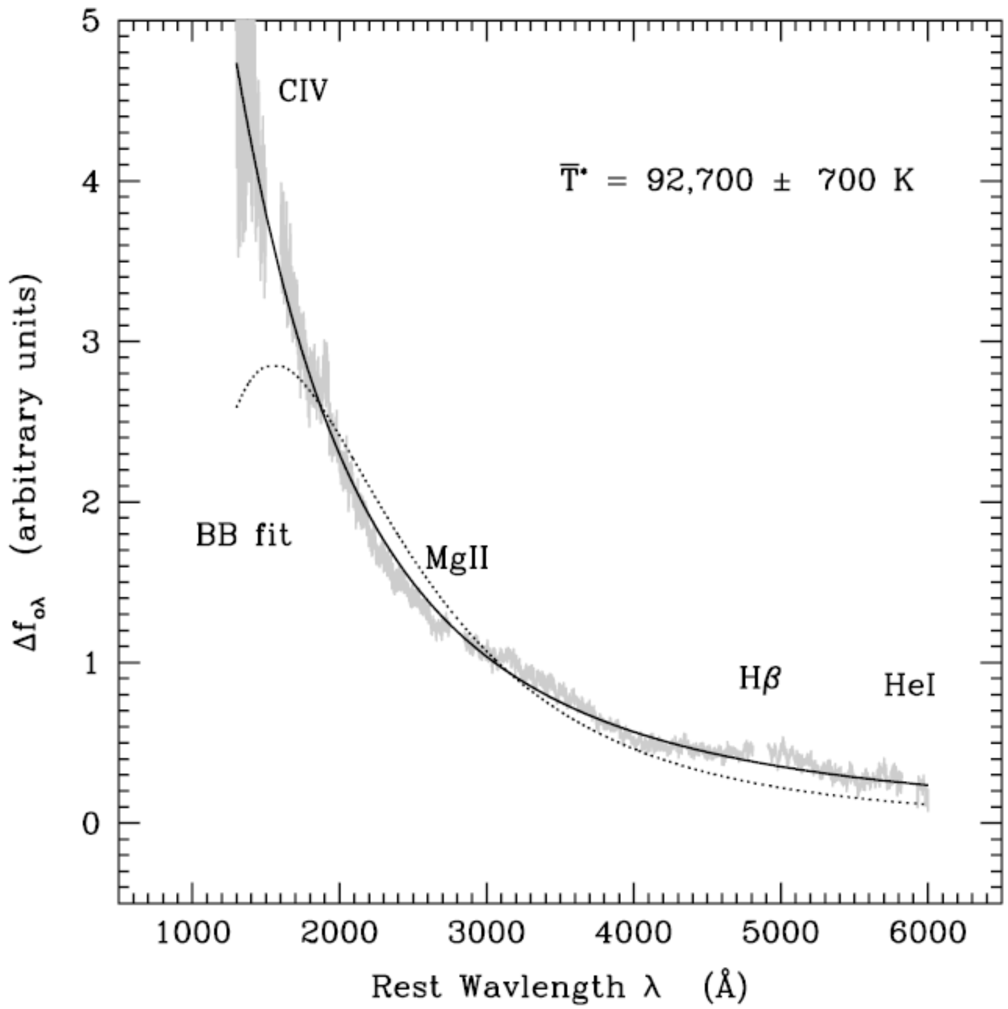
Changes in global accretion rate?

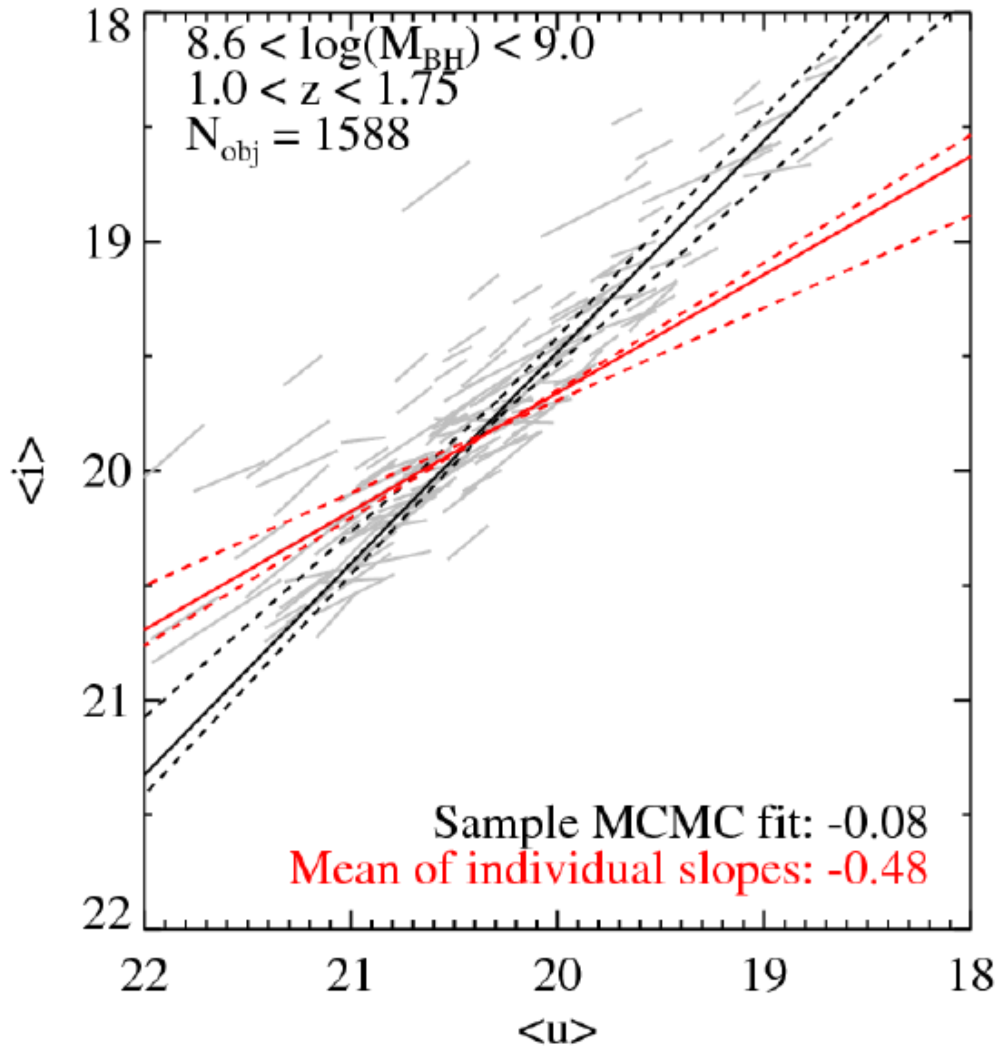


- **Pereyra et al. 2006 found that the co-added quasar variation spectra is fully consistent with standard accretion disk model (changes in accretion rate)**
- **Also by many other studies**
- **Higher accretion rate → stronger emission, higher disk temperature → "bluer when brighter"**
- **However, timescale issue?**

Changes in accretion rate?

Schmidt et al. 2011 :

color variations in individual quasars are more pronounced than the color difference seen in quasars with same black hole mass but different accretion rate.



Also see Kokubo's poster

Possible explanations to the "Bluer when Brighter" pattern

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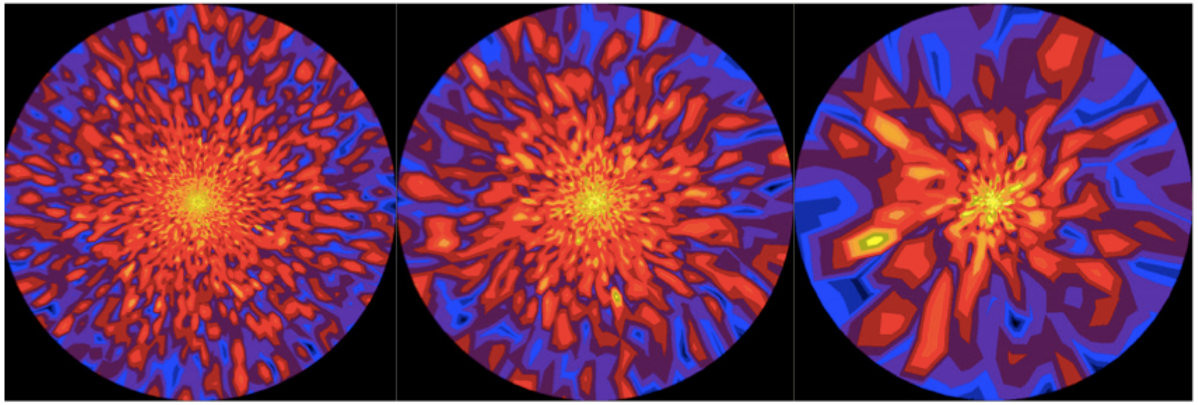
Pereyra et al. 2006; Li & Cao 2008; Sakata et al. 2011; Zuo et al. 2012; Gu & Li 2013, and ......

- Disk instability/thermal fluctuation?

Ruan et al. 2014

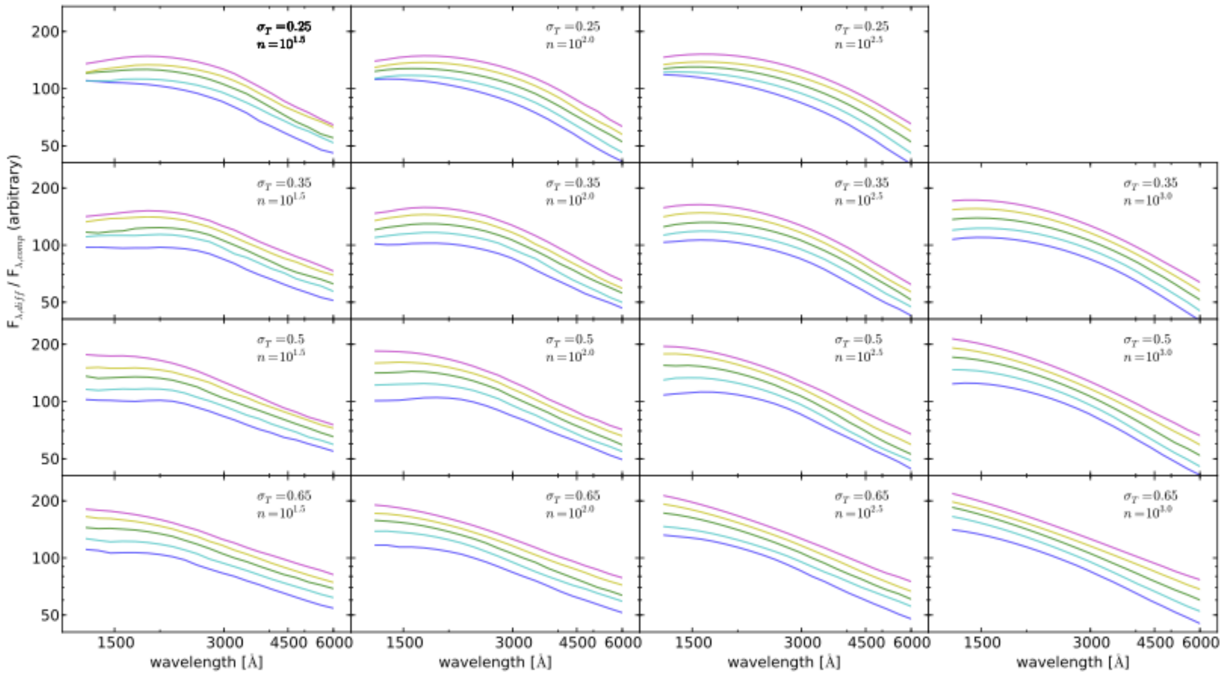
Disk thermal fluctuation → A toy model



Disk local T fluctuated randomly (Dexter & Agol 2011), may explain larger disk size measured with micro lensing observations

Ruan et al. 2014:

Such toy model can produce the "bluer when brighter" pattern



Further clues from observations?

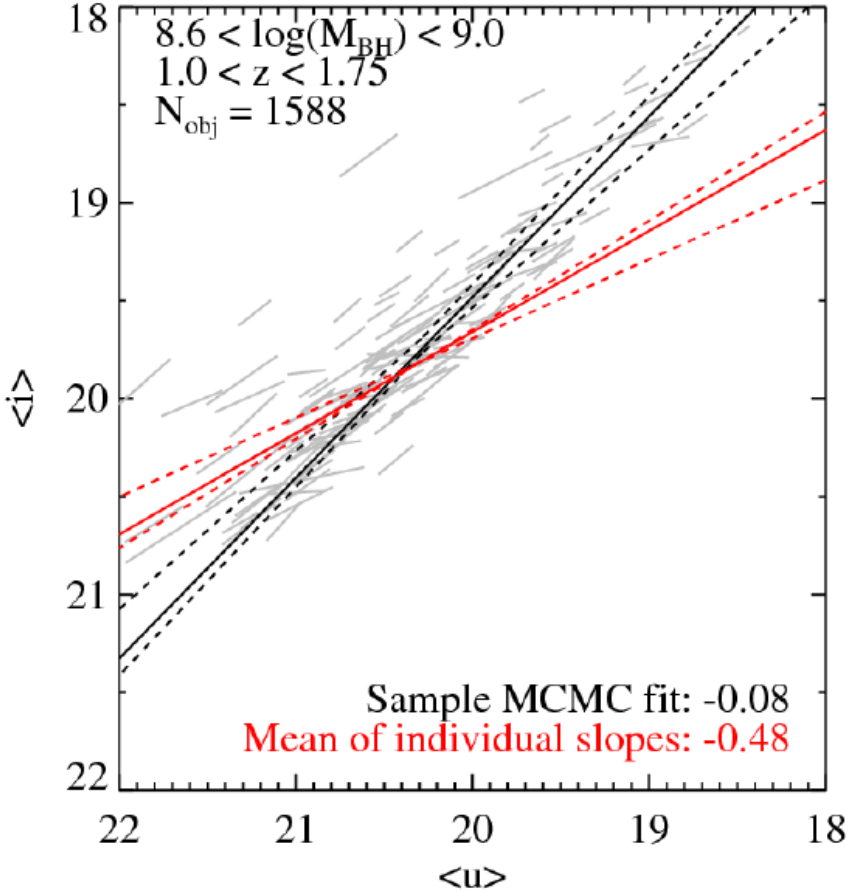
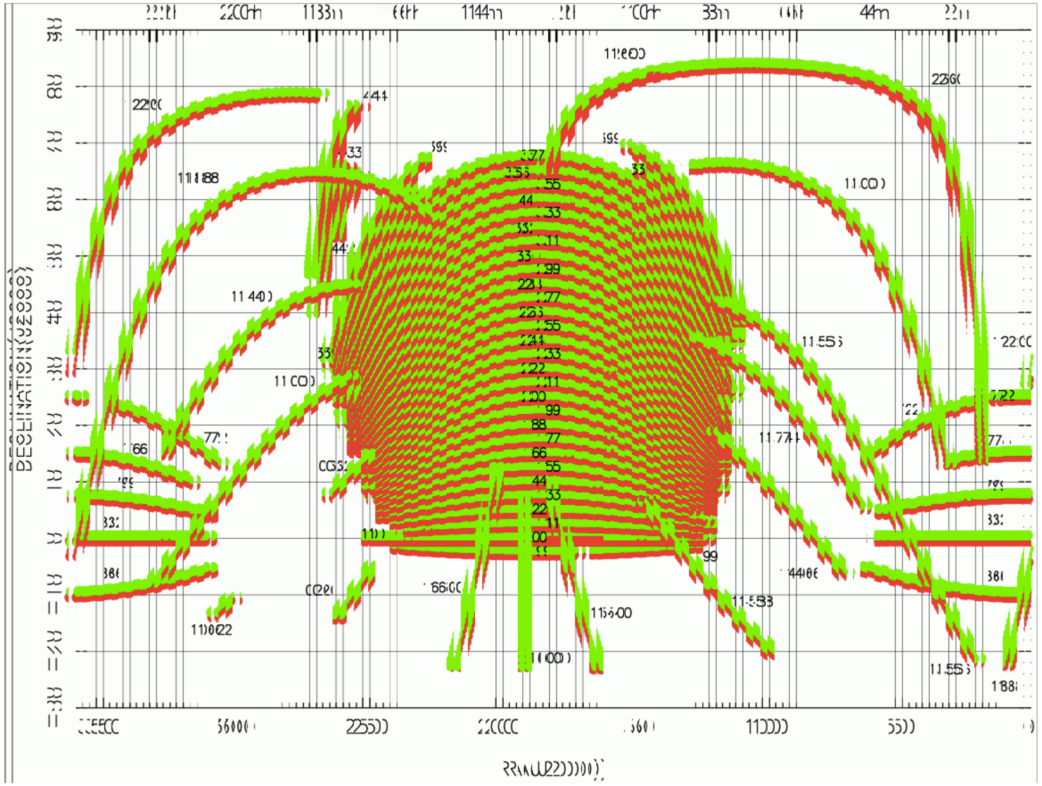
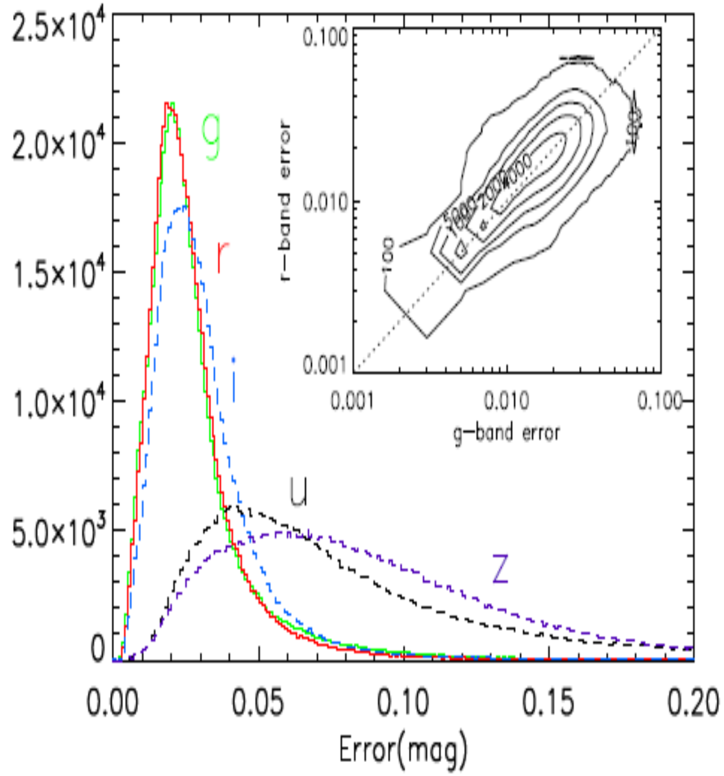


Figure from Schmidt et al. 2012

Variation in individual quasars → short term
Variation between different quasars → effectively long term
Color variation → timescale dependent?

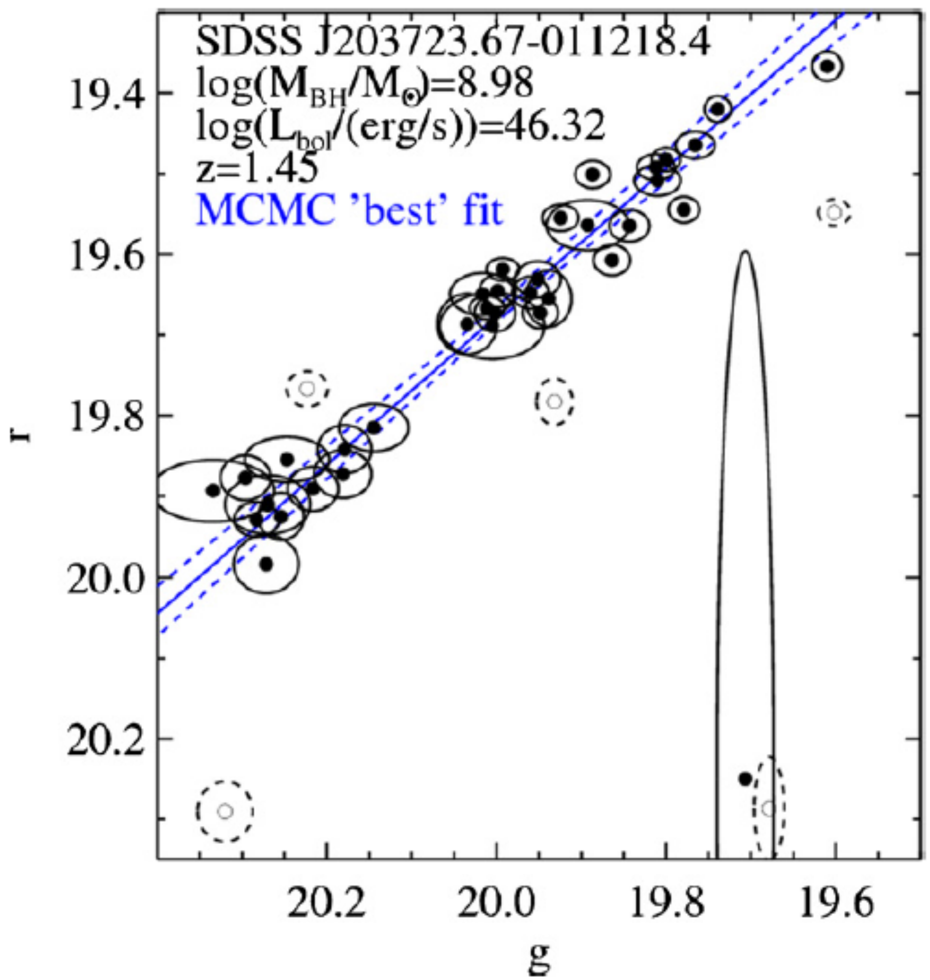
SDSS Stripe 82



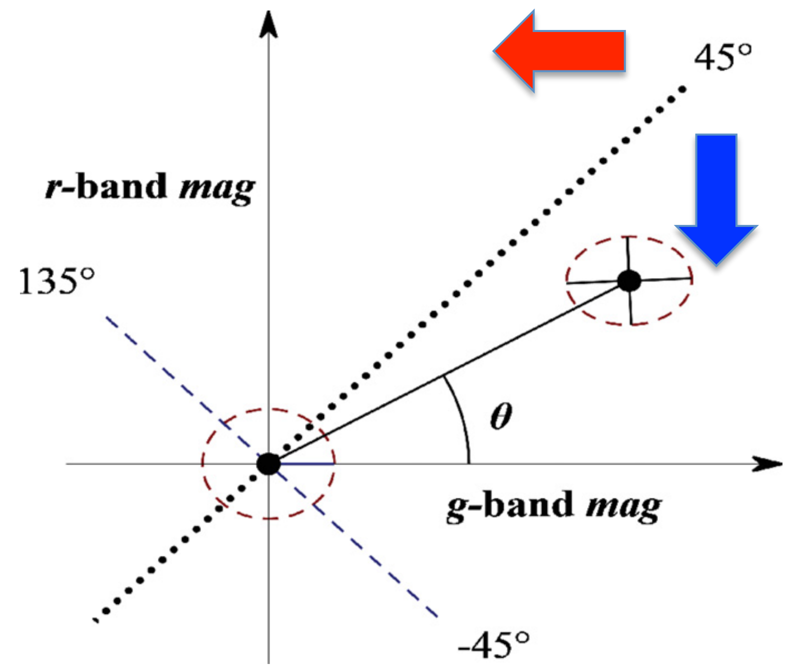


~ 10 years long, ~60 epochs, photometric light curves of around 9000 quasars
We focus on g & r band which have best photometry

Quantifying the color variability



Schmidt et al. 2012



$$\theta(\tau) = \arctan\left(\frac{m_r(t+\tau) - m_r(t)}{m_g(t+\tau) - m_g(t)}\right)$$

$$\bar{\theta}(\tau) = \frac{\sum_i^N \theta_i(\tau)}{N}$$

Sun et al. 2014 ApJ

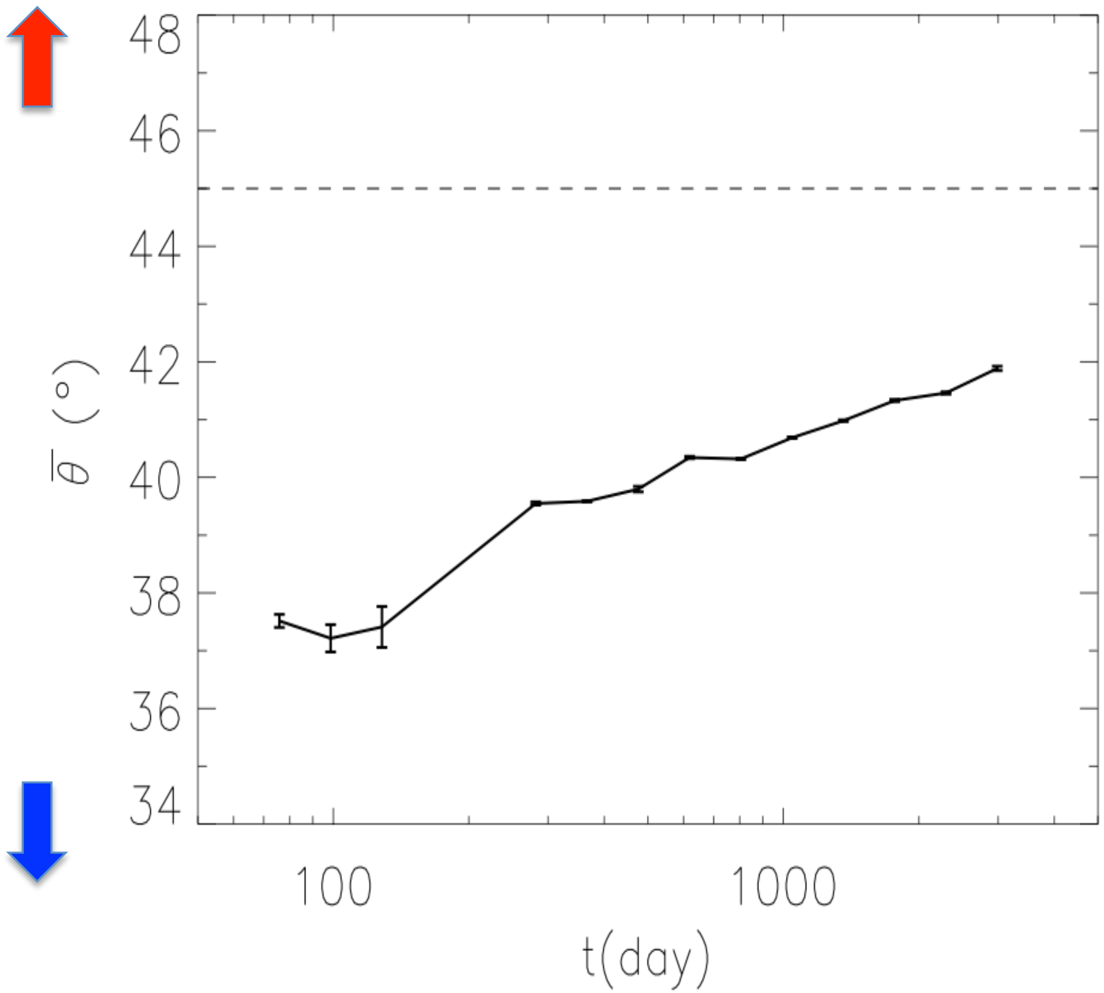
Discovery of Timescale dependent color variability

The amplitude of the color variation θ is timescale dependent.

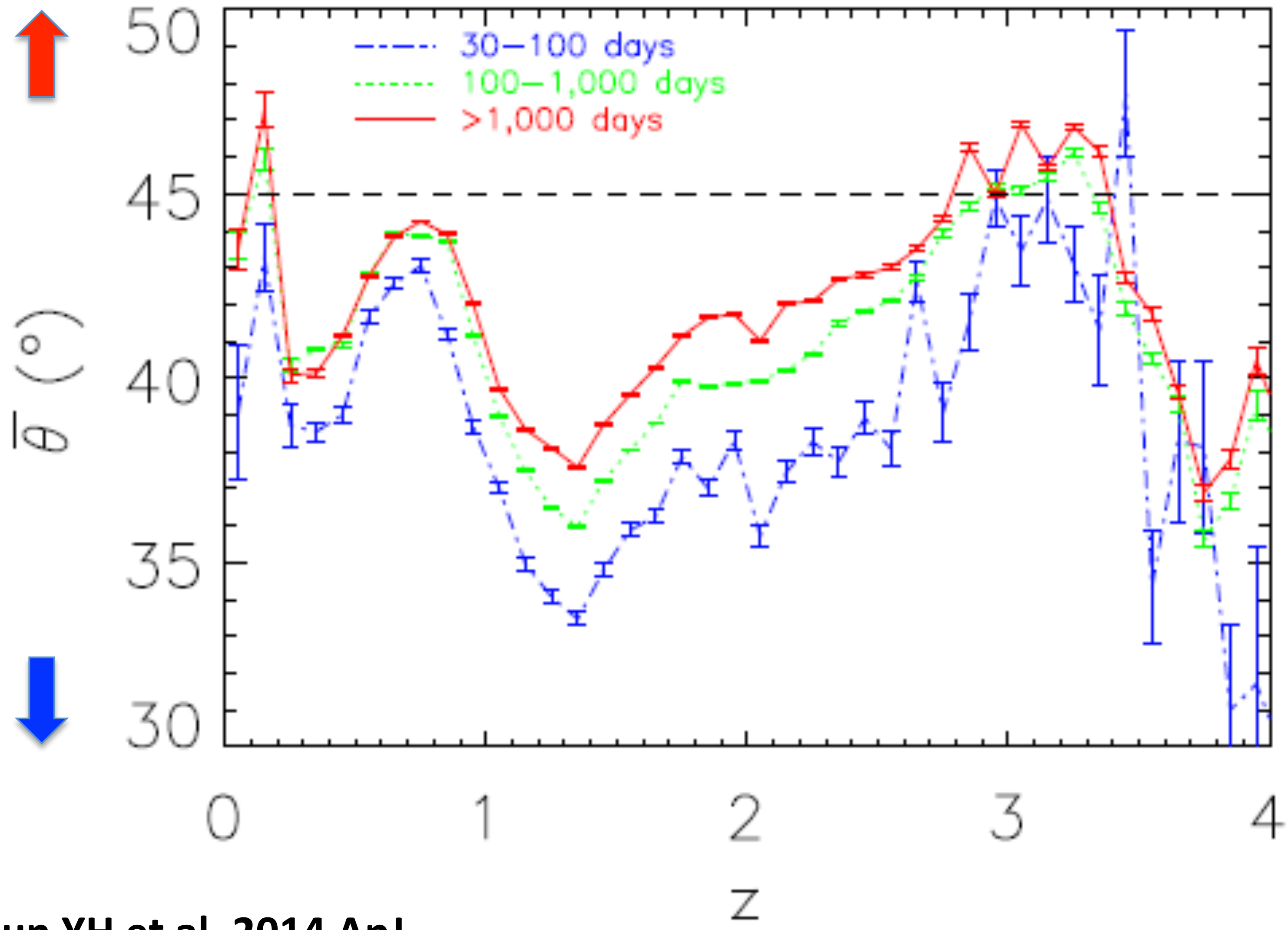
The shorter timescale, the bluer the variation is.

At timescale < 50 days, photometric accuracy is not good enough to measure the color variation

Sun YH et al. 2014 ApJ

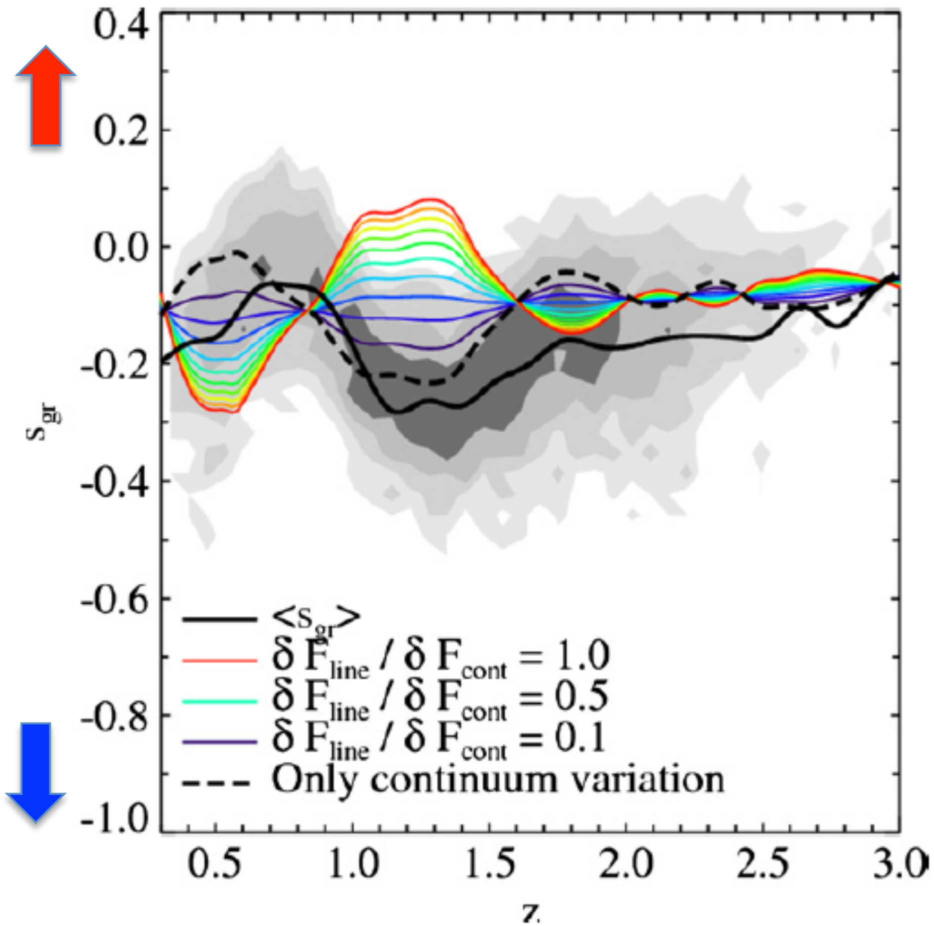


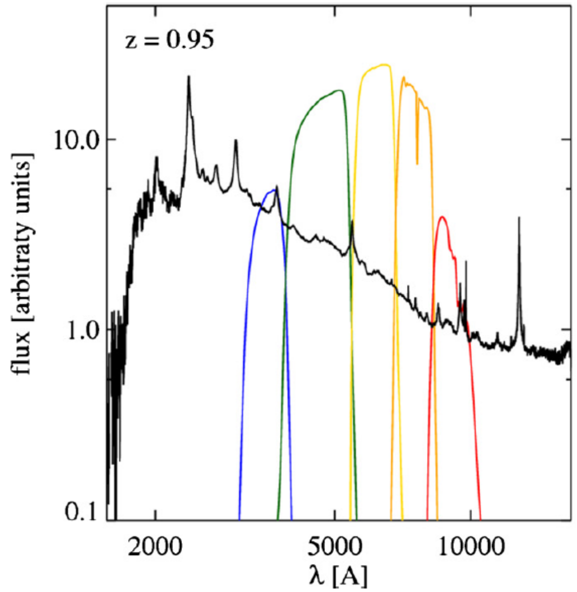
Discovery of Timescale dependent color variability



Sun YH et al. 2014 ApJ

Color variability amplitude versus z

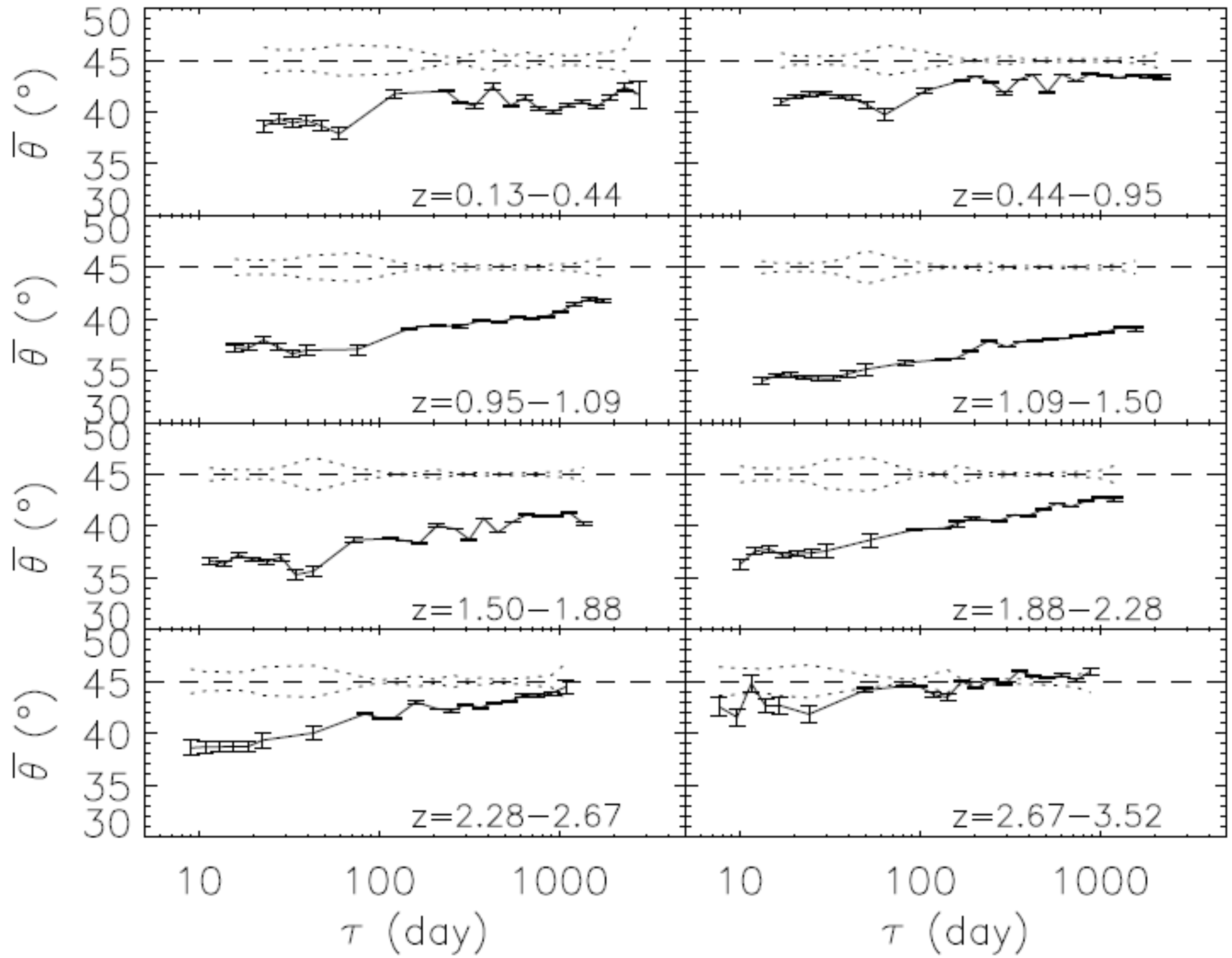




Contaminations from emission lines which do not vary rapidly well explains the redshift dependency of the color variability amplitude

Schmidt et al. 2012

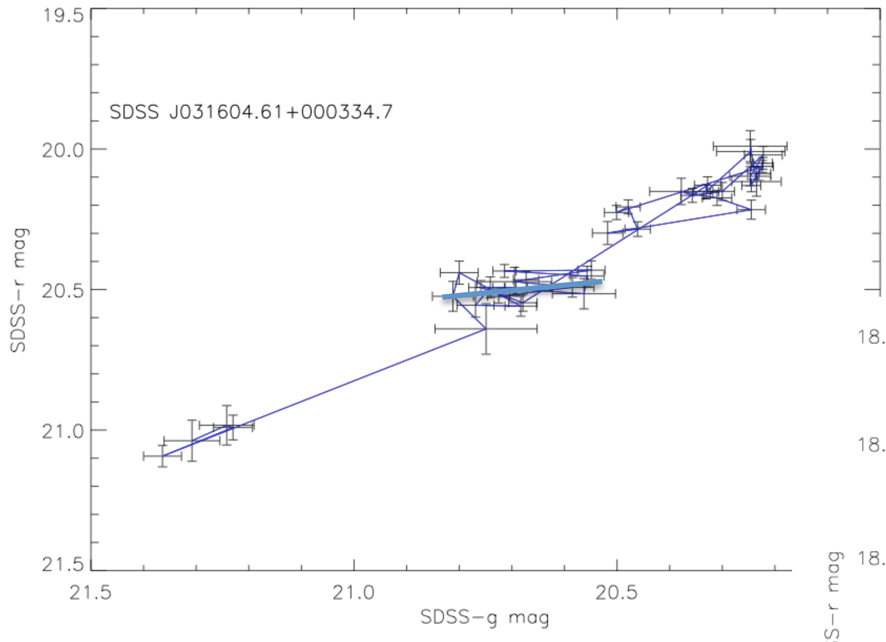
Consistently Seen In different redshift bins

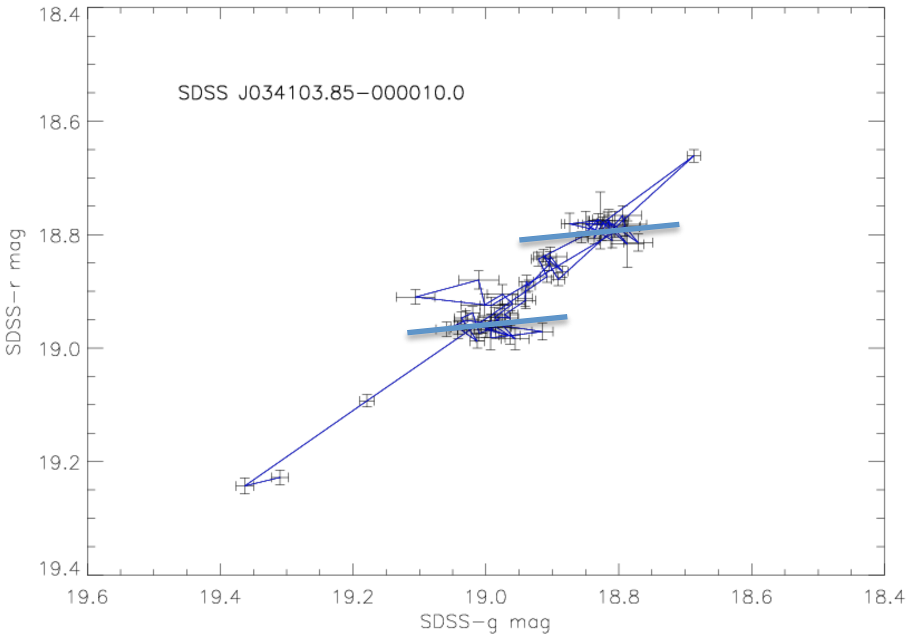


Not due to emission lines which do not respond to rapid variations!

Sun YH et al. 2014 ApJ

In Individual Sources





Interesting consequences

- Contamination from the host galaxy/ other none variable redder component — No
- Changes in global accretion rate — No
- Disk instability/thermal fluctuation — ?

Simulating disk temperature fluctuation

Damped random walk (DRW): τ & σ

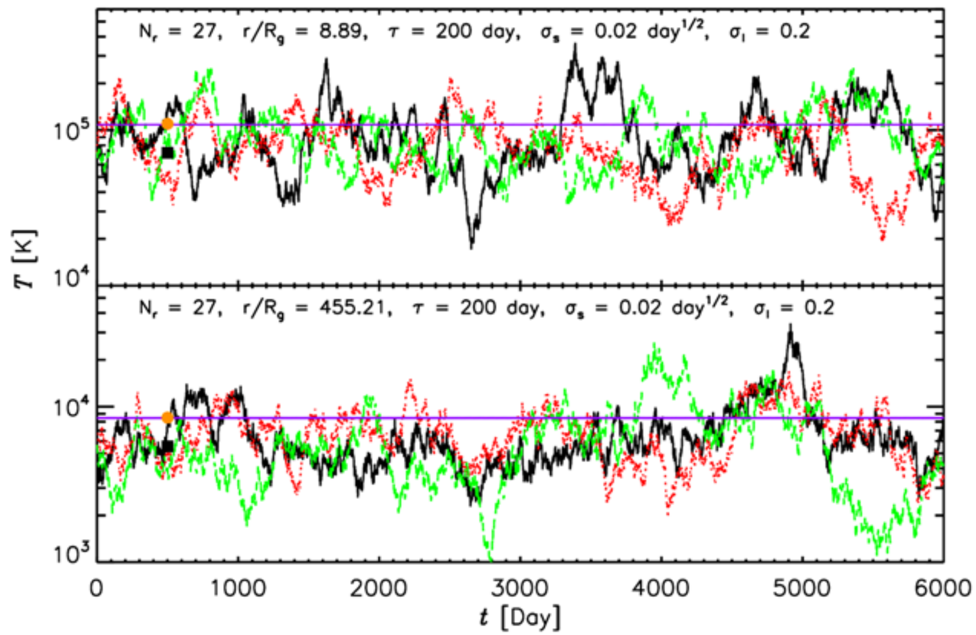
$$t = s + \Delta t$$

$$E[\log T(t)] = \log T_{\rm mid} + e^{-\Delta t/\tau}[\log T(s) - \log T_{\rm mid}]$$

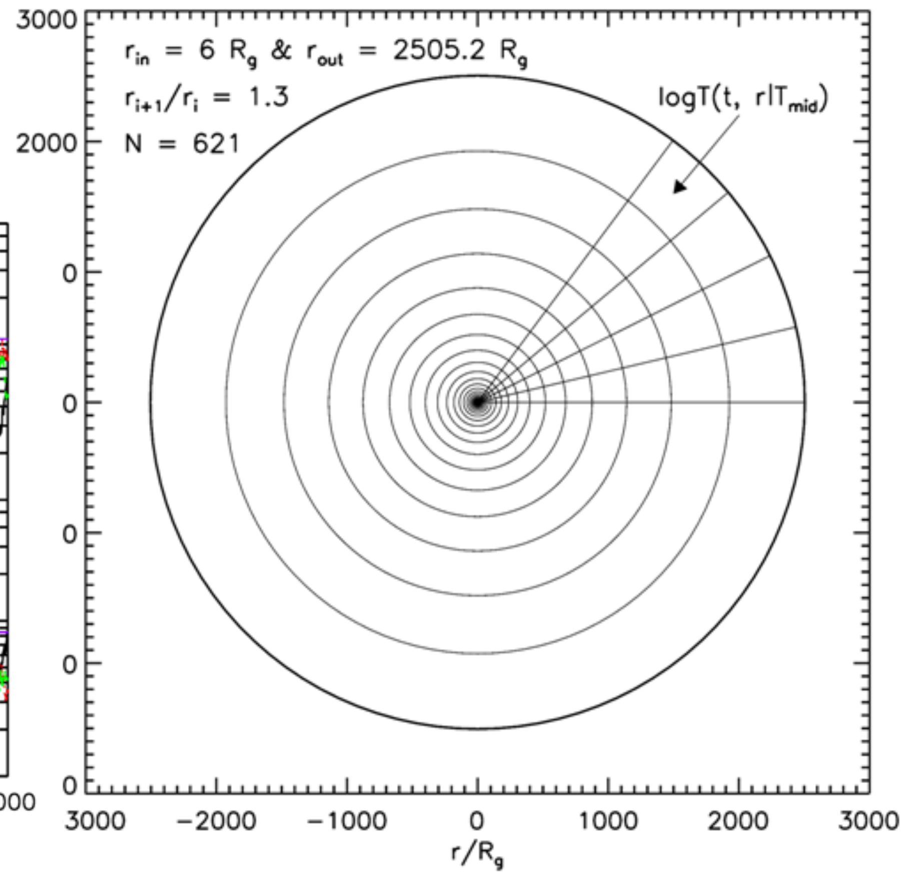
$$\mathrm{Var}[\log T(t)] = \frac{\tau\sigma_s^2}{2}(1 - e^{-2\Delta t/\tau})$$

$$\log T_{\rm mid} = \log T_{\rm sd} - \tau\sigma_s^2 \ln 10$$

Realizations of temperature fluctuation

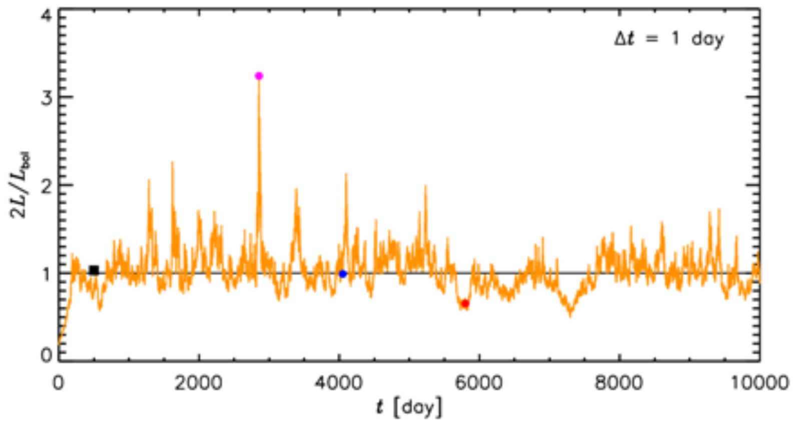


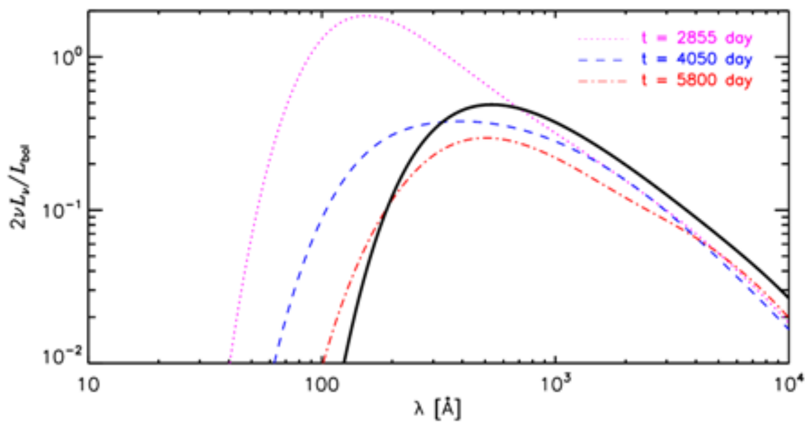
Splitting accretion disk, see Dexter & Agol 2011



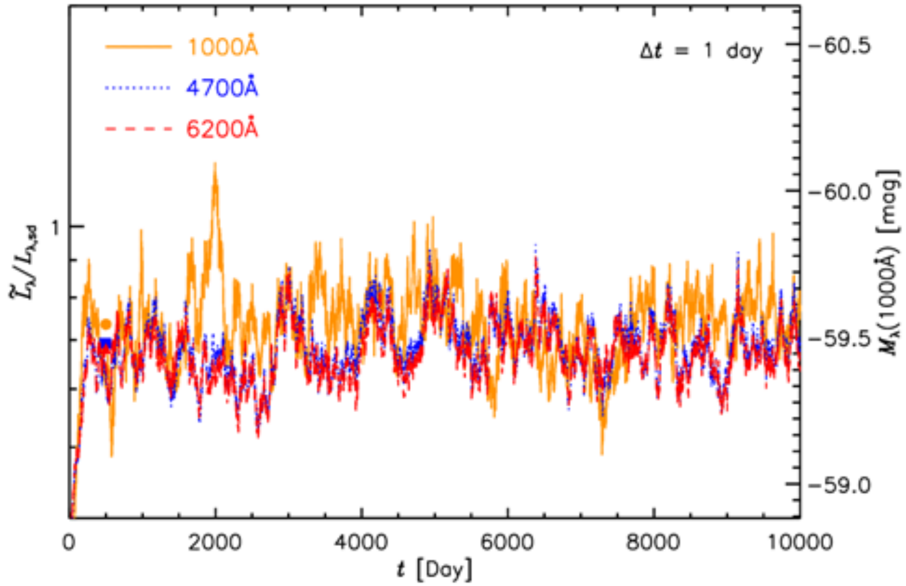
Simulated UV/optical QSO variability

Bolometric luminosity fluctuation and SED





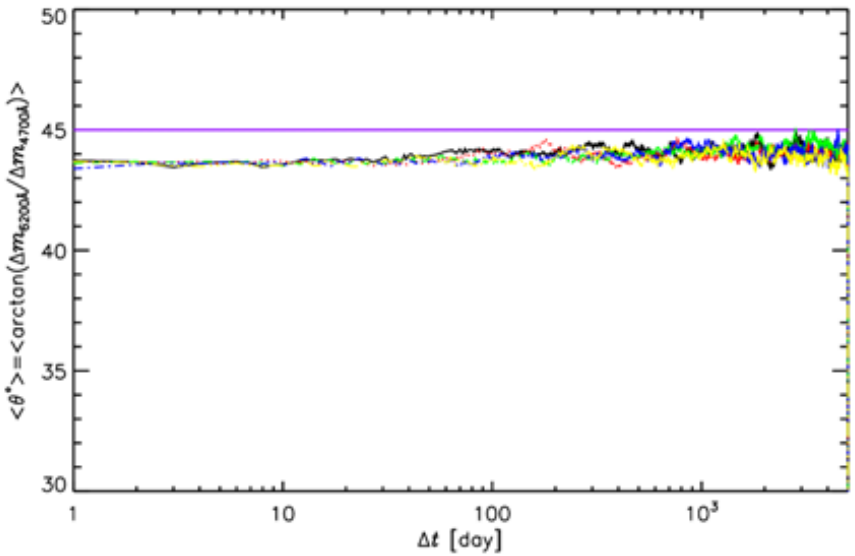
Monochromatic luminosity fluctuation

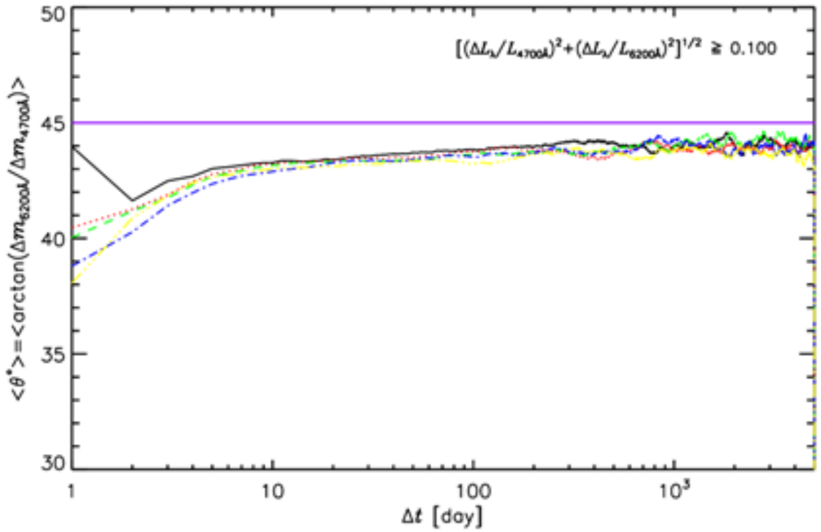


Cai ZY et al. in prep.

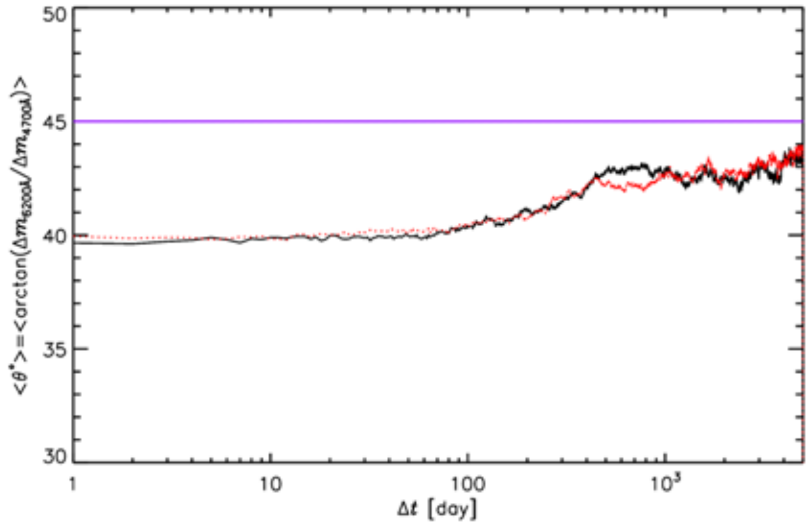
Simulated Timescale dependency of the color variability

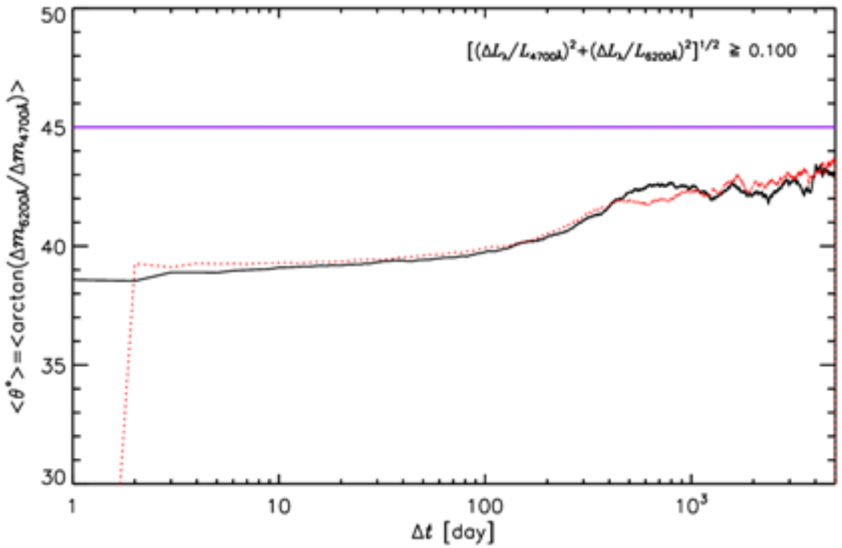
τ = const.





τ ~ r

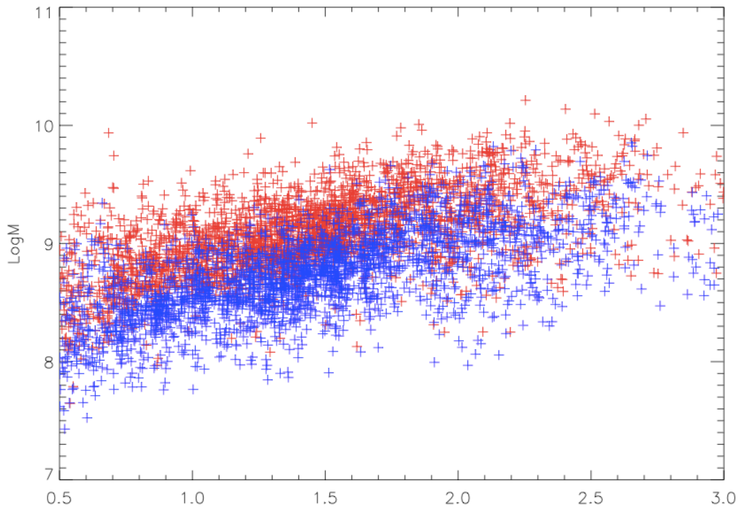


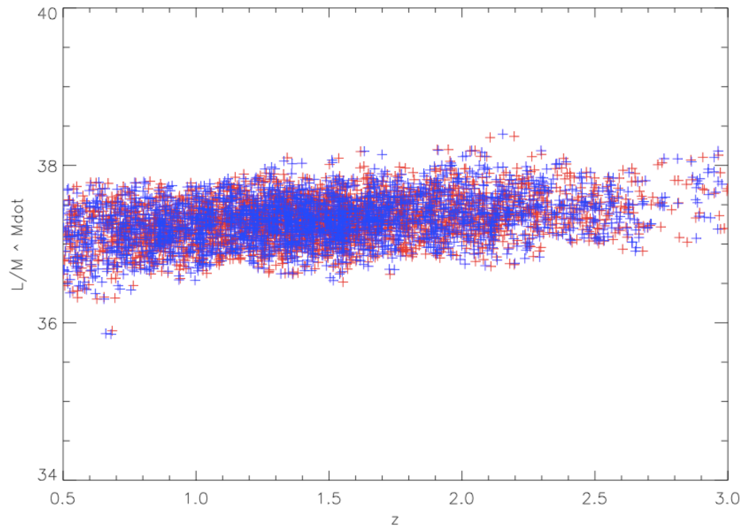


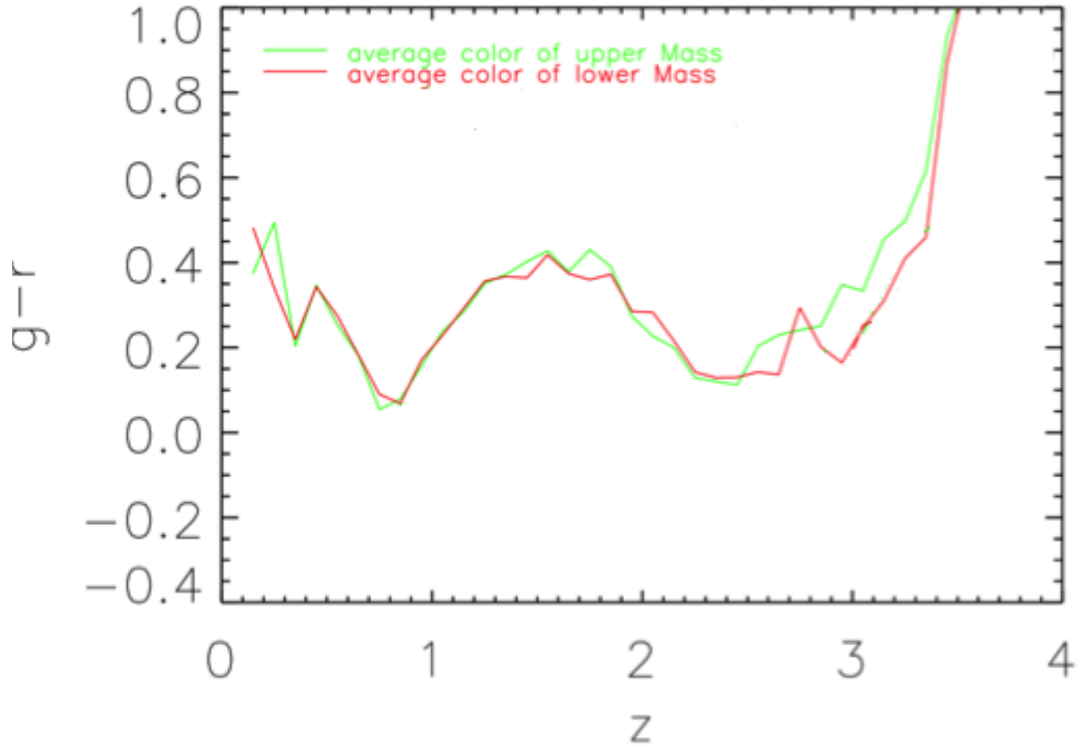
Interesting consequences

- Shorter variations from inner accretion disk
- Longer variations from larger scales
- Variation at different timescales (differential vs. integral) probes disk emission at different radii → spatially resolve the disk emission!

Test the physical parameter dependence

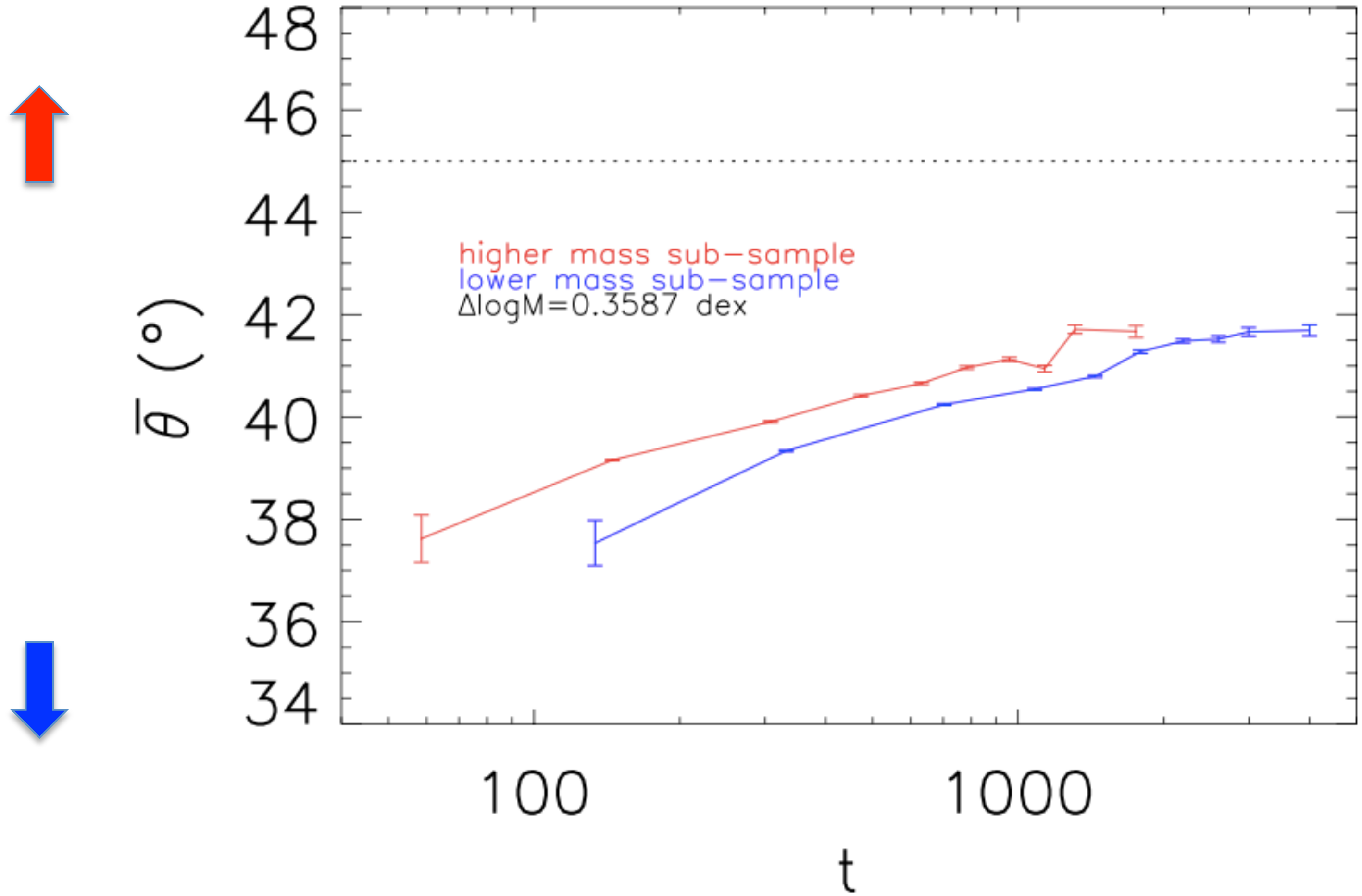






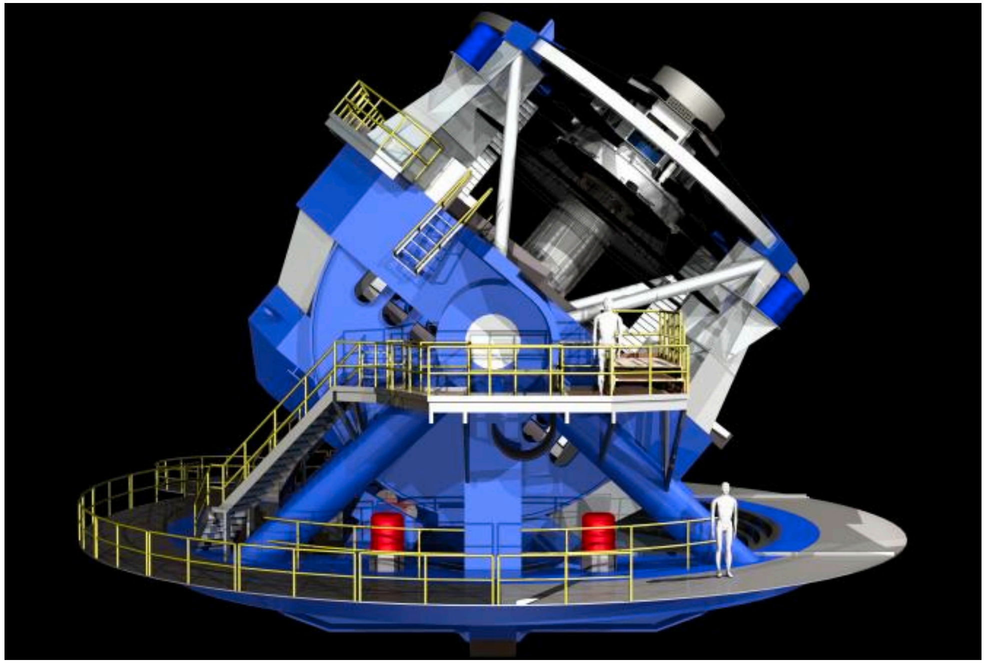
Quasars with different SMBH mass have the same colors.
Sun YH et al. in prep.

Smaller SMBHs do have hotter disks (after normalizing the timescale to mass)

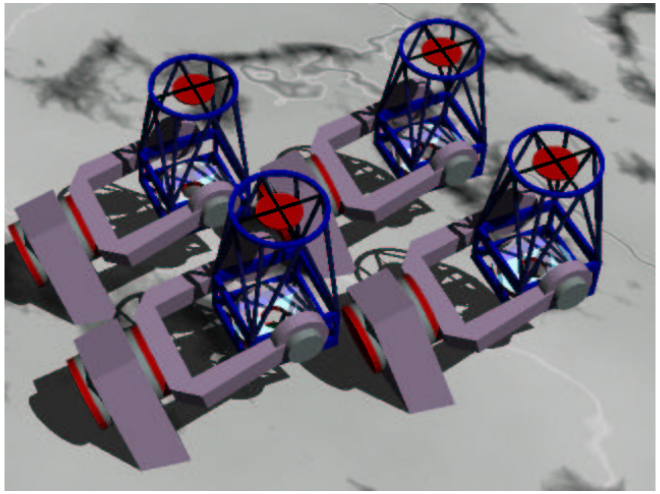


Next Step: to measure and model the SED of the variable emission at different timescales → spatially resolve the AD

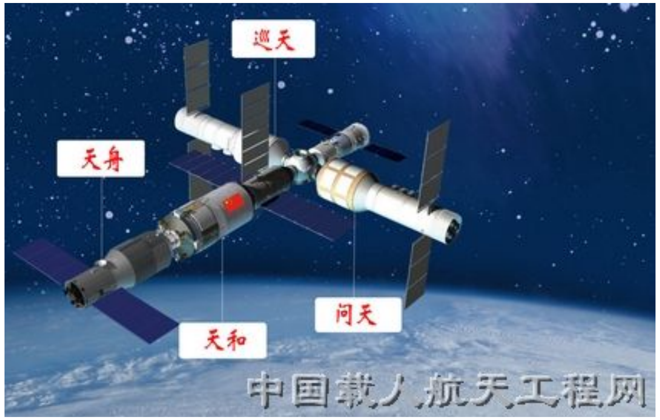
New subject in the era of time domain astronomy



LSST
6 bands, ~800 visits per quasar
Over 10 million quasars



Pan-STARRS4



Space Station Telescope

Summary

- The color variation in quasars is timescale dependent: shorter term variations are bluer
- Directly rules out two color variation models (host galaxy contamination, and changes in global accretion rate)
- Could be due to thermal fluctuations in the AD
- May use variable emission at different timescales to spatially resolve the accretion disk, thus to test the AD theory
- Shortest timescale variation probes the inner most disk emission (excluding pollution from BLR, etc)
- Smaller SMBHs do have hotter disks when comparing the color of variations at corresponding timescales (preliminary)!

Issues to be considered

- Accretion disk reprocessing
- Inter-band coherence (see Kokubo‘s poster)
- Continuum lags (instability propagation)
- Binary SMBHs
- ……

Further questions and comments?

jxw@ustc.edu.cn