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On the UV/optical variations of Active Galactic Nuclei

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OUTLINE:

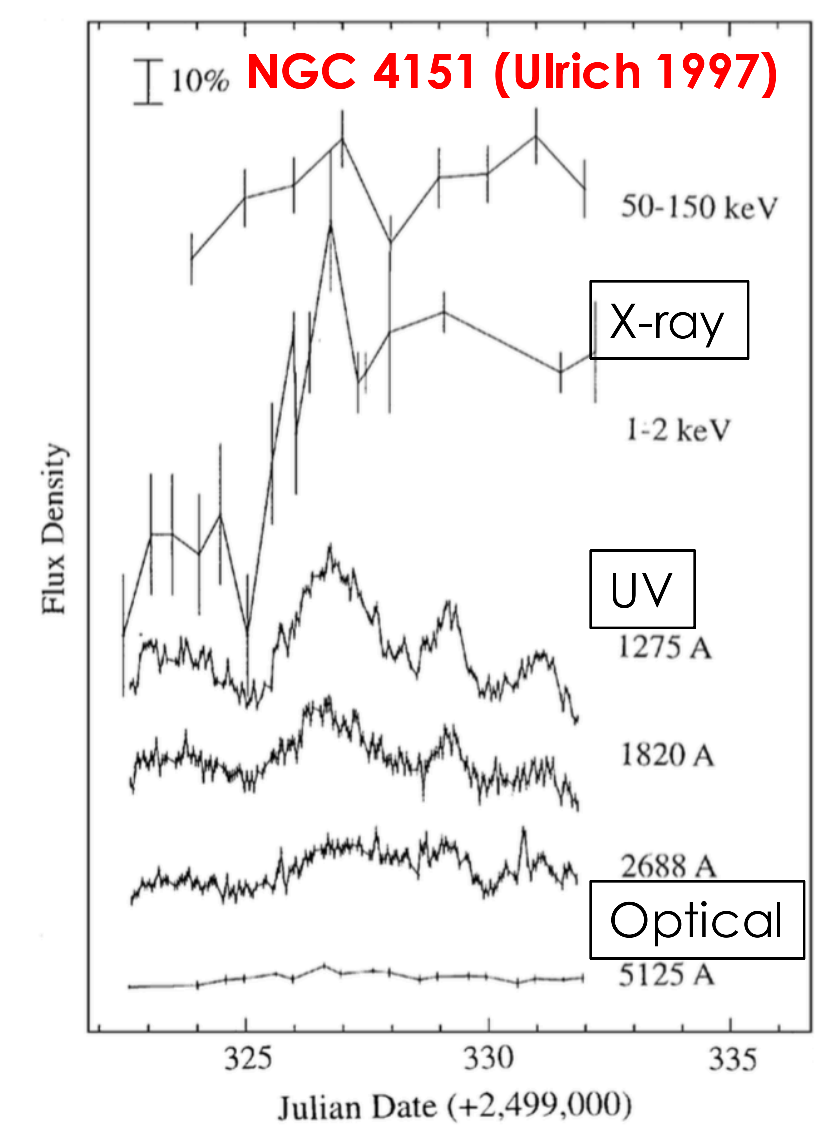
1. Introduction: variability and color variability

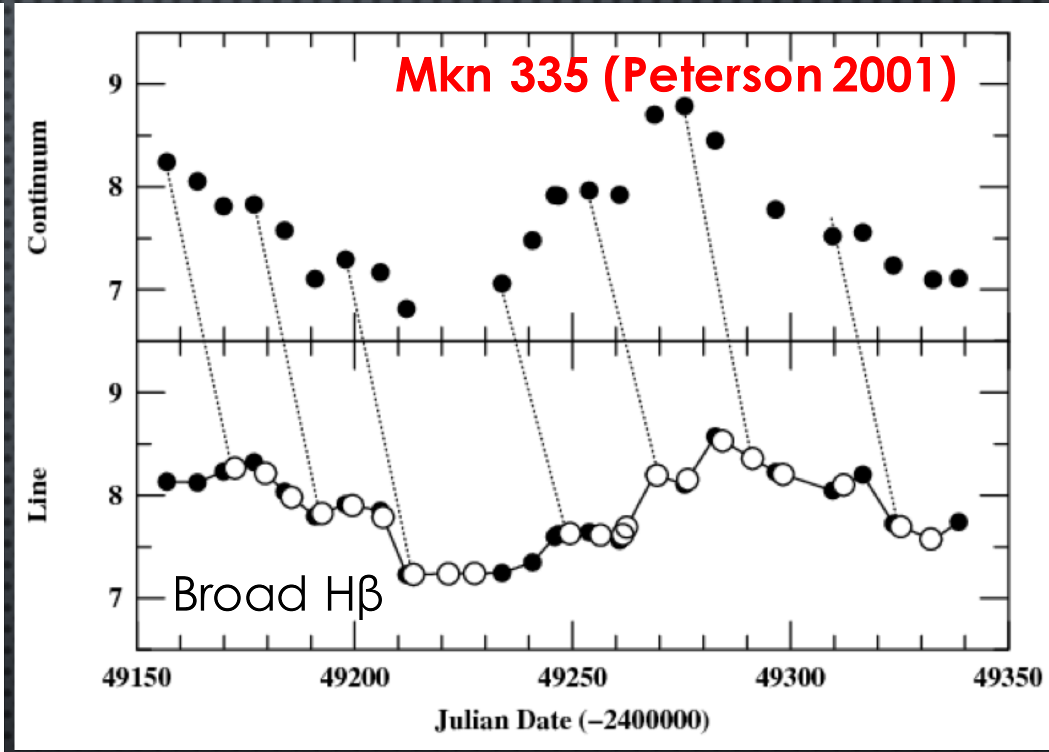
2. Timescale Dependent Color Variation
   1. The Discovery With SDSS
   2. Inhomogeneous Disk Model
   3. Confirmed With GALEX

3. The Reprocessing Model And Challenges

4. A New Challenge To The Reprocessing Diagram

1.1 VARIABILITY & STRUCTURE OF QUASARS





Variability:

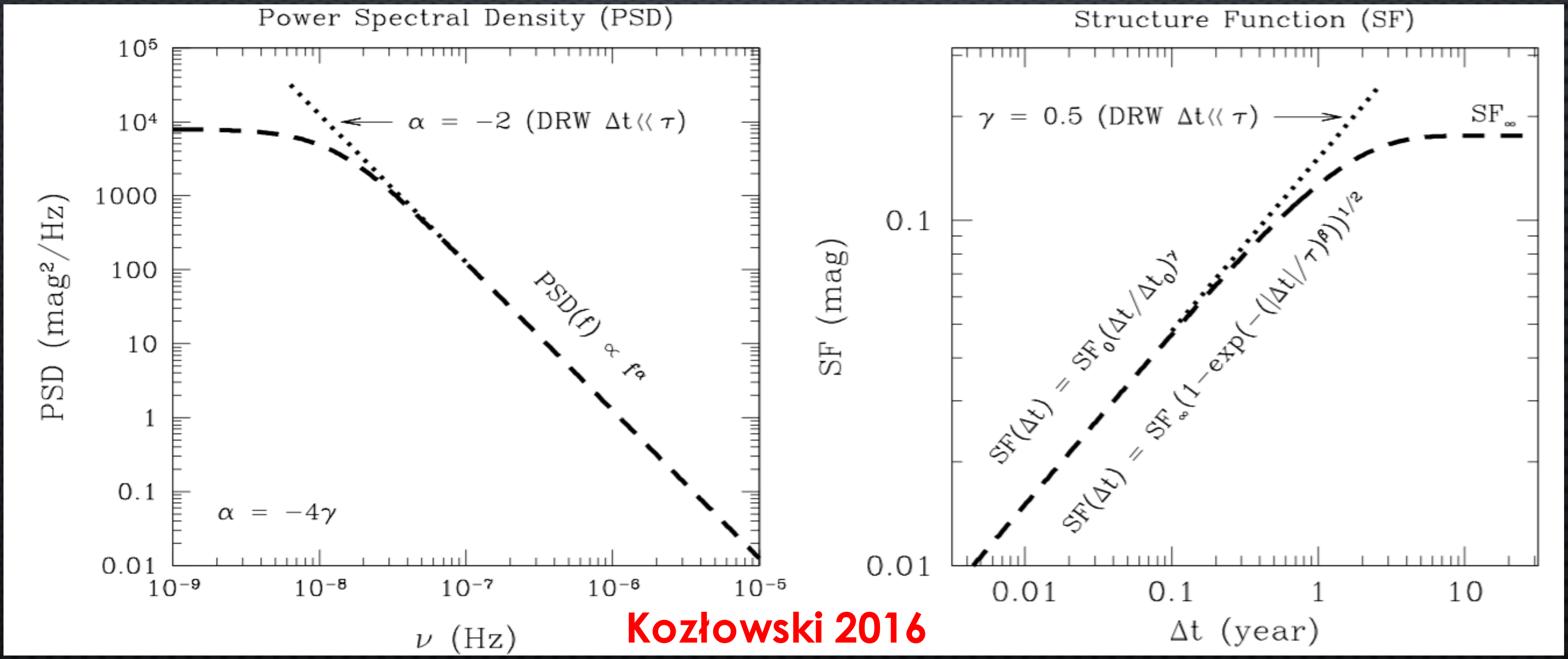
- Panchromatic
- Coordination(lags < 10 days)
- Lines echo continuum
- ➢ Intrinsic

1.2 ORIGIN OF VARIABILITY & DRW MODEL

- Disk originated
  - Change of accretion rate
  - Inhomogeneous accretion disk(Dexter&Agol2010)
- Corona originated
  - X-ray Reprocessing (Guilbert&Rees1988)

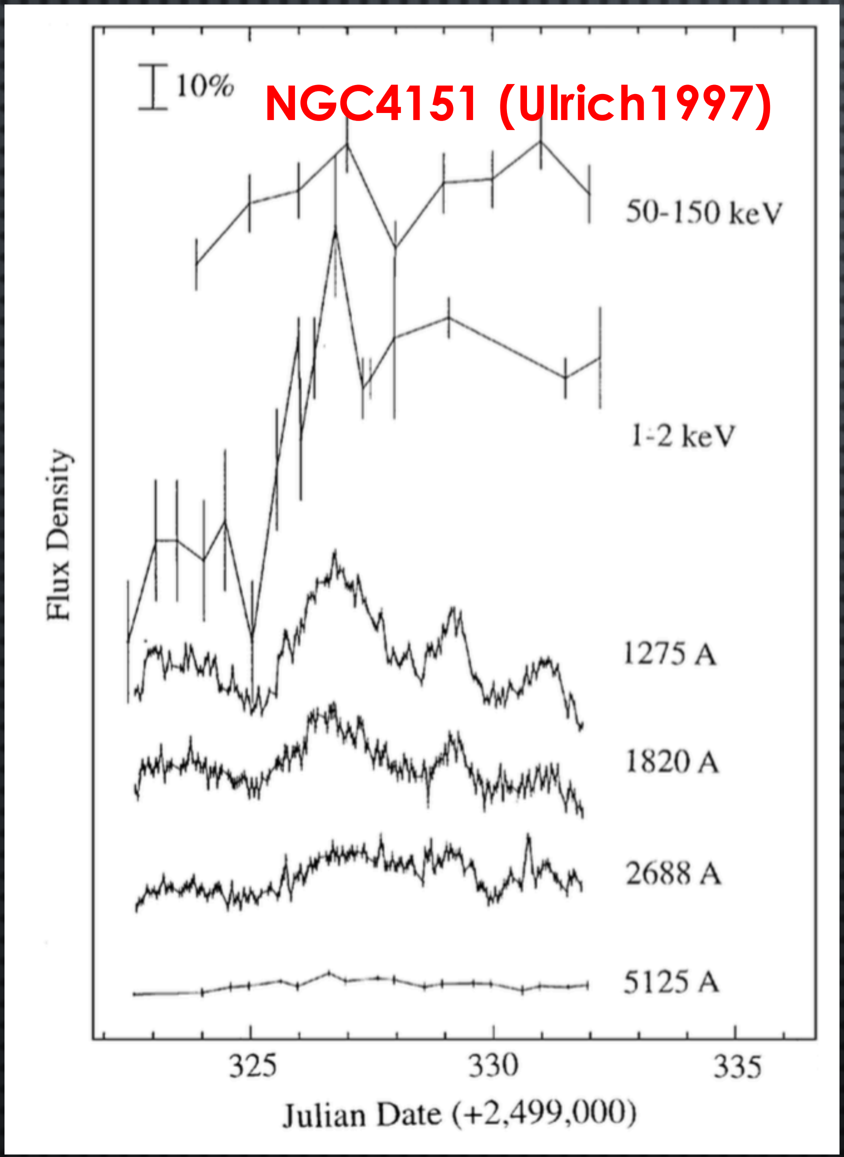
- Damped Random Walk

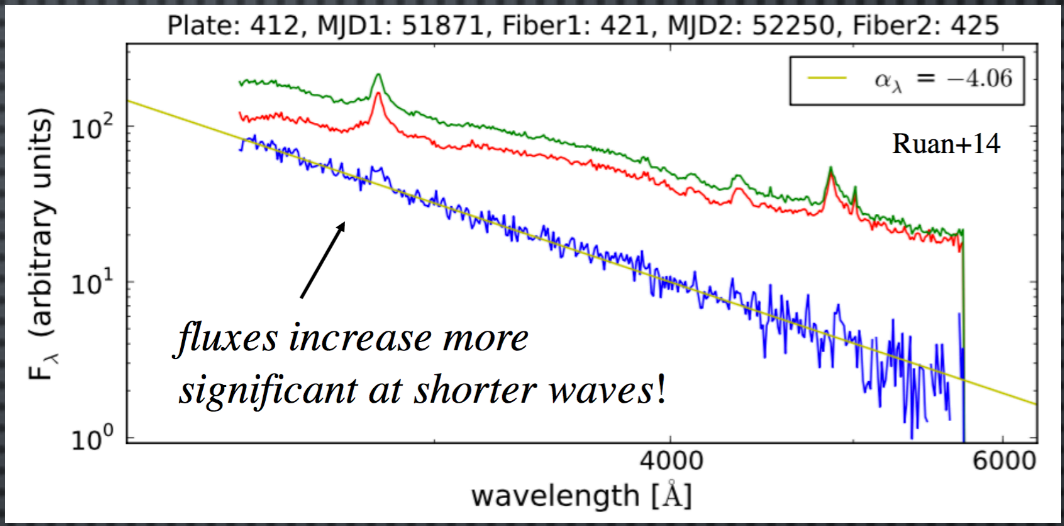
  Observationally, quasars' light curves can be well modelled by DRW processes.(Kelly2009)
- Statistical properties
  - PSD slope α=-2
  - SF slope γ=0.5



Kozłowski 2016

1.3 COLOR VARIABILITY





Simultaneous variation for different bands

+

Stronger variation for shorter/bluer bands

=

Bluer when brighter (≈94%, Guo 2016)

Wamsteker1990; Giveon1999; Wilhite2005; Sakata2011; Schmidt2012; Webb & Malkan 2000; Li S.L.& Cao X.W. 2008, Zuo W.2012, Gu MF&Li S.L. 2013; Zhang XG 2013 and many more

1.4 EXPLANATIONS FOR COLOR VARIABILITY

- ❈ Variable bluer quasar emission contaminated by invariable redder host component.

(Choloniewski81; Winkler92; Paltani&Walter96; Winkler97; Hawkins03; Woo07; Walsh09; Sakata10,11; Pozo Nuñez13; ...)

- ❈ Changes in the global accretion rate

(Pereyra06; Li & Cao08; Sakata11; Zuo12; Gu & Li13; Hung16)

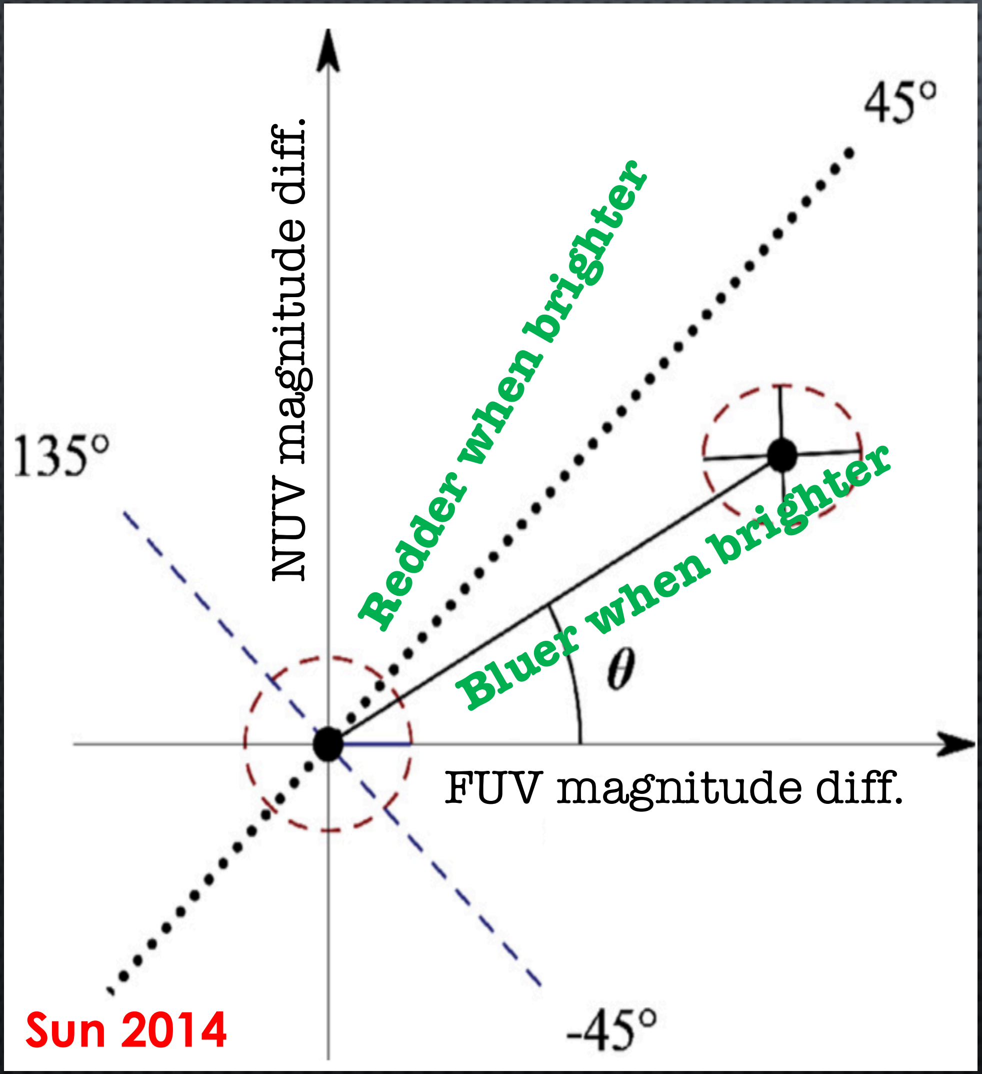
- ❈ Inhomogeneous accretion disk with local temperature fluctuations (which follows a DRW process)

(Kawaguchi1998; Dexter&Agol2011; Schmidt2012; Ruan14; Sun2014; Cai2016)

- ❈ And what about the X-ray reprocessing model?

2 QUANTIFY COLOR VARIABILITY

- ❄ And check its timescale dependency



For every two points on the two bands' light curves:

$$m_i^{NUV}, m_i^{FUV}, t_i \;\&\; m_j^{NUV}, m_j^{FUV}, t_j$$

They form a pair contributing to variability on timescale of:

$$\tau = |t_i - t_j|$$

Color variability of this pair is defined as:

$$\theta(\tau) = arctan\left(\frac{m^{NUV}(t+\tau) - m^{NUV}(t)}{m^{FUV}(t+\tau) - m^{FUV}(t)}\right)$$

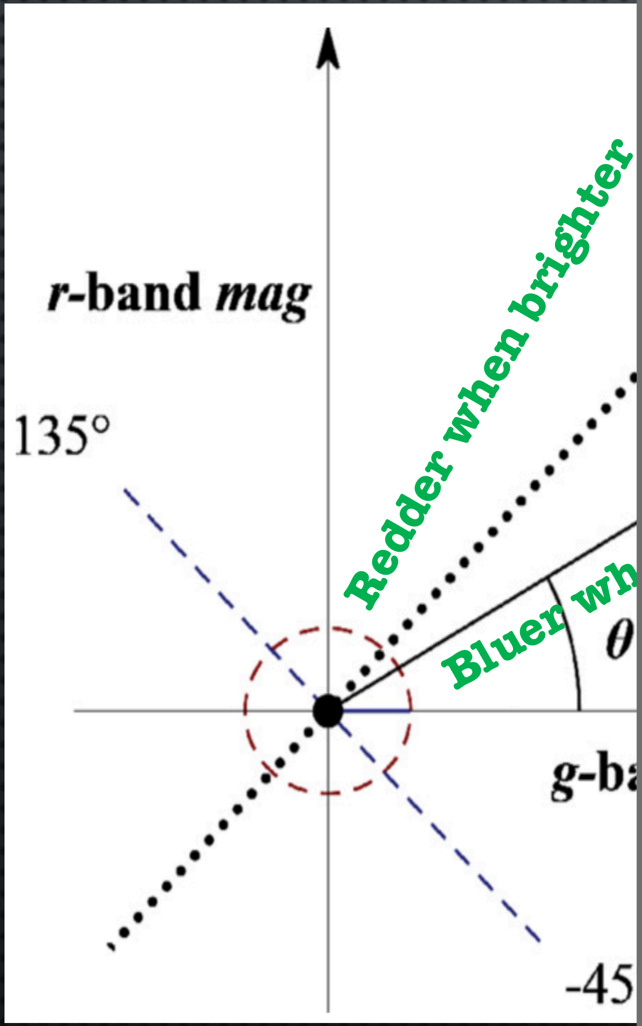
Color variability of certain timescale is then:

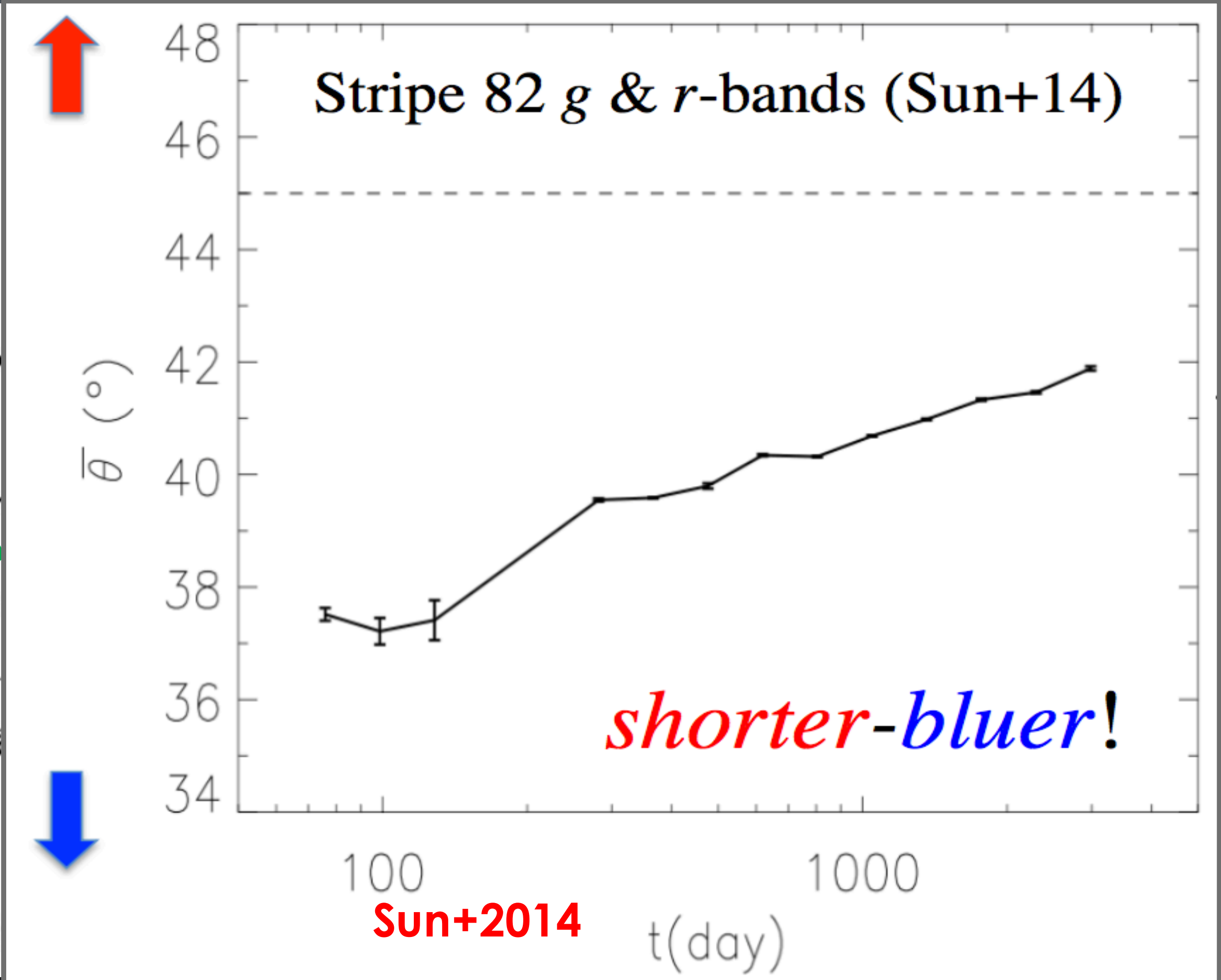
$$\overline{\theta}(\tau) = \frac{\sum_i^N \theta_i(\tau)}{N}.$$

2.1 TIMESCALE-DEPENDENT COLOR VARIABILITY

Color variability is more prominent on shorter timescales.

$$\theta(\tau) = arctan\left(\frac{m^r(t+\tau) - m^r(t)}{m^g(t+\tau) - m^g(t)}\right)$$





EXPLANATIONS FOR TIMESCALE-DEPENDENT COLOR VARIABILITY

- Variable bluer quasar emission contaminated by invariable redder host component.
  - Timescale independent.
- Changes in the global accretion rate
  - All optical bands share the same timescale.
- And what about the reprocessing model?
  - All optical bands share the same timescale.

- Inhomogeneous accretion disk with local temperature fluctuations (which follows a DRW process)
  - The disk is divided into multiple regions.
  - Each region fluctuates independently.
  - Radius-dependent (tau) fluctuations.(Cai+16)

2.2 INHOMOGENEOUS DISK MODEL

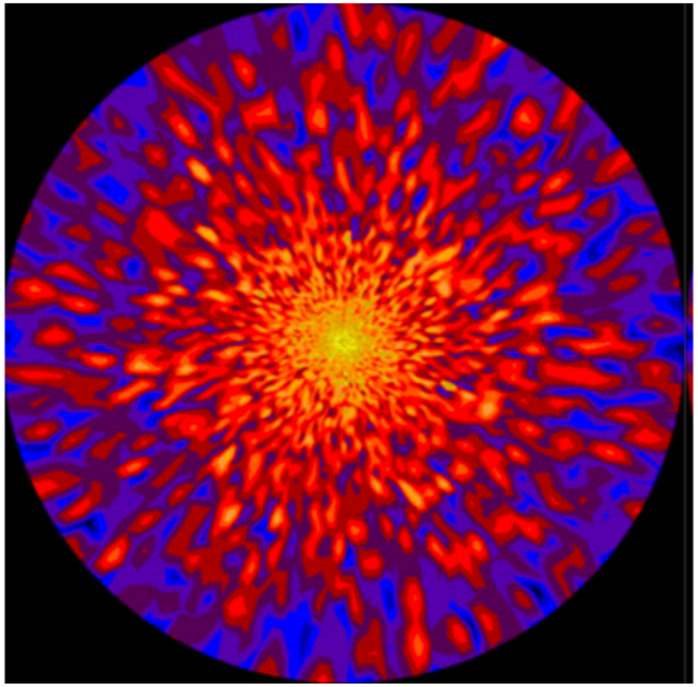
- standard thin disk: $T_{\rm sd}$
  $M_{\rm BH} = 5 \times 10^8 M_\odot$ & $\dot{M} = 1\ M_\odot\ {\rm yr}^{-1}$
- independently fluctuating zones
- damped random walk for temperature fluctuation: ($T_{\rm mid}$, τ, σ_l)

$$t = s + \Delta t$$

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

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

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

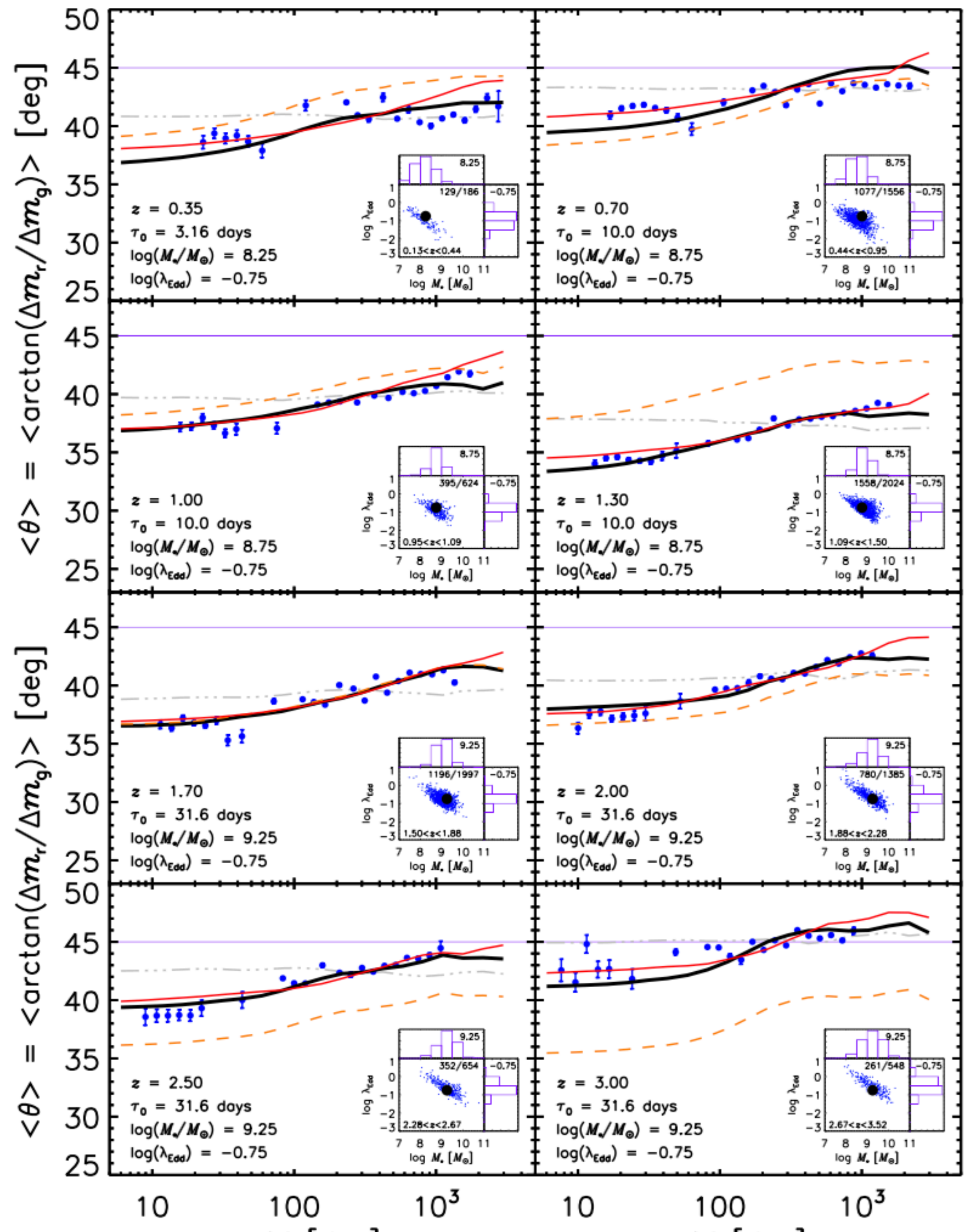


Dexter&Agol 2011
Cai + 2016

$\tau \propto r^\alpha$ and $\alpha > 0$; In the paper, $\alpha = 1$ is tested.

INHOMOGENEOUS DISK MODEL

- This model can match SDSS observed color variation quite well.
- Dark blue dot: SDSS observational results on color variability(Sun2014)
- Solid red line Predicted by DRW based inhomogeneous disk model(Cai2016)



Cai+2016

2.3 CONFIRMED WITH GALEX

- GALEX
  - GALaxy Evolution eXplorer
  - Space borne; working on UV photometry and spectra.
- FUV (1350 - 1785 Å)
- NUV (1710 – 2830 Å)

- Cross-match with SDSS DR7 quasar catalog
  - Matching-radius: 5 arcsec
  - 83228 quasars
- Further rejections of unreliable observations
  - Edge of the detector(0.55 degree)
  - Short exposure time(200s)
  - More than 2 epochs to form a light curve
- Final number of quasars: 5282

2.3 ENSEMBLE STRUCTURE FUNCTION

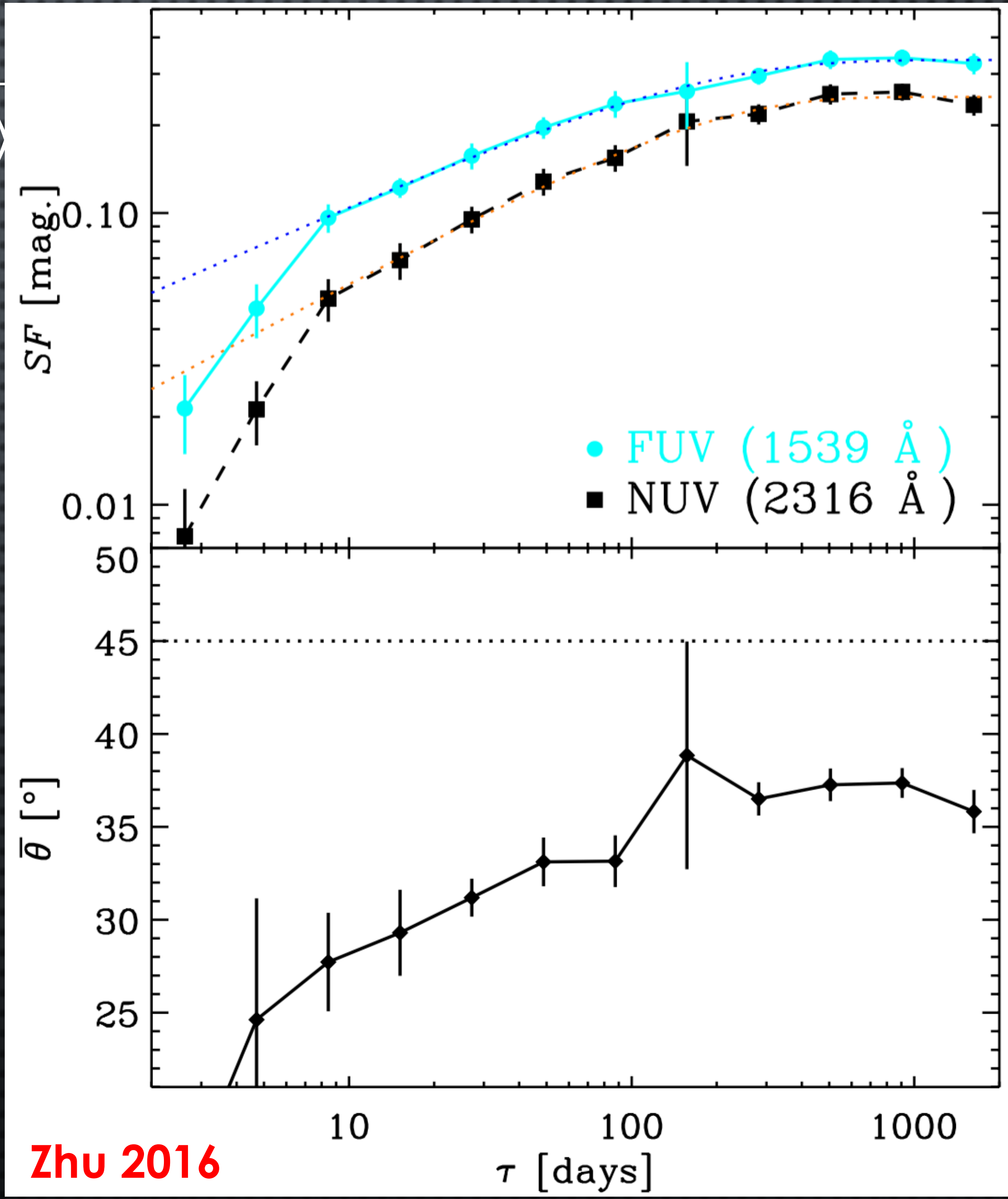
$$SF(\tau) = \sqrt{\frac{\pi}{2}\langle|m_i - m_j|\rangle^2 - \langle\sigma_i^2 + \sigma_j^2\rangle}$$

Results:

1) NUV varies less than FUV for all timescales.
2) The BWB trend is clearly presented again.
3) FUV SF deviates from that of DRW model.

Here we also introduce:

$$\theta_{SF-ratio}(\tau) = arctan\frac{SF_{NUV}(\tau)}{SF_{FUV}(\tau)}$$



2.3 ENSEMBLE STRUCTURE FUNCTION

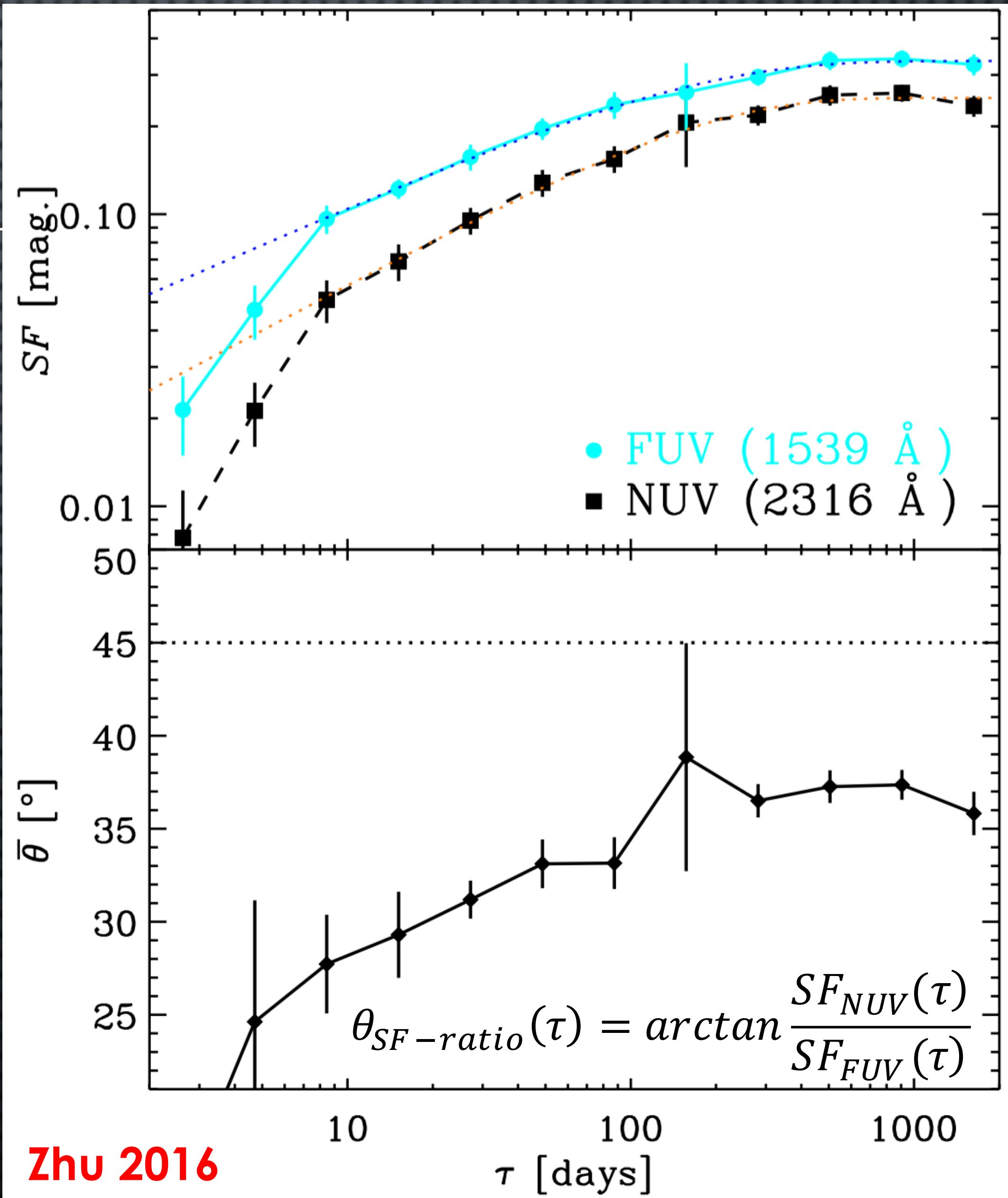
3) FUV SF deviates from that of DRW model.

$$SF(\tau) = SF_\infty \sqrt{1 - exp\left(-\frac{\tau}{\tau_c}\right)^\beta}$$

Fitting parameters:

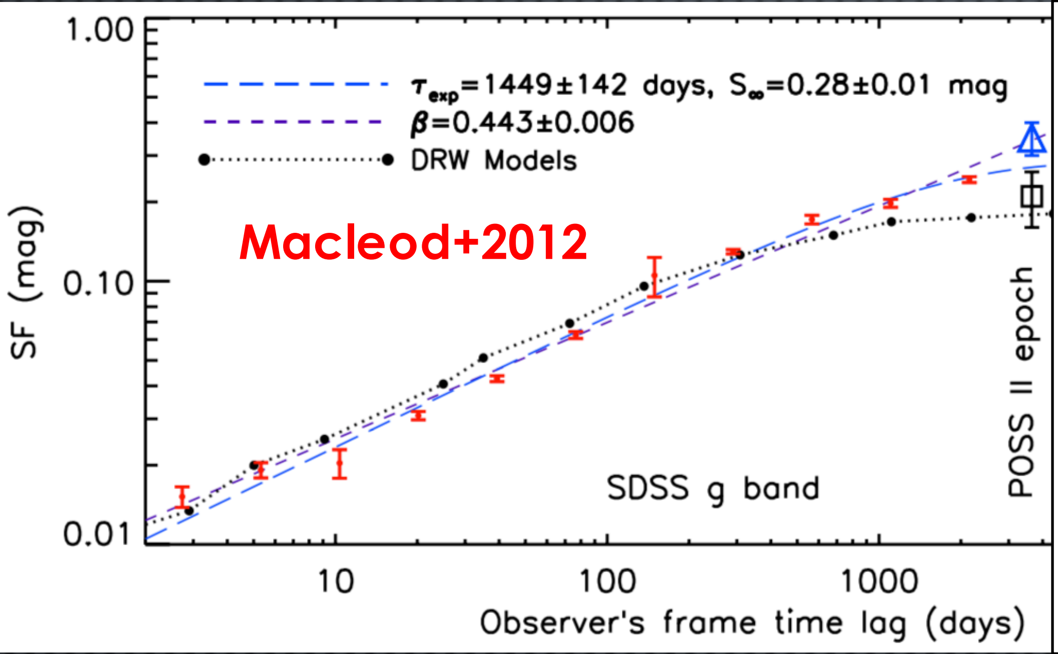
- SF_∞ : SF value when $\tau \to \infty$
- τ_c : turning point for SF
- β : $\beta = 1$ indicates DRW
- γ : slope of SF when $\tau \ll \tau_c$

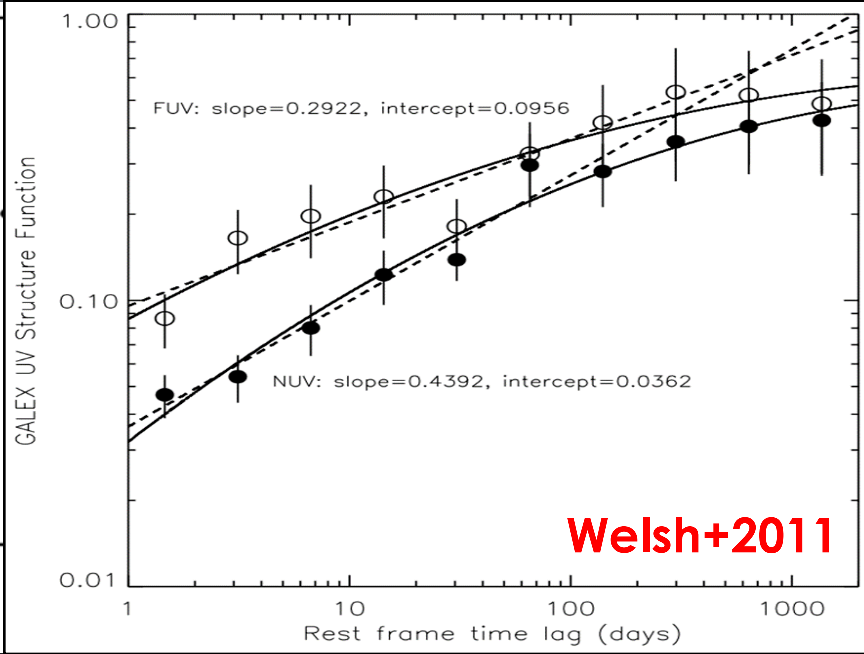
Par.	NUV	FUV
SF_∞	0.25±0.01	0.33±0.02
τ_c [days]	167±46	142±46
$\beta = 2\gamma$	1.04±0.13	0.84±0.11



Zhu 2016

2.3 ENSEMBLE SFs: DRW FAIL FOR UV





- Optical(r band) variability matches DRW well.
- That is not the case for FUV.
- DRW model fails for FUV.
- Physical implication:
  UV variability may be a combination of disk instability and the variation of corona.

Bands	SF slope	Source
DRW	0.5	Macleod+2012
r	0.52±0.06	Kozłowski+2016
g	0.44±0.06	Macleod+2012
NUV	0.43/0.5	Welsh+11/Zhu+16
FUV	0.29/0.42	Welsh+11/Zhu+16

2.3 QUANTIFY COLOR VARIABILITY

- **Bias effect**

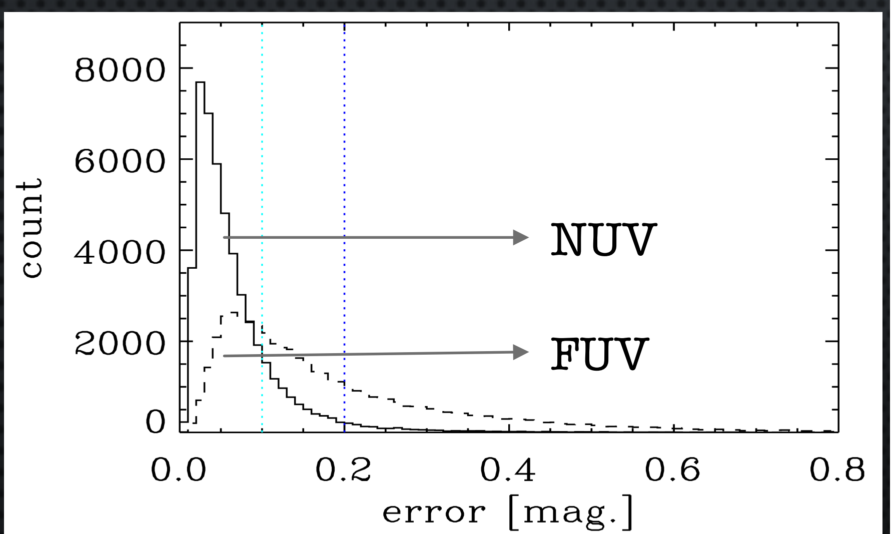
  The two bands has unmatched measurement uncertainties.

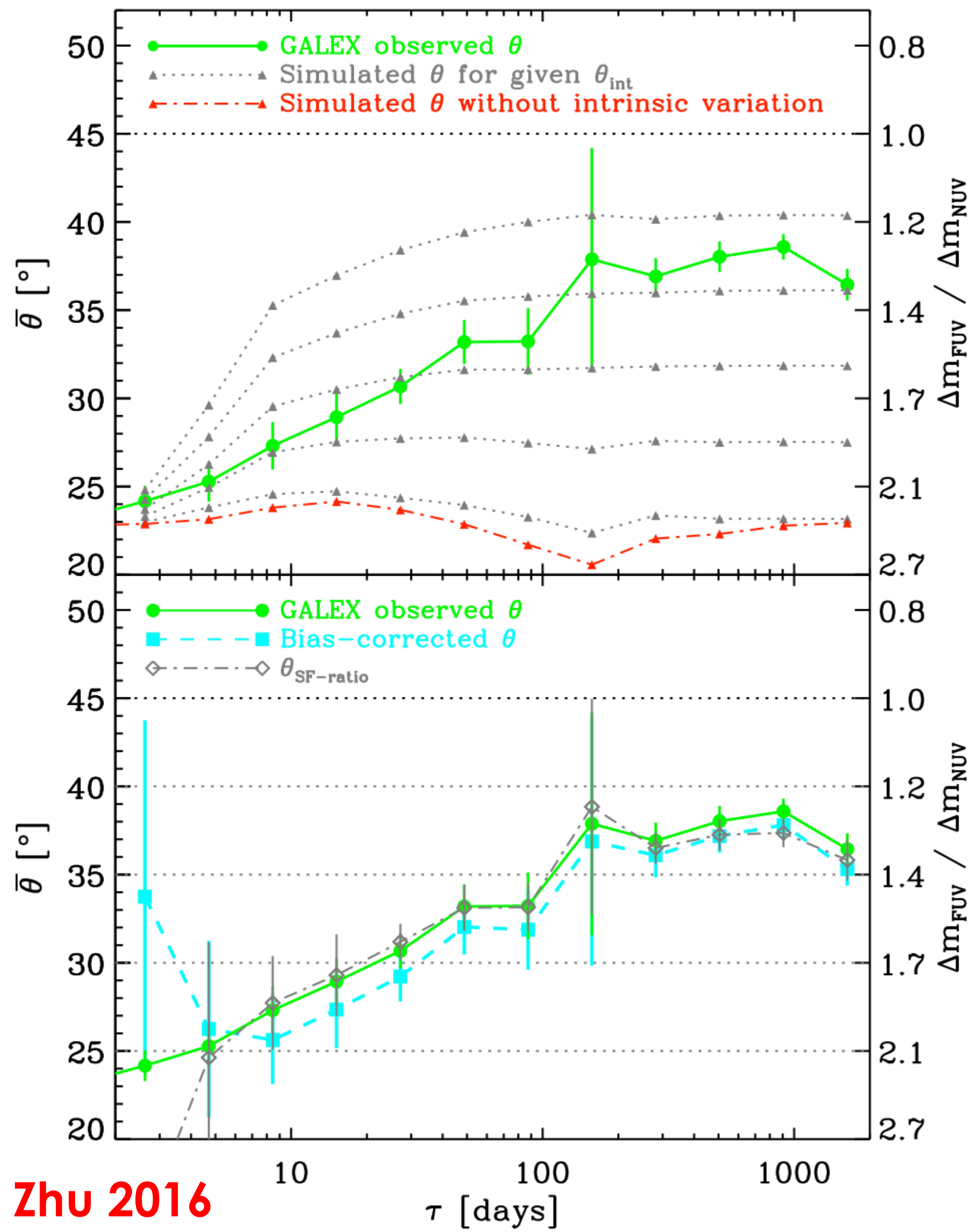
- **MC Simulations**

  The blue line

- **Result:**

  Timescale dependent color variability is clearly presented and confirmed.

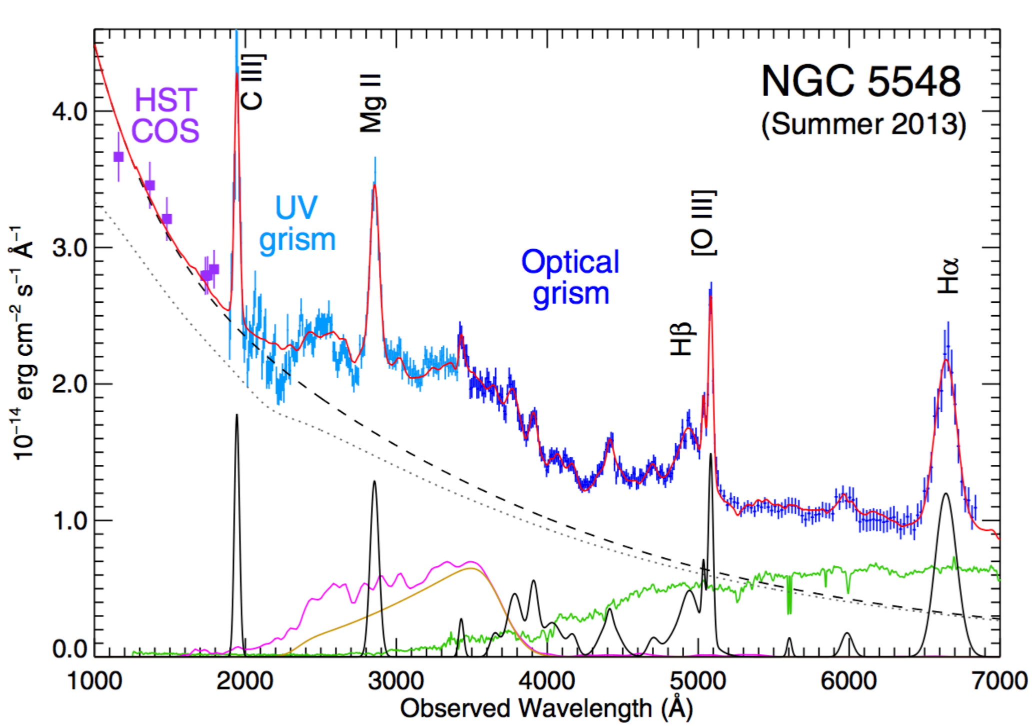




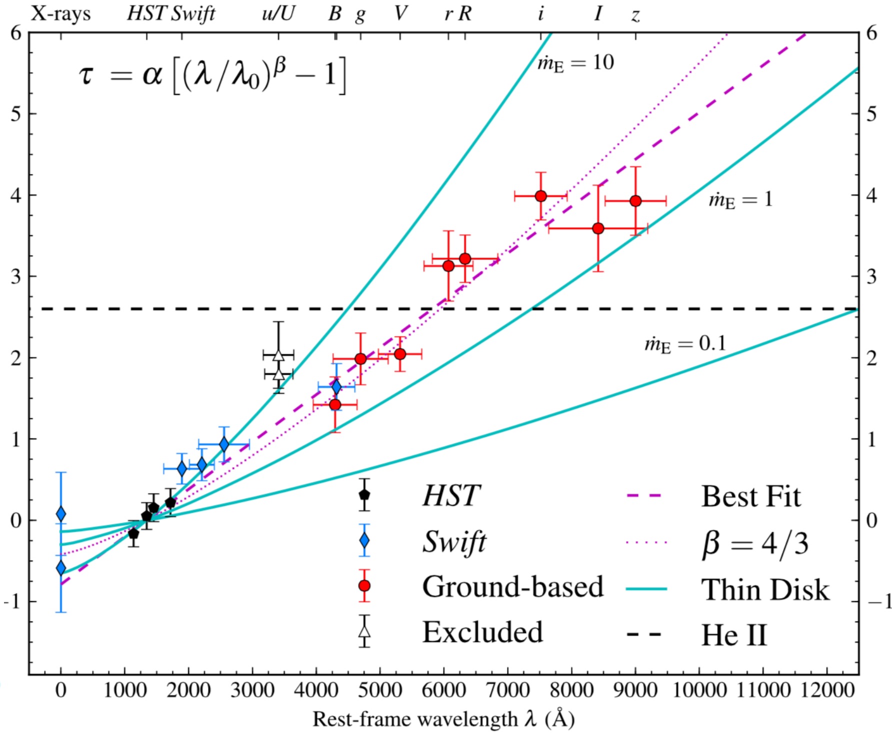
Zhu 2016

3 NGC 5548 & REPROCESSING MODEL

- Well studied with multiple wavelength photometry obs.
- U band suffer from the contamination of small blue bump.
- X-ray reprocessing is often invoked to explain UV/optical variability and lags between their light curves. (McHardy+14; Edelson+15; Fausnaugh+16)
- Special thanks go to *M. Mehdipour* for Swift UVOP light curves.



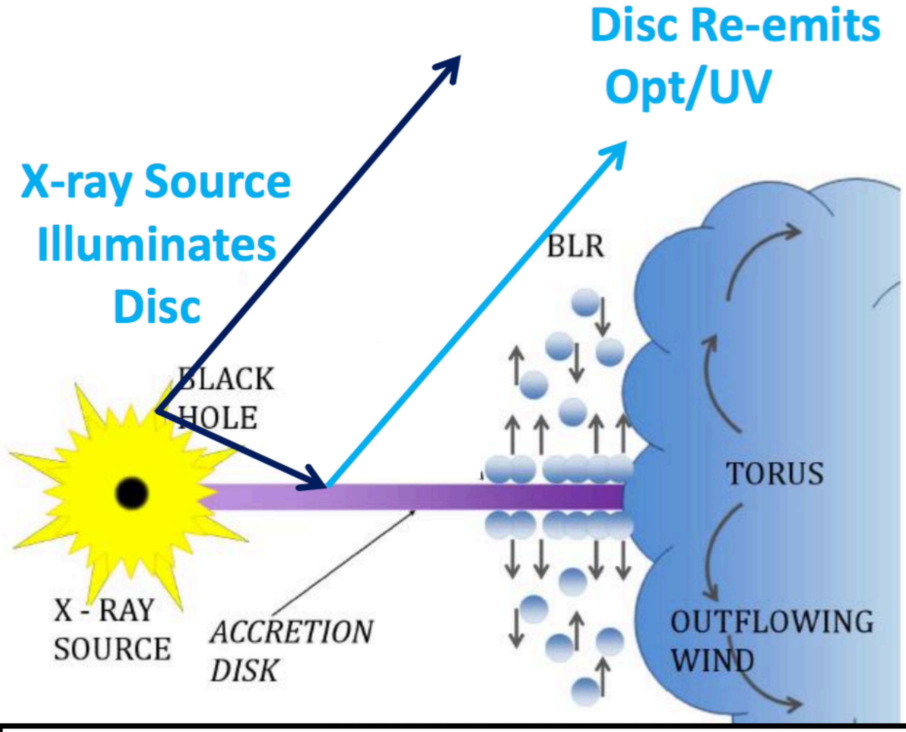
Mehdipour+15

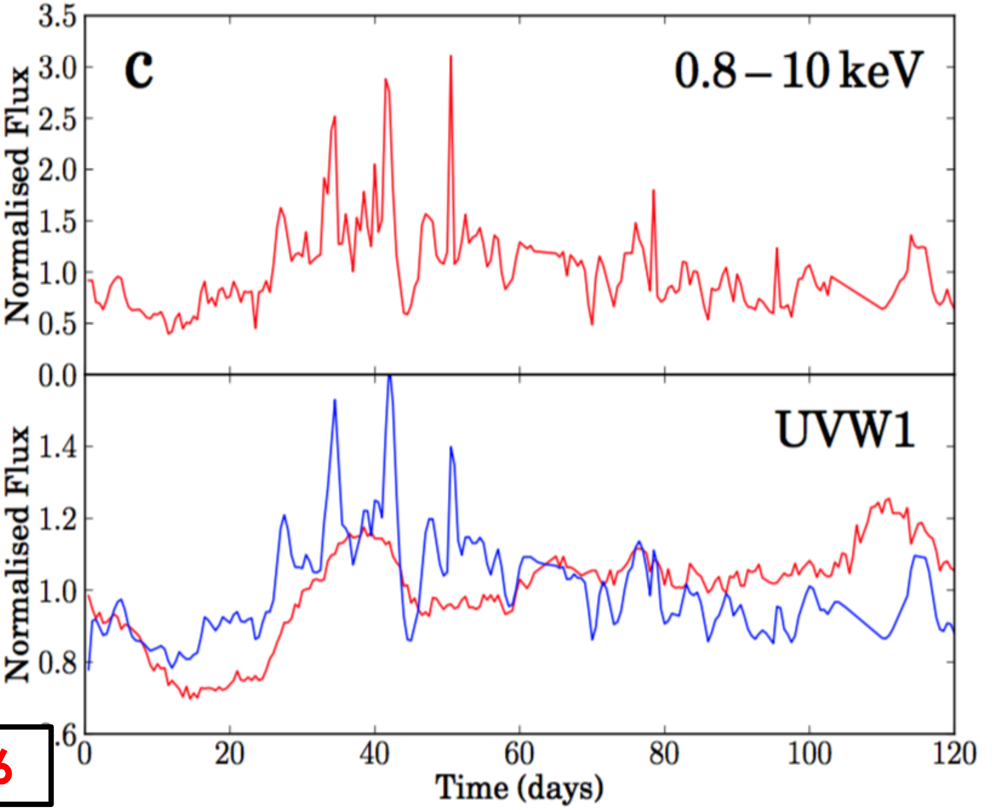


Fausnaugh+16

3 THE REPROCESSING MODEL (GARDNER 2016)

- Inner radiation modulates outer radiation.
- Time lags naturally arise as light-crossing time.
- Time lag also serve as smoothing timescale for redder radiation.
- Current issues: Model produced lag too short and too much fast variability. (Gardner & Done 2016)

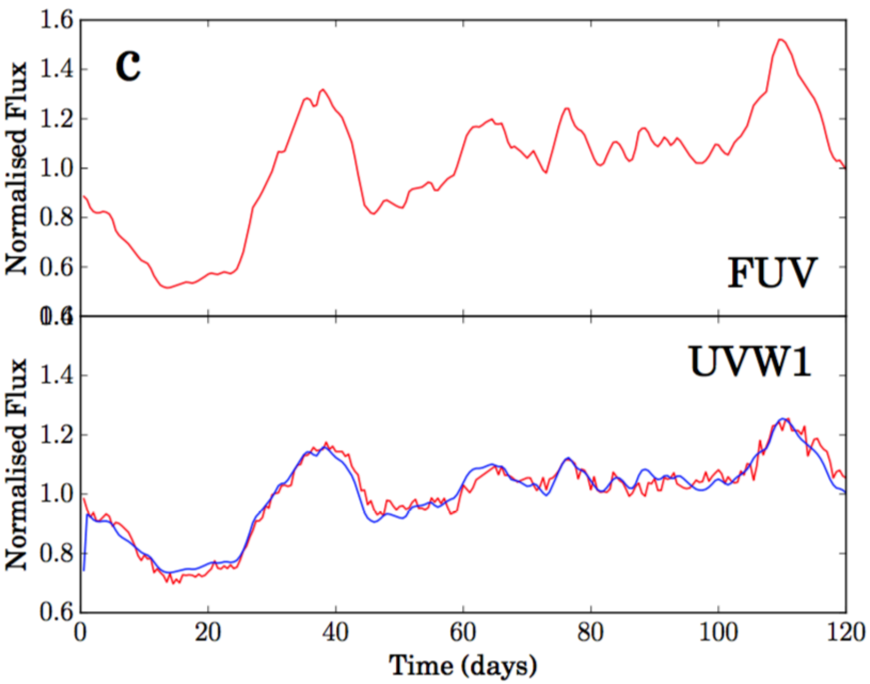


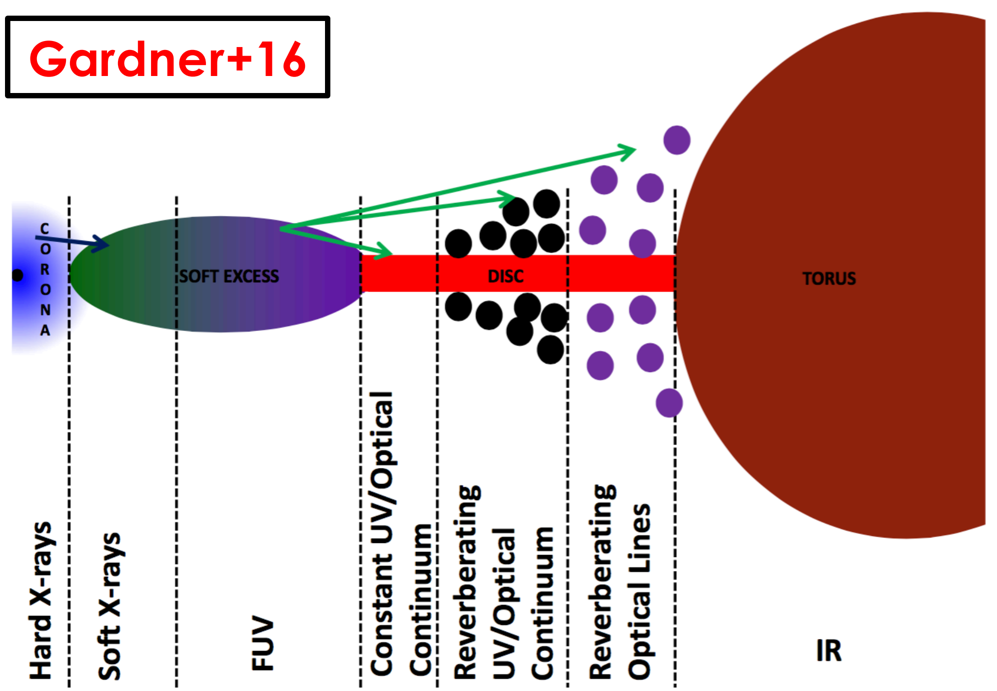


Adapted from Czerny+15 & Gardner+16

3 THE REPROCESSING MODEL (GARDNER 2016)

- Current issues: Model produced lag too short and too much fast variability. (Gardner & Done 2016)
- Soft X-ray emission region: warm comptonisation to produce UV and soft X-ray emission.
- Such region prevents hard X-ray illuminating the disk.
- UV from the outer edge illuminate the disk.
- Optically thick BLR clouds as reprocessors?



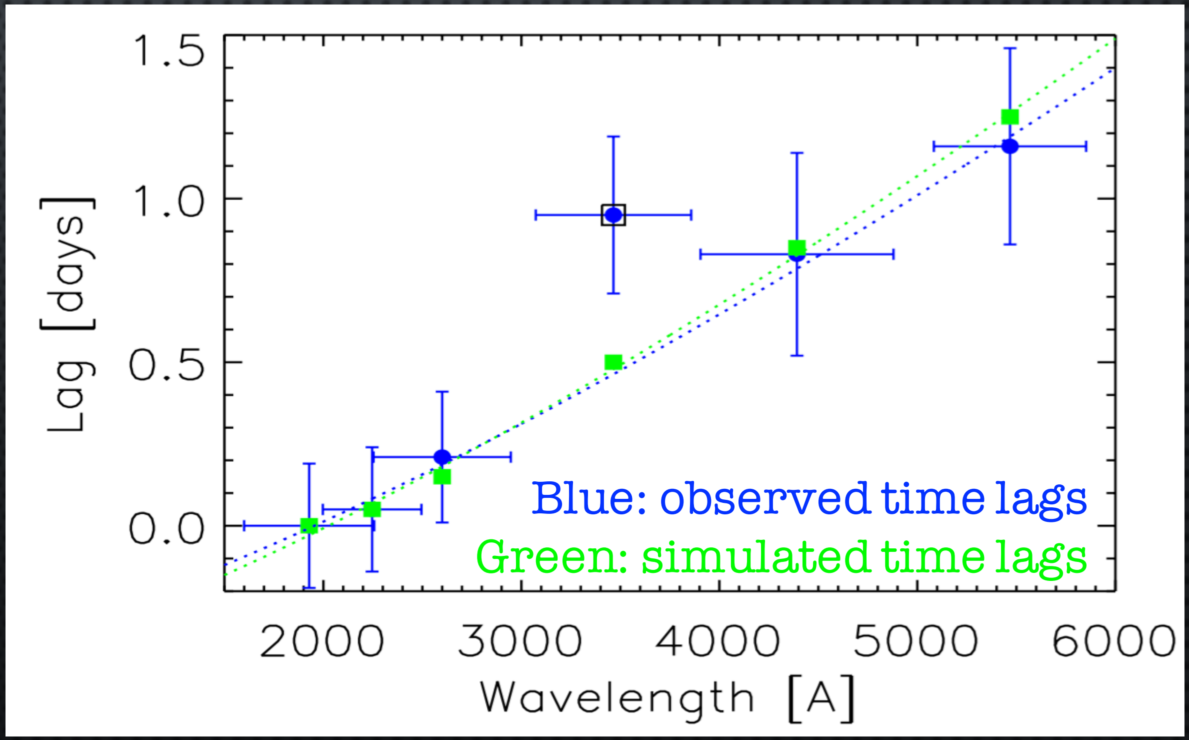


4 THE REPROCESSING MODEL

- Using the UW2 light curves as illumination source, we simulated the optical light curves.
- As already noted, model predicted lags falling short.
- To better match observed lags, we modified $M\dot{M}$, so that the model produced lag was amplified by 3.

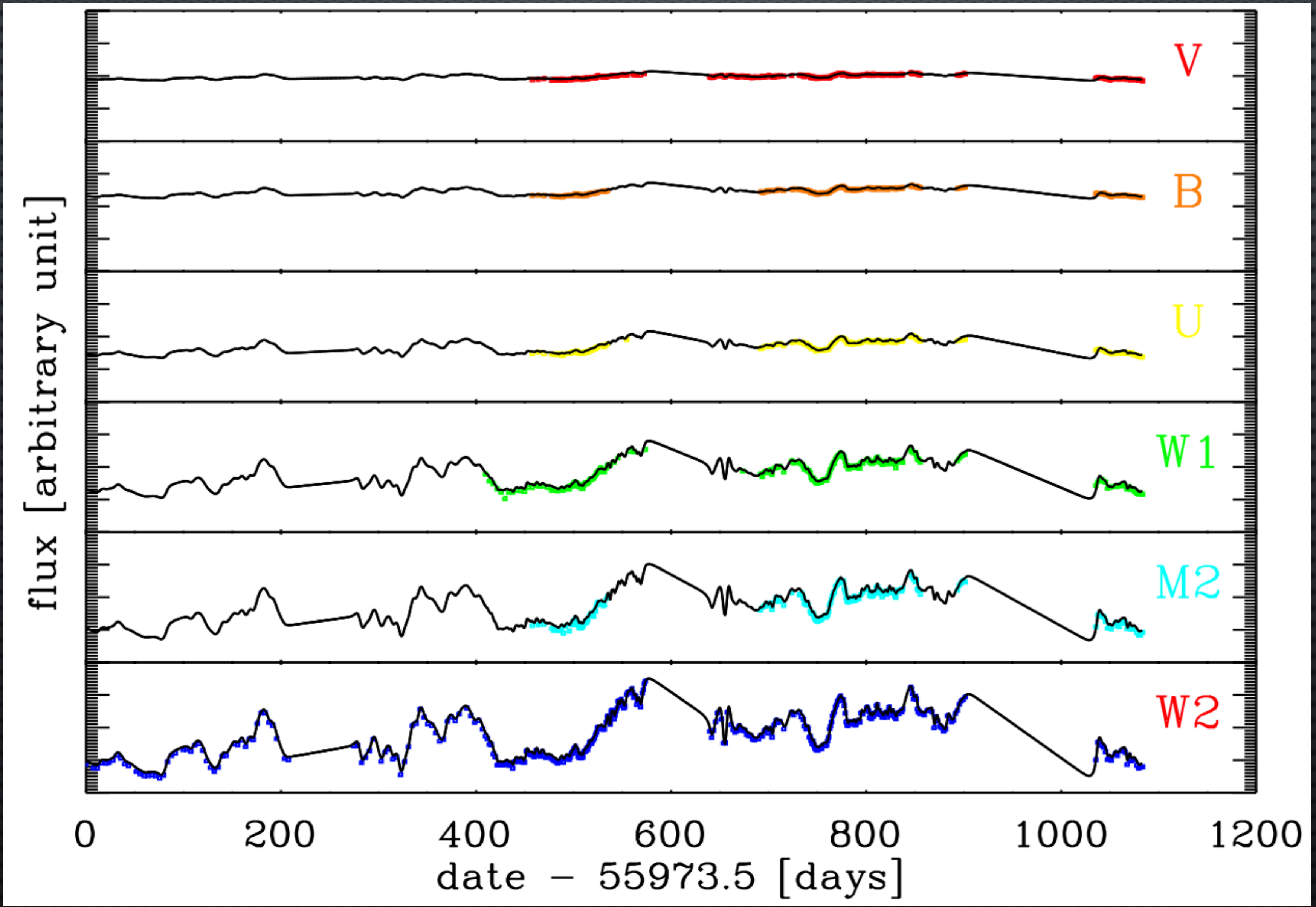
$$T(R) = \left[\left(\frac{3GM\dot{M}}{8\pi R^3 \sigma}\right) + \frac{(1-A)L_x H_x}{4\pi\sigma R_x^3}\right]^{1/4} \qquad \langle\tau\rangle \propto (M\dot{M})^{1/3}\lambda^{4/3}$$

- BH mass M
  $3.2 * 10^7\ M_{sun}$
- Inclination angle
  45°
- Bol. Luminosity
  $2.82 * 10^{44}$ erg/s
- X-ray luminosity
  15% L_{disk}
- X-ray height H_x
  $10\ R_g$
- Albedo A : 0.5



4 THE REPROCESSING MODEL

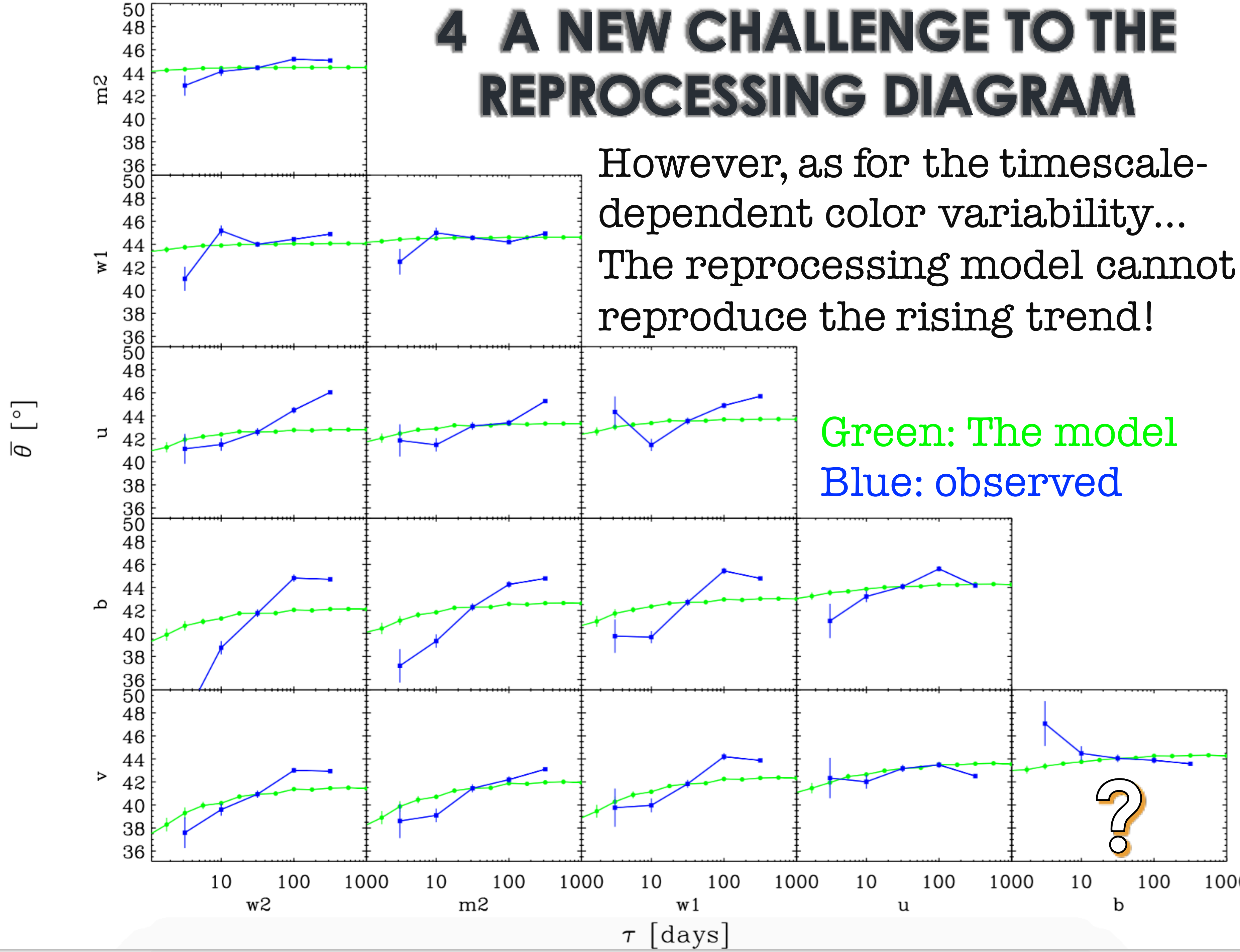
Visually, simulated curves match well with observed ones.



4 A NEW CHALLENGE TO THE REPROCESSING DIAGRAM

However, as for the timescale-dependent color variability... The reprocessing model cannot reproduce the rising trend!

Green: The model
Blue: observed



5 TAKE AWAY POINTS

- Timescale-dependent color variability is securely confirmed for even bluer radiation, including extreme UV.
- Could be due to radius-dependent temperature fluctuations in the accretion disk.
- UV variability deviates from DRW. This could relate to the contamination of corona radiation.
- Neither the X-ray nor UV reprocessing can solely reproduce timescale dependent color variability we saw in observations.