Variability Probes of AGN Accretion Disc Temperature Profiles

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Also, disc surface brightness is lower than expected. ☹

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Keith Horne, SUPA St Andrews.

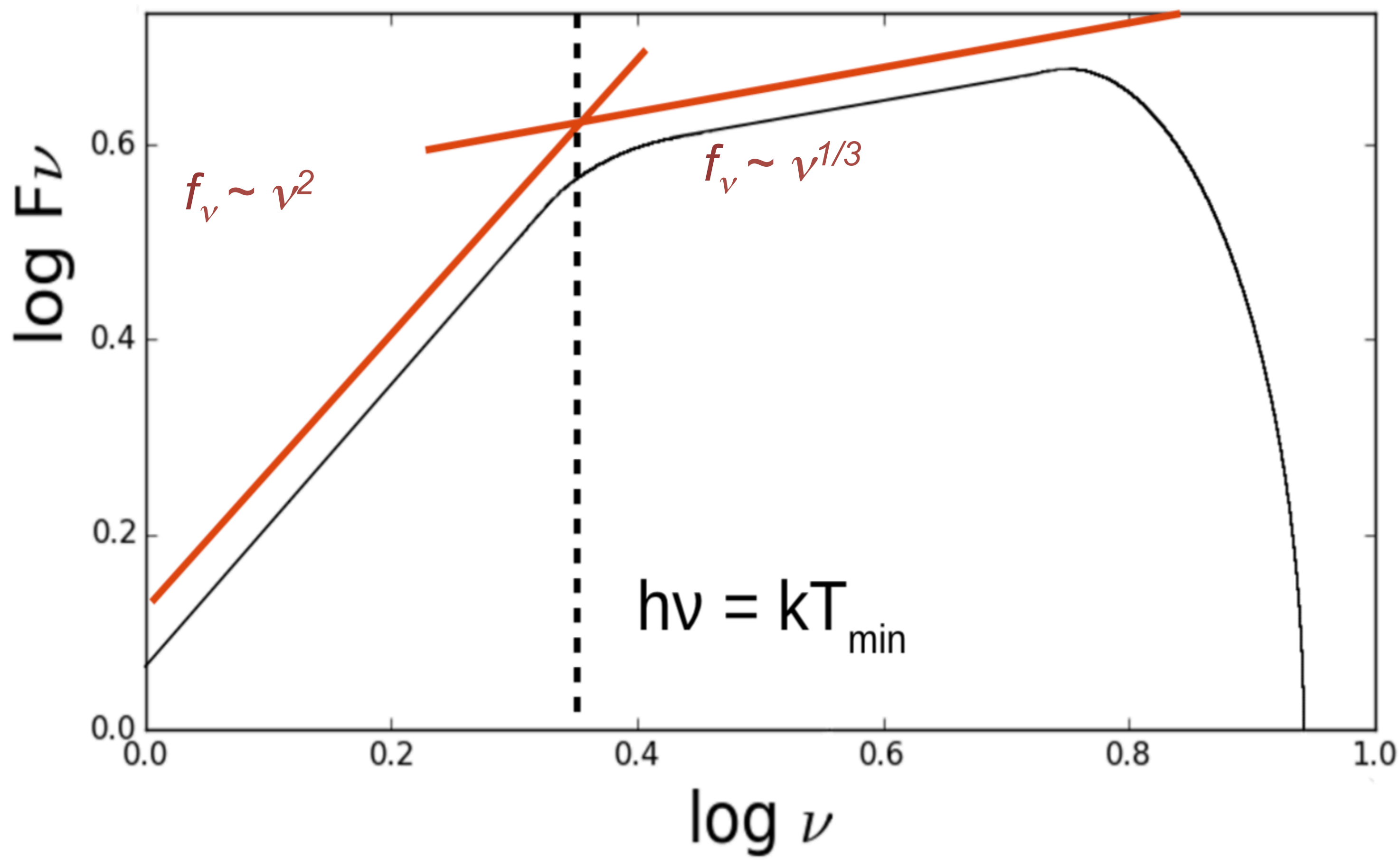
2019 Sep 21, Guilin

Steady Thin Blackbody Discs

Testable predictions of a simple and elegant accretion disc theory:

(Sakura & Sunyaev 1973)

$$T(r) = \left(\frac{3\, G\, M\, \dot{M}}{8\, \pi\, \sigma\, r^3} \right)^{1/4} \quad \rightarrow \quad \begin{array}{l} \tau \propto \lambda^{4/3} \\ f_\nu \propto \nu^{1/3} \end{array}$$



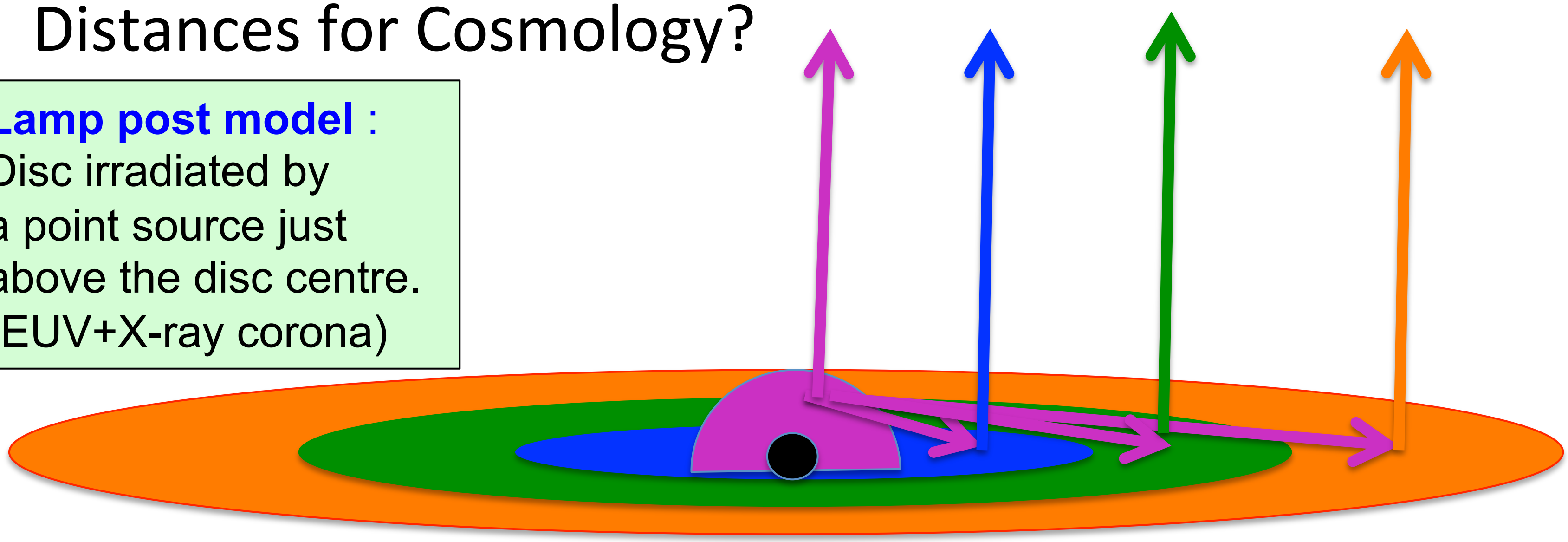
Continuum Echo Mapping
T(r) profiles of AGN Accretion Discs

- Measure the time delay spectrum $\tau(\lambda)$
- To find the disk temperature profile $T(r)$
- Test disc models

$$T(r) = \left(\frac{3\,G\,M\,\dot{M}}{8\,\pi\,\sigma\,r^3} \right)^{1/4} \rightarrow \begin{array}{l} \tau \propto \lambda^{4/3} \\ f_\nu \propto \nu^{1/3} \end{array}$$

- Distances for Cosmology?

Lamp post model :
Disc irradiated by
a point source just
above the disc centre.
(EUV+X-ray corona)



Accretion Disk Reverberations

Assumptions:

Light travel time: $R \sim c\tau$

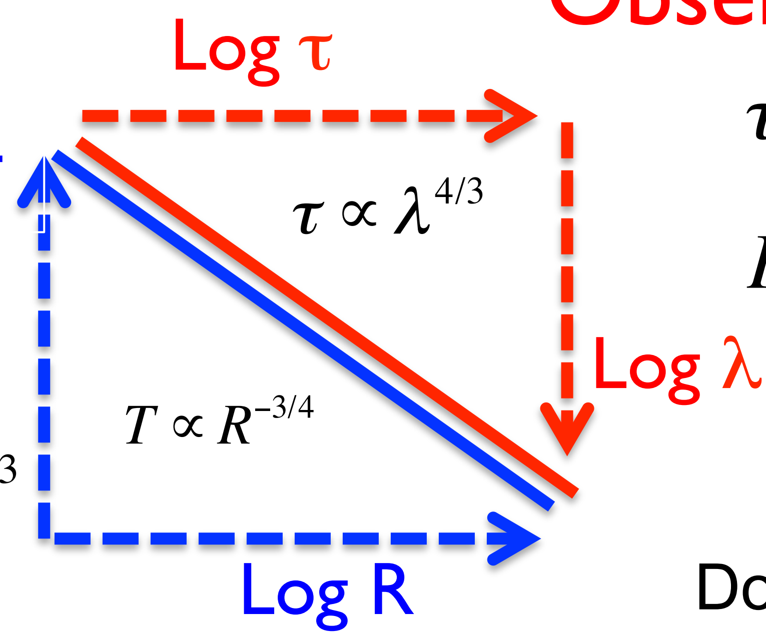
Thermal Emission: $T \sim \dfrac{hc}{5k\lambda}$

Flat geometry: $d\Omega = \dfrac{2\pi R\, dR \cos i}{D^2}$

Disc Theory:

$$T \propto \left(M\dot{M}\right)^{1/4} R^{-3/4}$$

$$L_\nu \propto \left(M\dot{M}\right)^{2/3} \lambda^{-1/3}$$



Observables:

$$\tau \propto \left(M\dot{M}\right)^{1/3} \lambda^{4/3}$$

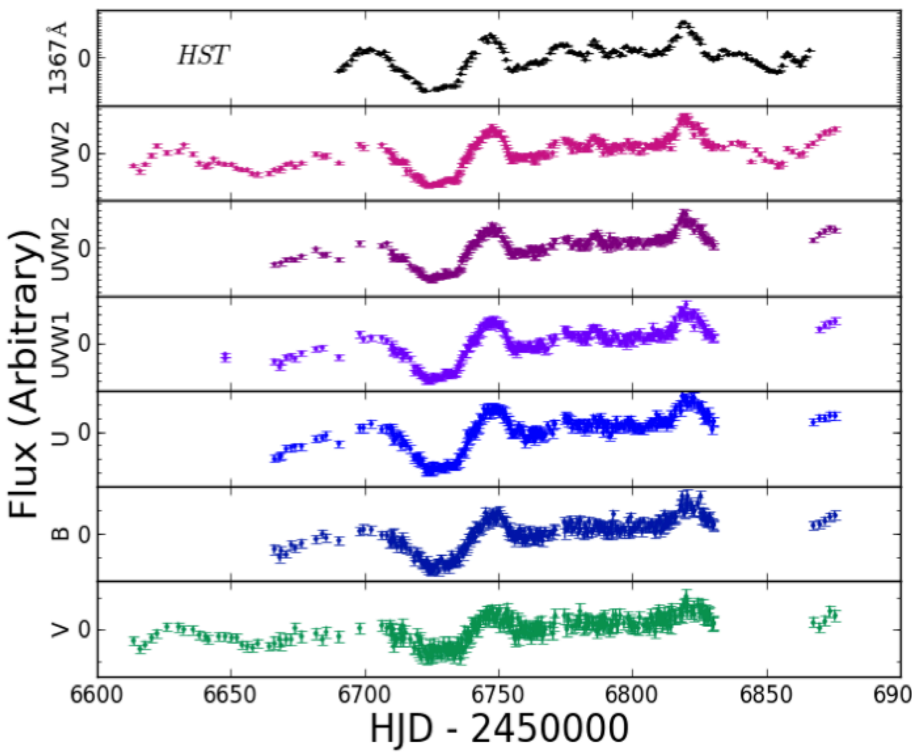
$$F_\nu \propto L_\nu \cos(i) / D^2$$

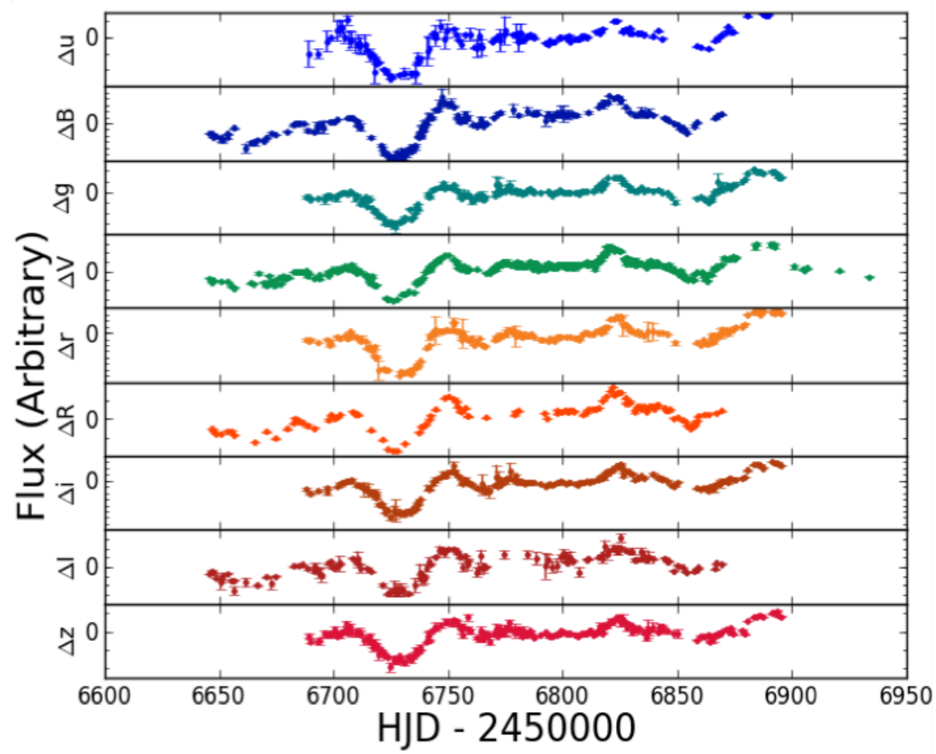
Do these agree?

STORM: UV, optical lightcurves

HST: 1/day *SWIFT:* 2 /day

Ground-based > 600 epochs

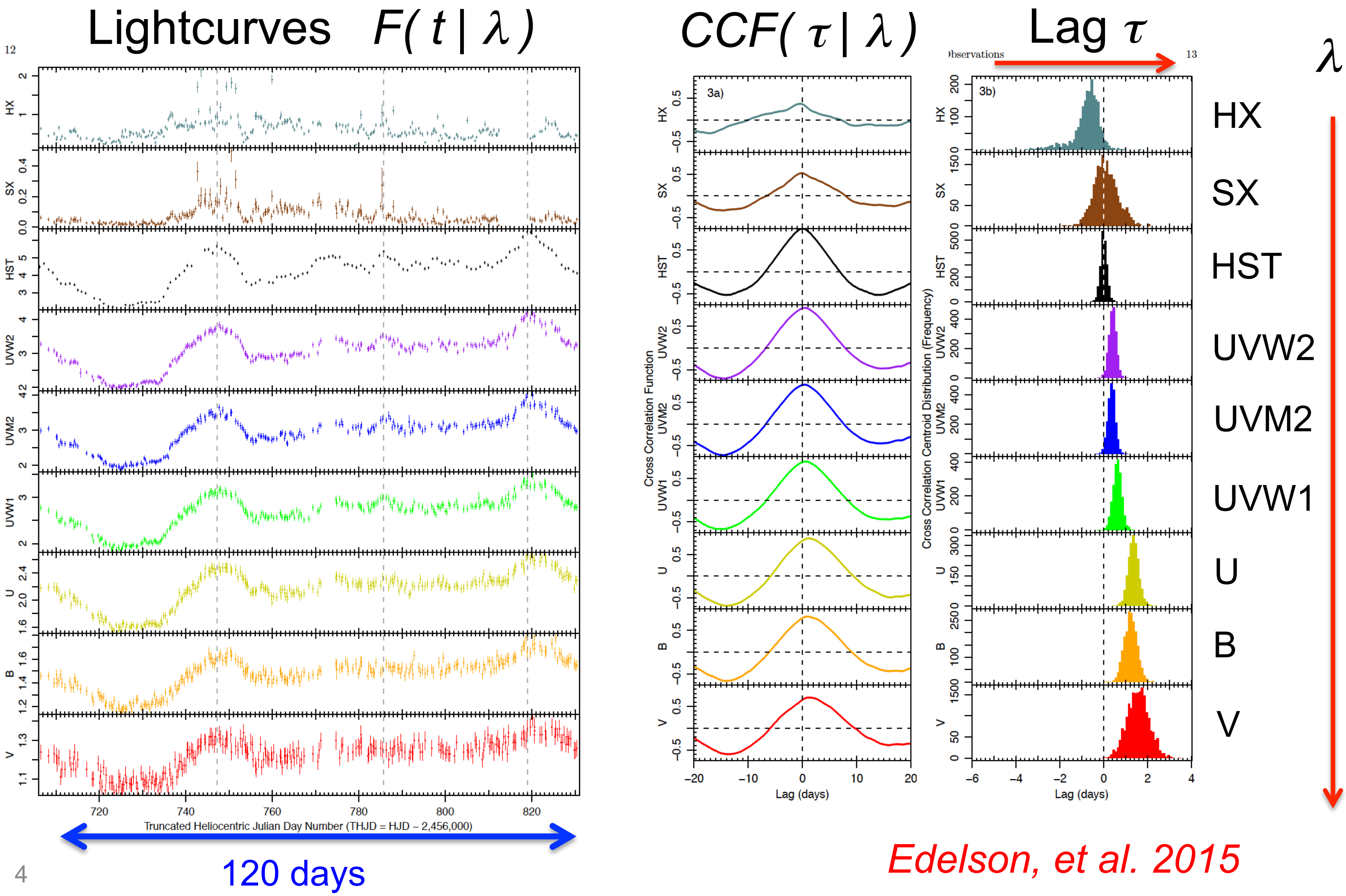




Edelson, et al. 2015

Fausnaugh, et al. 2016

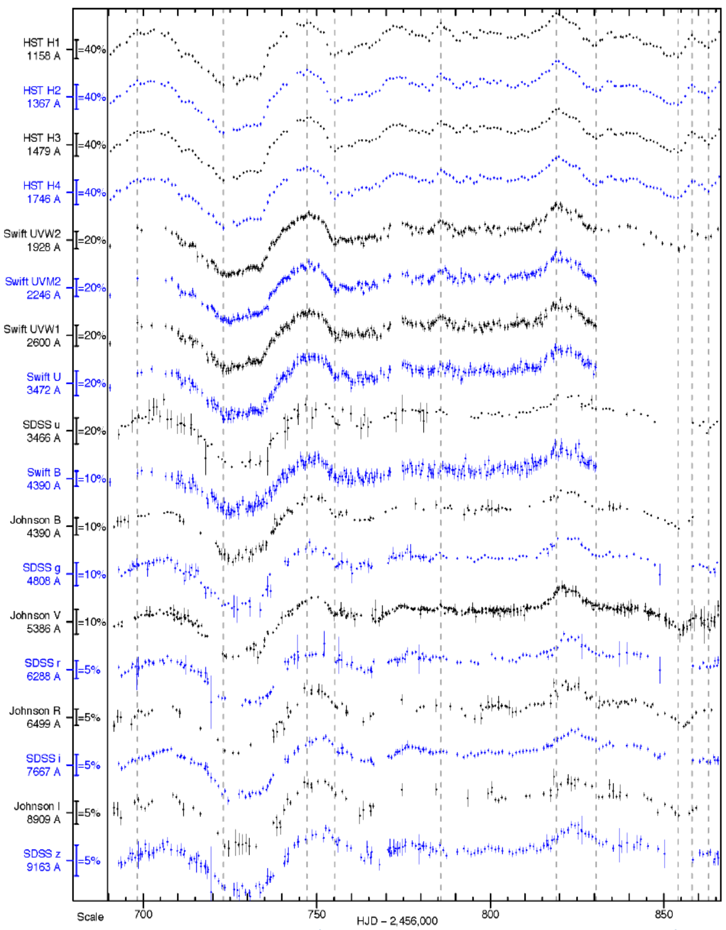
NGC 5548 STORM : Swift Data



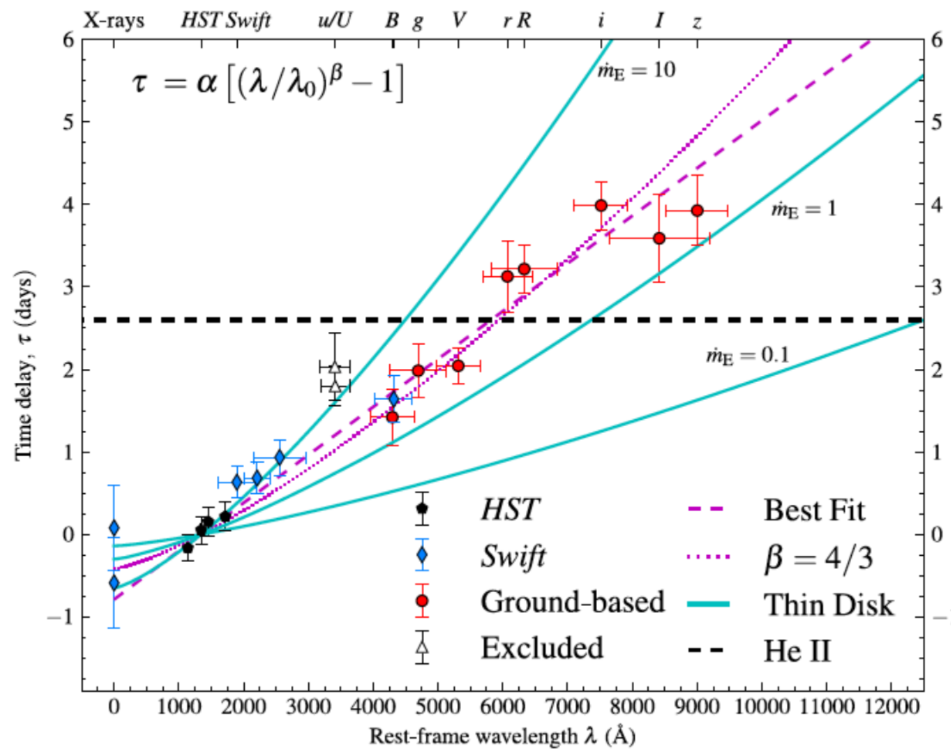
Edelson, et al. 2015

Lightcurves f(λ,t)=> CCF Lags τ(λ)

UV (1150 A)



Optical (9000 A)

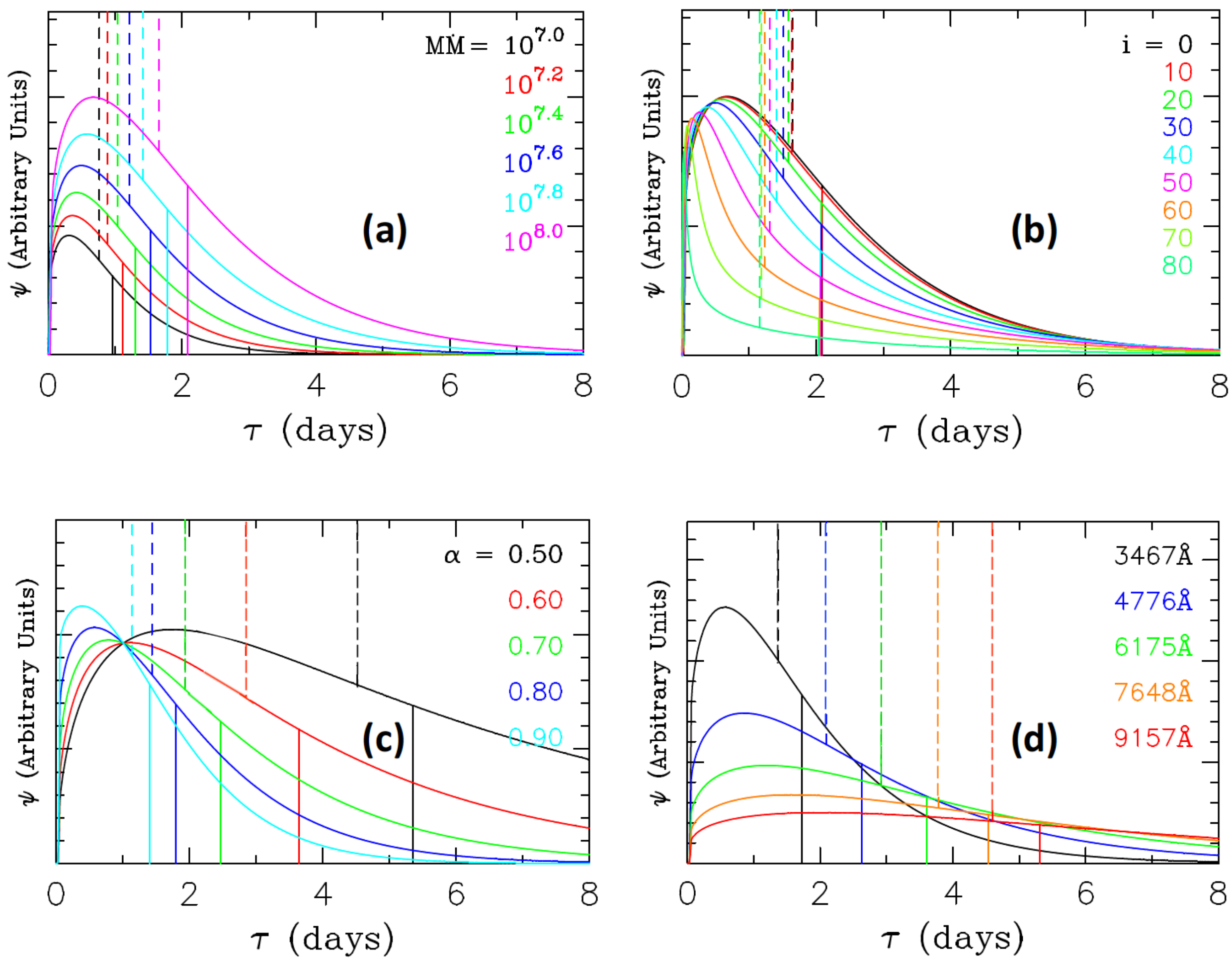


UV lightcurves (HST, Swift)
Optical lightcurves (LCO+LT+… many telescopes)
Cross-correlate to find time delay vs wavelength.

Fausnaugh, et al. 2016

Blackbody Disc Delay Maps

$$T(r) = T_1\,(r/r_1)^{-\alpha} \rightarrow \tau \propto \lambda^{-1/\alpha}$$



Mean delay
$< \tau >$ ~ *(M Mdot)*$^{1/3}$ $\lambda^{4/3}$
Independent of
disk inclination.

Delay map shape
depends on
disk inclination

And slope α of
T(r) ~ $R^{-\alpha}$
temperature profile

Theory: α = *3/4*

Starkey, et al. 2016

CREAM : MCMC fit to all 19 Lightcurves

Starkey, et al. 2017

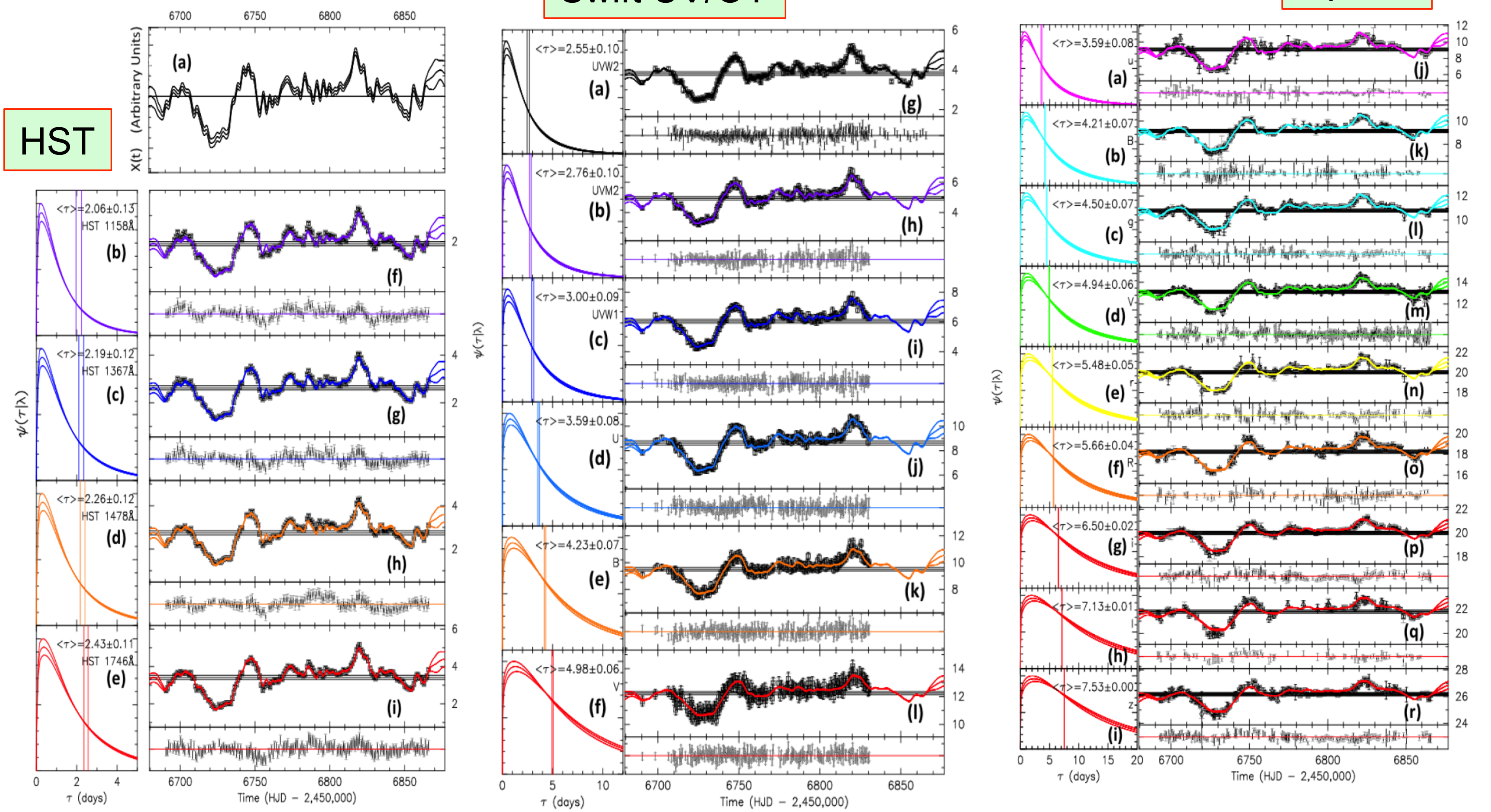
$$F(t,\lambda) = \bar{F}(\lambda) + \Delta F(\lambda) \int \Psi(\tau|\lambda)\, X(t-\tau)\, d\tau$$

Driving Lightcurve *X(t)*

Swift UV/OT

Optical

HST



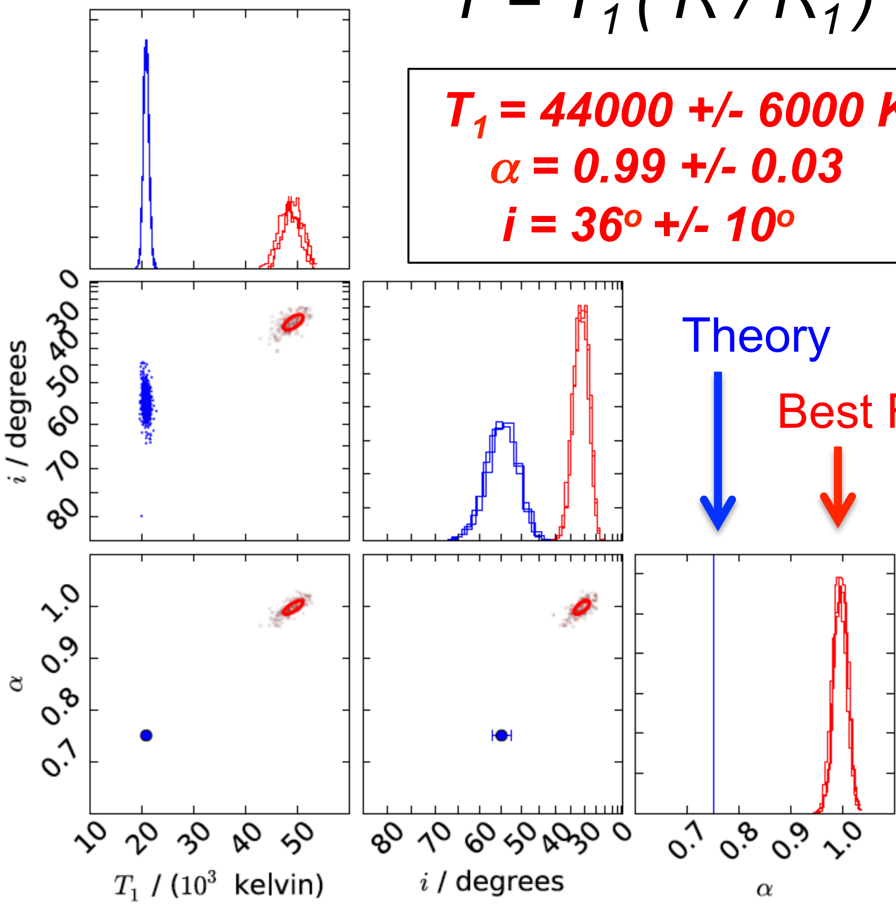
T(R) Profile

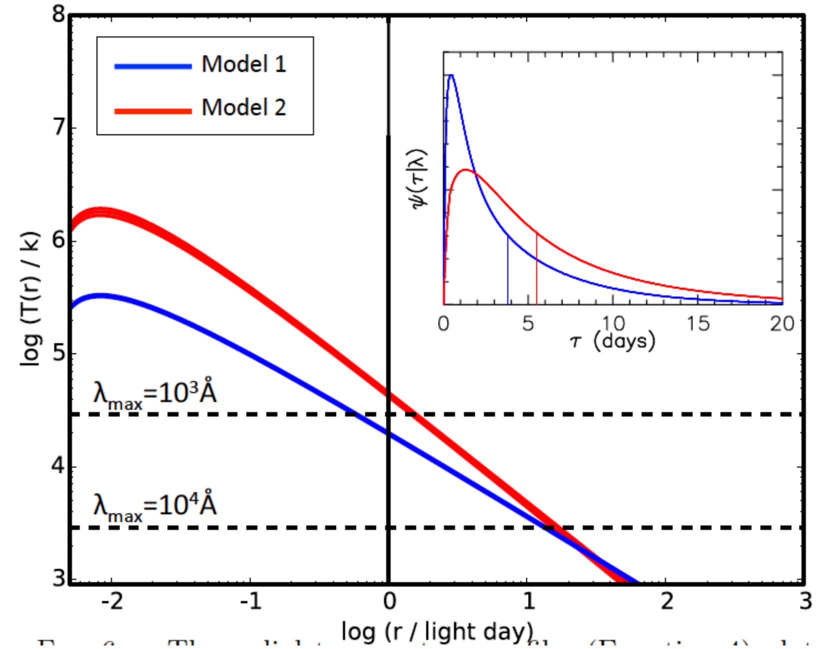
steeper than expected.

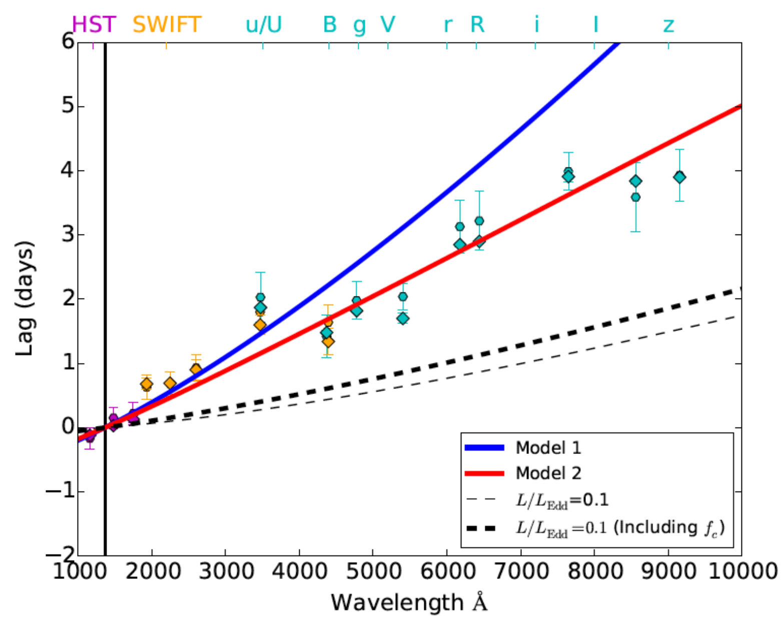
$T \sim R^{-1}$ rather than $R^{-3/4}$.

$$T = T_1 \, (R / R_1)^{-\alpha}$$

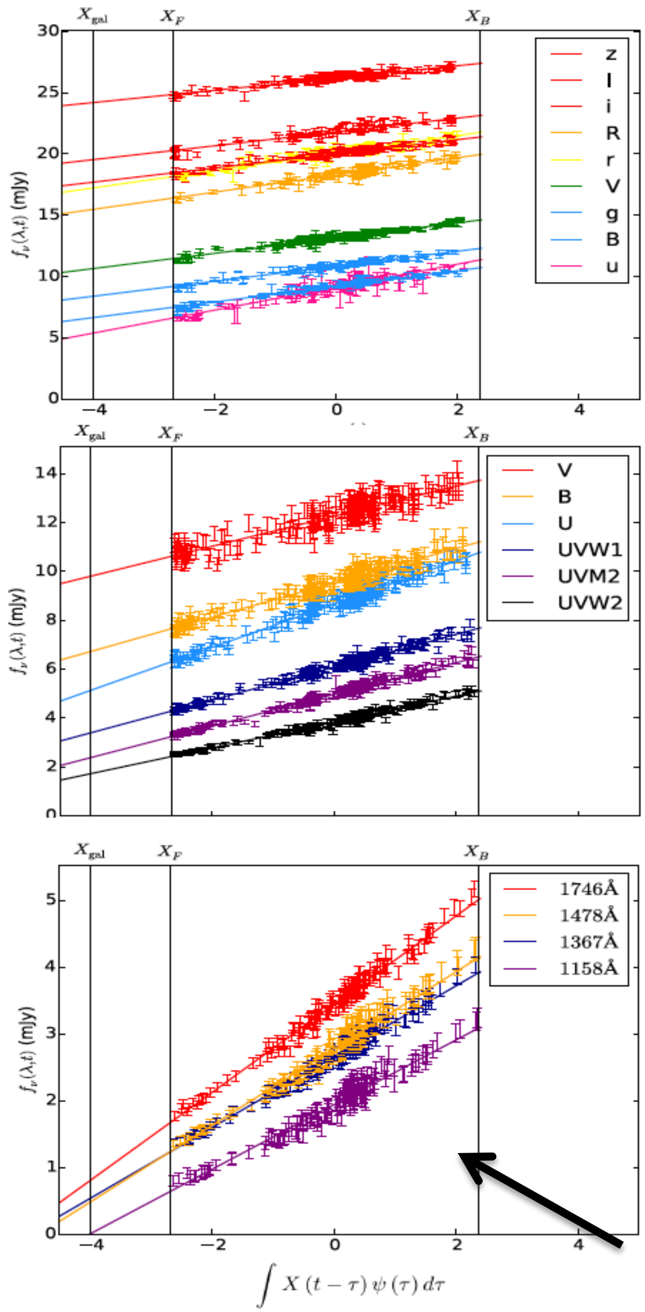
T_1 = 44000 +/- 6000 K
α = 0.99 +/- 0.03
i = 36° +/- 10°







Starkey, et al. 2017



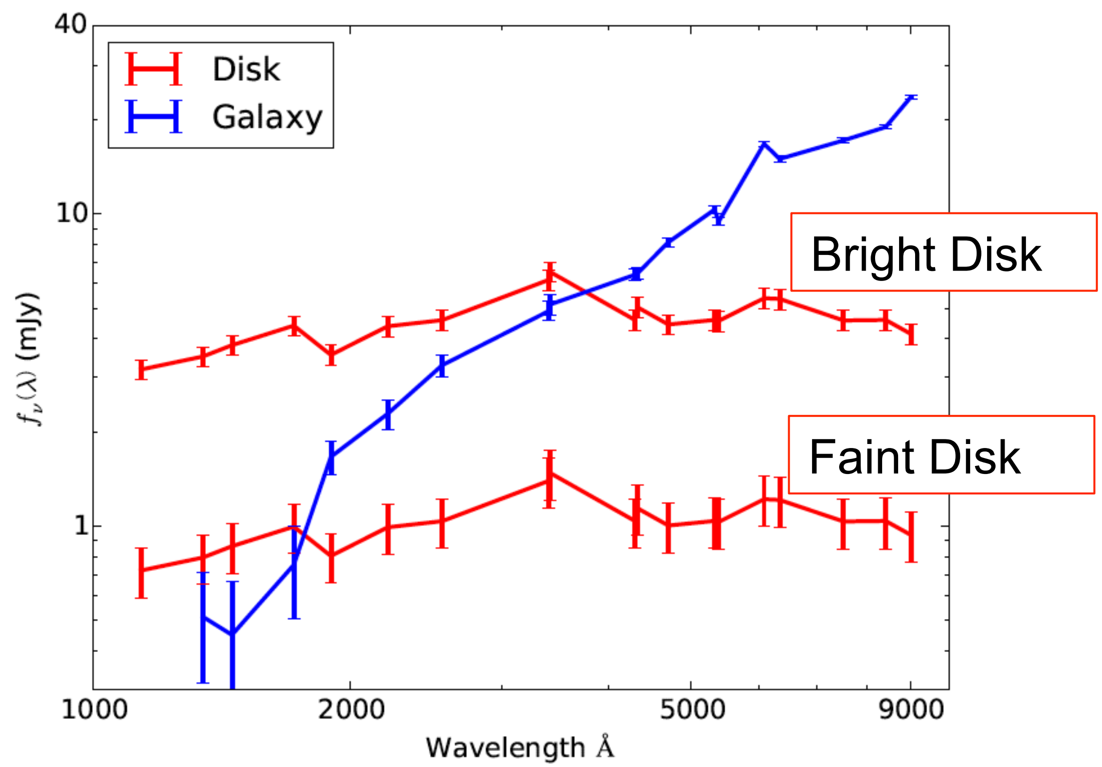
Disc Spectrum

Use ***variations*** to isolate the Disc Spectrum

$$F(\lambda, t) = A(\lambda) + S_{disk}(\lambda)\, X(t)$$

$$= G(\lambda) + S_{disk}(\lambda)\,(X(t) - X_G)$$

$$\langle X \rangle = 0 \qquad \langle X^2 \rangle = 1$$

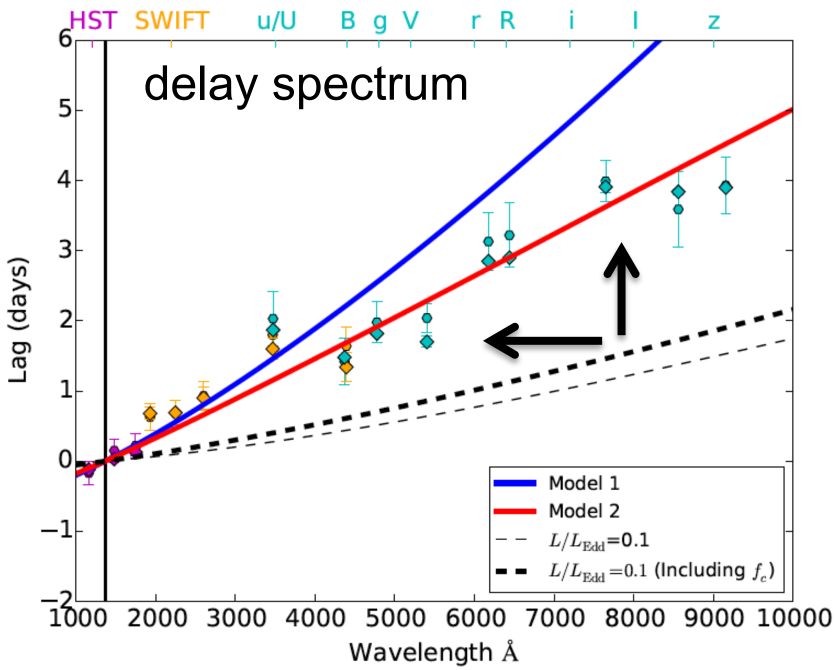


Note linear variations over x5 in flux at 1158A

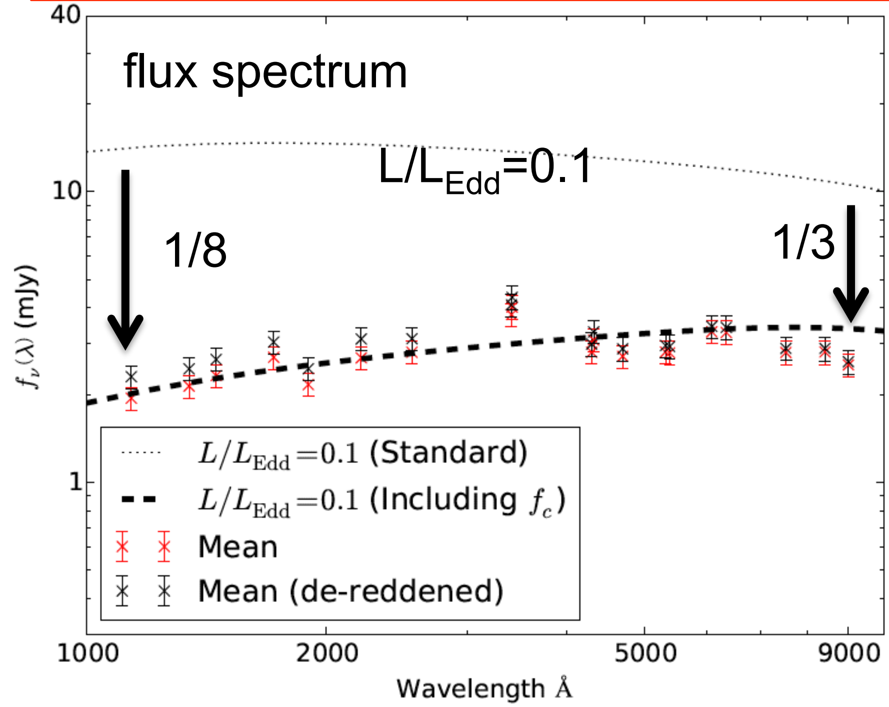
Starkey, et al. 2017

Standard Disc Model Fails ☹

Disc $\tau(\lambda)$ => T(R) steeper than expected ($T \sim R^{-1}$ vs $R^{-3/4}$)



Disc $f_\nu(\lambda)$ is fainter than expected (for L/L_{Edd}=0.1)



How does the standard disc model fail?

Disk is too hot (or large).

T(R) is too steep.

Surface brightness is too dim.

Starkey, et al. 2017

Why does the disc model fail ?

Dust ? (affects flux but not delay)

Wrong M_{BH}? (higher / lower L_{edd})

Diffuse continuum from BLR ?

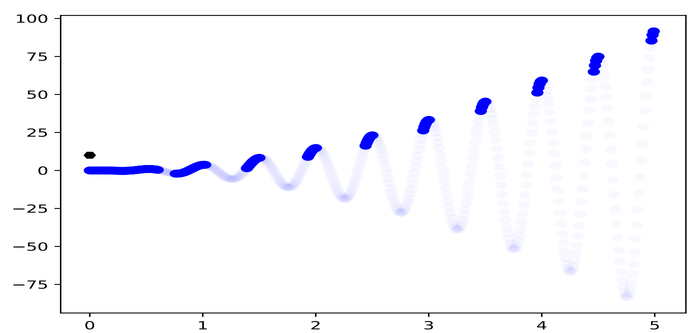
Patchy irradiation (shadows) ?

Tilted inner disc ?

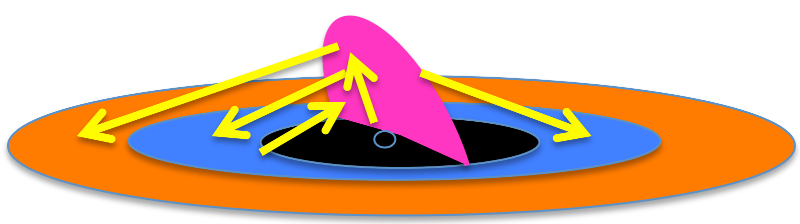
Warps/Waves/Ripples on the Disc ?

- Wave crests see the lamp-post.
- Shadows fill the troughs.
- Steepens *T(R)* profile, lowers surface brightness.

Starkey, Lin, Horne, in prep

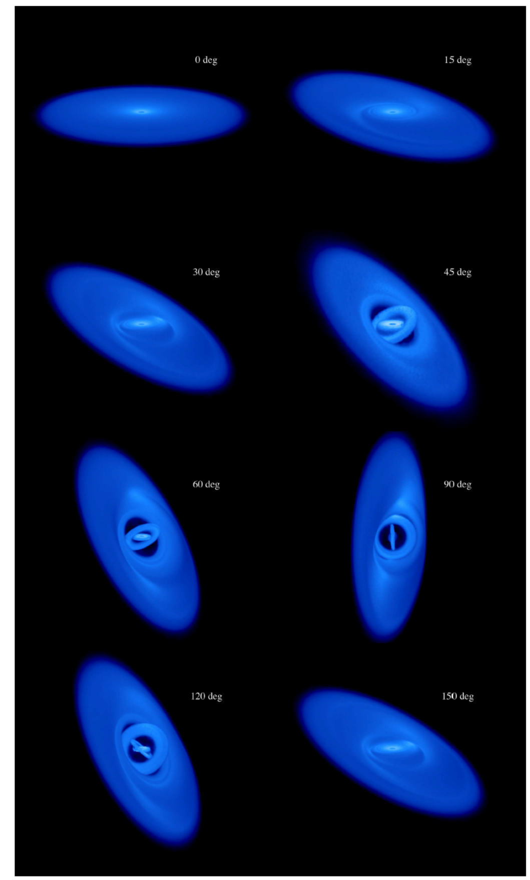


- Tilted inner disc (aligning with BH spin).
- Anisotropic irradiation, self-irradiation.
- Precession (rotating structure) observable?

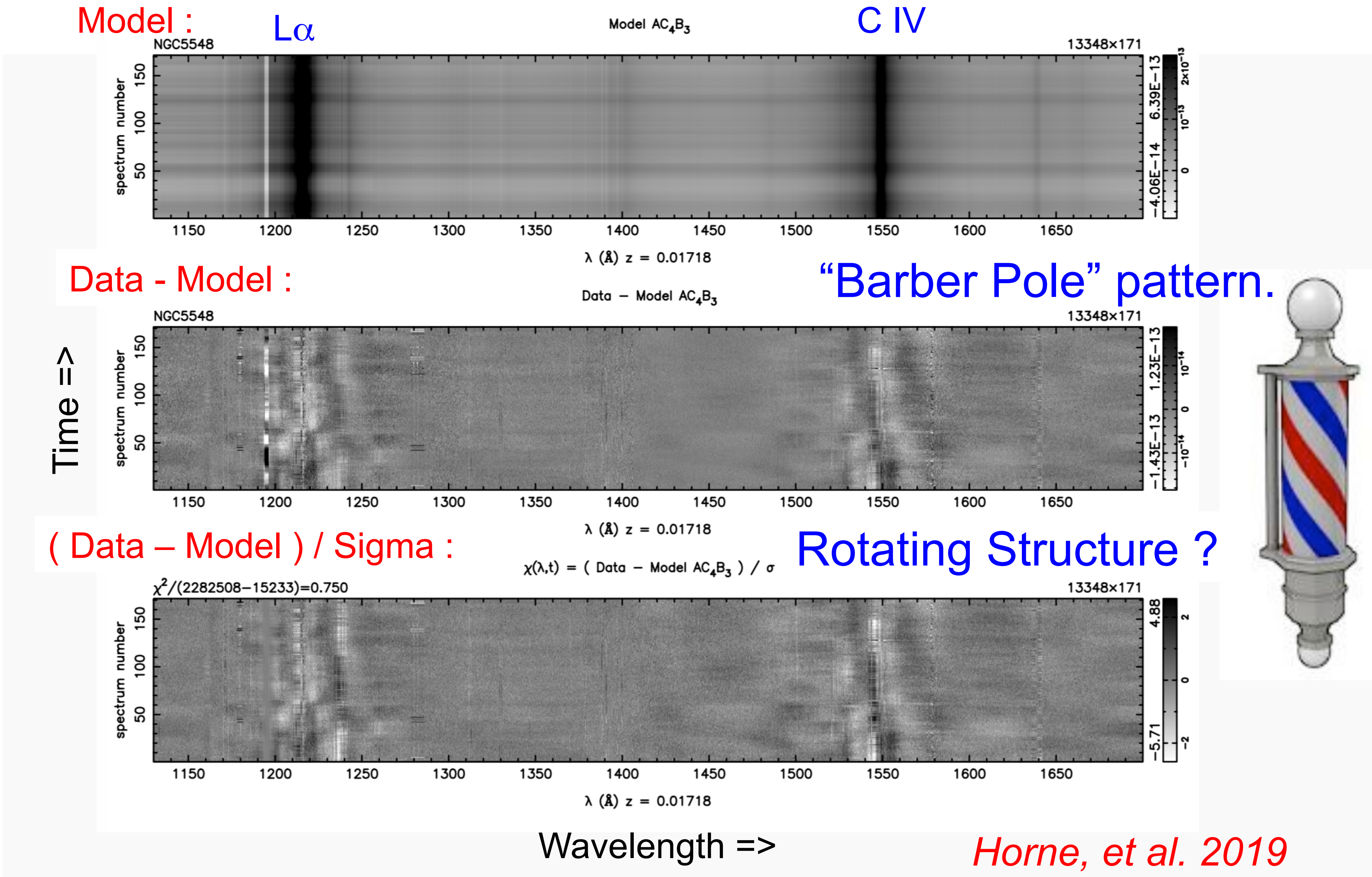


Nealon, Price, Nixon 2015 MNRAS

3d SPH simulations



HST Spectra of NGC 5548
“Barber-Pole” Residuals



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The RMS spectrum fits $f_\nu \sim \nu^{1/3}$ ☺

Keith Horne, SUPA St Andrews.

2019 Sep 21, Guilin

University of St Andrews

Danmarks Grundforskningsfond
Danish National Research Foundation

John R. Weaver

directly probing the quasar **accretion disc** with **multi-epoch photometry**

PhD Research Fellow

DAWN The Cosmic Dawn Center

Fellow, Royal Astronomical Society

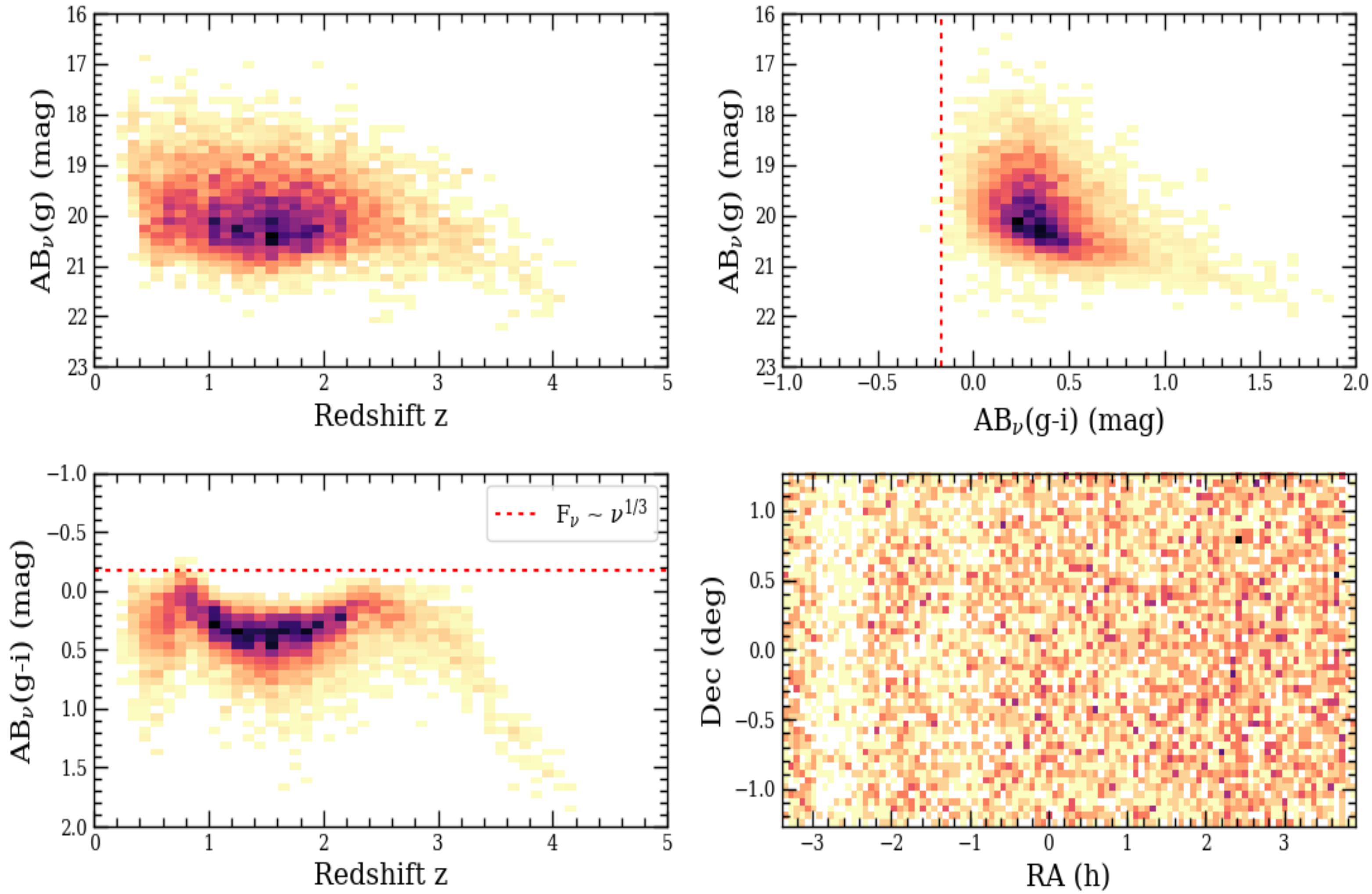
Niels Bohr Institute, University of Copenhagen
@astroweave |
john.weaver.astro@gmail.com

with **Keith Horne** (St Andrews)

SDSS Stripe 82 Sample: (Macleod et al. 2012)

9258 Quasars with u g r i z lightcurves over ~10 yr

Quasar Spectra are Redder than $F_\nu \sim \nu^{1/3}$.



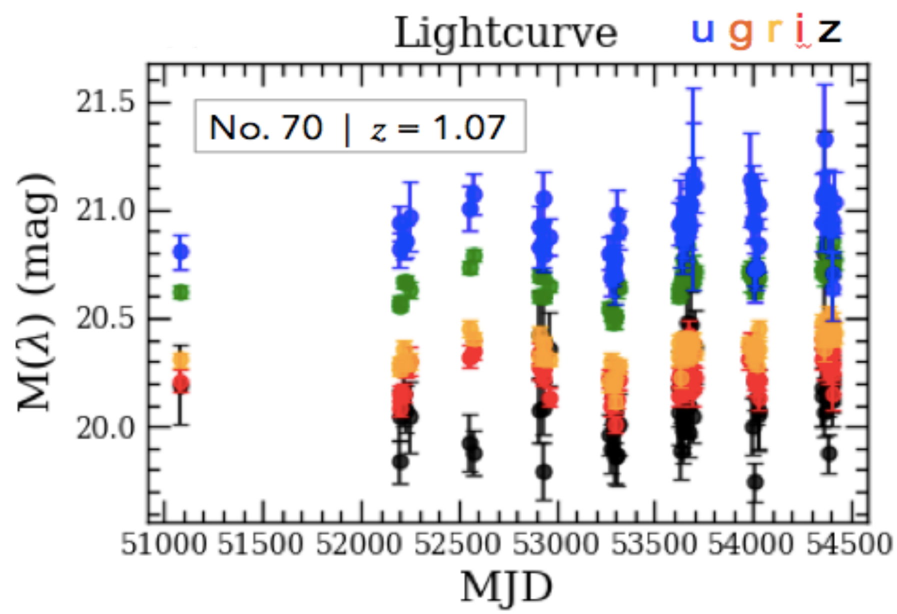
Variations can isolate the Disc Spectrum

Decompose **u g r i z lightcurves** into mean and variations for **each** of the 9258 quasars in Stripe 82

$$F(\lambda,t) = A(\lambda) + B(\lambda)\, L(t)$$

average   rms   variability

Solve for **A**(λ), **B**(λ), and **L**(t)



A(λ) = static component spectrum
= accretion disc + host galaxy starlight?

B(λ) = variable component spectrum
= **accretion disc ?**

Does the variable light have a $\nu^{1/3}$ **accretion disc** spectrum?

Decomposition of ugriz Lightcurves

$$F(\lambda,t) = A(\lambda) + B(\lambda)\, L(t)$$

average — rms — variability

Mean $\mathbf{A}(\lambda)$

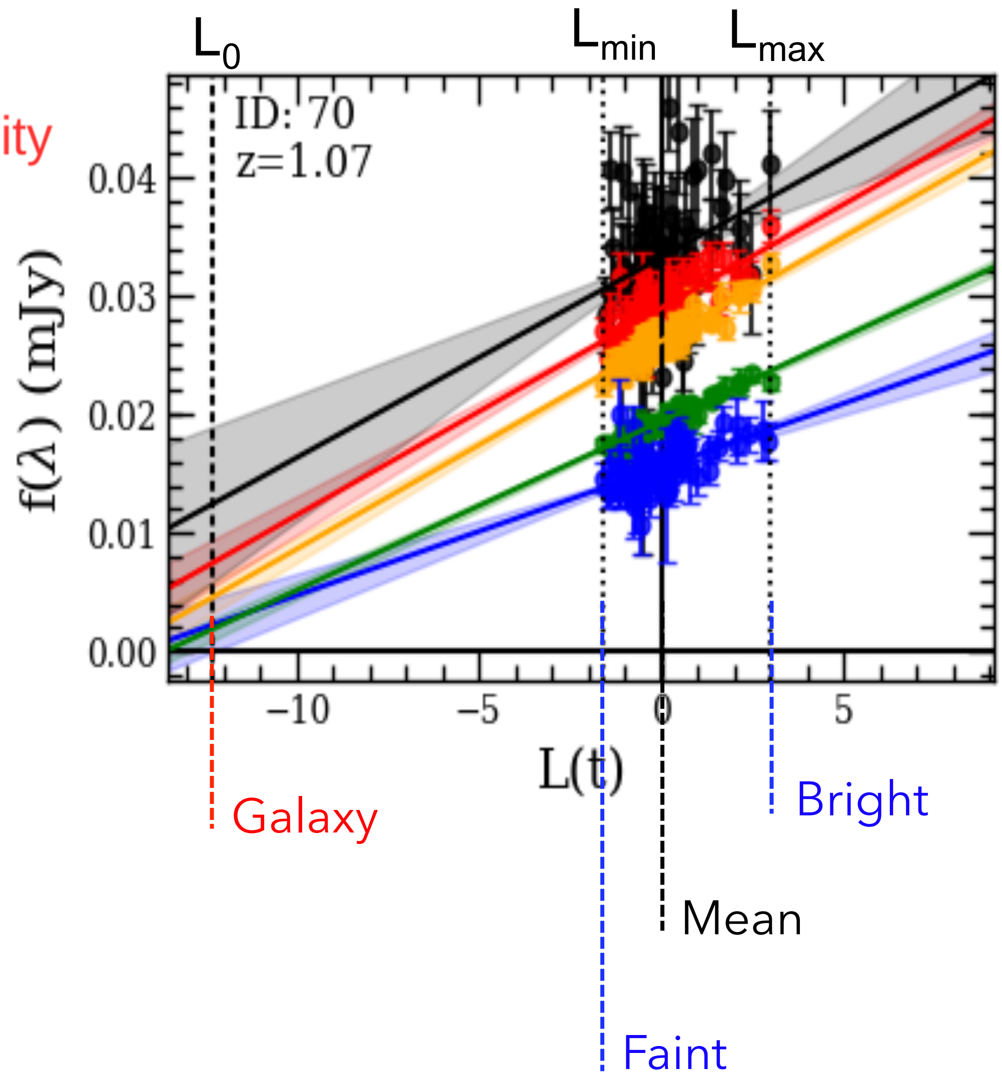
RMS $\mathbf{B}(\lambda)$

Bright $\mathbf{A}(\lambda) + \mathbf{B}(\lambda)\, \mathbf{L}_{max}$

Faint $\mathbf{A}(\lambda) + \mathbf{B}(\lambda)\, \mathbf{L}_{min}$

Galaxy $\mathbf{A}(\lambda) + \mathbf{B}(\lambda)\, \mathbf{L}_{0}$

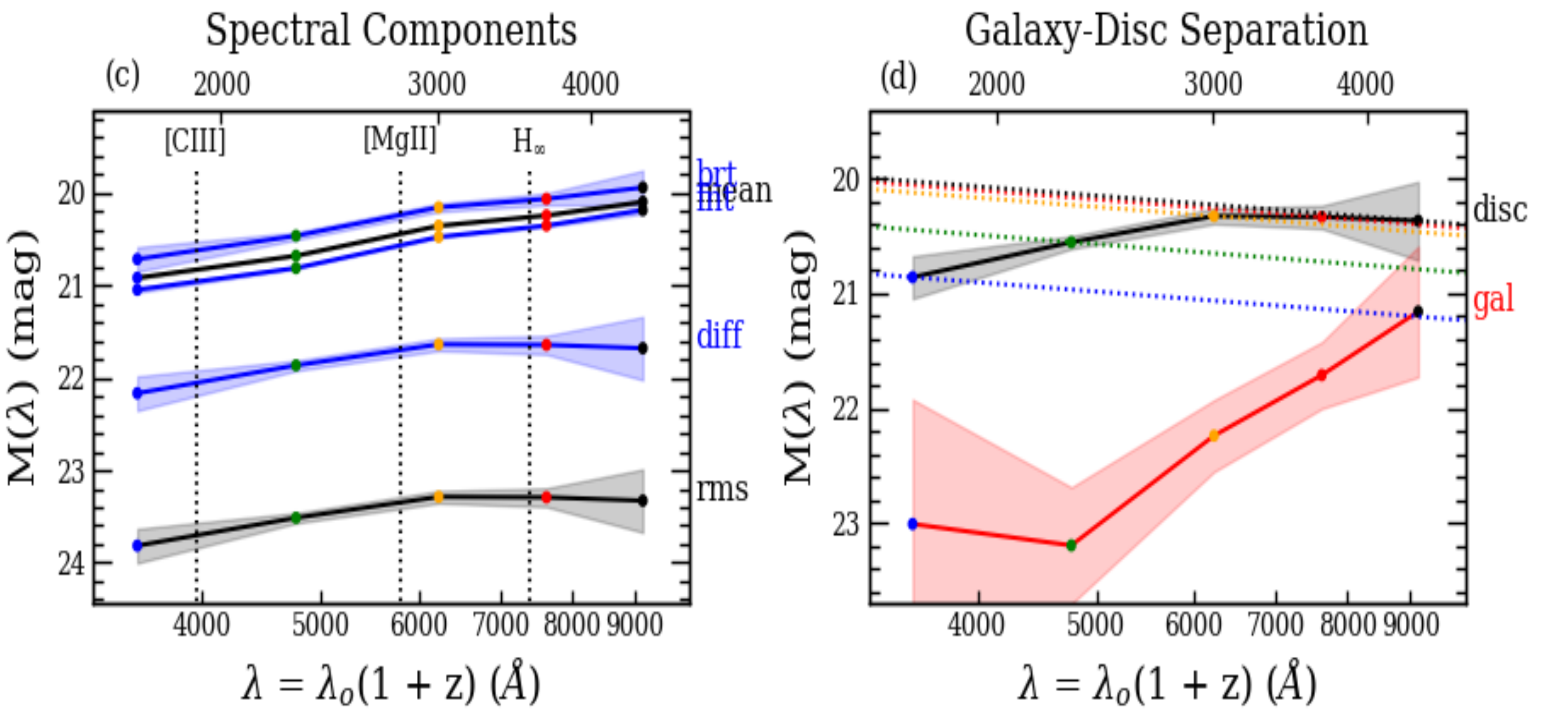
Bright Disc $\mathbf{B}(\lambda)\, (\mathbf{L}_{max} - \mathbf{L}_{0})$



The Disc and Galaxy Spectra

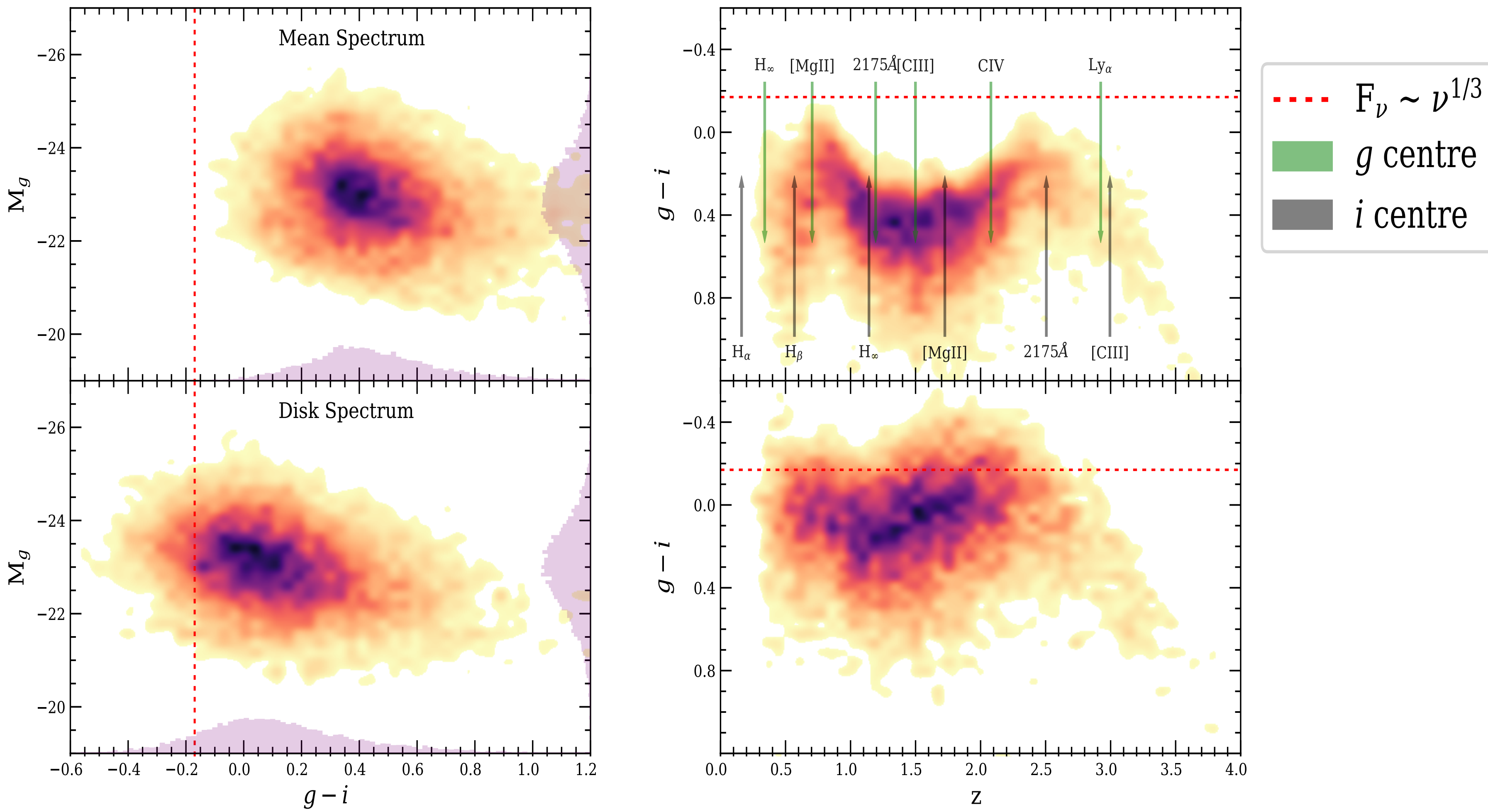
Separate **disc** and **galaxy** components

No. 70 | z = 1.07



Variable Component Demographics

Variable quasar light is closer to $\nu^{1/3}$, but still too red. ☹



Dust in the AGN or Host Galaxy ?

Quasar disc spectra may be **strongly affected by dust.**
Determine minimum dust extinction required to fit $F_\nu \sim \nu^{1/3}$
for **each** of the 9258 quasars in Stripe 82
to **constrain the best-fit dust law** for this sample.

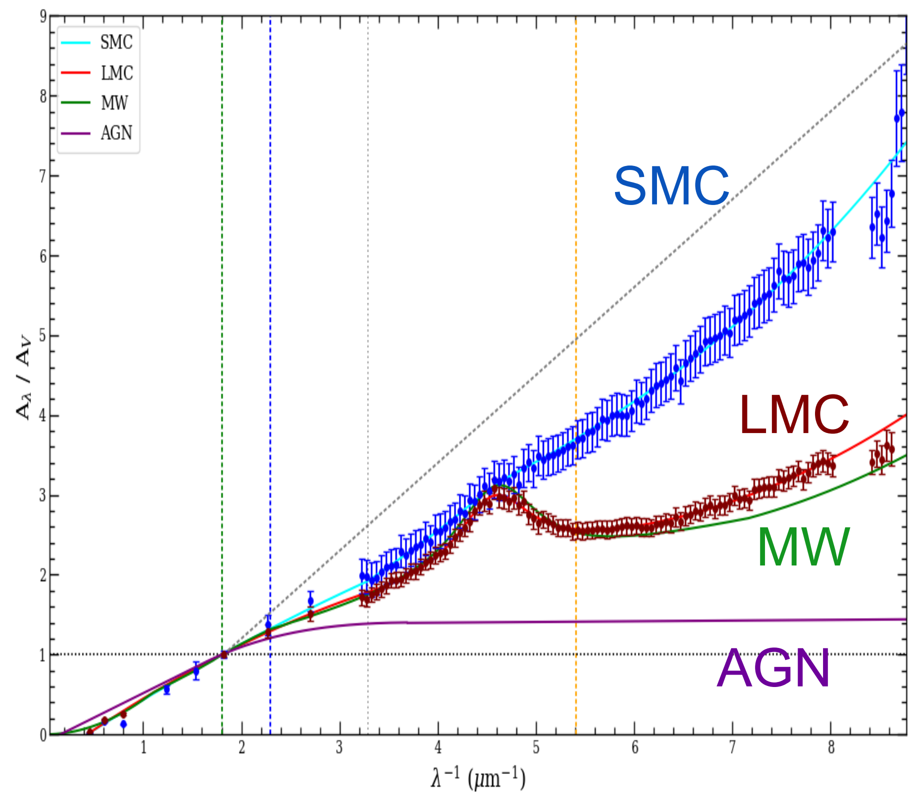
I – Small Magellanic Cloud
{Gordon et al. 2003}

II – Large Magellanic Cloud
{Gordon et al. 2003}

III – Milky Way
{Seaton et al. 1979; Nandy et al. 1975}

IV – Gaskell AGN
{Gaskell et al. 2004}

4 dust extinction laws



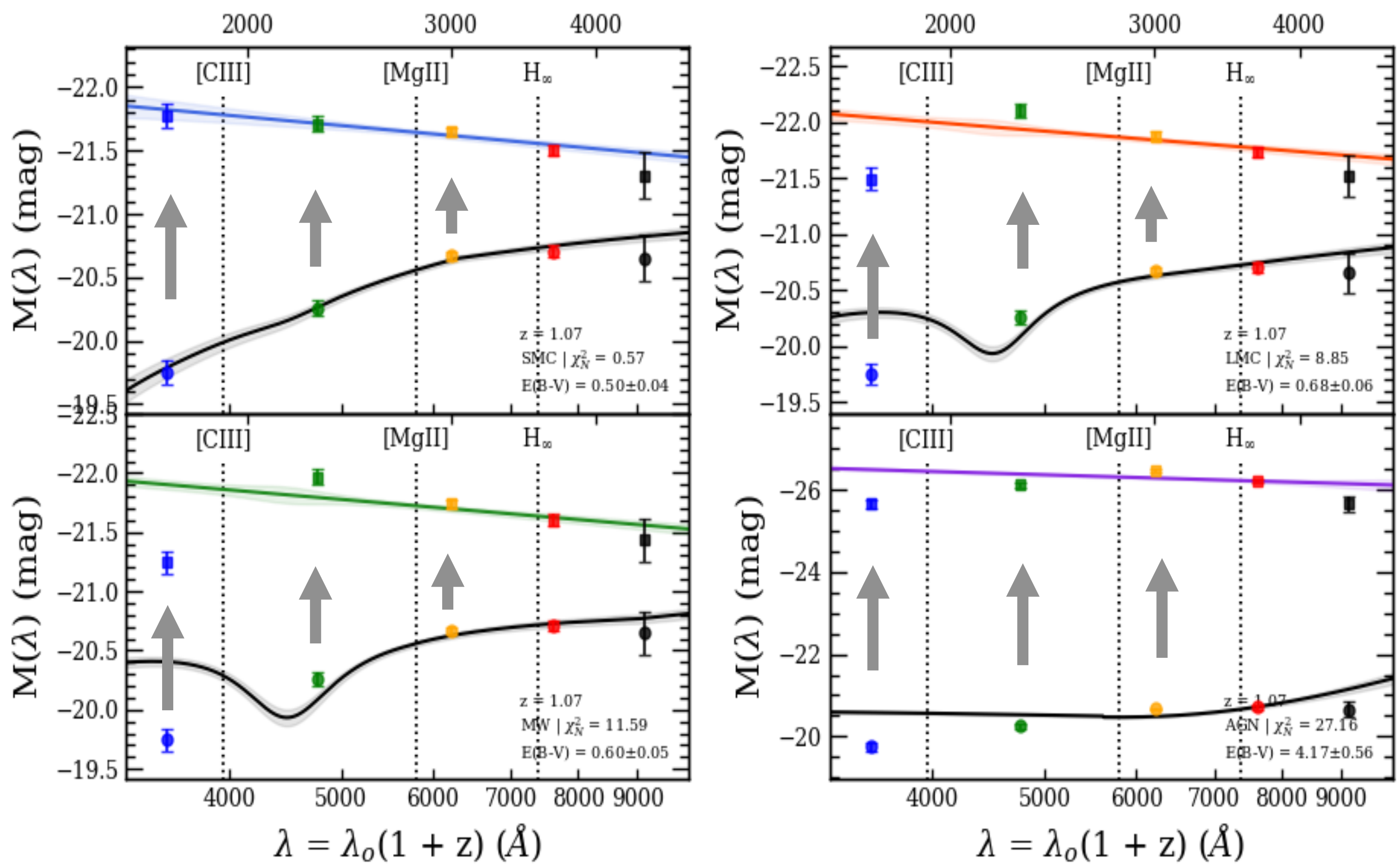
Dust Extinction Corrections

For each dust law, for each object:

I – determine best-fit **E(B-V)**

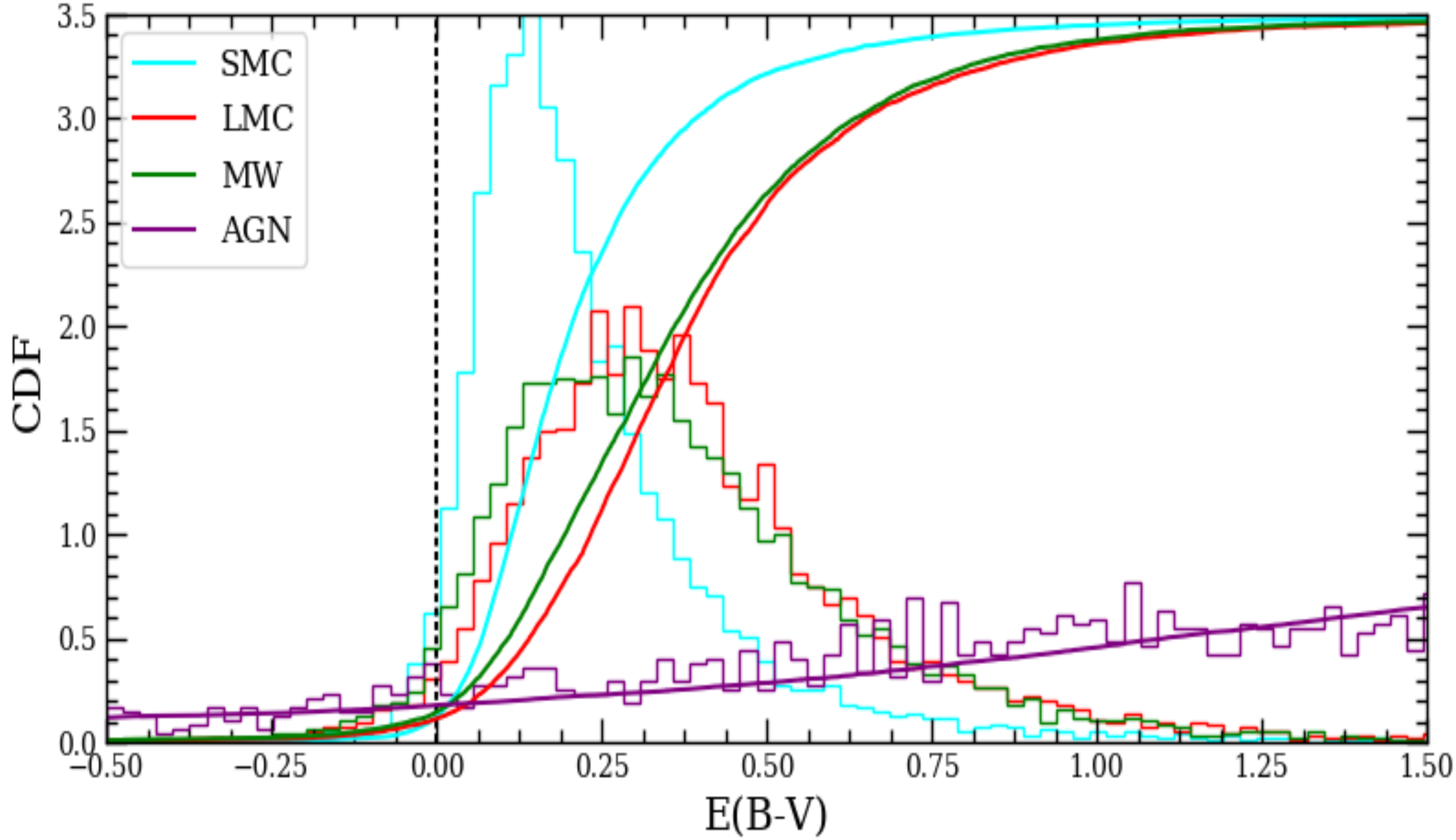
II – remove extinction term

No. 70 | z = 1.07



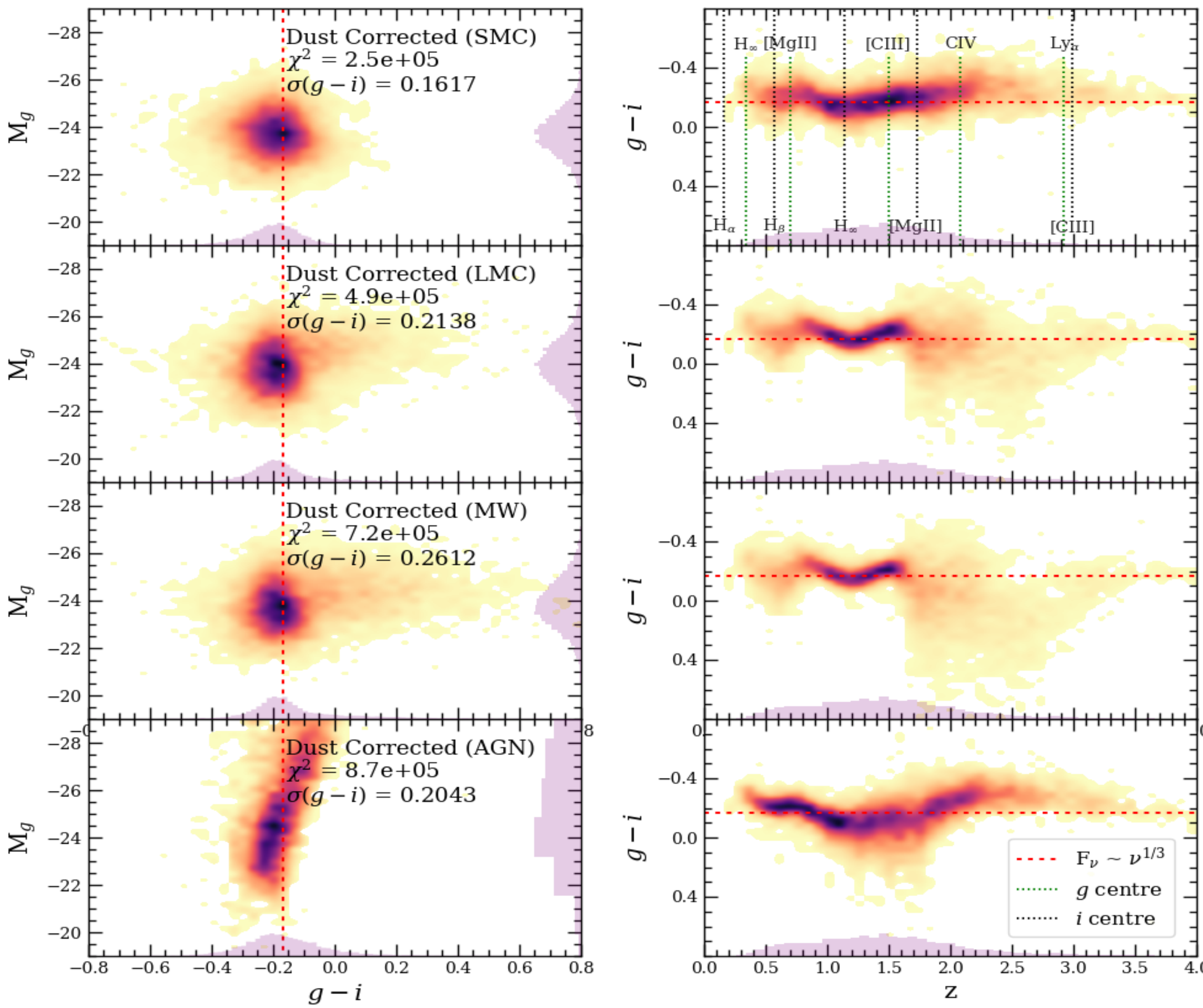
Dust Demographics

E(B-V) distributions for the 4 dust laws



SMC-like Dust fits best

SMC fit has smallest χ^2 and $\sigma(g-i)$

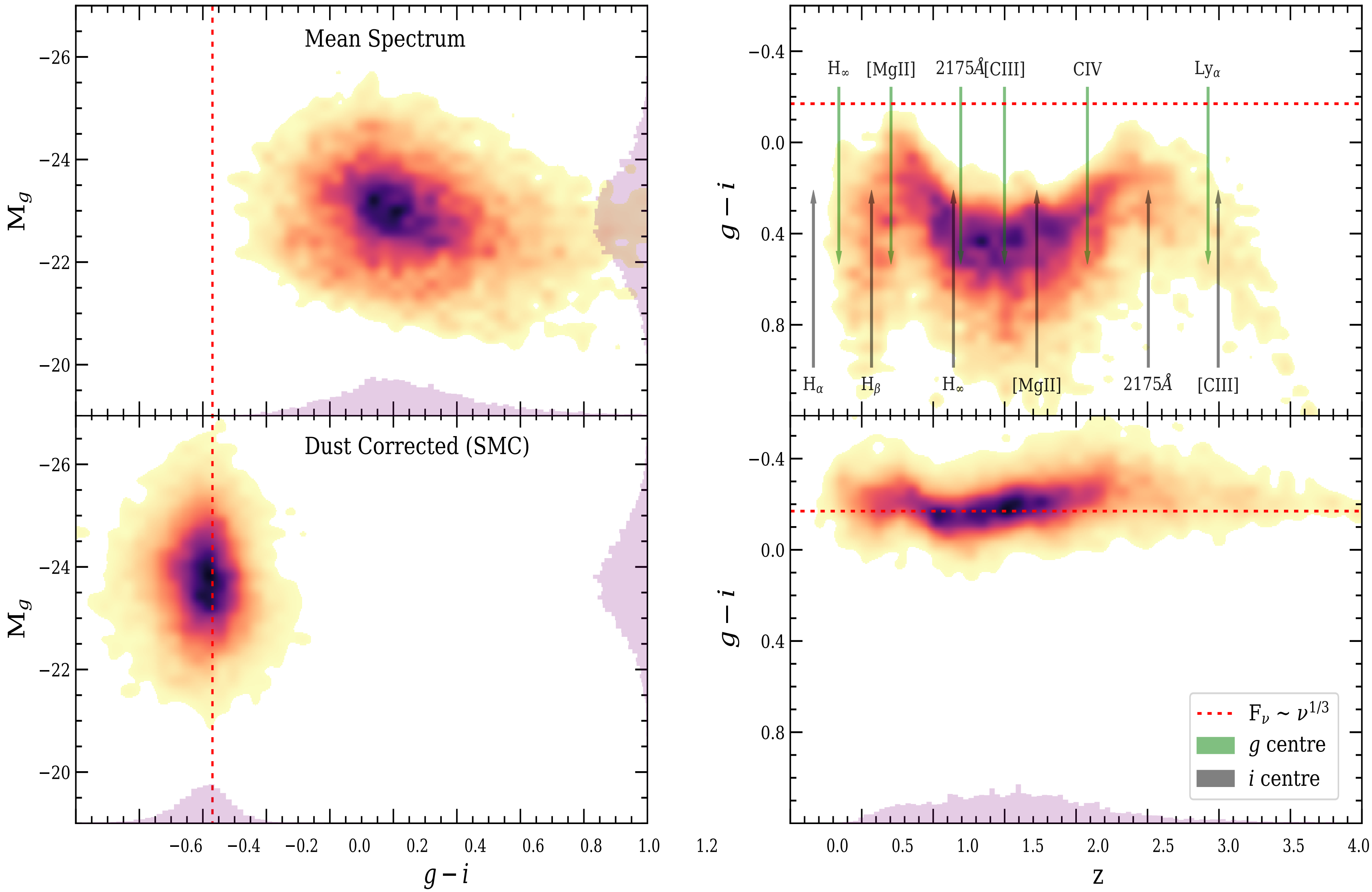


Best-fit fraction of quasars

SMC	56%
LMC	19%
MW	16%
AGN	9%

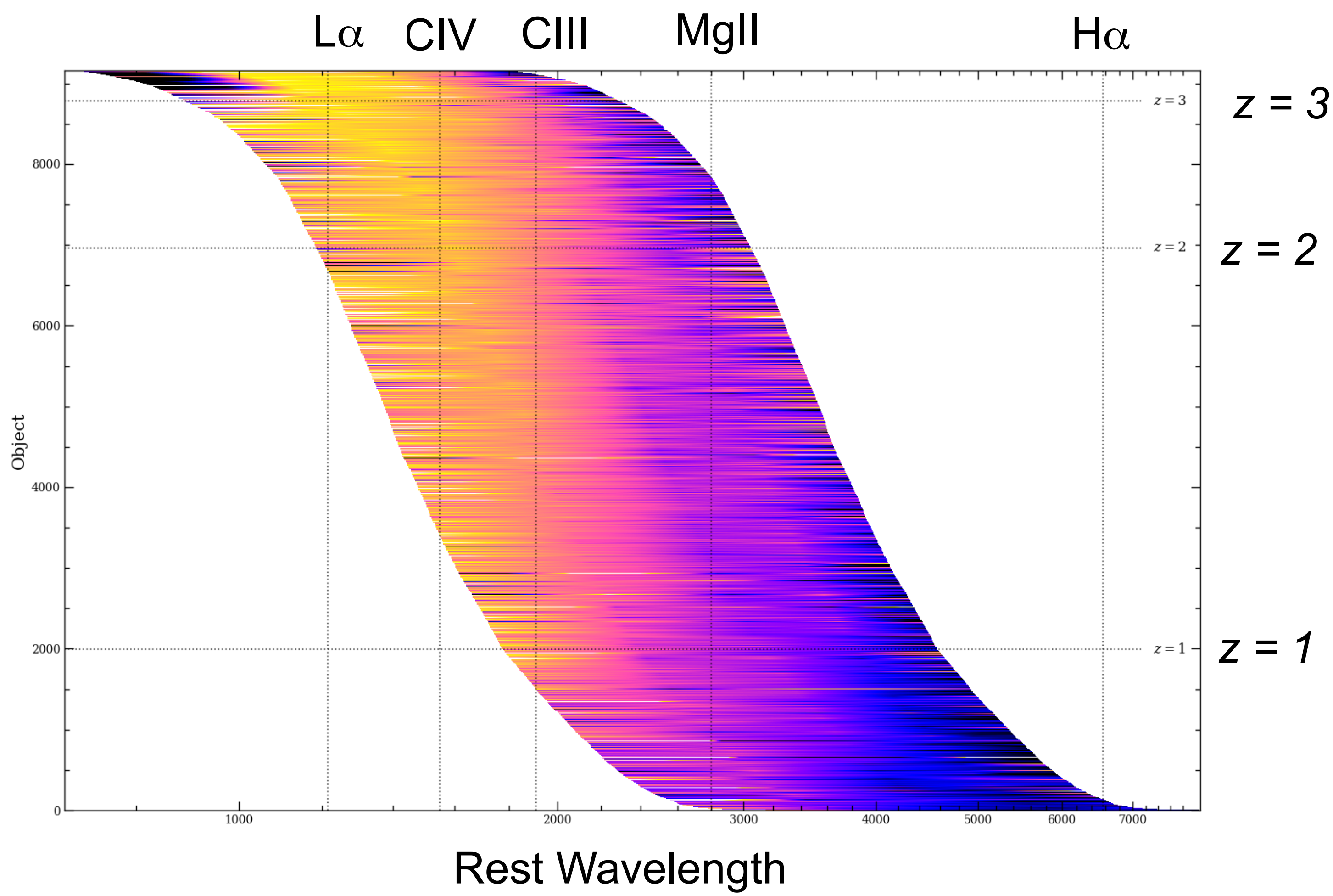
SMC Dust corrected Disc "Spectra"

Quasar Disc spectra now centre on the $\nu^{1/3}$ slope ☺

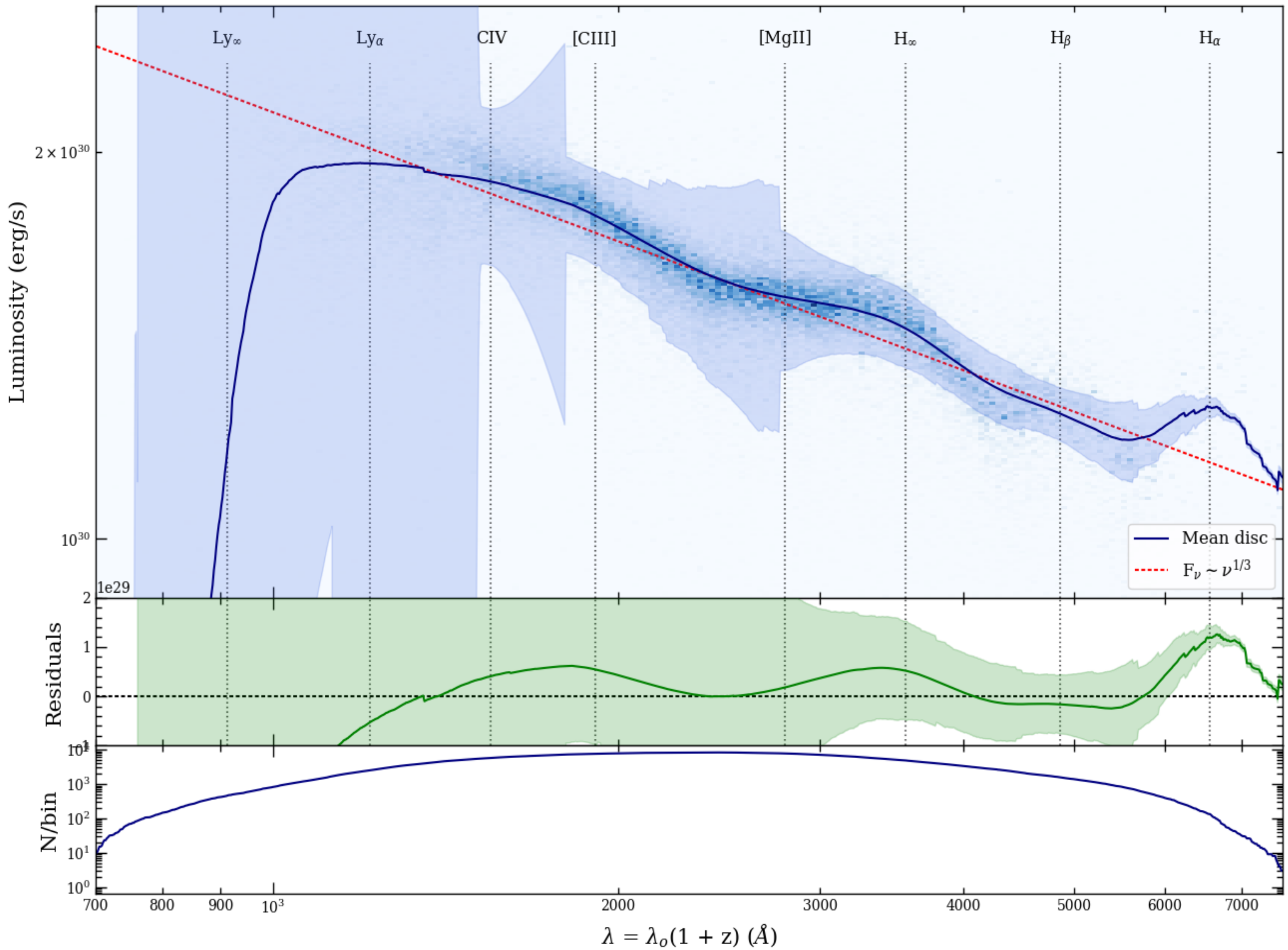


9258 Dust-Corrected Disc "Spectra"

assuming an SMC-like attenuation curve



Composite Disc "Spectrum"



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SDSS-RM Survey

- PI: Yue Shen
- SDSS spectroscopic monitoring of 849 quasars ($0.12<z<4.3$) (plus ~100 comparison stars.)
- SDSS-III (2014, 32 epochs/6mo)
- SDSS-IV (2015-2019..., 12 epochs /6mo)
- Bok+CFHT photometric (g,i) monitoring.

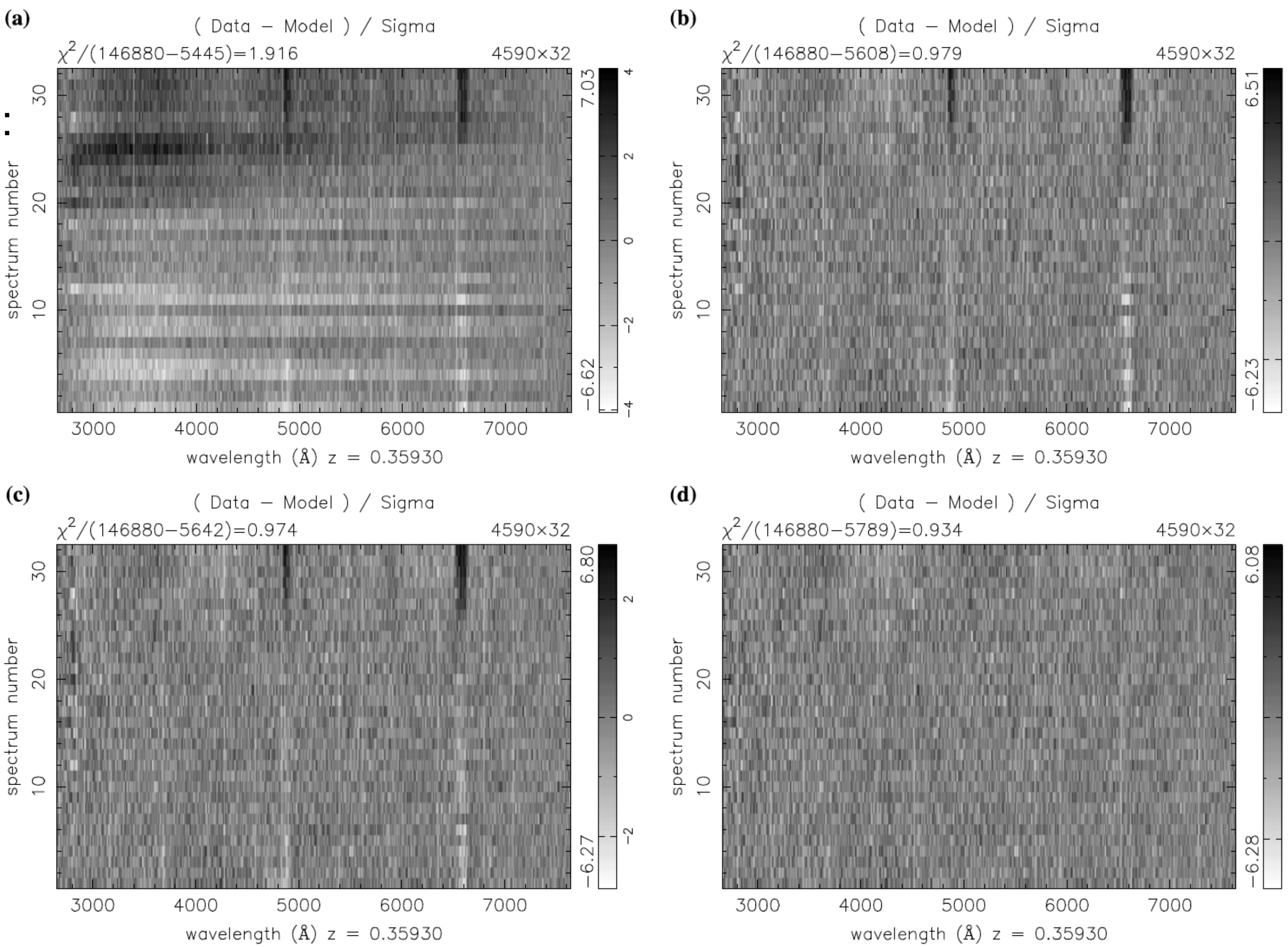
- Primary Goals: Measure light travel time delays.
- Emission-line lag vs continuum => black hole masses
- Continuum lag vs wavelength => accretion disk T(r) profiles.

- Pilot for SDSS-V => Black Hole Mapper

PrepSpec Analysis : Fit Residuals

Model: A

AC



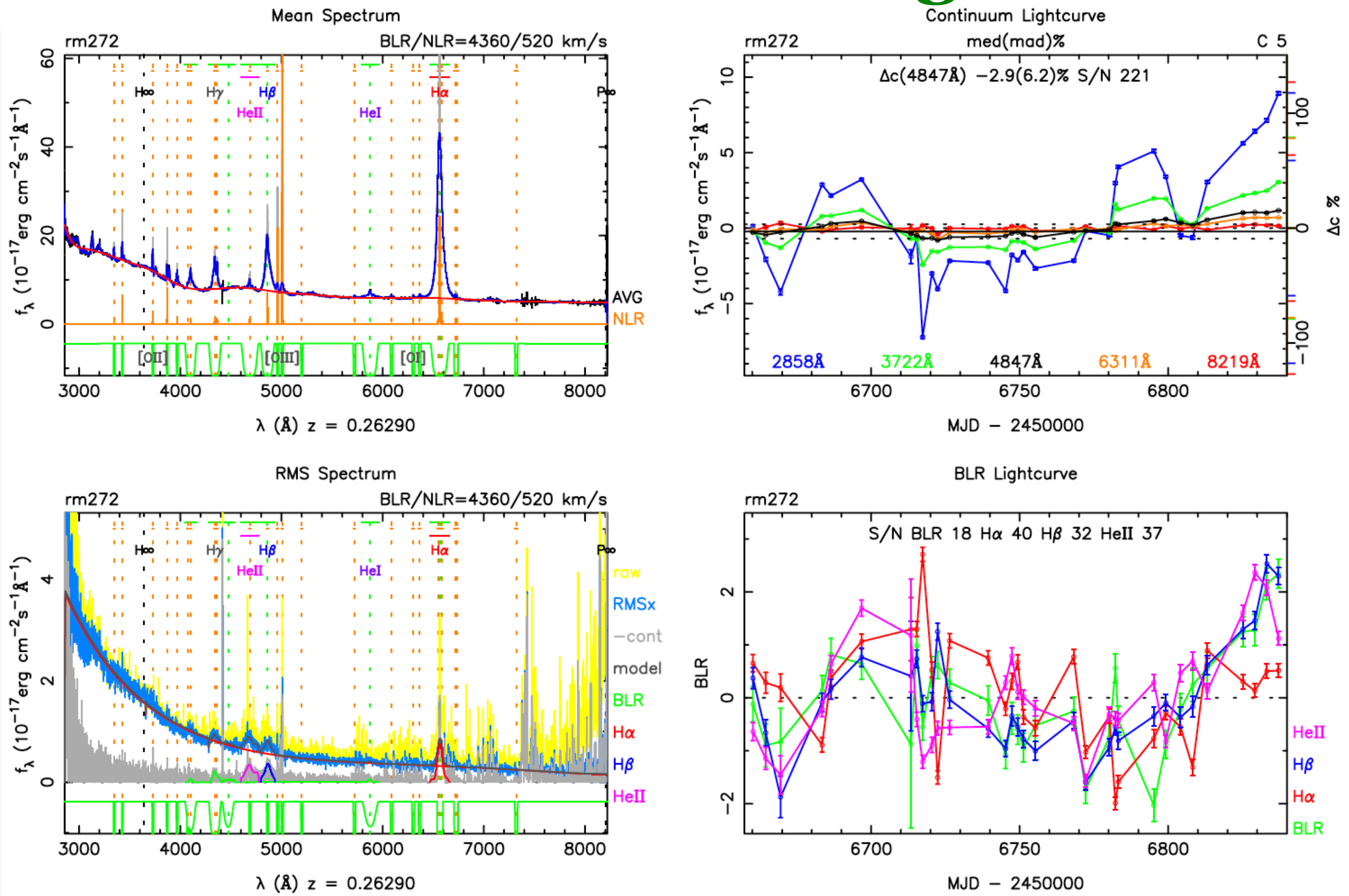
ACF

ACBF

Shen et al. 2016

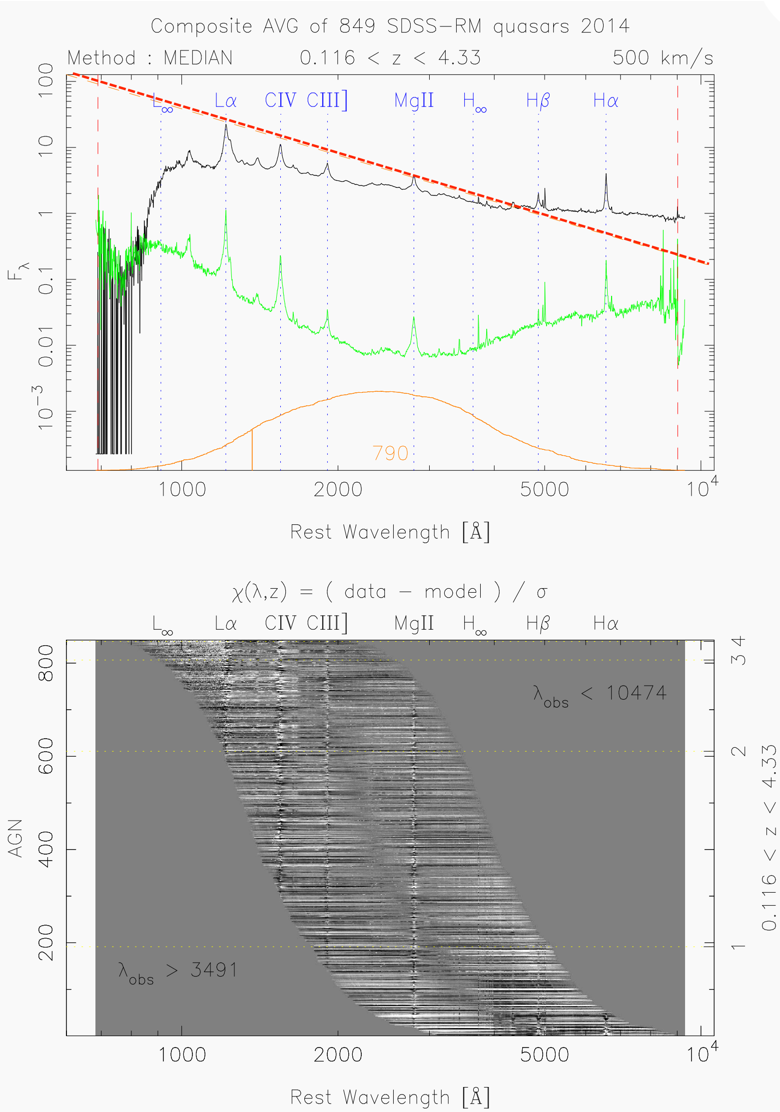
$$f(\lambda, t) = p(t)\ \left(A(\lambda) + B(\lambda, t) + C(\lambda, t)\right)$$

PrepSpec : Mean and RMS spectra, Line and Continuum Lightcurves

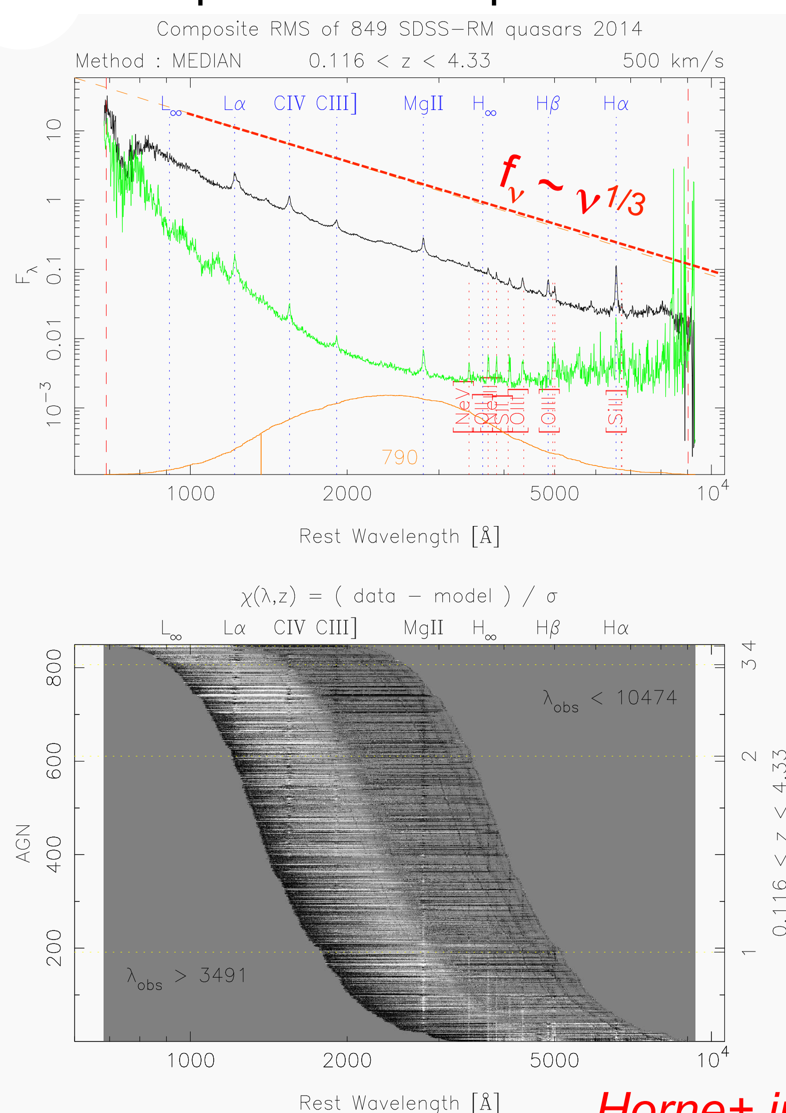


Composite Mean and RMS Spectra

- Composite Mean Spectrum



Composite RMS Spectrum

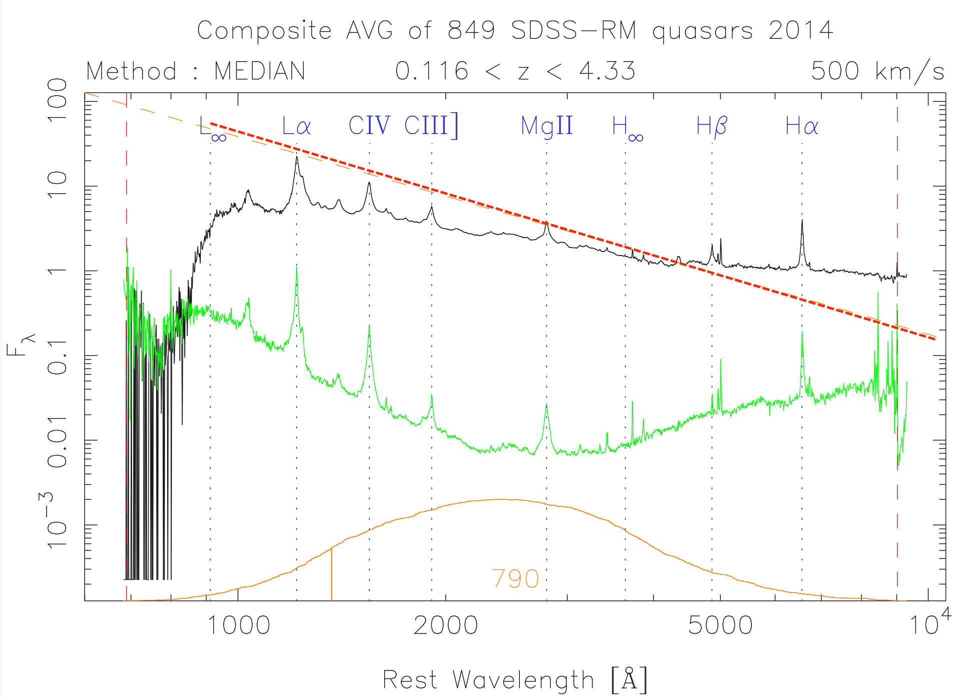


Horne+ in prep.

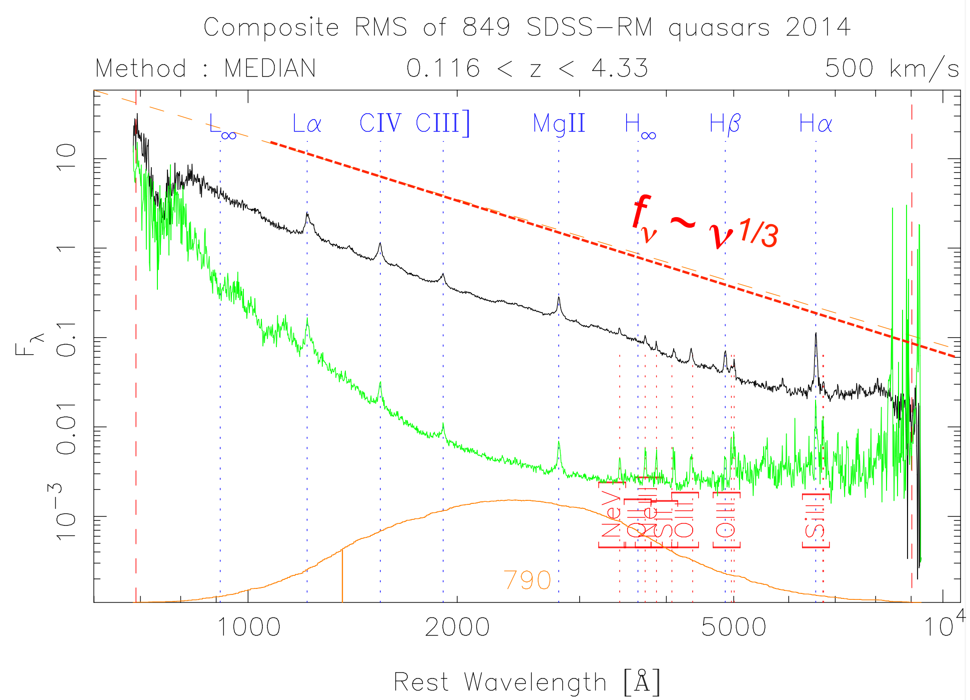
Composite Mean and RMS Spectra

- **Variations** isolate the Disc Spectrum:

Composite Mean Spectrum



Composite RMS Spectrum



Horne+ in prep.

$$T \propto r^{-3/4} \Rightarrow f_\nu \propto \nu^{1/3}$$

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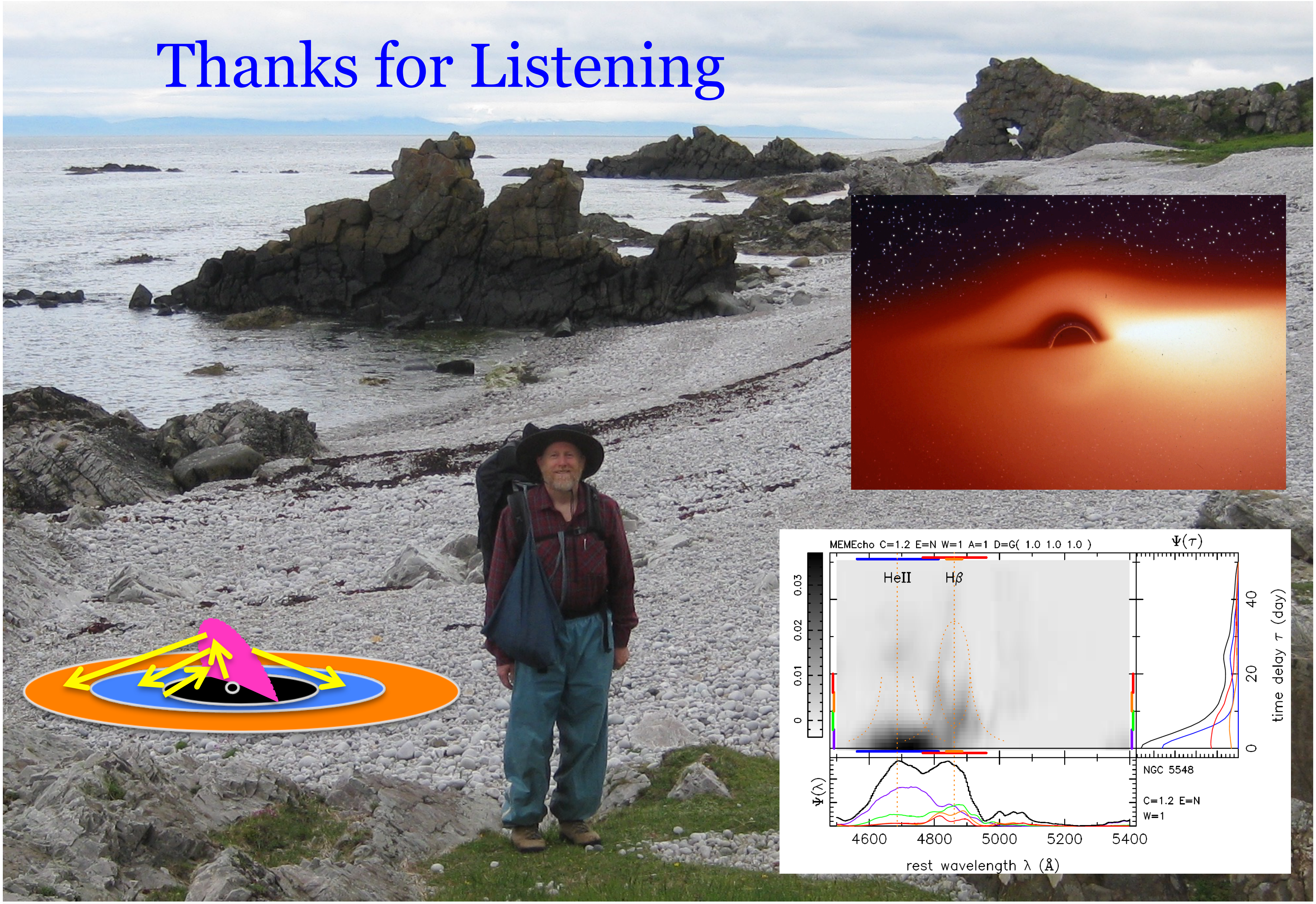
Perhaps the disc model is not quite dead yet.

Keith Horne, SUPA St Andrews.

2019 Sep 21, Guilin

Thanks for Listening



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Guilin, 2019 Sep 21