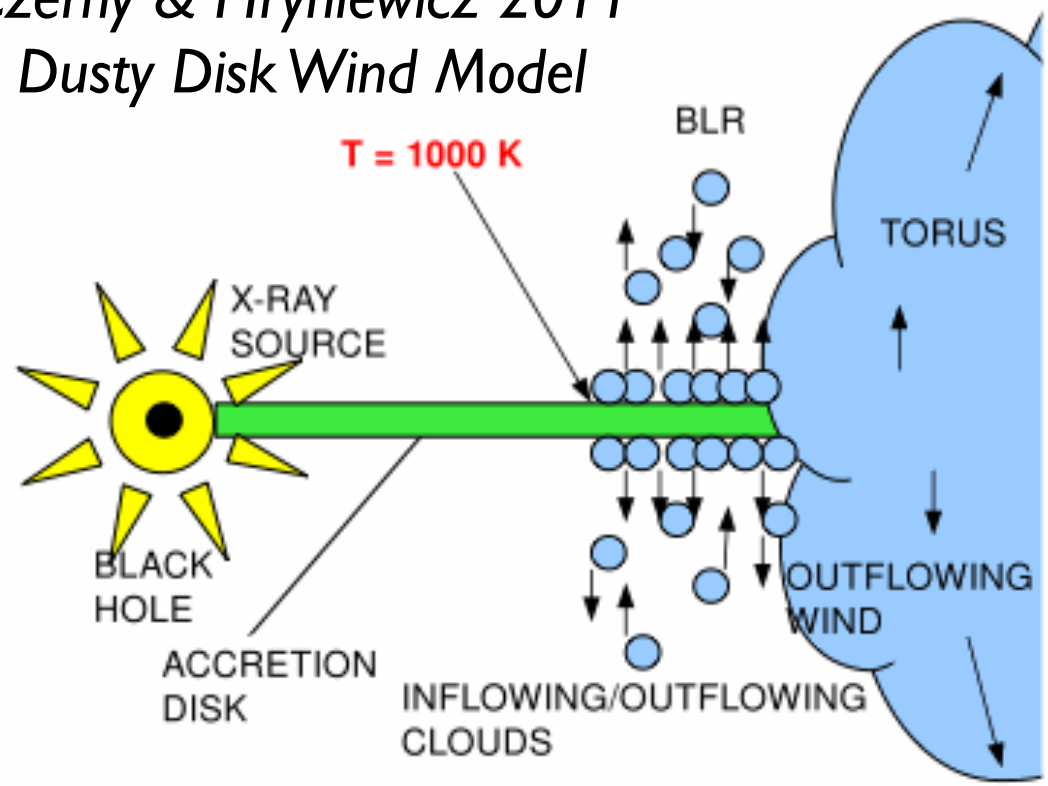
Echo Mapping of AGN Accretion Disks
AGN Distances for Cosmology

Czerny & Hryniewicz 2011
Dusty Disk Wind Model



Keith Horne
Pasquale Galianni

SUPA St Andrews

Echo Mapping:
micro-arcsec resolution
via light travel time delays

BH	Disk	BLR	Torus
hrs	days	weeks	months

Broad Emission-Line Reverberations

Correlated variations in the continuum and broad emission lines

Line variations lag behind the continuum

Light travel time delays.

13 years in the life of NGC 5548

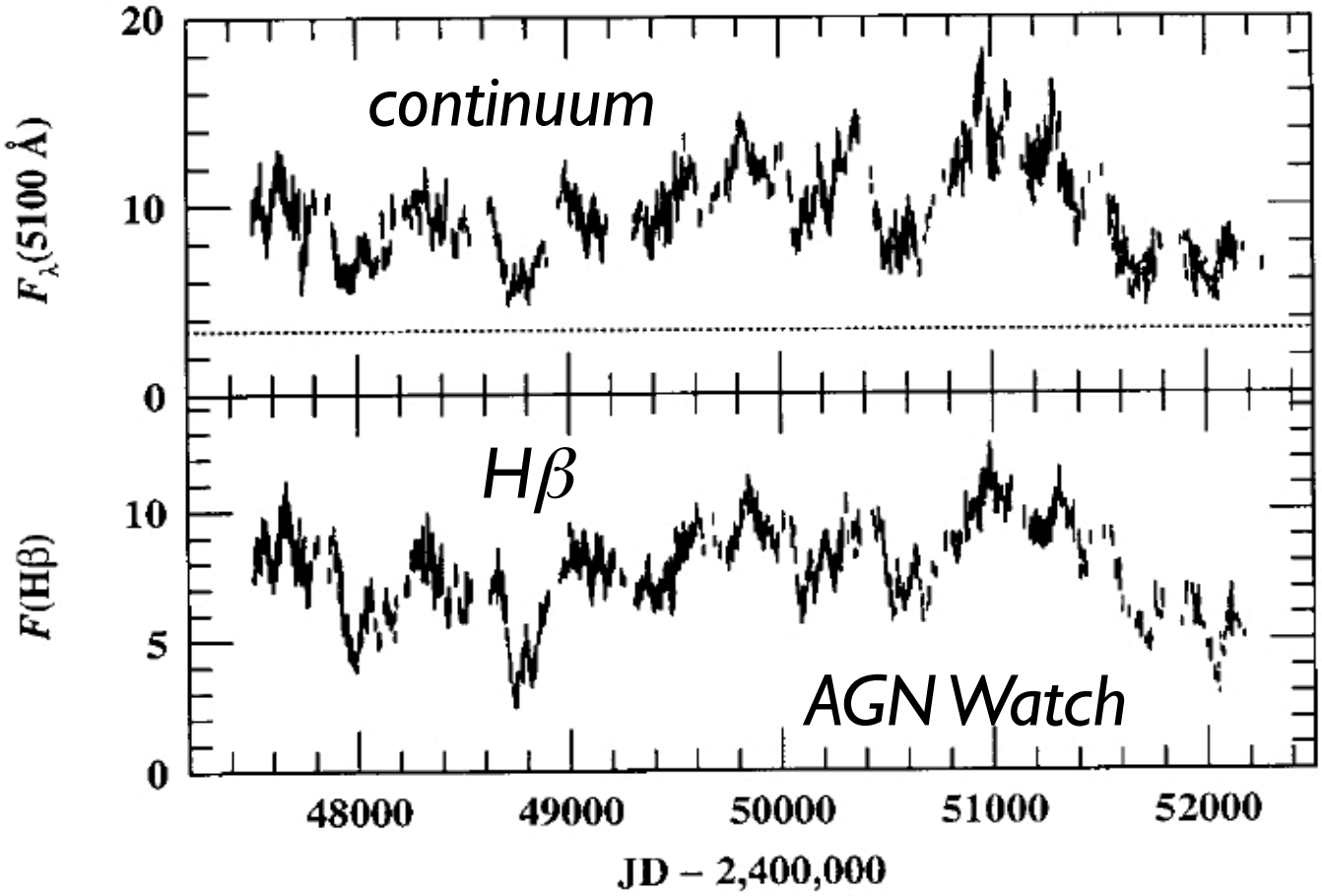


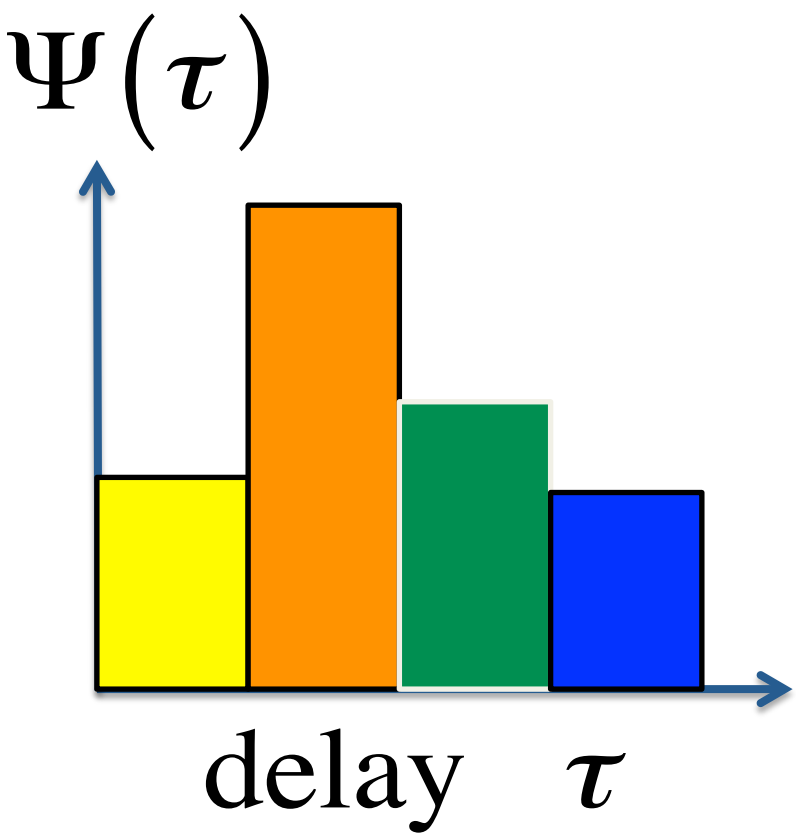
Photo-ionised and Doppler broadened emission lines

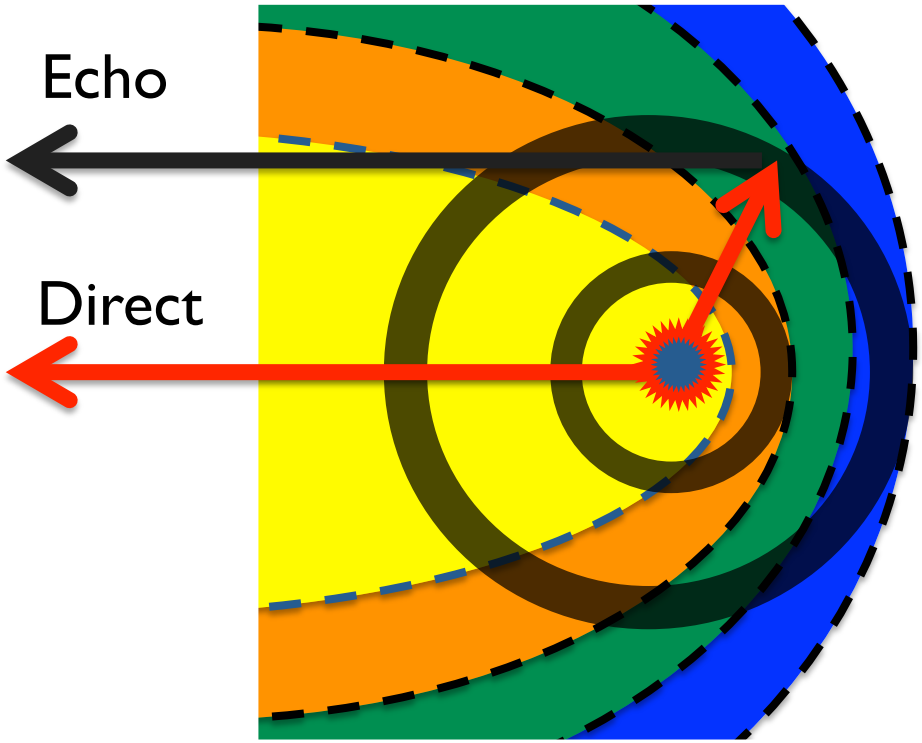
Echo Mapping

(aka Reverberation Mapping)

Micro-arcsecond Tomography of Acretion Flows

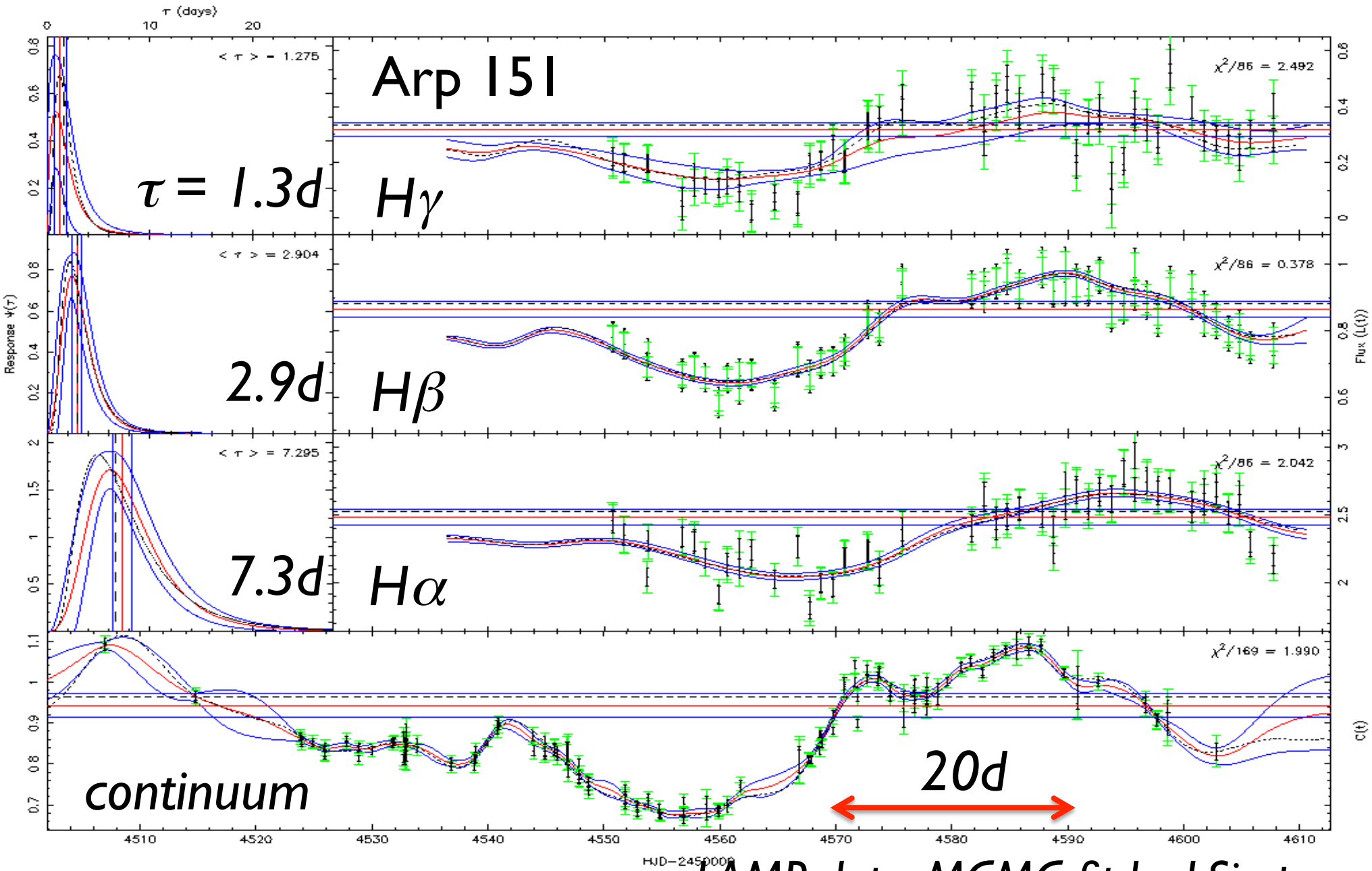
in Active Galactic Nuclei





$$\tau = \frac{R}{c}(1+\cos\theta)$$

Time Delays => BLR sizes

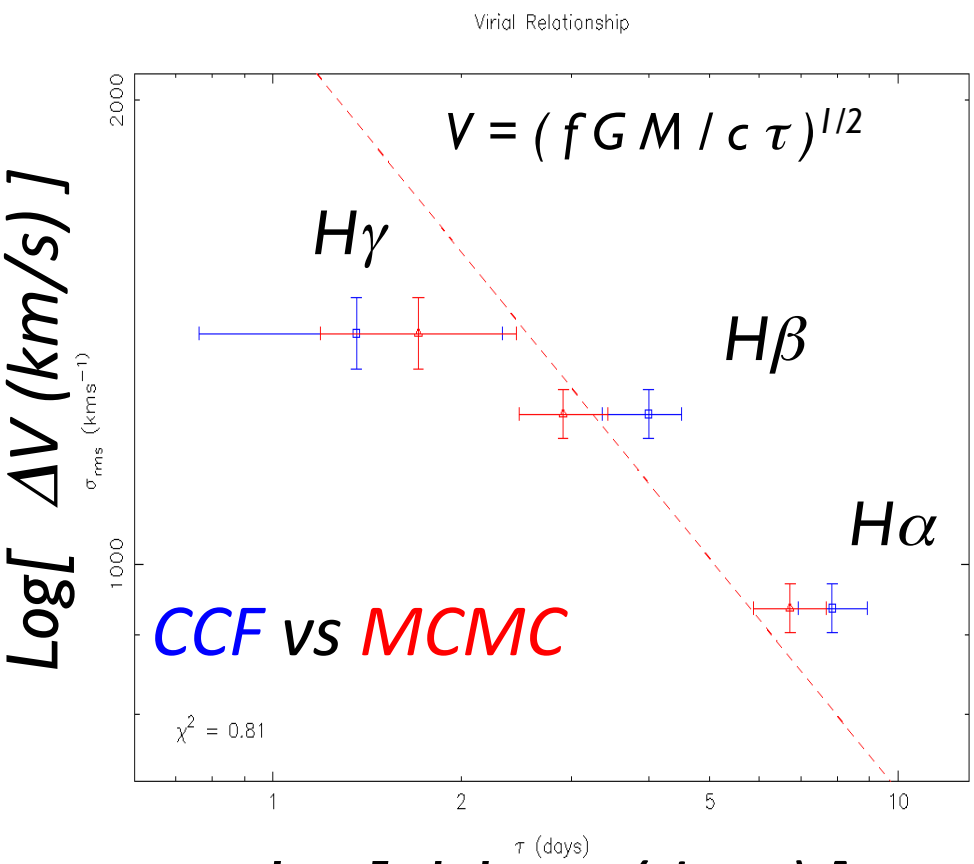


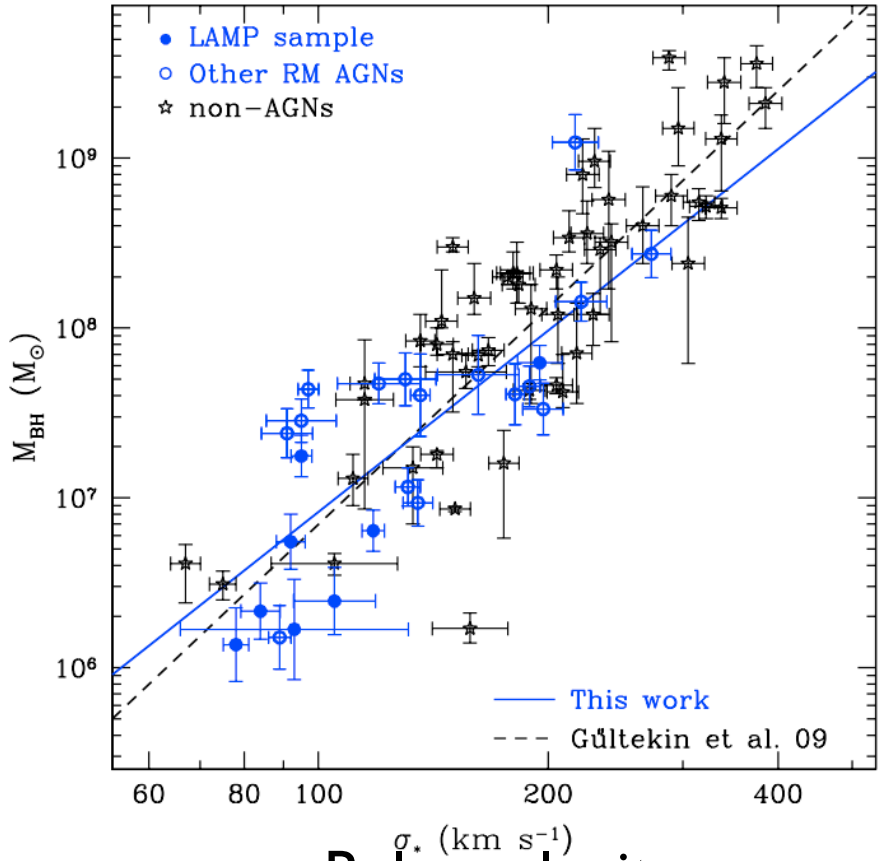
LAMP data, MCMC fit by J.Simpson

Black Hole Masses from BLR sizes

Virial Gas Motions

$$M_{BH} = \Delta V^2 c \tau / G f$$





Bulge velocity dispersion

Bentz, et al 2010

AGN Distances for Cosmology

$$D = (4\pi L / F)^{1/2} \sim \tau / F^{1/2}$$

(Walker, et al. 2011)	*(Collier et al. 1999, Cackett et al. 2007)*
BLR reverberations:	**Disk reverberations:**
Emission line time delays	Continuum time delays
$R_{BLR} \sim L^{1/2}$	$T \sim R^{-3/4} \Rightarrow \tau \sim \lambda^{4/3}$
$\Rightarrow D \sim \tau / F^{1/2}$	$\Rightarrow D \sim \tau (\cos(i) / \lambda^3 F_\nu)^{1/2}$
spectrophotometry	broadband Imaging
larger telescope	smaller telescope
long lags (weeks-months)	short lags (days)
photo-ionised clouds	irradiated disk

- Two independent methods.
- Disk reverberations might be simpler / faster ?

- Can "Standard Disks" compete with SN Ia "Standard Bombs" ?
- Visible to higher redshifts. Simpler physics ?

Accretion Disk Reverberations

Disk Theory:

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

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

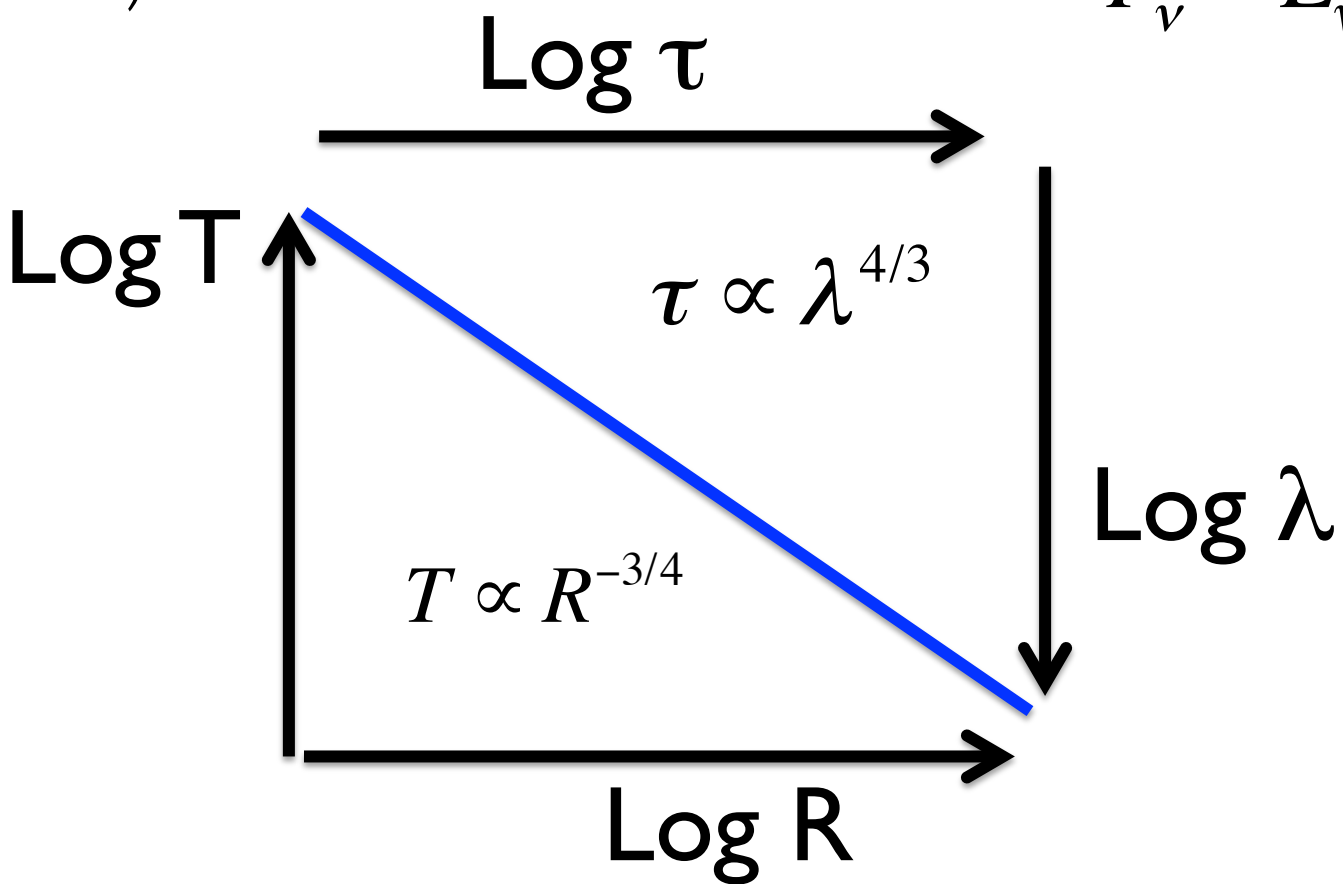
$$R = c\,\tau$$

$$T \sim \frac{h\,c}{k\,\lambda}$$

Observables:

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

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



AGN Distances from Disk Reverberations

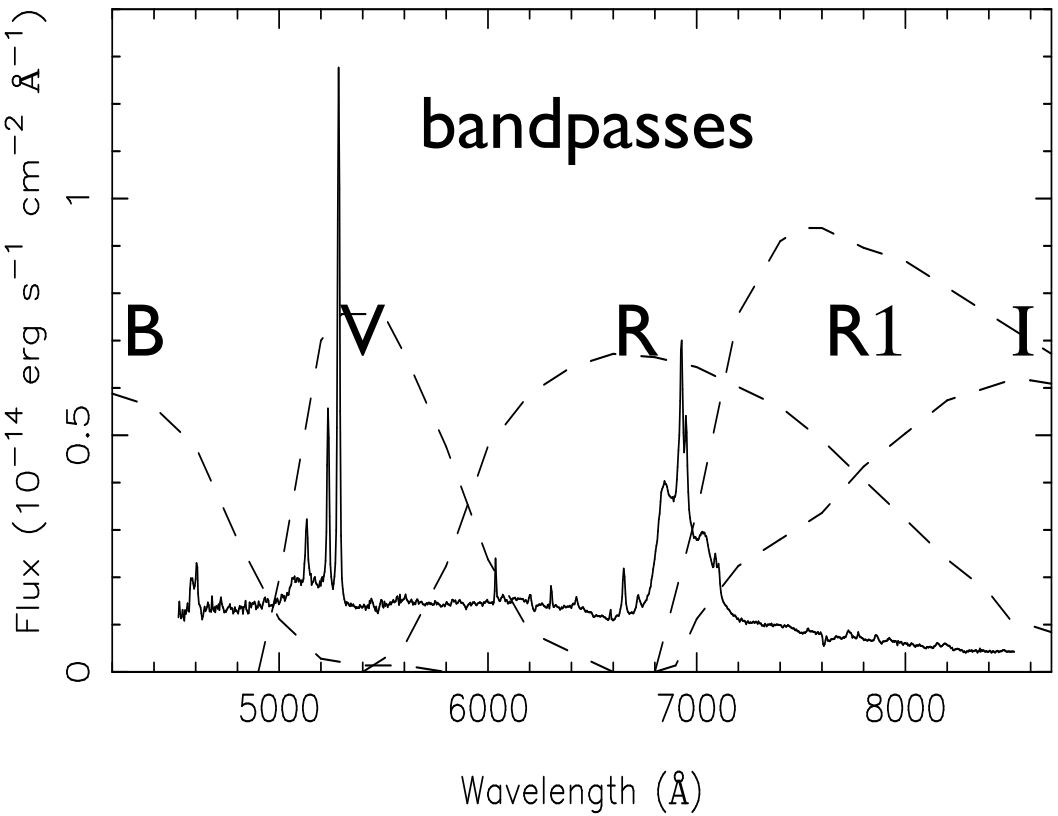
- Simple Assumptions:
- 1. Light travel time delays: $\tau = (1+z)R/c$
- 2. Flat geometry: $d\Omega = 2\pi R\, dR \cos(i) / D_L^2$
- 3. Blackbody emission: $I_\nu = B_\nu[T(R), \lambda]$
- For a steady disk: $T^4 = 3\,G\,M\,\dot{M}/8\,\pi\,\sigma\,R^3$
- Observe: $\tau \propto \lambda^{4/3} \left(M\,\dot{M}\right)^{1/3} (1+z)^{-1/3}$

$$f_\nu(\lambda) = \int B_\nu\left[\frac{\lambda}{1+z}, T(R)\right] \frac{2\,\pi\,R\,dR\cos i}{D^2} \propto \frac{(1+z)^{4/3}\left(M\,\dot{M}\right)^{2/3}\cos i}{\lambda^{1/3}\,D_L^2}$$

- Potential: Test $T(R)$ law, measure $M\,Mdot$, and $D_L(z)$.
- $$D_L = 6.3\ \mathrm{Mpc}\left(\frac{\tau}{\mathrm{day}}\right)\left(\frac{\lambda}{10^4\ \mathring{A}}\right)^{-3/2}\left(\frac{f_\nu/\cos i}{\mathrm{Jy}}\right)^{-1/2}(1+z)$$

Delay Measurements from Broad-band Lightcurves

Lightcurves from Sergeev et al. 2005



F(t,λ)

CCF(τ,λ) =>τ(λ)

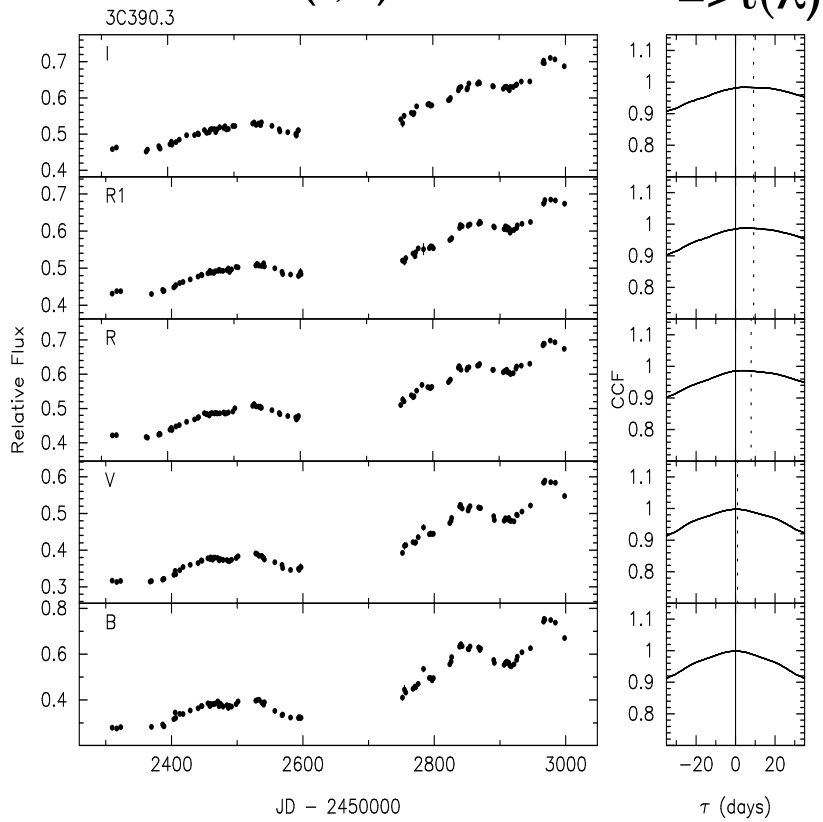


Figure 2: Left: 3C390.3 spectrum and the B,V,R,R',I bandpasses used in our previous analysis. Right: Lightcurves and cross-correlation functions. (from Cackett, Horne, Winkler 2007).

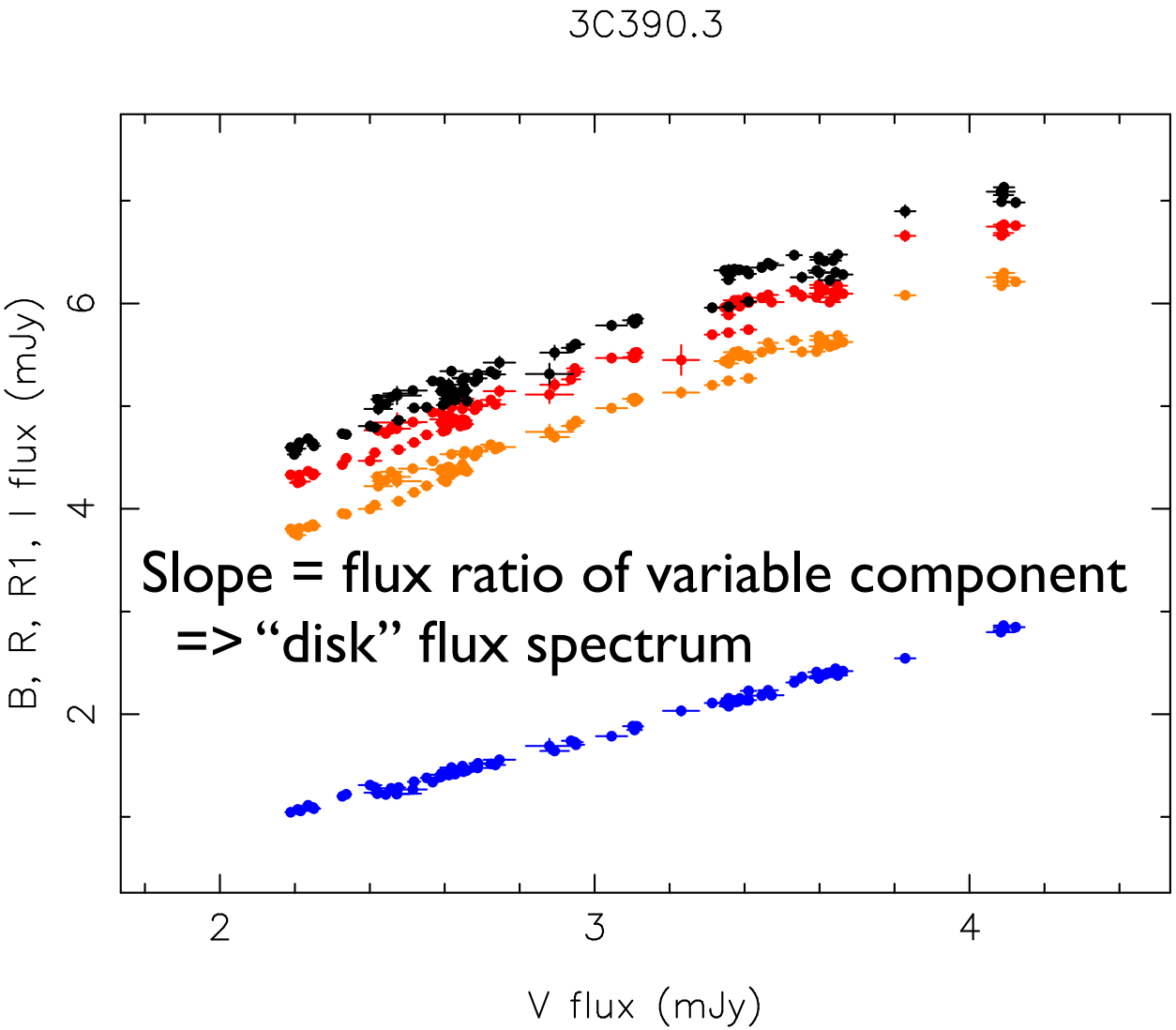
Cackett, Horne, Winkler 2007

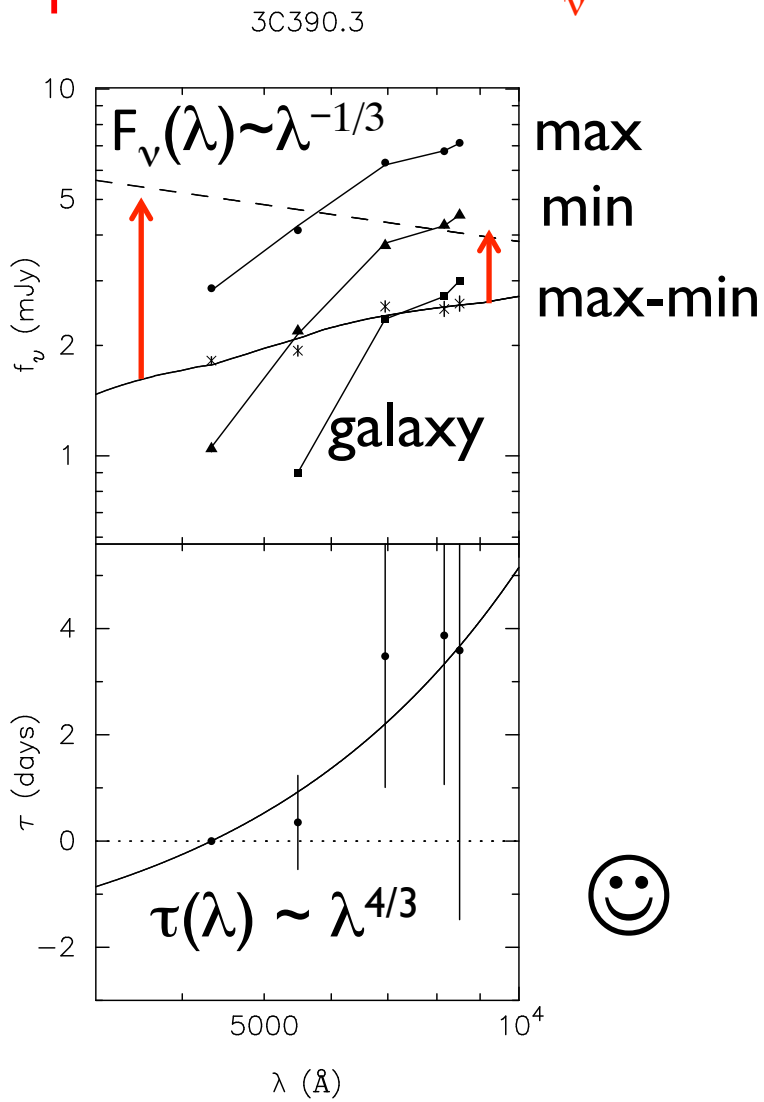
AGN Spectra redder than $F_\nu \sim \lambda^{-1/3}$ ☹

e.g. Host Galaxy Starlight contamination?

Variable Component isolates the **Disk Spectrum**

De-redden "disk" spectrum to match $F_\nu \sim \lambda^{-1/3}$

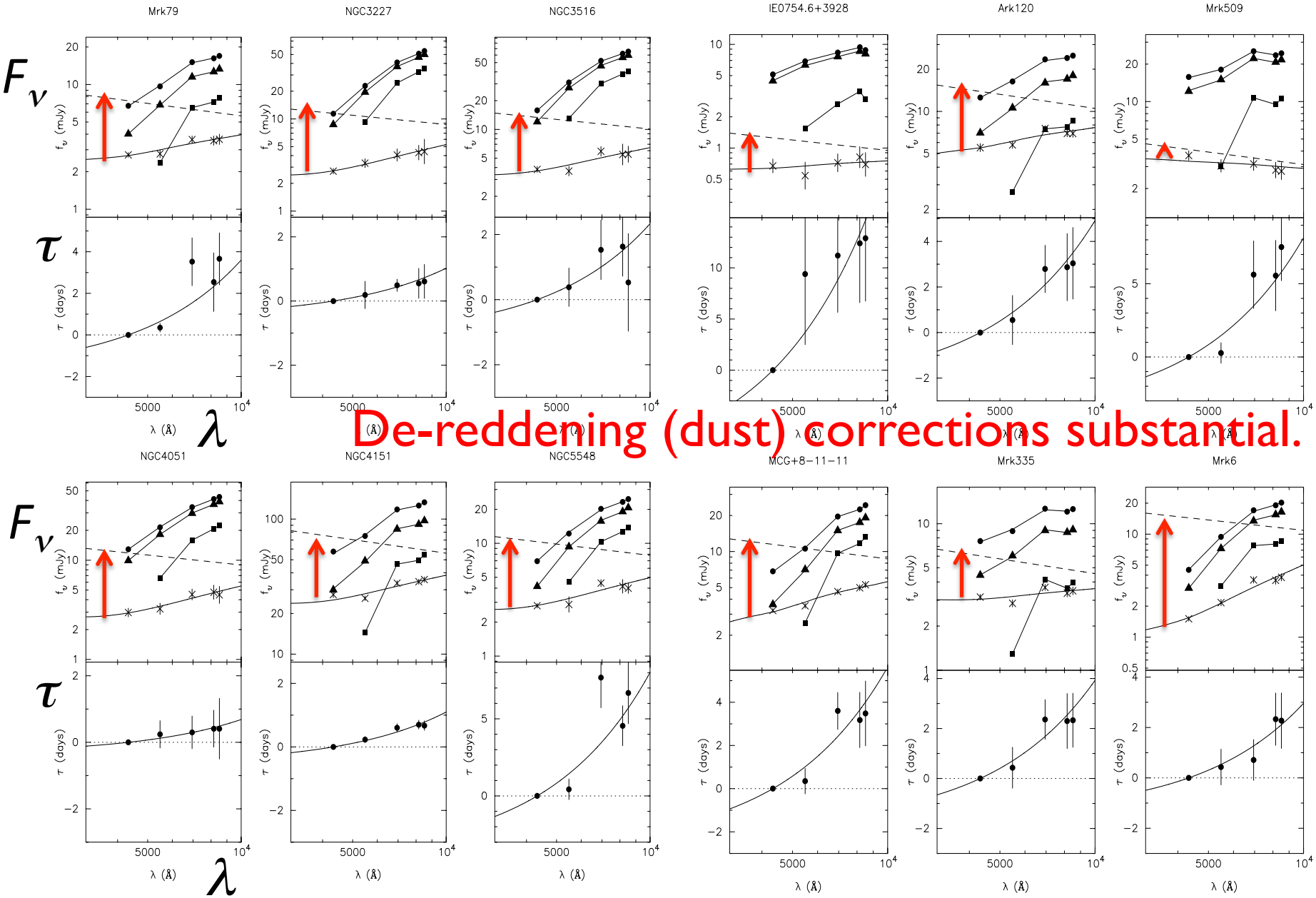




☺

Cackett, Horne, Winkler 2007

Disk maps for 12 more Seyferts (z<0.1)

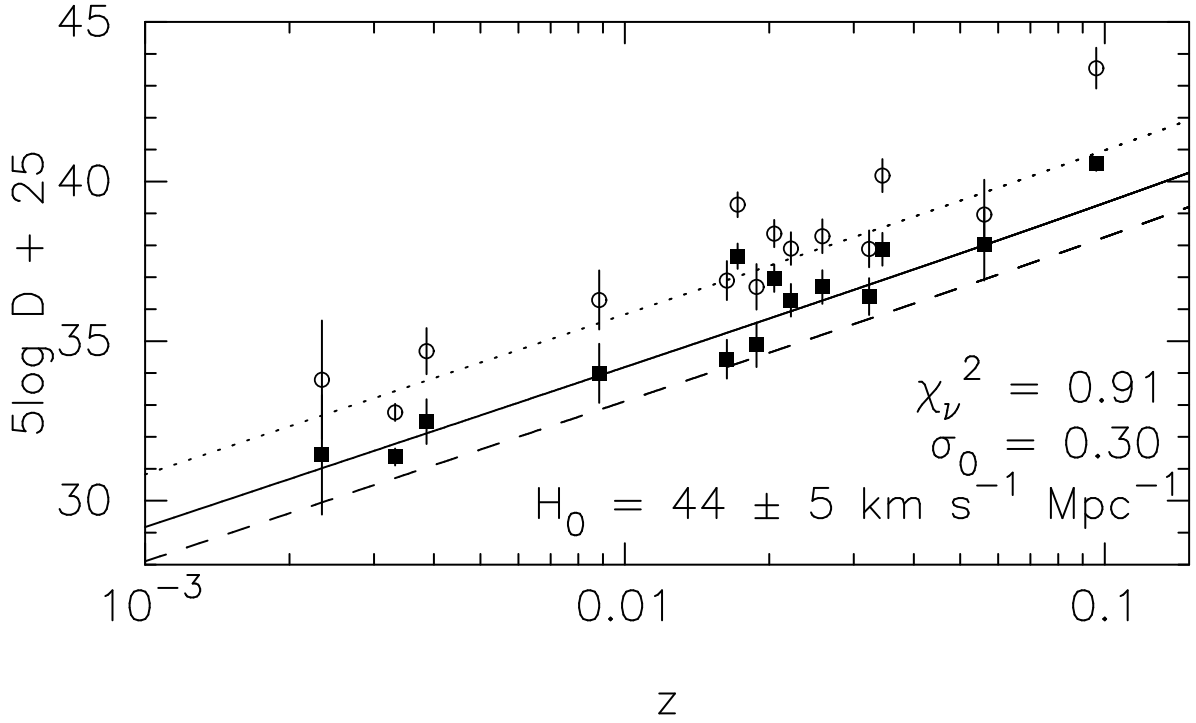


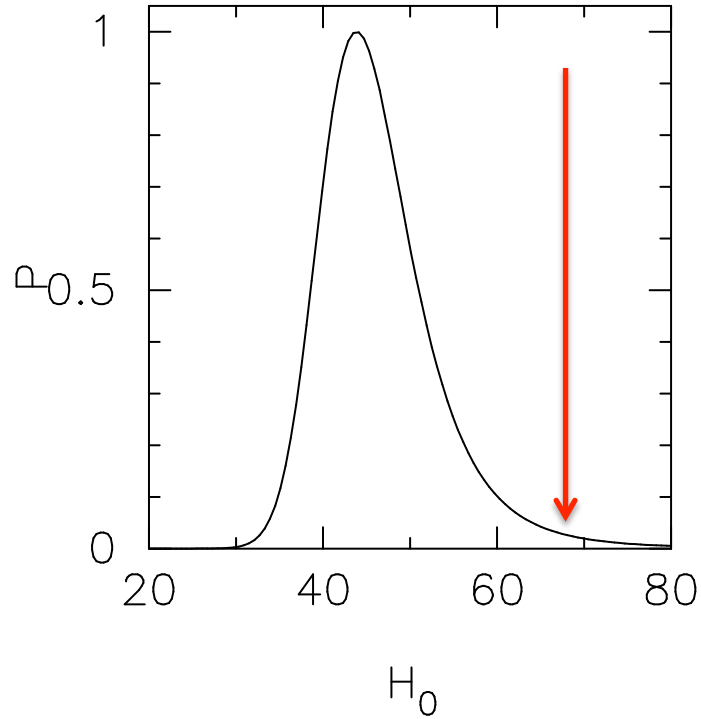
De-reddening (dust) corrections substantial. ☹

All are consistent with $\tau \sim \lambda^{4/3}$ ☺

Luminosity Distances for 13 Seyferts at z < 0.1

$$D_L = 6.3\ \mathrm{Mpc}\left(\frac{\tau}{\mathrm{day}}\right)\left(\frac{\lambda}{10^4\ \mathring{A}}\right)^{-3/2}\left(\frac{f_\nu/\cos i}{\mathrm{Jy}}\right)^{-1/2}(1+z)$$



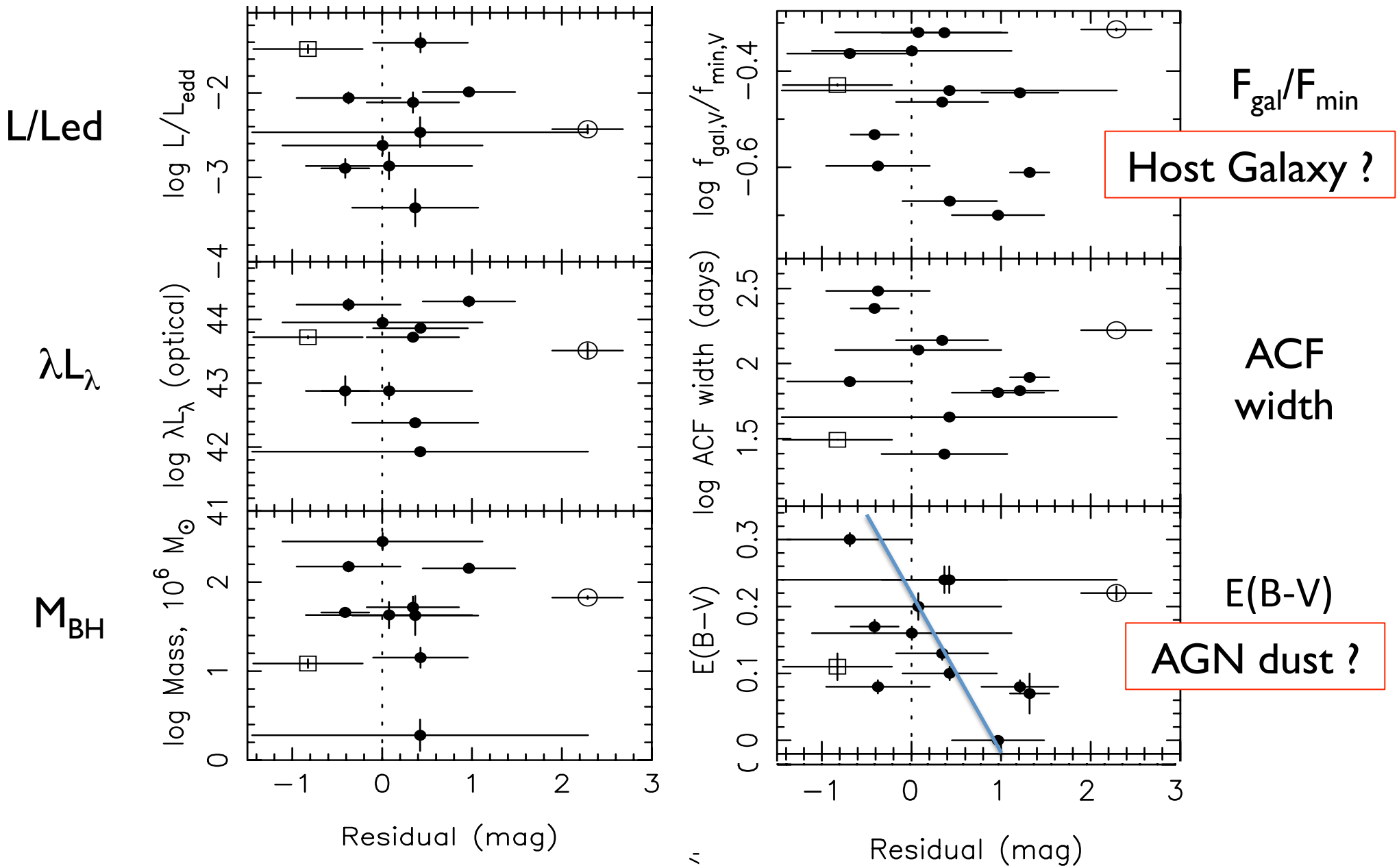


30% RMS scatter.

Disks are fainter than expected.

Cackett, Horne, Winkler 2007

What causes the scatter?

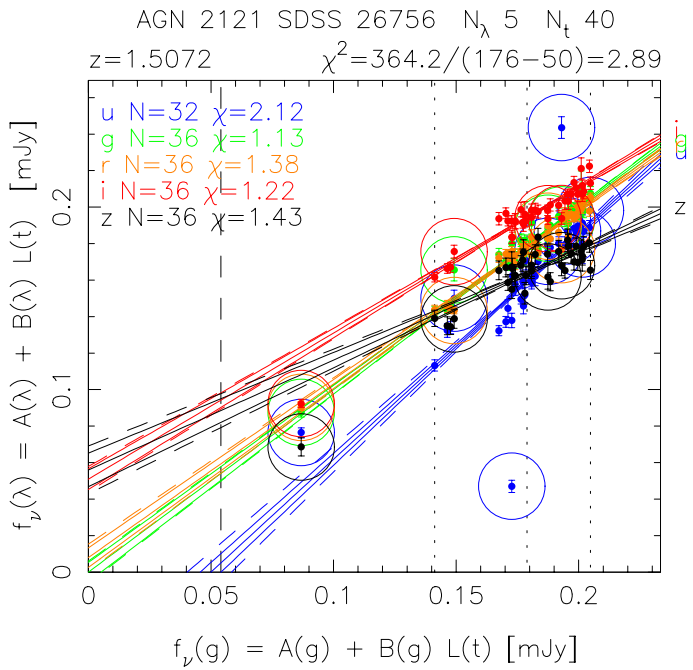


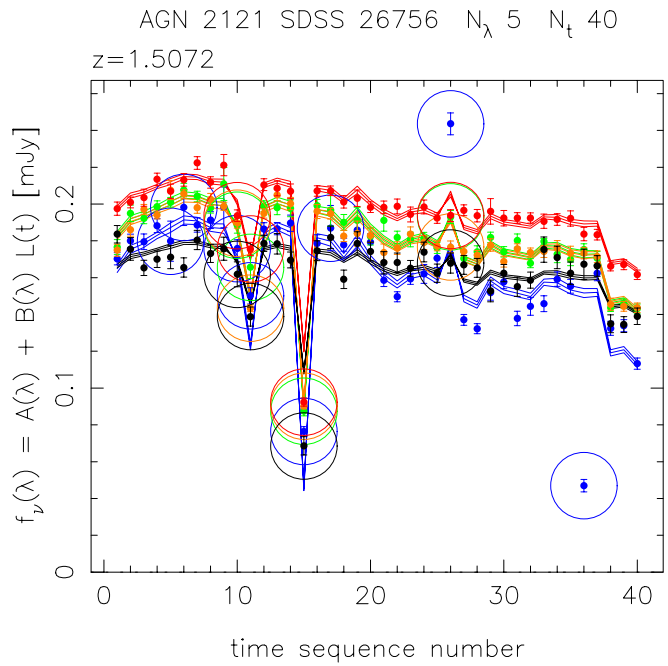
No sign of systematic errors over a factor 100 in M and L. ☺

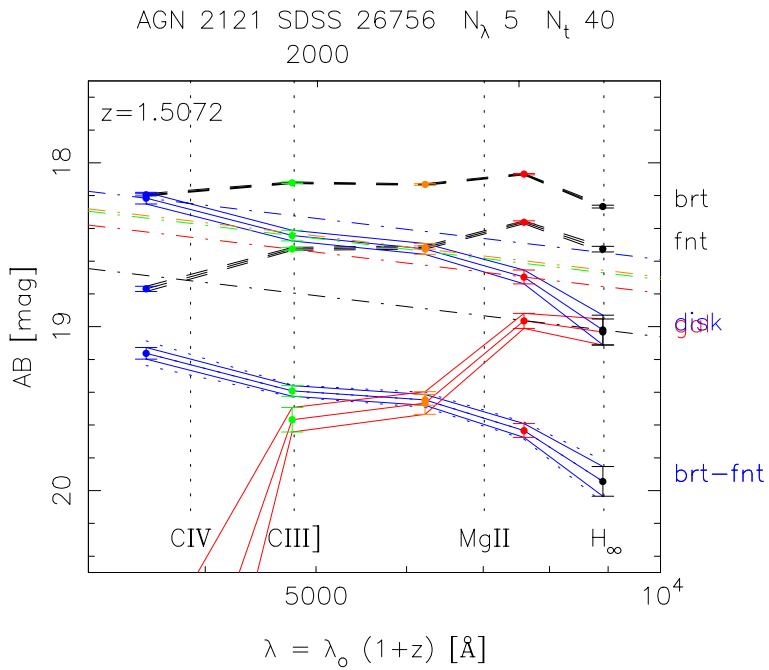
SDSS Quasars : Lightcurve Analysis

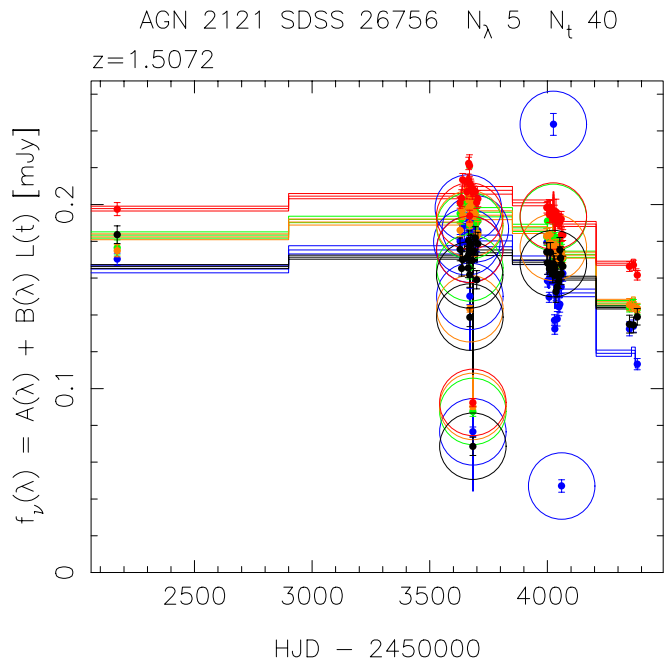
Variable component isolates the disk (removes host galaxy light).
☺

Variable component griz colours match those of a steady accretion disk. (e.g. little dust)
☺









9000 SDSS Quasars

Suitable targets (g<19) out to redshift z ~ 2.5

☺

Variable component griz colours match steady disk. (e.g. reddening is small)

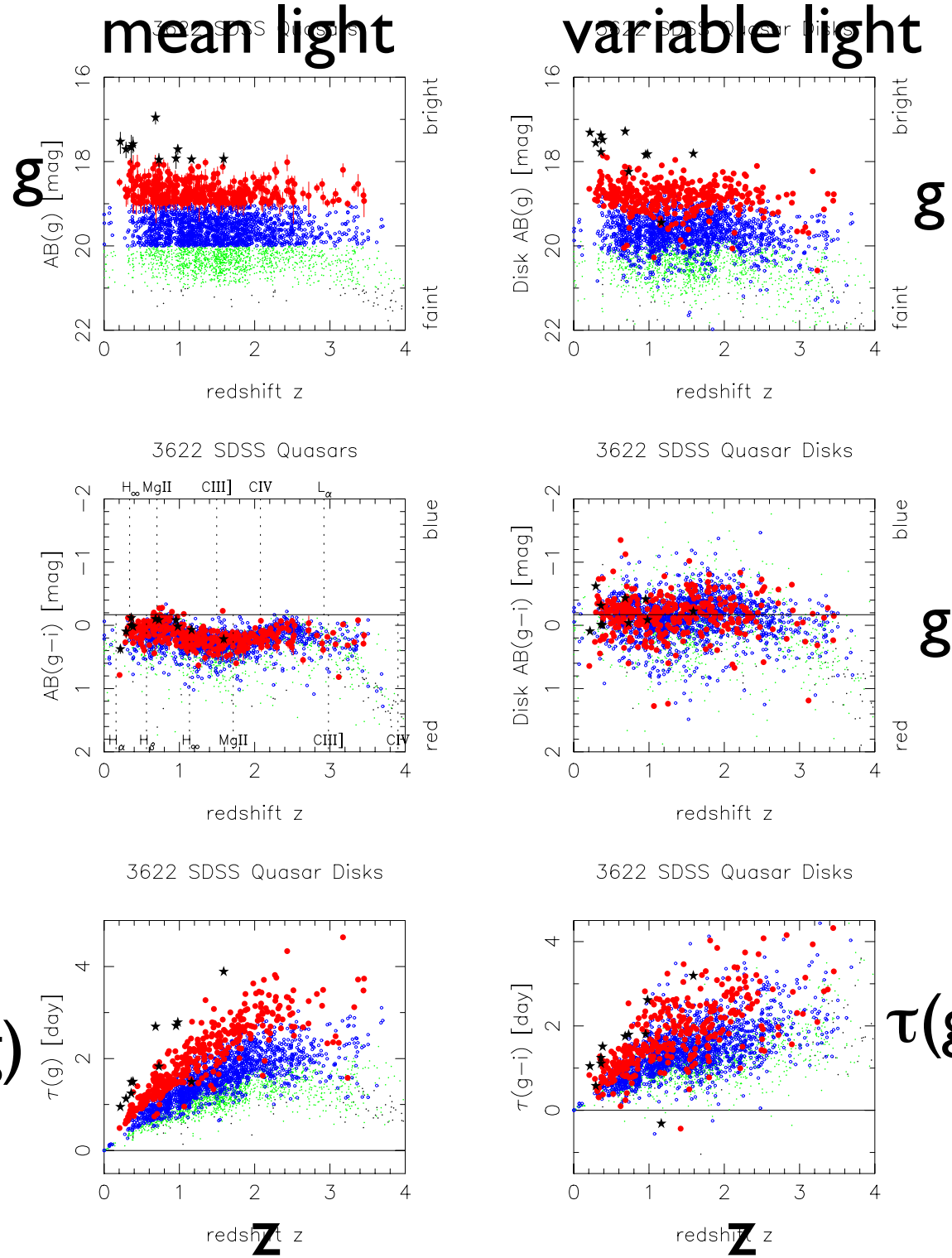
☺

Expect delays ~ few days

☺

mean light

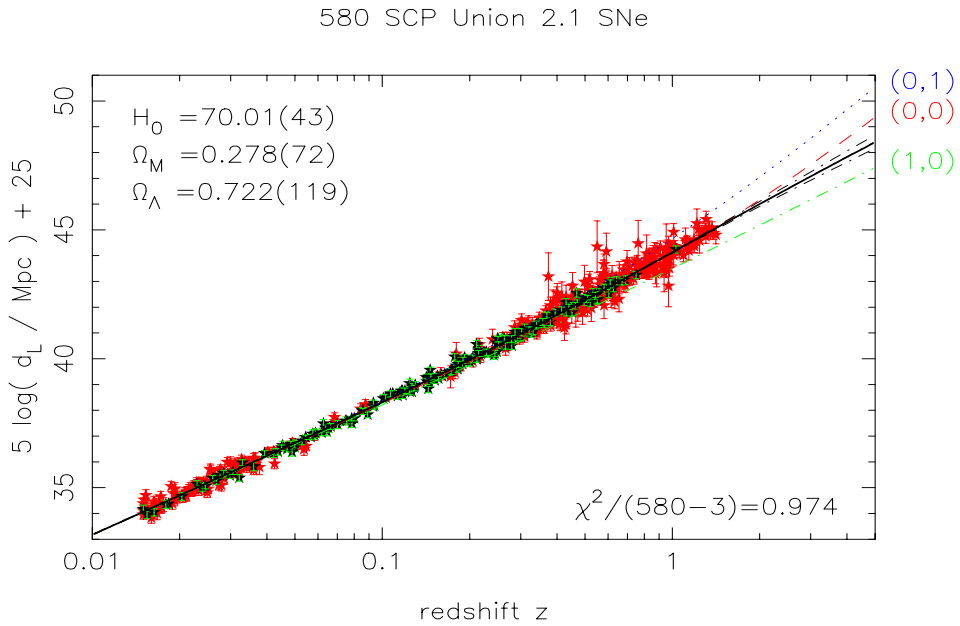
variable light

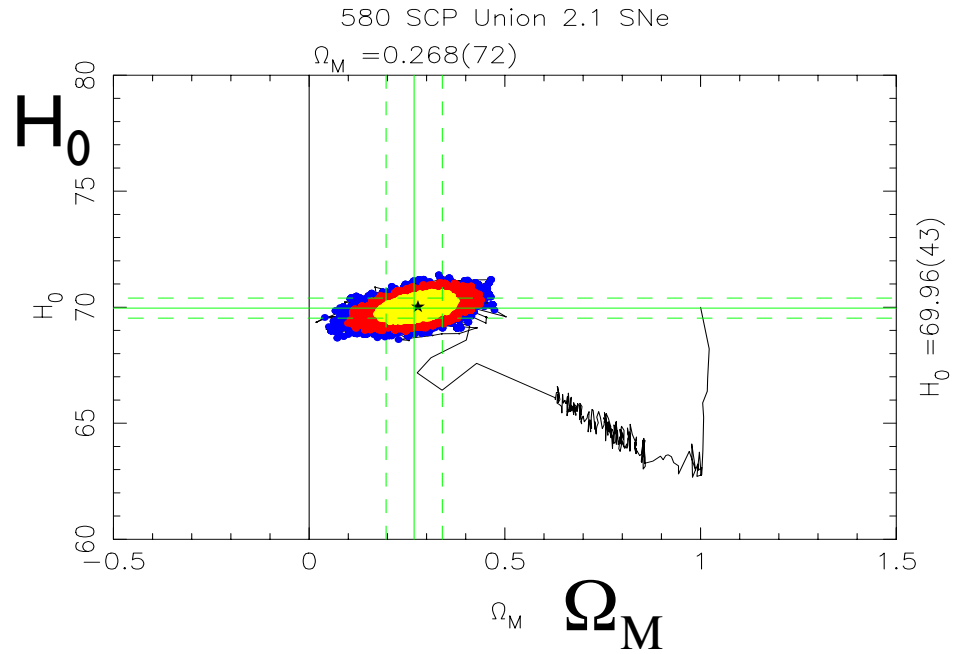


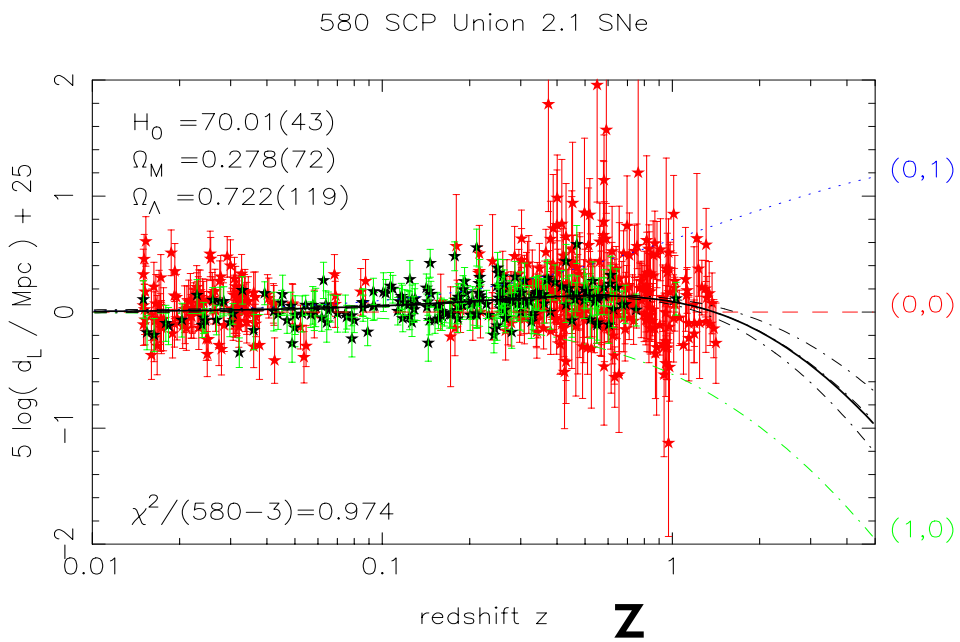
Goal: AGN Disk Distances for 10-100 SDSS quasars out to z = 3.

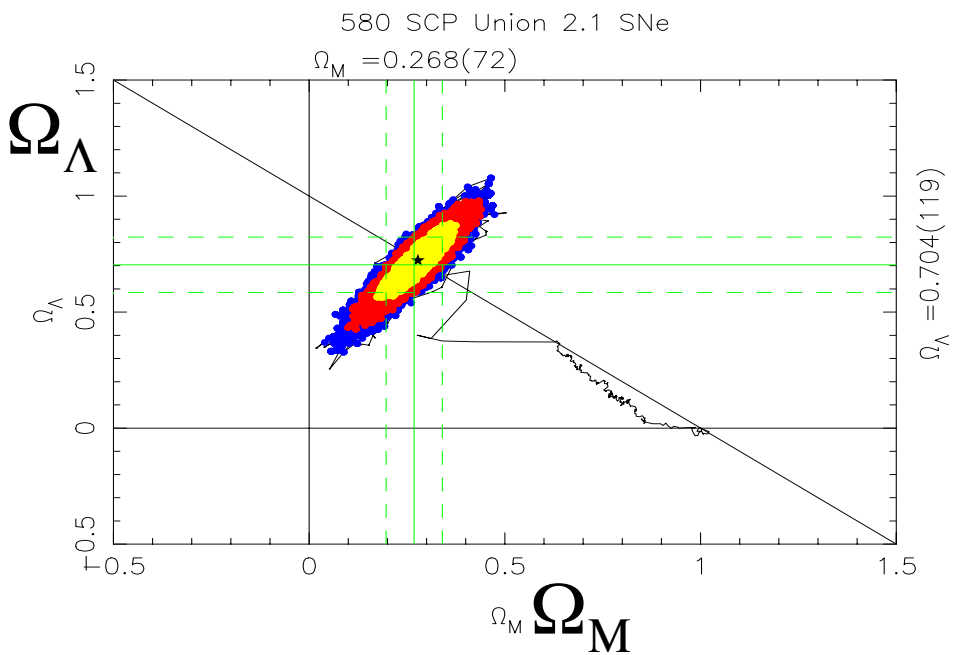
- **Robotic Telescope Network (LCOGT/SUPA):**
  8 x 1m scopes (SAAO,CTIO,SSO) => 1/3 day sampling.
- **Define the survey**: Analysis / simulations to understand the time delay accuracy (hence distance accuracy) given survey parameters (S/N, cadence, duration).
- **Small sample** (3-10 targets) first results + feasibility. SDSS data to preselect for variability and low reddening.
- **Optimise analysis:** Image analysis to extract lightcurve. Lightcurve analysis to measure disk parameters and distance.
- **Larger sample:** (50-100? targets). Optimise brightness and redshift range of sample.
- **Cosmology**: constraints on Ω_M, Ω_Λ, w_0, w_a

Cosmology from 580 SN Ia



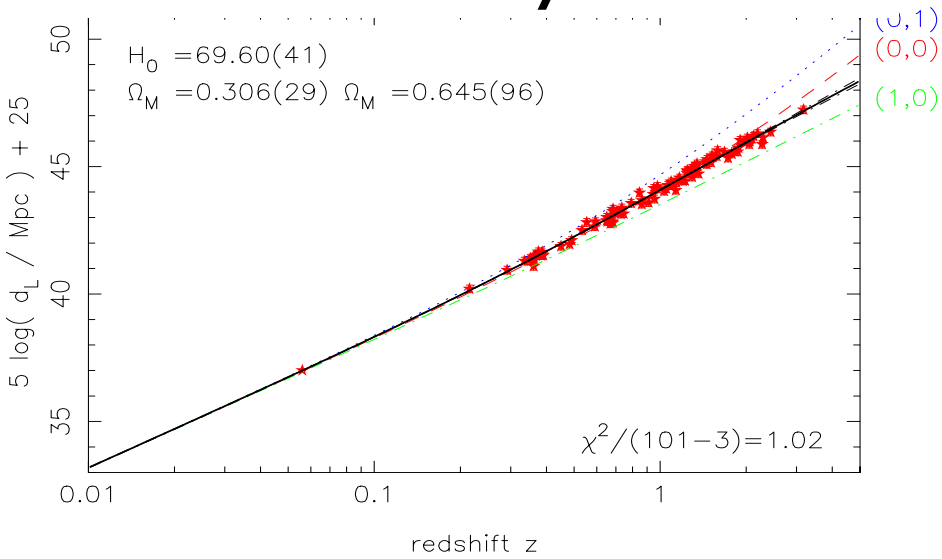


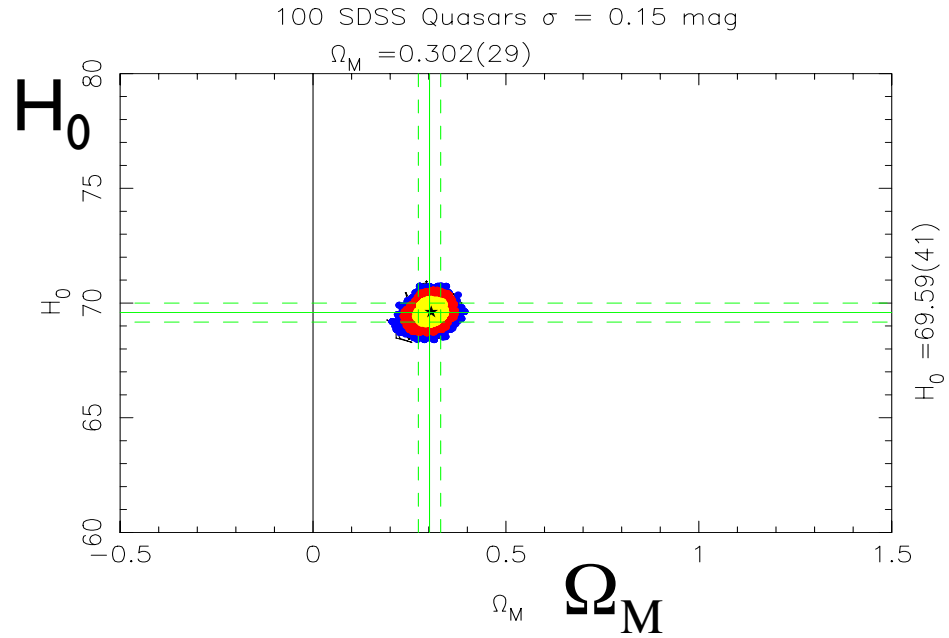


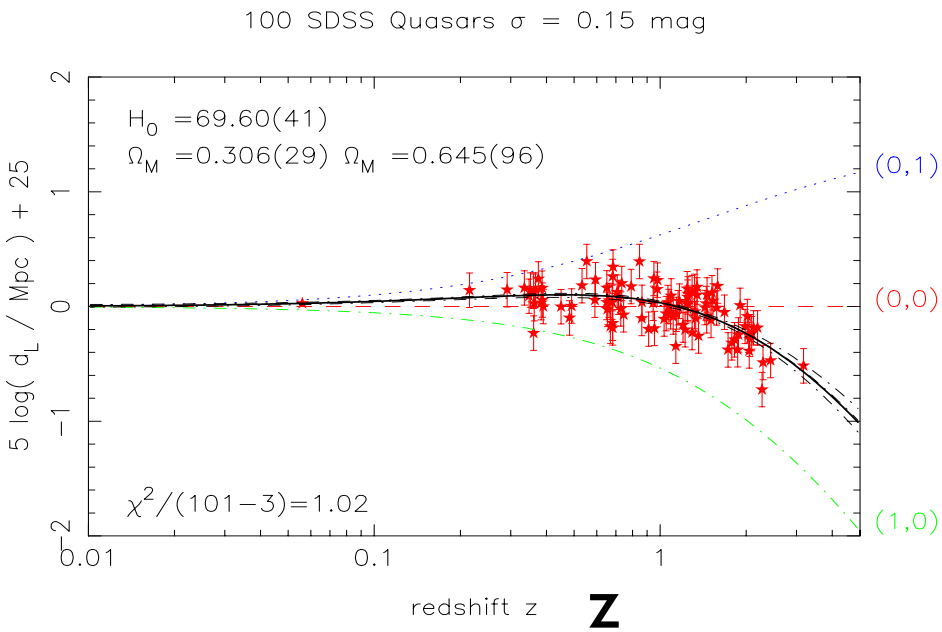


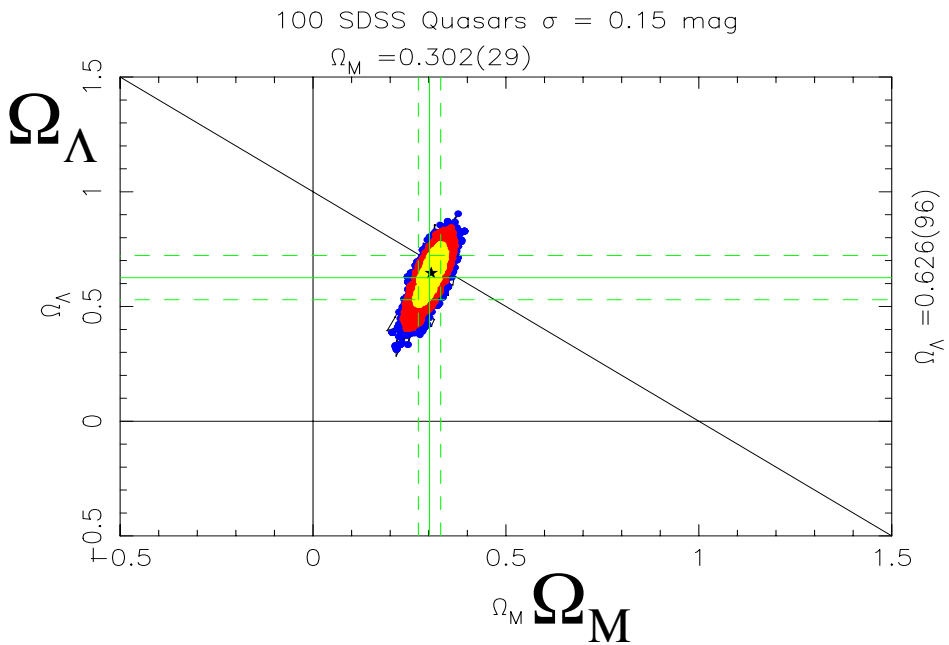
Cosmology from SDSS Quasars ?

Simulated Survey Results









Thanks for Listening

BLR Reverberations $\tau \sim$ weeks $D \sim \tau \ / \ F^{1/2}$
Accretion Disk $\tau \sim$ days $D \sim \tau \ (\cos(i) \ / \ \lambda^3 F_\nu)^{1/2}$

Now: 30% RMS in D for individual Seyferts
No obvious trend over factor 100 in L and M

SDSS Quasars brighter and less reddened than Seyferts
Robotic telescopes (LCOGT) for monitoring
Aim for10-100 useful Quasar distances to z ~ 3.

$D_L(z)$ from AGN Disks can check / extend those from SN Ia ?