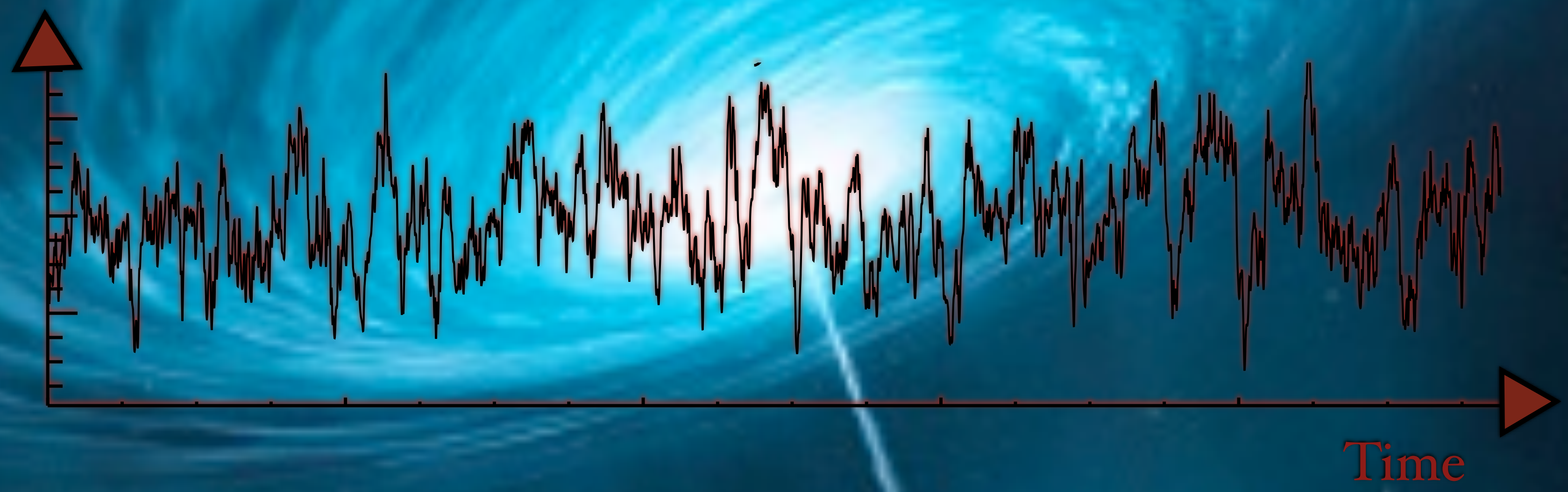
A Review of AGN Variability Studies using Survey Data: Prospects for LSST



Chelsea MacLeod (SAO)

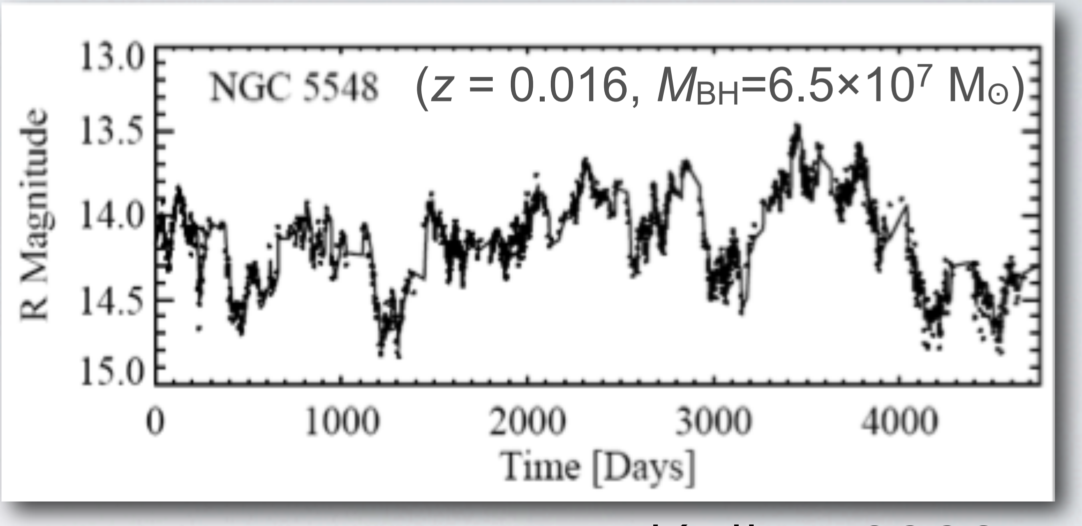
LSST AGN Science Roadmap Meeting -- Grapevine, TX -- 3 Jan 2017

Large Synoptic Survey Telescope

Optical Quasar Variability

Continuum:

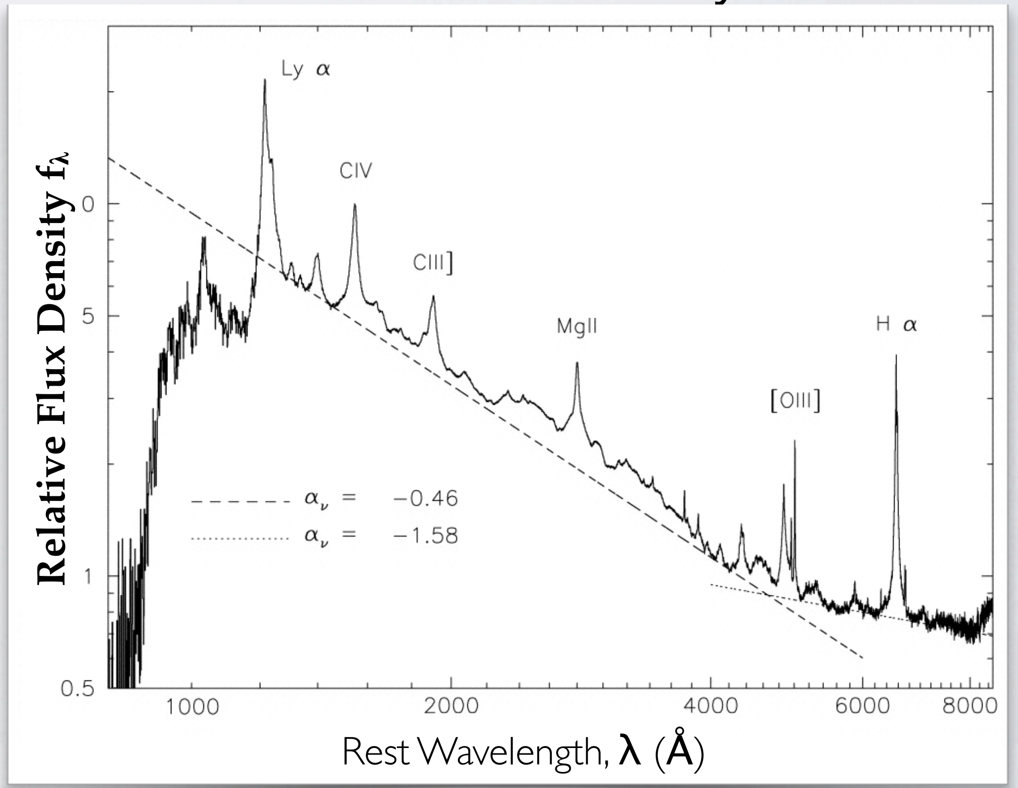
- rms ~ 0.2 mag over ~1 year
- Aperiodic, stochastic red noise
- Optical contains reprocessed UV emission (Edelson+ 2015)



Kelly+ 2009

Broad Emission Lines:

- Less variable, lagged ($t_{\mathrm{lt,BLR}}$)



Composite SDSS spectrum (Vanden Berk+ 2001)

Optical Quasar Variability

Continuum:

- rms ~ 0.2 mag over ~1 year
- Aperiodic, stochastic red noise
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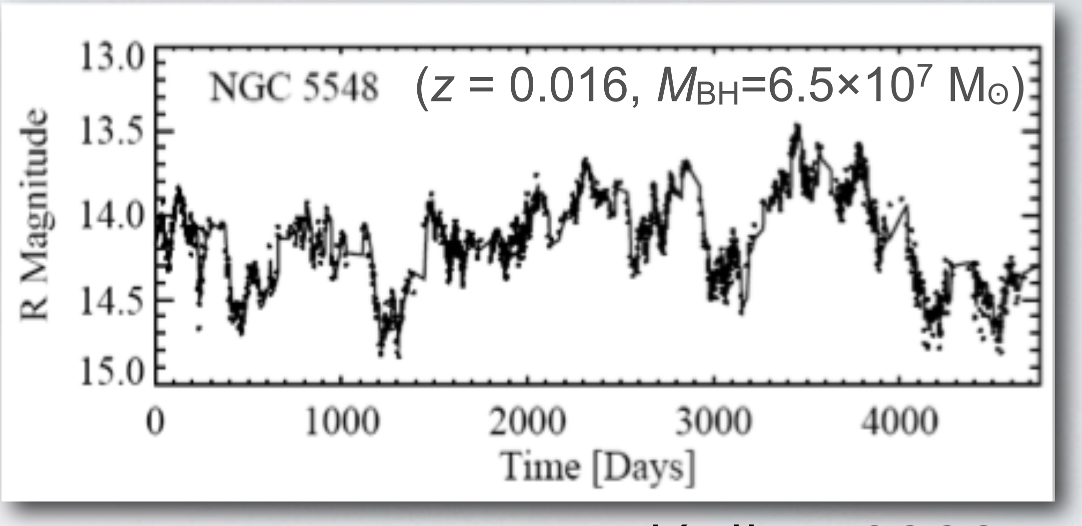
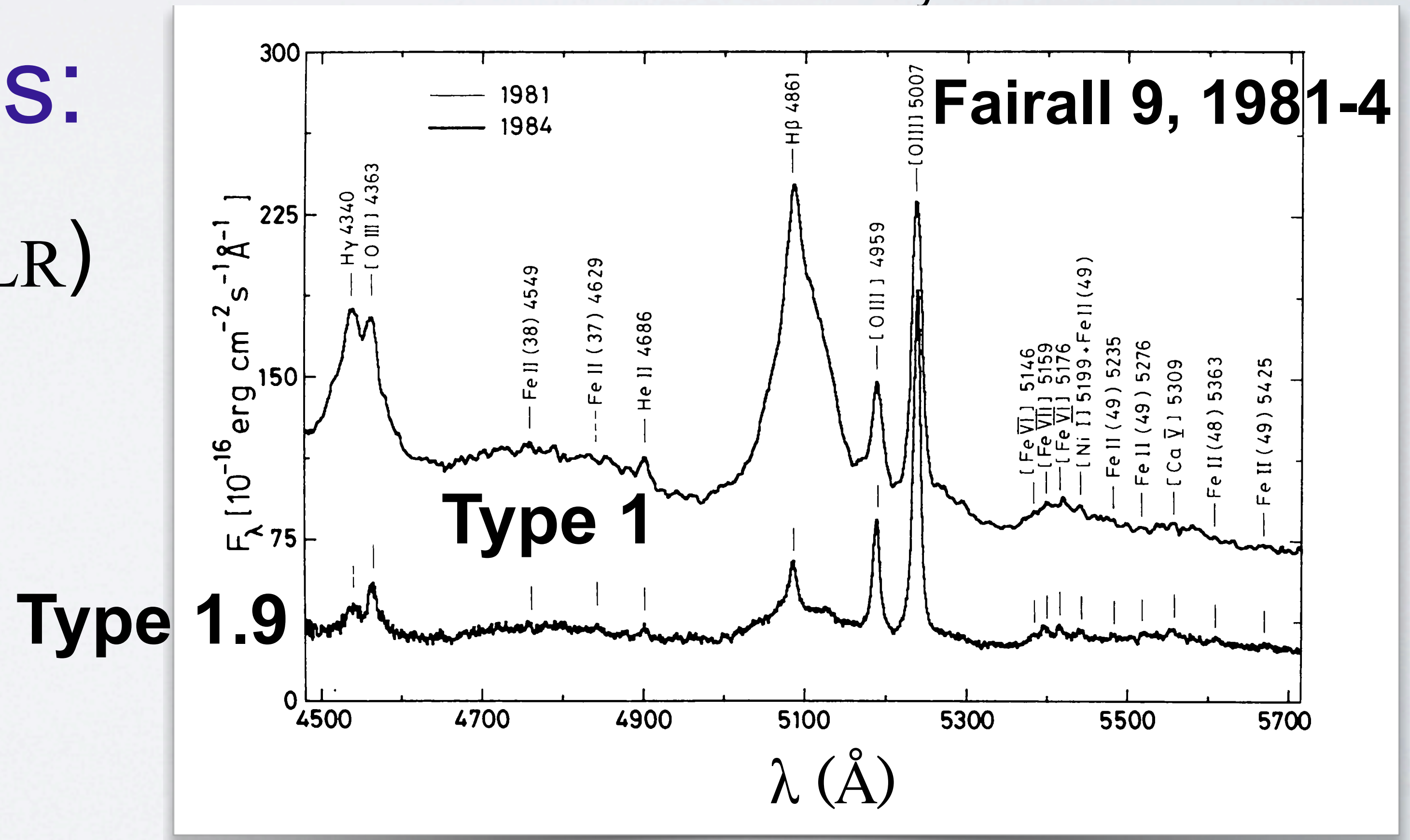


Kelly+ 2009

Broad Emission Lines:

- Less variable, lagged ($t_{\rm lt,BLR}$)
- Large changes rare



Kollatschny & Fricke 1985

LONG-TERM VARIABILITY WITH LSST

- Constrain the timescale for quasar variability
    - Modeling SDSS S82 light curves as a DRW
- Constrain physics through extreme variability
    - Changing-Look Quasars
- Determine incidence of transient AGN phenomena

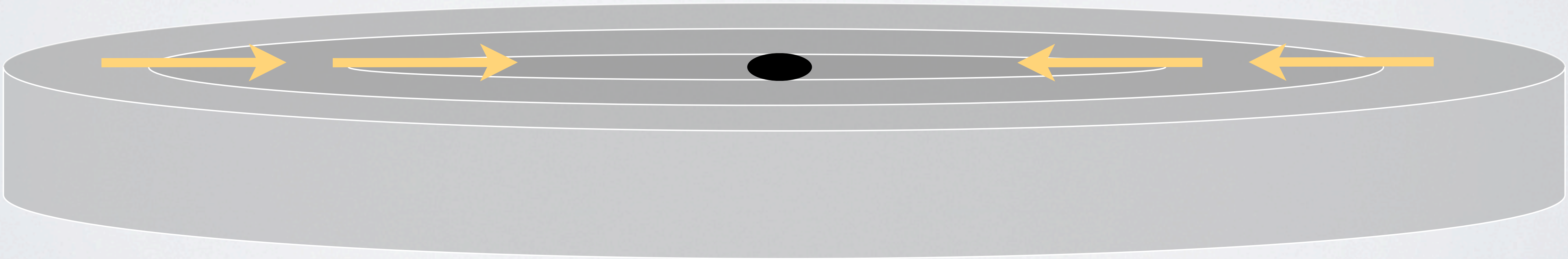
PHYSICAL TIMESCALES IN AGN

- **viscous** ("radial drift") timescale

  Optical: ~10,000 yrs

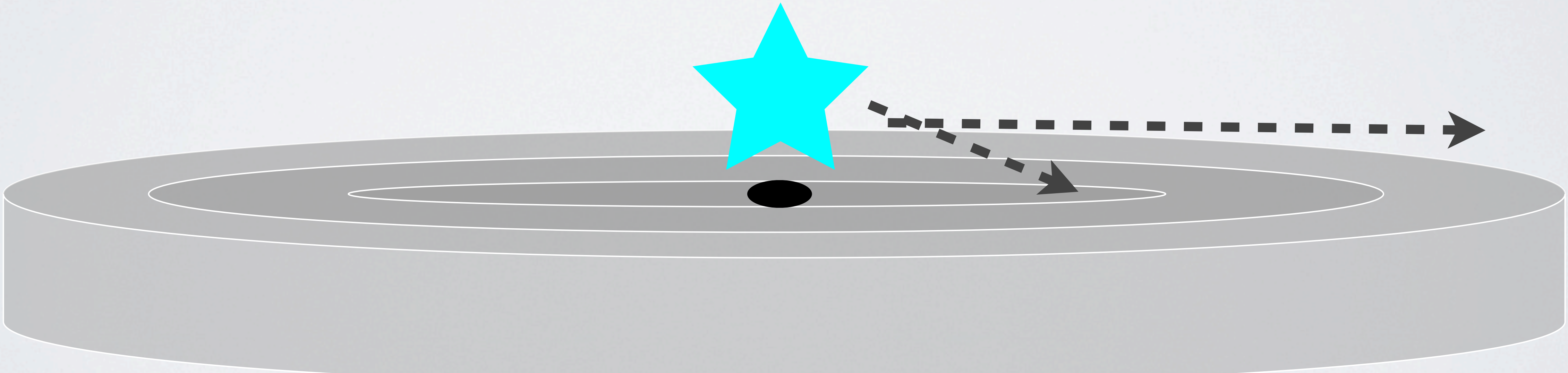
  UV: ~days

$$t_{\rm infl} = 5{\times}10^4 \left[\frac{\alpha}{0.1}\right]^{-1} \left[\frac{\lambda_{\rm Edd}}{0.05}\right]^{-2} \left[\frac{\eta}{0.1}\right]^{2} \left[\frac{r}{50R_{\rm S}}\right]^{7/2} \left[\frac{M_8}{2.1}\right] \, {\rm yr}.$$



PHYSICAL TIMESCALES IN AGN

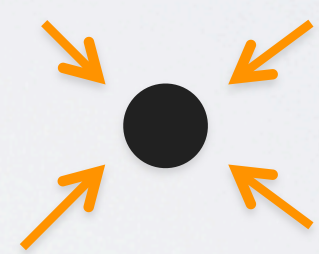
- viscous ("radial drift") timescale (~10,000 yrs)
- light travel timescale $t_{\rm lt} = R/c$ (~hrs; days for BLR)



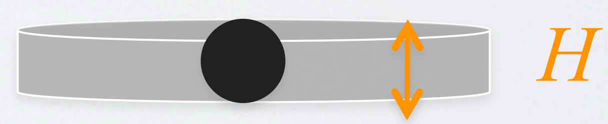
PHYSICAL TIMESCALES IN AGN

- viscous ("radial drift") timescale (~10,000 yrs)
- light travel timescale $t_{\mathrm{lt}} = R/c$ (~hrs; days for BLR)
- **dynamical** timescale t_{dyn} (~days; months-yrs for BLR)

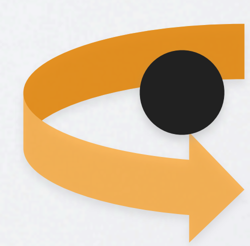
free-fall: $t_{ff} \sim (R/g)^{1/2}$



sound crossing: $t_s \sim H/c_s$



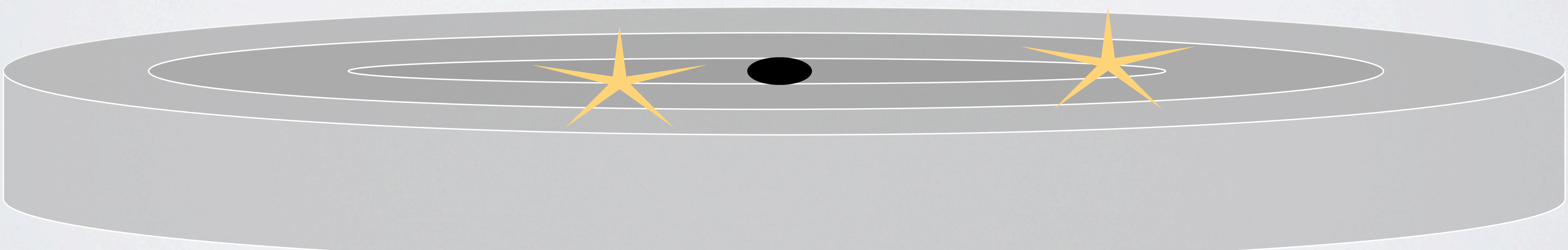
orbital: $t_{orb} \sim 2\pi\ t_{ff}$



PHYSICAL TIMESCALES IN AGN

- viscous ("radial drift") timescale (~10,000 yrs)
- light travel timescale $t_{\mathrm{lt}} = R/c$ (~hrs; days for BLR)
- dynamical timescale t_{dyn} (~days; yrs for BLR)
- **thermal** timescale t_{th} (days-yrs)

$$t_{th} = 4.6\ (\alpha/0.01)^{-1}\ (\mathrm{M}/10^{8}\mathrm{M}_{\odot})\ (R/100R_S)^{3/2}\ \mathrm{yr.}$$

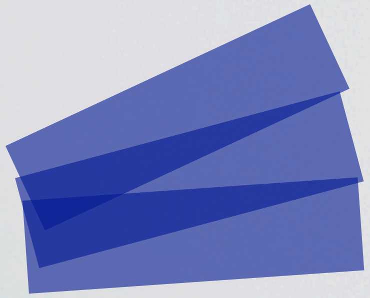


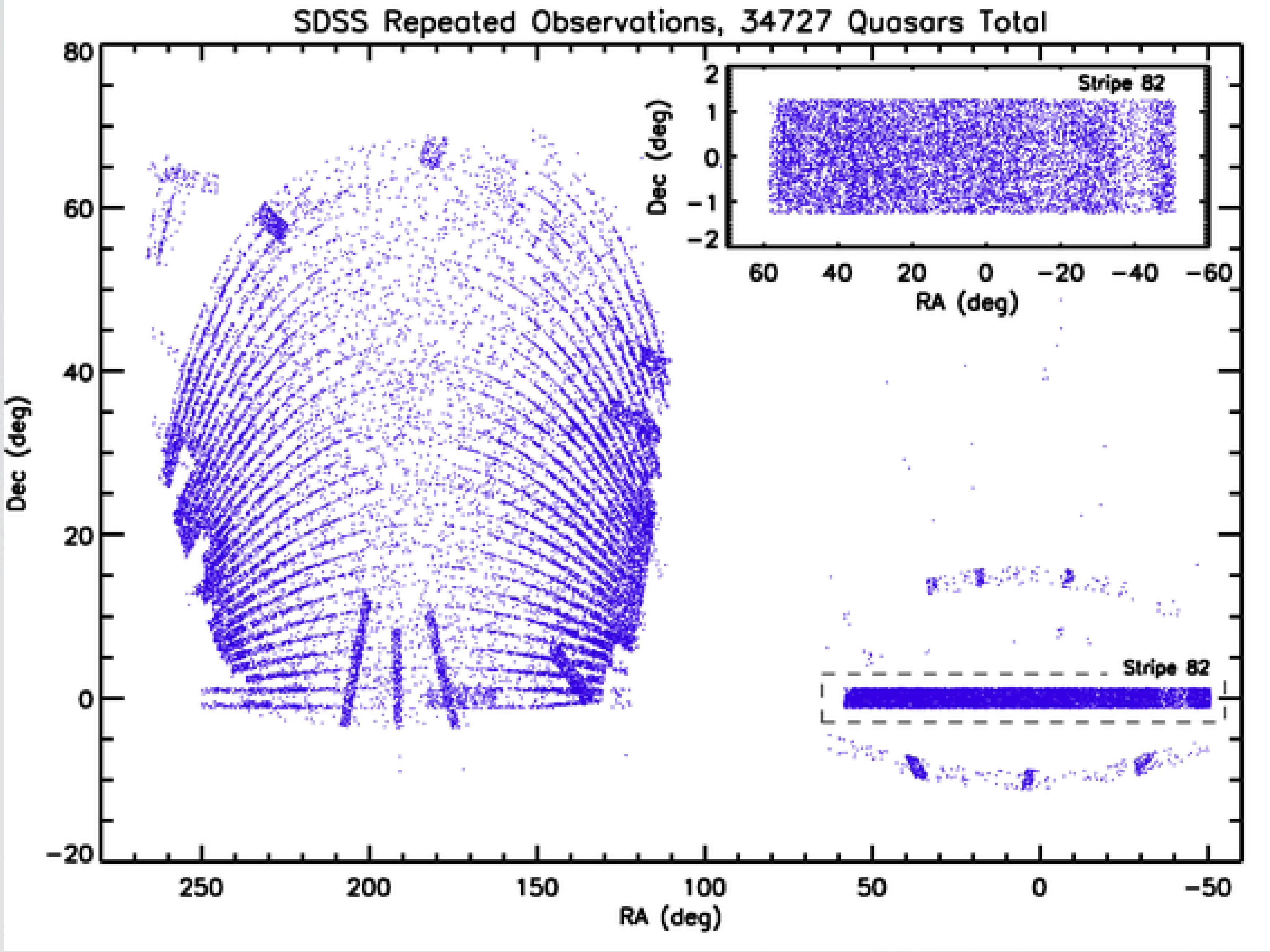
SDSS Repeated Imaging

- Stripe 82:
  ~60 epochs
  over 10 yr
  (N=9,275)

(Recalibrated data: Ivezic+ 2004)

- NGC:
  2-3 epochs
  (N=25,000)

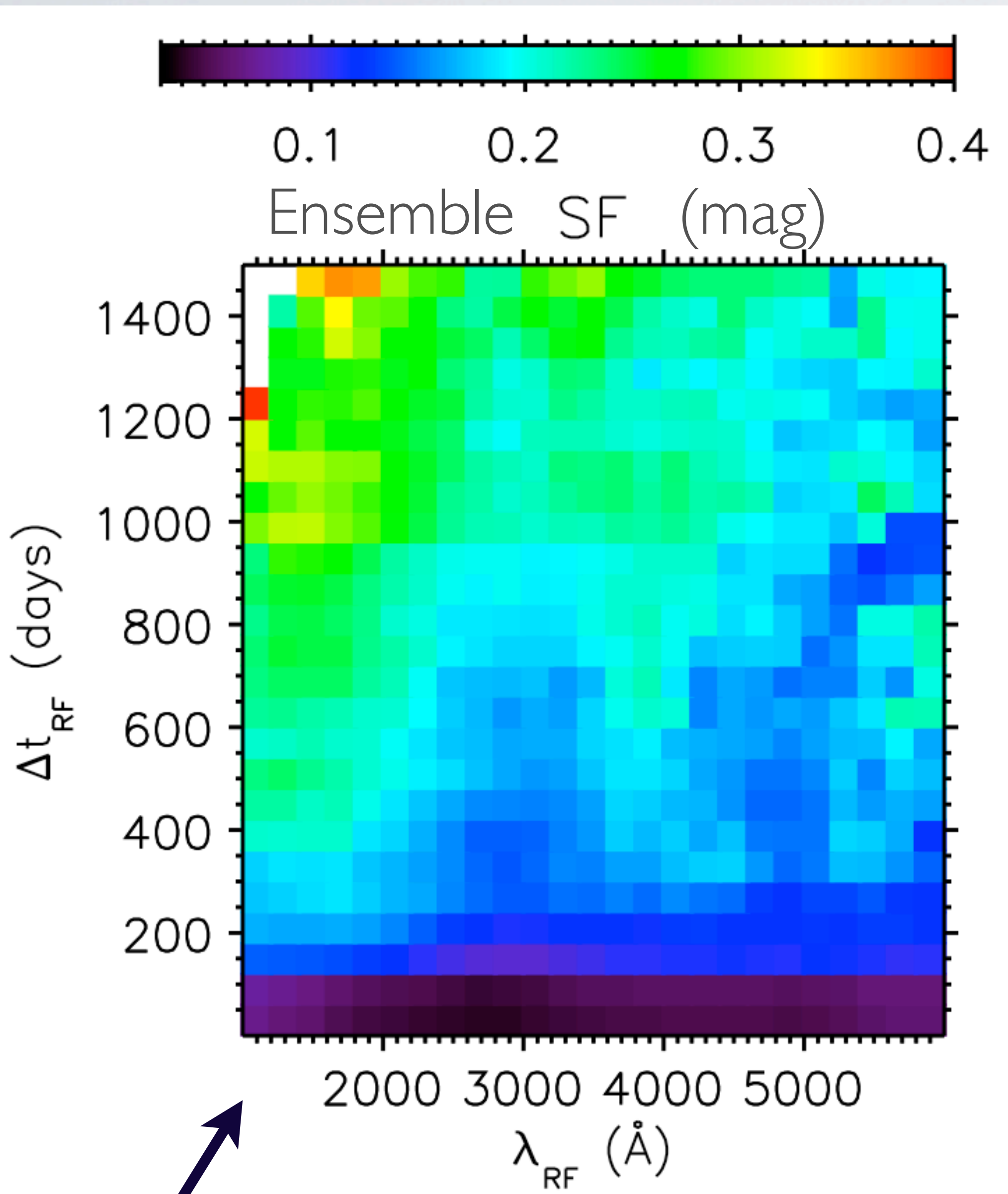


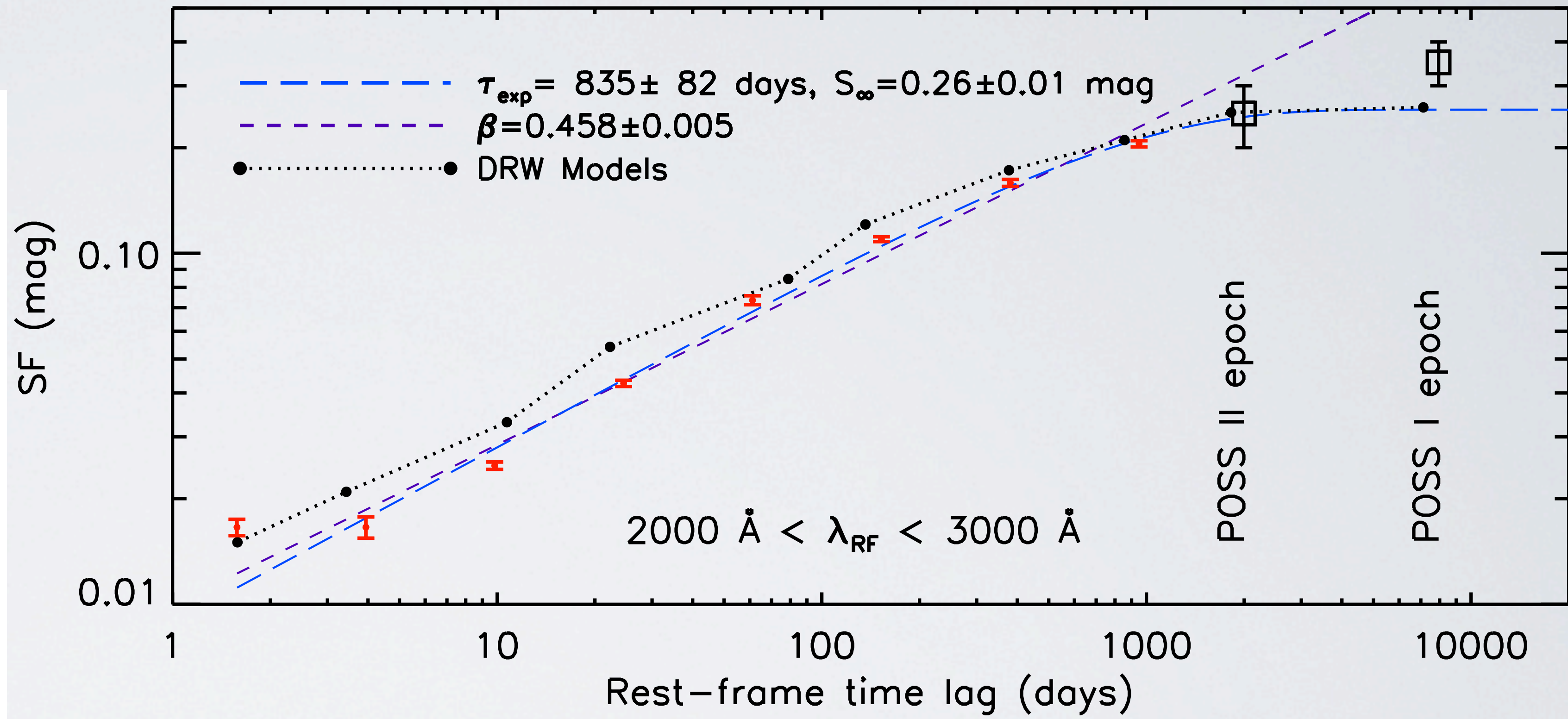


MacLeod+ 2012

Structure Function Analysis

For irregularly sampled data, statistical samples are best analyzed using the (model-independent) structure function





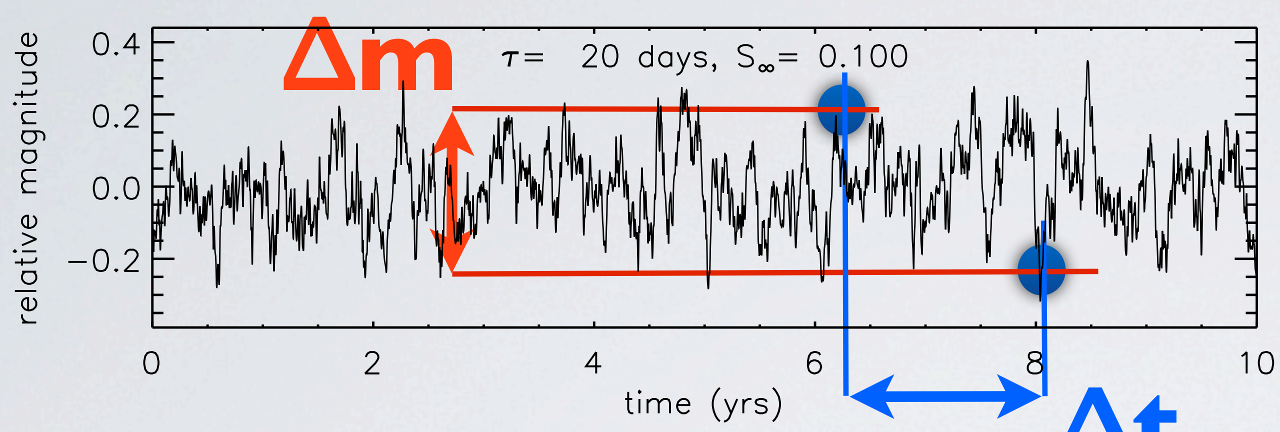
MacLeod+ 2012

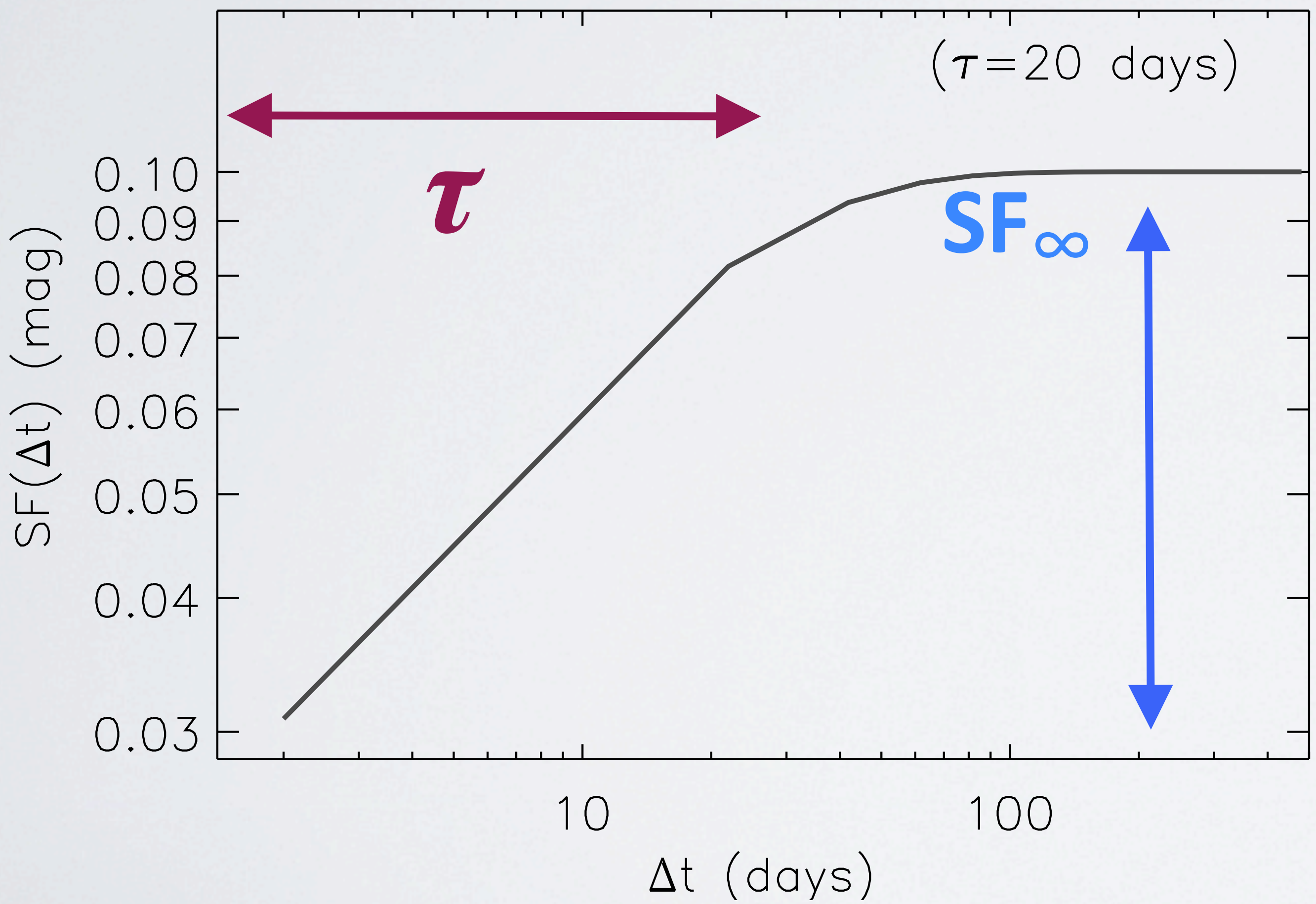
See also, e.g.:
Vandenberk+ 2004
Schmidt+ 2010
Morganson+ 2014
Kasliwal+ 2015
Peters+ 2015
Kozlowski 2016A

SF is larger on average at longer timescales, and smaller wavelengths.

FITTING LIGHTCURVES AS A DAMPED RANDOM WALK (DRW)

(also known as Ornstein-Uhlenbeck process and as CAR(1) process)





Simple, fast [O(N)]

Two variability parameters:

- **SF_∞:** asymptotic rms in Δm
- **τ:** characteristic time scale

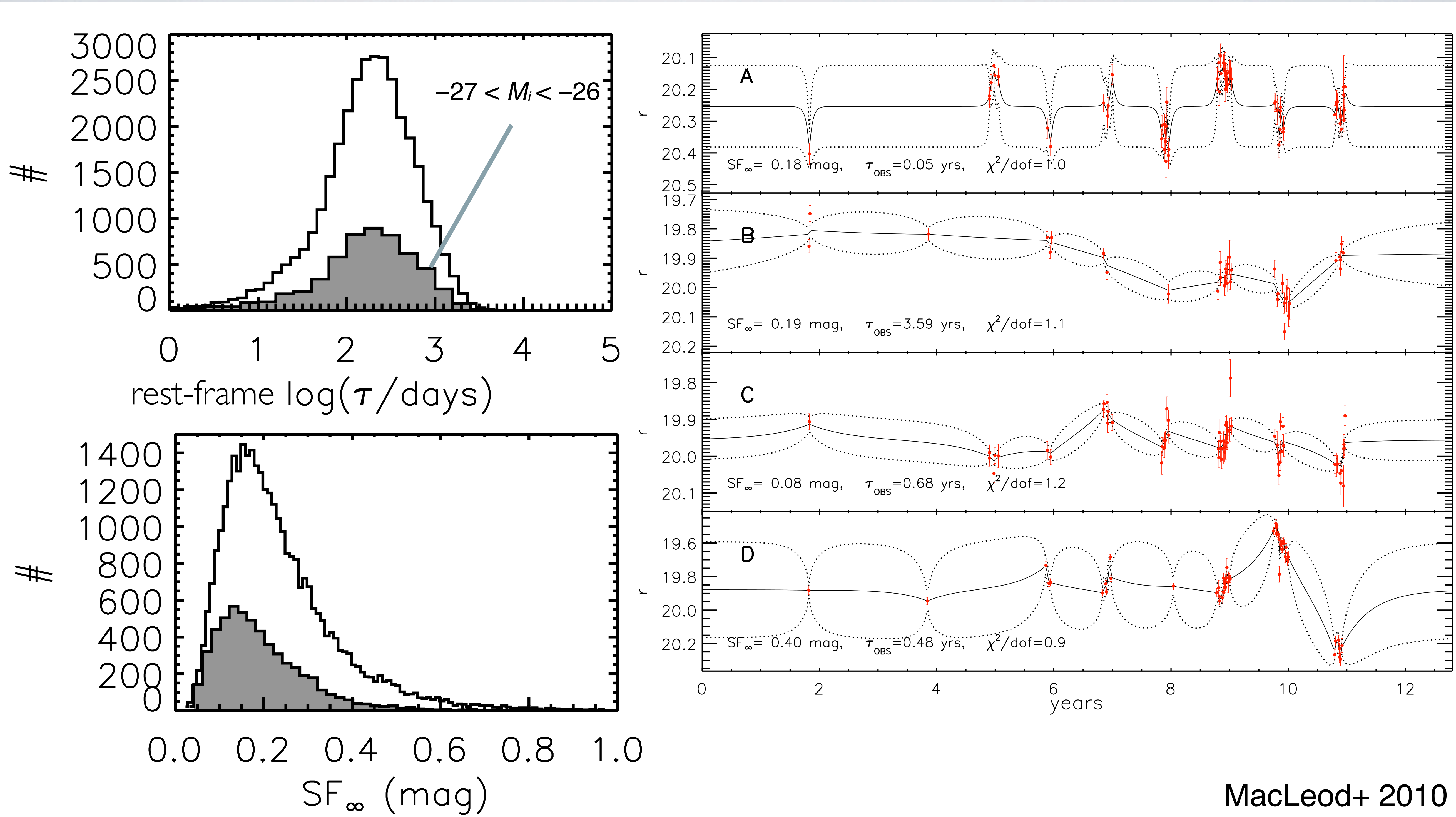
(Kelly+ 2009; Kozłowski+ 2010; Zu+ 2012)

Predicts exponential form for Structure Function:

$$\mathrm{SF}(\Delta t) = \mathrm{SF}_\infty (1 - e^{-|\Delta t|/\tau})^{1/2}$$

auto-correlation function

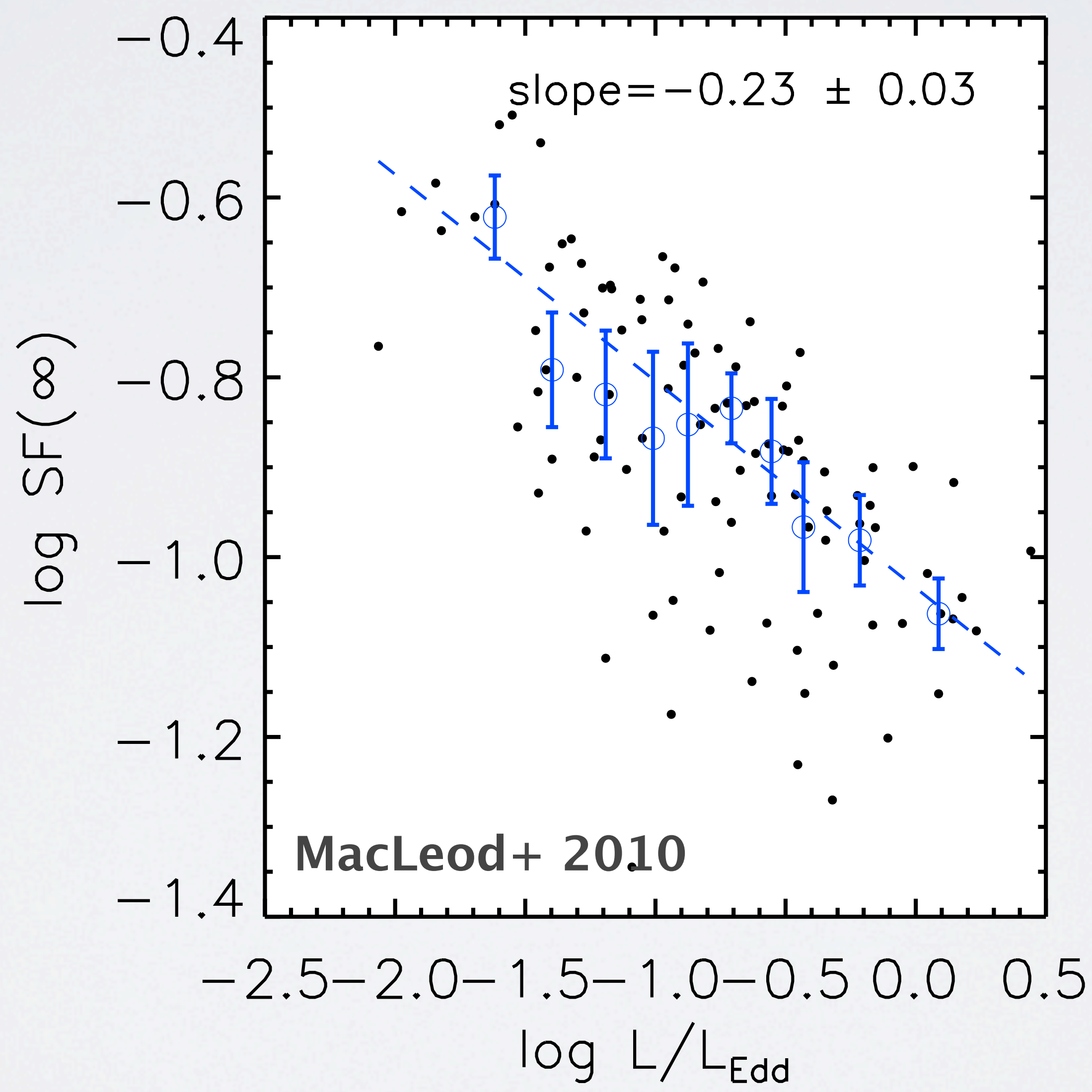
STRIPE 82: OBSERVED DRW PARAMETERS



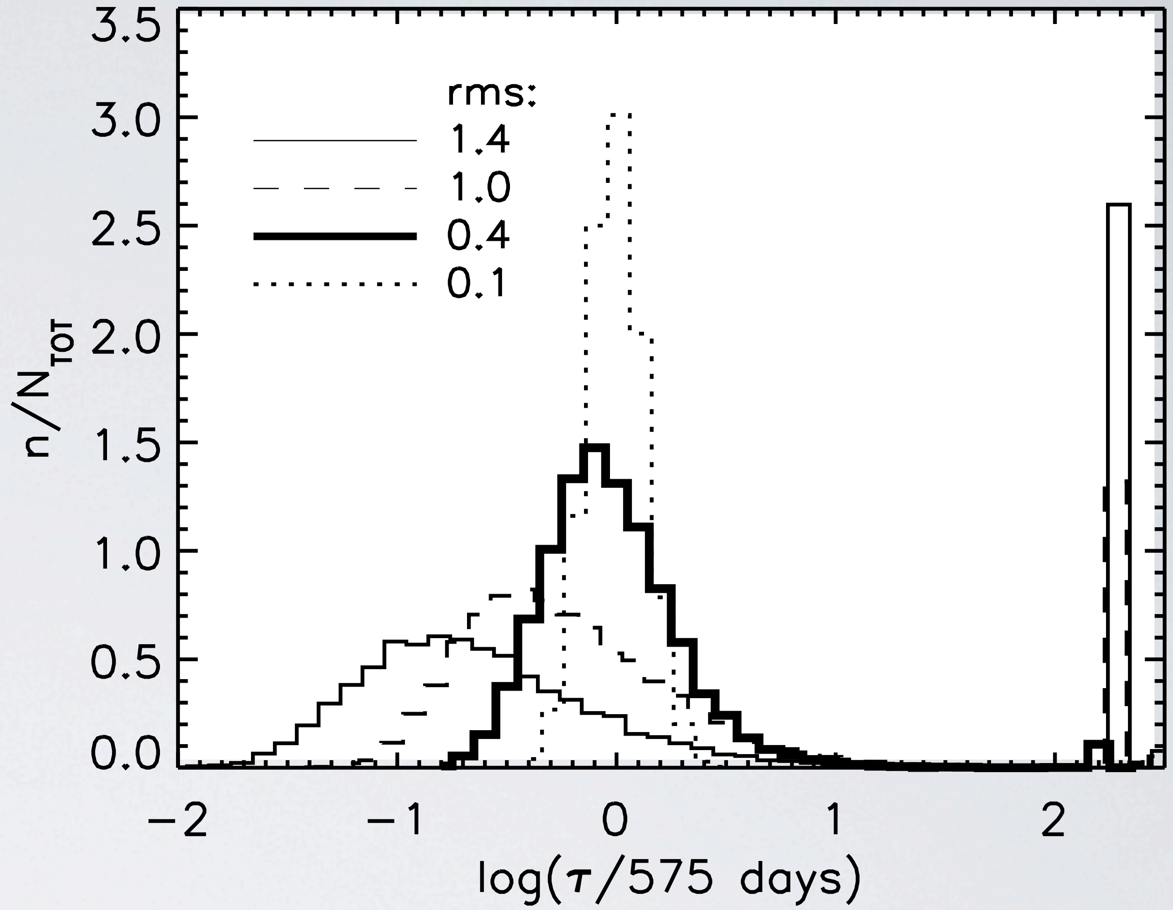
MacLeod+ 2010

EDDINGTON RATIO AS THE DRIVER OF VARIABILITY?

- With SDSS S82 data, can see clear dependence of variability on physical quantities such as Eddington ratio (see also SF analyses from Kozlowski 2016A; Wilhite+2005)



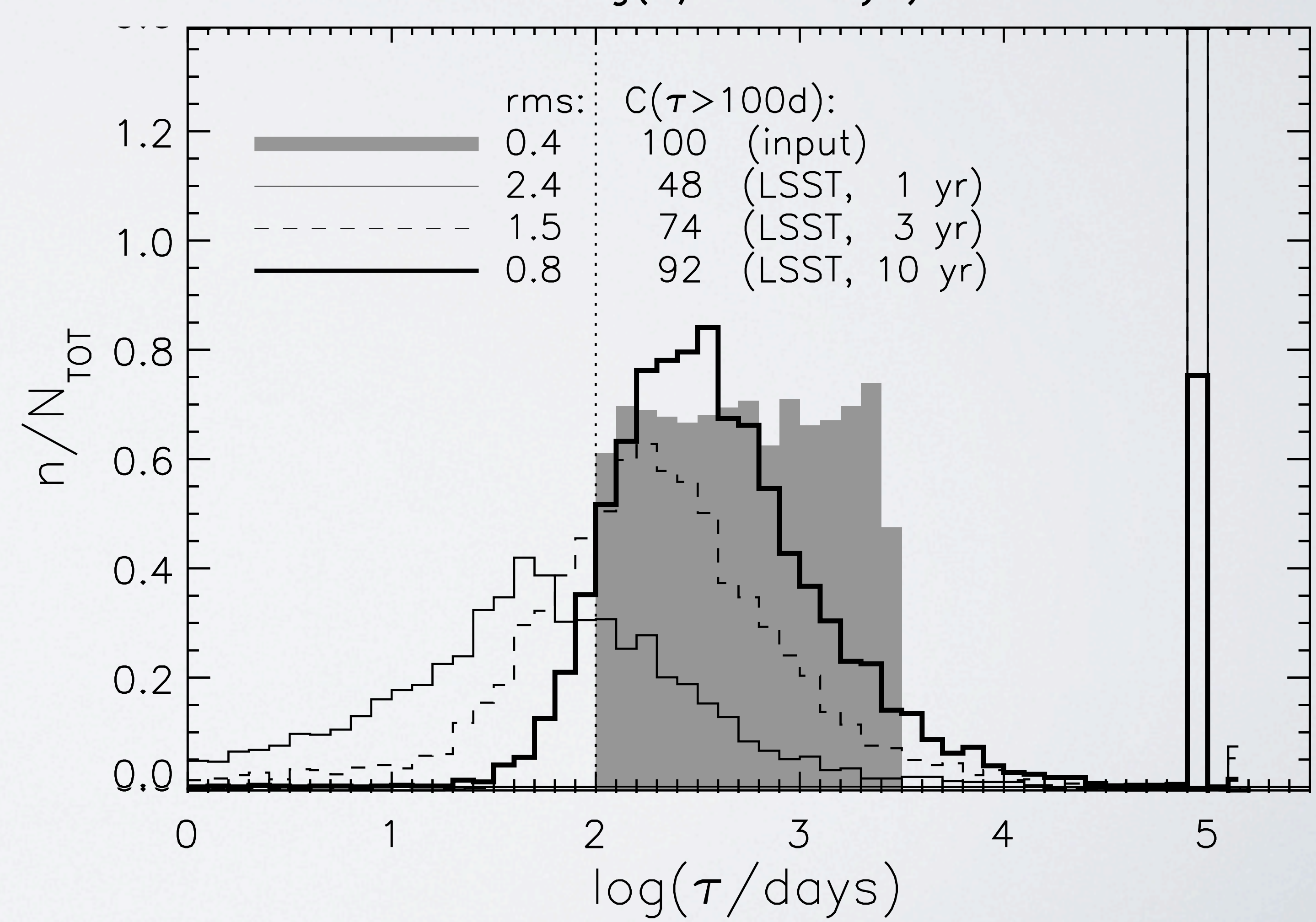
EFFECT OF SURVEY LENGTH



1 yr
3 yr
10 yr
40 yr

Due to intrinsic τ for quasars (+ time dilation), need **>10 yrs** (MacLeod+ 2011)

Can reliably constrain timescale for lengths **>10τ** (Kozlowski 2016c)



MacLeod+ 2011

Probing Long-term Variability with LSST

Large Synoptic Survey Telescope

- AGN variability studies will be based on millions of light curves with ~900 observations over 10 yrs
- LSST overlap with SDSS, Pan-STARRS, PTF, etc. yields 30 yr-long light curves for 20,000 quasars
- 10 yr-long light curves are sufficient at low z and light weight end of BH mass spectrum ($\tau \propto M^{0.4}$, Kozlowski 2016a)

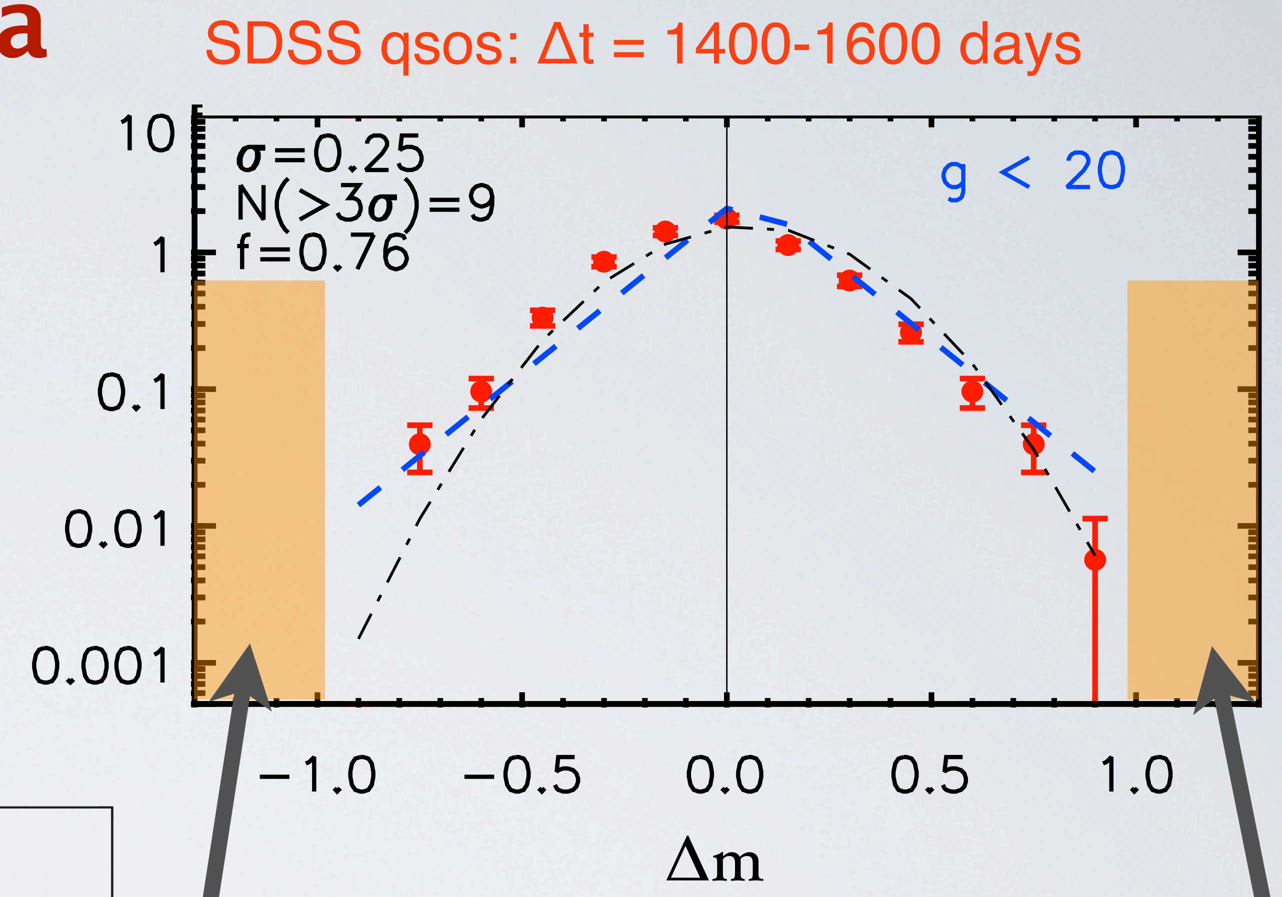
LSST: M_B = -23 at z ~ 2,

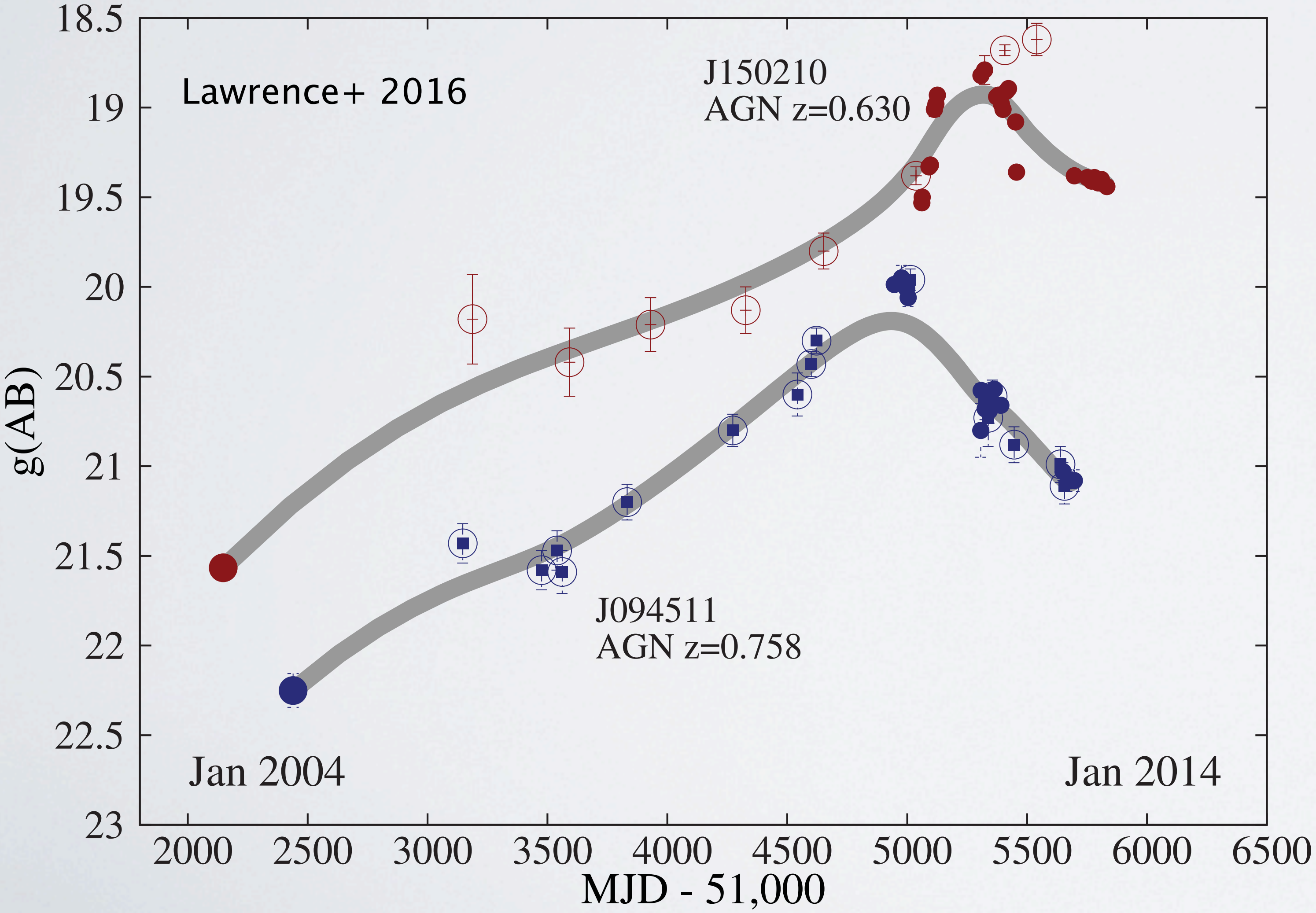
SDSS: M_B > -23 at z < 0.5

Transient AGN phenomena

- Tidal Disruption Events (e.g. Gezari+ 2012)

- Microlensing (Lawrence+ 2016)

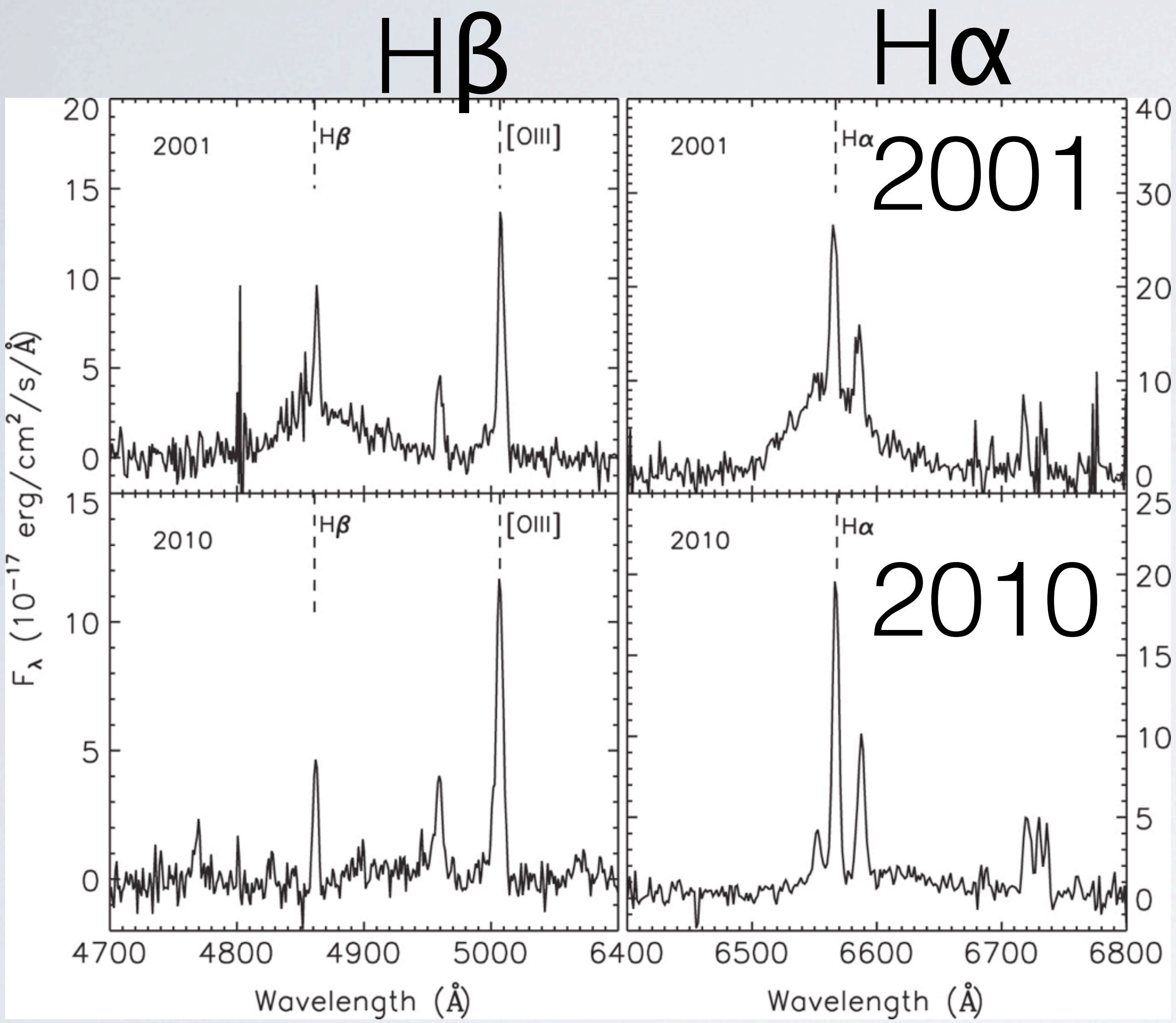


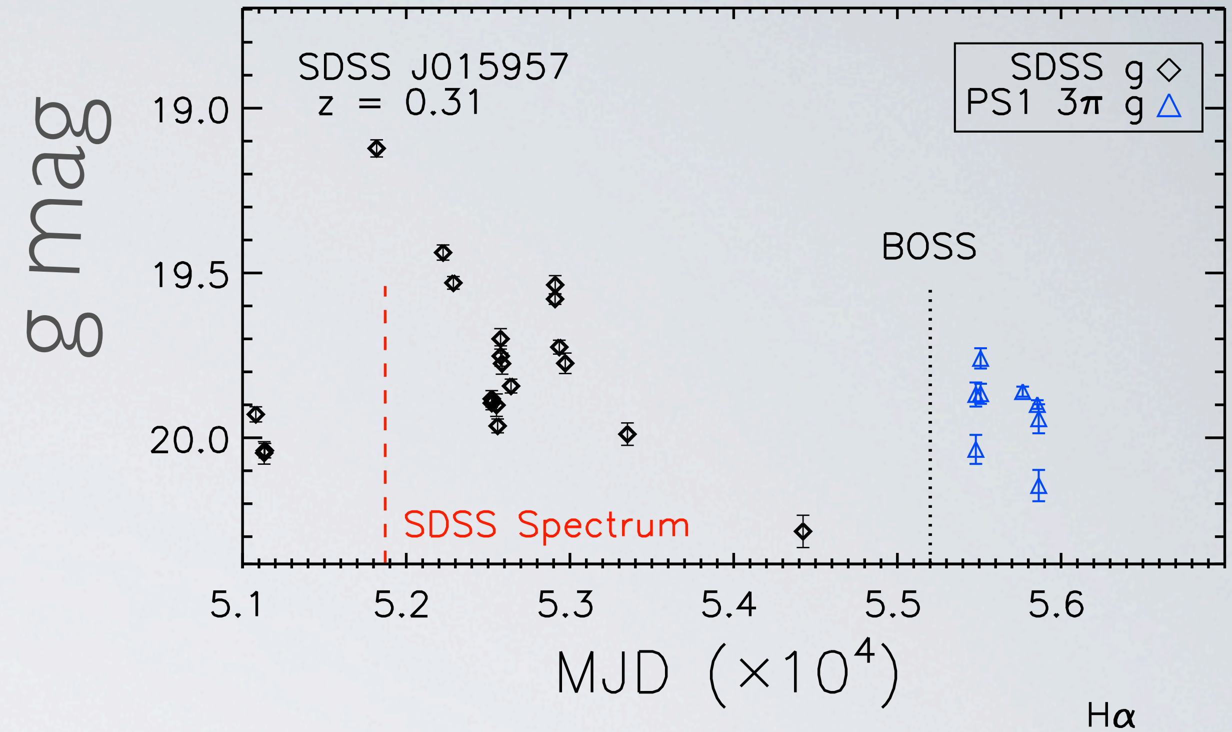


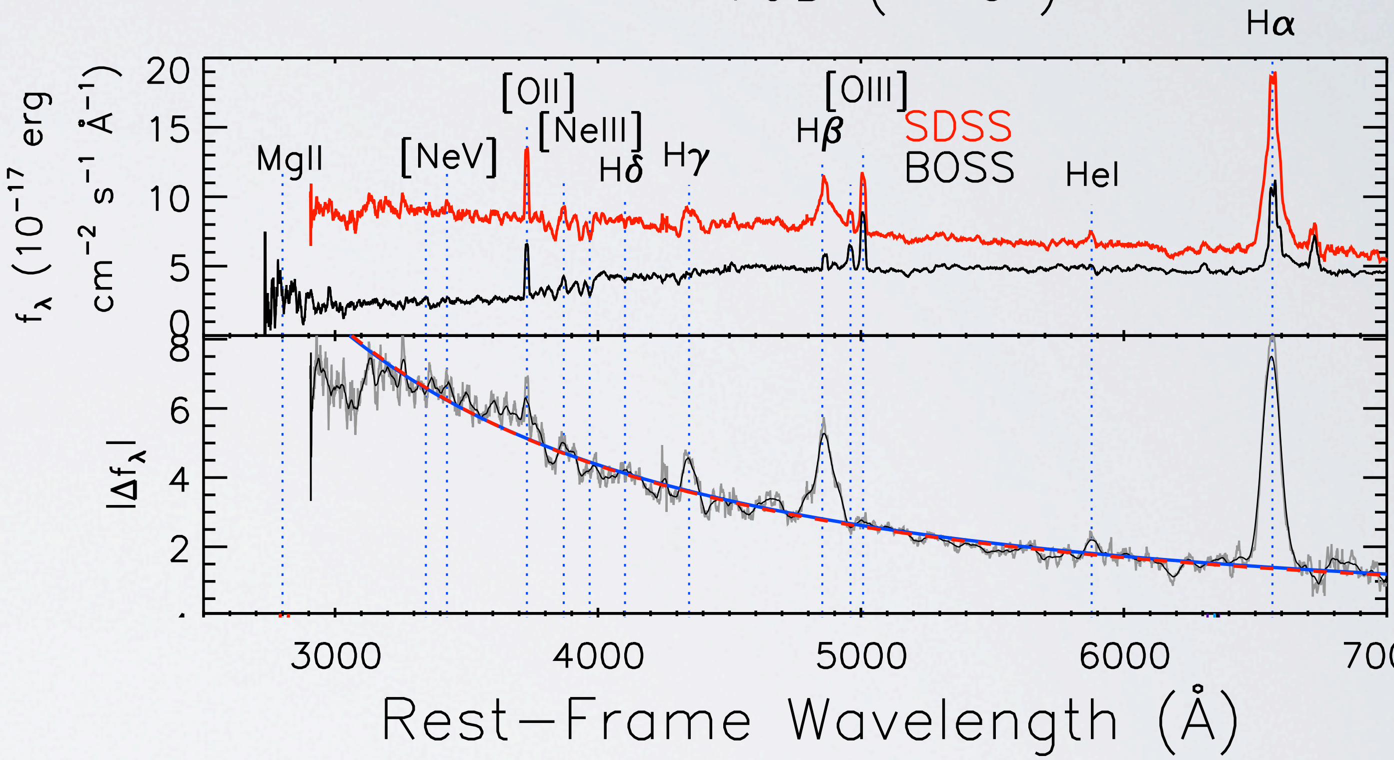
Beginning to probe tails on long Δt.

- Changing-Look Quasars!

CHANGING-LOOK QUASARS (CLQS)



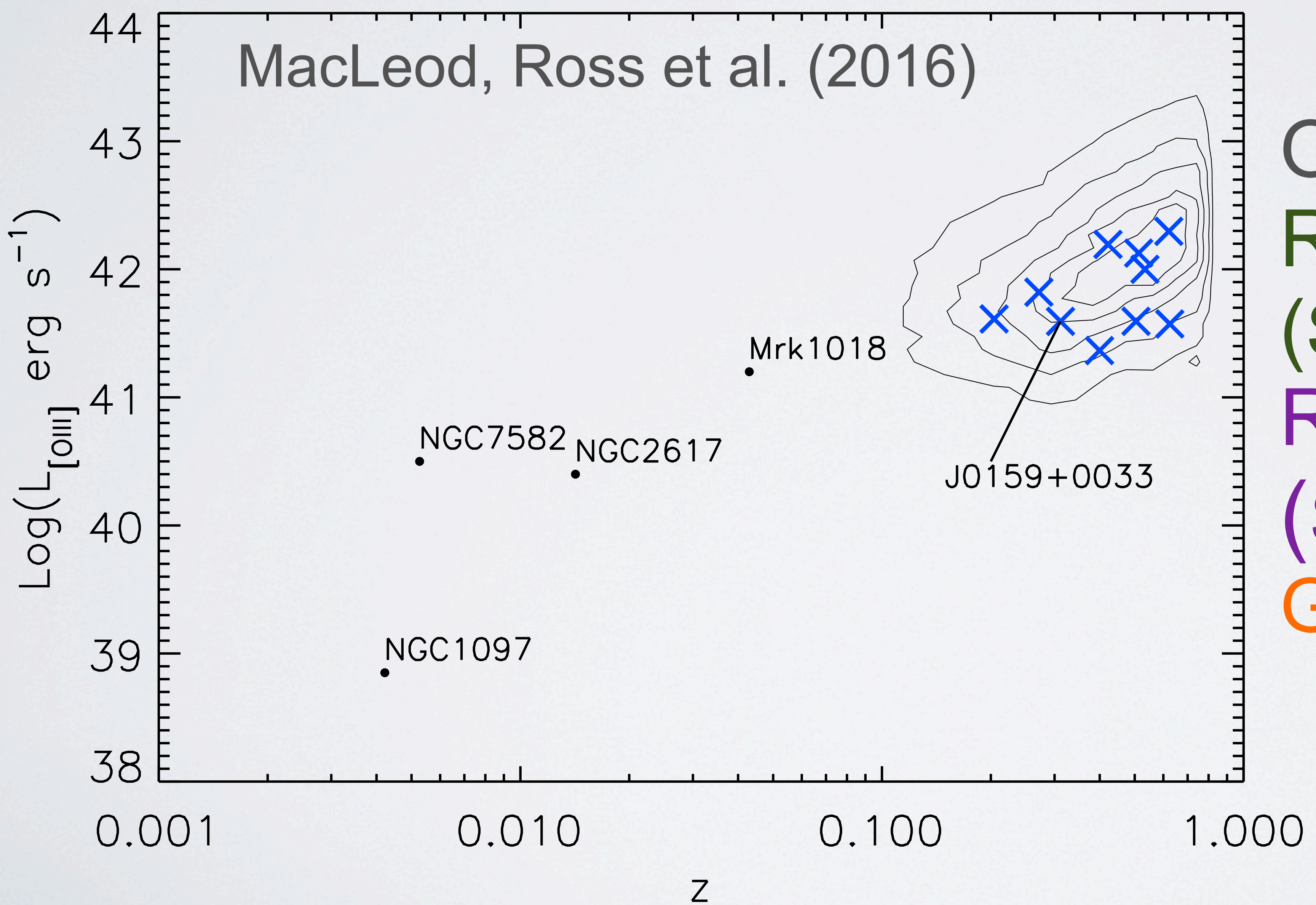




- Broad Balmer BEL (dis)appearance associated with ***large flux change***
- Serendipitous discovery for z = 0.31 QSO (LaMassa+2015)
- Archival X-ray observations rule out variable obscuration.

Systematic Search for CLQs

Selection	Total #	In S82
SDSS Quasars in DR7Q	105783	9474
with BOSS spectra	25484	2304
and $\lvert\Delta g\rvert > 1$ mag and $\sigma_g < 0.15$ mag	1011	287
and that show variable BELs	$\boxed{10}$	7



Other discoveries:

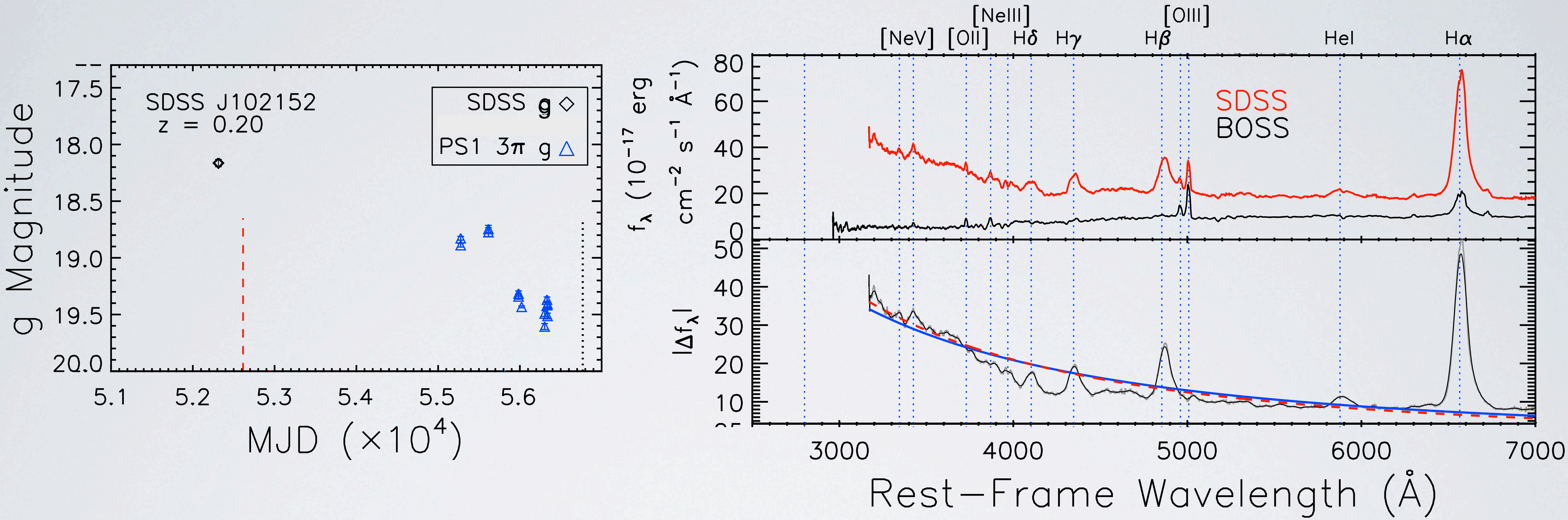
Ruan+ 2016 (SDSS/BOSS)

Runnoe+ 2016 (SDSS-IV TDSS)

Gezari+ 2016 (PTF)

MacLeod, Ross et al. (2016)

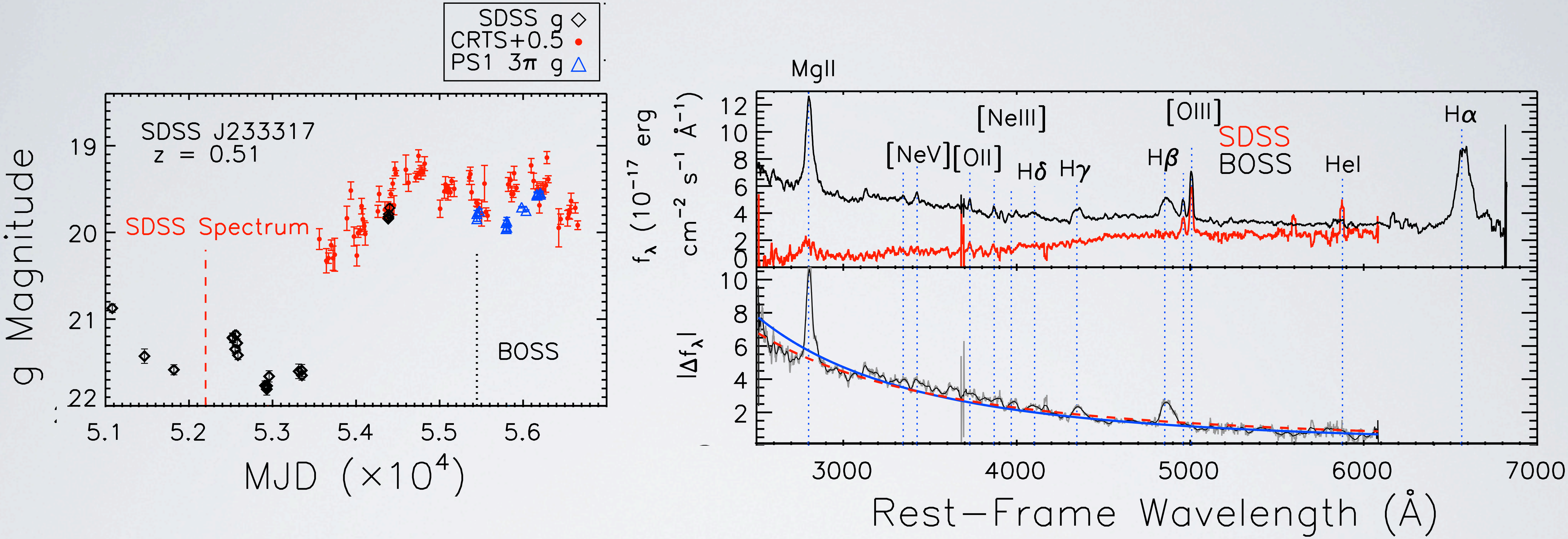
Changing-look Quasars in SDSS/BOSS



"Turn-off" CLQ from systematic archival search.

MacLeod, Ross et al (2016)

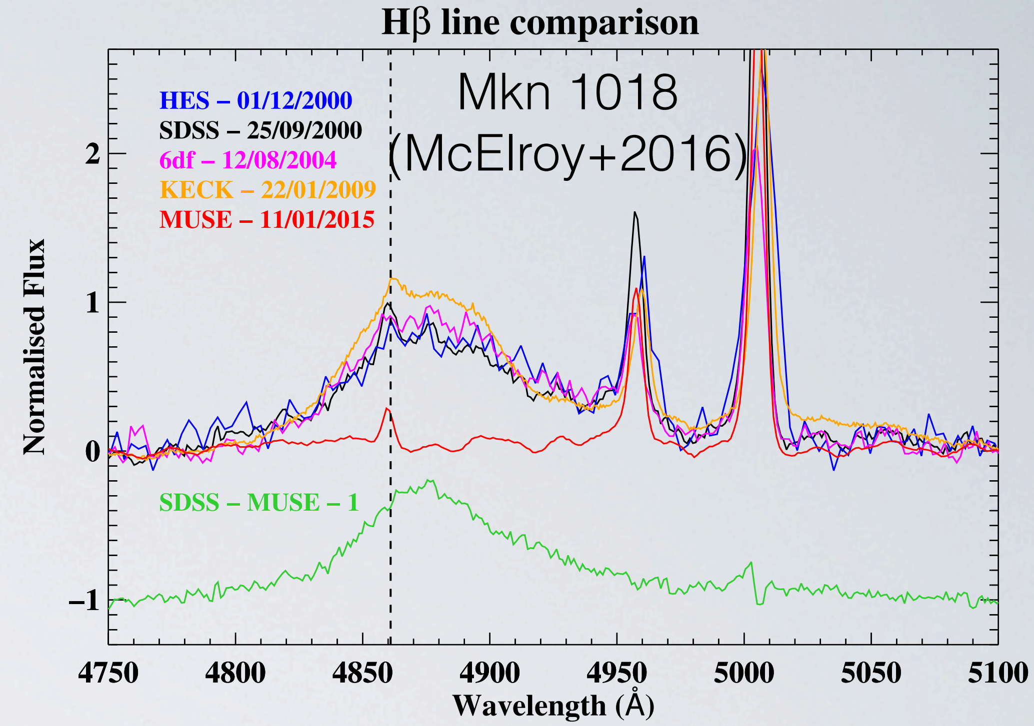
Changing-look Quasars in SDSS/BOSS



"Turn-on" CLQ from systematic archival search.

MacLeod, Ross et al. (2016)

PHYSICAL INTERPRETATIONS OF CLQS

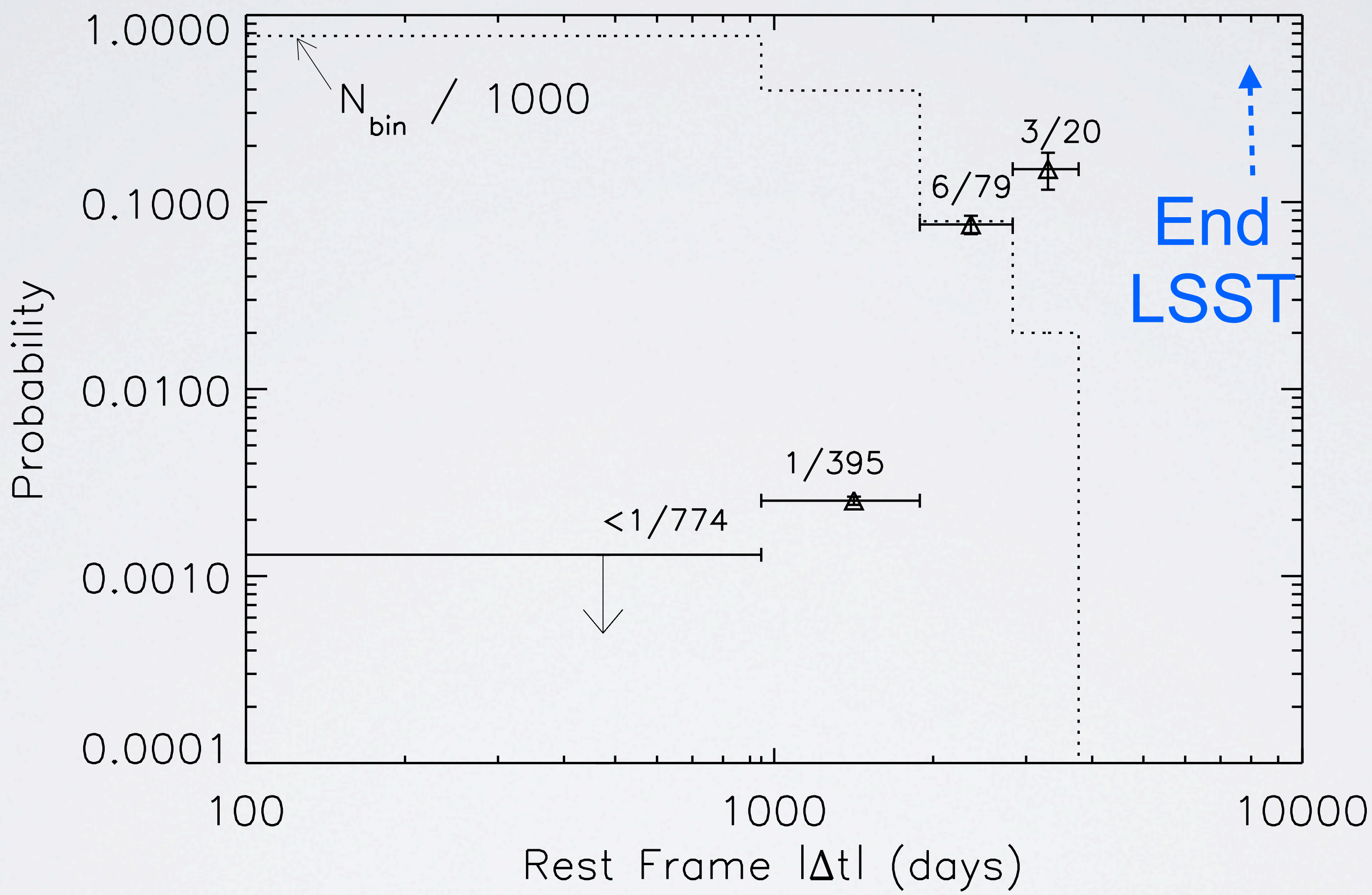


- Cold chaotic accretion models (Gaspari+2015)
- Thermal timescale for ***global temperature change*** (e.g. Mkn 1018, Husemann et al 2016)
- Thermal instability due to low metallicity (Jiang+2016)
- Structural change in BLR on $\tau_{\mathrm{dyn,BLR}}$
- Some may be tidal disruption events (Merloni+2015)

Systematic Search for CLQs

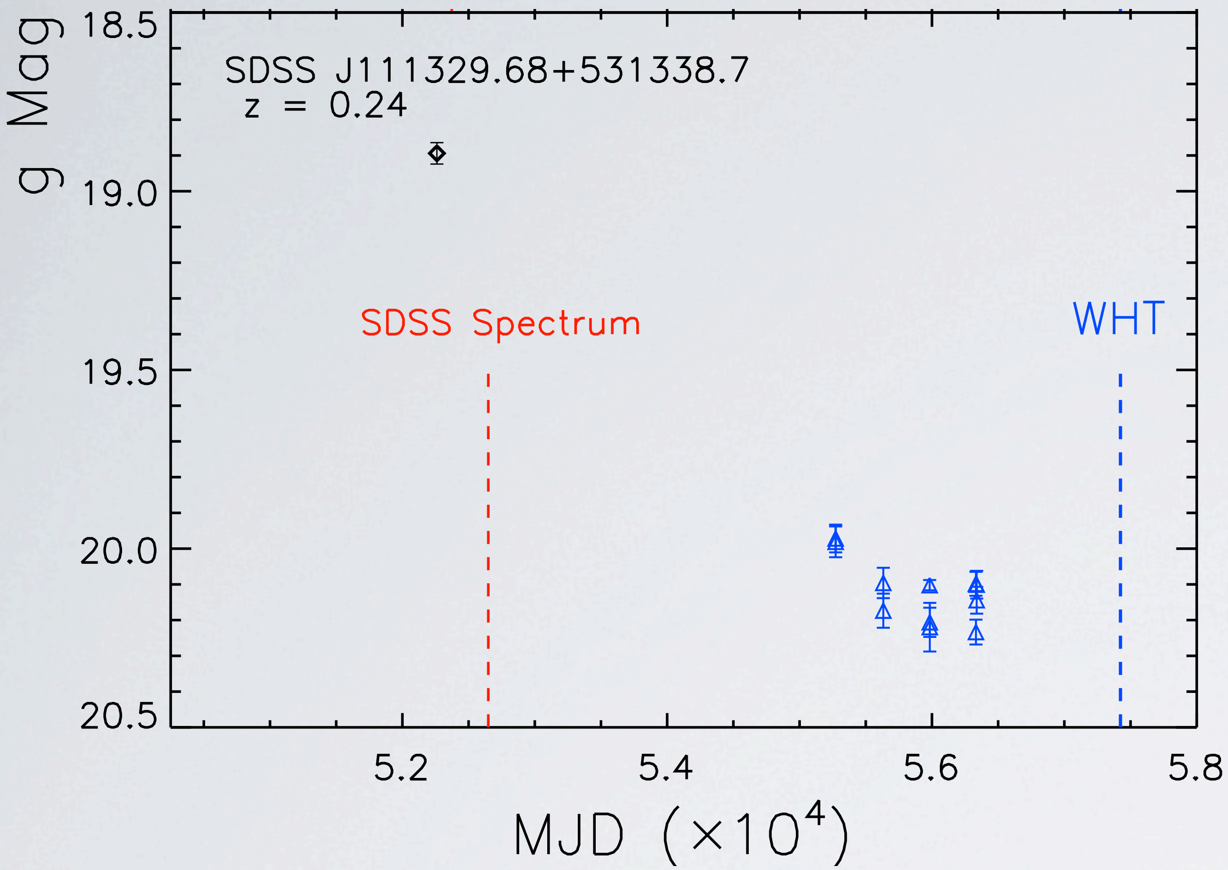
- Shortest timescales are ≲1yr (Gezari+2016)

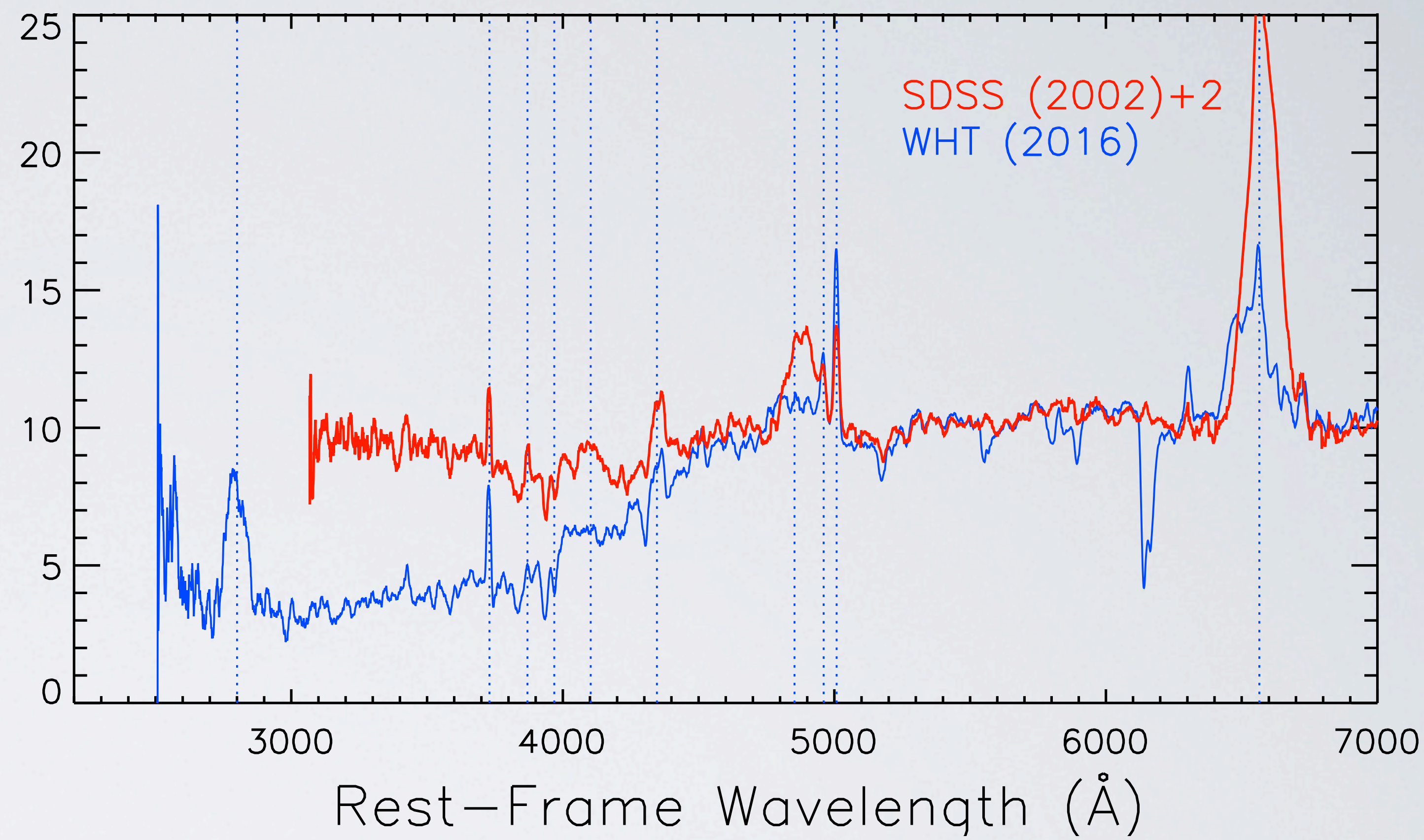
- Probability grows with time difference (MacLeod, Ross et al. 2016)



- Out of highly variable, |Δg| > 1 mag luminous ($L_{bol} \approx 10^{45}$ erg s^{-1}) quasars, CLQ fraction is ~20%.

CLAGN: PROSPECTS FOR LSST



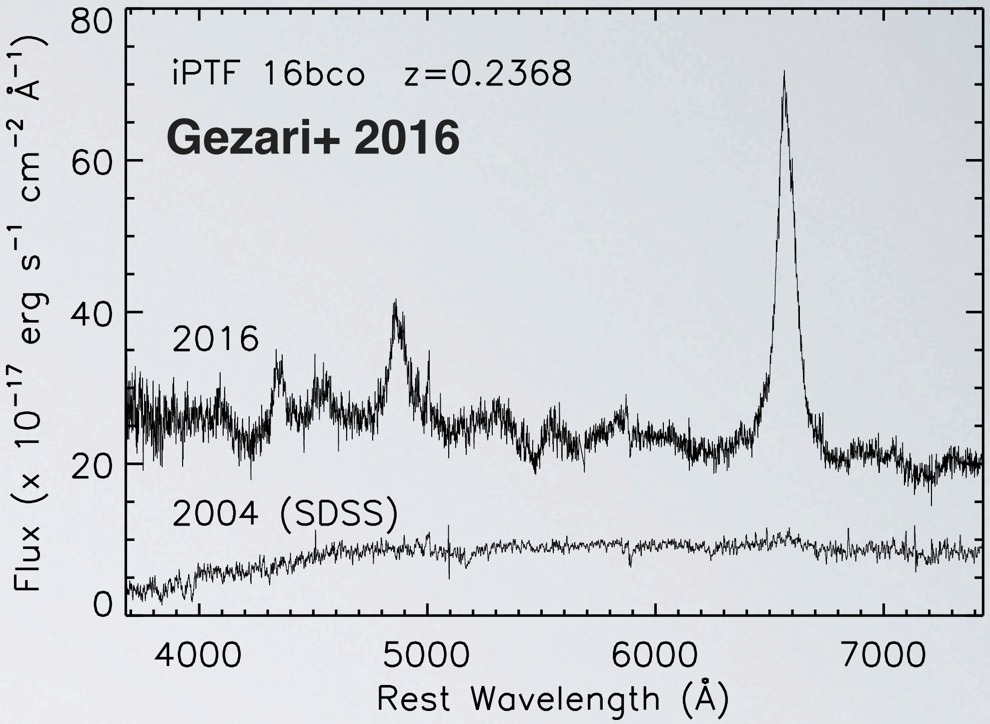


- Among 50 million AGN, will have thousands with |Δg|>1 mag; or more (variability increases with decreasing luminosity)

- CLQs: large changes in *g-r* (BBB) and *y* (Hα), X-ray flare (Shappee+2014)

- Follow-up spectroscopy: *i*) Find ***more CLQs*** in faint states. *ii*) Extend CLAGN population to ***fainter luminosities*** at z < 0.8

PREPARING FOR LSST

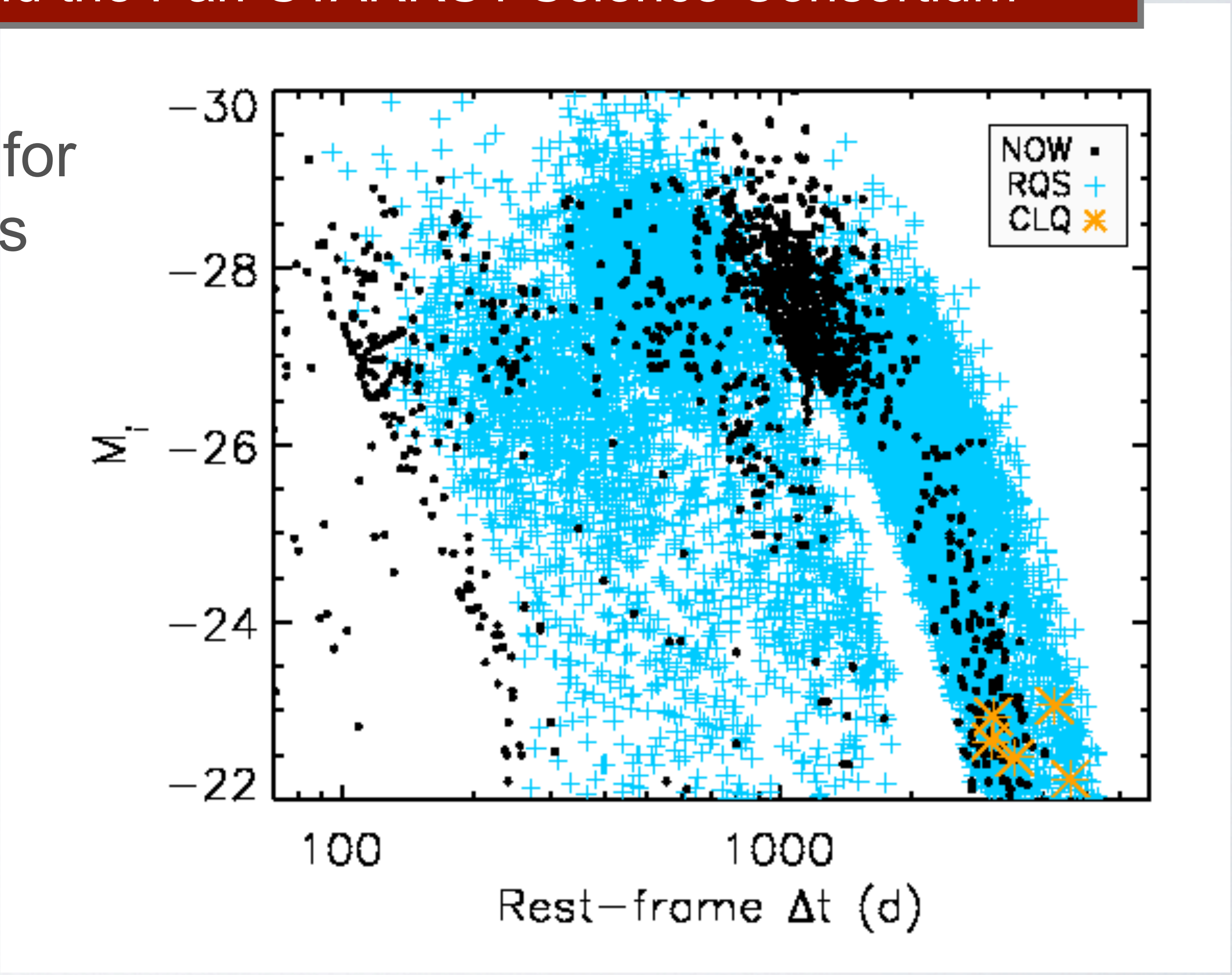


- Are changing-look quasars
  - ***a unique phenomenon,*** or
  - ***the tail of regular quasar variability?***
- Look for outliers in light curve parameters (e.g. Graham et al 2016, arxiv:1612.07271v1)
- Understand long-term spectroscopic variability using large samples of quasars with repeat spectra

SDSS IV Time Domain Spectroscopic Survey

Paul Green (P-I, SAO), Scott Anderson (P-I, UWa), Chelsea MacLeod (SAO), Michael Eracleous (PSU), Niel Brandt (PSU), Sean McGraw (PSU), Kate Grier (PSU), Jessie Runnoe (UMich), Eric Morganson (UIUC), John Ruan (UWa), Don Schneider (PSU), Yue Shen (UIUC), the TDSS Team, the SDSS-IV Collaboration, and the Pan-STARRS1 Science Consortium

- ★ Unbiased spectral survey for ~200,000 celestial variables (Morganson+ 2015; Ruan+ 2016)
- ★ Repeat spectra for 13K Quasars
- ★ Repeat spectra for ~1K Hypervariable Quasars (|Δm|>0.7 mag)



SUMMARY

- **S82 QSO variability data consistent with thermal timescales; accretion disk instabilities**

- **Constrain τ using LSST overlap with SDSS, DES, etc. for bright QSOs and at low-z, faint end**

- **Large amplitude, long-term QSO variability with *follow-up spectroscopy* gives us new insights into accretion physics**

➡ **Determine best follow-up strategy**

EXTRA SLIDES

DRW Model Refinements

- DRW Power Spectral Density:

$$P(f) \propto (f_0^{\,2} + f^{\,2})^{-1} \quad (f_0 = 1/\tau)$$

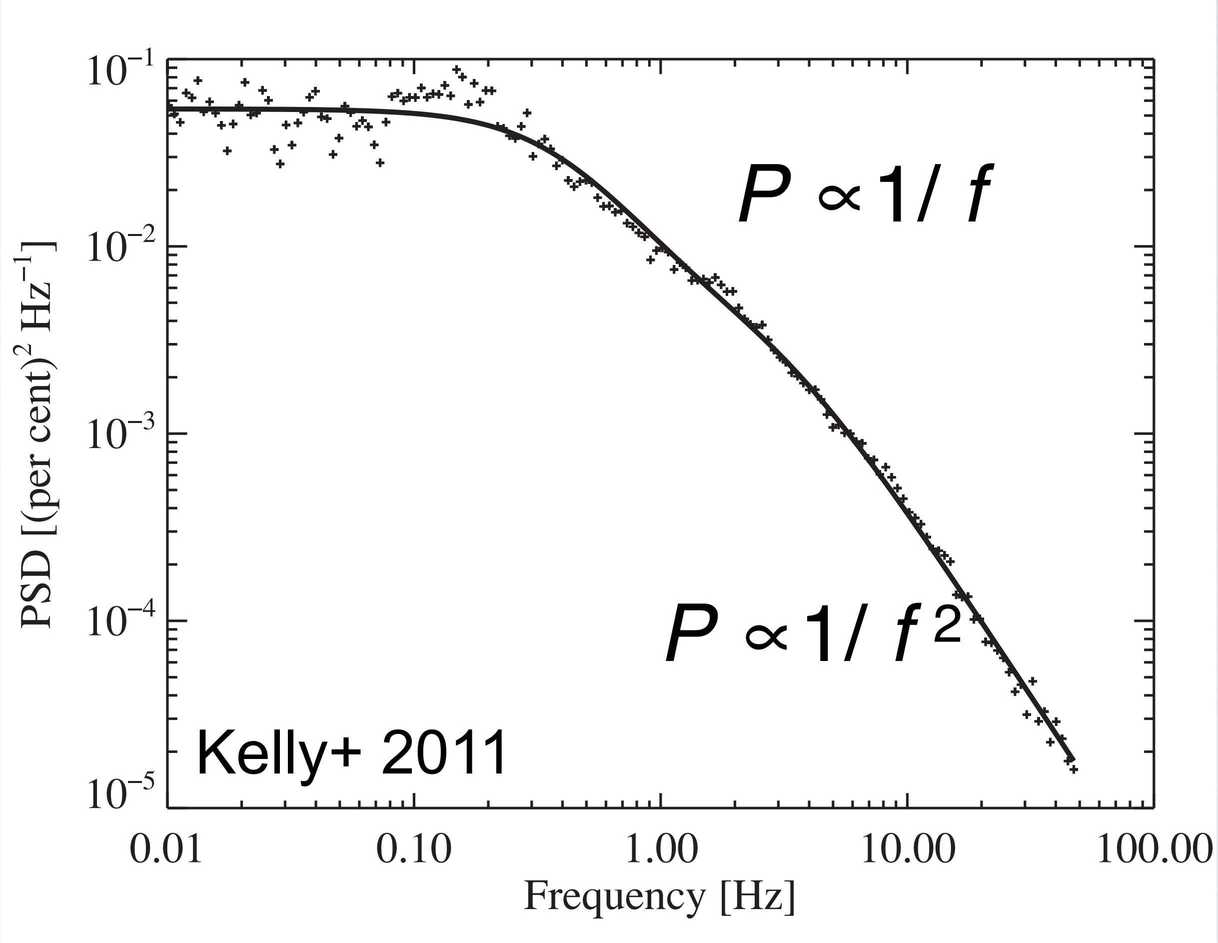
- XRBs/ X-ray AGN: Mixed OU process *(Kelly+ 2011)*

- Long Timescales (low *f*): cannot distinguish between f^{-1} or f^{0} in optical

- Short timescales (high *f*): Kepler data shows f^{-3} *(Mushotzky+2011; Kasliwal+2016)*

- CARMA: flexible models *(Kelly +2014; Simm+ 2015; Zinn+2016)*

Cygnus X-1 PSD



CARMA(2, r) = QPO
(= DRW when $\tau/P \ll 1$)

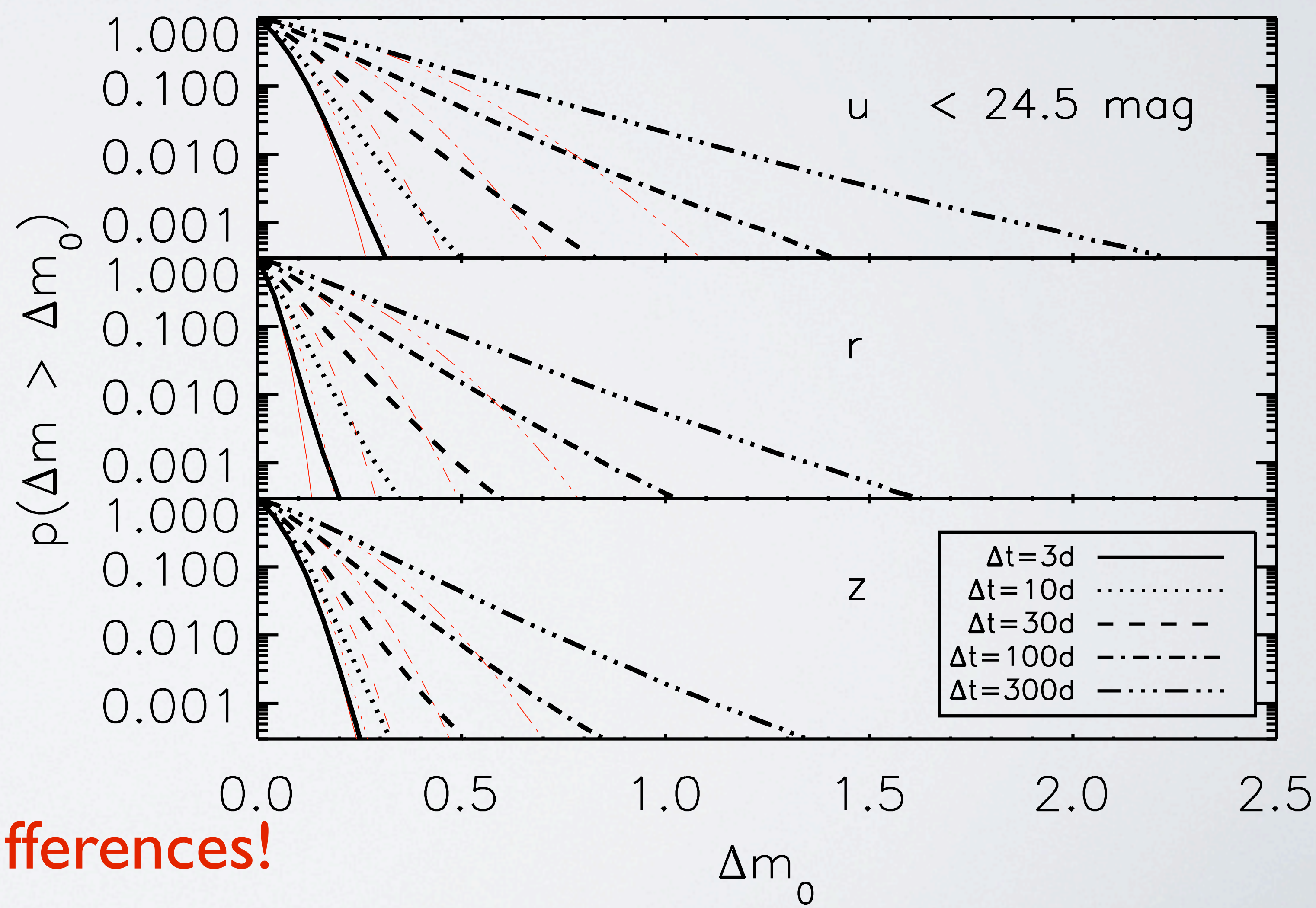
Probing Long-term Variability with LSST

Large Synoptic Survey Telescope

With an accurate long-term variability model to LSST depths, can determine ***incidence of AGN contamination*** in transient searches.

TABLE 1
PREDICTED Δm PROBABILITIES FOR $m_{faint} = 24.5$

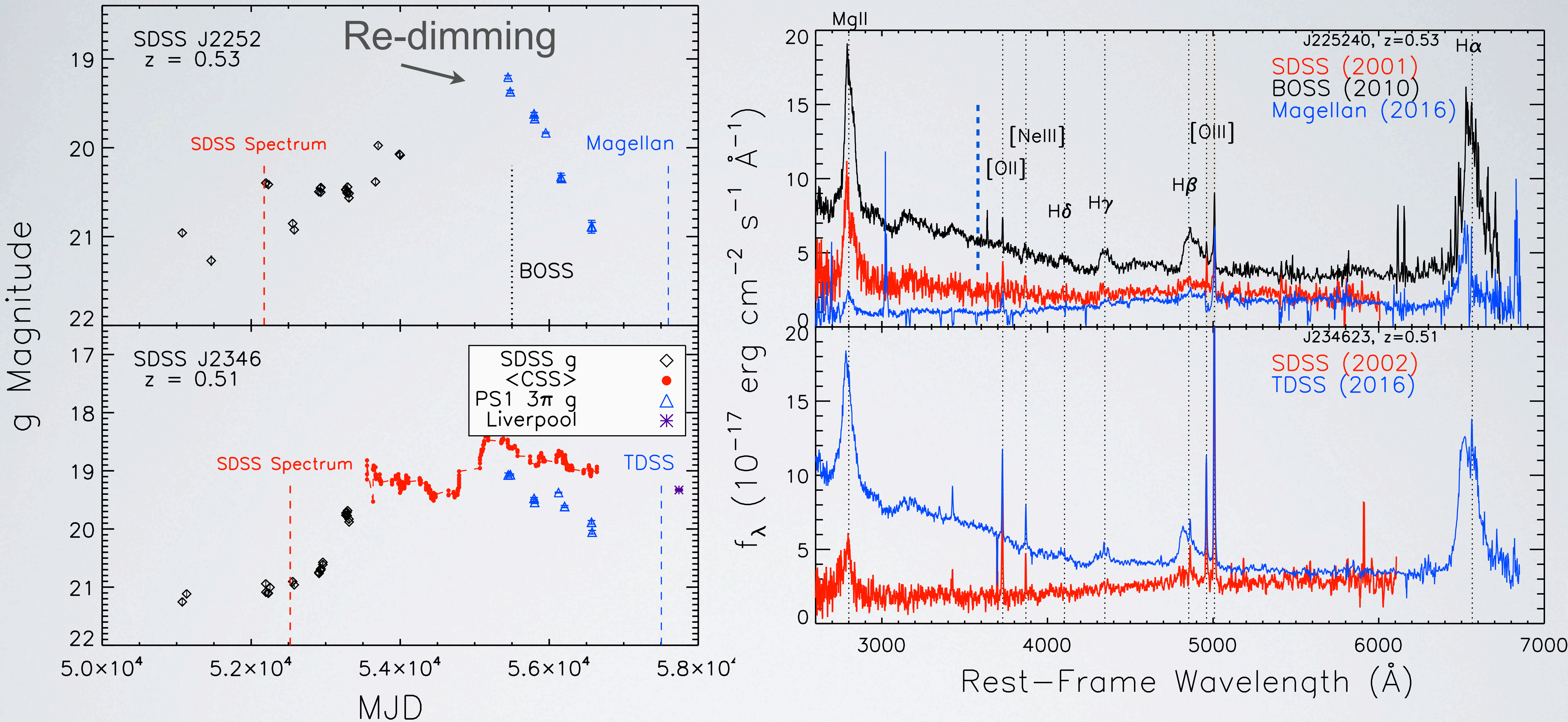
Δt (days)	Band	P($\Delta m > 1$ mag)	P($\Delta m > 2$ mag)
3	u	2×10^{-6}	2×10^{-6}
3	r	2×10^{-6}	2×10^{-6}
3	z	2×10^{-6}	2×10^{-6}
30	u	7×10^{-5}	2×10^{-6}
30	r	4×10^{-6}	2×10^{-6}
30	z	2×10^{-6}	2×10^{-6}
300	u	$\boxed{0.02}$	$\boxed{6 \times 10^{-4}}$
300	r	0.005	6×10^{-5}
300	z	0.002	1×10^{-5}



240K (7K) AGN for 1mag (2mag) differences!

MacLeod+2012

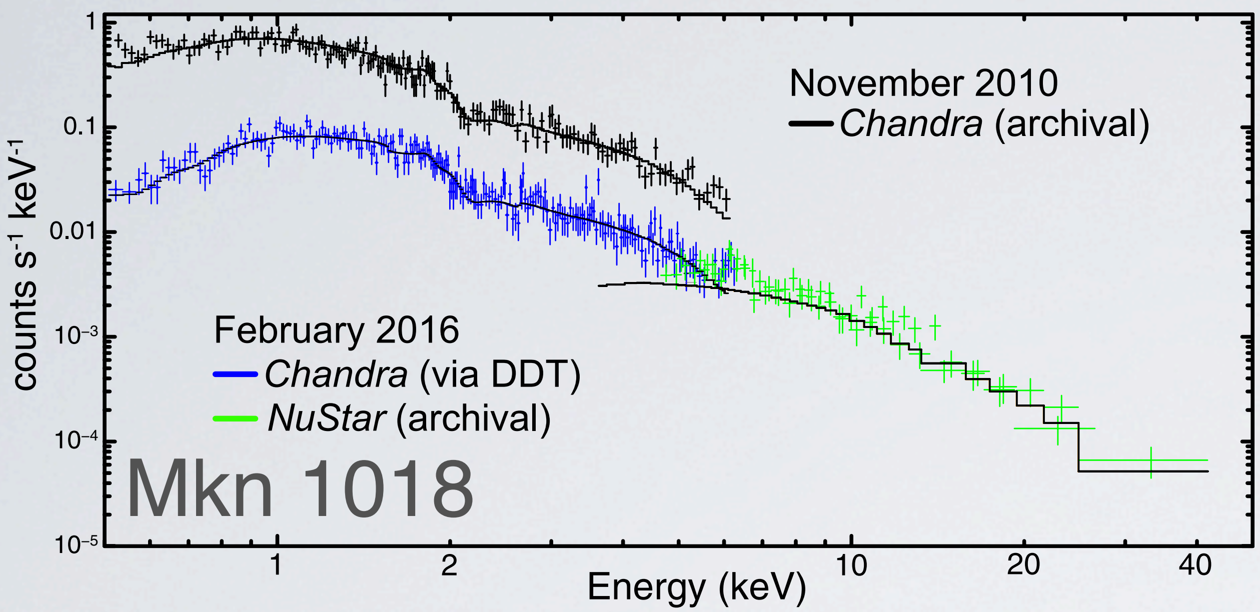
Followup Spectra of CLQ Candidates



(Redimming also seen in CLAGN Mkn 1018, McElroy et al 2016)

Is CLQ behavior a one-off event?

CLUES FROM X-RAYS



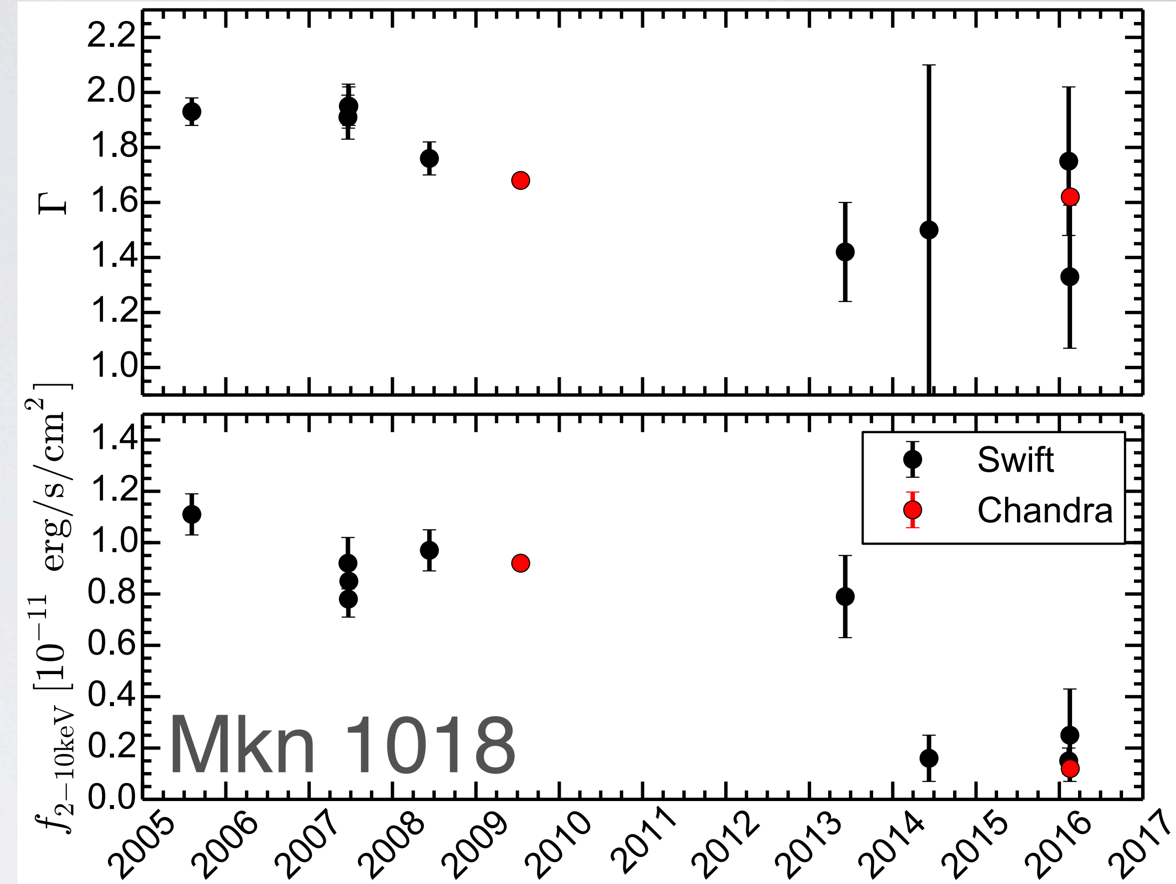
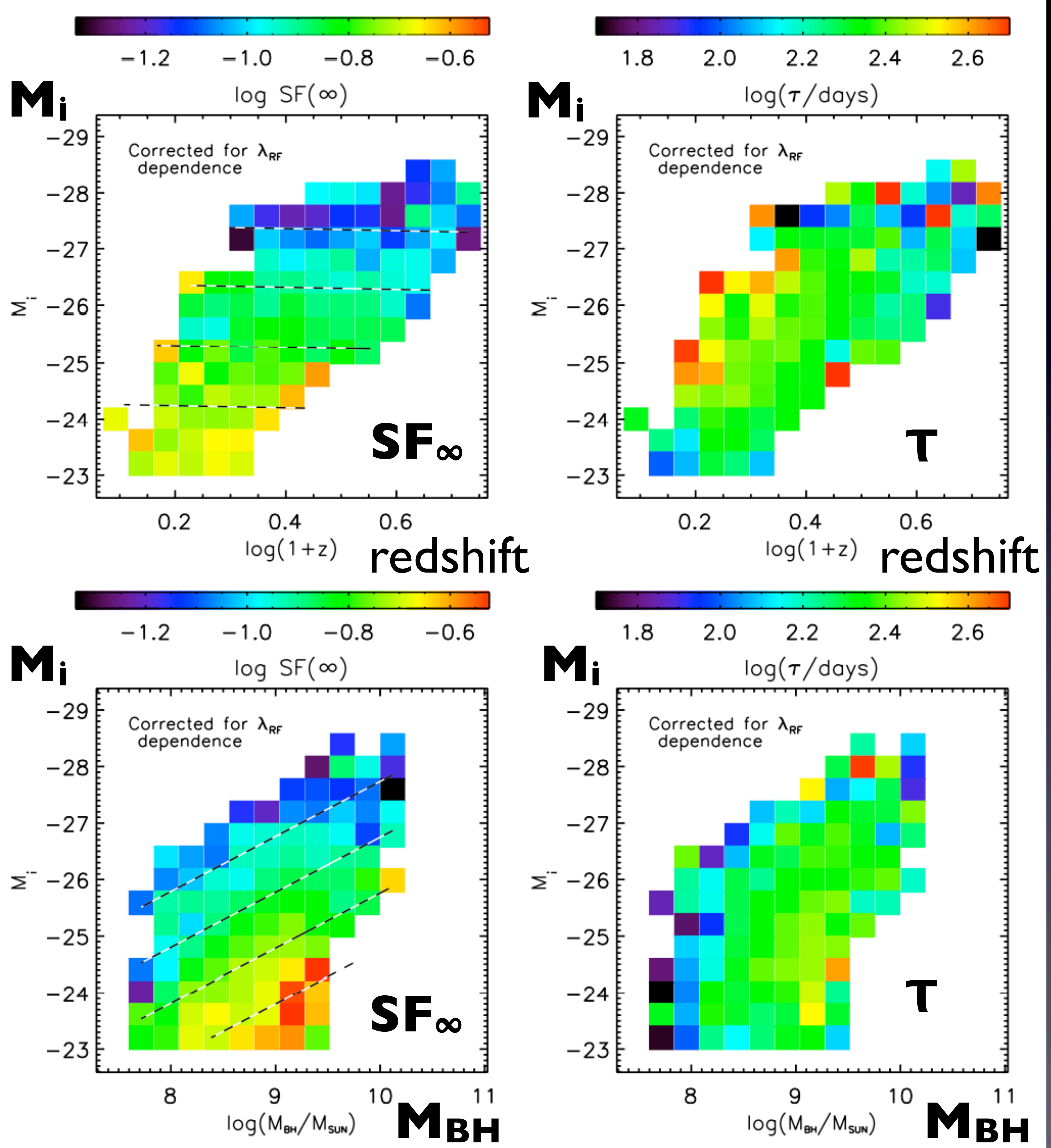


Fig. 2. Time evolution of the X-ray photon index Γ and the 2–10 keV flux from 2005 until 2016 based on the *Swift* and *Chandra* data.

- X-ray flux changes by factor:
  - 10 in Mkn1018 (Husemann+2016)
  - 12 in SDSSJ0159 (LaMassa+2015)
  - >3 in iPTF 16bco (Gezari+ 2016)
- No evidence for obscuration

Damped random walk

What can be learned from fitting individual light curves?



τ increases with wavelength and black hole mass, and is nearly constant with redshift and luminosity

SF_∞ increases with decreasing luminosity and rest-frame wavelength, and without a correlation with redshift

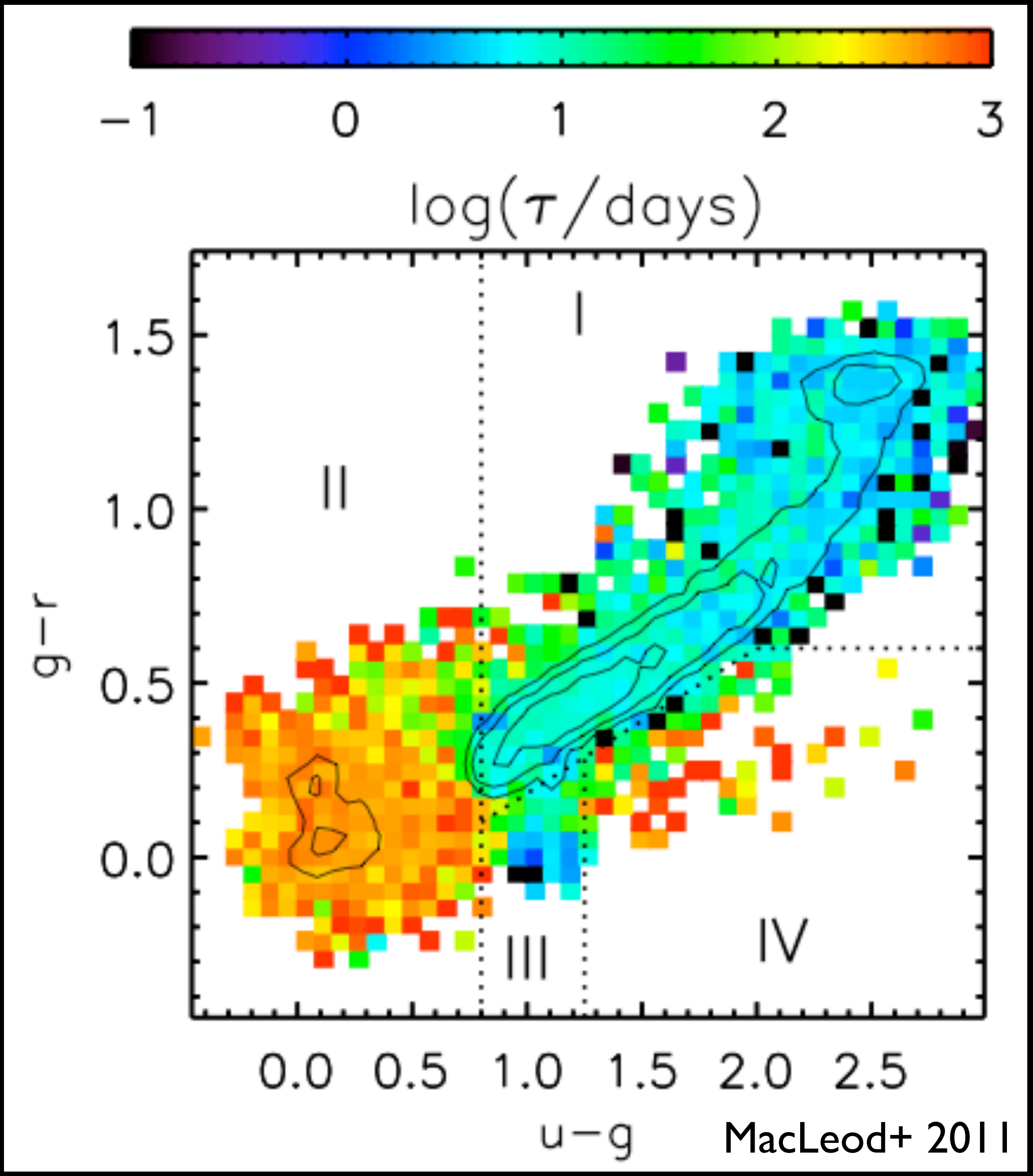
SF_∞ is correlated with black hole mass, independent of the anti-correlation with luminosity

SF_∞ is anti-correlated with the Eddington ratio, which suggests **a scenario where optical fluctuations are tied to variations in the accretion rate.**

MacLeod et al. 2010

S82 Variability-Based Quasar Selection

- DRW model:
  Butler & Bloom 2011;
  MacLeod+ 2011;
  Choi+ 2014 (extended AGN)
- SF rising slope:
  Schmidt+ 2010;
  Palanque-Delabrouille+ 2011;
  Peters+ 2015
- SDSS III: adding 78,086 qsos (Paris+ 2012)



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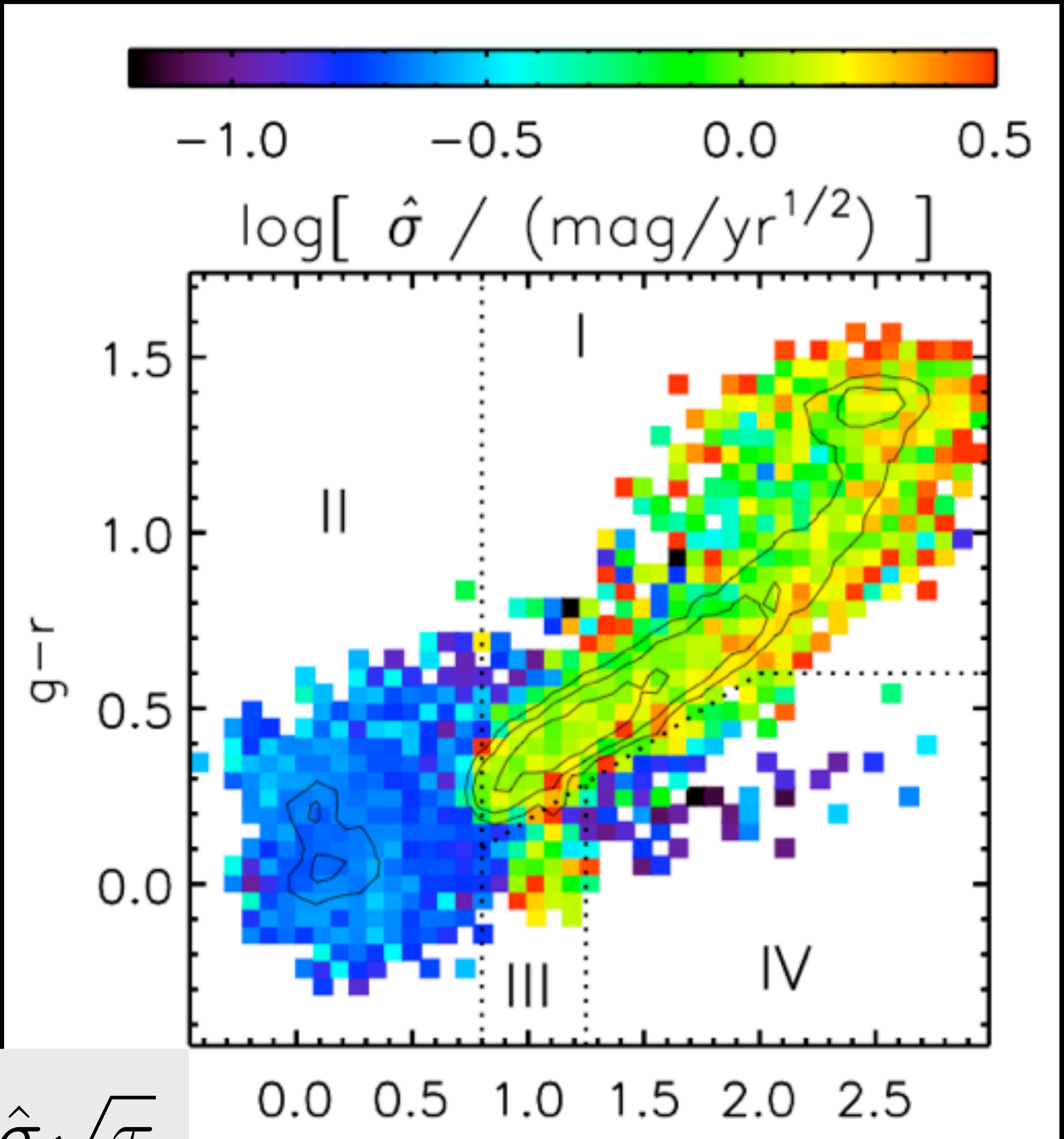

MacLeod+ 2011

$$SF_\infty = \hat{\sigma}\sqrt{\tau}$$