QSOs in the Time-Domain: Monitoring and Detection

Nat Butler

(UC Berkeley / ASU)

UCB Center for Time Domain Informatics

Berkeley (UCB):

Faculty/Staff

Josh Bloom, Dan Starr (Astro.), John Rice, Noureddine El Karoui (Stats), Martin Wainright, Masoud Nikravesh (CS)

Post-Docs

Dovi Poznanski, Brad Cenko, Joey Richards, Nino Cucchiara

Grad Students

Dan Perley, Adam Miller, Adam Morgan, Chris Klein, James Long, Sahand Negahban, John Brewer

Undergrads

Maxime Rischard, Justin Higgins, Rachel Kennedy, Jason Chu, Arien Crellin-Quick

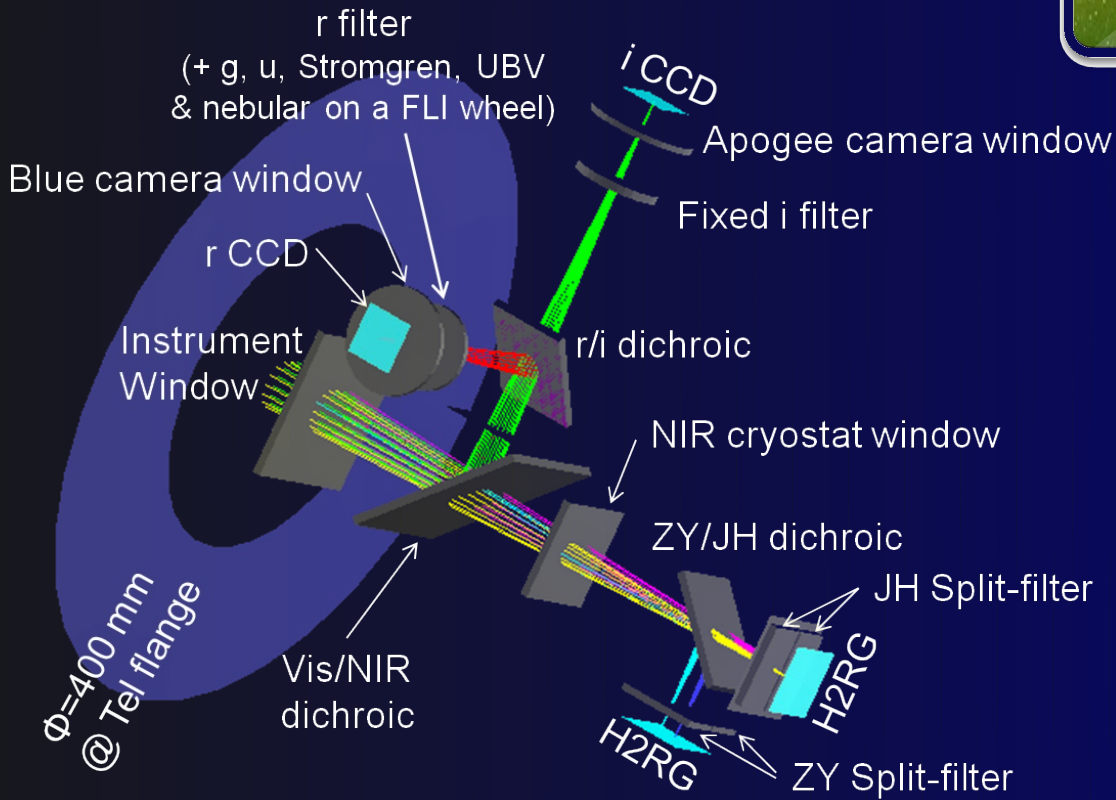
Lawrence Berkley Laboratory (LBNL):

Peter Nugent, David Schlegel, Nic Ross, Horst Simon

Non UCB-CfTDI, University of Washington:

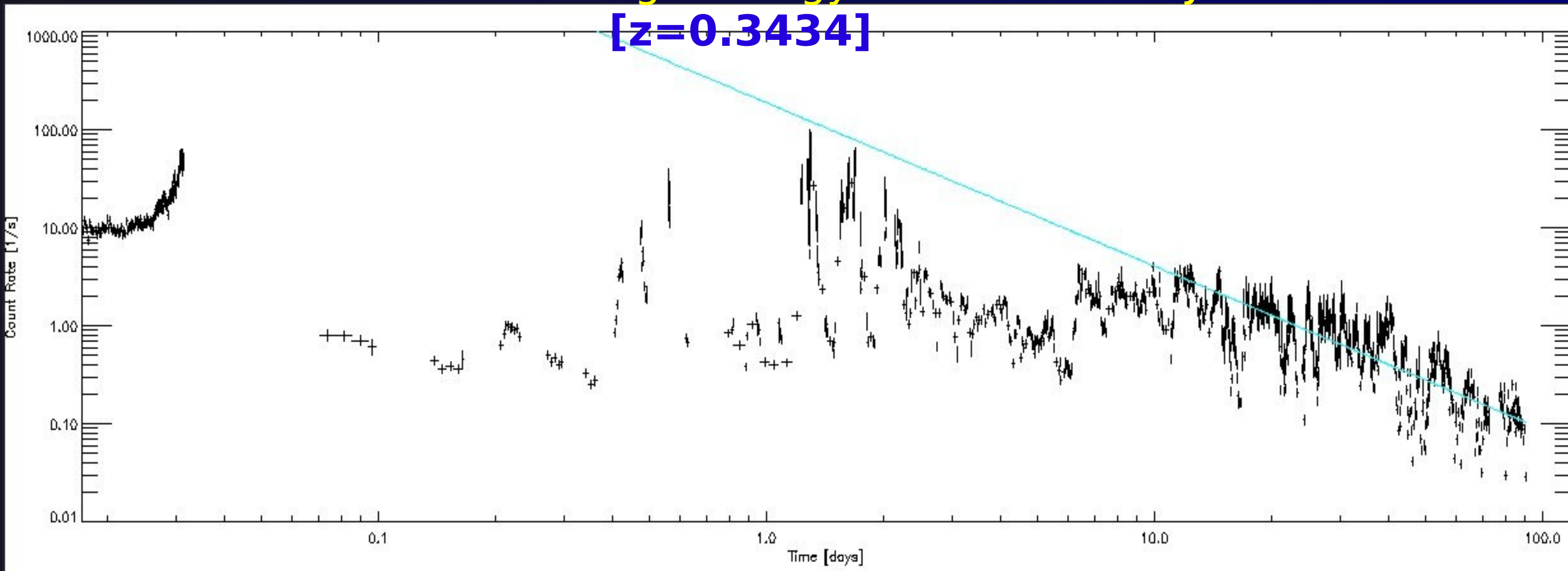
Chelsea Macleod, Zeljko Ivezic, Scott Anderson

THE REIONIZATION AND TRANSIENTS INFRARED/OPTICAL PROJECT
RATIR



Nuclear Transients

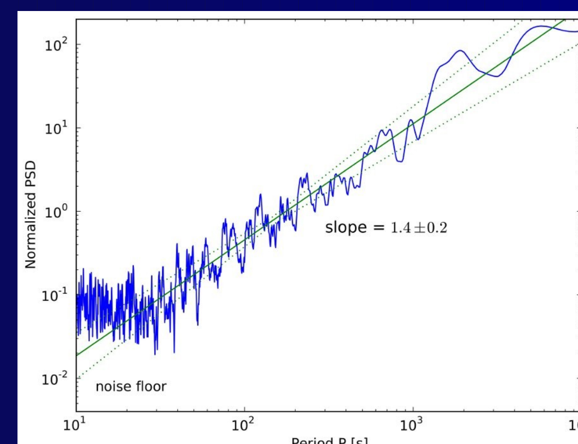
high-energy transient Swift J164449.3+573451
[z=0.3434]



Bloom++:

“A relativistic jetted outburst from a massive black hole fed by a tidally disrupted star”

(also, *Levan++*)



Transients from the Ground

SDSS-II ("stripe 82"): 2.5m Telescope, 290 deg sq. (total), ~3 day cadence over 6 years (mag > 21.5)

Palomar Transients Factory (PTF): 48" Telescope, 7.8 deg sq. field, 1hr - 1 day cadence (mag 21 in 60s).

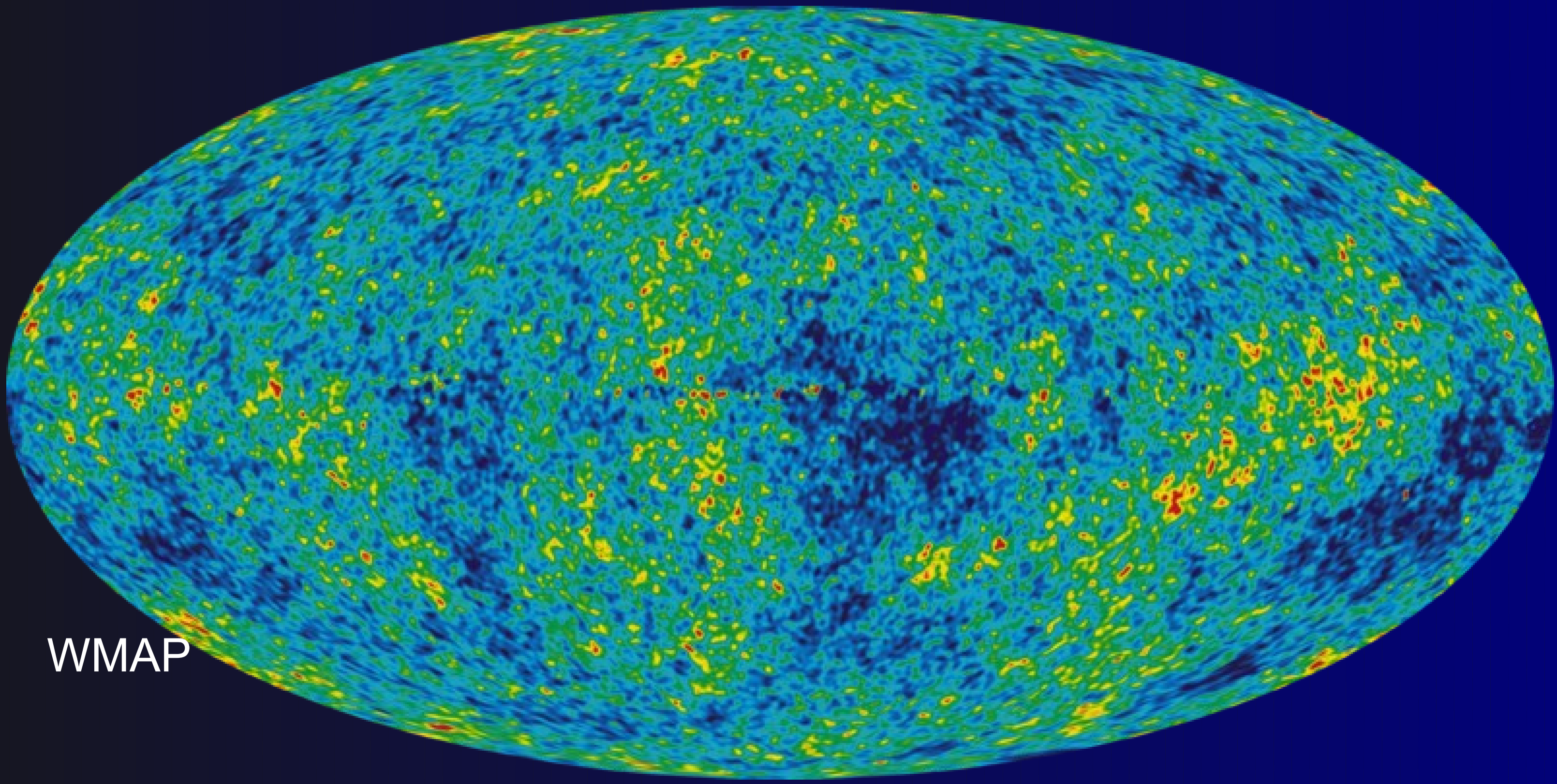
Pan-STARRS1: 4x1.8m Telescopes, 7 deg sq. field, whole sky every ~4 days (mag 23 in 30s).

LSST (2019): 8m Telescope, 10 deg sq field; all sky every 3 days (mag 24 in 15s).

Synoptic All-Sky InfraRed (SASIR) survey: 1 day cadence, followup, all-sky every 3 months

+ many others datasets
(HIPPARCOS, OGLE, ASAS, KEPLER,LINEAR...)

Endgame: BAO Targets



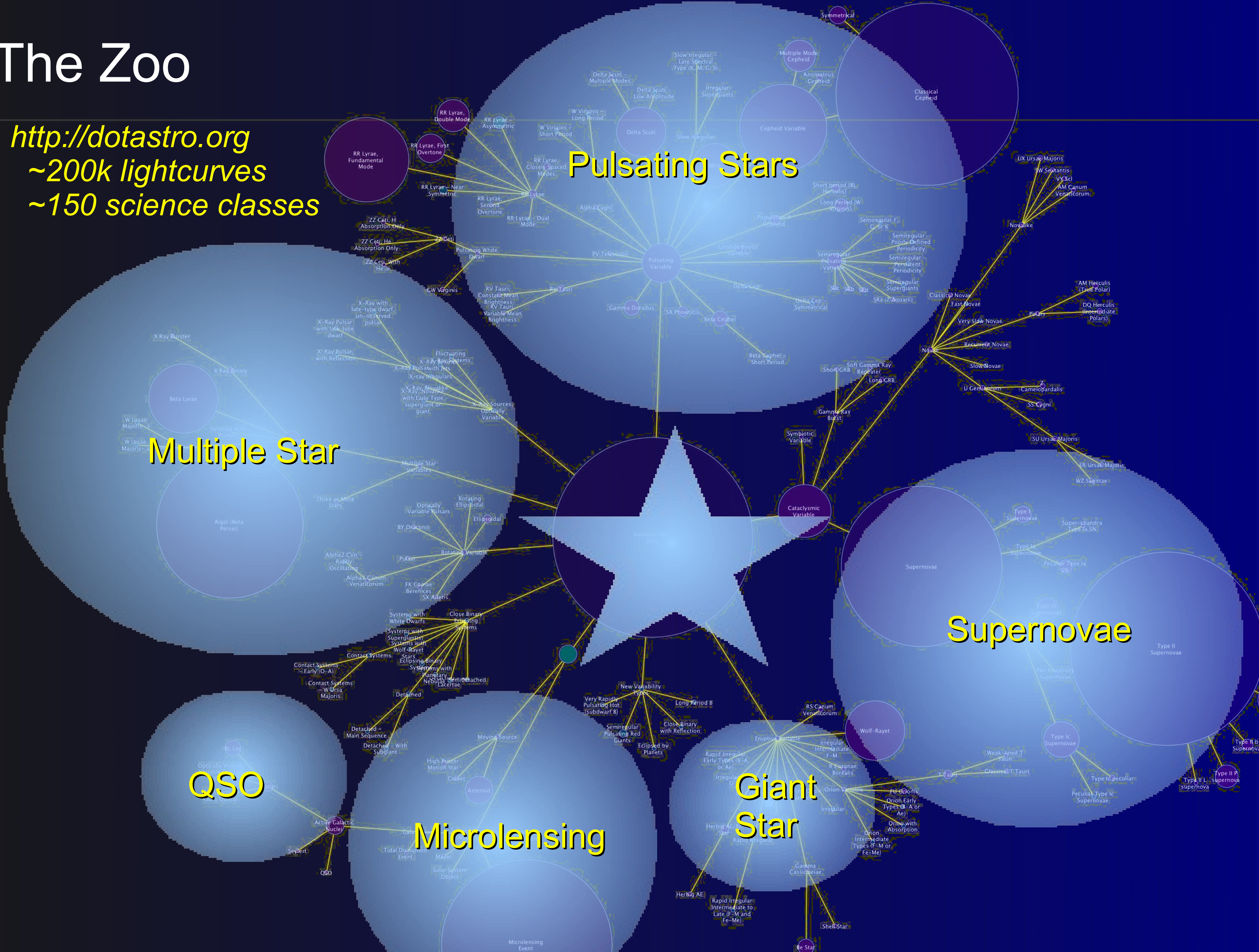
WMAP

QSO Clustering measurements require targets at a variety of redshifts!
[Next generation surveys ~10^6 QSOs]

(e.g., Schlegel et al 2009)

The Zoo

http://dotastro.org
~200k lightcurves
~150 science classes



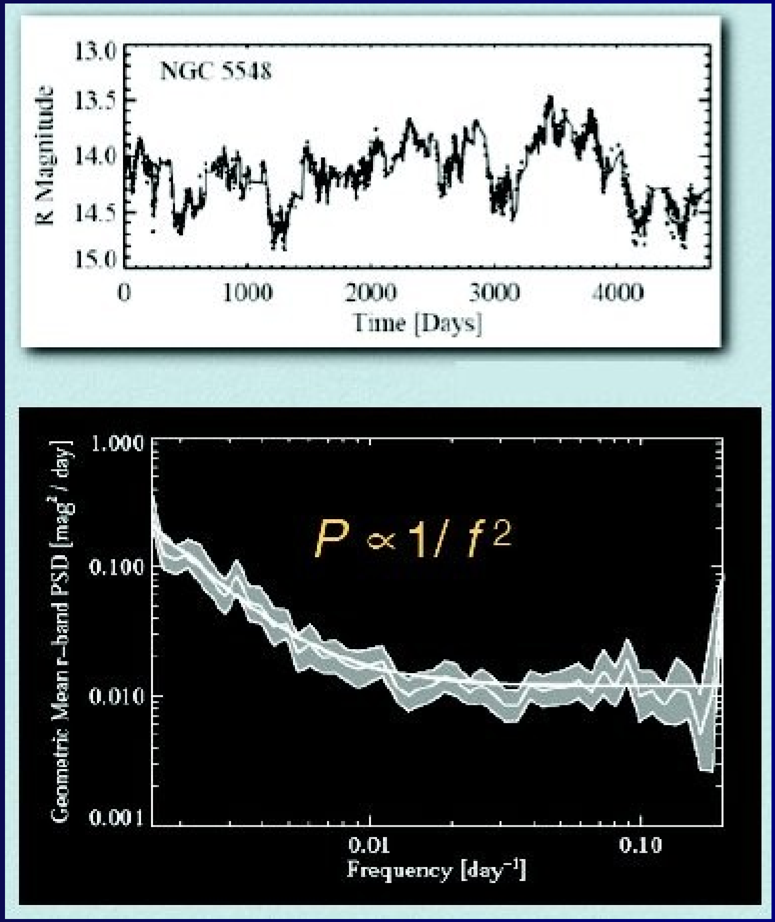
QSO Variability Intro

>90% of QSOs (*Sesar+07*)
[>99% *Butler&Bloom11*]

QSOs are variable!

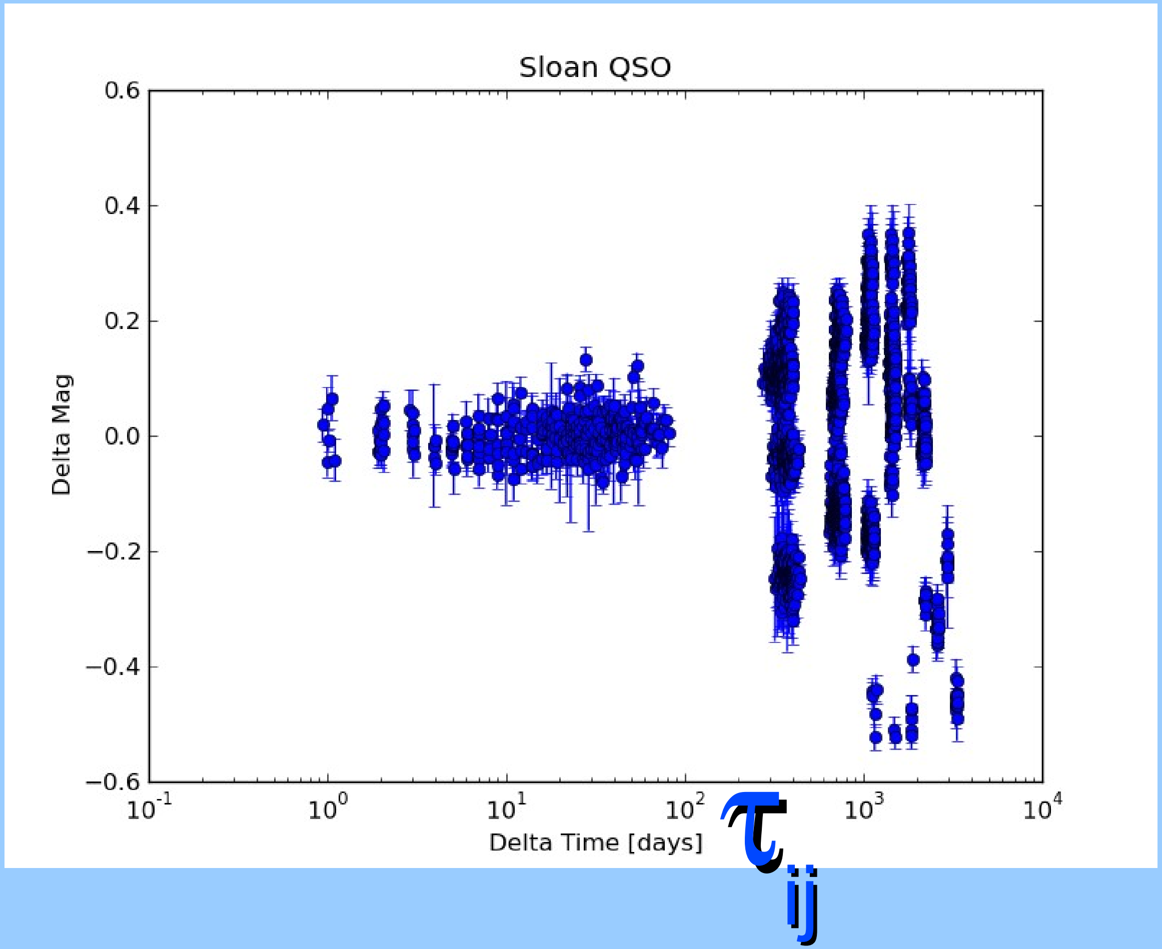
10-20% scale variability (rms)
In optical/NIR

Intrinsic! (accretion disk),
Aperiodic, and stochastic



Quasar Classification

(Butler & Bloom 2011; AJ, 143)

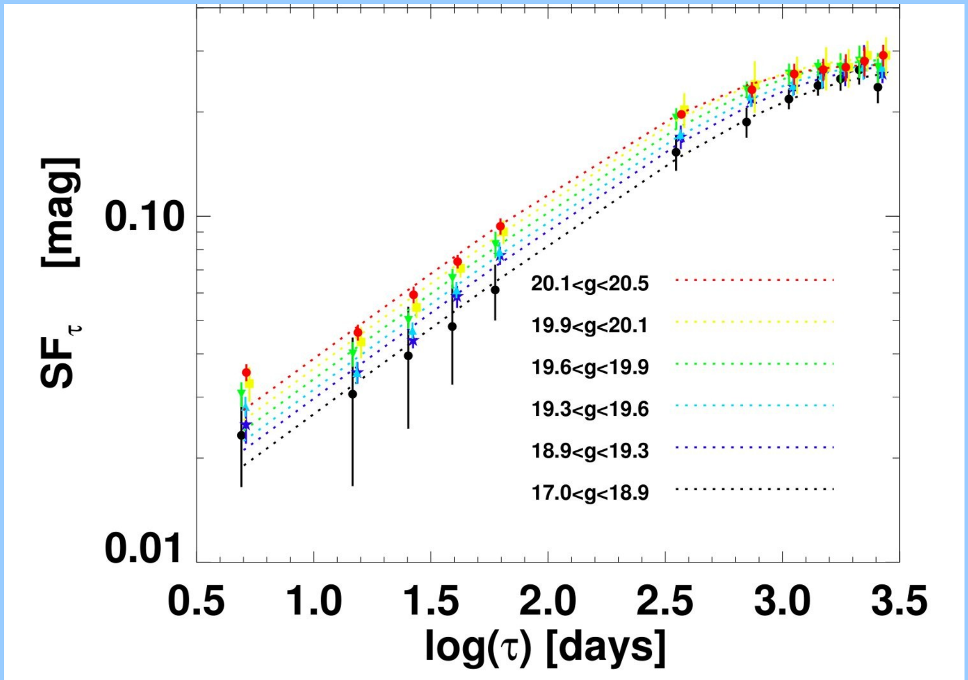


Model the Lightcurves.

Evaluate Likelihood $P(\Delta m|\tau)$.

Classify based on few epochs.

SDSS Stripe 82 “Structure Func.”



Exploit QSO “structure”

Model as damped random walk to get:

$$P(x|\hat{\sigma}^2, \tau_\circ) \propto |C|^{-1/2} \exp\left[-0.5(x - x_\circ)^T C^{-1} (x - x_\circ)\right]$$

$$-0.5\chi^2_{\rm QSO} = -0.5(x - x_{\circ,\rm best})^T C^{-1} (x - x_{\circ,\rm best})$$

$$SF_\tau \propto \hat{\sigma}\,\tau_\circ^{1/2}\left[1 - \exp\left(-\tau_{ij}/\tau_\circ\right)\right]^{1/2}$$

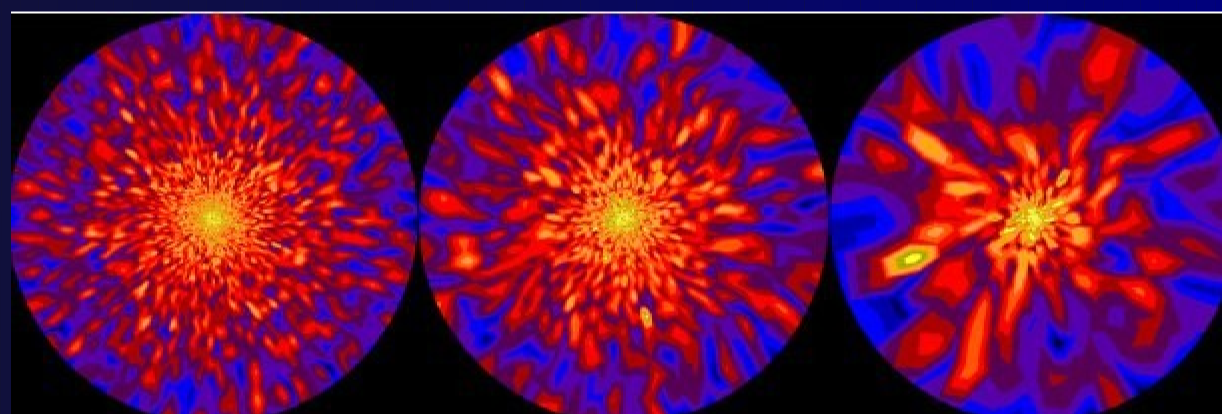
(Kelley at et al. 2009, Koslowski & Kochanek 2010) [Rybicki & Press 1994]

Implies Inhomogeneous Disk

$$SF_{\tau} \propto \hat{\sigma}\, \tau_{\circ}^{1/2} [1 - \exp(-\tau_{ij}/\tau_{\circ}))]^{1/2}$$

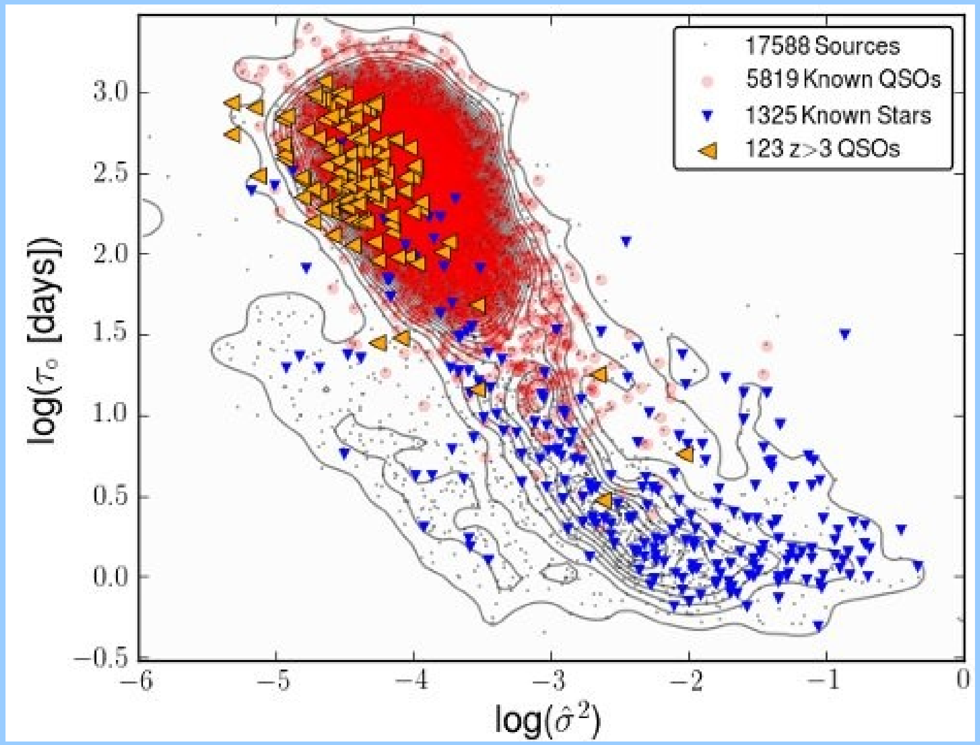
10-20% rms implies ~$N^{1/2}$ larger (order unity) variation

Disk must be patchy, hence instabilities



(Dexter & Agol 2011)

Deeper Questions

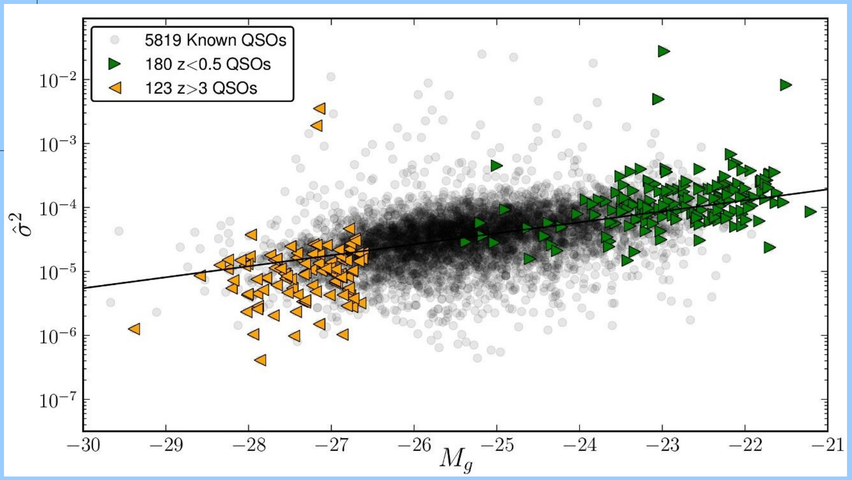


How do parameters relate to fundamental QSO processes?

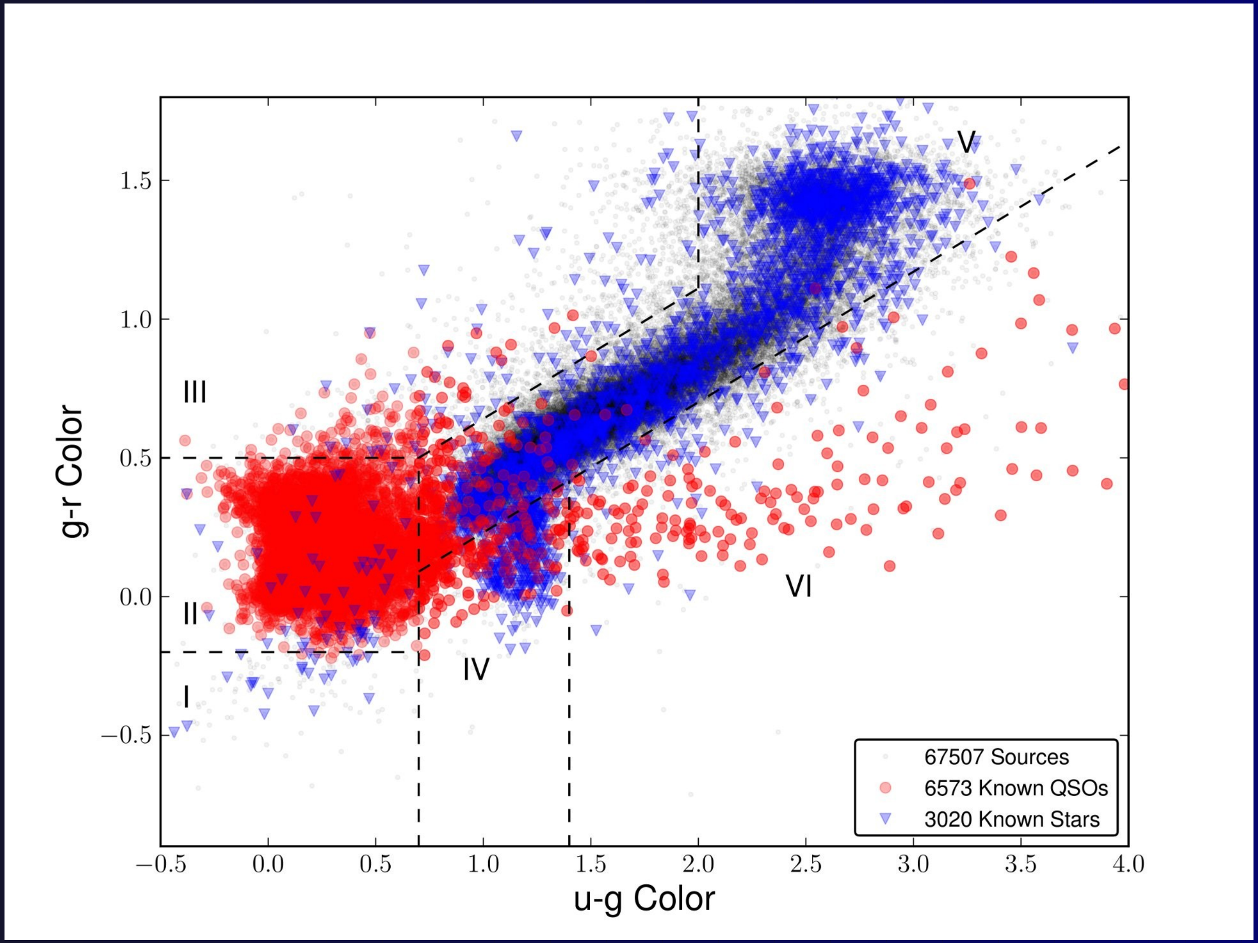
(*cf, Kelley+, MacLeod+*)

How to constrain based on instrinsic quantities?

$$SF_\tau \propto \hat{\sigma}\,\tau_\circ^{1/2}[1 - \exp(-\tau_{ij}/\tau_\circ)]^{1/2}$$

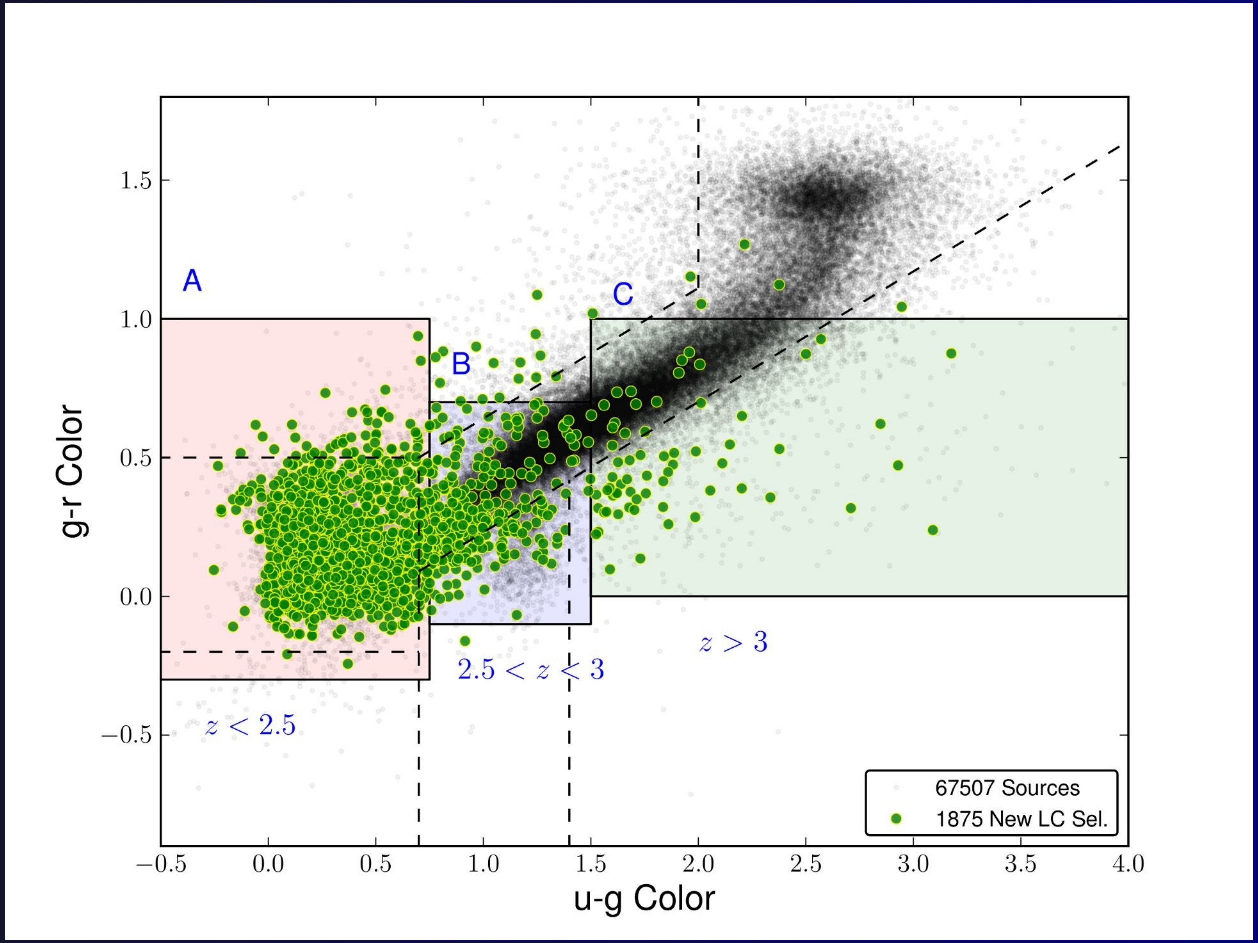


QSO/Variable Star Selection (color)

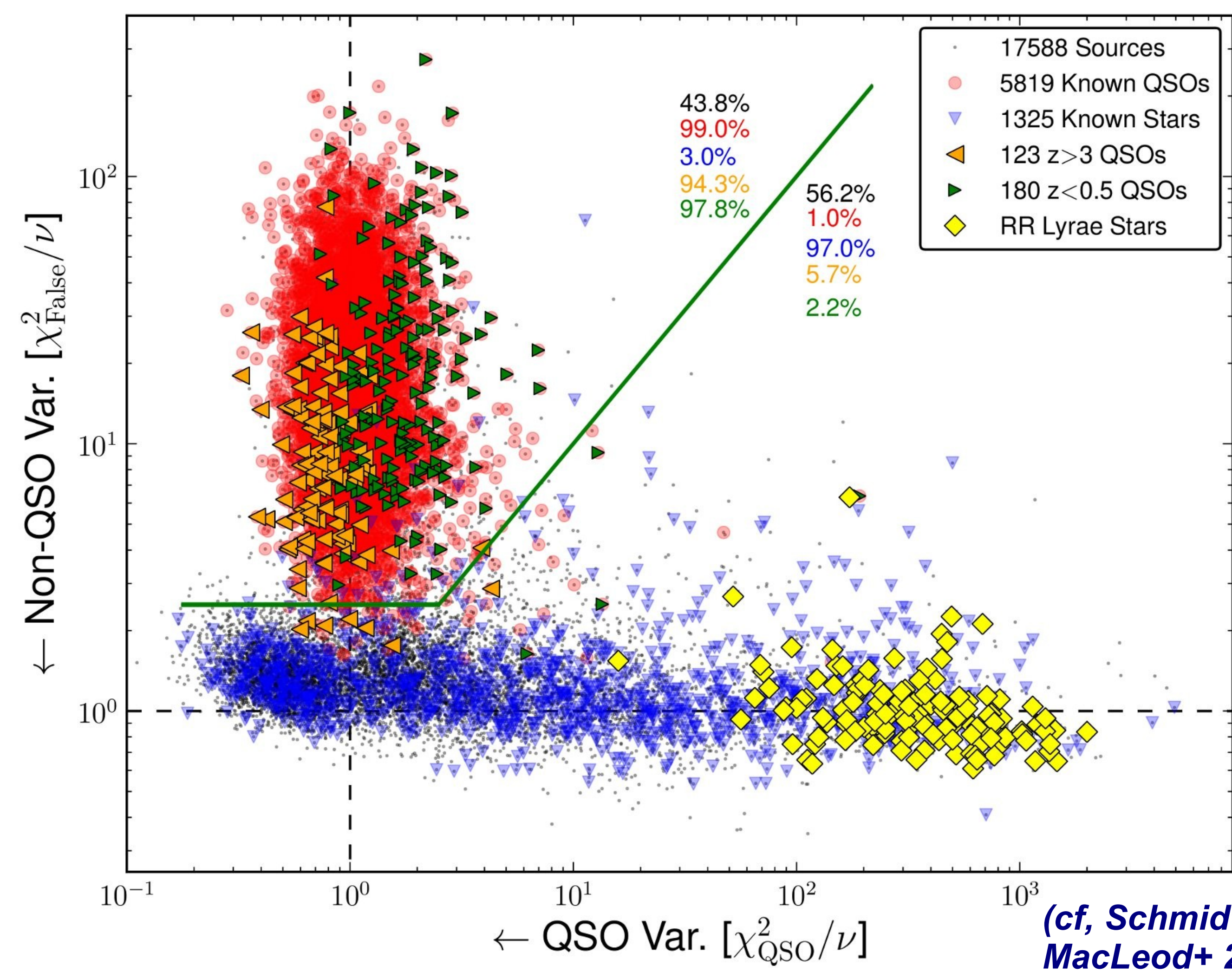


(e.g., Sesar et al. 2007)

Time Selection in Color-Color Space

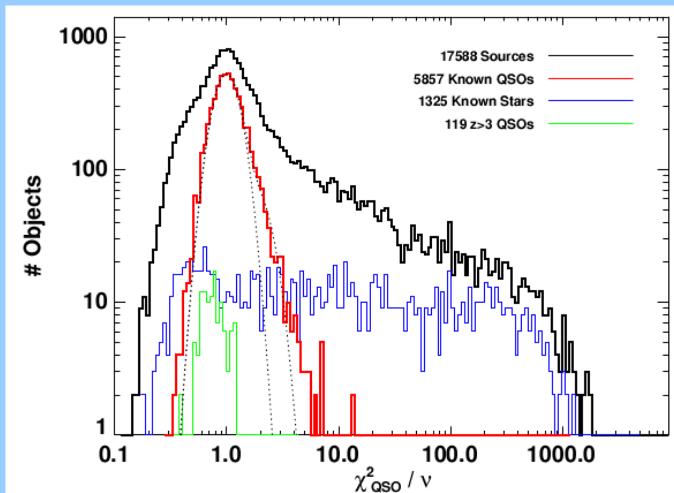


QSO/Variable Star Selection (time)

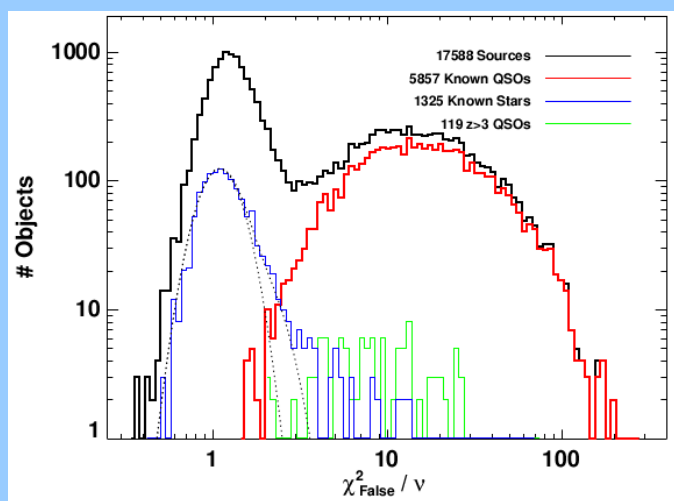


(cf, Schmidt+ 2010, MacLeod+ 2010)

Simple Case: Optimal Selection



QSOs



Stars

Model Mis-Specification & Data Scatter

$$P(\chi^2_{\rm QSO}|x, {\rm quasar}) \propto (y'[1-y'])^{(\nu-1)/2}$$

$$y' \equiv \nu/[\nu + \chi^2_{\rm QSO}]$$

$$P(\chi^2_{\rm QSO}|x, {\rm not\ quasar}) \propto (y[1-y])^{(\nu-1)/2}$$

$$y \equiv \chi^2_{\rm QSO}/[\chi^2_{\rm QSO} + v_x Tr(C^{-1})]$$

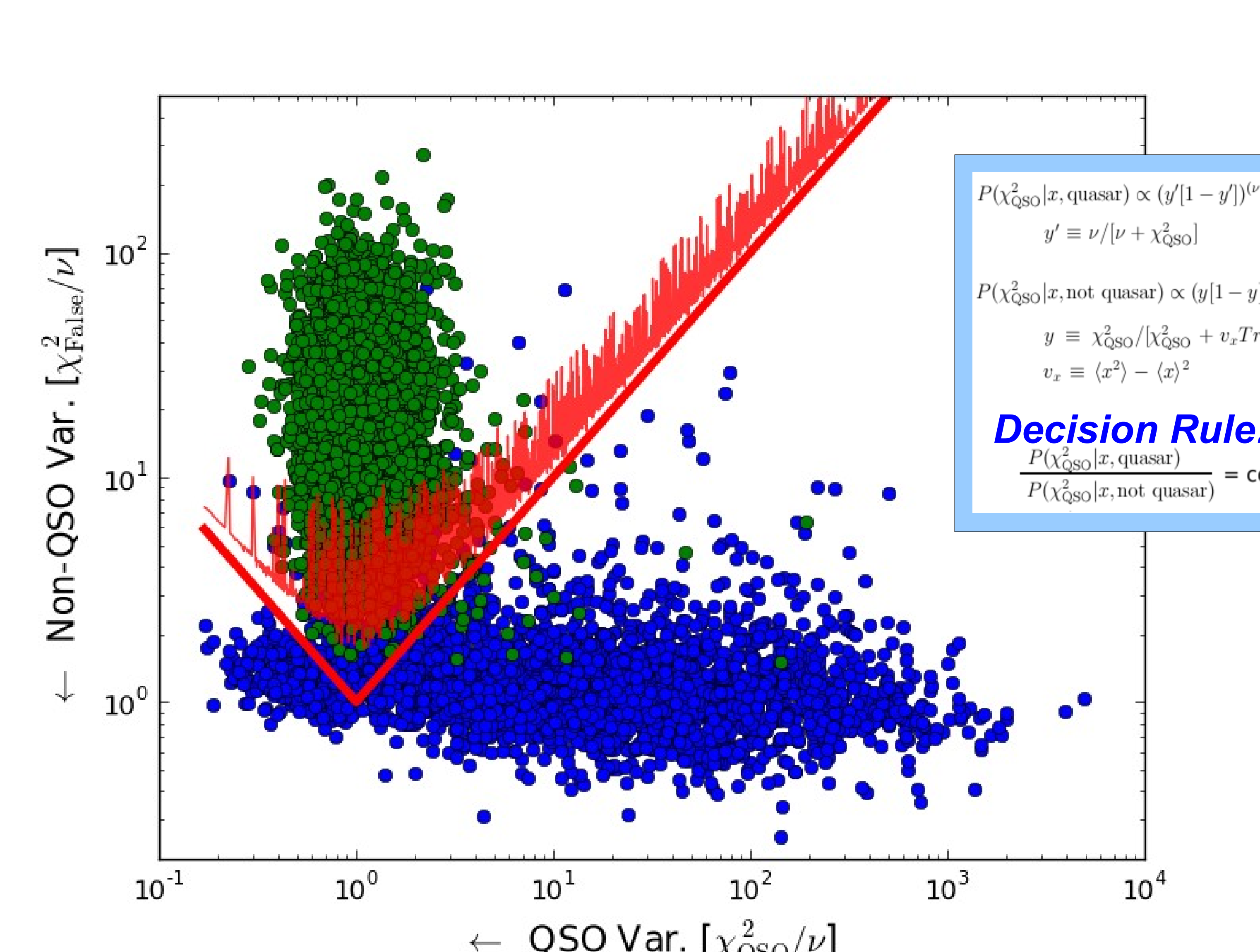
$$v_x \equiv \langle x^2 \rangle - \langle x \rangle^2$$

Decision Rule:

$$\frac{P(\chi^2_{\rm QSO}|x, {\rm quasar})}{P(\chi^2_{\rm QSO}|x, {\rm not\ quasar})} = {\rm const.}$$

(Neyman-Pearson Lemma)

QSO/Variable Star Selection (time)



$$P(\chi^2_{\rm QSO}|x,\text{quasar}) \propto (y'[1-y'])^{(\nu-1)/2}$$
$$y' \equiv \nu/[\nu+\chi^2_{\rm QSO}]$$

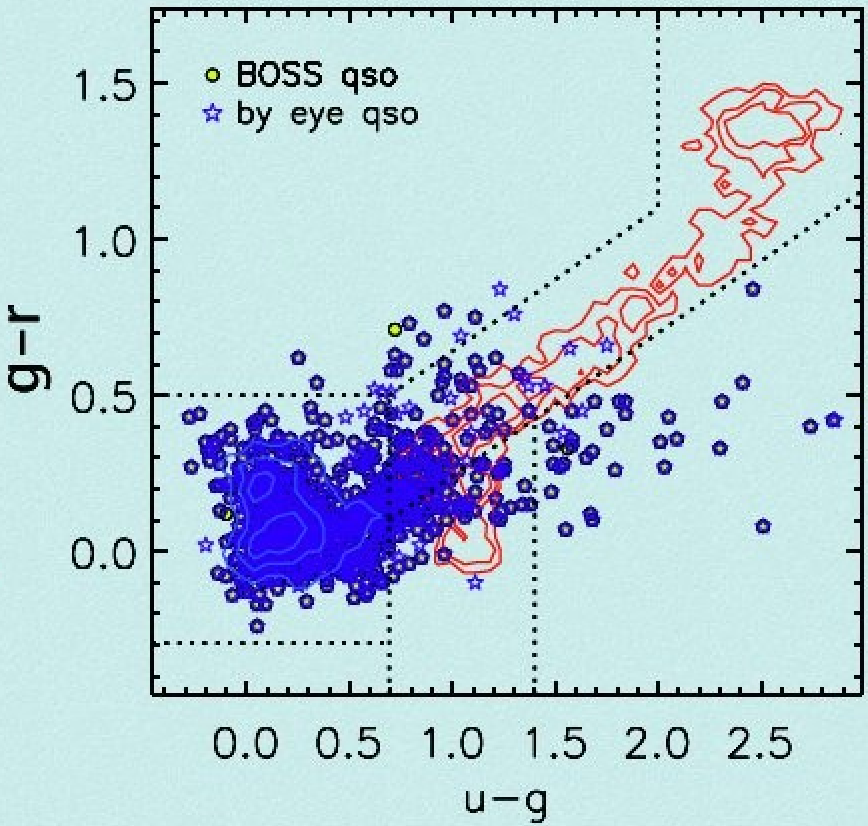
$$P(\chi^2_{\rm QSO}|x,\text{not quasar}) \propto (y[1-y])^{(\nu-1)/2}$$
$$y \equiv \chi^2_{\rm QSO}/[\chi^2_{\rm QSO}+v_x Tr(C^{-1})]$$
$$v_x \equiv \langle x^2\rangle - \langle x\rangle^2$$

Decision Rule:

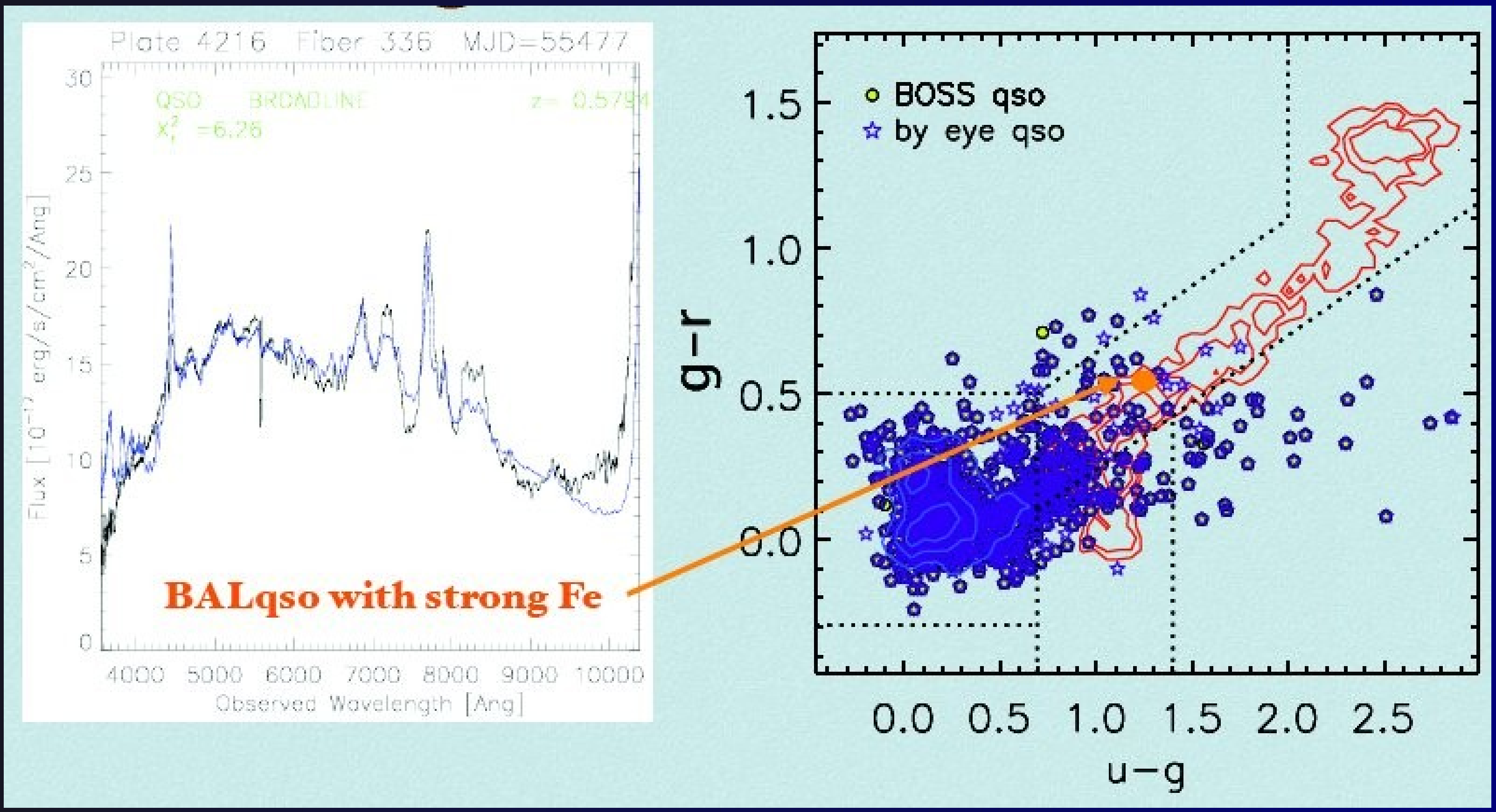
$$\frac{P(\chi^2_{\rm QSO}|x,\text{quasar})}{P(\chi^2_{\rm QSO}|x,\text{not quasar})} = \text{const.}$$

SDSS III: "No QSO Left Behind"

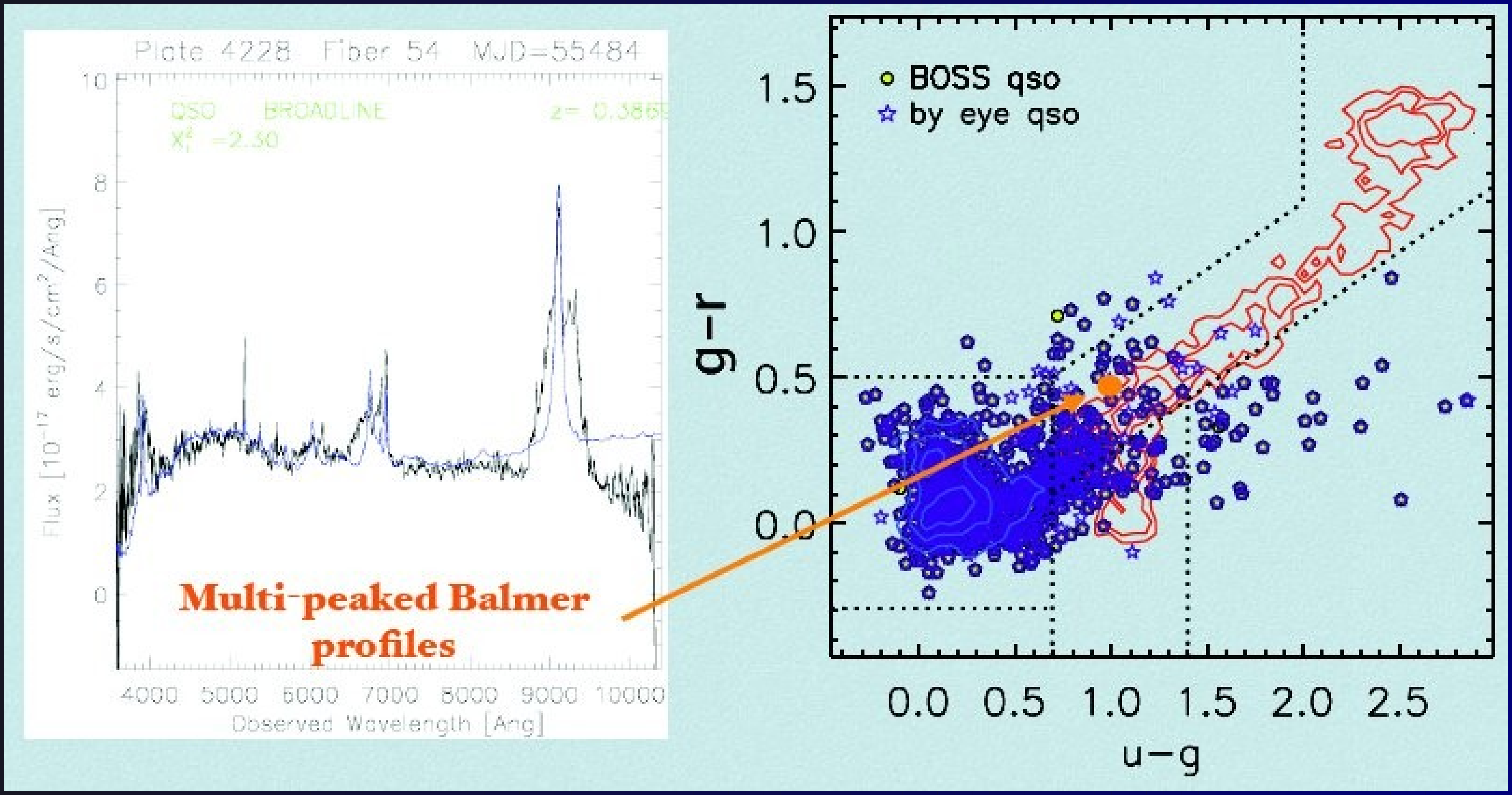
- 1500 targets (7 deg^{-2}), $16.2 < i < 20.5$, $(g-i) < 1.8$
- Results:
  - 917 BOSS "qsos"
  - 941 qsos according to by-eye spectral classification



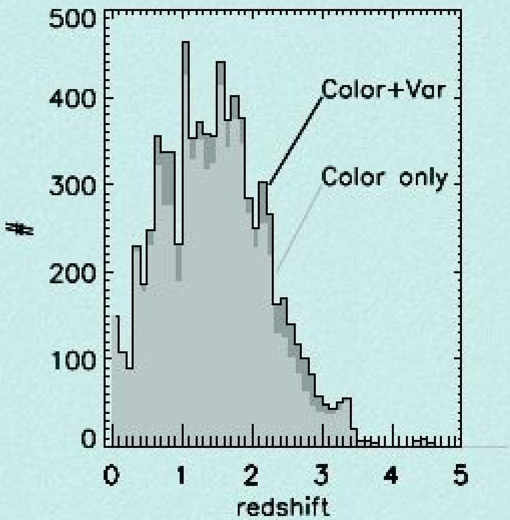
No Color Bias



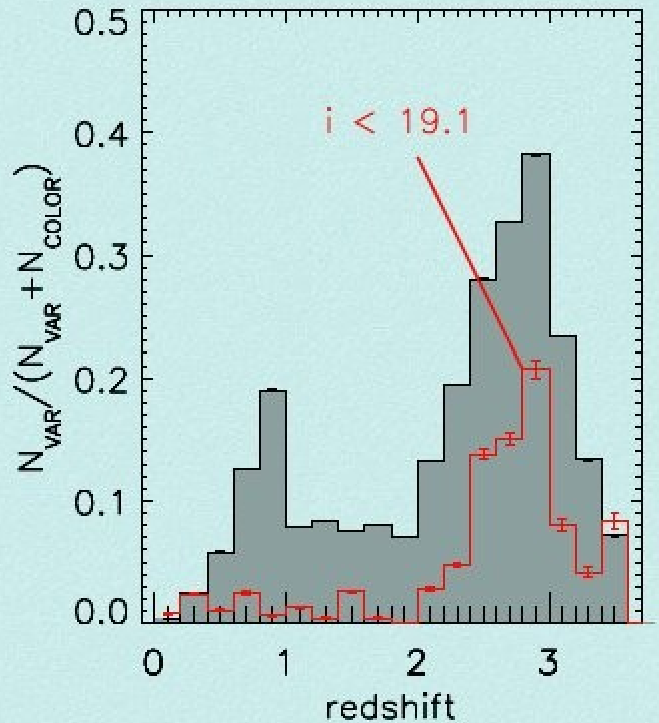
No Color Bias



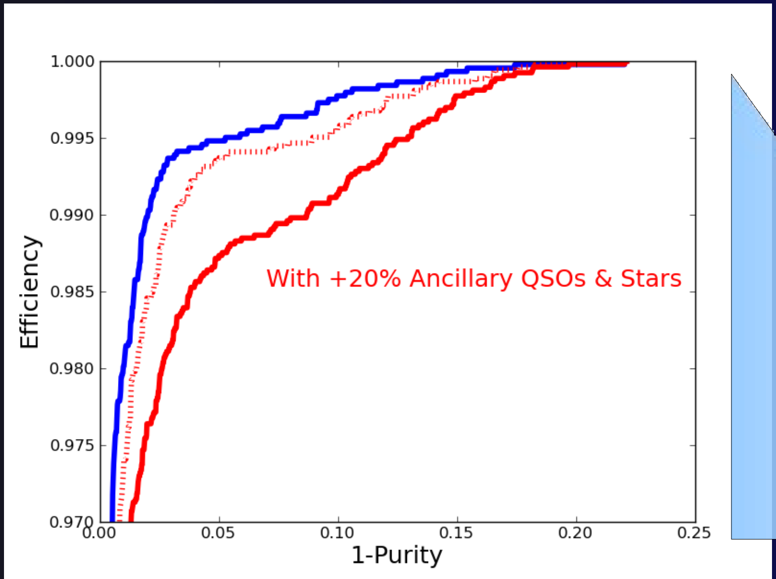
No Redshift Bias



** 17% of z>2.2 quasars in our sample not already targeted by BOSS! (BOSS_target1 = 0)



Classification is VERY Robust



$$P(\chi^2_{\rm QSO}|x,\text{quasar}) \propto (y'[1-y'])^{(\nu-1)/2}$$

$$y' \equiv \nu/[\nu + \chi^2_{\rm QSO}]$$

$$P(\chi^2_{\rm QSO}|x,\text{not quasar}) \propto (y[1-y])^{(\nu-1)/2}$$

$$y \equiv \chi^2_{\rm QSO}/[\chi^2_{\rm QSO} + v_x Tr(C^{-1})]$$

$$v_x \equiv \langle x^2 \rangle - \langle x \rangle^2$$

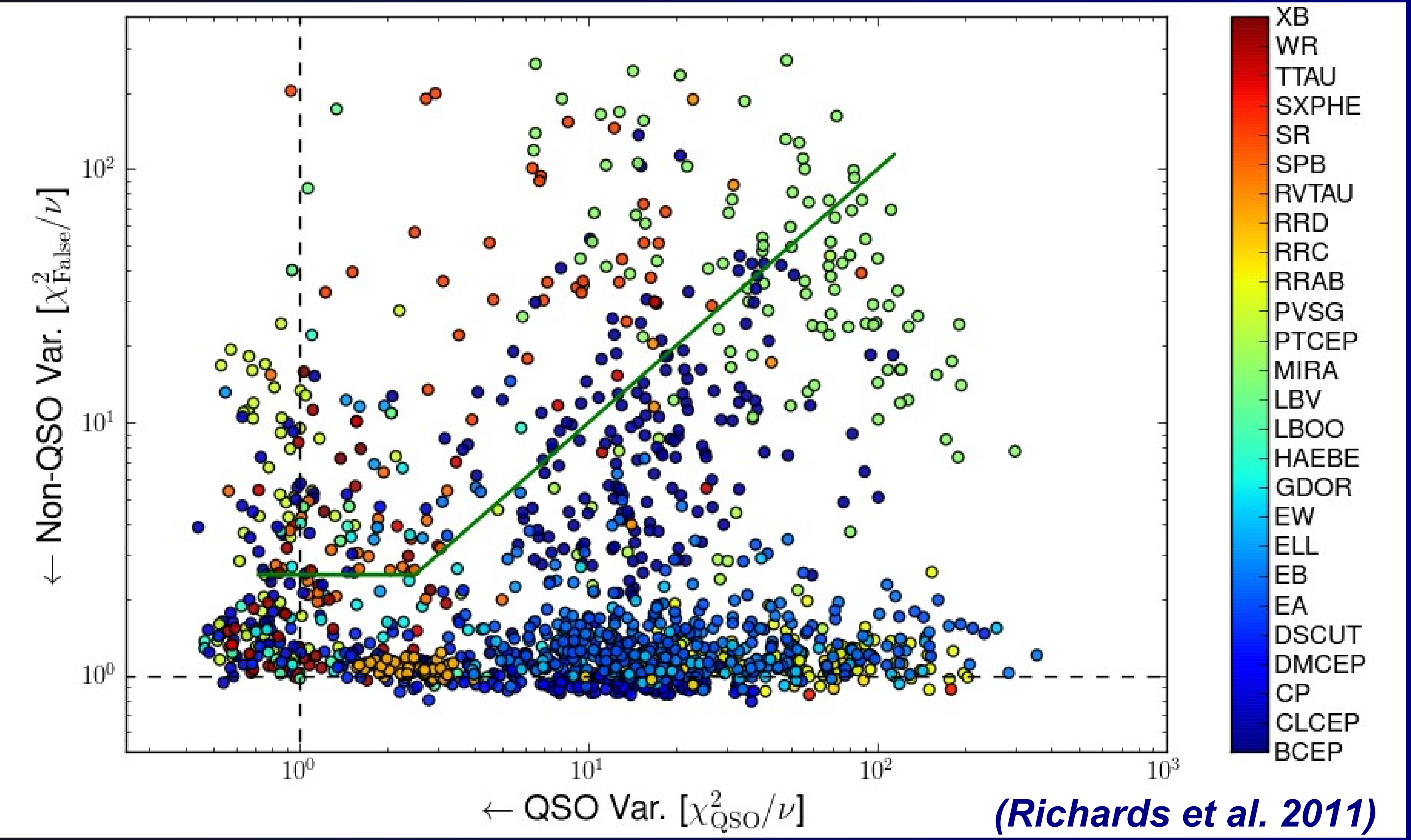
Decision Rule:

$$\frac{P(\chi^2_{\rm QSO}|x,\text{quasar})}{P(\chi^2_{\rm QSO}|x,\text{not quasar})} = \text{const.}$$

But there are many "unlabeled" (faint) sources in Stripe 82.

Will we detect the QSOs, reject the stars?

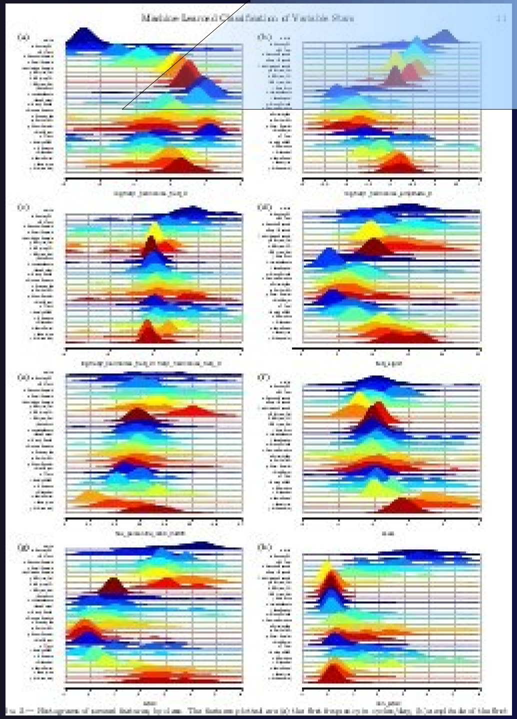
QSO Interlopers

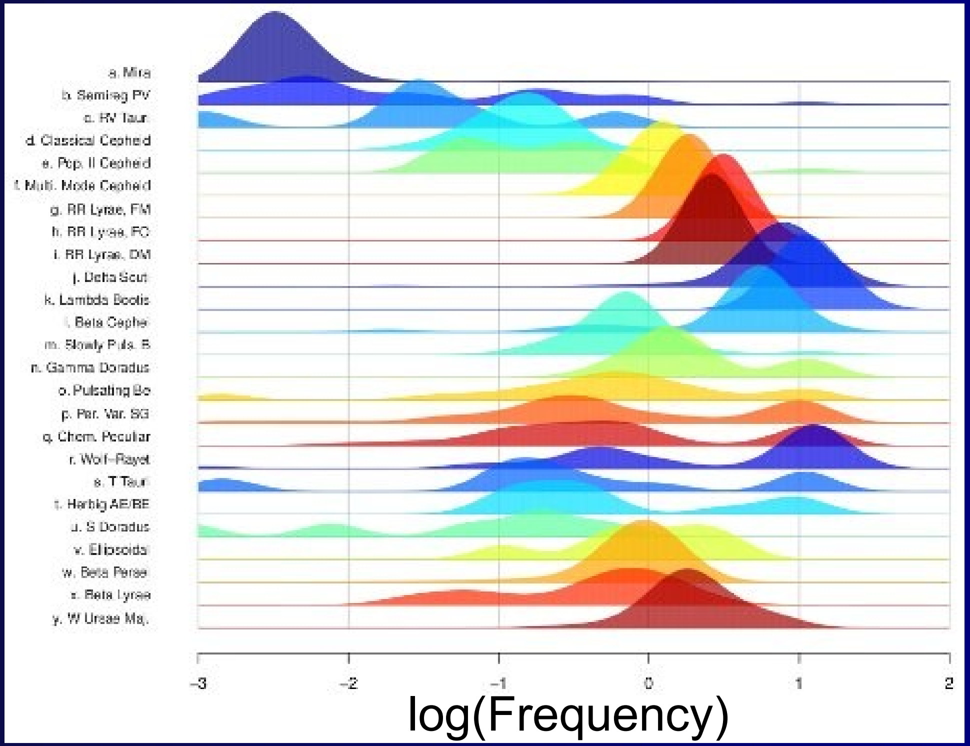


(Richards et al. 2011)

Supervised Variable Star Classification

(Joey Richards et al. 2011; ArXiv:1101.1959)





1542 Hipparcos + OGLE lightcurves →

52 “features” (mostly periodic) →

Decision Tree classification (25 classes)

Next Steps

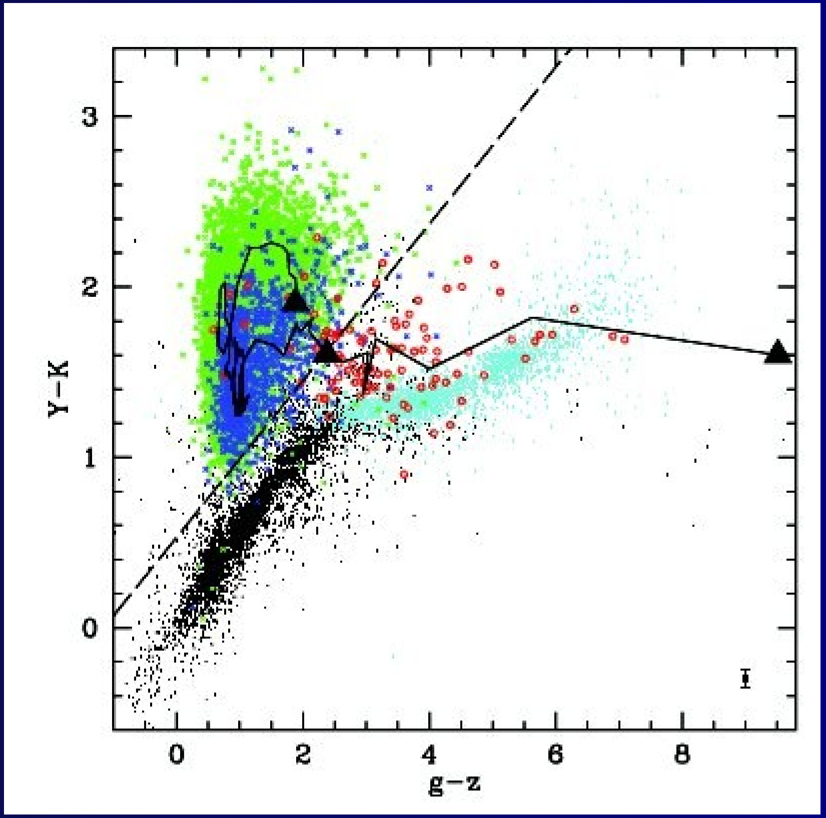
Pilot program to monitor quasars and Fermi blazars with PAIRITEL

Additional SDSS monitoring:

Hectospec spectroscopy (A. Morgan)
SDSS-3 no QSO left behind

Toward high-z QSO detection with SASIR

-Observations and Monitoring with RATIR



(Wu & Jia 2010; Wu++ 2011)