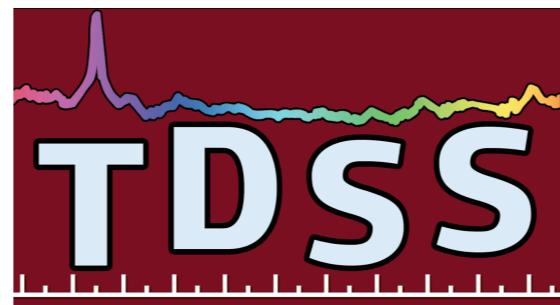


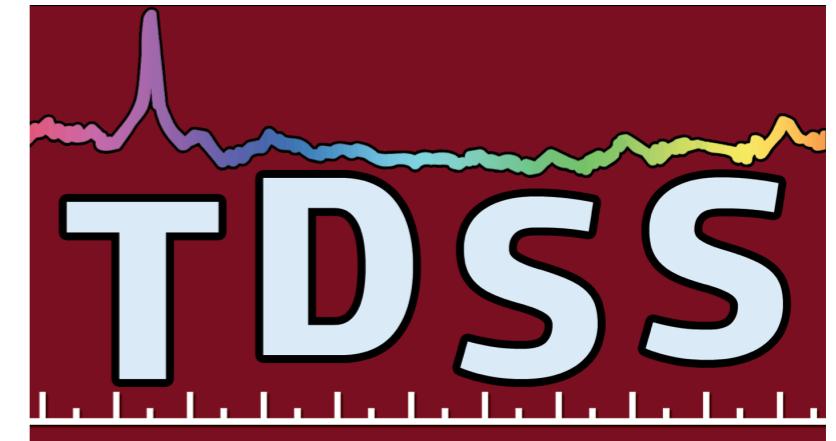
THE TIME DOMAIN SPECTROSCOPIC SURVEY

Benjamin Roulston (BU/SAO/CfA)
SDSS-IV Meeting, 2019
Ensenada, Mexico

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



SDSS-IV TIME DOMAIN SPECTROSCOPIC SURVEY



- Adds dedicated spectra to era of time domain imaging.
- First large-scale, *inclusive* spectroscopic survey of variable sources
 - No color selection
 - Generic variability, i.e., no requirement for periodicity, flares, etc.
- Extending Survey Science to the Time Domain/Spectroscopy through:
 - ***Systematic discovery*** of celestial variables
 - ***Population studies*** of variable stars and quasars
 - ***Exploring the unknown:*** rare objects

Overview:

Three principal components of TDSS, piggy-back on

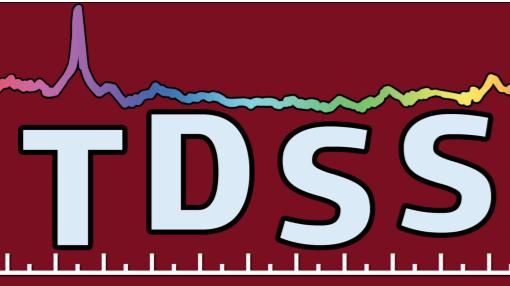


Main survey

- TDSS main (90%) survey: **SES**=single-epoch spectroscopy BOSS classification/characterization spectra of imaging variables from Pan-STARRS I, 3 π imaging survey (PSI); $\sim 10^5$ fibers in SDSS-IV ($10/\text{deg}^2$)
- TDSS (10%) **FES**=few-epoch spectroscopy of potential spectral variables of interest (e.g., known from SDSS I-IV spectra) $\sim 10^{3-4}$ fibers in SDSS-IV
- TDSS **RQS**=repeat quasar spectroscopy of SDSS I-IV quasars; $\sim 10^4$ fibers in SDSS-IV

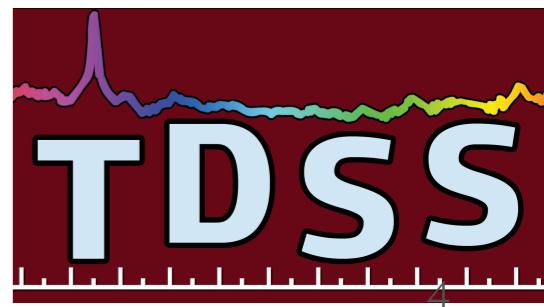
eBOSS ELG plates

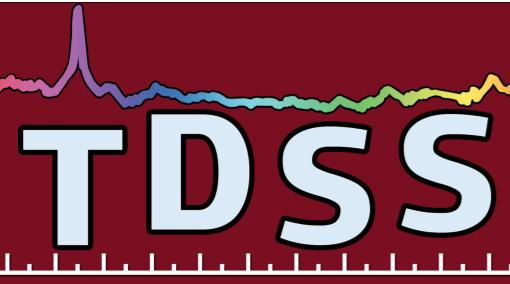




TDSS Spectroscopic Data: Early 2019

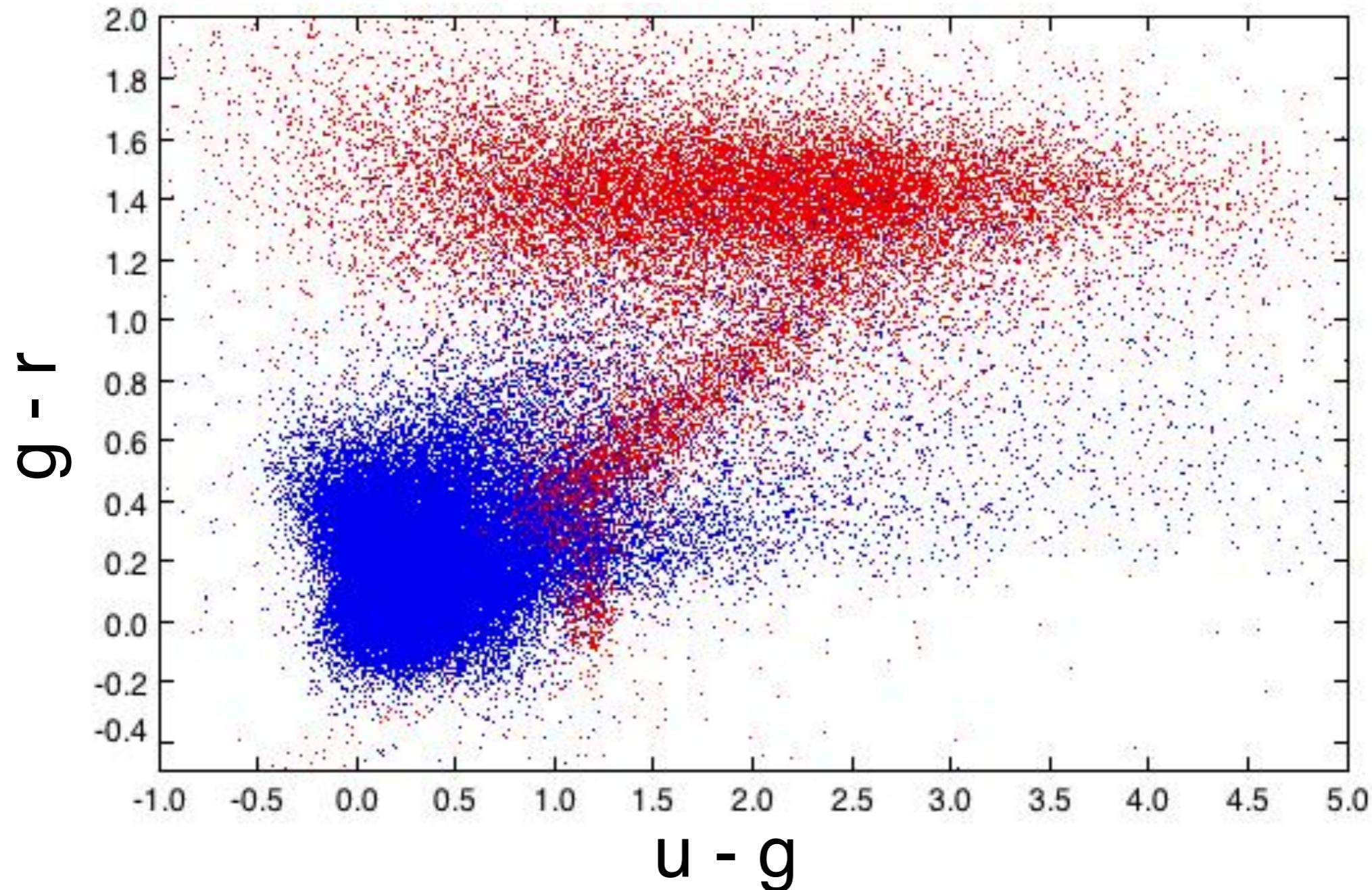
- 103,700 SES selected or co-selected targets (not including archival)
56,200 are quasars (~54% of SES targets)
- 6,500 FES targets, including 4700 FES quasars (~72% of FES)
- 16,500 RQS targets, all quasars
- From recent spAll TDSS file for SDSS-III+SDSS-IV (spans from earliest TDSS targets on SDSS-III SEQUELS plates, through January 2019 SDSS-IV plates).
Approx numbers:
 - 1350 good-quality plates, with more than 10^5 TDSS spectra taken through January 2019 (including ~77k of quasars)





TDSS/SES update (through DR14)

Pipeline: 53,912 QSOs, 25,035 stars, 2,210 other variables (galaxies/unks/glitches; not plotted)

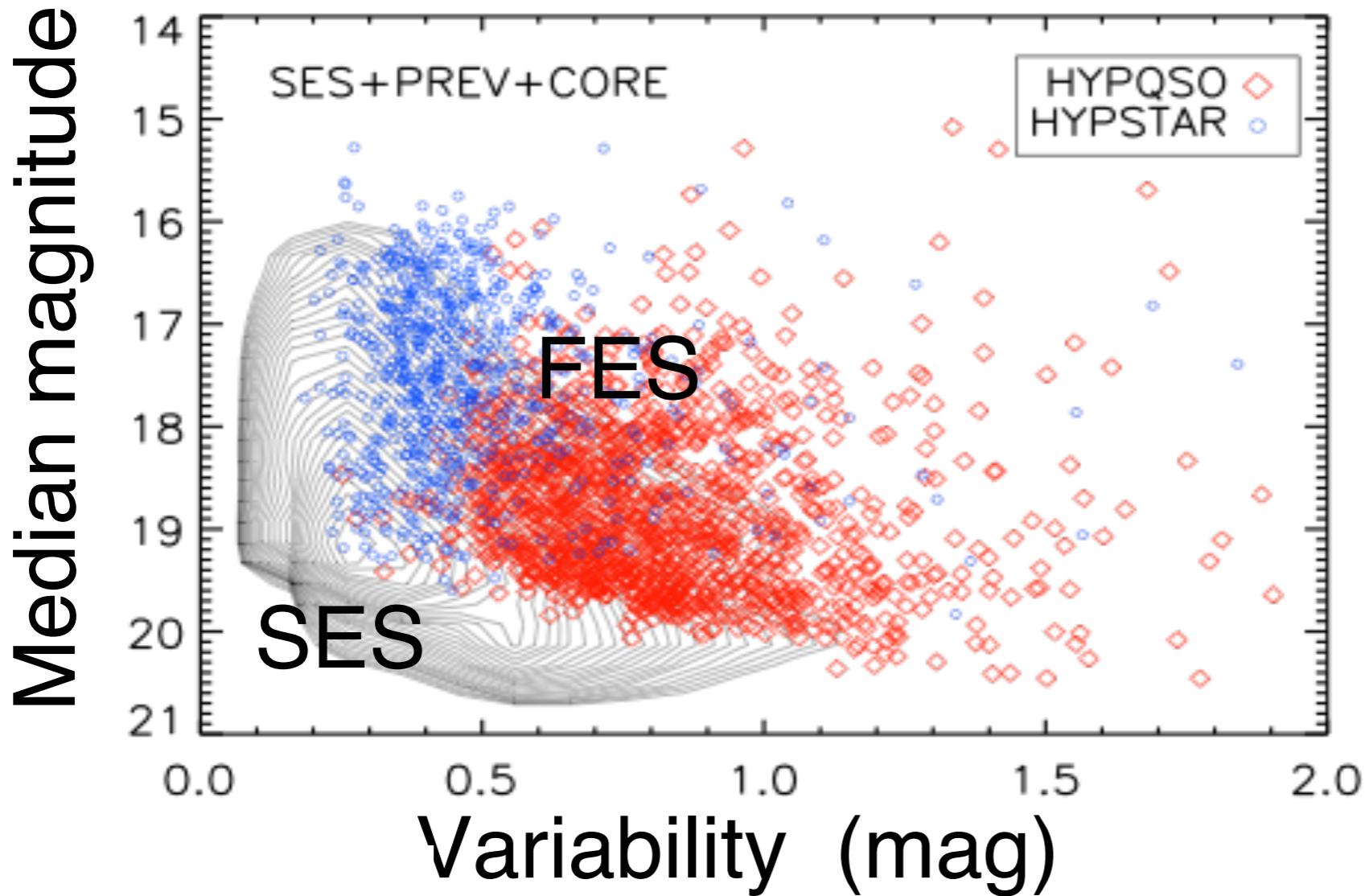


10% of TDSS fibers for special FES programs:

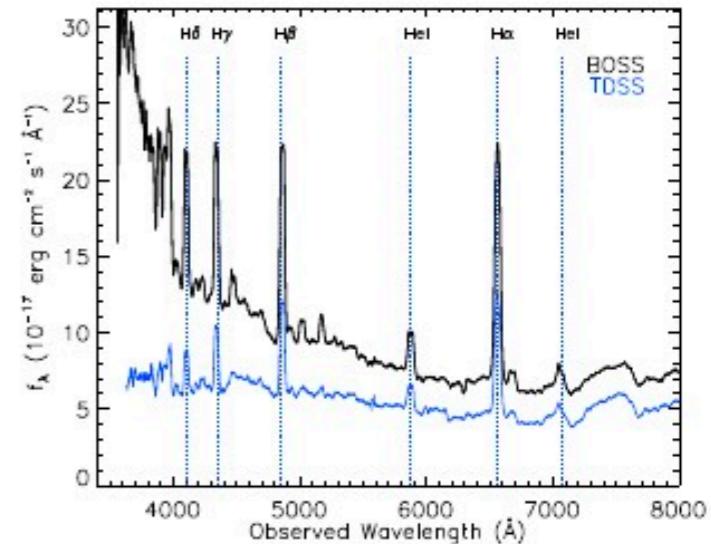
Target Type	Number	Observed (March '19)
Total (~1 deg⁻²)	9143	6261
WD/dM Binaries	1036	214
Dwarf Carbon Stars	830	370
Ultracool Dwarfs	402	556
Hypervariable Stars ($\geq 0.3m$)	1150	727
BAL Quasars	2900	1926
High S/N Quasars	1100	593
Double Peaked Emitters	900	576
QSO MGII Line Shifts	70	62
Hypervariable Quasars	1555	1237

(Target Selection Details in MacLeod et al. 2018)

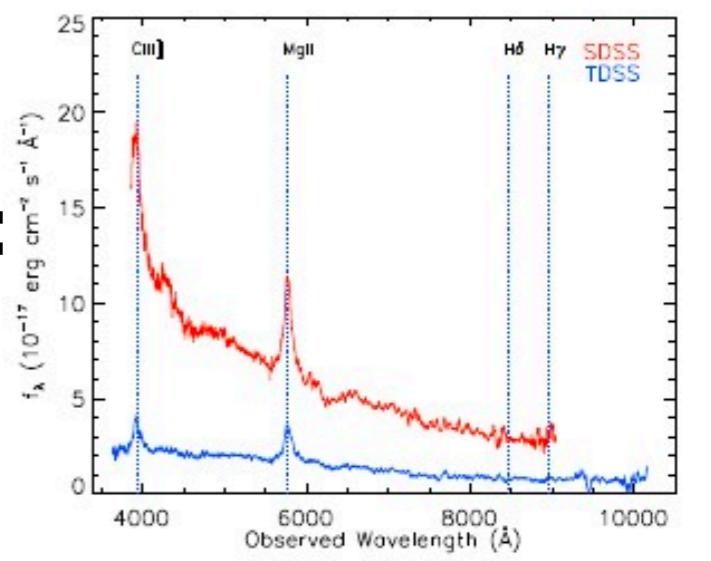
HYPERVARIABLES



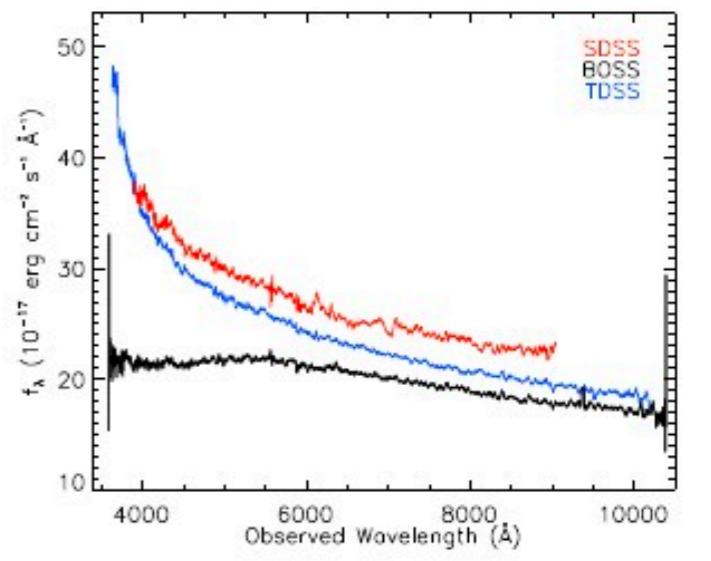
CV:



QSO:

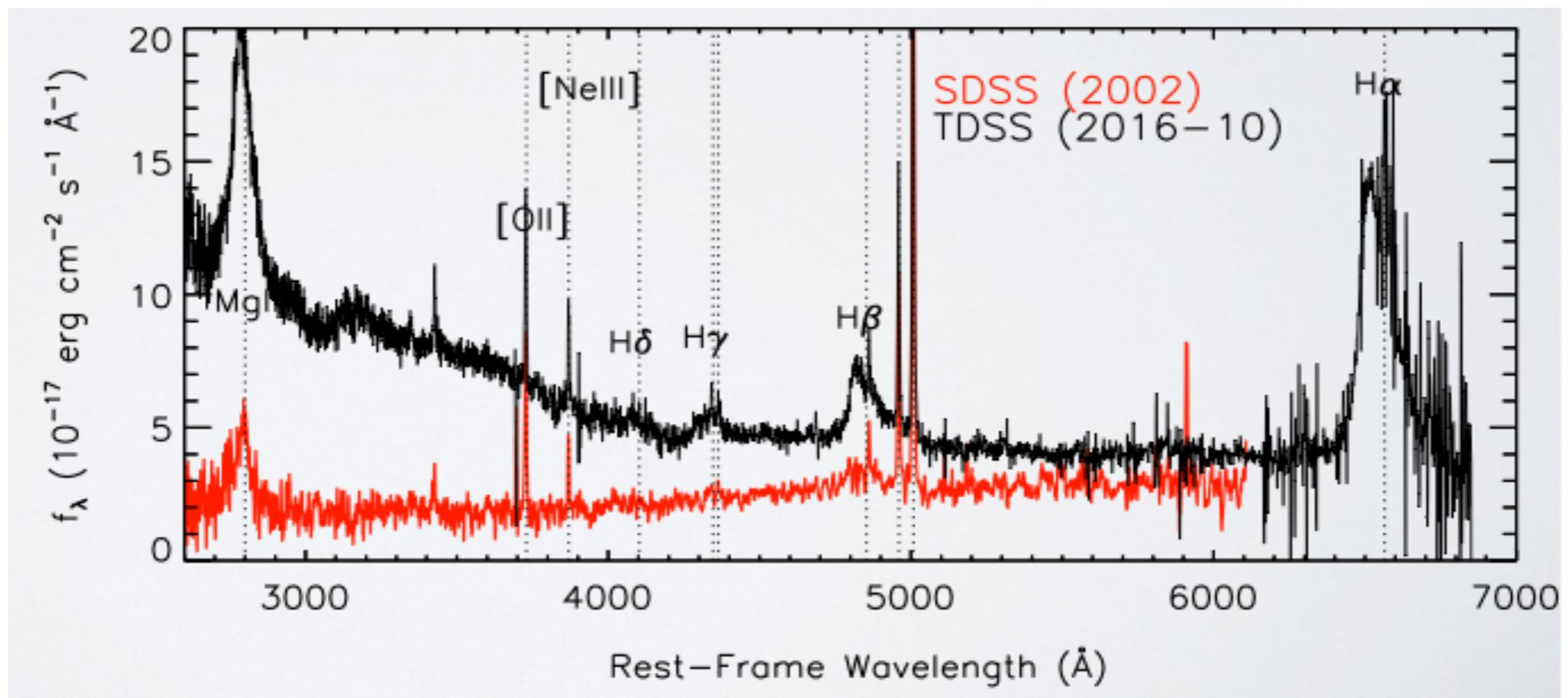


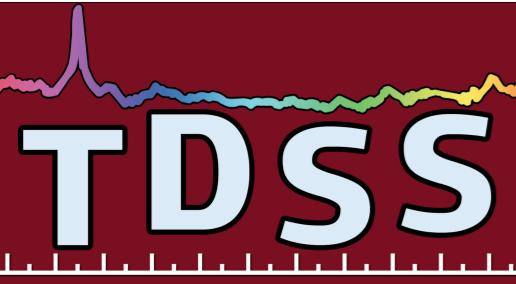
BLLac:



TDSS/RQS FES-like Extension (post-DR14) in ELG region: ***Repeat Quasar Spectroscopy*** (MacLeod et al. 2018)

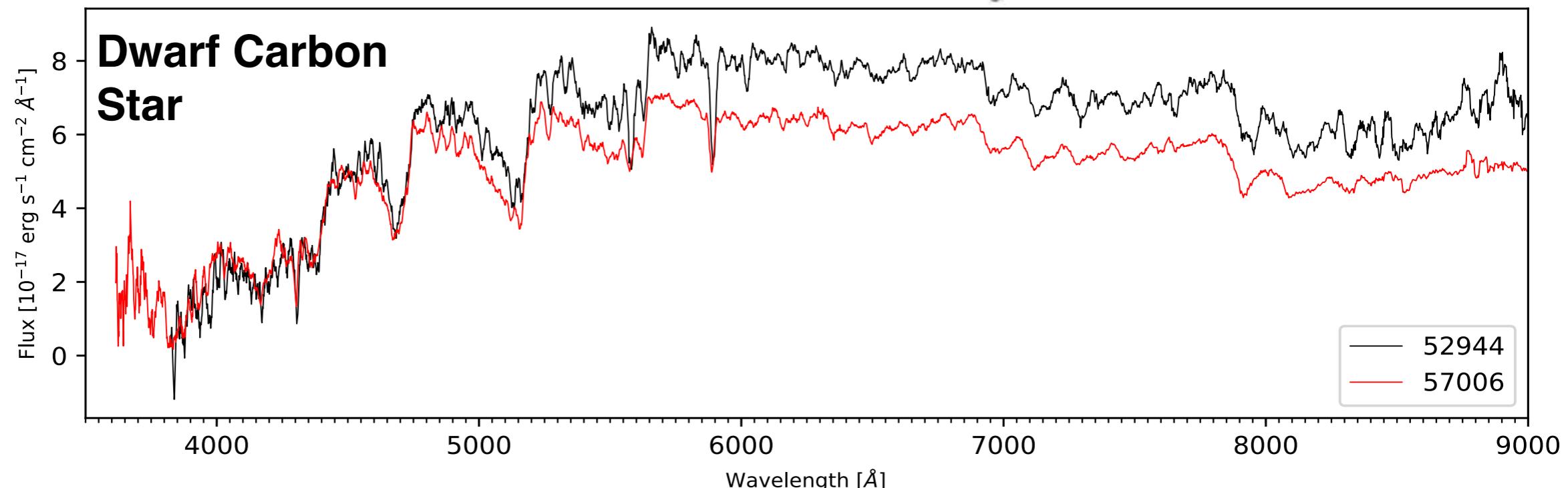
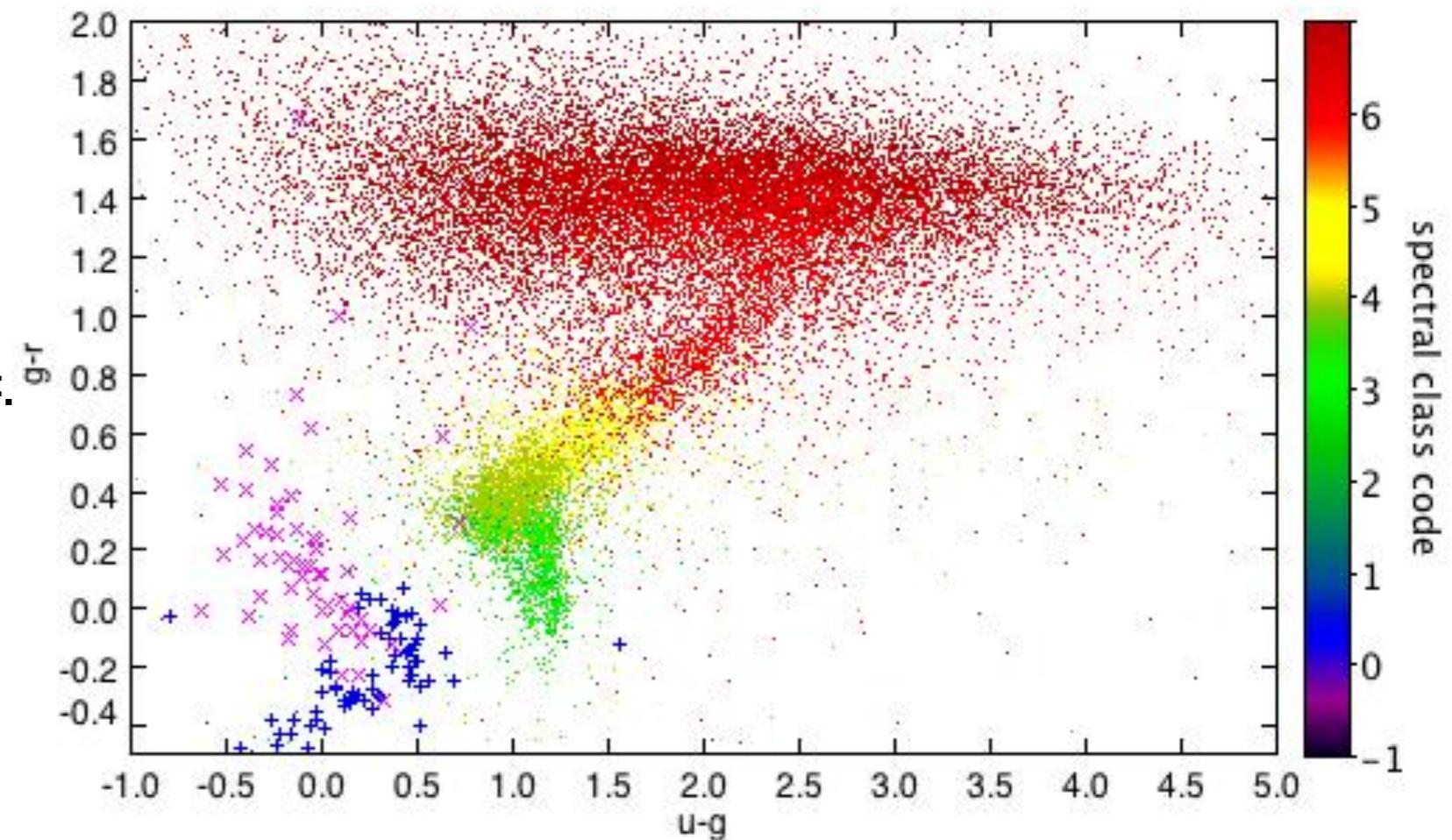
- 10 known QSOs \deg^{-2} $i < 20.5$, in $\sim 1200 \deg^2$ ELG region
- All DR7, DR12 + SDSS-IV QSOs $i < 19.1$ (+most-variable to $i < 20.5$)
- $\sim 16,000$ observed in most recent TDSS files
- RQS+FES provides dozens of new candidate “Changing Look Quasars”
e.g. LaMassa+2015, Ruan+, Runnoe+, & MacLeod+(all 2016).

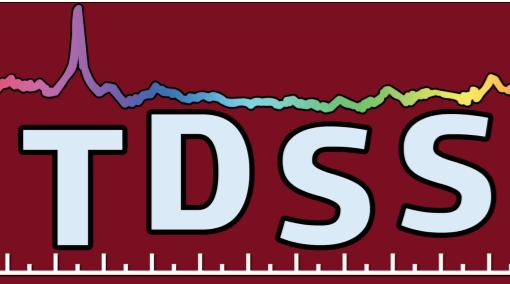




TDSS/SES update

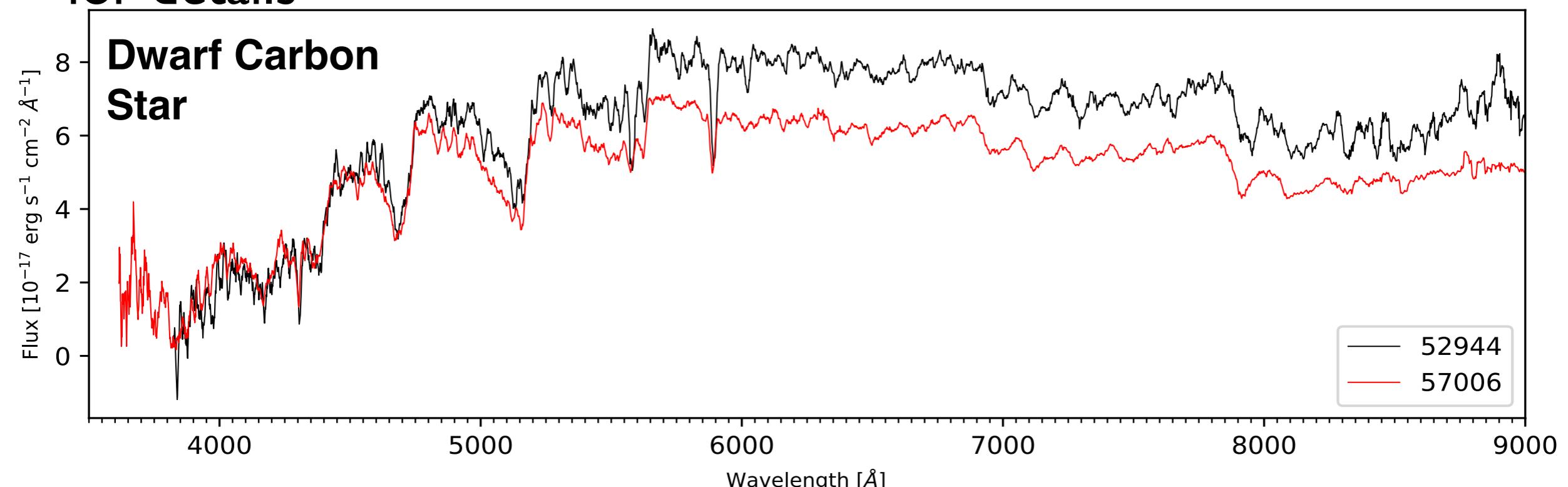
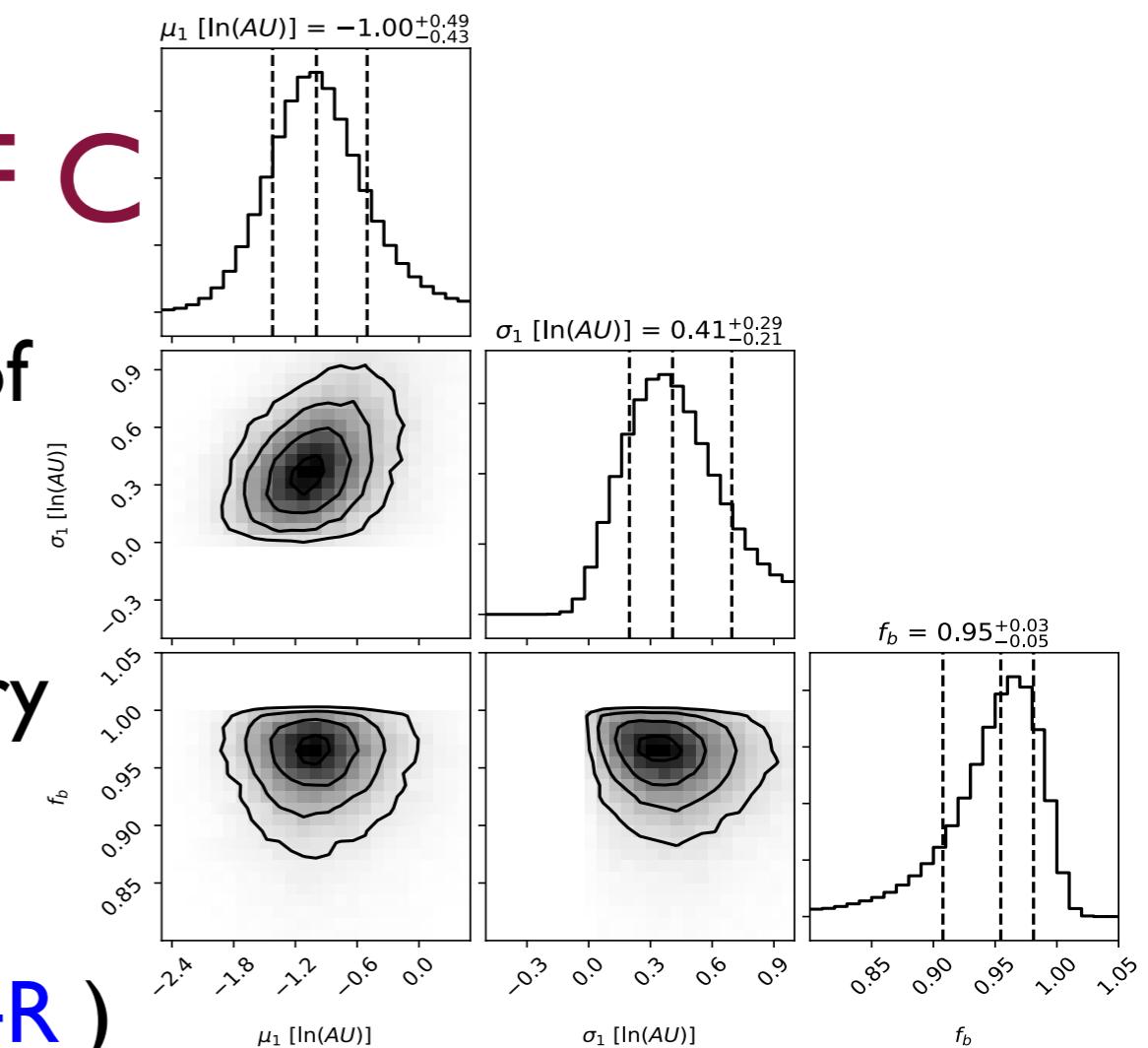
STAR subclasses (pipe) range from O/B, through A/F (green), to K/M (orange/red). Flaring M stars dominate, but thousands are in A/F-star regime that includes pulsating RR Lyrae. >710 have cataloged periodic light curves, e.g., also includes eclipsers. Large symbols highlight ~60 each CVs (purple x's) & variable WDs (blue +'s).

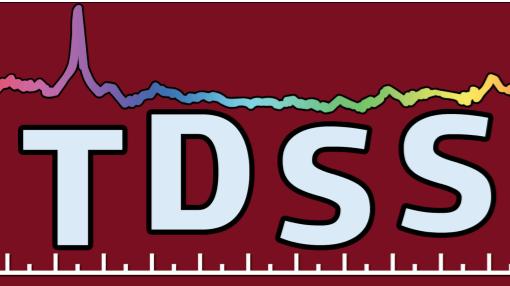




TDSS-FES DWARF C

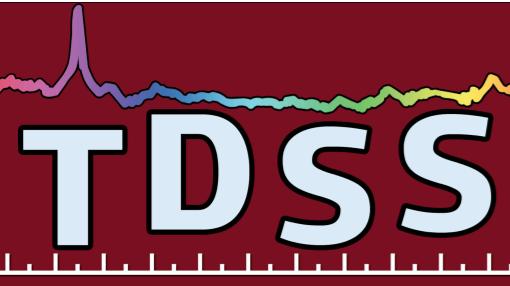
- FES program for repeat spectroscopy of dwarf carbon stars
- MCMC modeling confirms ~100% binary fraction
- See Roulston+2019 ([2019ApJ...877...44R](#)) for details





TDSS Stellar Science Opportunities

- Expect ~25,000 stellar variables in TDSS (pulsating, eclipsing, accreting, active)
 - ~ 4,000 off the main sequence
 - ~ 1,000 RR Lyr
 - ~ Handful of
 - WDs
 - CVs
 - Carbon stars
- ~10% of variables are periodic ($\log\text{Prob} < -10$)

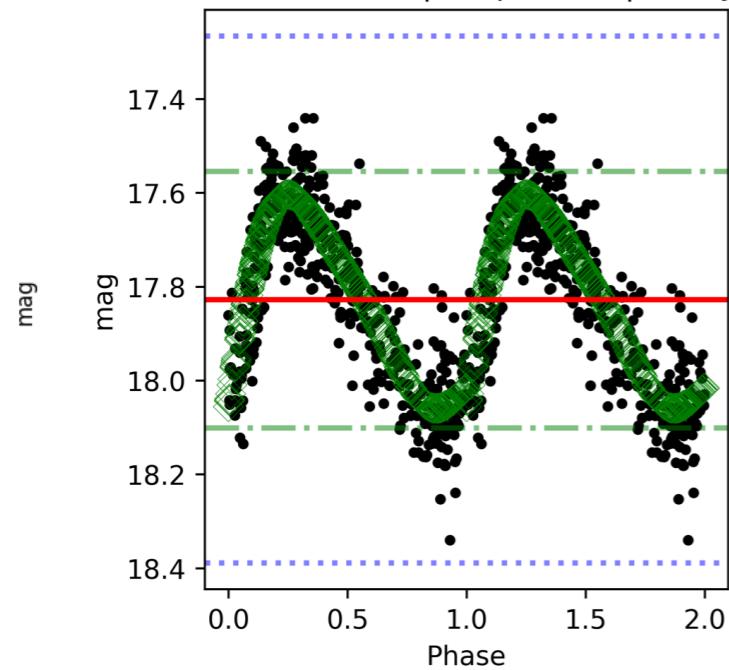


TDSS Stellar Science Opportunities

- Identify SB2s within the sample
- RR Lyr (study Galactic Halo, streams?)
- Flare stars
- WD+dM systems
- Classify all variables with RF/Clustering algorithms
 - Light curve features e.g. amplitude, period, skewness...
 - Spectral type and emission line activity
 - parallax and proper motions (Gaia DR2)
 - RV, space motions, kinematic population

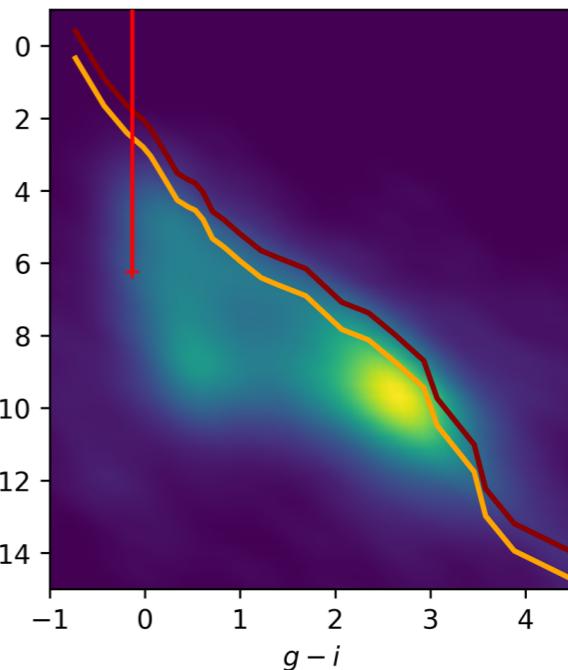
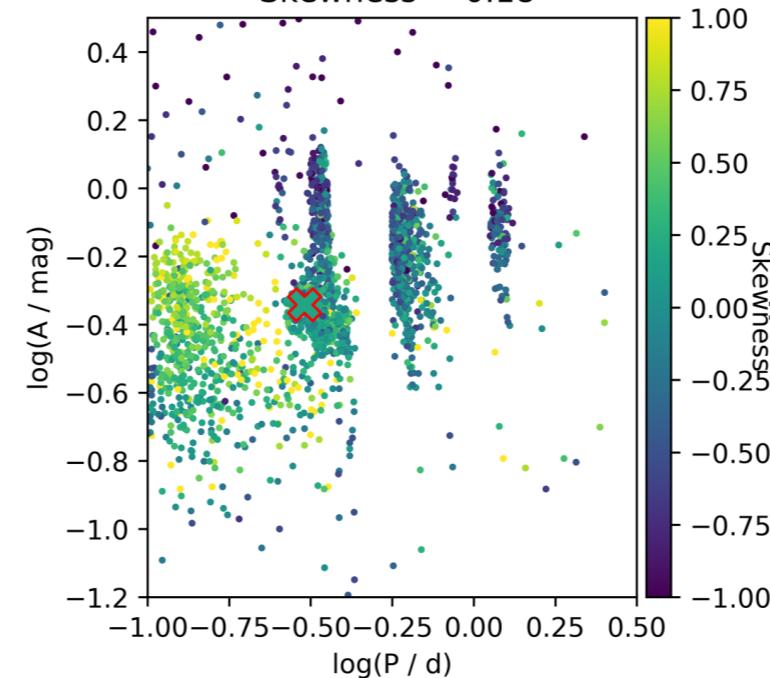
CSS ID: 1104014029251 | P= 0.303
logProb=-118.491 | Amp= 0.455
ngood=445 | nreject=2
nabove=25 (5%) | nbelow=36 (8%)

Drake: P=0.3029289 | Amp=0.48 | VarType=RRc



$$\begin{aligned}\log_{10}(P / \text{day}) &= -0.52 \\ \log_{10}(\text{Amp} / \text{mag}) &= -0.34 \\ \text{Skewness} &= 0.18\end{aligned}$$

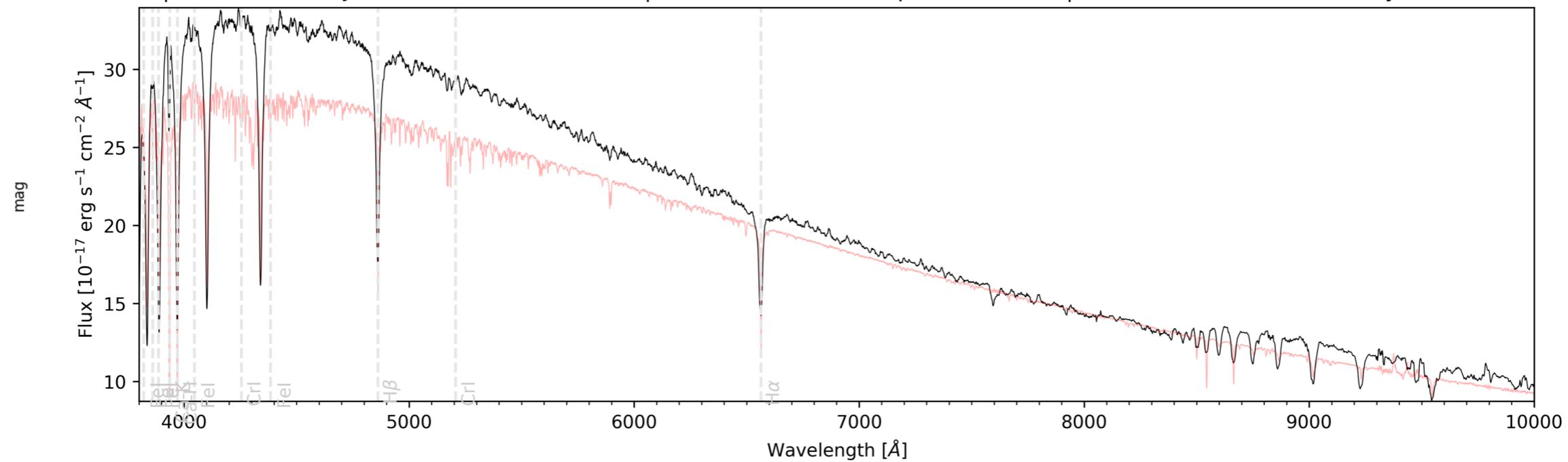
$M_i = 6.24$
 $g-i = -0.13$
UpperLim Dist = 84723 pc
LowerLim $M_i = -1.87$



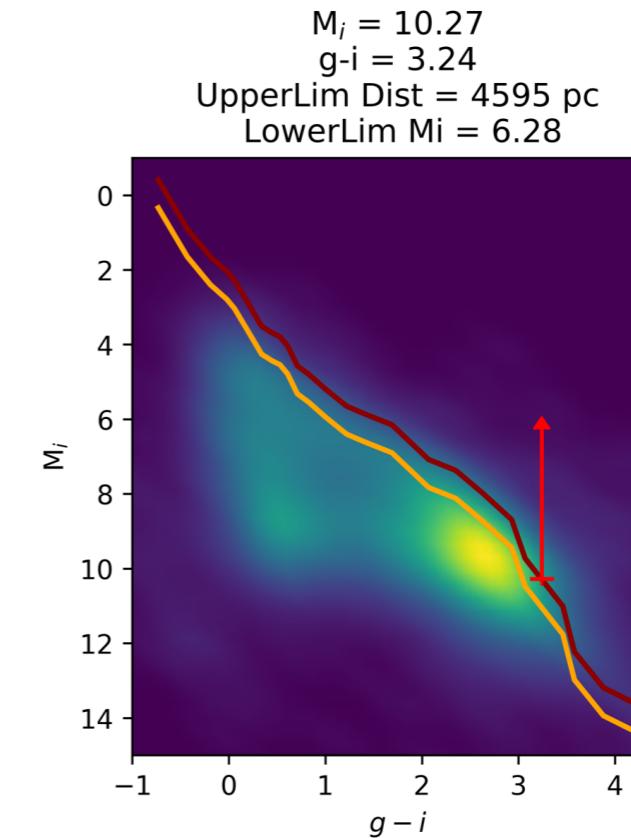
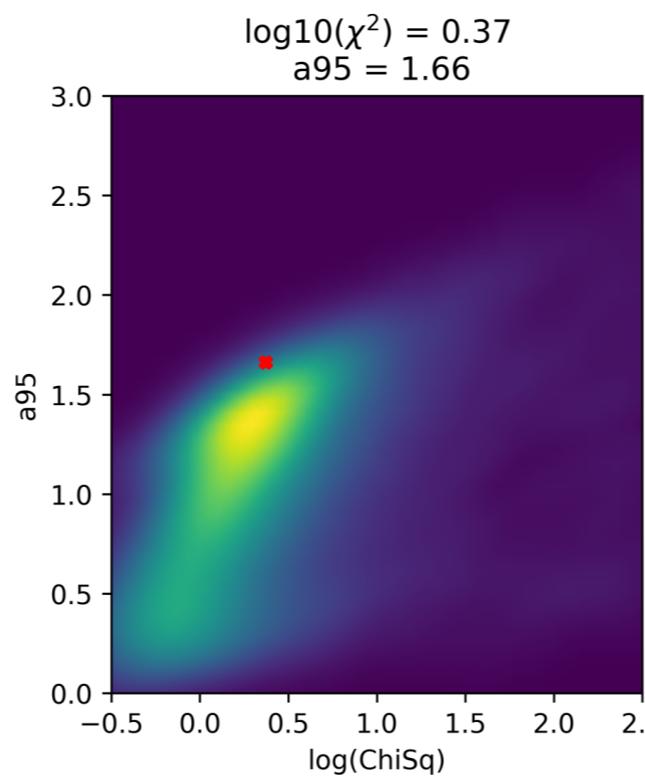
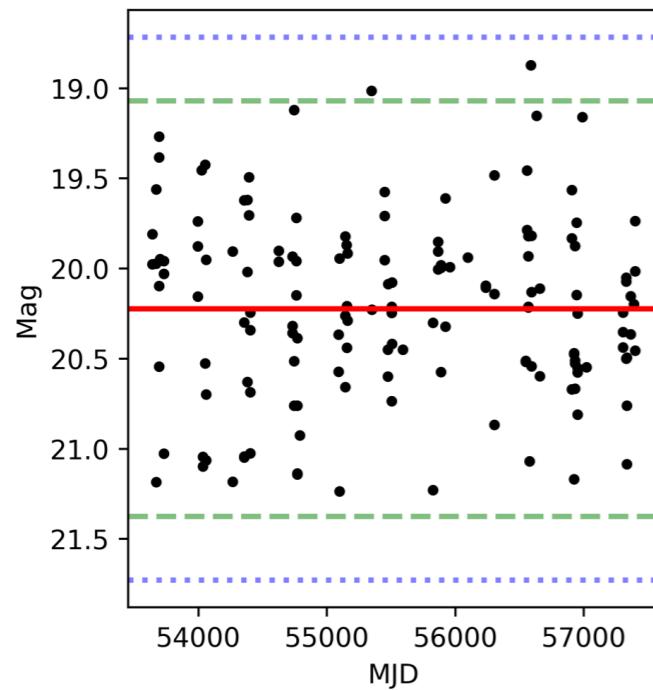
RA: 037.12508, DEC: +004.27536 | cz = -107.16±2.54 km s⁻¹ | SDSS Subclass = A4V

PyHammer = F7, RV = -121.6 km s⁻¹

DR | Plate = 8731 MJD = 57416 Fiberid = 0612 | GaiaDR2 Dist = 2023 pc (SNR=0.26) | GaiaDR2 PMtot = 1.46 mas/yr (SNR = 4.11)

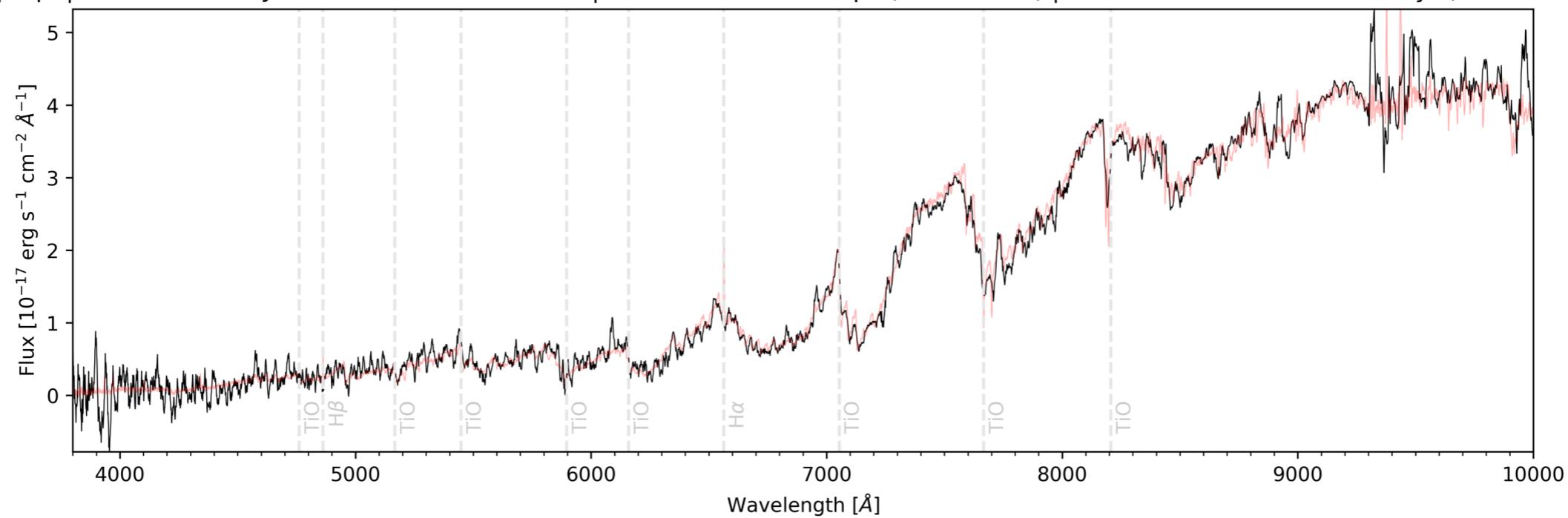


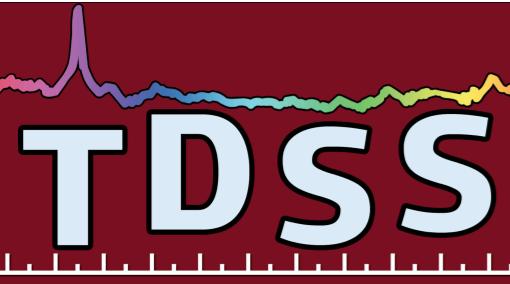
CSS ID: 1126001048461 | P= 0.374
 logProb= -1.721 | Amp= 1.061
 ngood=147 | nreject=1
 nabove=3 (2%) | nbelow=0 (0%)



RA: 000.07375, DEC: +027.35199 | $cz = -3.86 \pm 11.36 \text{ km s}^{-1}$ | SDSS Subclass = M5III
 PyHammer = M6, RV = 43.23 km s^{-1}

prop. | Plate = 7695 MJD = 57654 Fiberid = 0580 | GaiaDR2 Dist = 729 pc (SNR = 1.53) | GaiaDR2 PMtot = 27.47 mas/yr (SNR = 21.14)

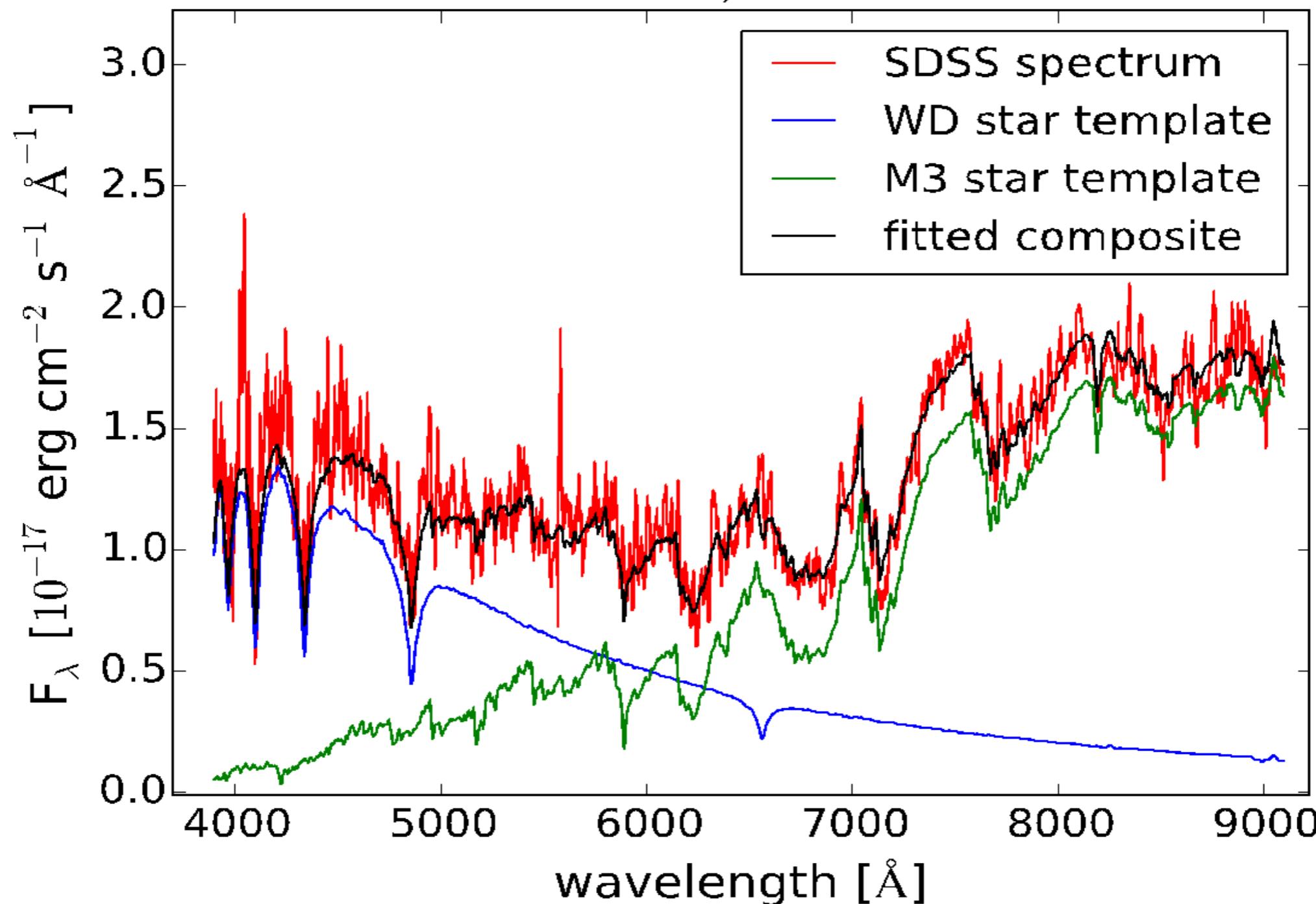


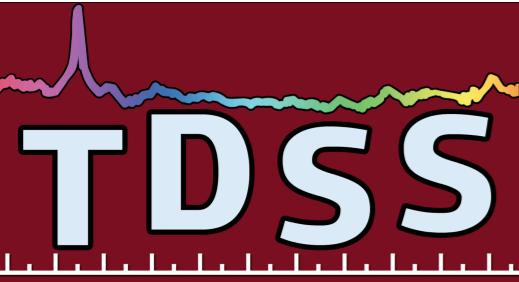


Composite-spectrum Binaries (a.k.a. SB2)

Can sometimes be obvious!

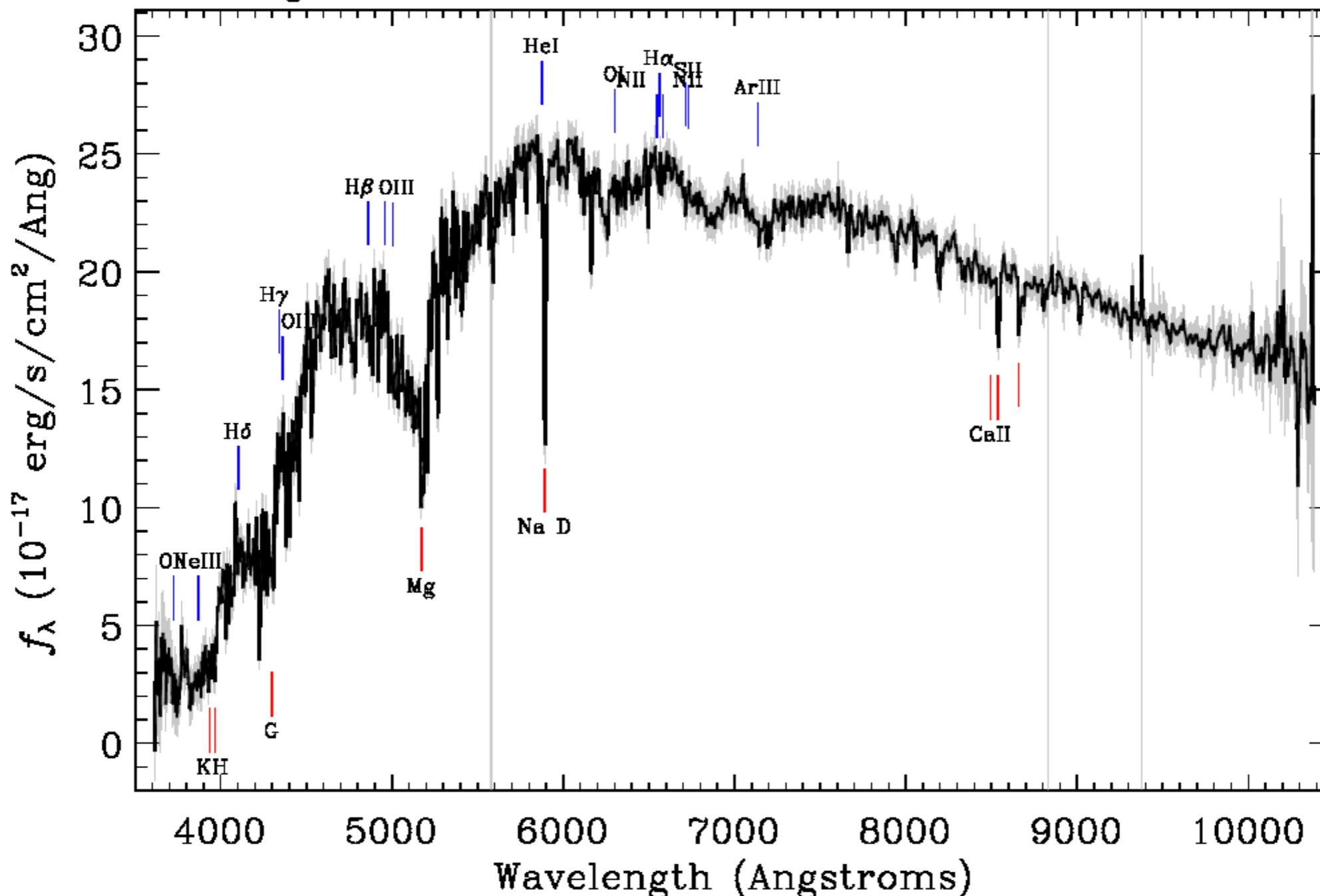
plate = 7413, mjd = 56769, fiber = 392
ra = 194.2458, dec = 45.89605

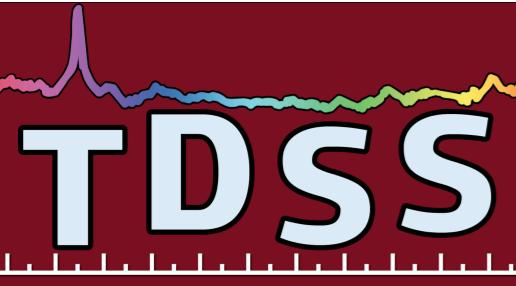




More Typical Composite-Spectrum Binaries

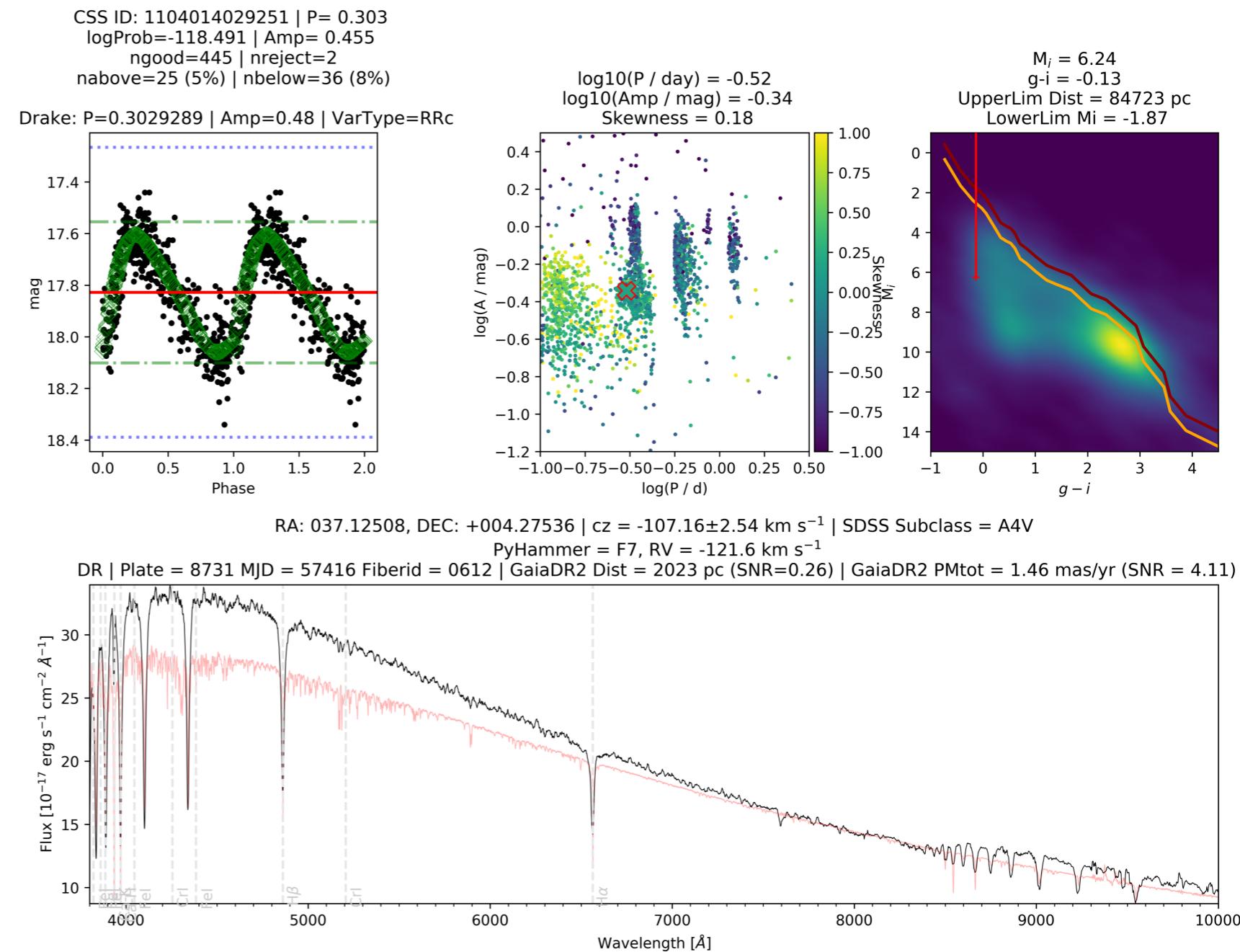
Survey: *eboss* Program: *eboss* Target:
RA=4.89498, Dec=28.38896, Plate=7662, Fiber=646, MJD=57358
 $cz=-88 \pm 3$ km/s Class=STAR K5Ve (118100)
No warnings.

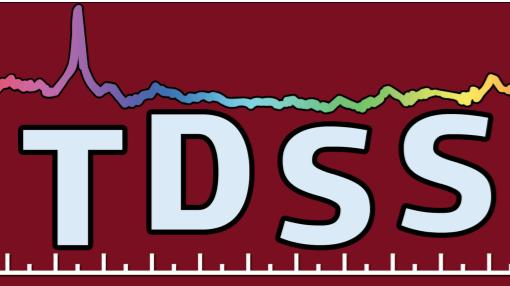




TDSS Stellar Variables

If you're interested in more information on the TDSS Stellar Variables, see my talk Thursday (27th) during the Stellar Templates Parallel V Session L, at 4:45pm.





TDSS Publications/Recent MoU Files

Published:

Morganson+2015

Ruan+2016

Grier+2016

Ruan+2016

Runnoe+2016

Wang+2016

McGraw+2017

MacLeod+2018

Roulston+2019

SES Target selection

SEQUELS (TDSS pilot)

BAL acceleration

CLQs

CLQs

Binary SMBH

BAL re-emergence/disappearance

RQS/FES Target selection

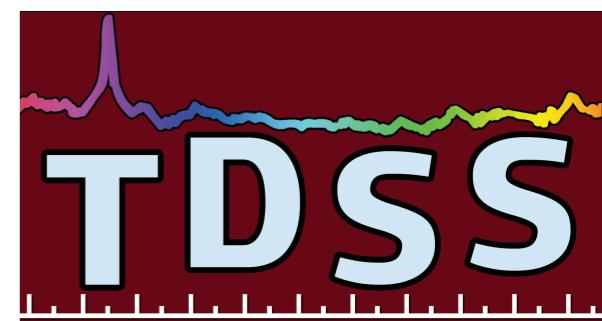
Radial velocity variations in dwarf carbon stars

*spTDSS-PSI file (PSI/SDSS-IV MoU data-sharing; spAll+PSI and SDSS imaging parameters) file on wiki and delivered to PSI

[spTDSS-PSI-v5_10_0-21Dec2016_DR14v0.txt.gz](#)

*And see K. Stassun's Filtergraph interface to latter

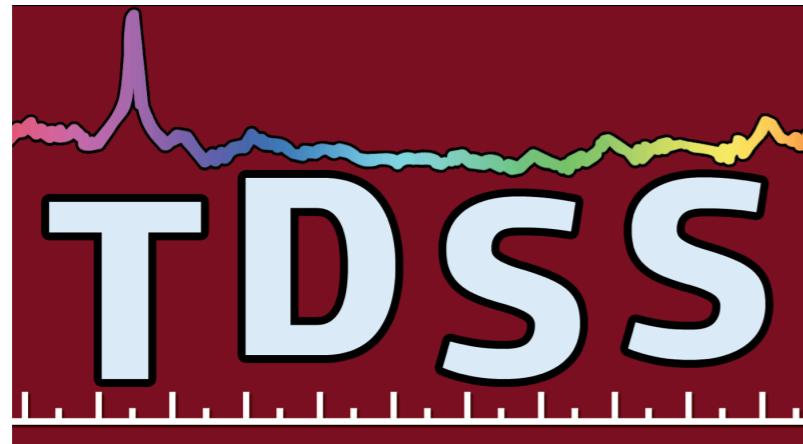
<https://filtergraph.com/tdss>



TDSS WIKI

<https://trac.sdss.org/wiki/TDSS>

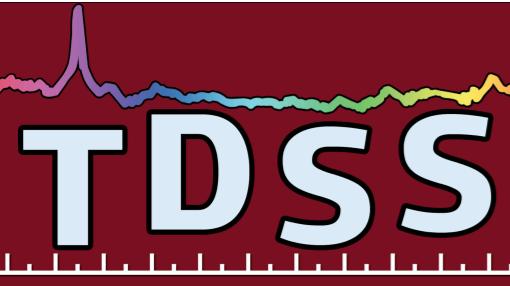
- Telecon number/minutes
- Documents and brief primer
- Instructions/software info for VIP (Ruan et al.)
- spAllTDSS file (an spAll file for TDSS targets, with SDSS-IV spectro pipeline parameters): **spAllTDSS-v5_10_01Jul2018_v0.txt**
- PS1/SDSS-IV data-sharing file



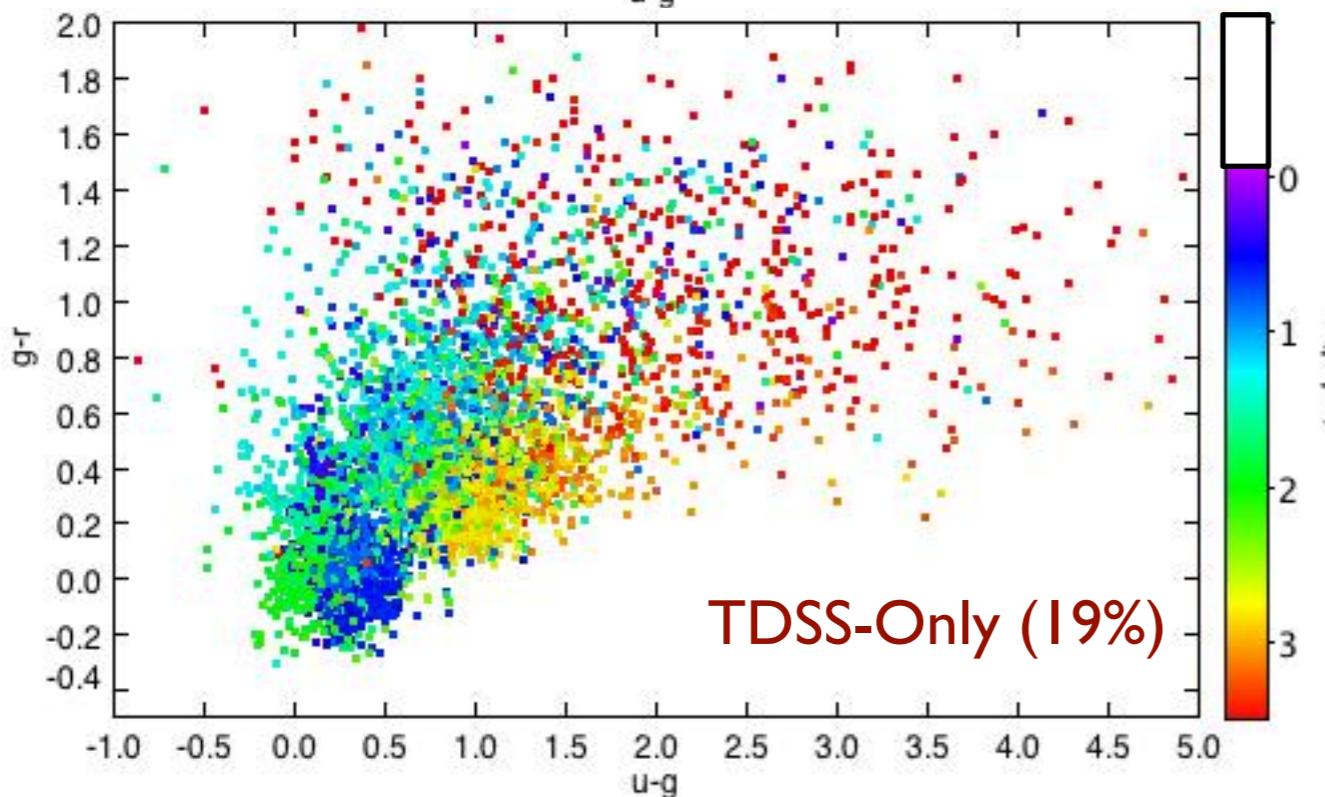
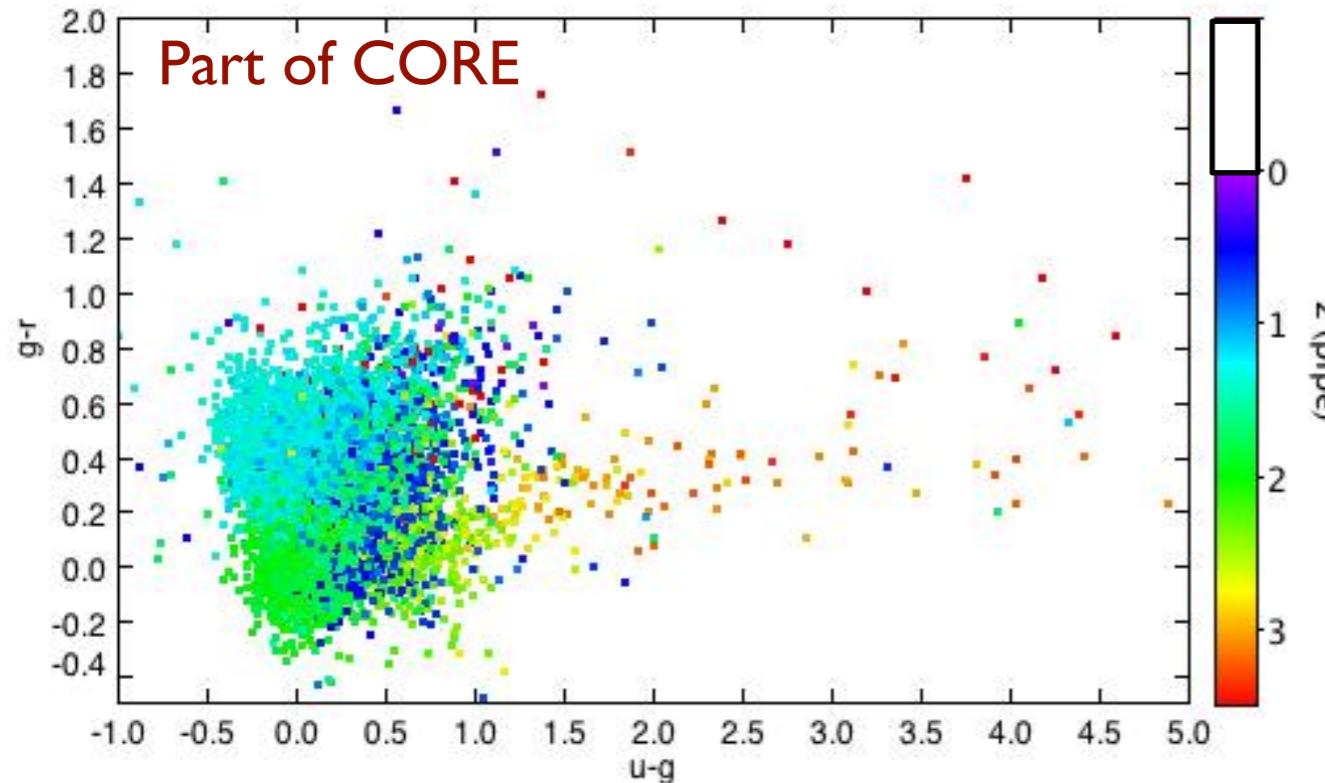
TEAM

S. Anderson (Uwa), C. Badenes (UPitt), M. Bershadsky (UWi), M. Blanton (NYU), N. Brandt (PSU), K. Chambers (IfA), J. Davenport (UW), K. Dawson (Utah), M. Eracleous (PSU), N. Filiz Ak (Erciyes), P. Garnavich (Notre Dame), A. Georgakakis (MPE), P. Green (CfA), J. Greene (Princeton), C. Grier (PSU), P. Hall (York), S. Hawley (UW), N. Kaiser (IfA), J.-P. Kneib (EPFL), C. MacLeod (CfA), Vivek Mariappan (Utah), I. McGreer (UA), A. Merloni (MPE), E. Morganson (UIUC), A. Myers (UWy), I. Paris (IAP), B. Roulston (SAO/BU), J. Ruan (UW), J. Runnoe (UMich), M. Salvato (MPE), E. Schlaufly (MPIA), D. Schlegel (LBNL), S. Schmidt (OSU), D. Schneider (PSU), Axel Schwone (AIP), B. Sesar (Caltech), T. Shanks (Durham), Y. Shen (UIUC), S. Smartt (Queen's U. Belfast), K. Stassun (Vander.), P. Szkody (UWa), J. Tonry (IfA), F. Walter (MPIA), D. York (UC), ... YOUR NAME
HERE

EXTRA SLIDES



TDSS/SES update (through DR14)



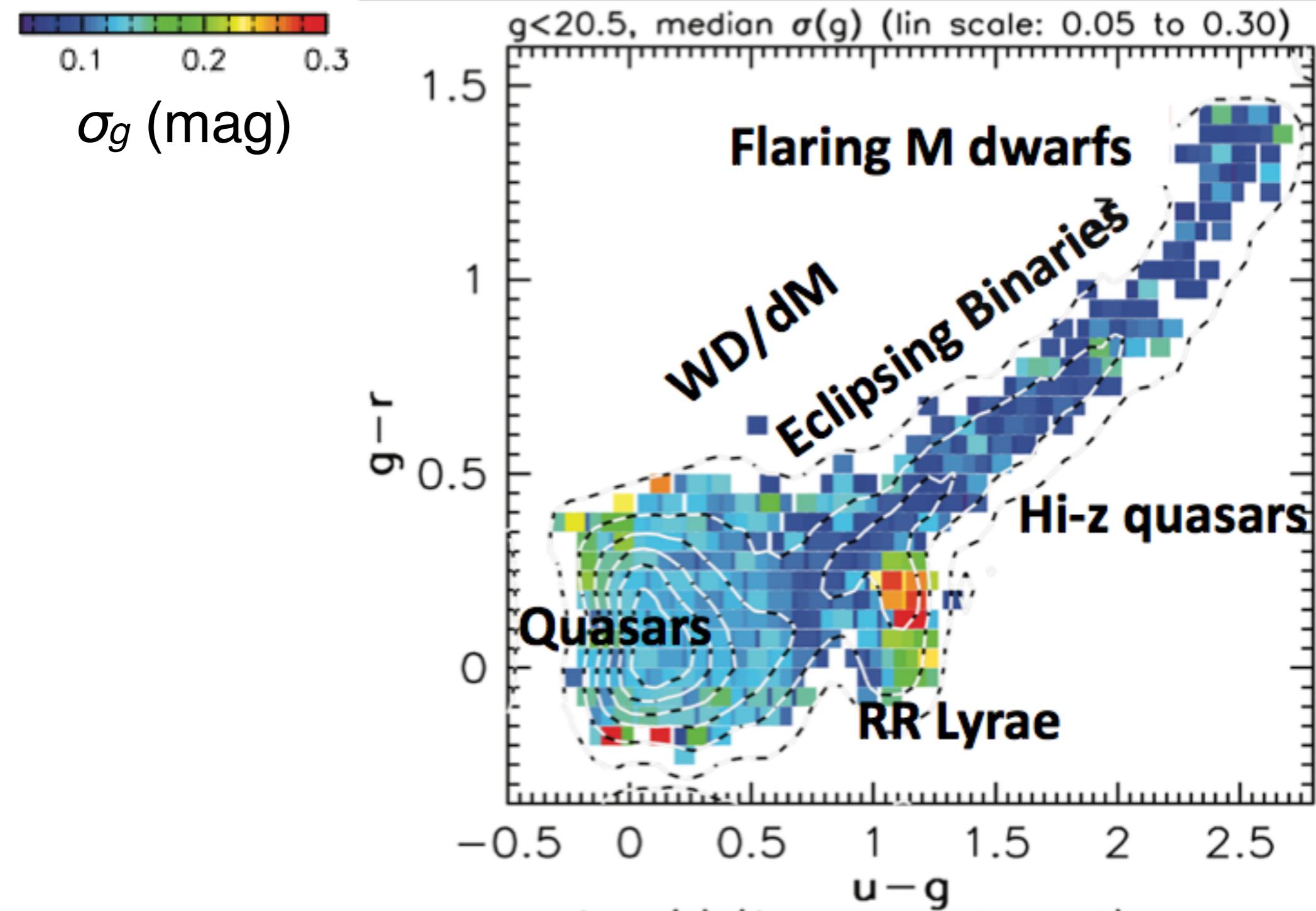
QSO redshifts (pipe). **UPPER:** also co-selected by eBOSS core (i.e., color selected too). **LOWER:** 19% of TDSS QSOs not co-selected by eBOSS core (e.g., variability, but not color selected). TDSS variability selection adds quasars, including redder, higher- z , and lower- z (e.g., see Ruan et al. 2016)

TDSS TECHNICAL DETAILS

- eBOSS subprogram in SDSS-IV (2014 - 2020; Blanton et al. 2017)
- Targets photometric variables from SDSS and
- ~140k new spectra + ~80k archival spectra
- 10 fibers deg⁻² on eBOSS spectrograph
- **Main Program:** single-epoch spectroscopy (“**SES**”)
 - 90K spectra for discovery/classification (Morganson et al. 2015)
- **Spectroscopic Variability:**
 - 10% fibers reserved for few-epoch spectroscopy (“**FES**”) programs
 - 12K Repeat Quasar Spectra (“**RQS**”) (MacLeod+2017)



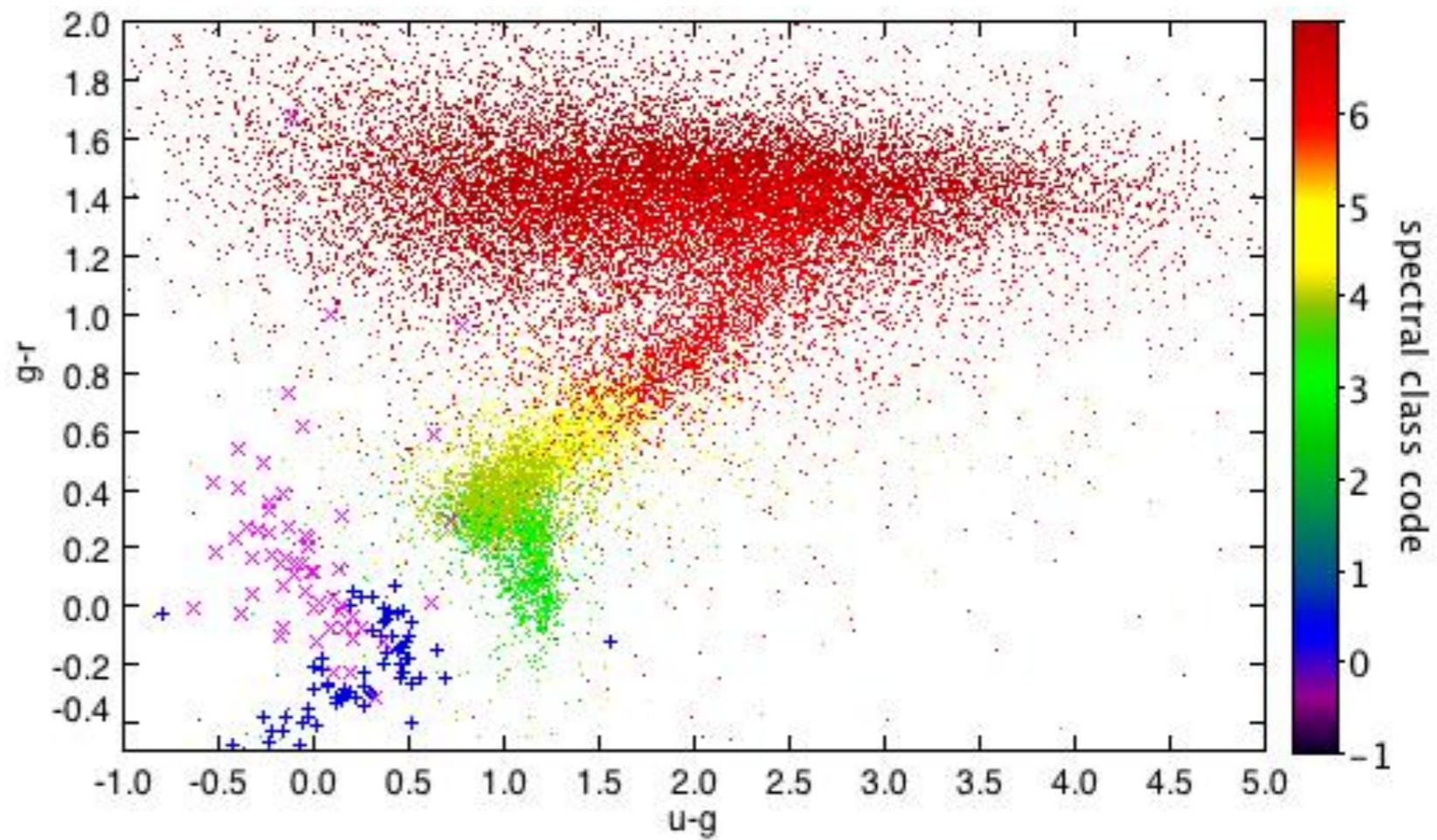
CELESTIAL VARIABLES



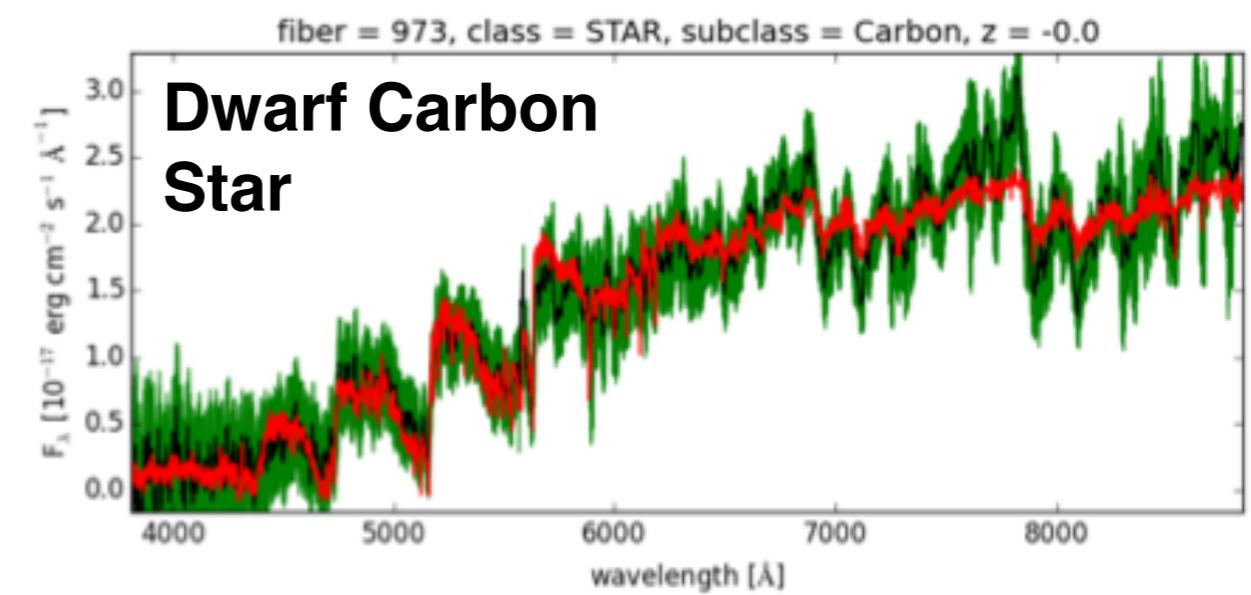
*“Exploring the Variable Sky with the Sloan Digital Sky Survey,”
Sesar et al. (2007)*

Sesar et al. 2007

TDSS/SES update (through DR14)



STAR subclasses (pipe) range from O/B, through A/F (green), to K/M (orange/red). Flaring M stars dominate, but thousands are in A/F-star regime that includes pulsating RR Lyrae. >710 have cataloged periodic light curves, e.g., also includes eclipsers. Large symbols highlight ~60 each CVs (purple x's) & variable WDs (blue +'s).



PURITY

- Must be robust to bad measurements
- Precision: 0.1 mags
- Sample of variable objects expected to be 96% pure and comprising the following:
 - 8 deg^{-2} with existing SDSS spectra,
 - 10 deg^{-2} with new TDSS spectra, and
 - 15 deg^{-2} with new spectra from eBOSS.

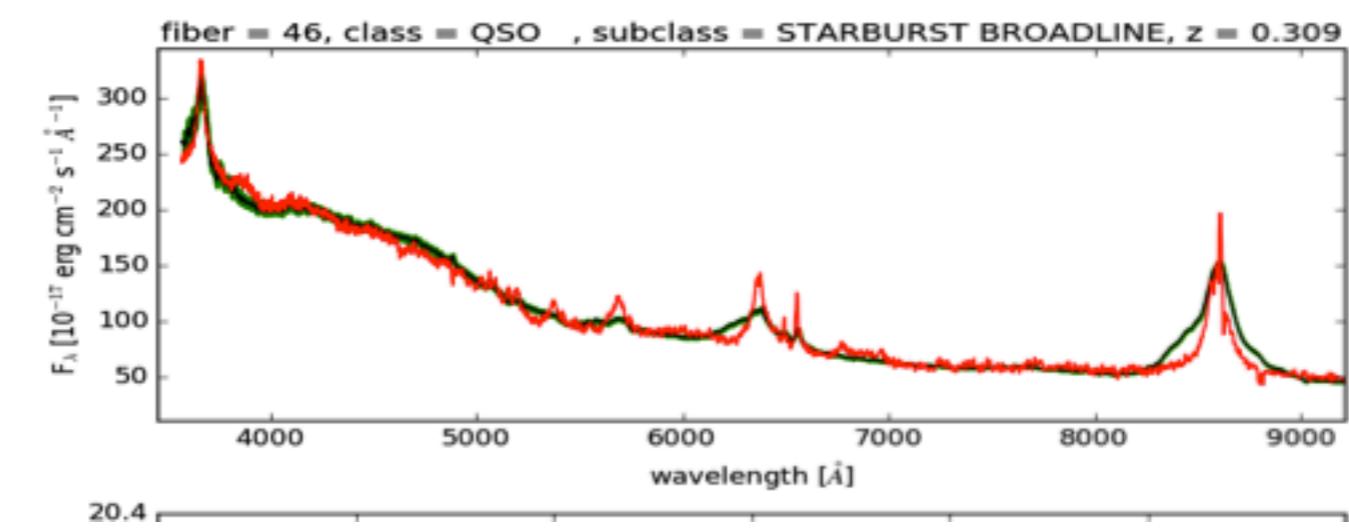
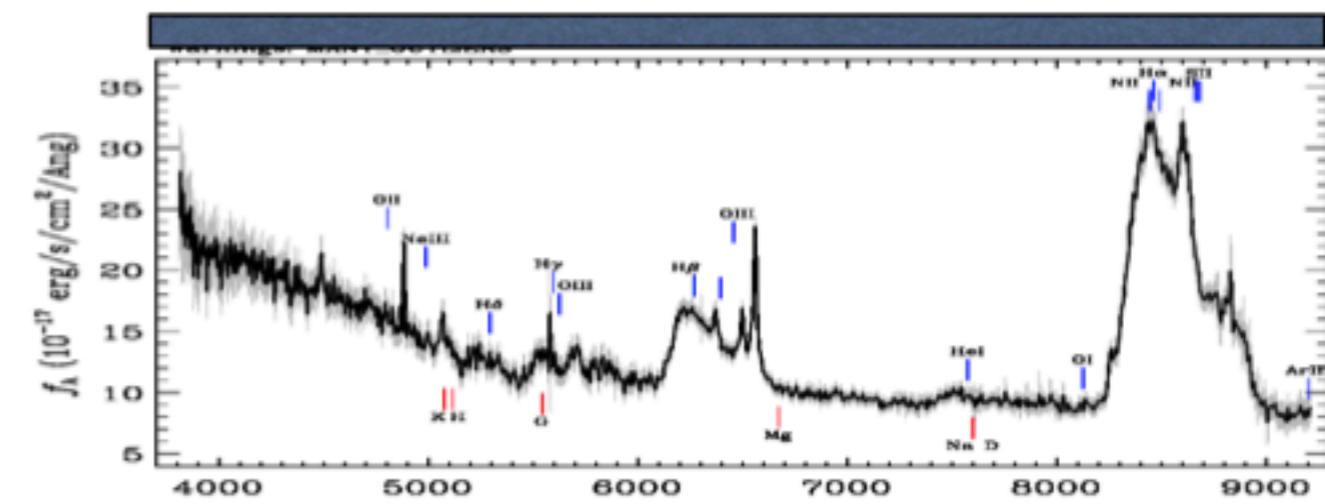
- Strateva et al (2003) found 5% ($116+32/3126$) DEs among $z < 0.33$ from DR1



- Eracleous et al. (2012) found 88 displaced-peaked emitters out of 15900 quasars at $z < 0.7$ ($z < 0.5$, in practice) from DR7, which

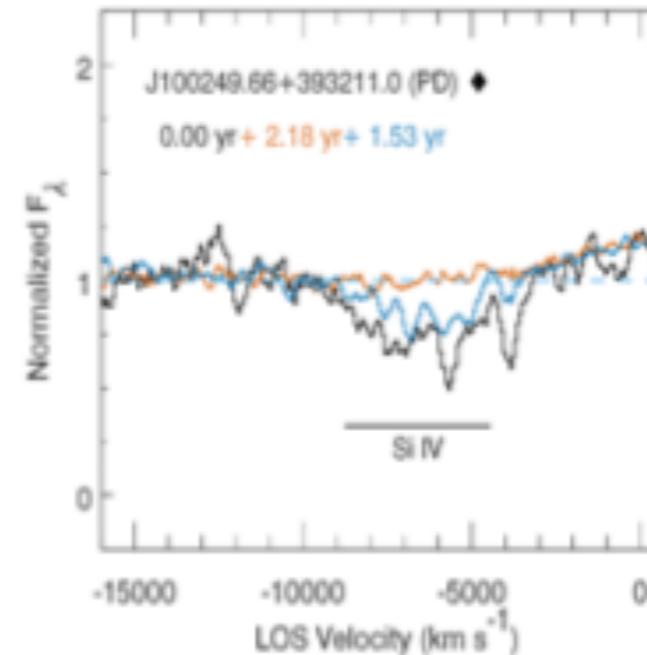
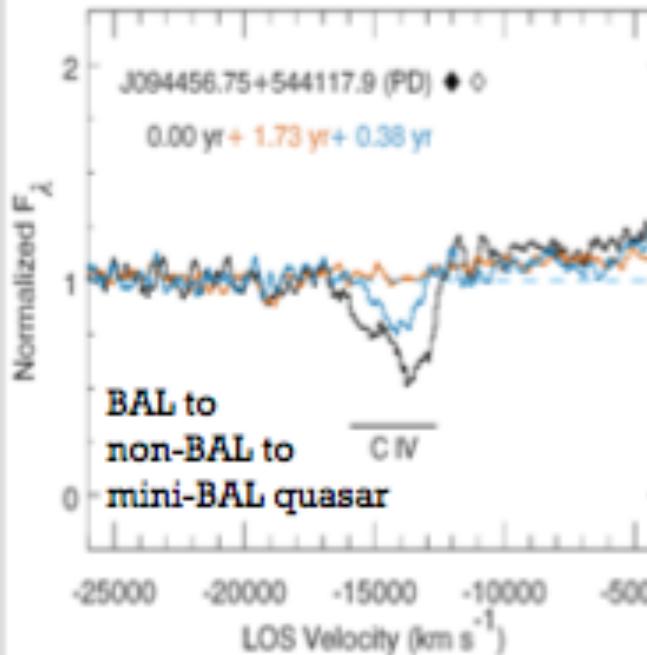
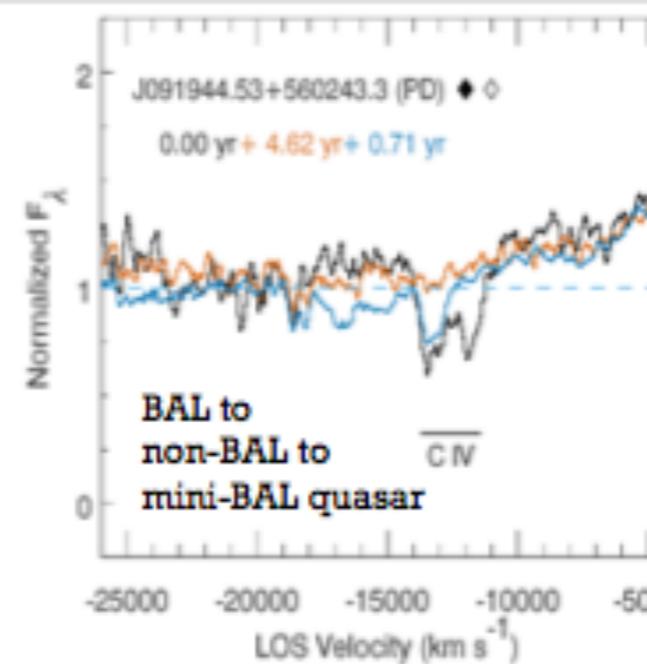
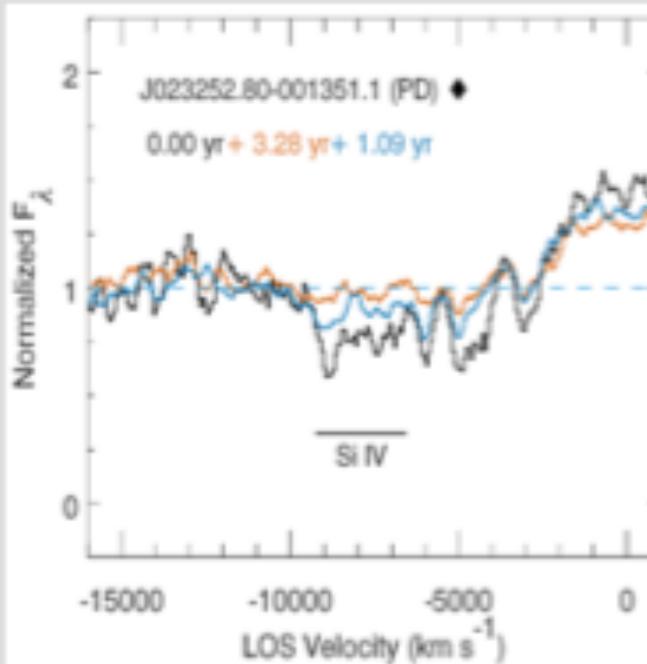


FES DE, HYPQSO (see Mike E.)



Recent TDSS FES BAL QSO Results: Three-Epoch Disappearance Follow-Up

Re-Emergence After Disappearance



Focused on sample with SDSS-I/II + BOSS + TDSS coverage – 470 BAL quasars.

14 new pristine cases of disappearing C IV and/or Si IV BALs.

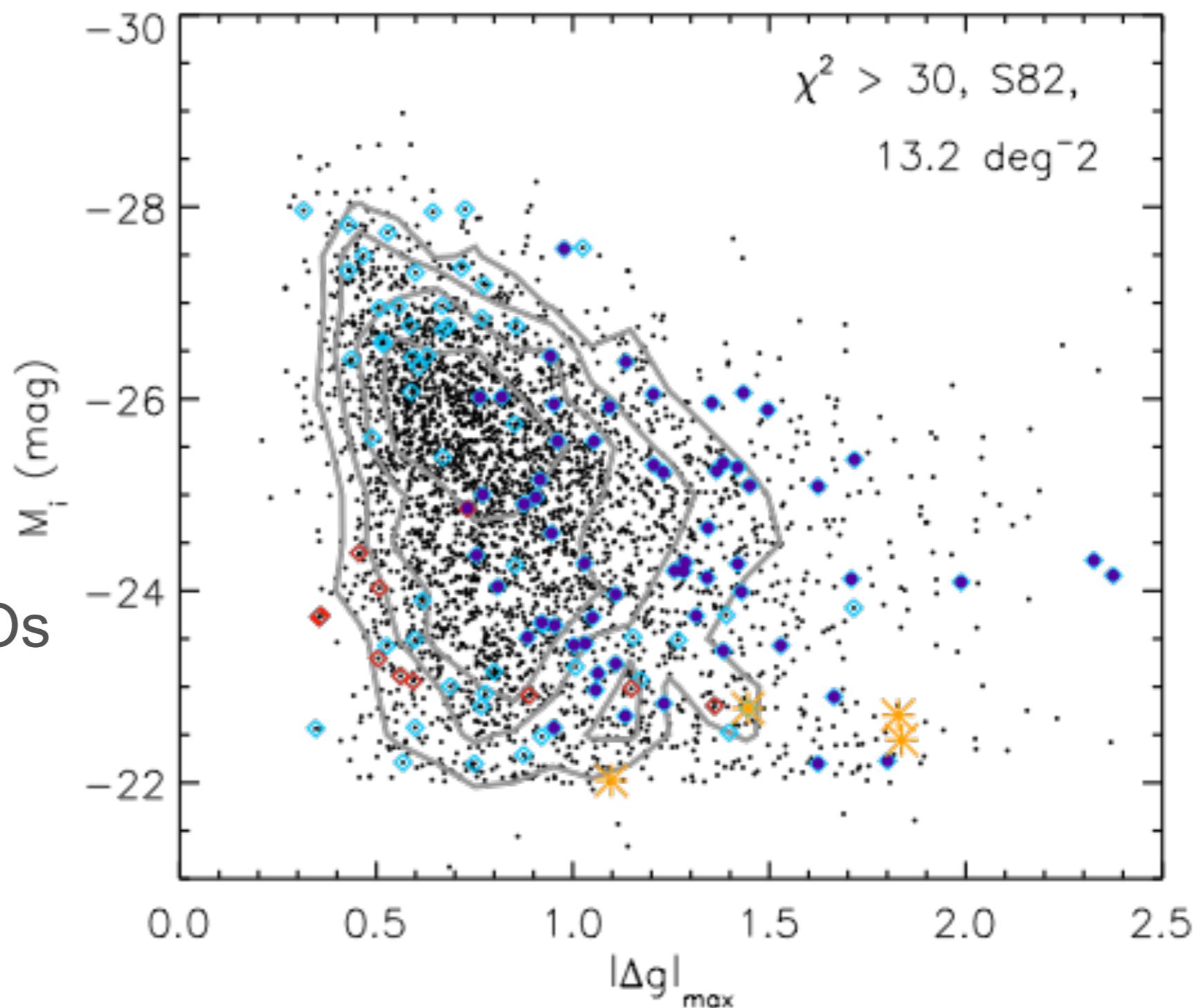
Four mini-BALs re-emerge in the third-epoch TDSS data – encore!

Re-emerge at roughly same velocity and with notable kinematic similarities.

Evidence for ionization changes causing the variability.

SDSS-IV TDSS REPEAT QUASAR SPECTROSCOPY (RQS)

- RQS Targets
- ◇ FES All
- FES HYPQSO
- ◇ FES HISN QSO
- ★ Changing-Look QSOs



Expected Periodic Stellar Variable Types to $r < 18.5$

Drake et al. 2014, ApJ, 213, 1

Type	Percent	Description
EW	49.93	contact eclipsing binary
EA	7.61	detached (Algol) eclipsing binary
beta Lyrae	0.45	semi-detached eclipsing binary
RRab	27.28	RR Lyrae (fundamental mode pulsators)
RRc	8.88	RR Lyrae (multi-period pulsators)
RRd	0.82	RR Lyrae (both)
Blazkho	0.36	RR Lyrae (quasi-periodic)
RSCVn	2.47	spotted rotator
ACEP	0.10	anomalous Cepheid
Cep-II	0.20	type II Cepheid
HADS	0.39	high amplitude delta Scuti
LPV	0.83	Mira or semi-regular AGB variables

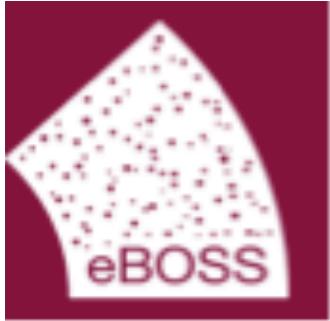


TDSS Spectroscopic Data: 2017 Update

- From a recent spAll TDSS file for SDSS-III+SDSS-IV (spans from earliest TDSS targets on SDSS-III SEQUELS plates, through latest SDSS-IV ELG plates):
 - 675 total good-quality plates taken through June 2017
 - 66618 SES targets selected or co-selected
 - 3266 FES targets
 - 2166 RQS targets
 - RQS (Repeat Quasar Spectroscopy)
 - 1443 RQSI
 - 344 RQS2
 - 29 RQS3
 - 176 RQS2v
 - 174 RQSv3
 - FES (Few Epoch Spectroscopy)

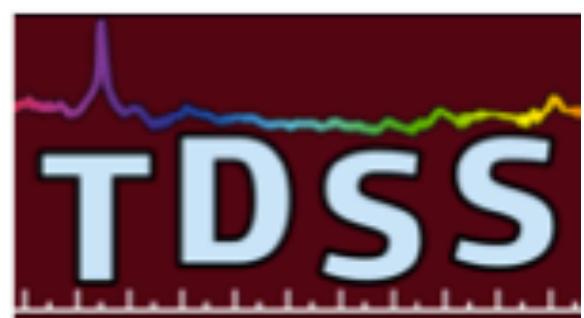
309 DE	195 ACTSTAR
526 HYPQSO	189 DWARFC
32 MGII	295 HYPSTAR
426 NQHISN	84 WDDM
1210 VARBAL	





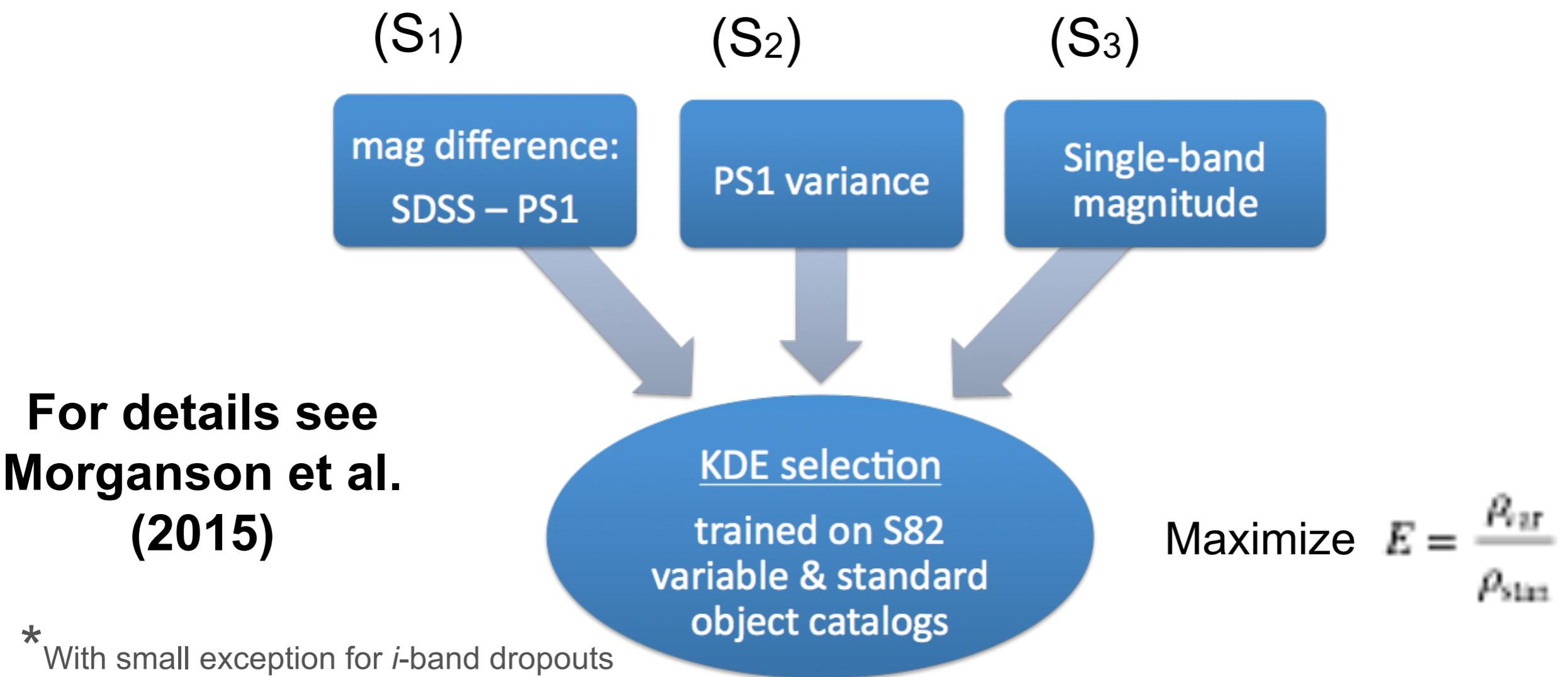
TDSS Spectroscopic Data: 2017 (SES)

- SES (Single Epoch Spectroscopy of PSI variables)
 - 17,511 TDSS_A (SEQUELS pilot, but very similar algorithm)
 - 25,016 TDSS_B (Morganson et al. 2015 final algorithm)
 - 24,091 TDSS_CP (""; most also chosen by eBOSS core)
- Among the total 66,618 SES-relevant TDSS spectral targets
 - 34,726 quasars (many also TDSS_CP) ~ 52%
 - 29,603 stars (mainly TDSS) ~ 45%
 - 2,289 galaxies, unknowns, etc ~ 3%
- Full SES sample now large enough to include reasonable subsamples of unusual/rare classes, e.g., $\sim 10^2$ each of variable CVs & WDs, and ~ 30 C stars
- There are further $\sim 6\text{-}8/\text{deg}^2$ spectra for additional TDSS/PSI photometric variables (mainly quasars) in the SDSS I-III archive (pre-SEQUELS,).
- So far from SDSS-IV, there are $\sim 35k$ TDSS-only spectra on-hand across SES, FES, and RQS (not counting TDSS co-selections w/ SDSS-IV fibers charged to others). This is $\sim 40\%$ of intended TDSS-only fiber allocation in SDSS-IV.



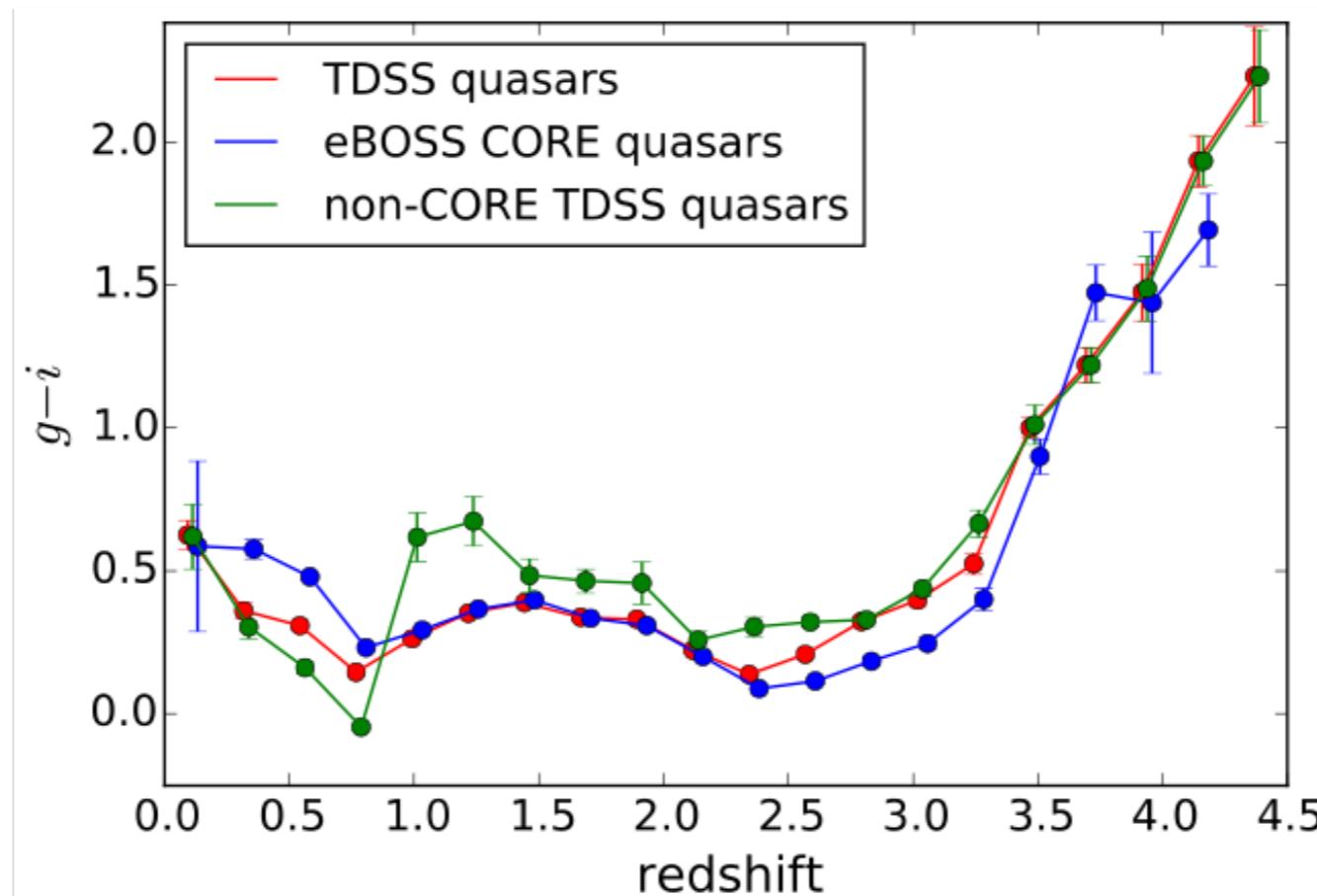
SES VARIABLE SELECTION

- $17 < i < 21$, unresolved sources
- Require 2* good bands (from among *griz*) in PS1, SDSS
- 3D Kernel Density Estimator



BASIC SES QUASAR RESULTS

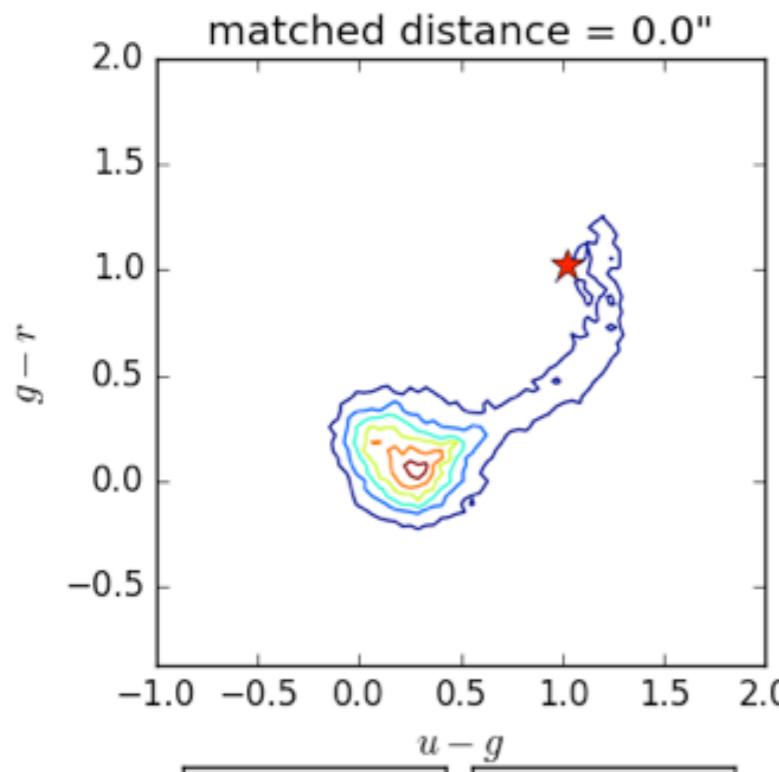
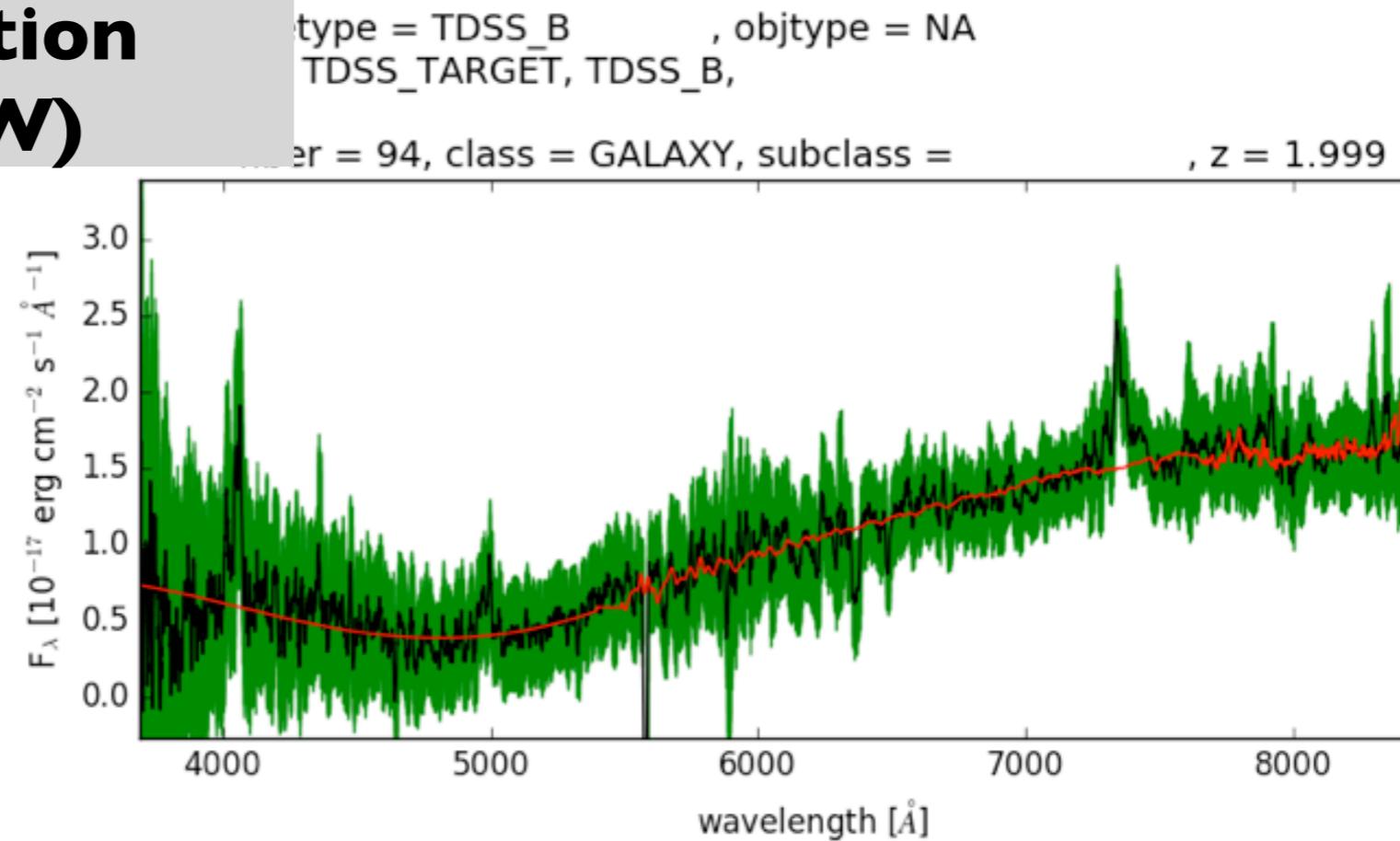
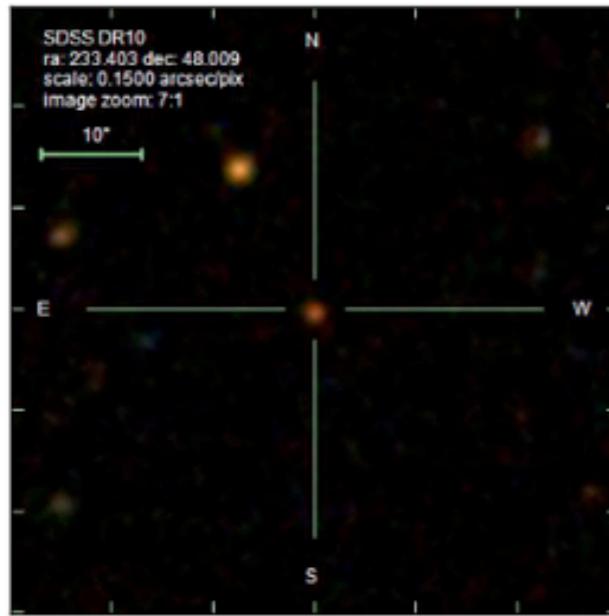
- TDSS selects redder quasars than eBOSS core sample
- TDSS mitigates redshift biases from color-selection
- TDSS produces smooth quasar redshift distribution
- TDSS selects higher fractions of peculiar AGN



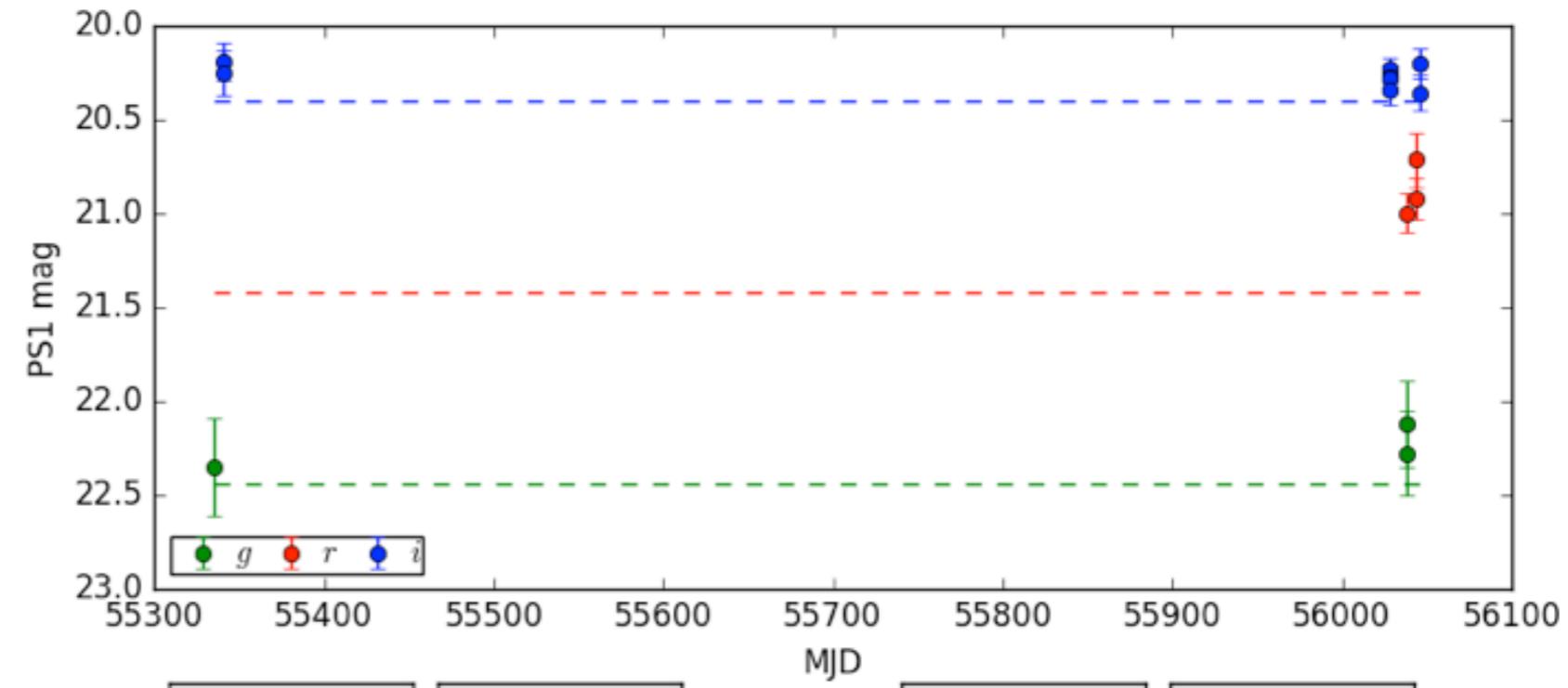
**TDSS pilot
program included
in SDSS-III
SEQUELS:
*Ruan et al. 2016***

RED QSO AT $z = 1.6$

Visual Inspection Pipeline (UW)



Back Comment

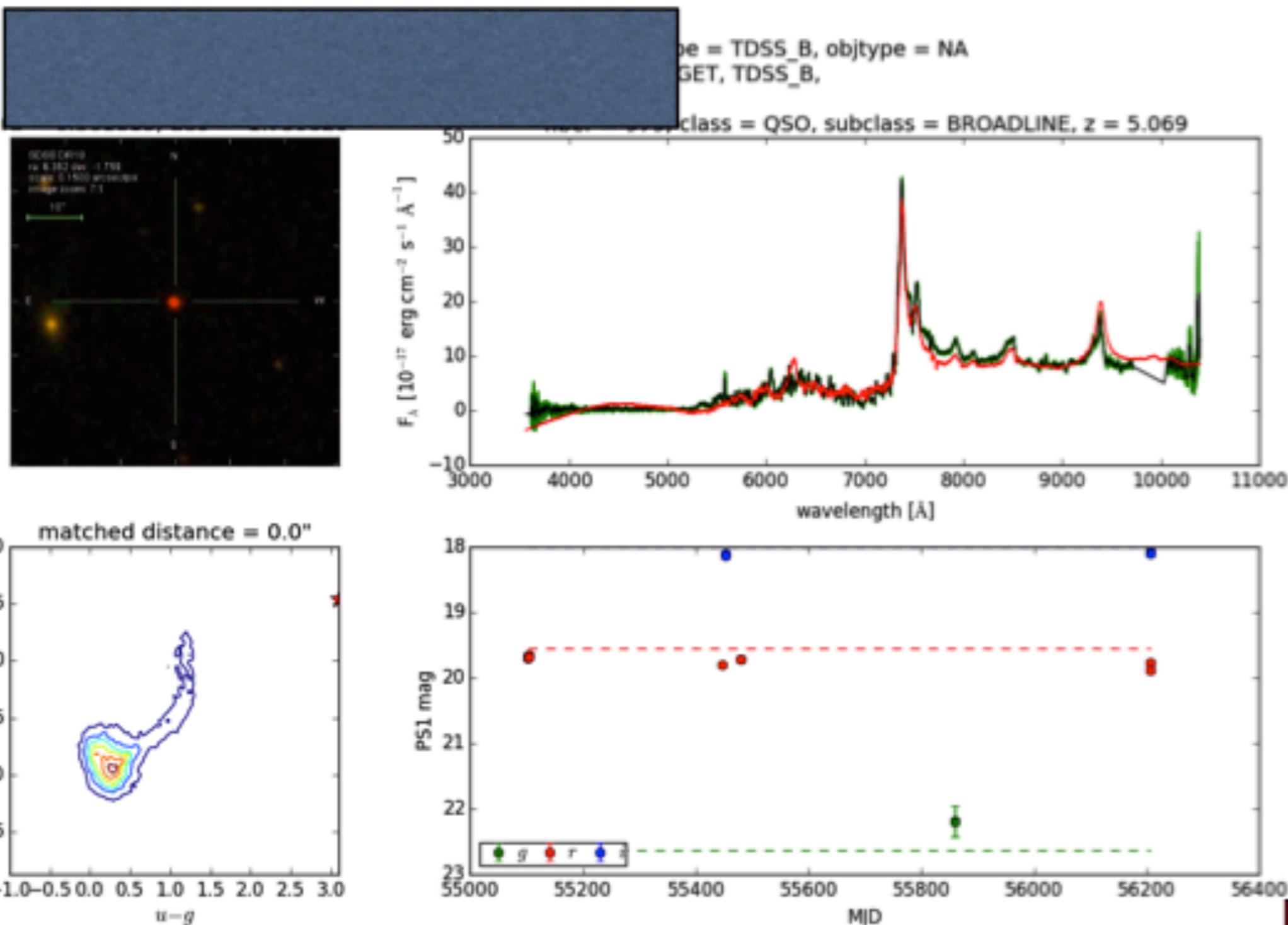


Obs Frame Rest Frame

Accept Flag

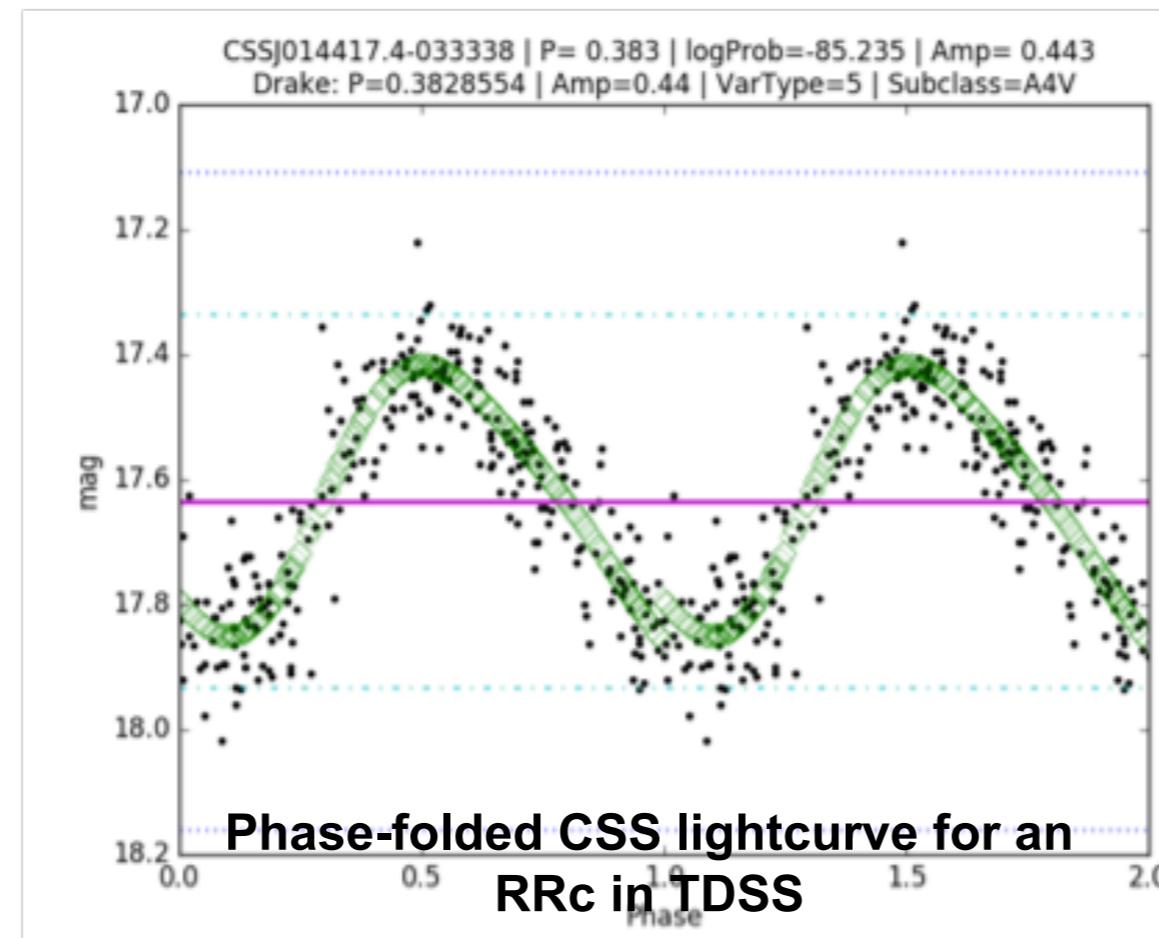


High-z Quasars in TDSS



BASIC SES STELLAR RESULTS

- TDSS selects large numbers of likely stellar pulsators and binaries
- TDSS selects higher fraction of active M dwarfs
- TDSS selects wide variety of peculiar stellar objects
- Many opportunities for stellar variability science - please contact us!



REPEAT QUASAR SPECTROSCOPY (RQS)

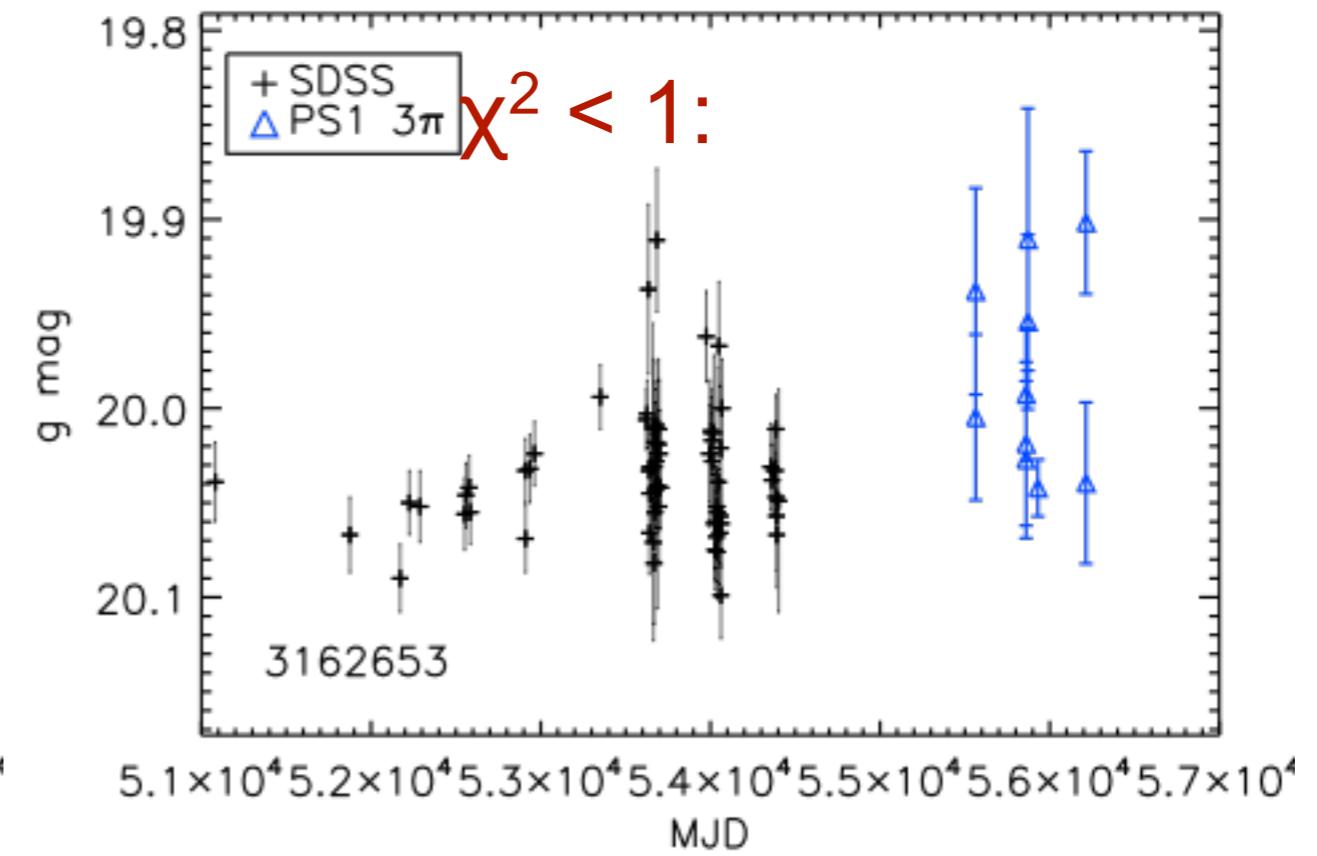
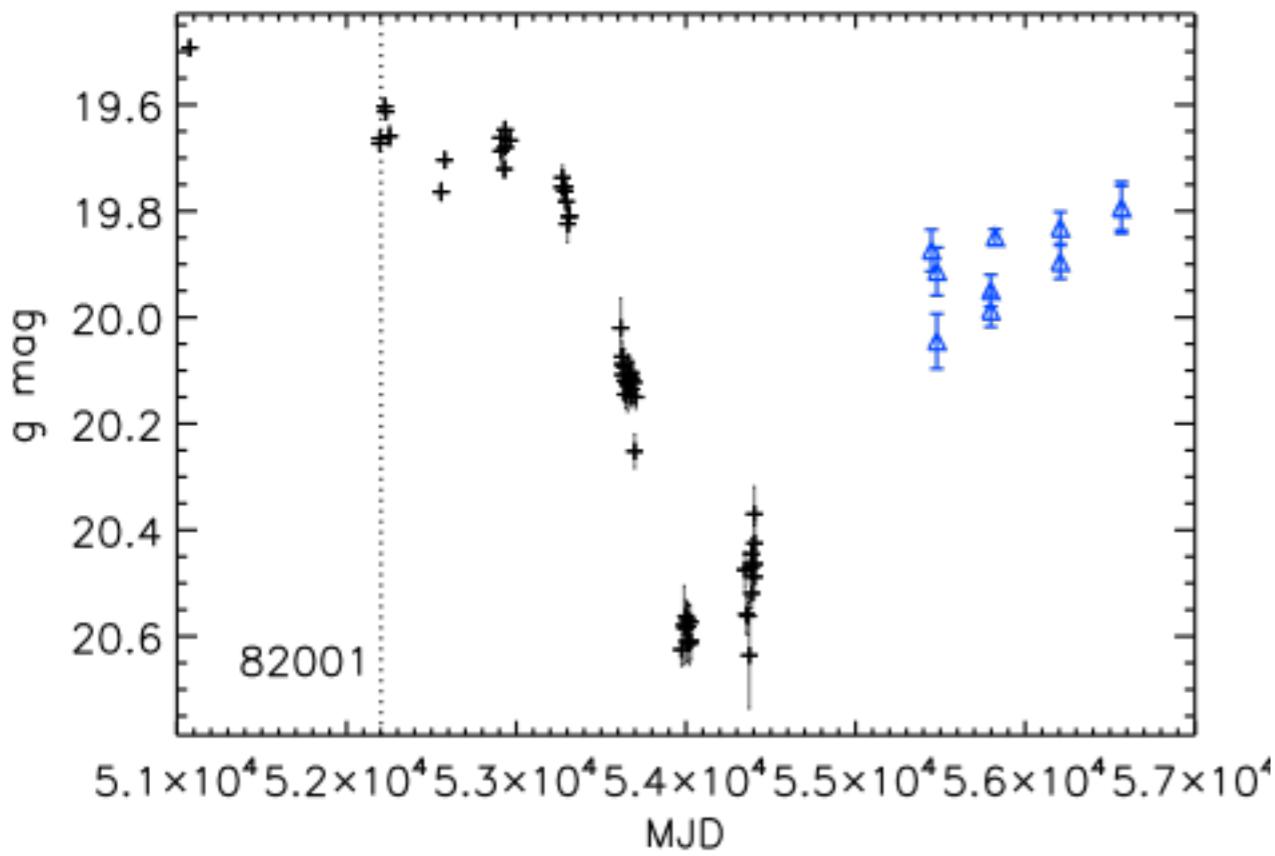
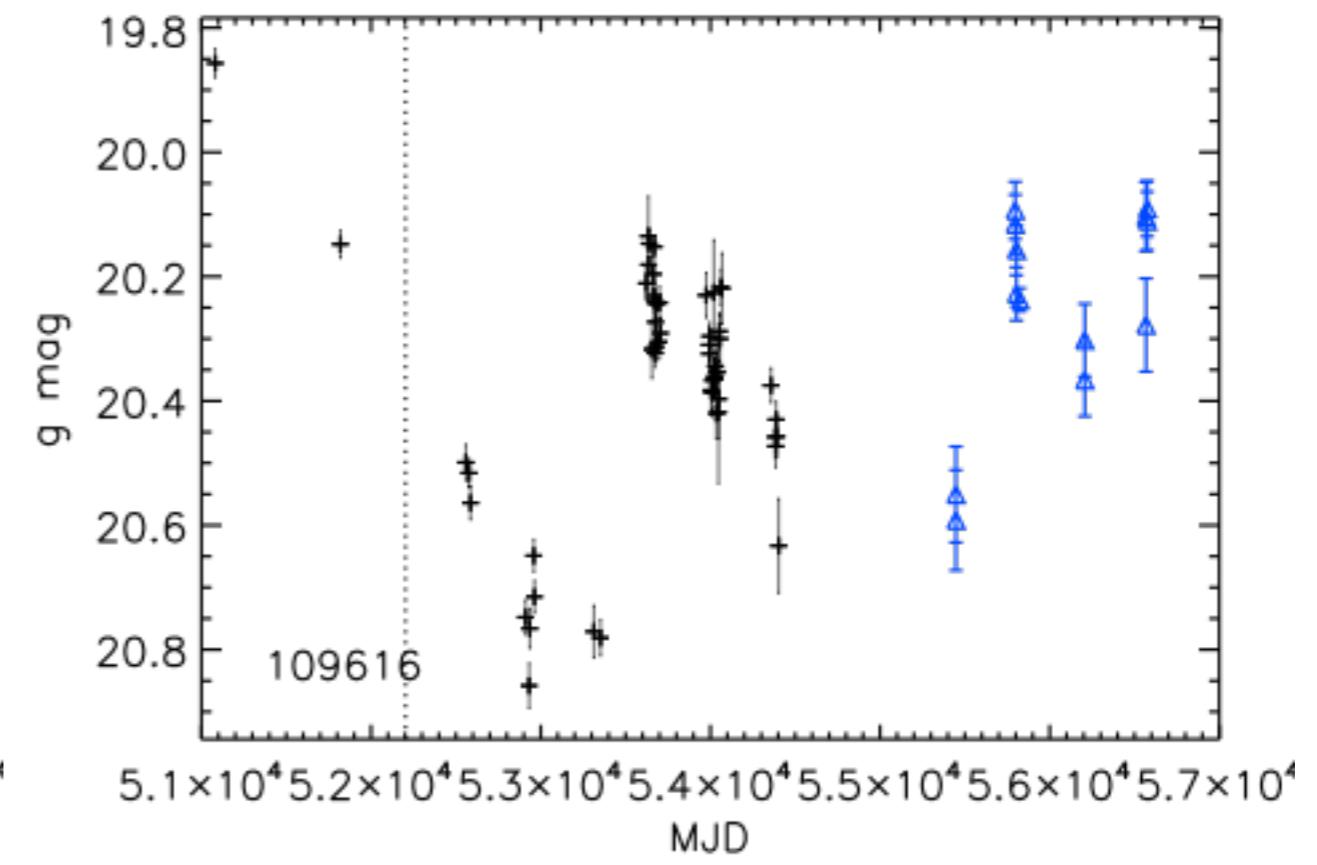
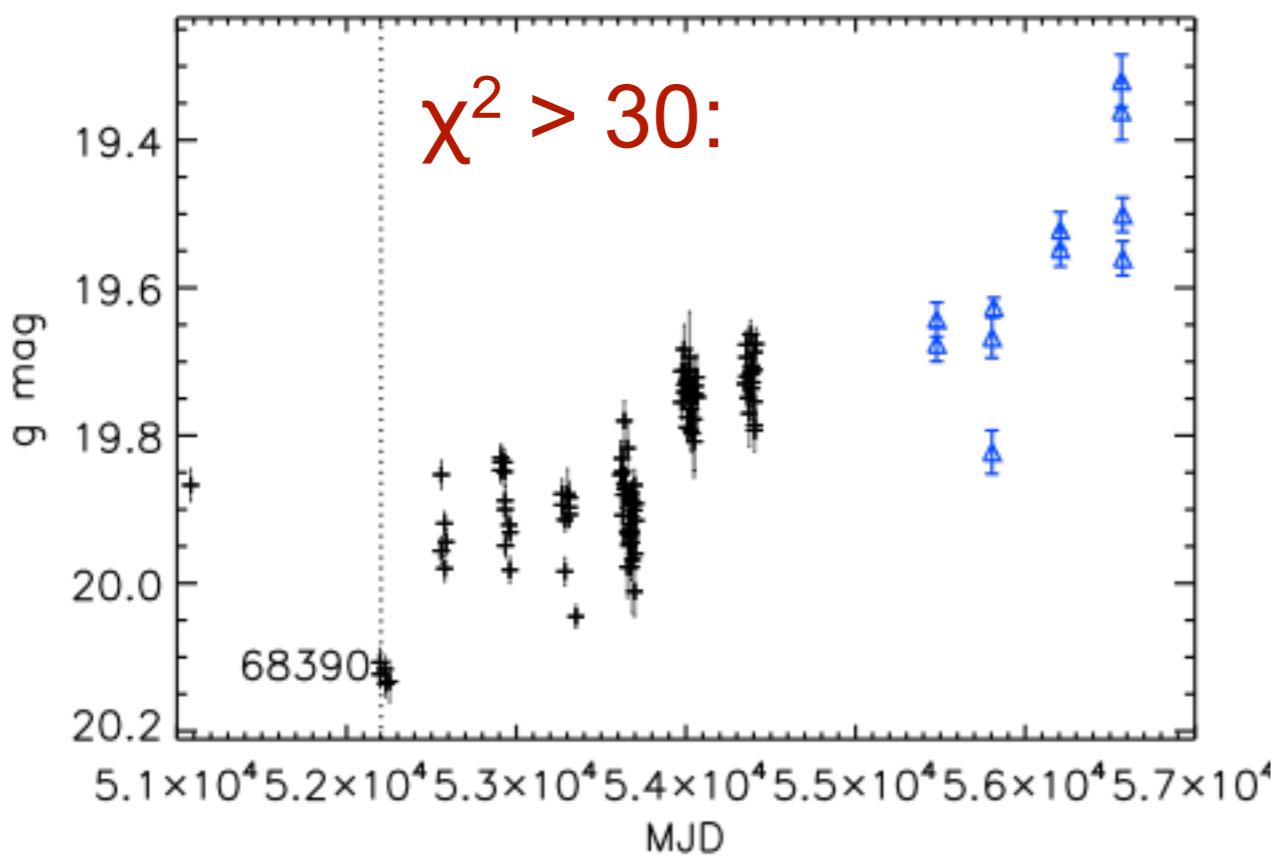
Population studies: How do QSOs typically vary on any given timescale?

- $\sim 10 \text{ deg}^2$ in 300 **ELG plates** (*Raichoor et al. 2017*)
- $\sim 1200 \text{ deg}^2$ total (SGC: 620 deg^2 , NGC: 600 deg^2)

Target selection:

- Start from DR7+DR12 QSO catalogs + new SDSS-IV QSOs
 - Includes extended quasars at lower redshifts
- Target all with SDSS **median $i < 19.1$**
- Fill remaining fibers with variability-selected QSOs ($\chi^2 > \sim 30 - 60$) with SDSS **median $i < 20.5$**

Typical rest-frame Δt : $\sim 1 - 6 \text{ yr}$ (samples few t_{dyn} , BLR)
For details, see *MacLeod et al. 2017*



REPEAT QUASAR SPECTROSCOPY (RQS)

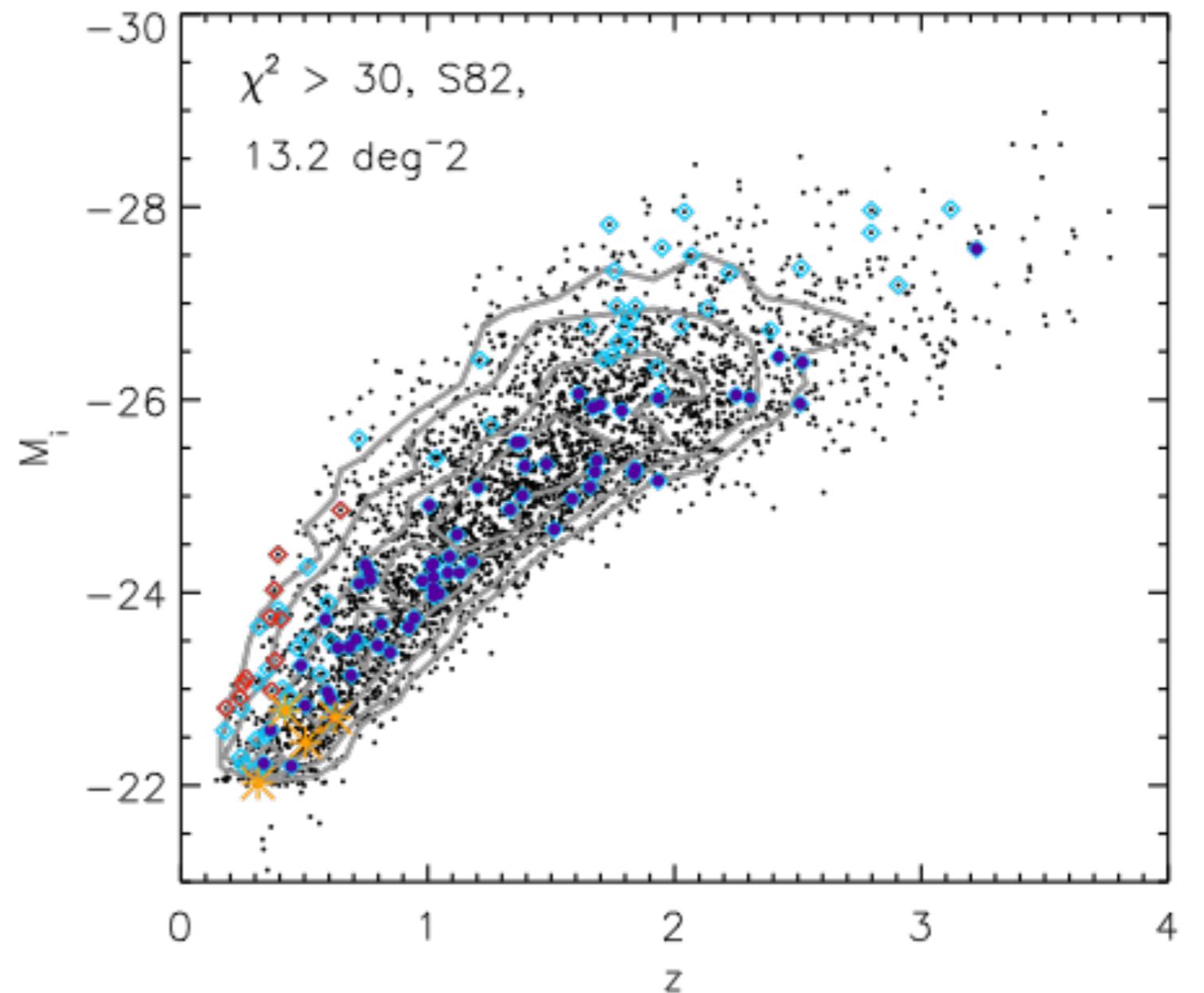
- RQS Targets

◆ FES HISN QSOs

● FES HYPQSO

◆ FES Other

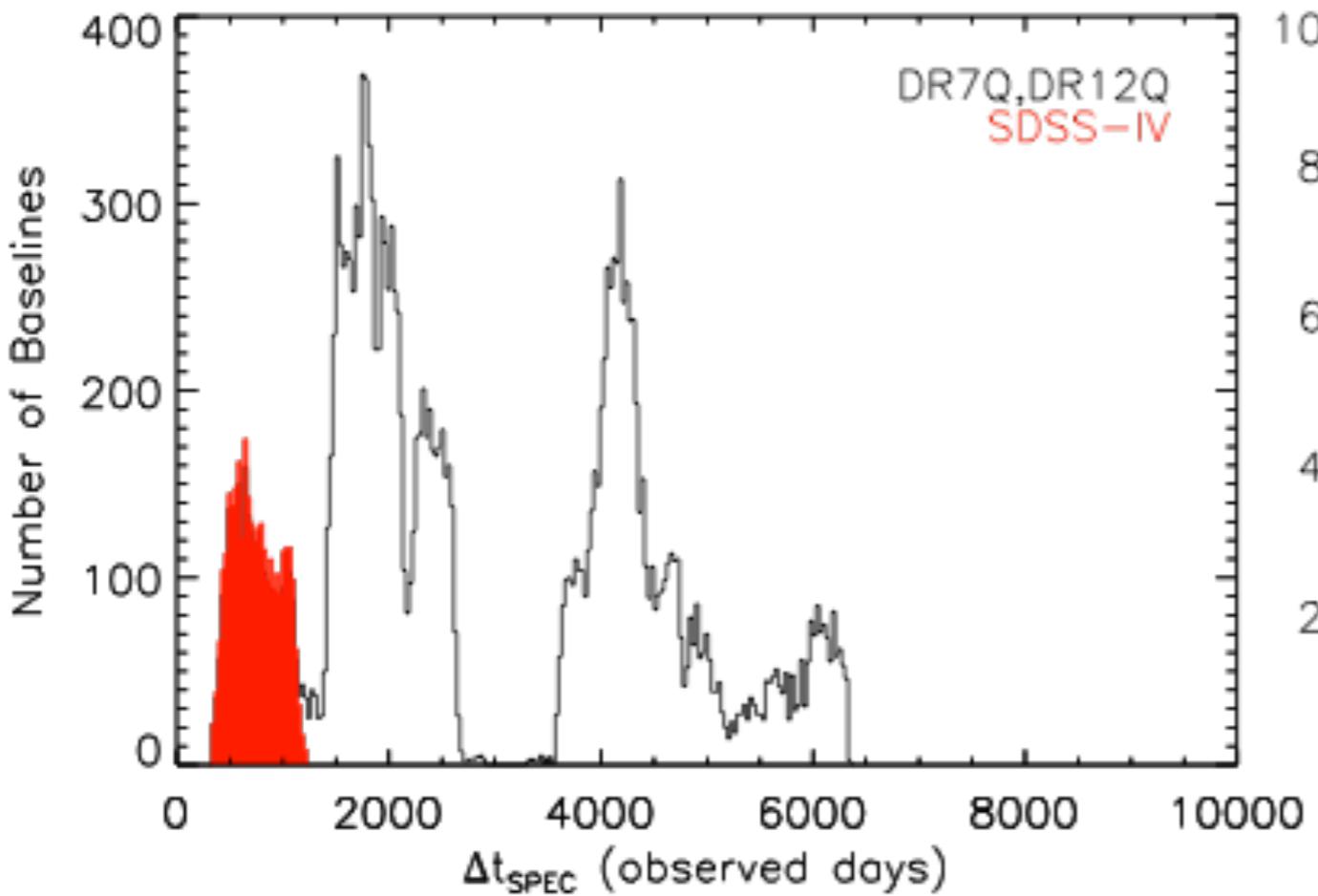
★ Known Changing-
Look QSOs



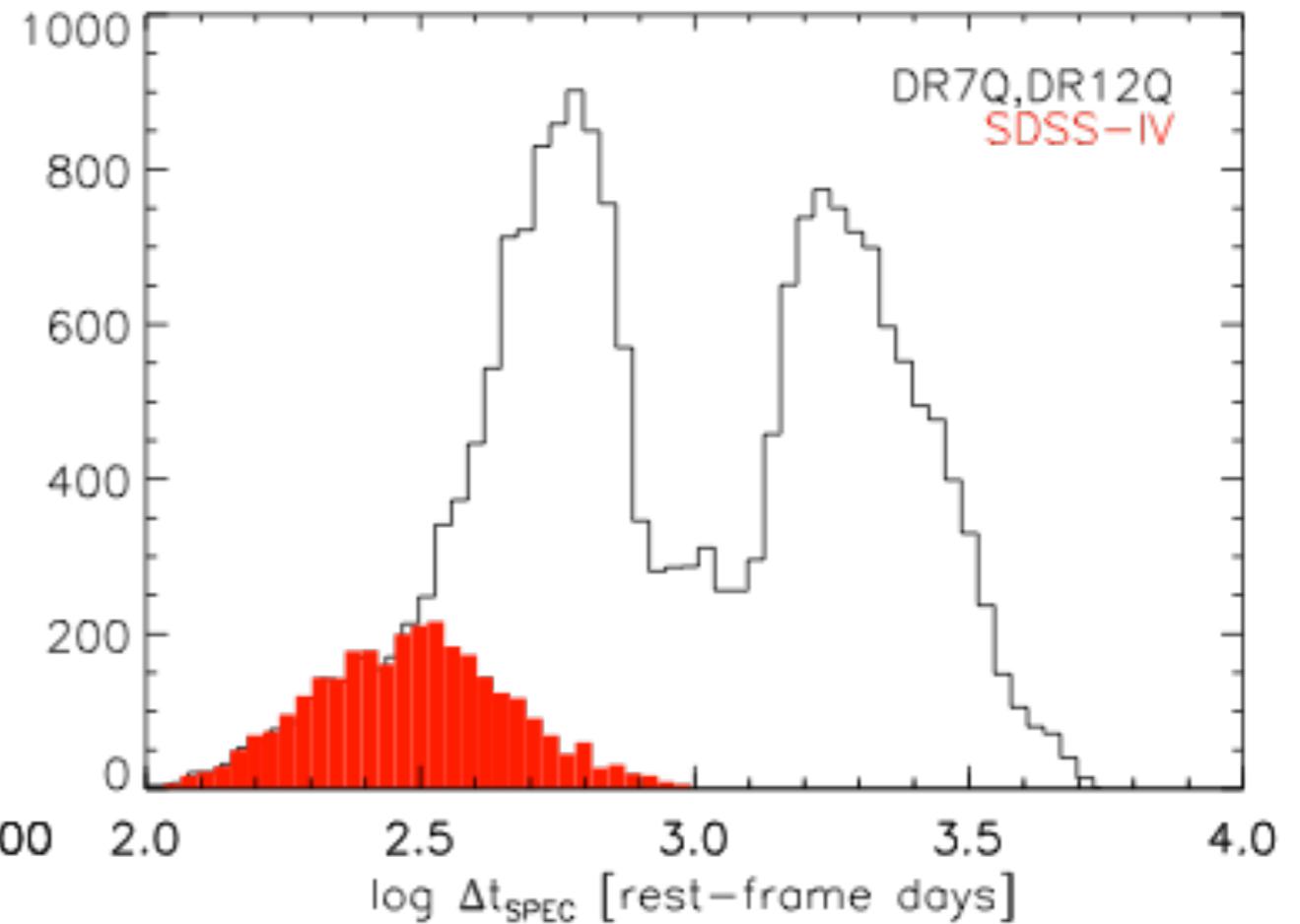
REPEAT QUASAR SPECTROSCOPY (RQS)

Will sample RF timescales from $\sim 1\text{--}6$ yr ($>$ few t_{dyn} , BLR)

Observed Frame:



Rest Frame:



MacLeod+2018