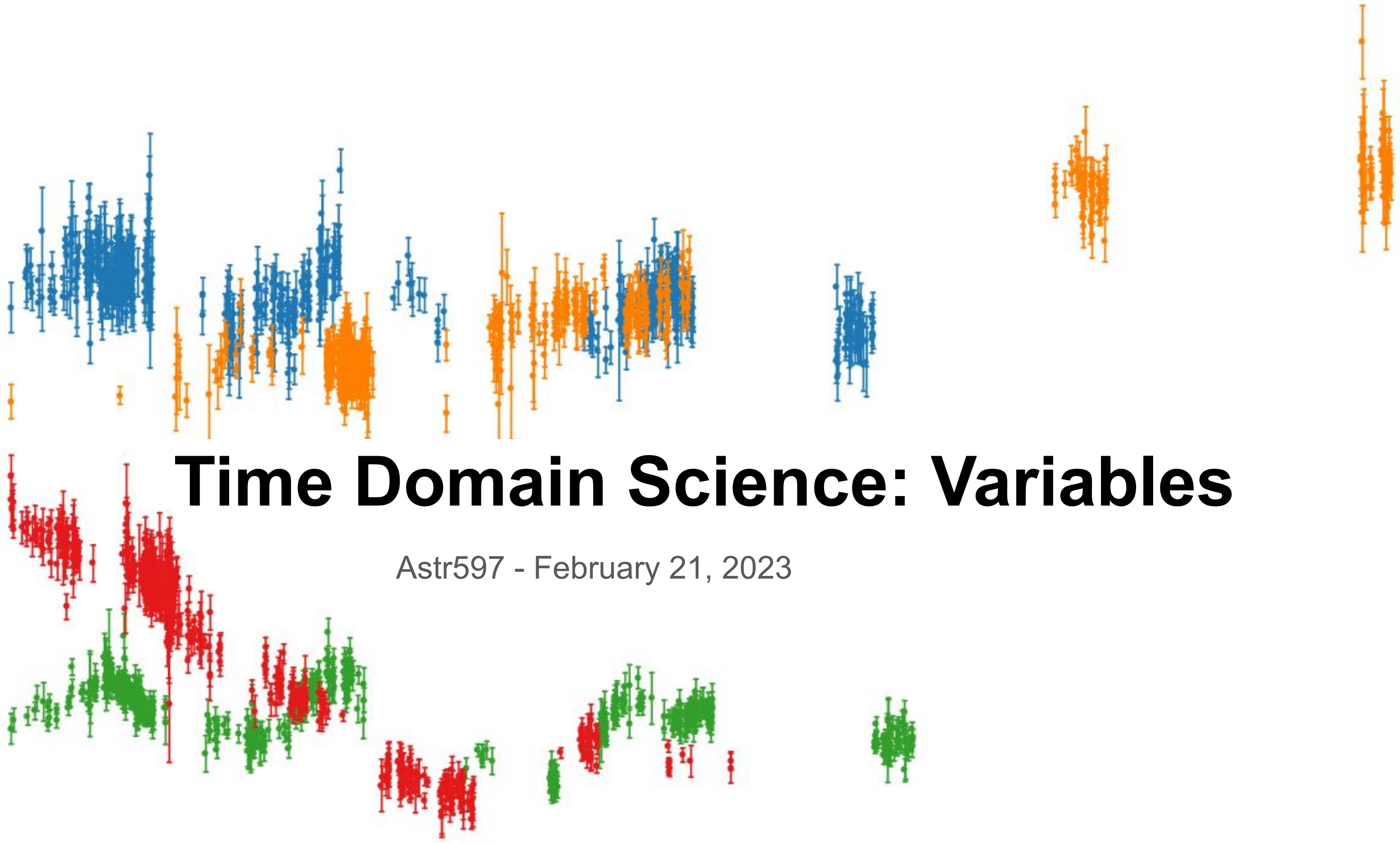


Time Domain Science: Variables

Astr597 - February 21, 2023

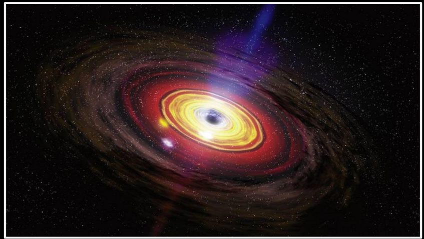
Astrophysical Transients on *Human Timescales*

Last week

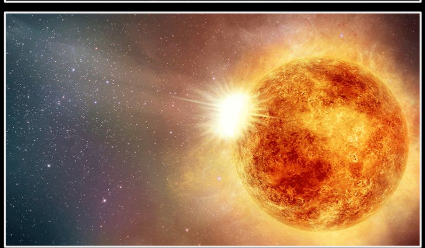
Astrophysical objects that change in brightness are transient *or* variable.
Transient behaviour lasts for a “short” time and does not repeat.

Today we’re focusing on *intrinsic* transients, and skipping *extrinsic* transients, changes in brightness with *external* causes, like microlensing events.

Some variables have *transient features*; we’re not covering these today either.



E.g., Active Galactic Nuclei (AGN)
- they turn on and off
- have “changing look” spectral features
- but are variable on human timescales



E.g., variable stars
- can flare or erupt

Betelgeuse gif credit: NASA, ESA, and E. Wheatley (STScI)

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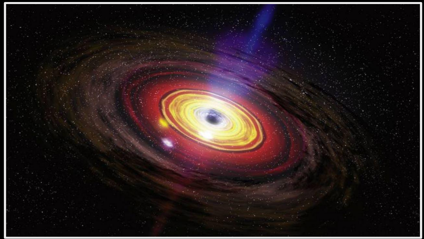

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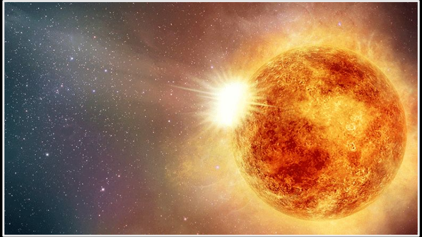

E.g., variable stars
- can flare or erupt (From Data to Software to Science, but no RR Lyrae and Lomb Scargle

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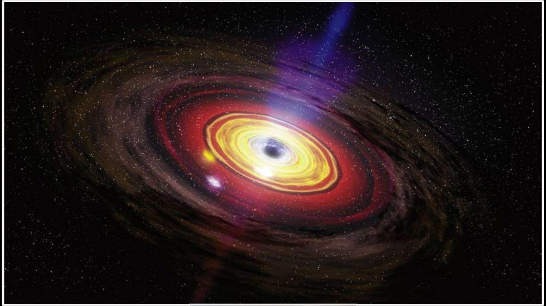

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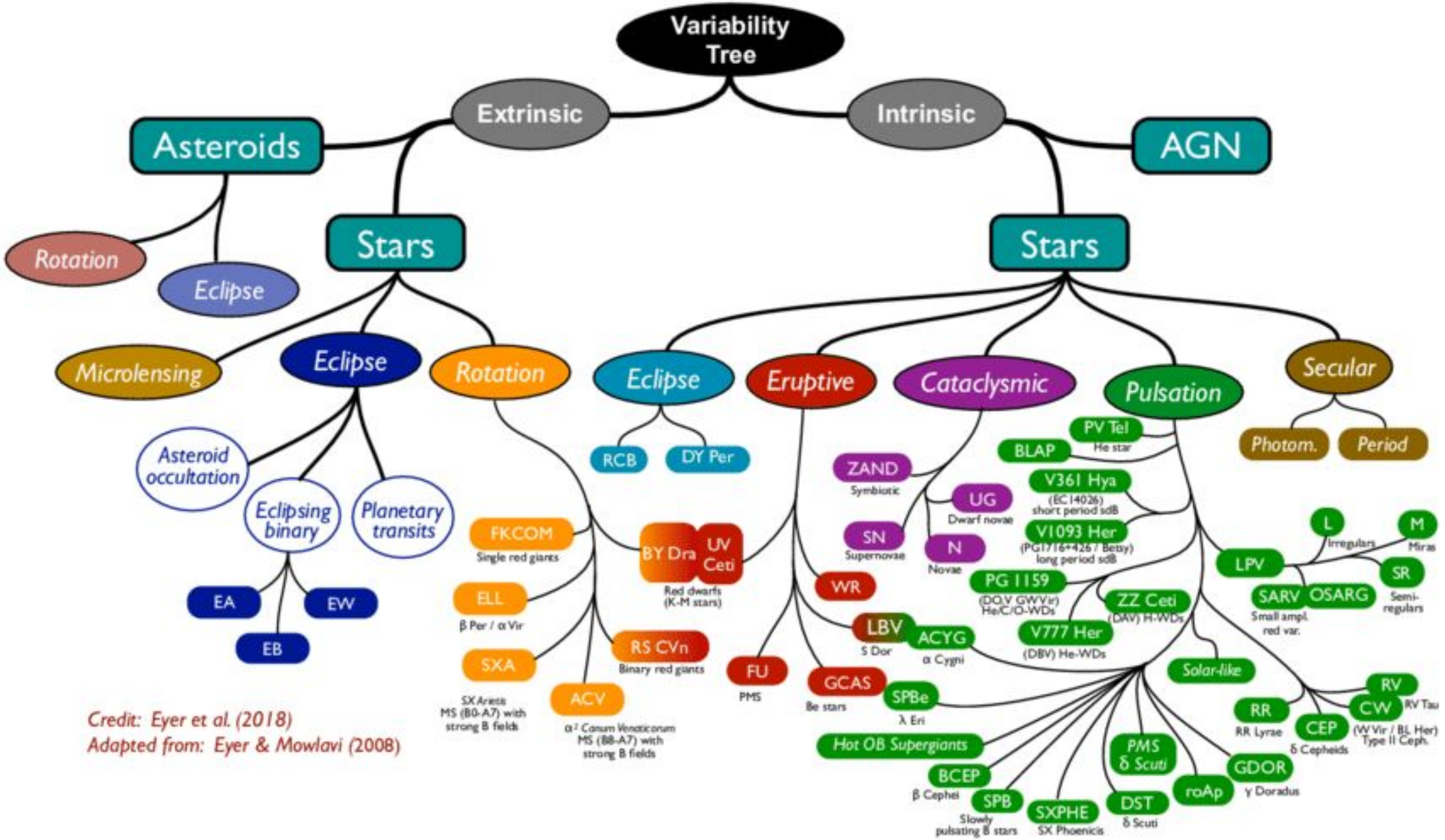


Credit: Eyer et al. (2018)
Adapted from: Eyer & Mowlavi (2008)

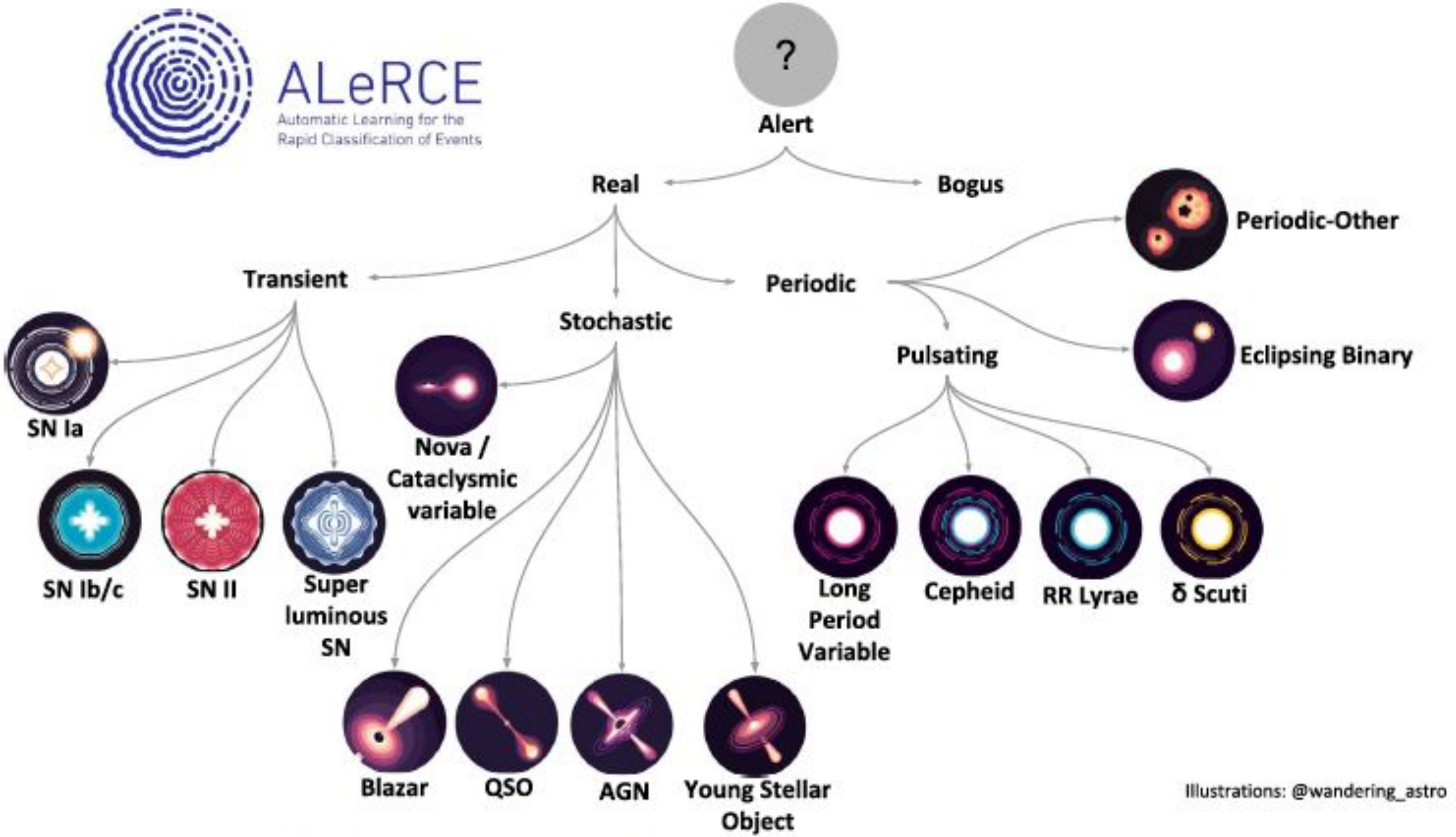
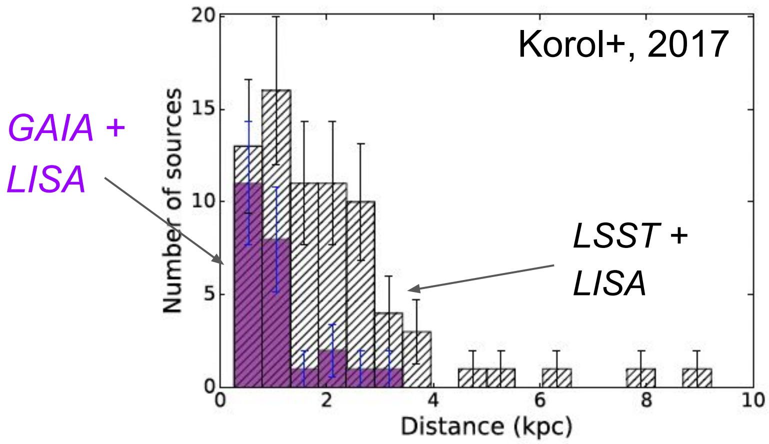
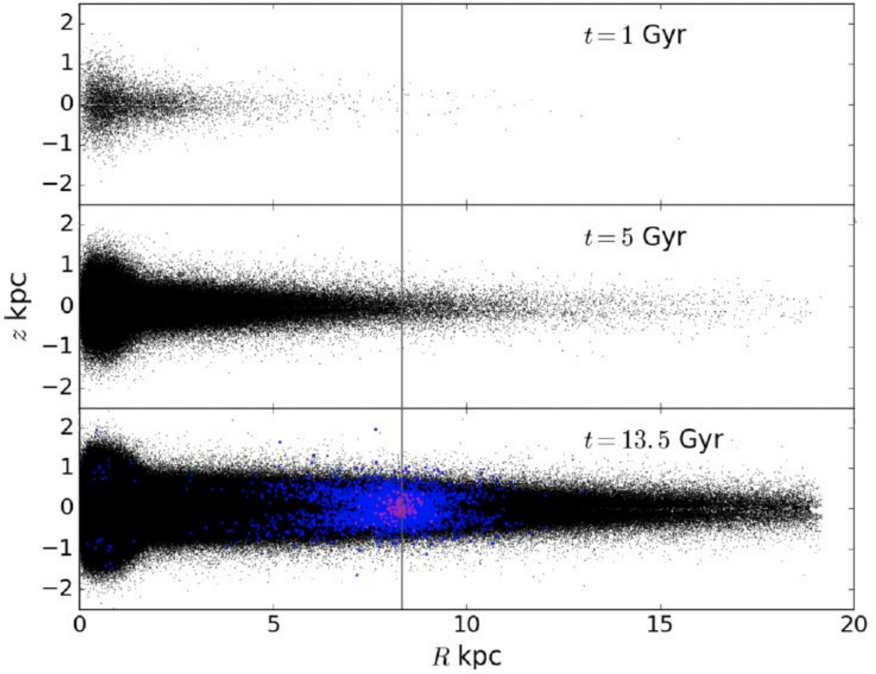


Figure 2. Taxonomy tree used in the current version of the ALeRCE light curve classifier.

Compact white dwarf binaries

- Double-degenerate compact white dwarf binaries will be dominant source of gravitational wave emission for the LISA mission.
- Around 100 systems are predicted to show measurable variations in both gravitational waves and electromagnetic radiation



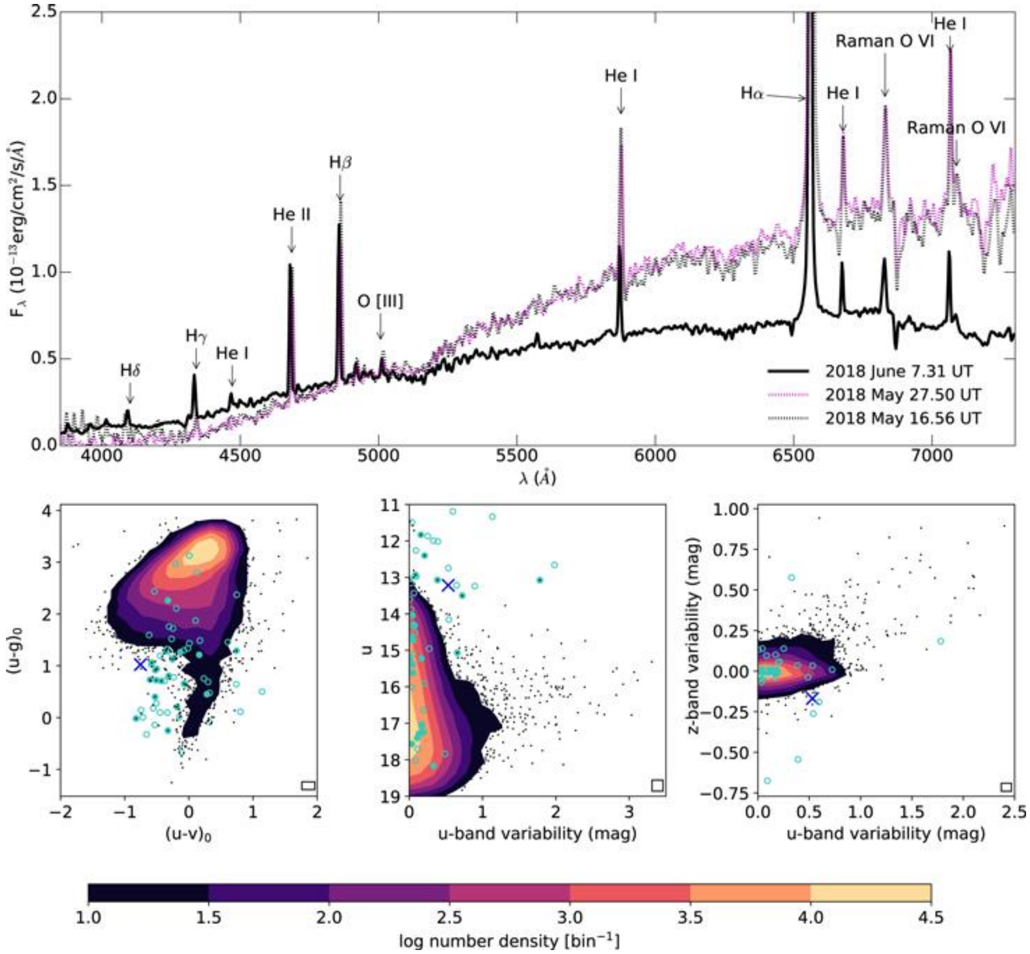


The distribution of WDB in the Galaxy. Magenta - accessible by GAIA, Blue, accessible by LSST

Symbiotic binaries

Symbiotics are accreting binaries where a white dwarf (or a neutron star) accretes from the wind of a red giant. So far, about 400 symbiotics are known in our Galaxy and the Local Group, but theory predicts about 10^5.

- Potential progenitors of Type Ia supernovae
- Shell-burning, luminous symbiotics can be detected by strong H-alpha lines
- Accretion powered (less luminous) display flickering

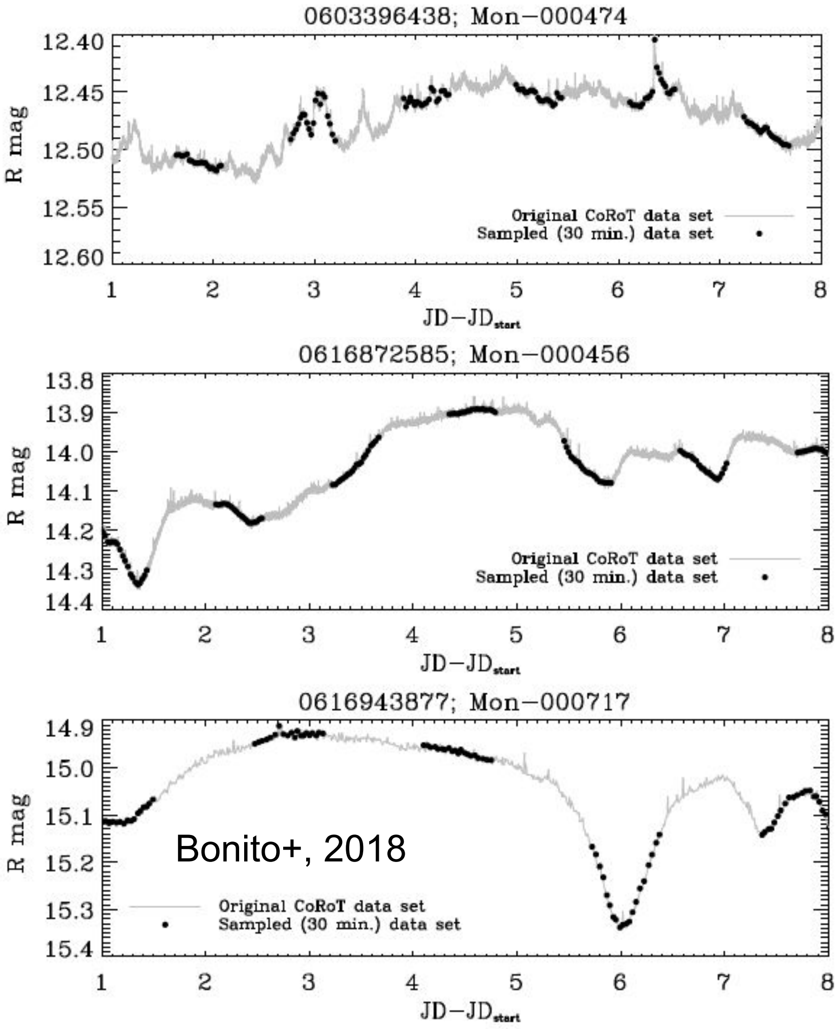


Young stellar objects

Wide range of processes causing photometric variability

- Mass accretion events from circumstellar disks
- Knots in stellar jets
- Stellar rotation and starspots
- Warps in envelopes and disks

The proposal is to observe star-forming regions, e.g., like Carina Nebula (11,000 member identified)



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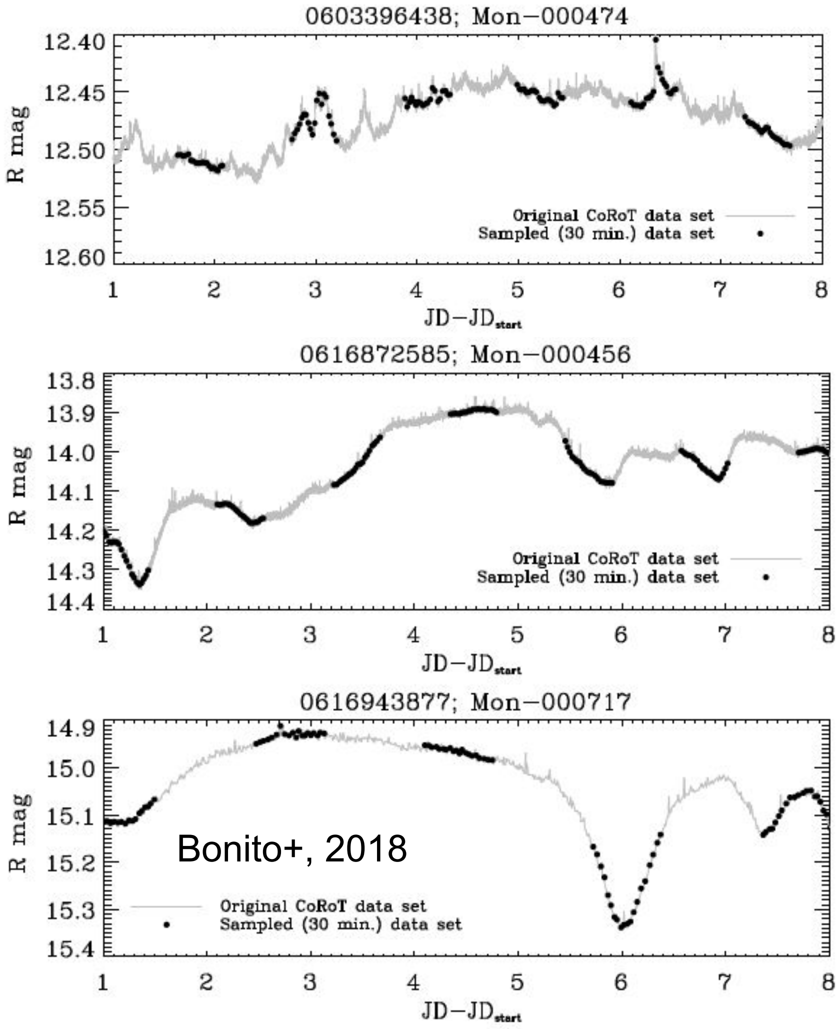
Survey Cadence Optimization Committee*: The YSO proposal (which includes the Carina Nebula and other star-forming regions): this proposal for time-series observations to characterize variable young stellar objects has not been shown to clearly take advantage of the unique characteristics of Rubin, and many of the scientific goals appear to be achievable with smaller field-of-view imagers, such as DECam. The number of YSOs per star-forming region as well as the number of different regions that need to be observed to accomplish the scientific goals are not justified clearly enough to demonstrate that the survey is time-sensitive to be undertaken in year 1 of Rubin operations.*



Bonito+, 2018

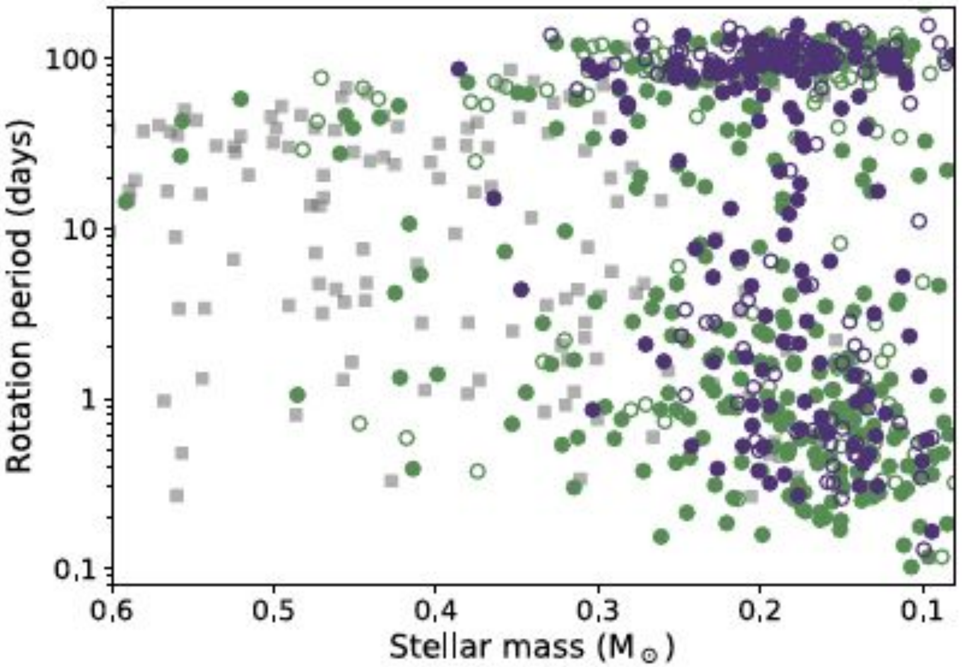
Long period M dwarf variability

Most common type of star, but difficult to observe due to their intrinsic low luminosities.

Most long-lived stars, making them important for understanding the oldest limits of gyrochronology.

Bimodal distribution of periods, with peaks at ~1 and ~100 days - but currently difficult to measure periods at >28 days.

``If the period distribution we have detected so far results from the age of the local thick disk and M dwarfs continue to slowly spindown at ages beyond this, we should see M dwarfs with >140 day rotation periods with LSST''



Microlensing

Street+, 2018

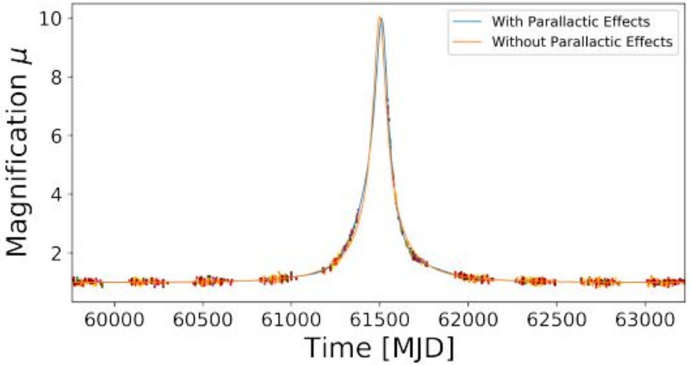
Foreground object (lens) passes directly between the observer and a luminous background source.

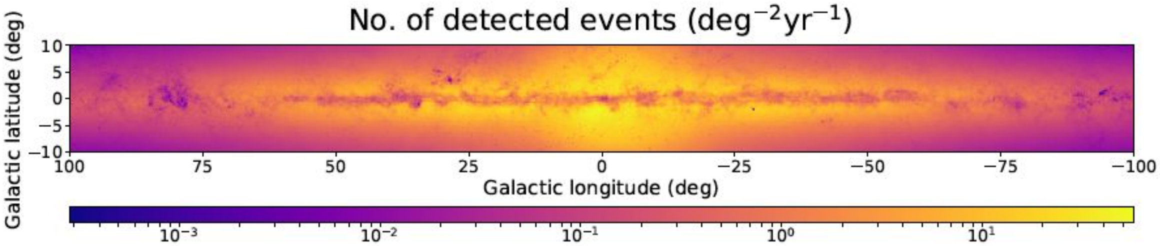
Timescale of the lensing is proportional to the lens mass (years for black holes)

By monitoring a few billion stars in the Galactic Plane we expect hundreds of black hole events.

Expand to other fields

High cadence survey of two fields in the SMC for microlensing: this proposal is not demonstrably time-sensitive to do in year 1 of Rubin operations.





Number of microlensing events detect by LSST per year per sq. deg assuming only baseline coverage

Why we study AGN

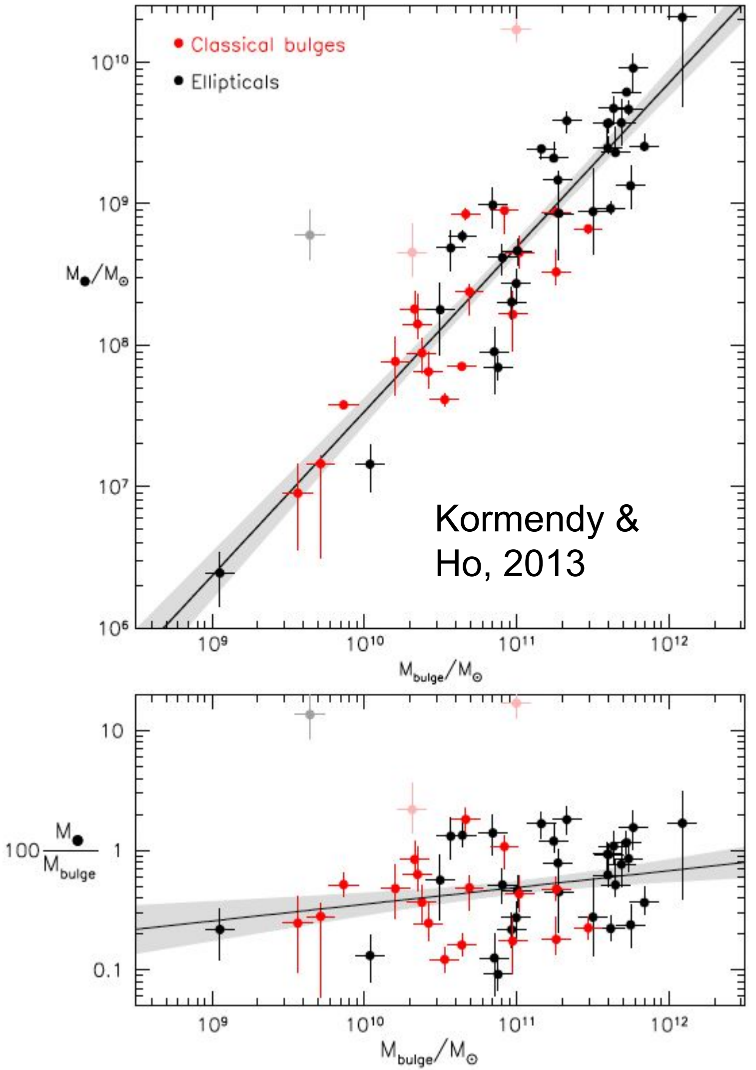
Closely connected with the evolution of galaxies and tied with output from black holes as AGN feedback regulates star formation

Mass is accreted onto a supermassive black hole. The accretion disk forms naturally. The viscosity in the disk acts as a mechanism by which angular momentum in transported outwards while mass moves towards the centre.

LSST will enable

- Statistical study of AGN population
- Comprehensive study of AGN variability

Let's start by how we select AGNs!



Kormendy & Ho, 2013

AGN Selection - Color Selection

At low redshifts AGNs are blue (especially in u-g, g-r) and well separated from the stars in ugrizy color-color space. This has been a standard method of AGN selection in wide-field optical surveys (e.g.,SDSS).

Sample contamination at z~3 as AGN overlap with stellar locust

At higher redshift, no u- and g- band flux makes things more complicated

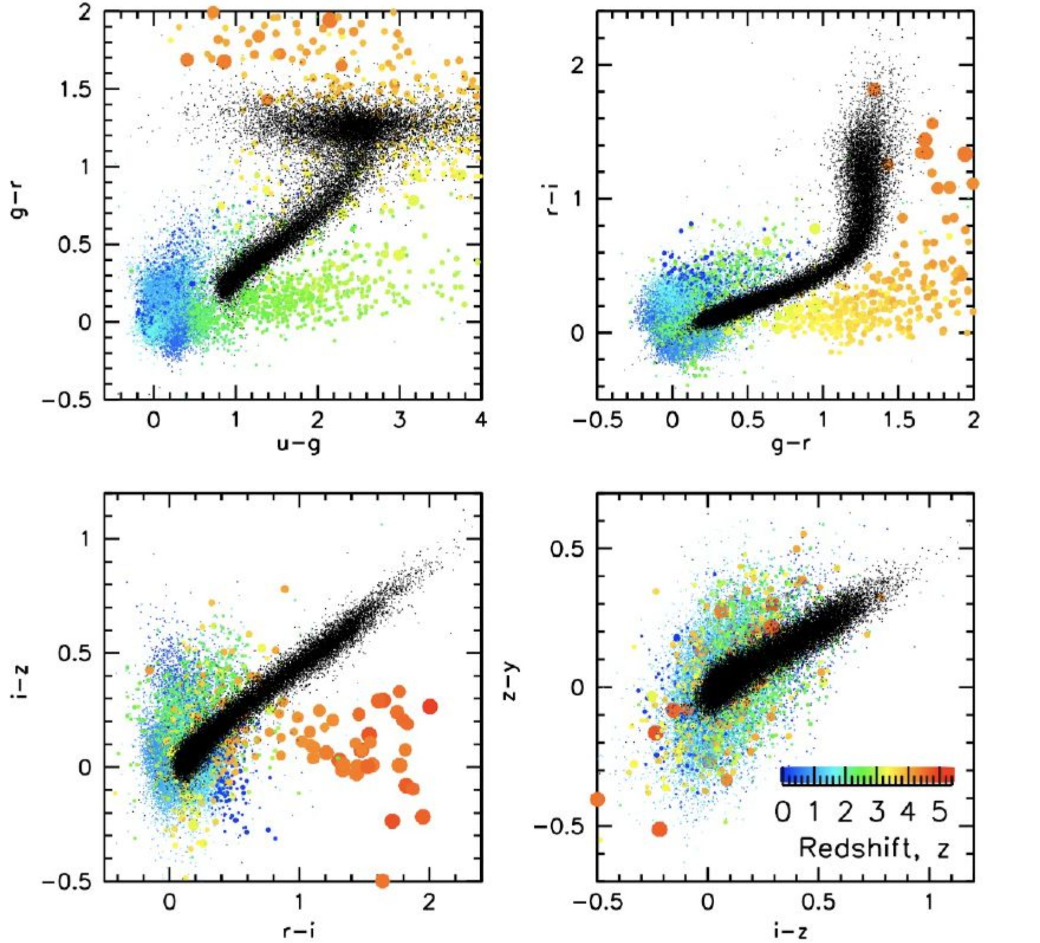


Figure 10.1: Color-color plots of known quasars from SDSS (colored dots) and stars (black dots) in the LSST photometric system. The quasars are color coded by redshift according to the color key, and for clarity, the dot size is inversely proportional to the expected surface density as a function of redshift. Since there is no y filter in the

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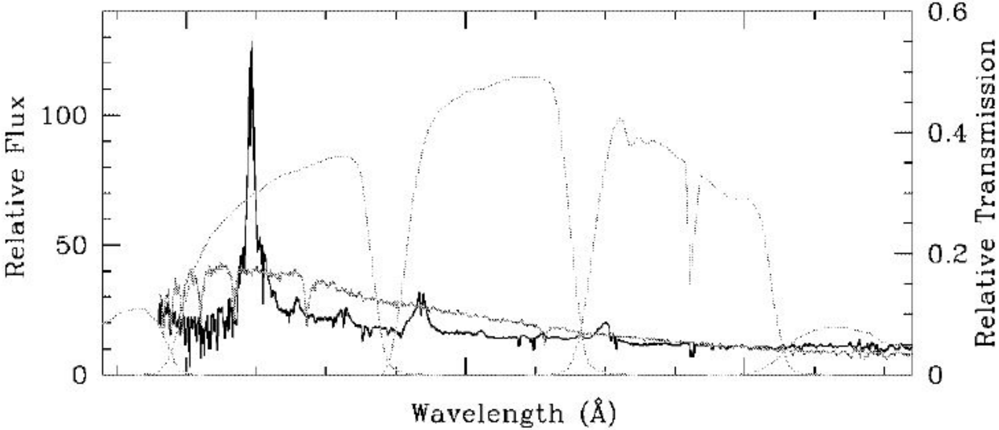


FIG. 9.—Spectra of a sample mid-z quasar ($z = 2.67$) and a star with similar colors superimposed on the SDSS filter curves. Note that the $g^* - r^*$ color is nearly the same for both objects. See Fig. 1 in Fan (1999), who used simulated spectra to demonstrate that this is true for $u^* - g^*$ as well.

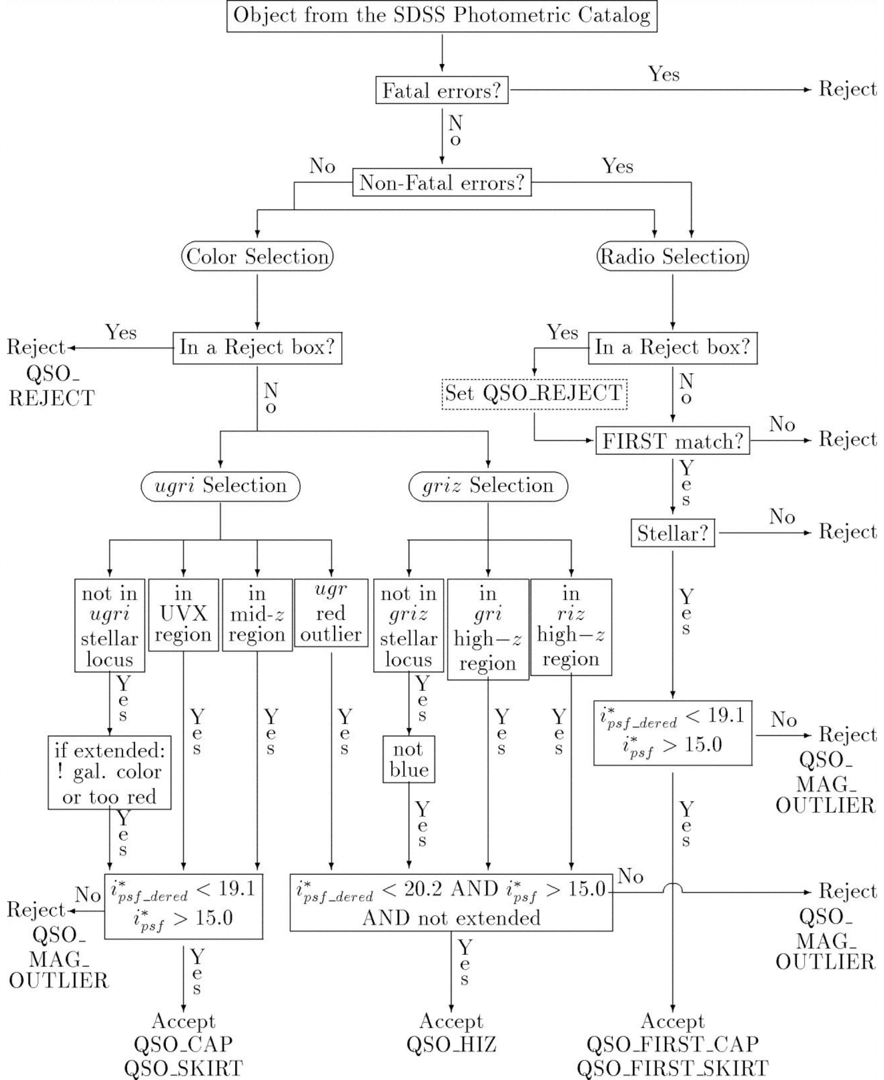
Richards+, 2002

AGN Selection - Color Selection

Quoting Gordon Richards:

- Perfectly fine when coupled with spectroscopy to find specific needles in haystack.
- Completely inadequate for LSST

Richards+, 2002



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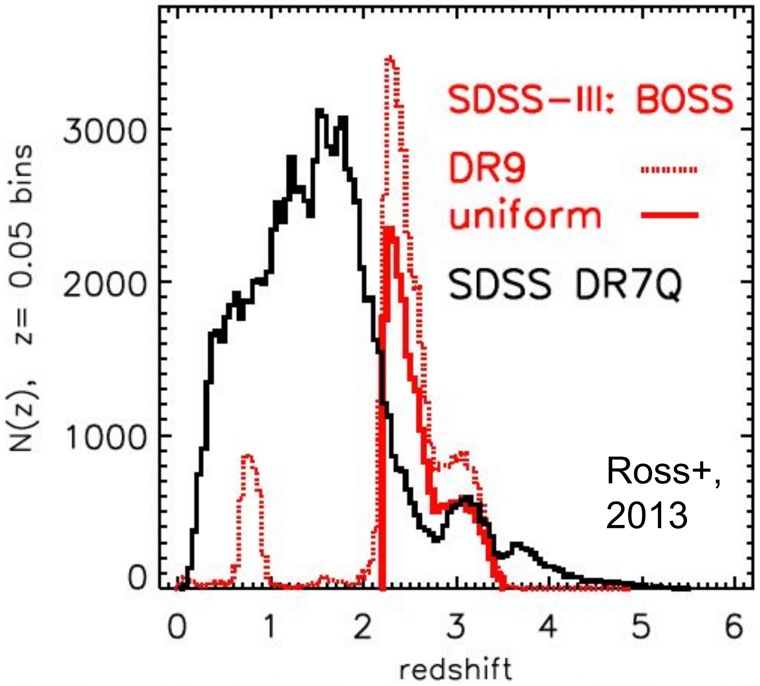


Ross+, 2013

Figure 2. Quasar $N(z)$ redshift distributions. The dotted red histogram shows the redshift distribution for the full SDSS-III: BOSS DR9 quasar dataset, while the solid red line shows those objects uniformly selected by the "XDQSO" method across $2.2 < z < 3.5$. The black histogram is the final distribution from the DR7Q catalog of Schneider et al. (2010).

AGN Selection - Lack of proper motion

3 sigma upper limit on proper motion in LSST - 3 mas at r=24, 0.6 mas at r=21 for 10 year survey.

With this it will be possible to eliminate the relatively nearby L and T dwarfs and to remove many of the white dwarfs and subdwarfs (which contaminate AGNs at z~3)

Table 10.1: Elimination of White Dwarf Contaminants

Quasar z	WD M_V for quasars $(V-I)$	WD T_{eff}	Distance (pc) at $r=24$	3σ limit v_{tan} km s^{-1}	Fraction excluded
3.2	13.7	6500	1260	17.6	77%
3.6	15.7	4500	660	9.4	88%
4.0	16.5	3500	500	7.1	92%

AGN Selection - Variability

The amplitude of AGN variability depends on

- Variability timescale
- Wavelength
- Luminosity

How to estimate the fractions of AGNs that may be detected as significantly variable in the LSST

- E.g., Calculate the magnitude difference at which only 1% of the non-variable stars will be flagged as variable candidates due to measurement uncertainty.

AGN Selection - Variability

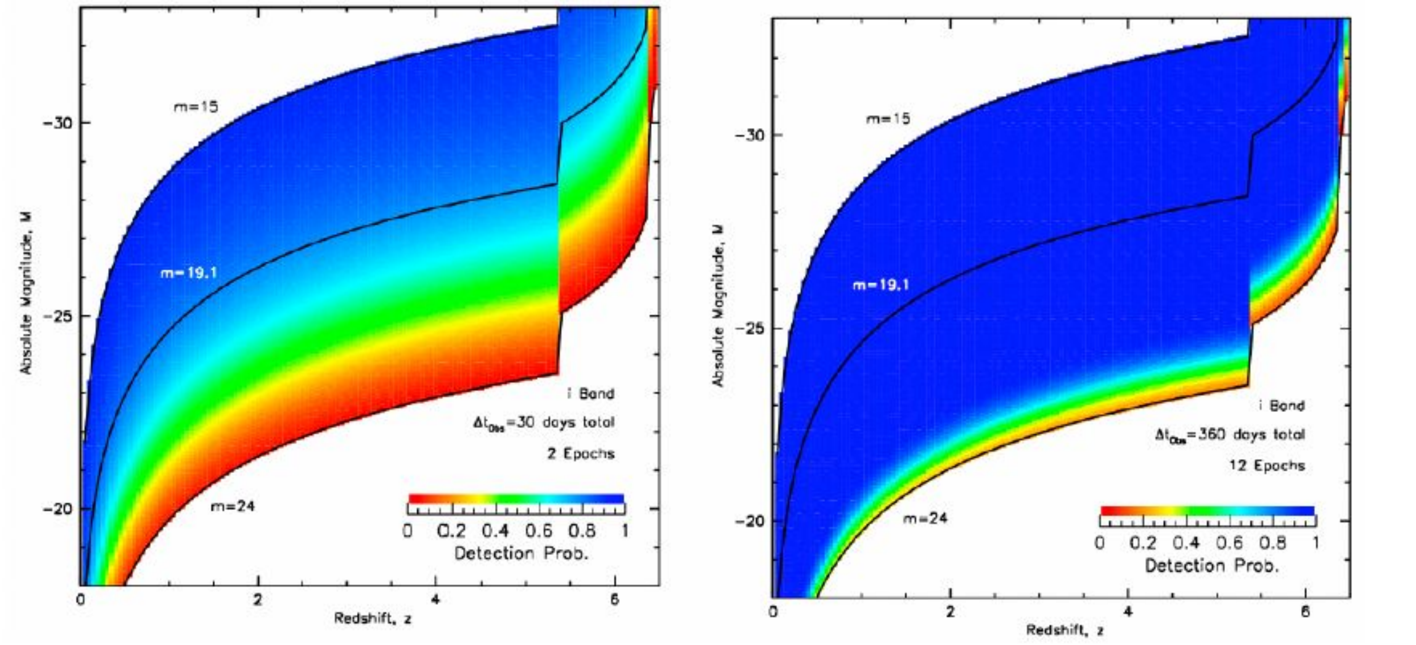
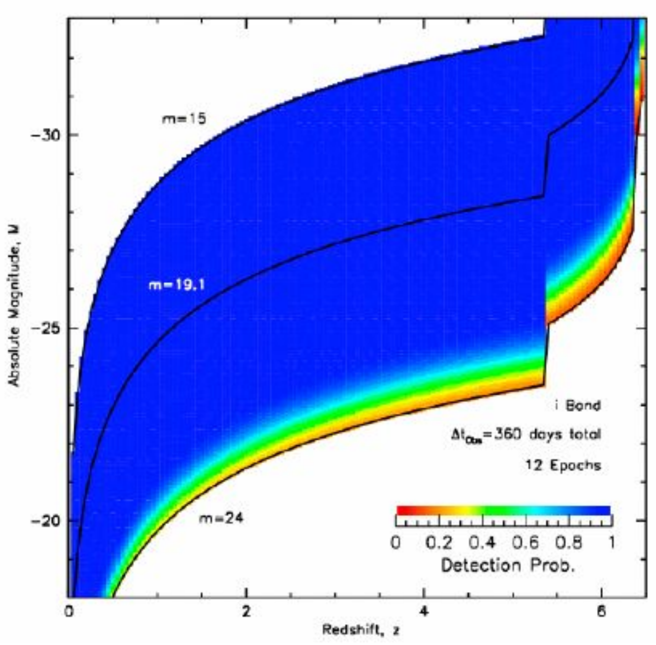


Figure 10.2: The probability of detecting an AGN as variable as a function of redshift and absolute magnitude. *Left:* two epochs separated by 30 days. *Right:* 12 epochs spanning a total of 360 days. Nearly all of the AGN between the limiting apparent magnitudes would be detected as variable after one year.

AGN Selection - Variability

Variability is particularly useful for selection because

- Sensitive to low-luminosity AGN which may have large galaxy contribution
  - But large galaxy contribution dilutes signal
- Ortogonal to color selection, especially useful at mid-redshifts (z~3)
  - But still, works even better when combined



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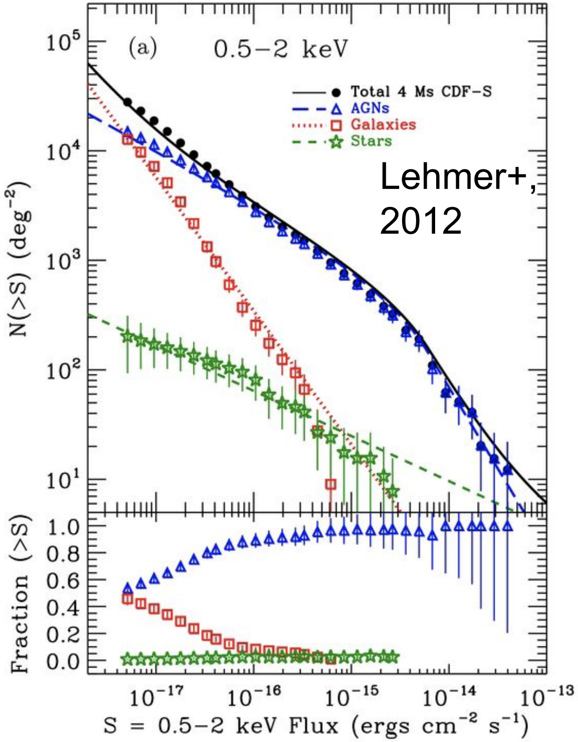
Alerce: *We encourage researchers interested in classifying stochastic and transient sources in particular to use the novel (or modified) features presented in this work, like the IAR_phi parameter, the MHPS features, the SPM features, and the non-detection features.*

- IAR_phi: Level of autocorrelation using a discrete-time representation of a damped random-walk model
- SPM: Supernova parametric model features (seven in total)
- MHPS: Mexican hat power spectrum

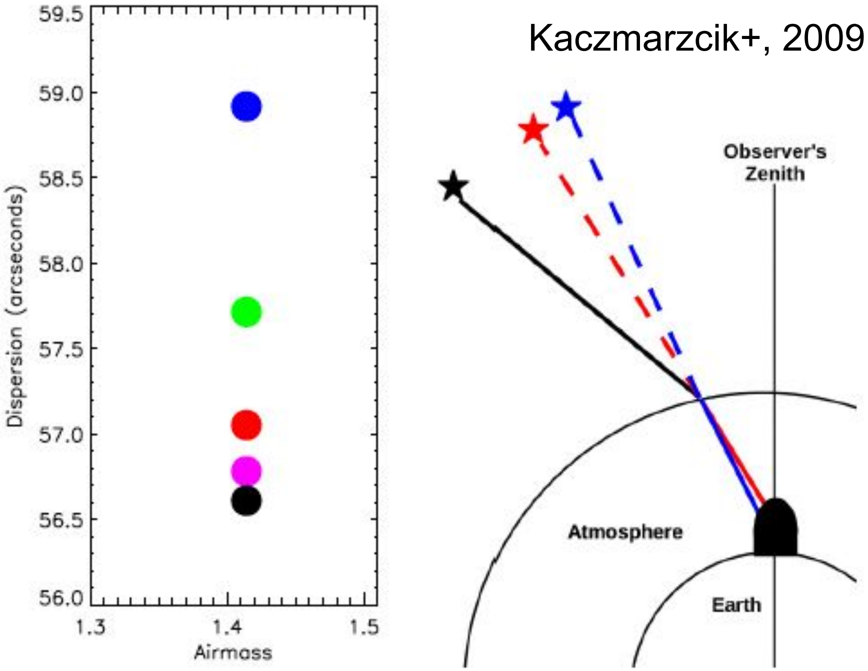
Multiwavelength + Differential Chromatic Refraction



Lehmer+, 2012

E.g., Bright x-ray sources are AGN

Kaczmarzcik+, 2009



DCR - in short: use the atmosphere as a prism; only works in u- and g-

AGN; Photometric Redshifts

Redshift estimates for the vast majority of LSST AGN will have to rely on photometric redshift.
AGNs (unobscured) have relatively simple spectrum

- Continuum longward of Lyman-alpha is a power law + emission lines
- Power law shape results in a degeneracy of the color-redshift space
- Emission lines with large equivalent widths (broad Balmer lines) can help break the degeneracy
- Stronger spectral feature (Ly-alpha, Lyman break, Lyman forest) can break degeneracy above z~2.5

SDSS was able to determine redshift for quasars to 0.3 accuracy for 80% of SDSS quasars (up to i~19).
LSST is expected to do as least that well up to i~24.

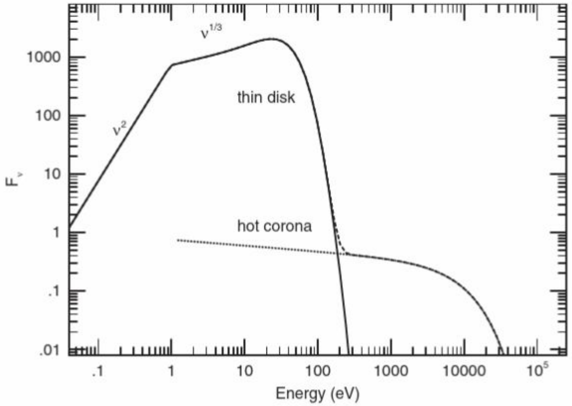


Figure 4.3. A schematic of a combined disk–corona spectrum. The maximum temperature of the geometrically thin, optically thick accretion disk is $T_{max} = 10^5$ K, and its outer boundary temperature is determined by the conditions at the self-gravity radius. The disk is surrounded by an optically thin corona with $T_{cor} = 10^8$ K.

Netzer, 2007

AGN - Expected Number

N~10 (1960s)
N~100 (1980s)
N~1000 (1990s)
N = 25000 (2dF QSO Redshift Survey Catalog - 2004)
N = 100000+ (SDSS, 2011)
N = 1 million (today)
N = 20 to 80 million

- ~300 million detected
  200-1000 AGNS at z~6.5-7.5

Browse this table...

MILLIQUAS - Million Quasars Catalog, Version 7.9 (5 February 2023)

HEASARC Archive

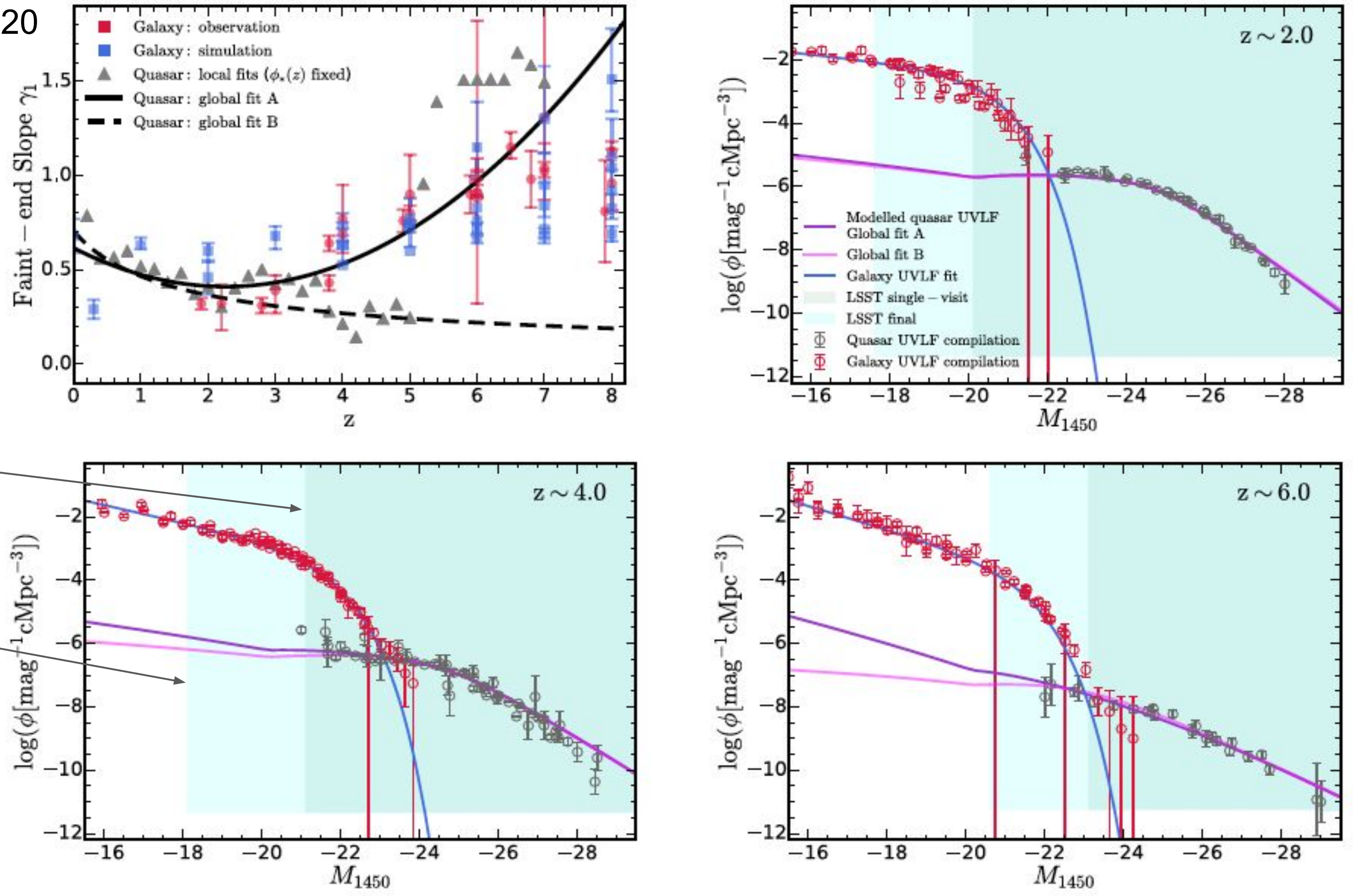
Overview

This table contains the Million Quasars (MILLIQUAS) Catalog, Version 7.9 (5 February 2023). It is a compendium of 844,587 type-I QSOs and AGN, largely complete from the literature to 5 February 2023. 568,956 QSO candidates are also included, which are those calculated (via radio/X-ray association including double radio lobes) to be 50%-100% likely to be quasars. Blazars and type-II objects are also included, bringing the total count to 1,461,834. About 73% of all objects show Gaia-EDR3 or Pan-STARRS astrometry.

(Richards): LSST alone will provide significant numbers of AGNs to z ~ 7.5 (to L_Opt ~ 10^44 erg/s)

- *LSST+Euclid: ~1360 at z>7 and 24 at z>10*
- *LSST+WFIRST: ~1490 at z>7 and ~29 at z>10*

Shen+ 2020



LSST single visit depth

LSST final depth

AGN - variability

Variability provides information about immediate surrounding of actively accreting super massive black hole, namely:

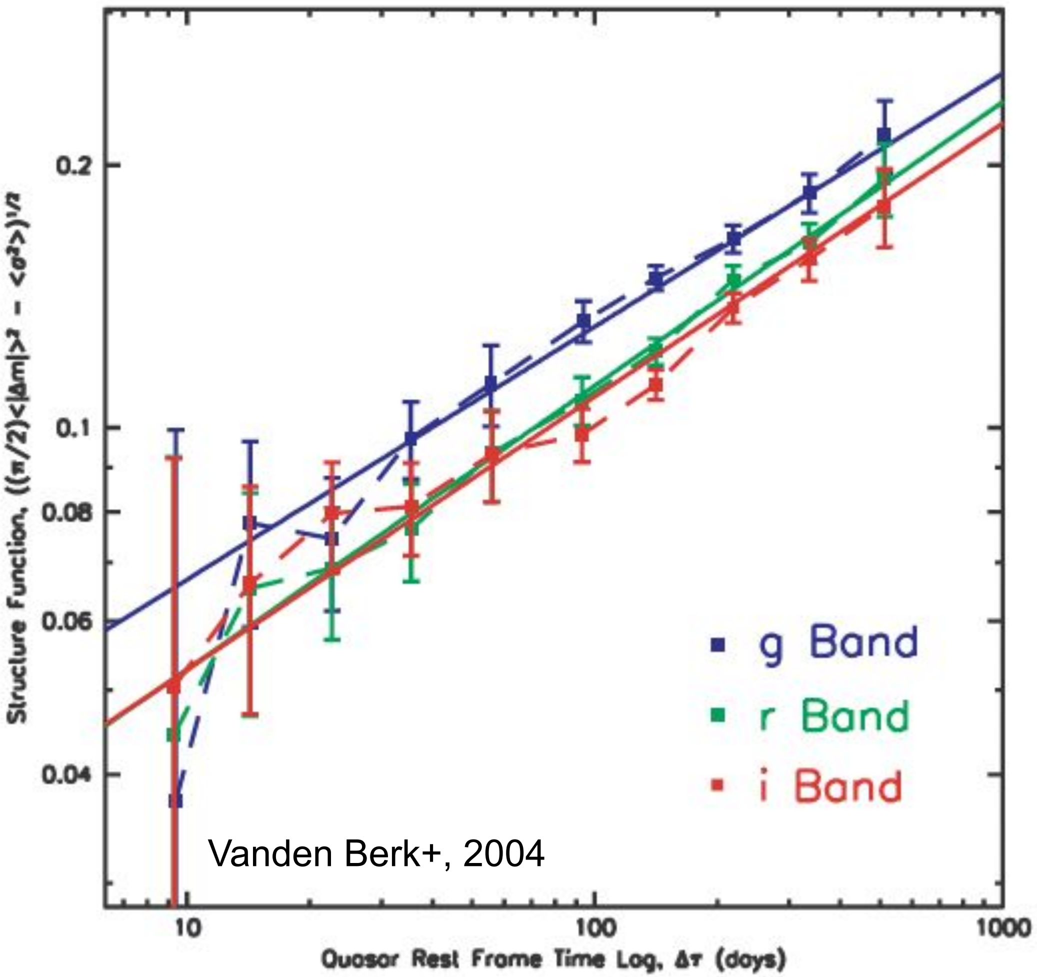
- Accretion disk
- Broad emission line region

What are possible explanations for the variability

- Accretion disk instabilites
- Changes in accretion rate
- Influence of hot corona
- Relativistic jet changes
- Line-of-sight absorption changes

AGN - variability (SF)

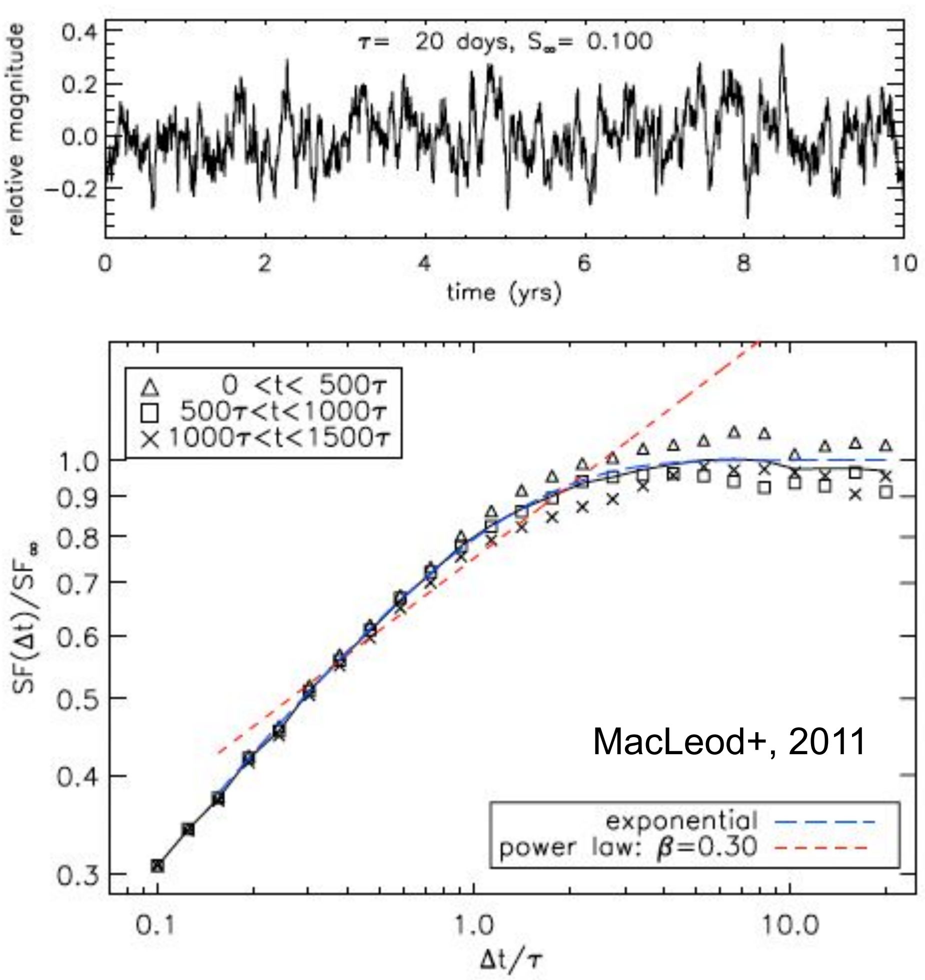
- 25000 AGN from SDSS in 2004
- Using two measurements for each AGN
- Compute structure function - effectively variance of measurements separated by some time
- Anticorrelation of amplitude with wavelength
- Anticorrelation of amplitude with luminosity
- Correlation with redshift?



Vanden Berk+, 2004

AGN - variability (SF)

Damped random walk explains *a lot* of AGN variability. The process has two parameters; basically amplitude and decorrelation time.



MacLeod+, 2011

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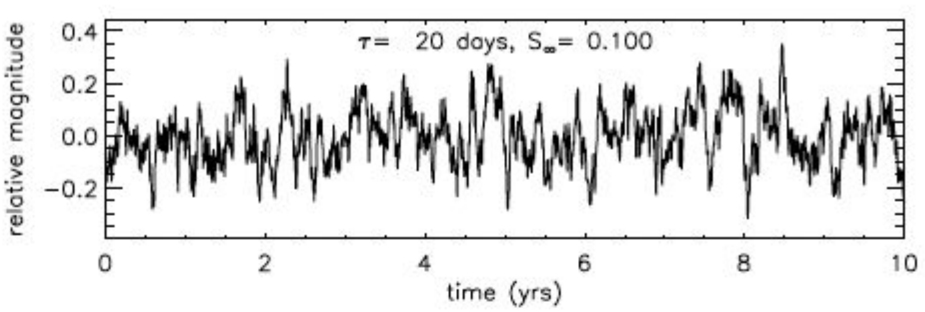
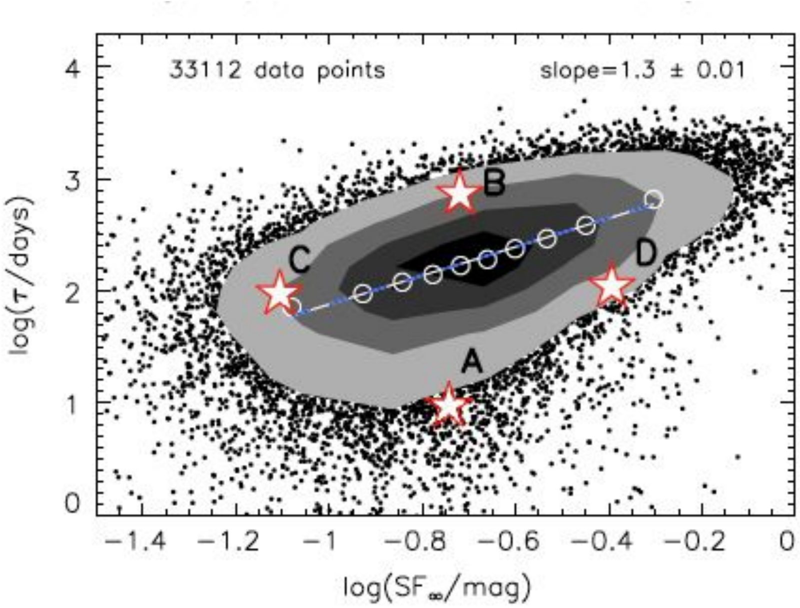
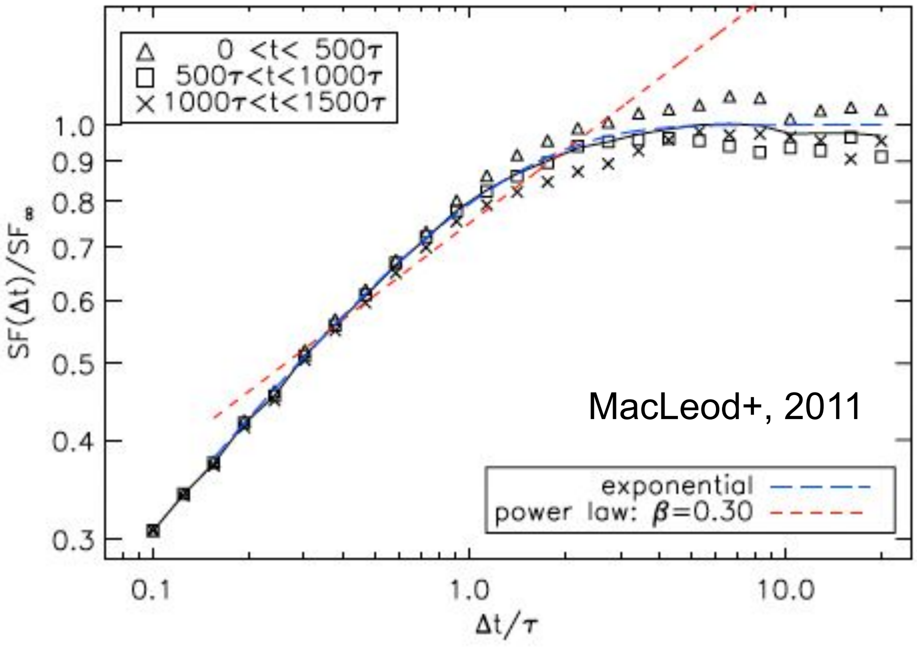




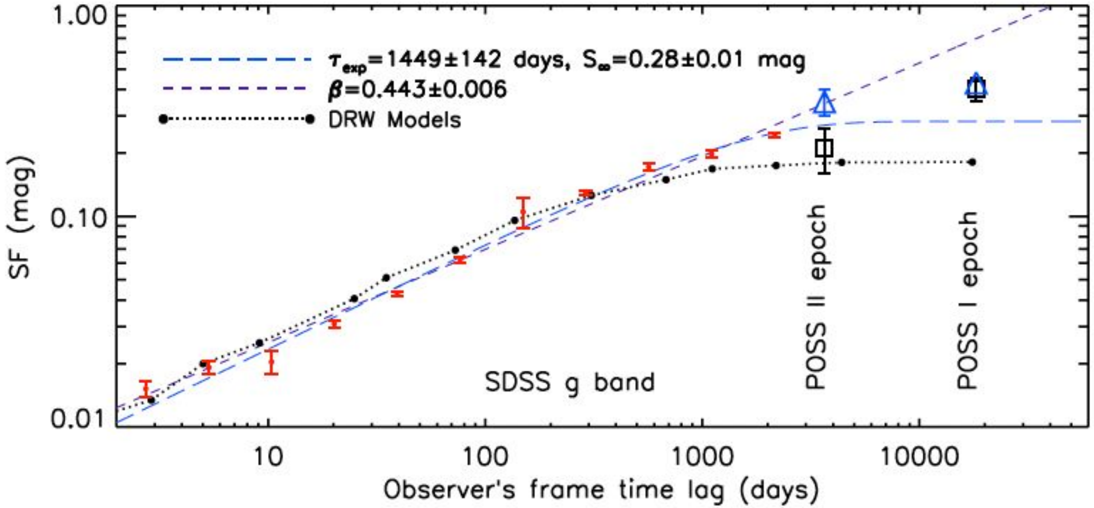


AGN - variability (SF)

MacLeod+, 2012

To be sensitive to decorrelation time-scale we have to observe AGN for (much) longer time than decorrelation scale.

So it is necessary to patch multiple surveys to get long enough baselines to accurately measure this behavior.



AGN - variability (SF)

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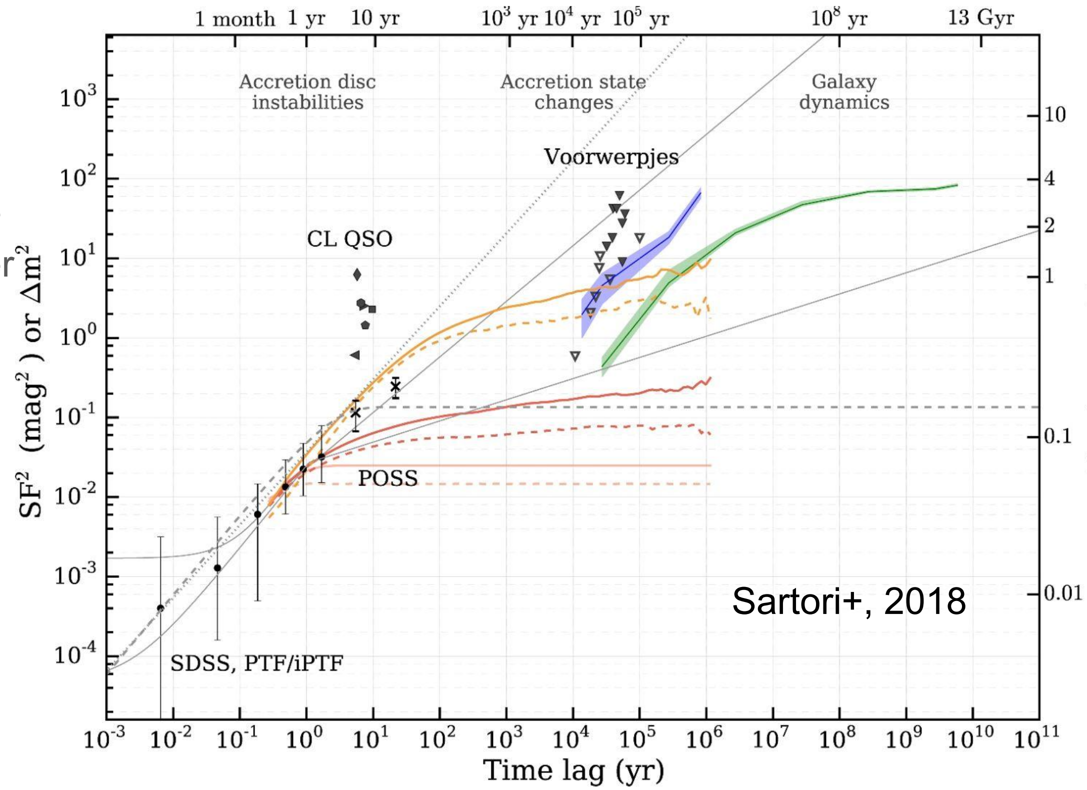
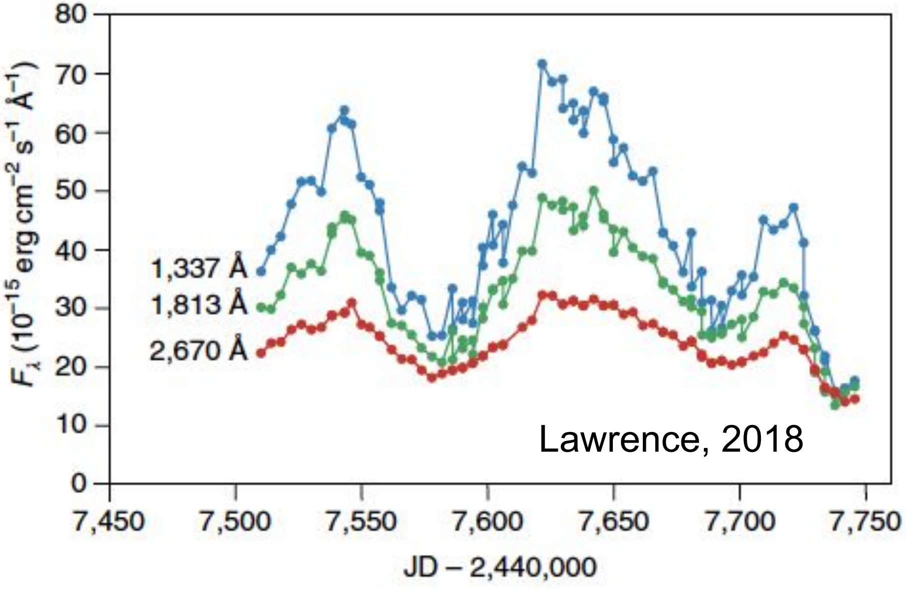
Potentially we can also connect with observations on even longer timescales/simulations



AGN - variability (disk)

Standard viscous disk theory has great difficulties explaining the observations. For instance, different wavelengths come from different radii, which means that changes should propagate through disk. But, the changes are way too quick!



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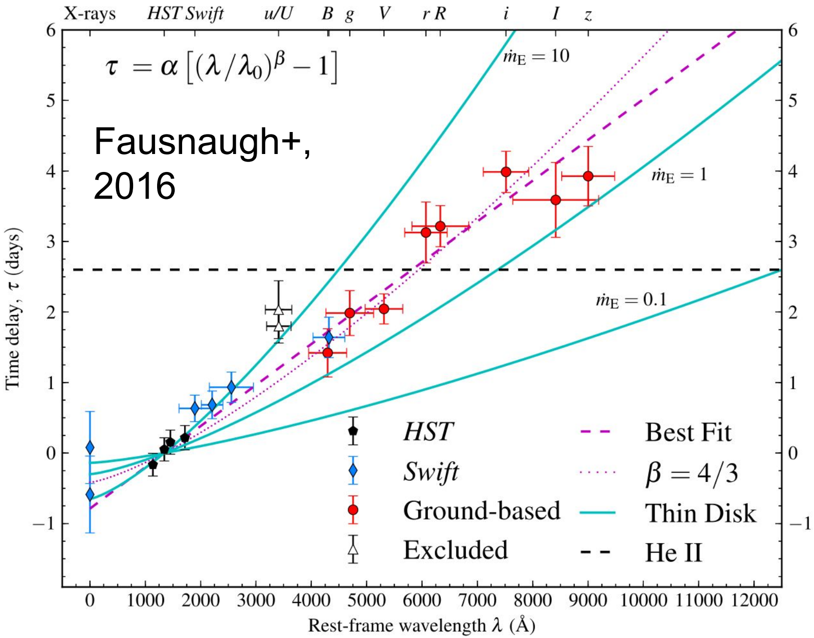

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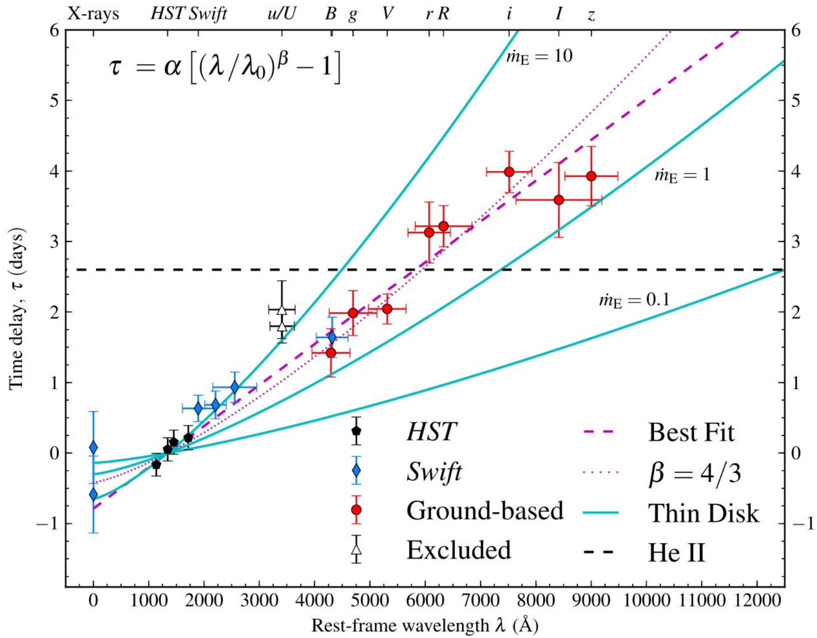
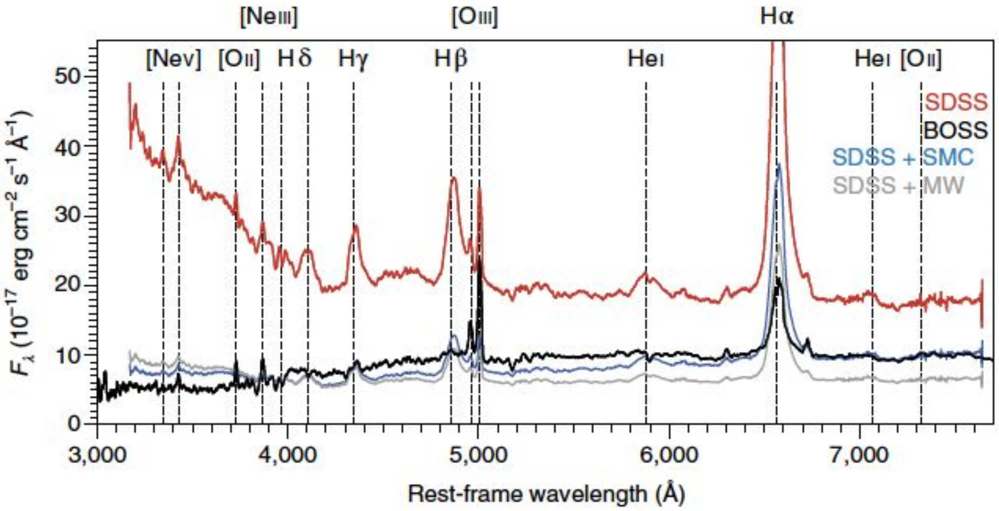
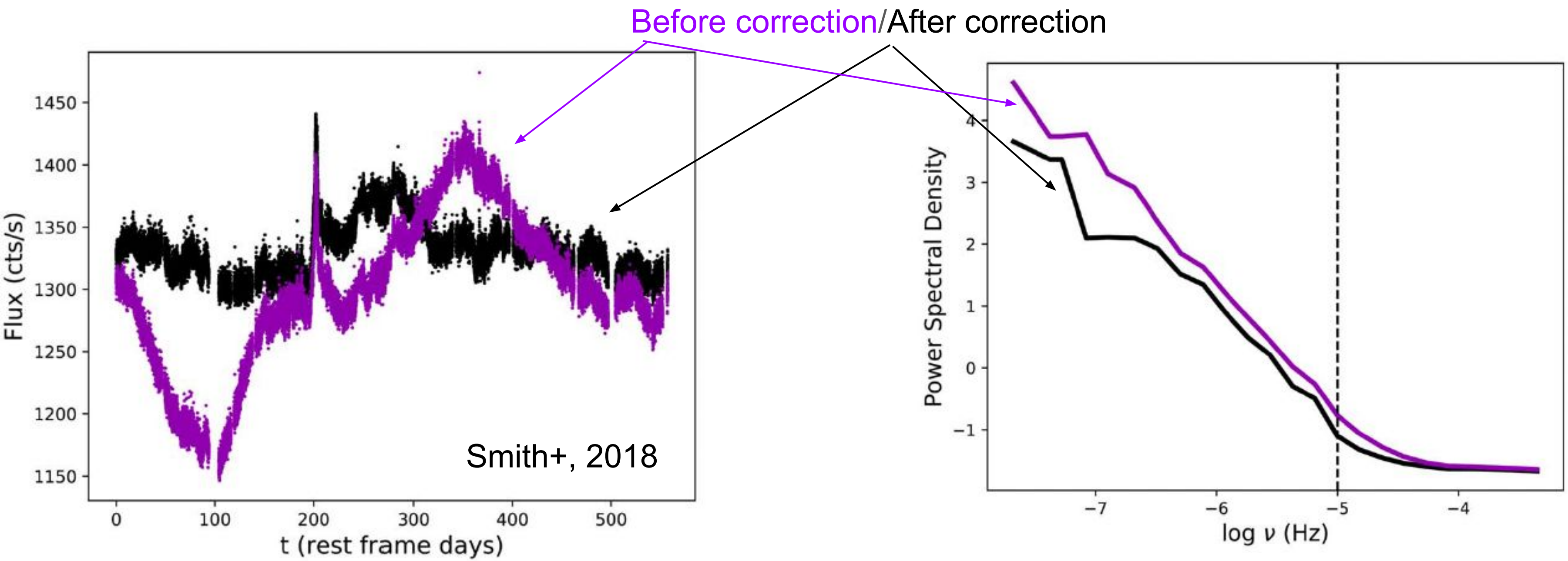




We are also finding more and more AGN that have gone change brightness and their spectrum dramatically (changing look AGN) - and - this can not be explained by obscuration.

AGN - variability (Kepler)

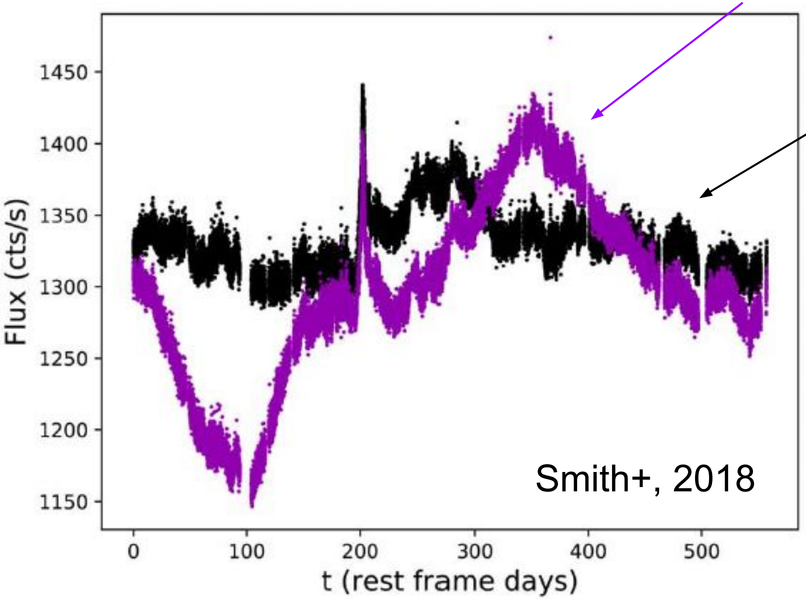
- There is a survey already that has exquisite precision and enables us to determine variability properties without virtually any interpolation and assumption - Kepler!
- But very difficult to calibrate!!!
- At short time scale (~days) stronger correlation than expected from random walk



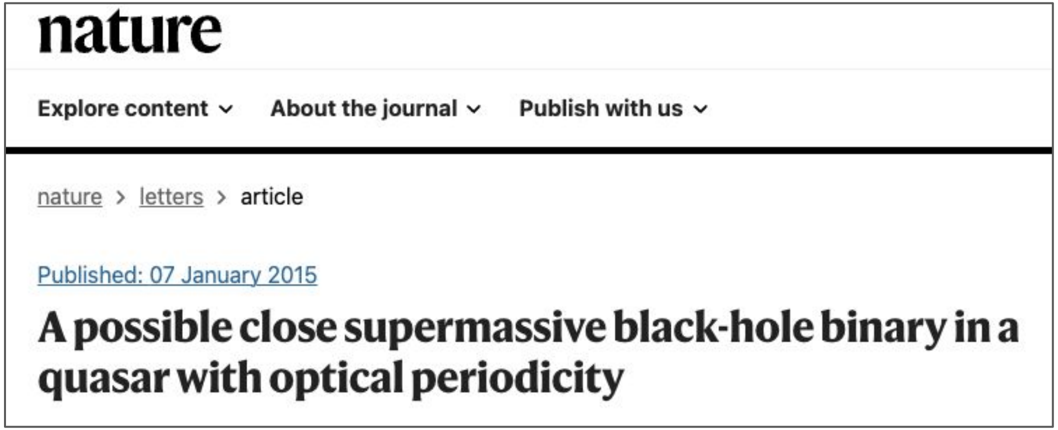
AGN - variability (Kepler)

- There is a survey already that has exquisite precision and enables us to determine variability properties without virtually any interpolation and assumption - Kepler!
- But very difficult to calibrate!!!
- At short time scale (~days) stronger correlation than expected from random walk

Before correction/After correction



AGN - variability (periods)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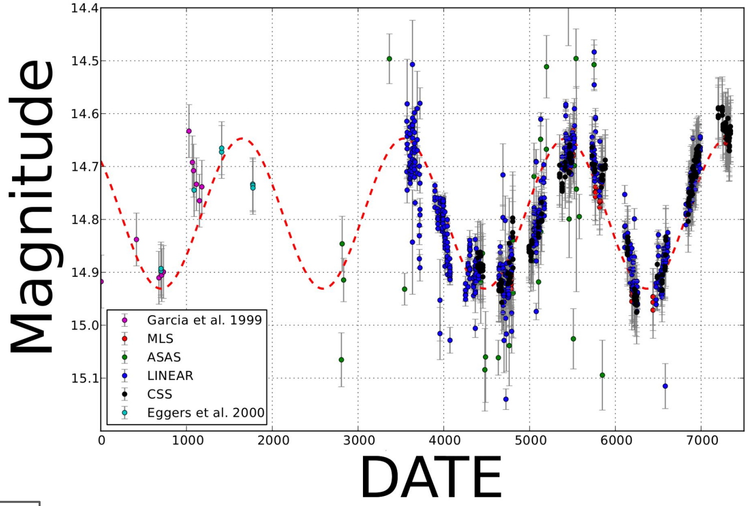
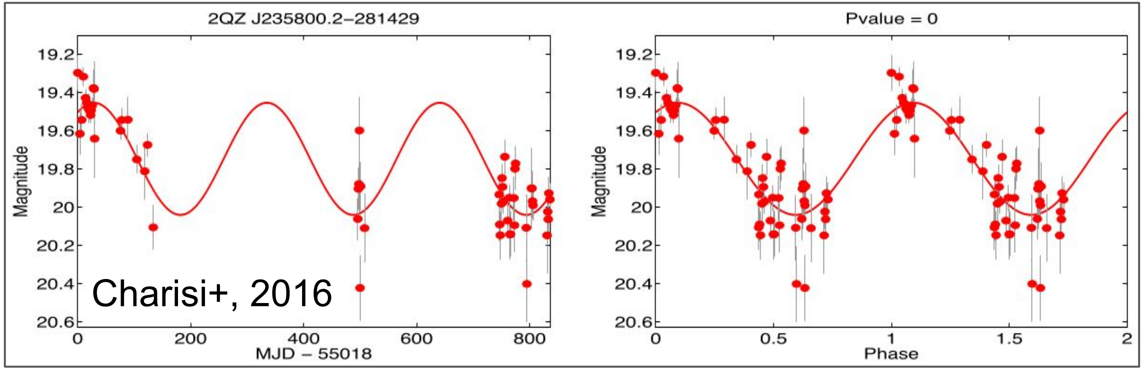
A possible close supermassive black-hole binary in a quasar with optical periodicity





Black hole binaries with a sub-parsec separation

Expected as a consequence of galaxy mergers

AGN - variability (periods)

False periodicities in quasar time-domain surveys

S. Vaughan,[1★] P. Uttley,[2] A. G. Markowitz,[3] D. Huppenkothen,[4] M. J. Middleton,[5] W. N. Alston,[5] J. D. Scargle[6] and W. M. Farr[7]

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Did ASAS-SN Kill the Supermassive Black Hole Binary Candidate PG1302-102?

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No Evidence of Periodic Variability in the Light Curve of Active Galaxy J0045+41

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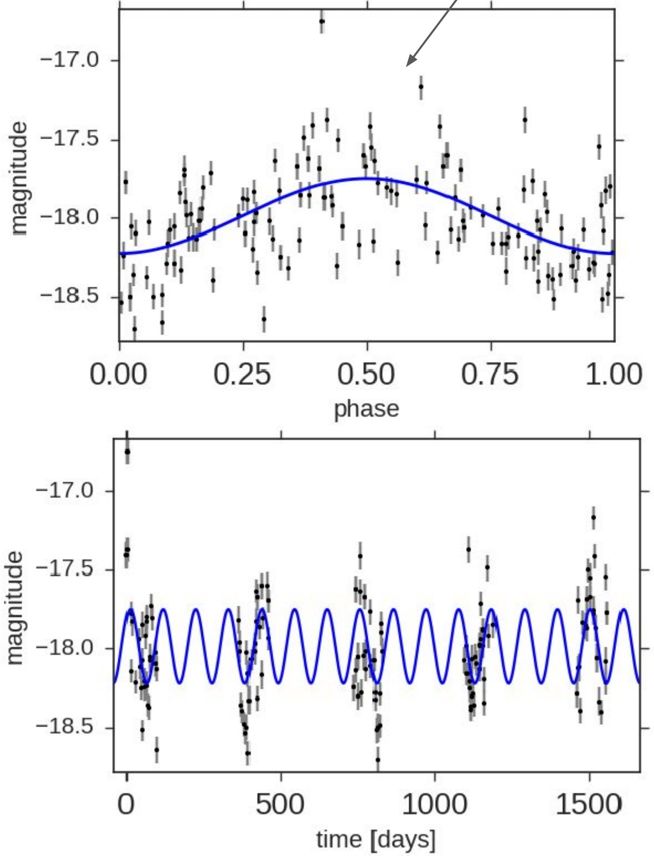
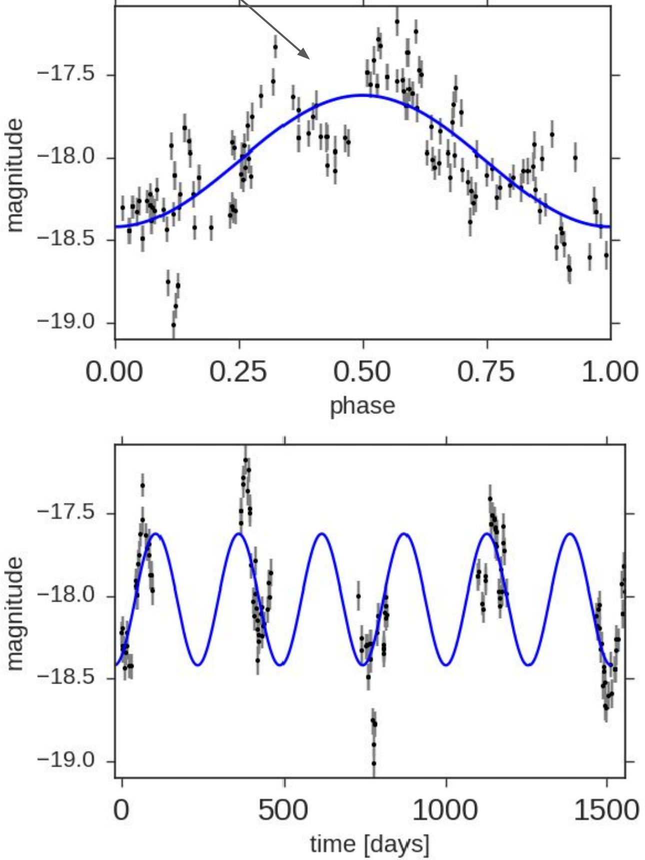
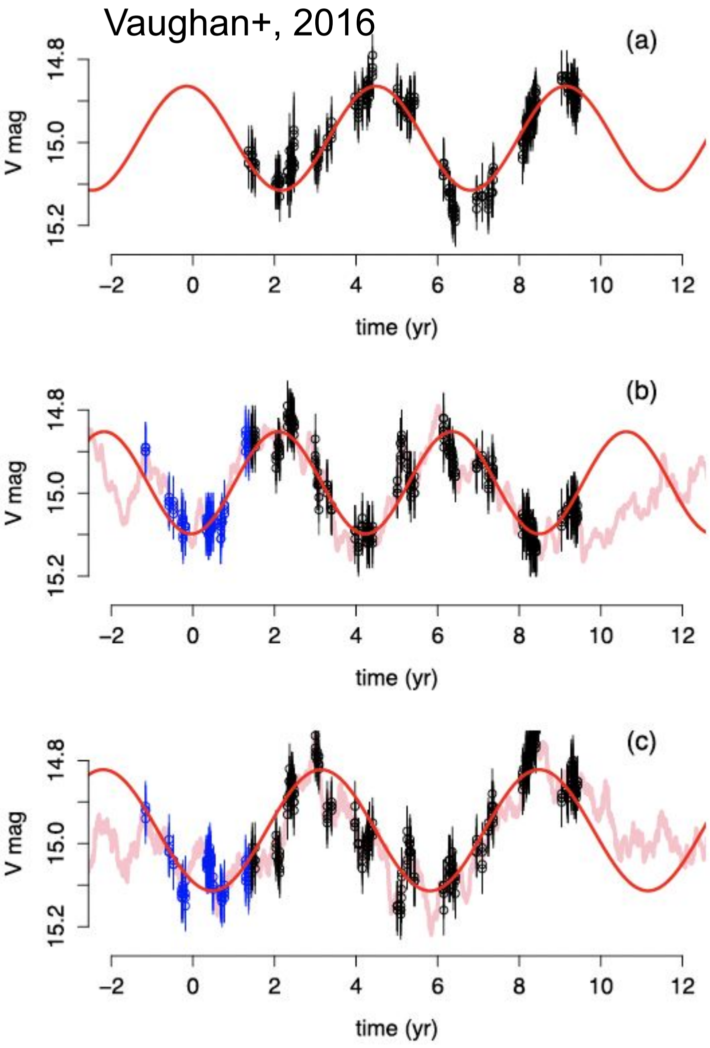
Received 2018 January 23; revised 2018 February 22; accepted 2018 February 28; published 2018 May 16

White noise/Red noise simulation, finding most periodic sources

AGN - variability (periods)







- Stochastic process can mimic periodicity
- How to disentangle?