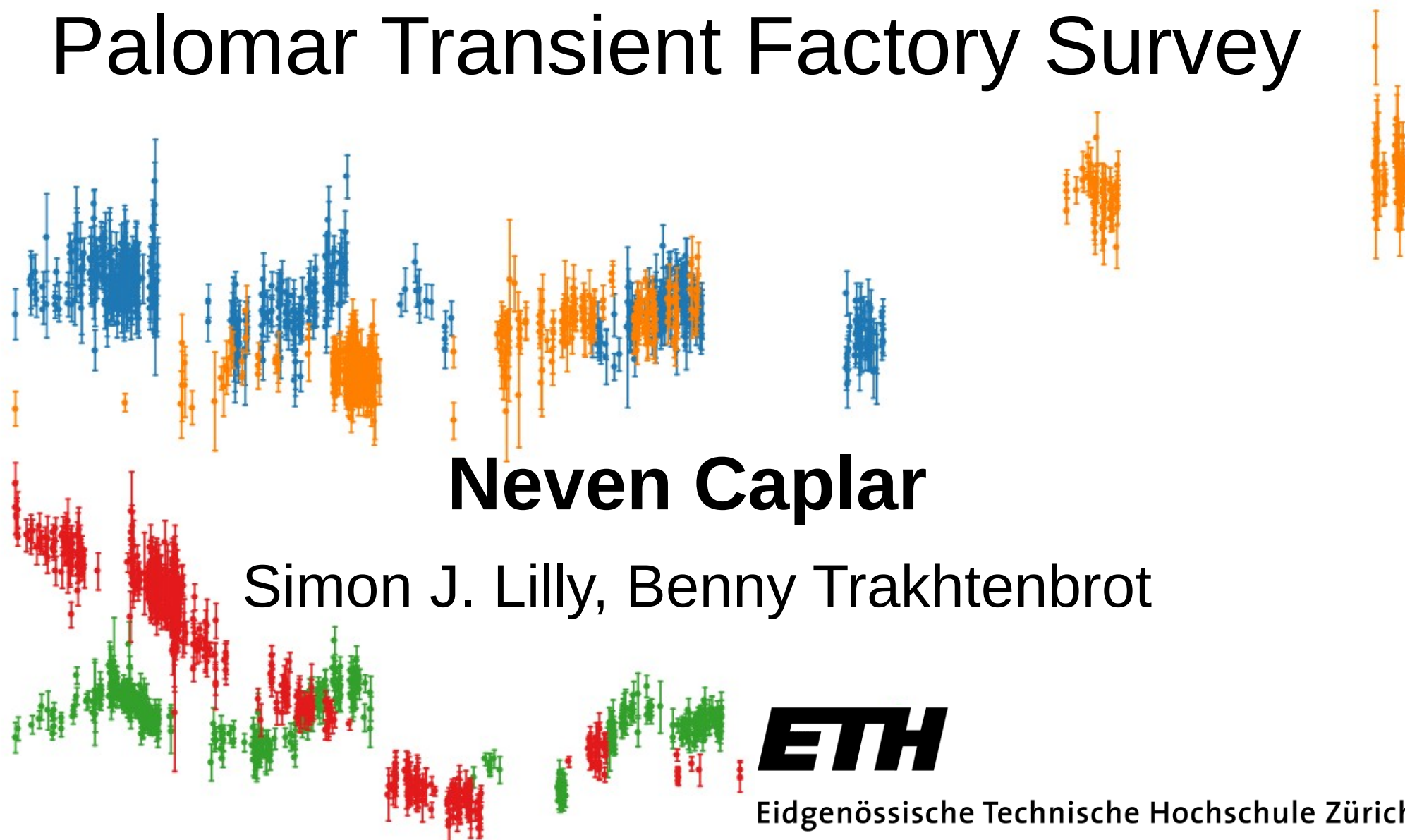


Quasar Variability in the Palomar Transient Factory Survey



Neven Caplar

Simon J. Lilly, Benny Trakhtenbrot

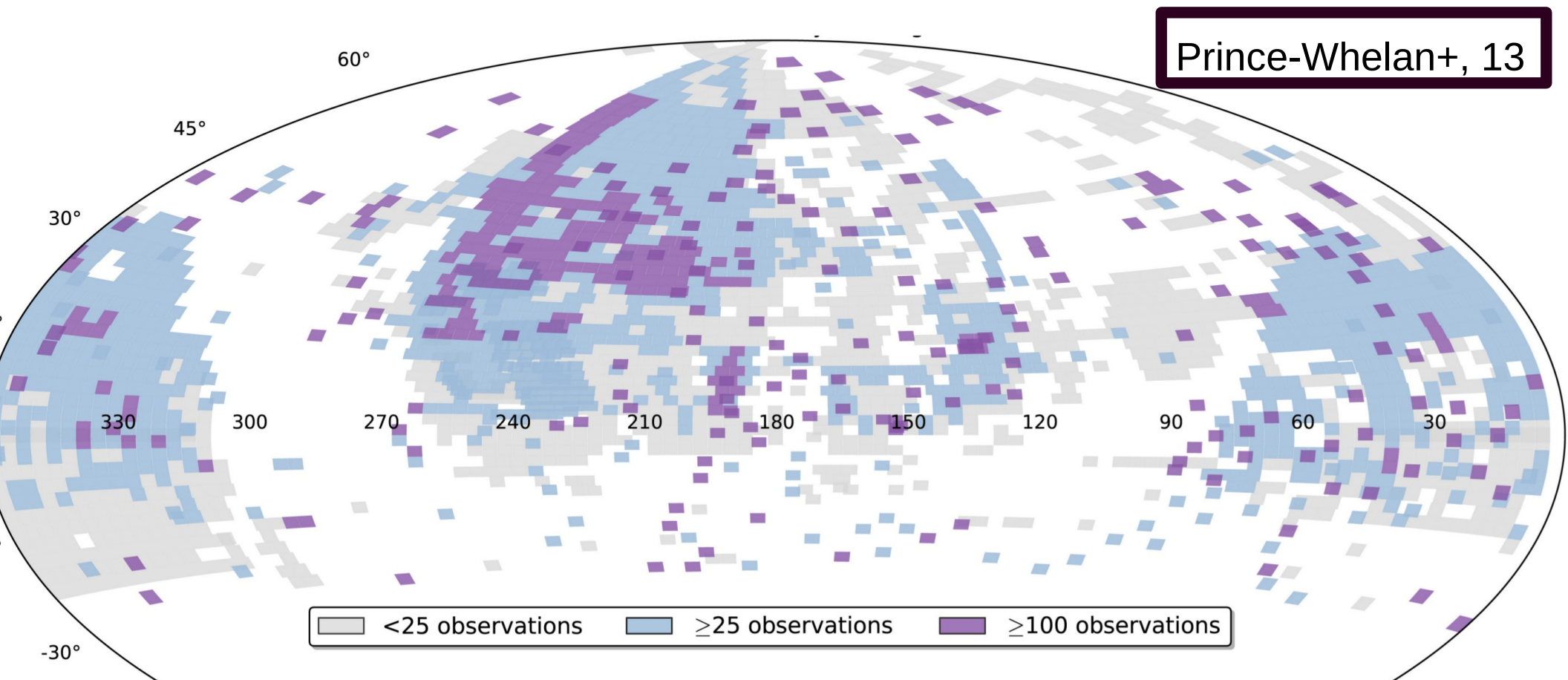


Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

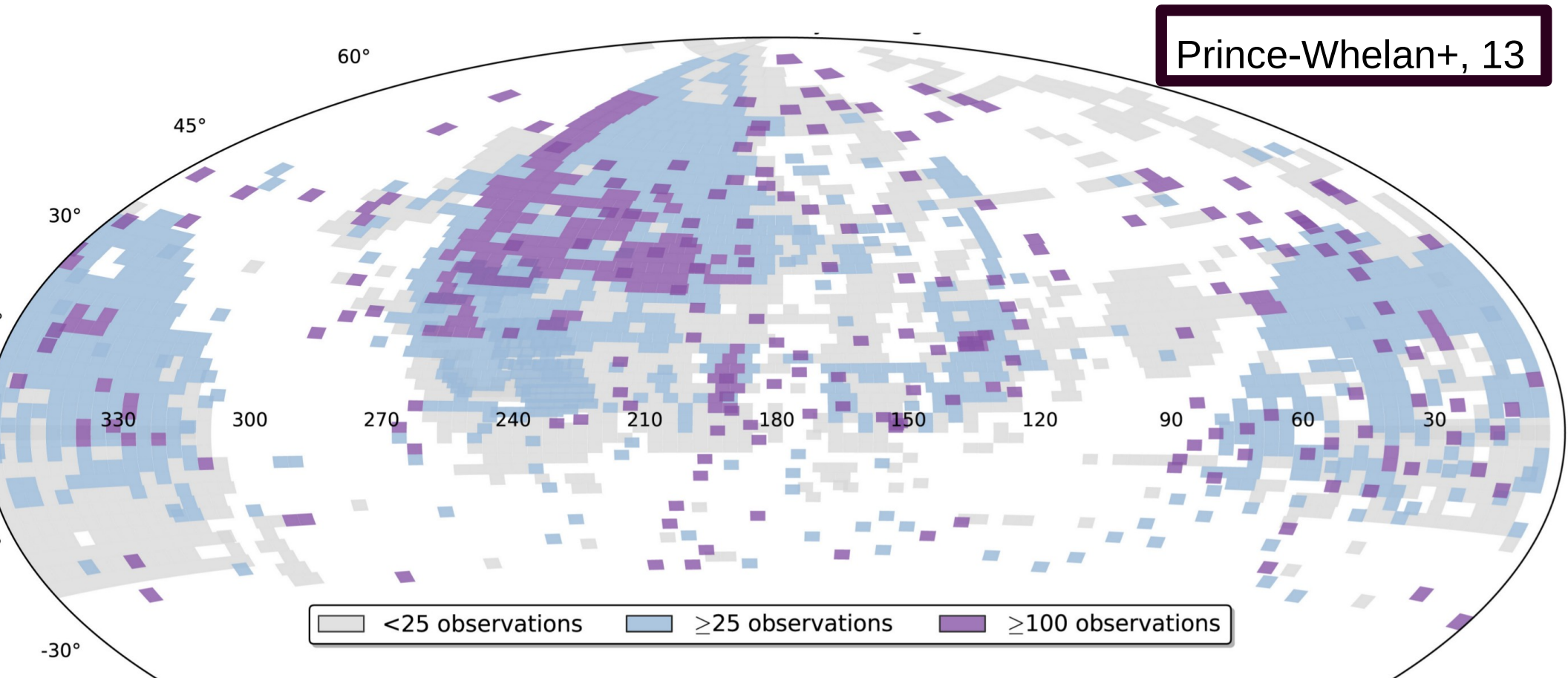
- 1.5 m telescope on Mount Palomar in south California
- Transient sky survey started in March 2009
- Data mostly in r band (centered at 6580 Å)



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- 1.5 m telescope on Mount Palomar in south California
- Transient sky survey started in March 2009
- Data mostly in r band (centered at 6580 Å)
- 28000 AGNs brighter than $r=19.1$
- 2.4 million data points = large calibrated single band dataset!



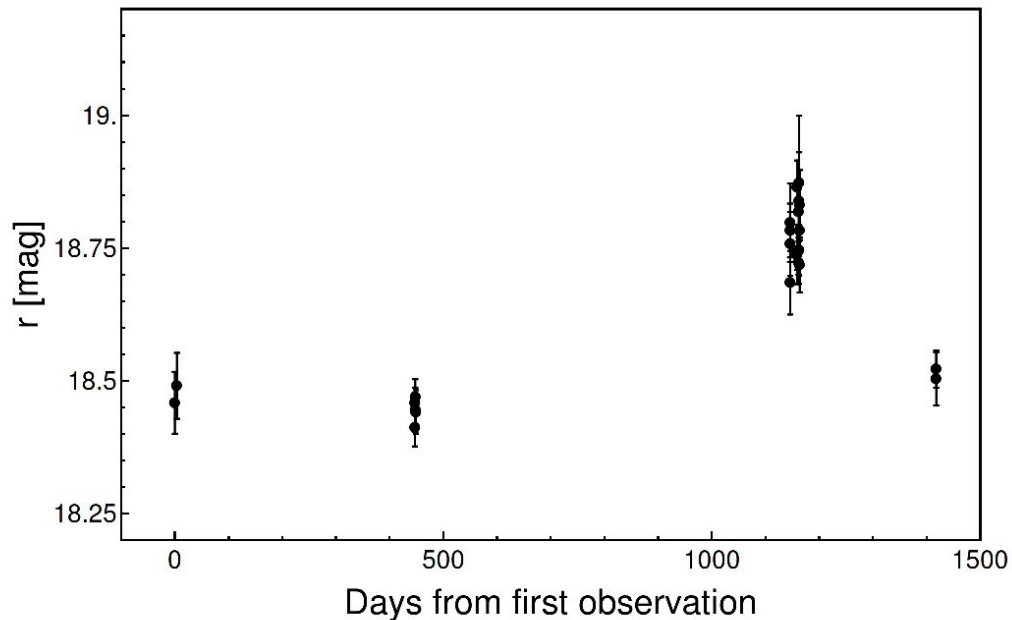
Re-calibration of survey

- AGN light-curves were re-calibrated
- We search for zeropoints which minimize the scatter of reference objects (stars) – based on Ofek+ 2011

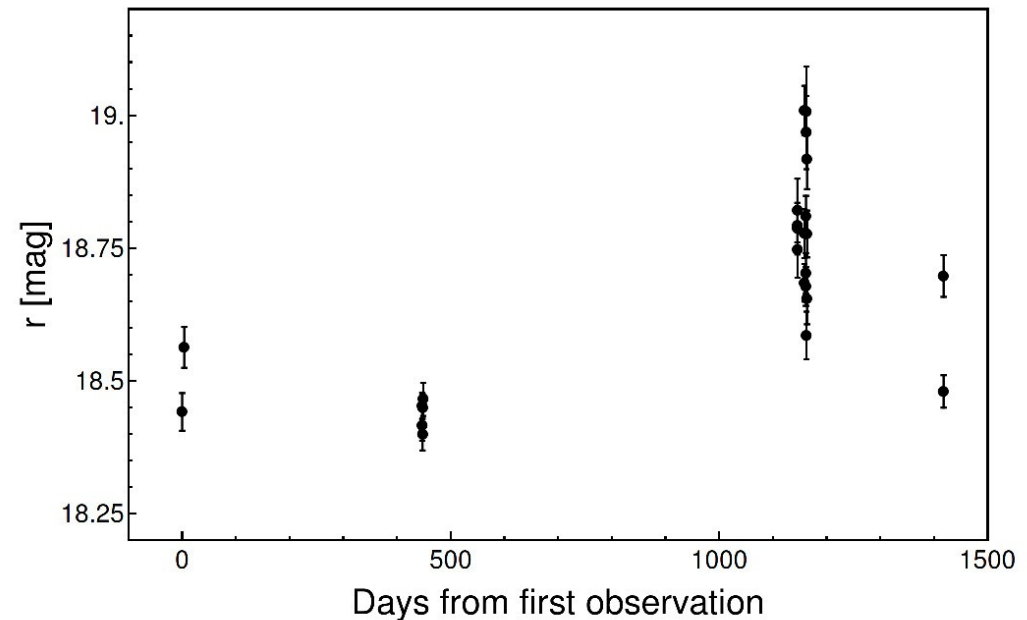
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Calibration from this work



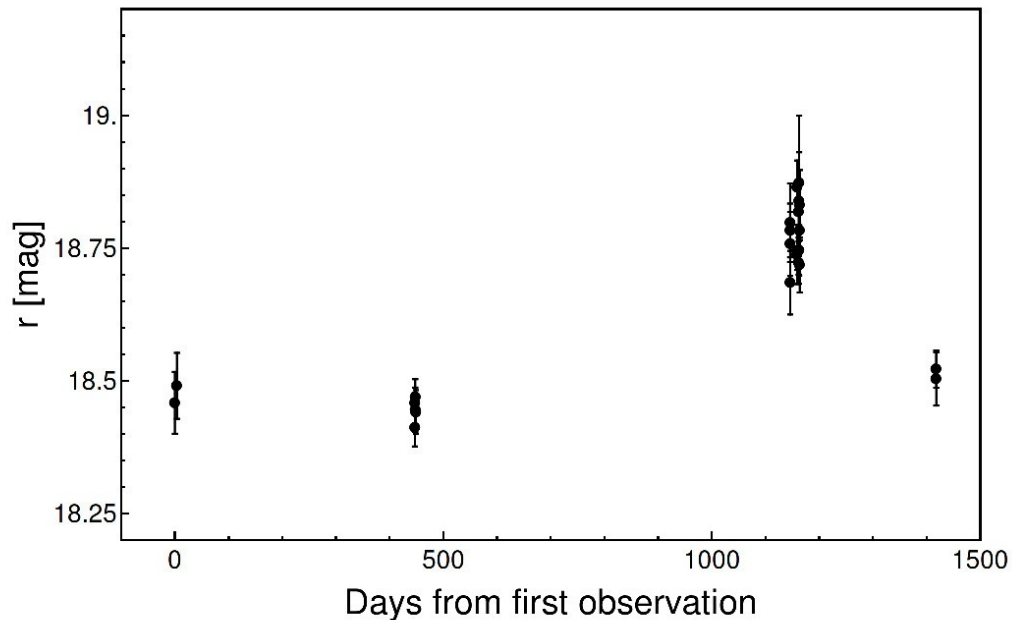
Calibration from Ofek et al. 2012



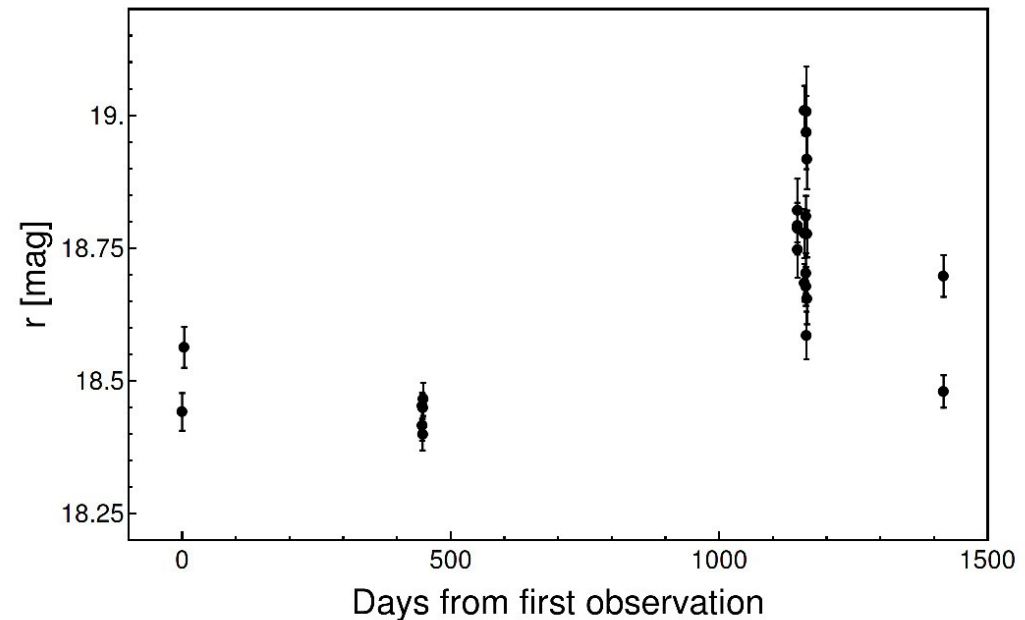
Re-calibration of survey

- AGN light-curves were re-calibrated
- We search for zeropoints which minimize the scatter of reference objects (stars) – based on Ofek+ 2011
- We achieve excellent performance; excess variance at short time-scales is consistent with zero for vast majority of AGNs
- Re-calibrated data is public: https://github.com/nevencaplar/PTF_AGN

Calibration from this work



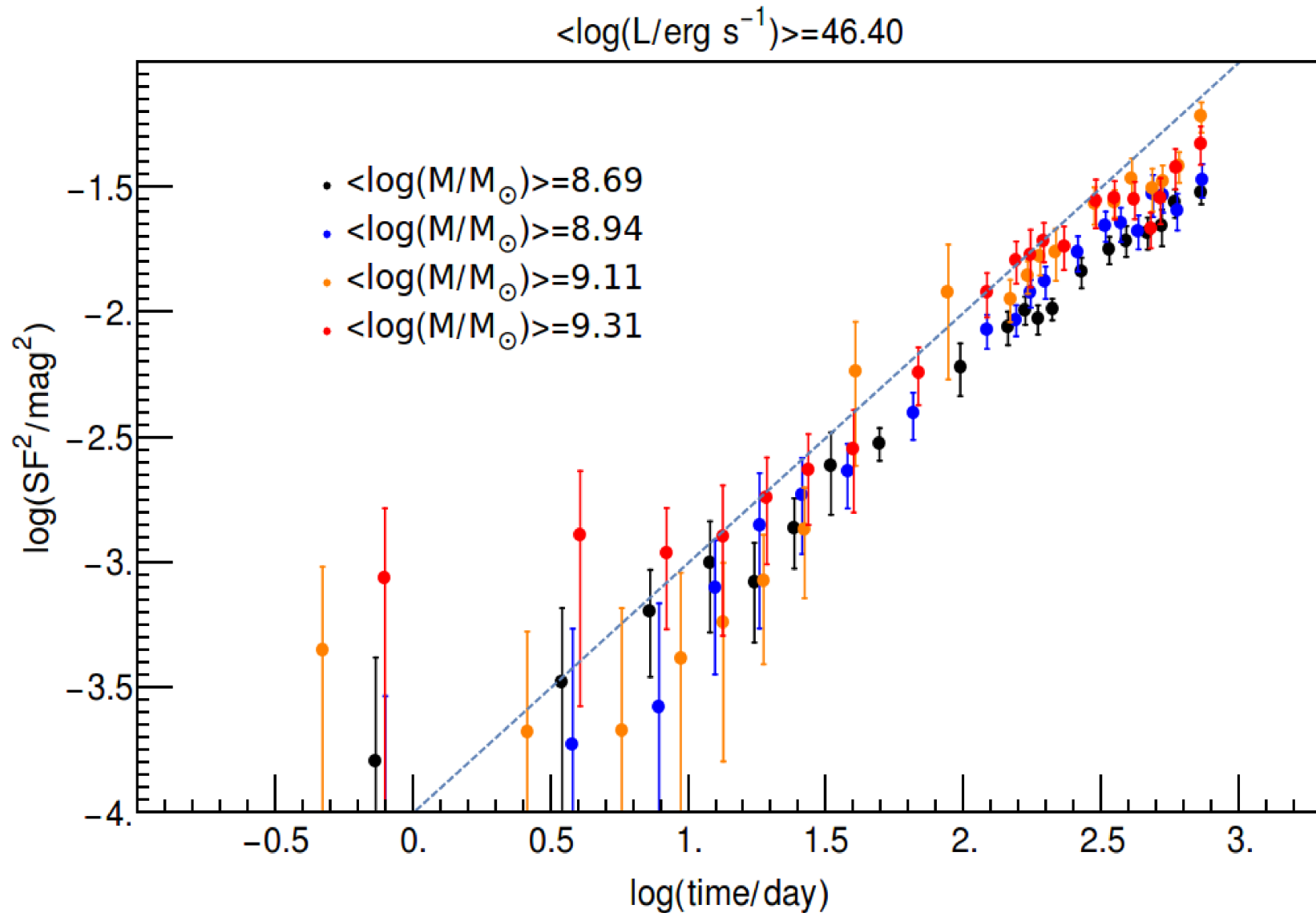
Calibration from Ofek et al. 2012

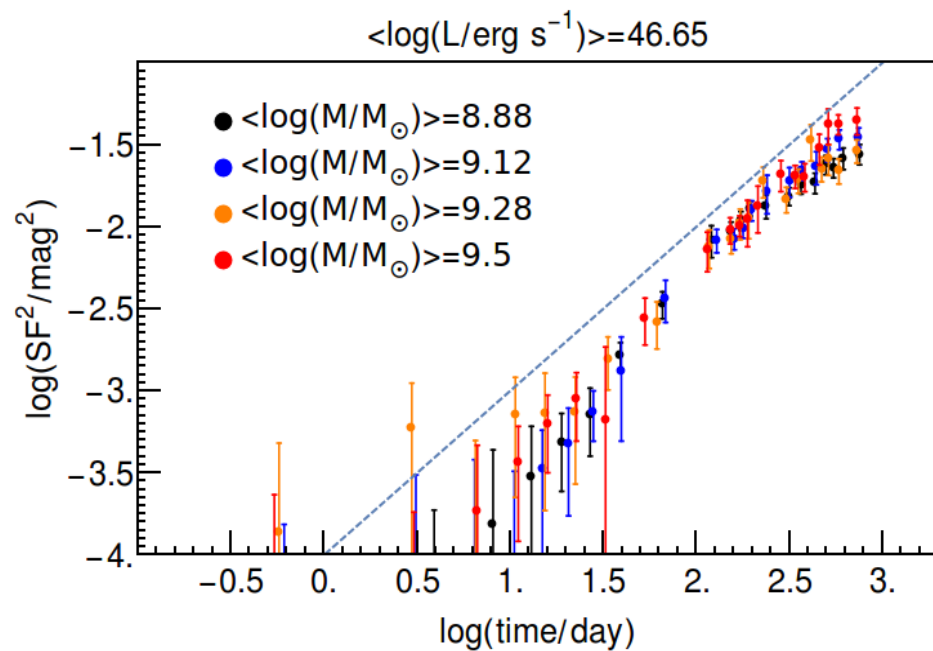
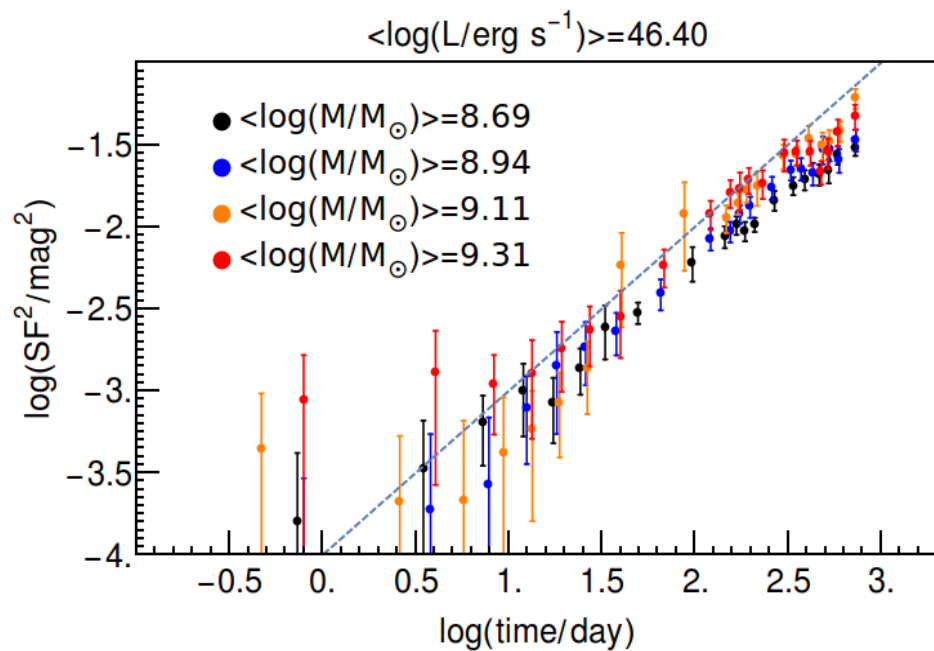
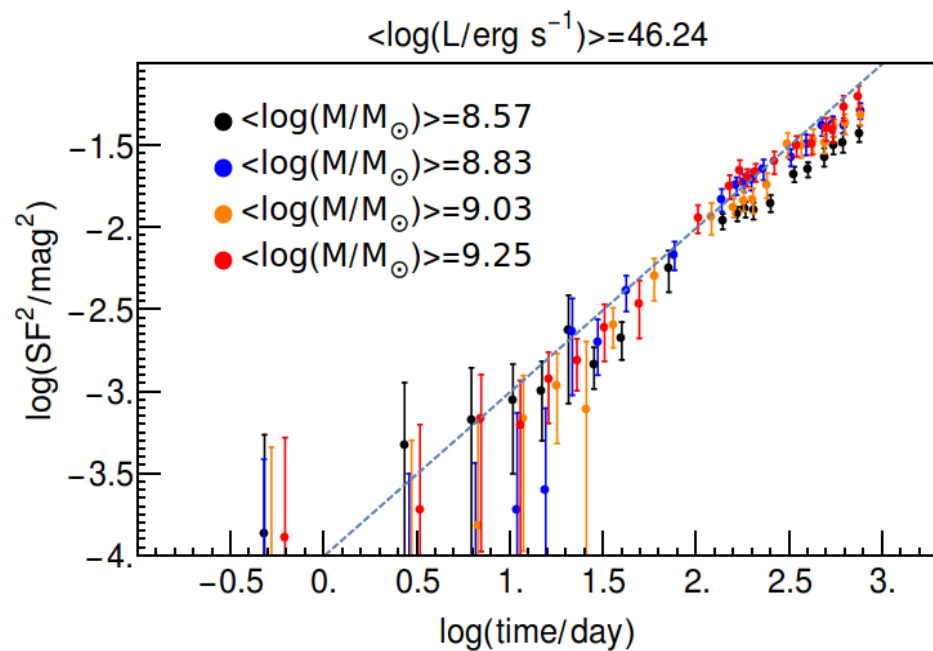
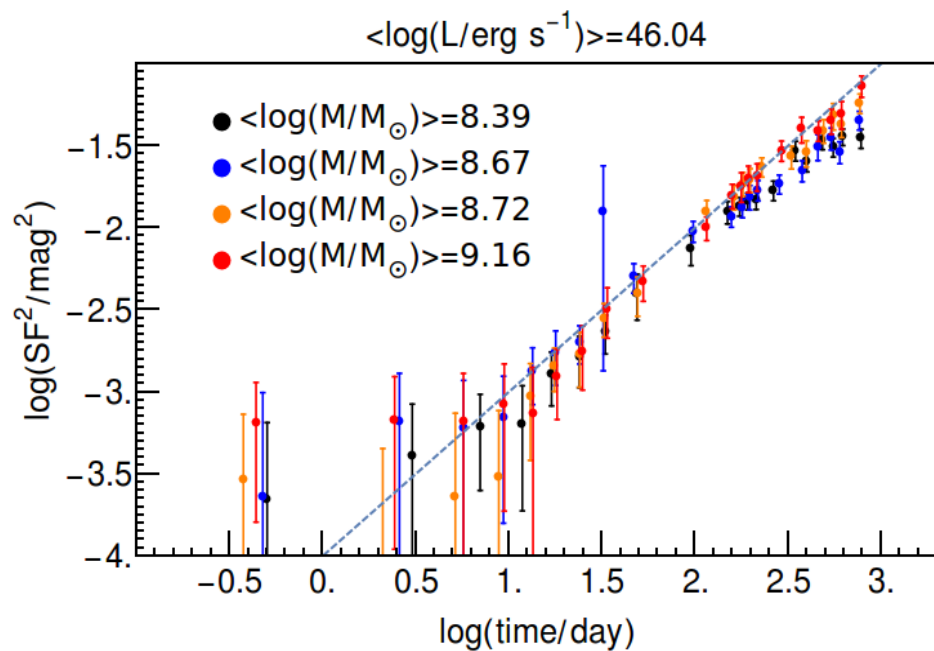


- SF² (structure function)² analysis
 - Variance of magnitude difference as a function of time lag between measurements
 - We use the method on ensemble, sample of AGNs with similar physical properties
- Power spectral density (PSD) analysis
 - Variability power per temporal frequency
 - We use CARMA modeling algorithm from Kelly+ (2015)
 - Used on well sampled, single objects

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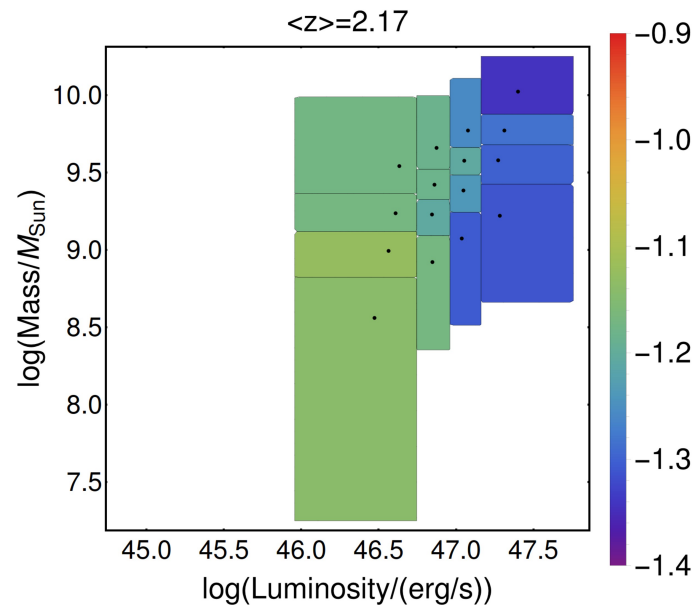
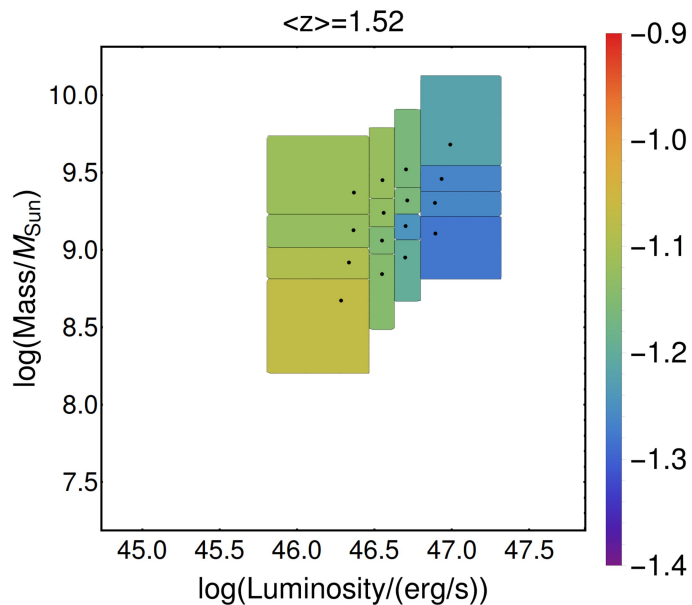
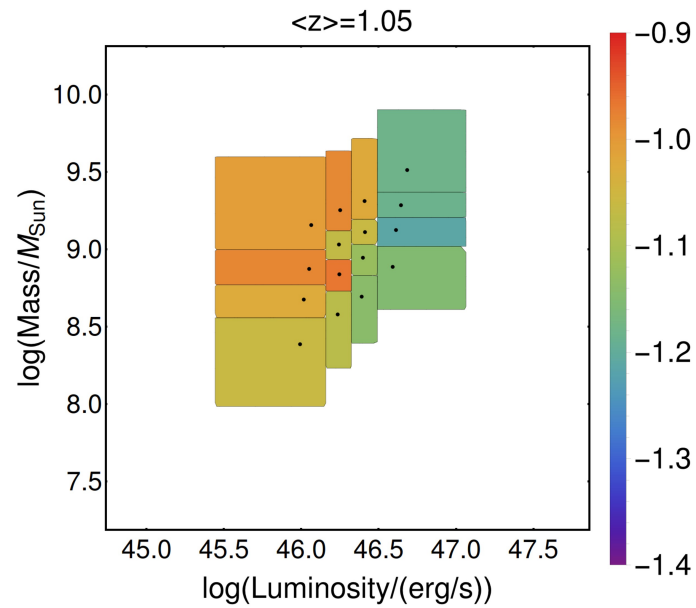
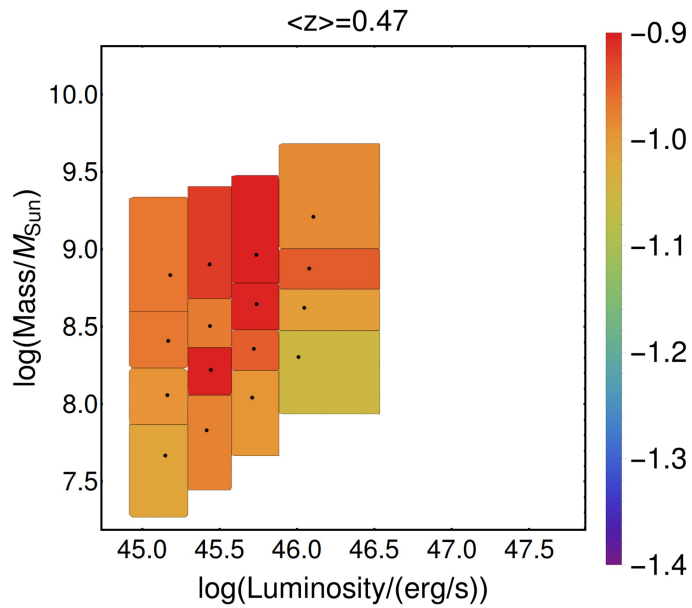
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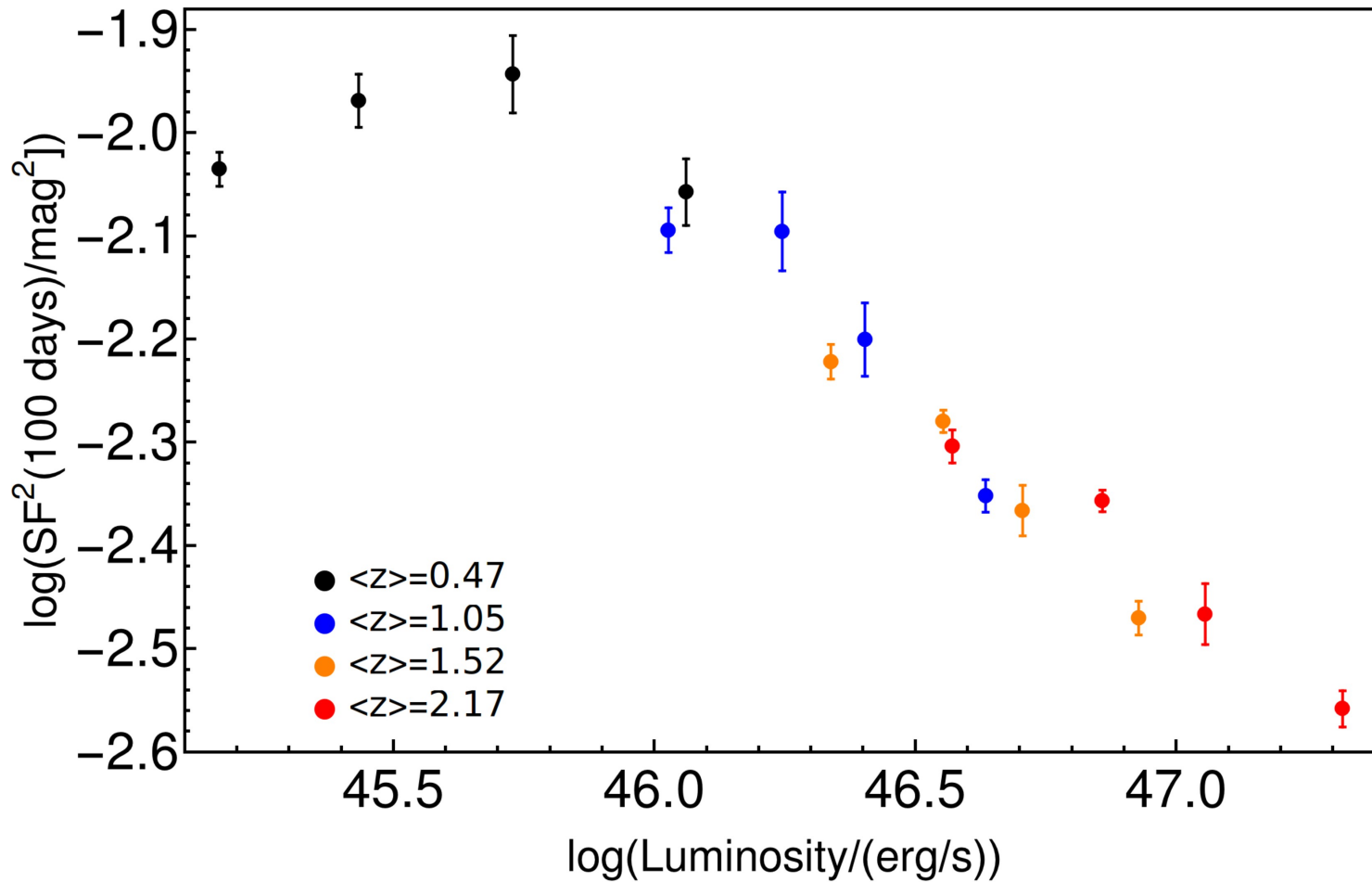


$\langle z \rangle = 1.05$

$\log(\text{SF}(100 \text{ days}_{\text{RF}})/\text{mag})$

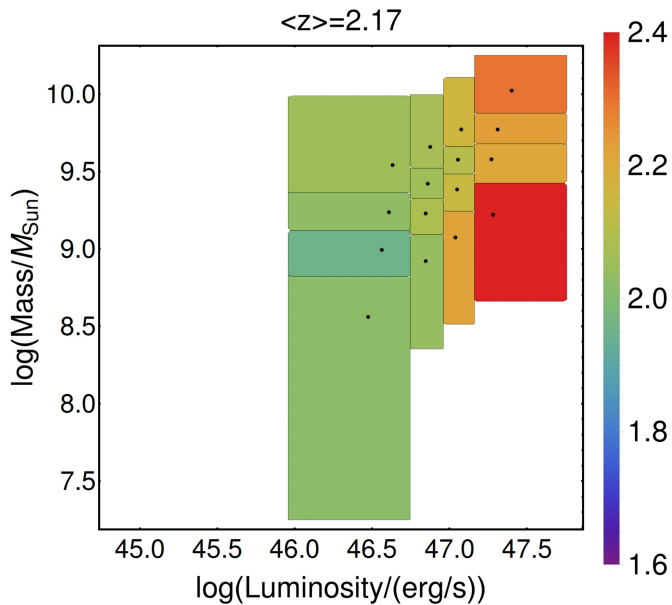
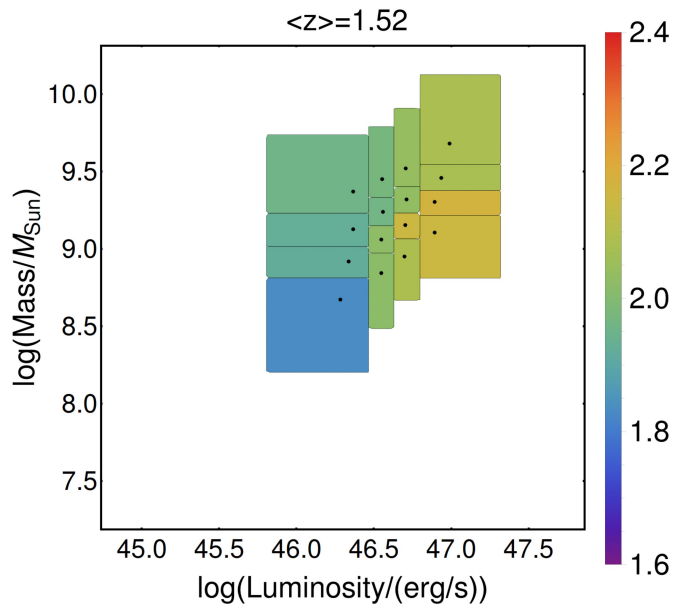
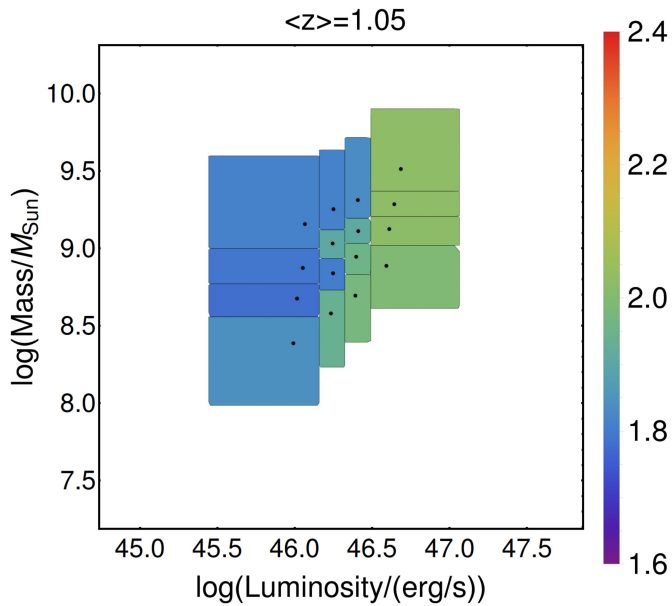
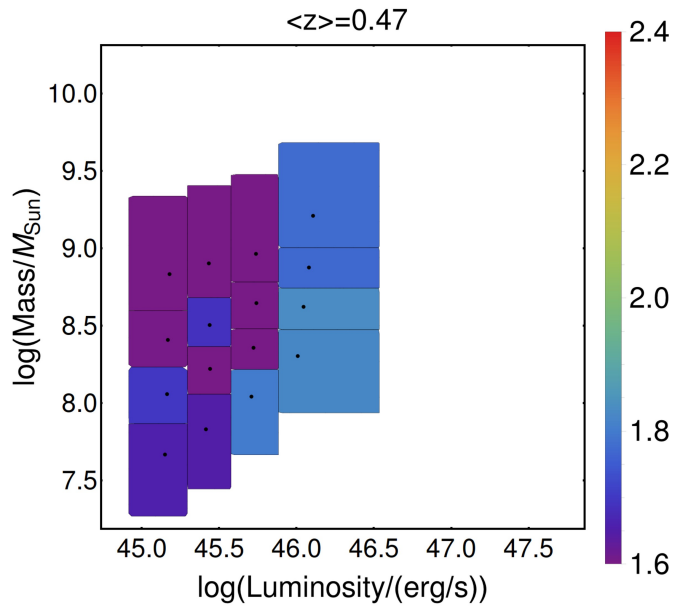


- Wavelength correction estimated from SDSS dataset to normalize to 4000 Å
- No correlation with redshift
- Little to no correlation with mass
- Clear dependence with luminosity



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$\log[\text{time}_{\text{RF}}/\text{days}_{\text{RF}}]$ for SF to reach 0.071 mag



- Alternative way to interpret the data – τ , time to reach certain variability

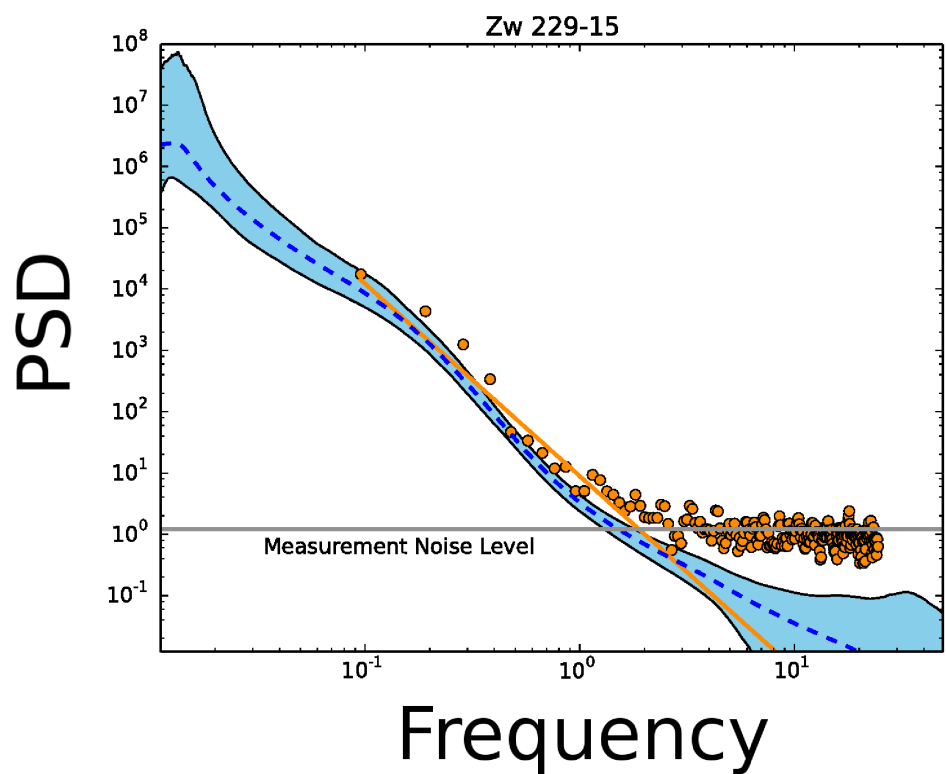
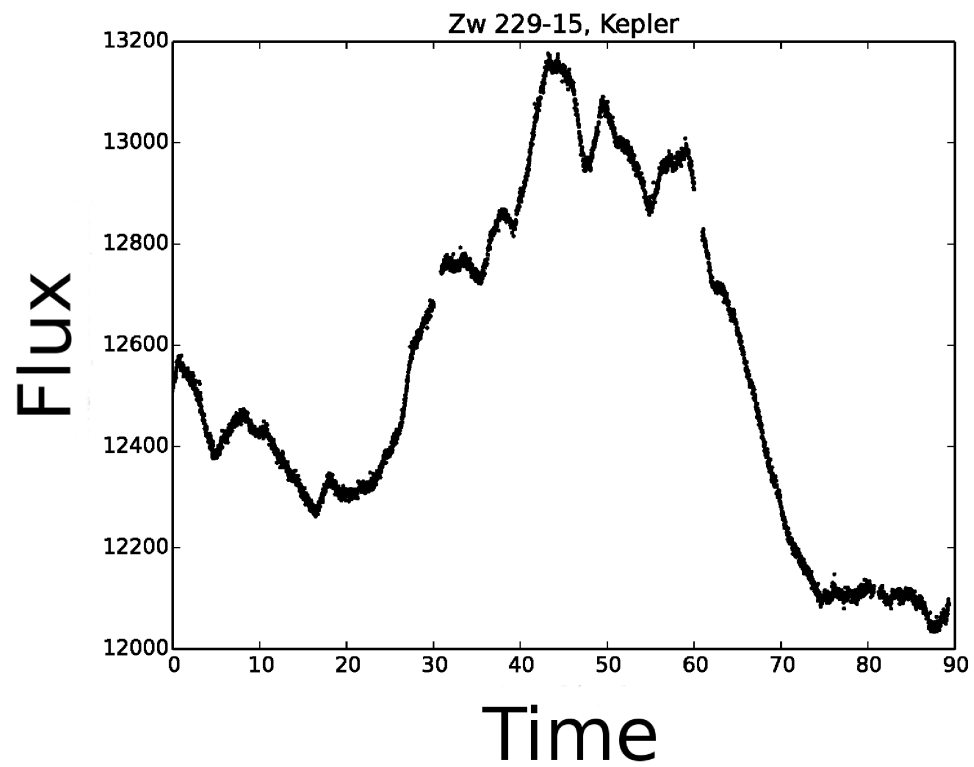
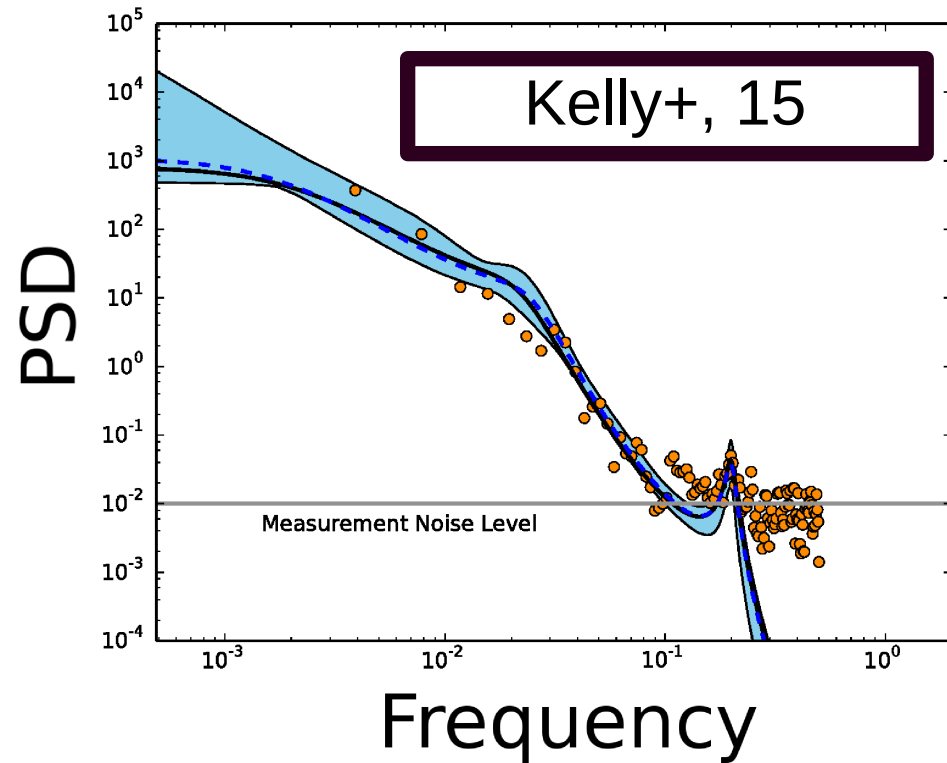
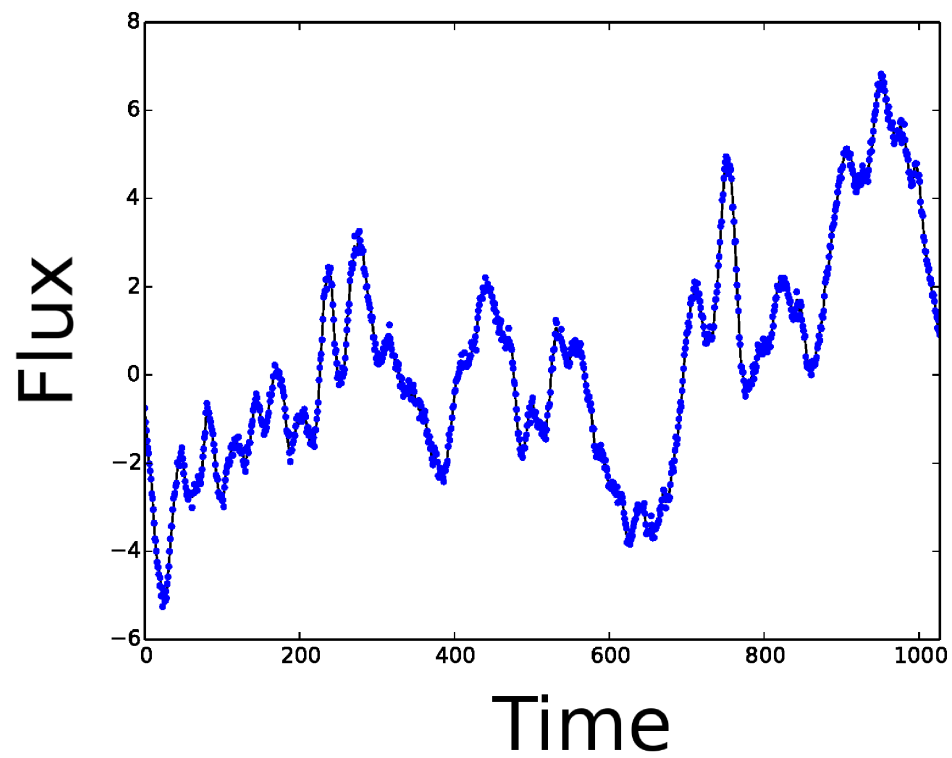
- From data $\tau \propto L^{0.4}$

- Simplest thin disk model and time scale of variability identified with Kelperian time scale

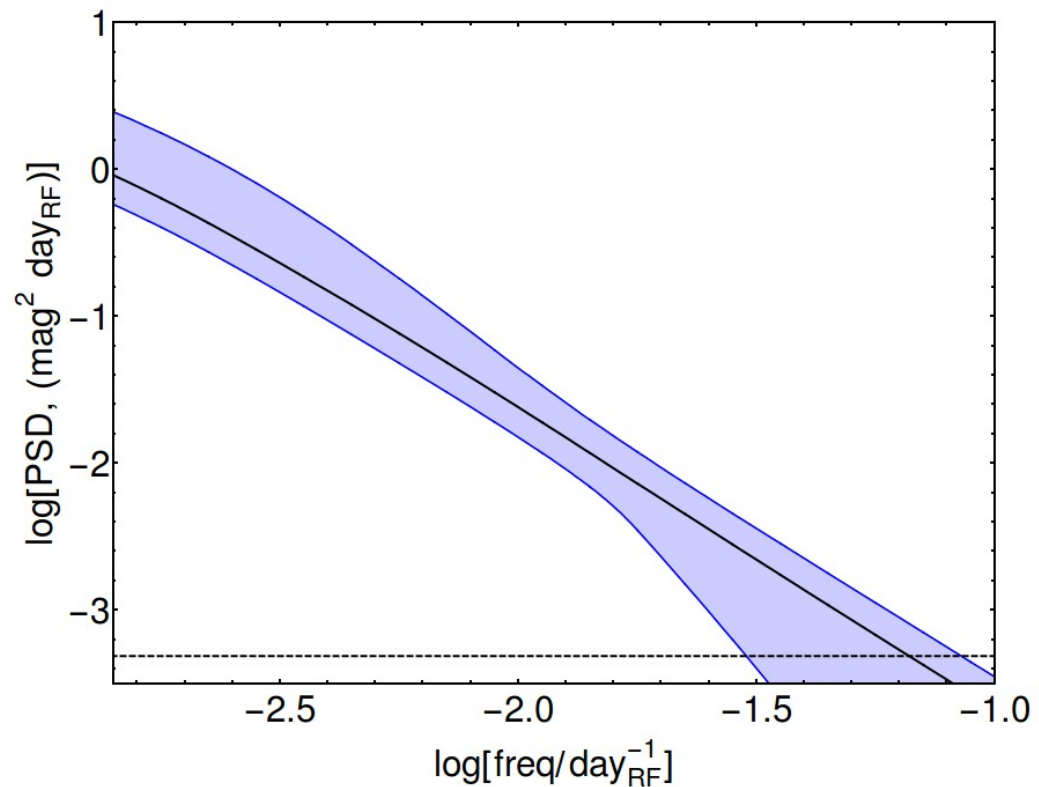
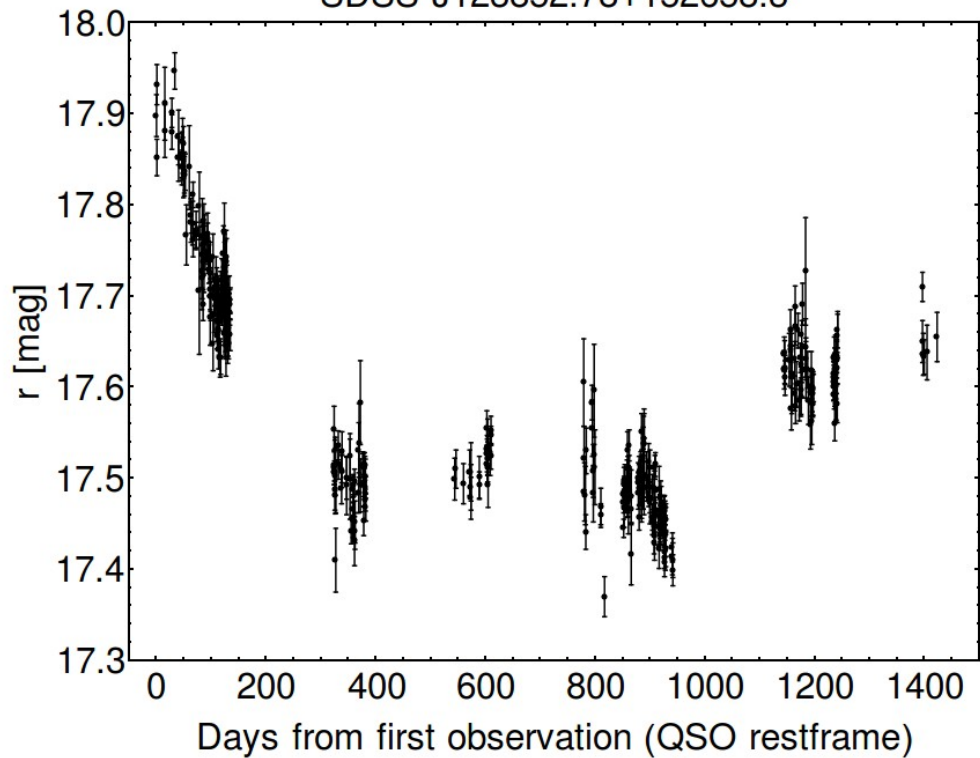
$$\tau \propto L^{0.5}$$

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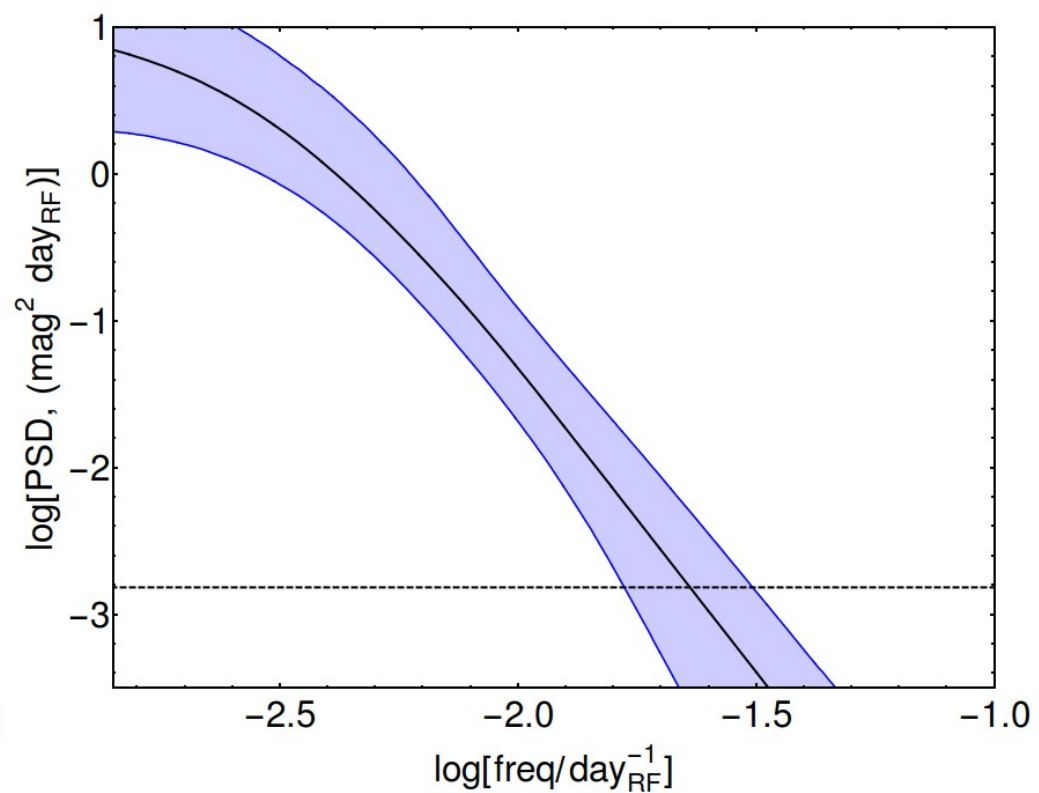
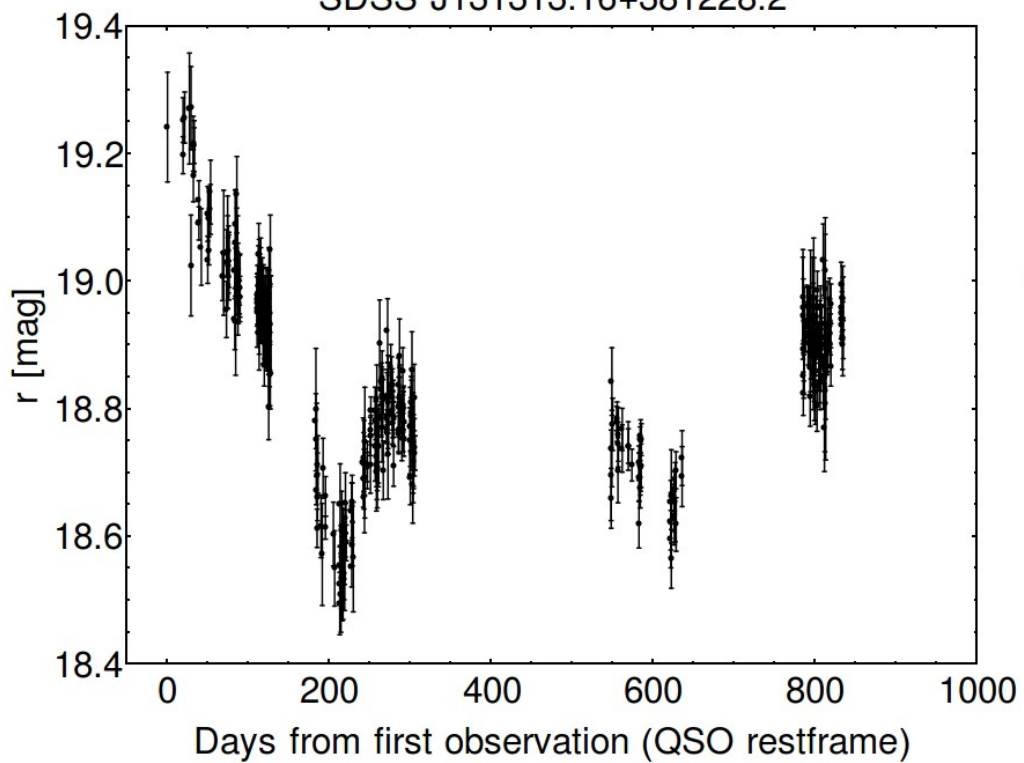
- Power spectral density (PSD) analysis
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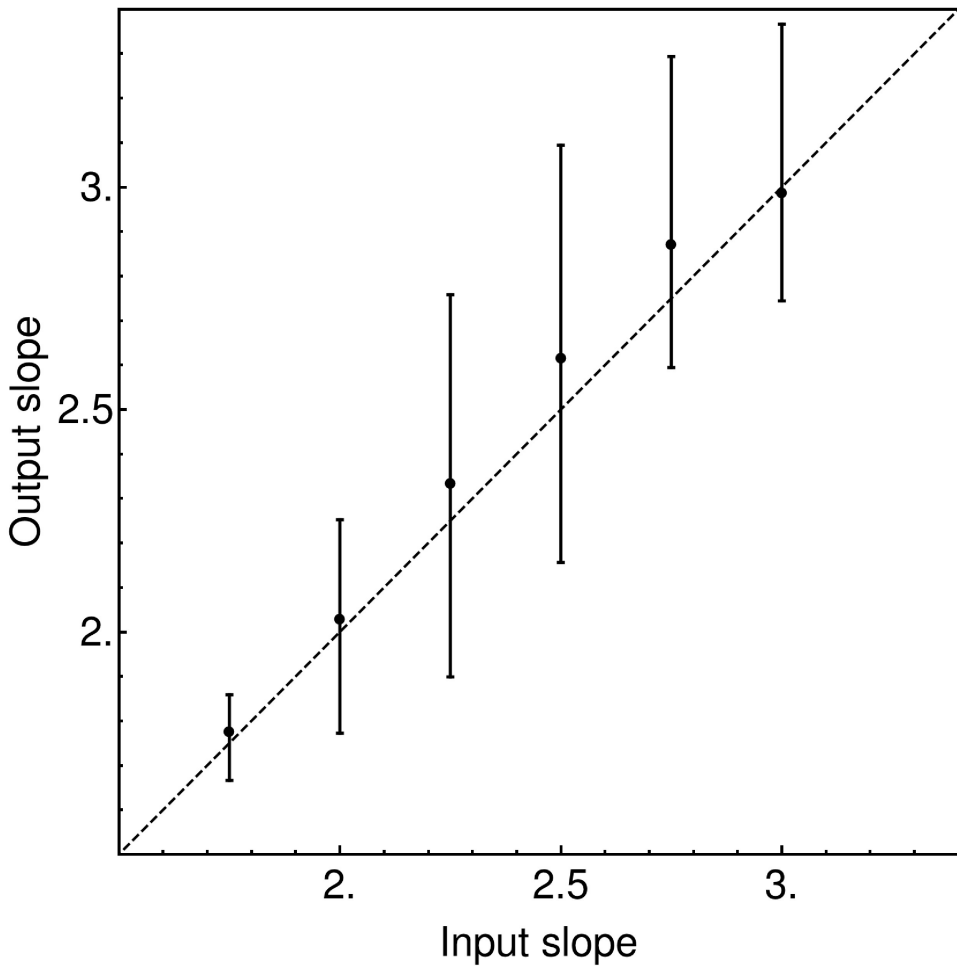


SDSS J123852.78+152658.3

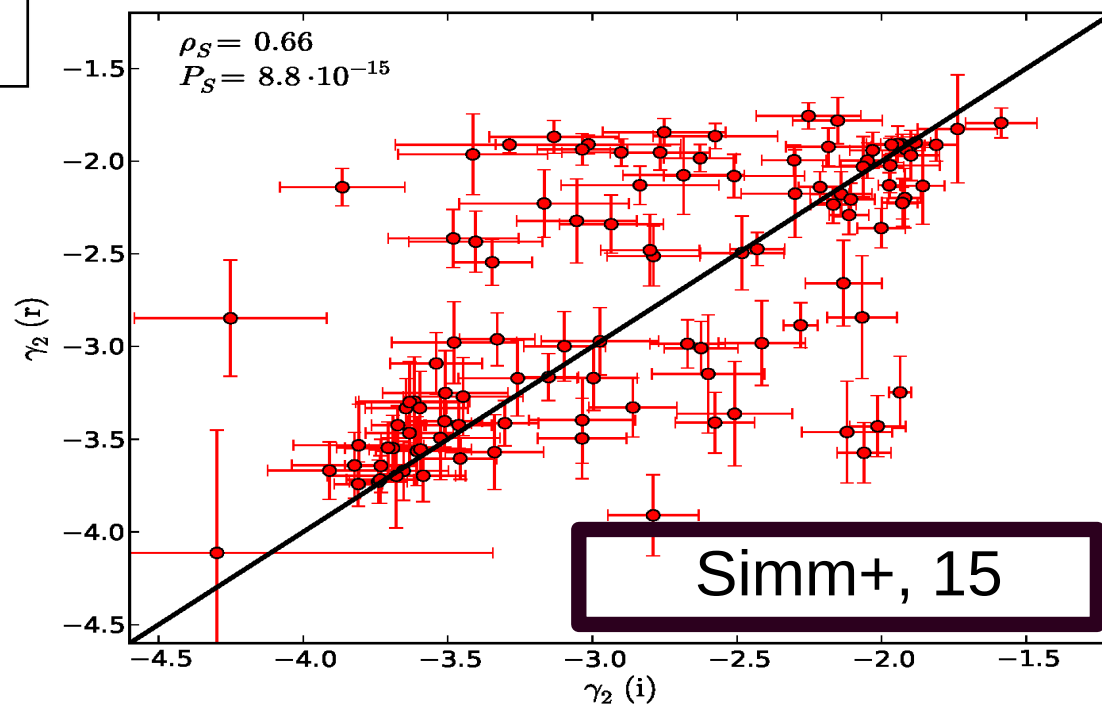


SDSS J131313.16+381228.2

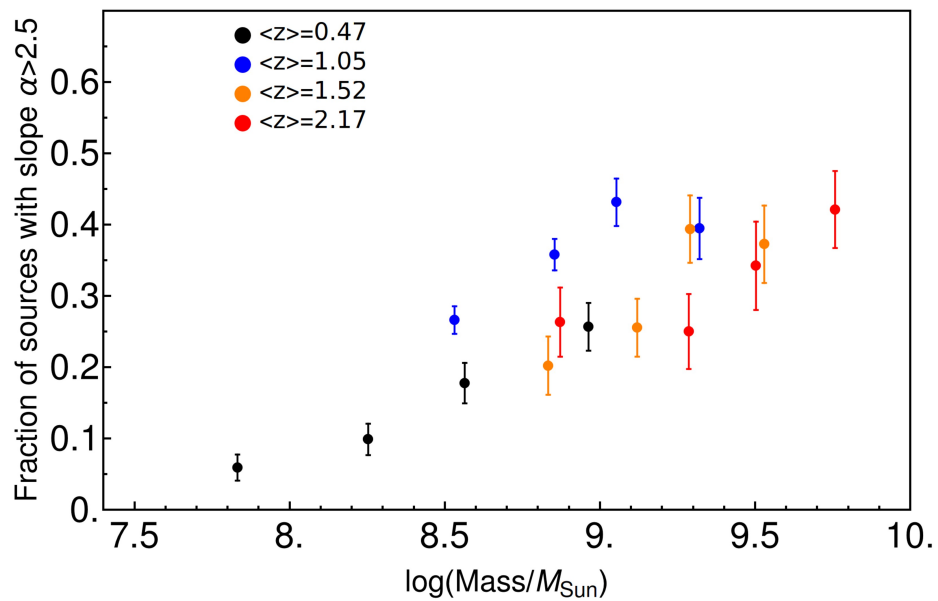




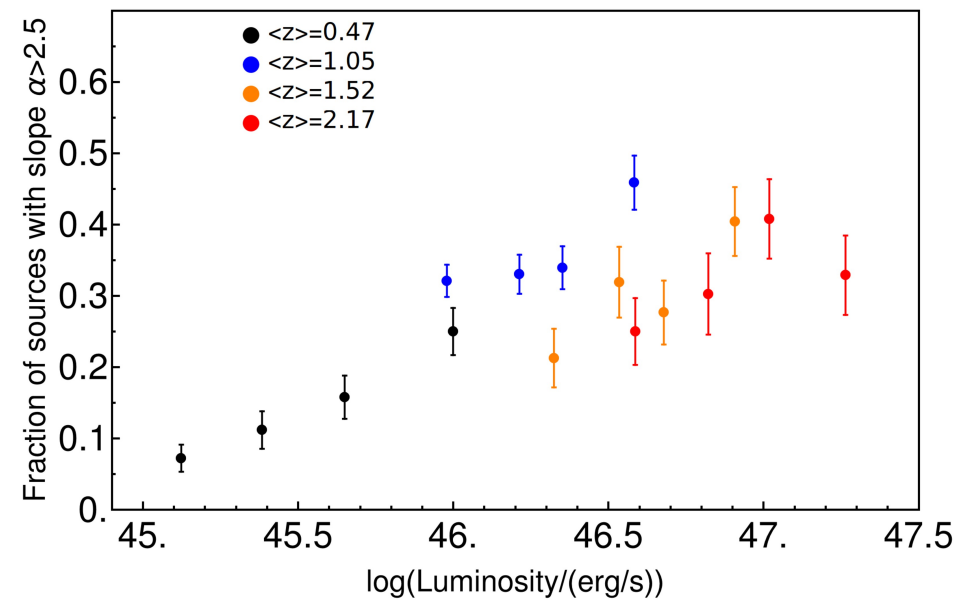
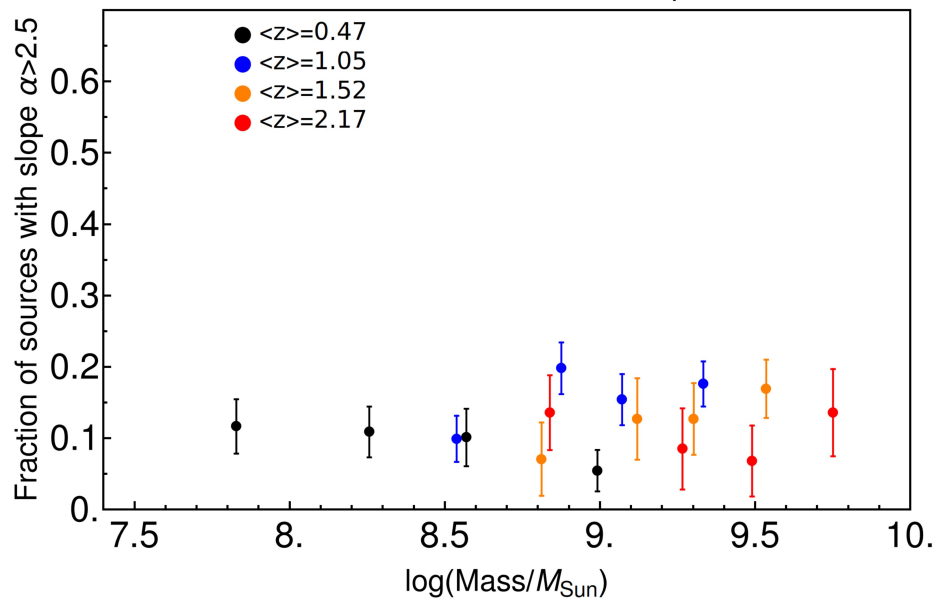
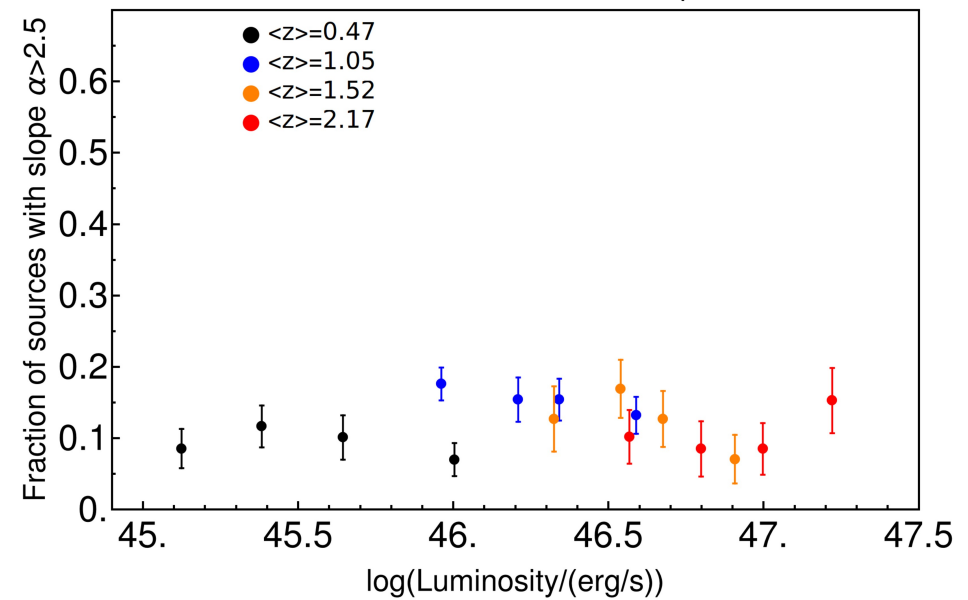
- New method → testing needed
- PSD estimates are highly uncertain → need a large statistical sample



PTF Data

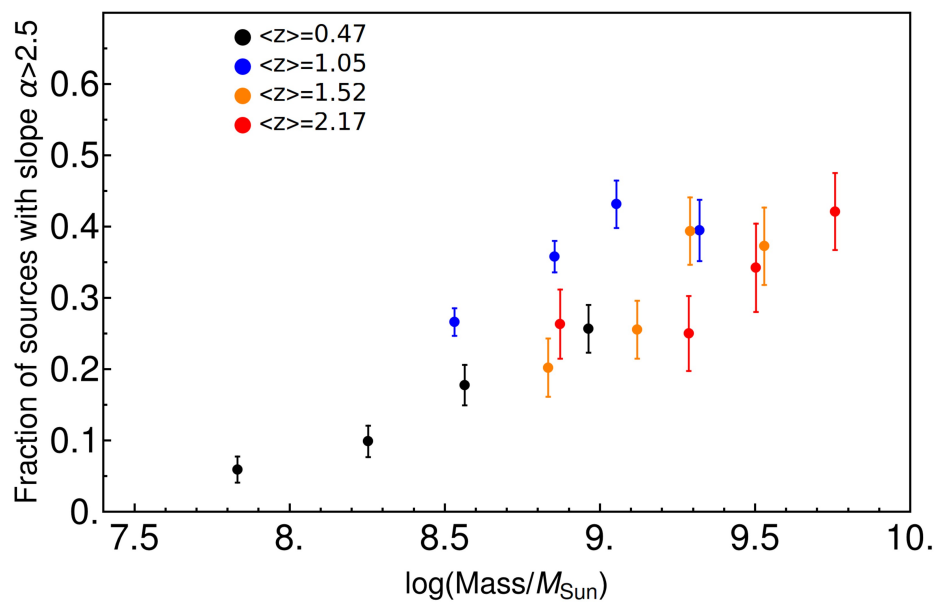


PTF Data

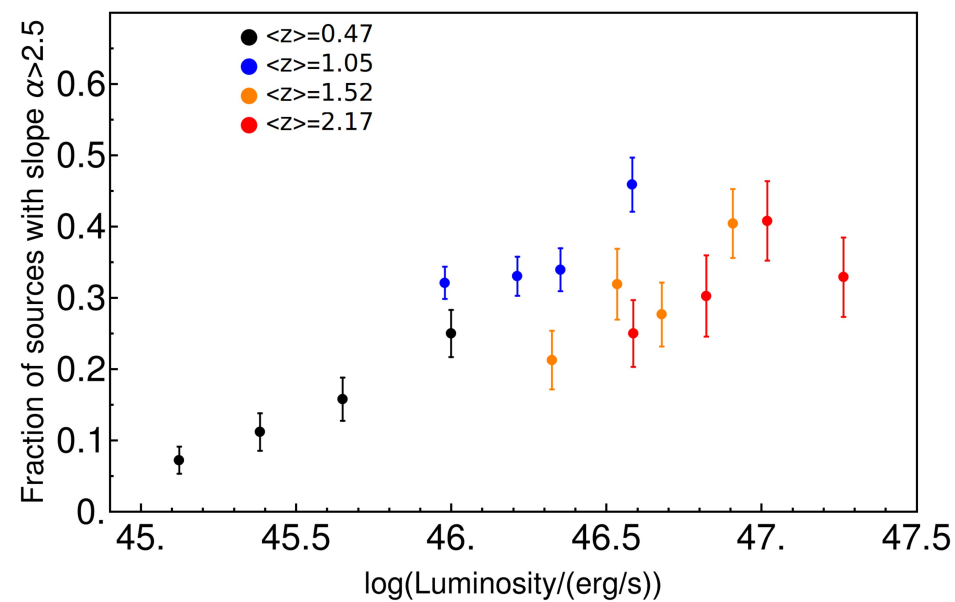
PTF Simulation with constant slope, $\alpha=2$ PTF Simulation with constant slope, $\alpha=2$ 

- Steepening of the slope with mass/luminosity

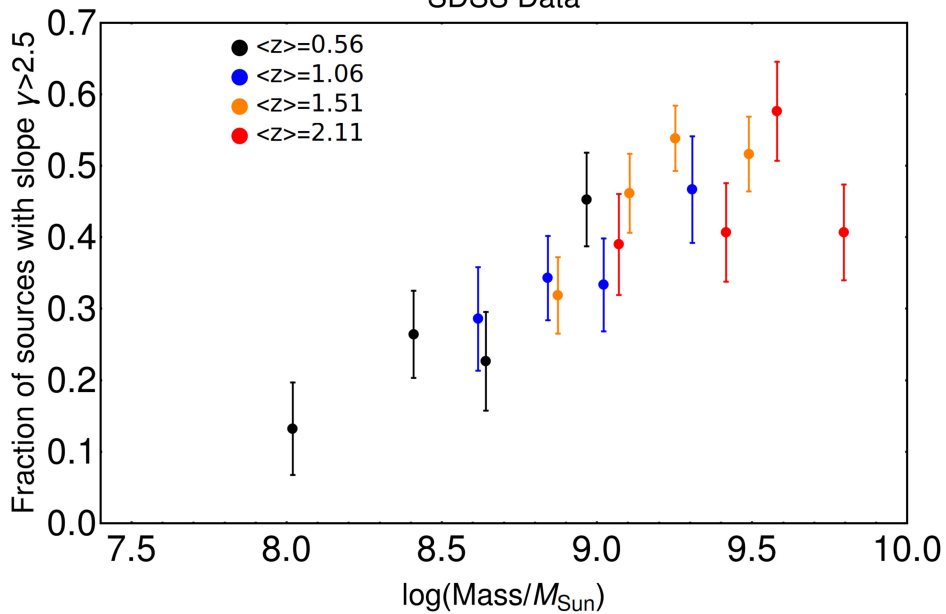
PTF Data



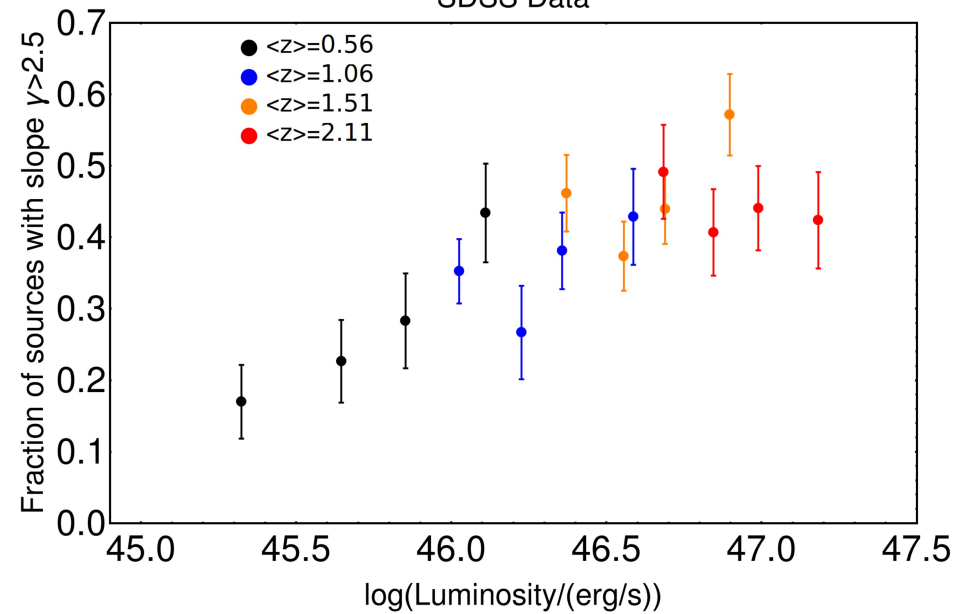
PTF Data



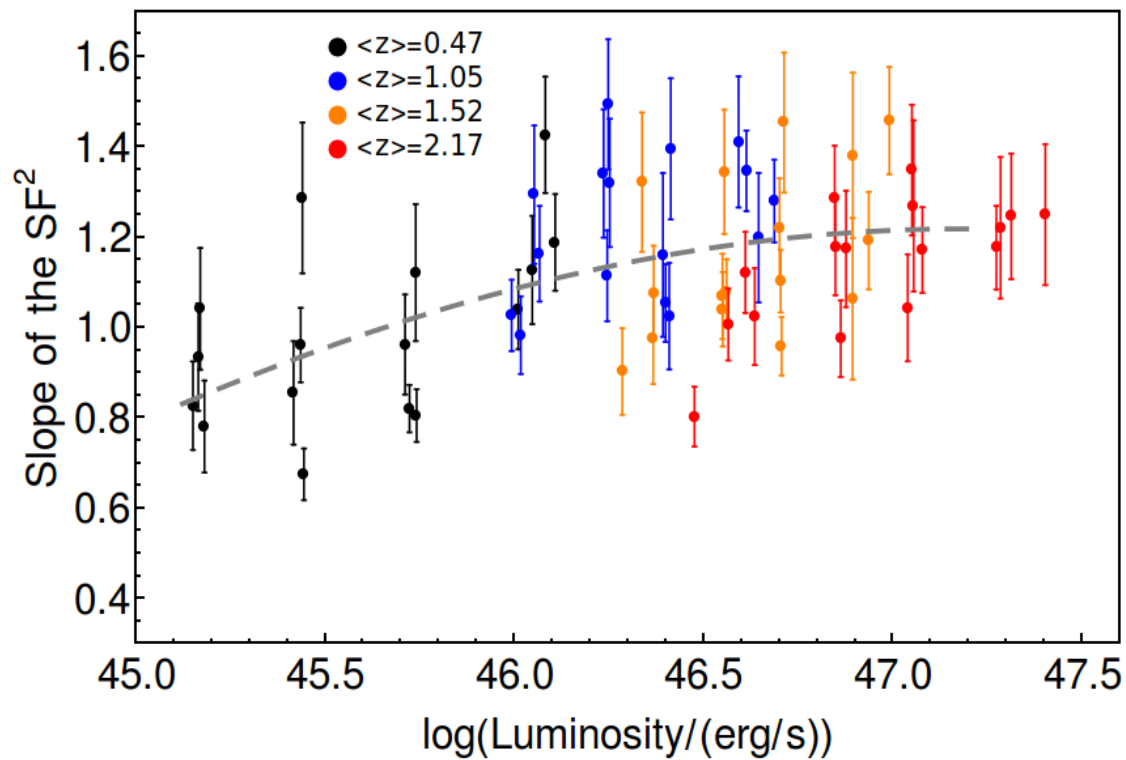
SDSS Data



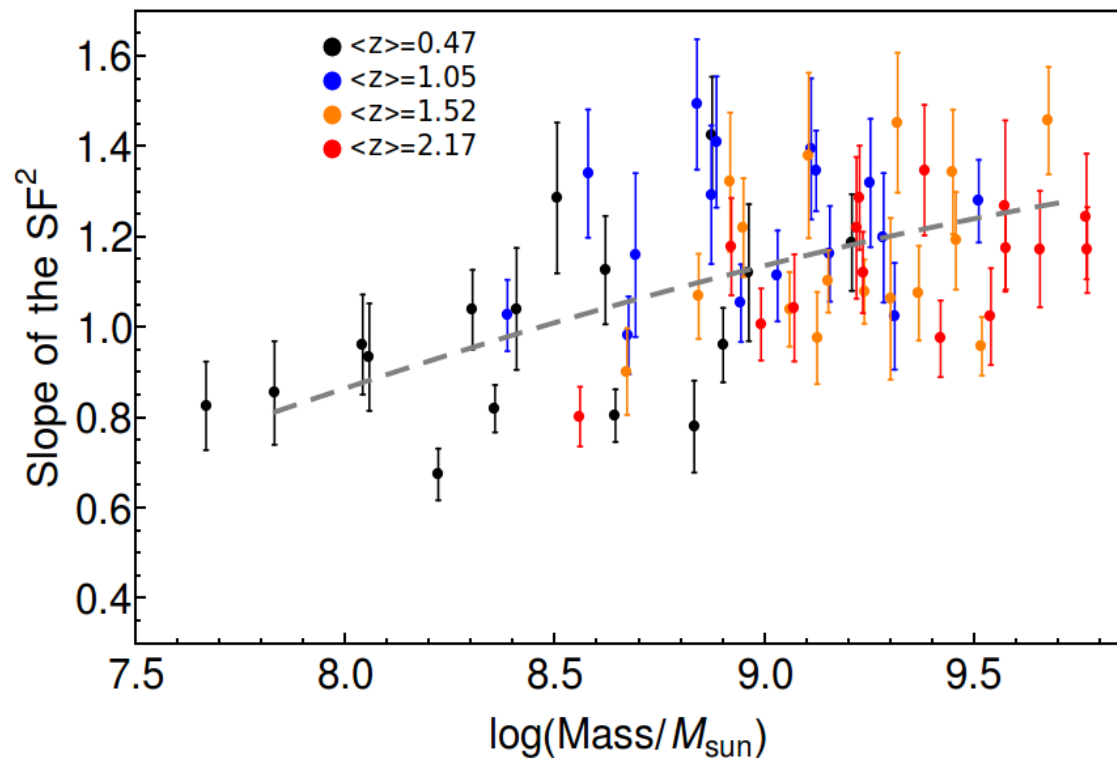
SDSS Data

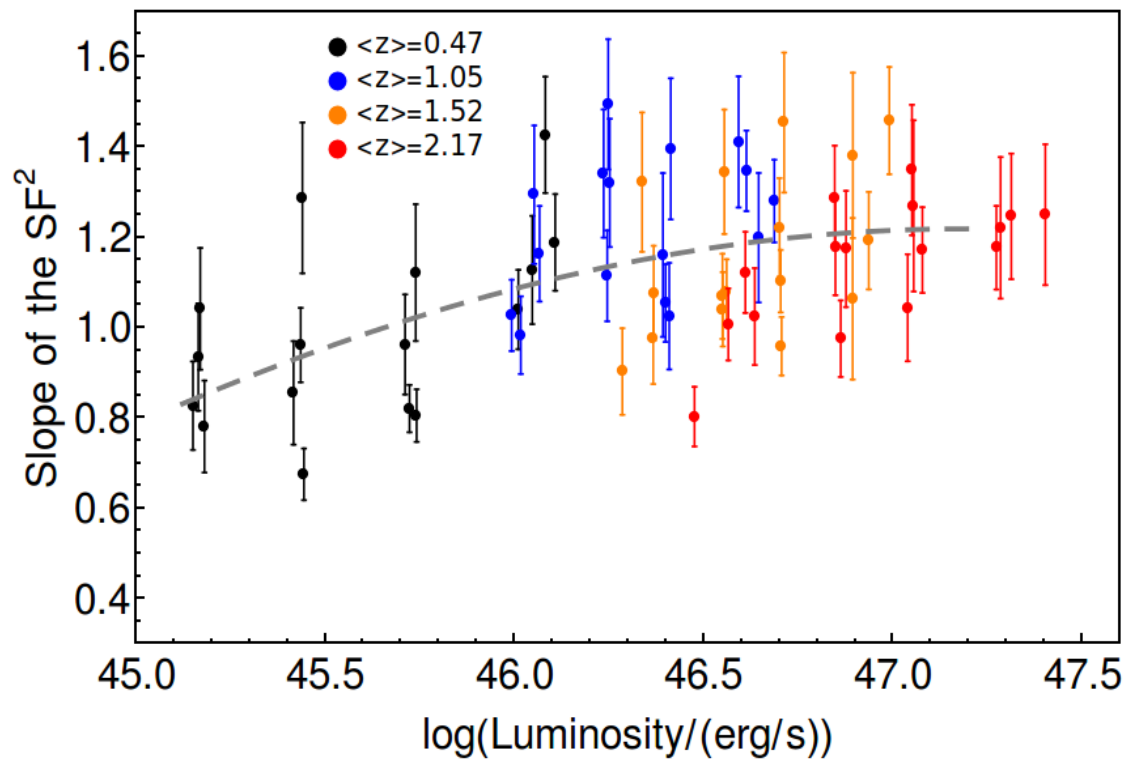


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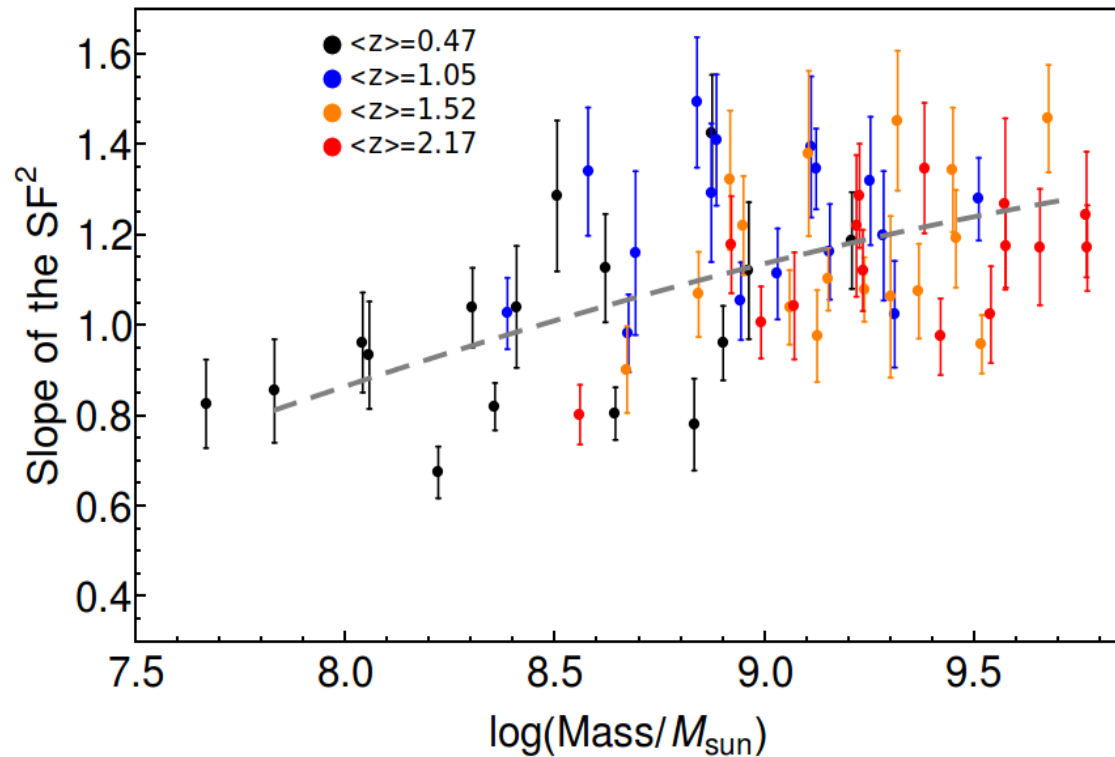


- Same steepening effect can be seen in the structure function analysis!
- Lines are deduced from PSD analysis, not fits!

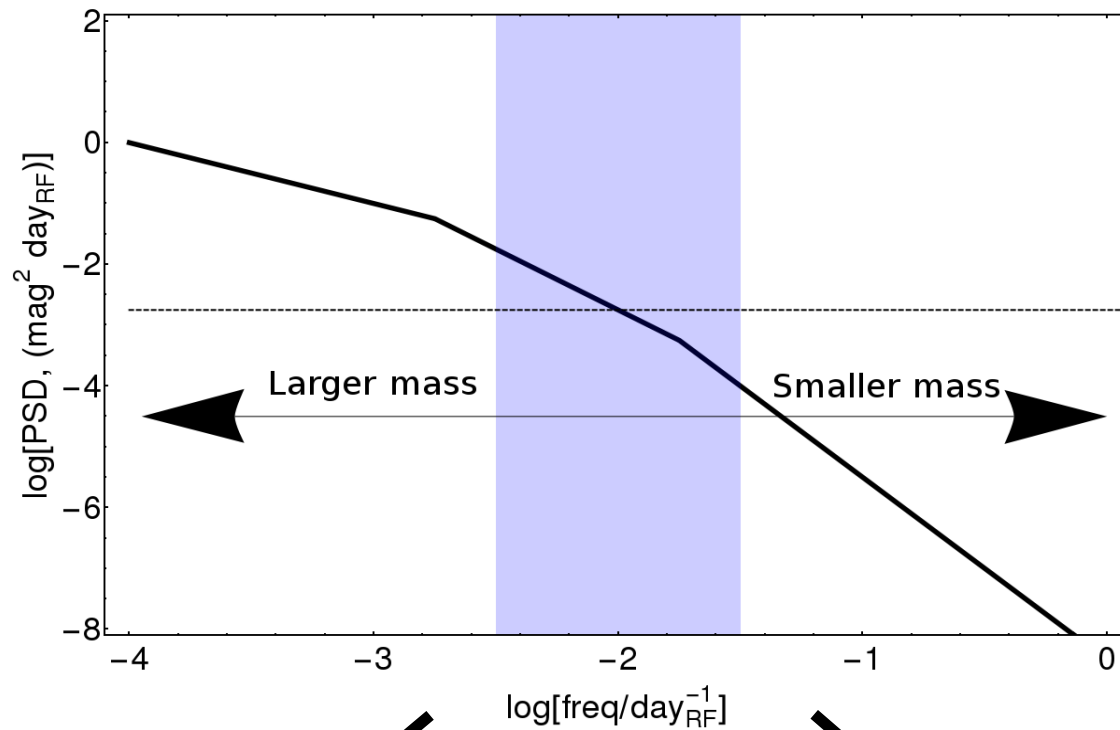




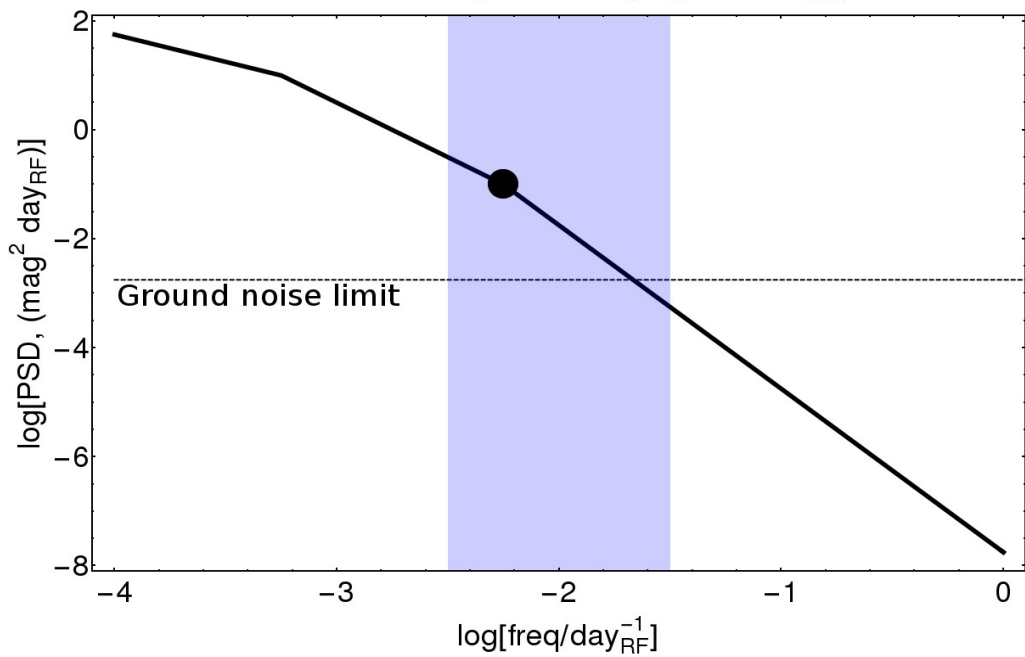
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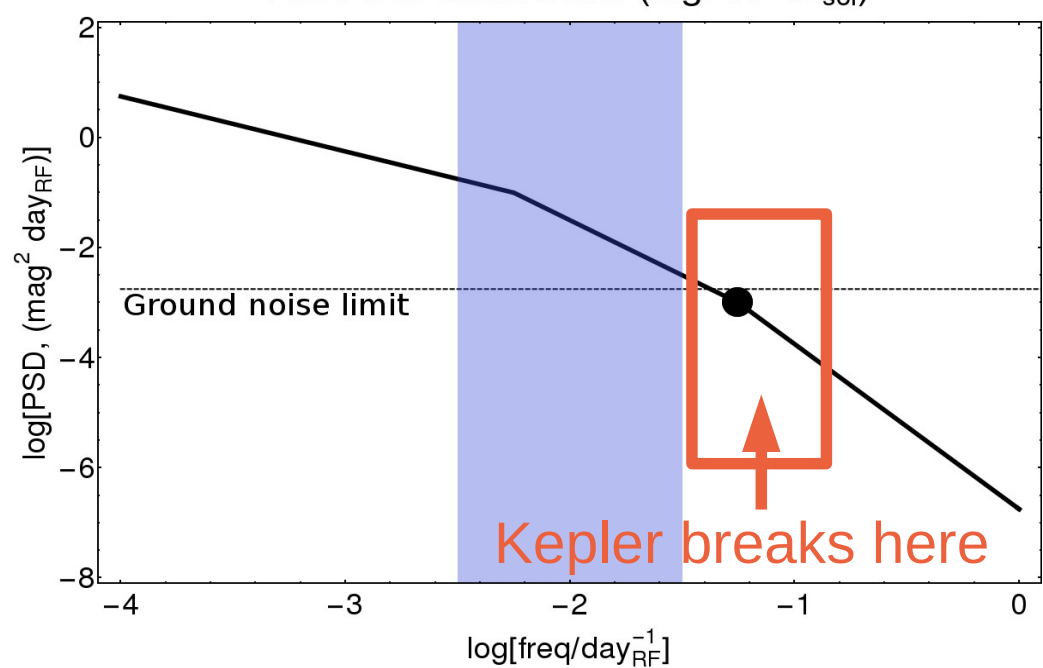
- Effect now seen with the SF analysis in PTF & SDSS (Kozłowski 16, and this work)
- Effect also seen in the PSD analysis in PTF, SDSS & Pan-STARRS1 (Simm+ 16, and this work)



AGN with large mass (e.g. $10^9 M_{\text{sol}}$)

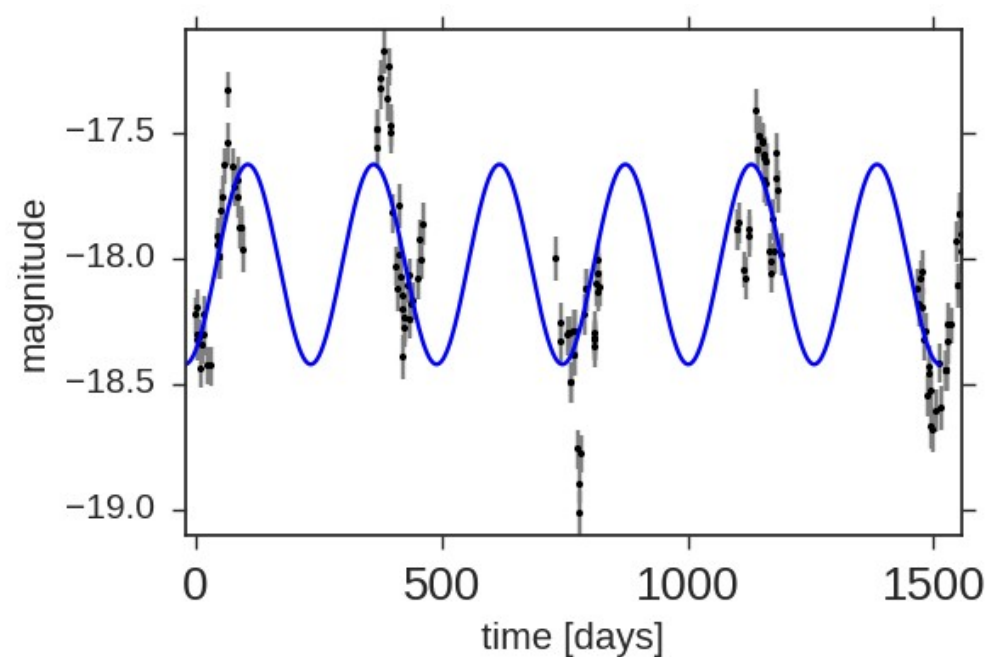
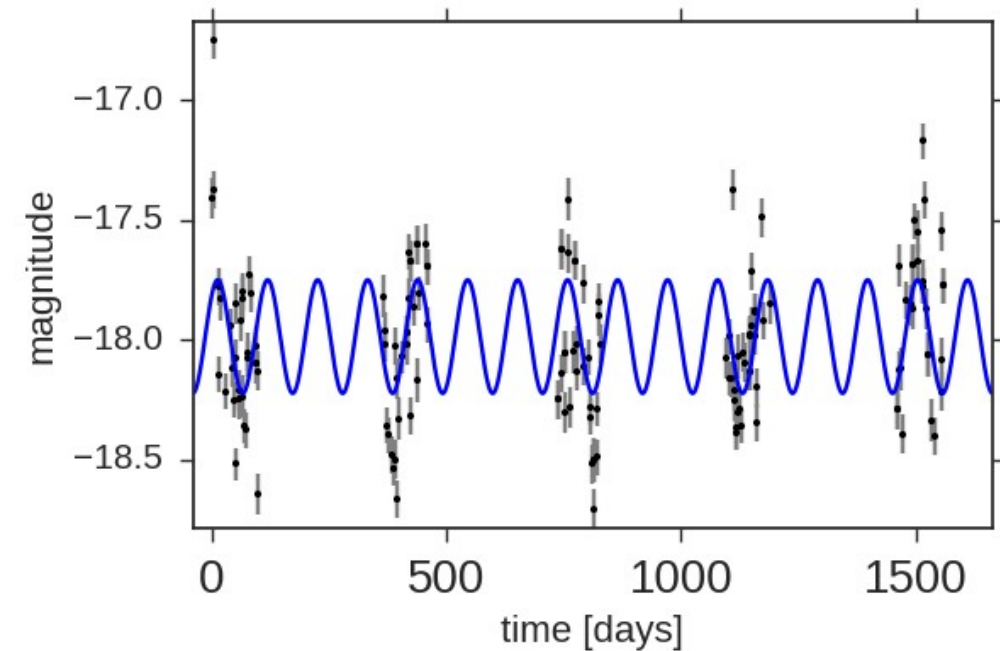
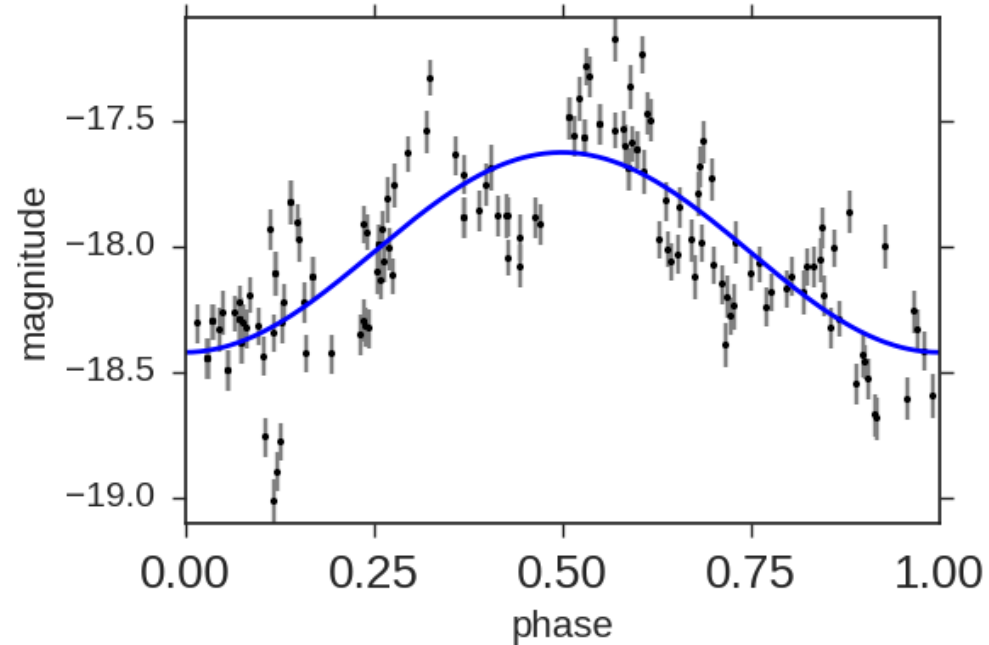
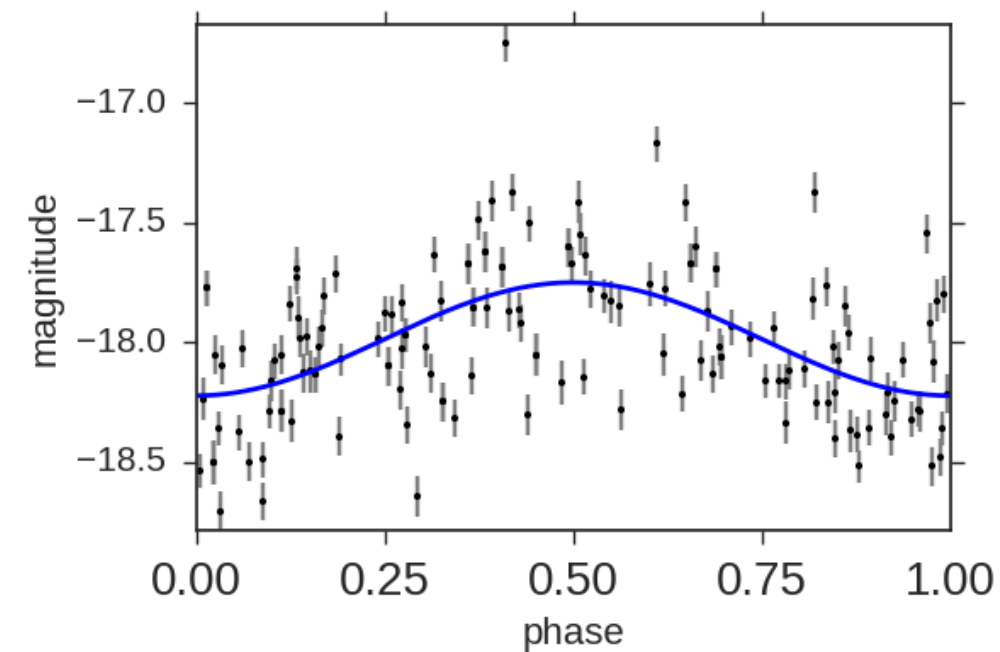


AGN with small mass (e.g. $10^7 M_{\text{sol}}$)



$\text{PSD} \propto f^{-1}$

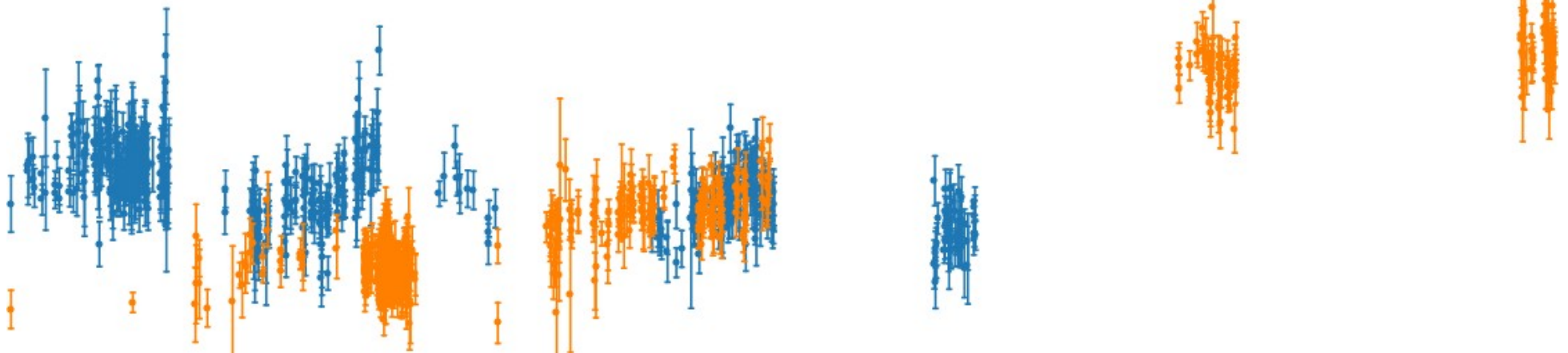
$\text{PSD} \propto f^{-3}$



- Steep PSDs are more likely to mimic periodic light-curves

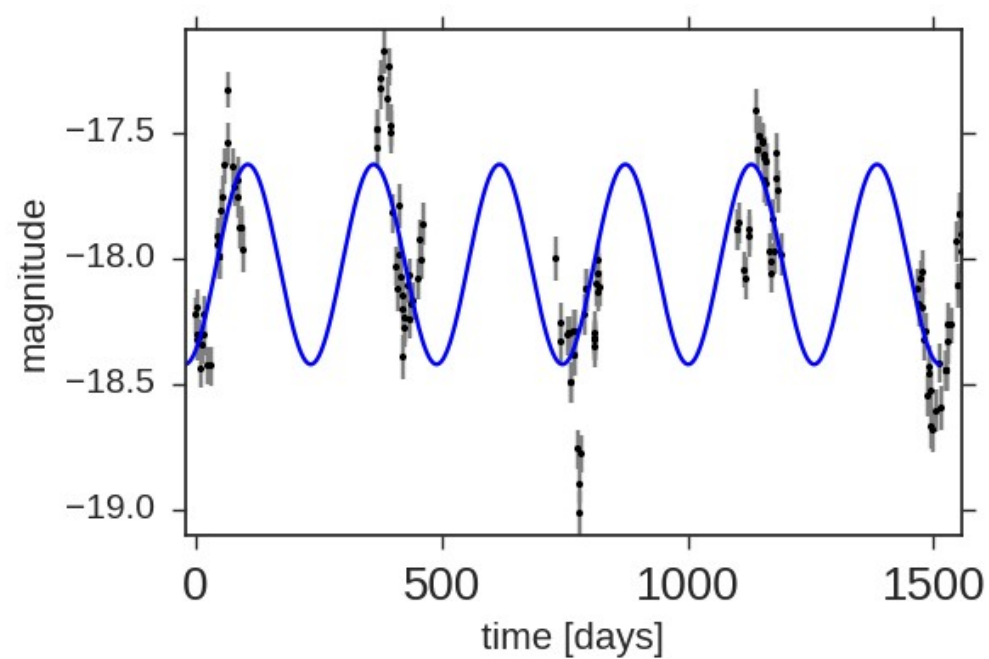
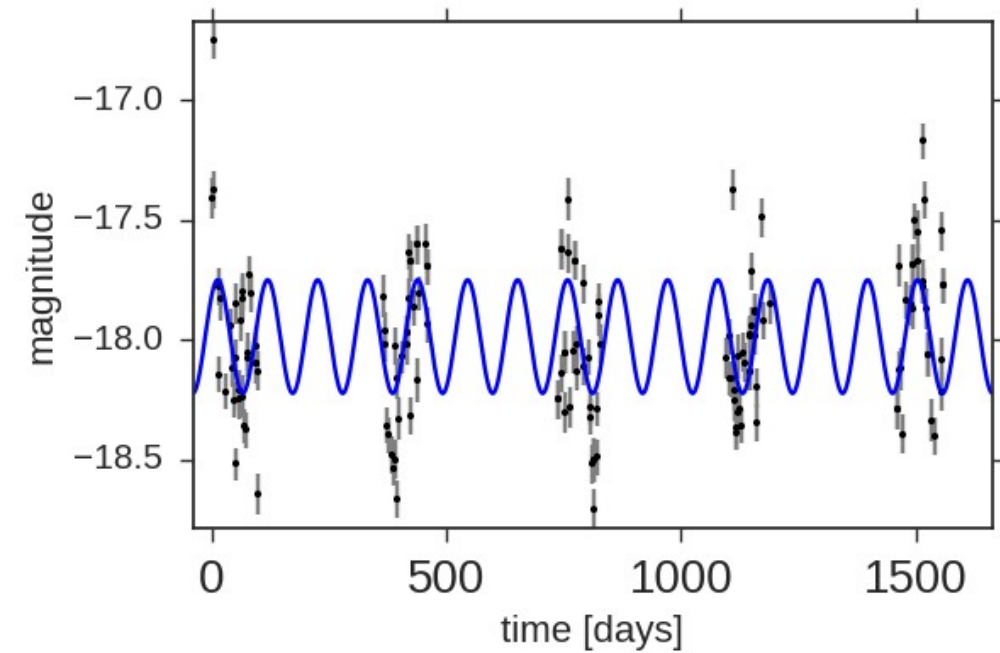
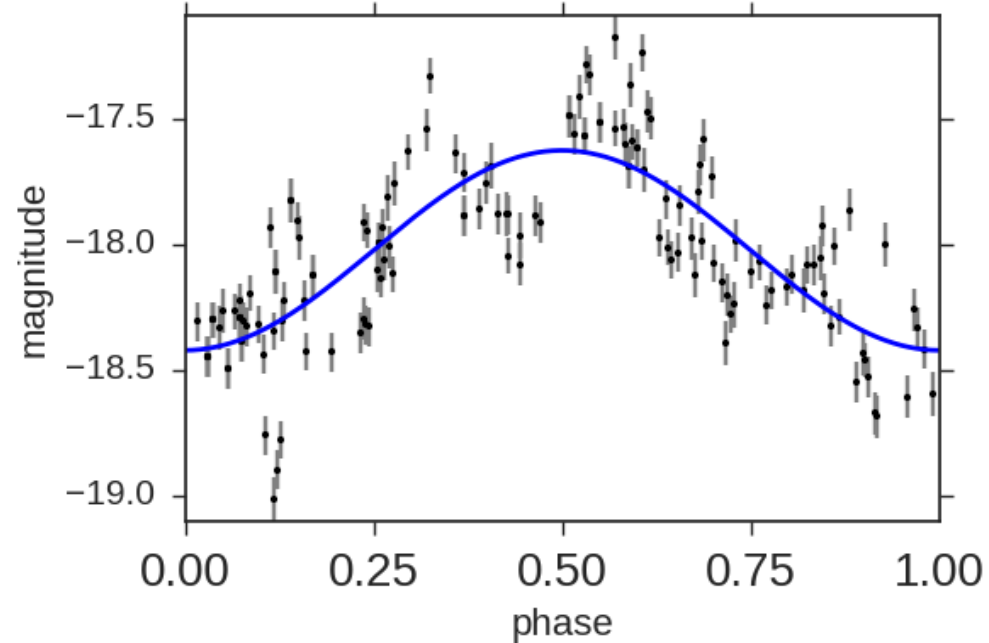
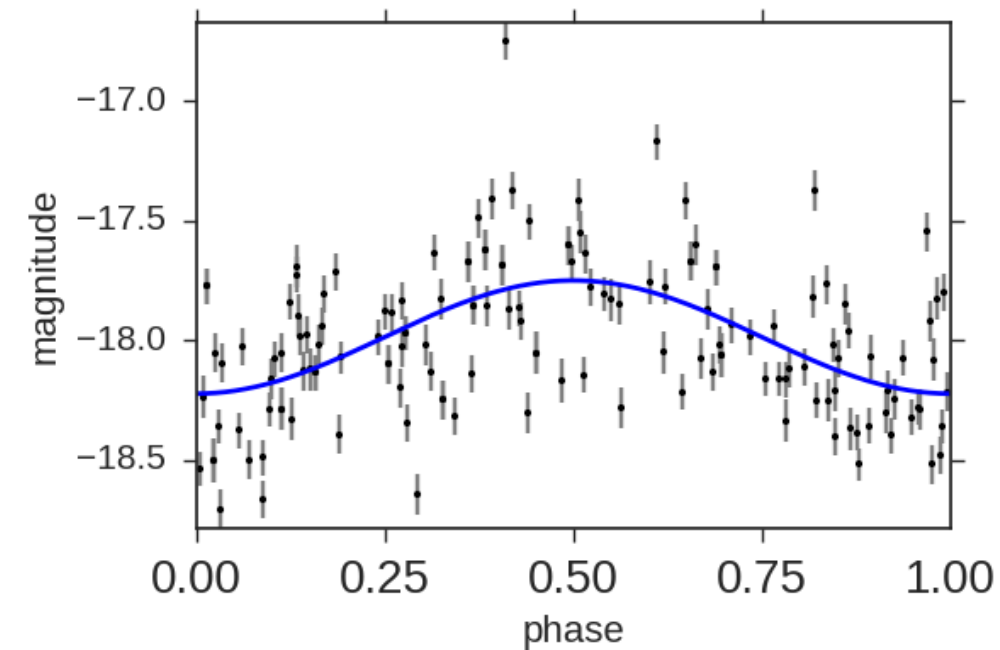
Summary

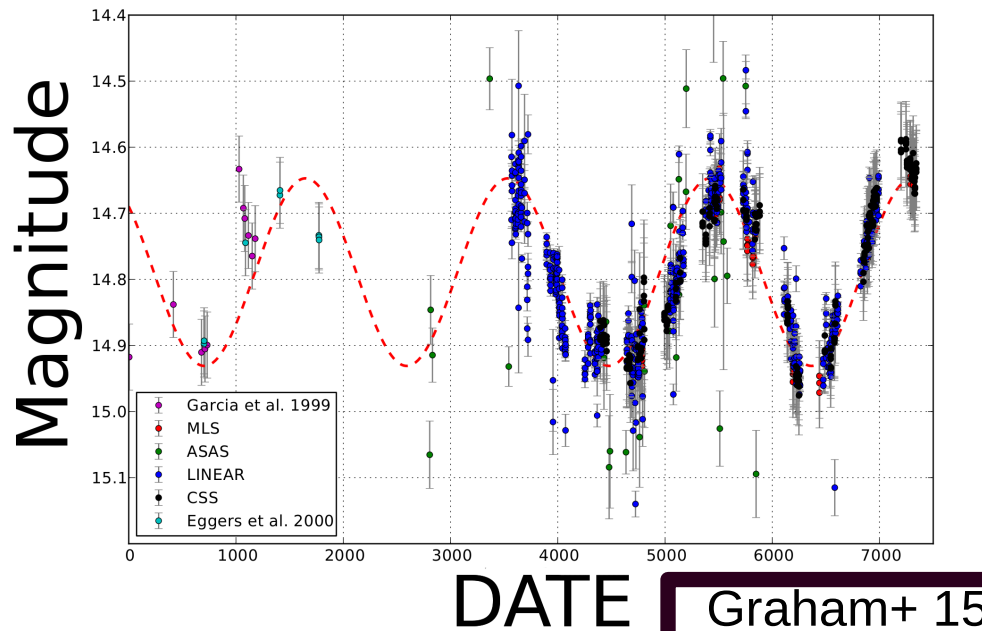
- PTF survey offers unique way to study AGN variability
 - Recalibrated data at https://github.com/nevencaplar/PTF_AGN
- Anti-correlation of variability with luminosity
 - If time to reach certain variability interpreted as time-scale τ , then $\tau \propto L^{0.4}$, similar to the prediction of the simplest model
- Evidence for steepening of the PSD slopes with mass
 - “Explanation” for Kepler steep slopes
 - More likely to create false periodicities



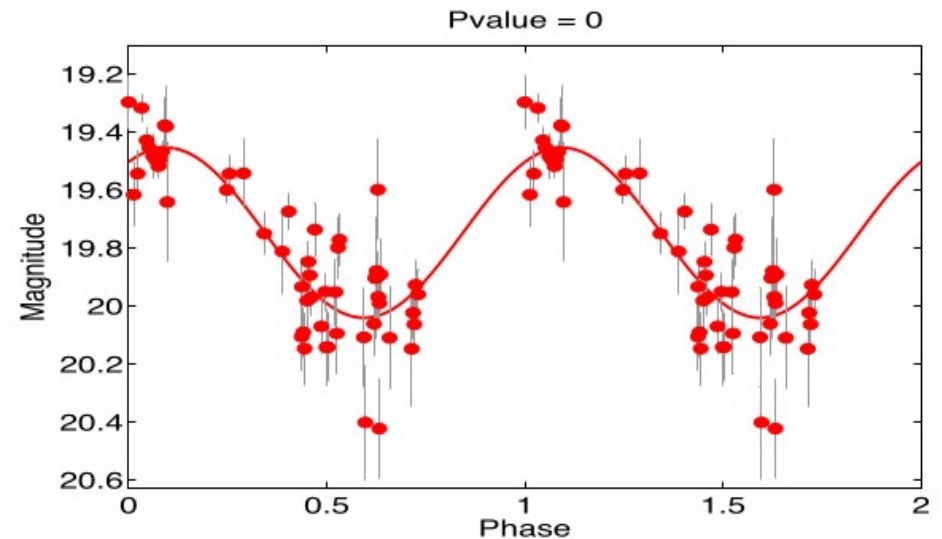
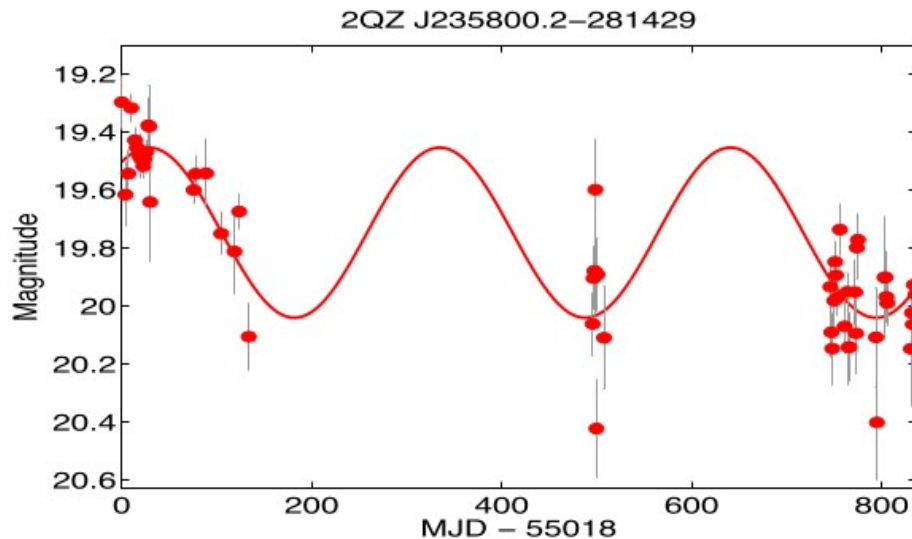
$\text{PSD} \propto f^{-1}$

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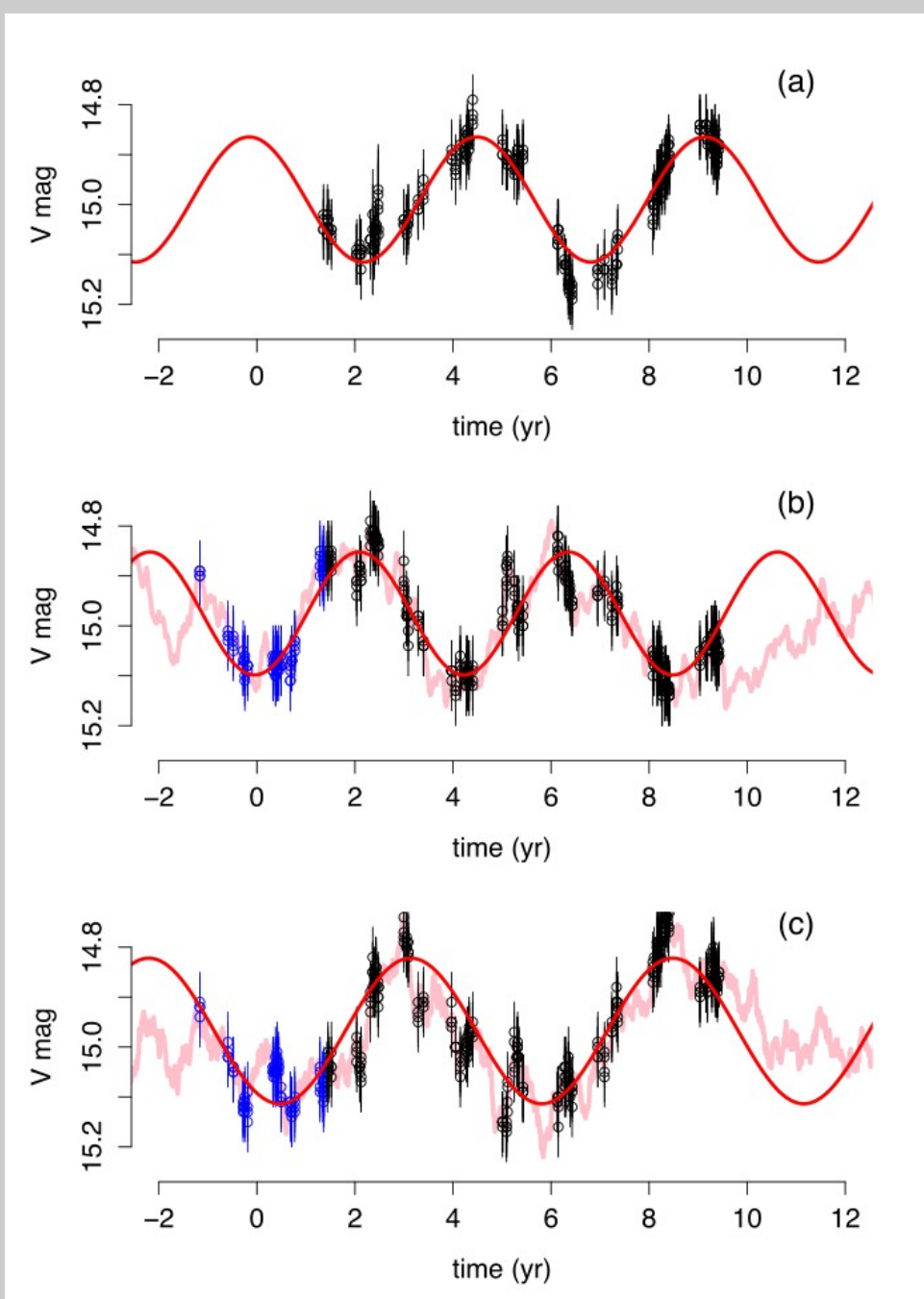




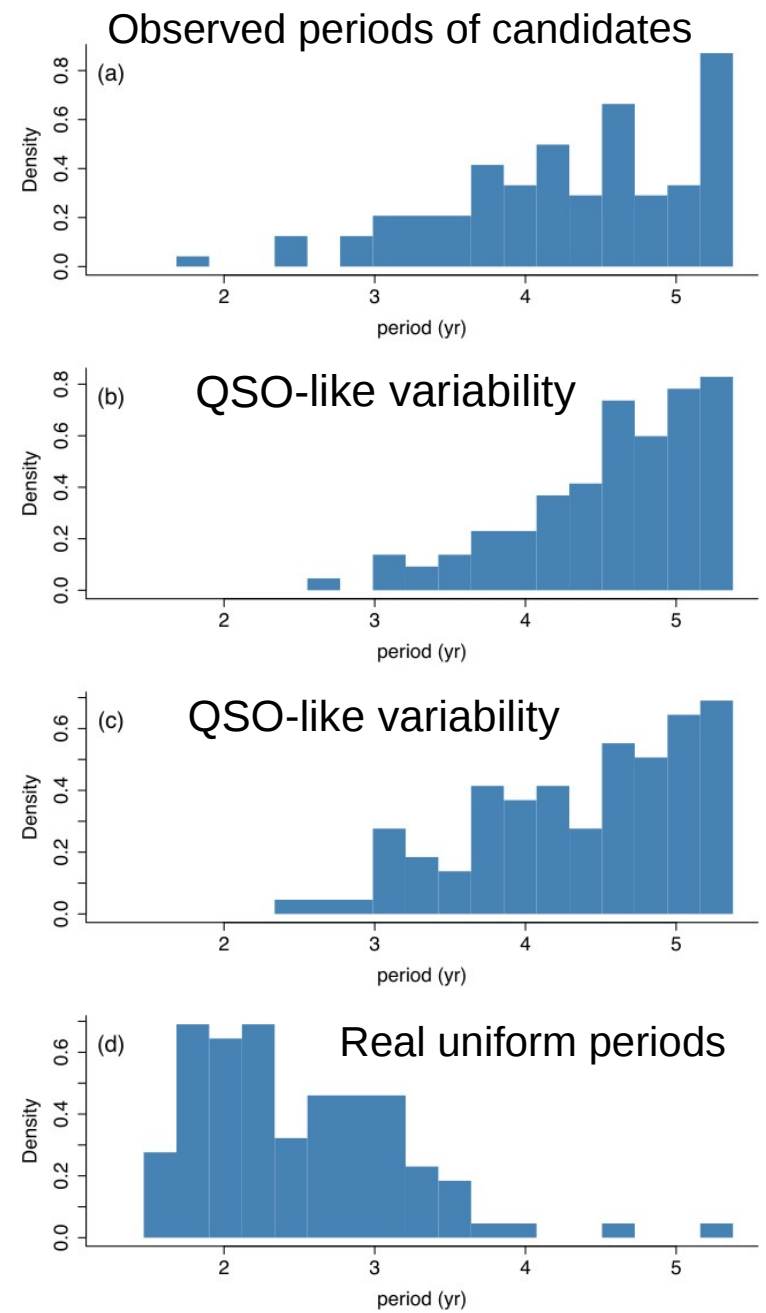
- Search for binaries of supermassive black holes with a sub-parsec separation
- Expected as a consequence of galaxy mergers



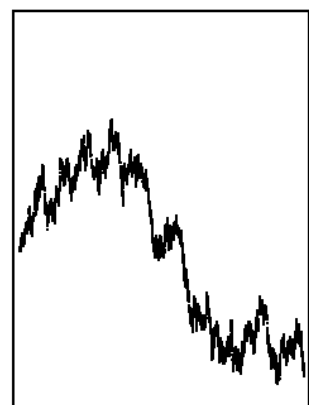
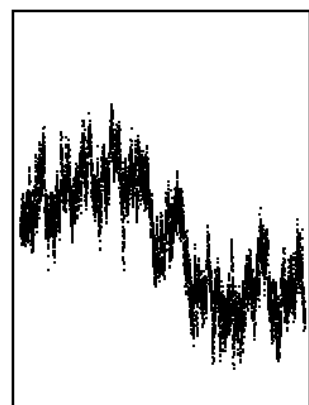
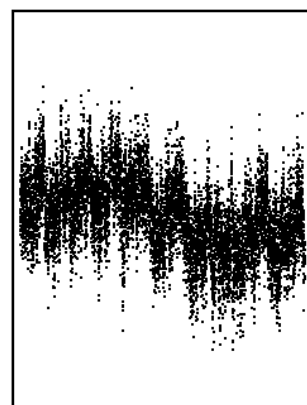
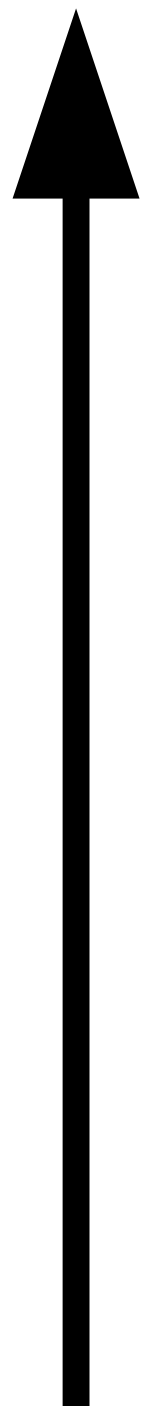
Charisi+ 16



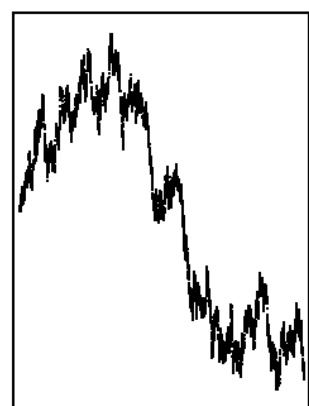
- But stochastic process can also mimic periodicity!



More variability



Magnitudes

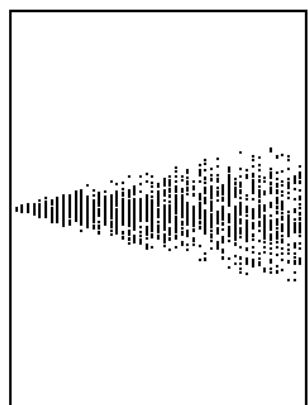
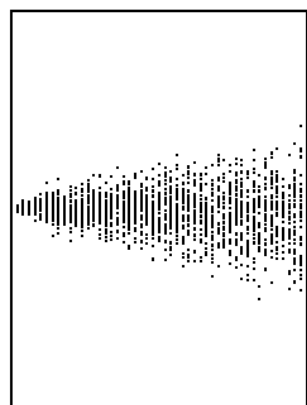
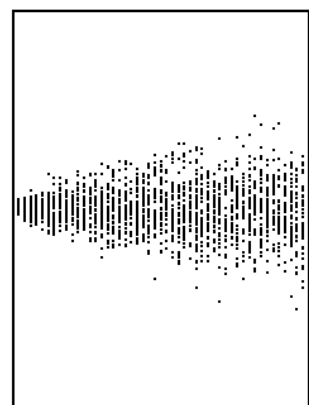
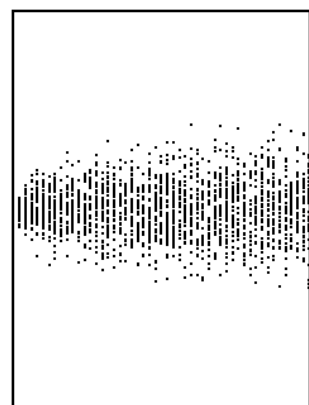
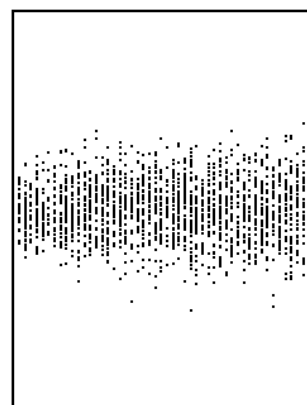


Time

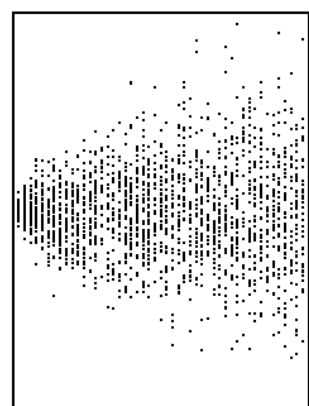
More "structure"



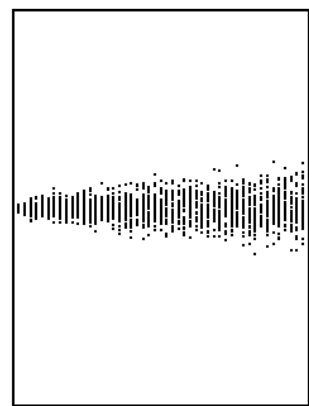
More variability



Δ mag



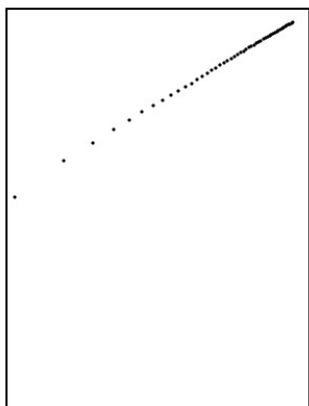
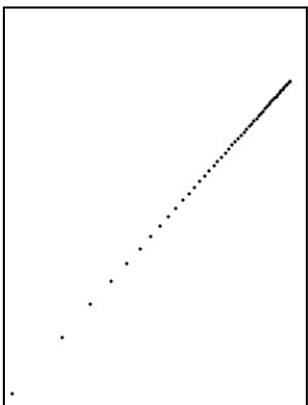
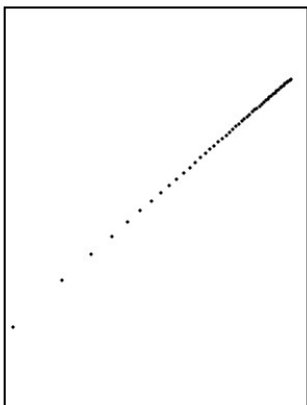
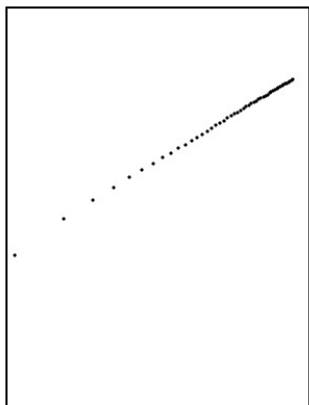
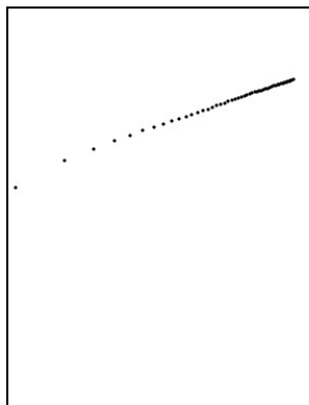
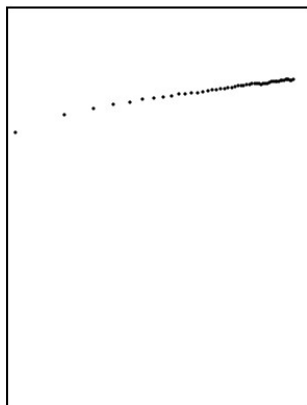
Time



More "structure"



More variability



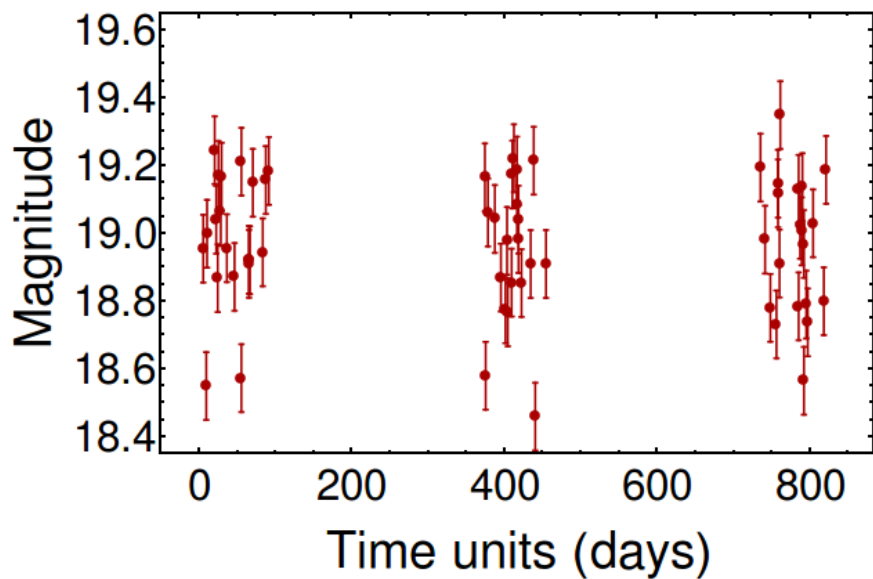
Log[SF²]

Log[Time]

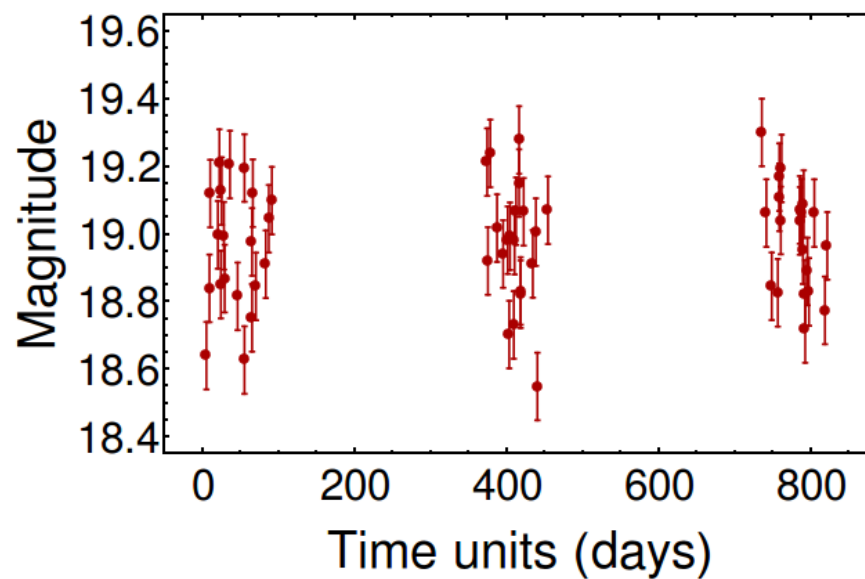
More "structure"



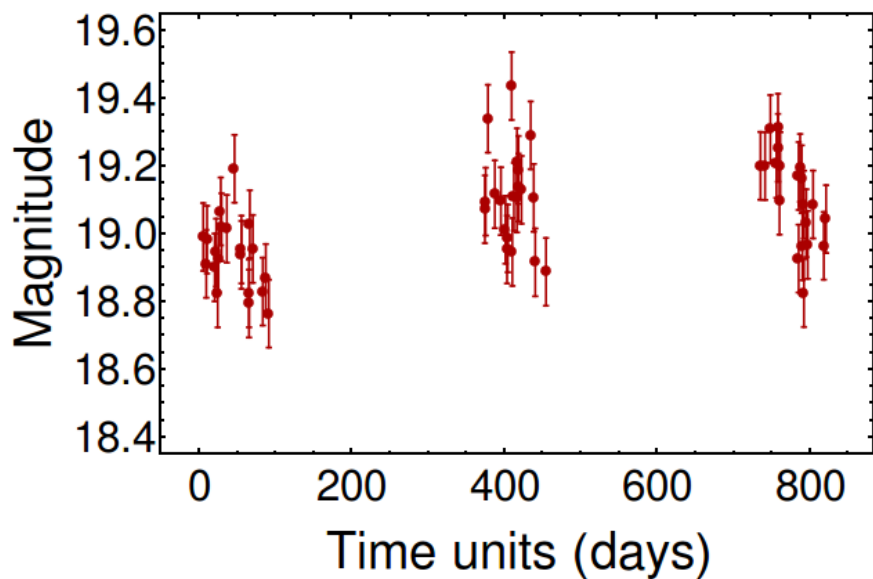
$$\text{PSD} \propto f^0$$



$$\text{PSD} \propto f^{-1}$$



$$\text{PSD} \propto f^{-2}$$



$$\text{PSD} \propto f^{-3}$$

