

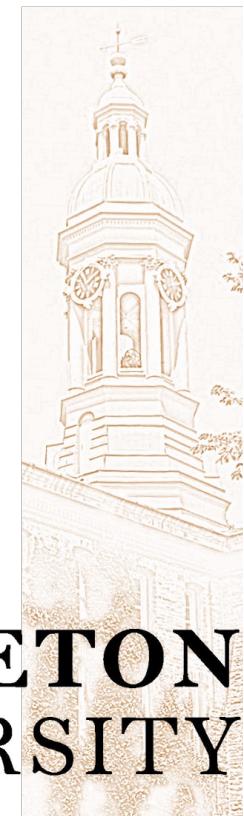
Stochastic view of AGN and galaxy evolution

Neven Caplar

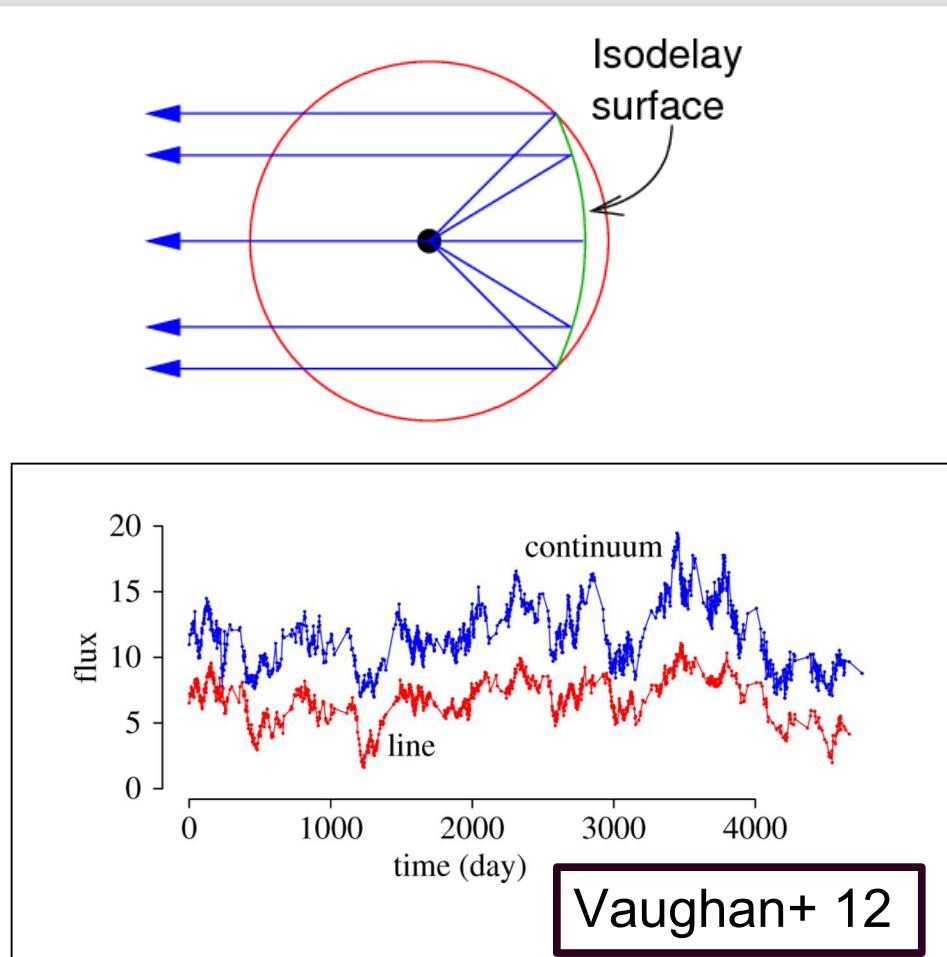
Sandro Tacchella, Simon Lilly,
Benny Trakhtenbrot, Kartheik Iyer



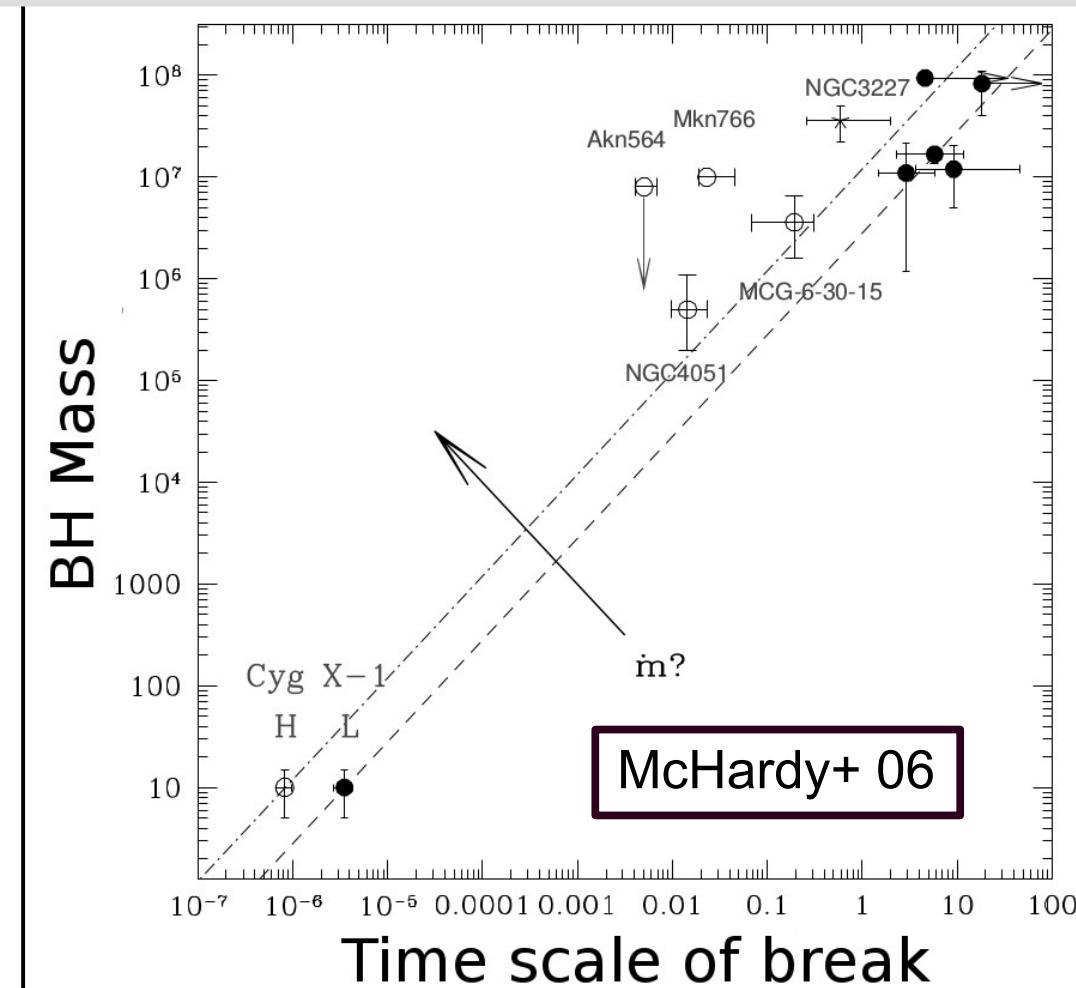
**PRINCETON
UNIVERSITY**



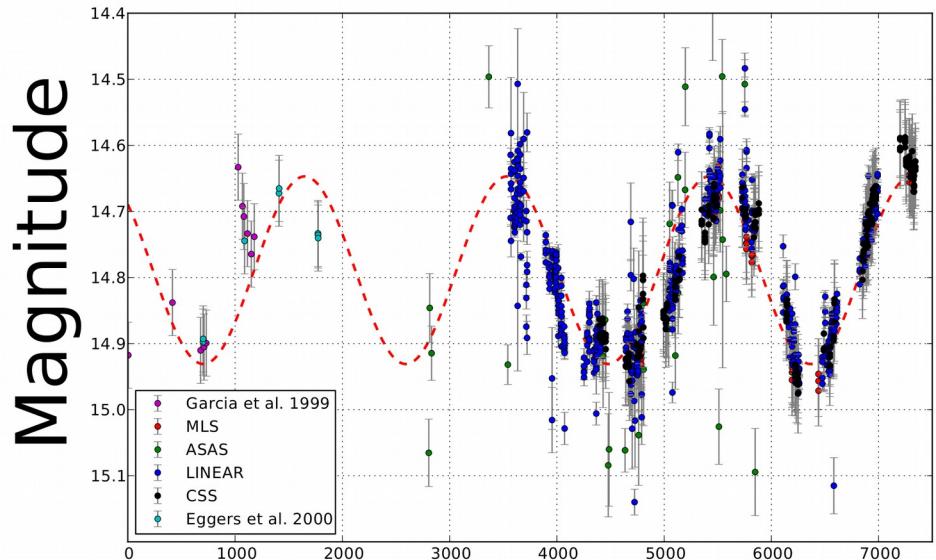
Why quasar variability?



- Reverberation mapping
- Probes structure of broad-line region
- Method to measure BH mass

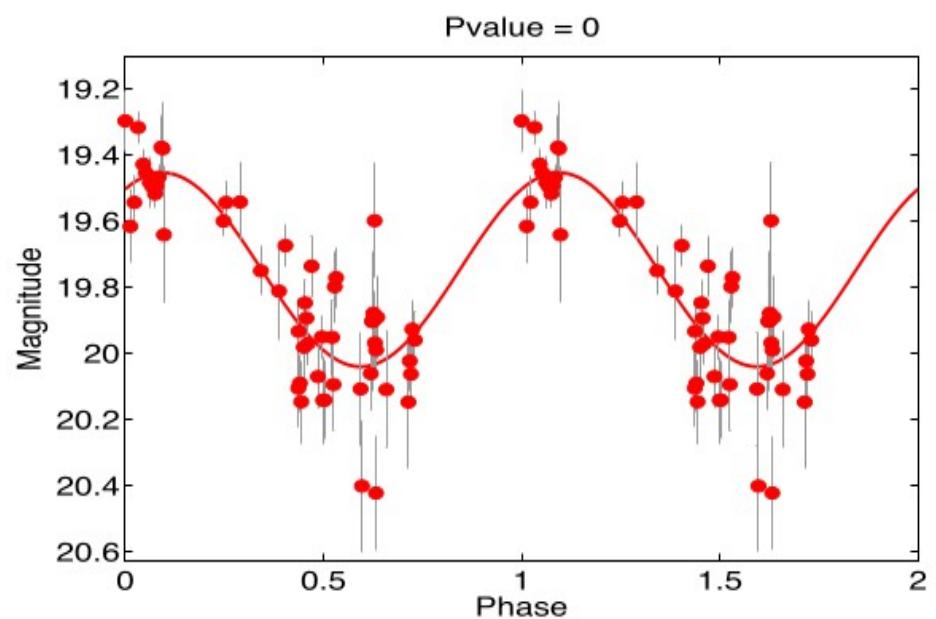
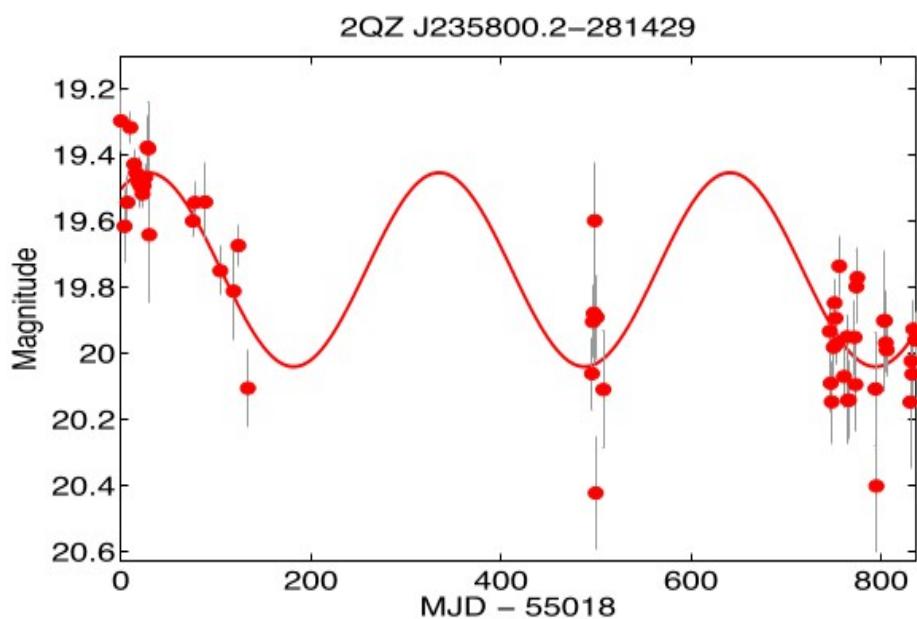


- BH mass correlated with with break in the X-ray power spectrum density

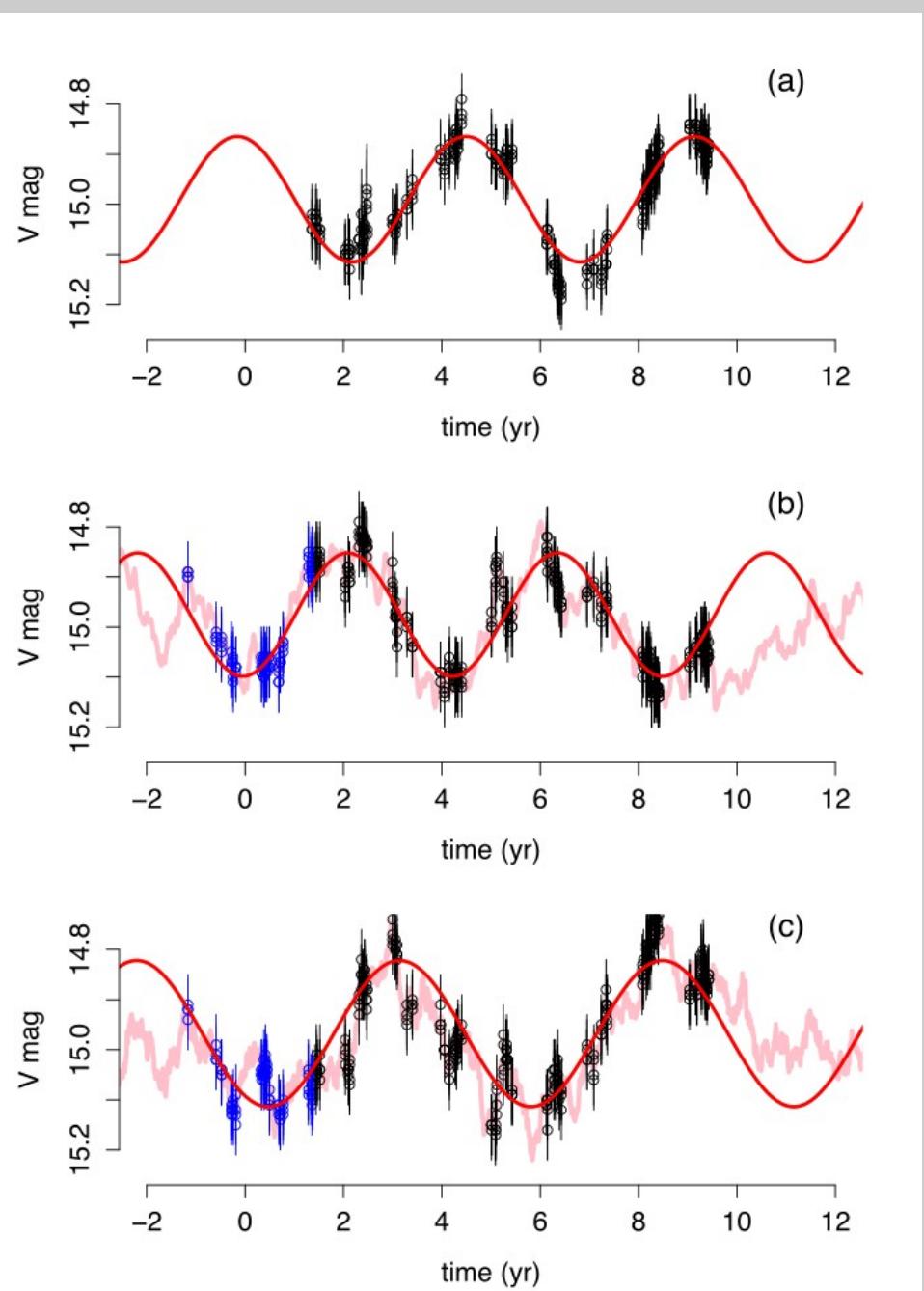


- Search for binaries of supermassive black holes with a sub-parsec separation
- Expected as a consequence of galaxy mergers

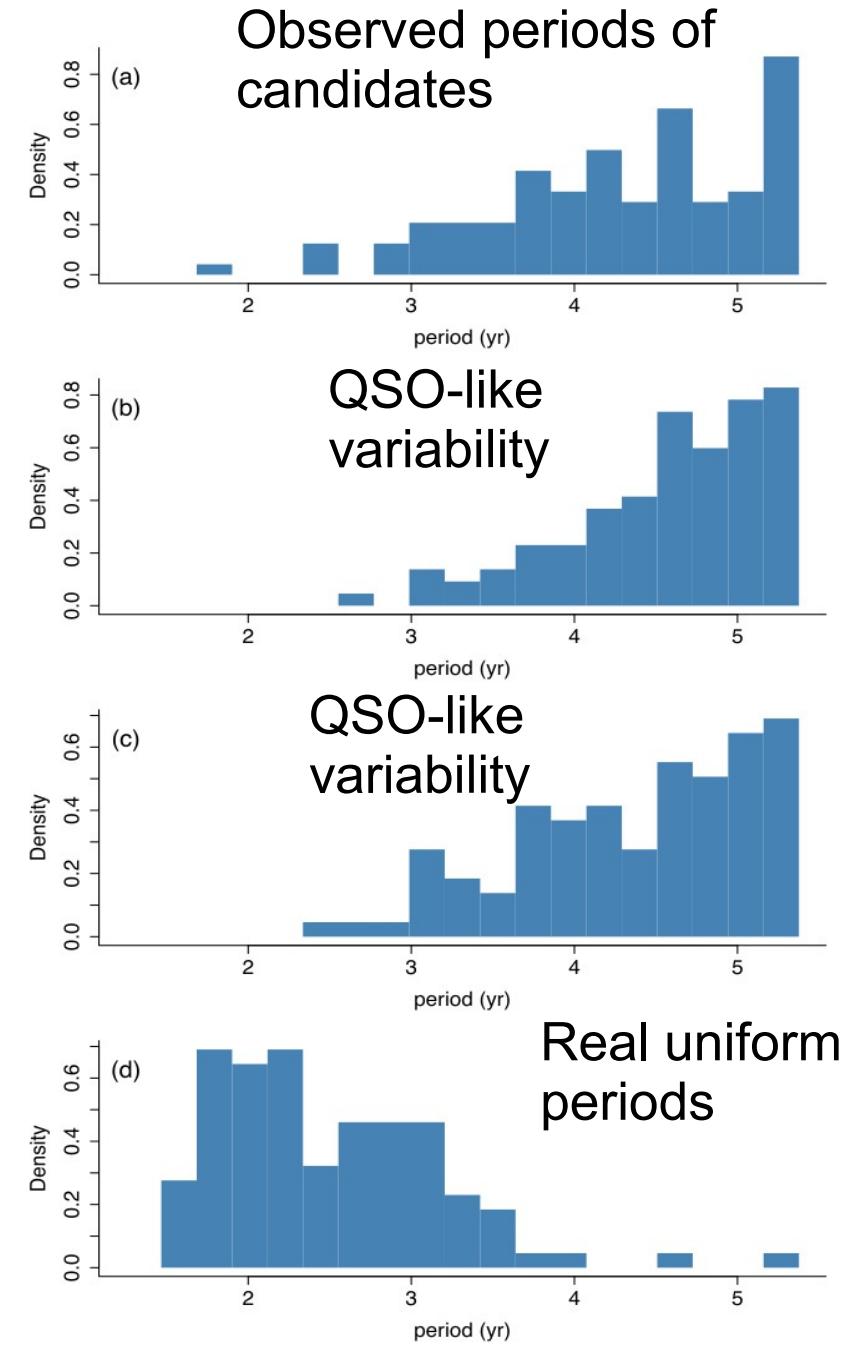
DATE Graham+ 15



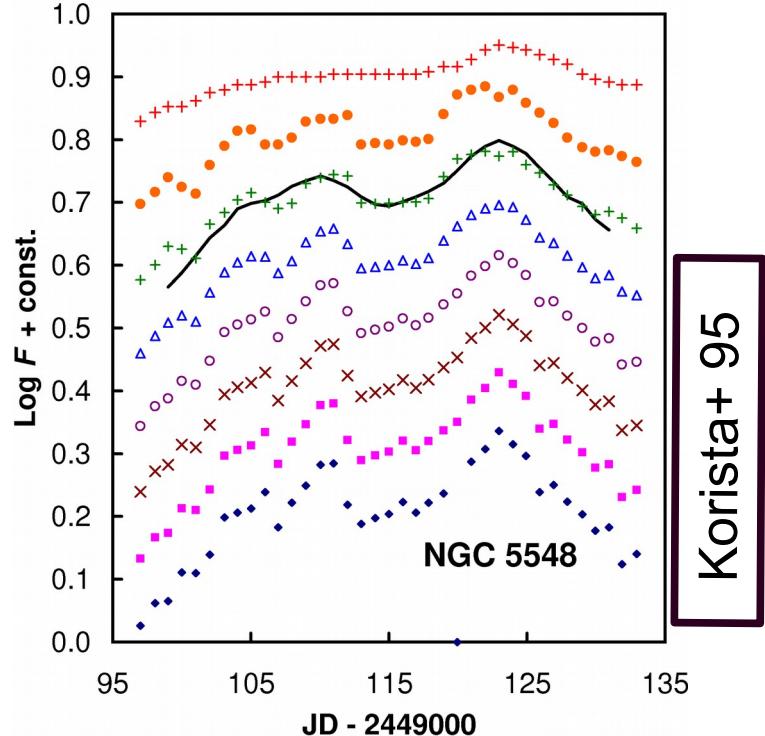
Charisi+ 16



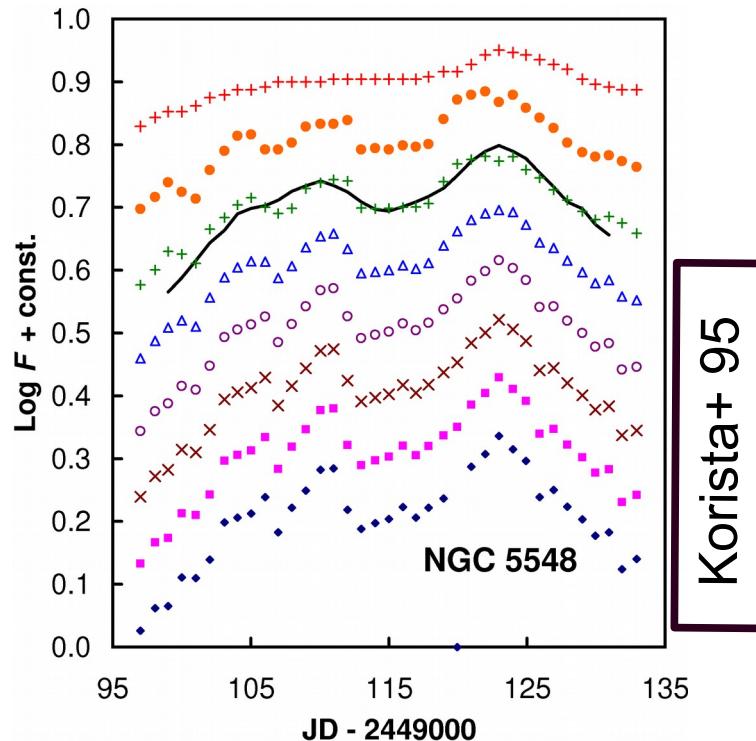
- But stochastic process can also mimic periodicity!



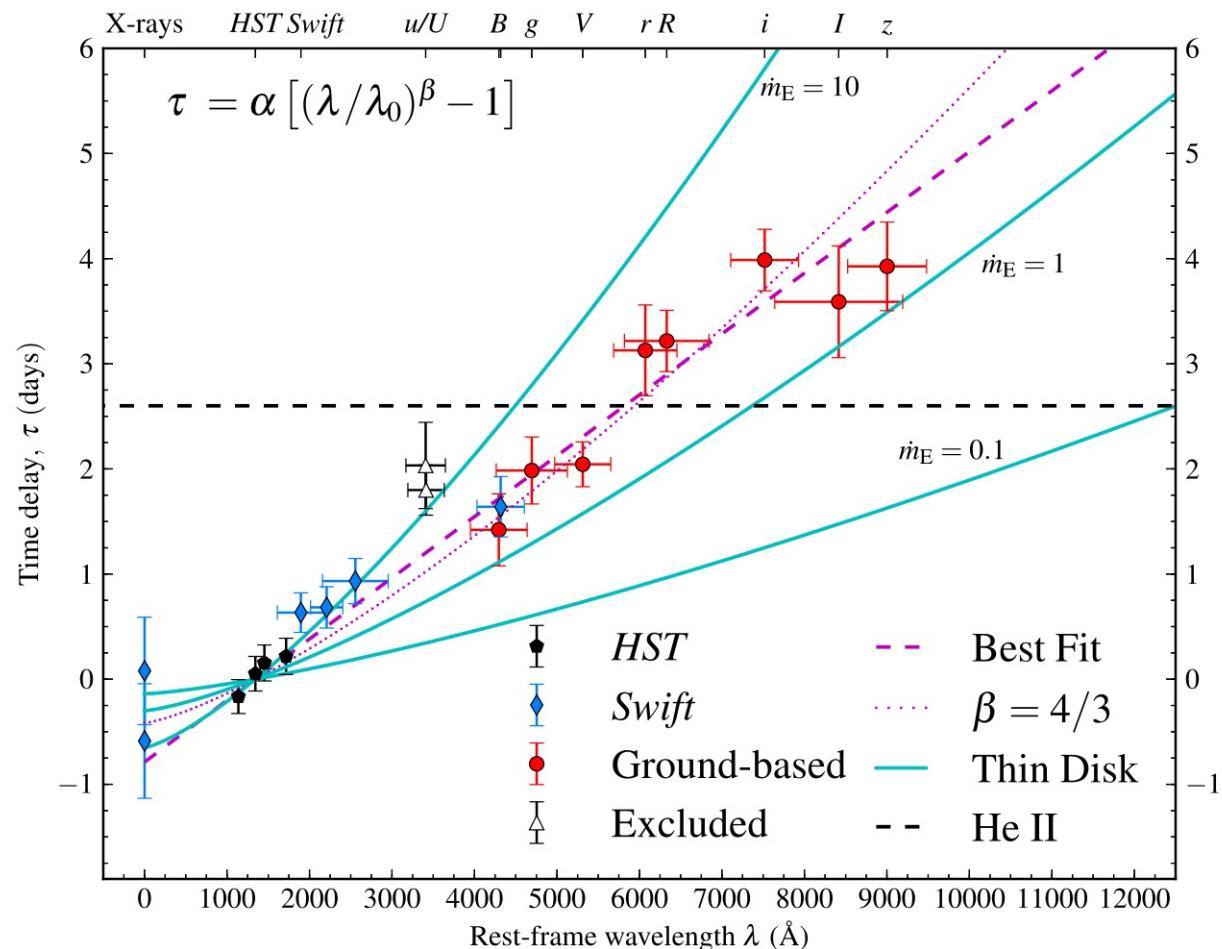
Vaughan+ 16



- Quasar variability as a test of accretion disk physics



- Quasar variability as a test of accretion disk physics



- Different wavebands are correlated
- Time delays of several days
- Comparable to light-travel time?

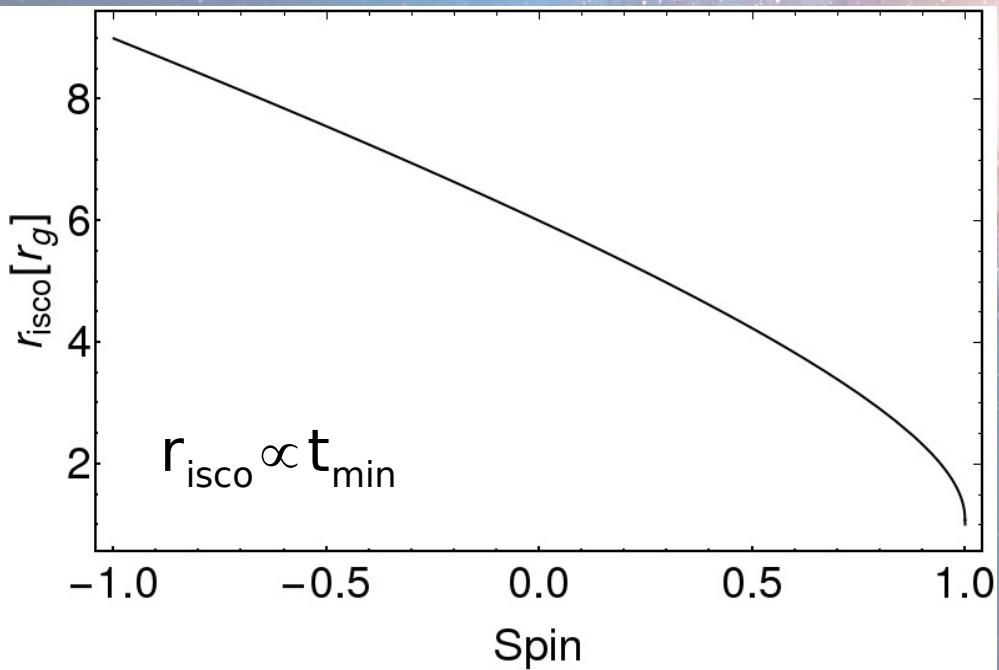
Fausnaugh+ 16

- Quasar variability as a method to measure spin



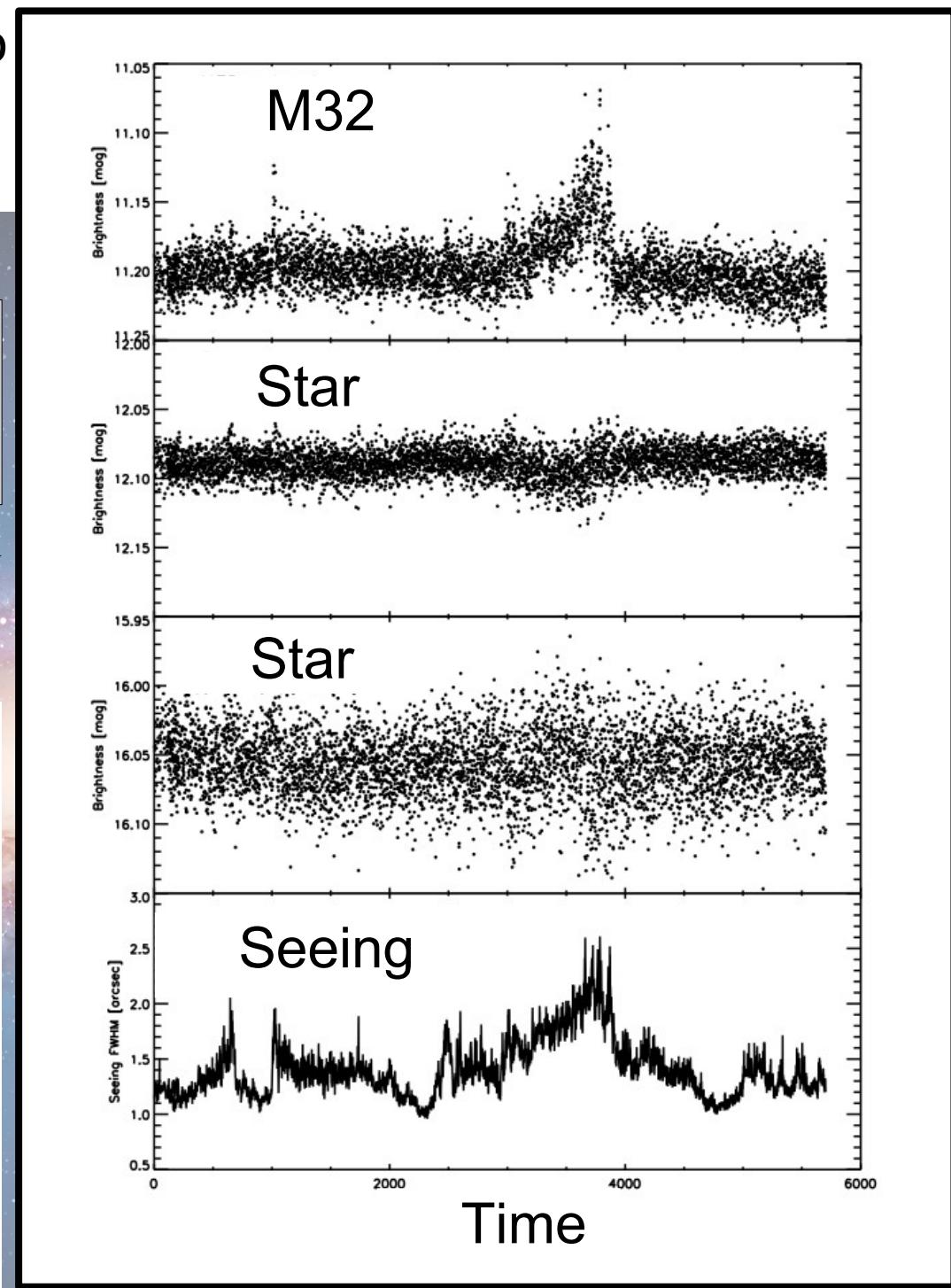
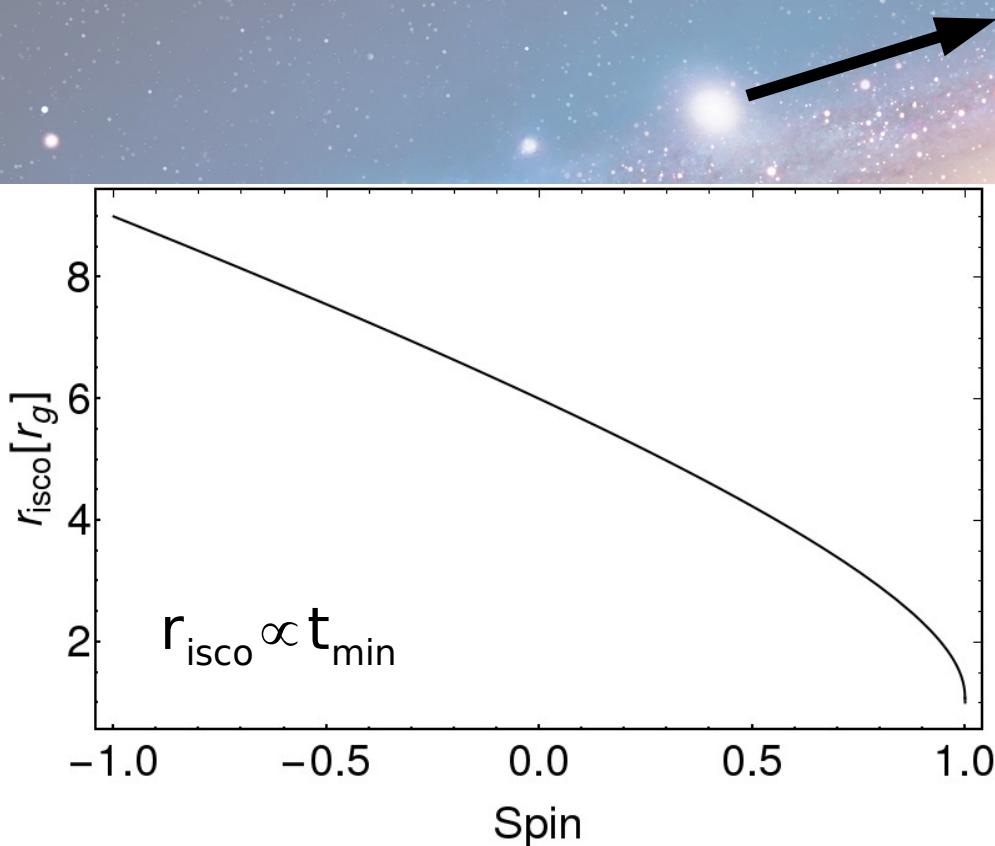
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Measure the shortest time-scale of the variability; connected with the radius of the last stable orbit



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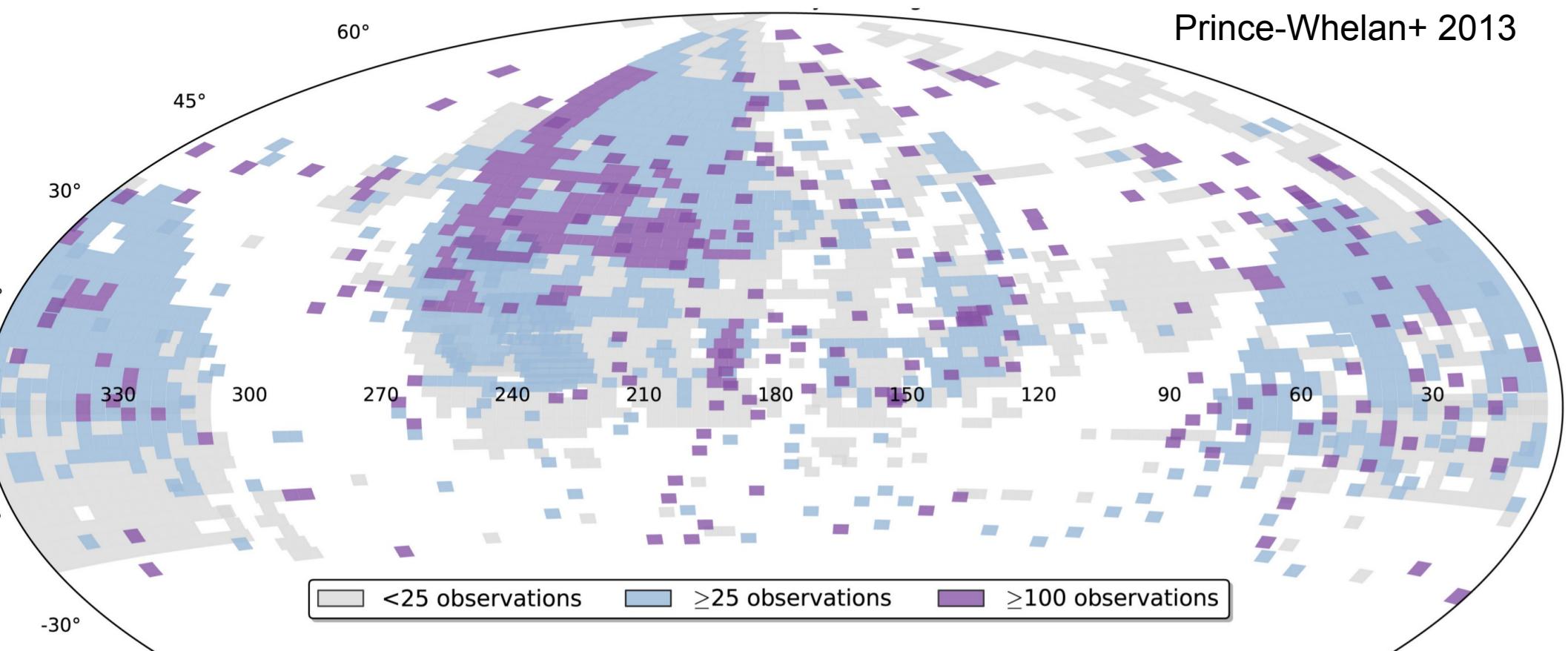
Overview

- Introduction to AGN variability and stochastic processes
- Observed optical variability of AGN
 - Palomar Transient Factory Survey
 - Analysis in time domain
 - Analysis in frequency domain
 - Discussion
 - What are we actually probing?
 - Binary AGN
 - Spin
- Variability of star-formation on 100 Myr+ scales
 - Can we model galaxies in the same way
 - Constraints on the variability from the data

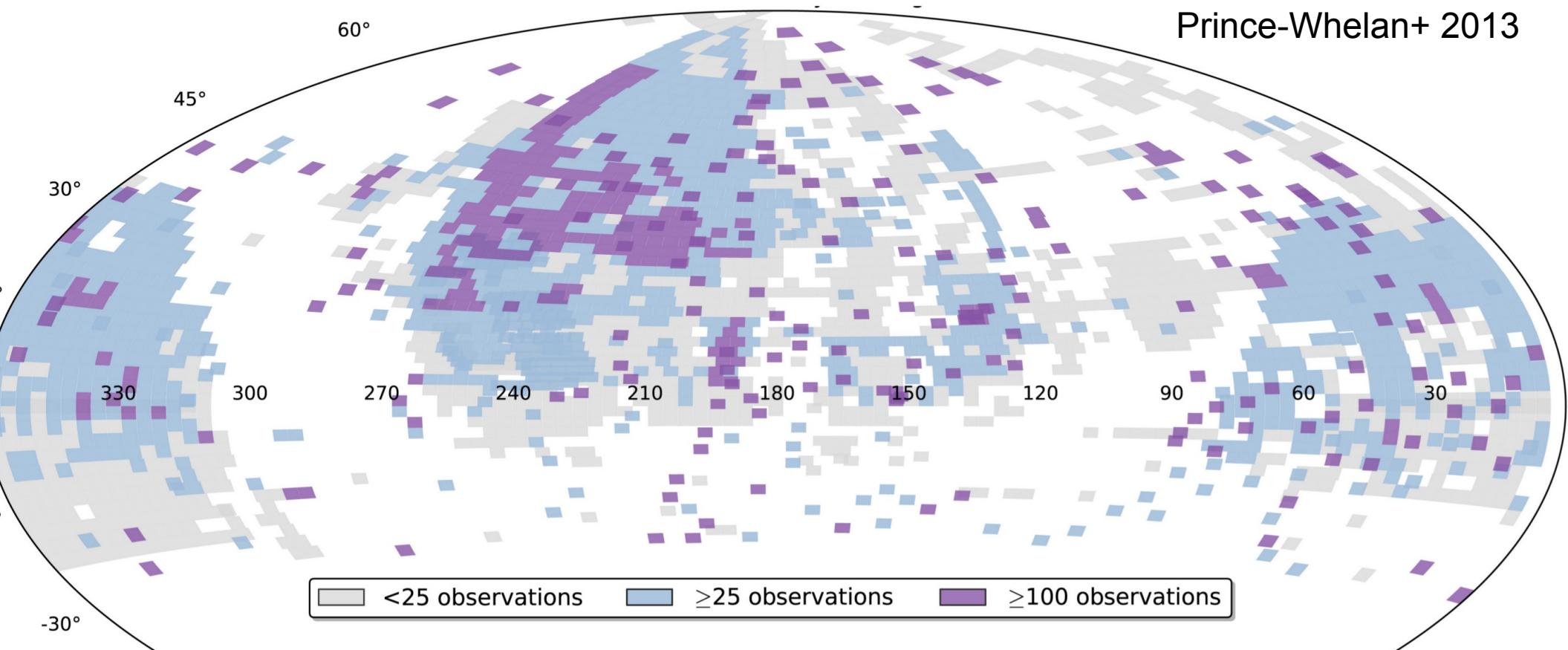
- 1.5 m telescope on Mount Palomar in south California
- Transient sky survey started in March 2009
- Data mostly in r band (centered at 6580 Å)



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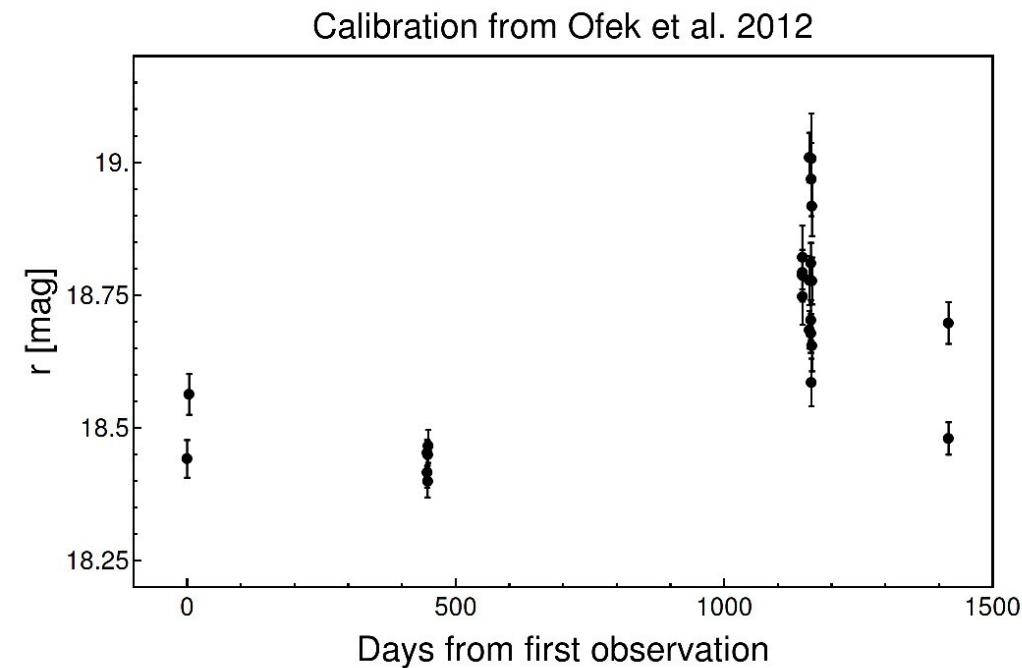
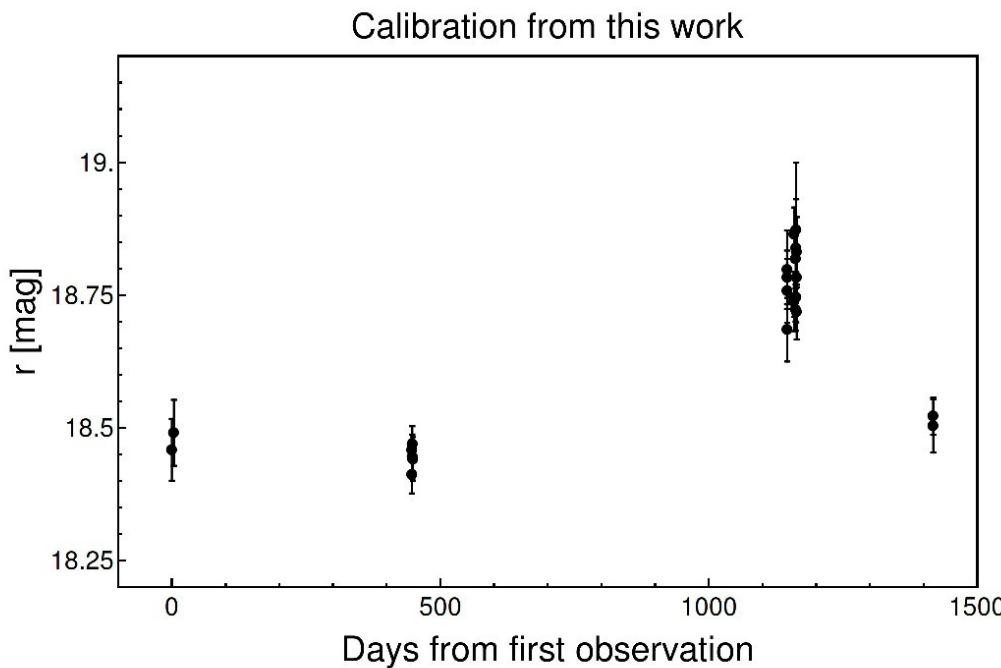


- 1.5 m telescope on Mount Palomar in south California
- Transient sky survey started in March 2009
- Data mostly in r band (centered at 6580 Å)
- 28000 AGNs brighter than $r=19.1$
- 2.4 million data points = largest calibrated single band dataset!



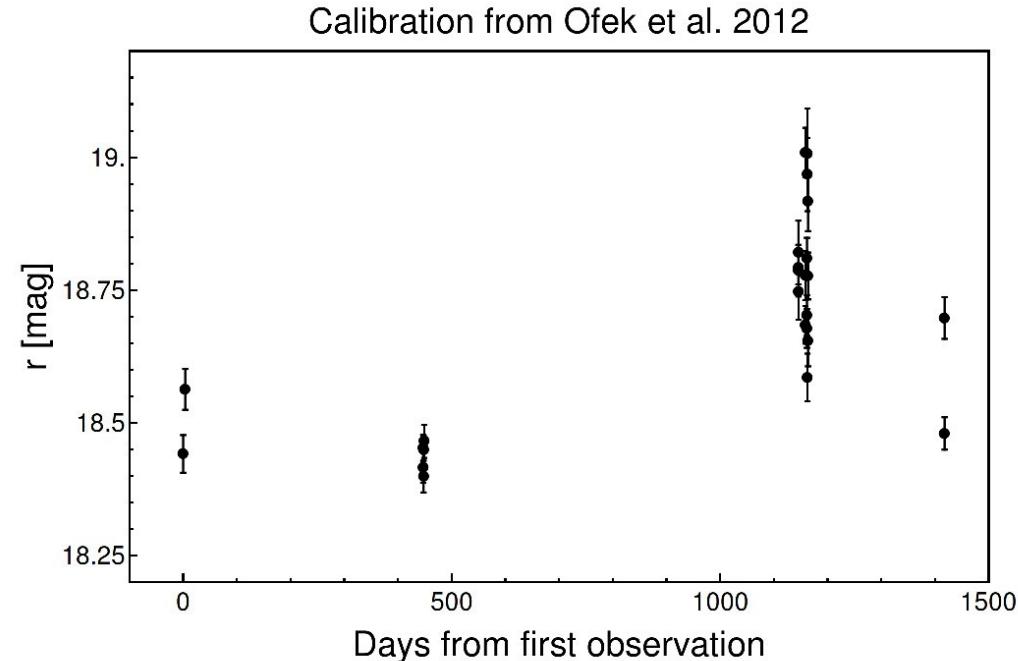
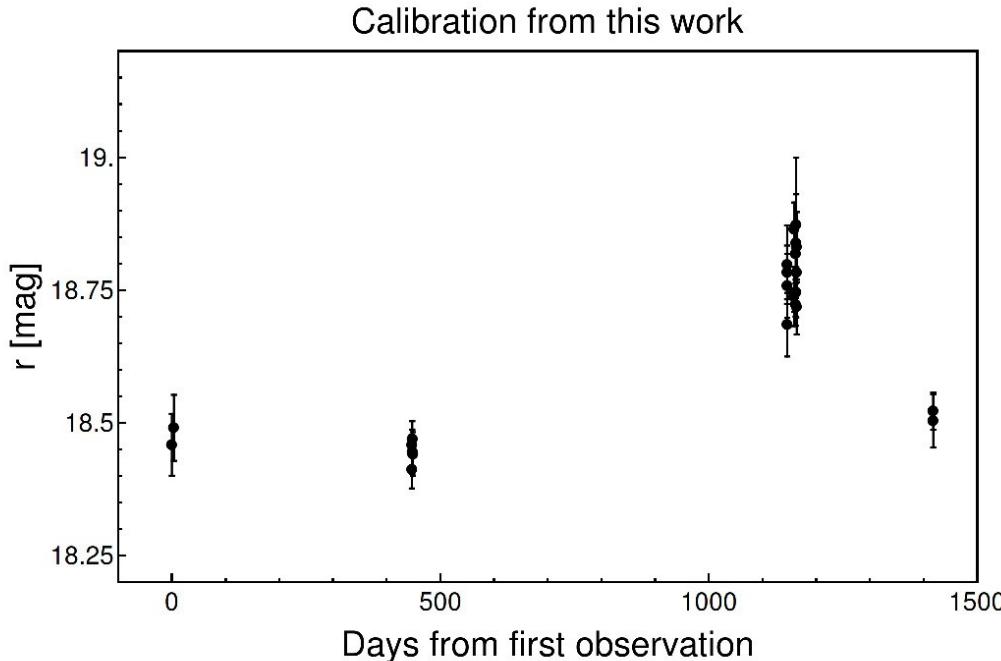
Re-calibration of survey

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



Re-calibration of survey

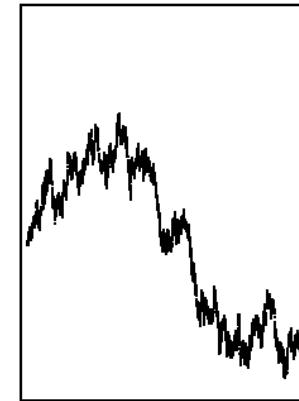
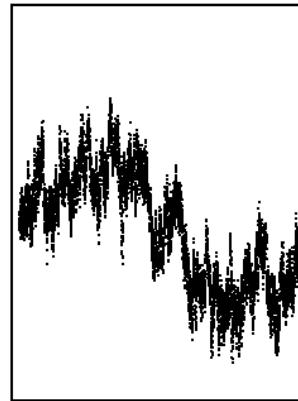
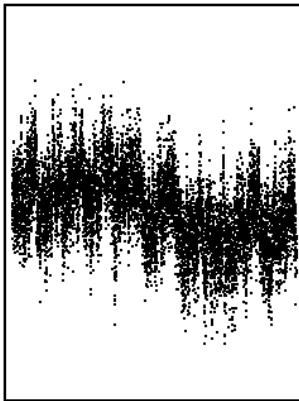
- AGN light-curves were re-calibrated
- We search for zeropoints which minimize the scatter of reference objects (stars) – based on Ofek+ 2011
- We achieve excellent performance; excess variance at short time-scales is consistent with zero for vast majority of AGNs
- Re-calibrated data is public:
https://github.com/nevencaplar/PTF_AGN



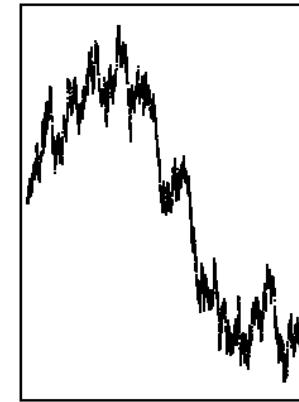
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Luminosity



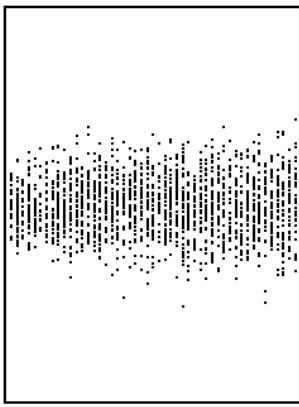
More “structure”



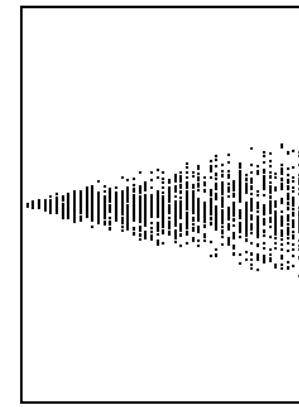
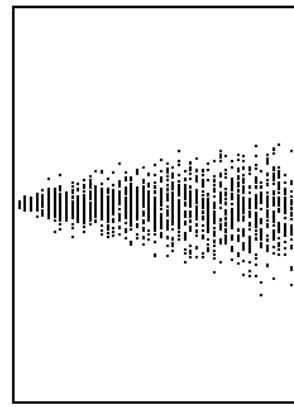
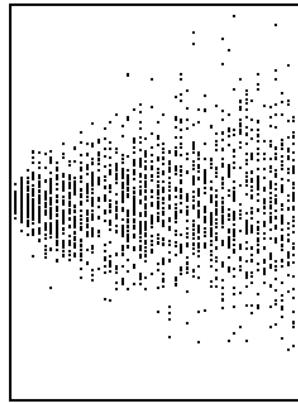
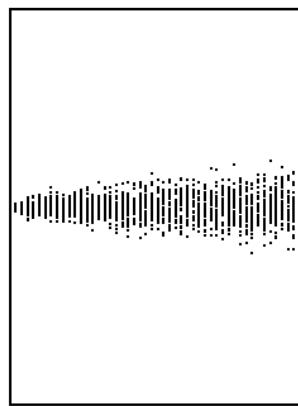
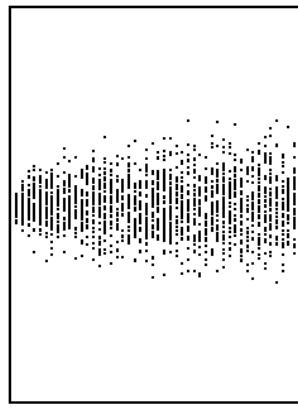
More variability



Δmag



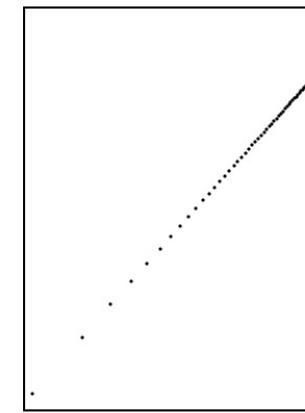
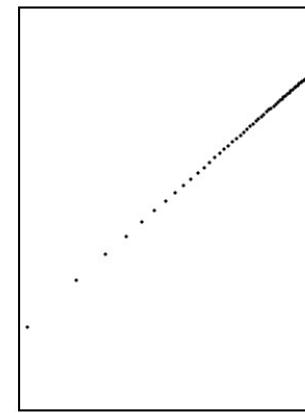
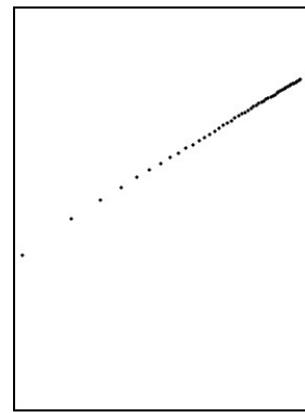
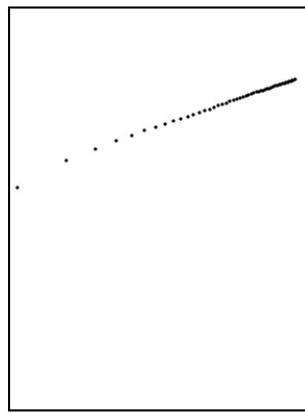
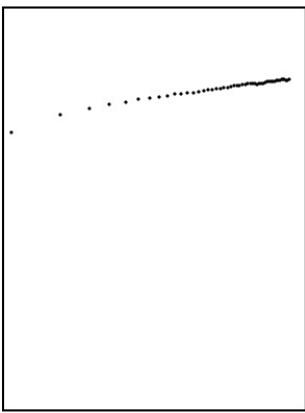
Δtime



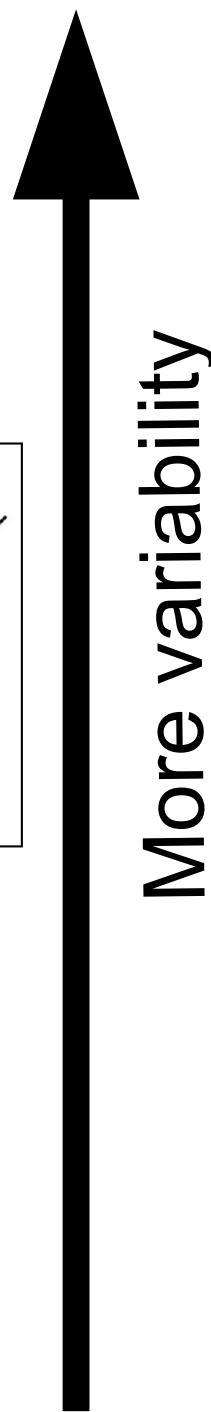
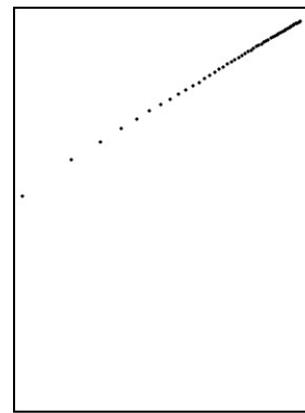
More variability

More “structure”

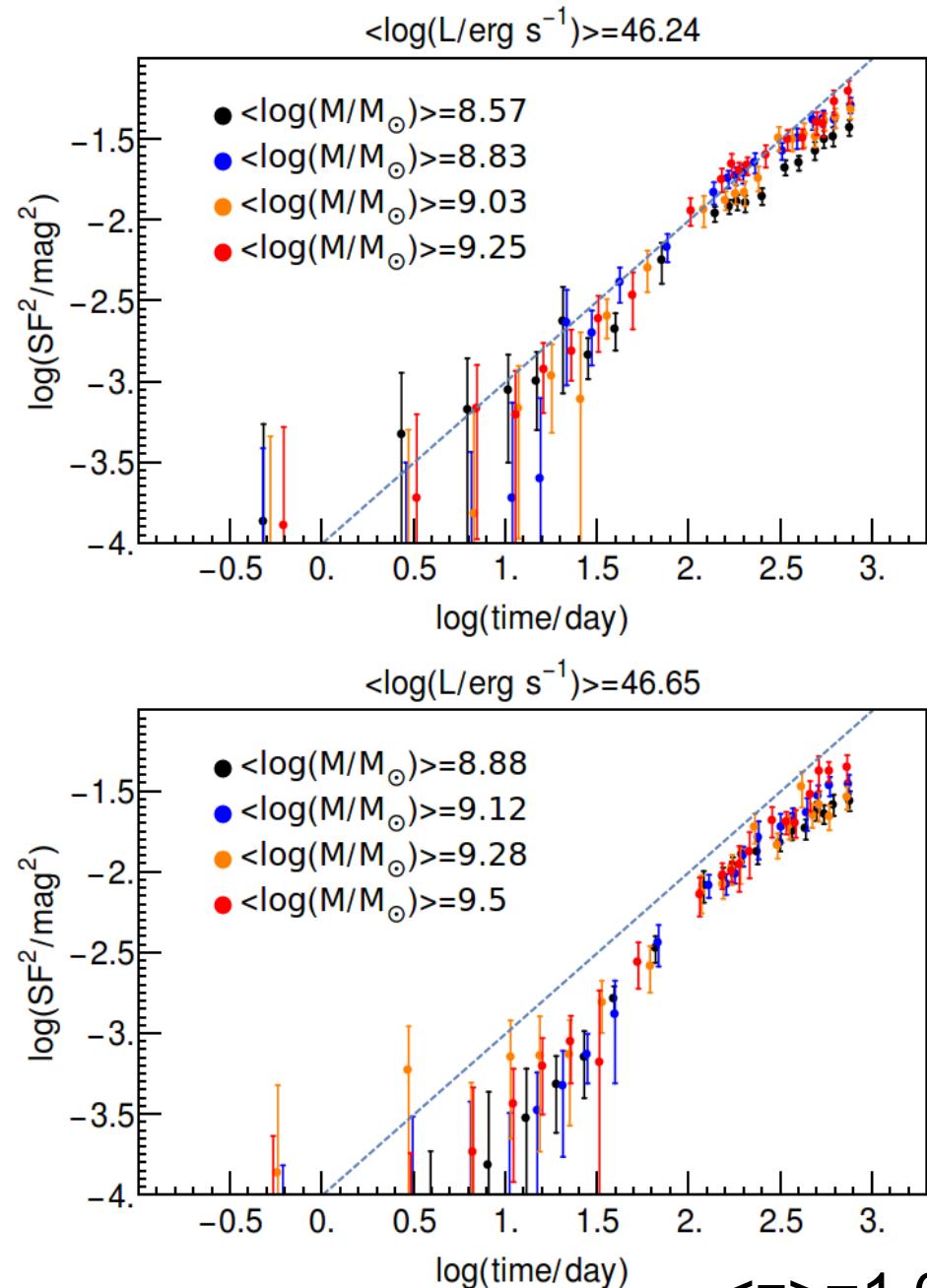
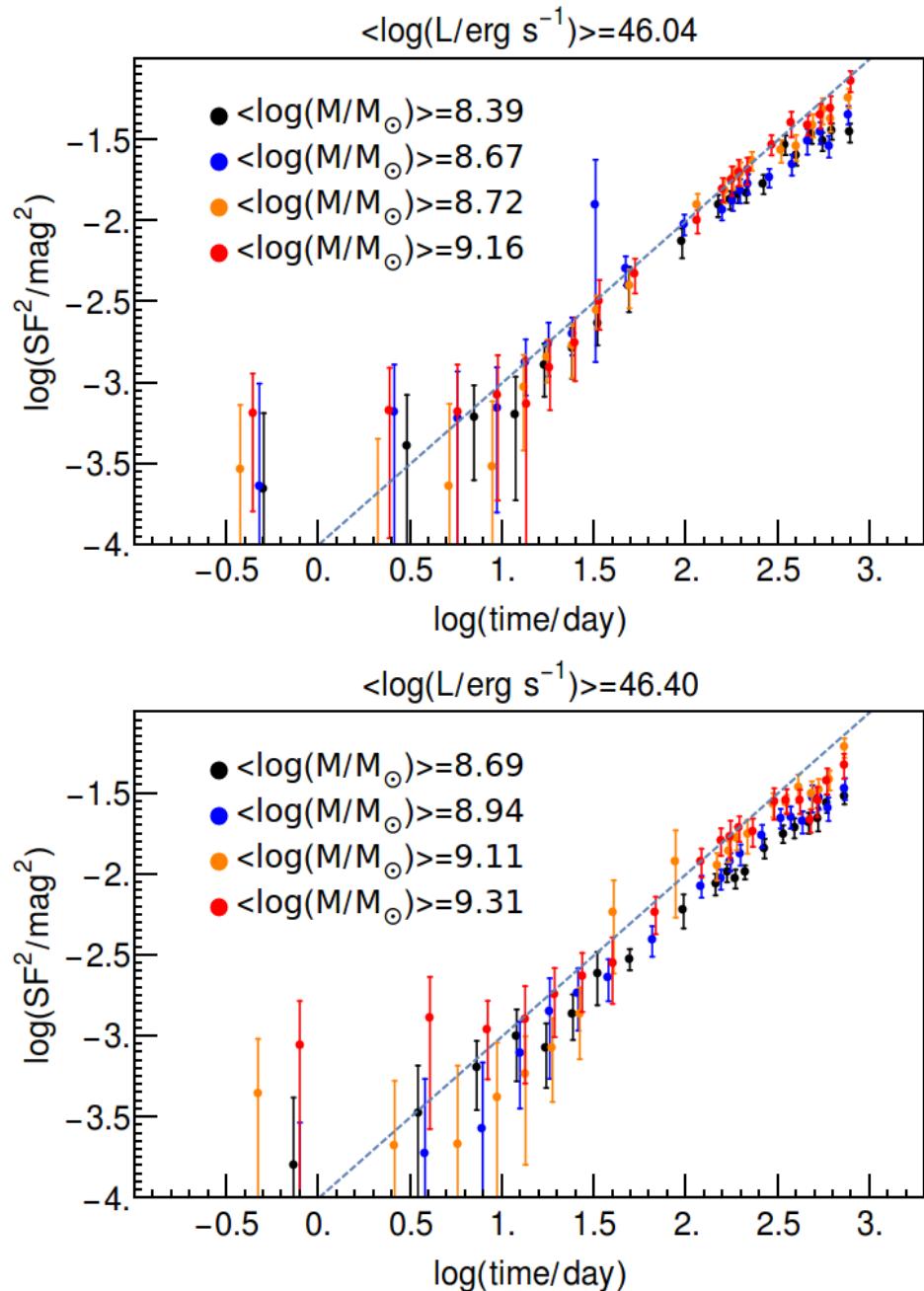
$\text{Log}[\text{SF}^2]$



More “structure”

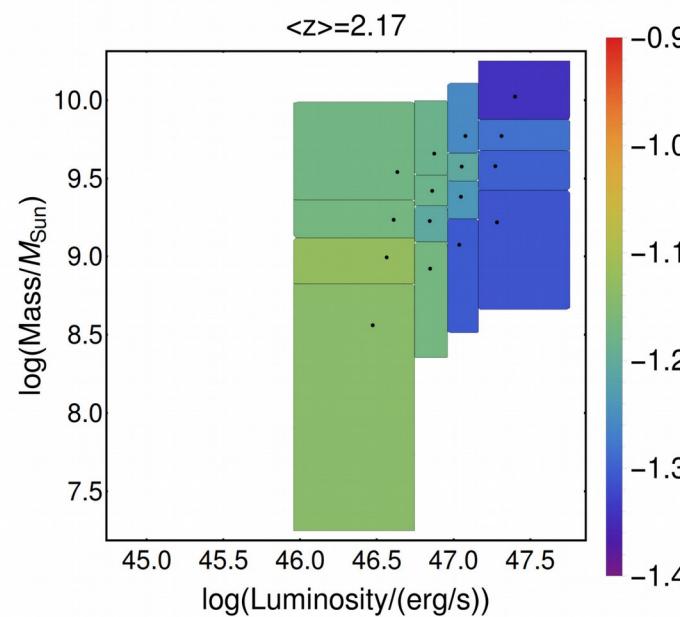
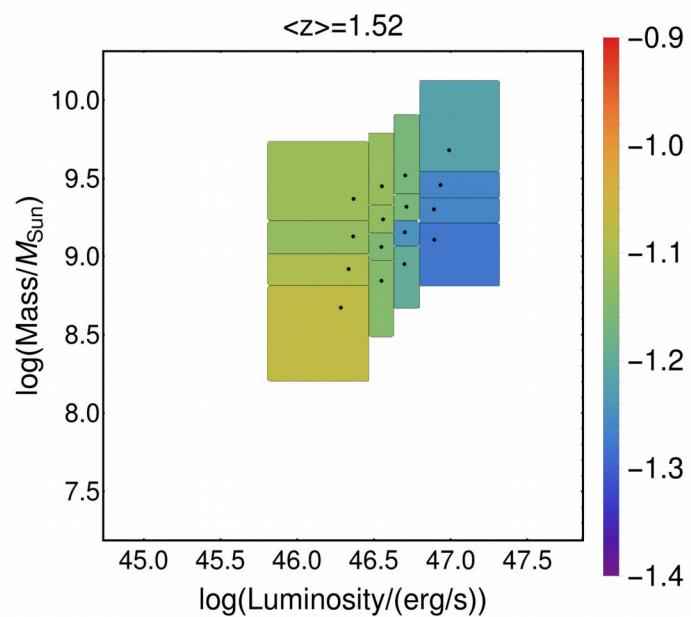
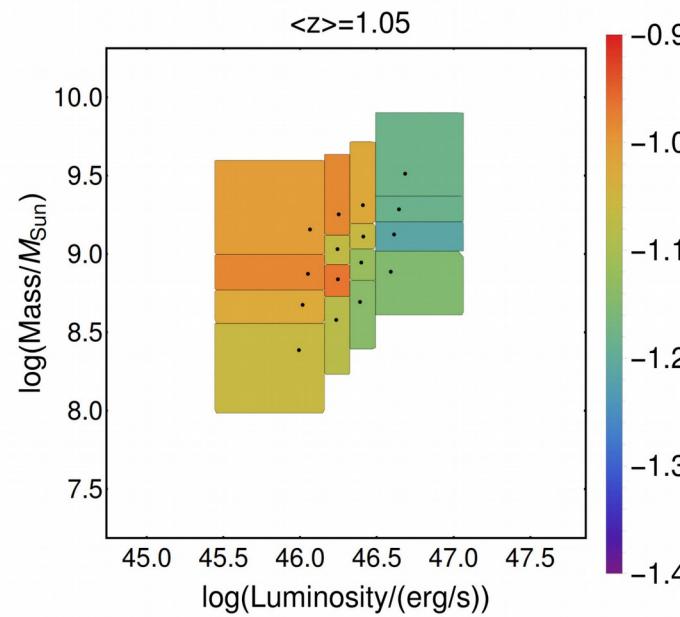
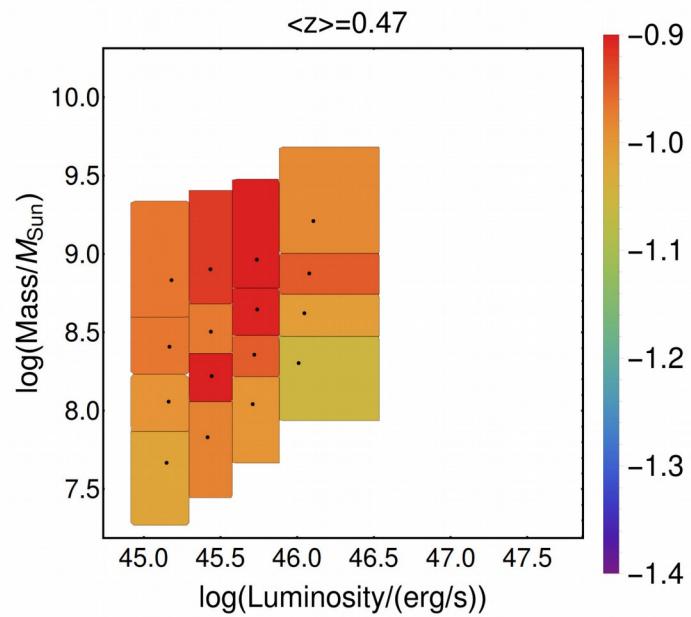


Variance of magnitude difference as a function of time lag between measurements



$\langle z \rangle = 1.05$

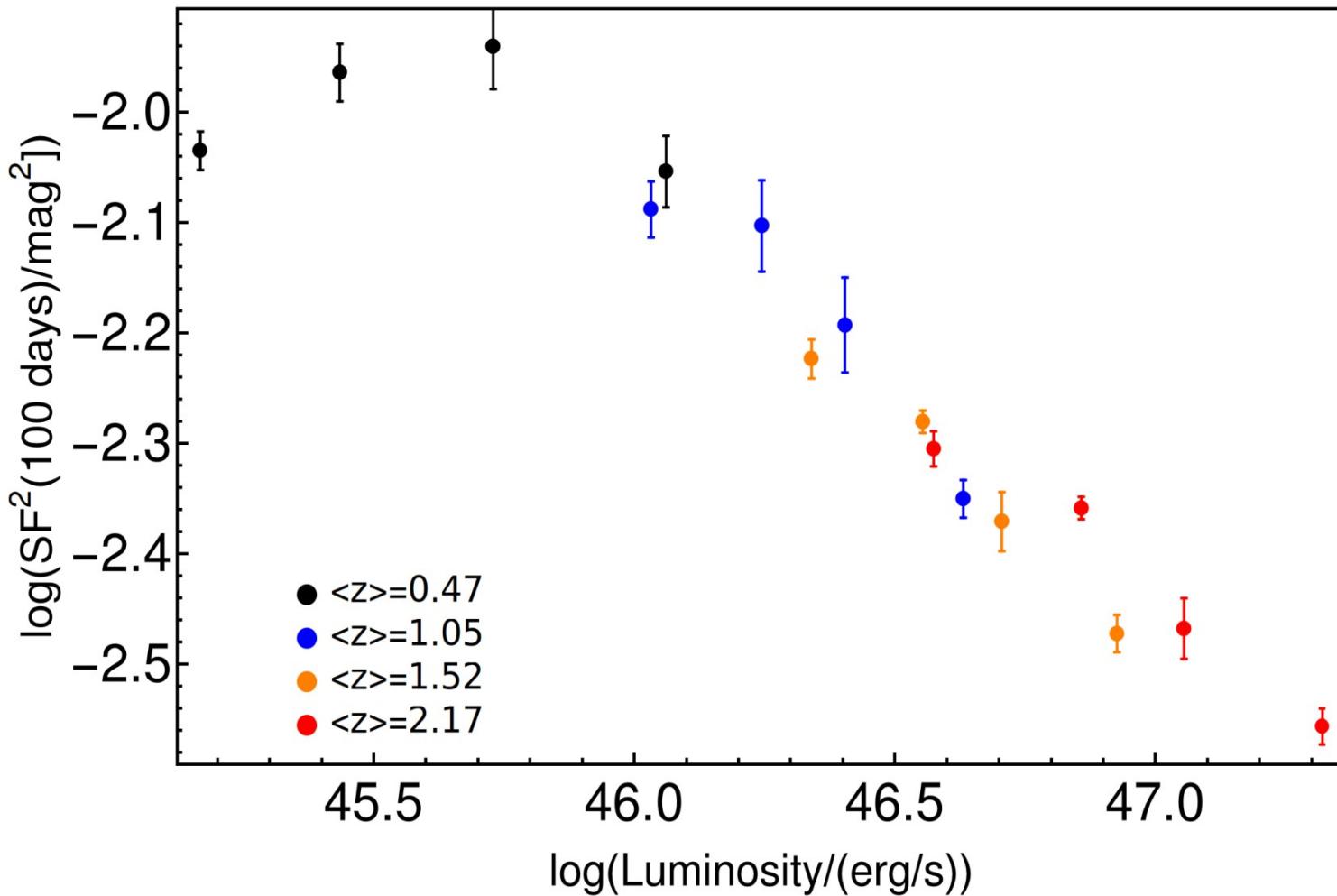
$\log(\text{SF}(100 \text{ days}_{\text{RF}})/\text{mag})$



- 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

- Clear dependence with luminosity
- In the simplest thin disk model where the time scale of variability is identified with the Keplerian time scale

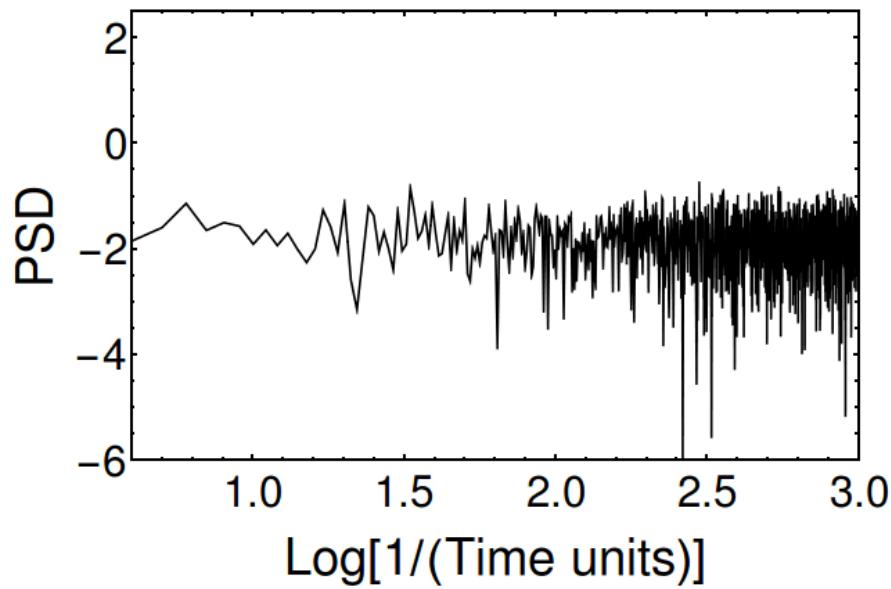
$$SF^2 \propto L^{0.5}$$



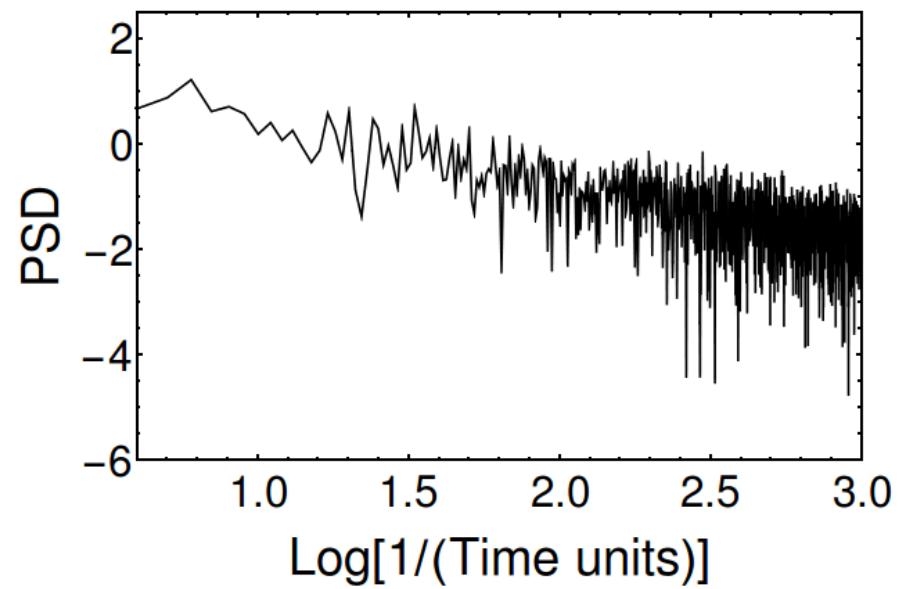
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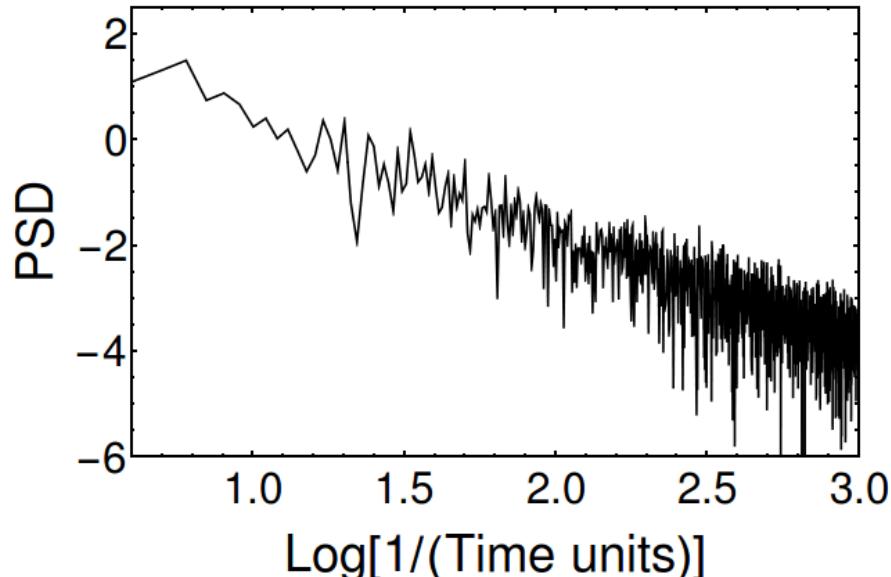
$\text{PSD} \propto f^0$



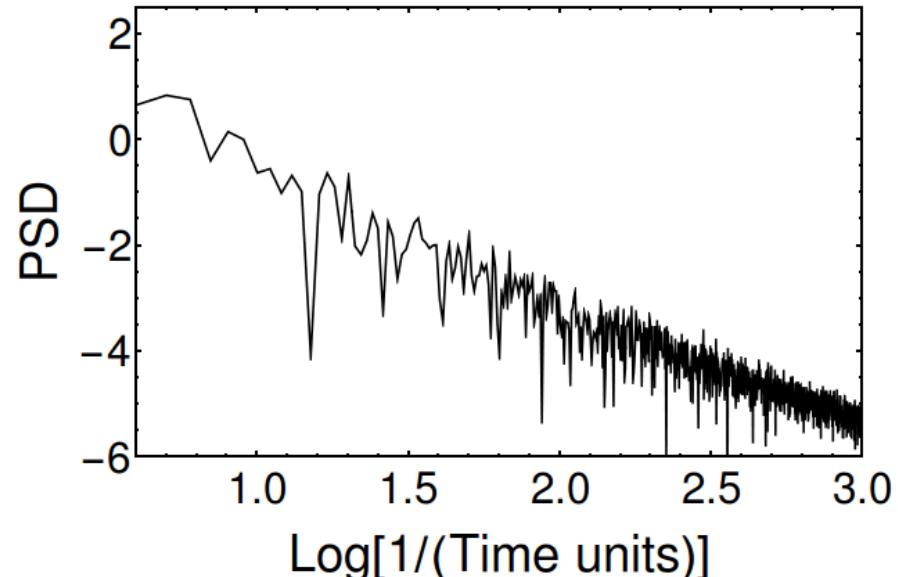
$\text{PSD} \propto f^{-1}$



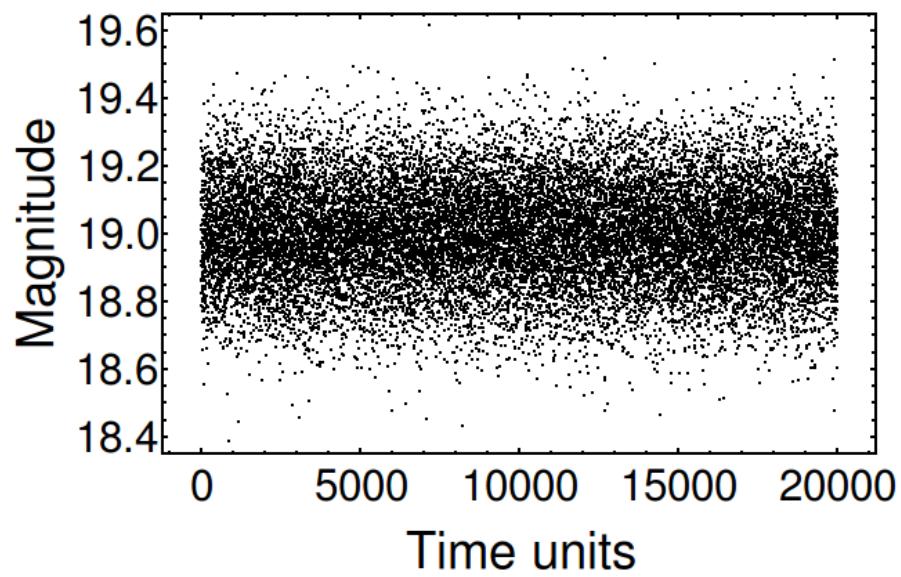
$\text{PSD} \propto f^{-2}$



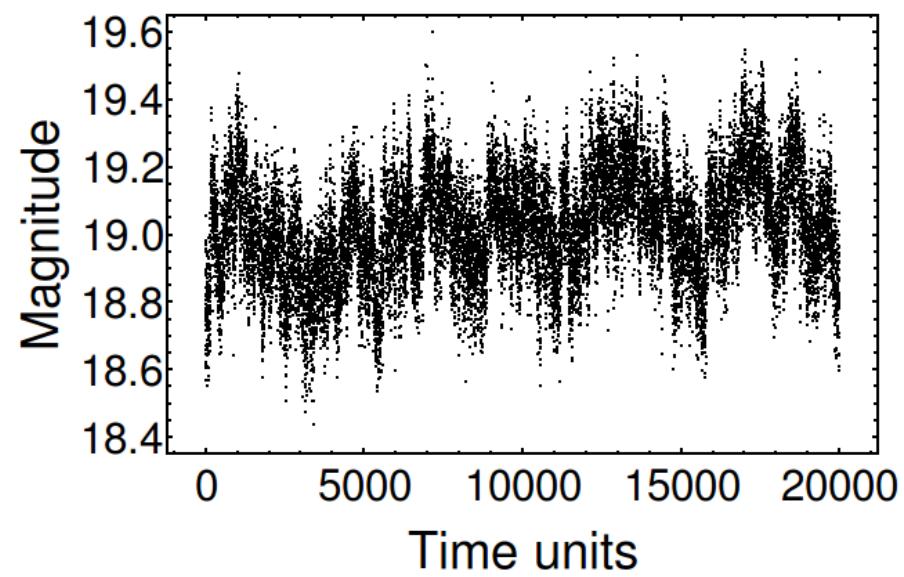
$\text{PSD} \propto f^{-3}$



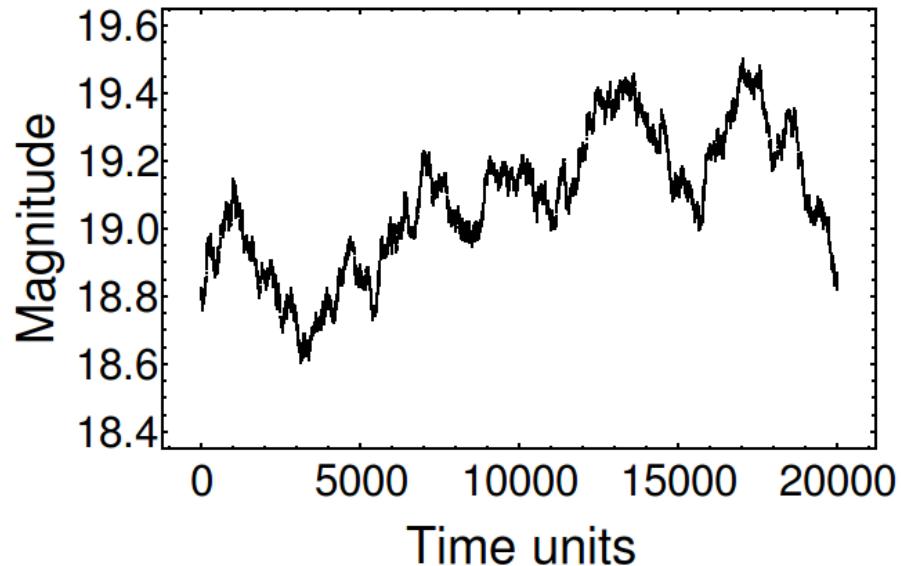
$\text{PSD}\alpha f^0$



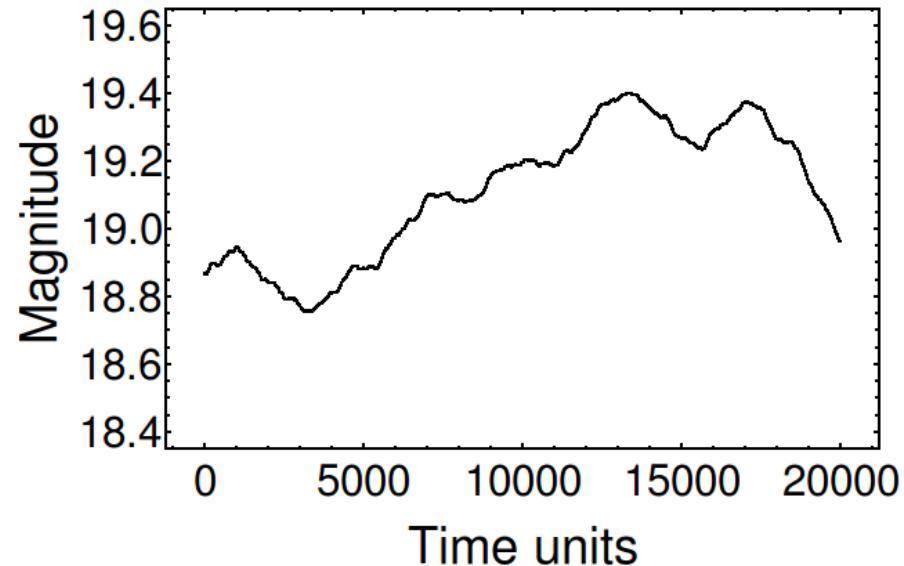
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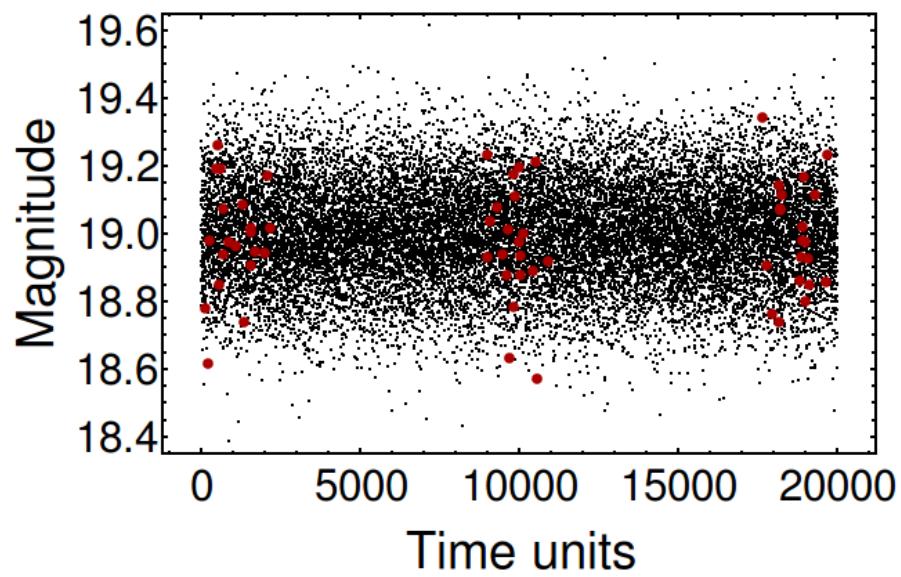
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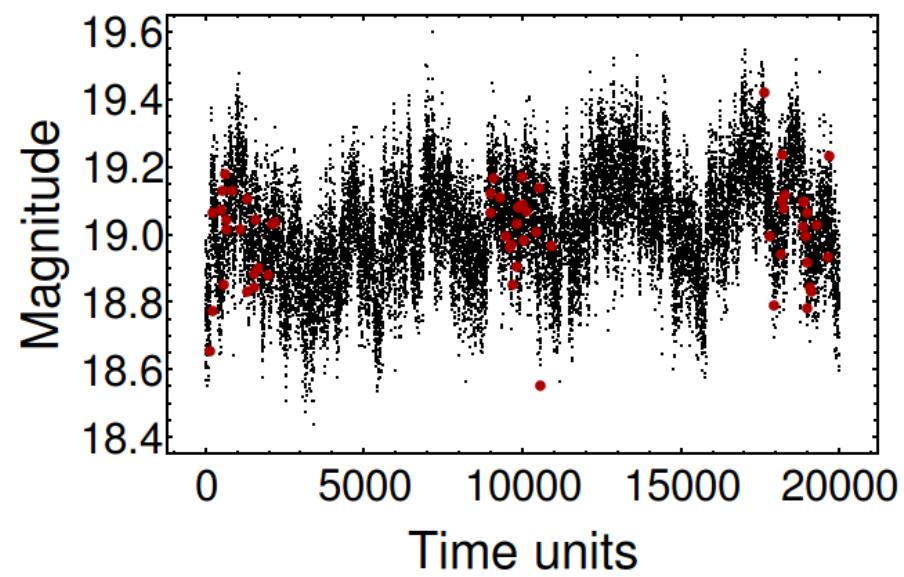
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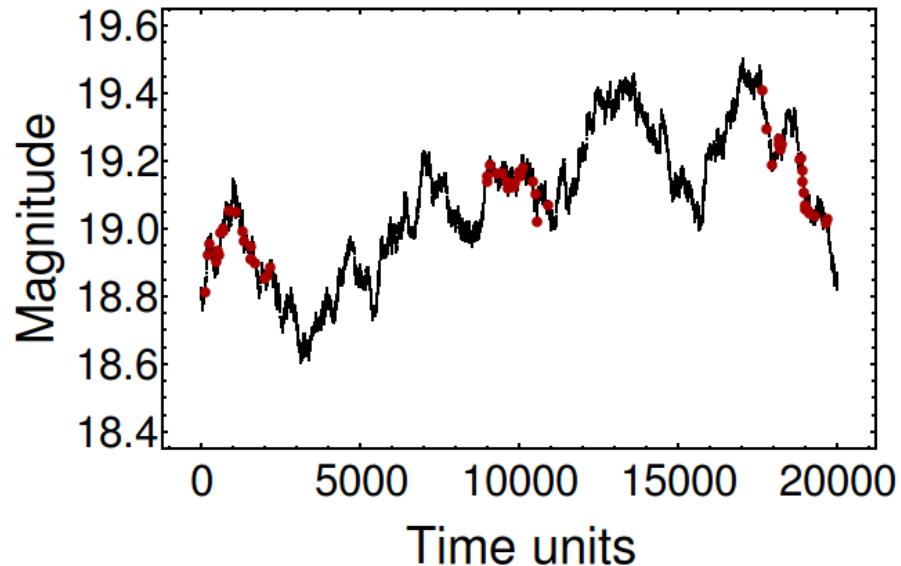
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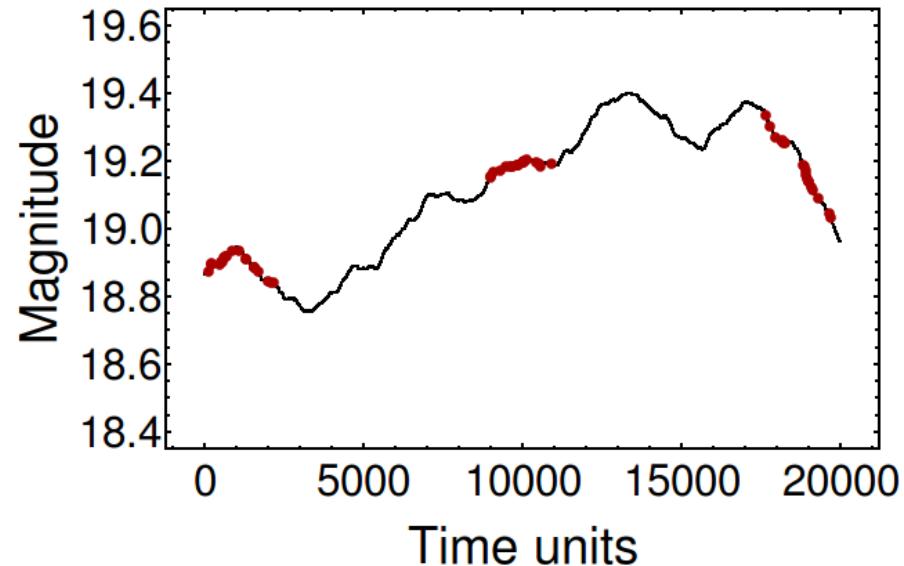
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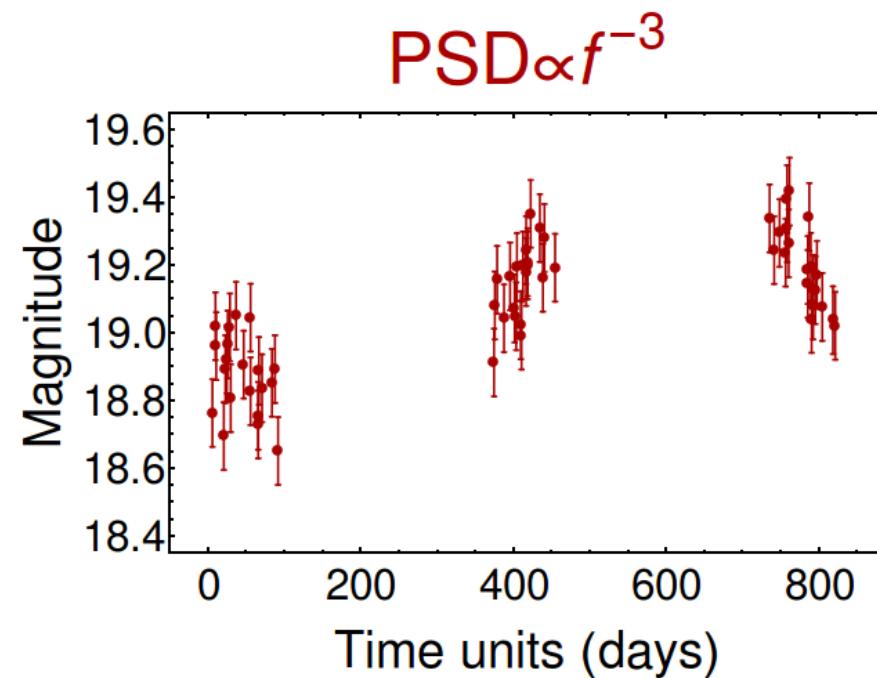
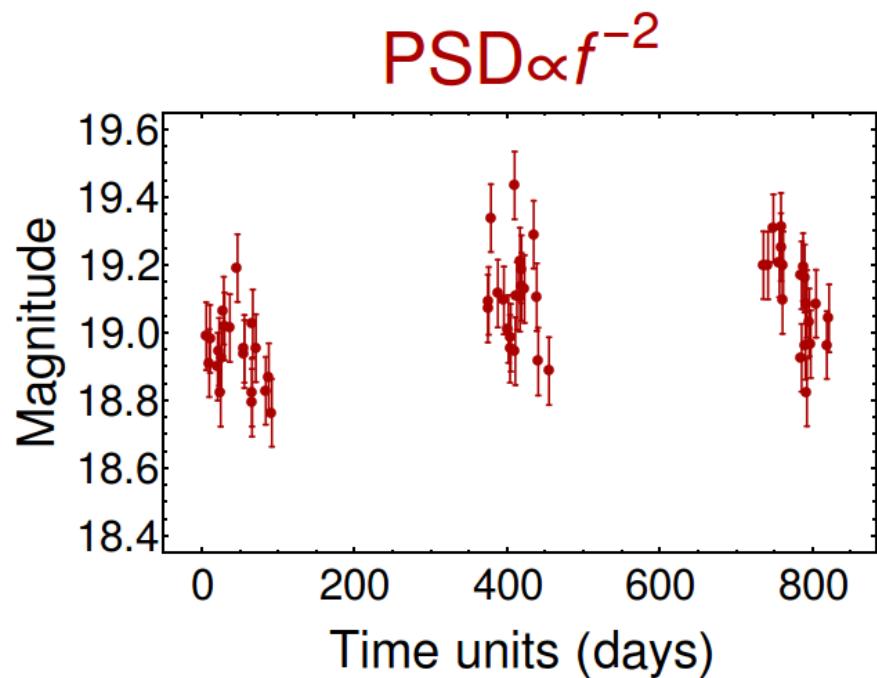
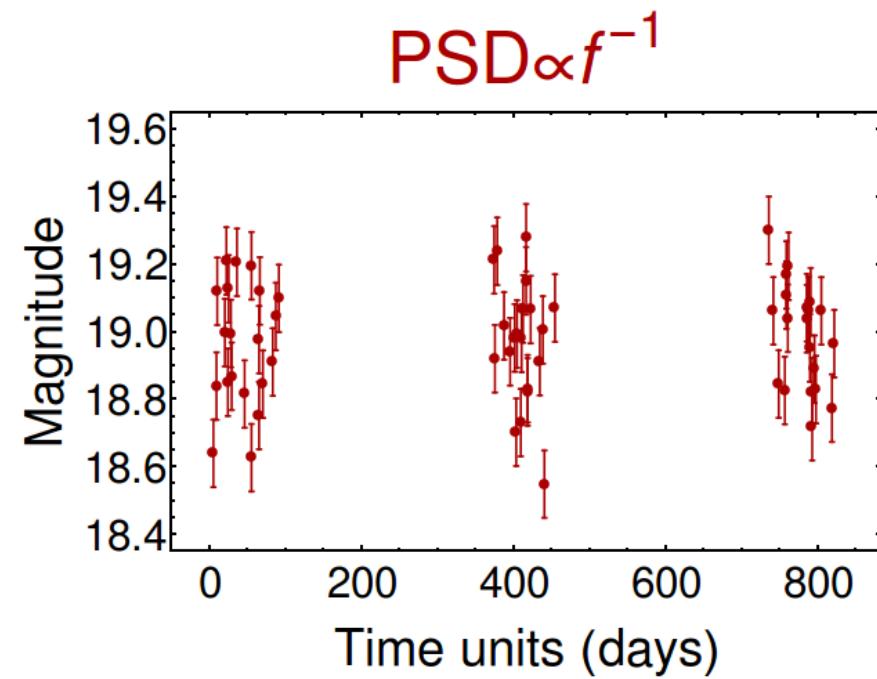
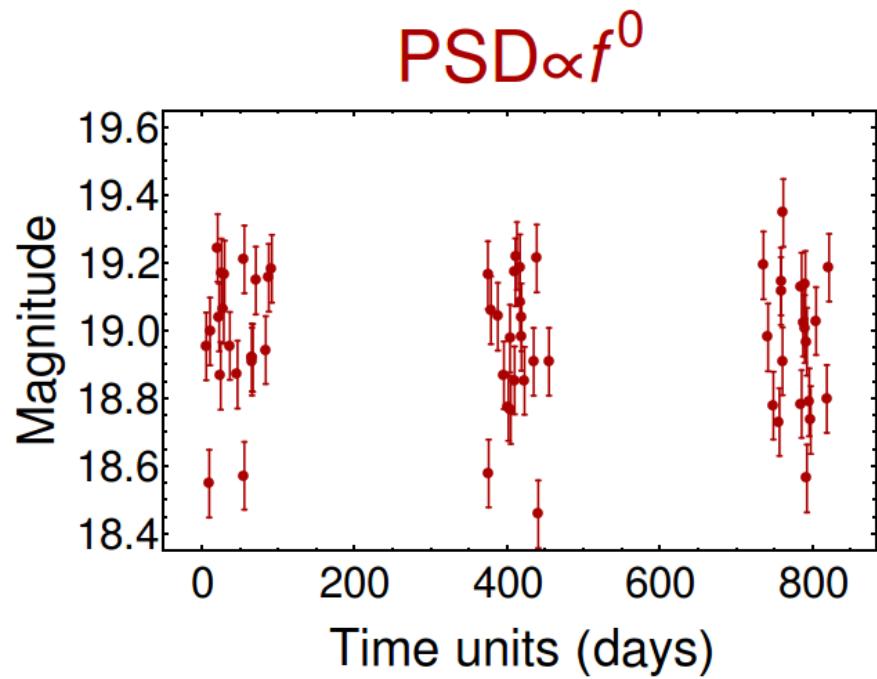


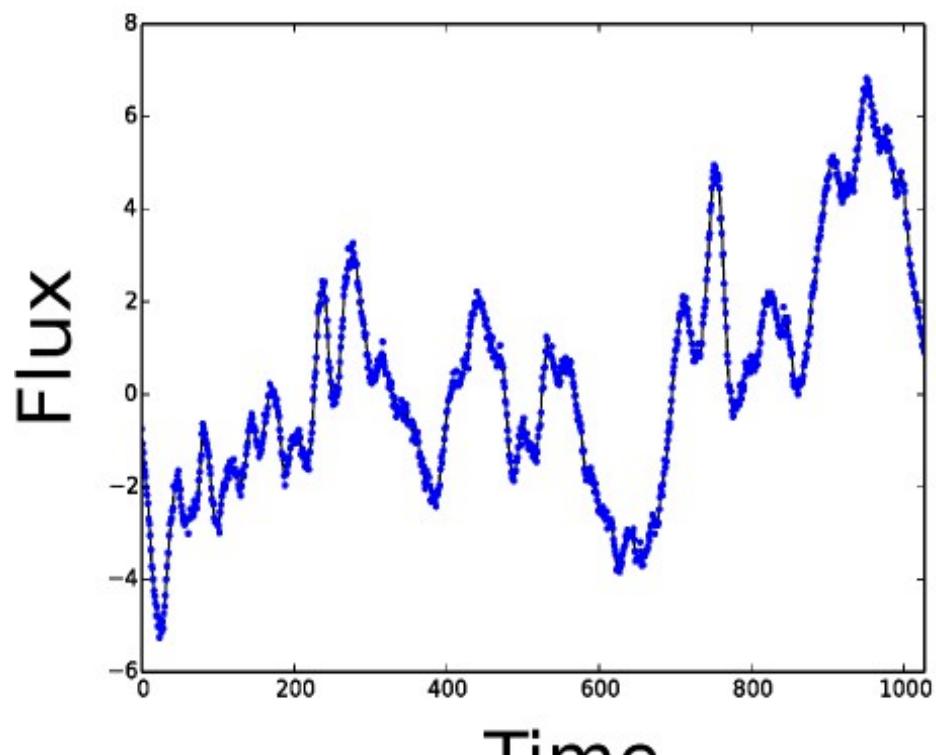
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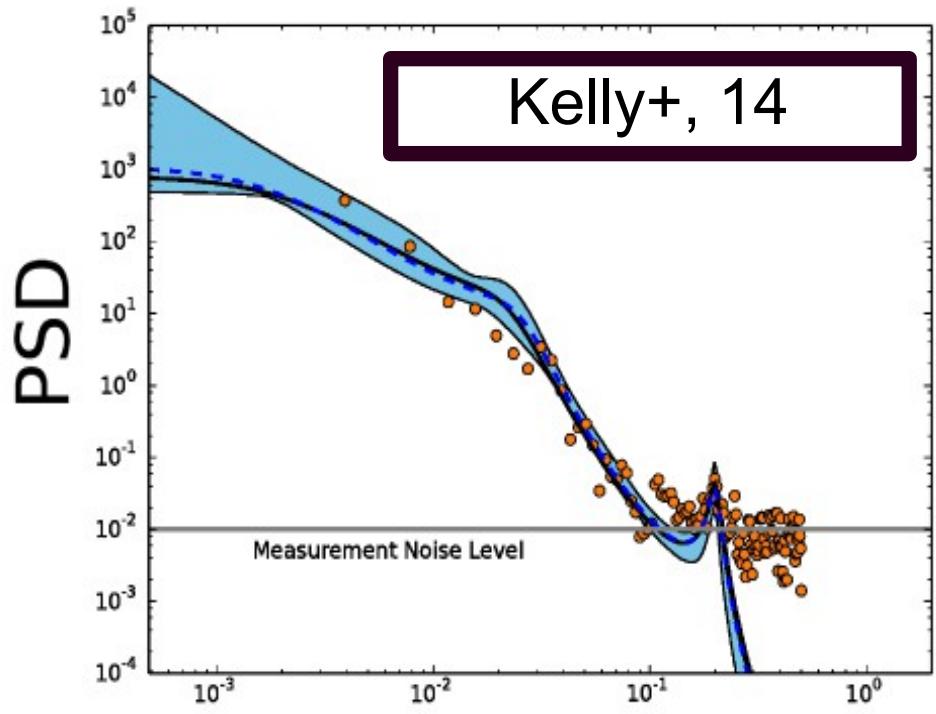
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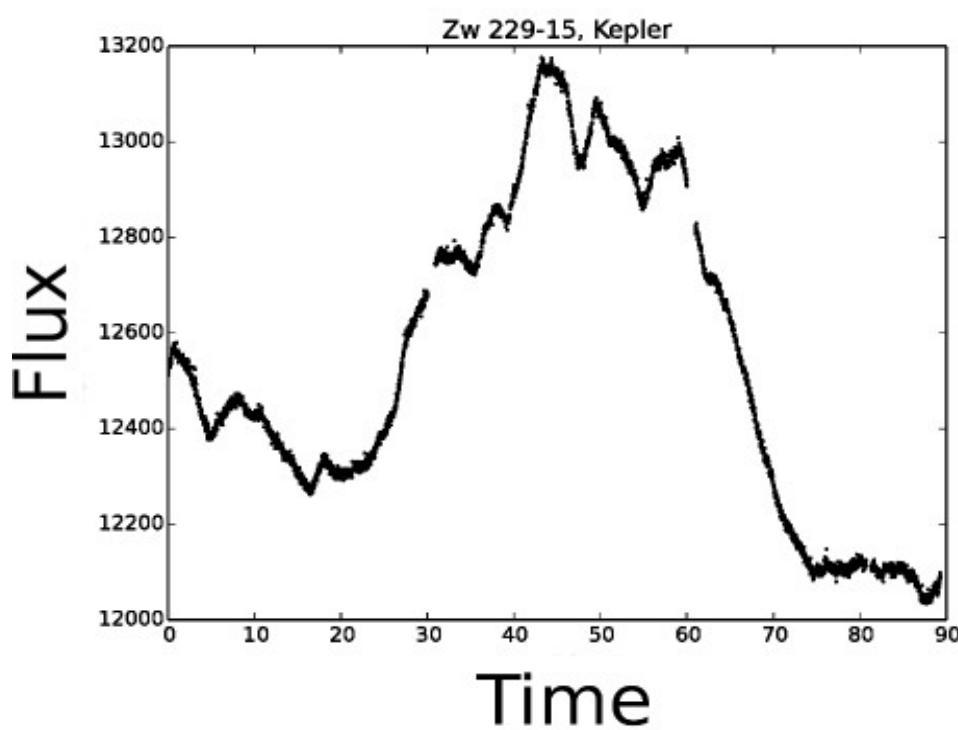




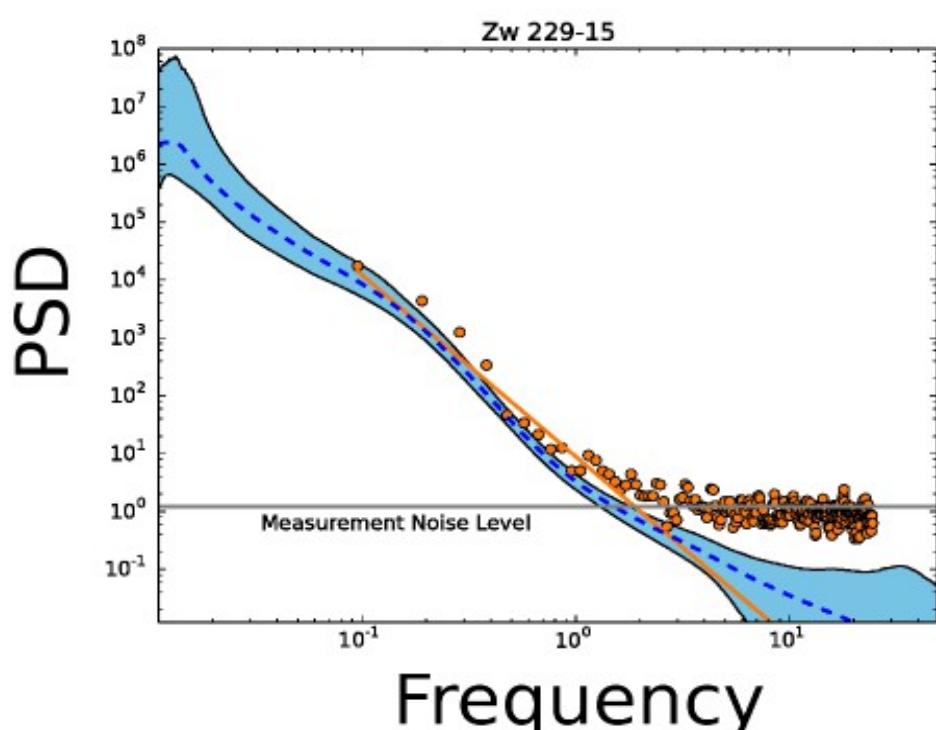
Time



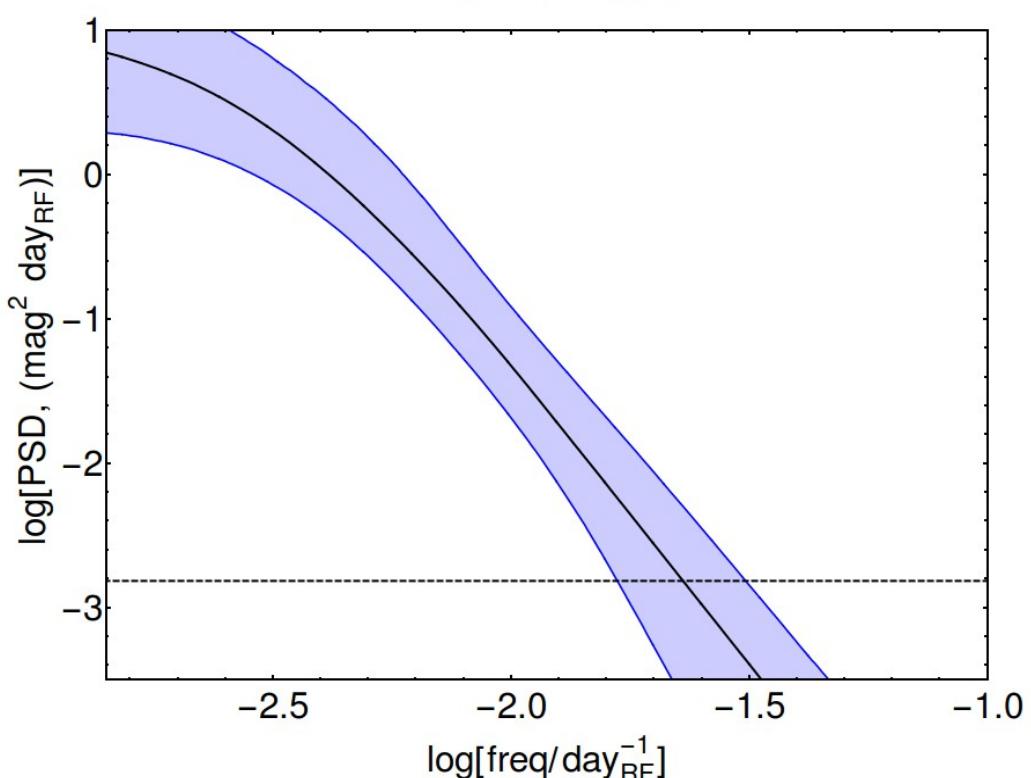
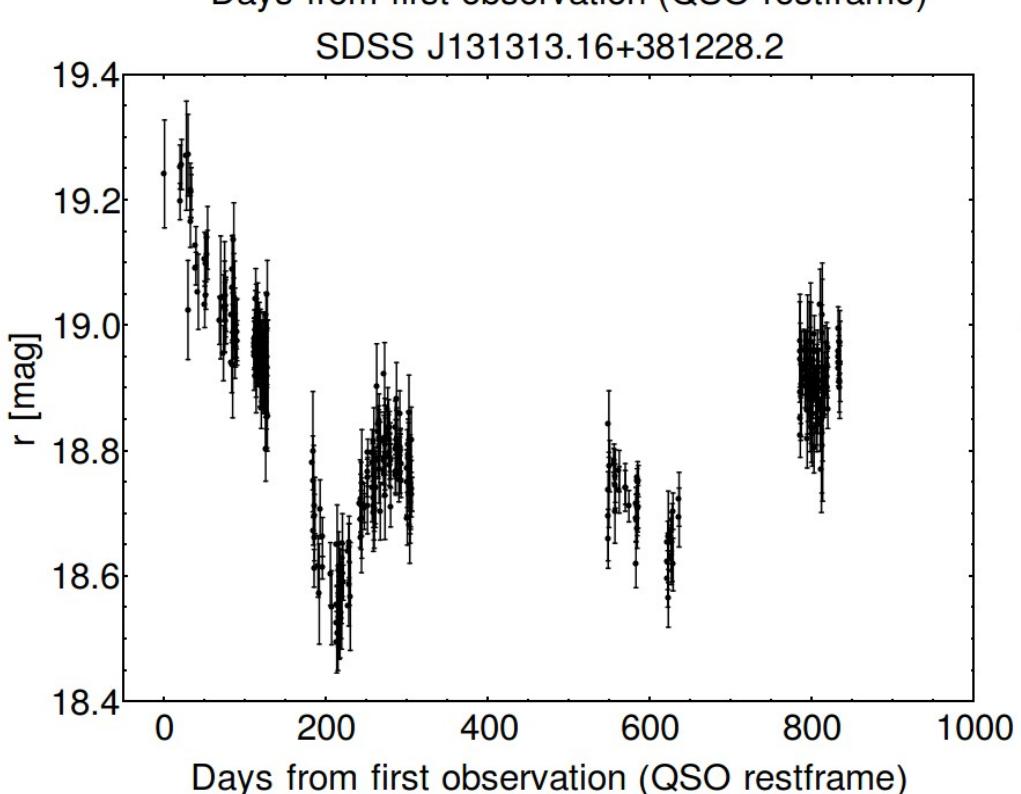
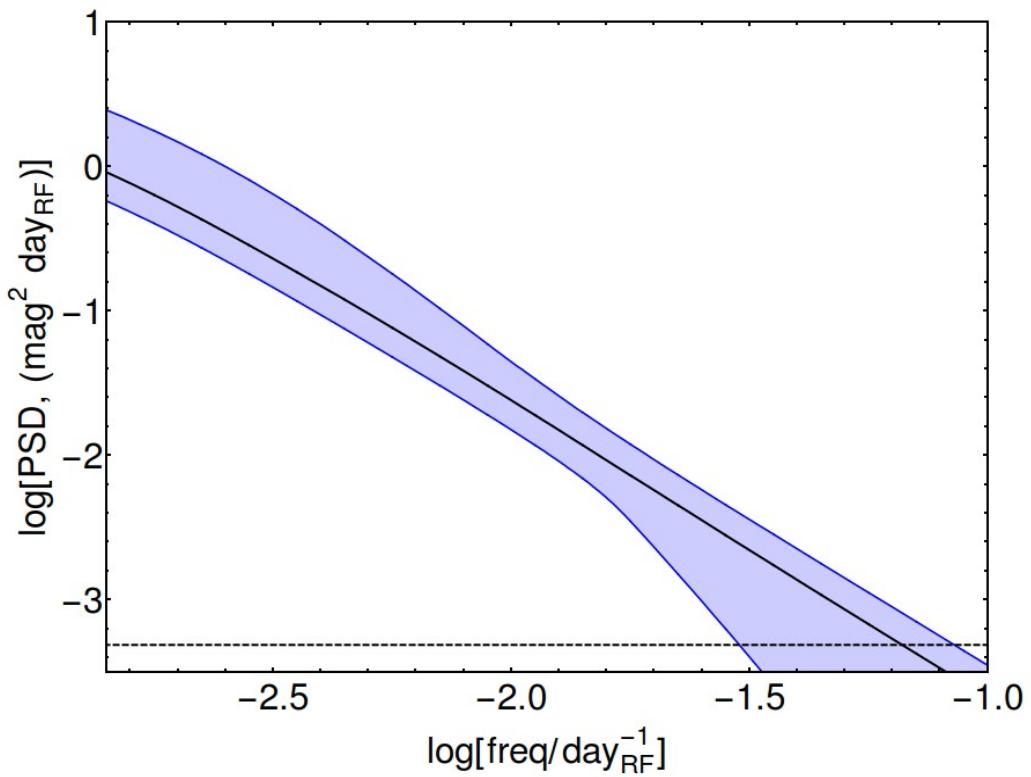
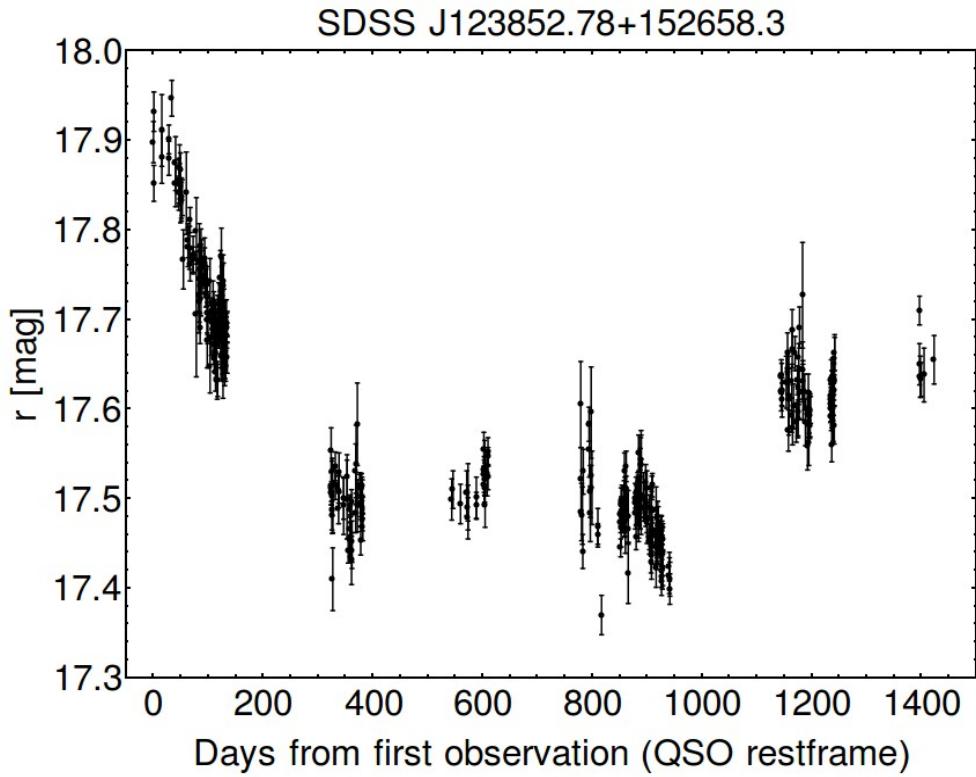
Frequency



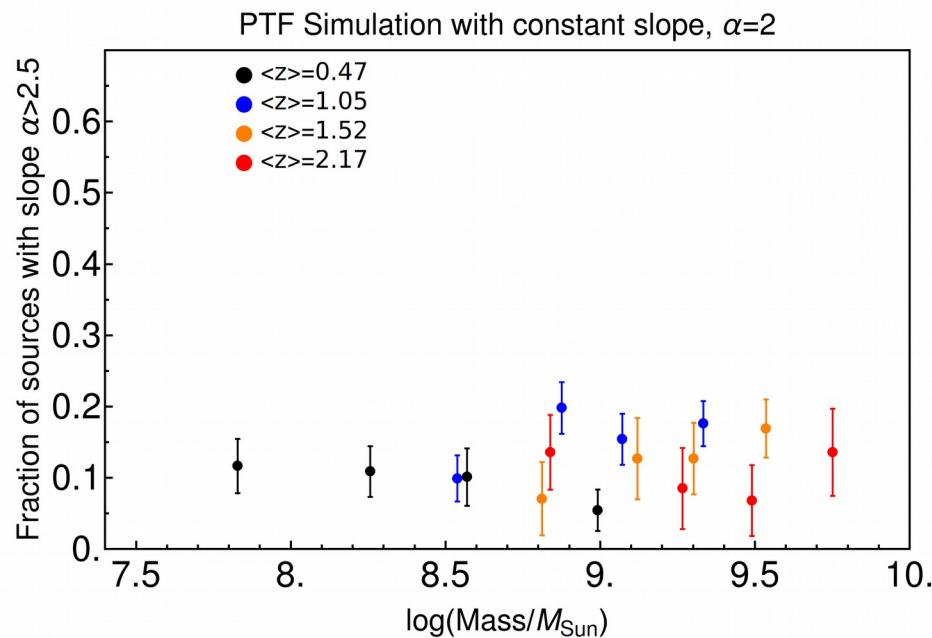
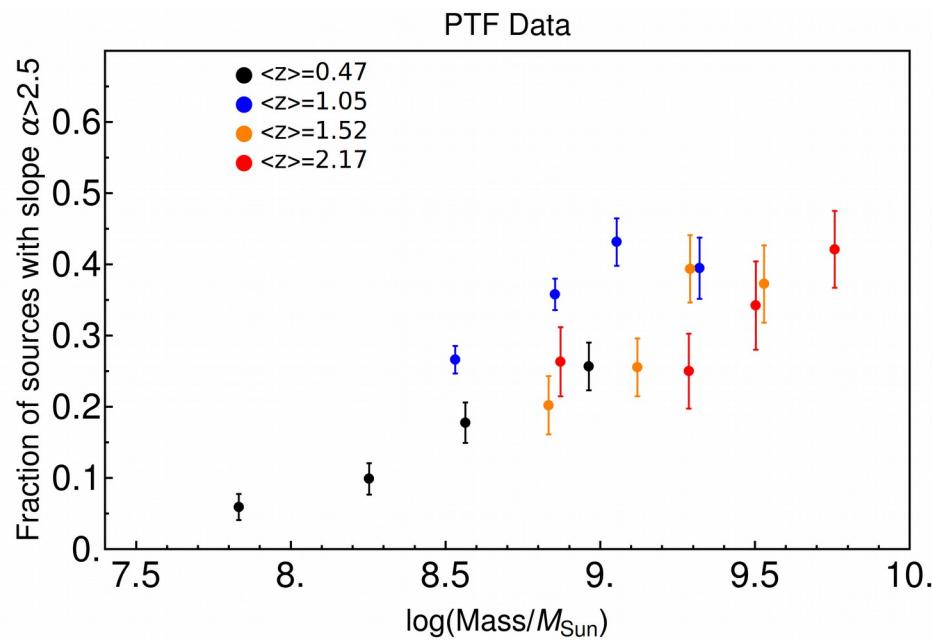
Time



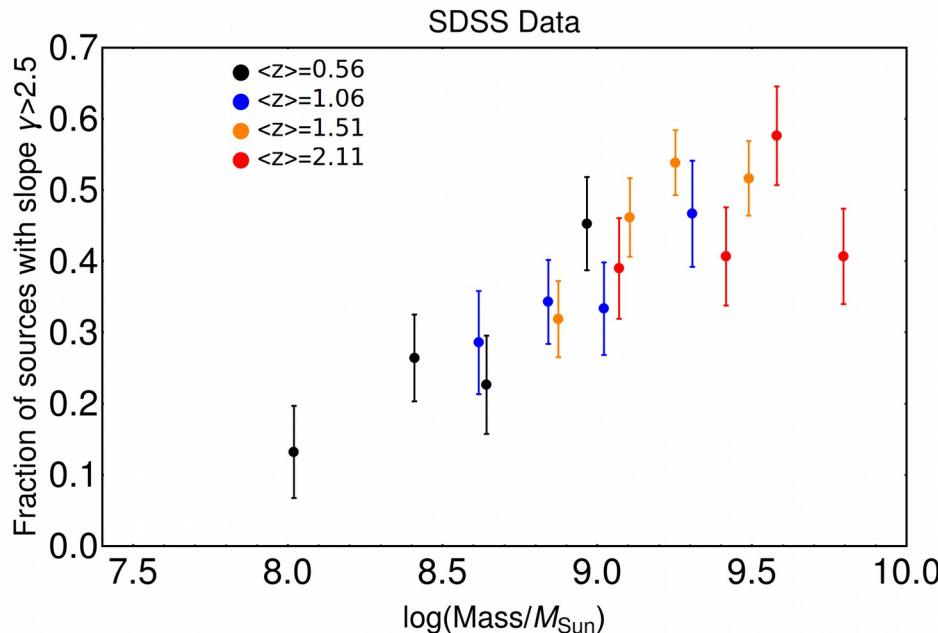
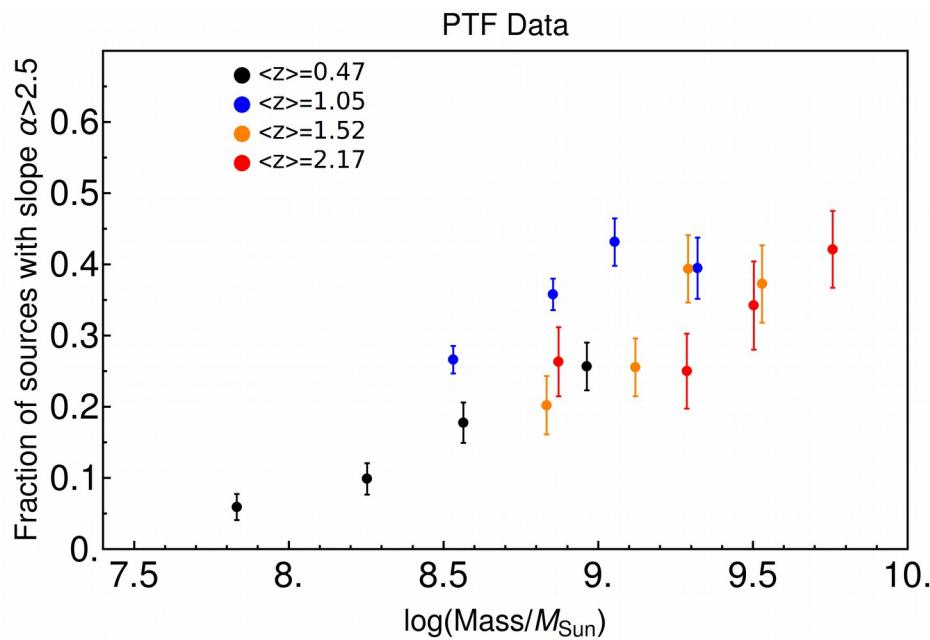
Frequency



Variability properties change as a function of mass

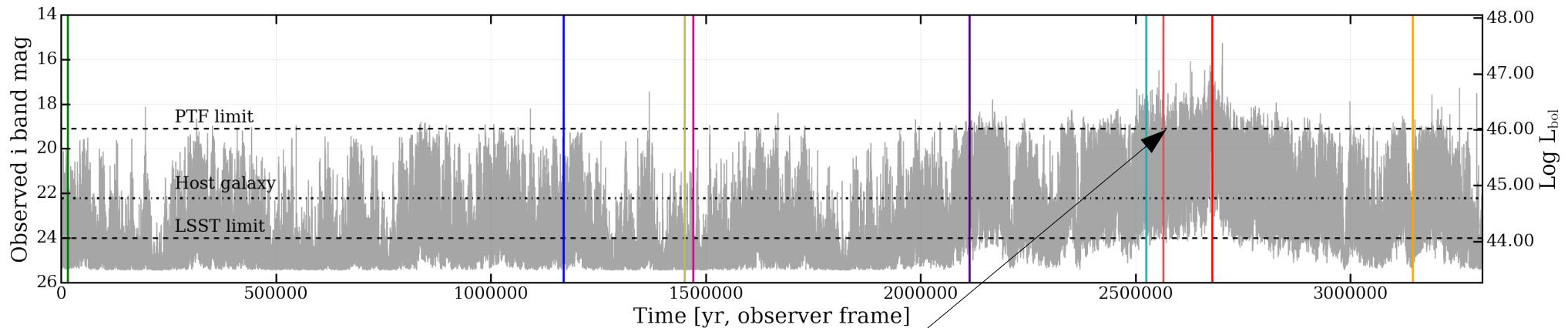


Variability properties change as a function of mass



- More massive AGN tend to have steeper slopes i.e., tend to be more correlated
- Hinted at in Simm+ 2016, using COSMOS data
- Confirmed also in the K2 data (Smith+, 2018)
- Low mass AGN transition their variability at short time scale (days) – detectable with Kepler
- Higher mass AGN transition their variability at longer time scales (100 days) – detectable with ground based surveys

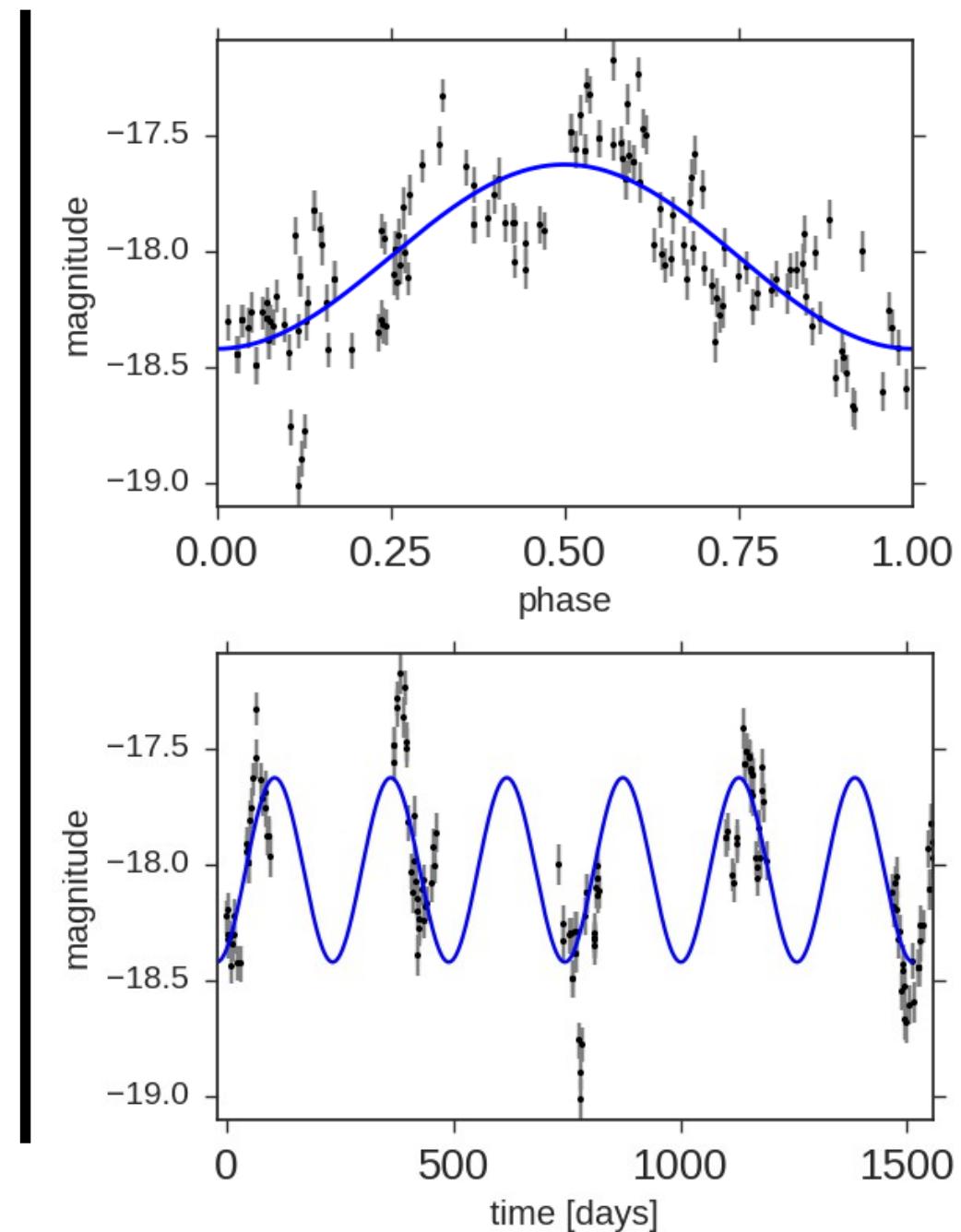
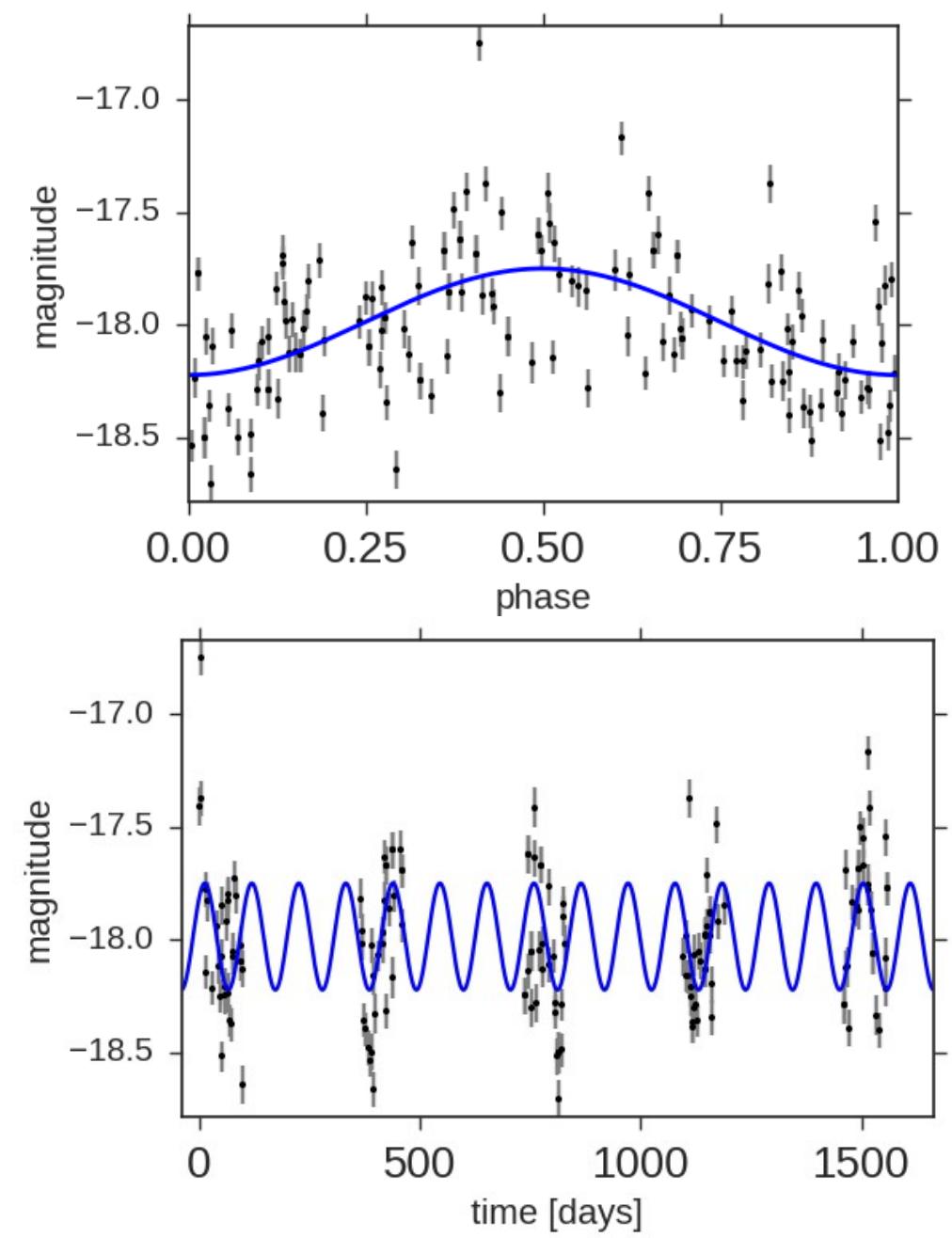
I. What are we looking at?



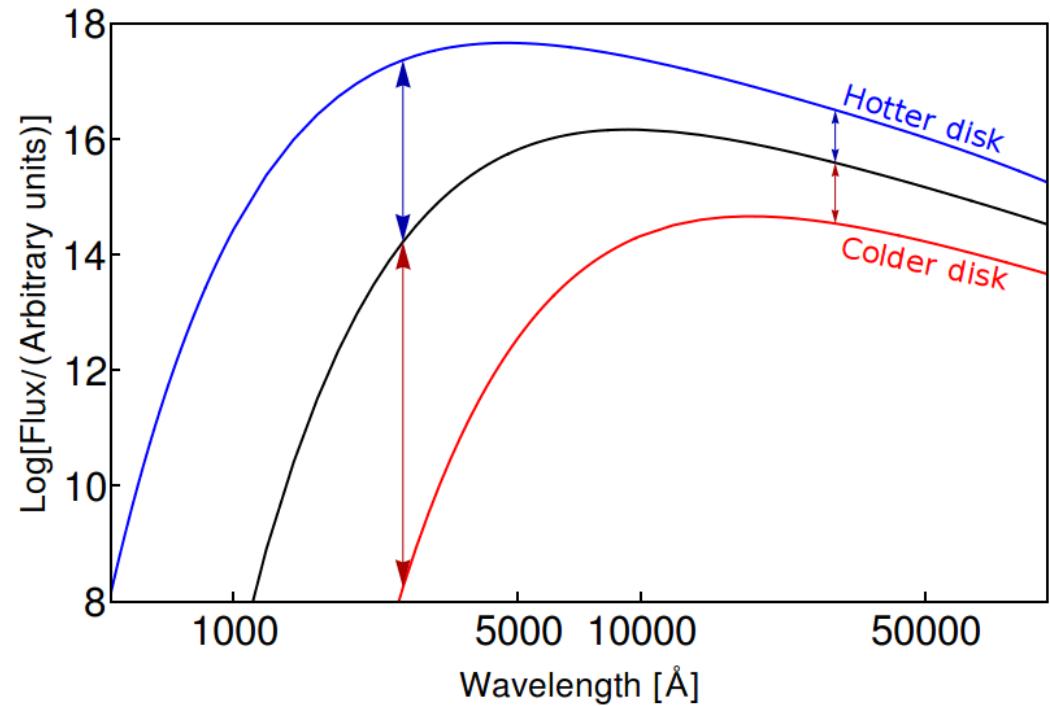
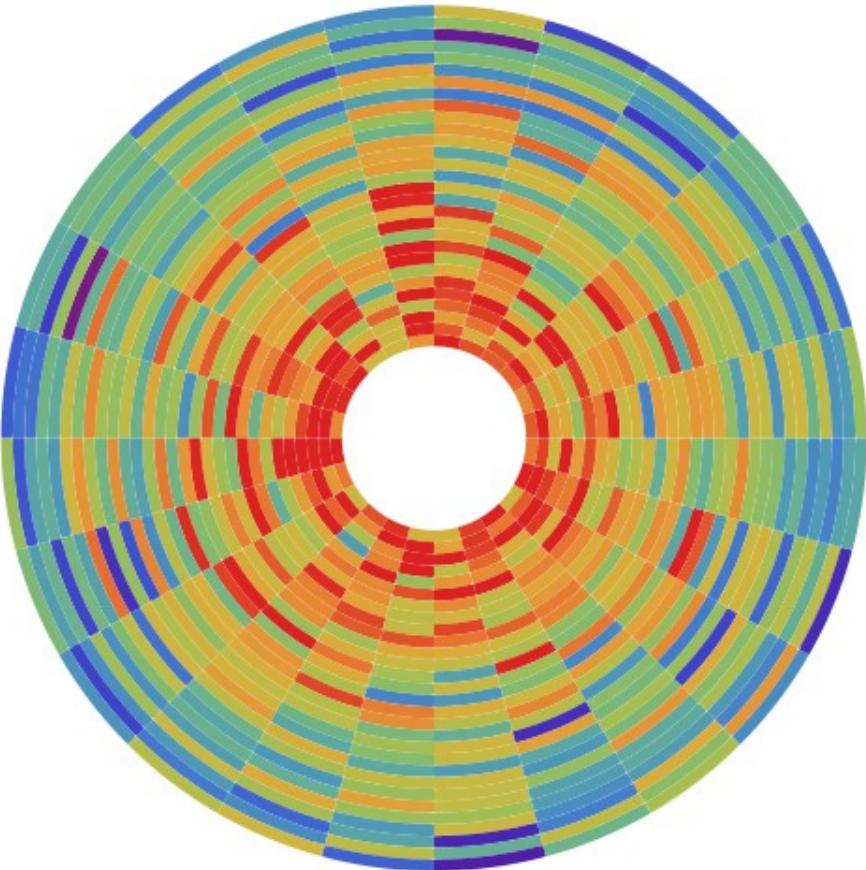
Sartori+, submitted

- ``Quasar selection'' targets very special time during the lifetime of an AGN
- LSST will be much deeper, but host galaxy contribution becomes significant!

II. Steeper PSD creates more false-positive AGN periods

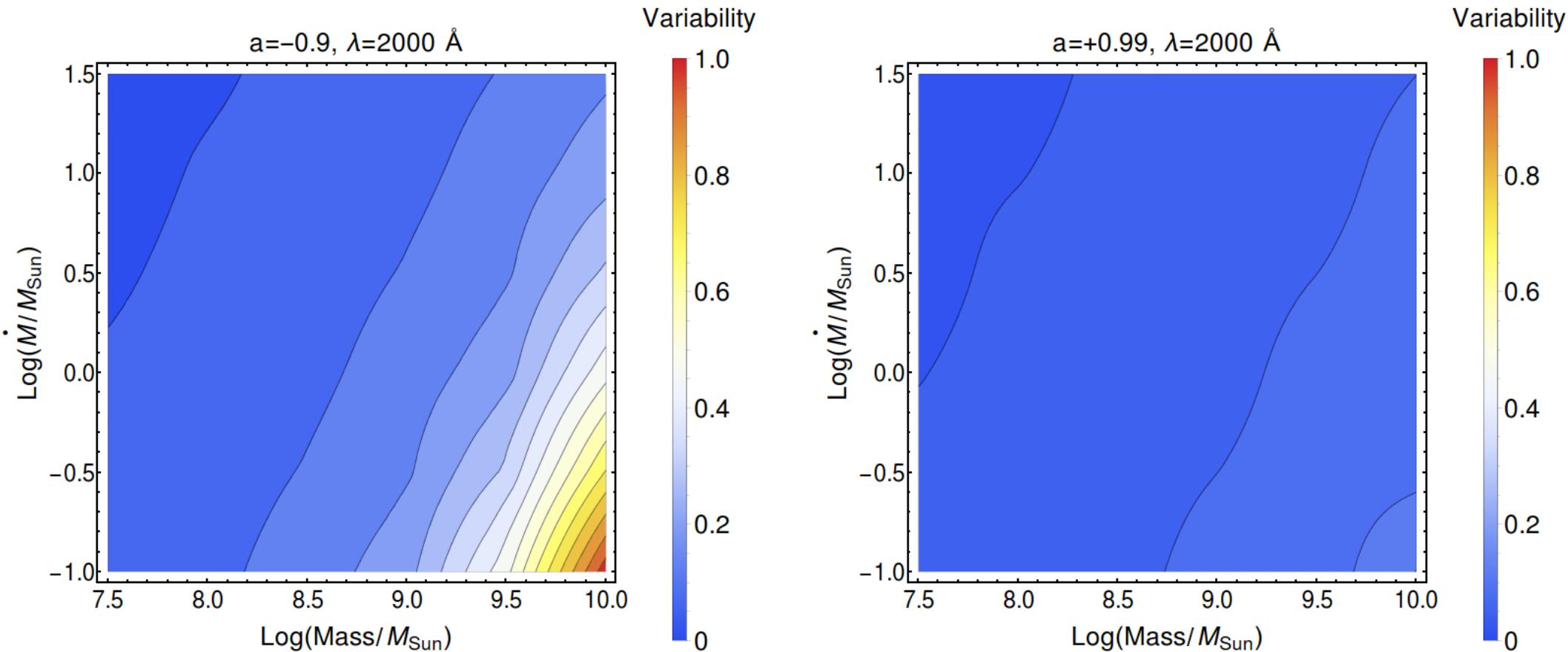


III. Constrain spin from variability?



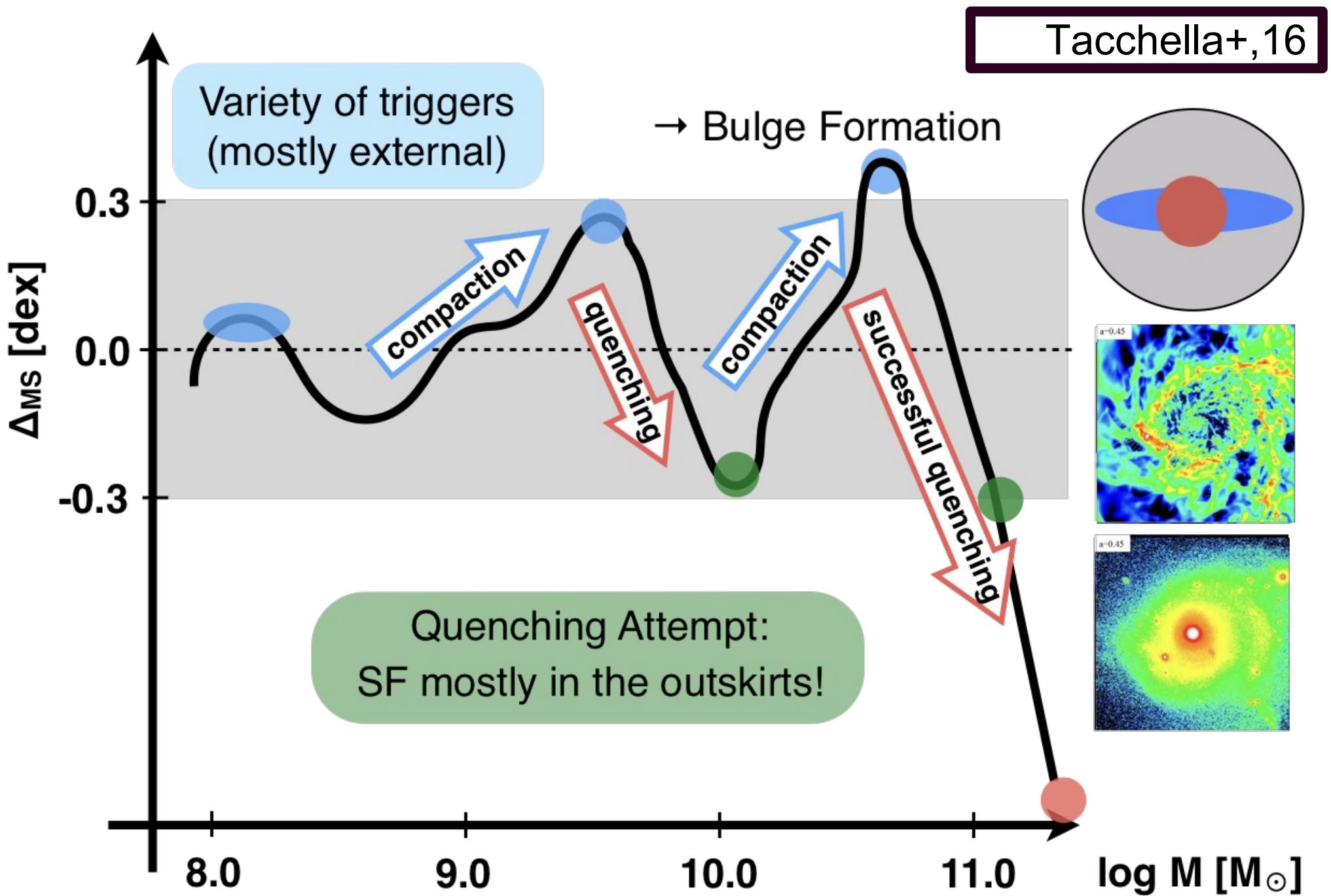
- Optical variability as a consequence of temperature variations in the disk (Dexter & Agol, 2011)
- Temperature: $T(r) \propto \Delta M^{1/4} M^{-1/2} f(r)^{3/4} (r/r_g)^{-3/4}$
 - Temperature correlated with spin (f parameter in equation above)

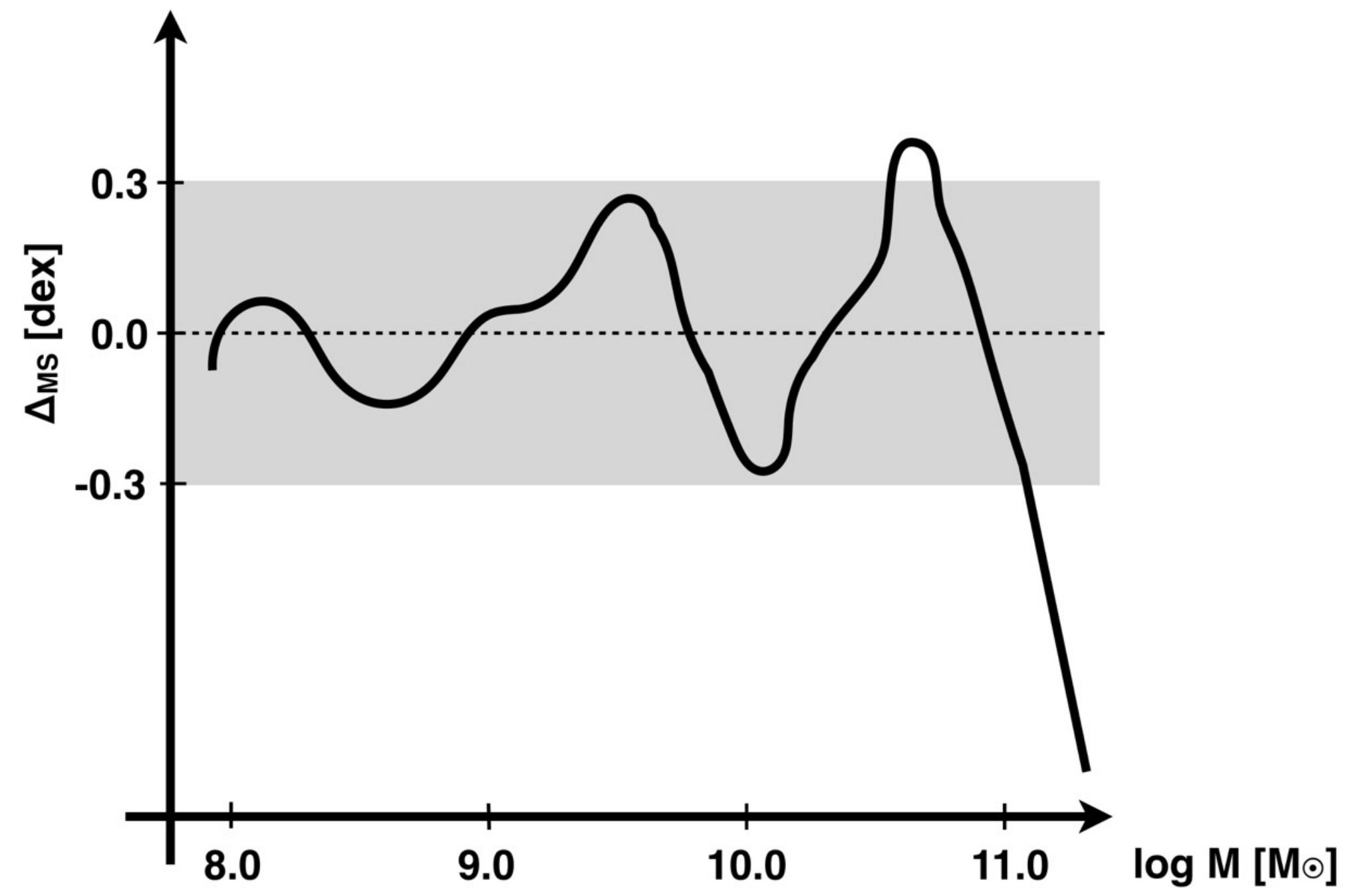
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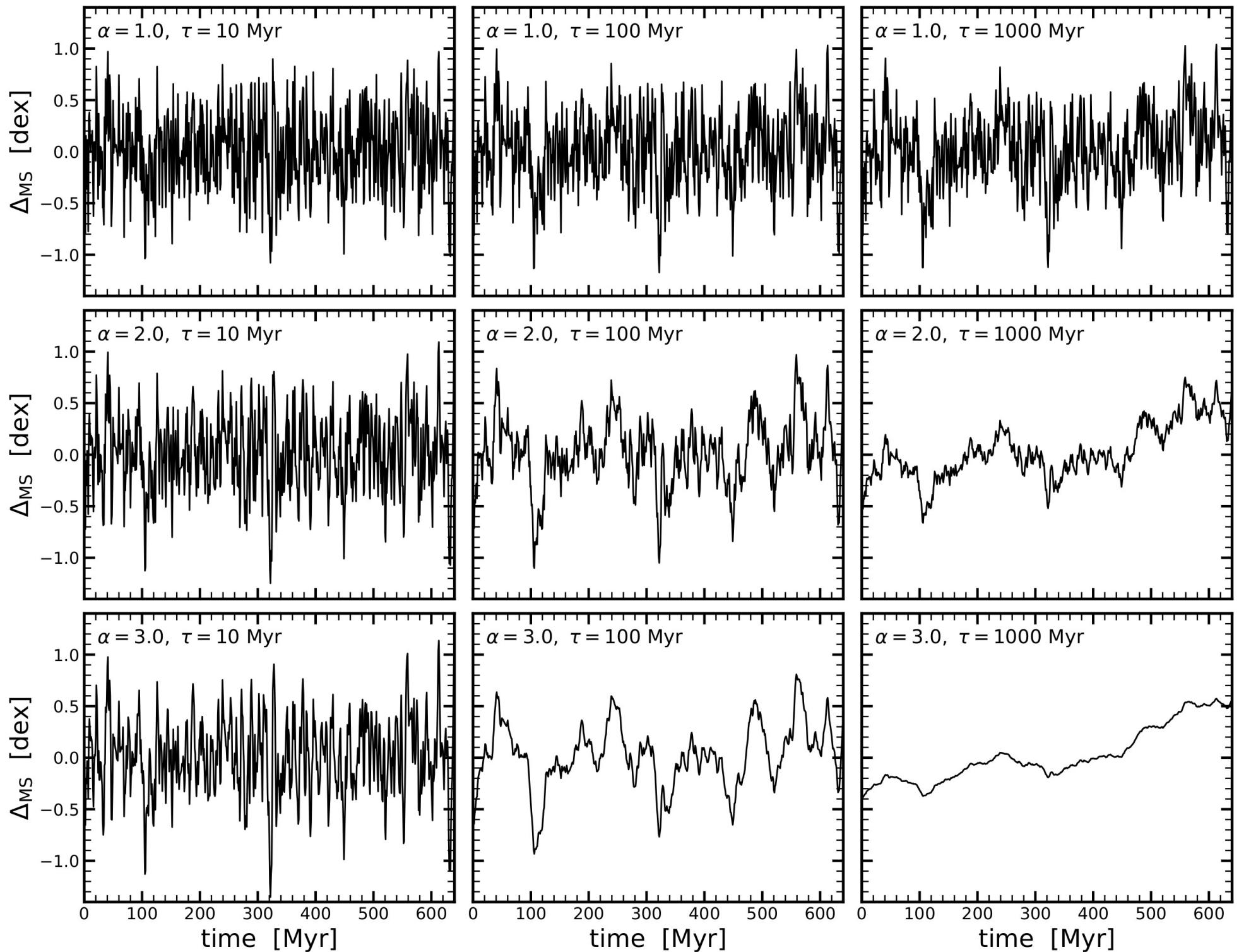


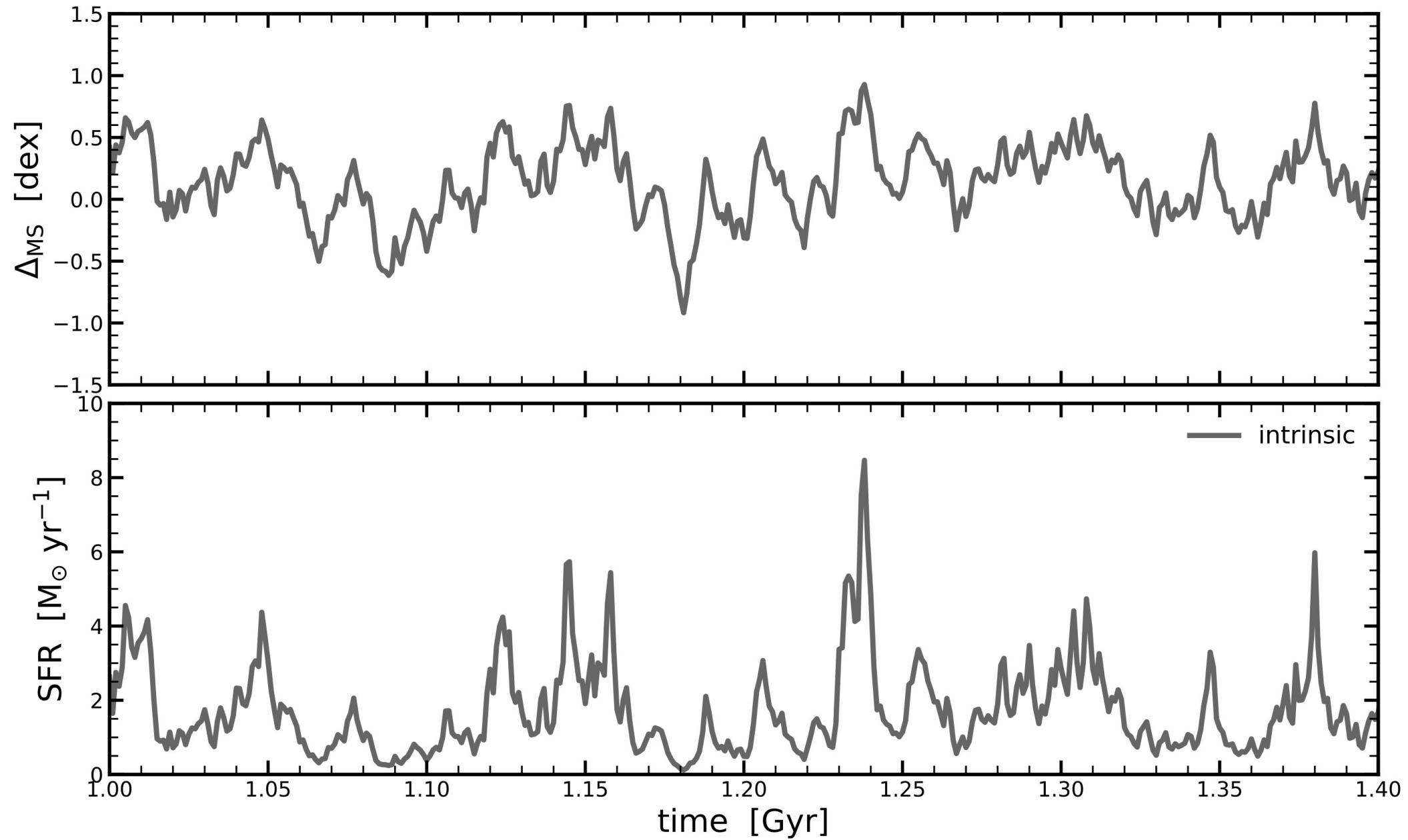
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Confinement of star-forming galaxies

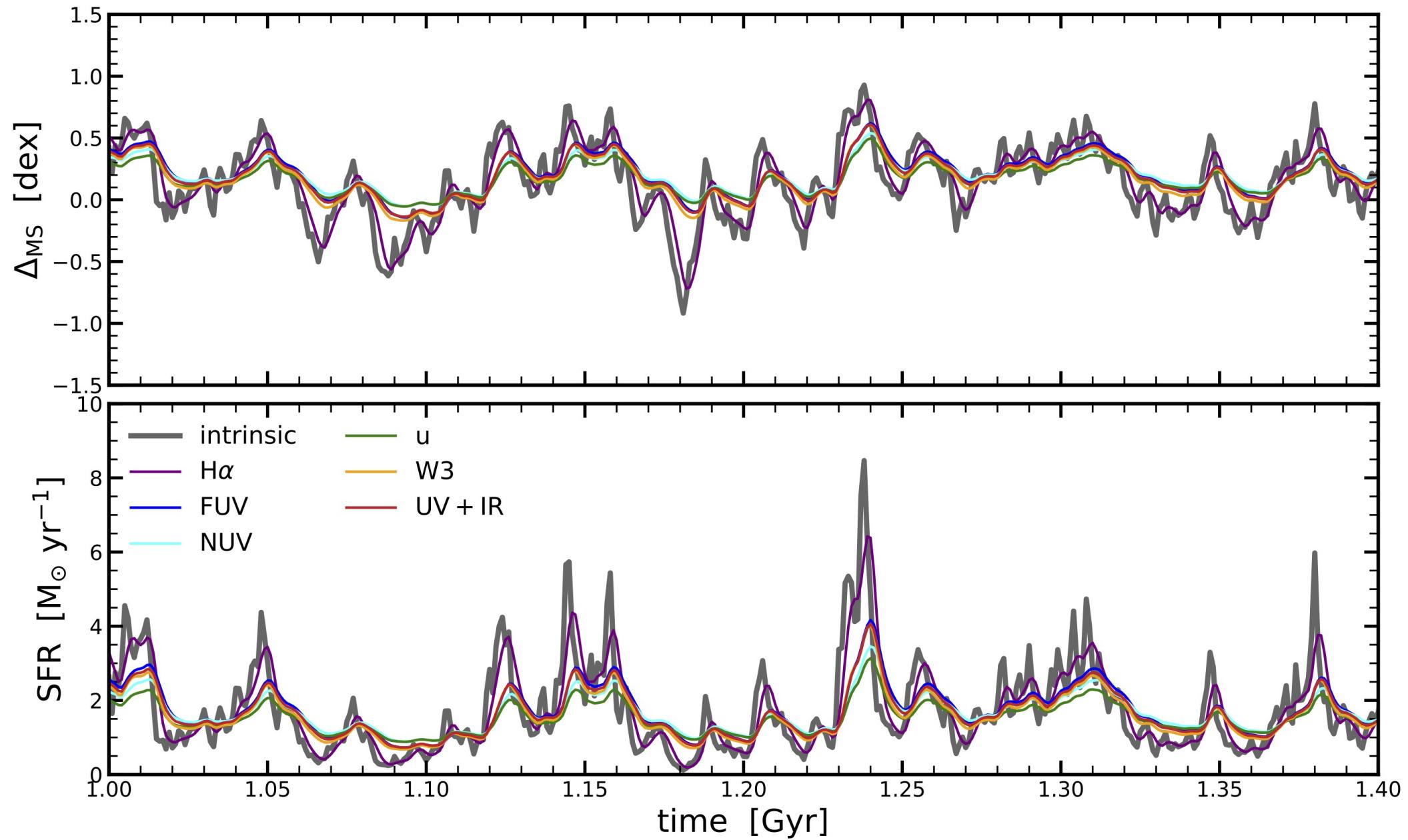




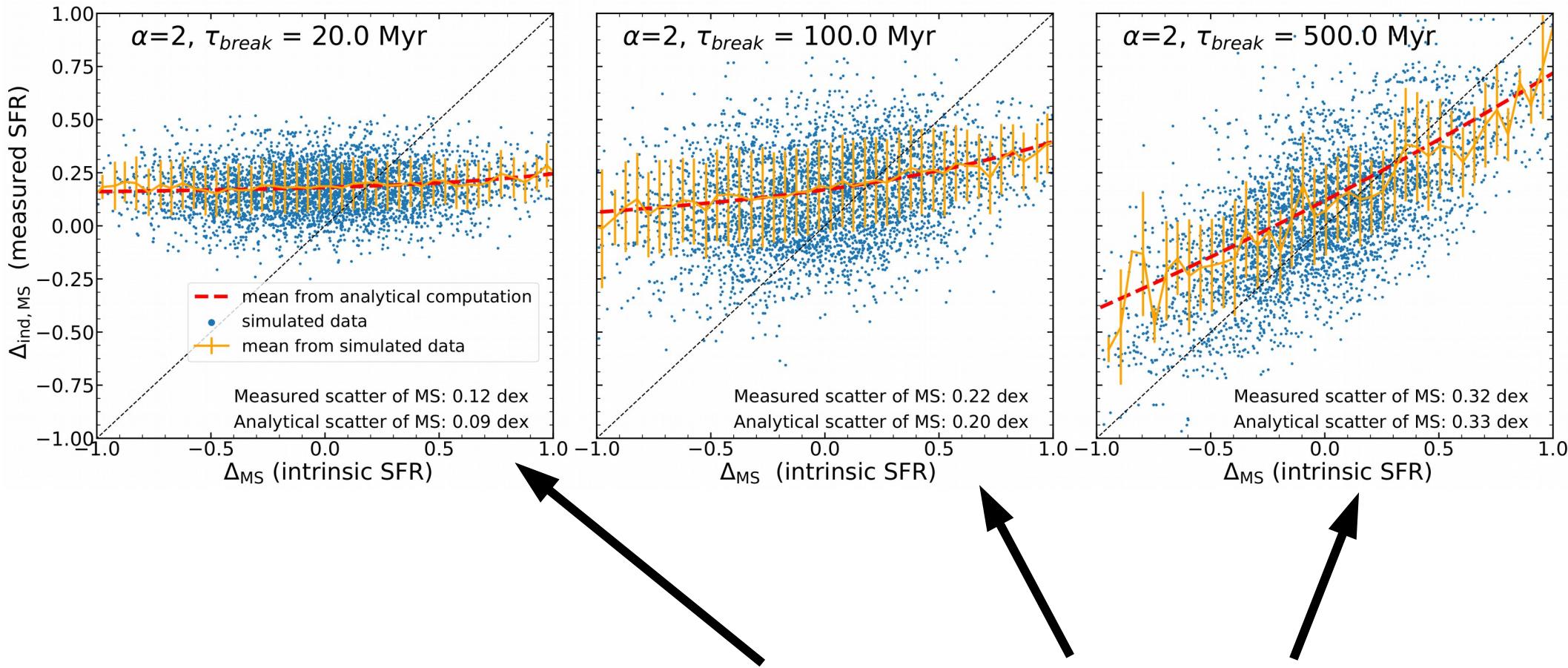




- We do not observe galaxies directly – but we observe different passbands

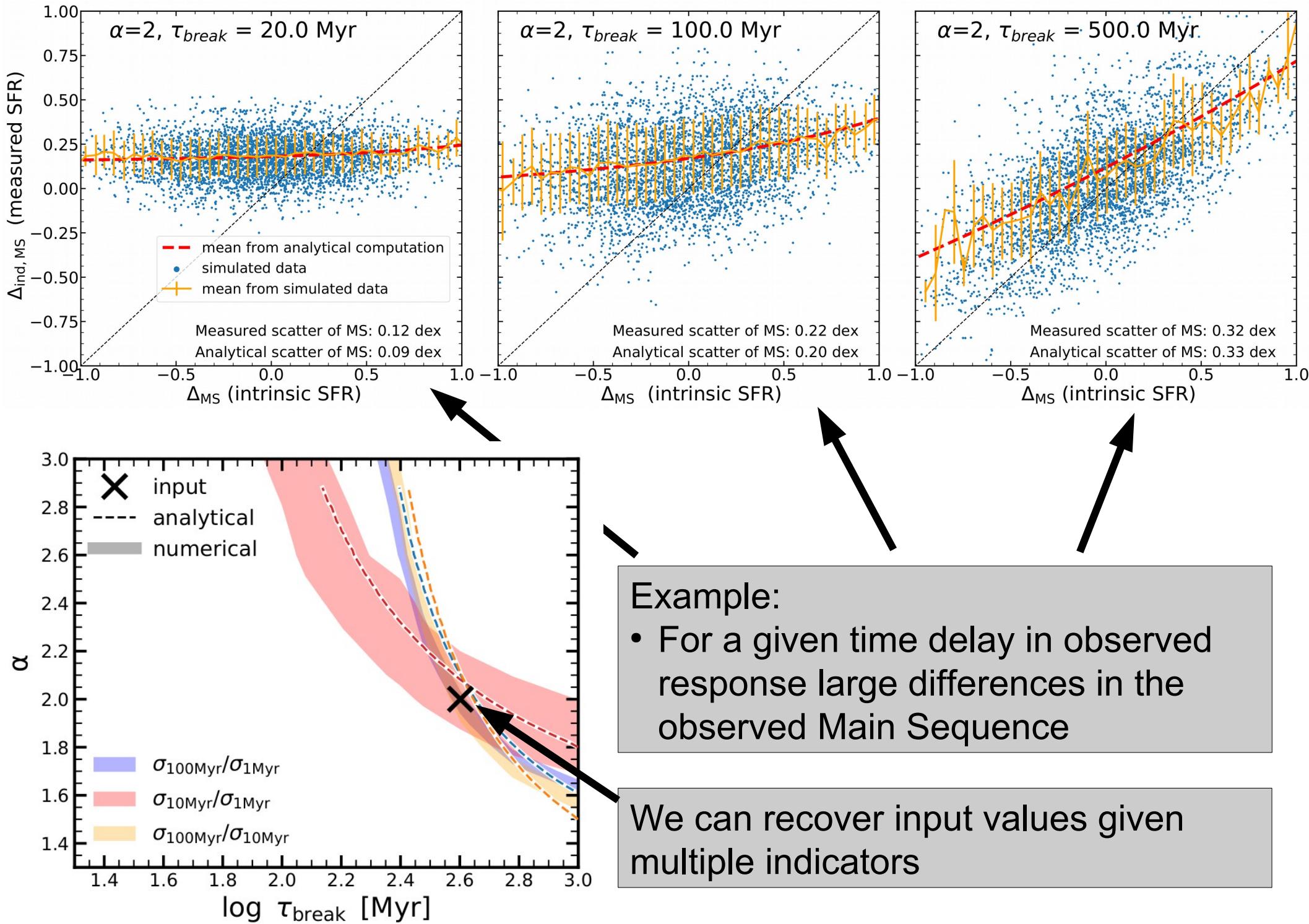


- We do not observe galaxies directly – but we observe different passbands



Example:

- For a given time delay in observed response large differences in the observed Main Sequence

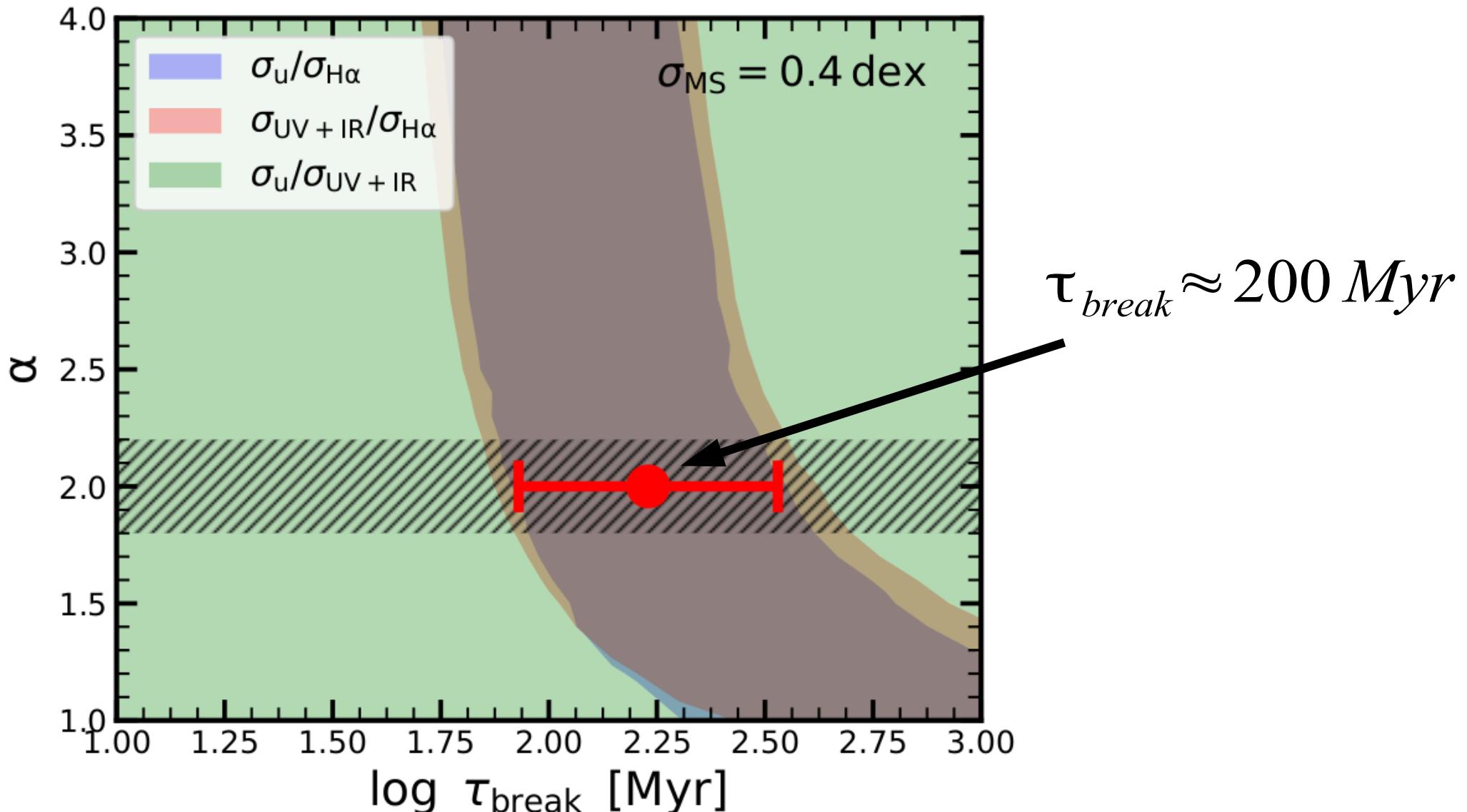


Observational data:

- GAMA survey; $z < 0.1$; 9000 galaxies
- focus here on $M_{\star} \approx 10^{10.5} M_{\odot}$
- Davies+ 2019, measured the MS scatter for different indicators and different star-forming galaxy samples

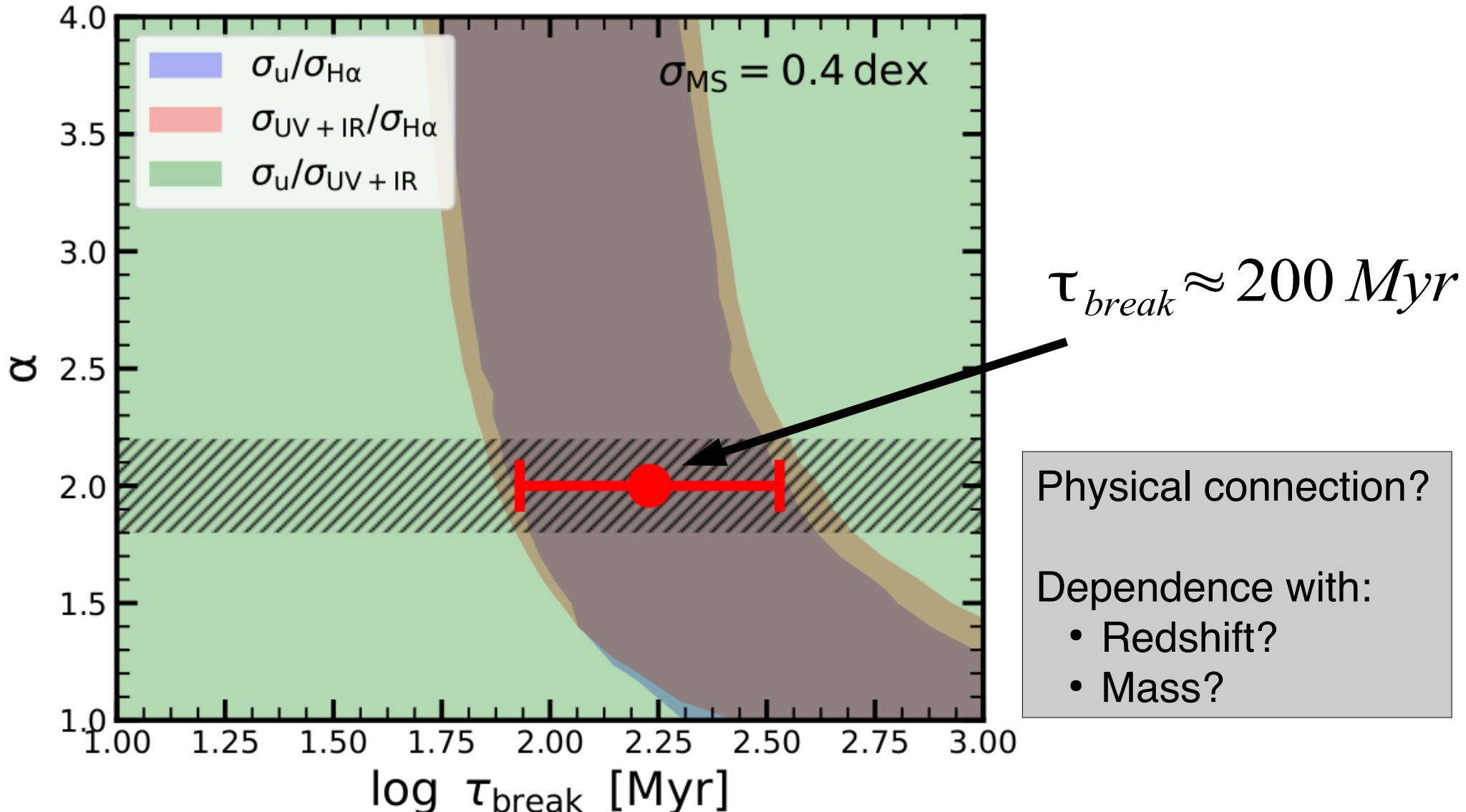
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Main-Sequence-Variability

The main file is the Main_Sequence_Variability.ipynb notebook. It has several examples

- overview of the autocorrelation functions and its connection with the parameters of the power spectrum density (high-frequency slope and timescale of the break)
- overview of the analytical results of the measured width of the Main Sequence, as a function of the parameters of the power spectrum density
- Figure 6 from the paper, showing the relation between the intrinsic Main Sequence and measured Main Sequence, in a toy model
- Analytical result for the Figure 7 from the manuscript, showing how we recover the parameters of the PSD from observations, in a toy model.

Dependencies are pandas, tqdm and DELCgen (<https://github.com/samconnolly/DELightcurveSimulation>).

Screenshot of the notebook is below:

```
Welcome to MS_variability package - you have just imported tabulated auto-correlation functions.  
These auto-correlation function have been computed numerically in Wolfram Mathematica (notebook also available in the Github folder) for  
PSD=1/(1+(f/f_bend)^(slope)), where tau=1/f_bend and f is frequency.  
They are tabulated as function of tau (inverse frequency of the break in the PSD), slope (high frequency slope of the PSD) and time.  
Available tau (in units of Myr) are: [ 10. 15. 20. 25. 30. 35. 40. 45. 50. 55.  
 60. 65. 70. 75. 80. 85. 90. 95. 100. 150.  
 200. 250. 300. 350. 400. 450. 500. 550. 600. 650.  
 700. 750. 800. 850. 900. 950. 1000.]  
Available slopes are: [ 0. 1.1 1.2 1.3 1.4 1.5 1.6 1.7 1.8 1.9 2. 2.1 2.2 2.3 2.4  
 2.5 2.6 2.7 2.8 2.9]  
Longest available time is [Myr]: 1000.0
```

1 Some theoretical plots to get started

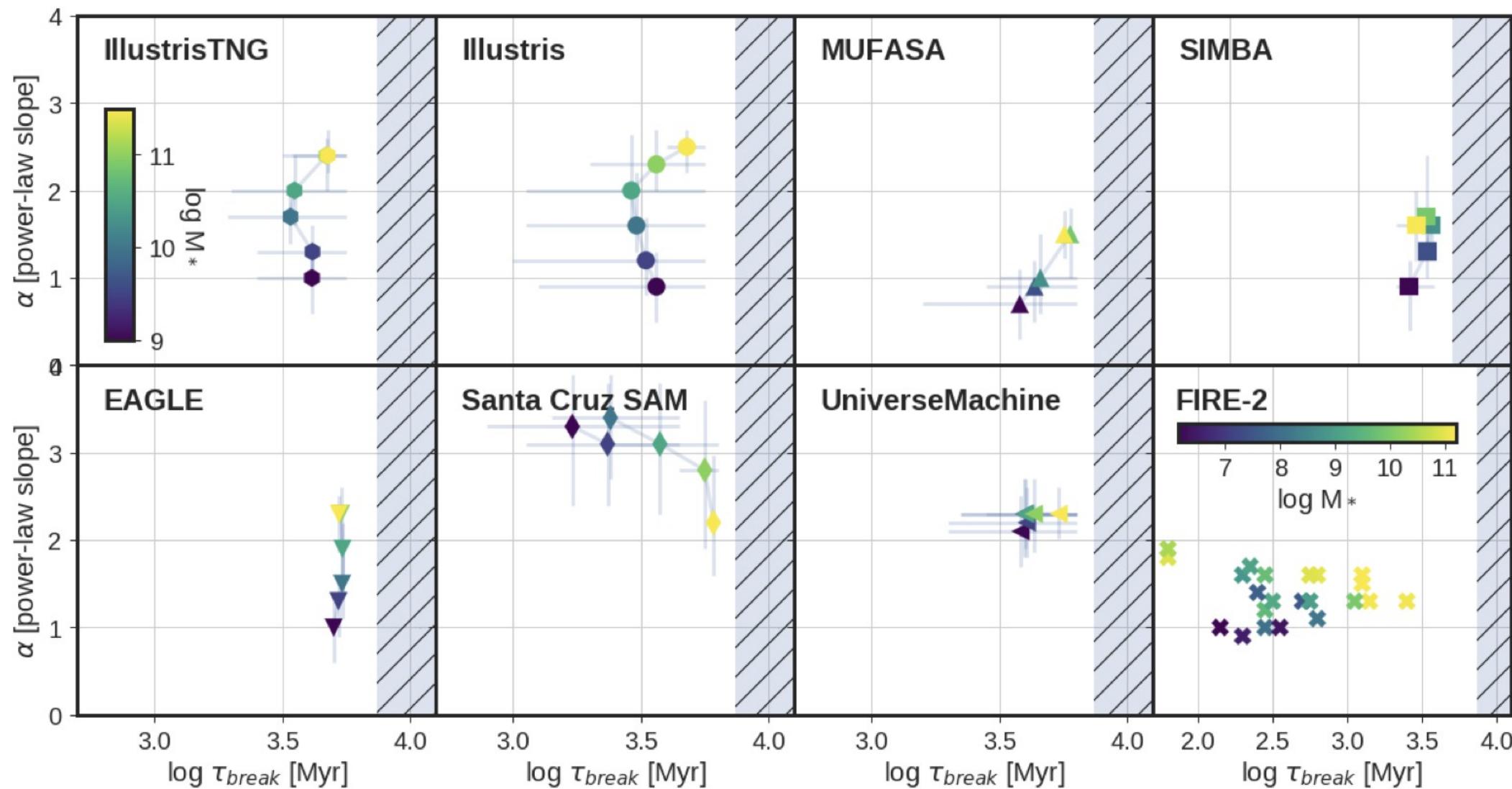
1.1 Looking at the ACF

[...]

1.2 Scatter of the main sequence in a toy model (Section 3 and left panel of Figure 5.)

[...]

PSDs in different models/simulations



Summary

- AGN variability offers unique way to study AGN accretion
 - Anti-correlation of variability with luminosity
 - If time to reach certain variability interpreted as time-scale τ , then $\tau \propto L^{0.5}$, similar to the prediction of the simplest model
 - Evidence for steepening of the PSD slopes with mass
 - More likely to create false periodicities
 - We are testing a very special AGN population!
 - Variability could be used to constrain spins of AGNs
-
- Can we use same formalism to describe star formation history of galaxies?
 - We do not observe histories directly, but we measure star-formation in different indicators
 - From the width of the Main Sequence we can determine parameters of the stochastic process
 - For a local sample, at $M_\star \approx 10^{10.5} M_\odot$ we find $\tau_{break} \approx 200$ Myr

