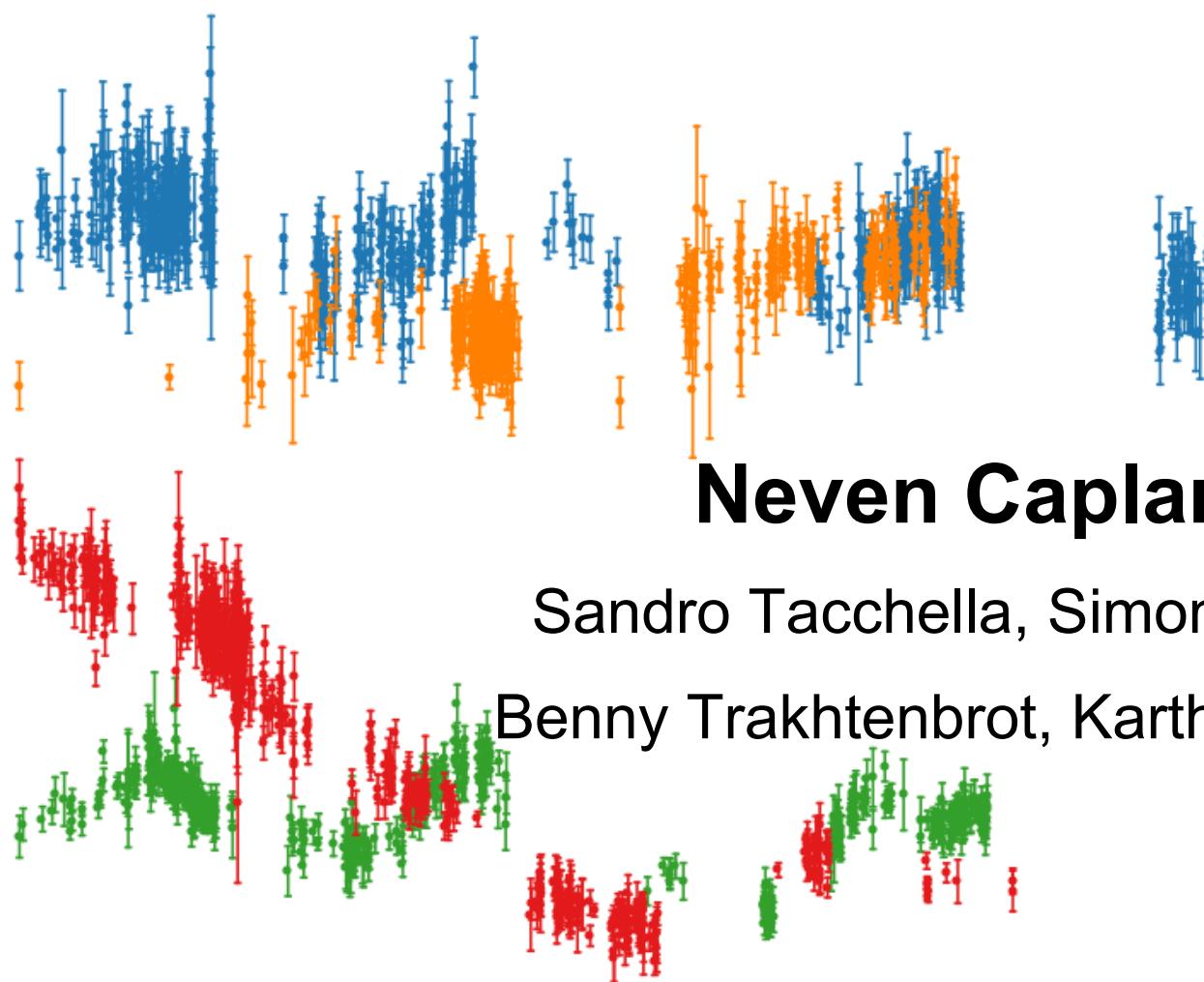


# Stochastic view of AGN and galaxy evolution

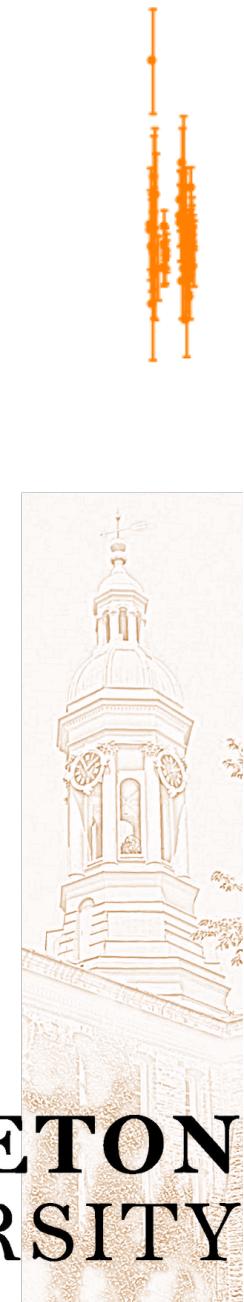


**Neven Caplar**

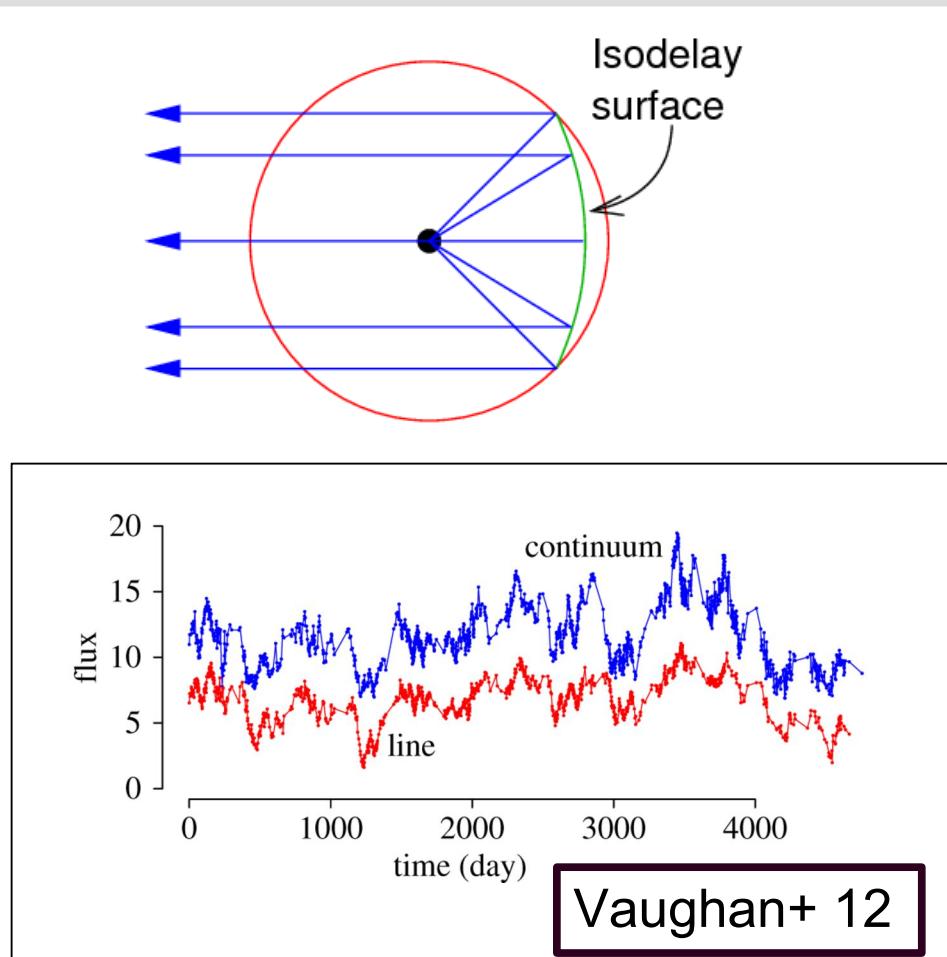
Sandro Tacchella, Simon Lilly,  
Benny Trakhtenbrot, Kartheik Iyer



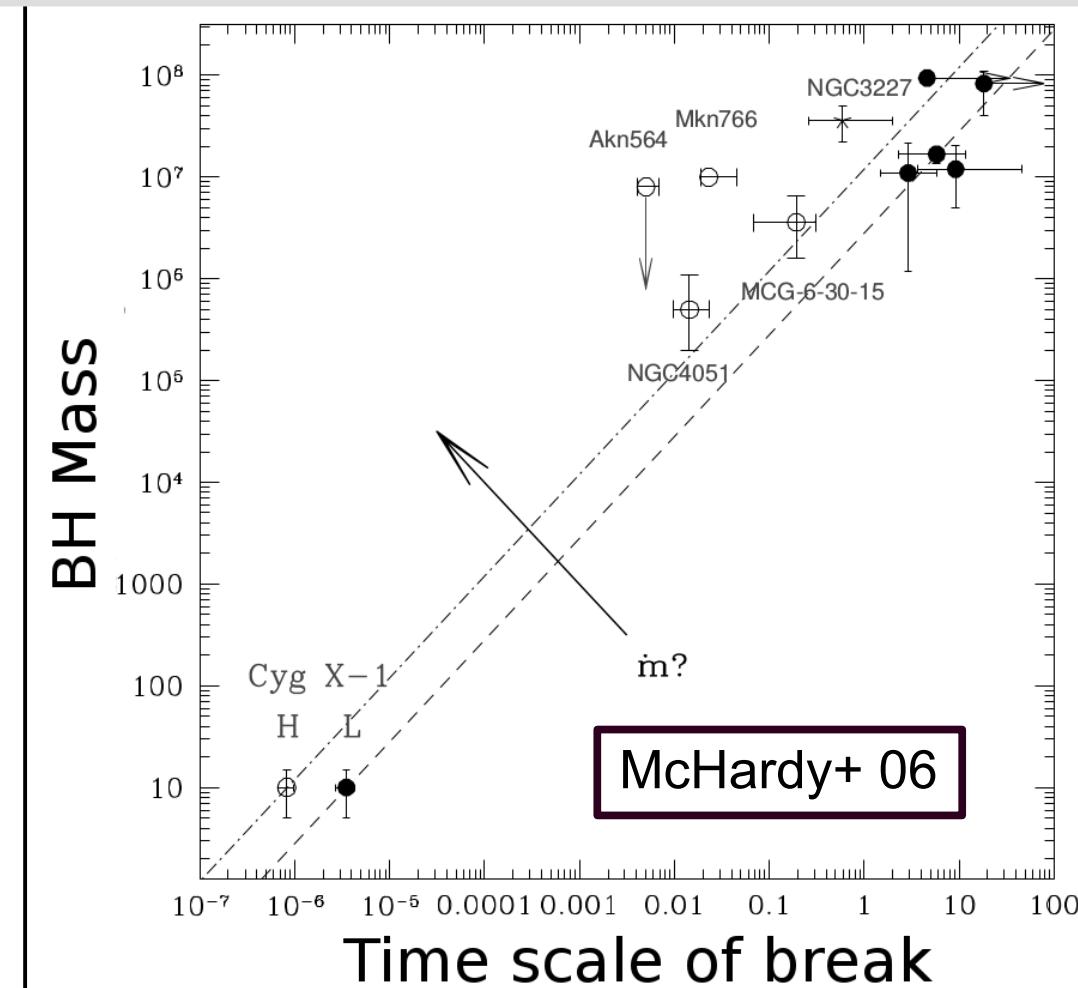
**PRINCETON  
UNIVERSITY**



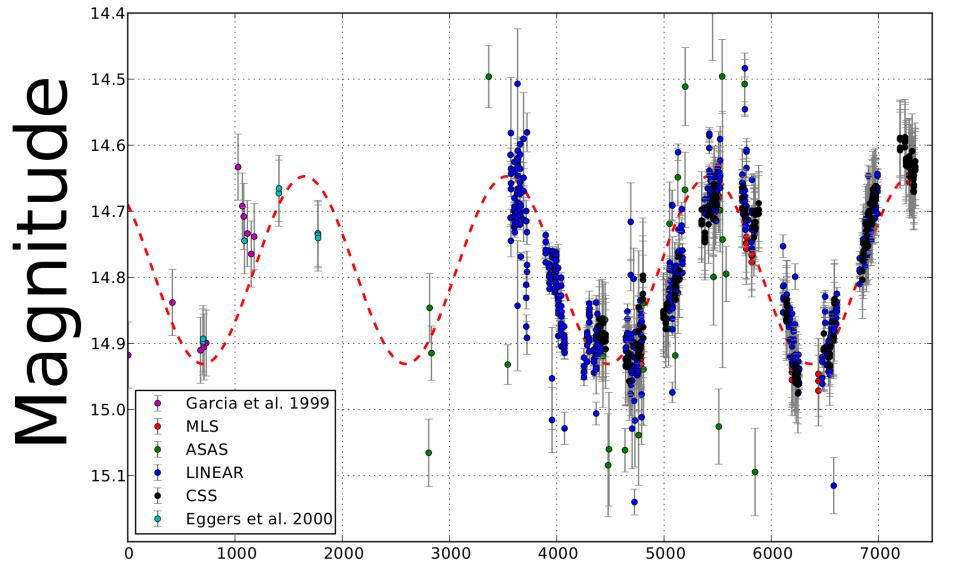
# Why quasar variability?



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

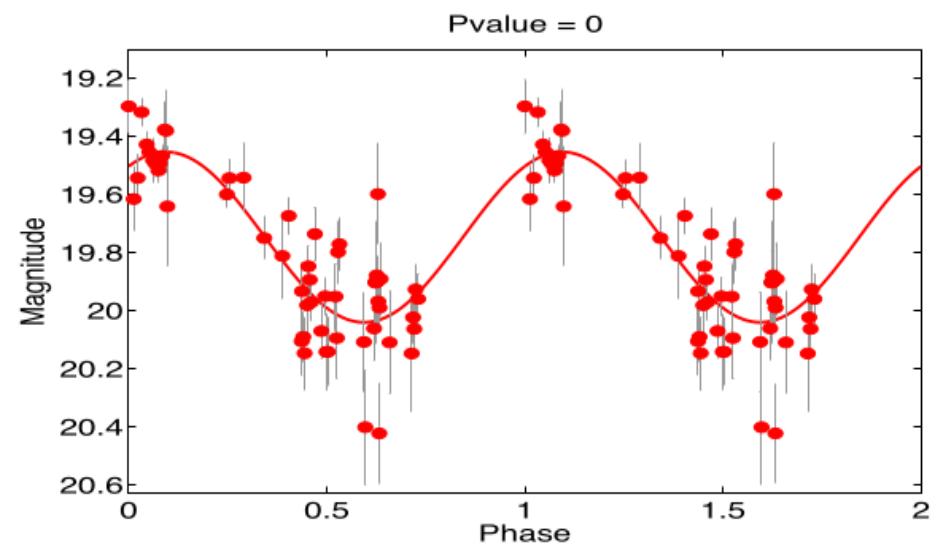
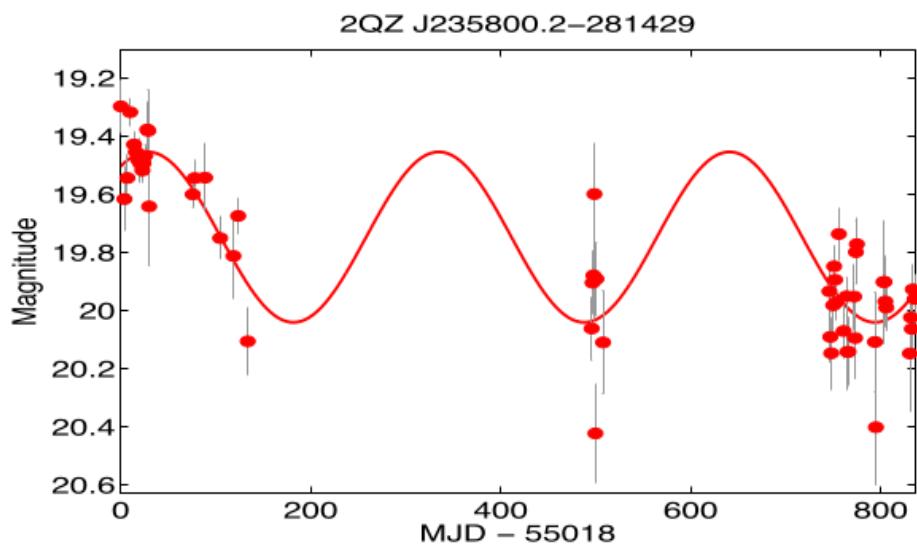


- BH mass correlated with with break in the X-ray power spectrum density

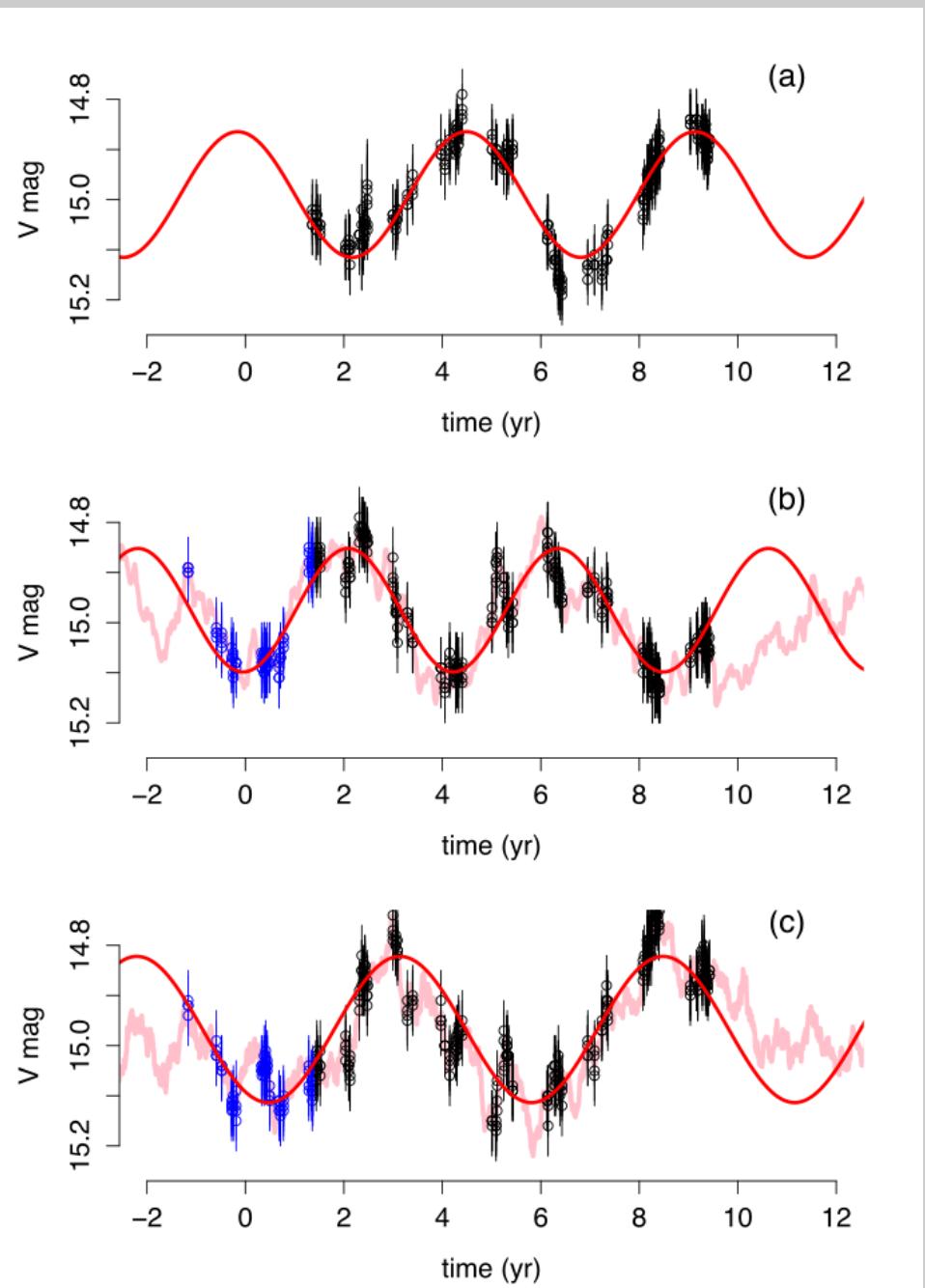


DATE Graham+ 15

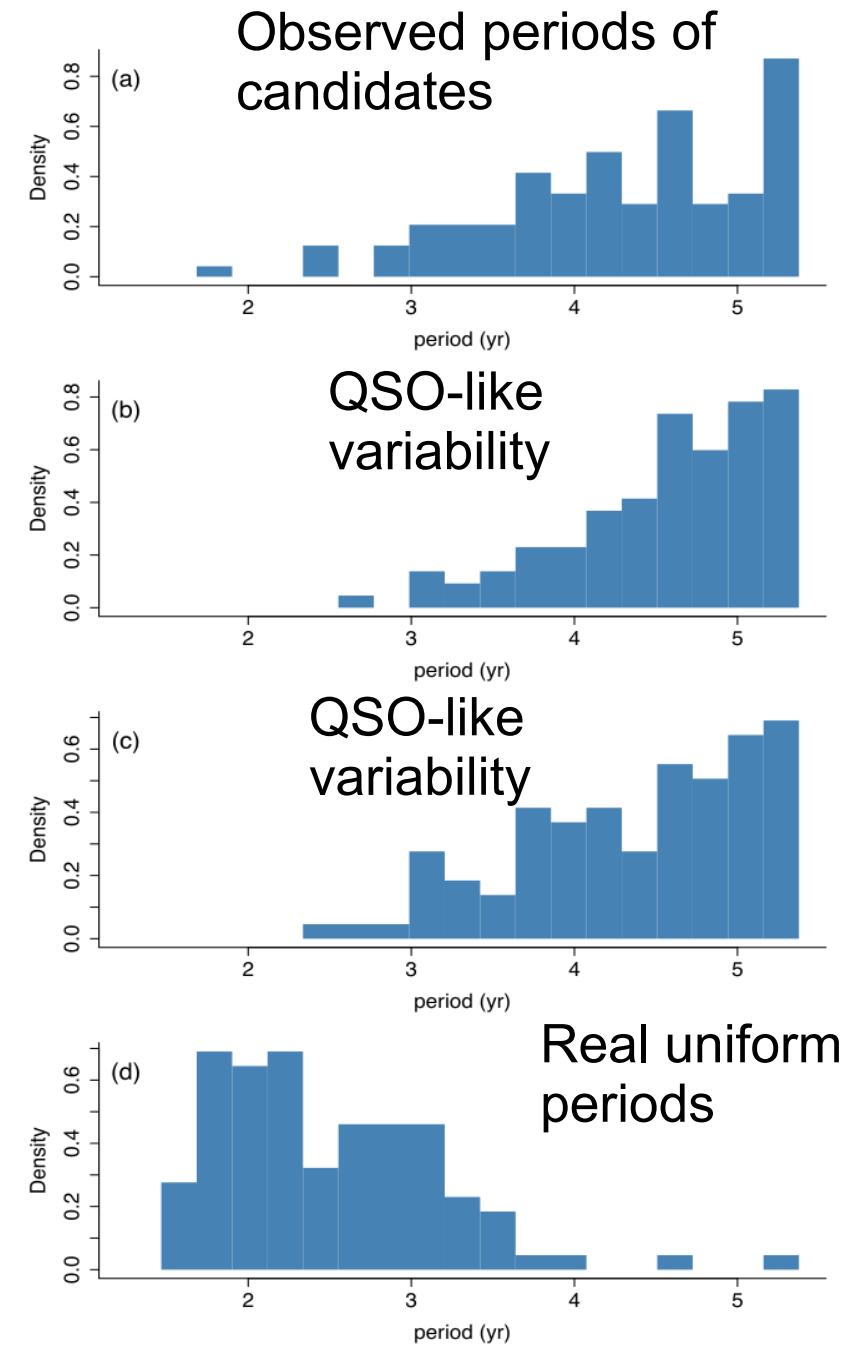
- Search for binaries of supermassive black holes with a sub-parsec separation
- Expected as a consequence of galaxy mergers



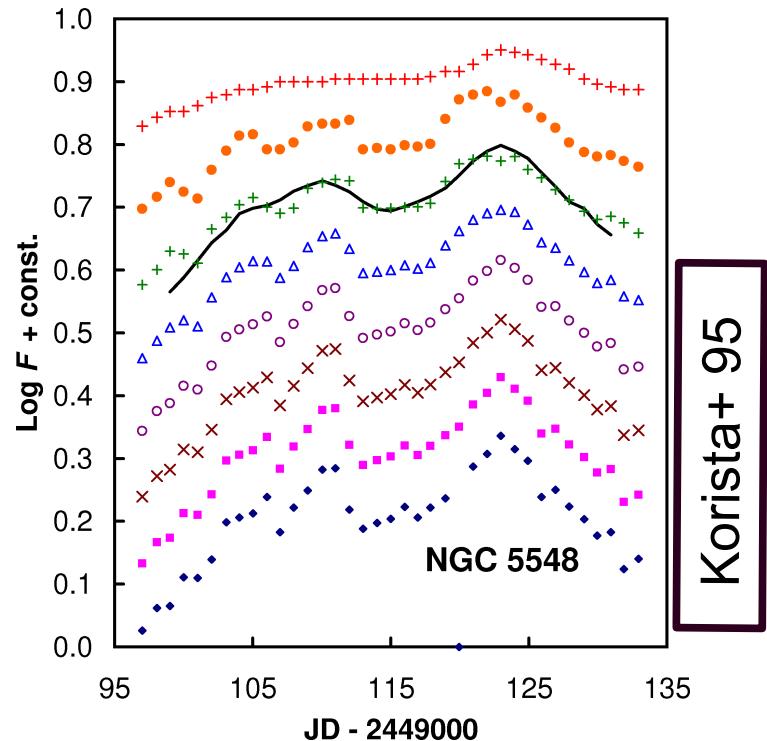
Charisi+ 16



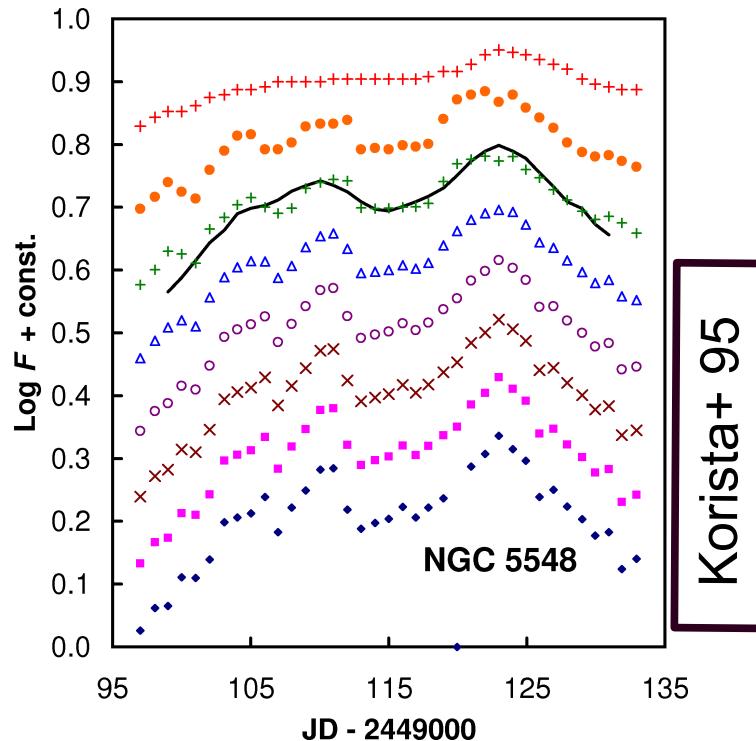
- But stochastic process can also mimic periodicity!



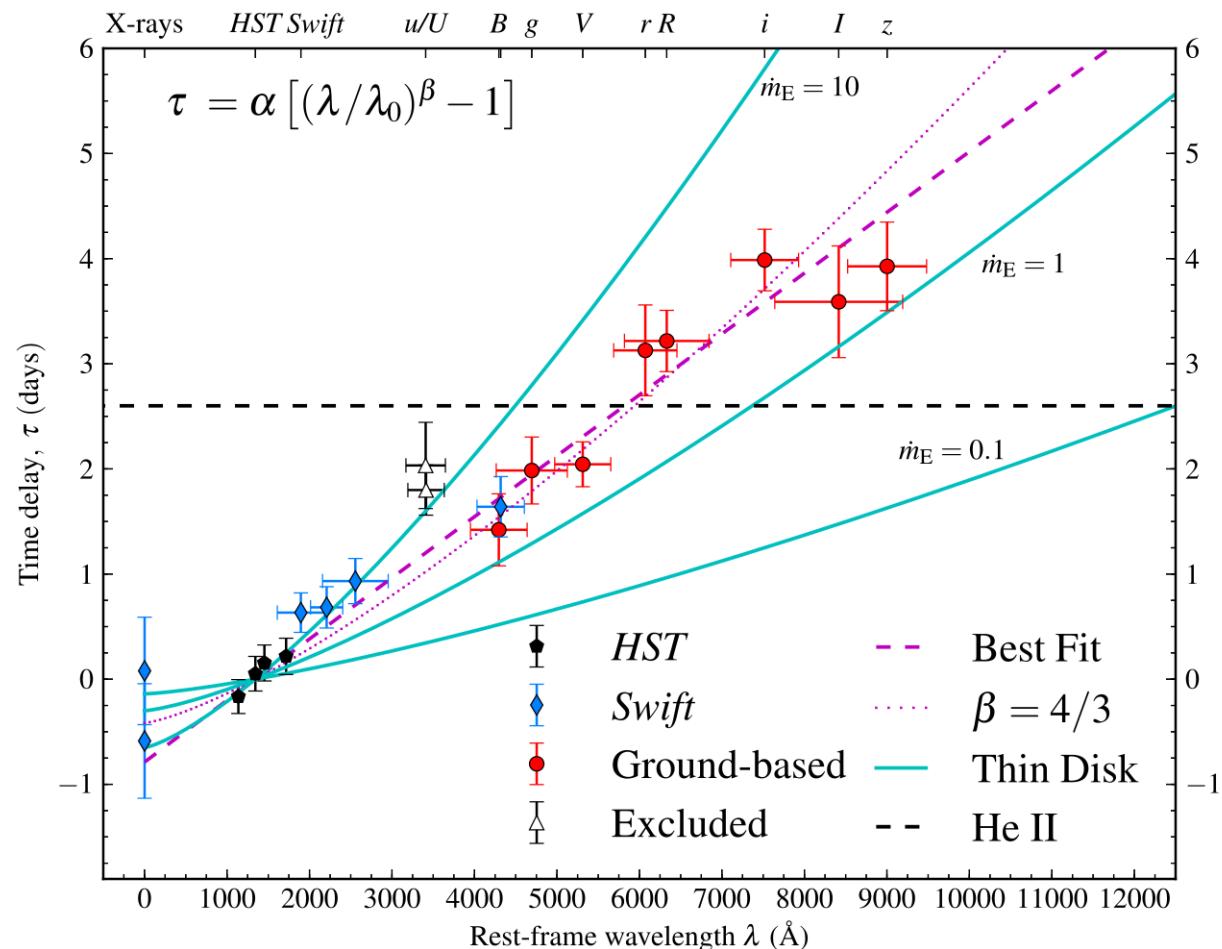
Vaughan+ 16



- 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?

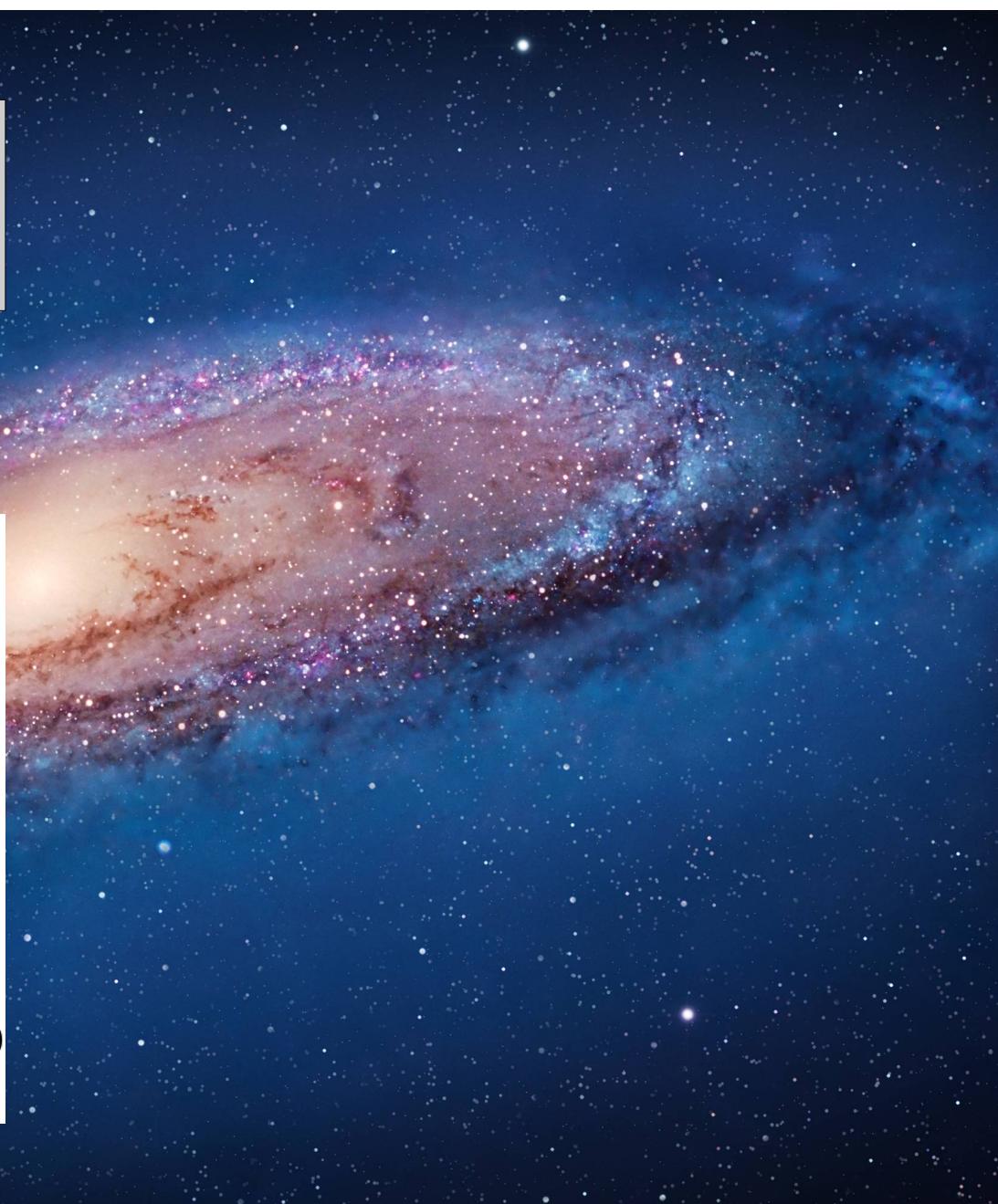
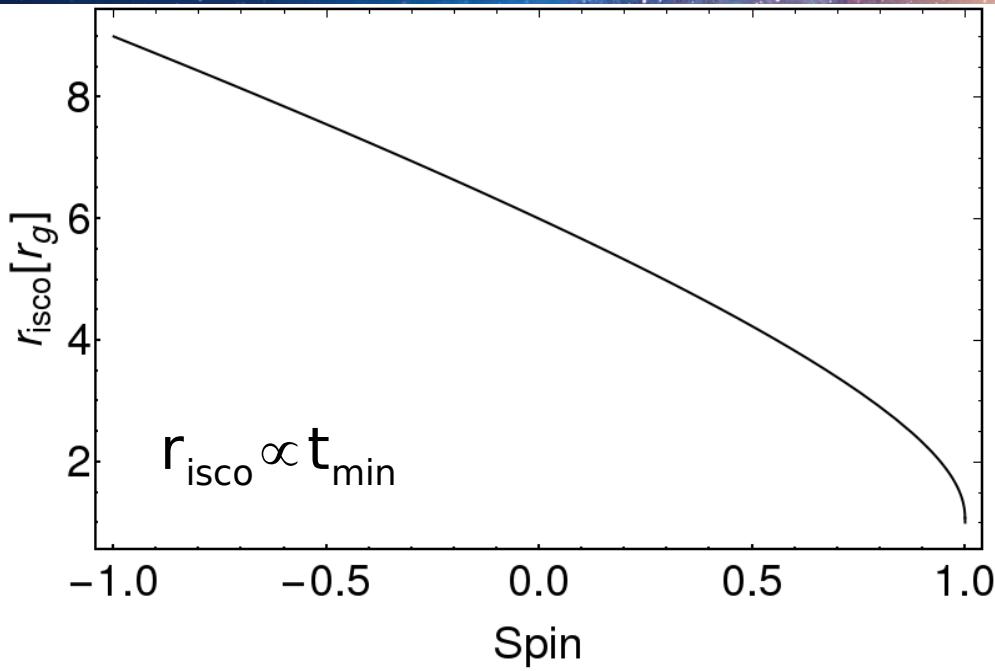
Fausnaugh+ 16

- Quasar variability as a method to measure spin



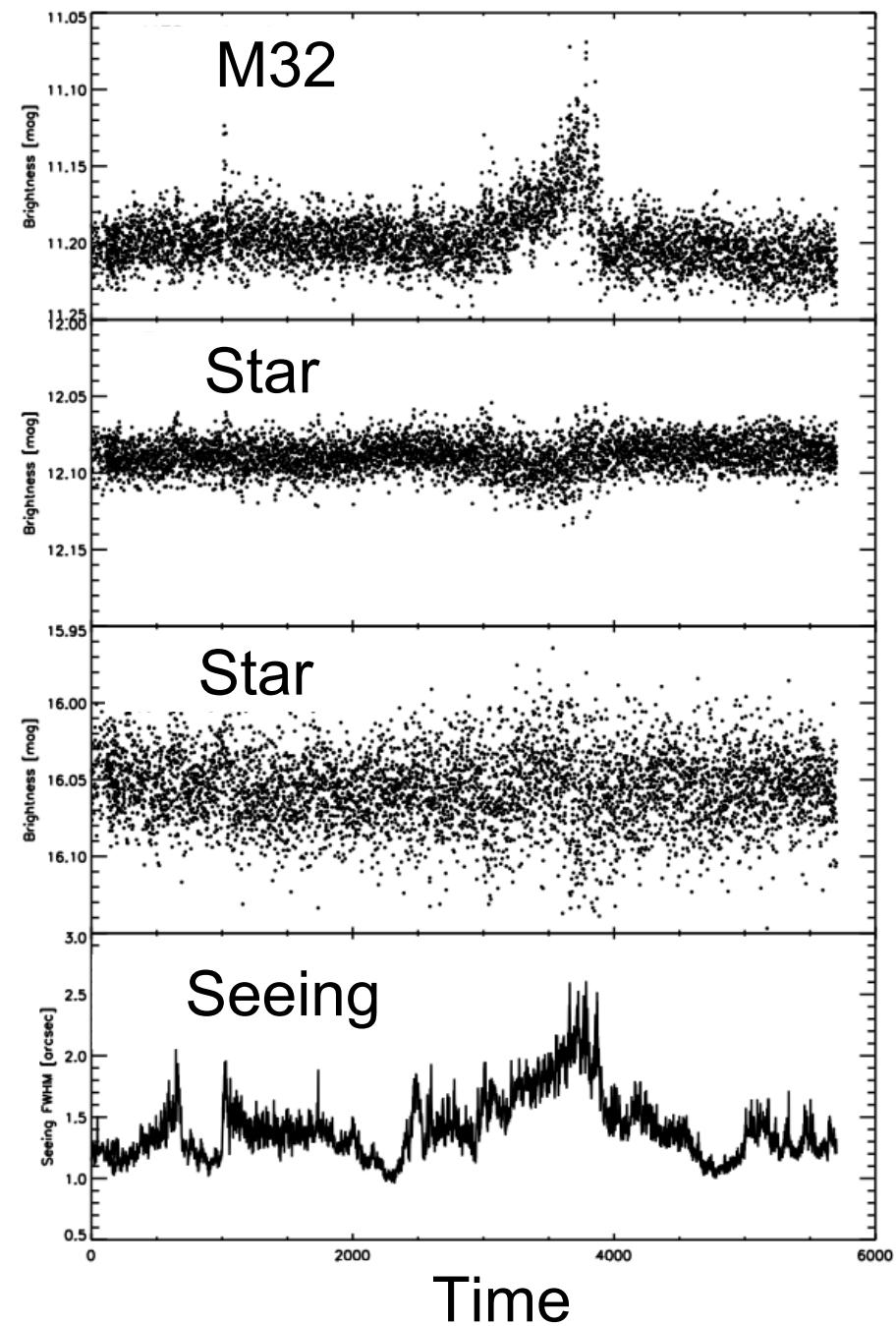
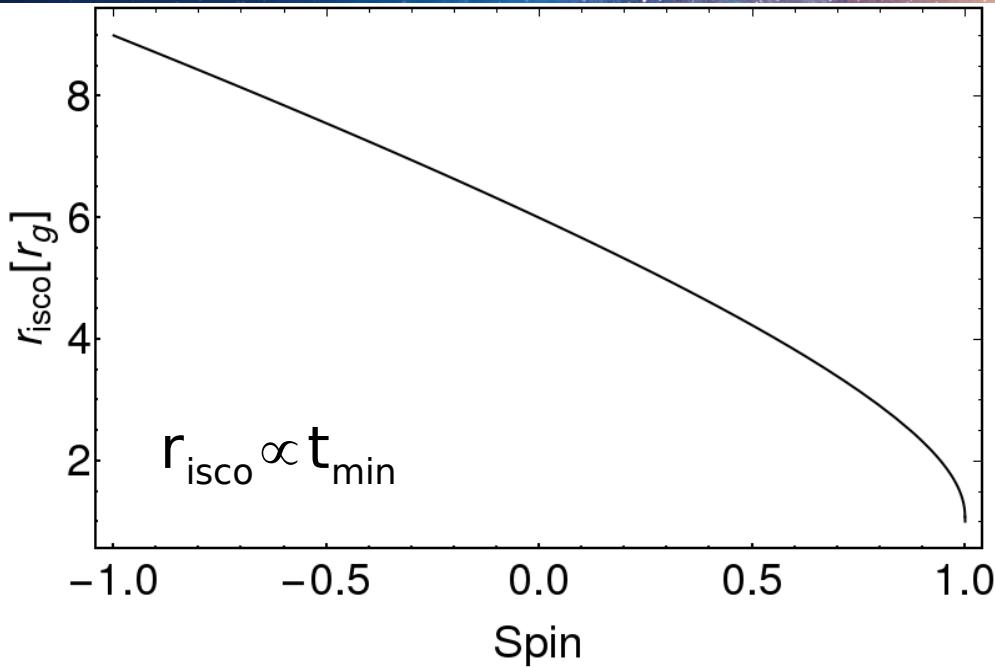
- Quasar variability as a method to measure spin

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



- Quasar variability as a method to measure spin

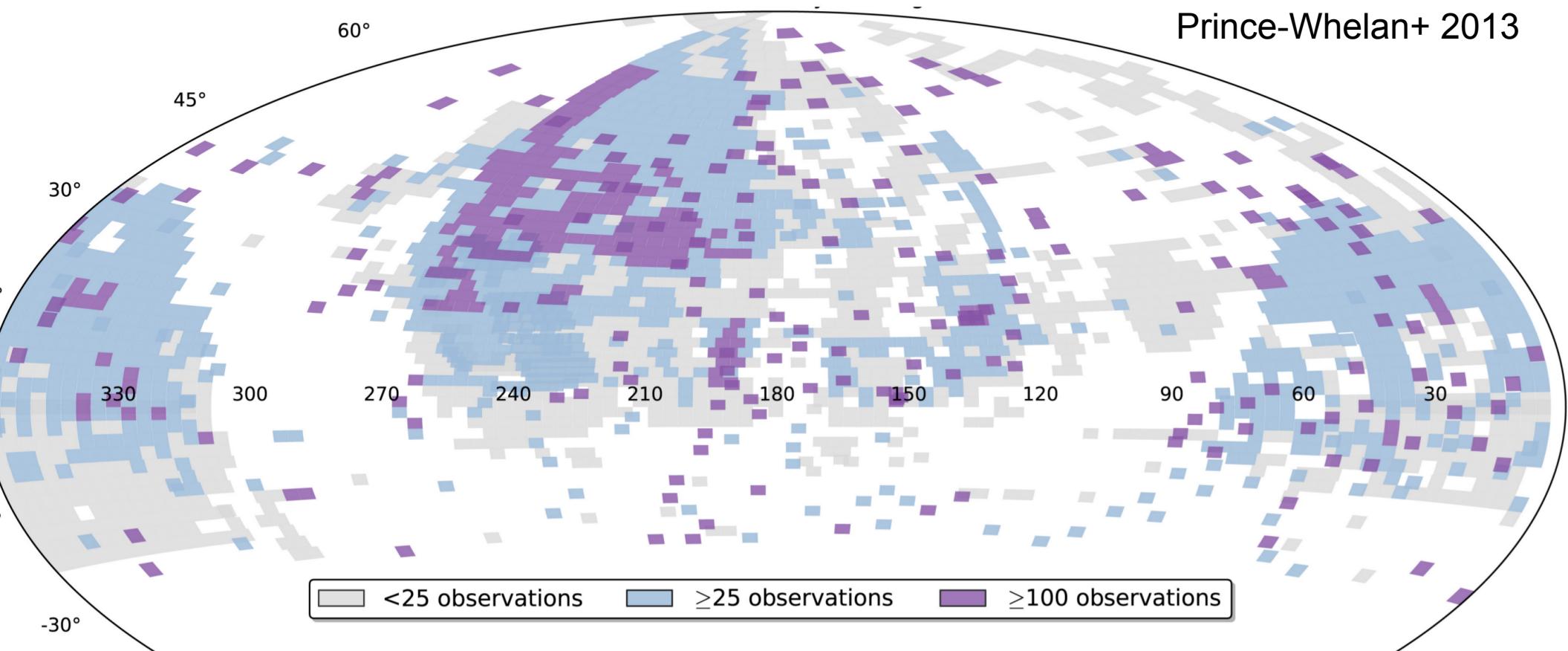
Measure the shortest time-scale of the variability; connected with the radius of the last stable orbit



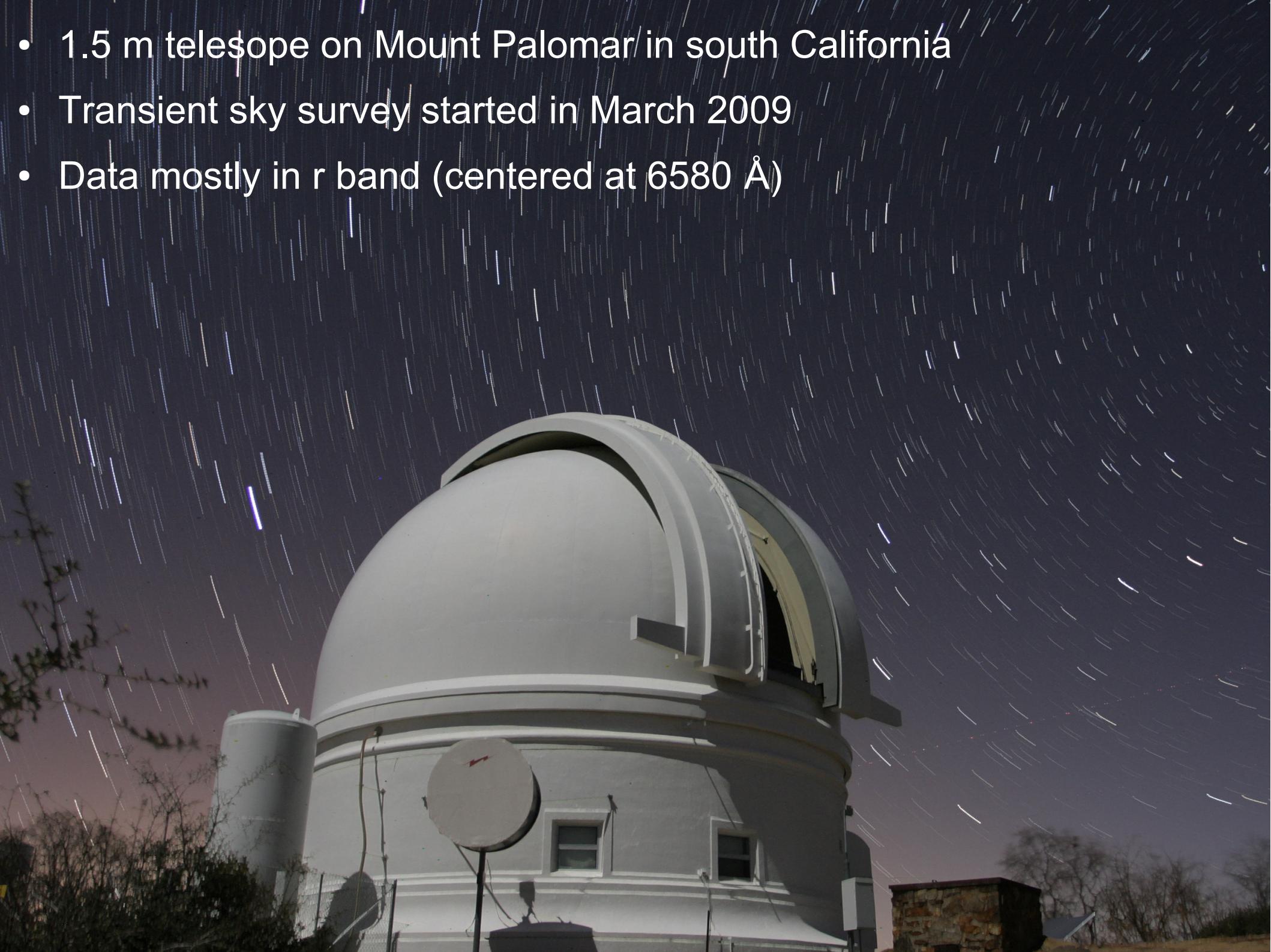
# Overview

- 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

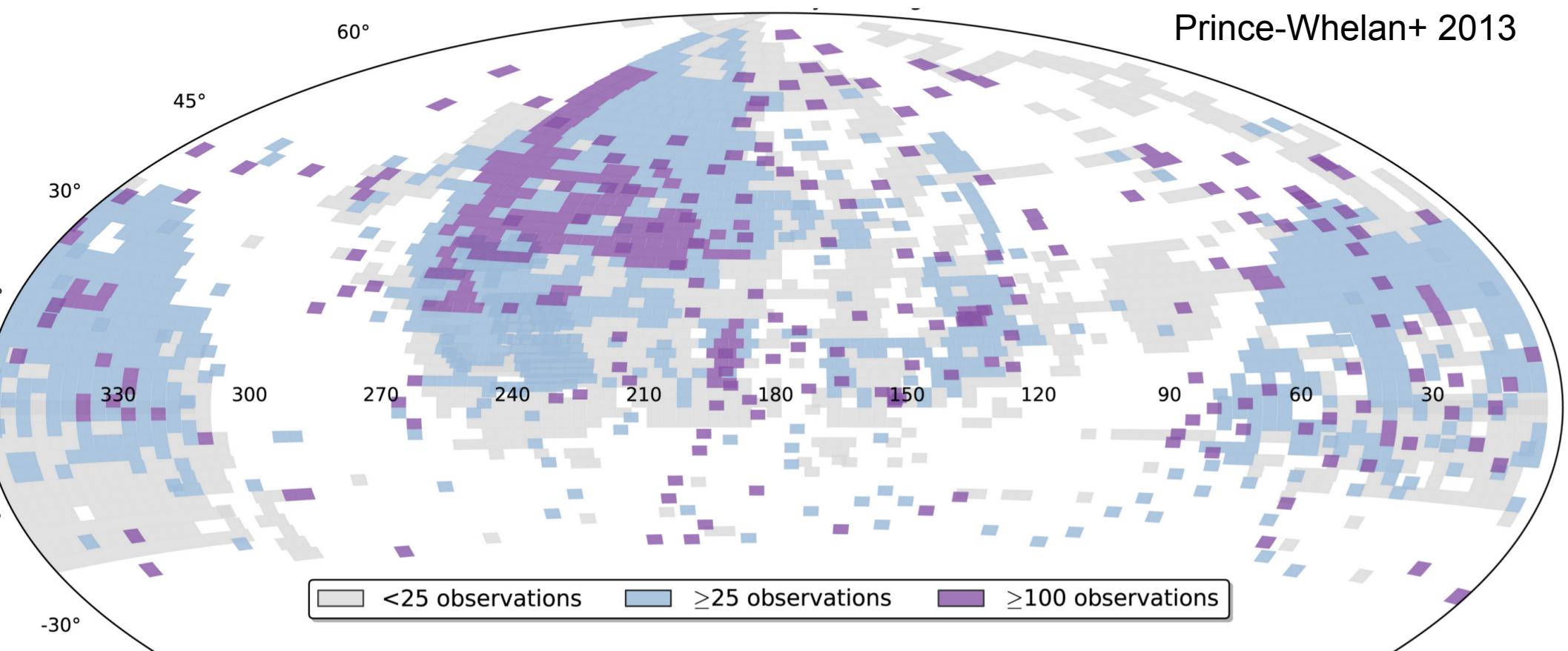
- 1.5 m telescope on Mount Palomar in south California
- Transient sky survey started in March 2009
- Data mostly in r band (centered at 6580 Å)
- 28000 AGNs brighter than  $r=19.1$
- 2.4 million data points = largest calibrated single band dataset!



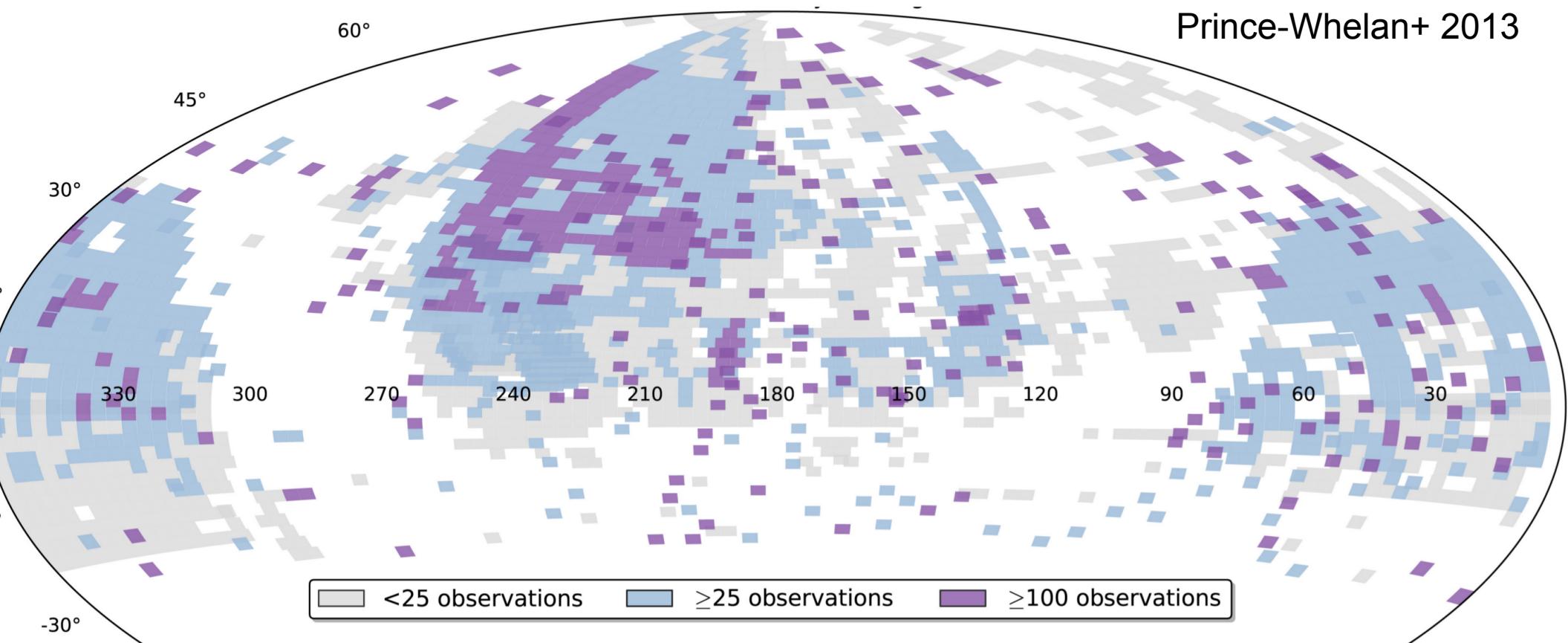
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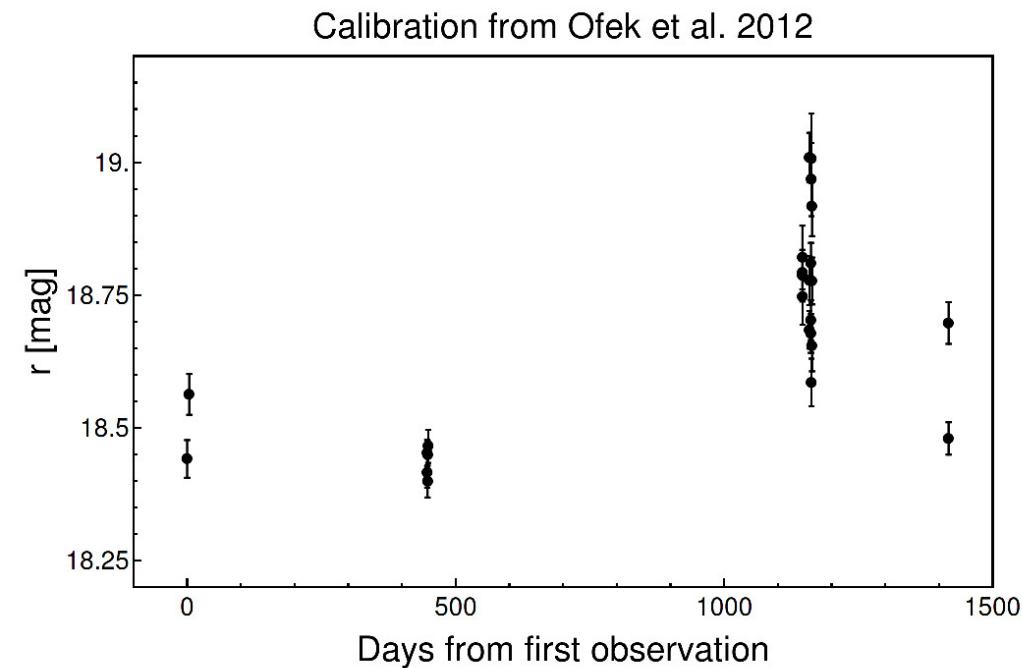
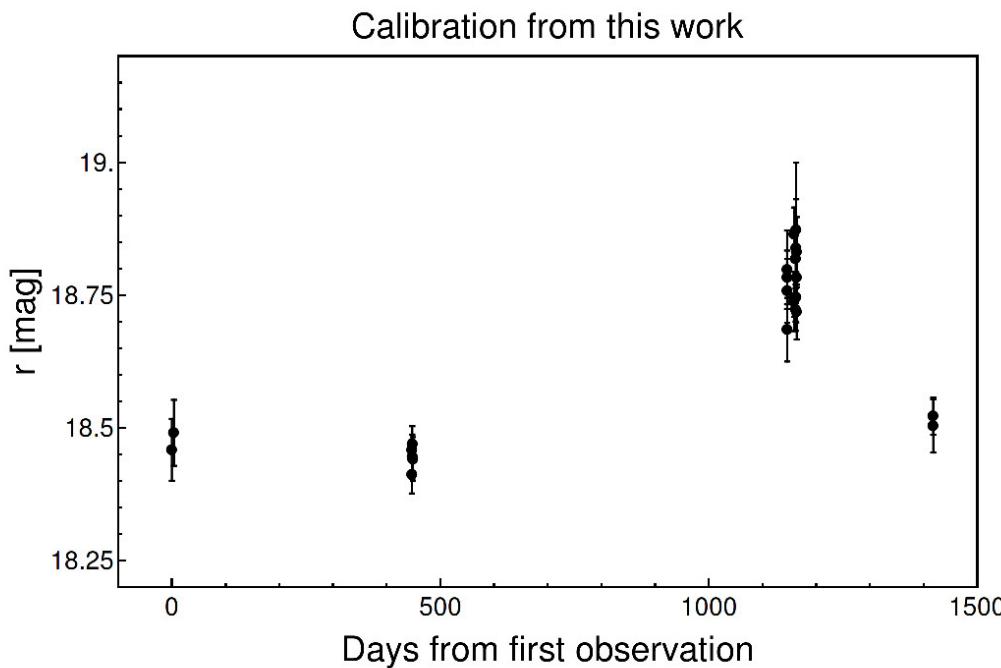


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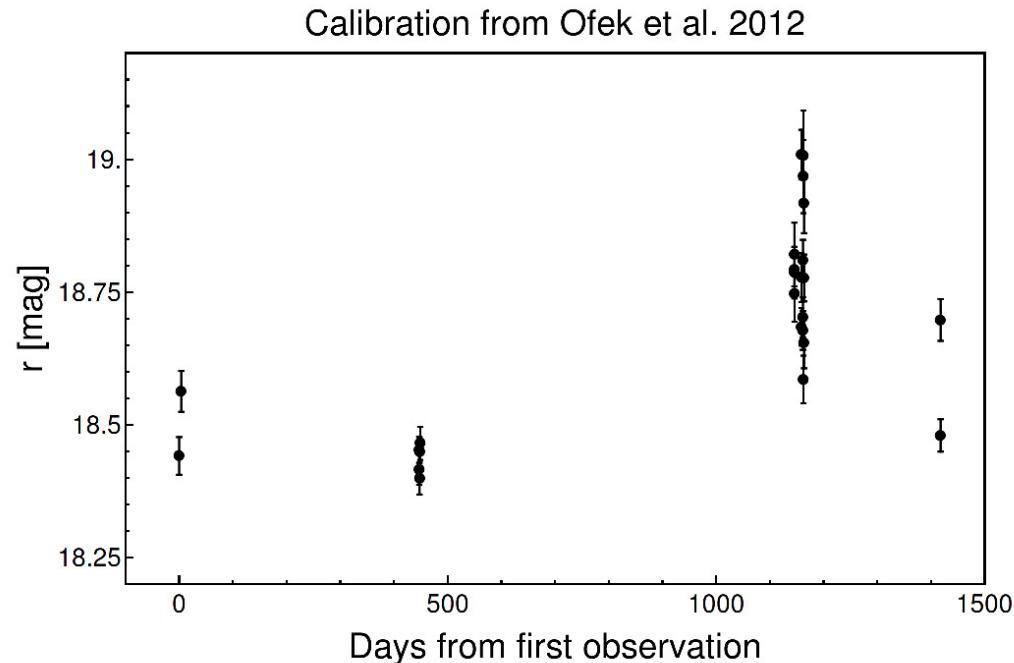
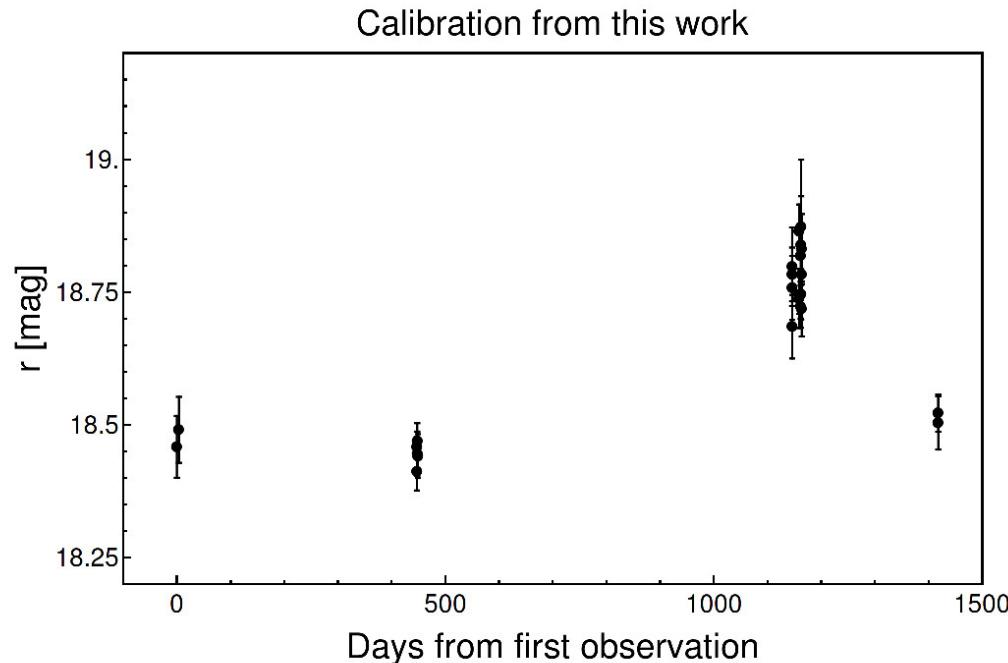
# Re-calibration of survey

- 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

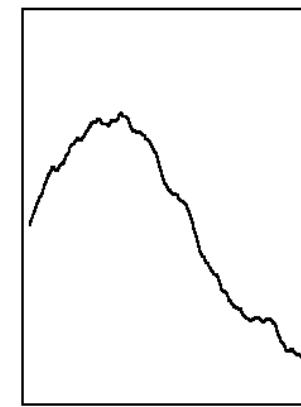
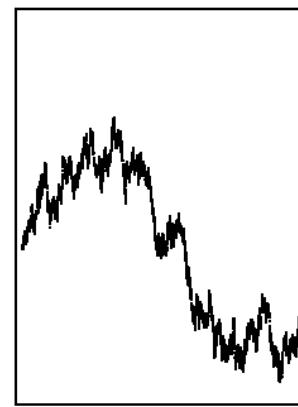
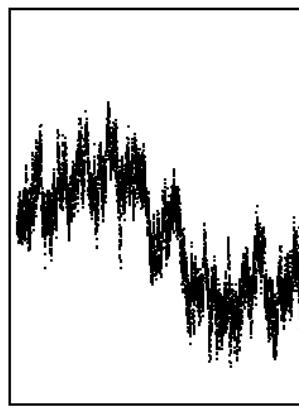
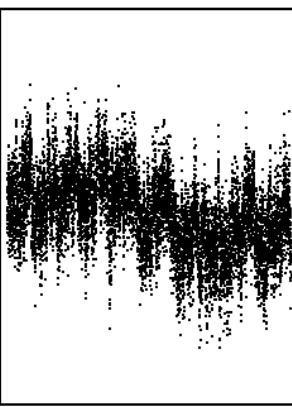
- AGN light-curves were re-calibrated
  - We search for zeropoints which minimize the scatter of reference objects (stars) – based on Ofek+ 2011
  - We achieve excellent performance; excess variance at short time-scales is consistent with zero for vast majority of AGNs
  - Re-calibrated data is public: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



- $SF^2$  (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

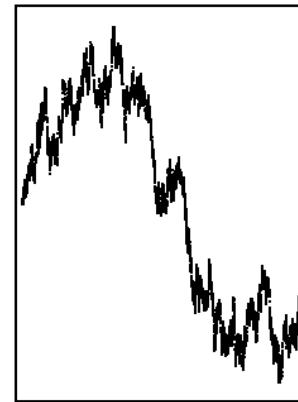
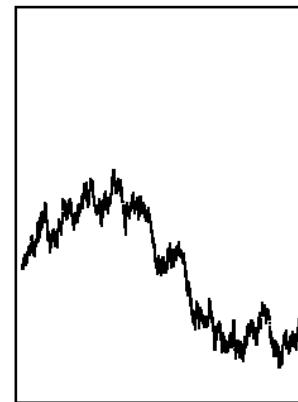
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Luminosity



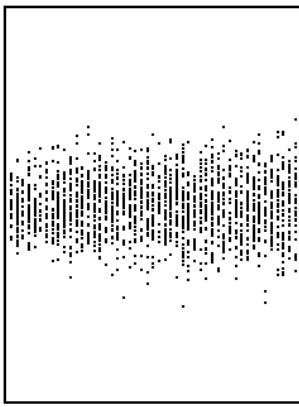
Time

More “structure”

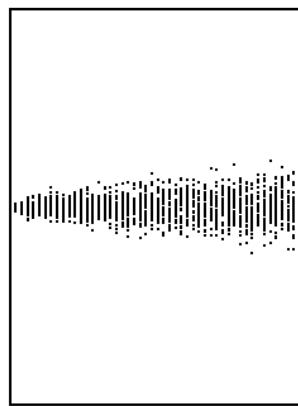
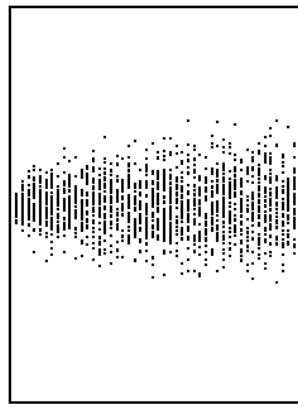


More variability

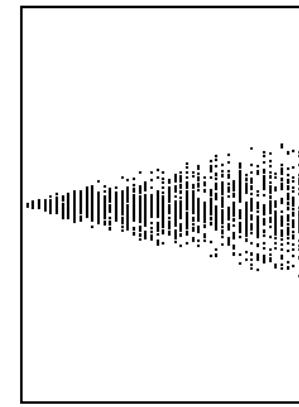
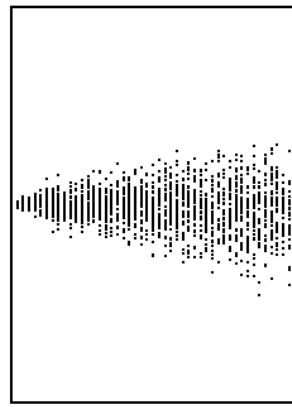
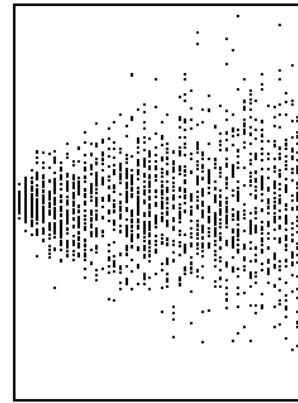
$\Delta \text{mag}$



$\Delta \text{time}$



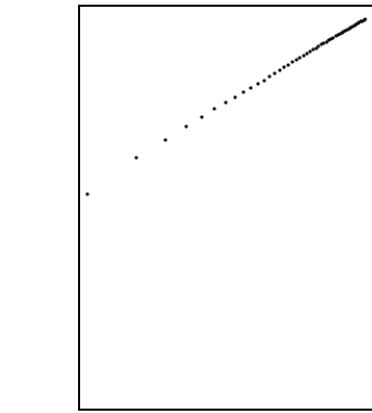
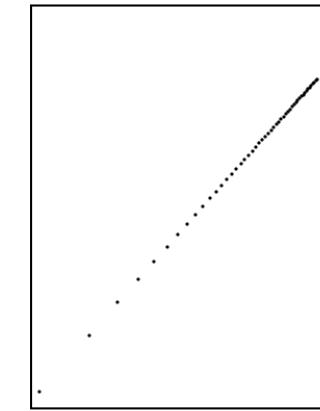
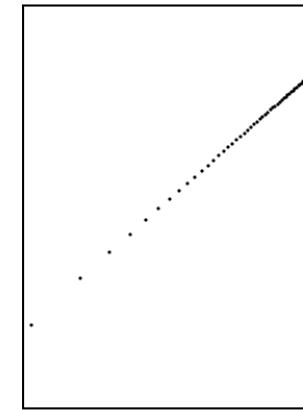
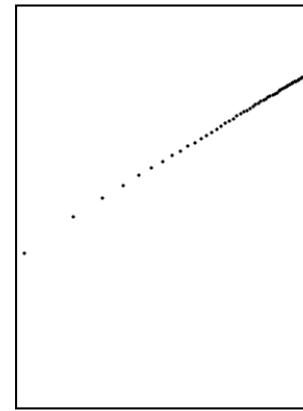
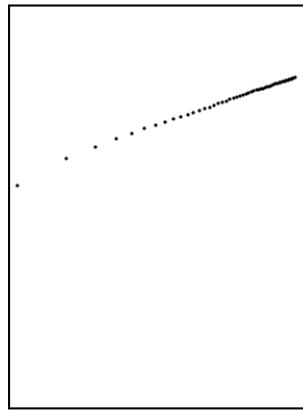
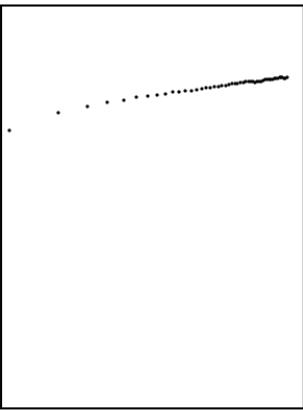
More “structure”



More variability



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

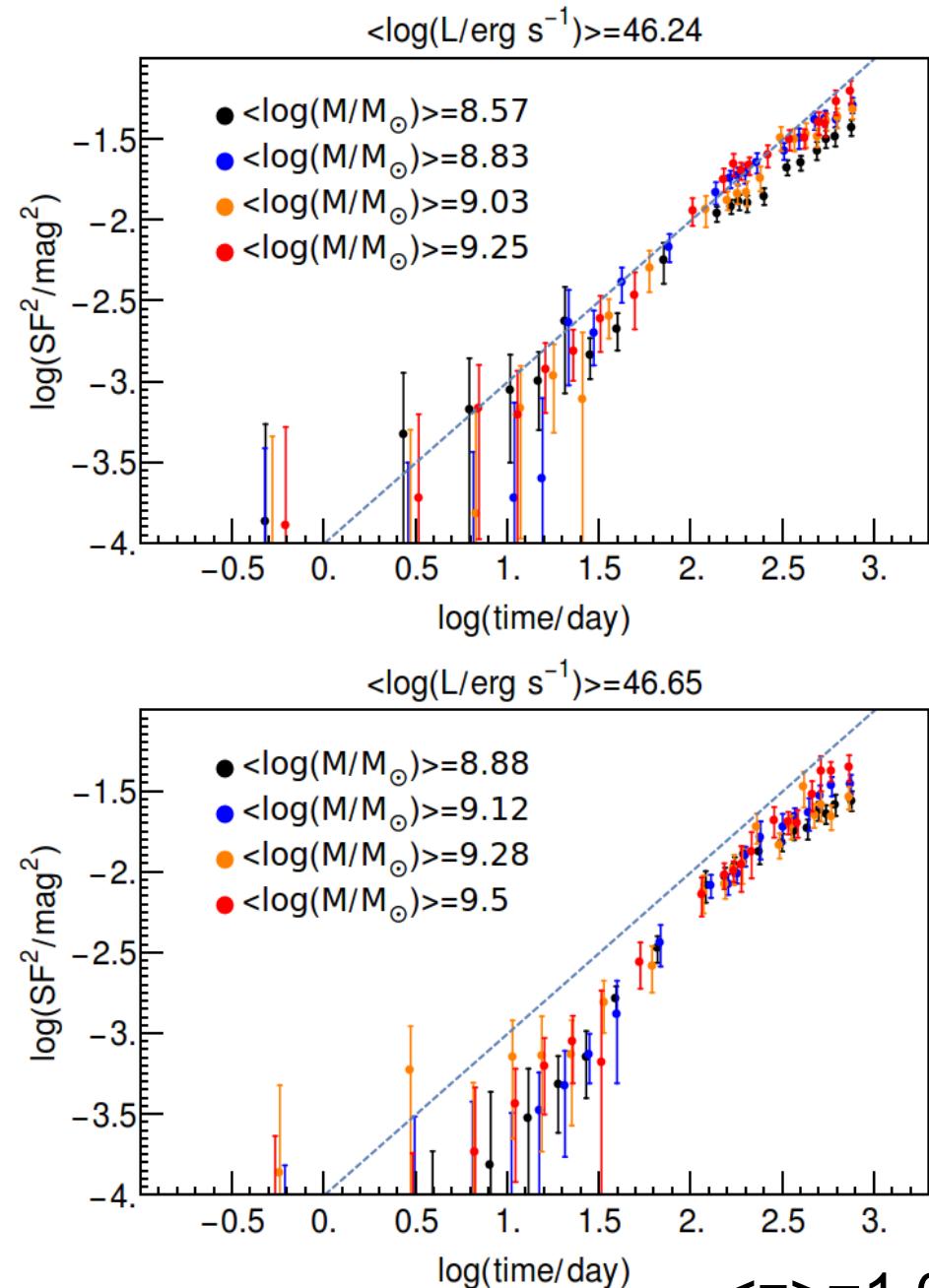
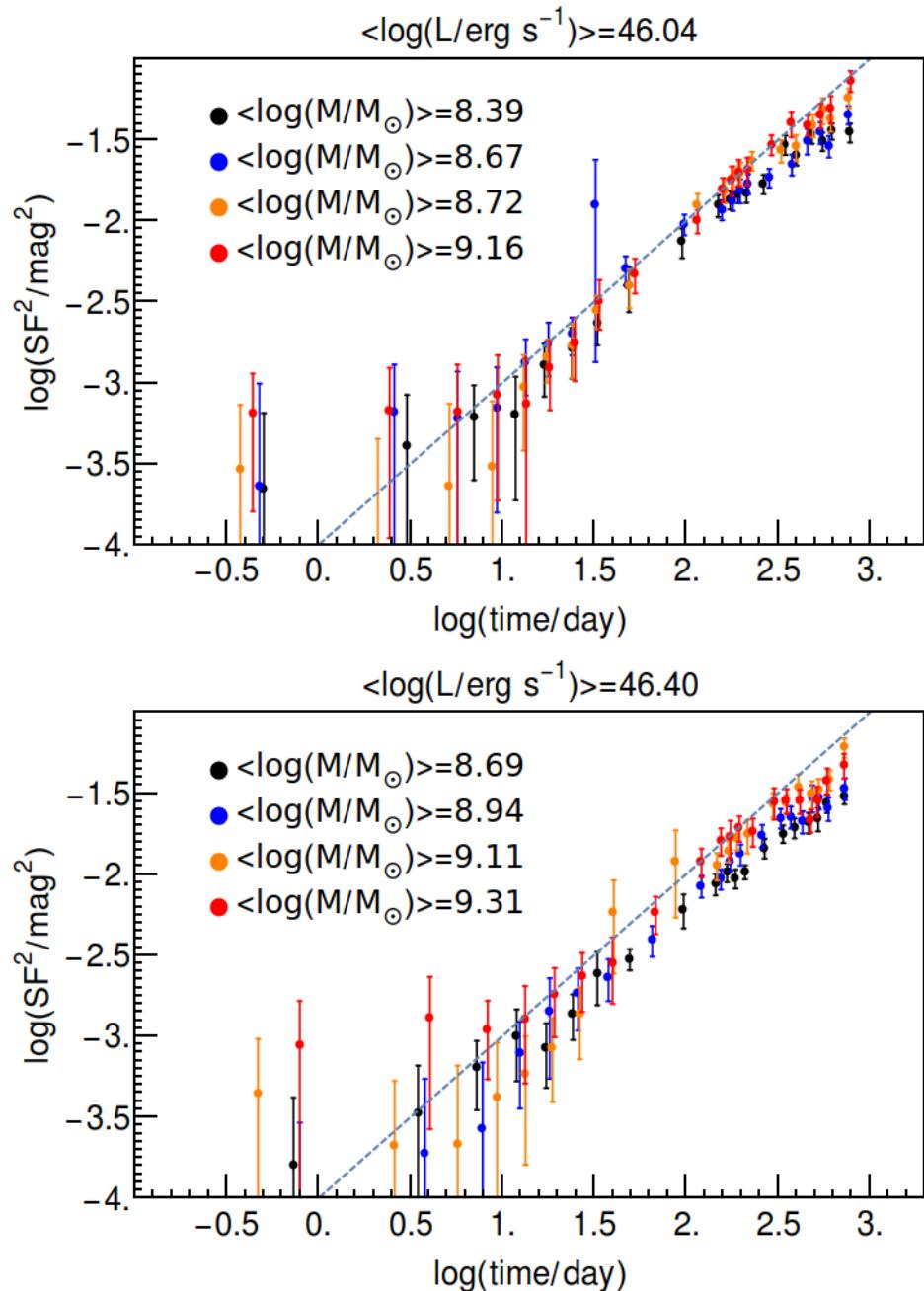


$\Delta \text{time}$

More “structure”

More variability

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



$\langle z \rangle = 1.05$

- 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

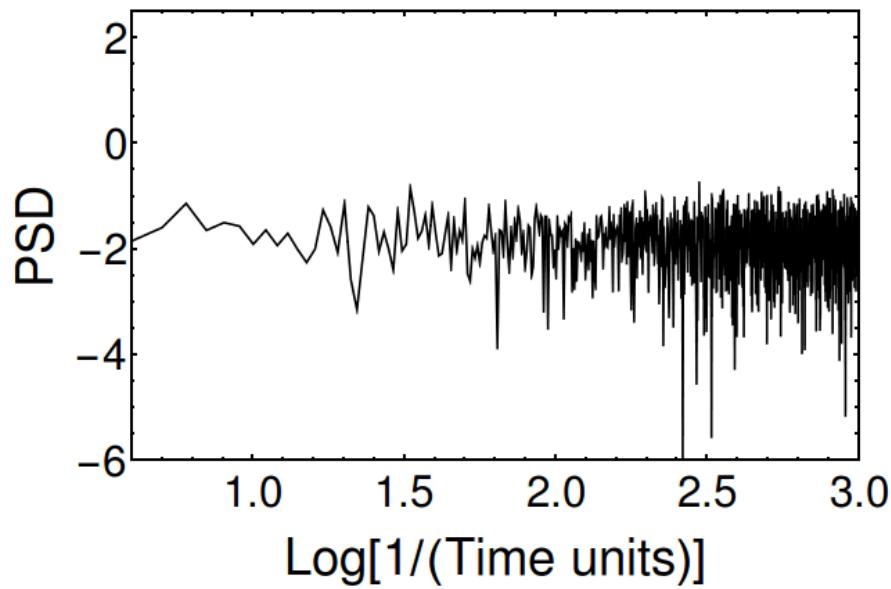
- Clear dependence with luminosity
- Simplest thin disk model and time scale of variability identified with Keplerian time scale

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

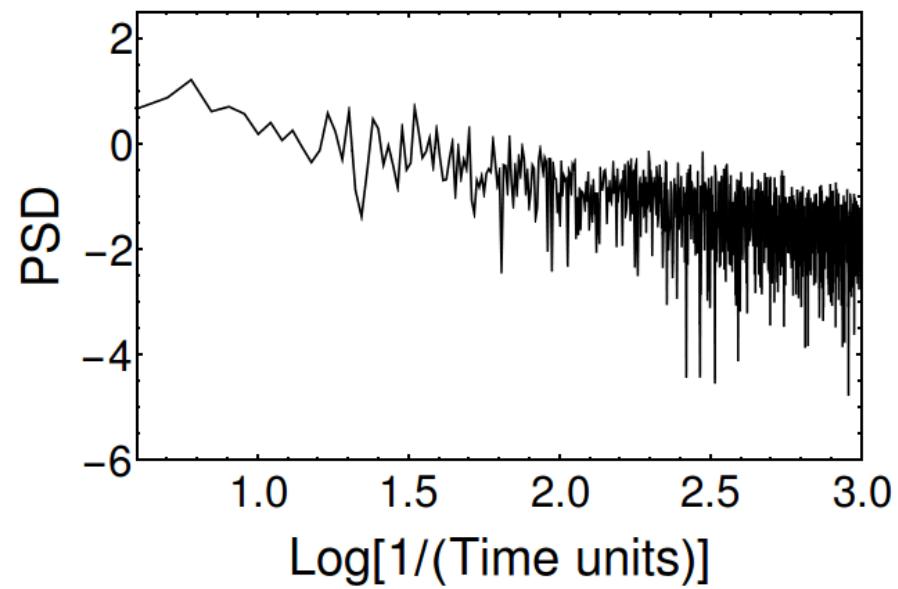
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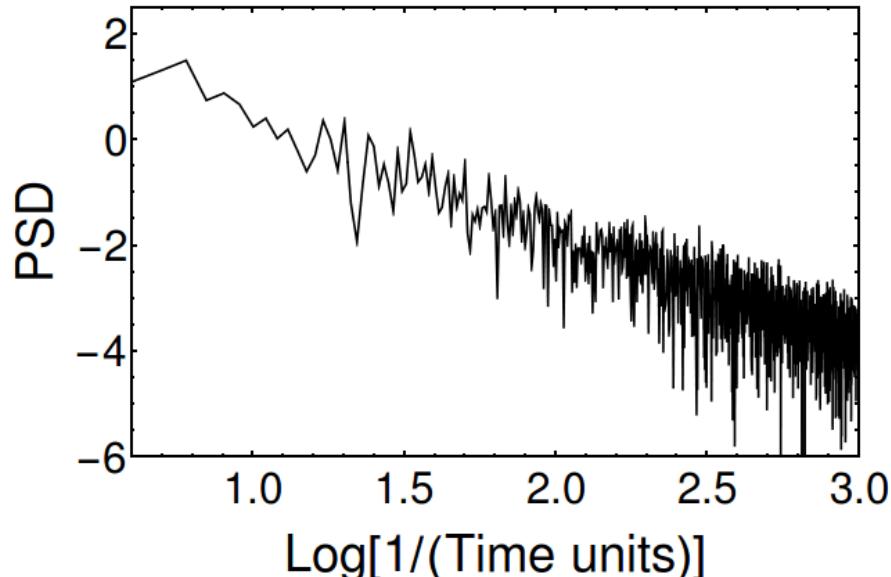
$\text{PSD} \propto f^0$



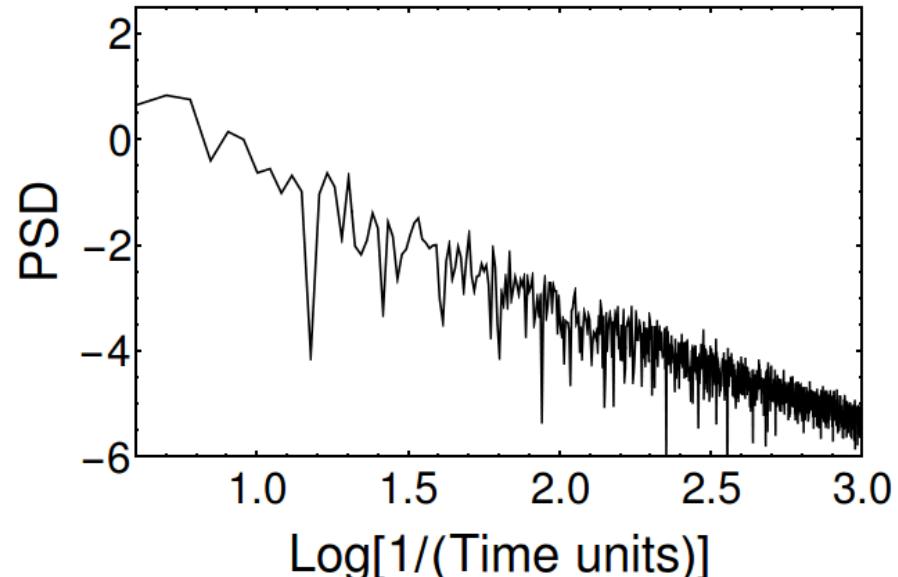
$\text{PSD} \propto f^{-1}$



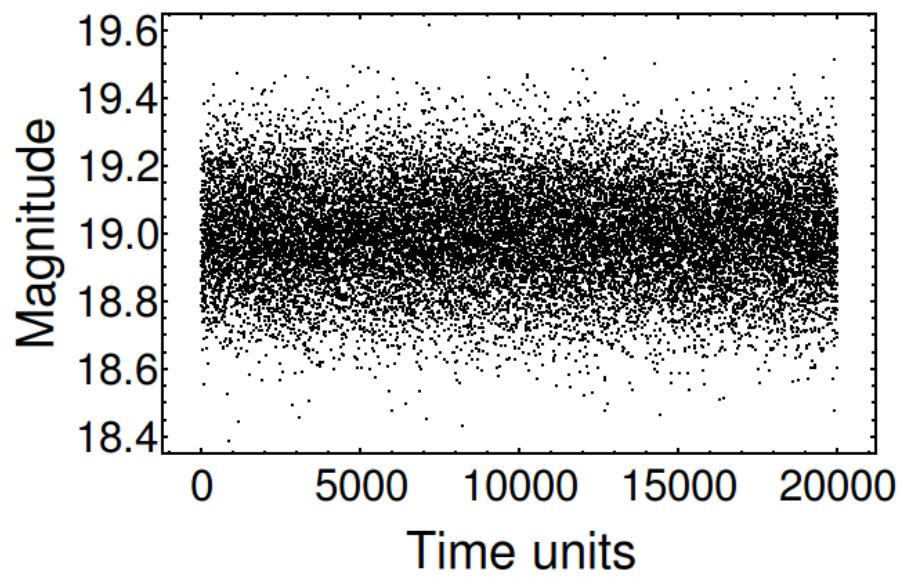
$\text{PSD} \propto f^{-2}$



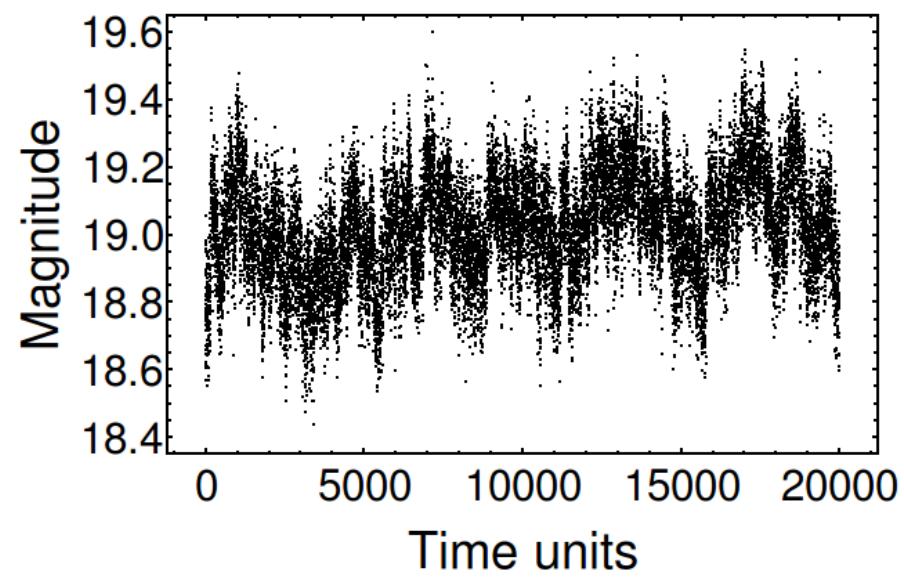
$\text{PSD} \propto f^{-3}$



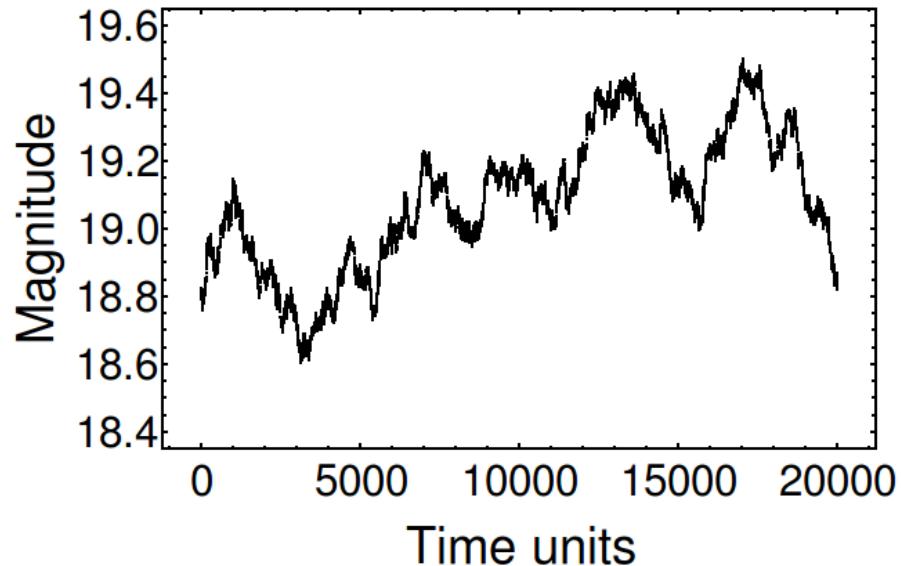
$\text{PSD}\alpha f^0$



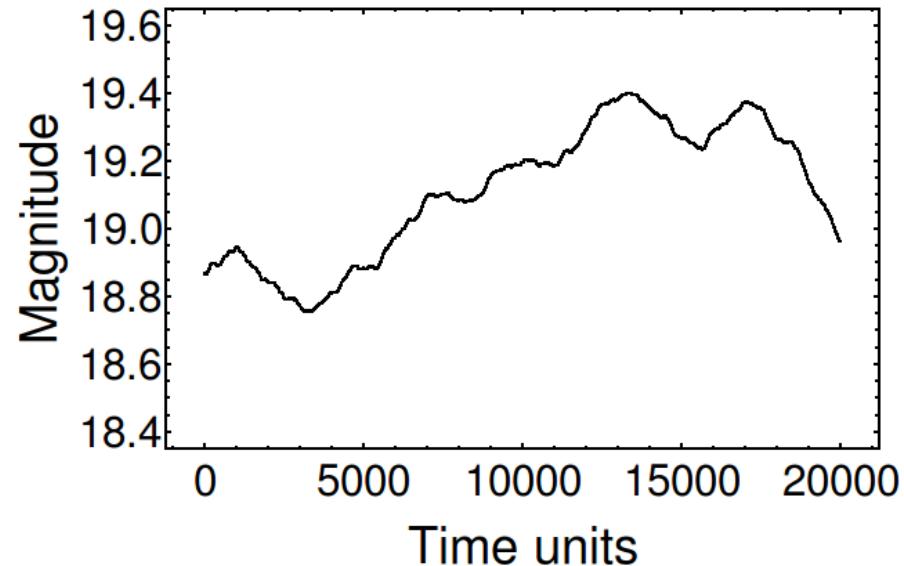
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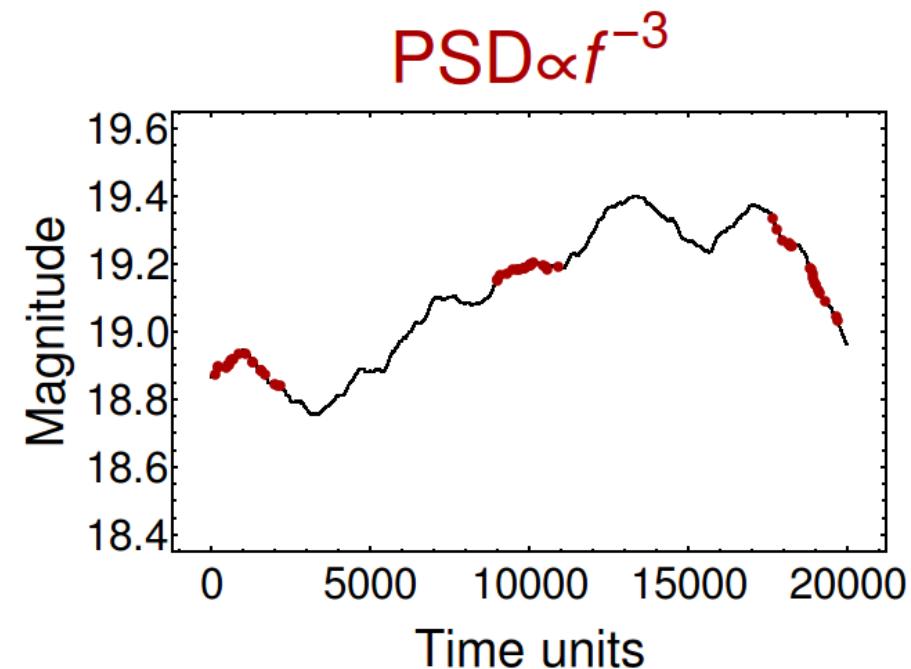
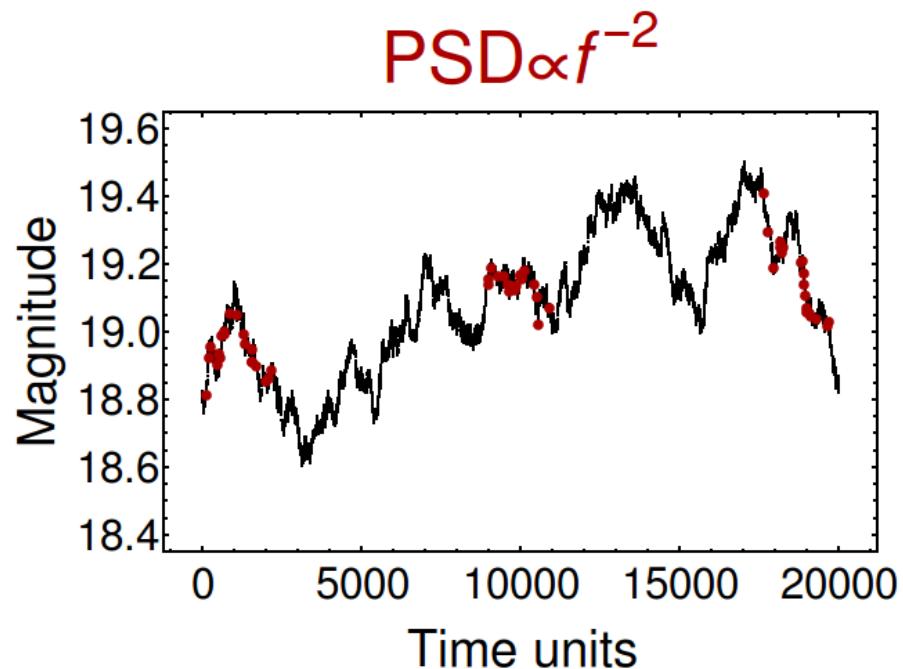
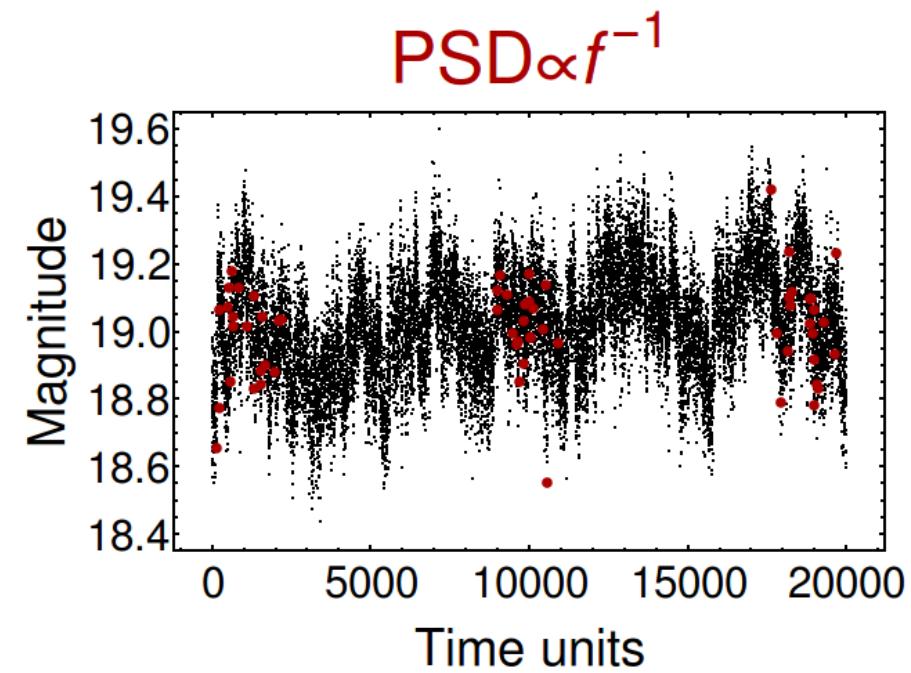
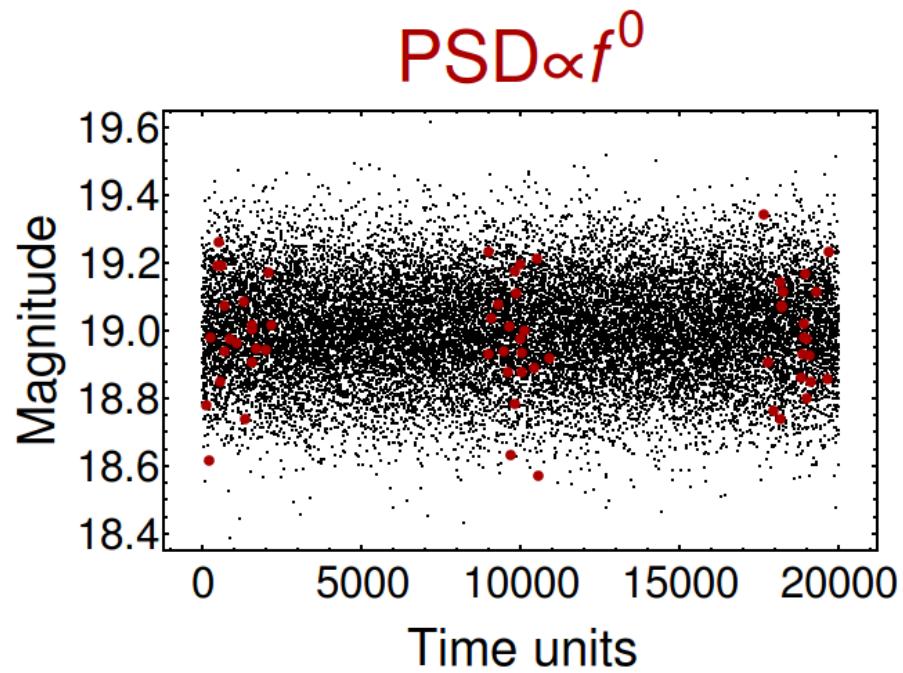


$\text{PSD}\alpha f^{-2}$

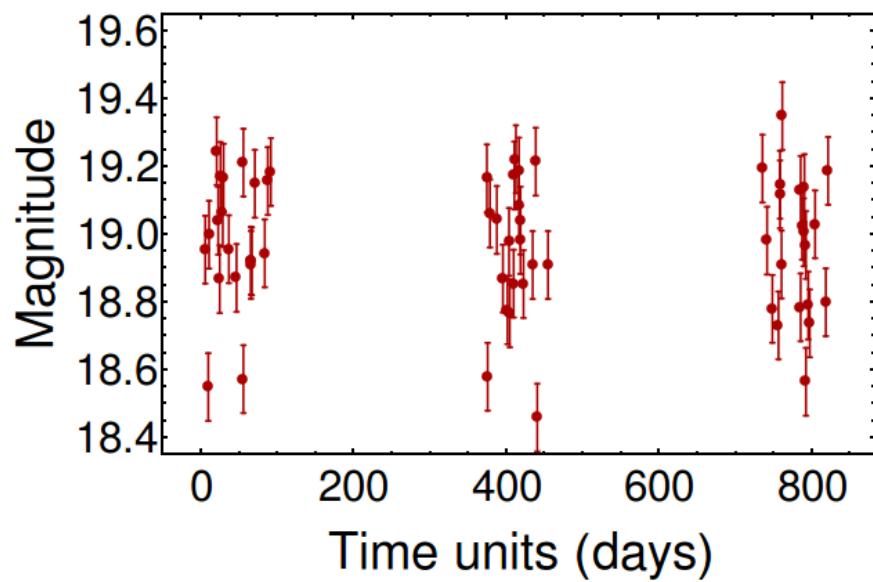


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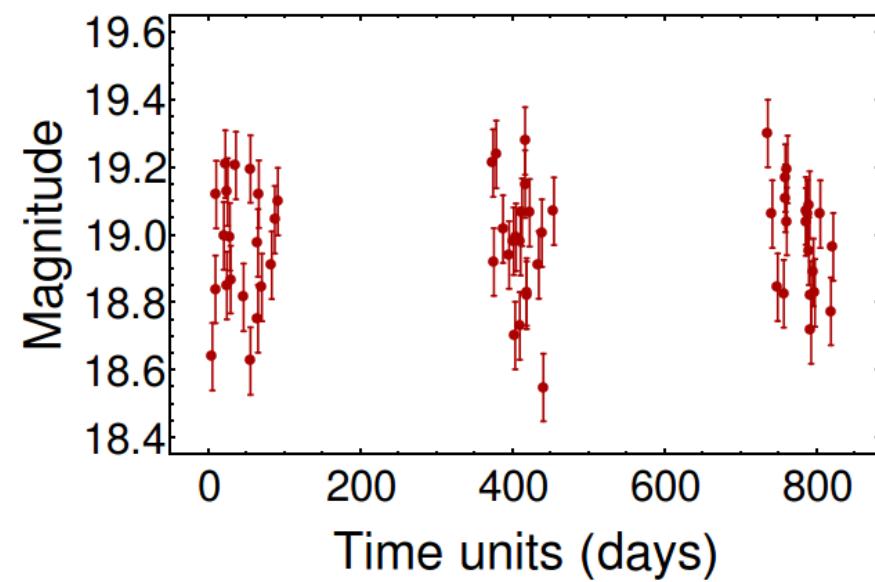




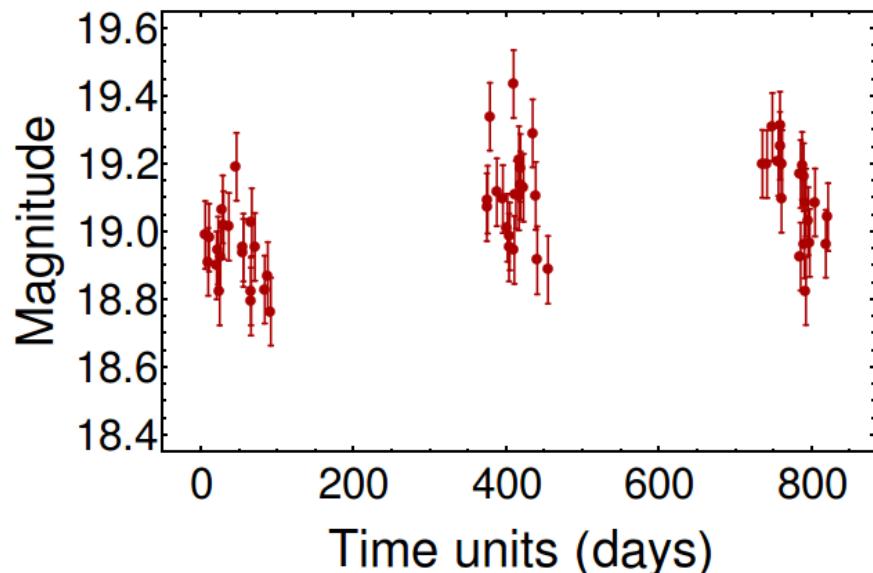
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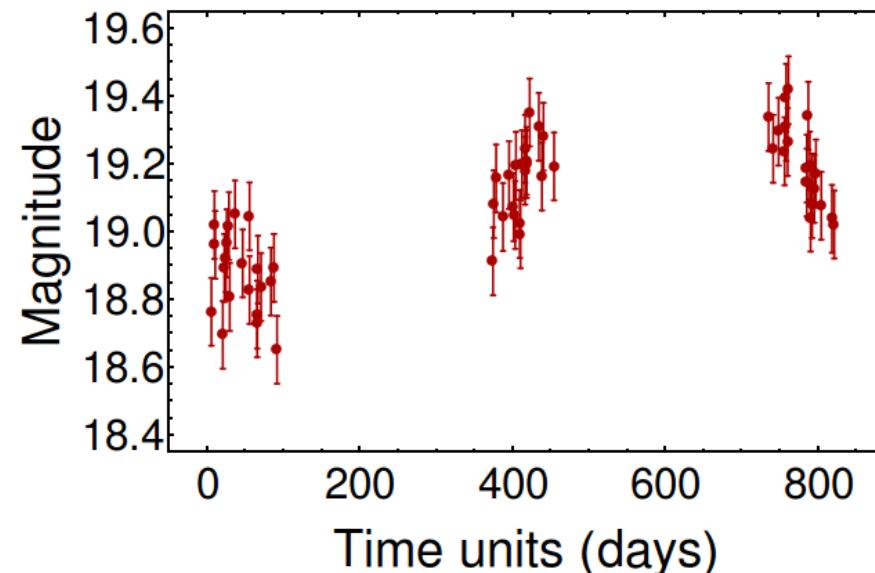
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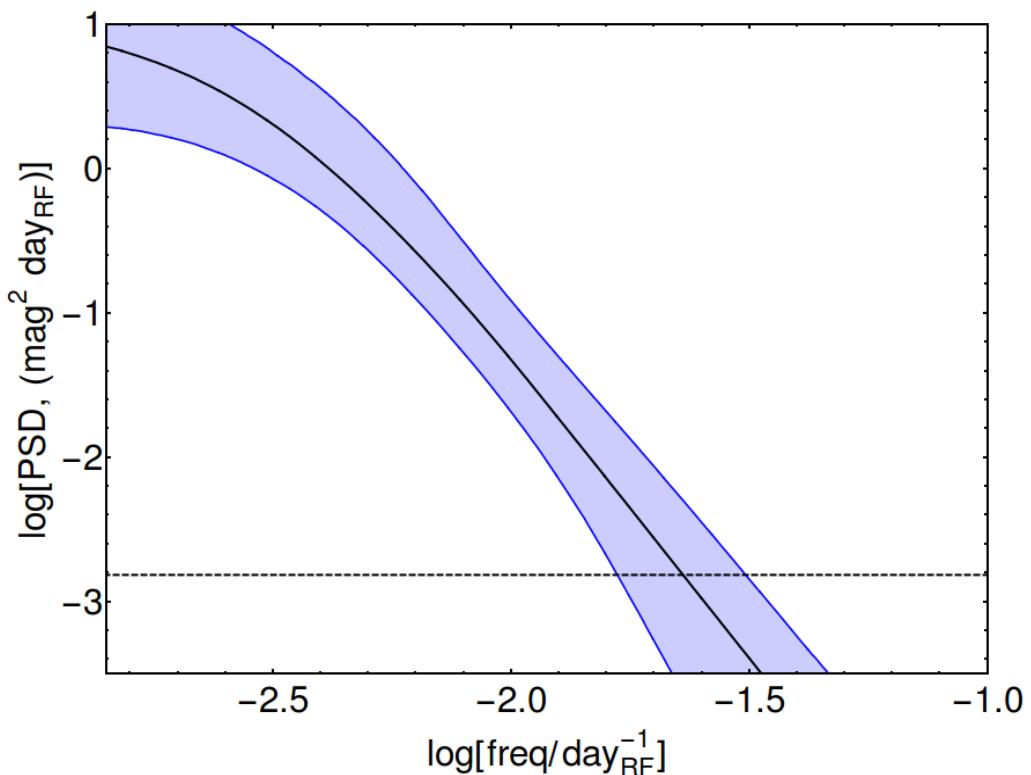
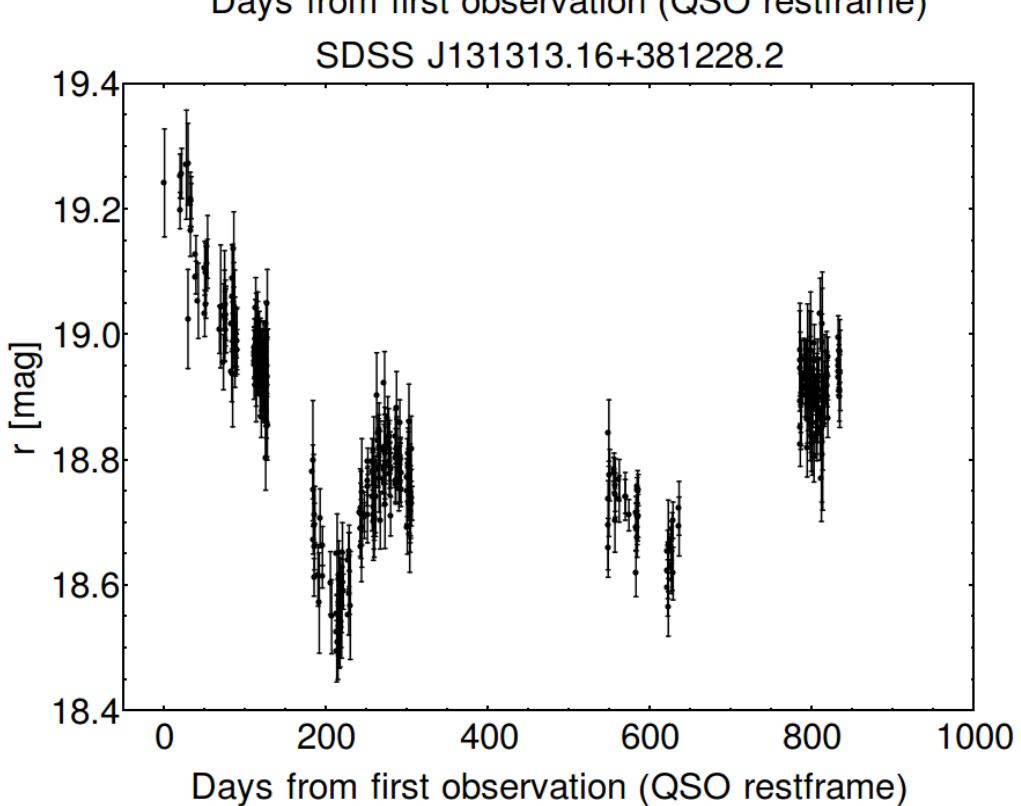
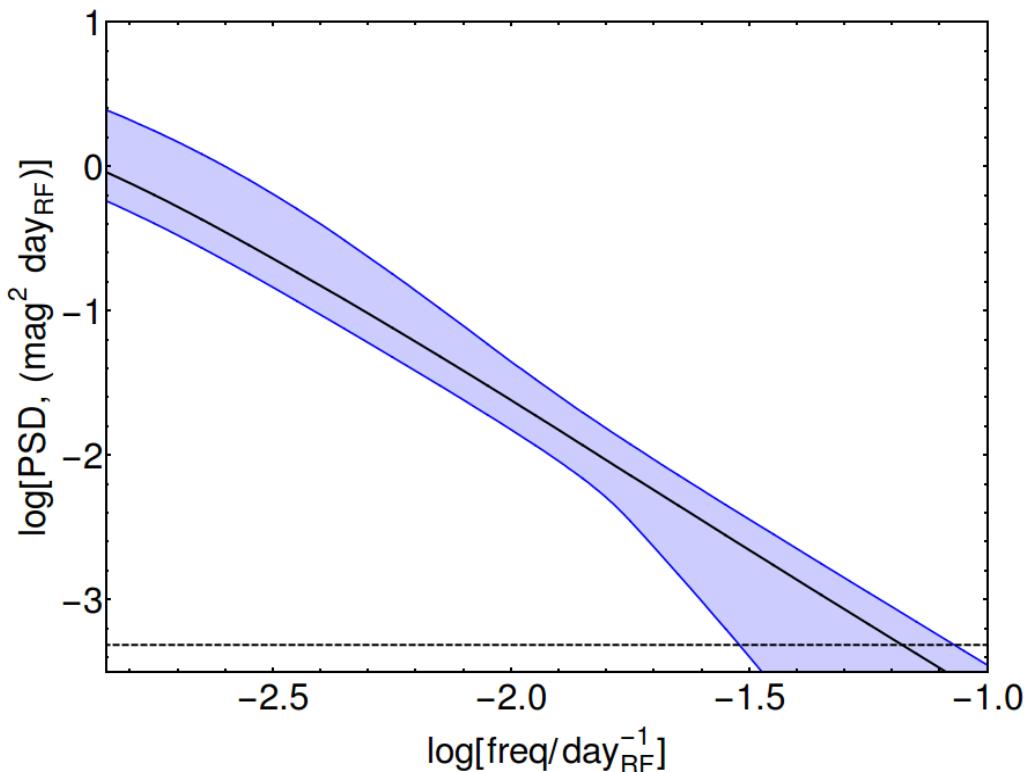
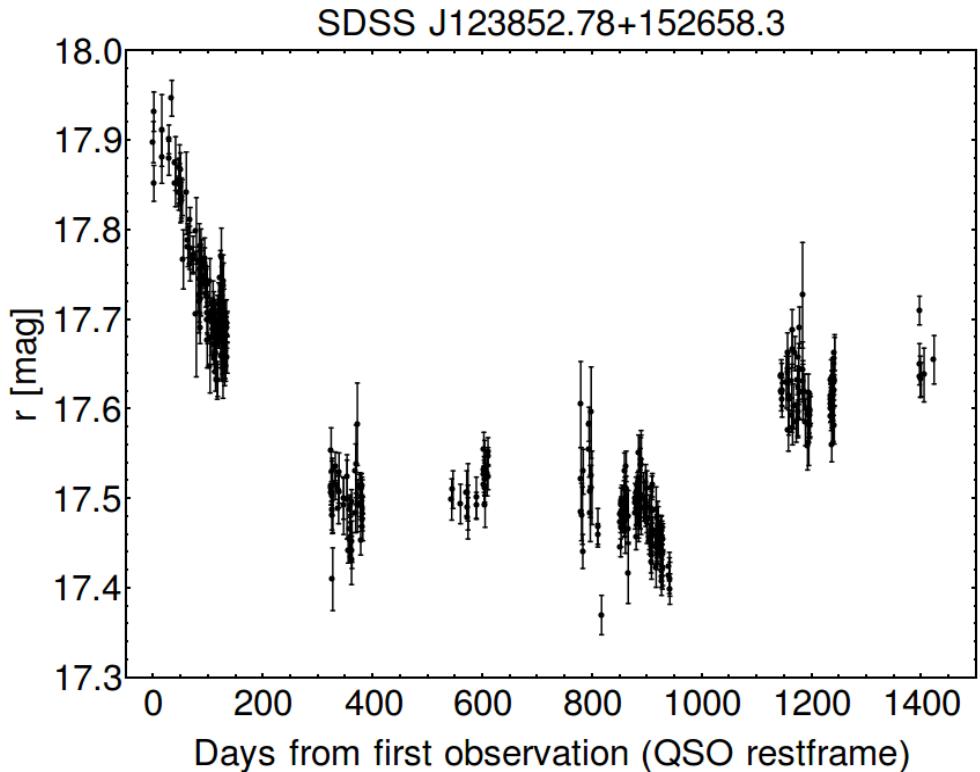
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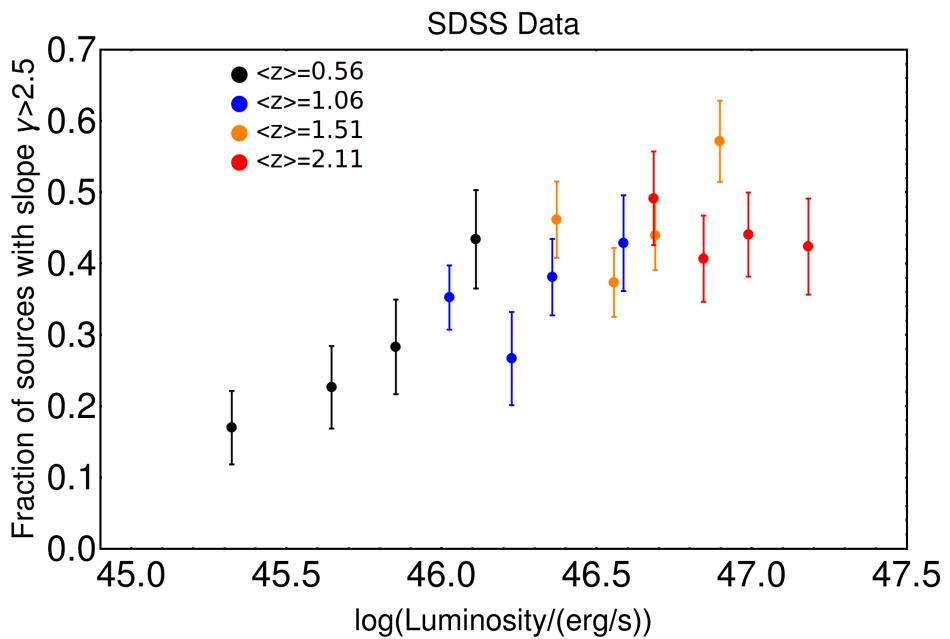
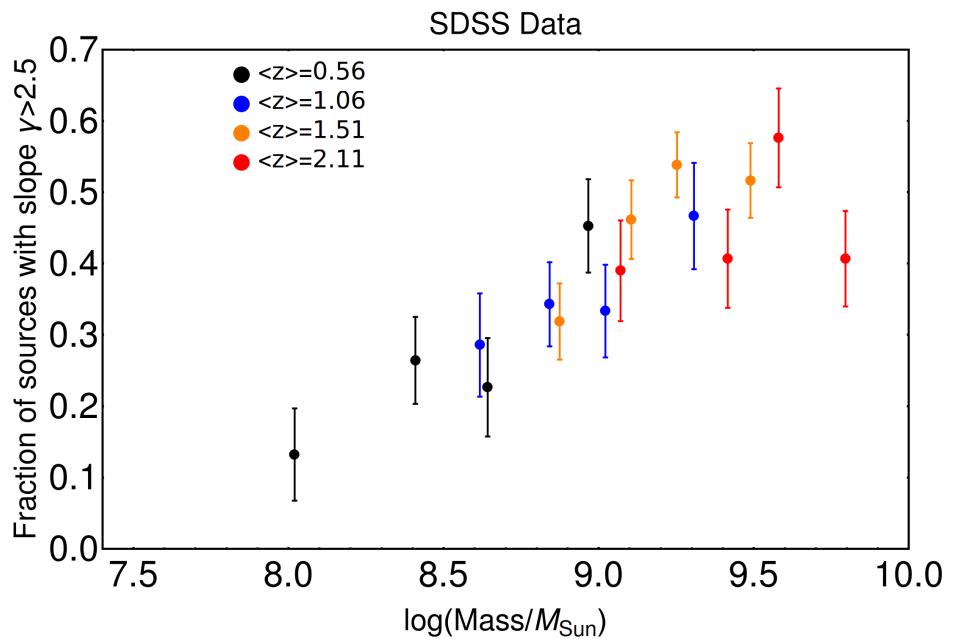
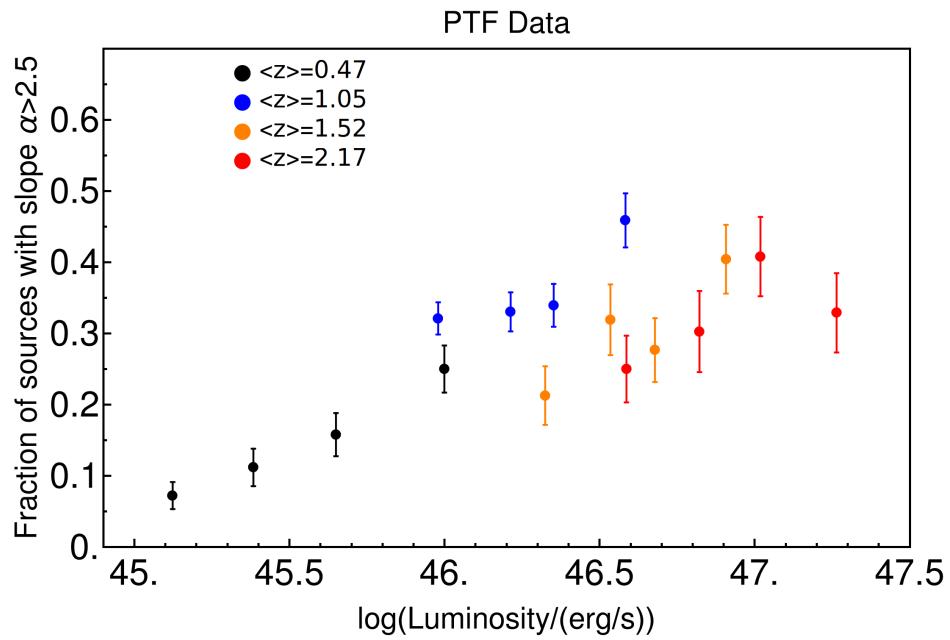
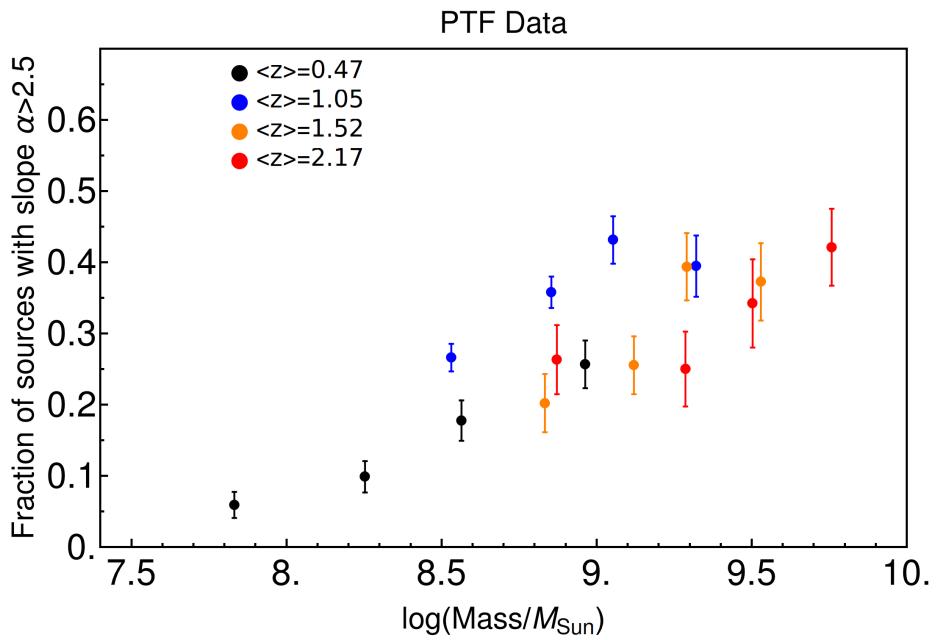


$\text{PSD}\alpha f^{-3}$

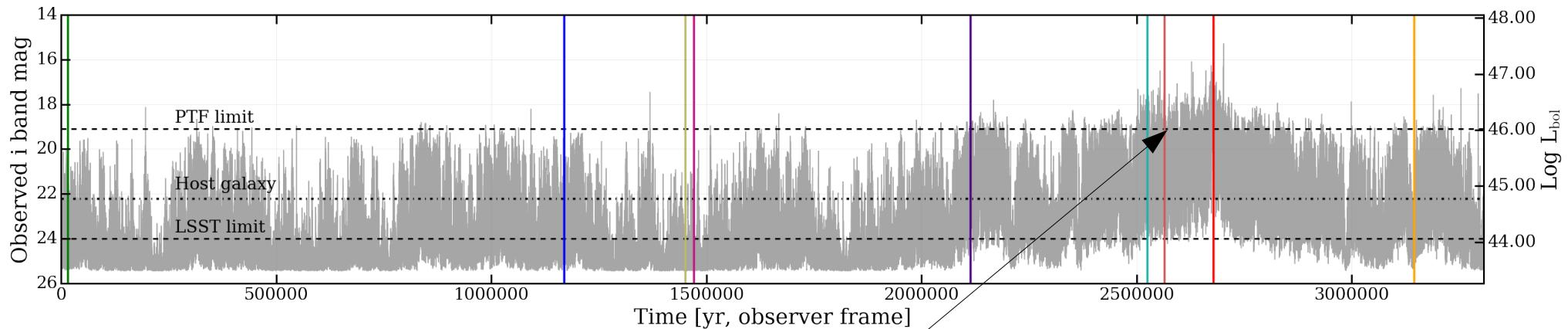


Kelly+, 14





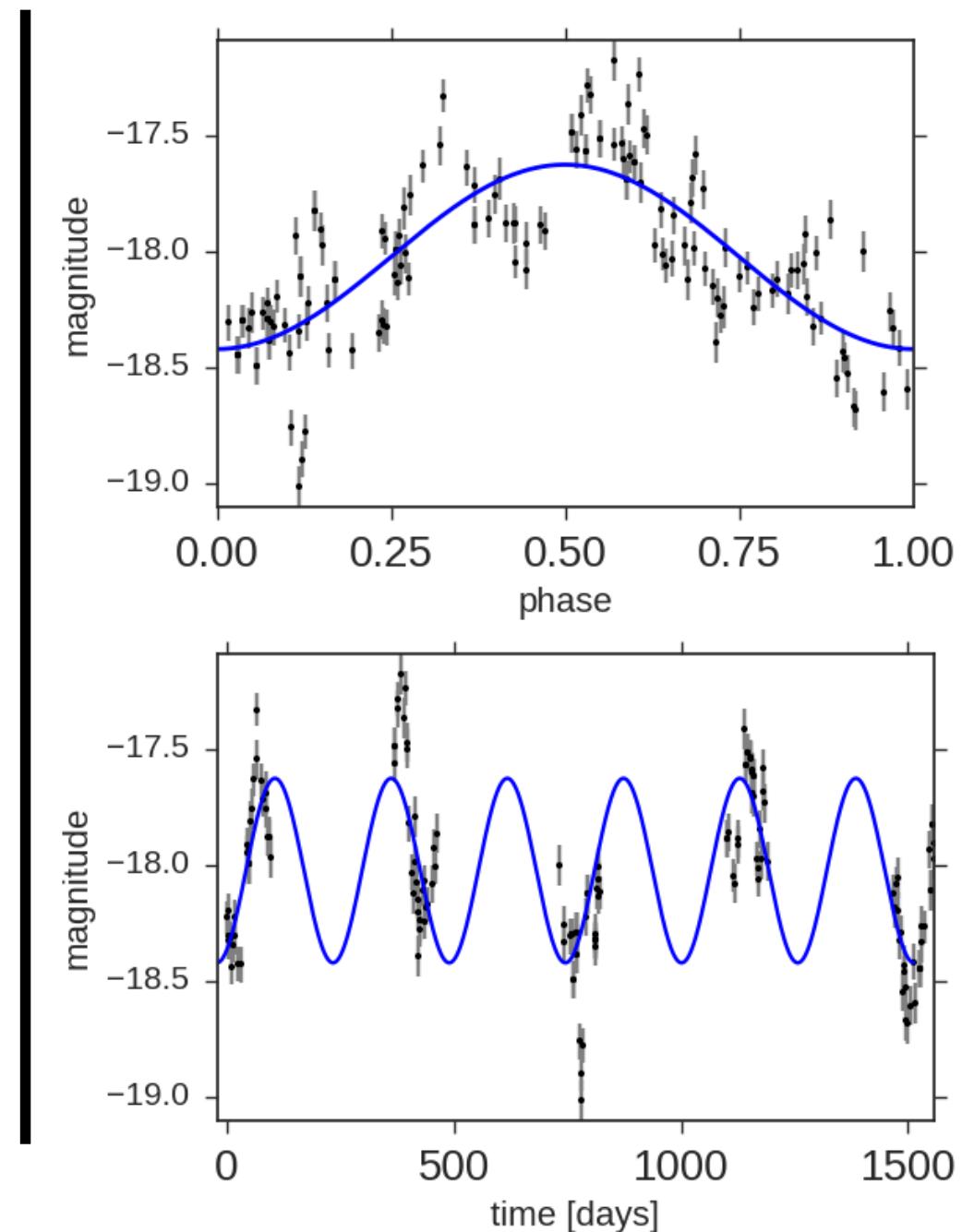
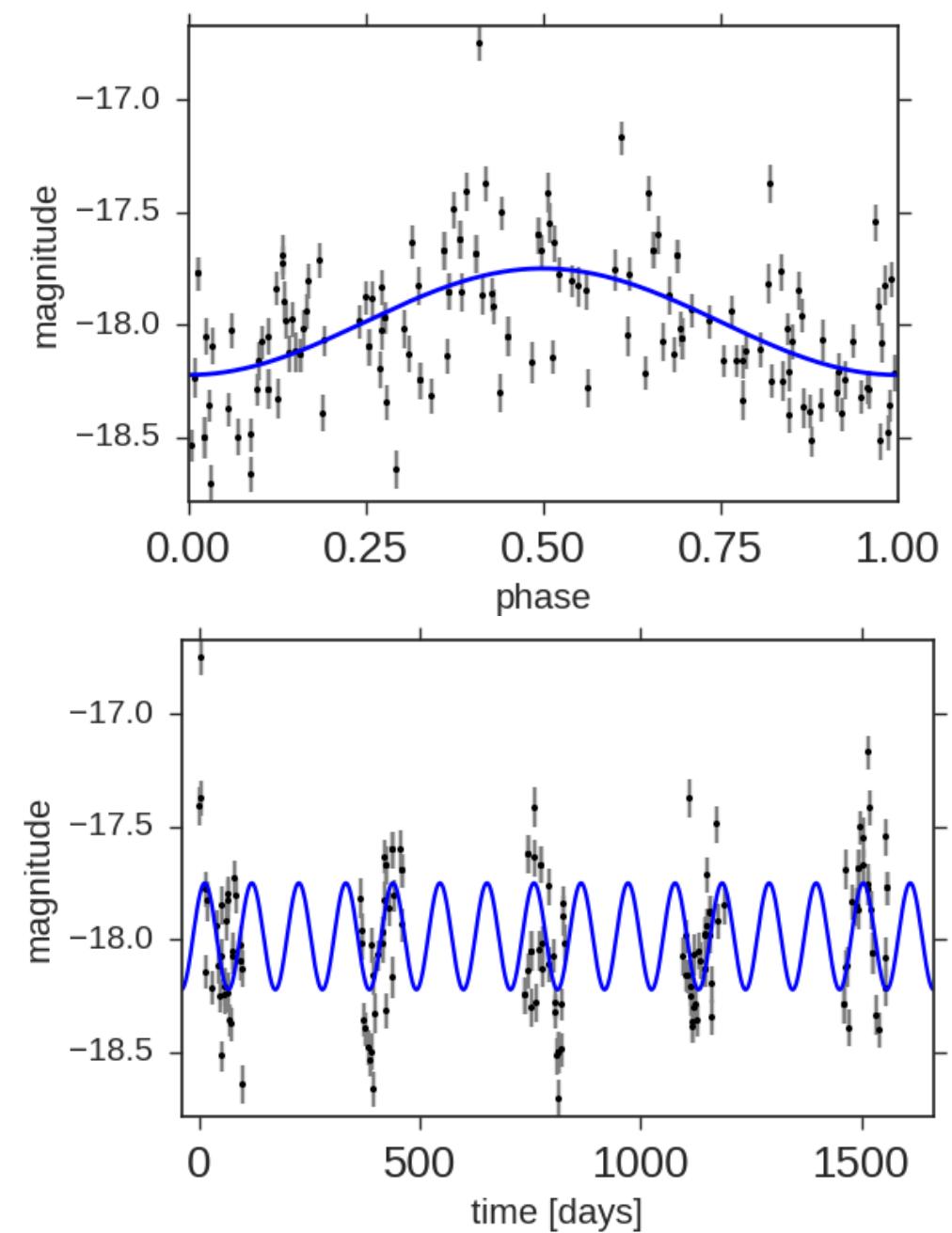
# I. What are we looking at?



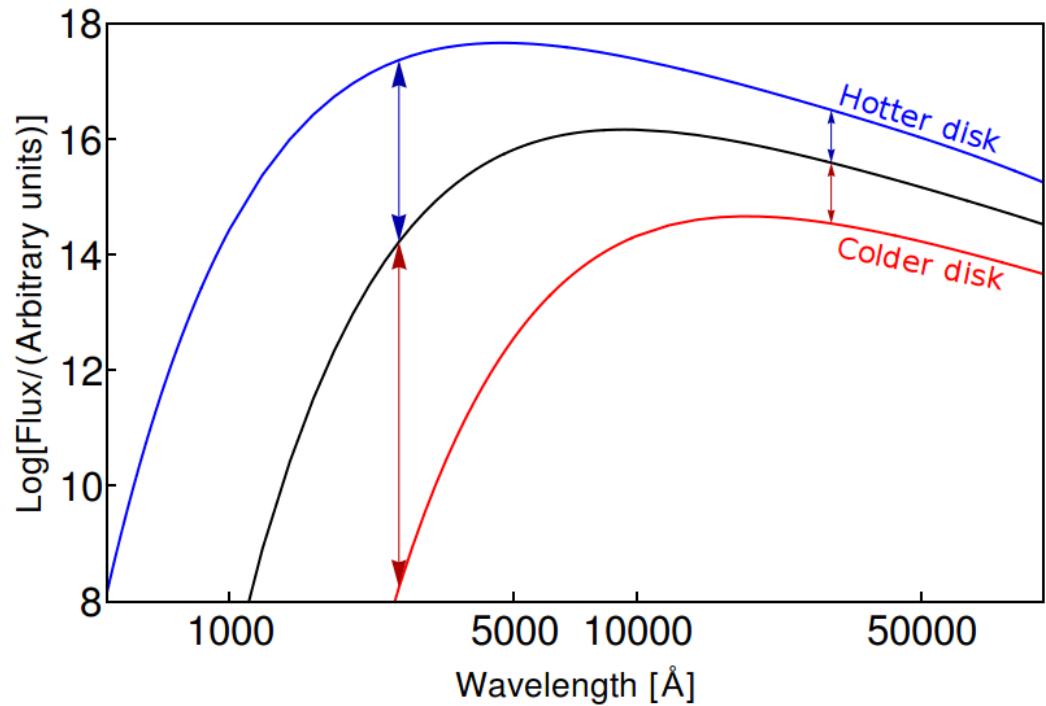
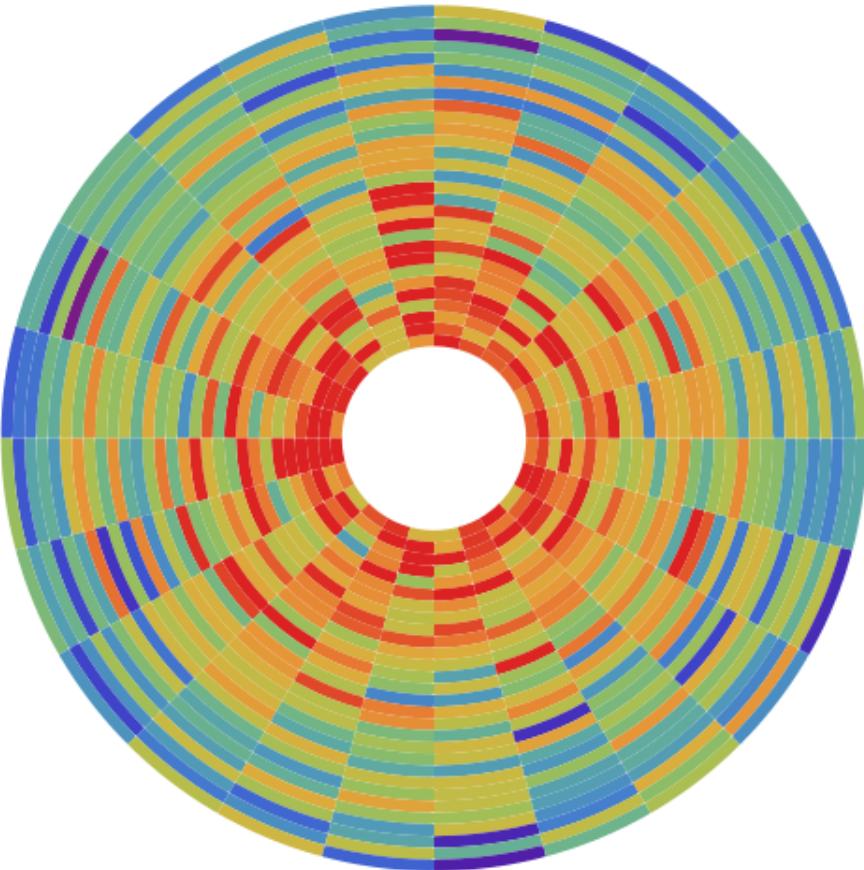
Sartori+, submitted

- ``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

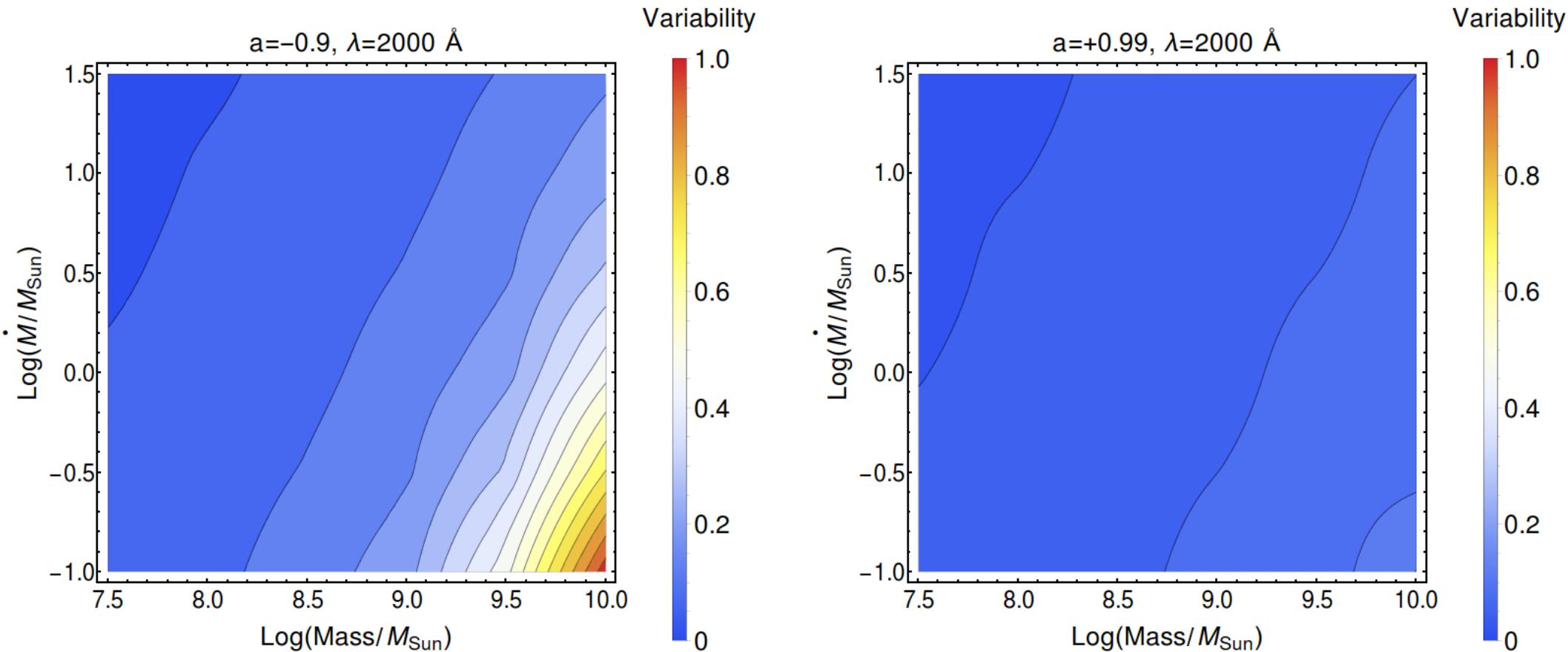


### III. Constrain spin from variability?



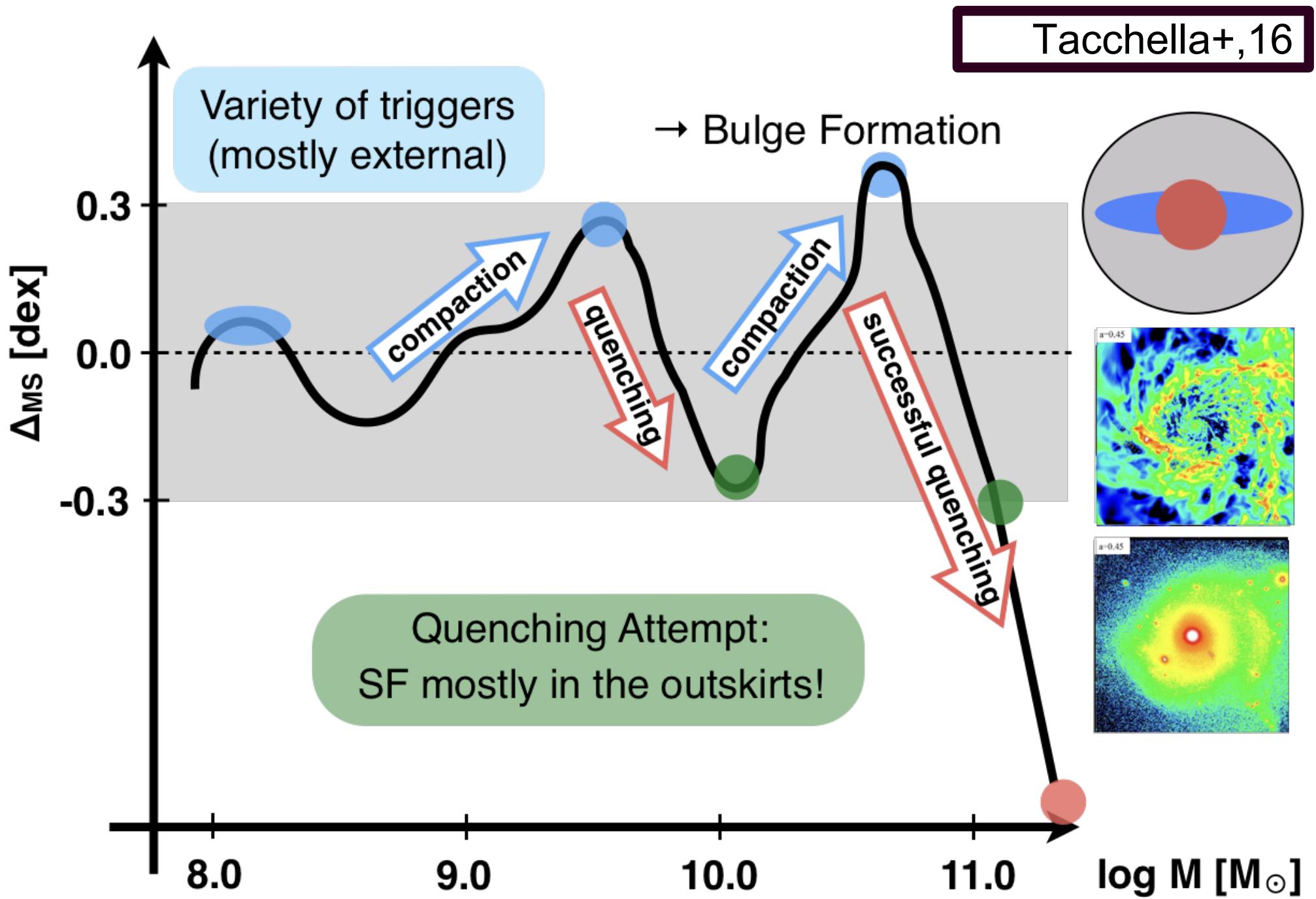
- Optical variability as a consequence of temperature variations in the disk (Dexter & Agol, 2011)
- Temperature:  $T(r) \propto \Delta M^{1/4} M^{-1/2} f(r)^{3/4} (r/r_g)^{-3/4}$ 
  - Temperature correlated with spin (f parameter in equation above)

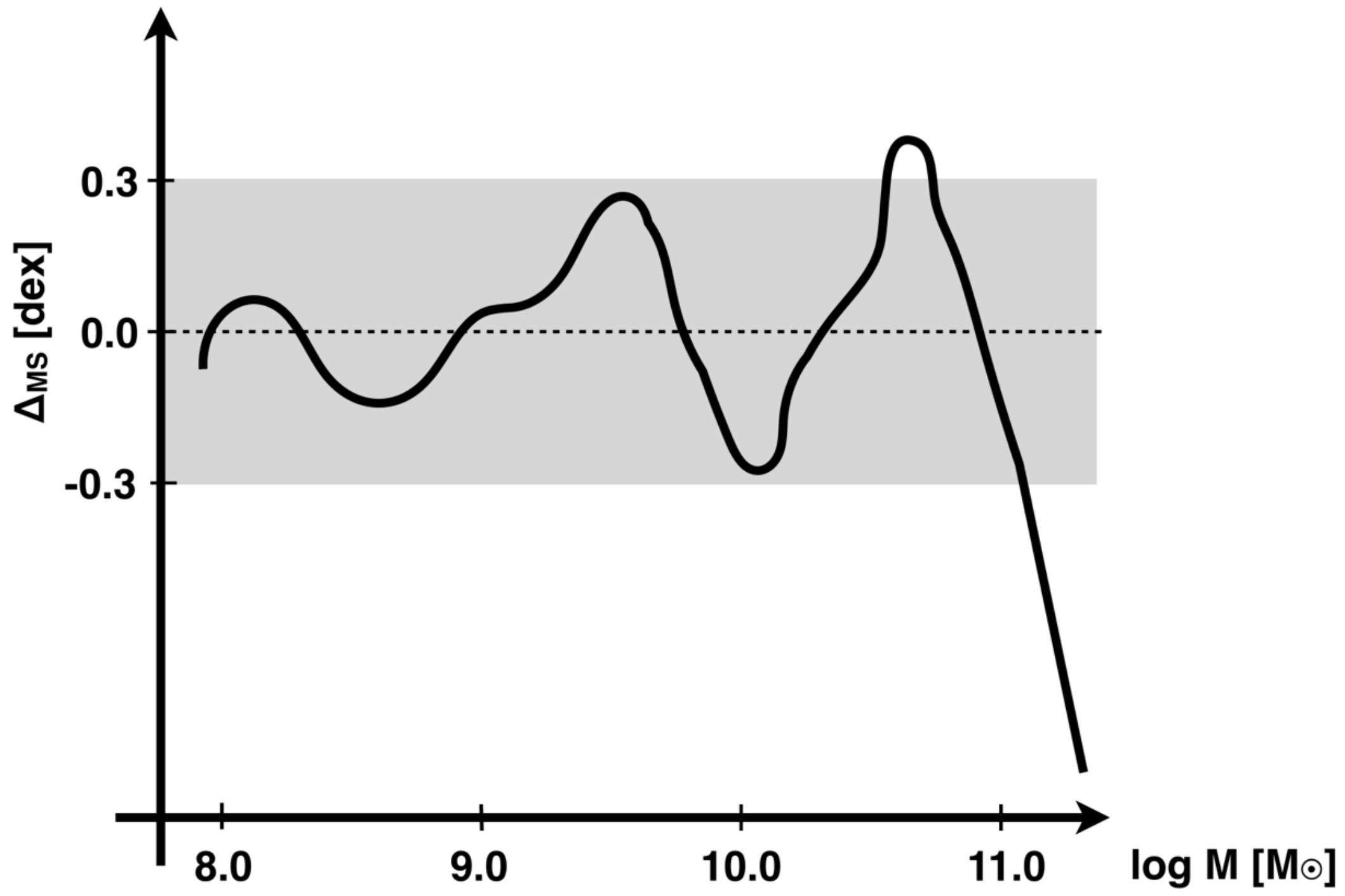
### III. Constrain spin from variability?

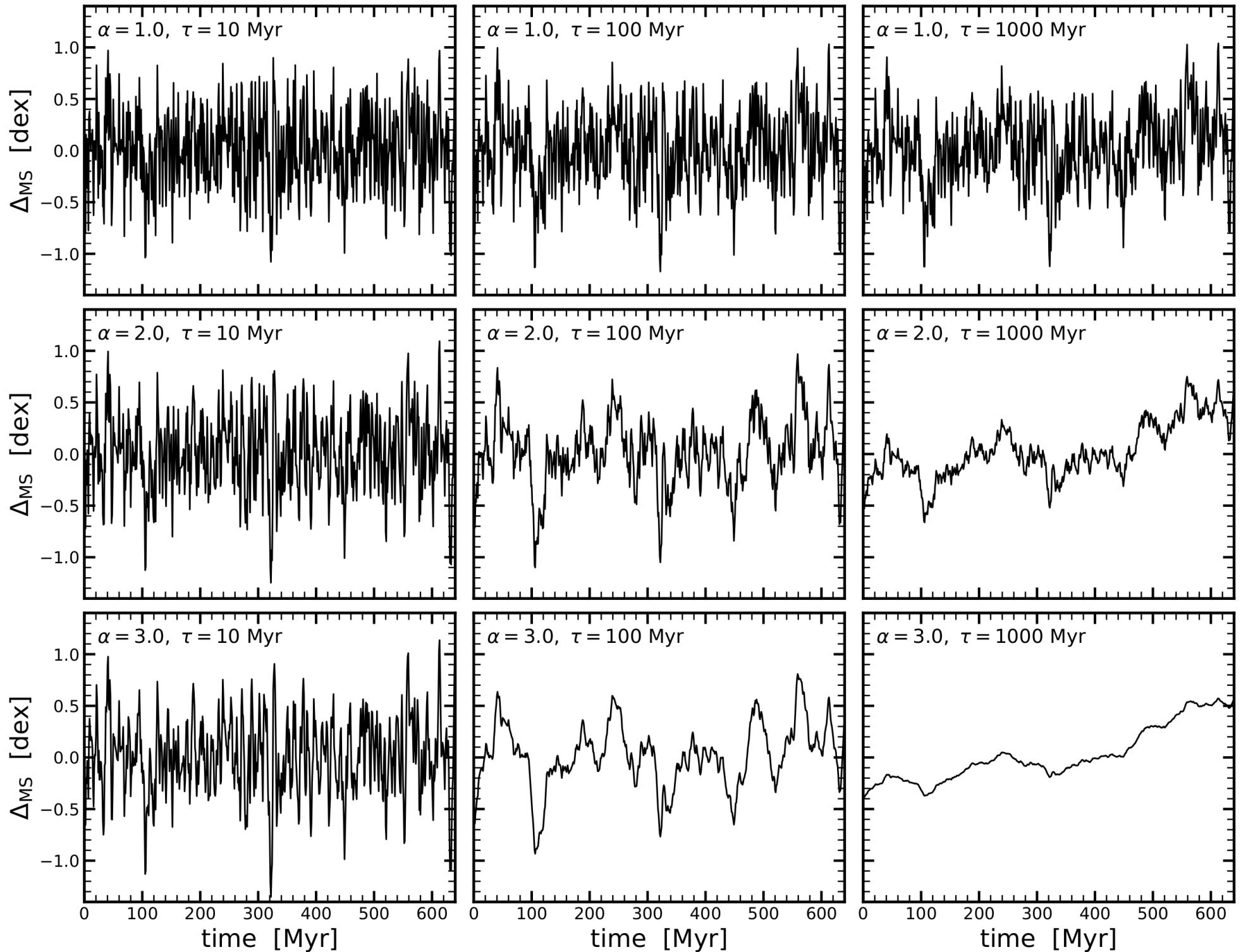


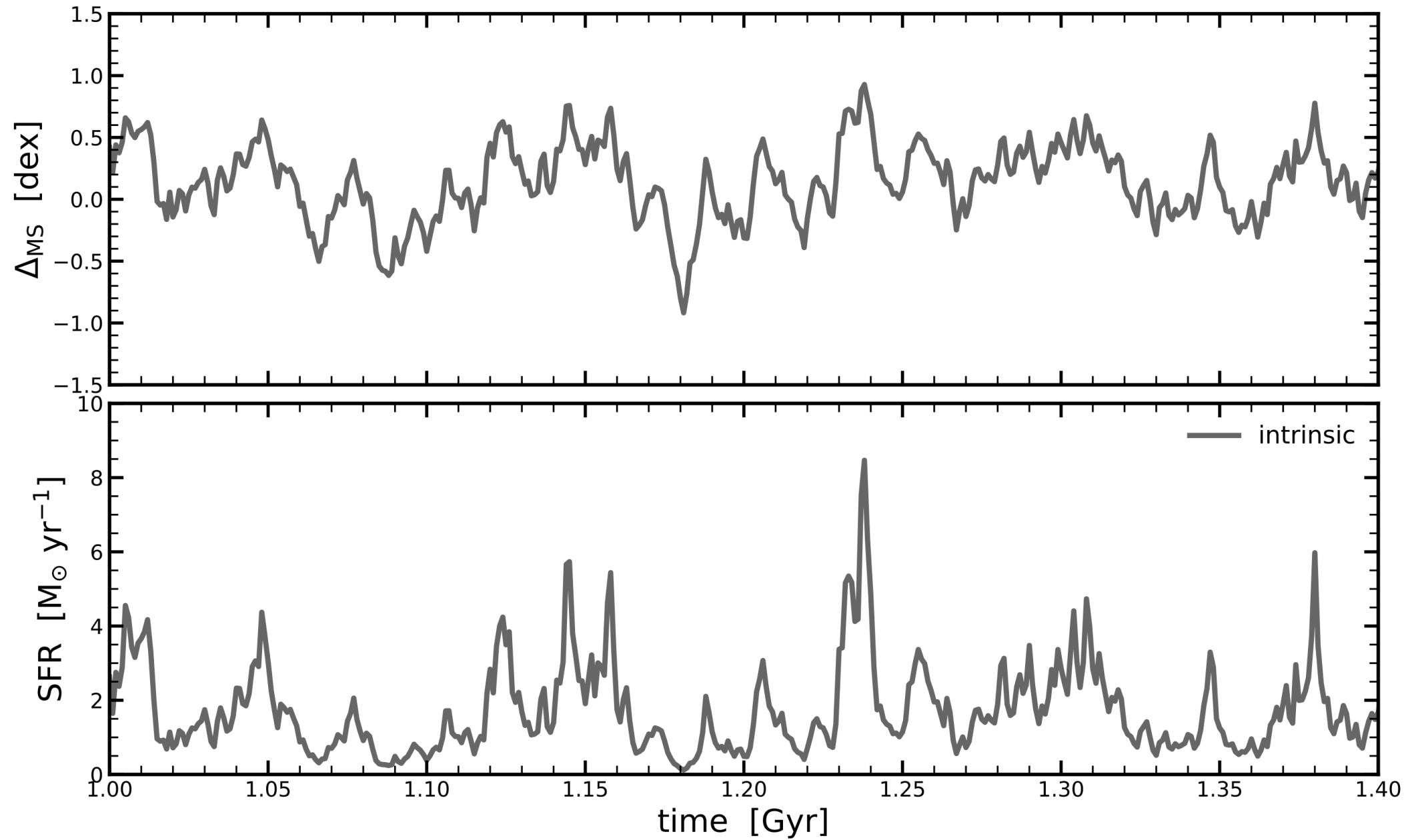
- Optical variability as a consequence of temperature variations in the disk (Dexter & Agol, 2011)
- Temperature:  $T(r) \propto \Delta M^{1/4} M^{-1/2} f(r)^{3/4} (r/r_g)^{-3/4}$ 
  - Temperature correlated with spin (f parameter in equation above)

# Confinement of star-forming galaxies

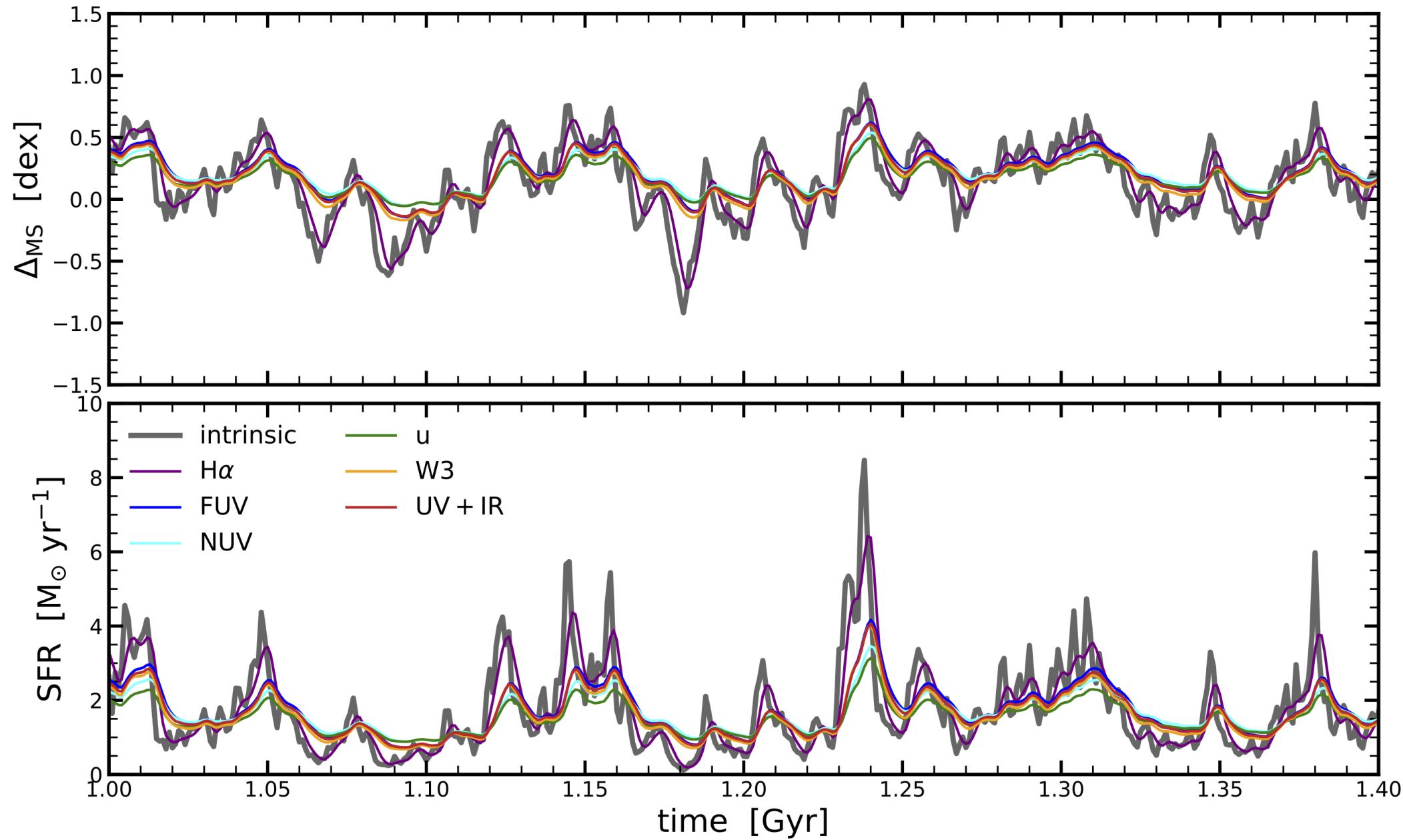




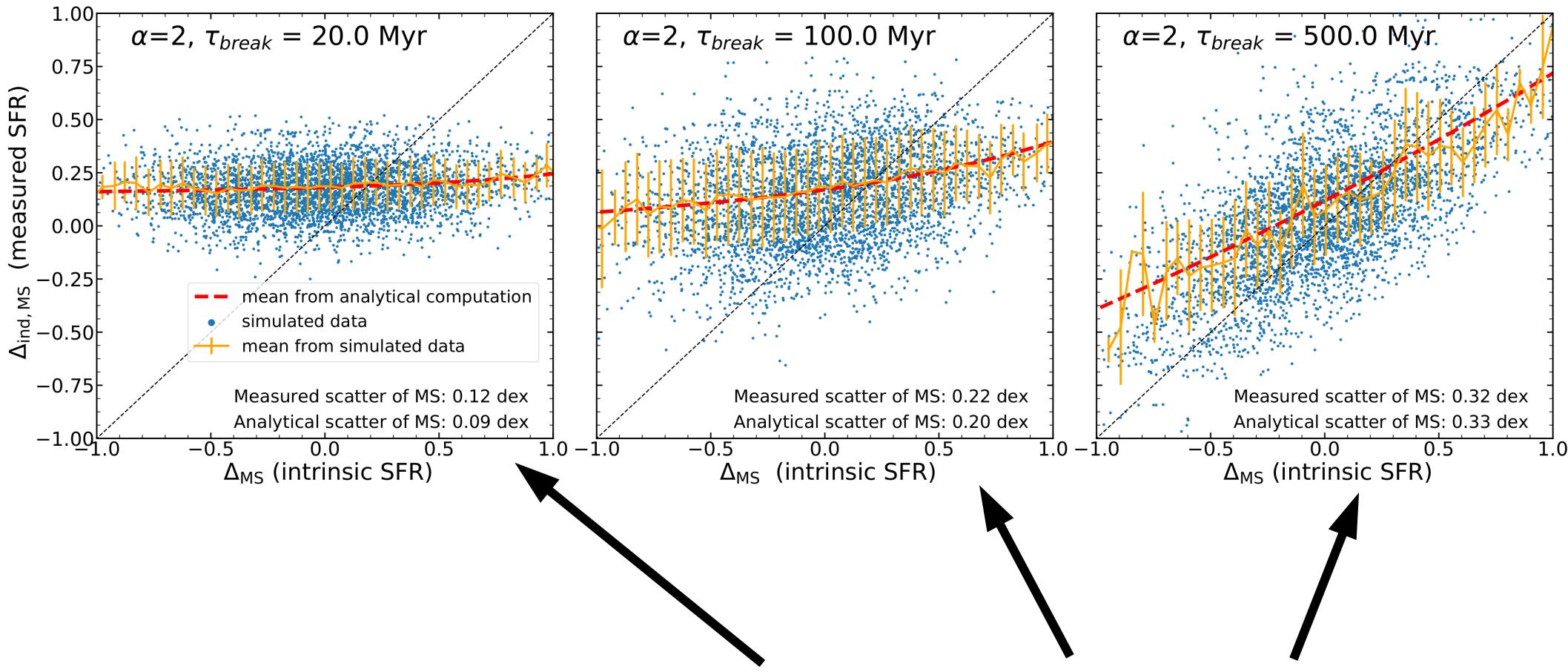




- We do not observe galaxies directly – but we observe different passbands

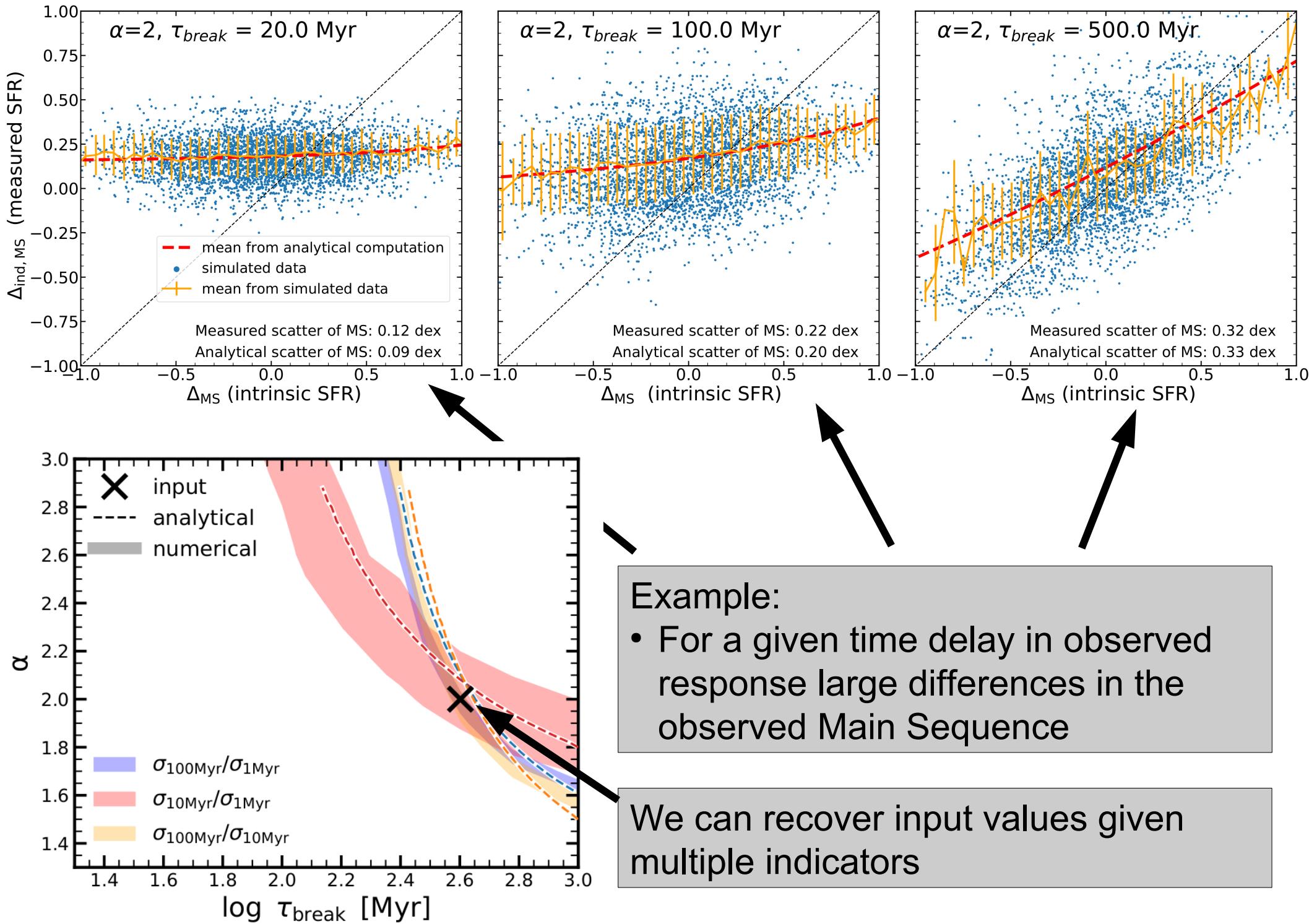


- We do not observe galaxies directly – but we observe different passbands



### Example:

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

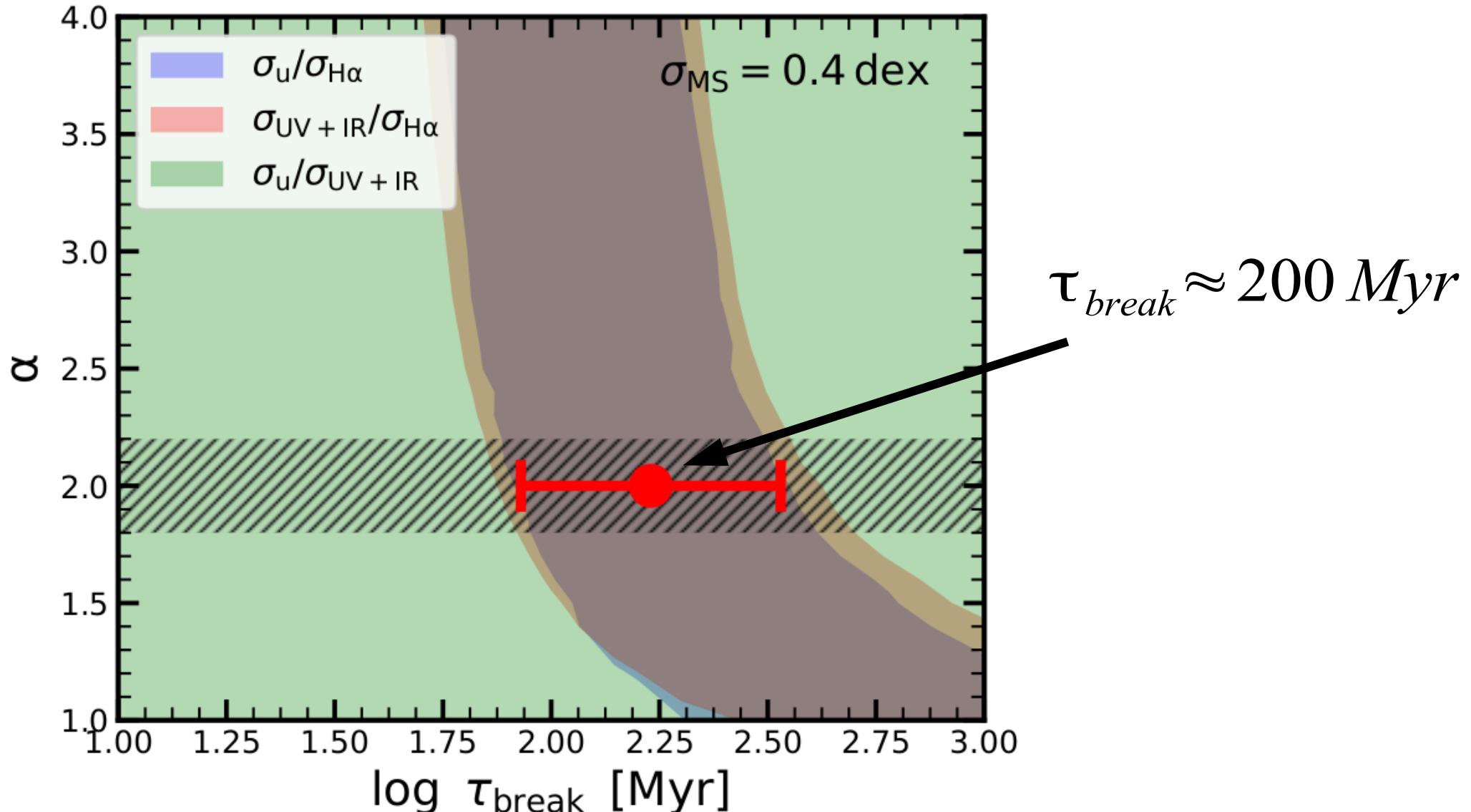


## Observational data:

- 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

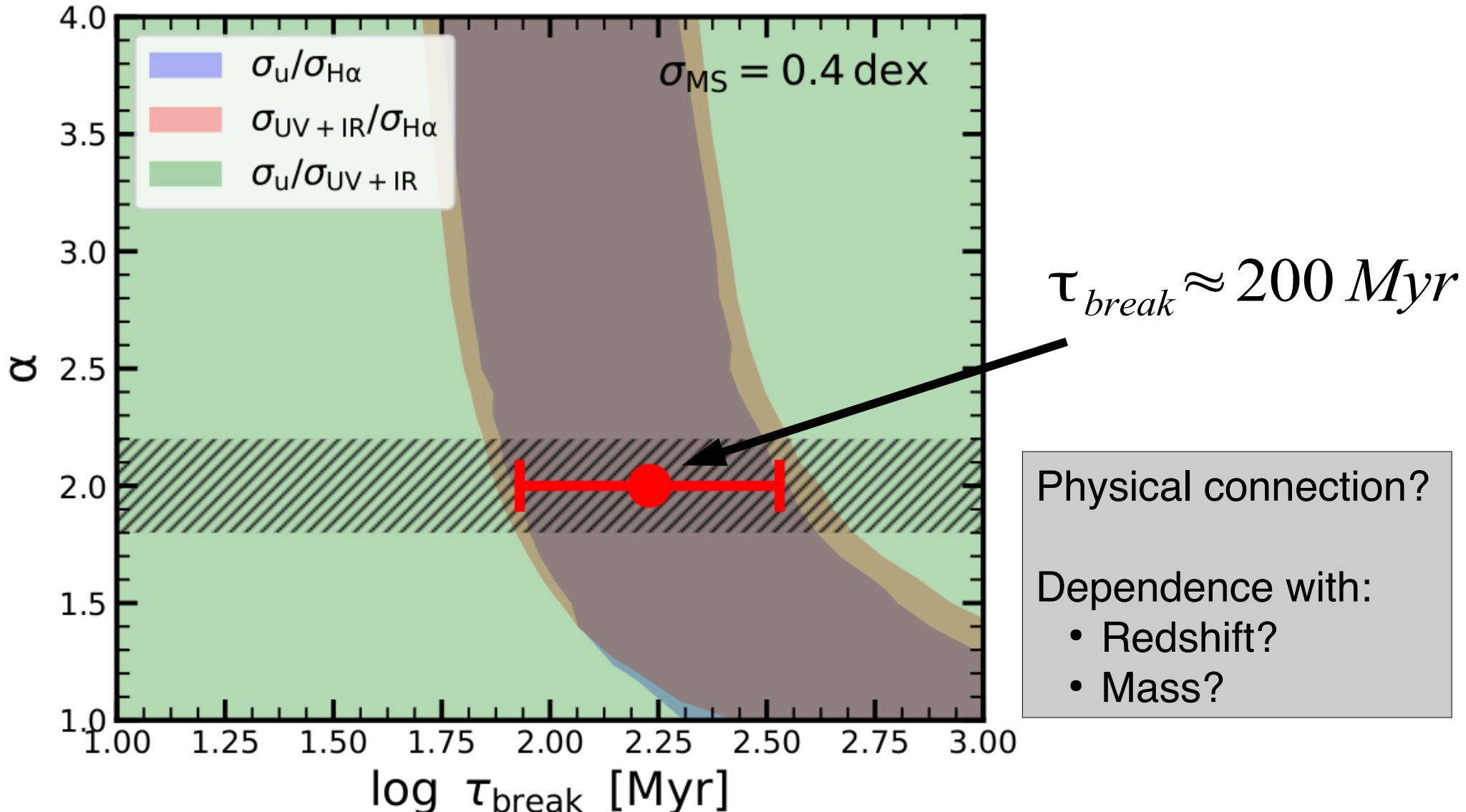
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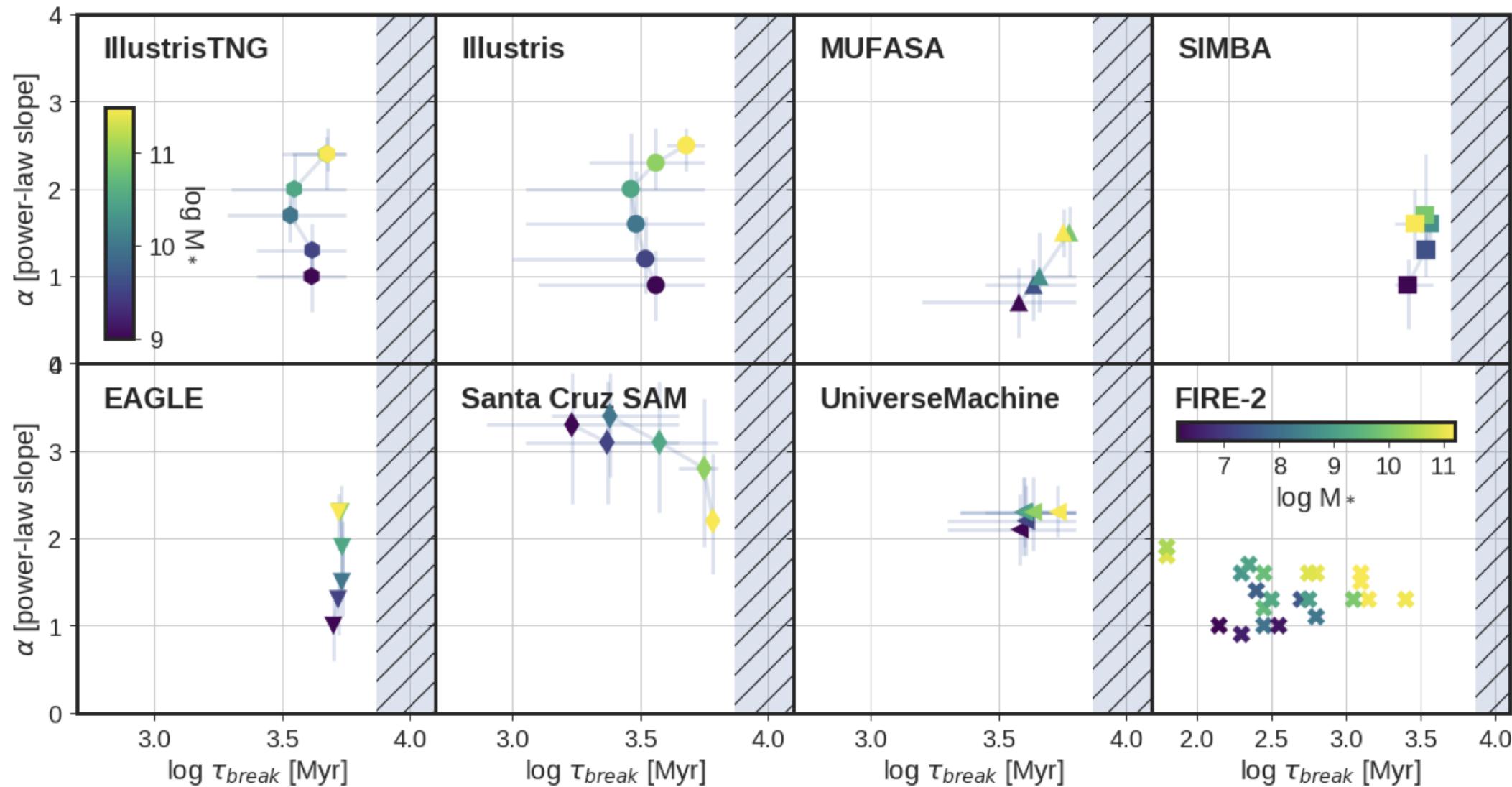


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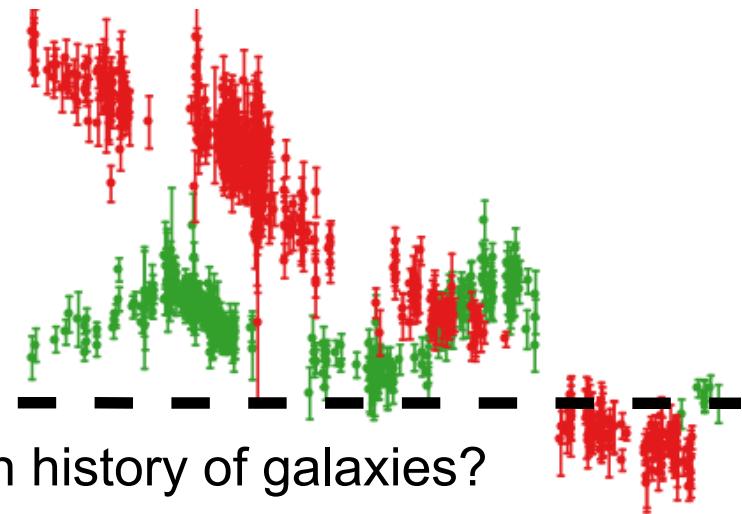


# PSDs in different models/simulations



# 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  $\tau$ , then  $\tau \propto L^{0.4}$ , 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



## II. Constrain spin from variability

- Accretion efficiency is dependent on the AGN spin
  - Considerable effect on the black hole-galaxy co-evolution
- AGN spins are observationally poorly constrained

