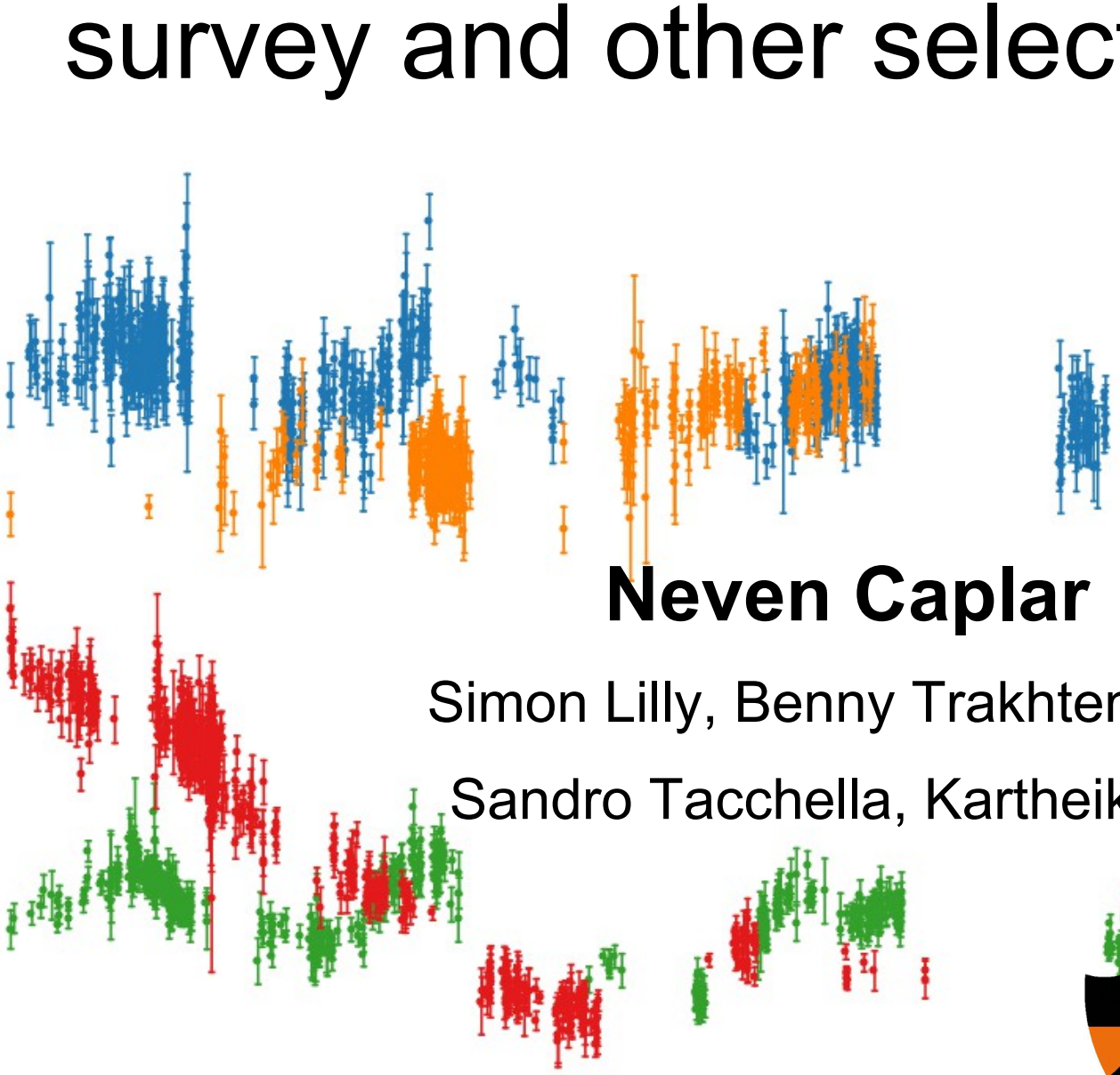
Optical variability of AGN: PTF survey and other selected topics

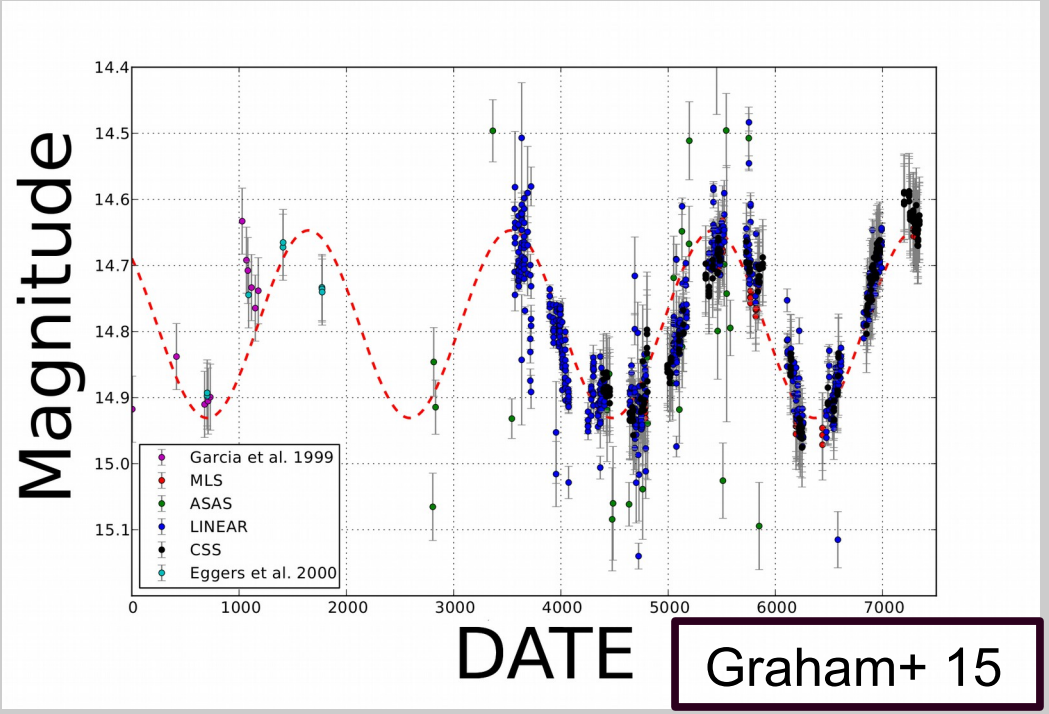


Neven Caplar

Simon Lilly, Benny Trakhtenbrot,

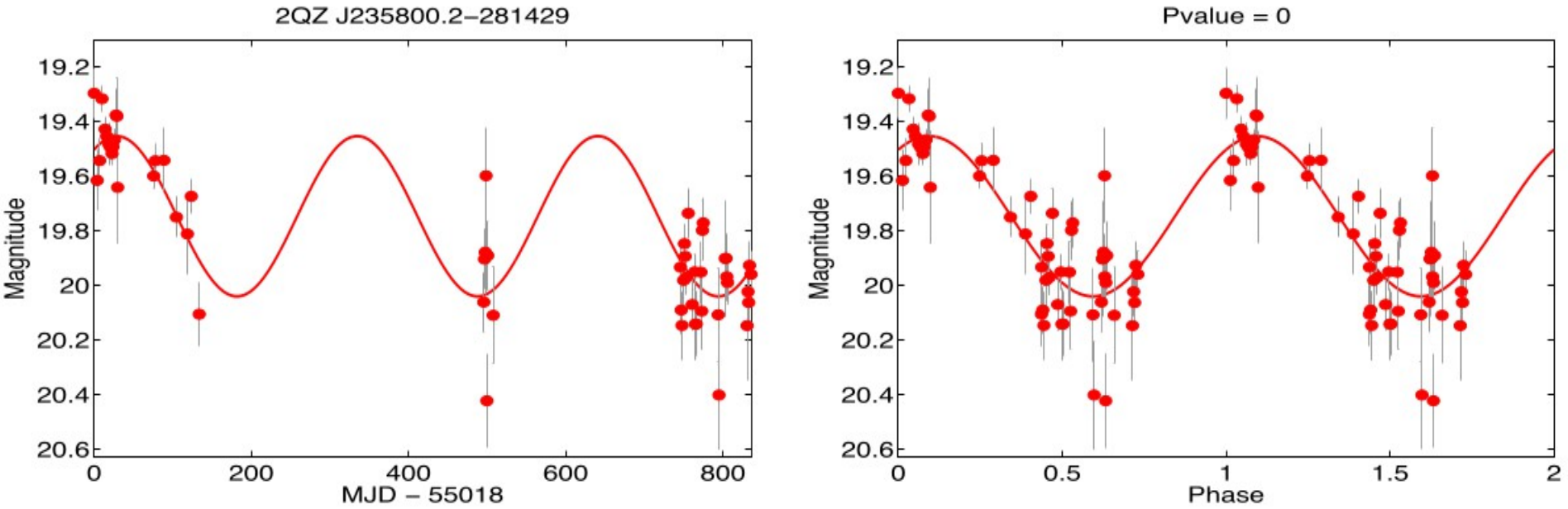
Sandro Tacchella, Kartheik Iyer

PRINCETON
UNIVERSITY

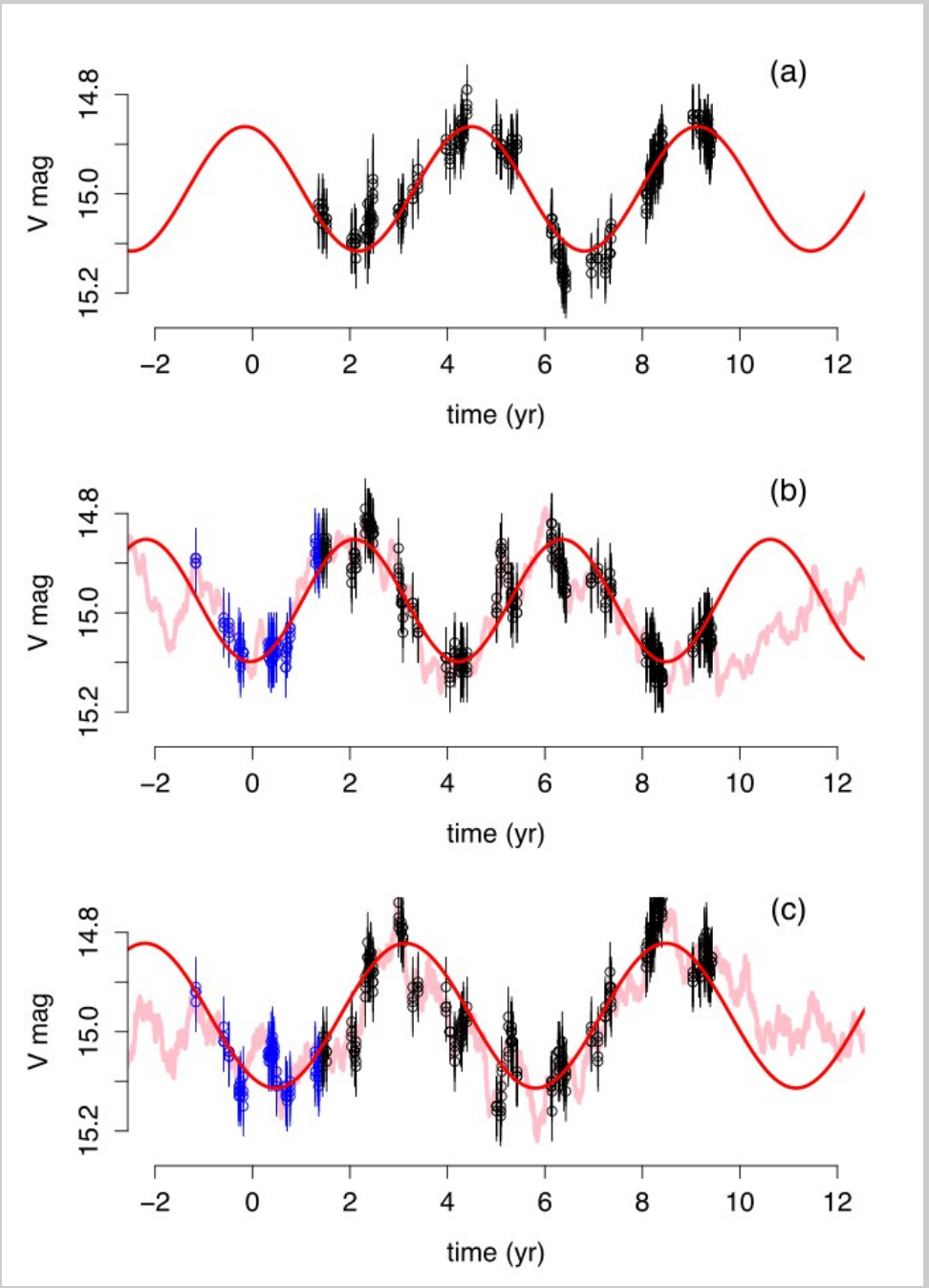


Graham+ 15

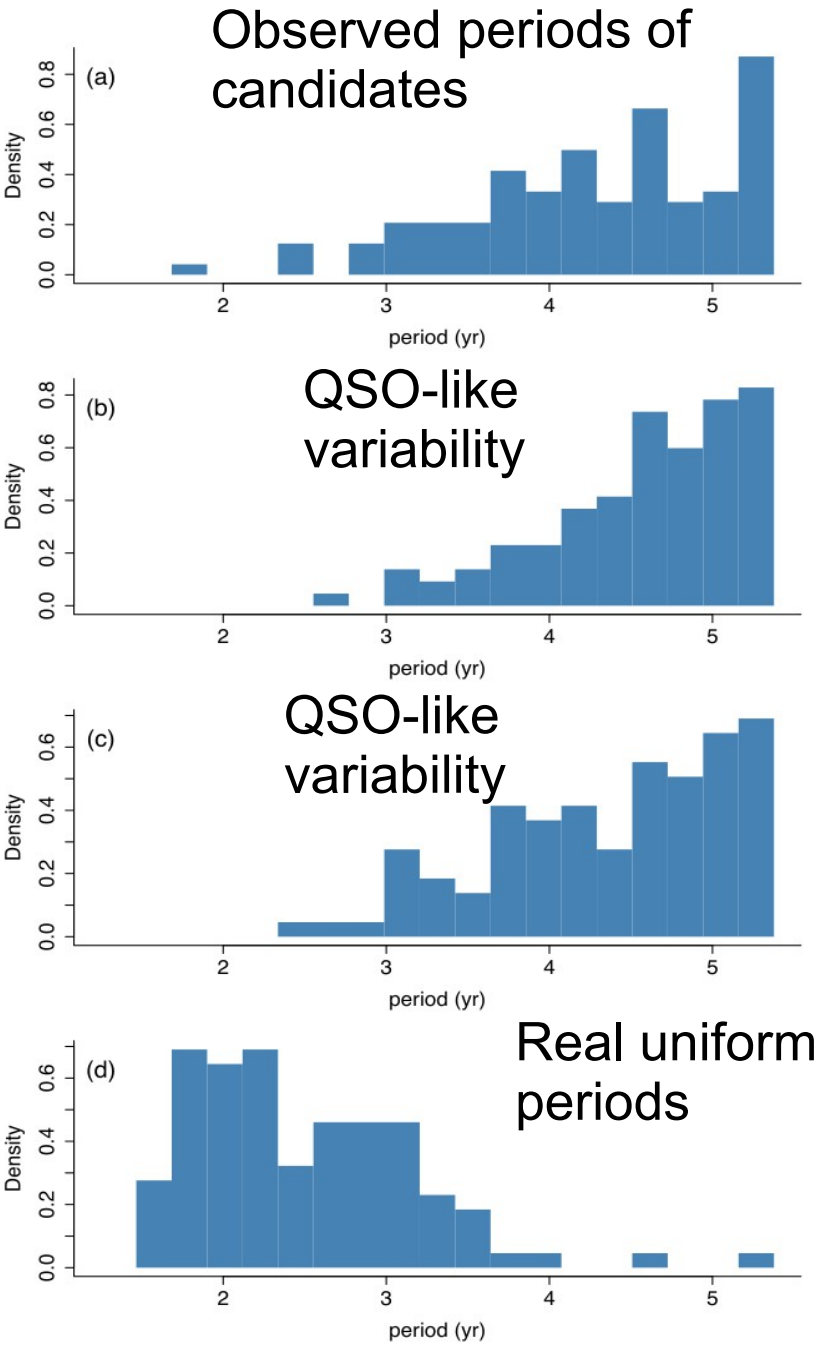
- Search for binaries of supermassive black holes with a sub-parsec separation
- Expected as a consequence of galaxy mergers



Charisi+ 16



- But stochastic process can also mimic periodicity!



Vaughan+ 16

- Quasar variability as a method to measure spin

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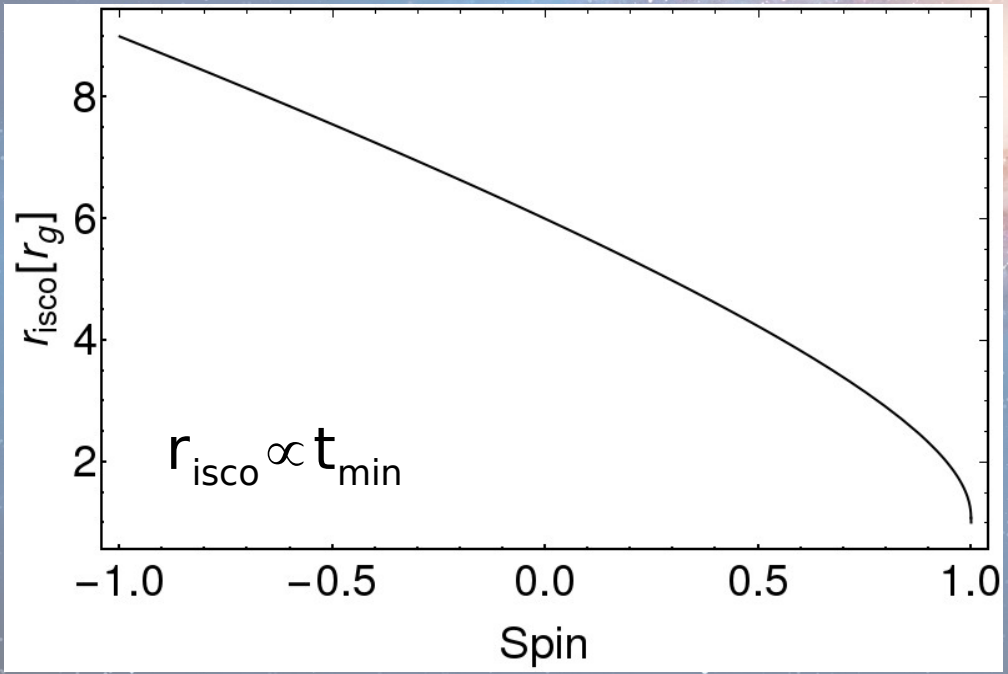
Measure the shortest time-scale of the variability; connected with the radius of the last stable orbit



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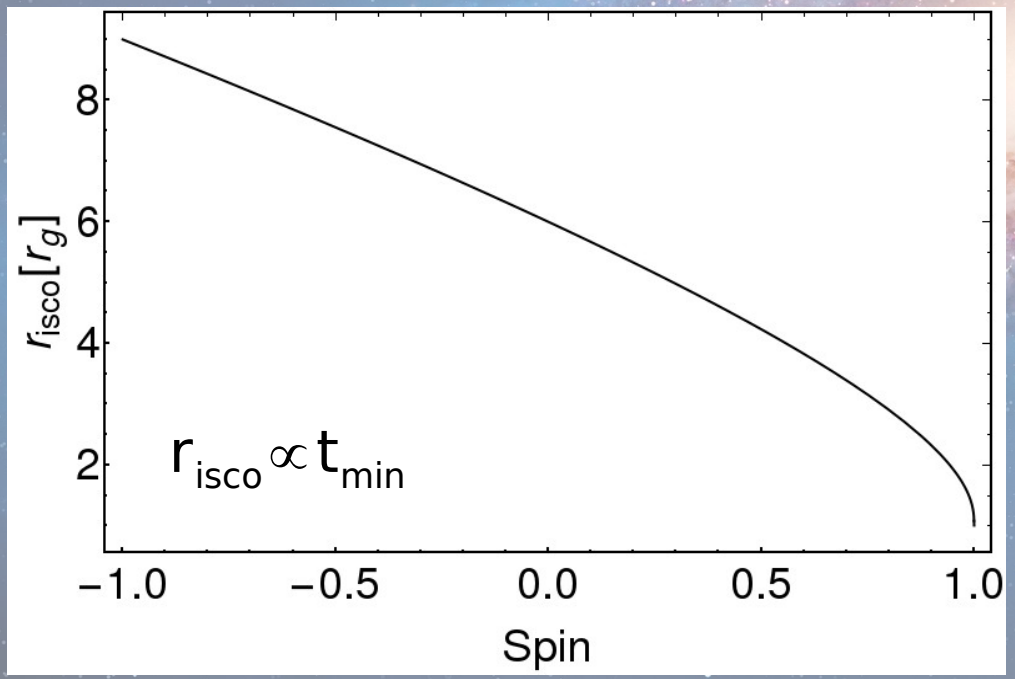
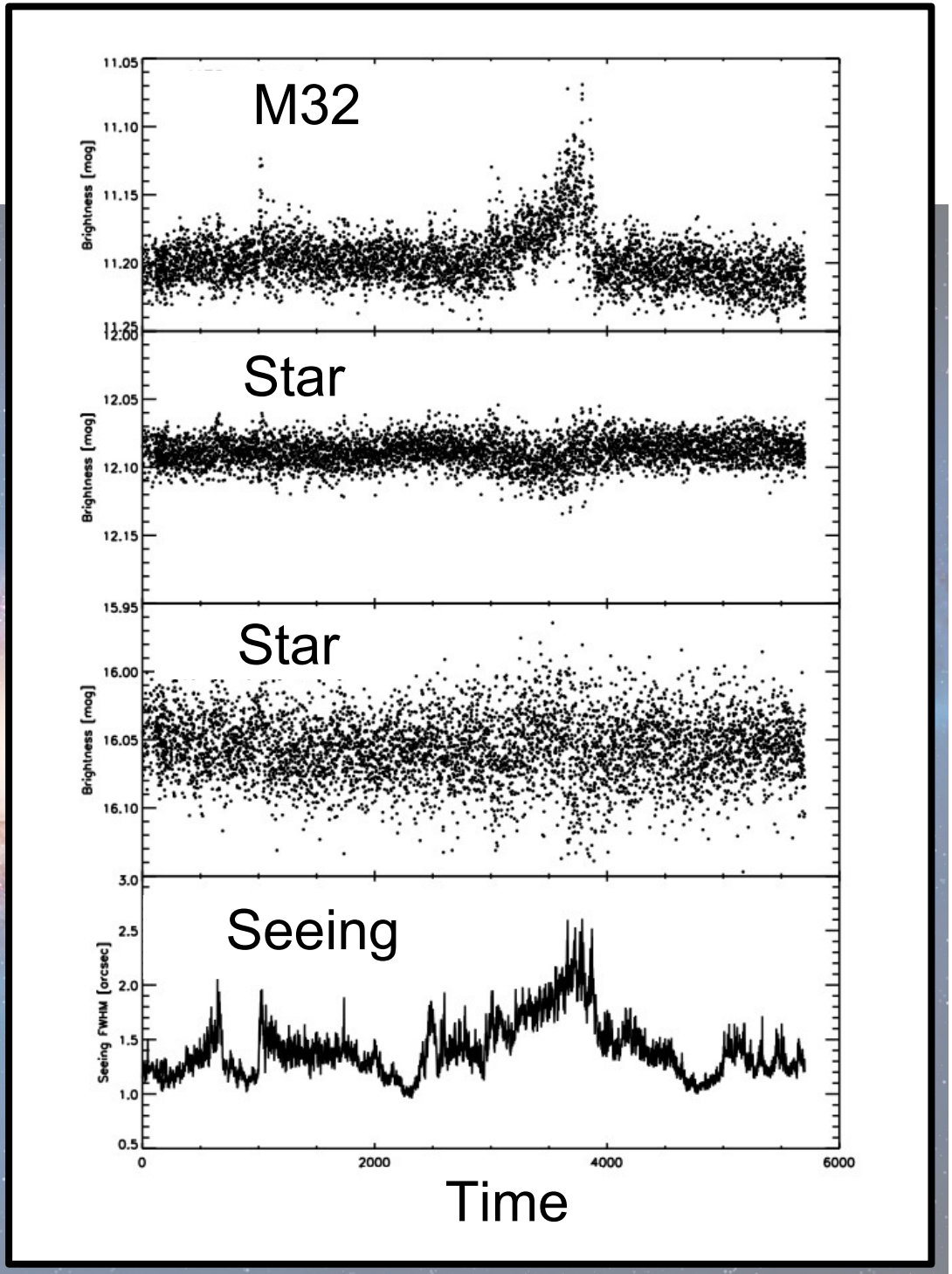


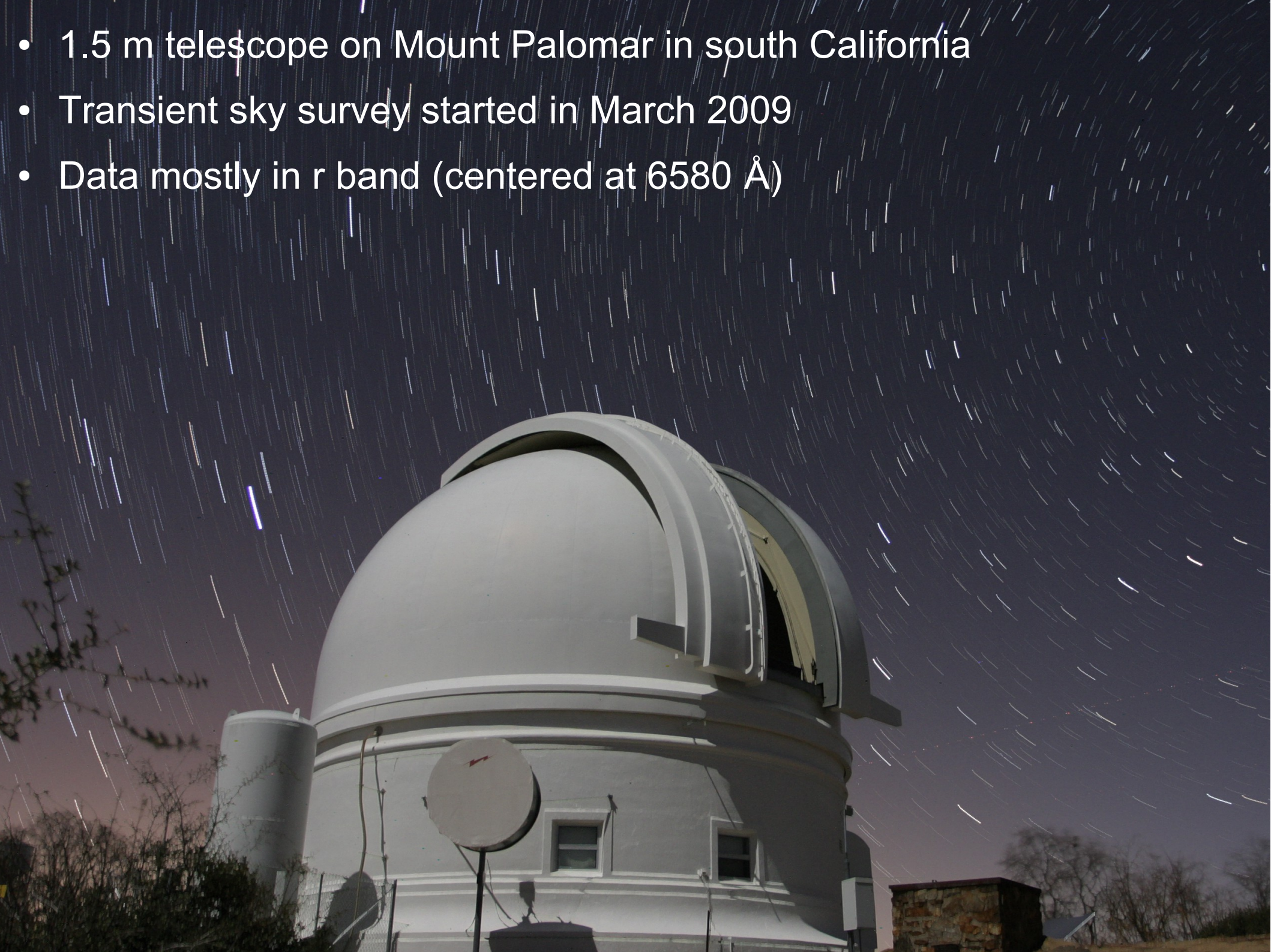


Chary+ 17

Overview

- Short intro – periodicity and spin via AGN variability
- Observed optical variability of AGN in Palomar Transient Factory Survey
  - Overview
  - Analysis in time domain
  - Analysis in frequency domain
  - Discussion
    - Binary AGN
    - HSC
    - What are we actually probing?
    - Spin

- Variability of star-formation on 100 Myr+ scales
  - Can we model galaxies in the same way
  - Constrains 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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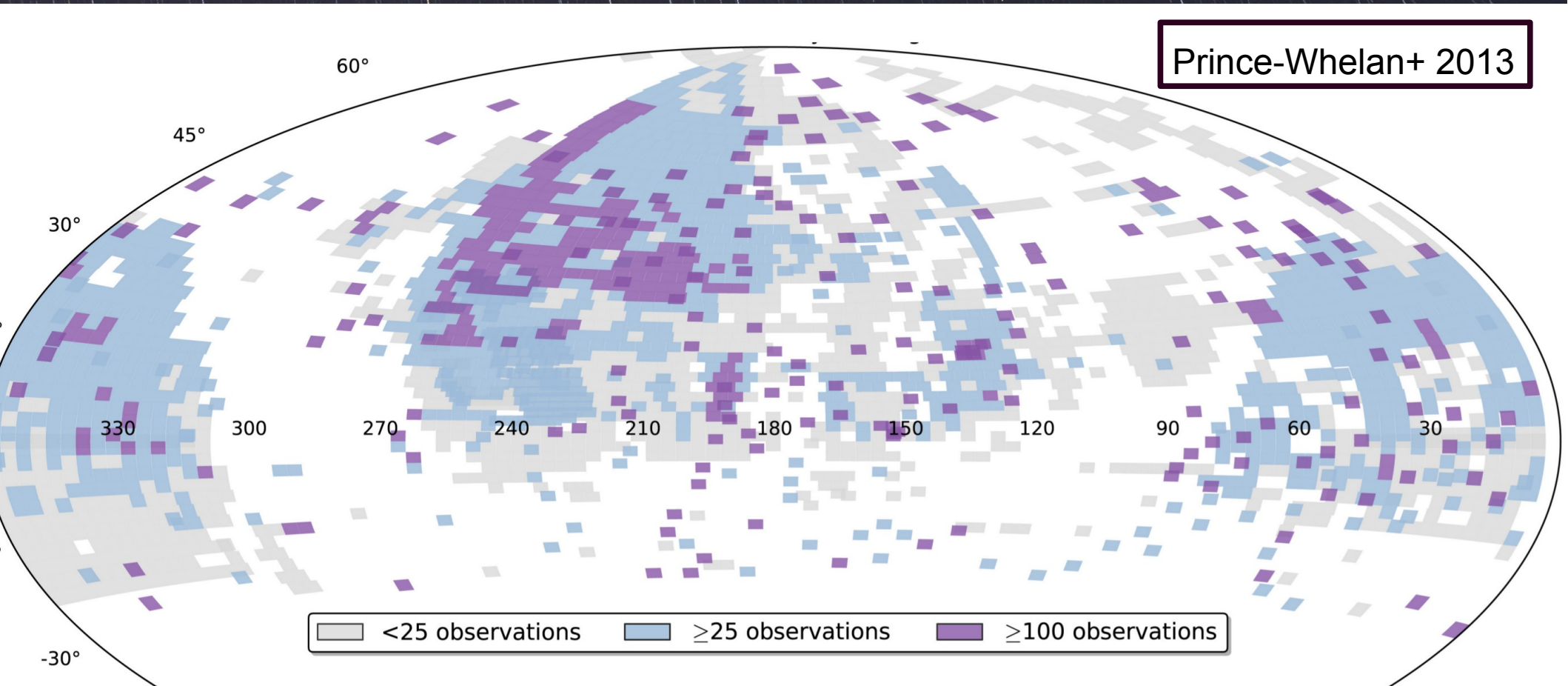

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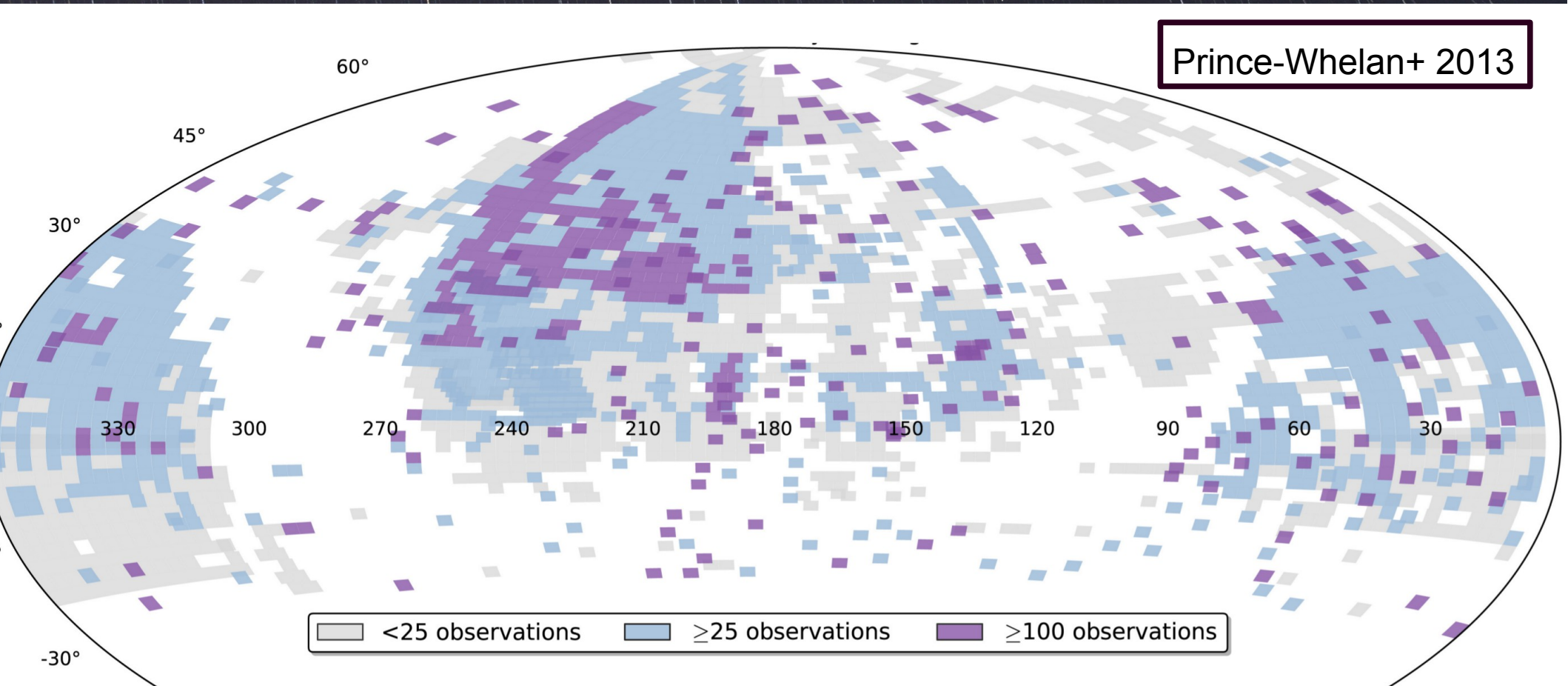
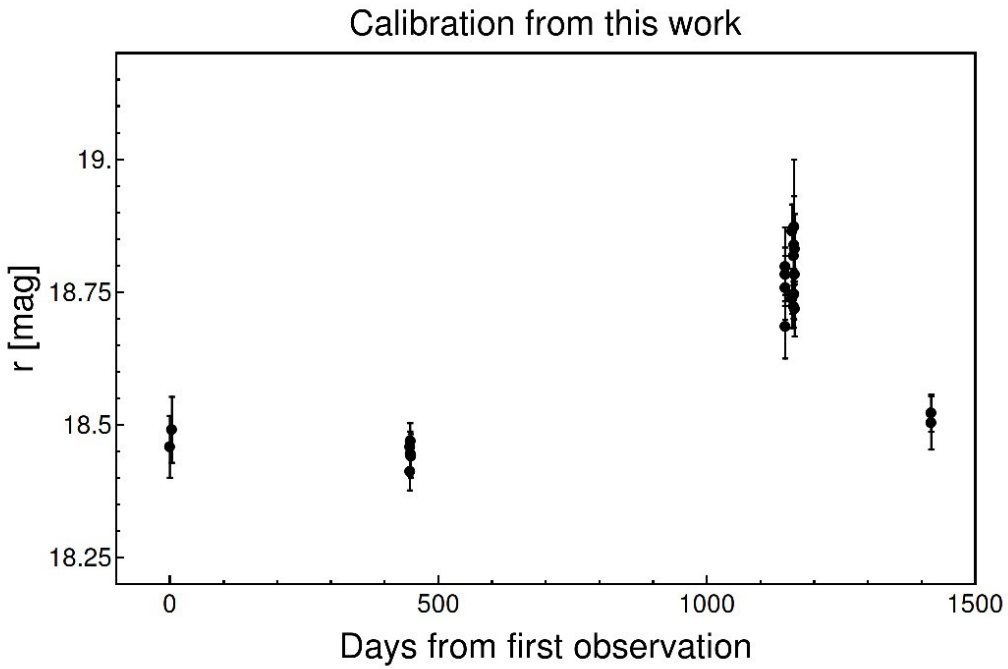
- Transient sky survey started in March 2009
- Data mostly in r band (centered at 6580 Å)

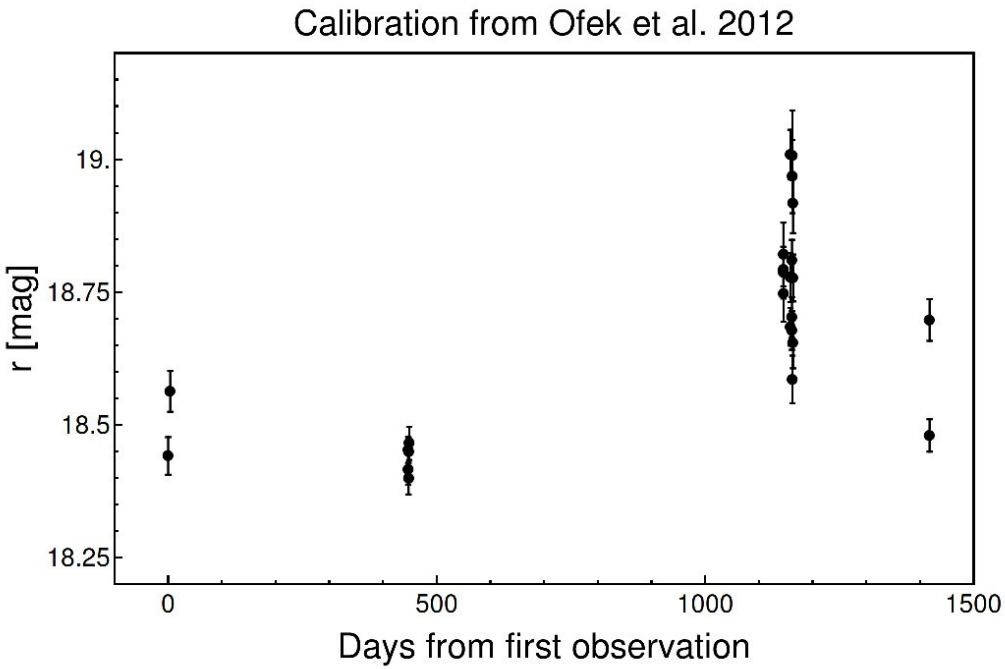
- 28000 AGNs brighter than r=19.1
- 2.4 million data points = largest calibrated single band dataset!



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

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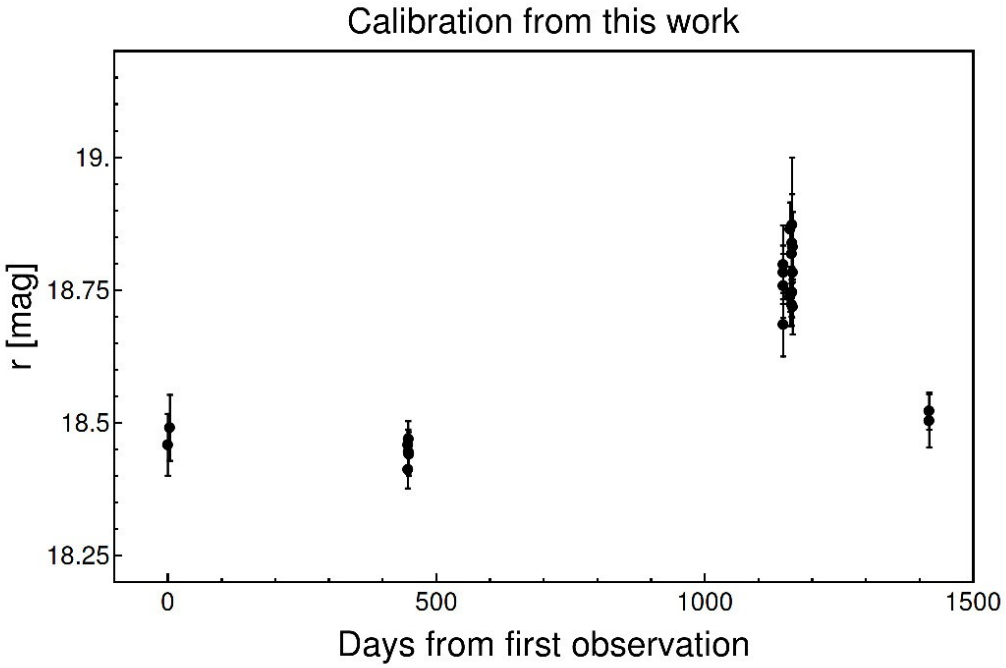
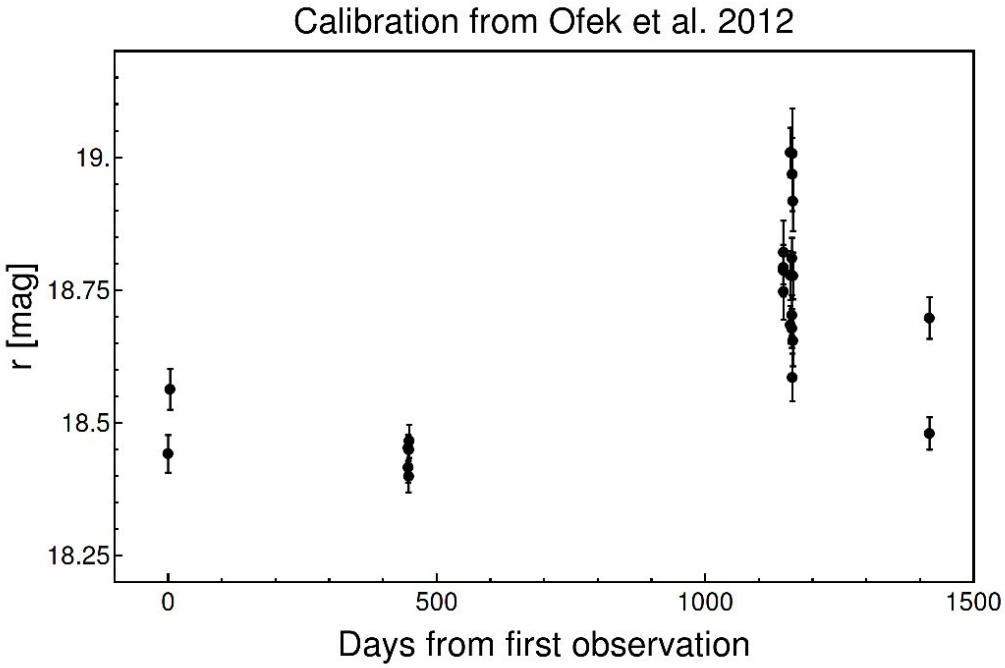
- We search for zeropoints which minimize the scatter of reference objects (stars) – based on Ofek+ 2011
- We achieve excellent performance; excess variance at short time-scales is consistent with zero for vast majority of AGNs
- Re-calibrated data is public: https://github.com/nevencaplar/PTF_AGN





- 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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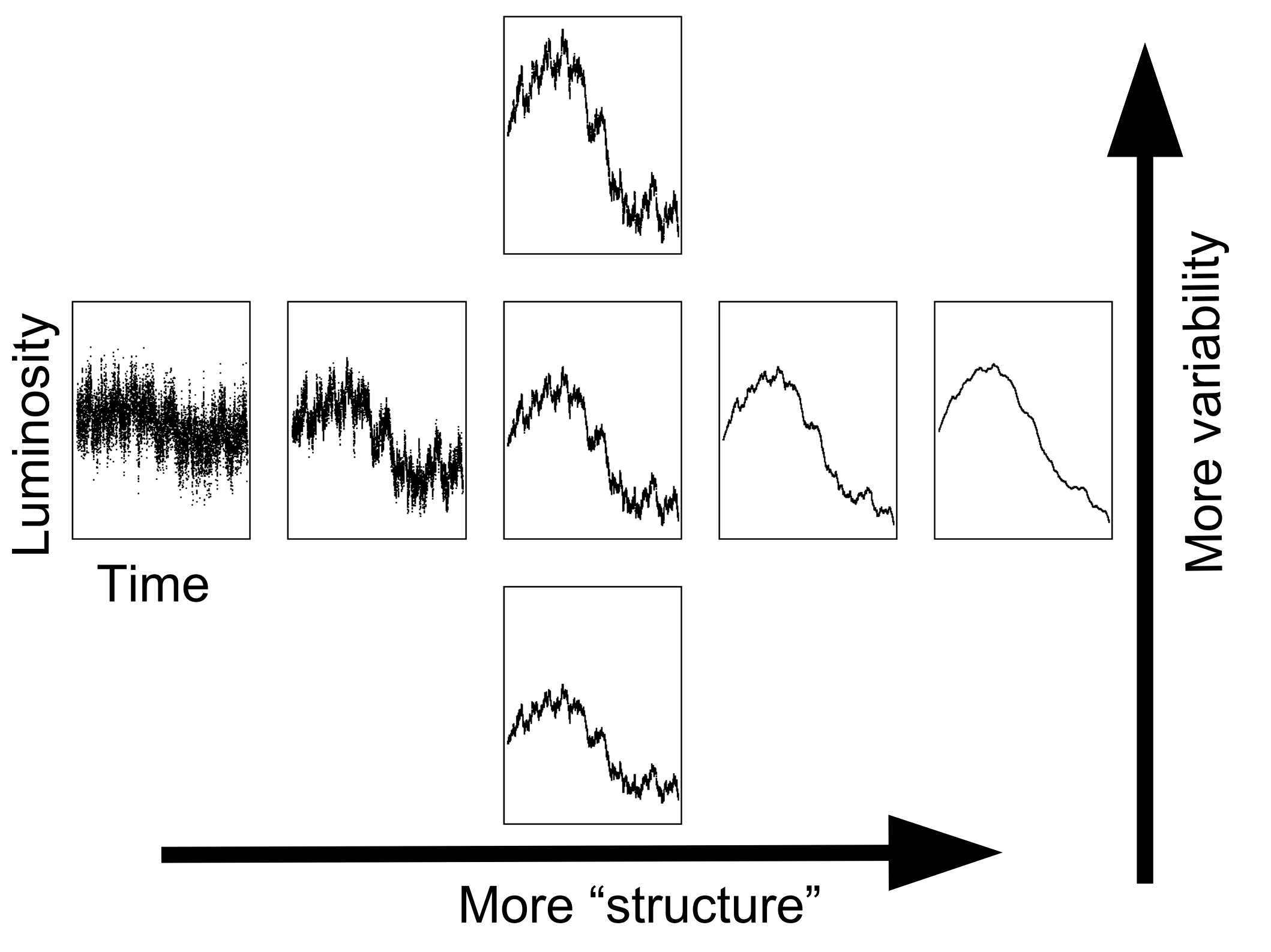
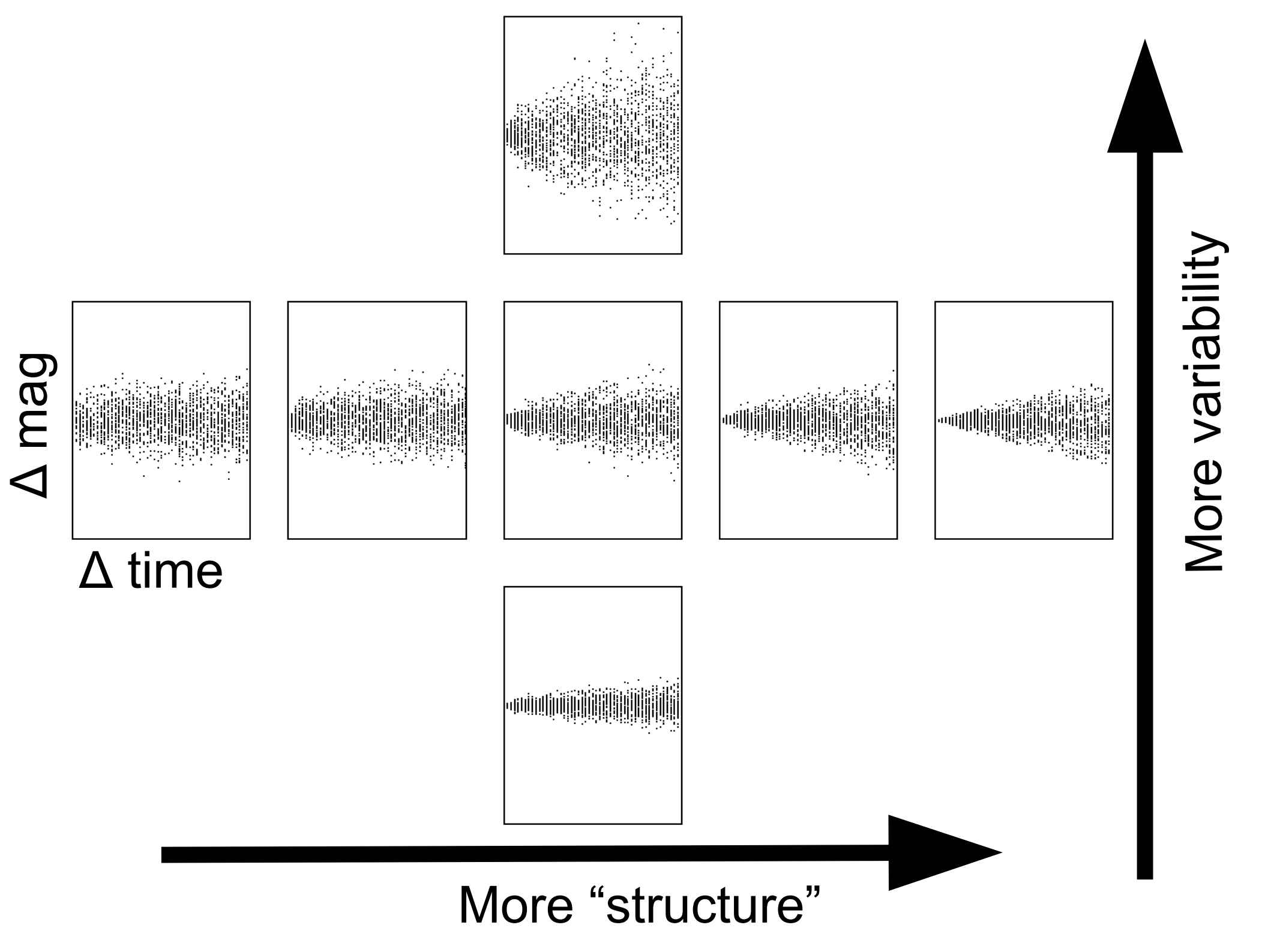
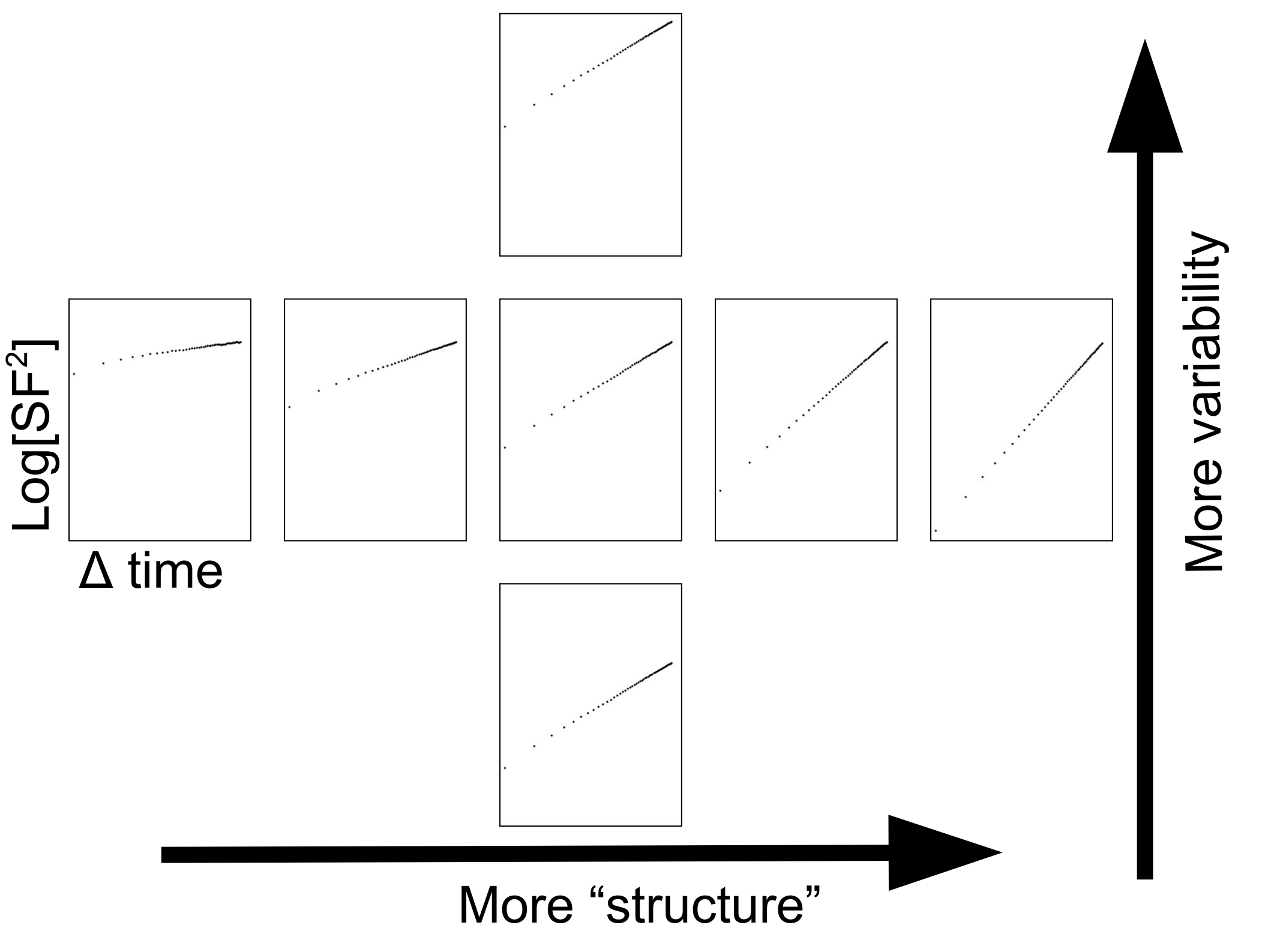
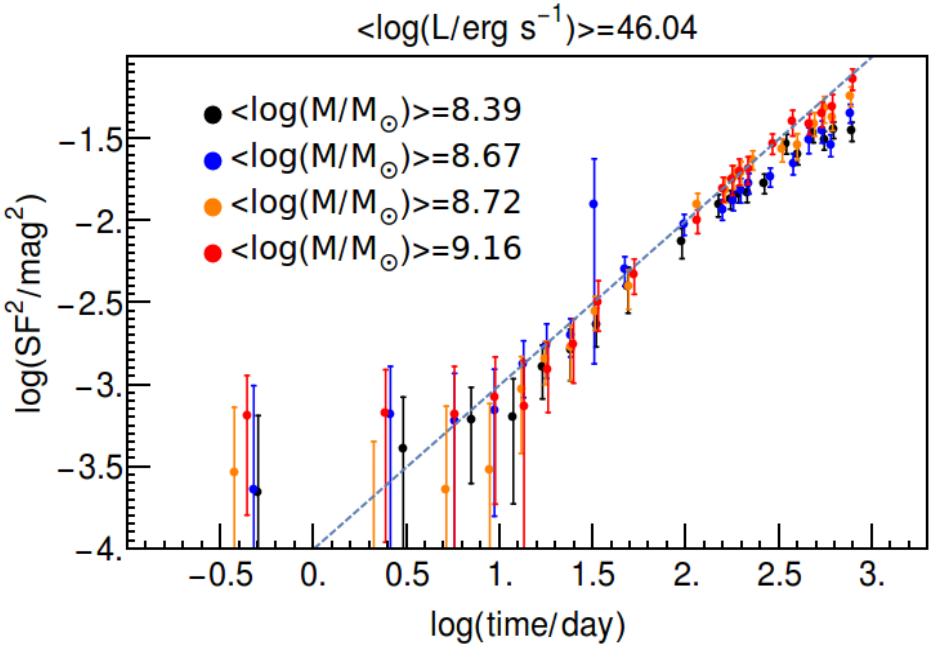
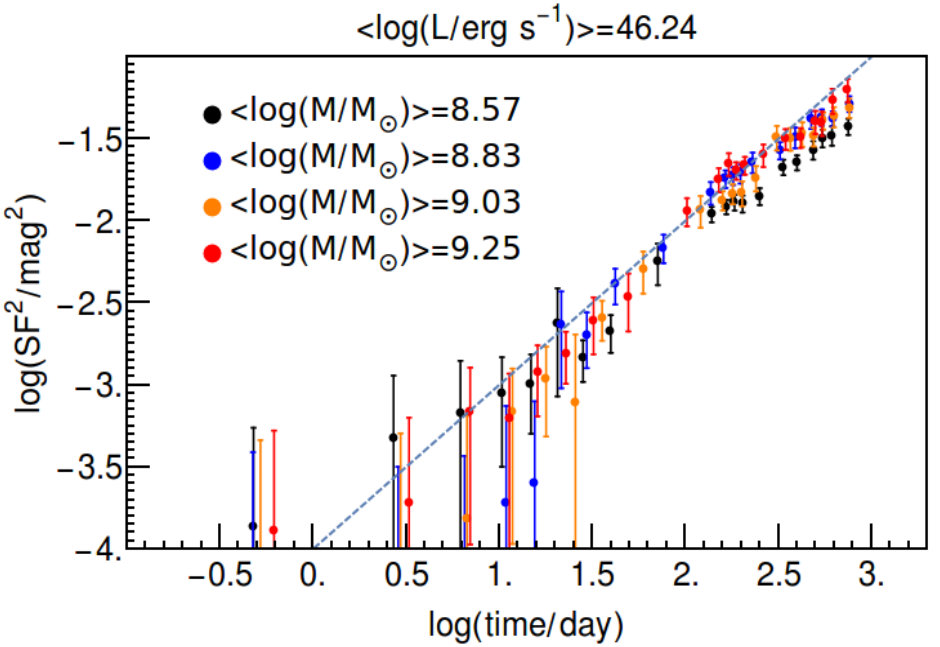

Luminosity
Time
More variability
More “structure”

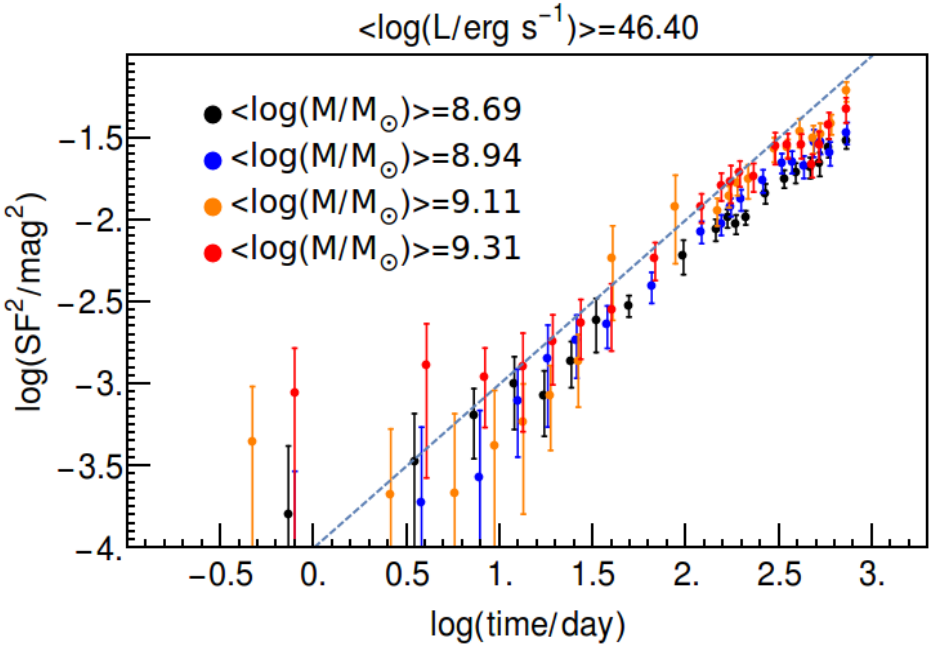

Δ mag
Δ time
More variability
More “structure”

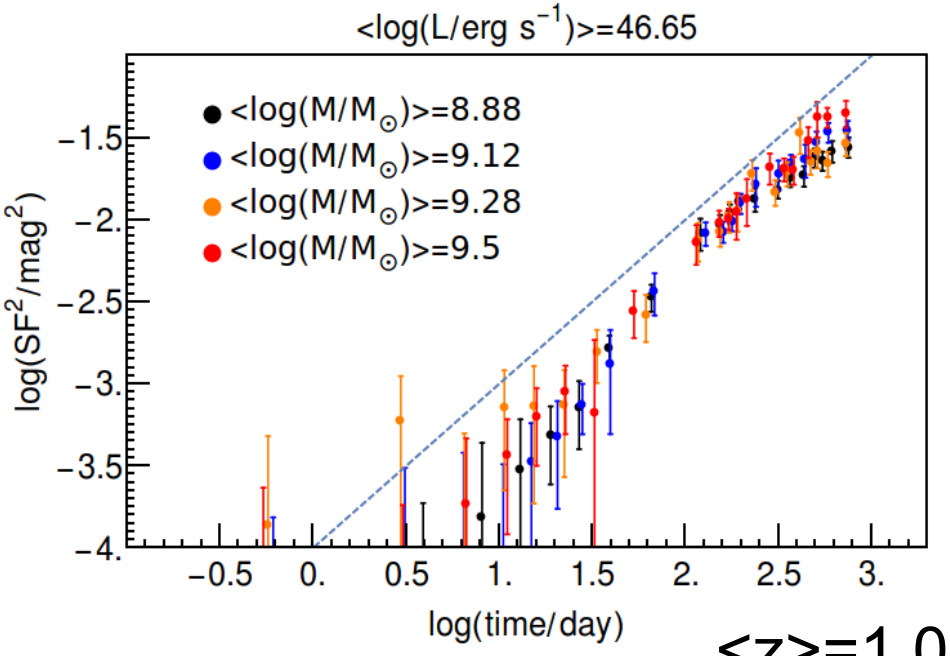

Log[SF²]
Δ time
More variability
More “structure”

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









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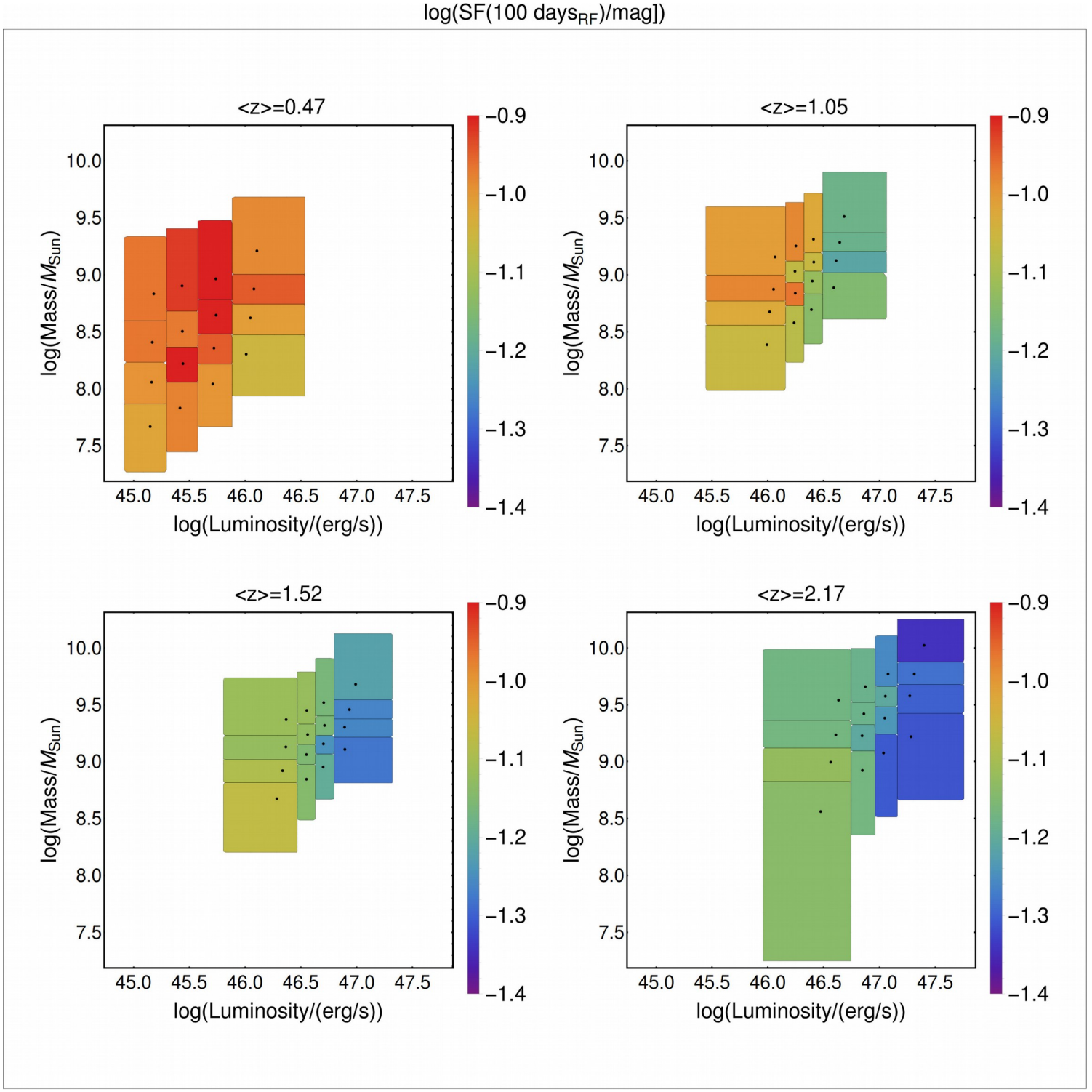
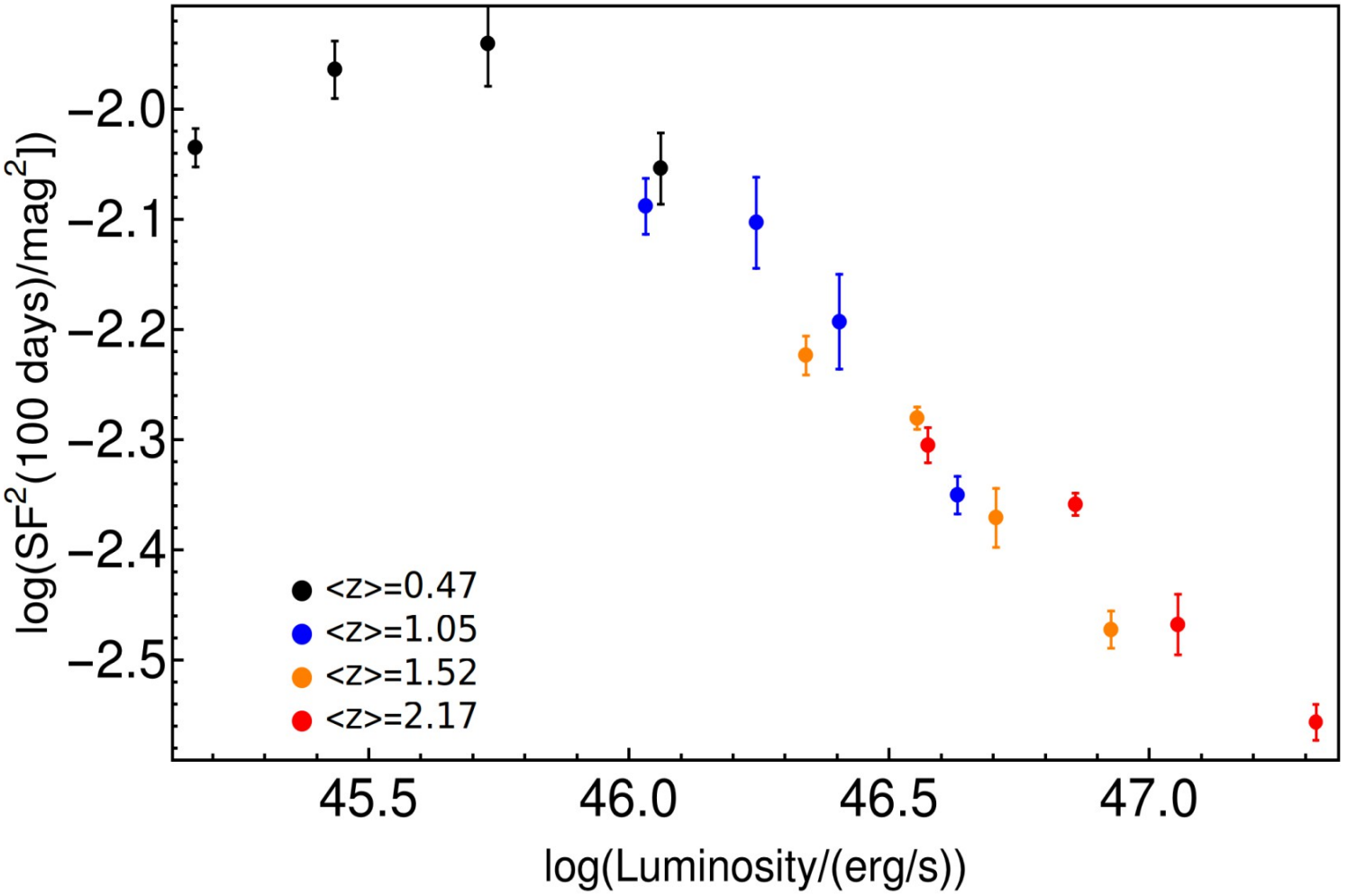


- Wavelength correction estimated from SDSS dataset to normalize to 4000 A
- No correlation with redshift
- Little to no correlation with mass
- Clear dependence with luminosity



- 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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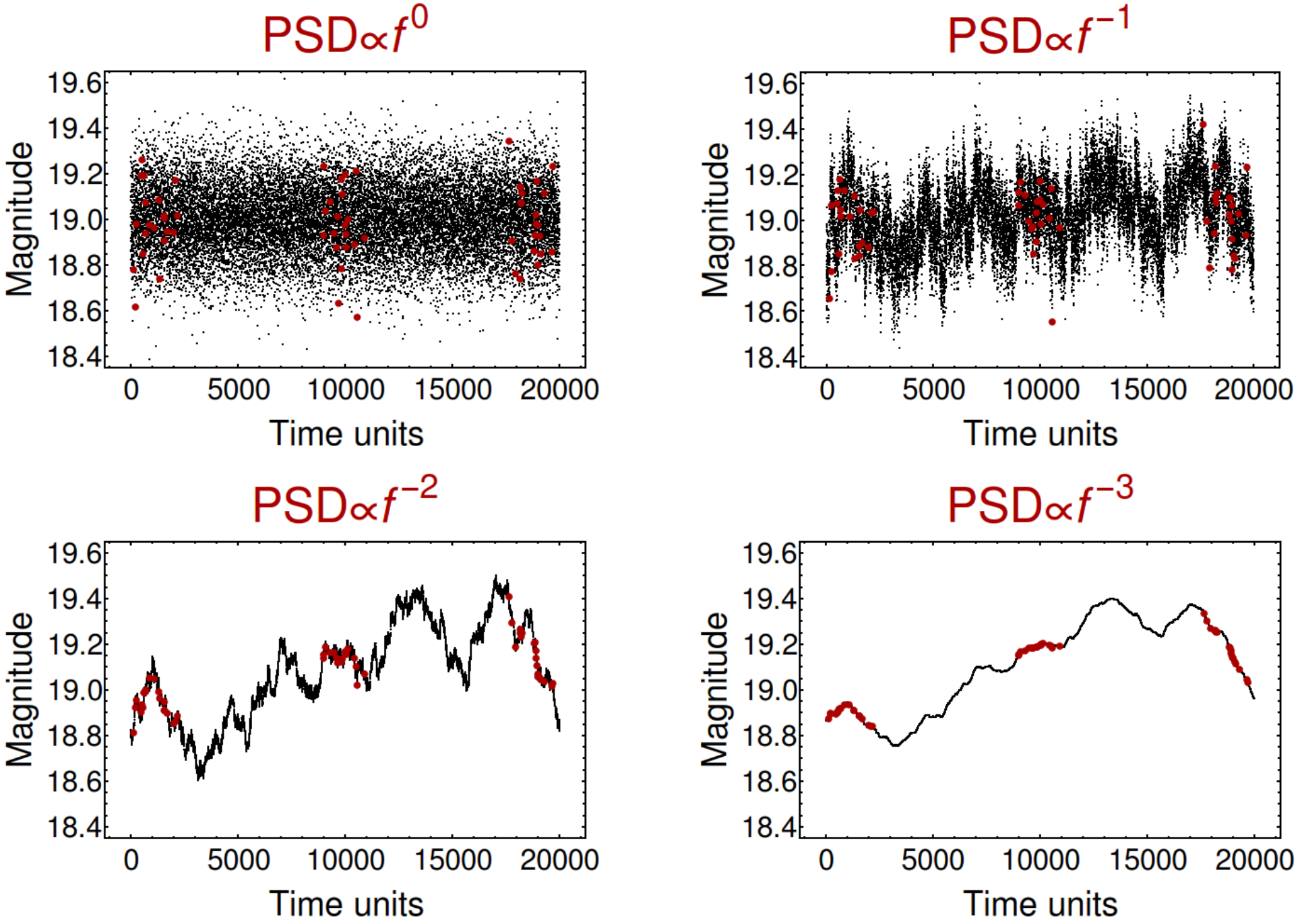
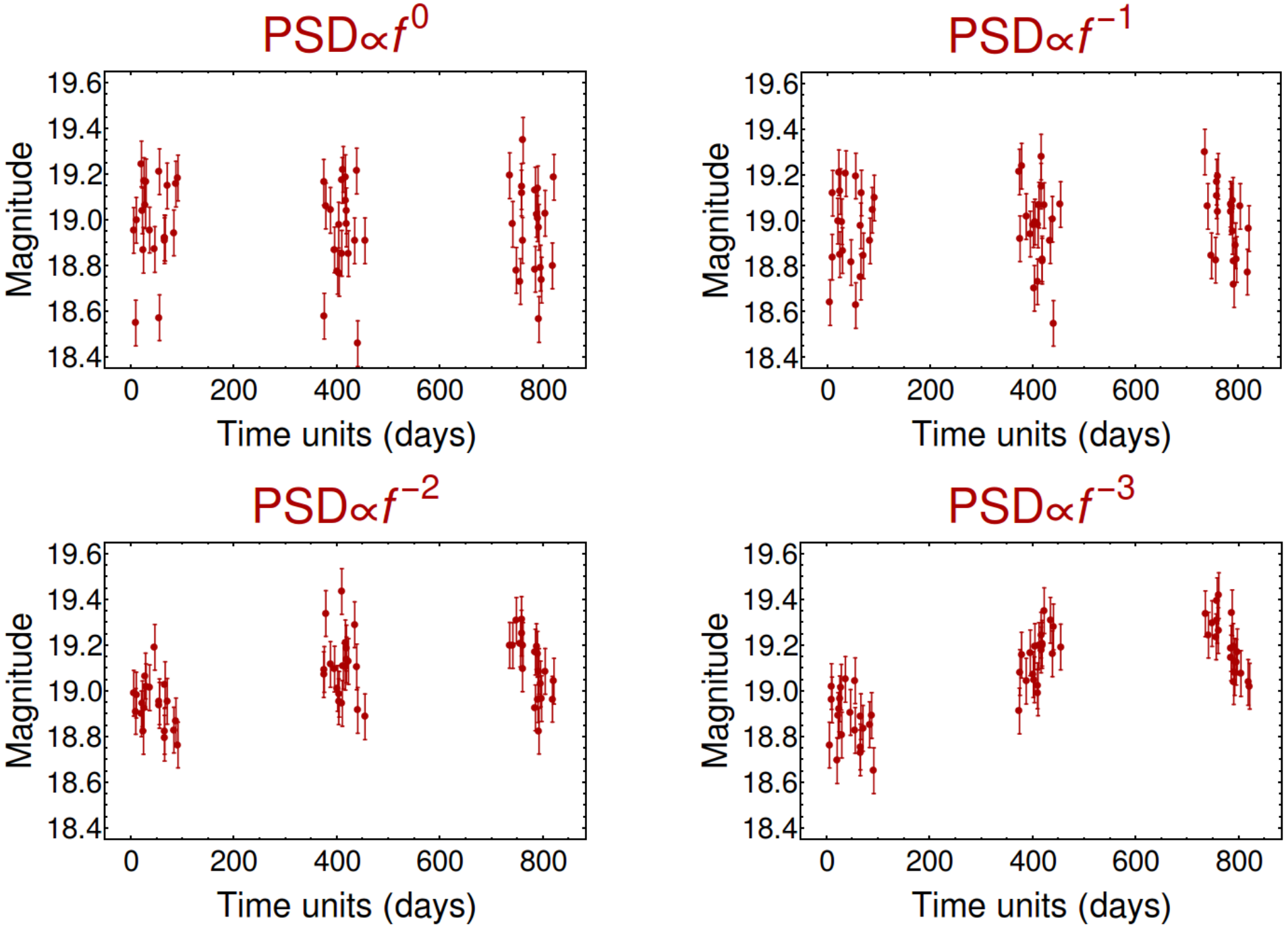
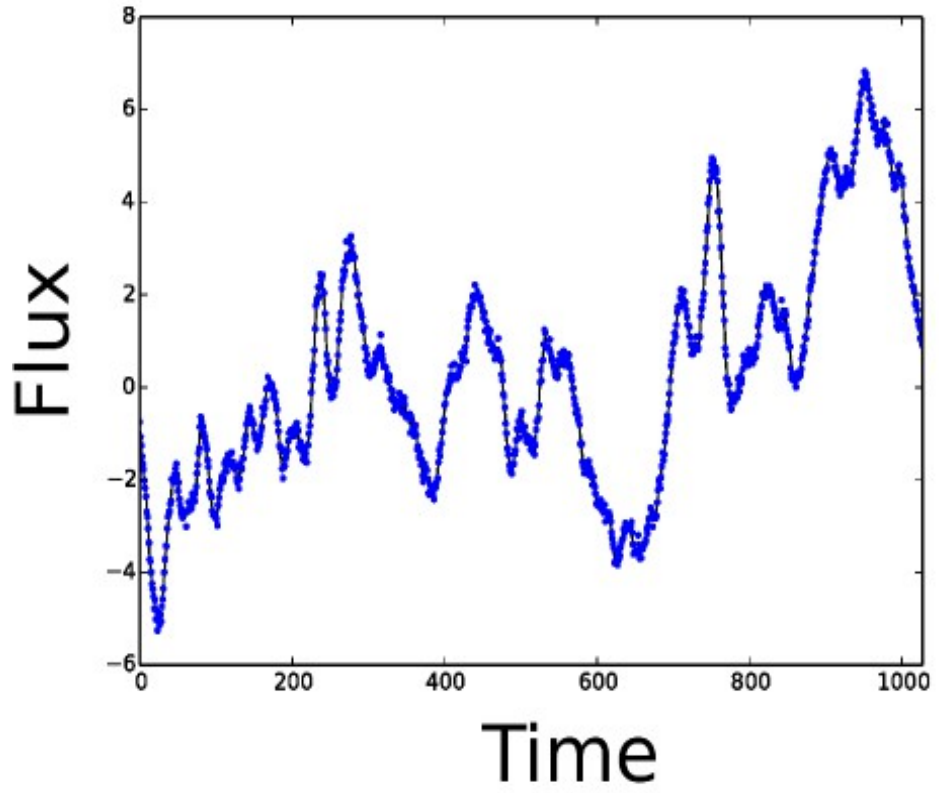
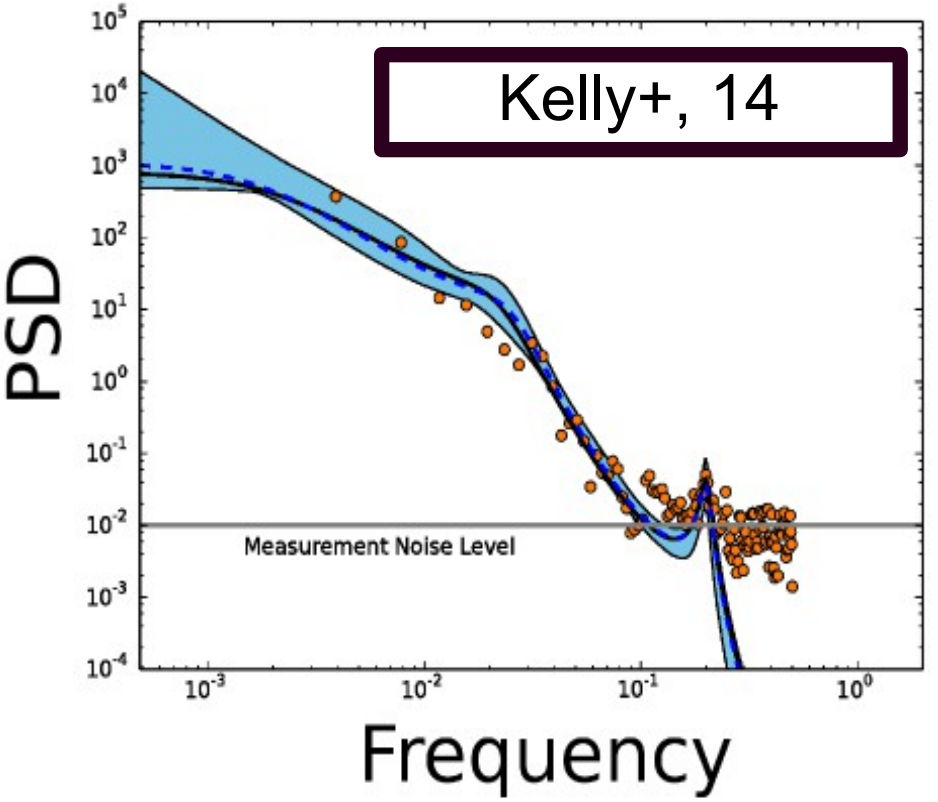
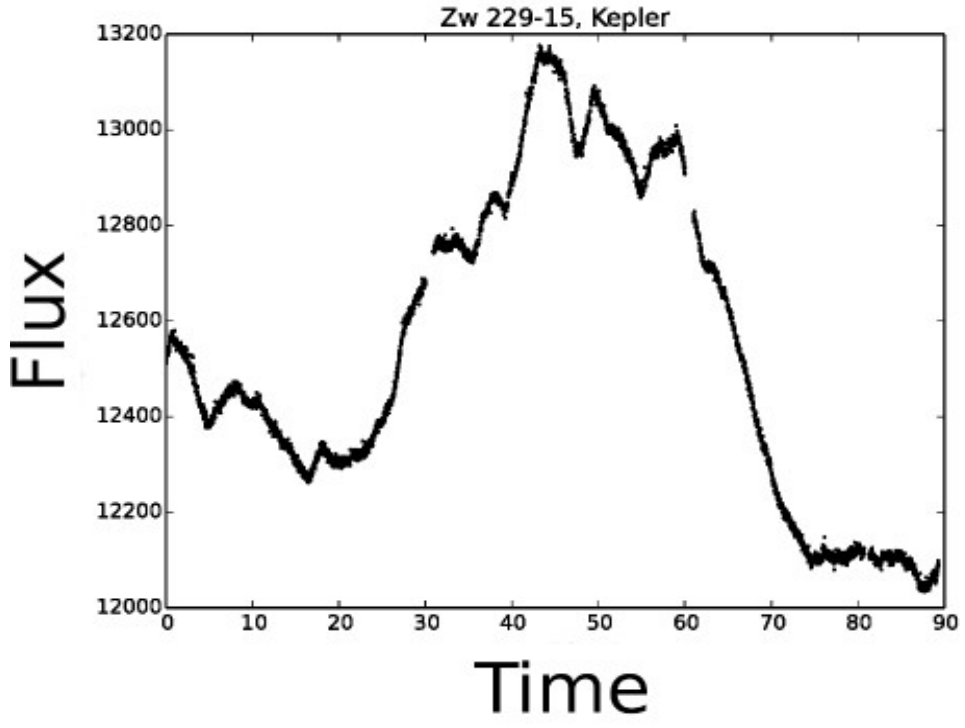
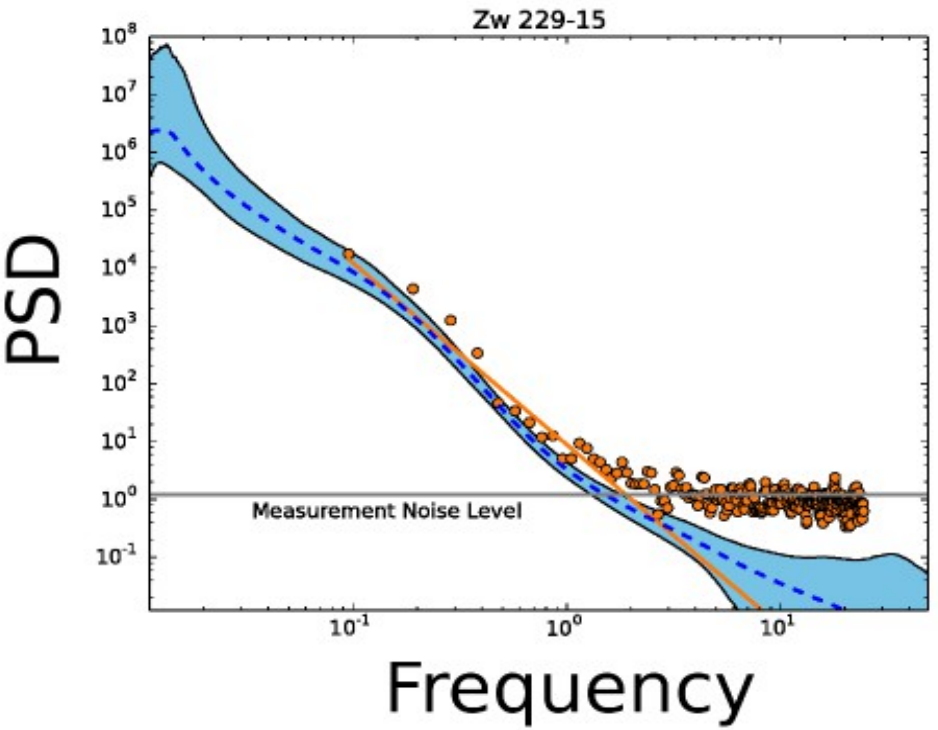

PSD∝f^0
PSD∝f^{-1}
PSD∝f^{-2}
PSD∝f^{-3}
Magnitude
Time units
19.6
19.4
19.2
19.0
18.8
18.6
18.4
0
5000
10000
15000
20000

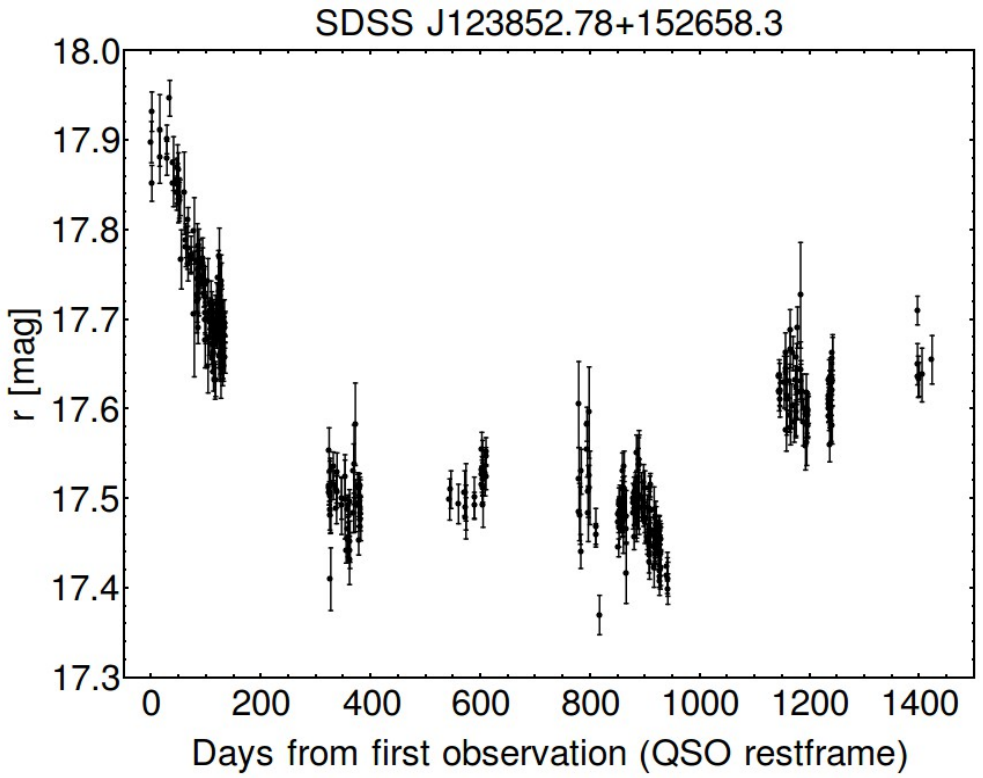

PSD∝f^0
PSD∝f^{-1}
PSD∝f^{-2}
PSD∝f^{-3}
Magnitude
19.6
19.4
19.2
19.0
18.8
18.6
18.4
0
200
400
600
800
Time units (days)

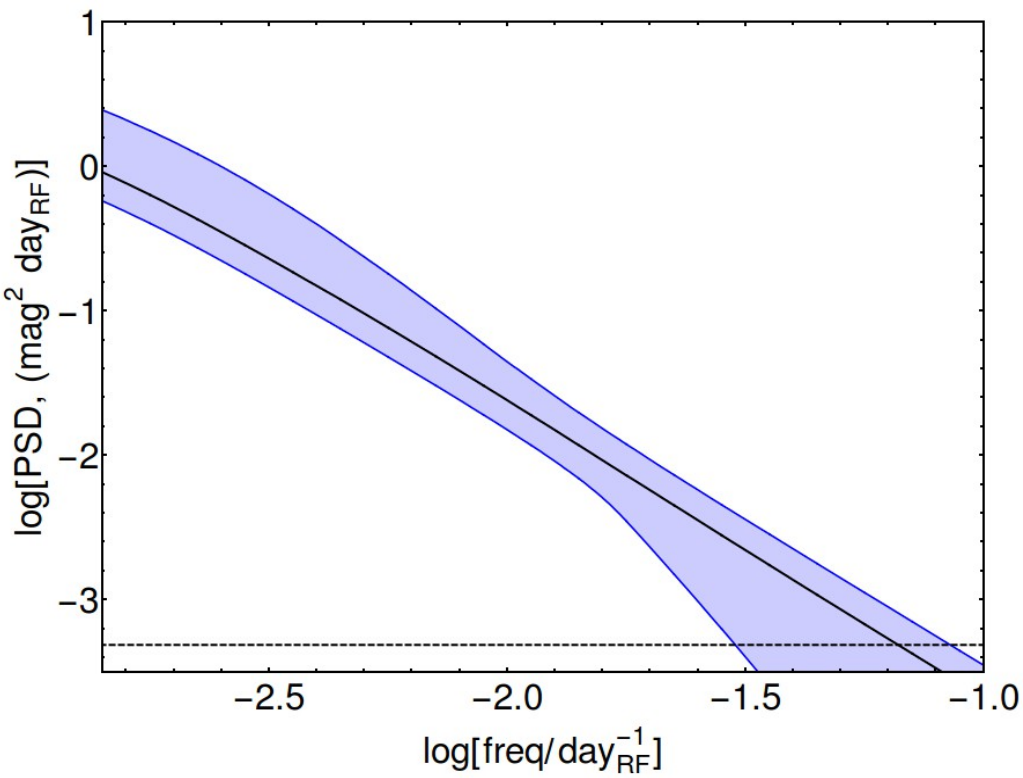

Flux
Time

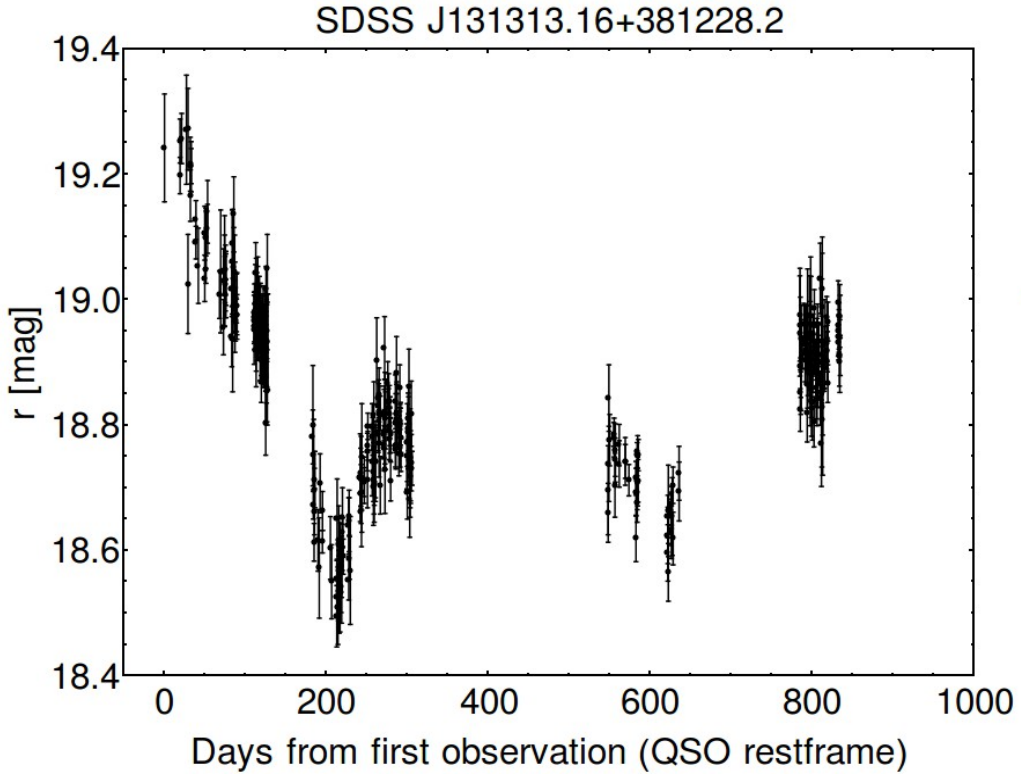

Kelly+, 14
PSD
Measurement Noise Level
Frequency

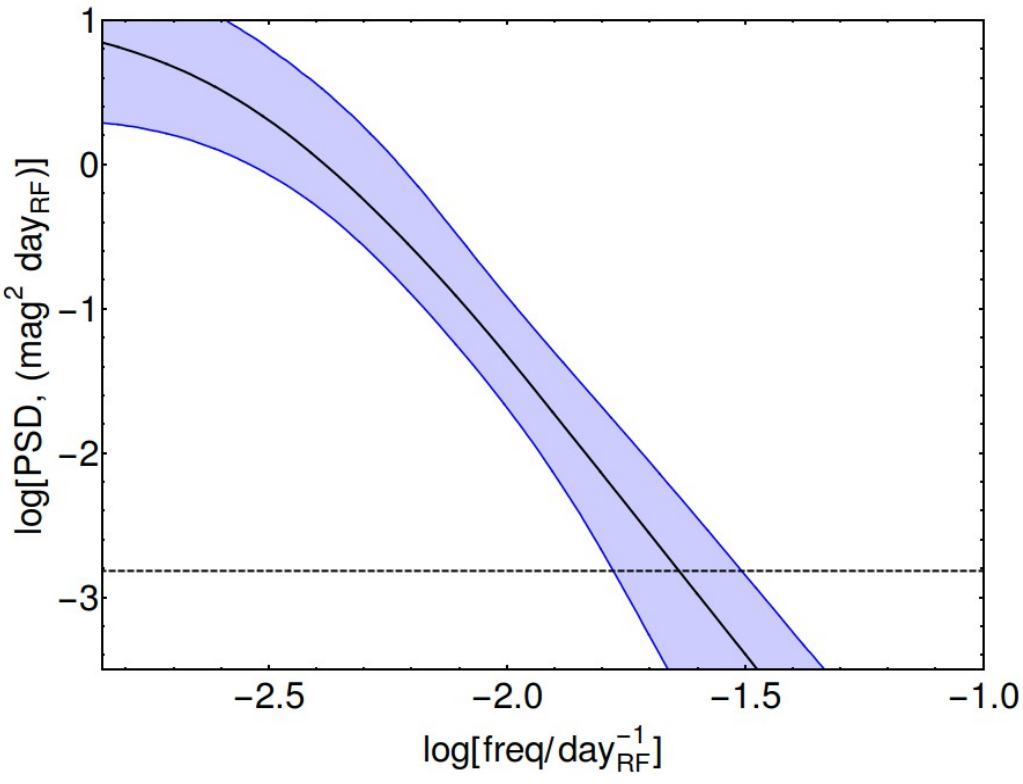

Zw 229-15, Kepler
Flux
Time


Zw 229-15
PSD
Measurement Noise Level
Frequency

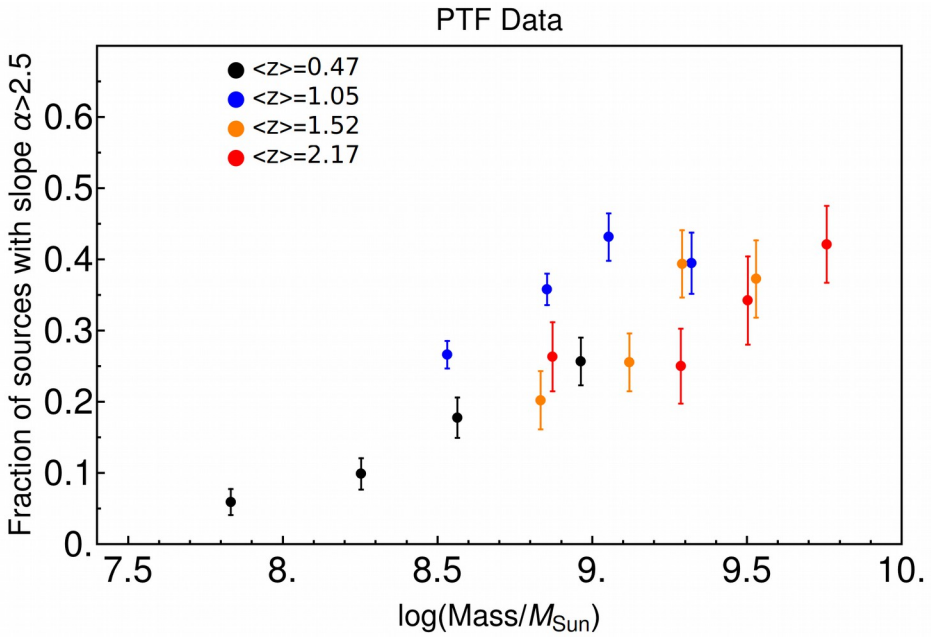

SDSS J123852.78+152658.3
r [mag]
Days from first observation (QSO restframe)

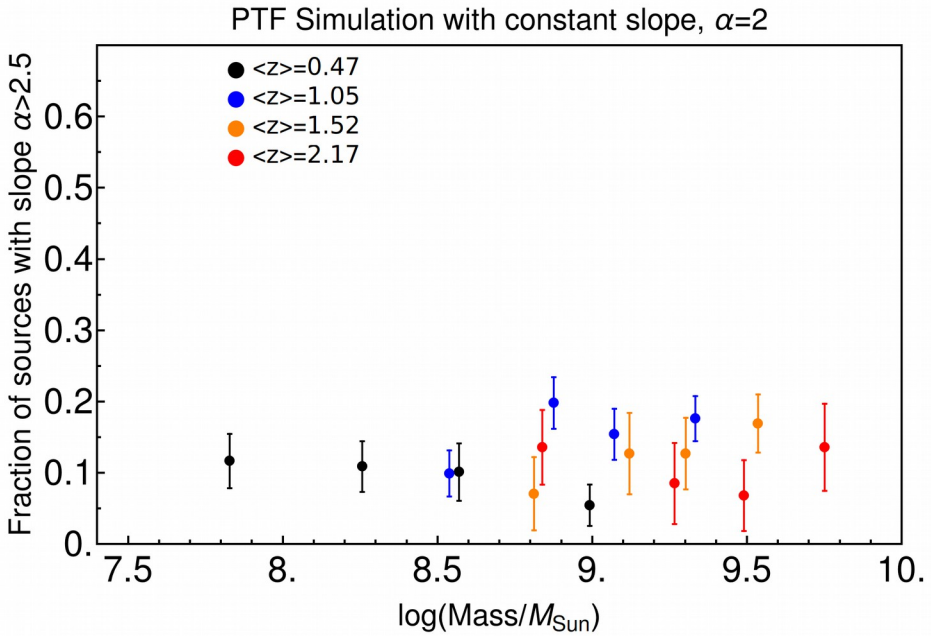

log[PSD, (mag^2 day$_{RF}$)]
log[freq/day$_{RF}^{-1}$]


SDSS J131313.16+381228.2
r [mag]
Days from first observation (QSO restframe)


log[PSD, (mag^2 day$_{RF}$)]
log[freq/day$_{RF}^{-1}$]

Variability properties change as a function of mass





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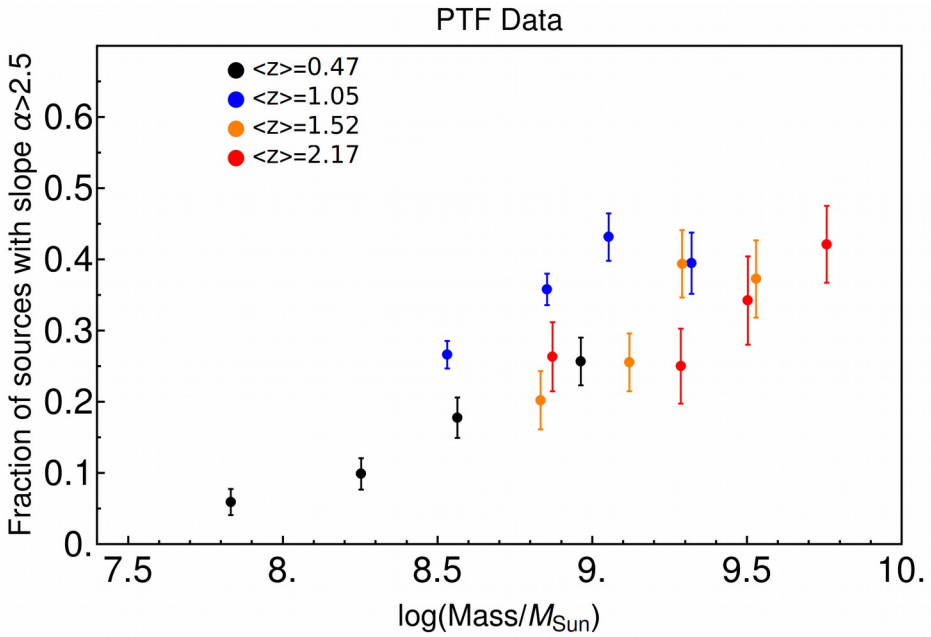
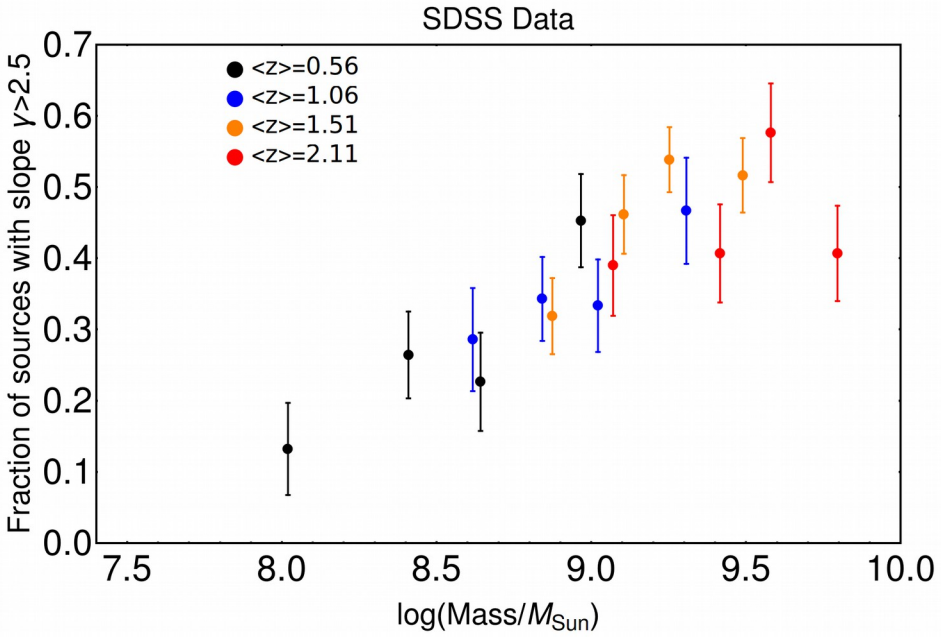
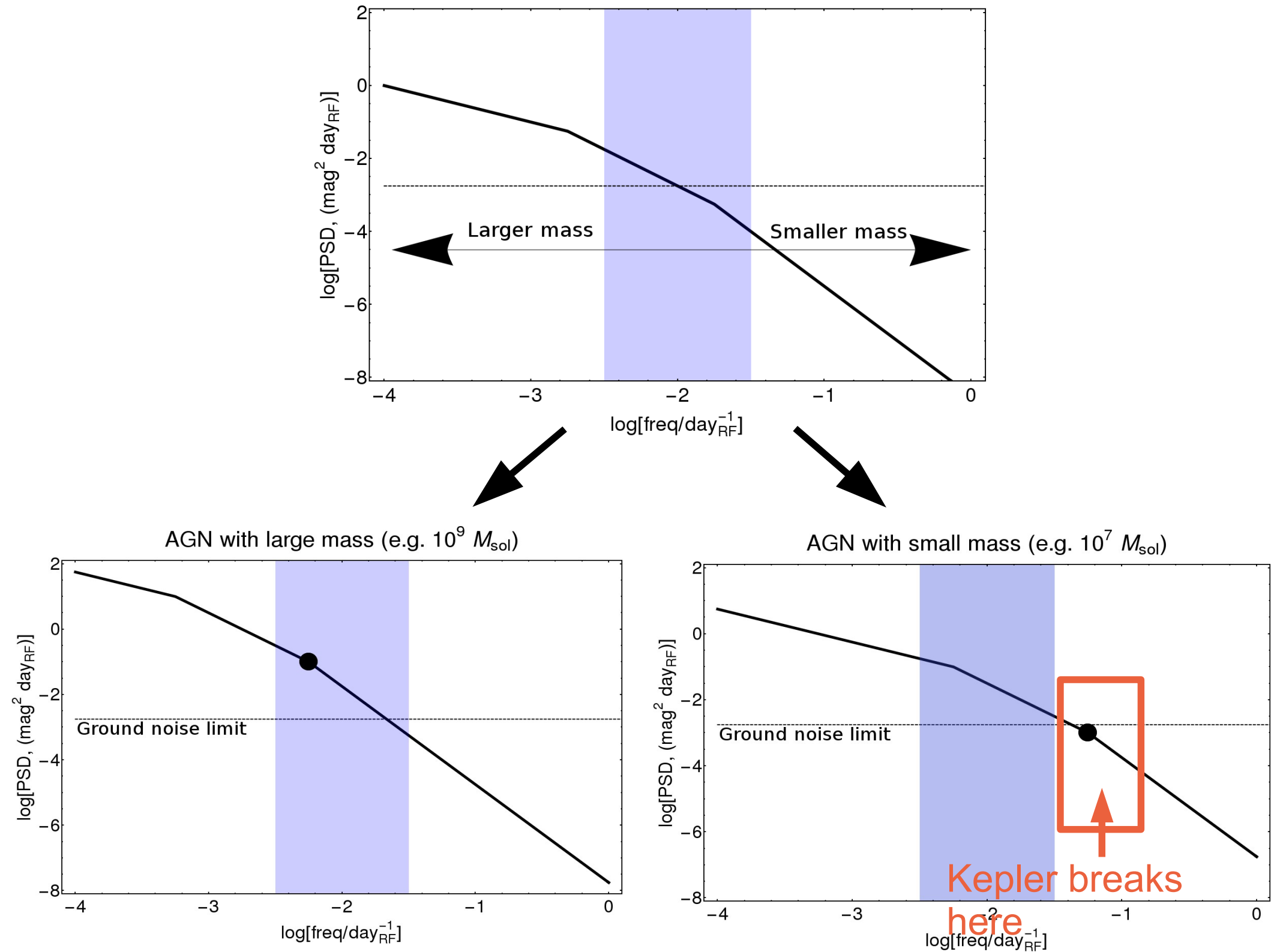
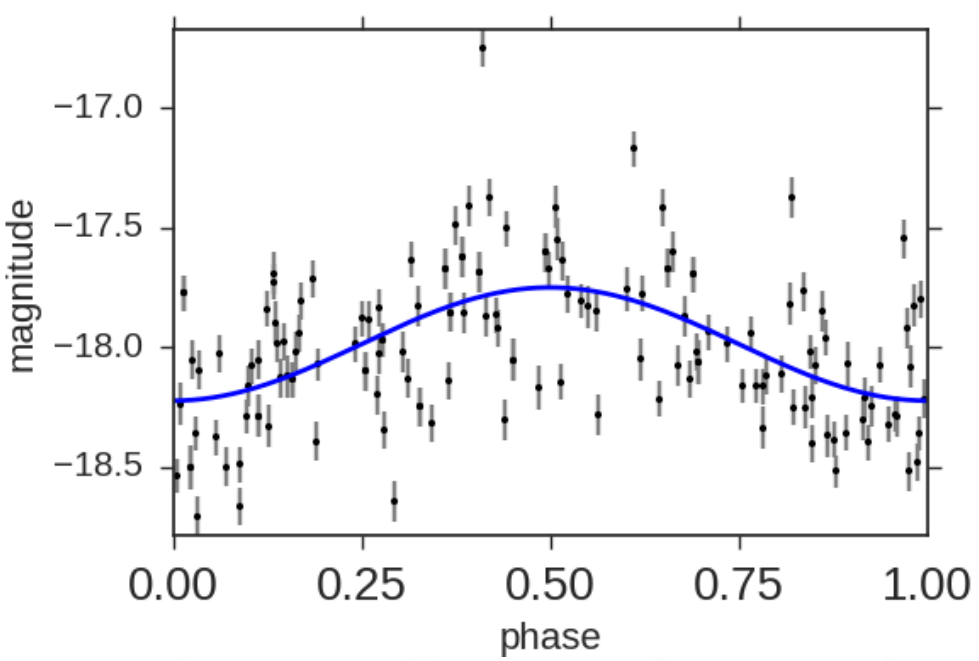


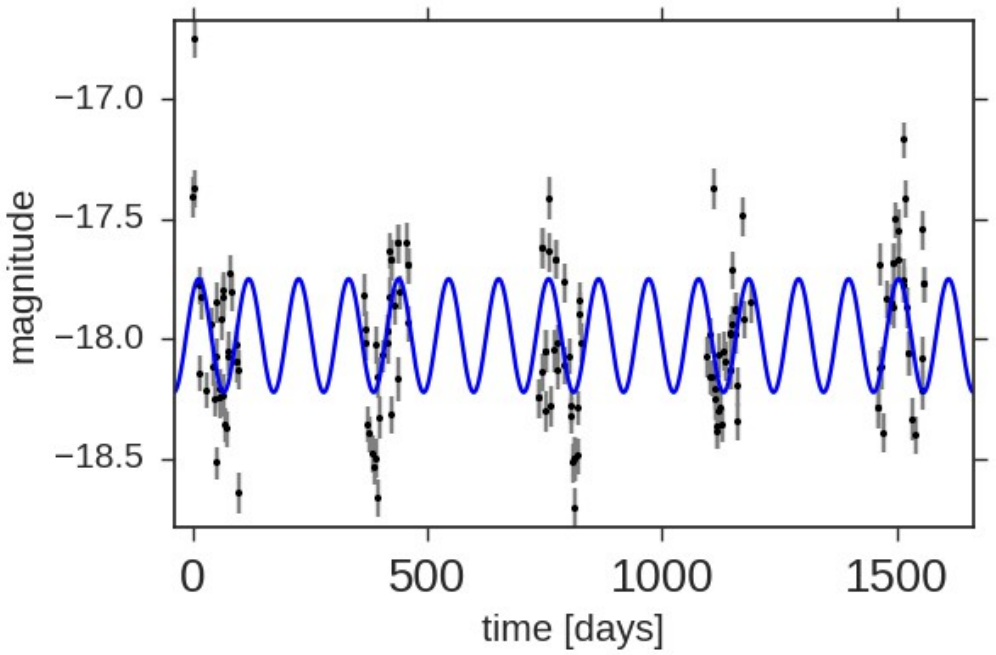


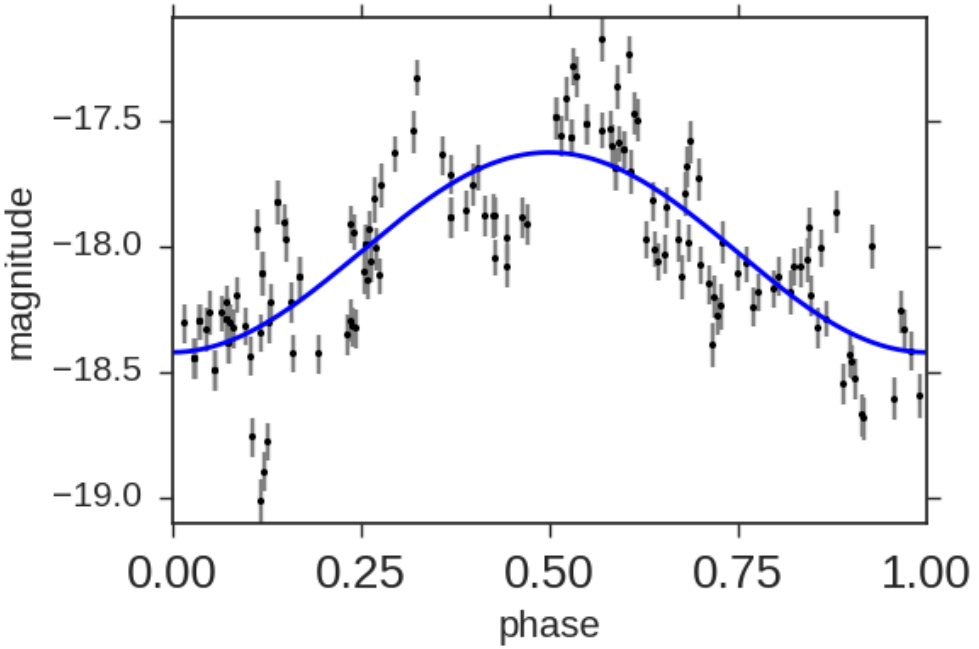
- More massive AGN tend to have steeper slopes i.e., tend to be more correlated
- Hinted at in Simm+ 2016, using COSMOS data
- Confirmed also in the K2 data (Smith+, 2018)
- Low mass AGN transition their variability at short time scale (days) – detectable with Kelpler
- Higher mass AGN transition their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

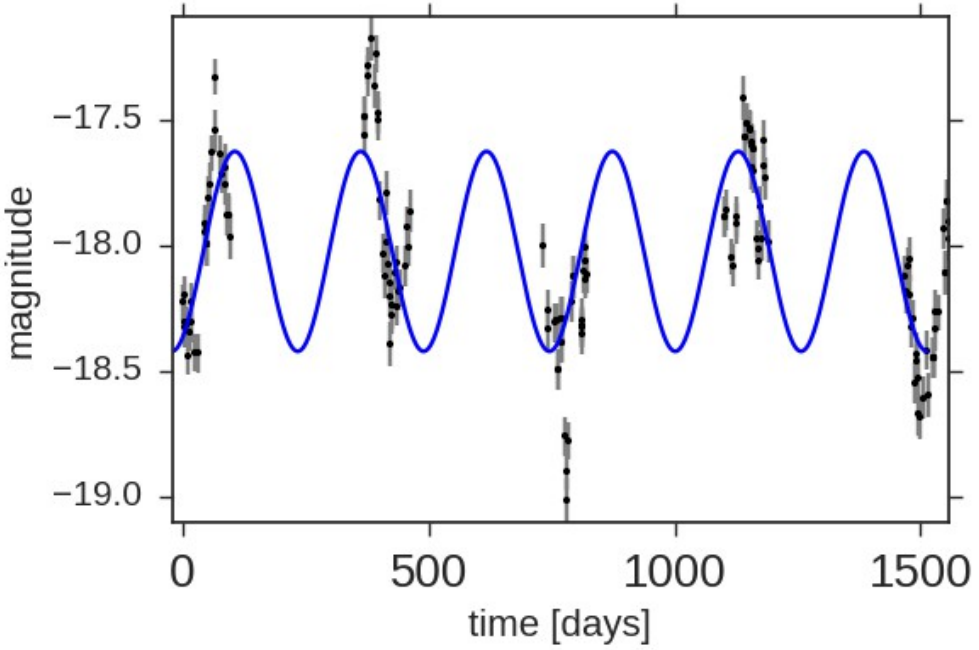

log[PSD, (mag^2 day$_{RF}$)]
log[freq/day$_{RF}^{-1}$]
Larger mass
Smaller mass
AGN with large mass (e.g. 10^9 M_{sol})
Ground noise limit
AGN with small mass (e.g. 10^7 M_{sol})
Kepler breaks here

I. Steeper PSD creates more false-positive AGN periods

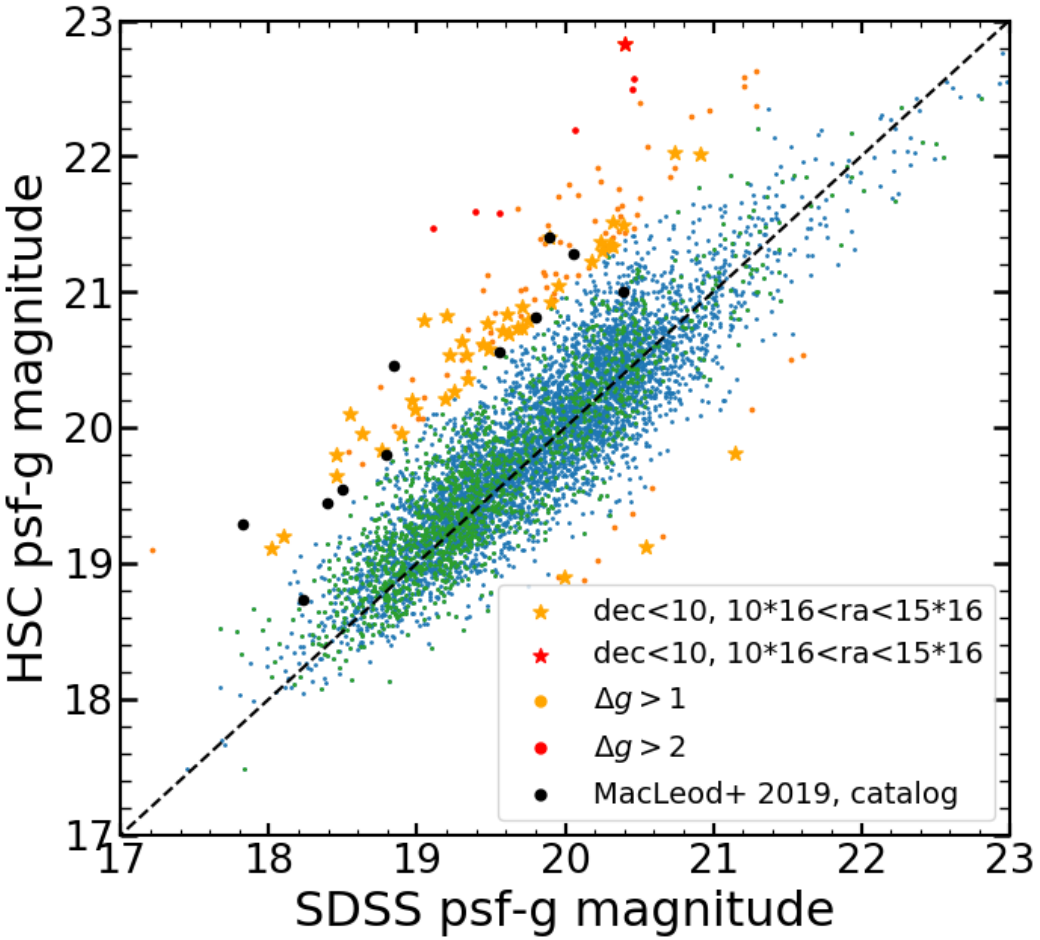


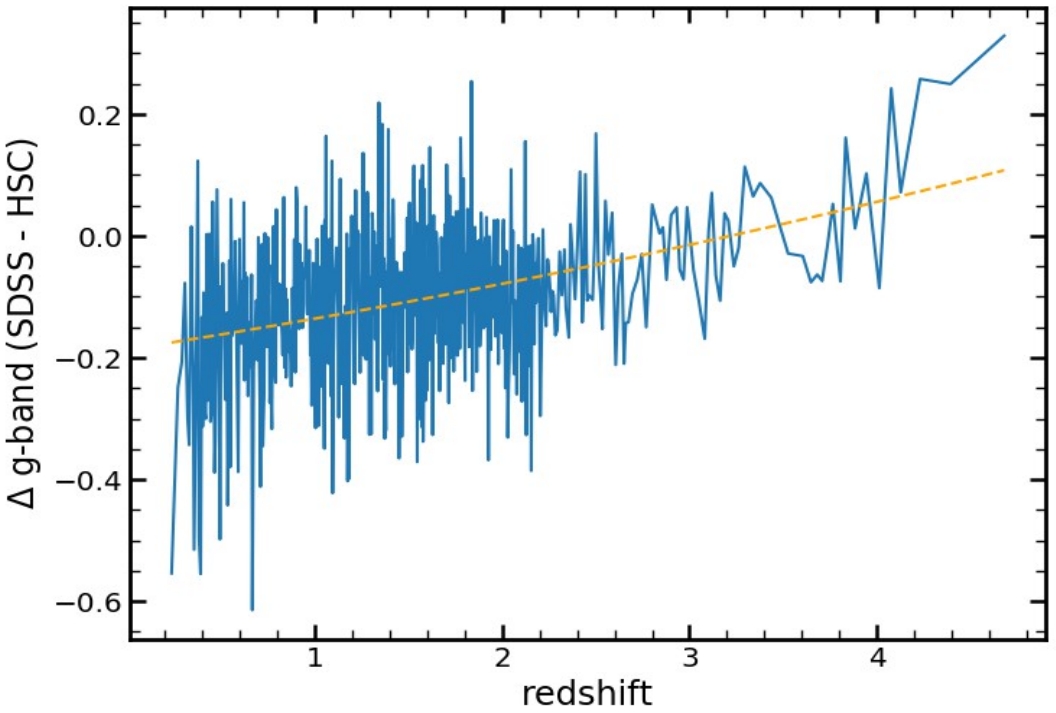






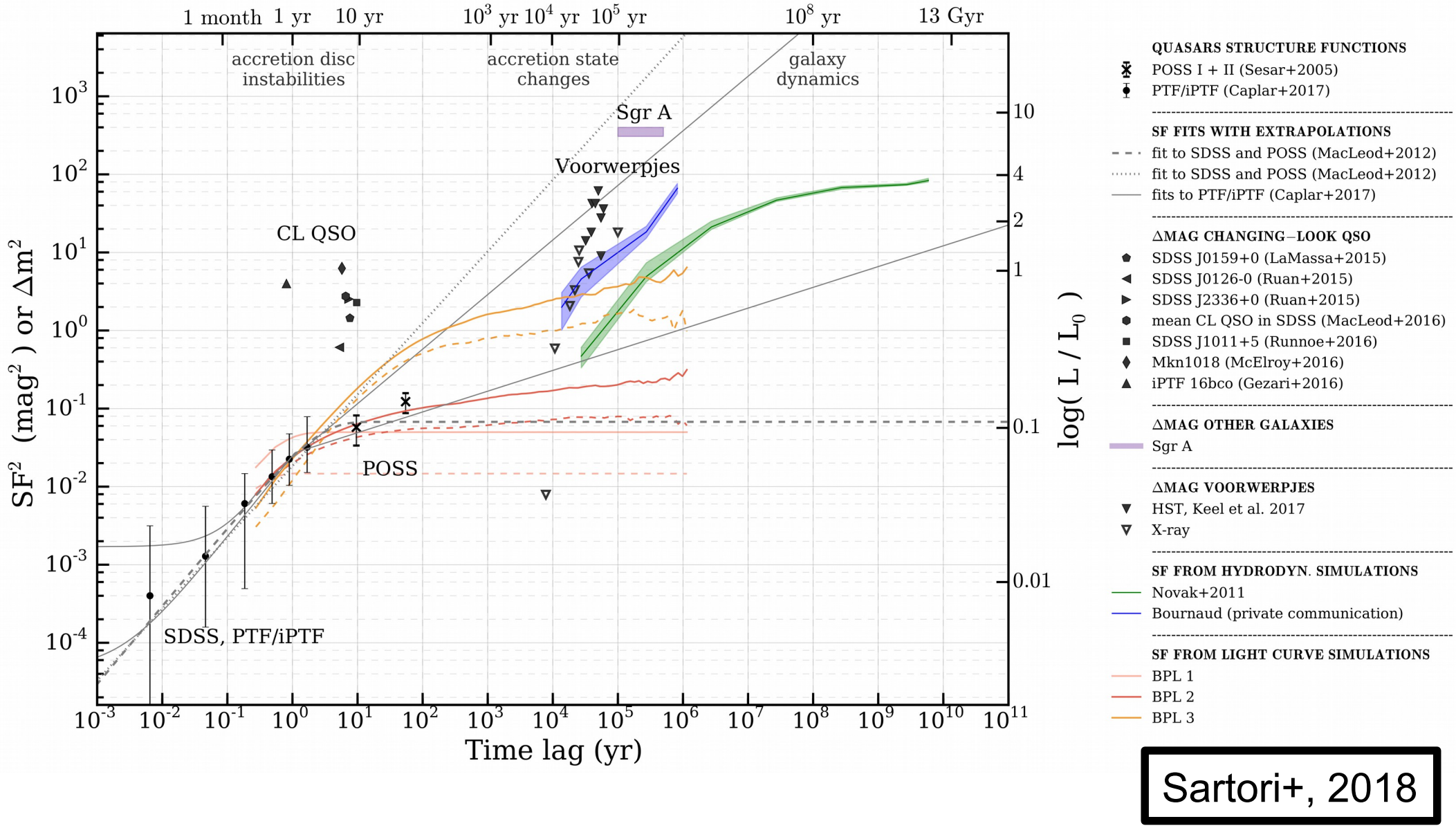
II. Hyper Suprime Cam





- Very large number of vary variable objects – calibration effects?!?
- Mean magnitude change has redshift dependence?!?
- COSMOS has a lot of exposures...

III. What are we looking at?



Sartori+, 2018

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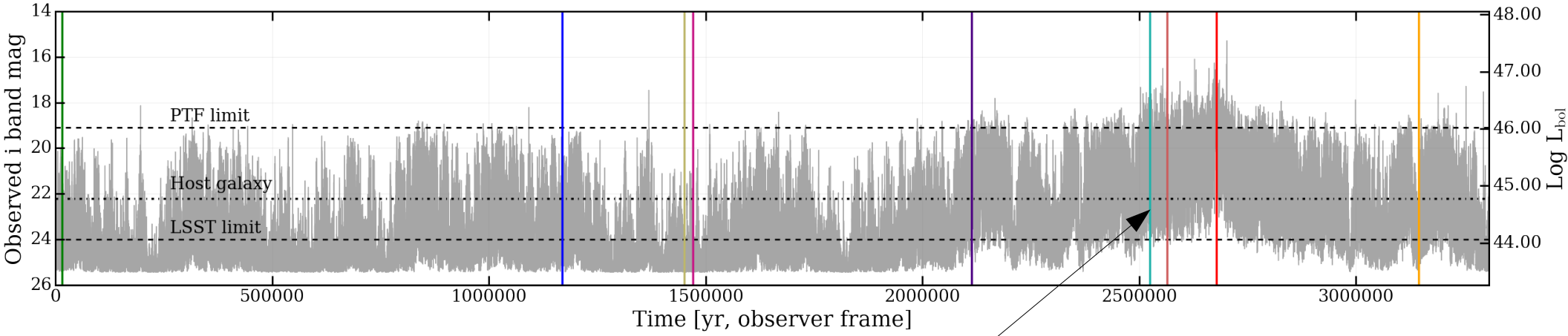
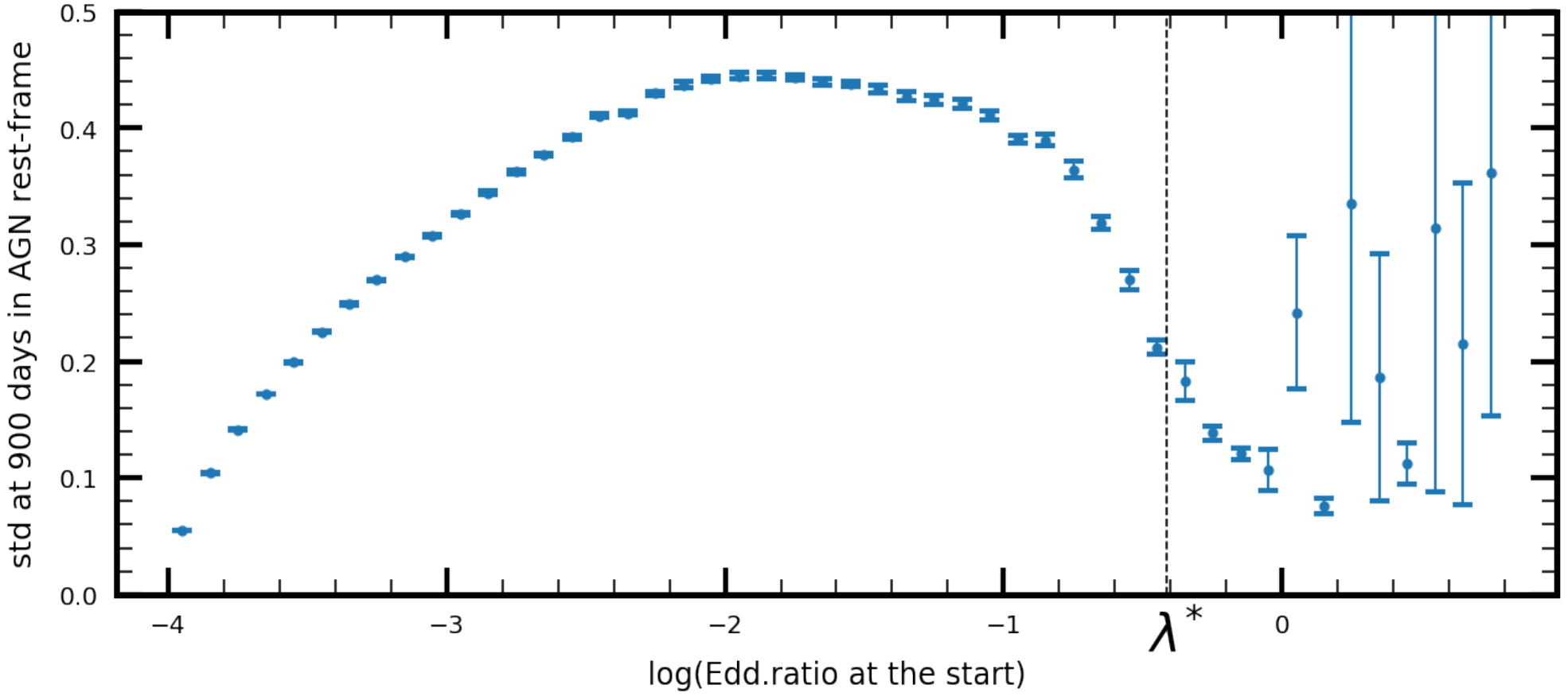


Sartori+, submitted

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

III. What are we looking at?



- Satisfies cosmological Edd. Ratio distribution – creates observable effects?!?

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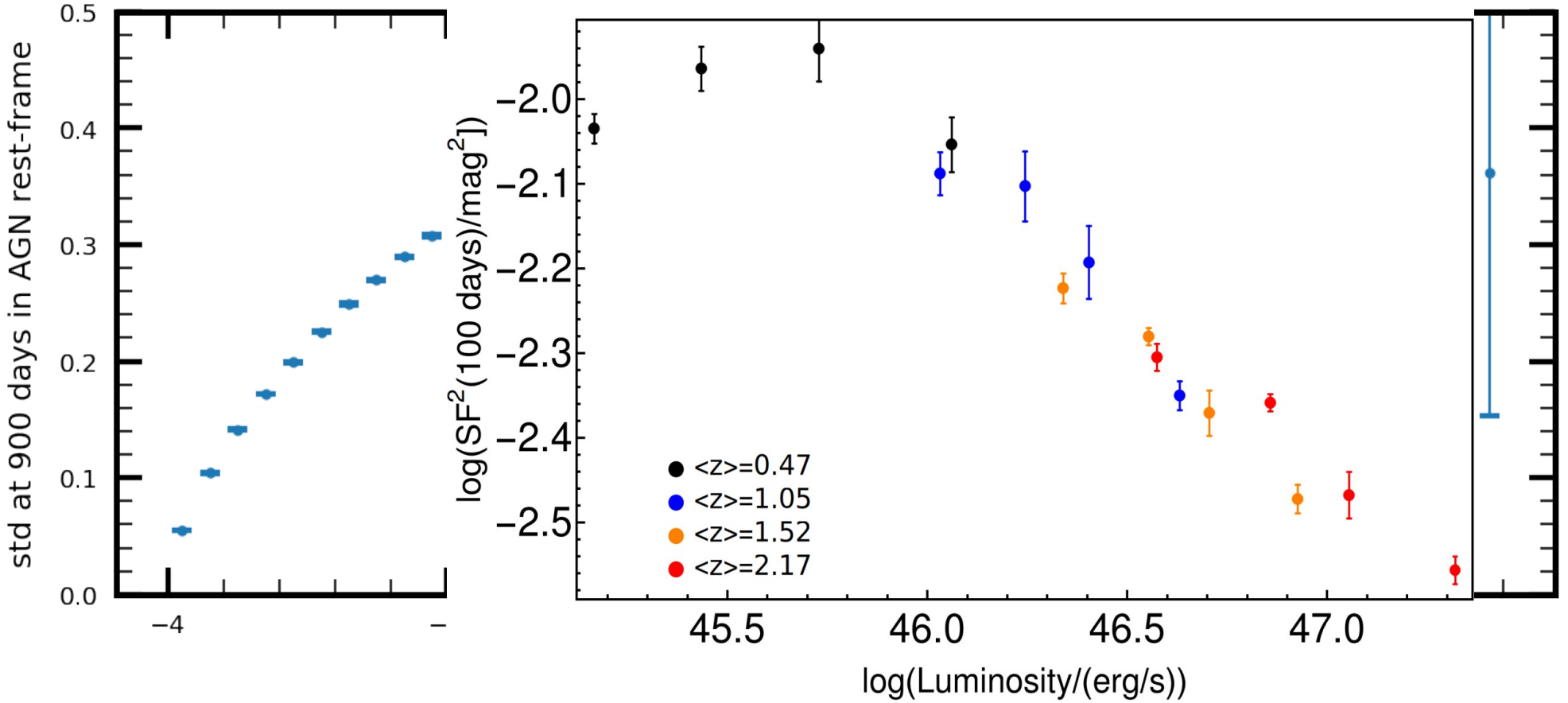
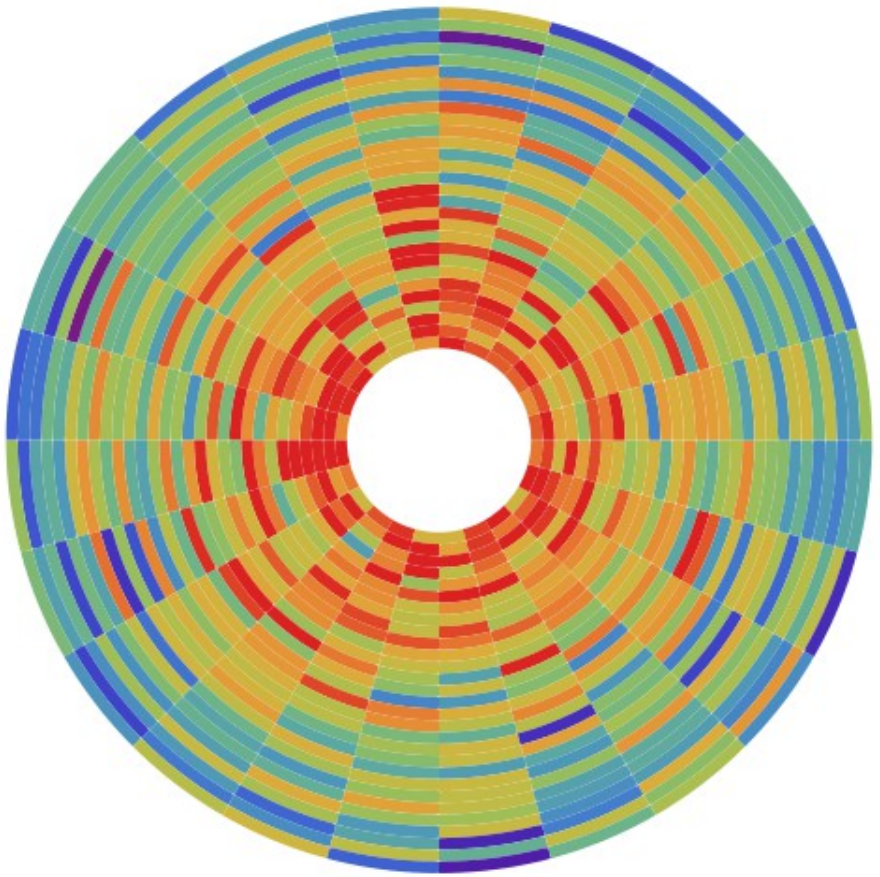
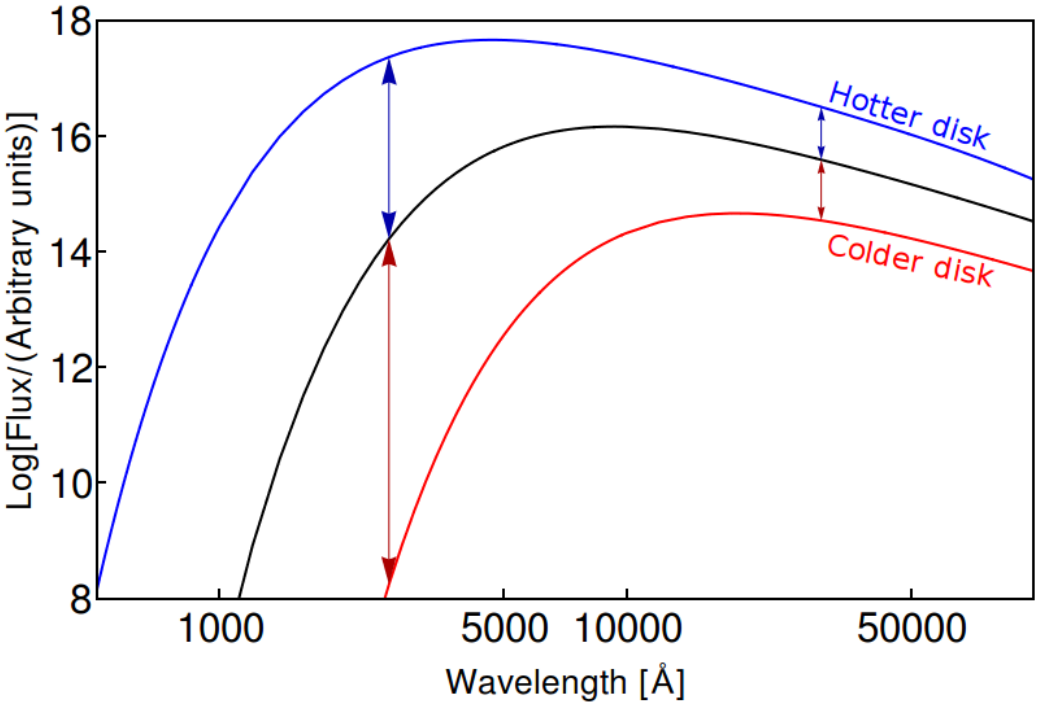


- Satisfies cosmological Edd. Ratio distribution – creates observable effects?!?

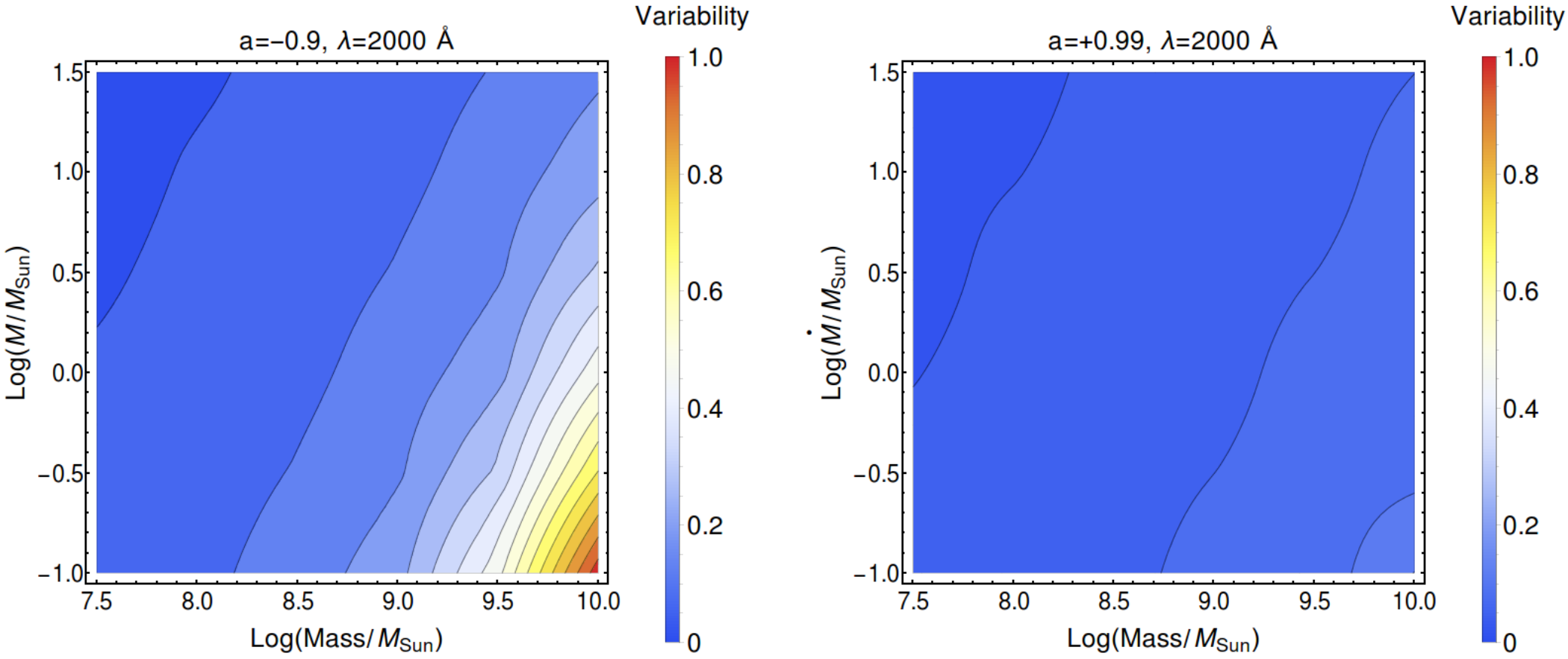
IV. Constrain spin from variability?





- 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)

IV. Constrain spin from variability?



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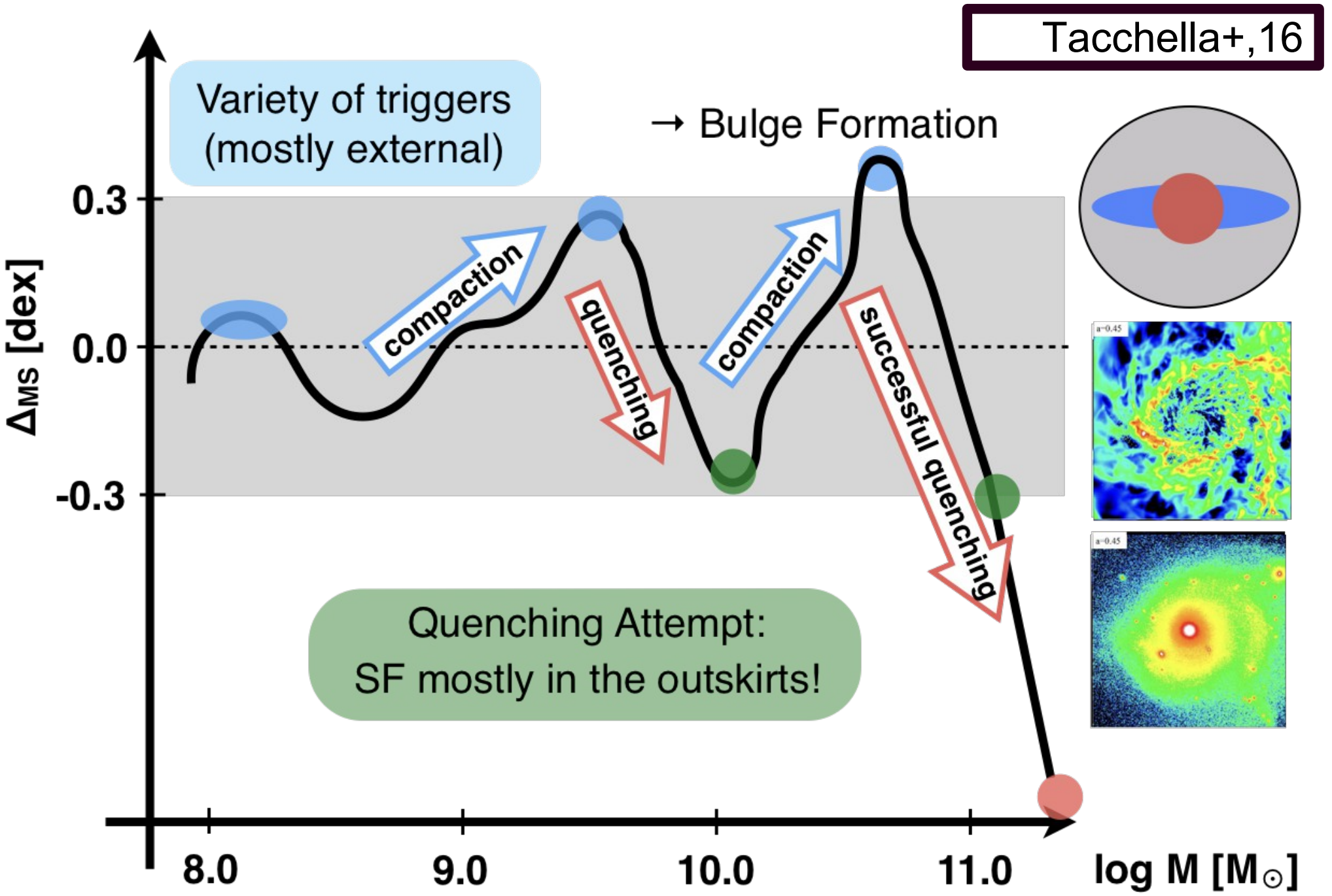
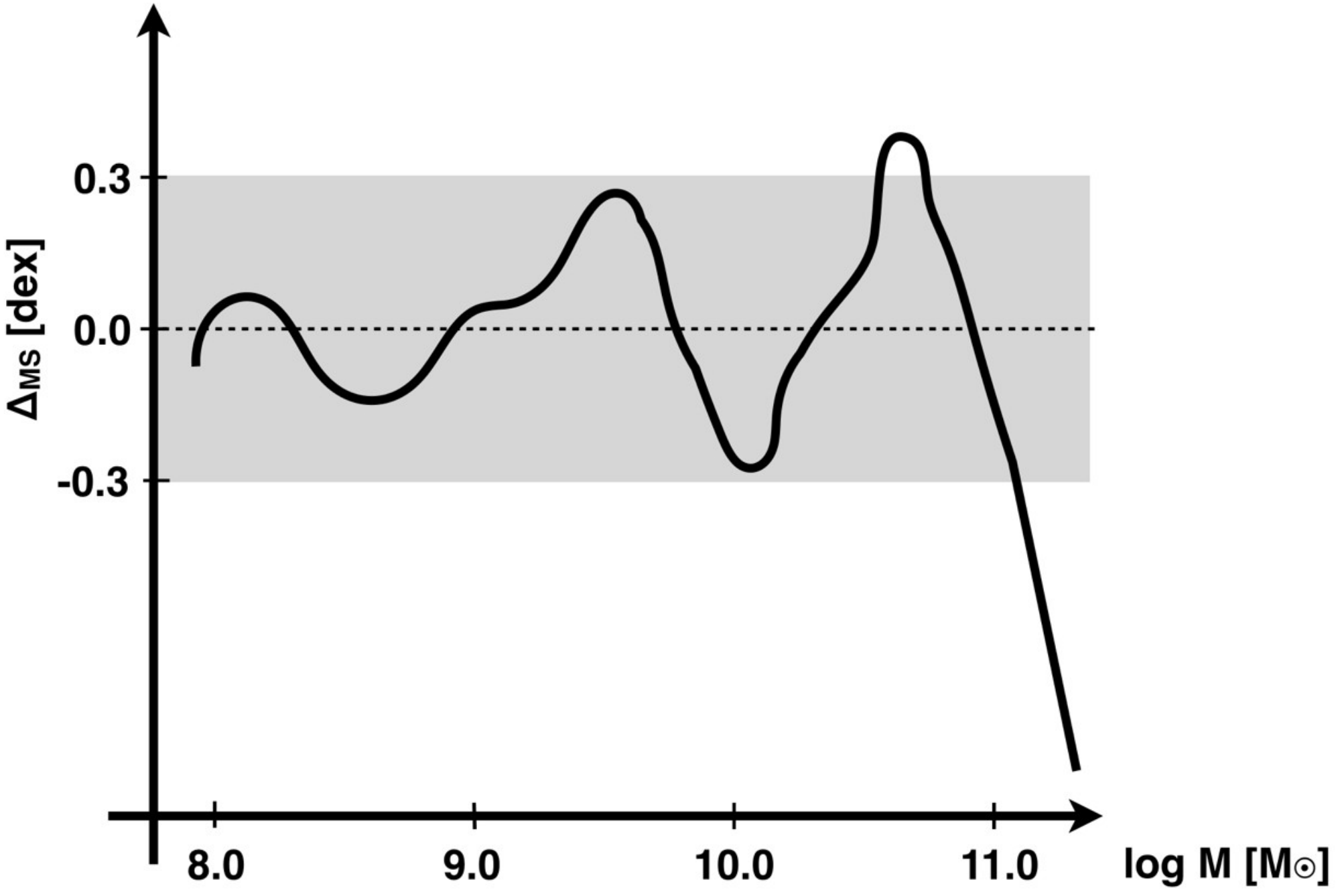
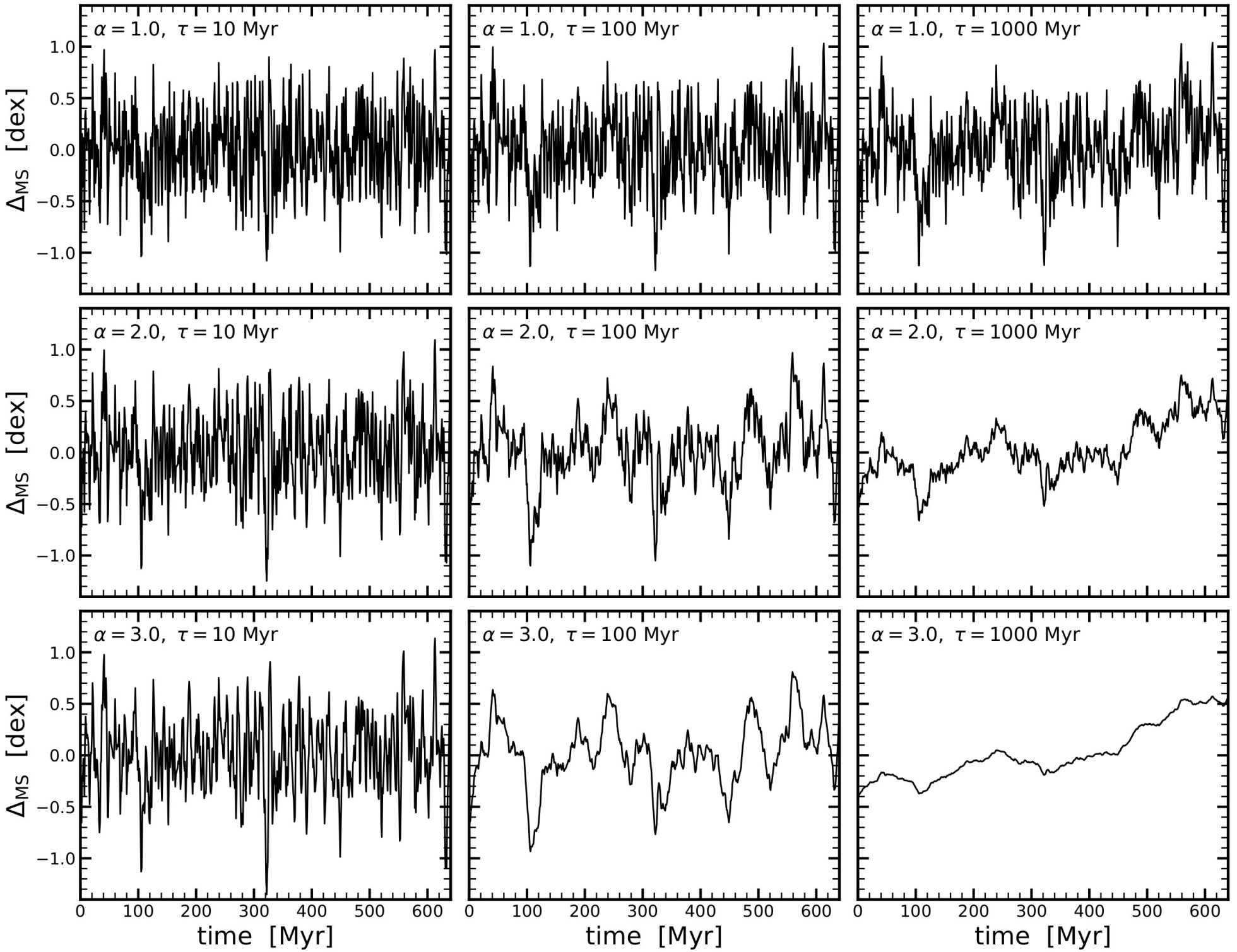
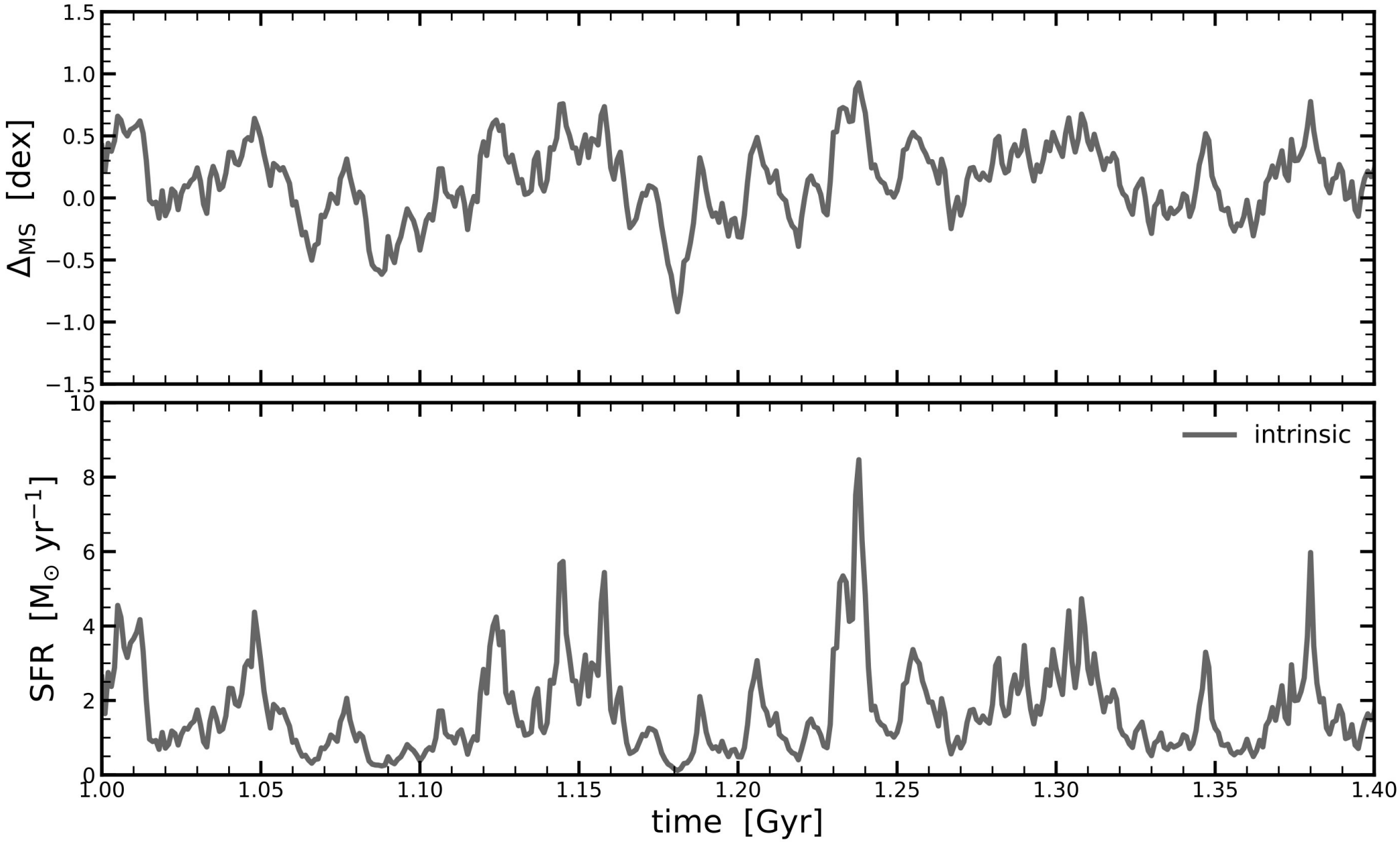
Confinement of star-forming galaxies

Tacchella+,16

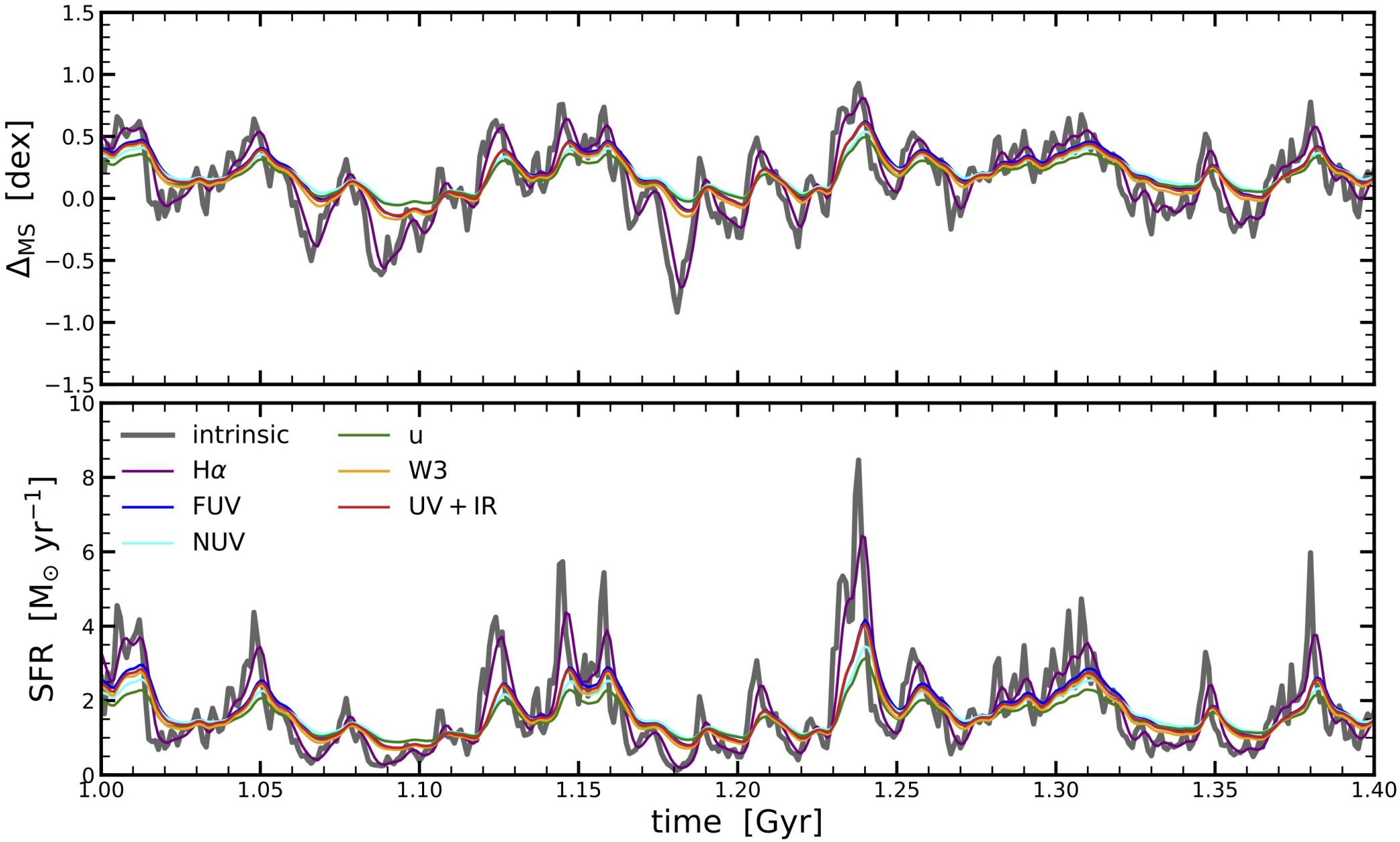



0.3
0.0
-0.3
Δ_{MS} [dex]
8.0
9.0
10.0
11.0
log M [M⊙]


α = 1.0, τ = 10 Myr
α = 1.0, τ = 100 Myr
α = 1.0, τ = 1000 Myr
α = 2.0, τ = 10 Myr
α = 2.0, τ = 100 Myr
α = 2.0, τ = 1000 Myr
α = 3.0, τ = 10 Myr
α = 3.0, τ = 100 Myr
α = 3.0, τ = 1000 Myr
Δ_MS [dex]
time [Myr]
1.0
0.5
0.0
−0.5
−1.0
0
100
200
300
400
500
600



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



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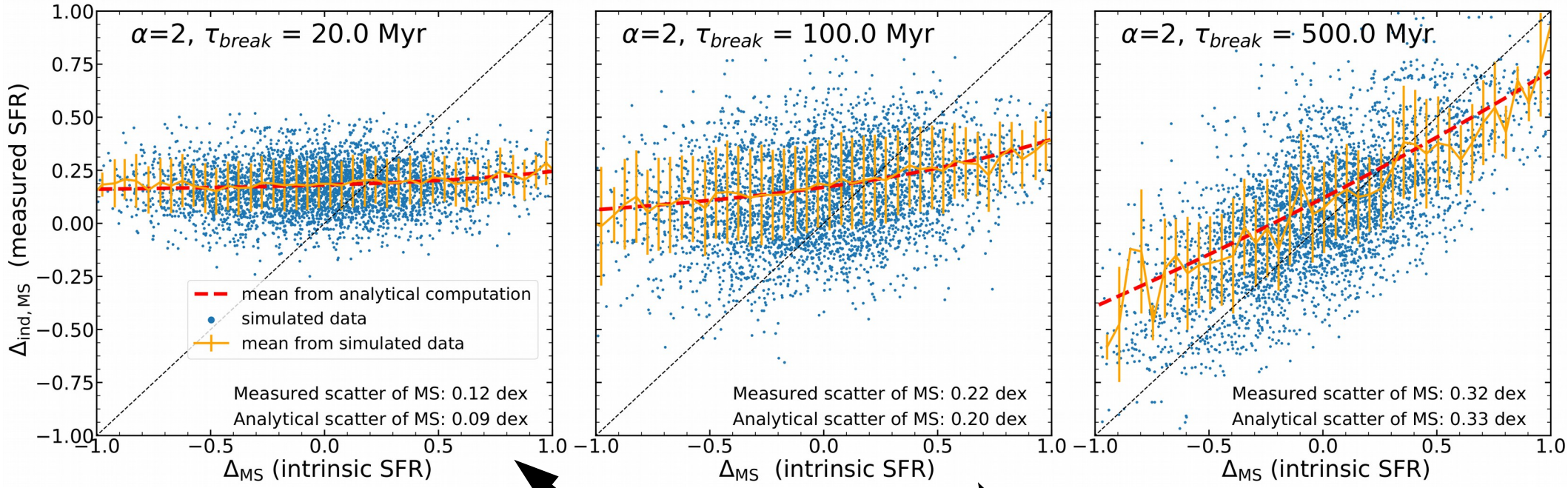
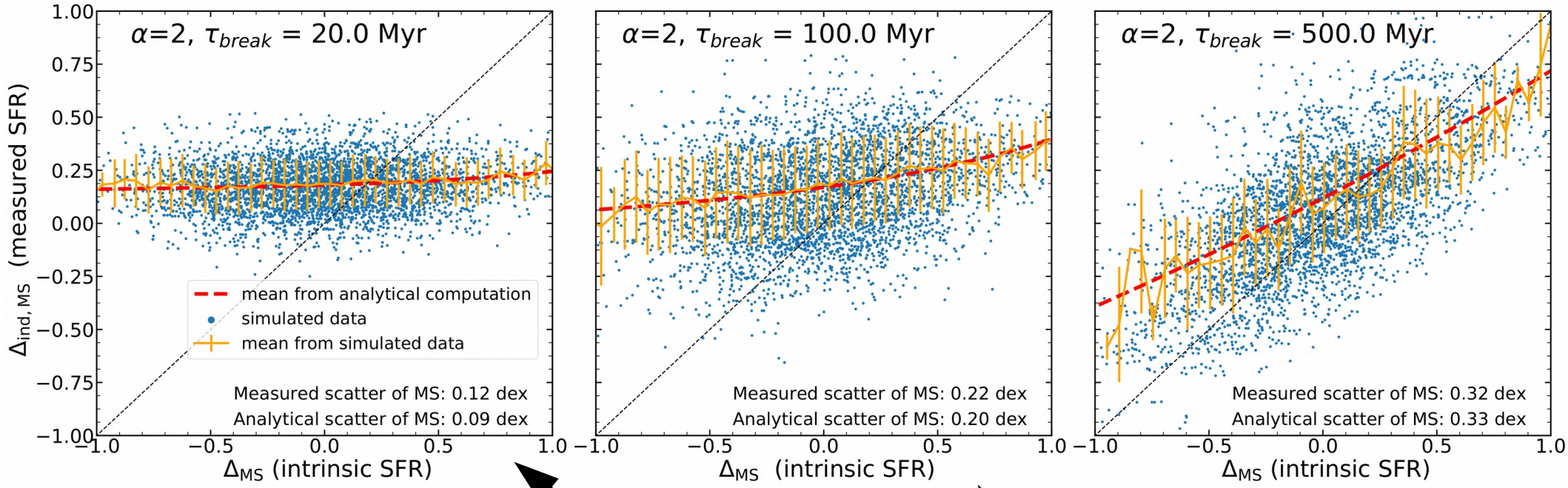
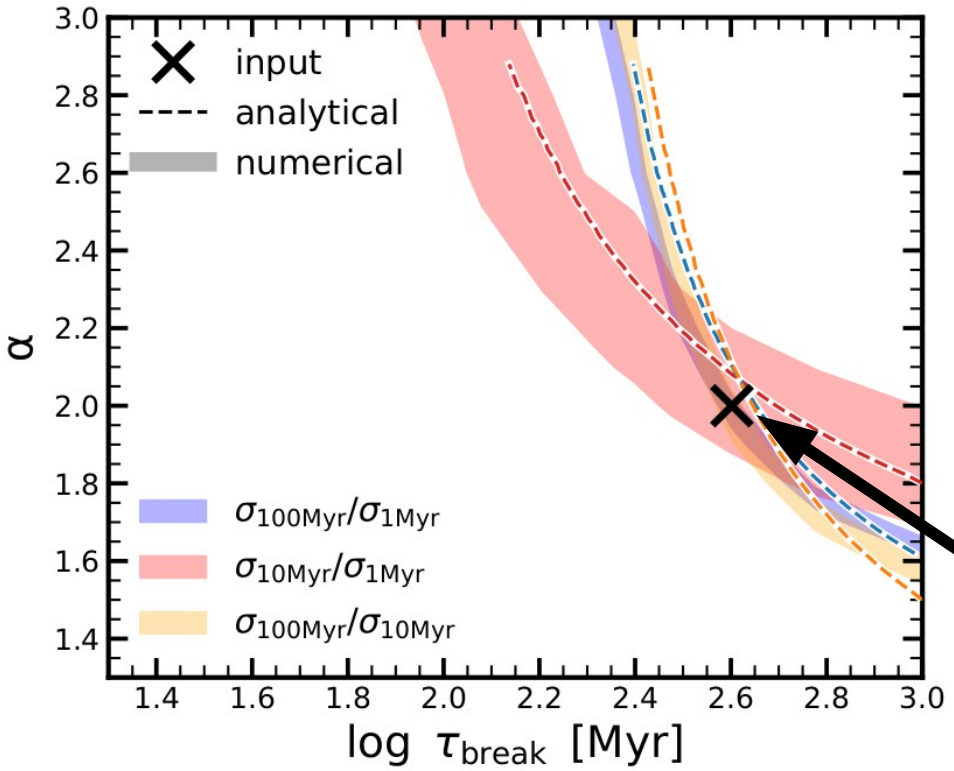


Example:

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





Example:

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

We can recover input values given multiple indicators

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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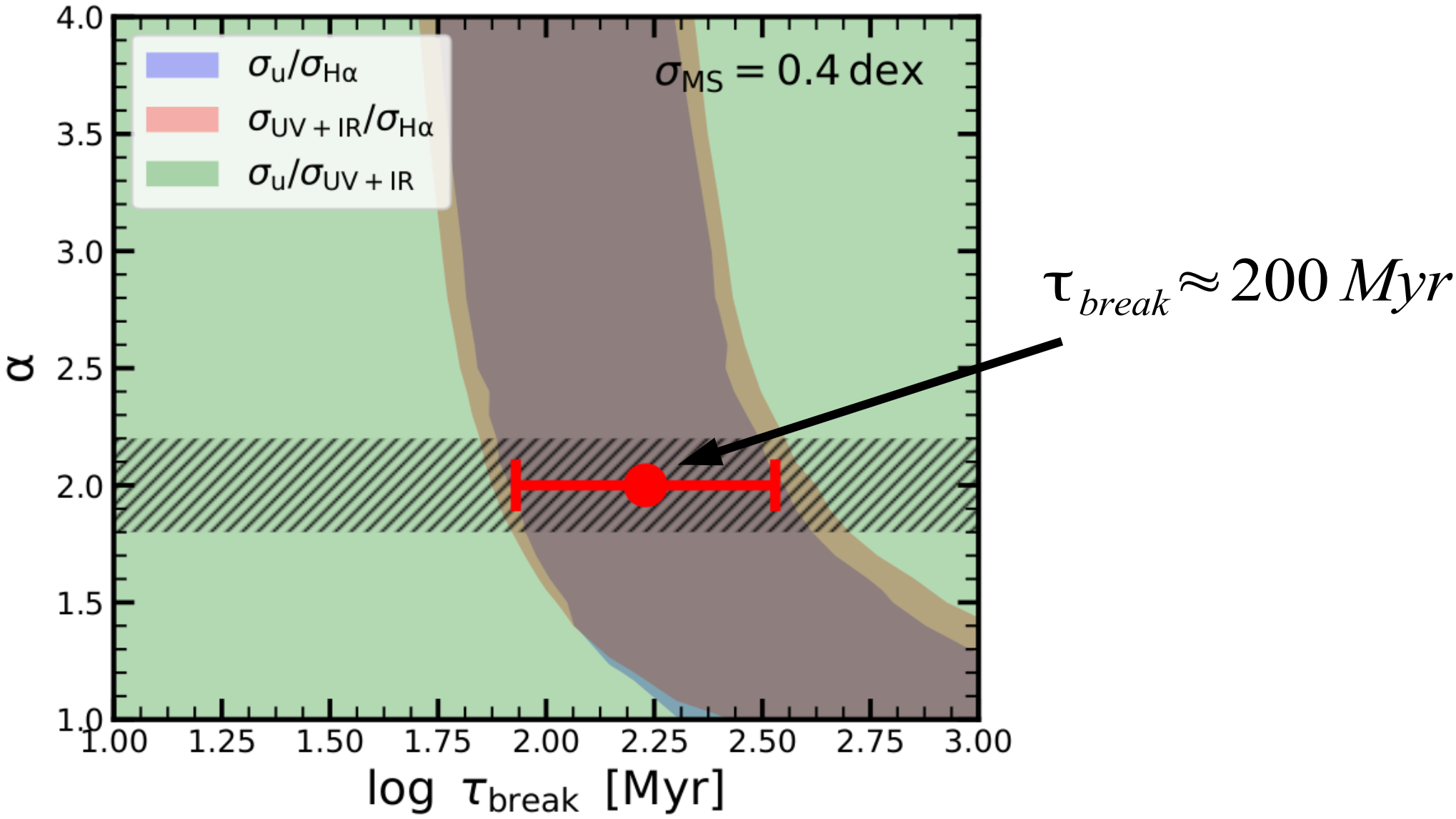


https://github.com/nevencaplar/Main-Sequence-Variability

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 avaliable 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 (invserse frequncy of the break in the PSD), slope (high frequency slope of the PSD) and time.
Avaliable 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.]
Avaliable 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 avaliable time is [Myr]: 1000.0
```

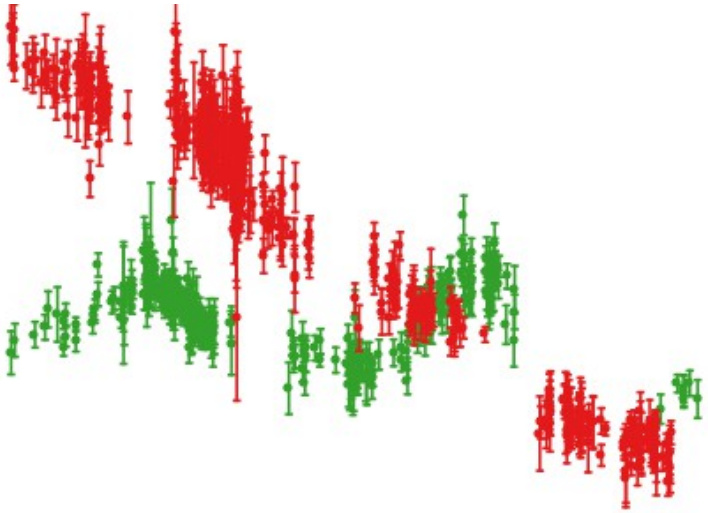
1 Some theoretical plots to get started

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.) [...]

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 τ∝$L^{0.5}$, 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?
- 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