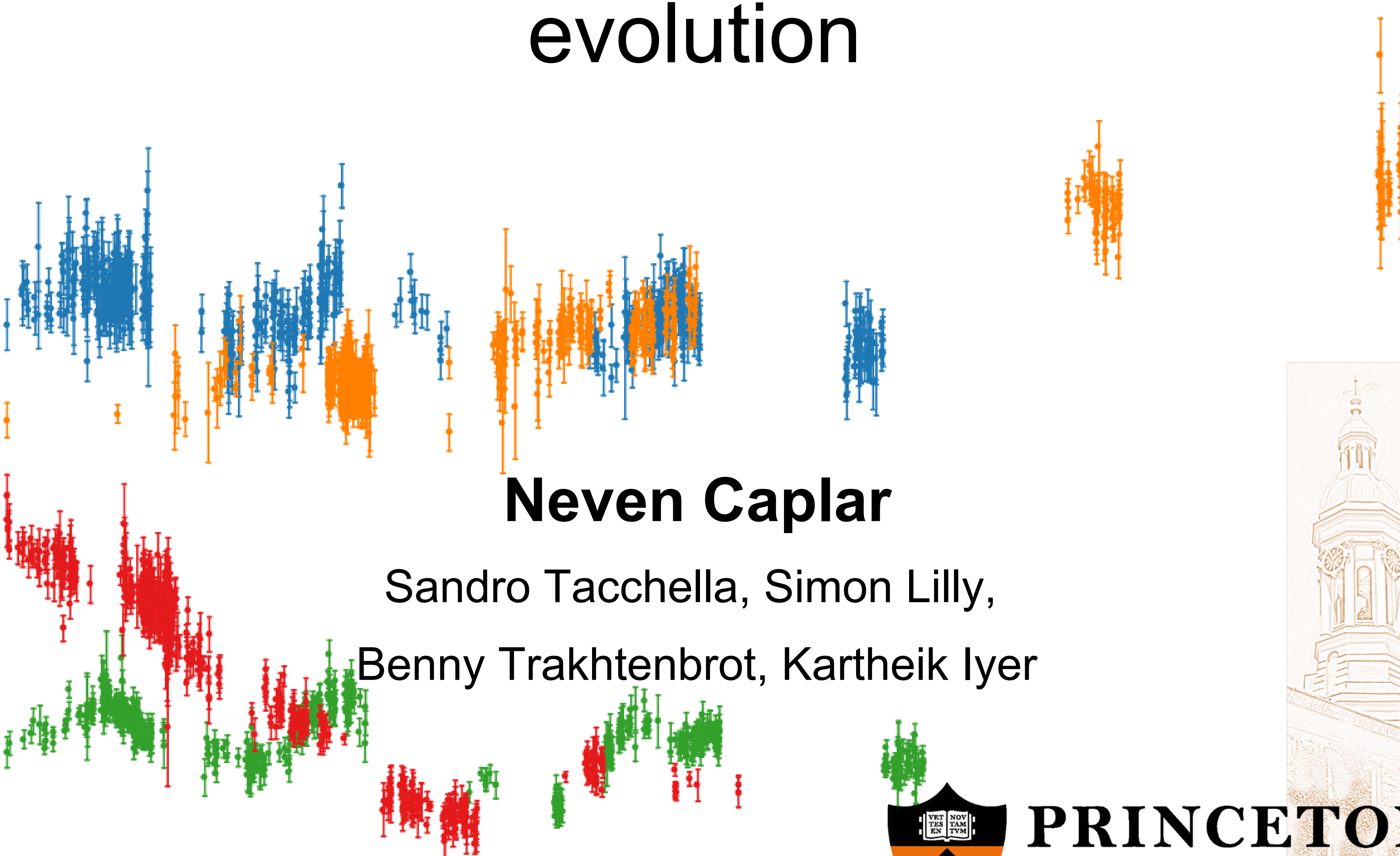
Stochastic view of AGN and galaxy evolution



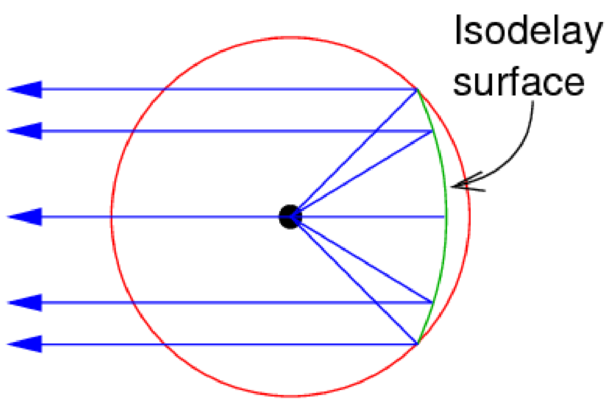
Neven Caplar

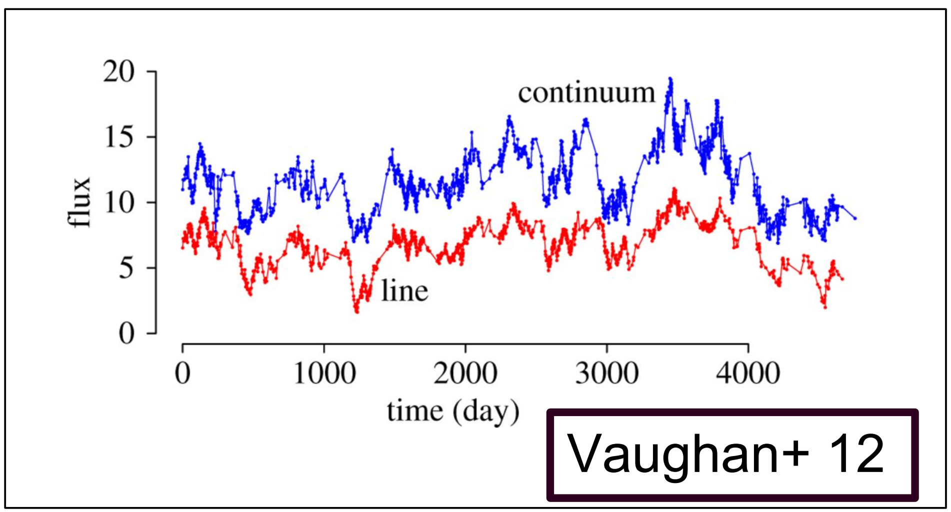
Sandro Tacchella, Simon Lilly,

Benny Trakhtenbrot, Kartheik Iyer

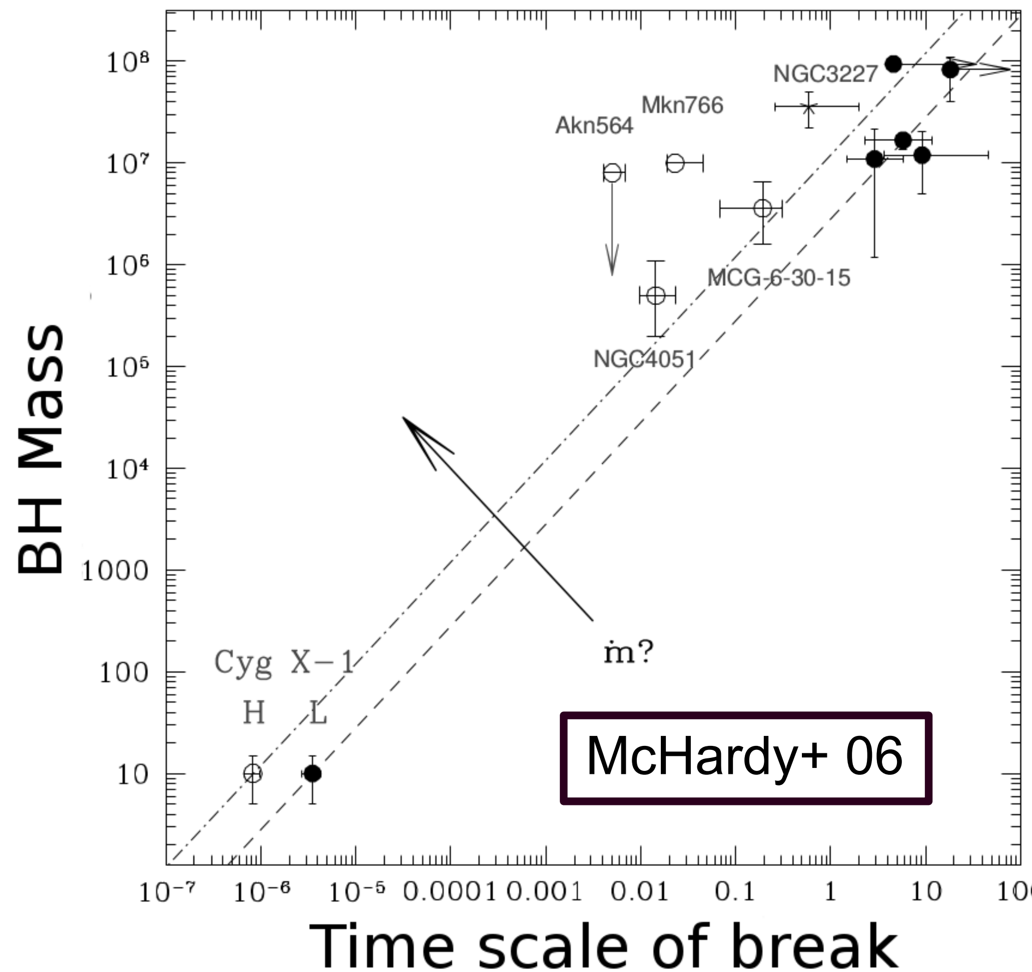
PRINCETON UNIVERSITY

Why quasar variability?

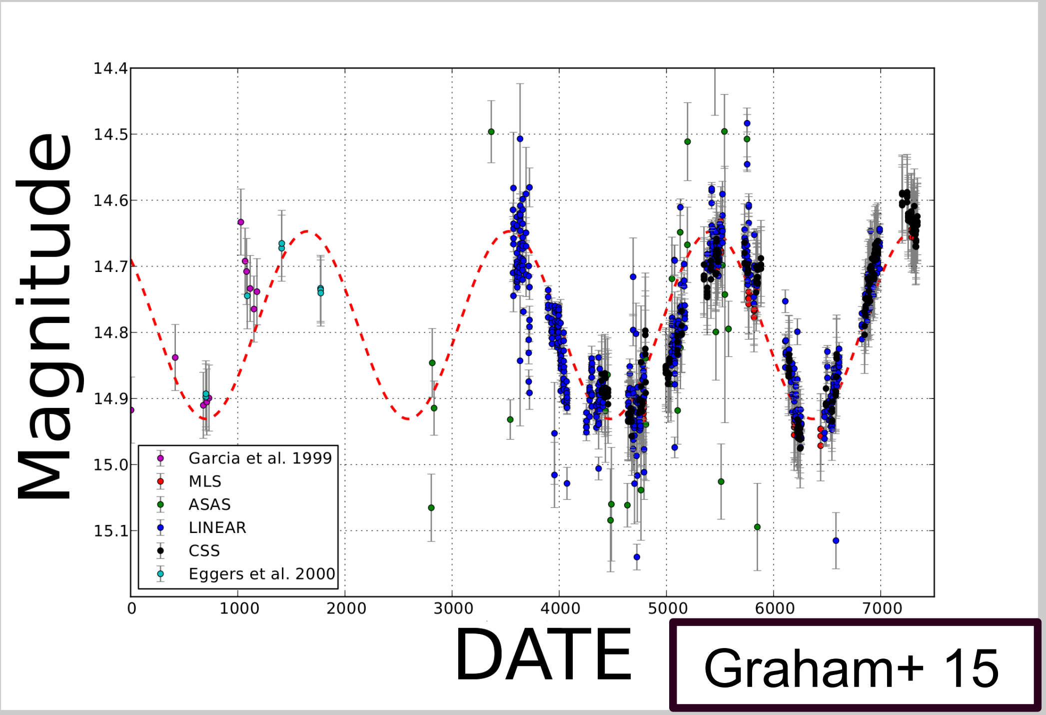




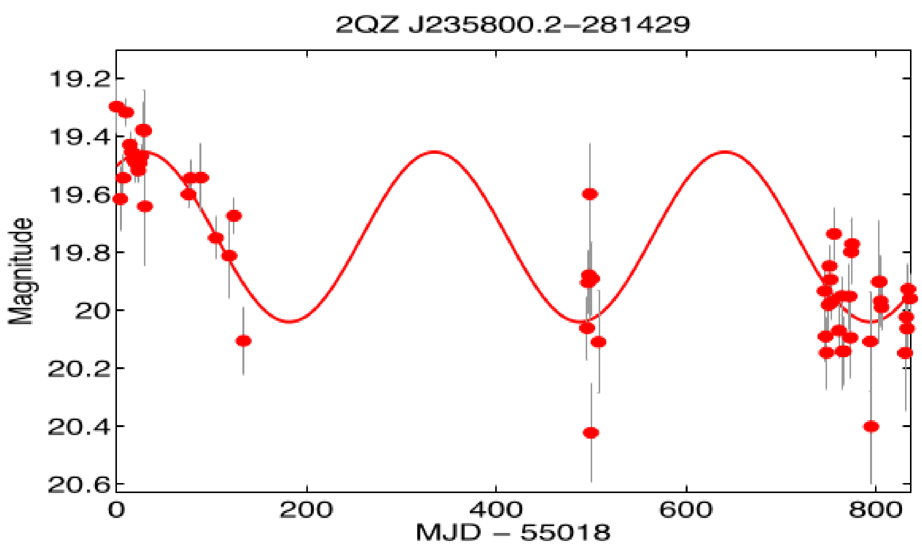
- Reverberation mapping
- Probes structure of broad-line region
- Method to measure BH mass

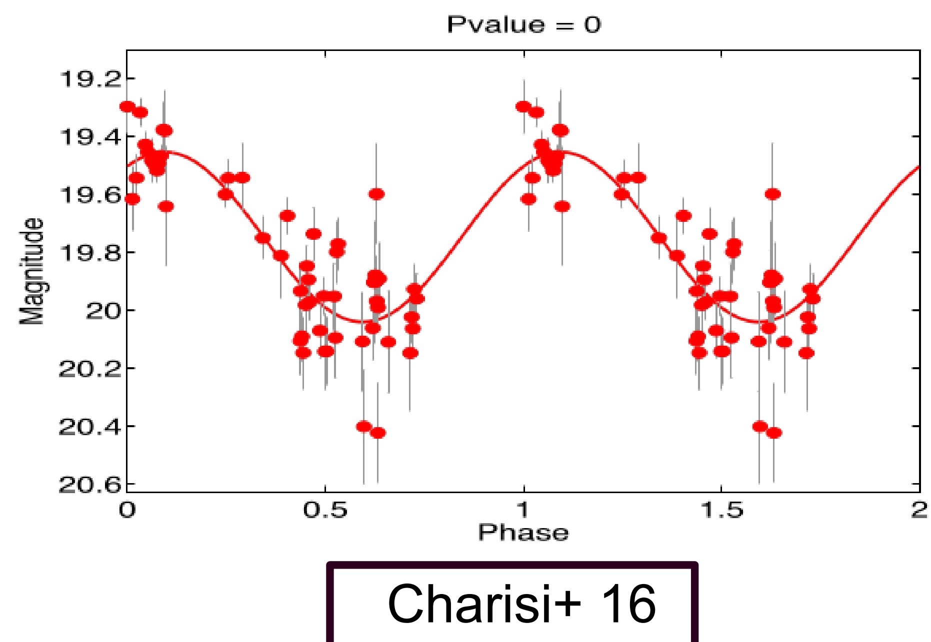


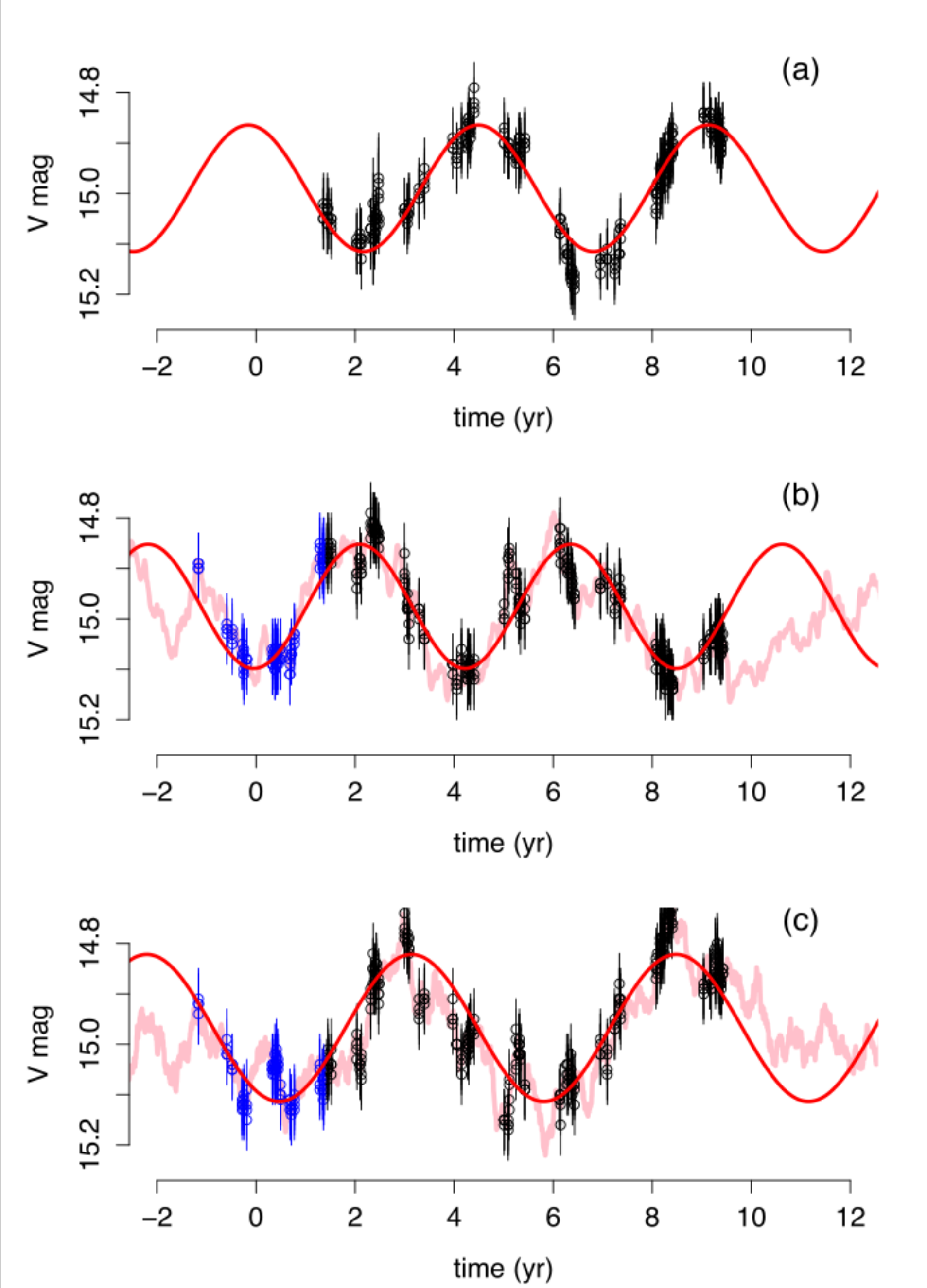
- BH mass correlated with with break in the X-ray power spectrum density

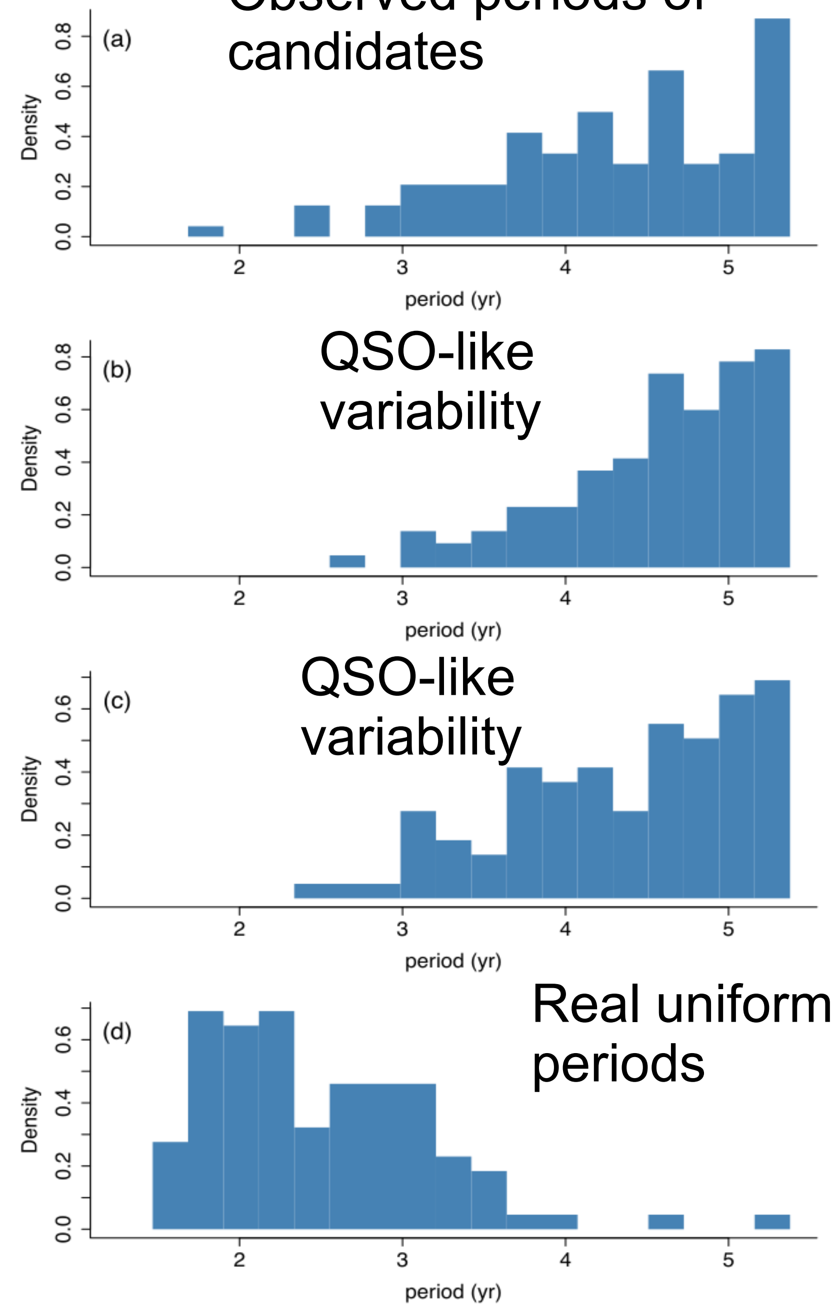


- Search for binaries of supermassive black holes with a sub-parsec separation
- Expected as a consequence of galaxy mergers





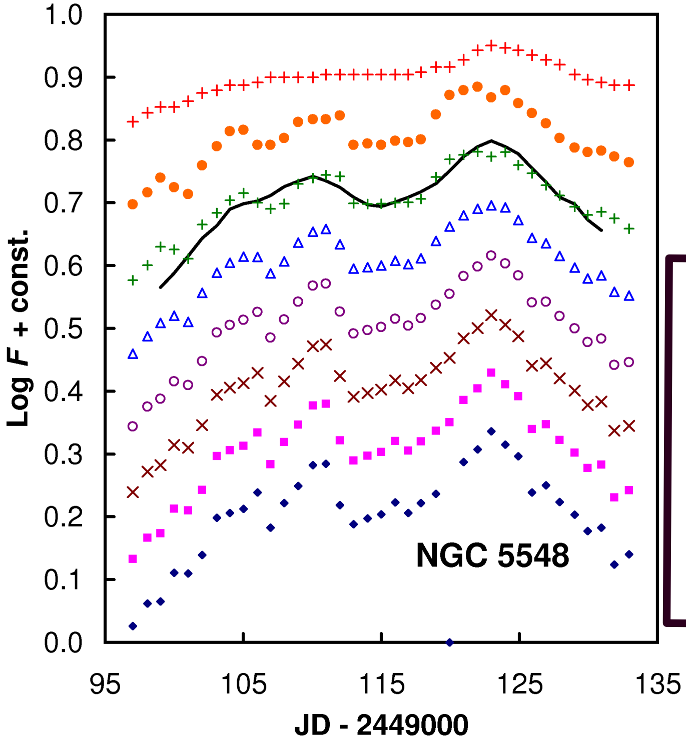




- But stochastic process can also mimic periodicity!

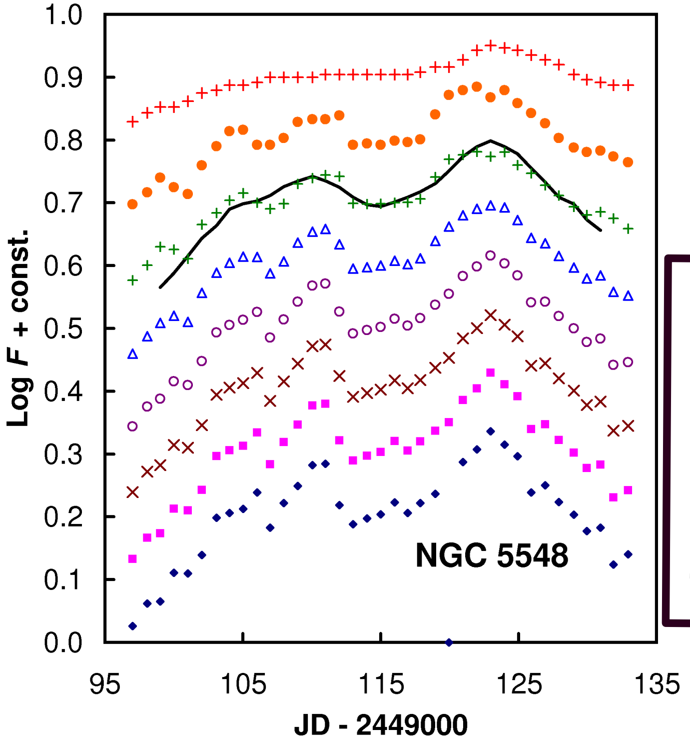
Vaughan+ 16

- Quasar variability as a test of accretion disk physics



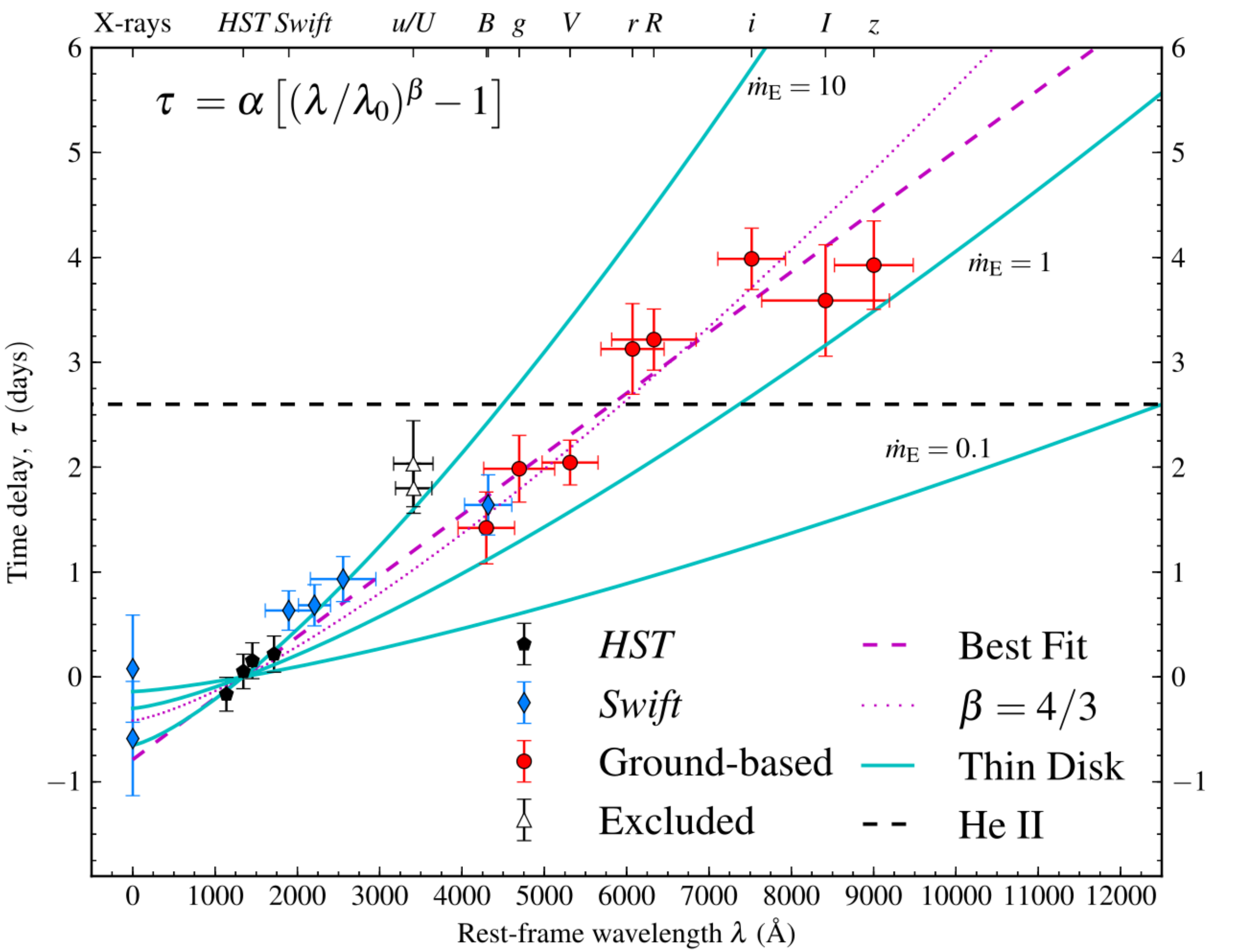
Korista+ 95

- Quasar variability as a test of accretion disk physics



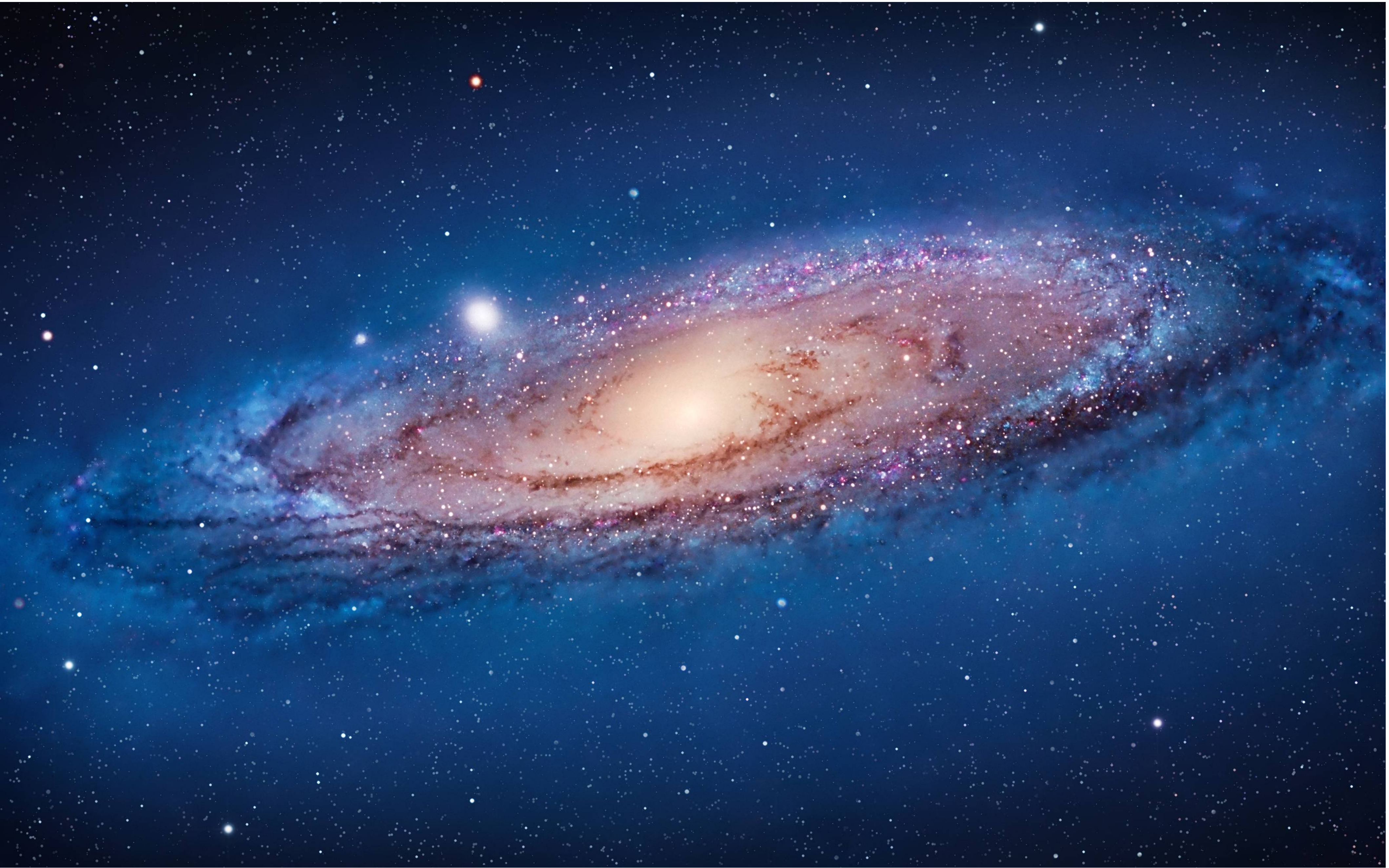
Korista+ 95

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



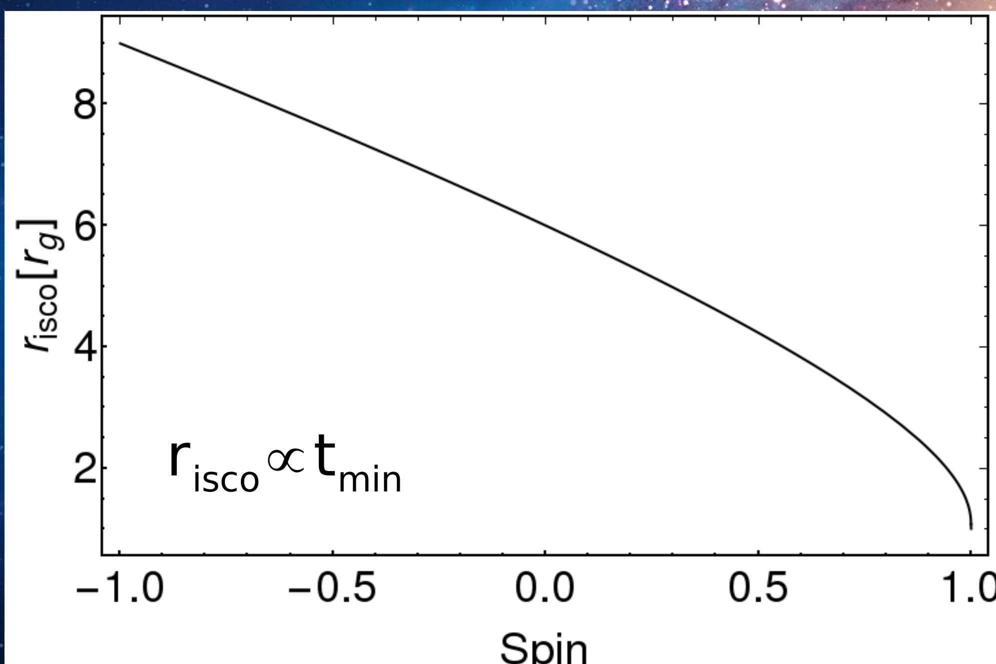
Fausnaugh+ 16

- Quasar variability as a method to measure spin



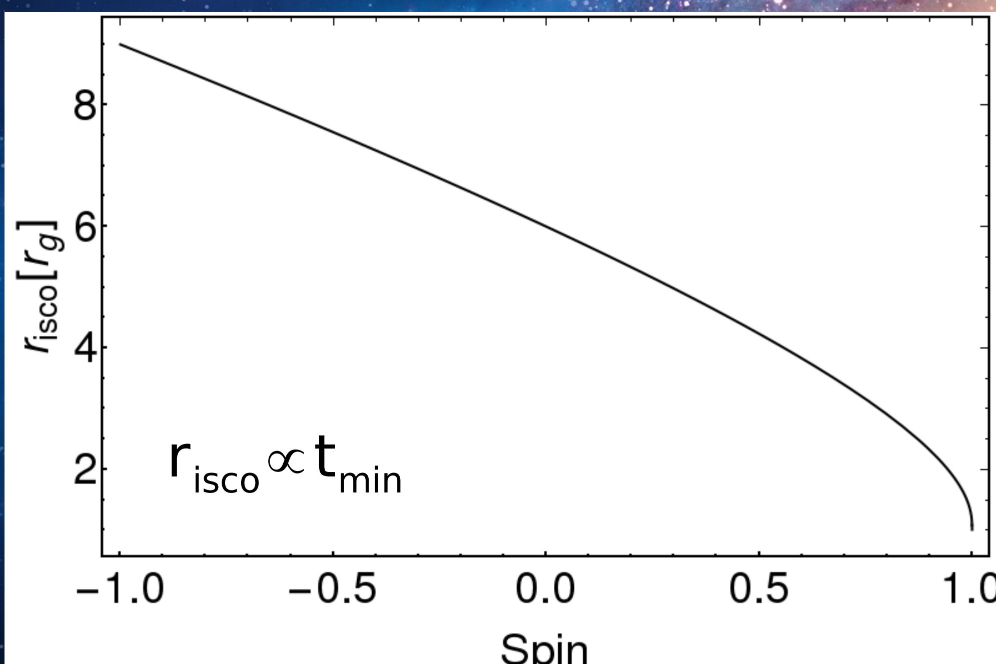
- Quasar variability as a method to measure spin

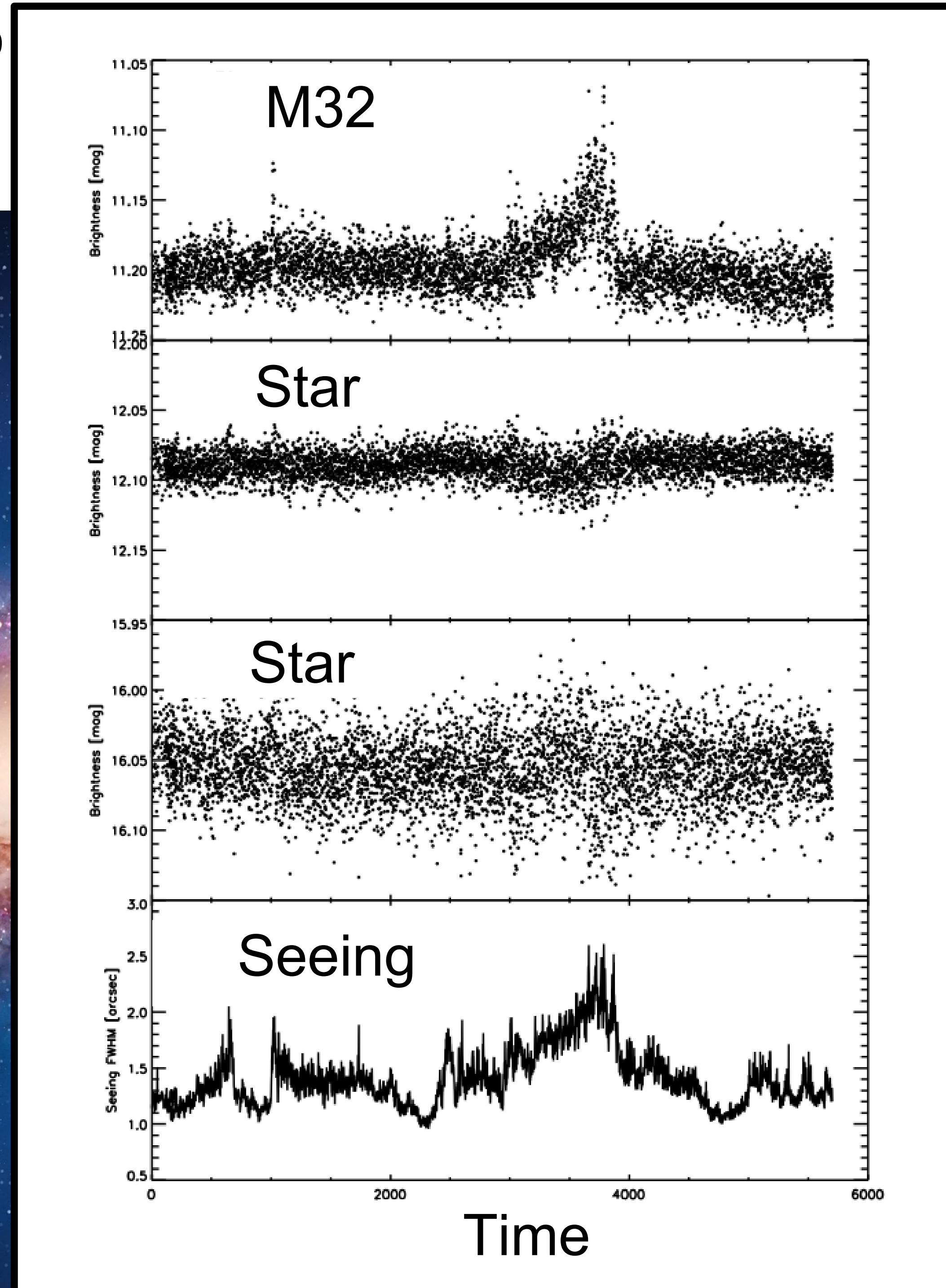
Measure the shortest time-scale of the variability; connected with the radius of the last stable orbit



- 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





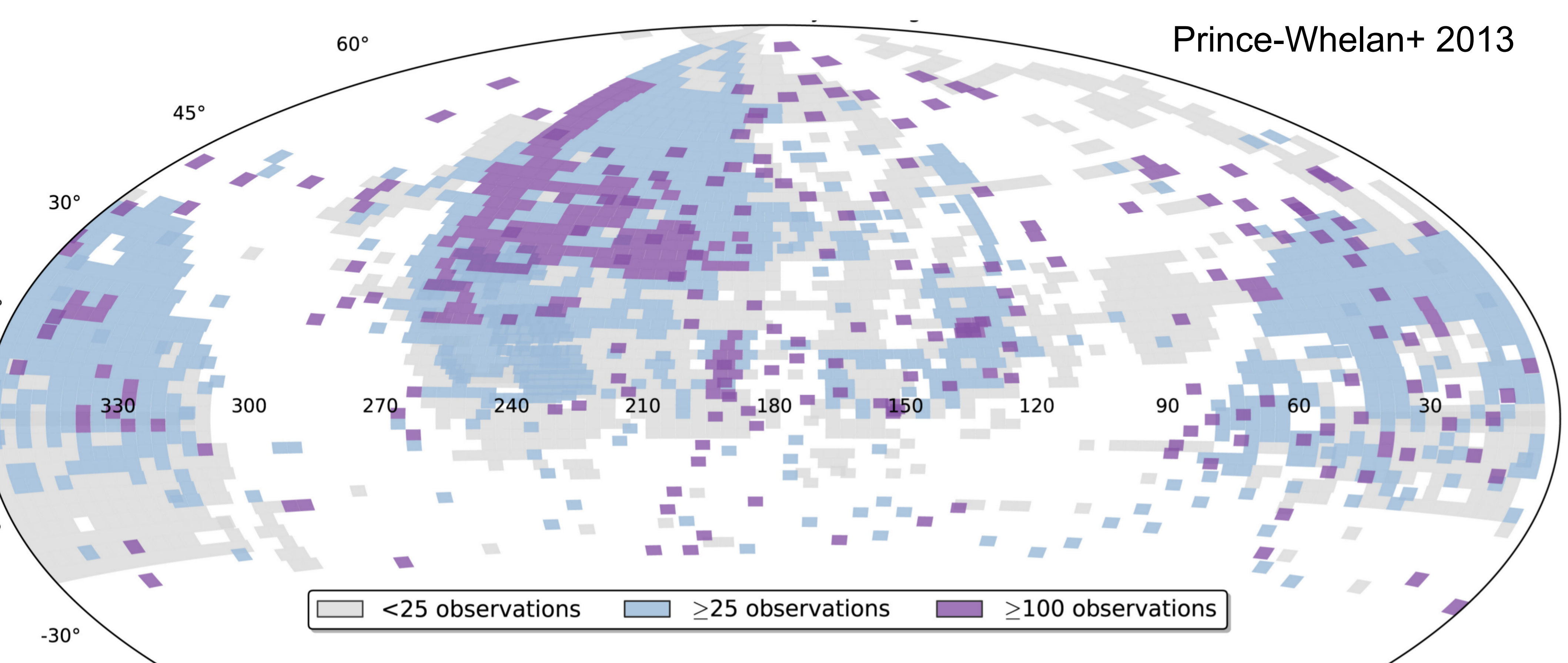
Chary+ 17

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
  - Constrains on the variability from the data

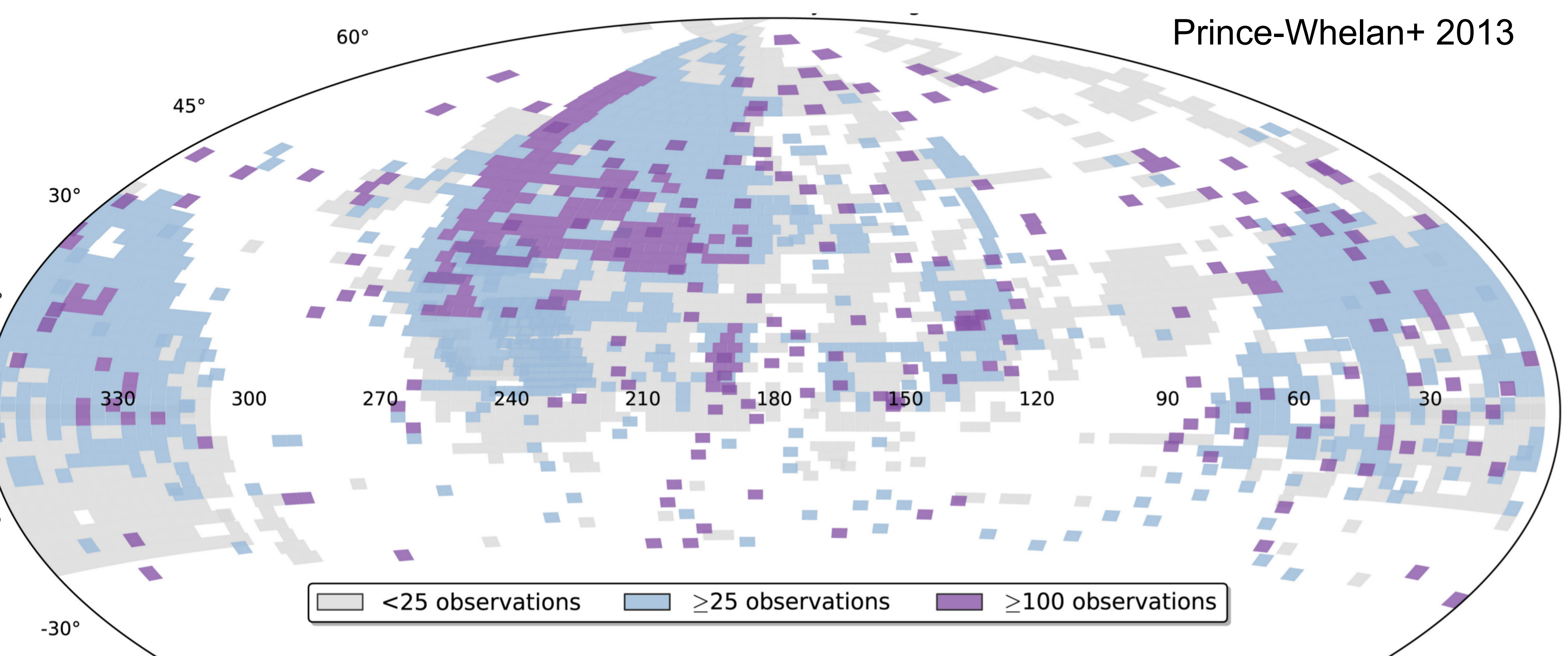
- 1.5 m telescope on Mount Palomar in south California
- Transient sky survey started in March 2009
- Data mostly in r band (centered at 6580 Å)

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



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

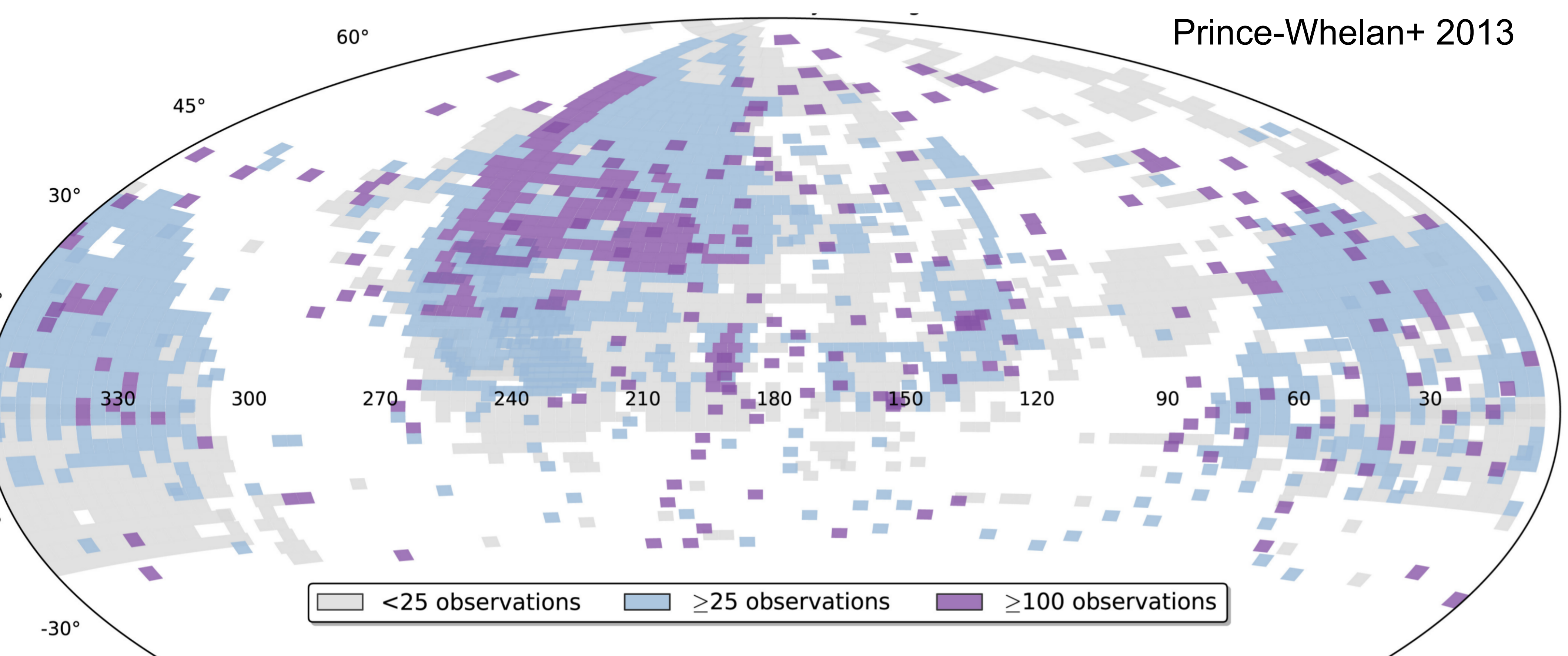
- 1.5 m telesope on Mount Palomar in south California
- Transient sky survey started in March 2009
- Data mostly in r band (centered at 6580 Å)



Prince-Whelan+ 2013

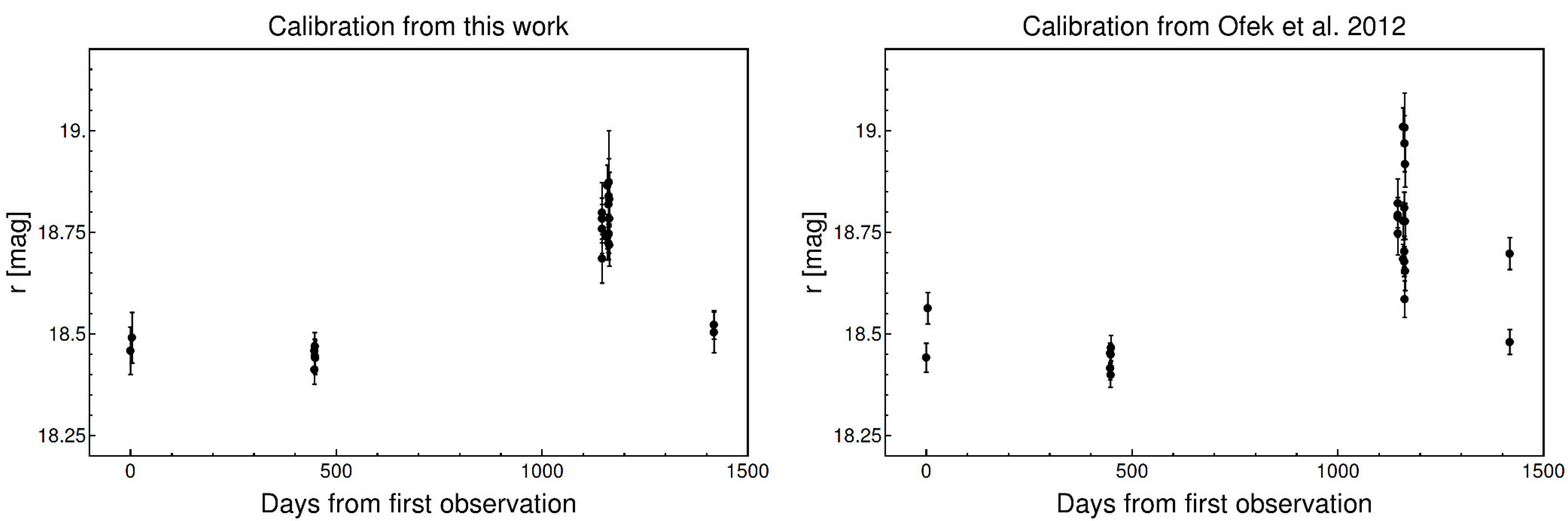
- 1.5 m telesope on Mount Palomar in south California
- Transient sky survey started in March 2009
- Data mostly in r band (centered at 6580 Å)

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



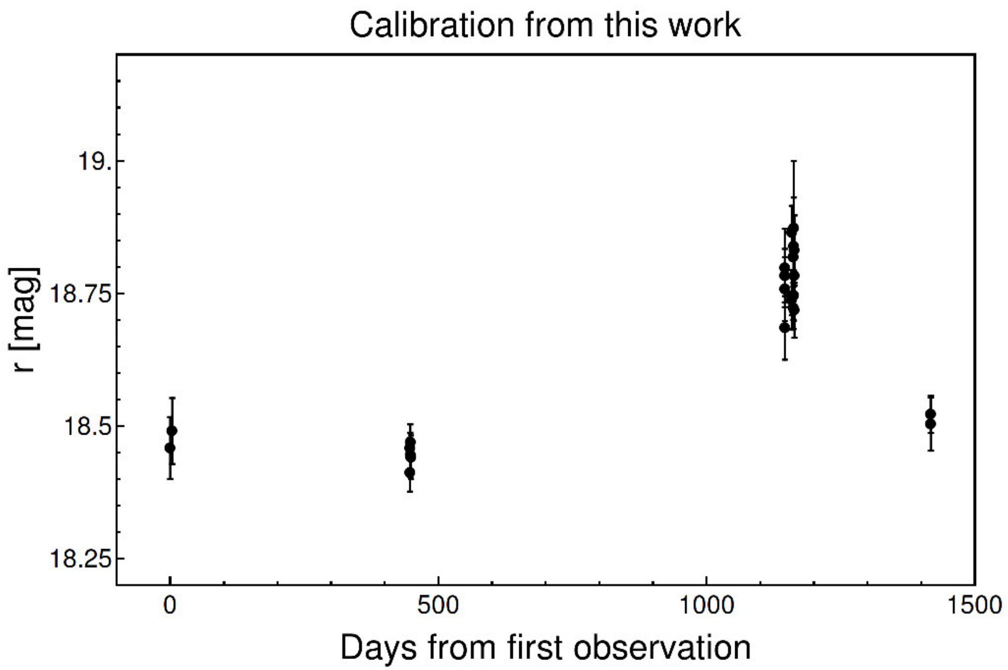
Re-calibration of survey

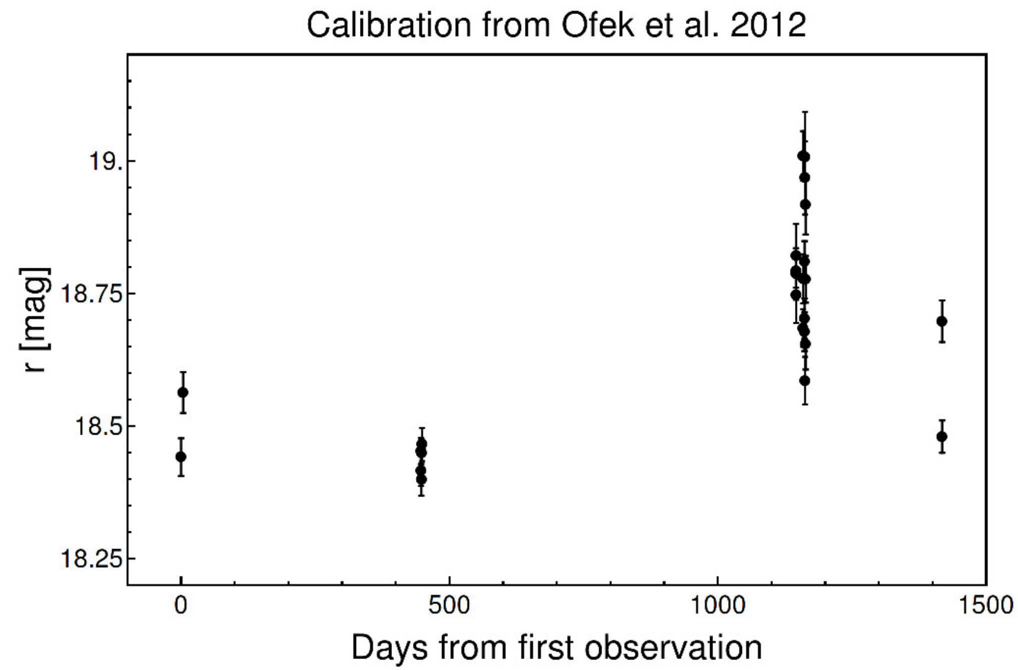
- AGN light-curves were re-calibrated
- We search for zeropoints which minimize the scatter of reference objects (stars) – based on Ofek+ 2011



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



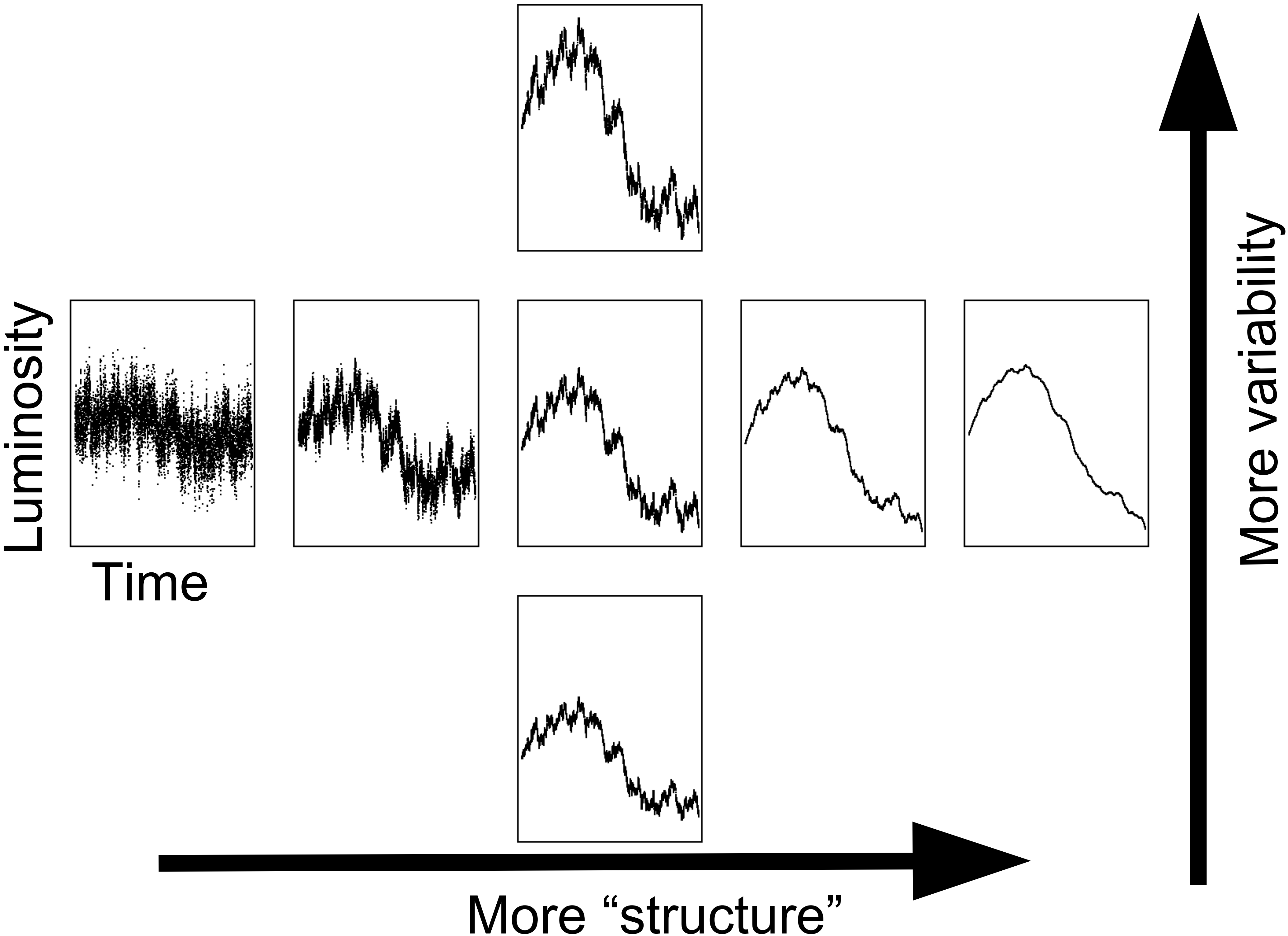


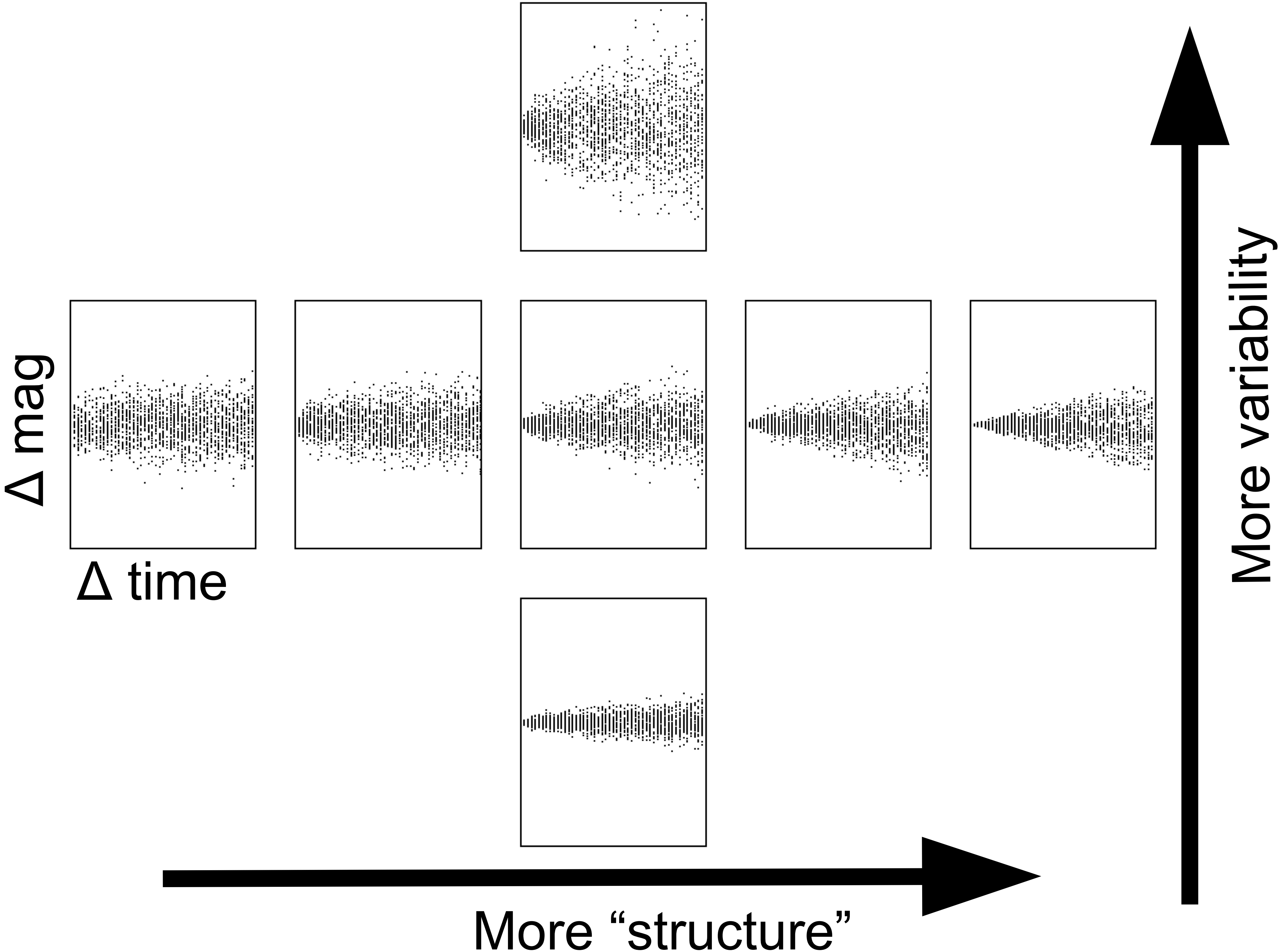
- SF^2 (structure function)^2 analysis
  - Variance of magnitude difference as a function of time lag between measurements
  - We use the method on ensemble, sample of AGNs with similar physical properties

- Power spectral density (PSD) analysis
  - Variability power per temporal frequency
  - We use CARMA modeling algorithm from Kelly+ (2015)
  - Used on well sampled, single objects

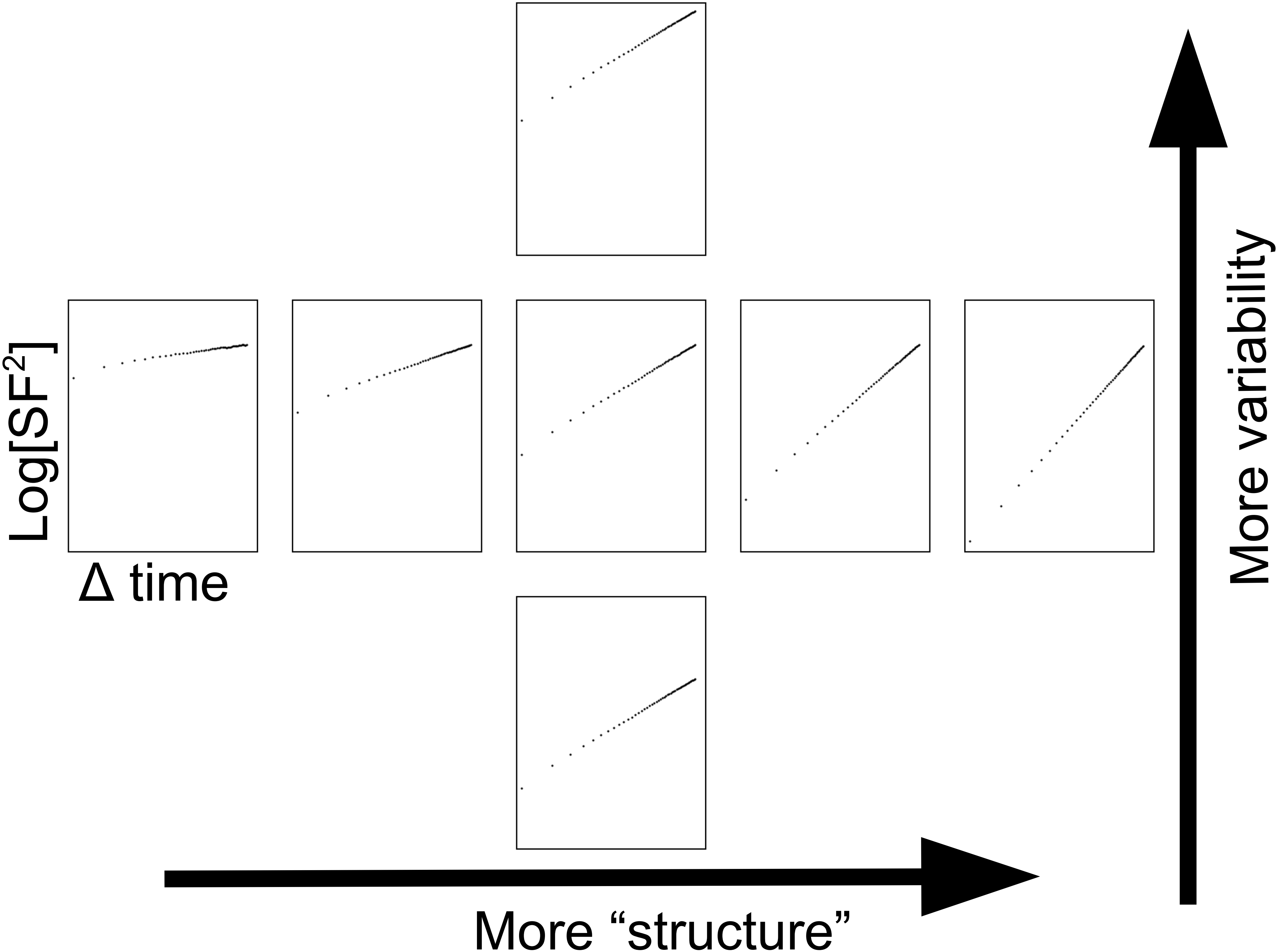
- SF^2 (structure function)^2 analysis
  - Variance of magnitude difference as a function of time lag between measurements
  - We use the method on ensemble, sample of AGNs with similar physical properties

- Power spectral density (PSD) analysis
  - Variability power per temporal frequency
  - We use CARMA modeling algorithm from Kelly+ (2015)
  - Used on well sampled, single objects


Luminosity
Time
More variability
More "structure"

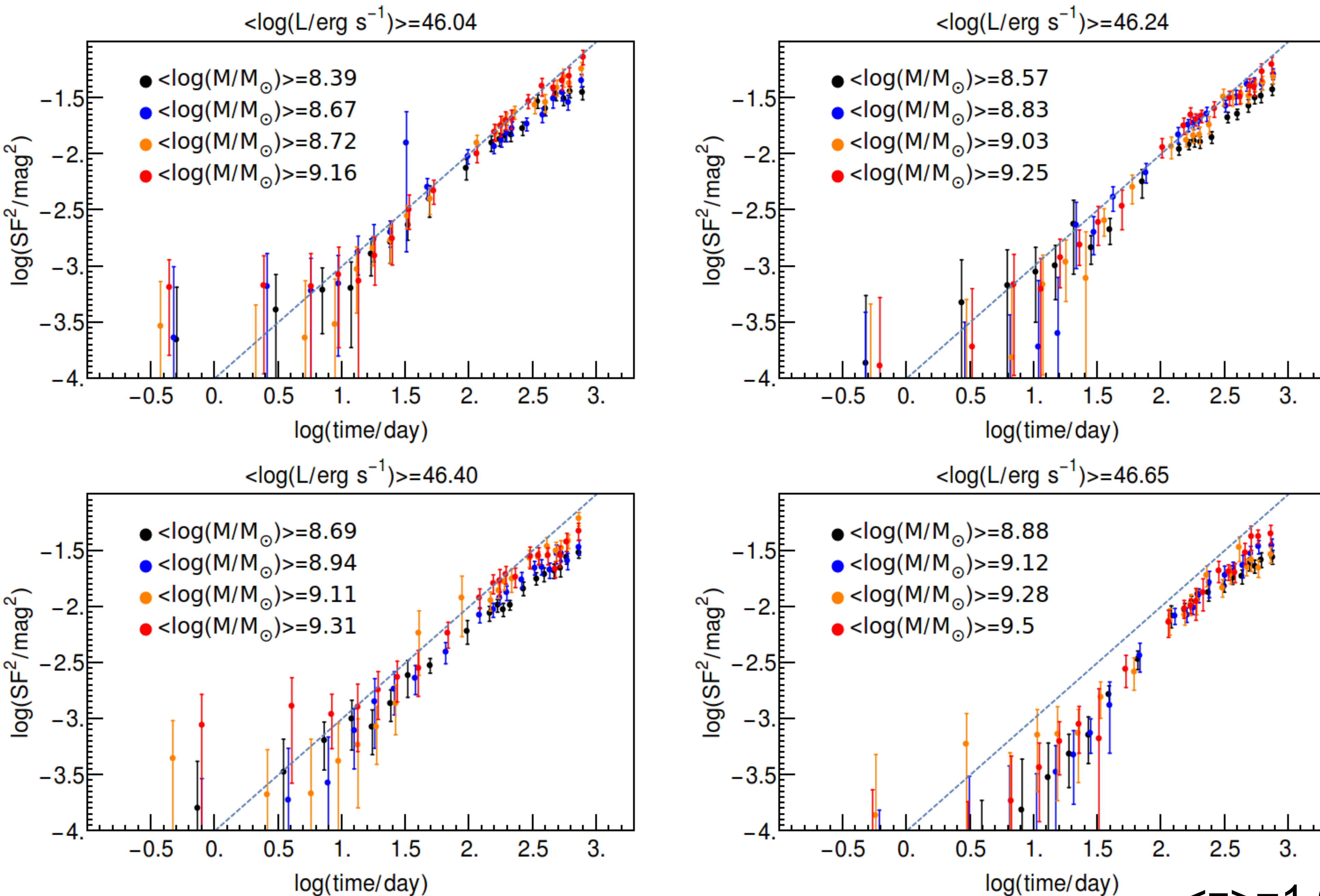


Δ mag
Δ time
More variability
More “structure”



Log[SF^2]
Δ time
More "structure"
More variability

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



<z>=1.05

- 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

- Wavelength correction estimated from SDSS dataset to normalize to 4000 A

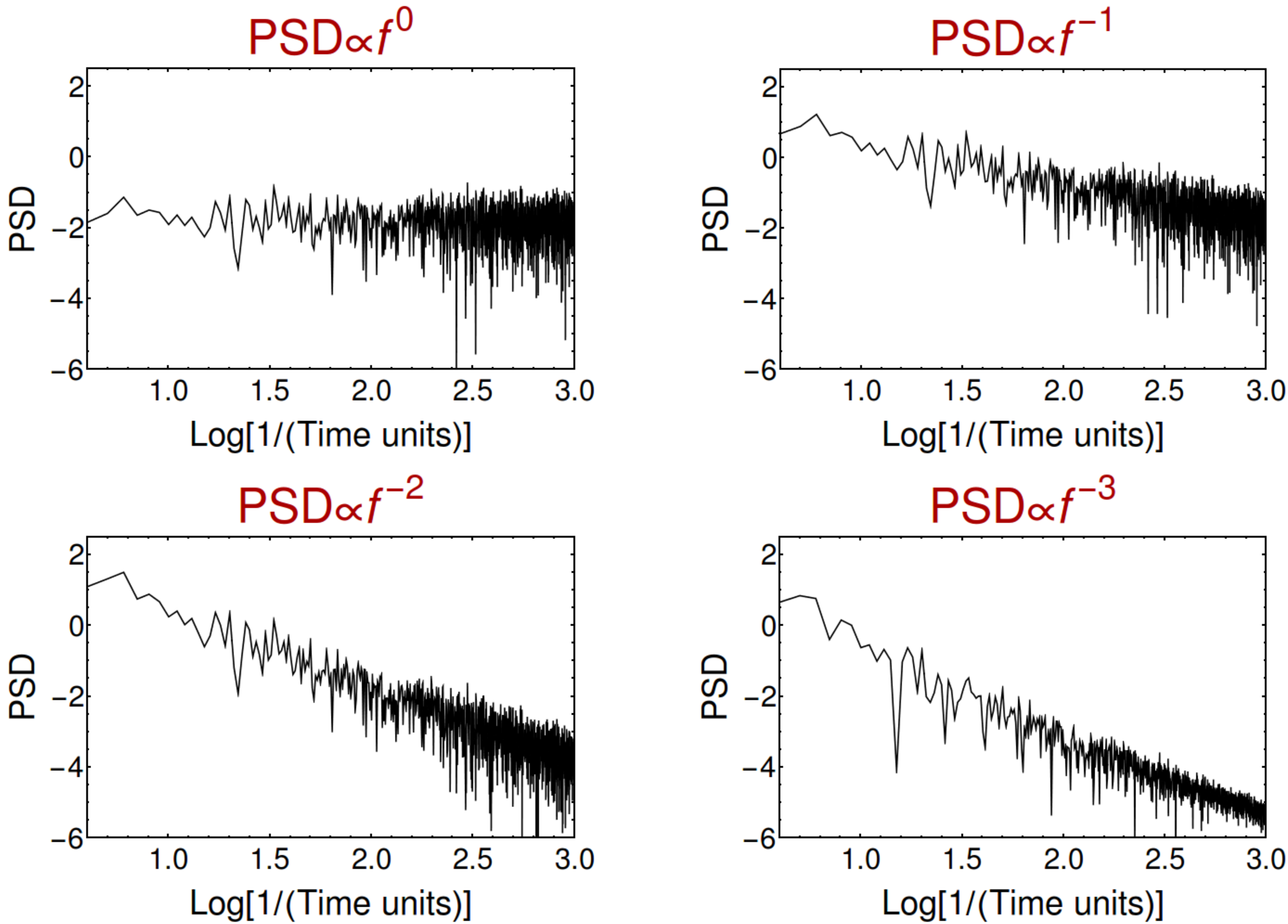
- No correlation with redshift

- Little to no correlation with mass

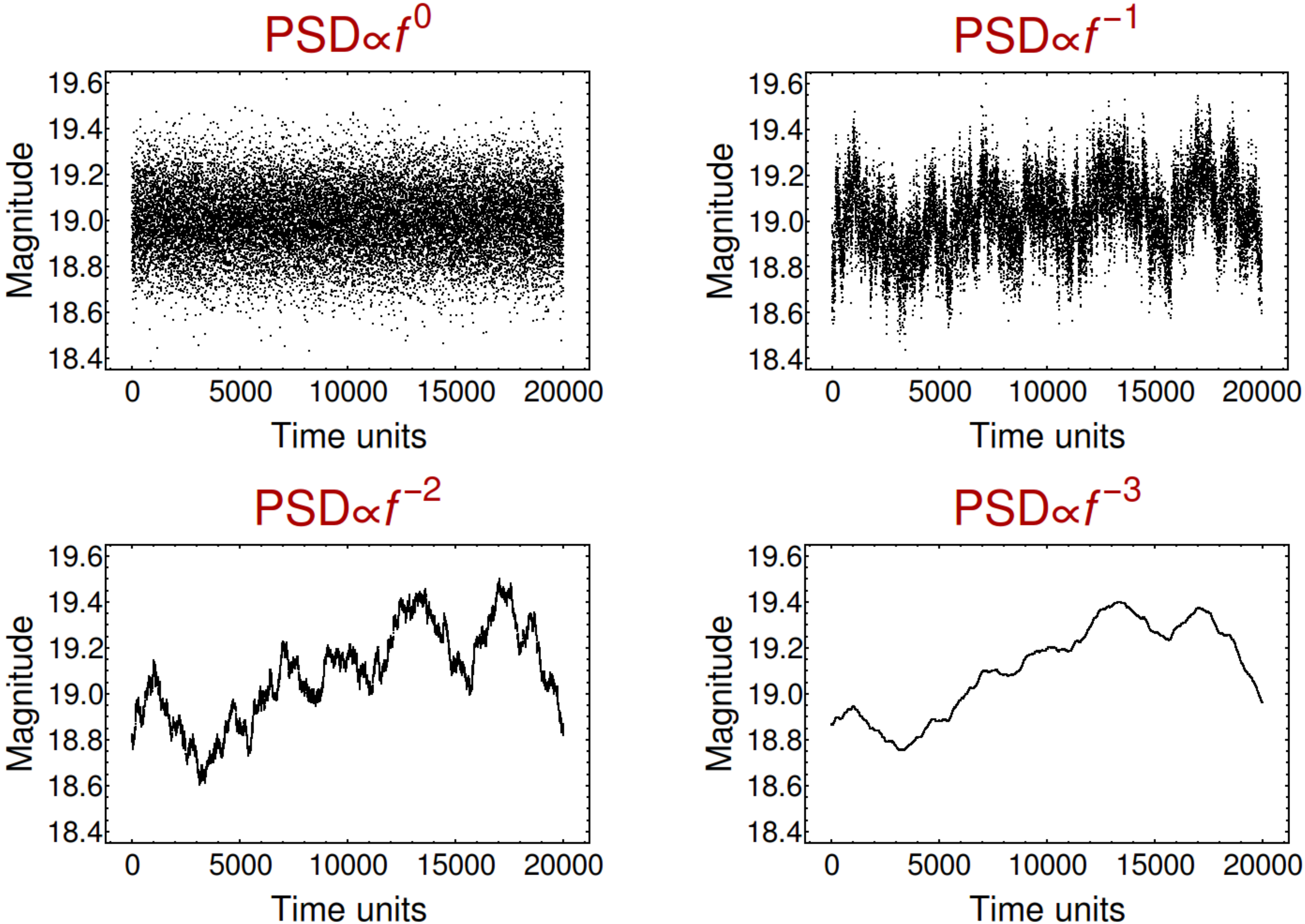
- Clear dependence with luminosity

- 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

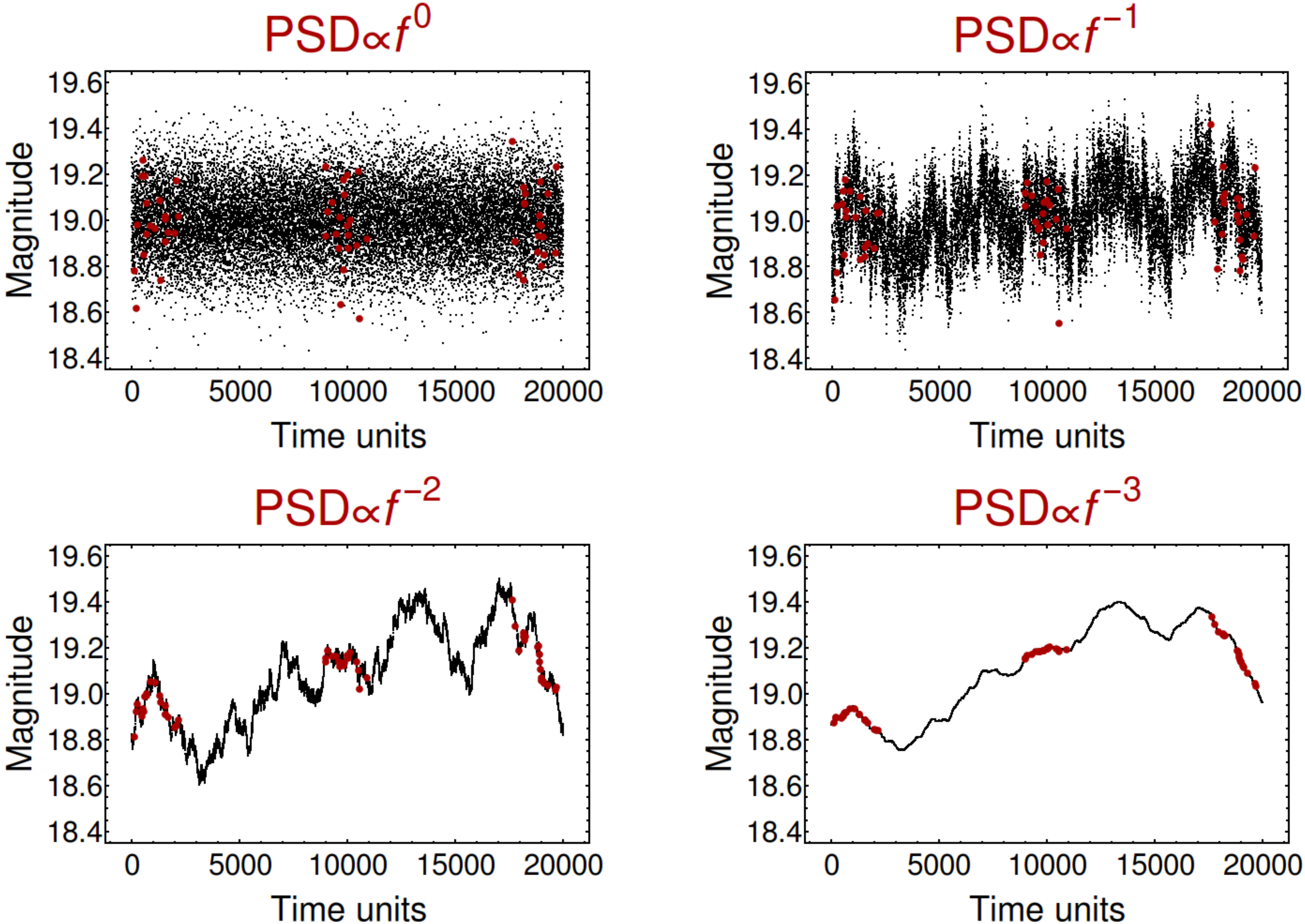
- Power spectral density (PSD) analysis
  - Variability power per temporal frequency
  - We use CARMA modeling algorithm from Kelly+ (2015)
  - Used on well sampled, single objects



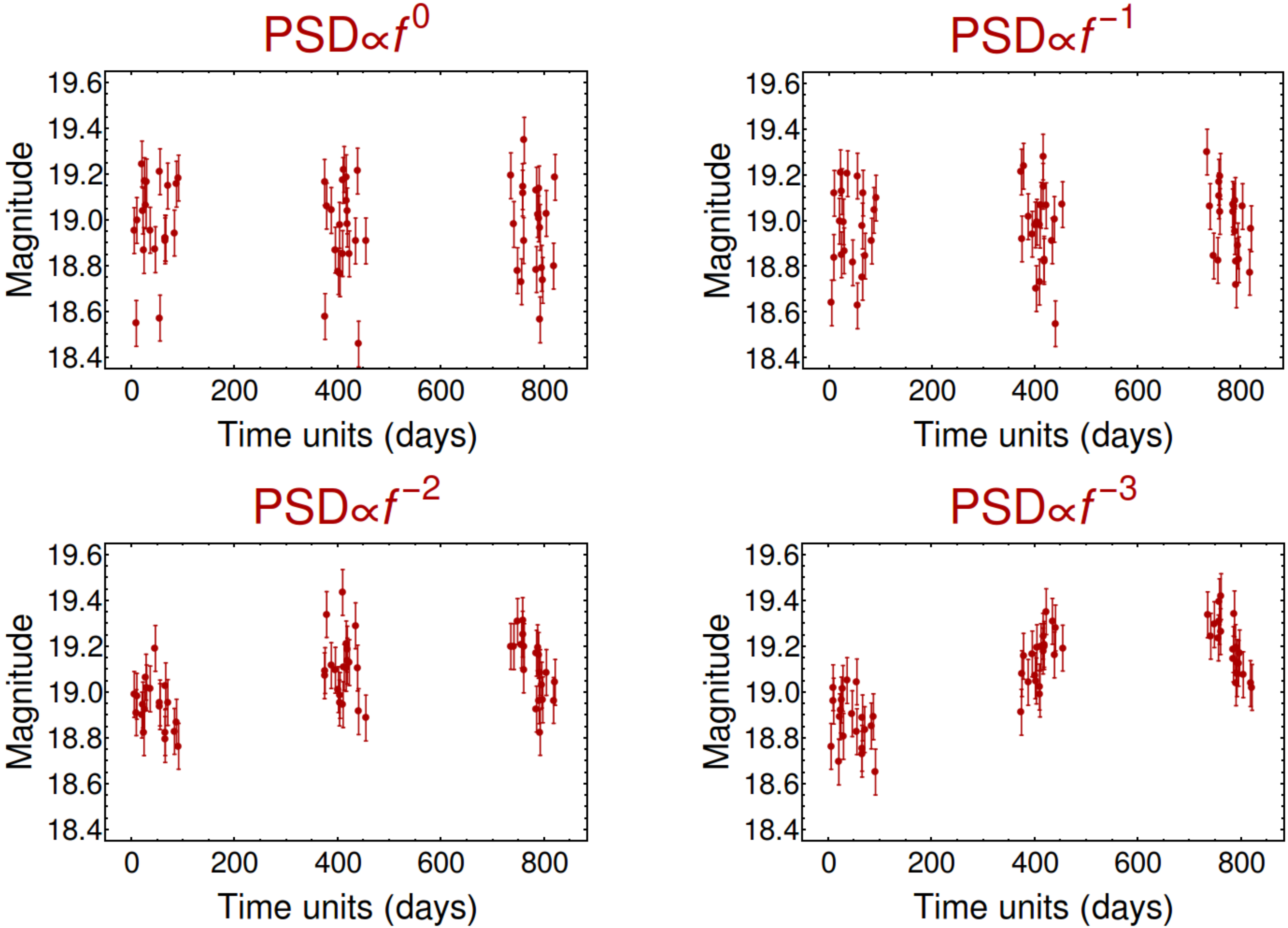
PSD∝f^0
PSD∝f^{-1}
PSD∝f^{-2}
PSD∝f^{-3}
PSD
Log[1/(Time units)]



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

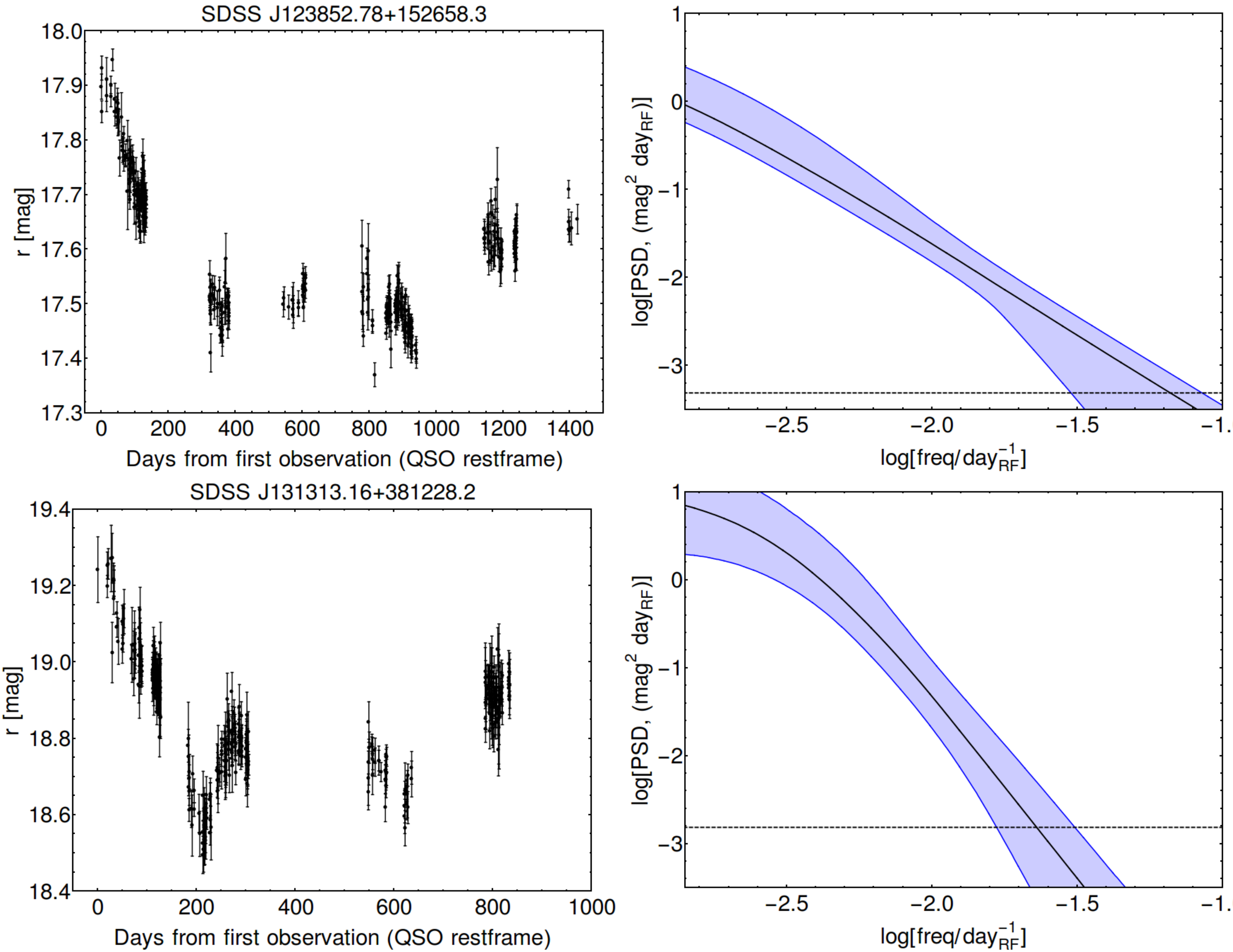


PSD∝f^0
PSD∝f^-1
PSD∝f^-2
PSD∝f^-3
Magnitude
Time units
19.6
19.4
19.2
19.0
18.8
18.6
18.4
0
5000
10000
15000
20000

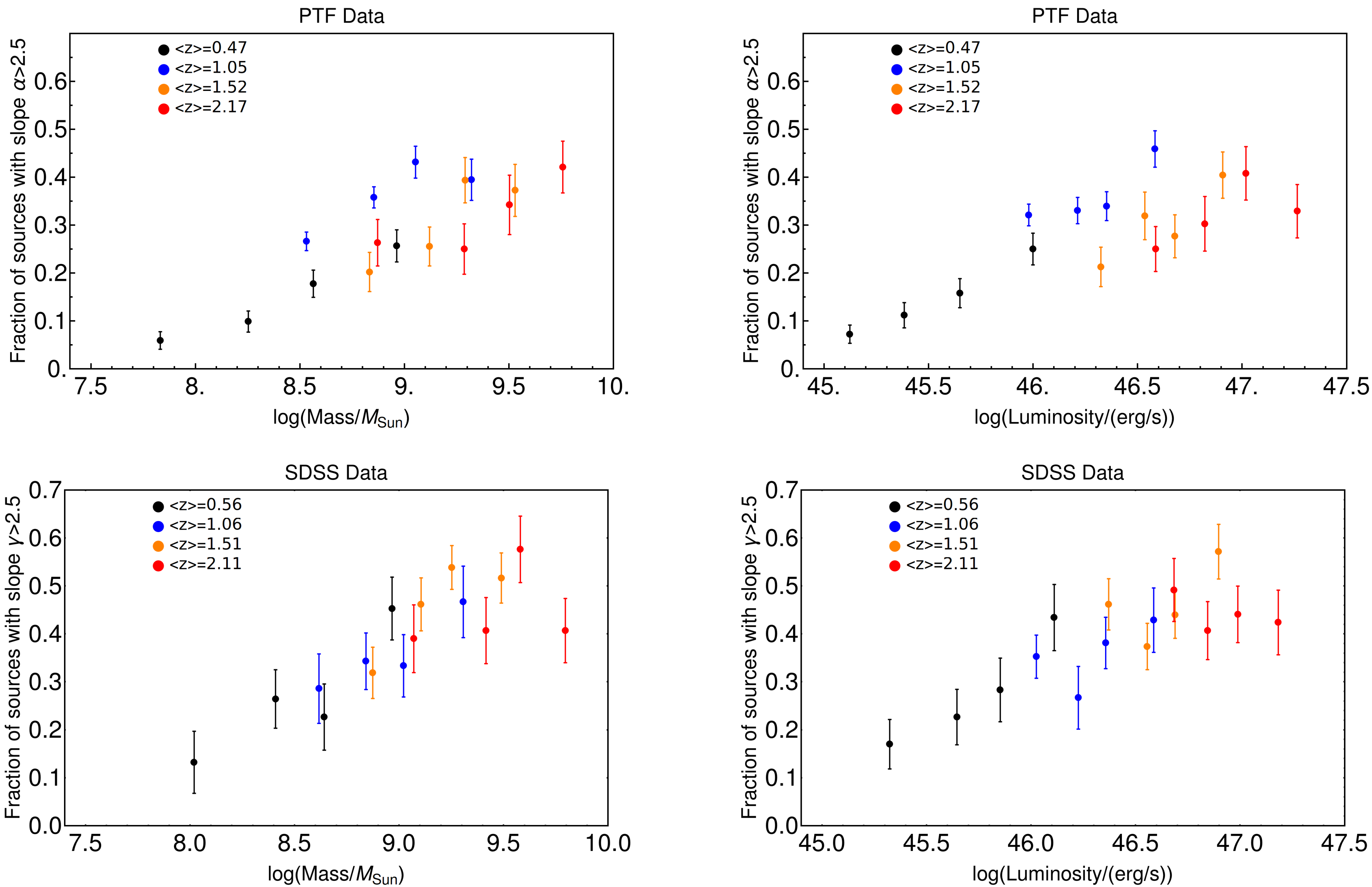


PSD∝f^0
PSD∝f^{-1}
PSD∝f^{-2}
PSD∝f^{-3}
Magnitude
Time units (days)
19.6
19.4
19.2
19.0
18.8
18.6
18.4
0
200
400
600
800

Kelly+, 14

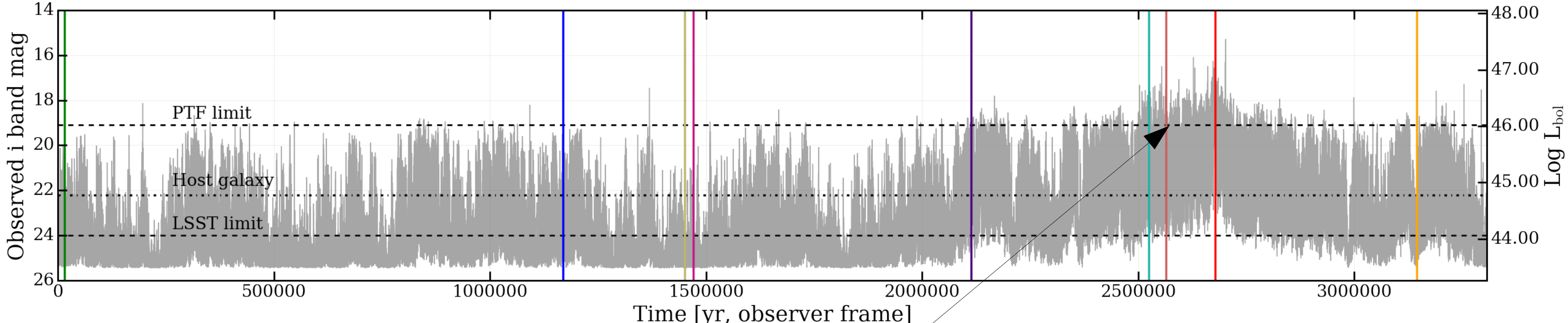


SDSS J123852.78+152658.3
r [mag]
Days from first observation (QSO restframe)
log[PSD, (mag^2 day$_{RF}$)]
log[freq/day$_{RF}^{-1}$]
SDSS J131313.16+381228.2
r [mag]
Days from first observation (QSO restframe)
log[PSD, (mag^2 day$_{RF}$)]
log[freq/day$_{RF}^{-1}$]



PTF Data
<z>=0.47
<z>=1.05
<z>=1.52
<z>=2.17
Fraction of sources with slope α>2.5
log(Mass/$M_{\rm Sun}$)
PTF Data
<z>=0.47
<z>=1.05
<z>=1.52
<z>=2.17
Fraction of sources with slope α>2.5
log(Luminosity/(erg/s))
SDSS Data
<z>=0.56
<z>=1.06
<z>=1.51
<z>=2.11
Fraction of sources with slope γ>2.5
log(Mass/$M_{\rm Sun}$)
SDSS Data
<z>=0.56
<z>=1.06
<z>=1.51
<z>=2.11
Fraction of sources with slope γ>2.5
log(Luminosity/(erg/s))

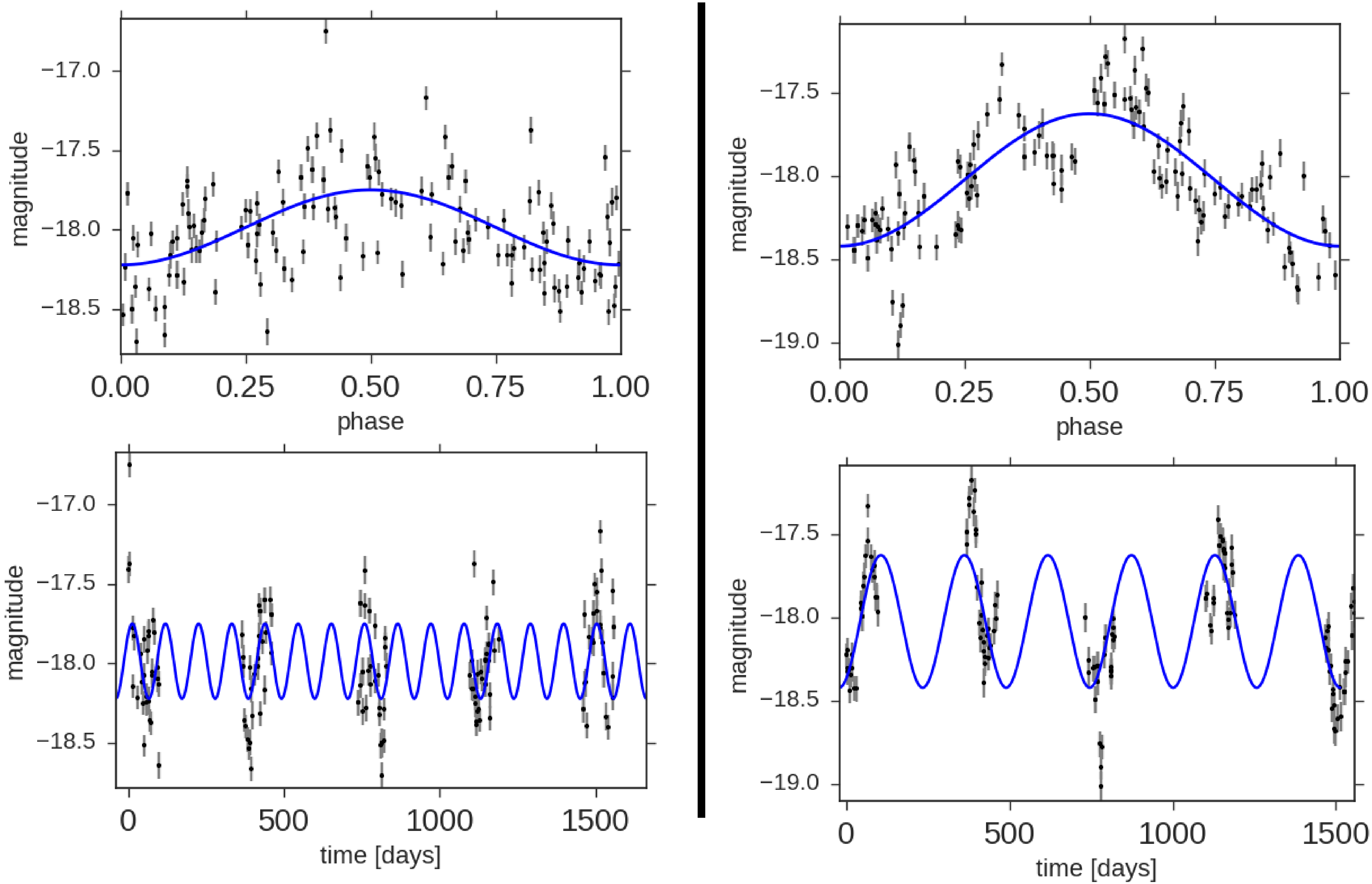
I. What are we looking at?



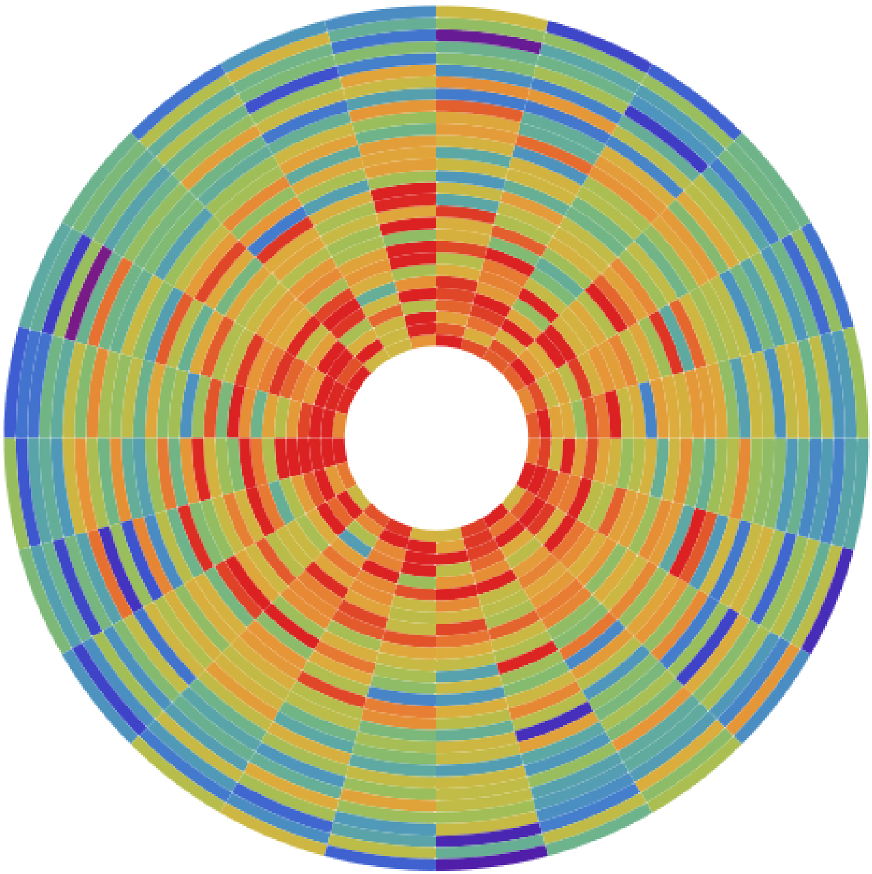
Sartori+, submitted

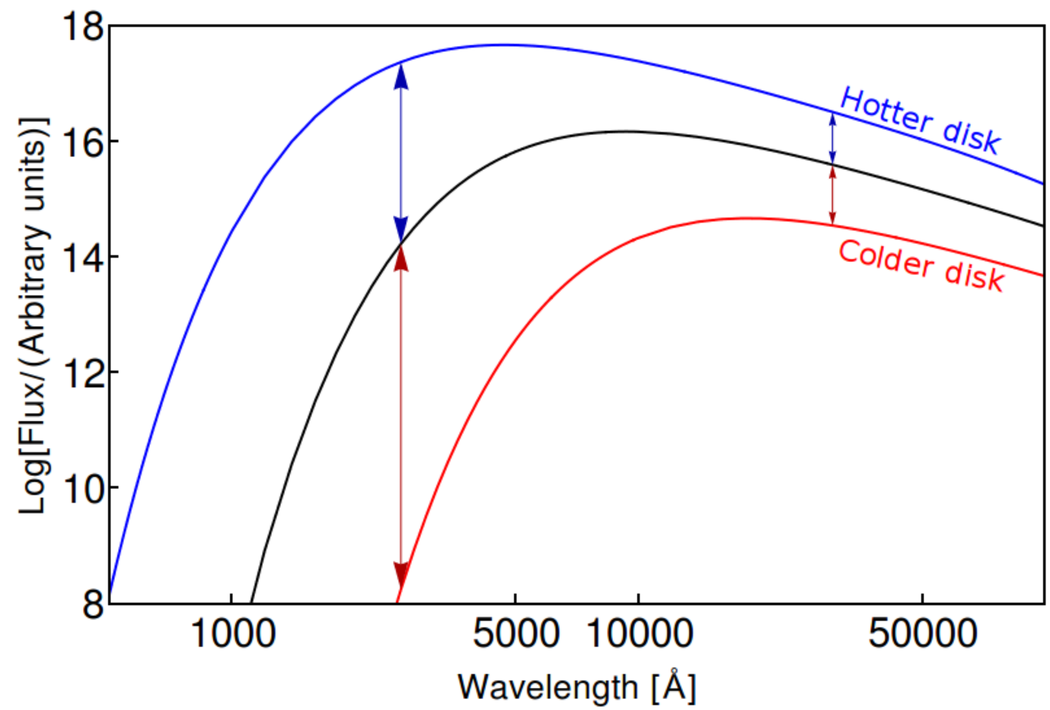
- ``Quasar selection'' targets very special time during the lifetime of an AGN
- LSST will be much deeper, but host galaxy contribution becomes significant!

II. Steeper PSD creates more false-positive AGN periods



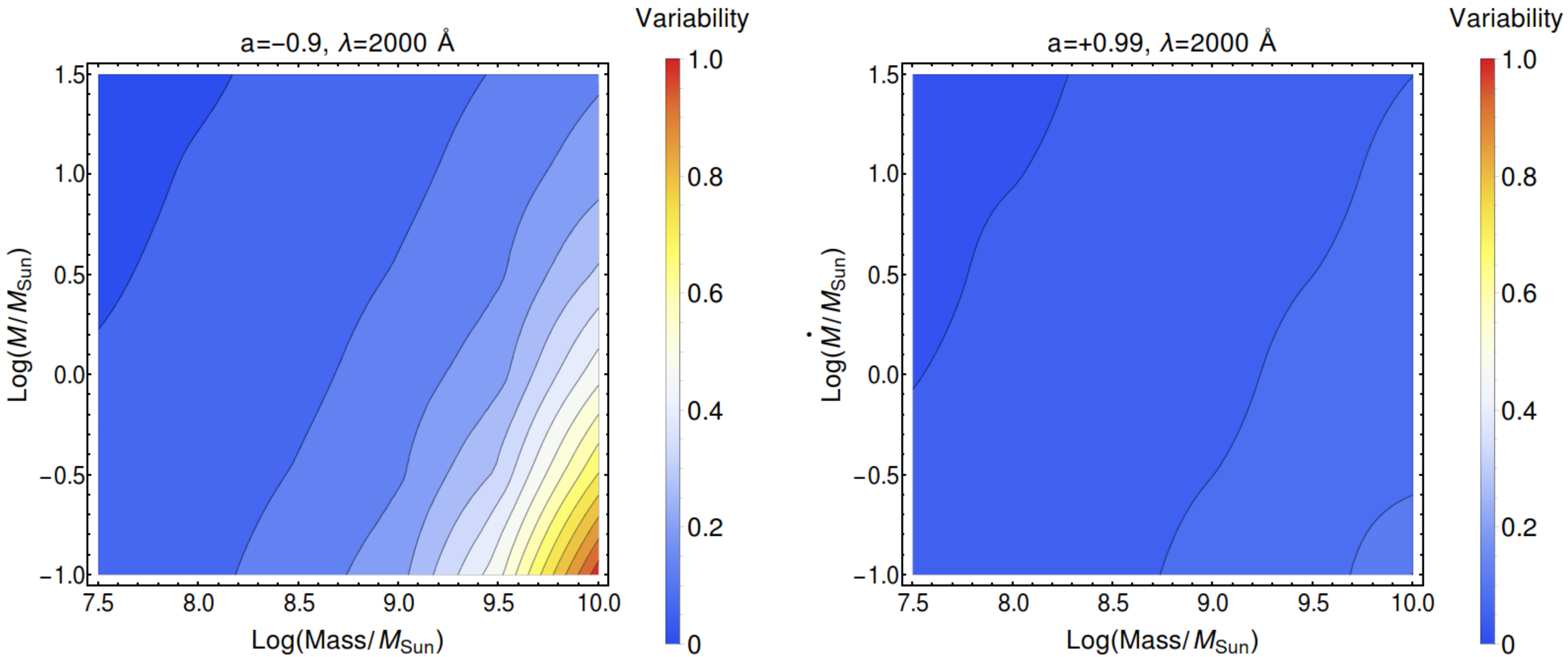
III. Constrain spin from variability?





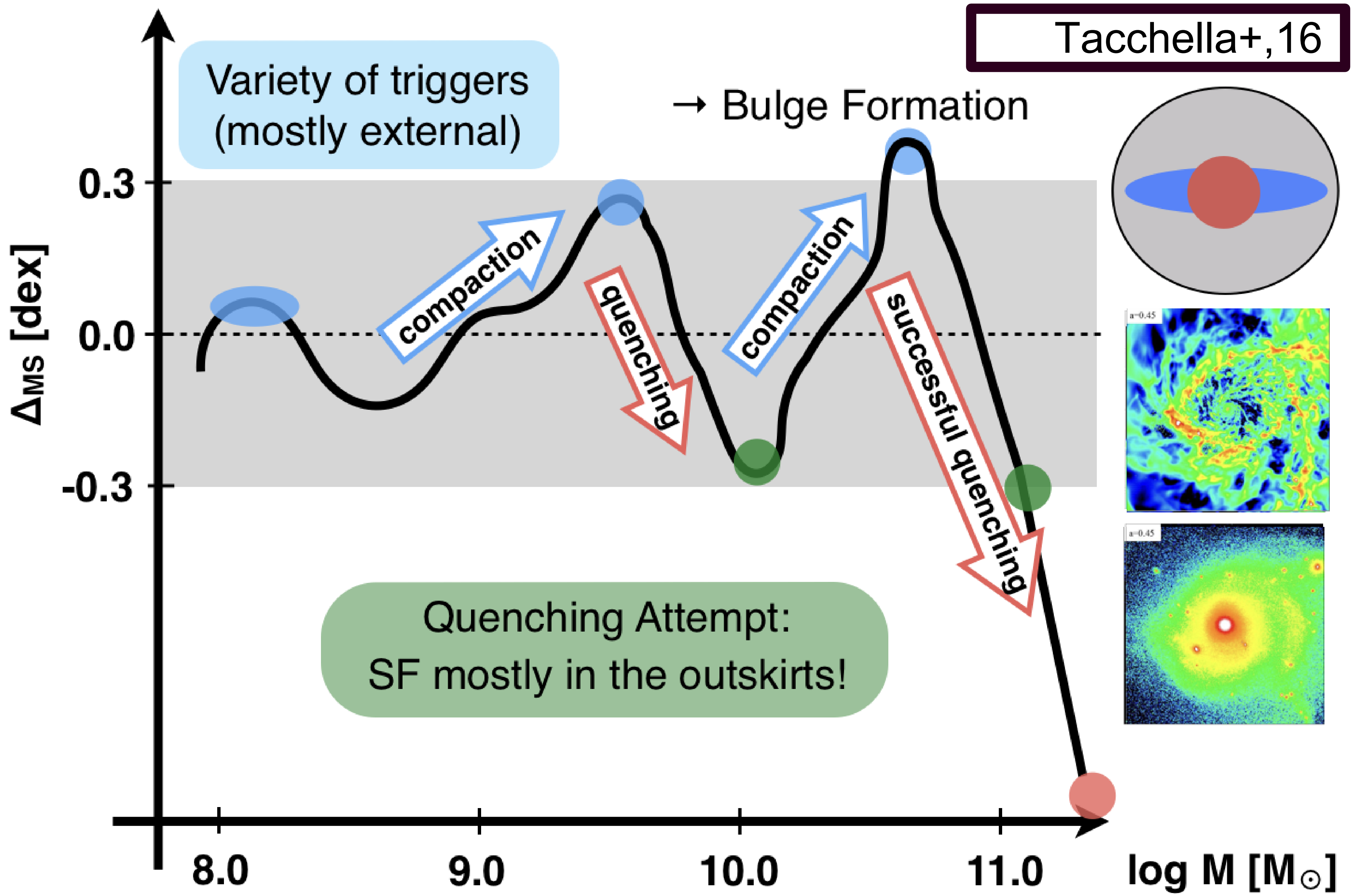
- Optical variability as a consequence of temperature variations in the disk (Dexter & Agol, 2011)
- Temperature: $T(r) \propto \Delta M^{1/4} M^{-1/2} f(r)^{3/4} (r/r_g)^{-3/4}$
  - Temperature correlated with spin (f parameter in equation above)

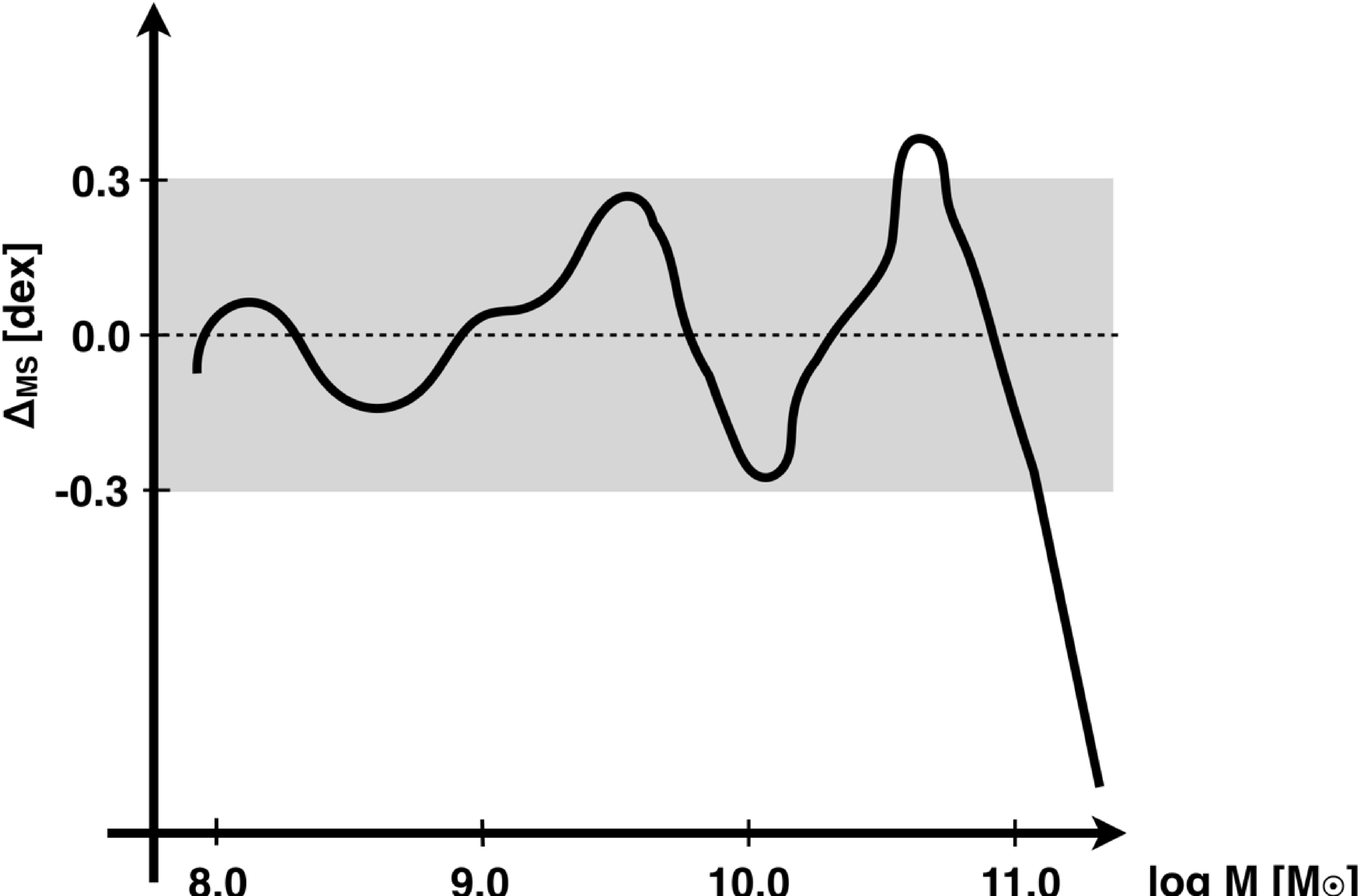
III. Constrain spin from variability?

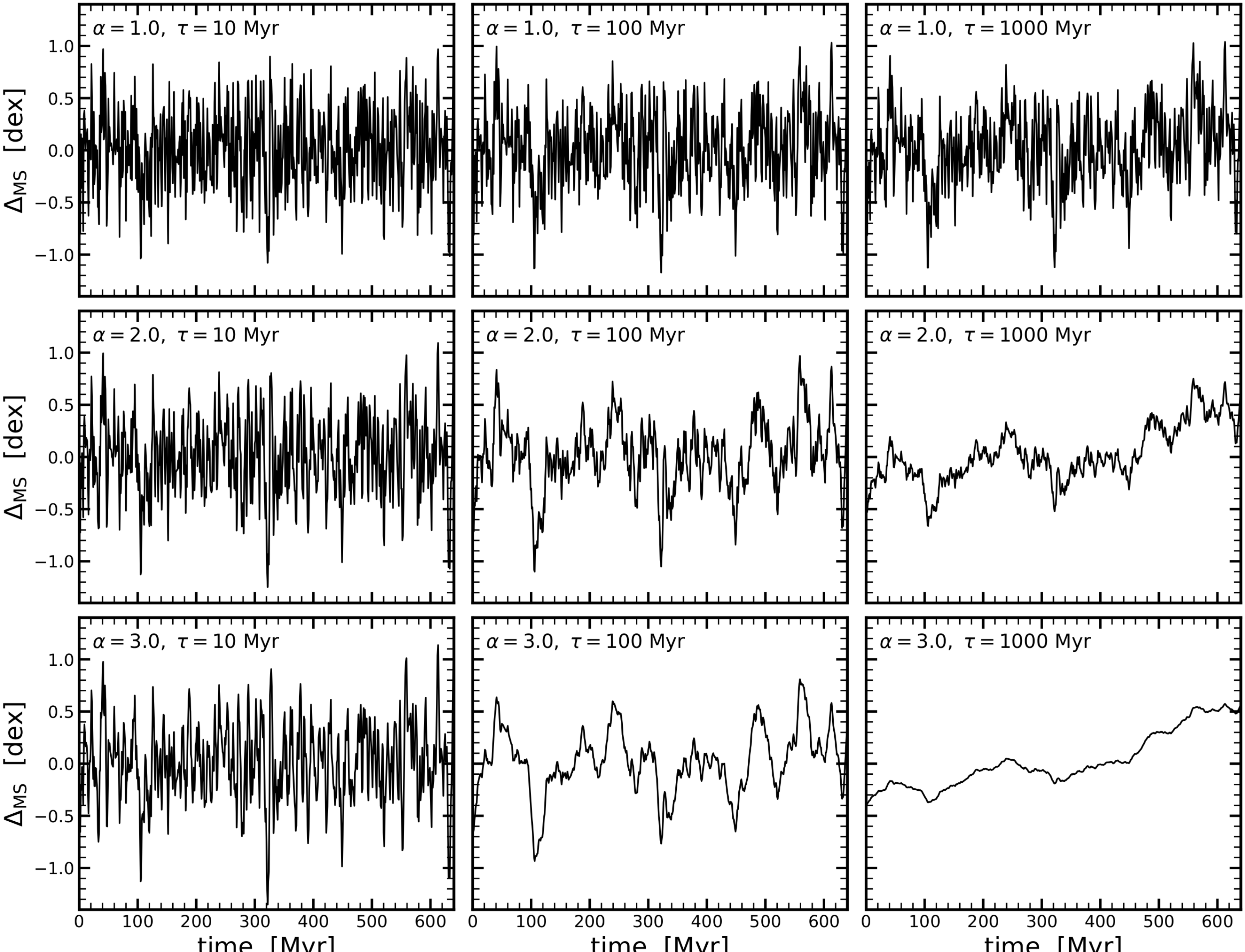


- Optical variability as a consequence of temeperature variations in the disk (Dexter & Agol, 2011)
- Temperature: $T(r) \propto \Delta M^{1/4} M^{-1/2} f(r)^{3/4} (r/r_g)^{-3/4}$
  - Temperature correlated with spin (f parameter in equation above)

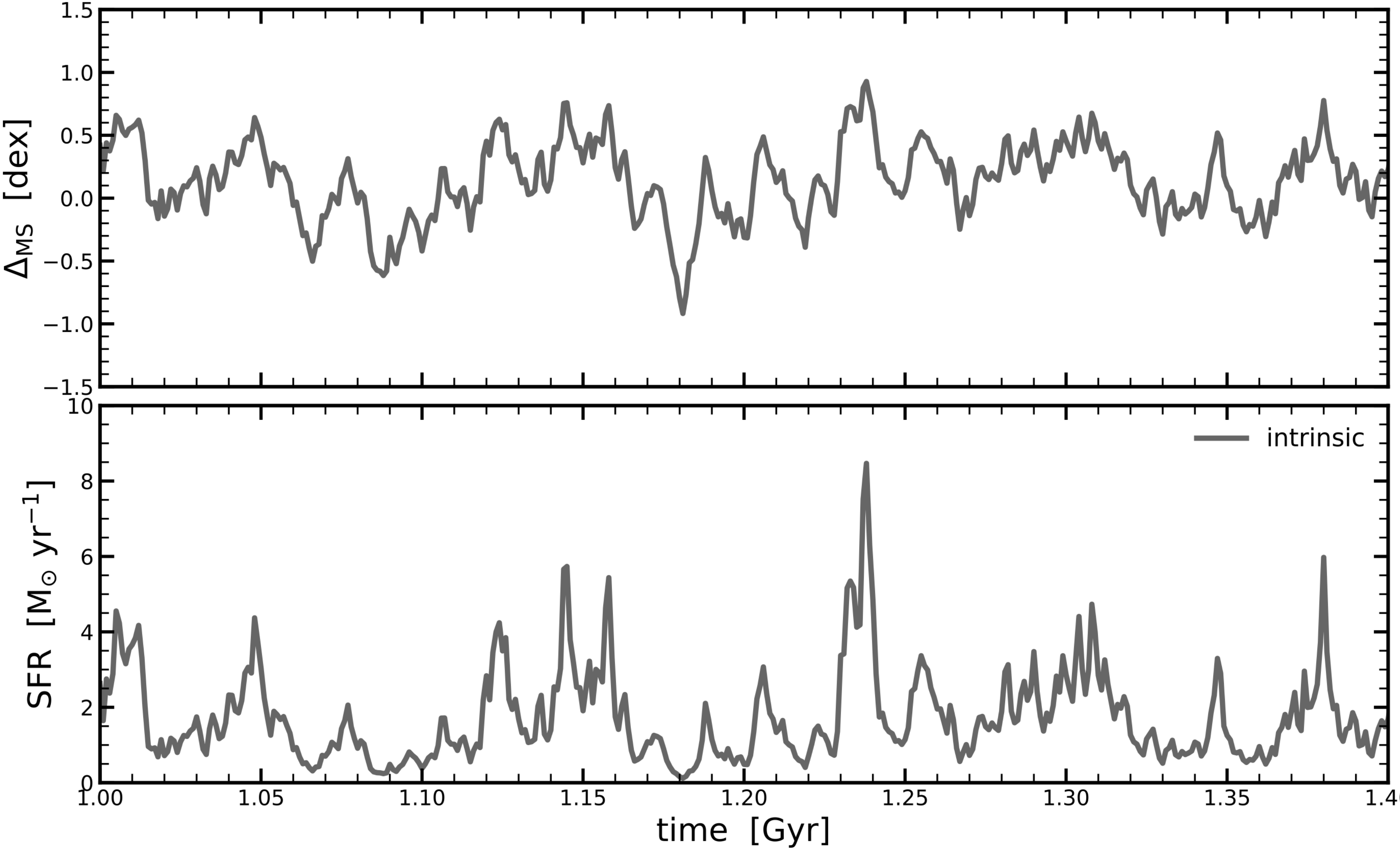
Confinement of star-forming galaxies



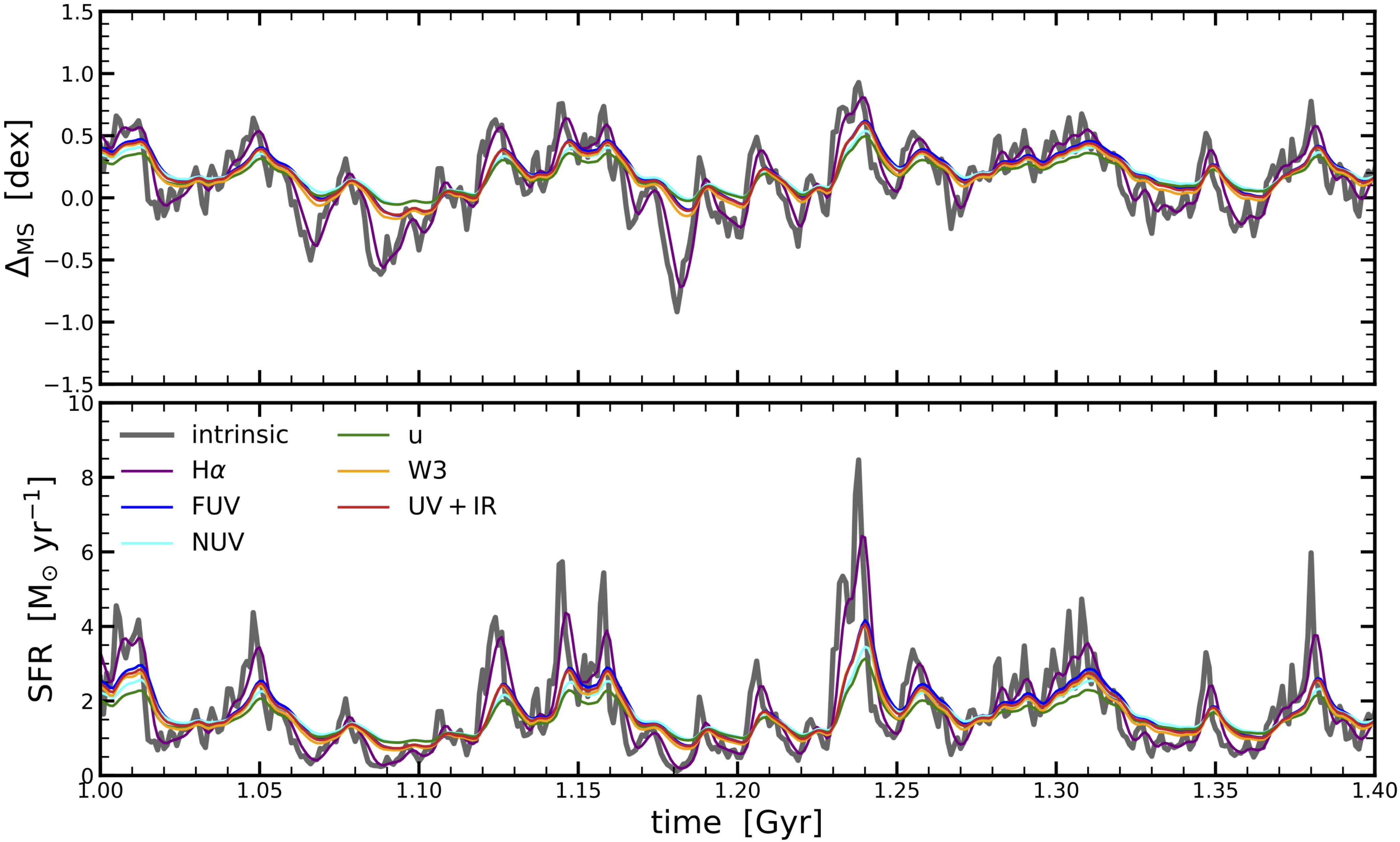

0.3
0.0
-0.3
Δ_{MS} [dex]
8.0
9.0
10.0
11.0
log M [$M_\odot$]



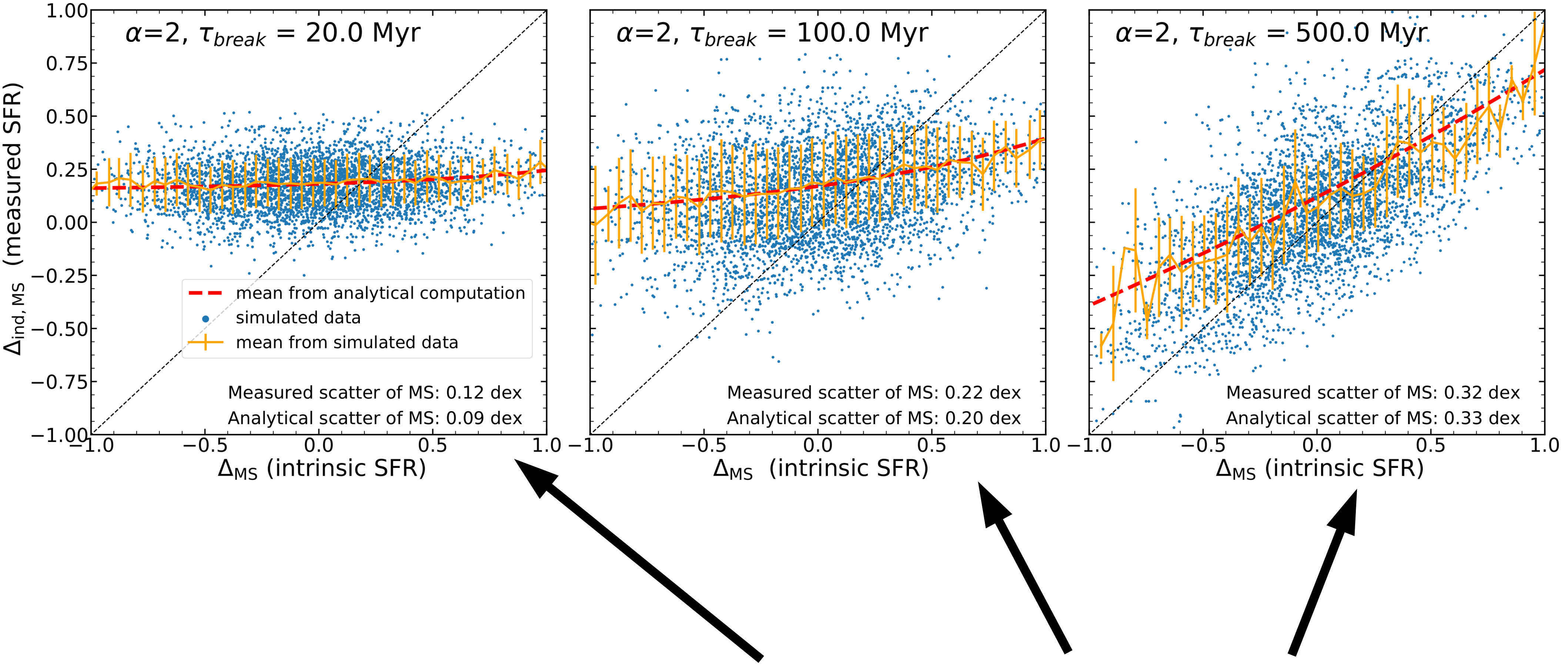
$\alpha = 1.0,\ \tau = 10$ Myr
$\alpha = 1.0,\ \tau = 100$ Myr
$\alpha = 1.0,\ \tau = 1000$ Myr
$\alpha = 2.0,\ \tau = 10$ Myr
$\alpha = 2.0,\ \tau = 100$ Myr
$\alpha = 2.0,\ \tau = 1000$ Myr
$\alpha = 3.0,\ \tau = 10$ Myr
$\alpha = 3.0,\ \tau = 100$ Myr
$\alpha = 3.0,\ \tau = 1000$ Myr
$\Delta_{\rm MS}$ [dex]
time [Myr]



- We do not observe galaxies directly

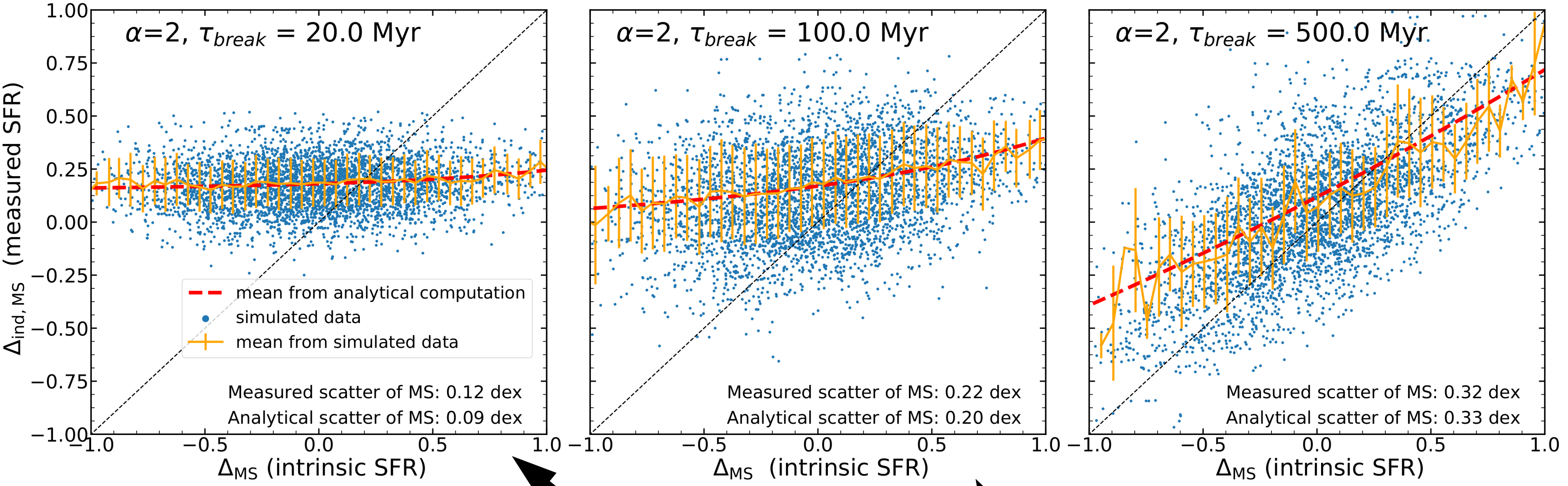


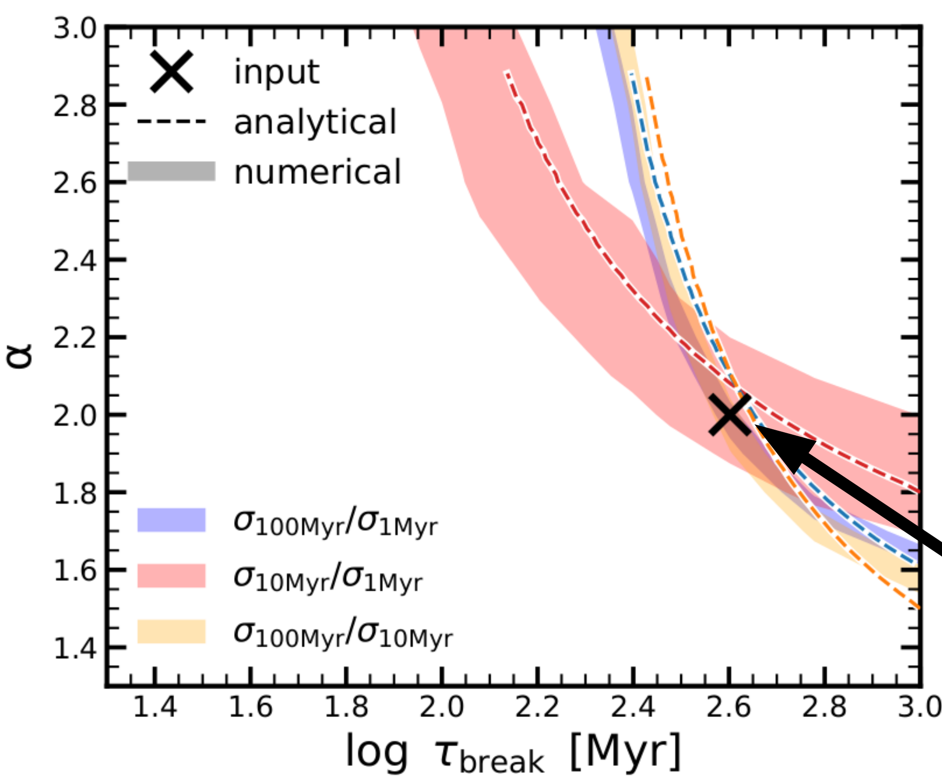
- We do not observe galaxies directly – but we observe more passbands



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

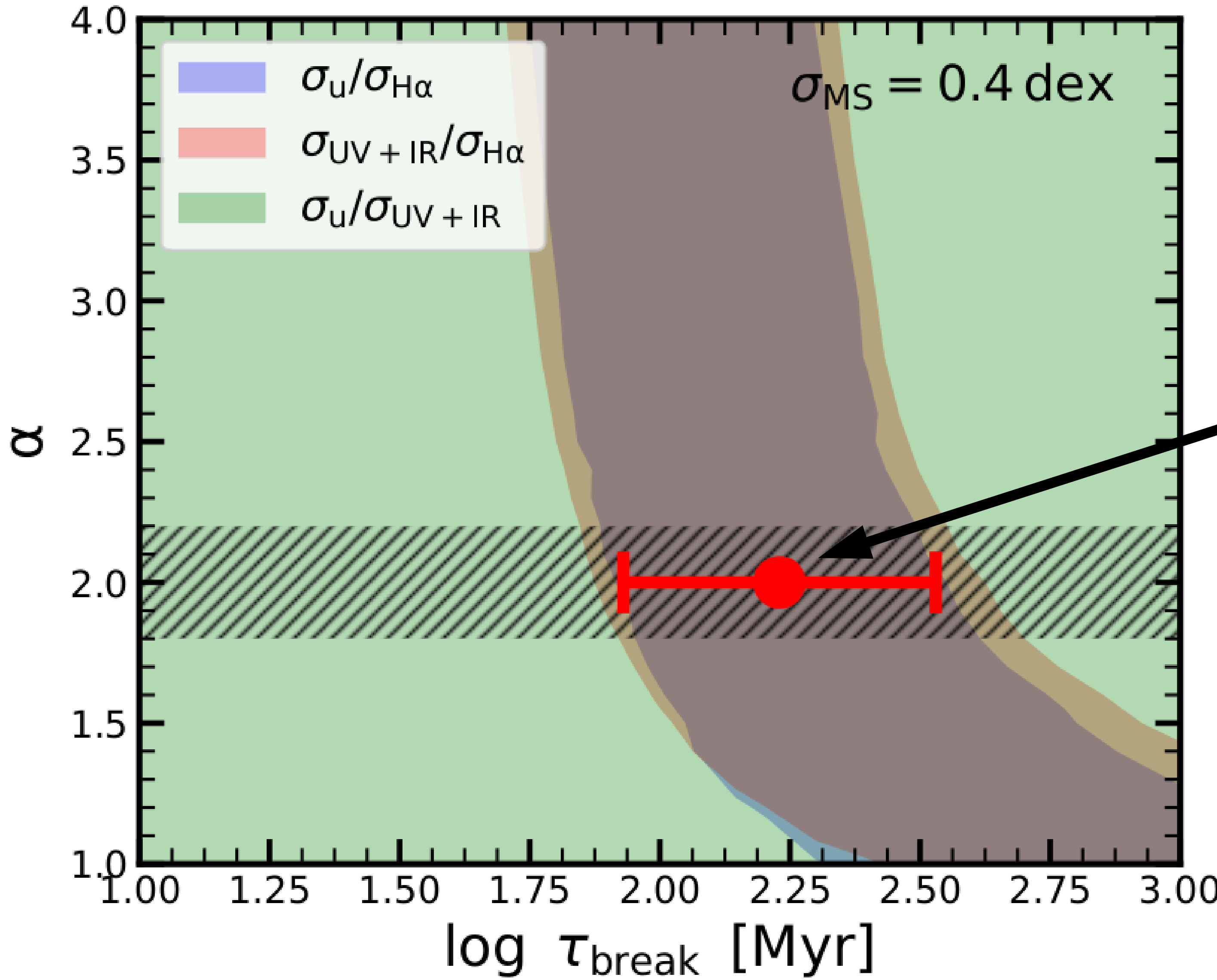
We can recover input values given multiple indicators

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

Observational data:

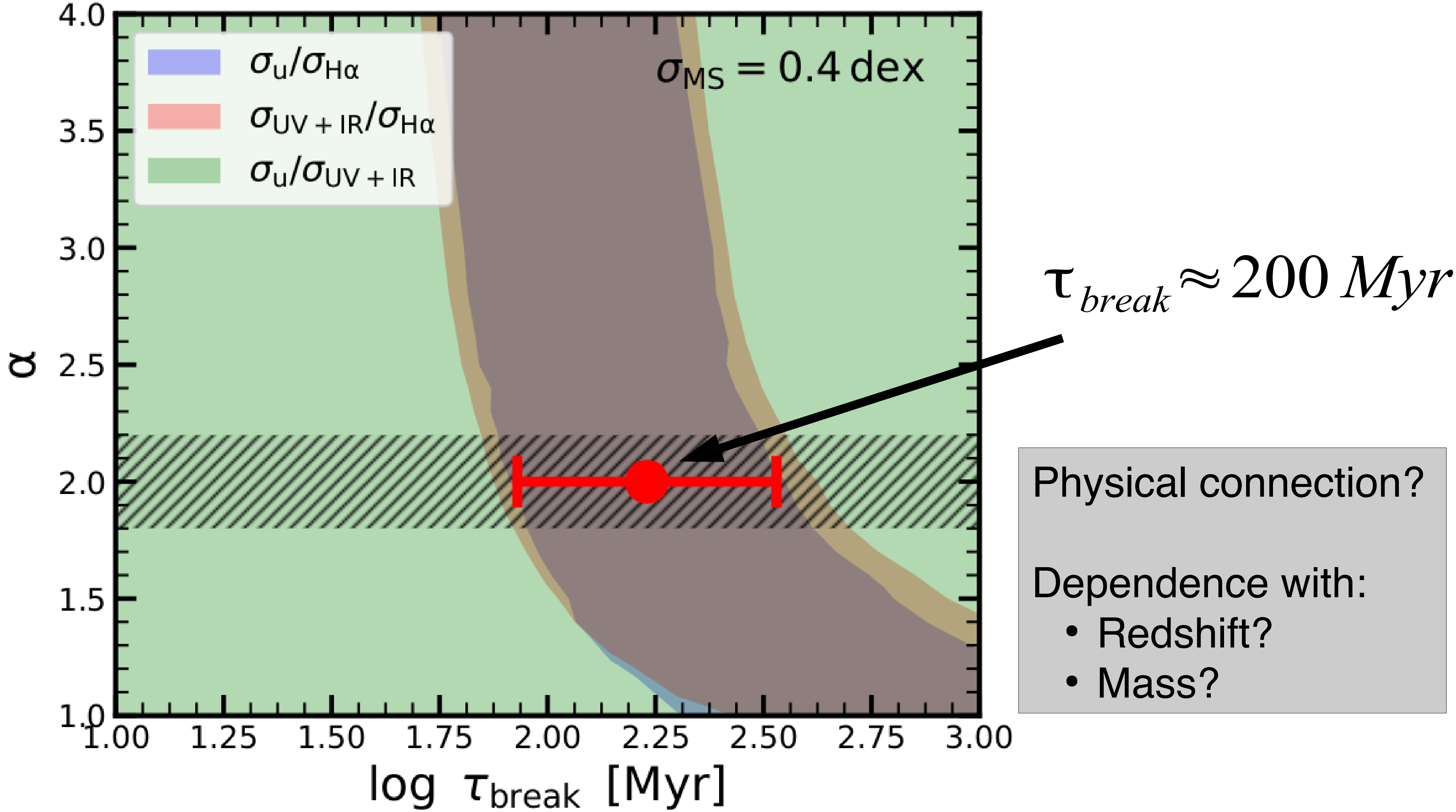
- GAMA survey; z<0.1; 9000 galaxies
- focus here on $M_\star \approx 10^{(10.5)}\ M_\odot$
- Davies+ 2019, measured the MS scatter for different indicators and different star-forming galaxy samples



$\tau_{break} \approx 200\ Myr$

Observational data:

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



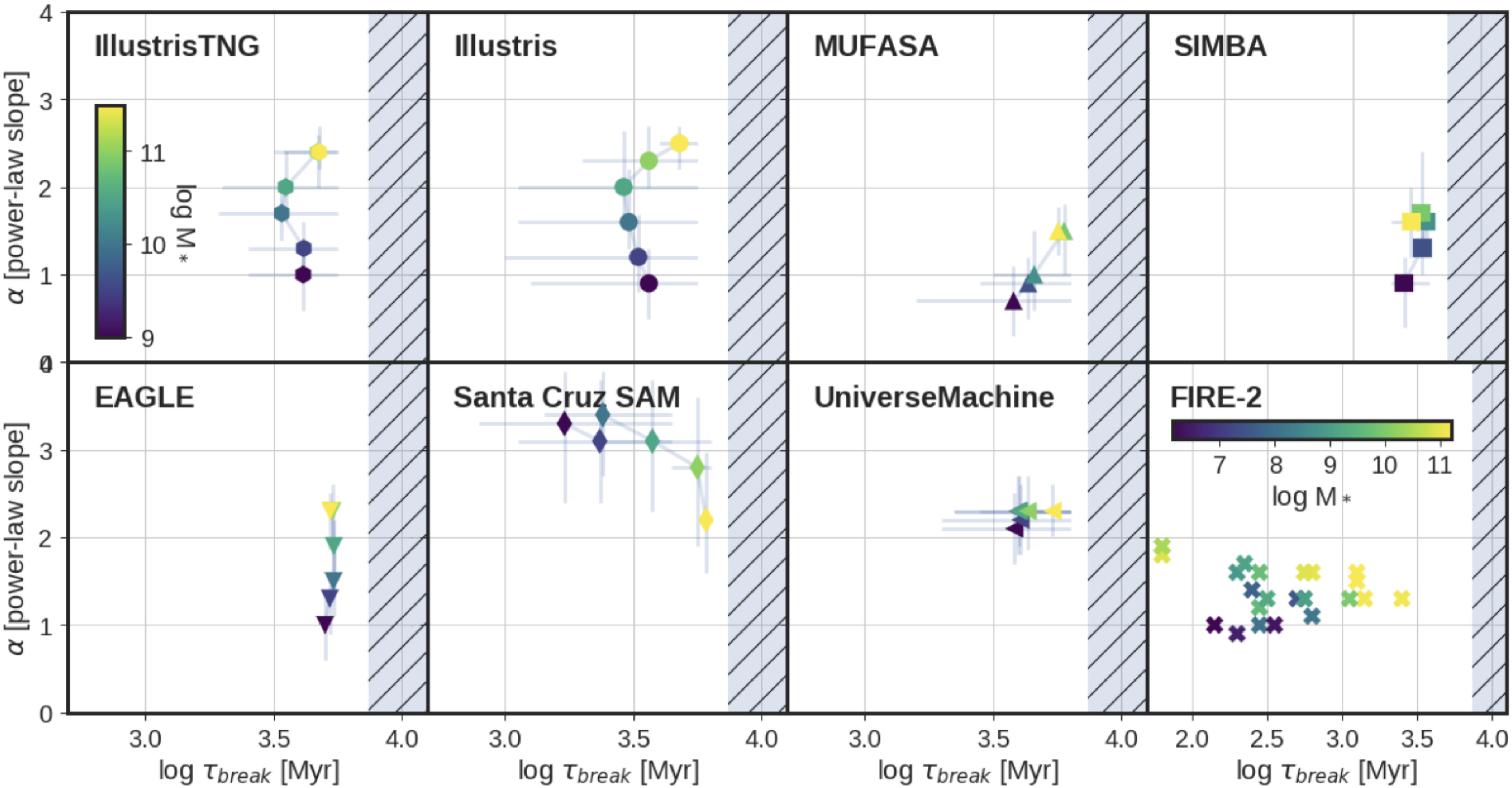
Physical connection?

Dependence with:

- Redshift?
- Mass?

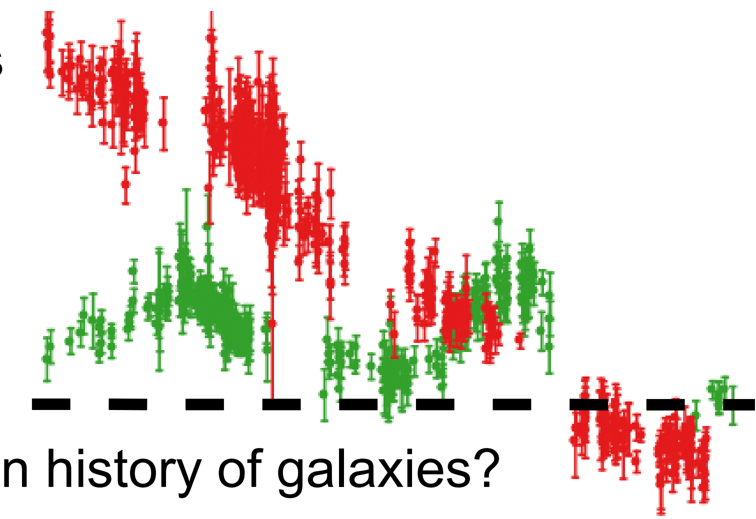
PSDs in different models/simulations

KAVLI SUMMER PROGRAM IN ASTROPHYSICS



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