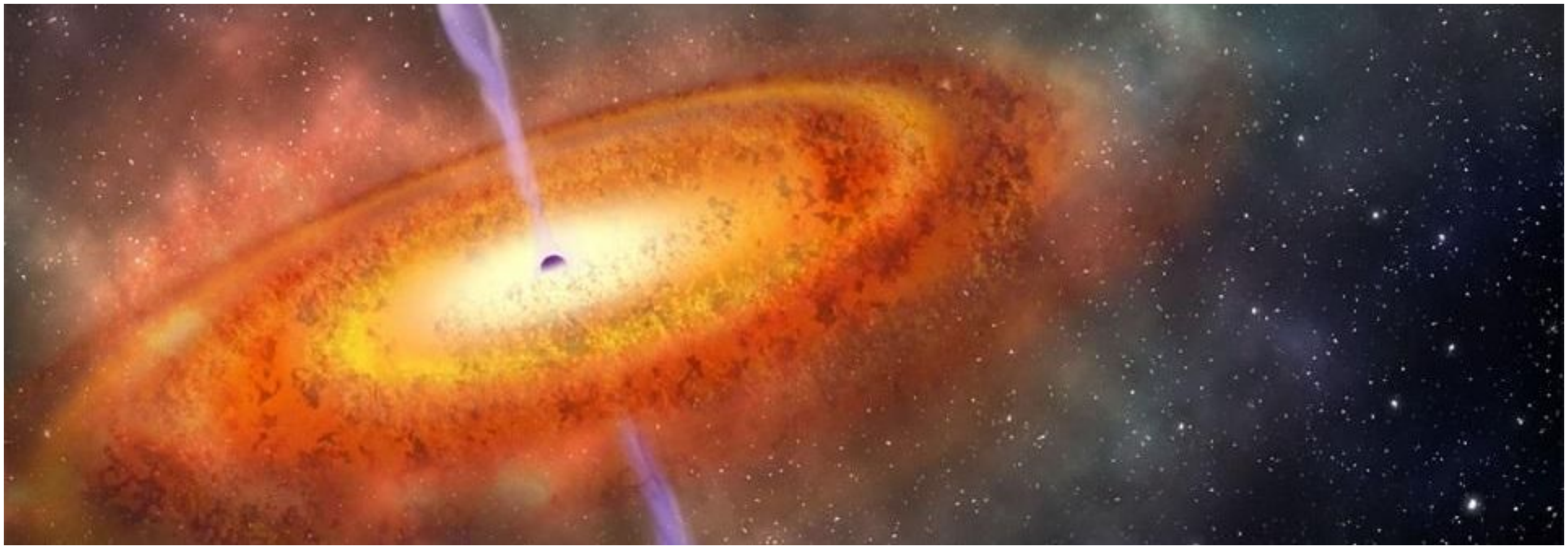
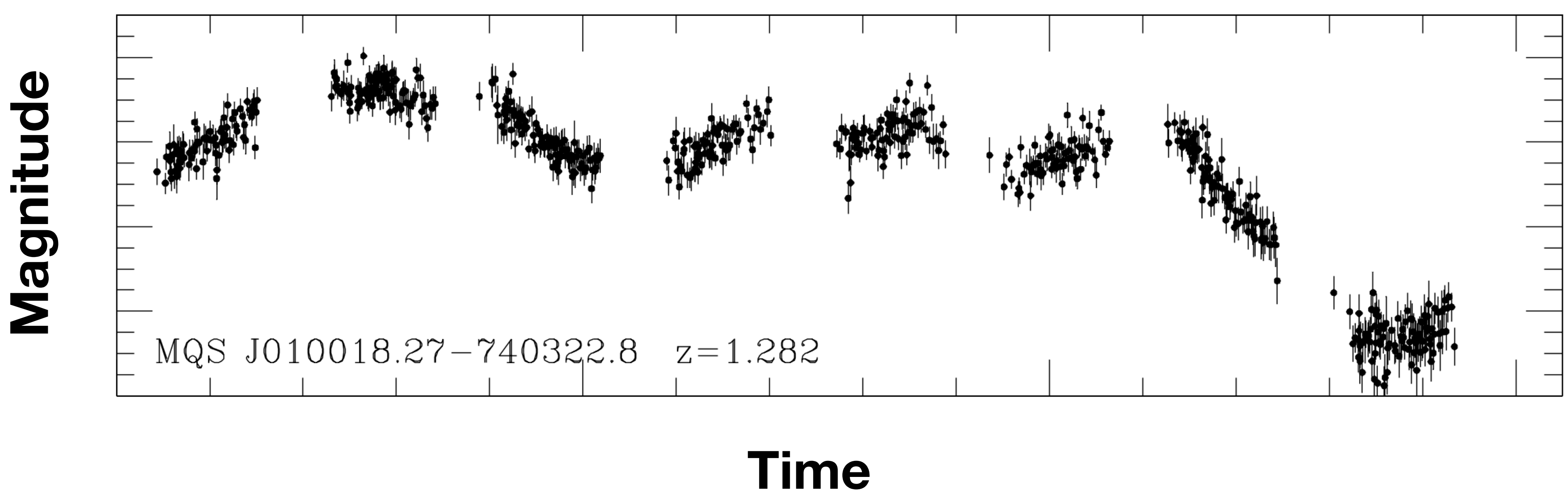
# Time Series Analysis in the Study of Supermassive Black Holes

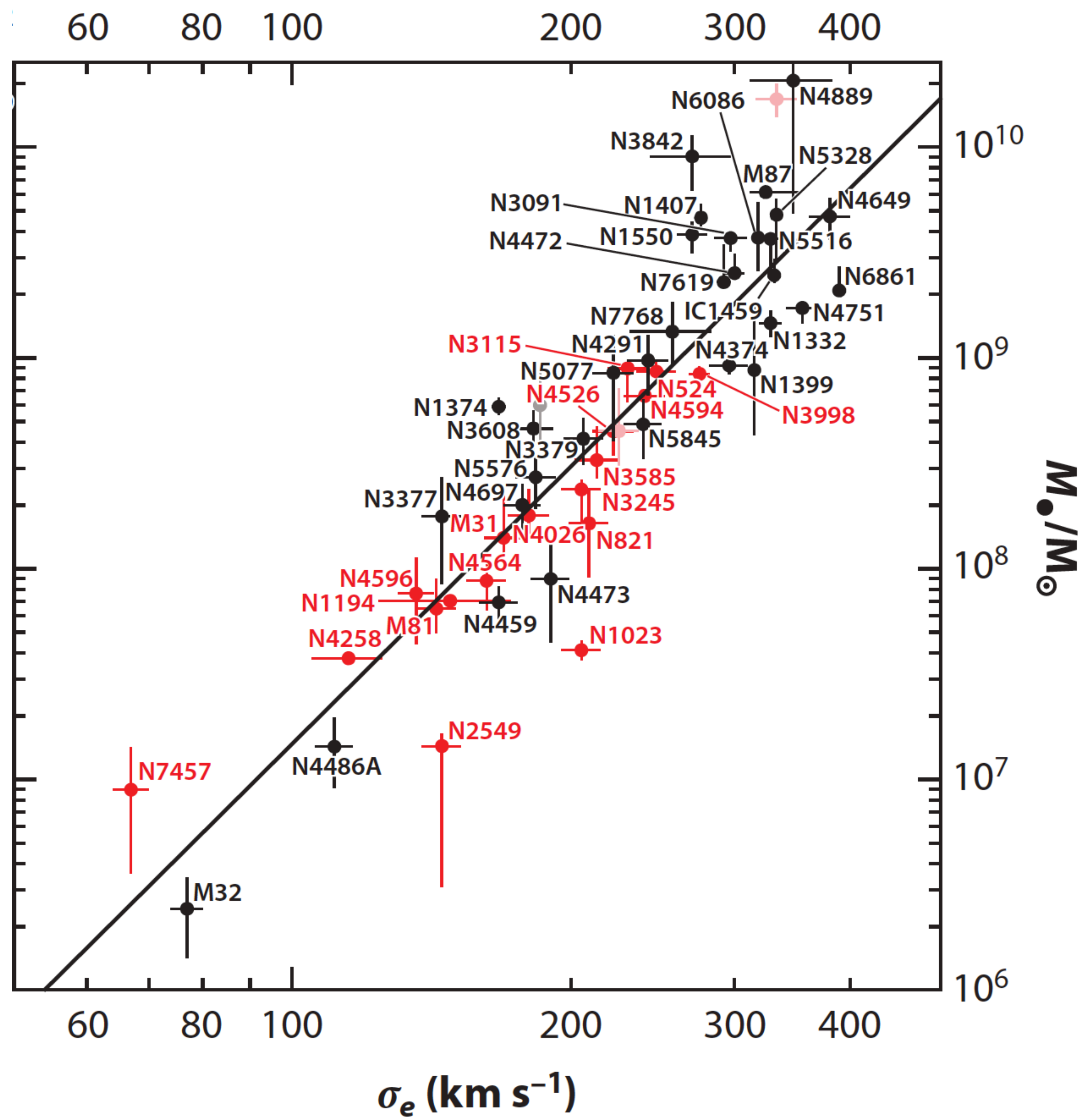
Haowen Zhang

# What are Supermassive Black Holes and Active Galactic Nuclei?



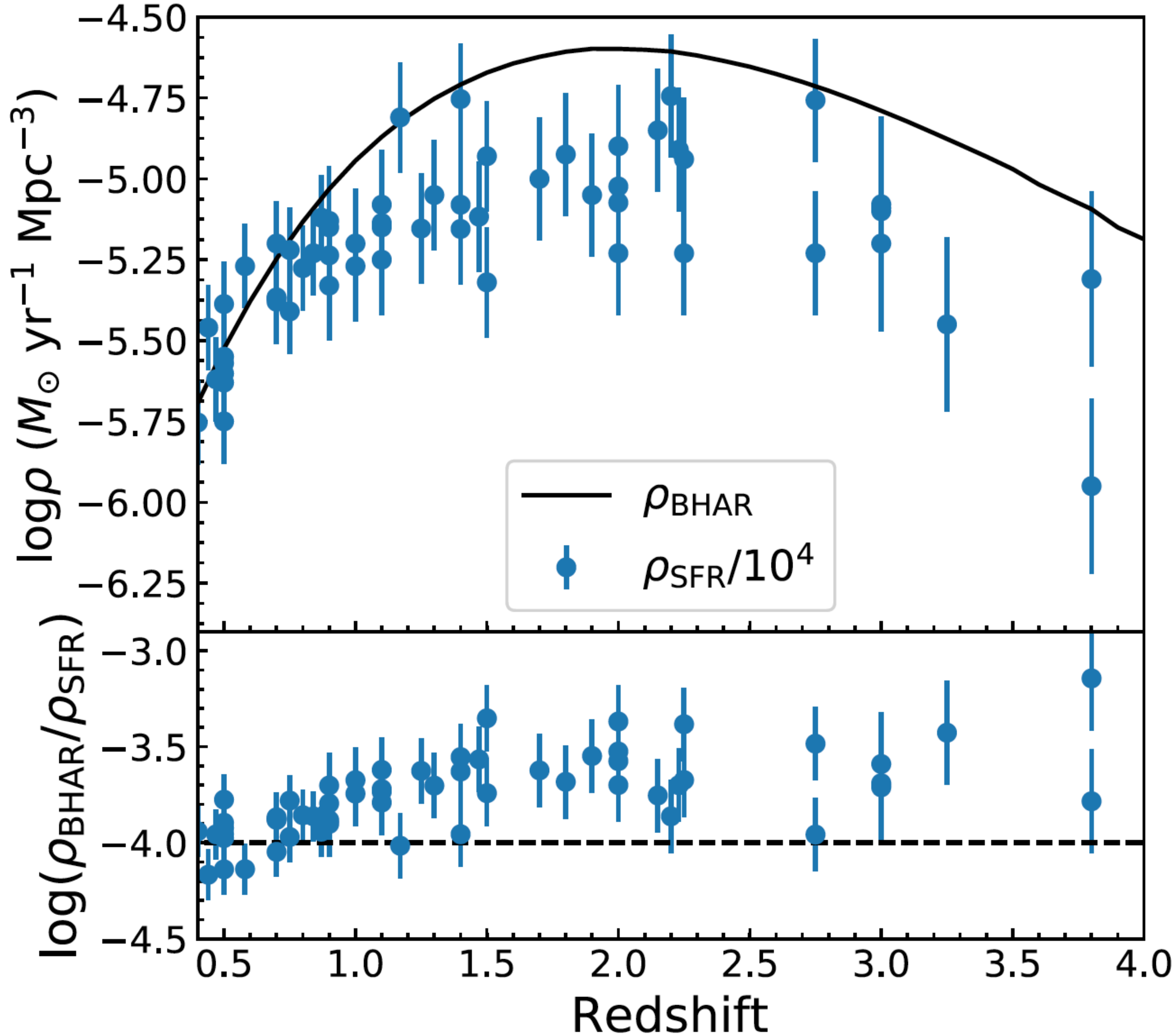


# Why do we care?



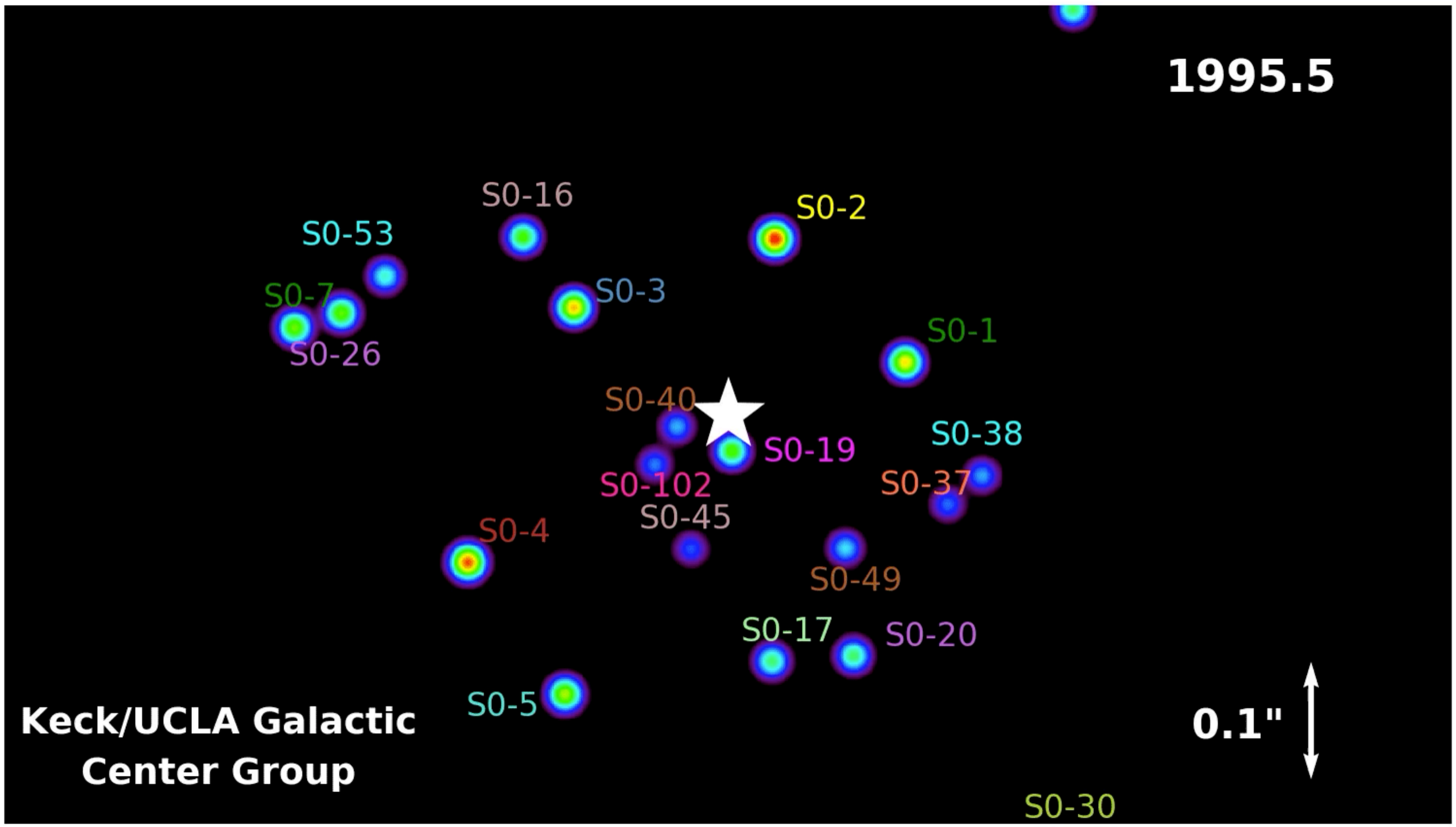

Kormendy & Ho (2013)

# Why do we care?




Yang et al. (2018)

# How to study them?



# How to study them?

Event Horizon Telescope Collaboration

# Beyond z~0?

- Telescopes are too small…

- Possible ways:
  - Accreting SMBHs, or AGN
  - Merging SMBHs

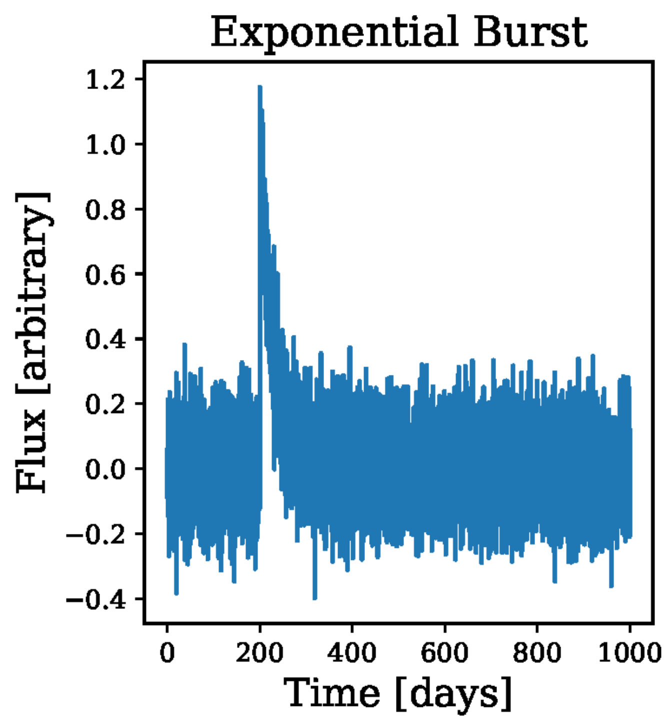
# Step 1: Quantify the Variability

$$\mathrm{CCF}\left(\Delta t\right) = \lim_{T \to +\infty} \frac{\frac{1}{T}\int_{(T)} g\left(t\right) y\left(t + \Delta t\right) dt}{\sigma_g \sigma_y}$$

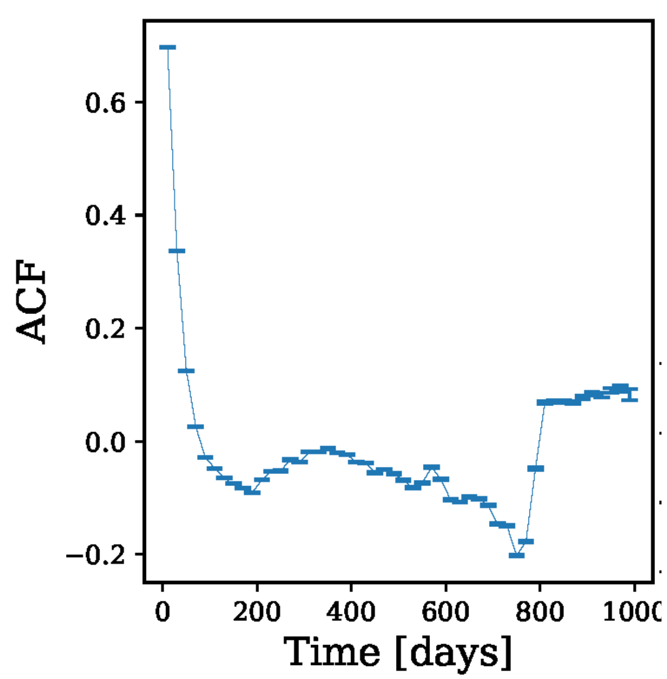
$$\mathrm{SF}\left(\Delta t\right) = \mathrm{SF}_\infty \left(1 - \mathrm{ACF}\left(\Delta t\right)\right)^{1/2}$$

$$\mathrm{SF}_\infty = \lim_{(t_1 - t_2) \to +\infty} \sqrt{\mathrm{Var}\left[y\left(t_1\right) - y\left(t_2\right)\right]}$$

# Examples

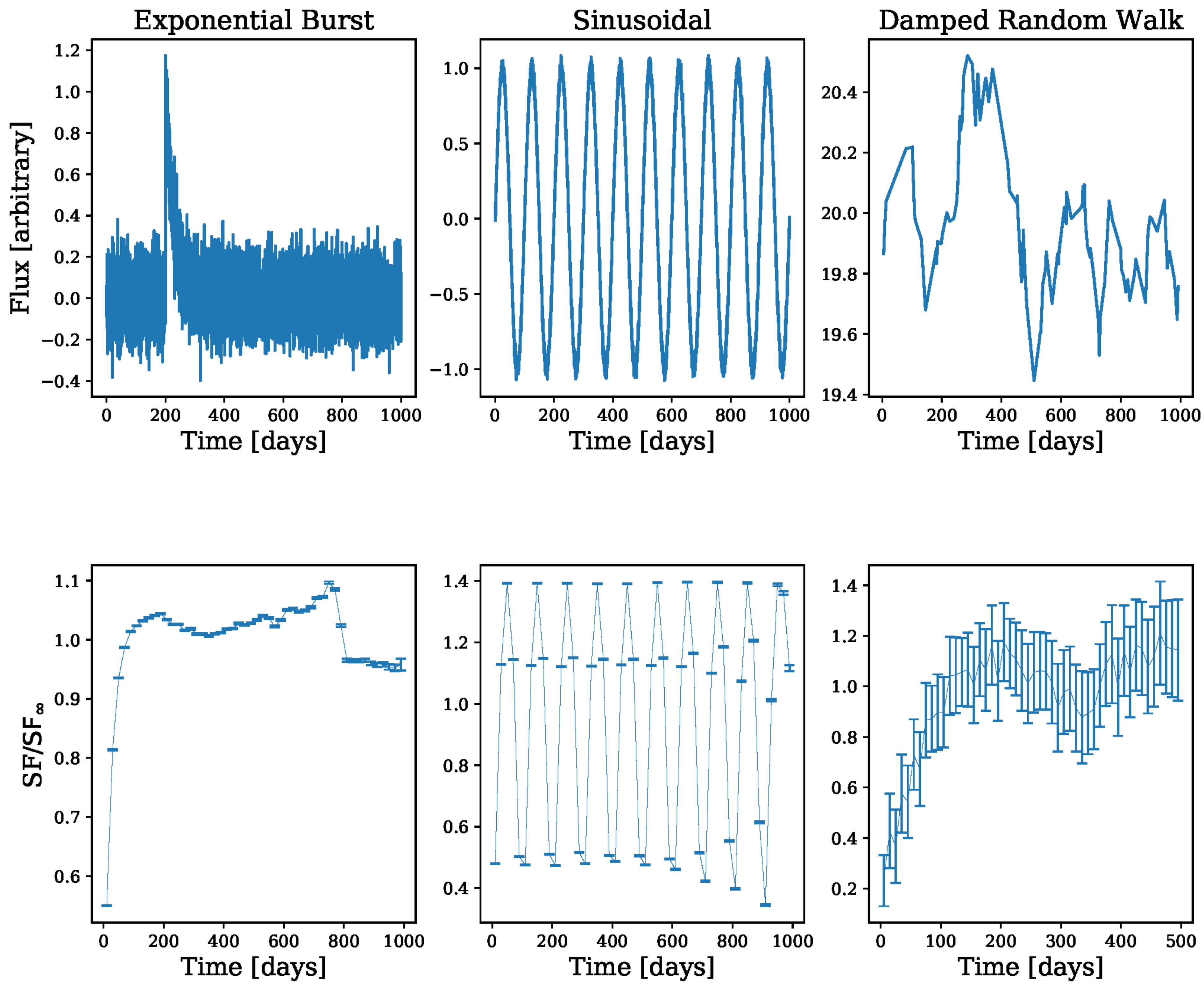


Exponential Burst
Flux [arbitrary]
1.2
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
0
200
400
600
800
1000
Time [days]

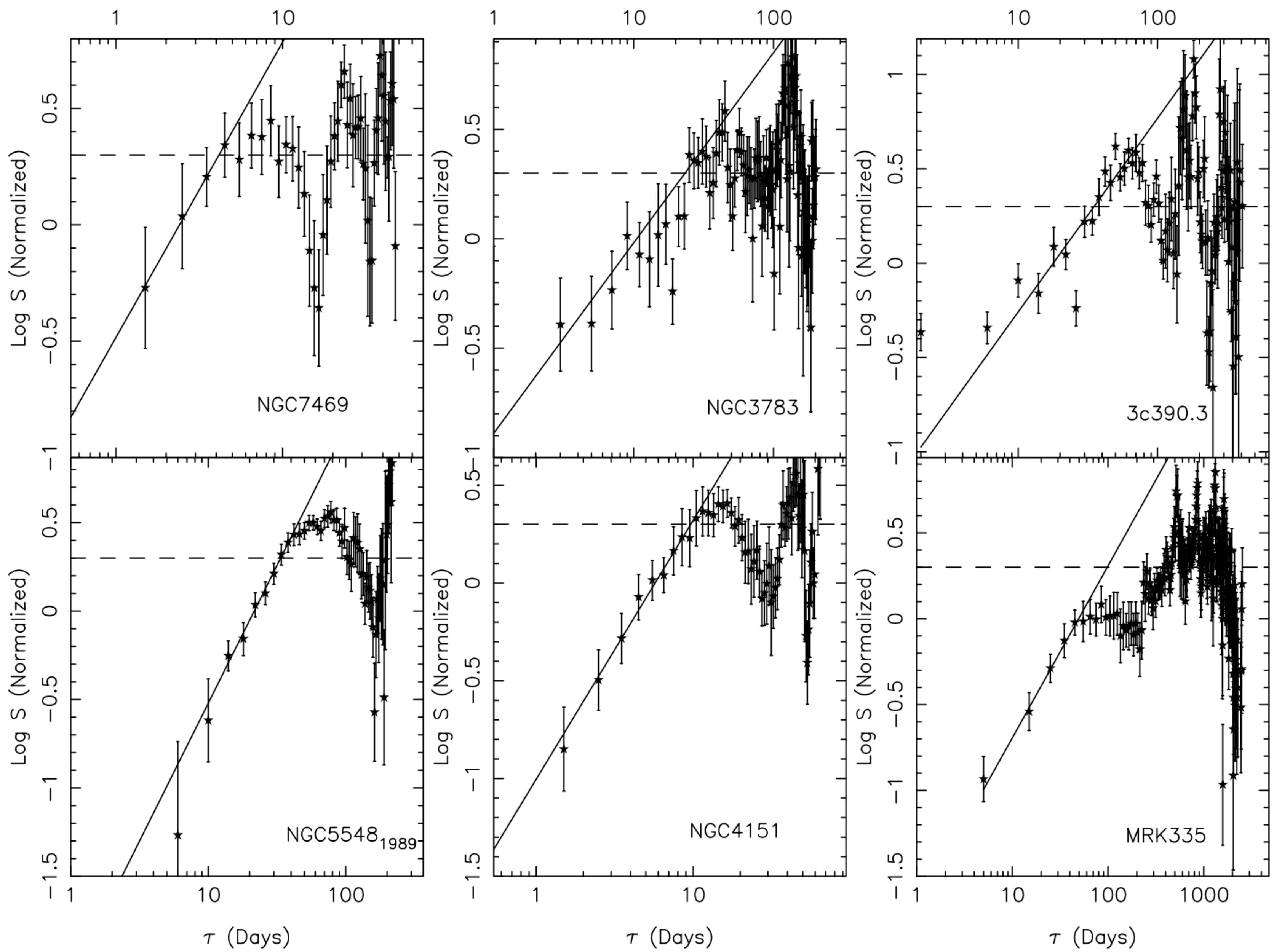
ACF
0.6
0.4
0.2
0.0
−0.2
0
200
400
600
800
Time [days]

# Examples



Exponential Burst
Sinusoidal
Damped Random Walk
Flux [arbitrary]
SF/SF$_\infty$
Time [days]

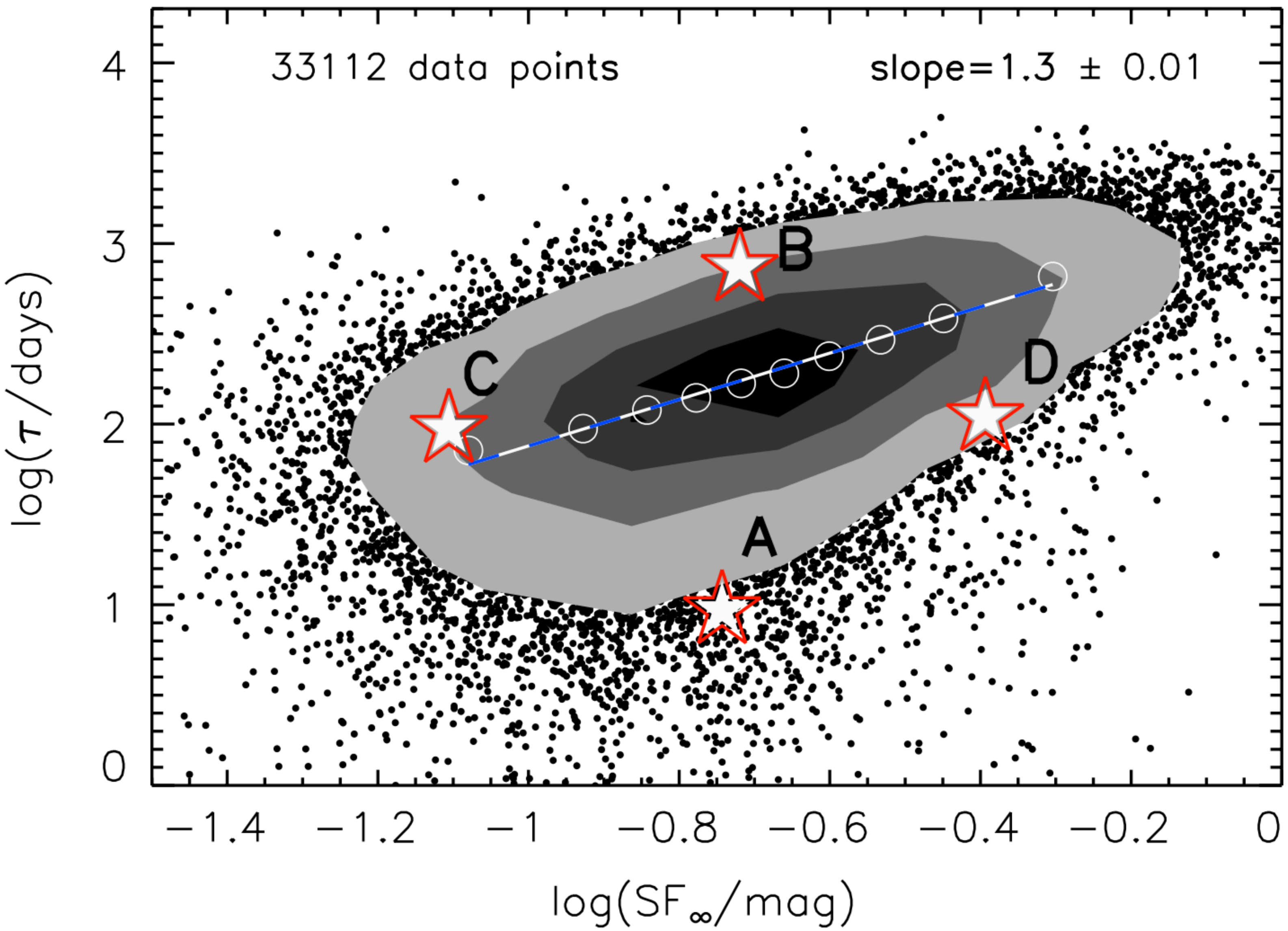
# What does SF tell us?




Collier & Peterson 2001

$$\mathrm{SF}\left(\Delta t\right) = \mathrm{SF}_{\infty}\left(1 - e^{-|\Delta t|/\tau}\right)^{1/2} \qquad \mathrm{ACF}\left(\Delta t\right) = e^{-|\Delta t|/\tau}$$

# What does SF tell us?




$$\tau_{\rm th} \propto L^{1/2}\lambda_{\rm RF}^{2}$$

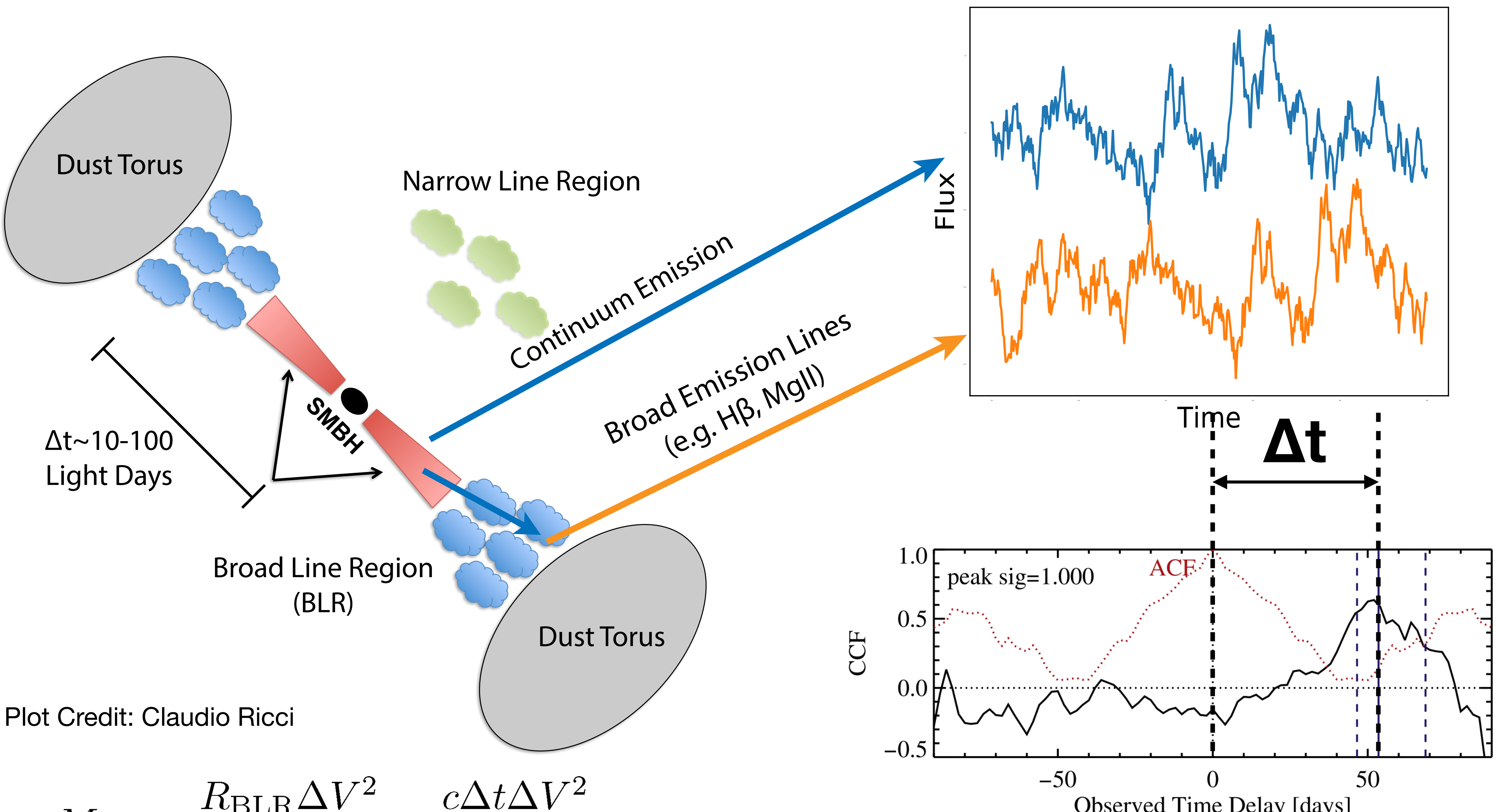
$$\neq$$

$$\tau \propto L^{-0.075}\lambda_{\rm RF}^{0.17}M_{\rm BH}^{0.21}$$

$$\tau_{\rm RF},\ {\rm SF}_{\infty} \propto (1+z)^{0}$$

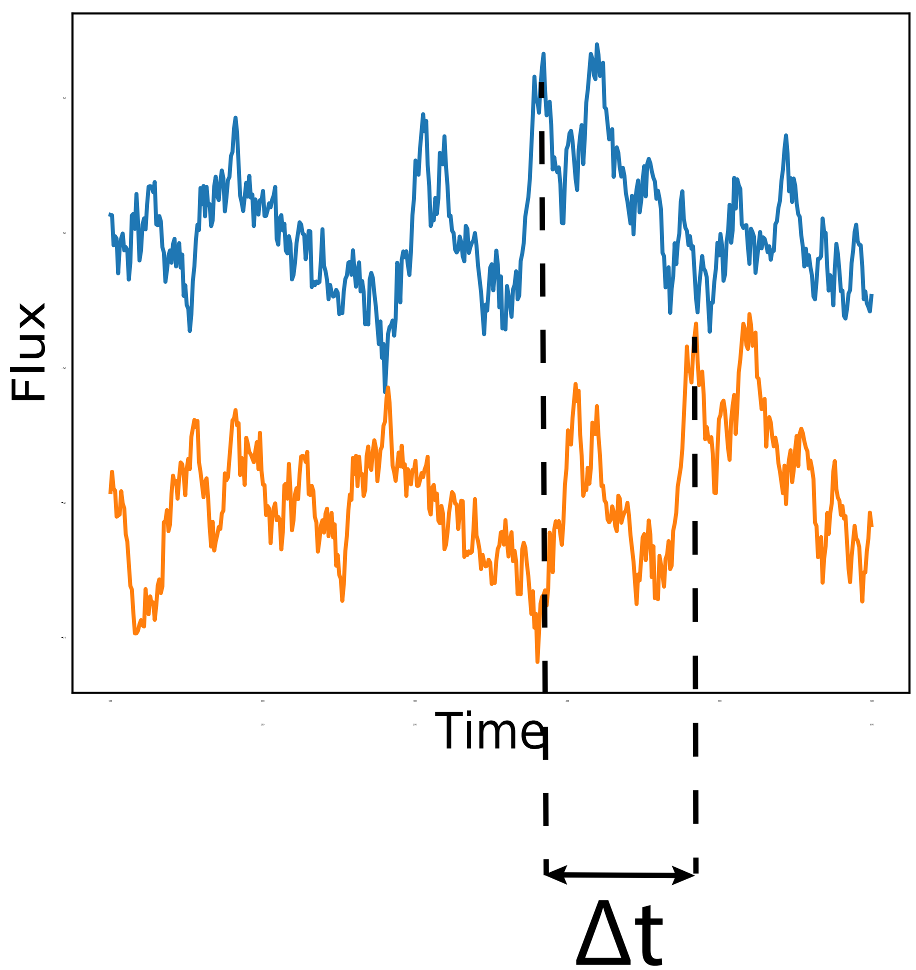
Macleod et al. (2010)

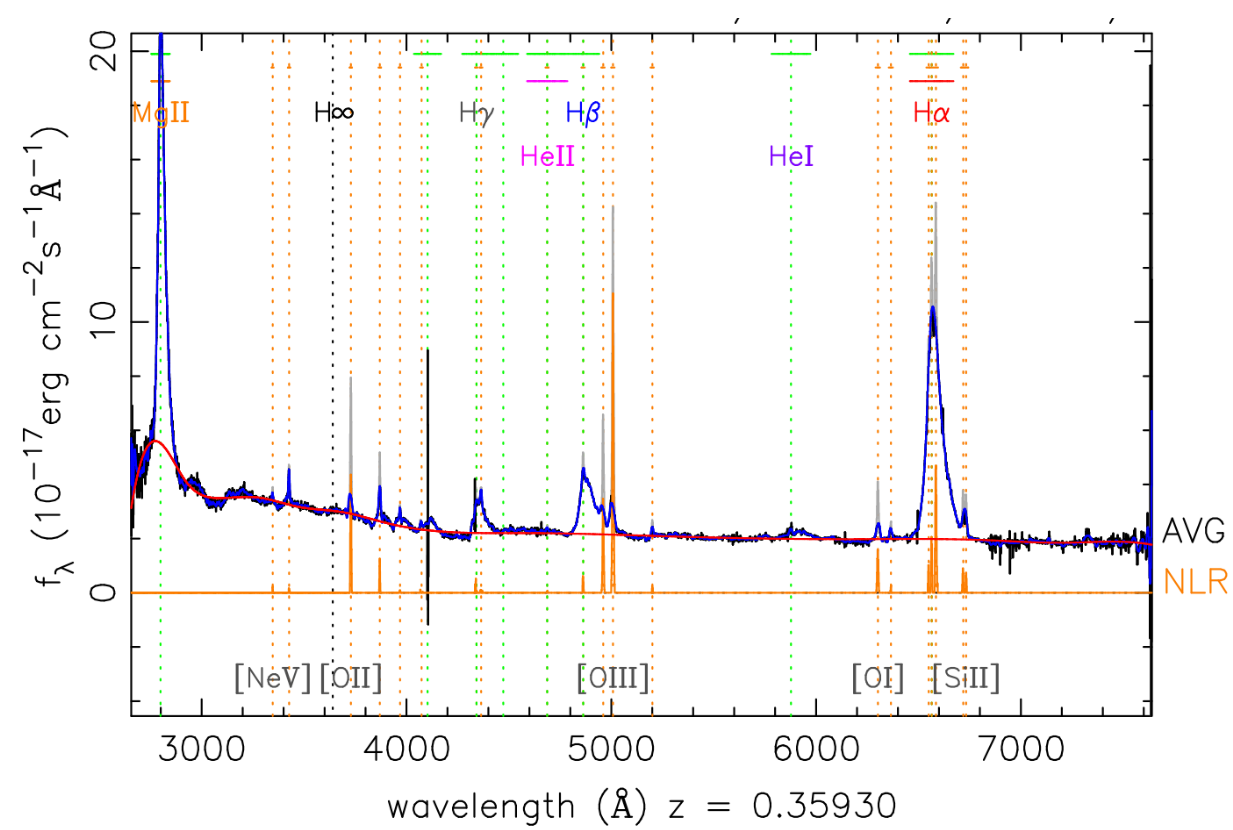
# Reverberation Mapping: Measuring BH mass with AGN variability




Plot Credit: Claudio Ricci

$$M_{\rm BH} \sim \frac{R_{\rm BLR}\Delta V^2}{G} = \frac{c\Delta t \Delta V^2}{G}$$




ΔV

$$M_{\rm BH} \sim \frac{R_{\rm BLR}\Delta V^2}{G} = \frac{c\Delta t\Delta V^2}{G}$$

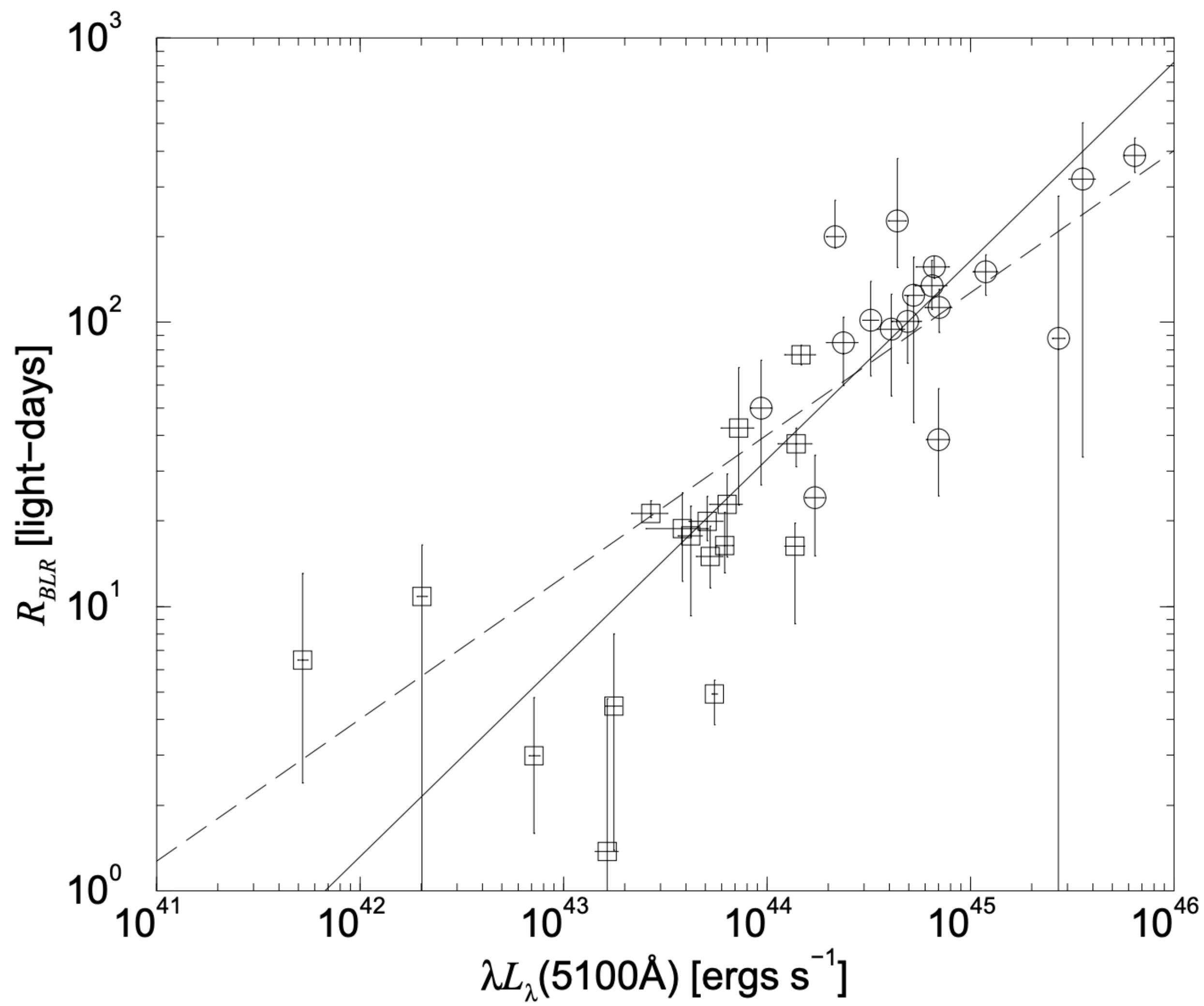
# Downsides?

- Expensive observations: Intensive spectroscopic monitoring

# Solutions?

- Observe many objects at a time (SDSS reverberation mapping, or SDSS V Black Hole Mapper)
- Come up with some scaling relations that require only one spectra
- Use photometry instead of spectroscopy

# Solution: BH Mass Estimation using a single spectra



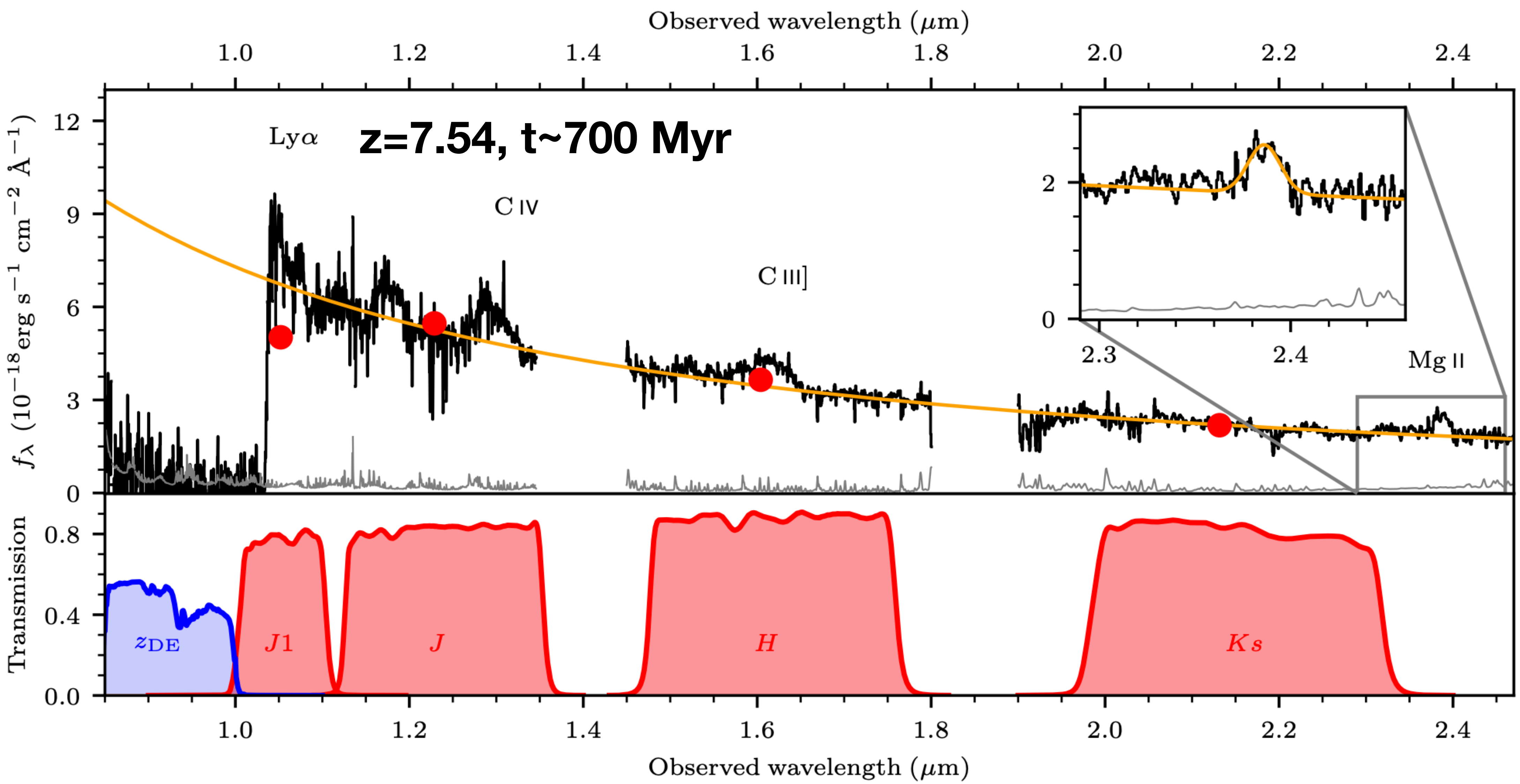

Kaspi et al. (2000)

$$\boxed{\begin{aligned} &R_{\mathrm{BLR}} = K\,(\lambda L_\lambda)^\alpha \\ &M_{\mathrm{BH}} \sim \frac{R_{\mathrm{BLR}}\Delta V^2}{G} = \frac{c\Delta t \Delta V^2}{G} \end{aligned}}$$

$$\downarrow$$

$$M_{\mathrm{BH}} \sim \frac{K\,(\lambda L_\lambda)^\alpha\,\Delta V^2}{G}$$

# Application: Weigh the most distant SMBH




**+ 0.55 dex from the scaling relation!**

$$M_{\rm BH} = 7.8\boxed{^{+3.3}_{-1.9}} \times 10^8 M_\odot$$

Bañados et al. (2017)

# Downsides?

- Expensive observations: Intensive spectroscopic monitoring

# Solutions?

- Observe many objects at a time (SDSS reverberation mapping, or SDSS V Black Hole Mapper)
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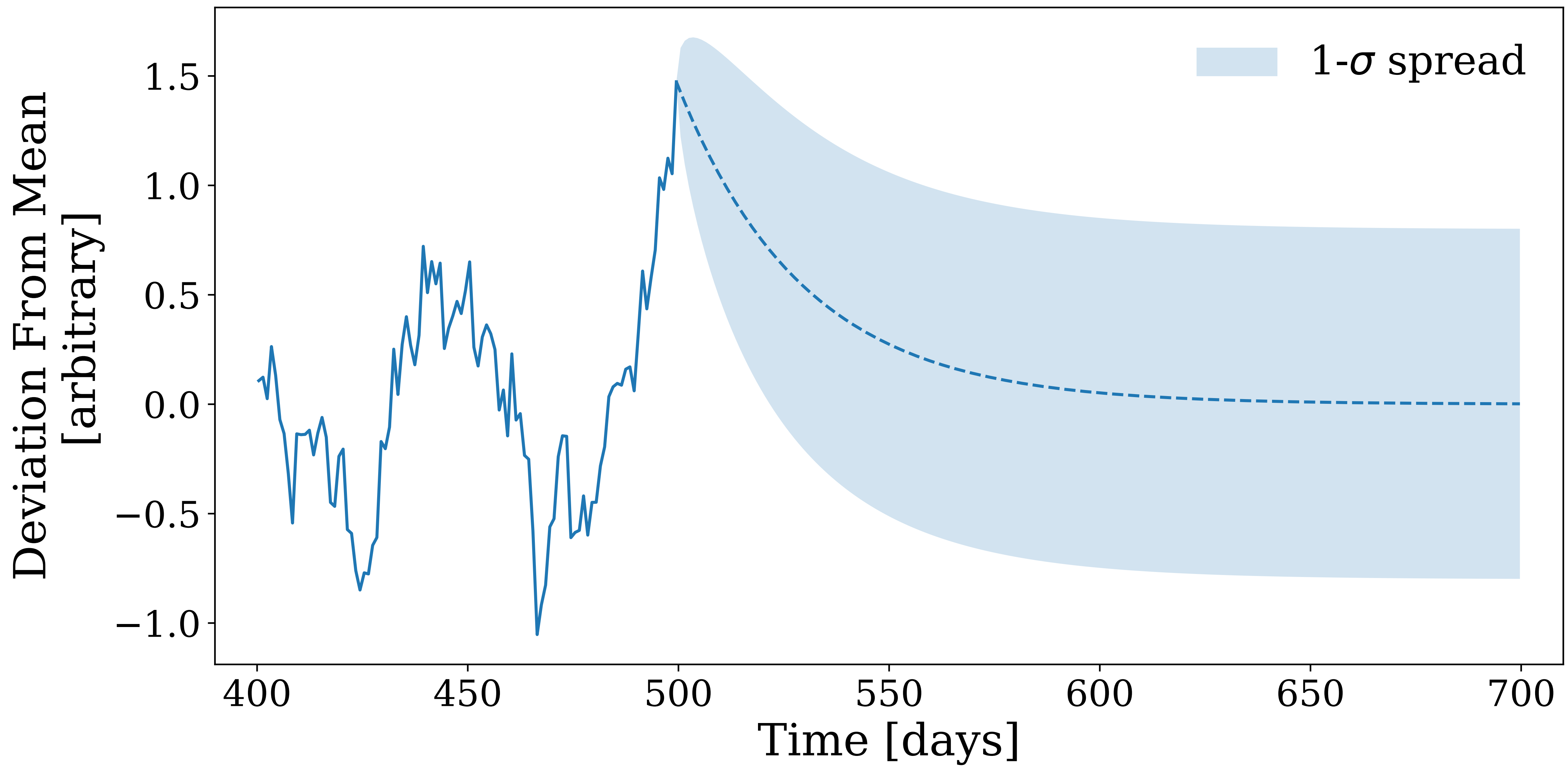
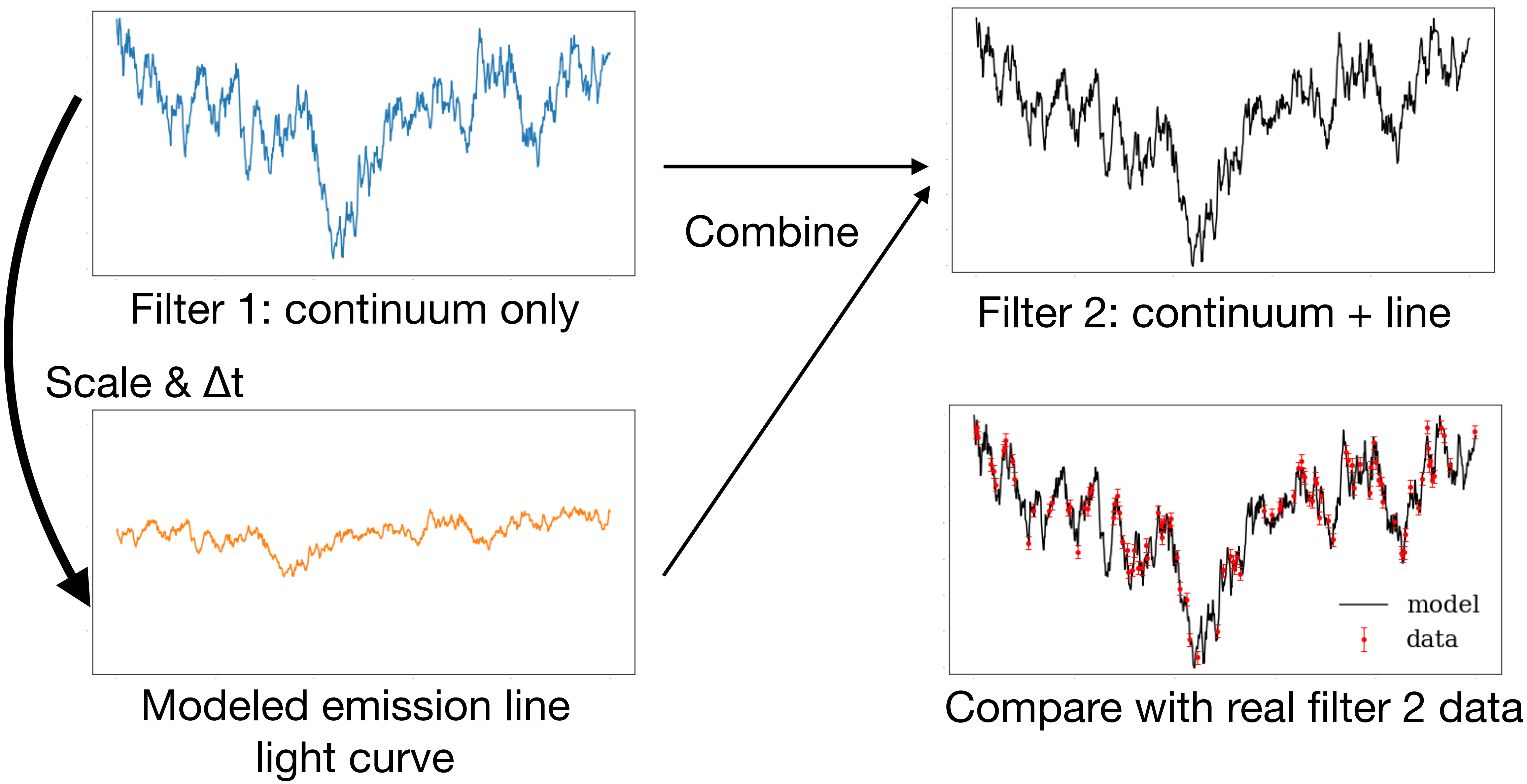
# Solution: Photometric Reverberation Mapping




$$E\left(X\left(t\right)|X\left(t-\Delta t\right)\right)=X\left(t-\Delta t\right)e^{-\Delta t/\tau}+\mu\left(1-e^{-\Delta t/\tau}\right)$$

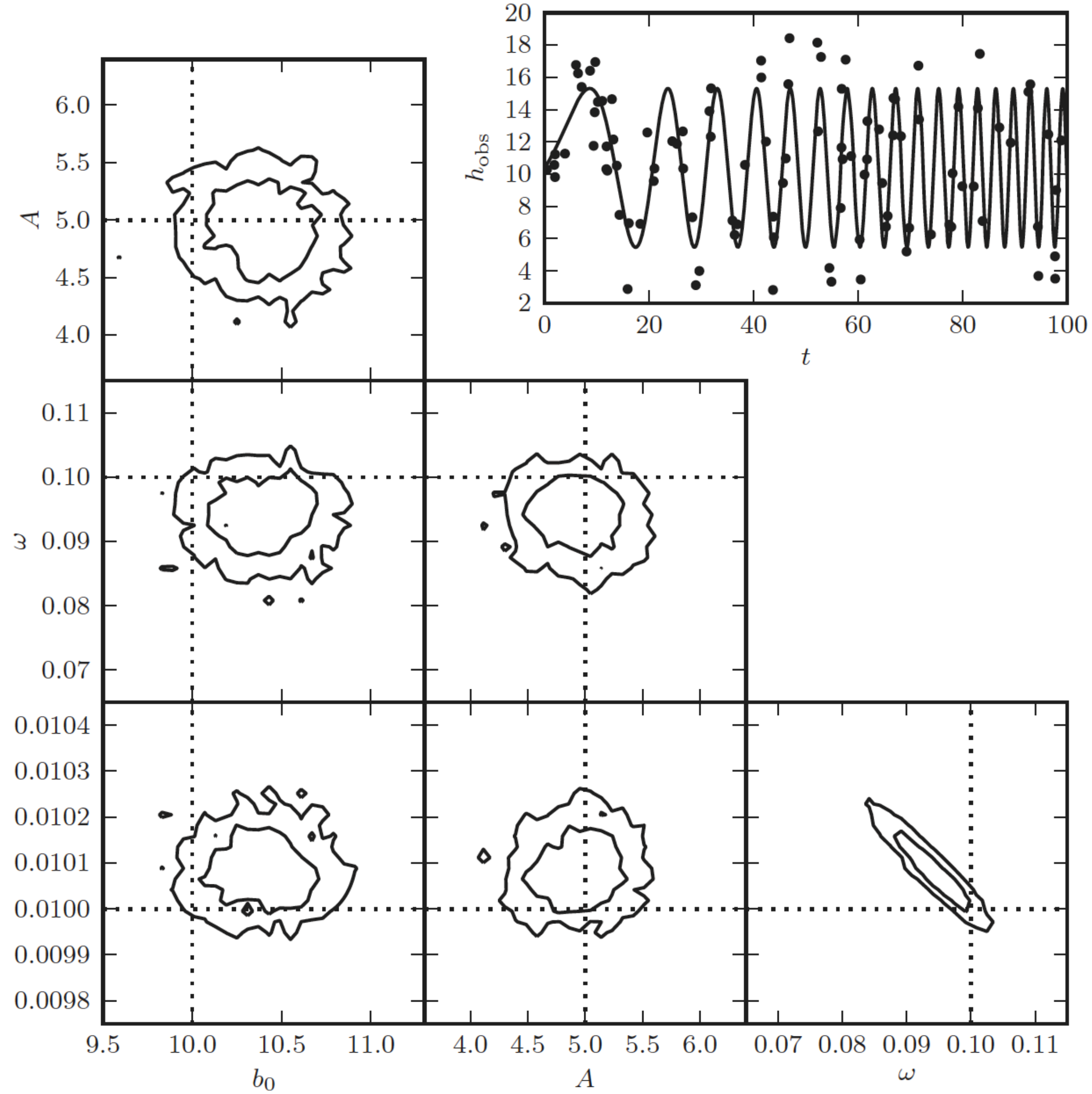
$$\mathrm{Var}\left(X\left(t\right)|X\left(t-\Delta t\right)\right)=\frac{\sigma^2}{2}\left(1-e^{-2\Delta t/\tau}\right)$$

# Modeling AGN Light Curves




$$M_{\mathrm{BH}} \sim \frac{R_{\mathrm{BLR}} \Delta V^2}{G} = \frac{c \Delta t \Delta V^2}{G}$$

# Merging SMBHs?




$$y(t) = b_0 + A\sin[\omega t + \beta t^2]$$

# Takeaways

- AGN variability: Key to accretion disk physics and SMBH mass measurements
- Study of AGN autocorrelation functions or structure functions: Physical origin of variability
- Reverberation mapping: measure the size of broad line regions (BLR) to infer BH mass
- Damped Random Walk: good fit to AGN variability.