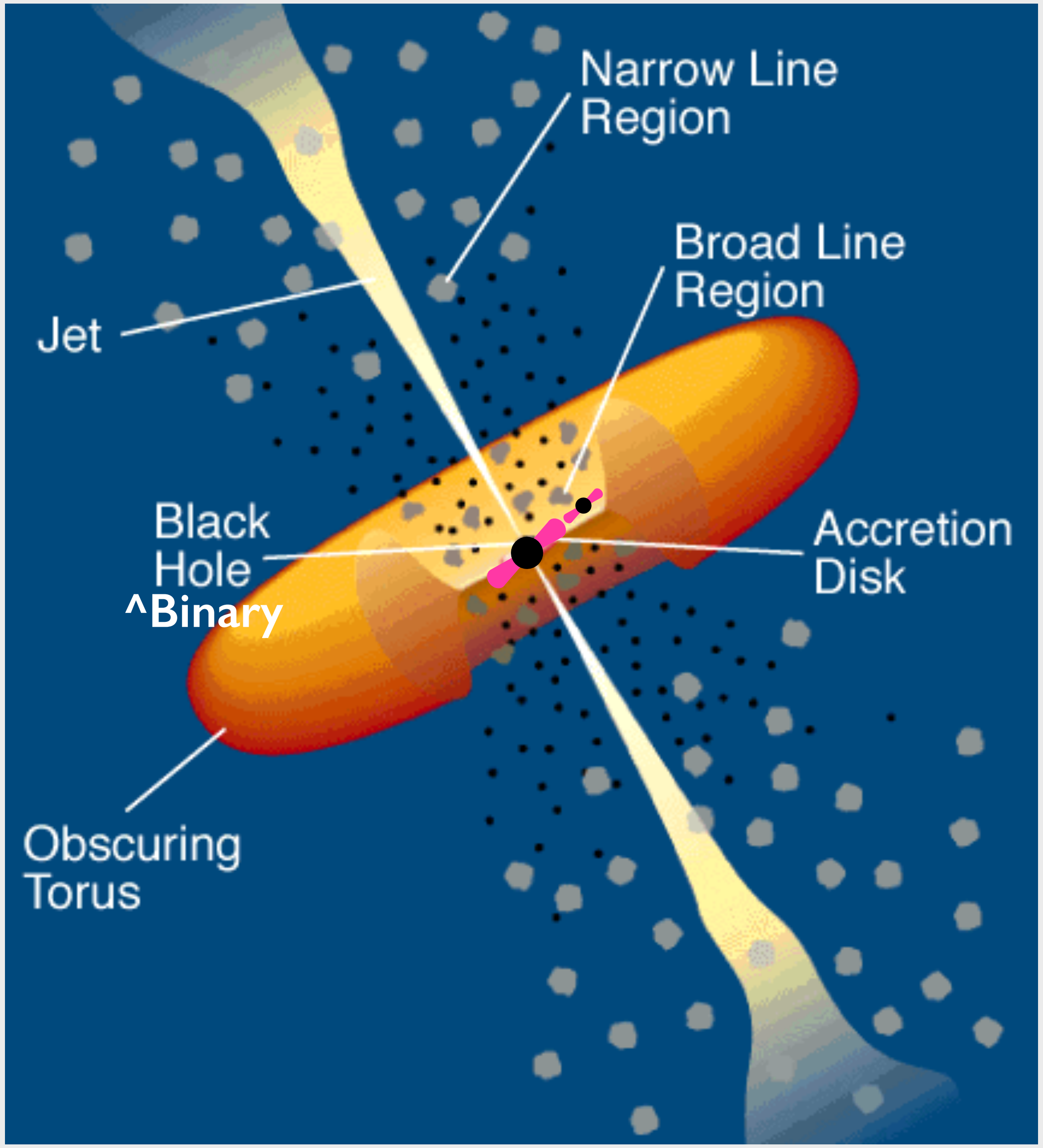
Tips For Finding Massive Black Hole Binaries:
(have any?)

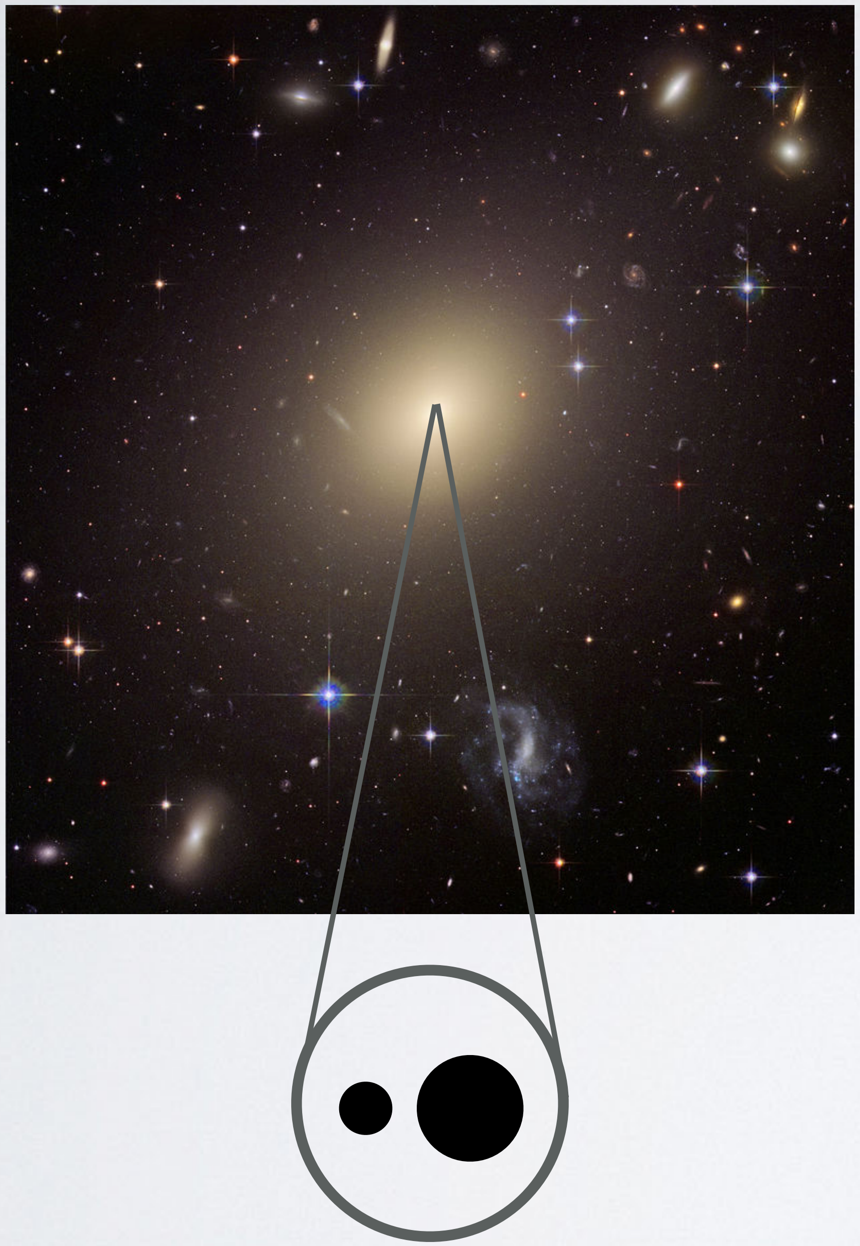


Daniel J. D'Orazio

Einstein Fellowship Symposium

Wednesday October 19, 2016

Massive Black Hole Binaries (MBHBs)

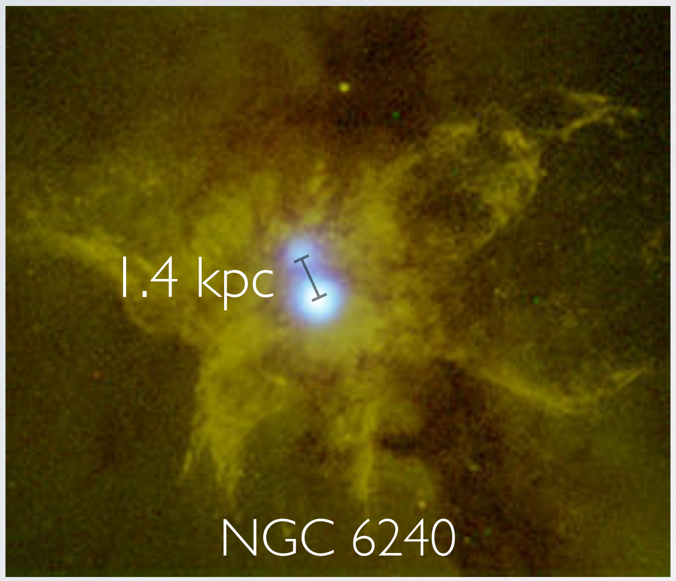


$$M_{\rm bin} \sim 10^6 \rightarrow 10^{10} {\rm M}_\odot$$

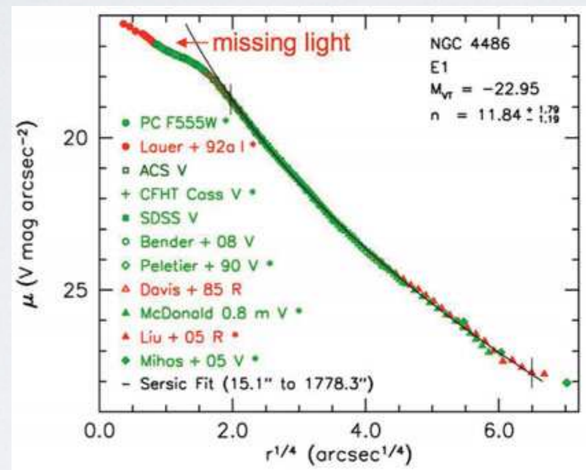
* Most energetic gravitational wave sources in the Universe - probe of gravity
* Can teach us about the mutual evolution of galaxies and MBHs
* How do we find them? They don't (necessarily) exist in vacuum!

Electromagnetic MBHB evidence/searches

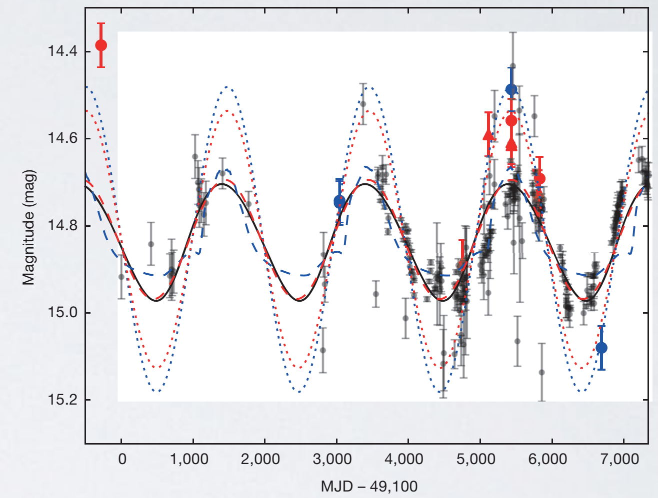
Dual AGN



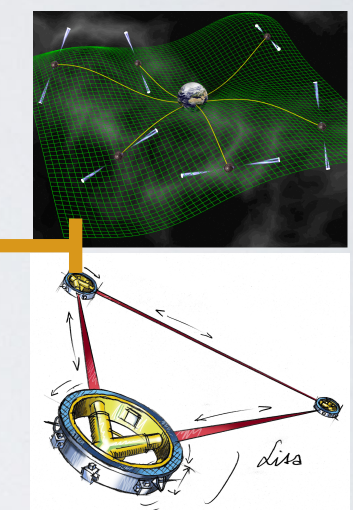
Core ellipticals



Periodic light curves



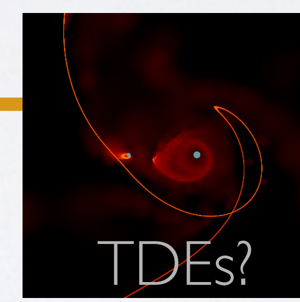
Grav waves



Separation

~kpc

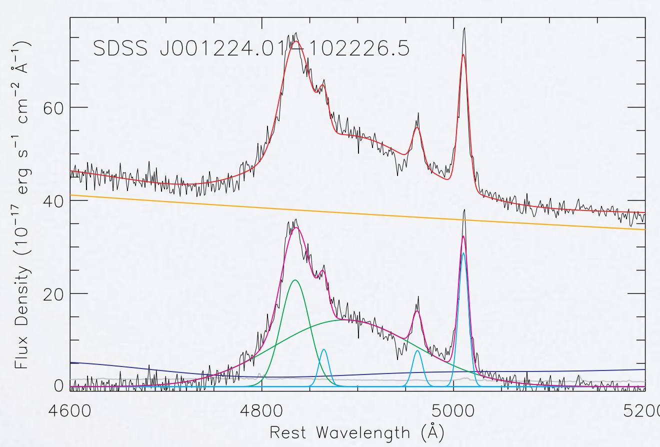
~pc

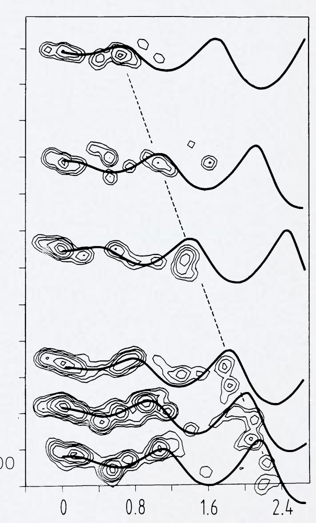


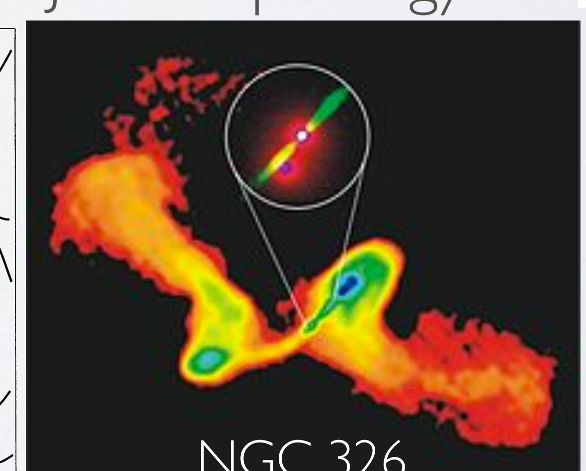
~sub-pc

Jet morphology

Broad line monitoring



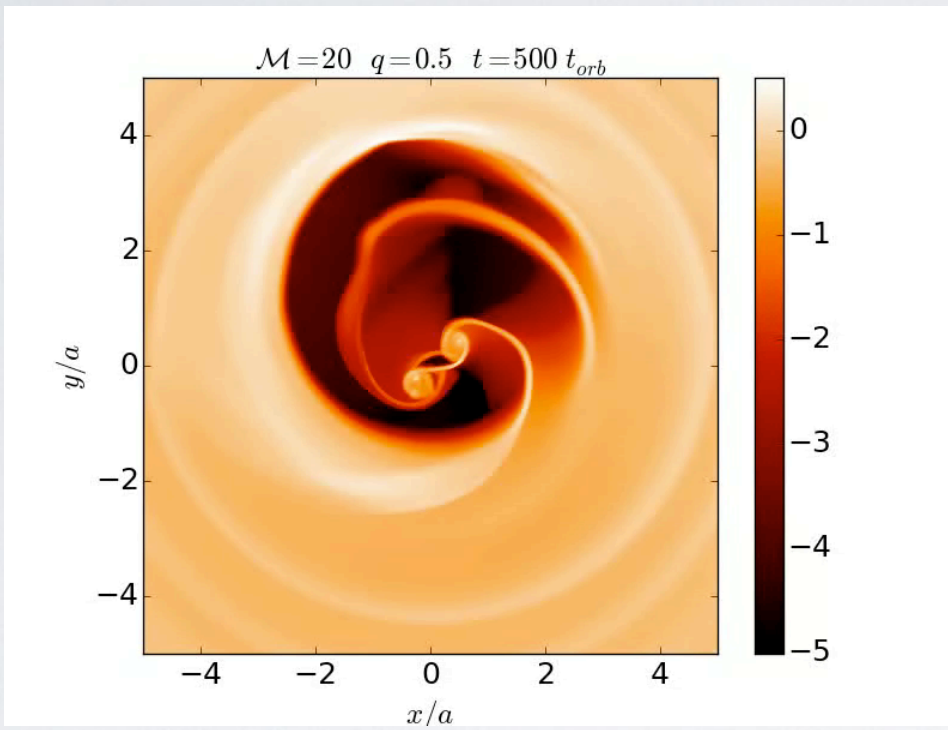




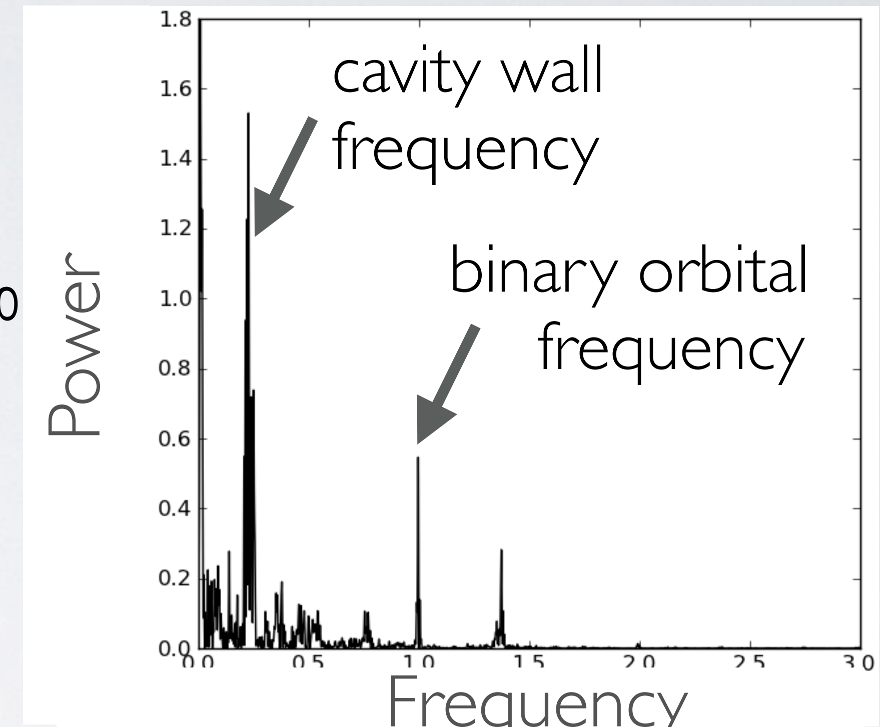
EM signatures: Binary gas accretion

Periodic accretion

Surface Density



Accretion-rate Periodogram



Binary BH accretion rate:

*can exceed the rate for a single BH

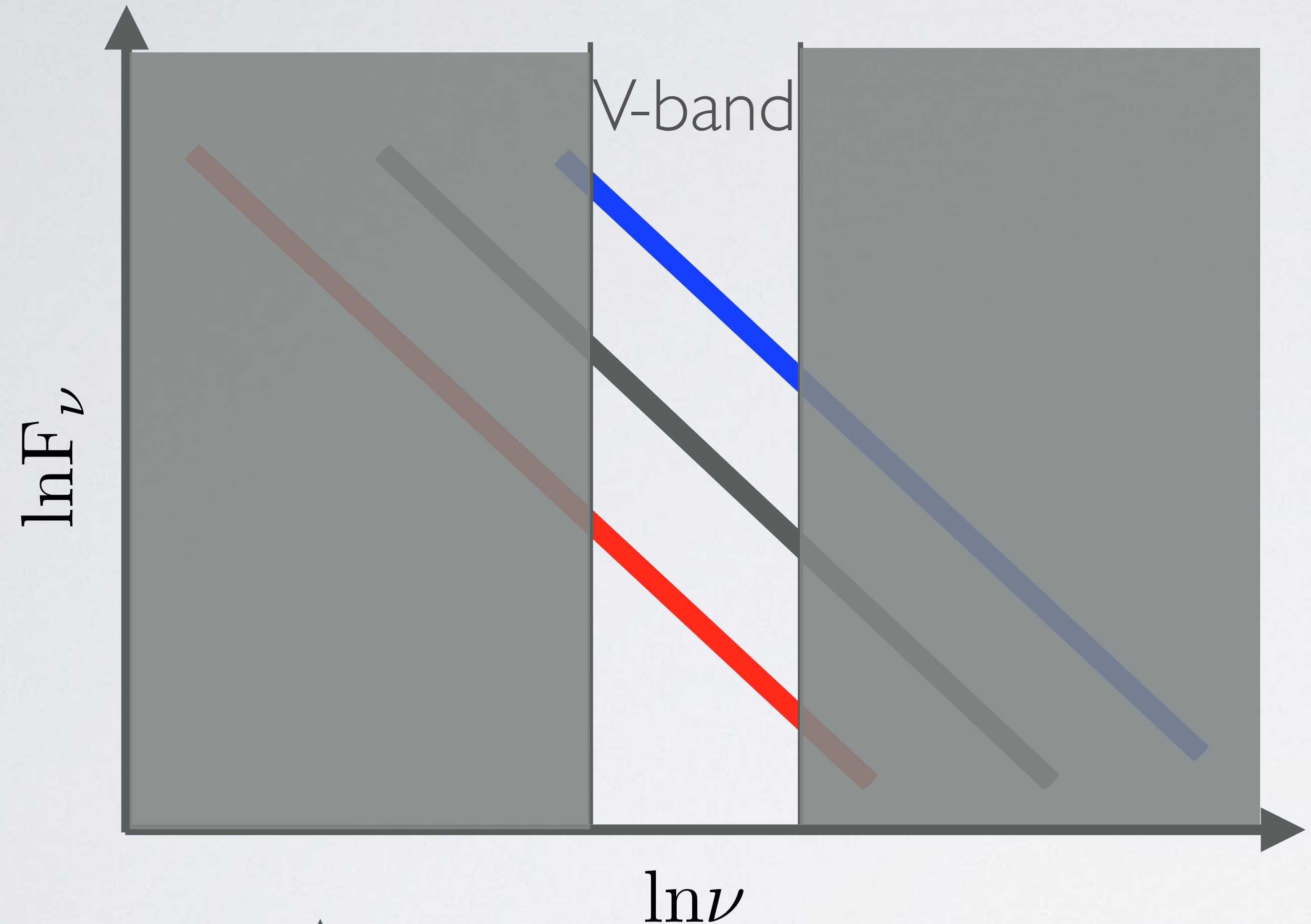
*can be uniquely modulated

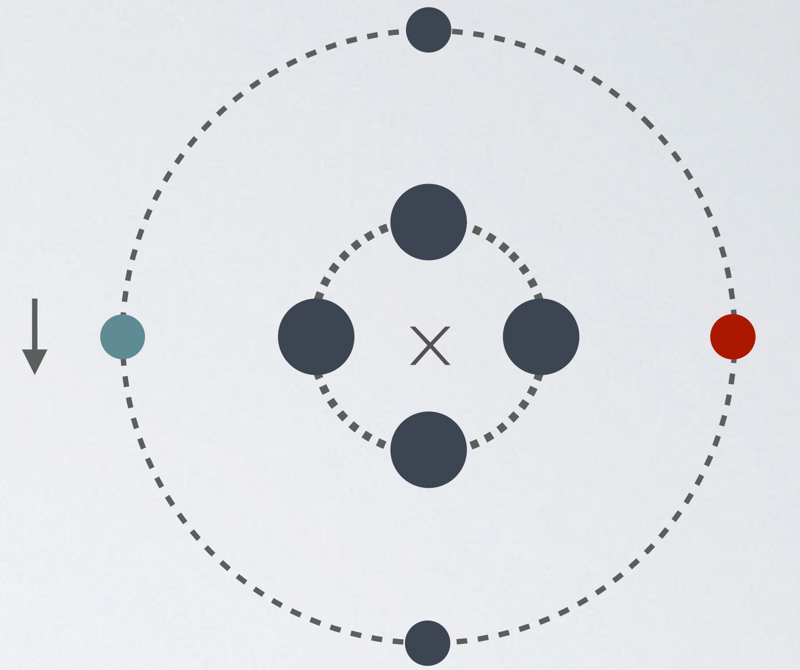
D'Orazio+2016, Shi & Krolik 2015, Farris+2014

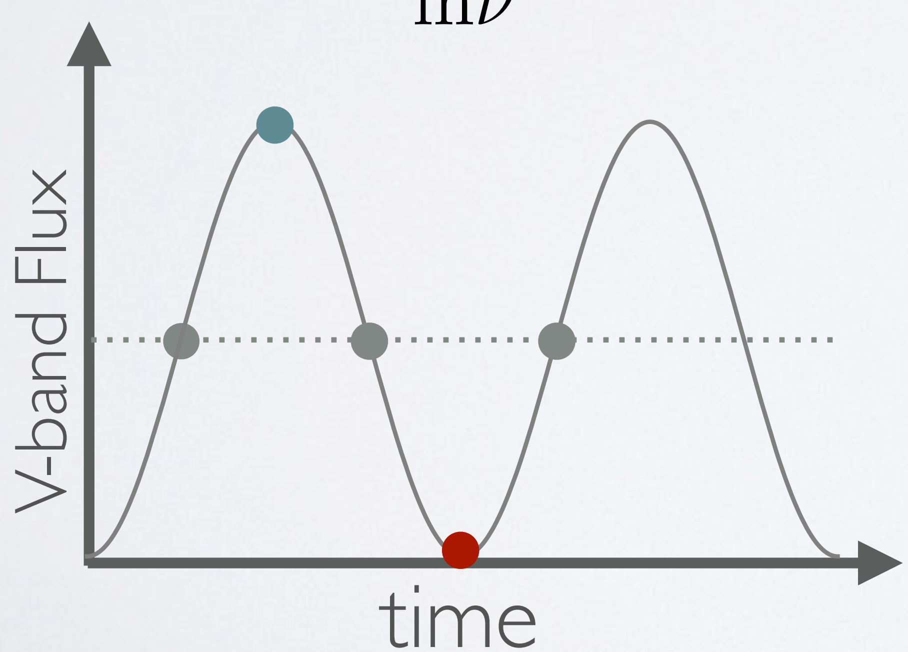
D'Orazio, Haiman, & MacFadyen (2013)

EM signatures: Binary gas accretion

Doppler-boosted modulation





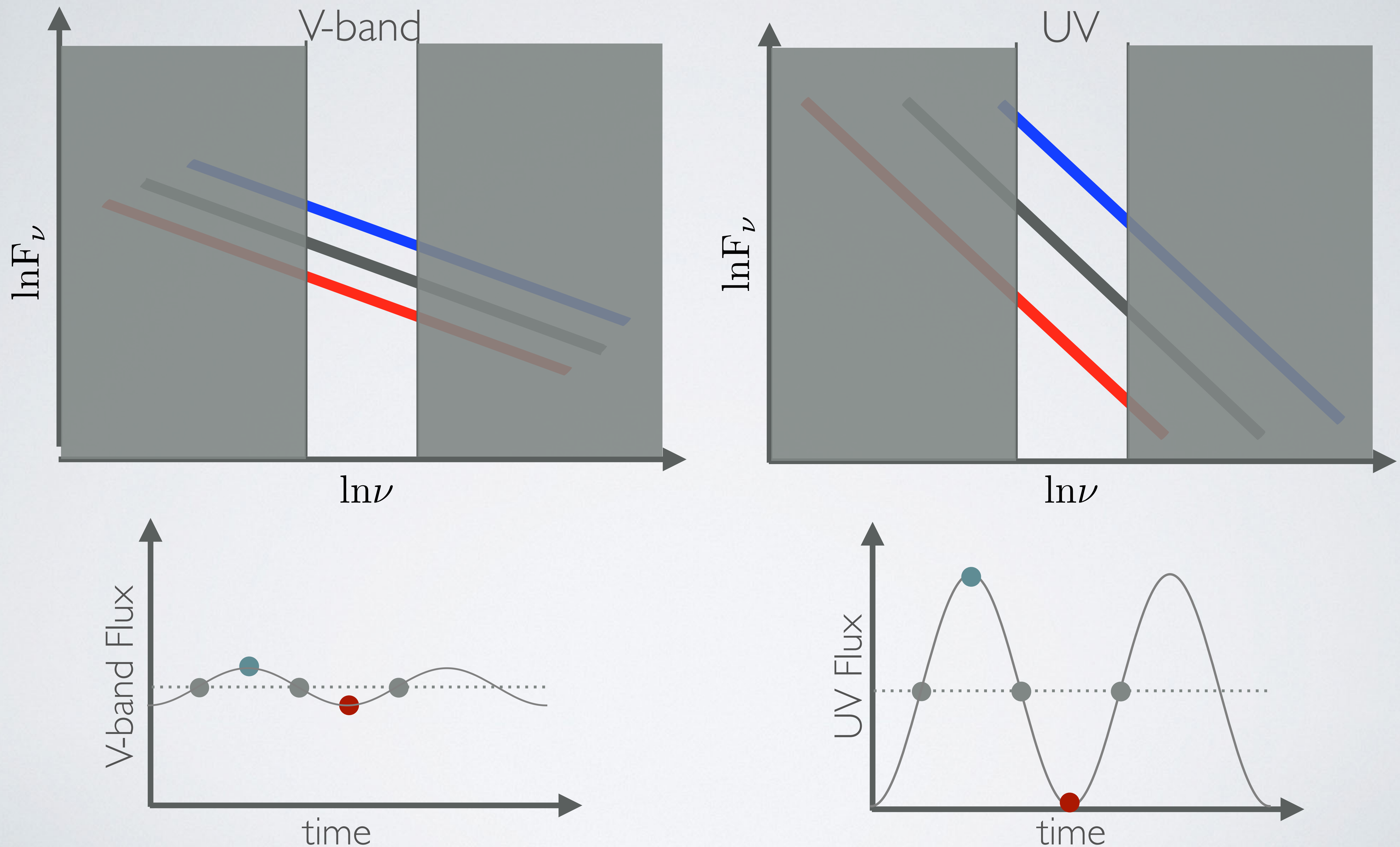


$$F_\nu^{\rm obs} = D^{3-\alpha} F_\nu^{\rm rest}$$

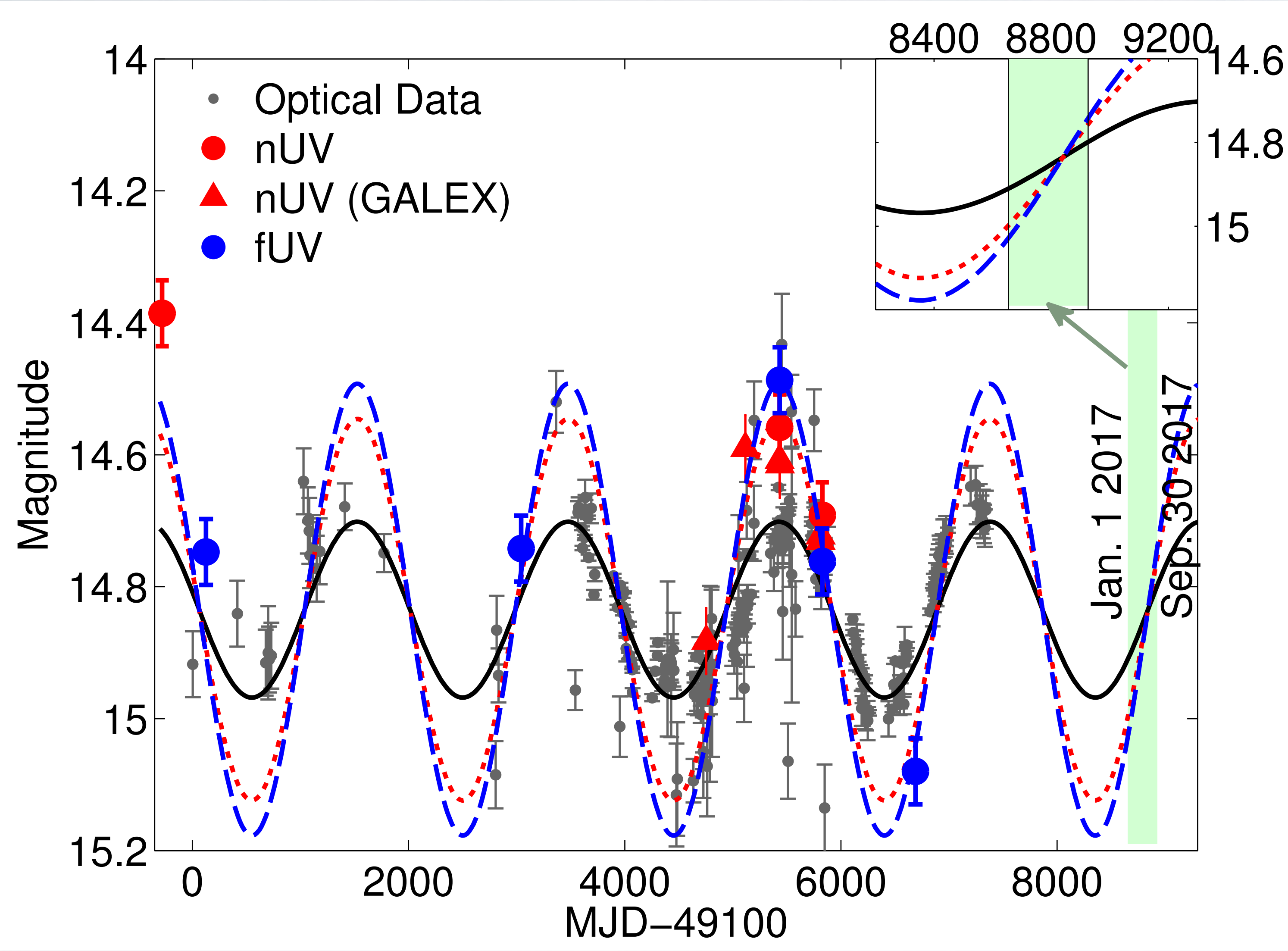
$$\alpha = \frac{d\ln F_\nu}{d\ln\nu}$$

EM signatures: Binary gas accretion

Doppler-boosted modulation



MBHB candidate: PG 1302-102



$z = 0.28$

Optical variability

$P_{\rm obs} \approx 5.2{\rm yr}$

$P_{\rm rest} \approx 4.1{\rm yr}$

$M = 10^{8.3} \rightarrow 10^{9.4} M_\odot$

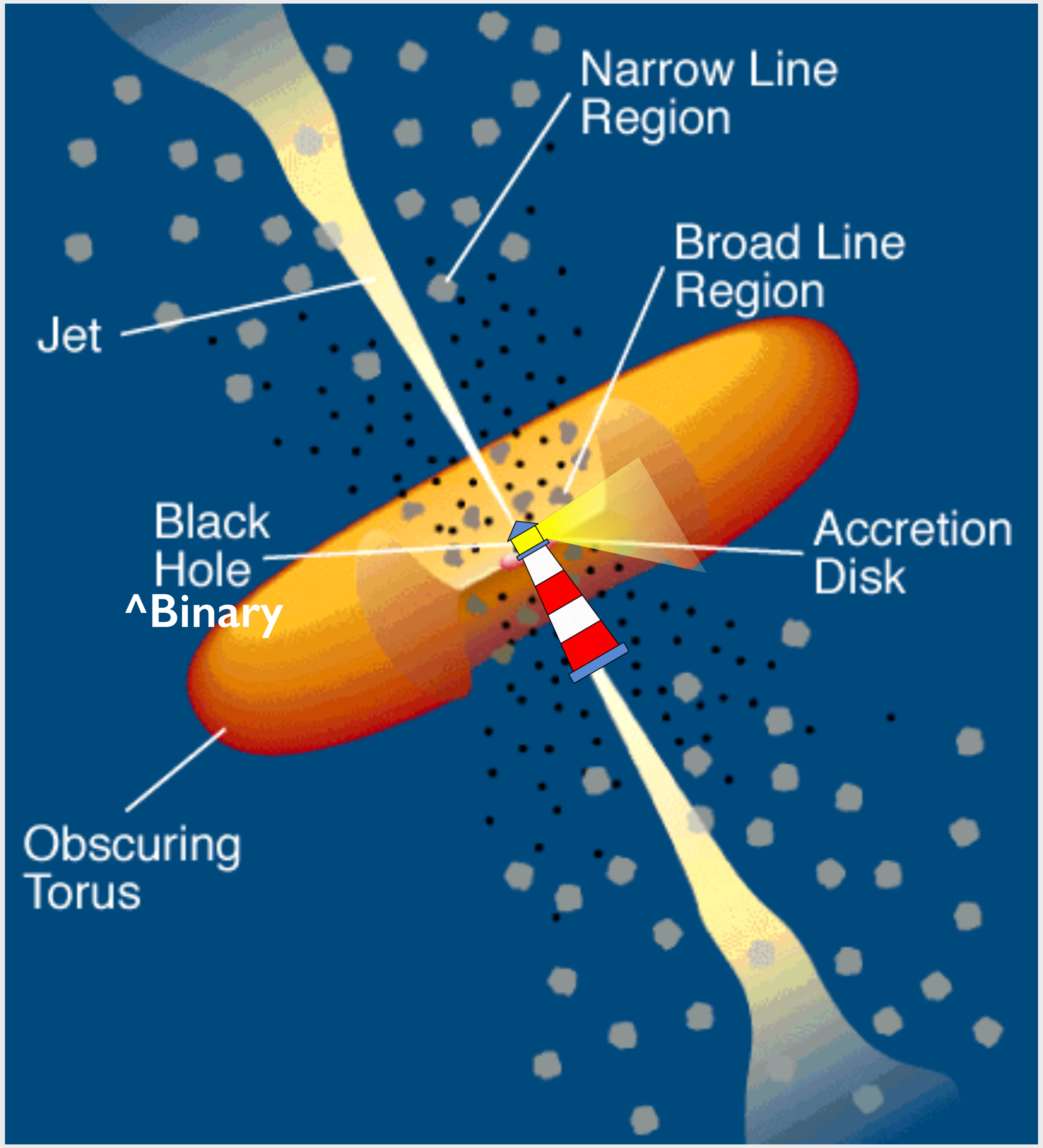
Inferred orbital separation:

$$a = 0.01{\rm pc} \left(\frac{\rm P_{bin}}{4.1{\rm yr}}\right)^{2/3} \left(\frac{\rm M}{10^9 {\rm M}_\odot}\right)^{1/3}$$

Graham+2015, *Nature*

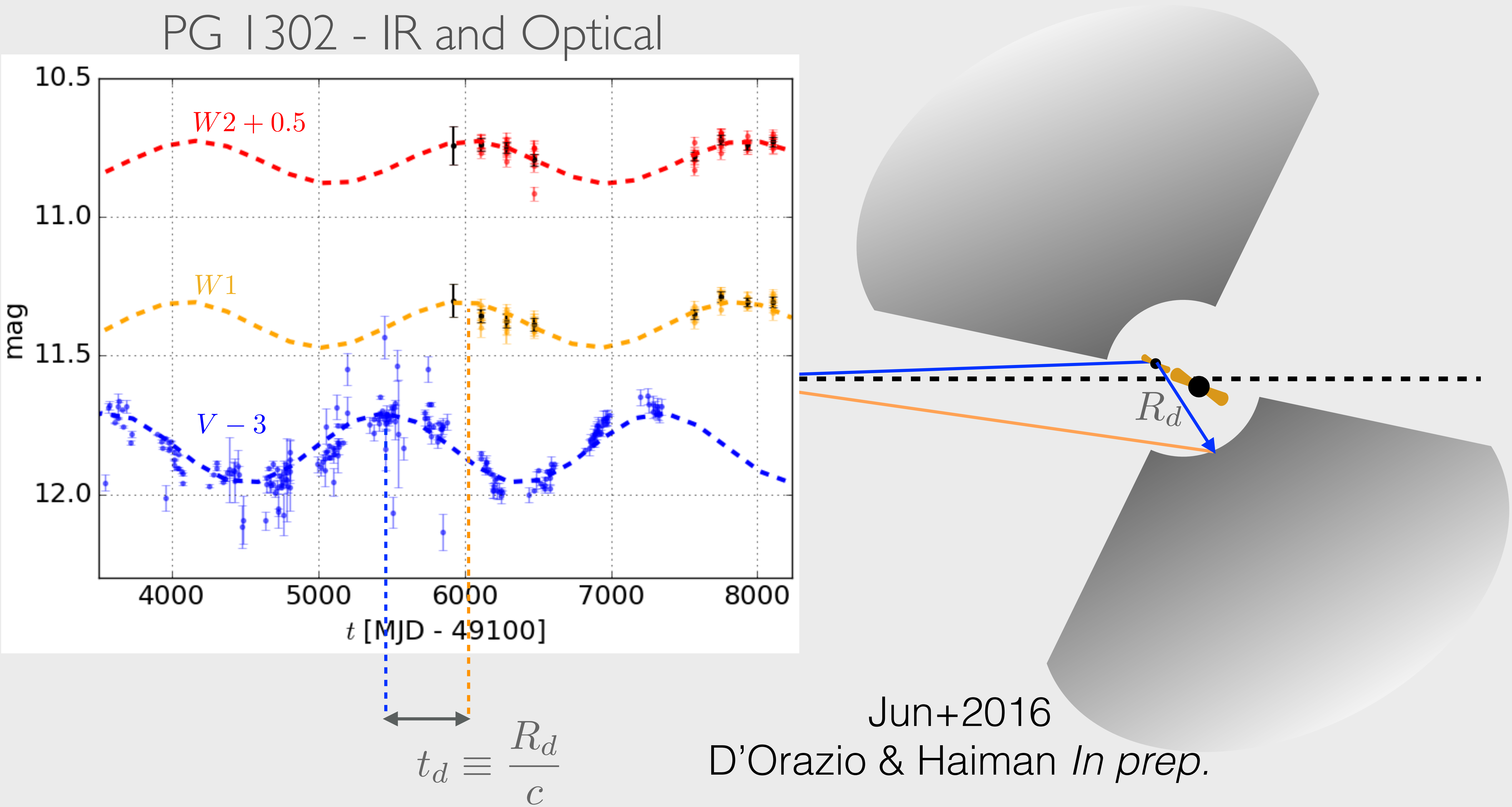
D'Orazio, Haiman, Schiminovich 2015, *Nature*

Variability in the IR: A lighthouse in the dust?



Variability in the IR: A lighthouse in the dust?

PG 1302 - IR and Optical



Jun+2016

D'Orazio & Haiman *In prep.*

IR light curves: phase shifted + diminished amplitude

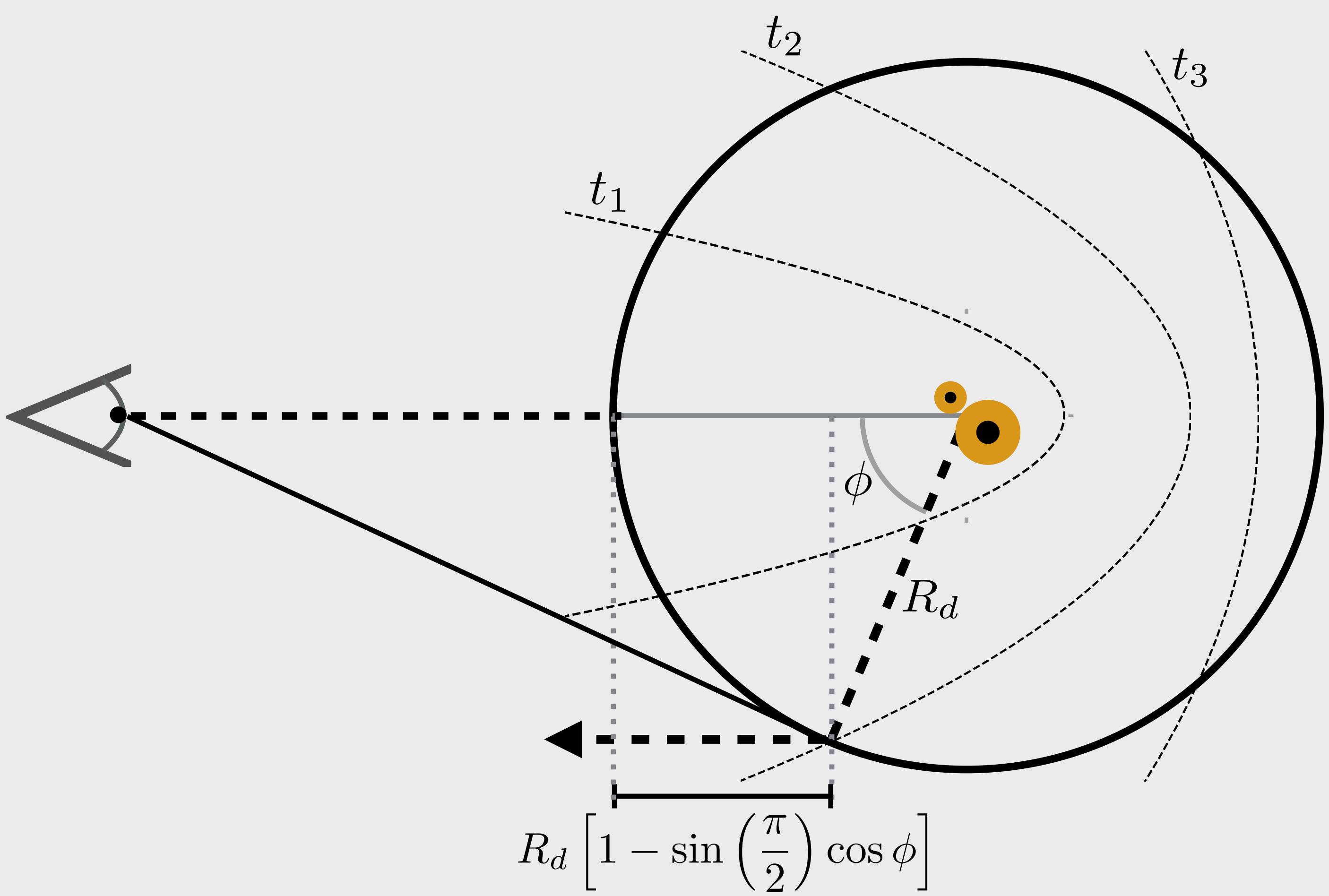
Dust Reverberation Model

*Dust is in a torus centered on the periodic MBHB source

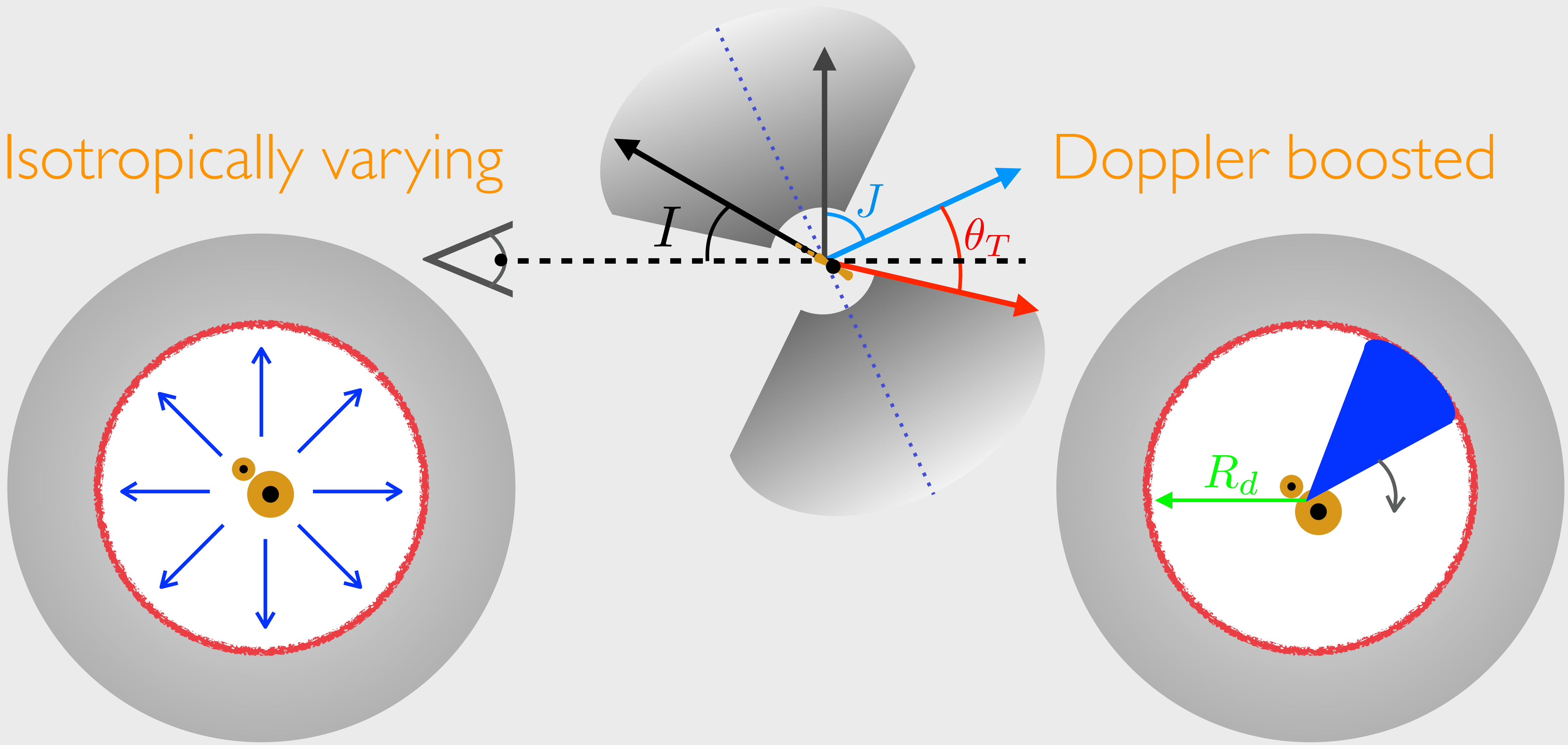
*Dust is optically thick to UV/optical and optically thin to IR

*Integrated blackbody flux observed at retarded time

$$t_{\rm ret} = t - \frac{R_d}{c}\left(1 - \cos\phi\right)$$



Dust Reverberation Model

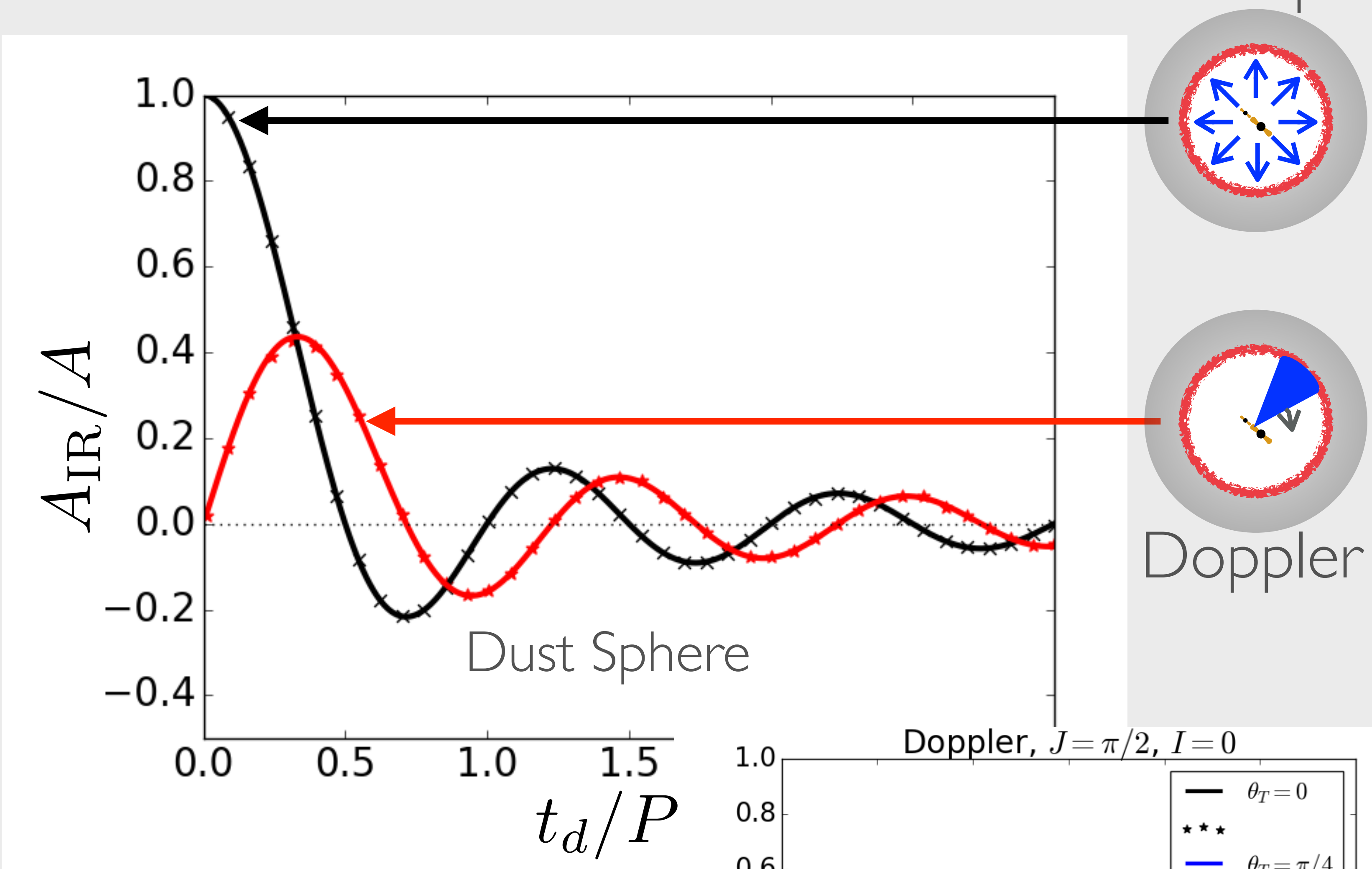


In: Binary period and inclination, torus inner radius, inclination and opening angle

Out: IR amplitude and phase relative to UV/optical

(Analytic) Results

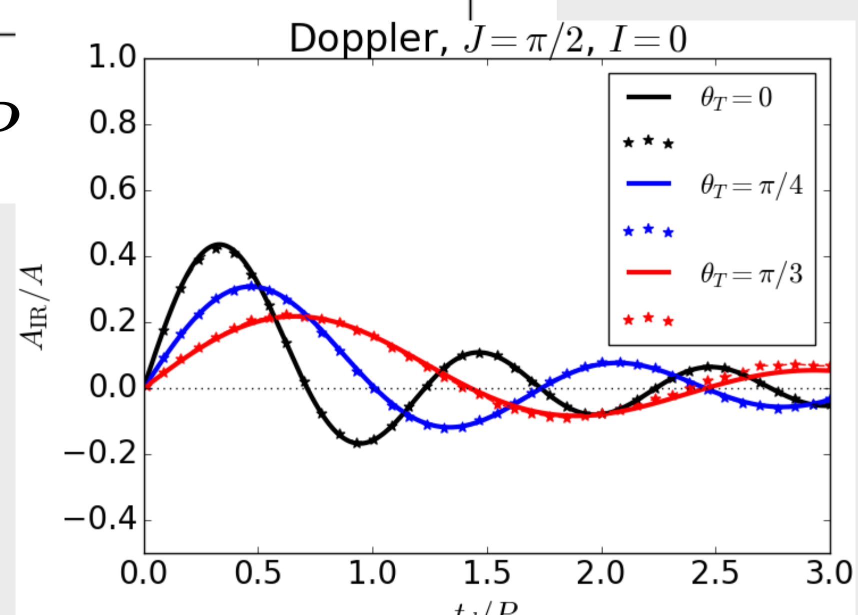
Relative IR amplitude

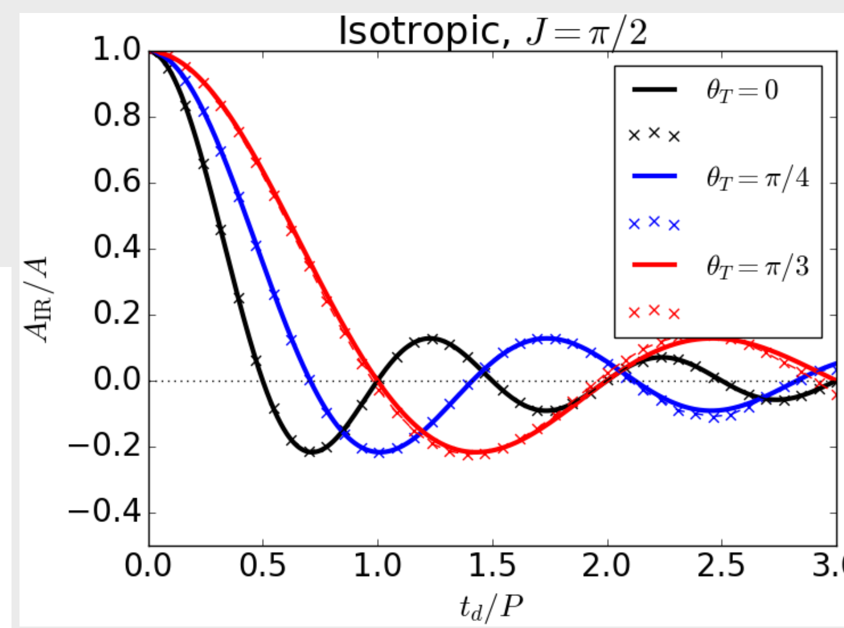


Phase lag

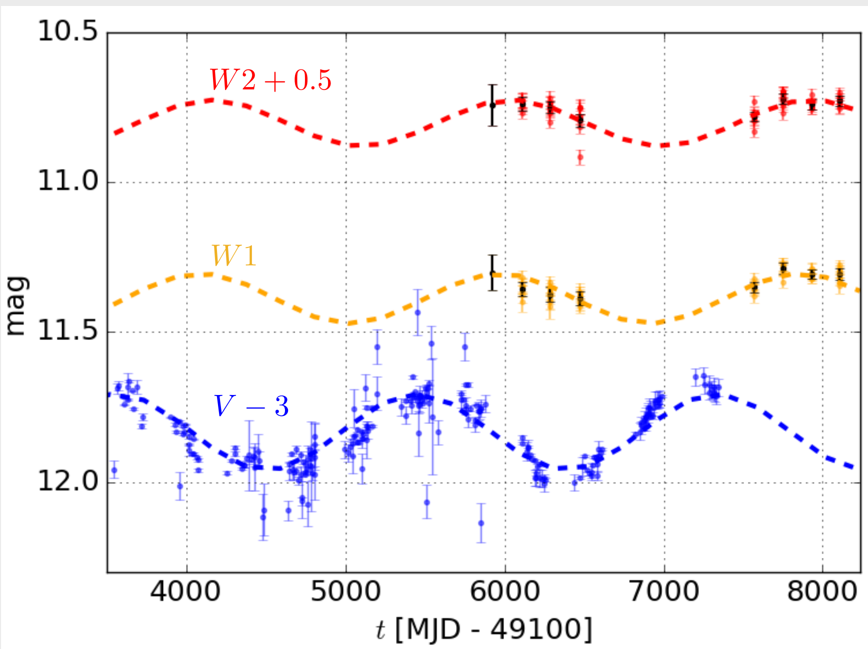
$$\frac{t_d}{P} \text{ cycles}$$

$$\frac{t_d}{P} - \frac{1}{4} \text{ cycles}$$





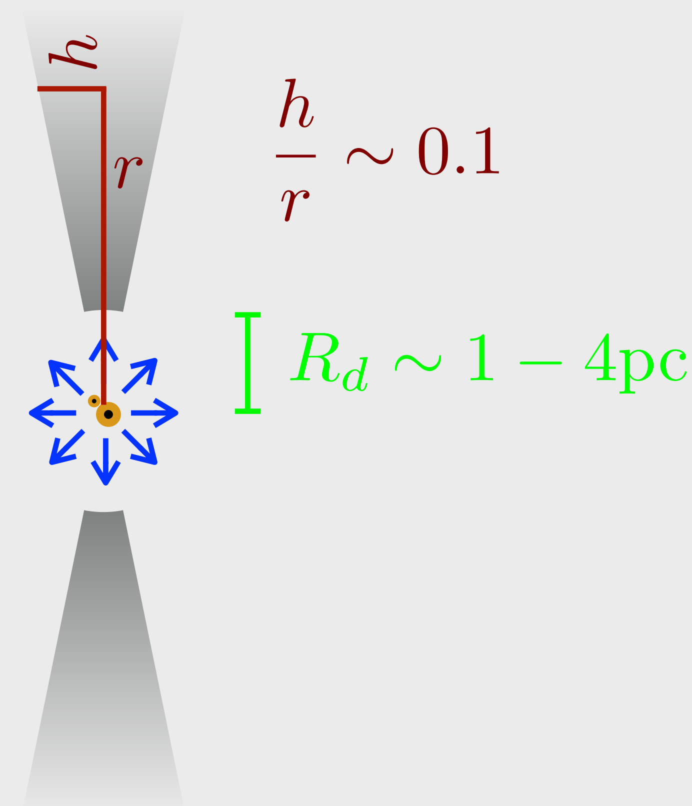
Implication for PG 1302?

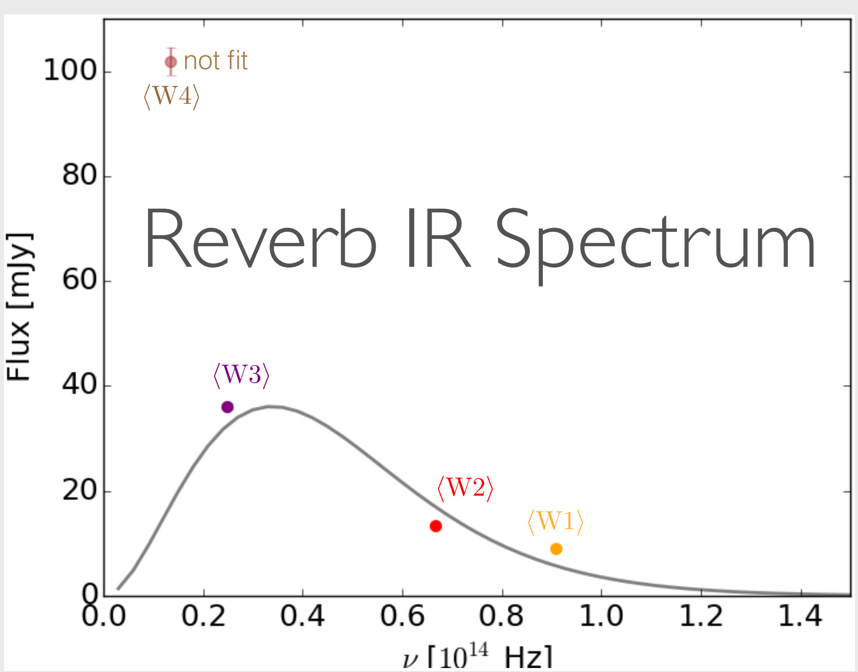


Constrains:

$$A_{\mathrm{IR}}/A$$

$$t_d/P$$

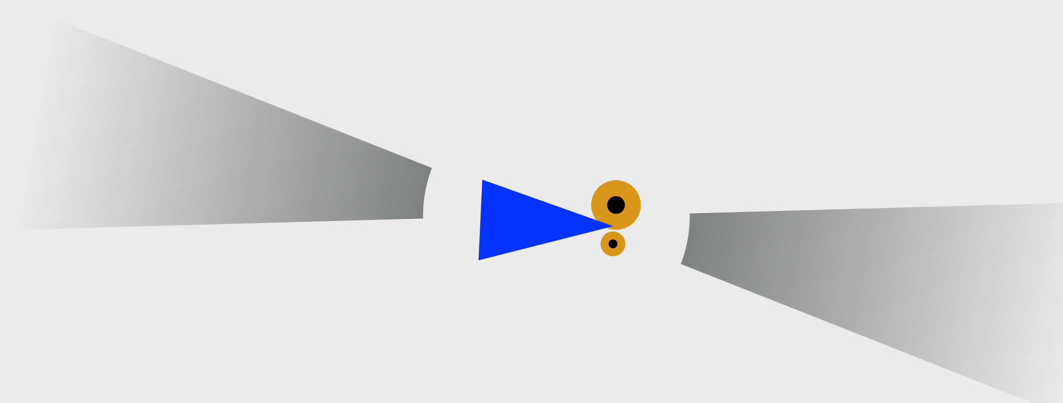




Constrains:

$$\theta_T$$

$$R_d$$



Summary for IR from MBHB systems

Relative Variability Amplitude - Depends on ratio of dust light travel time to source variability period

IR Phase Lags - Quarter cycle difference between isotropic and Doppler sources

Orphan IR variability - IR periodic variability, with no UV/optical component

PG 1302 - IR emission consistent with dust reprocessing by a thin dusty disk at ~1-4pc - cannot yet distinguish between Doppler and isotropic cases.

Inferring the MBHB population IR predictions provide more evidence for vetting MBHB candidates

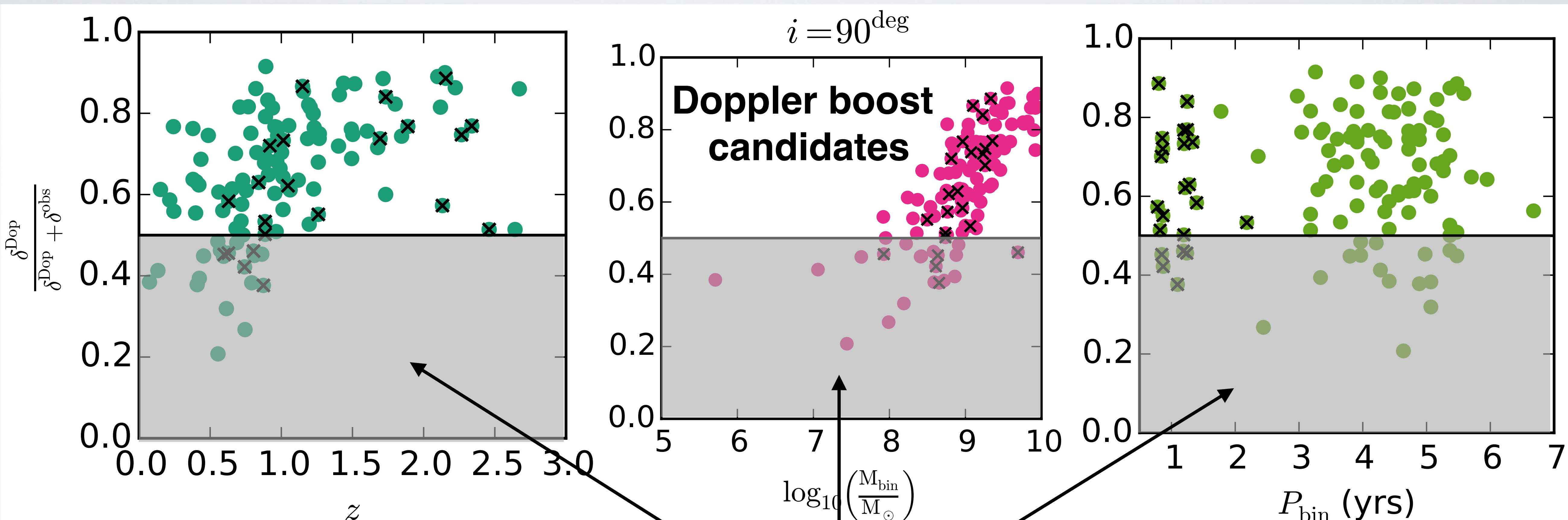
To come:

Multi-wavelength Population Studies

~150 new MBHB Candidates from

Graham+2015b

Charisi+2015(x's)



Cannot be Doppler boost candidate