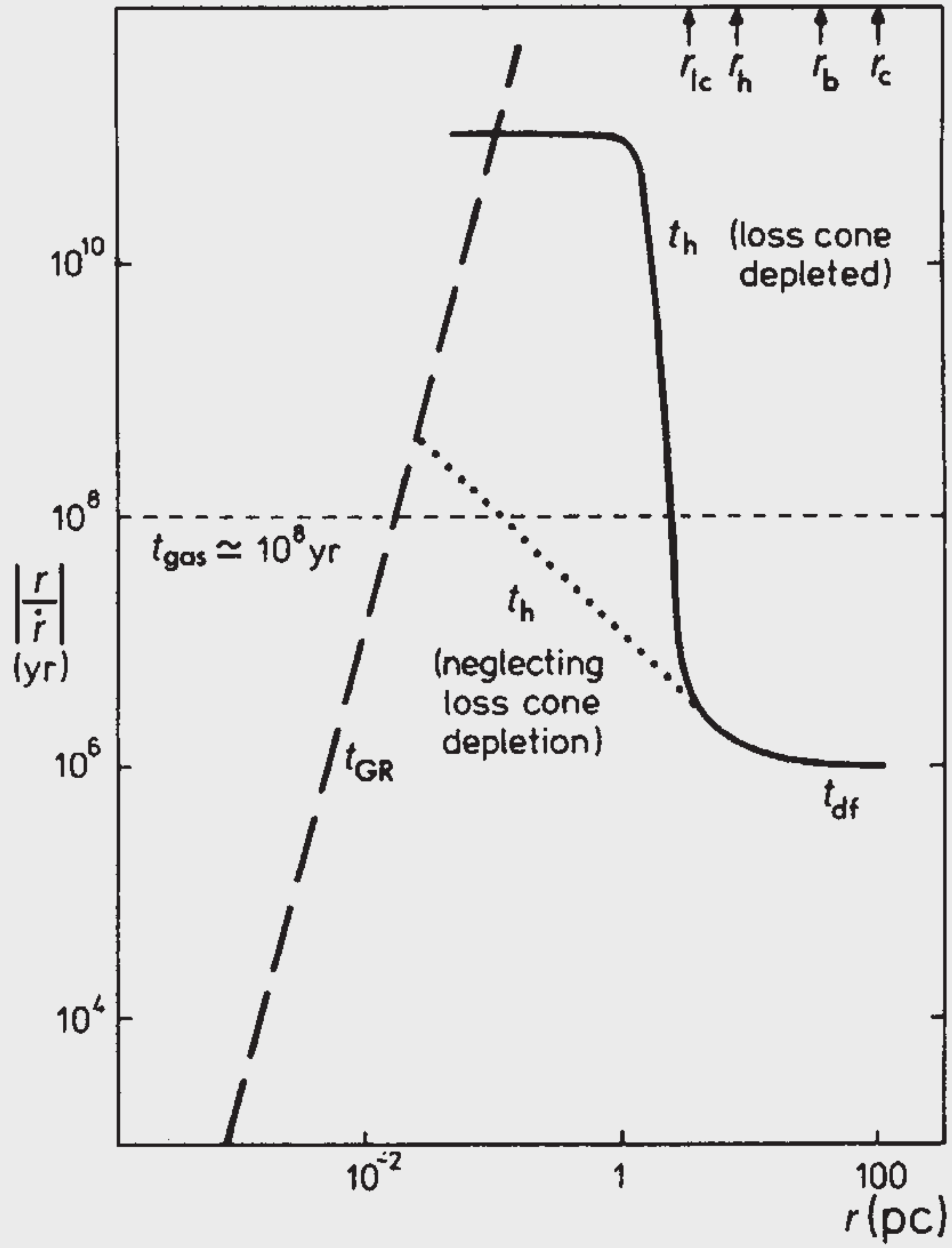
(More) Tools for Characterizing a Population of Massive Black Hole Binaries

Daniel J. D'Orazio

2017 Einstein Symposium

Galaxies merge, but do the black holes?



Begelman, Blandford, Rees 1980

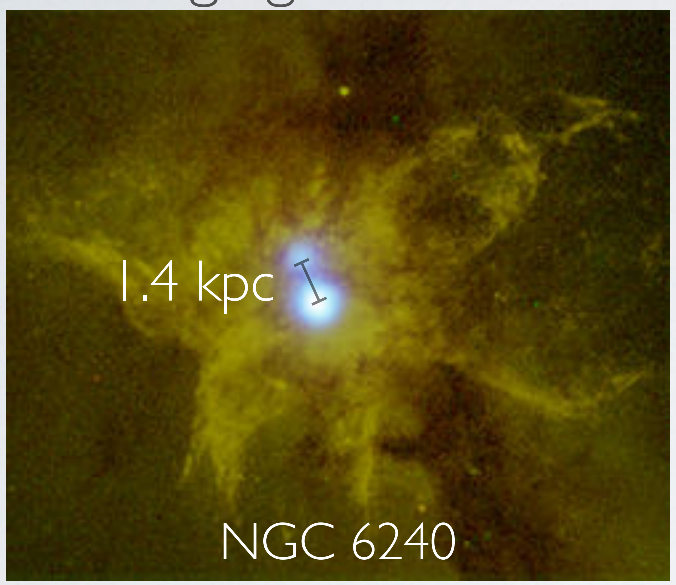
- **Step 1:** *Dynamical friction* quickly brings the black holes to the inner few parsecs of the new galaxy - forming a binary
- **Step 2:** Binary either stalls at ~1pc, or gas, non-spherical stellar distribution, or… shrinks the orbit further
- **Step 3:** If the binary orbit can decay to ~0.01-0.1pc, *gravitational radiation* will merge the binary in less than a Hubble time

Galaxies merge, but do the black holes?
How do we find out?

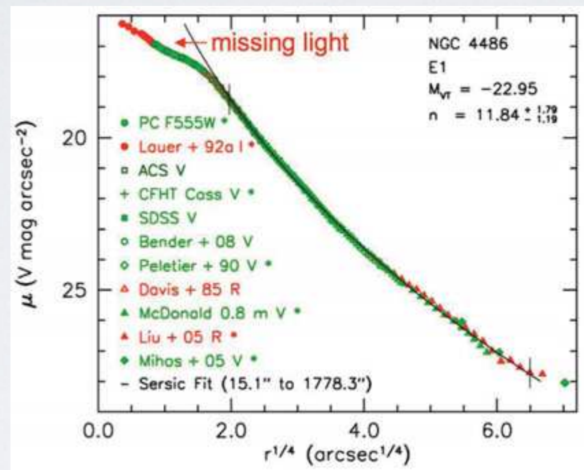
* The fraction of MBHBs at different separations would elucidate the mechanisms which bring MBHBs together
    * The low frequency gravitational wave background and merger events will probe the MBHB environment at late inspiral
    * Electromagnetically identified population could directly trace MBHB evolution over a wider range of evolutionary states (orbital separations)

Electromagnetic MBHB evidence/searches

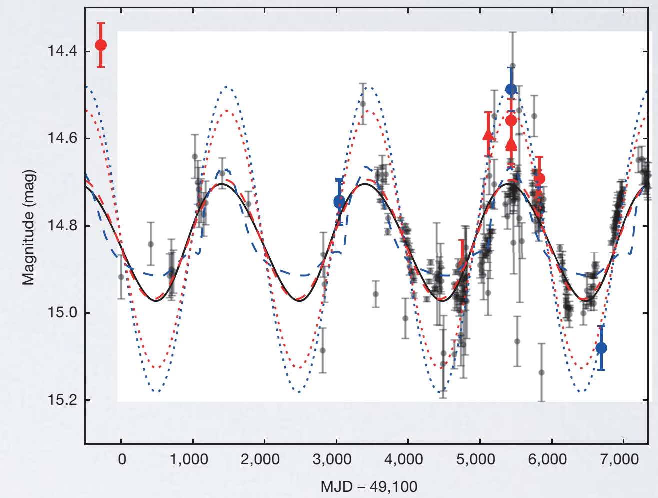
Imaging dual AGN



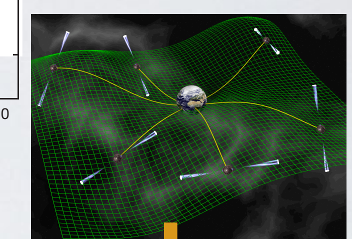
Core ellipticals

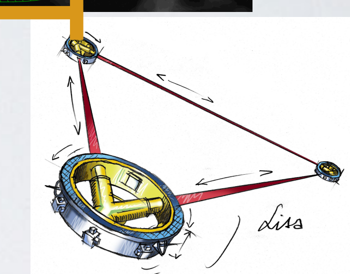


Periodic light curves



Grav waves

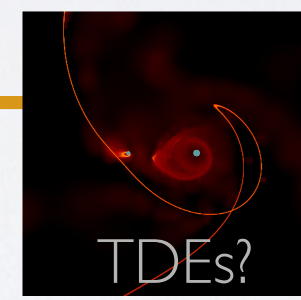




Separation

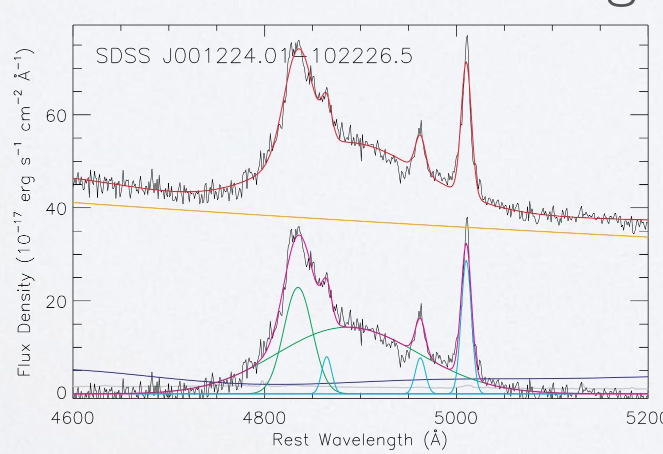
~kpc

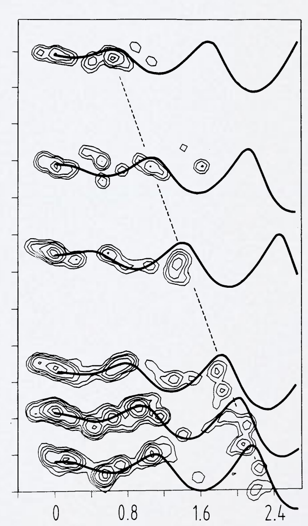
~pc



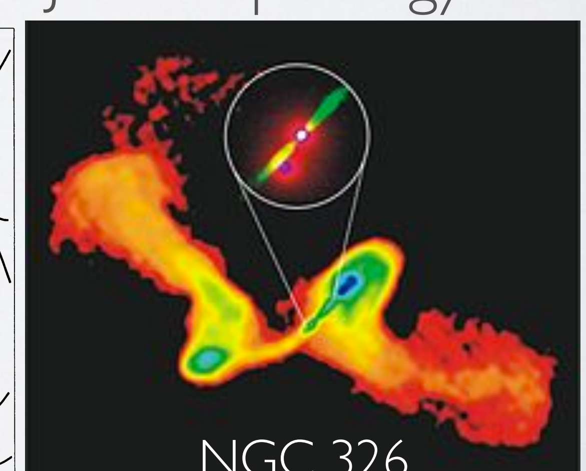
~sub-pc

Broad line monitoring

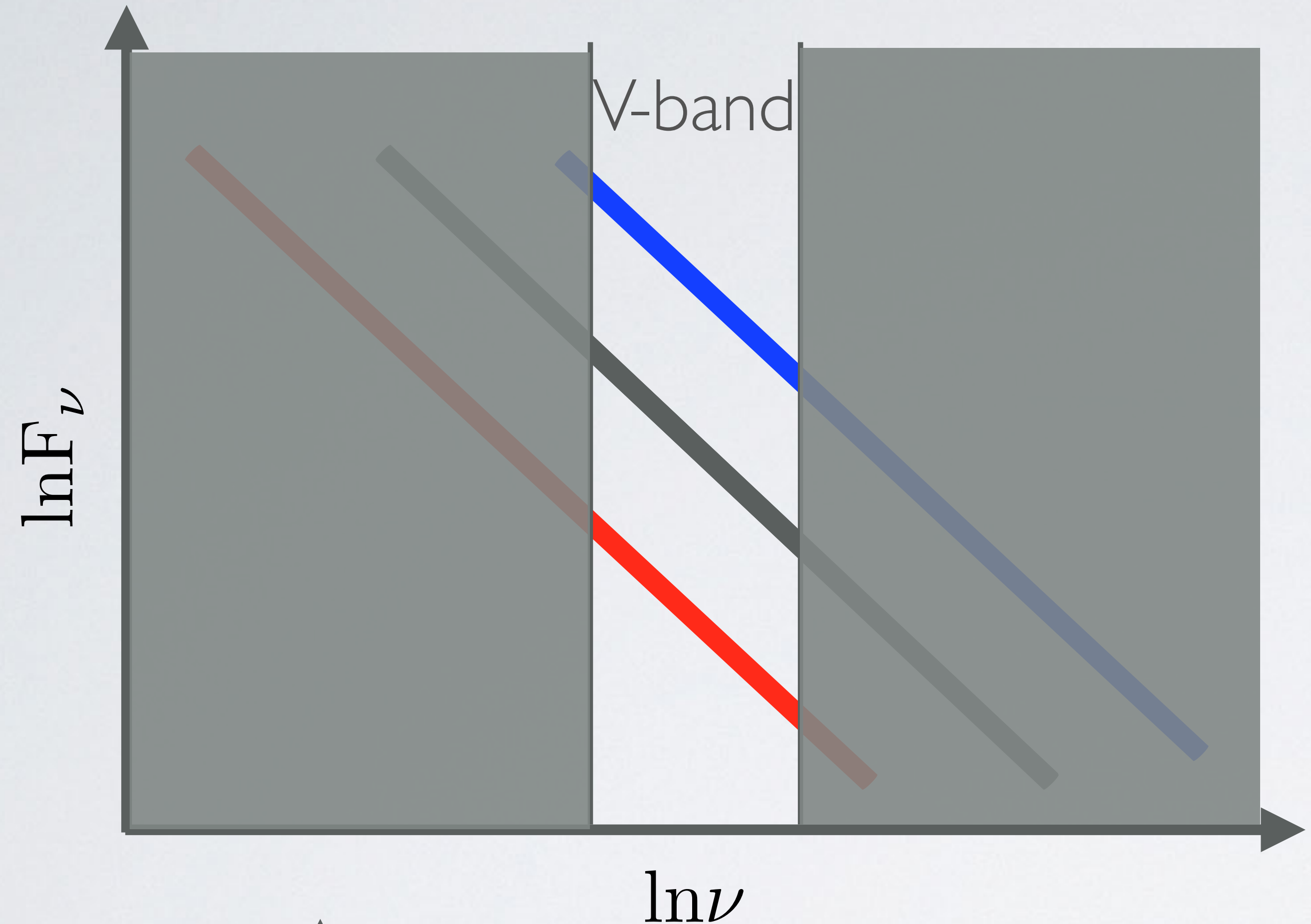


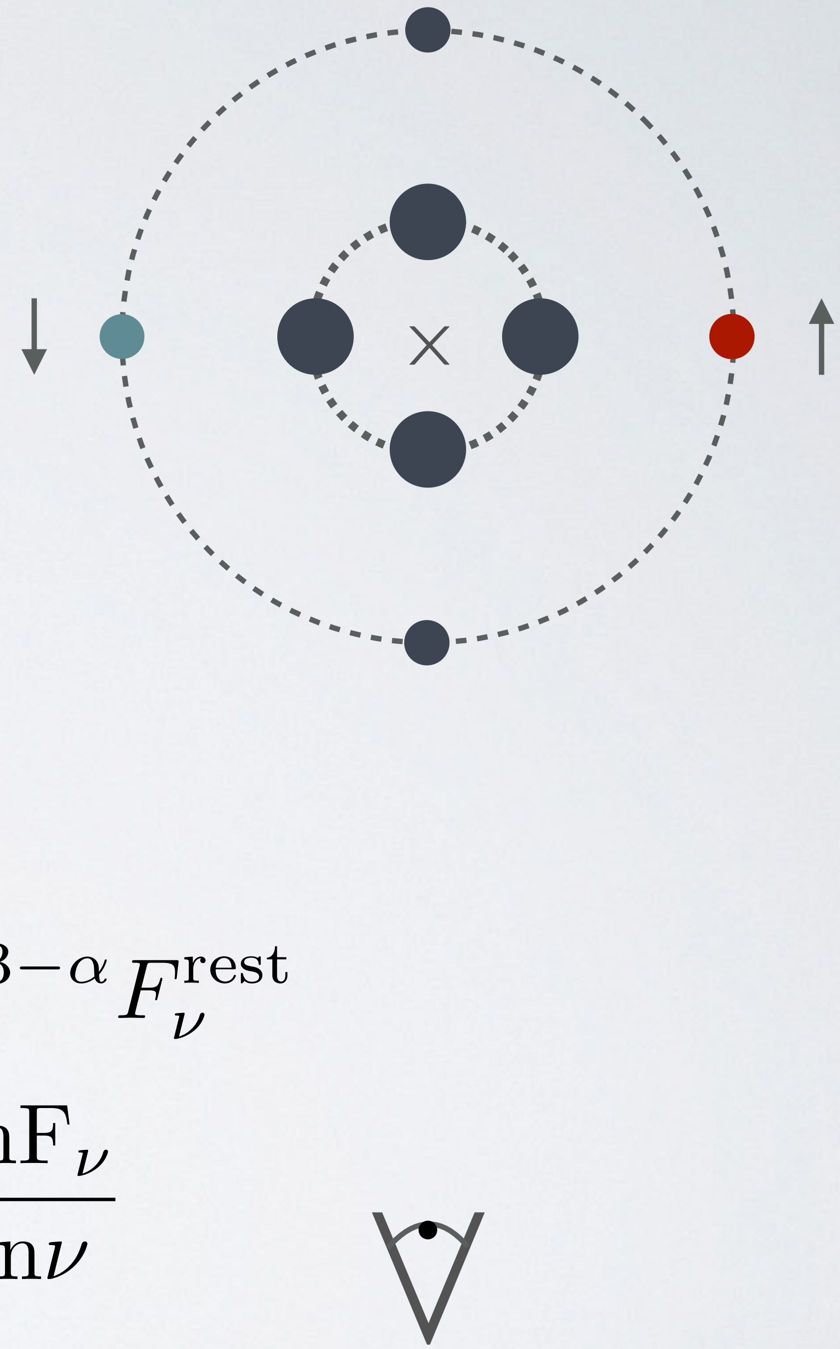


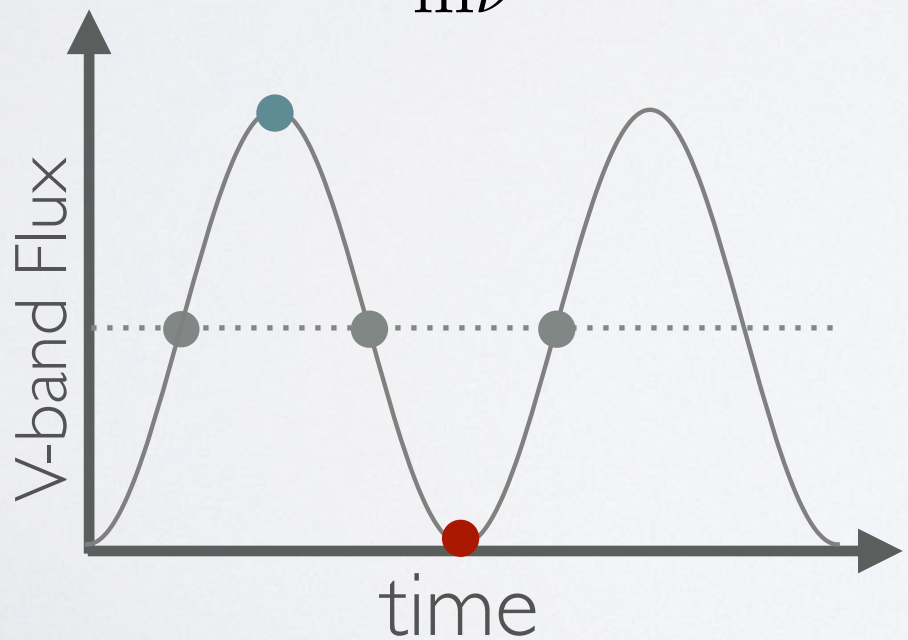
Jet morphology



Relativistic Doppler boost as the cause of periodic variability





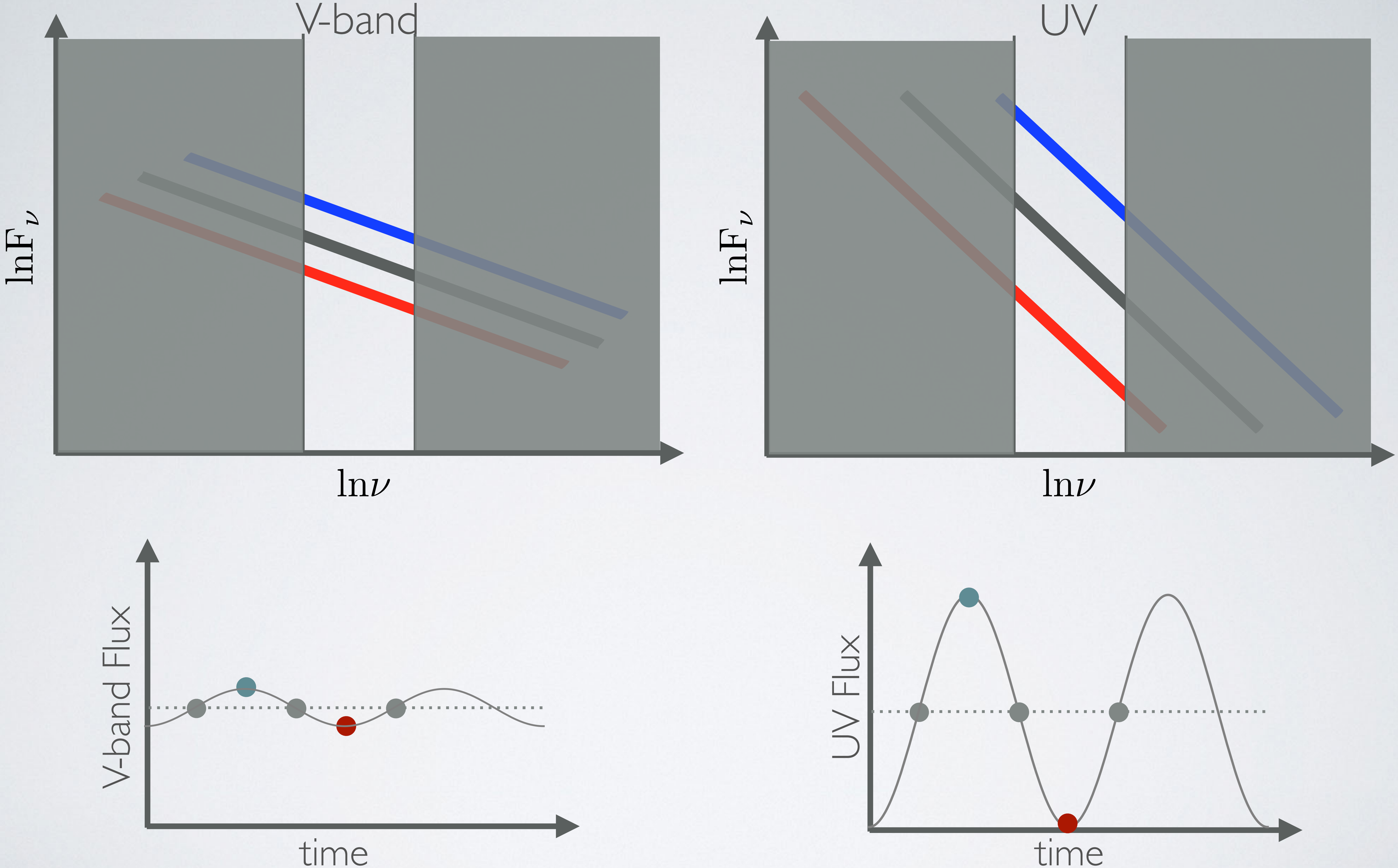


$$F_\nu^{\rm obs} = D^{3-\alpha} F_\nu^{\rm rest}$$

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

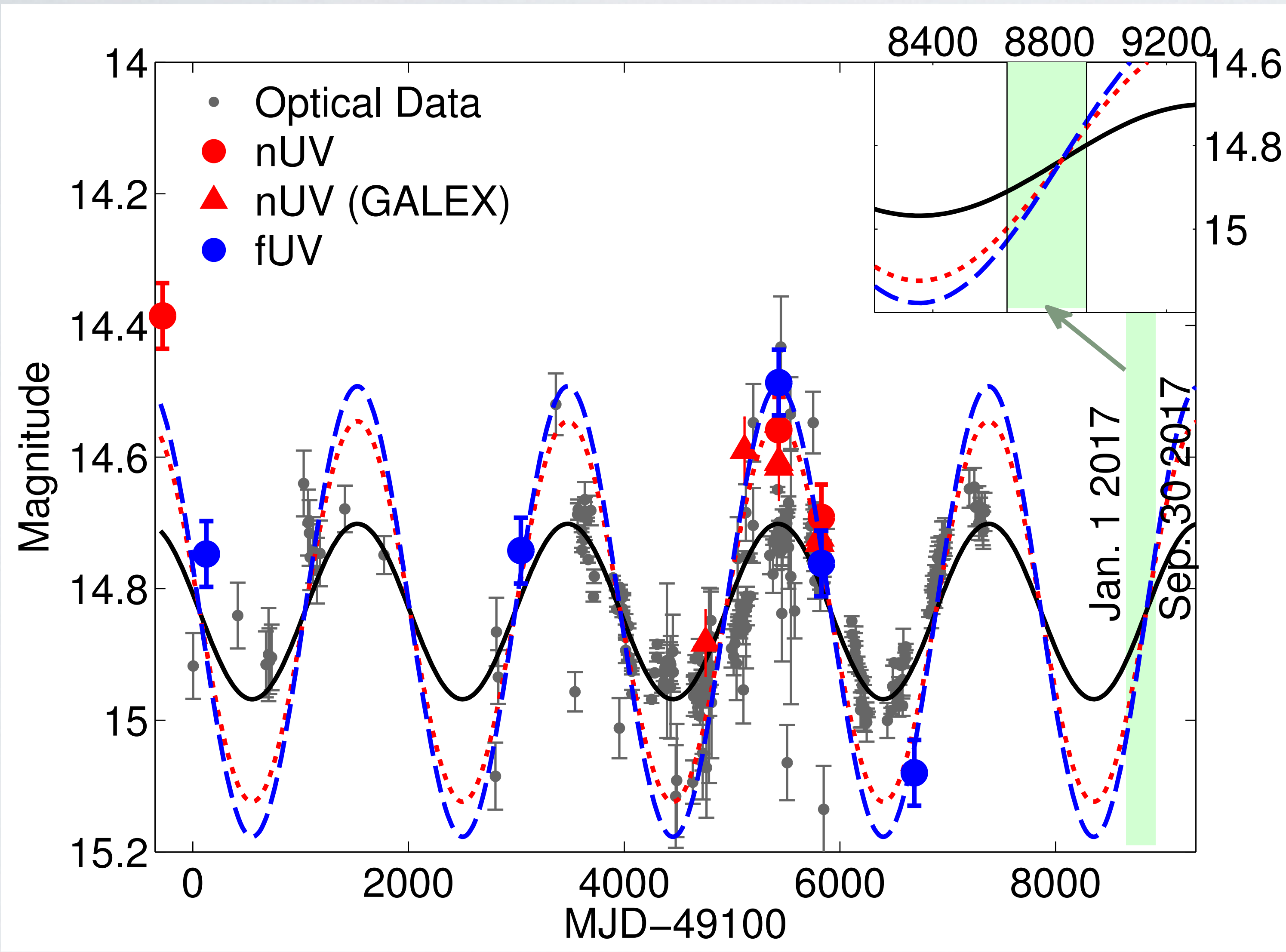
D'Orazio, Haiman, Schiminovich 2015, *Nature; arXiv:1509.04301*

Relativistic Doppler Boost as the cause of periodic variability



D'Orazio, Haiman, Schiminovich 2015, *Nature; arXiv:1509.04301*

MBHB candidate: PG 1302



$z = 0.28$

Optical variability

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

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

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

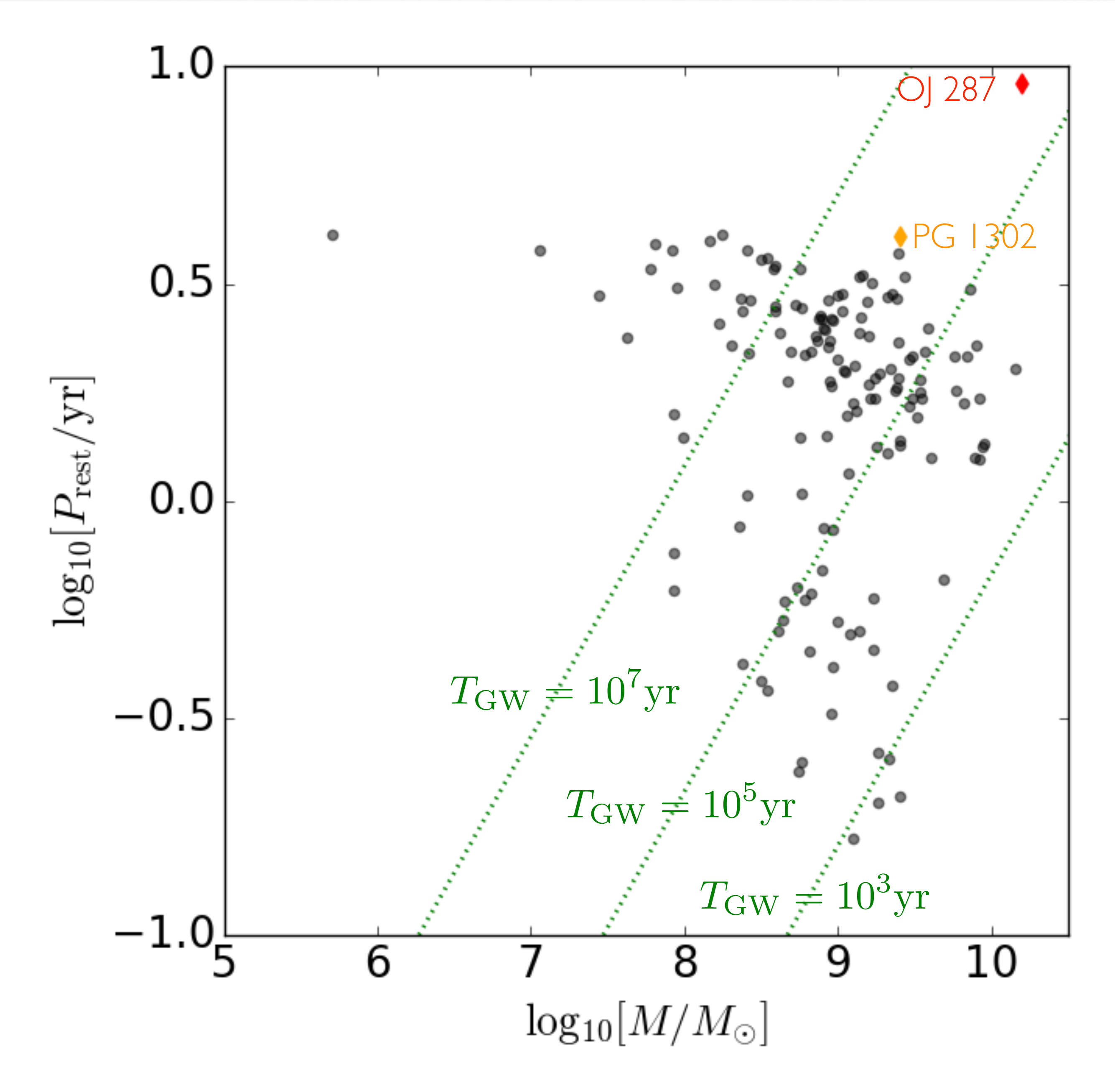
Inferred orbital separation:

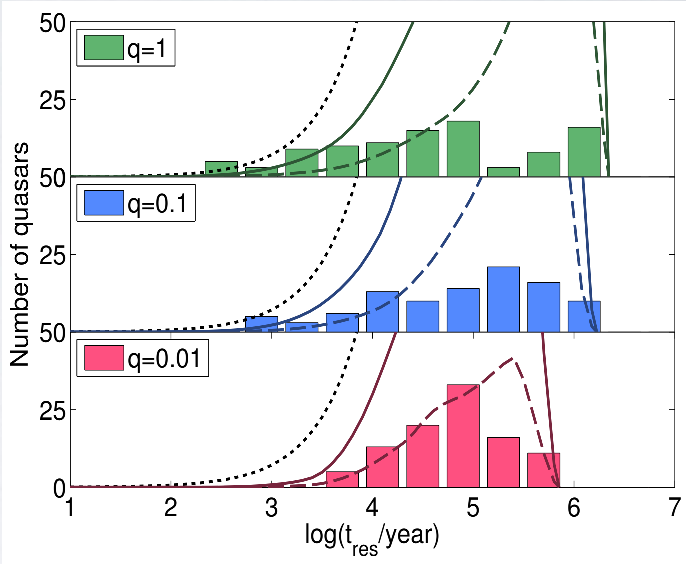
$$a = 0.01\mathrm{pc} \left(\frac{\mathrm{P_{bin}}}{4.1\mathrm{yr}}\right)^{2/3} \left(\frac{\mathrm{M}}{10^9 \mathrm{M}_\odot}\right)^{1/3}$$

Graham+2015, *Nature*

D'Orazio, Haiman, Schiminovich 2015, *Nature; arXiv:1509.04301*

MBHB Candidates from periodic quasar searches





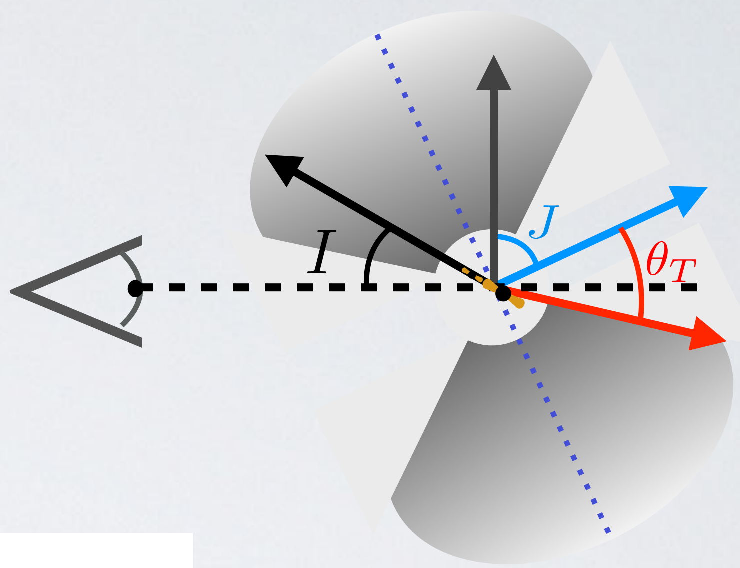
~150 MBHB Candidates from

Graham+2015b (CRTS)

Charisi+2016(PTF)

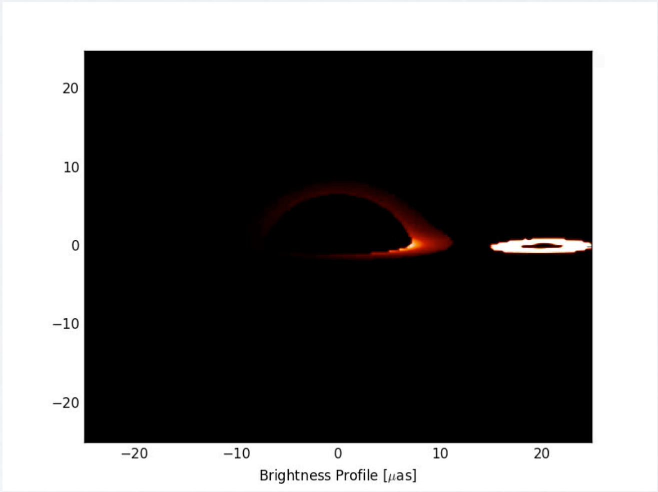
How do we know if these are real?

* Some new tools?



1) Infrared light echoes of periodic emission from MBHBs

arXiv:1702.01219

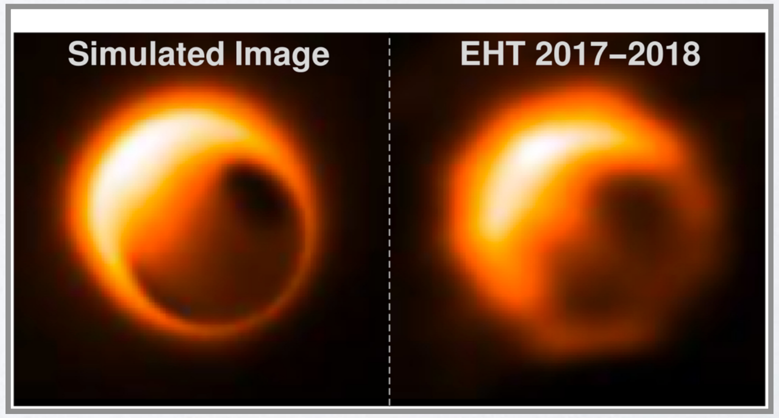


2) MBHB self lensing

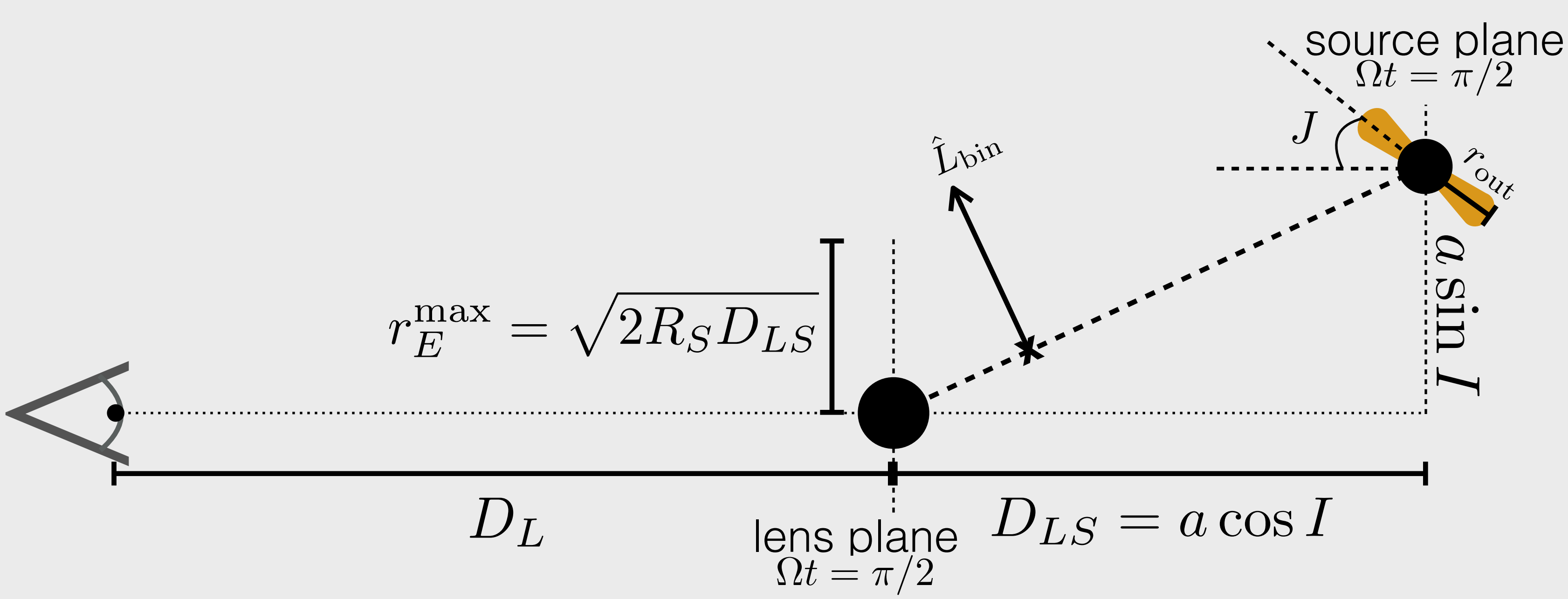
arXiv:1707.02335

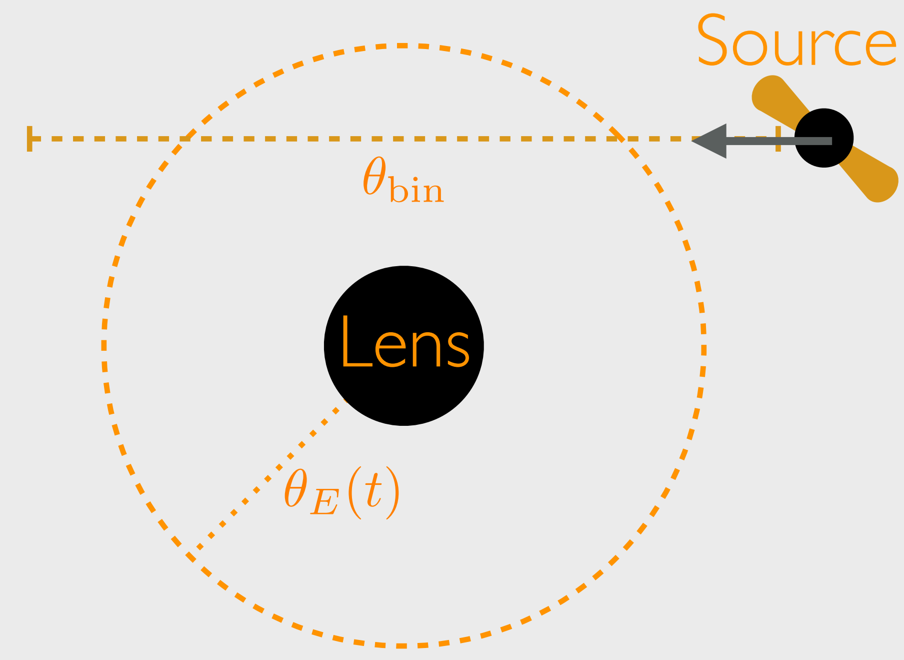
3) Sub-mm VLBI Imaging!?

arXiv:1710.?????



MBHB self lensing: further evidence for MBHBs?





$$\theta_E \leq \sqrt{\frac{4GM}{c^2}\frac{D_{LS}}{D_L D_S}} \approx \sqrt{\frac{2R_s a}{D^2}}$$

Probability = $\frac{\Delta I \text{ less than Einstein rad}}{\text{All Inclinations}} \approx \frac{\theta_E}{\theta_{\rm bin}}$

assuming observation for >1 orbit

$$\theta_{\rm bin} \leq \frac{a}{D}$$

$$\frac{\theta_E}{\theta_{\rm bin}} \approx \sqrt{\frac{2R_s}{a}} = \sqrt{\frac{2}{n_a}}$$

Timescale = $\frac{\text{Extent of Einstein radius}}{\text{Orbital Extent}} \times \text{Period} \approx \frac{\theta_E}{\theta_{\rm bin}} P$

D'Orazio & Di Stefano 2017 (*arXiv:1707.02335*)

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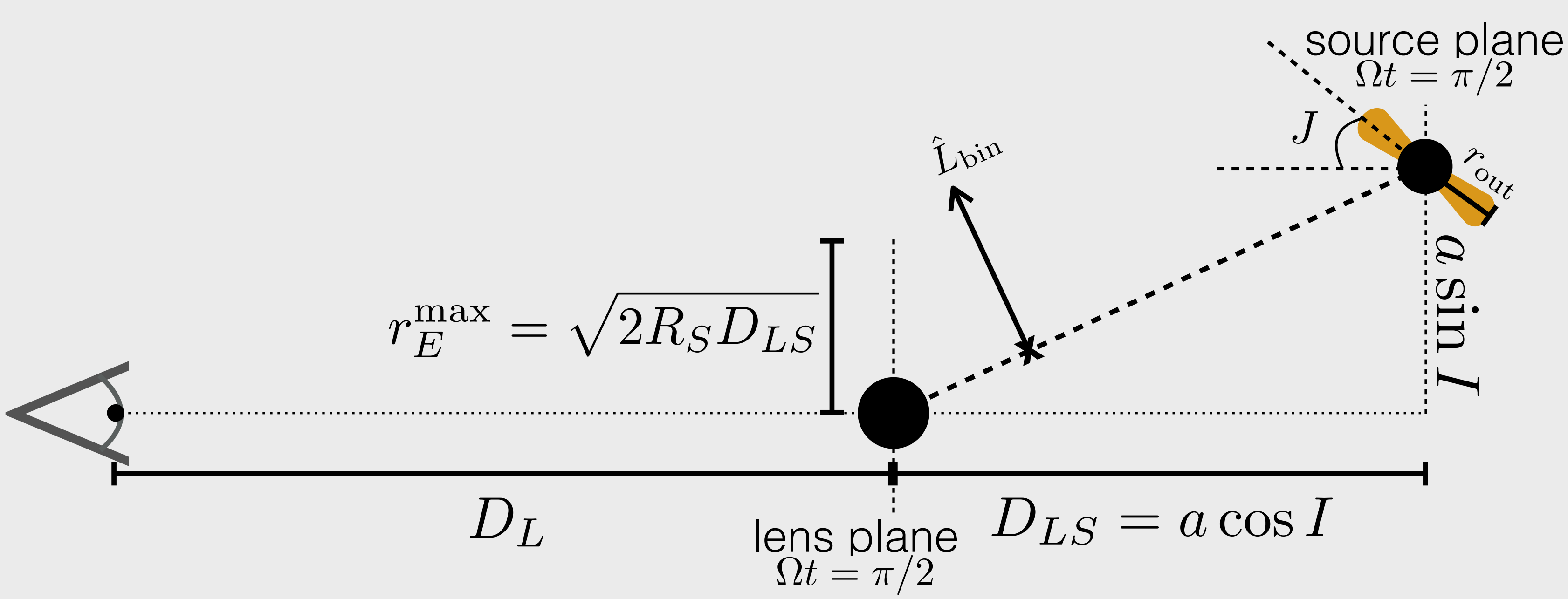
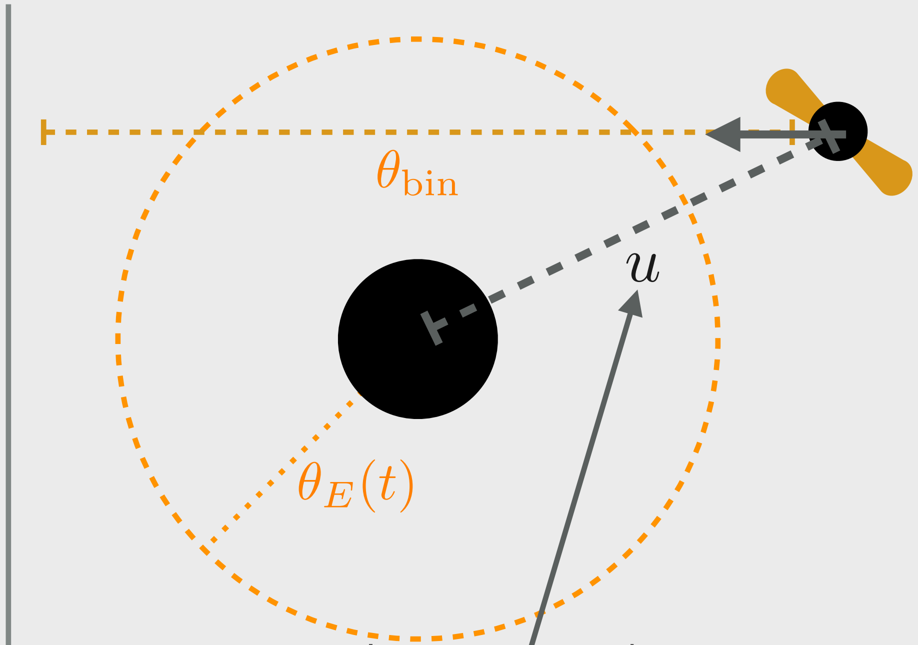
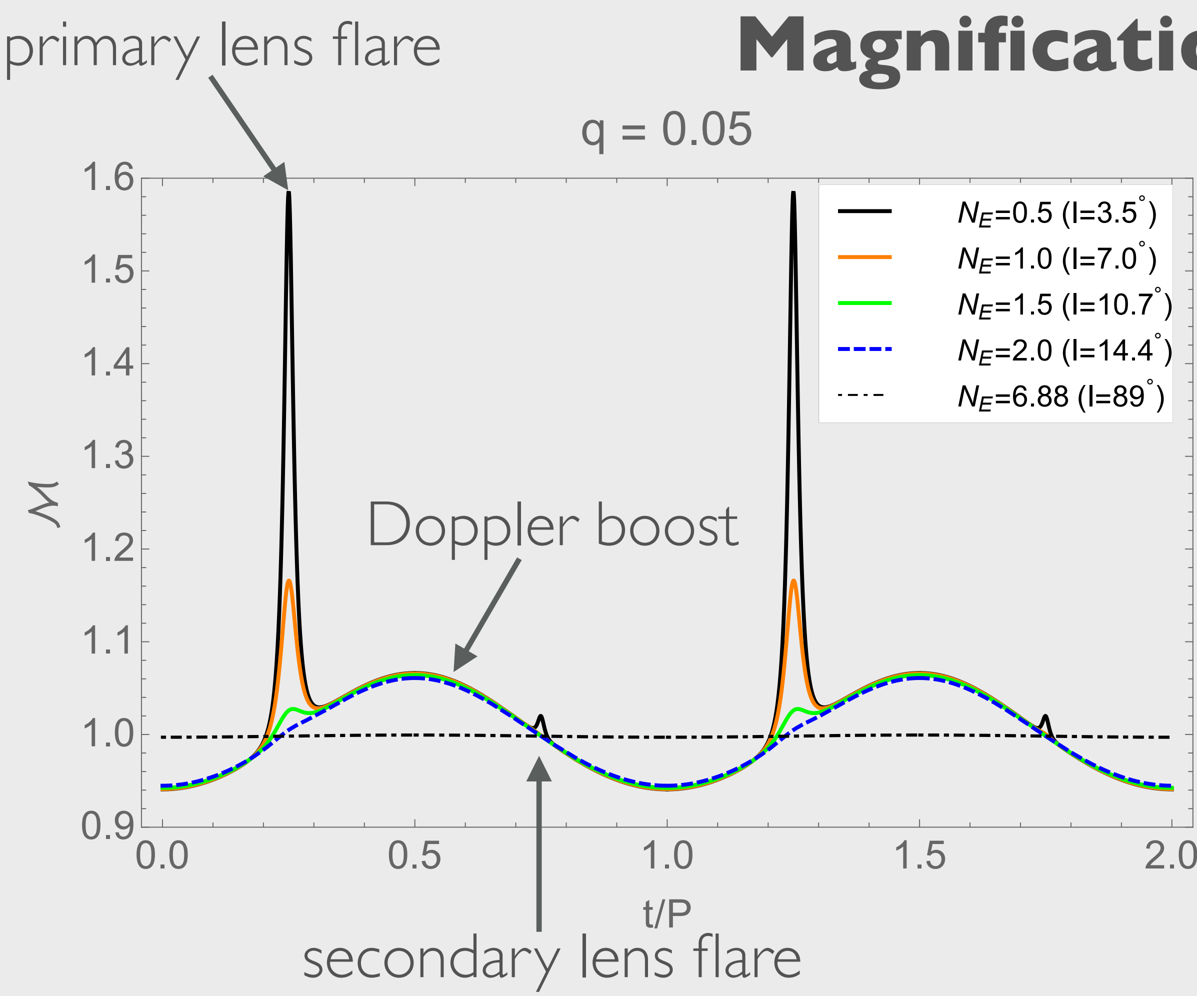
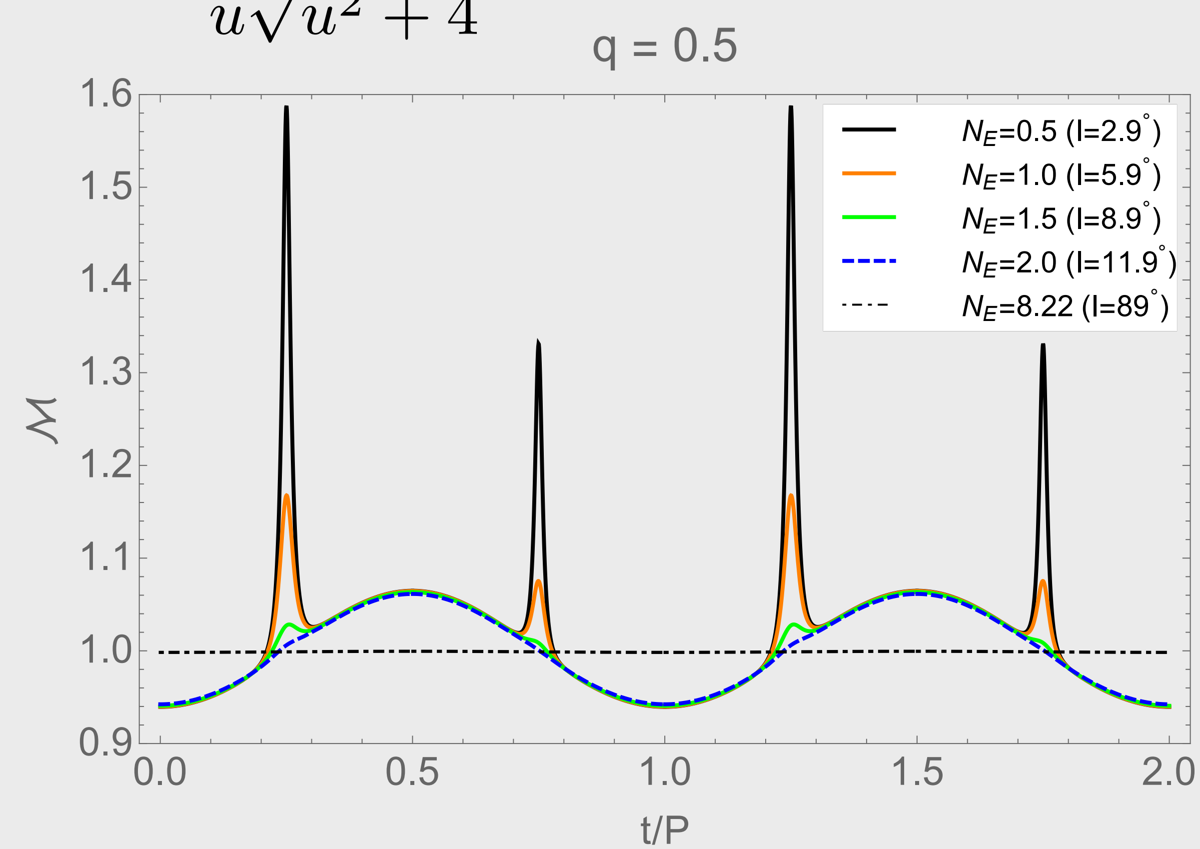




angular separation in Einstein Radii

Magnification $\mathcal{M}_{PS} = \dfrac{u^2+2}{u\sqrt{u^2+4}}$





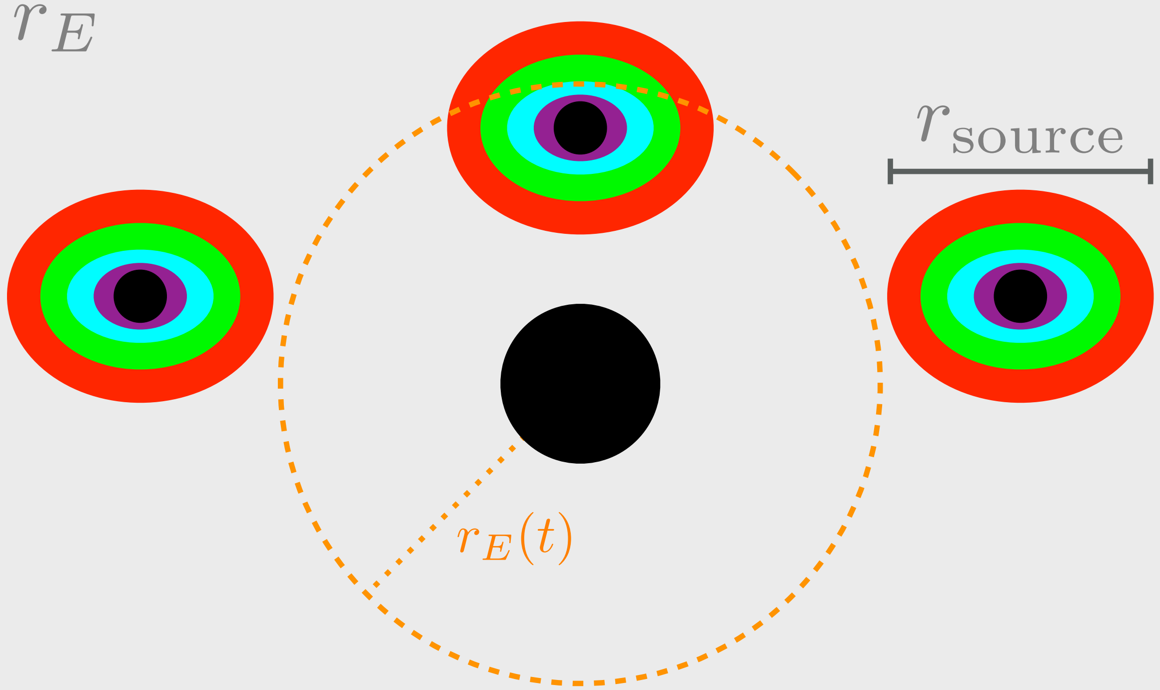
D'Orazio & Di Stefano 2017 (*arXiv:1707.02335*)

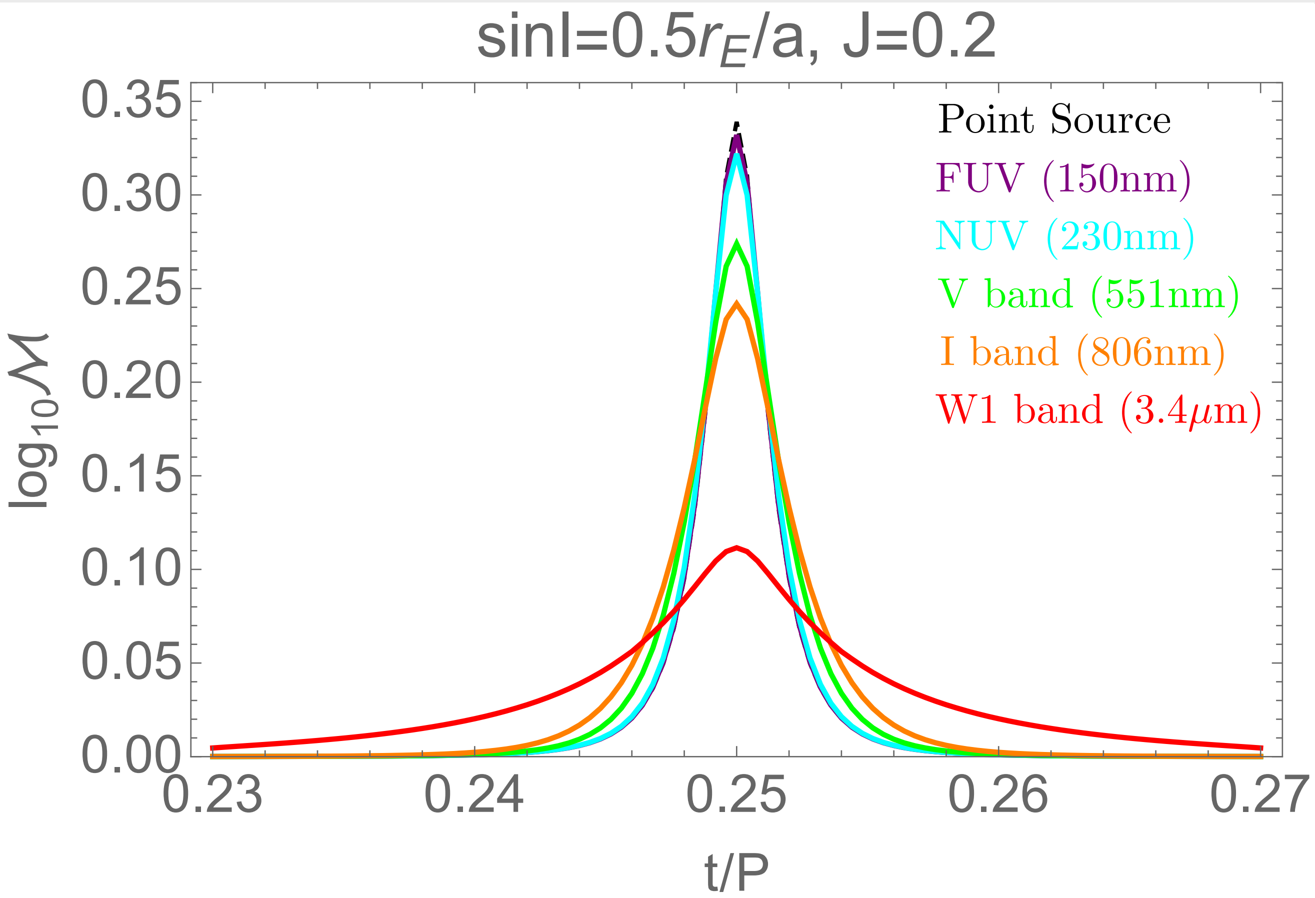
MBHB self lensing: a direct probe of binary accretion?

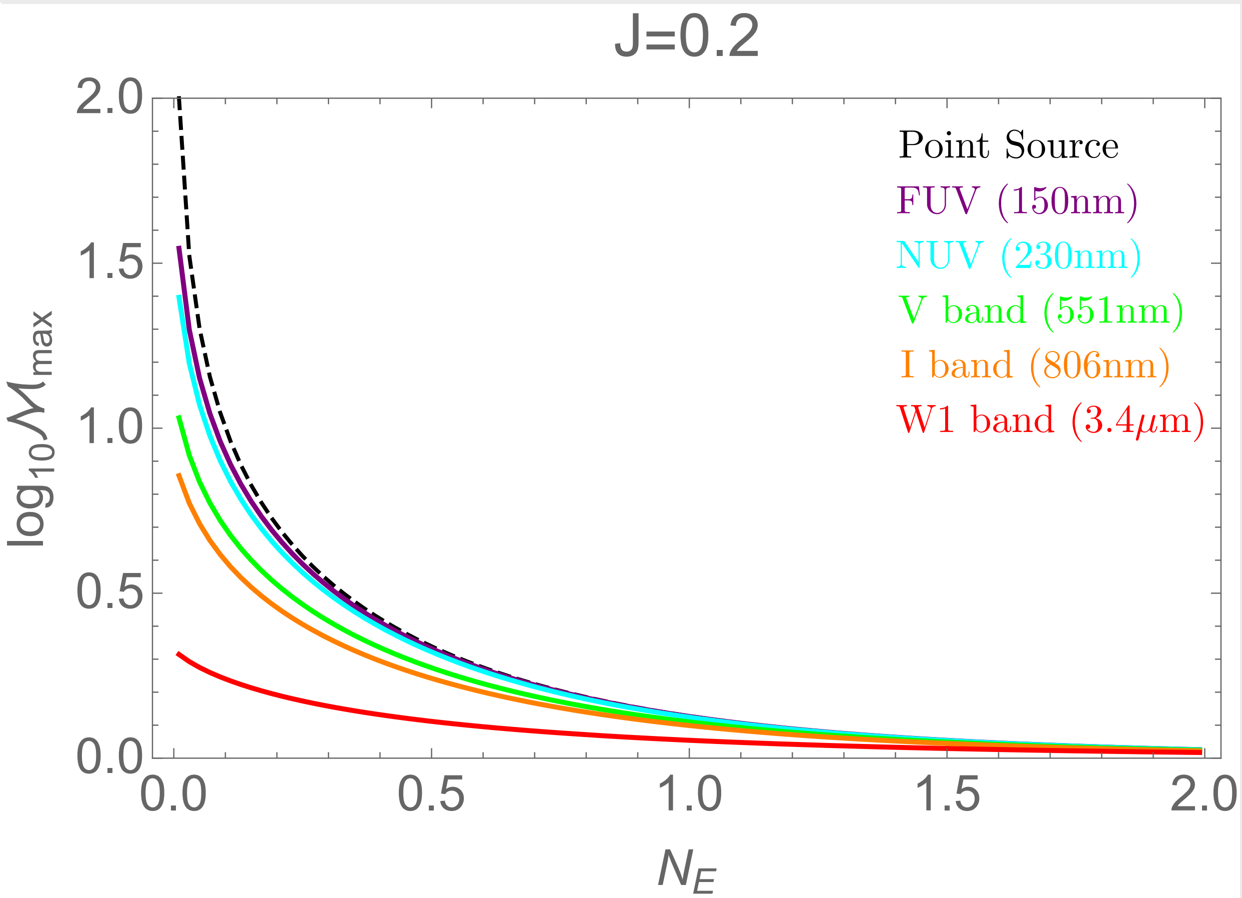
Finite source size effects when $r_{\rm source} \geq r_E$

$$r_E \approx \sqrt{2 R_s a}$$

$$r_{\rm source} \approx 0.27 q^{0.3} a \text{ (tidal truncation)}$$







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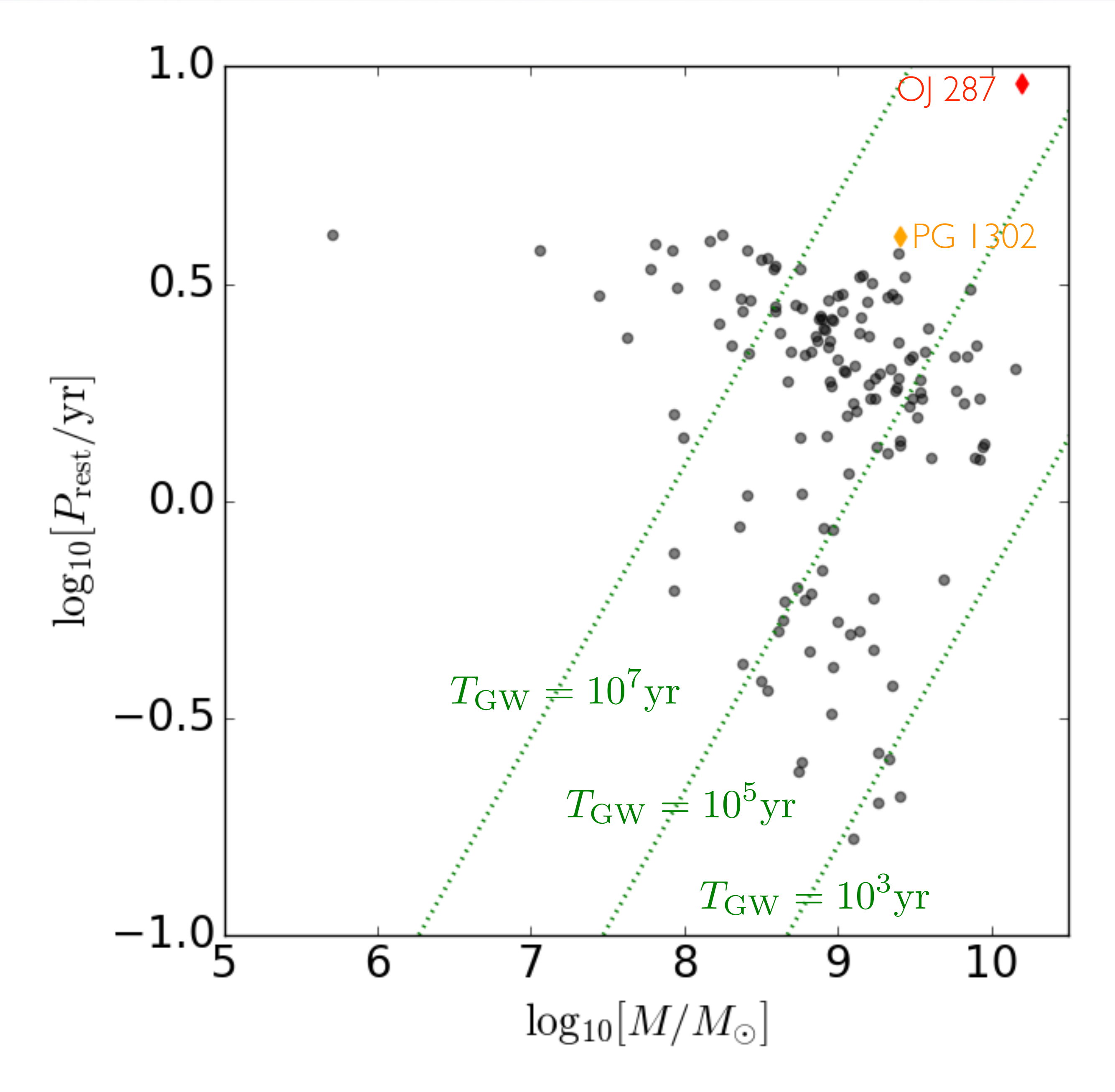

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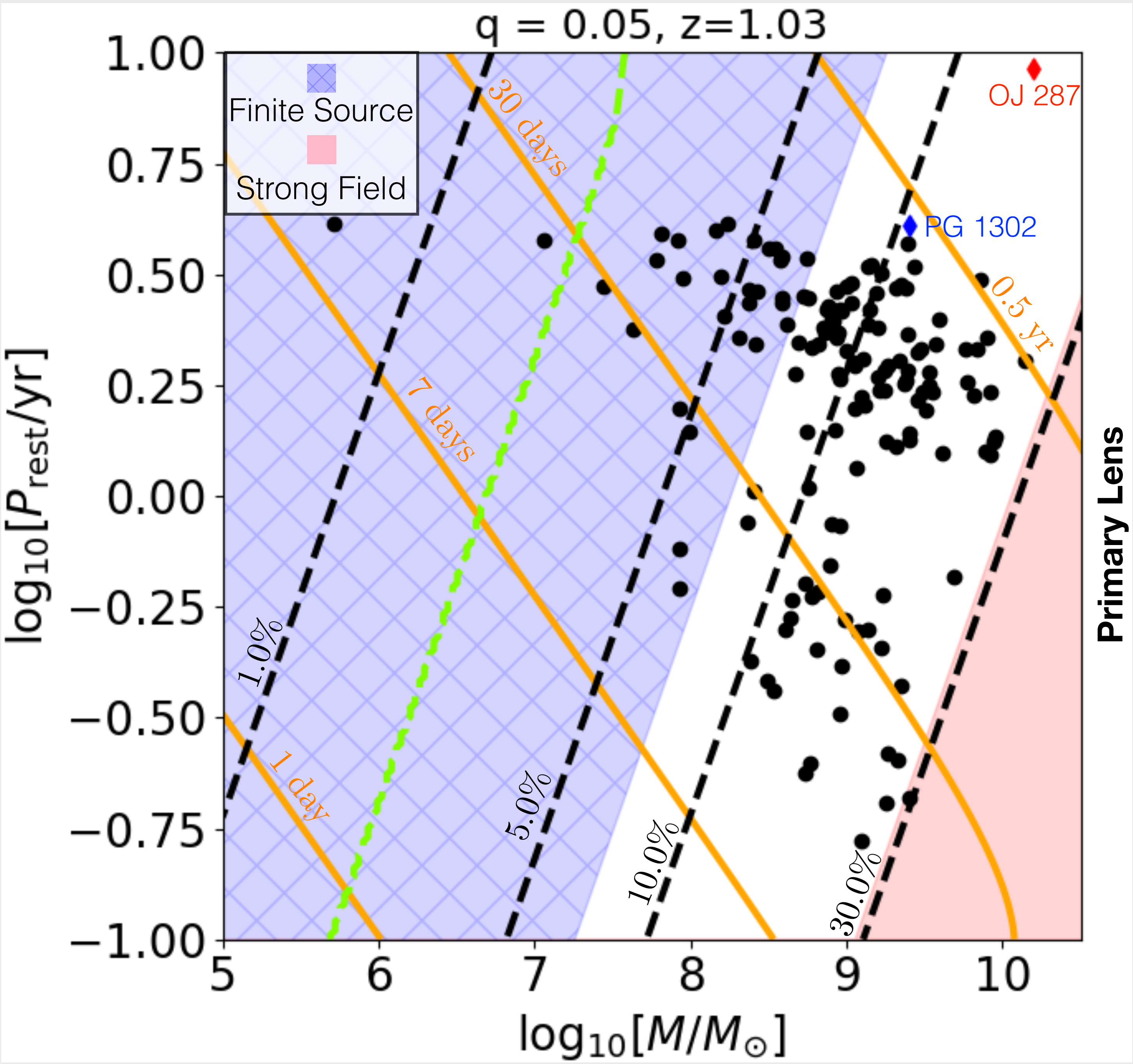


*~few to 10's of % probability for self-lensing (~5 should have flares)

*Flare durations of ~weeks-months

*Should we be seeing these lensing flares already?

-obscuration?

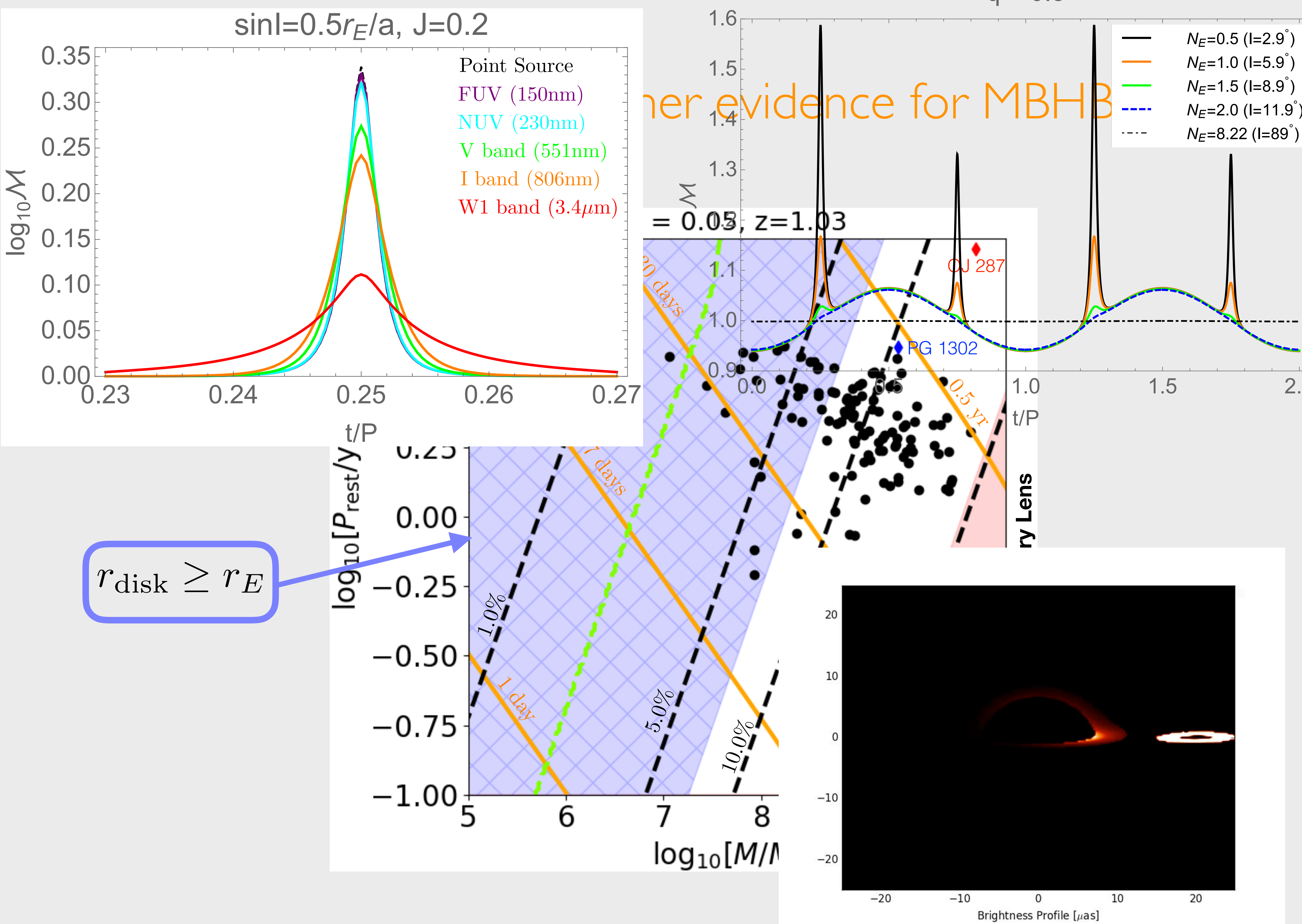
-not really MBHBs?

-sample bias - look for spikes

-low mag - other light sources

*Point-source and finite-source events

D'Orazio & Di Stefano 2017 (*arXiv:1707.02335*)



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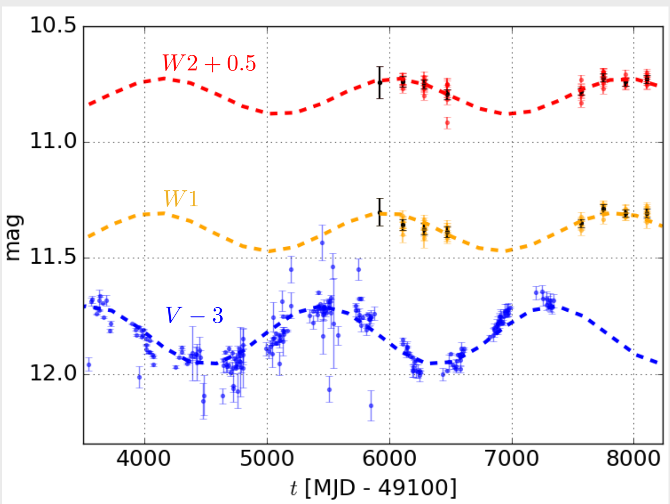
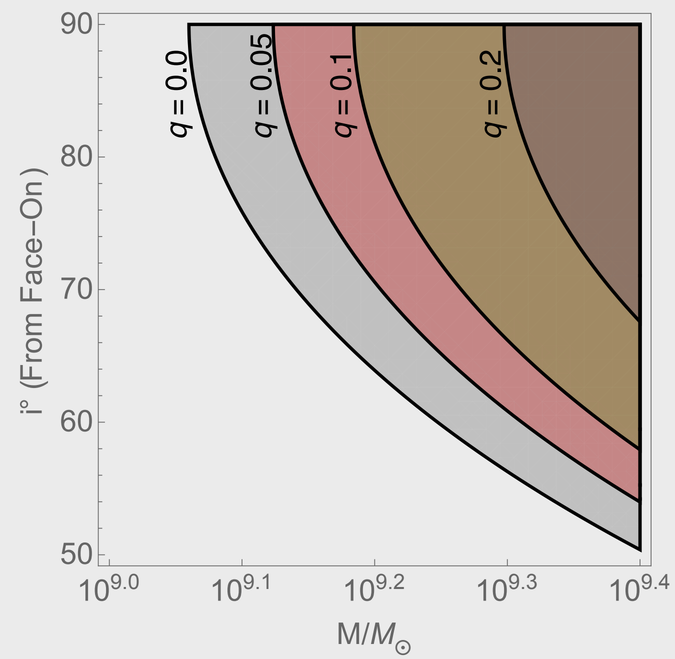
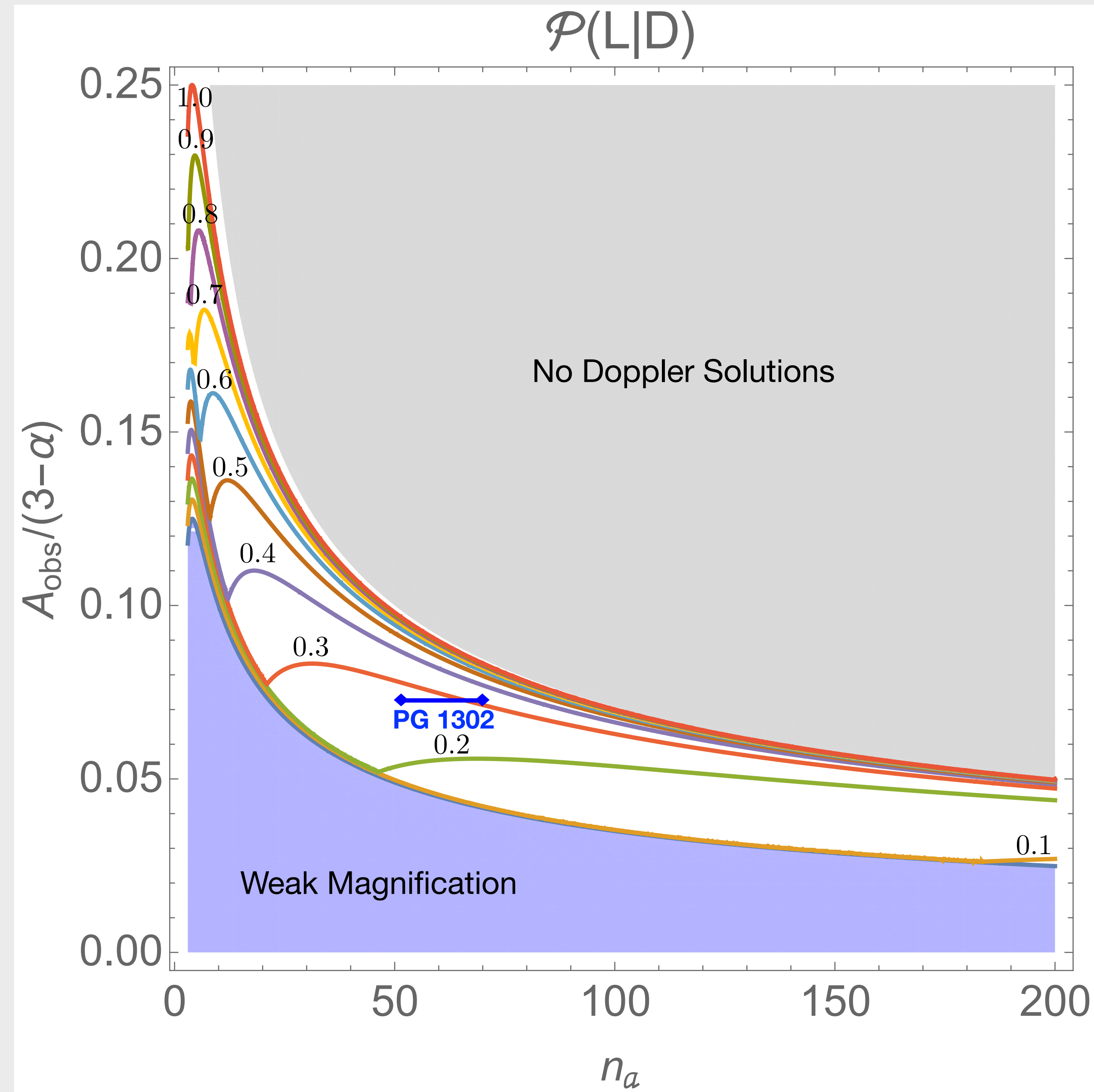
MBHB self lensing: Doppler + lensing

Doppler restricts possible inclinations ⟶ increased probability of lensing

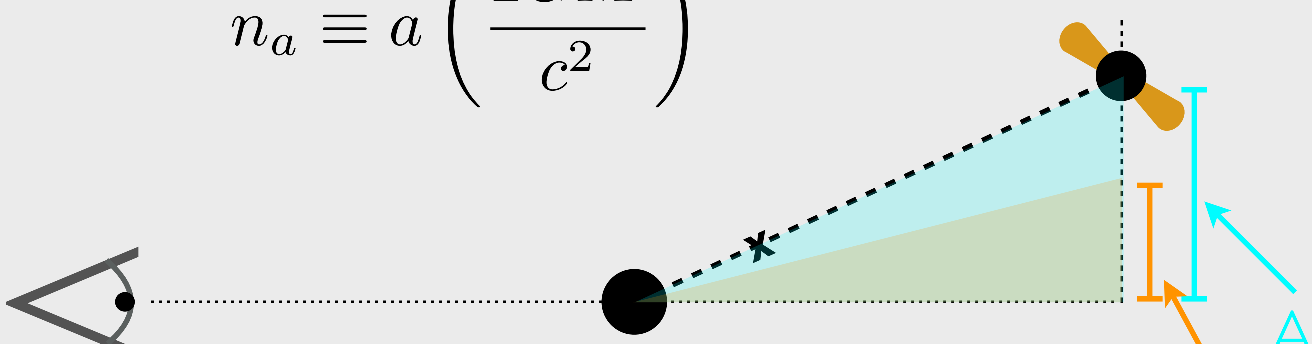






$$I(q) = \cos^{-1}\left[(1+q)\frac{A_{\mathrm{obs}}}{3-\alpha}\sqrt{n_a}\right]$$

$$n_a \equiv a\left(\frac{2GM}{c^2}\right)^{-1}$$



Allowed Doppler inclinations

Allowed lensing inclinations

D'Orazio & Di Stefano 2017 (*arXiv:1707.02335*)

Summary

* Characterization of MBHB population with EM signatures can constrain expected gravitational wave background as well as astrophysics (accretion, mutual growth of BHs and galaxies)

* New tool for finding MBHBs: self lensing

* MBHB self-lensing provides:
  * Unique identifier: achromatic and known phase if coupled with Doppler boost
  * Probe of accretion physics - finite source lensing
  * Constraints on binary inclination and mass-ratio
  * Orbit tracker - precession?
  * Population constraints: in unison with e.g. PTA GWB

* Must look for spiky periodic flaring, which may have been missed so far!