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

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Massive Black Hole Binaries (MBHBs)

- 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!

\[ M_{\text{bin}} \sim 10^6 \rightarrow 10^{10} M_\odot \]
Electromagnetic MBHB evidence/searches

Dual AGN

Core ellipticals

Periodic light curves

Grav waves

Separation

~kpc

~pc

~sub-pc

Broad line monitoring

Jet morphology

NGC 6240

1.4 kpc
EM signatures: Binary gas accretion
Periodic accretion

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

\[ F_{\nu}^{\text{obs}} = D^{3-\alpha} F_{\nu}^{\text{rest}} \]

\[ \alpha = \frac{d\ln F_{\nu}}{d\ln \nu} \]
EM signatures: Binary gas accretion
Doppler-boosted modulation
MBHB candidate: PG 1302-102

\[ z = 0.28 \]

Optical variability

\[ P_{\text{obs}} \approx 5.2 \text{yr} \]
\[ P_{\text{rest}} \approx 4.1 \text{yr} \]

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

Inferred orbital separation:

\[ a = 0.01 \text{pc} \left( \frac{P_{\text{bin}}}{4.1 \text{yr}} \right)^{2/3} \left( \frac{M}{10^9 M_\odot} \right)^{1/3} \]

Graham+2015, Nature
D’Orazio, Haiman, Schiminovich 2015, Nature
Variability in the IR: A lighthouse in the dust?
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PG 1302 - IR and Optical

IR light curves: phase shifted + diminished amplitude

Jun+2016
D’Orazio & Haiman *In prep.*
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

\[ t_{\text{ret}} = t - \frac{R_d}{c} \left( 1 - \cos \phi \right) \]
Dust Reverberation Model

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

**Out:** IR amplitude and phase relative to UV/optical
Relative IR amplitude

Phase lag

\[ \frac{t_d}{P} \] cycles

\[ \frac{t_d}{P} - \frac{1}{4} \] cycles

Isotropic

Dust Sphere

Doppler

(Analytic) Results
Implication for PG 1302?

**Reverb IR Spectrum**

- Constrains: $A_{\text{IR}}/A$
- $t_{d}/P$

**Figure B2.** Top: best blackbody fits to the average WISE fluxes, with one standard deviation errors (error bars are smaller than data points for the W1, W2, and W3 bands). Bottom: posterior distributions of parameters from MCMC sampling. The left includes the W1, W2, and W3 band fluxes while the right includes only the W1 and W2 band fluxes. Each fit uses 32 walkers on chains of length 8192 steps to sample the posterior distribution.

- Constrains: $\theta_{T}$

- $R_{d} \sim 1 - 4\text{pc}$

- $h/r \sim 0.1$
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