Tools for Characterizing a Population of Massive Black Hole Binaries
(Imaging gravitational wave driven binaries?)

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The Gravitational Wave Spectrum

Sources

Quantum fluctuations in early universe

Binary Supermassive Black Holes in galactic nuclei

Compact Binaries in our Galaxy & beyond

Compact objects captured by Supermassive Black Holes

Rotating NS, Supernovae

wave period

age of universe

years

hours

sec

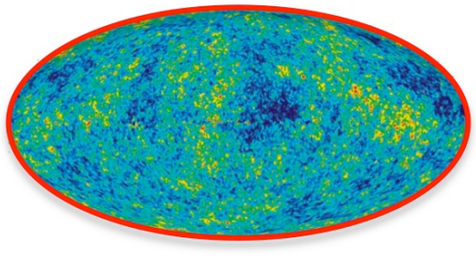
ms

log(frequency)

-16 -14 -12 -10 -8 -6 -4 -2 0 +2

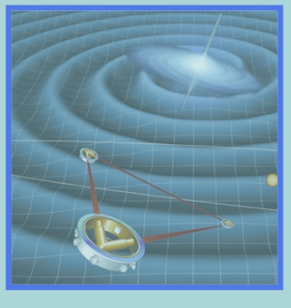
Detectors

Cosmic microwave background polarization



Pulsar Timing

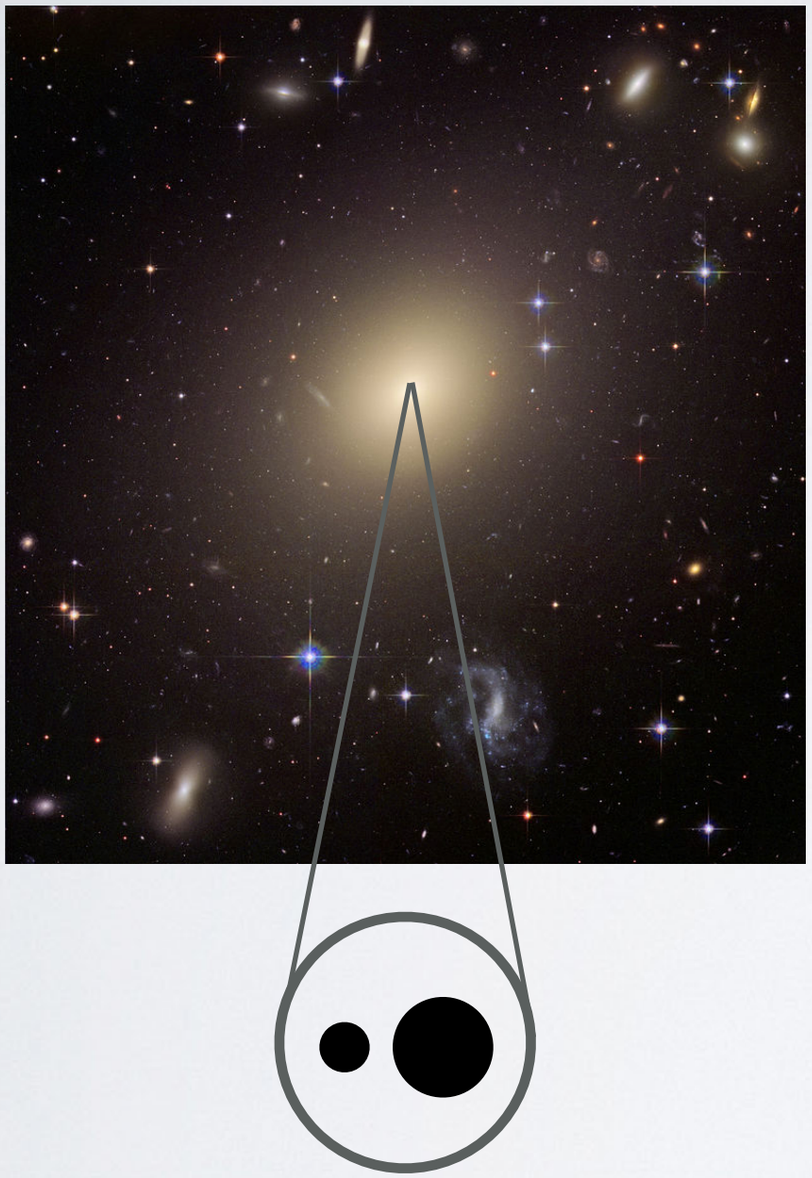
Space Interferometers



Terrestrial interferometers

Source: NASA

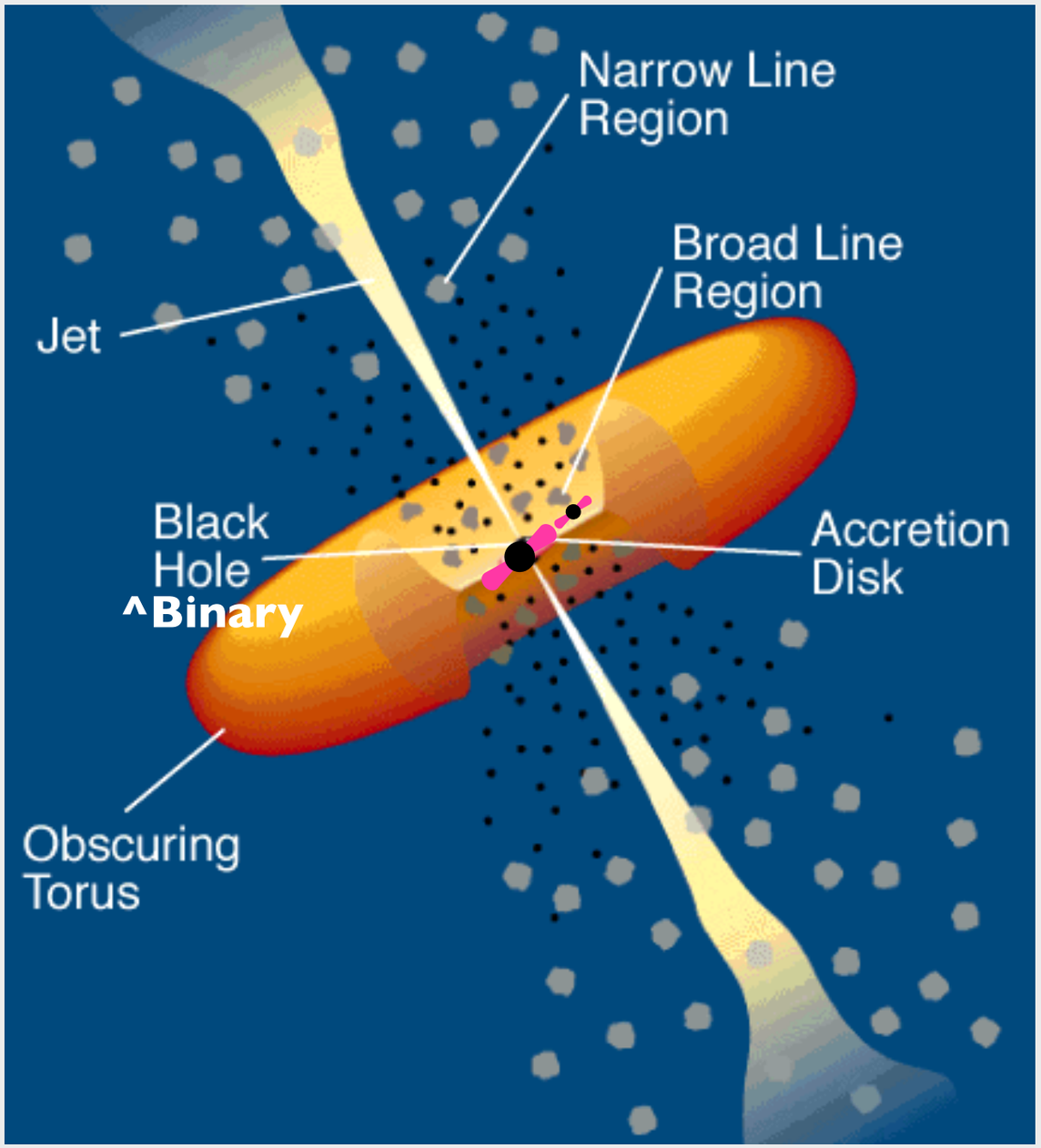
Massive Black Hole Binaries (MBHBs)



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

* Primary (known) sources of low frequency gravitational waves
* Can teach us about the mutual evolution of galaxies and MBHs
* Characterization of MBHB population by EM signatures can inform/compliment characterization by gravitational wave background…
* How do we find them? They don't (necessarily) merge in vacuum!

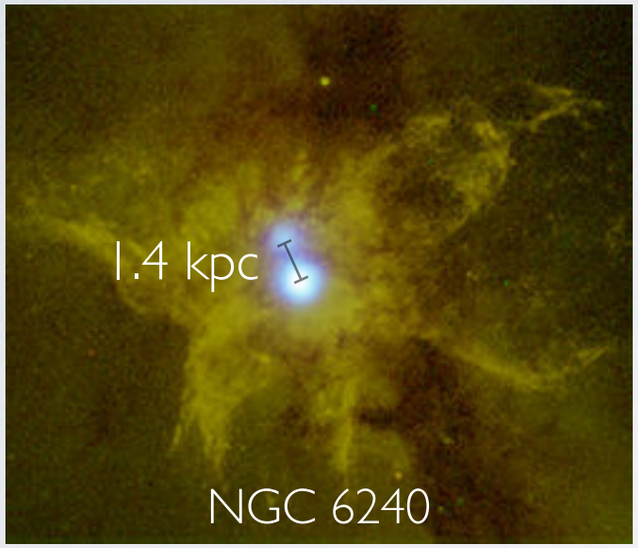
Quasar Anatomy: where MBHBs hang out



Electromagnetic MBHB evidence/searches

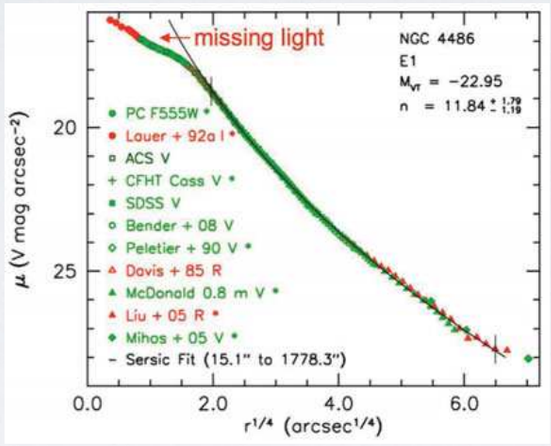
Separation

Dual AGN

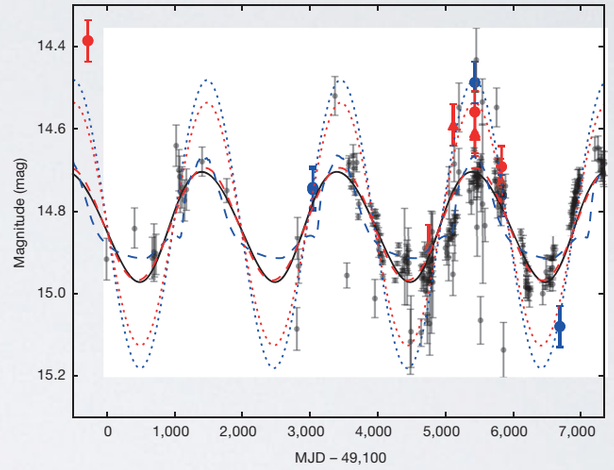


~kpc

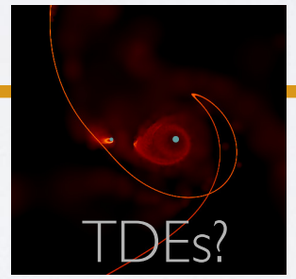
Core ellipticals



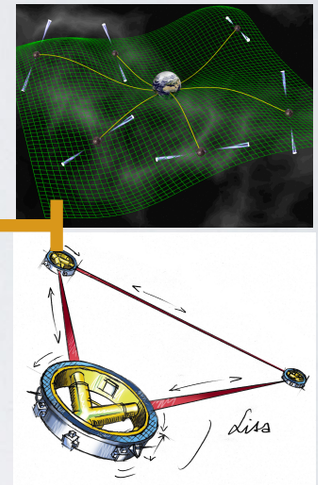
Periodic light curves



~pc

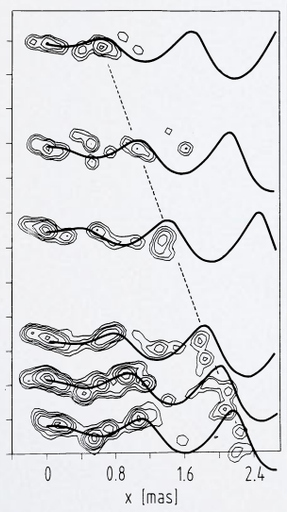


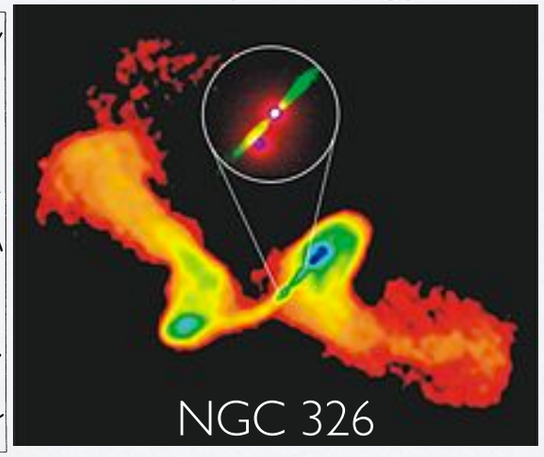
Grav waves



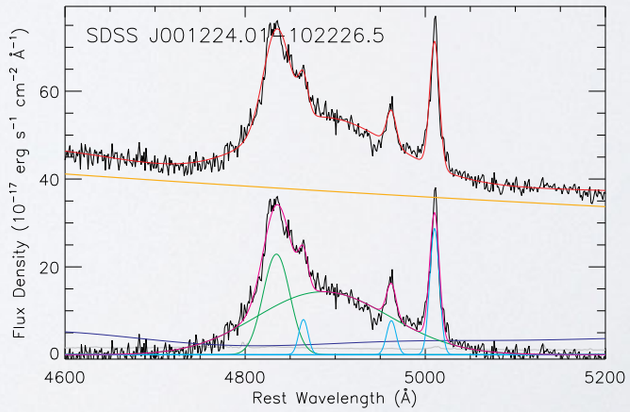
~sub-pc

Jet morphology

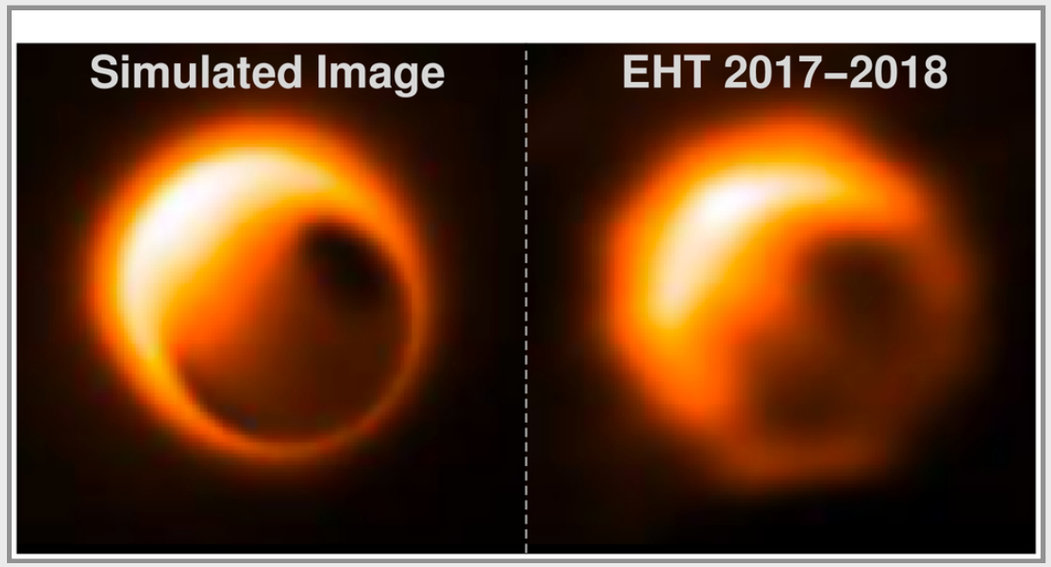




Broad line monitoring

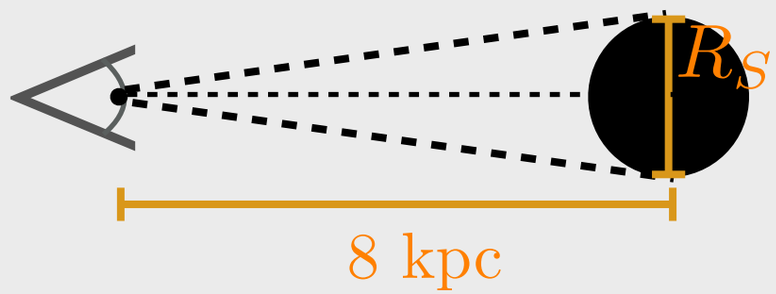


The Event Horizon Telescope: Milky Way Black Hole

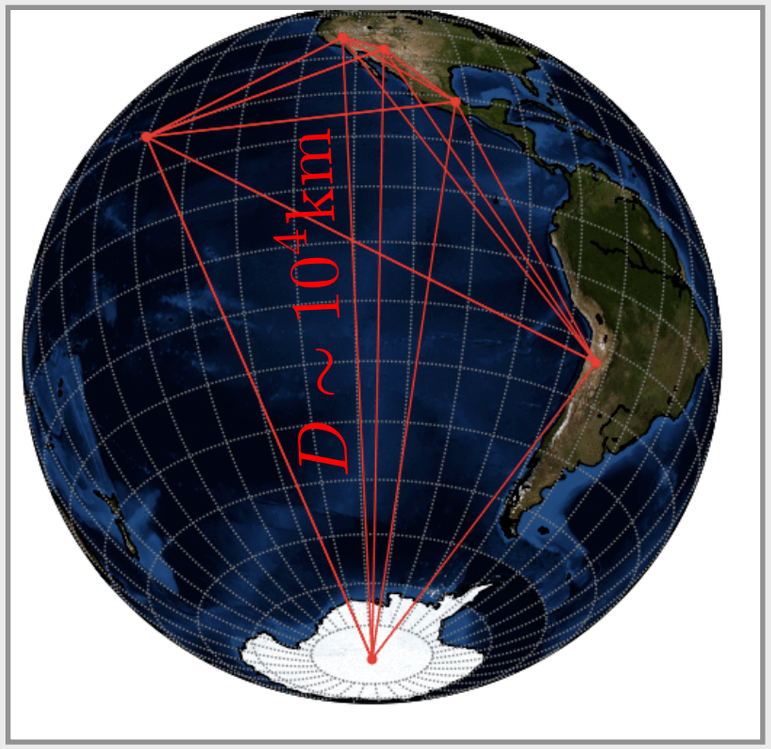


Doeleman+2009, Fish+2012, Lu+2014

Milky Way Black Hole:



$$\theta_{EH} \sim \frac{R_S}{8\mathrm{kpc}} \sim 10\mu as$$



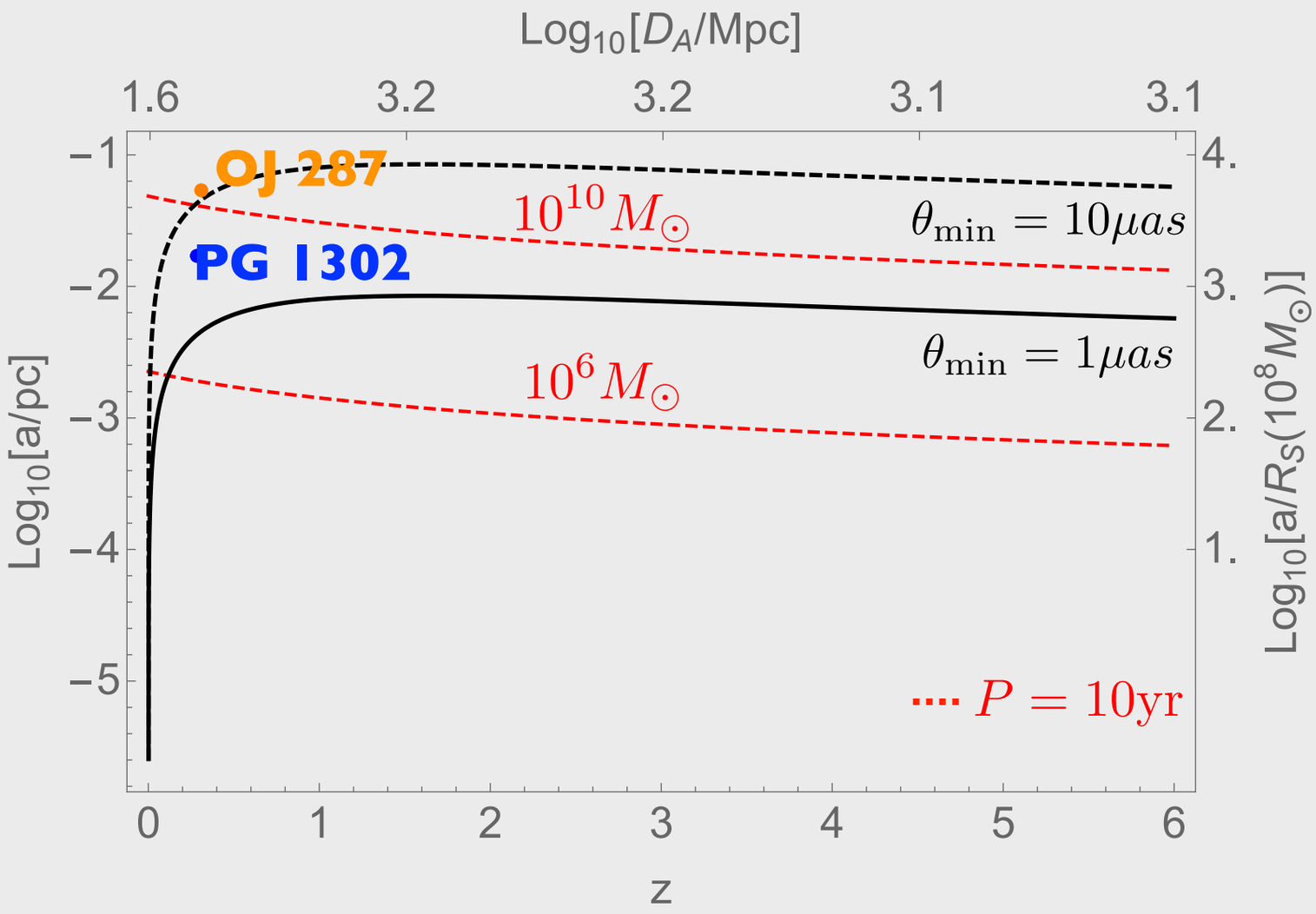
Diffraction limited resolution

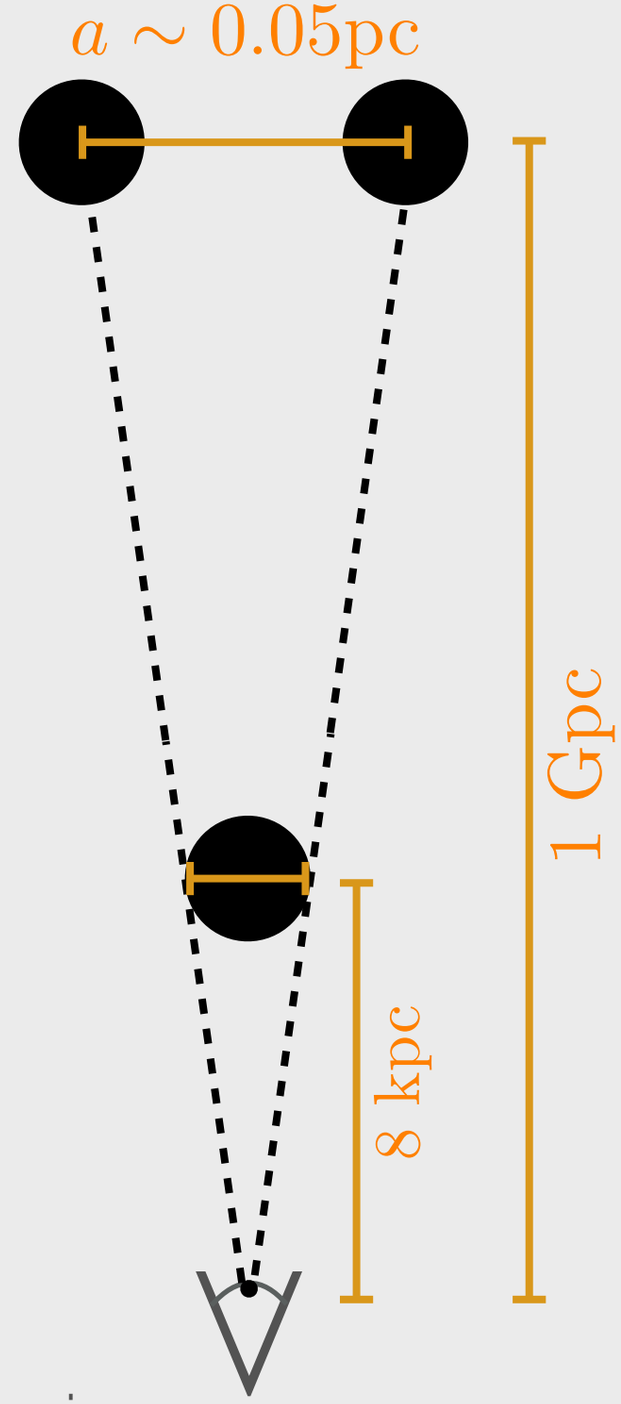
$$\theta \sim \frac{\lambda}{D} = \frac{1\mathrm{mm}}{10^4\mathrm{km}} \rightarrow 20\mu as$$

*Can push astrometric precision to $\sim 1\mu as$

(Broderick, Loeb, Reid 2011)

The Event Horizon Telescope: MBHBs





Could resolve binaries in GW driven regime

(work with Avi Loeb)

How many binary's could we Image with the EHT?

*Assume a fraction of all AGN are triggered by binaries:

Requirements:

Ingredients:

$$\frac{N_{\rm EHT}(z)}{\Delta\Omega\Delta z} \approx \frac{dV}{dzd\Omega}\int_{L_{mm}^{\rm min}}^{\infty}\frac{dN}{dL_{mm}dV}\mathcal{F}(L_{mm},z)dL_{mm}$$

* Bright in (sub)-mm (preferably both BHs)

→ sub-mm luminosity function:
From observationally constructed AGN radio luminosity functions

* Minimum binary separation set by EHT resolution

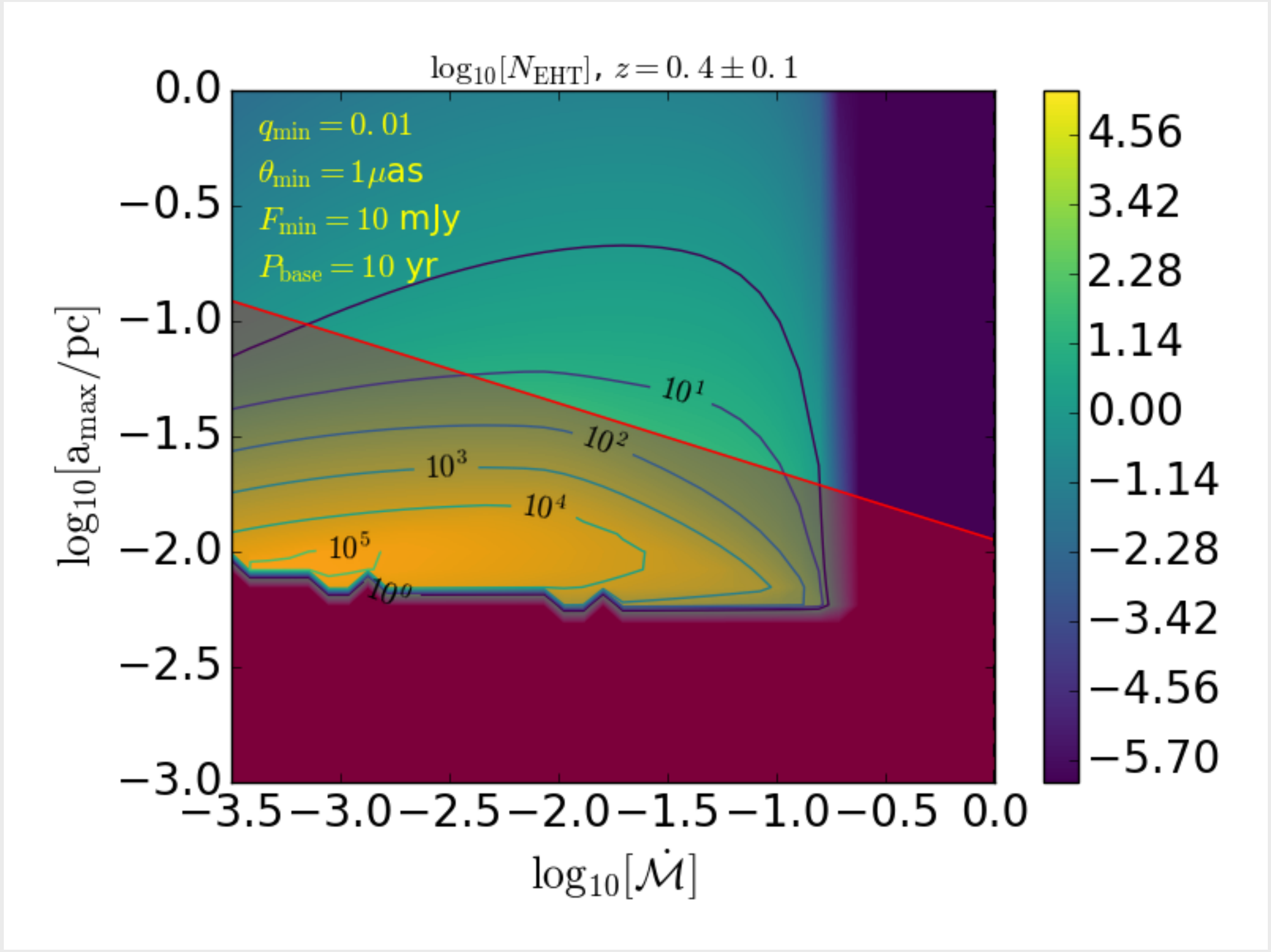
* Maximum binary separation set by observable orbital period (<10 years)

→ Binary Probability:
Calculated from residence time at required separations

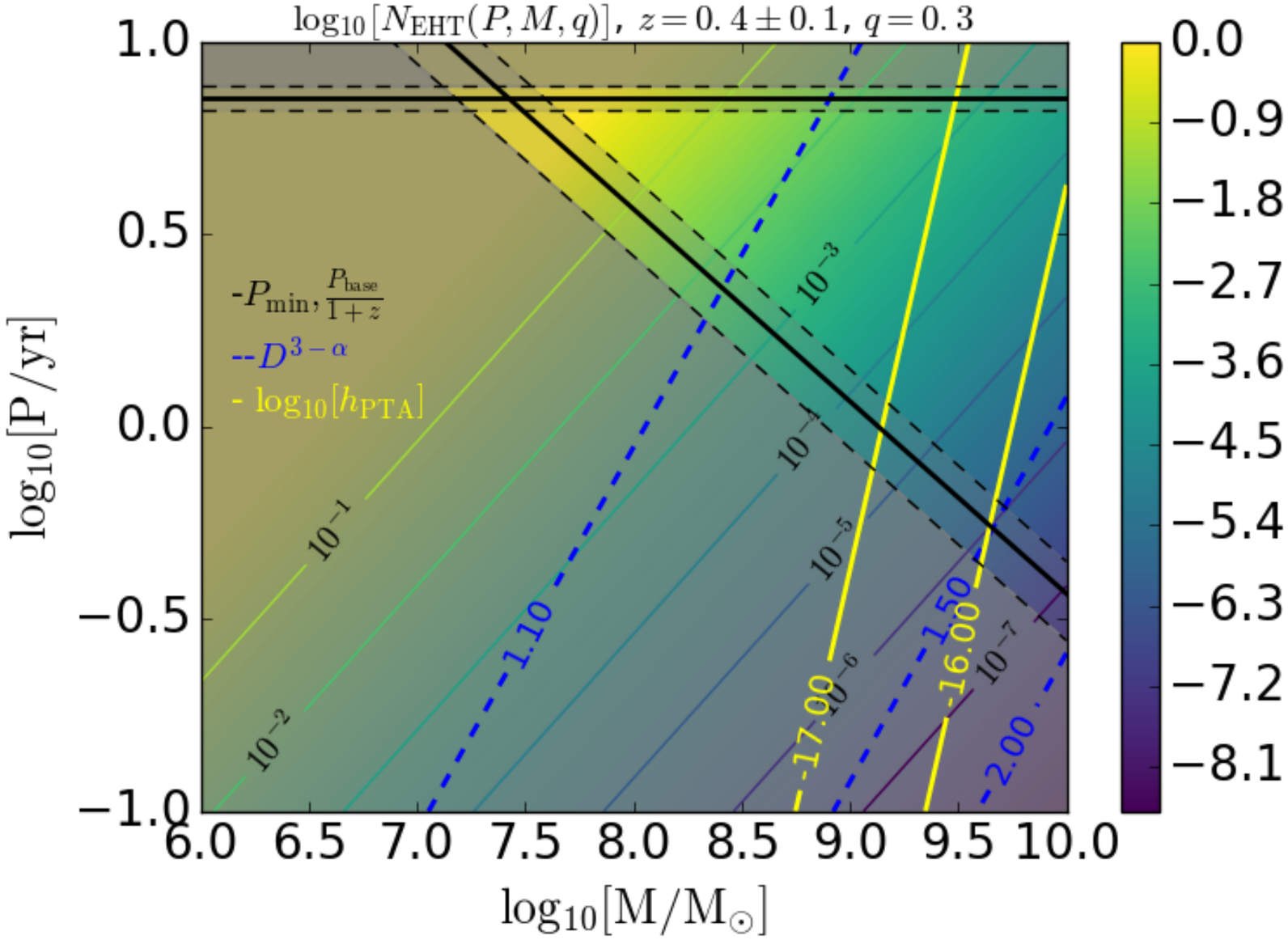
$$t_{\rm res} = \frac{\dot{a}}{a}$$

Assume:
Gas + Gravitational waves

How many binary's could we Image with the EHT?



Demographics



* Orbital velocities could allow large Doppler-boost modulations

* In PTA band, but strain below current GWB limits

Implications

* Aid in narrowing down mechanisms which drive MBHBs to merger -> constrain GWB

* Assume cosmology: precise measurement of the binary mass

$$GM = \left(\frac{\Omega}{1+z}\right)^2 (\theta_{\max} D_A(z))^3$$

* Measure binary mass: measurement of Hubble constant

Summary

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

* The EHT could resolve the orbital separations of MBHBs on short enough periods to watch entire orbits

* Beyond imaging such elusive objects, this could allow precise binary mass measurements, a measurement of the Hubble constant, test of the speed of gravitational waves, or…