In Search of a Final-Parsec Telescope:

Tracking the orbits of (super)massive black hole binaries at sub-parsec separations (Tips for finding MBHBs III)

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Einstein Fellows Symposium

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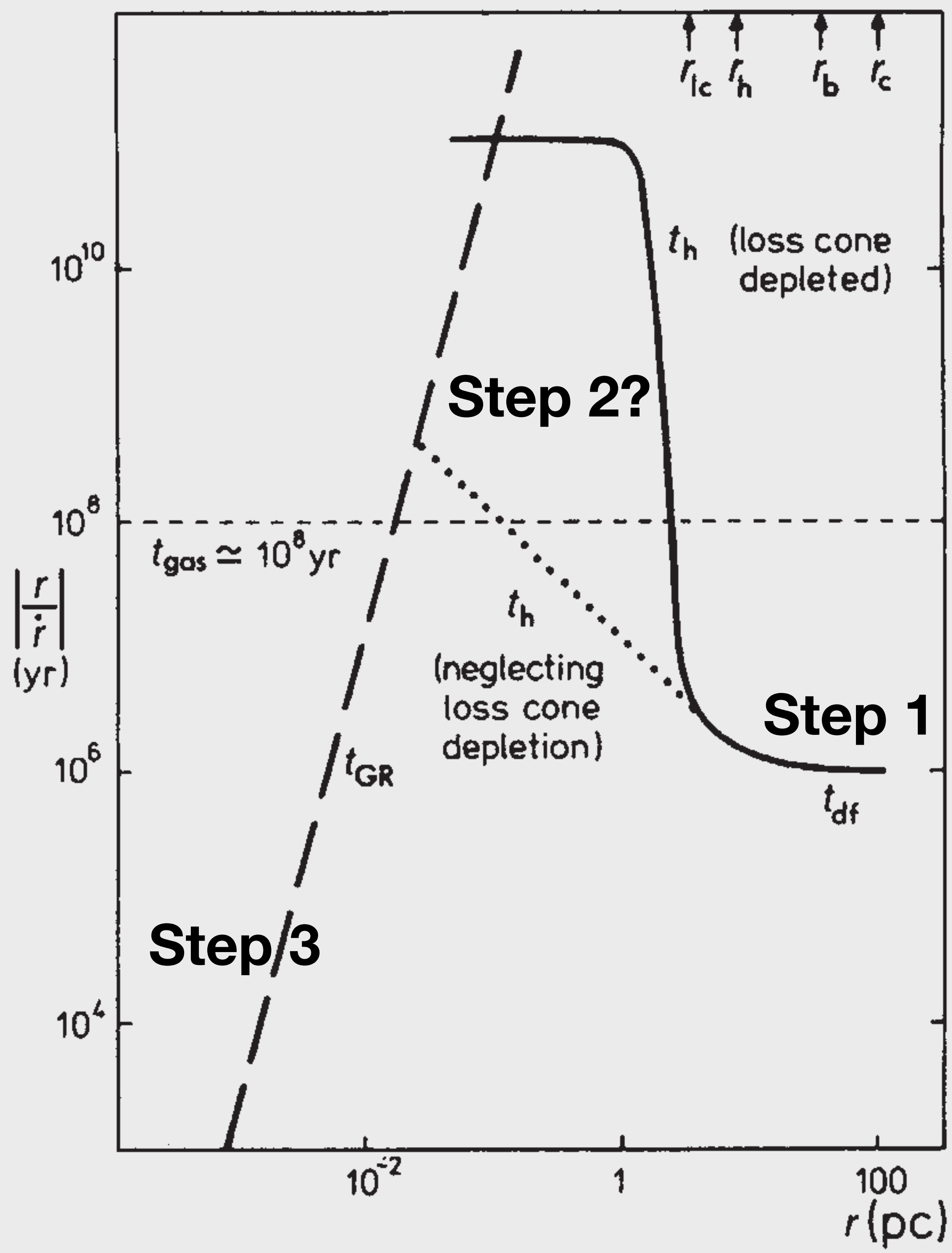
Galaxies merge, but do the black holes?



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

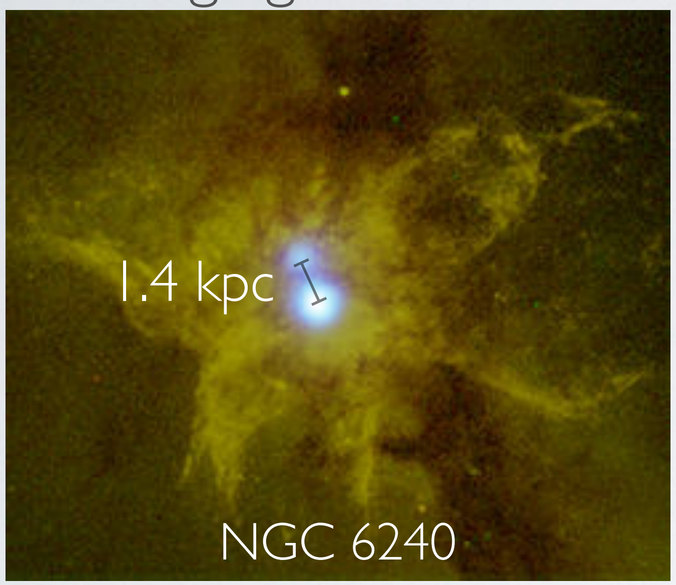
Galaxies merge, but do the black holes?
How do we find out?

* MBHB Demography:
  The fraction of MBHBs at different separations would elucidate the mechanisms which bring MBHBs together
    * The low frequency gravitational wave background (PTAs) and merger events (LISA) 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

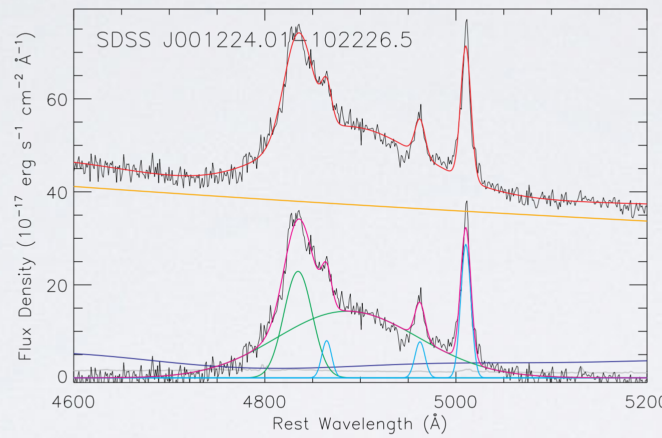
Step 1

Imaging dual AGN

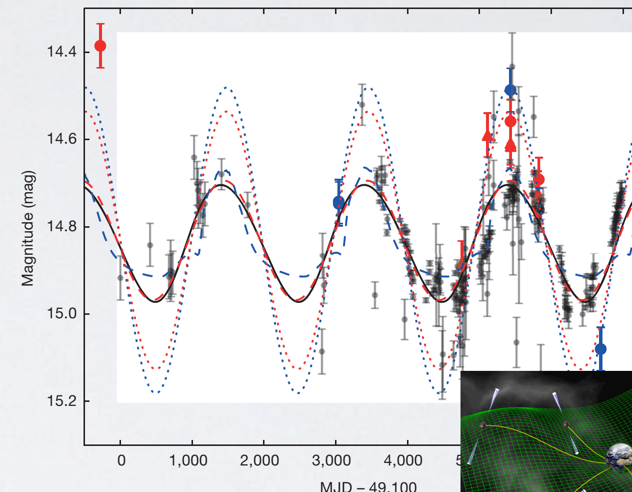


Step 2?

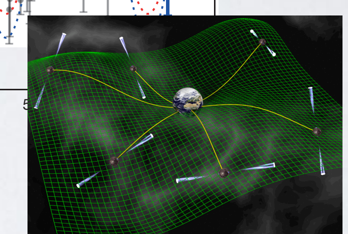
Broad line monitoring



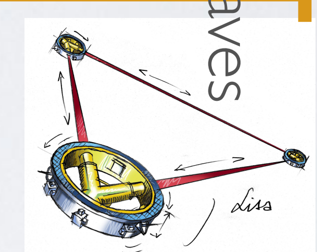
Periodic light curves



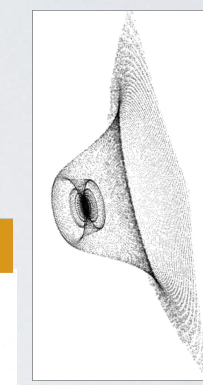
Step 3



Grav waves



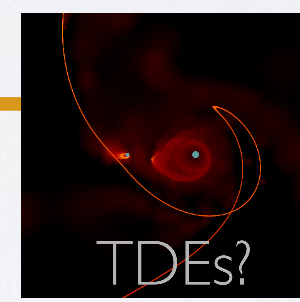
Recoil



Binary Separation

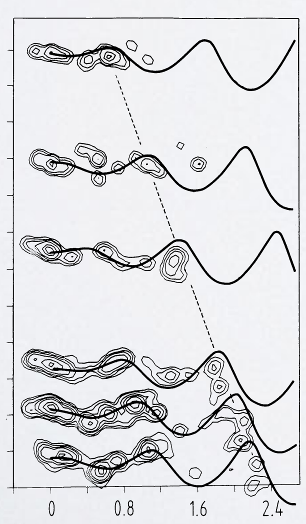
~kpc

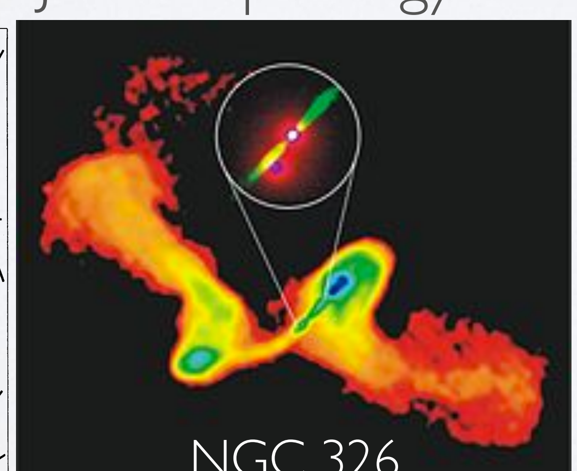
~pc



~sub-pc

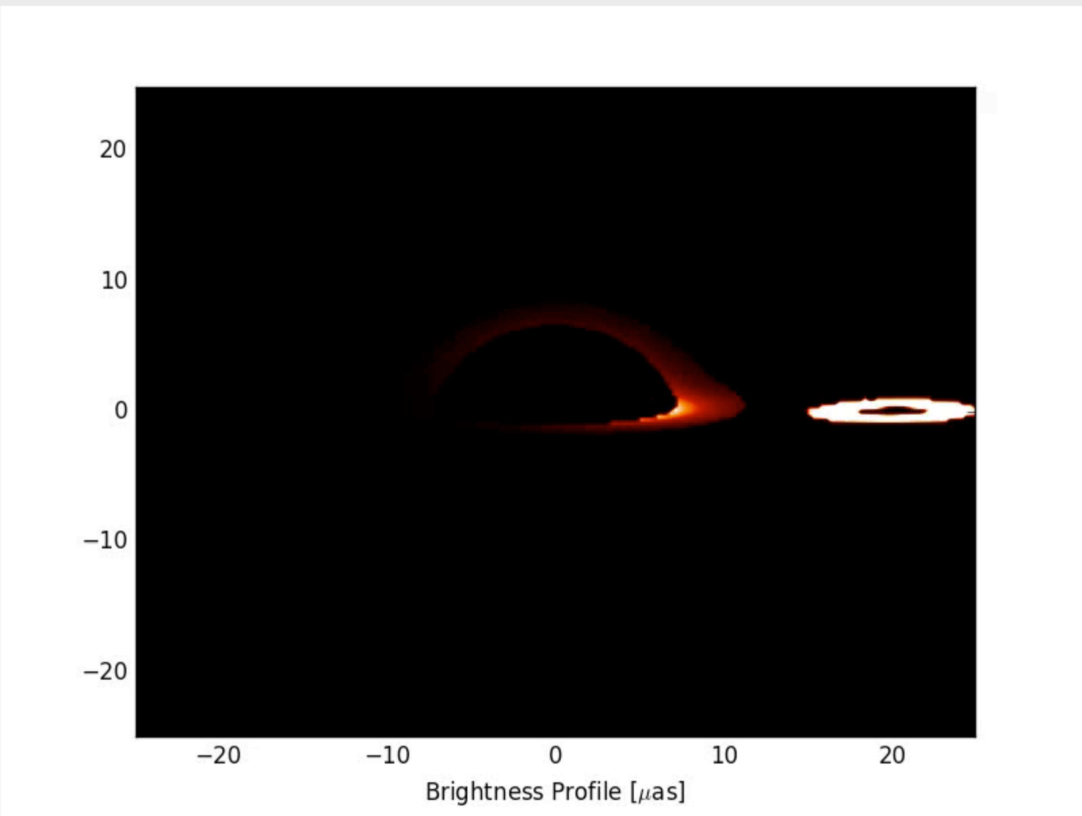
Jet morphology

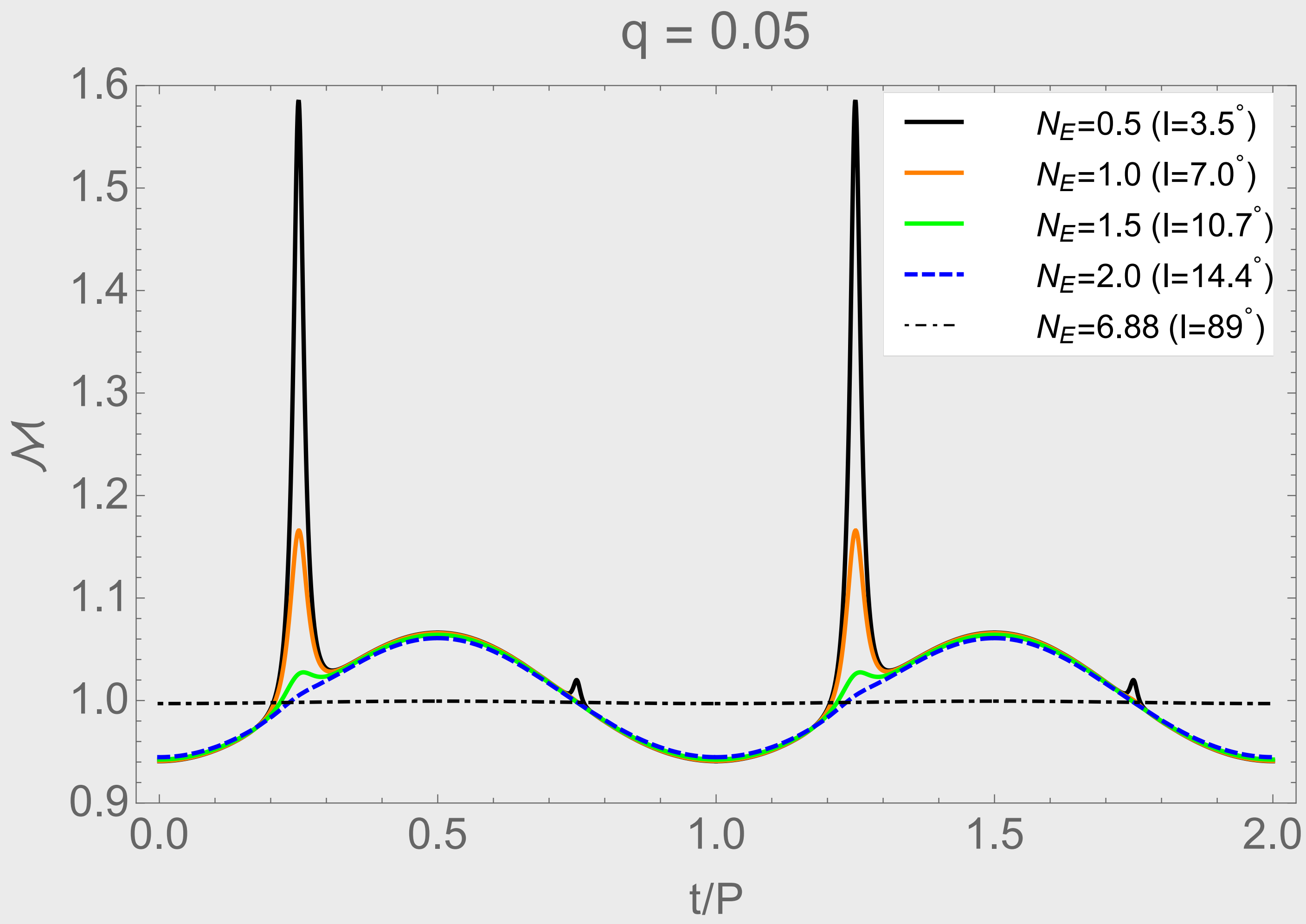




In-direct, but promising: Relativistic Doppler Boost Plus Gravitational Lensing

From "Tips for finding MBHBs II"





D'Orazio, Haiman, Schiminovich 2015; arXiv:1509.04301
D'Orazio & Di Stefano 2018; arXiv1707.02335

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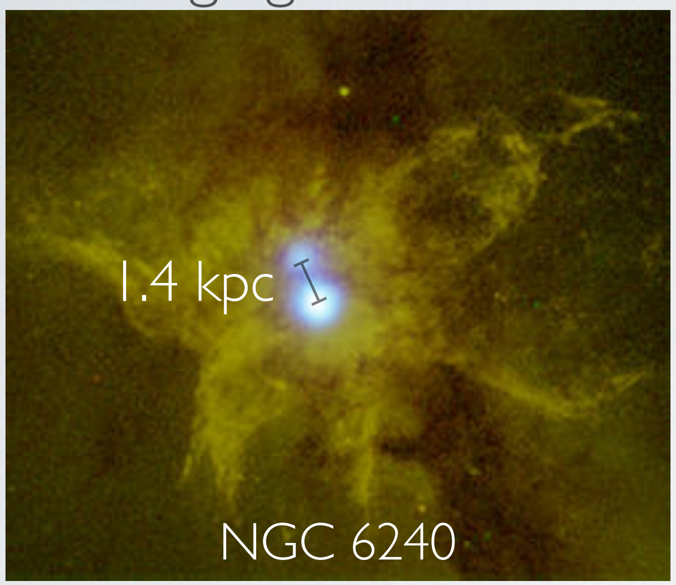

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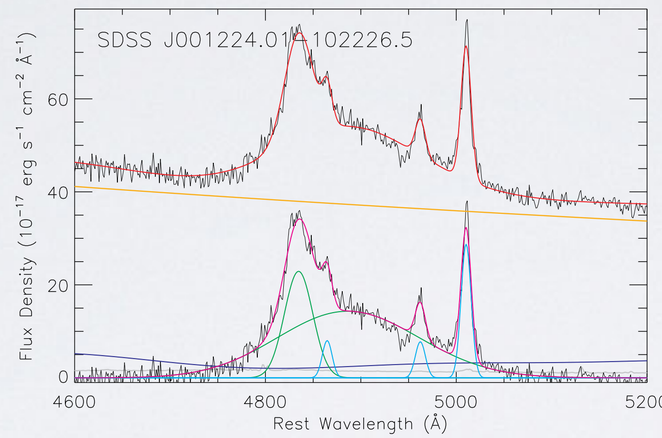

Step 3

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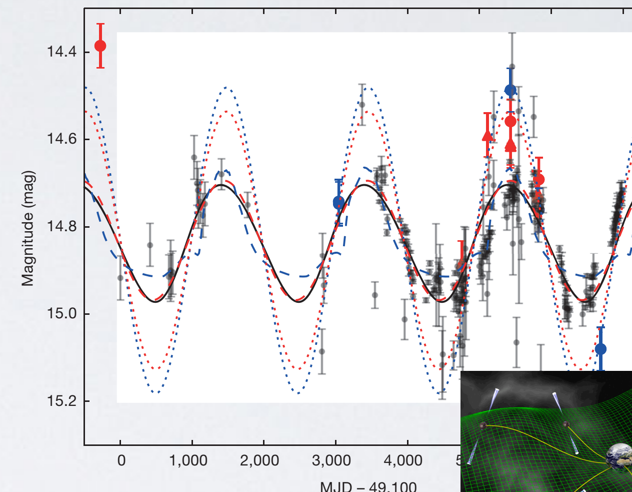

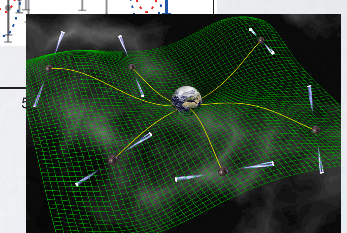

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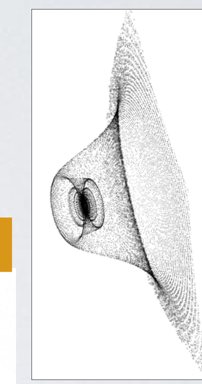
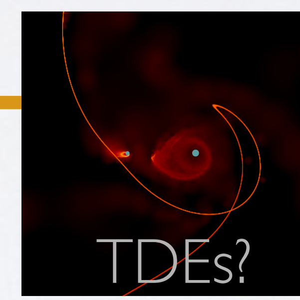


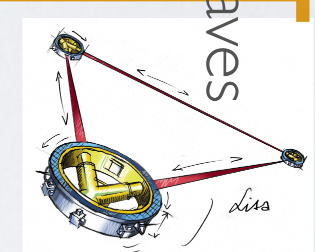
Binary Separation

~kpc

~pc



~sub-pc



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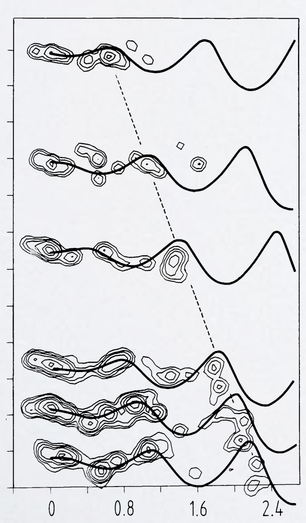
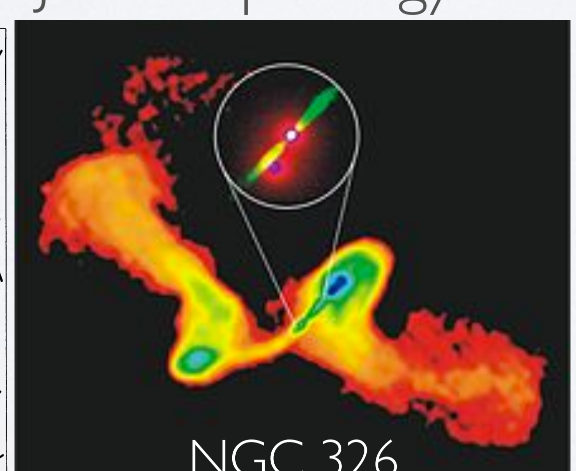
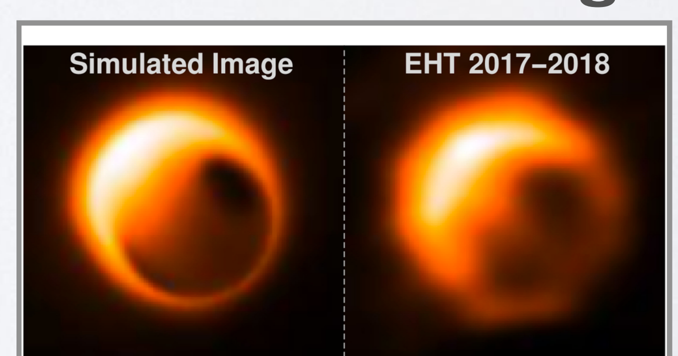




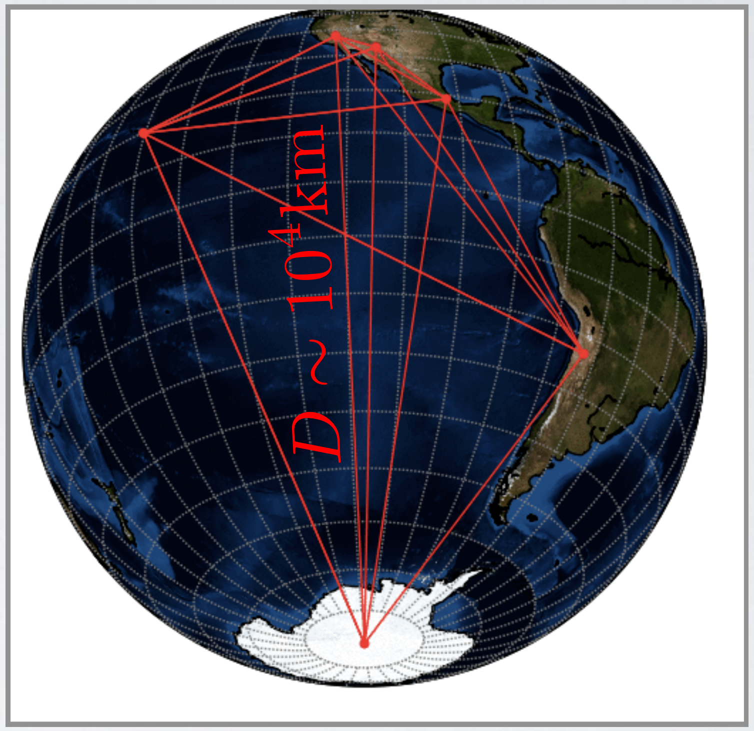
Direct orbital tracking



Seeing is believing?

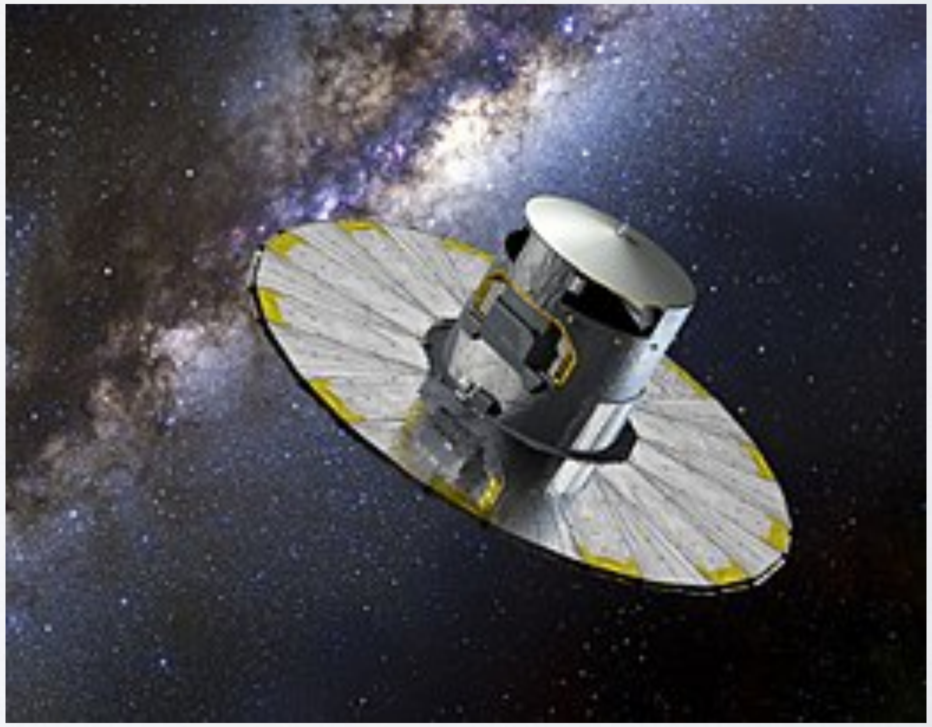
Part I: millimeter VLBI

D'Orazio & Loeb arXiv:1712.02362

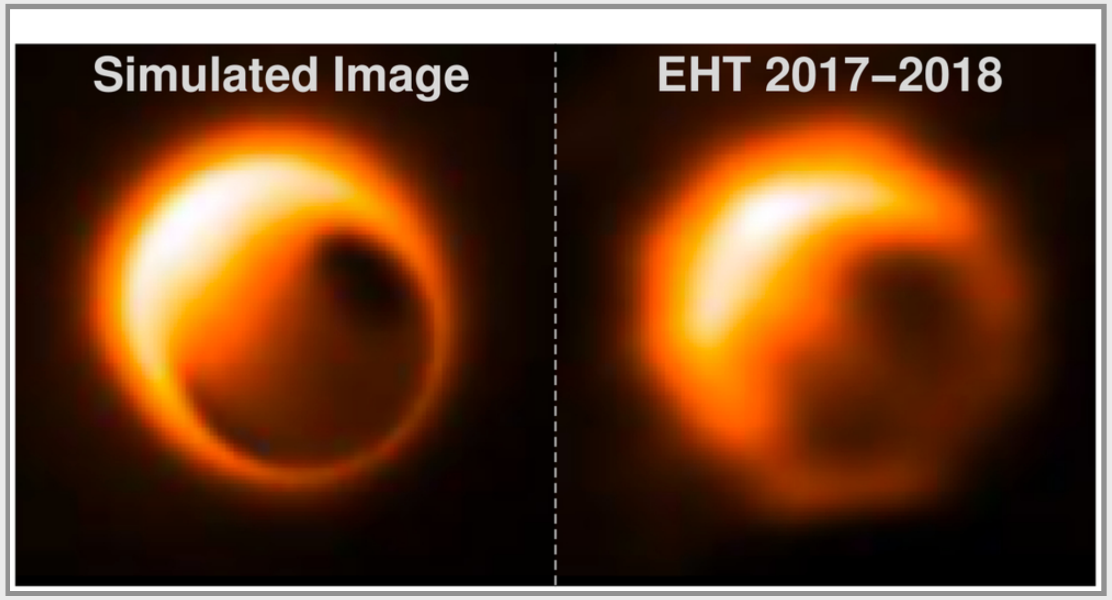


Part II: Gaia

D'Orazio & Loeb arXiv:1808.09974

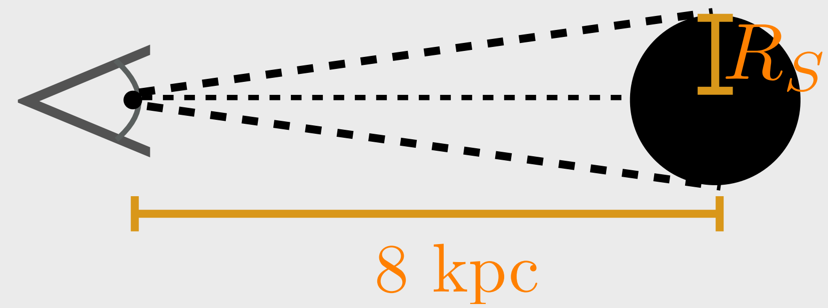


mm VLBI: Milky Way black hole (Event Horizon Telescope)

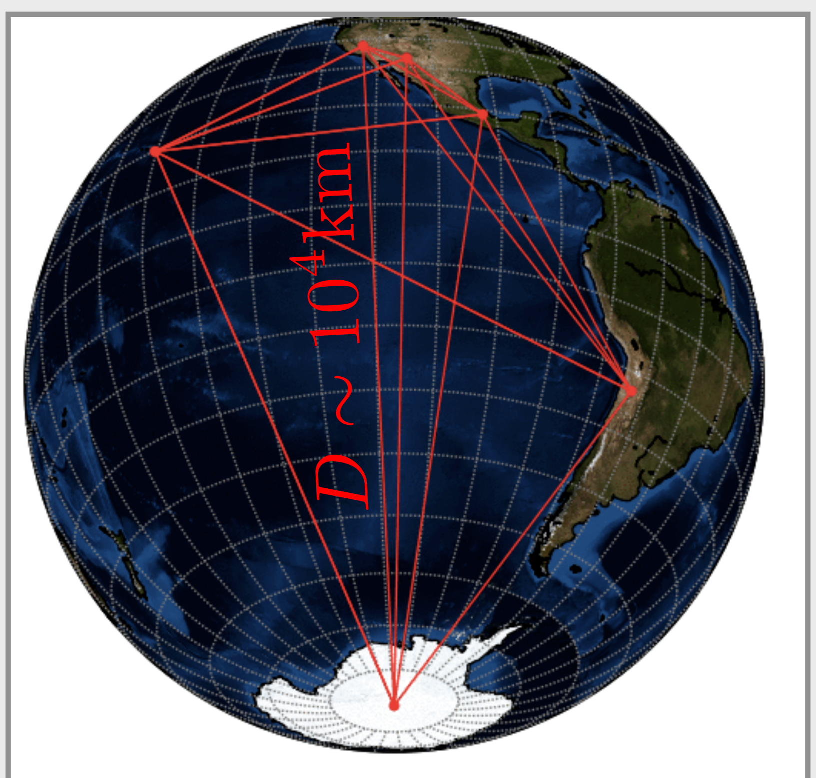


Doeleman+2009, Fish+2012, Lu+2014

Milky Way black hole:



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

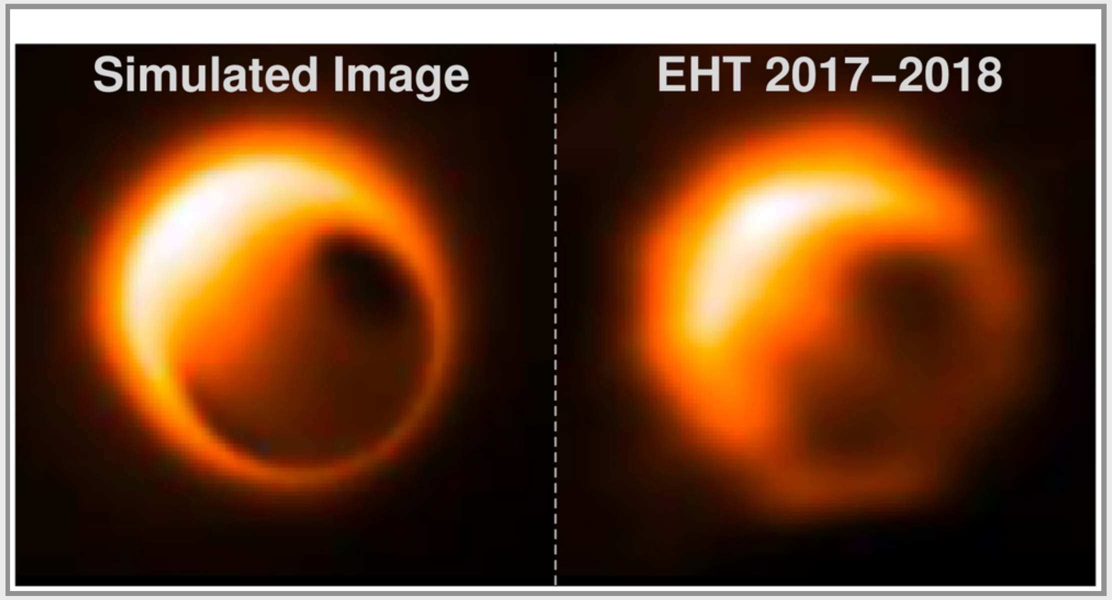


Diffraction limited resolution

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

*Can push relative astrometric precision to $\sim 1\mu as$
(Broderick, Loeb, Reid 2011)

mm VLBI: MBHBs
(Final Parsec Telescope?)



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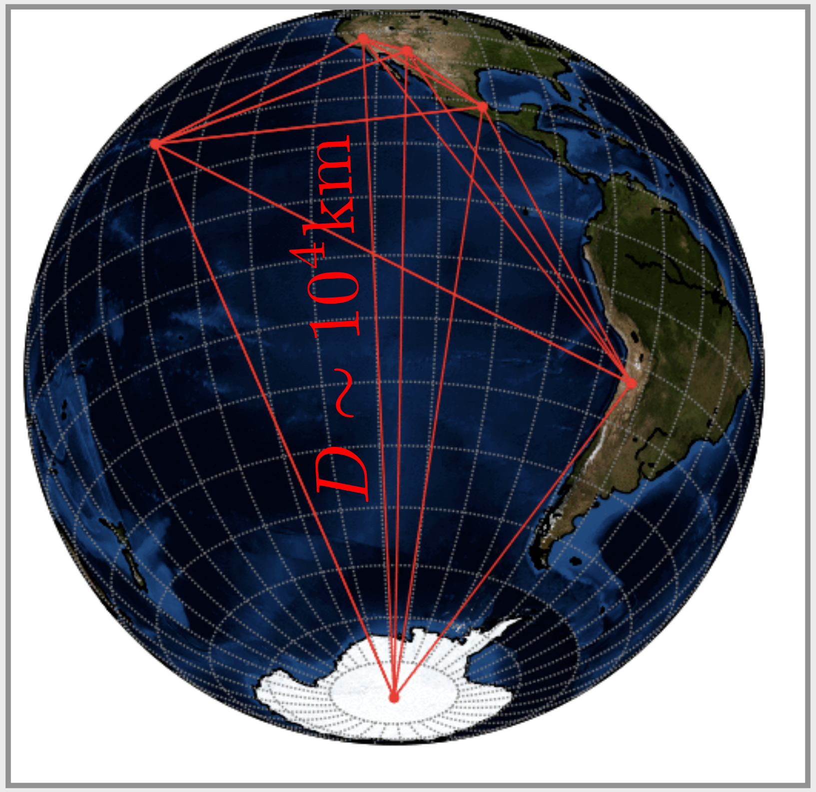
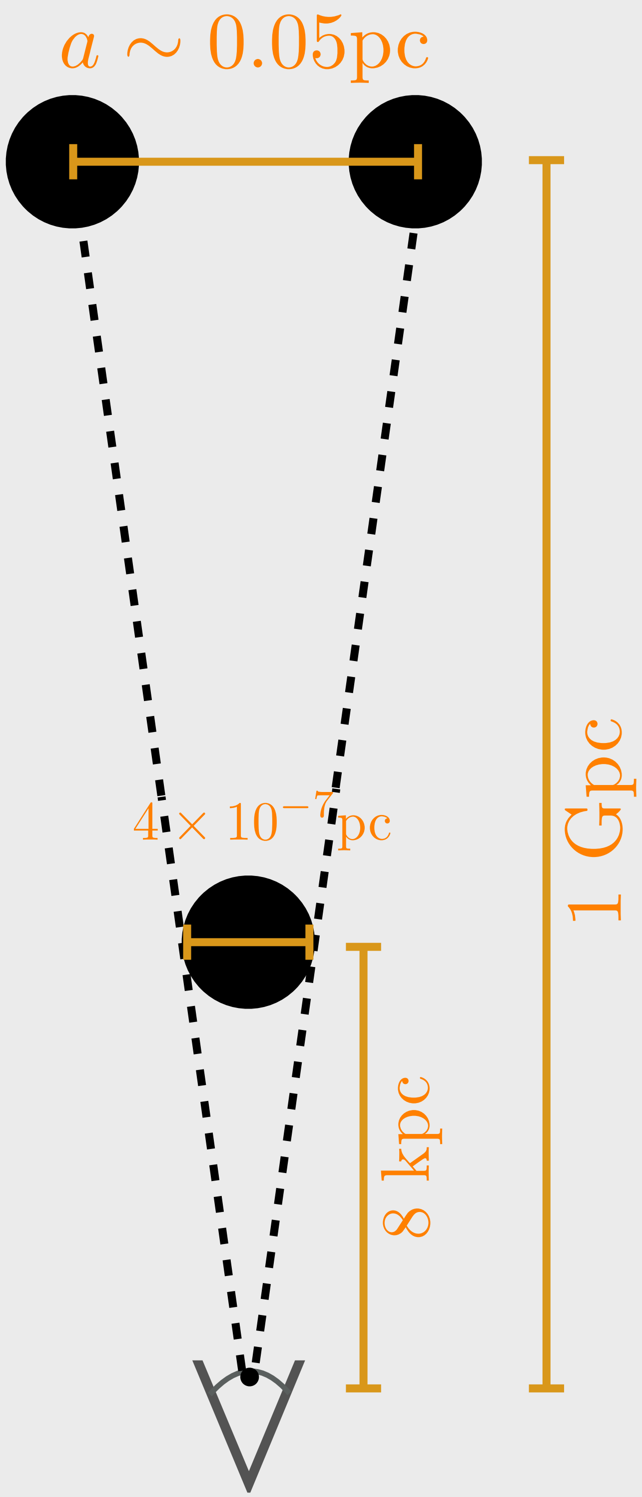




D'Orazio & Loeb arXiv:1712.02362

mm VLBI:
How many MBHB orbits can we "image"?

* **Requirements:**

1) Resolvable: Orbital separation > minimum VLBI resolution

2) Trackable: Period < 10 years to track entire orbit

3) Distinguishable: Emission region smaller than orbital separation
Low luminosity AGN (LLAGN) may be ideal for this

4) Referenced: Both binary components are bright for relative astrometry (or nearby calibrator)

D'Orazio & Loeb arXiv:1712.02362

mm VLBI:
How many MBHB orbits can we "image"?

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

Requirements:

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

* Minimum binary separation set by EHT resolution
* Emission region < separation
* Maximum binary separation set by observable orbital period (<10 years)

Ingredients:

$$N_{\mathrm{EHT}} \approx 4\pi \int_0^z \frac{d^2V}{dz d\Omega} \int_{L_{mm}^{\mathrm{min}}}^{\infty} \frac{d^2N}{dL_{mm} dV} \mathcal{F}(\chi; L_{mm}, z) dL_{mm} dz$$

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

Binary Probability:
Calculated from residence time at required separations

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

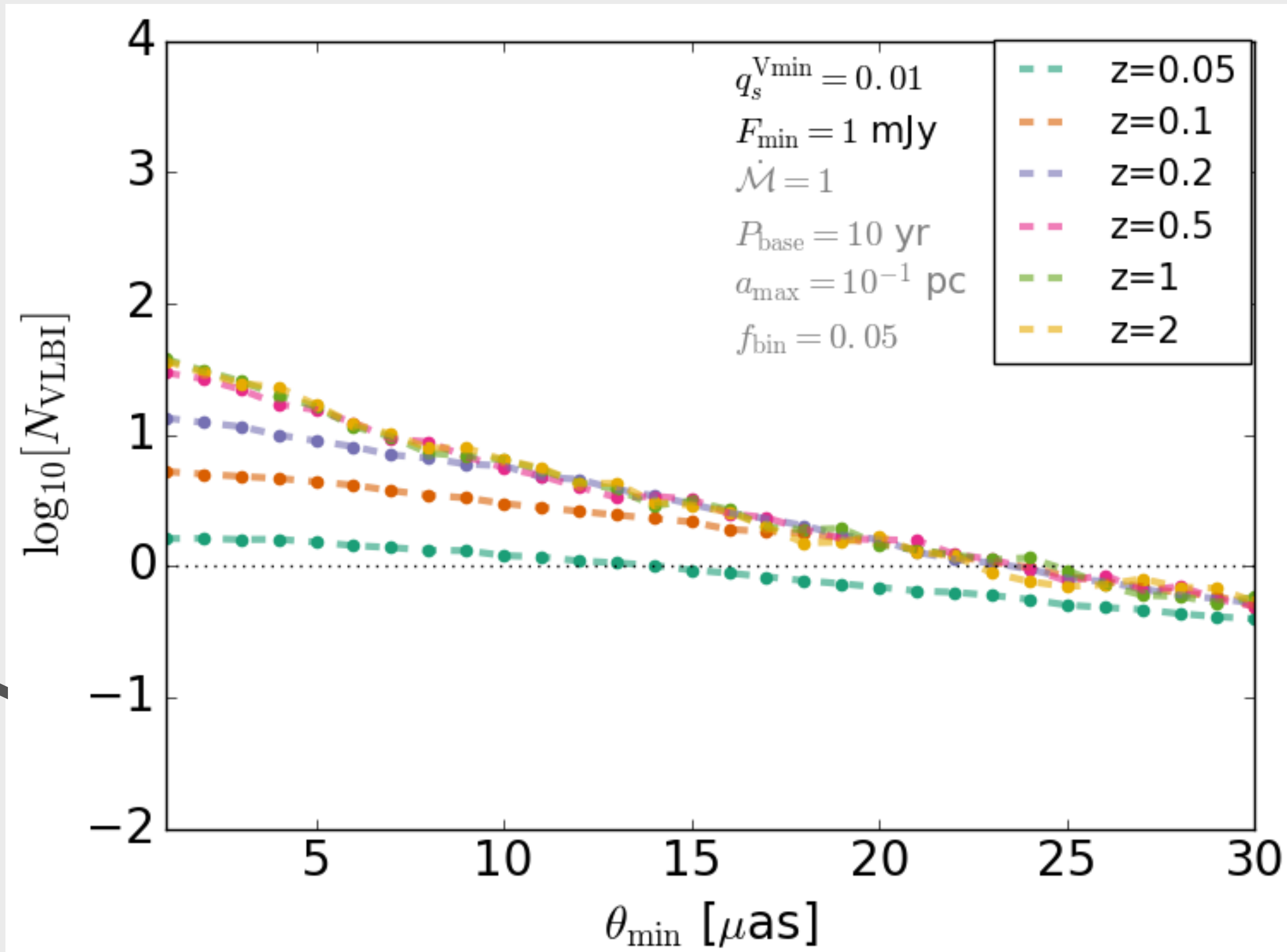
Assume:
Gas + Gravitational waves

Made to be consistent with GWB upper limits

mm VLBI:
How many MBHB orbits can we "image"?

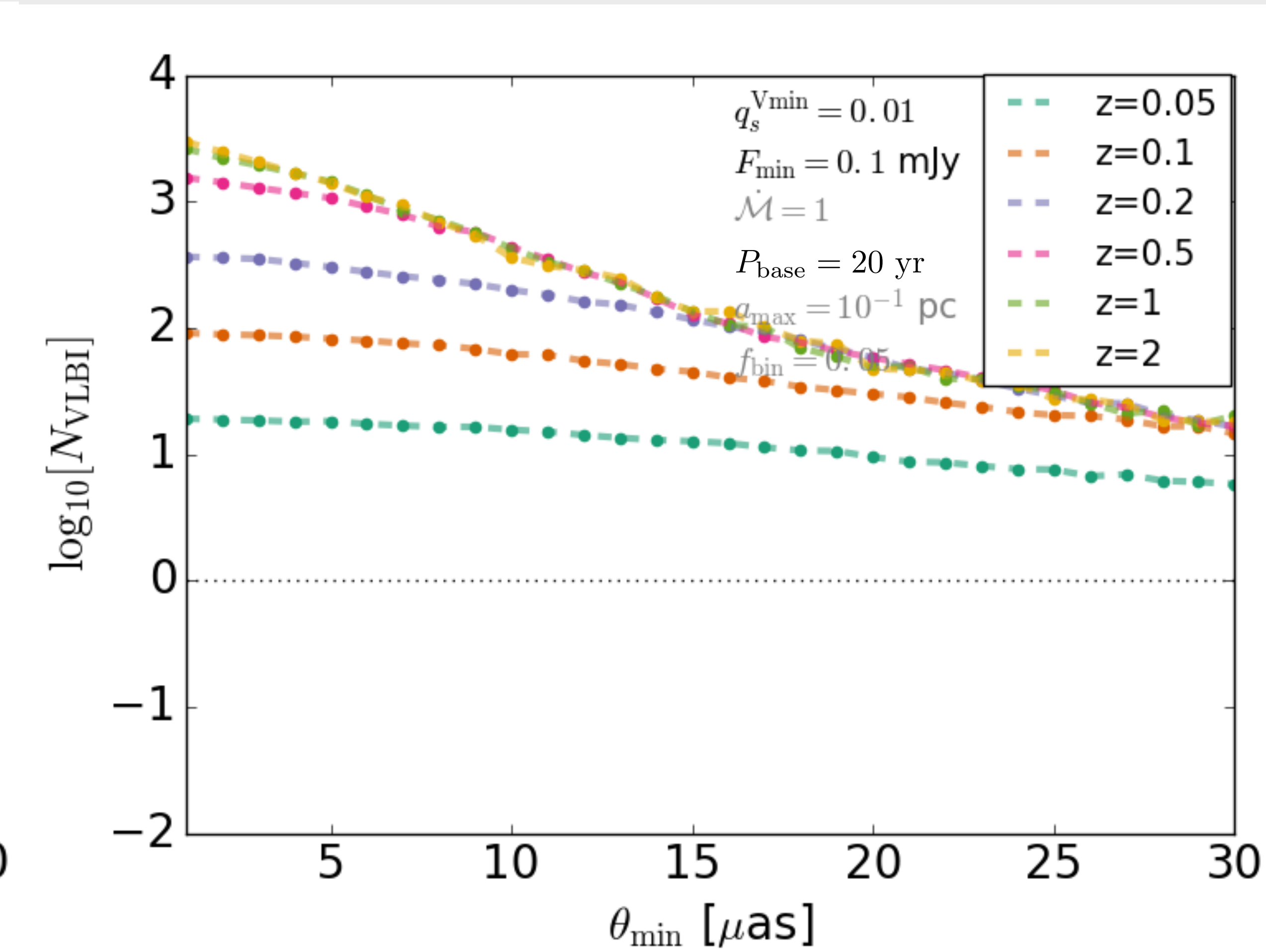
All sky resolvable binaries

Pbase = 10 yrs, Fmin = 1 mJy



Best possible spatial resolution

2x longer period , 10x Better Sensitivity



Best possible spatial resolution

~1000s of MBHB resolvable by mm-VLBI out to z=1.0

D'Orazio & Loeb arXiv:1712.02362

mm-VLBI Observational Strategy

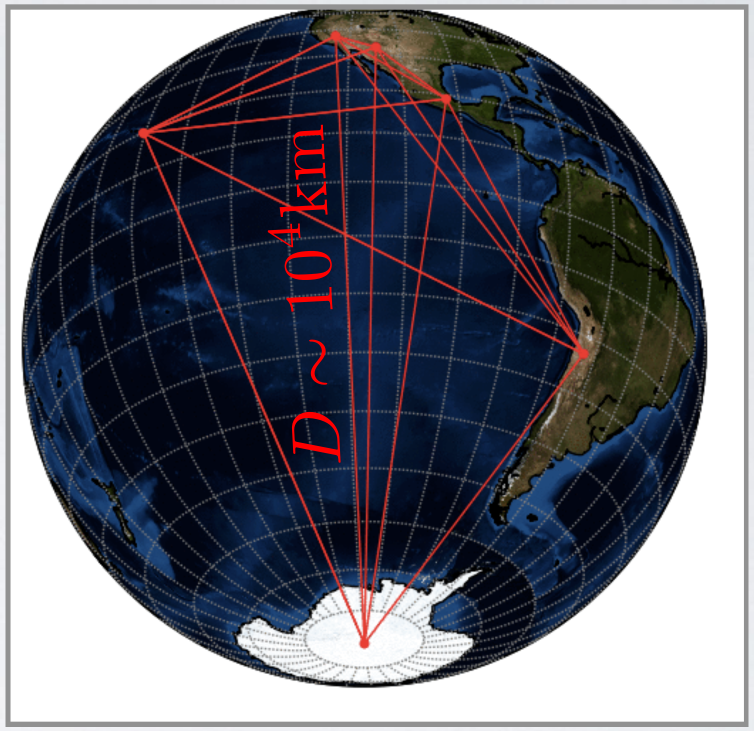
* Find MBHB candidates with resolvable separations from periodic AGN light curves (in progress…)
* Follow up with radio/mm single dish observations to determine brightness (SMA proposal…)
* Observe with mm-VLBI to determine if two point sources (or nearby calibrator)
* Monitor over ~an orbital time with mm-VLBI

D'Orazio & Loeb arXiv:1712.02362

Seeing is believing?

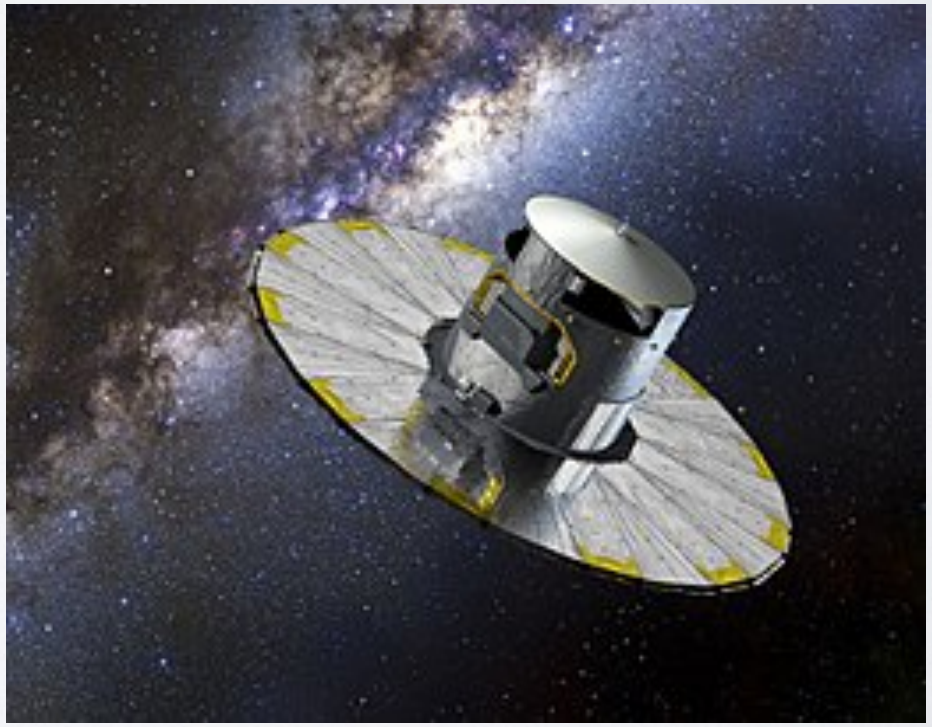
Part I: millimeter VLBI

D'Orazio & Loeb arXiv:1712.02362



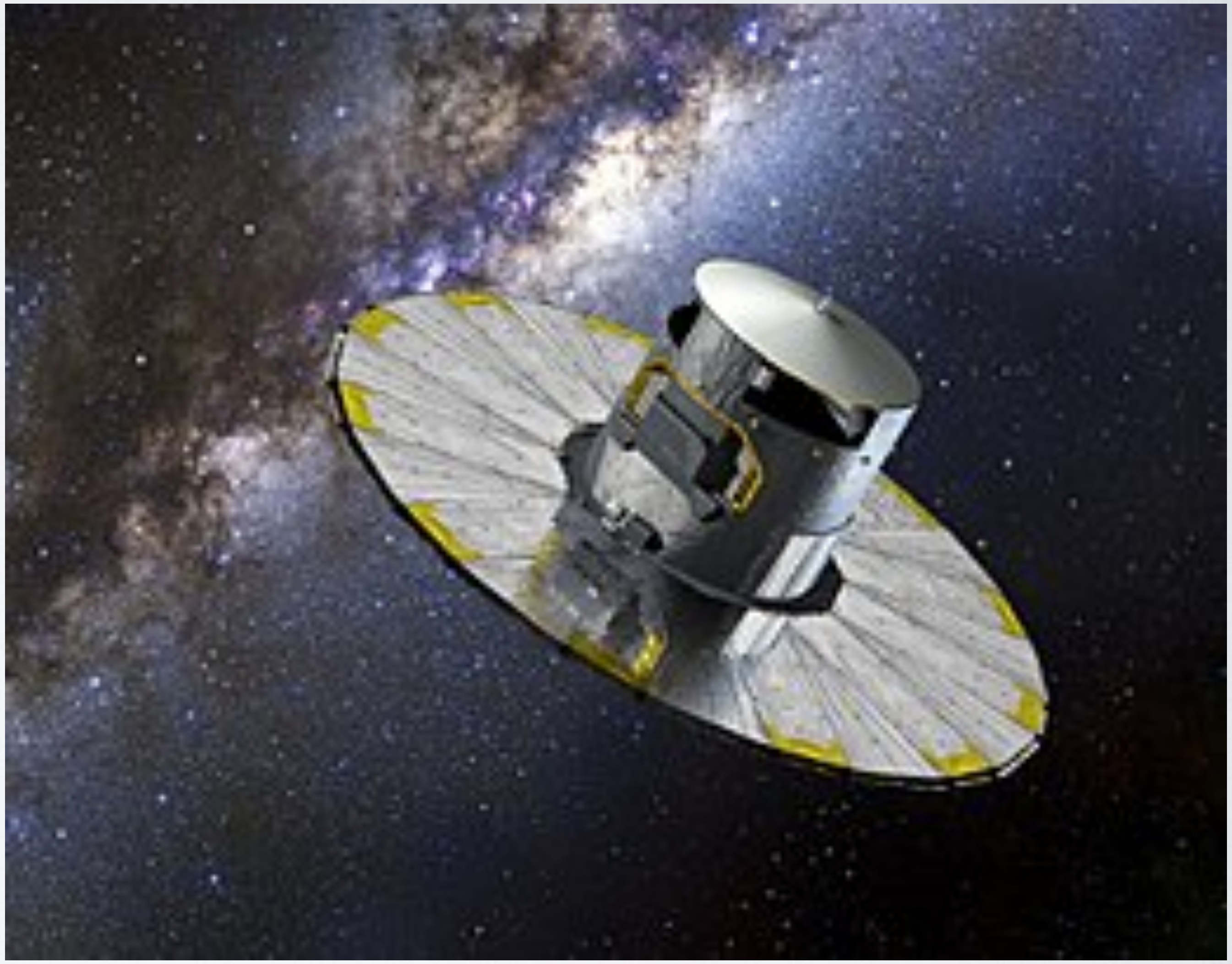
Part II: Gaia

D'Orazio & Loeb arXiv:1808.09974

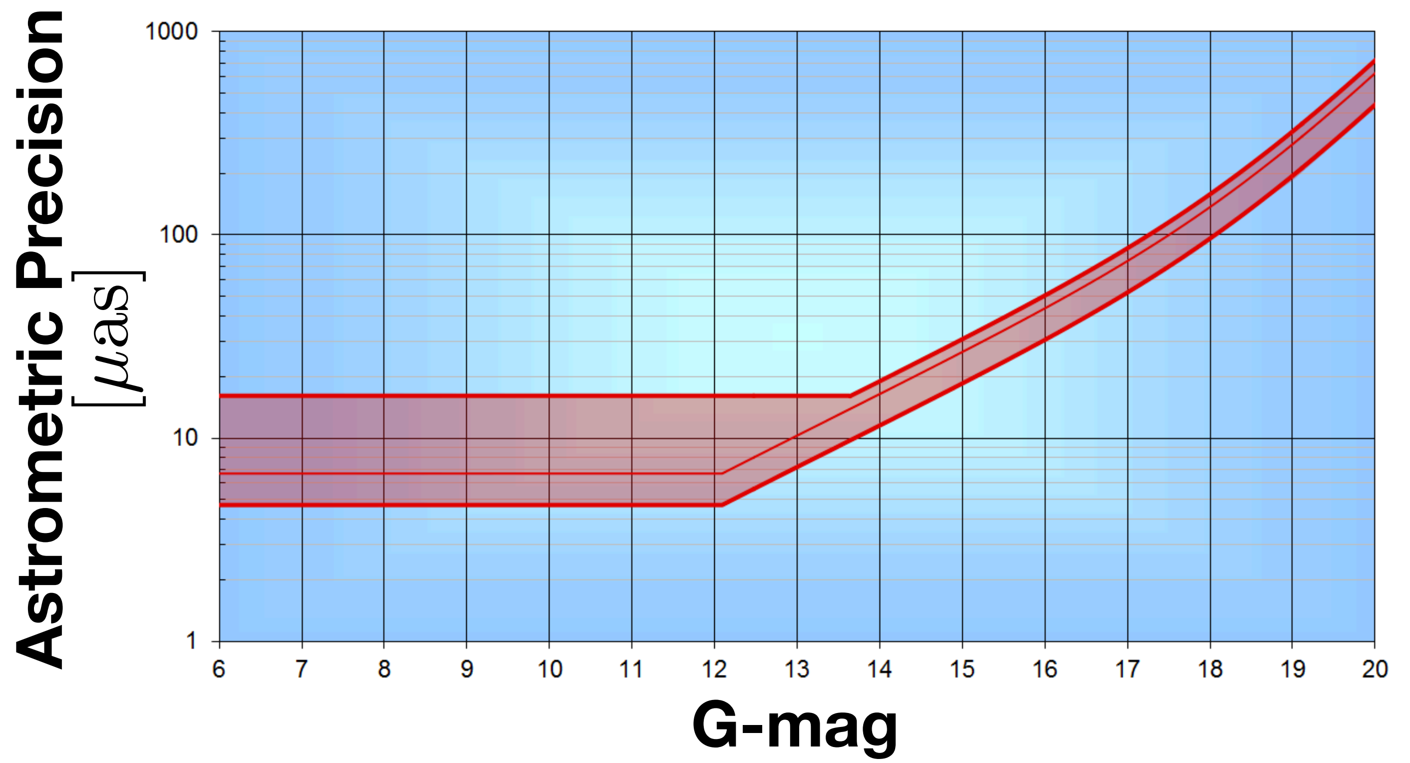


The Gaia Mission

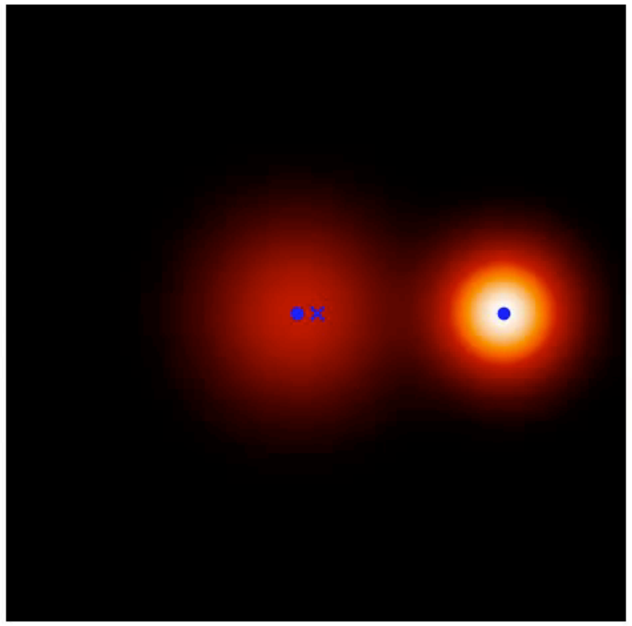
* All sky, G-mag<20
* Each object observed median of 72 times over 5 year mission
* Micro-arcsecond absolute astrometry
* 0.01 mag precision photometry
* Spectroscopy for G-mag<16



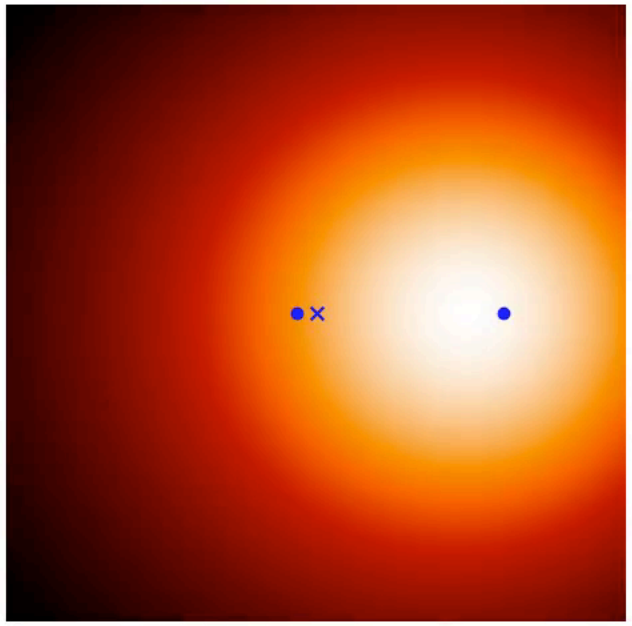
Can Gaia also track MBHB orbits, but in optical



$$\theta_{\rm orb} = \frac{2a}{D_A(z)}\left(\frac{1}{1+q} - \frac{\xi}{1+\xi q}\right) \qquad q = \frac{M_2}{M_1} \quad \xi = \frac{f_{\rm Edd,1}}{f_{\rm Edd,2}}$$



Resolved



Unresolved

Gaia:
How many MBHB orbits could we "track"?

Quasar Luminosity Function — **Binary Probability** — **Orbital Period Restriction**

$$N_{\rm SBHB} = f_{\rm bin} \int_0^\infty \left\{ 4\pi \frac{d^2V}{dz d\Omega} \int_{\log L_{\rm min}(z)}^\infty \frac{d^2 N}{d\log L dV} \mathcal{F}(P, M, q_s) \times \mathcal{H}\left[P_{\rm max} - P_{\rm min}(L,z)\right] \right\} d\log L \, dz,$$

$$\mathcal{F}(P, M, q_s) = {\rm Min}\left[t_{\rm res}(P, M, q_s)/t_{\rm Q}, 1\right]$$

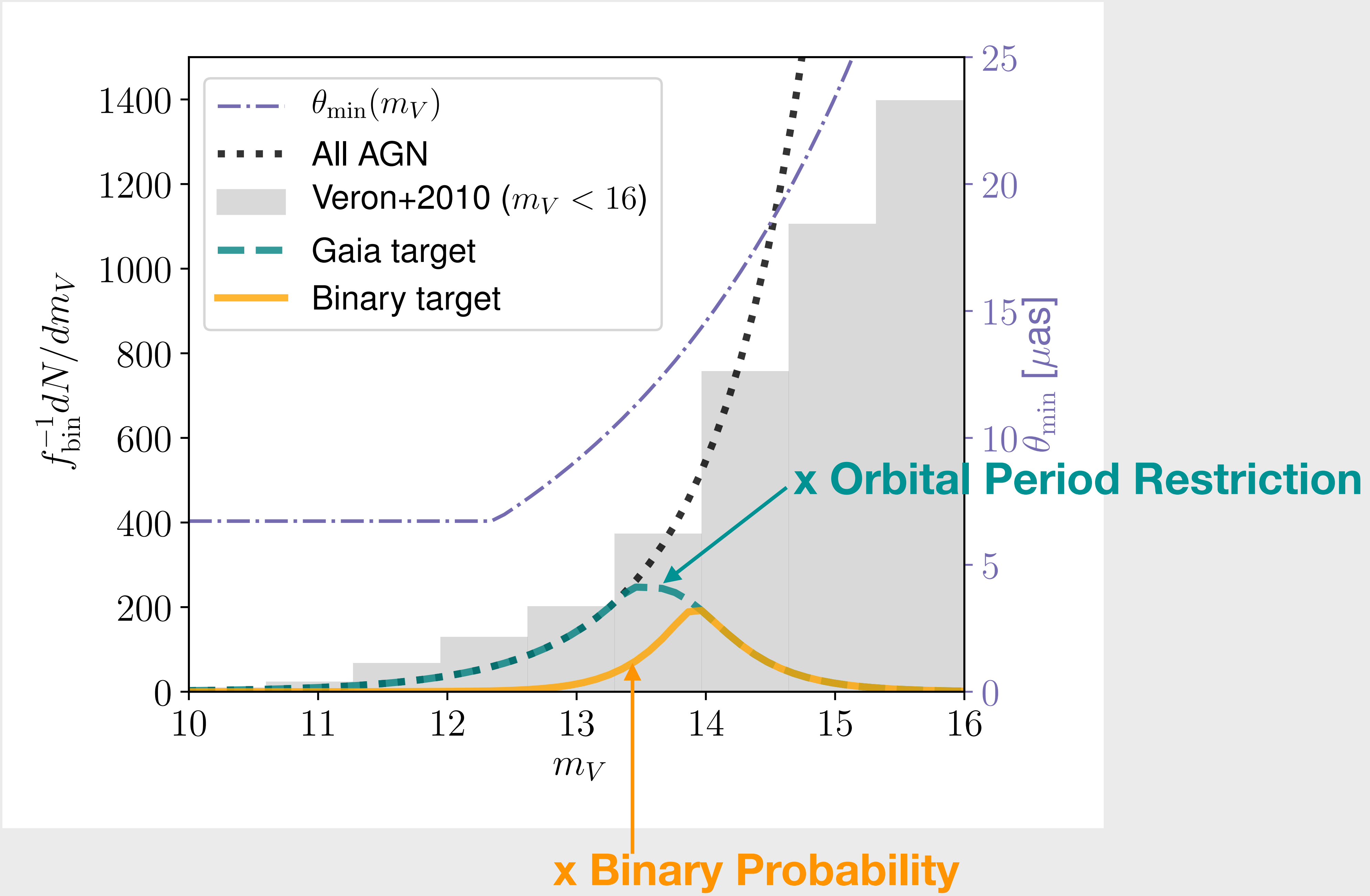
$$P_{\rm min}(L,z) = \frac{2\pi \left[\theta_{\rm min}(L,z) D_A(z)\right]^{3/2}}{\sqrt{GM(L, f_{\rm Edd})}}$$

$$P_{\rm max} = 2 \times 5{\rm yr}$$ ← Gaia lifetime

Parameter	Meaning	Fiducial	Optimistic	Pessimistic
$f_{\rm bin}$	The fraction of AGN harboring SBHBs	0.1	"	"
$f_{\rm Edd}$	The Eddington fraction of bright AGN	0.1	"	"
BC	Bolometric correction from V-band	10.0	"	"
t_Q	The AGN lifetime	10^7 yrs	5×10^6 yrs	10^8 yrs
$V - I_c$	A mean color for nearby AGN	1.0	2.0	0.0
$P_{\rm max}$	The maximum detectable orbital period	10 yrs	18 yrs	5 yrs
$q_s (q)$	Binary symmetric mass ratio (mass ratio)	0.33 (0.1)	0.18 (0.05)	1.0 (1.0)
$\mathbf{N}_{\rm SBHB}$	**The total number of detectable SBHBs**	**19**	**67**	**3**

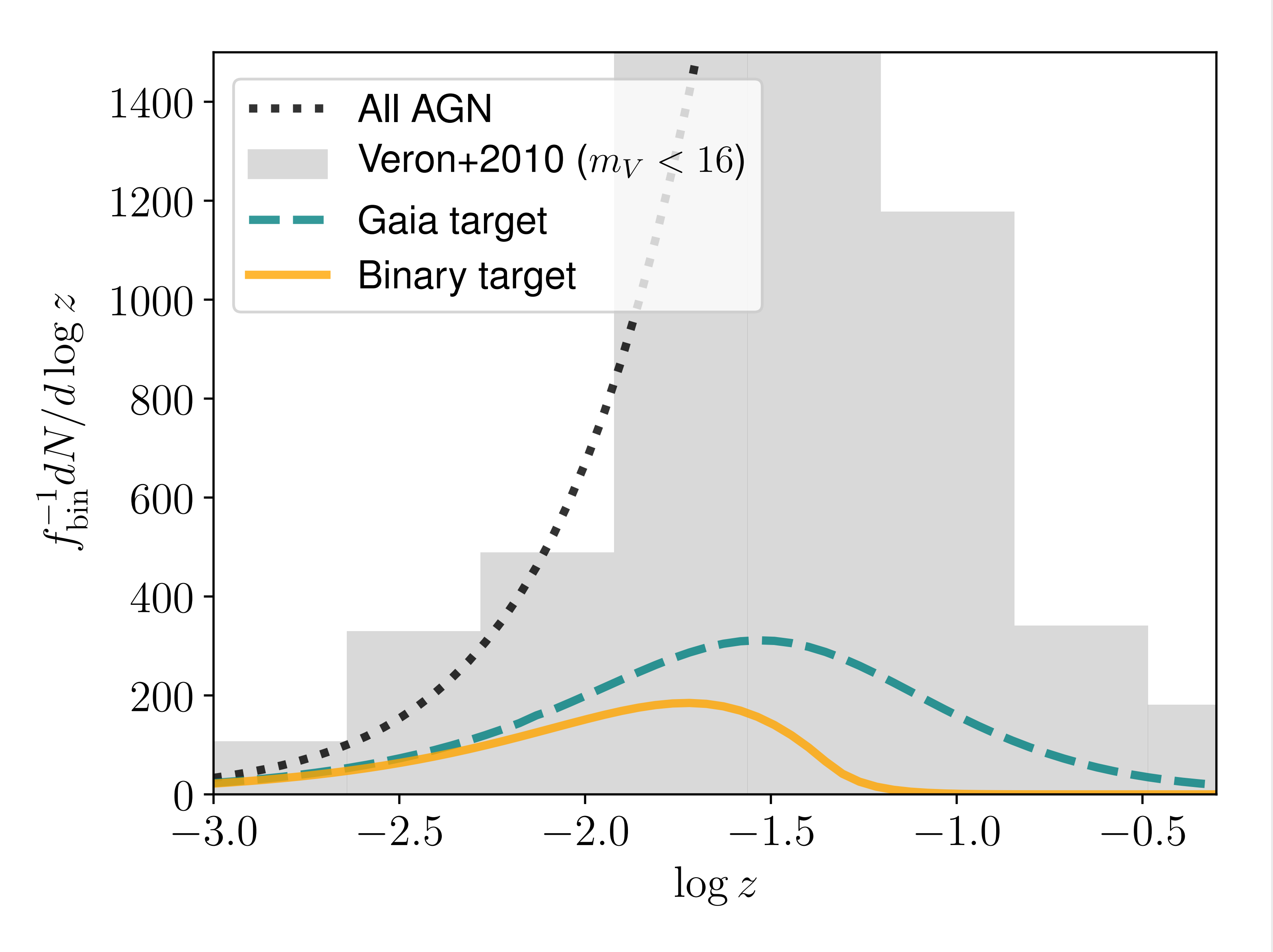
D'Orazio & Loeb arXiv:1808.09974

Gaia:
MBHB candidates per V-band magnitude



D'Orazio & Loeb arXiv:1808.09974

Gaia:
MBHB candidates per log-redshift



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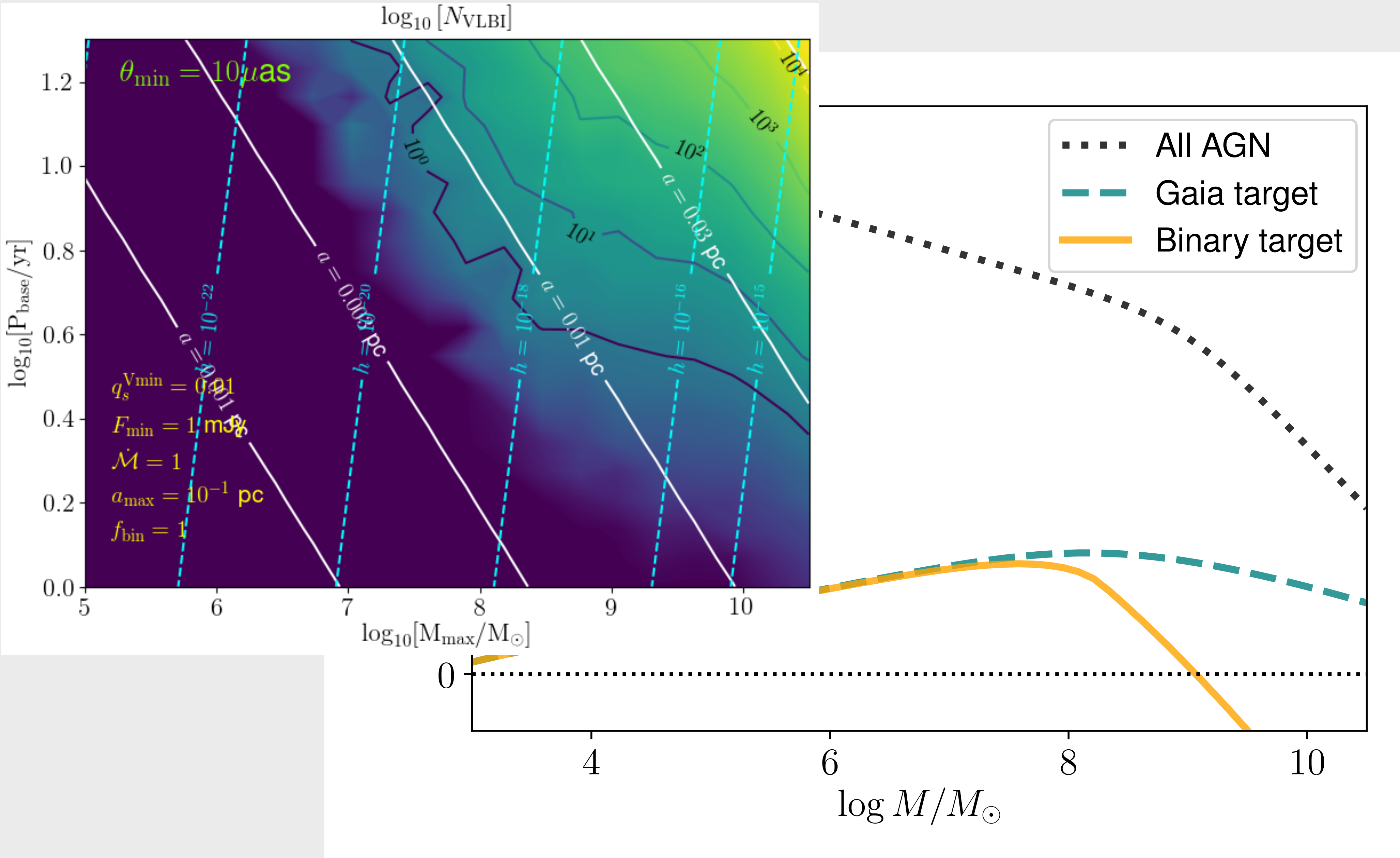
Gaia:
MBHB candidates per binary mass



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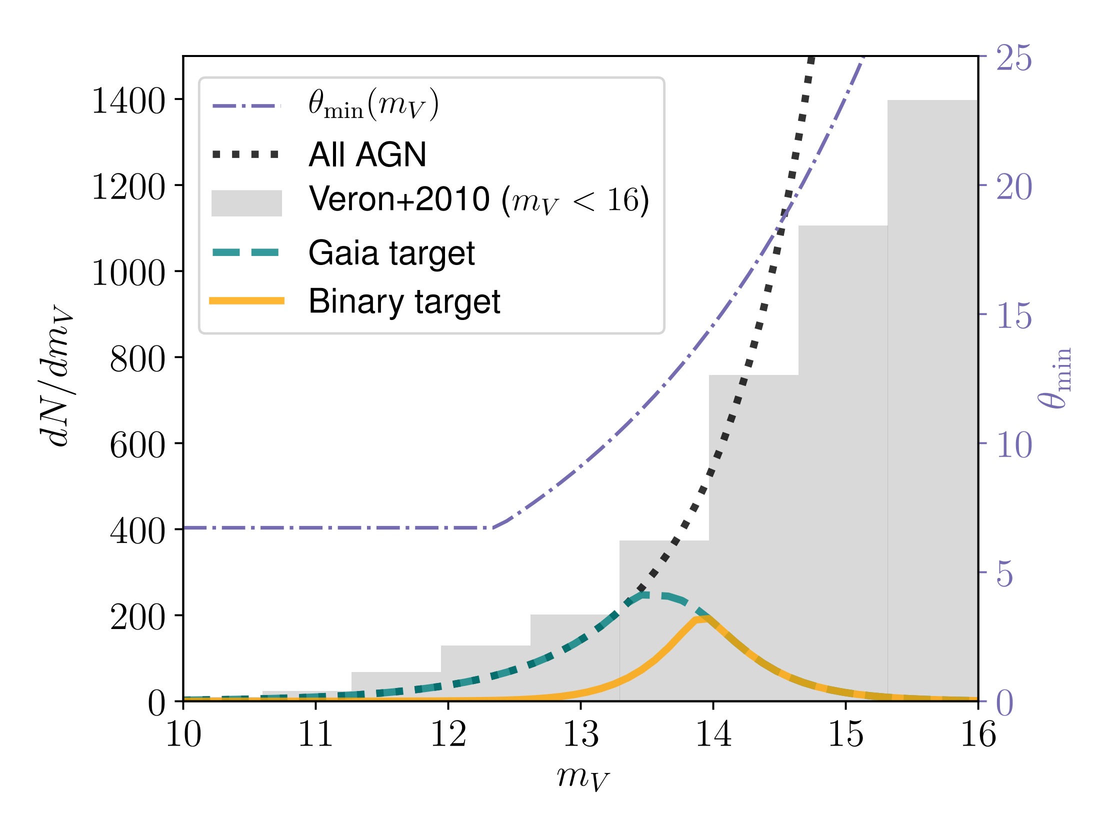
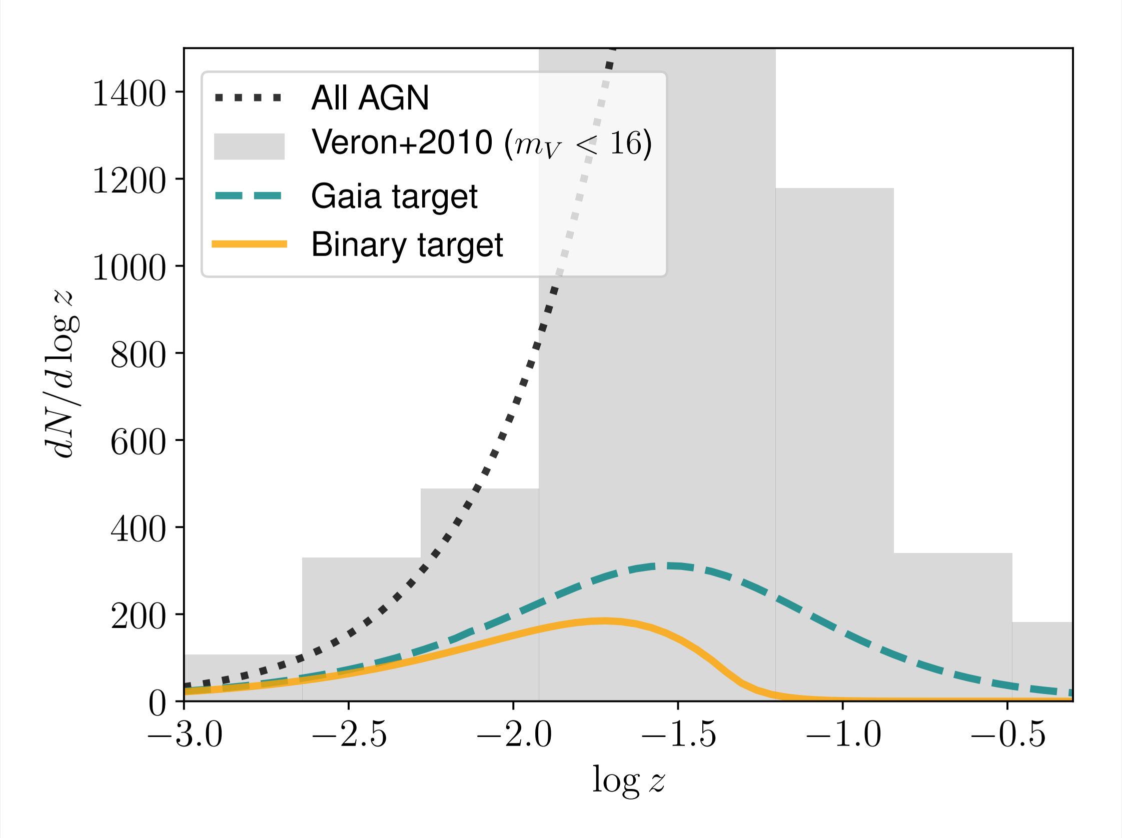
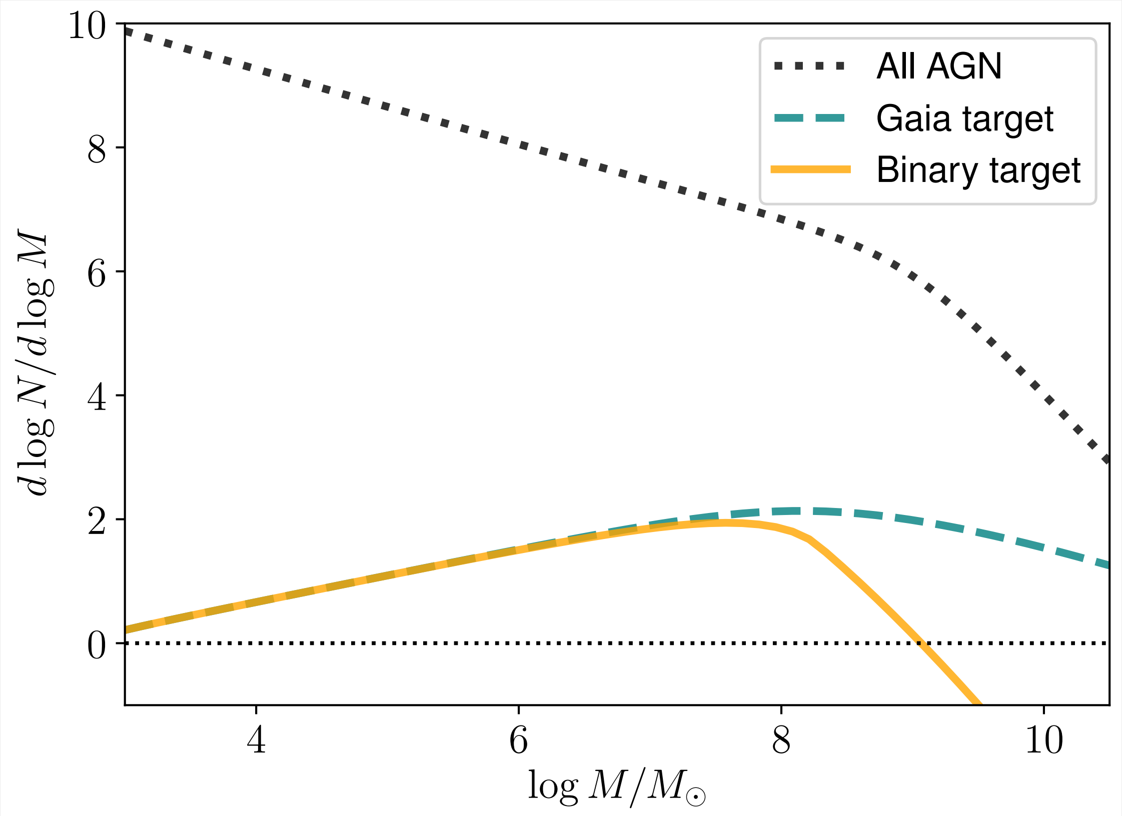
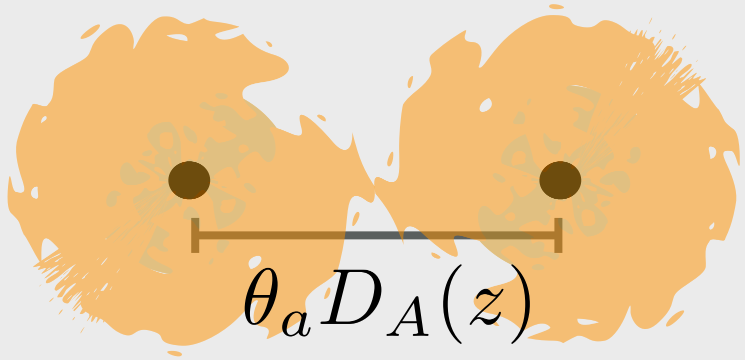
Gaia:
(A Final-Parsec Telescope?)







~<100s of MBHB resolvable by Gaia out to z=0.1



Applications

* High precision binary mass measurement

$$GM = \left(\frac{2\pi}{P(1+z)}\right)^2 (\theta_a D_A(z))^3$$

$$\frac{\delta M}{M} \approx \left[\left(2\frac{\delta P}{P}\right)^2 + \left(3\frac{\delta\theta_a}{\theta_a}\right)^2\right]^{1/2}$$

$$0.3 \lesssim \left.\frac{\delta M}{M}\right|_{\mathrm{VLBI}} \lesssim 4$$

*Novel measurement of the Hubble Constant
-with Doppler boost or mass measurement

$$\dot{\theta} D_A(z) = v_{\mathrm{orb}}$$

Track proper motions

From Doppler boost and shape of orbit on sky

Gives $H_0(z_{\mathrm{bin}}, \Omega_M, \Omega_\Lambda)$

Applications

* Precise Binary Mass Measurement
* Novel Measure of the Hubble Constant
* If simultaneous gravity waves…can measure the speed of gravitons relative to photons
* Aid in narrowing down mechanisms which drive MBHBs to merger -> constrain GW Background from EM side

Summary

* mm-VLBI and Gaia could definitively identify sub-pc separation MBHBs for the first time and vet other identification strategies
* The most promising MBHBs to image with mm-VLBI are likely those residing in LLAGN
* The most promising MBHBs to image with Gaia are in the brightest nearby AGN
* Tracking an entire orbit would also allow
    * a precise measurement of the binary mass
    * a novel measurement of the Hubble constant
* There may already be existing MBHB candidates to look for
  PG 1302-102 ~4 muas separation
  OJ 287 ~4-24 muas! (e=0.7)
  3C 273? 20 muas?
  +more…