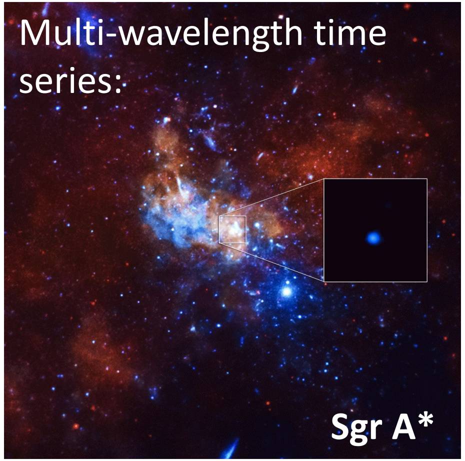
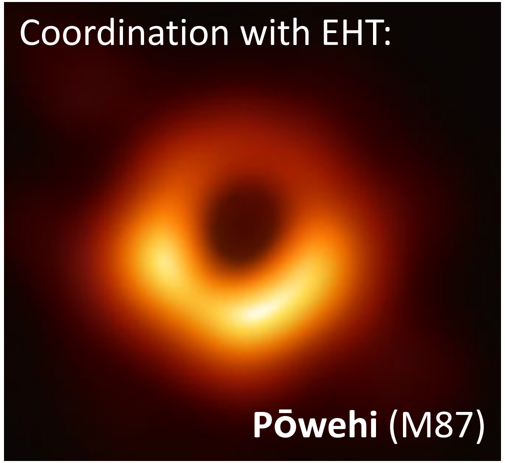
SMBH Binaries: Observations II

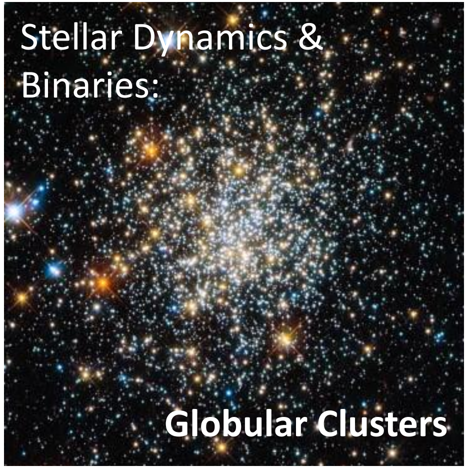
Chengcheng Xin (Columbia) & Daryl Haggard (McGill)

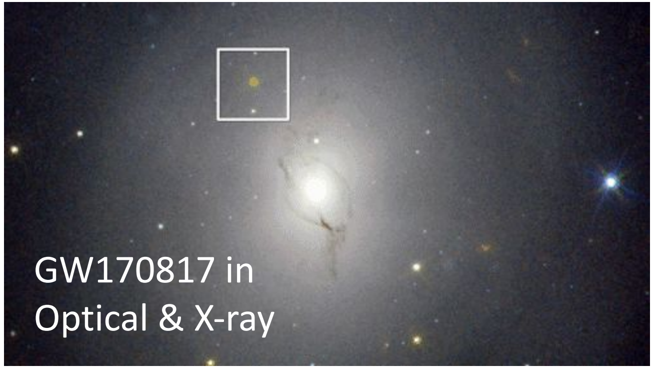
KITP Binary meeting **March 2022**

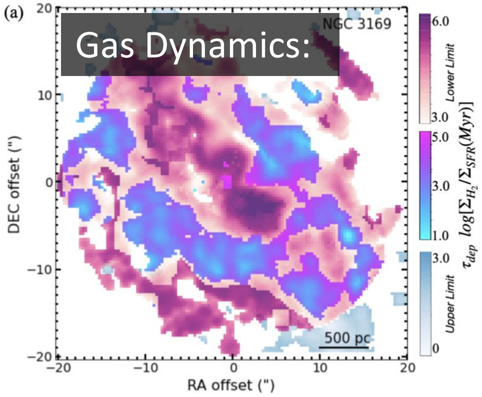
Daryl Haggard (McGill University)











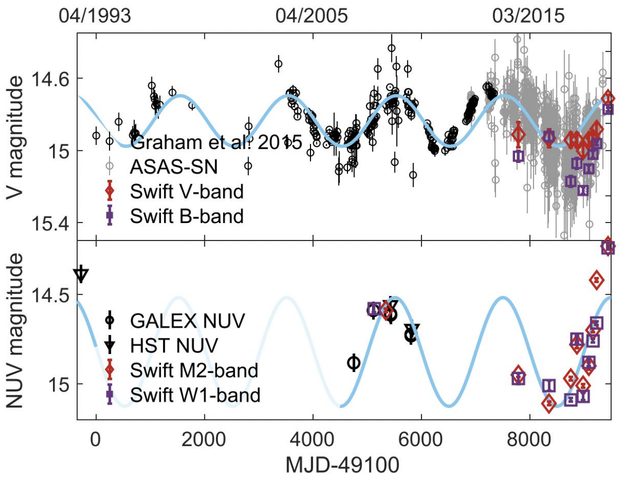
I work on… observations of black holes (and neutron stars) w/ time domain, multi-wavelength and multi-messenger obs

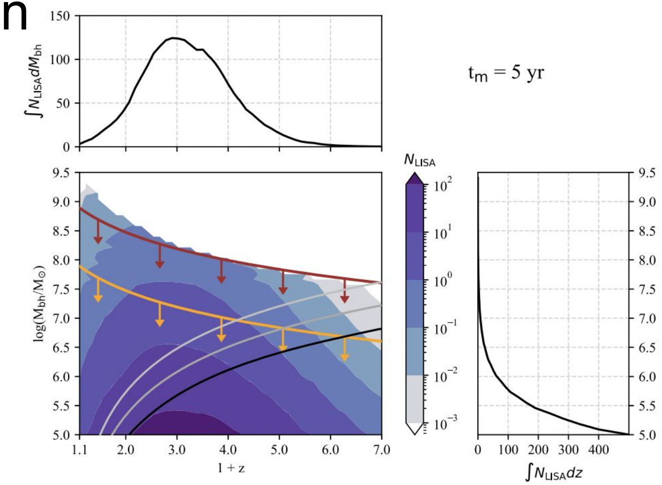
At KITP I want to… study variability signatures of accretion in BH binaries and how we combine EM and GW to learn more

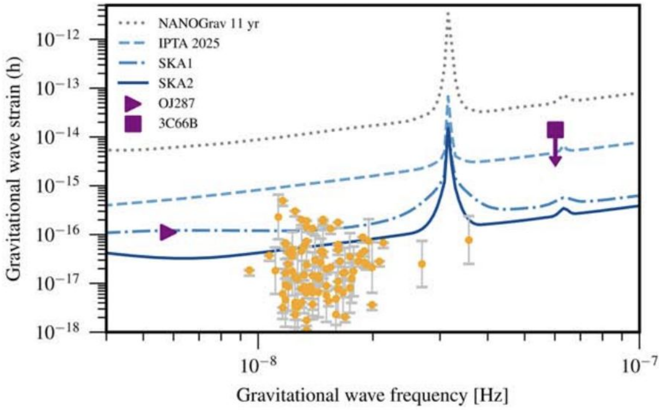
Curious to here more… prospects for binary black hole detection and characterization with ngEHT and ngVLA

Chengcheng Xin (Columbia)

PhD advisor: Zoltan Haiman







PG1302-102 (Graham+2015, D'Orazio+2015, Charisi+2017, Xin+2020)

Previously..

- UV/Optical Variability of quasars
- SMBH binary candidate – PG1302-102
- PTA constraints on SMBHB candidates (traced by periodic light curves)
- LSST SMBH binary candidates as verification binaries in LISA

Coming soon,

- Dissecting Z-dependent microphysics of massive star radii

Open Questions: SMBH Observations

1. How well can we pin down the masses (and mass ratios) for SMBH binary candidates? How much uncertainty does this introduce to our models?
   a. Reverberation mapping
   b. Width spectral line
   c. Gravitational wave observations
   d. Mbh-Mbulge, M-sigma
   e. Etc. (?)
2. What other parameters are key src of uncertainty (period, separation, selection bias …)?
3. How comparable (or not) are the sensitivities of different GW instruments (e.g., PTA, LIGO, LISA), in terms of SNR?
4. What do we do with all of the different EM markers for SMBHB candidates? What are the false signals for each?
   a. Astrometry → confusion, variability on larger scales, precessing disk features
   b. Emission lines → orbiting disk instabilities, clumps or features in the disk
   c. Jets → binarity vs. remnants from precession
   d. Light curve periodicity → QSO variability/damped random walks, red noise, TDE flares
   e. (Micro)lensing
   f. Transits
   g. Fe K-alpha “radial velocity” (+line shapes and variability)

SMBH Binary Candidates

- **Table/database** of current SMBHB candidates
- Started a spreadsheet (please add your favorites and/or fill out properties); could be converted to searchable table
- Sarah Burke-Spolaor may have a table in progress (or maybe you do?)
- *Your contributions welcome!!*

Direct methods:
Resolved imaging (radio)
Spectroscopic binaries
BLR velocity shifts
Periodicity/variability
AGN flaring
microlensing
transits
FeKalpha 'radial velocity'
Indirect methods:
QSO populations
Dual AGN
Galaxy mergers

Name
B3 0402+379
SDSSJ1430+2303 (Tik Tok)
QSO J0854+2006 (OJ 287)
PKS 2131–021
3C 75
COSMOS J100043+020637
NGC 6240
SDSS J1502+115
PG1302-102 (candidate)
KIC 11606854 (Spikey; cand)
3C66B (candidate)

Name	Discovery	Host Type/ Name	R.A.	Dec.	z	*log M [Msun]*	*Period*	*q*	*e*	Messenger/ Wavelengths	Claimed Binary Signature(s)	Proj Sep	Conf.	Citation
B3 0402+379	2011	Radio AGN	04:05:49.26	+38:03:32.2	0.0545					radio VLBI	resolved cores, per	7.3 pc	high	Rodriguez+2006; Burke-Spolaor+2011, Bansal+2017
SDSSJ1430+2303 (Tik Tok)	2022	Seyfert 1	14:30:16.05	+23:03:44.4	0.081					optical/IR, X-ray	shrinking orbital period		low	arXiv:2201.11633
QSO J0854+2006 (OJ 287)	1960s	BL Lac	08:54:48.87	+20:06:30.6	0.306				0.7	multi-wavelength	periodicity (obs bac	~0.1 pc	high	numerous; e.g., arXiv:2112.05067; Sillanpaa et al. 1988; Valt et al. 2016; Dey et al. 2021
PKS 2131–021		Blazar			1.285									ApJ open access
3C 75											radio jets	7.2 kpc		Owen et al. 1985
COSMOS J100043+020637	2009				0.36						BLR shift 1300 km/	2.5 kpc		Comeford+09, Civano+10, Blecha+2013
NGC 6240	2003													
SDSS J1502+115	2011													
PG1302-102 (candidate)	2015		13:05:33	-10:33:19	0.27	~8.3-9.4	5.2 yr	~>0.3		Optical, UV, X(?)	periodicity (relativis	~0.009pc		Graham+2015b, D'Orazio+2015b, Xin+2020, etc.
KIC 11606854 (Spikey; cand)	2020				0.918	~7.5	418 d	~0.2	0.5		Doppler boost+self lensin			Hu+2020
3C66B (candidate)	2021													Sudou+2003; Arzoumanian et al. 2020

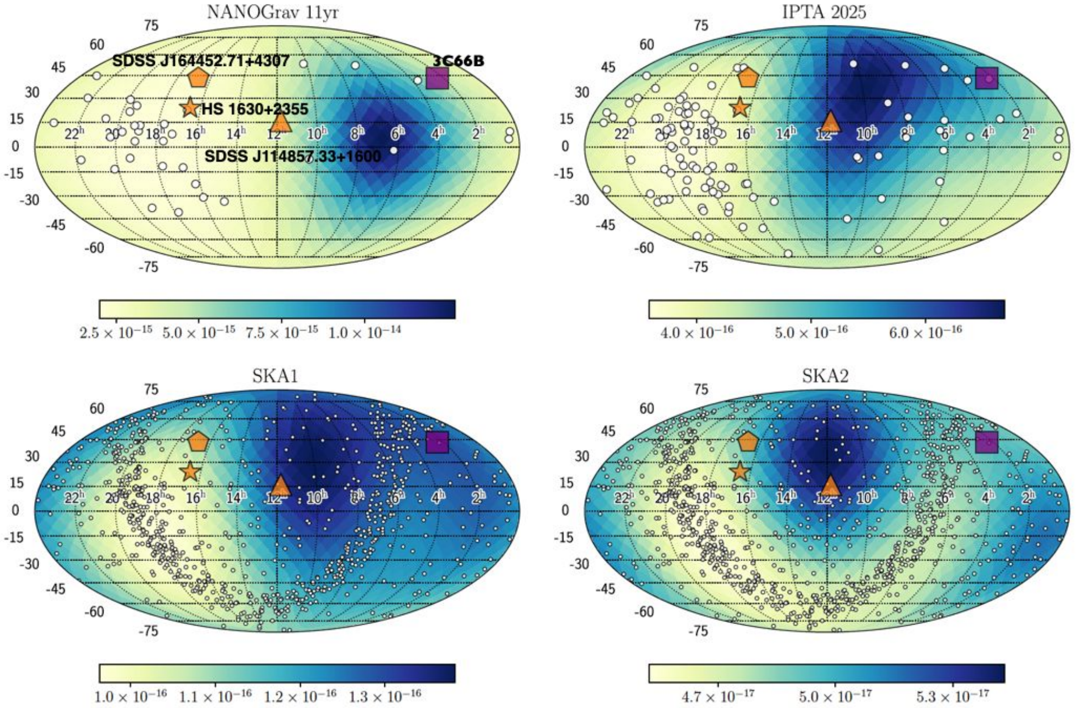
WORK IN PROGRESS…

Contributor: *ME + YOU*!!!!

Detection of individual supermassive black hole binaries

- Simulations show that SMBHB may be traced by periodic light curves (*Farris et al. 2014; Roedig et al. 2014; D'Orazio et al. 2016; and more!*).
- Huge MM efforts recently to identify SMBHB host galaxies (*Mingarelli et al. 2017; Sesana et al. 2018; Kelley et al. 2019; Arzoumanian et al. 2021, corr author M. Charisi*)
- Knowing sky location can improve strain by factor of 2, and frequency info improves strain by an OOM (Arzoumanian et al. 2020, *corr authors C. Witt; Aggarwal et al. 2019 corr. author S. Vigeland)*

Minimum detectable strain at 12 nHz



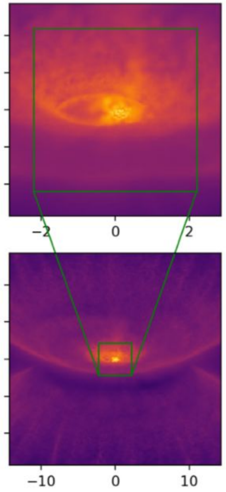
Contributor: Chiara Mingarelli

New pulsars with short timespans very useful!

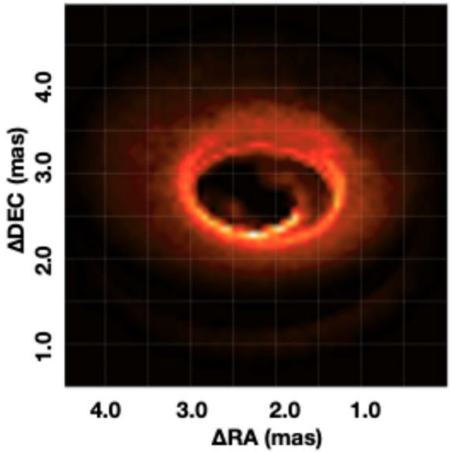
<u>Around **12** SMBHBs by the end of the decade — may induce anisotropy in GWB</u>

Xin, Mingarelli, Hazboun (2021), pulsar population based on Keane et al. (2015)

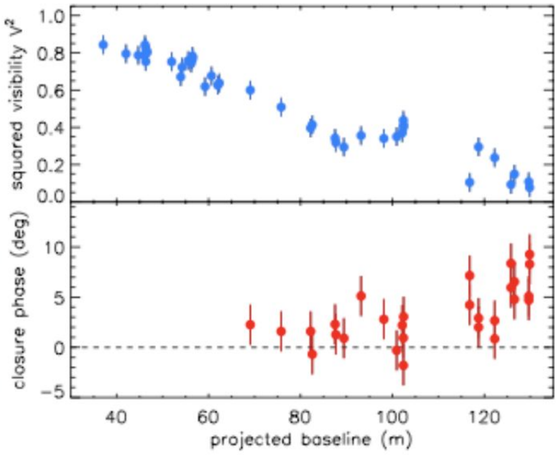
Near-IR images and interferometry from 3D RHD



IR images



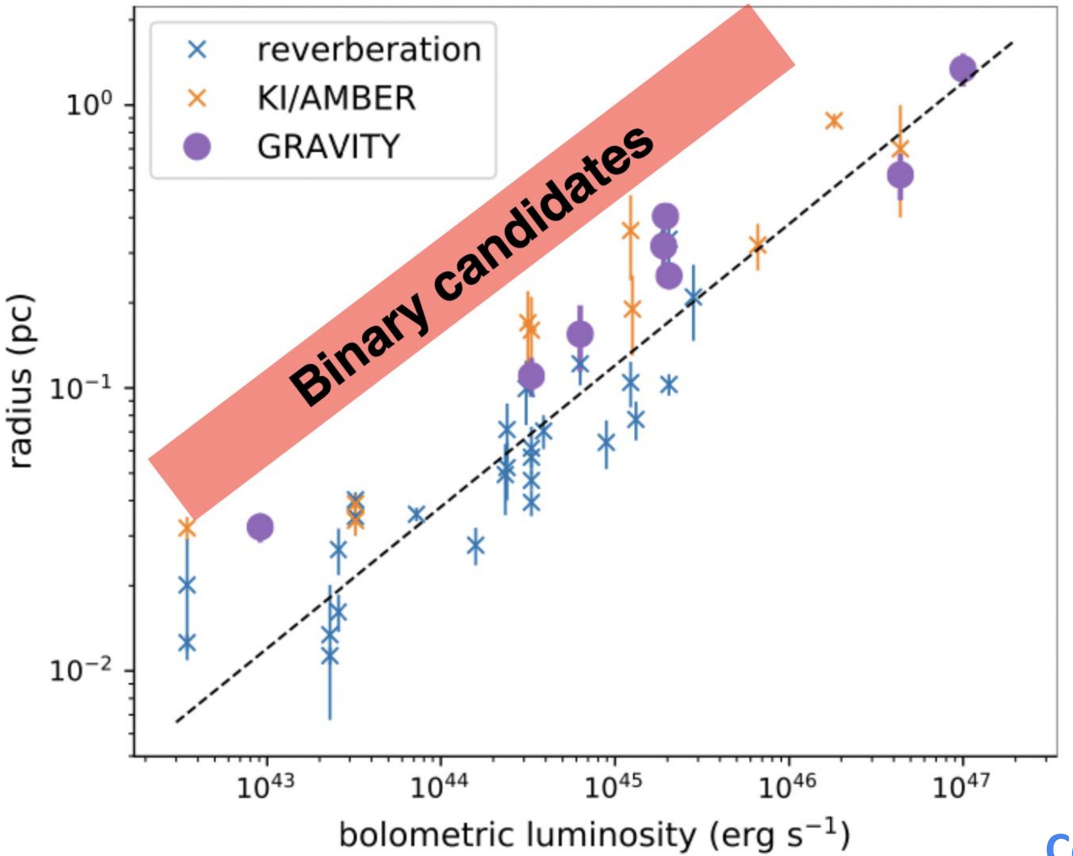
GRAVITY+ visibilities and phases



- Winds/structure **similar to single AGN on large scales** (10+ pc)
- Small scales: one (or 2) mini-torus + CBD emission
  - size **~8-10x sublimation radius** (visibilities)
  - "oddities" in the **near-IR SED** → hot-dust poor? to be nailed down
  - strong phase signal → may not be unique
- GRAVITY+ sensitivity: primarily **nearby universe ($z \lesssim 0.15$)**

Contributor: Sebastian Hoenig

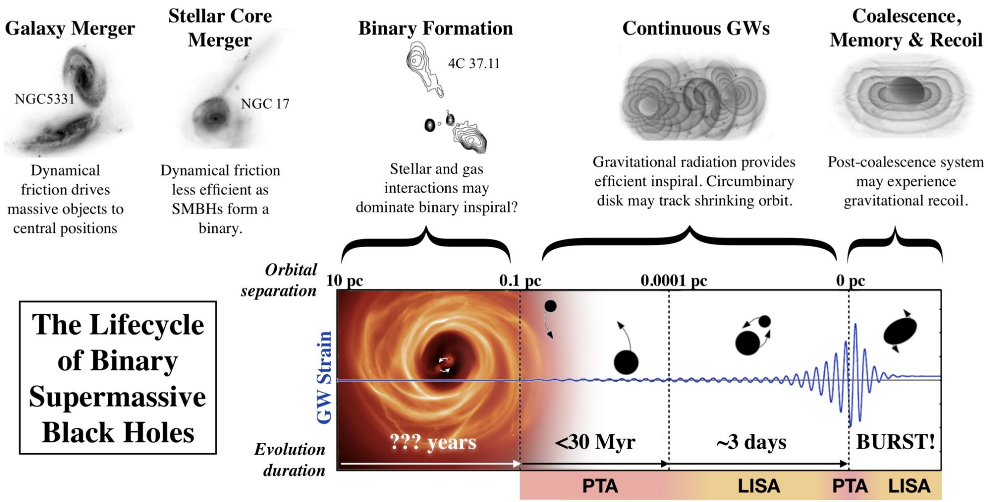
Candidate selection from size-luminosity relationship



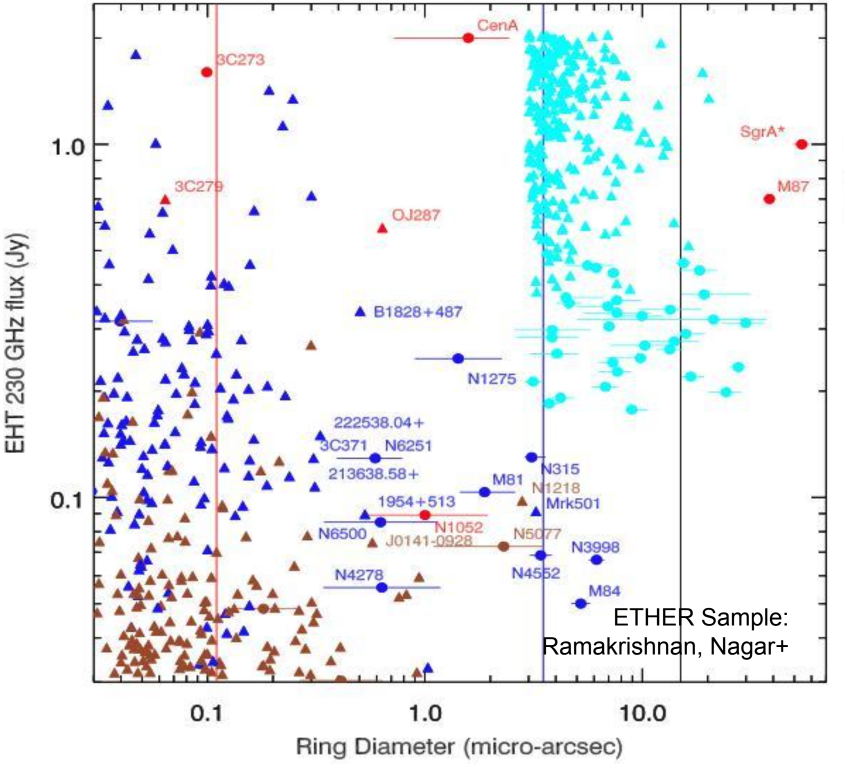
Contributor: Sebastian Hoenig

Resolving Massive BH Binaries

- **Final-parsec problem:** How do supermassive black hole binaries merge over cosmic time?
- Good fraction of ngEHT's SMBH binaries should emit **nano-Hz GWs**: **synergy with PTAs** NanoGRAV/EPTA/PPTA (& IPTA) and eventually **LISA** mission



Burke-Spolaor + (2019)



Contributor: Daryl Haggard

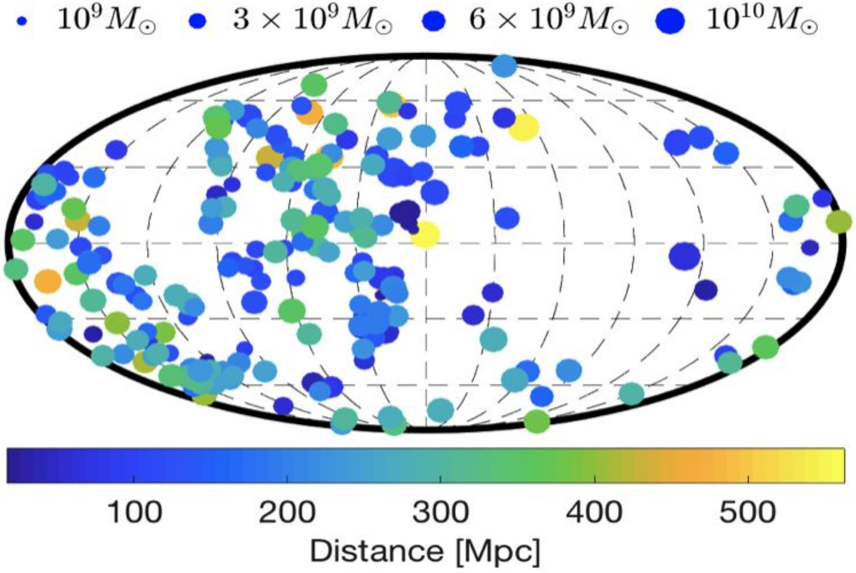
Slide Credit: ngEHT BH WG

Limits on SMBHBs in Galaxies within 500Mpc **GW First**

Dr. Maria Charisi

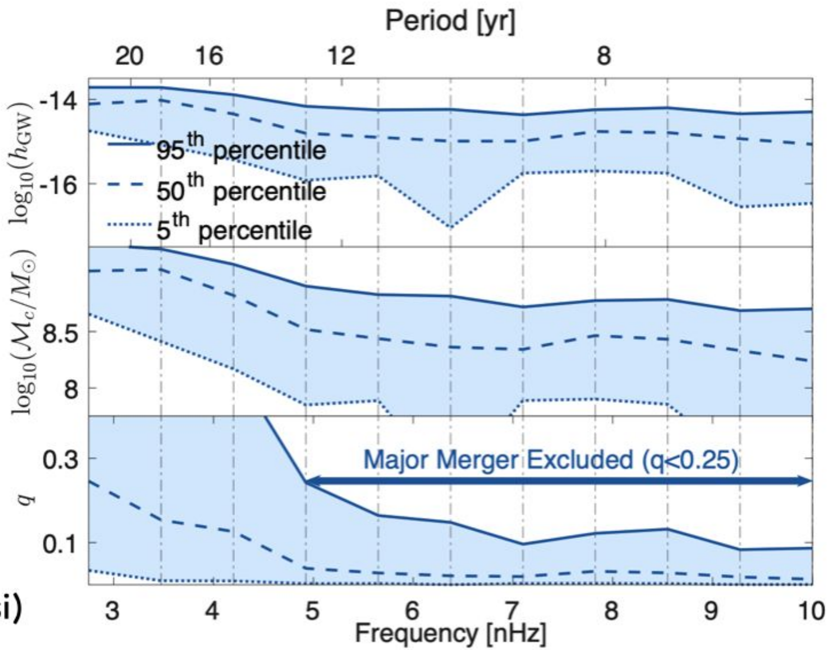
Contributor: Stephan Taylor

200 massive galaxies in the NANOGrav volume.



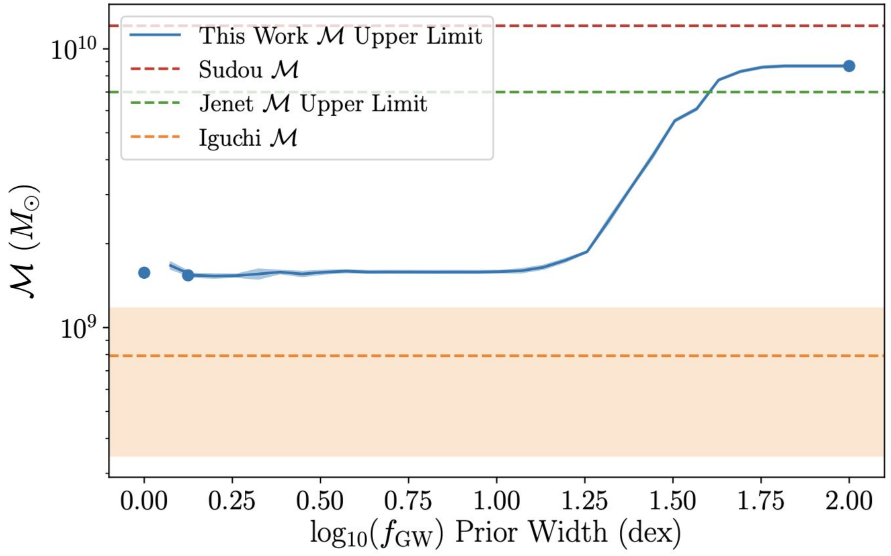
Arzoumanian+2021, arXiv:2101.02716 **(led by Maria Charisi)**

Constraints on mass ratio comparable to Milky Way.



Multi-Messenger Gravitational Wave Searches with Pulsar Timing Arrays: Application to 3C66B Using the NANOGrav 11-year Data Set

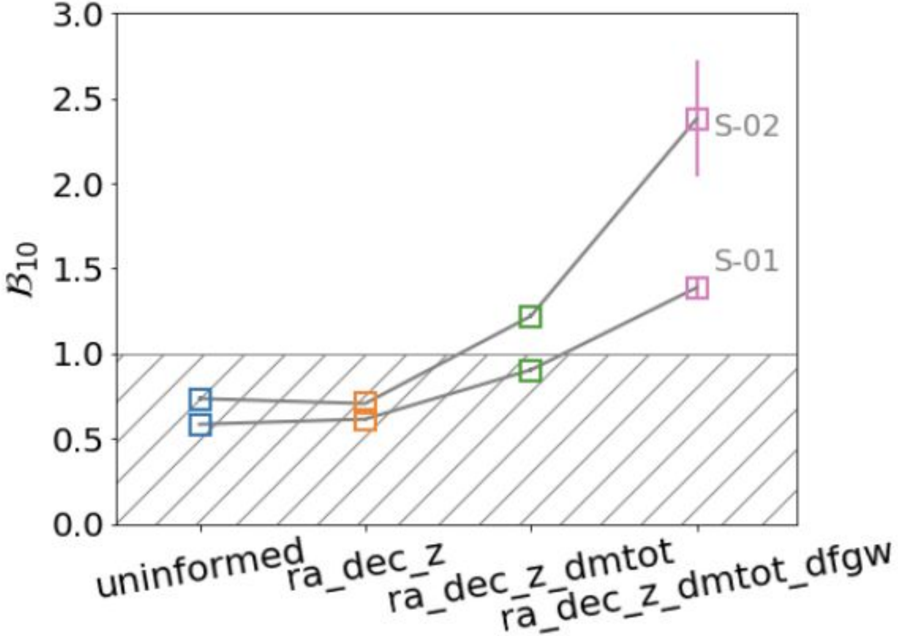
Arzoumanian et al. (2021) [led by Caitlin Witt], arXiv:2005.07123



Period and sky-location constraints really help. ***But which period are we seeing in the light-curve?***

MM Approaches to SMBHB Detection and Parameter Estimation: Implications for Nanohertz GW Searches with PTAs

Liu & Vigeland, arXiv:2105.08087



Exploring detection and PE improvements across the binary parameter space.

Contributor: Stephan Taylor

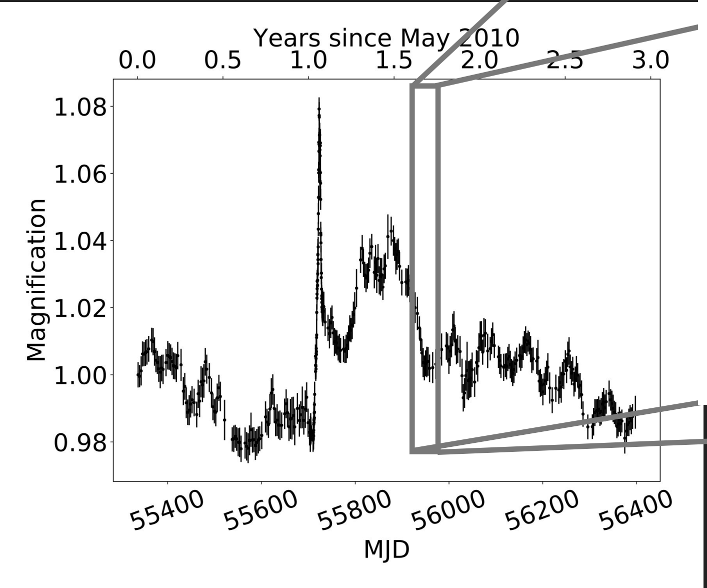
SPIKEY: SELF-LENSING CANDIDATE

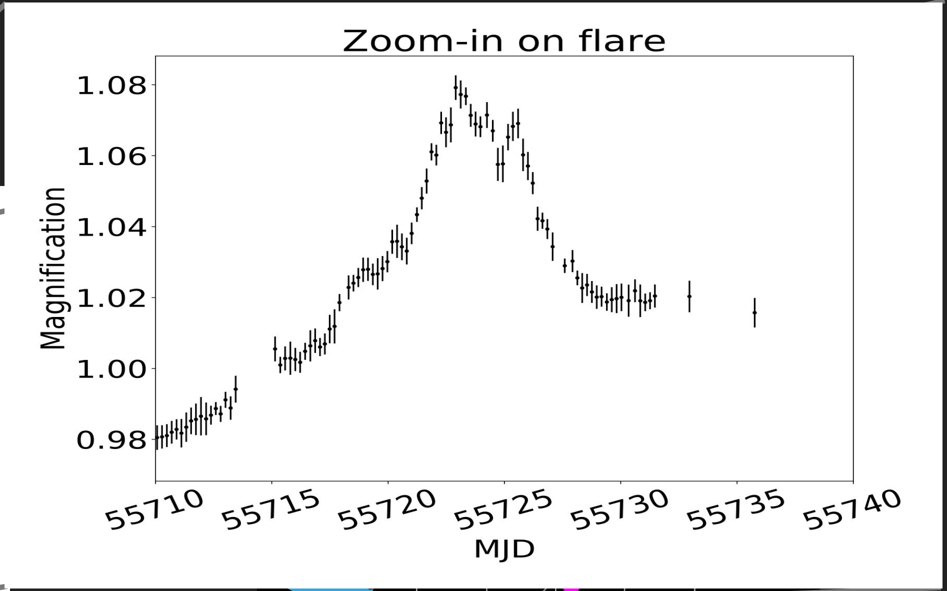
Spikey: Kepler identified AGN at z=0.918 (Smith, K.+2018)

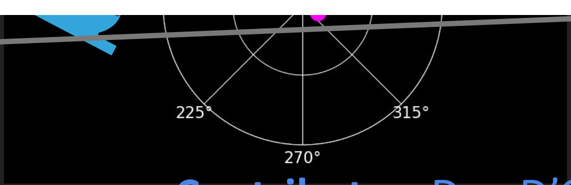
10 param. Doppler+lensing model:

$$P_{\rm orb} \quad M \quad q \quad e \quad \bar{\omega}$$

$$t_0 \quad I \quad v_z \quad \alpha \quad f_L$$







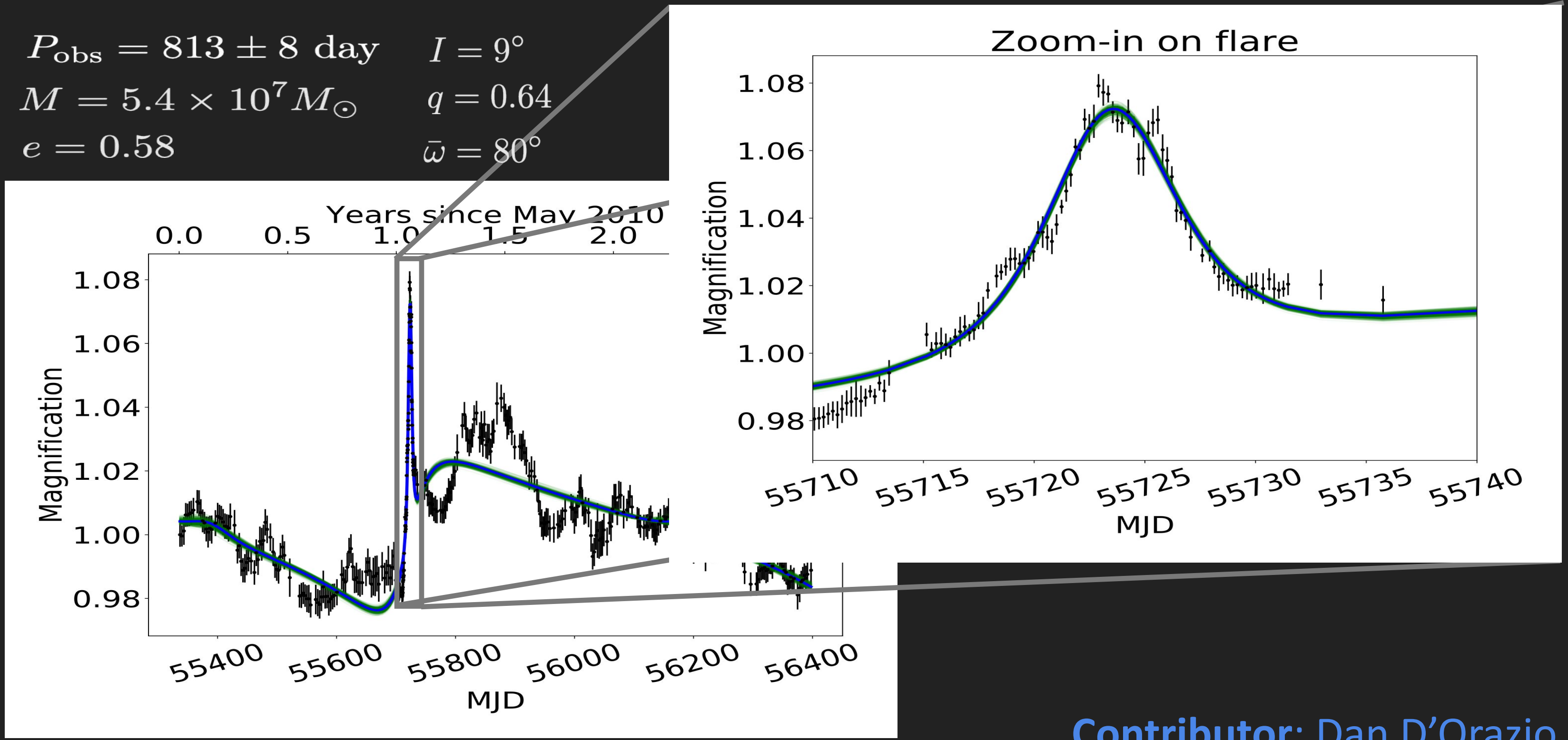
Contributor: Dan D'Orazio

Hu, D'Orazio, et al., MNRAS 495, 4061 (2020)

SPIKEY: SELF-LENSING CANDIDATE

Spikey: Kepler identified AGN at z=0.918 (Smith, K.+2018)

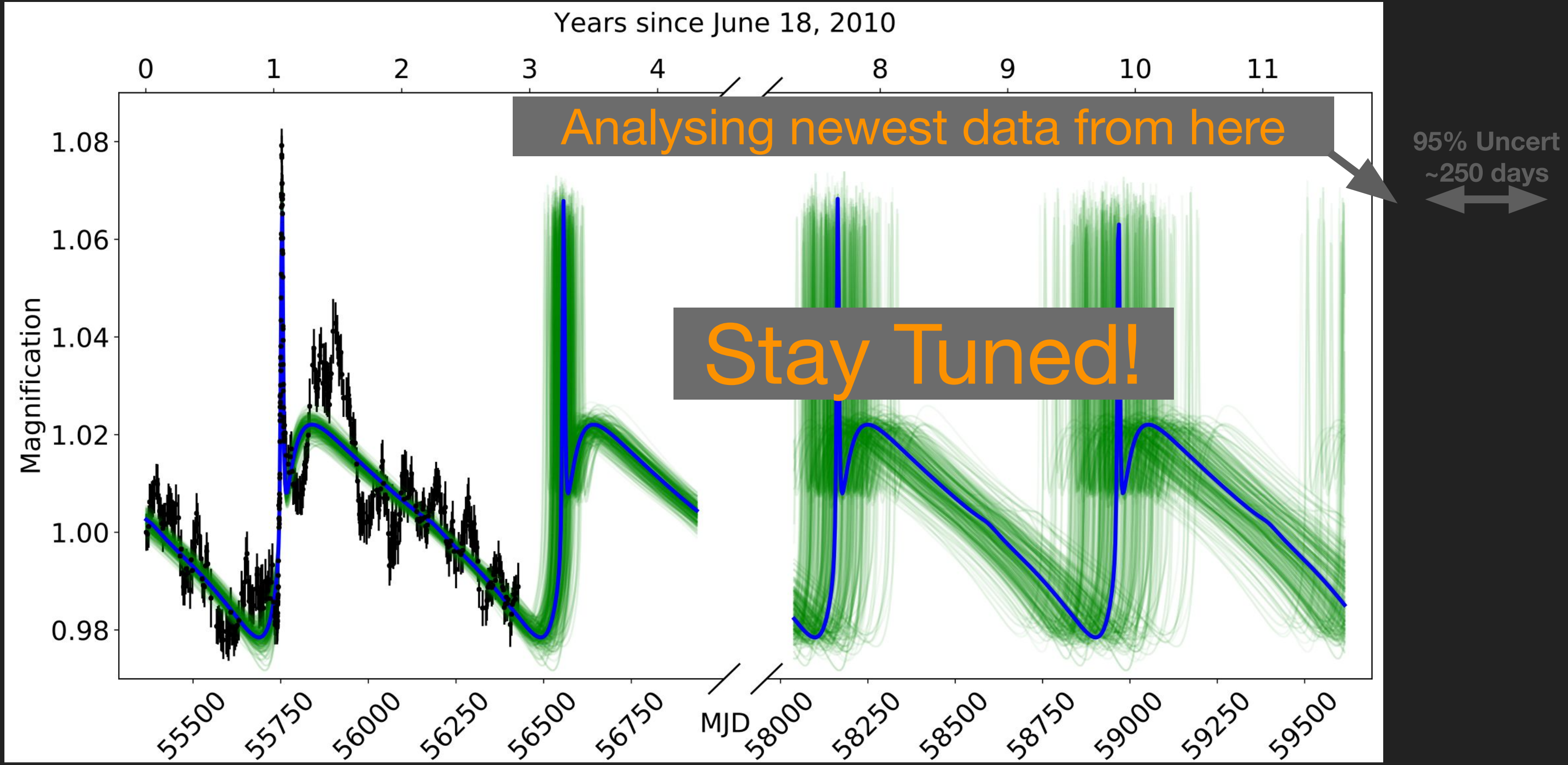
$$P_{\rm obs} = 813 \pm 8 \text{ day} \qquad I = 9^\circ$$
$$M = 5.4 \times 10^7 M_\odot \qquad q = 0.64$$
$$e = 0.58 \qquad \bar{\omega} = 80^\circ$$



Contributor: Dan D'Orazio

Hu, D'Orazio, et al., MNRAS 495, 4061 (2020)

SPIKEY: SELF-LENSING CANDIDATE



Hu, D'Orazio, et al., MNRAS 495, 4061 (2020)

Contributor: Dan D'Orazio

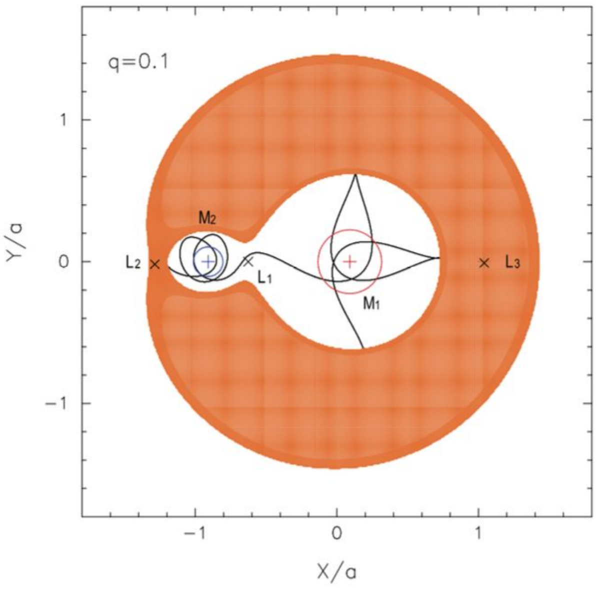
Tidal disruption of a star by SMBH binaries

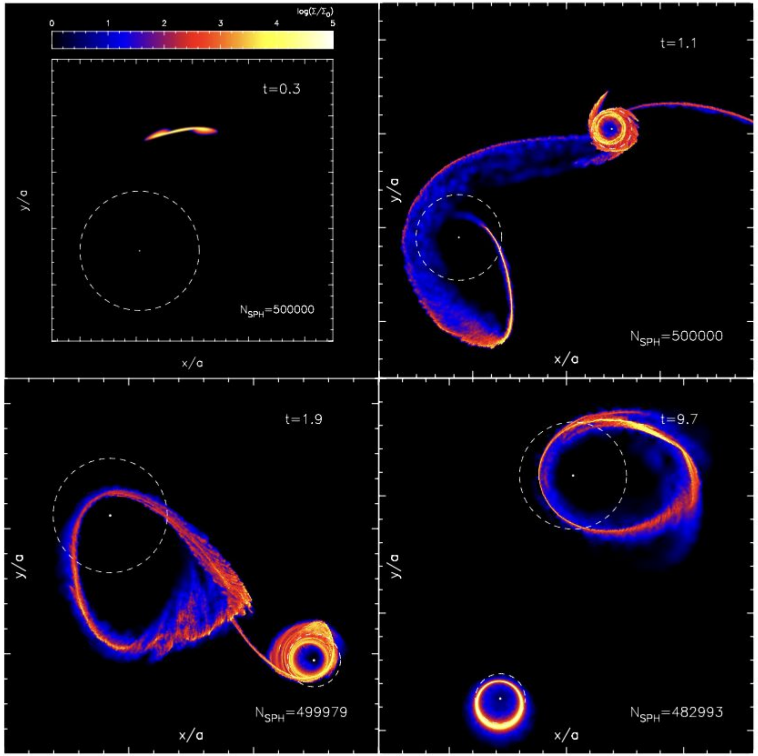
Hayasaki & Loeb (2016)

Contributor: Kimi Hayasaki

SPH simulation

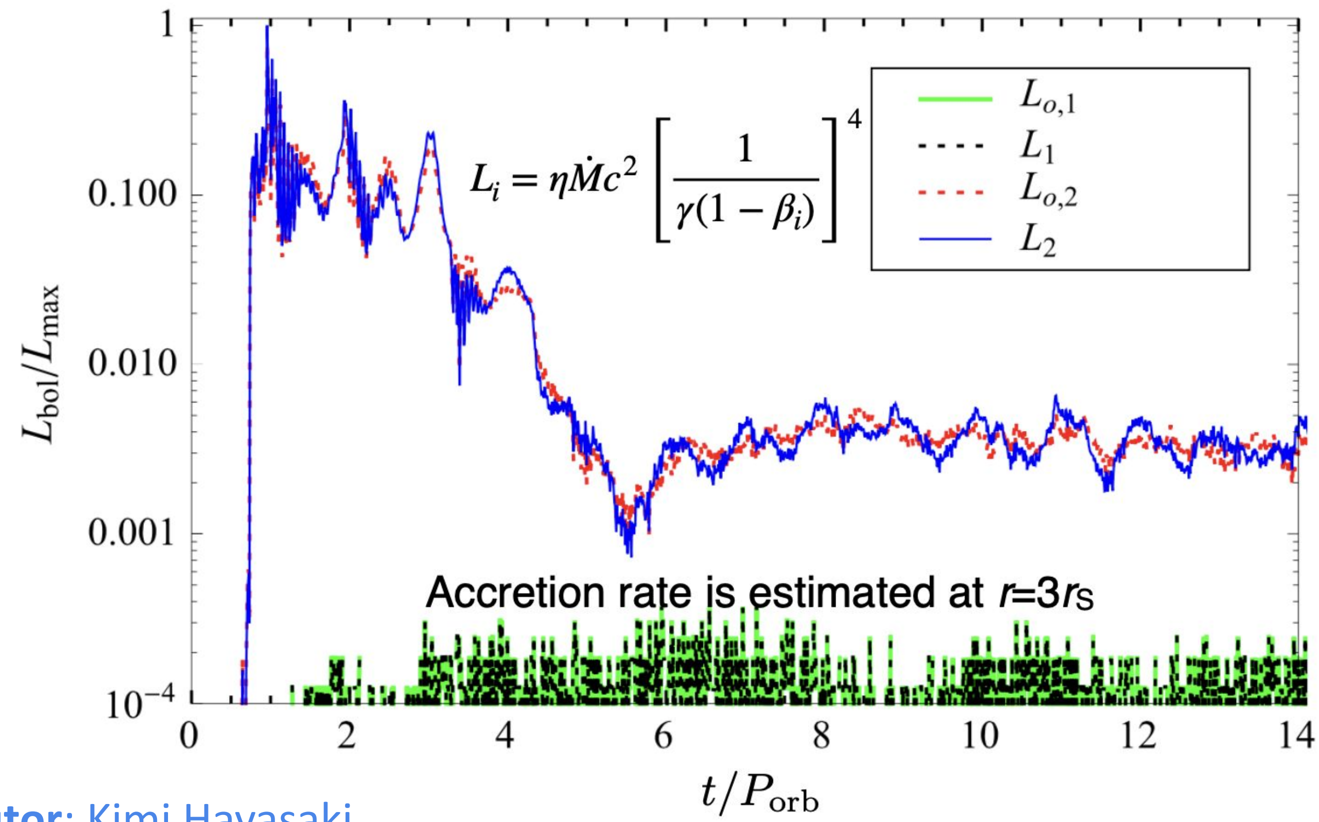
Test particle simulation





$$m_* = 1M_\odot,\ r_* = 1R_\odot,\ M_{\rm BH} = 10^6 M_\odot,\ a = 100 r_{\rm S},\ \text{and}\ q = 0.1$$

Doppler-boosted periodic light curves



Contributor: Kimi Hayasaki

The secondary's luminosity ($\dot{M}$) is much larger