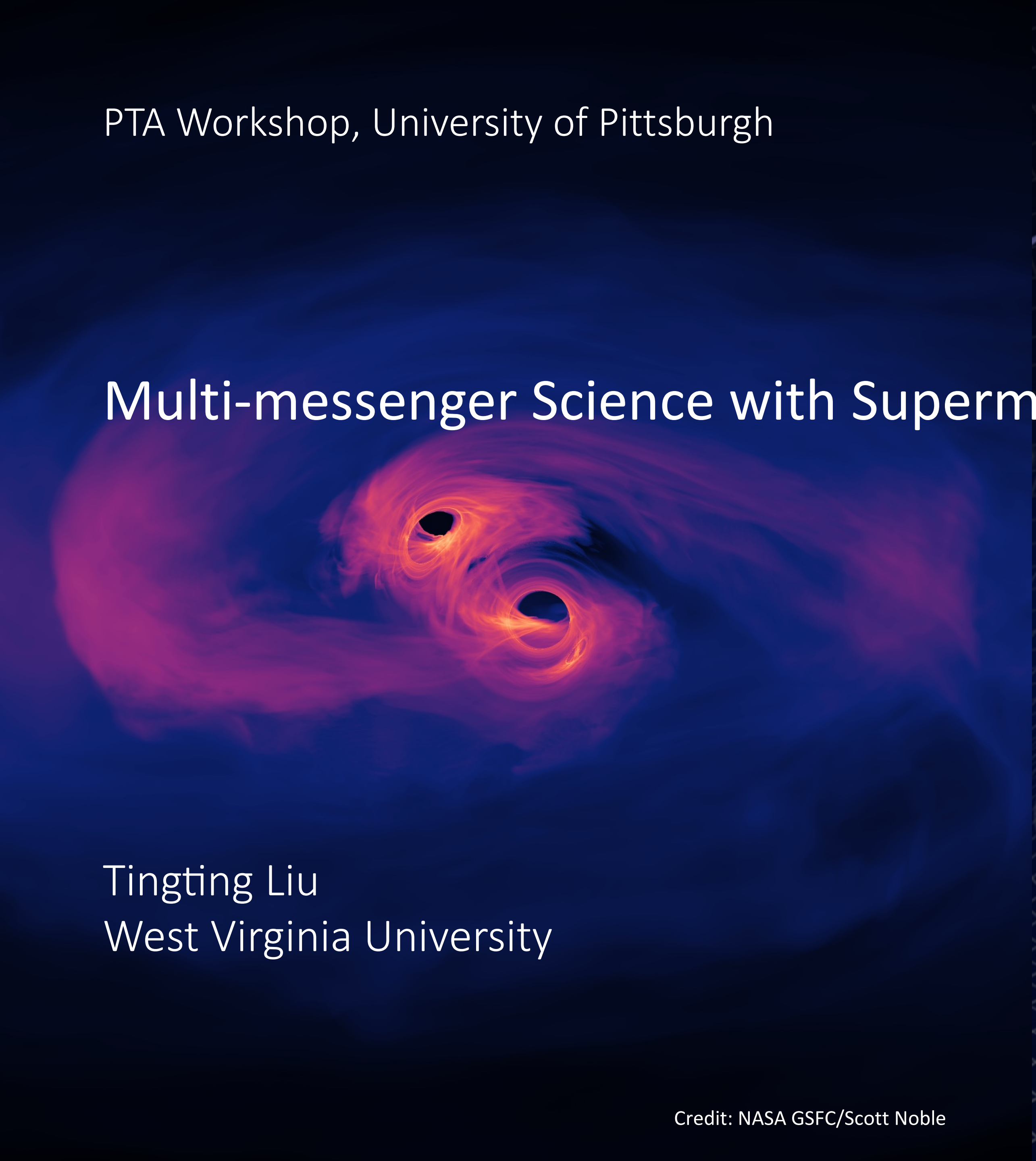
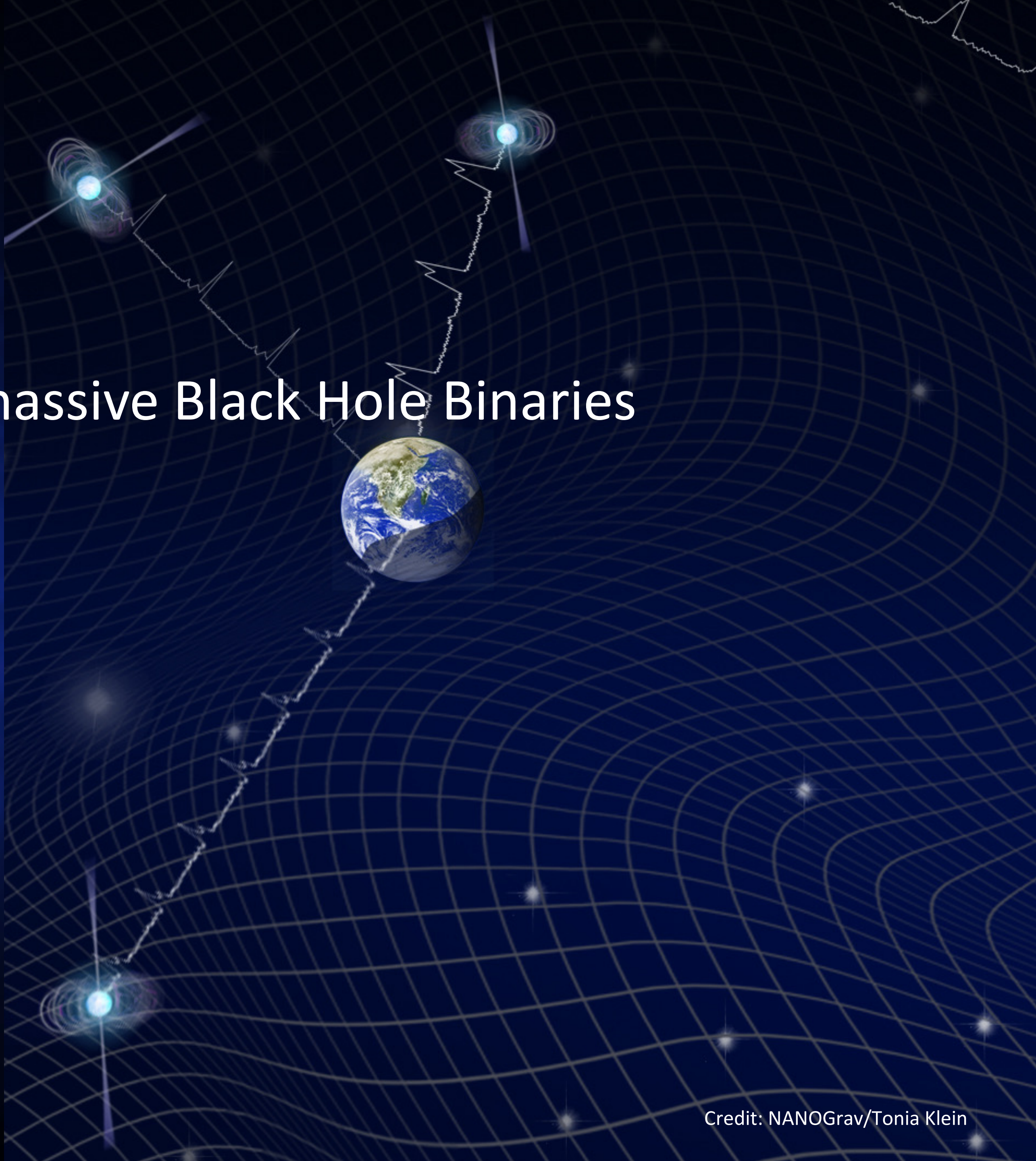
PTA Workshop, University of Pittsburgh

Multi-messenger Science with Supermassive Black Hole Binaries

Tingting Liu
West Virginia University



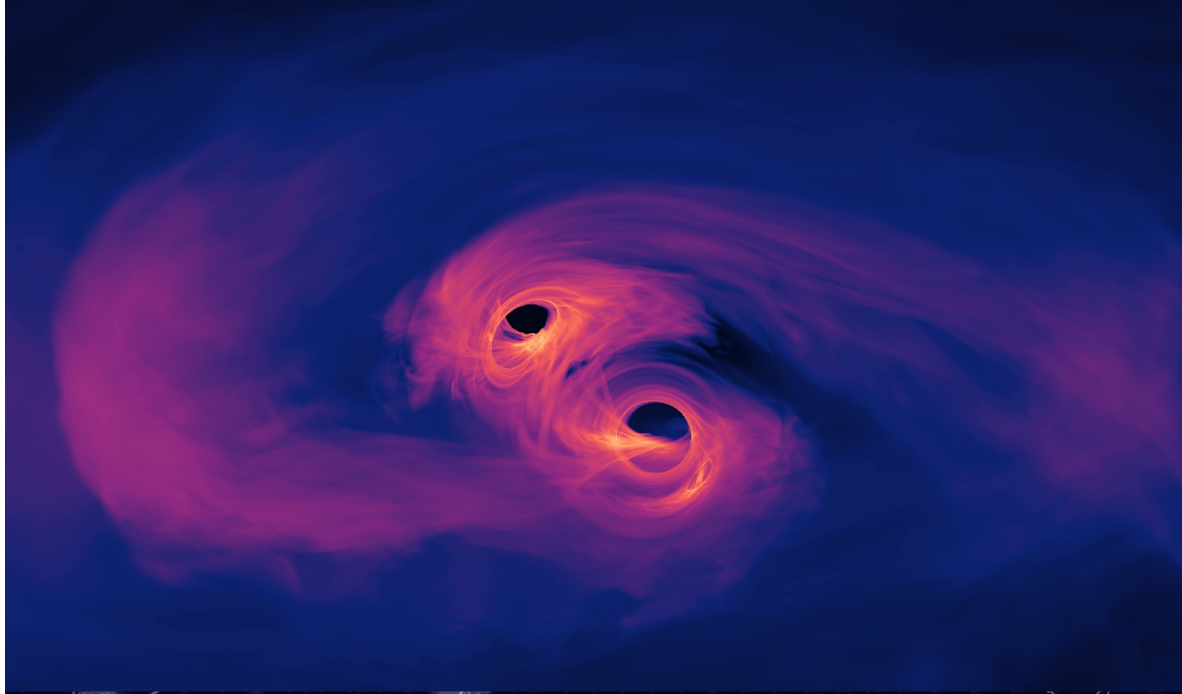
Credit: NASA GSFC/Scott Noble

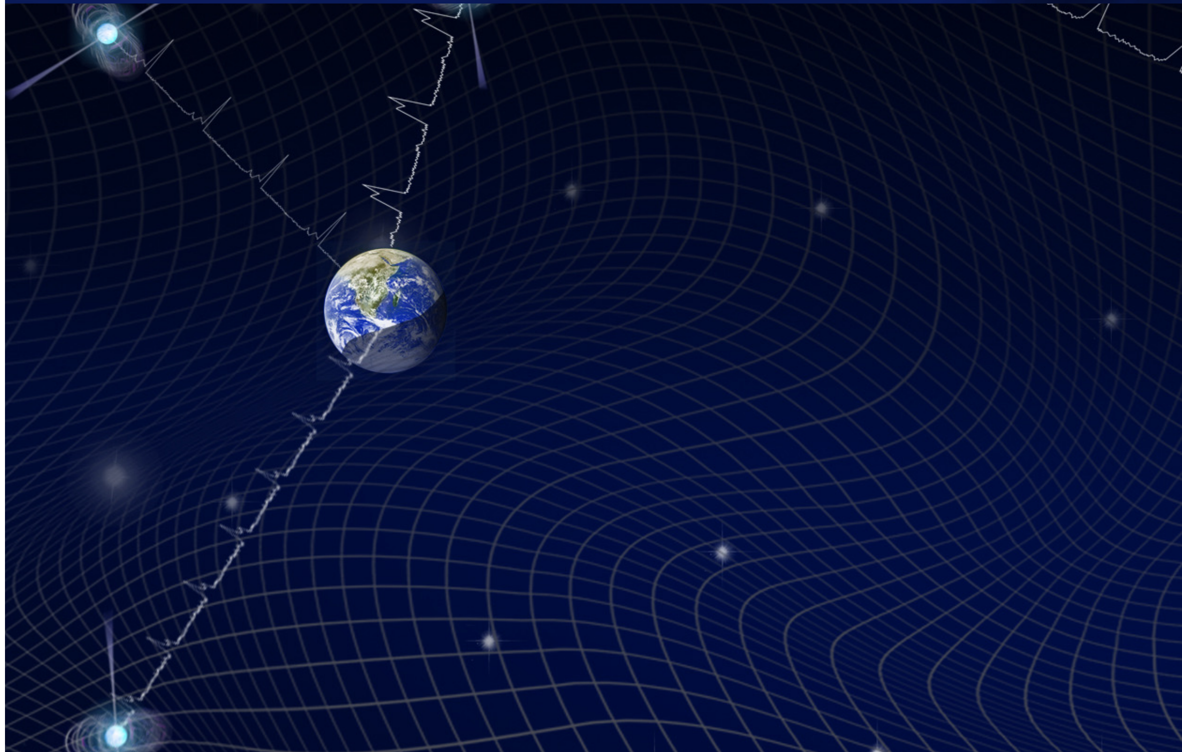


Credit: NANOGrav/Tonia Klein

Outline

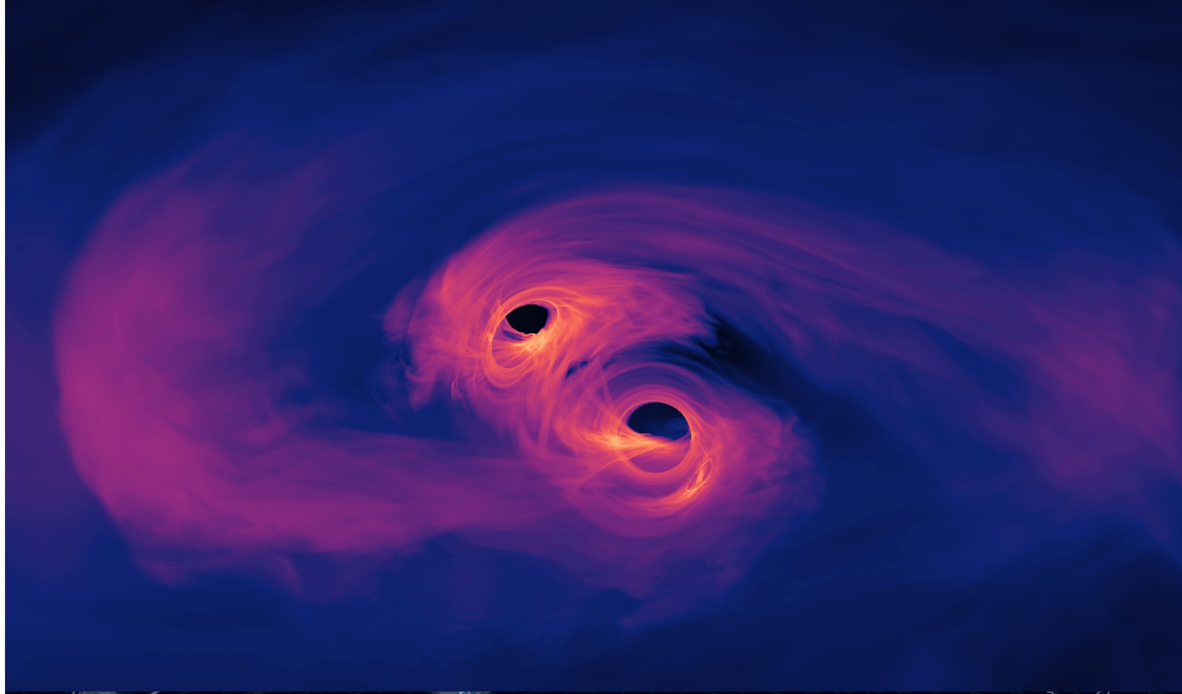
- Electromagnetic signatures of SMBHBs
  - Theory and observations

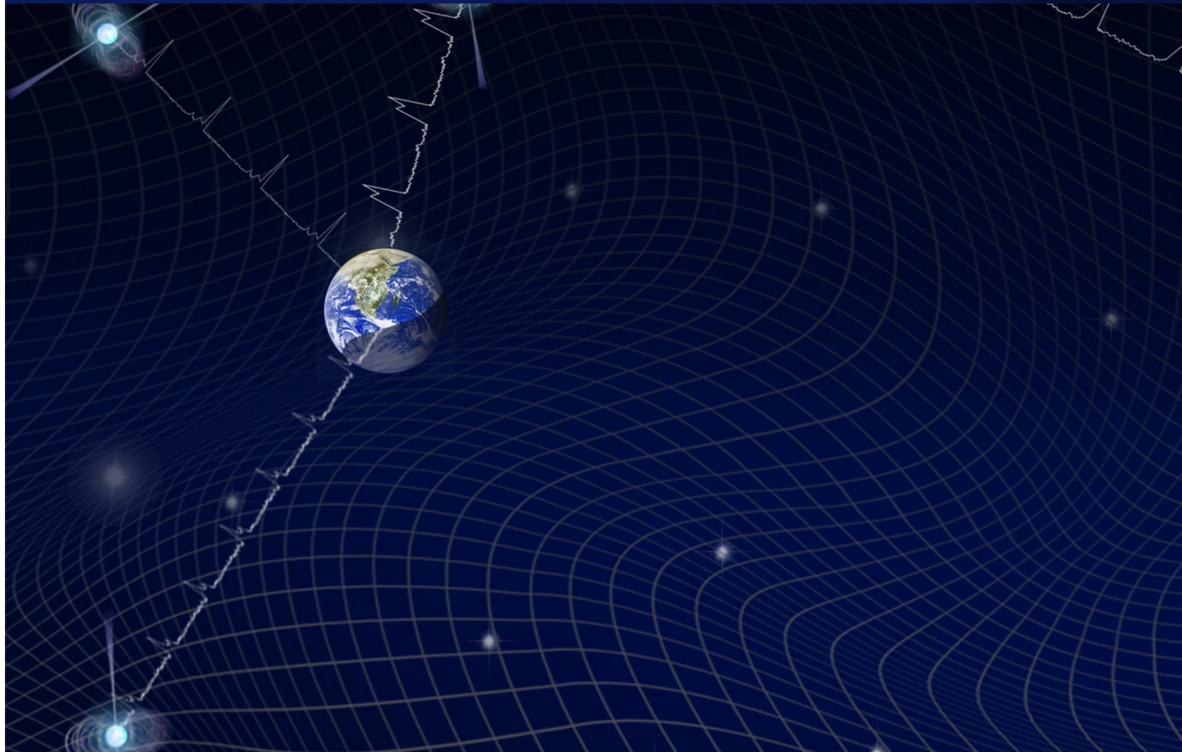




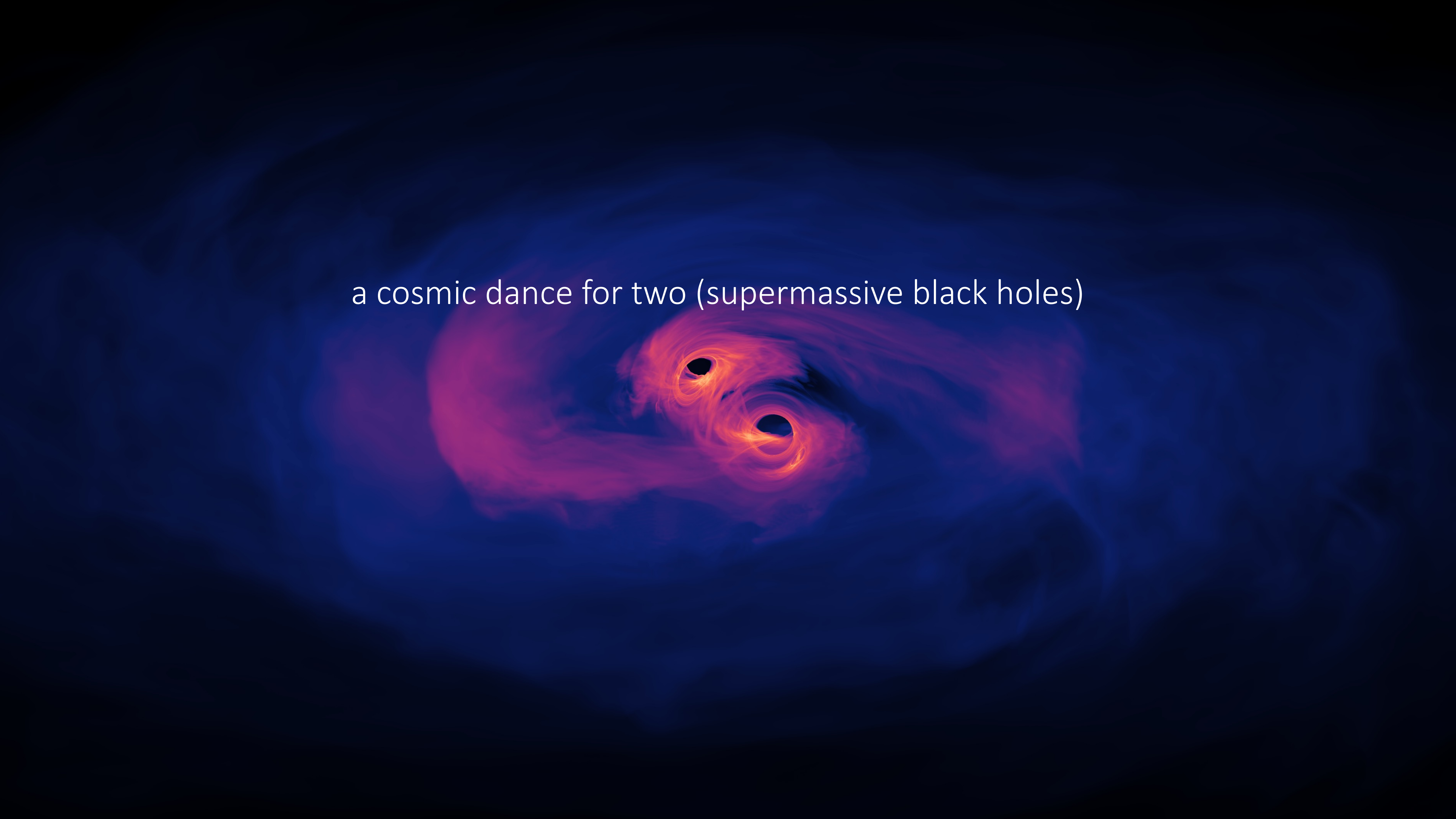
Outline

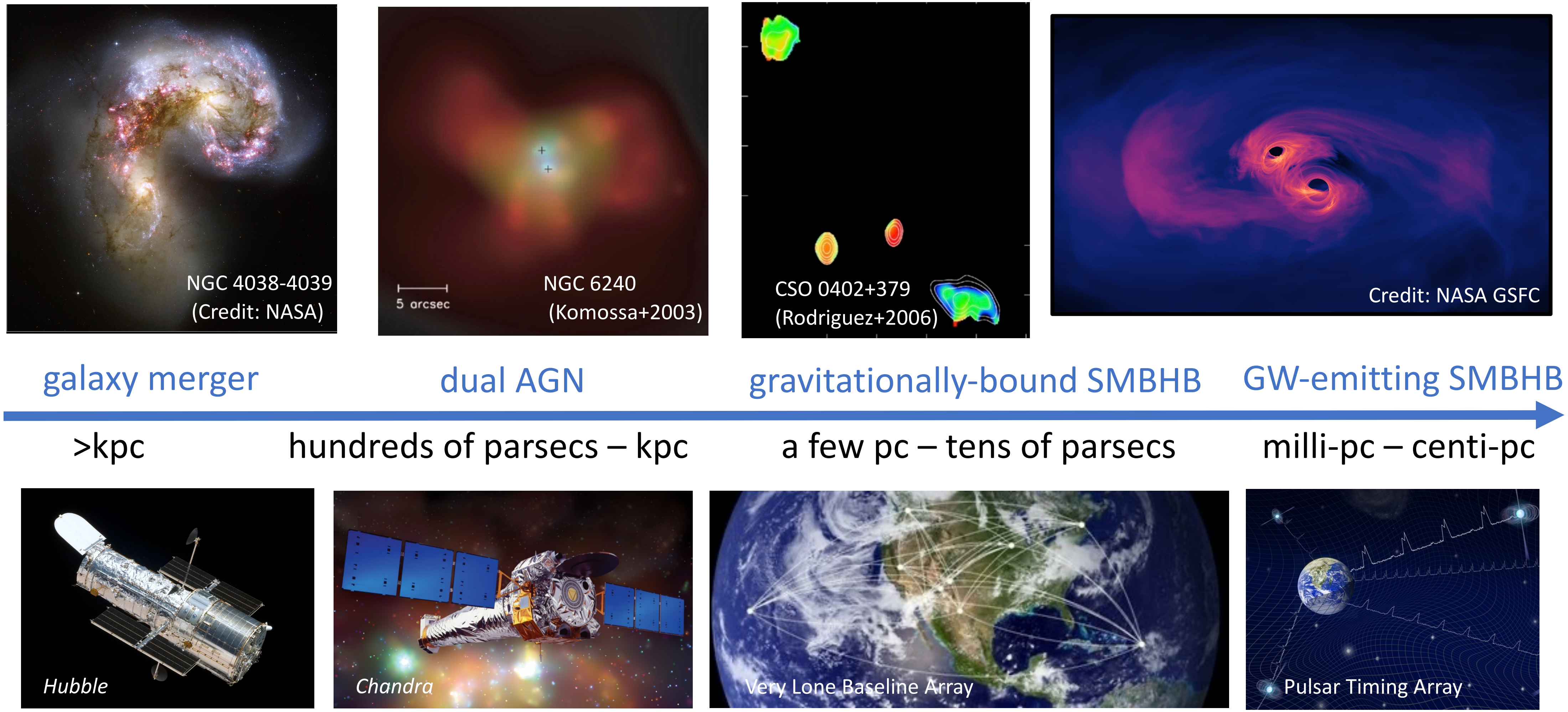
- Electromagnetic signatures of SMBHBs
  - Theory and observations
- Simultaneous EM-GW observations of SMBHBs
  - Multi-messenger science with PTAs





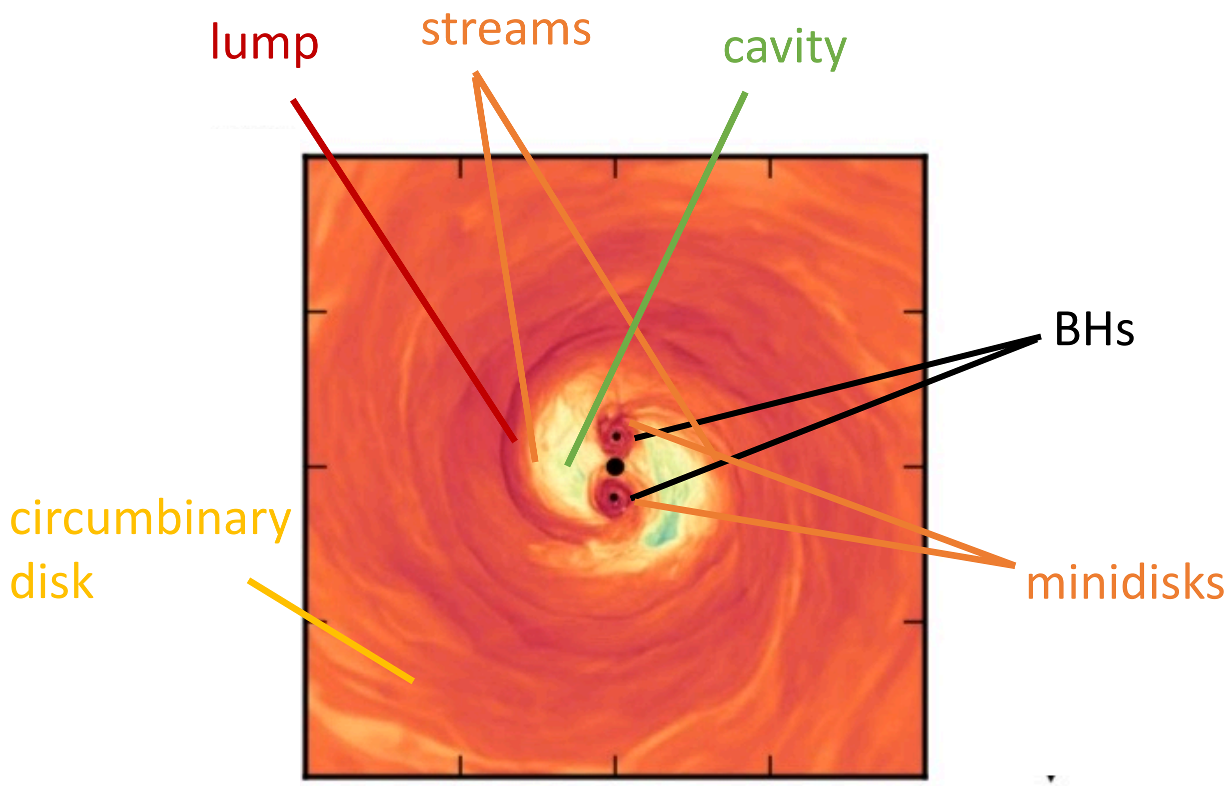
a cosmic dance for two (supermassive black holes)





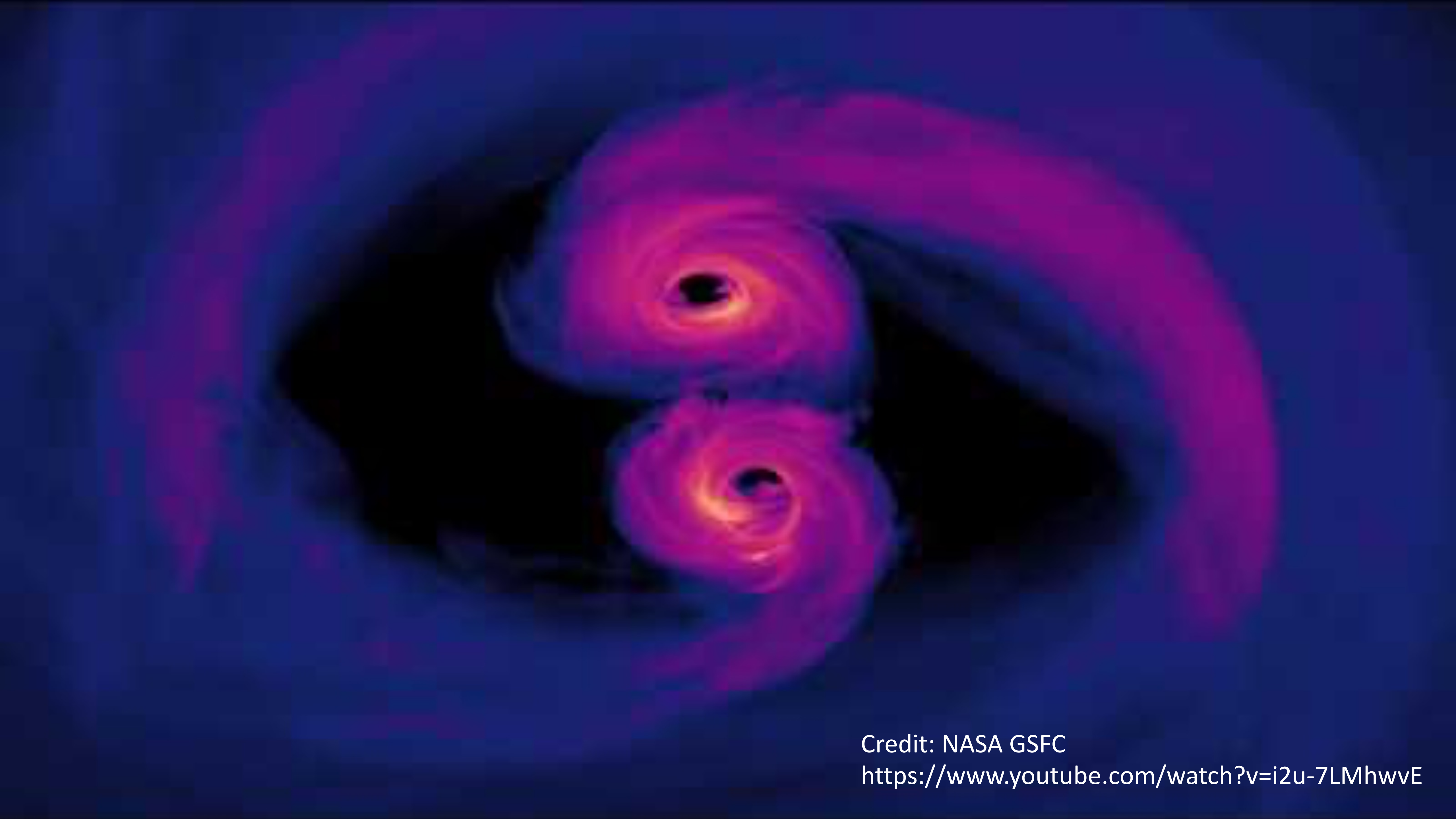
kpc ~ size of a galaxy pc ~ distance between stars milli-pc ~ distance light travels in ~1 day

Anatomy of an SMBHB



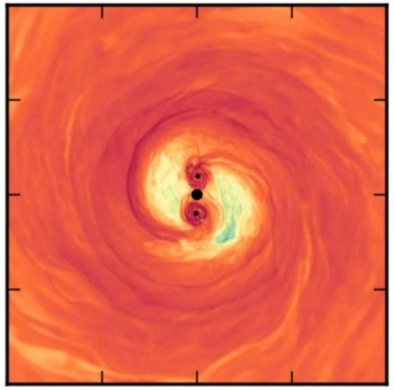
Adapted from d'Ascoli+2018

see also: Farris+2014, Muñoz & Lai 2016, Tang+2017, Bowen+ 2018, Paschalidis+2021, Combi+2022, Avara+2023 …

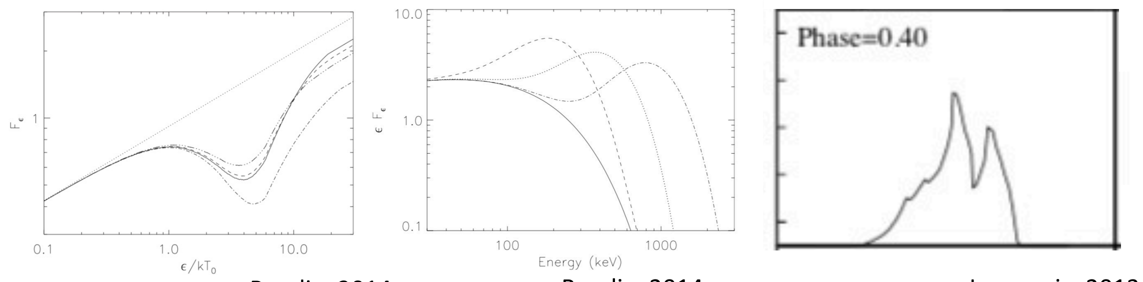


Credit: NASA GSFC
https://www.youtube.com/watch?v=i2u-7LMhwvE

Electromagnetic signatures



Spectra

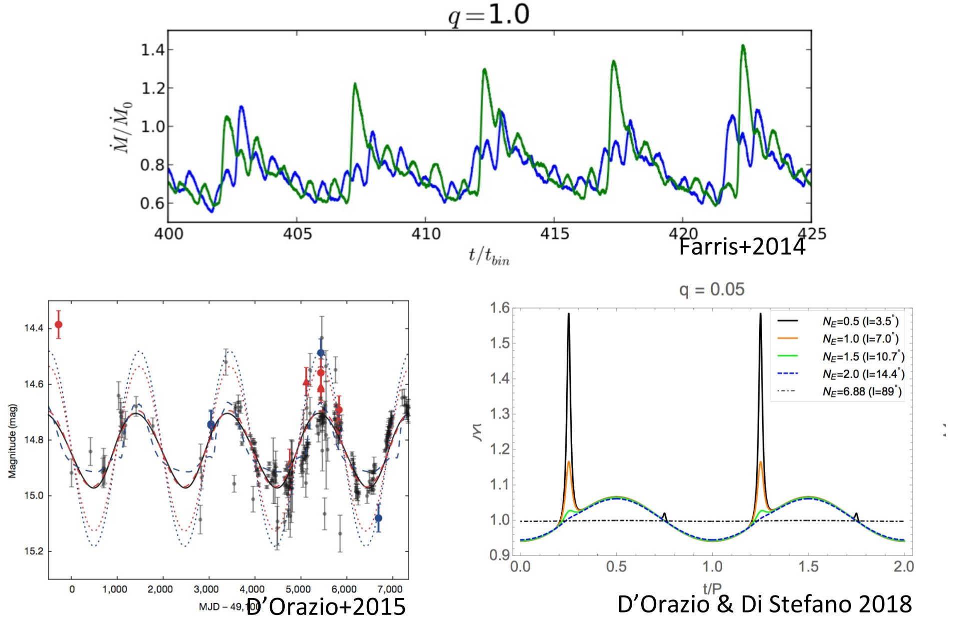


Roedig+2014 Roedig+2014 Jovanovic+2013

EM imprint of the disk structure

also: BH-disk impact (e.g., Lehto & Valtonen 1996), tidal disruption by an SMBHB (e.g., Ricarte+2014), microlensing (e.g., Millon+2022)

Variability (light curves)



Farris+2014

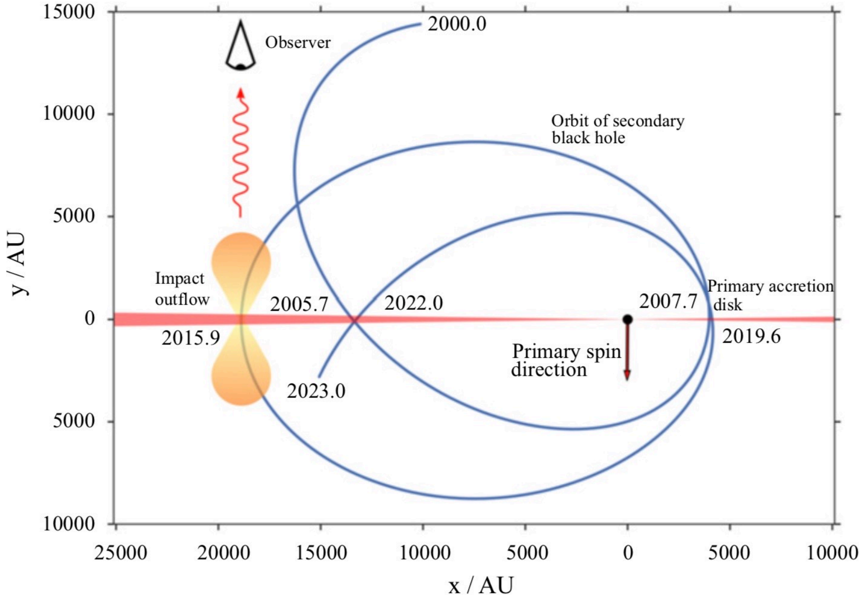
D'Orazio+2015 D'Orazio & Di Stefano 2018

EM imprint of the orbital motion

EM signatures – variability

- OJ 287 – ”Rosetta stone” of SMBHBs?

Theory



Valtonen+2016

Predicts: pair of flares due to BH-disk impact

EM signatures – variability

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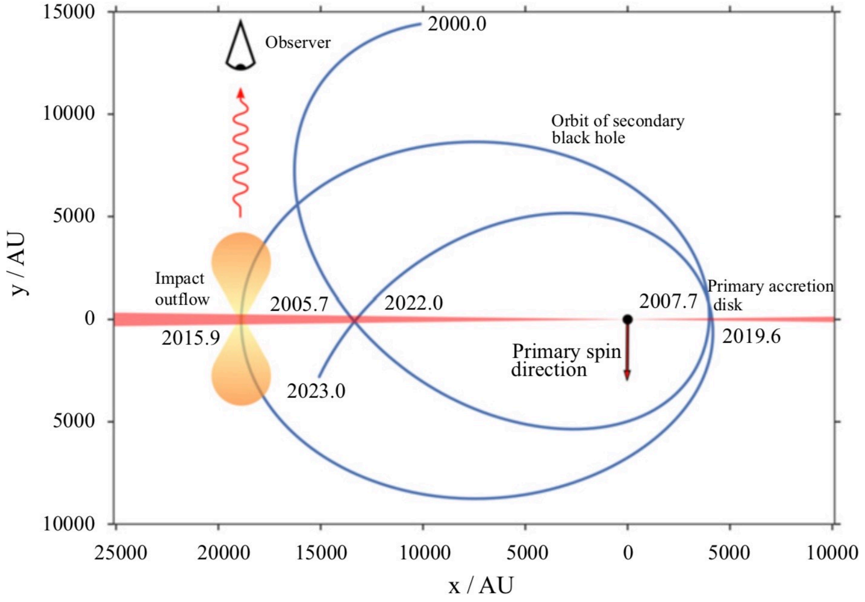
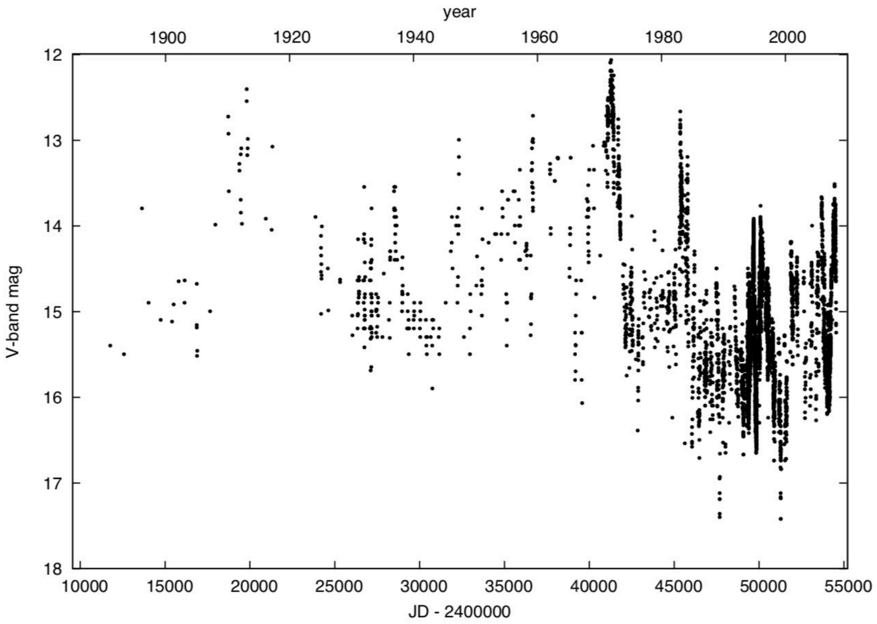
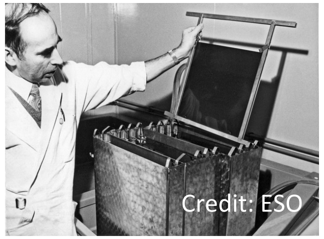


Valtonen+2016

Observations



Valtonen+2008b



Predicts: pair of flares due to BH-disk impact

EM signatures – variability

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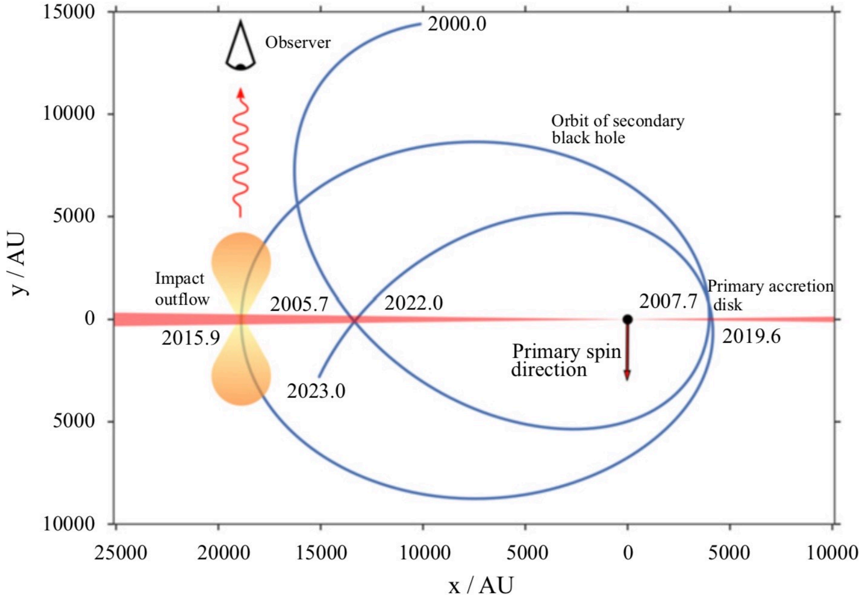
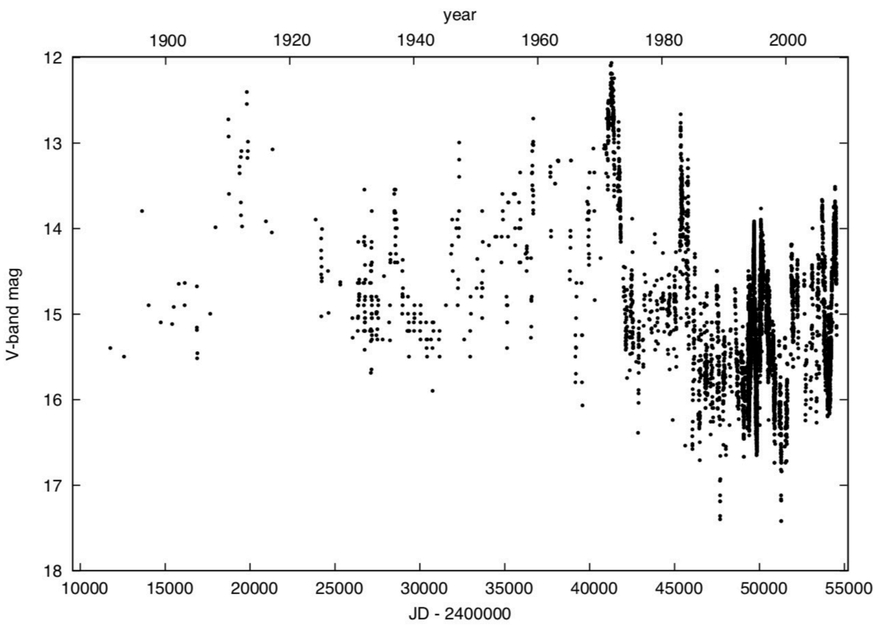
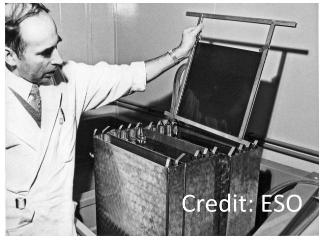
Theory

Observations

12 yr







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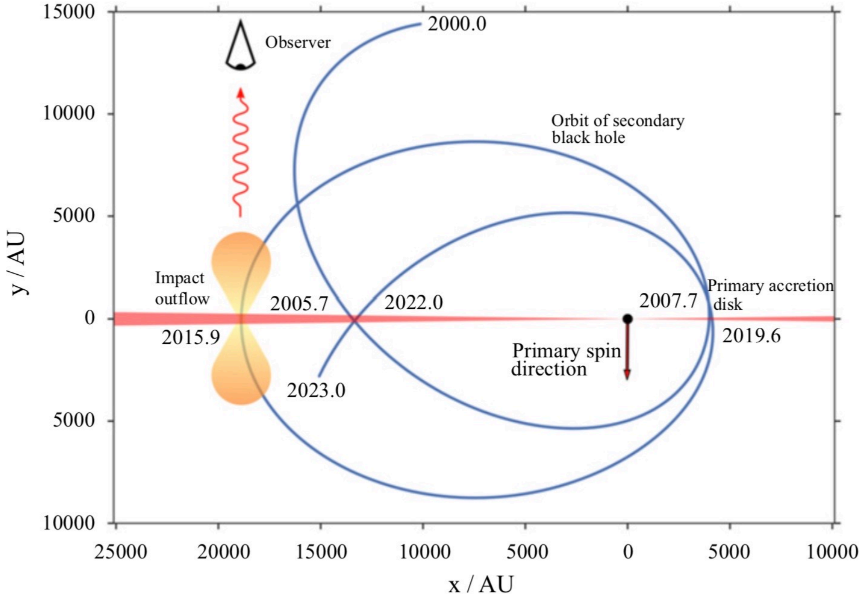
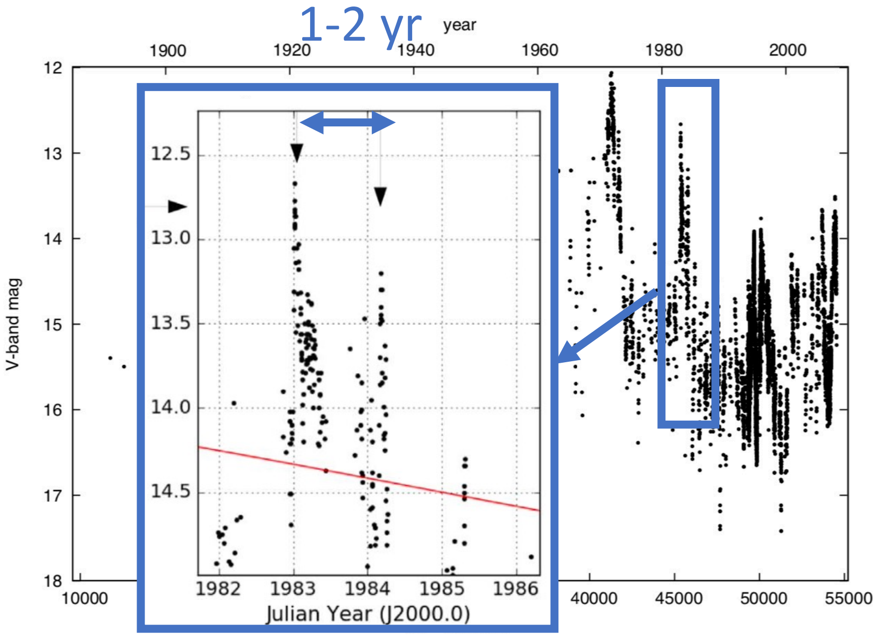


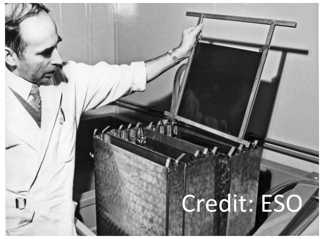
Valtonen+2016

Observations



Dey+2018

Valtonen+2008b



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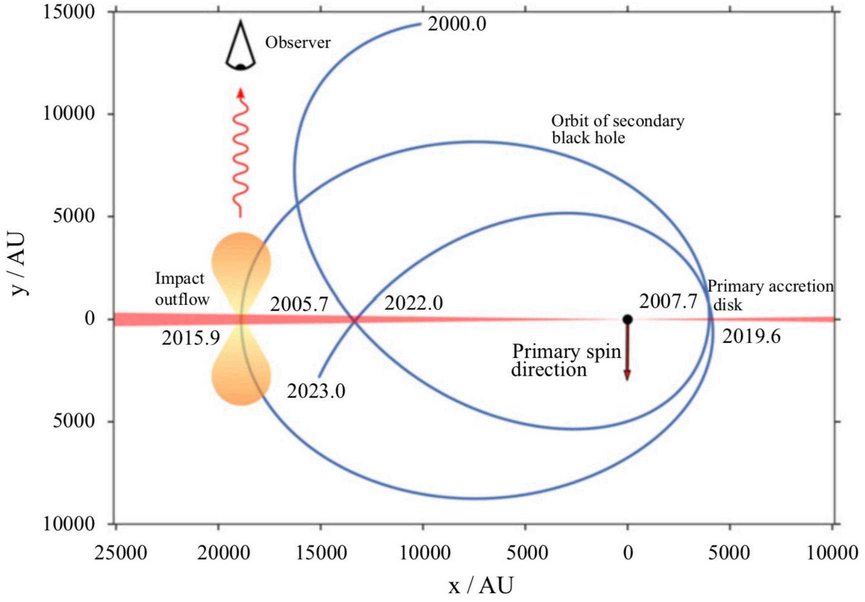

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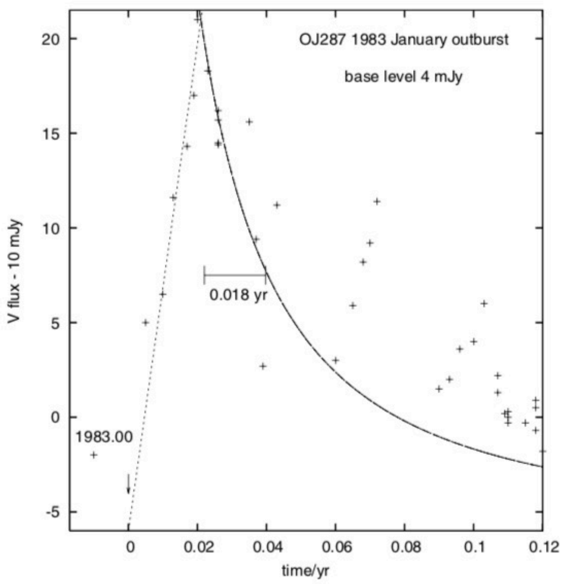

Valtonen+2008a
(outburst in 1983)

EM signatures – variability

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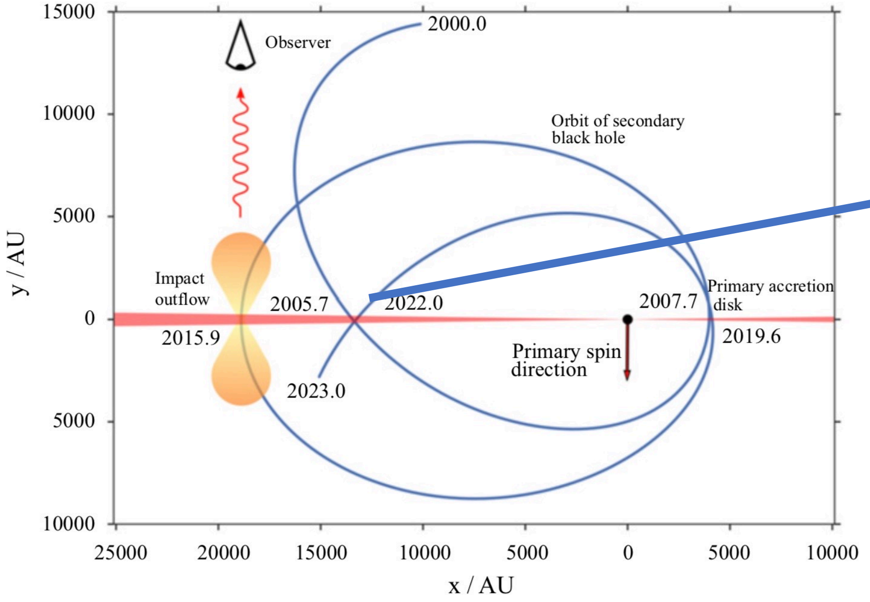
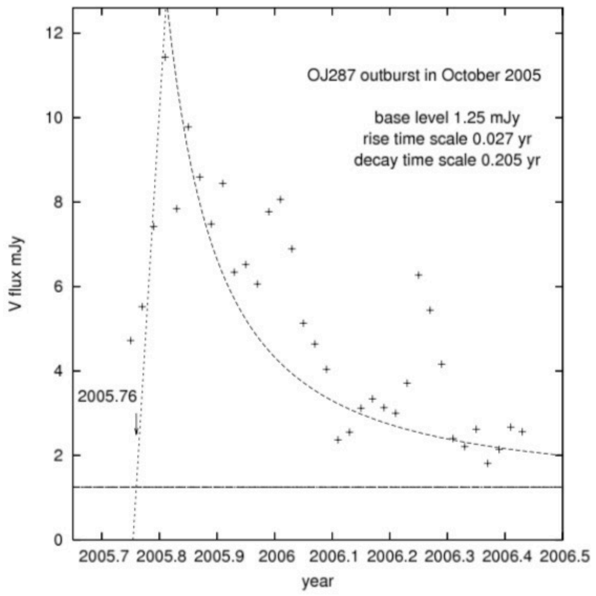


Valtonen+2016

Predicts: pair of flares due to BH-disk impact

Observations



Valtonen+2008a
(outburst in 2005)

EM signatures – variability

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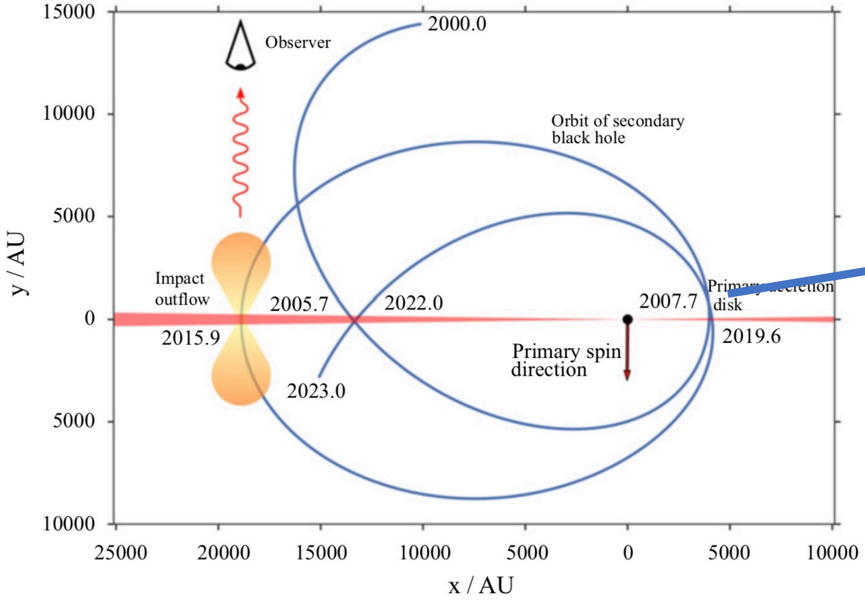
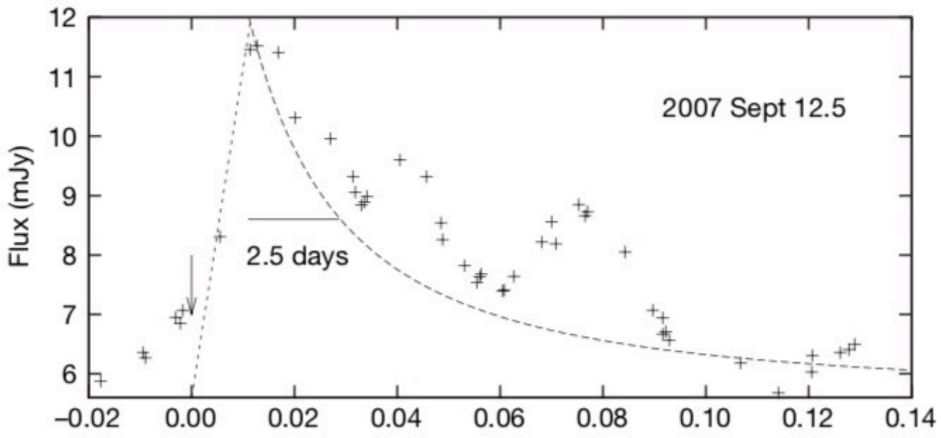


Valtonen+2016

Predicts: pair of flares due to BH-disk impact

Observations



Valtonen+2008b
(outburst in 2007)

EM signatures – variability

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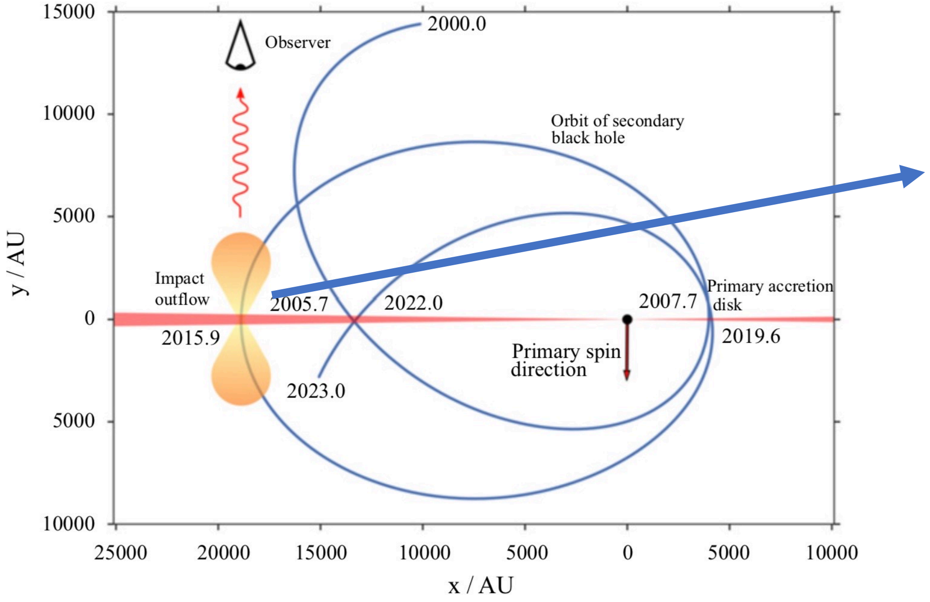
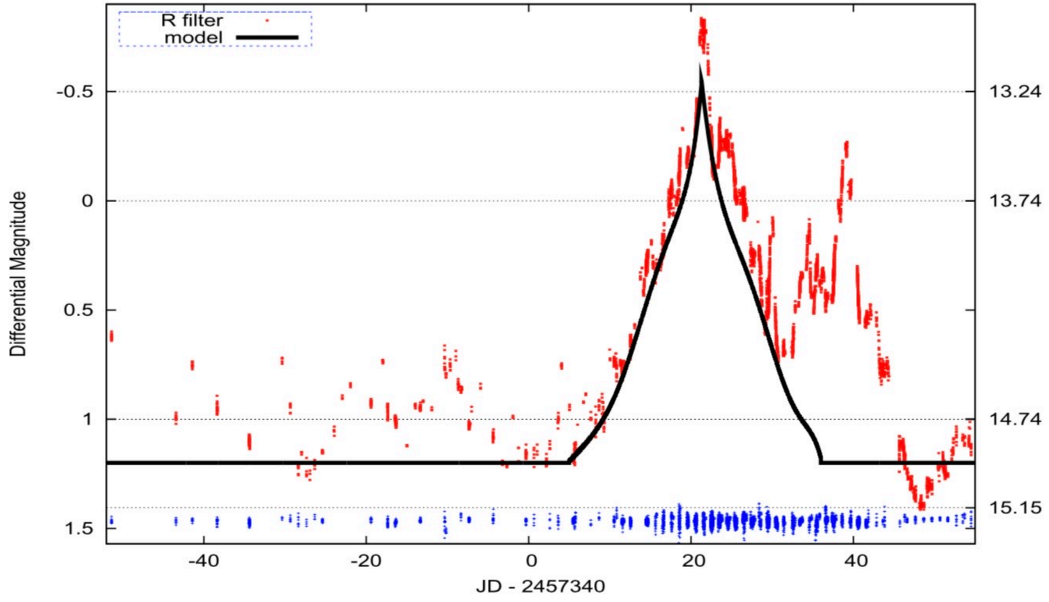


Valtonen+2016

Predicts: pair of flares due to BH-disk impact

Observations



Valtonen+2016
(“centenary flare” in 2015)

EM signatures – variability

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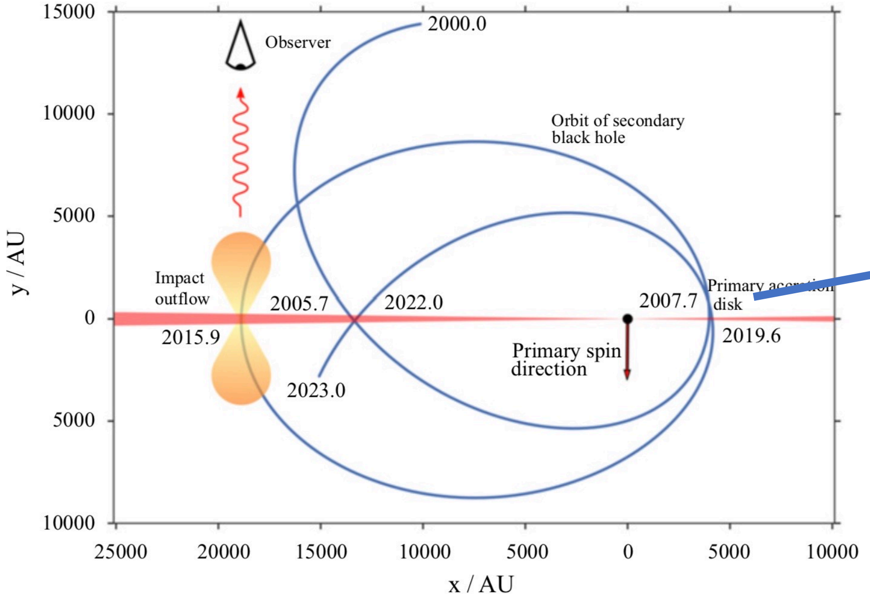
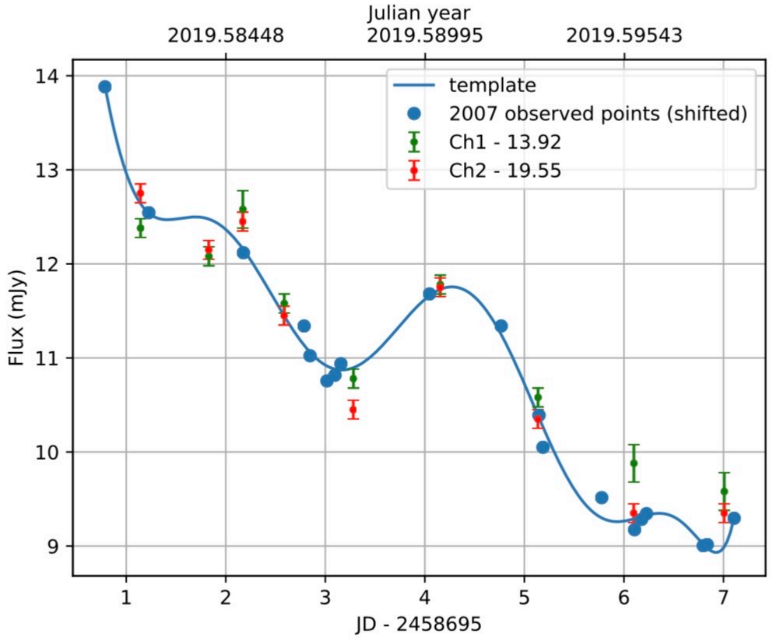
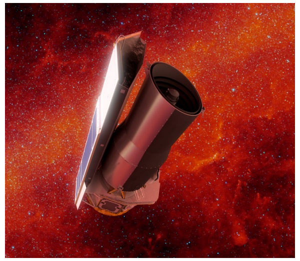


Valtonen+2016

Predicts: pair of flares due to BH-disk impact

Observations



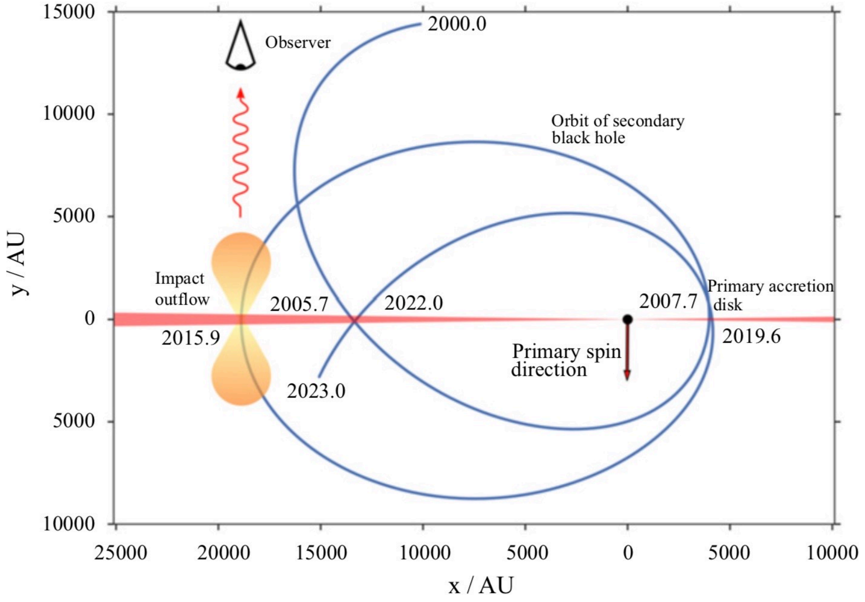


Laine+2020 (Spitzer)
(“Eddington flare” in 2019)

EM signatures – variability

- OJ 287 – ”Rosetta stone” of SMBHBs?

Theory



Valtonen+2016

Predicts: pair of flares due to BH-disk impact

Binary parameters

Table 2.
Independent and Dependent Parameters of the BBH System in OJ 287
According to our Orbit Solution

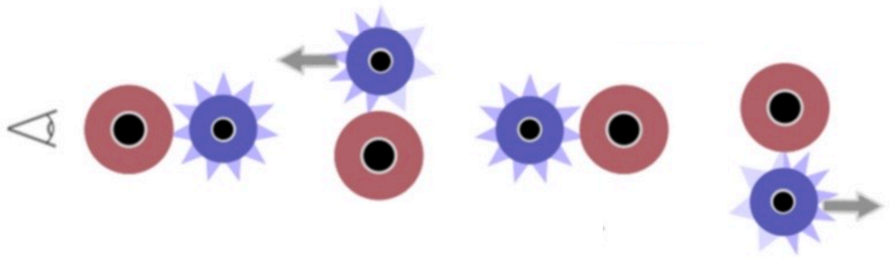
(1)	Parameter (2)	Value (3)	Unit (4)	Error (5)
	m_1	18348	$10^6\ M_\odot$	± 7.92
	m_2	150.13	$10^6\ M_\odot$	± 0.25
	χ_1	0.381		± 0.004
	h	0.900		± 0.001
Independent	d	0.776		± 0.004
	$\Delta\Phi$	38.62	deg	± 0.01
	Θ_0	55.42	deg	± 0.17
	e_0	0.657		± 0.001
	γ_{obs}	1.304		± 0.008
Derived	P_{orb}^{2017}	12.062	year	± 0.007
	$\dot{P}_{orb}$	0.00099		± 0.00006

Dey+2018

EM signatures – variability

- Relativistic beaming

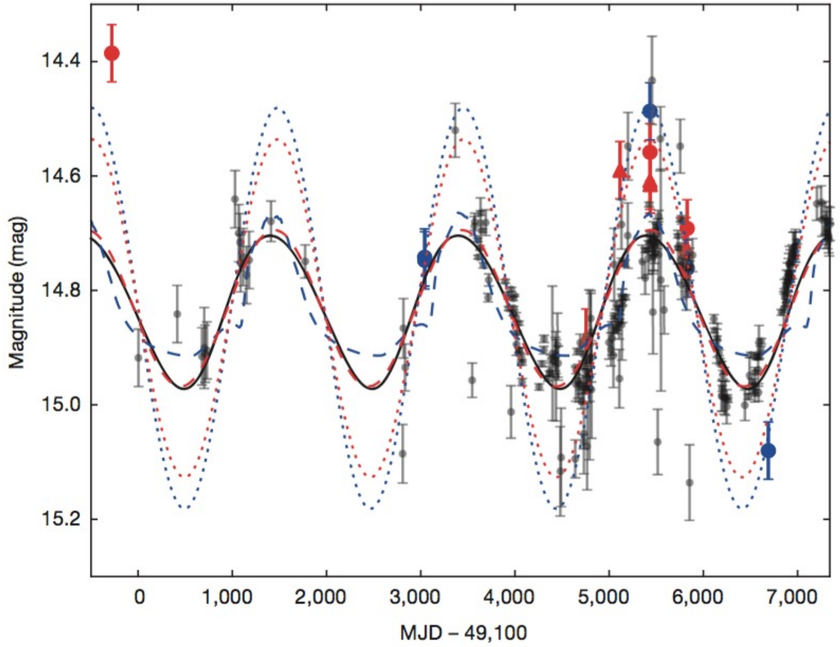
Theory

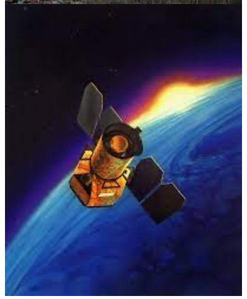


Credit: Kelley+2019

Predicts: smooth, quasi-sinusoidal light curve profile, UV-optical variability amplitude ratio

Observations



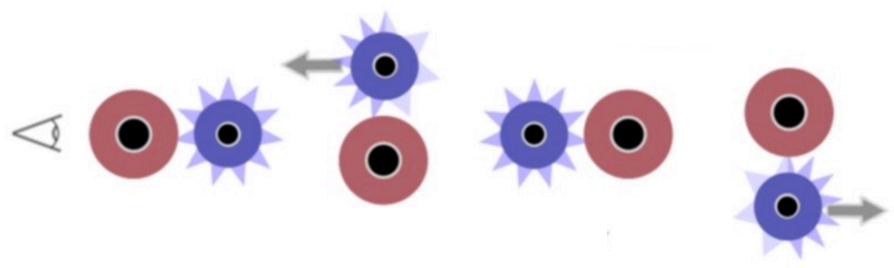


D'Orazio+2015
(CRTS light curve from Graham+2015a, UV light curves from GALEX)

EM signatures – variability

- Relativistic beaming

Theory



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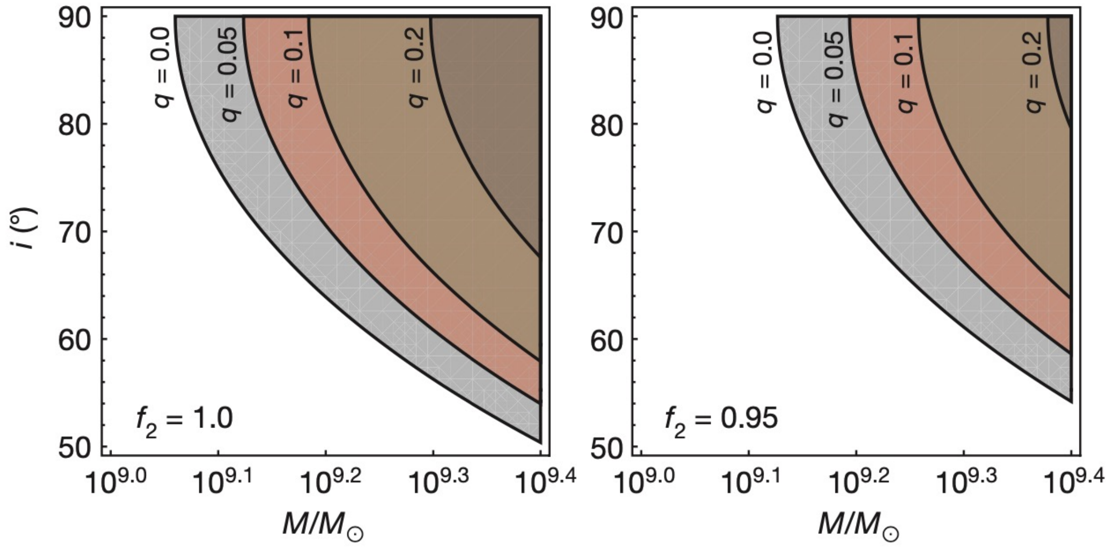
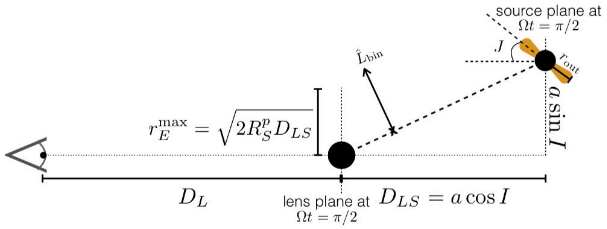


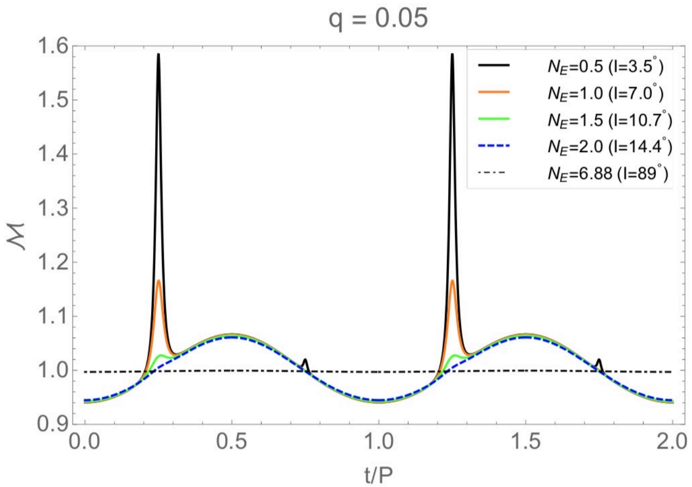
D'Orazio+2015

EM signatures – variability

- Binary self-lensing

Theory

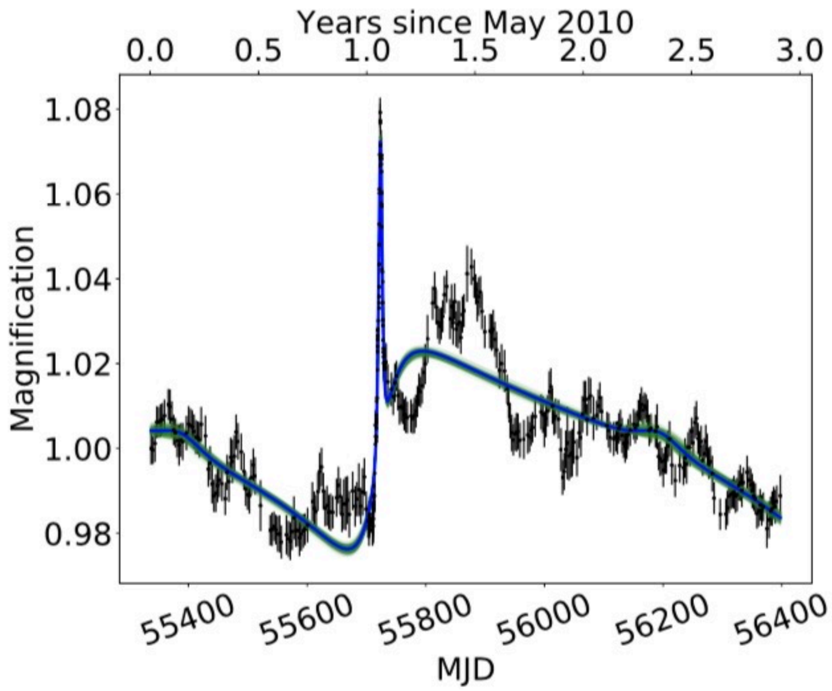


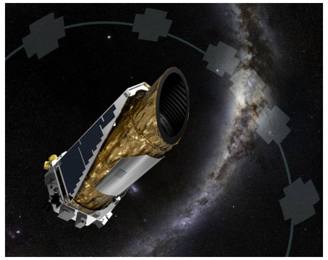


D'Orazio & Di Stefano 2018

Predicts: sharp flares

Observations



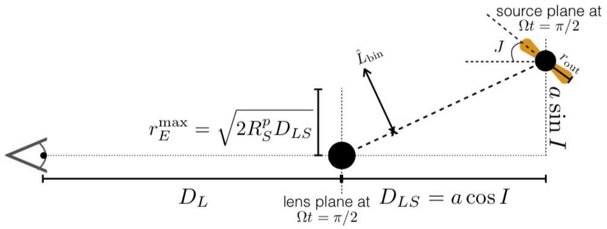


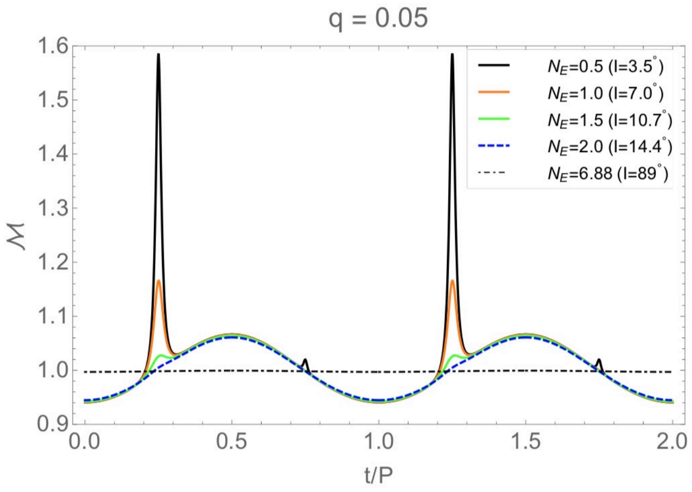
Hu+2020
(Kepler/K2 light curve from Smith+2018a)

EM signatures – variability

- Binary self-lensing

Theory





D'Orazio & Di Stefano 2018

Predicts: sharp flares

Binary parameters

Parameter	Meaning	Spikey
v_z [c]	velocity of barycenter along line of sight	$-0.003^{+0.000}_{-0.001}$
ω [rad]	argument of periapse	$1.387^{+0.026}_{-0.034}$
e	eccentricity	$0.579^{+0.011}_{-0.010}$
T [yrs]	period	$1.155^{+0.011}_{-0.011}$
I [rad]	inclination	$1.410^{+0.008}_{-0.008}$
M_1 [$M_\odot$]	mass of primary BH	$3.281^{+0.393}_{-0.330} \times 10^7$
M_2 [$M_\odot$]	mass of secondary BH	$2.101^{+0.420}_{-0.419} \times 10^7$
f_L	luminosity ratio	$0.575^{+0.419}_{-0.392}$
t_0 [yrs]	arbitrary reference time	$1.702^{+0.011}_{-0.011}$
α	spectral index	$0.825^{+1.001}_{-2.575}$

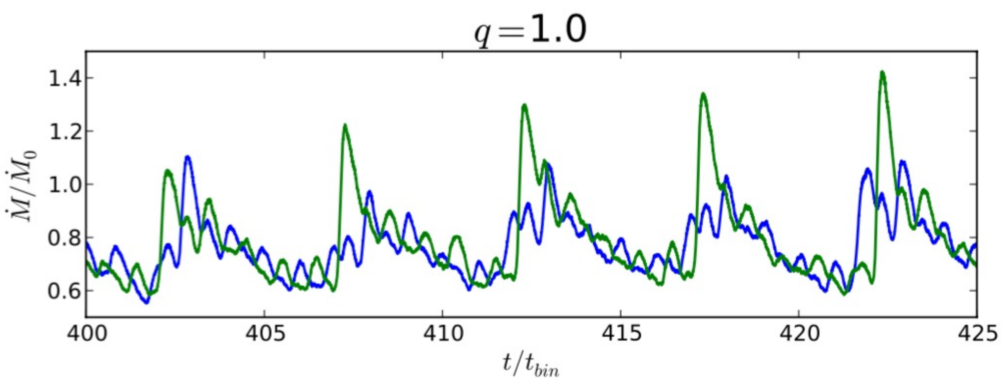
Table 1. Light curve best-fit model parameters and assumed priors.

Hu+2020

EM signatures – variability

- Binary-modulated accretion

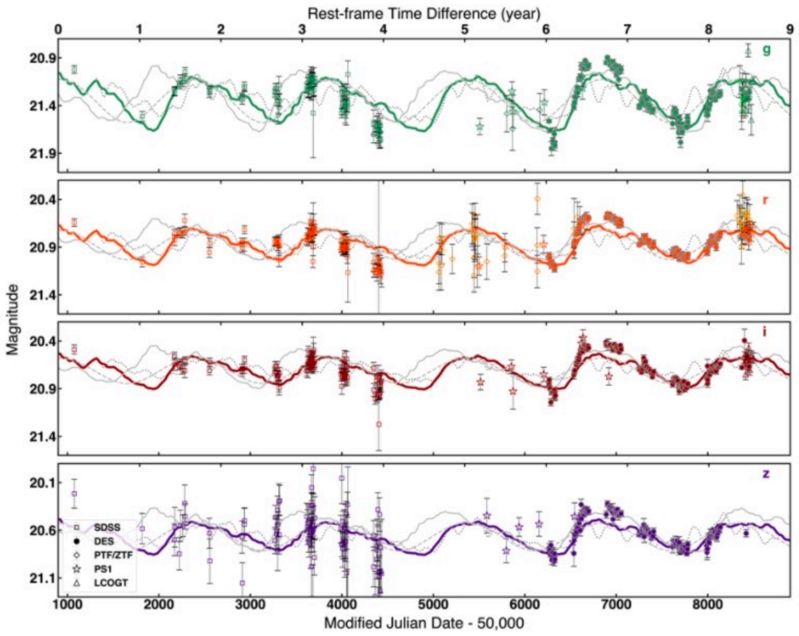
Theory

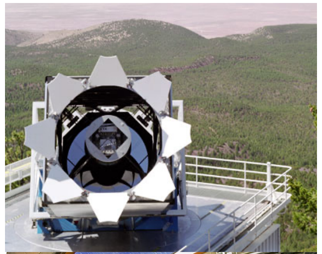


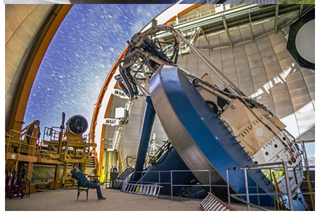
Farris+2014
(see also Duffell+2020)

Predicts: bursty, `sawtooth' light curve profile

Observations







Liao+2020 (DES+SDSS)

EM signatures – variability

- Binary-modulated accretion

Theory

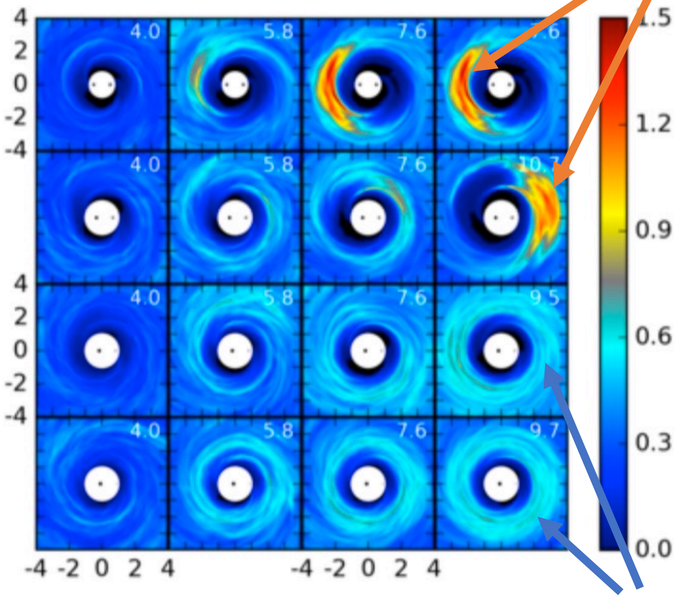
'lump'

q = 1

q =0.5

q = 0.2

q = 0.1

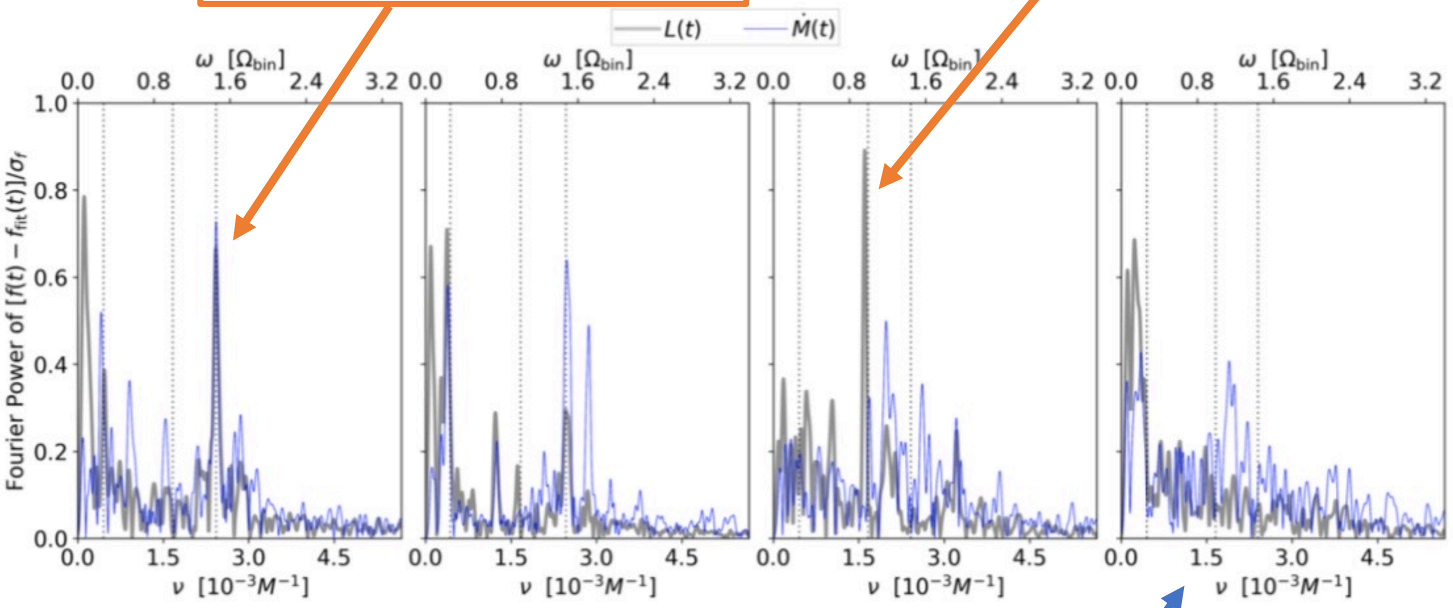


no lump

Noble+2021
(see also Farris+2014, D'Orazio+2013)

2x beat frequency between lump and binary

orbital frequency



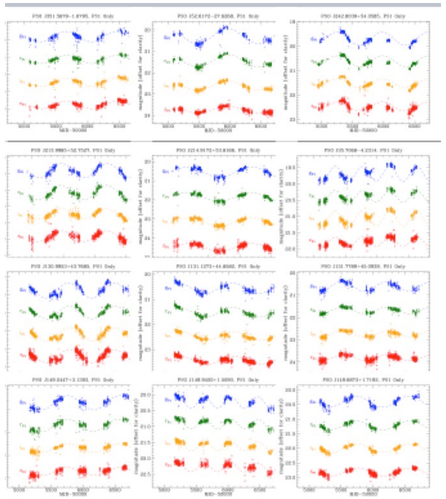
q = 1 0.5 0.2 0.1

no periodicity

EM signatures – variability

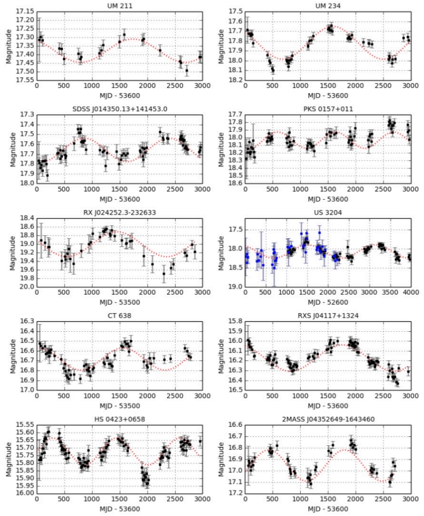
- Systematic searches for periodic AGN in time-domain surveys – hundreds of candidates

Pan-STARRS1
(T. Liu+2015, 2016, 2019)

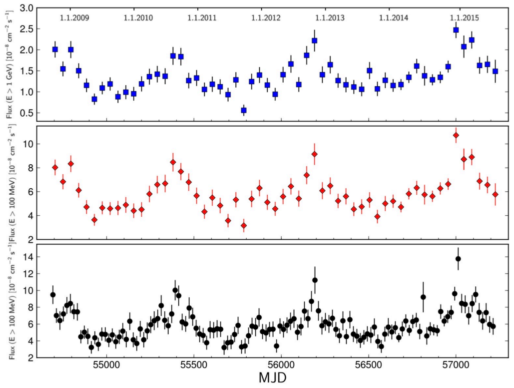


CRTS
(Graham+2015a,2015b)

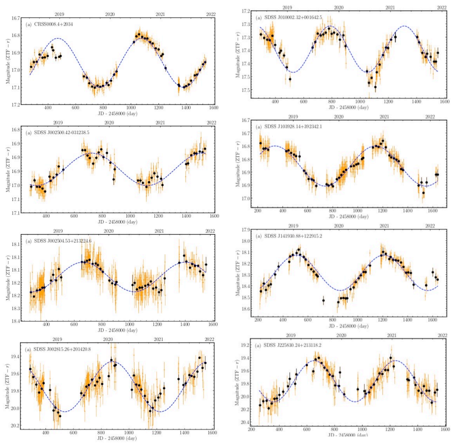
Also: PTF/iPTF (Charisi+2016),
DES+SDSS (Liao+2020,Chen+2020)



Fermi
(Ackermann+2015)

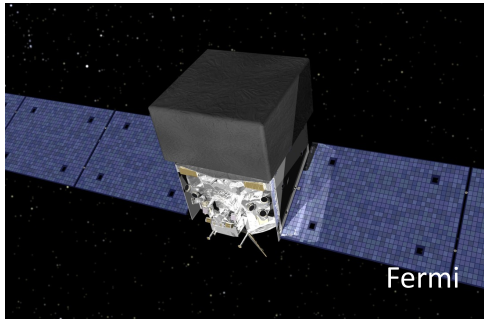


ZTF
(Chen+2022)



Rubin LSST
(~2025-2035)

?



EM signatures – variability

- Systematic searches for periodic AGN in time-domain surveys – hundreds of candidates
- Number estimates for LSST
  - Modulated accretion – N~40–600
  - Doppler boosting – N~6–50
  - Self-lensing – N~10–100

Pan-STARRS1 (T. Liu+2015, 2016, 2019)

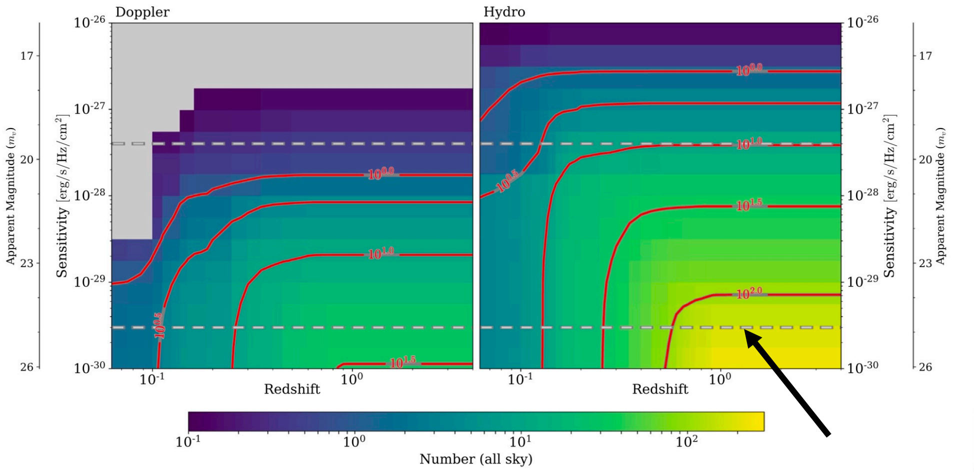
CRTS (Graham+2015a,2015b)

DES+SDSS (Liao+2020, Chen+2020)

Fermi (Ackermann+2015)

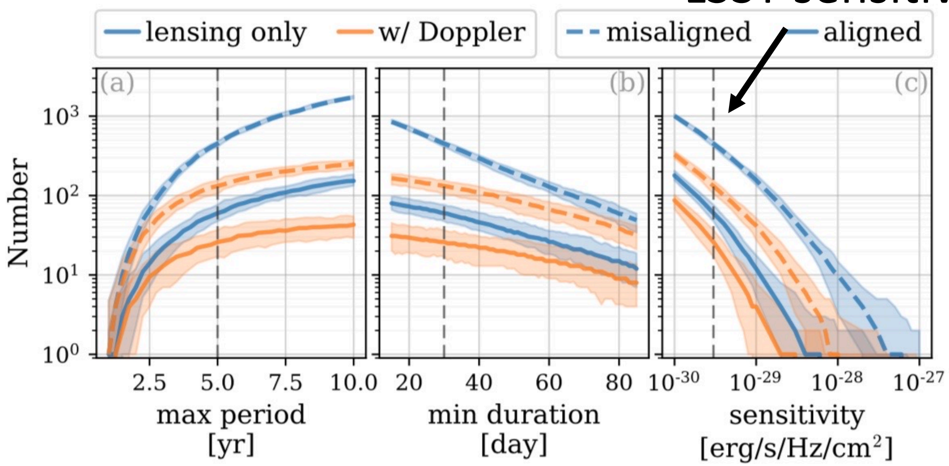
ZTF (Chen+2022)

Rubin LSST (~2025-2035)



Kelley+2019

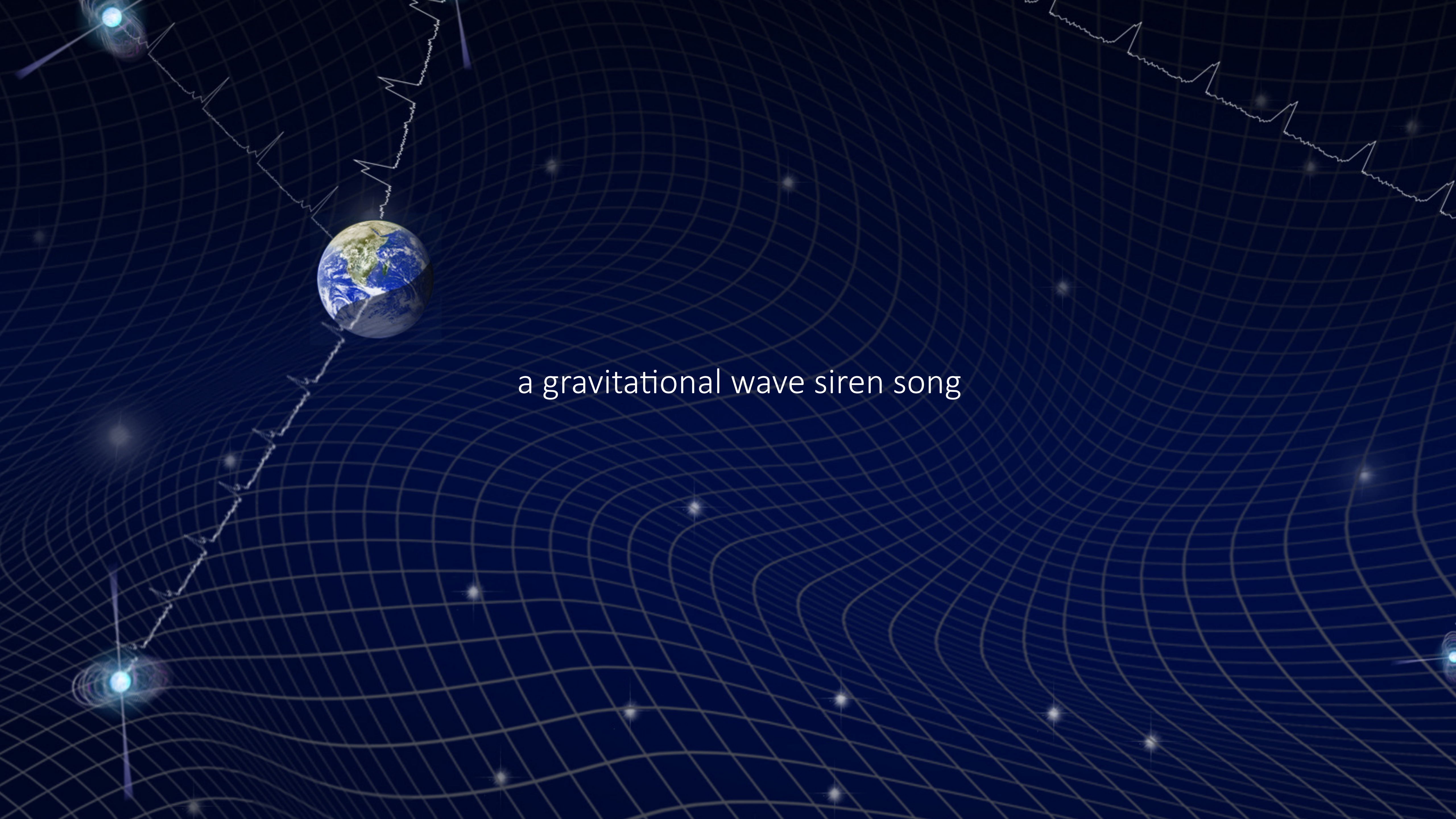
LSST sensitivity



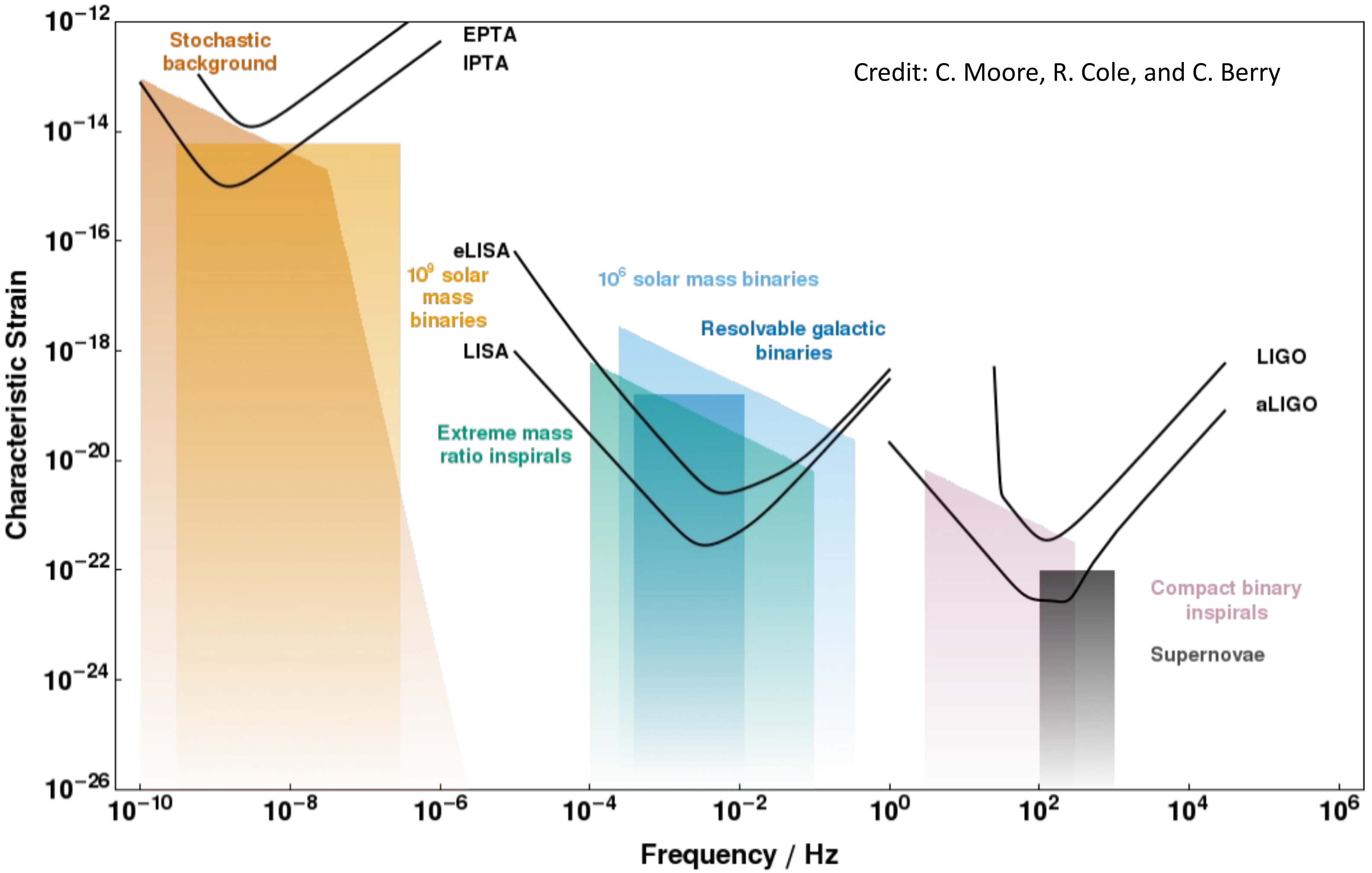
LSST sensitivity

Kelley+ 2021

?


a gravitational wave siren song

The GW chorus



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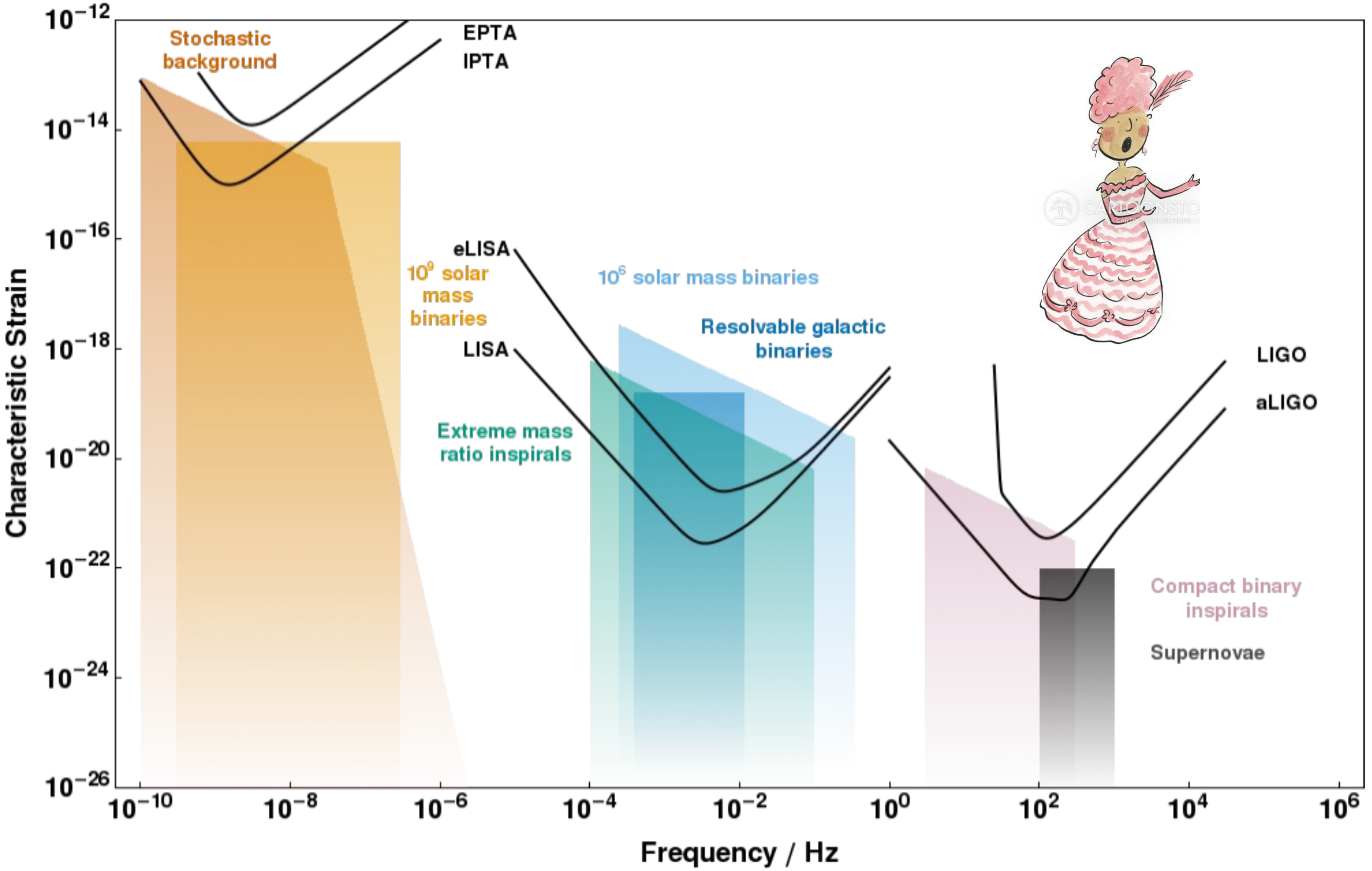
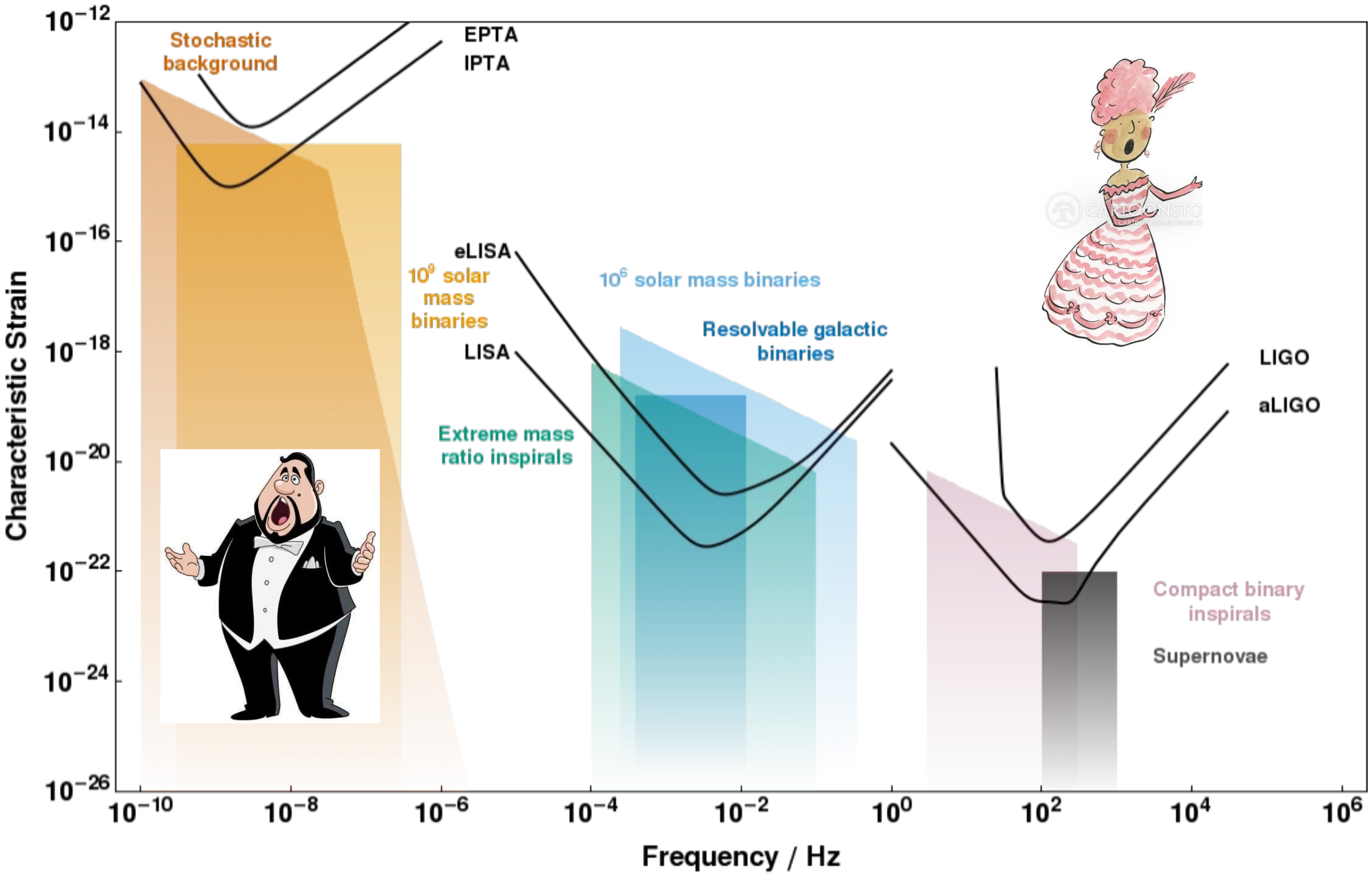
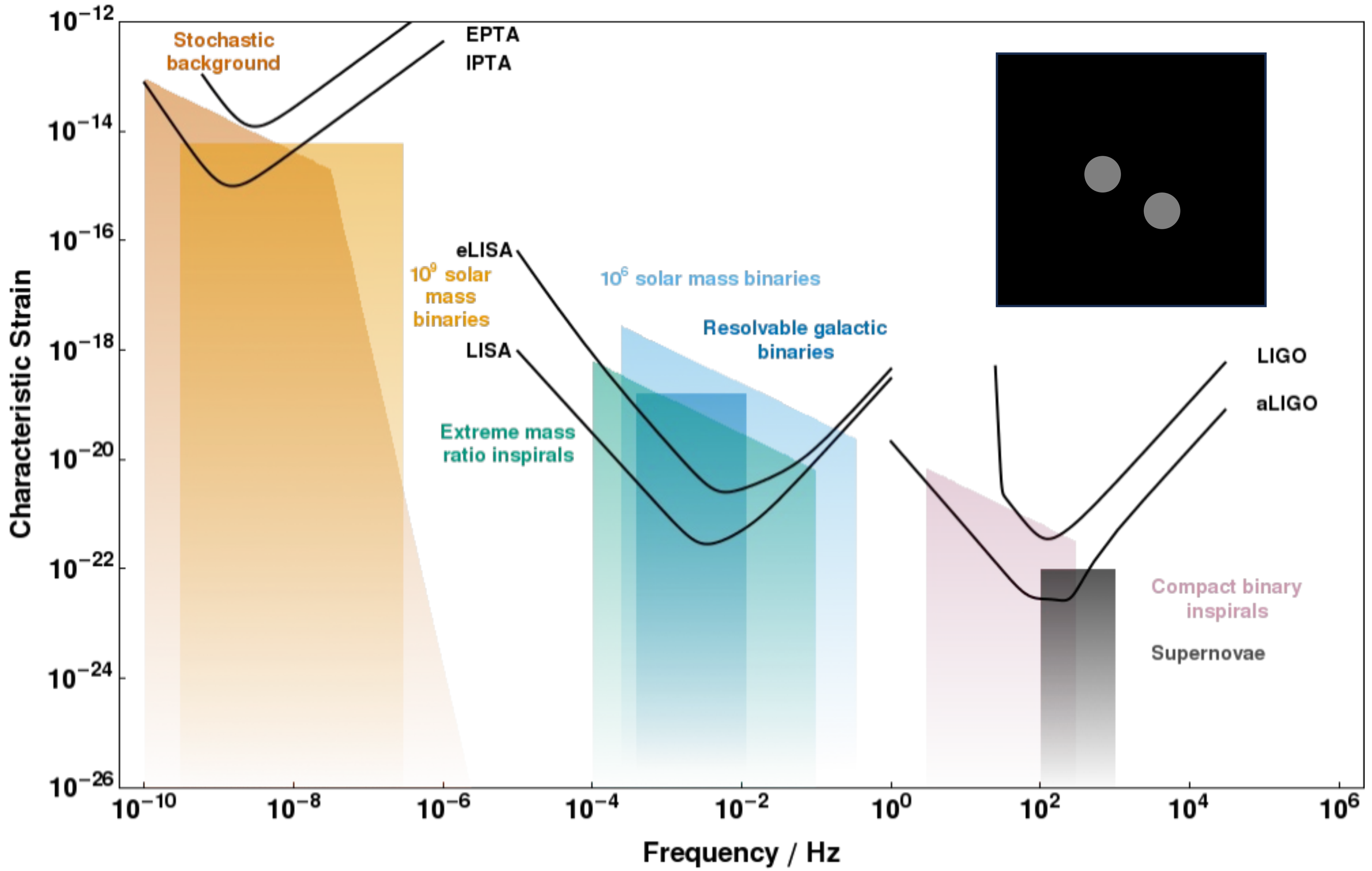


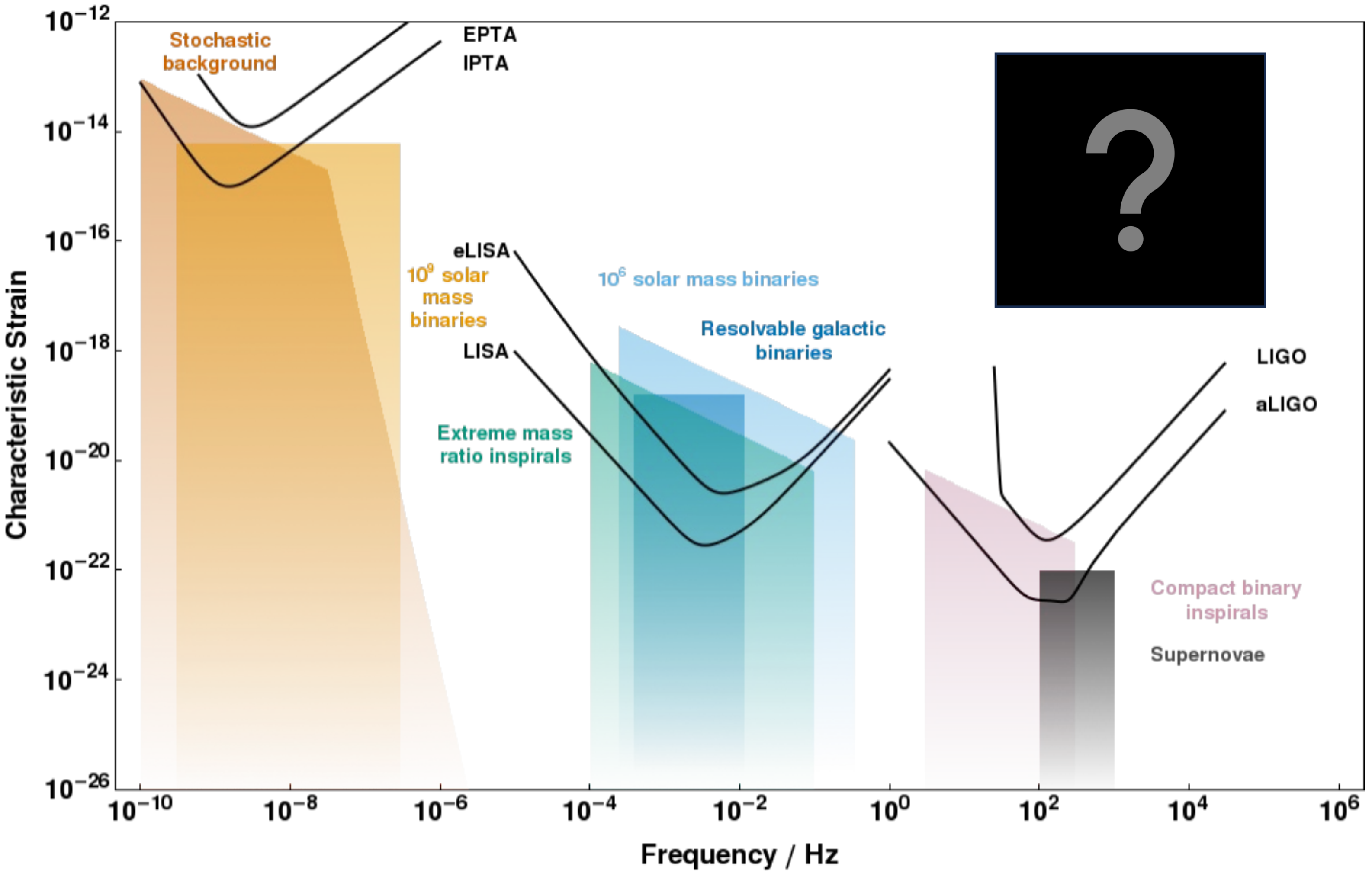
The GW chorus



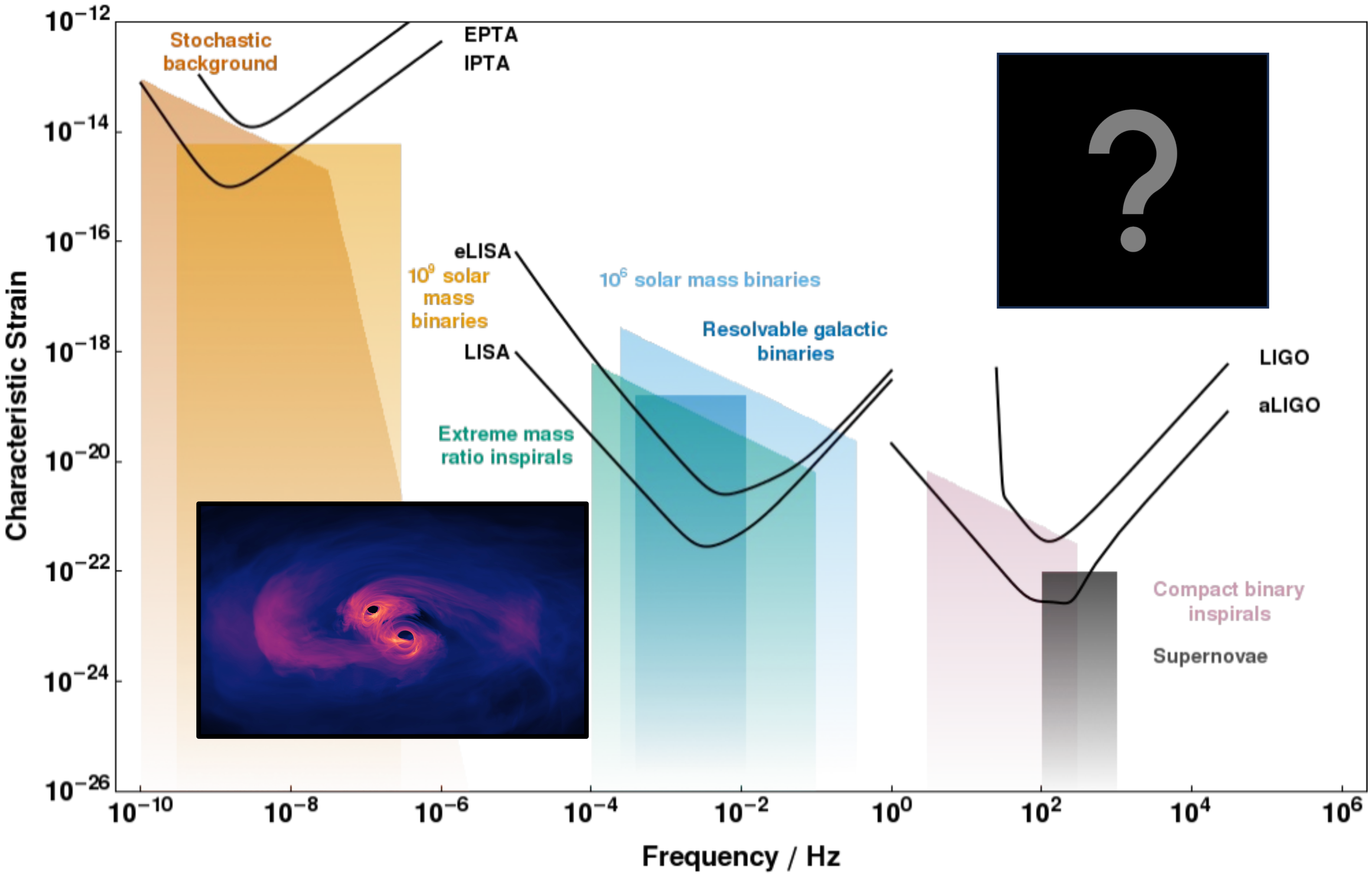
The GW chorus



The GW chorus



The GW chorus

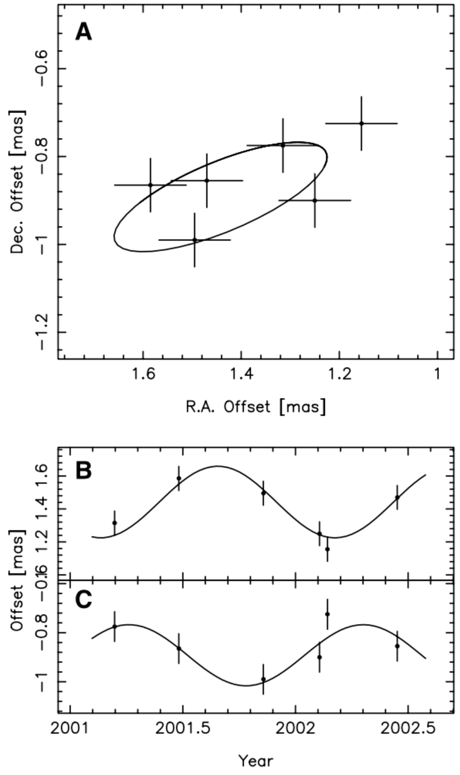


Multi-messenger SMBHB searches

- Targeted searches
  - Searching for GWs at the known sky location of the (EM-identified) source
  - Using known source parameters (e.g. mass, frequency) as priors
  - Combining GW and EM information

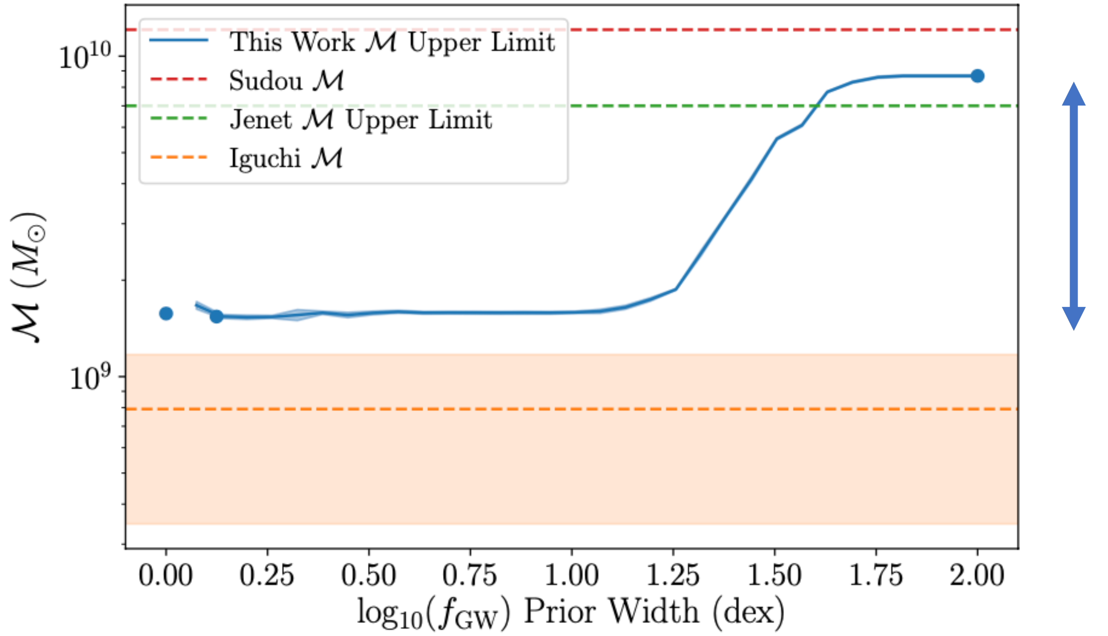
Multi-messenger SMBHB searches – upper limits

- Targeted searches increase PTA sensitivity by ~ an order of magnitude



Sudou et al 2003
(3C 66B)

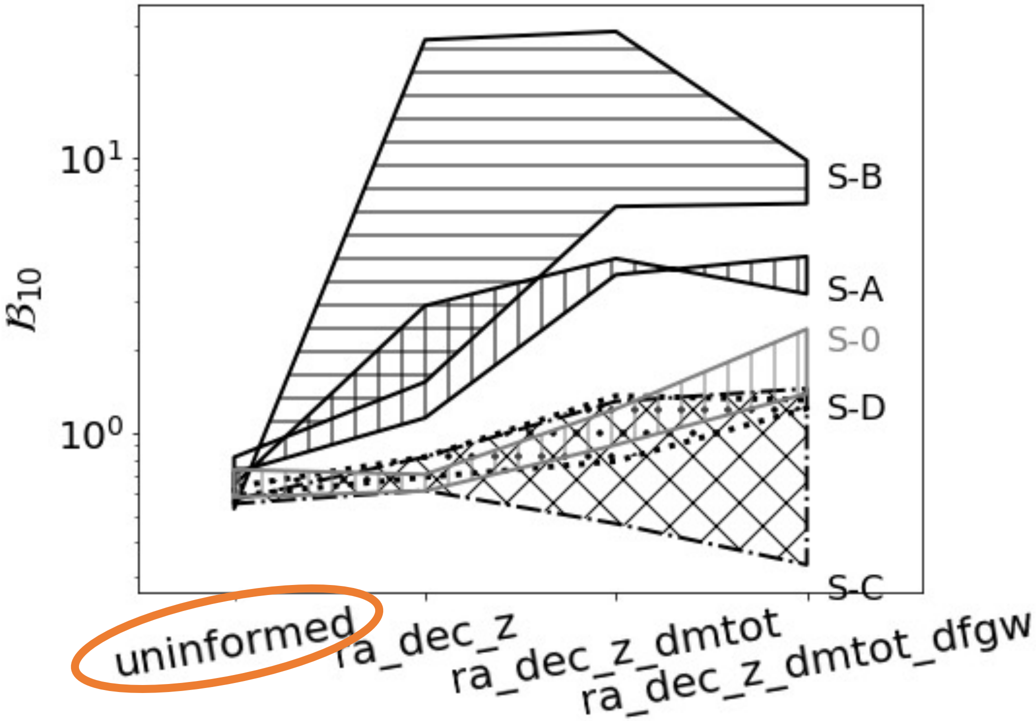
frequency

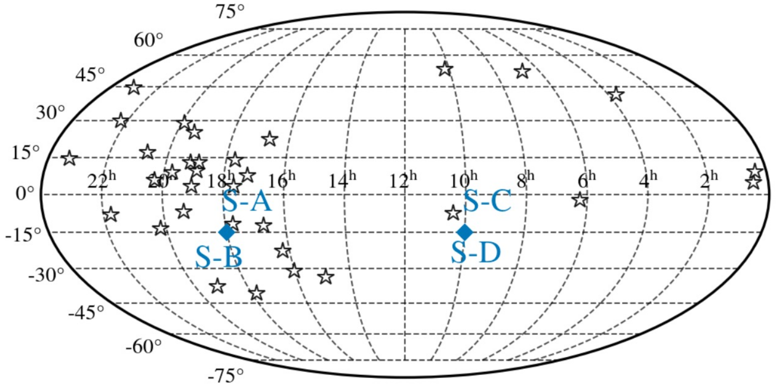


NANOGrav Collaboration 2020

Multi-messenger SMBHB searches – detection and parameter estimation

- Targeted searches increase source *detectability and parameter measurability* by ~ an order of magnitude





T. Liu & Vigeland 2021

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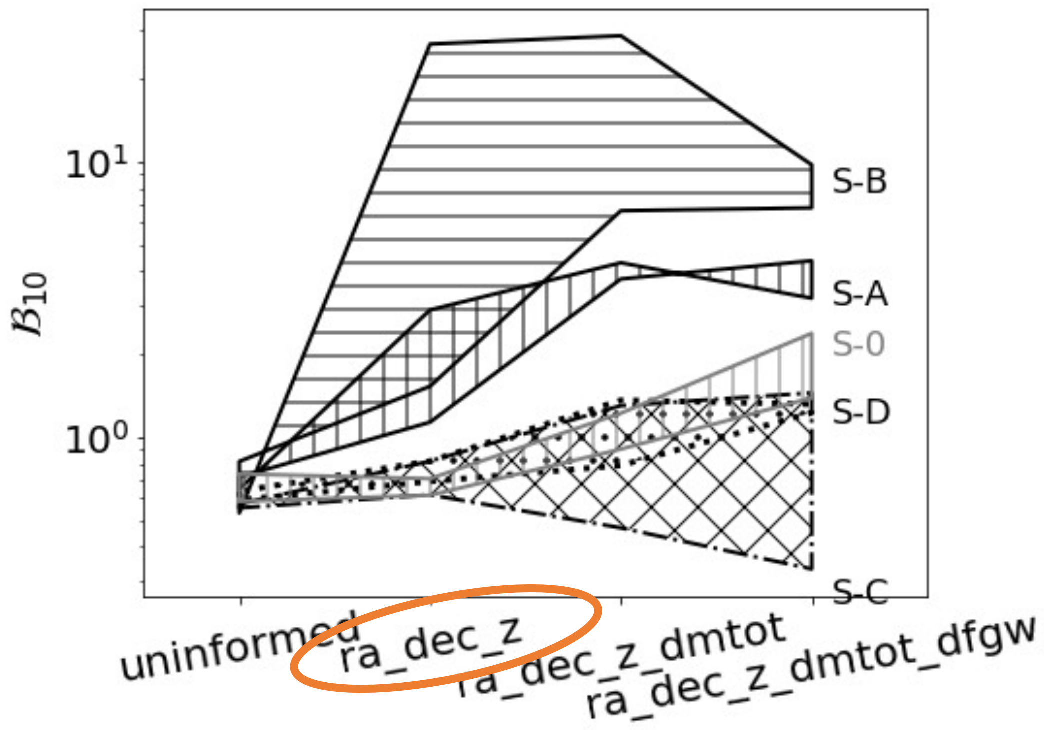

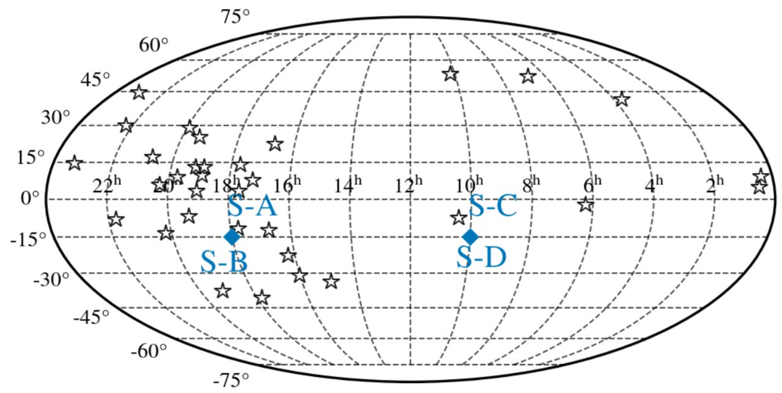

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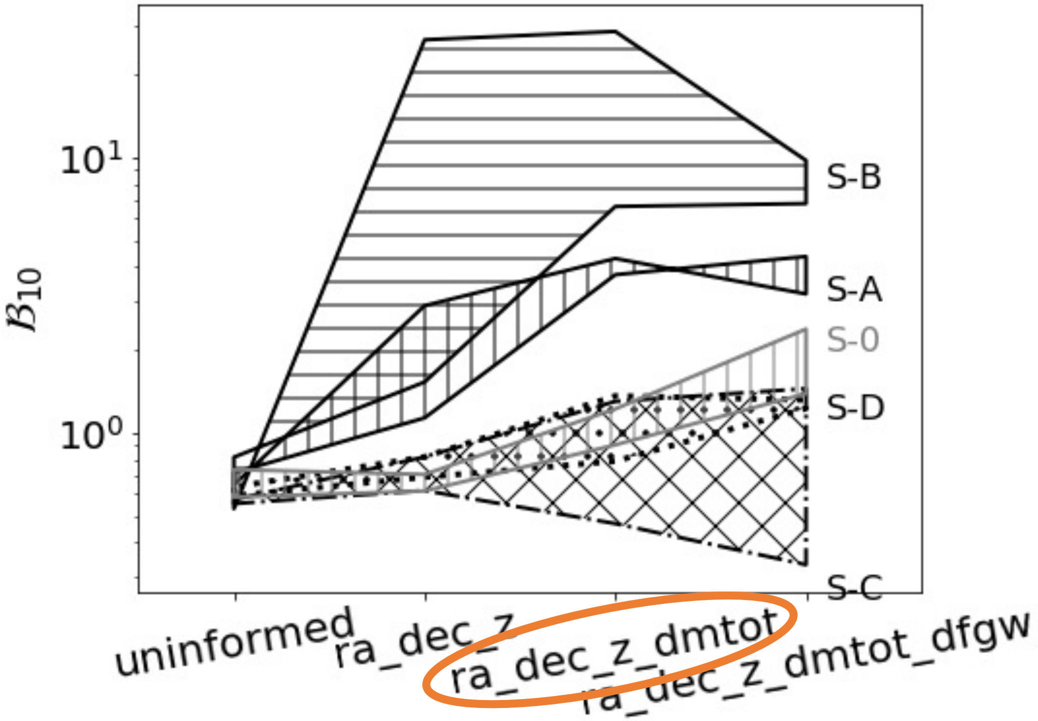

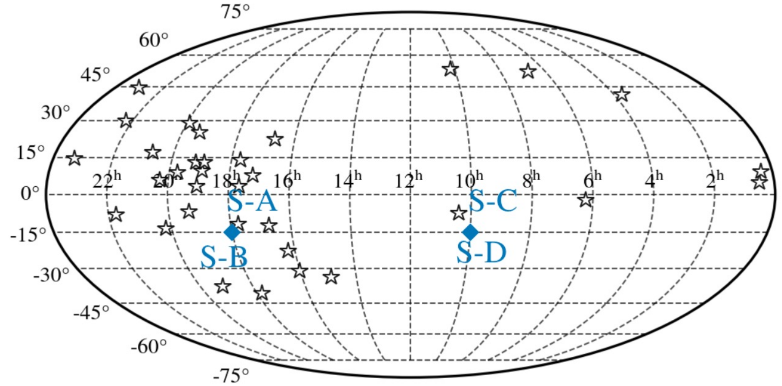

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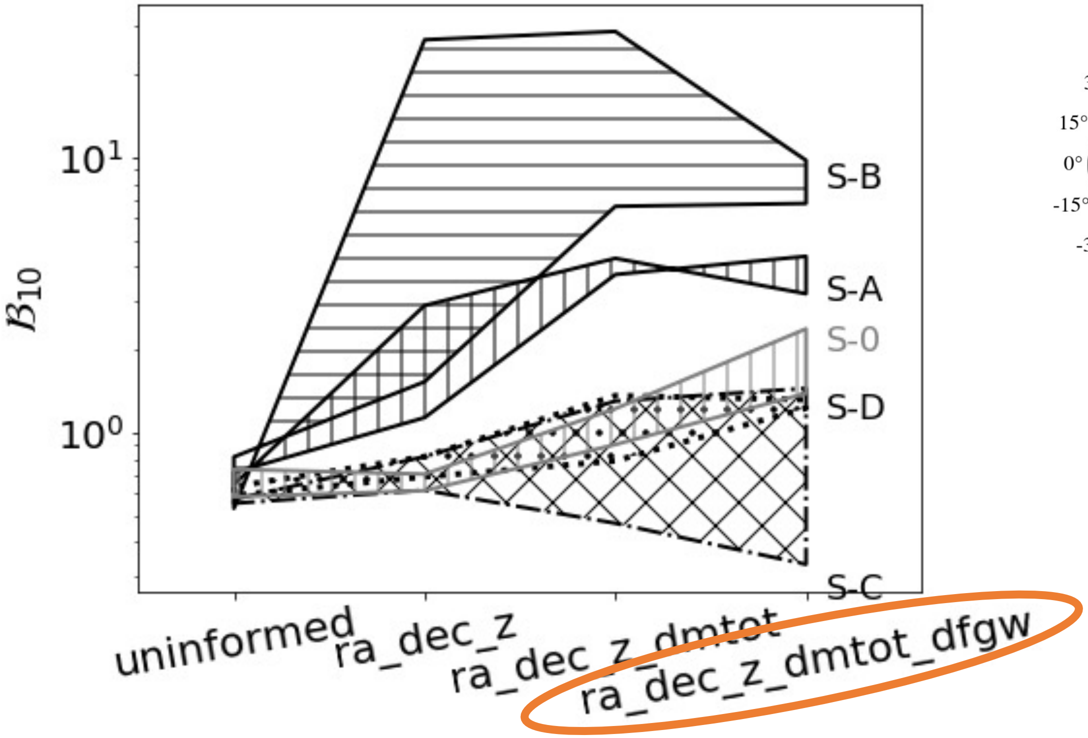

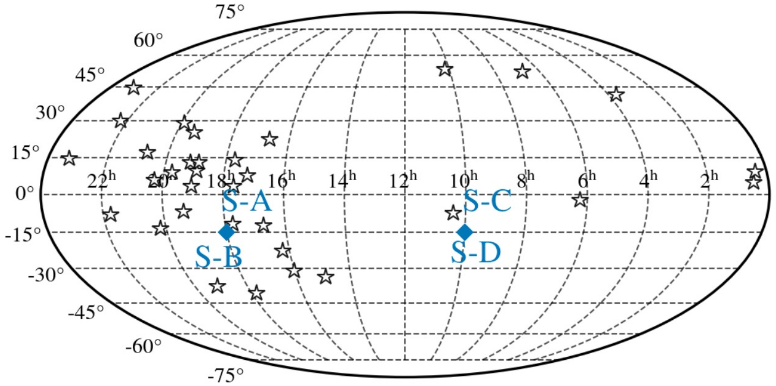

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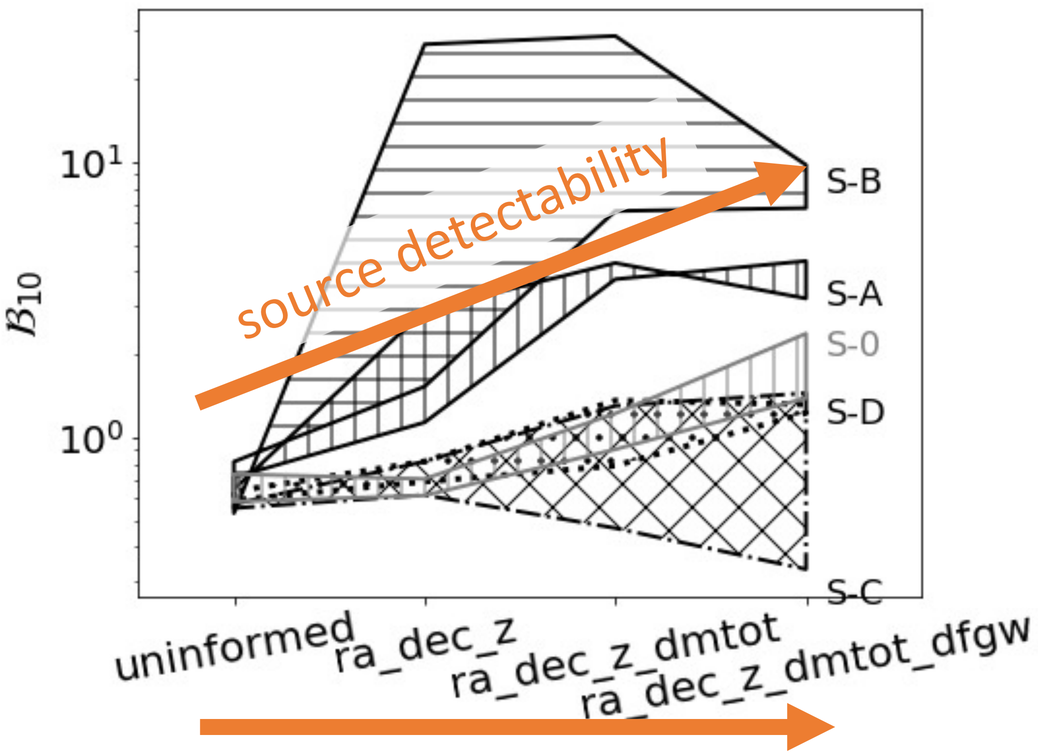
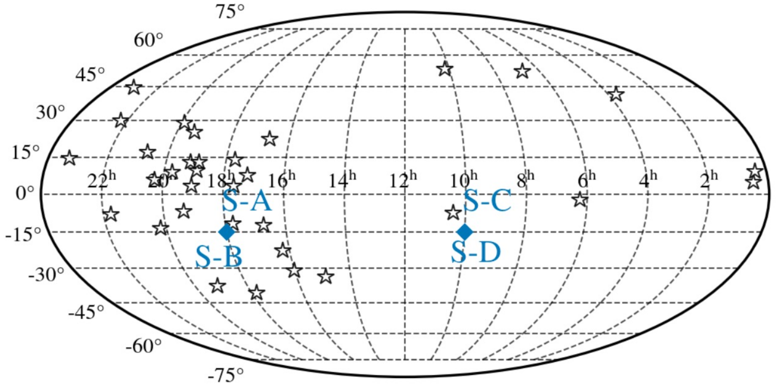


number of EM-measured binary parameters



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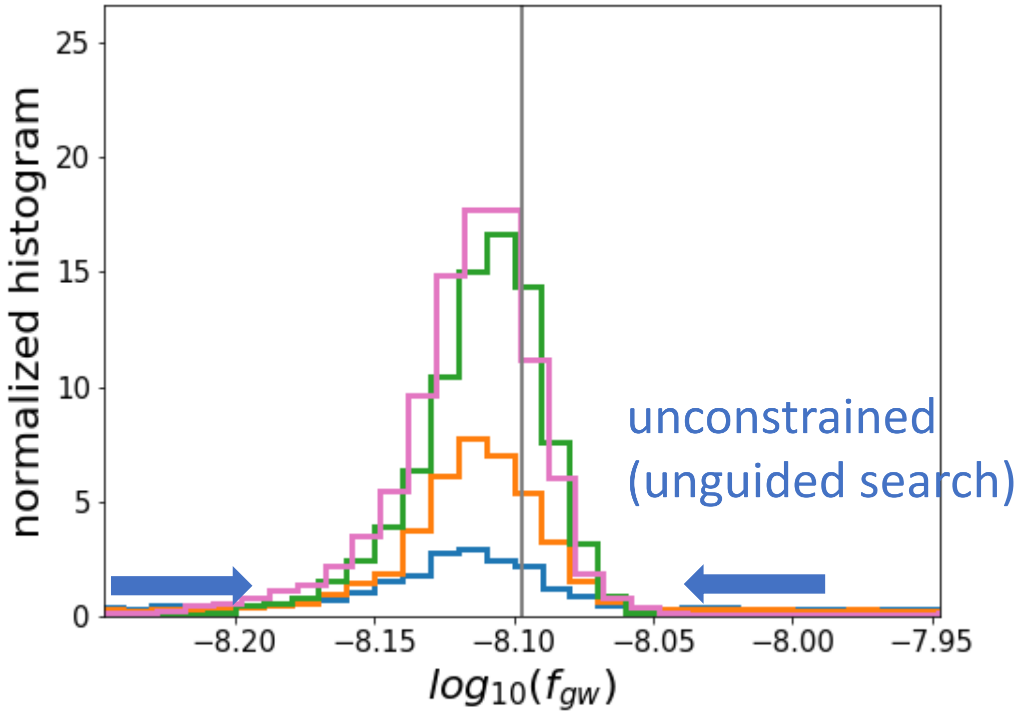

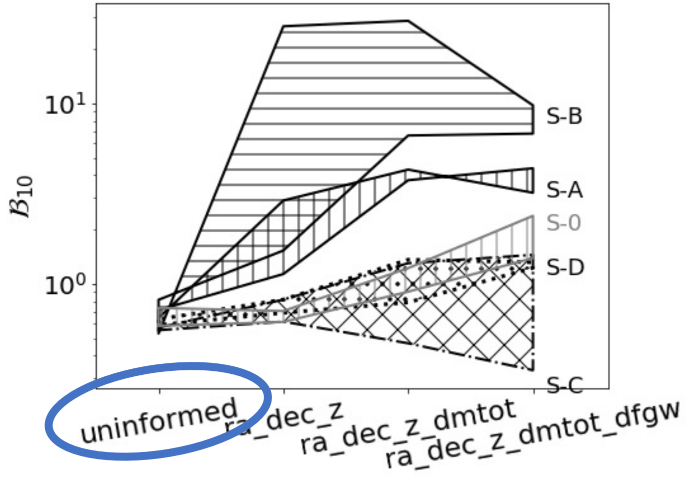

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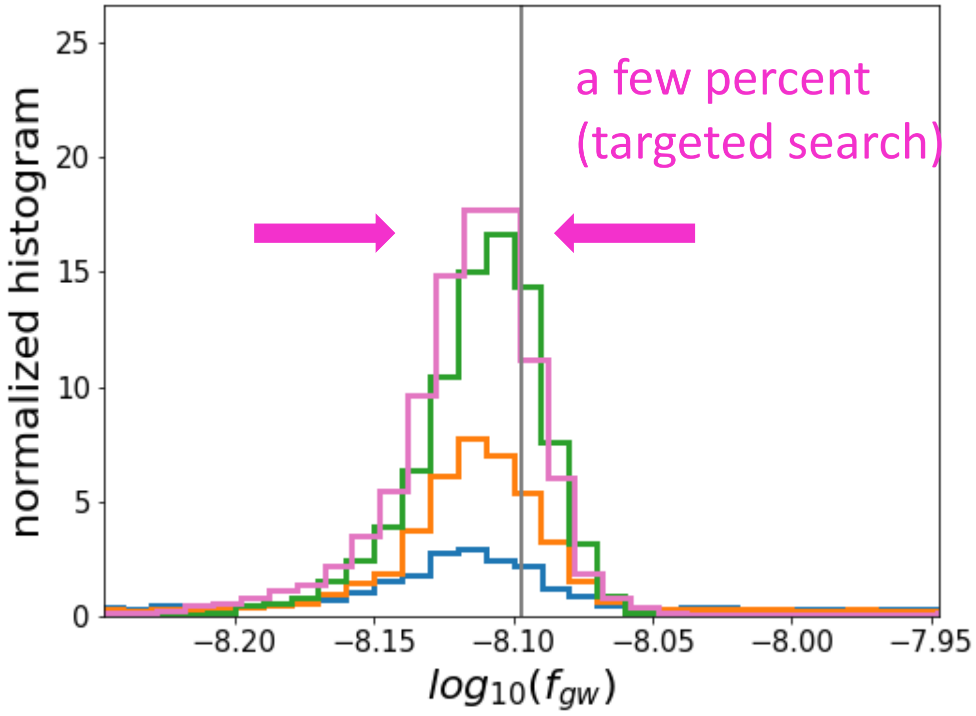

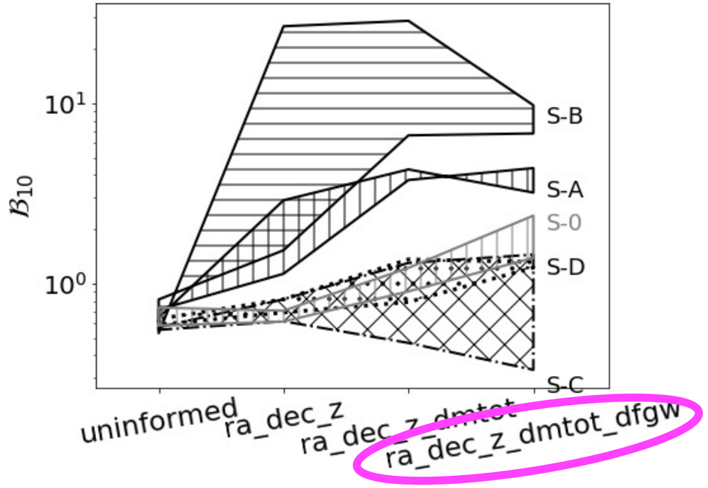

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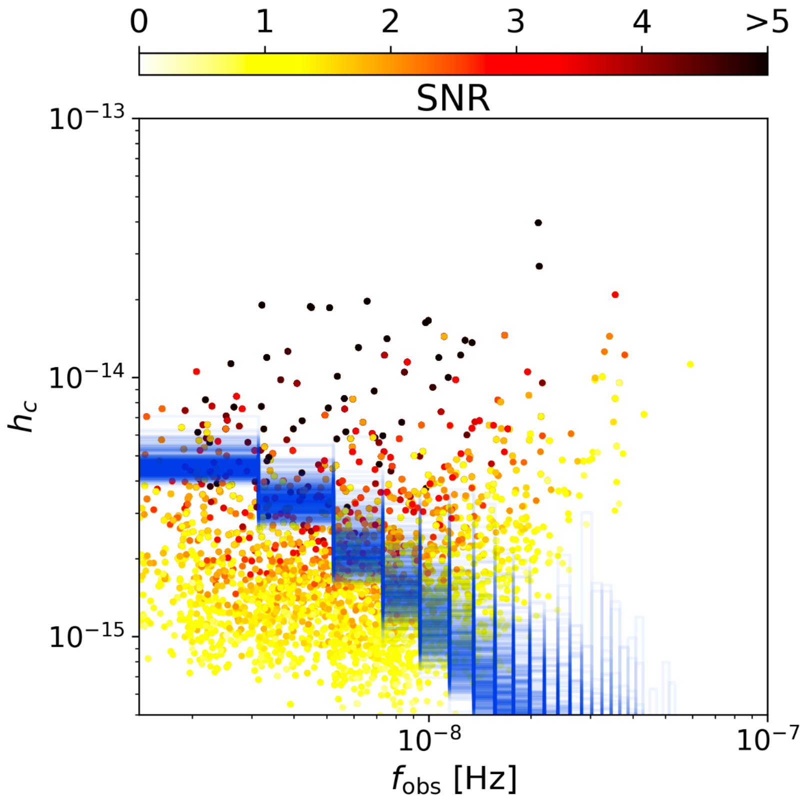
Multi-messenger SMBHB searches – future prospects

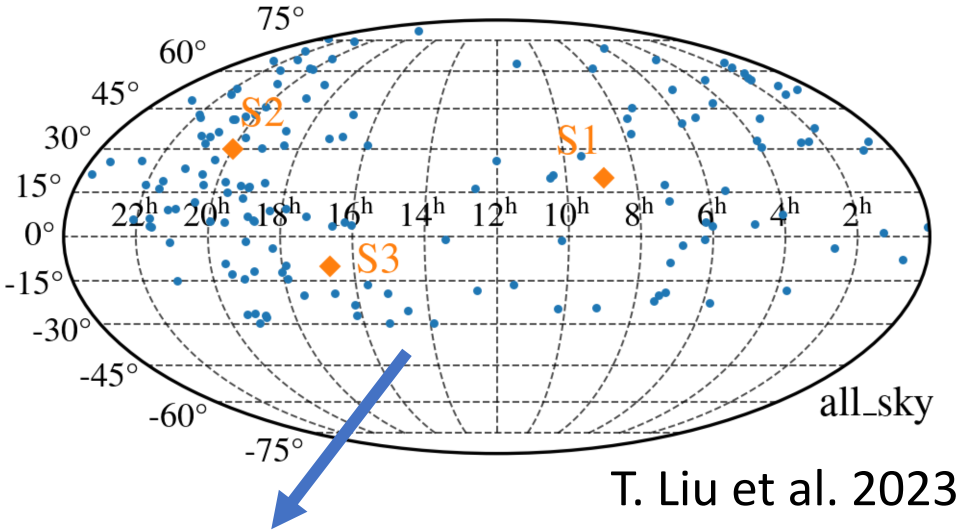
- Individual sources may be detectable within the next few years – decade



Becsy+2022 (see also Kelley+2018)

Multi-messenger SMBHB searches – future prospects

- Next-generation PTA experiment with the Deep Synoptic Array-2000 (~2026–) will significantly enhance single source detection prospects



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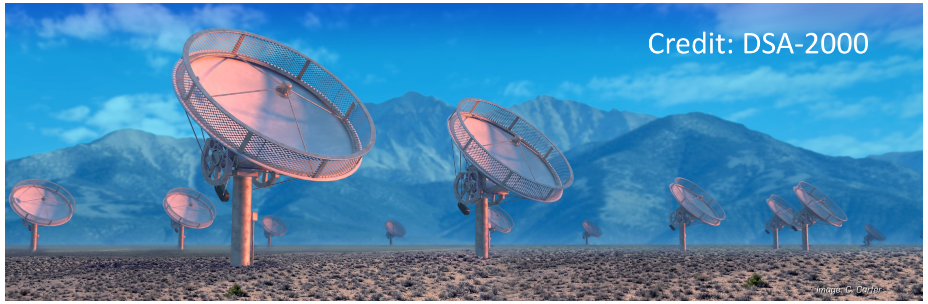
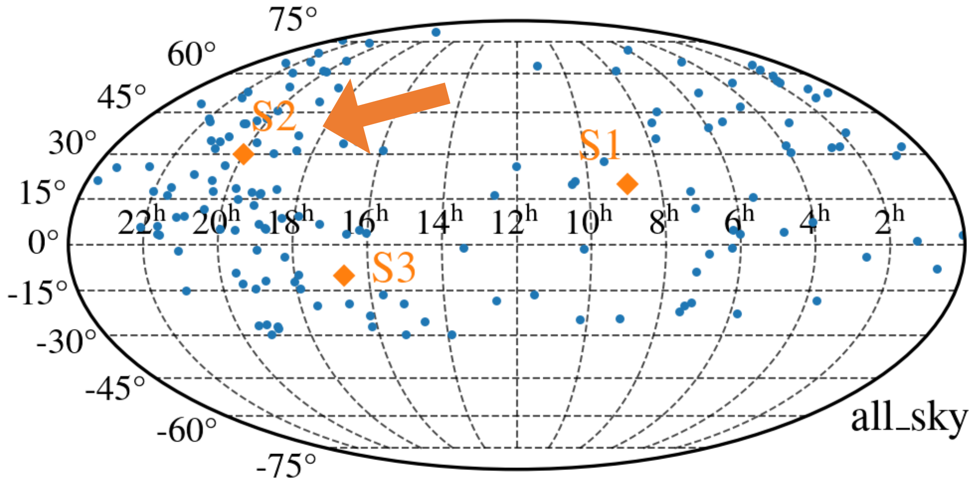
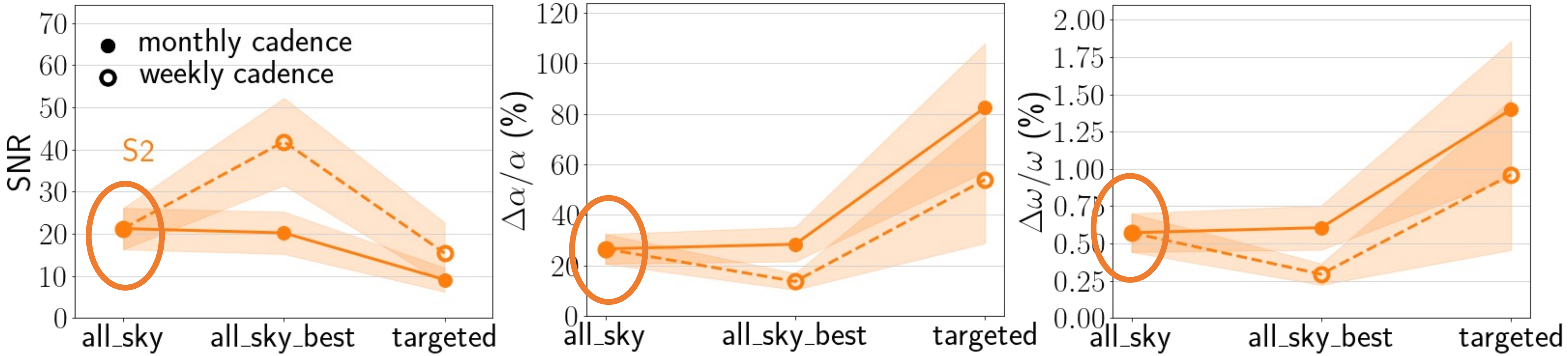


~150 millisecond pulsars (~2x NANOGrav) with
~400 ns timing noise (~1/2x NANOGrav)

Multi-messenger SMBHB searches – future prospects

- *Targeted* observations of an intermediate-SNR source
  - Measurement uncertainty of GW amplitude~20%
    - EM: ~100%
  - GW frequency: ~0.5%
    - EM: a factor of a few – no constraints





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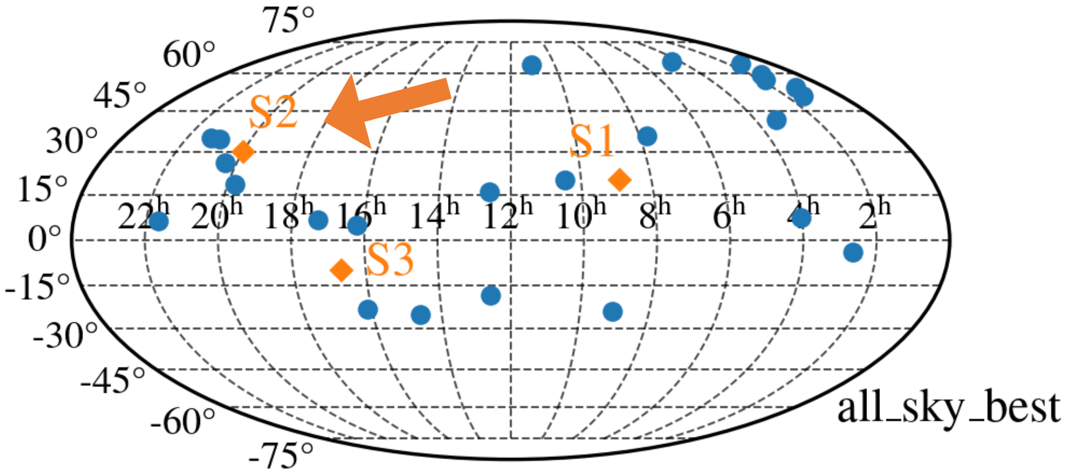

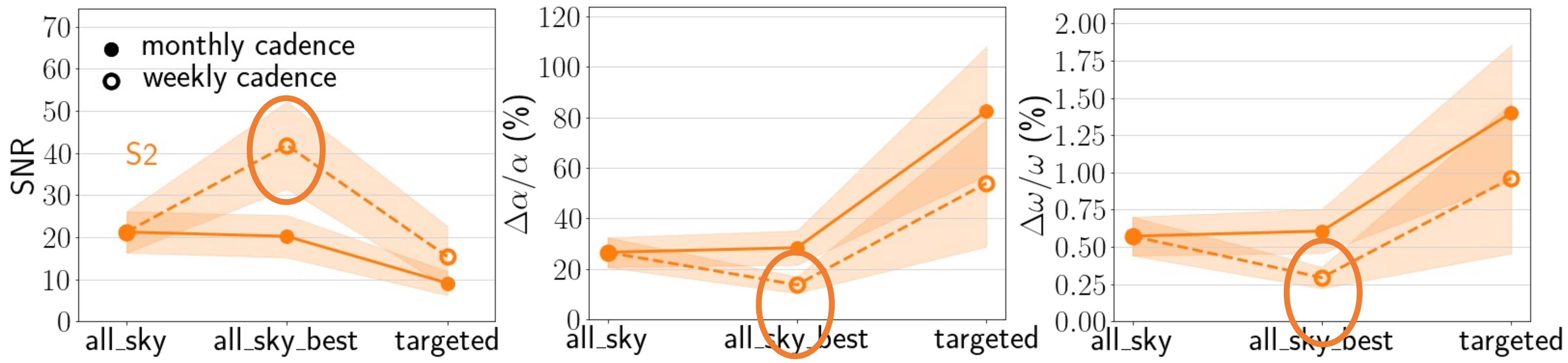

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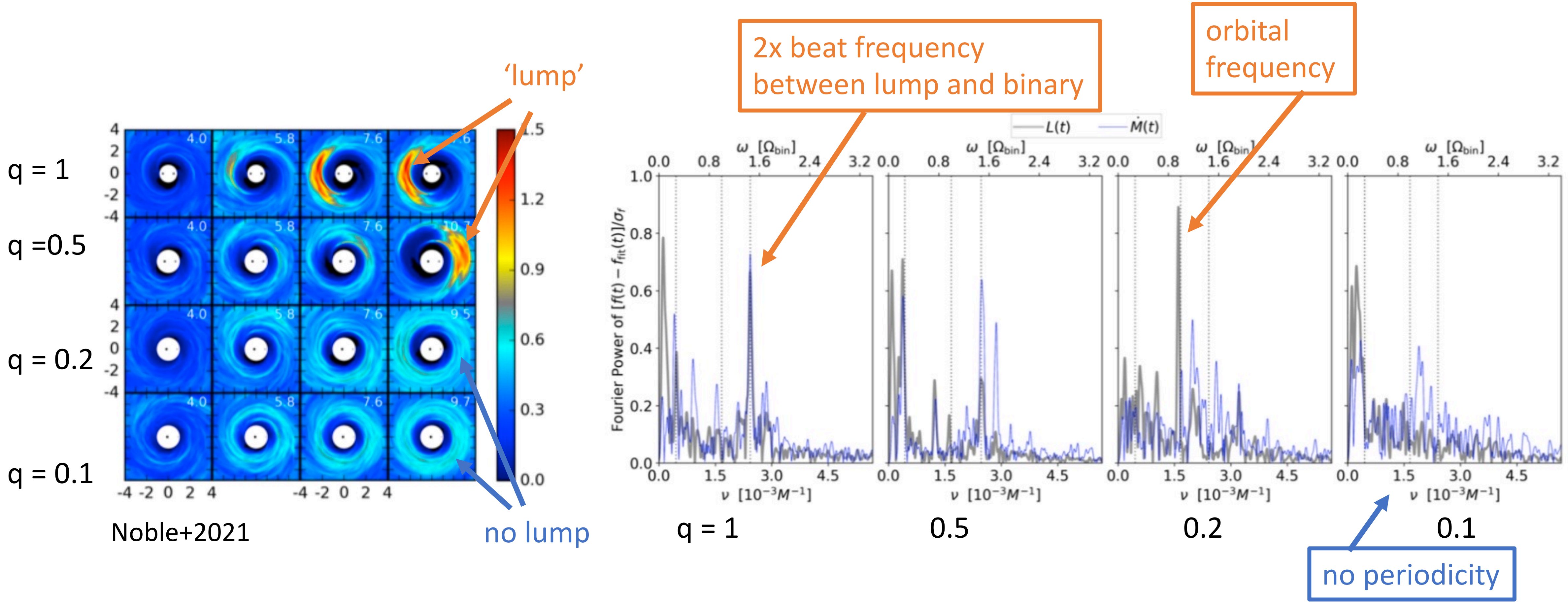
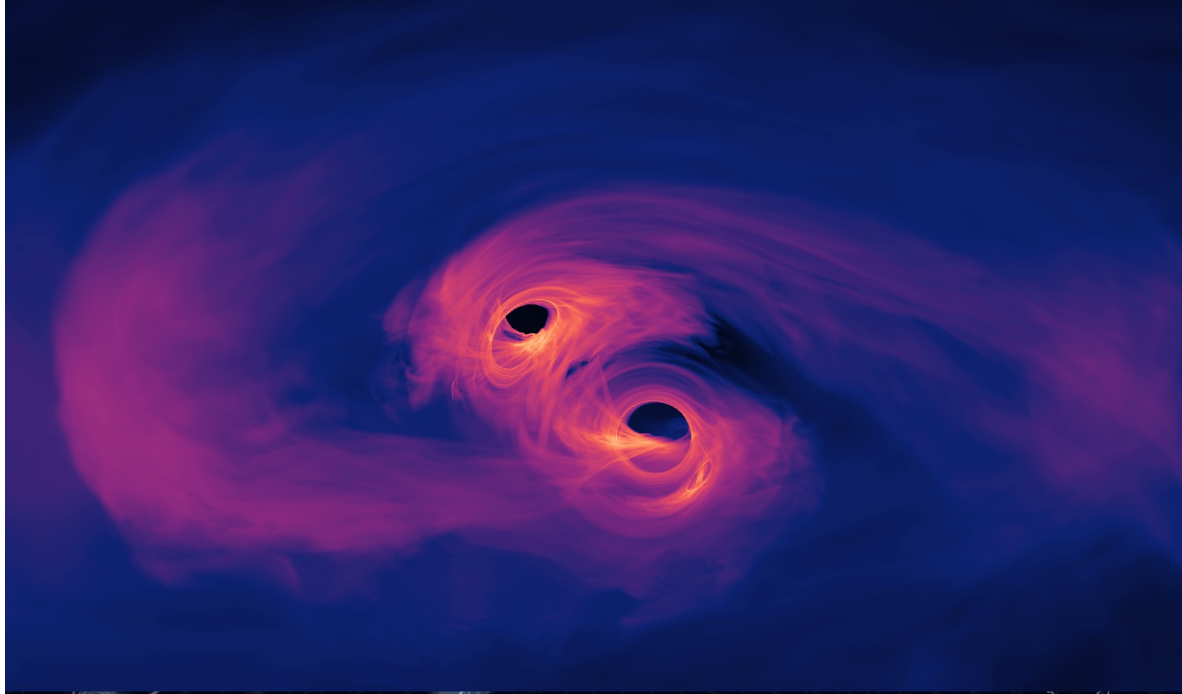
Understanding binary accretion with multi-messenger observations

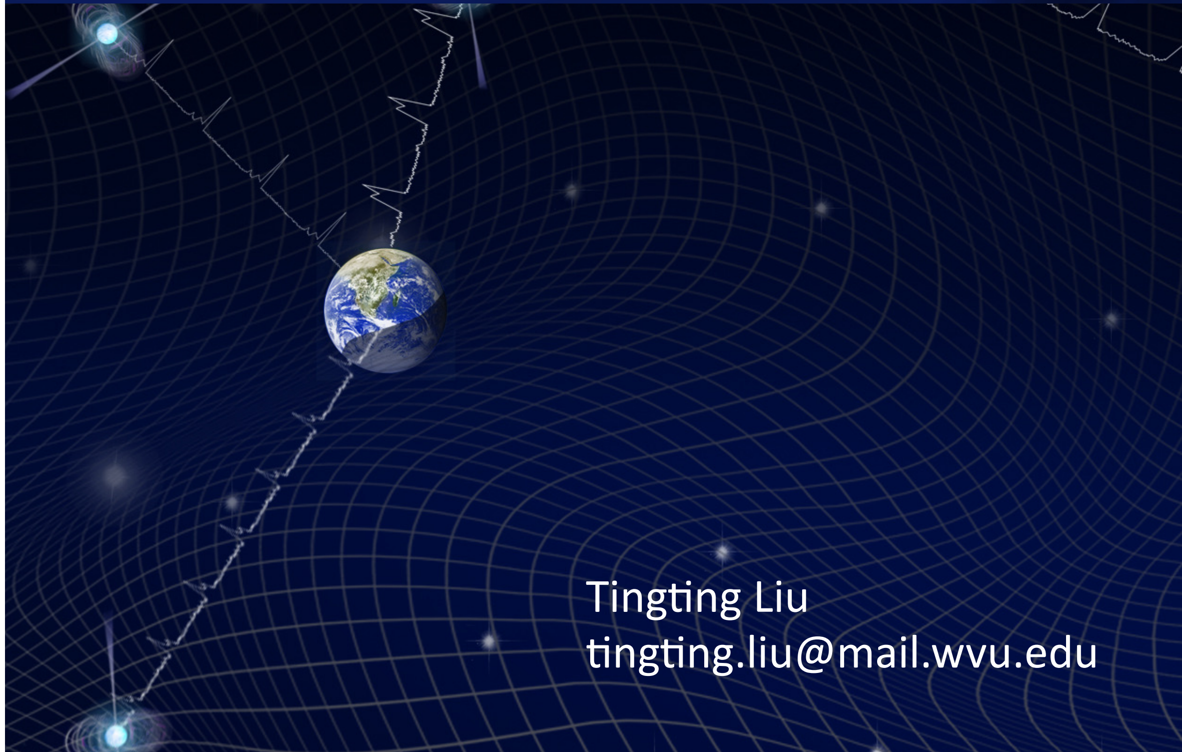
- Accretion onto binary is periodically modulated by binary orbit
  - -> Observable AGN periodicity at ~binary orbital frequency
- Dependence of accretion pattern on mass ratio
  - -> Need GW info to break degeneracy (and test predictions)



Takeaways

- SMBHBs (binary AGN) are variable, multi-wavelength, and multi-messenger objects
- The science of SMBHBs is rich
  - The role of mergers in SMBH growth
  - Laboratories for accretion physics in dynamic spacetimes
  - EM counterparts to low-frequency GW sources
- 2020s/2030s will be the golden age for studying SMBHBs
  - Rubin LSST
  - DSA-2000
  - Joint EM-GW observations





Tingting Liu
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