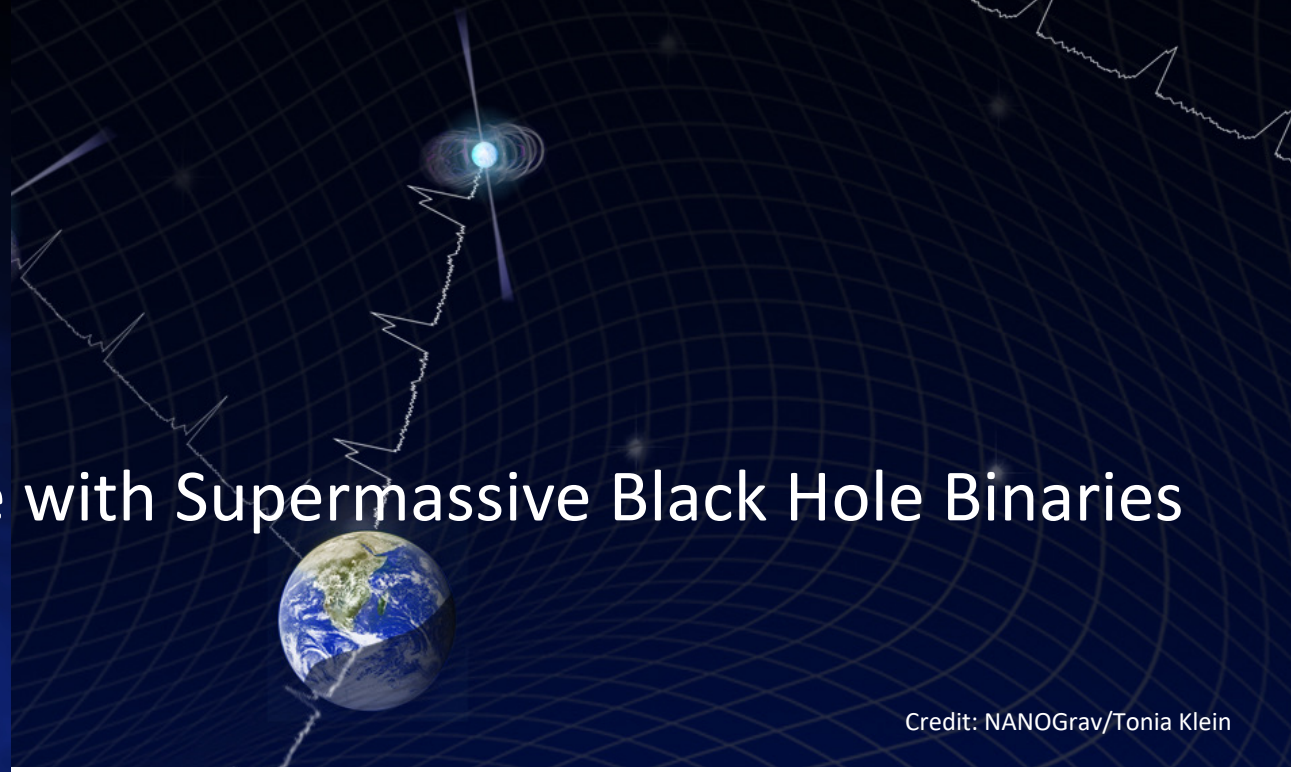
AAS 243 – New Orleans

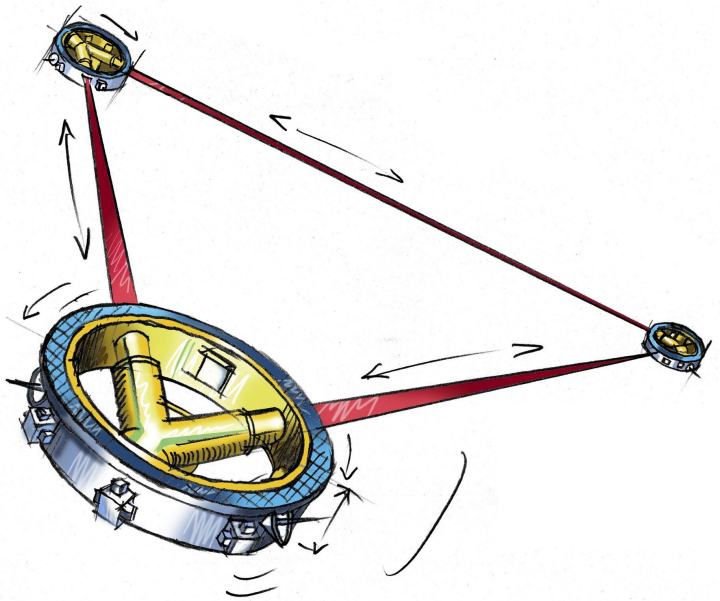
Prospects for Multi-messenger Science with Supermassive Black Hole Binaries and Implications for PTAs and LISA

Tingting Liu
West Virginia University

Credit: NASA GSFC/Scott Noble



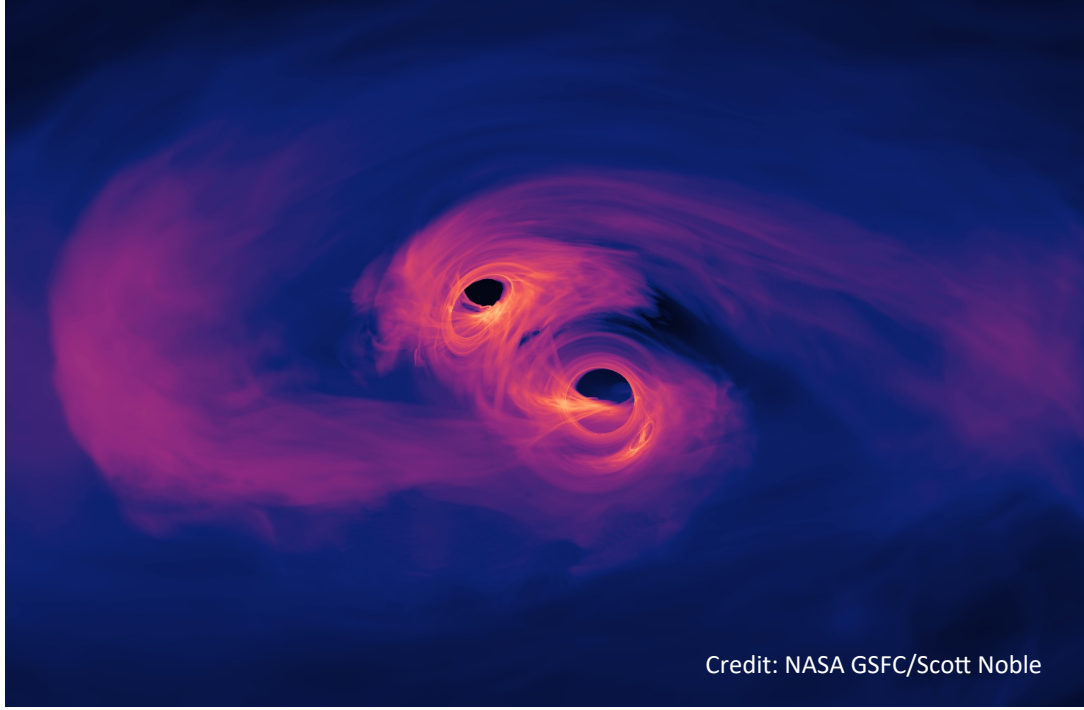
Credit: NANOGrav/Tonia Klein



Credit: ESA

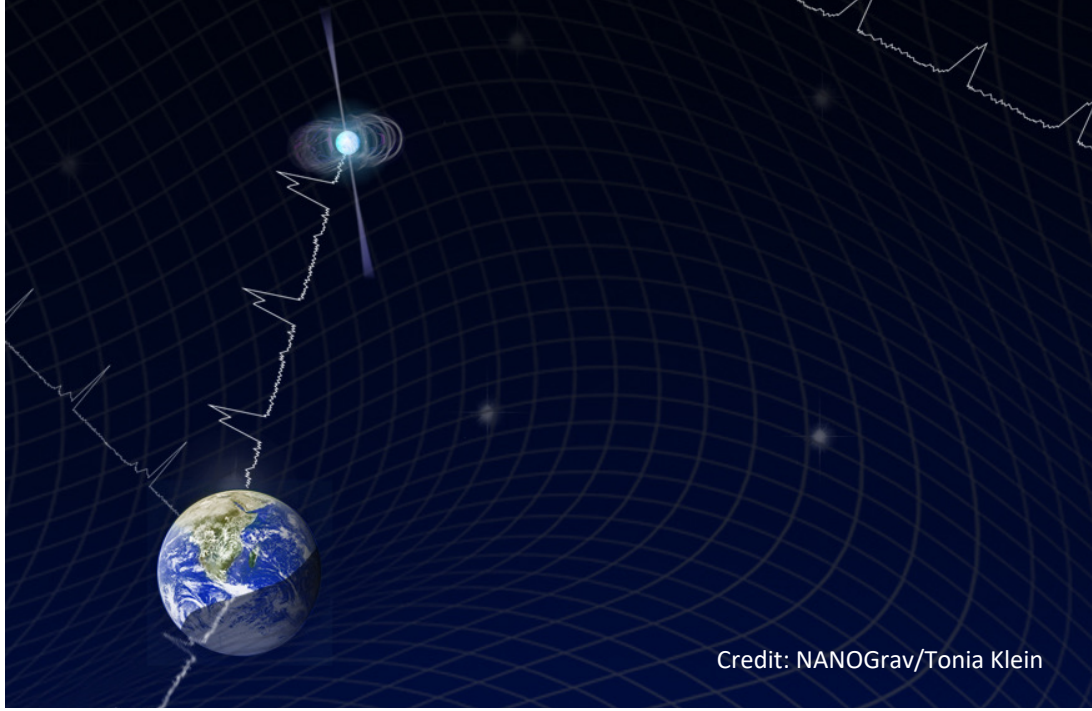
Outline

- Electromagnetic signatures of SMBHBs
  - Theory and observations



Outline

- Electromagnetic signatures of SMBHBs
  - Theory and observations
- Multi-messenger observations
  - Pulsar timing arrays (PTAs) and LISA



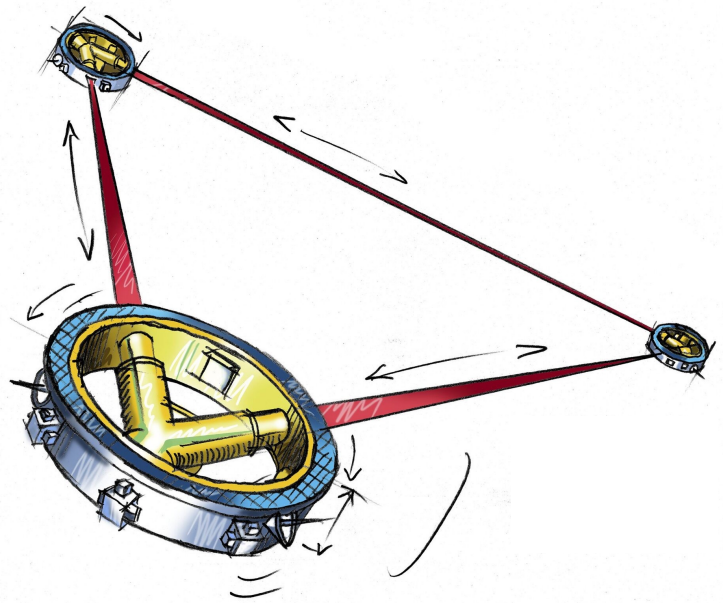
GWs at AAS 243

Steve Taylor – The Dawn of Gravitational-wave Astronomy at Light-year Wavelengths

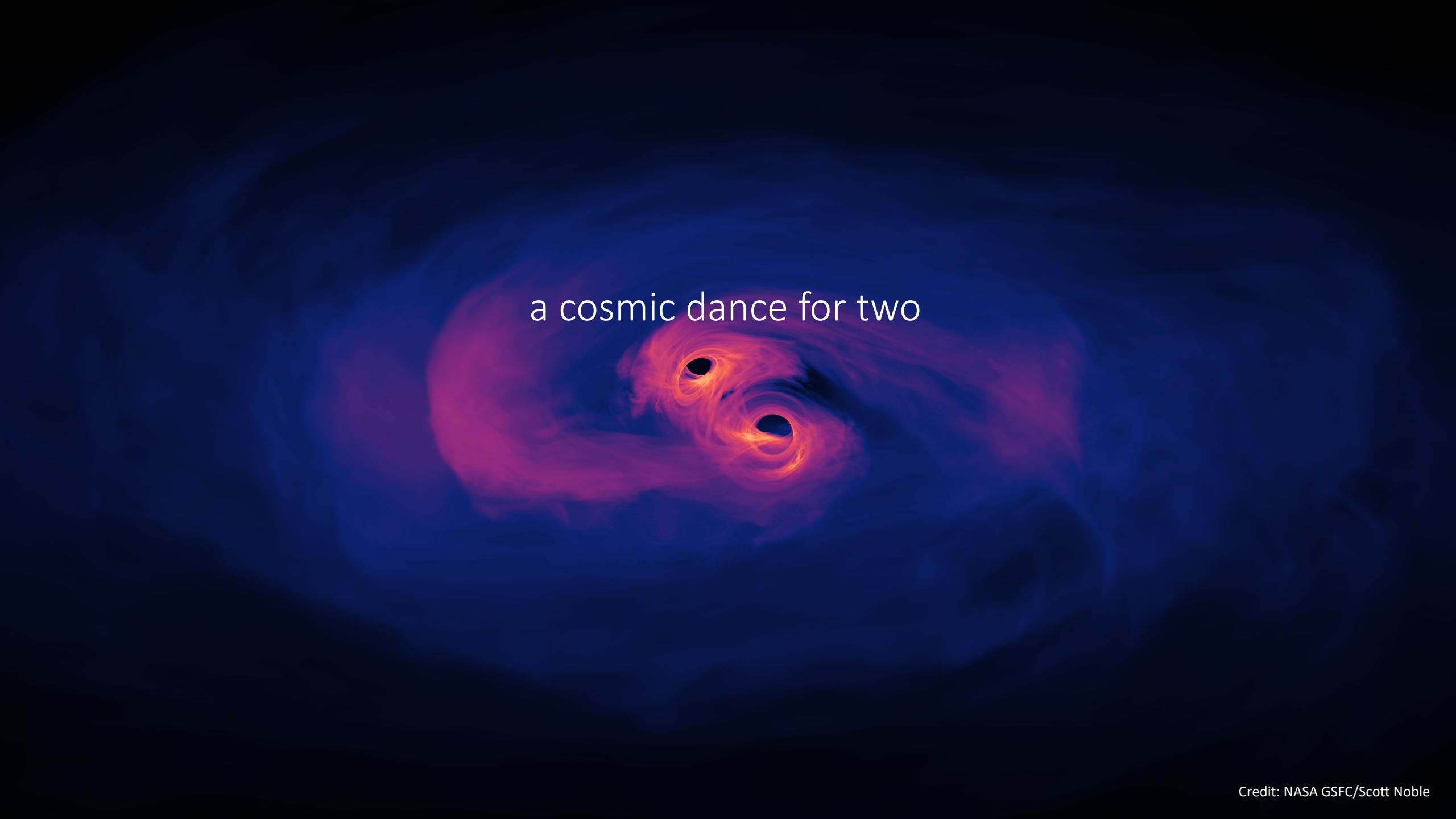
Special Session “NANOGrav: The Dawn of Galaxy-scale Gravitational-wave Astronomy”

Oral Session “Supermassive Black Hole Binaries and Pulsar Timing Arrays”

And many more

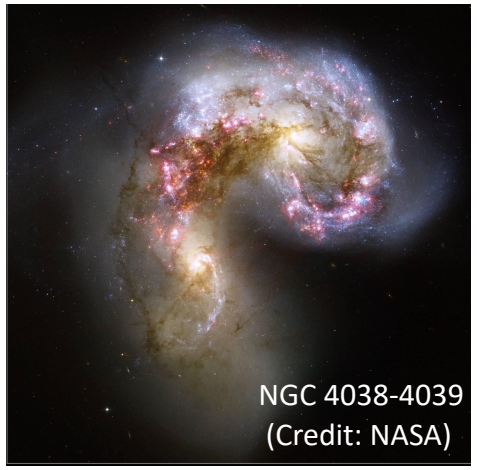


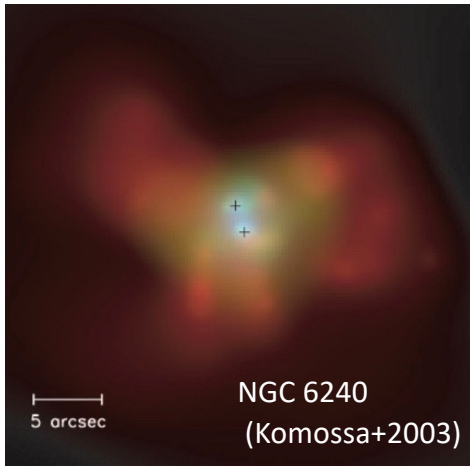
Credit: ESA

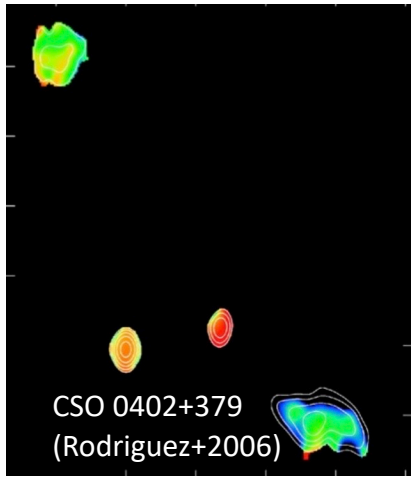


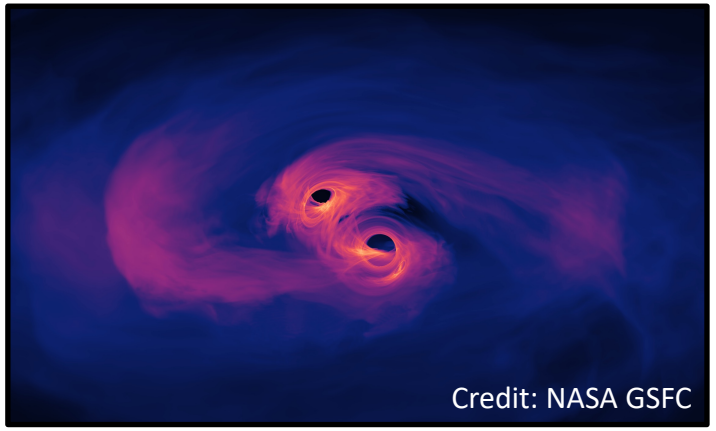
Credit: NASA GSFC/Scott Noble

A cosmic dance for two (supermassive black holes)



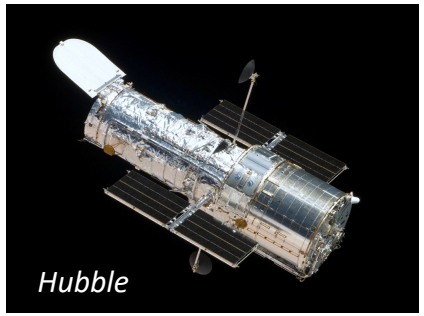




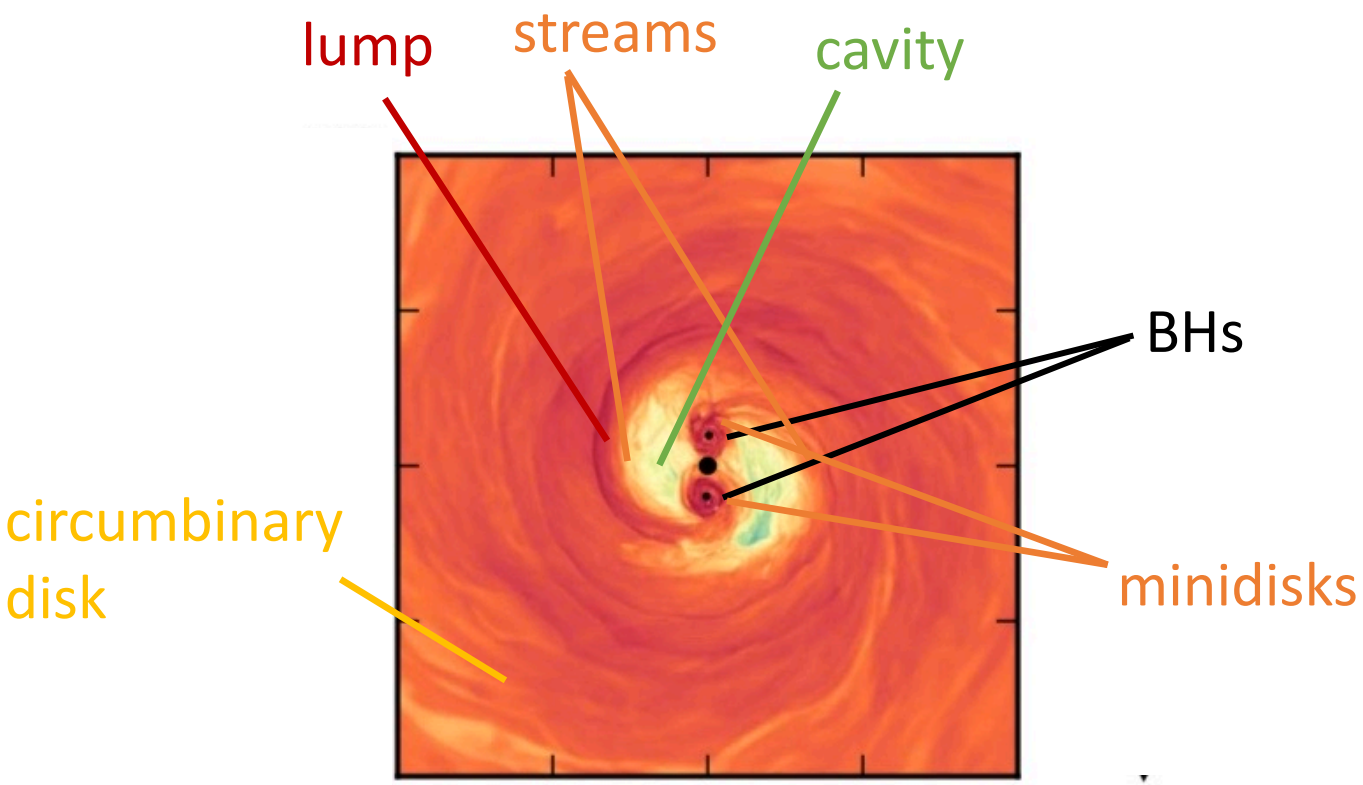


galaxy merger — dual AGN — gravitationally-bound SMBHB — GW-emitting SMBHB

>kpc — hundreds of parsecs – kpc — a few pc – tens of parsecs — milli-pc – centi-pc



Anatomy of an SMBHB



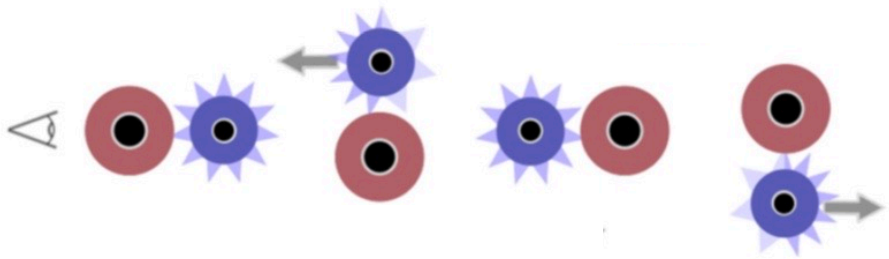
Adapted from d'Ascoli+2018

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

EM signatures – variability

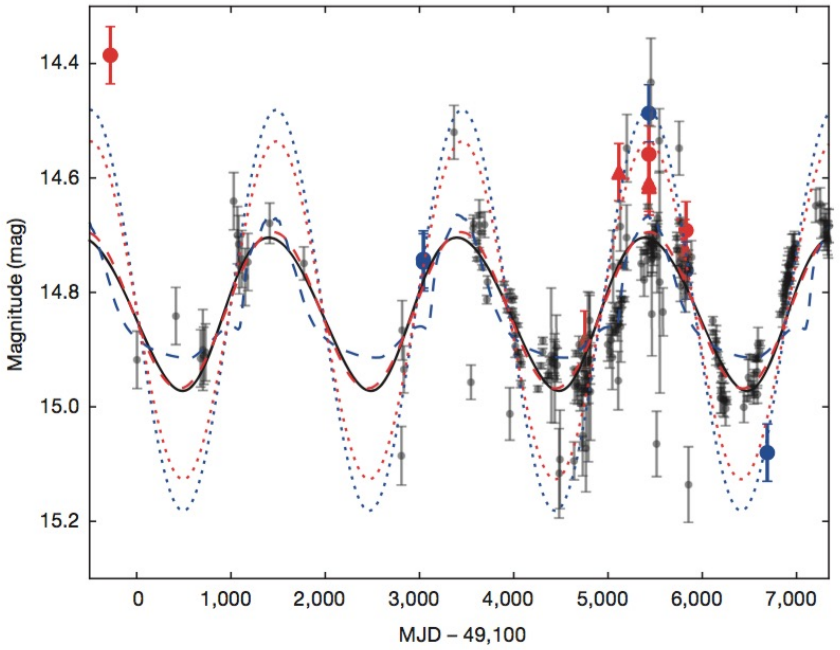
- Relativistic beaming

Theory



Credit: Kelley+2019

Observations



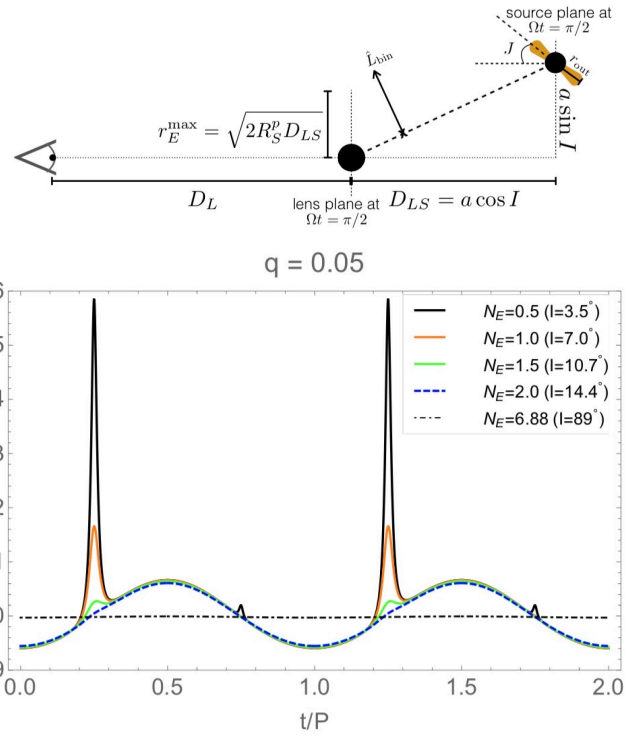
D'Orazio+2015
(CRTS light curve from Graham+2015a,
UV light curves from GALEX)

Tingting Liu "Swift and LCO Reverberation Mapping of a Supermassive Black Hole Binary Candidate" (Monday 3:20 pm; Room 217)

EM signatures – variability

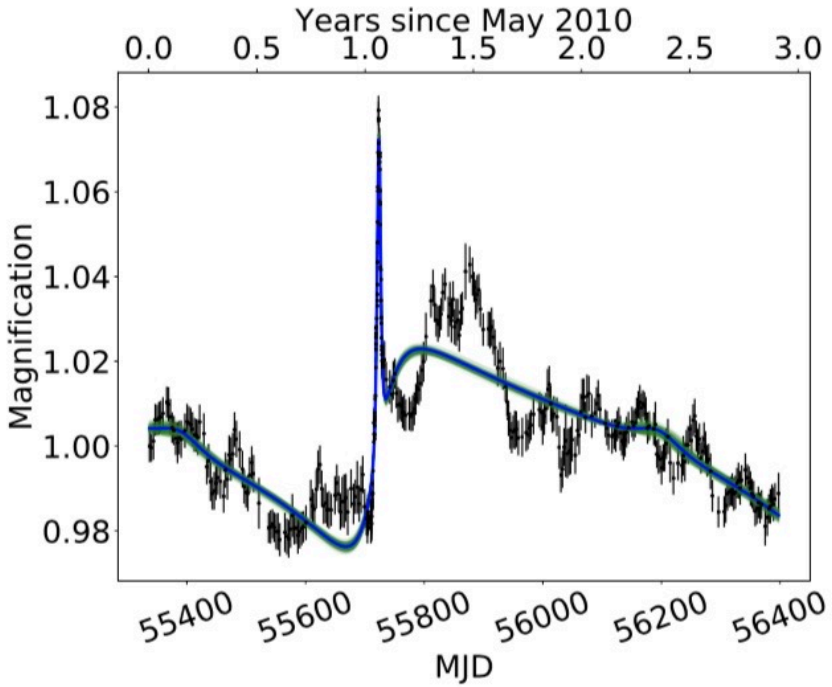
- Binary self-lensing

Theory



D'Orazio & Di Stefano 2018

Observations

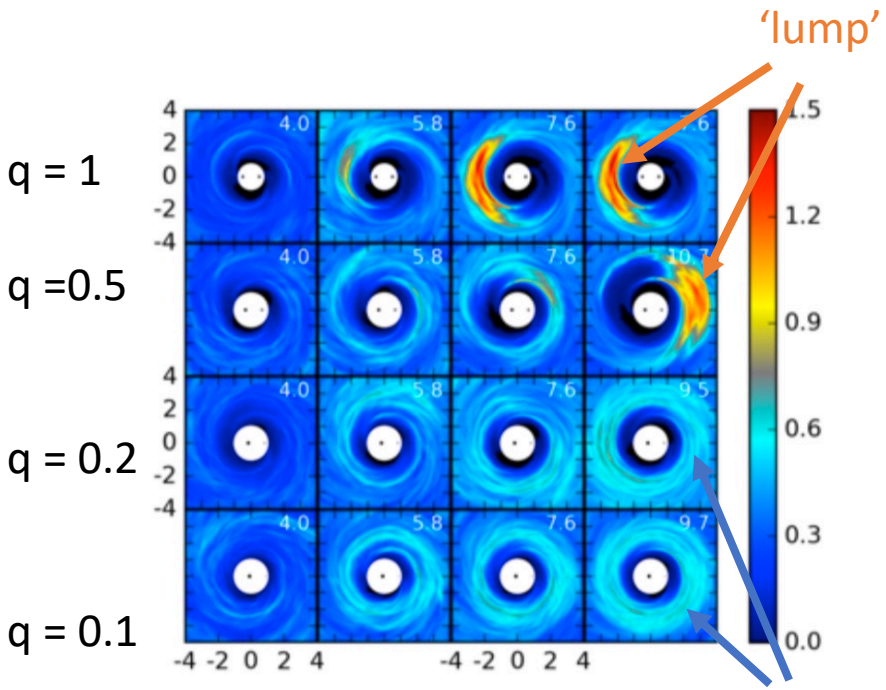


Hu+2020
(Kepler/K2 light curve from Smith+2018a)

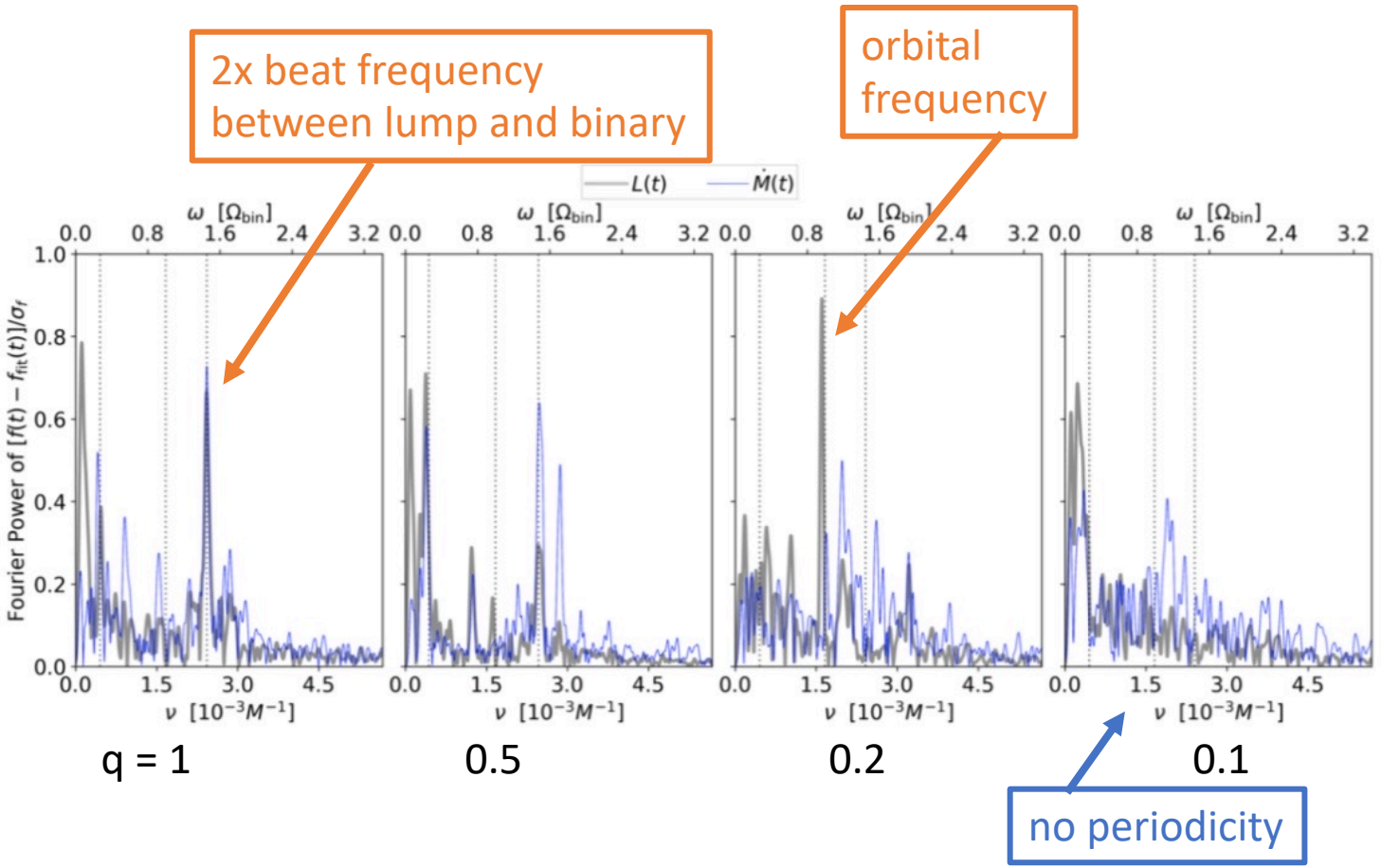
EM signatures – variability

- Binary-modulated accretion

Theory



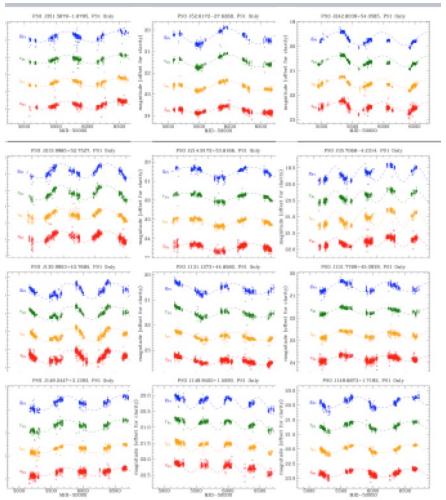
Noble+2021
(see also e.g., D'Orazio+2013, Farris+2014)



EM signatures – variability

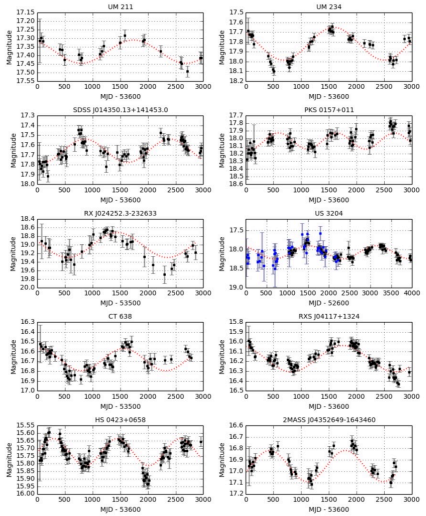
- Systematic searches for periodic AGN in time-domain surveys – hundreds of candidates

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

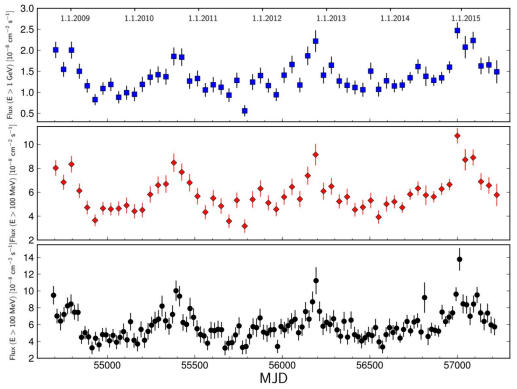


CRTS
(Graham+2015a,2015b)

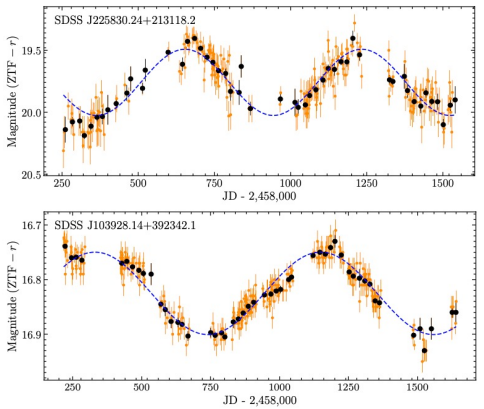
Also: PTF/iPTF (Charisi+2016),
DES+SDSS (Liao+2020,Chen+2020)



Fermi
(Ackermann+2015)

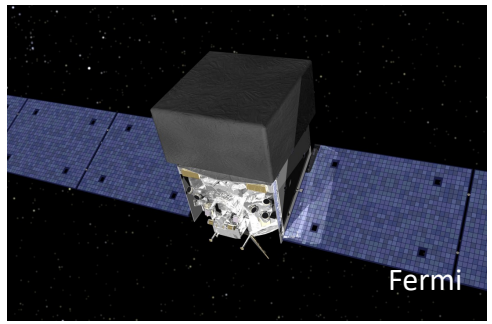


ZTF
(Chen+2023)



Rubin LSST
(~2025-2035)

?



EM signatures – variability

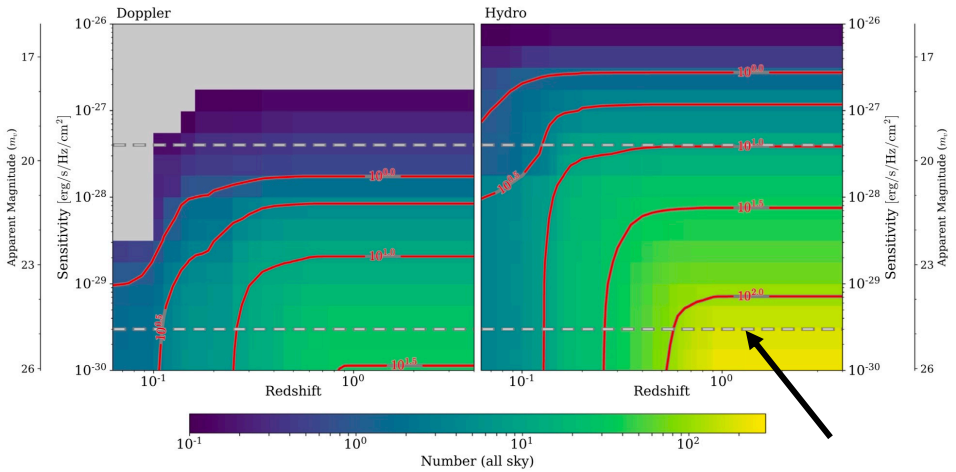
- Systematic searches for periodic AGN in time-domain surveys – hundreds of candidates
- Number estimates for LSST
  - Modulated accretion – N~40–600
  - Doppler boosting – N~6–50
  - Self-lensing – N~10–100

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

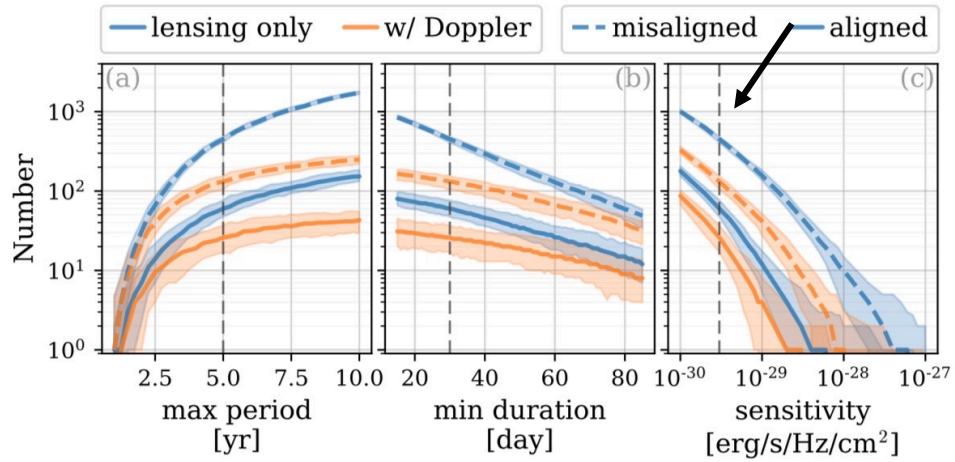
CRTS (Graham+2015a,2015b)

Fermi (Ackermann+2015)

ZTF (Chen+2023)



Kelley+2019

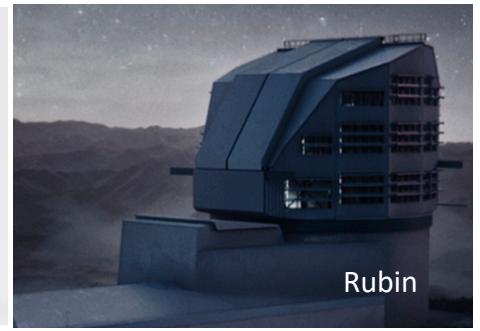


LSST sensitivity

Kelley+ 2021

Rubin LSST (~2025-2035)

?



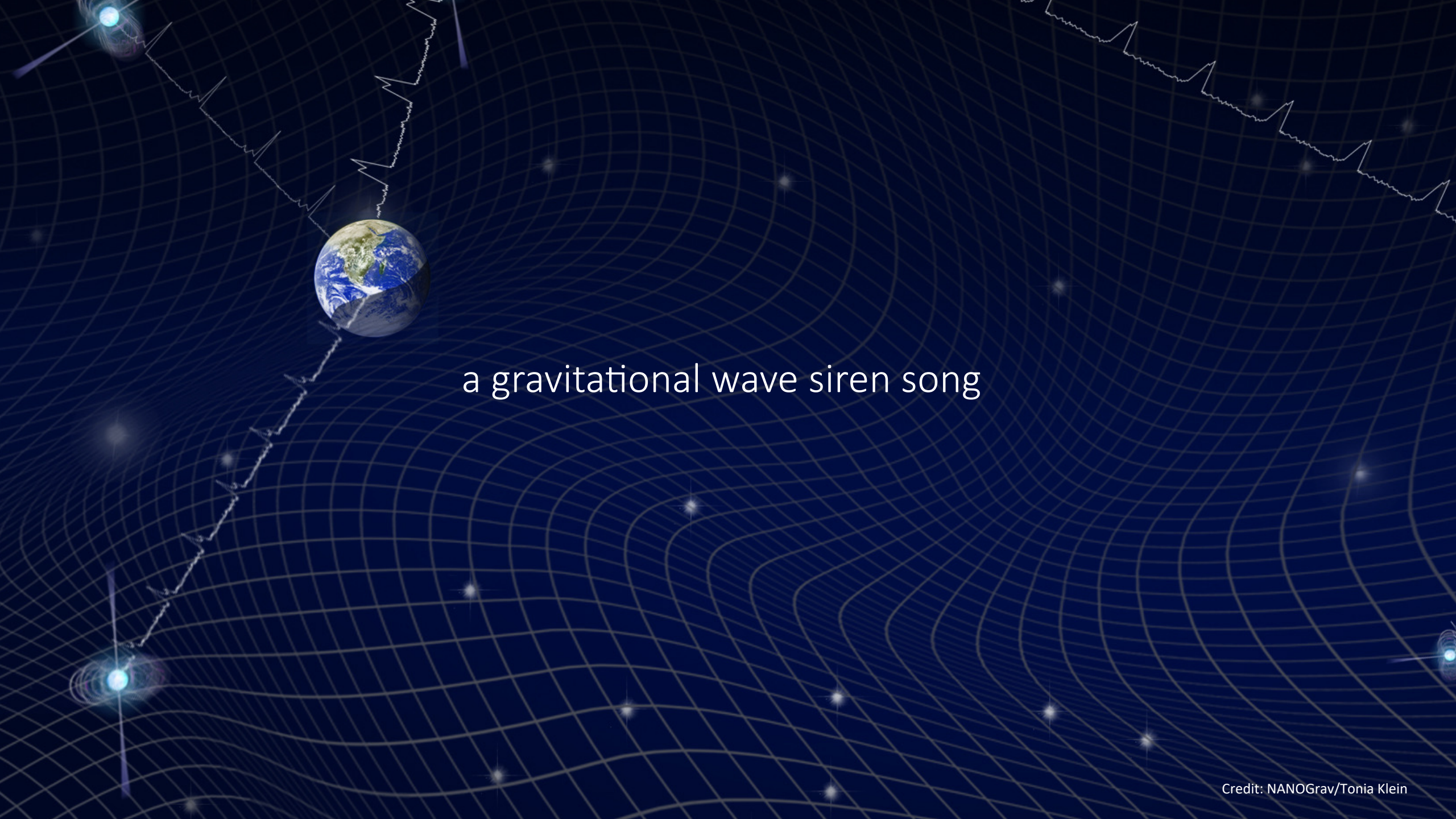
PS1

CSS

LSST sensitivity

Fermi

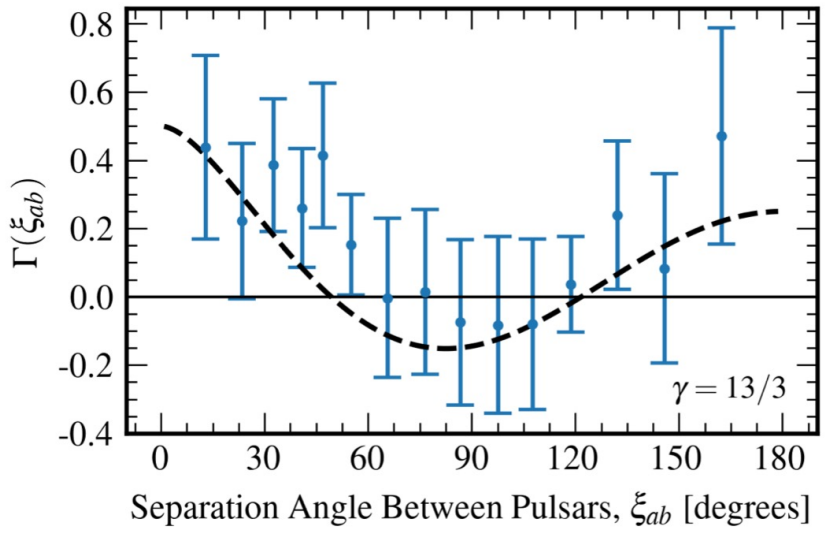
Palomar



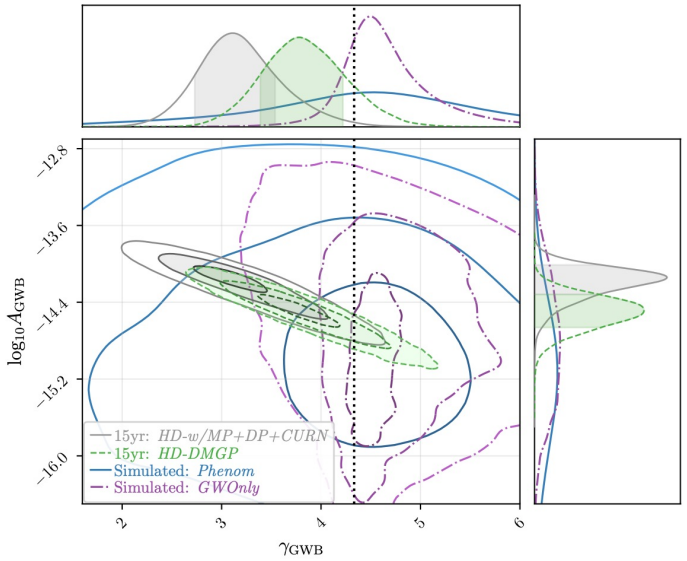
Credit: NANOGrav/Tonia Klein

Multi-messenger SMBHB searches with PTAs – future prospects

- PTAs have seen evidence for a stochastic gravitational-wave background consistent with SMBHBs



NANOGrav Collaboration (including T. Liu) 2023 ApJL 951 L8
See also Antoniadis+ 2023, Reardon+ 2023, Xu+2023

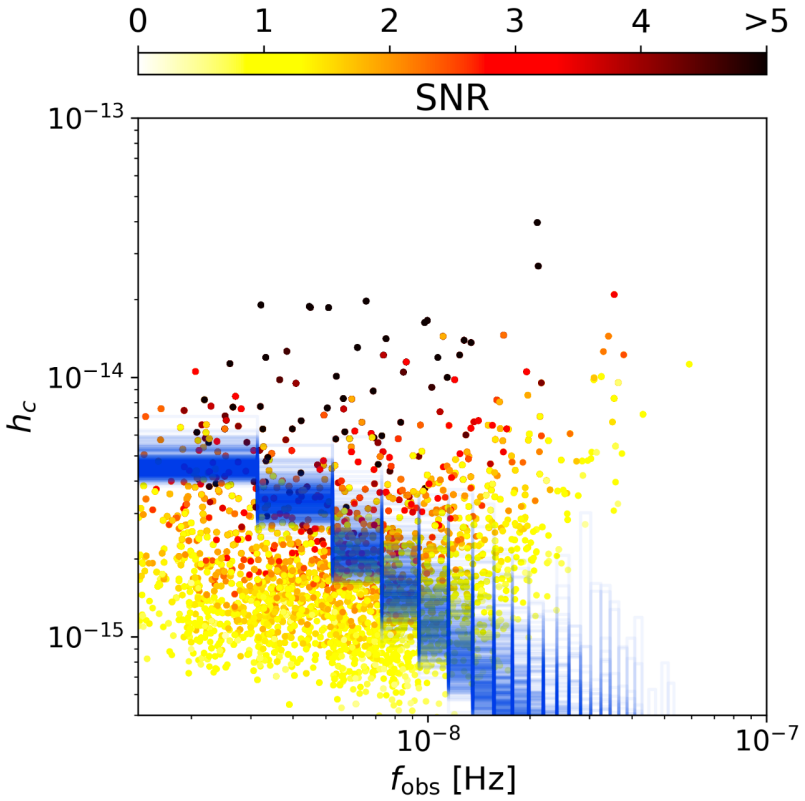


NANOGrav Collaboration (including T. Liu) 2023 ApJL 952 L37
See also Antoniadis+ 2023

Steve Taylor's plenary talk "The Dawn of Gravitational-wave Astronomy at Light-year Wavelengths" (Monday; 8:20 am)

Multi-messenger SMBHB searches with PTAs – future prospects

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

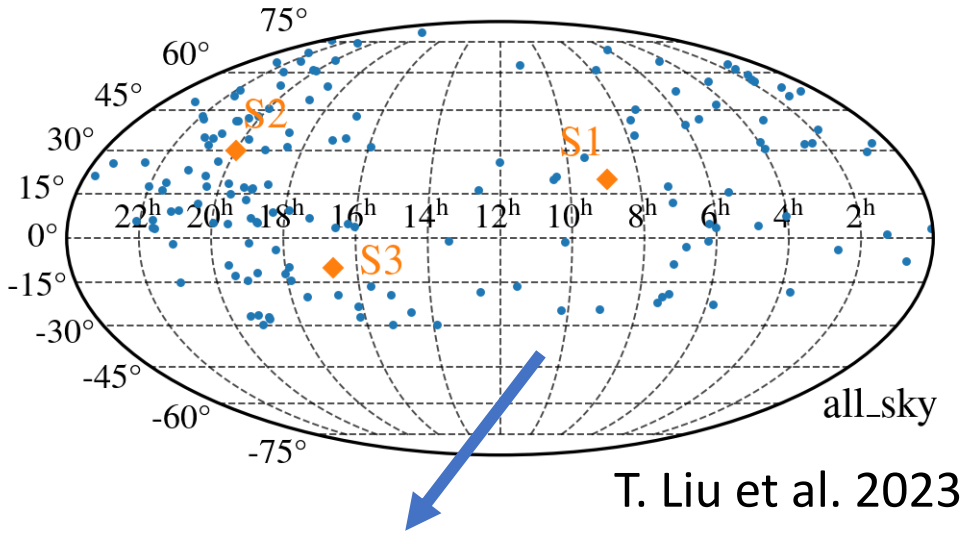


Becsy+2022
(see also e.g., Mingarelli+2017, Kelley+2018)

Oral Session “Supermassive Black Hole Binaries and Pulsar Timing Arrays” (Tuesday 11 am; Room 227)
Special Session “NANOGrav: The Dawn of Galaxy-scale Gravitational-wave Astronomy” (Tuesday 2 pm; Room 226)

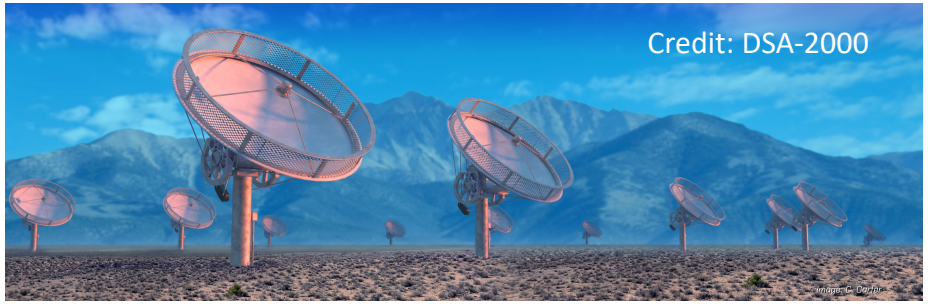
Multi-messenger SMBHB searches with PTAs – future prospects

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



T. Liu et al. 2023

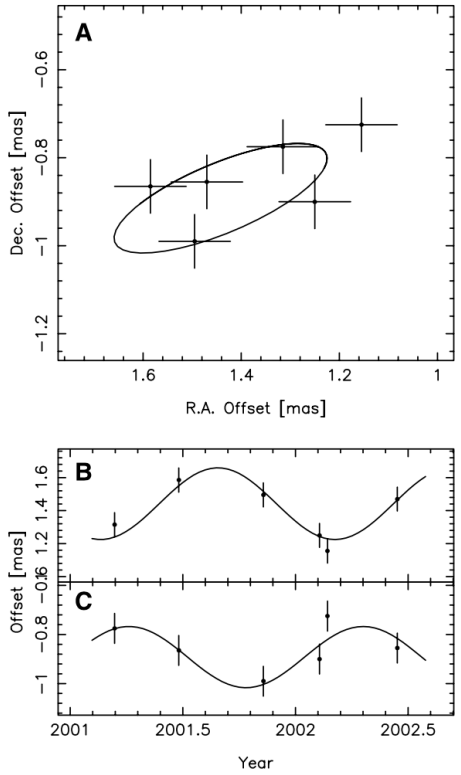
~150 millisecond pulsars (~2x NANOGrav) with ~400 ns timing noise (~1/2x NANOGrav)



Gregg Hallinan "The DSA-2000 Radio Camera" (Tuesday 2:40 pm; Room 208)
The DSA-2000 at the Exhibit Hall

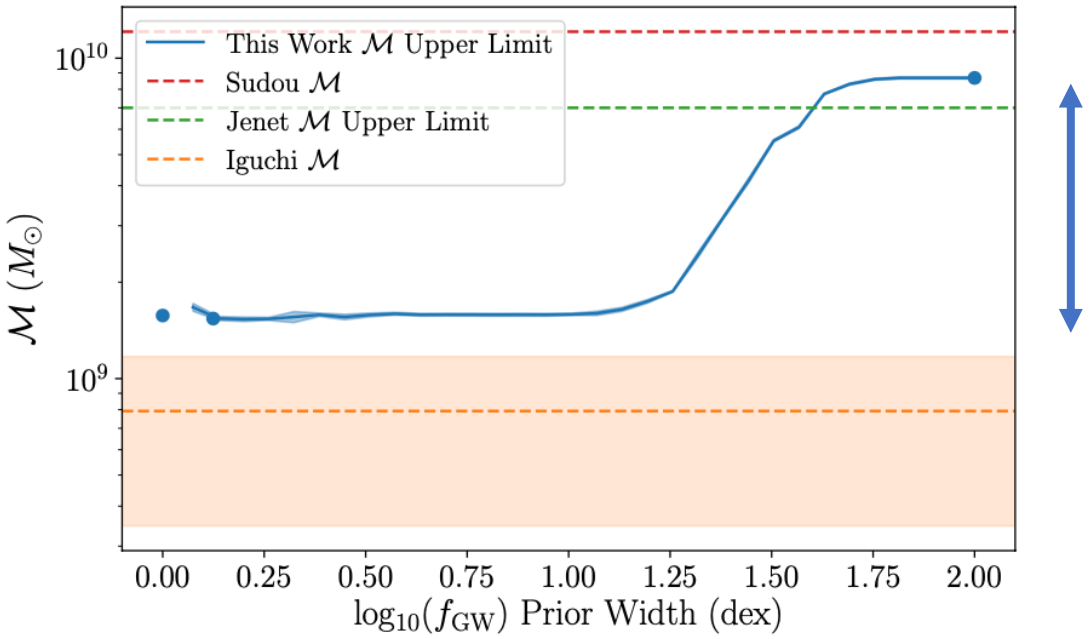
Multi-messenger SMBHB searches with PTAs – upper limits

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



Sudou et al 2003
(3C 66B)

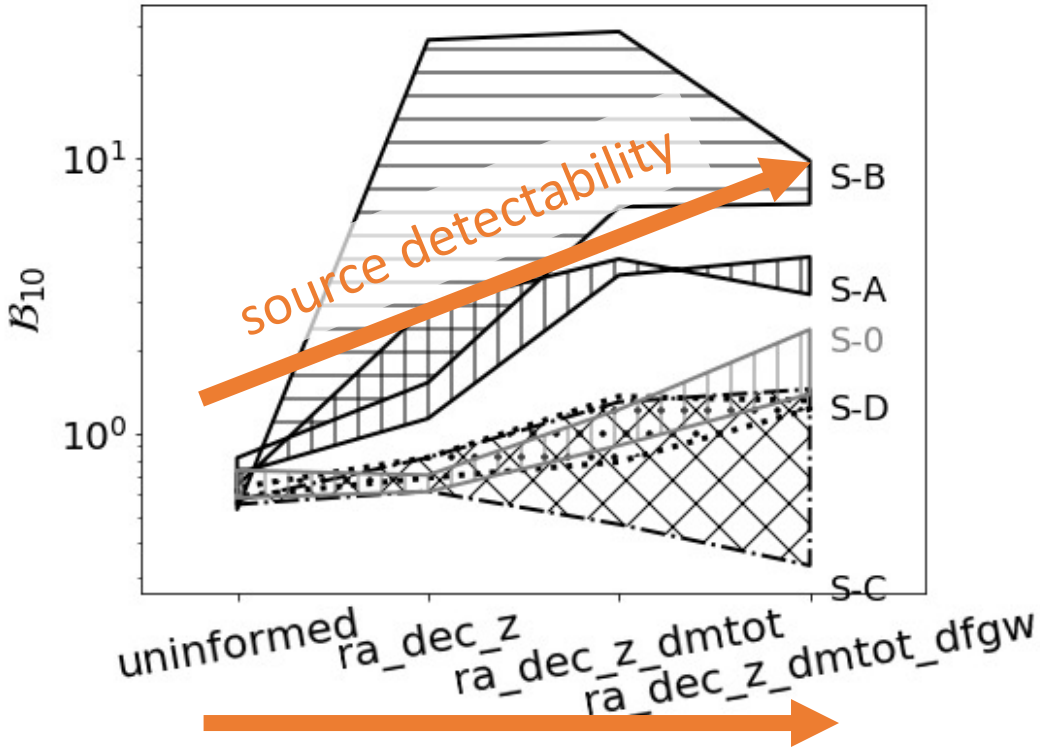
frequency

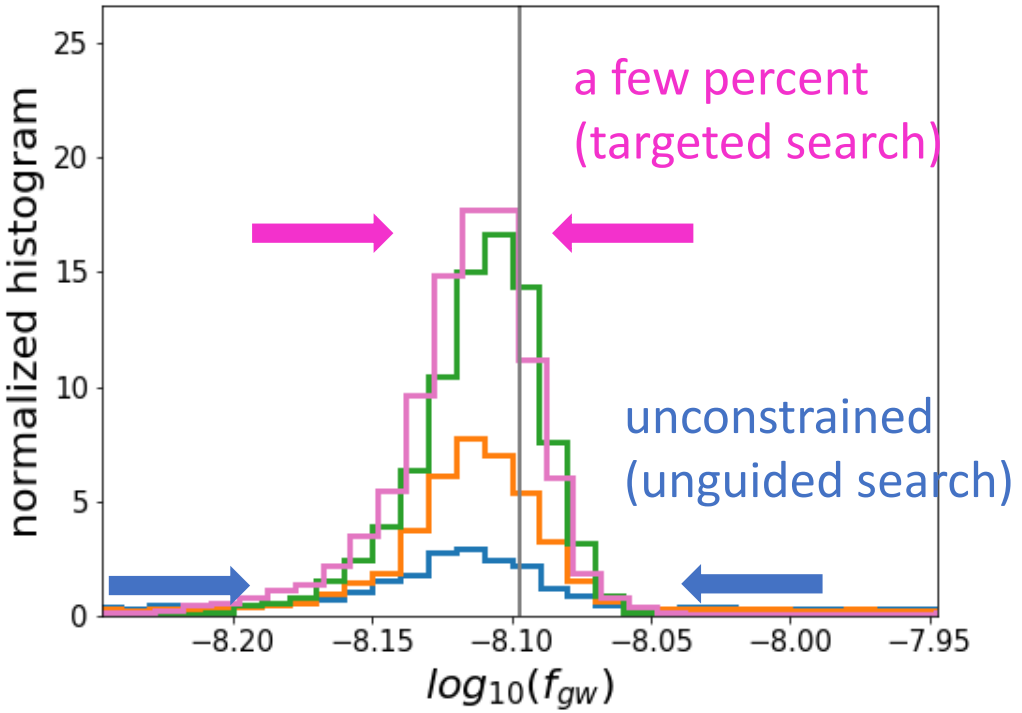


NANOGrav Collaboration 2020

Multi-messenger SMBHB searches with PTAs – detection and parameter estimation

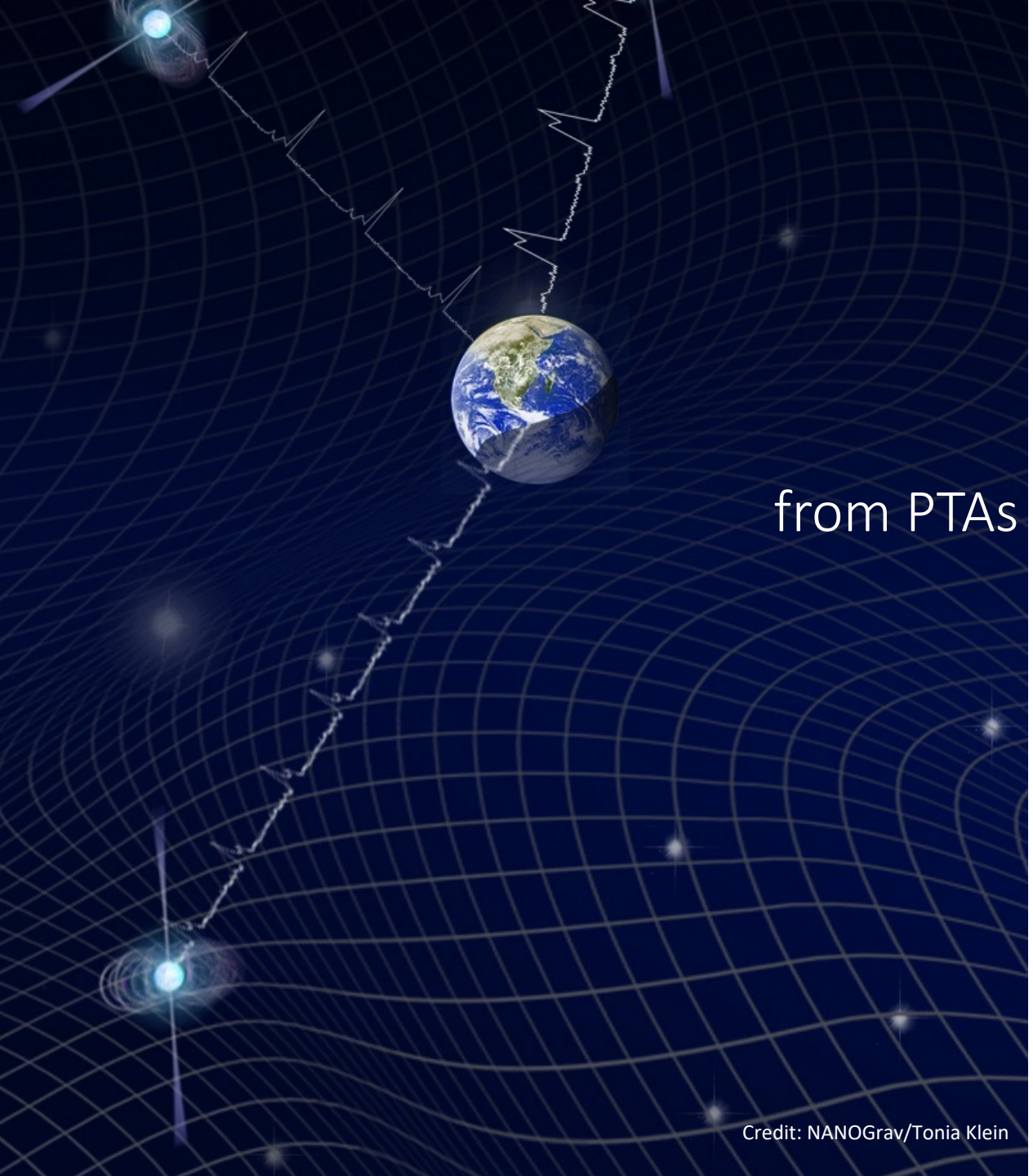
- Targeted searches increase source *detectability and parameter measurability* by ~ an order of magnitude



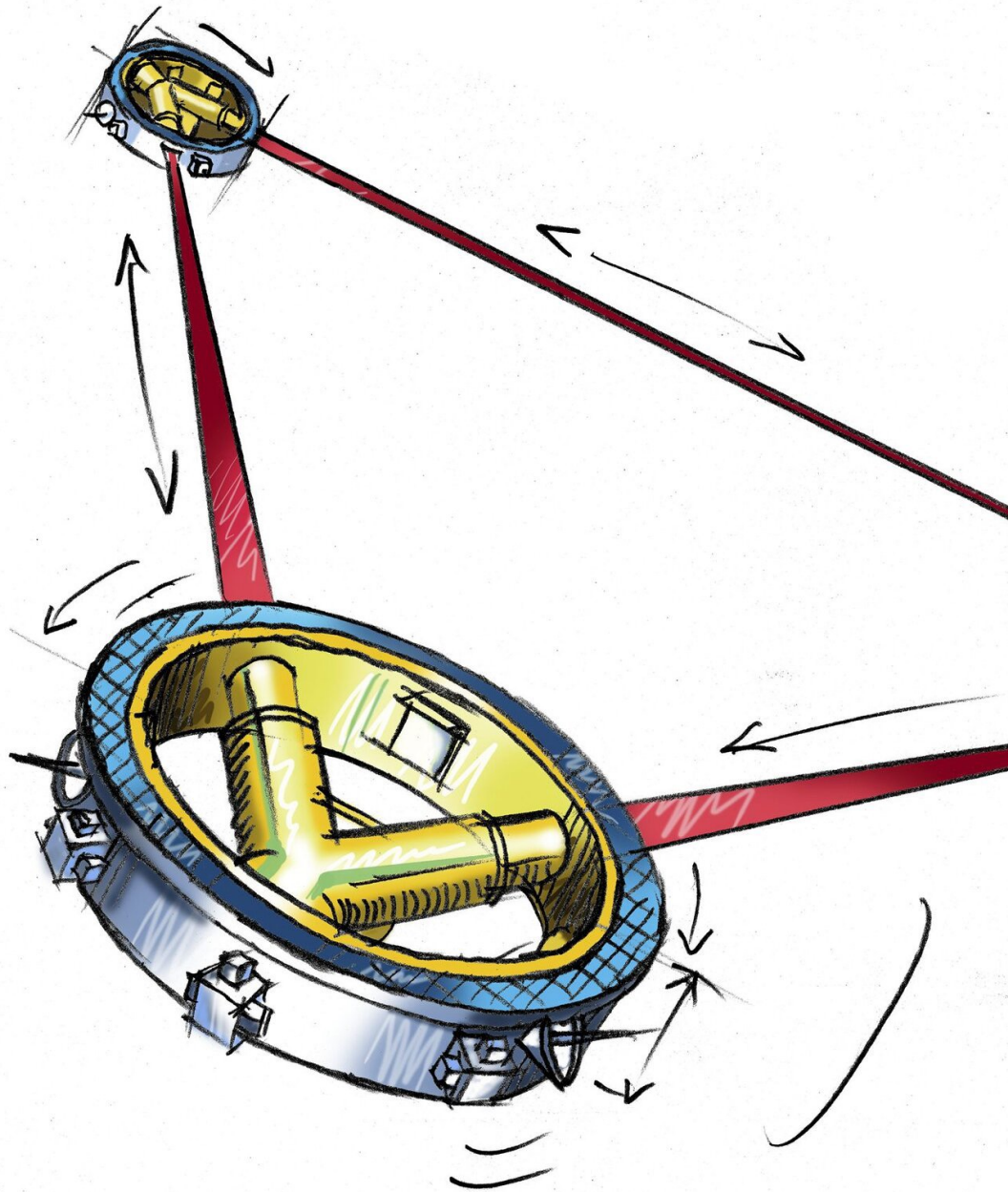


T. Liu & Vigeland 2021

from PTAs to LISA



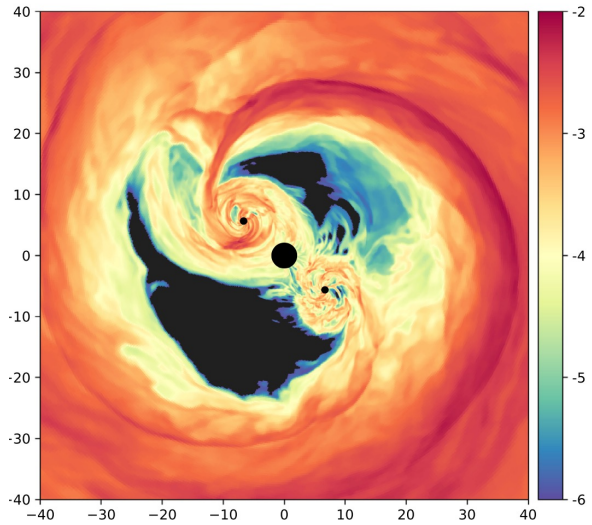
Credit: NANOGrav/Tonia Klein

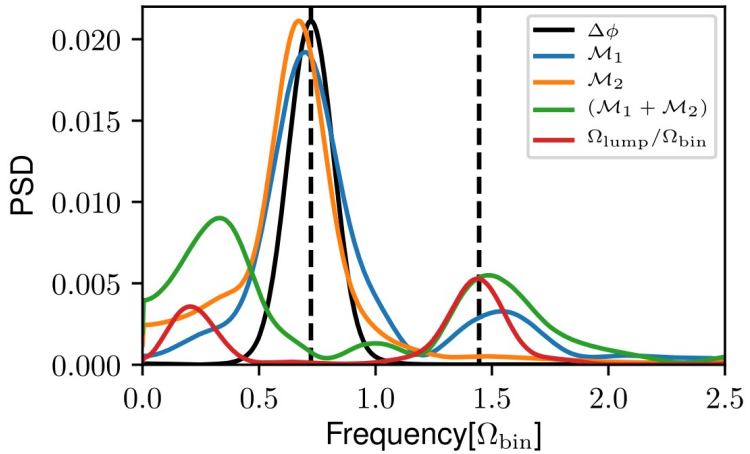


Credit: ESA

Multi-messenger MBHB science with LISA

- Binary accretion in the relativistic regime

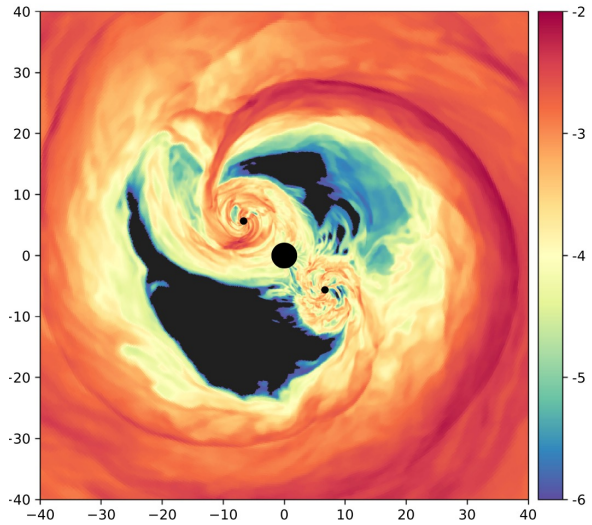


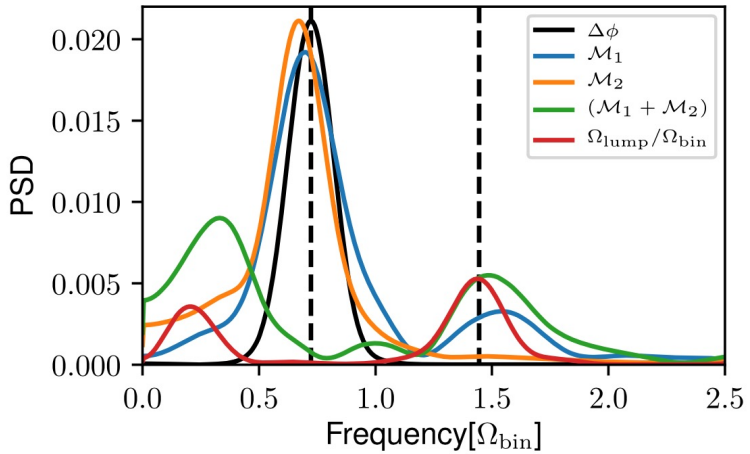


Bowen+2019; see also Combi+2021

Multi-messenger MBHB science with LISA

- Binary accretion in the relativistic regime

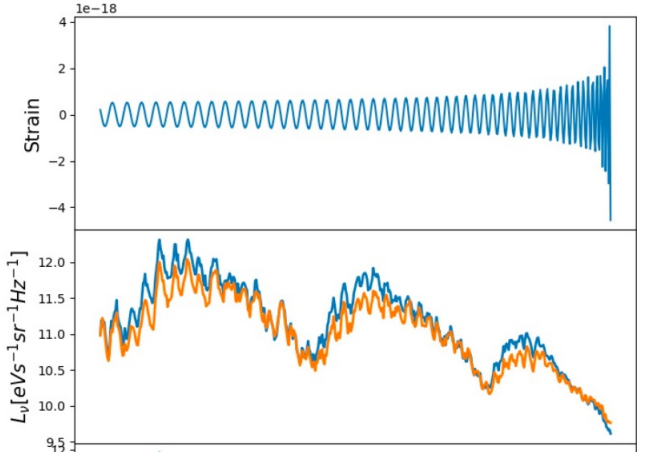




Bowen+2019; see also Combi+2021

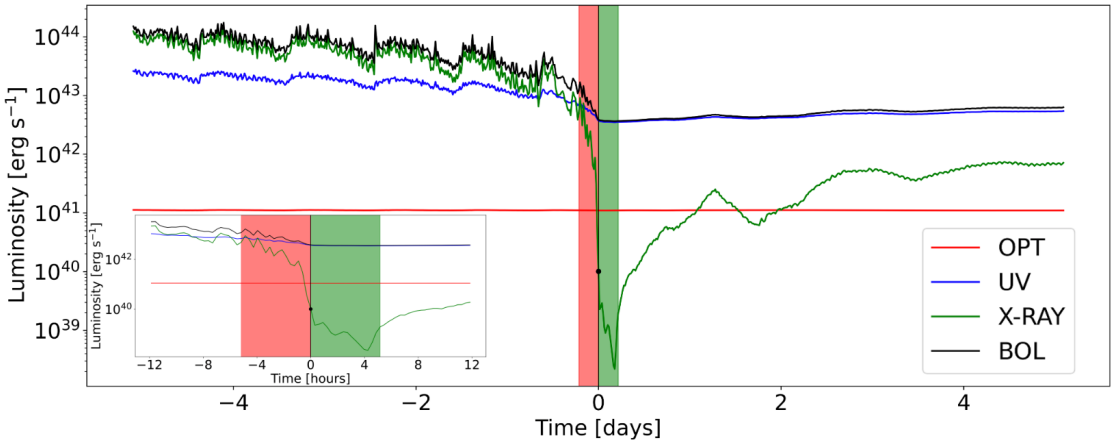
- Pre-merger signatures

EM chirping in X-rays



Tang+2018

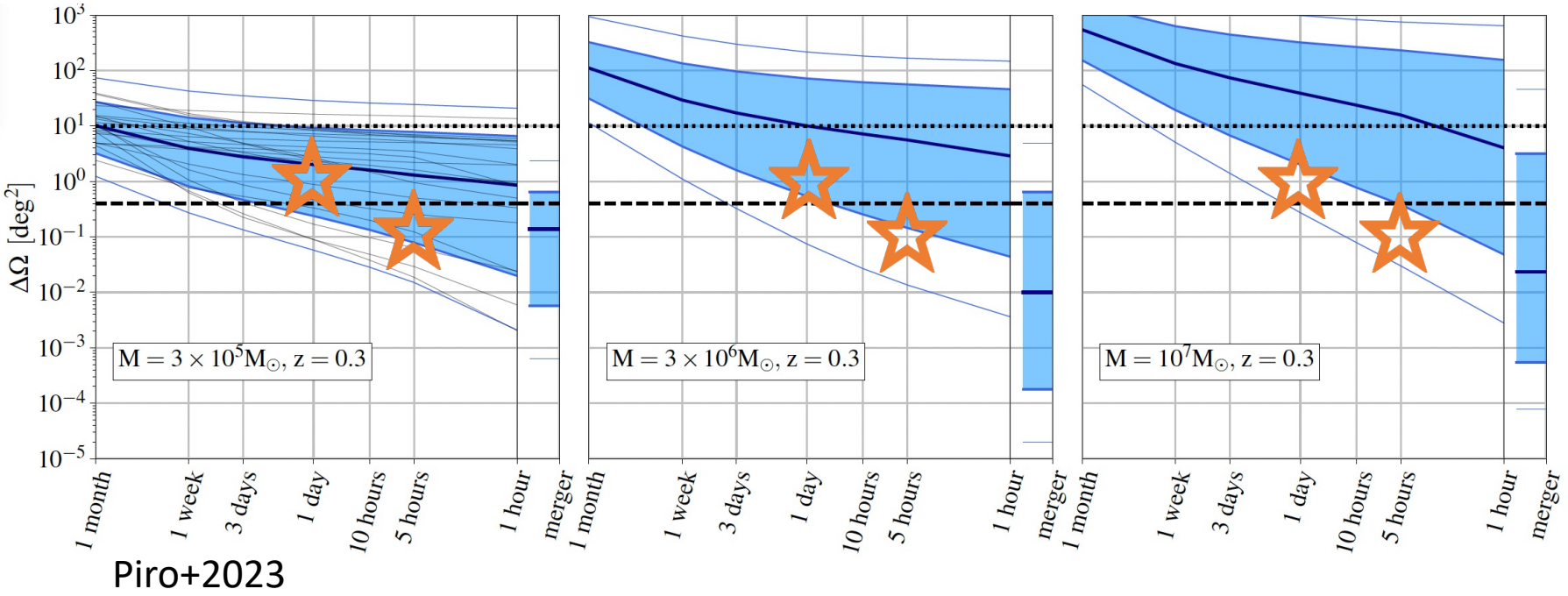
decrease in X-ray flux



Krauth+ 2023; see also Dittmann+2023

Multi-messenger MBHB science with LISA

- LISA localization within 1 deg^2 (0.1 deg^2) ~ 1 day (5 hours) before merger is possible for systems at low redshifts

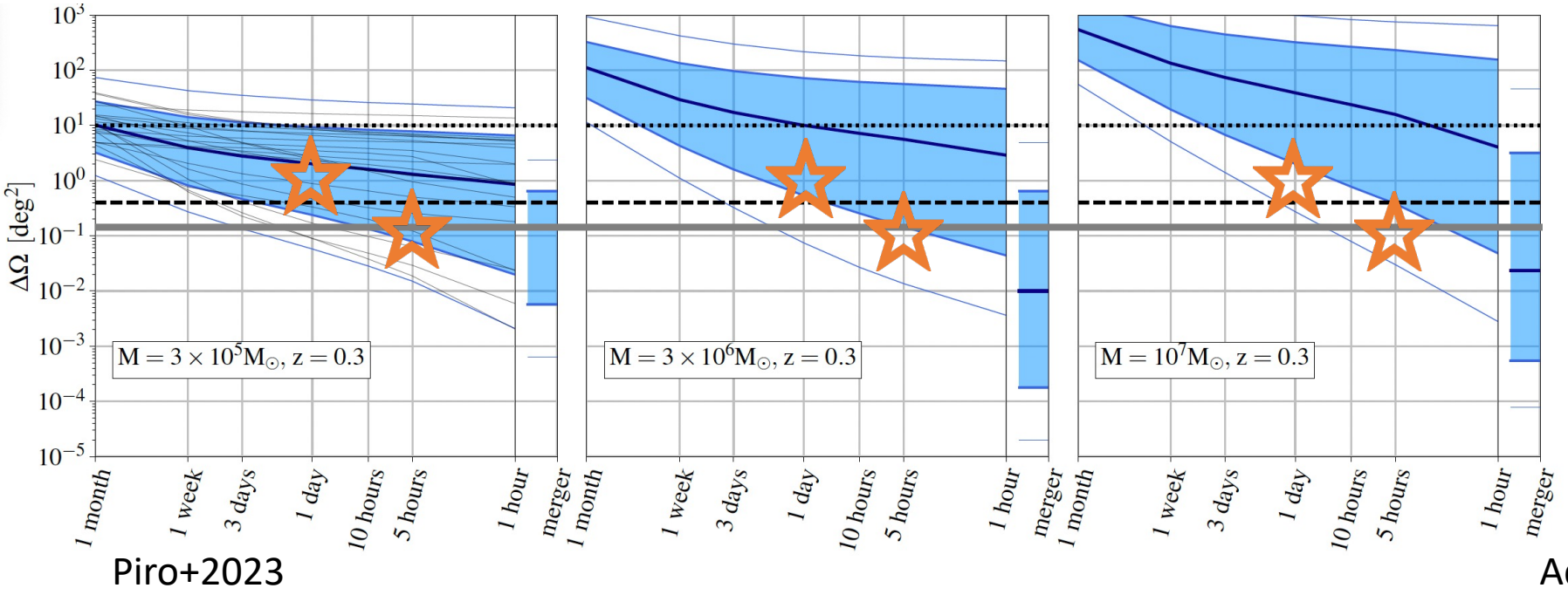


Piro+2023

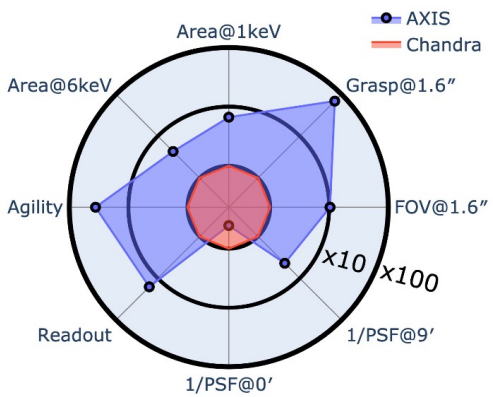
An X-ray telescope with a large FOV and rapid response time could catch MBH mergers in the act

Multi-messenger MBHB science with LISA

- LISA localization within 1 deg^2 (0.1 deg^2) ~ 1 day (5 hours) before merger is possible for systems at low redshifts

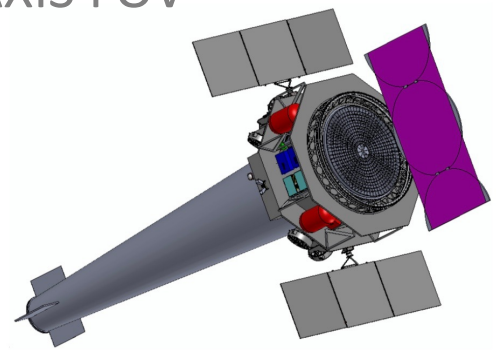


Piro+2023



Reynolds+ 2023

AXIS FOV



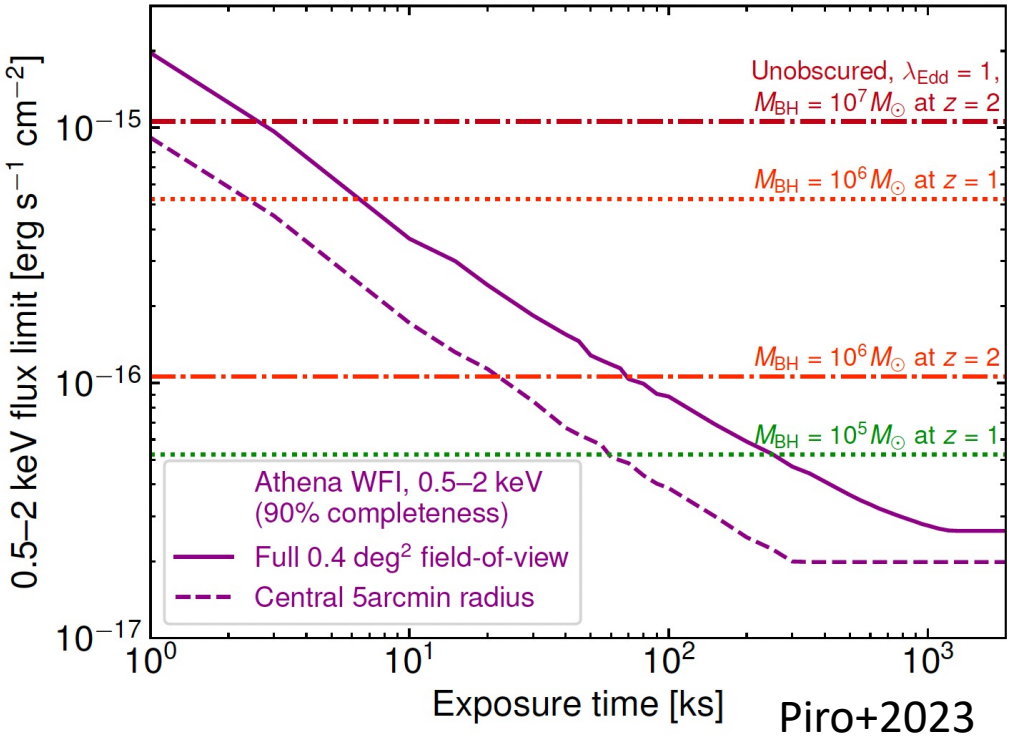
Advanced X-ray Imaging Satellite
Reynolds+ 2023

An X-ray telescope with a large FOV and rapid response time could catch MBH mergers in the act

Foord, Cappelluti, T. Liu,+ 2023
AXIS TDAMM WG (including T. Liu) 2023
and the AXIS White Paper Series

Multi-messenger MBHB science with LISA

- Post-merger emission



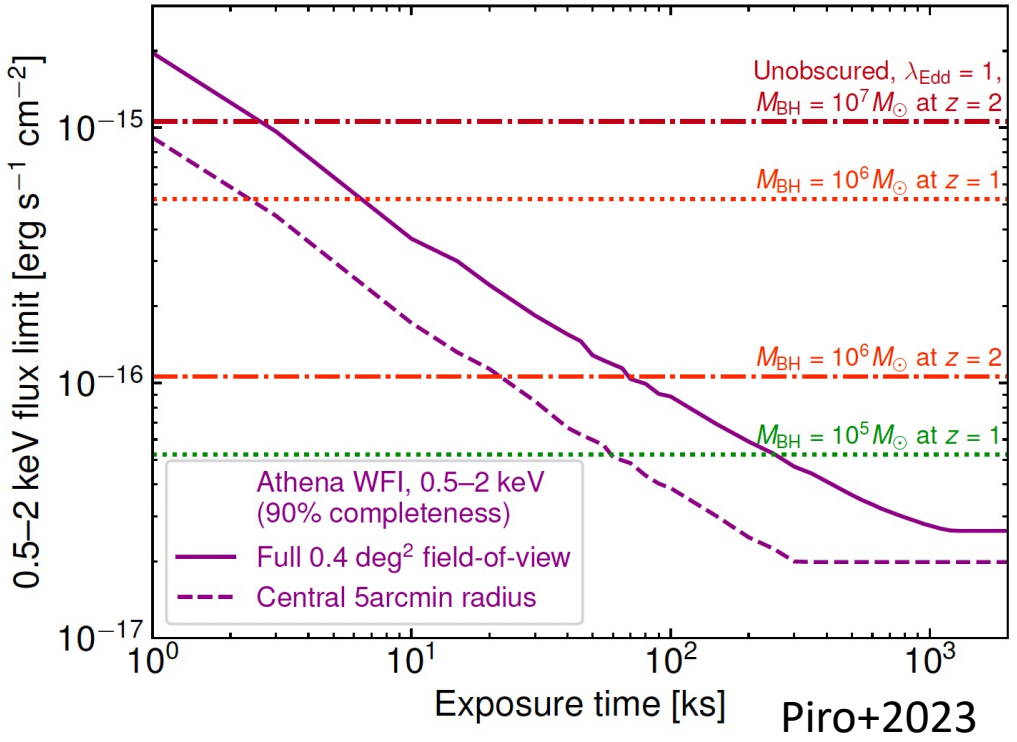
Piro+2023

Athena confusion limit

A sensitive X-ray telescope with high angular resolution could witness the (re)birth of an AGN

Multi-messenger MBHB science with LISA

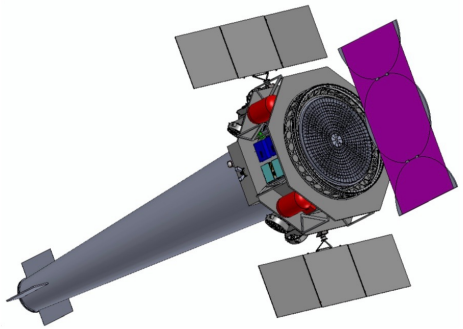
- Post-merger emission



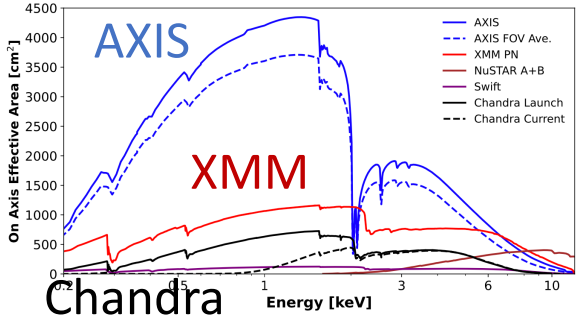
Piro+2023

Athena
confusion limit

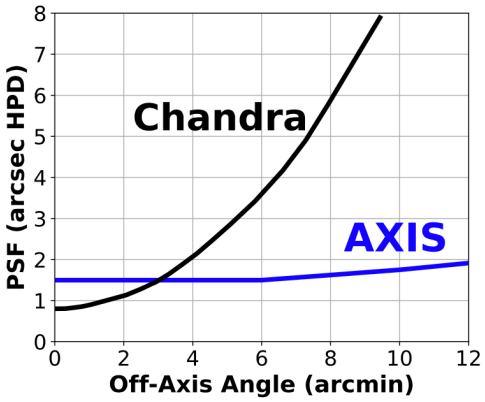
AXIS
confusion limit



Reynolds+ 2023



Chandra



A sensitive X-ray telescope with high angular resolution could witness the (re)birth of an AGN

Takeaways

- The science of individual SMBHBs (binary AGN) is rich
  - Understanding SMBH growth and evolution
  - Laboratories for accretion physics in dynamic spacetimes
- They are promising multi-messenger sources for PTAs and LISA
- The EM observations of SMBHBs in the PTA band will also be test beds for LISA

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