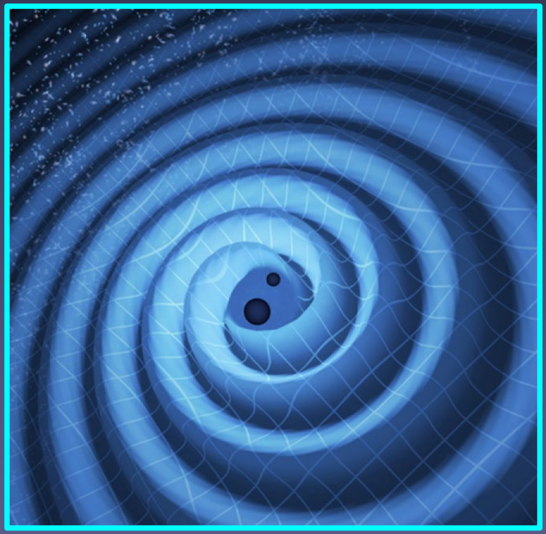
Electromagnetic counterparts of massive black hole mergers

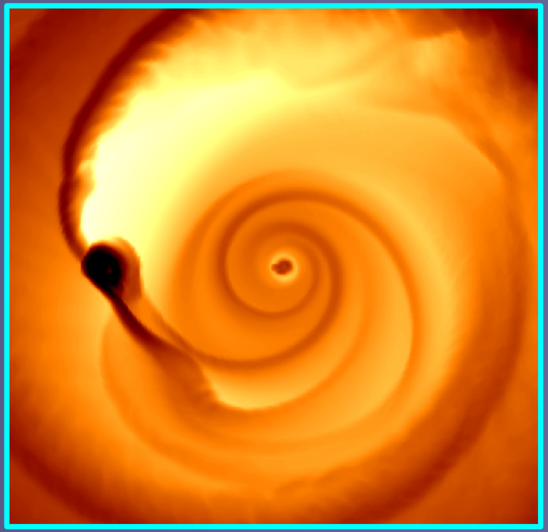


Zoltán Haiman

Columbia University

↓

ISTA



Collaborators:

Ágnes Kis-Tóth, Kevin Park, Chengcheng Xin, David O'Neill
Ryan Westernacher-Schneider, Jordy Davelaar, Chris Tiede, Luke Krauth, Max Isi
Maria Charisi, Daniel D'Orazio, Jonathan Zrake, Andrew MacFadyen, Will Farr, Zsolt Frei

"Ten Years to LISA" *JPL* *1-3 April 2025*

Institute for Science and Technology Austria (ISTA)

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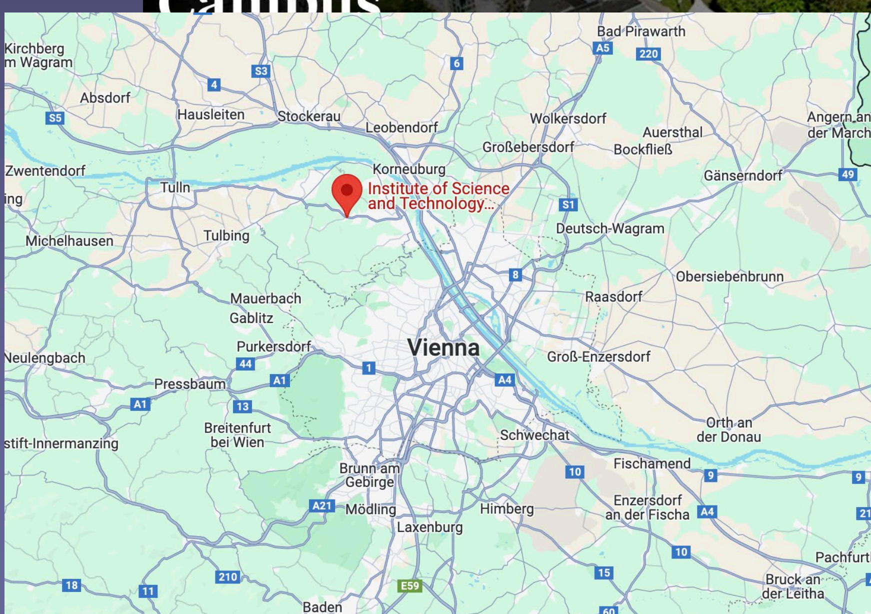

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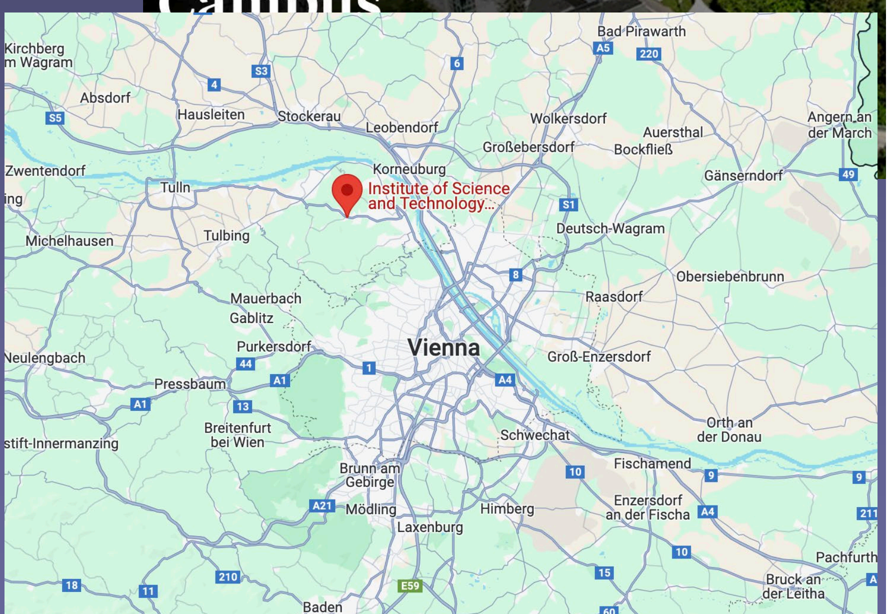

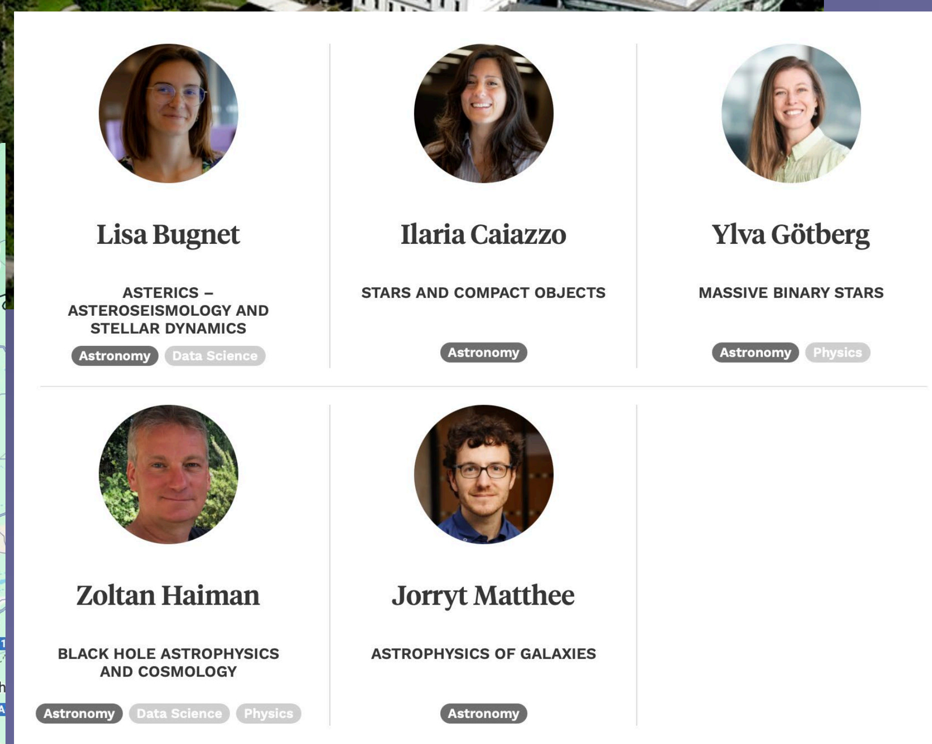

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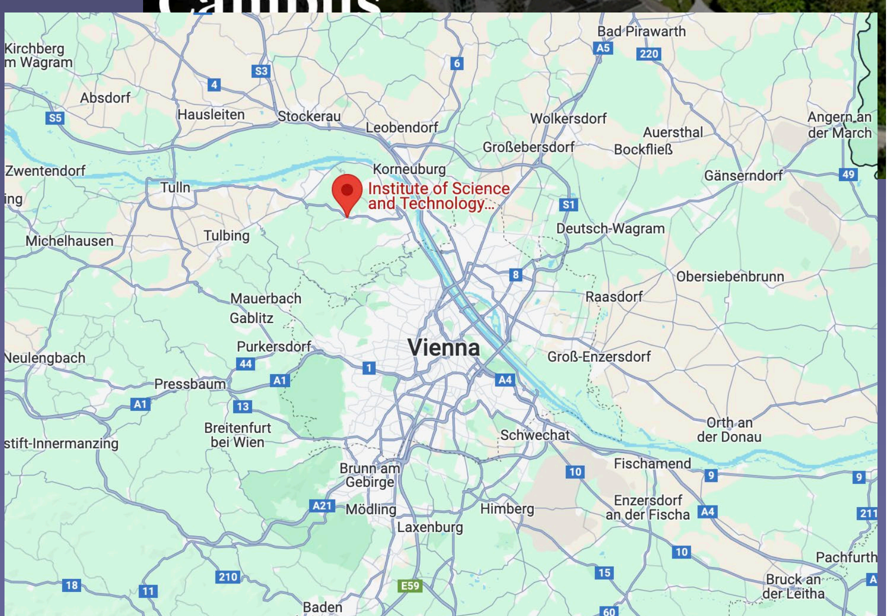
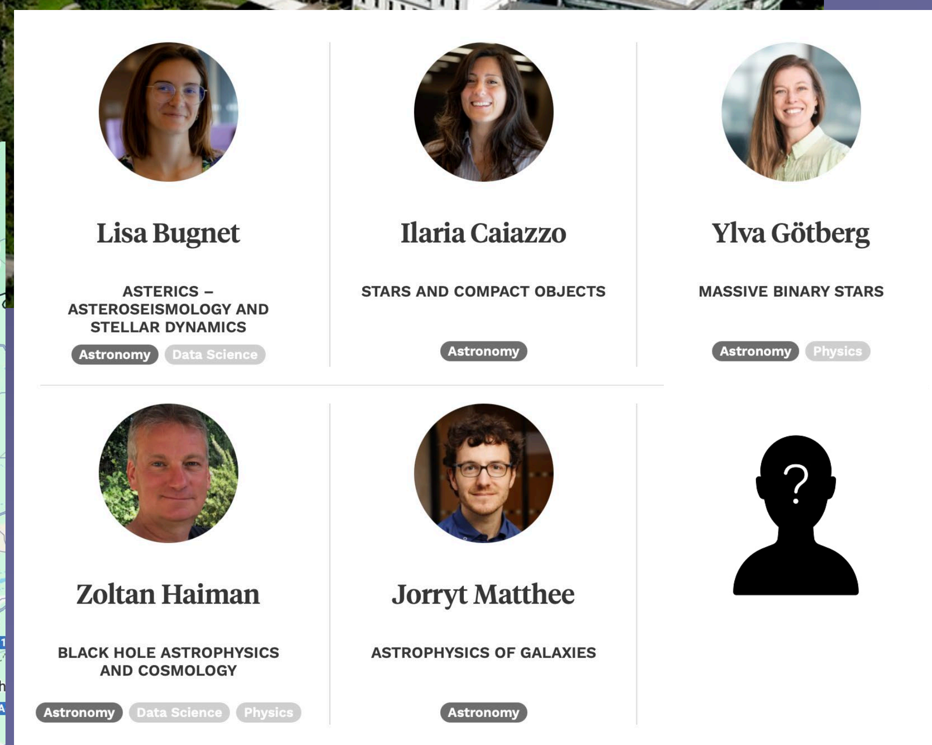
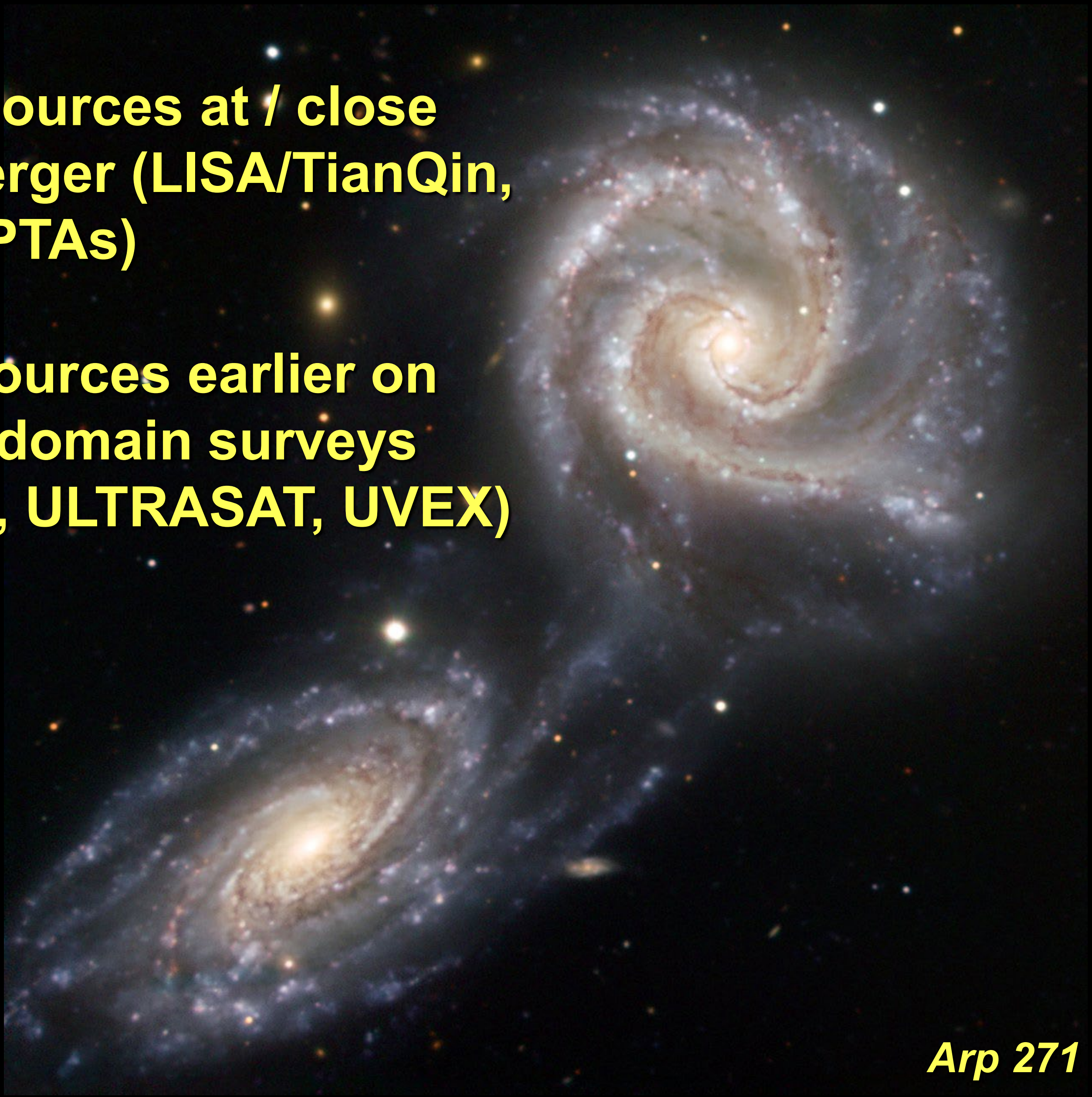




Massive BH binaries in galactic nuclei

→ GW sources at / close to merger (LISA/TianQin, Taiji/PTAs)

→ EM sources earlier on (time-domain surveys LSST, ULTRASAT, UVEX)



Arp 271 (credit: ESO)

Novel science from GW + EM detections

Astronomy & astrophysics
quasar/galaxy (co)evolution
accretion physics
environments of merging black holes

Fundamental physics & cosmology
geometric cosmological measurements
novel tests of beyond-GR gravity
graviton mass, extra dimensions

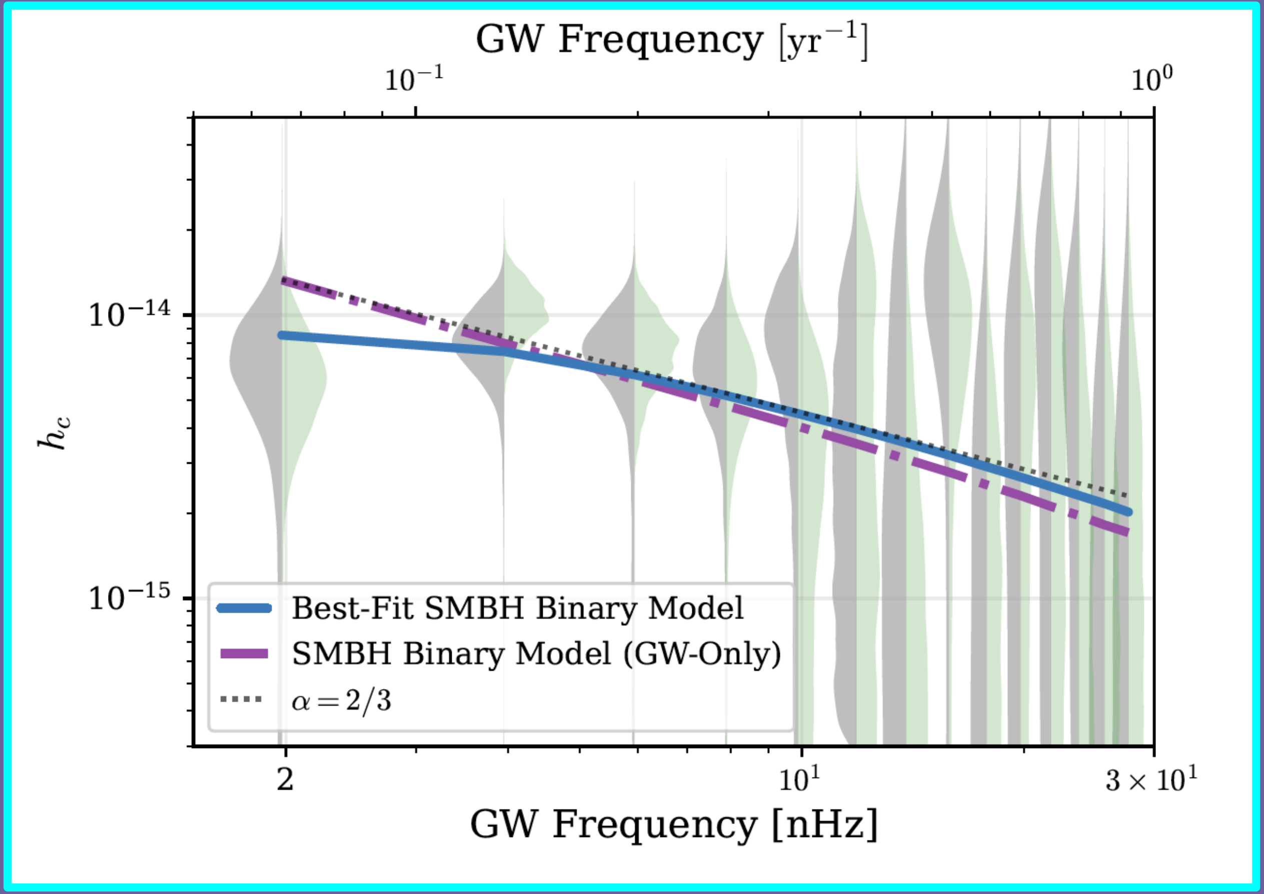
Practical benefits
EM counterpart can increase confidence of marginal GW detections
known EM source location can help break GW parameter degeneracies

need to find EM counterparts or precursors of GW sources

Have we already detected SMBH binaries in both GW and EM ?

NANOGrav15 GWB

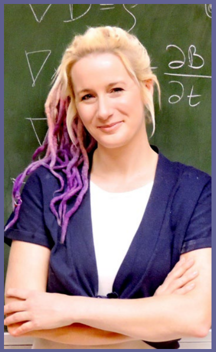
Agazie+2023



From quasars to GWB

Kis-Tóth, ZH & Frei (2025; arXiv:2412.12726)

- **Common approach:** predict GWB by modeling the cosmic population of SMBH mergers (sims, SAMs)
- **Simplified approach:** assume 1-1 correspondence between quasars and SMBH mergers



Ágnes Kis-Tóth

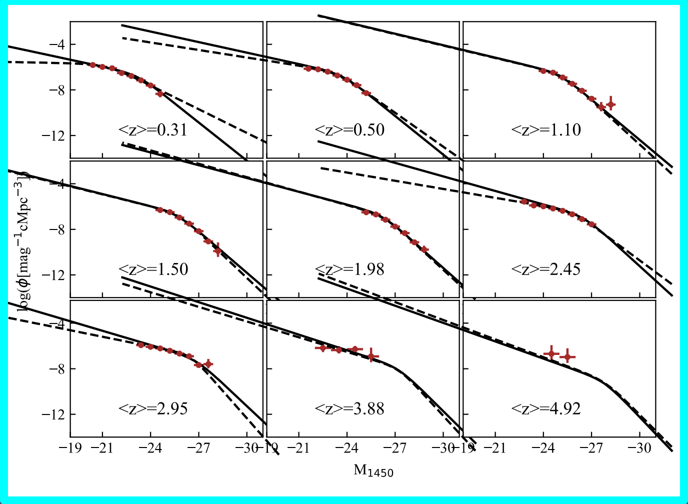
Eötvös Loránd Univ.

activates quasars

SMBH binaries & gravitational waves

Quasars

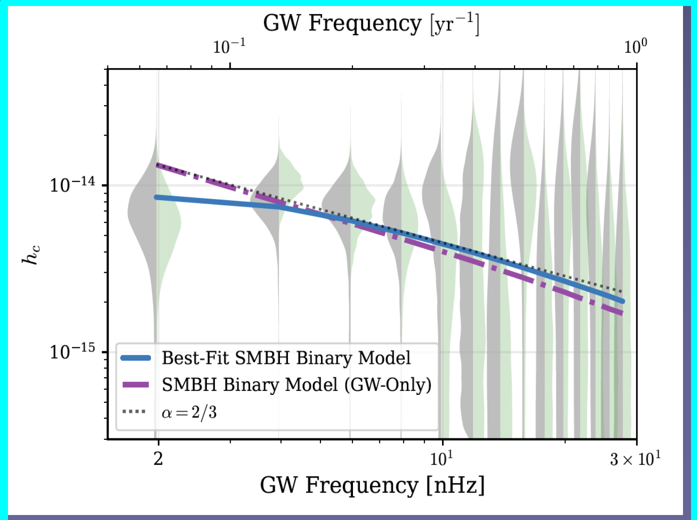
luminosity function



Xin & ZH 2021; Kulkarni+2019

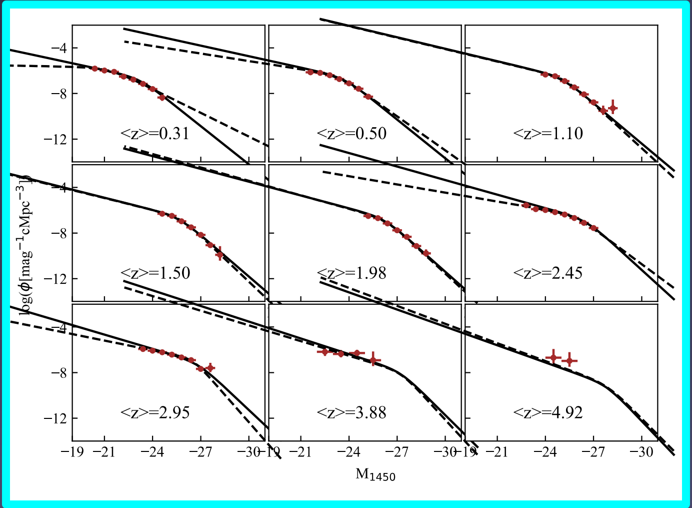
Gravitational waves

Agazie+2023; NANOGrav15



Quasars

luminosity function



Xin & ZH 2021; Kulkarni+2019

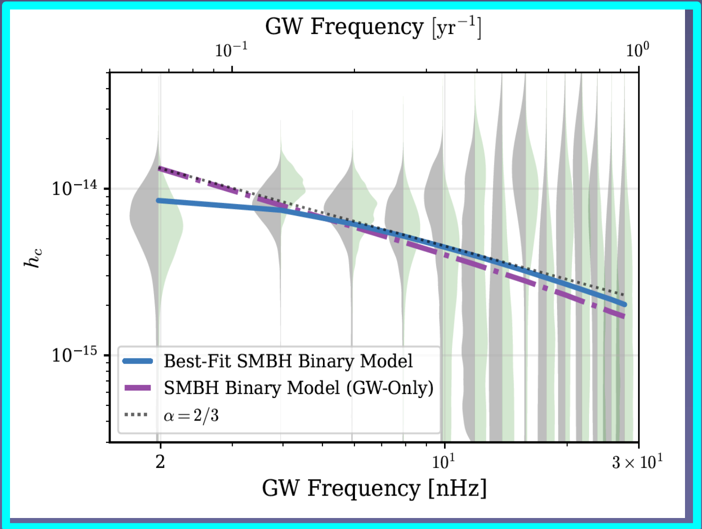
SMBH merger rate density

$$\frac{d^3n}{dMdqdz}(M,q,z)$$

quasar lifetime ($\sim 3\times 10^8$ yr)
Eddington ratio ($f_{Edd} \sim 0.25$)
SMBH mass ratio ($q \sim 1$)
binary fraction ($f_{bin} \sim 1$)

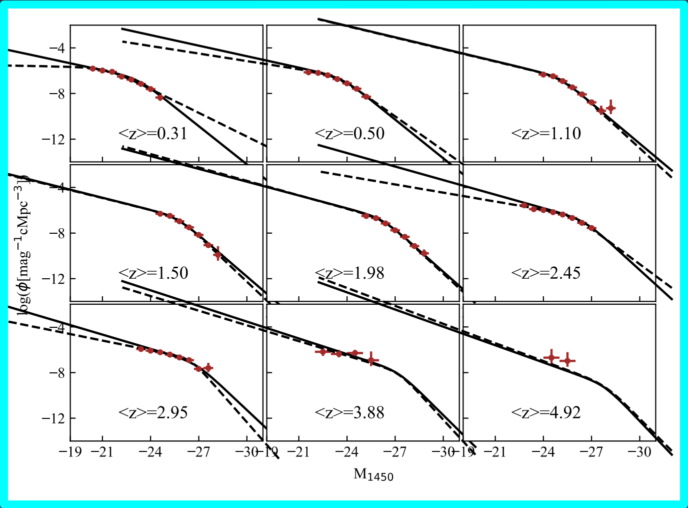
Gravitational waves

Agazie+2023; NANOGrav15



Quasars

luminosity function



Xin & ZH 2021; Kulkarni+2019

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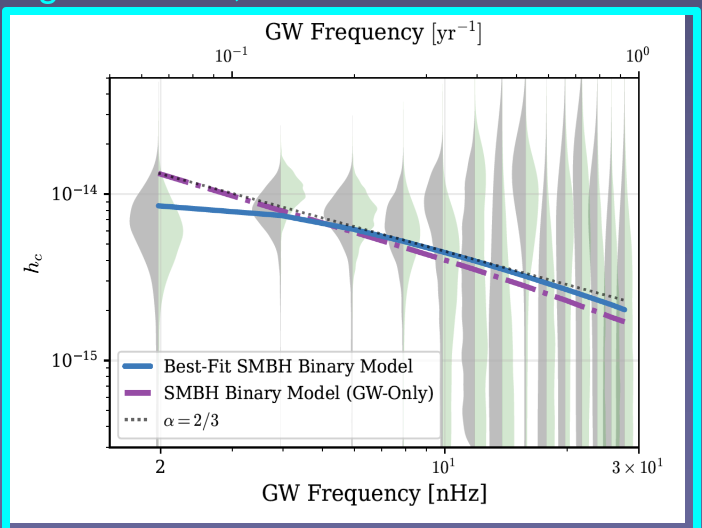
inspiral rate

(GWs + gas
Agazie+23)

Gravitational waves

Agazie+2023; NANOGrav15

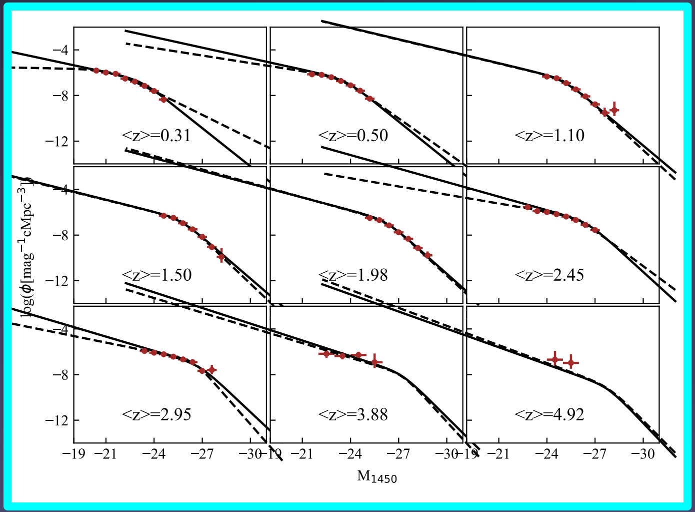


$$\frac{dE_f}{d\ln f}(M, q, z, f)$$

(Peters 1964)

Quasars

luminosity function



Xin & ZH 2021; Kulkarni+2019

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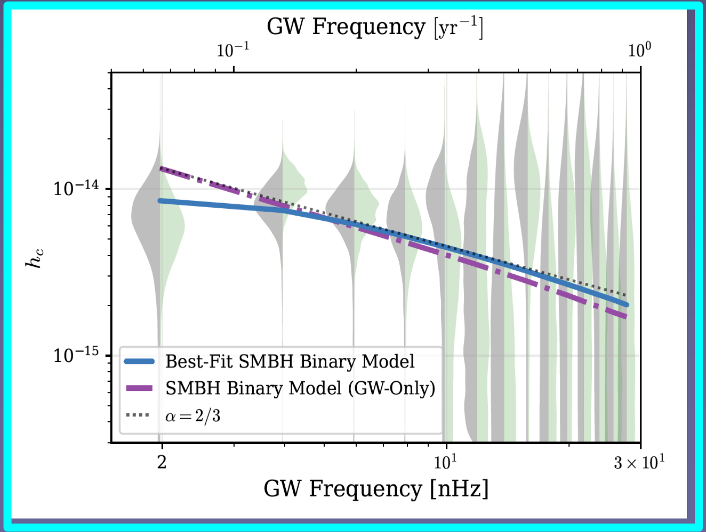
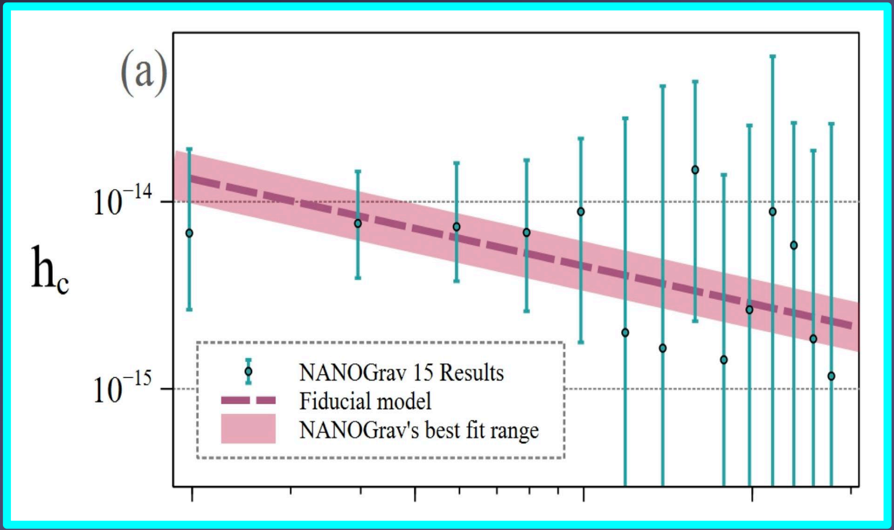


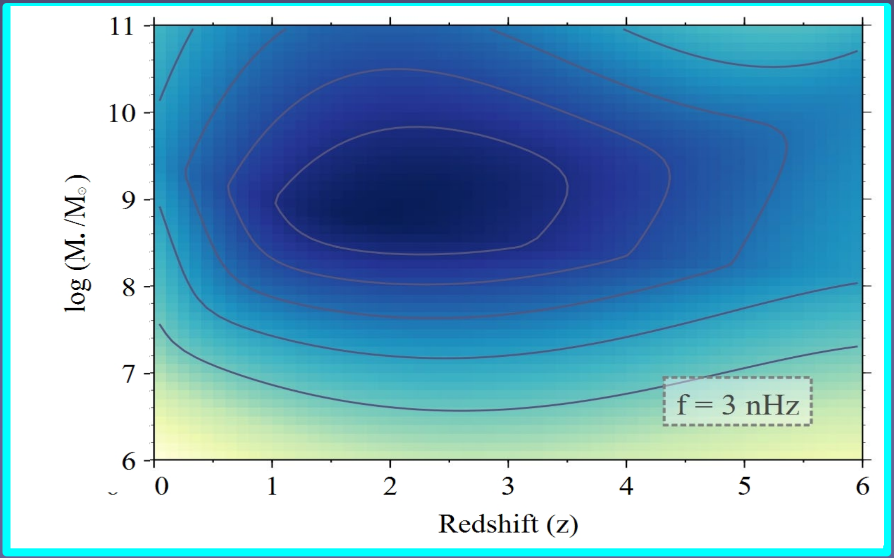
$$\frac{dE_f}{d\ln f}(M, q, z, f)$$

(Peters 1964)

Result



matches the NANOGrav background



dominant contribution from M~10^9 M☉ at z ~ 2-3

impact on GWB:
spectrum, stochasticity, anisotropy, single source

OK, but can we identify the actual EM counterpart of an individual LISA source?

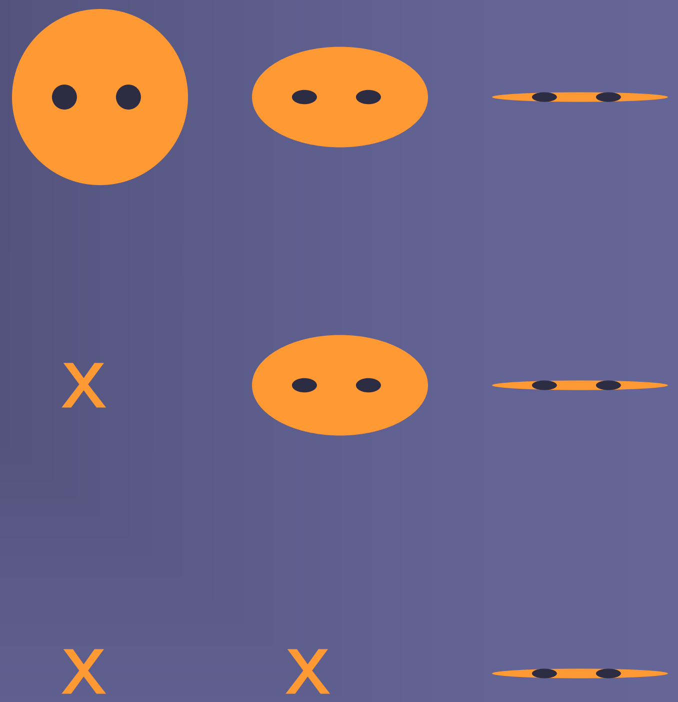
Binary Black Holes are Periodic

three reasons

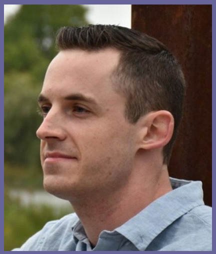
I. **Hydrodynamical modulations**
for near-equal mass

II. **Doppler effects**
for unequal mass, inclined

III. **Self-lensing**
for near-equal mass, edge-on



Equal-mass, circular binary



Ryan Westernacher
-Schneider

Westernacher-Schneider et al. (2022)

Sailfish; **GPU-enabled 2D hydro code, Cartesian coö's**

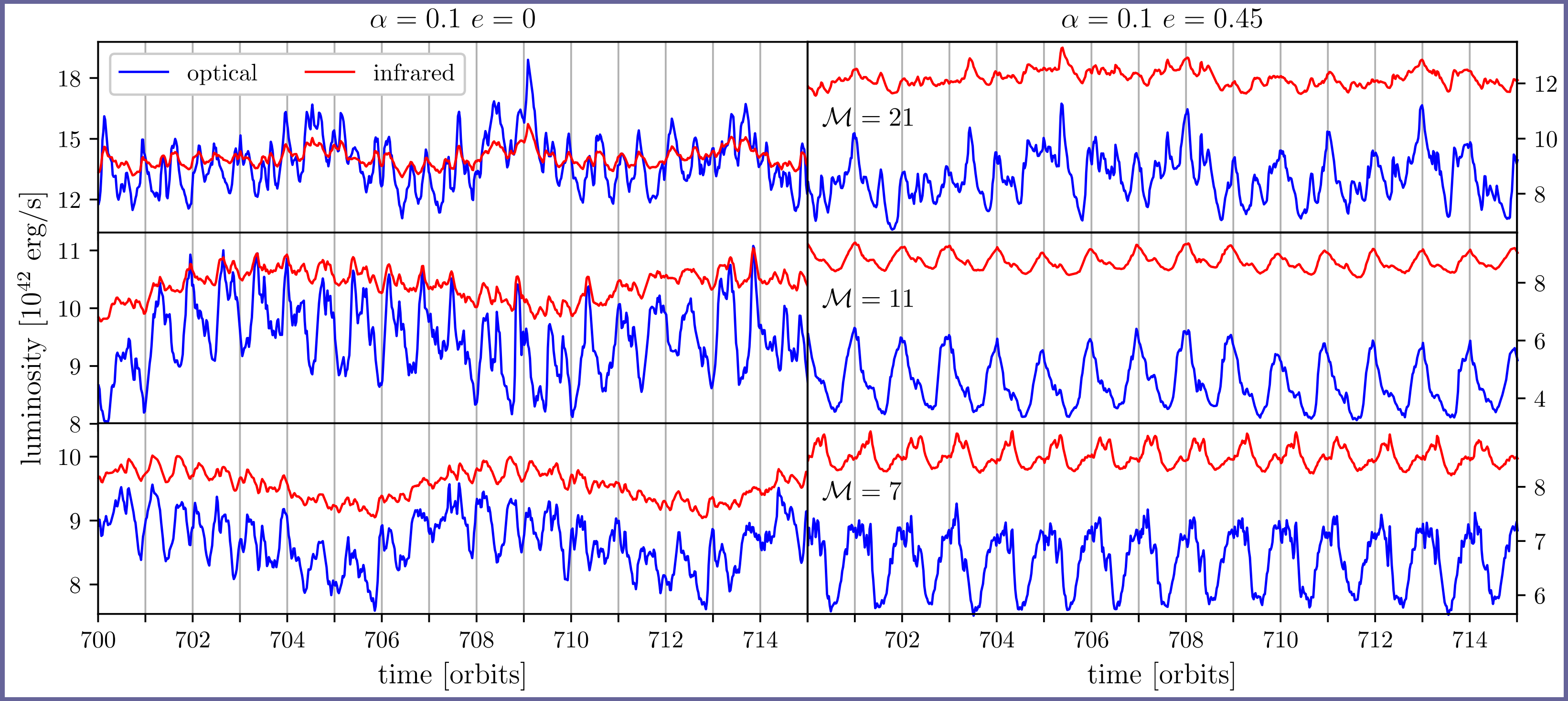
mass ratio (q), eccentricity (e), temperature ($\mathscr{M}$)

Periodicity from hydrodynamics

Thermal emission; optical and IR

Ryan Westernacher -Schneider

Circular *Eccentric*



colder

warmer

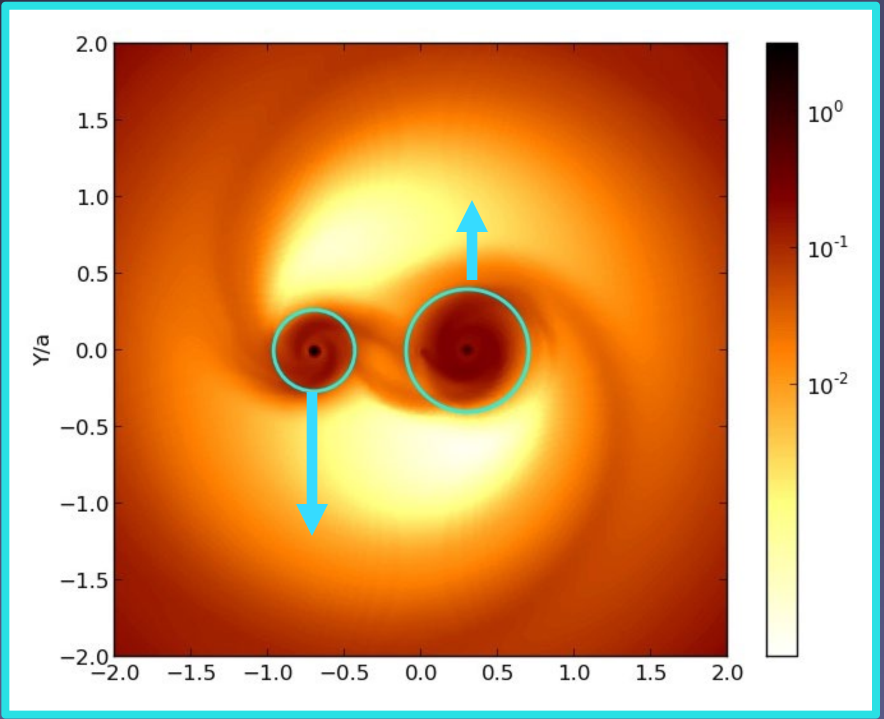
* also interesting dependence on mass ratio: Duffell+20

q≲0.05: *steady* 0.05 ≲ q ≲ 0.3 *single sinusoid* q≳0.3: *lump*

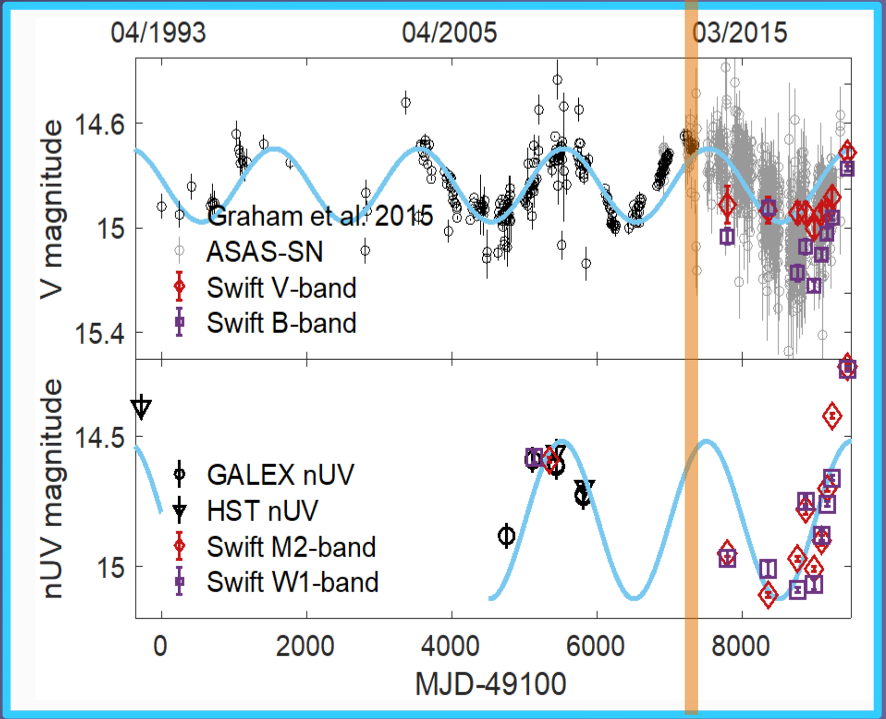
* additional beat frequencies from precession Westernacher-Schneider+23

Periodicity from Doppler boost ("EM chirp")

ZH 2017, D'Orazio+2016, Duffell+2020



Graham+2015, Dorazi+2016, Xin+2020



compact LISA binary

X-ray emission from quasars: few R_g

Minidisk = X-ray corona of single BH

Doppler brightness modulation O(v/c) ~ 0.1

Wide EM binary

opt/UV from ~ few 100 R_g

minidisk = AGN disk

P~yr → v/c ~ 0.01

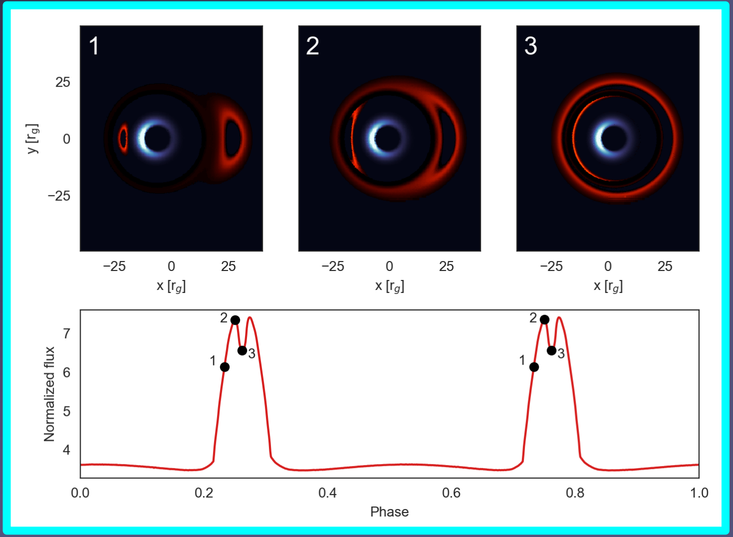
→ dominates over hydro-variability for $q=M_2/M_1 \lesssim 0.05$ ←

Recurring Self-Lensing Spikes

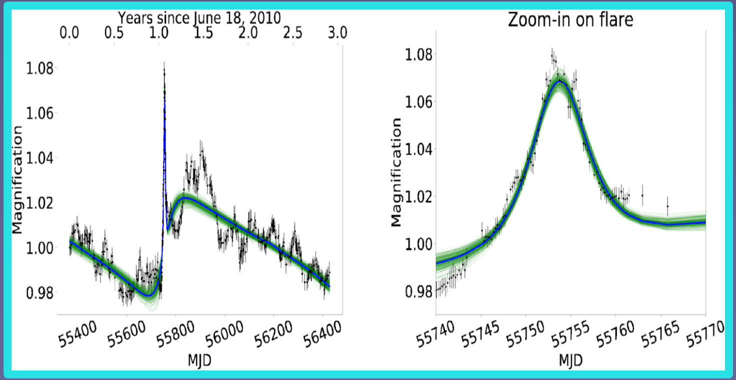
note: $\theta_E/\theta_{bin} = (2a_{bin}/R_s)^{-1/2}$

toy disks
Davelaar & ZH (2022a,b)

compact ($d=100\ R_s$) edge-on binary $i = 90°$



"Spikey"
Hu+2020



- flares visible within $\pm$3-30° of edge-on
- shadow visible if $\pm$1-10° of edge-on
- week-long flares in periodic quasars
- 10x higher chance for LISA binaries (already compact)

→ 100s detectable by Vera Rubin Observatory (LSST, 2024+)
Park et al. (2024)

Can we find LISA counterparts?

OK, binaries are periodic… but:

1. **What happens after GW-driven runaway, near merger?**
   Is there still gas? Do binaries remain bright & periodic ?

2. **How do we find these periodic sources?**
   Pre-merger LISA localization seems too poor
   for a triggered search.

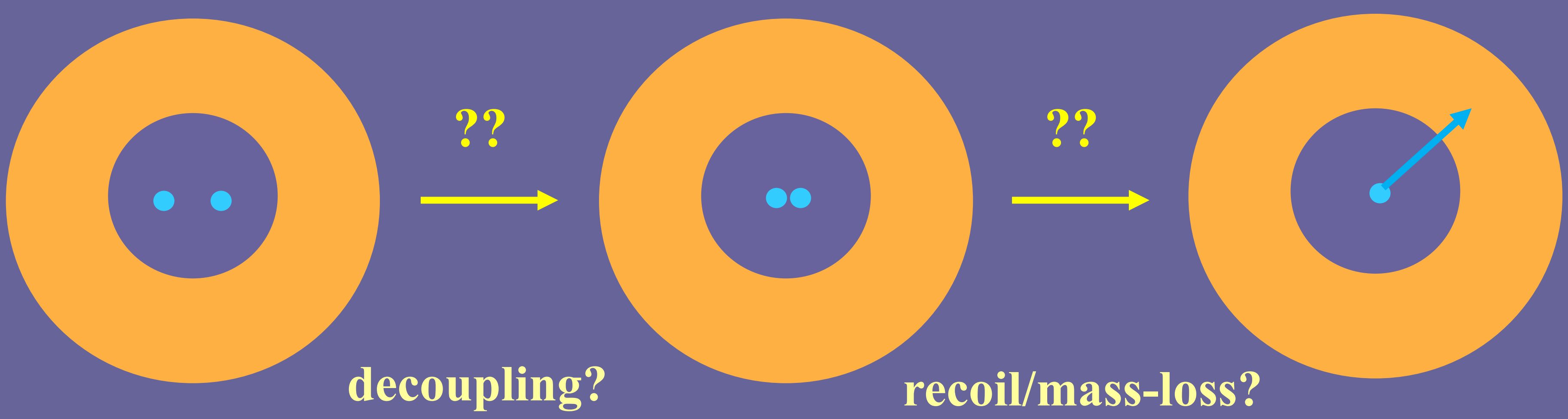
EM signatures at merger

Luke Krauth et al. (2023)

Luke Krauth

Follow GW inspiral ($10^6\ M_\odot$) for last ~month before merger (~1000 orbits)

Follow post-merger disk including recoil and mass-loss of remnant



Disappearing minidisks!

Binary suddenly vanishes in X-rays?

But stays in optical UV and infrared

Can catch this with Athena (use LSST or its archival data)

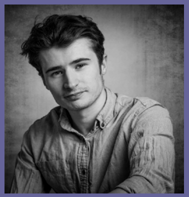
No need for pre-merger localization and monitoring

Beyond vanilla circular inspiral….

Retrogade inspiral:

→ no minidisks, earlier rebrightening, QPEs

O’Nell, Tiede, D’Orazio, ZH, MacFadyen (arXiv:2501.11679)



David O’Neill

Unequal-mass inspiral:

→ cavity smaller, X-ray drop delayed, preceded by flare

Krauth+(arXiv:2503.01494)

Luke Krauth

GR precession:

→ extra EM periodicity measurable for
$M=10^5$—$10^7\,M_\odot$ with $e>0.25$ and $a=100-1000\ R_s$

de Laurentiis, ZH, + (arXiv:2405.07897)

Stan de Laurentiis

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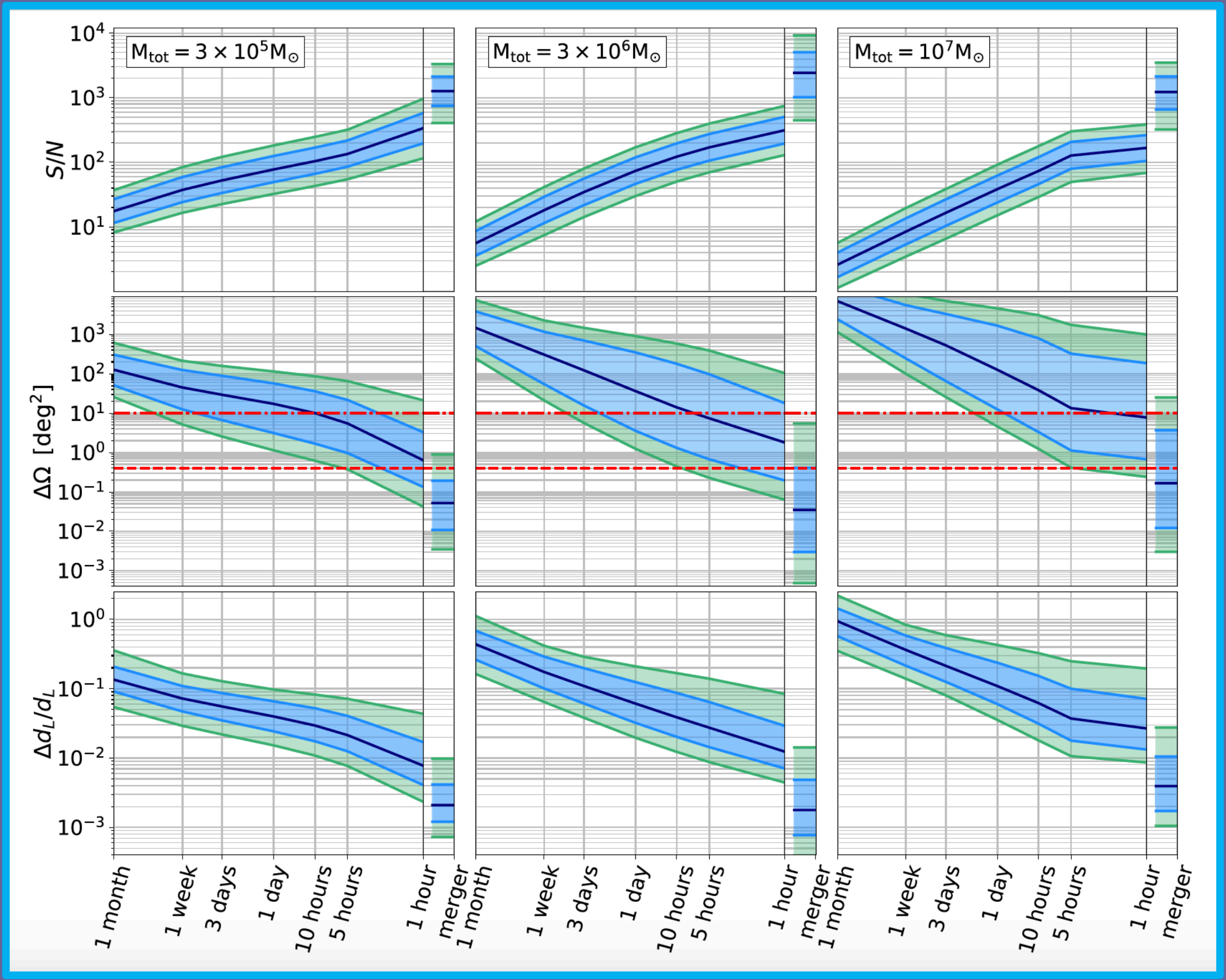
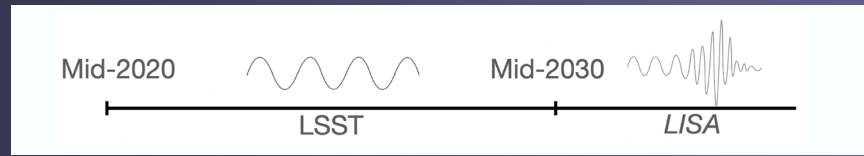
Pre-merger localization - ouch

Mangiagli et al. 2020



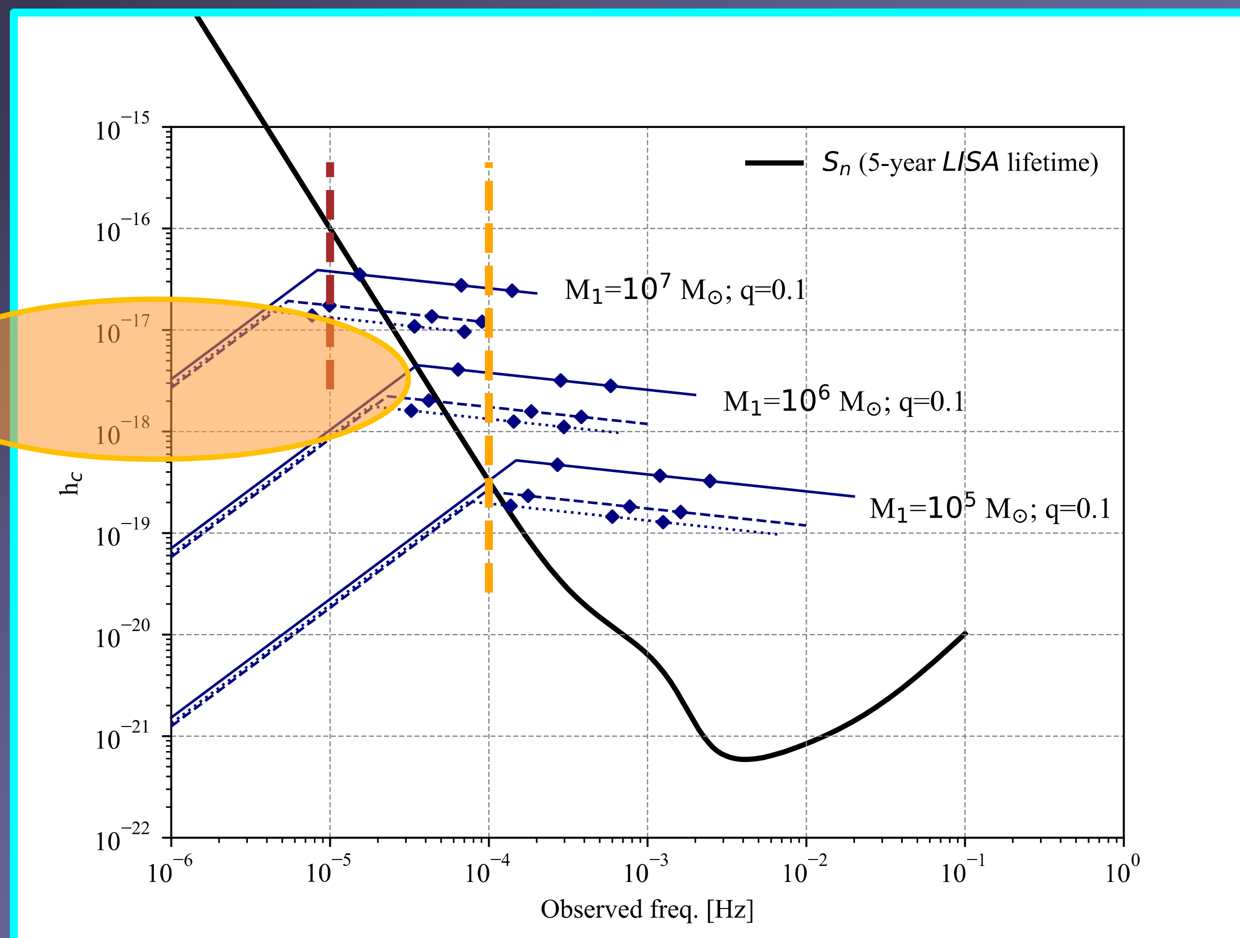
Look for targets in LSST archival catalog

Chengcheng Xin



Xin+ZH (2024)
Xin+ZH (2021)

O(100) binaries
$M \sim 10^5$ - 10^6 $M_\odot$
$z \sim 1$-2
$P \sim$ day
in LSST →

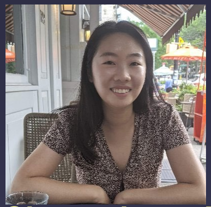


perfect for
this search:

1. wide
2. deep
3. high cadence

1 year **1 day** **1 hr**

Look for targets in LSST archival catalog



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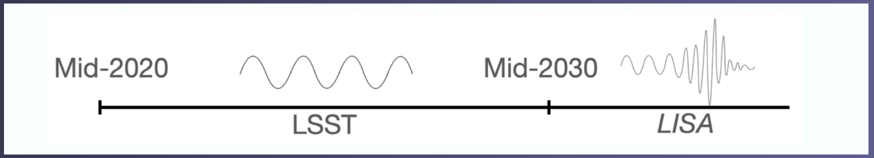
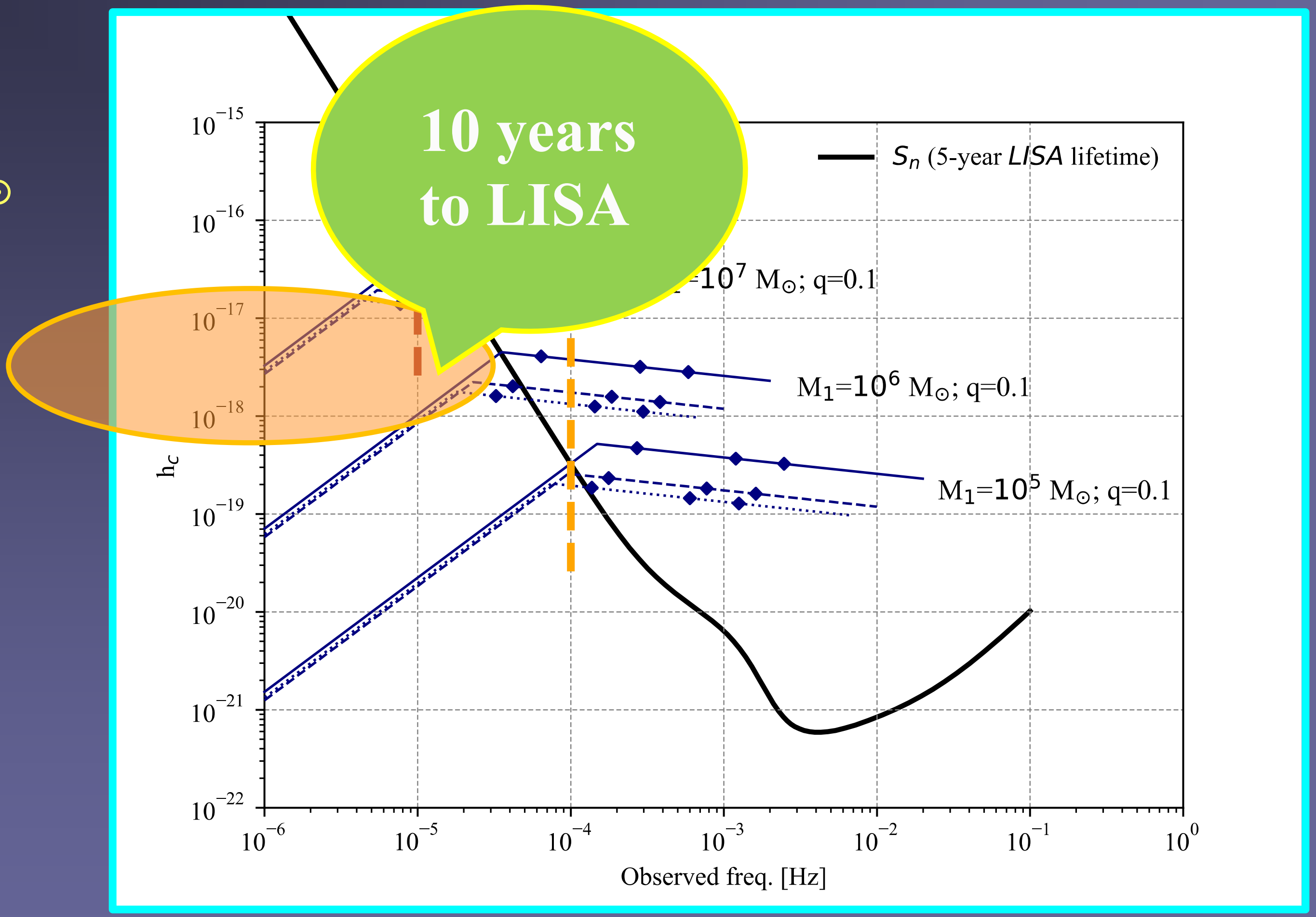


Xin+ZH (2024)
Xin+ZH (2021)

O(100) binaries
$M \sim 10^5$ - 10^6 $M_\odot$
z ~ 1-2
P ~ day
in LSST

perfect for
this search:

1. wide
2. deep
3. high cadence



1 year **1 day** **1 hr**

Identifying LISA counterparts

Option 1. Detect unfolding merger by LISA first

Identify counterpart in LSST archive from historical chirp — Xin+ZH (2024)

False alarm probability to mimic chirp signal is $\ll 1$

**** OR ****

Option 2: Identify binary in LSST data alone

Few hundred will become LISA source (rapid EM chirp) — Xin+ZH (2021)

Many more wider binaries 100 or 1000 years from merger — Xin+ in prep

**** IN EITHER CASE ****

Follow-up campaign: deep EM (e.g. X-ray) observations

works as long as merging binaries are often AGN

Conclusions

0. "Quasars=binaries" appears consistent with NANOGrav
1. Binaries are periodic: hydro, Doppler, self-lensing
2. Binaries remain bright but disappear in X-rays in last ~20 orbits
3. LSST archives will contain LISA source, permit triggered search
4. Many more wider precursors in LSST, ~10^4 lensing flares