Institute for Computational Science (ICS)
Center for Theoretical Astrophysics and Cosmology

University of Zurich[UZH]

Prof. Lucio Mayer, Director ICS
Prof. Ravit Helled, Deputy Director ICS

As of September 2022 ICS hosts 11 professors, 2 permanent research staff members, and 42 among PhD Students and Postdoctoral Researchers

Main research areas with group leaders

I. Supercomputer simulations for astrophysics and cosmology

(Mayer, Stadel, Feldmann, Schneider)

Development of major parallel supercomputer codes employed by international community

(PKDGRAV3, GASOLINE2/ChaNGa,GENGA, GIZMO, **SPH-EXA — collaboration with University of Basel, University of Washington, Caltech, McMaster University, University of Oslo, UC Santa Cruz, Princeton University**)

Focus applications: cosmological structure and galaxy formation, (super) massive black holes growth and evolution

II. Theoretical Cosmology

(Yoo, Adamek, Schneider). Relativistic effects in structure formation

III. Black Hole and Gravitational Wave Astrophysics

(Mayer) - Supermassive Black Hole Binaries and Waveform Physics

IV. Planetary Science

(Helled, Mayer, Moore, Stadel. Mazzola) - Interiors and Formation

V. Data Science for Natural Sciences

(Wegner, Feldmann)

ICS researchers have strong Involvement in LISA Consortium and LISA Astrophysics Working Group (WG)

LISA CONSORTIUM

Current group members involved in GW research:

Pedro Capelo, Andrea Derdzinski (Postdocs), Lorenz Zwick, Mudit Garg, Lara Bohnenblust, Noemi Fabri (PhD students), Simone Pacuraru (exchange Msc student with Universita' Milano-Bicocca)

Affiliate Group Member: Prof. Harald Ita + postdoc expert in scattering amplitude calculations (in hiring phase)

() LISA Astrophysics Working Group leadership: Mayer Co-Chair since 2018

()LISA Astrophysics White Paper: 3 coordinators from ICS

()Sub-Workpackage "Massive BHs" Group Leader: Pedro Capelo

()Contributors to LISA Red Book (Mayer and Capelo for MBHs, Zwick and Derdzinski for EMRIs/IMRIs)

() LISA Astro WG collaborative projects: leadership of new "DiscIMRI" code comparison

Research topics in GW science

1. **Multi-scale simulations of LISA massive black hole binaries in Galactic nuclei (from kpc to 10^{-2} pc scales) w/newtonian hydrodynamics, post-newtonian gravity (in some cases)**

2. Formation of the seeds of LISA massive black holes at high redshift *(recall LISA has, in principle, the power to distinguish between different BH seed models via even rate distribution as a function of redshift).* **Analytical models and simulations**

3. Simulations of early in-spiral phases of IMRIs embedded in gaseous accretion disk —-> *evolution of orbital parameters and disk-driven torques as perturbations to waveforms*

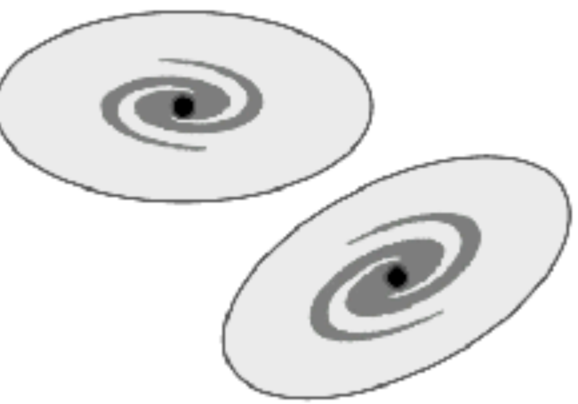
4. (Semi)analytical models of waveform perturbations due to environment and their detectability Study using toy model (eg "Dirty Waveforms" — Zwick et al. 2022, and Garg et al. 2022)

5. In-situ generation of IMRIs, EMRIs and stellar BH sources in accretion disks around SMBHs (with semi-analytical models and hydro+MHD simulations)

6. Scattering amplitude methods borrowed from QCD as new tools to construct accurate waveforms for highly eccentric sources in the PM approximation

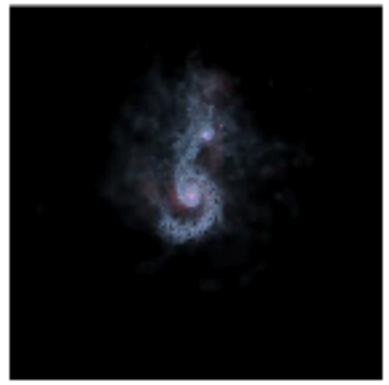
The four key stages of MBH binary evolution until onset of GW emission: multi-scale numerical simulations

Credit: Lupi et al. (2019)

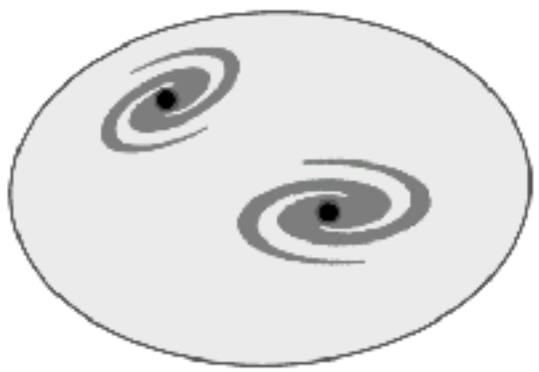


Mpcs:
The large scale structure

Influence of the large scale environment on: black hole seeding, frequency of mergers, galaxy transformation

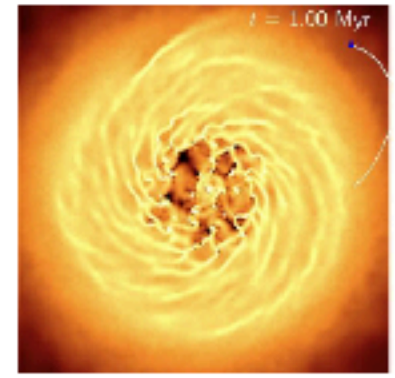


Credit: Capelo et al. (2015)



1-100s kpcs:
Galaxy interactions/merger

Details of the merger have influence on: black hole growth via gas accretion, formation of a black hole binary, galaxy transformation



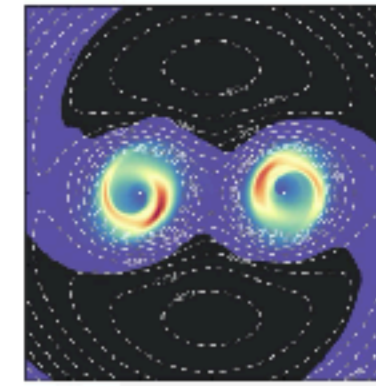
Credit: Souza Lima et al. (2017)

Circumnuclear gas disk (CND) stage

1-10s pc:
Formation of a bound binary

The host properties have influence on: hardening of the binary, accretion episodes

Degree of clumpiness of gas disk matters for orbital evolution, accretion etc.



Credit: Bowen et al. 2017

Circumbinary gas disk stage

<1 pc:
Hardening of the binary

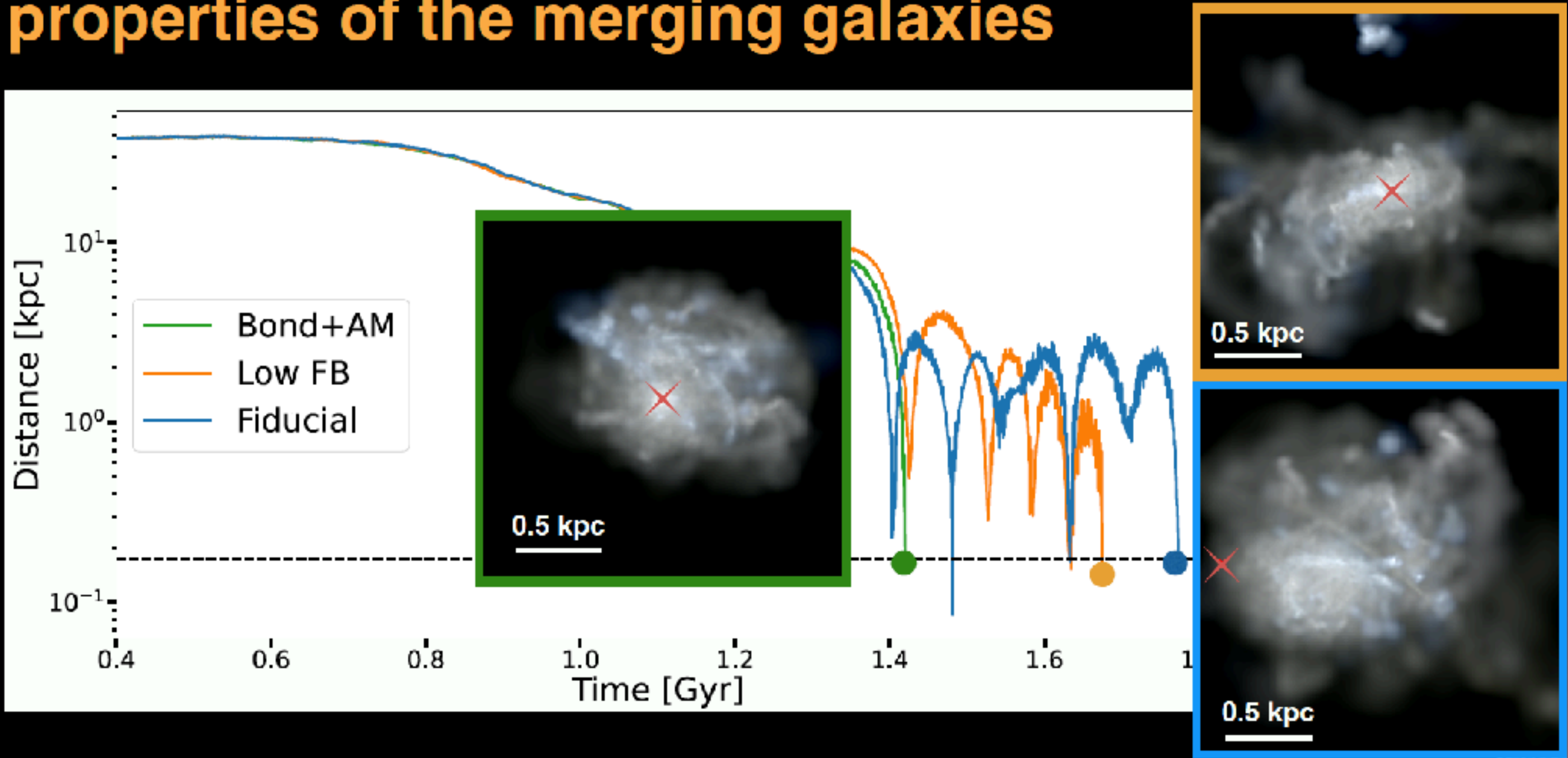
The host properties have influence on: timescale of hardening
Effect of circumbinary disc
Three-body interactions (hyper-velocity stars)

From LISA Astrophysics White Paper

Cosmological hydro simulations of galaxies with embedded massive BHs in the LISA band

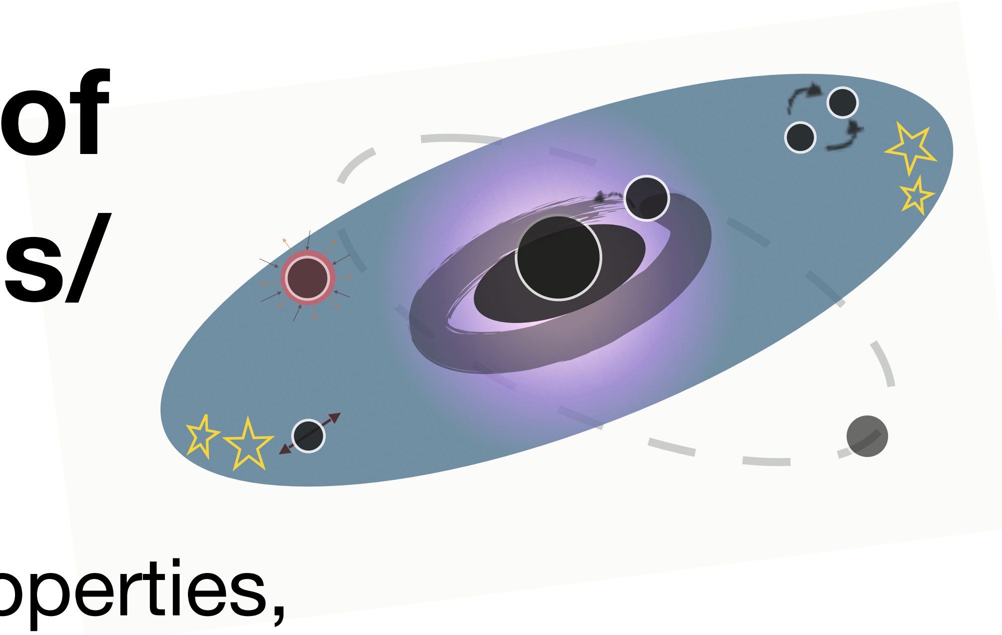
Dynamical Evolution of Massive Black Hole Pairs

The BH merger timescale is affected by the properties of the merging galaxies

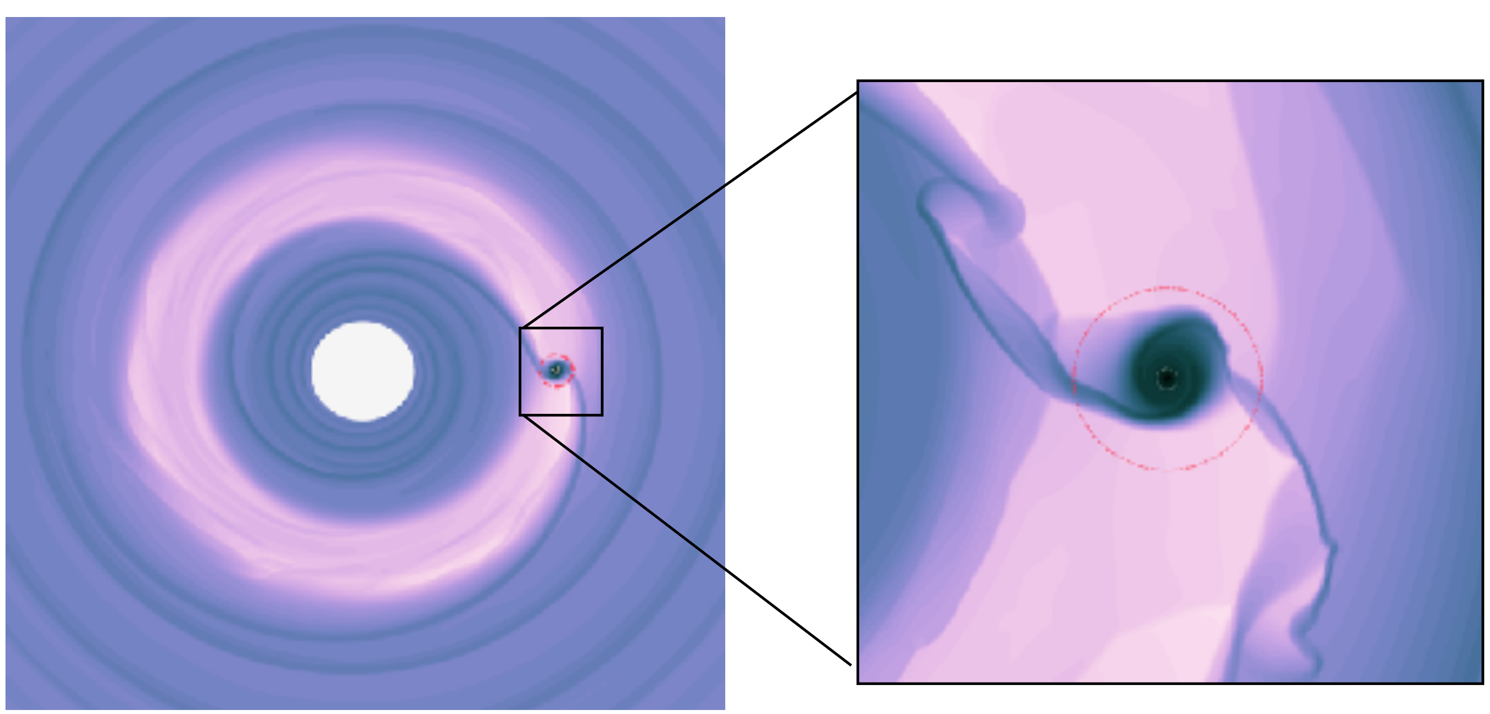


Above: same dwarf galaxy merger with different models for radiation feedback by massive black hole at center (Tremmel et al. in preparation)

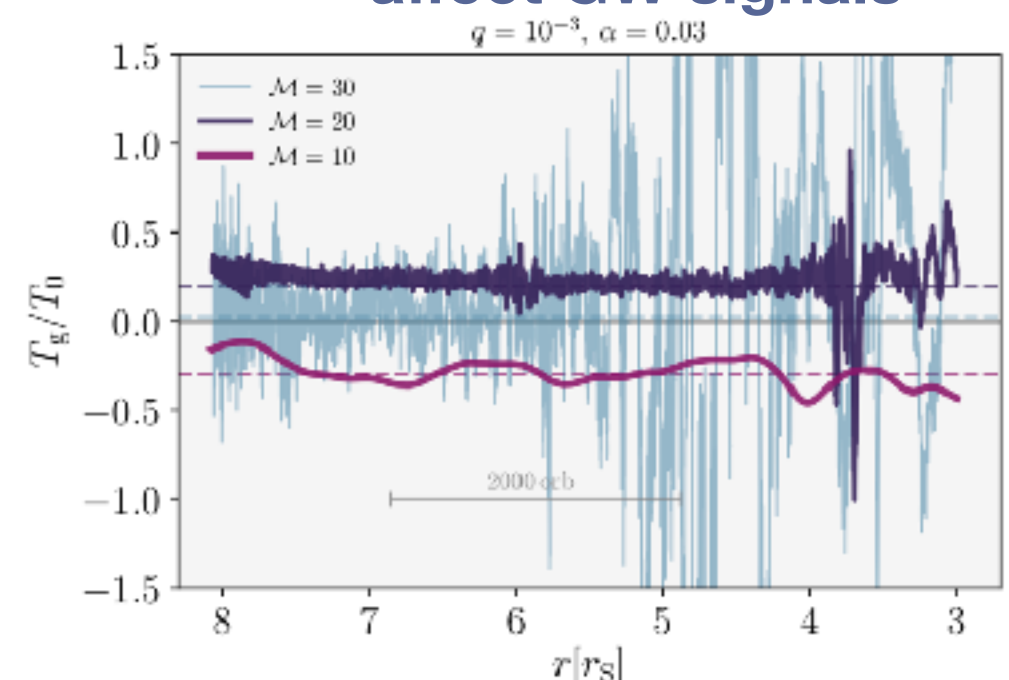
Hydrodynamical simulations of unequal mass BHs and EMRIs/ IMRIs in accretion disks



- Gas interaction determines rates, orbital properties, and evolution *during* GW early in-spiral phase
- EMRIs produced via in-situ star formation in massive AGN disks can outnumber the conventional EMRI rate in star clusters
  Derdzinski & Mayer (2022:arXiv220510382D) $R_{\rm AGN} \sim 0.5 - 10\ {\rm yr}^{-1}{\rm Gpc}^{-3}$

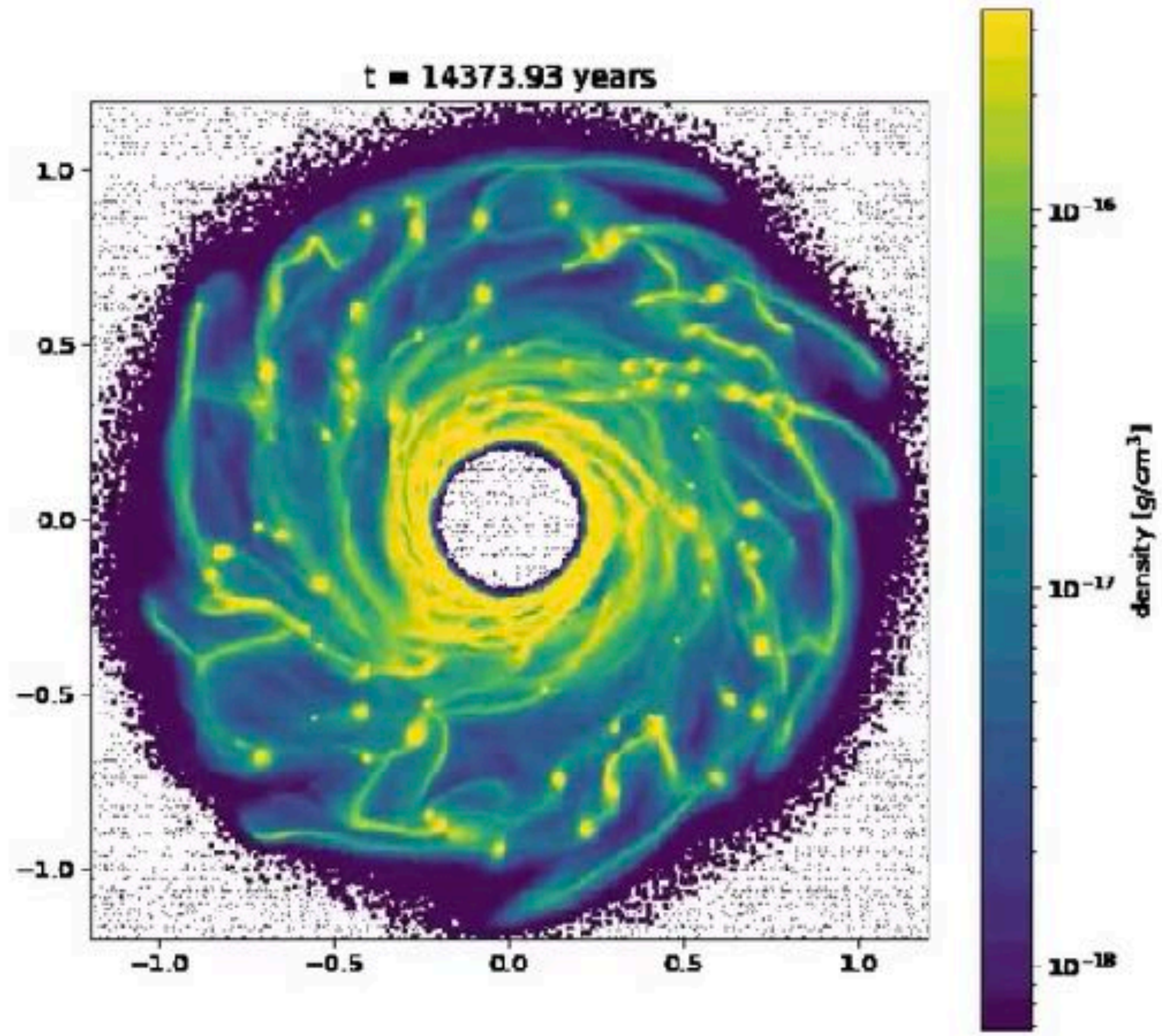


Torques exerted by gas affect GW signals



Derdzinski+ 2021

- In-situ population of massive stellar remnants interact with gas and with each other —> generation of LISA EMRIs and LIGO/Virgo Stellar BH sources, as well as multi-band sources (IMBHs at the LISA-LIGO interface)
- Binaries as well as unbound encounters/scatterings



3D GIZMO-MFM simulation of a fragmenting accretion disk to study directly the formation and dynamics of population of stellar remnants (simulation by Simona Pacuraru)

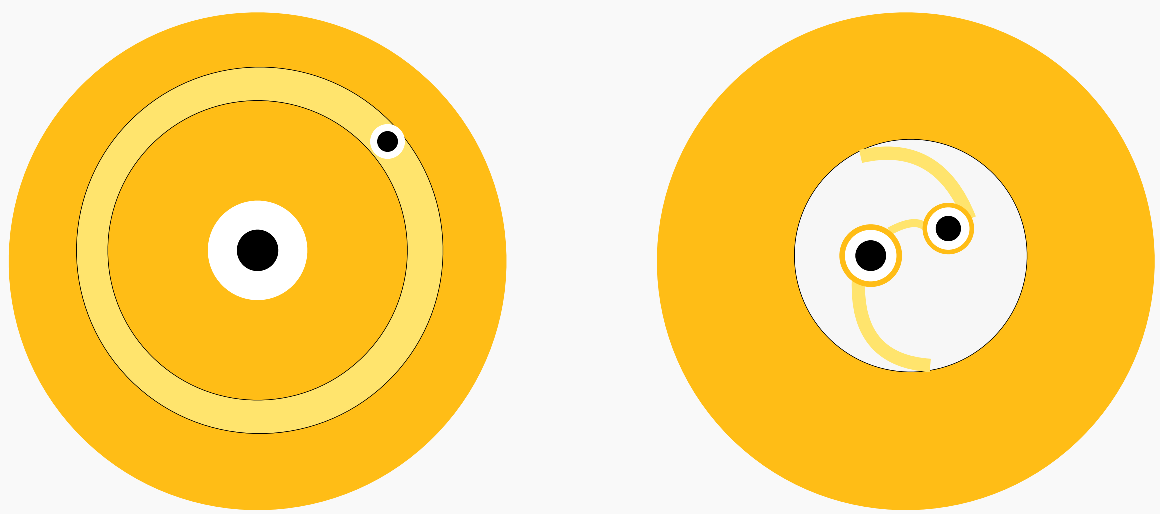
INTERMEDIATE MASS BLACK HOLES (IMBH) BINARIES: Golden sources for LISA

Garg et al. 2022, (MNRAS517, 1339): study of the detectability of environmentally induced phase-shifts in the LISA band

Features

- Can enter LISA band at separation> 100 Rs
- Can spend > 100 orbits
- Can accumulate SNR
- Can constrain gas physics at small scale

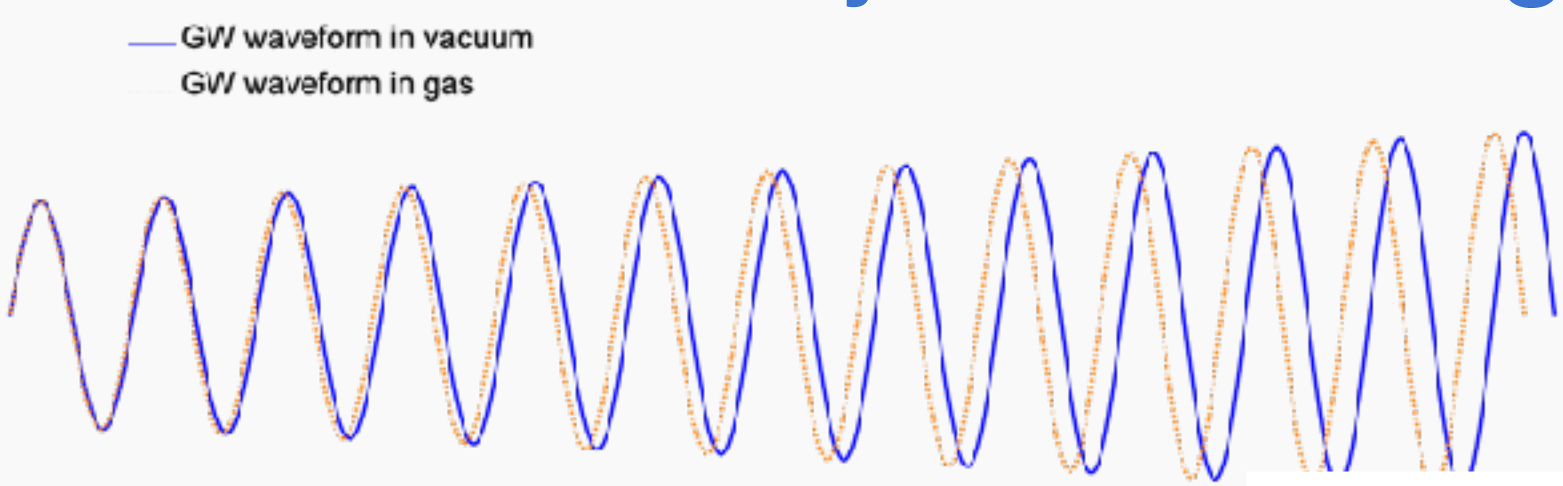
Open Gap/Cavity



Simple analytical disk and torque model "normalized" with results of numerical simulations of Derdzinski et al. (2021)

Disk torque = (0.1-10) x Viscous torque

IMBHB GW waveform carry signature of torques by surrounding gas



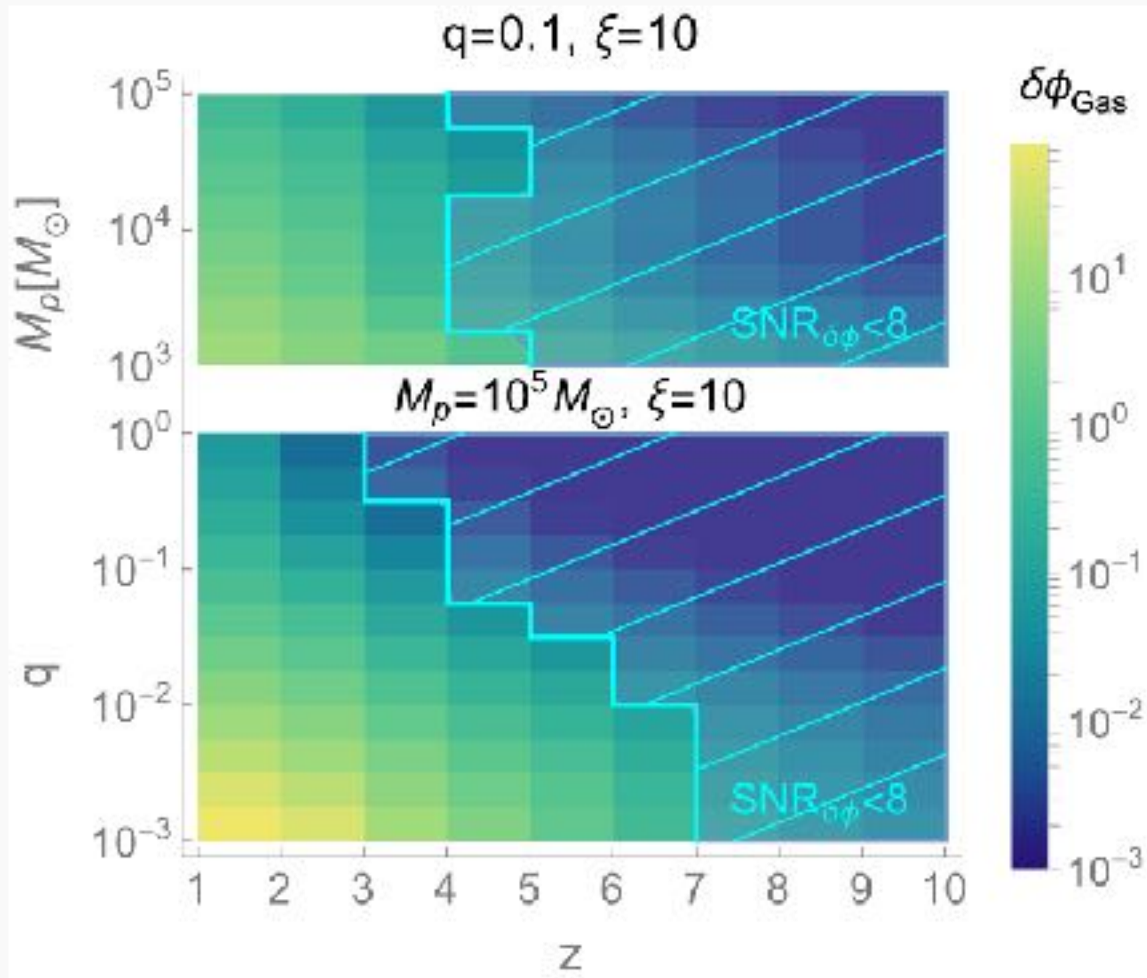
$$\Phi = 2\pi \int_{r_{\rm min}}^{r_{\rm max}} {\rm d}r\, \frac{f_{\rm r}}{\dot r}$$

$$\delta\phi = |\Phi(\dot r_{\rm GW}) - \Phi(\dot r_{\rm GW} + \dot r_{\rm gas})| \approx 2\pi \int_{r_{\rm min}}^{r_{\rm max}} {\rm d}r\, f_{\rm r}\, \frac{\dot r_{\rm gas}}{\dot r_{\rm GW}^2}$$

$$\dot r_{\rm gas} \ll \dot r_{\rm GW}$$

BHs decay faster (i.e BHs perform more orbits) than with just GW emission alone —> corresponds to phase change

Garg et al. (2022)



Detectable dephasing

Up to radians or GW cycles

See also:
Kocsis et al. (2011), Yunes et al. (2011), Barausse et al. (2014), Derdzinski et al. (2019, 2021)

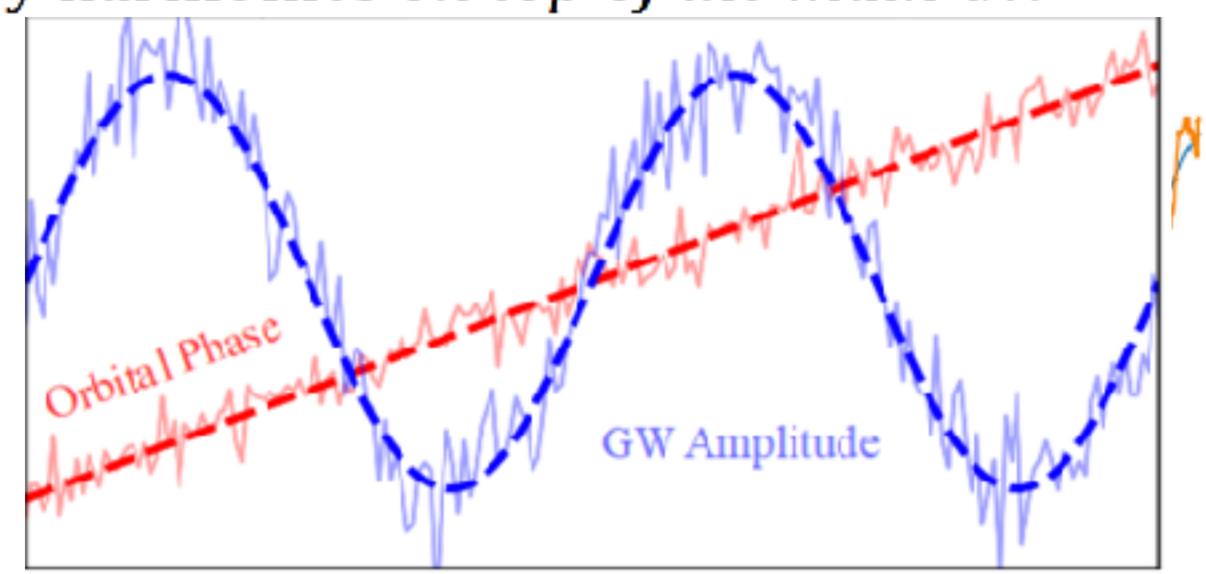
The imprint of disk torque fluctuations due to hydro and MHD turbulence as additional harmonics of waveform (also add secular energy drift): **“DIRTY WAVEFORMS (DWFs)”**
(Zwick et al. 2022, MNRAS, 511, 6143)

Torque fluctuations on small mass ratio secondary → Buffet the secondary's orbit on superorbital frequencies → Quadrupole moment is affected by the acceleration

Generates high frequency harmonics *on top of the main GW*

Strain of n^{th} DWF harmonic

$$|h_n^{\mathrm{DW}}| \sim \sigma_n \frac{4G\dot{L}_{\mathrm{lin}}}{c^4 D_{\mathrm{L}}}$$



Fluctuation spectrum

$$\sigma_n = \sigma \left(\frac{l}{n}\right)^j$$

Calibrated with hydro sims + turbulence model

Typically: 10^{-5} to 10^{-3} of carrier
Typically: $10^2/q$ harmonics

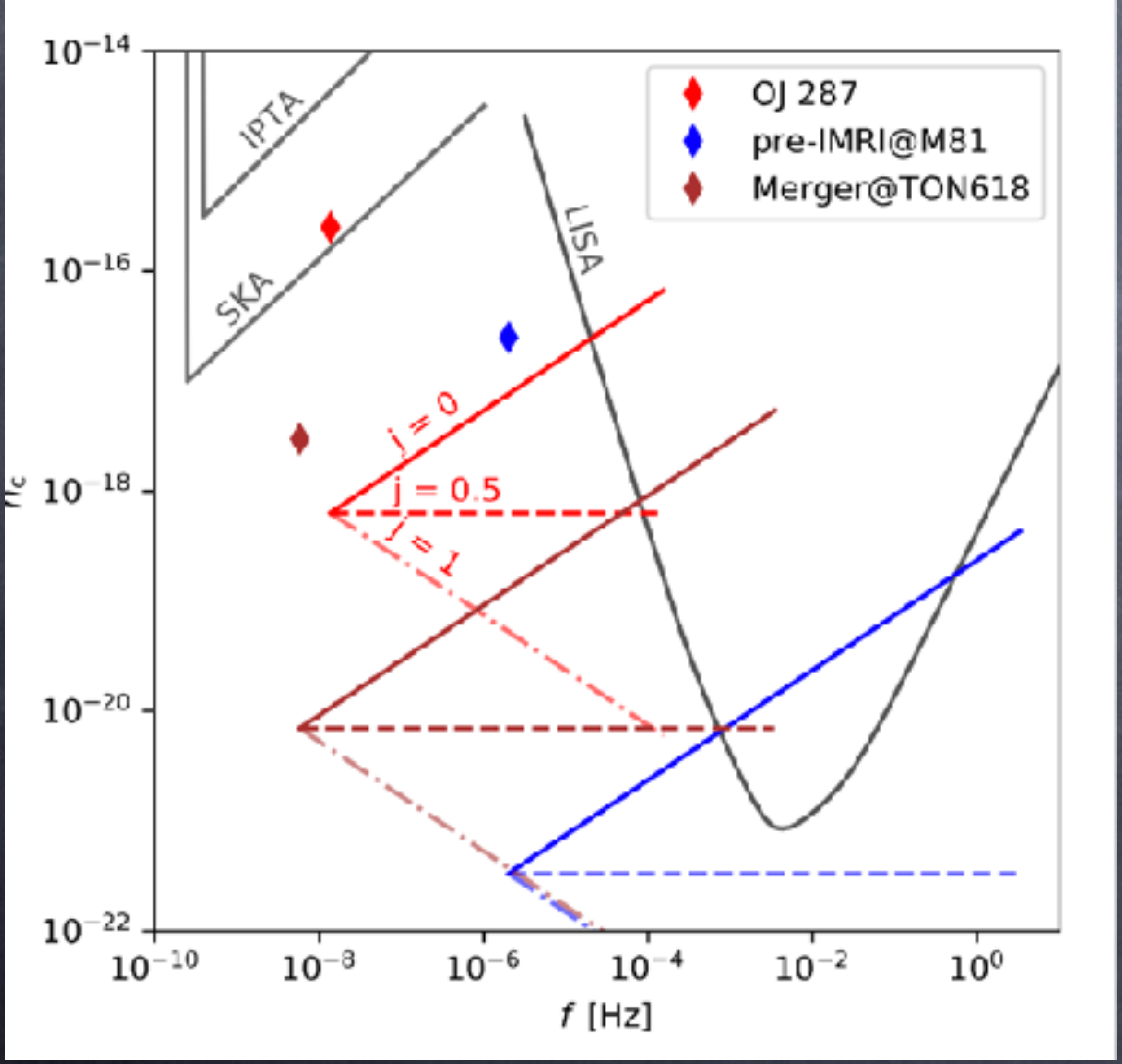
l= number of orbits
n= harmonic number
q= mass ratio

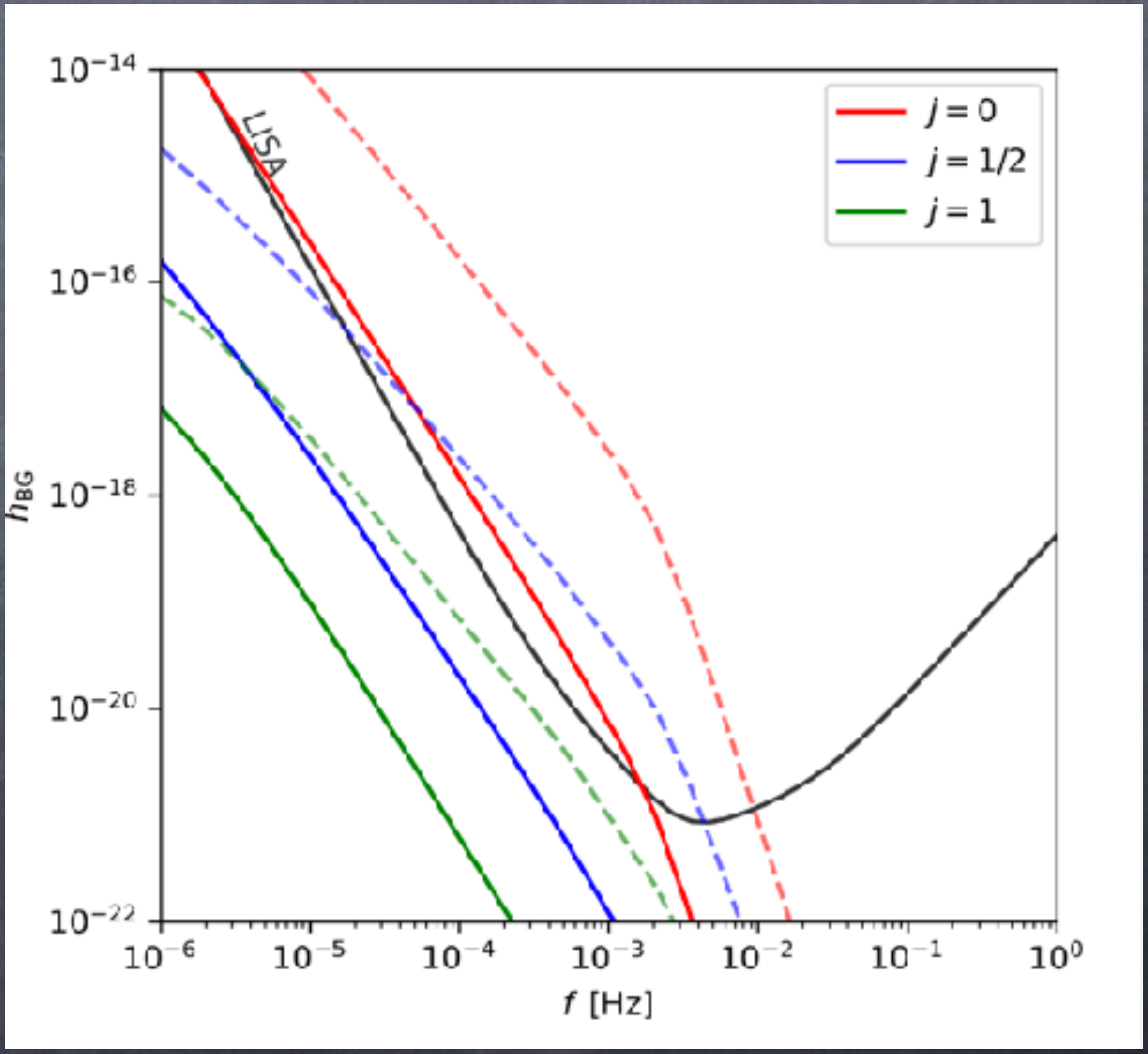
OBSERVATIONAL CONSEQUENCES IN LISA WINDOW

(I) low-frequency Pulsar Timing Array sources produce high-frequency DWs signal in LISA band (higher SNR compared to LISA source because SMBHs much bigger)

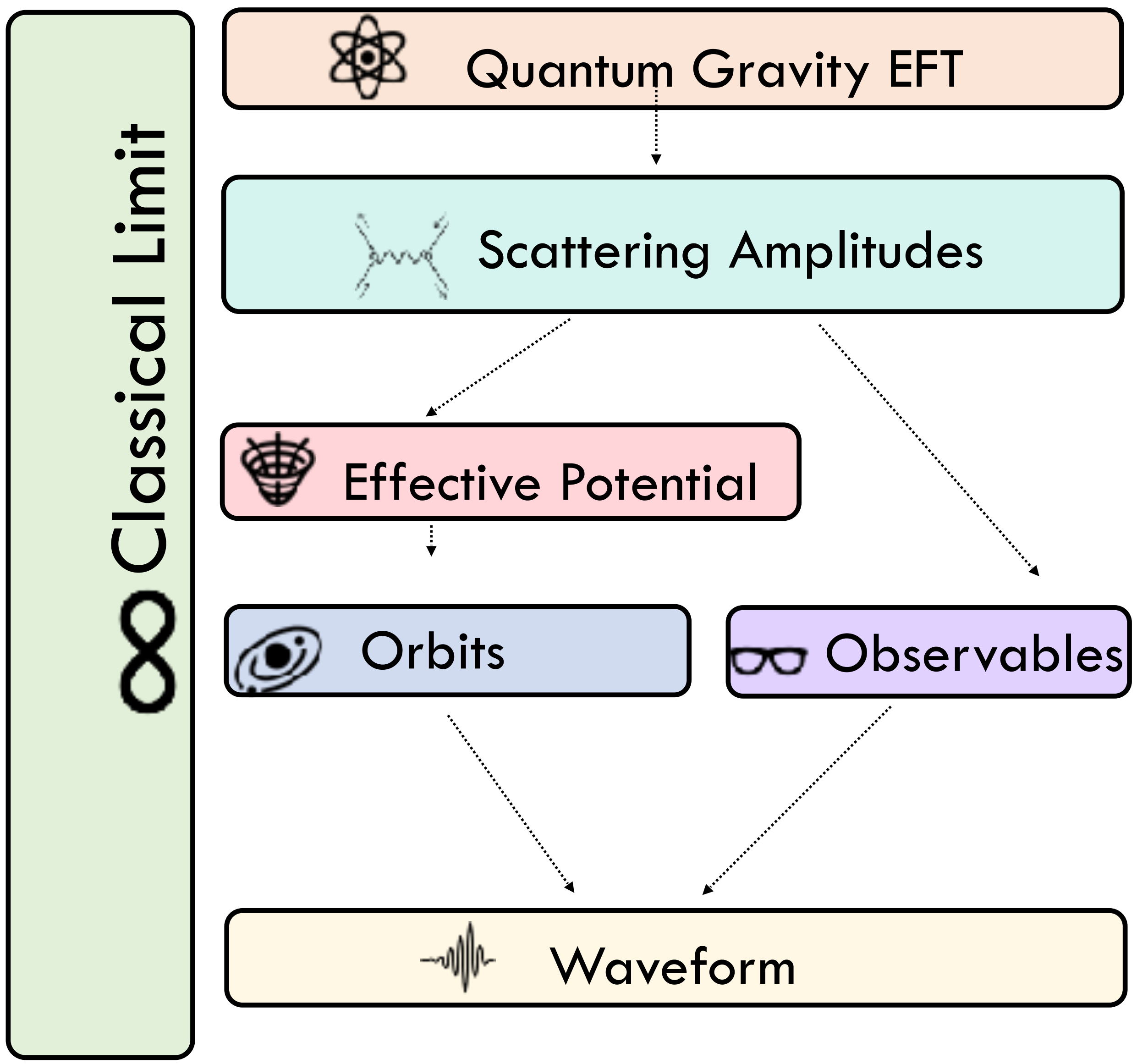
(III) The combination of dirty waveforms from many PTA sources produces new GW background in LISA —> PROPERTIES DEPEND ON ASTROPHYSICAL FLOWS GENERATING FLUCTUATIONS

—> NEW PROBE OF ACCRETION DISK PHYSICS!





Waveforms from scattering Amplitude Methods in the PM limit



PhD students Lara Bohnenblust and Noemi Fabri Co-supervised by Mayer and Ita

Collaboration with groups of Prof. Zvi Bern (UCLA) and Prof. David Kosower (CEA, Saclay), the pioneers of scattering amplitudes applications to gravity

PN vs. PM

Post-Newtonian (PN) is the **slow motion** and **weak field** approximation:

$$v/c \ll 1 \quad r_S/r \sim G \ll 1$$

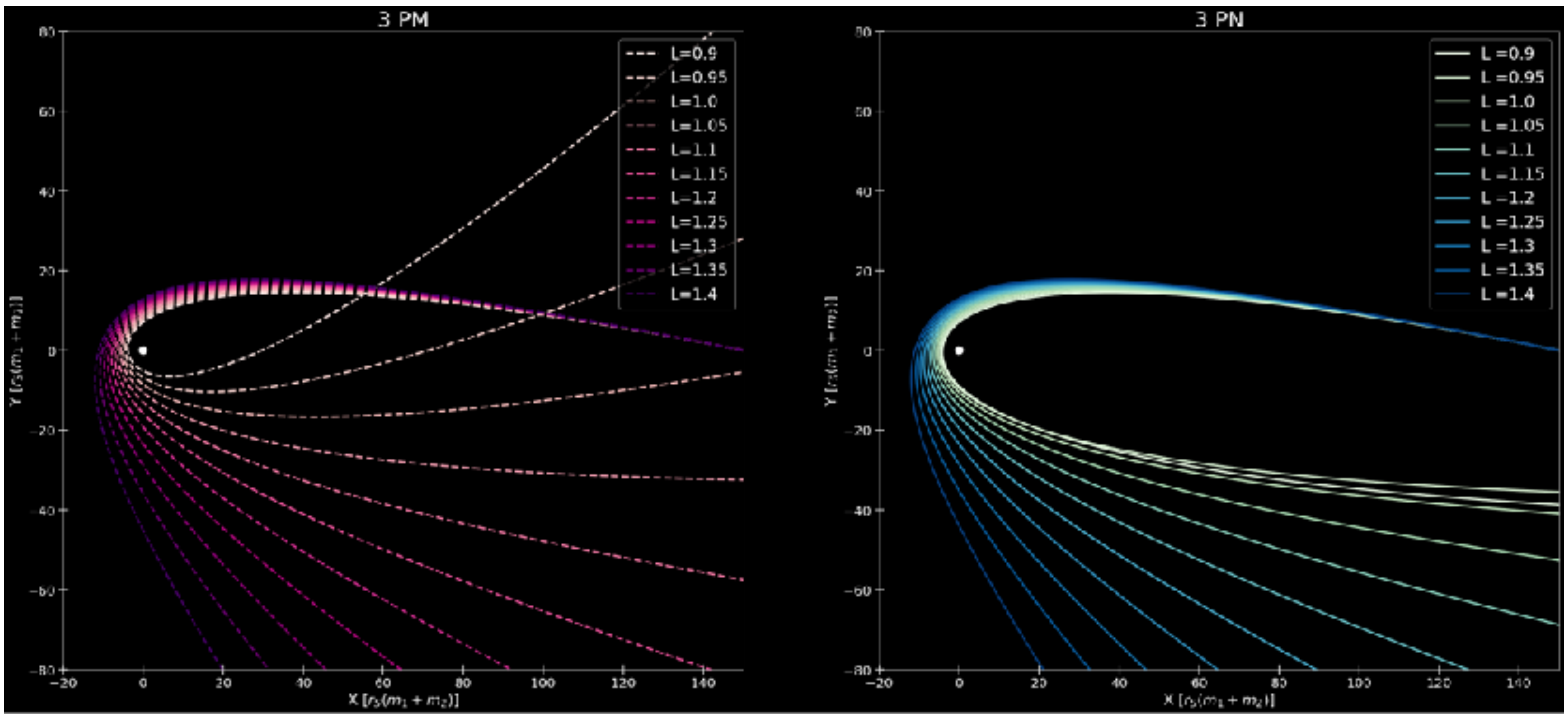
Post-Minkowskian (PM) is only the **weak field** approximation: $r_S/r \sim G \ll 1$

	0PN	1PN	2PN	3PN	4PN	5PN	6PN	7PN		
1PM	$(1$	$+\, v^2$	$+\, v^4$	$+\, v^6$	$+\, v^8$	$+\, v^{10}$	$+\, v^{12}$	$+\, v^{14}$	$+ \dots)$	G^1
2PM		$(1$	$+\, v^2$	$+\, v^4$	$+\, v^6$	$+\, v^8$	$+\, v^{10}$	$+\, v^{12}$	$+ \dots)$	G^2
3PM			$(1$	$+\, v^2$	$+\, v^4$	$+\, v^6$	$+\, v^8$	$+\, v^{10}$	$+ \dots)$	G^3
4PM				$(1$	$+\, v^2$	$+\, v^4$	$+\, v^6$	$+\, v^8$	$+ \dots)$	G^4
5PM					$(1$	$+\, v^2$	$+\, v^4$	$+\, v^6$	$+ \dots)$	G^5
6PM						$(1$	$+\, v^2$	$+\, v^4$	$+ \dots)$	G^6
						$\vdots$				

Bern et al., 2019

Black Hole Pairs on Hyperbolic Orbits

Results from Orbit Integration PM vs. PN (Bohnenblust et al. in preparation)
Method of Integration: *Implicit midpoint method* with adaptive timestep



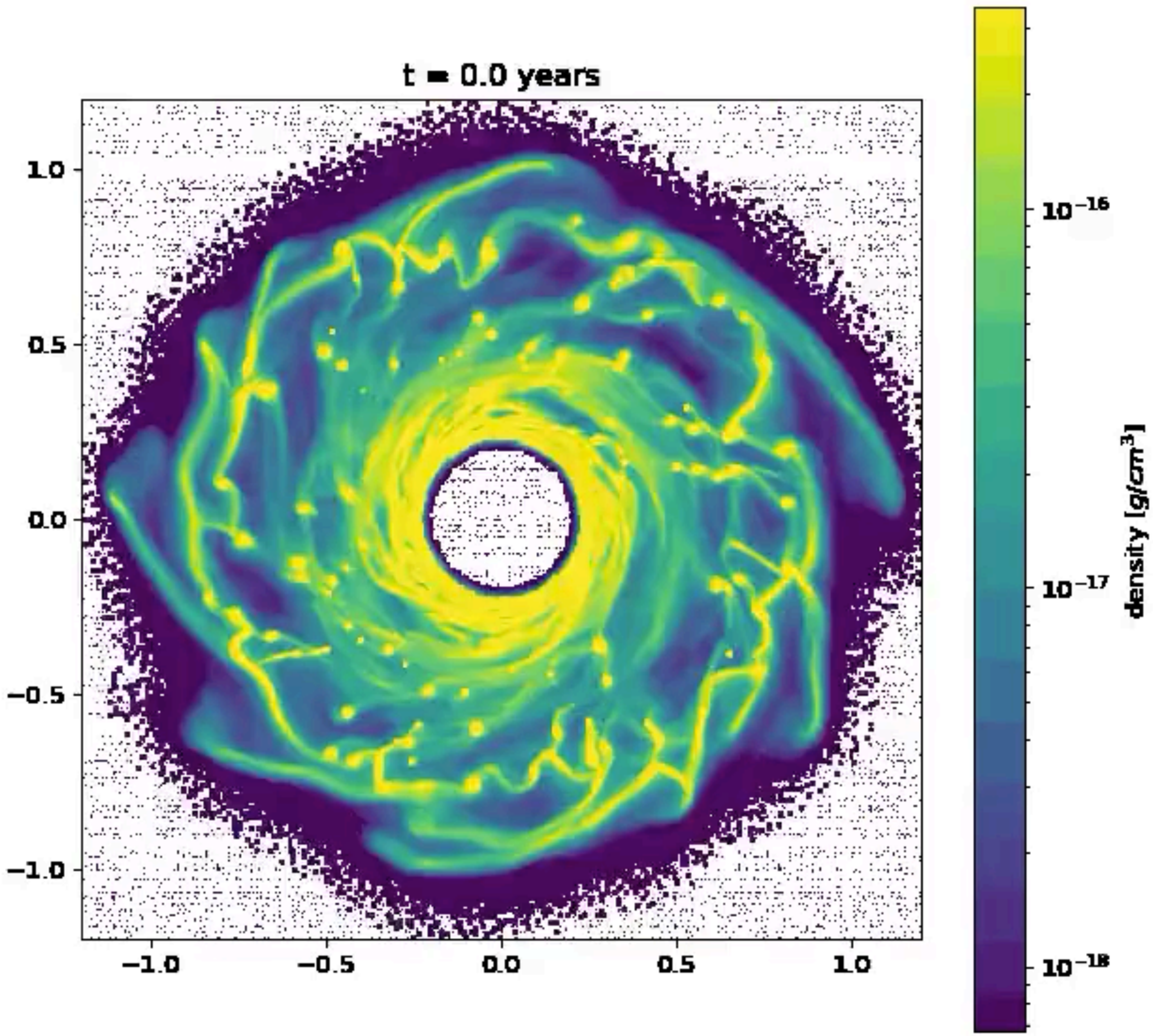
$b \sim 30\, r_s$

$L = 1 \leftrightarrow E_{\rm bind}^{\rm 3PM} = 0$

$v_{\rm max} \sim 0.24 - 0.4\, c$

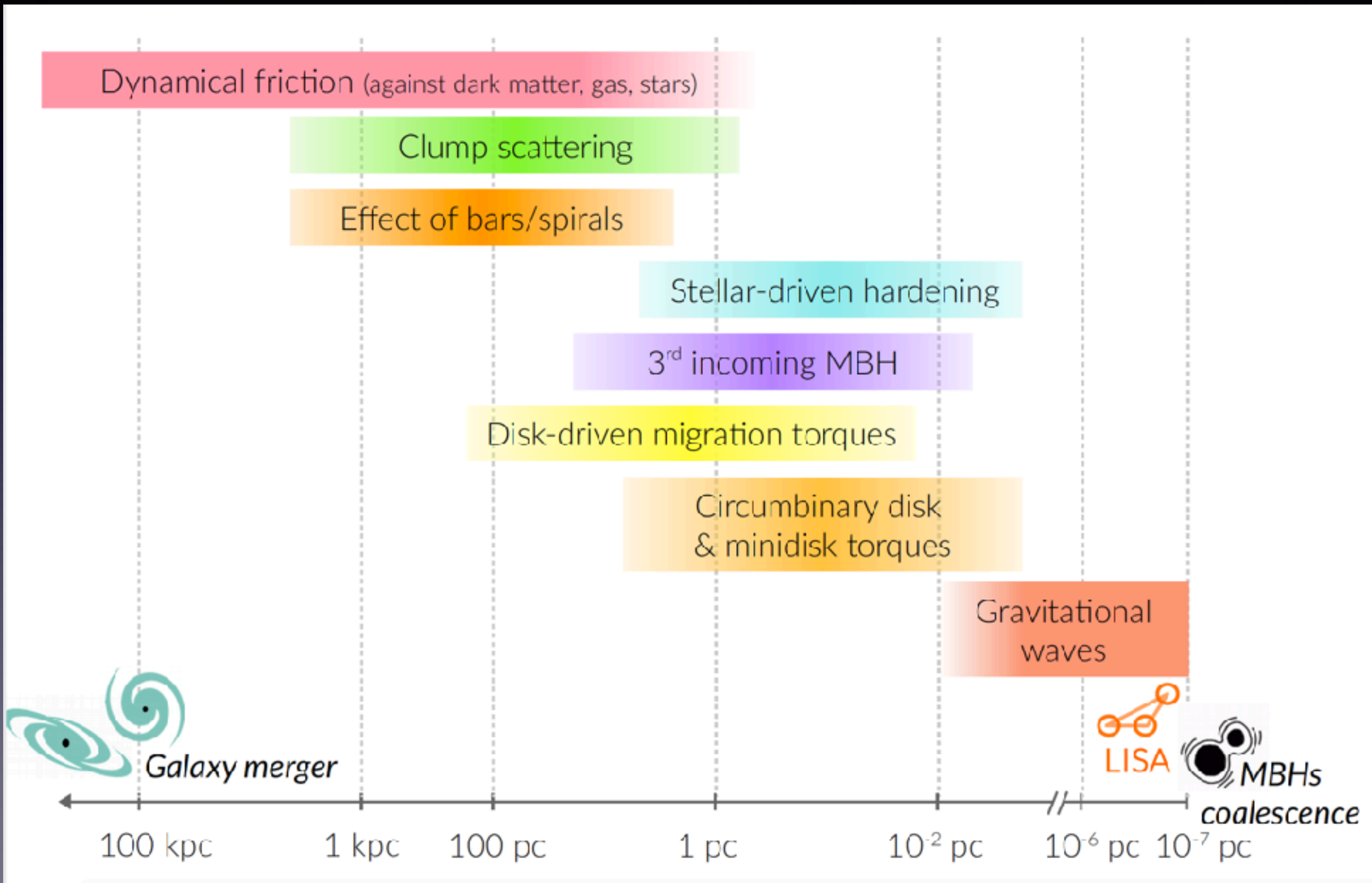
$r_{\rm min} \sim 4 - 10\, r_s$

Note: only existing published work so far used PN approximation (Cho et al. 2018)

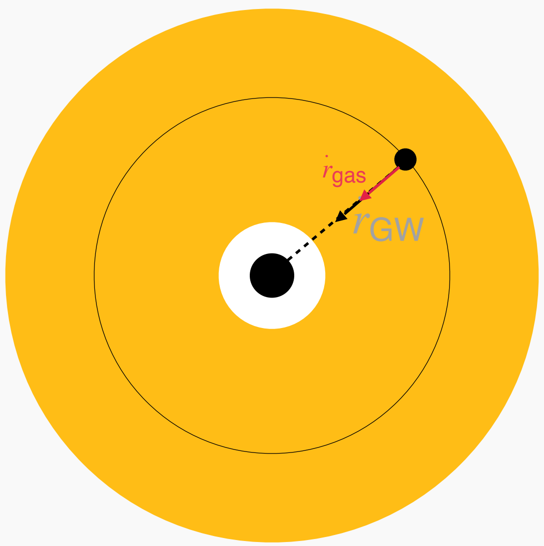

t = 0.0 years
1.0
0.5
0.0
−0.5
−1.0
−1.0
−0.5
0.0
0.5
1.0
10^{-16}
10^{-17}
10^{-18}
density [g/cm^3]

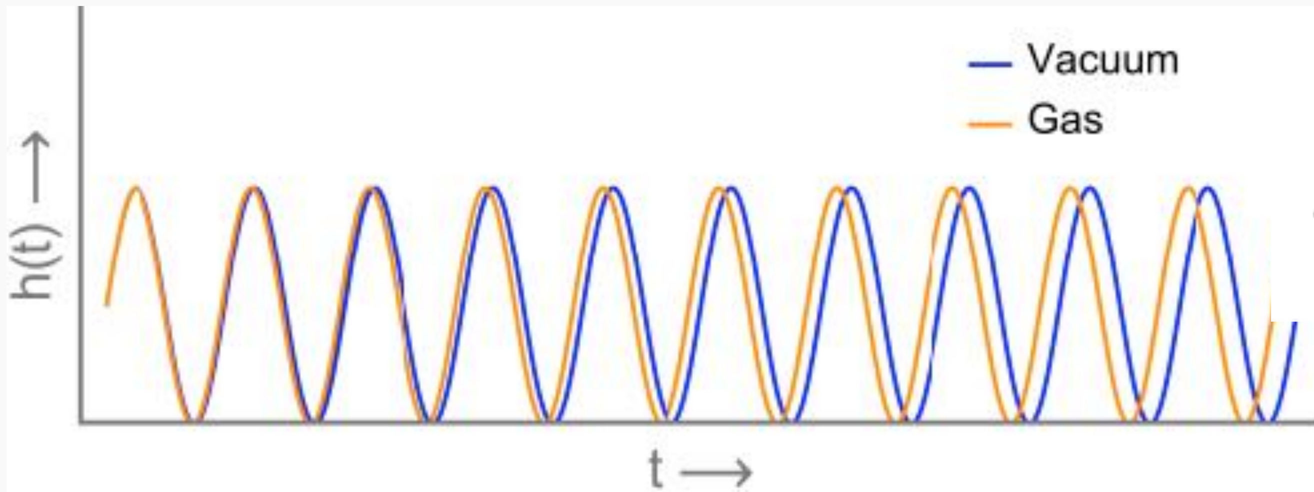
(a) Code comparison on MBH binary decay in circumnuclear and circumbinary disks: background motivation

The path to MBH binary formation and coalescence



Effect #1: De-phasing in the GW waveform induced by gas torques (Garg et al, to be submitted)





$$\Phi = 2\pi \int_{r_{\rm min}}^{r_{\rm max}} {\rm d}r \, \frac{f_{\rm r}}{\dot r}$$

$$\delta\phi = |\Phi(\dot r_{\rm GW}) - \Phi(\dot r_{\rm GW} + \dot r_{\rm gas})| \approx$$

$$\dot r_{\rm gas} \ll \dot r_{\rm GW}$$

BHs decay faster (i.e BHs perform more orbits) than with just GW emission alone —> corresponds to phase change

Assumptions & Relations

- Stationary phase approximation: gas affect phase not amplitude
- between LISA entry and exit/ISCO
- change in the number of orbits

See also:
Kocsis et al. (2011), Yunes et al. (2011),
Barausse et al. (2014), Derdzinski et al. (2019, 2021)