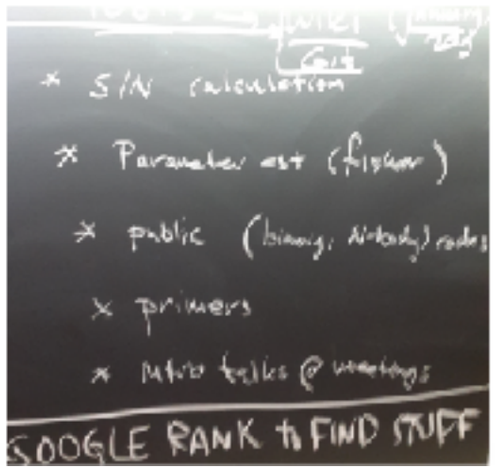
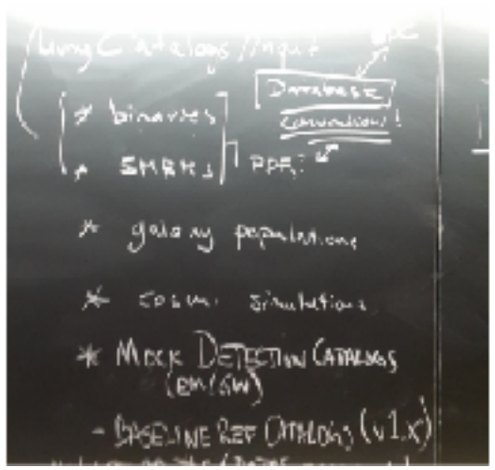
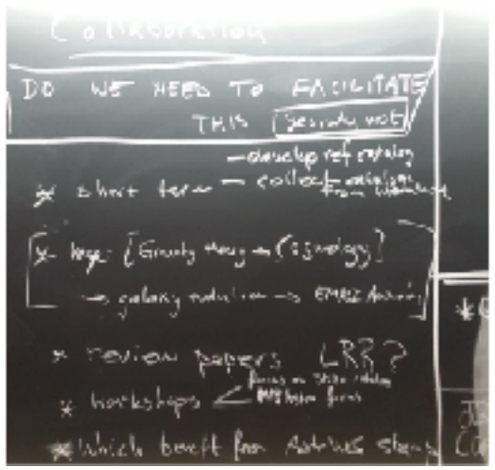
LISA Astrophysics Working Group

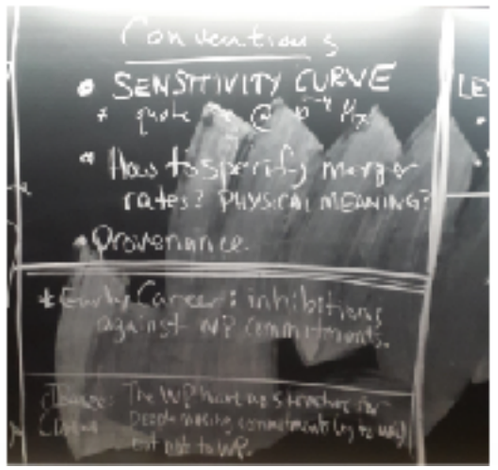
Astrophysics Working Group Overview, IPhU , July 7, 2021

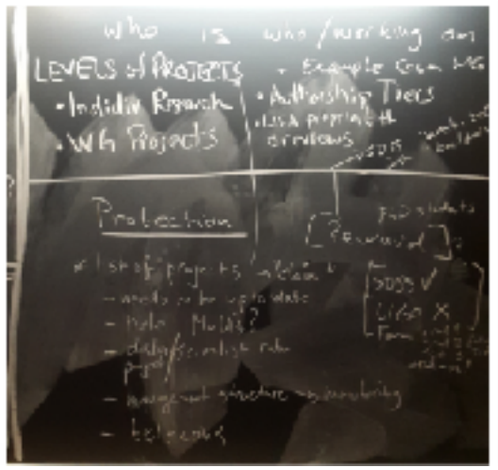
Lucio Mayer (Center for Theoretical Astrophysics and Cosmology, Institute for Computational Science, University of Zurich)











Lucio Mayer, Marta Volonteri, Shane Larson, Gijs Nelemans
(AstroWG Chairs — astro-wg-chairs@lisamission.org)

Mission of Working Group (since 2018)

https://lisa.pages.in2p3.fr/consortium-userguide/wg_astro.html

()**Foster work and collaboration on any astrophysical subject and problem** relevant to any question that LISA can address.
—-> strengthen the community of astrophysicists working on LISA science
—-> serve as a valuable **repository of expertise** for the whole Consortium

()**Topics of interest and methodologies highly diverse throughout WG. Enable and enhance synergy on key science objectives such as:**

— **Characterisation** of astrophysical sources of gravitational waves
— **Formulation** of aspects of their origin, evolution, and demographics, and of the nature of their environments, that can be addressed using the LISA datastream, as well as by combining GWs with EM observations.

— Enable **exchange** of knowledge on **methods of inference** ranging from fundamental theory and observations to supercomputer simulations and population synthesis models, as well as artificial intelligence techniques for model and data analysis.

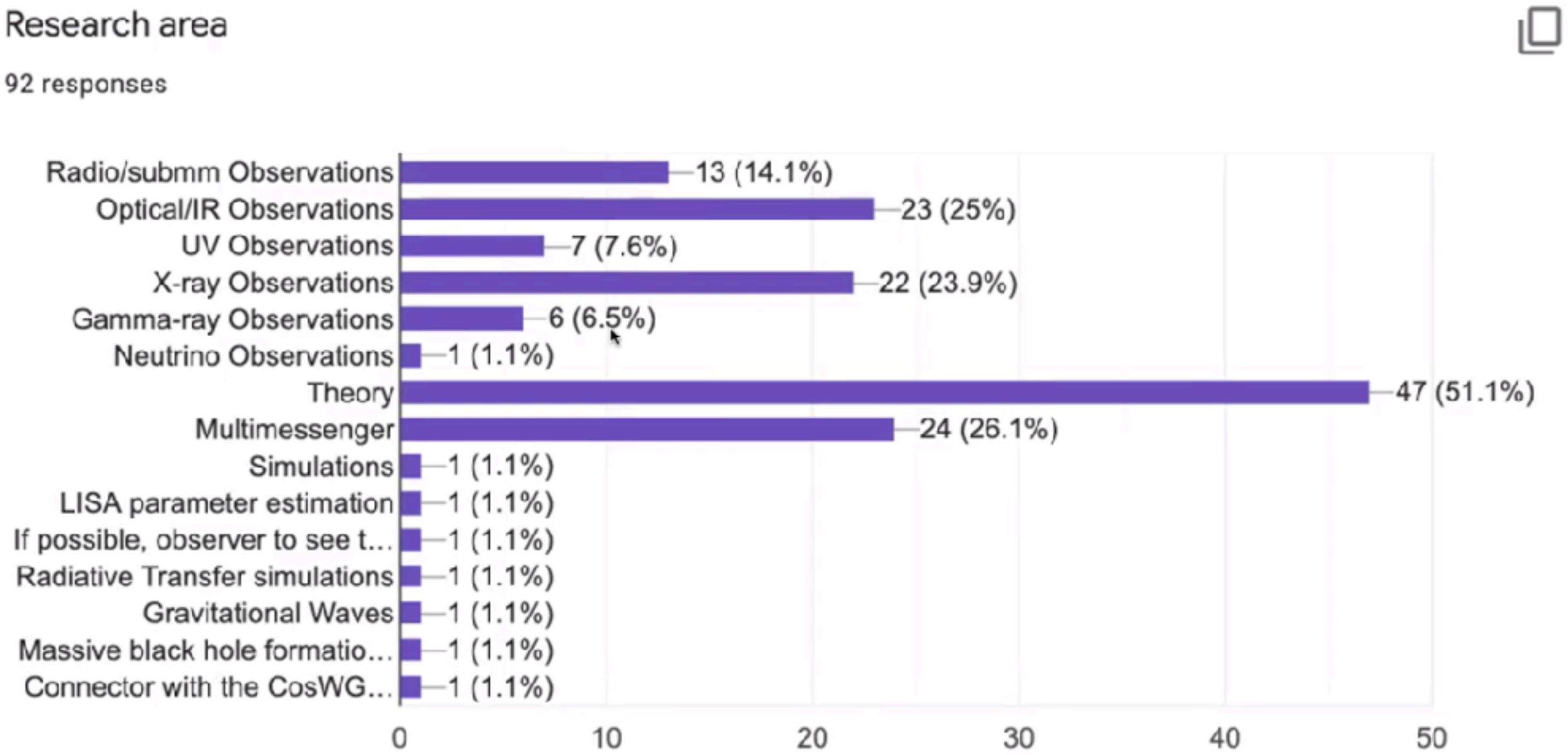
()**Four main themes:**

Galactic Compact Binaries (WDs, NS, BHs)
Massive Black Holes
Extreme and Intermediate Mass Ratio Inspirals (EMRIs/IMRIs)
Multi-Messenger Astrophysics.

()**Two-way interaction with Work Packages and Sub-Work Packages of LISA Consortium**
Provide new input as well as support work ongoing at the WPs level through internal expertise of WG

()**Opportunities for collaborations and synergies with other WGs** (especially Cosmology, Fundamental Physics, Waveforms, LISA Data Challenges)

Survey of expertise inside LISA AstroWG (responses from ~ 1/5 of current 500 members)



Working Group Status

Current Membership: nearly 500 members

Current Chairs (since 2018): Marta Volonteri, Gijs Nelemans, Lucio Mayer, Shane Larson Chair rotation starts this Fall (Nelemans out, Early Career Scientist in from LECS membership)

AstroWG Meetings since inception (2018)

December 2018: kick-off meeting at IAP Paris (~ 120 participants)
General orientation

March 2020: hybrid meeting at Radboud, Njimegen (~ 70 participants)
Kick-off of White Paper

June 2021: virtual meeting hosted by the University of Zurich (Institute of Computational Science)
>~ 150 registered participants — **kick-off of WG-wide collaborative projects.** ***Recordings of the meeting available on Atrium***

Main Activities in current status

- **White paper** (ongoing)

First “community building” activity. Note that by culture most AstroWG sub-communities not used to work in large collaborations

- Wiki with tools, reviews, catalogs from population models (ongoing)

Central place to collect information

https://wiki-lisa.in2p3.fr/AWG/Contacts

- Collect expertise areas to foster collaboration (ongoing)

https://forms.gle/z97VPNbVhSakgQh8A

- **Pre-LISA EM observations subgroup** (started)

Initiative of Tom Prince, objective to discuss and develop what is needed on the EM observations side to best prepare for LISA. First meeting was in April 2021

- **Collaborative projects** (just announced at June AstroWG meeting, upcoming) — Next level of community building

As of this month new members receive a welcome email with a summary of all the links, websites, slack channels and documents.

White Paper: Overview and Status

Structure — Three Chapters

(1)Stellar-Origin Binaries and Multiples (WDs, NS, BHs)
(2)Massive Black Holes
(3)Extreme and Intermediate Mass Ratio Inspirals
(Multi-messenger aspect trasversal to three chapters)

Organization: Chapter Coordinators + Section Writing Teams
(AstroWG Chairs as readers/internal reviewers)

~ 100 active contributors, ~225 pages content, ~ 1500 refs

Aim and Content

Review of astrophysical background along with elaboration of a synthesis focused towards areas of relevance for LISA
Living document to be updated on a certain cadence

Further added value

•Contact points with the historical and modern literature

•LISA contact with other areas of astronomy & astrophysics

Outline open questions (for pre- and post-flight era)

- What currently needs work and attention — connection with Work Packages of LISA Consortium (eg Science Interpretation WP)
- What are contact points with other WGs (overlap with Cosmology, etc)
- What are interesting questions where little work has been done? •

New & Unpublished Ideas and Work

• Should be redirected to a new publication; included in next revision

Early Editing Phase

Following the first complete draft in November 2020 WG Chairs have made high level pass in December. Writing teams have addressed main comments by January/February 2021, then distribution to whole AstroWG for comments followed

Intermediate Editing Phase (ongoing)

Working Group Chairs editing —-> Homogenization (includes shortening)

- Common treatments across all chapters (including terminology, acronyms..)
- Streamlining discussions, move aside unsupported sections
- Level out and polish discussion, finalise reference list

Editing currently limited to WG chairs

- Small text changes are being made in place
- Large changes are being done in consultation with Coordinators and involving directly writers of specific sections (a significant part is to shorten by removing or re-elaborating text that is not directly relevant to LISA)

Final Editing Phase (upcoming, to be concluded by early 2022)

P&P Committee / Consortium delivery

P&P proposes reviewers from outside AstroWG and a reviewer from within who was not writing on WP

- Preparation for Journal Submission (likely to **Living Reviews in Relativity**)
- Structures and format, including page limits, have to conform to journal standards
- After journal submission, expect a round of referee responses

AstroWG Collaborative Projects

Kick-off of WG project activity expected after WP finalised, namely during Late Fall 2021
Initial activity will be focused on **Large Collaborative WG-wide Projects**.
Target is creation of WG “flagship” projects that foster the community building approach, take advantage of the wide expertise of the AstroWG, and address key aspects of the LISA science goals

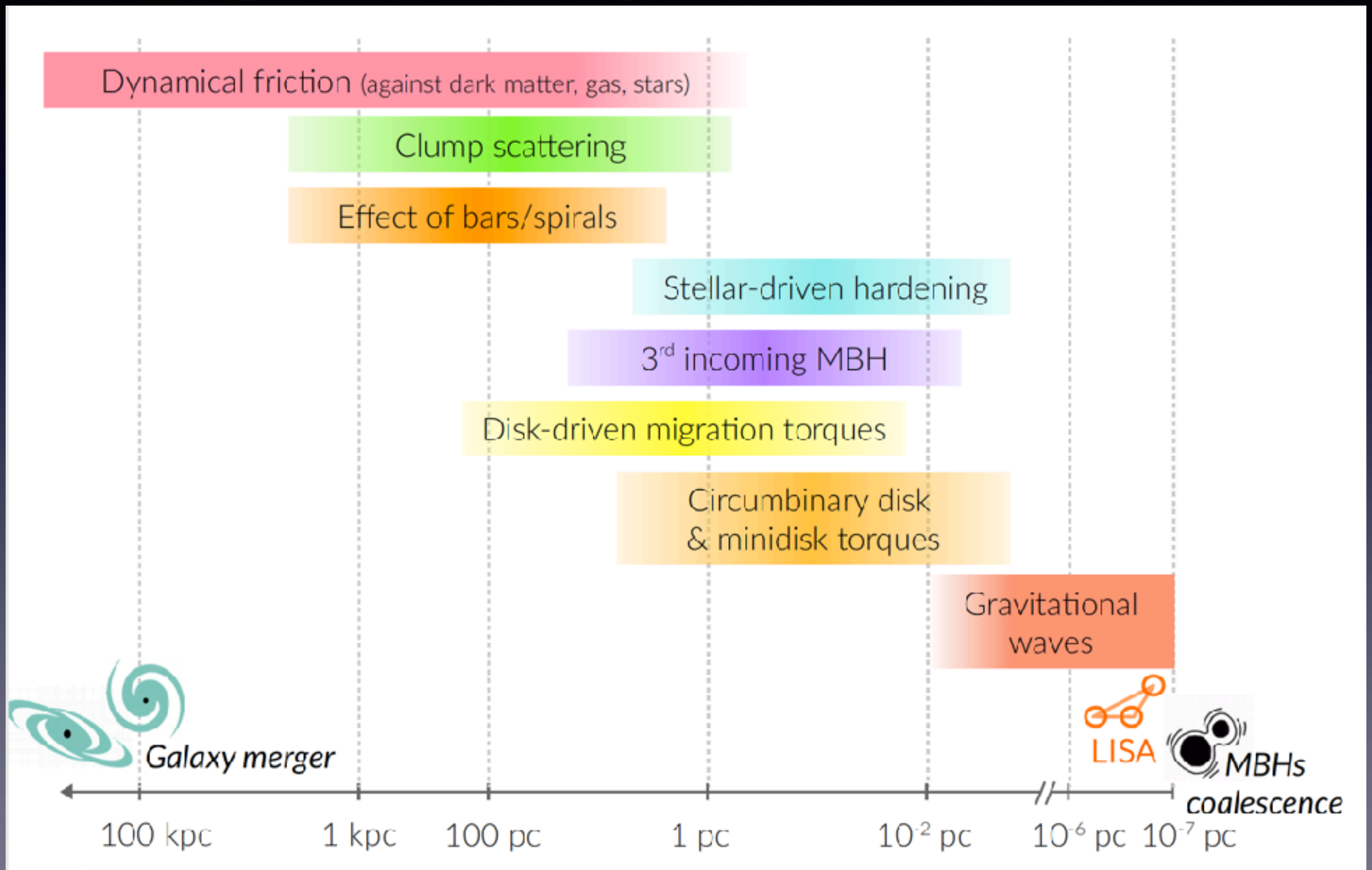
Large projects will be open to all WG members, with a sign-up procedure to be defined (stay tuned for communications by AstroWG Chairs during next Fall!)
Chairs are coming up with structured proposals following internal discussions.

Three WG-wide projects were agreed upon at June21 AstroWG Meeting.
“Groups of interest” to be formed soon for in-depth definition, structuring and pursuit of individual projects (first virtual meeting foreseen during next Fall).

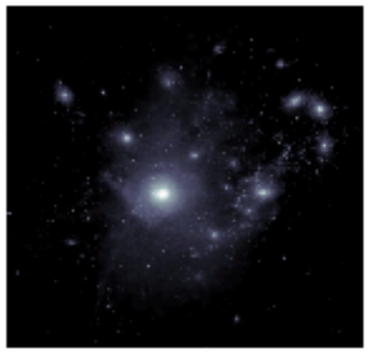
(a) Hydro/MHD code comparison on MBH binary decay in circumnuclear and circumbinary disks
(b) Comparison of MBH binary synthetic populations (and later LISA Flagship Cosmological Simulation)
(c) Expected numbers of stellar-origin binaries/multiples - a comparison of population synthesis codes

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

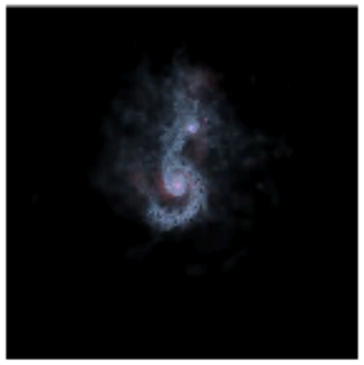
The path to MBH binary formation and coalescence



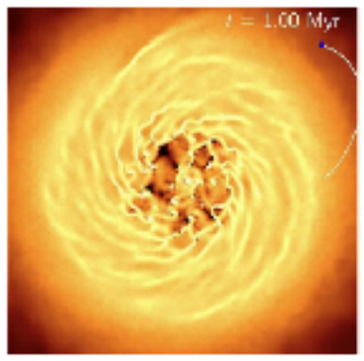
The four key stages of MBH binary evolution before onset of GW emission (from AstroWG paper)



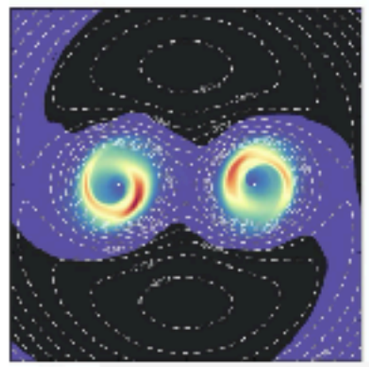
Credit: Lupi et al. (2019)



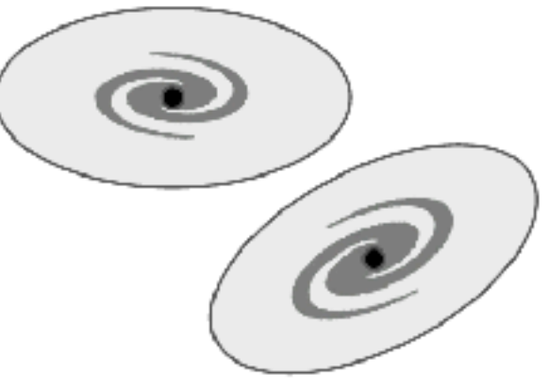
Credit: Capelo et al. (2015)



Credit: Souza Lima et al. (2017)

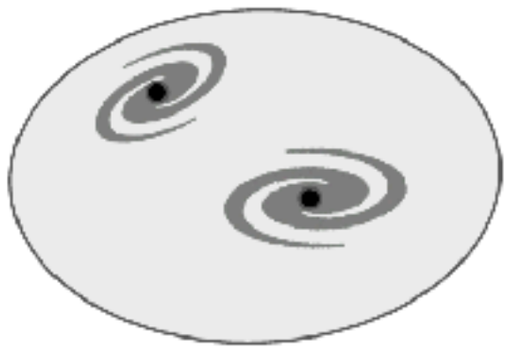


Credit: Bowen et al. 2017



Mpcs:
The large scale structure

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



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

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.

Circumbinary gas disk stage

<1 pc:
Hardening of the binary

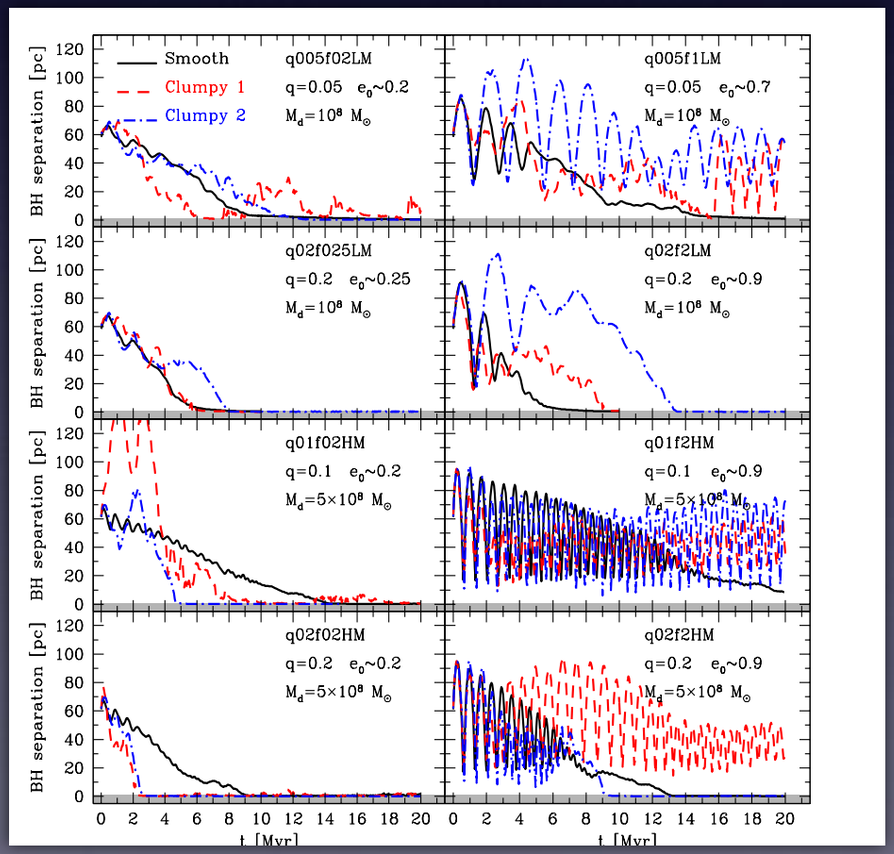
The host properties have influence on: timescale of hardening
Effect of circumbinary disc
Three-body interactions (hyper-velocity stars)

Code comparison=compare numerical methods (hydro/MHD/gravity, 2D vs. 3D)+ physics implemented (radiation, BH accretion, feedback)

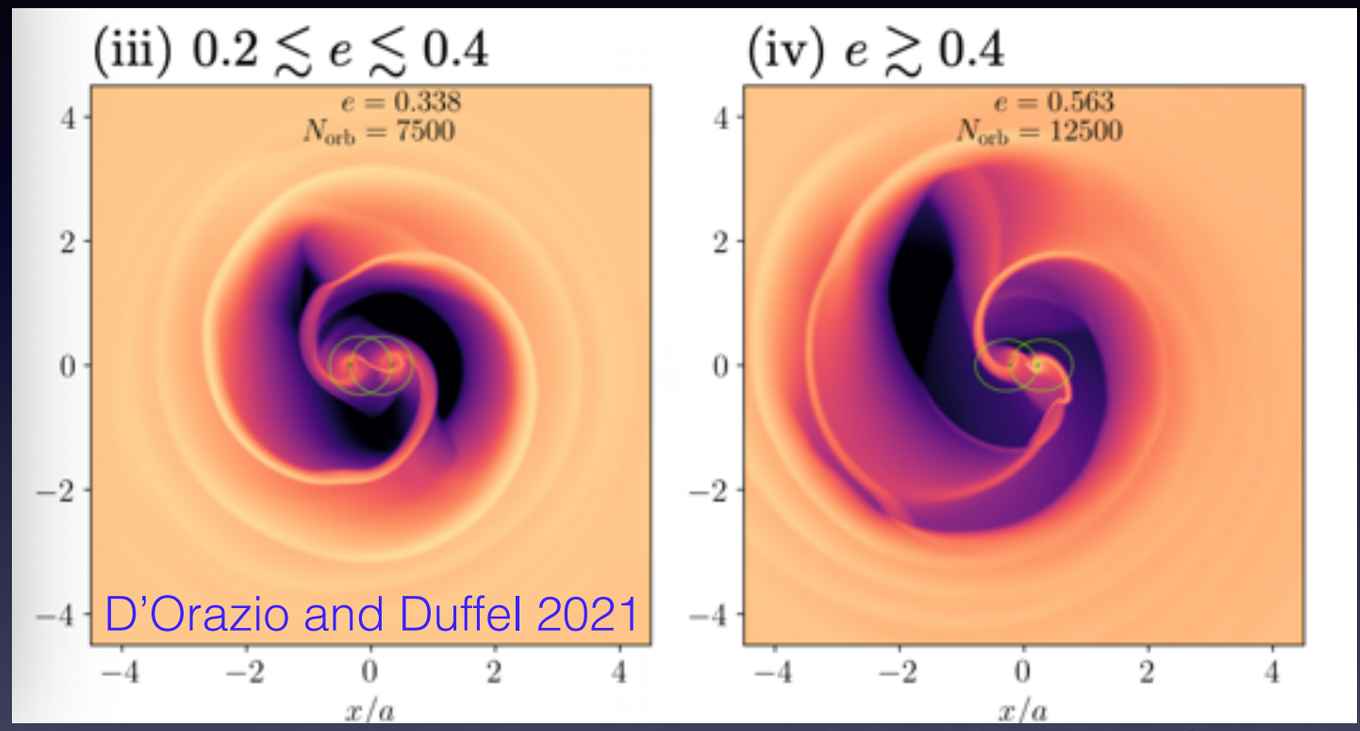
MBH binaries in clumpy circumnuclear disks (100 pc-1 pc)

decaying or not decaying?

(eg Fiacconi et al. 2013 vs. del Valle et al. 2014)



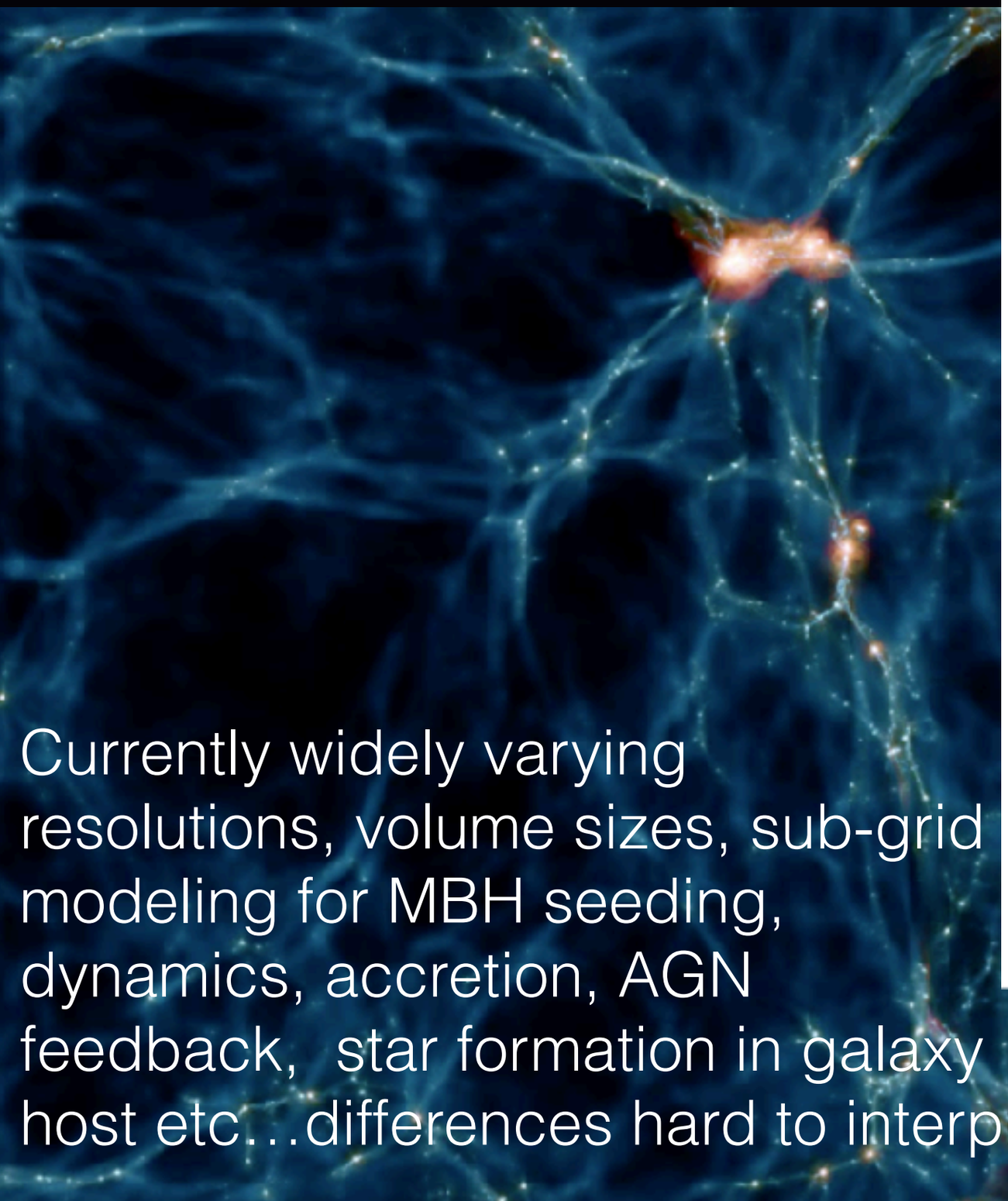
Sub-pc scales: circumbinary disks



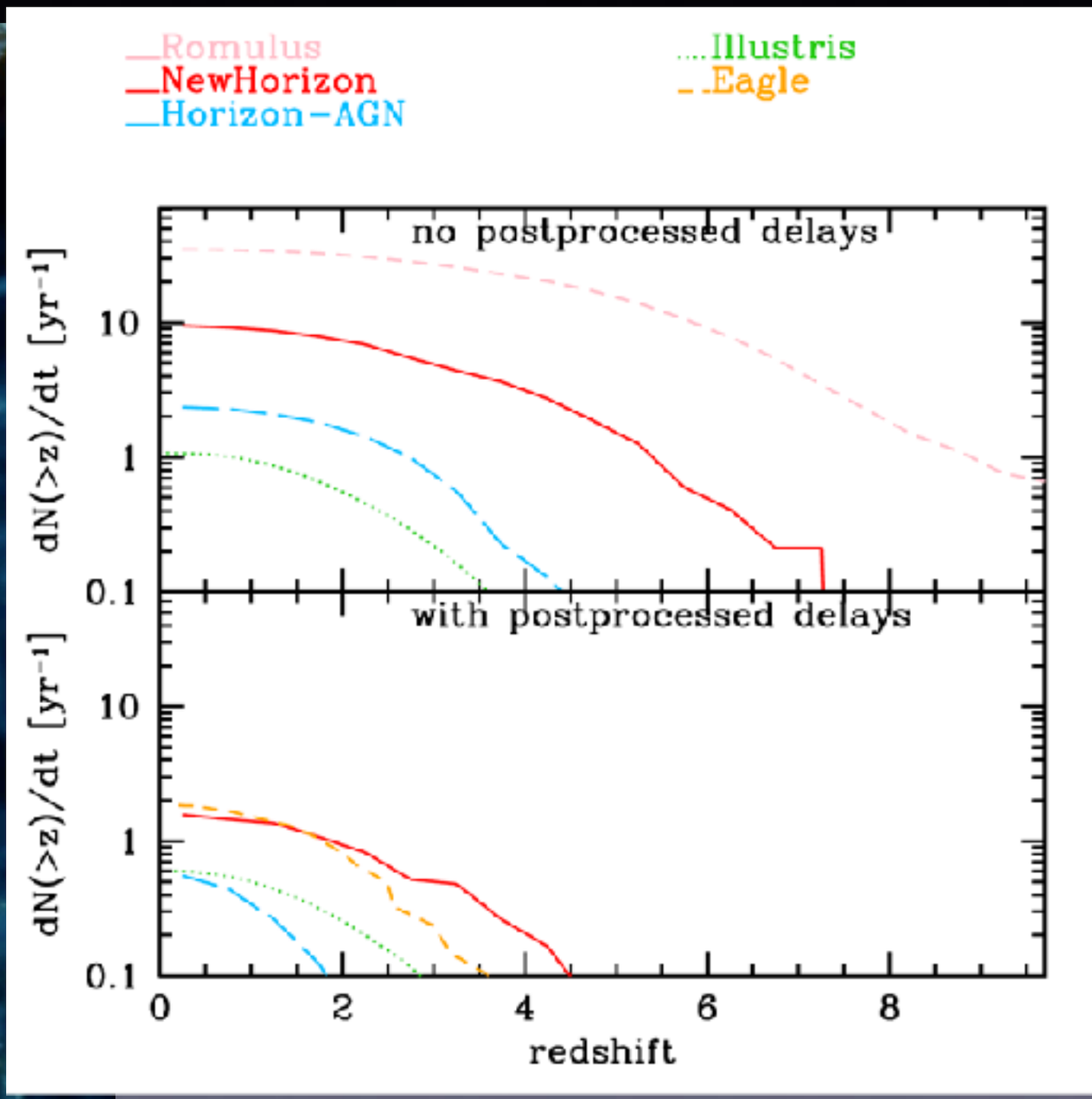
Both decaying and expanding binaries? Different circumbinary disk physical regimes or depends on numerics? No coverging picture from literature (eg Munoz et al 2019; Moody et al. 2019; Duffell et al. 2020; Franchini et al. 2021)

Key starting point:common set of initial conditions AND common physical model

(b)Comparing population models of MBH binaries in cosmological simulations —> assess MBH merger rate forecasts <u>with uncertanties</u>, build “standard” catalogs for LISA



Currently widely varying resolutions, volume sizes, sub-grid modeling for MBH seeding, dynamics, accretion, AGN feedback, star formation in galaxy host etc…differences hard to interpret



From White Paper, courtesy of Marta Volonteri and Alessandro Lupi

(c)Population synthesis code comparison for stellar binaries

Not done so far despite very many codes and wide range of predicted LISA merger rates. Important for forecasts but also for data analysis pipeline **(—>> assess astrophysical uncertainties)**

Table 1.5: Population synthesis codes used by the community at the time of writing. Binary_c, COSMIC, MOBSE are based on the BSE code (Hurley et al., 2002).

Code name	Reference	Publicly available
Binary_c	Izzard (2004); Izzard et al. (2006, 2009)	No
BSE	Hurley et al. (2002)	Yes
BPASS	Stanway & Eldridge (2018)	No
ComBinE	Kruckow et al. (2018)	No
COMPAS	Stevenson et al. (2017a)	Yes
COSMIC	Breivik et al. (2020a)	Yes
MOBSE	Giacobbo et al. (2018)	No
POSYDON	Bavera et al. (2020a); Román-Garza et al. (2020)	No
Scenario Machine	Lipunov et al. (1996, 2009)	?
SEVN	Spera et al. (2015)	Yes
SeBa	Portegies Zwart & Verbunt (1996); Toonen et al. (2012)	Yes
StarTrack	Belczynski et al. (2008)	No
TRES	Toonen et al. (2016)	Yes

Source	$\mathcal{N}$ [MWG^{-1}]	$\mathcal{N}^{\rm detected}$ [MWG^{-1}]
WD | WD	$\sim 10^8$	6,000–10,000
NS+WD	$\sim 10^7$	100–300
BH | WD	$\sim 10^6$	0–3
NS | NS	$\sim 10^5$	2–100
BH+NS	$\sim 10^4 - 10^5$	0–20
BH | BH	$\sim 10^6$	0–70

Predicted merger rates of galactic binaries detectable with LISA, for different instrumental specs and population codes

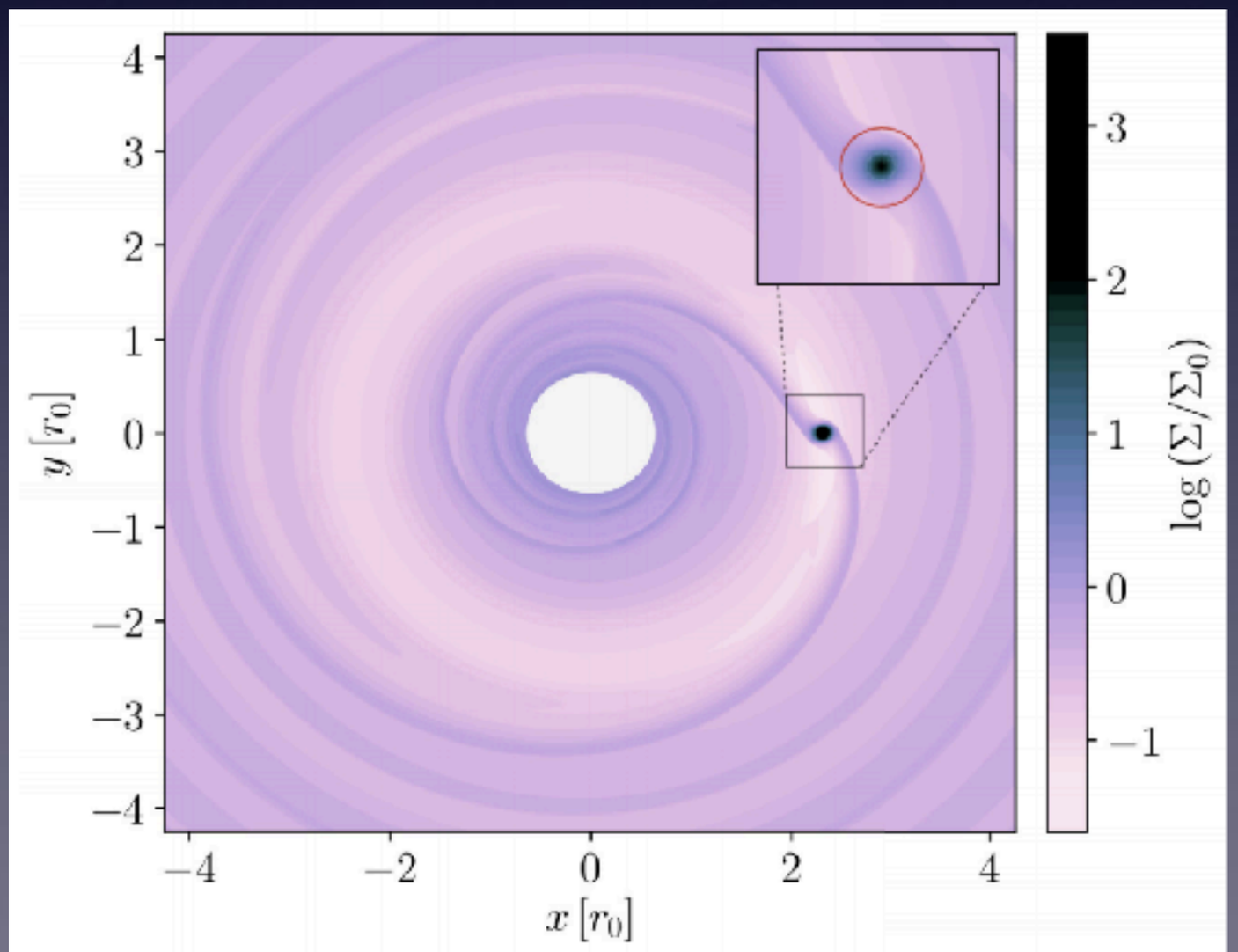
Potential additional project discussed at June AstroWG meeting (for the longer term):

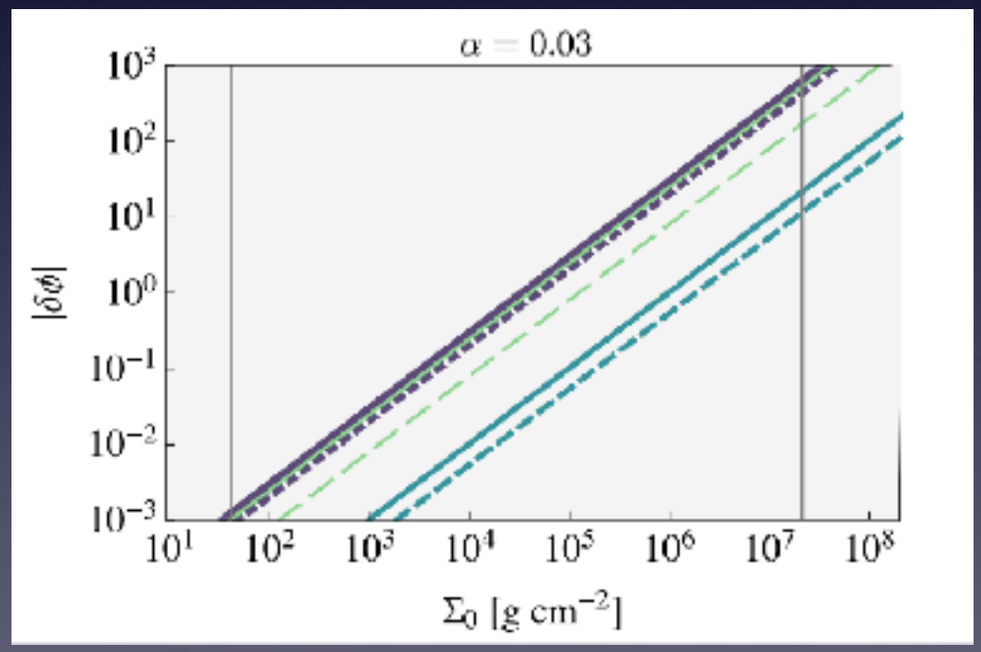
Effects of astrophysical background on waveforms

Eg residual drag/torque from surrounding plasma during GW-driven in-spiral phase.

Particularly for EMRIs/IMRIs, evaluate if extra drag component comparable/stronger than a given high PN corrections.

Conversely, if effect relevant would enhance the astrophysical information that can be extracted from waveforms





Phase shift resulting from gas disk-driven torques in early in-spiral phase of IMRIs (Derdzinski et al. 2019;2021 — see also Zwick et al. 2021)

Pre-LISA EM observations

- Aim: collect needs for and options for pre-LISA EM observations and where needed work towards enabling (new proposals, new instruments)

- First brainstorm telecon: April 9, ≥50 participants
- Structure
  - Split by source type: stellar binaries, massive black holes, EMRIs (TDEs)
  - Few talks about needs and current work
  - General discussion

- After meeting;
  - broader WG contacted
  - Slack channel started to further brainstorm and spontaneous working sub-groups (https://join.slack.com/t/prelisaemobse-zr25396/shared_invite/zt-ow5tcjcm-iQpdBi9Dy6Z5nkqC_j3cCg)

Coordinators of each “source type” identified at recent June WG meeting (Delphine Porquet and Alessandra de Rosa for MBHs, Gijs Nelemans, Tom Prince and Thomas Kupfer for stellar binaries, for now no lead on EMRIs/TDEs)

- Last day at June WG meeting dedicated to pre-LISA EM (please watch recording on Atrium!). Tentatively planning of regular bi-monthly meetings starting next Fall
- Two separate discussions on the MBHs and SBs, then last 45 minutes of general discussion and action items for future meetings

- From June AstroWG meeting two take-away message and action items;

(i) Need review of current “knowledge status” for potential EM precursor sources even when binary still at large separations (eg dual AGNs in the case of MBHs). Use that to design new EM surveys to improve the characterisation of such systems and the knowledge of their astrophysical environments (—> relevant also for the tight sub-pc scale binaries that are harder to detect with EM observations)

(ii) Develop more targeted use of numerical simulations to guide observations, for instance by developing multi-wavelength synthetic observations for continuum, line emission as well as polarisation of signals **—> clear observational diagnostics**

Need to make sure the required expertise on all wavelengths is in place within AstroWG, if not each out outside WG to seek additional expertise and accordingly acquire new Consortium members (projects to remain inside LISA Consortium)