The astroWG projects

Marta Volonteri on behalf of the astroWG chairs and the project coordinators

astroWG chairs: Matteo Bonetti, Valeriya Korol, Shane Larson, Marta Volonteri

UCBcatalogs: Katie Breivik, Alexey Bobrick

MBHcatalogs: Melanie Habouzit, Luke Kelley, Alessia Gualandris, Silvia Bonoli, David Izquierdo, Matteo Bonetti, Marta Volonteri

DiscIMRIs: Andrea Derdzinski, Alessandro Lupi, Alessia Franchini, Alex Dittman, Lucio Mayer

Overview and goals

Target is creation of WG “flagship” projects that foster the community building approach and address key aspects of the LISA science goals:

- **Provide basis for the Consortium’s science exploitation of LISA data**
- **Catalogs to build your next Data Challenge**
- **Assess astrophysical uncertainties, e.g., for figures of merit etc**

These projects are open to all astroWG members, with a sign-up procedure: ~100 people have signed up for the proposed projects

Experts who are not part of the astroWG/Consortium can also join

MBHCatalogs: Creation and comparison of MBH binary catalogues
UCBCatalogs: Expected number of Galactic binaries
DiscIMRIs: Numerical hydrodynamics code comparison on sinking MBHs and IMRIs

Creation and comparison of MBH binary catalogs (MBHCatalogs)

Theoretical predictions for MBH merger events involving LISA are varied, because of the different techniques used (e.g., semi-analytical models, empirical models, simulations) and because of the different physical assumptions made (seeding, growth, dynamics). Each technique has strengths and weaknesses, and the physical assumptions vary for technical reasons, but also because of choices made by the scientists, e.g., which model(s) of MBH formation include, which dynamical evolution channels, which forms of feedback.

In this project we propose that different groups (i) compare the results in order to quantify the spread in predictions, i.e., the global astrophysical uncertainties, and (ii) identify what are the robust model-independent predictions.

Current predictions on MBH mergers for LISA: from <1 to >100 per year

(different techniques and resolution, different physical assumptions on MBH seeding , growth, dynamics, different galaxy formation models, etc)

The project:

Exhaustive comparison of existing predictions on MBH merger rates and LISA event rates + new predictions ?

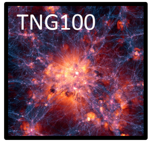
The goals relevant for this workshop:

1. Evaluation of the global astrophysical uncertainties on the LISA event rate
2. Provide simulated catalogs to test pipelines
3. Provide simulated catalogs to validate LISA catalogs

Slide credit: M. Habouzit

Modelling MBH evolution in a cosmological context

Cosmological simulations

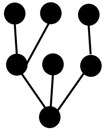


- Evolution of MBHs and galaxies.
- Spatial resolution: 1kpc - 10 pc.

✓
- Include variety of environments, galaxies, MBH mass ratios.

✗
- Computationally expensive.
- Trade-off simulated volume vs mass and spatial resolution.
- Small halos where MBH formation happens not resolved.
- Full LISA's MBH band not captured.

Semi-analytical models



- Evolution of MBHs and galaxies tied to those of dark matter halos.
- Press-Schechter formalism or N-body simulations.

✓
- Can probe smaller and larger halos than in simulations.
- Statistical exploration of the parameter space.

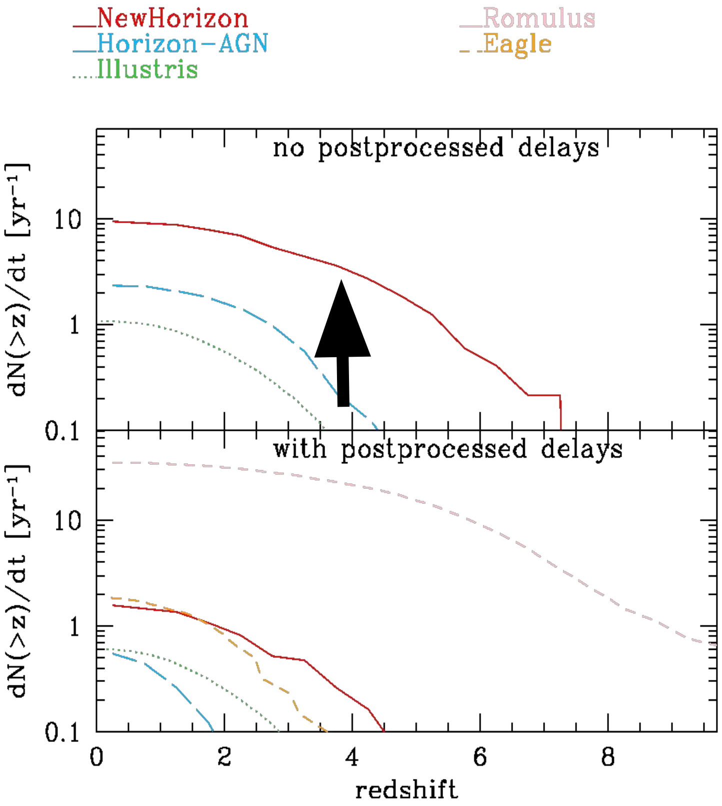
✗
- Can lack spatial information and large-scale environment.
- Limited by resolution.

⚠
- If small halos hosting LISA MBHs are not resolved, the predicted merger rate is a lower limit to the real merger rate.

Slide credit: M. Habouzit

MBH merger rate in cosmological simulations

(all MBHs are included, not only those in the LISA band)

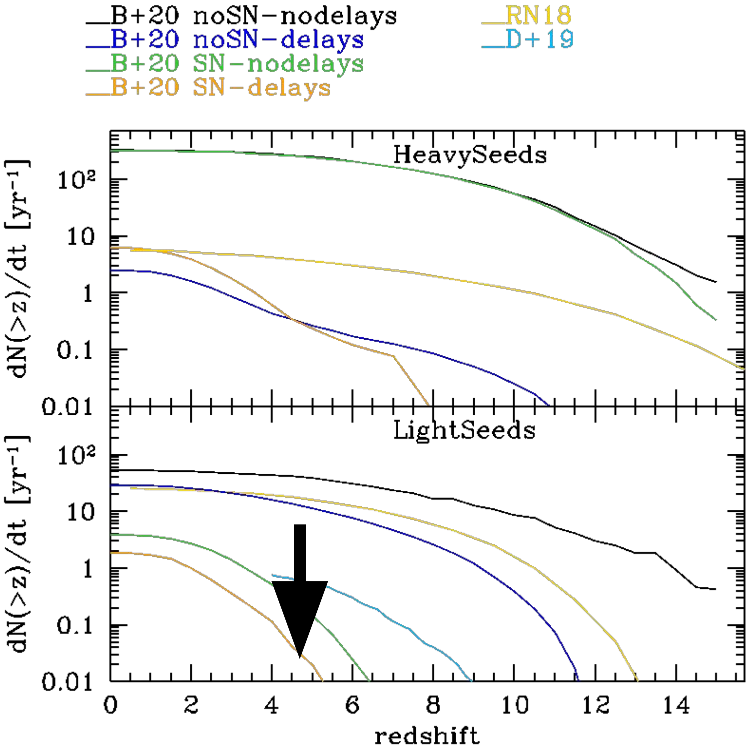


- ➢ Simulations which do not resolve galaxies with $M_{star} < 10^9\ M_{sun}$ can under estimate MBH merger rates (if MBHs exist in these galaxies).
- ➢ Post-processed delays lower MBH merger rates.
- ➢ Post-processed delays do not account for MBH evolution after dynamical friction, during hardening and circumbinary disc phase.

Slide credit: M. Habouzit

Astrophysics with LISA, LRR (2023)

MBH merger rate in semi-analytical models

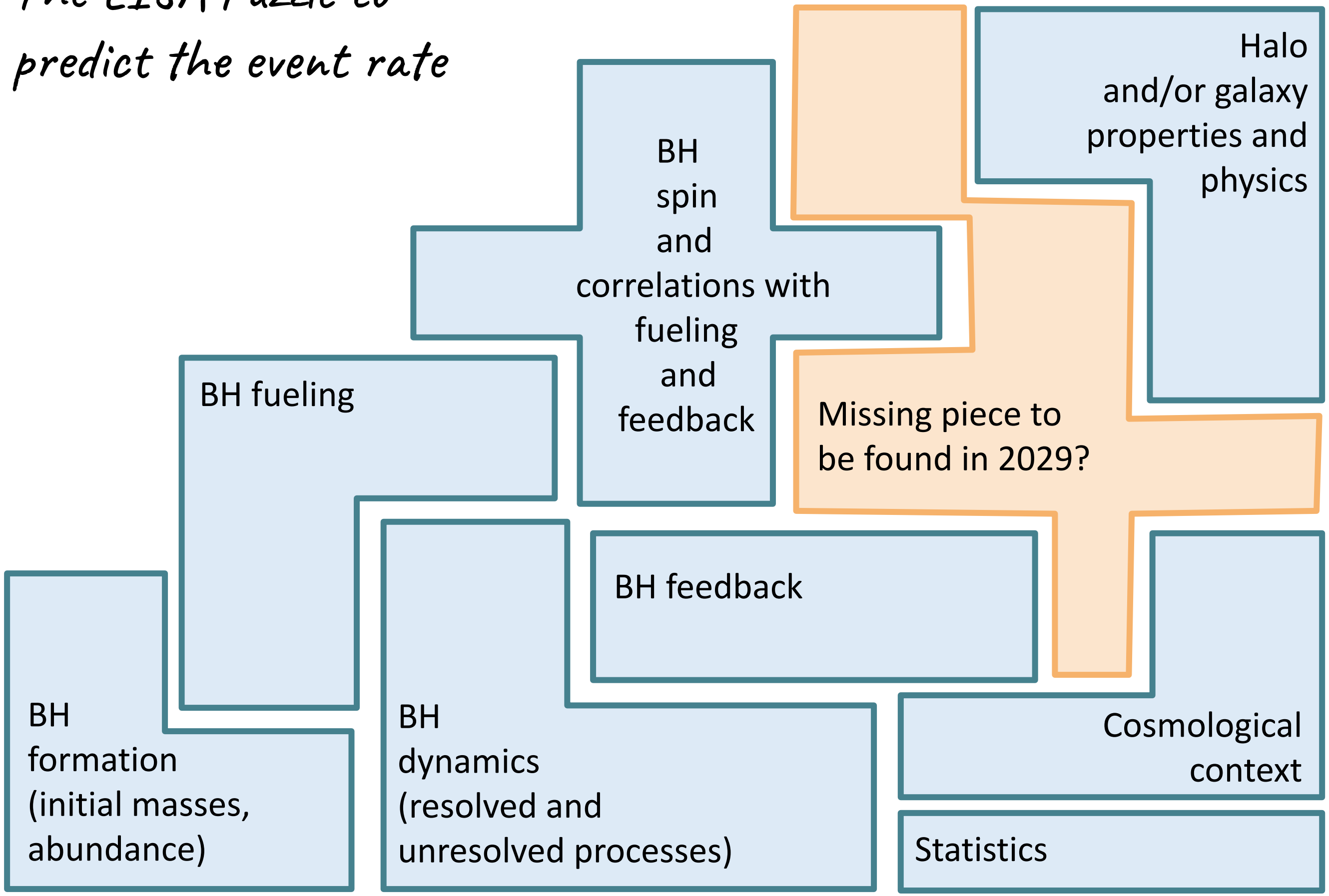


- ➢ Results suggest that different seeding models would impact LISA event rate differently.
- ➢ Event rate mostly driven by mergers of growing light seeds.
- ➢ Role of SN feedback and stochastic processes

Slide credit: M. Habouzit

Astrophysics with LISA, LRR (2023)

The LISA Puzzle to predict the event rate



Slide credit: M. Habouzit

Initial list

L-Galaxies	
Barausse's SAM (I shoud find a fancy	
NewHorizon	
Astrid	Check on post-processed delayes
Romulus	Needs post-processing delays
KETJU simulations	Can rates be calculated? Sequences of mergers rather than normal zoom
Illustris TNG 100	Need to include delays bc of repositioning. Check on disappearing BHs?
Illustris TNG 50	Need to include delays bc of repositioning
CAT(Cosmic Archaeology Tool)	Evolution of GQD to include a larger range of halo mass. Dynamics
SIMBA	Need to include delays bc of repositioning. Better BH masses but worse galaxy
Illustris (2014)	Need to include delays. BH masses borderline
Horizon-AGN	BH masses borderline, delays in postprocessing calculated
EAGLE	Need to include delays. BH masses borderline
MassiveBlackII	Check this vs Astrid and BlueTides? Choose one?

SHARK	No dynamics, requires delays
Astraeus	Also stops at z=4.5. Needs to add delays (BHs merge as soon as halo merge)
DELPHI	Better to use for merger rates or for a comparison with Renaissance and
FLARES	Only z>4, no dynamics, requires delays
Obelisk	only z>3.5, no rates, but MBH properties, mode effective dyn fric compared
Uchuu	No black holes, borderline for LISA BH masses. Requires a large amount of
A-SLOTH	Little black hole physics, small volume
GQD (Galaxy and Quasars with	Only 1e13 Msun halos at z>>0. No dynamics
Renaissance	No black holes, no rates. Interesting to check light seeds: compare
TRINITY	not ready for merger rates?
Illustris TNG 300	Use smaller volumes instead
Ricarte/Natarajan	Silvia will contact
Sesana/Chen/Middleton/etc models	
BlueTides	Check BlueTides vs MassiveBlackII and Astrid? Choose one?

Participating models

L-Galaxies
Barausse's SAM
New Horizon
Astrid
Romulus
KETJU
TNG50 and TNG100
CAT
SIMBA
Illustris
HorizonAGN
EAGLE
MassiveBlackII
SHARK
Astraeus
Delphi
FLARES
Obelisk
Renaissance

- "Best" catalog(s) from each group
- "Homogenous" catalogs where choices are as similar as possible , at increasing levels of complexity
- Some models are used only for specific science cases (MBH seeds, dynamics, host galaxy properties)

Expected number of Galactic binaries/multiples (UCB Catalogues)

The current estimates of the expected number of Galactic/stellar-mass binaries in the LISA band are based on a rather limited number of calculations using population synthesis codes. In this project we will collect the existing results and get together representatives of as many population synthesis codes as possible to do a dedicated set of calculations. In this project we will assess the differences and similarities in the codes and the resulting differences in the expected number of Galactic stellar-mass binaries in the LISA band.

In this way we will: (i) get a better understanding of the astrophysical uncertainties in the expected number of LISA detections, (ii) get a better understanding of the differences between the codes and their importance for the LISA results, (iii) get insight in the most important uncertainties in the models that need further study to improve the results and reduce the astrophysical uncertainties.

Note. This project is also related to one of the pre-LISA EM projects: Calibrating the expected LISA population with pre-LISA data

PopCORN project
Toonen, Claeys, Mennekens, and Ruiter
arXiv:1311.6503

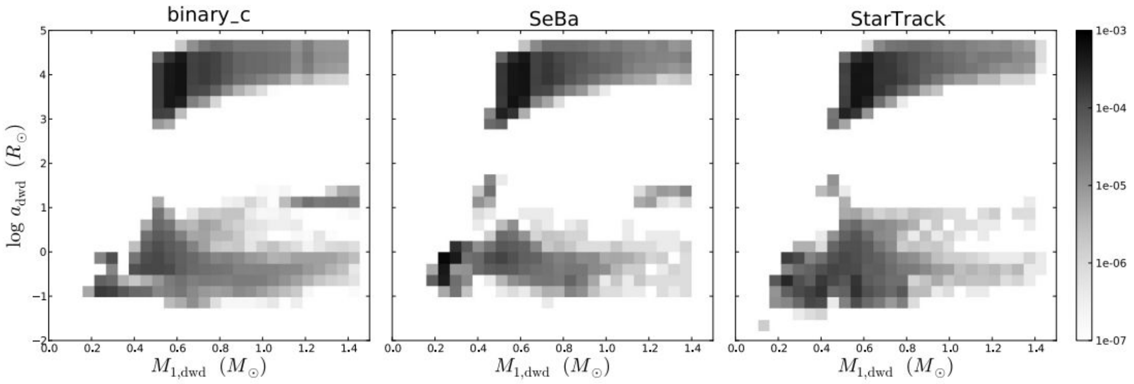


Fig. 8. Orbital separation versus primary WD mass for all DWDs in the full mass range at the time of DWD formation.

Project 1: Expected number of Galactic binaries/multiples (UCB Catalogues)

Project goals

Code comparison: **What are the differences between the predictions of existing population synthesis codes, assuming the same astrophysics?**

Astro uncertainties: **What is the spread in our population predictions given what we know about the astrophysics?**

Target: End of 2023

Main products:

- DWD Galactic distributions
- Population properties (chirp masses, periods)
- Parametrized range of uncertainties

\+ Tools and insights for broader binary evolution community

Project 1: Expected number of Galactic binaries/multiples (UCB Catalogues)

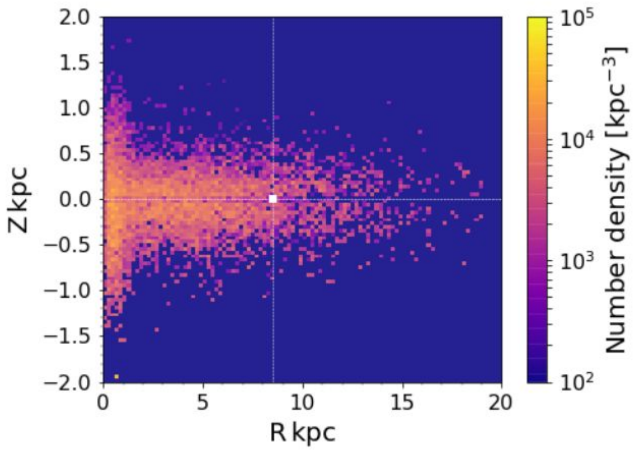
Modelling performed in waves (phases):

- Effects of single evolution
- Effects of binary initial conditions
- Effects of the Galactic models
- Effects of binary interaction models
- Possible effects of the LISA pipeline

Tools and teams:

- Code execution (+sub-threads)
- Standardized outputs
- Visualistions
- Literature review (+sub-threads)
- Paper writing

Example synthetic population of DWDs for LISA from Korol+2018



Project 1: Codes involved in the comparison

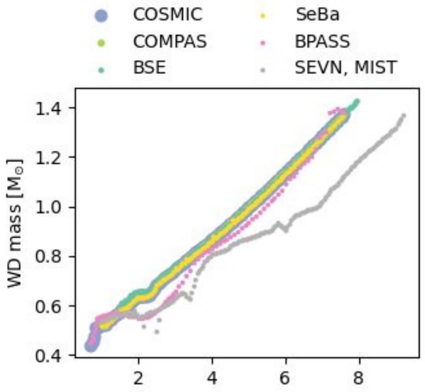
	rapid	hybrid	detailed
Stellar evolution	Hurley+2000 fits to single stars & analytic binary evolution	Single star grids from MESA, PARSEC, BEC & analytic binary evolution	Binary star grids from MESA or STARS
Codes involved	SeBa, COMPAS, COSMIC, BSE	SEVN, ComBinE	BPASS, POSYDON
Population synthesis	Always fast due to single star fits	Fast if grids are already present; ~1-4 weeks if not	Fast if grids are already present; >1 month if not

Accuracy →

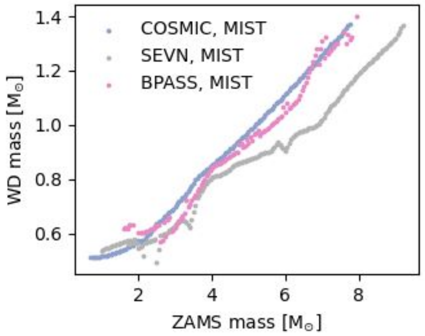
Flexibility ←

Project 1: results so far

Single star code comparison

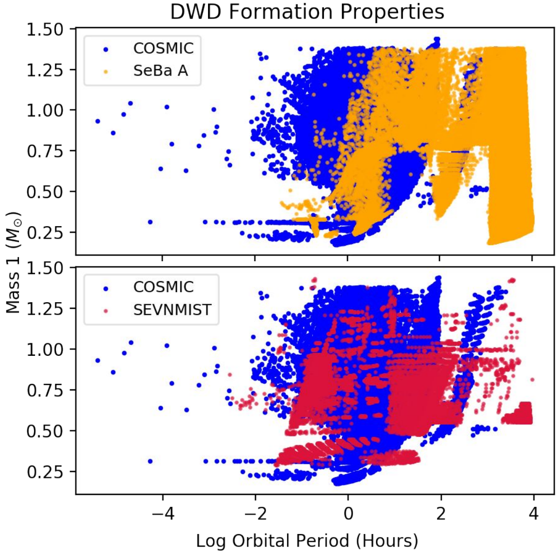


Rapid codes agree (they should!) but this is not trivial since there are 4 different implementations!



Similar WD masses with same wind prescriptions (MIST) but different stellar evolution engines lead to WD mass differences

Binary grid code comparison



Different binary evolution algorithms (top) and different stellar evolution engines (bottom) produce different results

Project 3: Numerical hydrodynamics code comparison on sinking MBHs and IMRIs (DiscIMRIs)

Science target : determine convergence of torques and gas flow properties for highly unequal mass black hole binaries, so-called Extreme and Intermediate Mass Ratio Inspirals (E/IMRIs).

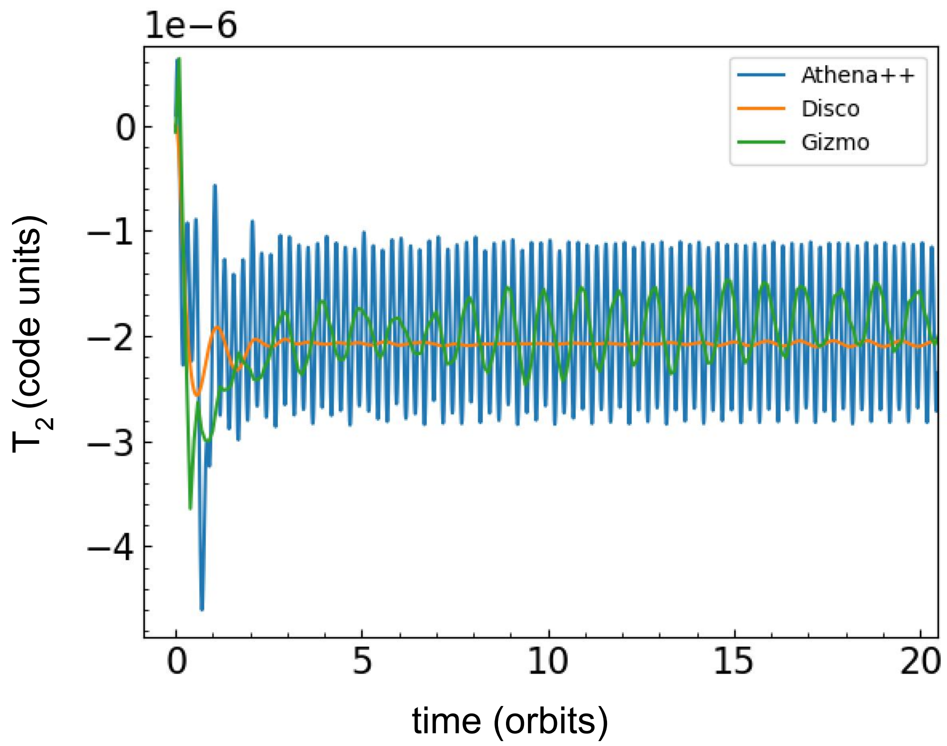
We compare the gas torques exerted on the primary and secondary from the various regions of the disc, their time evolution and dependence on the disc parameters. 2D and 3D codes/simulations

Applications : Quantifying uncertainties in the sub-parsec gas-driven evolution of MBH binaries

- constrain LISA event rates and expected binary properties in gas-rich nuclei
- inform waveform catalogs of environmental signatures in GW waveforms

Numerical hydrodynamics code comparison on sinking MBHs and IMRIs (DiscIMRIs)

PRELIMINARY RESULTS - Gravitational torque on the secondary



Parameters for the initial alignment run

Binary parameters

$$q = \frac{M_2}{M_1} = 10^{-4}$$

$$a = 1 \quad e = 0$$

$$M_1 + M_2 = 1$$

Disc parameters

$$\nu = \alpha \, c_s \, H$$

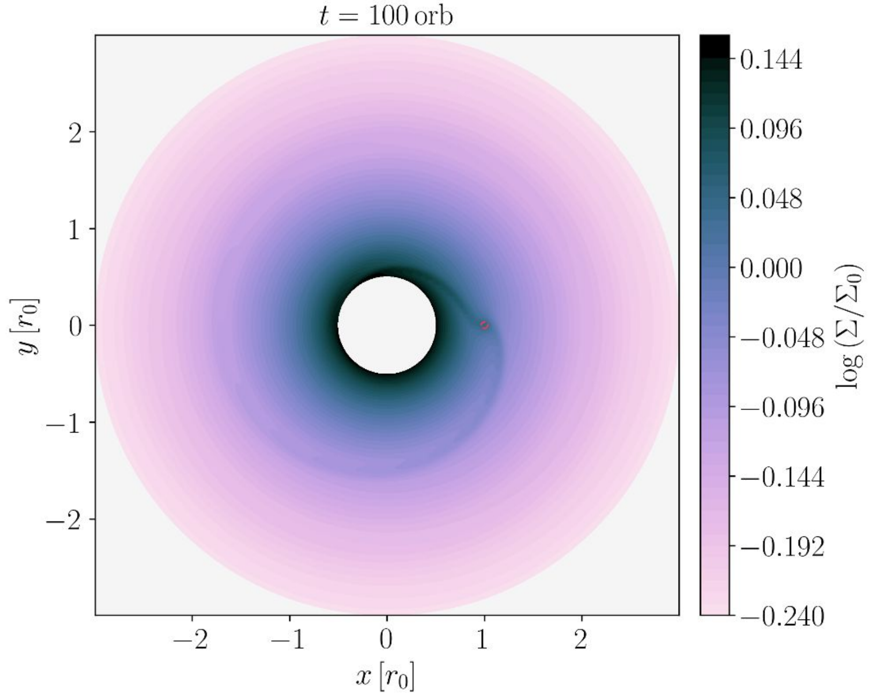
$$\alpha = 0.1$$

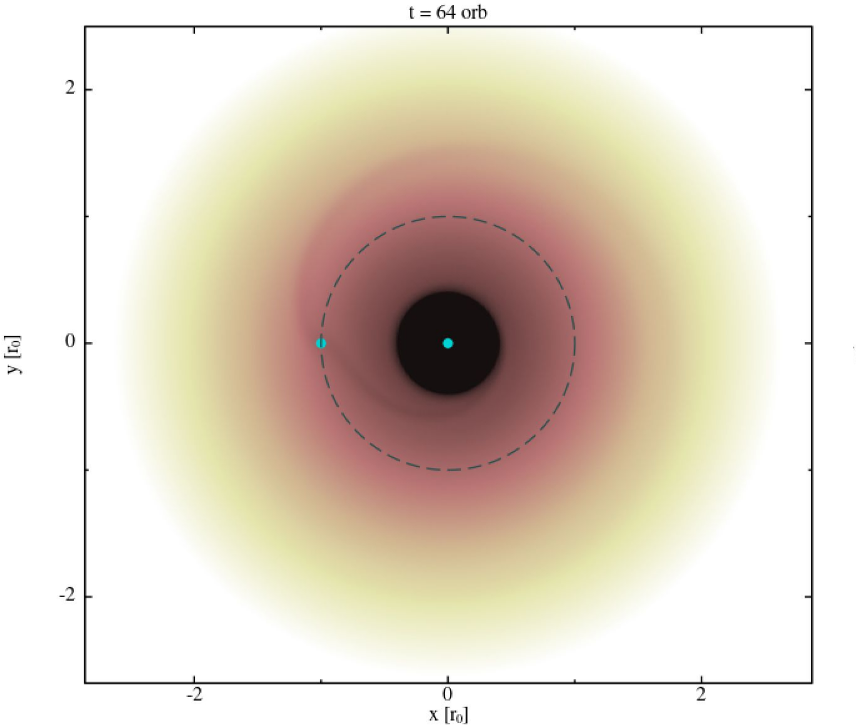
$$\frac{H}{R} = 0.1 \qquad \text{constant}$$

$$\Sigma(r) = \Sigma_0 (r/r_0)^{-1/2}$$

Project 3: Numerical hydrodynamics code comparison on sinking MBHs and IMRIs (DiscIMRIs)

PRELIMINARY RESULTS - Disco (left) and Gizmo (right)





Project 3: Numerical hydrodynamics code comparison on sinking MBHs and IMRIs (DiscIMRIs)

- Preliminary torques are in agreement but with different variability timescales
- Next steps will quantify the range of torques for a set of AGN-like disk parameters

Numerical codes involved:

- Arepo (Springel 2010) - moving mesh
- Athena++ (Stone et al. 2020) - grid based finite volume
- Disco (Duffell 2016) - grid based finite volume
- Dyablo (P. Kestener, A. Durocher, M. Delorme) - grid based adaptive mesh
- Fargo 3D (P. Benítez Llambay, F. Masset) - grid based
- Gasoline/ChaNga (Wadsley et al. 2004) - SPH
- Gizmo-MFM (Hopkins 2015) - meshless finite mass
- Phantom (Price et al. 2018) - SPH
- Ramses (R. Teyssier) - grid based adaptive mesh
- Rossbi (S. Rendon Restrepo/C. Surville) - finite volume