The status of black hole binary waveform modeling and the requirements for LISA

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10 Years to LISA
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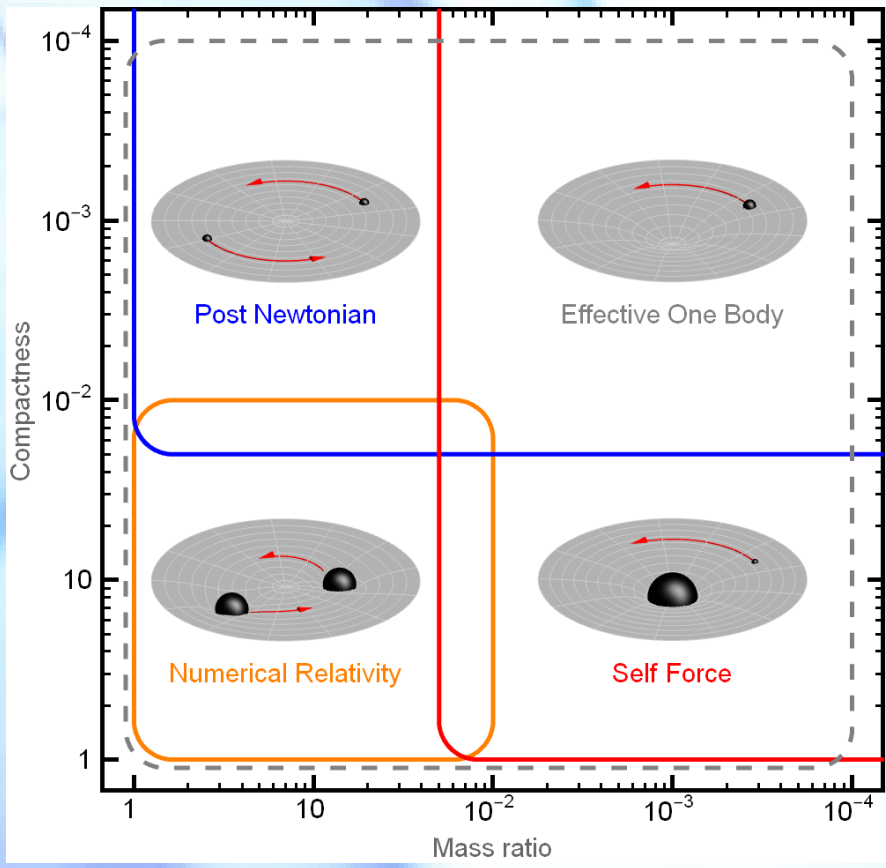
Modeling comparable masses

- NR hybrid surrogates attach PN to NR and interpolate.
  - Pro: potentially as accurate as NR
  - Cons: NR isn't accurate enough for LISA, interpolation has errors and can be slow.
- EOB-based models (SEOBNR, TEOB) are built on PN, calibrate to NR and self force.
  - Pro: can leverage all other approaches
  - Cons: less accurate than NR, ODEs or interpolation can be slow
- Neither approach tells you **why** the signal looks how it does.



Based on e.g. Van de Meent and Pfeiffer PRL (2020)

PN State-of-the-art

	Dynamics				Dissipative flux			
PN order	non-spinning	spinning			non-spinning	spinning		
		SO	SS	higher spins		SO	SS	higher spins
0	√	-	-	-	-	-	-	-
1	√	-	-	-	-	-	-	-
1.5	-	√	-	-	-	-	-	-
2	√	-	√	-	-	-	-	-
2.5	√	√	-	-	√	-	-	-
3	√	-	√	-	-	-	-	-
3.5	√	√	-	√ (S^3)	√	-	-	-
4	√	-	√	√ (S^4)	√	√	-	-
4.5	*	√	-	√ (S^3)	√	-	√	-
5	*	-	√	√ (S^4)	√	√	-	-
5.5	*			√ (S^5)	√	√	√	-
6				√ (S^6)	√	√	√	√ (S^3)
6.5				⋆	√	√	√	
7				⋆	√			

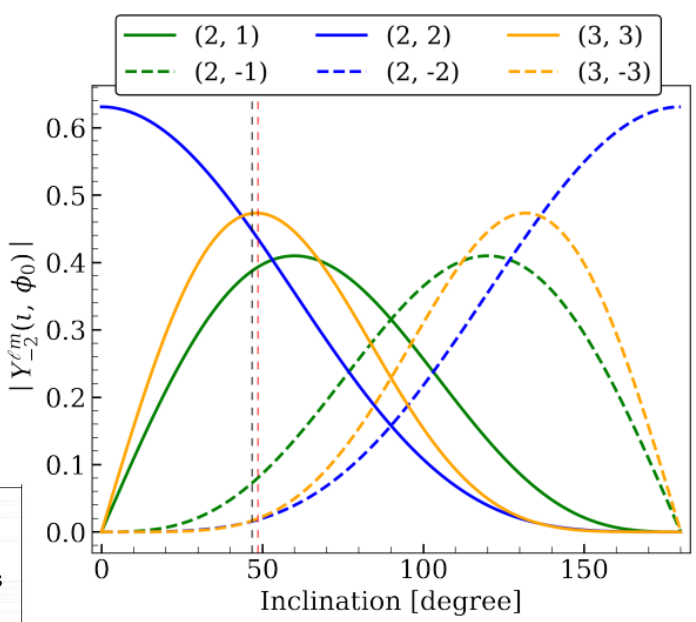
LISA WavWG WP (2023)

NR Codes

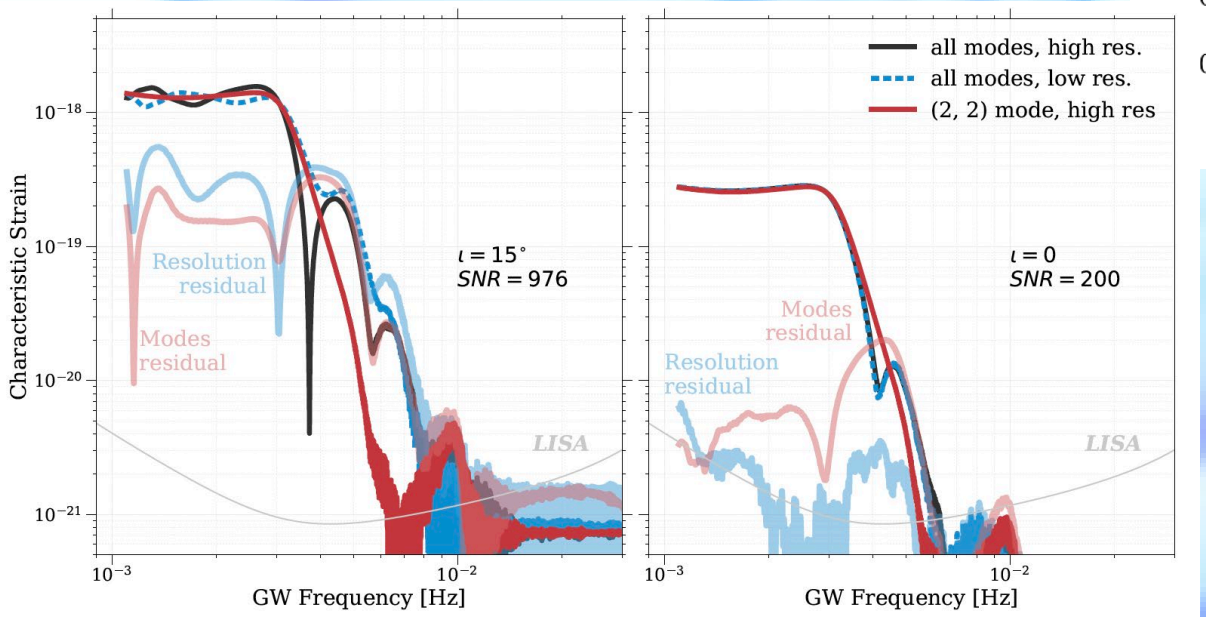
	Open Source	Public catalog	Formulation	Hydro	Beyond GR
AMSS-NCKU [552, 613–615]	Y	–	BSSN/Z4c	–	Y
BAM [582, 616–618]	–	[524, 619, 620]	BSSN/Z4c	Y	–
BAMPS [621–623]	–	–	GHG	Y	–
COFFEE[624, 625]	Y	–	GCFE	–	Y
Dendro-GR [626, 627]	Y	–	BSSN/CCZ4	–	Y
Einstein Toolkit [628, 629]	Y	–	BSSN/Z4c	Y	Y
*Canuda [366, 367, 630]	Y	–	BSSN	–	Y
*IllinoisGRMHD [631]	Y	–	BSSN	Y	–
*LazEv [515, 632]	–	[633–636]	BSSN/CCZ4	–	–
*Lean [637, 638]	Partially	–	BSSN	–	Y
*MAYA [639]	–	[639]	BSSN	–	Y
*NRPy+ [640]	Y	–	BSSN	Y	–
*SphericalNR [641, 642]	–	–	spherical BSSN	Y	–
*Spritz [643, 644]	Y	–	BSSN	Y	–
*THC [645–647]	Y	[619]	BSSN/Z4c	Y	–
*WhiskyMHD [648]	–	[649]	BSSN	Y	–
ExaHyPE [650]	Y	–	CCZ4	Y	–
FIL[651]	–	–	BSSN/Z4c/CCZ4	Y	–
GR-Athena++ [652]	Y	–	Z4c	Y	–
GRChombo [653–655]	Y	–	BSSN/CCZ4	–	Y
HAD [656–658]	–	–	CCZ4	Y	Y
Illinois GRMHD [659, 660]	–	–	BSSN	Y	–
MANGA/NRPy+ [661]	Partially	–	BSSN	Y	–
BH@H/NRPy+ [640, 662]	–	–	BSSN	–	–
MHDuet [663–665]	Y	–	CCZ4	Y	Y
SACRA [666–670]	–	[671]	BSSN/Z4c	Y	Y
SACRA-SFS2D [672, 673]	–	–	BSSN/Z4c	Y	–
SpEC [523, 674]	–	[521, 523, 675]	GHG	Y	Y
SpECTRE [676, 677]	Y	–	GHG	Y	–
SPHINCS_BSSN [678]		–	BSSN	SPH	–

Accuracy Requirements

- Required accuracy depends on SNR and parameters.
- Most stringent for the loudest "golden" signals that will tell us the most about strong gravity



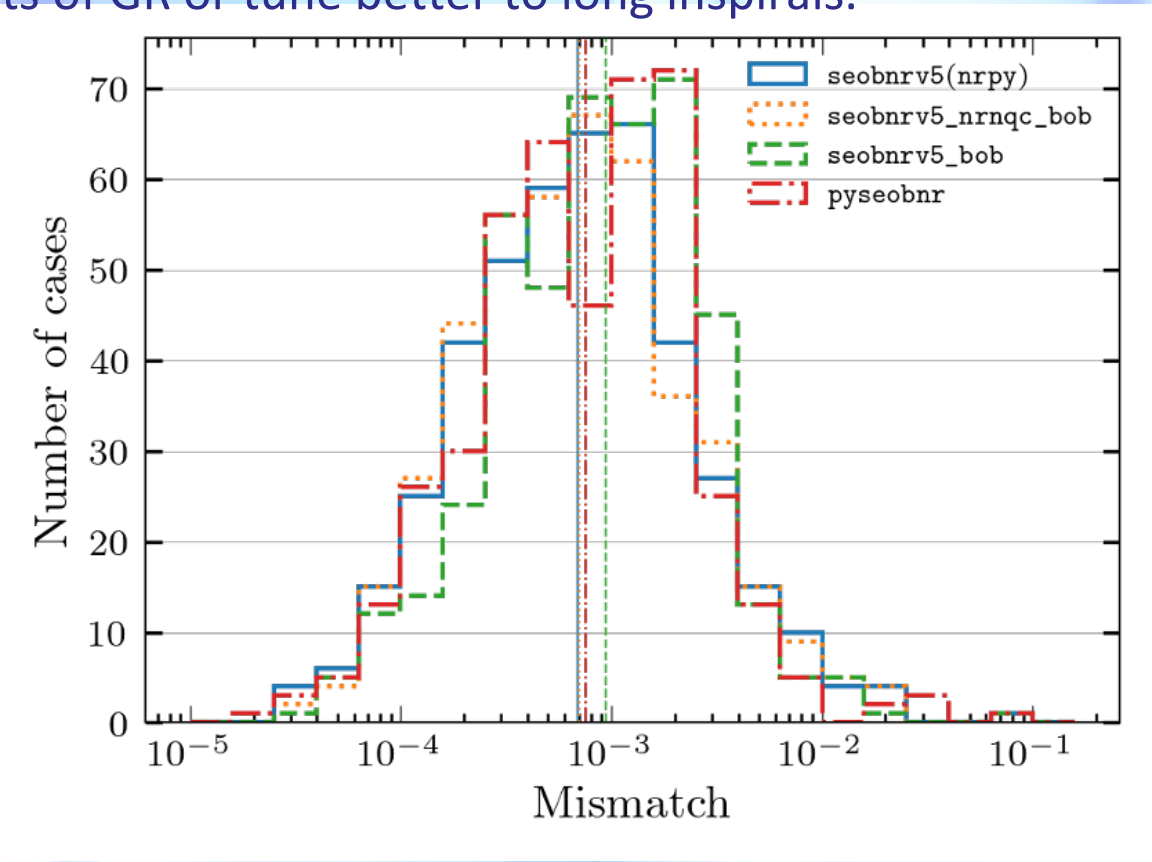
Puecher et al. (2022)



LISA WavWG WP (2023)

Accuracy Requirements

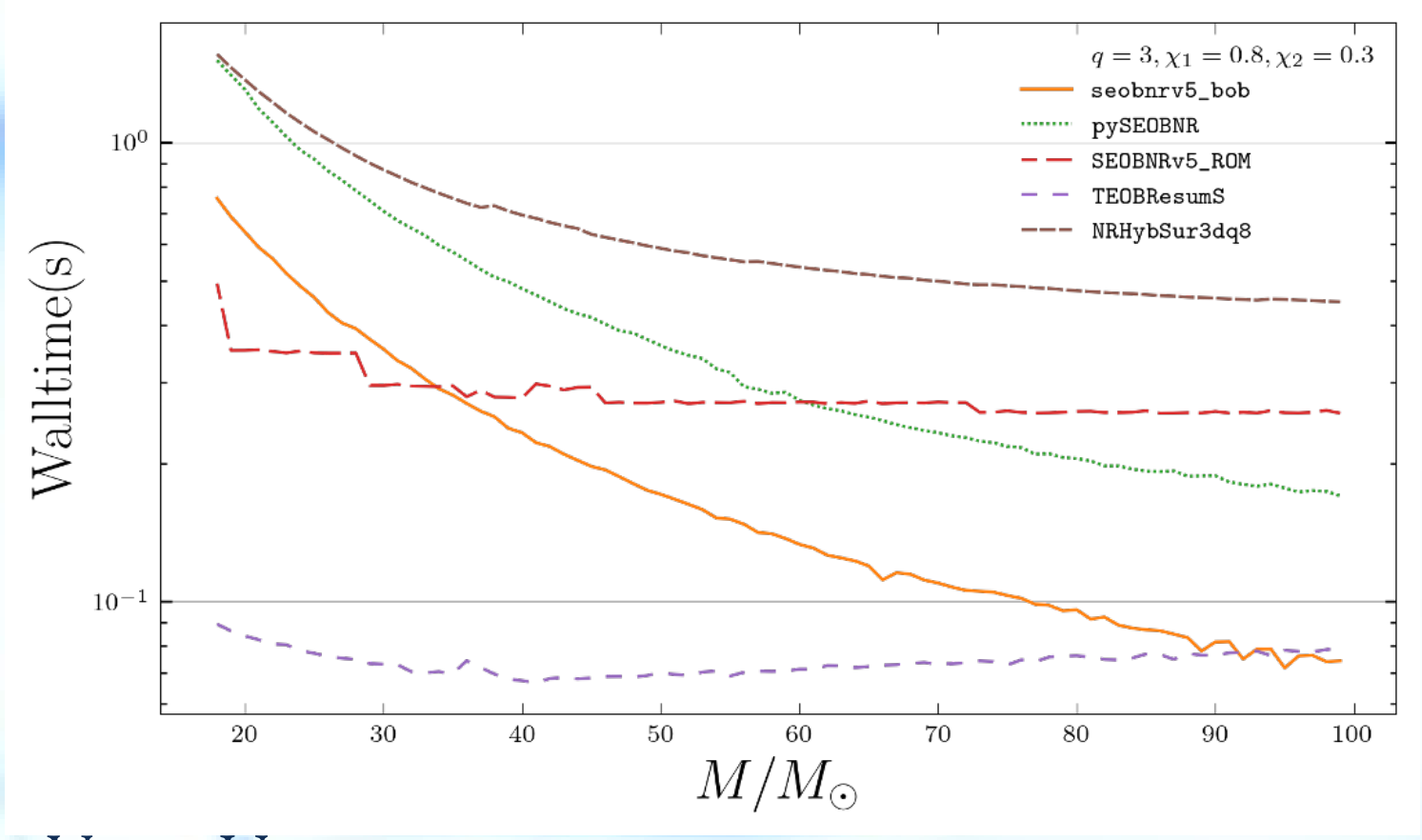
- LISA needs mismatches of 10^{-6} for inference on astro interpretation of individual sources, 10^{-7} for joint inference on MBHB population.
- 3-4 orders of magnitude away from where we need to be
- SEOBBOB uses 50% as many tuning dofs; by eliminating dofs during merger, can improve tests of GR or tune better to long inspirals.



Mahesh, STM, and Etienne (2025, in prep)

Efficiency Requirements

- LISA needs WF generation in < 1 s on 1 CPU.
- ROMs+interpolation may be too slow.
- Post-adiabatic will be too inaccurate.
- We are evolving the full Hamiltonian as fast as ROMs using NRPy.



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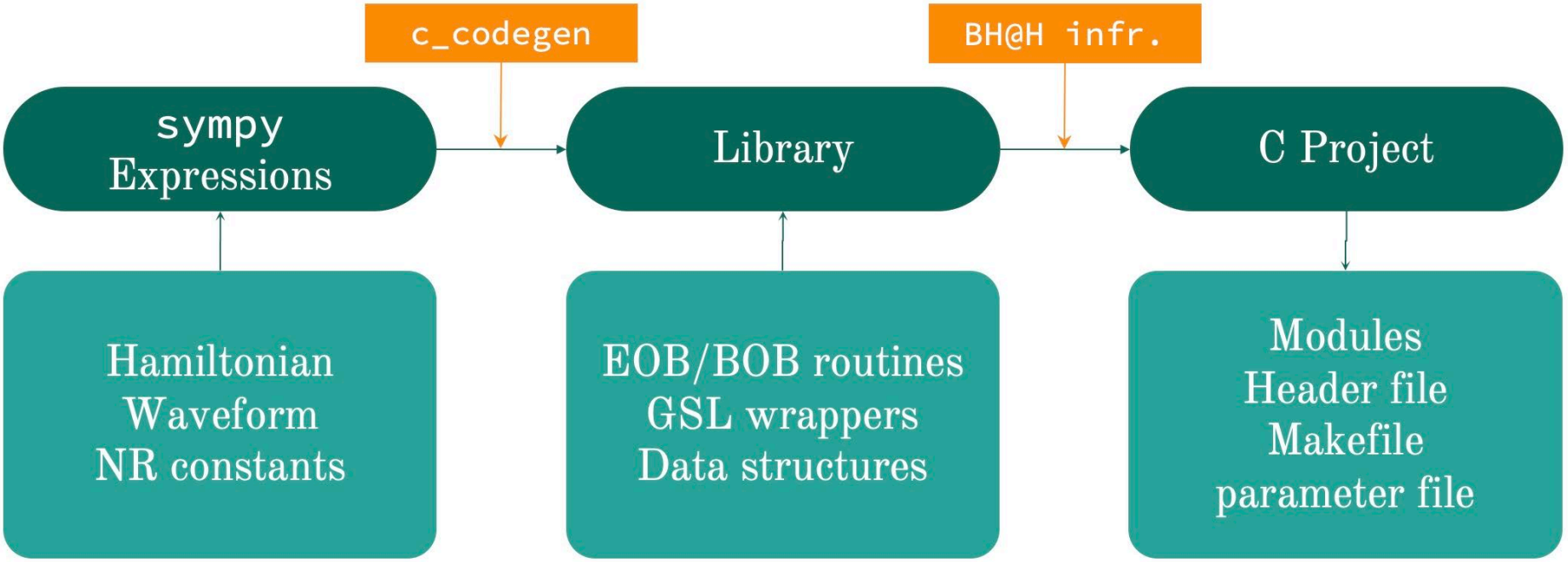
Efficiency Requirements

- NRPy takes in documented code in Python using sympy, outputs optimized C libraries.
- Easy integration with BH@H (also in NRPy) for calibrating to NR



https://github.com/nrpy/nrpy/

```
pip install nrpy
python -m
nrpy.examples.seobnrv5_aligned_spin_inspiral
```