Waveform modeling and systematics

PAX-X and CE Symposium, University of Illinois

Panelists:
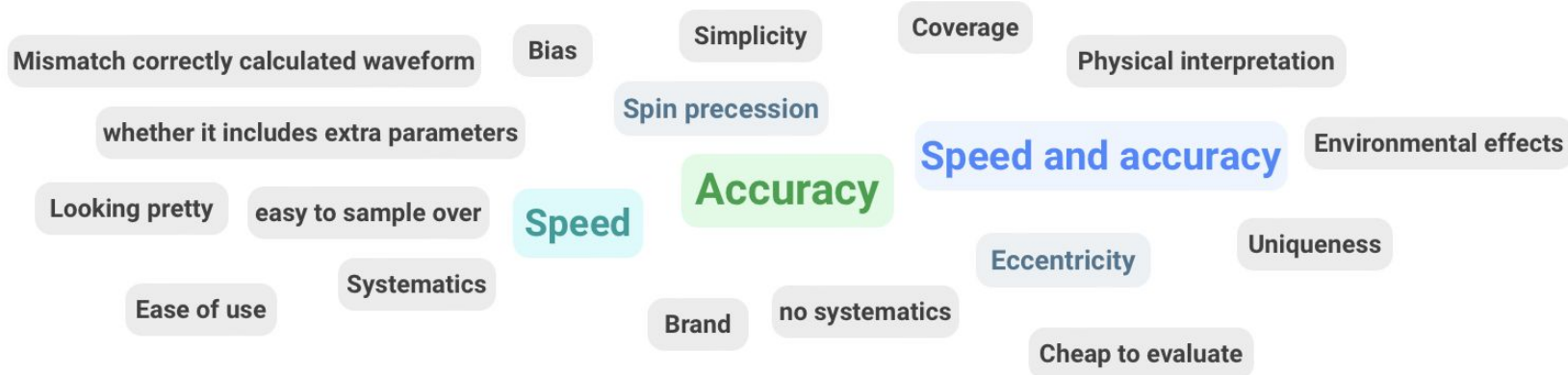
Rossella Gamba , Shrobana Ghosh, Lucy M. Thomas

Chair:
Marta Colleoni

When choosing a GW model for your research, what aspects do you prioritise?

Review answers 20

Mismatch correctly calculated waveform

Bias

Simplicity

Coverage

Physical interpretation

whether it includes extra parameters

Spin precession

Speed and accuracy

Environmental effects

Looking pretty

easy to sample over

Speed

Accuracy

Eccentricity

Uniqueness

Ease of use

Systematics

Brand

no systematics

Cheap to evaluate

# Do we need (semi-)analytic waveform models?

YES!

- Flexible in their coverage of parameter space and signal length

- Cross-comparisons and cross-validation between independent frameworks: no "one-to-rule-them-all waveform"

- Useful to build physical intuition

- Modular nature:
  - test impact of specific assumptions
  - easy to extend use case (e.g. extreme matter, environment)

- Convenient baseline for parameterized tests of GR

NO!

- We can estimate GW source properties directly with NR waveforms

- Why would one use inaccurate (semi-)analytic models when we have super-duper NR surrogates??

- Waveform models have long and incomprehensible names only developers understand

- …

Waveform models: recent progress and challenges

Progress
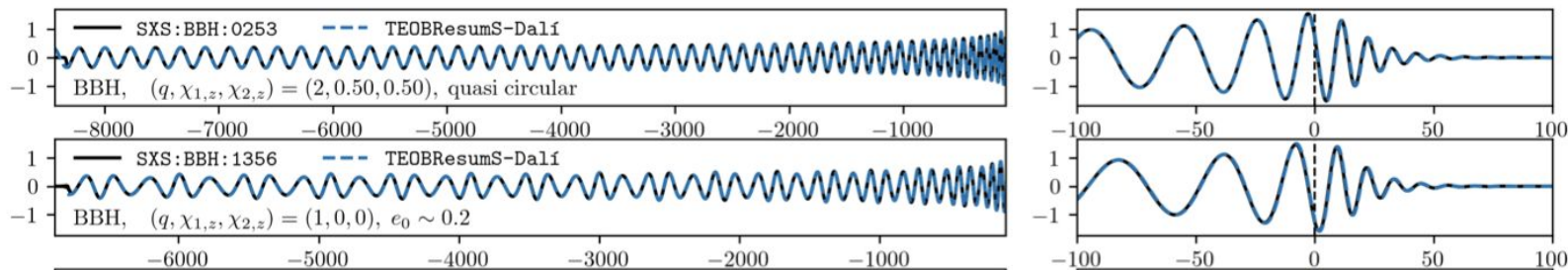
Albanesi+ 2025,
arXiv:2503.14580 **[gr-qc]**

- Precession + eccentricity: see Rossella's presentation this morning!
- Many efforts to add "subdominant effects" in prep for future detectors (e.g. subdominant harmonics, mode-asymmetries, GW memory, etc…)

… challenges…

- Prospects of precessing&eccentric NR surrogates?
    - Sparse NR coverage
    - Need to find best way to represent complex waveforms in terms of easy-to-model data pieces (see e.g. Islam+ 25)
    - Semi-analytic models can help in finding good ways to do that!
- WF systematics visible even even under quasi-circular assumption at current detector sensitivity
- Merger-ringdown dominated signals can be particularly challenging!
- Need to standardise definitions of certain quantities to avoid apples-to-oranges comparisons (e.g. eccentricity)

…and more challenges: Scatterings and captures

- If ET/CE/LISA are going to see "all BHBHs in the universe" at least **some** of them are bound (pun intended) to be on hyperbolic orbits

- Fairly recent, increasing interest due to developments in post-minkowskian calculations…

- How to treat ringdown? Some developments, but no full model (yet?)

NR & Surrogates

NR and surrogates

- Building a surrogate implies choosing a fiducial set of waveforms and a way to break down the data into "simpler pieces"
- NR waveforms don't have infinite accuracy (Ferguson+ 21, Jan+ 23); long simulations computationally demanding
- When validating a model against NR, not always straightforward if we are "within error bars":
  - More cross-code comparisons to quantify impact of potential sources of error? (Radice+ 25, Babiuc-Hamilton+ 24, Kuan+ 2025)
  - Heterogenous calibration datasets? (Khan+ 2023)
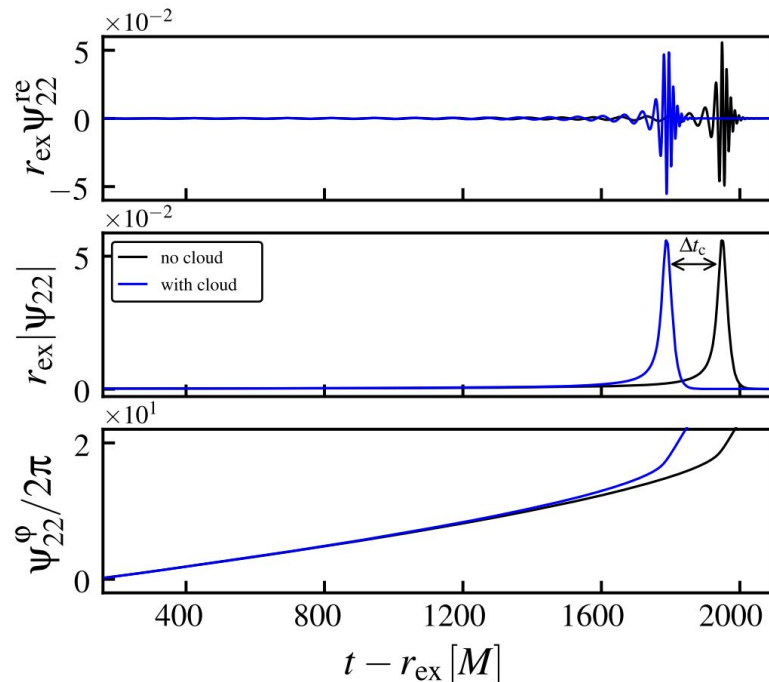- Will surrogate be key to speed up inference?
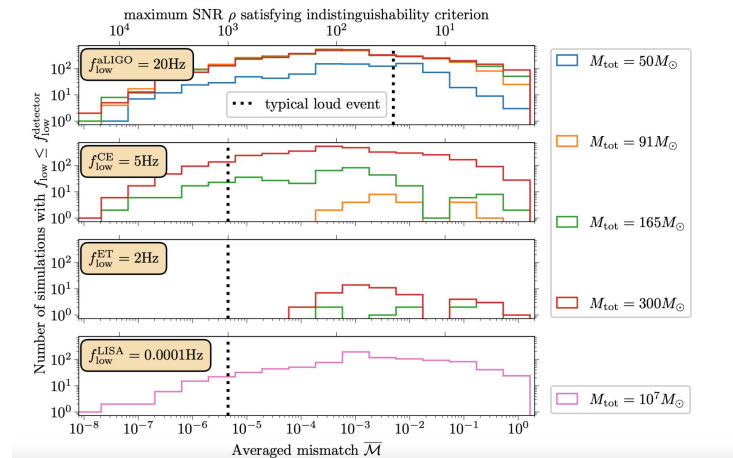
Scheel+, arXiv:2505.13378 [gr-qc]

Environment & exotica

Signals for alternative scenario

- Equal mass BBH in dark matter cloud
- Phase-time optimization in matched filtering will label this as CBC in vacuum
- What if signals are incompatible with our inference techniques ?

PRL 2024

Identifiable features – guide modeling efforts

- Several dedicated modeling efforts based on nature of exotic object – is crucial
- Effective spin is not physical, but "effective"
- PhenomDECO - tracking the amplitude profile
- Not a waveform, rather a tool to shed light on potentially "dark" stars

arxiv:2505.16380
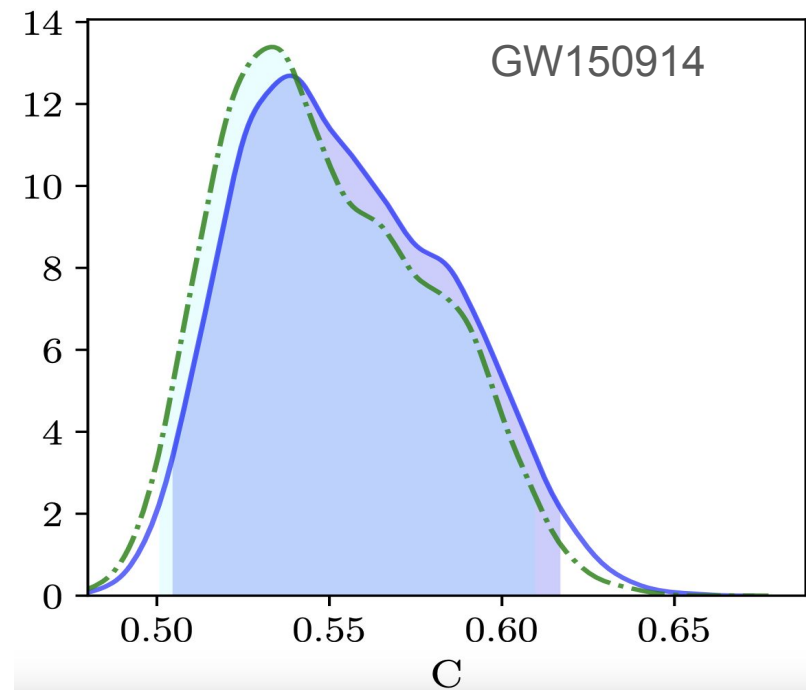
Extreme matter

Matter effects (on non-circularized orbits!)

- Matter effects are complicated as they are, but until now the assumption is that they mostly affect the late inspiral-plunge-merger-postmerger (~true for quasi-circular CBCs) → fully phenomenological models informed by NR
- If the assumption is relaxed, matter effects very clear **in the inspiral**!
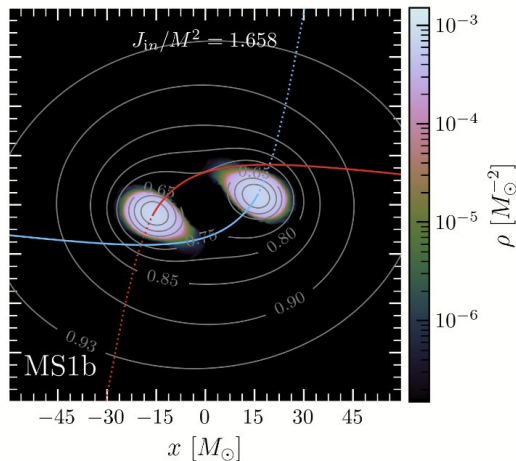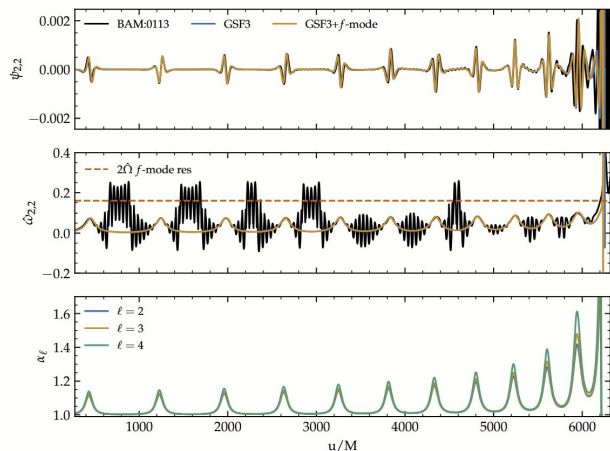
BHNS?
Probably even more tidal disruption! Relevant, because Morras+24, [confirmed by other independent analyses]
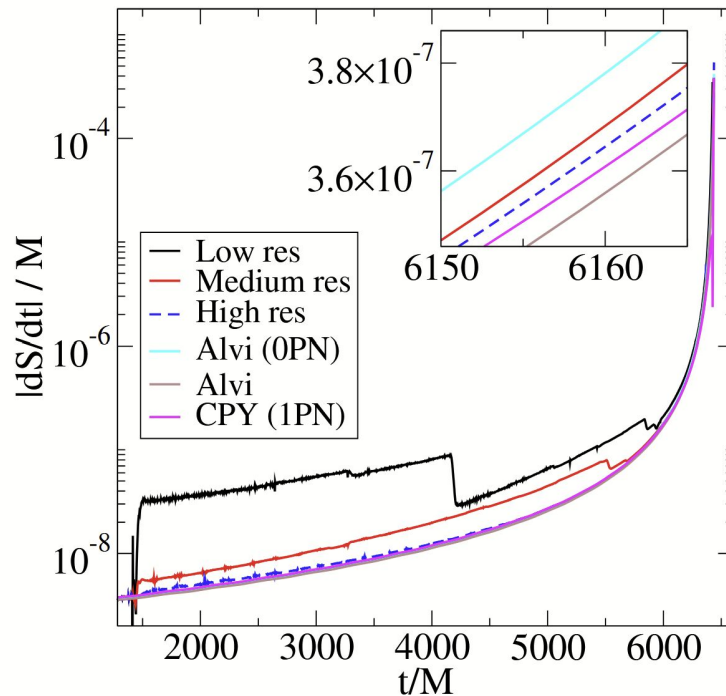
Matter effects (on non-circularized orbits)

- How to deal with this?
  - If it's "just" modes excitations, semi-analytical models must/should be possible (& NR needed for validation)
  - If there is disruption & ejecta… well, I have no idea. Time varying masses & spins + approximate model for the mass/momentum transfer?
- People should start thinking about it!
  - It's fun
  - It's (mostly) unexplored, at least on the GW modeling side
  - There are a lot of things to study: kilonova? GRBs? Amplifications of magnetic fields?

Backup slides

Horizon physics

- BHs have one very interesting feature: an horizon!
- (pretty small but non-zero) mass and spins variations **during the evolution!**
- Intrinsically related to area law
  - currently, included "phenomenologically" in quasi-circular binaries (= fits to NR take care of these effects automatically in terms of GW phasing)
  - Could be used to distinguish between horizon-less objects and BHs? Yes for EMRIs, how about other scenarios?
  - Are there scenarios in which mass/spin variations could become relevant and need to be accounted for?

https://arxiv.org/pdf/1412.1803