Waveforms: Status & challenges

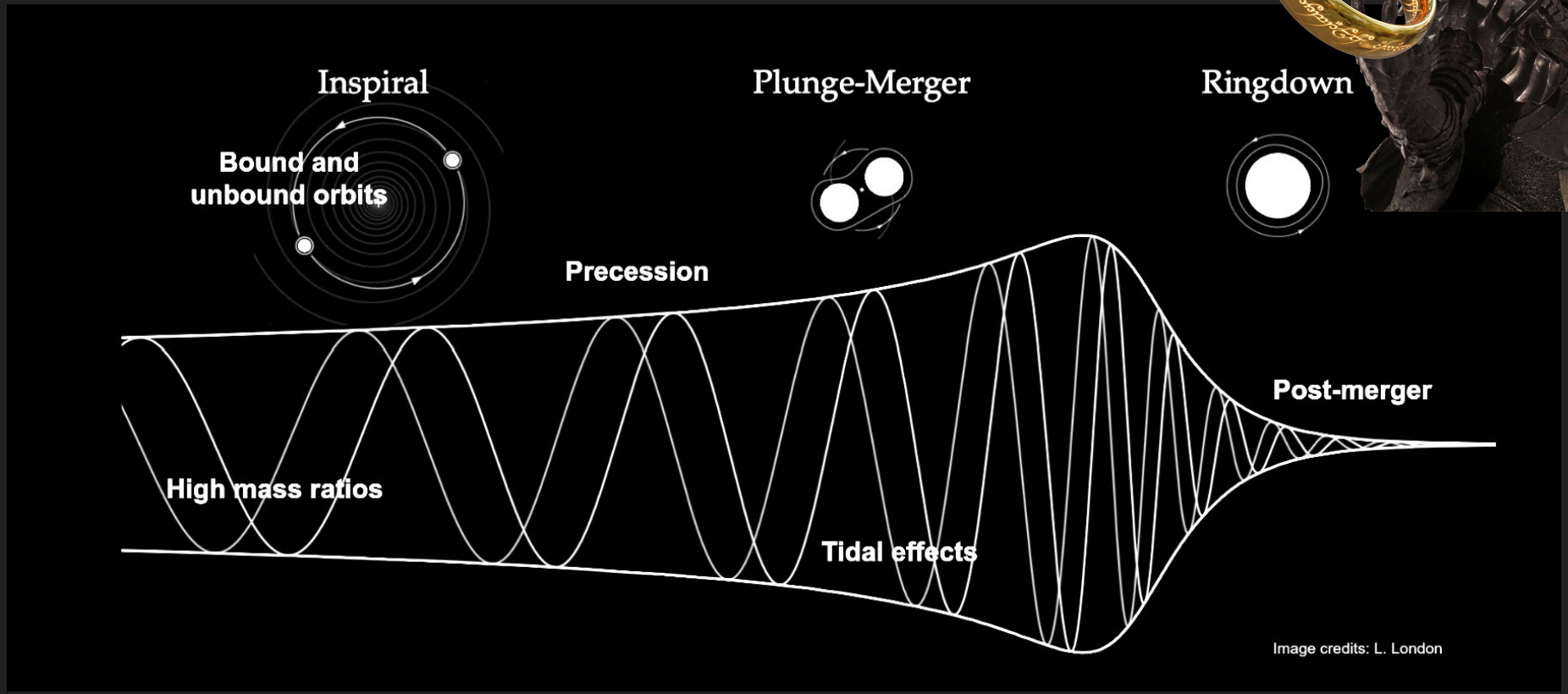
& opportunities

PAX X – waveforms

R. Gamba, M. Colleoni, S. Ghosh, L. Thomas




Status of the two body problem



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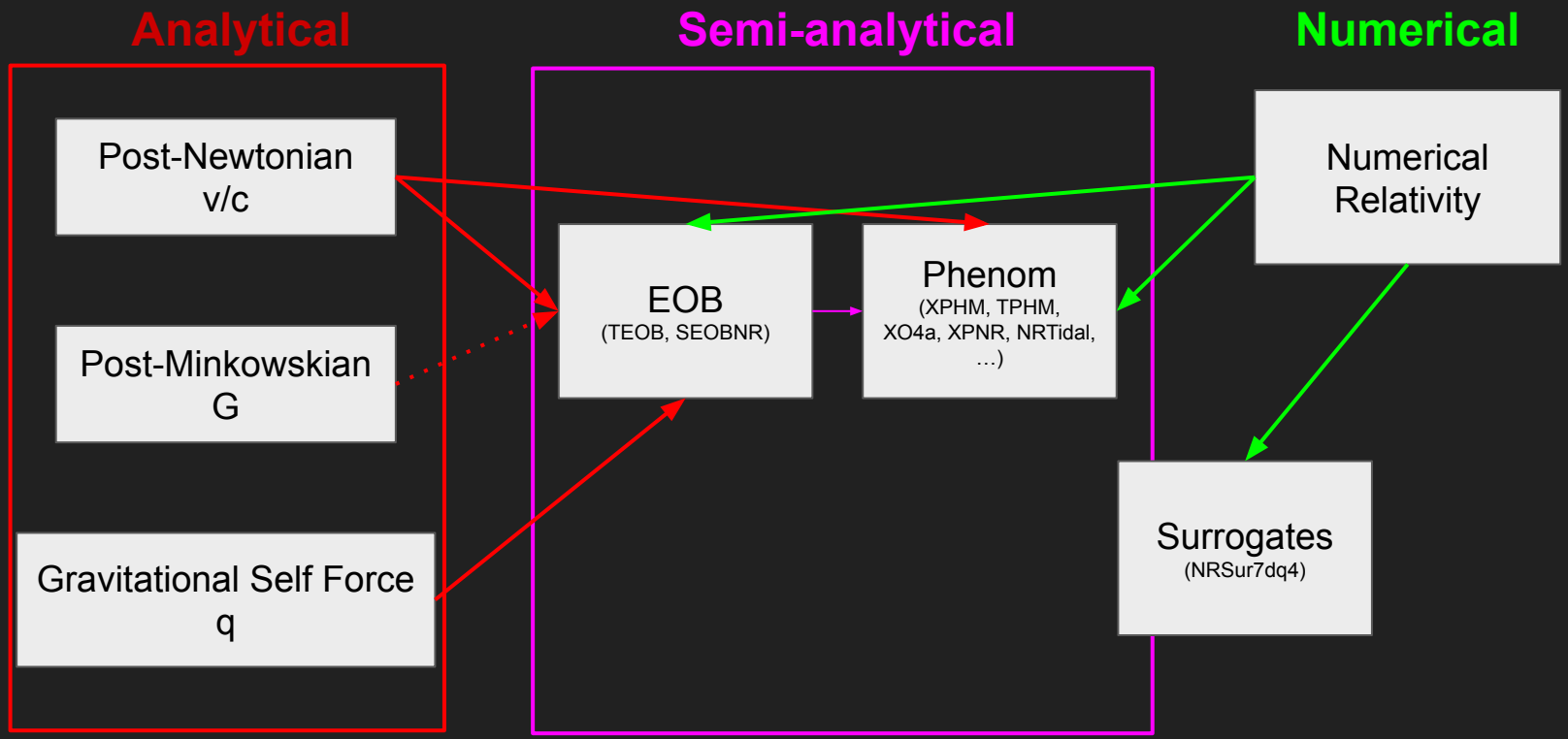

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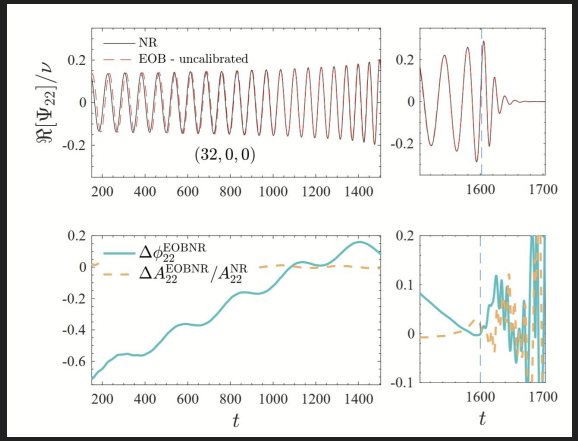
- Memory in TPHM, TEOB
- Efforts to compute/include horizon fluxes beyond LO (explicitly)
- More NR-calibrated tidal models: v5THM and PhenomXP_NRTidalv3
- PM in EOB: SEOBNR-PM and LEOB
- Efforts in comparing different NR codes:
  - SACRA vs BAM, (vs THC, SpEC) , evolution & ID
  - SpEC vs GRAthena++
- New NR codes:
  - GRoovy (GRHD) & superB/NRPy
  - AthenaK
  - SpECTRE
- New/larger catalogs! SXS, …



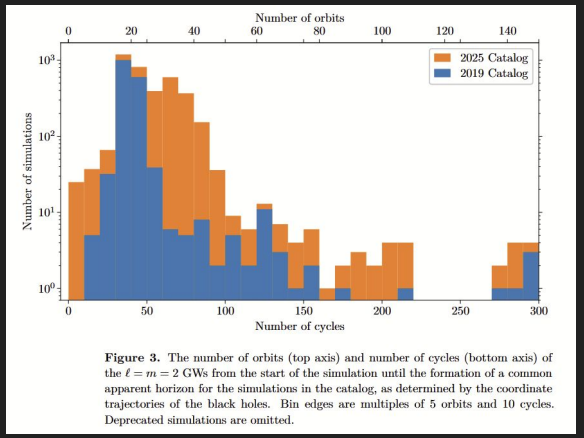
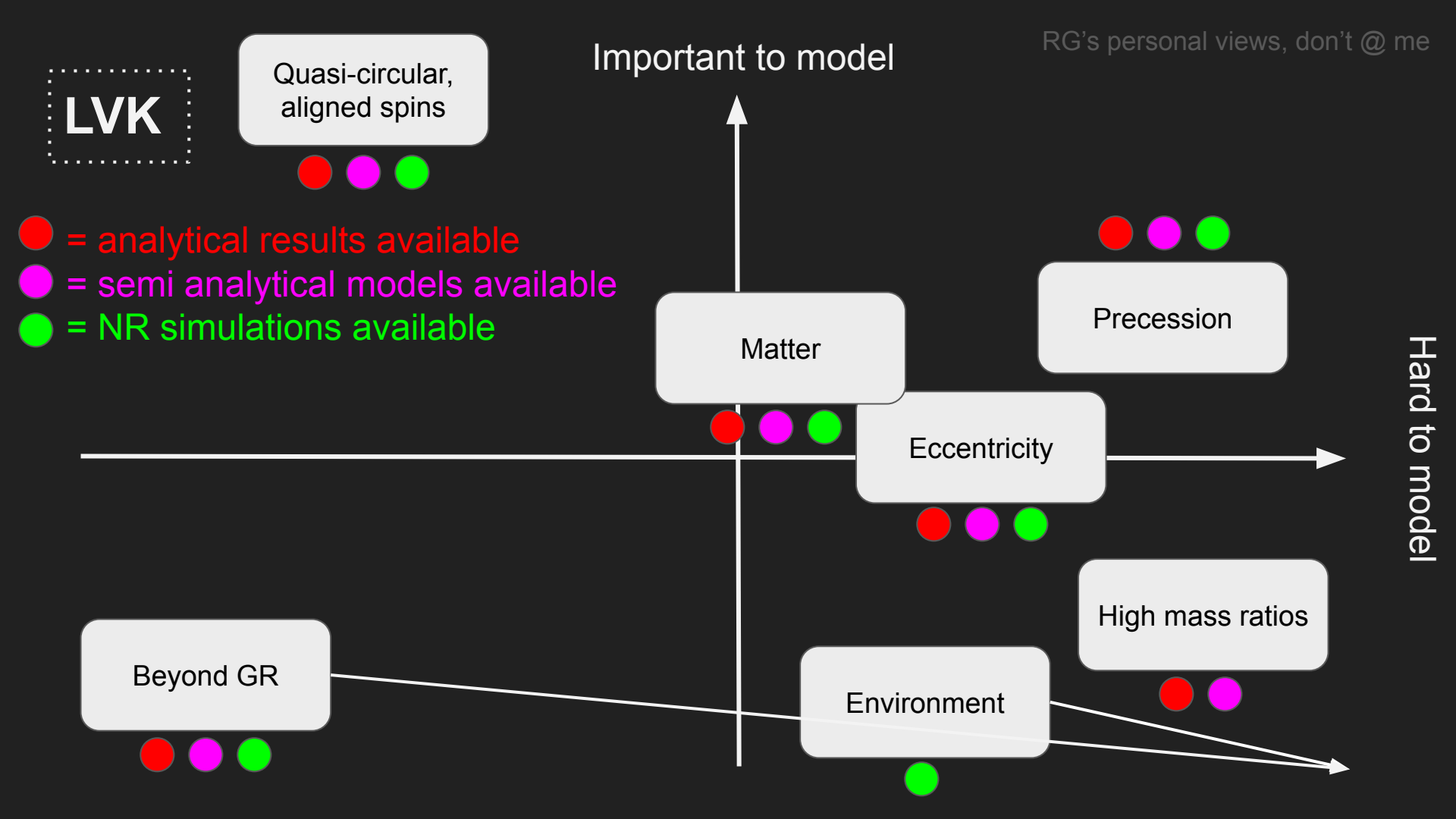
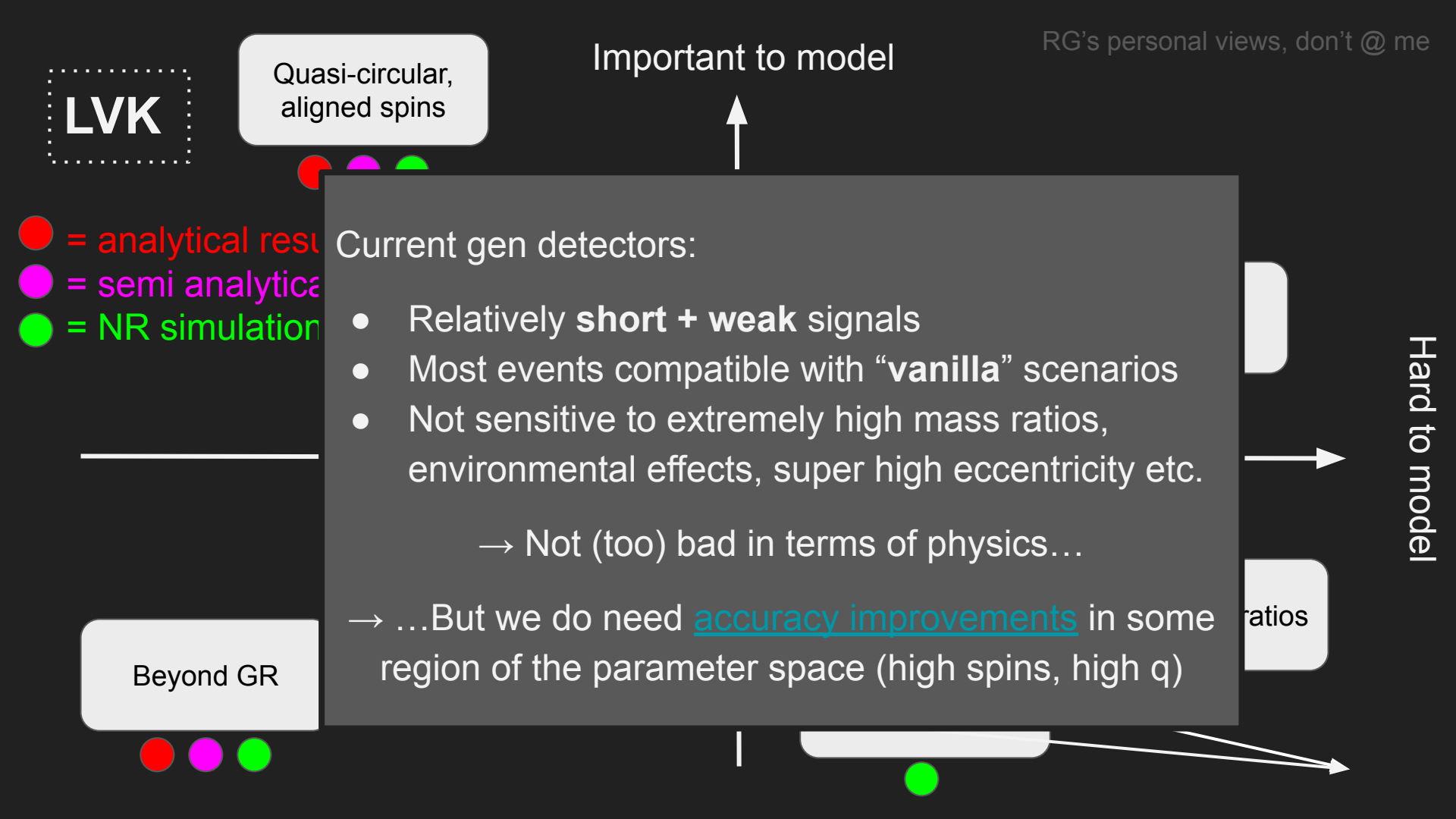


Figure 3. The number of orbits (top axis) and number of cycles (bottom axis) of the $\ell = m = 2$ GWs from the start of the simulation until the formation of a common apparent horizon for the simulations in the catalog, as determined by the coordinate trajectories of the black holes. Bin edges are multiples of 5 orbits and 10 cycles. Deprecated simulations are omitted.

Status of the two body problem

	EOB	Phenom	NR Surrogates
Quasi-circ	MM < 1e-3	MM < 1e-3	“Exact”
Precession	spin evo + twist	spin evo + twist, NR informed	“Exact”
Eccentricity	Aligned spins, steps towards precession	Aligned spins	non-spinning only
Unbound	Yes (with PM)	No	Psi4 for scatterings
Matter	Yes (NR informed)	Yes (NRTidal-like)	No(t yet?)
Beyond GR	Mostly parameterized	Mostly parameterized	No
Environment	No	Simplified	No
High q	Yes	No	Yes


LVK
Quasi-circular, aligned spins
= analytical results available
= semi analytical models available
= NR simulations available
Important to model
Hard to model
Matter
Precession
Eccentricity
High mass ratios
Beyond GR
Environment
RG's personal views, don't @ me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Quasi-circular, aligned spins
Important to model
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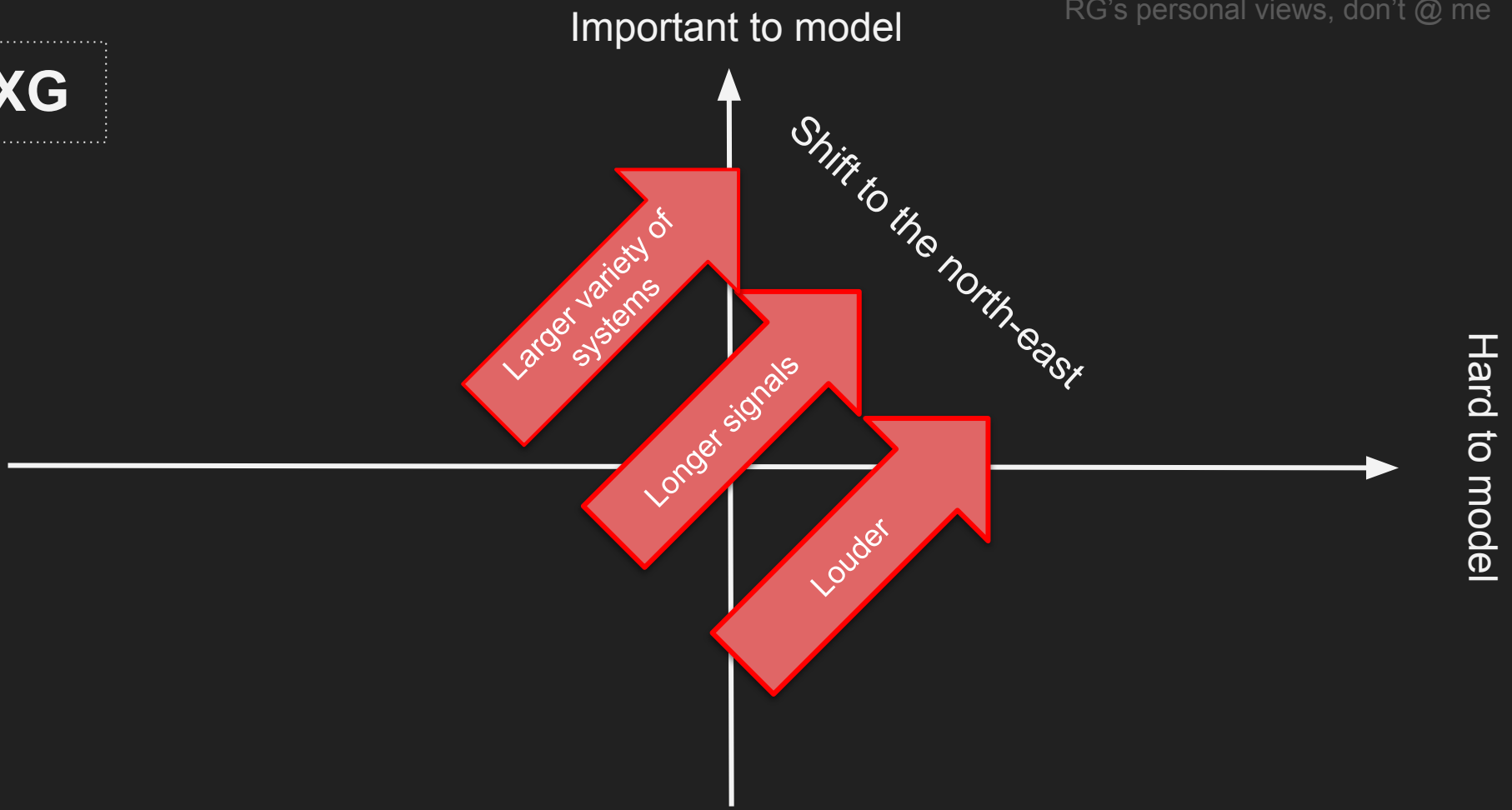
= analytical resu
= semi analytica
= NR simulation
Current gen detectors:
Relatively short + weak signals
Most events compatible with "vanilla" scenarios
Not sensitive to extremely high mass ratios, environmental effects, super high eccentricity etc.
→ Not (too) bad in terms of physics…
→ …But we do need accuracy improvements in some region of the parameter space (high spins, high q)
Hard to model
ratios
Beyond GR

RG's personal views, don't @ me

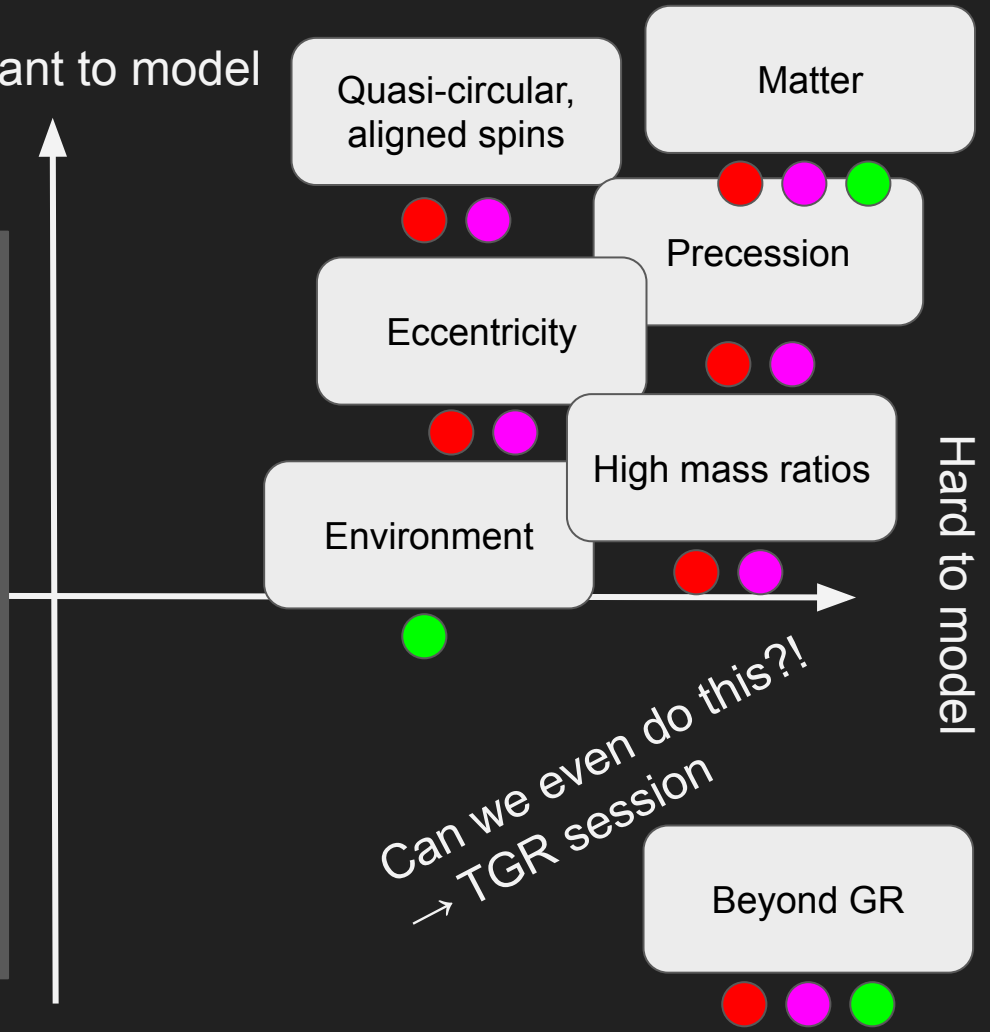
XG



XG

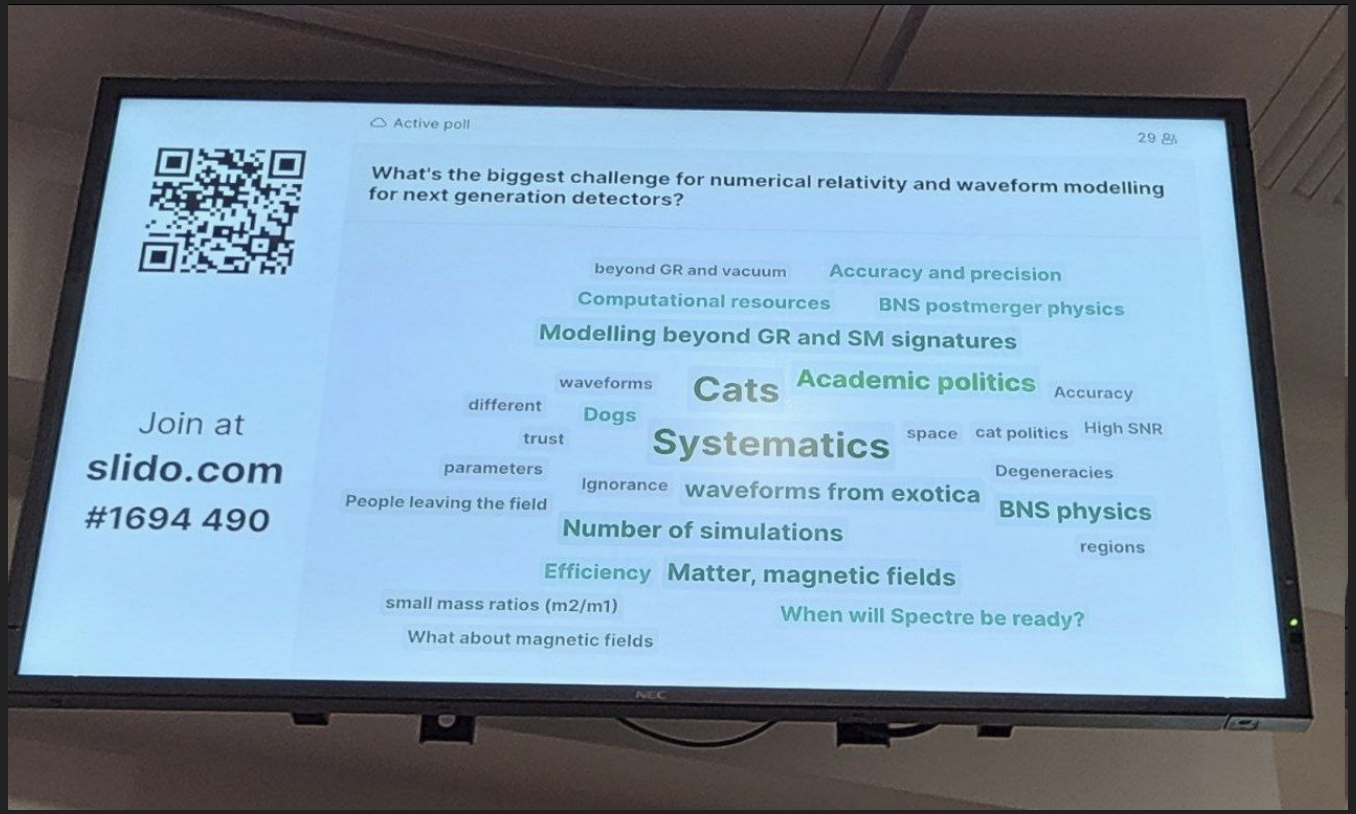
Everything is hard AND important!

- More than merger-ringdown, length of signals & hybridization
- For waveforms with matter, post-merger
- High mass ratios + eccentricity + precession

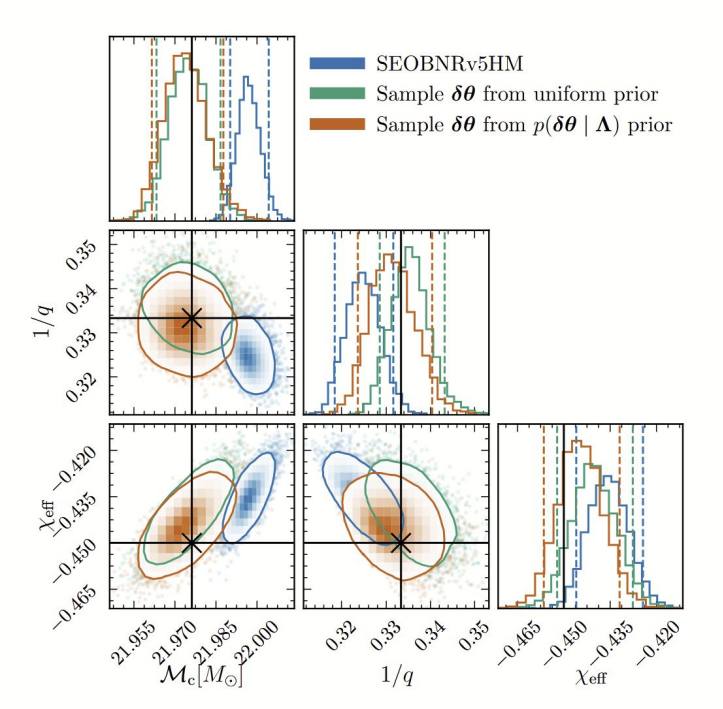


Challenges

From PAX IX



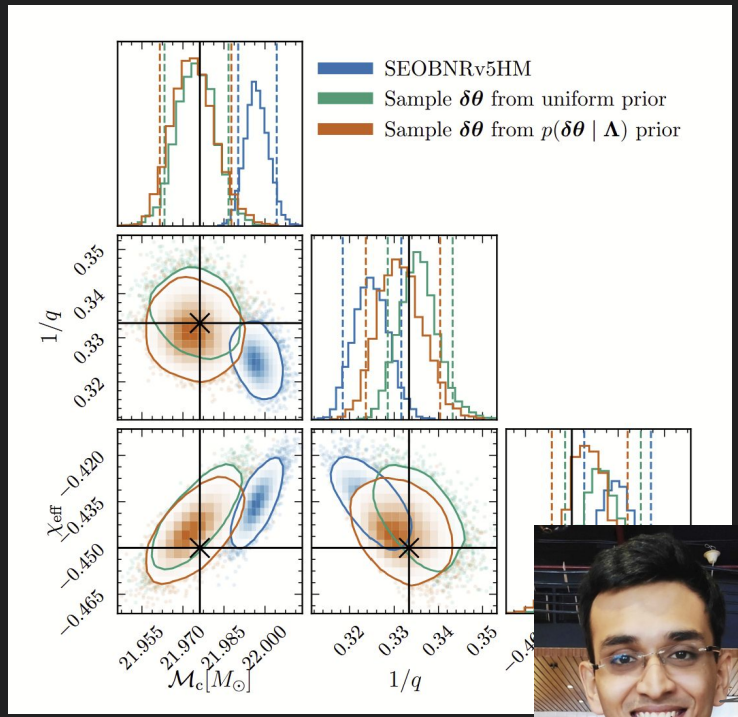
Challenges



At the expense of some precision, one can mitigate systematics due to accuracy:

- Marginalize over uncertainty in a model NR-informed parameters
- Add “calibration envelopes”-like parameters
- Combine posteriors from various models (based on evidence or during sampling)
- …

Challenges



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-

Just build better models guys

Challenges

Accuracy requirement? Not clear! Possible to estimate SNR at which bias will appear via:

$$1 - \mathcal{O}_T(s_0, h(\theta_0)) \leq \frac{n_p \left(1 - \frac{2}{9n_p} + 1.3\sqrt{\frac{2}{9n_p}}\right)^3}{2\mathrm{SNR}_T^2} + 1 - \mathrm{FF}_T(s_0, h)$$

From Thompson+25:

early estimates from Ref. [24]. In particular, we note that the bias SNRs depend on an individual model's construction, and in principle a "conservative" estimate of the bias SNR can sometimes be correct. This leads to a far more stringent accuracy requirement than in Ref. [24]: model mismatch uncertainties must be below 10^{-6} to be free of bias in observations with SNRs of ~1000, an improvement of four orders of magnitude over some current models. On the

Warm-to-hot takes: 

- For BBHs in vacuum, I think models will reach NR in ~15y time…
  …But will NR reach the accuracy level that is needed (whatever that may be)?

- Matter and environmental effects are going to be MUCH more challenging to model than reaching the accuracy threshold for vacuum GR

- WF generation speed has not been discussed, because I think it's a non-issue → See Koustav's talk on Wednesday

On the flip side: if (when?) we **do** manage to get all this under control, there is so much science to be done! So much to learn!

In conclusion!

- Waveform modeling is both ***competitive*** (who has the best model) and ***collaborative*** (we ~~steal~~ borrow ideas from one another all the time!)
  → we progress fast!

- We are in a decent place for current gen detectors (with some exceptions in the parameter space)

- Plenty of stuff to work on: **what should the focus be?**
  - If you have strong opinions, make sure to attend the panel this afternoon!
  - If you do not have strong opinions, attend either way: it will be fun I promise

Backup slides

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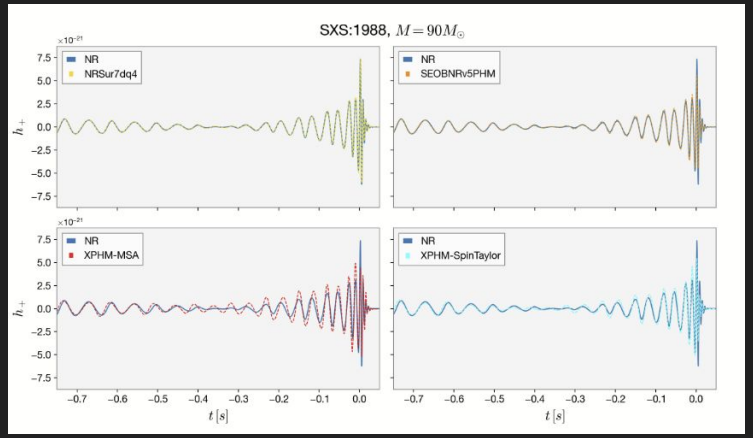

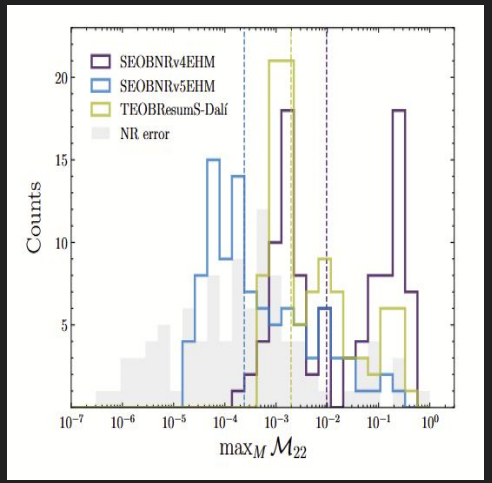

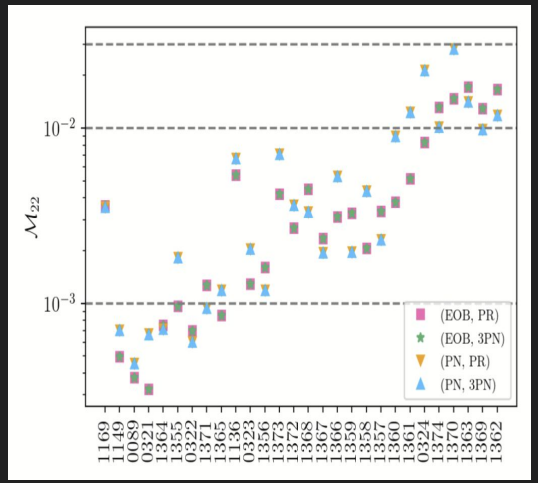

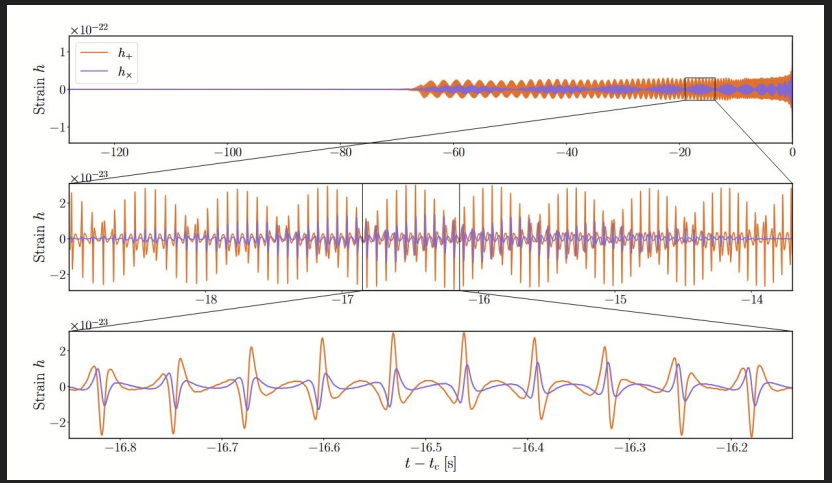

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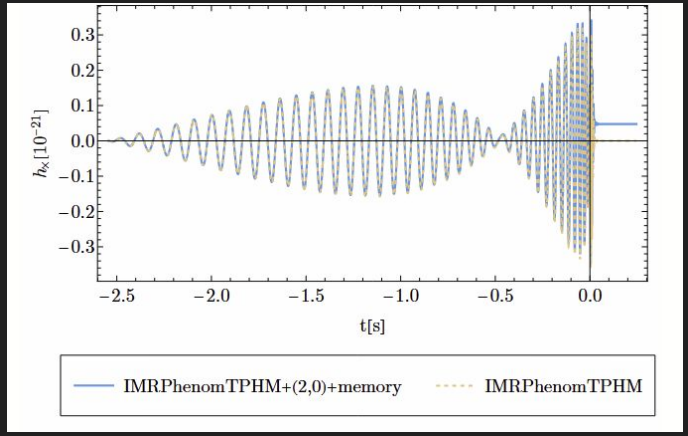

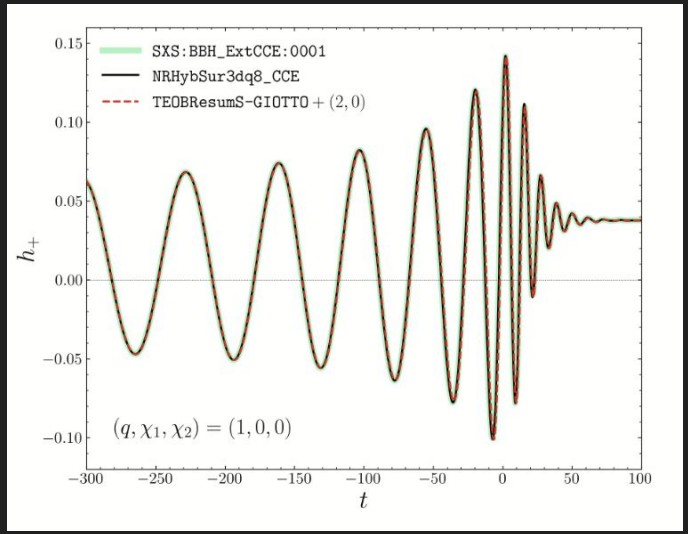

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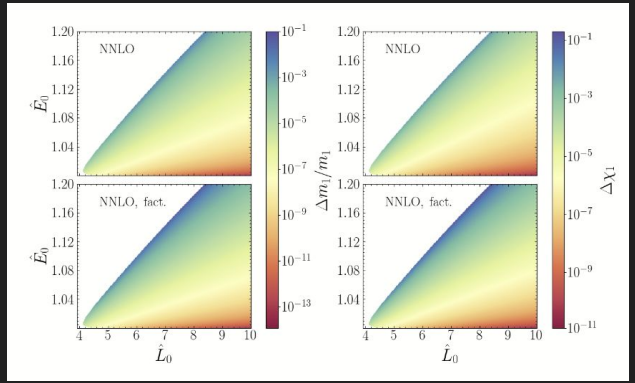

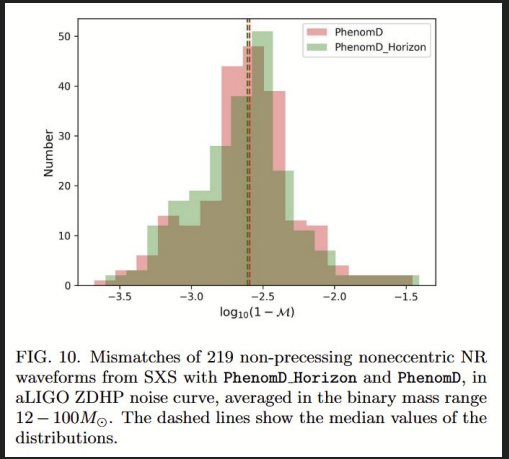

FIG. 10. Mismatches of 219 non-precessing noneccentric NR waveforms from SXS with `PhenomD_Horizon` and `PhenomD`, in aLIGO ZDHP noise curve, averaged in the binary mass range $12-100M_\odot$. The dashed lines show the median values of the distributions.

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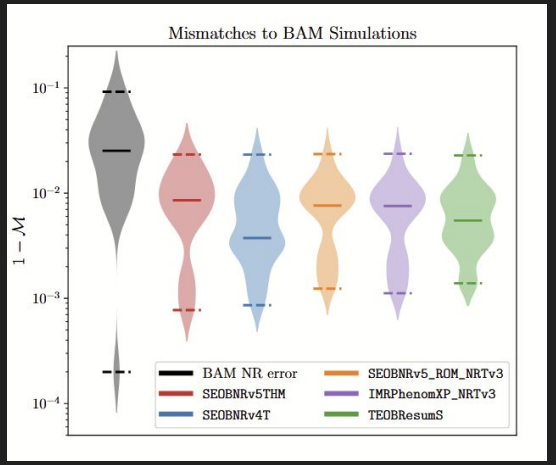

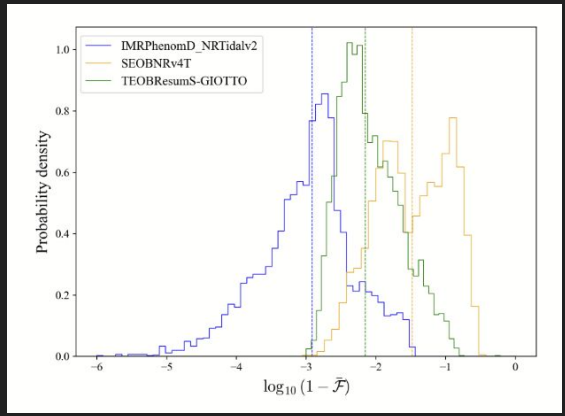

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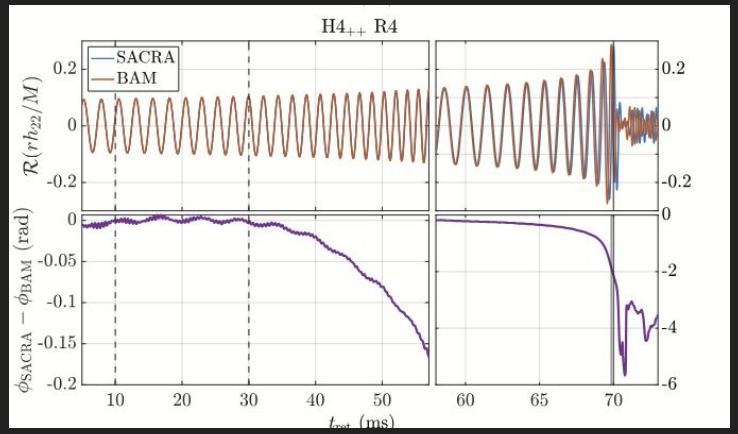

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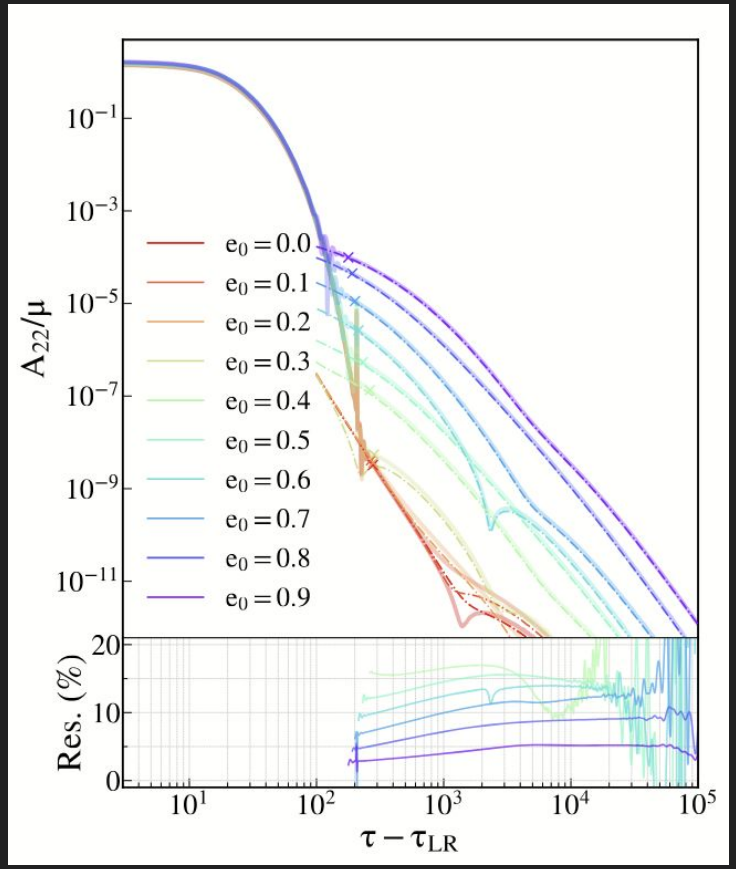
- Tails! From theory/test-mass to simulations



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- Relativistic non-linear tides, tidal spin

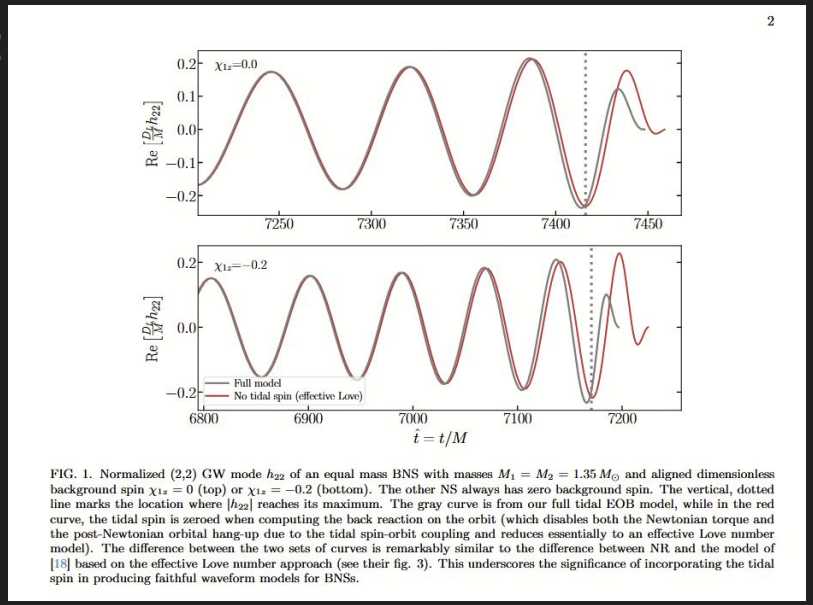

FIG. 1. Normalized (2,2) GW mode h_{22} of an equal mass BNS with masses $M_1 = M_2 = 1.35\,M_\odot$ and aligned dimensionless background spin $\chi_{1z} = 0$ (top) or $\chi_{1z} = -0.2$ (bottom). The other NS always has zero background spin. The vertical, dotted line marks the location where $|h_{22}|$ reaches its maximum. The gray curve is from our full tidal EOB model, while in the red curve, the tidal spin is zeroed when computing the back reaction on the orbit (which disables both the Newtonian torque and the post-Newtonian orbital hang-up due to the tidal spin-orbit coupling and reduces essentially to an effective Love number model). The difference between the two sets of curves is remarkably similar to the difference between NR and the model of [18] based on the effective Love number approach (see their fig. 3). This underscores the significance of incorporating the tidal spin in producing faithful waveform models for BNSs.