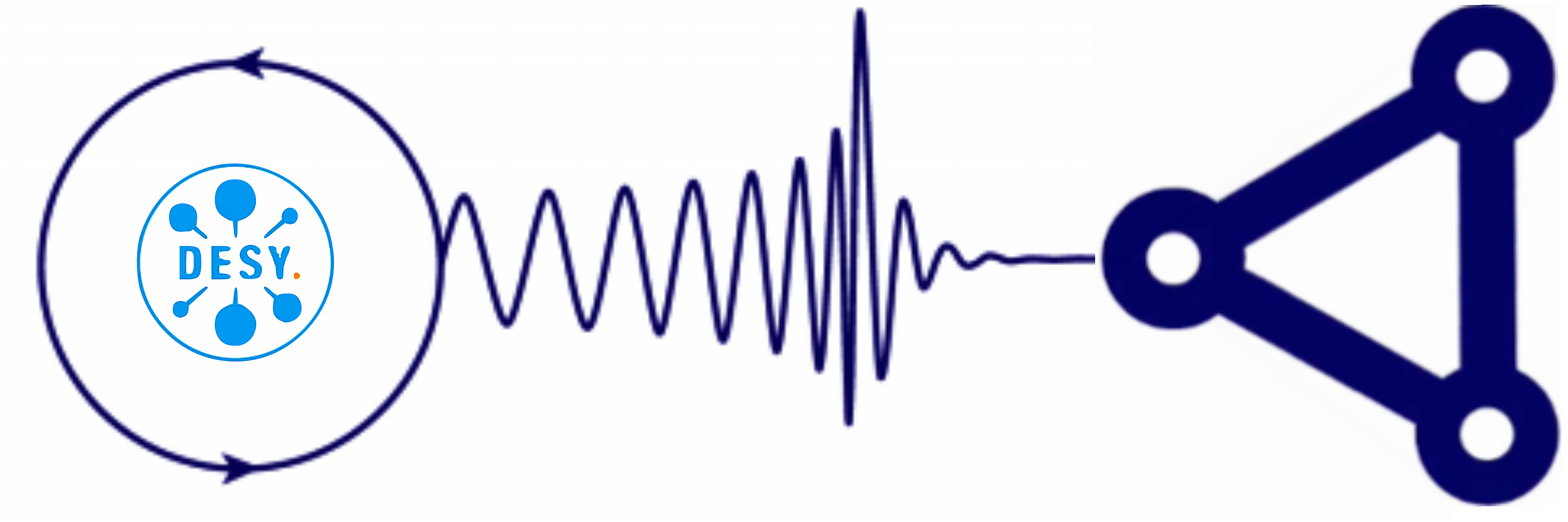
Einstein Telescope 2nd Annual Meeting

Fundamental Physics with the Einstein Telescope

ET Blue Book status report



Rafael A. Porto

On behalf of the **ET OSB Div1** (“Fundamental Physics”)

Coordinators: Chris Van den Broeck, Paolo Pani, Rafael A. Porto

Einstein Telescope 2nd Annual Meeting

Fundamental Physics with the Einstein Telescope

ET OSB Div1

Aims of the division:

- Coordinate research on “fundamental physics” with GWs
  —**Investigate the science case for the Einstein Telescope (ET)**

- Synergies with other divisions
  —Improved characterization of (exotic) compact objects
  —fundamental aspects of two-body problem in gravity
  —…

- Telecons once a month https://wiki.et-gw.eu/OSB/FundamentalPhysics/Meetings
  —Typically 25-35 participants — status reports and physics discussions

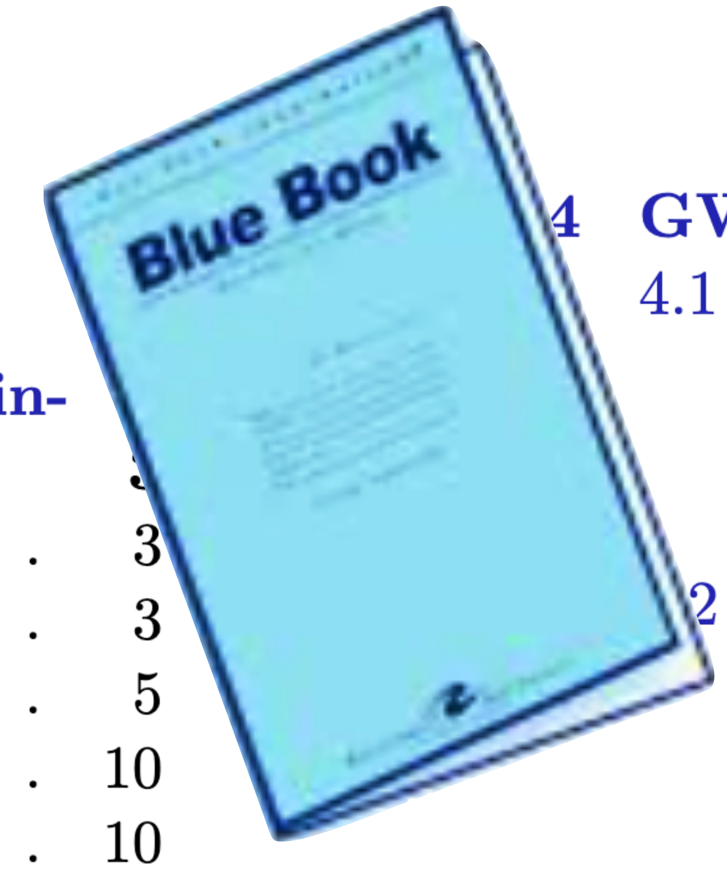
Condense this into to the **ET Blue Book**

https://www.overleaf.com/project/60c07afe8d5f7d310fcdb3b6

Einstein Telescope 2nd Annual Meeting

Fundamental Physics with the Einstein Telescope

Contents



- All sections have one or more coordinators and several contributors associated with it.
- In every telecon, we invite coordinators to give a status report and/or research talk.
- From now on we are fully focused on finishing up the writing

Einstein Telescope 2nd Annual Meeting

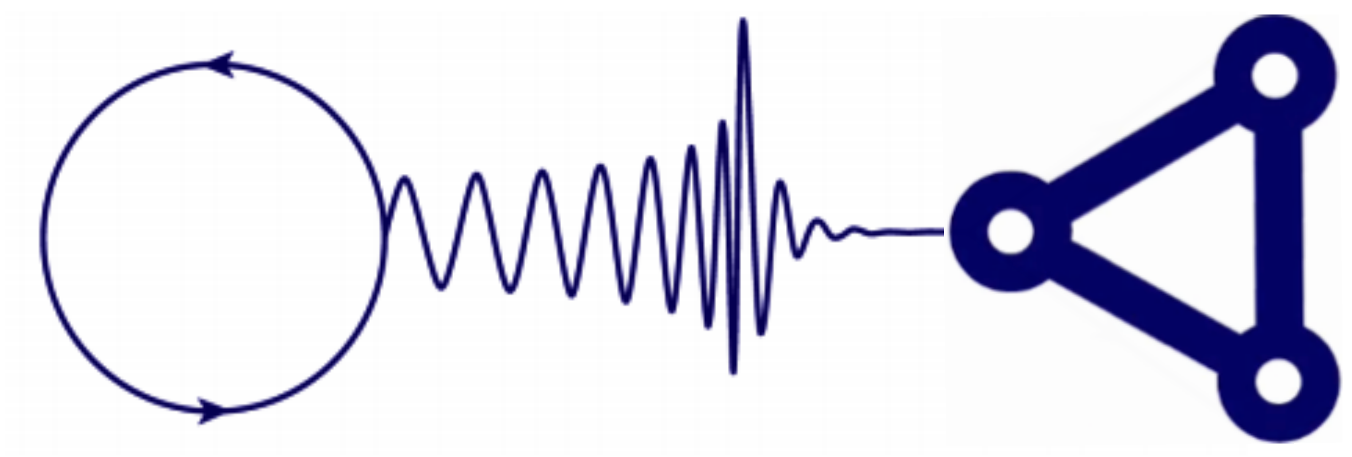
Fundamental Physics with the Einstein Telescope

1 Introduction

Some general tips:

- Remember to obtain licenses for any published figures, tables or other material, and include it in the figures folder, so they can be submitted with the review without violating copyright. Or if covered by a GNU public license, include the appropriate phrase in the caption. "Credit from" may be appropriate in a journalism context, but not with scientific publishers.
- Check consistency with acronyms (e.g. if they are already defined
- Put emphasis on ET science, in particular give priority to plots forecasting ET capabilities
- When needed, we could use/re-adapt results of the CoBA study.
- In general, prefer the following standard ET configurations (main ones of the CoBA paper): triangle, 10km and 2L, 15km, rotated by 45degree

One of the fundamental science objectives of ET is to test the theory of general relativity (GR), the nature of compact objects, and our understanding of matter and particle physics at the most extreme conditions. These goals have profound implications for cosmology, nuclear and particle physics, dark matter searches, as well as for certain quantum-gravity programs. In parallel, the discovery potential in GW science has reinvigorated the ongoing efforts to construct high-accuracy waveforms, in particular using sophisticated computational methods from particle physics that have been instrumental to search for "new physics" at colliders through precision data.



Einstein Telescope 2nd Annual Meeting

Fundamental Physics with the Einstein Telescope

2 Testing the fundamental principles of the gravitational interactions

2.2 Ringdown tests

Coordinators: S. Bhagwat, R. Brito, A. Nagar, A. Nielsen, C. Pacilio
Contributors: Daniela Doneva,Stoytcho Yazadjiev, Leonardo Gualtieri, Andrea Maselli, Michele Lenzi

Ringdown refers to the behaviour of a perturbed black hole as it settles down from a perturbed state into a quiescent state, predominantly through the emission of gravitational waves. The prospects for observing ringdown signals with ET are extremely promising. It is reasonable to expect tens of thousands of events per year with observable ringdown signals [1]. The majority of these events will be observed from the resulting final black hole after the merger of two black holes. The form that ringdown gravitational waves take is exactly predicted within Einstein's theory of general relativity. Many modified gravity theories make alternative predictions. Computing these predictions and producing efficient templates for data analysis is needed to derive maximum benefit from ET observations.

Since ringdown signals are very clean tests of the nature of black hole spacetimes, a key science objective will be to test no hair theorems of black holes. This is achieved by observing multiple ringdown modes from a single source. Einstein's theory of general relativity predicts a precise relation between these different ringdown modes. ET is expected to mark the transition

2.4 Numerical simulations beyond GR

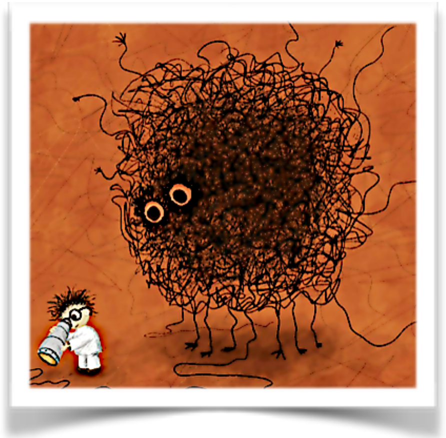
Coordinators: Daniela Doneva, Stoytcho Yazadjiev, Leonardo Gualtieri, Raissa Mendes, Nico Sanchis-Gual

2.4.1 Binary BH mergers

The merger of two BHs can not be described with perturbative approaches; its modelling requires fully non-linear numerical simulations, also called numerical relativity (NR) simulations. While these are viable in GR (see e.g. [98] and references therein), performing NR simulations beyond GR can be a challenging task, not only because of the technical difficulties of the problem, but also because such simulations require a well-posed formulation. In most of the possible modifications and extensions of GR, even the existence of such formulation is still an open issue.

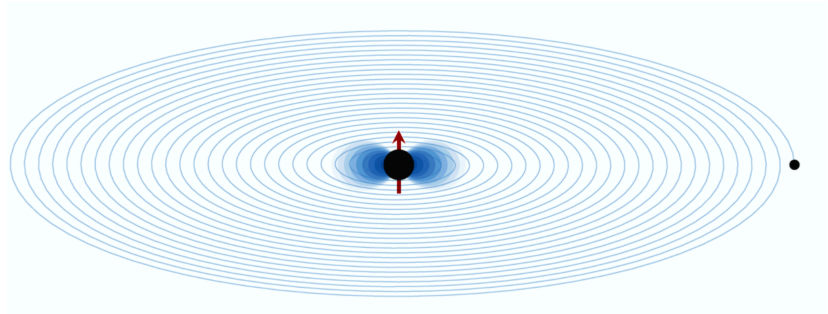
2.4.2 Binary NS mergers

Raissa Mendes
Numerical relativity simulations can help shed light into the strong-field and highly dynamical regime that operates in the late inspiral and merger phases of a binary compact object coalescence. In the case of a binary NS merger that gives rise to a NS remnant, numerical relativity simulations within GR have also proved essential to unveil the rich structure of the post-merger (ringdown) phase, and the same could be expected for modified theories of gravity.



Einstein Telescope 2nd Annual Meeting

Fundamental Physics with the Einstein Telescope



3 Testing the nature of compact objects and horizon-scale physics

3.3 Ringdown tests: QNMs and echoes

Contributors: Elisa Maggio, Roberto Casadio, Alexander Kamenshchik, Alessandro Tronconi, Alessandro Pesci

- Quasi-normal mode (QNM) spectrum of ECOs: i) axial and polar modes are not isospectral and form a doublet; ii) for $\epsilon \to 0$, the QNMs are low-frequencies and long-lived (see Figs. 2, 3 in [250]).
- GW echo morphology:
  - How loud are GW echoes? The amplitude of GW echoes depends on the boundary conditions describing the compact object and the initial conditions of the perturbation [254, 255, 256, 257, 258, 259].
- Prospects with ET and next-generation detectors [260, 266, 277, 258].
  - Fig. 1 in [266] shows the detectability of a ringdown+echo signal for an object with $30M_\odot$ at a distance of 400 Mpc. In the frequency domain, low-frequency resonances are excited at the QNMs of the horizonless compact object. Models with $\mathcal{R} \approx 1$ can be detected or ruled out by aLIGO/Virgo; whereas ET/CE can detect models with generic reflectivities.

4 GW-based searches for dark-matter candidates and new fields

4.2 Environmental and dark-matter effects on GW signals

Contributors: Richard Brito, Valerio De Luca, Pippa Cole, Andrea Maselli, Soumen Roy, Gimmy Tomaselli, Giada Caneva Santoro

4.2.1 Signatures in binary systems

- Resonant transitions, floating, sinking and kicked orbits

  [R. Brito: Something to highlight here: low-frequency sensitivity might be important to directly observe transitions.]

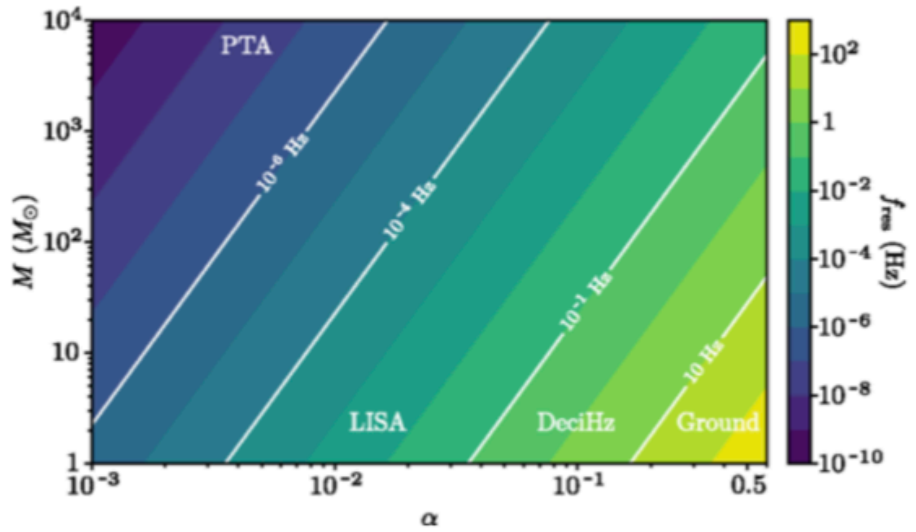
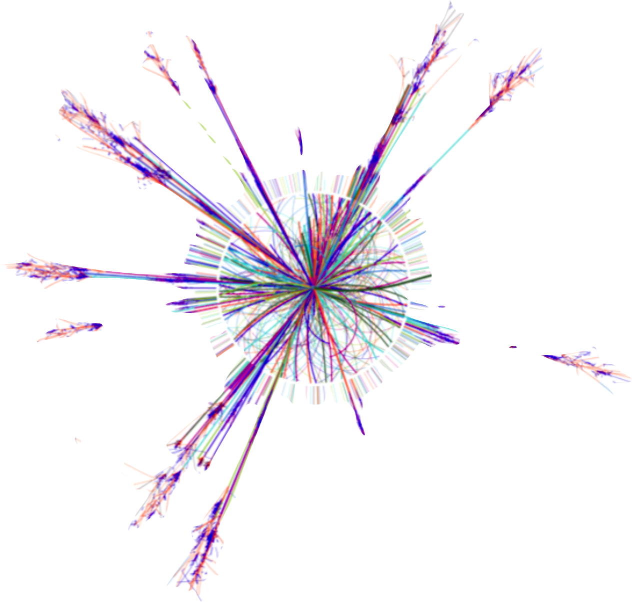


Figure 9: [R. Brito: caption adapted from [324]] Resonance frequency of the Bohr transition, as a function of M and $\alpha \equiv M\mu$. This is representative for all Bohr transitions. From Ref. [324].

- Ionization and accretion [325, 326] [GMT: In addition to a review, I can re-run the evolution for $q = \mathcal{O}(1)$][R. Brito: Thanks, that would be nice]



Einstein Telescope 2nd Annual Meeting

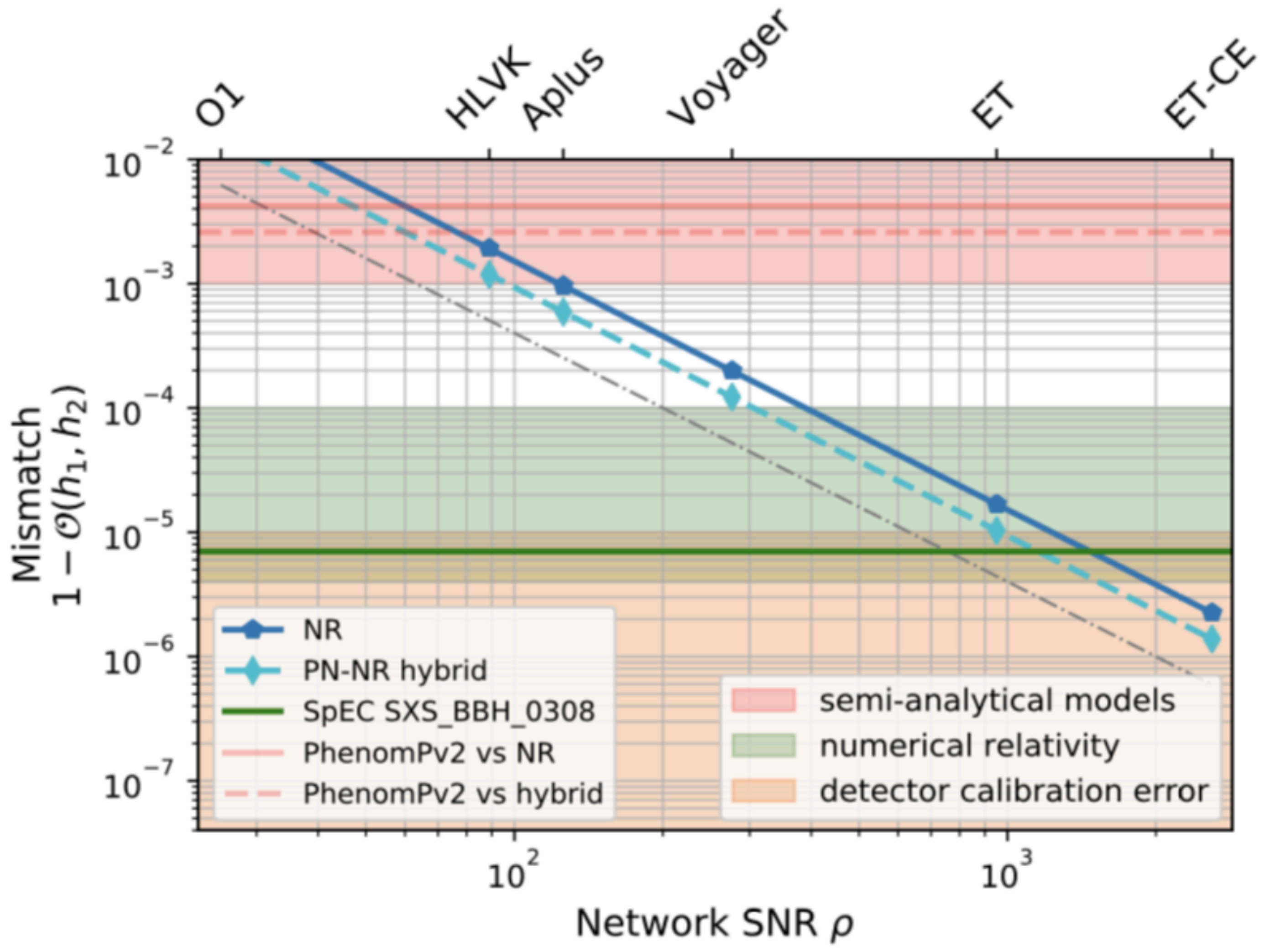
Fundamental Physics with the Einstein Telescope

A Synergies with other Divisions

A.1 Improve current (GR and beyond) waveform models to match ET requirements [with Div8:Waveform sytematics and accuracy requirements]

Contributors: Stefano Foffa, Maria Haney, Adam Pound, Riccardo Sturani

A.1.1 State of the art



A.2 Fundamental aspects of the two-body problem in GR [with Div8:Techniques for waveform modeling]

Contributors: Stefano Foffa, Maria Haney, Adam Pound, Riccardo Sturani

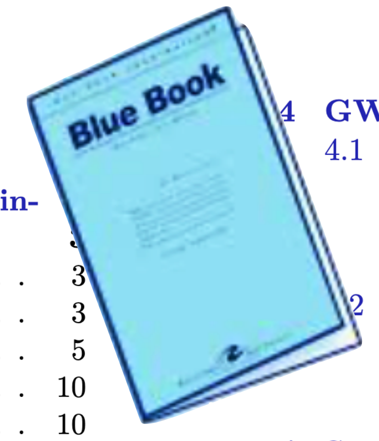
As the quest towards more precise waveforms proceeds, it should be remembered that the two-body dynamics in general relativity is a deep and challenging theoretical problem *per se* and some fundamental issues are still open:

- PN convergence is believed to be only asymptotic, yet the known PN-expansion term so-far are "unreasonably" well converging, even close to the nonperturbative part of the signal [355].
- EFT approach, PM: double copy, scattering-bound [356, 357, 358, 359].
- Self-force: polynomiality [357].
- Hereditary terms and radiation reaction: problem solved at 3PM [360, 361], still work to do at 4PM [362, 363, 364, 365, 366] and in general systematic understanding.
- Tidal effects, and BH absorption.

Einstein Telescope 2nd Annual Meeting

Fundamental Physics with the Einstein Telescope

Contents



First draft of div1 chapter

Almost ready!

Thank you!

Steps forward

- Fill up few subsections still to be done (only titles)
- Unify coherence among different sections (many coordinators and contributions — **luckily! Thank you!**)
- Streamline connection to ET
- Synergy between divisions
- Polish text (avoid duplication)
- Finish introduction and add Conclusions (?)