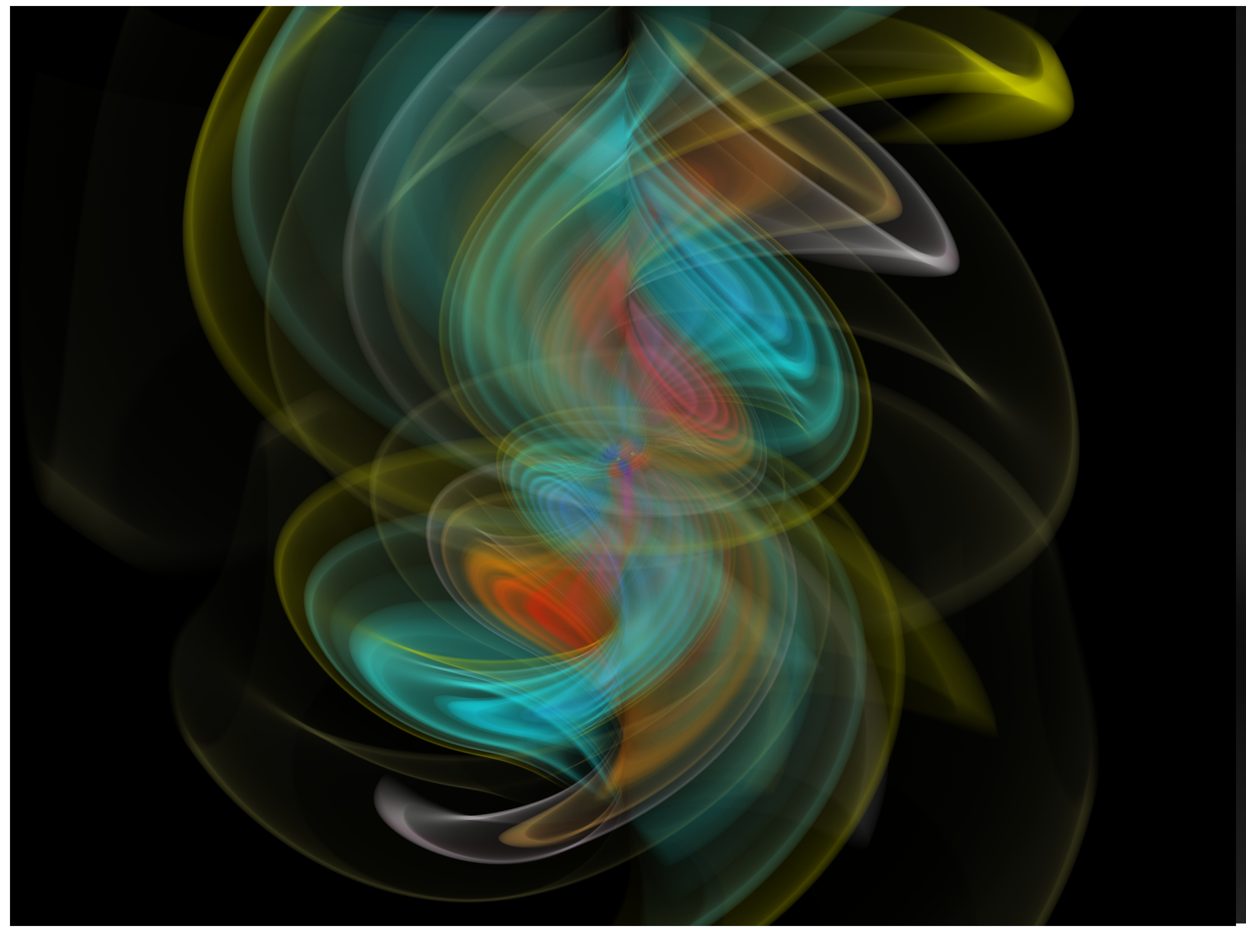
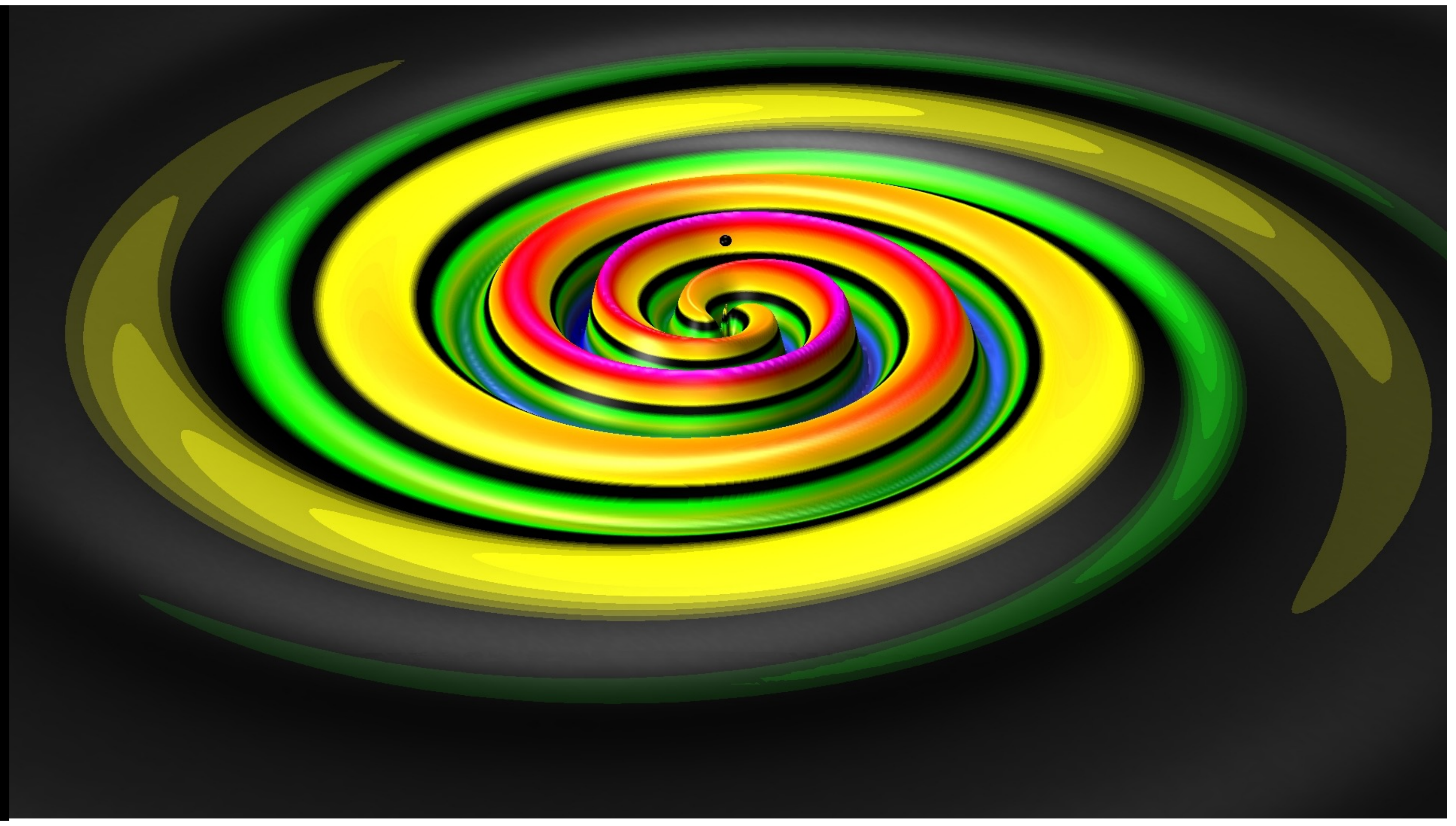
Universitat de les Illes Balears | IAC3 Institute of Applied Computing & Community Code.

Computing and Waveform models for the Einstein Telescope

focus on compact binary coalescence (CBC), but also supernovas, …

Sascha Husa, University of the Balearic Islands





ET-EIB workshop - 10/03/2023

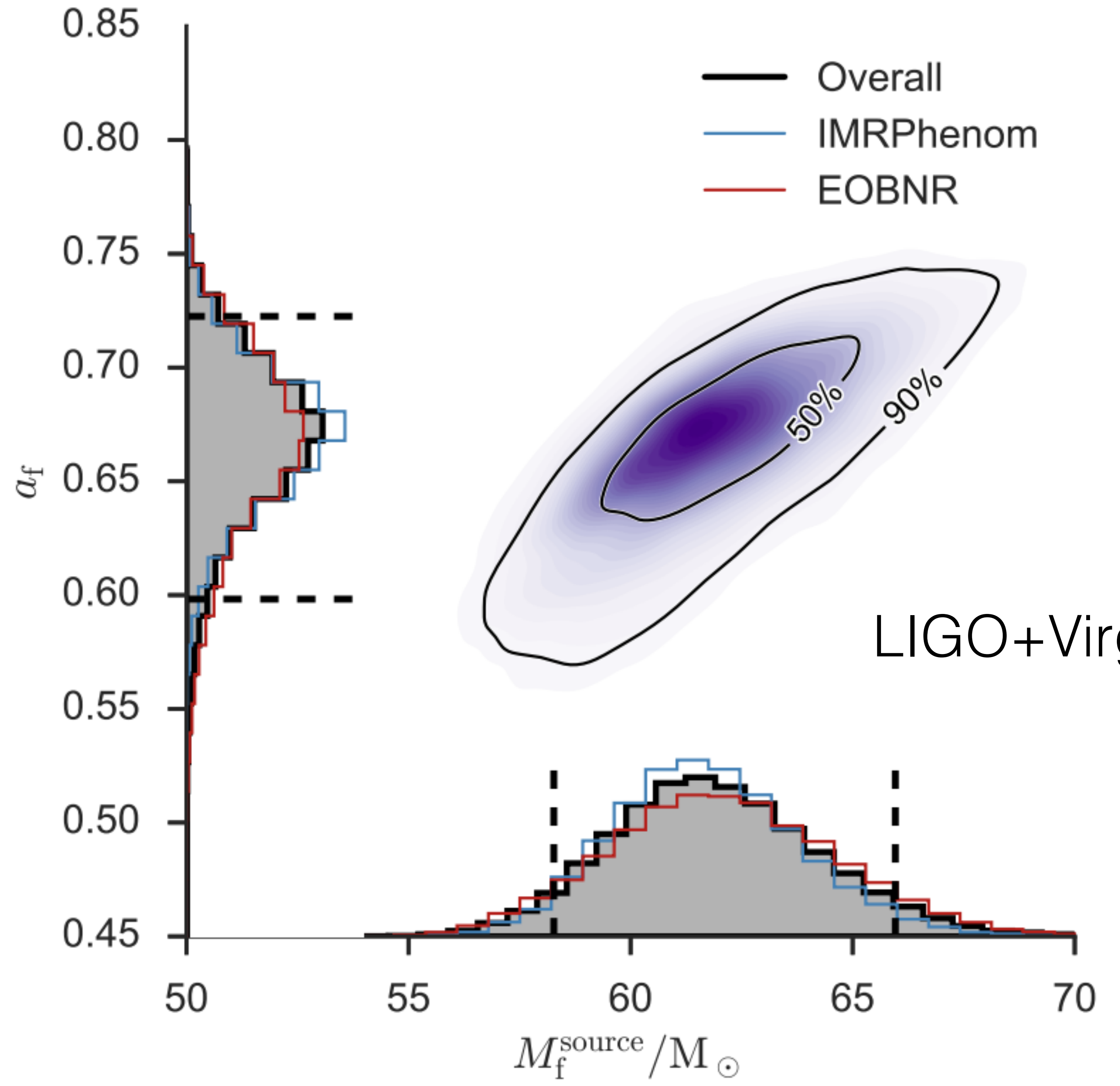
UIB GRG · Govern de les Illes Balears · Gobierno de España, Ministerio de Economía y Competitividad · IEEC Institut d'Estudis Espacials de Catalunya

GW data analysis needs waveform models

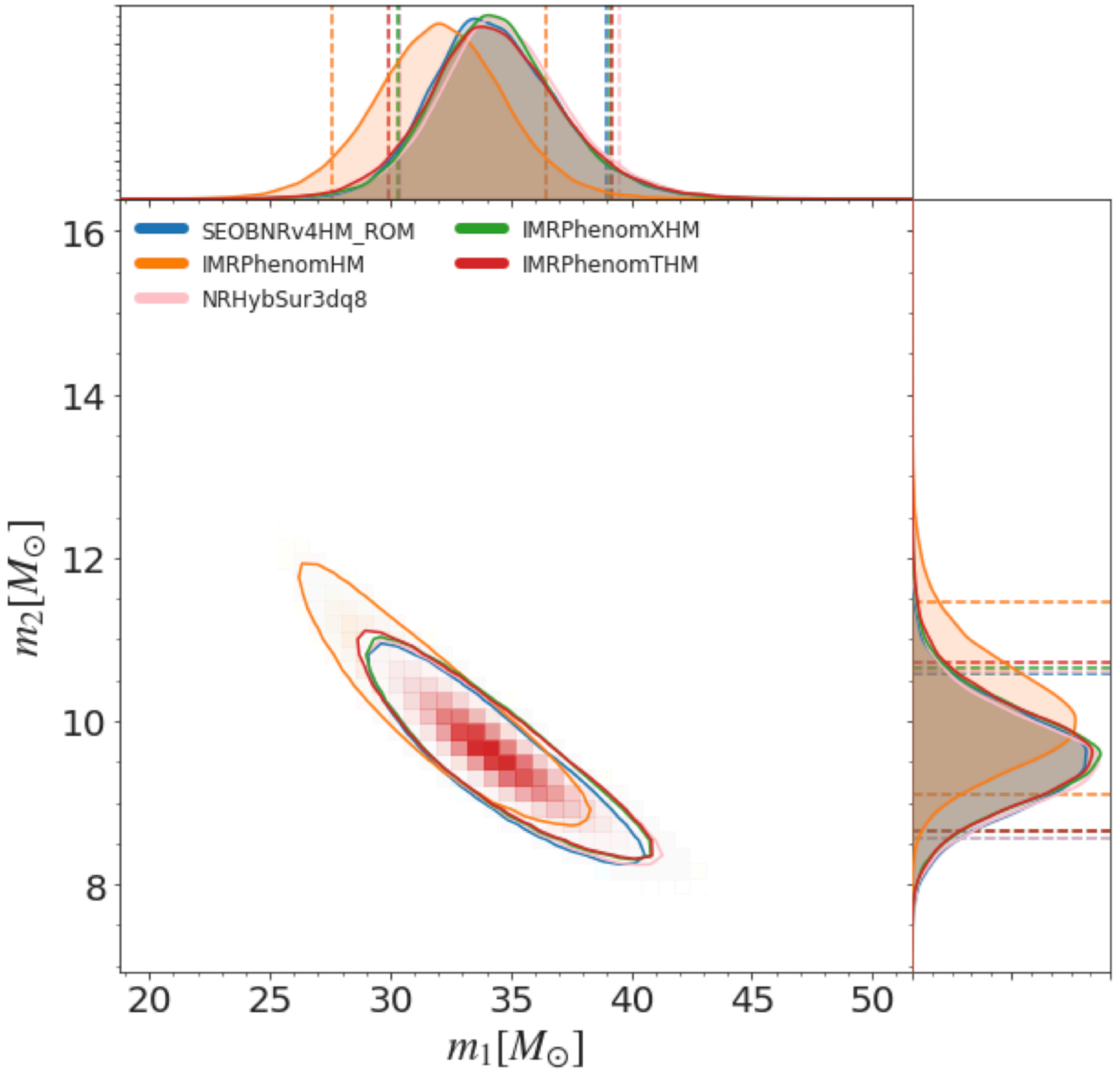
- **Searches -> detection:**
  what is the statistical evidence of seeing a signal above background, **fixed template bank or unmodeled searches** (detect coherent excess power, **e.g. for supernovae**).
  - Test pipeline sensitivity with waveform injections -> astrophysical rates
- **Bayesian parameter estimation for signals that can be modelled, such as CBCs - based on matched filtering.**
  vary templates with random walks in parameter space, using MCMC …

•Identification of sources is limited by detector sensitivity + accuracy of waveforms.

=> need accurate waveform models across astrophysically plausible parameter space.

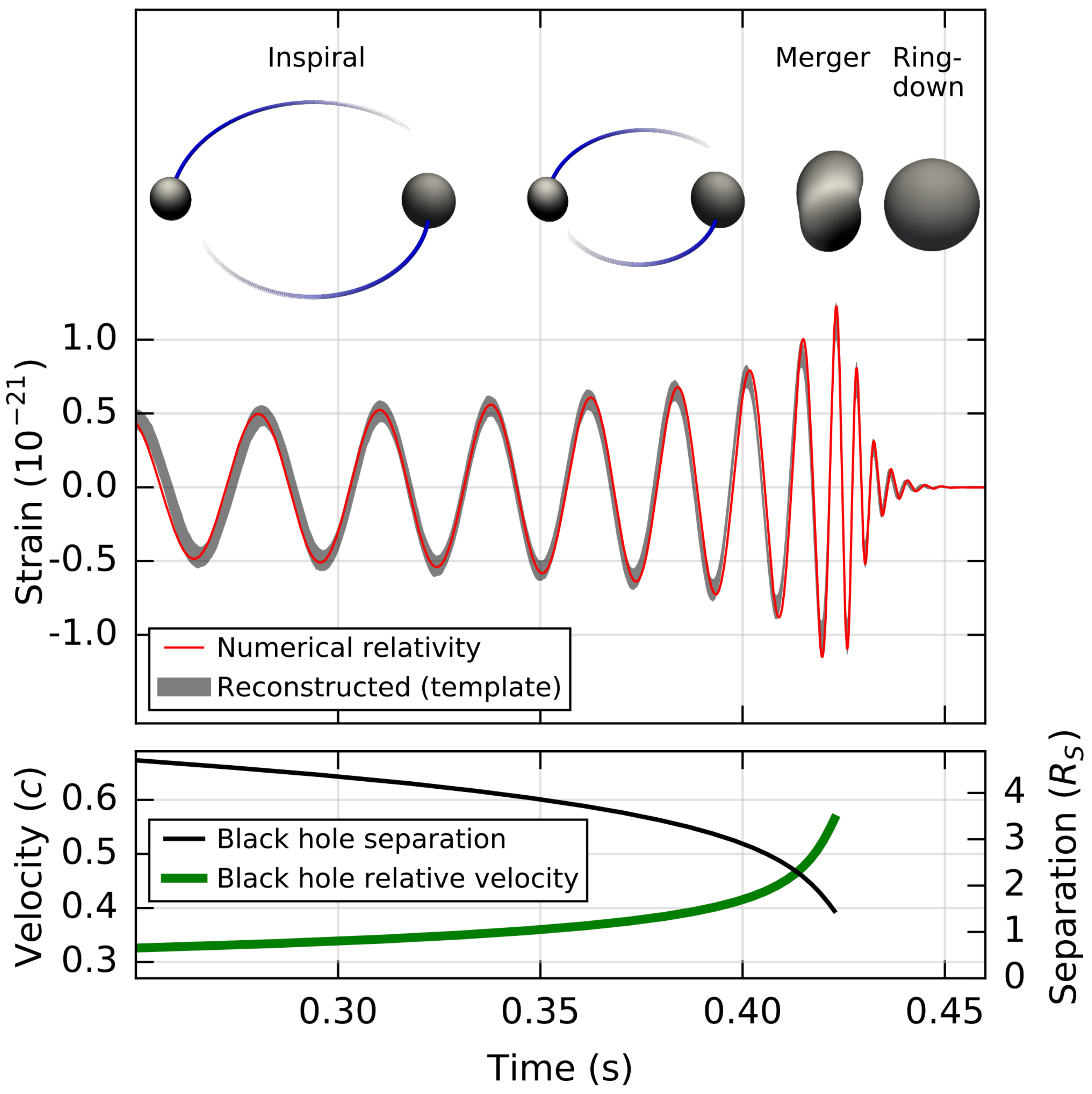


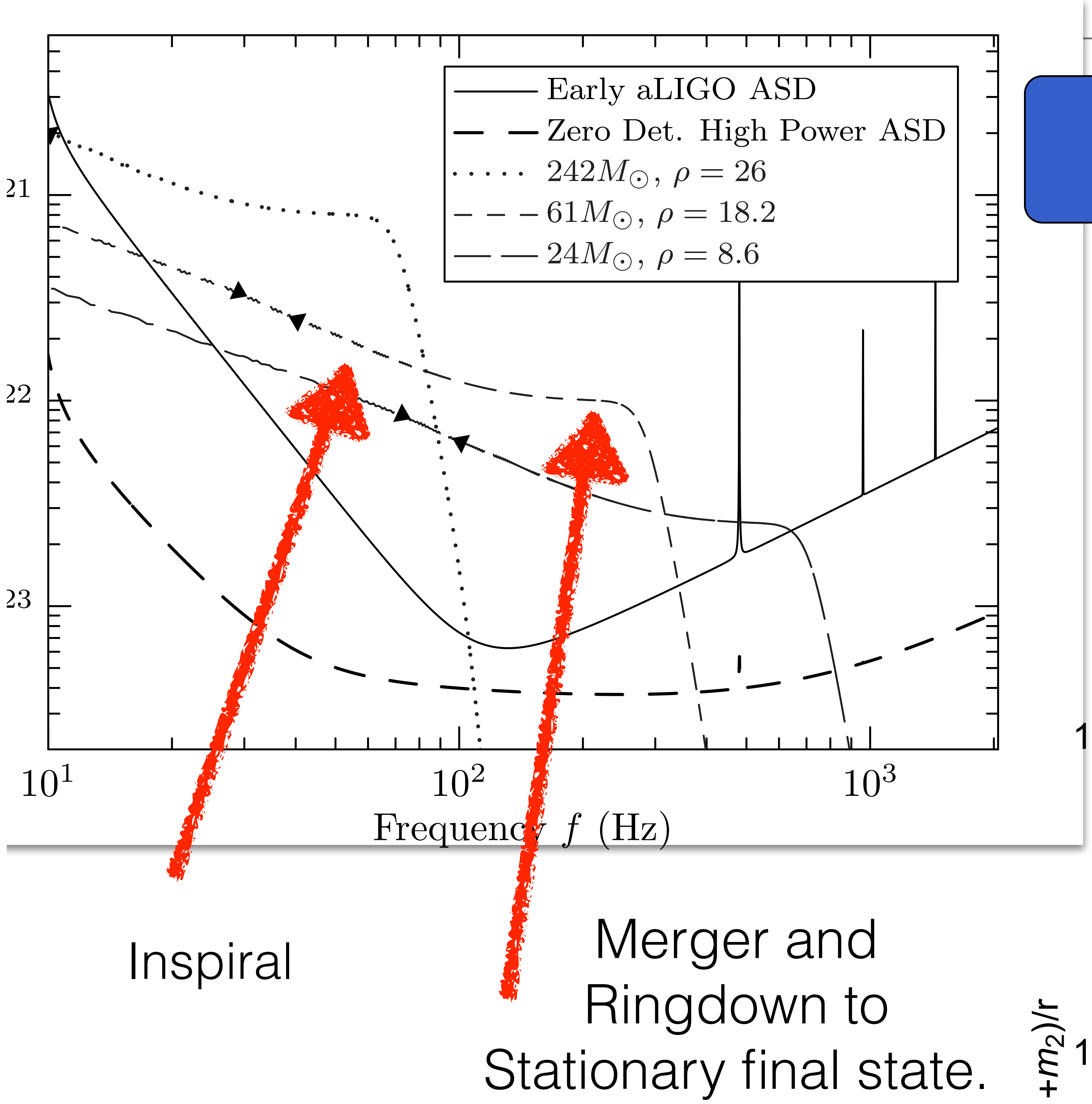
LIGO+Virgo, PRL2016



PE results for GW190412
[Colleoni+, PRD 103, 024029 (2021)]

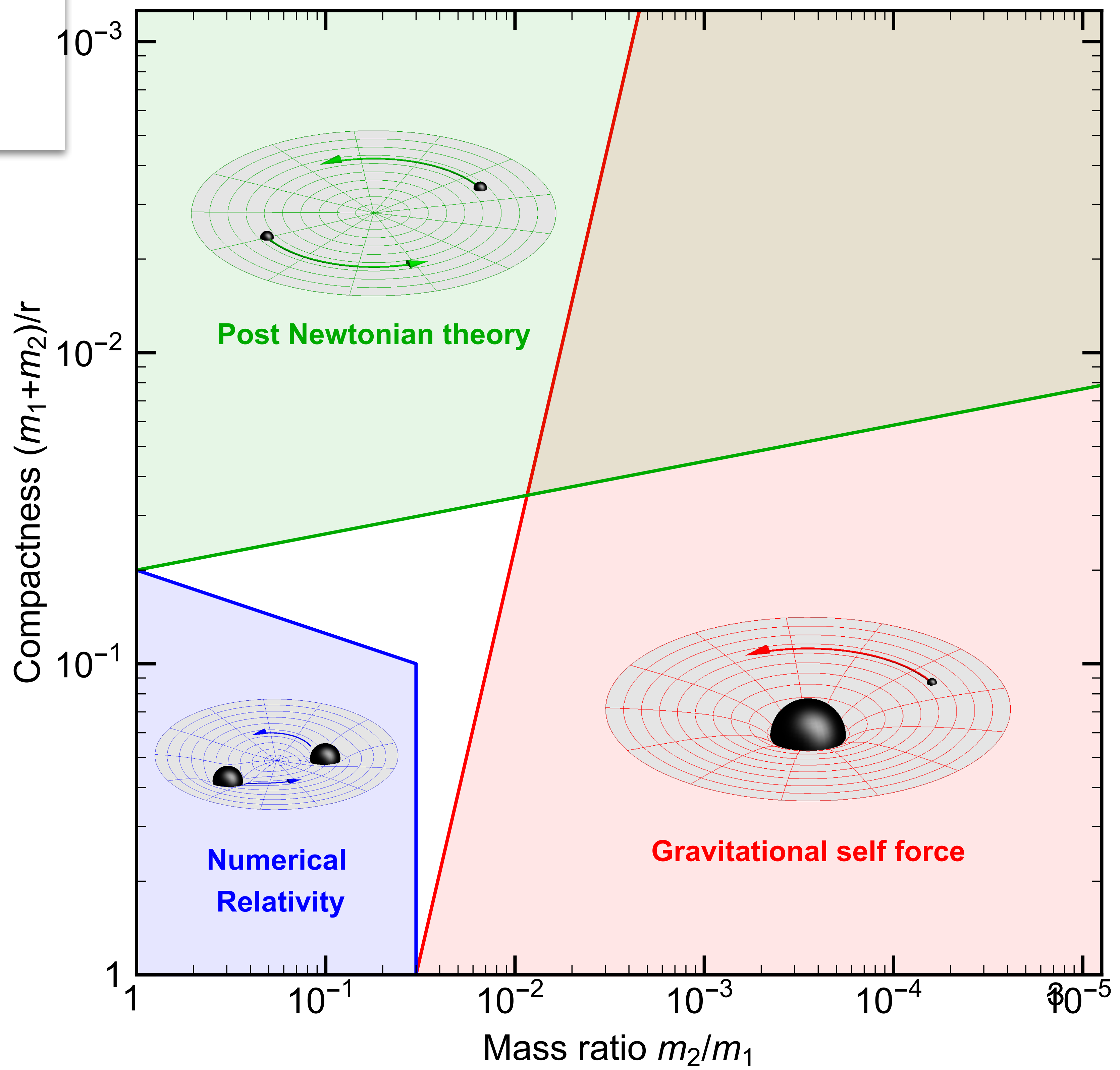
CBC: Need perturbative approaches + numerical relativity





$$T_{coalescence} \approx \eta^{-1} f_{initial}^{-8/3} M \qquad \eta = \frac{m_1 m_2}{(m_1+m_2)^2}$$

Covering low frequencies with numerical simulations is very expensive.



Inspiral: Post-Newtonian expansion in v/c

Breaks down for the last orbits

State of the art: mostly $(v/c)^7$

Self-force
Expansion in mass ratio

State of the art: recent breakthrough for second order.

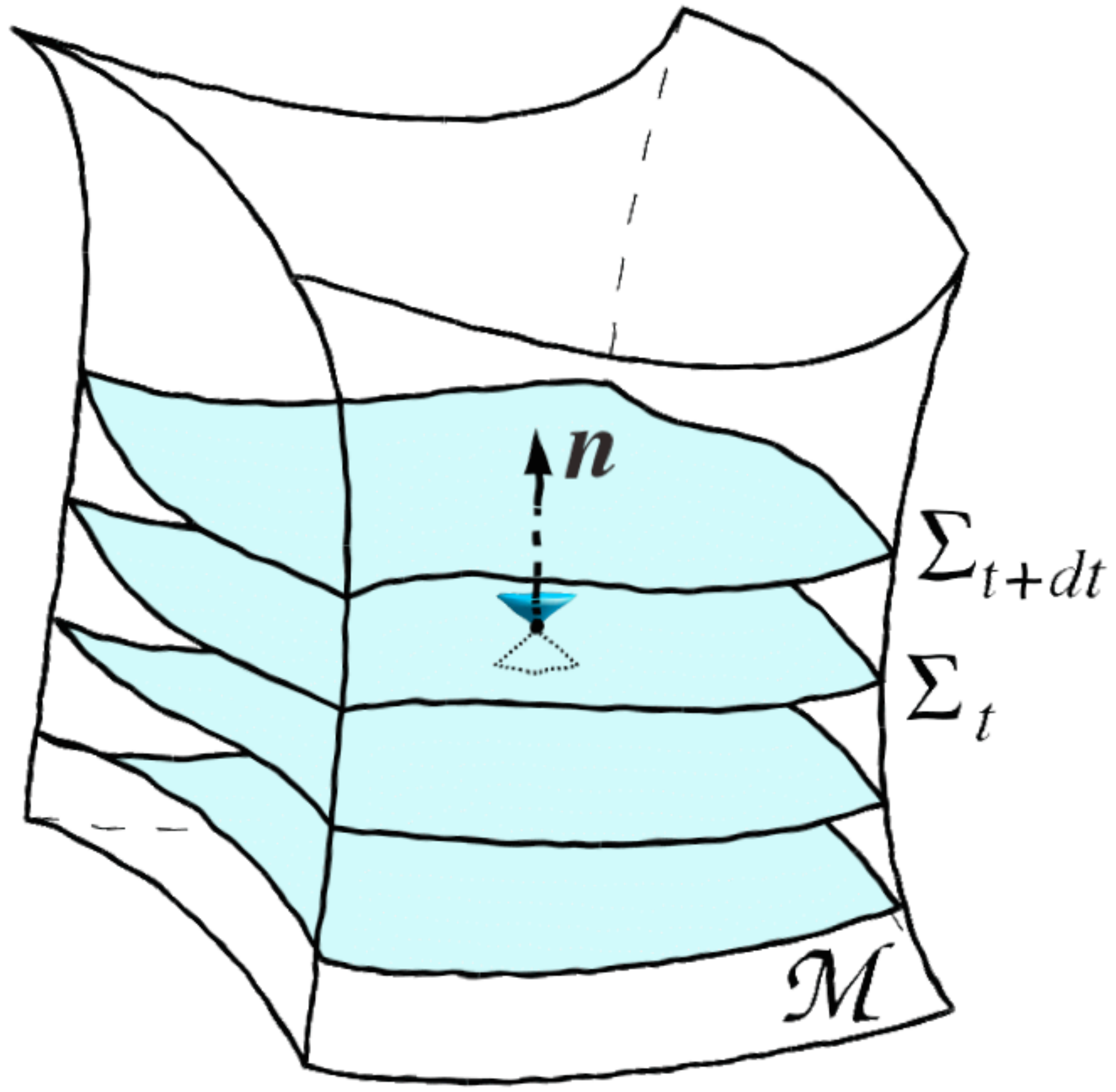
Waveform models: synthesised from NR, PN, EOB, GSF…

- 3 main approaches have developed in the LVK context
  - EOB, IMRPhenom**,** ROM/surrogates
  - Development of main “current” model families has become part of the LVK, need to broaden to ET (and LISA)
- Address trade-offs in different ways - 3 main strategies with different emphasis.
- **effective one body (EOB)** - analytical methods to compute waves from dynamics
  - model energy + flux/wave amplitude of a particle in effective metric => integrate ODEs numerically.
  - Slow - need a fast model of the phenomenological EOB model, or fast PE, e.g. with ML
- **“Surrogate models”** - algorithms to interpolate large parameter spaces
  - Fast evaluation of EOB or NR data directly.
- **phenomenological models** - model waveform directly
  - piecewise closed form expressions - **extreme compression of information**, fast.
    used by LIGO-Virgo for all events to date.

“Holy grail” problem: numerically evolve black holes

$$G_{ab} = \frac{8\pi G}{c^4} T_{ab}$$

-— starting 1950’s -—>

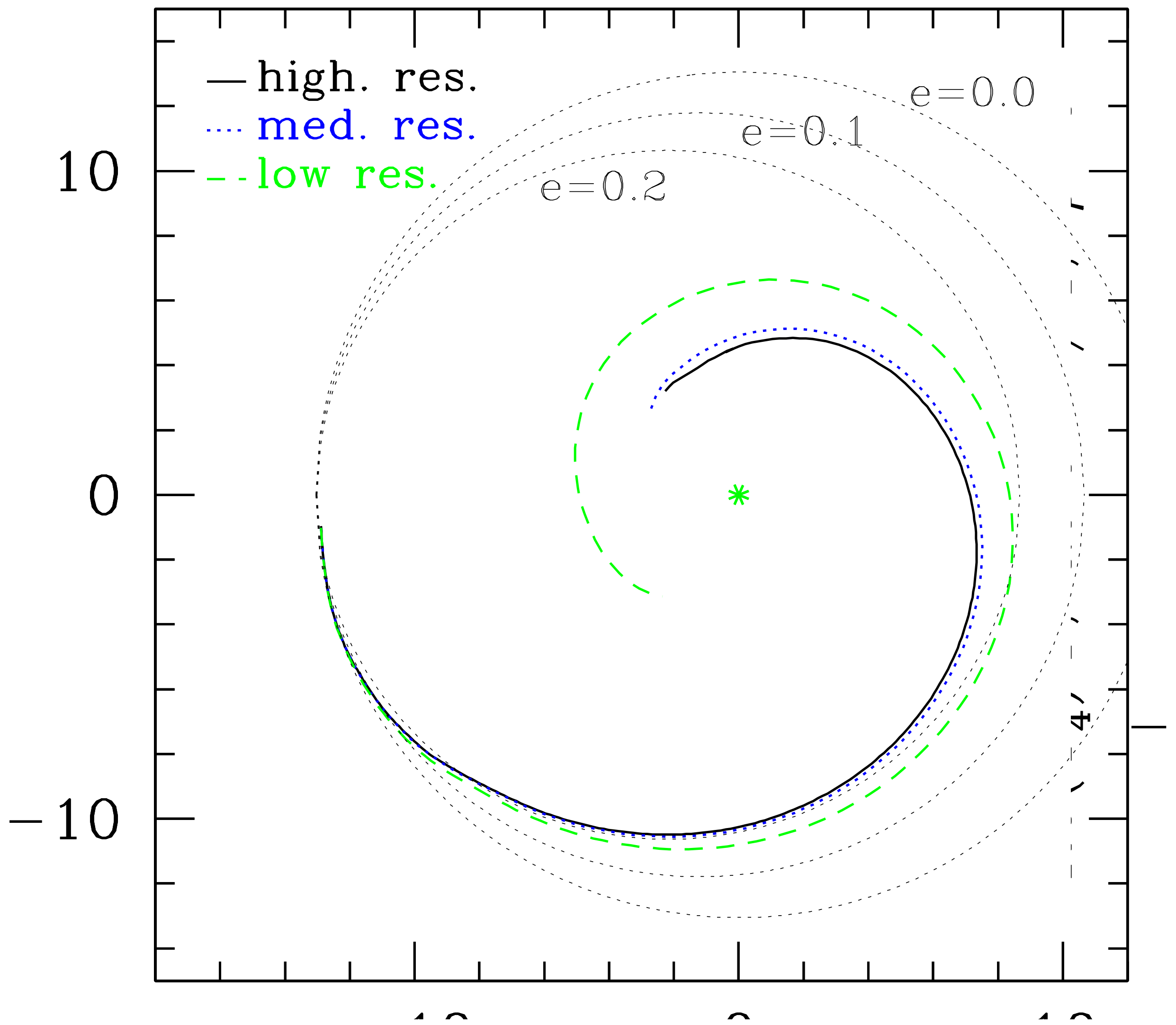


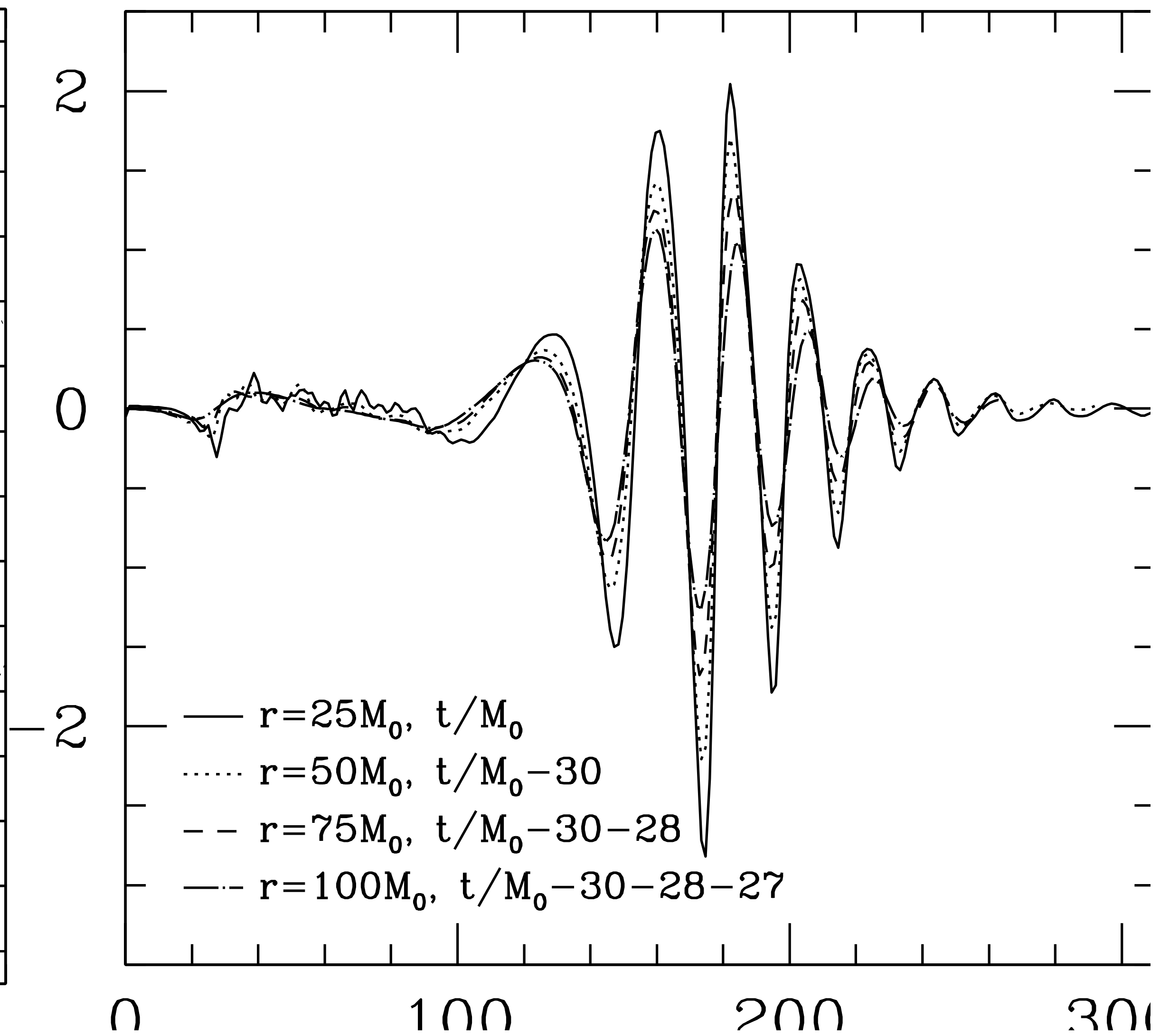
First (short) NR simulation:
1963, Hahn & Lindquist
With IBM 7090

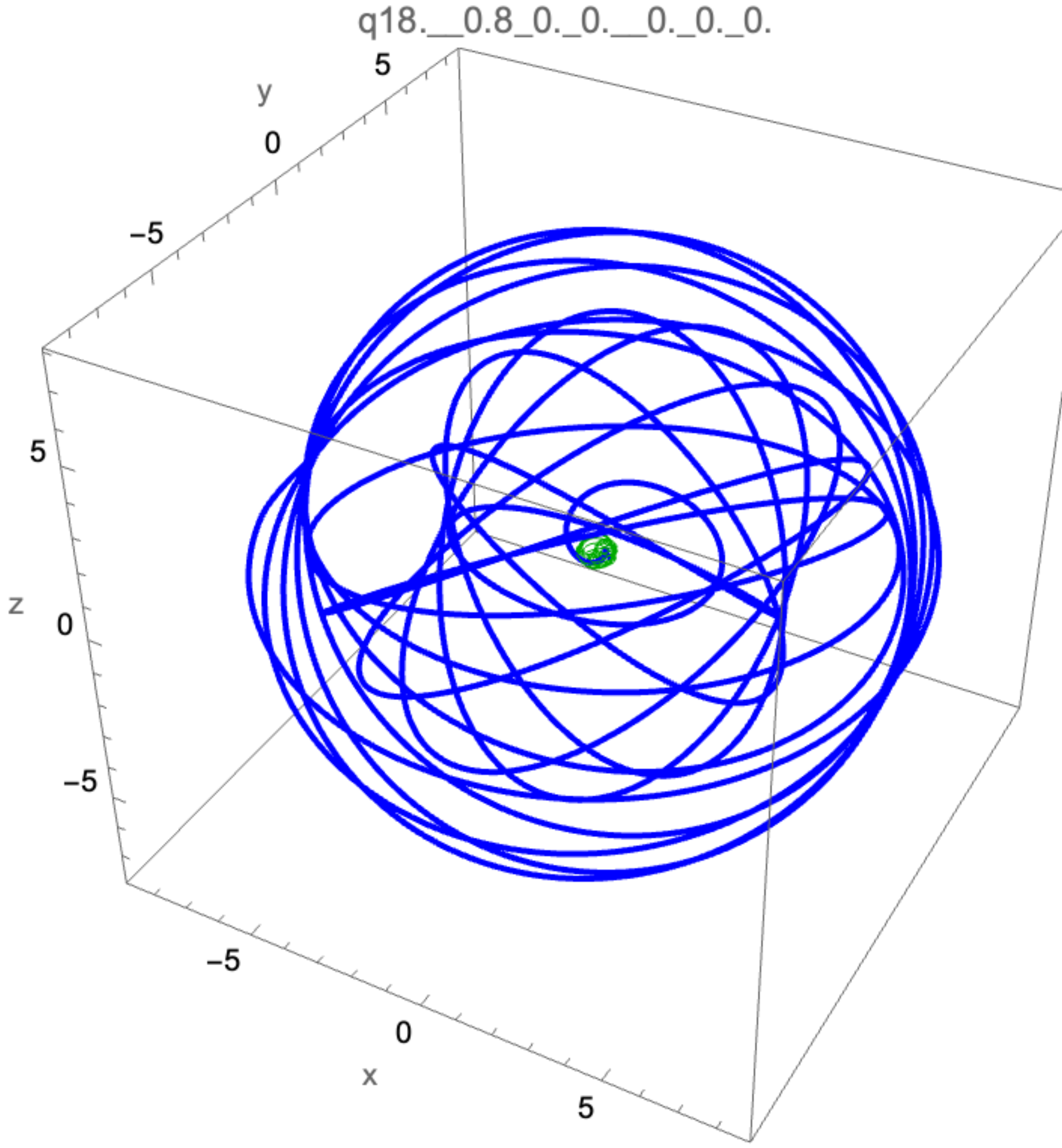
Choose coordinates for spacetime =>
~ 10 coupled nonlinear wave eqs., complex sources.

GR is a gauge theory like E&M, Yang-Mills -> constraints

- **First orbit + GWs: Pretorius 2005**
- Surprise breakthrough after 4 decades of unstable formulations and problems to excise the BH singularity.
- => Gold-rush of improved methods and results
- **Detection of first GW with inspiral-merger-ringdown waveform models 10 years later.**







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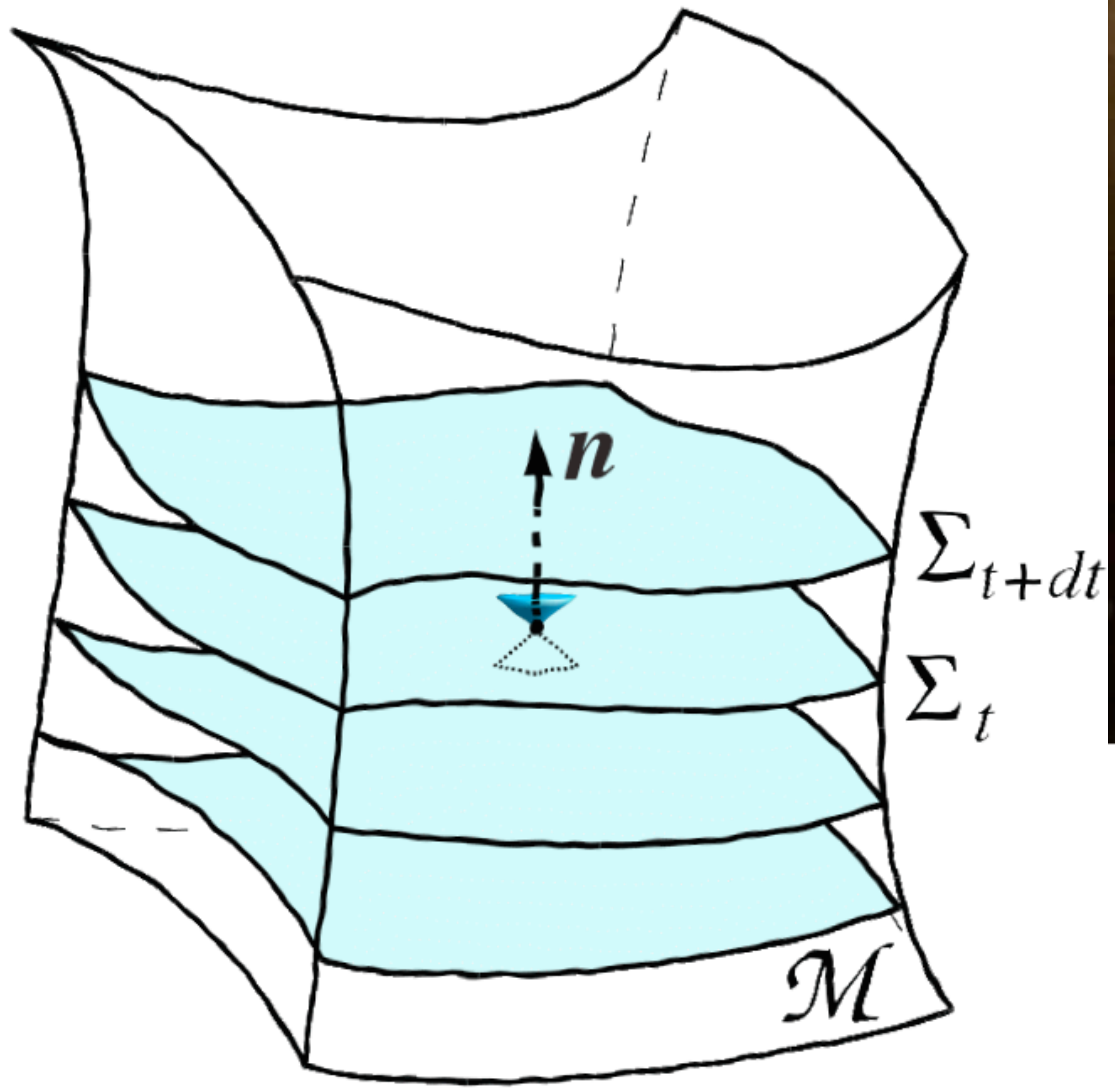

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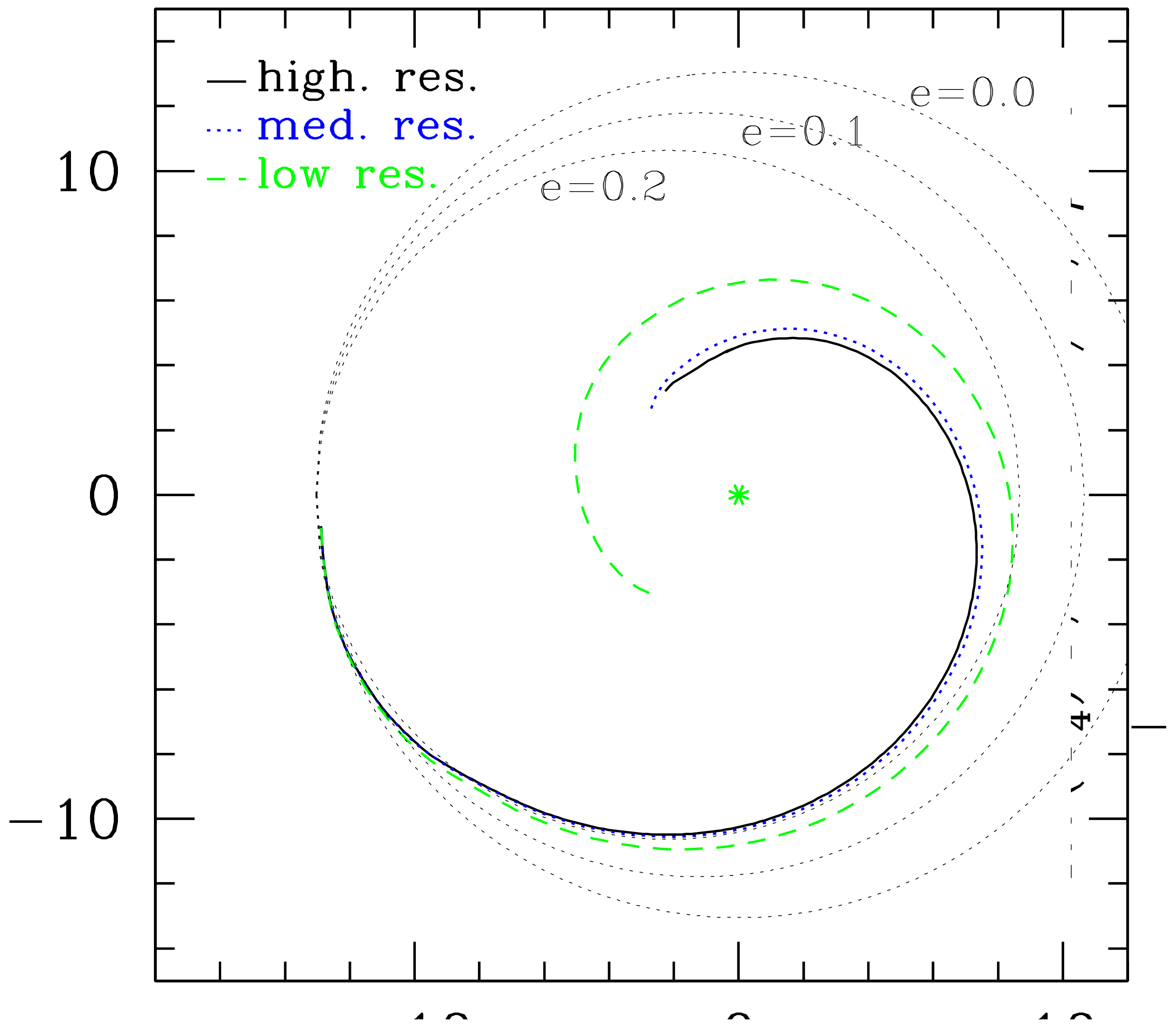
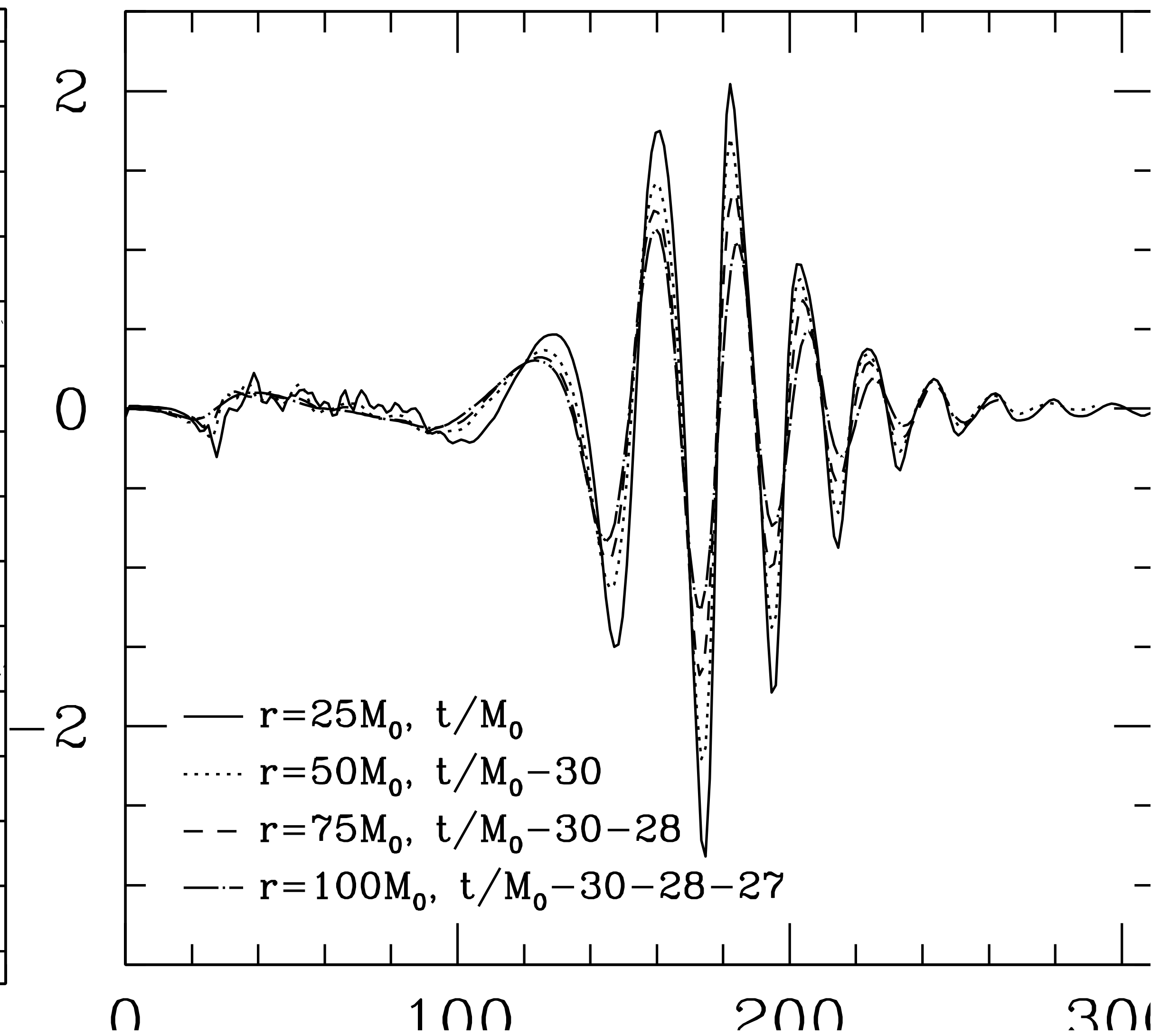
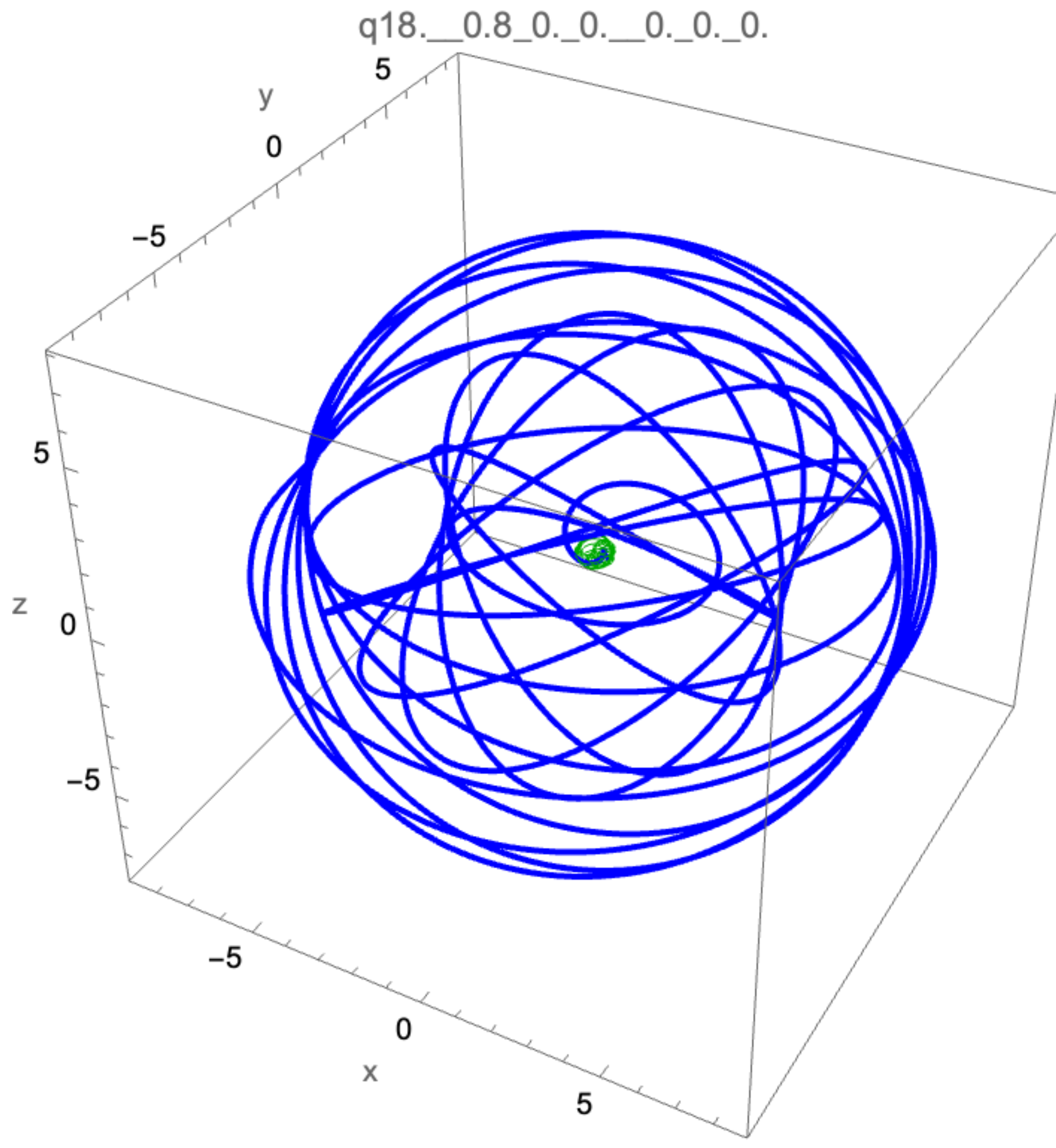
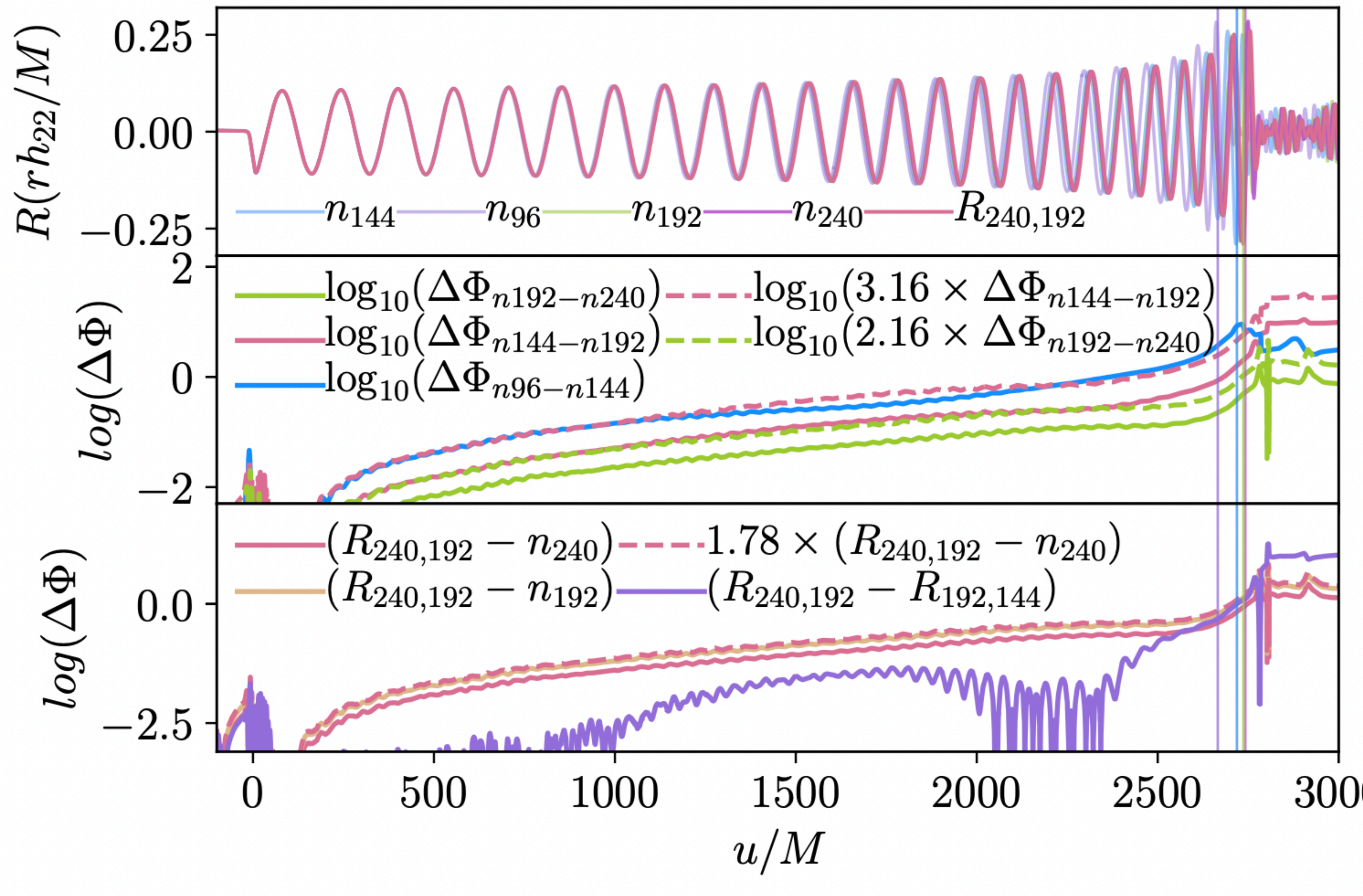


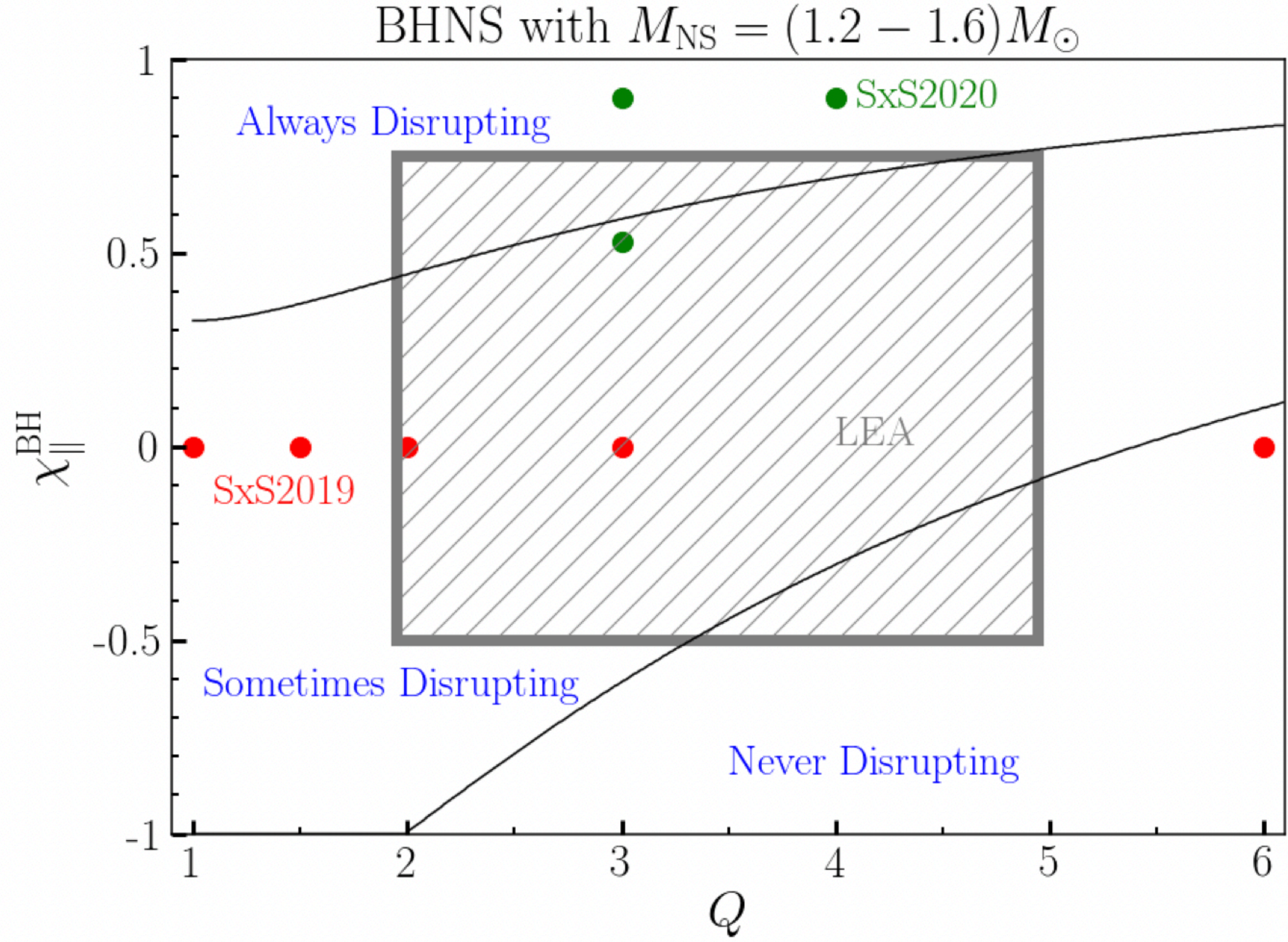




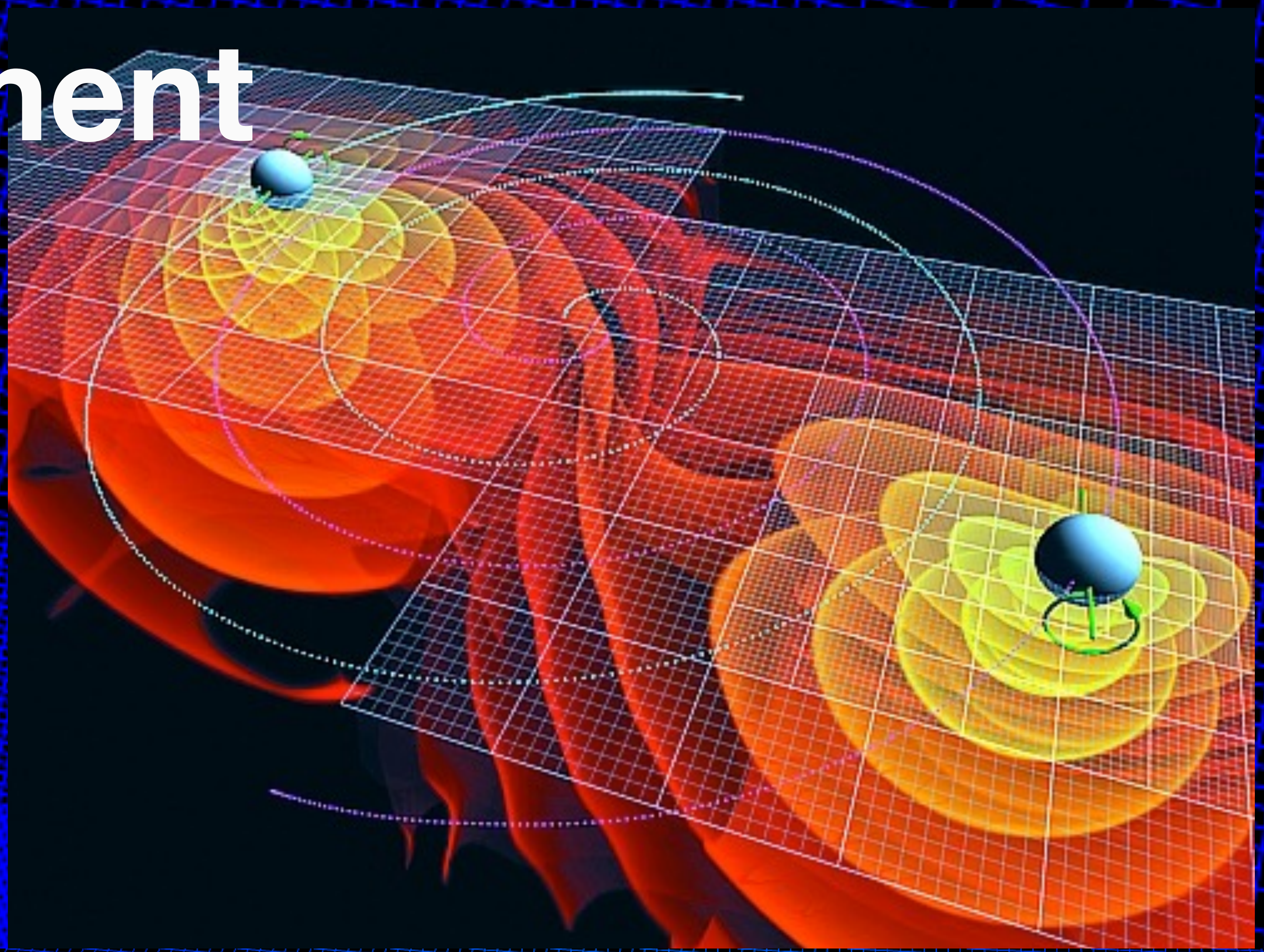
Extreme matter: Neutron stars in binaries

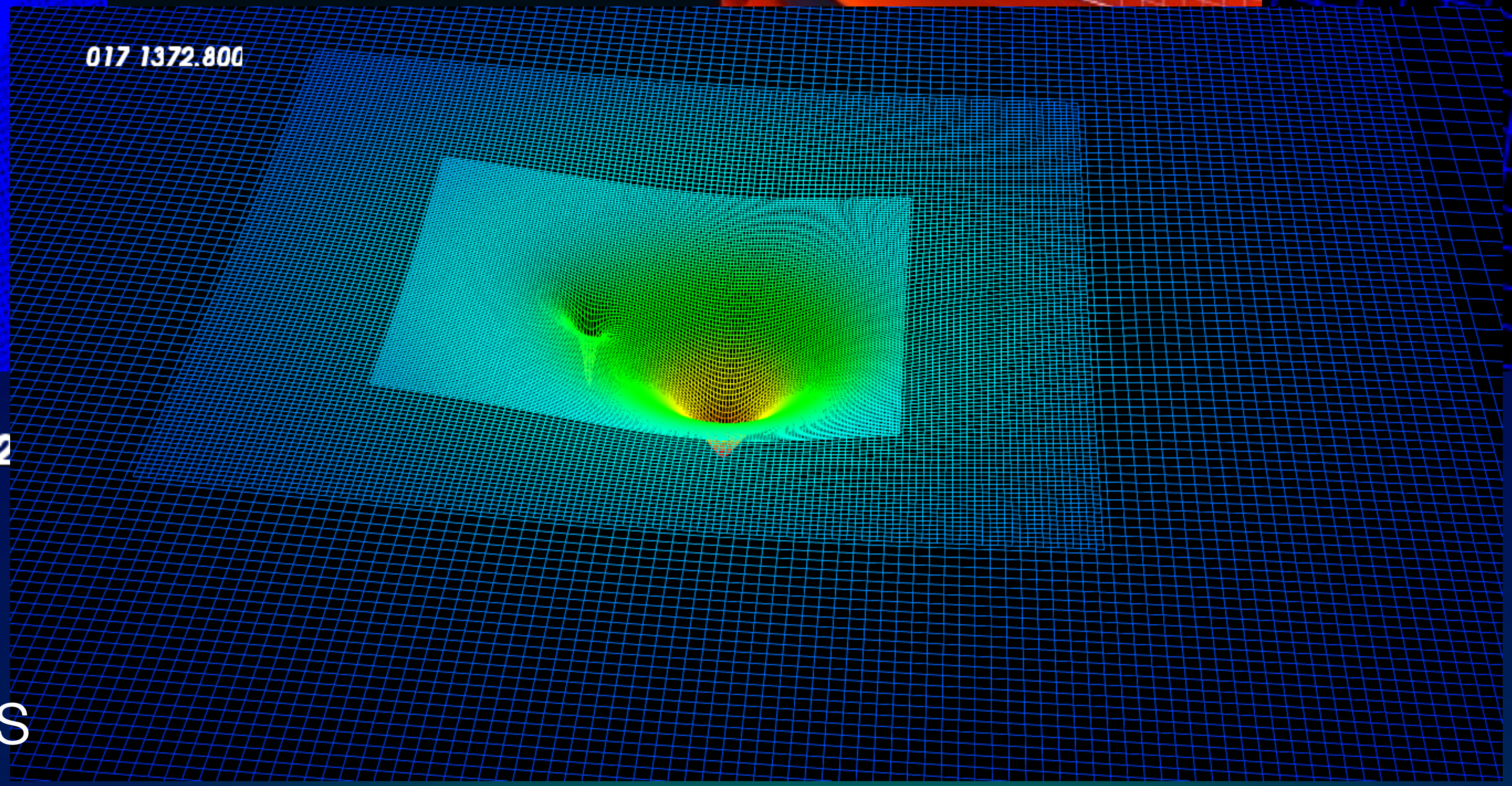
- **BNS: Small mass - long waveforms in band**
  - Need fast and accurate models for thousands of cycles
  - Dynamical tides, EM emissions during/after merger, possibly during inspiral.
  - post-merger waveforms are being developed
- **NSBH:** Essential: long and accurate NR simulations, map disruption in parameter space.
  - Latest (SXS): Foucart+, PRD 103, 064007 (2021)
- **Spinning neutron stars emit continuous wave signal**
  - Once detected, a continuous wave source can be observed for a long term to extract ever more precise information.
- **Supernovae: signal catalogs are important for training unmodeled search methods**





Numerics, Scales & mesh refinement





- **Solutions are smooth without matter: high order (6-8) finite differencing or spectral methods.**
- Matter: high resolution shock capturing, discontinuous galerkin, neutrino transport, …
- **Several length & time scales:**
  - individual compact objects
  - orbital scale
  - wave frequency increases ~ factor of 10
  - causally isolate boundaries
- **Need aggressive spatial and temporal mesh refinement -> strong scaling is challenging** for Berger-Oliger type algorithms
- BBH simulations ~ 10^5 - 10^6 core hours, > 10^9 core hours in total so far ~150 million hours UIB group, currently 30 million/year.
- BBH: ~ 10^4 simulations available for 9-dimensional parameter space < 3 points/dimension (mass ratio, 2 spin vectors, 2 parameters for eccentricity)

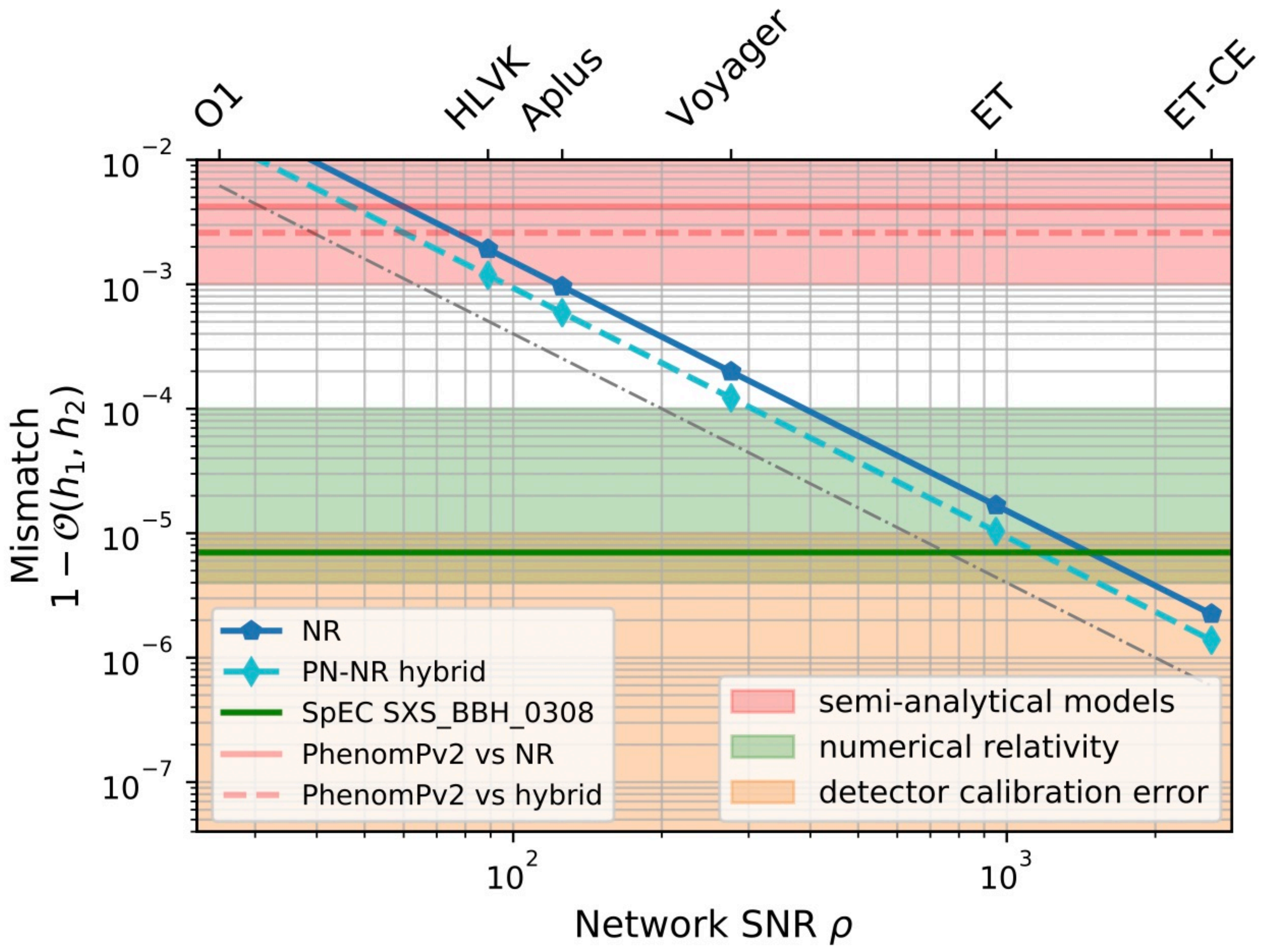
Are waveforms accurate enough?

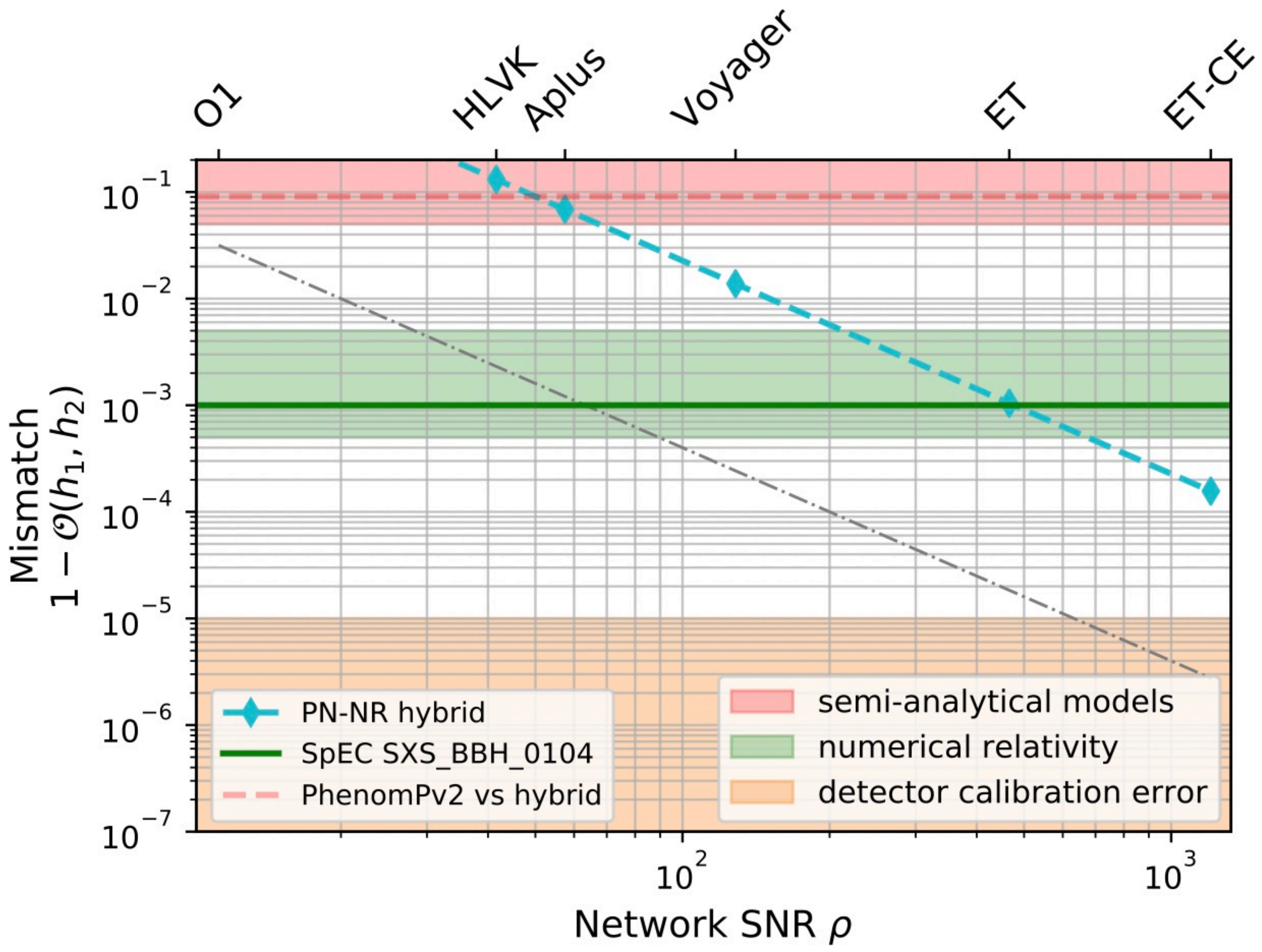
Systematics studies are complicated and expensive ~ effort of improving waveform models

Mismatch = 1 - cos(angle between waveforms)

$$\mathcal{M} < \frac{\#(\text{model parameters})}{2\,\text{SNR}^2}$$

Indistinguishability criterion:
For higher SNR
we need more accurate wavefoms



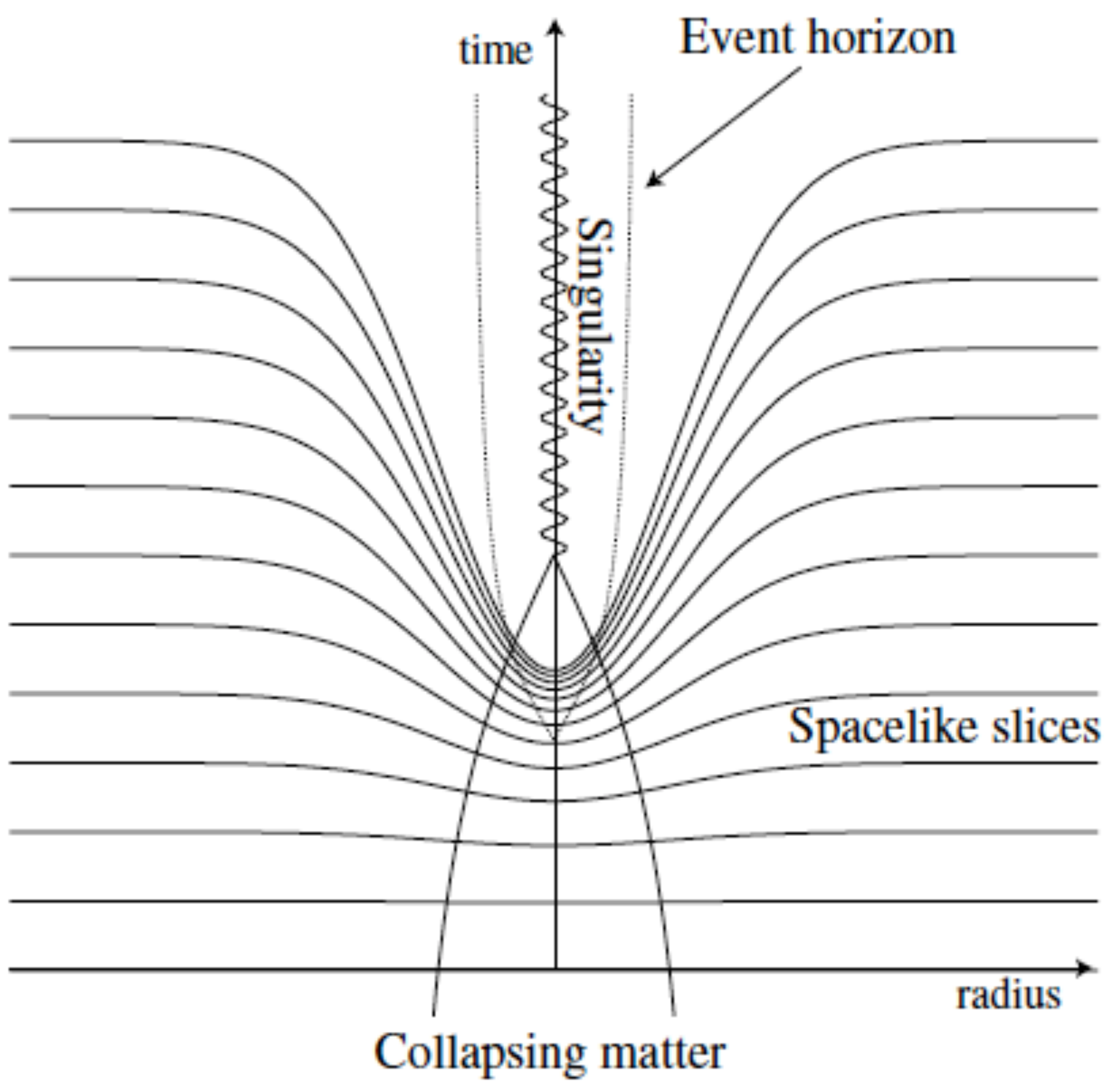


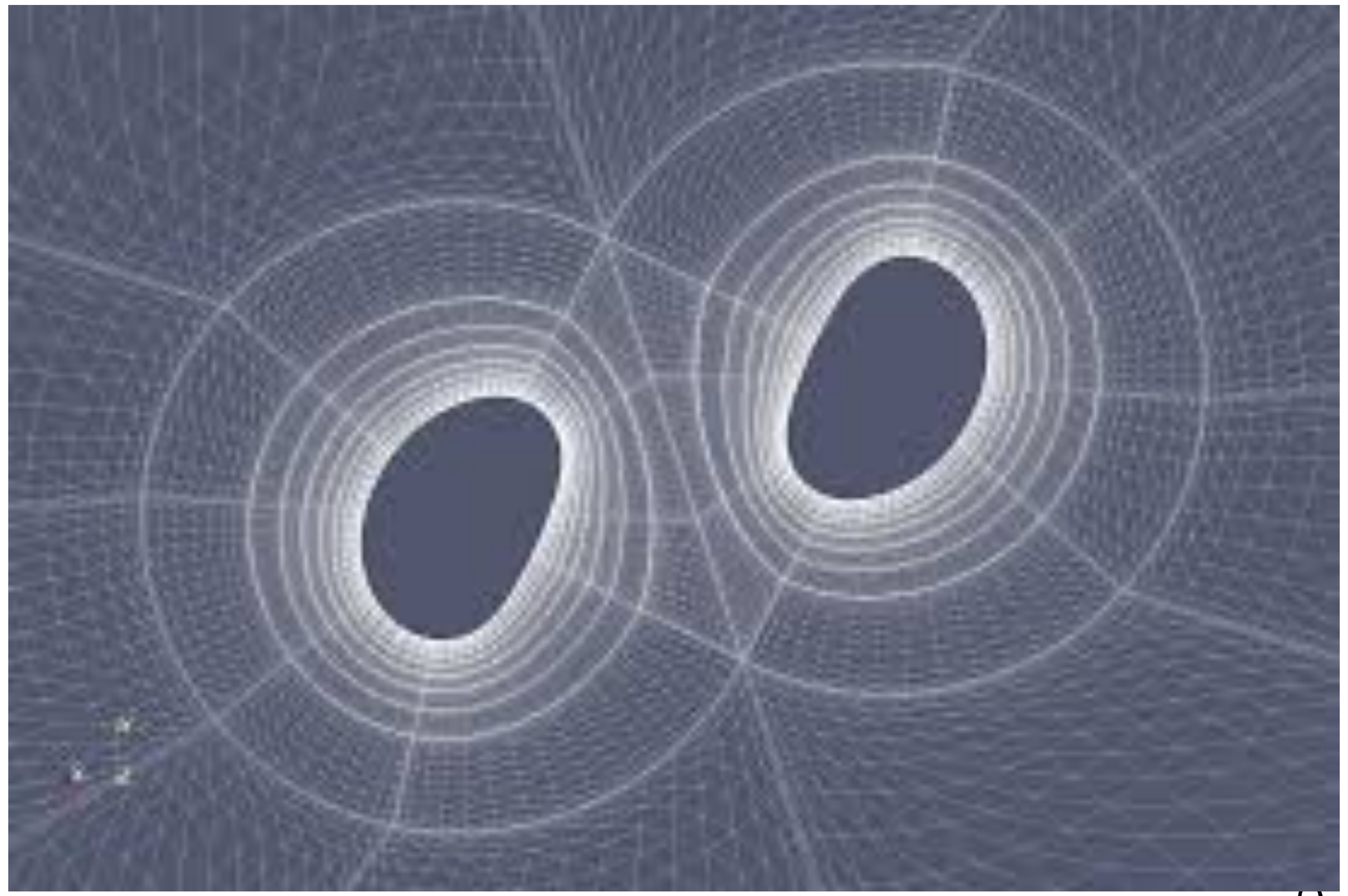
Pürrer+Haster,
Phys. Rev. Research **2**,
023151 (2020)

NR can meet ET accuracy requirements for BHs, but not across entire parameter space (high spins, high mass ratios are more challenging; waveform models still need more work to catch up.

Codes to evolve compact binaries (and more)

- **Finite difference codes, based on “moving puncture paradigm”:**
  - Temporal excision for black holes, FD order 4-8
  - Einstein Toolkit community code - various codes within the framework
  - BAM (closed source)
  - GRChombo based on Chombo AMR library
  - BlackHoles@home (BOINC) based on SENR/NRPy code
  - GR-Athena++ block based AMR instead of Berger-Oliger variant.
  - …
- **SXS collaboration: spatial excision of singularity inside BH**
  - SpEC - pseudospectral methods, closed code
  - SpECTRE - discontinuous Galerkin multi-physics code, open development





Computing context **Opportunistic**

- Einstein equations are very complex: ~150 grid functions, many operations per grid point
  - **High memory/core needs:** 2 GByte/core minimum, more is better.
  - Parts of codes are typically generated by computer algebra.
- NR codes run on **traditional HPC** systems: European Tier-0 and Tier-1 centers. **So far based on CPUs.**
  - **Simple work flows**: use slurm or other queuing systems
  - Job-bundling can be used to created big jobs.
  - **Long evolutions:** jobs can run for several weeks or months with checkpointing.
- Codes **mix MPI and OpenMP** parallelism.
- **Spatial and temporal mesh refinement**
  - Hard to get strong scaling across more than a few hundred cores **- but need large parameter space maps.**
  - Drop temporal mesh refinement?
- **Use task-based libraries for parallelisation? Charm++ (spectre code), Athena++ …**

NR Computing scenarios for ET and needs

- **We are far away from having generic (precession+eccentricity for BHs, accurate extreme matter treatment) waveform models calibrated to NR - need progress along several directions:**

- **Development:** Current production codes are rooted in codes developed before 2005. Need more modern open source community codes - requires not only human resources+community building but also computing resources.
  - Development of new numerical methods and improvements of the formulation of continuum problems (gauge conditions, …)
  - Development of tools to automatising parameter space maps.

- **Cover parameter space with NR simulations for waveform model development:**
  - Need to broaden parameter space coverage now - hard to fund e.g. at PRACE level.
  - Need several hundred million core hours/year?
  - Repeat later at higher accuracy with more efficient codes.
  - Make NR waveforms accessible to waveform modelling community.

- **Follow up**, e.g. of golden events
  - For highest SNR events, discovery of new phenomena: refine models in patches around estimated parameters of event to boost accuracy.
  - Requires ability to run challenging simulations very fast, with high degree of parallelisation.