Gravitational aspects of binary dynamics: waveform models and their systematics

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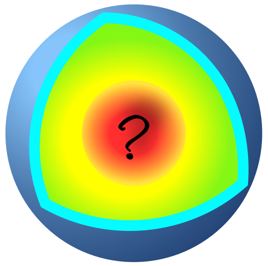
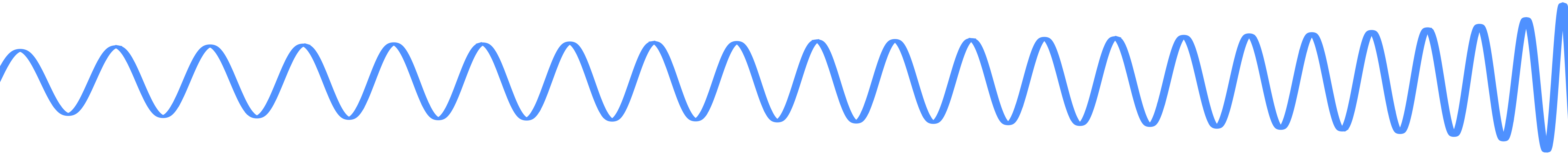
Overview

- Gravitational waves (GWs) now accessible as probes of dense matter
  - For binary systems:

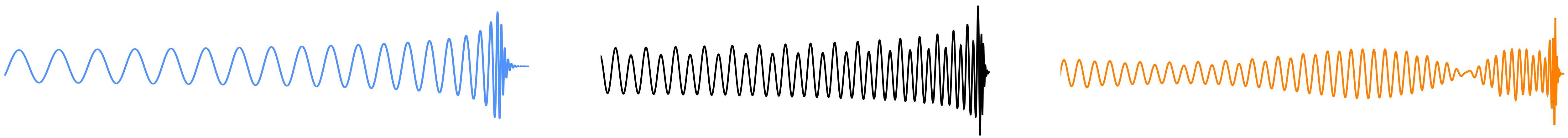
    interpreting the data requires detailed theoretical understanding & accurate modeling
  - Brief glimpse of challenges, approaches, and status of models that include matter effects
- Outlook: unique scientific prospects with future measurements but only with significant further advances in modeling





GW measurements (binary systems)

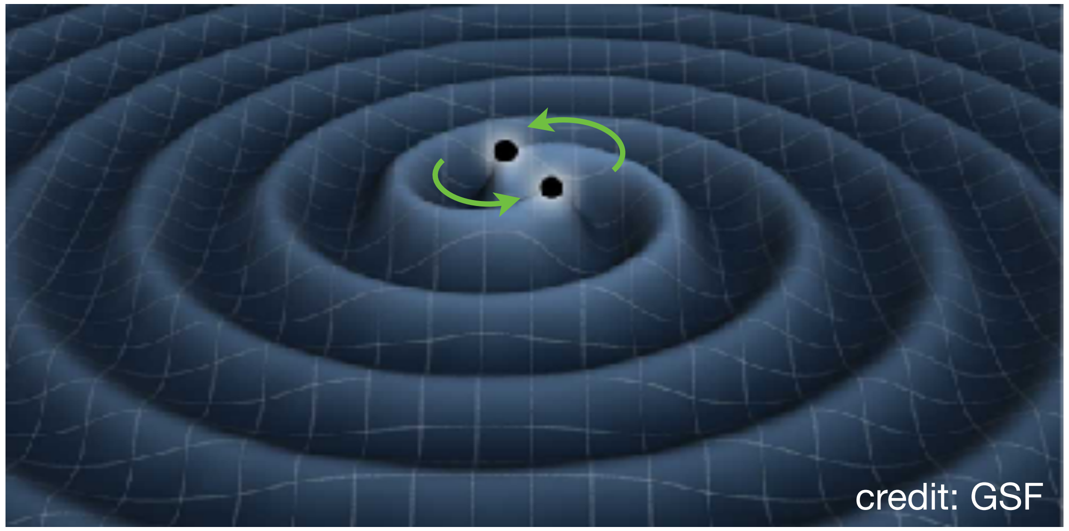
- Details of the waveforms encode fundamental source properties (masses, spins, …)



- Measurements cross-correlate millions of template models with the data to determine the source parameters

- Computation of template waveforms is very challenging:

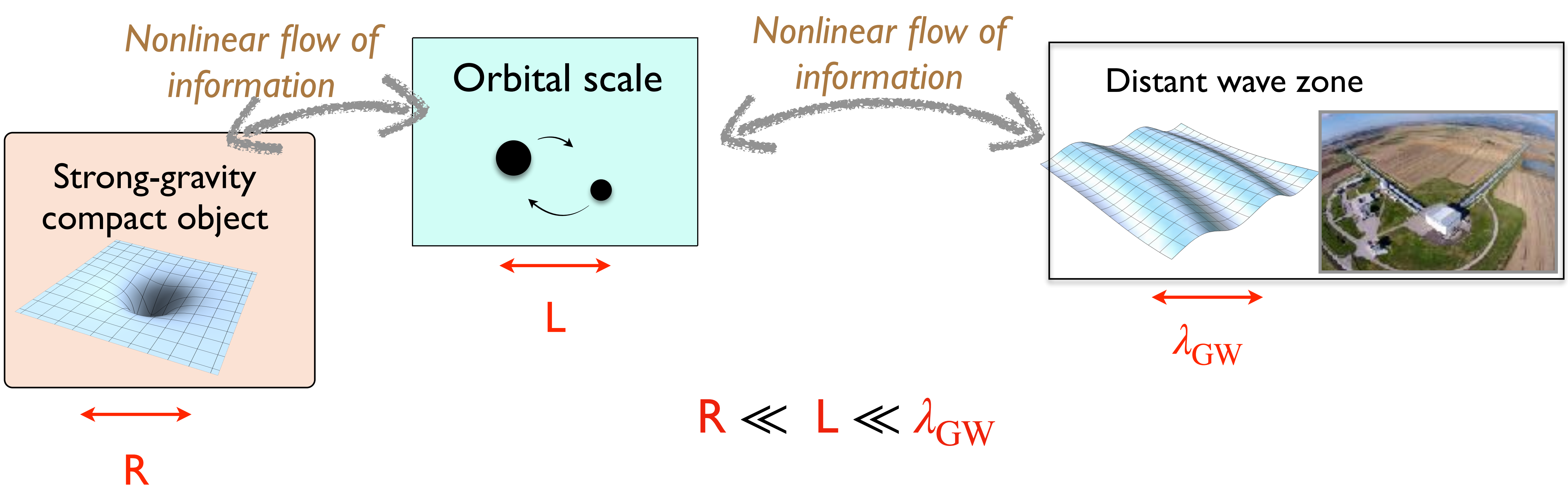
Must solve the nonlinear Einstein Field equations coupled with the matter equations of motion for the dynamical spacetime



Approaches to computing waveforms

- Numerical relativity simulations: access to complex merger regimes … limited in parameter space … sometimes difficult to identify fundamental physics parameters based solely on numerical outputs
- When different physics dominate at different scales:
  - tapestry of approximation schemes in different patches of spacetime

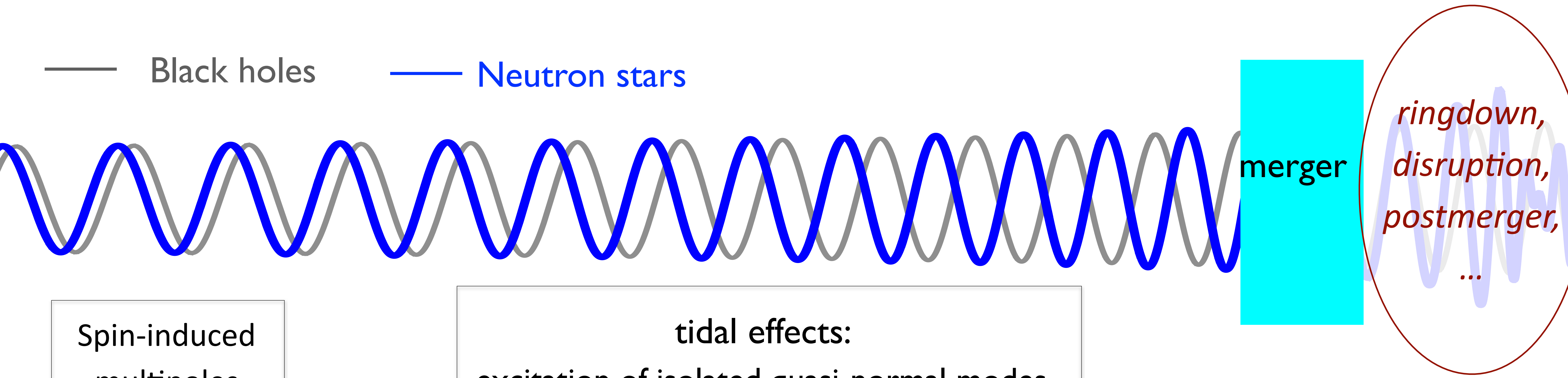
Example for comparable-mass inspirals:



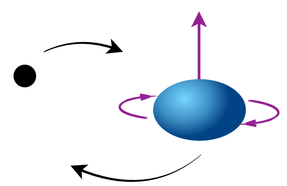
$$R \ll L \ll \lambda_{GW}$$

~10km ~400km ~4000 km

Main GW signatures of matter

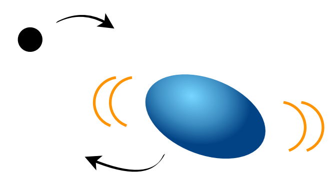


Spin-induced multipoles



tidal effects:

excitation of isolated quasi-normal modes



resonant +

non-resonant

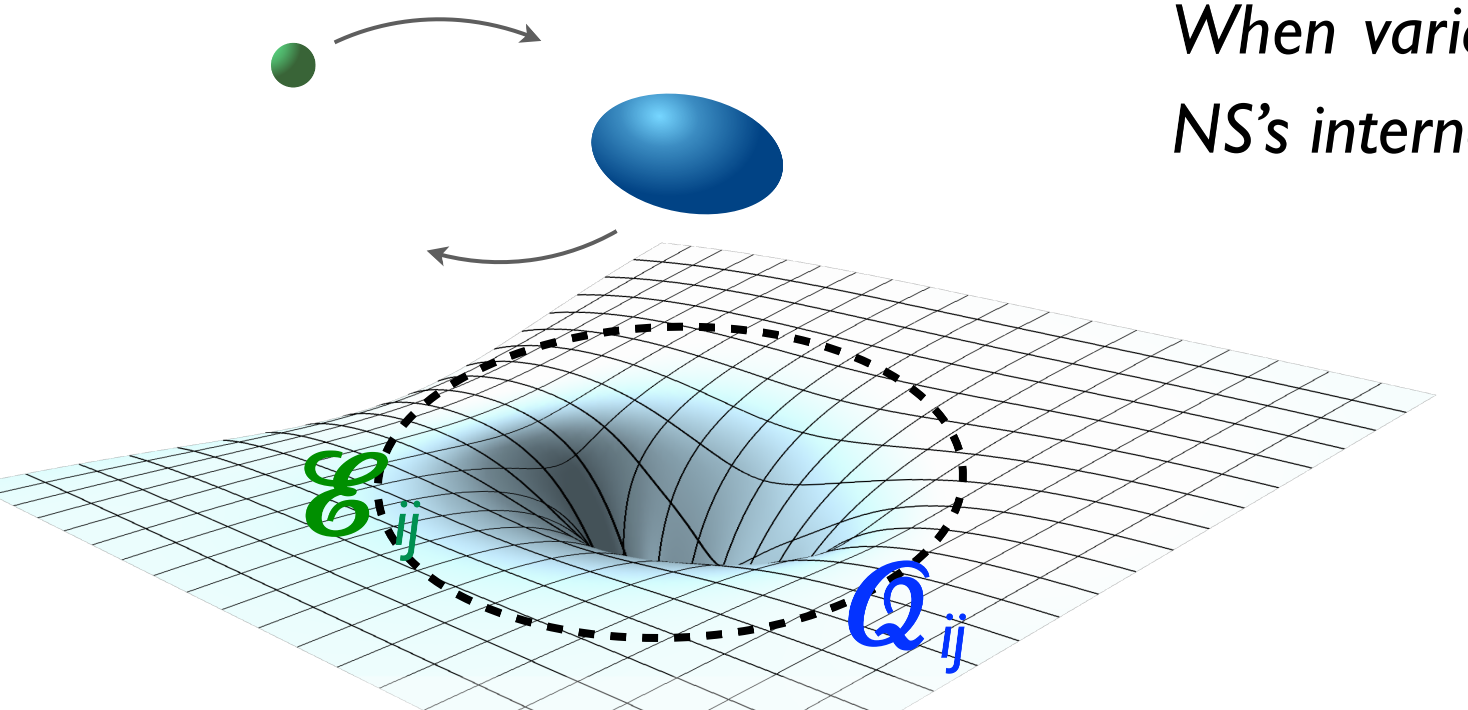
GW spectroscopy of matter

+ multi messenger counterparts

Inspiral: small effects but clean and cumulative, accessible with current detectors

Dominant tidal effects

- In a binary: tidal field $\mathcal{E}_{ij} = R_{0i0j}$ due to spacetime curvature from companion



Quadrupole deformation of spacetime away from spherical symmetry

When variations in tidal field are much faster than NS's internal timescales (adiabatic limit):

Induced deformation:

$$Q_{ij} = -\lambda \mathcal{E}_{ij}$$

tidal deformability parameter

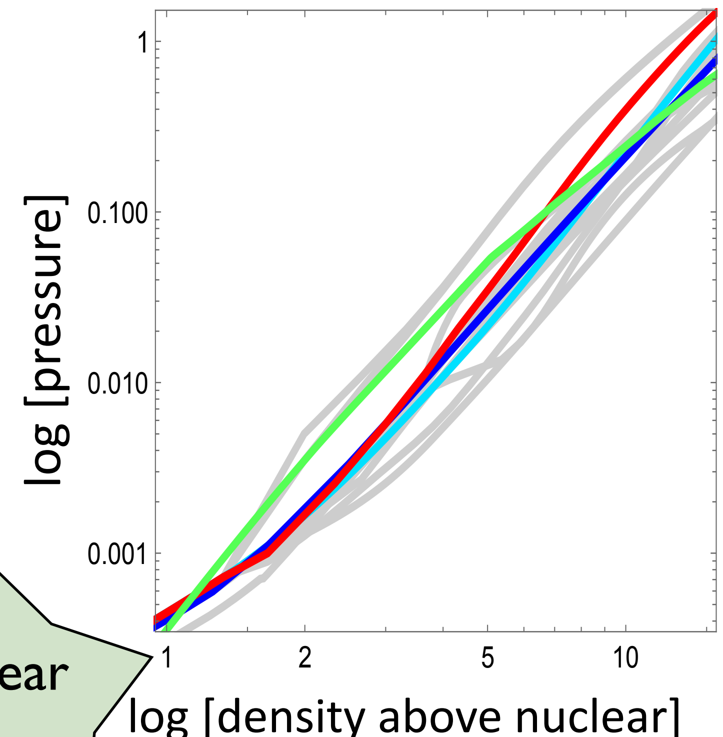
=0 for a black hole

Similarly for higher multipoles

Properties of NS matter reflected in tidal deformability

NS matter models
(equations of state EoS)

Perturbative QCD



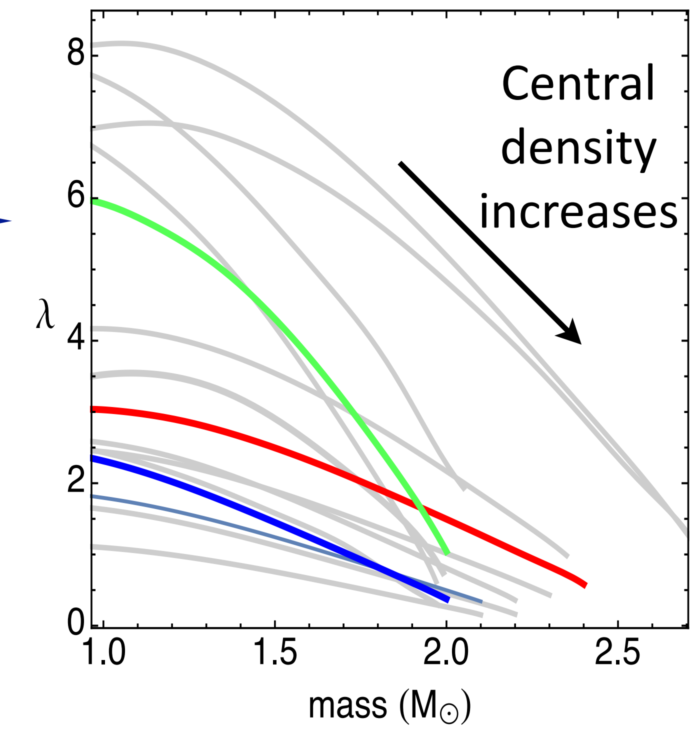
Nuclear EFT, …

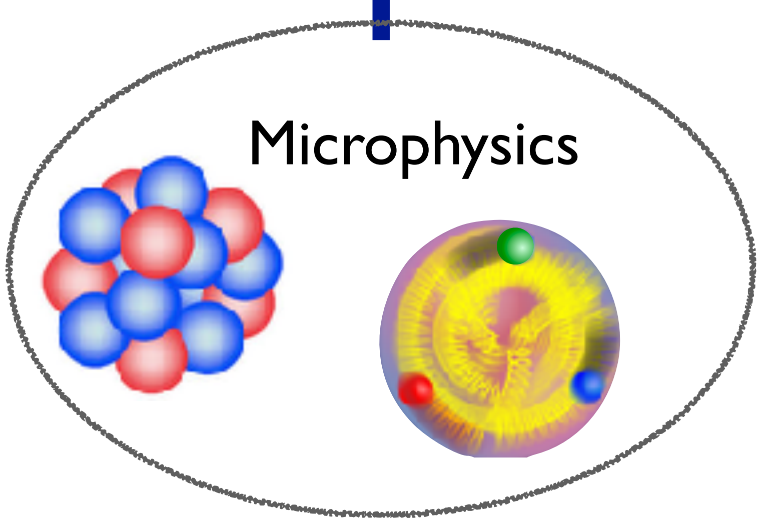
Einstein field equations &

Matter equations of motion

Stationary perturbations to equilibrium
or wave scattering

Tidal deformability λ vs. mass



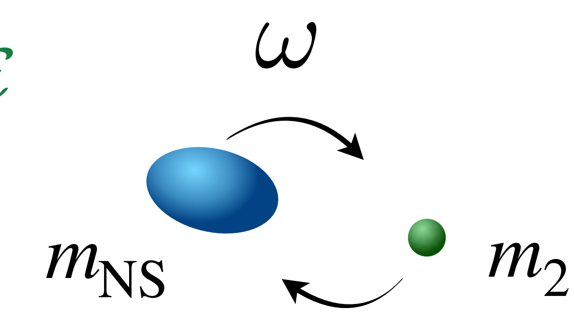


Main influence on GWs

- Energy goes into deforming the NS:

$$E \sim E_{\text{orbit}} + \frac{1}{4}\mathcal{Q}\,\mathcal{E}$$

$$\mathcal{Q} = -\lambda\,\mathcal{E}$$



- moving multipoles contribute to gravitational radiation

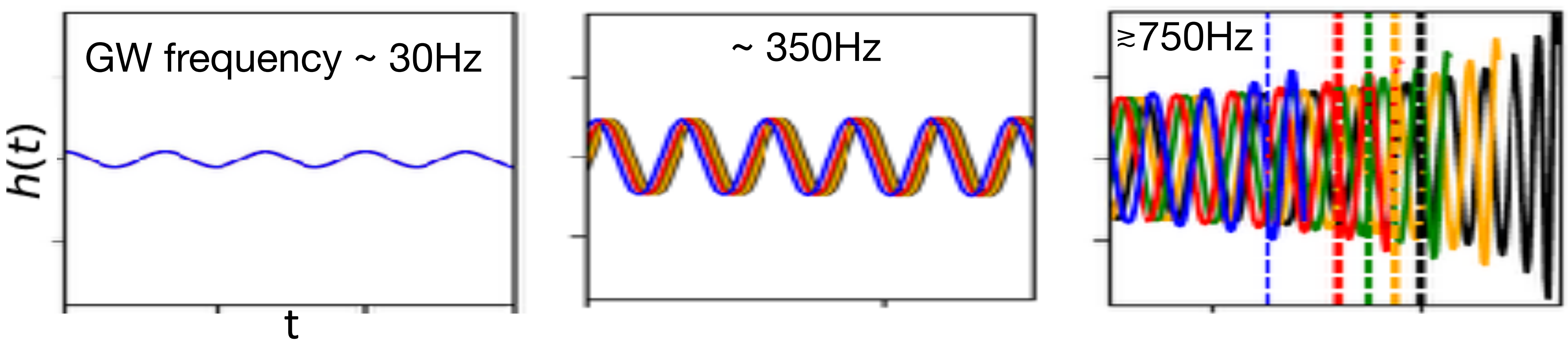
$$M = m_{\text{NS}} + m_2$$

$$\dot{E}_{\text{GW}} \sim \left[\frac{d^3}{dt^3}\left(Q_{\text{orbit}} + \mathcal{Q}\right)\right]^2$$

- approx. GW phase evolution from energy balance:

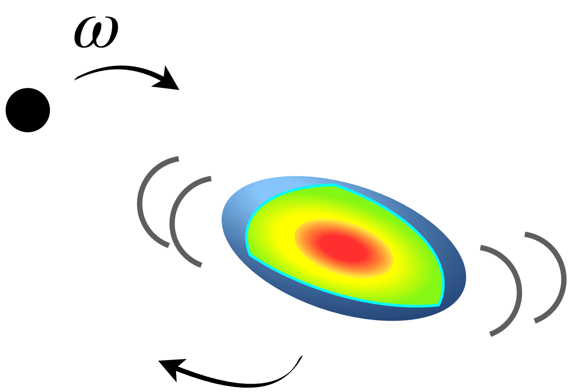
$$\Delta\phi_{\text{GW}}^{\text{tidal}} \sim \lambda\,\frac{(M\omega)^{10/3}}{M^5}$$

Examples for different EoSs aligned at 30 Hz



Dashed lines: 1kHz

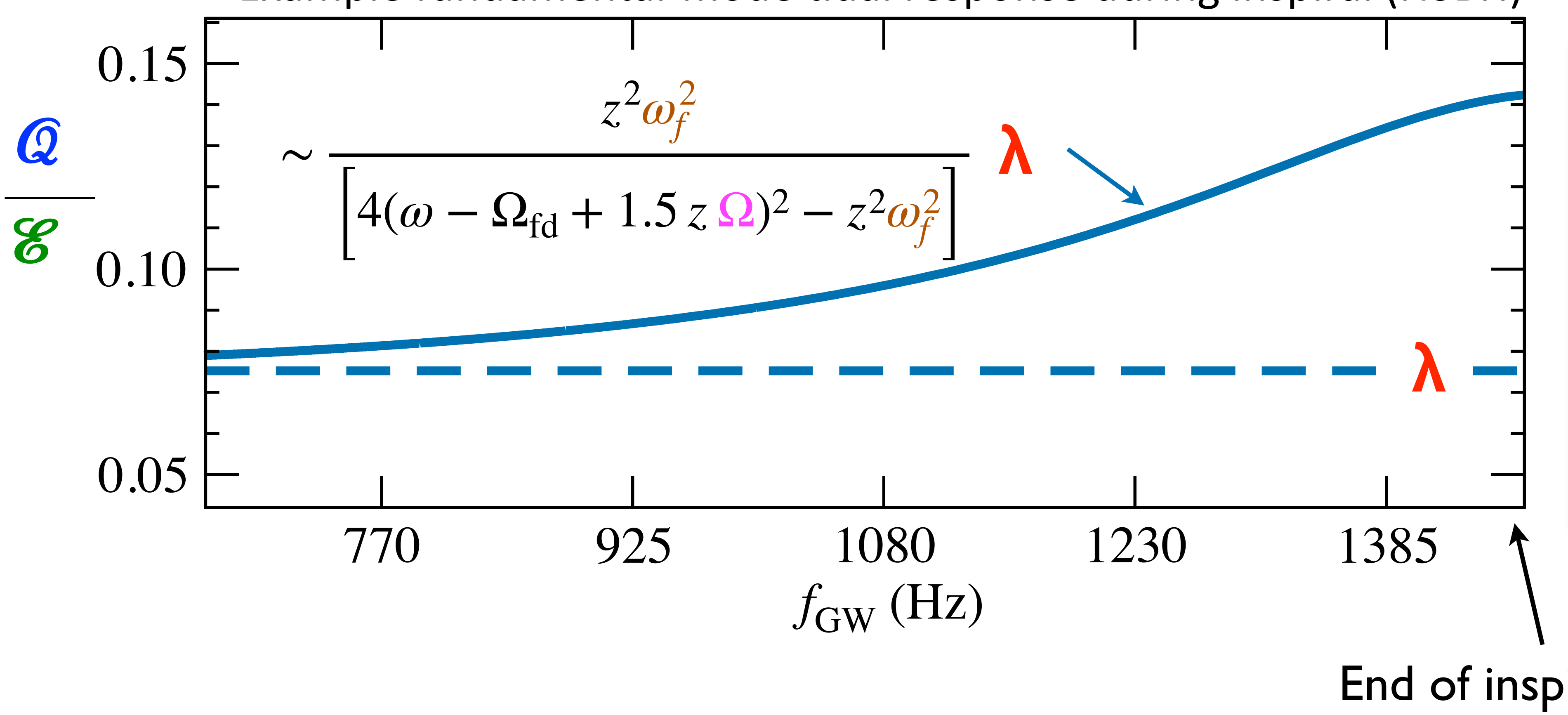
More realistic descriptions of tidal effects



- NSs have a rich spectrum of quasi-normal oscillation modes
- For some: tidal excitations in inspirals
- Spectroscopy of NS interiors, possible EM flares

- Even non-resonant excitations can lead to significant effects, e.g. fundamental modes with ω_f

Example fundamental-mode tidal response during inspiral (NSBH)

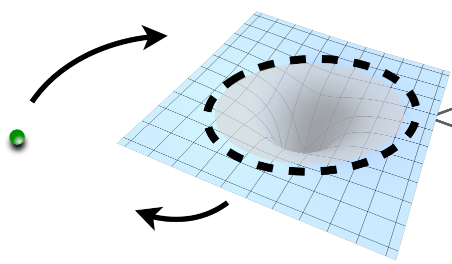


Response also impacted by:

- relativistic redshift z
- frame dragging $\Omega_{\rm fd}$ (GR, companion spin)
- NS's spin Ω

More realistic description of matter effects on the dynamics

spacetime near the NS viewed on the orbital scale:



worldline + multipoles

$m, S^i, Q^{ij}, Q^{ij}_{\mathcal{B}}, \dots$

tidally induced mass & (matter contributions to) current multipoles

Gravitomagnetic modes

Effective action describing the binary dynamics:

Internal dynamics of the multipoles (modes)

redshift

$$S \approx S_{pp} + \int d\tau \left[-\frac{z}{2} Q_{ij}\mathcal{E}_{ij} - \frac{z}{2}\dot{Q}^{\mathcal{B}}_{ij}\mathcal{B}_{ij} + L^{\rm Coriolis} + L^{\rm FD} + L^{\rm osc} + \dots \right]$$

point-particle part

multipoles interact with companion's spacetime curvature

Effects of NS's spin on tidal response & restoring force for gravitomagnetic modes

Q's angular momentum interacts with orbital angular momentum & companion's spin

More realistic couplings of matter to orbital dynamics

Multipoles behave as harmonic oscillators:

$$L^{\rm osc} \approx \sum_n \frac{z}{4\lambda_{(n)} z^2 \omega_{(n)}^2} \frac{dQ_{ij}^{(n)}}{d\tau} \frac{dQ_{ij}^{(n)}}{d\tau} - \frac{z}{4\lambda_{(n)}} Q_{ij}^{(n)} Q_{ij}^{(n)} + \dots$$

Different quadrupolar modes contribute, dominated by fundamental modes

+ similarly for higher multipoles

$$+ \frac{3z}{32(\sigma_{\rm stat} - \sigma_{\rm irrot})} \frac{d\dot{Q}_{ij}^{\mathcal{B}}}{d\tau} \frac{d\dot{Q}_{ij}^{\mathcal{B}}}{d\tau} + \frac{2z\sigma_{\rm stat}}{3} \mathcal{B}_{ij}\mathcal{B}_{ij} + \dots$$

subdominant but important for future GW detections

two different magnetic tidal deformabilities

$$S \approx S_{pp} + \int d\tau \left[-\frac{z}{2} Q_{ij}\mathcal{E}_{ij} - \frac{z}{2} \dot{Q}_{ij}^{\mathcal{B}} \mathcal{B}_{ij} + L^{\rm Coriolis} + L^{\rm FD} + L^{\rm osc} + \dots \right]$$

point-particle part

multipoles interact with companion's spacetime curvature

Effects of NS's spin on tidal response & restoring force for gravitomagnetic modes

Q's angular momentum interacts with orbital angular momentum & companion's spin

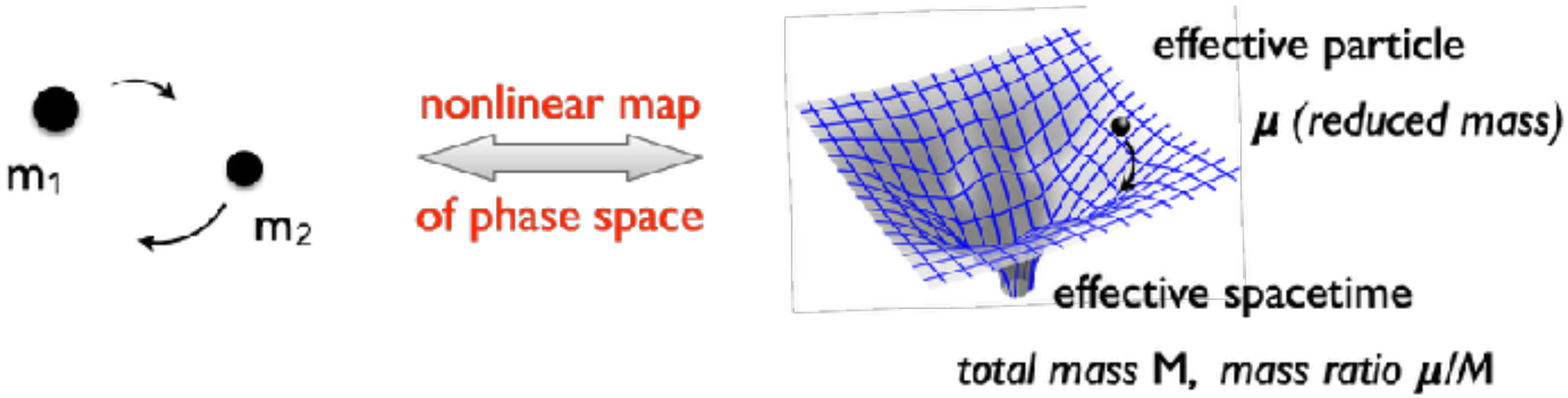
[Steinhoff, TH +2016, 2020, 2021]

Finite size effects included in models for data analysis

Matter effects on top of full black hole baseline models

Effective one body (EOB) models:

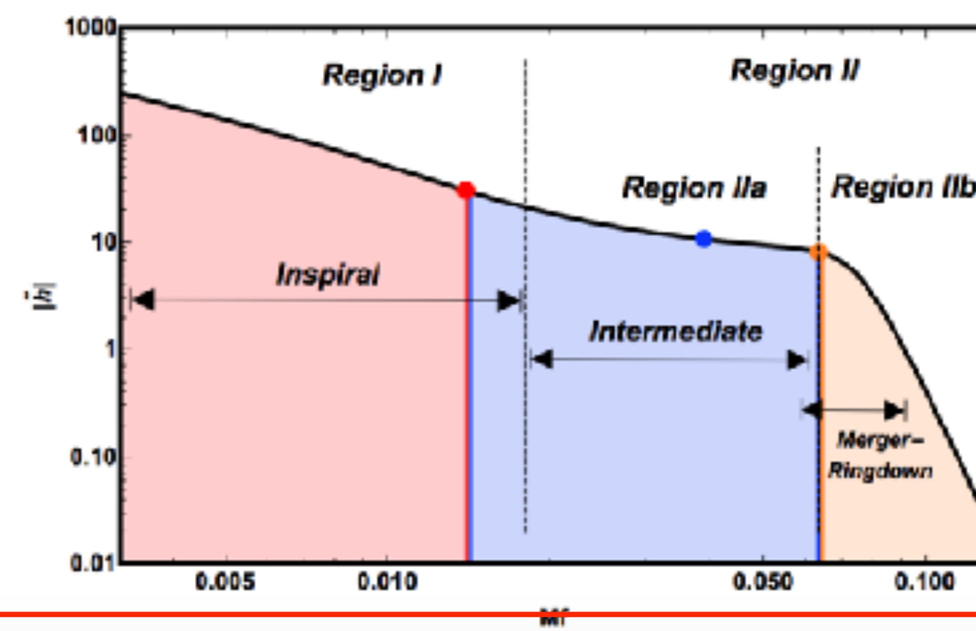
resummation of information



Phenomenological (Phenom) models:

closed-form expressions for frequency-domain GWs

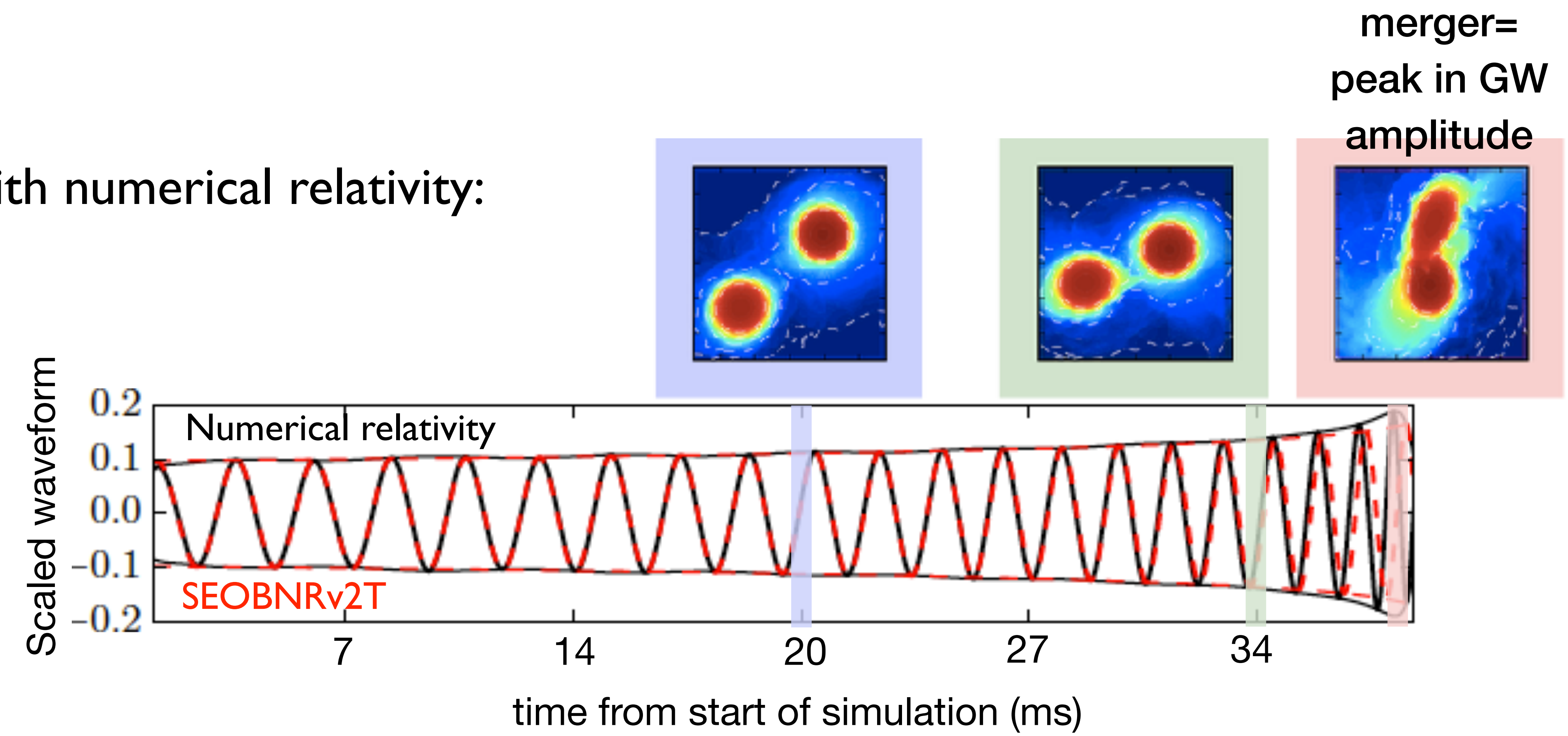
GW amplitude



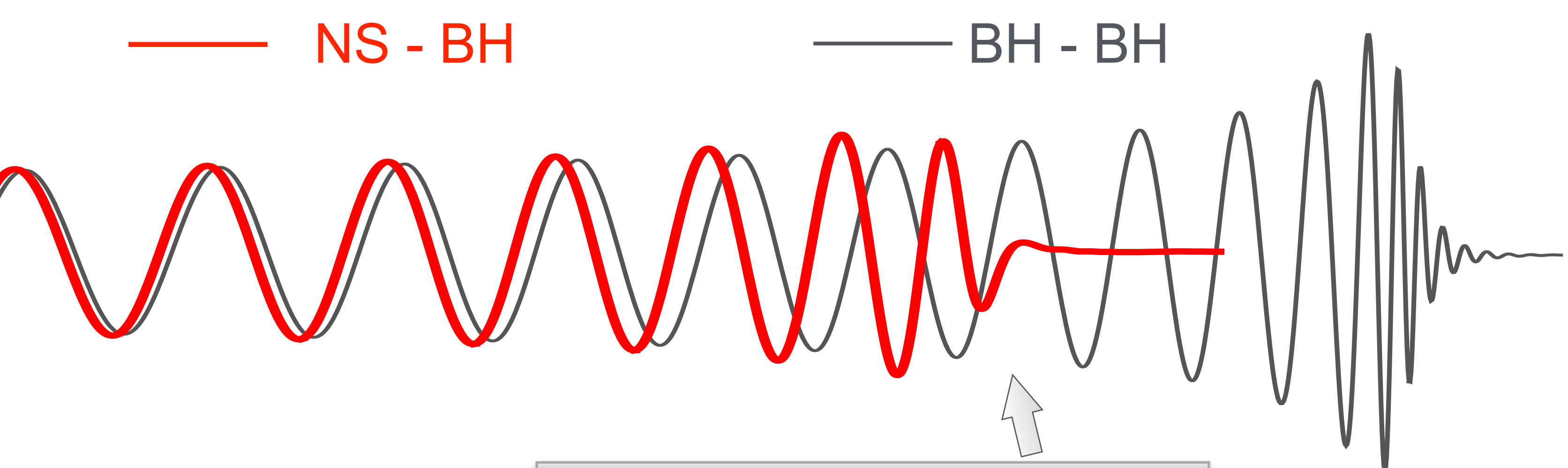
Matter effects in models for data analysis

- For inspirals: variety of physics & assumptions, e.g. some but not all of the models
  - Rely on quasi-universal relations used to reduce matter parameters to λ_1, λ_2
  - Are calibrated to numerical relativity
  - Include some dynamical tidal effects
  - …

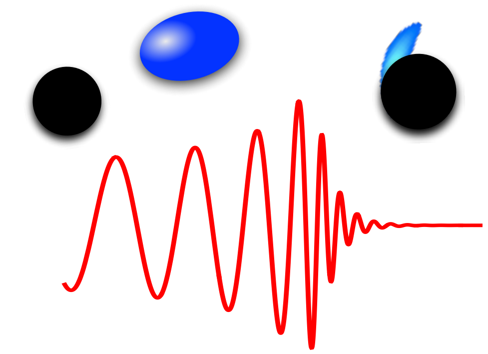
Comparison with numerical relativity:



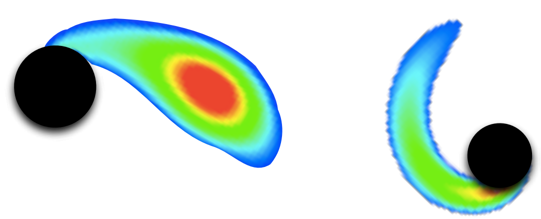
GW signal from NS-black hole (BH) binaries



- alternative outcome: plunge



tidal disruption



Key signature:
'shutoff' in GW
amplitude

Shutoff frequency depends on parameters
(mass ratio, spins, EoS, …)

+ Multimessenger counterparts

Modeling uncertainties

sources of inaccuracies:

- Same 'physics', different modeling choices

  (e.g. EOB, Phenom families, various tidal models)

- Missing physics

  a lot is missing … but also not *all* micro details are probed by GW measurements

- For events measured to date:

  impact of modeling uncertainties still subdominant compared to statistical errors, as far as could be determined, but starting to become noticeable in some cases

Abbot+2020, GWTC-2 (Appendix on waveform systematics)

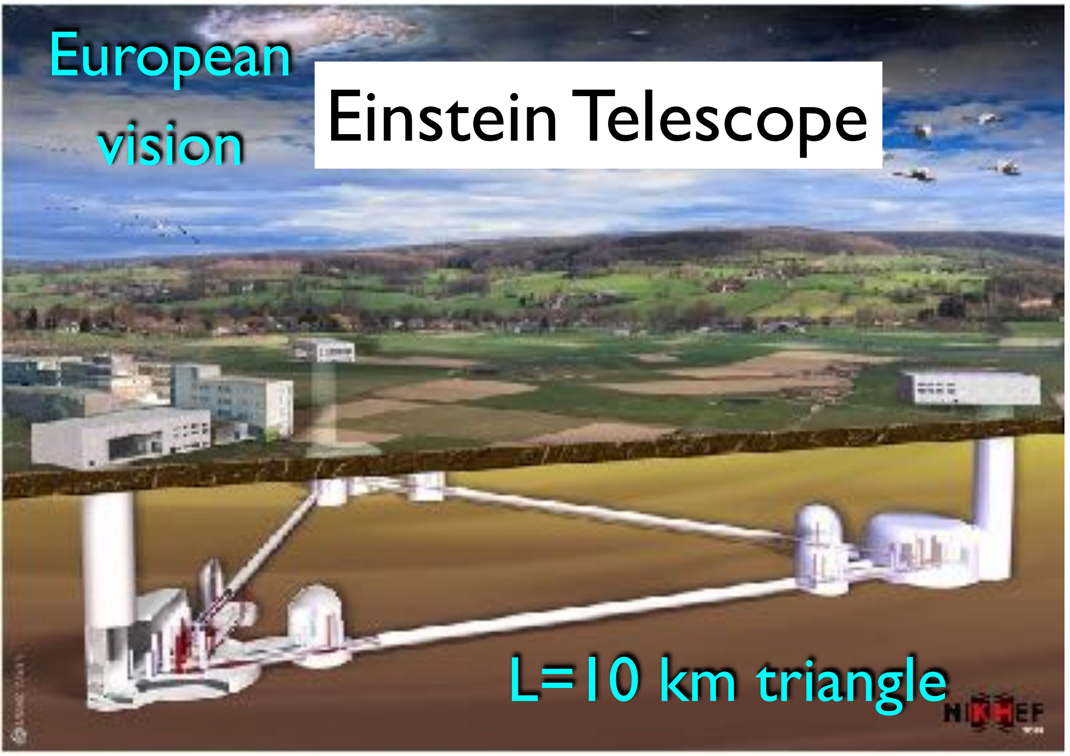
Near-term future prospects

next observing run O4: LIGO/Virgo near/reaching design sensitivity

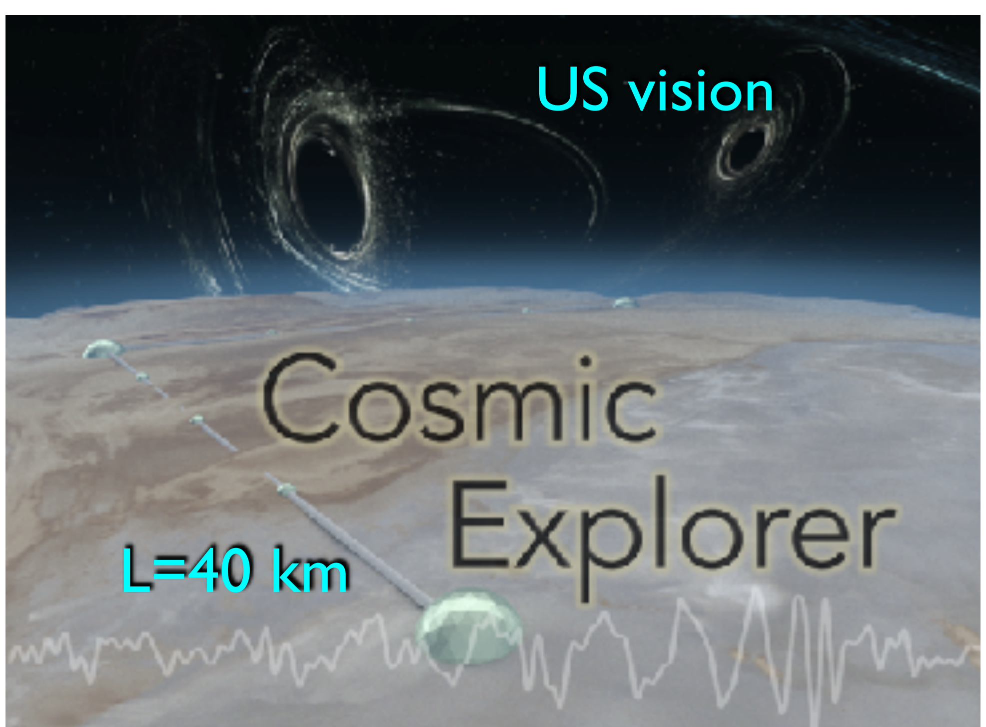
Further upgrades scheduled

- More accurate measurements of nearby sources
- greater number & diversity of events

Plans for next-generation detectors moving ahead



- Prototype being built in Maastricht



O(100 000) binary merger detections per year

High precision studies of nearby sources

Wider frequency range:

- Low-frequency:
  - tidal resonances, …
  - infer 'initial state' & 'control parameters' of the collision
  - Early alerts for EM
- High frequency:
  - measure tidal disruptions
  - Probe NS mergers & beyond

A few examples of remaining theoretical challenges

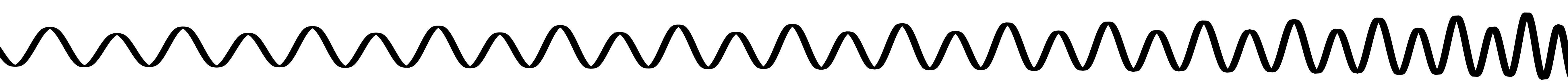
- high-accuracy and efficient waveforms over wide parameter space

- Inspirals/tidal disruptions: more matter effects & relativistic corrections, higher GW modes, arbitrary spins, role of beyond zero-temperature, equilibrium matter?, eccentricity, …

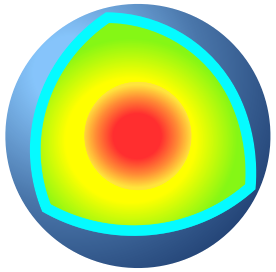
- Deeper understanding of complex NS-NS merger regimes with more realistic physics, robustly quantify numerical errors, ….

- degeneracies (e.g. modified gravity, dark matter), …

- …..



Summary and outlook



- GWs are new probes of NS physics: clean gravitational channel of information
- Exciting near- & longer-term prospects with larger & more precise datasets
- Simultaneous advances in modeling are essential to fully realize the science potential, reduce biases in measurements and interpretation
- Significant recent progress on understanding, methods, modeling of relevant phenomena but much work remains
- Synergy of theoretical approaches (different analytical approximations + numerical relativity) important
- Interdisciplinary cooperation needed on connections and fundamental inputs