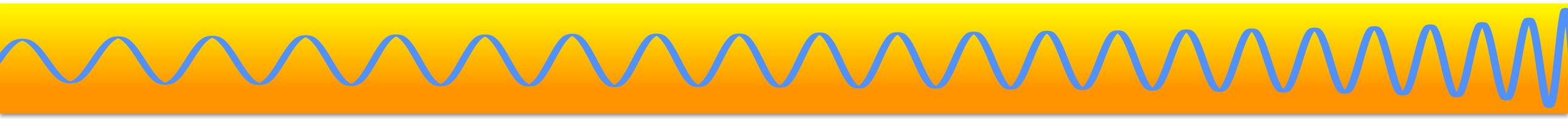
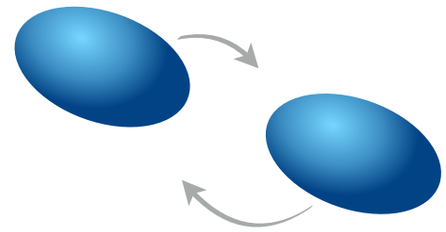


Matter effects in the gravitational waves from inspiraling neutron star binaries

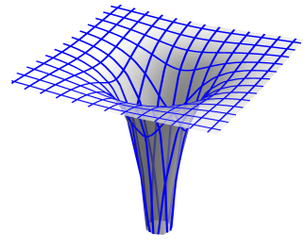
Tanja Hinderer

Excellence Fellow

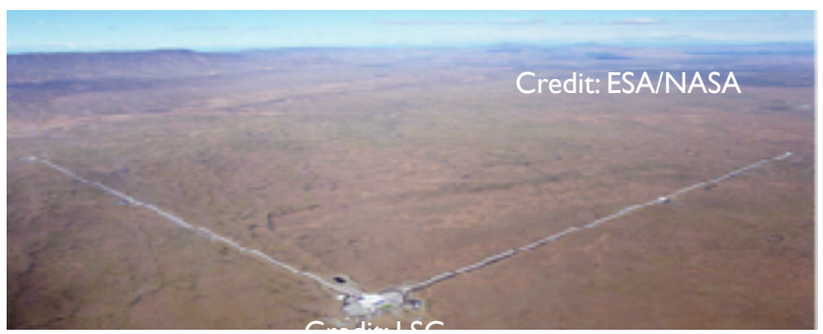
Radboud University Nijmegen

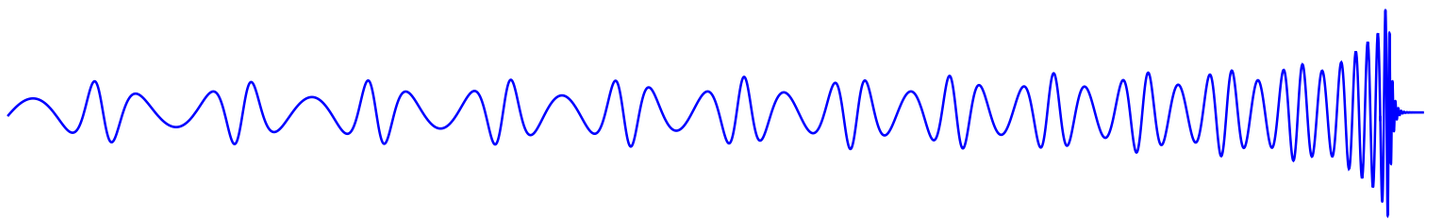


Outline of this talk

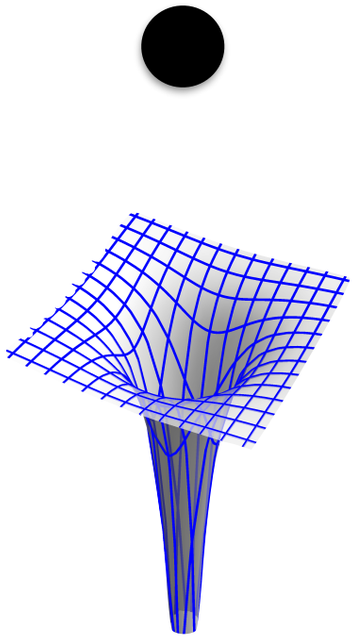


- Gravitational waves GWs: a new tool for exploring the universe
- Theoretical models needed to extract the unique information they encode
- Main focus of this talk: imprints of NS matter during the *inspiral*
- Outlook



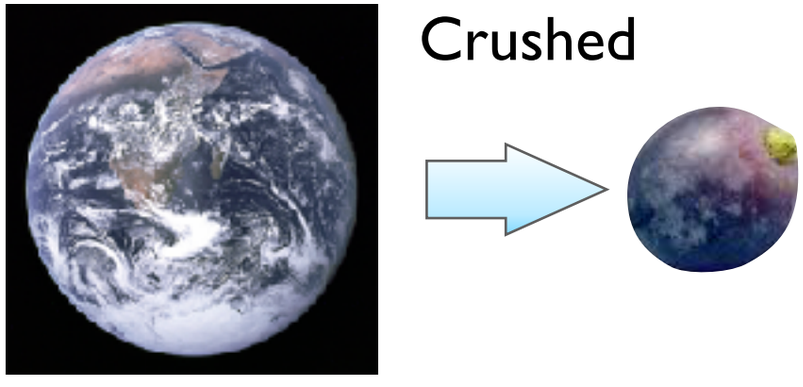


Preliminary: black holes and neutron stars



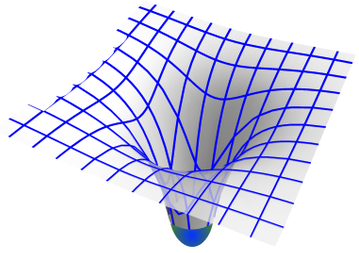
Black hole (BH)

- Consist only of extreme spacetime curvature
- Characterized entirely by mass & spin



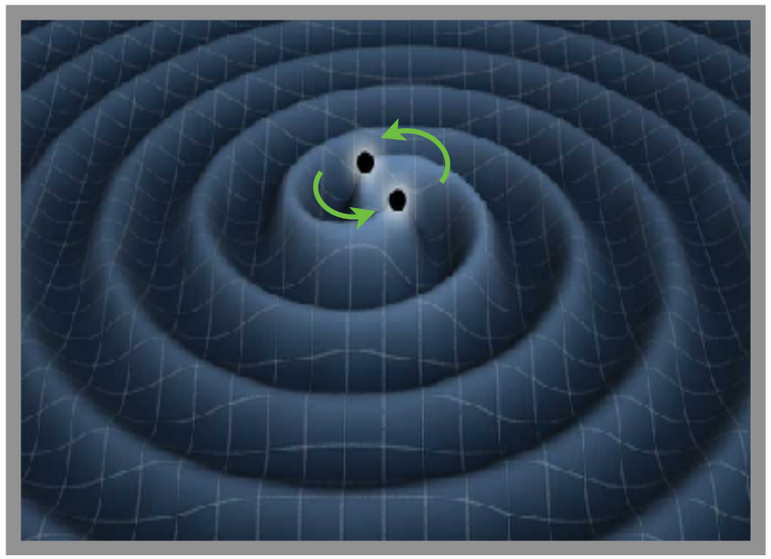
Neutron star (NS)

- extreme matter



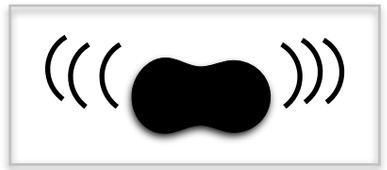
GW signals from black-hole binary systems

Binary inspiral



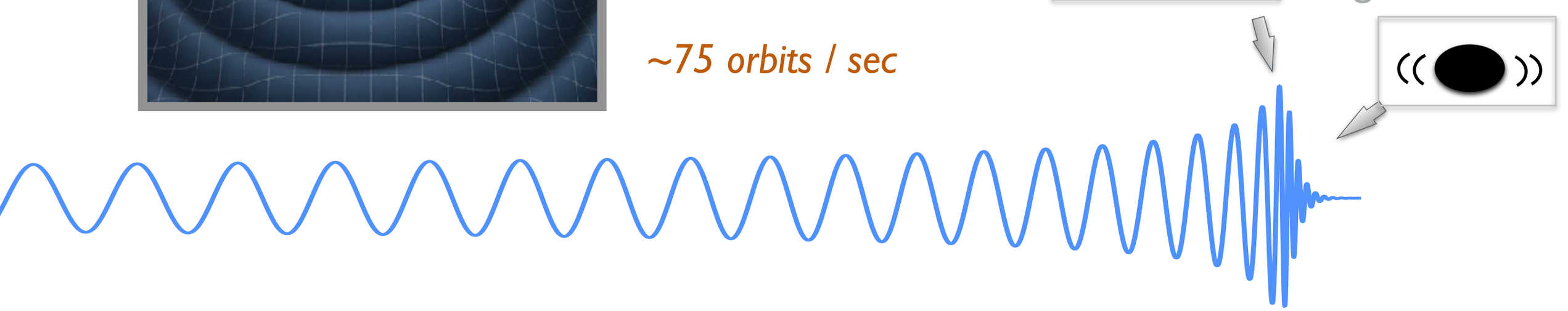
the orbit shrinks …

… until they collide

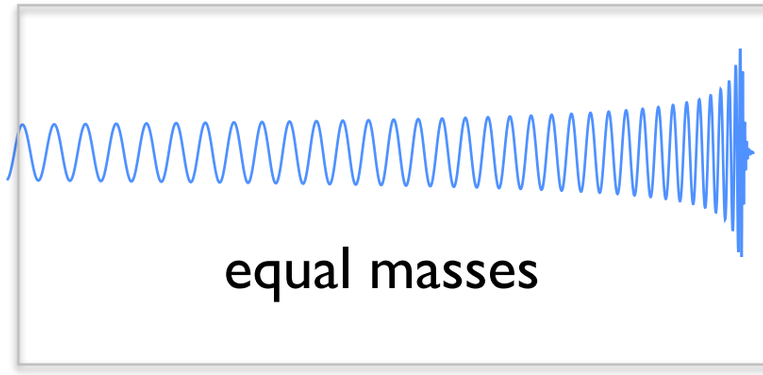


… and form a single black hole

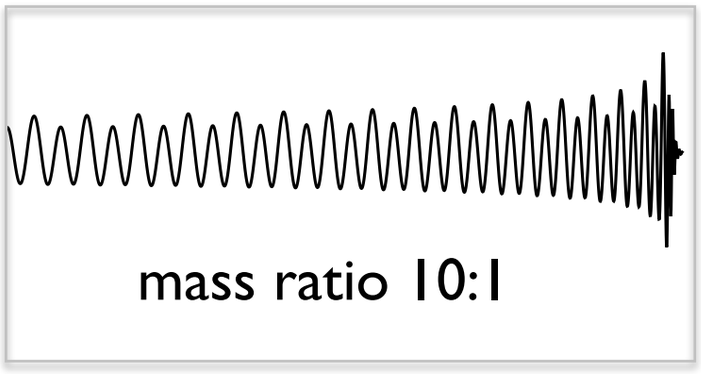
~75 orbits / sec



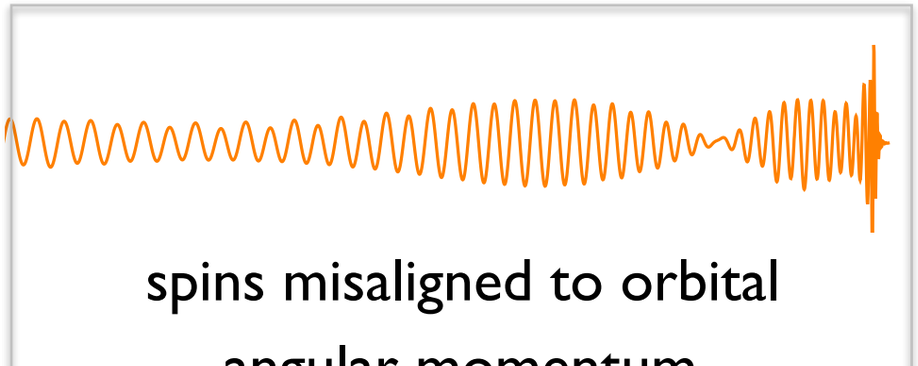
- Details of the waveform encode fundamental source properties



equal masses



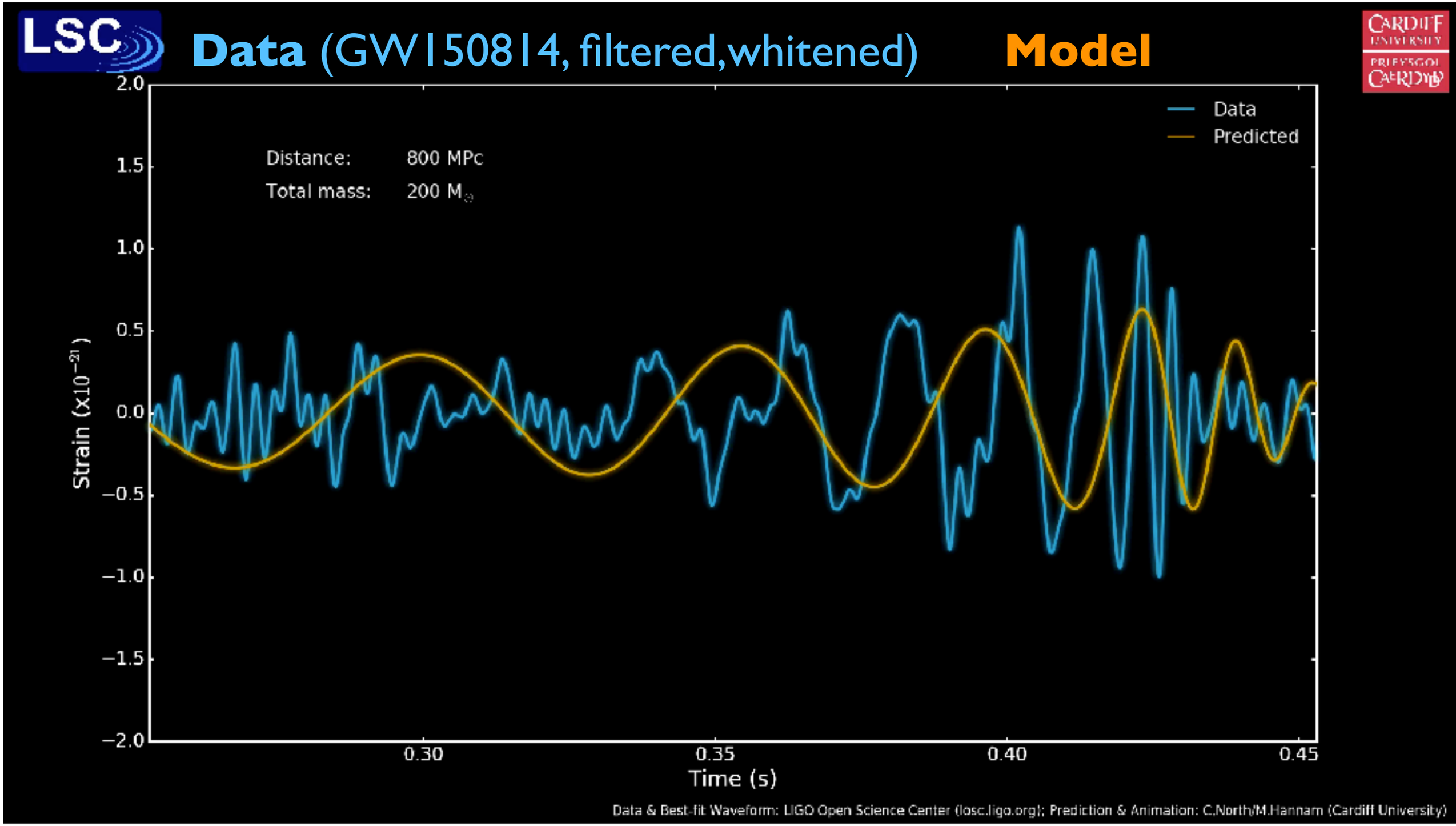
mass ratio 10:1



spins misaligned to orbital angular momentum

Interpreting GW signals via matched filtering

here: only total mass of the binary and distance vary



Very sensitive to the phasing

Challenges for computing templates

- must solve for the dynamical spacetime of the binary system.

Newtonian gravity

field equations:

Gravitational potential *Mass density*

$$\nabla^2 \Phi = 4\pi G \rho$$

equations of motion:

$$\ddot{x}^i = -\frac{\partial \Phi}{\partial x^i}$$

General Relativity

dynamical spacetime geometry *sources*

$$G_{\mu\nu}\left[\, g_{\alpha\beta} \,\right] = \frac{8\pi G}{c^4} T_{\mu\nu}$$

highly nonlinear differential operator

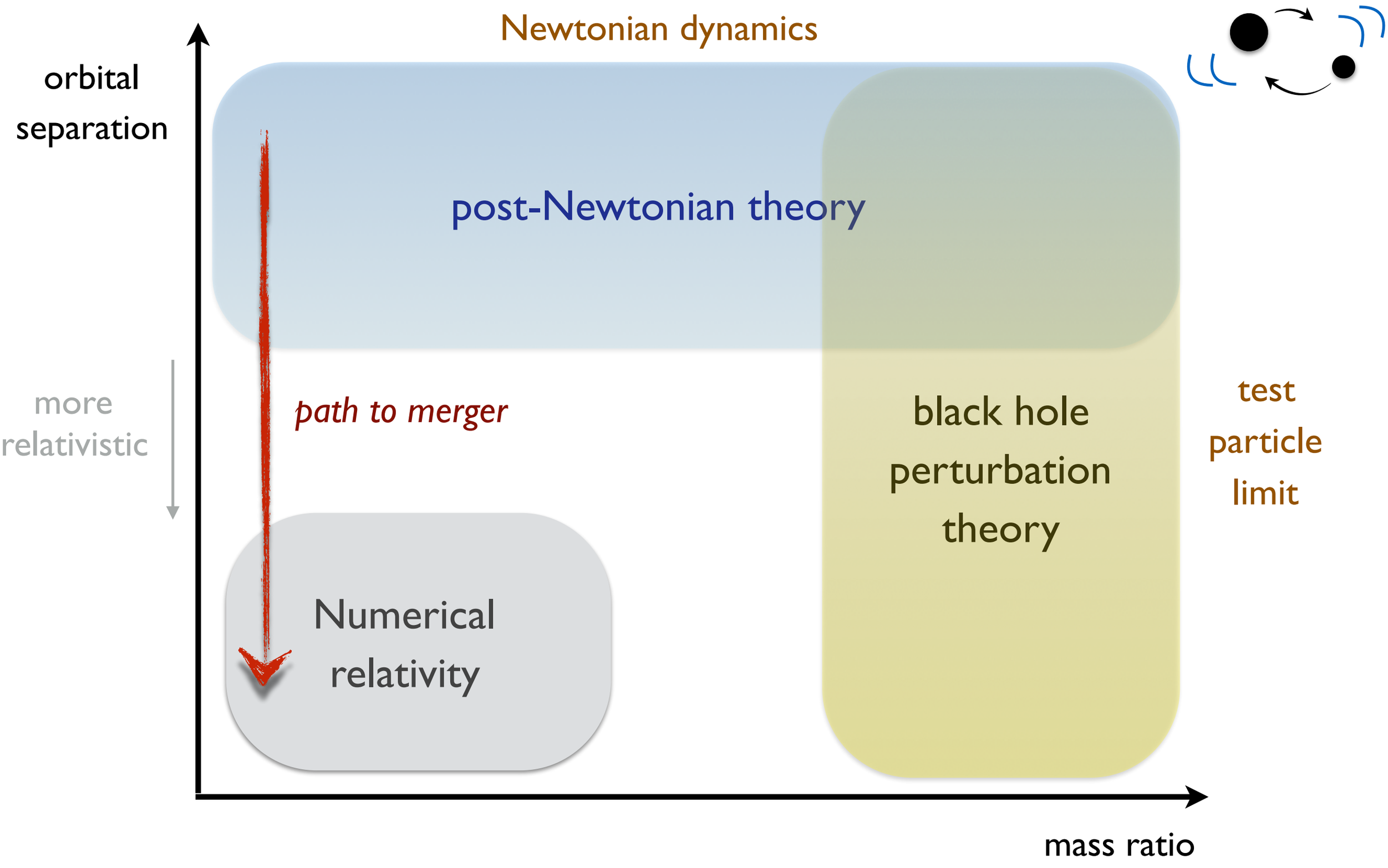
density, pressure, flow of energy & momentum, …

6 coupled eqs. in 6 variables

$$\nabla^\nu G_{\mu\nu}\left[\, g_{\alpha\beta} \,\right] = 0$$

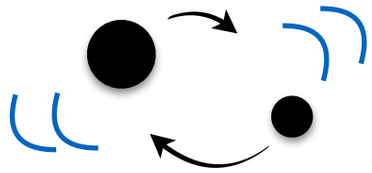
complicated differential eqs.

Approaches to computing templates



Complete waveform model for comparable-mass binaries

Newtonian dynamics



orbital

sep

rel

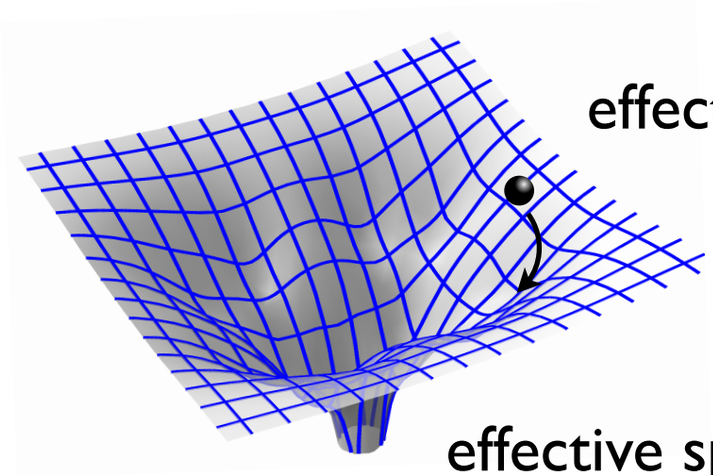
Effective one body (EOB) approach

Binary problem

MAP

[Buonanno, Damour 1999, 2000]

Effective description



effective particle

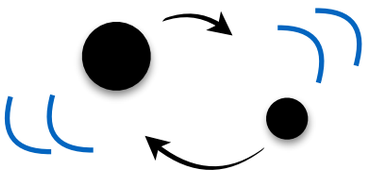
μ *(reduced mass)*

effective spacetime

total mass M, *mass ratio* μ/M

mass ratio

Complete waveform model for comparable-mass binaries

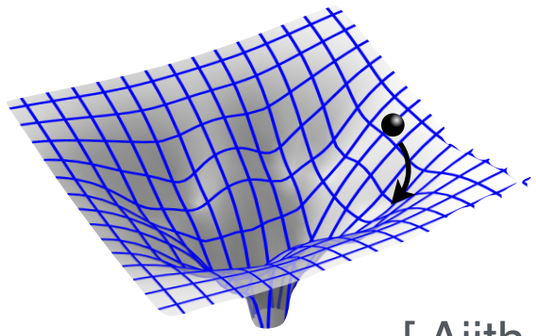


Newtonian dynamics

orbital

sep

Phenomenological approach



[Ajith+ 08, Hannam+ 14, Khan+16]

Efficient frequency-domain waveforms

rel

theory

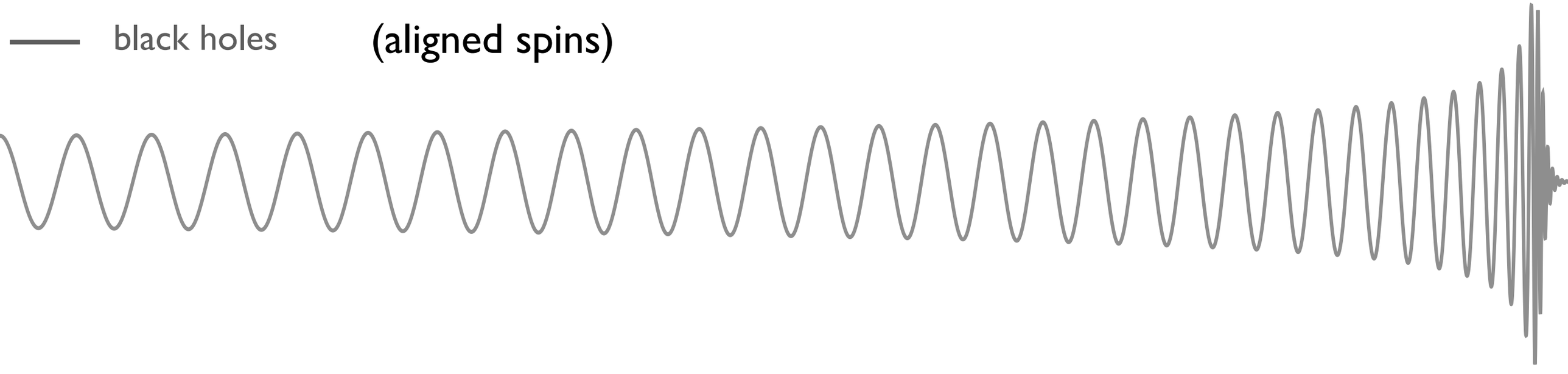
black hole perturbation theory

test particle limit

mass ratio

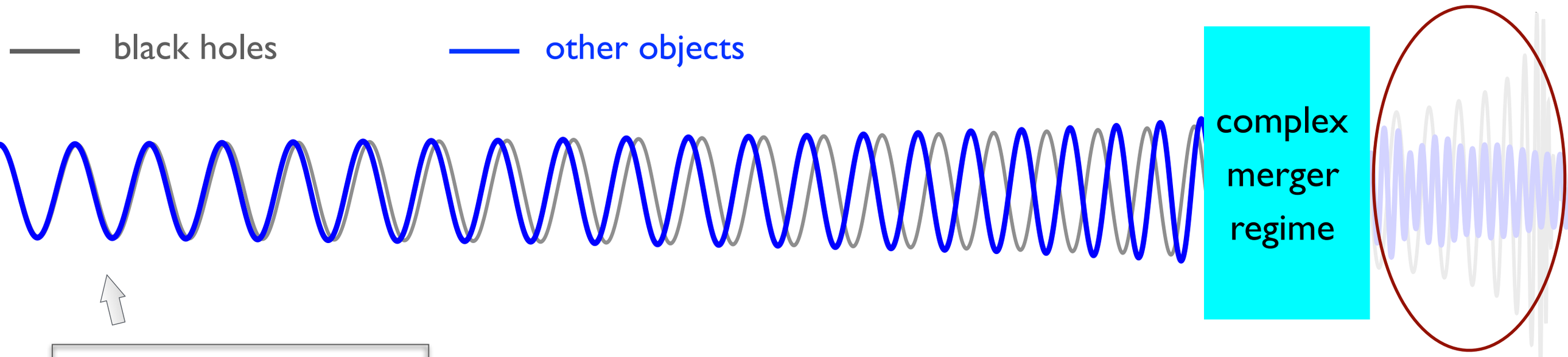
Imprints of objects' internal structure on GWs

black holes (aligned spins)



What changes for other objects?

Imprints of objects' internal structure on GWs



≈ point-masses,
same signals

[~10^3 cycles for few-Msun objects in LIGO]

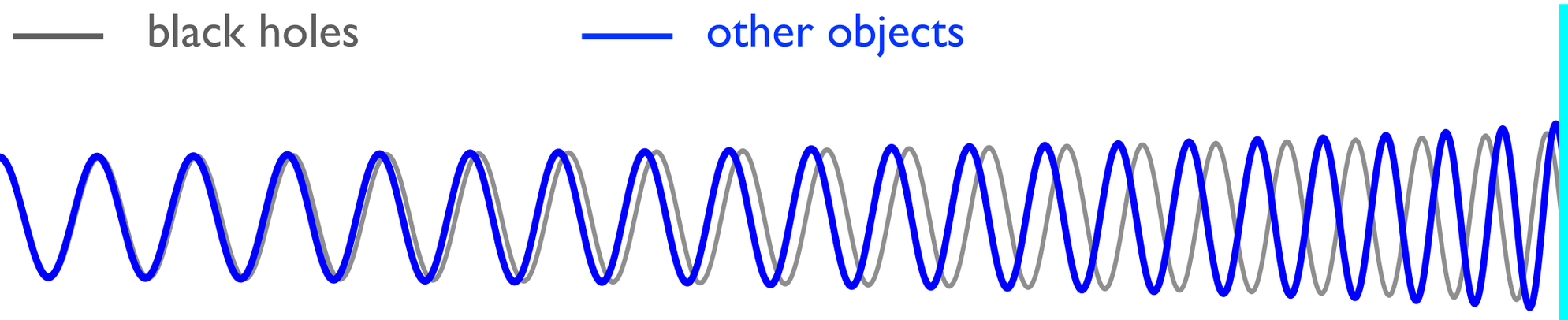
echoes,
ringdown,
tidal disruption,
postmerger,
…

[outside sensitive band for few-Msun objects in LIGO]

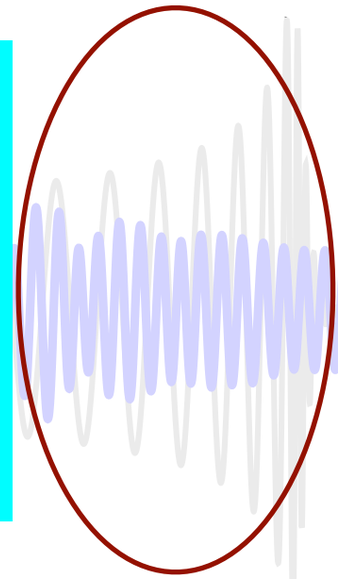
Imprints of objects' internal structure on GWs

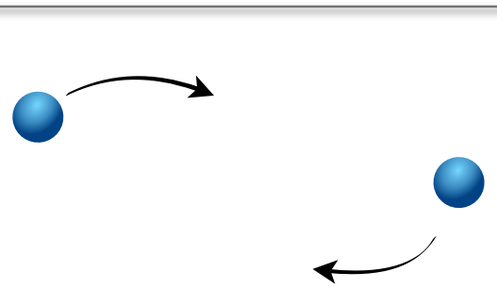
black holes

other objects



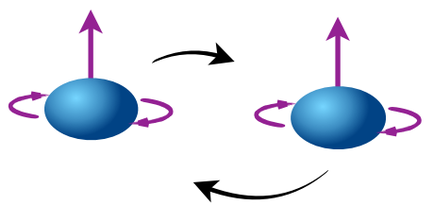
complex merger regime



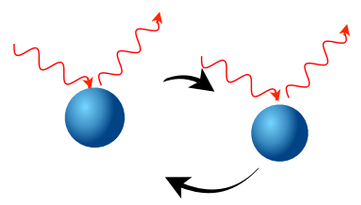


≈ point-masses, same signals

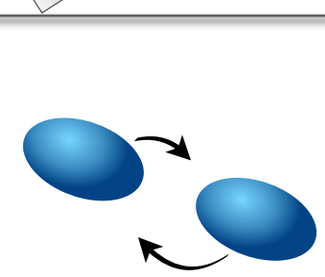
[~10^3 cycles for few-Msun objects in LIGO]



rotational deformations



absence of horizon (absorption)



tidal effects

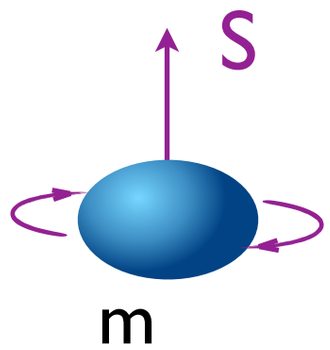
+ tidal excitation of internal oscillation modes

echoes, ringdown, tidal disruption, postmerger, …

[outside sensitive band for few-Msun objects in LIGO]

Rotational quadrupole effect

- Spin-induced deformation:



[Poisson 1997, Larakkers +1997, Mora,+2006]

$$Q_{\rm spin} = -\kappa\, \chi^2 m^3$$

matter-dependent

=1 for a black hole

≲ 15 for neutron stars

S

dimensionless spin parameter $\chi = \frac{S}{m^2}$

≤1 for black holes

≲ 0.4 for millisecond pulsars

- Effects important for $\chi \gtrsim 0.1$ (depending on parameters, LIGO)

I. Harry & **TH** arXiv:1801.09972

Basic framework for describing tidal effects

- In GR, are there new (non-tidal) interactions that impact the inspiral?

  [numerical studies by Wilson+ 1995, several follow-ups

  sociological: Kennefick 2000 ``Star crushing: theoretical practice & the theoretician's regress"]

- Rigorous analysis: [Flanagan 1998]

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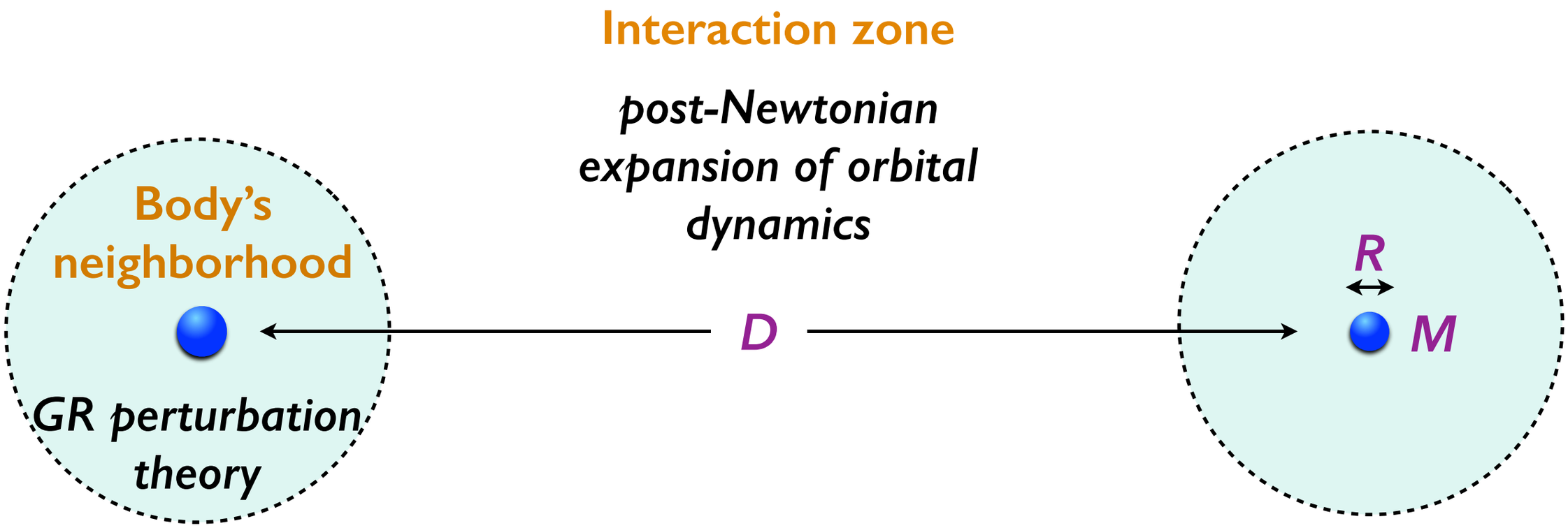

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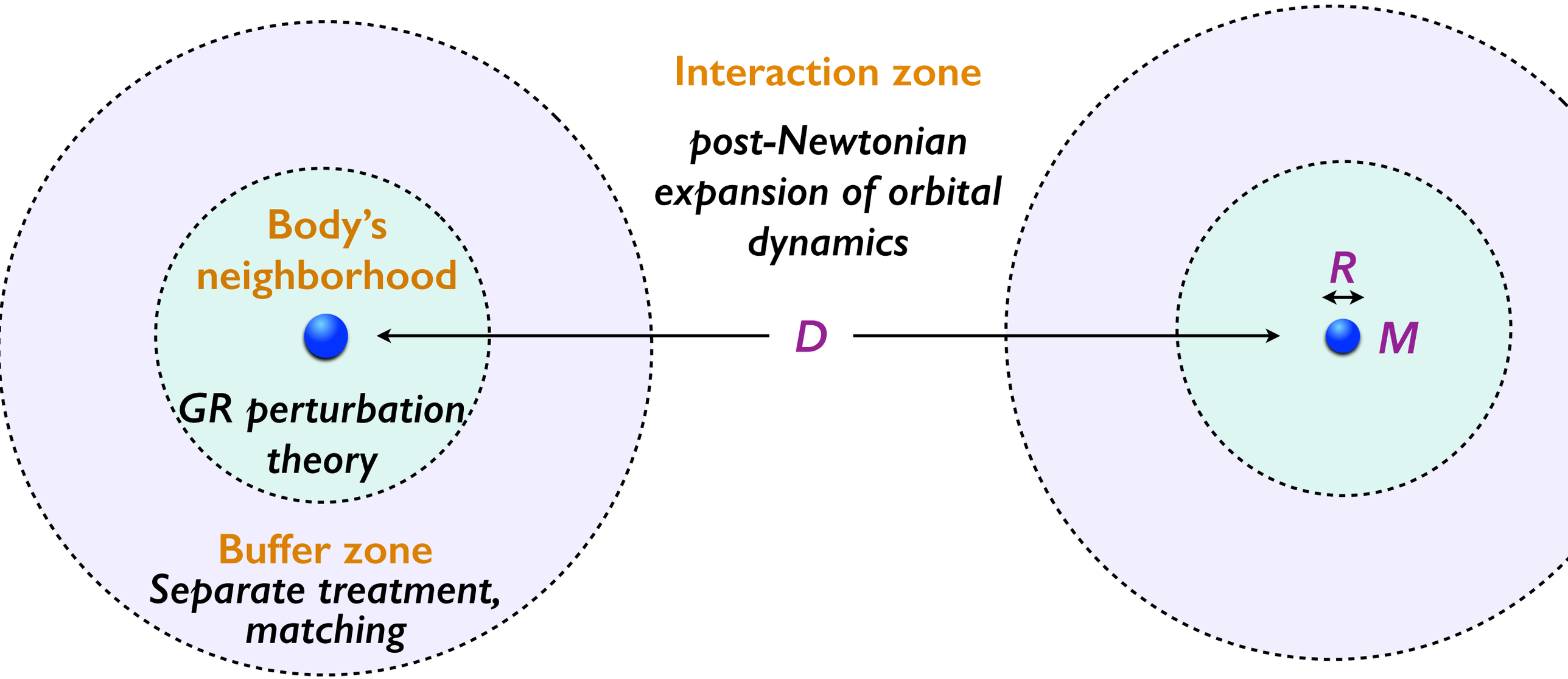

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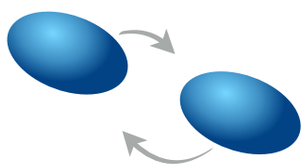
- Rigorous analysis: [Flanagan 1998]

- Matched asymptotic expansions (for $D>>R$, no initial spins)
  - There are NO GR non-tidal interactions (but new kinds of tides)
  - derive the effects on the bodies and on the dynamics
- Then compute the GWs and back-reaction on the binary

Tidal effects for neutron stars

- dominant effect:



deformation $Q_{\rm NS} = \lambda \mathcal{E}_{\rm tidal}$ ← tidal field (companion)

tidal deformability

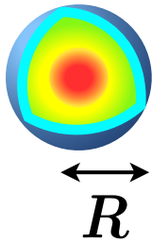
TH 2008, E. Flanagan & **TH**, 2008

=0 for a black hole

[computed from Einstein's equations]

$$\lambda = \frac{2}{3} k_2 R^5$$

dimensionless Love number



Straightforward extension to higher multipoles Damour, Nagar 2009, Binnington, Poisson 2009

Computation of the tidal deformability for NSs

- equilibrium NS structure + ODE for y (~ deformed NS's gravitational potential):

$$0 = \frac{dy}{dr} + y^2 + A(r)y + B(r)$$

involve mass, pressure, density

- boundary condition: $y(r=0)=2$

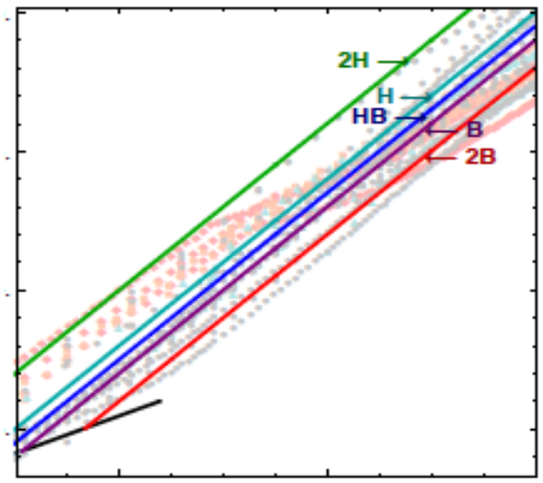
- evaluate $Y=y(R)$

- substitute into $\lambda = \frac{2}{3} k_2(Y, C) R^5$ $\qquad C = \frac{m_{\rm NS}}{R}$

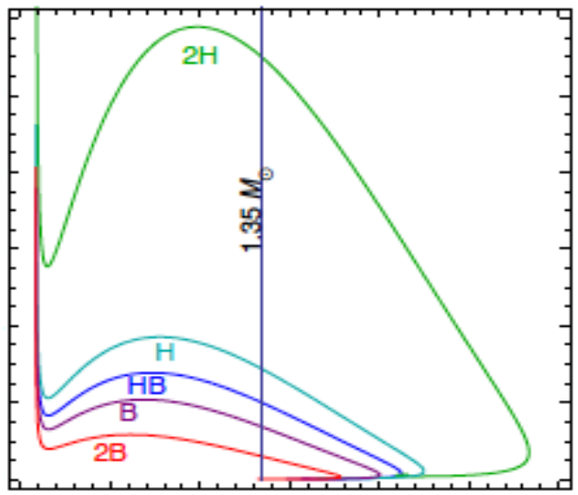
explicit algebraic expression

- Dimensionless deformability: $\Lambda = \frac{\lambda}{m_{\rm NS}^5}$

log (pressure - density)



λ vs. mass

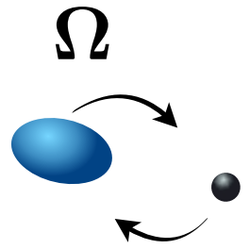


Credit: B. Lackey

Influence on the GWs

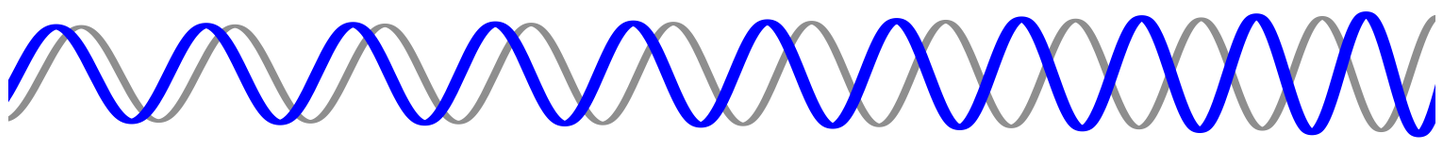
- Energy goes into deforming the NS
- moving tidal bulges contribute to gravitational radiation
- Imprint in GW phasing:

$$\Delta\phi^{\rm tidal}_{\rm GW} \sim \lambda \frac{(M\Omega)^{10/3}}{M^5}$$



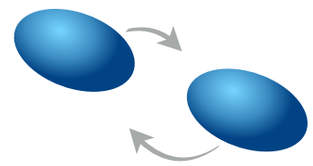
$$Q_{\rm NS} = \lambda\, \mathcal{E}_{\rm tidal}$$

$$M = m_1 + m_2$$



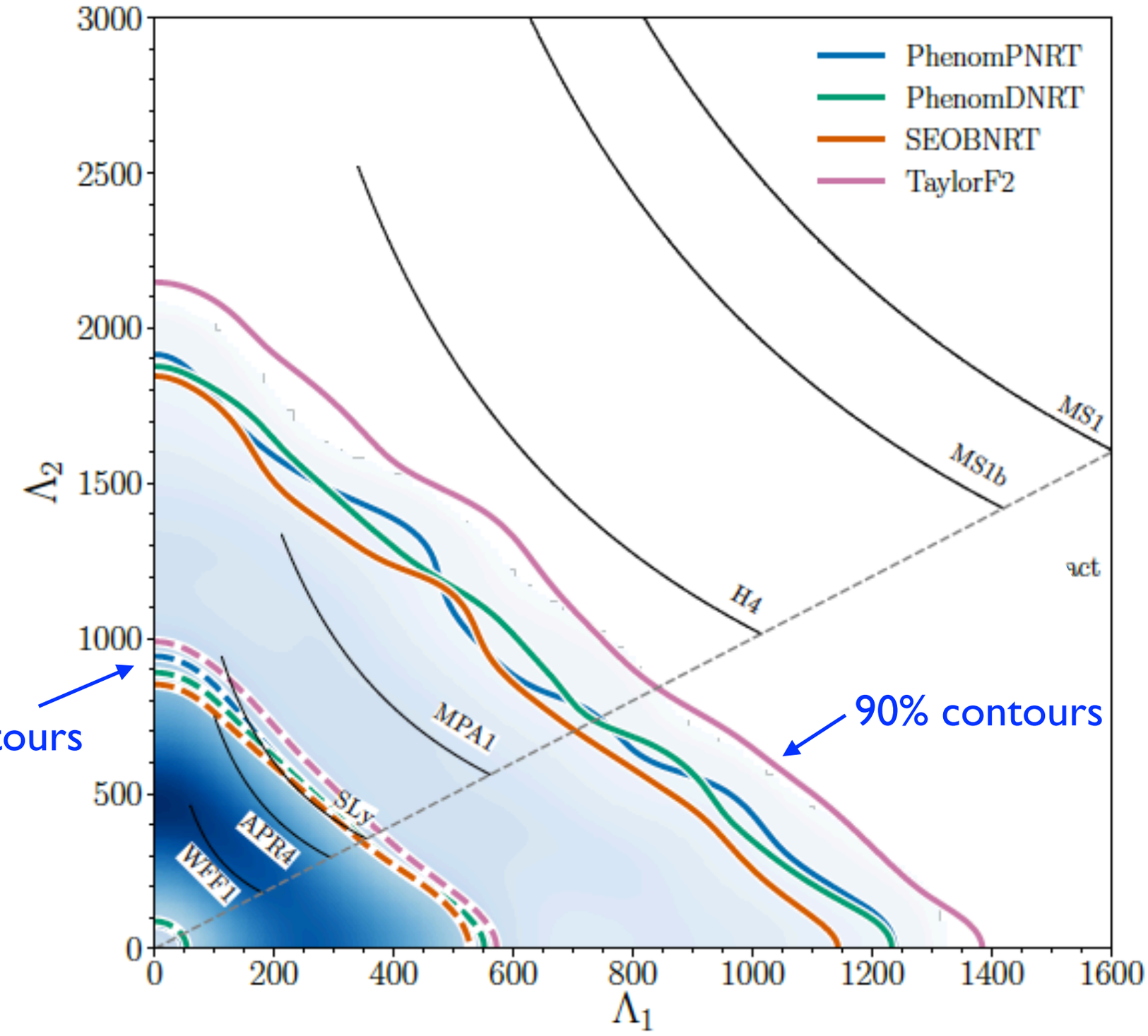
- for NS-NS: most sensitive to the weighted average:

$$\tilde{\Lambda} = \frac{1}{26}\left[\left(1 + 12\frac{m_2}{m_1}\right)\lambda_1 + \left(1 + 12\frac{m_1}{m_2}\right)\lambda_2\right]$$



[Flanagan & TH, 2008,
Vines, Flanagan & TH 2011]

Measurement of the tidal deformability GW170817



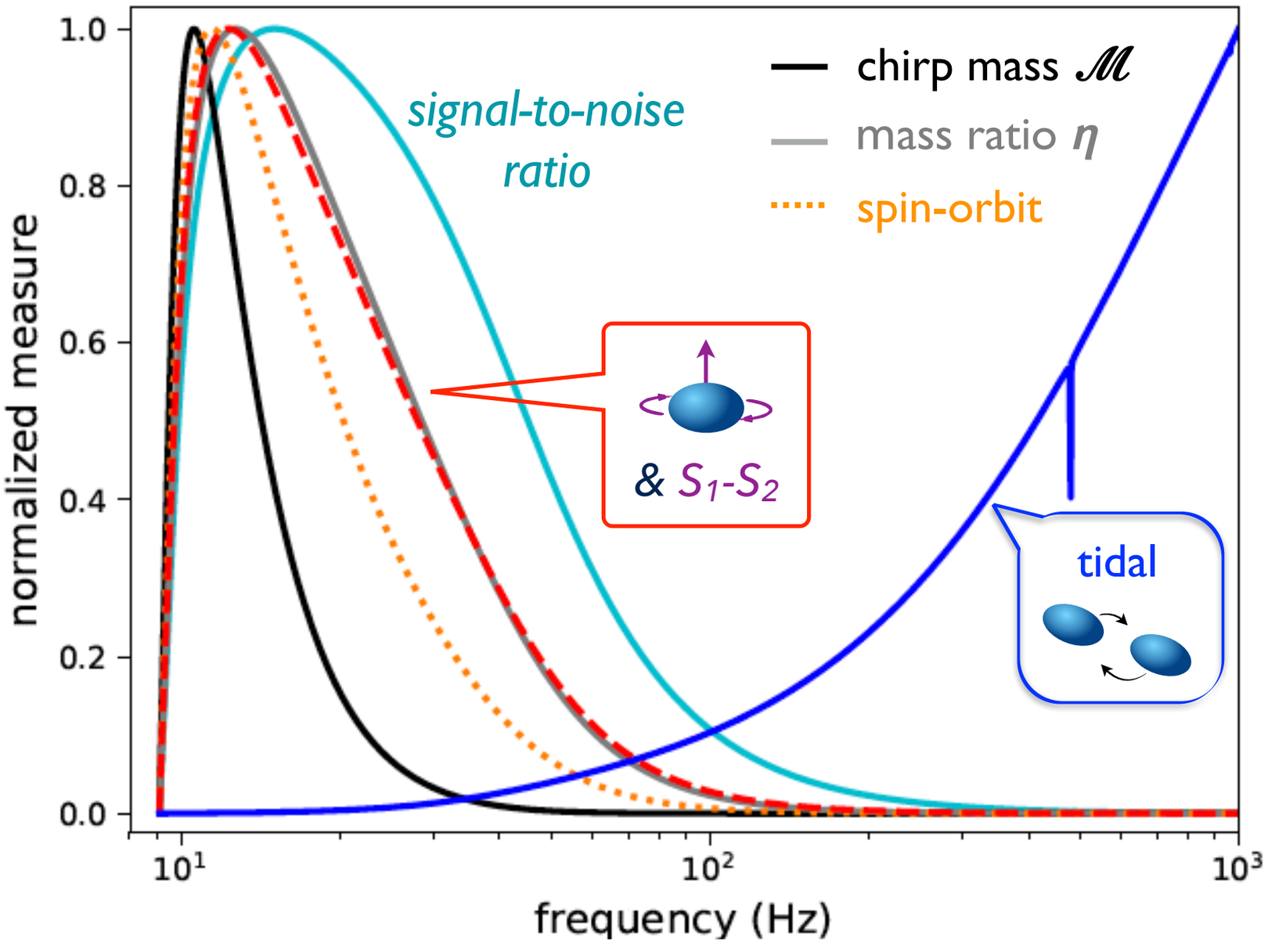
50% contours

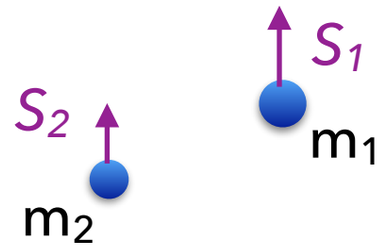
90% contours

LVC 2018

Accumulation of information about source properties

Where in frequency does information about different source parameters come from (for LIGO)?



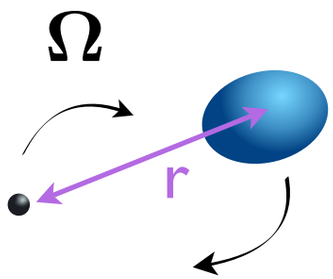


$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

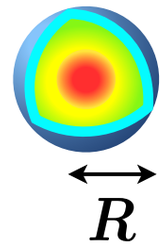
$$\eta = \frac{m_1 m_2}{(m_1 + m_2)^2}$$

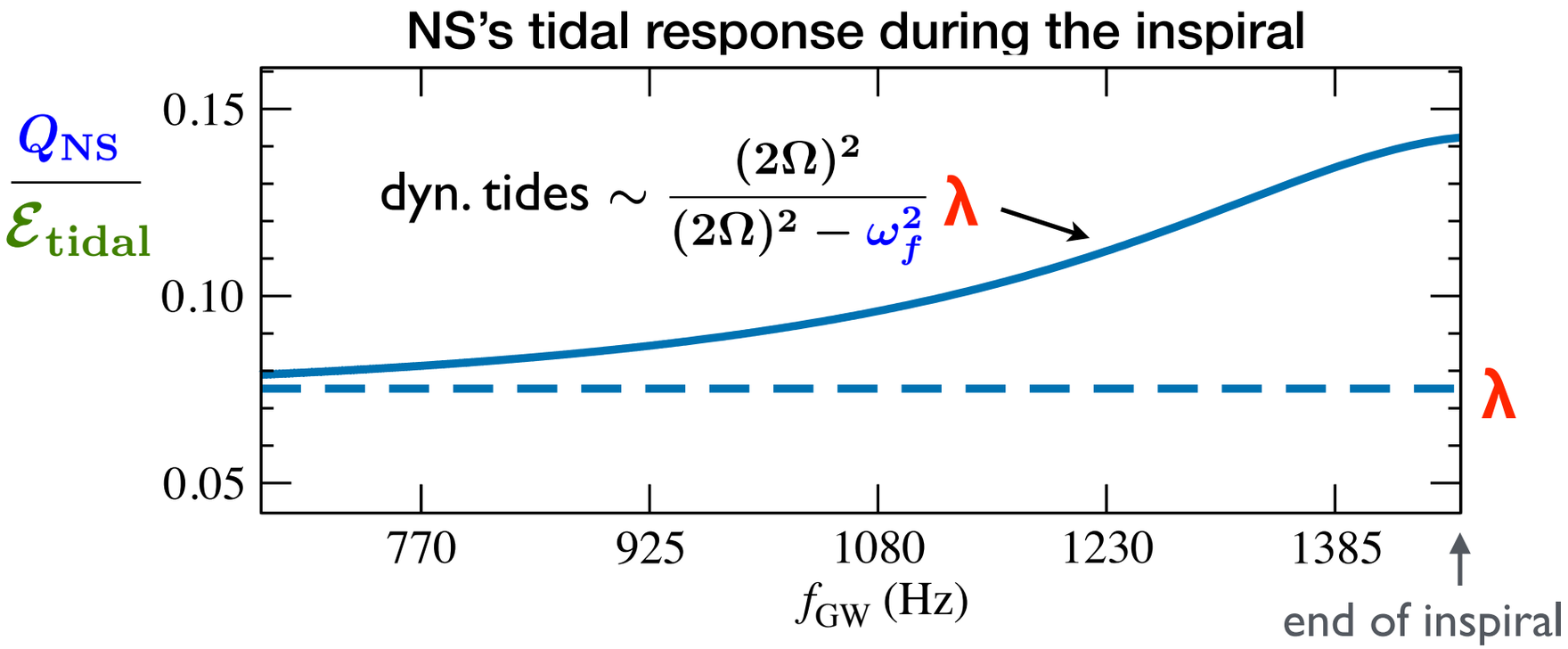
I. Harry & **TH** arXiv:1801.09972

Dynamical f-mode tides



- Q_{NS} corresponds (mainly) to the NS's fundamental oscillation modes
- f-mode frequency: $\omega_f \sim \sqrt{m_{\rm NS}/R^3}$ (internal structure - dependent)
- **tidal forcing** frequency: $\sim 2\Omega \sim 2\sqrt{M/r^3}$





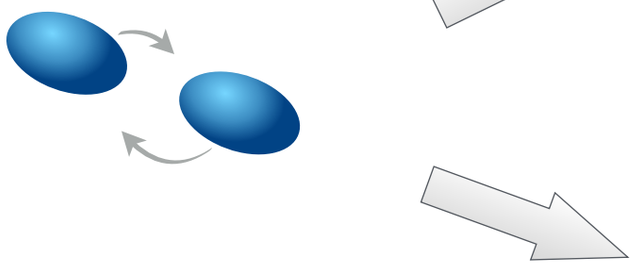
[**TH**+, PRL 2016, Steinhoff, **TH** + 2016]

Enhancement of tidal effects also seen in affine approach [Ferrari+2011,12]

& in numerical-relativity-based models [Dietrich+2017, Kawaguchi+2018]

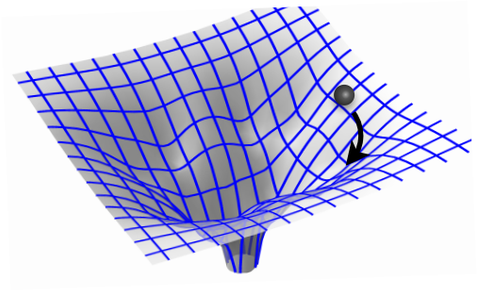
Including tidal effects in waveform models

- Need baseline point-mass models that include relativistic effects
- Effective one body model (EOB):



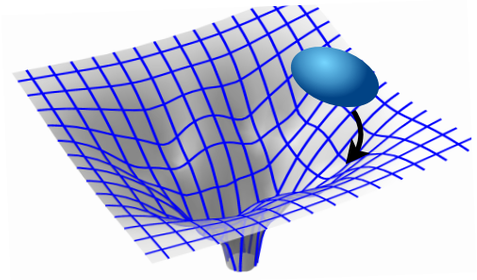
MAP

- Adiabatic tides



[Damour, Nagar, Bini, Faye, Bernuzzi+2009-2014]

- Dynamical f-mode tides

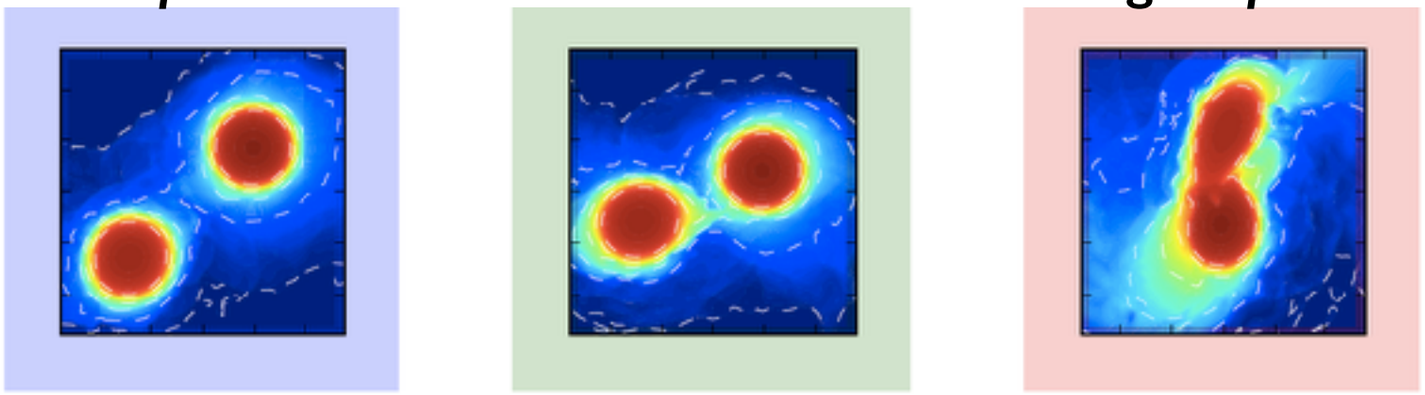


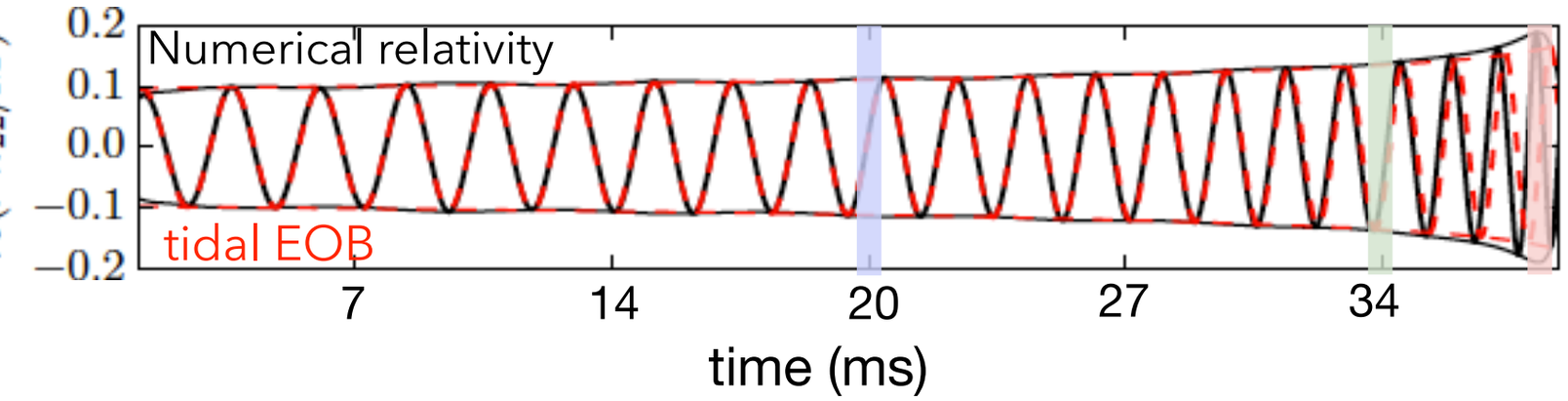
[TH+2016, Steinhoff+2017]

- Phenomenological models:
  - post-Newtonian tides *[Vines+2011, Damour+2012]*
  - fits to numerical-relativity results *[Dietrich+2017, Kawaguchi+2017]*

NS-NS binary inspiral

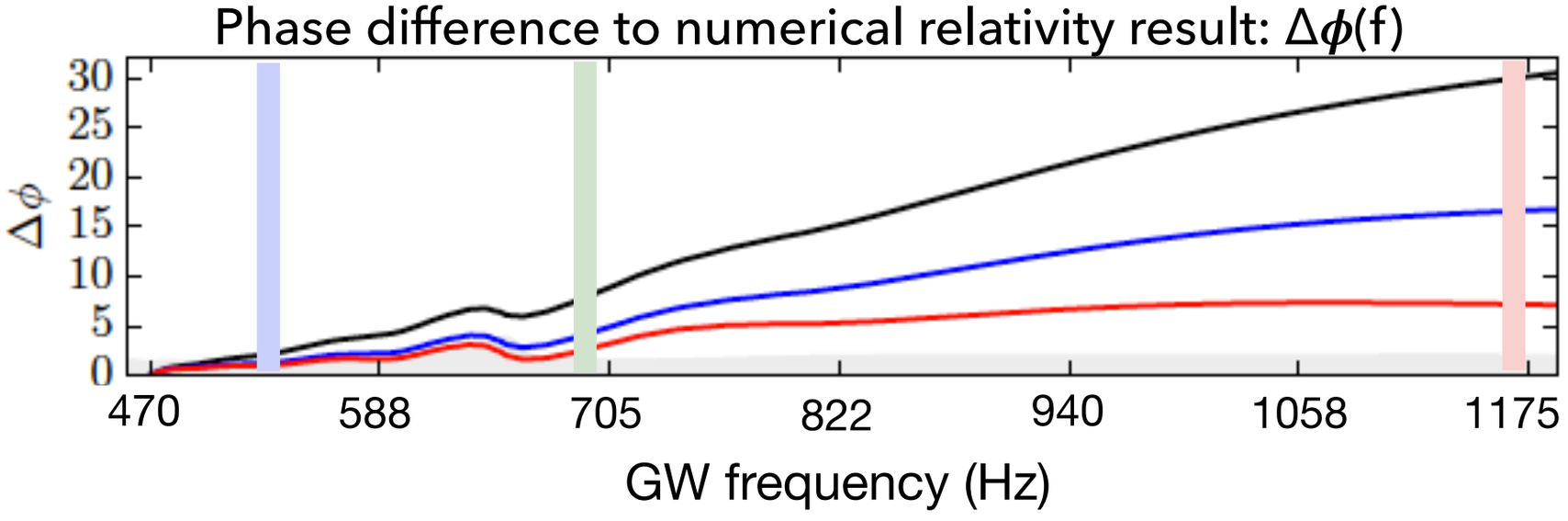
inspiral ***~ contact*** ***merger=peak in GW amplitude***





Numerical relativity simulations by T. Dietrich

Similar results for simulations by K. Hotokezaka and F. Foucart

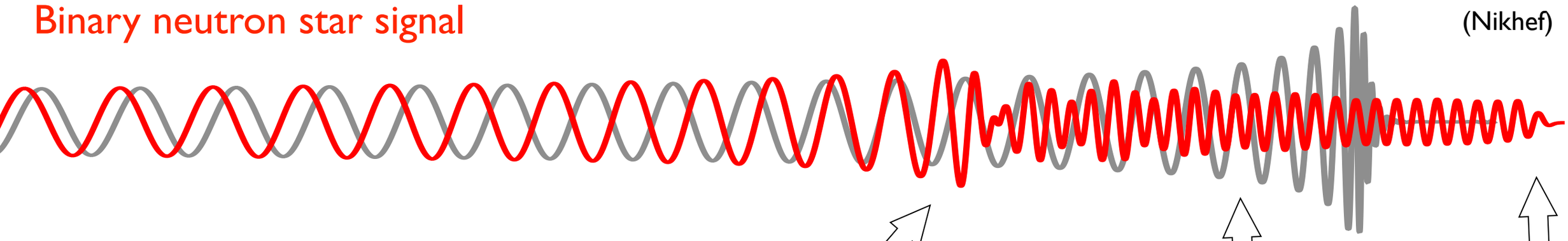


[Dietrich & TH, 2017]

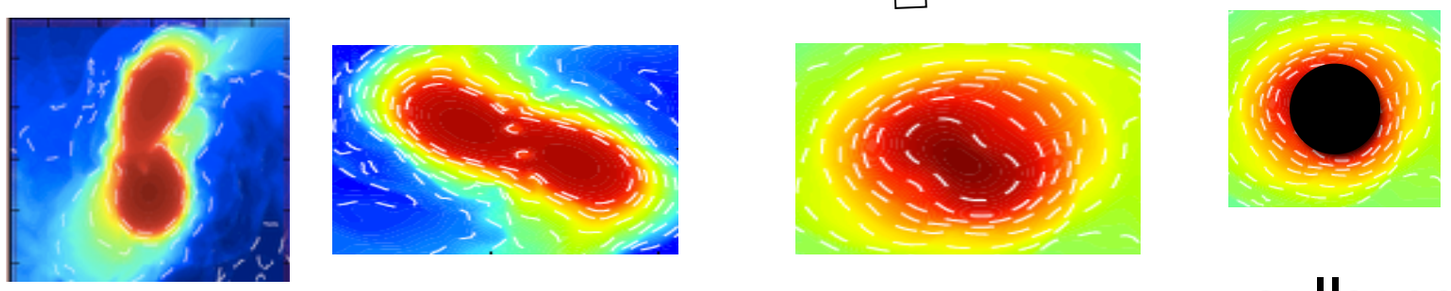
What happened post-inspiral?

Binary neutron star signal

NR data: T. Dietrich (Nikhef)



Plausible scenario:



merger

postmerger

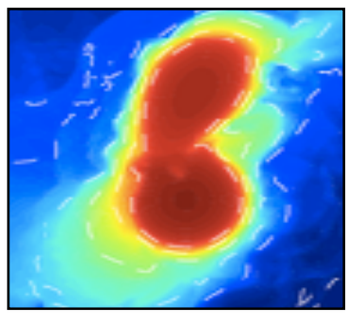
collapse to BH

Couldn't tell anything about their fate from GWs ……

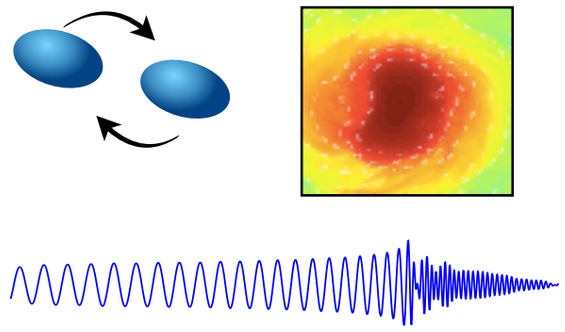
…. but spectacular electromagnetic counterparts at all wavelengths

Remaining challenges

late inspiral



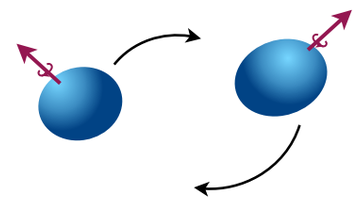
complete model



- test, refine models
- robust parameter space coverage
- more realistic physics
- accurate numerical-relativity simulations are key

spins: new phenomena, possible enhancement of small effects

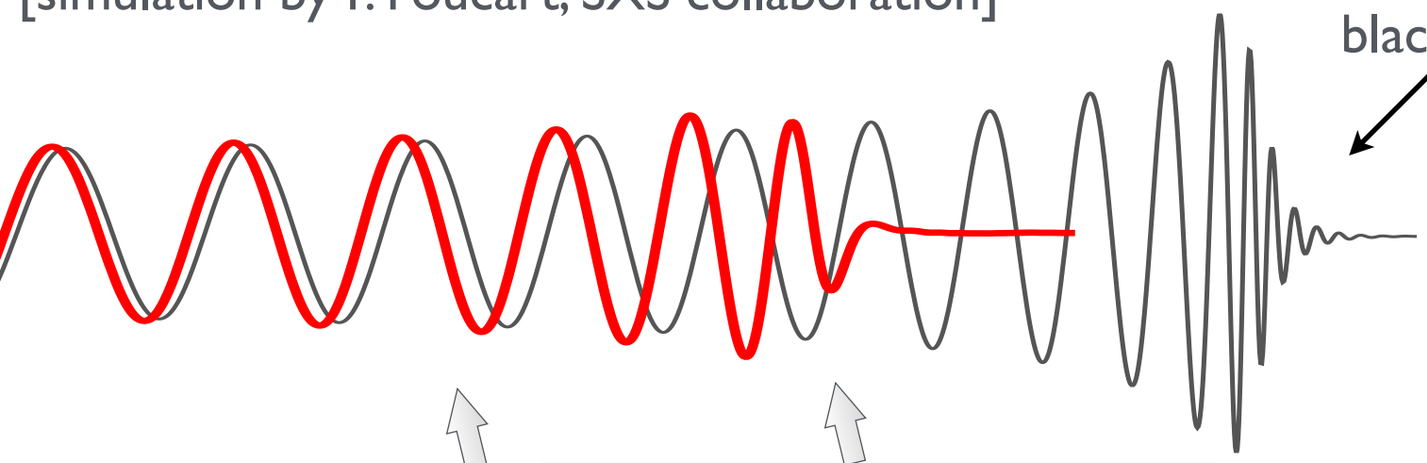
Prospects for probing more details of NS interiors

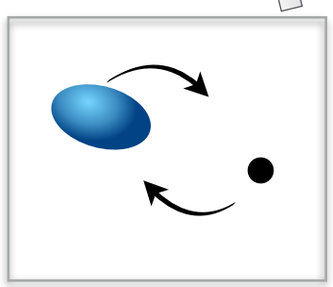


- shifts of NS mode resonances (f-,g-,r-modes most interesting for inspirals) [Ho & Lai 2000]
- new tidal interactions and parameters [Pani+ 2016, Landry 2017]
- gravitomagnetic effects [Poisson, Landry, Vines]

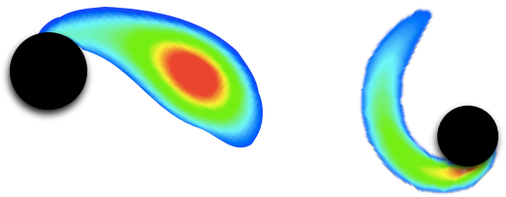
Anticipated next discovery: neutron star + black hole

[simulation by F. Foucart, SXS collaboration]





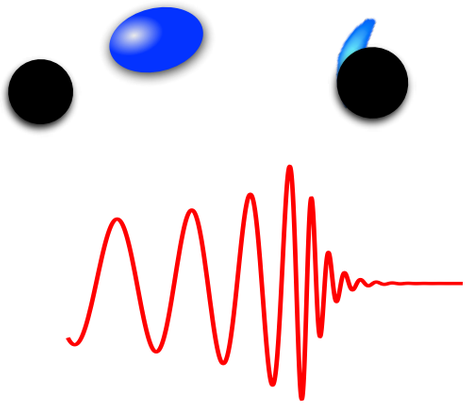
tidal disruption



GW 'shutoff' can be in LIGO band

EM counterpart

- for large mass ratios, low spin, soft EoS:

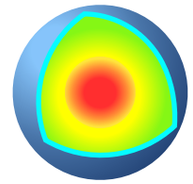


- Challenges for NS-BH models:
  - mass ratios 1-20+
  - high BH spin, NS spin
  - Spin precession [Kawaguchi+2017]
  - NS matter

Summary & outlook

- Abundant scientific opportunities with GWs,

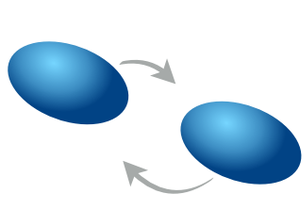
  tremendously more with complementary multimessenger information

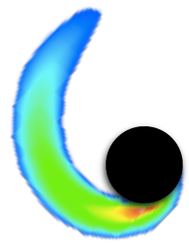


- Accurate models essential to realize full GW science potential & gain deeper understanding

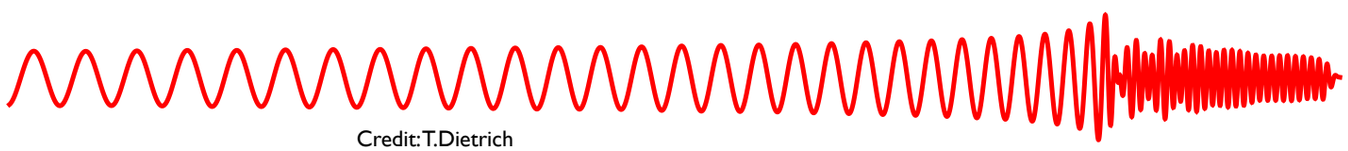
- Much recent progress but further advances needed

  - GW source modeling
  - Link to EM counterparts
  - Combined data analysis strategy & tools
  - Connection with developments in nuclear physics / pulsars





- Expect a wealth of new insights in the coming years



Credit: T. Dietrich