Effects of neutron star dynamic tides on gravitational waveforms within the Effective One-Body approach

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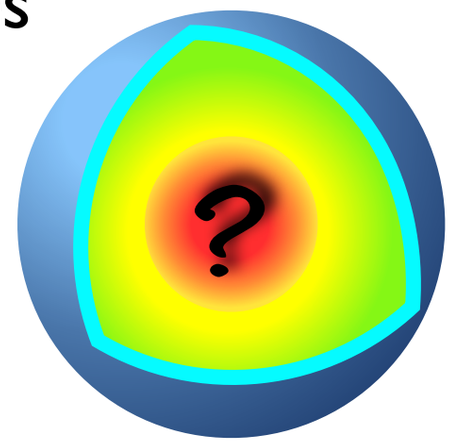
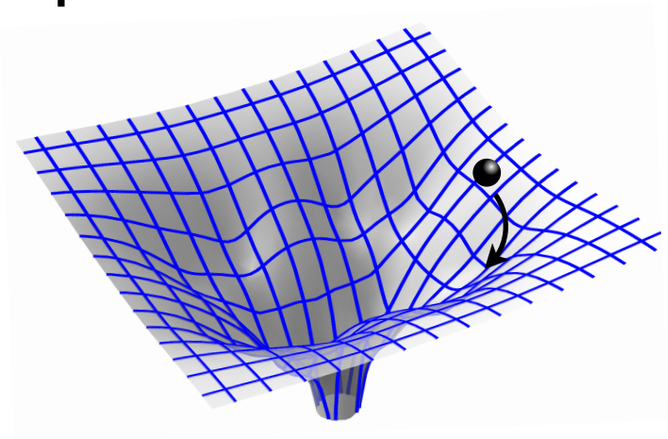
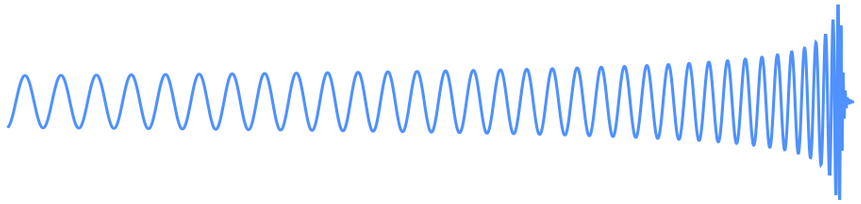
Overview

- Motivation: potential to determine properties of ultra-dense matter using gravitational waves from NS-NS and NS-BH binaries
  - multimessenger studies (sGRBs, afterglows, neutrinos)
  - sources of r-process elements



- Requires robust models
- Recent improvements: dynamical tides during inspiral
- Tidal Effective One-Body model
- Conclusions





Neutron stars (NSs)

- strongest gravitational environment where matter can stably exist
- other extremes of physics:

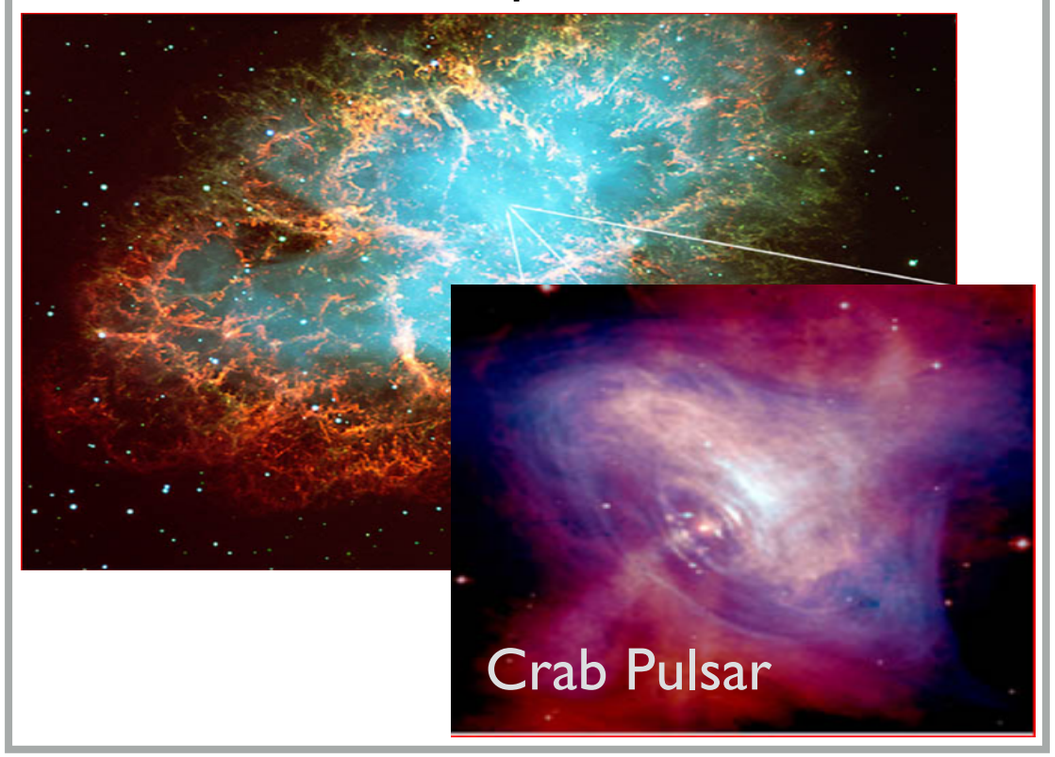
  spins up to 38000 rpm, huge magnetic fields,

  superfluidity, superconductivity, solid crust, …

- 1939: theoretical prediction *[Oppenheimer & Volkoff]*
- 1968: discovery of pulsars *[Hewish, Bell,+]*
- 1969: pulsars = neutron stars *[Gold]*

- > 2000 observed to date (~1/1000 stars)
- masses ≳ Msun, radii ~ 10km
- matter compressed to several times nuclear density

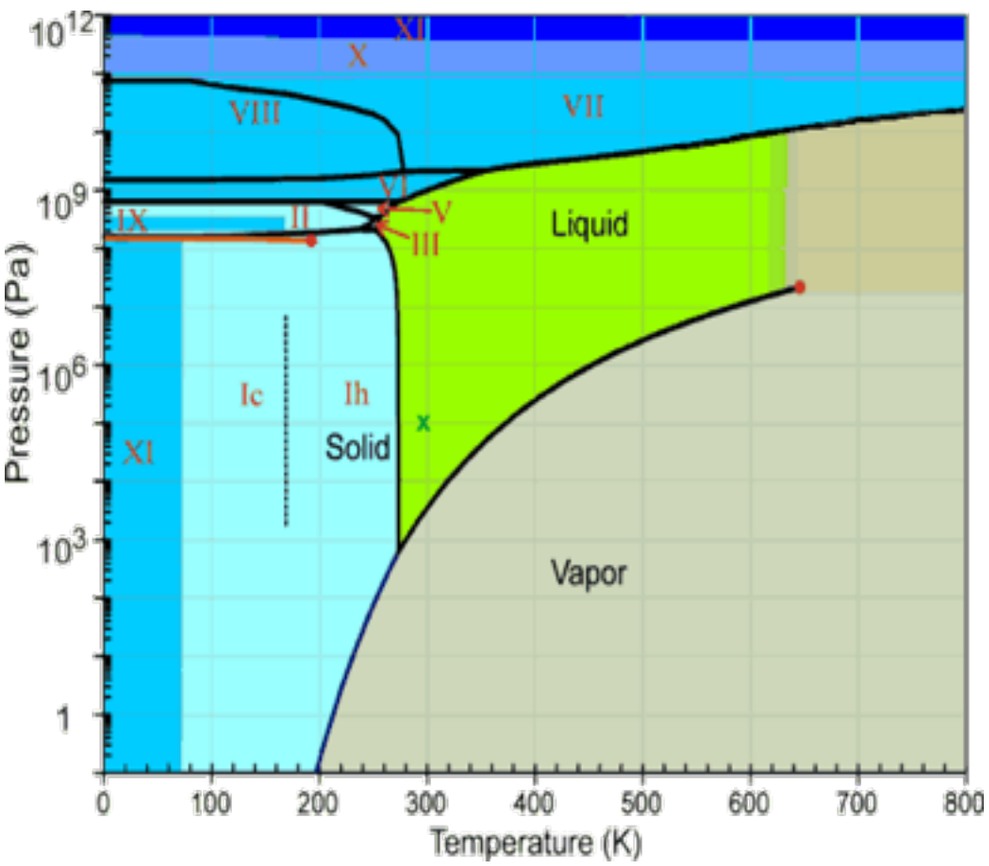
Debris from a supernova in 1054



What is the nature of matter in such extreme conditions?

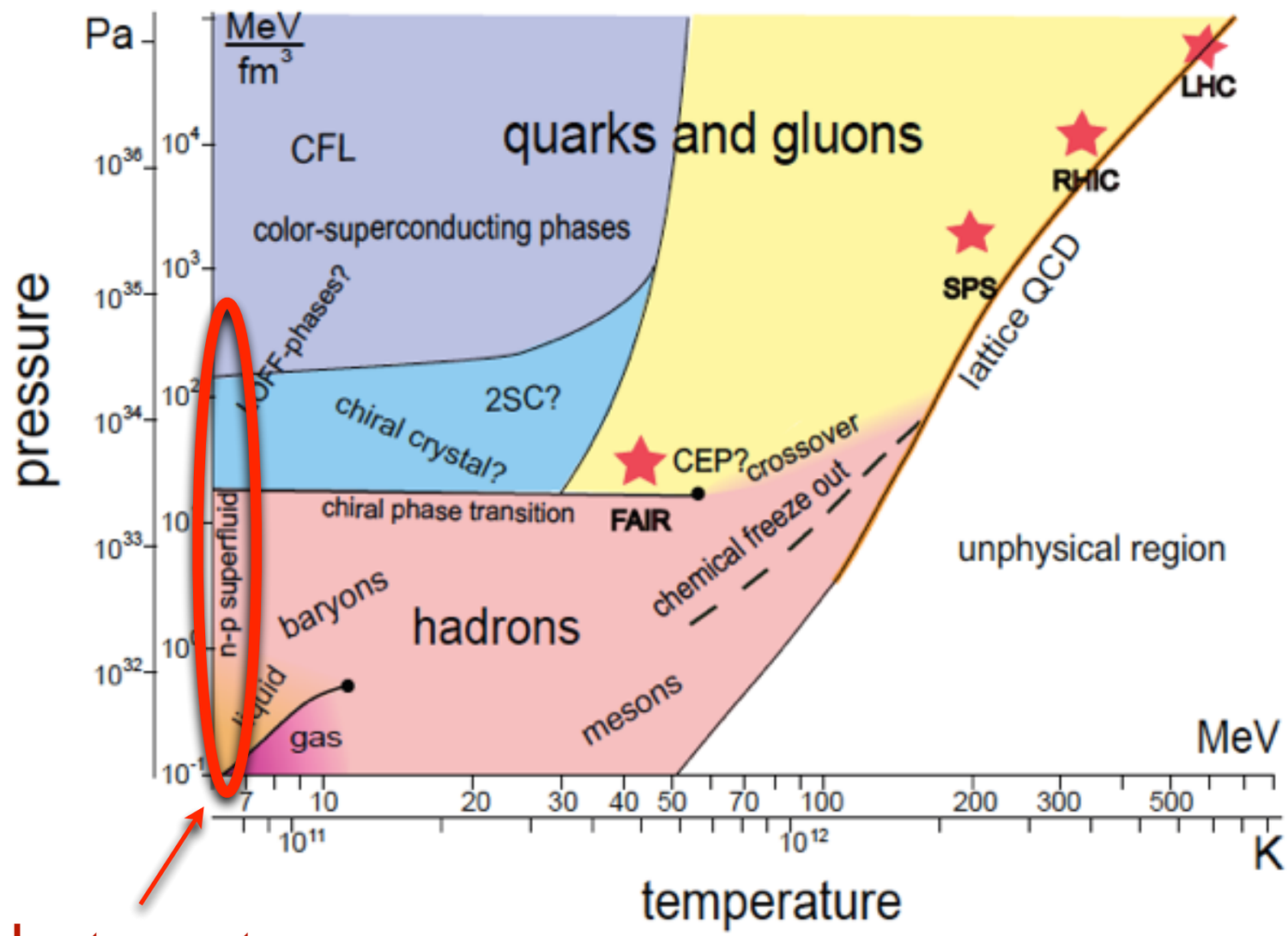
Phases of the strong force

H_2O



[credit: Garrido]

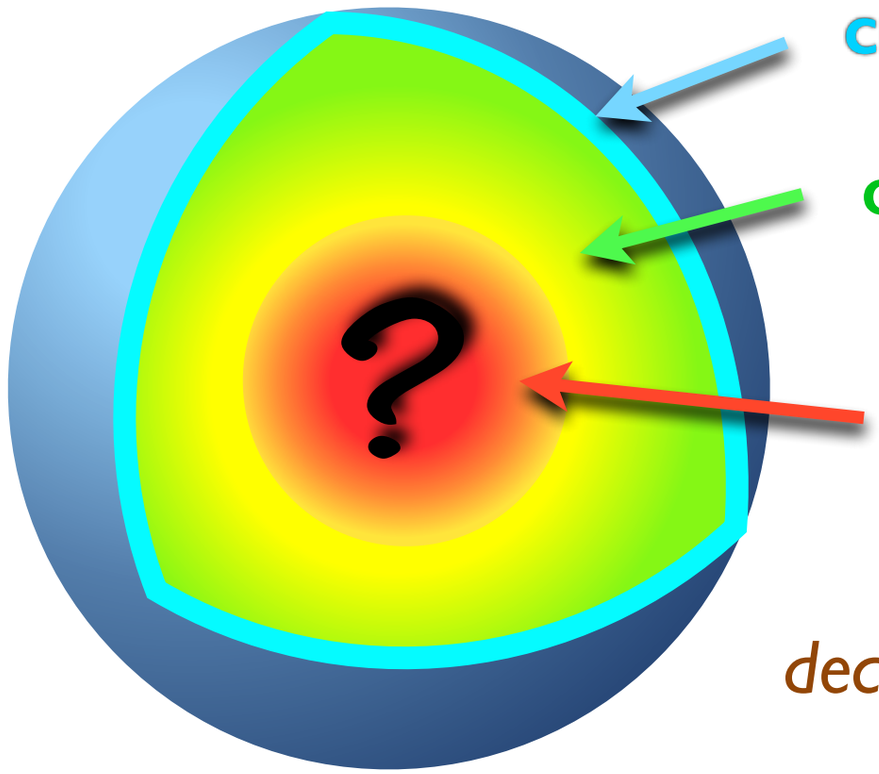
QCD (conjectured)



Neutron stars (NSs)

[Wambach+2011]

NS structure



crust: ~ *km*

outer core: ~ *few km*

uniform liquid?

deep core: $\gtrsim 2 \times \rho_{\text{nuclear}}$

exotic states of matter?

deconfined quarks? condensates?

- Theoretical difficulties:
  - many-body problem with strong interactions
  - unknown composition and equation of state (EoS)
- Experiments: properties of neutron-rich nuclei, phases of the strong force

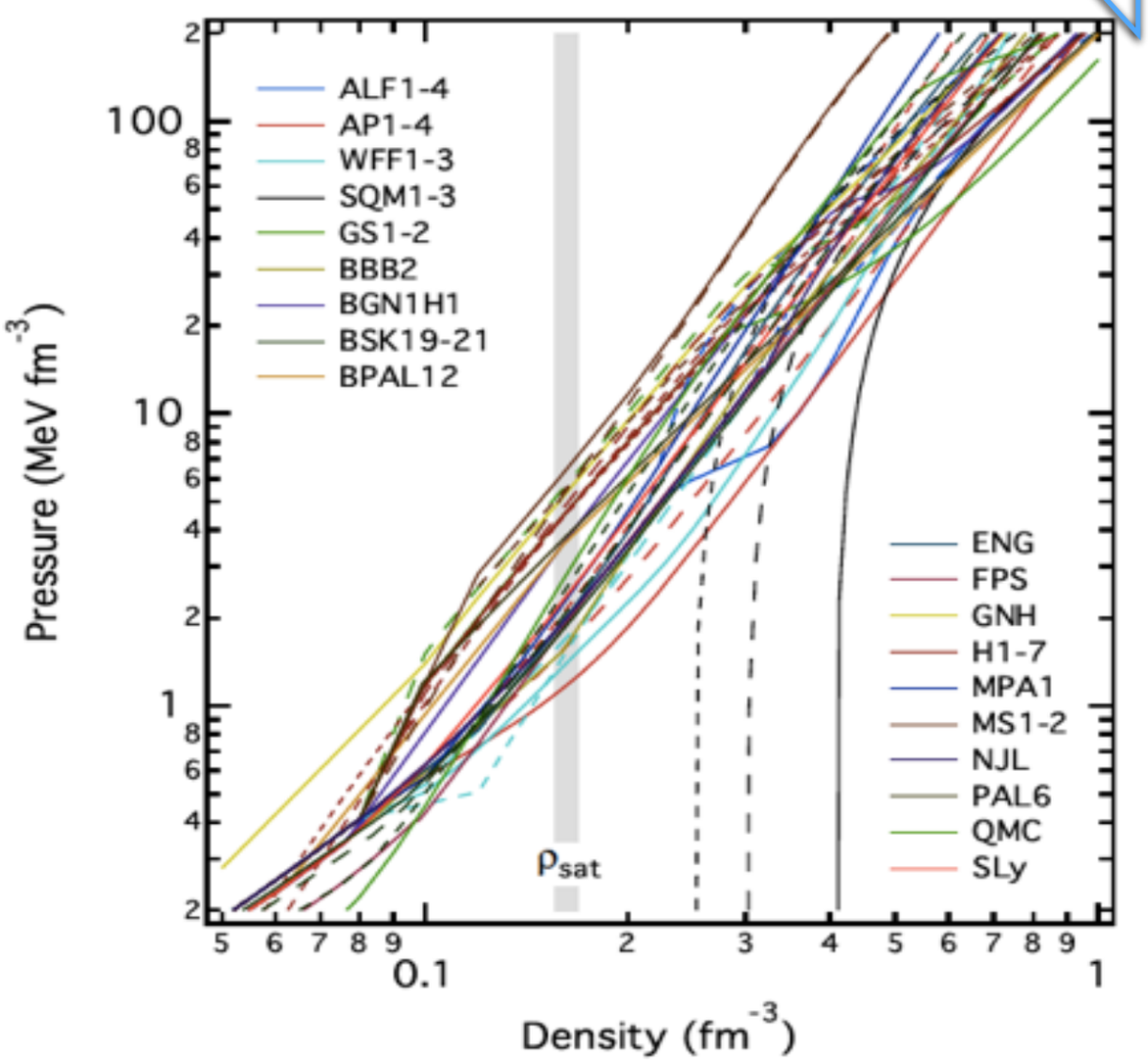
  impossible to reproduce conditions in NSs

NS global properties from microphysics

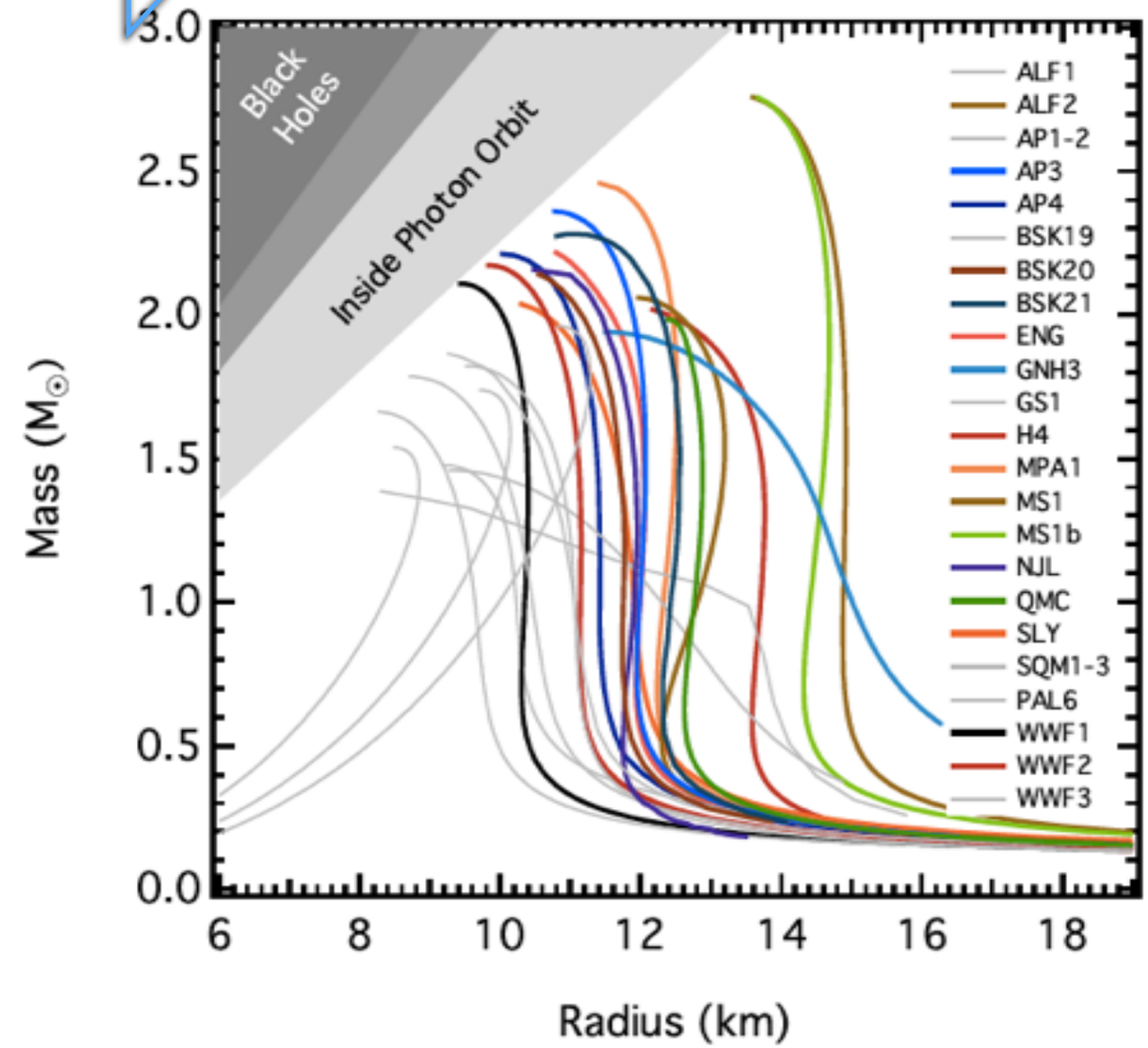
- composition, multi-body forces, etc., reflected in the EoS
- EoS determines observables (mass, radius, …)

Einstein's field equations

pressure vs. density



mass vs. radius



[Özel & Freire 2016]

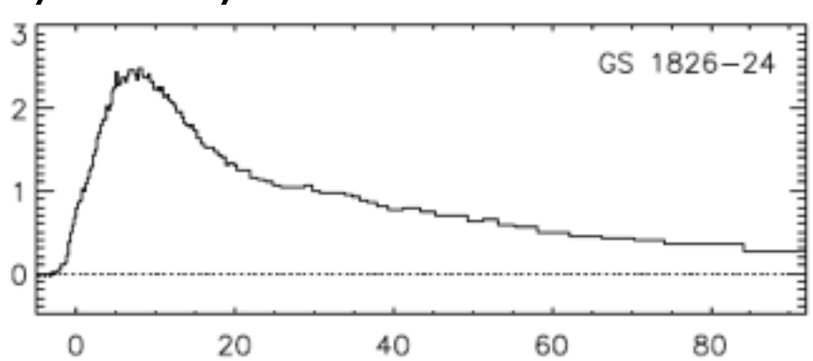
NS radius measurements

- Masses: to ~0.0001% from pulsar timing
- Radii: difficult to determine

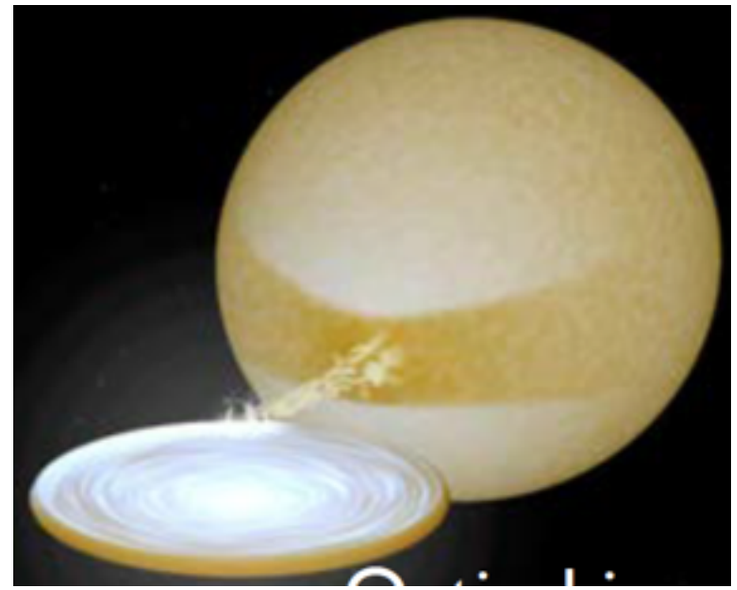
Thermonuclear X-ray bursts

[image B. Rutledge]

x-ray intensity vs. time relative to burst start



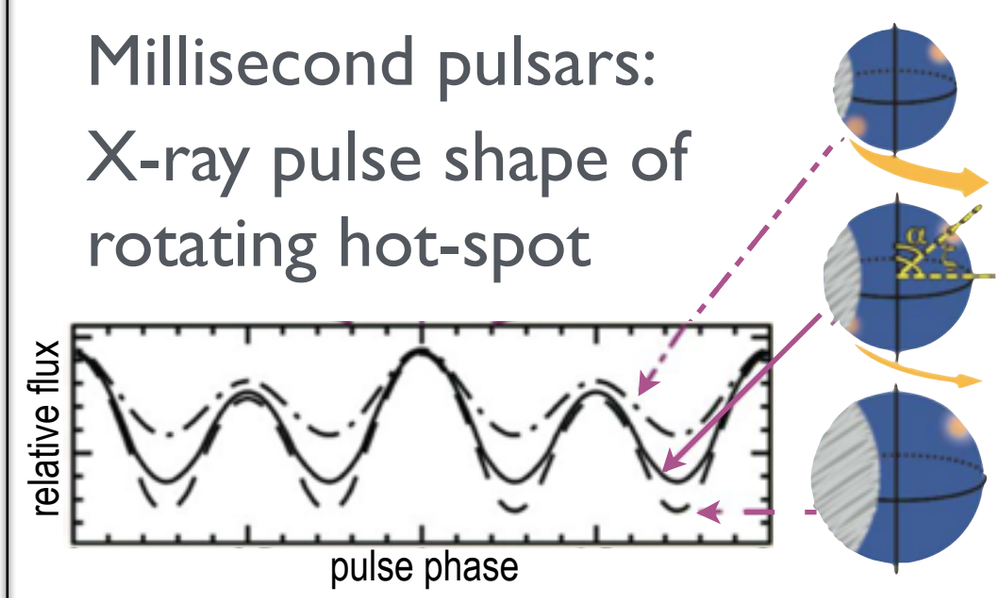
[Galloway+2006]



Quiescent low-mass X-ray binaries, isolated cooling NS

[image B. Rutledge]

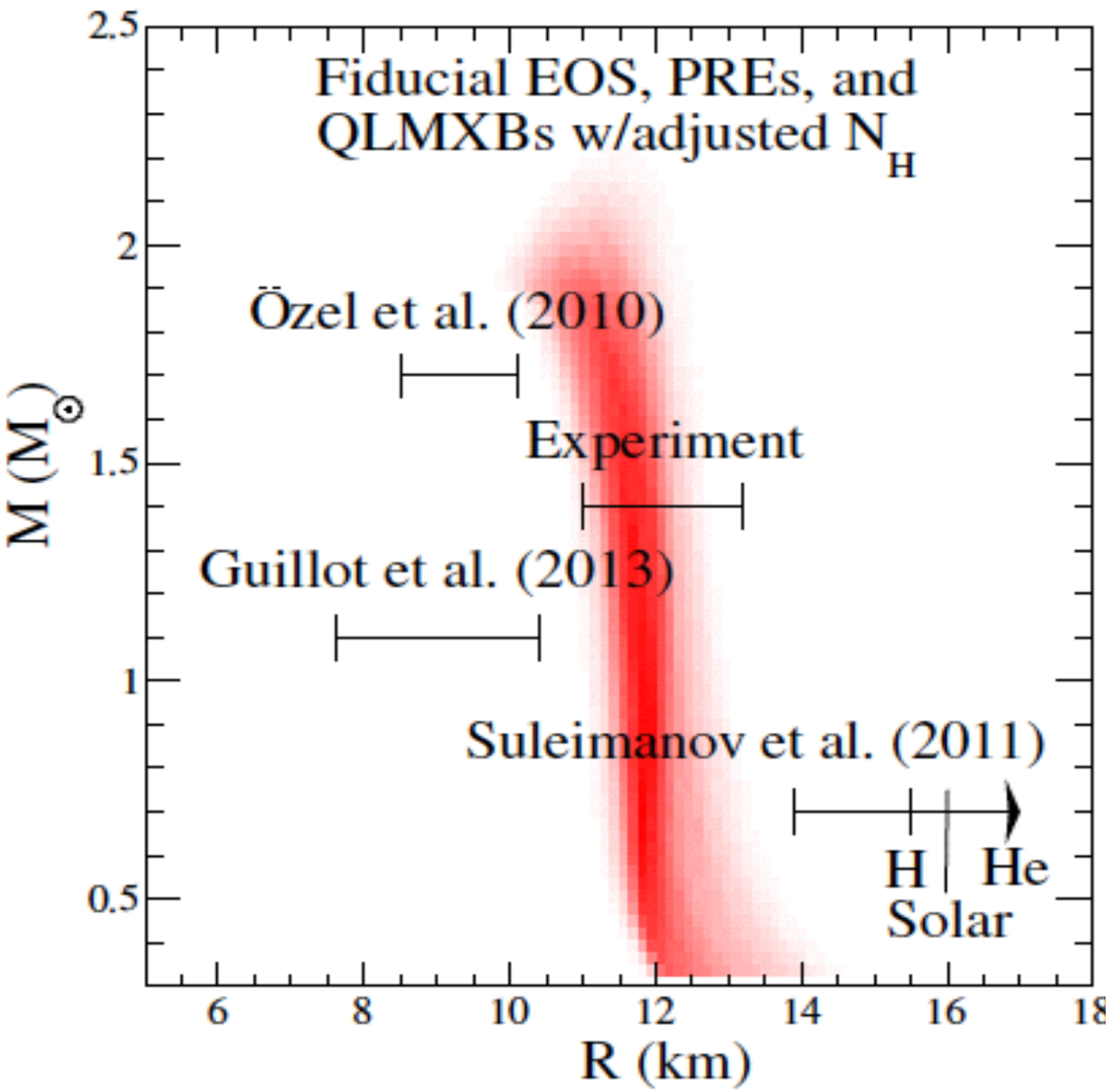
Millisecond pulsars: X-ray pulse shape of rotating hot-spot



[image: K. Gendreau]

Results for NS radii

Examples of results



[Lattimer & Steiner 2014]

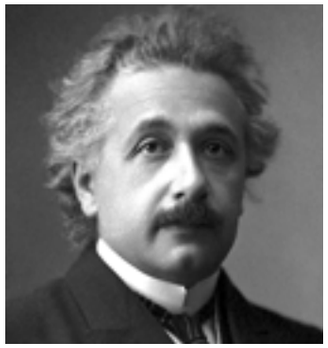
systematic uncertainties:

- distance
- atmosphere
- size of emitting region
- surface composition
- identification of spectral features
- magnetic field
- ….

potentially more robust EoS measurements with gravitational waves (GWs)

- asymmetric rotating NSs (crust physics)
- coalescing binaries

Gravitational waves (GWs) in brief



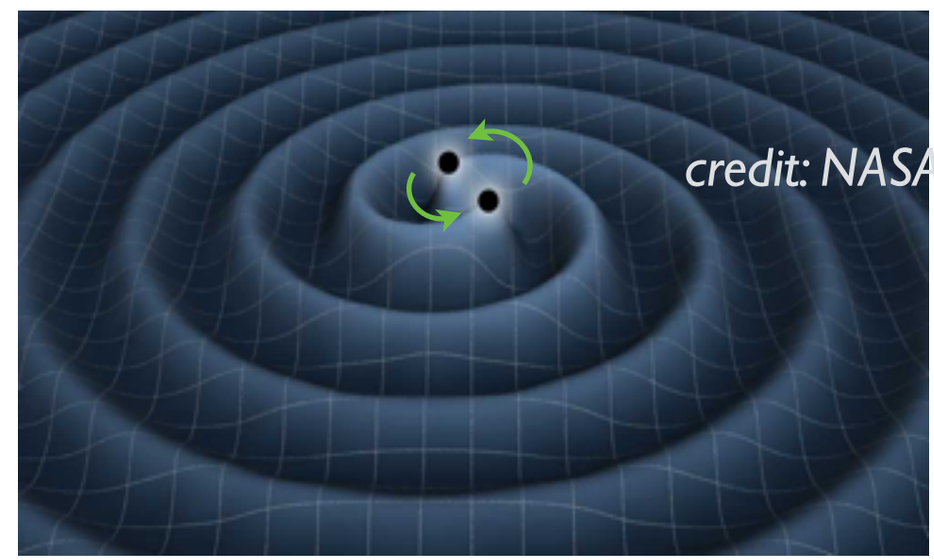
- Matter and energy curve space and warp time
- That curvature is responsible for gravity

- Accelerating masses generate ripples in curvature: GWs.
- Fractional deviation away from flat space:

$$h \sim \frac{G}{c^4}\frac{\ddot{\mathcal{I}}}{D} \sim \frac{G}{c^4}\frac{mv^2}{D} \sim 10^{-22}$$

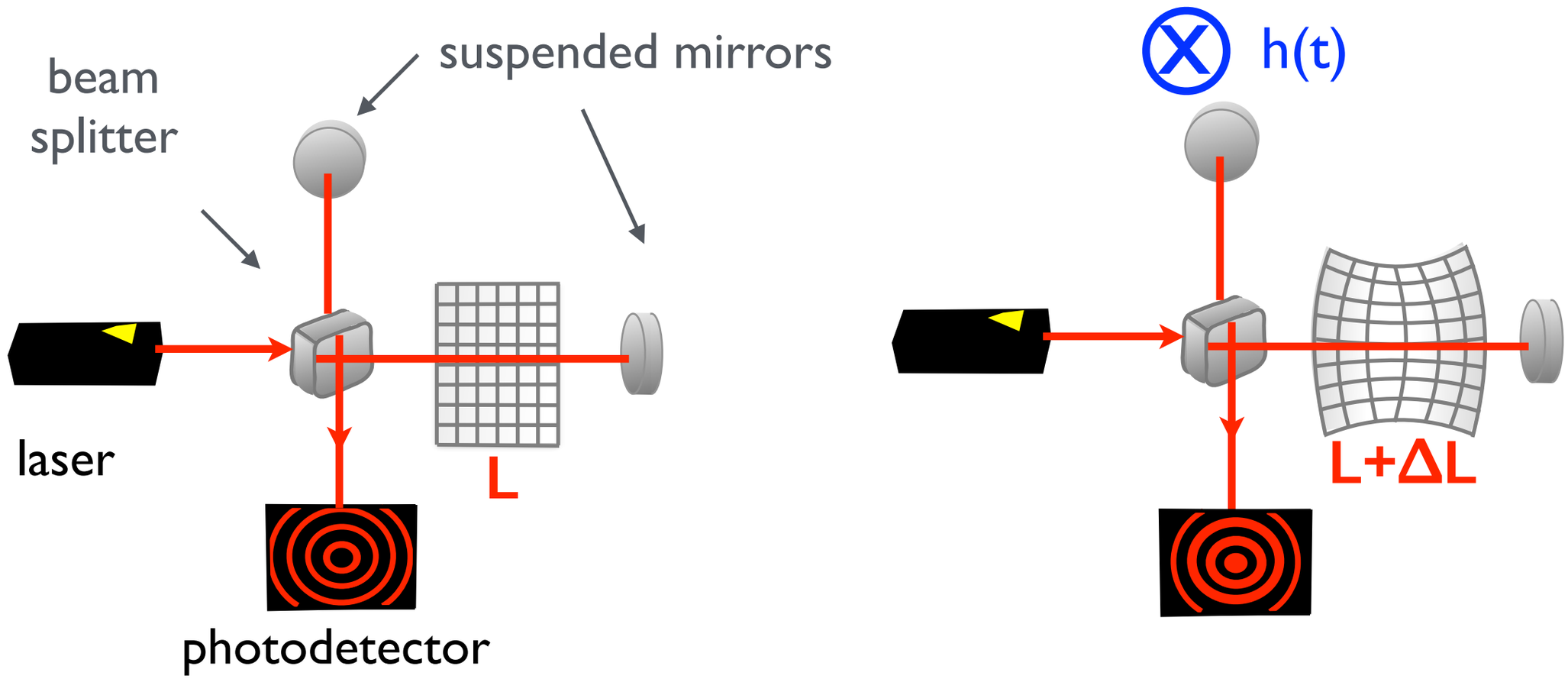
$$\approx 8 \times 10^{-45}\,\frac{\mathrm{s}^2}{\mathrm{kg\,m}}$$

distance to source



- Carry enormous power: $\approx 10^{51}$ Watts (c.f. sun radiates $\approx 10^{26}$ Watts)
- Interact very weakly with matter.
- Also produced by processes in the early universe, supernova explosions, asymmetric pulsars …

Measuring GWs with interferometers



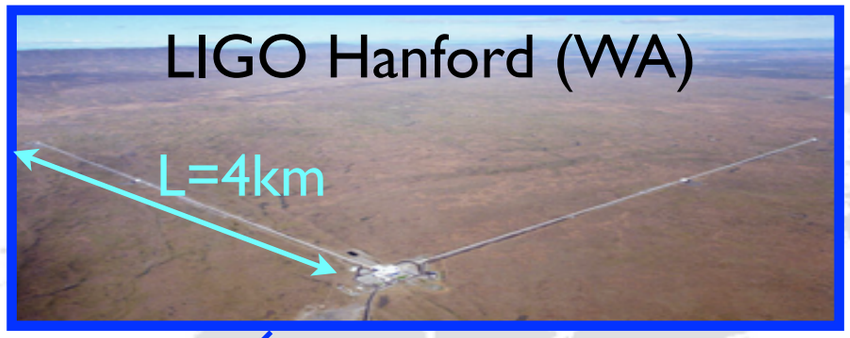
- change in intensity due to difference in phase:

$$\Delta\phi = 2\pi f \frac{2\Delta L}{c} = \frac{4\pi f}{c} h(t) L$$

laser frequency

extra roundtrip travel time in the arm

Worldwide network of GW detectors



GEO 600

Advanced LIGO

first observing run completed

~ 2019 design sensitivity

Advanced Virgo

major hardware upgrade almost completed

indigo

LIGO India

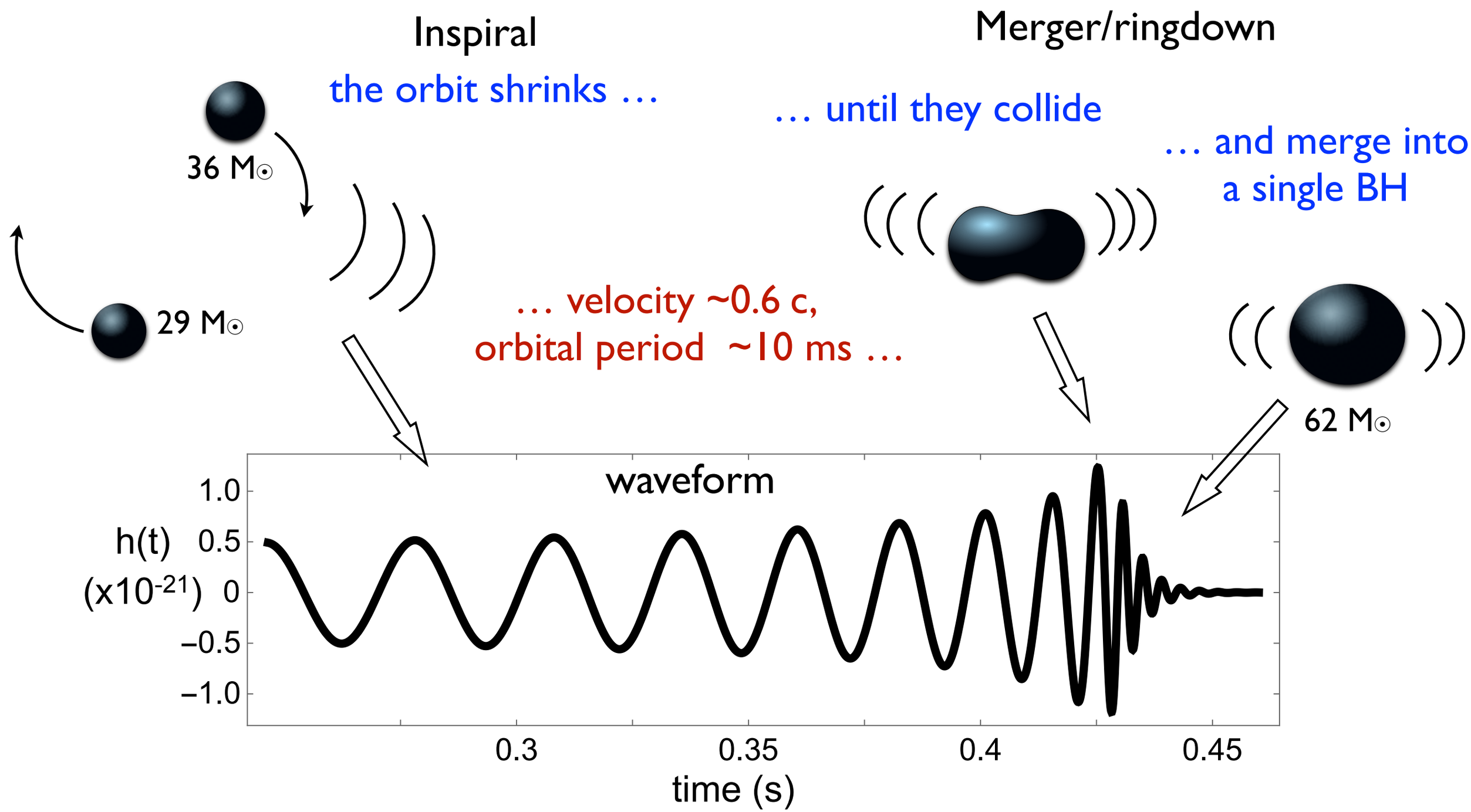
~2020 +

KAGRA

~2020 +

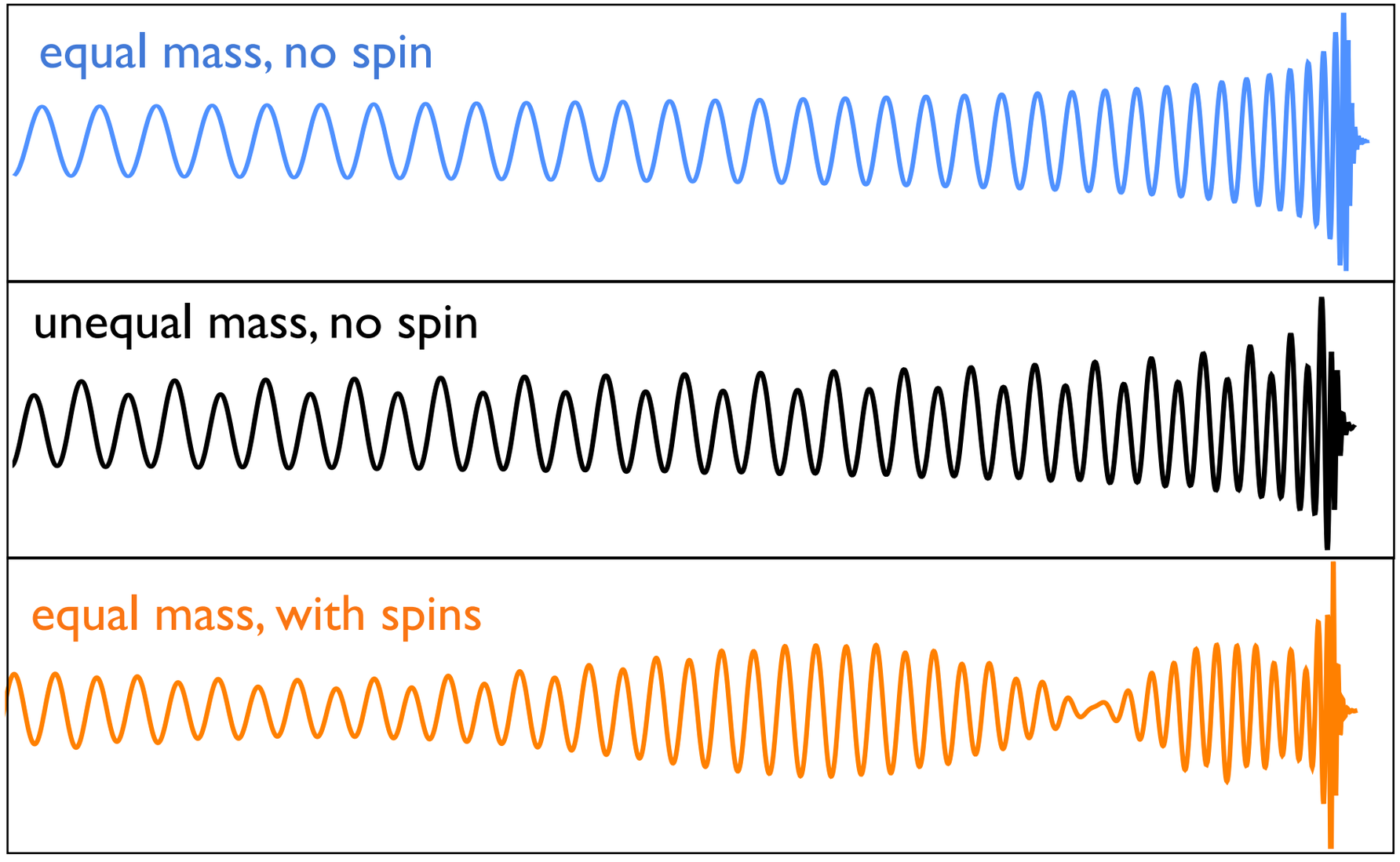
GW signal from black hole (BH) binaries

- BHs: regions of extreme spacetime curvature, characterized completely by only mass & spin



GW signal from BH binaries

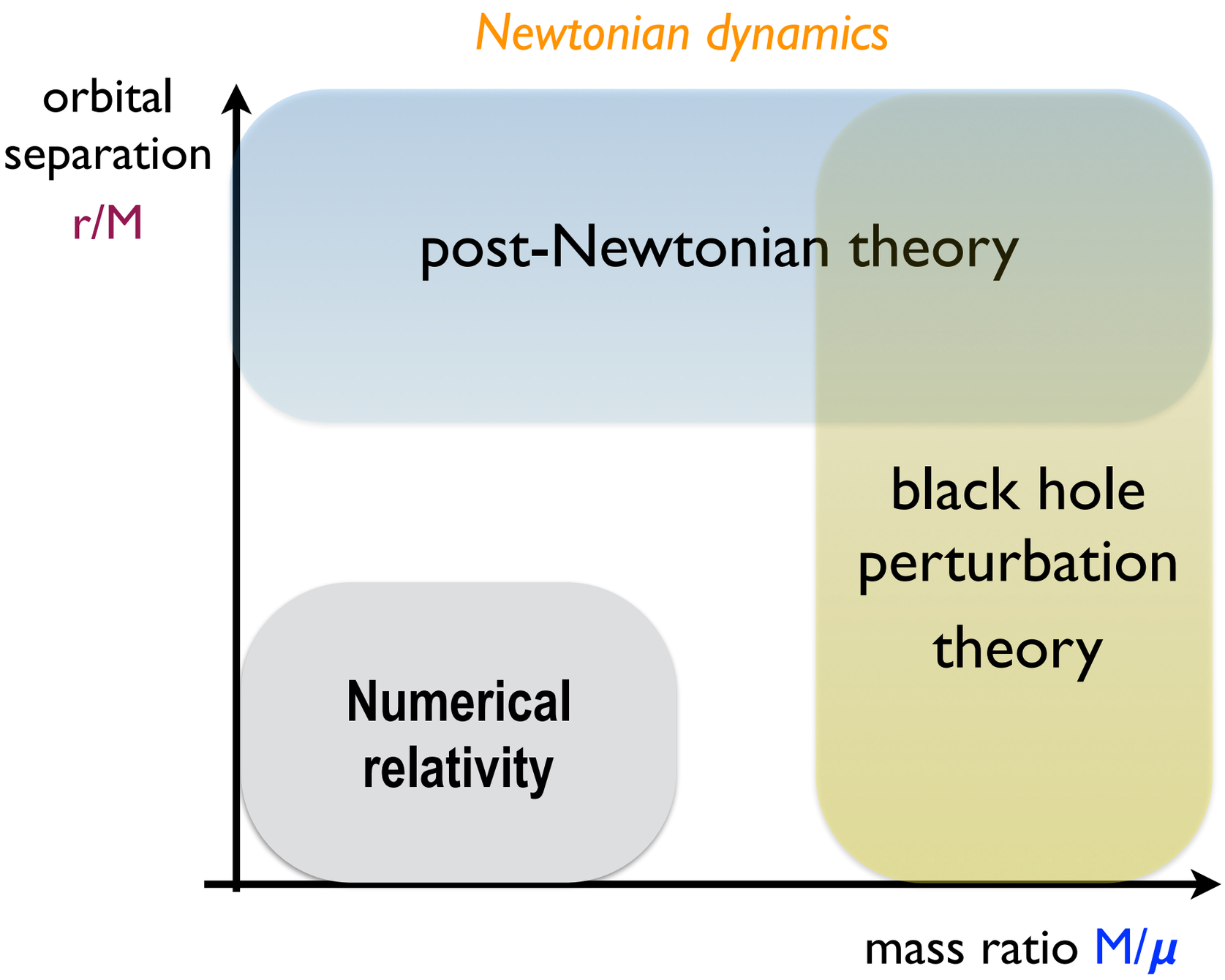
- details of the waveform depend on the parameters (masses, spins, …)

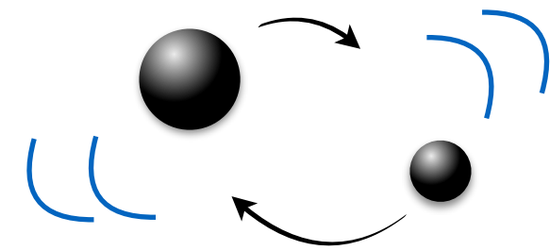


courtesy A. Taracchini

- extracting the information from the signal requires highly accurate models as templates for data analysis

Approaches to the two-body problem





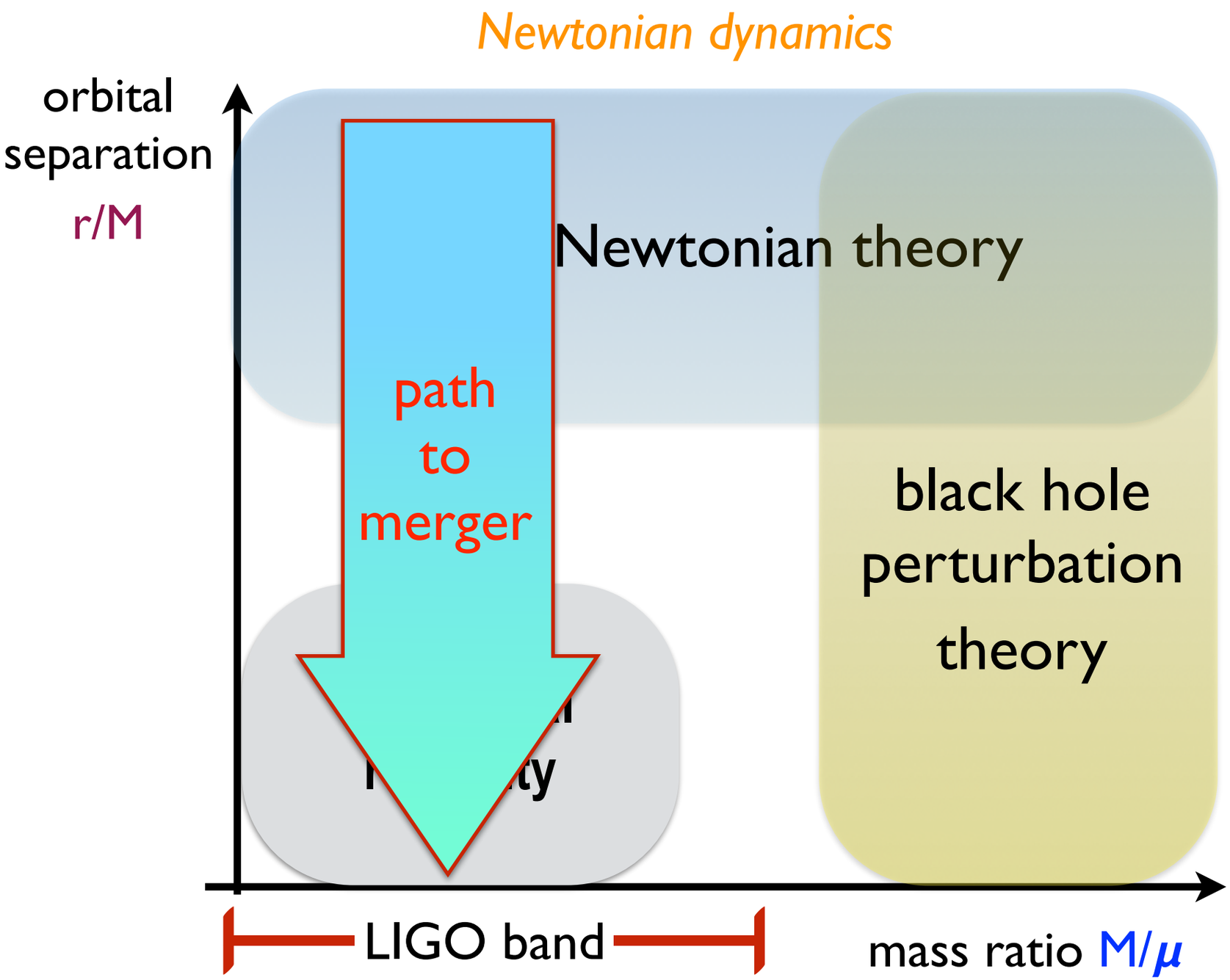
test particle limit

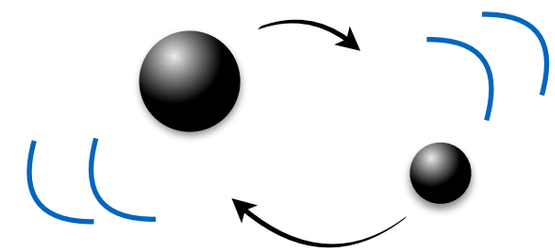
timescales:

$$T_{\rm orbit} \sim M \left(\frac{r}{M}\right)^{3/2}$$

$$T_{\rm inspiral} \sim M \left(\frac{M}{\mu}\right) \left(\frac{r}{M}\right)^{4}$$

Approaches to the two-body problem





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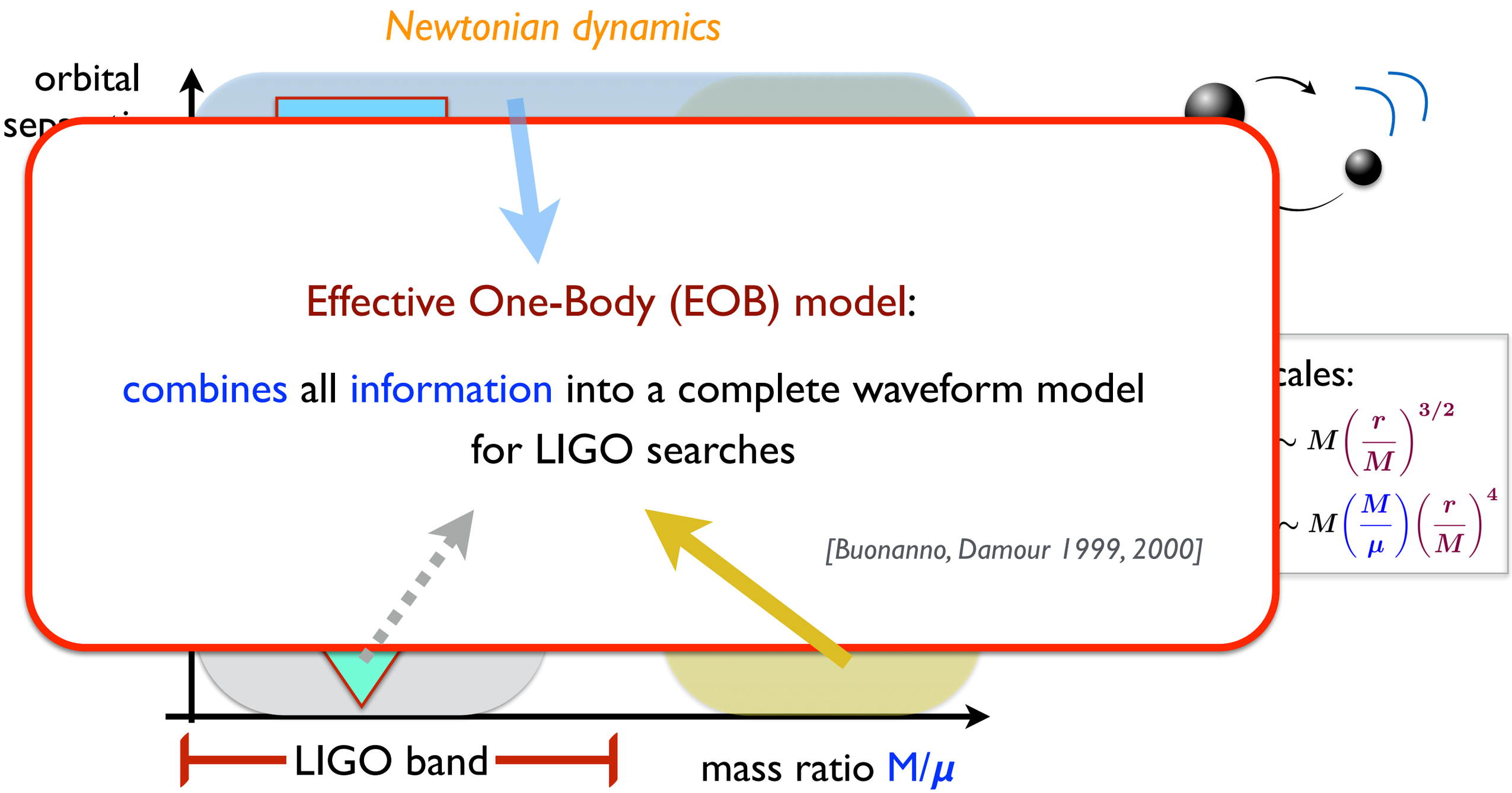
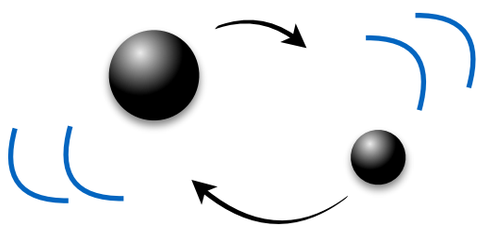


Effective-One-Body (EOB) approach

Binary problem

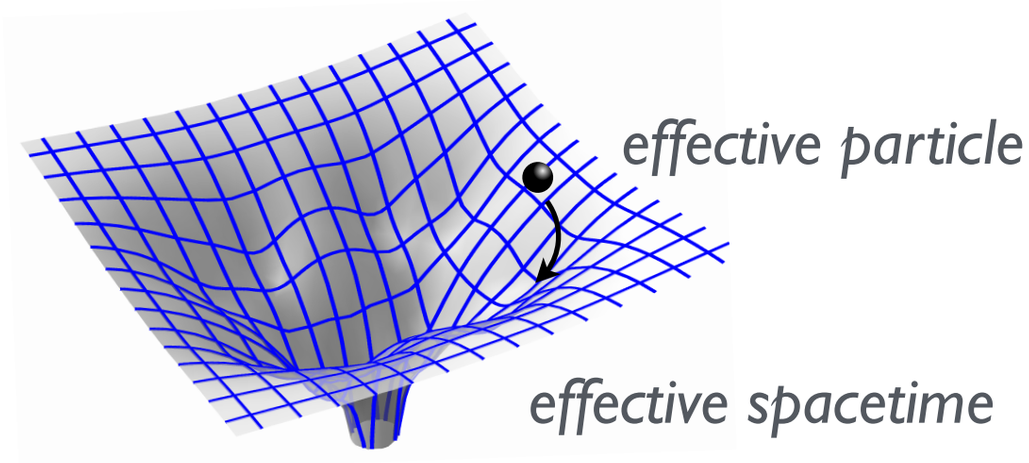


lengthy PN description

MAP

$\nu = \mu / M$

Effective description



$$\mathrm{d}s^2_{\mathrm{eff}} = -A(M,\nu,r)\mathrm{d}t^2 + B(M,\nu,r)\mathrm{d}r^2 + r^2 d\phi^2$$

$$A = 1 - \frac{2M}{r} + \nu\,\delta A^{\mathrm{PN}}(r; M, \nu)$$

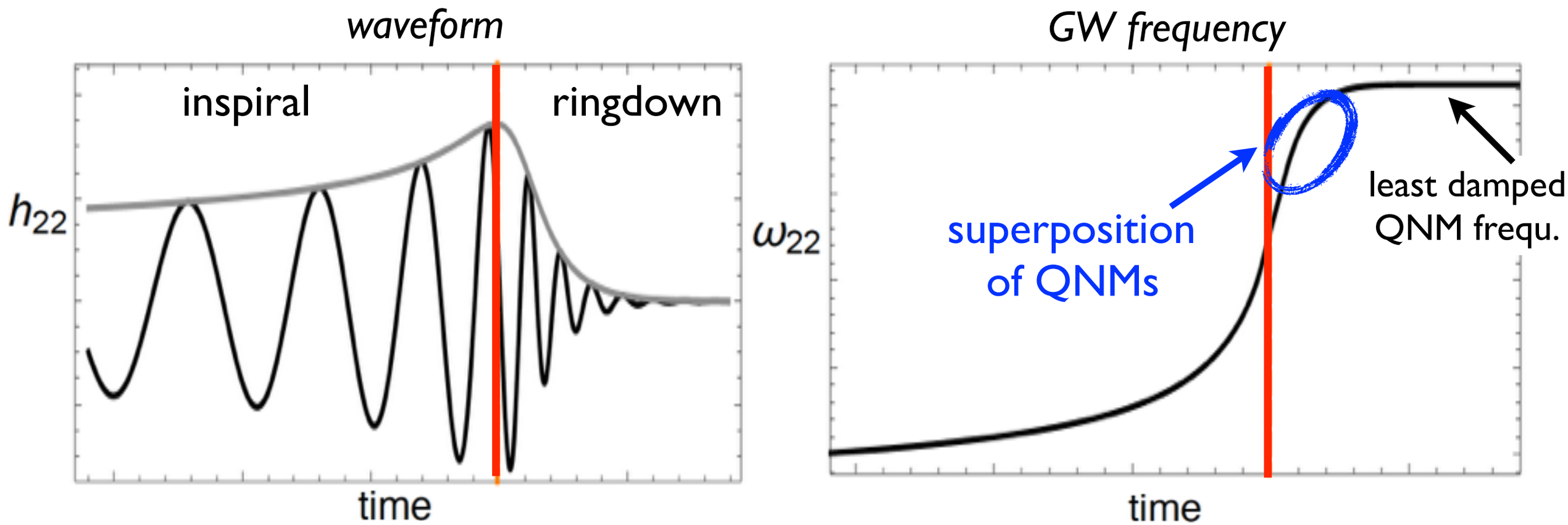
effective Hamiltonian H_{eff}

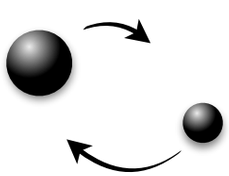
- Hamiltonian for the dynamics:

$$H_{\mathrm{EOB}}(r, p_r, p_\phi; M, \nu) = M\sqrt{1 + 2\nu\left(\frac{H_{\mathrm{eff}}}{\mu} - 1\right)}$$

- radiation reaction forces
- factorized waveforms

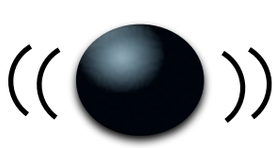
Complete EOB waveforms





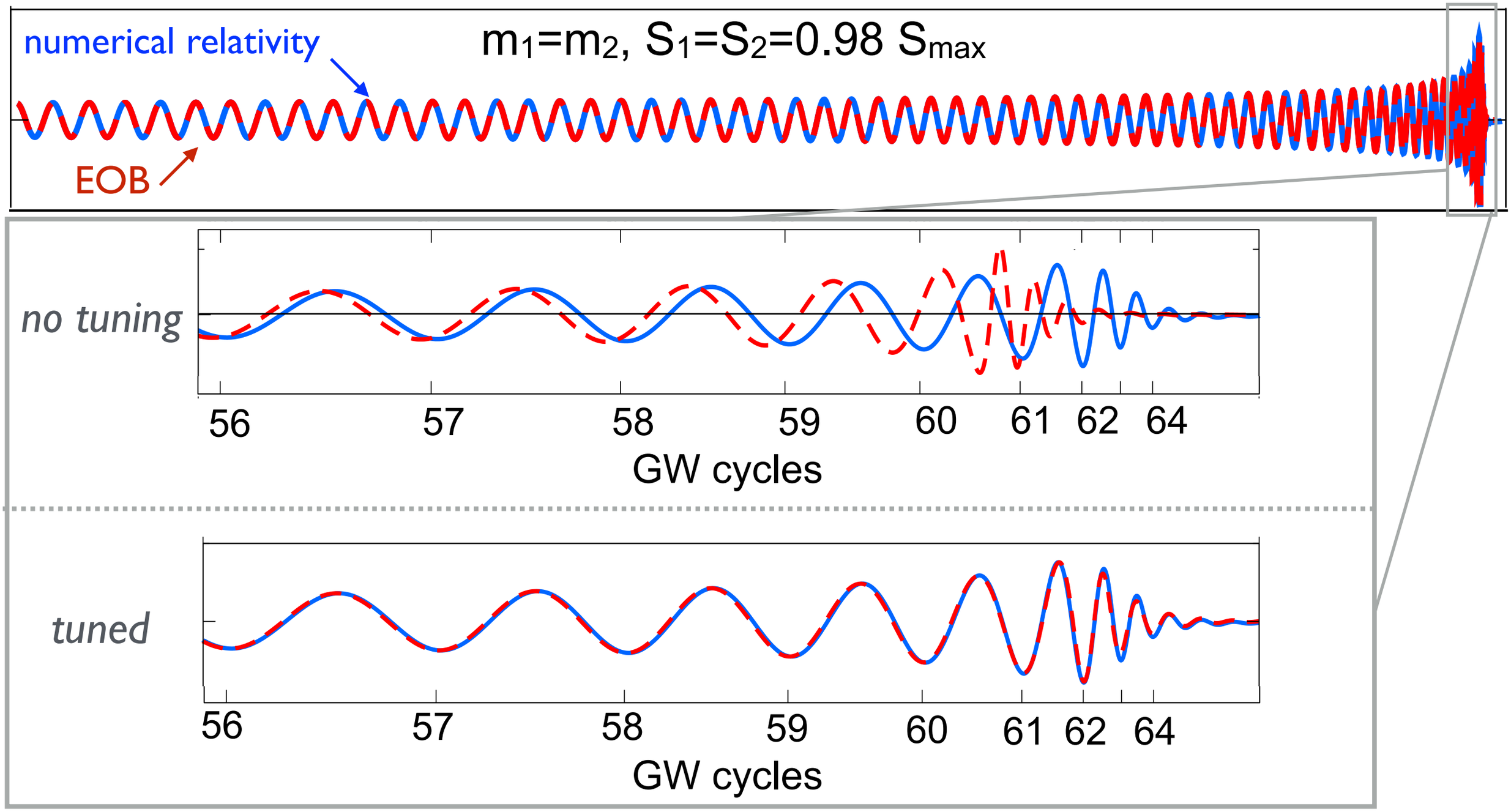
Evolve the two-body dynamics up to the **light ring** (spherical photon orbit)

Smooth transition



Ringdown: quasinormal modes (QNM) of final BH

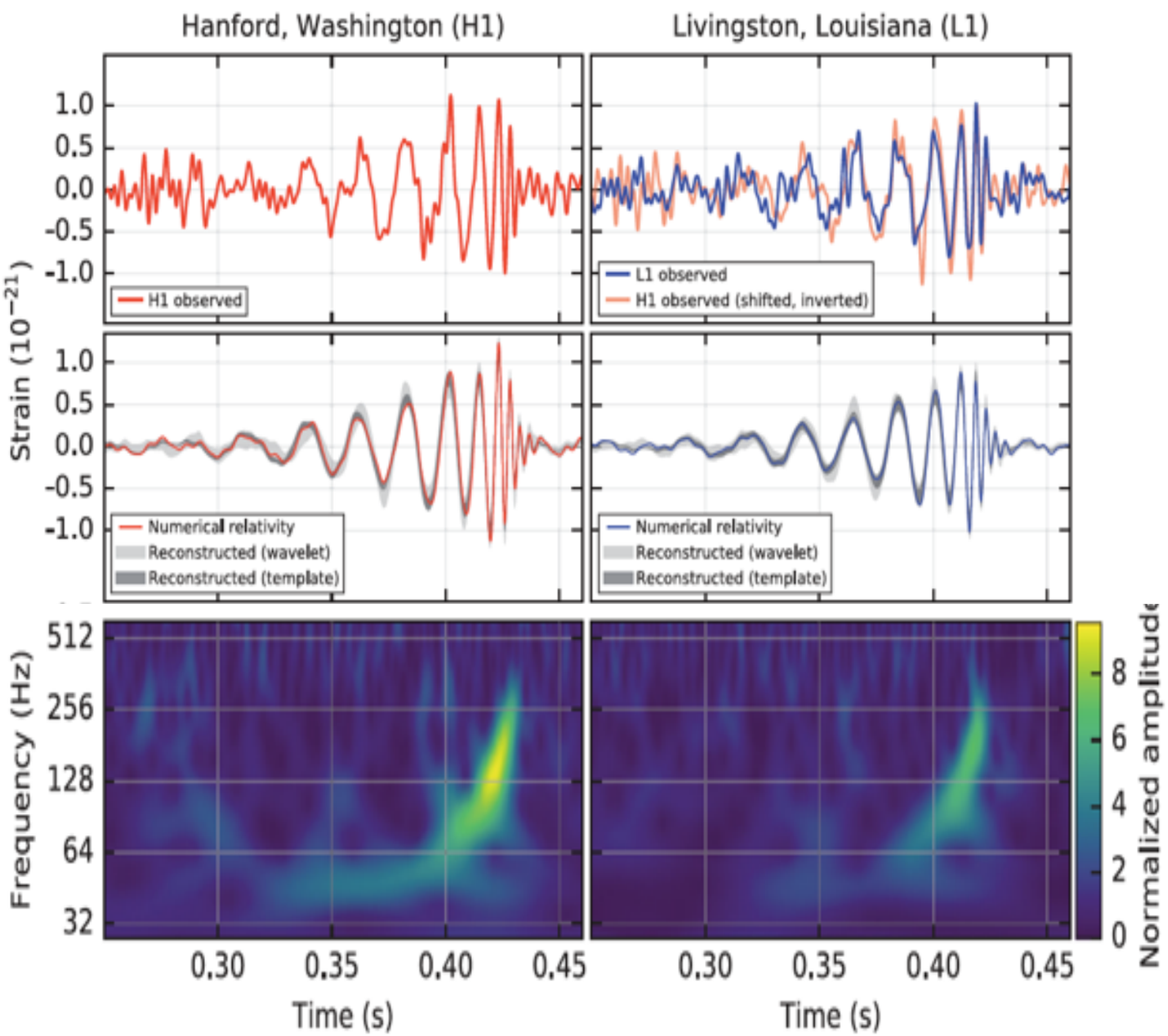
Performance of EOB waveforms



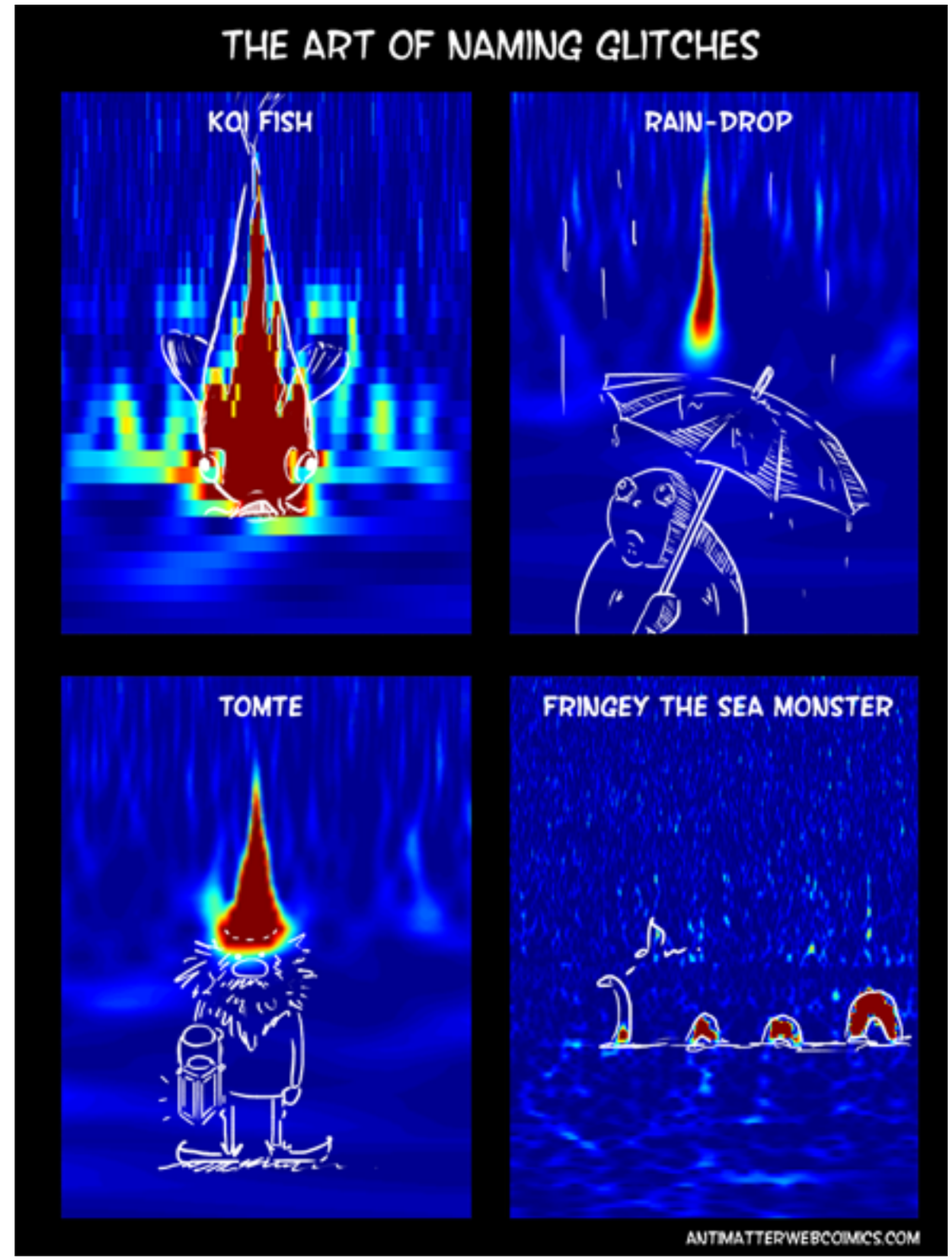
[courtesy A. Taracchini]

- recent extension to precessing spins *[Taracchini+ 2016]*

GW150914 detected by LIGO

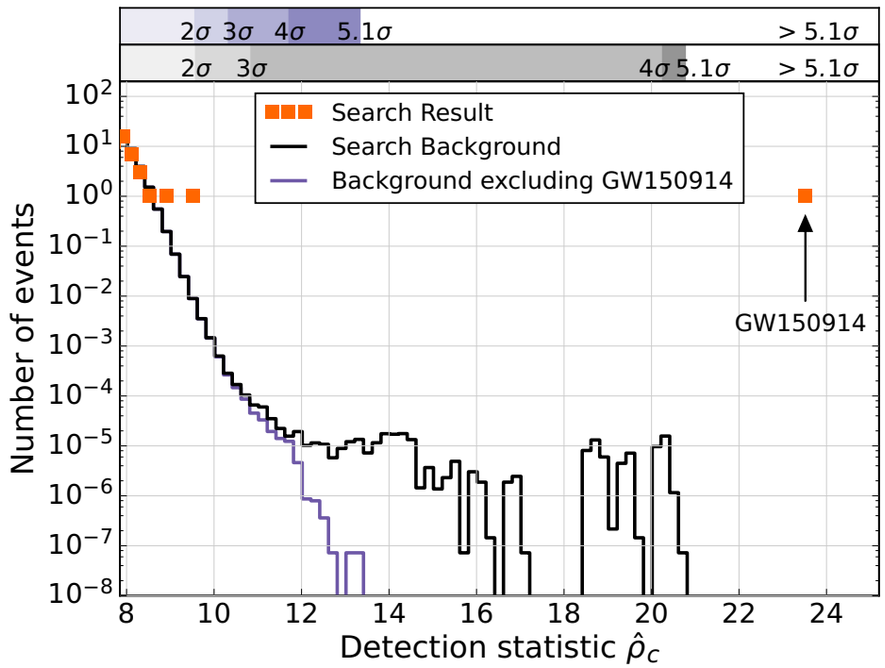


[LSC 2016]

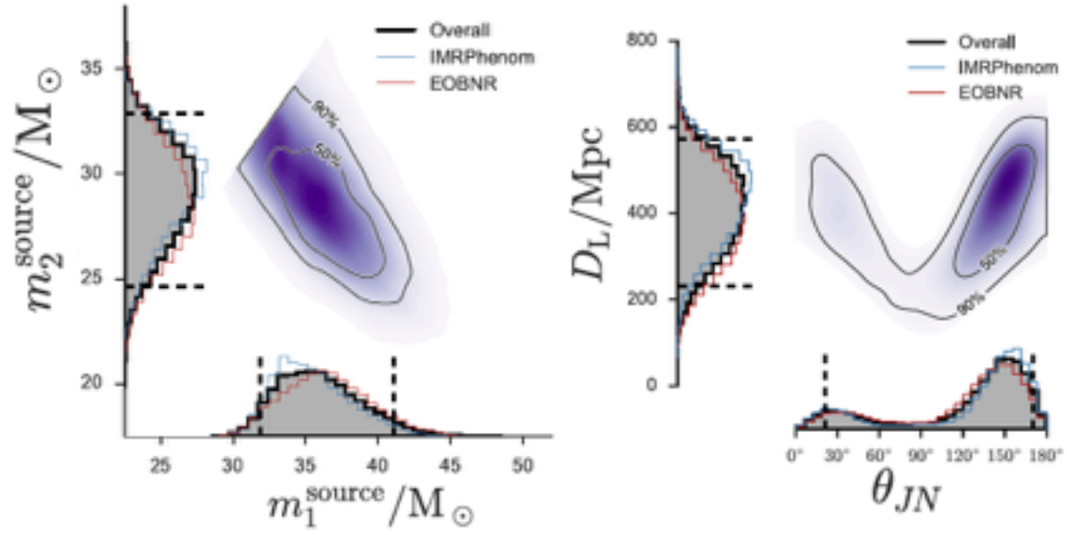


The importance of models for GW150914

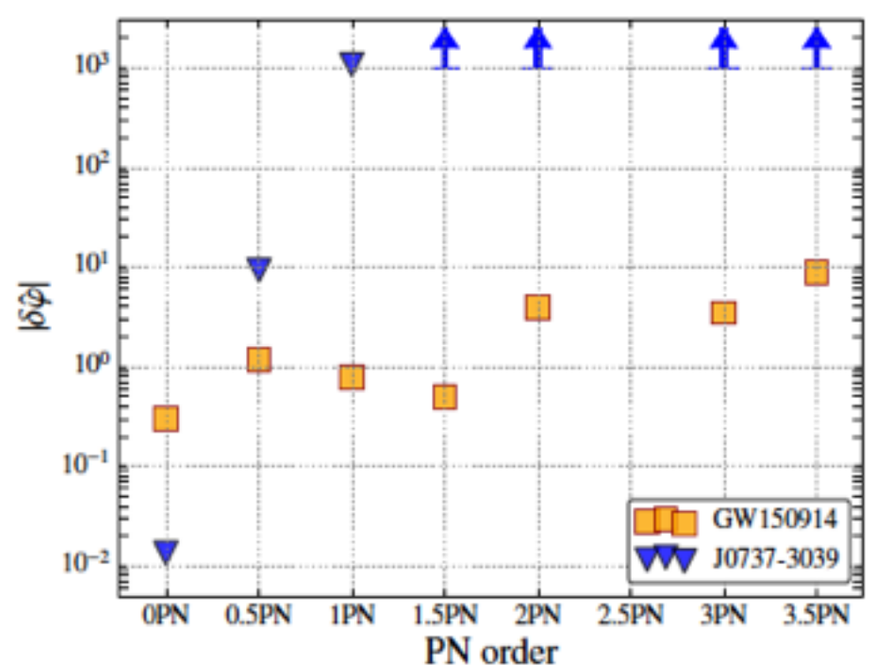
- establish >5σ detection significance



- measure source properties



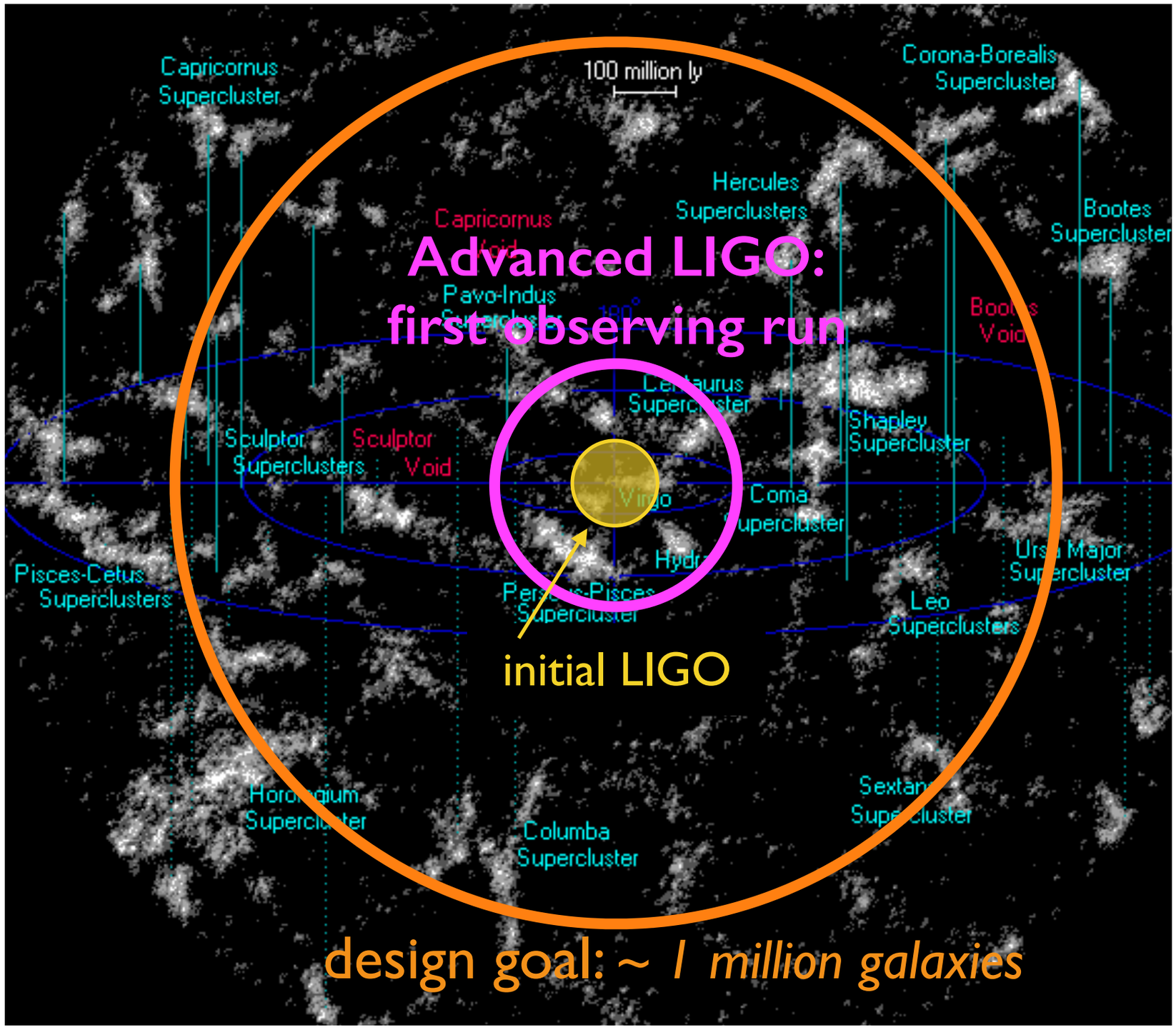
- perform tests of general relativity



[LSC 2016]

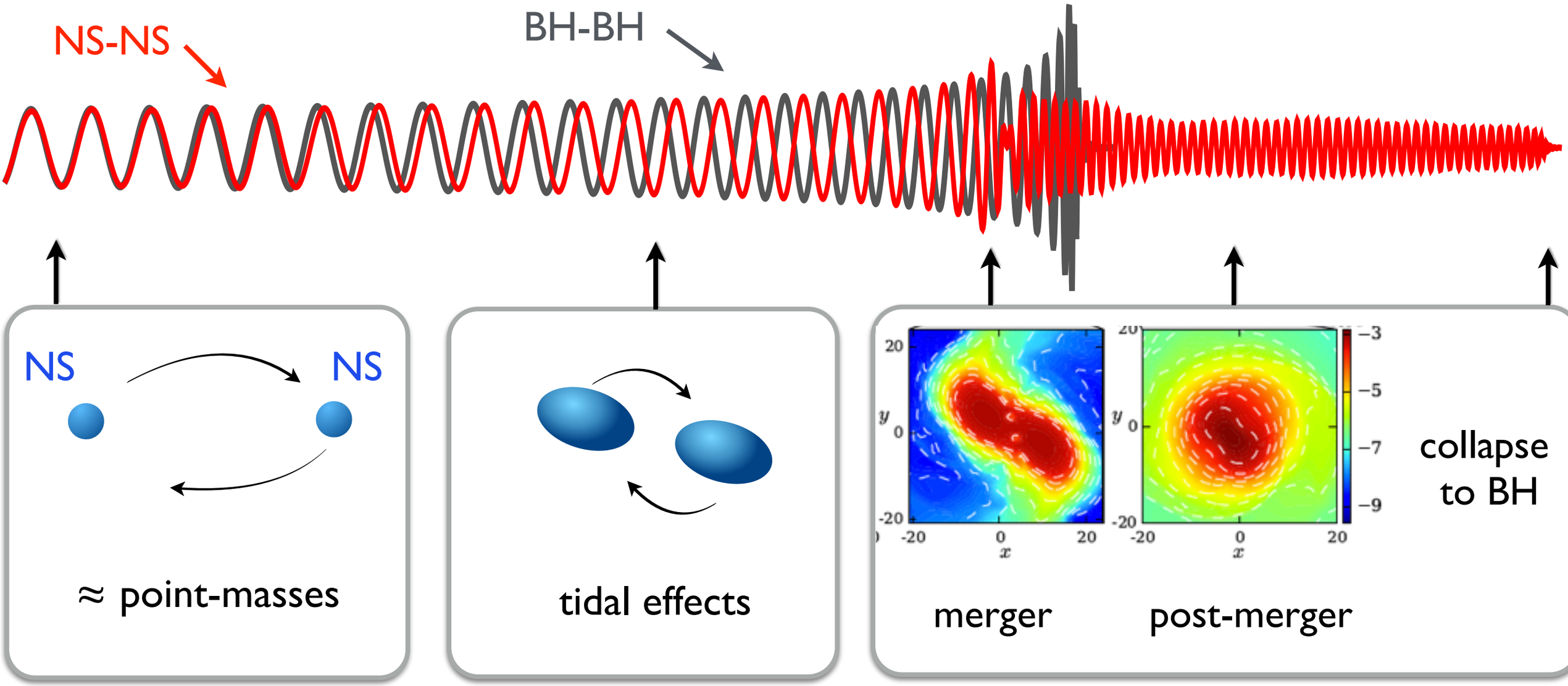
Experimental progress

- LIGO's visible volume of the universe for GWs from double neutron stars:



credit: atlasoftheuniverse

GW signal from NS-NS binaries



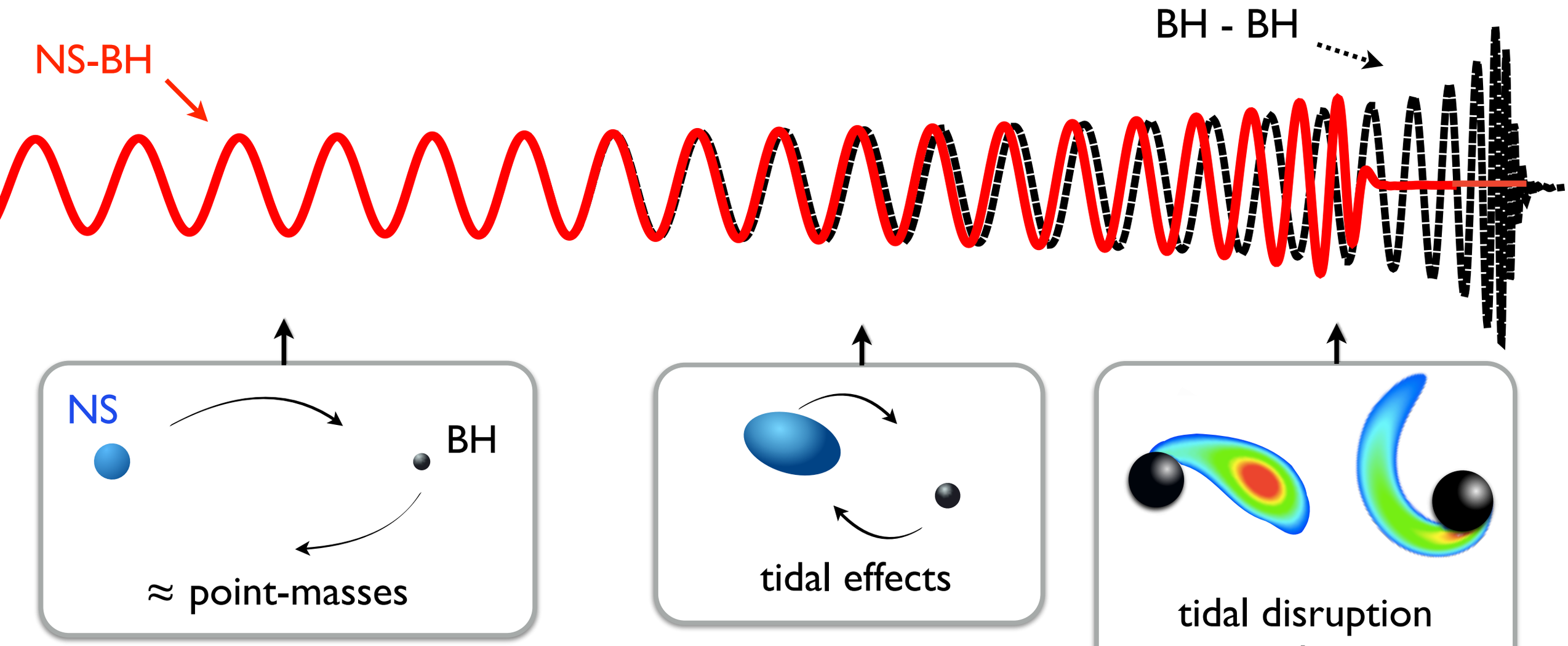
>10³ GW cycles

last ~ 20 cycles

rich characteristic frequency spectrum > kHz

[data from T. Dietrich]

GW signal from NS-BH binaries



larger modeling uncertainty in point-mass GWs than for NS-NS

small $\sim \dfrac{1}{(1+q)^5}$

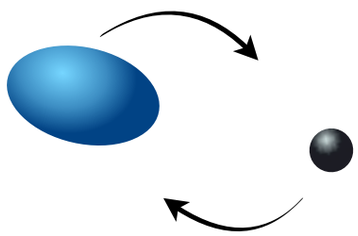
$$q = \frac{m_{\rm BH}}{m_{\rm NS}}$$

GW shutoff can be in aLIGO band

[data from F. Foucart]

Tidal effects during inspiral

- dominant effect:



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

induced quadrupole

tidal deformability

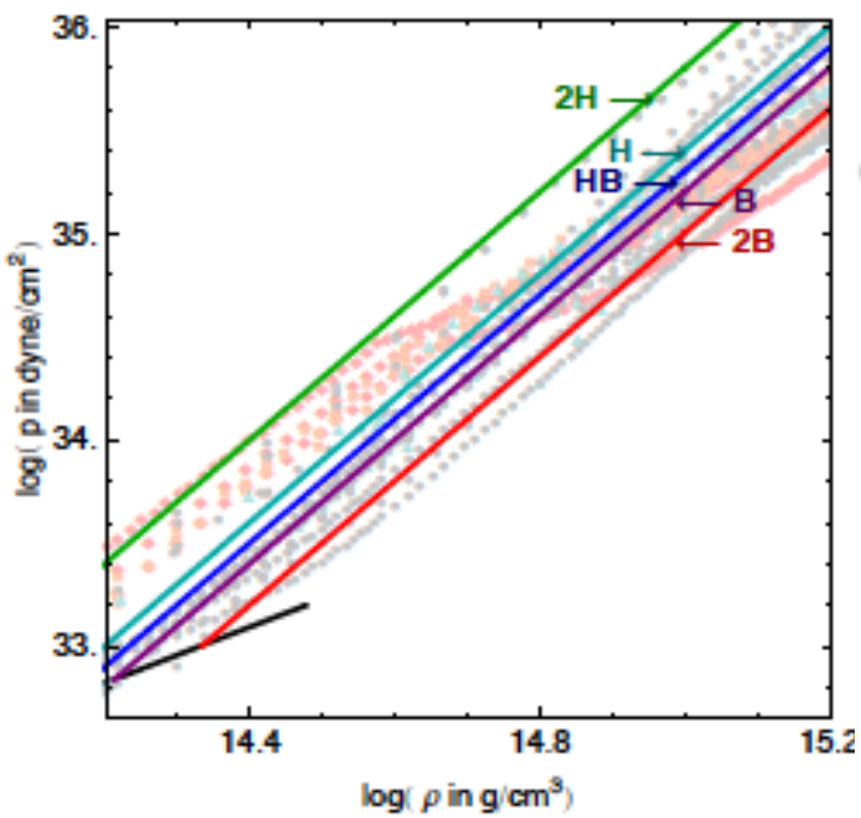
companion's tidal field

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

Love number

NS radius

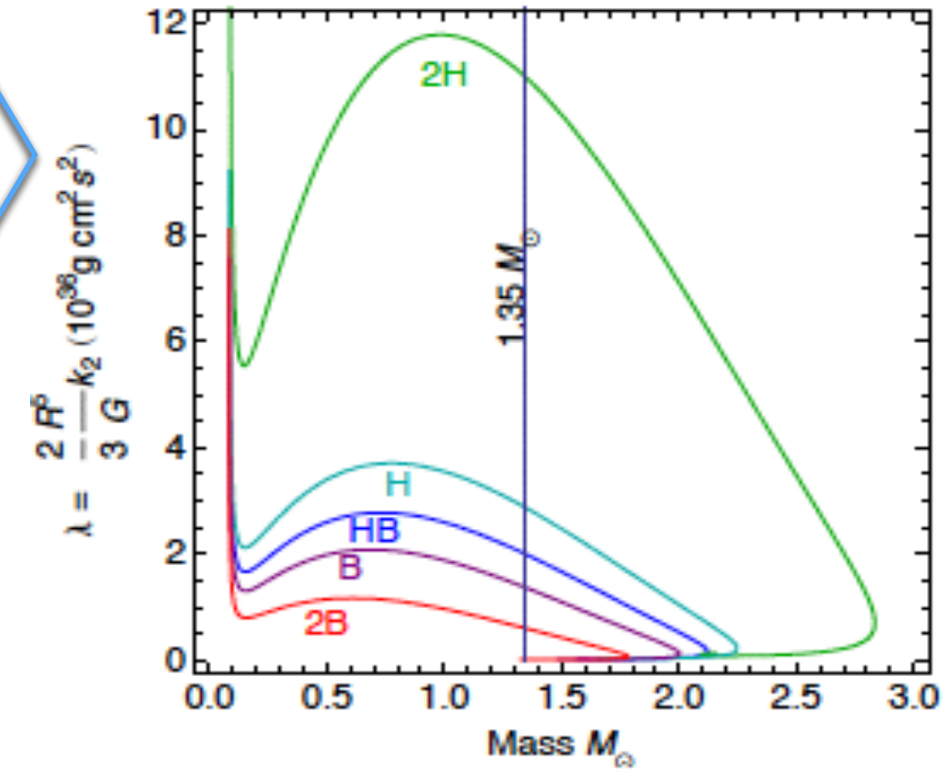
pressure - density



Einstein's Eqs: linear perturbations to equilibrium sol.

[One 2nd order ODE]

λ- mass

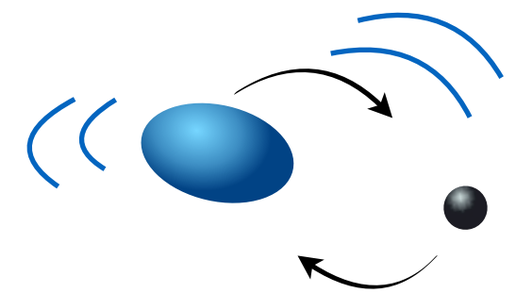


credit: B. Lackey

Influence on the GWs

- Energy goes into deforming the NS

$$E \sim E_{\rm orbit} - \frac{1}{4} Q_{\rm NS} \mathcal{E}_{\rm tidal}$$



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

- moving tidal bulges contribute to gravitational radiation

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

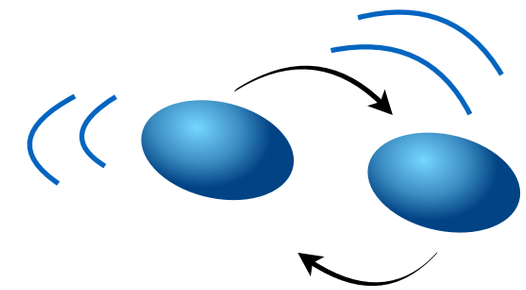
- GW phase from energy balance: $\frac{d\phi_{\rm GW}}{dt} = 2\Omega, \quad \frac{d\Omega}{dt} = \frac{\dot{E}_{\rm GW}}{dE/d\Omega}$

tidal contribution: $\boxed{\Delta\phi_{\rm GW}^{\rm tidal} \sim \lambda \frac{(v/c)^{10}}{M^5}}$

[Flanagan & TH 2008, Vines+ 2011]

Influence on the GW phase

- Tidal phase contribution in the stationary phase approx. :



$$\psi_{\rm tidal} = \frac{3}{128\nu x^{5/2}}\left[-\frac{39}{2}\tilde{\Lambda}x^5 + \left(-\frac{3115}{64}\tilde{\Lambda} + \frac{6595}{364}\sqrt{1-4\nu}\,\delta\tilde{\Lambda}\right)x^6\right]$$

$x = (\pi M f)^{2/3}$

$\nu = \mu/M$

- most sensitive to the weighted average:

$$\tilde{\Lambda} = \frac{8}{13}\left[\left(1+7\nu-31\nu^2\right)\left(\frac{\lambda_1}{m_1^5}+\frac{\lambda_2}{m_2^5}\right) + \sqrt{1-4\nu}\left(1+9\nu-11\nu^2\right)\left(\frac{\lambda_1}{m_1^5}-\frac{\lambda_2}{m_2^5}\right)\right]$$

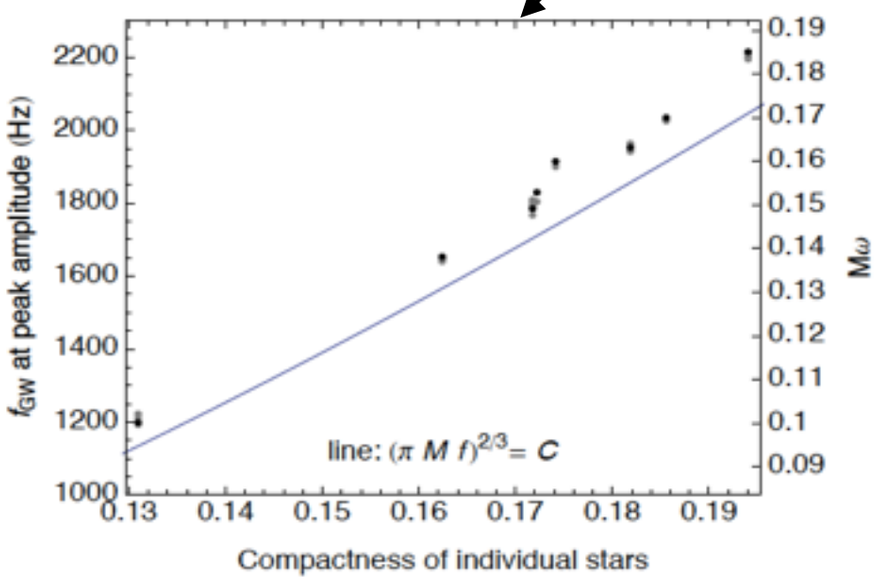
- for identical NSs:

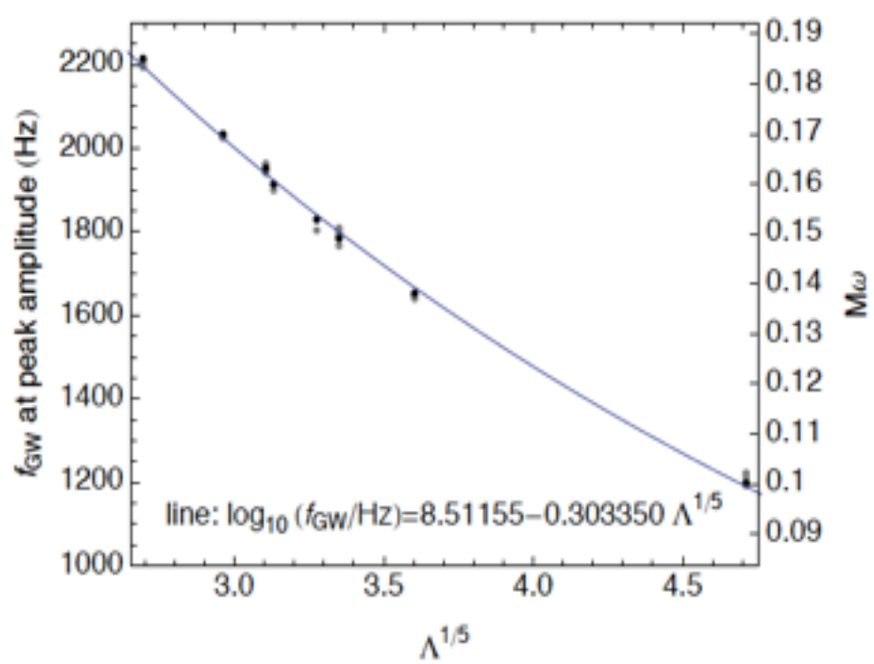
$$\tilde{\Lambda} = \frac{\lambda}{m_{\rm NS}^5} \qquad \delta\tilde{\Lambda} = 0$$

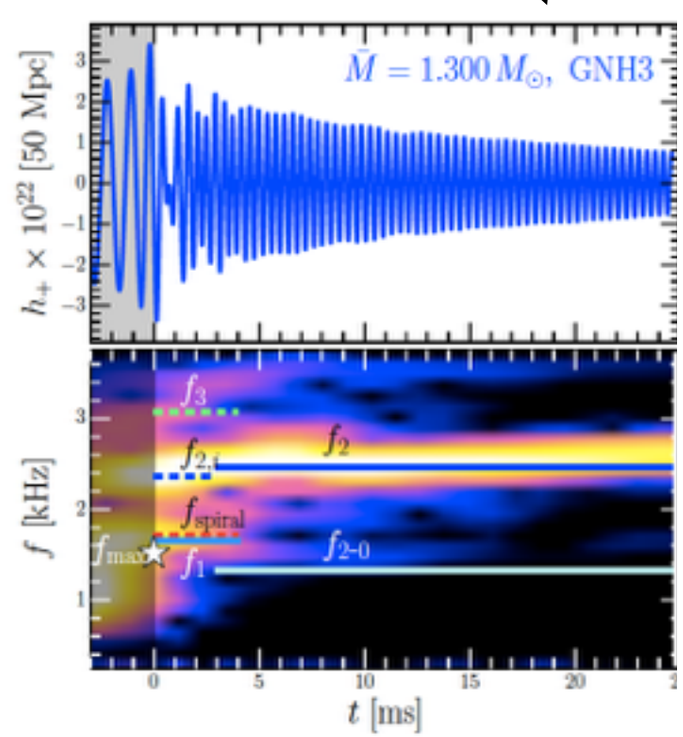
Approximate universality

- weak EoS-dependence between many NS quantities, e.g.:
  - " I - Love - Q " [moment of inertia, tidal Love number, rotational quadrupole]
  - NS binaries: merger frequency f_{peak}, post-merger spectrum

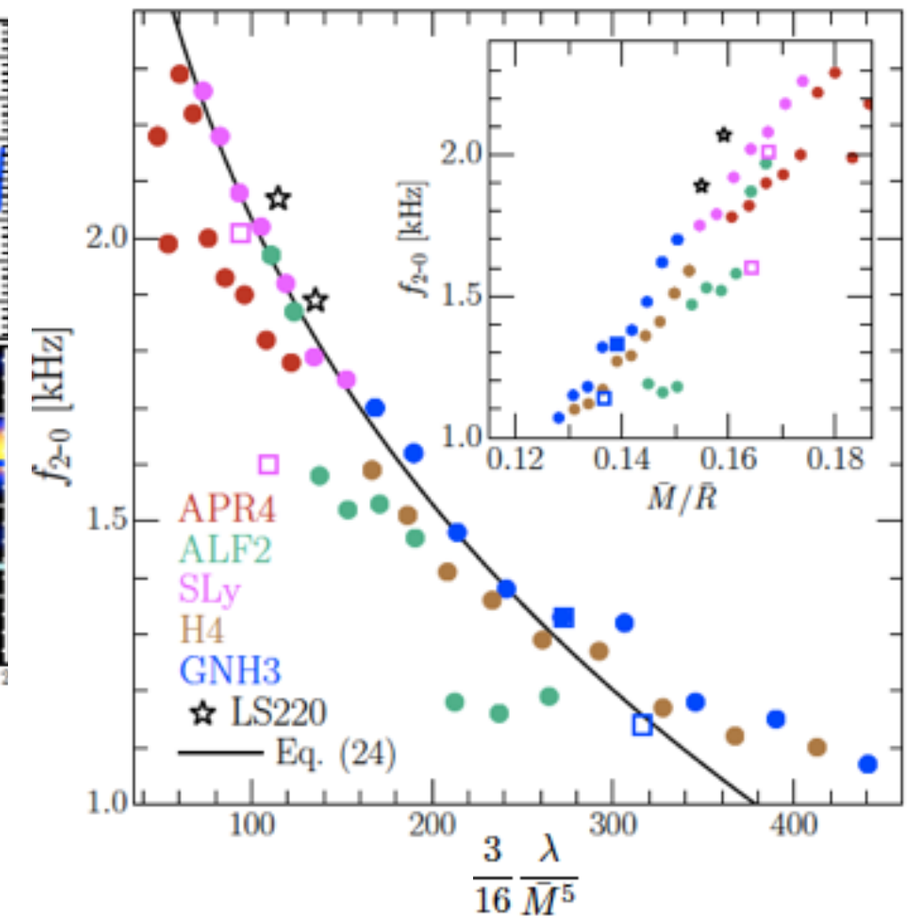
[Yagi & Yunes 2013]







[Read+2013]



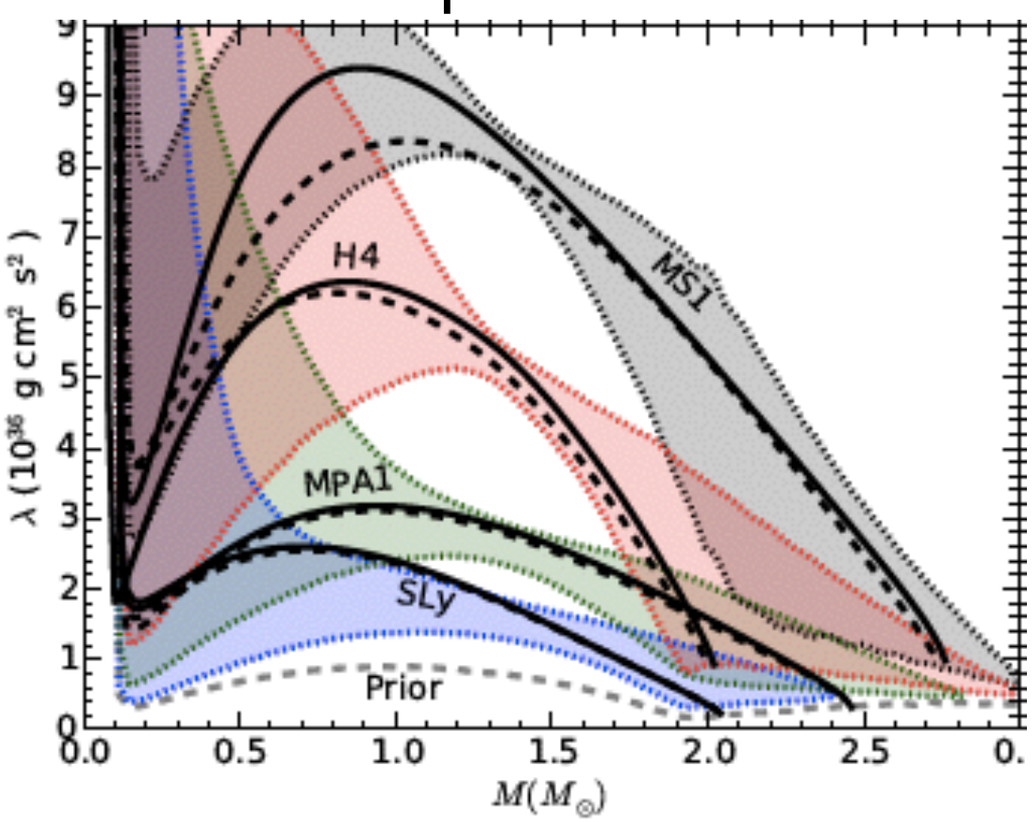
[Rezzolla&Takami 2016]

What to expect from aLIGO+Virgo

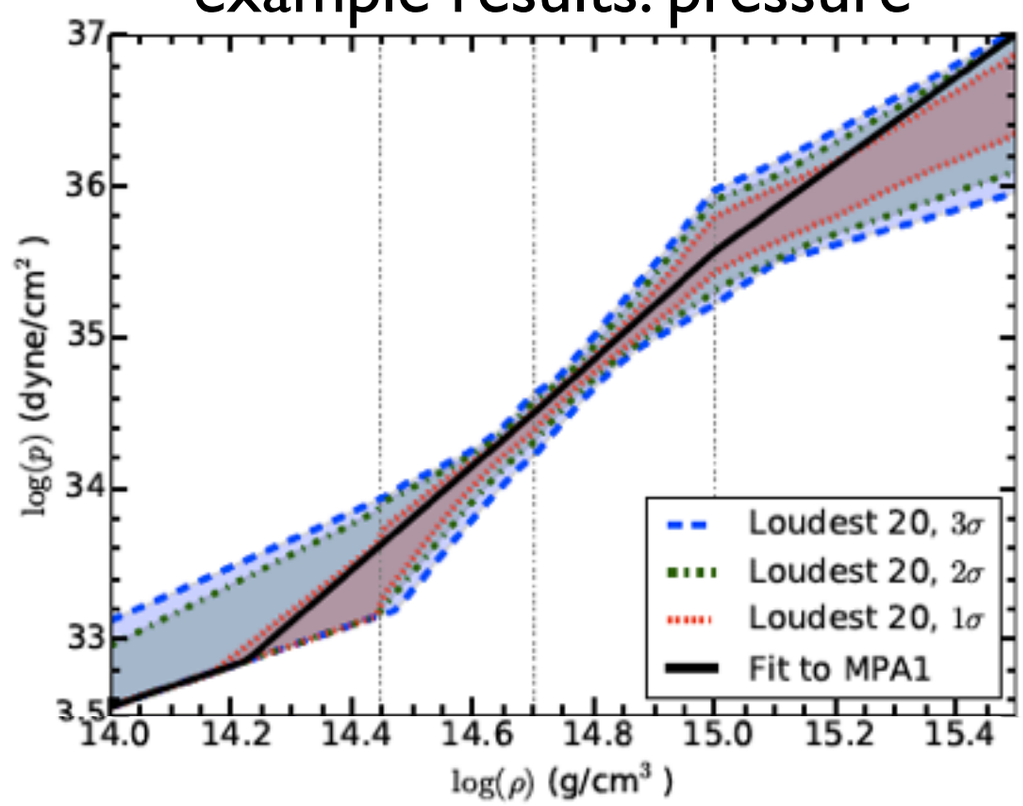
- "standard" NS-NS event rate (40/yr), ~1 yr of data [some caveats with the analysis]:
  - λ to ~10-50 %, radius to ~1-2 km, pressure to ~ factor of 2 *[Lackey+2014]*
- similar conclusions with hybrid NR waveforms *[Shibata+2016]*
- NS-BH systems: λ/m^5 to ~ 10-100 % *[Lackey+ 2013]*

many caveats

example results: λ



example results: pressure

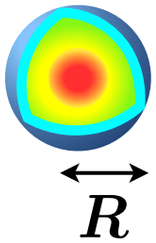


[Lackey+2014]

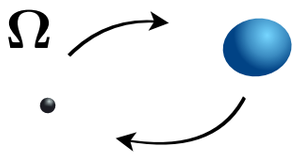
Recent model improvement: dynamic tides

- $Q_{\rm NS}$ corresponds to the NS's fundamental oscillation modes

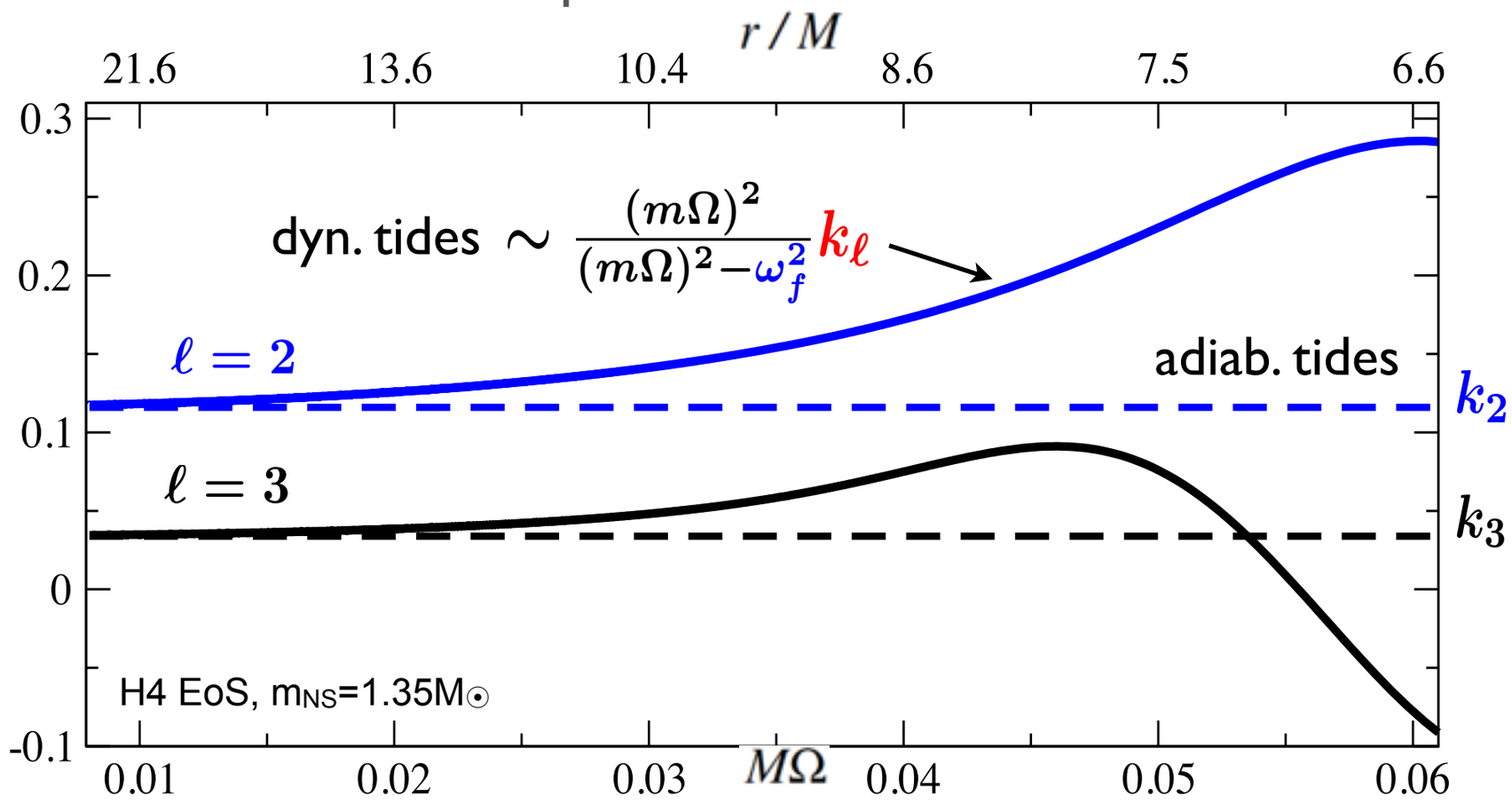
  eigenfrequency: $\omega_f \sim \sqrt{m_{\rm NS}/R^3}$ (internal structure - dependent)



- **tidal forcing** frequency: $m\Omega \sim m\sqrt{M/r^3}$



NS's response to the tidal field

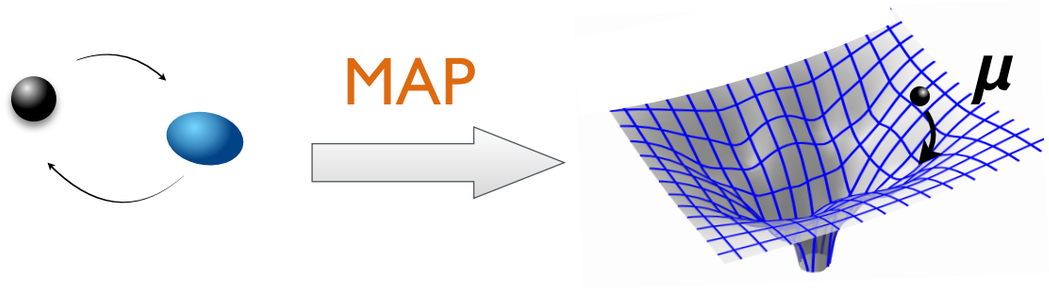


$$\lambda_\ell = \frac{2(\ell-2)}{(2\ell-1)!!} k_\ell R^{2\ell+1}$$

↑

Love number

EOB Hamiltonian with tidal effects

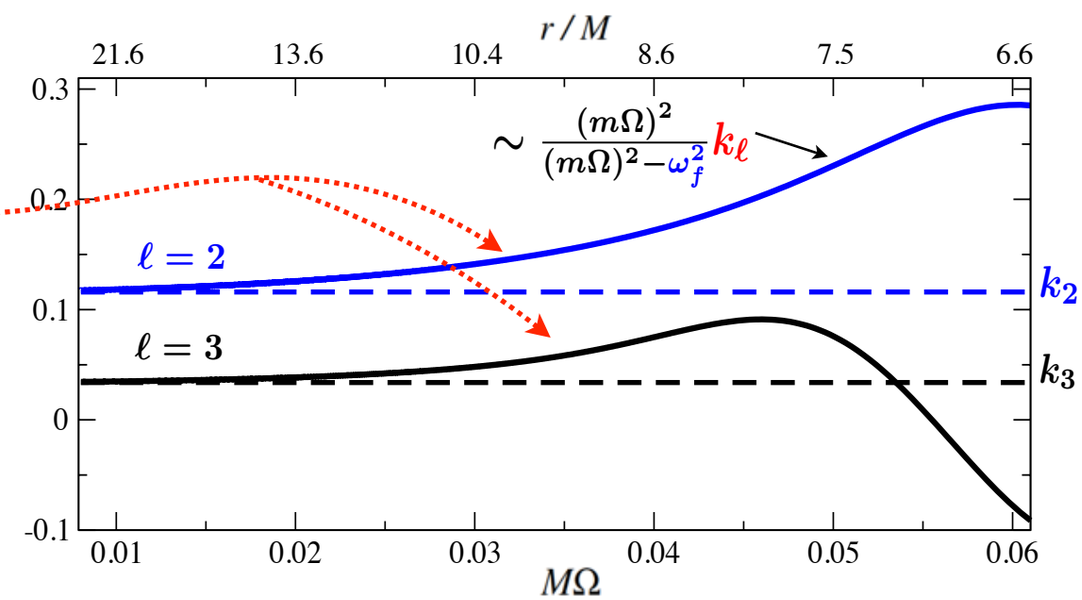


$$\mathrm{d}s^2_{\mathrm{eff}} = -A\mathrm{d}t^2 + B\mathrm{d}r^2 + r^2 d\phi^2$$

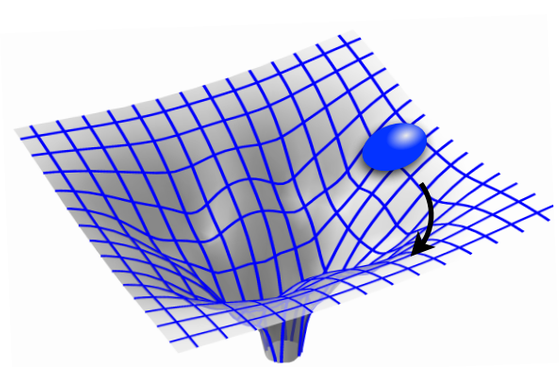
- *adiabatic* tides (AT): $A = A^{\mathrm{pp}}(M,\nu,r) + \lambda_\ell A^{\mathrm{AT}}(M,\nu,r)$ *[Damour, Nagar, Bini+2009-2014]*

- *dynamic* tides: effective description of from approximate solutions for Q_{NS}:

$$A = A^{\mathrm{pp}}(M,\nu,r) + \lambda_\ell^{\mathrm{eff}}(M,\nu,r,\lambda_\ell,\omega_f) A^{\mathrm{AT}}(M,\nu,r)$$



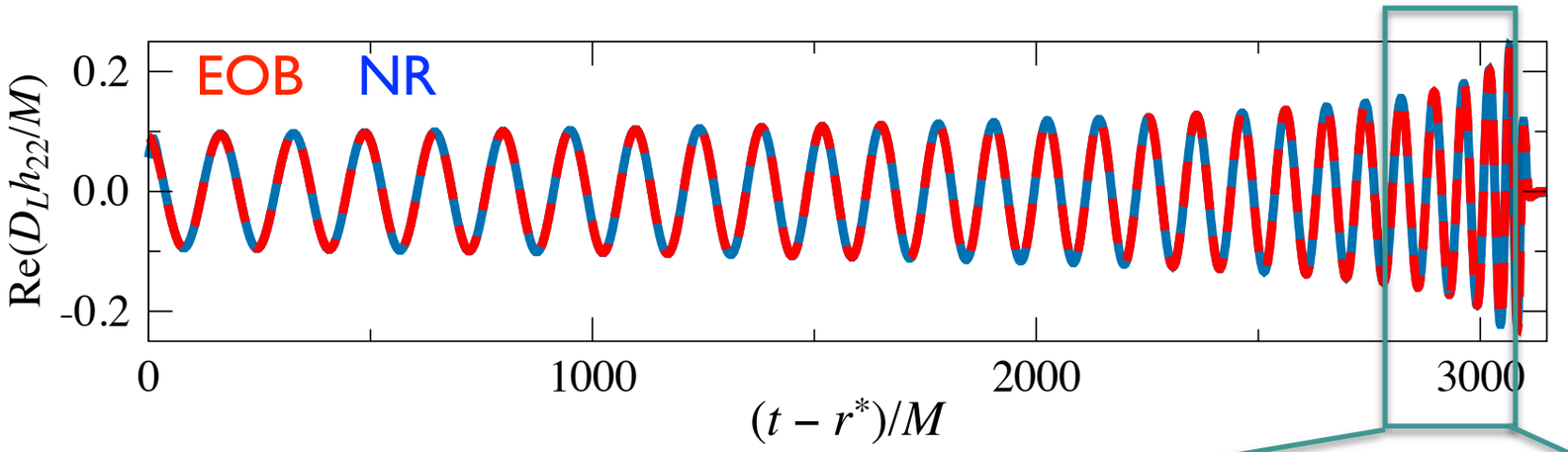
- good agreement with full evolution:



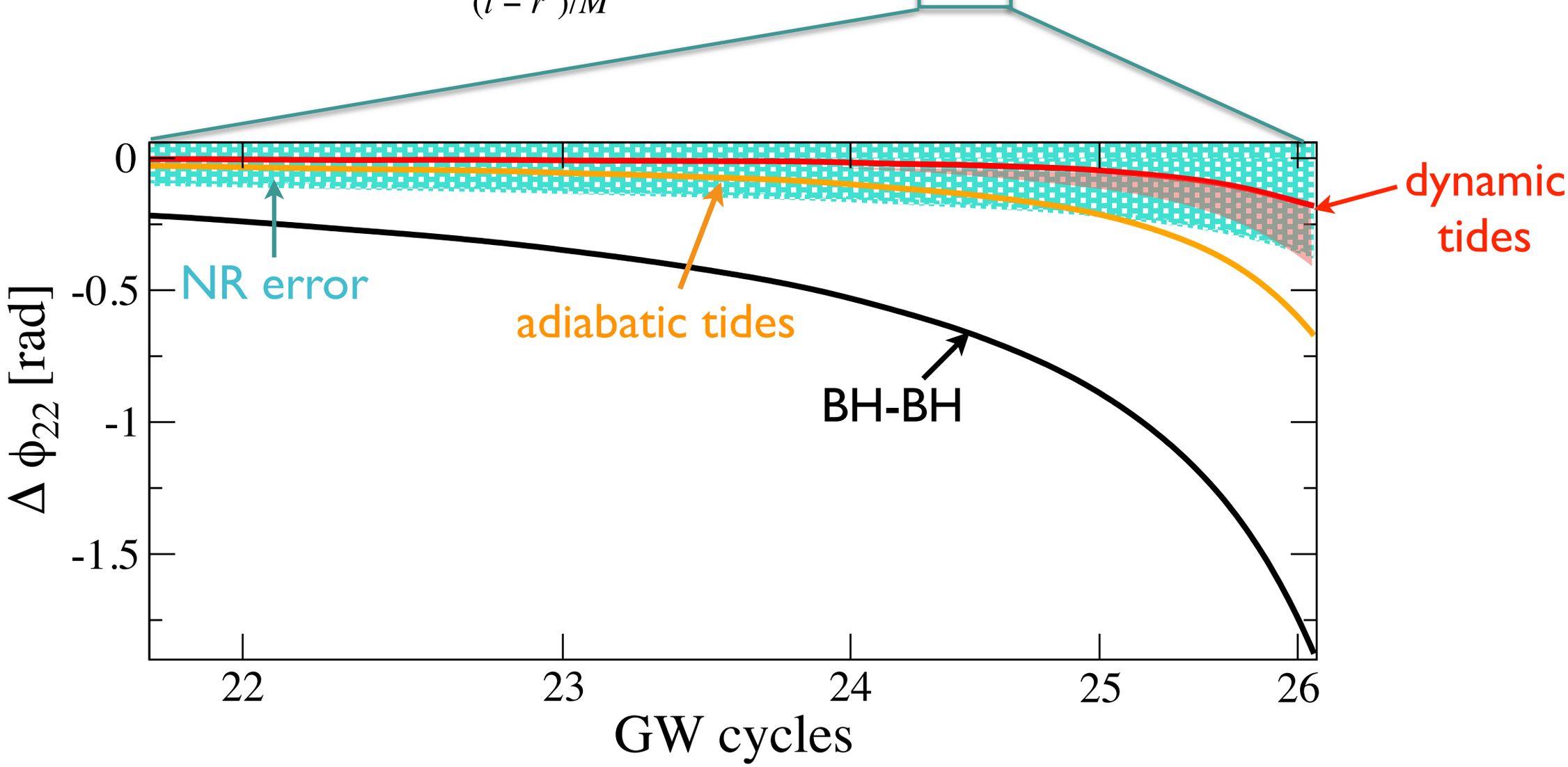
$$H_{\mathrm{EOB}}(r, p_r, p_\phi, Q_{\ell m}, P_{\ell m}; M, \nu, \lambda_\ell, \omega_f)$$

[TH+2016]

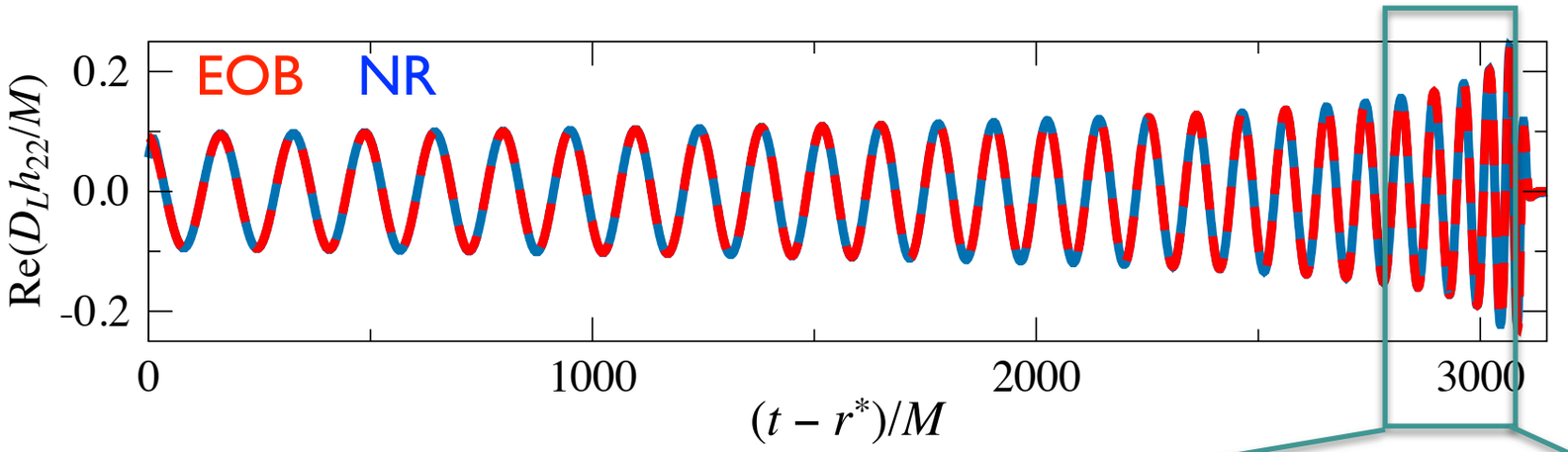
Performance of the tidal EOB model



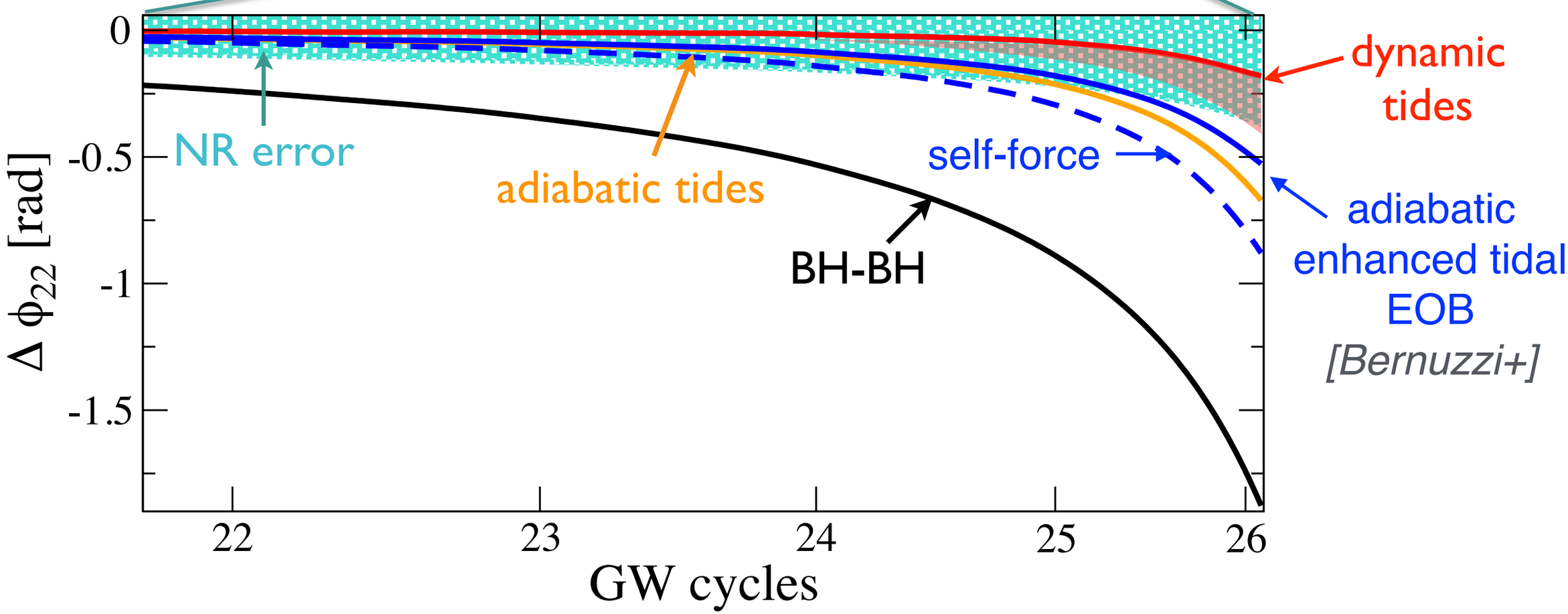
nonspinng NS-BH
mass ratio 2:1
Γ=2 polytropic
C=0.1444



Performance of the tidal EOB model

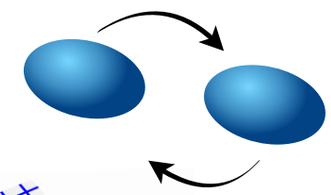


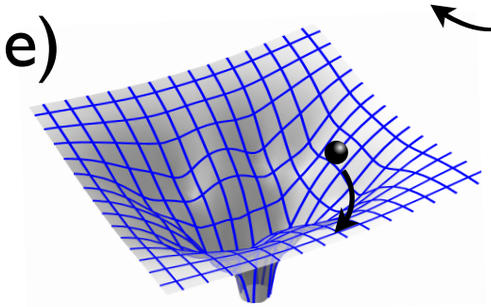
nonspinng NS-BH
mass ratio 2:1
Γ=2 polytropic
C=0.1444

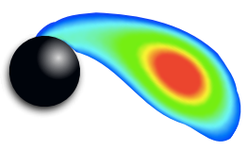


Conclusions

- Main imprint of NS microphysics in the GWs from inspirals: tidal effects
- Dynamic f-mode tides can be significant, now included in EOB
- Also included: NS-BH tidal disruption signal (nonspinning case)

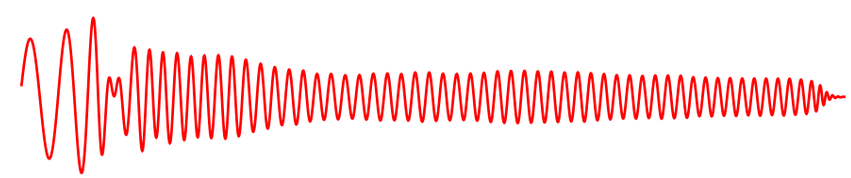




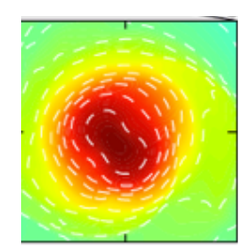


Outlook:

- Further improve models and measurement potential, reduce systematics (inspiral, NS-BH tidal disruption, NS-NS merger/post-merger)
- Include more realistic physics



- Accurate NR simulations are crucial to inform model developments
- data analysis strategies (e.g. parameterization)
- connection with multimessenger signals



Thank you