Title: Probing nuclear physics with gravitational waves from neutron star binary inspirals

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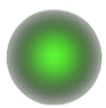
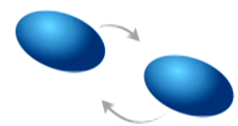
Abstract: <p>The gravitational waves from a binary inspiral carry unique information about the internal structure of compact objects. This information is of major interest for neutron stars, offering the possibility for advancing our understanding matter and fundamental interactions in unexplored regimes. I will discuss the imprints of an objectâ€™s internal structure, and in particular neutron star matter, on the gravitational waves generated during an inspiral, methods for analytically modeling these effects, and what we have learned from GW170817. I will also outline future prospects and challenges.</p>

Probing the fundamental physics of supra-dense cold matter with gravitational waves from neutron star binary inspirals





Tanja Hinderer

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University of Amsterdam

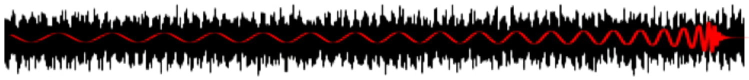
Perimeter Institute

Nov 2018

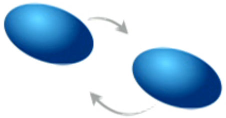
Outline of this talk

- Gravitational waves (GWs): a new tool for probing fundamental physics in unexplored regimes

- Theoretical models needed to extract the information encoded in GWs from binary systems

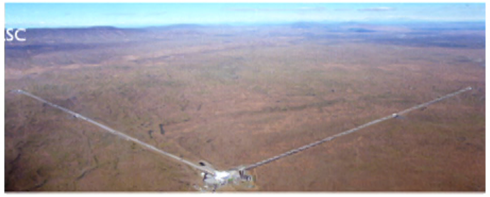


- Most readily measurable generic imprints of source physics beyond GR black holes on GWs during an inspiral



- Main application to neutron stars, broader uses

- Outlook



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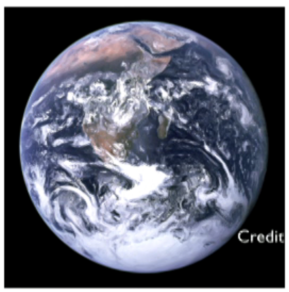
Neutron stars (NSs)

- densest stable material objects known in the universe
- 1939: theoretical description *[Oppenheimer & Volkoff]*
- thousands observed to date

debris from a supernova explosion in 1054

Crab Pulsar
(NS rotating at 30 rev/sec)



crushed to neutron-star compactness

crushed

Black hole

What is the nature of matter in such extreme conditions?

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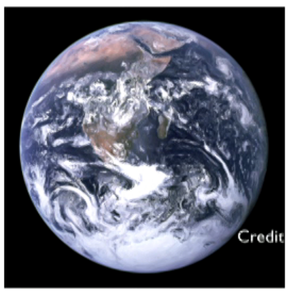

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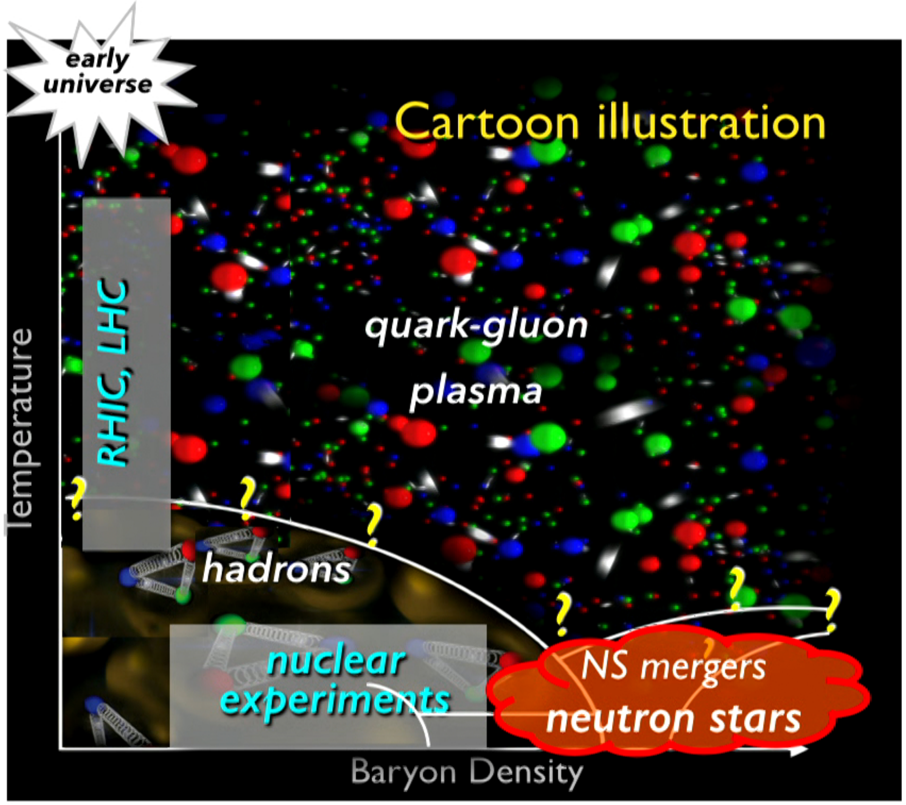
Black hole

What is the nature of matter in such extreme conditions?

Phases of QCD



Credit: F. Linde

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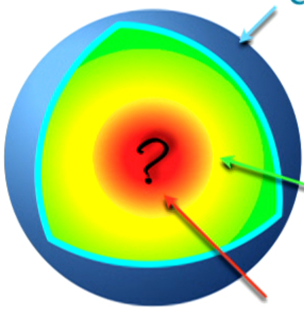
Conjectured Neutron Star (NS) structure

[iron ~ 10 g/cm³]



crust ~ *km*
neutron rich ions,
free neutrons

$\sim 10^6$ g/cm³ inverse β-decay

$\sim 10^{11}$ g/cm³ neutron drip

outer core
uniform liquid

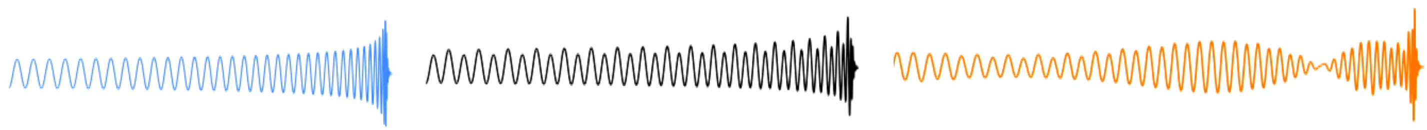
deep core
~2-10x nuclear density
exotic states of matter?
deconfined quarks?
signatures of new physics?

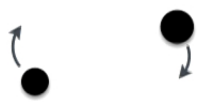
$\sim 10^{15}$ g/cm³

- many theoretical difficulties
- far extrapolations from known physics

Recall: GW signal detection and measurement process

- Matched filtering to detect and interpret signals
- Cross-correlates the data with theoretical models (templates)

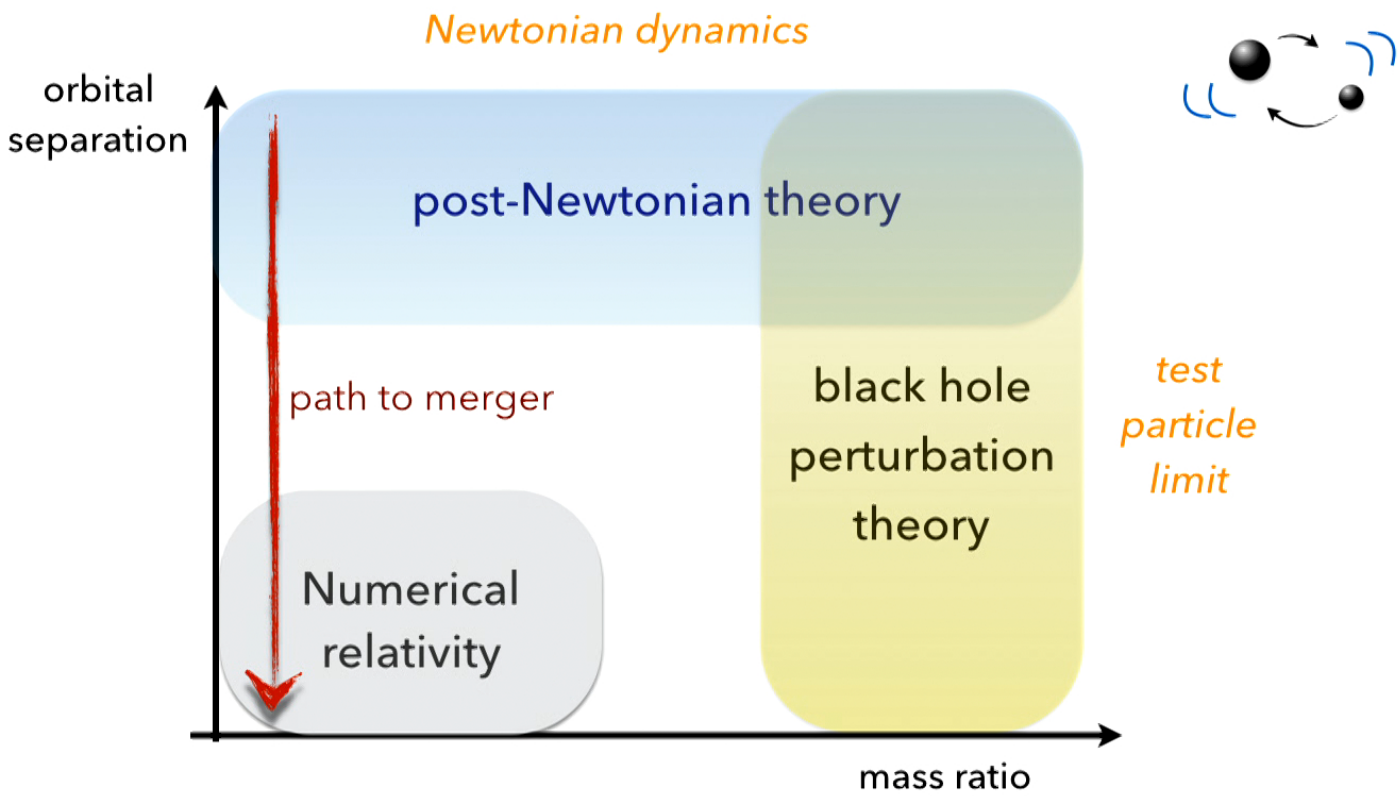




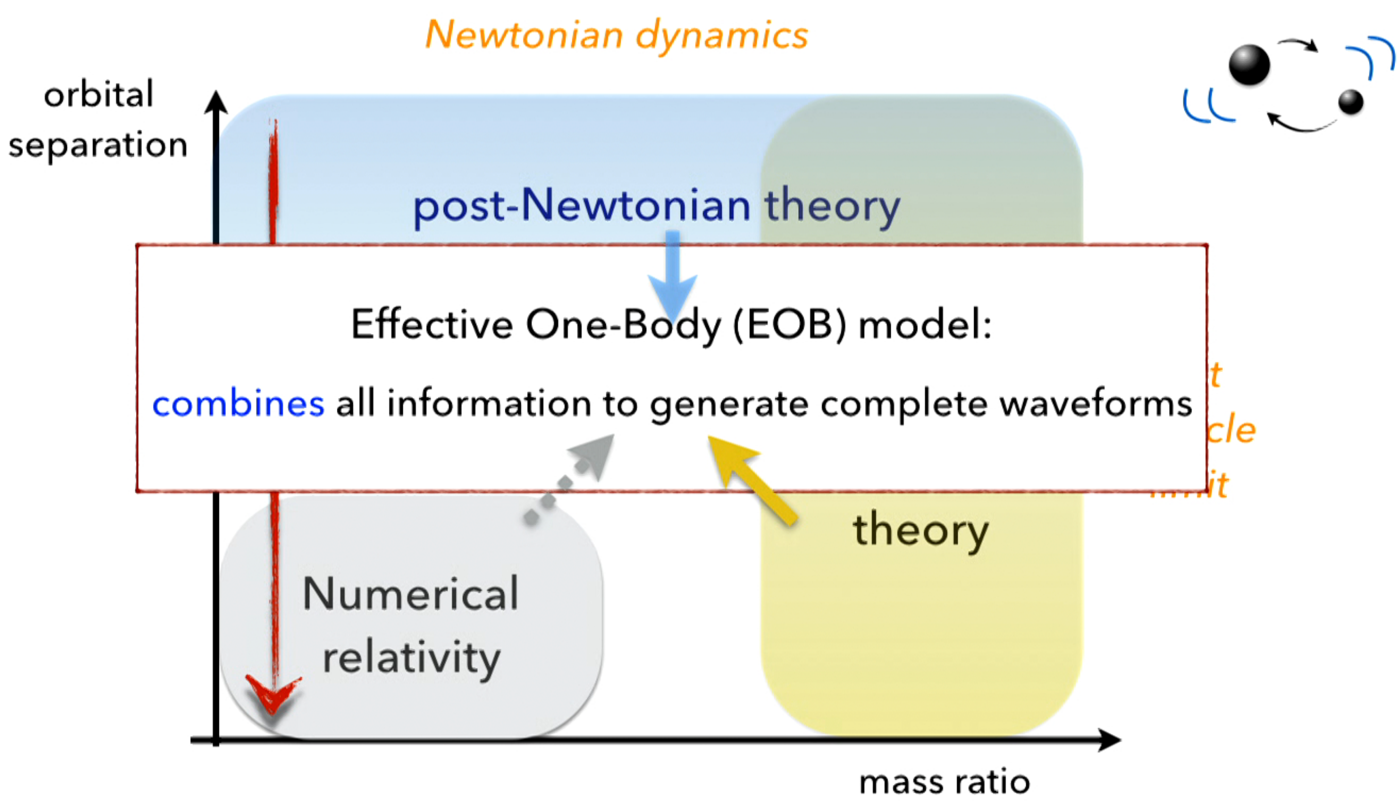
- Requirements on measurement templates:
  - phase accuracy better than ~1 radian out of ~10^4
  - Cover entire parameter space

Theoretical challenge: solve for the dynamical spacetime describing the binary

Approaches to computing templates



Approaches to computing templates



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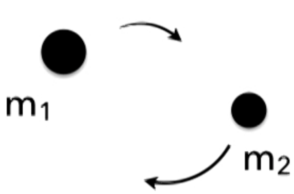
Effective One-Body (EOB) model: basic approach

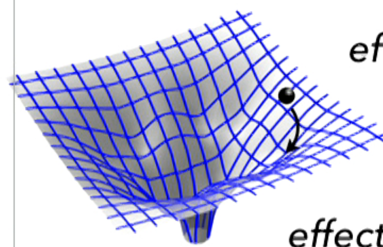
- for non-spinning black holes: [Buonanno, Damour 1999, 2000]

Binary problem



Map
of phase space
dynamics

Effective description



effective particle

$$\mu = \frac{m_1 m_2}{m_1 + m_2}$$

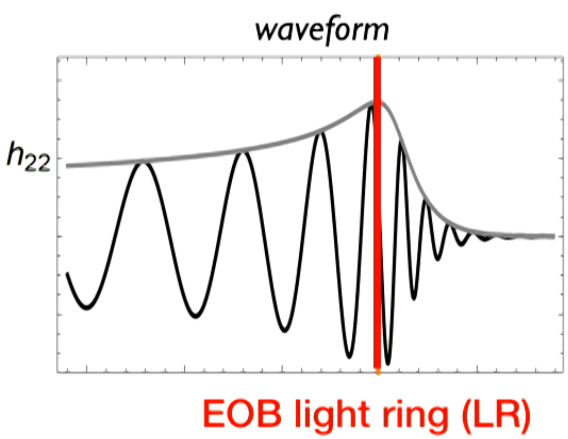
effective spacetime

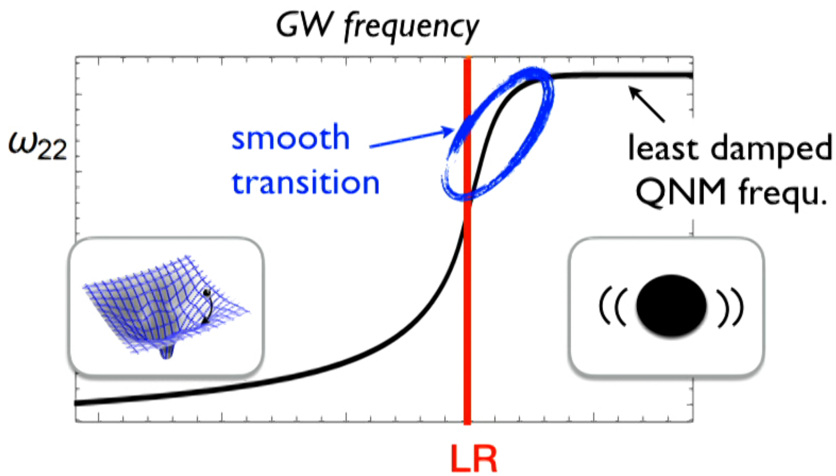
$M = m_1 + m_2 \quad \nu = \mu/M \in [0, 1/4]$

$$H_{\rm EOB} = M\sqrt{1 + 2\nu\left(\frac{H_{\rm eff}}{\mu} - 1\right)}$$

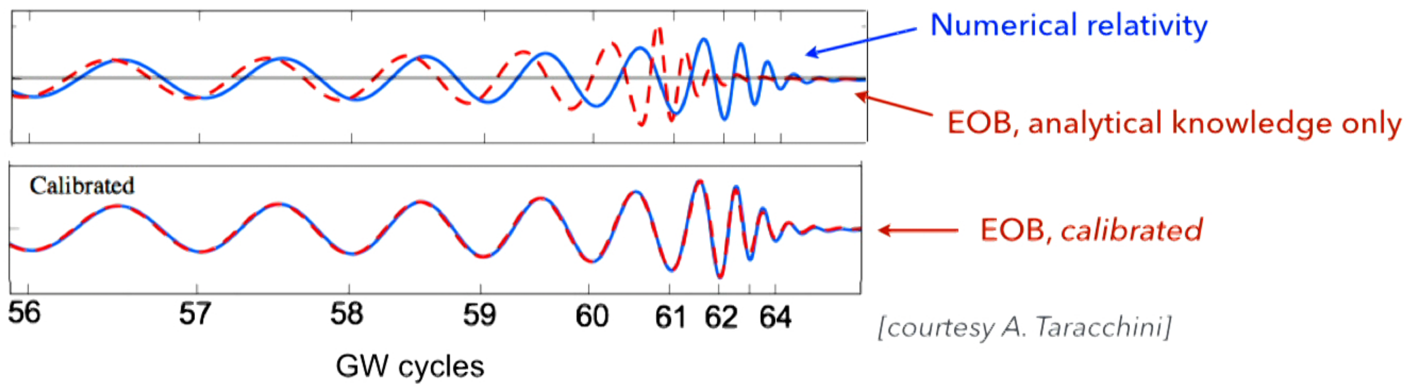
EOB Hamiltonian + GW dissipation + wave generation

Complete EOB waveforms for black hole binaries



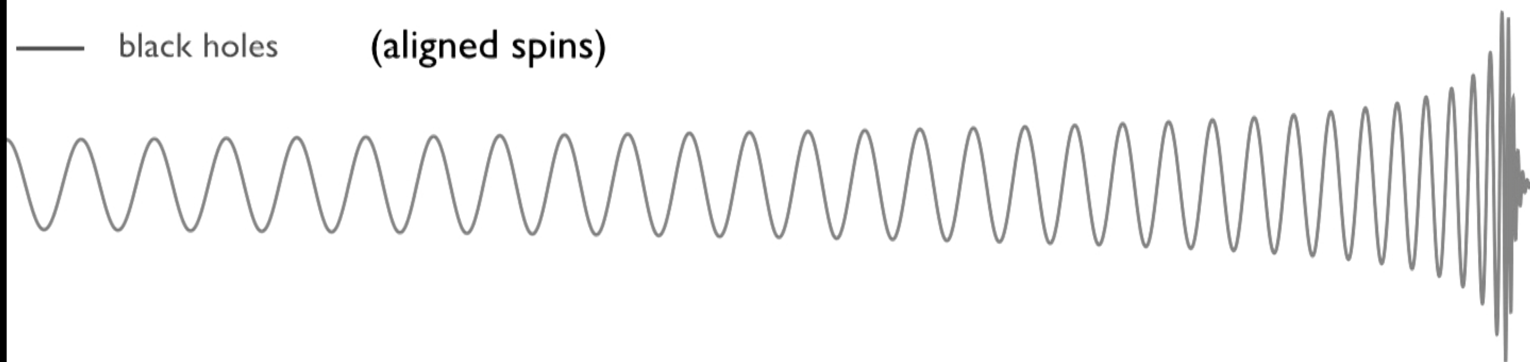


- performance of EOB waveforms:



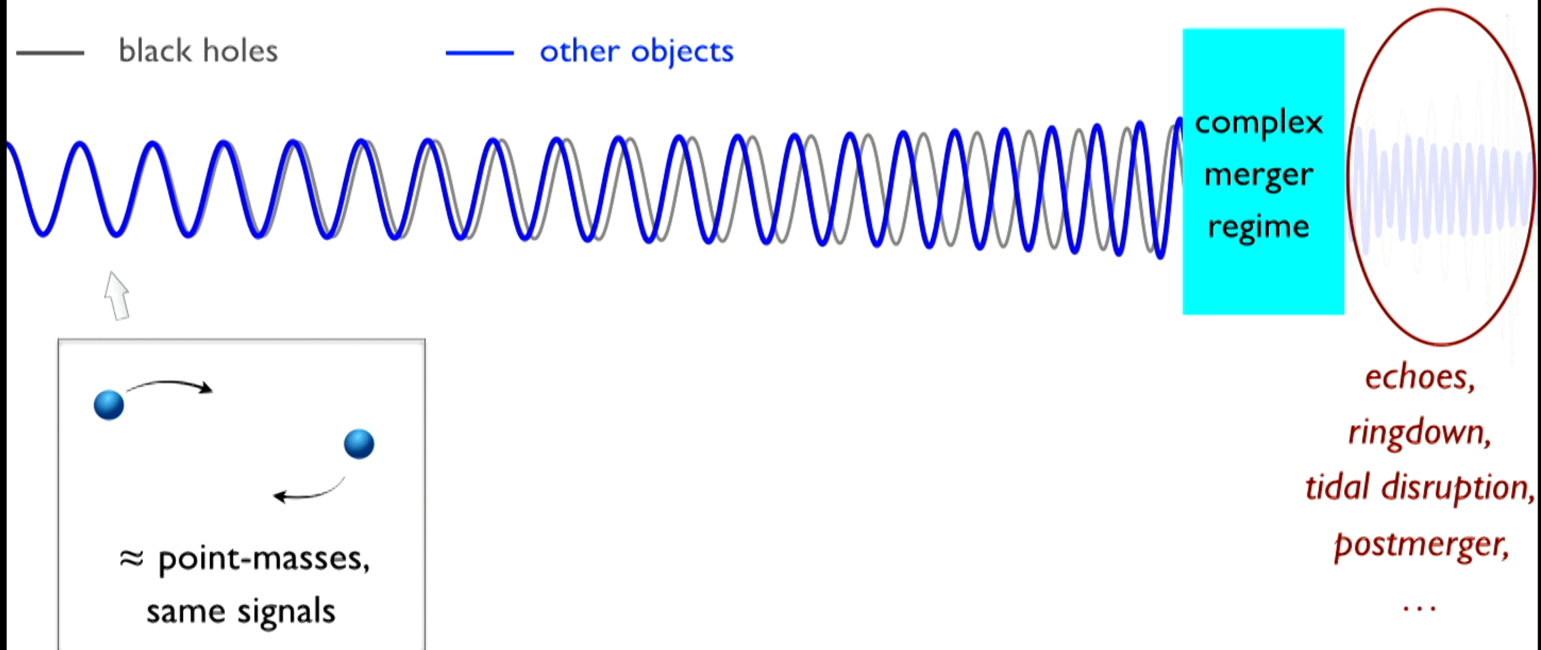
[courtesy A. Taracchini]

Imprints of objects' internal structure on GWs



What changes for non-black hole objects?

Imprints of objects' internal structure on GWs



[~10³ cycles for few-Msun objects in LIGO]

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

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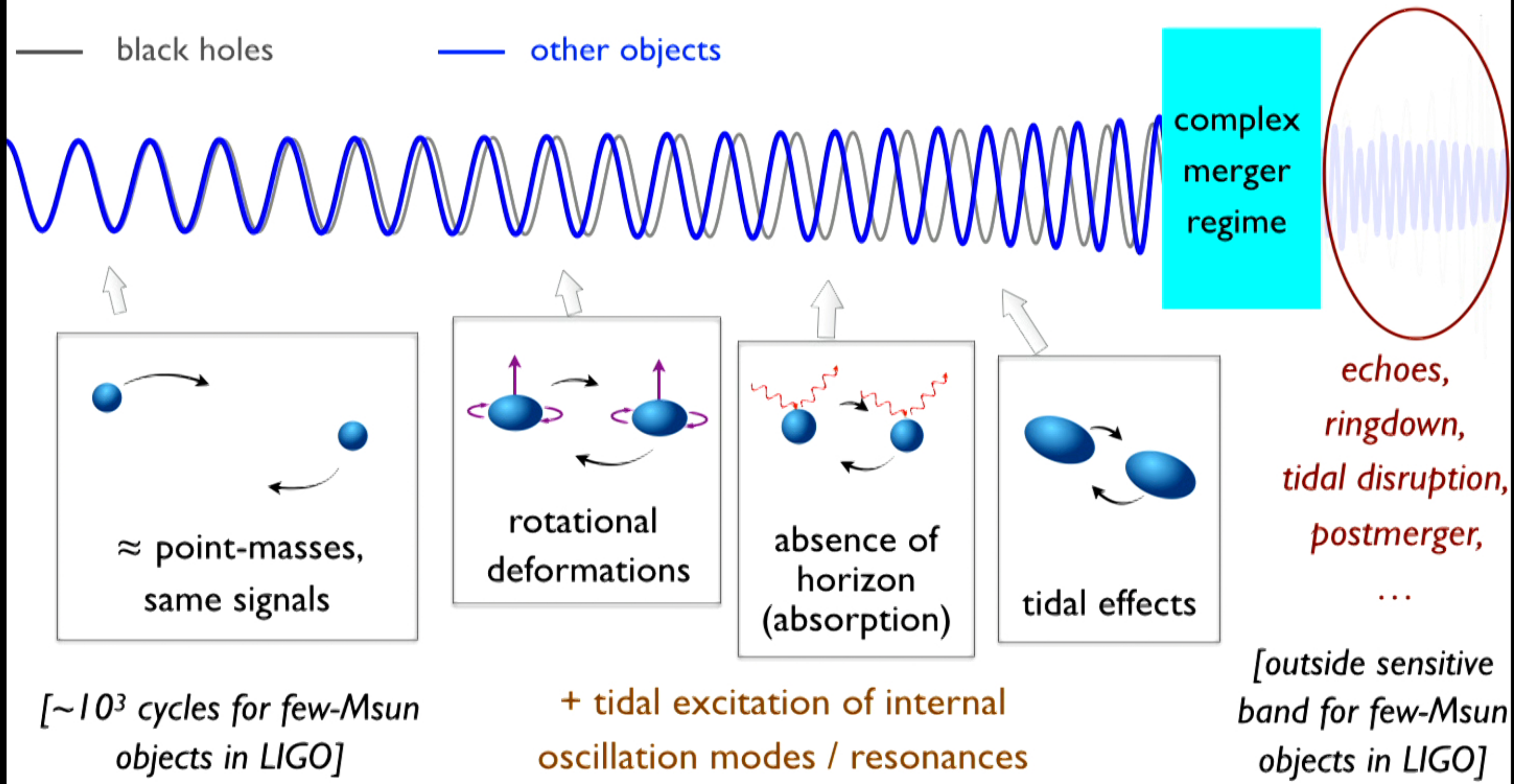
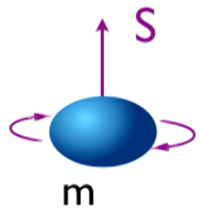
Imprints of objects' internal structure on GWs



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

$\lesssim$ 15 for neutron stars

nonzero for many exotic objects

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

$\leq$1 for black holes

$\lesssim$ 0.4 for millisecond pulsars

- Effects known in post-Newtonian (PN) theory: first enters at 2PN order

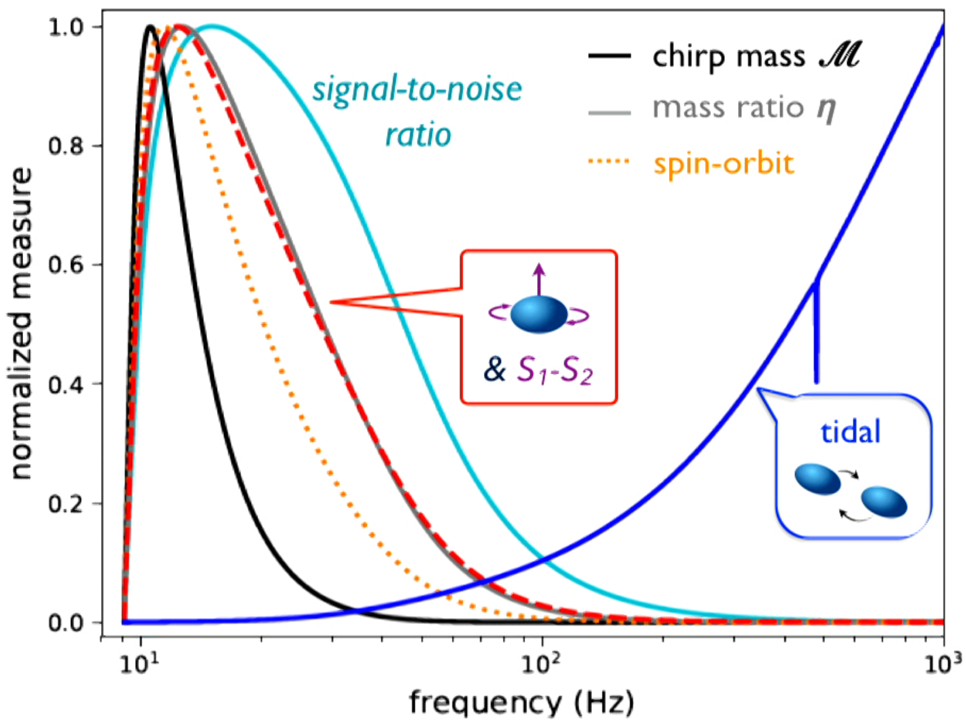
[see Arun+ 2017 for a recent compilation

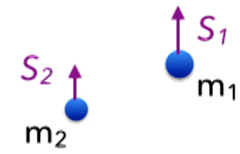
- also included in EOB

[Nagar+ 2017, Vines, Marsat+ 2017]

Accumulation of information about source properties

Where in frequency does information about different source parameters come from [aLIGO]?





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

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

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

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]

Characteristic dimensionless parameters:

$$\epsilon = \frac{m}{R} \qquad \alpha = \frac{R}{D} \qquad \epsilon_{\rm orbit} = \frac{M}{D}$$

Internal gravity | *Tidal expansion* | *post-Newtonian expansion*

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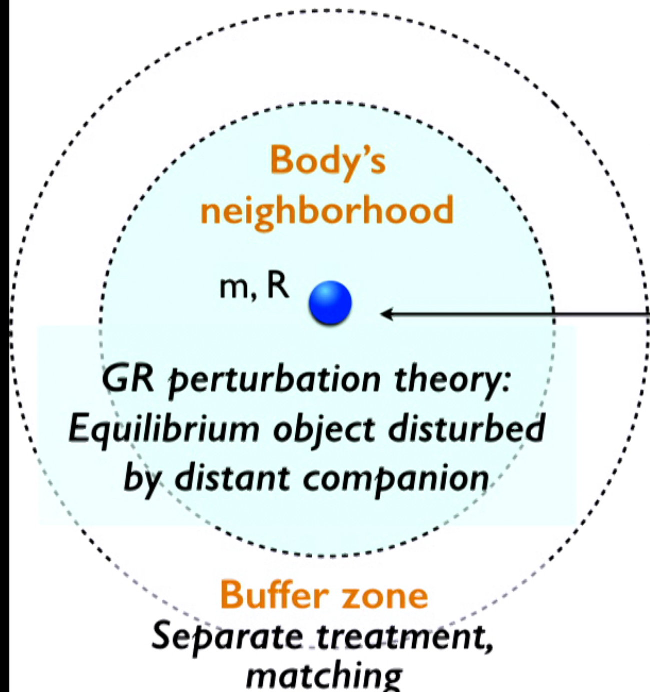

Interaction zone

post-Newtonian expansion of orbital dynamics (& EOB resummation): Point-masses + finite-size effects

D

Characteristic dimensionless parameters:

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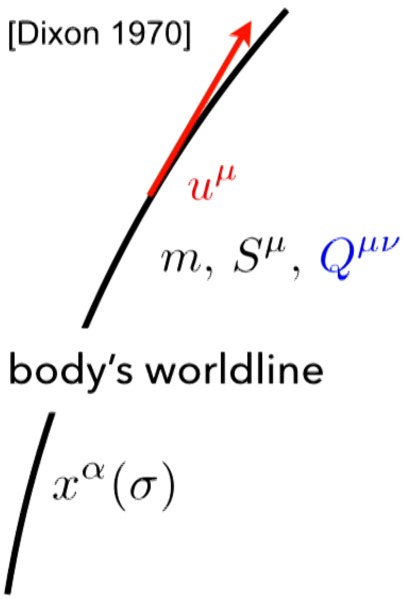
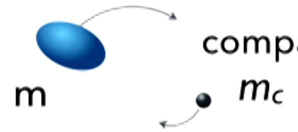
Internal gravity — *Tidal expansion* — *post-Newtonian expansion*

Tidal effects on the dynamics (quadrupole only, no spin)

World-line-skeleton for extended bodies

[Dixon 1970]





Dynamics described by an effective action:

$$S = S_{\rm pp} + \int d\sigma\, \left[L_{\rm tidal} + L_{\rm internal}\right]$$

point-mass contribution

dynamics of quadrupole $Q^{\mu\nu}$

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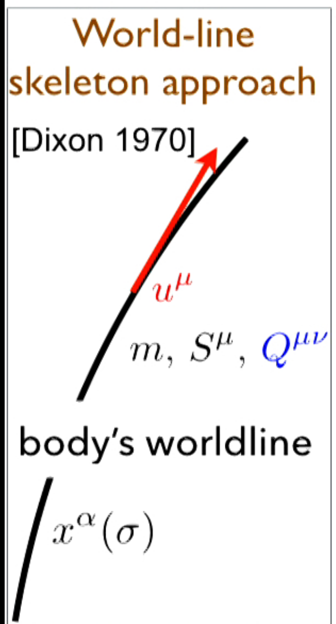
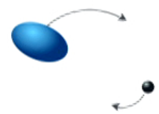
Tidal effects on the dynamics (quadrupole only, no spin)





$$S = S_{\rm pp} + \int d\sigma\ [L_{\rm tidal} + L_{\rm internal}]$$

$$L_{\rm tidal} = -\frac{z}{2}\mathcal{E}_{\mu\nu}Q^{\mu\nu}$$

$$z = \sqrt{-u_\mu u^\mu}$$

$$\mathcal{E}_{\mu\nu} = C_{\mu\alpha\nu\beta}\frac{u^\alpha u^\beta}{z^2}$$

Weyl tensor (companion)

$$\frac{D}{d\sigma} = u^\alpha \nabla_\alpha$$

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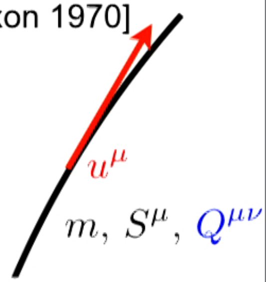
Tidal effects on the dynamics (quadrupole only, no spin)

World-line skeleton approach

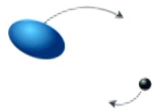
[Dixon 1970]



body's worldline

$x^\alpha(\sigma)$

$$\frac{D}{d\sigma} = u^\alpha \nabla_\alpha$$



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Weyl tensor (companion)

Induced multipoles behave approximately as harmonic oscillators:

$$L_{\rm internal} = \frac{z}{4\,\lambda\, z^2\,\omega_f^2}\left[\frac{DQ^{\mu\nu}}{d\sigma}\frac{DQ_{\mu\nu}}{d\sigma} - z^2\,\omega_f^2\,Q^{\mu\nu}Q_{\mu\nu}\right] + \dots$$

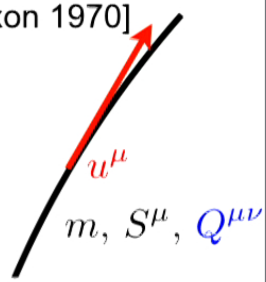
Tidal deformability parameter

other l=2 modes & other stuff e.g. from mode incompleteness

Tidal effects on the dynamics (quadrupole only, no spin)

World-line skeleton approach

[Dixon 1970]



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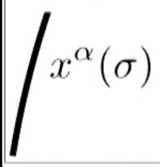

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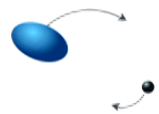

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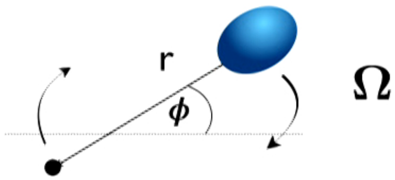
Tidal deformability parameter

fundamental oscillation mode frequency

other l=2 modes & other stuff e.g. from mode incompleteness

Reduce to physical degrees of freedom

- 3+1 split & spherical-harmonic decomposition



$$L_{\rm tidal} = -\frac{z}{2}\sum_{m=-2}^{2} Q_m \mathcal{E}_m e^{-im\phi}$$

$$L_{\rm int} = \frac{1}{4\lambda z \omega_f^2}\sum_{m=-2}^{2}\left(\dot{Q}_m^2 - z^2\omega_f^2 Q_m^2\right) + L_{\rm frame}$$

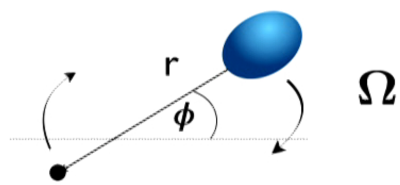
coupling of orbital and
Q's angular momentum

$$S_Q^{ij} = \frac{2}{\lambda\,\omega_f^2} Q^{k[i}\dot{Q}^{j]k}$$

Reduce to physical degrees of freedom

- 3+1 split & spherical-harmonic decomposition

$$L_{\rm tidal} = -\frac{z}{2}\sum_{m=-2}^{2} Q_m \mathcal{E}_m e^{-im\phi}$$



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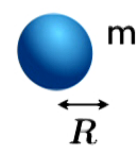
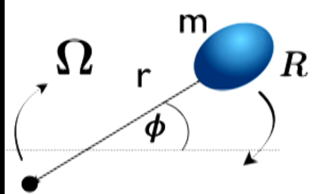
Scalings: • *f*-mode frequency: $\omega_f \sim \sqrt{m/R^3}$ (internal structure - dependent)



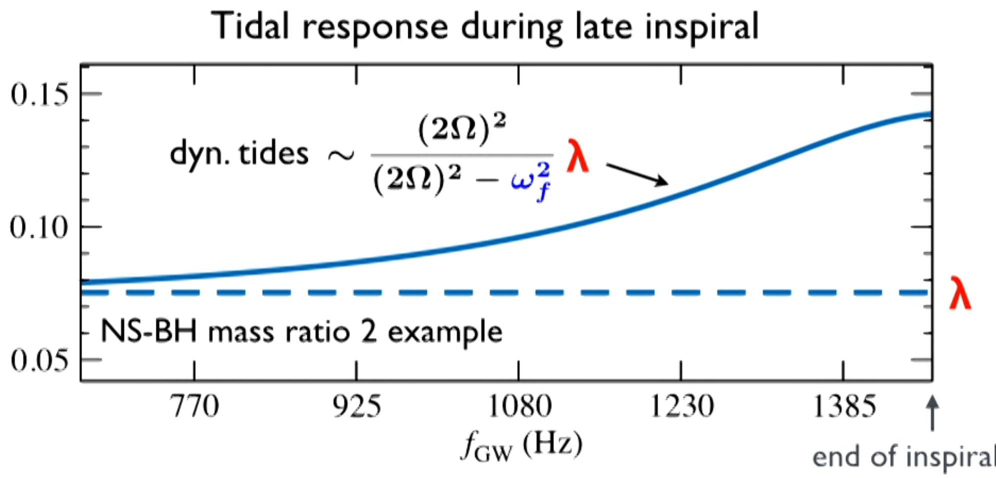
- **tidal forcing** frequency: $\sim 2\Omega \sim 2\sqrt{M/r^3}$

- adiabatic limit $2\Omega \ll \omega_f$: equilibrium solutions $Q_m = -\lambda\, \mathcal{E}_m e^{-im\phi}$

Tidal response during an inspiral



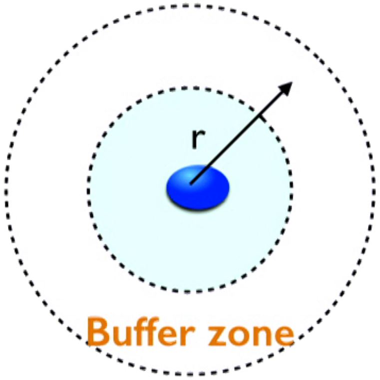
$$\sum_m \frac{Q_m \mathcal{E}_m}{\mathcal{E}_m^2}$$



TH +(2016) , Steinhoff, **TH**+ (2016)

Tidal deformability parameter

- adiabatic limit $2\Omega \ll \omega_f$
- Sufficient to consider m=0: $\mathcal{Q} = -\lambda\,\mathcal{E}$
- quantities defined by the asymptotic metric (buffer zone) e.g. in the object's local rest frame:



$$\frac{(1+g_{tt})}{2} = -\frac{\mathrm{m}}{r} - \frac{3\,\mathcal{Q}\,Y_{20}(\theta,\phi)}{2\,r^3} + \dots$$
$$+\frac{1}{2}\,\mathcal{E}\,r^2\,Y_{20}(\theta,\phi) + \dots$$

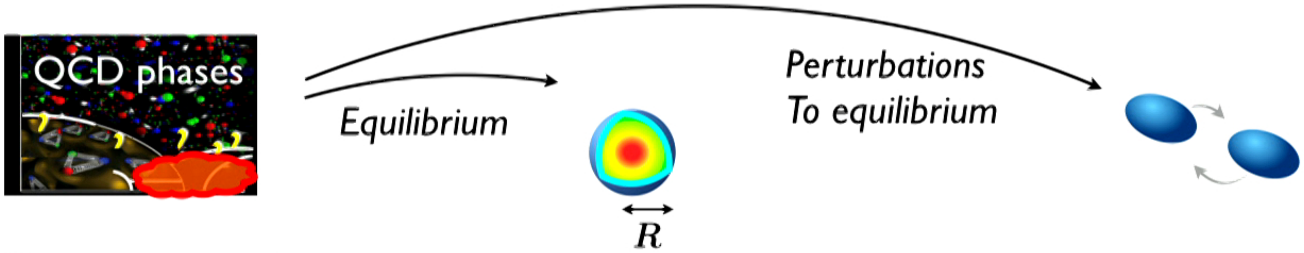
[TH 2008, Flanagan & TH 2008]

- Determined from Einstein's equations: linear static perturbations to equilibrium

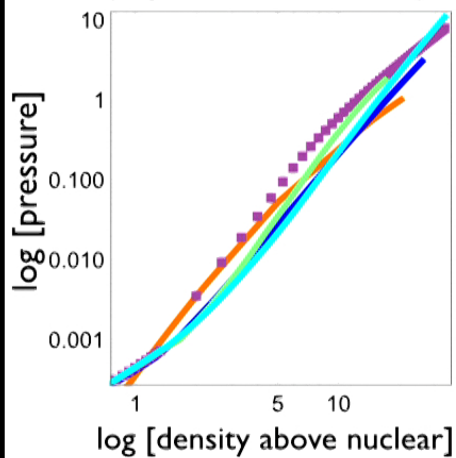
- λ=0 for a nonspinning BH [e.g. Kol & Smolkin 2011]

Similar method for higher multipoles [Damour, Nagar 2009, Binnington, Poisson 2009]

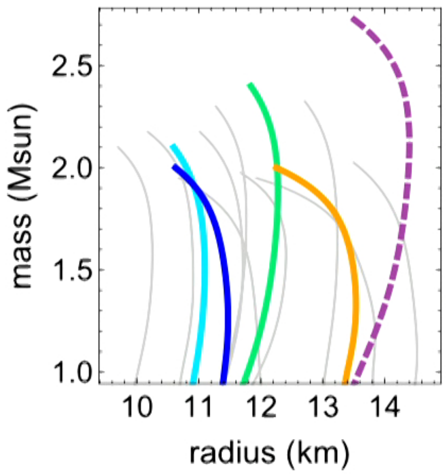
Properties of NS matter reflected in global observables



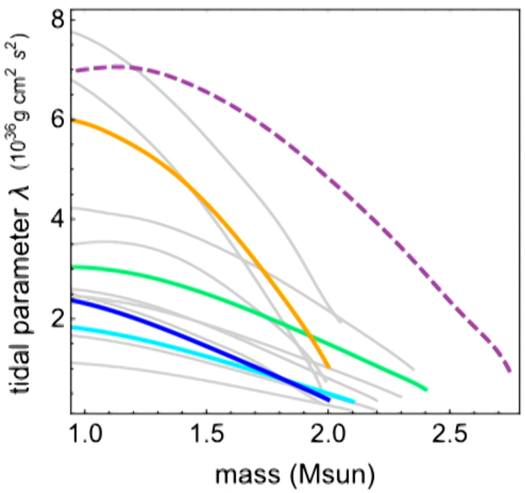
NS matter models (equations of state)



Mass vs. radius



tidal deformability λ vs. mass

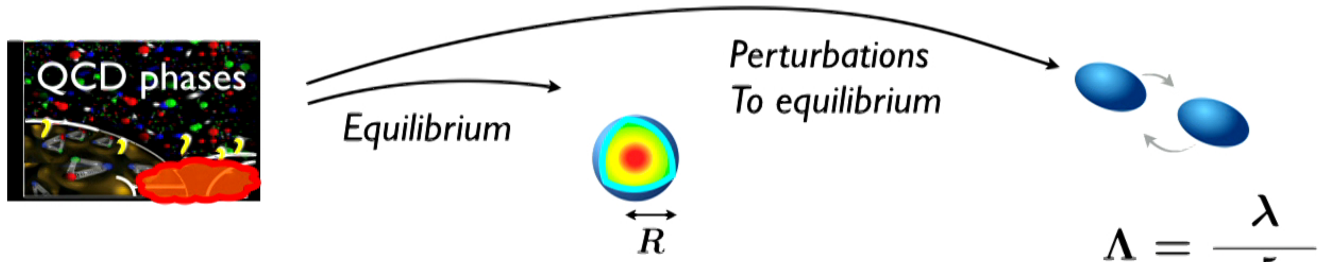


$$\lambda = \frac{2}{3} k_2 R^5$$

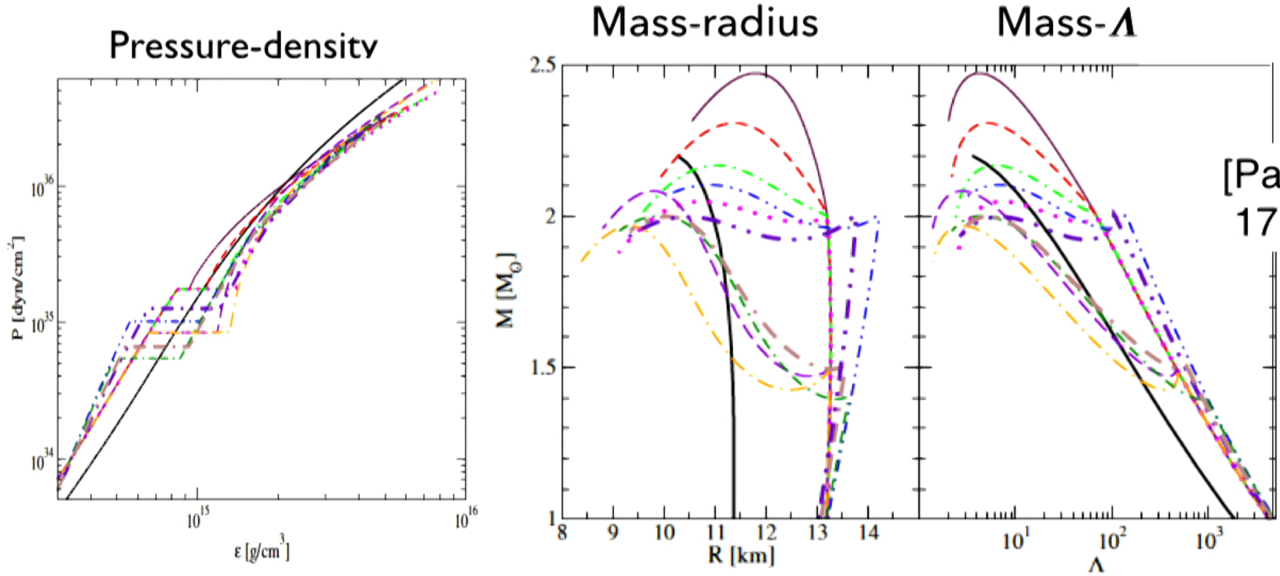
dimensionless Love number

[TH+ 2010]

Effect of a phase transition to quark matter



$$\Lambda = \frac{\lambda}{m_{\rm NS}^5}$$



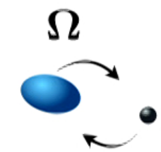
[Paschalidis+ 1712.00451]

+ expect signatures in oscillation modes that can get tidally excited during inspiral

Influence on the GWs

- Energy goes into deforming the NS

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



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

- moving tidal bulges contribute to gravitational radiation

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

$$M = m_1 + m_2$$

- approx. GW phase:

$$\frac{d\phi_{\rm GW}}{dt} = 2\Omega, \qquad \frac{d\Omega}{dt} = \frac{\dot{E}_{\rm GW}}{dE/d\Omega}$$

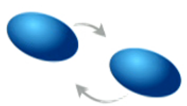
Adiabatic tidal contribution:

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

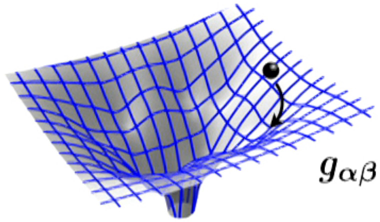
[Flanagan & TH, 2008, Vines, Flanagan & TH 2011]

- for NS-NS, tidal analogue of the chirp mass is:

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



Adiabatic tidal effects in the EOB model

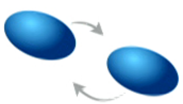


$$g_{\alpha\beta} \sim g_{\alpha\beta}^{\mathrm{Kerr}} + \nu\, \delta g_{\alpha\beta} + \lambda\, \delta g_{\alpha\beta}^{\mathrm{Tidal}}$$

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

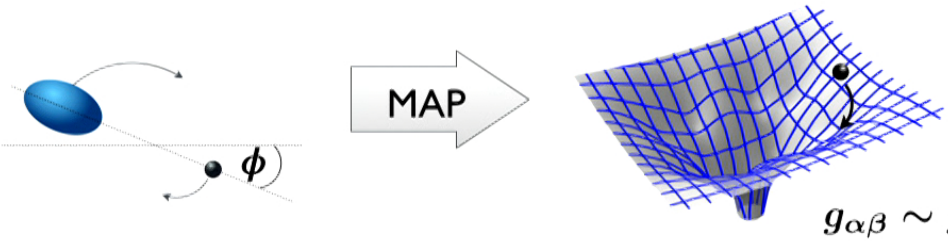
- for NS-NS: dominant tidal contribution to the energy (and EOB Hamiltonian) characterized by

$$\kappa_2^T = 3\left(\frac{m_2}{m_1}\lambda_1 + \frac{m_1}{m_2}\lambda_2\right)$$



+ tidal correction to GW amplitude [Damour+2012]

EOB with *approximate* dynamic tides



$$g_{\alpha\beta} \sim g^{\rm Kerr}_{\alpha\beta} + \nu\, \delta g_{\alpha\beta} + \lambda^{\rm eff}\, \delta g^{\rm Tidal}_{\alpha\beta}$$

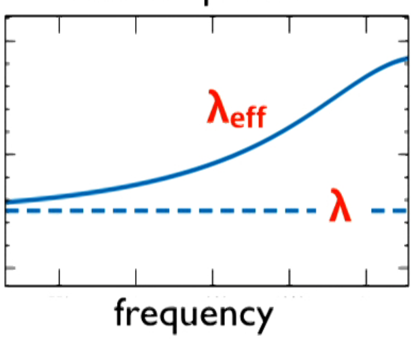
- effective tidal deformability approximates dynamical tides:

$$\frac{\lambda_\ell^{\rm eff}}{\lambda_\ell} \sim \frac{\omega_f^2}{\omega_f^2 - (m\Omega)^2} \;\&\; \frac{\omega_f^2}{(\phi - \phi_f)} \;\&\; \cos\left[(\phi-\phi_f)^2\right] {\rm FresnelS}(\phi - \phi_f)$$

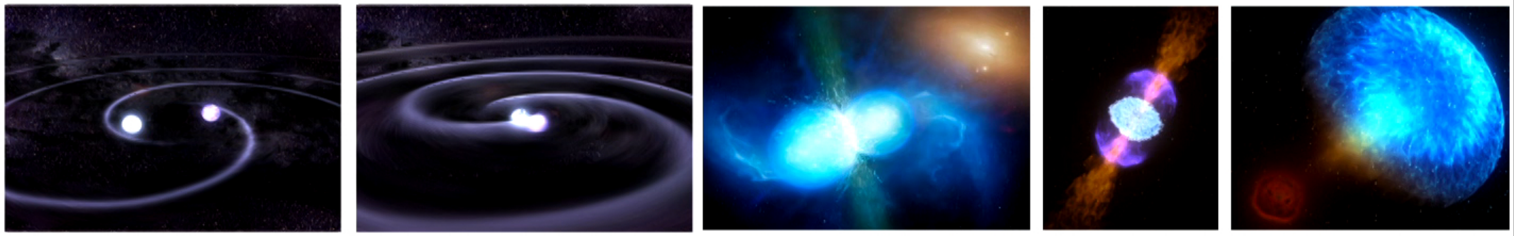
before resonance — common term — near resonance where $\phi \sim \phi_f$

all fns. of $\{M, \nu, \omega_f, r\}$

Tidal response



GW170817



credit: NASA/GSF

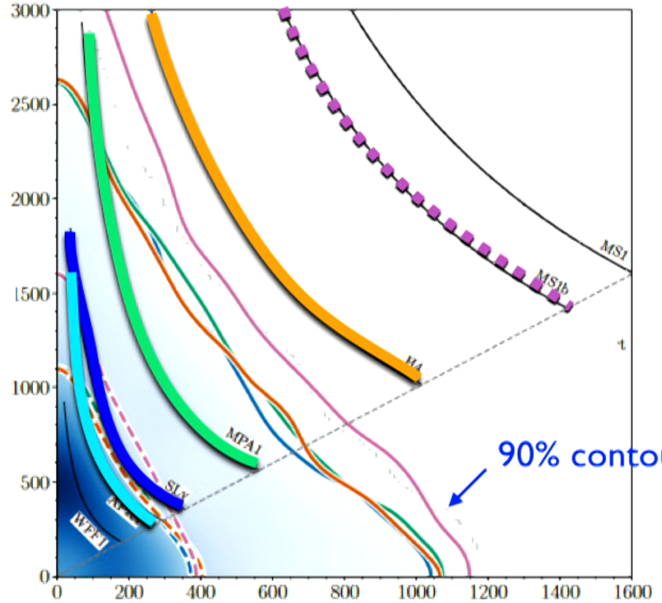
Distance: ~40 Mpc, total mass: ~ 2.74 Msun

Loudest & closest event so far, rich science gains:

- Strong-field, dynamical gravity with matter
- Cosmic Enrichment
- Stellar and binary evolution
- Cosmology
- *Physics of matter and fundamental forces in extreme conditions*

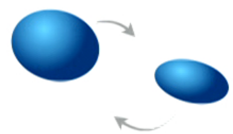
Measurements of tidal deformability for GW170817

- Results for dimensionless tidal deformability $\Lambda = \dfrac{\lambda}{m_{\rm NS}^5}$



Λ_2

Λ_1



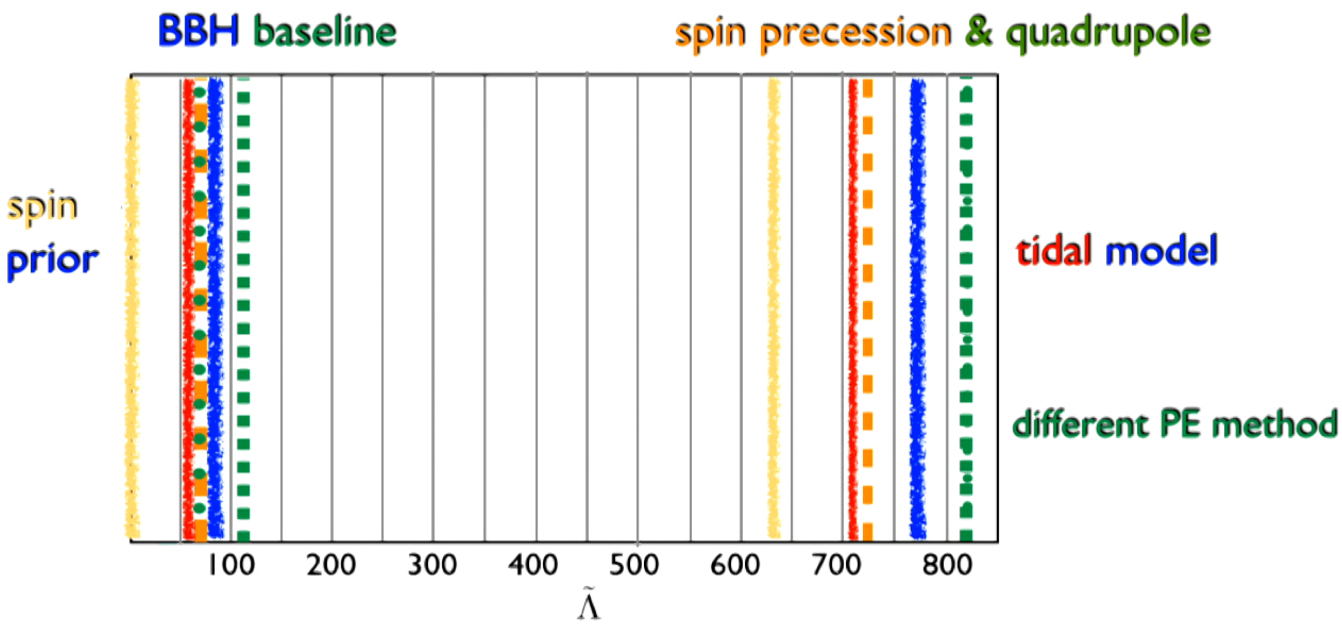
LVC arXiv:1805.11579

90% contours with different GW models

22

Systematic uncertainties due to modeling (estimated, in $\tilde{\Lambda}$)

LVC 1805.11579

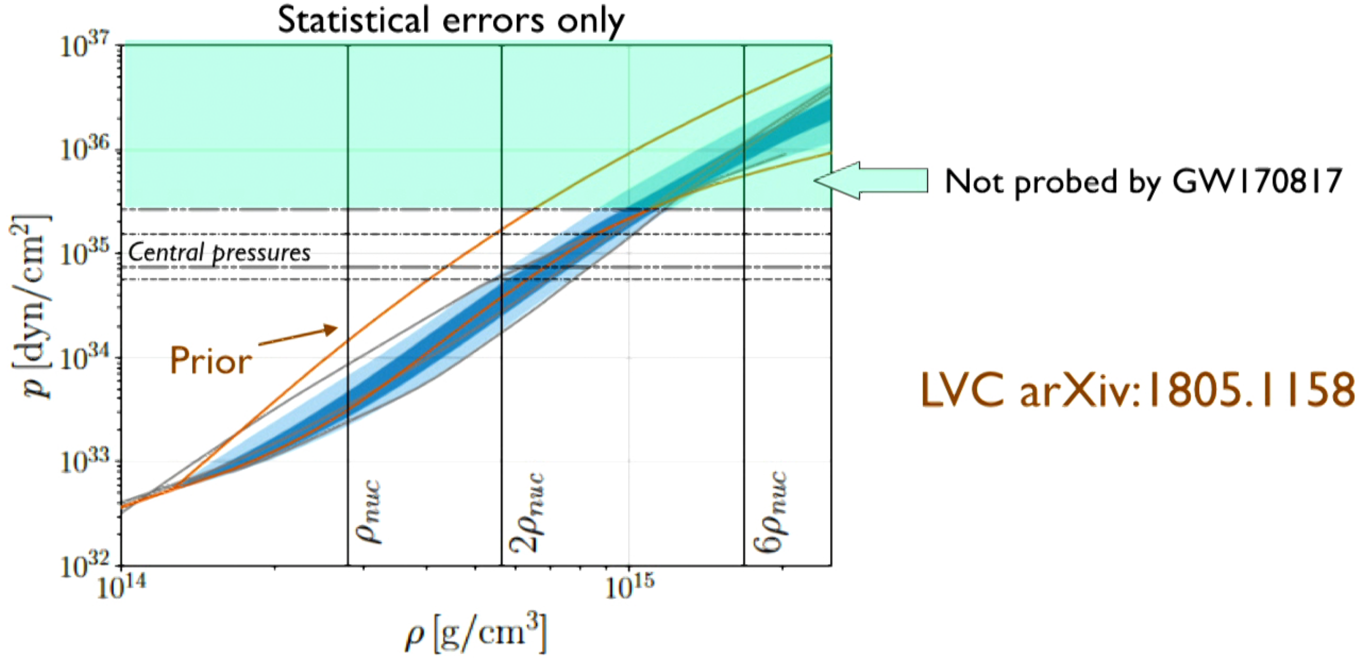


+ detector calibration uncertainty not considered here

Inferring the EoS (restrictive assumptions)

- low-spin priors χ<0.05
- both objects have the same equation of state (EoS)
- Waveform model calibrated to NR for NS-NS binaries

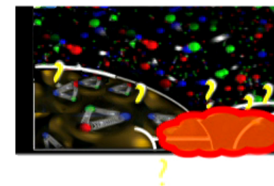
- Results with spectral EoS parameterization [Lindblom] incl. ~1.97Msun constraint



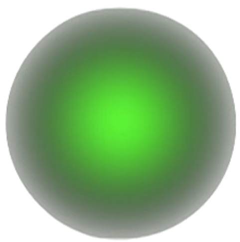
LVC arXiv:1805.11581

Examples of broader uses of tidal deformability

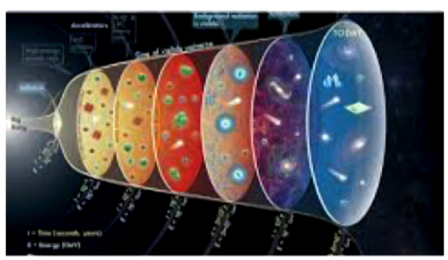
- Nuclear physics: Symmetry energy, vector interactions,…
- astrophysics: NS radius
- Nuclear experiments: neutron skin thickness of lead 208



[Fattoyev+ 1711.06615]



- exotic objects [e.g. Mendes+, Cardoso, Pani,+, Sennett+, Johnson-McDaniel+, ….
- axion clouds [e.g. Baumann+1804.03208, Brito+ 2018,…]
- dark matter halos [e.g. Nelson + arXiv:1803.03266v1, …]

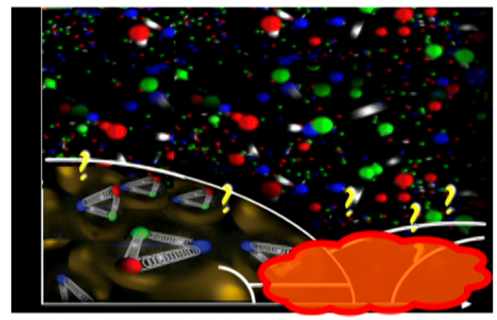


- Test models for cosmological constant as vacuum energy of a QFT

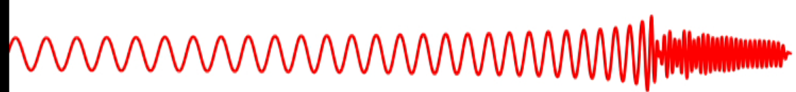
[Csaki+ arXiv:1802.04813]

Outlook

- Anticipated detector improvements ~2020:
  - observe binary NSs ~ 2x further away (or at same distance with better accuracy)
  - Improve high-frequency sensitivity by ~ factor of 5
    - Populations
    - Measure subdominant effects?
    - Oscillation modes - asteroseismology?
    - Observe merger/postmerger, tidal disruption?



- Third-generation detectors ~ 10x better sensitivity



- Expect a wealth of new insights in the coming years
- Requires significant further advances (modeling, analysis)