Gravitational Waves and Fundamental Physics

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After a huge experimental and theoretical effort, we have finally detected GWs

From September 2015, five (maybe six) coalescences BH-BH and one NS-NS have been observed by the LIGO & Virgo interferometers (*see Gemme's talk*) opening a new window to the Universe:

for the first time, we can observe the strong-field, large-curvature regime of gravity

In this regime, new fundamental physics questions can be addressed, such as:

- How does gravity behave in the strong-field regime?
- How does matter behave at supranuclear densities?

In this talk I will focus on these questions, discussing why they are important and how GWs can help us addressing them.

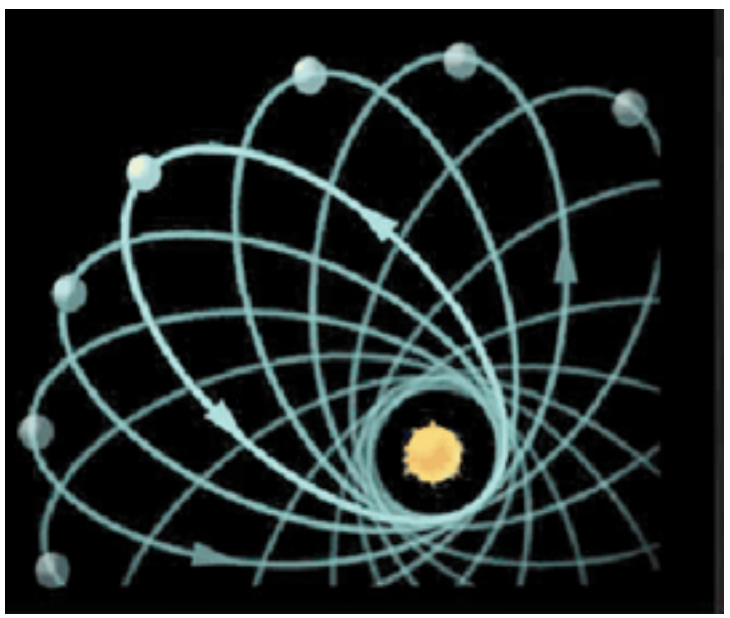
GWs can also help addressing other, equally important, questions about astrophysical processes and phenomena, which will not be discussed here (see Brocato's talk)

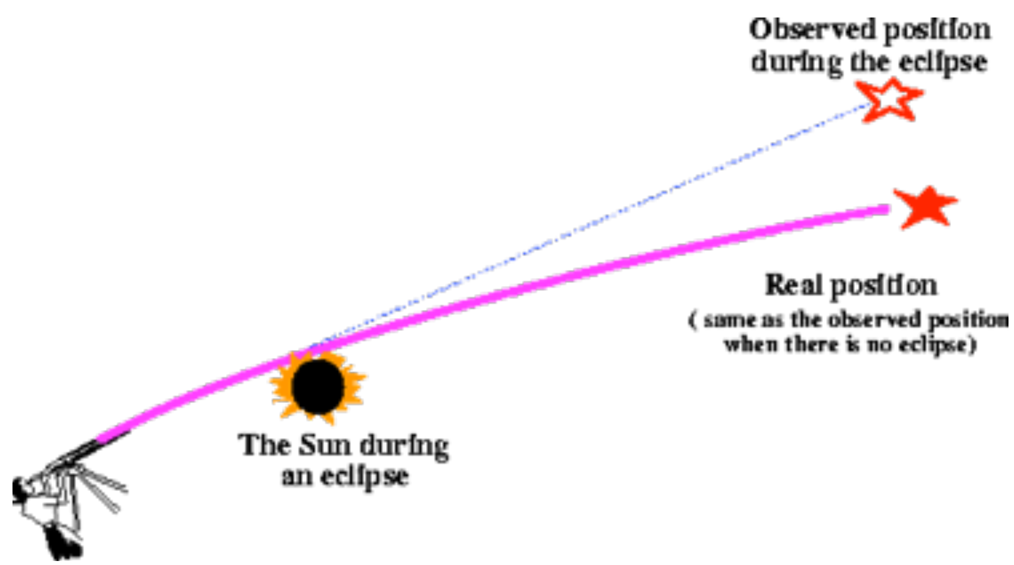
1) How does gravity behave in the strong-field regime?

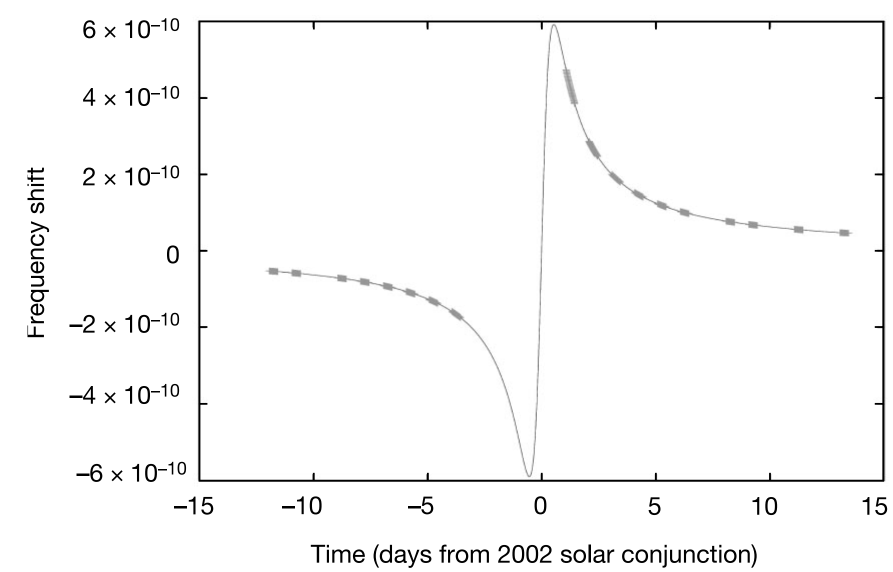
Gravity, the weakest of fundamental interactions, has been observed for centuries, in which General Relativity (GR) has passed several tests with flying colors:

- Solar system tests

Started when GR was first formulated, one century ago (perihelion precession, light deflection, gravitational redshift), solar system tests became more and more accurate, up to the measurement of Shapiro delay from Cassini spacecraft in 2002 with an accuracy ~10^5







Bertotti et al., Nature '03

1) How does gravity behave in the strong-field regime?

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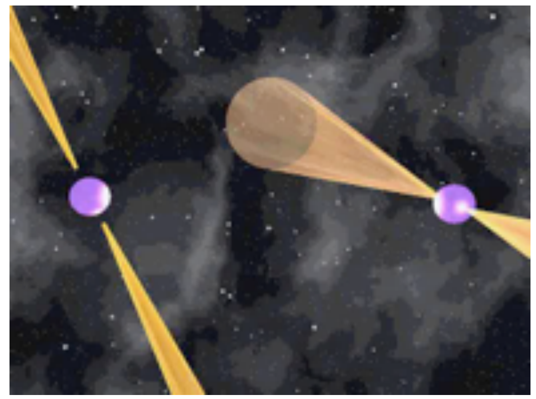
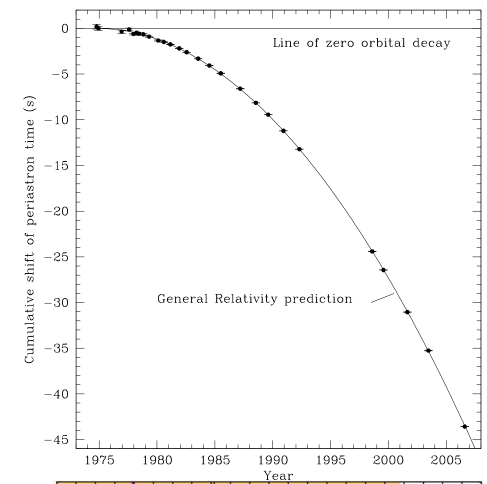
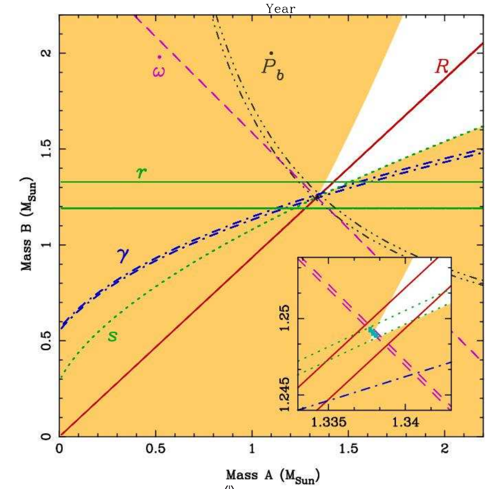
- Binary pulsar tests





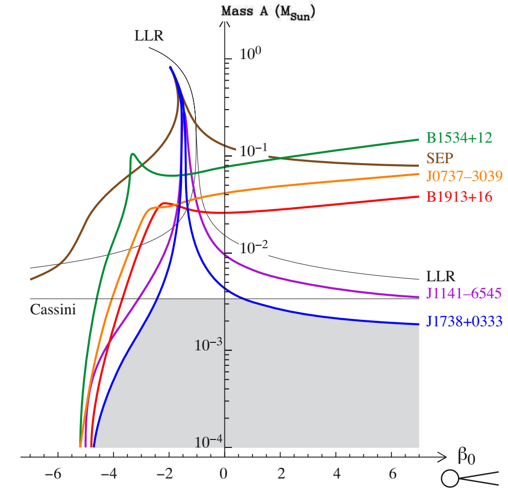
Weisberg et al., '10

- PSR 1913+16:
  inspiral, and decrease of orbital period,
  due to energy loss through GW emission
  (first indirect proof of the existence of GWs)



Kramer et al., '06

- PSR J0737-3039 (discovered here in Cagliari by Burgay, Possenti, D'Amico *et al.*):
  double pulsar, "the most relativistic" system,
  provides strong tests of GR



Freire et al., '12

- PSR J1738+0333 (and J0348+0432):
  NS-WD systems, best to constrain parameter
  space of scalar-tensor gravity

1) How does gravity behave in the strong-field regime?

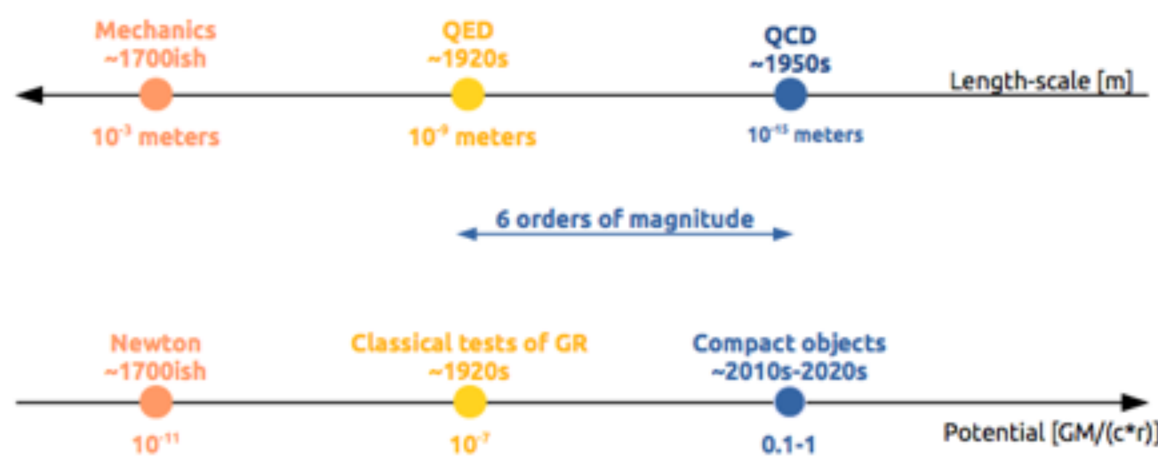
Gravity, the weakest of fundamental interactions, has been observed for centuries, in which General Relativity (GR) has passed several tests with flying colors:

- Solar system tests

- Binary pulsar tests

Problem: these tests mostly probed the weak-field, small-curvature regime of gravity!

- There is no fundamental reason to believe that gravity behaves in the same way in strong-field regime!



Credits: Pani, '15

- Theoretical issues (unification with the quantum world, singularities and other weird features of GR)

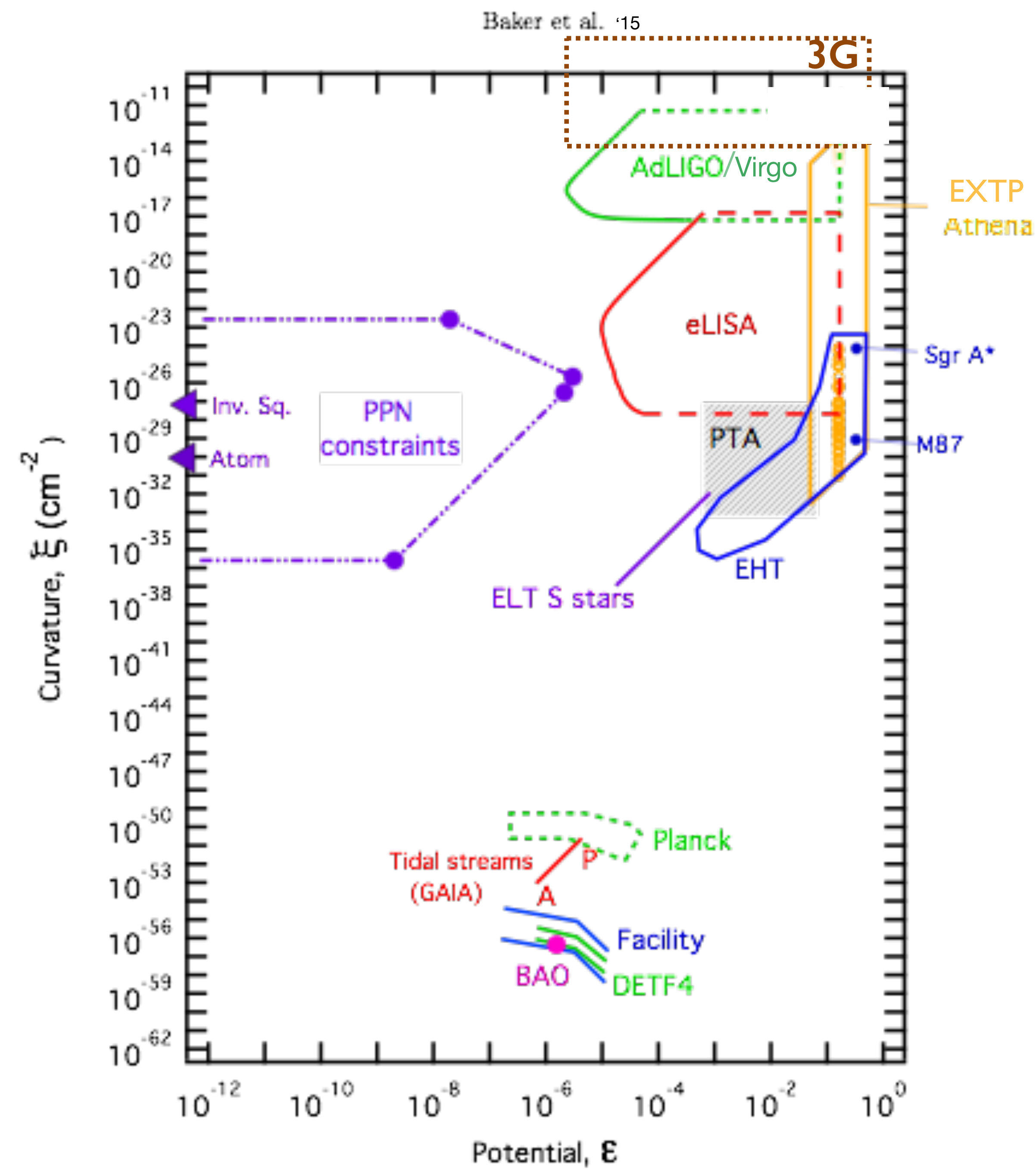
- Observational issues (dark matter & energy)

1) How does gravity behave in the strong-field regime?

The strength of gravity can be parametrized either by gravitational potential ε=GM/r or by spacetime curvature ξ=GM/r^3

GWs are the perfect probe of the strong-field, large-curvature regime of gravity:

- only generated in strong-field processes
- sensitive to generation and propagation, which give complementary information
- do not interact when travelling



1) How does gravity behave in the strong-field regime?

Testing GR with GWs & with astrophysical observations *(e.g. Berti et al. CQG '15, arXiv:1501.7274)*

One can follow either a bottom-up or a top-down approach.

Bottom-up approach:

- choose the phenomenology to be studied, and the quantities most appropriate to describe it
- devise a parametrization of these quantities
- typically, each parameter is associated to the violation/modification of some GR property
- compute observables in terms of the parameters
- perform observations/experiments, setting bounds to the parameters

- PPN (parametrized post-Newtonian) expansion (*Eddington '22; Nordtvedt '68; Will '71*)
  PN expansion of the spacetime metric of e.g. 2-body system is extended including free parameters.
  e.g.:
  $$ds^2 = -\left(1 - 2\frac{M}{r} + 2\beta\frac{M^2}{r^2} + \ldots\right)dt^2 + \left(1 + 2\gamma\frac{M}{r} + \ldots\right)(dr^2 + r^2 d\theta^2 + r^2 \sin^2\theta d\phi^2)$$
  In GR β=0, γ=1. Appropriate framework for solar system tests

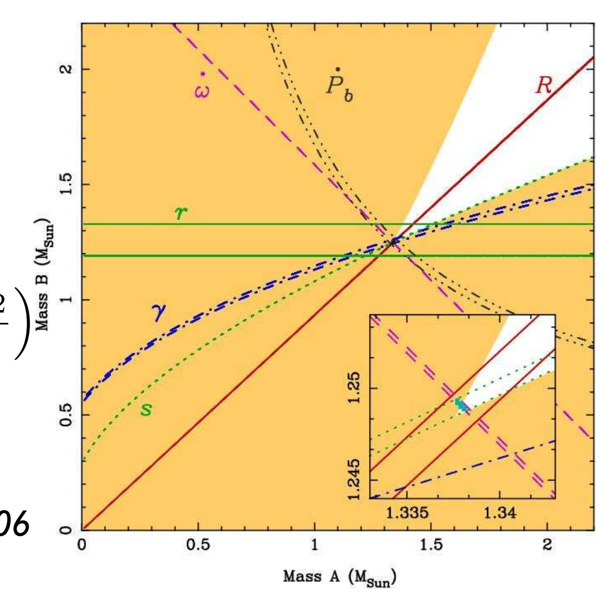
- PPK (parametrized post-Keplerian) expansion (*Damour & Taylor '92*)
  motion of compact binary characterized by Keplerian and post-Keplerian parameters. Appropriate framework for binary pulsar tests:

perhielion precession: $\langle\dot{\omega}\rangle = 6\pi f_{\rm b}(2\pi m f_{\rm b})^{2/3}(1-e^2)^{-1},$

time dilation: $\gamma' = e(2\pi f_{\rm b})^{-1}(2\pi m f_{\rm b})^{2/3}\frac{m_2}{m}\left(1+\frac{m_2}{m}\right)$

period decrease (inspiralling): $\dot{P}_{\rm b} = -\frac{192\pi}{5}(2\pi\mathcal{M} f_{\rm b})^{5/3}F(e),$

Shapiro delay: $r = m_2,$ $s = \sin i,$



Kramer et al., '06

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- PPE (parametrized post-Einstenian) expansion (*Yunes & Pretorius '09*)
  GW compact binary waveform is directly parametrized:

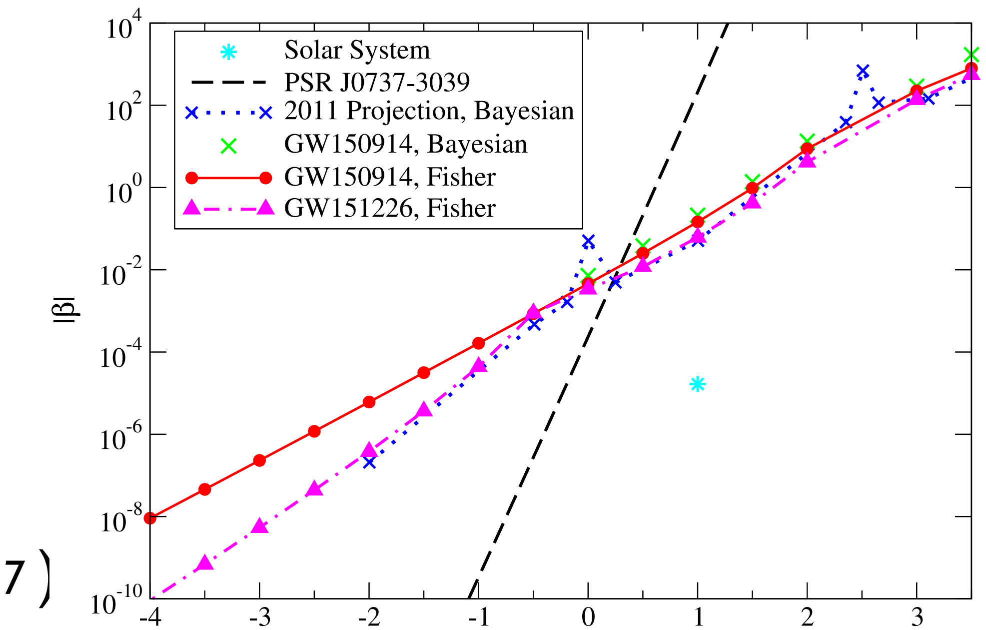
$$h(f) = A_{GR}(f)(1+\alpha x^a)e^{i\Psi_{GR}(f)+i\beta x^b}$$

ppE paramters:

α,β (=0 inGR): amplitude of modification;

a,b: PN order $x=(2\pi Mf)^{2/3}$

mapping: (α,β,a,b) <=> specific theories



(Yunes et al., PRD '16)

- PPF (parametrized post-Friedmannian) expansion (*Hu & Sawitcki '07*)
  cosmological quantities & equations are parametrized

1) How does gravity behave in the strong-field regime?

Top-down approach:

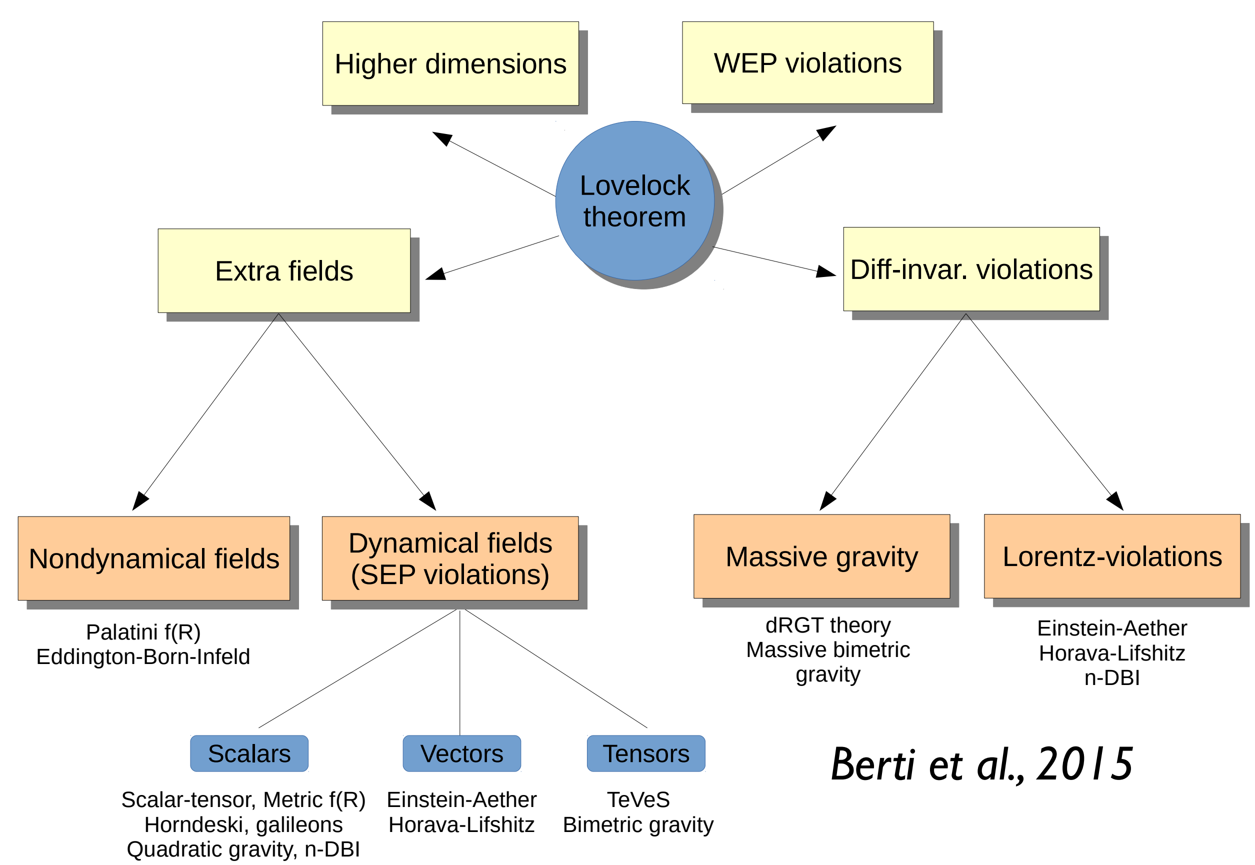
- consider GR modifications, possibly inspired by fundamental physics considerations
- work out observational consequences of these modifications

  (they typically depend on parameters describing the amplitude of the modification)
- compare with observations, setting bounds on the parameters

Remarks:

- in most cases we are looking to tiny modifications (parameters small due to existing data)
- often difficult to disentangle from poorly known "standard" physics effects (BHs better than NSs)
- best (when possible) would be to find *new effects* (smoking-guns),

There are several ways to modify GR…

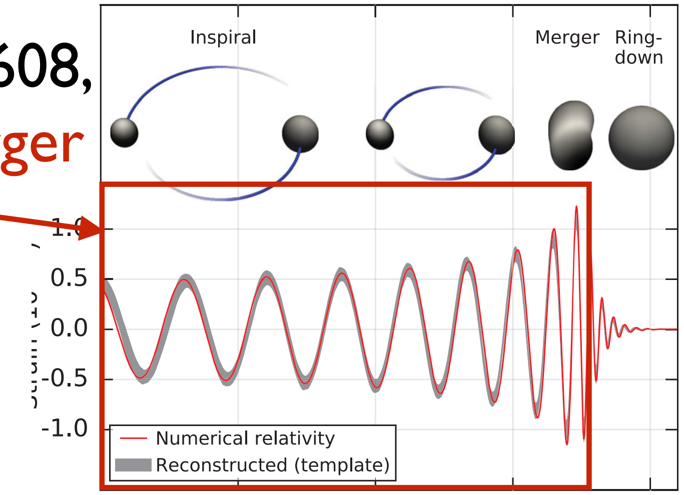


Berti et al., 2015

Testing General Relativity with Gravitational Waves

- Inspiral and merger

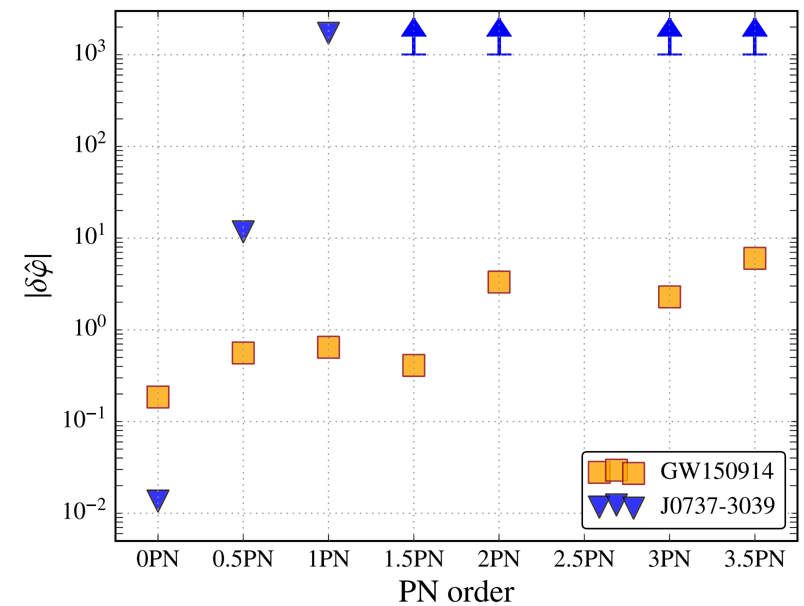
Most of the information of GW150914, GW151226, GW170104, GW170608, GW170814, GW170817 has been extracted from the inspiral and the merger



Current tests (see Gemme's talk):

- Test of the PN coefficients:

comparing the signal with extended PN model of inspiral and late-inspiral, we set strict upper bounds on the PN coefficients modifications.
This is a test of several possible deviations.



(Abbot et al., Testing of GR with GW150914, PRL '16)

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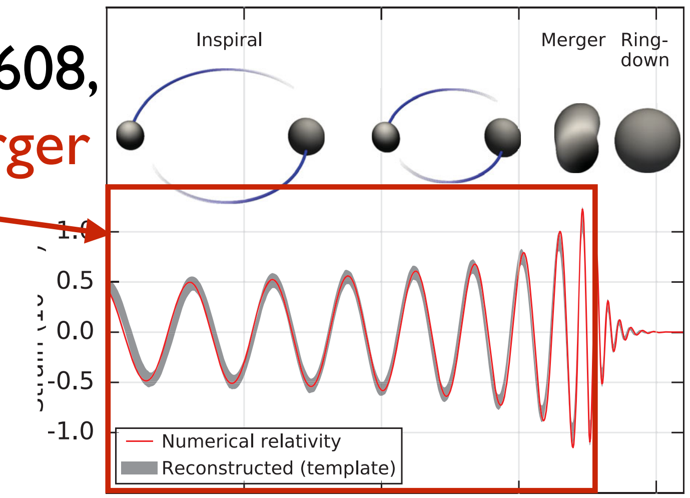

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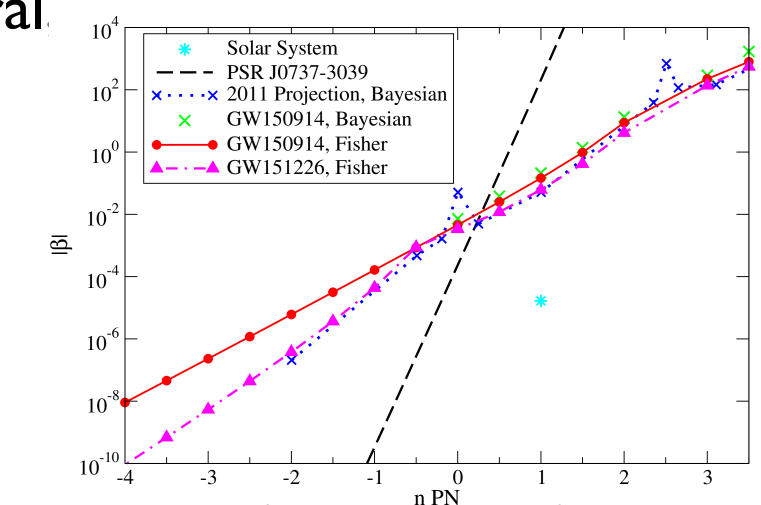


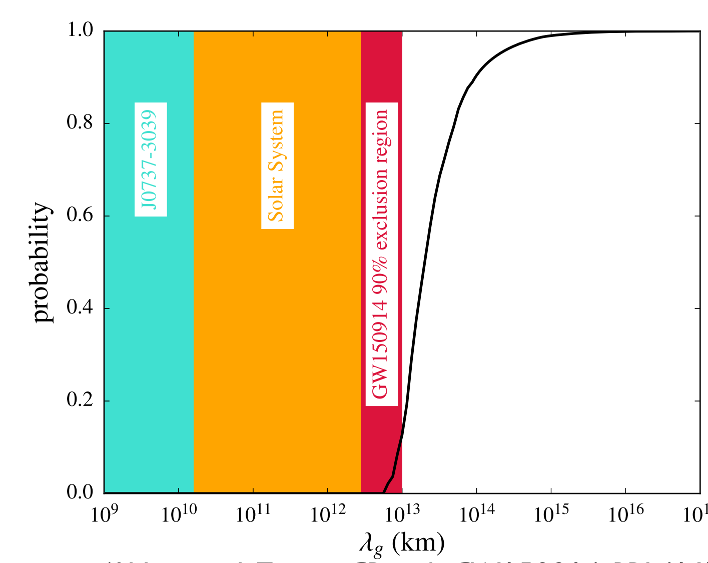
(Yunes et al., PRD '16)

As mentioned, it has been extended through the ppE approach.

- Test of dispersion relation (and thus of graviton mass):

if $m_g \neq 0$, $$E^2 = p^2c^2 + m_g^2 c^4 \ , \quad \lambda_g = \frac{h}{mc} \ , \quad \frac{v_g^2}{c^2} = 1 - \frac{h^2c^2}{\lambda_g^2 E^2}$$

We get $\lambda_g > 10^{13}$km and then $m_g < 10^{-22}$eV/c^2



(Abbot et al., Testing GR with GW150914, PRL '16)

- Test of polarization: GW170814 detected by LIGO & Virgo, purely tensor polarization favored wrt scalar/vector ones

(Abbot et al., PRL '17)

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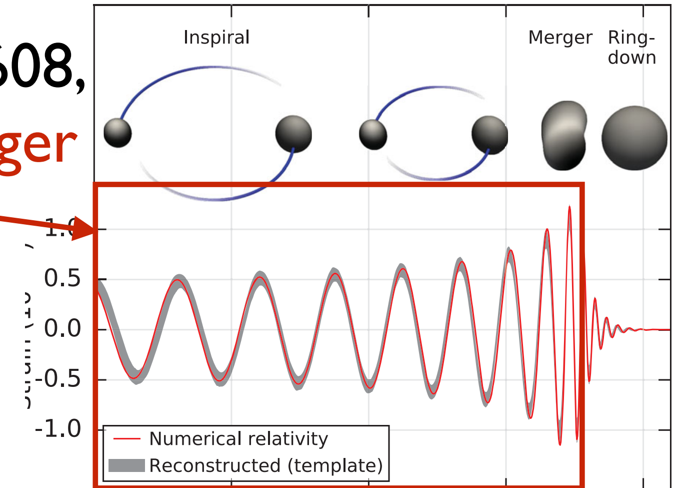


Future tests: *(e.g. Barausse et al., PRL '16; Yunes et al., PRD '16):*

- Bounds on dipole emission, predicted by several GR modifications (can be activated in late inspiral, thus escaping binary pulsar bounds)

(-1)-PN effect! relevant in early inspiral $\rightarrow \dot{E}_{\rm GW} = \dot{E}_{\rm GR}\left[1 + B\left(\frac{Gm}{r_{12}c^2}\right)^{-1}\right]$

better with LISA, best with multi-band LISA-3G analysis

- Bounds on more general deviations of radiated flux (due to extra dimensions, violations of Lorentz invariance, time-varying G due to extra fields, etc.)
- Bounds on modification of GW propagation (graviton mass, dispersion relation, etc.)
- Bounds on violations of the strong equivalence principle

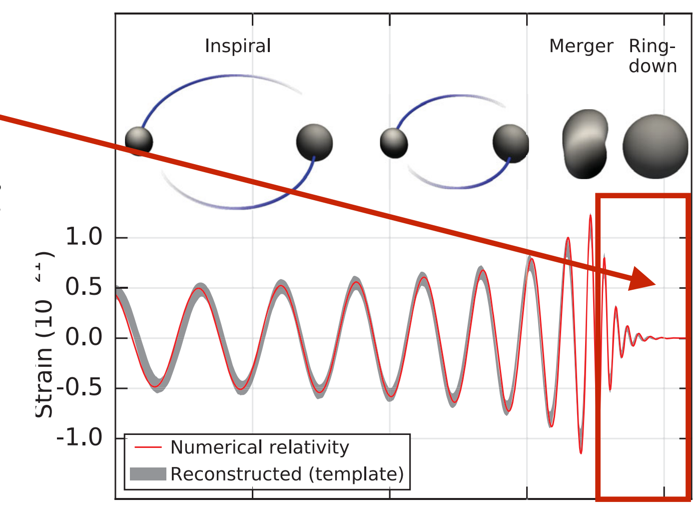
Late inspiral and merger probe regime currently unconstrained by binary pulsars!

- Theoretical challenge: we need numerical relativity simulations in modified gravity theories!
- Experimental challenge: we need much larger signal-to-noise ratio (3G detectors!)

Testing General Relativity with Gravitational Waves

- Ringdown:

signal emitted by the final BH,
strongly excited from the violent merger process,
which rapidly settles down to a stationary configuration,
oscillating and emitting GW at its proper (damped) oscillation frequencies:
the quasi-normal modes of the BH.



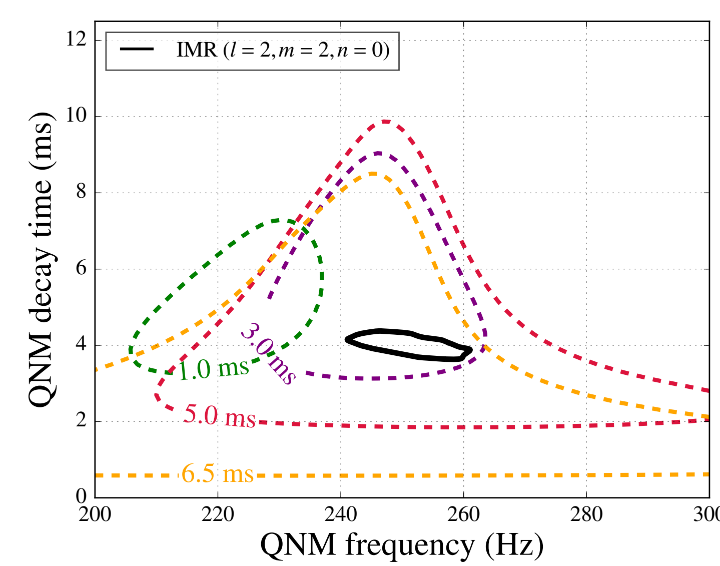
	$M\omega_0 + iM\omega_i$		$M\omega_0 + iM\omega_i$
$\ell = 2$	0.3737+i0.0890	$\ell = 3$	0.5994+i0.0927
	0.3467+i0.2739		0.5826+i0.2813
	0.3011+i0.4783		0.5517+i0.4791
	0.2515+i0.7051		0.5120+i0.6903

Caution: only *late* ringdown really containts the QNMs,
at the beginning it is determined by background (see later)

Current tests (see Gemme's talk):

GW150914 had SNR~25 in the *entire* signal
but only SNR~7 in the ringdown,
so only weak test has been possible:

- final M obtained from inspiral+merger, matching NR
- computed the corresponding QNM frequency (*f*~251Hz)
- consistency check between this value and the signal
  (they are indeed consistent with more than 90% confidence)

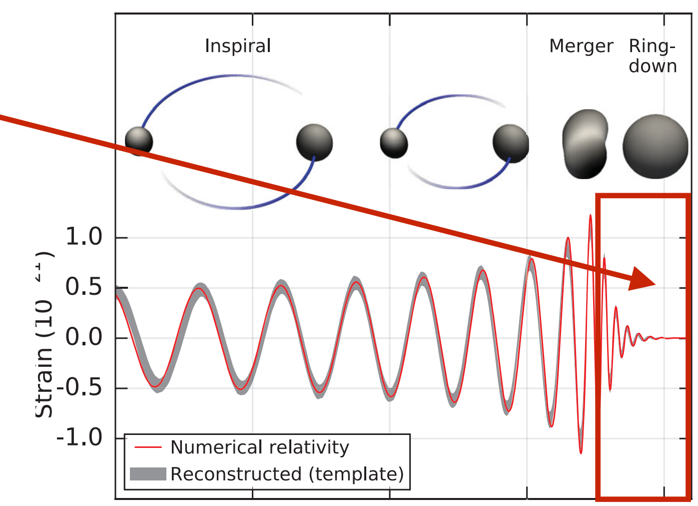


(Abbot et al., Testing GR with GW150914, PRL '16)

Testing General Relativity with Gravitational Waves

- Ringdown

QNMs are a great probe of strong gravity:
BH spectroscopy!



- sensible to strong-curvature corrections
- sensible to the most dynamical content of the theory
- carry the imprint of the underlying gravity theory
  (caution: only *late* ringdown contains actual QNMs)

Problems for future tests:

- We do not expect do detect a strong enough ringdown signal soon
  - interesting proposal: stacking several detections
  - better with 3G detector

- We still know very few about BH QNMs in modified gravity theories.
  It should be important to:
  - derive QNMs of stationary BHs in different modified gravity theories
  - find how to extract information from data
  - possibly, find a parametrization of the mode shifts

Testing General Relativity with Gravitational Waves

- Ringdown

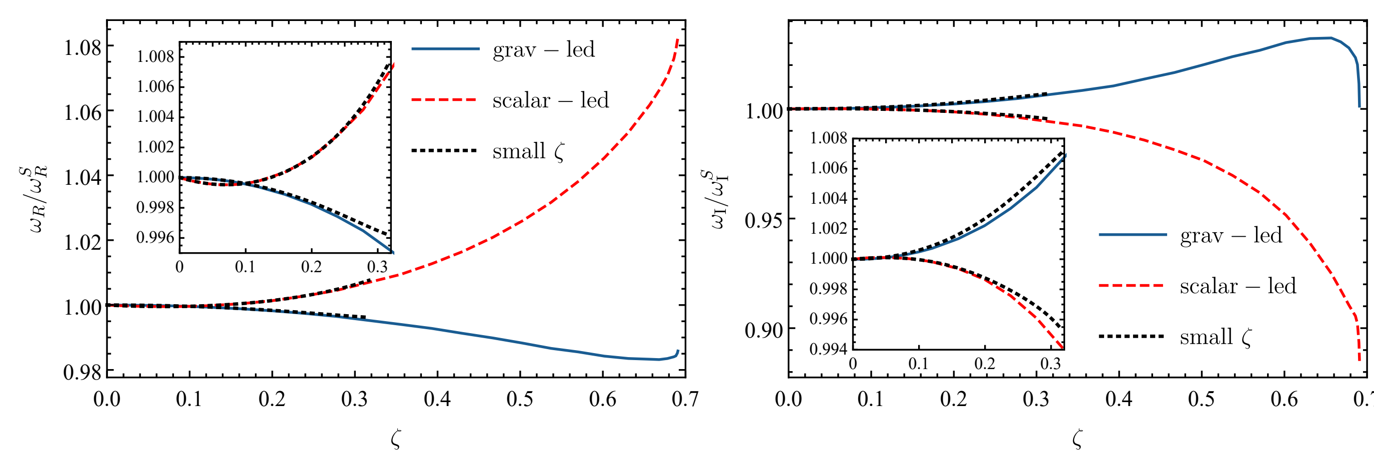
In recent years QNM of static BHs have been determined in a large class of modified gravity theories

General pattern: (*Cardoso & Gualtieri PRD '09; Molina et al., PRD'10, 16,Salcedo et al., PRD. '16*):

- new classes of modes in the GW spectrum, due to coupling to extra fields
- a (small) shift in the modes predicted by GR

- The new classes of modes is likely to be poorly excited in BH coalescences.
- The shift in the "old" modes could be detectable, if SNR is large enough.

At leading order, the mode shift is O(ζ)
where ζ is the coupling parameter
of the theory



First, preliminary results:

bound on the coupling parameter of the order of $$\alpha^{1/2} \lesssim 11 \left(\frac{50}{\rho}\right)^{1/4} \left(\frac{M}{10M_\odot}\right) \text{km}\,;$$

In order to measure this shift, we would need at least an SNR
ρ~100, which can only be obtained with 3G detectors.

Testing General Relativity with Gravitational Waves

- and after the ringdown… echos?

Did we really detect a BH?

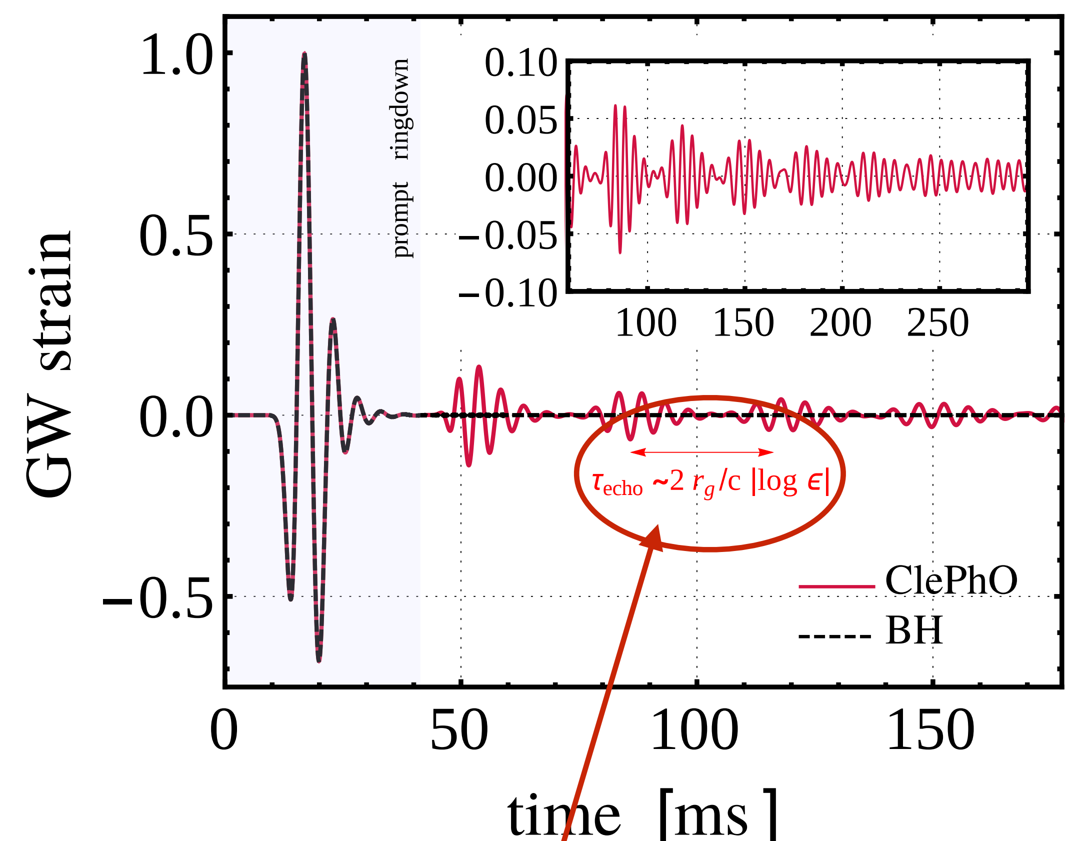
Several models of semiclassical & quantum gravity predict
- horizonless compact objects (e.g. fuzzballs) *(Mathur et al., 2007-2017)*
- new physics at the horizon scale (e.g. fireballs) *(Polcinsky et al., Giddings et al., 2012-2016)*

Different effects (even Planck-scale modifications!)
on the BH-BH waveform:
tidal heating, tidal deformation
(Cardoso et al. '17, Sennet et al., '17, Maselli et al. '18)

The most promising is post-ringdown emission:
these "exotic compact objects" would have
the same ringdown signal as BHs,
followed by "echoes" at late time.
(Ferrari & Kokkotas '00, Cardoso et al., '16, Cardoso & Pani Nat. Astr. '17)

Problems: limitation in templates, controversial results
(Abedi et al. '17, Conklin et al. '17, Ashton et al., '17, Westerwek et al. '17)

Remark: even "classical physics" effects may lead to echos
e.g. exotic matter *(Pani & Ferrari, '18)*



(Cardoso & Pani Nat. Astr. '17)

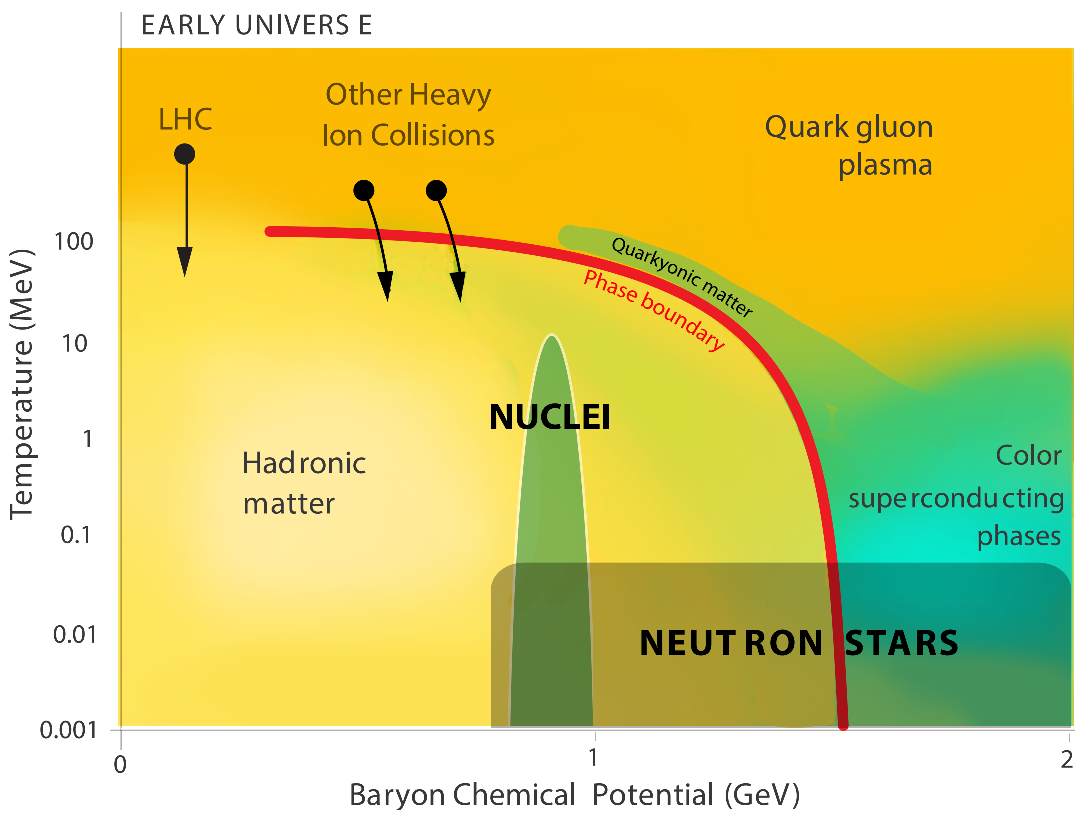
Planck scale within reach!

2) How does matter behave at supranuclear densities?

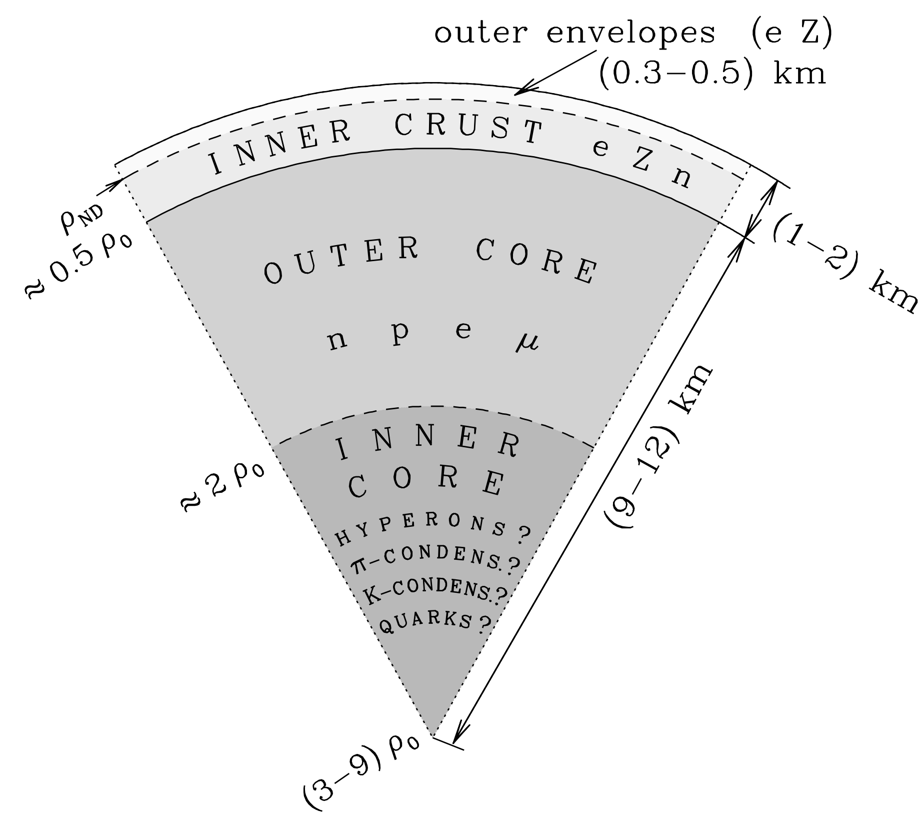
Which is the equation of state (EOS) $p(\varepsilon)$ of matter in the inner core of neutron stars?

Extreme conditions ($\varepsilon \gtrsim 10^{15}$ g/cm^3, $\nu \sim 1$ kHz, $B \sim 10^{10\text{-}15}$ G)

- can not be reproduced in lab,
- are a challenge for the the theory (nonperturbative regime of QCD)



Neutron star structure



$$\rho_0 \simeq 2.67 \times 10^{14} \mathrm{g\ cm^{-3}}$$

Lattimer & Prakash, 2007
Caplan & Horowitz 2017

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- can not be reproduced in lab,
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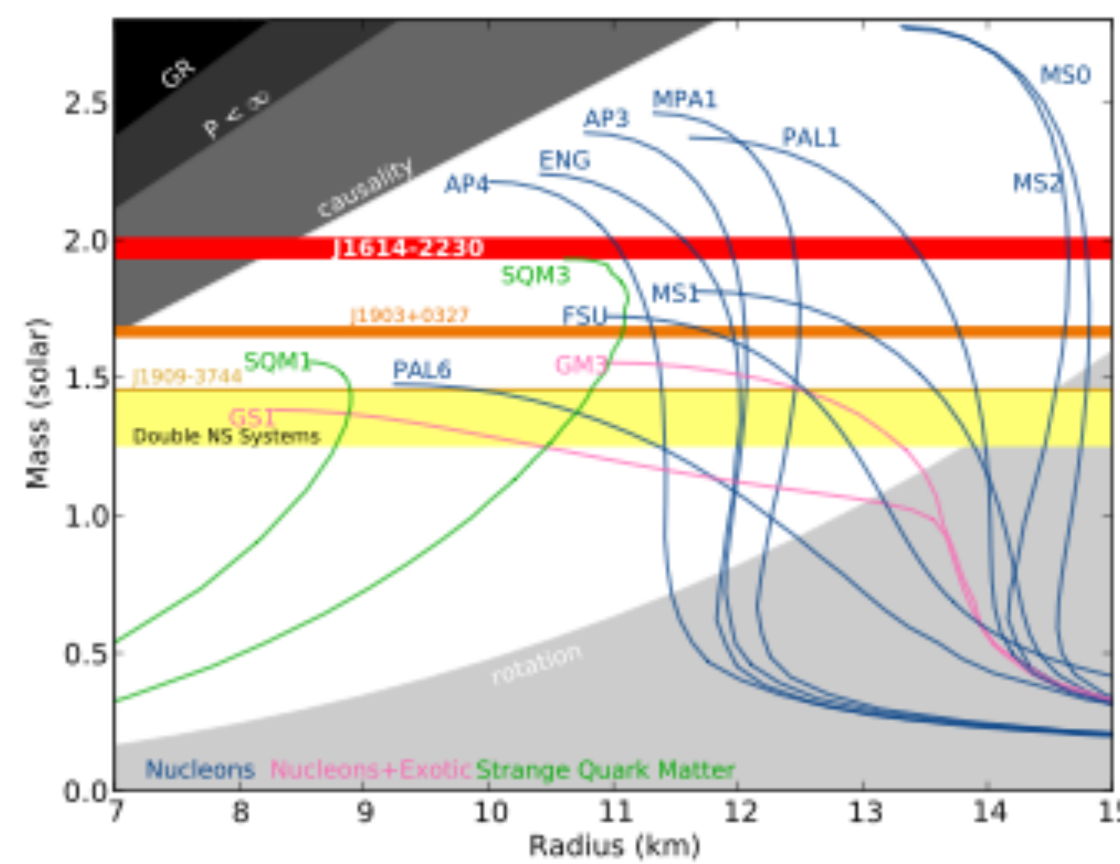
Even the particle content is not clear:
Hadrons? Hyperons? Meson condensates?
Deconfined quark matter?

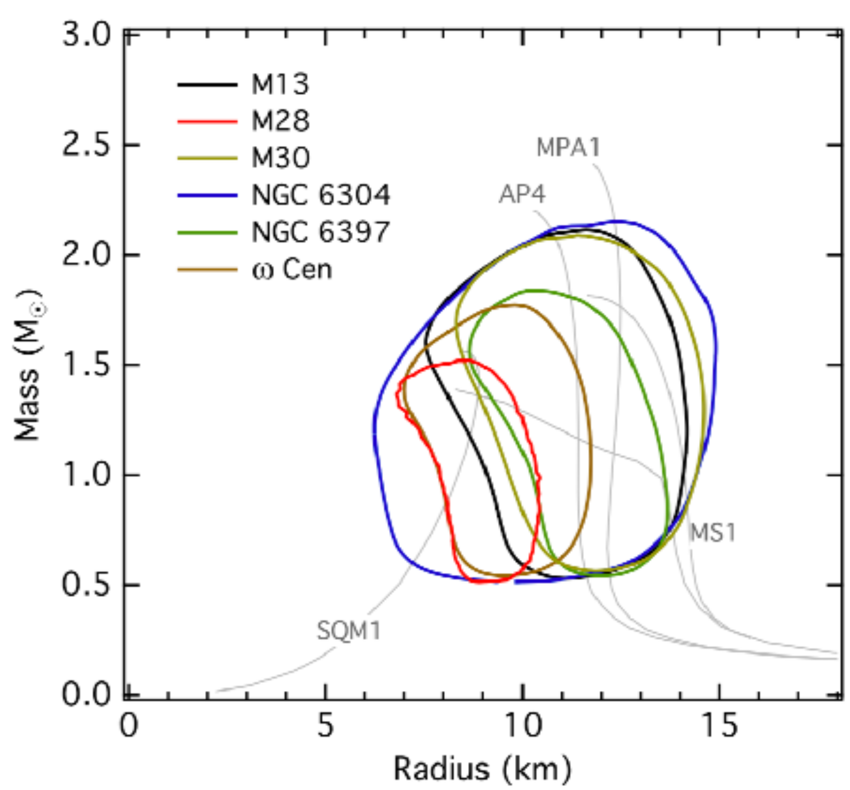
Astrophysical observations are useful to constrain the EoS
but only GWs can give a definite answer!

Credits: D. Page



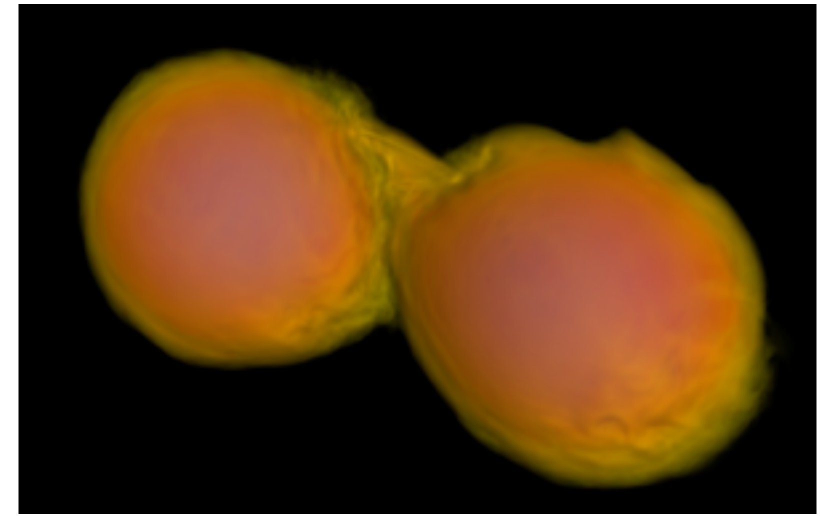
Demorest et al., '13

Ozel et al., 2016



Neutron Star EOS from Gravitational Waves

NS-NS coalescence is a primary source
for ground-based interferometers LIGO/Virgo
During the early inspiral phase the NSs behave
as *point particles*, but in the *late inspiral* they are
deformed by tidal interaction.
Tidal deformation carry the imprint of the NS
structure, and it affects GW emission!



Credits: AEI

Relativistic theory of tidal deformations:

(Flanagan & Hinderer PRD '08; Hinderer ApJ '08; Binnington & Poisson PRD '09; Damour & Nagar PRD '09)

Main idea: in the timescale of orbital motion, << proper oscillations
tidal deformations can be treated as stationary
=> multipole moments proportional to moments of the exterior tidal field.

The proportionality constants are the Love numbers, which characterize
the deformatility properties of the star and strongly depend on the NS EoS.

Most important is the quadrupolar tidal deformation:

$$Q_{ij} = -\frac{2}{3} k_2 R^5 \mathcal{E}_{ij} = -\lambda_2 \mathcal{E}_{ij}$$

Quadrupole tensor

l=2 electric tidal
Love number

Tidal deformability

Tidal tensor

Neutron Star EOS from Gravitational Waves

Tidal deformation affects the PN waveform of late inspiral through λ_2

$$h_{PN}(x) = \mathcal{A}(x) e^{\mathrm{i}[\Psi_{PP}(x)+\Psi_T(x)]}$$

$$x = (\pi m f)^{2/3} \qquad m = m_1 + m_2 \qquad \nu = m_1 m_2 / m^2 \qquad \mathcal{M} = m\nu^{3/5}$$

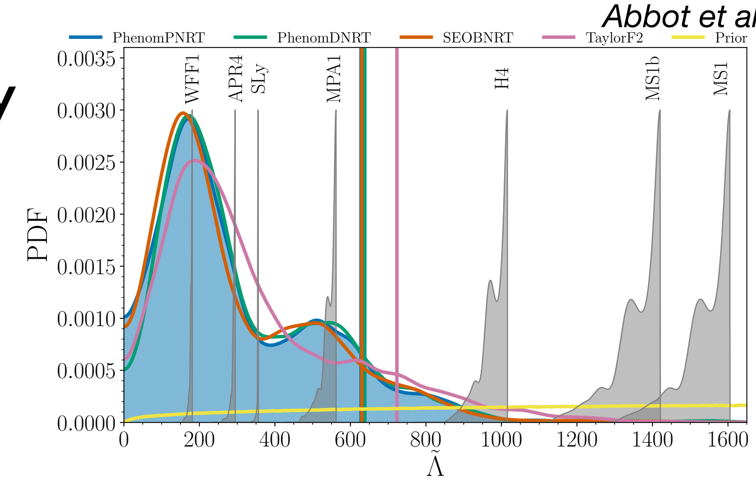
$$\mathcal{A}(x) = \sqrt{\frac{5}{24}} \frac{\mathcal{M}^{5/6}}{\pi^{2/3} d} f^{-7/6} \left[1 + \beta_1 x + \beta_2 x^2 + \ldots\right]$$

$$\Psi_{PP}(x) = 2\pi f t_c - \phi_c + \frac{3}{128 \nu x^{5/2}} \left[1 + \alpha_2 x + \alpha_3 x^{3/2} + \alpha_4 x^2 + \ldots\right]$$

$$\Psi_T(x) = -\frac{117\tilde{\lambda}}{8\nu m^5} x^{5/2} \left[1 + \tilde{\alpha}_2 x + \tilde{\alpha}_3 x^{3/2} + \ldots\right] \qquad \tilde{\lambda} = \frac{m_1 + 12 m_2}{26 m_2}$$

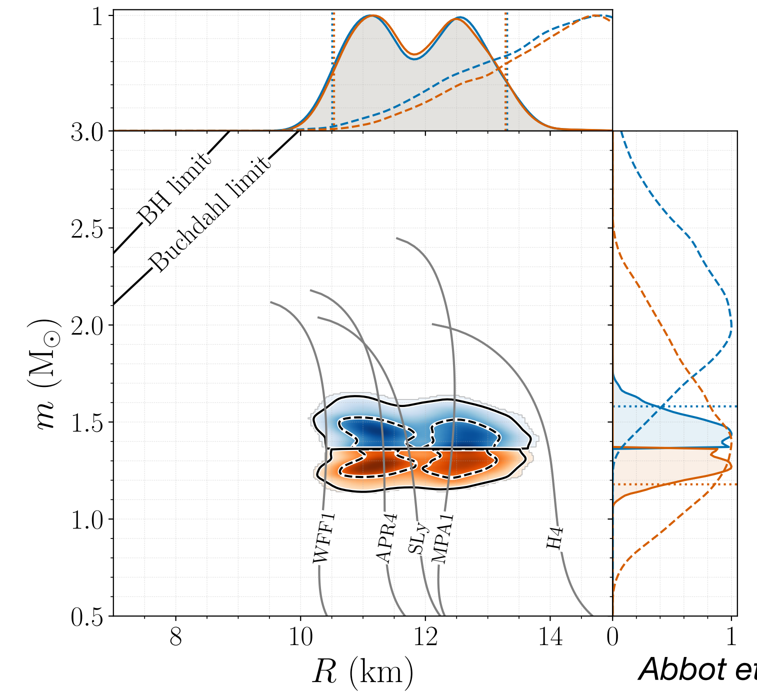
(formally 5PN, but $\lambda \sim R^5$ => $\lambda/m^5 \sim (R/m)^5 >> 1$)

Neutron Star EOS from Gravitational Waves

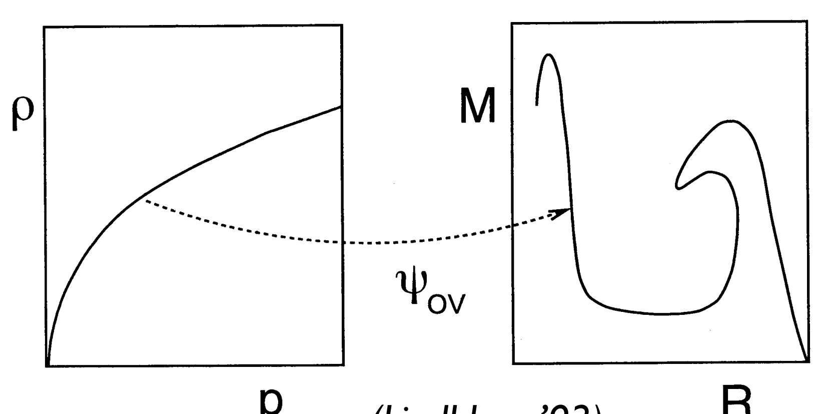


GW170817 allowed to set constraints on the tidal deformability and, indirectly, on the NS radius (see Gemme's talk) thus providing valuable information on the NS EOS!

However, comparison with a set of tabulated EOS is not enough. To overcome our limited theoretical understanding we would need several NS-NS detections with much higher signal-to-noise ratio (note that tidal interaction sets in at late inspiral, poorly observed in GW170817)



This would allow an inverse problem approach:
(Lindblom '92, Abdelsalhin et al. '18)
every measurement of (M,R) or (M,λ) can be translated in a couple (p,ε) thus reconstructing the EOS profile



(Lindblom '92)

This would only be possible with an instrument more sensitive at high frequencies, i.e. a 3G detector such as ET