Gravitational Waves as a probe of Fundamental Physics

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New physics with gravitational waves
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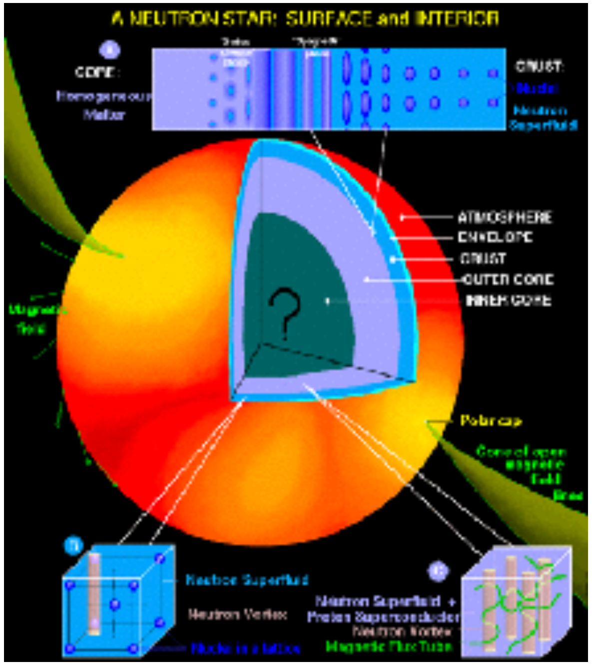
Open questions in Fundamental Physics

- How matter behave at supranuclear densities?

- How gravity behave in the strong field, high curvature regime?

Which detectors do we need to answer these questions?



credits D. Page

NEUTRON STARS:

observed mass: [1-2] $M_\odot$

radius: difficult to measure (about 13-15 % accuracy)
[10-15] km (teoretical)

In the inner part of the core of a neutron star, the density can be larger than the equilibrium density of nuclear matter

$\rho_0 = 2.67 \mathrm{x} 10^{14}$ g /cm3

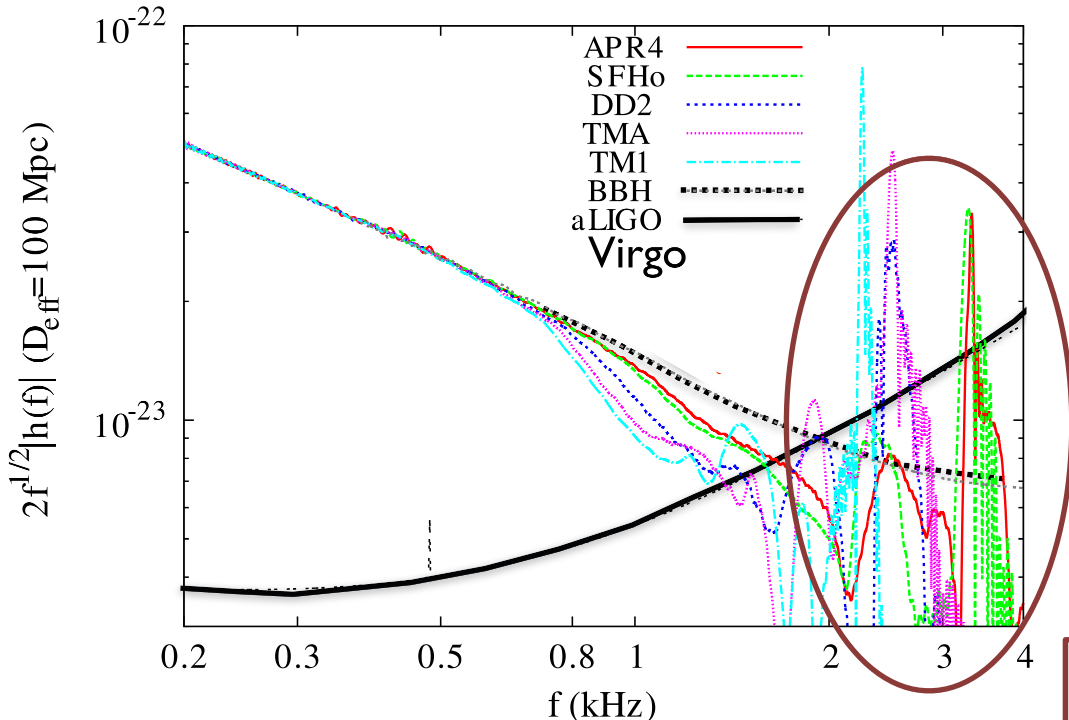
typical densities ≈ 2-5 ρ_0 or more

At these densities (unreachable in a laboratory) hadrons interactions cannot be neglected, and have to be treated in the framework of the theory of Quantum Cromo Dynamics

even the particle content is unknown: Hyperons? Meson condensates?
Deconfined quark matter?

Several different models have been proposed which have to be tested

Hotokezaka, Kyutoku, Sekiguchi, Shibata, PRD 93 (2016)



Signal emitted in the coalescence of two neutron stars with mass 1.35M⊙, modeled using different Equations of state (EoSs)

signal emitted by two coalescing black holes with the same mass

part of the signal emitted in the merger+post-merger

to detect this part of the signal detectors much more sensitive at high frequency will be needed

However, differences among different EoSs become appreciable earlier, when the two stars are still inspiralling and very close to the merging

why is the inspiral signal emitted by black holes different from that of NS binaries ??

Because stars are tidally deformed by the companion

Deformability properties are encoded in the Love numbers

The Newtonian Theory of Tides:

The Love numbers were introduced by August E. H. Love in 1911: they are a set of dimensionless parameters which measure how the shape of a planetary body changes in response to an external tidal potential.

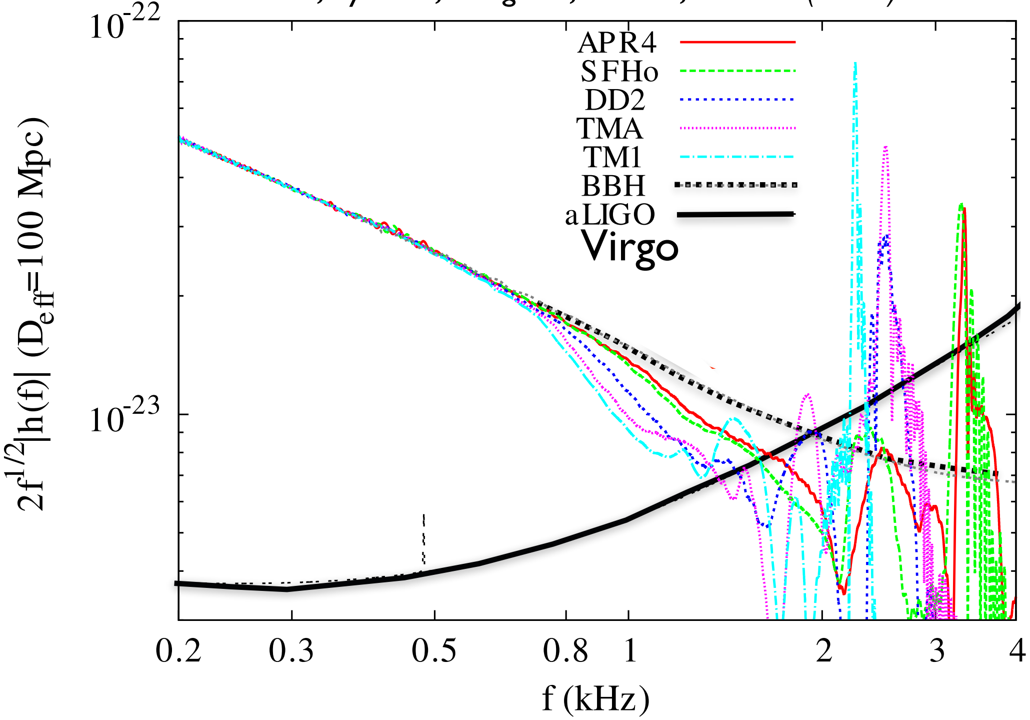
These numbers can be generalized for stars in General Relativity:
If a star is placed in an external tidal field C_{ij}, it develops a quadrupole moment Q_{ij}

$$Q_{ij} = \lambda C_{ij}$$

λ is the tidal deformability, which is related to the l=2 tidal Love number

λ depends on the stellar compactness, therefore it depends on the equation of state of matter inside the star

Hotokezaka, Kyutoku, Sekiguchi, Shibata, PRD 93 (2016)



EOS's can be classified in terms of their stiffness/softness

softer EOS's:
speeds of sound is lower
more compressible matter
smaller radius
larger average densities

stars with softer EoS are less deformable

M=1.35 M⊙

EoS	stiffness	Radius (km)	λ
APR4	soft	11,09	322
SFHo	moderately soft	11,91	420
DD2	moderately stiff	13.20	854
TMA	stiff	13.85	1192
TM1	very stiff	14,48	1428

Stiffness/softness of the EoS depends on how hadron interactions are modeled, and on the particle content.

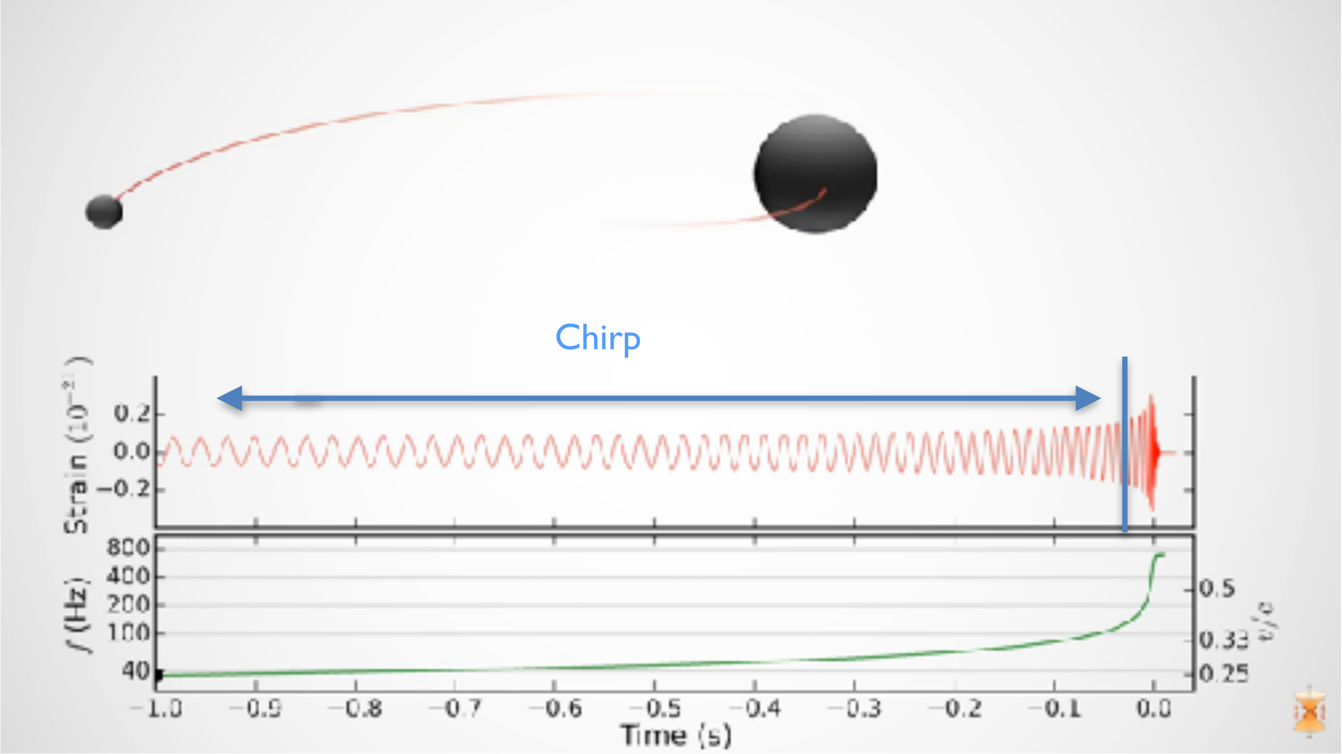
How can we measure the tidal deformability?

The inspiralling part of the signal is modeled by using a post-Newtonian (PN) expansion of the equations of motion in GR + radiation reaction

the expansion parameter is

$$x = (m\pi f)^{5/3}$$

where m is the total mass and f the wave frequency



The tidal deformability enters in the waveforms emitted during the inspiralling

$$h(f) = \mathcal{A}(f) e^{i\psi(f)}$$

$$\psi(f) = \psi_{PP} + \psi_{\bar{Q}} + \psi_{\bar{\lambda}}$$

$x = (m\pi f)^{5/3}$ PN expansion parameter

$$m = m_1 + m_2$$
$$\eta = m_1 m_2 / m^2$$

point-particle contribution

$$\psi_{PP}(f) = 2\pi f t_c - \phi_c - \frac{\pi}{4} + \frac{3}{128}(\mathcal{M}\pi f)^{-5/3}\left\{1 + \left(\frac{3715}{756} + \frac{55}{9}\eta\right) x - (16\pi - 4\beta) x^{3/2} + \left(\frac{15293365}{508032} + \frac{27145}{504}\eta + \frac{3085}{72}\eta^2 - 10\sigma\right) x^2 + \mathcal{O}(x^{5/2})\right\}$$

σ contains spin-spin and spin-orbit terms. Note that it appears in the 2-PN term (x^2)

Quadrupole induced by rotation

$$\psi_{\bar{Q}} = \frac{3}{128}(\mathcal{M}\pi f)^{-5/3}\left\{-50\left[\left(\frac{m_1^2}{m^2}\chi_1^2 + \frac{m_2^2}{m^2}\chi_2^2\right)(Q_S - 1) + \left(\frac{m_1^2}{m^2}\chi_1^2 - \frac{m_2^2}{m^2}\chi_2^2\right) Q_a\right] x^2\right\}$$

$$Q_S = \frac{\bar{Q}_1 + \bar{Q}_2}{2}, \quad Q_a = \frac{\bar{Q}_1 - \bar{Q}_2}{2}$$

Tidal contribution:

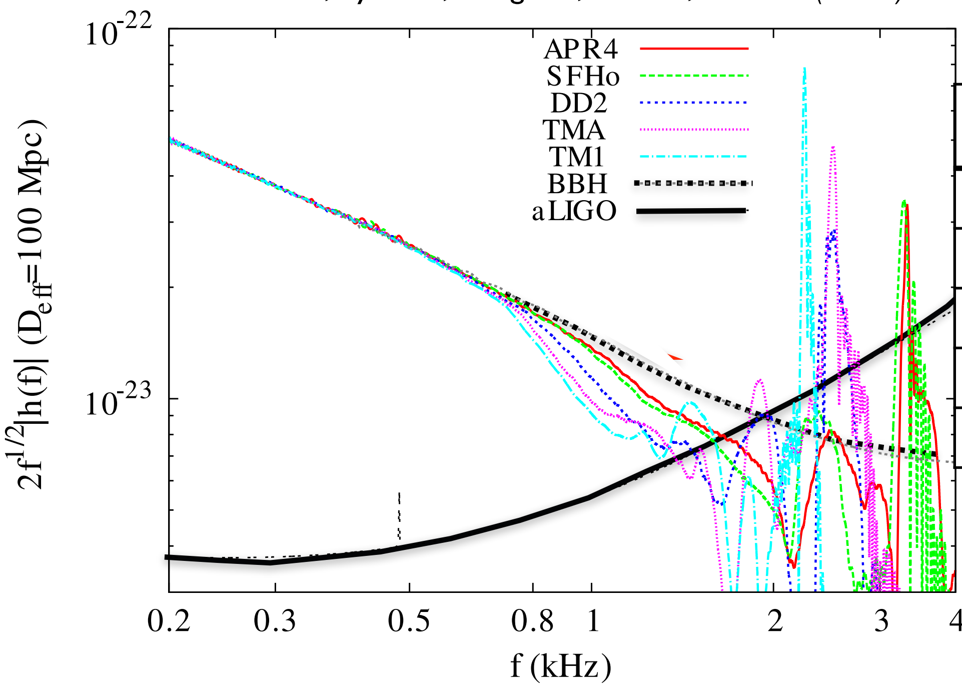
$$\psi_{\bar{\lambda}} = -\frac{3}{128}(\mathcal{M}\pi f)^{-5/3}\left\{24[(1 + 7\eta - 31\eta^2)\lambda_S + (1 + 9\eta - 11\eta^2)\lambda_a \delta m] x^5 + \right\} + \mathcal{O}(x^6)$$

$$\lambda_S = \frac{\bar{\lambda}_1 + \bar{\lambda}_2}{2}, \quad \lambda_a = \frac{\bar{\lambda}_1 - \bar{\lambda}_2}{2} \qquad \delta m = \frac{m_1 - m_2}{m}$$

Tidal contributions become relevant when the NS velocities are high, i.e. before merging

Coalescing NSs with mass 1.35 M⊙ each

Hotokezaka, Kyutoku, Sekiguchi, Shibata, PRD 93 (2016)



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To measure the tidal deformability λ and gain information on the equation of state of matter in the inner core of the stars we need detectors more sensitive at frequencies larger than ~ 500-700 Hz

Beyond binary coalescence NSs emit gravitational waves in different phases of their life and in several astrophysical processes

Neutron star pulsations are of particular interest because:

- ✶ Gravitational Waves are emitted at the pulsation frequencies
- ✶ The pulsation frequencies depend on the Equation of State of matter inside the star

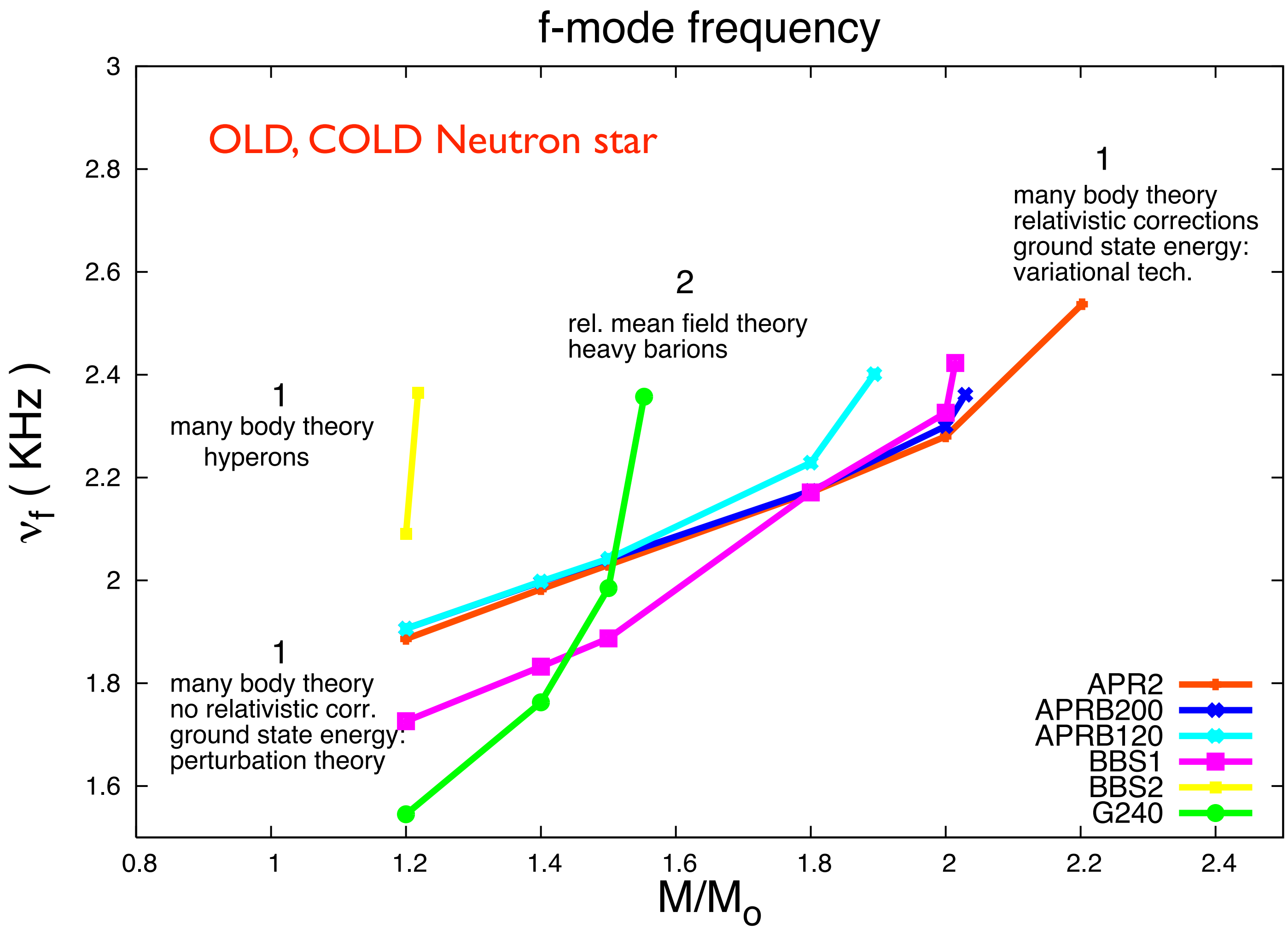
Neutron star pulsations can be excited when

- ❖ the star is old and cold: it may oscillate and emit gravitational waves due to an external or internal perturbation
  Gualtieri, Benhar, Pons, Ferrari, Phys. Rev. D 2004
- ❖ it has just been formed in a gravitational core collapse or in NS-NS coalescence, it is hot and rapidly evolving
  Ferrari, Miniutti, Pons, MNRAS 2004, Burgio, Ferrari, Gualtieri, Schultze, Phys. Rev. D 2011
  Camelio, Lovato, Gualtieri, Benhar, Pons, Ferrari, Phys. Rev. D 2017

Other processes which may be associated to GW emission in isolated NS or in NS in LMXRB

- f-mode or r-mode instabilities
- deviation form axisymmetry

Glampedakis & Gualtieri arXiv: 1709.07049 CQG to appear 2017



Benhar, Ferrari, Gualtieri, Phys. Rev. D (2004)

different ways of modeling hadronic interactions affect the pulsation properties of the star

Do we have a chance to detect a signal from an old, cold neutron star oscillating in its fundamental mode?

A typical GW signal from a neutron star pulsation mode has the form of a damped sinusoid

$$h(t) = \boxed{\mathcal{A}} e^{-(t-t_0)/\boxed{\tau_d}} \sin[2\pi \boxed{f} (t-t_0)] \quad \text{for } t > t_0$$

$$\boxed{\mathcal{A}} \approx 7.6\times 10^{-24} \sqrt{\frac{\Delta E_\odot}{10^{-12}} \frac{1\ \mathrm{s}}{\tau_d}} \left(\frac{1\ \mathrm{kpc}}{d}\right)\left(\frac{1\ \mathrm{kHz}}{f}\right) .$$

$$\boxed{\Delta E_\odot = \Delta E_{GW}/M_\odot c^2} = \text{total energy}$$

How much energy would need to be channeled into a mode?

For mature neutron stars we can take as a bench-mark the energy involved in a typical pulsar glitch, in which case

$$\Delta E_{GW} = 10^{-13} M_\odot c^2$$

Assuming $f \sim 1500$ Hz, $\tau_d \sim 0.1$ s, $d = 1$ kpc, $\mathcal{A} \approx 5\times 10^{-24}$

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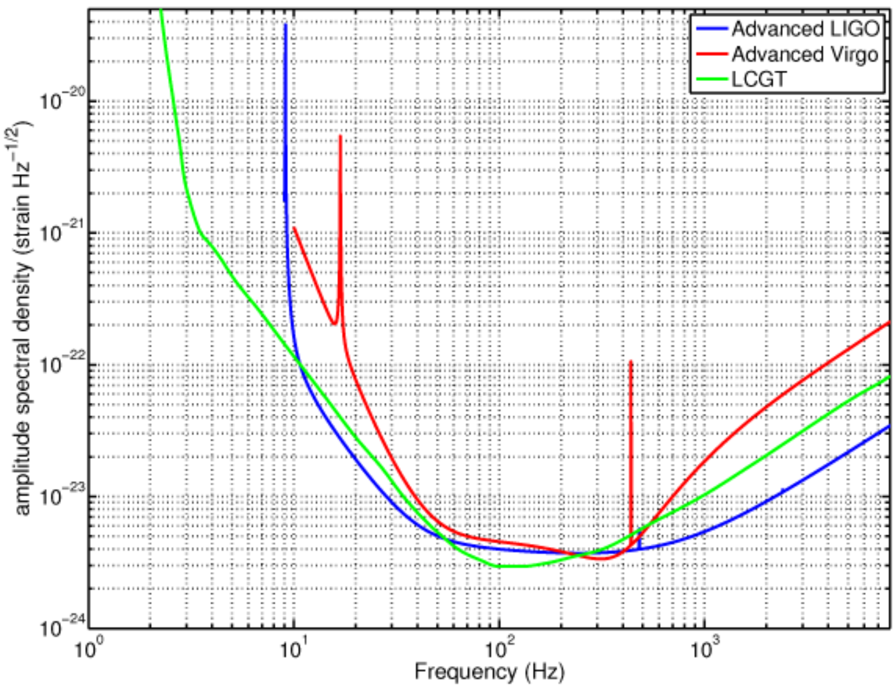
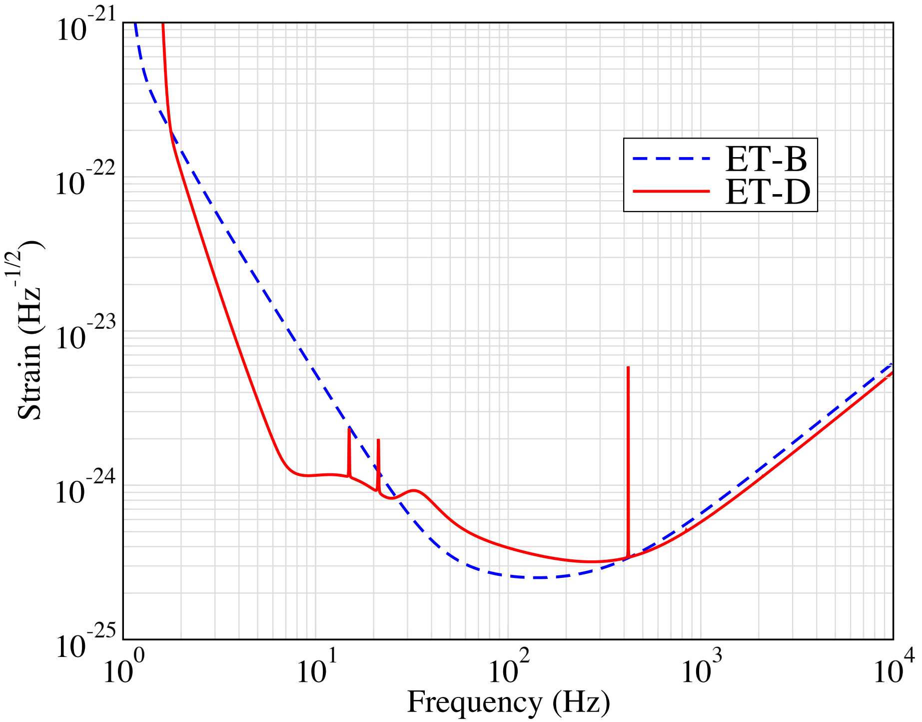
Advanced LIGO and Virgo



future



3rd generation detectors are needed to detect signals from old neutron stars

Gravitational waves emitted by NS in different processes,if detected, will be a probe to explore the behaviour of matter at supranuclear densities.

From NS binary coalescence we will be able to gain information on the stiffness of the EoS, and set constraints on the particle content

With third generation detectors we will hopefully be able to measure the frequencies at which stars oscillate emitting GWs:

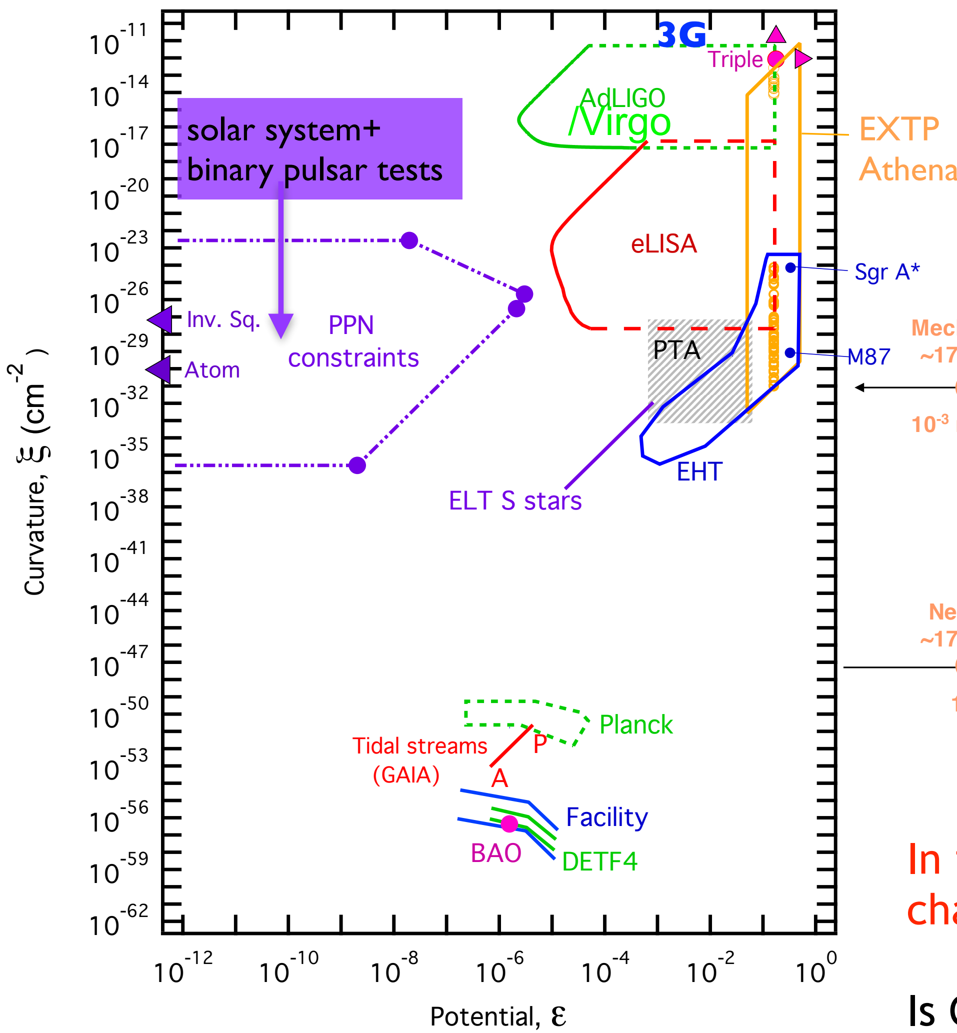
gravitational wave asteroseismology

Observing the birth of a NS through GWs will provide infomation on the hot EoS and on the dynamics of the early evolution of the newly born NS

Do we need to test GR?

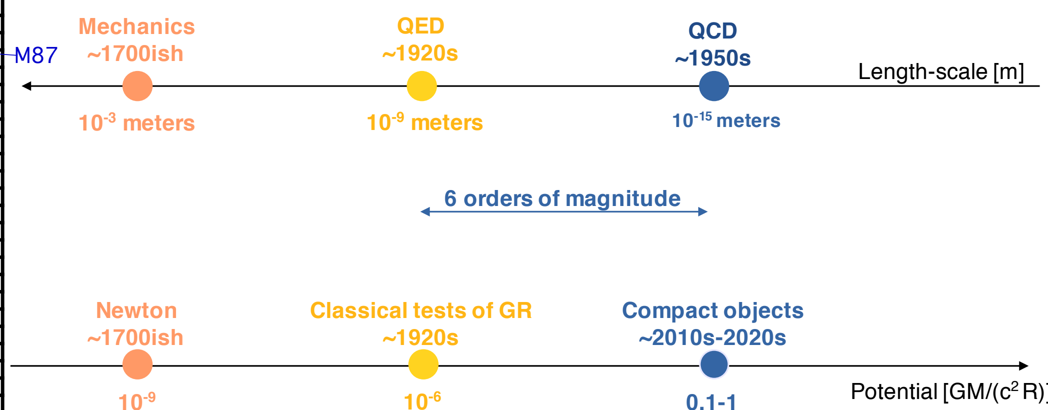
- **Before GW150914, we had tested only the weak-field regime of gravity (solar system tests, binary pulsars) Now, the realm of strong gravity is open to exploration!**

Baker et al. 2015



$$\epsilon = \frac{GM}{r} \text{ gravitational potential}$$

$$\zeta = \frac{GM}{r^3} \text{ spacetime curvature}$$



credit P.Pani

In the past, when changing scale interaction also changed!

Is General Relativity appropriate to describe the behaviour of gravity at the horizon scale?

- Theoretical issues

unification with the quantum world :
the theory becomes renormalizable if we add quadratic curvature terms—i.e., high- energy/high-curvature corrections—to the Einstein–Hilbert action.

Candidate theories of quantum gravity (such as string theory and loop quantum gravity) provide indications on how GR should be modified at high energies.

singularities: high- energy corrections can avoid the formation of singularities (Hawking-Penrose singularity theorem)

- Observational issues

cosmological measurements provide evidence for dark matter and a nonzero cosmological constant ('dark energy'). How to explain why the cosmological constant is so small and the corresponding energy density is so close to the present matter density? low-energy corrections to GR seems unavoidable

These arguments suggest that gravity should be modified at both low and high energies

How to navigate in the sea of alternative/modified theories of gravity?

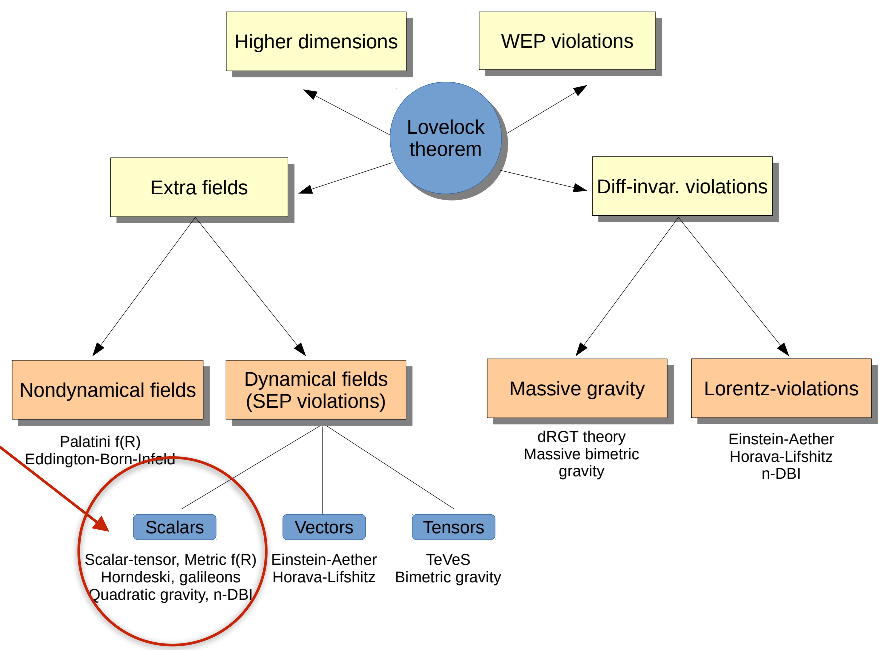
Lovelock Theorem

In 4-dimensional spacetime, the only divergence free, symmetric, rank-2 tensor which can be constructed from the metric tensor $g_{\mu\nu}$ and its first and second derivatives, preserving diffeomorfism invariance is the Einstein tensor plus a cosmological term

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Simple modifications:
extra scalar fields

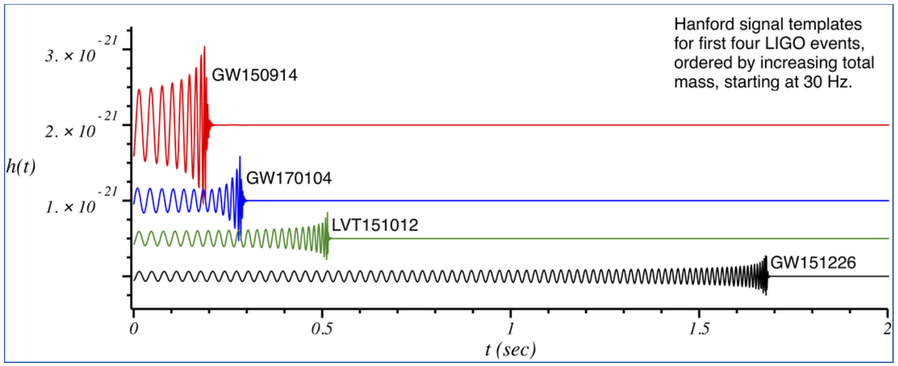
higher-order
curvature terms

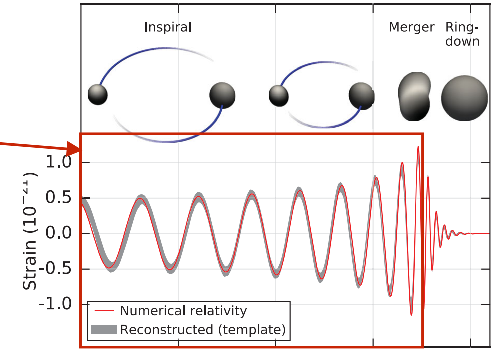


(see e.g. *Berti, Barausse, Cardoso, Gualtieri, Pani et al., CQG 2015*)

Information on GR deviations we may extract from gravitational waves

Most of the information of GW150914, GW151226, GW170104 has been extracted from the inspiral phase





credits: Favata

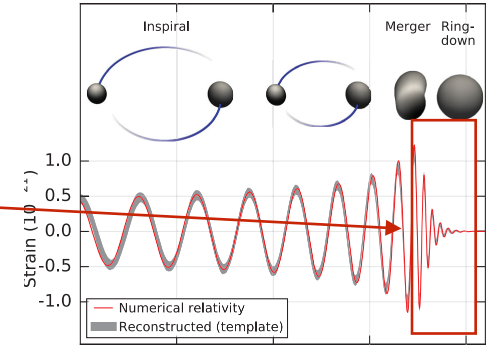
- Bounds on dipole emission, predicted in several GR deviations (in some of them it is activated in late inspiral, thus escaping binary pulsar bounds) (*Barausse et al., PRL '16; Yunes et al., PRD '16*):

- 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, polarization, etc.)

No significant bounds can be put on the strong-curvature regime using the inspiral part of the GW signal

Information on GR deviations we may extract from GWs: strong-curvature regime



Quasi-normal modes (QNM) of black holes

emitted by the final BH of a binary coalescence, strongly excited by the violent merger process.

Their frequencies are sensible to strong-curvature corrections and carry the imprint of the underlying gravity theory

In General Relativity the QNM frequencies depends only on the black hole mass and angular momentum (no hair theorem). For a non-rotating BH the frequency and damping time of the lowest mode are

$$\mathbf{M = nM_\odot \qquad \nu_0 \sim (12/n)kHz \qquad \tau \sim n \cdot 5.5 \times 10^{-5}\ s}$$

In recent years QNM of non rotating BHs have been determined in quadratic gravity theories

General pattern

- new classes of modes in the GW spectrum, due to coupling to extra field (poorly excited in BH coalescence)
- a (small) shift in the modes predicted by GR, detectable if SNR is ρ~100, which can only be obtained with 3G detectors.

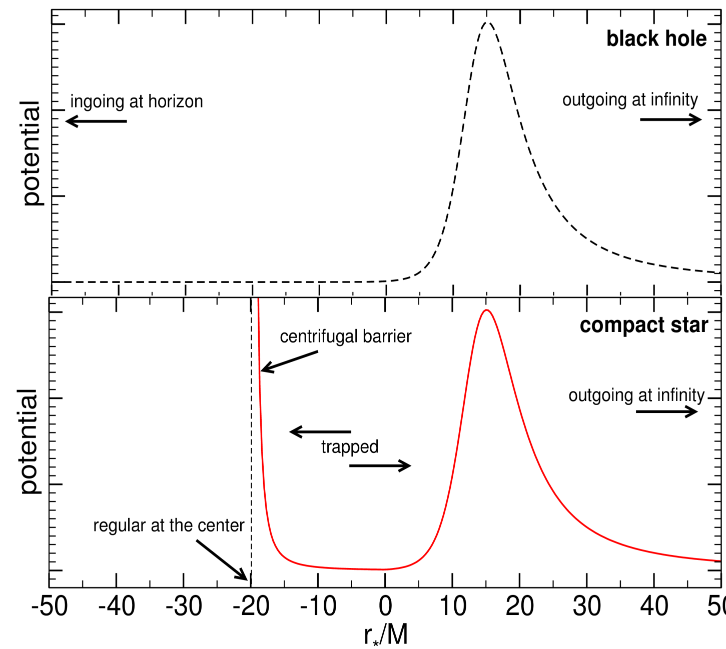
(Cardoso & Gualtieri PRD '09; Salcedo, Macedo,Cardoso,Ferrari,Gualtieri,Khoo,Kunz,Pani, PRD. '16, Molina et al., PRD'10, 16,):

Testing the nature of compact objects in the ringdown phase

Ultracompact stars generically support *trapped modes*

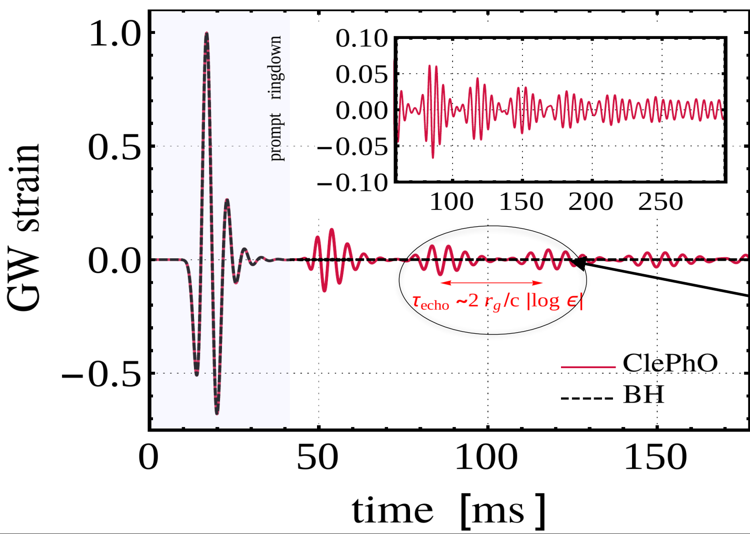
(Chandrasekhar & Ferrari, 1991)

$$\frac{\partial^2 \Psi_{\ell m}}{\partial t^2} - \frac{\partial^2 \Psi_{\ell m}}{\partial r^2} + V_{\ell m}(r_*) = 0$$



Prompt ringdown of BHs and of ECOs identical, but "echoes" at late time

(Ferrari & Kokkotas PRD 2000, Cardoso Franzin & Pani PRL 2016, Cardoso & Pani Nature Astronomy 2017)



$$\tau_{\rm echo} \sim -2M \log\left(\frac{R}{2M} - 1\right)$$

Delay time, R→2M

$$R - 2M \sim 10^{-33}\,{\rm cm} \Rightarrow \tau_{\rm echo} \sim \mathcal{O}(50\,{\rm ms})$$

More sensitive detectors will probe regions closer and closer to the horizon

Even Planck-scale corrections near horizon are within reach!

OPEN PROBLEMS

Neutron Star Physics

EoS modeling: need of a better parametrization to extract physical information
need better calculations of oscillation frequencies for rotating stars

extract information on the EoS using both gravitational and astrophysical observations: data analysis algorithms dedicated to the problem

Testing General Relativity

Full inspiral-merger-ringdown template in different modified gravity theories are needed

Presently, no NR simulations in modified gravity theories!

Exotic compact objects: how do they form? are they stable?
Echo template, parameter estimations

Several groups (including ourselves) are working on this exciting challenge!