Neutron Star Mergers Chirp About Vacuum Energy

[arXiv:1802.04813 [astro-ph.HE]]

Gabriele Rigo (Syracuse)

Csaba Csáki (Cornell), Cem Eröncel (Syracuse),
Jay Hubisz (Syracuse), John Terning (Davis)

Phenomenology Symposium

8 May 2018

My Goal Today

It is possible to learn about fundamental physics from the observation of gravitational waves.

The Cosmological Constant Problem

Today the cosmological constant is very small:

$$\Lambda \sim (10^{-3}\,\mathsf{eV})^4 \ll \mathsf{TeV}^4, M_{\mathsf{Pl}}^4.$$

There are still a lot of questions:

- Should we interpret it as vacuum energy of the underlying QFT?
- Why so small? Why not zero?
- Is it always small? Is there an adjustment mechanism?

The Cosmological Constant Problem

Today the cosmological constant is very small:

$$\Lambda \sim (10^{-3}\,\mathsf{eV})^4 \ll \mathsf{TeV}^4, M_{\mathsf{Pl}}^4.$$

There are still a lot of questions:

- Should we interpret it as vacuum energy of the underlying QFT?
- Why so small? Why not zero?
- Is it always small? Is there an adjustment mechanism?

Testing the CC Picture

If the CC results from microphysics, we expect it to jump at every phase transition:

$$\Delta\Lambda \sim f_{\text{crit}}^4 .$$

How to test phases of the SM different from the usual one?

NEUTRON STARS

- In the core there might be an unconventional QCD phase at low temperature T and large chemical potential μ
- The VE is an $\mathcal{O}(1)$ fraction of the total energy
- Jump in VE vs adjustment mechanism

Testing the CC Picture

If the CC results from microphysics, we expect it to jump at every phase transition:

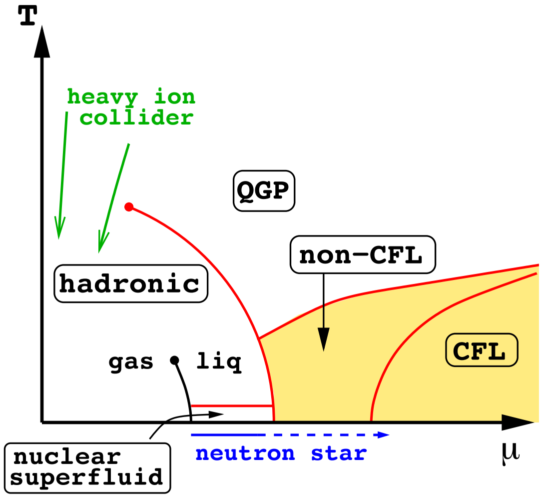
$$\Delta\Lambda \sim f_{\text{crit}}^4 .$$

How to test phases of the SM different from the usual one?

NEUTRON STARS

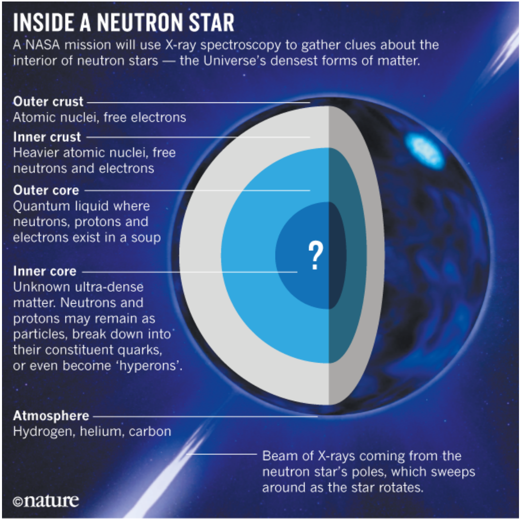
- In the core there might be an unconventional QCD phase at low temperature T and large chemical potential μ
- The VE is an $\mathcal{O}(1)$ fraction of the total energy
- Jump in VE vs adjustment mechanism

QCD Phase Diagram



M. G. Alford, A. Schmitt, K. Rajagopal, T. Schäfer, "Color Superconductivity in Dense Quark Matter", *Rev. Mod. Phys.* **80**, 1455 (2008) [arXiv:0709.4635 [hep-ph]].

Dissecting Neutron Stars



INSIDE A NEUTRON STAR

A NASA mission will use X-ray spectroscopy to gather clues about the interior of neutron stars — the Universe's densest forms of matter.

Outer crust
Atomic nuclei, free electrons

Inner crust
Heavier atomic nuclei, free neutrons and electrons

Outer core
Quantum liquid where neutrons, protons and electrons exist in a soup

Inner core
Unknown ultra-dense matter. Neutrons and protons may remain as particles, break down into their constituent quarks, or even become 'hyperons'.

Atmosphere
Hydrogen, helium, carbon

Beam of X-rays coming from the neutron star's poles, which sweeps around as the star rotates.

©nature

E. Gibney, "Neutron Stars Set to Open Their Heavy Hearts", *Nature* **546**, 18 (2017).

Equation of State

The internal structure of neutron stars is very complicated:

- Hard to obtain the EoS from first principles, i.e. QCD
- Piecewise polytropic parametrization with 7 layers
- After imposing continuity there are 16 free parameters

For the outer 6 layers,

$$p = K_i \rho^{\gamma_i}, \qquad p_{i-1} \leq p \leq p_i.$$

The energy density enters the Einstein equations and can be calculated from the first law of thermodynamics:

$$\epsilon = (1 + a_i)\rho + \frac{K_i}{\gamma_i - 1}\rho^{\gamma_i}, \qquad \rho_{i-1} \leq \rho \leq \rho_i.$$

Equation of State

The internal structure of neutron stars is very complicated:

- Hard to obtain the EoS from first principles, i.e. QCD
- Piecewise polytropic parametrization with 7 layers
- After imposing continuity there are 16 free parameters

For the outer 6 layers,

$$p = K_i \rho^{\gamma_i}, \qquad p_{i-1} \leq p \leq p_i.$$

The energy density enters the Einstein equations and can be calculated from the first law of thermodynamics:

$$\epsilon = (1 + a_i)\rho + \frac{K_i}{\gamma_i - 1}\rho^{\gamma_i}, \qquad \rho_{i-1} \leq \rho \leq \rho_i.$$

Effects of Vacuum Energy in the Core

Let's assume that the core is in a different phase of QCD.

By definition we introduce a vacuum energy contribution as

$$p = K_7 \rho^{\gamma_7} - \Lambda,$$

$$\epsilon = (1 + a_7)\rho + \frac{K_7}{\gamma_7 - 1}\rho^{\gamma_7} + \Lambda.$$

Notice that:

- We assume the phase transition to be first order: mass and energy density have to jump from ρ_- to ρ_+ and from ϵ_- to ϵ_+
- We parametrize the phase transition as $\epsilon_+ - \epsilon_- = \alpha|\Lambda|$

Effects of Vacuum Energy in the Core

Let's assume that the core is in a different phase of QCD.

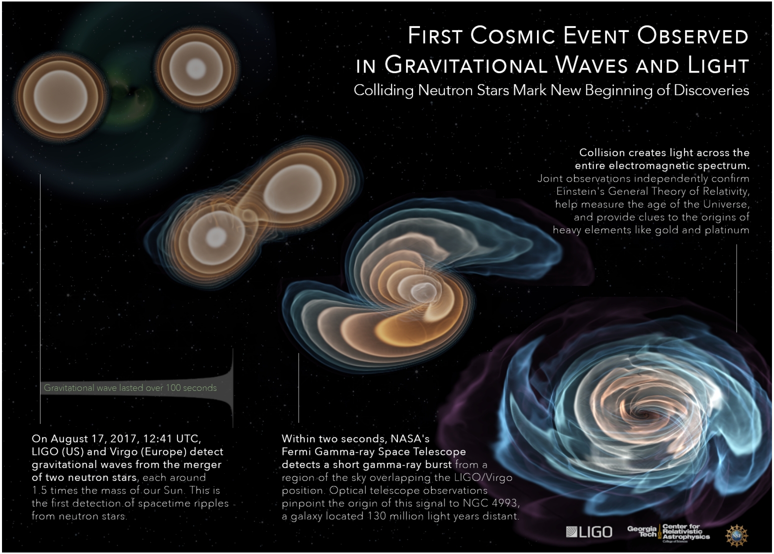
By definition we introduce a vacuum energy contribution as

$$p = K_7 \rho^{\gamma_7} - \Lambda,$$
$$\epsilon = (1 + a_7)\rho + \frac{K_7}{\gamma_7 - 1}\rho^{\gamma_7} + \Lambda.$$

Notice that:

- We assume the phase transition to be first order: mass and energy density have to jump from ρ_- to ρ_+ and from ϵ_- to ϵ_+
- We parametrize the phase transition as $\epsilon_+ - \epsilon_- = \alpha|\Lambda|$

GW170817



FIRST COSMIC EVENT OBSERVED IN GRAVITATIONAL WAVES AND LIGHT

Colliding Neutron Stars Mark New Beginning of Discoveries

Collision creates light across the entire electromagnetic spectrum. Joint observations independently confirm Einstein's General Theory of Relativity, help measure the age of the Universe, and provide clues to the origins of heavy elements like gold and platinum

On August 17, 2017, 12:41 UTC, LIGO (US) and Virgo (Europe) detect gravitational waves from the merger of two neutron stars, each around 1.5 times the mass of our Sun. This is the first detection of spacetime ripples from neutron stars.

Within two seconds, NASA's Fermi Gamma-ray Space Telescope detects a short gamma-ray burst from a region of the sky overlapping the LIGO/Virgo position. Optical telescope observations pinpoint the origin of this signal to NGC 4993, a galaxy located 130 million light years distant.

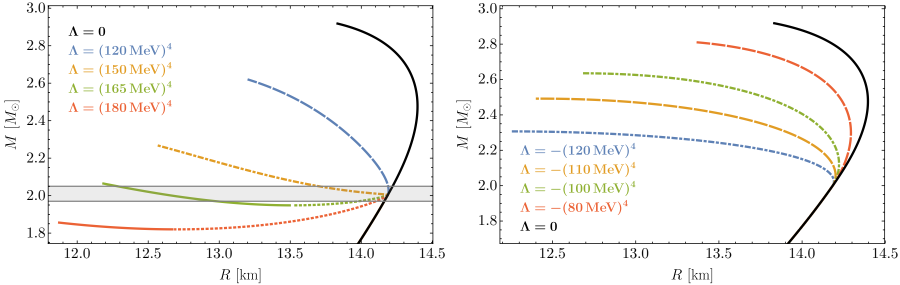
Spherically Symmetric Solution

With a spherically symmetric metric ansatz, the Einstein equations become the TOV equations:

$$\begin{aligned} m'(r) &= 4\pi r^2 \epsilon(r), \\ p'(r) &= -\frac{p(r)+\epsilon(r)}{r(r-2Gm(r))} G\big[m(r) + 4\pi r^3 p(r)\big], \\ \nu'(r) &= -\frac{2p'(r)}{p(r)+\epsilon(r)}. \end{aligned}$$

These provide the unperturbed solutions for the stars.

$M(R)$ Curves: Hebeler et al. EoS



- We obtain each curve by varying the central pressure of the star
- For a high enough pressure the core is in the exotic phase
- The neutron star solution must be stable: $\partial M/\partial p_{\text{center}} \geq 0$
- For some positive Λ we obtain disconnected branches characteristic of phase transitions

Tidal Deformability

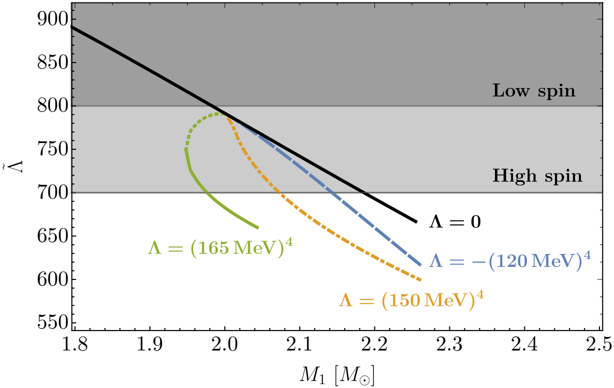
The presence of the second neutron star acts as an external perturbation. The combined dimensionless tidal deformability is

$$\tilde{\Lambda} \equiv \tilde{\Lambda}(M_1, M_2, \mathsf{EoS}_1, \mathsf{EoS}_2).$$

This quantity:

- Describes how the stars deform
- Is determined by the internal structure, i.e. by the EoS
- Shows up in the expansion of the gravitational waveform
- Is one of the main physical observables of LIGO/Virgo

Money Plot



- Hebeler et al. parametrization with the chirp mass of GW170817
- VE can significantly alter the allowed mass range
- It should be taken into account when comparing EoSs

Conclusions

- Vacuum energy is an important part of our standard picture of cosmology and particle physics, yet it is not very well understood
- It can contribute to the equation of state of neutron stars if the core contains a new phase of QCD at large densities
- This significantly affects the mass versus radius curves and LIGO/Virgo observables such as tidal deformabilities
- As the sensitivities of the experiments evolve and more events are observed, neutron star mergers can provide a new test of the gravitational properties of vacuum energy

Thank you!