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**Superfluidity and rotation in merging neutron star systems and effects related to gravitational wave emission**

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# Superfluidity and rotation in merging Neutron Star systems and effects related to gravitational wave emission

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# Gravitational wave sources.

The most common sources of gravitational radiation are:

- Compact Binary Coalescences (CBC).
- Continuous waves (Pulsars).
- Bursts (Supernovae).
- The Stochastic Gravitational-Wave Background (SGWB).

# Continuous waves

Continuous waves are sinusoidal signals coming often from our own galaxy

- There are $10^4$electromagnetically quiet neutron stars within 500 pc
- Continuous waves can be detected even by a single detector (frequency and amplitude modulation)
- Search methods well known but computationally very intensive
- Great astrophysical impact

# Bursts

Bursts are associated with star collapses, type II supernovae and black hole formation

- Sources: instabilities in NS, $\gamma$-ray bursts, unknown events
- Theoretical understanding is very poor
- Very difficult to detect: waveform unknown, very short signals, glitches in the detectors
- No detection claim if no electromagnetic (or neutrino) counterpart.

# The Stochastic GW Background

The Stochastic Gravitational-Wave Background (SGWB) is the random radiation emitted by many individual sources which are

- Independent
- Uncorrelated
- Unresolved (spatially and/or in frequency)
- With the possible exception of an astrophysical component, the SGWB comes from processes which took place immediatelyafter the Big-Bang.
- The SGWB could be **the link between highly-theoretical quantum gravity theories and experimental data**

## Compact Binary Coalescences

- Our **greatest hope** to detect gravitational waves: coalescences of NS and/or BH binaries
- Three phases: inspirals, mergers, ringdown. Detection based on matched filter: $\int s(t)\cdot h(t)\mathrm{d}t = \int h^2(t)\mathrm{d}t + \int n(t)\cdot h(t)\mathrm{d}t$. Computationally intensive.
- Event rate: 0.01-0.1/year (NS/NS, current detectors); 10-100/year (advanced detectors).
- Important source of science: Precision tests of GR, BH QNM, **Neutron Star EoS.**

# Black Holes

Black Holes are extremely fascinating objects but to the extent of gravitational wave emission they can be treated as elementary particles, characterised only by their mass and angular momentum. Numerical methods widely used to model merger phase. Supermassive ($M \geq 10^8 M_\odot$) black holes targeted by future space missions and Pulsar Timing Array (PTA) experiments.

# Neutron Stars

Neutron stars have a very complex structure that is the subject of deep investigation and can affect the emitted gravitational radiation. Amongst the phenomena we observe

- Deconfined quark matter
- Superfluidity and superconductivity with $T_c \sim 10^{10}$ K
- Large neutrino opacities
- Magnetic fields in excess of $10^{13}$ G
- **Neutron stars are the ideal connection between astrophysics, nuclear physics and particle physics.**

# Gravitational waves from neutron stars

Gravitational waves are expected from

- Mergers involving two neutron stars (or a neutron star and a black hole)
- Asymmetrically spinning neutron stars
- Gravitational collapses of supernovae which lead to neutron star formation

# Neutron star mergers

- Thought to be the central engine short gamma-ray bursts (multimessenger astronomy)
- Gravitational wave signal made up of a chirp signal, the burts amplitude from the very final plunge and the quasi-periodic post-merger signal.
- General Relativity dominates the inspiral phase but nuclear and particle physics become relevant during and after the merging
- **The GW signal is expected therefore to contain information about binary parameters (mass, spin) but also about the nuclear EoS and the internal dynamics of the star.**

# Superfluidity

For temperatures less than $\sim 0.1\,\mathrm{MeV}$ and densities above the neutron drip $\rho \geq 4 \times 10^{11}\ \mathrm{g/cm^3}$ the crustal neutron fluid forms a $^1S_0$ superfluid that alters the specific heat and the neutrino emissivity of the crust, therefore affecting how neutron stars cool. Superfluids have zero viscosity however an array of quantised vortices lead to an effective viscosity through the so-called entrainement effect: the momentum of the neutrons carries along part of the mass of the protons and thus triggers a scattering of the electrons off the entrained protons.

# Physics of the superfluid

- The superfluid is supposed to play a major role in the r-mode instability problem
- The superfluid is a reservoir of angular momentum that, being coupled to the crust, caused the pulsar glitch phenomenon
- Any change in the superfluid will affect the evolution of the individual neutron star and of the binary system.

## Pulsar glitches

Pulsar glitches are the occasional disruption of otherwise regular spindown by magnetic torquing. Leading model: angular momentum transfer from the superfluid to the normal component. Both are spinning but the normal crust is decelerated by the pulsar's magnetic dipole radiation. The superfluid is very weakly coupled to normal matter and its rotation rate is not diminished. But when the spin rate difference becomes too large, something happens and the spin rates are brought into closer alignment.

# Neutron star binaries

An individual neutron star spins **down** during its standard cooling process. This has been investigated. A neutron star in a binary system is forced by tidal coupling and accretion torques. The neutron superfluid is constrained to rotate on pinning sites. The spin up of the interior causes strong glitching and dissipation. The picture is radically different from that of an isolated neutron star.

# Questions

- Is the dissipation observable by Virgo as GW emission?
- Can we extract information about the superfluid and superconductor state from the merger waveform?
- Does this effect depend on the EoS (although the energy of the condensate is much smaller than the Fermi energy)?
- How is this picture modified in the case of a BH/NS system, for example in the tidal disruption of a neutron star?

# Merger rate

Models of galactic evolution provide rates of production for neutron stars through continued star formation. Standard picture: double degenerates can produce, through magnetically mediated spin-orbit coupling, the initial approach for the components to the point where energy loss is dominated by gravitational radiation.
The same is not true if the system is made up of two neutron stars. The interior structure of each component will depend on the EoS, and so will the evolution of the system. Depending on the radius -which is also EoS dependent- tidal couplings between the components sets in at different orbital frequencies.

# Superfluid turbulence

Superfluid turbilence leads to a global readjustement of the angular momentum distribution. However, in merging systems, there is a spin-up as the orbit decays.

- What happens to the vortices in the case of spin-up?
- Is there a phase transition?
- Will the superfluid disappear entirely into the normal component?
- We have started this investigation, Stay tuned for the results....

## Summary

- The coalescence of a NS/NS binary system is the most promising source of GW for advanced detectors
- The internal structure of neutron stars could lead to effects that are unaccounted for so far. In particular the superfluid of the star might change the expected waveform.
- These effects are related to the EoS, and could shed light on this hot topic, thus providing a link between gravitational-wave physics and fundamental physics.