Neutron Stars, Gravitational Waves & ultra-dense Matter

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Cold, β-equilibrated neutron stars

Neutron stars are born in the center of core-collapse supernovae. After a few minutes, and the formation of a crust, thermal effects on the structure are becoming negligible.

Composite image of Cassiopeia A
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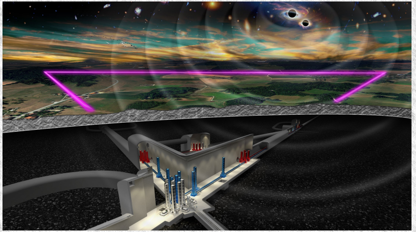
- $\Rightarrow$ T $\sim$ 0: cold nuclear matter;
- β-equilibrium has been reached in most parts of the star: $n \to p + e^- + \bar{\nu}_e$, and $p + e^- \to n + \nu_e$;
- many neutron stars observed as pulsars: rotation up to ~ 700 Hz;
- From simple estimate $GM/Rc^2 \sim 0.2 \Rightarrow$ compact object: general-relativistic effects are non-negligible.

Gravitational waves

Detectors for neutron star interior

From the mass range of neutron stars, high frequencies ($\sim$ few 100 Hz) are the best to detect the last stages of binary neutron star (BNS) coalescence.

LIGO-Virgo-Kagra: current ground-based detectors (USA – France-Italy-Netherlands+ – Japan)

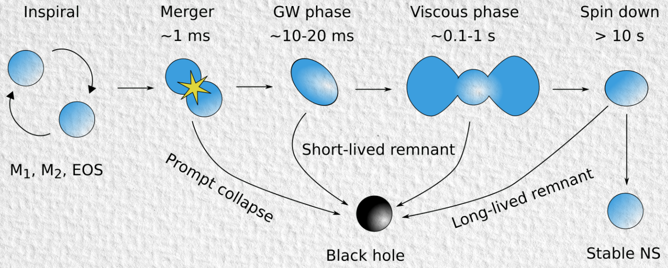


Einstein Telescope (European project $\Rightarrow$ 2040?)

Binary Neutron Stars

Coalescence, merger, ...

Binary systems of compact objects are the main sources of gravitational radiation: binary black holes (BBH), neutron stars (BNS) and mixed (NSBH).



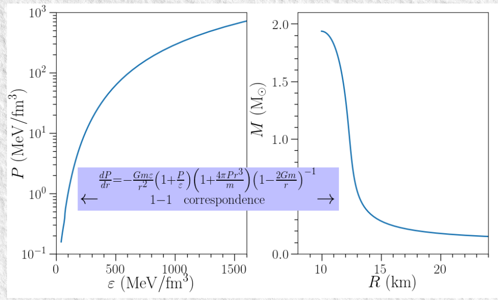
[Radice+ 2020]

- **GW170817** was the first BNS detected with gravitational waves,
- only inspiral phase ⇒ measure/constraints of masses, spins and tidal deformabilities.

Neutron Star Matter

Equation of State

Equation of state (EoS): relation between thermodynamic variables $(P, \epsilon, n_B, \ldots)$, e.g. $P(\epsilon)$ and describes microphysical properties of matter.
EoS is computed from properties of nuclear matter, at densities around nuclear saturation density and above.



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Assuming spherical symmetry, one-to-one relation between the EoS and the $M - R$ relation of neutron star equilibrium states.

⇒what is the EoS for (cold β-equilibrated) neutron star matter?

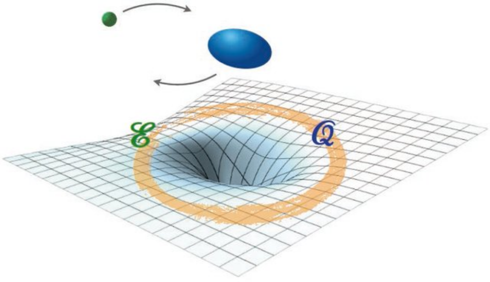
Tidal Deformability & Gravitational Waves

A (spherical) neutron star in a binary system is deformed by the companion's tidal gravitational field:

- $\mathcal{Q}$: quadrupole tensor
- $\mathcal{E}$: tidal field from the companion

$$\mathcal{Q}_{\text{tidal}} = -\lambda \mathcal{E}_{\text{tidal}}$$

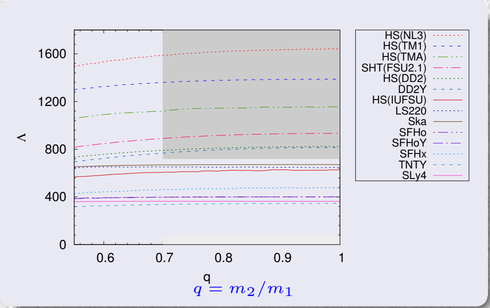
and $\Lambda = G\lambda \left[c^2/(GM)\right]^5$.



[Dietrich+ 2021]

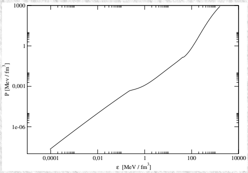
Waveforms for binary systems depend on each body's mass, spin and tidal deformability (Λ).
$\Rightarrow$ Λ is the only source of information about the internal structure . . . and depends on the EoS.

GW170817: A FIRST CONSTRAINT



Detection of the first BNS merger with multimessenger astronomy $\Rightarrow$ constraints on Λ

First (and only) constraint on Λ, excluding some EoSs . . .



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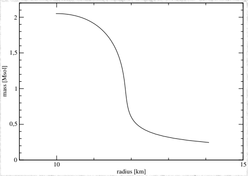
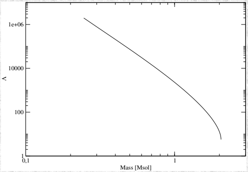


$\Longleftrightarrow$



$\Rightarrow$ to get EoS information, reconstruct from $M(\Lambda)$ from more precise (upgrades / next generation) instruments.

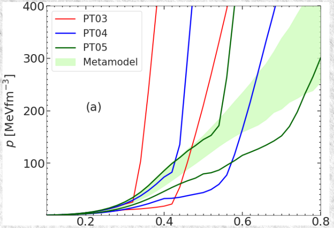
Phase transition?

In principle OK, but needs many detections …

Is it possible to get information about a possible phase transition from one detection of third-generation instruments (ET and Cosmic Explorer) ?

Detectability of a phase transition

- Metamodel approach to nuclear matter [Dinh Thi+2021] and quark matter (constant sound speed) [Mondal+2023]
- Injected EoS chosen within the ranges covered
- Three possible phase transition onset densities



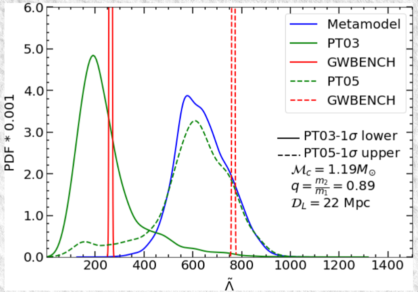
[Mondal+2023]

- Simulate observations with 3rd generation detector network (ET +2CE)
  - Detector response estimated using Fisher matrix formalism within GWBENCH [Borhanian2021].
  - Fixing spins and inclination, varying distance and two component masses

Detectability of a phase transition

Bayesian analysis with one loud event

- 450 simulated events (distance, component masses, injected EoS):
  - Mass ratio has little effect.
  - Higher chirp mass can make it easier to distinguish.
  - The smaller the distance the easier.
  - A high-density PT is difficult to distinguish.



[Mondal+2023]

- Possible to identify a strong PT with an onset at low density, high density onset masked.
- Analysis with accumulation of events to be done.

Summary – Outlook

Summary

- Virgo group, participated to the study of possible upgrade after $\sim$ 2030 (Virgo_nEXT).
- ET group, participated to the science case for nuclear physics
- Excellent opportunities for neutron star physics: EoS and phase transition.

Outlook

- Continue on the search of third-generation detectors to detect phase transition signature in BNS mergers, with a "realistic" BNS population.
- Study dynamics and oscillation modes of BNS post-merger phase, relating them to nuclear matter properties (Gaël's PhD + ANR project).
- Look for EM precursor signal from interacting magnetospheres in BNS merger.

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Thank you!