Gravitational waves from neutron stars in the ET era

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Where in France?

Neutron star physics and observations

Nuclear Physics (IN2P3)

- GANIL – Caen
- IJC Lab – Orsay
- IP2I – Lyon
- LPC – Caen

Theory (INP)

- IAP / GReCo – Paris
- LMPT – Tours
- LUTh – Meudon

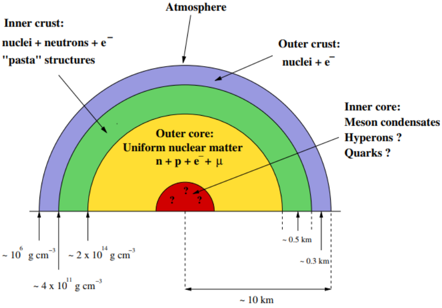
Astrophysics (INSU)

- AIM – Saclay
- CENBG – Bordeaux (IN2P3)
- IAP / High Energy – Paris
- IPAG – Grenoble
- IRAP – Toulouse
- LPC2E – Orléans
- LUTh – Meudon
- ObAS – Strasbourg

Neutron stars

Introduction

- end-products of stellar evolution during core-collapse supernova events
- predicted as such by Baade & Zwicky 1934
- first observed as a radio pulsar in 1967
- complex structure, with density around nuclear saturation density $\rho_0 \simeq 2.7 \times 10^{14}$ g cm^{-3}.

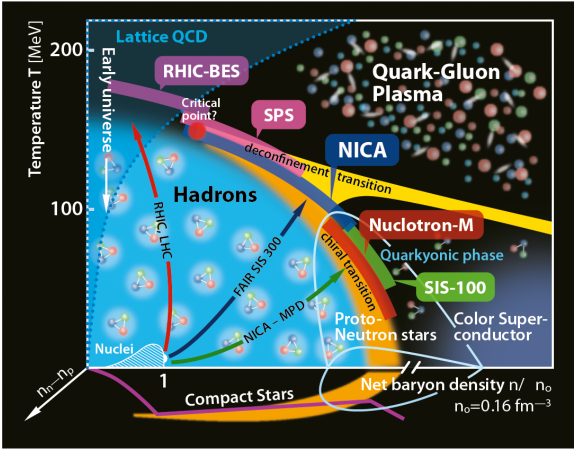


Credits: Isaac Vidaña

Neutron stars

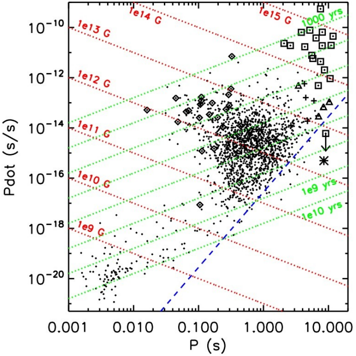
QCD phase diagram

Macroscopic objects with extreme density $\Rightarrow$ probe matter in conditions where the strong interaction is dominant



Which hadrons? Transition to quark matter?

Over 2000 pulsars have been observed + accreting neutron stars



- pulsar ⇒ spin period, magnetic field, age
- binary system ⇒ mass
- accretion, light bending ⇒ crust properties, radius

Electromagnetic signals coming from the surface or above ⇒ model-dependent.

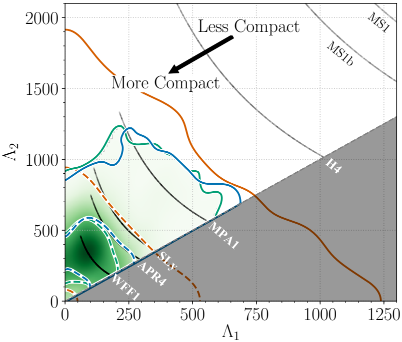
Many constraints have already been put, but interior (core) composition remains largely unknown.

Binary neutron stars

Gravitational Waves

GW can bring information from the inside of neutron stars!

- GW170817 and following put first constraints from GW to neutron star's equation of state
- determination of tidal deformability Λ: a parameter entering the waveform post-Newtonian templates for the inspiral phase
- gives a constraint, not the equation of state $p(\rho)$

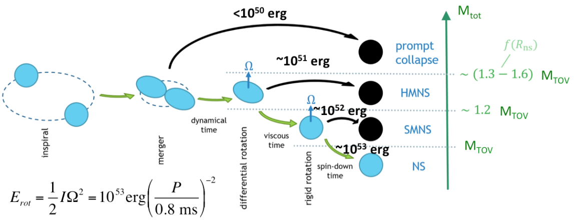


LVC: Abbott *et al.* (2018)

Binary neutron stars

post-merger scenarios

Post-merger phase not detected yet with GW. . .



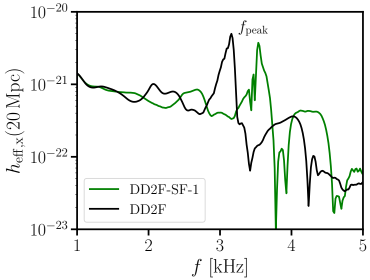
Metzger (2019)

- formation of a long lived metastable neutron star
- differential rotation, $T \neq 0$ effects, neutrinos, magnetic field, . . .
- much richer than the inspiral phase
- but complicated numerical models

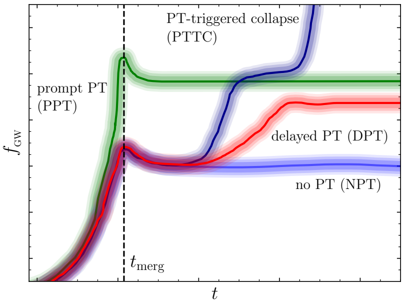
$\Rightarrow$ explore larger space of the QCD phase diagram ($T > 0$, out of β-equilibrium)

$\Rightarrow$ GW from oscillations of the (hyper-)massive neutron star

Two examples showing possibilities of characterizing a phase transition



Bauswein *et al.* (2019)

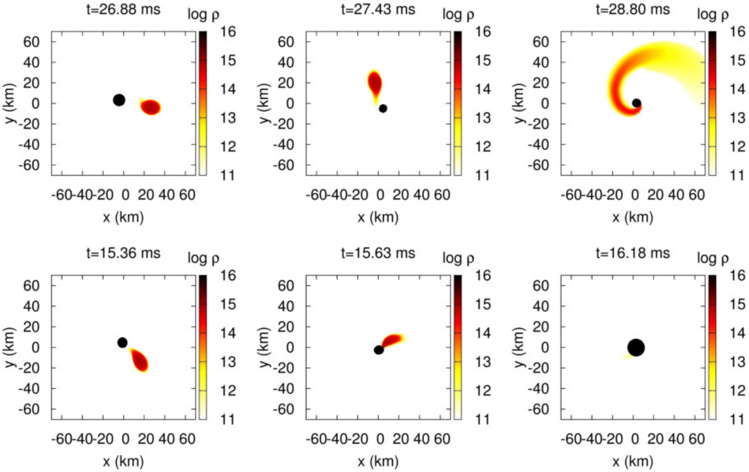


Weih *et al.* (2020)

Probe of different regions of QCD diagram than heavy-ion colliders.

BH-NS binaries

Different scenarios: tidal disruption / plunge of the neutron star

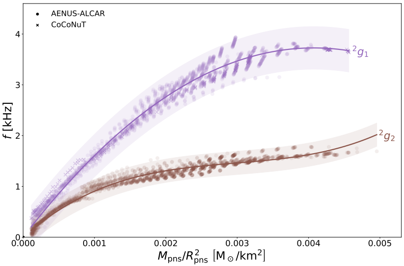


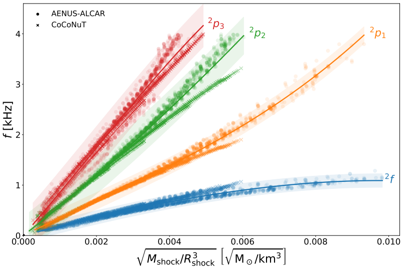
Kyutoku *et al.* (2011)

Depends on many parameters, including the equation of state

Core-collapse supernovae

Rare detectable events: galactic supernova ?



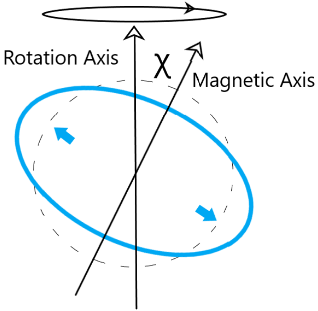


Torres-Forné *et al.* (2019)

Identification of GW emitting modes can provide information about mass & radius of the proto-neutron star

$\Rightarrow$ may be difficult to deduce properties of the underlying equation of state (Préau *et al.* 2021)

Continuous waves



- principal source of continuous GW are spinning neutron stars, deformed
- deformation comes from non-axisymmetric deformation (w.r.t rotation axis)
- magnetic field, "mountains" in the crust, accretion, r-mode instability, ...
- not detected yet, but well-identified sources (pulsars)

constraints on some sources below the spin-down limit

$\Rightarrow$ detection may bring valuable information on the crust

Conclusions

- neutron stars represent incredible probes for matter at extreme (nuclear) densities
- O2 and O3 results from LVC/LVK have shown the huge potential for neutron star physics
- ET would not only improve on these results: allow for exploring the post-merger phase of binary neutron star coalescence
- more than mere constraints on the equation of state: phase transition, temperature effects, etc probe the QCD phase diagram
- + improvement on the probability of observing other sources: core-collapse supernovas, spinning neutron stars, with different type of information

$\Rightarrow$ For binary neutron stars ET can bring good characterization of masses and spins (low frequencies) + follow-up of post-merger phase (high frequencies).