Can we detect phase transitions in neutron star matter with gravitational waves?

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Assemblée générale GdR Ondes Gravitationnelles, Lyon, October 10-11, 2019

A neutron star : a star made of neutrons....

- 1932, Landau (Phys. Z. Sowjetunion, 1, 285)
  Possibility of stars with a central density comparable to that of nuclei
- 1934, Baade and Zwicky (Phys. Rev. 45, 138)
  Prediction of the existence of neutron stars : *With all reserve we advance the view that supernovae represent the transition from ordinary stars into neutron stars, which in their final stages consist of extremely closed packed neutrons.*
- 1939, Tolman, Oppenheimer, and Volkov
  General relativistic neutron star models : $M \approx 1.5 M_\odot$ and $r \sim 10$ km $\longrightarrow$ density $\sim 0.1\ \mathrm{fm}^{-3}$

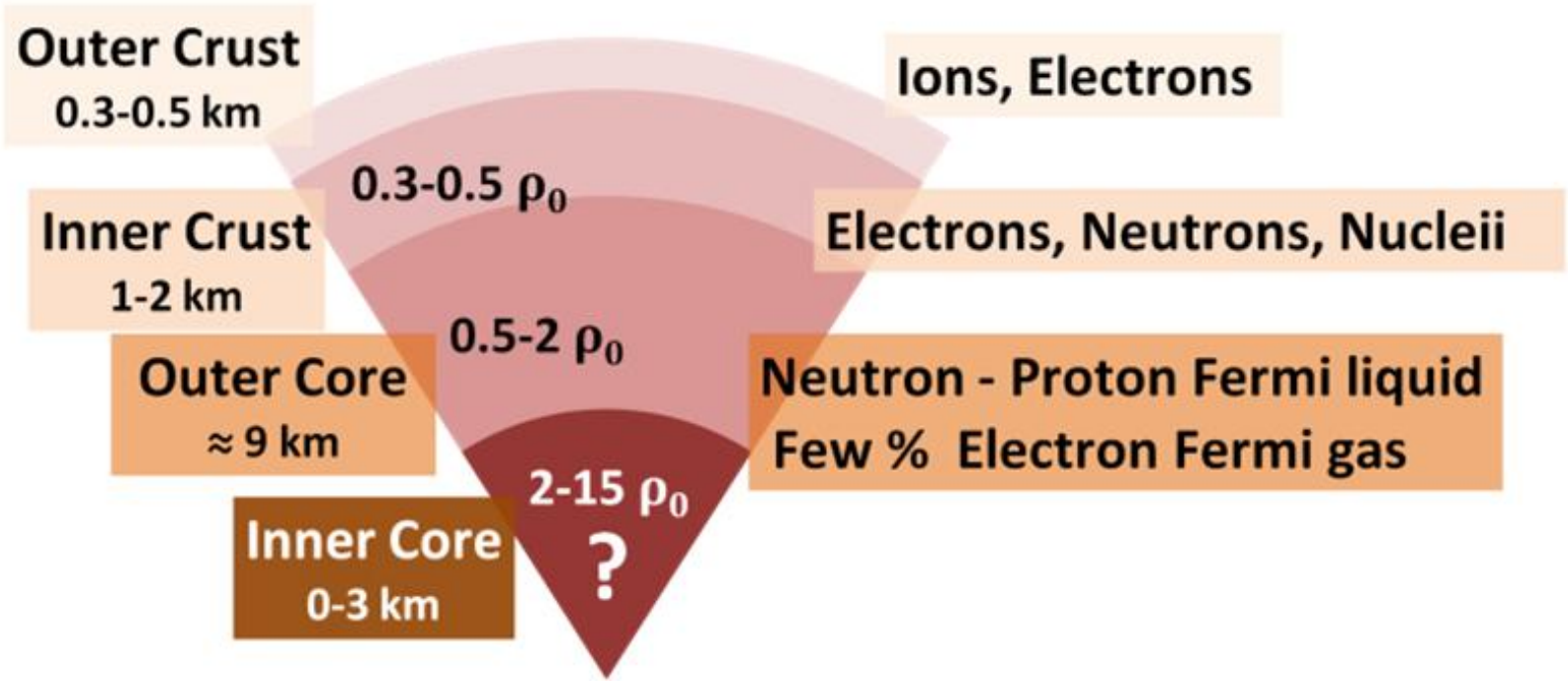
Walter Baade

Fritz Zwicky

Laboratoire Univers et Théories

It is slightly more complicated

Standard picture of the inner structure



- crust formed of nuclei, neutron gas in inner crust
- transition to the core characterised by transition to homogeneous matter
- composition close to the center almost unknown (hyperons, kaon/pion condensate, quark matter . . . ?)

What happens if additional particles appear?

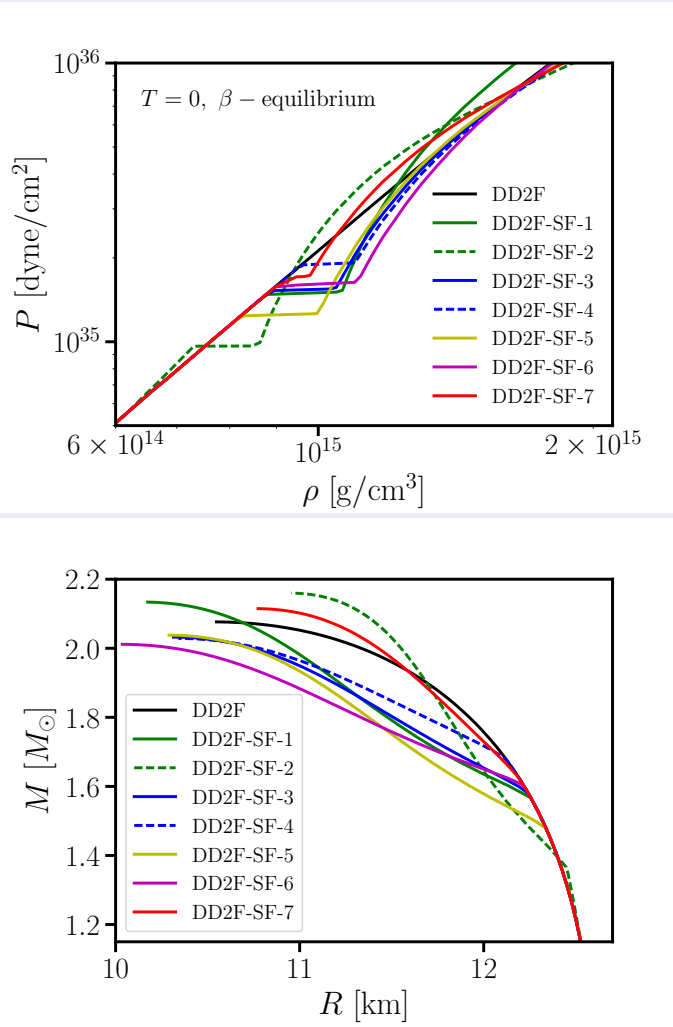
Phase transitions in the dense core

- Example : Hyperons (strange baryons, known from experiments)

  They can appear if the chemical potential is high enough to make conversion $N \rightarrow Y$ energetically favorable $\rightarrow$ onset density

  At onset density : smooth transition or first order phase transition
- Phase transition $\rightarrow$ jump in (energy) density
- Hadron-quark phase transition possible in the core of neutron stars
- Possibly additional superconducting phase transitions in quark matter core

EoS and TOV solutions with phase transition



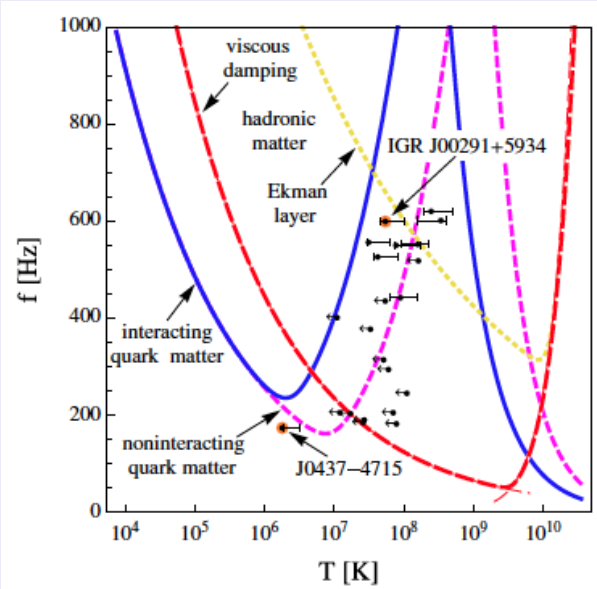
[Bauswein et al. 2019]

Signatures of a phase transition ?

- Heavy-ion collision experiments study transition from hadronic matter to quark-gluon plasm at low density and high temperatures
- QCD lattice simulations study similar domain
- First order phase transition in dense and cold matter not accessible in terrestrial laboratories nor to ab-inito calculations $\longrightarrow$ neutron stars

- Global properties based on the equation of state would need a very (!) precise M and R to distinguish
- Transport properties very sensitive to matter constituents and phases (thermal evolution), but many different possibilities ...
- Oscillations (e.g. r-mode instabilities) and GW from binary mergers

r-mode instabilities regions



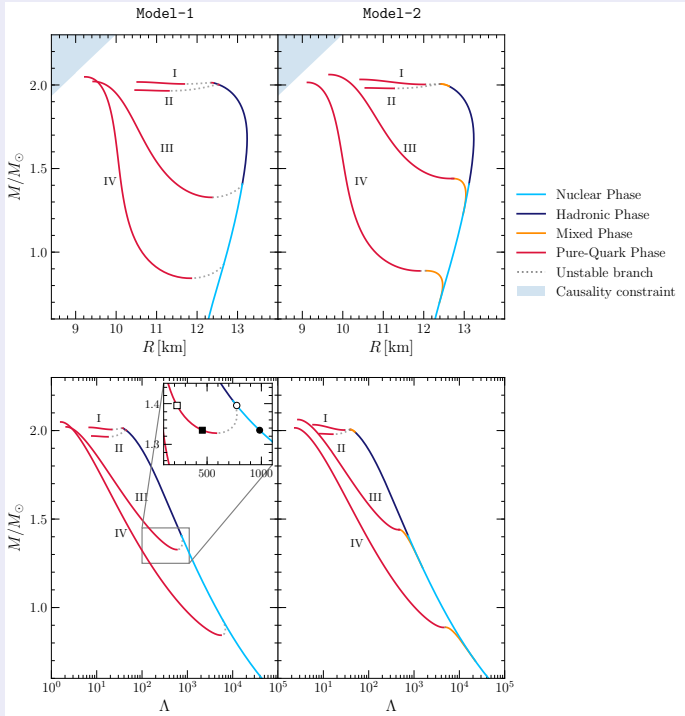
[Alford & Schwenzer]

Can we detect a phase transition in binary mergers ?

Tidal deformability [Sieniawska 2018, Tews 2018, Montana 2018, Han 2018, Christian 2018...]

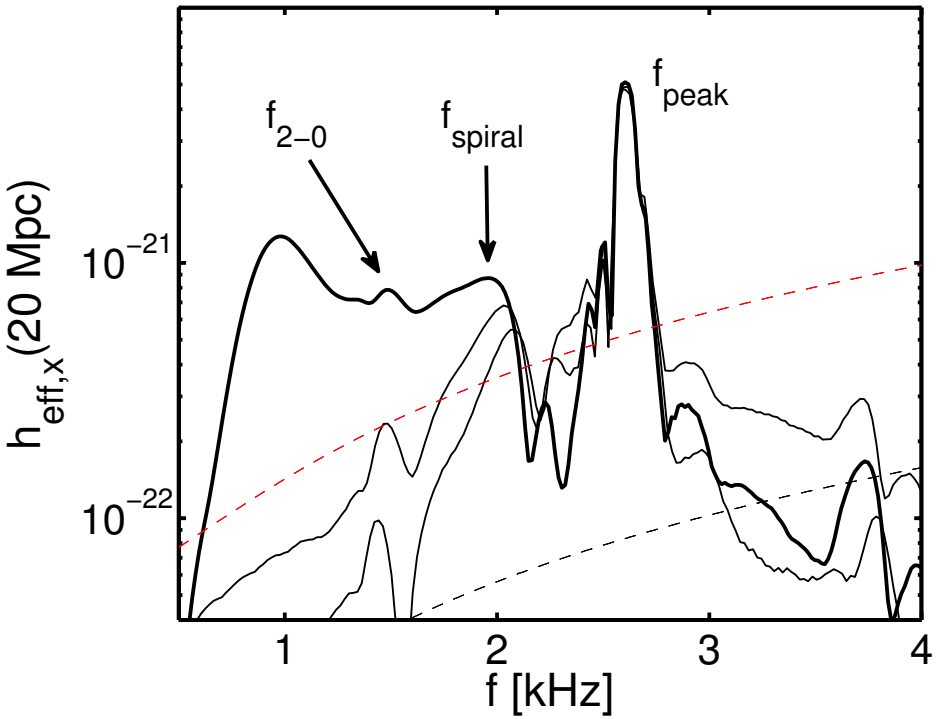
- Λ(M) deviates if non-nucleonic particles appear
- Strong first order phase transition with unstable branch
  $\rightarrow$ discontinuity
- Relation Λ-R not obvious to extract (twin branch with two R for same M)
- Imprint on GW signal depends on mass for onset of phase transition
- Confirm transition with several tens of detections ? [Chen 2019]

Λ vs gravitational mass with phase transition



[Montana 2018]

Post merger oscillations



[Bauswein 2016]

- Post-merger oscillations very sensitive to matter properties and EoS
- Similar oscillation pattern in all simulations
- Peak frequency correlated with NS properties
  - Radius [Bauswein et al]
  - Tidal deformability

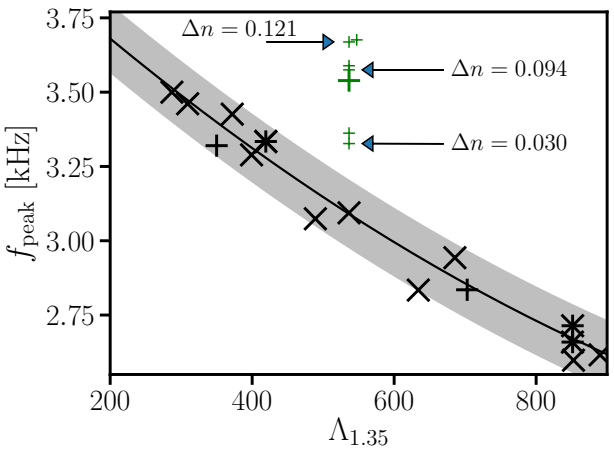
  [Takami & Rezzolla]

- Correlation slightly scattered if asymmetric progenitors [Kiuchi& Shibata]
- Not yet detected (frequency range $\sim$ kHz), but in the range of detectors in near future

In binary mergers

Post merger signal [Bauswein 2019, Most 2018, Ecker 2019...]

- Even if NS prior to merger do not contain quark core, the dense merger remnant might
- Different cases
  - Very strong phase transition with no stable hybrid NS [Most 2018, Ecker 2019, ...]
    $\rightarrow$ almost immediate collapse to BH at onset of phase transition
    $\rightarrow$ almost no identifiable signal



[Bauswein 2019]

- Strong phase transition with stable hybrid NS and considerable quark core in merger remnant [Bauswein 2019]
  $\rightarrow$ Oscillations frequencies show imprint of matter properties
  $\rightarrow$ Clear signal of phase transition
- Smooth transition leads to softening of EoS, but not distinguishable from EoS dependence of signal