NEUTRON STARS AND THE DENSE MATTER EOS

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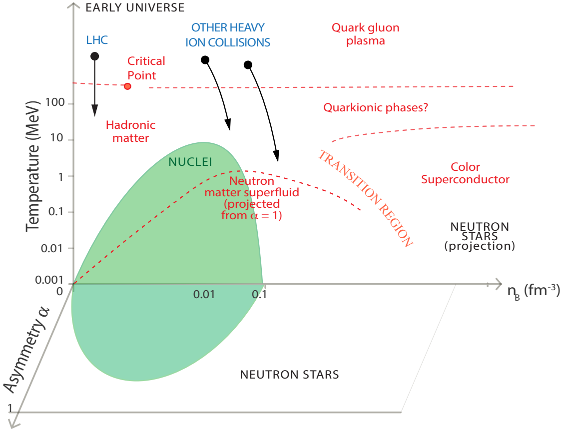
- Brandon has been involved in
  - Relativistic superfluid hydrodynamics (Nils' and Nicolas' presentations)
  - Neutron star crust structure (band theory and elasticity)
  - and . . .

- The SNNS meetings at Orsay in the early 2000's :
  collaboration with the nuclear physics community on neutron star physics
- Bring relativity and nuclear physicists together

A NUCLEAR PHYSICISTS POINT OF VIEW

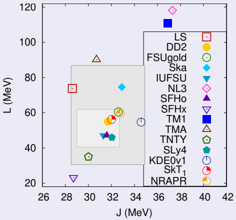


[Watts+2015]

Neutron star matter is strongly interacting matter under extreme conditions not accessible in terrestrial laboratories (density, asymmetry) nor to ab-inito calculations

CONSTRAINTS FROM NUCLEAR PHYSICS

EXAMPLE : SYMMETRY ENERGY AND SLOPE
(LATTIMER & LIM 2013, MO+ 2017)

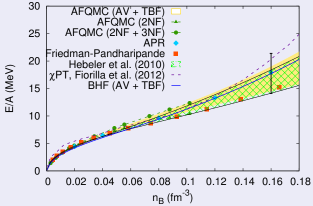


- Nuclear masses (binding energies) for many nuclei close to stability
- Extracting parameters of symmetric nuclear matter around saturation (n_0, E_B, K, J, L)
- Data from heavy ion collisions (flow constraint, meson production, . . .)

- Data on nucleon-nucleon interaction fixing startpoint of many-body calculations
- Low density neutron matter : Monte-Carlo simulations and EFT approaches

Many uncertainties about composition at high densities

DIFFERENT AB INITIO NEUTRON MATTER CALCULATIONS [MO+2017]



ON THE ASTROPHYSICAL SIDE

NEUTRON STAR MASSES

- Observed masses in binary systems (NS-NS, NS-WD, X-ray binaries) with most precise measurements from double neutron star systems.
- Three precise mass measurements in NS-WD binaries
  - PSR J1614-2230 : $M = 1.908 \pm 0.016 M_\odot$ [Fonseca et al 2021]
  - PSR J0348+0432 : $M = 2.01 \pm 0.04 M_\odot$ [Antoniadis et al 2013]
  - PSR J0740+6620 : $M = 2.08 \pm 0.07 M_\odot$ [Fonseca et al. 2021]

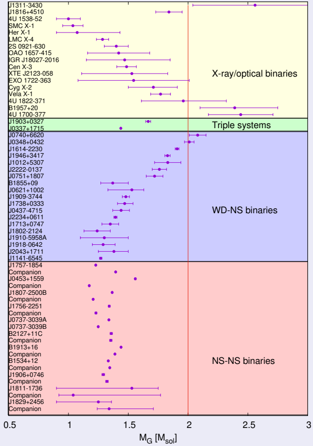
GIVEN EOS ⇔ MAXIMUM MASS

Additional particles add d.o.f.

→ softening of the EoS

→ lower maximum mass

→ constraint on core composition



[update from Lattimer & Prakash, 1012.3208]

On the astrophysical side

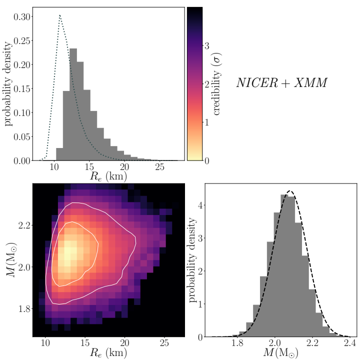
Radius estimates from x-ray observations

- Radii from different types of objects, but very model dependent :
  - Atmosphere modelling
  - Interstellar absorption (X-ray observations)
  - Distance, magnetic fields, rotation, . . .

Many discussions

Consensus : radius of a fiducial $M = 1.4 M_\odot$ star 10-15 km

NICER+XMM Newton PSR J0470+6620



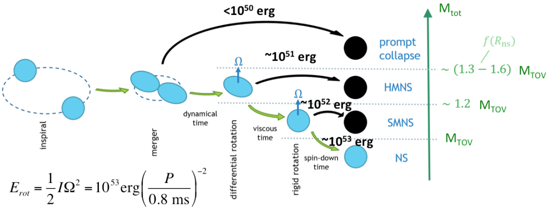
[Miller+ 2021]

- NICER results gave for the first time mass and radius of the same star ! Uncertainties from unknown thermal distribution on the NS surface

On the astrophysical side

Gravitational waves

- GW170817 : first detection of a NS-NS merger with LIGO/Virgo detectors
- Information from different phases
  - Inspiral → masses of objects
  - Late inspiral → tidal deformability $\tilde{\Lambda}$



[Metzger 2019]

  - Post merger GW emission not yet detected but in reach for 3rd generation detectors
  - Electromagnetic counterpart with information about ejecta properties, kilonova, . . .
- GW200105 and GW200115 : first detection of two BH-NS merger events with LIGO/Virgo detectors
- Galatic supernova is in reach for current detectors

WHAT HAPPENS IF THERE ARE NOT ONLY NUCLEONS

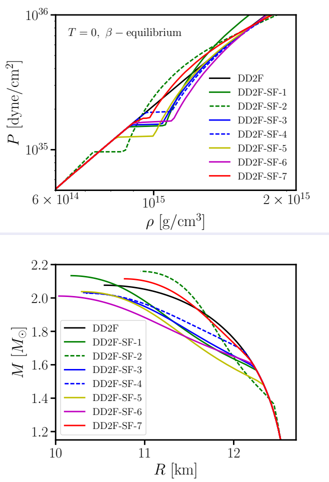
PHASE TRANSITIONS IN THE DENSE CORE

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

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

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

EOS AND TOV SOLUTIONS WITH PHASE TRANSITION

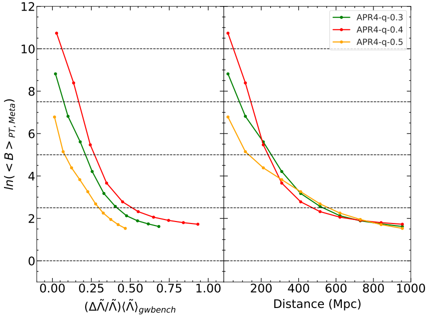


[Bauswein+ 2019]

DETECT A PHASE TRANSITION IN BINARY MERGERS ?

INSPIRAL

- Tidal deformability depends on matter properties [Read+, Faber & Rasio, Hinderer+,. . .] ; matter not considerably heated up before merger
  → NS radius and cold β-equilibrated EoS
- Even if the cold NS EoS can be determined, no information a priori about composition in absence of a phase transition [Mondal& Gulminelli 2021]



[Mondal+ in prep]

- Detectability of a phase transition during inspiral depends on the onset density and the masses of the coalescing star(s)

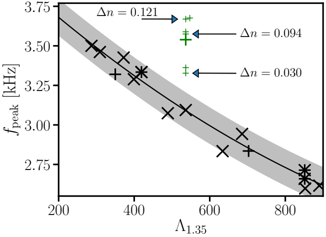
  [Sieniawska+2018, Tews+2018, Montana+2018, Han+2018, Christian+2018. . .]

  and on distance and detector properties
- Reasonable hope for 3rd generation detectors

DETECT A PHASE TRANSITION IN BINARY MERGERS ?

POST-MERGER PHASE

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



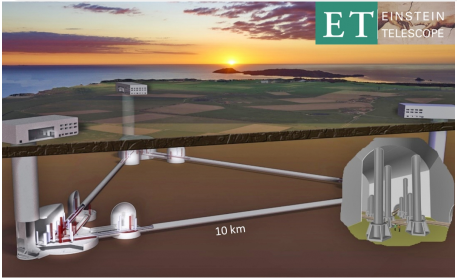
[Bauswein+2019]

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

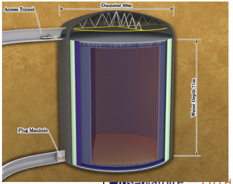
OUTLOOK

- Many other experimental/observational projects underway or planned :
  - Pulsar observations (SKA and precursors) with precise NS mass determinations, moment of inertia, . . .
  - NS radius determinations from x-ray and GW (tidal deformability) detections with high precision from Advanced and 3rd generation detectors
  - GW from BNS post-merger phase in reach for 3rd generation detectors
  - Neutrinos from next galactic supernova with efficient detectors (Super/Hyper-Kamiokande, . . .)

→ need precise modelisation combining theory of gravity, microphysics input, (superfluid) hydrodynamics, magnetic fields



[SKA radio telescope project]



[Schematic view of the Hyper-Kamiokande neutrino