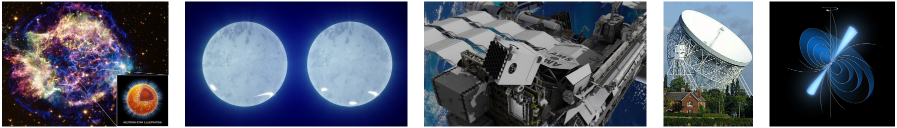
Prospectives nationales 2020–2030 : Atelier “Physique Théorique des deux infinis”

Theoretical Modeling of the Neutron Star Crust

Marco Antonelli[1→2], Anthea Fantina[3], Marcella Grasso[4], Francesca Gulminelli[2],
Elias Khan[4], Jérôme Margueron[5], Micaela Oertel[6], Michael Urban[4]

[1]CAMK (Warsaw), [2]LPC Caen, [3]GANIL (Caen), [4]IJCLab (Orsay),
[5]IP2I (Lyon), [6]LUTH (Meudon)

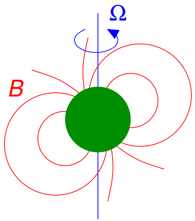


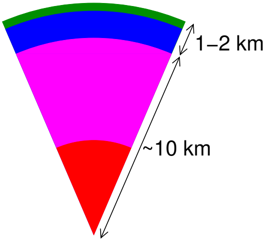
Outline

1. Neutron stars
2. Why are we studying the crust?
3. Uniform matter at low density
4. Crust composition
5. Glitches
6. Crust breaking
7. Conclusion

Neutron stars

- Compact objects ($\sim$ 2000 are known in our galaxy) produced in core-collapse supernovae at the end of the life of intermediate-mass stars
- Mass $M \sim 1 - 2M_{\odot} = 2 - 4 \times 10^{30}$ kg in a radius of $R \sim 10$ km: density $\rho >$ nuclear saturation density $\rho_0 = 2.7 \times 10^{14}$ g/cm^3, $n_0 = 0.16$ fm^{-3}
- Typical rotation periods range from few s to few ms
- strong magnetic field B: typically $\sim 10^{12}$ G, magnetars: $B_{\text{surf}} \sim 10^{14} - 10^{15}$ G
- B not aligned with the rotation axis leads to periodic e.m. emission (pulsar) and slows down the rotation
- A neutron star has a complex inner structure:





outer crust: Coulomb lattice of neutron rich nuclei in a degenerate electron gas

inner crust: unbound neutrons form a neutron gas between the nuclei (clusters)

outer core: homogeneous matter (n, p, e^-)

inner core: hyperons? quark matter?

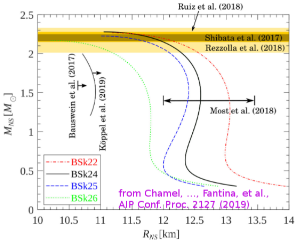
Why are we studying the crust?

(1) Effect on astrophysical observables

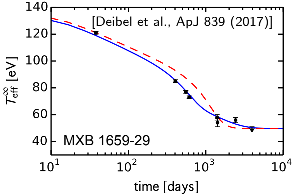
- Crust composition
  $\leftrightarrow$ equation of state for $n \lesssim 0.08\,\mathrm{fm}^{-3}$
  $\leftrightarrow$ $M(R)$ relation
- Heat transport through the crust
  $\leftrightarrow$ observed surface temperatures
- Nuclei in the crust form a Coulomb crystal
  $\leftrightarrow$ elasticity, cracks, crustquakes
- Unbound neutrons in the inner crust are superfluid
  $\leftrightarrow$ glitches, cooling, oscillation modes

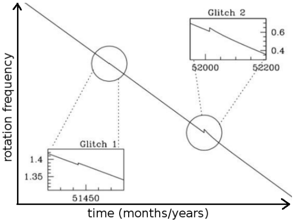
(2) Crust as nuclear physics laboratory

- Energy-density functional at low density and large asymmetry
- Study of pairing and superfluidity
- Testing ground for many-body theories (ab-initio calculations, links with ultracold atoms)



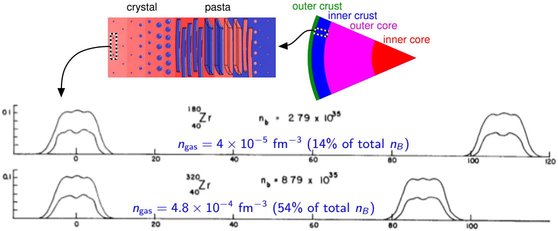
from Chamel, ..., Fantina, et al., AIP Conf. Proc. 2127 (2019)





Equation of state of uniform matter at low density (1)

- Inner crust:
  large regions of very
  dilute neutron matter
  (between the clusters)

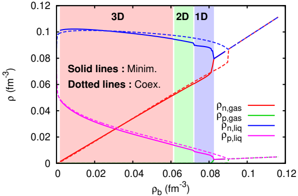


$n_{\text{gas}} = 4 \times 10^{-5}$ fm^{-3} (14% of total n_B)

$n_{\text{gas}} = 4.8 \times 10^{-4}$ fm^{-3} (54% of total n_B)

- Low densities most suitable
  for ab-initio descriptions
  (e.g. with chiral interactions)

- Composition of the inner crust is
  approximately determined by the
  EOS of uniform matter
  (liquid-gas phase coexistence)

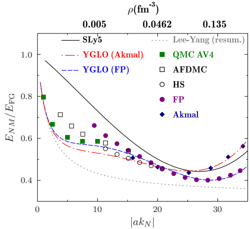


[Martin and Urban, PRC (2015)]

- Uniform matter is the first step in constructing an energy-density functional

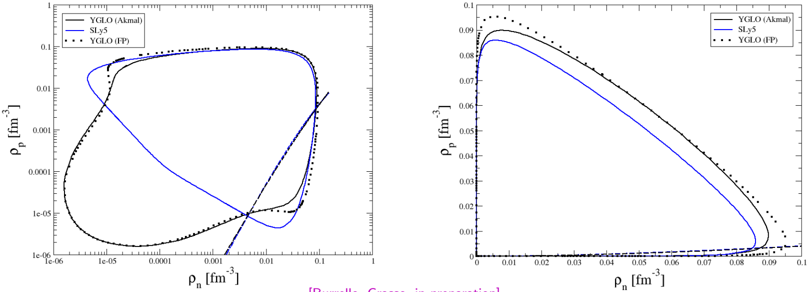
Equation of state of uniform matter at low density (2)

- Example: YGLO functional reproduces both the low-density EOS known from $k_F a$ expansion and phenomenological EOS around saturation



[Yang, Grasso, Lacroix, PRC 94 (2016)]

- Drastic change of the region of the spinodal instability, especially at low density



[Burrello, Grasso, in preparation]

- Important effect on neutron-drip density and inner-crust composition expected!

Pairing in uniform neutron matter

- Superfluidity of the neutron gas in the inner crust is responsible for glitches

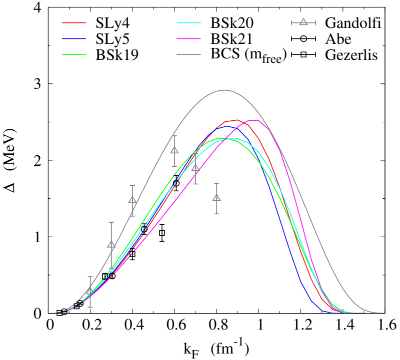
- The pairing gap Δ affects also cooling: suppression of the specific heat, new neutrino-emission mechanism (pair breaking and formation)

- Dilute neutron matter similar to ultracold atoms ($R < 1/k_F < |a_{nn}|$)

- Medium polarization (screening) effects reduce the gap compared to BCS theory

- Density where the gap tends to zero is strongly model dependent

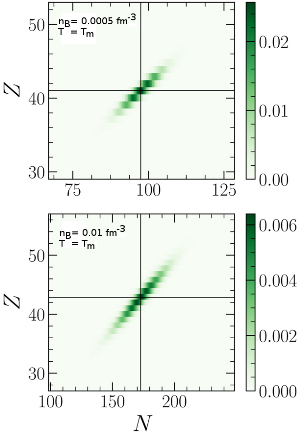
- Ab-initio calculations needed!



[Ramanan and Urban, EPJ ST (2021)]

Composition of the crust

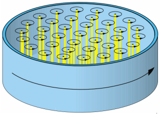
- Crust is not made of uniform matter but a crystal of nuclei (outer crust) or clusters in a neutron gas (inner crust)
- Composition determined by energy minimization: HFB for the outer crust [Pearson,. . . , Fantina, et al. MNRAS (2018)], usually ETF or similar approximations for the inner crust [Martin and Urban, PRC (2015)]
- Problematic to consistently match different EOS for outer crust, inner crust, and core: use unified EOS
- Finite crystallization temperature
  $\longrightarrow$ distribution of (N, Z) around the energy minimum
  $\longrightarrow$ prediction for the impurity parameter Q_{imp}



[Carreau, Fantina, and Gulminelli, A&A (2020)]

- Q_{imp} has important effect on transport properties (electric conductivity, heat conductivity) and may also have impact on the entrainment

Glitches



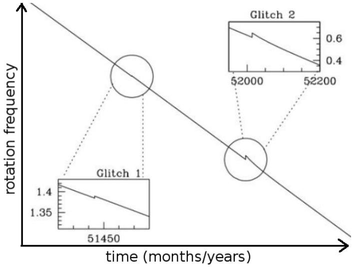
- Superfluid neutrons in the inner crust can only rotate by forming quantized vortices
- If vortices are **pinned** to the nuclei, their number cannot change and the superfluid does not follow the slowdown of the star

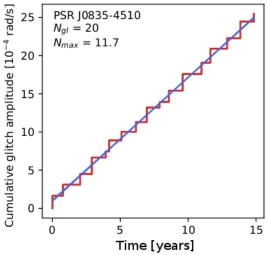
  ⟶ superfluid rotates faster than the rest
- When the difference becomes too big, vortices will be unpinned and move outwards

  ⟶ superfluid transfers angular momentum

  ⟶ **sudden spin up = glitch**
- Some of the unbound neutrons are **entrained** by the lattice of nuclei

  ⟶ superfluid density in the crust is reduced
- Is it still enough to explain Vela's **glitch activity** (average slope)?

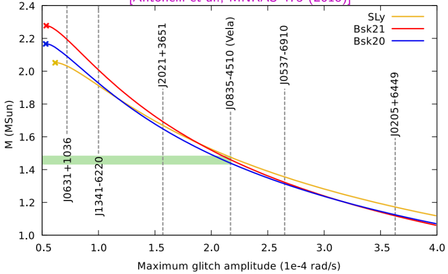




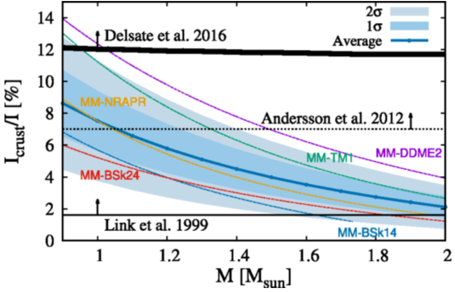
Static constraints from glitches

- The pinning force determines the maximum glitch amplitude
- If pinning force and EOS known $\longrightarrow$ constraint on M
- The entrainment determines the maximum glitch activity
- Band-structure theory [Chamel] gives strong entrainment that is incompatible with realistic M
- Superfluid hydrodynamics predicts much weaker entrainment [Martin and Urban, PRC 94 (2016)]
- Microscopic studies of pinning force and entrainment needed!

[Antonelli et al., MNRAS 475 (2018)]

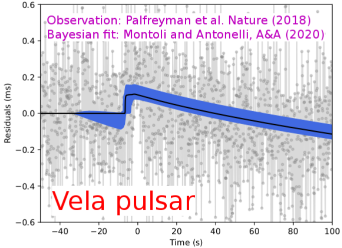


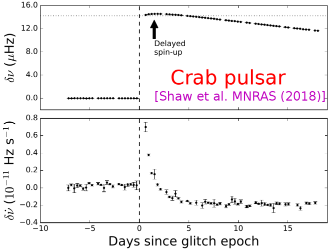
[Carreau, Gulminelli and Margueron, PRC (2019)]

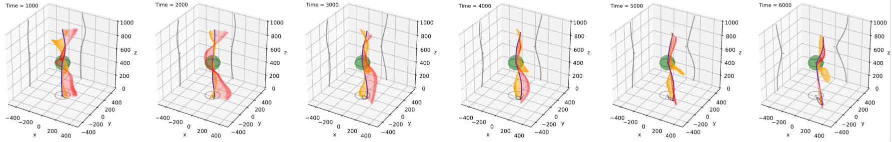


Dynamics of glitches

- Permanent monitoring of pulsars will allow for the observation of the dynamics of the glitch
  - Why are the time scales in Vela and Crab so different?
  - Is there a slow-down before the glitch?
- To understand the spin-up and the following post-glitch relaxation, we have to model the hydrodynamic friction which depends on the average vortex motion
- Program: simulation of vortex motion in the crust environment
- Example: repinning of a vortex





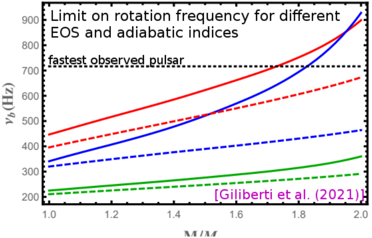


Breaking of the crust

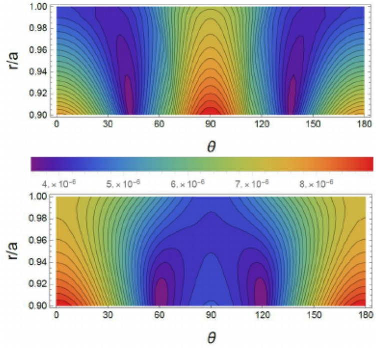
- Like every elastic material, the crust will break or deform plastically beyond some maximum strain
- Crust breaking can emit X-ray bursts
- Crustquakes, generate gravitational waves
- Limit on the rotation frequency of spinning-up accreting ms pulsars [Fattoyev et al. (2018)]
- Spinning-down pulsars: crustquakes as triggers for glitches? [Akbal and Alpar (2018)]
- Depending on mass, EOS, and adiabatic index, the crust breaks at the equator or at the poles
- Role of crust breaking in neutron-star mergers

  [Pereira, Andersson et al. (2020) claim effect is small]
- Breaking strain very uncertain: depends on defects and polycristalline structure

  (theoretical estimates of the breaking strain for ordinary materials sometimes wrong by two orders of magnitudes)



[Giliberti, Antonelli, et al. (2019)]



Conclusion

- The modeling of the crust is crucial for the understanding of many neutron-star observables
- Crust physics is extremely rich as it involves many different scales:

microscopic:	nuclear energy-density functional, pairing, structure of nuclei/clusters, vortex pinning, . . .
mesoscopic	impurities, transport properties, vortex dynamics, entrainment, breaking strain, . . .
macroscopic:	$M(R)$ relation, star cooling, oscillations, glitches, crustquakes, . . .

- Expertise in mesoscopic and macroscopic physics needed to be able to link neutron-star observations to microphysics
- French community active in all these directions (only selected topics presented here).