Some open questions in neutron star physics
(with QMC in ambush)

Jérôme Margueron, IPN Lyon & INT Seattle

- Pairing in non-uniform systems
- Pairing at finite-T and re-entrance phenomenon
- NS mergers, tidal deformability, dense matter EOS
The structure of Neutron stars

The interior of a neutron star has a complex structure exhibiting various matter configurations:

- Outer crust: nuclei
- Inner crust: nuclei + neutron gas
  Rod- and plate-like structures
- Uniform nuclear matter
- Condensates of $\pi$, $K$, $\Sigma$, ...?
- Quarks?

Strong relation with condensed matter physics

Nuclear physics

Hadron physics

$0.001\rho_0$

$\rho_0$

$2-3\rho_0$
Nuclear physics and neutron star crust

Properties of finite systems:
masses, radii, pairing,
evolution of the shells,
deformation, collective modes, molecular states, ...

Energy Density Functional approach is well suited to explore a large number of neutron rich nuclei.
Energy Density Functional approach

Going towards very N rich nuclei

Properties of finite systems:
masses, radii, pairing, evolution of the shells, deformation, collective modes, molecular states, ...

General properties of matter:
incompressibility, symmetry energy equation of state, ...

Application to neutron stars and supernovae:
Masses, radii, cooling, Glitches, neutrinos processes, ...

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Nuclear Landscape

stable nuclei

known nuclei

unknown nuclei

Nuclear clusters in NS crust

Exotic nuclei

Dilute nuclei

Finite T, Beyond drip line.

Nuclear matter
From stable nuclei to nuclear matter

Increasing density
Increasing number of neutrons
\[ e + p \rightarrow n + \nu \]

**Finite-T nuclei & neutron star inner crust**

- NS masses-radii
- cooling
- Phase transitions

- glitches (vortex pinning)
- crust thermal relaxation

**Properties**
- binding, radii, neutron skins
- quasiparticle excitations
Superfluidity in uniform and non-uniform systems
Pairing gap in neutron matter: comparisons of different approaches

BCS, BCS+polarisation, QMC, AFDMC, ...


In the crust of NS, matter is however not uniform...
Pairing gap in non uniform matter
DFT approach


1- Calibrate a pairing functional or interaction / uniform matter results

Contact density-dependent pairing interaction:

$$\langle k | v_{nn} | k' \rangle = \frac{1 - P_\sigma}{2} v_0 g[\rho_n, \rho_p] \theta(k, k'),$$

Adjust $v_0$ on NN phase shift ($^1S_0$)

Adjust $g[r]$ on uniform matter predictions

Does condensation energy from QMC and DFT coincide?

2- Solve the pairing in non-uniform matter (Hartree-Fock-Bogoliubov)
Example of semi-magic isotopes

BCS with isovector term reproduce better the isotopic trend.

BCS++ (screened) is too weak.

JM, Sagawa, Hagino, PRC 77 (2008)
**Application to crust thermal relaxation**

**Fast cooling of the core:**

- after ~1 year: $T_{\text{core}} \ll T_{\text{crust}} \sim 0.5$ MeV,
- next ~10-100 years: **thermalisation** of the crust:

$$\tau \propto \frac{d^2}{D}$$

with

$$D = \frac{K}{\sum_i C_{v,i}} \approx C_{v,n}$$

$K$, conductivity

$C_{v,n}$ neutron specific heat

depend on the cluster structure in the neutron star crust

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Lattimer et al., APJ 425 (1994)
Fast cooling of the core:

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depend on the cluster structure in the neutron star crust

Effect of clusters is larger for weak pairing.
Superfluidity and cooling of neutron stars

Fortin et al., PRC 88 (2010)

- Suppression of $C_v$ in the superfluid phase
- Increase the diffusivity in the crust ($D = K/C_v$)
- Reduces the thermal relaxation time of the crust ($\tau = R^2/D$)

Relaxation time of LMXRT
cooling of young neutron stars
Finite temperature in non-uniform matter
Neutrons specific heat in $^{500}$Zr: $C_v(T)$

N=460, Z=40

Pairing field profile at various temperatures:

Disappearance of superfluidity:

in the neutron gas in the cluster
Pairing reentrance in Sn at the drip

Temperature populates excited states:
1- kinetic energy cost induces a quenching of pairing,
2- in some cases, pairing occurs among thermally occupied excited states.

JM & Khan, PRC 2012
**Pairing reentrance phenomenon**

*Superfluidity is destroyed by increasing the temperature…
But a bit of temperature sometimes helps in restoring superfluidity!*

**Pairing reentrance in asymmetric systems:**

- **Pairing in symmetric systems**
- **Asymmetry destroys pairing**
- **Temperature in asymmetric systems restore superfluidity**

**In nuclear matter: pairing in the T=0 (deuteron) channel**

Sedrakian, Alm, Lombardo, PRC 55, R582 (1997)

**In spin-asymmetric cold atom gas**

Castorina, Grasso, Oertel, Urban, Zappala, PRA 72, 025601 (2005)
Chien, Chen, He, Levin, PRL 97, 090402 (2006)

**In highly polarized Liquid $^3$He, $^4$He**

Frossati, Bedell, Wiegers, Vermeulen, PRL 57 (1986)

**Pairing reentrance in finite systems:**

In magic nuclei, the presence of low-energy resonances, populated at low temperature, can help superfluidity to appear.

JM, Khan, PRC 2012
Microscopic picture around the neutron drip

- Weakly bound nuclei
- N-drip
- Neutron star crust

*With continuum coupling*

*Usual picture*

*Approximately occupied*

*Really occupied*
Superfluidy in non-uniform matter

Structure of neutron stars:

The inner crust is made of a lattice of nuclei (cluster) + unbound particles (e, n).

We need pairing gaps (and condensation energies):
- at different densities ($10^{11}$ g/cm$^3$ to $10^{14}$ g/cm$^3$),
- temperatures (few 10 keV to ~1 MeV).

Direct QMC in non-uniform matter?
Dense matter EOS
August, 17\textsuperscript{th} 2017 (GW170817)

First detection of GW from the merger of two neutron stars

From https://www.ligo.caltech.edu/page/press-release-gw170817

See Abbott et al., the LVC, PRL 2017

Can we learn more about nuclear EOS?
The gravitational wave signal

When a GW shakes the interferometer → a chirp!

Ear it at https://youtu.be/_SQbaLIpjY

The wavefront signal
Wavefront & tidal deformability

- Tidal field $E_{ij}$ from companion star induces a quadrupole moment $Q_{ij}$ in the NS
- Amount of deformation depends on stiffness of EOS via the tidal deformability $\Lambda$:

\[ Q_{ij} = -\Lambda(EOS, m) m^5 \varepsilon_{ij} \]

Post-Newtonian expansion of the wavefront:
Tidal effect enters at 5\textsuperscript{th} order

Hinderer+, PRL 116, 181101 (2016)

GW170817: $70 \leq \Lambda \leq 720$

→ What can we learn for the EOS?
Prediction for dense matter EOS

We contrast:
- a meta-model for the nucleonic EOS (minimal model, MM),
- a more general and contains strong first order phase transition (maximal model, CSM).

QMC calculations with local chiral potentials

Solution of the non-rotating TOV eqs.

Tews, Carlson, Gandolfi, Reddy, arXiv:1801.01923

Tews, JM, Reddy, arXiv:1804.0273
CSM versus MM (same constrains)

Range of tidal polarizabilities:
CSM: 80 – 570
MM: 260 – 500

Tews, JM, Reddy, arXiv:1804.0273
Prediction for dense matter EOS

- Both MM and CSM can reproduce existing observations.
- More constraints are needed (NICER soon, more GWs, ...)
  + additional observables: cooling, glitches, ...
- Nuclear physics is still more constraining than GW.
- Required GW accuracy to improve our knowledge:

\[ \Delta \tilde{\Lambda} \approx 300-400 \]  
Probe EOS from 1 to \(2n_{\text{sat}}\)

\[ \Delta \tilde{\Lambda} \approx 100-200 \]  
Probe matter composition above \(2n_{\text{sat}}\)

\[ n_{\text{tr}} = 0.32 \text{fm}^{-3} \]
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Conclusions

We addressed:

• Pairing in non-uniform systems
• Pairing at finite-T and re-entrance phenomenon
• NS mergers, tidal deformability, dense matter EOS

Energy Density Functional could be better constrained by more microscopic approaches (e.g. condensation energy).

Extend the domain of application of QMC to non-uniform systems?
Nuclear Physics and Compact Stars

How to probe nuclear matter properties?

What is the role of nuclear physics?
How to interpret the observations?


Neutron Stars 1: Equation of State and Structure
Haensel, Potekhin, Yakovlev

Neutron Star Crust, Bertulani and Piekarewicz, Nova Science

Topical issue on Nuclear Symmetry Energy.
Guest editors: Bao-An Li, Ramos, Verde, Vidaña
What GW170817 tell about dense matter?

The masquerade issue

A meta-model for nucleonic EOS (minimal model)

Confronting MM with CSM for GW170817

Tews, JM, Reddy arXiv:1804.0273,
JM, Casali, Gulminelli, PRC 97, 025805 & 025806 (2018)
The masquerade issue
A hybrid star which looks nuclear

Are we condemned to this ambiguity issue?
Are all nucleonic EOS masqueraded by QM? Are all QM masqueraded by nucleonic EOS?
Parametric forms for general EOSs

Piecewise polytrope:

3 points: J. Read et al, PRD 2009
5 points: F. Ozel, PRD 2010

Parametric phase transition:

Zdunik & Haensel 2012,
Alford, Han, Prakash 2013

Sound velocity based model (CSM):

Tews, Carlson, Reddy, Gandolfi 2018

All together they set consistent boundaries of all possible EOS. But they don’t say much about matter composition.
Comparison to GW170817 observation

\[ \tilde{\Lambda} = 800 \] rules out NS with large radii (>13.6km)

Can GW170817 (or future detection) say something about matter composition?

A minimal model is needed \(\rightarrow\) boundaries for nucleonic EOS.
Towards a generic nucleonic EOS (minimal model)

We use a meta-model for nucleonic EOS which assumes:

- Nuclear potential quadratic in \( \delta \) (isospin asymmetry),
- The EoS is continuous,
- Satisfies causality and stability

Determined by a set of empirical parameters:

\[
e_{\text{sat}}(n) = E_{\text{sat}} + \frac{1}{2} K_{\text{sat}} x^2 + \frac{1}{6} Q_{\text{sat}} x^3 + \frac{1}{24} Z_{\text{sat}} x^4 + \ldots
\]

\[
e_{\text{sym}}(n) = E_{\text{sym}} + L_{\text{sym}} x + \frac{1}{2} K_{\text{sym}} x^2 + \frac{1}{6} Q_{\text{sym}} x^3 + \frac{1}{24} Z_{\text{sym}} x^4 + \ldots
\]

\[x = (n - n_{\text{sat}})/(3n_{\text{sat}})\]

A large number of nucleonic EOS can be reproduced by this meta-model (maybe all?).

Prediction boundaries are related to empirical parameters boundaries.
From a detailed analysis of experimental predictions, phenomenological and ab-initio models

Around \( n_{\text{sat}} \):

\[
\frac{E}{A}(n, \delta) \approx e_{\text{sat}}(n) + e_{\text{sym}}(n)\delta^2 + e_{\text{sym,4}}(n)\delta^4 + \ldots
\]

with

\[
e_{\text{sat}}(n) = E_{\text{sat}} + \frac{1}{2}K_{\text{sat}}x^2 + \frac{1}{6}Q_{\text{sat}}x^3 + \frac{1}{24}Z_{\text{sat}}x^4 + \ldots
\]

\[
e_{\text{sym}}(n) = E_{\text{sym}} + L_{\text{sym}}x + \frac{1}{2}K_{\text{sym}}x^2 + \frac{1}{6}Q_{\text{sym}}x^3 + \frac{1}{24}Z_{\text{sym}}x^4 + \ldots
\]

In the following, we consider the following central values and uncertainties (1\( \sigma \)):

\[
\begin{array}{cccccccccccc}
| P_\alpha | & E_{\text{sat}} & E_{\text{sym}} & n_{\text{sat}} & L_{\text{sym}} & K_{\text{sat}} & K_{\text{sym}} & Q_{\text{sat}} & Q_{\text{sym}} & Z_{\text{sat}} & Z_{\text{sym}} & m_{\text{sat}}/m & \Delta m_{\text{sat}}/m \\
| \langle P_\alpha \rangle | & -15.8 & 32 & 0.155 & 60 & 230 & -100 & 300 & 0 & -500 & -500 & 0.75 & 0.1 \\
| \sigma_{P_\alpha} | & \pm 0.3 & \pm 2 & \pm 0.005 & \pm 15 & \pm 100 & \pm 400 & \pm 400 & \pm 1000 & \pm 1000 & \pm 0.1 & \pm 0.1 \\
\end{array}
\]

Small uncertainties  Large uncertainties  Large uncertainties

\( \Rightarrow \) Impact on the nuclear EOS

JM, Casali, Gulminelli, PRC 2018
Impact of the isoscalar empirical parameters

Small impact of these parameters

JM, Casali, Gulminelli, PRC 2018
Impact of the isovector empirical parameters

Largest source of uncertainty: L_{sym} and K_{sym}
Impact of the “exp” unknown on the Mass/Radius relation

Models condense in some parts of the MR diagram

Transform into a statistical information
CSM versus MM (same constraints)

\[ n_{tr} = 0.32 \text{fm}^{-3} \]

\[ q = 1 \]

\[ q = 0.7 \]

Radice et al. (2018)

Rezzolla et al. (2018)

Shibata et al. (2017)

Margalit et al. (2017)

Tews, JM, Reddy, arXiv:1804.0273
Tidal deformability

For a single NS:

\[ \Lambda = \frac{2}{3} k_2 \left( \frac{R}{m} \right)^5 \]

- \( k_2 \) (love number) depends on the EOS and compactness
- \( k_2 \sim 0.05-0.15 \) (Hinderer 2008, 2010, Postnikov 2010)

For the binary NS:

\[ \tilde{\Lambda} = \frac{16 (m_1 + 12m_2)m_1^4}{13} \frac{\Lambda_1}{(m_1 + m_2)^5} + (m_2 + 12m_1)m_2^4 \frac{\Lambda_2}{(m_1 + m_2)^5} \]

Tidal interactions lead to accumulated phase shift at high frequencies:

\[ \delta \Phi_t = -\frac{117}{256} \frac{(1+q)^4}{q^2} \left( \frac{\pi f_{GW} GM}{c^3} \right)^{5/3} \tilde{\Lambda} \]
Kilonova (macronova) AT2017gfo

Interpretation of the EM observations