Cérémonie du prix Joliot-Curie 2022

modeling finite nuclei and dense matter in neutron stars

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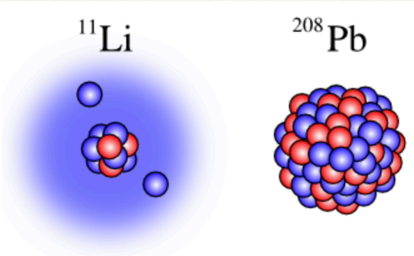
halo nuclei

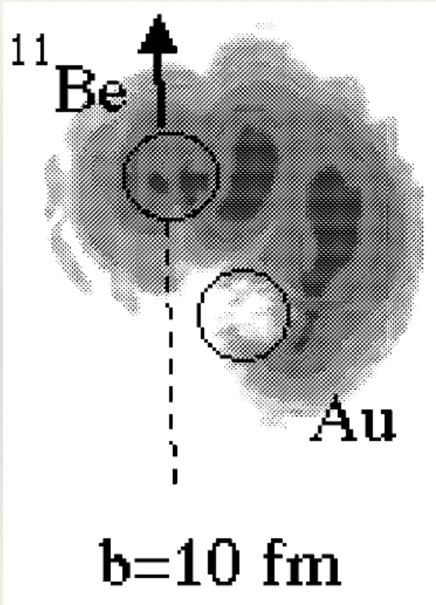
1 or 2 weakly bound nucleons change the size of the nucleus tremendously!



Also called Borromean nuclei (in reference to the flag of the Italian House of Borromeo).

Break-up mechanism: simple expressions for the break-up of halo nuclei including non-perturbative Coulomb-nuclear interference effects.

Towing mode:



$$i\hbar\frac{\partial\phi(\mathbf{r},\mathbf{d},t)}{\partial t} = \left(H_r + V_{\mathrm{nt}}(\mathbf{r}+\mathbf{R}(t)) + V_{\mathrm{eff}}(\mathbf{r},\mathbf{R}(t))\right)\phi(\mathbf{r},\mathbf{d},t)$$

$$g_{\mathrm{CN}}^{\mathrm{BBM\,1}} \approx g_{\mathrm{C}}^{\mathrm{pert\,1}} + g_{\mathrm{N}}^{\mathrm{pert\,1}} + \left(g_{\mathrm{CN}}^{\mathrm{sudd}} - g_{\mathrm{C}}^{\mathrm{sudd\,1}} - g_{\mathrm{N}}^{\mathrm{sudd\,1}}\right)$$
$$\equiv g_{\mathrm{C}}^{\mathrm{pert\,1}} + \left(g_{\mathrm{CN}}^{\mathrm{sudd}} - g_{\mathrm{C}}^{\mathrm{sudd\,1}}\right).$$

Quantum SuSy transformations for state removal and phase equivalent potentials:

Angela Bonaccorso, INFN Pise
David Brink, Oxford University, UK

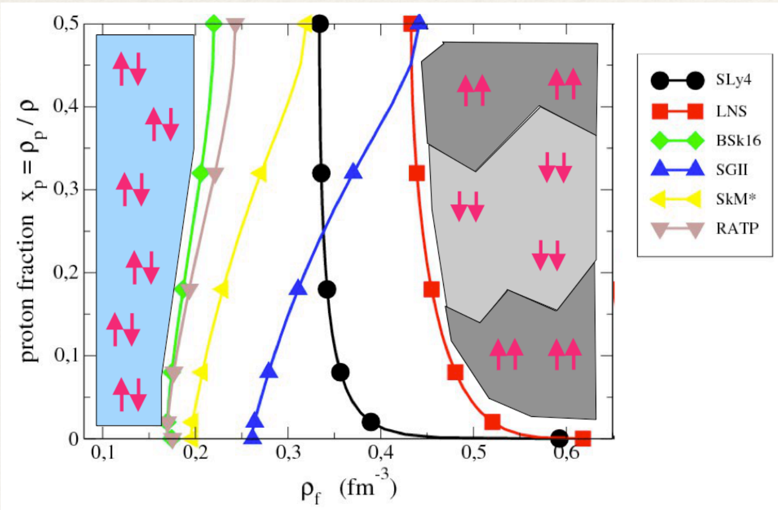
Jean-Antoine Scarpaci, IPN Orsay
Muriel Fallot, Subatech Nantes

Denis Lacroix, LPC Caen
Philippe Chomaz, GANIL Caen

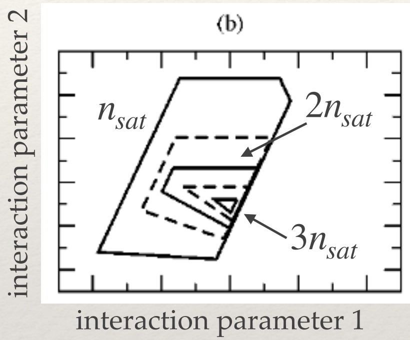
instabilities in the mean field

Many predictions in finite nuclei and in dense matter are based on Skyrme-type interactions. These functionals however predict some instabilities of the ground-state.

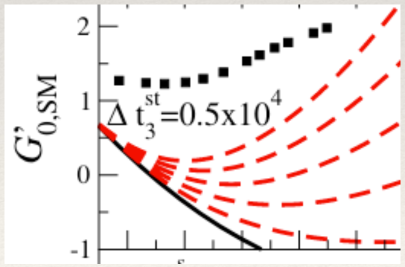
Spin instability



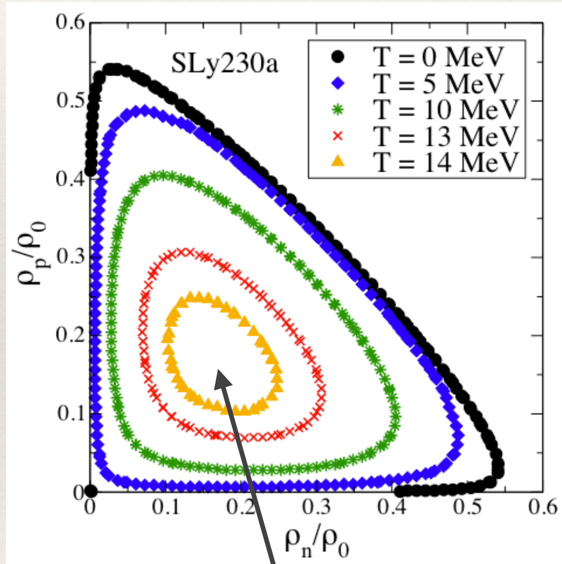
Skyrme interactions instabilities



Extended Skyrme interactions with no spin long-range instability



liquid-gas phase transition:
Spinodal zone is an exemple of expected instability



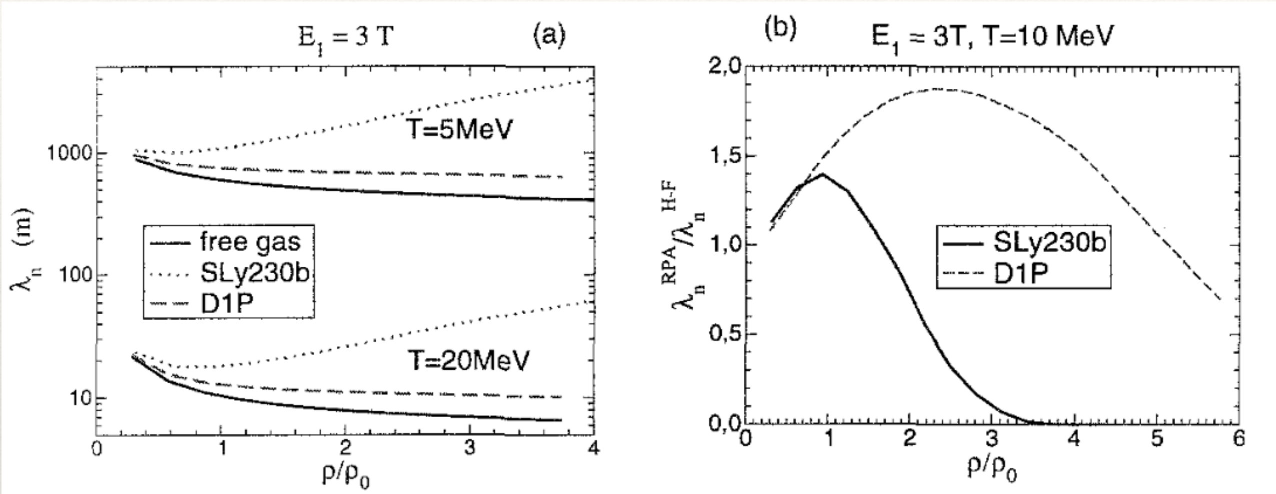
Critical point

Dominique Vautherin, IPN Orsay
Nguyen Van Giai, IPN Orsay
Jesus Navarro, IFIC Valencia
Hiroyuki Sagawa, Aizu University
Stéphane Goriely, ULB Bruxelles
Gianluca Colò, Univ. Milano
Marcella Grasso, IPN Orsay

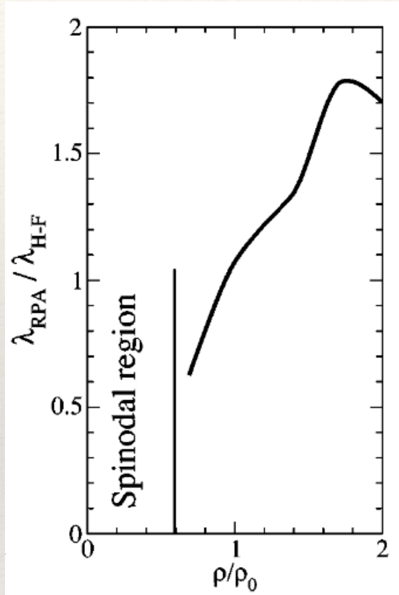
ANR SN2NS

core-collapse supernovae: neutrino propagation

neutrino mean free path in dense matter



neutrino trapping near the liquid-gas phase transition



critical opalescence

↓

A new scenario where neutrino are delayed further more before they escape the central object. They also shift the beta equilibrium and increase the pressure in the crust —> second shock (efficient transfer of energy to matter).

Dominique Vautherin, IPN Orsay
Nguyen Van Giai, IPN Orsay

Jesus Navarro, IFIC Valencia
Patrick Blottiau, Bruyères-le-châtel

Ignazio Bombaci, INFN Pise
Isaac Vidana, INFN Pise

Sanjay Reddy, INT Seattle
Alexandro Roggero, INT Seattle

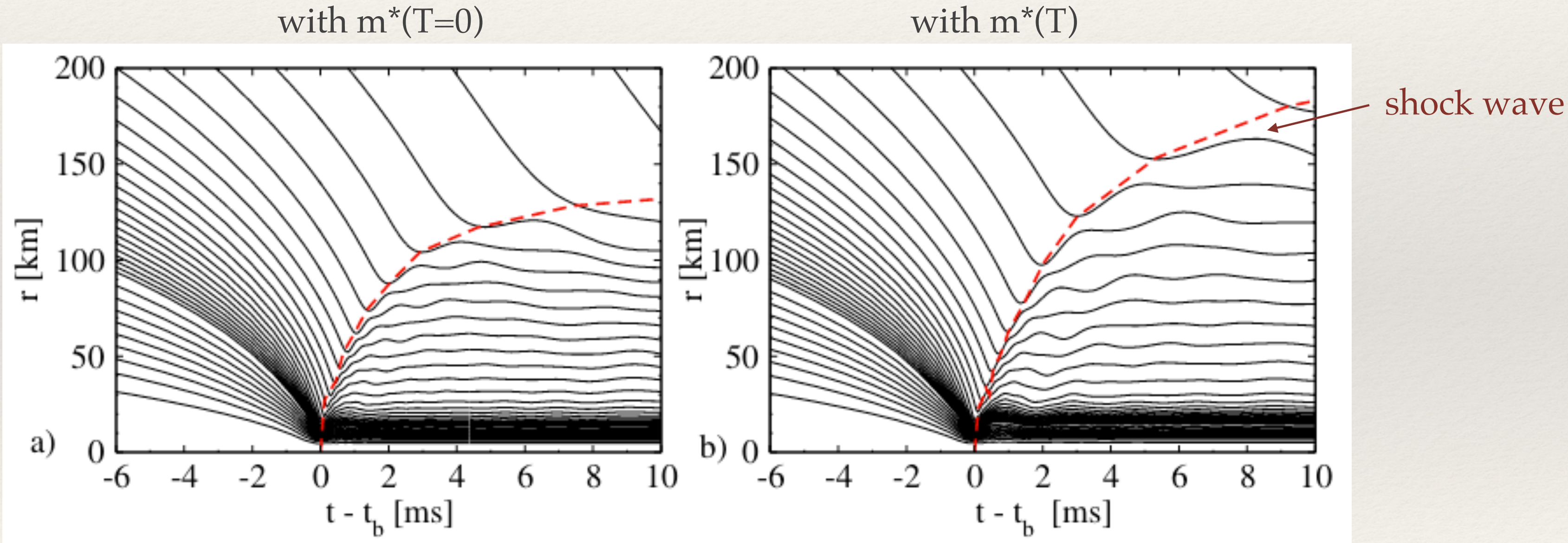
Andrew Steiner, UTK
Zidu Lin, UTK

core-collapse supernovae: effect of nuclear correlations

Effect of m*(T) on the symmetry energy

The symmetry energy is the cost in energy to convert symmetric matter into neutron rich matter (Neutron Stars).
Except at sat, it is poorly known and can be modified by nuclear dynamical correlations, i.e., m*(T).

1D core-collapse supernova simulation:



Pierre Pizzochero, University of Milano
Anthea Fantina, PhD IPN Orsay
Patrick Blottiau, CEA Bruyères-le-châtel
Philippe Mellor, CEA Bruyères-le-châtel
Thierry Foglizzo, CEA Saclay
Micaela Oertel, LUTH Meudon
Jérôme Novak, LUTH Meudon

superfluidity in neutron stars

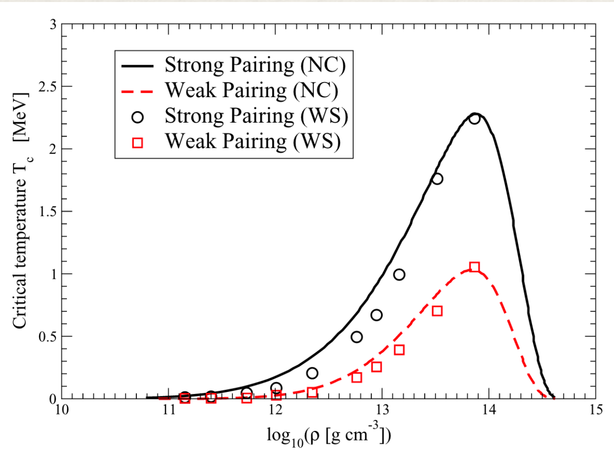
thermal relaxation in neutron stars
Relativistic heat equation:

$$\frac{\partial}{\partial r}\left[\frac{K r^2}{\Gamma(r)} e^{\phi} \frac{\partial}{\partial r}(e^{\phi} T)\right] = r^2 \Gamma(r) e^{\phi}\left(C_V \frac{\partial T}{\partial t} + e^{\phi} Q_{\nu}\right)$$

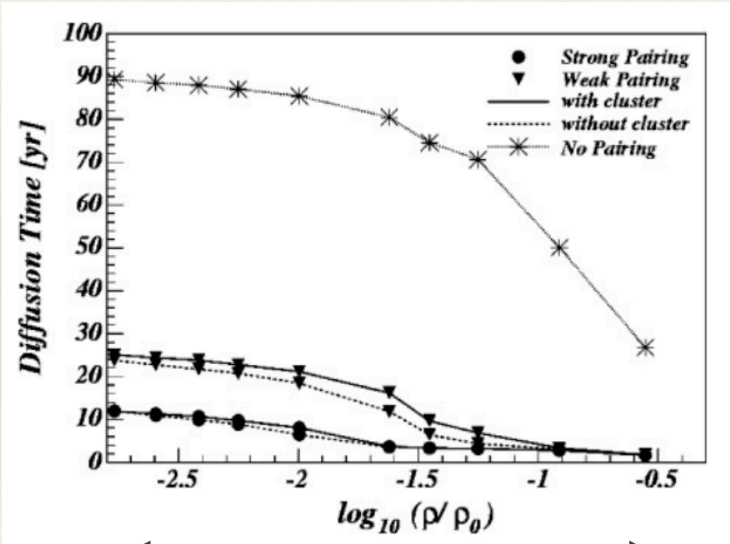
neutrino emission rate

specific heat

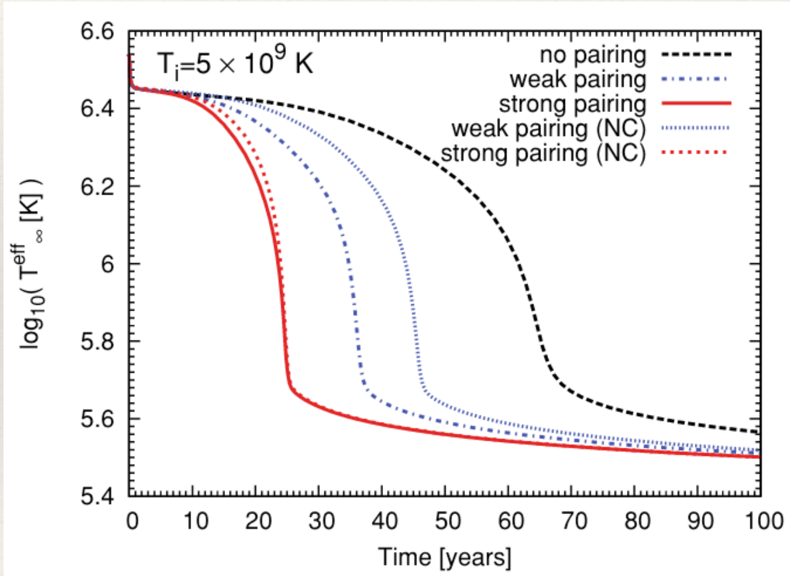
The pairing gap in the crust of neutron stars is poorly known.



crust



crust



Nicolae Sandulescu, NIPNE Bucharest
Nguyen Van Giai, IPN Orsay

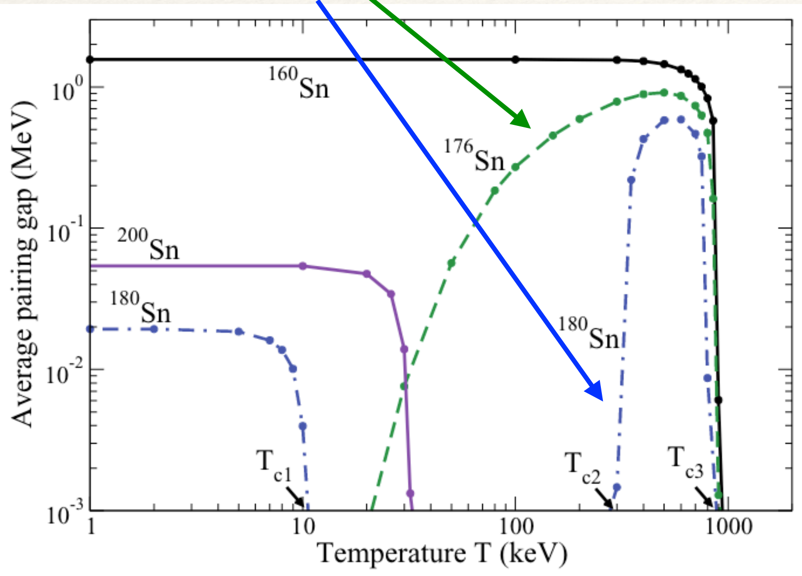
Elias Khan, IPN Orsay
Marcella Grasso, IPN Orsay

Nicolas Chamel, ULB Bruxelles
Charlotte Monrozeau, IPN Orsay

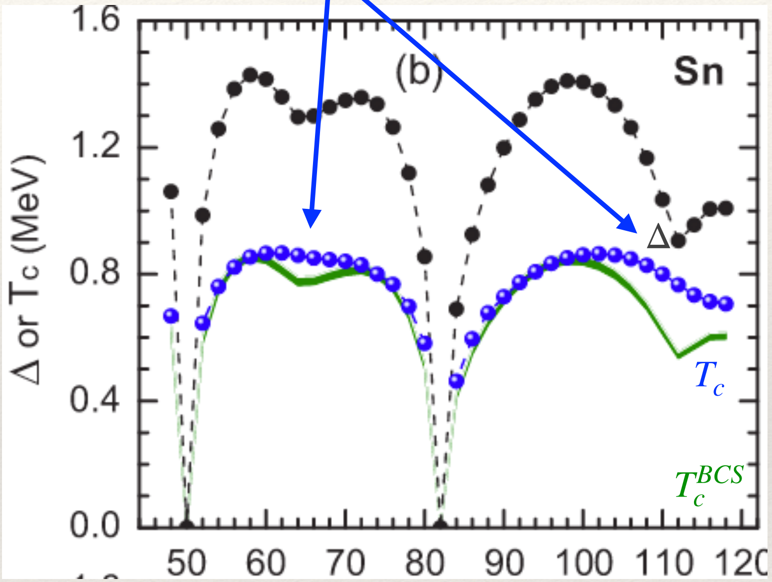
Morgane Fortin, ENS Paris
Dany Page, UNAM Mexico

nuclear pairing

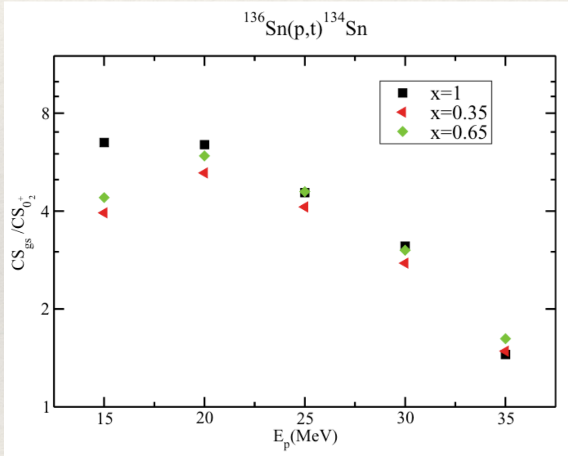
pairing re-entrance



pairing persistence



Experimental test of the impact of different pairing force on 2-neutron transfert reactions at various incident energies:



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Marcella Grasso, IPN Orsay

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Masayuki Yamagami, Aizu University

Kuichi Hagino, University of Sendai
Alessandro Pastore, IPN Lyon

Didier Beaumel, IPN Orsay
Else Pllumbi, University of Pisa

Jia Jie Li, Lanzhou
Wen Hui Long, Lanzhou

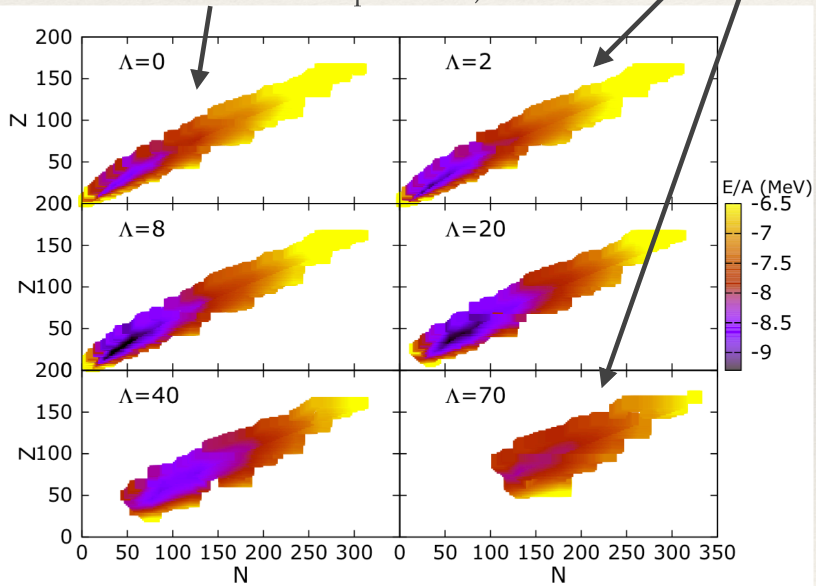
hypernuclei

=nuclei with hyperons (Λ, Ξ, or Σ)

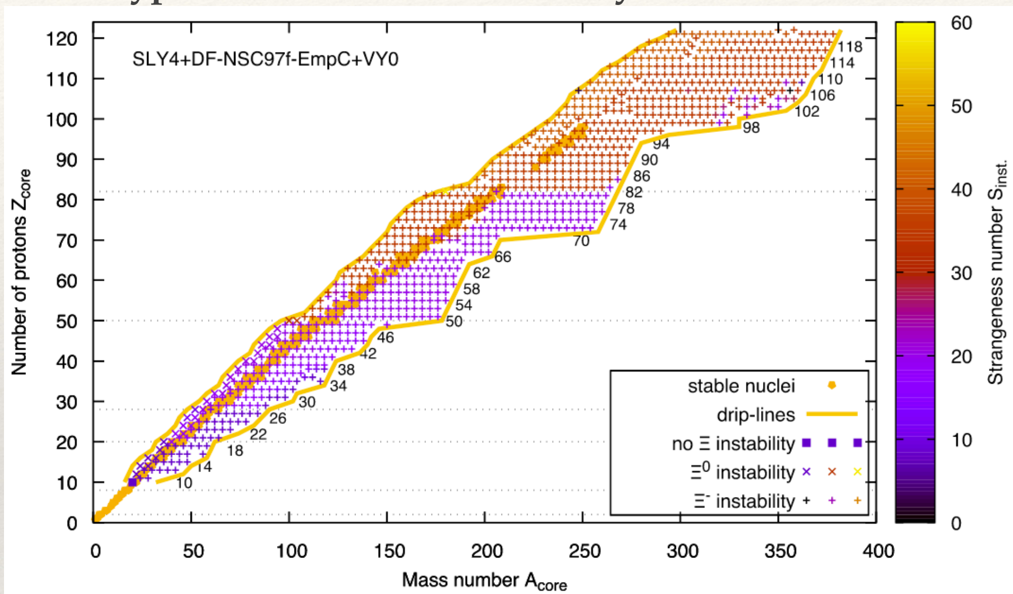
The hyper-Nuclear chart (with only Λ)

Normal nuclear chart (less than 1/2 of the total number of nuclei have been produced)

hyper-nuclear chart with various number of Λ.



The hyper-Nuclear chart (with only Λ and Ξ)



Ordinary nuclei: about 8,000 (total), about 3,300 have been produced.
hypernuclei: about 600,000 (total), about 20 have been produced.

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Kutsal Bozkurt, Yildiz university
Hasim Güven, Yildiz university

Adriana Raduta, IFIN-HH Bucharest
Francesca Gulminelli, LPC Caen

meta-modeling of extreme matter EoS

Energy in asymmetric matter: $e(n,\delta) \approx e_{\rm sat}(n) + e_{\rm sym,2}(n)\delta^2 + e_{\rm sym,4}(n)\delta^4 + \dots$ with $\delta = (n_n - n_p)/(n_n + n_p)$

where the isoscalar and isovector terms are expressed as a Taylor expansion in x:

$$e_{sat}(n) = E_{sat} + \frac{1}{2}K_{sat}x^2 + \frac{1}{6}Q_{sat}x^3 + \frac{1}{24}Z_{sat}x^4 + \dots \qquad e_{sym}(n) = E_{sym} + L_{sym}x + \frac{1}{2}K_{sym}x^2 + \frac{1}{6}Q_{sym}x^3 + \frac{1}{24}Z_{sym}x^4 + \dots$$

with $x = (n - n_{sat})/(3n_{sat})$

The **nuclear empirical parameters** (NEP) capture the (topological) properties of the EoS around n_{sat}.

	Small uncertainties					Large uncertainties					Some uncertainties	
P_α	E_{sat} MeV	E_{sym} MeV	n_{sat} fm^{-3}	L_{sym} MeV	K_{sat} MeV	K_{sym} MeV	Q_{sat} MeV	Q_{sym} MeV	Z_{sat} MeV	Z_{sym} MeV	m^*_{sat}/m	$\Delta m^*_{sat}/m$
$\langle P_\alpha \rangle$	-15.8	32	0.155	60	230	-100	300	0	-500	-500	0.75 (Small impact at T=0)	0.1
σ_{P_α}	±0.3	±2	±0.005	±15	±20	±100	±400	±400	±1000	±1000	±0.1	±0.1

⚠ These parameters are correlated among each other.

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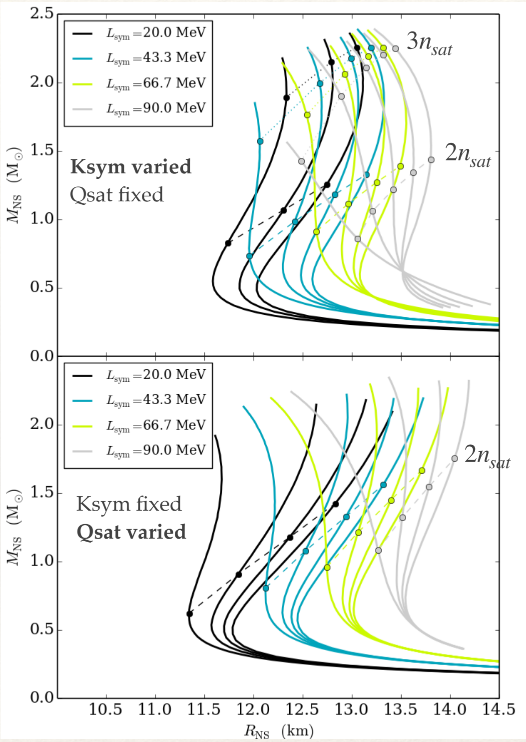
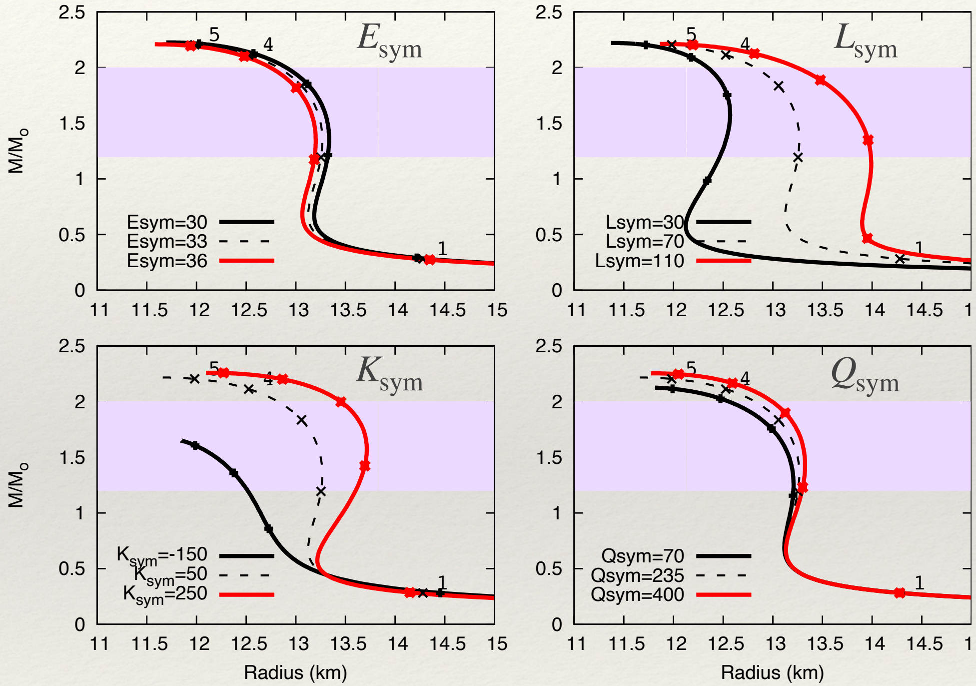
Camille Ducoin, University of Coimbra
Elias Khan, IPN Orsay
Rahul Somasundaram, IP2I Lyon
Guilherme Grams, IP2I Lyon

meta-modeling of extreme matter EoS

Impact of changing the NEP on the MR relation of neutron stars:



Isovector channel



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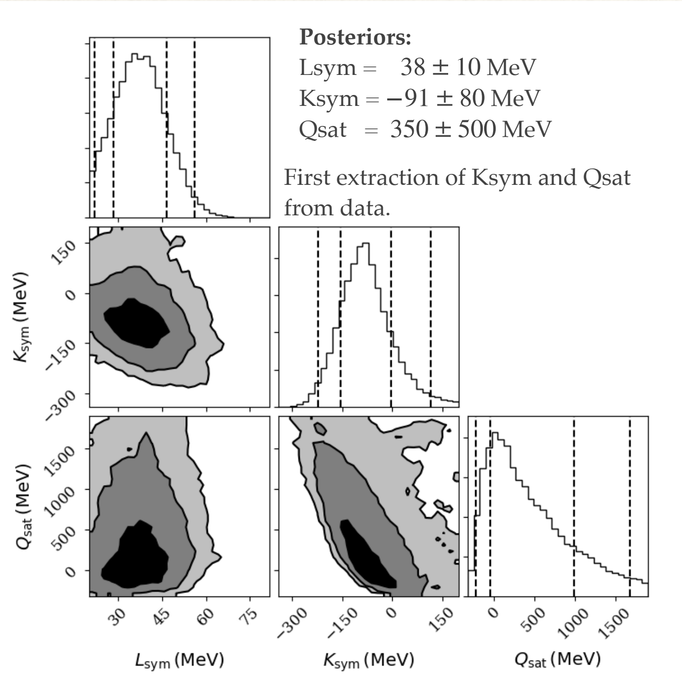
confrontation to data with Bayesian statistics

Confronting qLMXB with nuclear EOS:



There are a lot of new data which brings information on dense matter properties.

Astro data:
- radio-astronomy,
- x-ray thermal emission from qLMXB,
- gravitational waves from binary neutron stars (LVK),
- non-thermal x-ray emission (NICER).

Theory:
- causality and stability of dense matter,
- chiral effective field theory,
- perturbative QCD,
- phase transitions

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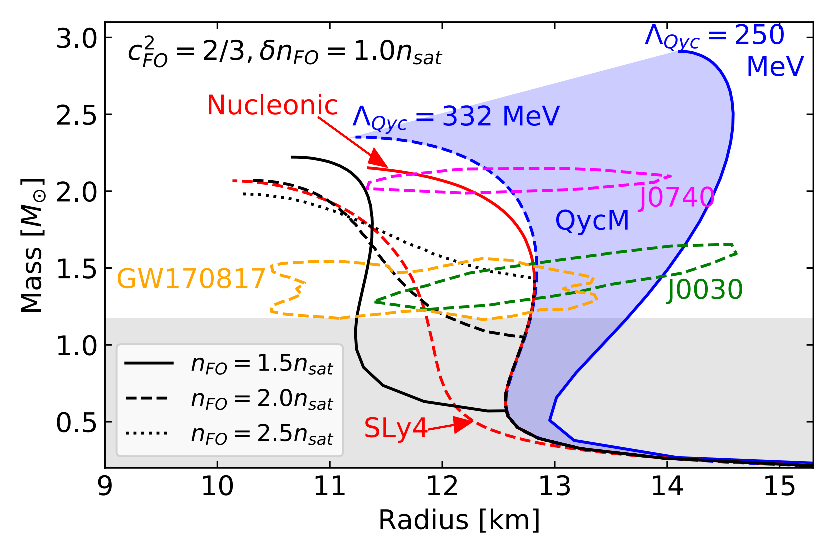
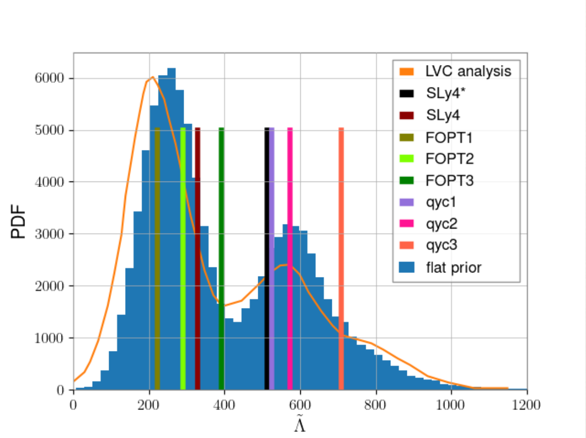
confrontation to data with Bayesian statistics

Impact of phase transitions in the core of neutron stars

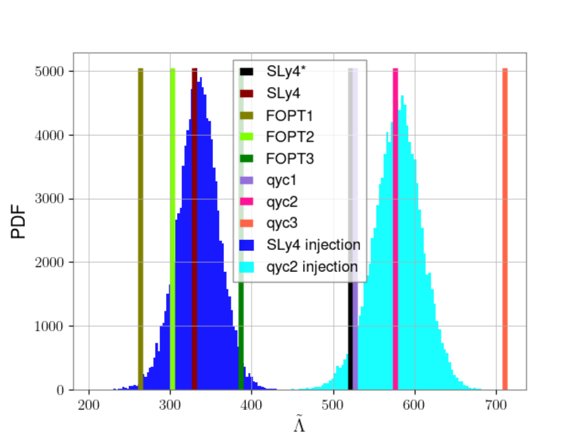


Expectations from GW analysis:

Observation in 2017:



As it would be seen if detected in 2024:



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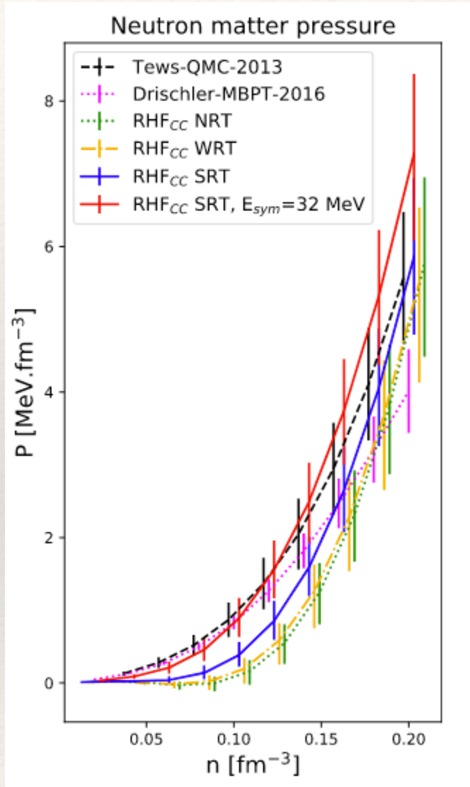
Viola Sordini, IP2I Lyon
Roberto Chierici, IP2I Lyon
Hubert Hansen, IP2I Lyon

covariant approaches for dense matter

Above n_{sat} the sound speed in dense matter overcomes 10% of the light speed —> covariant approaches are necessary.
A modern covariant model (by Guy Chanfray) includes chiral symmetry breaking, quark confinement, nucleon form factor and short-range correlations + contraints from NJL quark model and Lattice QCD calculations.

$$
\begin{aligned}
\mathcal{L}_s =&\left(M_N - M_N(s)\right)\bar{\psi}\psi - v(s) + \frac{1}{2}\partial^\mu s \partial_\mu s\,,\\
\mathcal{L}_\omega =& - g_\omega \omega_\mu \bar{\psi}\gamma^\mu \psi + \frac{1}{2} m_\omega^2 \omega^\mu \omega_\mu - \frac{1}{4} F^{\mu\nu} F_{\mu\nu}\,,\\
\mathcal{L}_\rho =& - g_\rho \rho_{a\mu} \bar{\psi}\gamma^\mu \tau_a \psi + g_\rho \frac{\kappa_\rho}{2M_N} \partial_\nu \rho_{a\mu} \bar{\psi}\sigma^{\mu\nu}\tau_a\psi\\
&+ \frac{1}{2} m_\rho^2 \rho_{a\mu}\rho_a^\mu - \frac{1}{4} G_a^{\mu\nu} G_{a\mu\nu}\,,\\
\mathcal{L}_\delta =& - g_\delta \delta_a \bar{\psi}\tau_a\psi - \frac{1}{2} m_\delta \delta_a \delta_a + \frac{1}{2}\partial^\mu \delta_a \partial_\mu \delta_a\,,\\
\mathcal{L}_\pi =& \frac{g_A}{2 f_\pi} \partial_\mu \varphi_{\pi a} \bar{\psi}\gamma^\mu \gamma^5 \tau_a \psi - \frac{1}{2} m_\pi^2 \varphi_{\pi a}\varphi_{\pi a}\\
&+ \frac{1}{2}\partial^\mu \varphi_{\pi a}\partial_\mu \varphi_{\pi a}\,,
\end{aligned}
$$

—> RHF-CC —>



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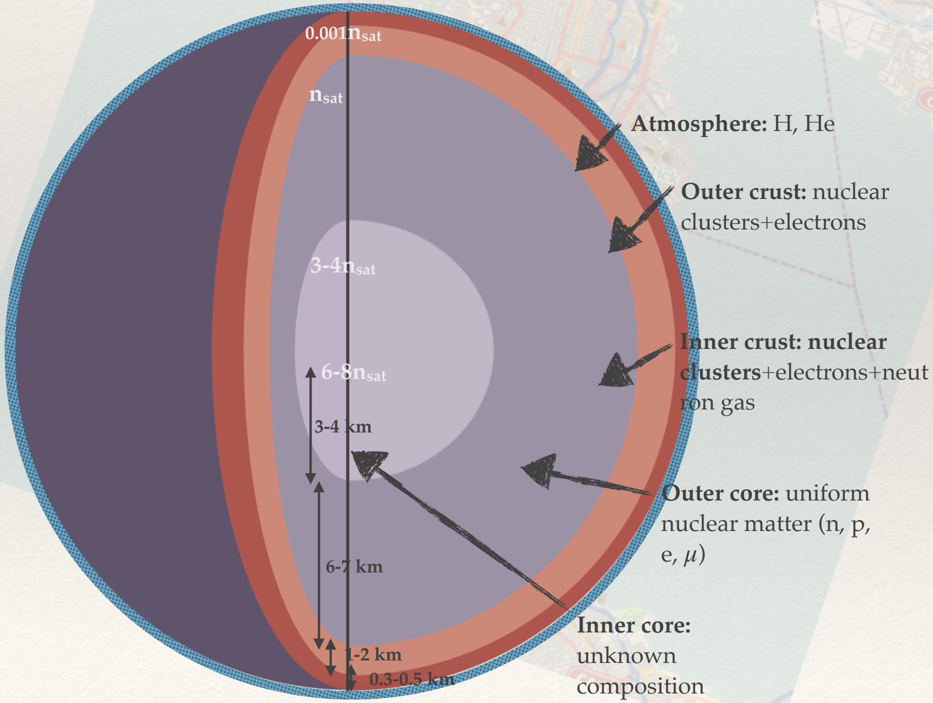
Hubert Hansen, IP2I Lyon

Elias Khan, IJCLab Orsay
Jean-Paul Ebran, Bruyères-le-châtel

Rahul Somasundaram, IP2I Lyon
Mohamad Chamseddine, IP2I Lyon

tentative conclusions

The near future will see an accumulation of more and more data containing dense matter properties.
It is very possible that the question of the existence of phase transition(s) in the core of neutron stars will get an answer in the next 10 years.



But, it will not necessarily be easy since:

- The properties of neutron star core at the densities above n_{sat} are yet impossible to determine from first principle.

- Data alone may not be accurate enough (despite tremendous progress in nuclear experiments and astrophysical observations).

Future discoveries require :
- reliable model(s) for dense matter,
- new data with improved accuracy,
- and an efficient way to combine data and model together.