# The symmetry energy and neutron star properties

Constança Providência

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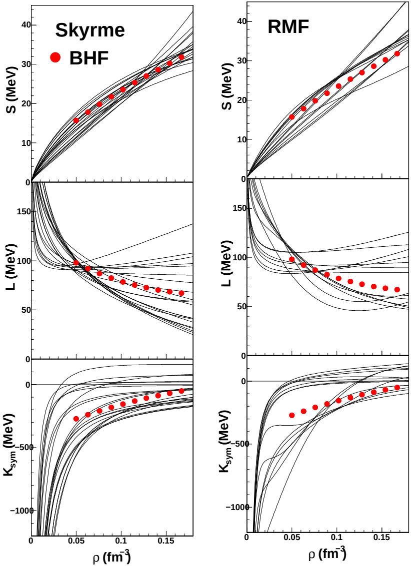
# Motivation

- How do compact star properties depend on the $\epsilon_{sym}$?
  - the crust-core transition?
  - inner crust structure?
  - strangeness content?

# Symmetry energy



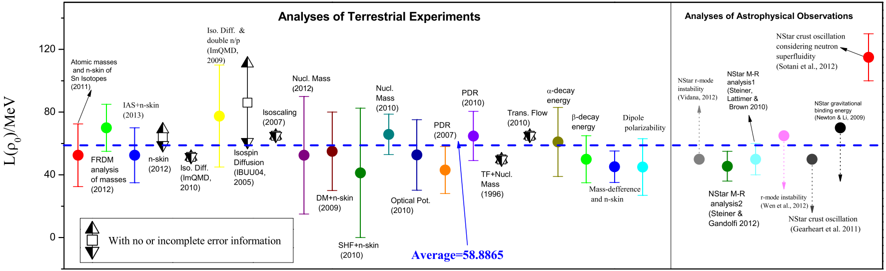

(Ducoin *et al* PRC83)

Fitting of parameters to properties of nuclei:

$S$: crossing at $\sim 0.12$ fm$^{-3}$

$L$: tendency to cross at $\sim \rho/3\rho_0$

# L: experimental overview




from B-A Li and X. Han PLB727 (2013)

# Outline

Equation of state

Inner crust and pasta phases

Crust-core transition

Strangeness

# EOS

## RMF Lagrangian for stellar matter

- Lagrangian density

$$\mathcal{L}_{NLWM} = \sum_{B=baryons} \mathcal{L}_B + \mathcal{L}_{mesons} + \mathcal{L}_l,$$

- Nucleon contribution: $\mathcal{L}_B = \bar{\psi}_B \left[\gamma_\mu D^\mu_B - M^*_B\right] \psi_B,$
  $D^\mu_B = i\partial^\mu - g_{\omega B}\omega^\mu - \frac{g_{\rho B}}{2}\boldsymbol{\tau} \cdot \mathbf{b}^\mu - g_{\phi B}\phi^\mu$
  $M^*_B = M_B - g_{\sigma B}\sigma - g_{\sigma^* B}\sigma^*$
- Meson contribution

$$\mathcal{L}_{mesons} = \mathcal{L}_\sigma + \mathcal{L}_\omega + \mathcal{L}_\rho + \mathcal{L}_{\sigma^*} + \mathcal{L}_\phi + \mathcal{L}_{non-linear}$$

- Lepton contribution: $\mathcal{L}_l = \sum_l \bar{\psi}_l \left[\gamma_\mu i\partial^\mu - m_l\right] \psi_l$

# EOS

## RMF Lagrangian for stellar matter

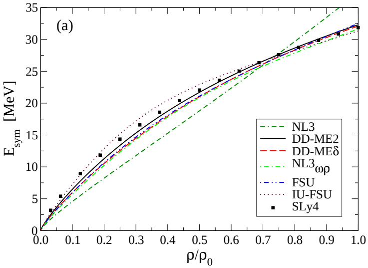
- Meson Lagrangian

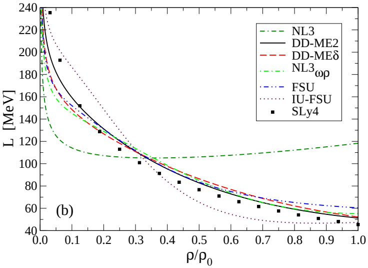
$$
\begin{aligned}
\mathcal{L}_\sigma &= \frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma - \frac{1}{2}m_\sigma^2\sigma^2 - \frac{1}{3!}k\sigma^3 - \frac{1}{4!}\lambda\sigma^4 \\
\mathcal{L}_\omega &= -\frac{1}{4}\Omega_{\mu\nu}\,\Omega^{\mu\nu} + \frac{1}{2}m_\omega^2\,\omega_\mu\omega^\mu + \frac{1}{4!}\xi g_\omega^4\,(\omega_\mu\omega^\mu)^2 \\
\mathcal{L}_\rho &= -\frac{1}{4}\vec{R}_{\mu\nu}\cdot\vec{R}^{\mu\nu} + \frac{1}{2}m_\rho^2\,\vec{\rho}_\mu\cdot\vec{\rho}^\mu \\
\mathcal{L}_{\sigma^*} &= \frac{1}{2}\partial_\mu\sigma^*\partial^\mu\sigma^* - \frac{1}{2}m_{\sigma^*}^2\sigma^{*2} \\
\mathcal{L}_\phi &= -\frac{1}{4}\Phi_{\mu\nu}\,\Phi^{\mu\nu} + \frac{1}{2}m_\phi^2\,\phi_\mu\phi^\mu \\
\mathcal{L}_{\rho\omega} &= \Lambda_v g_\rho^2\vec{\rho}_\mu\cdot\vec{\rho}^\mu g_\omega^2\omega_\mu\omega^\mu
\end{aligned}
$$

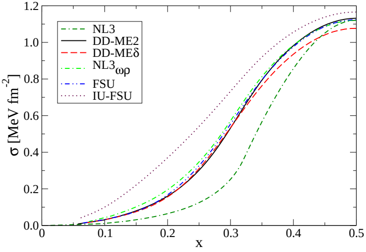
# Pasta phase EOS

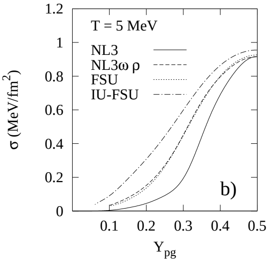
- $\beta$-equilibrium non-homgeneous matter within a TF calculation
- assumed a preferred single geometry (least free energy) for a given $T$, $\rho$ and $y_p$
- only five possible shapes are considered: droplets, rods, slabs, tubes and bubbles
- $\beta$-equilibrium: $y_P$ is very small and only three shapes are energetically favorable: droplets, rods and slabs.
- a regular lattice in the Wigner-Seitz approximation is considered, the WS cell having the shape of the clusters
- a fixed Z and N number at a given density determines the WS volume, $\beta$-equilibrium condition determines N

# Symmetry energy and surface energy

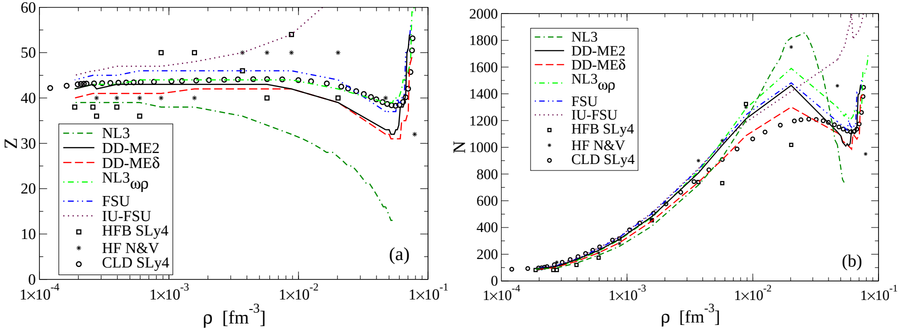


# Z and N in clusters

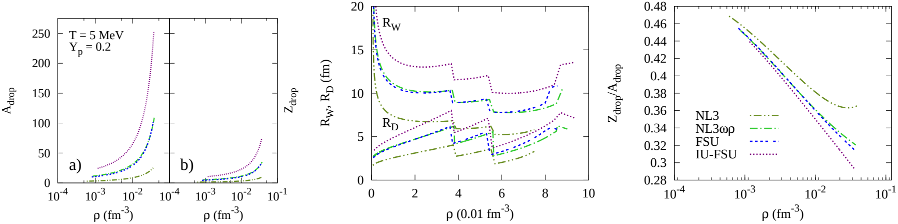



Only spherical: HFB with Sly4 (Grill PRC84 065801,2011); HF (Negele & Vautherin NPA207, 1973), CDM with Sly4 (Douchin & Haensel, A& A380,2001)

droplets, rods, slabs: TF and RMF (Grill PRC85 055808, 2012)

# Properties of pasta phases

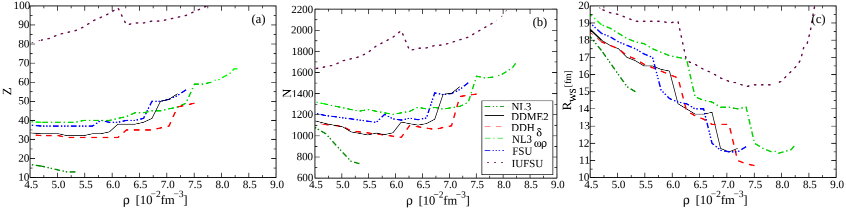
## $T = 5\,\text{MeV}$ and $Y_p = 0.2$.




- NL3 vs NL3$\omega\rho$: smaller $L$ $\rightarrow$ clusters with larger $A$
- smaller $L$ $\rightarrow$ larger surface energy, neutrons do not drip so easily
- $L$ defines the size of the WS cell
- Proton fraction in the clusters: larger for models with larger $L$, because neutrons drip easily

# Properties of pasta phases

## Thomas Fermi approach

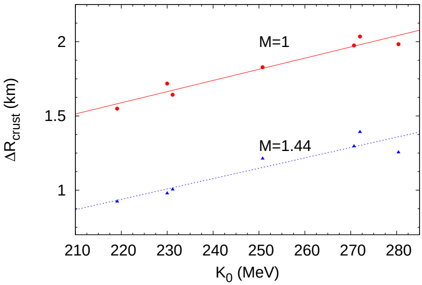


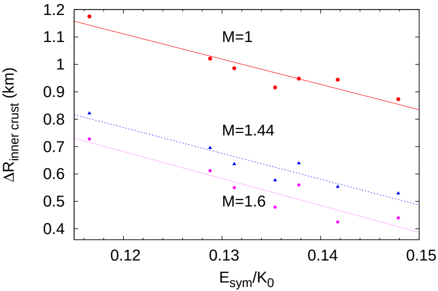

- smaller $L$ $\rightarrow$ larger cells, larger Z and N but smaller $y_p$
- models with similar $\epsilon_{sym}$ and $L$ behave in a similar way
- NL3, with a large $\epsilon_{sym}$ and $L$, and IU-FSU, with a quite small L, have quite different behaviors

# Thickness and structure of the crust

- EOS for $\beta$-equilibrium, charge neutral matter
  - outer crust: BPS
  - inner crust: TF pasta calculation
  - core: np matter in $\beta$-equilibrium
- density profile of stars with $M = 1.0,\ 1.44,\ 1.6\,M_\odot$

# Inner crust

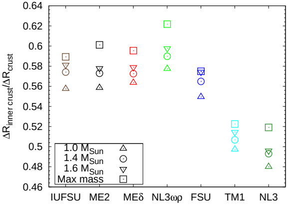


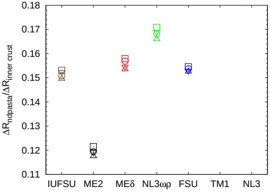



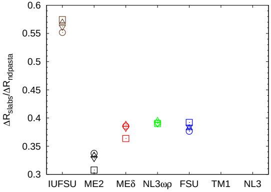

- The extension of the total crust seems to be mainly defined by the incompressibility of the EOS
- Both $K_0$ and the $\epsilon_{sym}(\rho)$ affect the size of the inner crust

# Thickness and structure of the crust

- NL3 and TM1: no non-droplet pasta, large $L$
- inner crust occupies $\gtrsim$ 55%, except NL3 and TM1 ( $\sim$ 50%)
- % inner crust increases with $M$
- non-droplet phase is $\sim$ 15% total inner crust
- slab phase $> \frac{1}{3}$ non-droplet phase
- but IUFSU: slab phase $> \frac{1}{2}$ non-droplet phase due to small surface energy
- rod/slab phase: elastic solid or a liquid phase? (Gearhart MNRS418,2011)

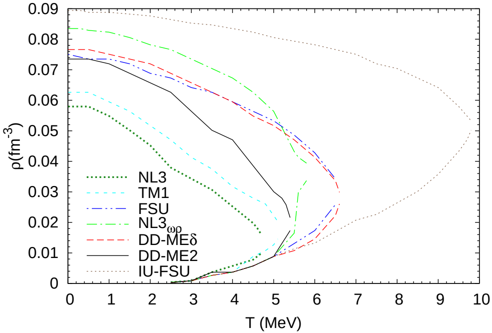


# Effect of T on pasta extention

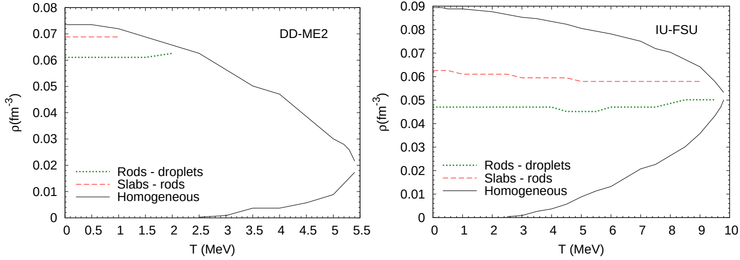
$\beta$-equilibrium matter




- The critical temperature $T_{crit}$ is model dependent
- $T_{crit}$ depends on density dependence of $\epsilon_{sym}$ and $K$:
  - a smaller value of $L$ and a smaller $K_0$ favor the existence of clusterization at large temperatures

# Effect of T on pasta extention

## Extension of different geometries



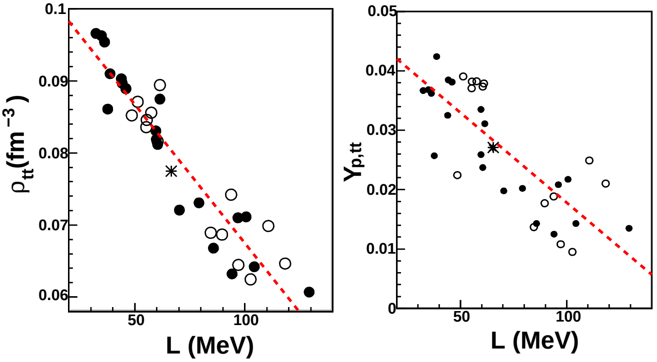

- The droplet-rod and the rod-slab transition densities do not depend on the temperature.
- the melting temperature depends on geometry: droplets survive up to higher temperatures.

# The inner crust and the symmetry energy

- inner crust: smaller $L$
  - steeper crust density profile
  - inner crust is a larger fraction of total crust
  - may enhance slab phase (IUFSU)
- Pasta phase at finite temperature
  - non-homogeneous matter is expected for $T < 5 - 6$ MeV
  - non-droplet structures melt at 2-3.5 MeV ( rods), 1-3 MeV (slabs)
  - onset density of rod-like or slab-like clusters is independent of $T$
- lasagna like structures:
  - all models except NL3 and TM1
  - important contribution to the specific heat? (DiGallo PRC84) )

# Crust-core transition: transition $\rho$ and $Y_p$ versus L

From thermodynamical spinodal



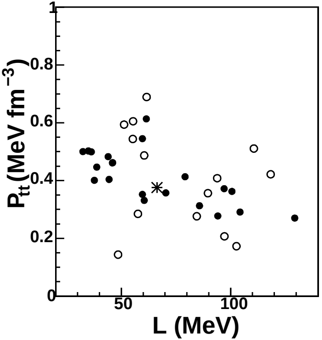

different nuclear models: Skyrme (full), RMF (empty), BHF (asterisk).

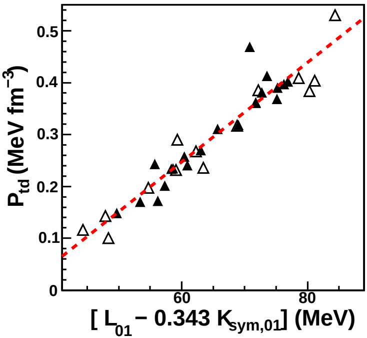
(Ducoin *et al* PRC83, 045810 (2011))

- $\rho_{tt}$ and $Y_{p,tt}$ are well correlated with $L$

# Transition pressure versus L

## From thermodynamical spinodal




nuclear models: Skyrme (full), RMF (empty), BHF (asterisk).

(Ducoin *et al*PRC83, 045810 (2011))

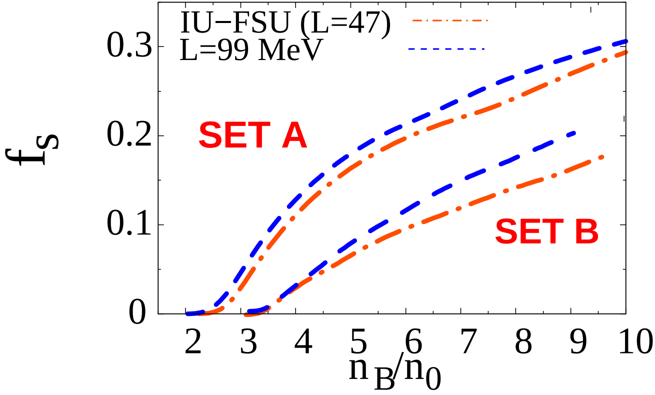
- $P_{tt}$ and $L$ are badly correlated
- but good correlation between $P_{td}$ and a linear combination of $L_{0.1} - 0.343K_{\mathrm{sym},0.1}$, for $\rho = 0.1\mathrm{fm}^{-3}$

# Hyperon content and $L$

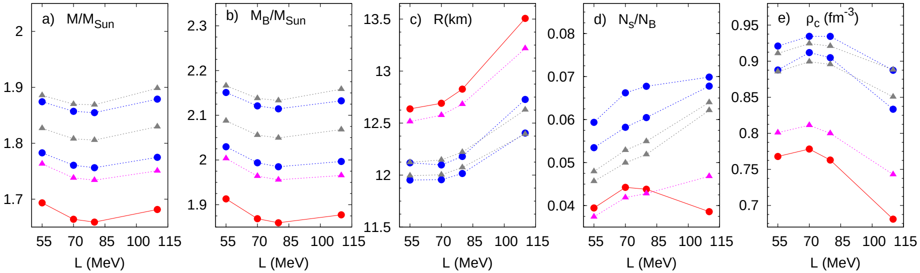
## Hyperon content depends on:

- hyperon-meson interaction
- properties of nucleonic EOS

  example: effect of $\epsilon_{sym}(\rho)$
  ($L$(IUFSU)= 47.2 MeV, $L$(set 7)=99.2 MeV)



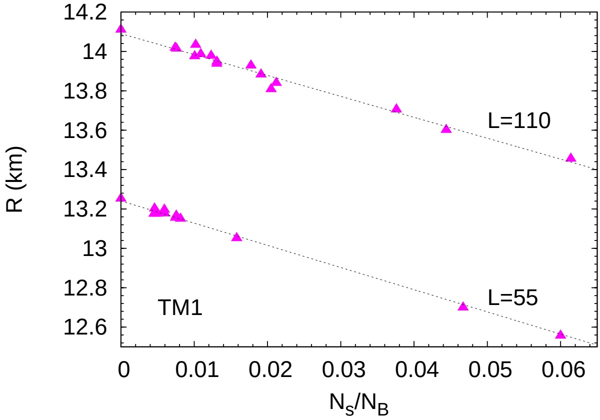
# Maximum mass stars




- $U_\Lambda = -28$ MeV, $U_\Sigma = 30$ MeV,
- $U_\Xi = -18$ MeV without (circles) (**red**), with (**blue**) $YY$
  $U_\Xi = +18$ MeV without (triangles) (**pink**), with (**grey**) $YY$

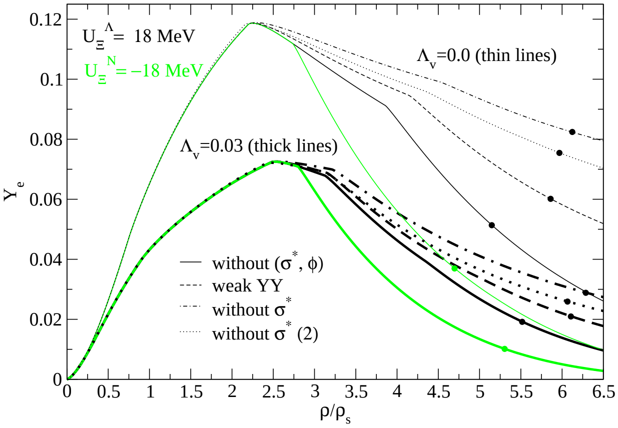
# Radius versus strangeness

## Star with M=1.67 $M_\odot$




slope(L=110)=-11.27 $\pm$4% km
slope(L=55)=-10.62 $\pm$1% km

# electron fraction




- Smaller $L \rightarrow$ smaller electron fraction for a given density
- cooling is affected: smaller electron fraction $\rightarrow$ larger $\nu$ fraction in $\nu$ trapped matter.

# Hyperons in compact stars

- Strangeness in compact stars
  - smaller strangeness content for a smaller $L$

    $\rightarrow$ smaller effect of the hyperon interaction uncertainty on NS properties
- Mass/radius properties of compact stars
  - sensitive to the high density dependence of the EOS and the hyperon interaction
  - $R$ is clearly correlated with $L$
  - smaller radius for a smaller $L$, larger differences for *np* stars
    - uncertainty in hyperon interaction ($V_\Xi$ and $\sigma^*, \phi$)) : $\sim 0.2\, M_\odot$
  - $R$ is correlated with the strangeness fraction
  - J1614-2230 mass: does not exclude hyperons from the EOS taking into account our lack of knowledge on the EOS at high densities and hyperon interaction

# Collaborators

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- Isaac Vidaña, Fabrizio Grill, Silvia Chiacchiera (UC, Portugal)
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- Camille Ducoin, Jérôme Margueron (Lyon, France)

# Thank you !