Towards a unified equation of state (not only!) for astrophysical simulations

Espresso Seminars

Laboratori Nazionali del Sud

Catania, 8^{th} March, 2023

Author: S. Burrello

Outline of the presentation

1. **Introduction**
   - Equation of State of nuclear matter: general concepts
   - Role in astrophysical simulations and nuclear studies
   - Source of information and recent constraints

2. **Theoretical models**
   - Mean-field approximation and phenomenological approaches
   - Energy density functionals: nuclear structure and reactions

3. **Recent developments and results**
   - Connection with ab-initio: improving description at low-density
   - Beyond mean-field: many-body correlations and clustering phenomena

4. **Summary and conclusions**

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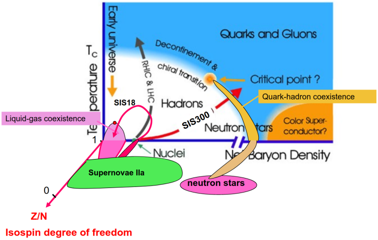
Introduction: Equation of State of nuclear matter

- **Equation of State** (EoS) of nuclear matter (NM)
  - Extensive $\overset{eq.}{\longleftrightarrow}$ intensive variables $(E = E(\rho, \delta, T))$
- Essential ingredient for **compact star** modelization
  - **Mass-radius** relation of neutron stars (NS)
    $\Rightarrow$ **General relativity** idrostatic equilibrium
  - Core-collapse supernovae, binary **mergers**, ...



- Links with nuclear **structure** and **reaction** properties
  - Collective excitations, neutron skins, clustering, ...

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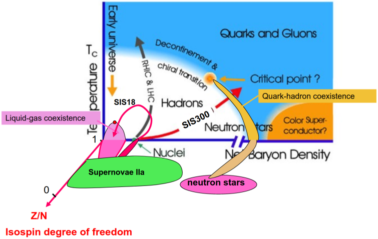

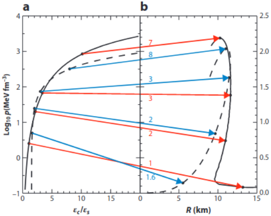

TOV equation

$$\frac{dp}{dR} = -\frac{(\varepsilon + p)(M + 4\pi r^3 p)}{R(R - 2M)}$$

$$\frac{dM}{dR} = 4\pi R^2 \varepsilon,$$

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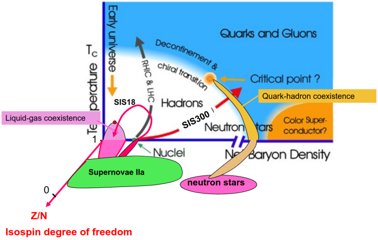

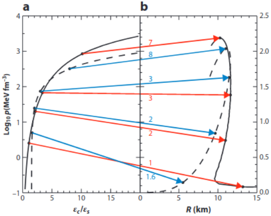

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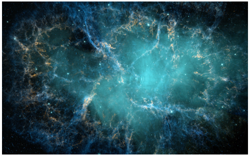

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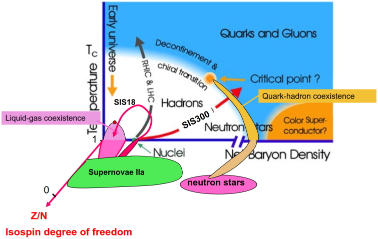

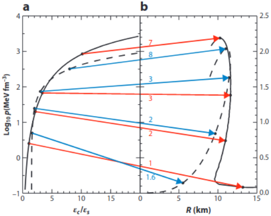

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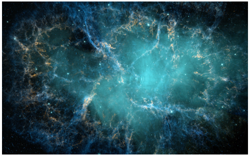

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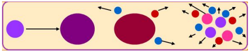

Multi-messenger astronomy and EoS constraints

- Extracting **information** on EoS $\Rightarrow$ **Multi-disciplinary** approach
  - **Theory** + astrophysical **observations** + nuclear **experiments**
- Compact stars probe interaction in **unexplored** regimes
  - Bayesian estimations of ms **pulsar** $M > 2M_{\odot}$ (NICER coll.)

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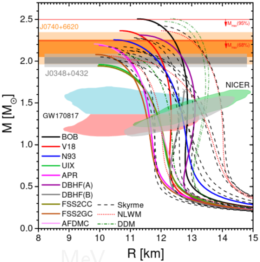

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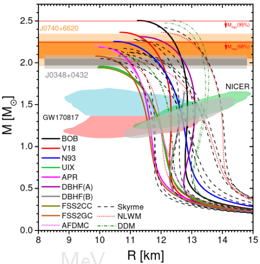

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    $\Rightarrow$ **Symmetry energy** $S(\rho)$

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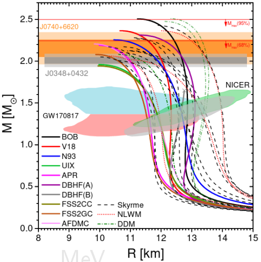

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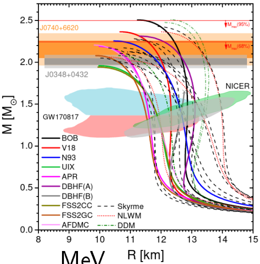

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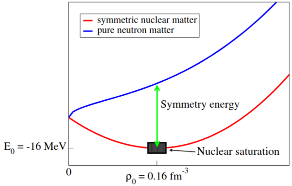
$$\frac{E}{A}(\rho,\delta) \approx \frac{E}{A}(\rho,\delta=0) + S(\rho)\delta^2$$



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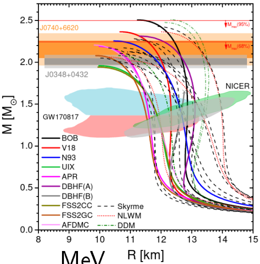

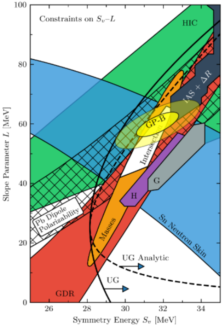

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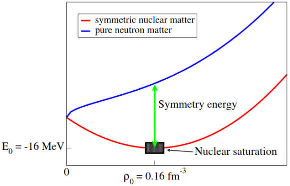
    ⇒ **symmetry energy** $S(\rho)$ far from **saturation** ρ_0

$$\frac{E}{A}(\rho,\delta) \approx \frac{E}{A}(\rho,\delta=0) + S(\rho)\delta^2$$

$$S(\rho) = J + L\left(\frac{\rho-\rho_0}{3\rho_0}\right) + \dots$$



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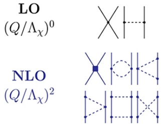
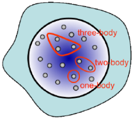
Theoretical models for EoS and finite nuclei

- **Ab-initio** approaches based on **many-body** expansion
  - Realistic or **effective field theory** (EFT) interactions
    ⇒ Diagrammatic hierarchy (**power counting**)





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  - Fit of **parameters** to reproduce various data

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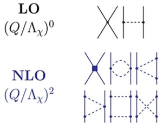

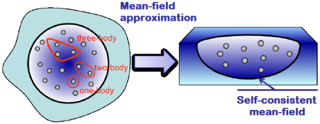

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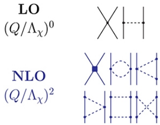

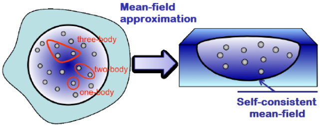

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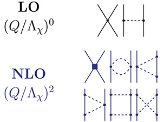

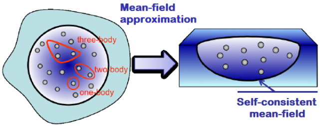

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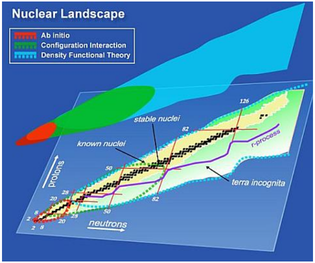

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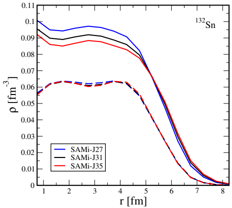
$\Rightarrow$ Description of HI **ground state** and **excitations**

Nuclear structure: symmetry energy and slope

- Structure of **neutron-rich** nuclei

[S. Burrello et al., PRC C99(5), 054314 (2019)]

- Neutron skin thickness $\Delta r_{np} \Leftrightarrow L$



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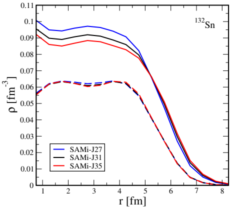

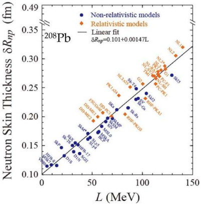

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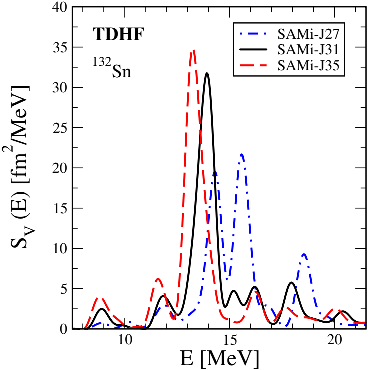

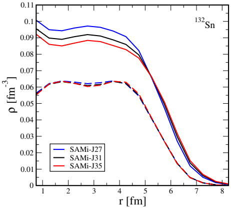

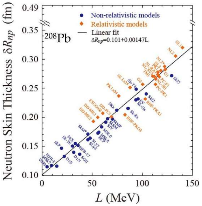

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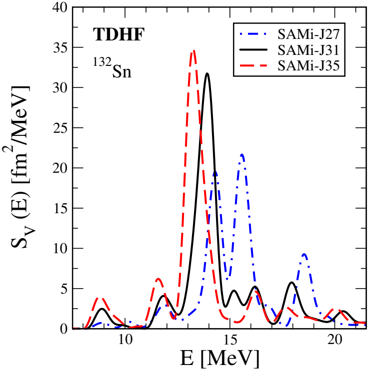

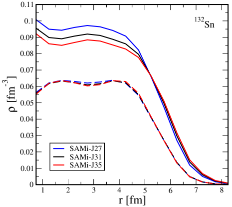

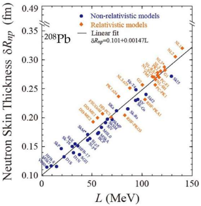

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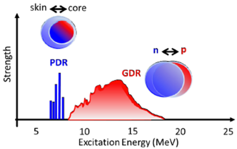

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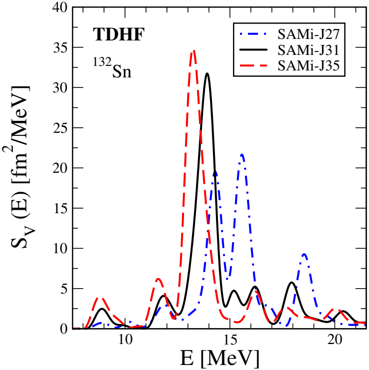
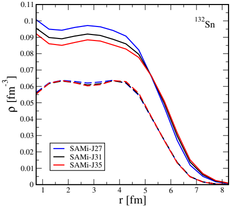
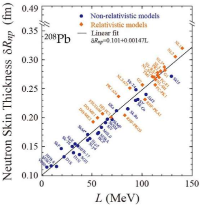


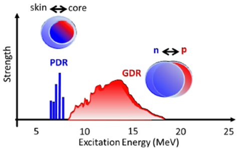


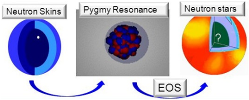


- Time-Dependent-Hartree-Fock **(TDHF)**

$$i\hbar\dot{\hat{\rho}}(t) + \left[\hat{\rho}, \hat{\mathcal{H}}_{eff}[\rho]\right] = 0$$

- **Isovector dipole** (collective) excitations:
  - **Pygmy** Dipole Resonance (**PDR**)





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  [H. Zheng, S. Burrello, M. Colonna, V. Baran, PLB 769 (2017)]

- Interplay between fusion and **quasi-fission** processes
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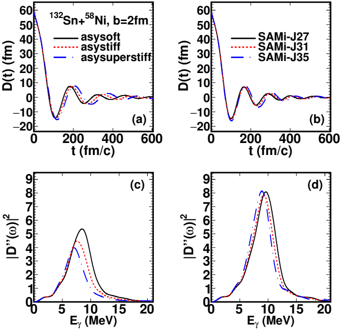

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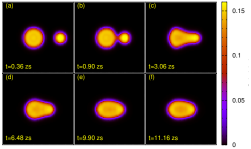

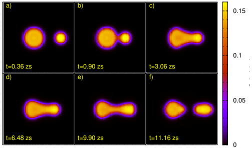

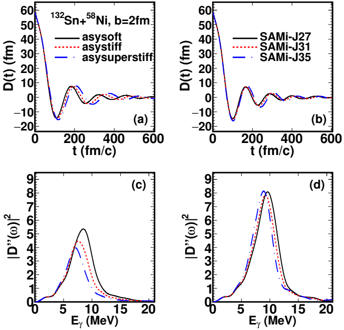

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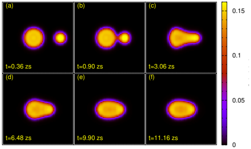

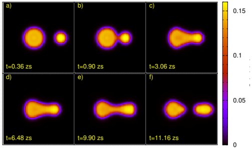

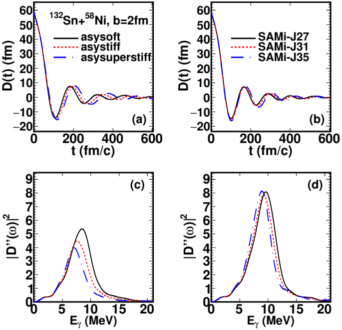

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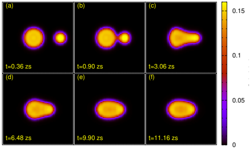

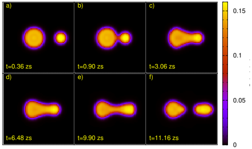

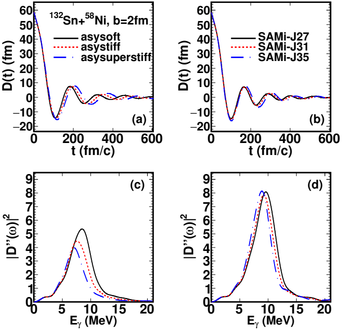

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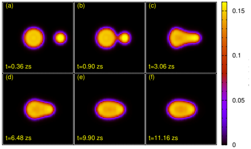

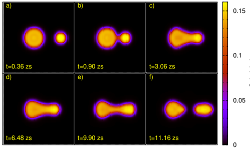

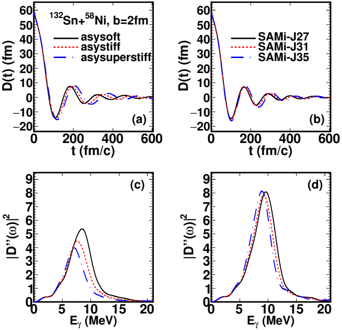

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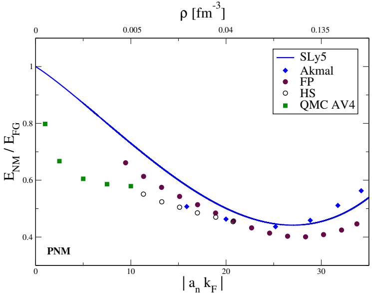

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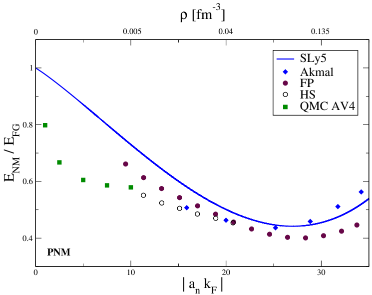

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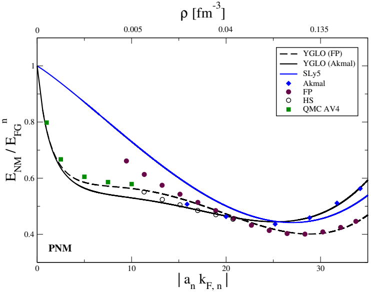

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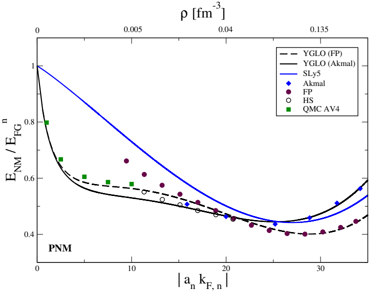

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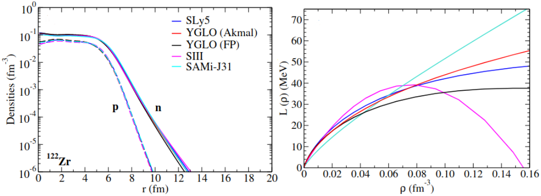

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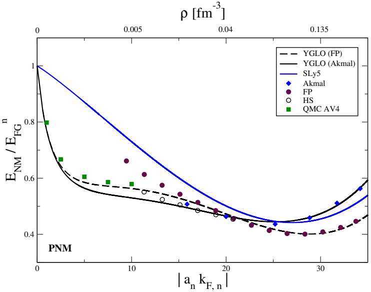

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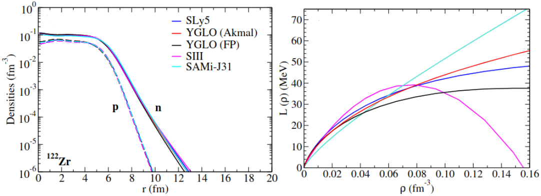

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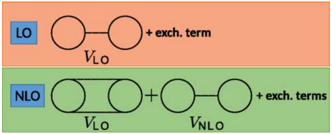
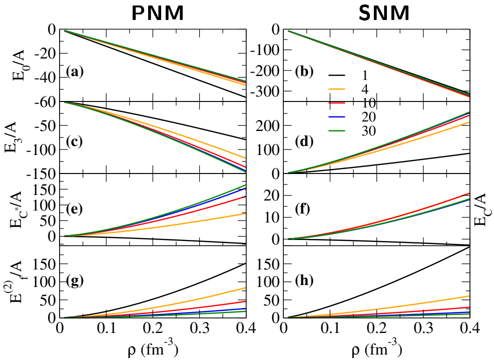
Outline of the presentation

1. Introduction
   - Equation of State of nuclear matter: general concepts
   - Role in astrophysical simulations and nuclear studies
   - Source of information and recent constraints
2. Theoretical models
   - Mean-field approximation and phenomenological approaches
   - Energy density functionals: nuclear structure and reactions
3. **Recent developments and results**
   - Connection with ab-initio: improving description at low-density
   - Beyond mean-field: many-body correlations and clustering phenomena
4. Summary and conclusions

Beyond MF: towards a power counting in EDF

- Beyond MF ⇒ **correlations** explicitly taken into account (**double-counting**)
  - **Hierarchy** of interaction (and EoS) contributions ⇒ **power counting** in EDF
- **EoSs** at next-to-leading order (**NLO**) for symmetric NM (SNM) and PNM





- **Renormalizability** analysis
  ⇒ **perturbative** scheme
- **Next-to-NLO** (in progress):
  - Expansion parameter
  - Breakdown scale

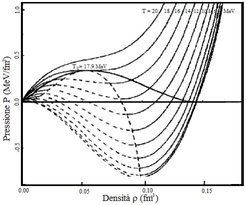
[S. Burrello, C.J. Yang, M. Grasso, PLB 811, 13593 (2020)]

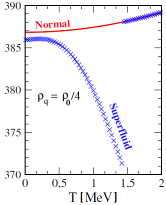
- **BMF** study of **closed-shell** nuclei [C.J. Yang et al., PRC 106 (1), L011305 (2022)]

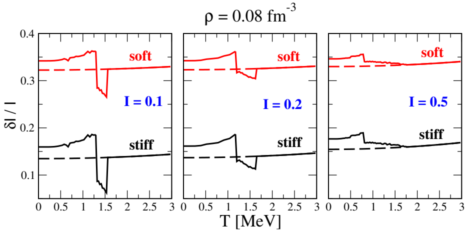
Pairing correlations and nuclear superfluidity

- **Pairing** effects on mechanical (**spinodal**) instability in low-density **nuclear matter**
  $\Rightarrow$ variation on **compressibility** and **isotopic content** of the **clusterized** matter

  [S. Burrello, M. Colonna, F. Matera, PRC 89 (2014)]

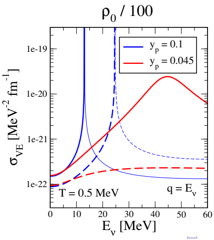


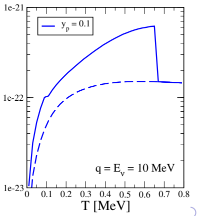




- Homogenous **stellar matter**:
  impact of **superfluidity** on **ν-scattering**
  $\Rightarrow$ **cooling** process in **proto-NS** (PNS)
  or pre-bounce of **supernova** explosions

  [S. Burrello, M. Colonna, F. Matera, PRC 94 (2016)]





Clustering phenomena and neutron star crust

- Many-body (**short-range**) correlations (SRCs) below ρ_0
  - Formation of **bound** state of nucleons (**clustering**)
- **Phenomenological** models with **clusters**
  - **Dilute** matter as a **mixture** of nucleons and nuclei
    $\Rightarrow$ Nuclear statistical equilibrium (**NSE**) model

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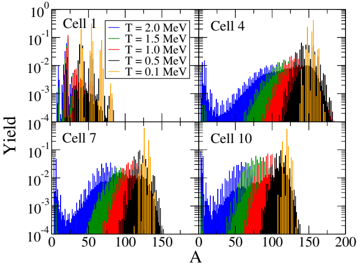

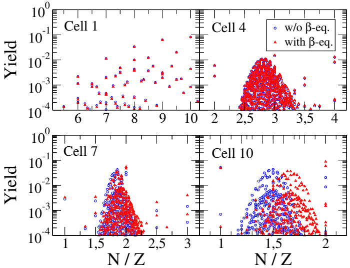

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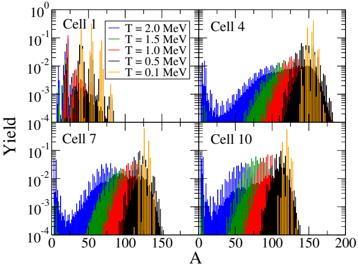

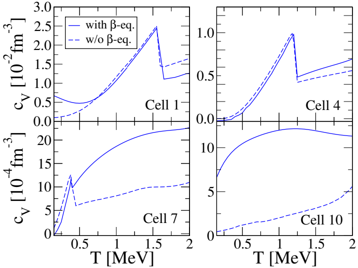

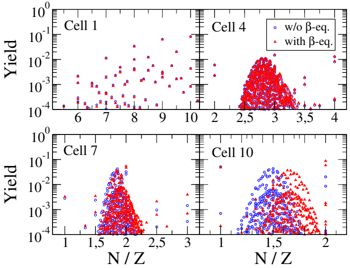

Short-range correlations and EoS at high density

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  [O. Hen et al. (CLAS coll.), Science 346, 614 (2014)]
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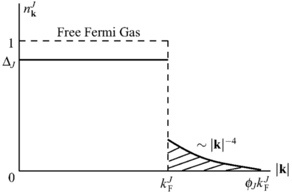

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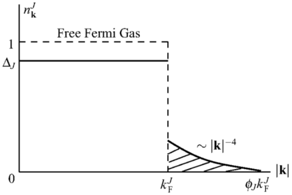

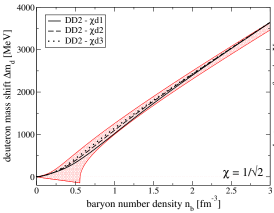

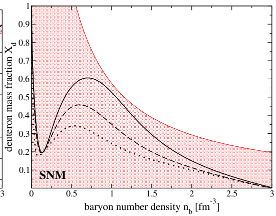

Short-range correlations and EoS at high density

- Nucleon knock-out in **inelastic electron scattering**
  [O. Hen et al. (CLAS coll.), Science 346, 614 (2014)]
  - **Smearing** of Fermi surface (high-**k** tail at T=0)
  - SRCs from **tensor** components or **repulsive** core
- **Quasi-deuterons** to embed SRCs in **relativistic** MF
  [S. Burrello & S. Typel, EPJA 58, 120 (2022)]

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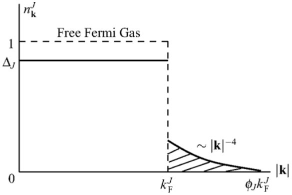

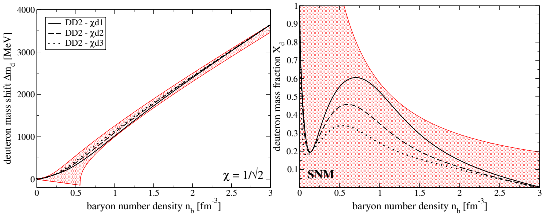

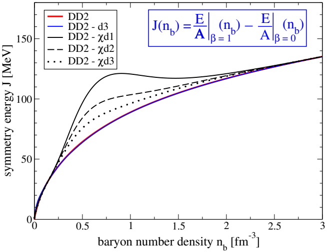

Outline of the presentation

1. **Introduction**
   - Equation of State of nuclear matter: general concepts
   - Role in astrophysical simulations and nuclear studies
   - Source of information and recent constraints
2. **Theoretical models**
   - Mean-field approximation and phenomenological approaches
   - Energy density functionals: nuclear structure and reactions
3. **Recent developments and results**
   - Connection with ab-initio: improving description at low-density
   - Beyond mean-field: many-body correlations and clustering phenomena
4. **Summary and conclusions**

Final remarks and conclusions

Main topic

- **EoS** of nuclear matter: importance for **nuclear** and **astrophysical** processes
- Theoretical **modelization** in light of recent **multi-messenger** constraints

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- Inclusion of **pairing**, short-range **correlations** and **cluster** degrees of freedom
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- Stringent **constraints** from spectral **pion ratio** and **Einstein telescope**
- **Unified** EoS for nuclear **structure**, **reactions** and **astrophysical simulations**

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THANK YOU FOR YOUR ATTENTION!

Best wishes to all women!