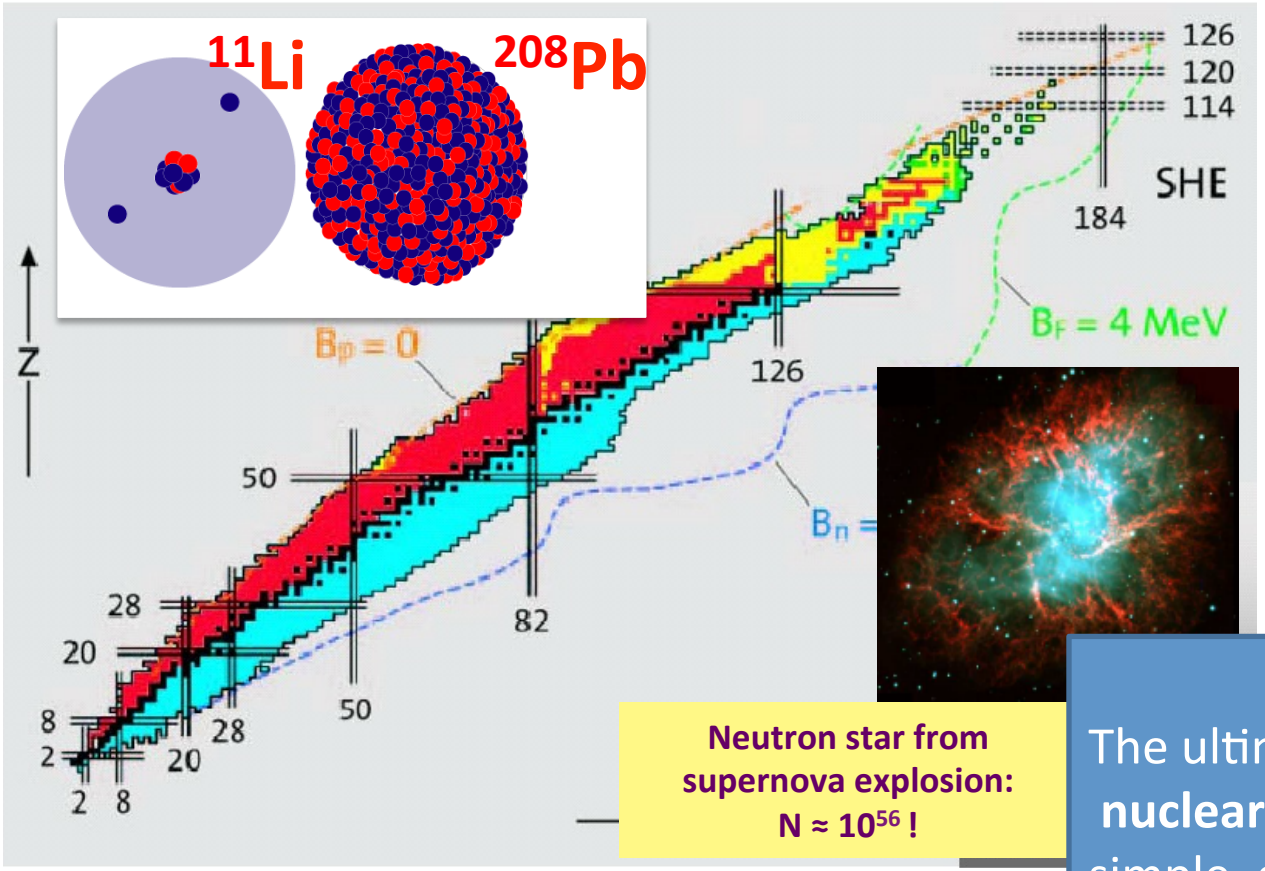
Possibilities for studies (Master and PhD theses) connected to the RIB physics

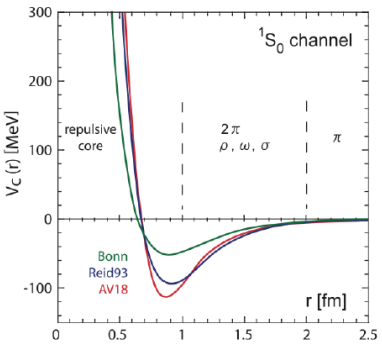
Rewriting Nuclear Physics textbooks:
30 years with RIB physics

20th-24th July, 2015
Pisa (Italy)
Visit to LNL
July, 24th, 2015

Maria Colonna
INFN - Laboratori Nazionali del Sud (Catania)



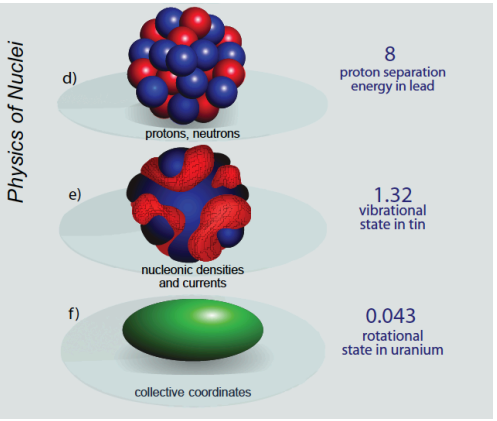
Neutron star from supernova explosion: N ≈ 10^{56} !



The ultimate goal of **nuclear structure** is to develop a simple, coherent, comprehensive **theory** for understanding **nuclei** and **nuclear reactions** starting from the **interaction** between free protons and neutrons

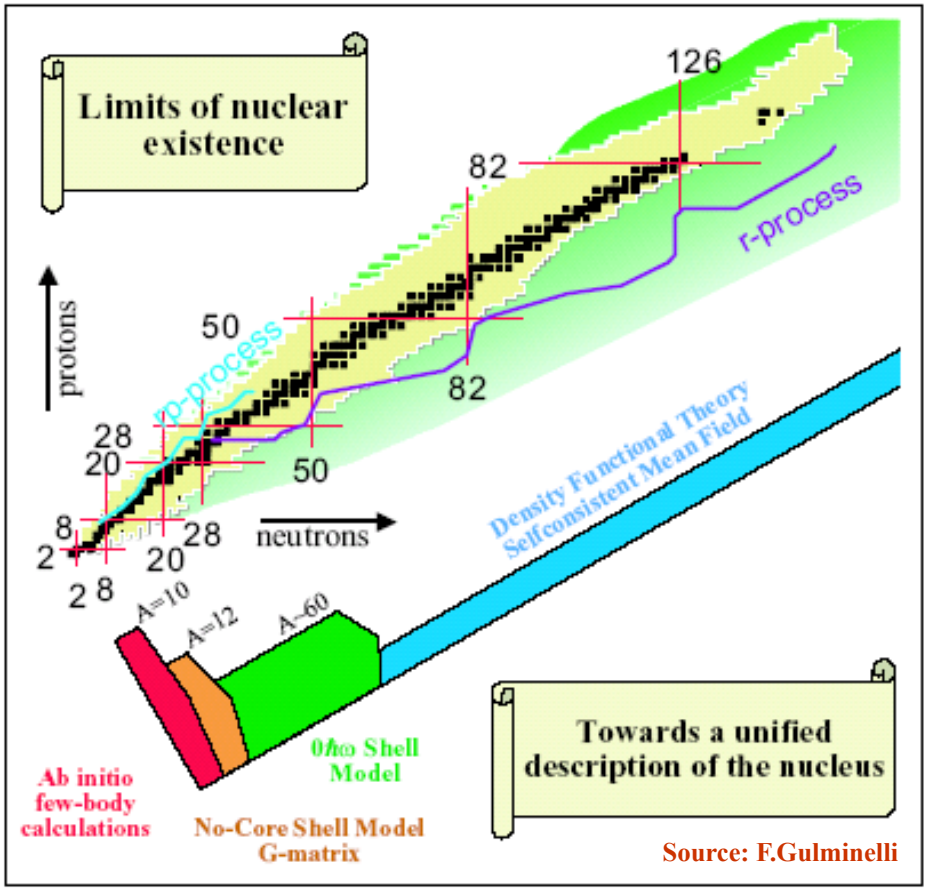
Some ‘fundamental‘ questions

- *What is the nature of the nuclear force that binds protons and neutrons into stable nuclei and rare isotopes ?*
- *What is the origin of simple patterns in complex nuclei ?*
- *How to explain the observed , so different, reaction cross sections ?*
- *What is the origin of the elements in the cosmos ?*
- *Which elements are still to be discovered (superheavy) ?*



Study of vast numbers of unstable nuclei
far from the valley of stability → interesting new phenomena !

New data will provide stringent boundaries to the present nuclear models making possible to answer fundamental questions



Light systems: Ab-initio few-body methods

Medium systems: Shell model

Medium-heavy systems:
Density functional theories
Self-consistent mean-field
⟶ Nuclear matter **EOS**

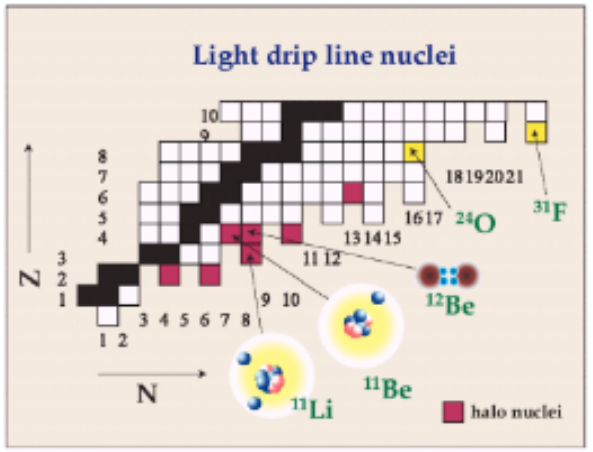
Structure and Reactions with light systems: Pisa, Padova, Trento

Master/PhD theses

- ***Efimov effect and universality***

Universal character of low-energy processes in three-boson systems . Particle-dimer scattering and recombination

The plan is to extend this study to fermion systems, to describe light nuclei and halo nuclei



- ***Study of four-nucleon continuum***

Theoretical study of three- and four-nucleon continuum within the hyperspherical harmonics method, with different potentials (phenom., Chiral, low-k)

Ex: p-d and p-3 scattering observables at selected energies and comparison with the available experimental data

http://www.df.unipi.it/~marcucci/theses.html

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- ***Electro-weak structure of ligh nuclei***

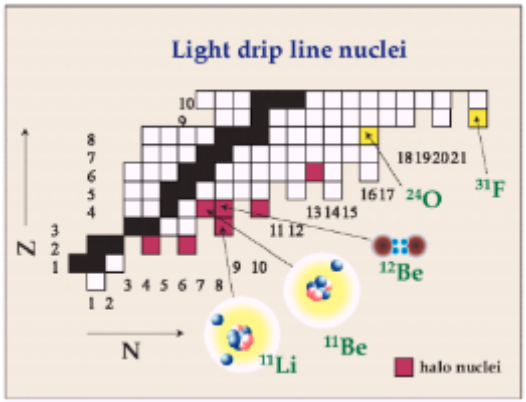
Nuclear EW currents and nuclear interaction are derived consistently from Chiral Effective Theory

Study of p-p weak capture (to form deuterons) - astrophysical interest

Pisa

○ ***Giant and pigmy dipole resonances in 4He, 16,22O, and 40Ca from chiral n-n interactions***

Combine the Coupled-Cluster method and the Lorentz integral transform for the computation of inelastic reactions into the continuum
Response to electromagnetic probes



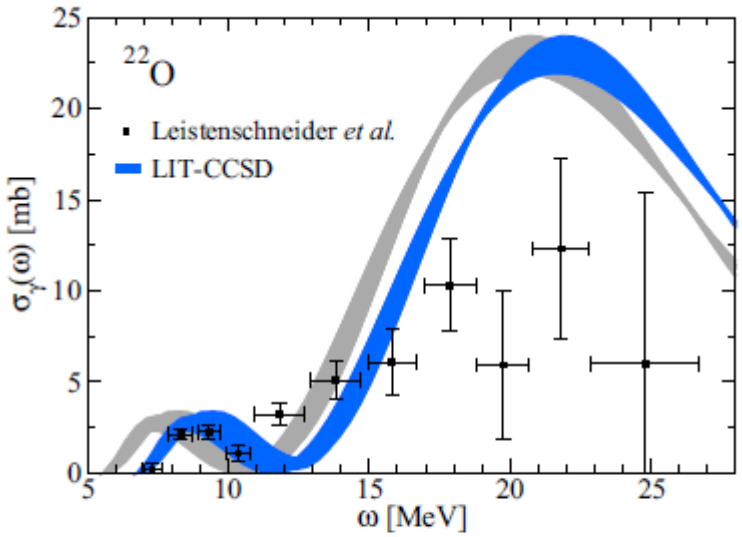


FIG. 12. (Color online) Comparison of the LIT-CCSD dipole cross section of ^{22}O with the photoneutron data of Ref. [2]. The gray curve starts from the theoretical threshold, while the dark (blue) curve is shifted to the experimental threshold.

Dipole cross section

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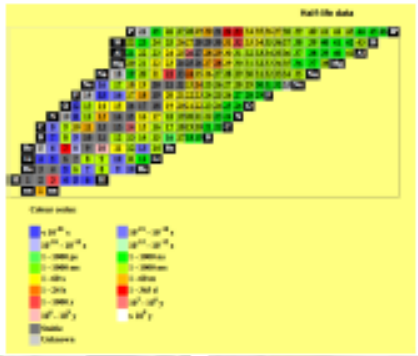
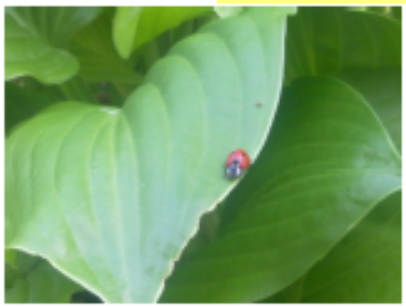
Trento

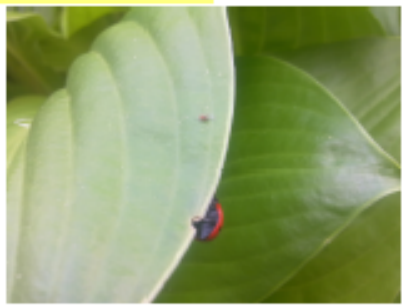
Master/PhD theses

Exotic nuclei studied with breakup and transfer to the continuum

Entering the world of exotic nuclei: probing the unbound by walking at the drip line.



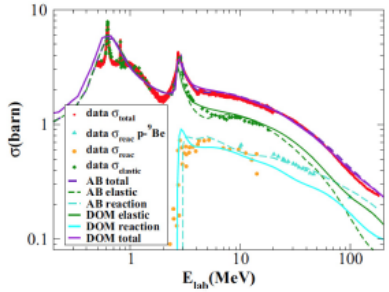




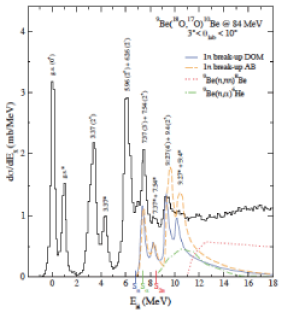
- Can we do Nuclear Physics beyond the dripline?
- Extend our understanding of the *residual* nuclear force.
- Check the limits of validity of structure models such as the SHELL MODEL or "ab initio" models.
- Challenges in breakup reaction theory.

1) Elastic scattering and microscopic calculations of optical potentials including the breakup channel.
2) Folding potentials.
3) Breakup of neutron and proton rich nuclei like ^{9}C e ^{7}Be from the *hot* *pp*-chain of the explosive nucleosyntesis to understand the reaction mechanism and obtain spectroscopic information.
$p(p,\beta+\nu)d(p,\gamma)^{3}He(\alpha,\gamma)^{7}Be(p,\gamma)^{8}B(p,\gamma)^{9}C(\beta^{+}\nu)^{9}B(p)^{8}B(\alpha)\alpha,$
4) Unbound nuclei studied via transfer to the continuum and/or projectile fragmentation also to obtain information on the pairing interaction.

n-^{9}Be optical potential:
A.B, R.J. Charity, PRC89, 024619 (2014)
data from https://www-nds.iaea.org/exfor/exfor.htm



Low energy transfer to ^{10}Be resonances, missing mass experiment.
D. Carbone et al., PRC 90, 064621 (2014)



Activity in PISA https://www.df.unipi.it/ angela/
Teaching: Nuclear Reaction Theory
http://unimap.unipi.it/registri/registri.php

A.Bonaccorso, bonac@df.unipi.it

The core-target movement is treated in a semiclassical way, but neutron-target and/or neutron-core with a full QM method.
AB and DM Brink, PRC38, 1776 (1988), PRC43, 299 (1991), PRC44, 1559 (1991).

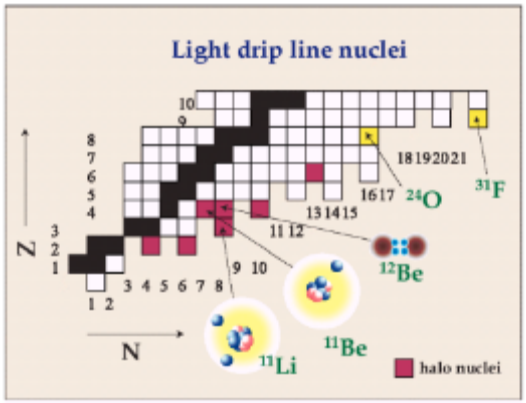
Early eikonal model: I. Tanihata, Prog. Part. Nucl. Phys. 35, 505 (1995), halo-core decoupling.

$$\frac{d\sigma}{d\xi} = C^2S \int_0^\infty d\mathbf{b_c} \frac{dP_{-n}(b_c)}{d\xi} P_{ct}(b_c)$$

Master/PhD theses

Padova
(Master and PhD theses)

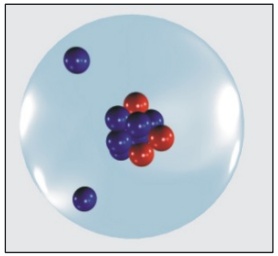
Nuclear structure:



- Cluster models for light nuclei
- Few-body models for nuclei far from the valley of stability
- Collective geometrical model applied to nuclear spectroscopy
- Methods to solve the many-body Schrödinger equation

Nuclear reactions:

- Break-up reactions in nuclei far from the valley of stability
- Semi-classical approach to neutron transfer close to the Coulomb barrier



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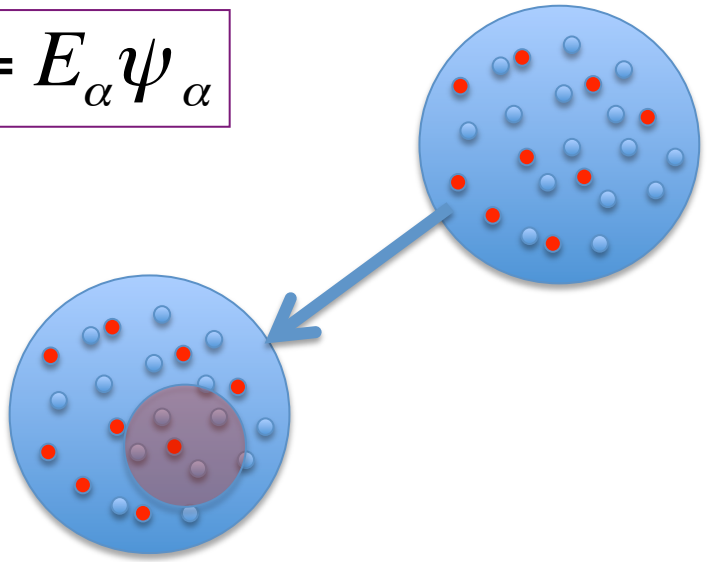
A microscopic approach to nuclear structure: Realistic shell model

A nuclear system with A nucleons is described by the Schrödinger equation

$$H\psi_\alpha = [T + V_{NN} + V_{NNN} + \ldots)]\psi_\alpha = E_\alpha \psi_\alpha$$

Shell-model equation for N nucleons in a truncated space

$$H_{eff}\psi'_\alpha = E_\alpha \psi'_\alpha$$



where E_α belong to the set of eigenvalues of H and H_{eff} is derived from H by using many-body perturbative techniques

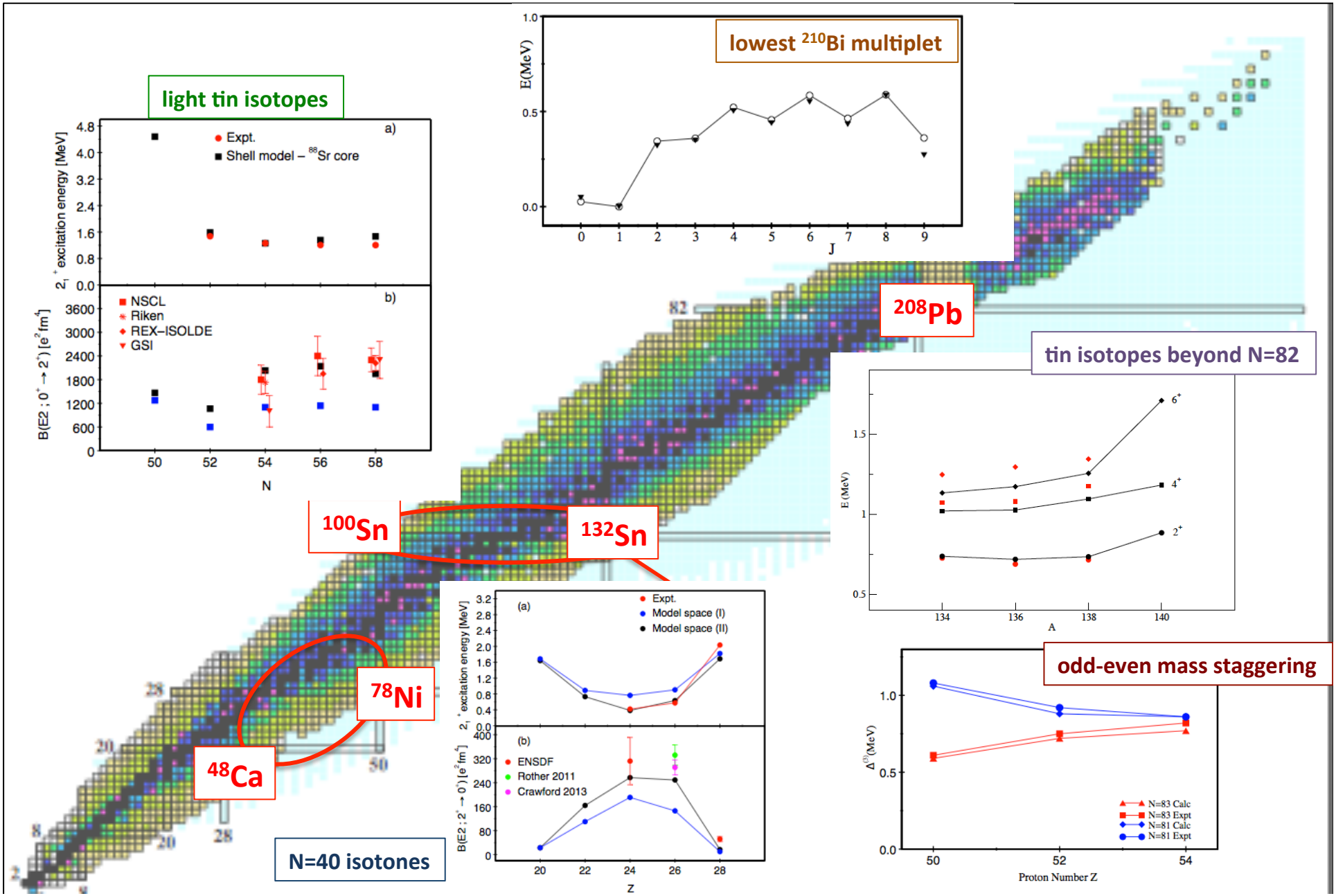
Needed tools

- Free nuclear potentials
- Effective theories
- Folded diagram expansion
- Shell-model codes

Napoli

***Collaboration members*:** L. Coraggio, A. Gargano, N. Itaco (INFN Napoli and UNINA), T.T.S. Kuo (Stony Brook, USA)

Some examples of realistic shell-model calculations



Structure of medium nuclei: shell model

- Realistic shell-model calculations for exotic nuclei
- Microscopic studies of nuclear matter with chiral potentials
- Neutrinoless double beta decay: shell-model calculation of the nuclear matrix element

Napoli

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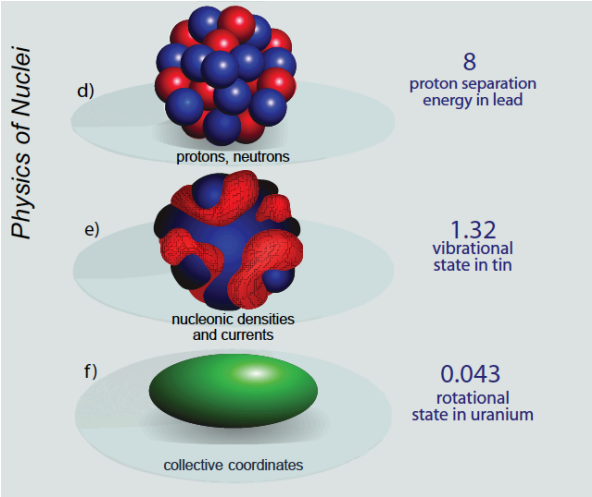

- Isospin symmetry breaking in proton-rich nuclei (realistic interactions)
- Nuclear structure in neutron-rich nuclei, far from the valley of stability

Padova

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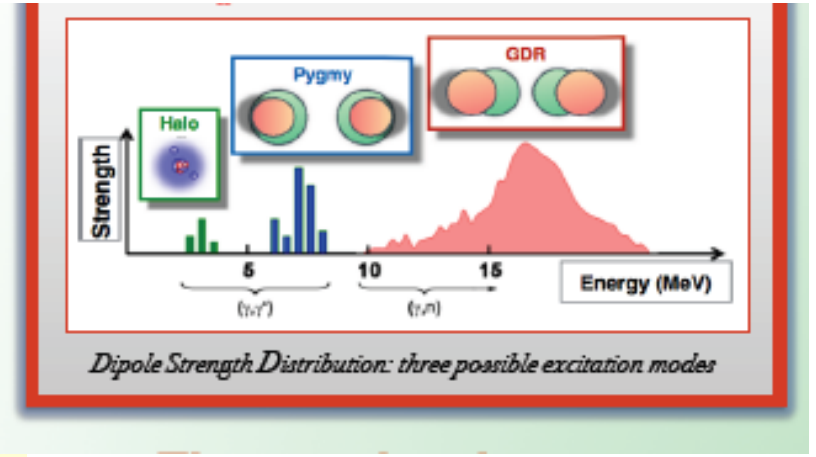
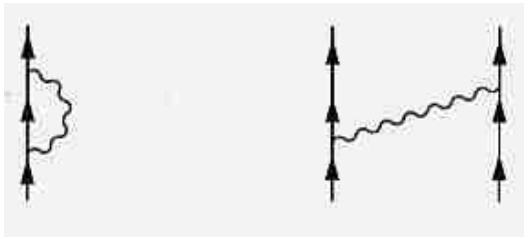
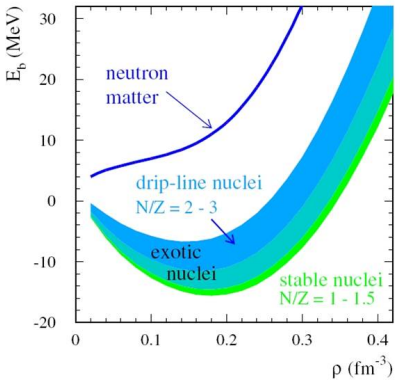
Medium-heavy systems: self-consistent mean-field
Some hot topics

- New effective interactions and pairing correlations
- Study of nuclear vibrations (monopole, dipole, quadrupole)
- Reactions with electro- and hadron probes: How to excite nuclear collective motion ?
- Nuclear Field Theory: Particle-Vibration coupling
- Electro-weak decay (ex. β decay)



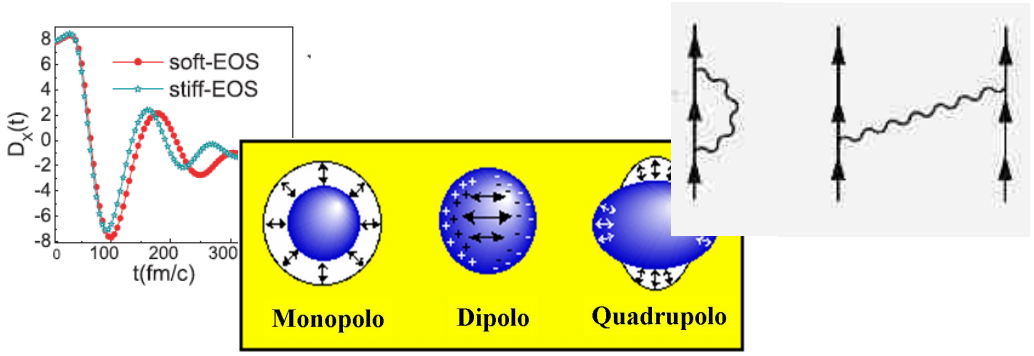
Dipole Strength Distribution: three possible excitation modes





→ *Connection to the nuclear EOS*

Master and PhD theses



- Simple nuclear models with short-range phenomenological potentials (Master)
- Second-order perturbation theory for single-particle motion (M)

Milano

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- N=Z nuclei within the formalism of quartets (Master/PhD)

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- Coupling to the continuum in mean-field models (HF, RPA) (PhD)
- Collective excitations in exotic nuclei and deformed systems (PhD)

Catania

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- Connection between PDR strength and symmetry energy (Master)
- The pygmy resonance in deformed nuclei (PhD)

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- Collective motion in semi-classical approaches (Master)

LNS-Catania

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- New effective interactions and pairing correlations

New parameter-free effective interactions, including tensor forces, able to describe all nuclei at once (applications to exotic nuclei)

Lecce

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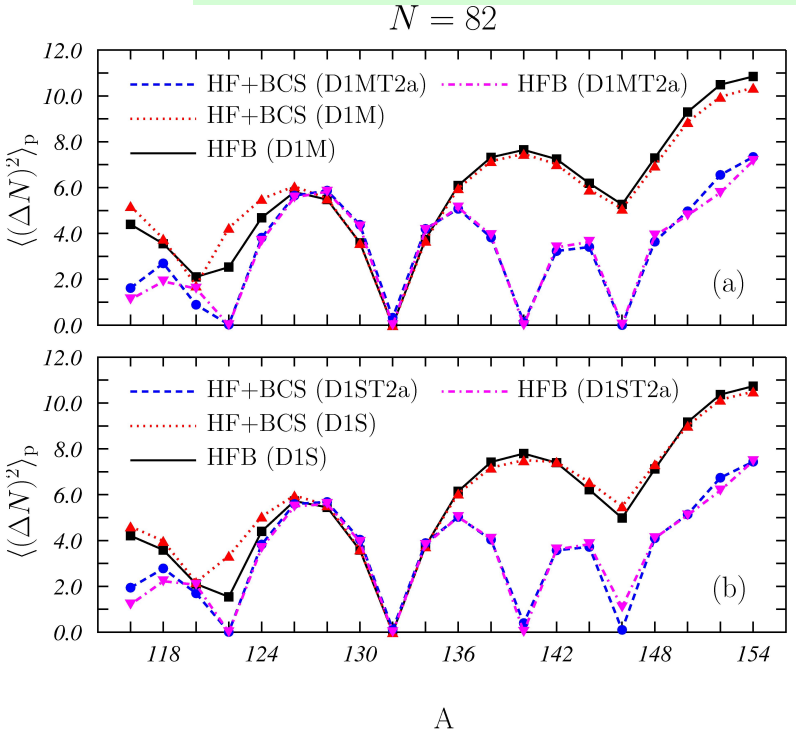
Nucleon number fluctuations



- Elastic and quasi-elastic scattering with electro-weak probes
  - extension to hadronic probes

RMF models for nuclear structure
Ex: The weak charge density is closely connected to the neutron distribution

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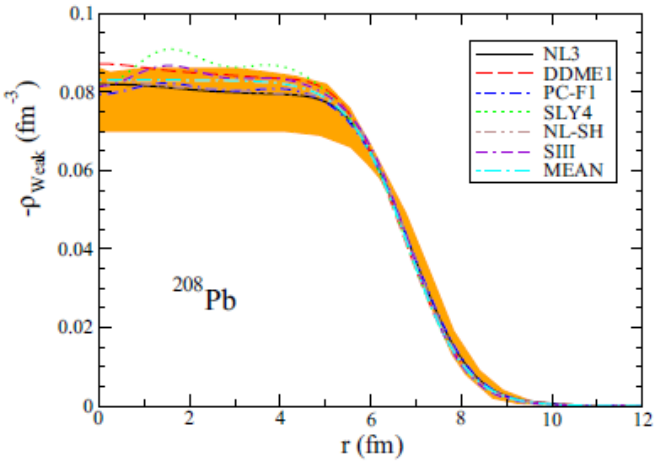
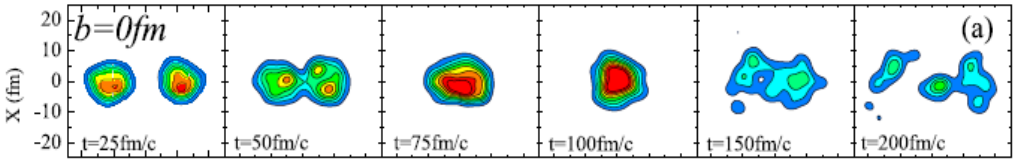


Weak charge density

Phenomenology of Heavy Ion Collisions: A way to explore the nuclear matter phase diagram



Master and PhD theses

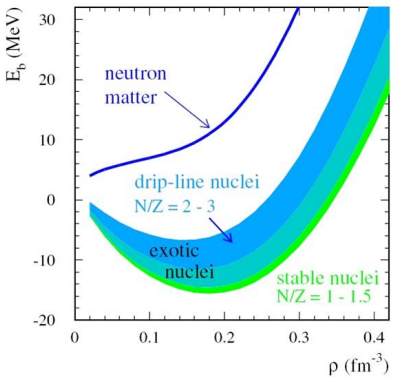
TDHF (and extensions)

Semi-classical approximation:
time evolution of the
one-body distribution function in phase space

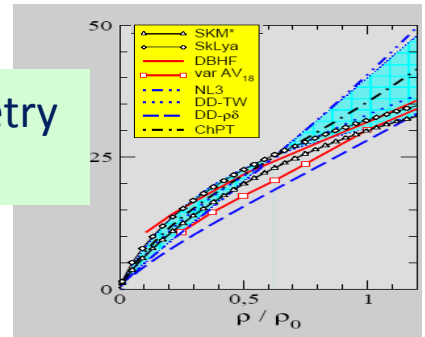
$f(r,p,t)$: $\frac{\partial}{\partial t} f + \{f, H\} = I_{coll}$

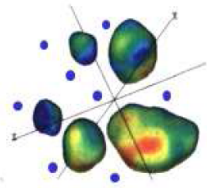
*using **effective interactions***

- Excitation of collective motion in low-energy collisions
- Isospin effects in fragment production (HIC at Fermi energies)
- Cluster formation in low-density matter



Symmetry energy





LNS group

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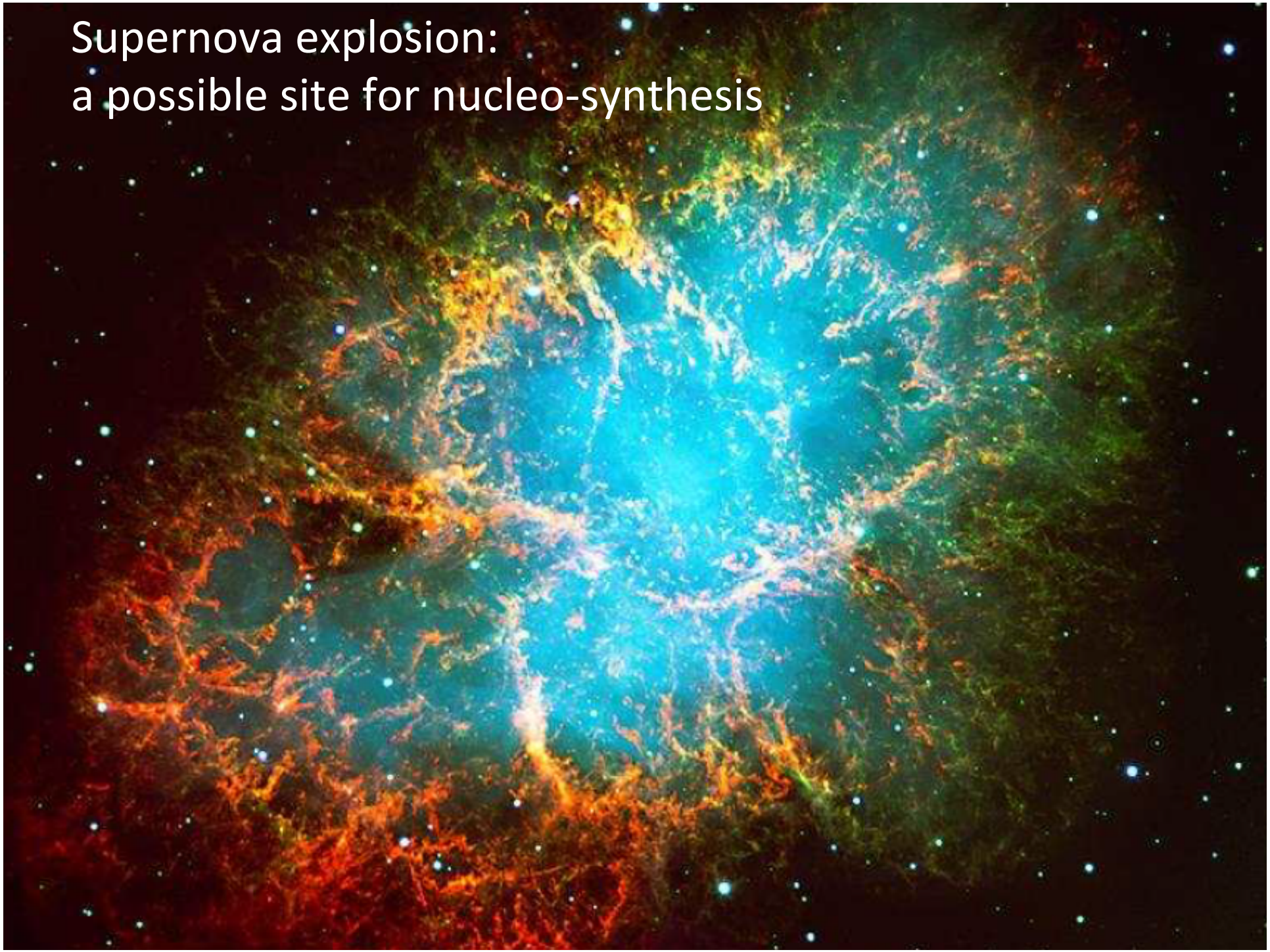
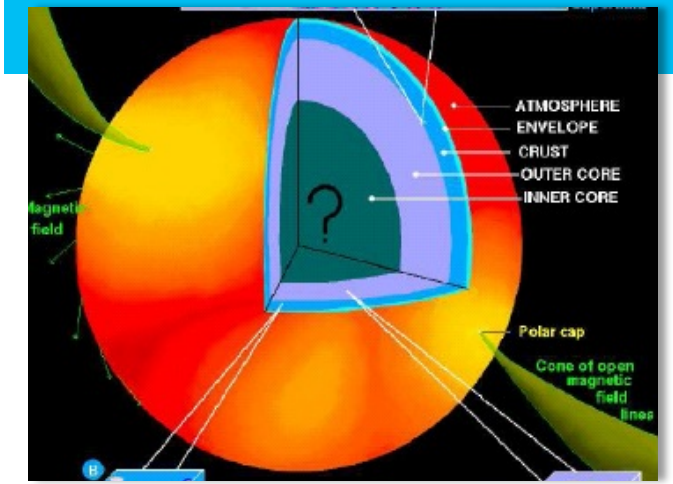
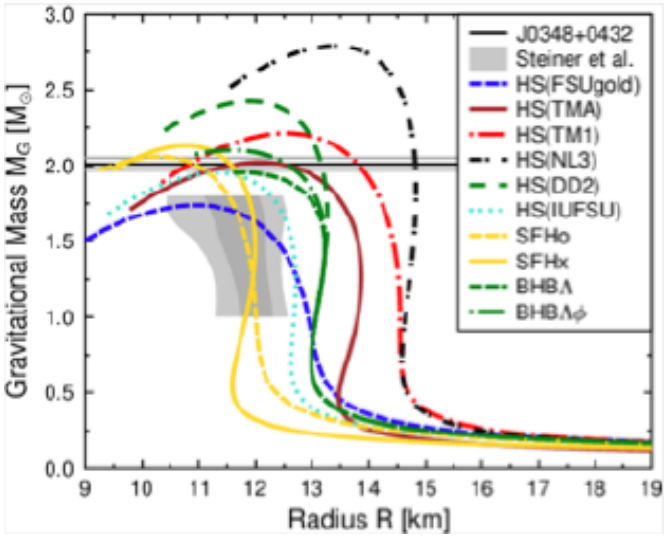

Supernova explosion:
a possible site for nucleo-synthesis

Nuclear Matter EOS and neutron stars:

Milano, Catania, Ferrara, LNS



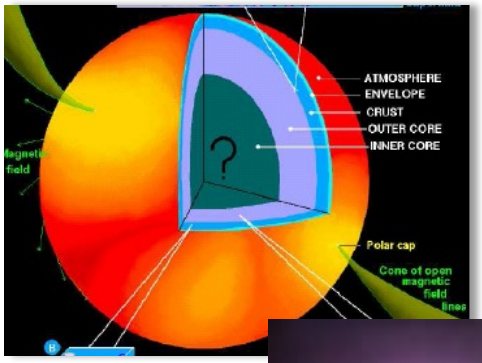


- The stability of neutron stars, their **total mass** (≈1.4-2 M_{Sun}) and their **radius** (≈ 1-10 km) are determined by the balance betwen **gravitational** and **nuclear** forces (symmetry energy).

- Nuclear Physics *Inputs* are important also for **simulations** of **supernova explosion** (cooling of proto-neutron stars ...)

These systems allow one to study "exotic" nuclear matter at densities equal 3-4 times normal density !

Master / PhD theses



- Magnetic-field effects on the neutron star crust
- Electron capture reactions
- Neutrino mean-free path (star cooling)

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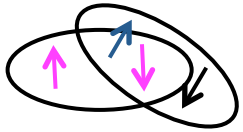
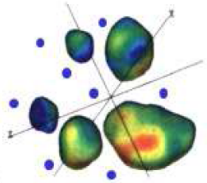


BCS

Cooper pairs

- Pairing effects on low-density clustering phenomena
- Pairing effects on density fluctuations and neutrino mean-free path



LNS & Catania colonna@lns.infn.it, lombardo@lns.infn.it

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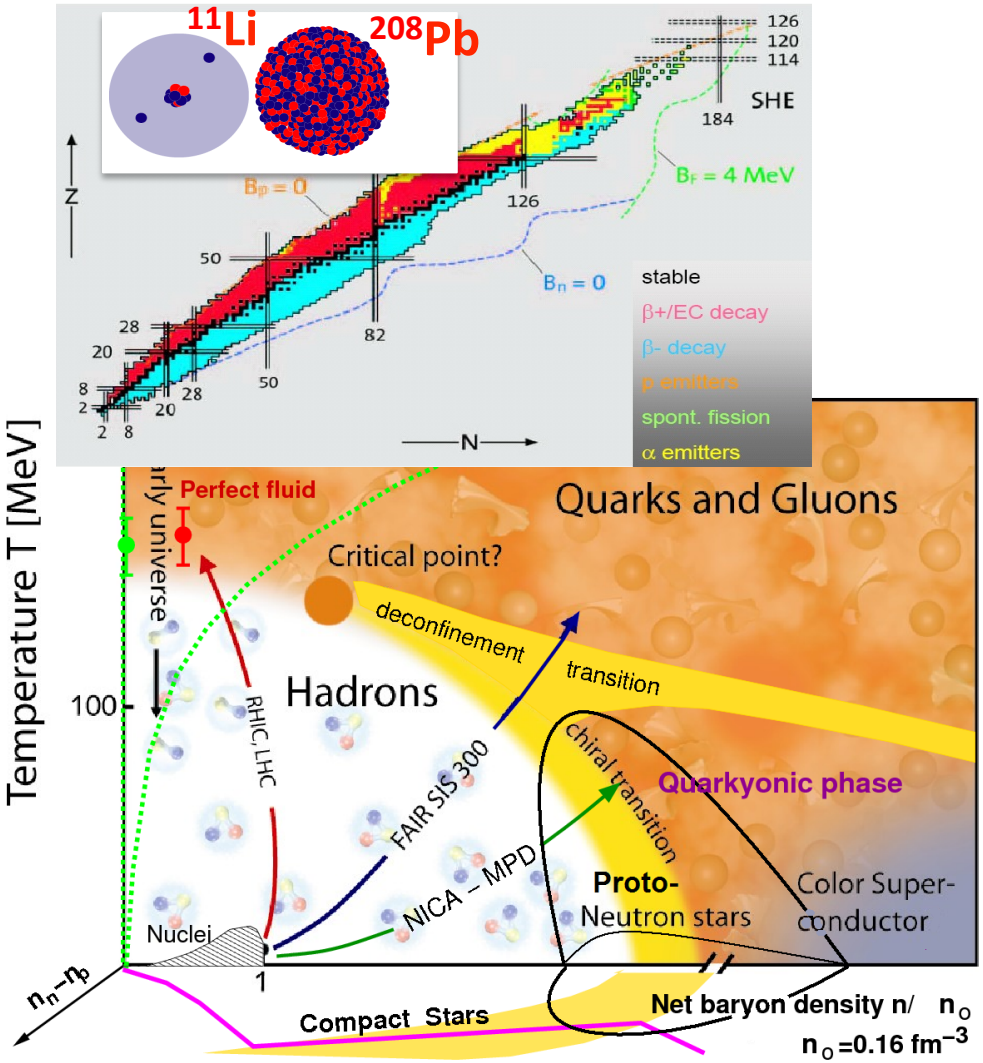

Many interesting subjects : from exotic nuclei to exotic nuclear matter !!

Strong synergies with experiments at

existing facilities and, in perspective, new facilities like SPES

Thanks for your attention !