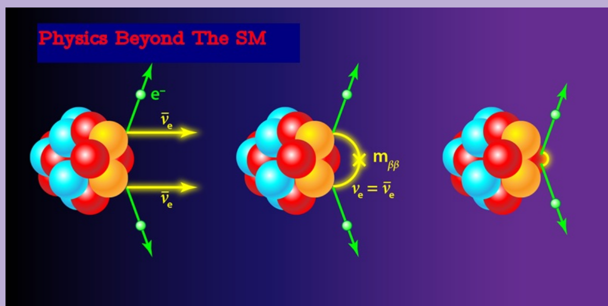
Theoretical activities supporting the experiments at LNS

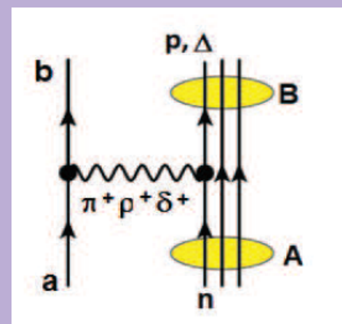
Danilo Gambacurta
(On behalf of the LNS theoretical group)
Laboratori Nazionali del Sud (Catania)

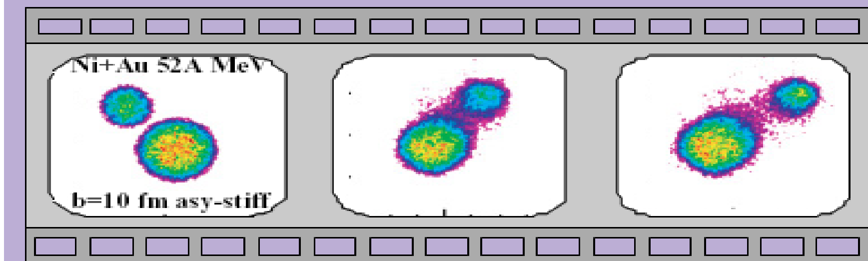
LNS Users Annual Meeting – 19.12.2022

Research activities within the INFN "Specific Initiatives"

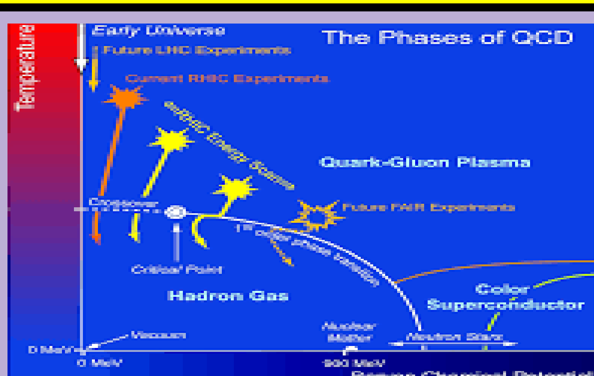
MONSTRE: MOdeling Nuclear STructure and REactions

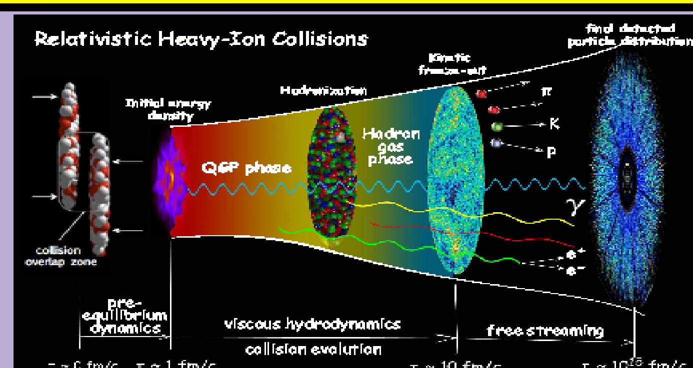






SIM: Strongly Interacting Matter at high density and temperature



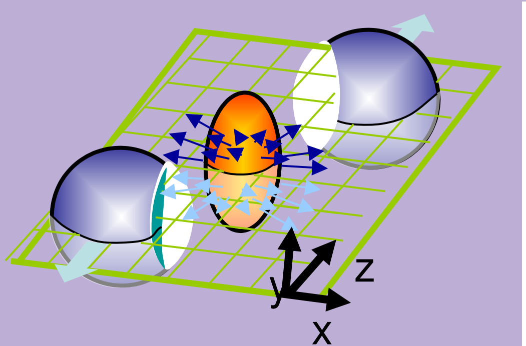


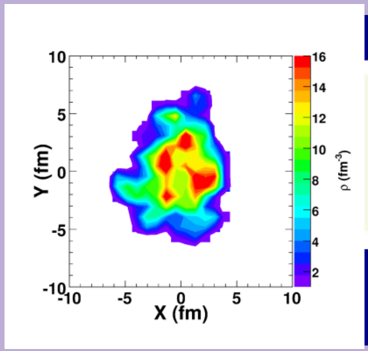
SIM: Strongly Interacting Matter at high temperature and density

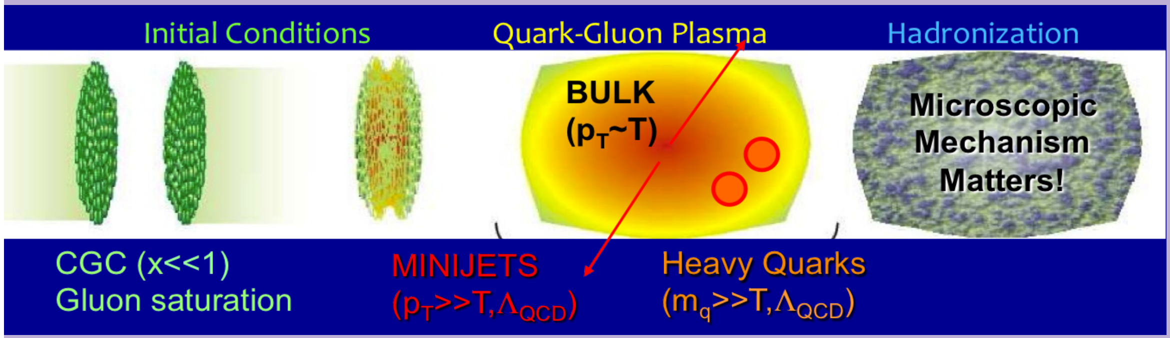
Phenomenology of Quark Gluon Plasma with Transport Theories

- **Hadronization mechanisms**
- **Heavy quark dynamics: charm and bottom**
- **Non-equilibrium dynamics in AA, pA and pp collisions**

Ref. Prof. V. Greco

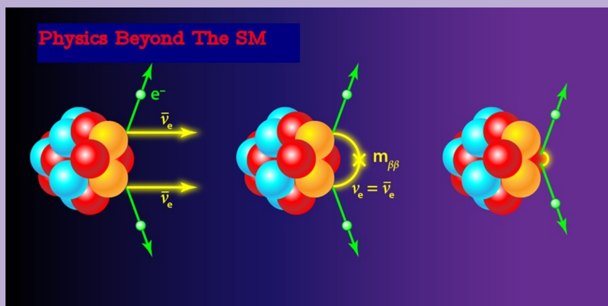


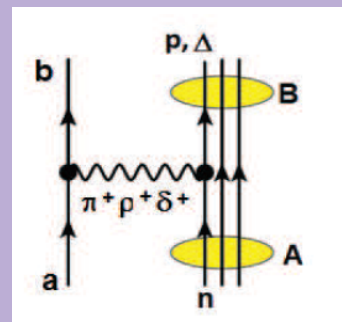


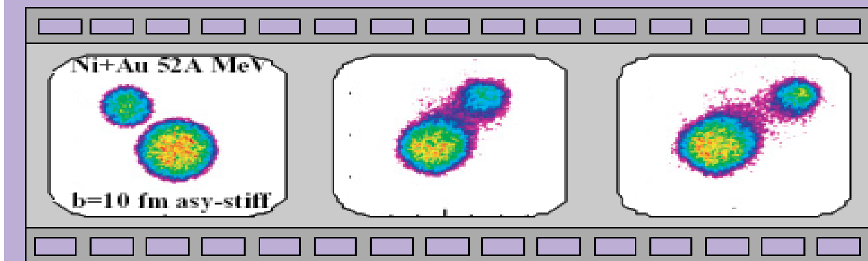


Research activities within the INFN "Specific Initiatives"

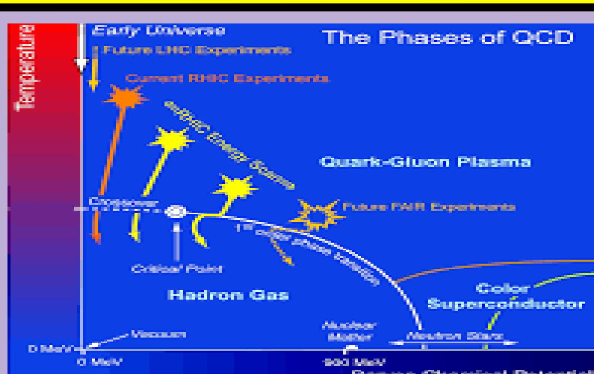
MONSTRE: **MO**deling **N**uclear **ST**ructure and **RE**actions

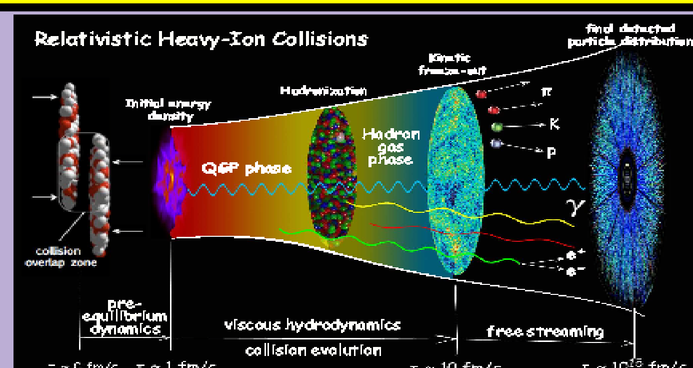






SIM: **S**trongly **I**nteracting **M**atter at high density and temperature





Nuclear Structure Studies

Theoretical Models and Techniques

- ✓ ***Energy Density Functional(EDF)*** *Framework (**Skyrme-Gogny**)*
- ✓ ***HF, HF+BCS, HFB*** *(ground state and low lying spectroscopy)*
- ✓ ***RPA, QRPA, Second RPA, TDHF*** *(nuclear response and excitations)*
- ✓ ***Spherical and Deformed, also superfluid,*** *systems can be studied*
- ✓ ***Transport theories based on EDF***

Main Physical Cases of Interest

- ✓ ***Collective nuclear excitations,*** *especially in neutron-rich and exotic nuclei (Giant Resonances, Pygmy Dipole Resonance, ...)*
- ✓ ***EoS of asymmetric matter*** *(symmetry energy, ...)*
- ✓ ***Charge exchange excitations*** *(Gamow-Teller, Fermi, etc,)*
- ✓ ***Beta Decay*** *(single and double, with or without neutrinos)*
- ✓ ***Interdisciplinary aspects between nuclear and neutrino physics***
- ✓ ***Proton – Neutron pairing*** *in Z~N nuclei*

Nuclear Reaction Studies

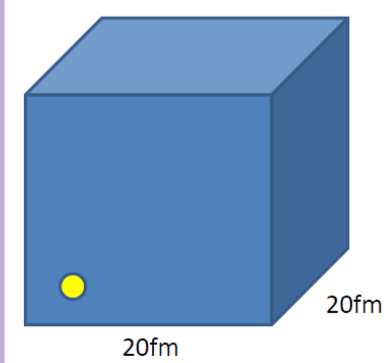
Theoretical Models and Techniques

- ***Semi-classical transport theories,*** *incorporating many-body correlations*
- ***DWBA and/or coupled channel calculations***
- ***Formulation of scattering theory*** *for double Charge Exchange (CE) Reactions*

Main Physical Cases of Interest

- ***Nuclear reactions at Fermi/intermediate energies***
- ***Direct reaction*** *(transfer, charge exchange, probing spin-isospin channels)*
- **Fragmentation reactions,** also for medical applications
- ***Impact of Eos on nuclear reactions***
- ***Double Charge Excitations*** *and the connection to double beta decay*
- ***Reactions of astrophysics interest*** *(light systems, cluster structures)*

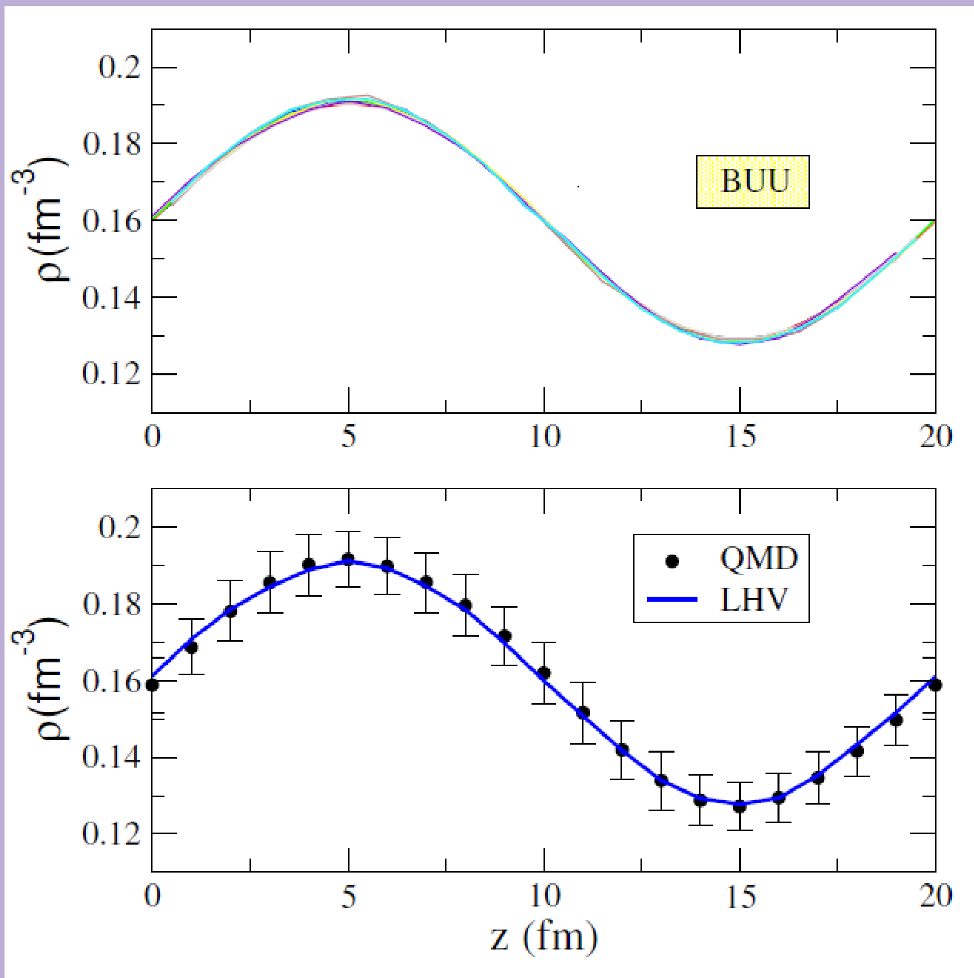
A (few) recent Applications and Studies



Reaction dynamics in semi-classical stochastic approaches

Transport Model Evaluation Project

Box simulations: test of mean-field dynamics



M.Colonna et al., PRC 104, 024603 (2021)

- Sinusoidal perturbation: $\rho(z,t=t_0) = \rho_0 + a_\rho \sin(kz)$

$k = 2\pi/L, \quad L = 20\ fm \qquad a_\rho = 0.2\ \rho_0$

- *Fermi sphere defined as a function of the local density*

Symmetric matter zero temperature

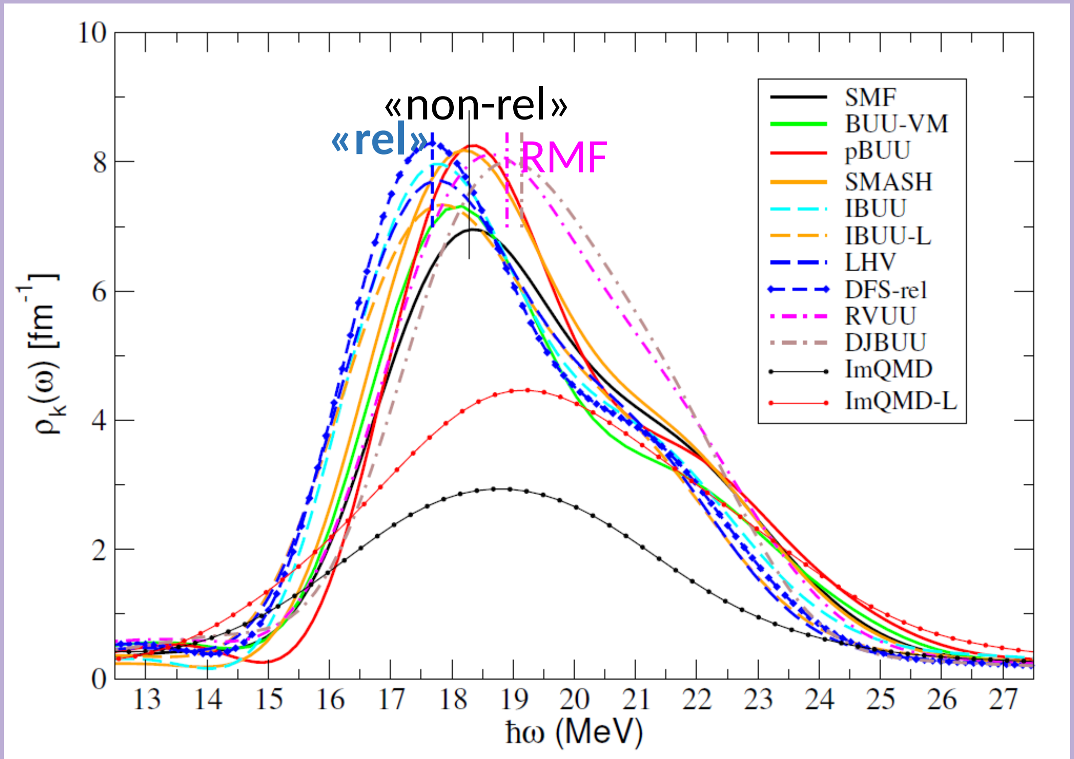
- Only mean-field potential
- No surface terms
- Compressibility K = 500 MeV

Simulations:
200 runs for QMD-like codes
10 runs for BUU-like codes, with N_{TP} = 100

Results of all codes

Response function:

$$\rho_k(\omega) = \int_{t_{in}}^{t_{fin}} dt\, \rho_k(t)\, \cos(\omega(t - t_{in}))$$

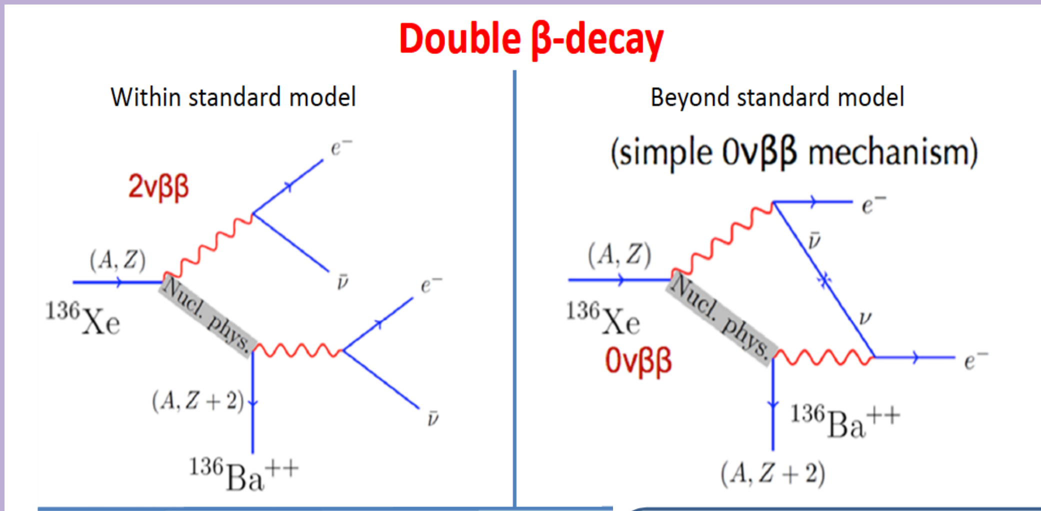


- Differences between **BUU** codes are compatible with different treatment of kinematics and/or mean-field
- **QMD** codes:
  - frequency affected by less repulsive many-body term (can be cured with Lattice method)
  - large damping effects

***M.Colonna et al.*, PRC 104, 024603 (2021)**

Theoretical part of NUMEN project (Resp. M. Colonna)

For *single charge exchange* (**SCE**) Nuclear Reactions are a well tested approach to probe single β decay… MAGNEX at LNS allow to access *double charge exchange* (**DCE**)



$$1/T^{0\nu}_{1/2}(0^+ \to 0^+) = G_{0\nu} \left|M^{\beta\beta 0\nu}\right|^2 \left|\frac{\langle m_\nu \rangle}{m_e}\right|^2$$

Nuclear Matrix Element (NME)!

$$\left|M^{\beta\beta 0\nu}_{\varepsilon}\right|^2 = \left|\left\langle \Psi_f \left| \hat{O}^{\beta\beta 0\nu}_{\varepsilon} \right| \Psi_i \right\rangle\right|^2$$

$$T^{(2)}_{\beta\alpha} = \langle \chi^{(-)}_{\beta} | (b | V_{res} G_c V_{res} | a) | \chi^{(+)}_{\alpha} \rangle =$$

Double

$$= \sum_c \int \frac{d^3k_\gamma}{(2\pi)^3} \langle \chi^{(-)}_{\beta} | (b | V_{res} | c) | \chi^{(+)}_{\gamma} \rangle \cdot \frac{1}{E_\alpha - E_\gamma + i\eta}$$

Single

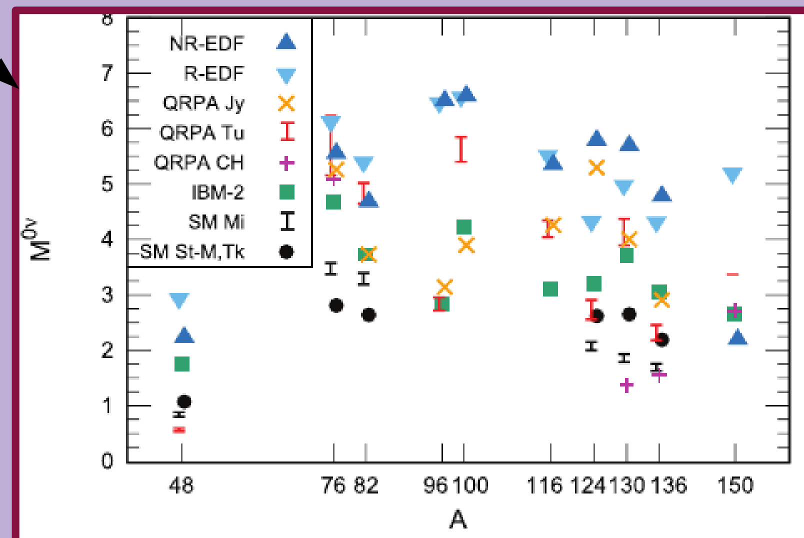
$$\cdot \langle \tilde{\chi}^{(+)}_{\gamma} | (c | V_{res} | a) | \chi^{(+)}_{\alpha} \rangle)$$

Single

① Modellizzazione meccanismo di reazione per **SCE / DCE fattorizzazione anche in AA**

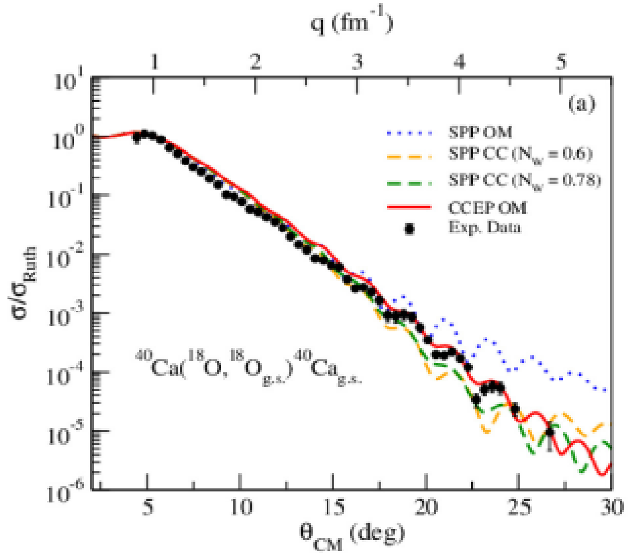
② Doppio scambio come convoluzione di 2 processi singoli => link with Double-beta decay

③ *Modelli struttura nucleare per meccanismi SCE/DCE*

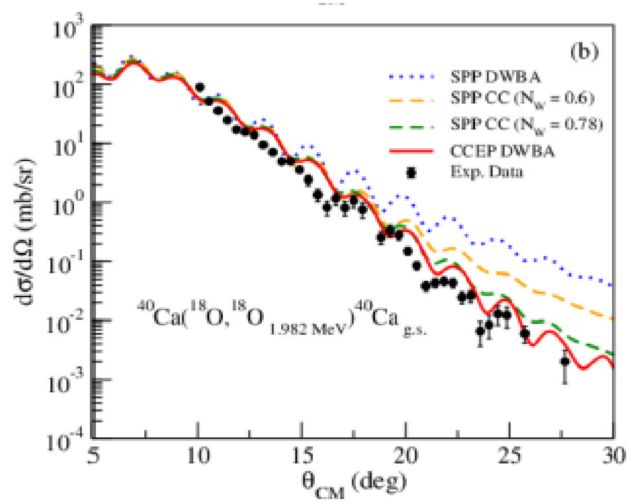


$^{40}Ca(^{18}O,^{18}F)^{40}K$

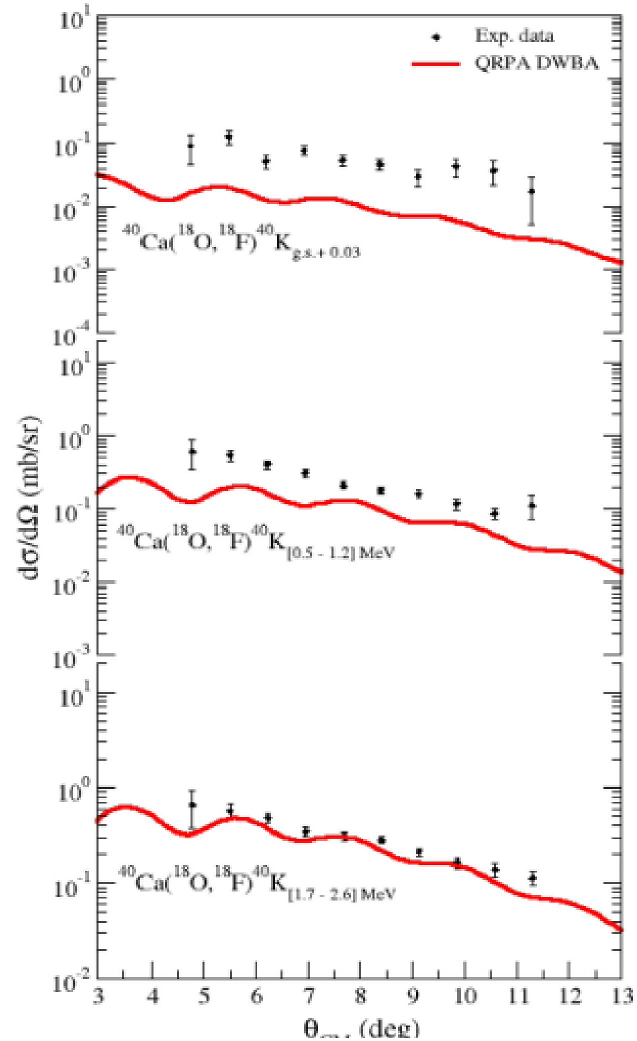
A Constrained Analysis of the $^{40}Ca(^{18}O,^{18}F)^{40}K$ Direct Charge Exchange Reaction Mechanism at 275 MeV, M. Cavallaro et al. Frontiers in Aston. And Space Sci. 8, 659815 (2021)



elastic



inelastic



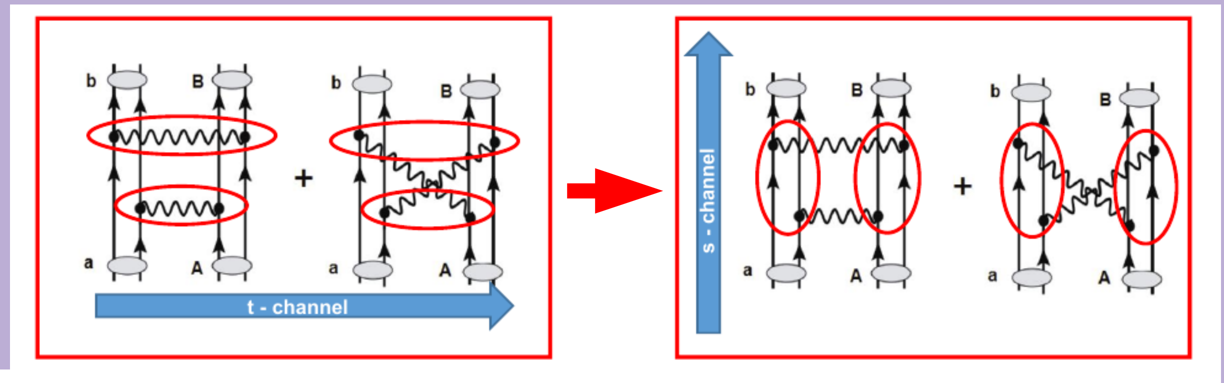
SCE

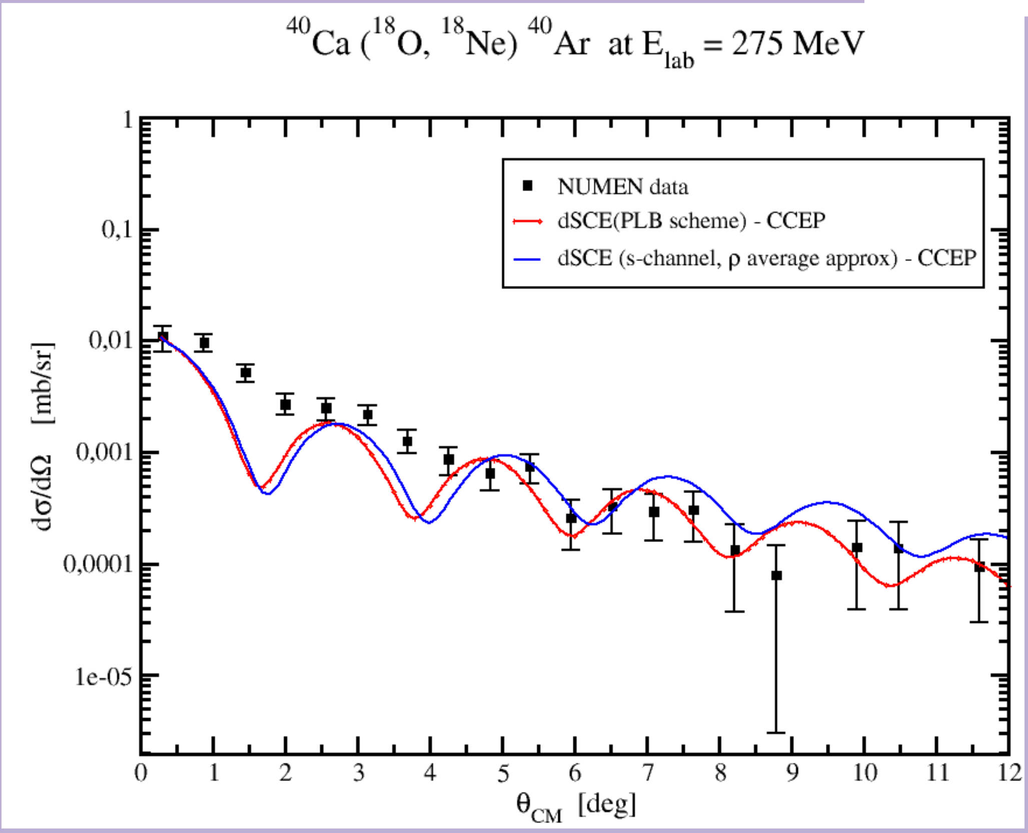
good agreement

➢ DSCE Cross Section - $^{40}Ca(^{18}O,^{18}Ne_{g.s.})^{40}Ar_{g.s.}$

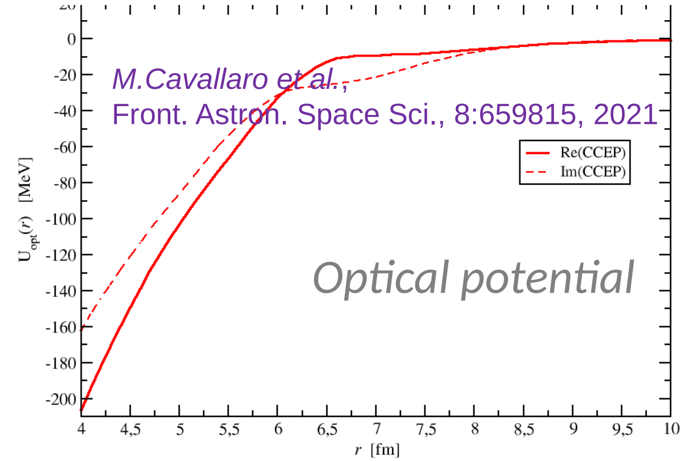
H. Lenske, J.I. Bellone, M. Colonna, D. Gambacurta, **Universe 7 (2021) 4, 98**

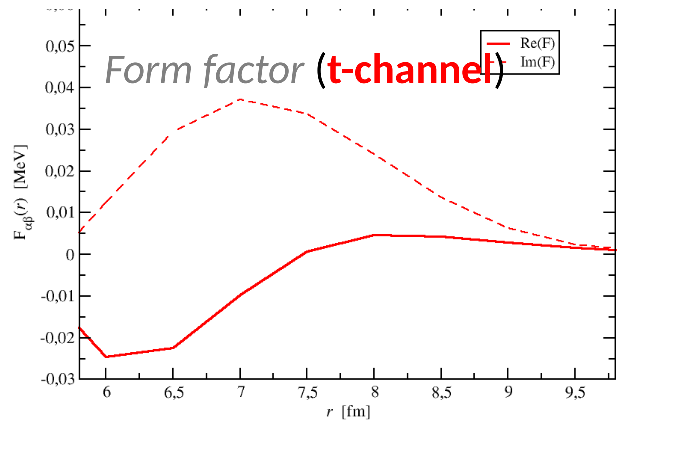
J.I.Bellone et al., **PLB 807 (2020) 135528**





s-channel (approx)

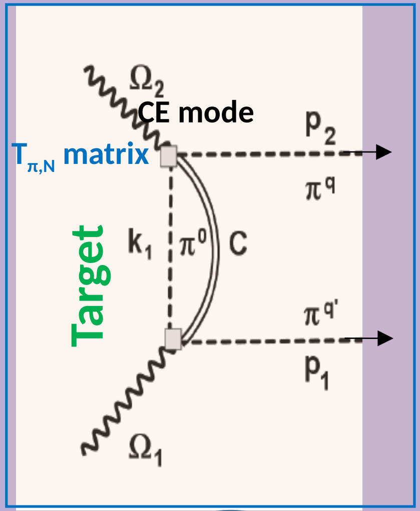


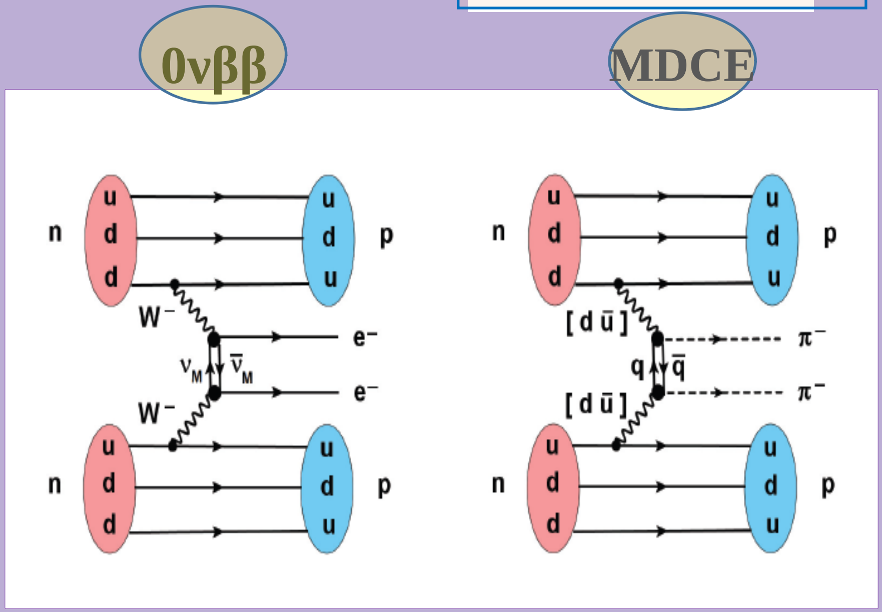


DCE reactions by double meson exchange: MDCE

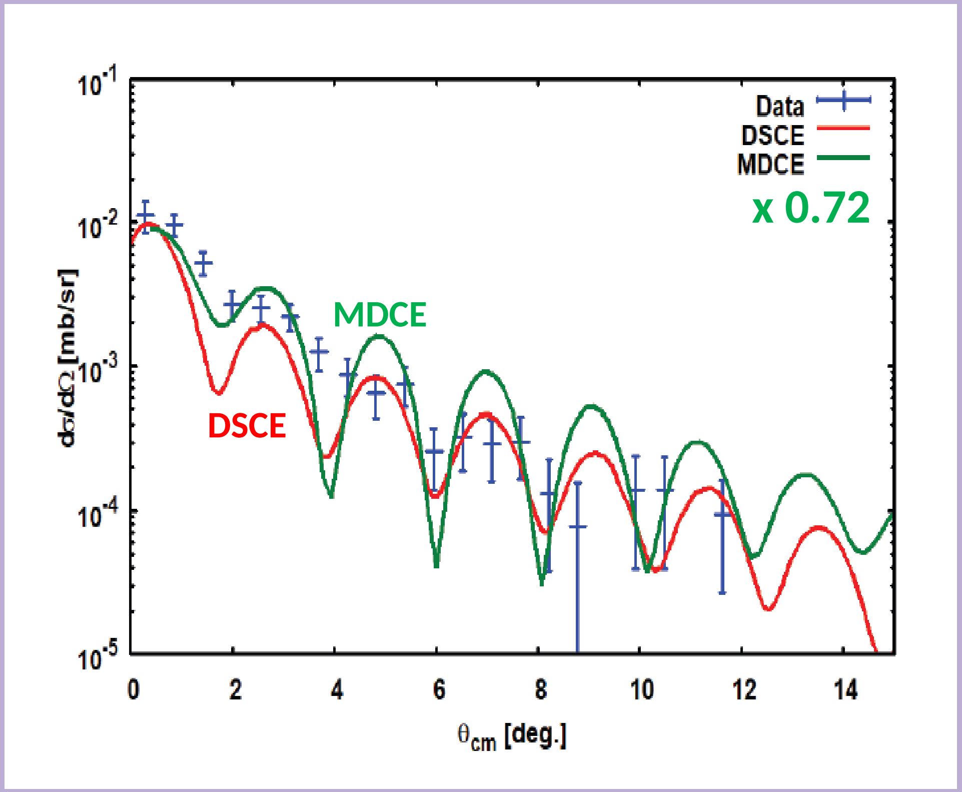
- Analogies with 0νββ matrix elements
  ▭ Majorana-like DCE (MDCE)

H. Lenske et al., Progr. in Part. and Nucl. Phys. 109 (2019) 103716
F. Cappuzzello, *H.Lenske et al.*, PPNP (2022), submitted





- **MDCE** differential cross section
  (*diagonal s-wave and p-wave* $T_{\pi,N}$ *contributions in* NMEs)



$^{40}Ca(^{18}O,^{18}Ne_{g.s.})^{40}Ar_{g.s.}$ @ 15 MeV/u

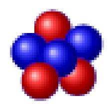
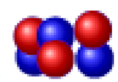
DWBA reaction calculations for light systems for astrophysics studies

Goal

Study the influence of ground-state ("static") structure on the reaction dynamics in a fully quantum framework.

- Explicit evaluation of the cross-section in terms of the properties and interactions of reactants.
- No adjusting on reaction experimental data.

Study of ${}^6\mathrm{Li} + \mathrm{p} \to \alpha + {}^3\mathrm{He}$ transfer, focus on ${}^6\mathrm{Li}$ structure.

- Two-cluster models: $|{}^6\mathrm{Li}$  $\rangle = |\alpha\, \mathrm{d}$  $\rangle$

Process dominated by quantum tunnelling of the Coulomb barrier.

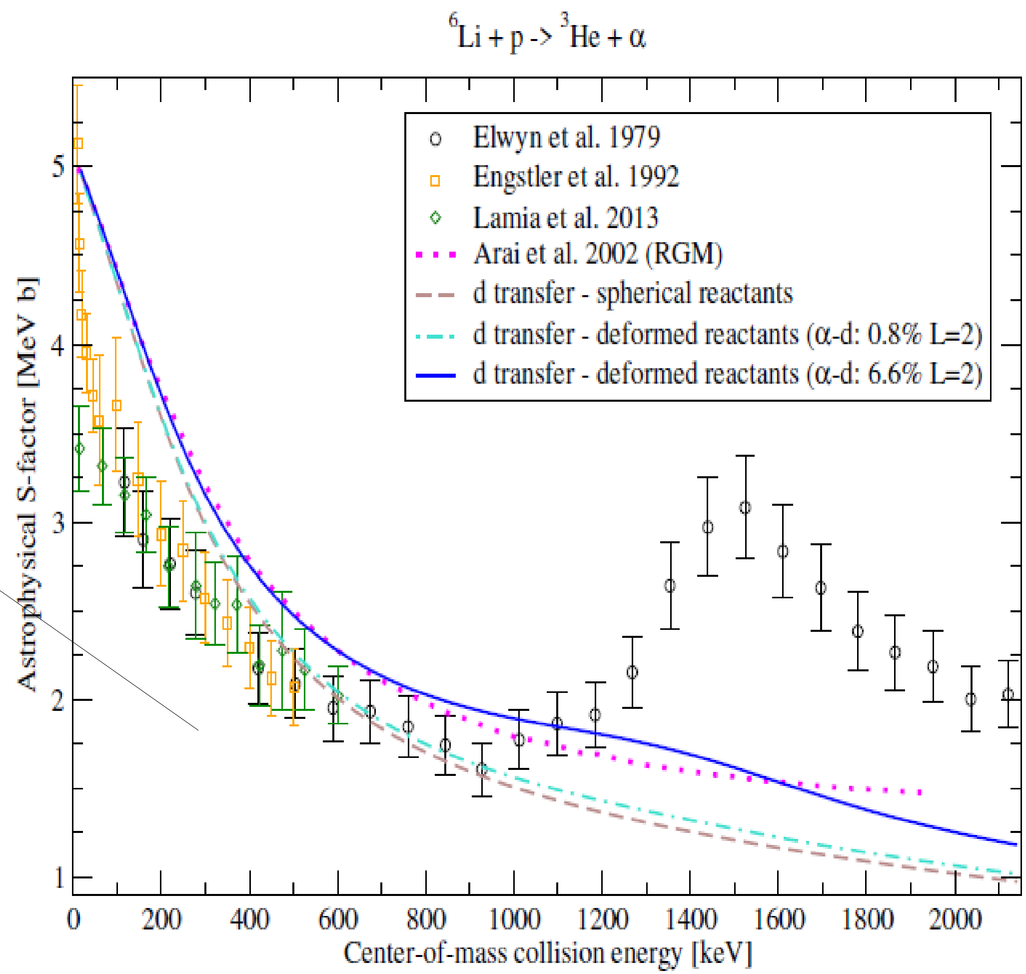
Astrophysical S-factor:

$$S(E) = E\, e^{2\pi\eta(E)}\sigma(E) \quad , \quad \eta(E) = \alpha_e Z_1 Z_2 \sqrt{\frac{\mu c^2}{2E}}$$

(σ angle-integrated cross-section, E center-of-mass collision energy,
Z_i reactants charge number, α_e fine-structure constant,
μ reactants reduced mass, c speed of light).

$^6Li + p \rightarrow {}^3He + \alpha$: deuteron transfer

Models usually underestimate
The low-energy part which
Is important for astrophysical studies



Brown dashed line: point-like d transfer, α−d motion in $L = 0$

Blue solid line: point-like d transfer, 6.6 % of $L = 2$ in α−d motion

S. Perrotta, M. Colonna and J.A. Lay in preparation

PHYSICAL REVIEW C **105**, 034325 (2022)

Proton-neutron pairing and binding energies of nuclei close to the $N = Z$ line

D. Negrea and N. Sandulescu*
National Institute of Physics and Nuclear Engineering, 077125 Măgurele, Romania

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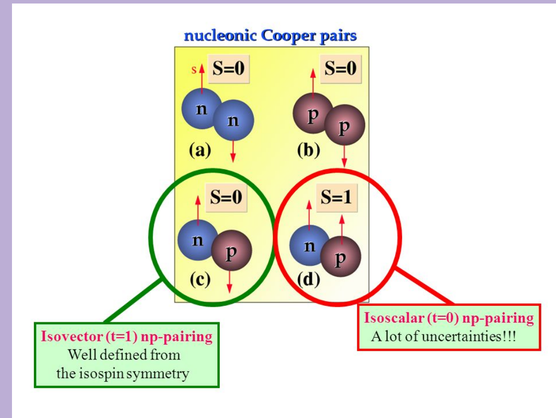
INFN-LNS, Laboratori Nazionali del Sud, 95123 Catania, Italy

(Received 1 November 2021; accepted 18 February 2022; published 23 March 2022)



- pp and nn pairing is well understood (BCS)
- p-n pairing not clear and very much studied both th. and exp.

- BCS description fails!!!
- We developed a new approach to treat all the pairing channels consistently
- Quartet Condensate Model (QCM) preserves particle and isospin symmetries
- Skyrme HF plus QCM calculations along all the nuclear chart 20<A<100, including deformation
- Better agreement with data than HF plus BCS

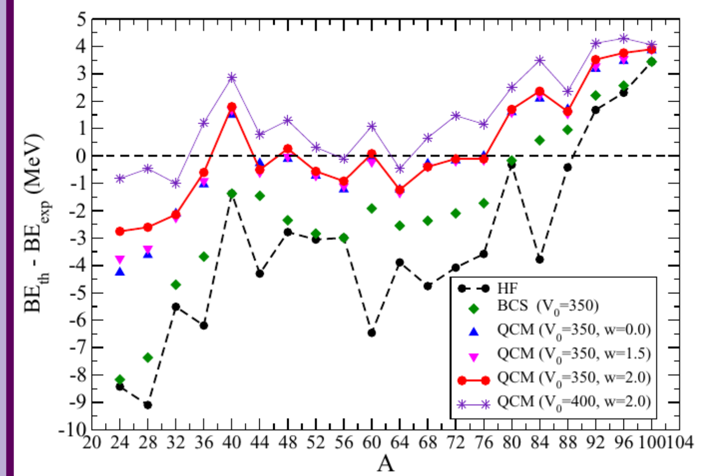
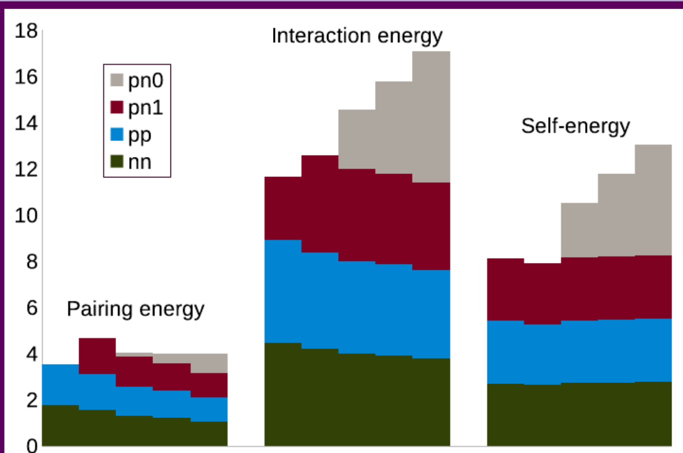


FIG. 1. Binding-energy residuals, in MeV, for even-even $N = Z$ nuclei as a function of $A = N + Z$. The results correspond to the pairing forces and the approximations indicated in the figure.

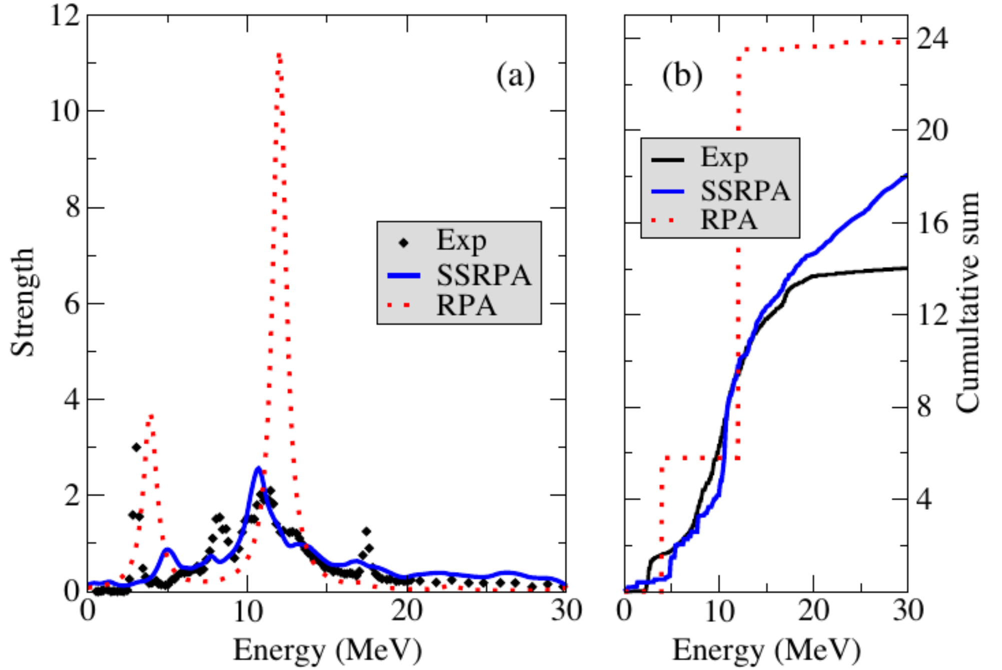


- Isovector and isoscalar p-n pairing coexist but the isoscalar one is typically much weaker
- Next step: QCM in pair or alpha transfer

PHYSICAL REVIEW LETTERS 125, 212501 (2020)

Gamow-Teller Strength in ^{48}Ca and ^{78}Ni with the Charge-Exchange Subtracted Second Random-Phase Approximation

D. Gambacurta,[1] M. Grasso,[2] and J. Engel[3]



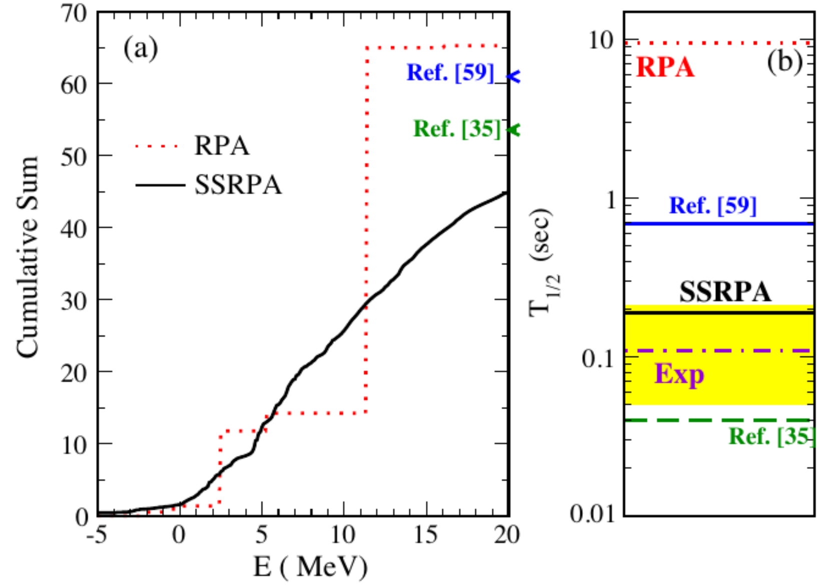


FIG. 4. (a) Cumulative sum for different models (see legend and text) for the nucleus ^{78}Ni; (b) β-decay half-life for ^{78}Ni predicted by SSRPA, compared with predictions of other models and the experimental value [58]. The yellow band represents the experimental uncertainty.

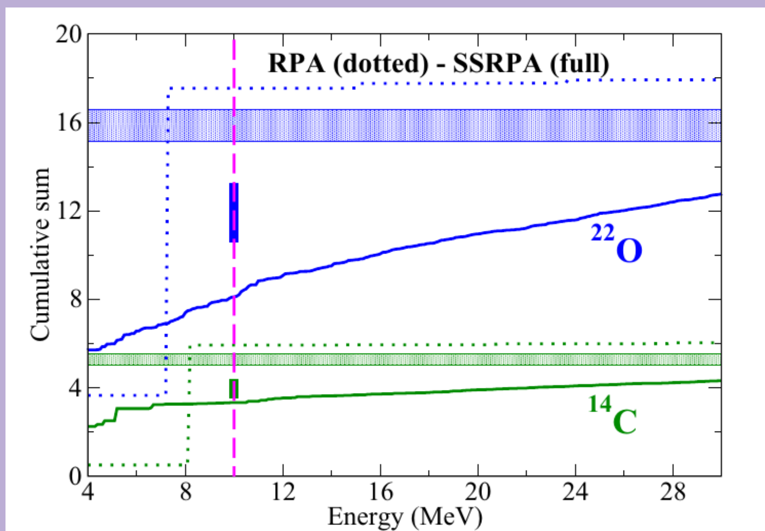
- Extension to treat **Charge Exchange Excitations**
- **Open problem**: Models need quenching factor (~0.7) to reproduce data
- First application where **2p2h configurations** are introduced (together with 1p1h)
- Agreement with data **without *ad hoc*** quenching factor

PHYSICAL REVIEW C **105**, 014321 (2022)

Quenching of Gamow-Teller strengths and two-particle–two-hole configurations

Danilo Gambacurta[1] and Marcella Grasso[2]
[1]INFN-LNS, Laboratori Nazionali del Sud, 95123 Catania, Italy
[2]Université Paris-Saclay, CNRS/IN2P3, IJCLab, 91405 Orsay, France

Comparison with *Ab initio* results including two body currents



Calculations for heavy nuclei: 90Zr and 132Sn

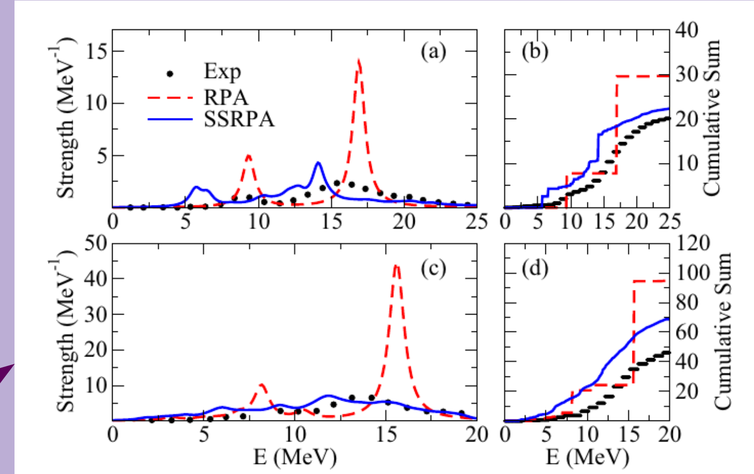


FIG. 6. (a) GT$^-$ SSRPA and RPA folded spectra obtained with the Skyrme interaction SGII for the nucleus ^{90}Zr. The experimental results Ref. [28] are also shown. (b) Strengths of panel (a) integrated up to 25 MeV. (c) Same as in (a) but for the nucleus ^{132}Sn. The experimental results are extracted from Ref. [29]. (d) Strengths of panel (c) integrated up to 20 MeV.

Quality of approximated schemes for future studies

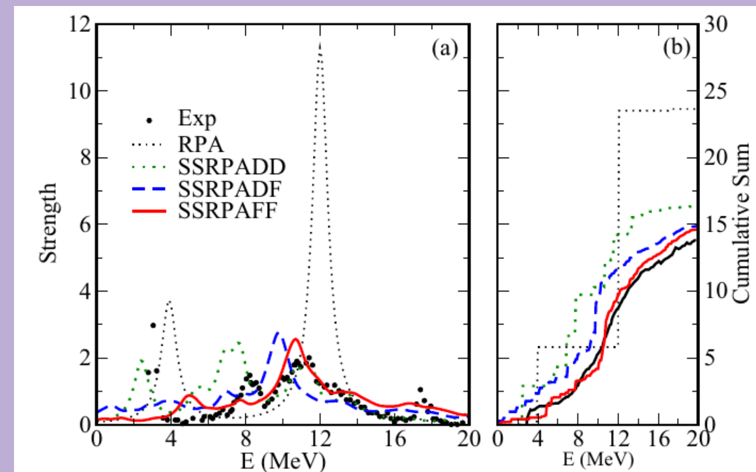


FIG. 1. (a) GT$^-$ strengths obtained with the Skyrme interaction SGII for the nucleus ^{48}Ca in MeV^{-1}. Experimental data are extracted from Ref. [7]. RPA and all SSRPA strengths are obtained by folding with a Lorentzian having a width of 1 MeV. (b) Cumulative sum of the strength up to the excitation energy of 20 MeV. See text for more details.

- Implications for NME in **neutrino-less double-β decay** and **NUMEN project**

Thank you

Nuclear Structure: Main Physical Cases of Interest

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- ✓ ***EoS of asymmetric matter*** *(symmetry energy, ...)*
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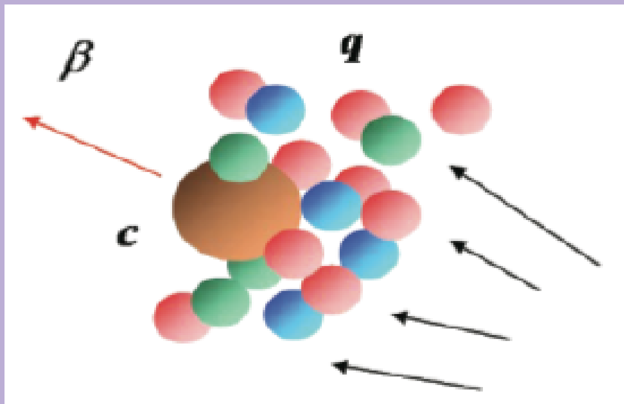
- ✓ ***Impact of Eos on nuclear reactions***
- ✓ ***Double Charge Excitations*** *and the connection to double beta decay*
- ✓ ***Reactions of astrophysics interest*** *(light systems, cluster structures)*

Gruppo IV - LNS

- Stefano Burrello — Ricercatore INFN (dal 1.11.2022)
- Colonna Maria — Dirigente di Ricerca [20% in CS3]
- Gambacurta Danilo — Primo ricercatore Ricercatore [20% in CS3]
- Greco Vincenzo — Professore Ordinario (Inc. Ric.) [10% in CS2]
- Salvatore Plumari — Prof. Associato, UniCT
- Vincenzo Minissale — Assegnista di Ricerca
- Jessica Bellone — Assegnista di Ricerca NURE
- Simone Perrotta — Assegnista di Ricerca
- Maria Lucia Sambataro — Assegnista di Ricerca UnicT
- Angelo Asta — Dottorando II anno
- Adriele Arena — Laureando (laurea 15 Luglio 2022)
- Vincenzo Nugara — Laureando (Ottobre 2022)

FTE INFN: ~10

An elephant in the liquid: Heavy Charm Quark



QGP composto al 99% da g e q=u,d,s, $\mathbf{m_q \approx 10\ MeV}$

+ qualche Charm Quarks: $\mathbf{M_c \approx 1400\ MeV}$

→ Poorly dragged & long thermalization time (!?)

$$\tau_{C,therm} \approx O(10^2) >> \tau_{QGP} >> \tau_{q,therm} \approx O(1)\ \text{fm/c}$$

Moto Browniano

$$\frac{\partial f_{c,b}}{\partial t} = \Gamma \frac{\partial (p f_{c,b})}{\partial p} + D_p \frac{\partial^2 f_{c,b}}{\partial p^2}$$

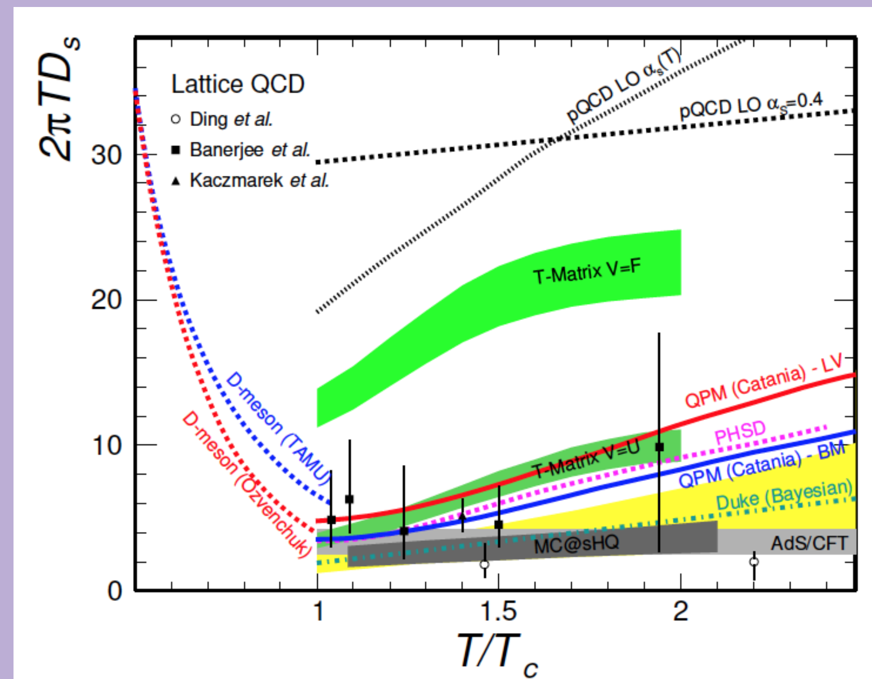
Drag Diffusion

Tempo di termalizzazione
e coefficiente Diffusione

$$\tau_{th} = \frac{M}{2\pi T^2}(2\pi T D_s) \cong 1.8\,\frac{2\pi T D_s}{(T/T_c)^2}\ \text{fm/c}$$

$\Gamma_{coll} \approx D_s^{-1} \approx 0.5\text{-}1\ \text{GeV} \approx M_{q,g}(T)$

barely quasi-particle states

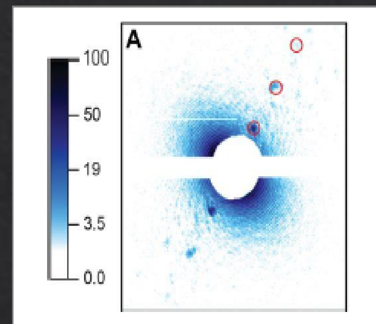


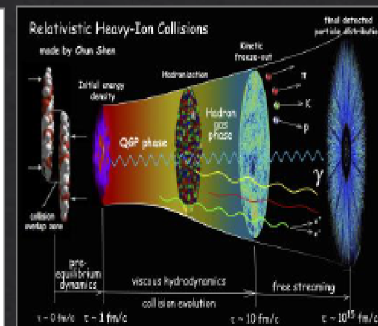
Not a model fit to lQCD data!

Phenomenology ≈ lattice QCD

Strong fields in relativistic nuclear collisions

✓ HUGE ANGULAR MOMENTUM GENERATING A STRONG VORTICITY





vorticity ω

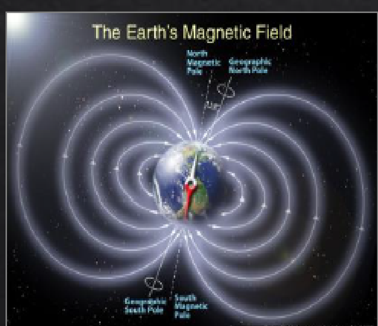
tornado cores $\sim 10^{-1}\ s^{-1}$

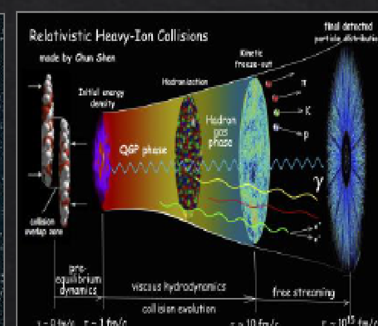
Jupiter's spot $\sim 10^{-4}\ s^{-1}$

He nanodroplets $\sim 10^{7}\ s^{-1}$

urHICs $\sim 10^{22}$–$10^{23}\ s^{-1}$

✓ INTENSE ELECTROMAGNETIC FIELDS (EMF)





magnetic field B

Earth's field ~ 1 G

laboratory $\sim 10^{6}$ G

magnetars $\sim 10^{14}$–10^{15} G

urHICs $\sim 10^{18}$–10^{19} G