Nuclear Matter,
Phase transitions and Clustering

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Les grandes questions en Physique nucléaire fondamentale
Journées SFP-BTN, 21 - 22 Juin 2016

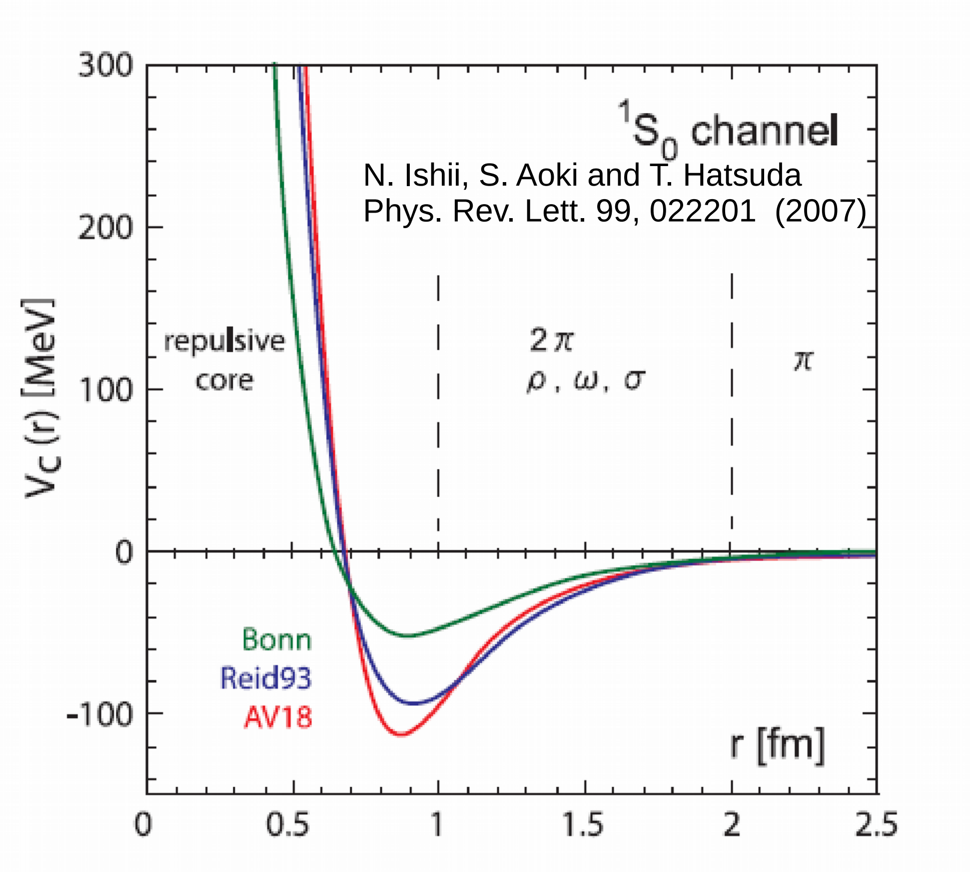
Equation of state

of

Nuclear matter

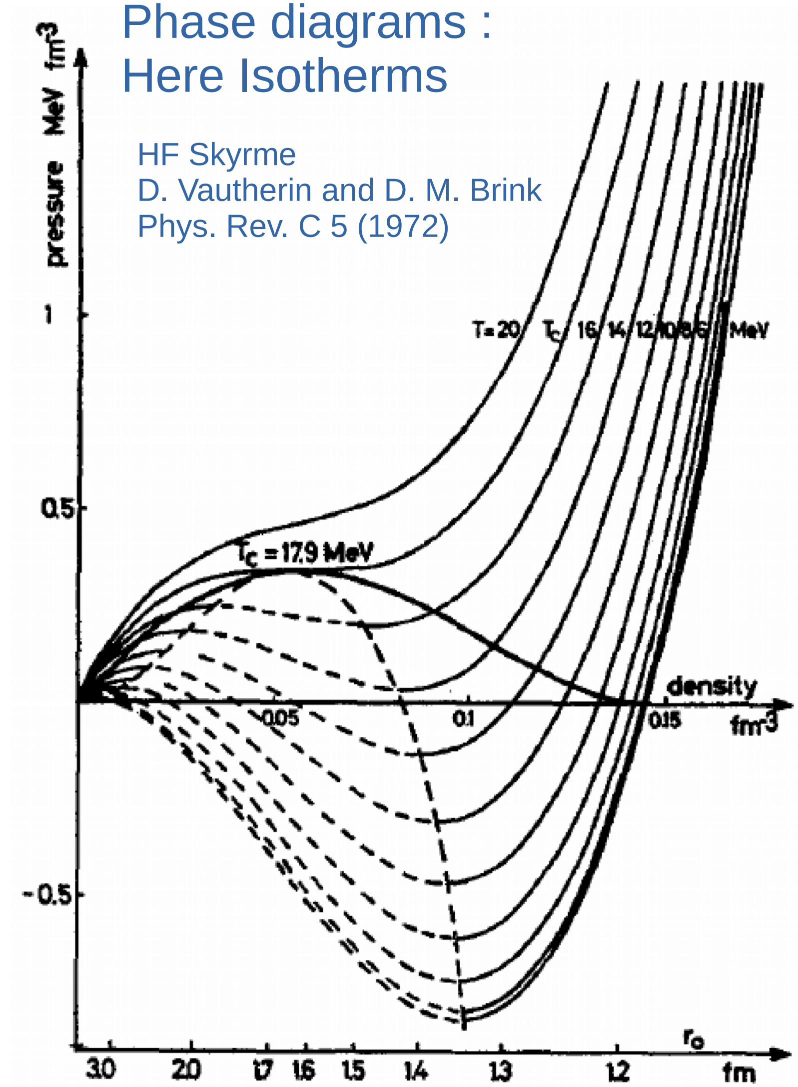
Nuclear Equation of State

Analogy between the nuclear interaction and van der Waals interaction in fluids



Phase diagrams :
Here Isotherms

HF Skyrme
D. Vautherin and D. M. Brink
Phys. Rev. C 5 (1972)



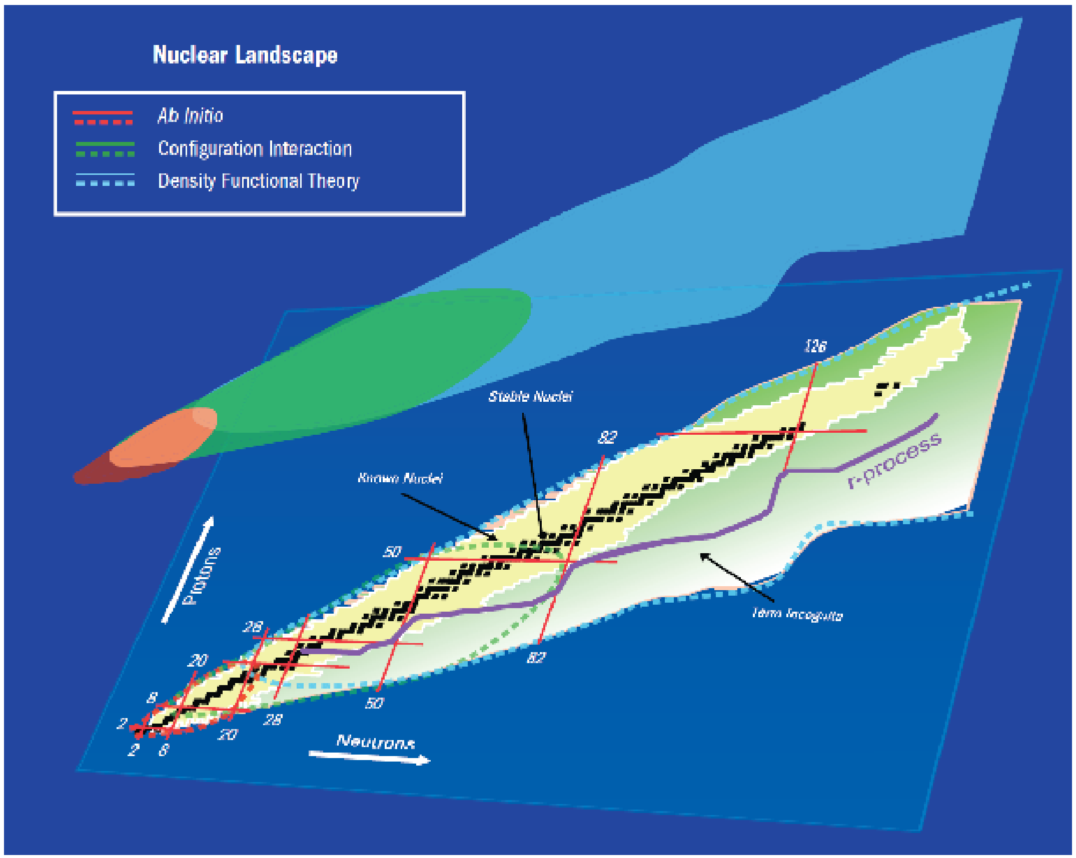
→ **Liquid**, **gas** and **supercritical** phases exist

→ LG **Coexistence** (1st order), critical **température** (2nd order)

→ Zone for **Mechanical Instabilities** (density fluctuations) : **spinodal zone**

Microscopic Description of Nuclei

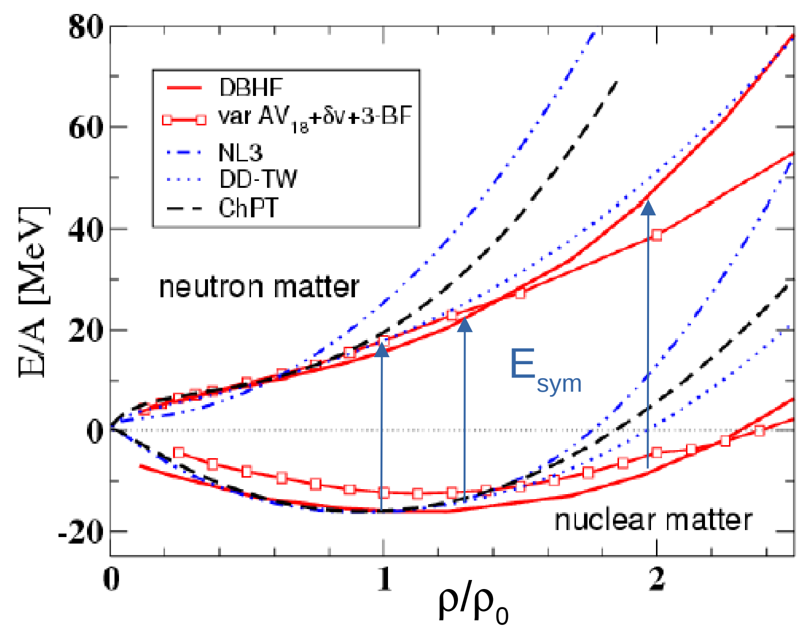
Self-consistent Mean-Field calculations are probably the only possible framework to understand the structure of medium and heavy nuclei.



$$E = \langle \psi \mid H \mid \psi \rangle$$
$$H = \langle \varphi \mid H_{eff} \mid \varphi \rangle$$

$$\boldsymbol{H = E[\rho]}$$

Energy-Density Functionals



Direct link to *EOS* and Symmetry Energy

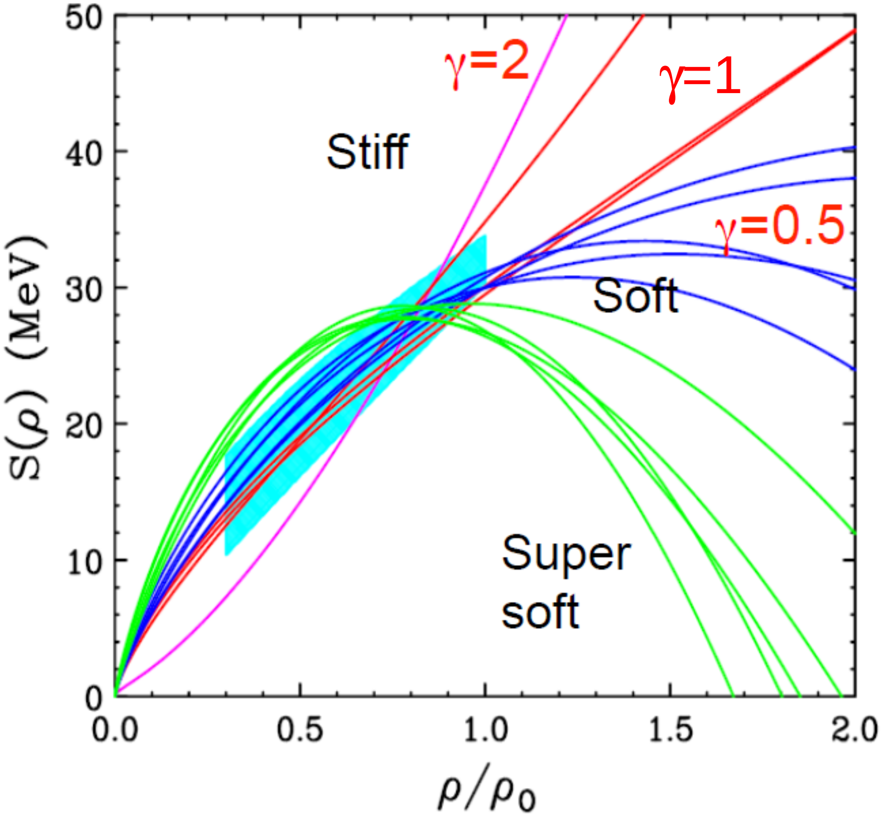
Symmetry Energy (at low density)

$$E/A(\rho,\delta) = E/A(\rho,0) + \delta^2 \cdot S(\rho)$$

$$\delta = (\rho_n - \rho_p)/(\rho_n + \rho_p) = (N-Z)/A$$

- Constraints for **Astrophysics** (NS) and for laboratory experiments
- Needed for **transport models** and nuclear matter studies (Thermodyn.)
- Link to the ***NN* interaction** (isovector) in the nuclear medium

M.B. Tsang, Prog. Part.Nucl.Phys. 66, 400 (2011)
Brown, Phys. Rev. Lett. 85, 5296 (2001)



$$S(\rho) = S_k(\rho/\rho_0)^{2/3} + S_i(\rho/\rho_0)^{\gamma}$$

Density dependence for SE

EOS : connection with nuclei

$$E = f(\rho, T, \delta)$$

Astrophysical context (NS)

Nuclear matter :
Bulk properties

Extensive systems
(volume)

Symmetric NM
or pure neutron matter
(δ=0,1)

Terrestrian Labs (HIC)

Nuclei :
Finite-size effects

Non-extensive systems
(surface, Coulomb)

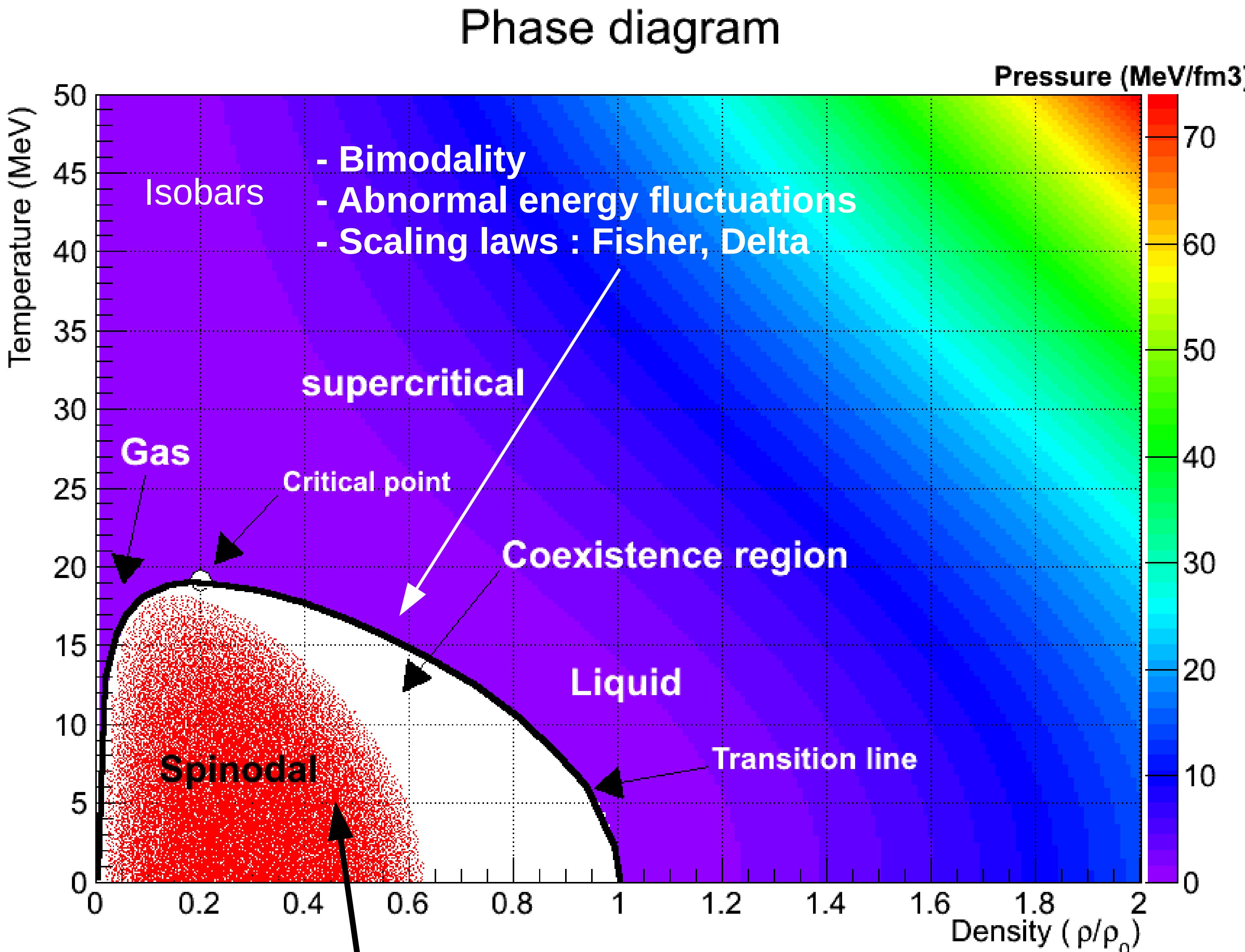
Asymetric NM
($|\delta|$~0-0.5, E_{sym})

Phase Diagram and **Phase Transitions** for **strongly correlated finite-sized** systems **: (non)-extensivity and quantality**

Thermodynamics :

Phase transitions
in nuclei

Phases and Transitions



Dynamical origin of **multifragmentation** as a **spinodal decomposition**...

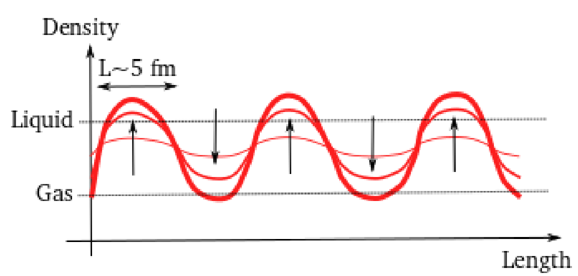
Charge correlation : spinodal decomposition ?

Intra-event correlation :

$$\Delta Z = \frac{1}{M}\Sigma_i^M (Z_i - \langle Z \rangle)$$

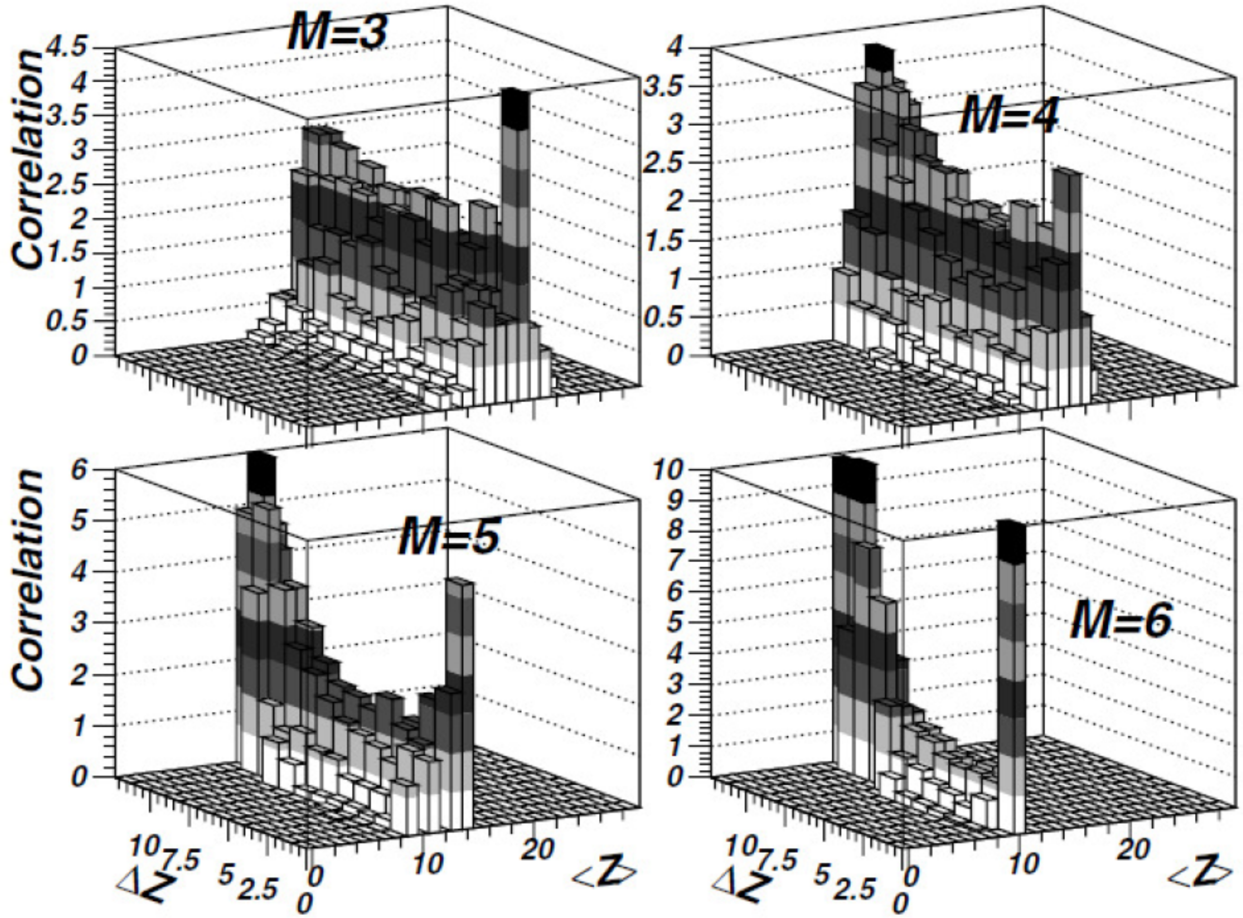
Correlation Function :

$$R(\Delta Z) = \frac{Y(\Delta Z)}{Y'(\Delta Z)}$$



Wavelengthes $L\sim10$ fm are favoured => overproduction of fragments with size $L/2$, thus around $A\sim20\text{-}30$

Xe + Sn *32A MeV*



B. Borderie, *et al.* (INDRA coll.)
Phys. Rev. Lett. 86, R217 (2001)

- Signal is weak (fossile) → more statistics is needed !
- Mass and *N/Z* dependence ?

Dynamics :

Diffusion and Transport properties

Theoretical background on transport properties

- Mean-Field effects : **1-body dissipation** → **viscosity/friction**
  Collective properties : **nuclear** degrees of freedom (Mean-Field)

- *NN* collisions : **2-body dissipation** → $\lambda_{NN}^{*}, \sigma_{NN}^{*}$
  Individual properties : **nucleonic** degrees of freedom (collisions)

- **Transition** in incident energy should be observed where
  MF weakens and *NN* collisions become more and more likely → $E_t \approx E_{Fermi}$

- **In-medium effects** for *NN* collisions :

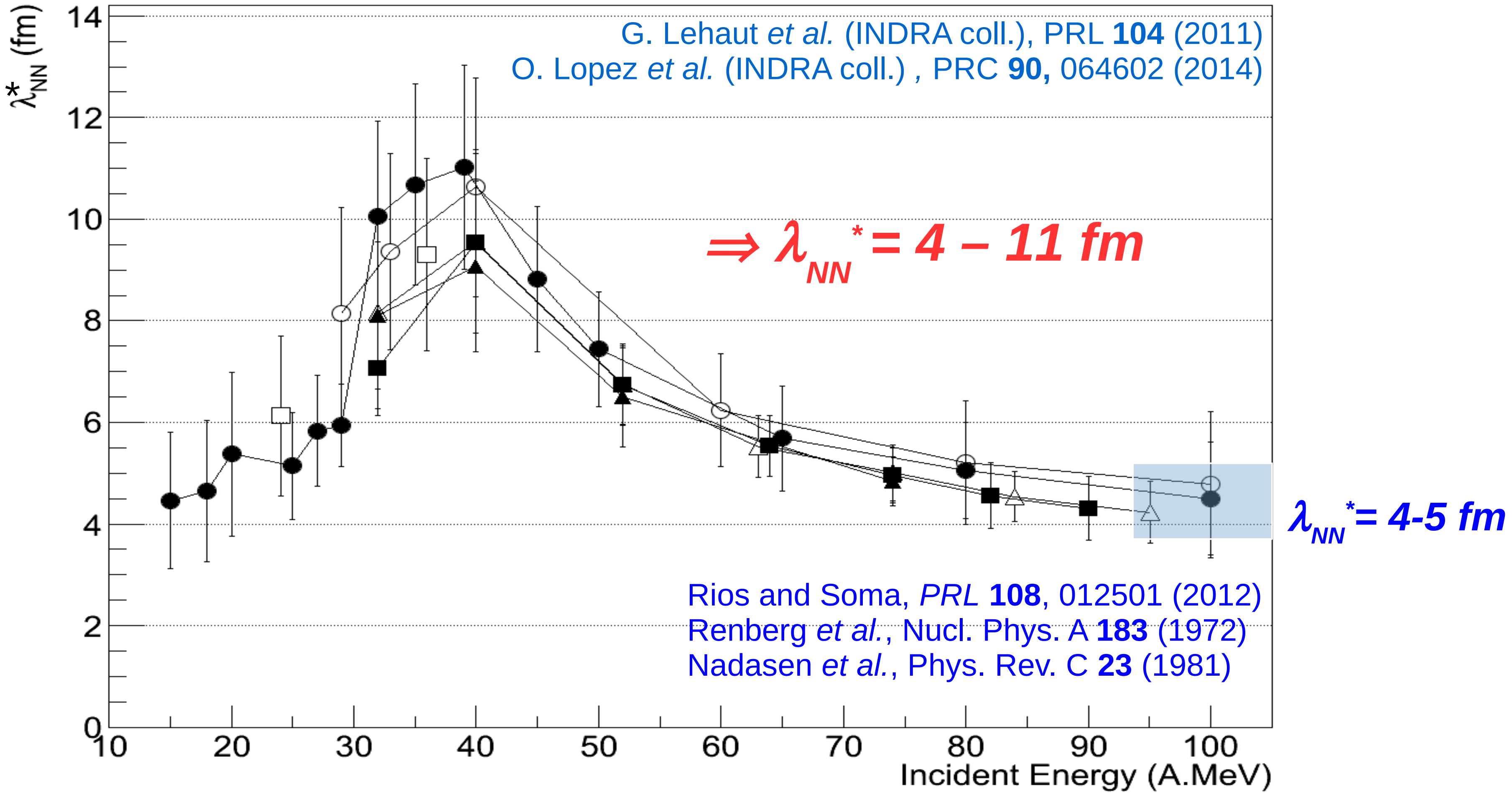
  - **Renormalization** of σ_{NN} as compared to vacuum: **quenching factor**
  - Due to **Pauli blocking** (2-body) but also to **higher-order correlations** (density effects *via* many-body correlations).

Mean free path (rather) constrained both theoretically and experimentally above $E_{inc}/A>100$ *MeV* : λ_{NN} = 4-5 *fm* but not below…

Experimental probe is the stopping : transparency/translucency

Nucleon mean free path in nuclear medium

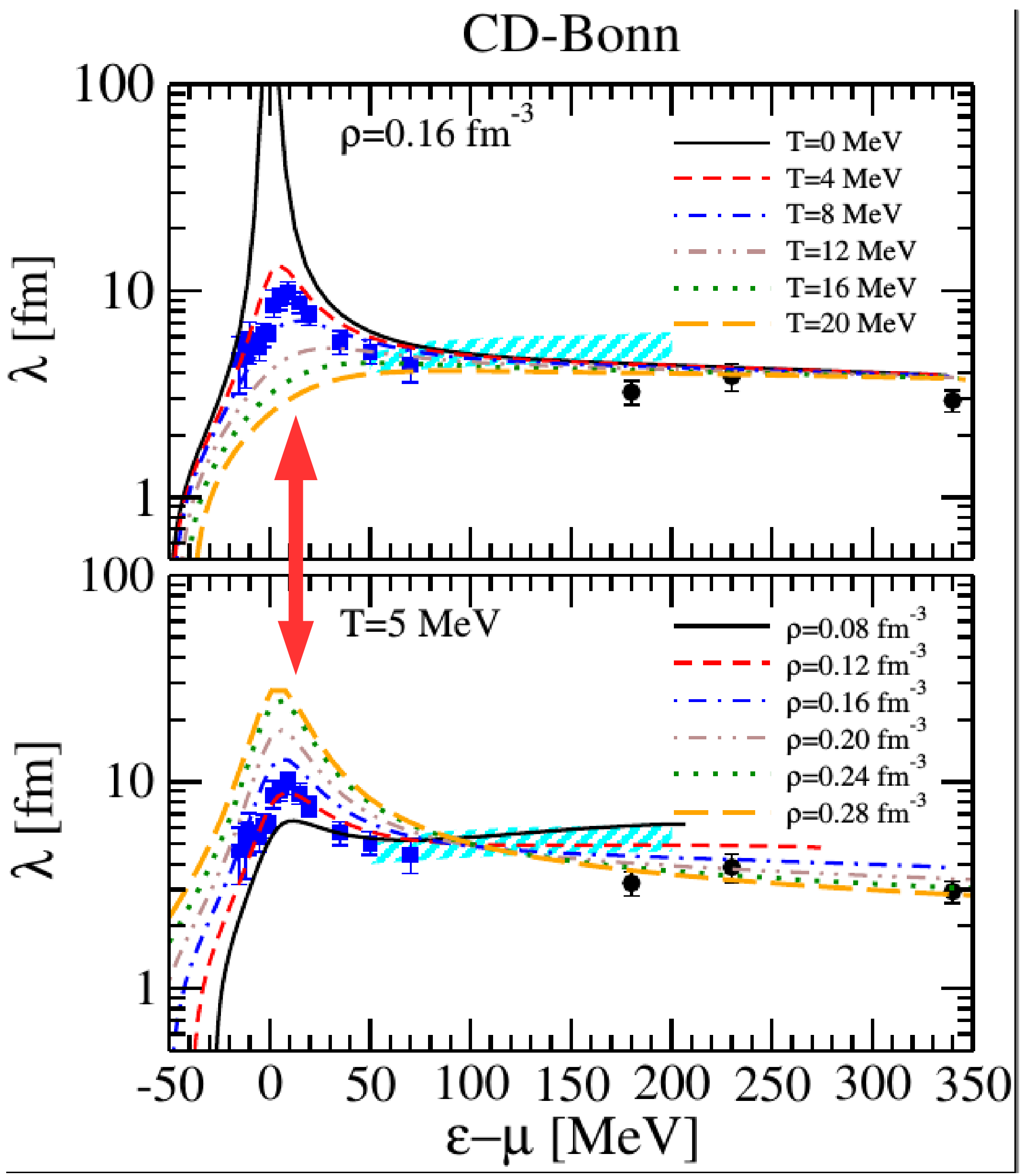
- For the first time : **experimental systematics** in the Fermi energy domain



- $\lambda_{NN} \geq R$ **: complete stopping and thermalization not achieved...**
  J. Su and F.S. Zhang, PRC 87, 017602 (2013) [AMD]

- **Contradictory findings** with *SMF* by E. Bonnet, *et al.*, PRC 89, 034608 (2014)

Mean free path in microscopic theories



QFT-SCGF + CD-Bonn int.
A. Rios and V. Soma, *PRL* **108**, 012501 (2012)

- Calculations at $\rho=\rho_0$ for different temperatures

T= 4-8 MeV

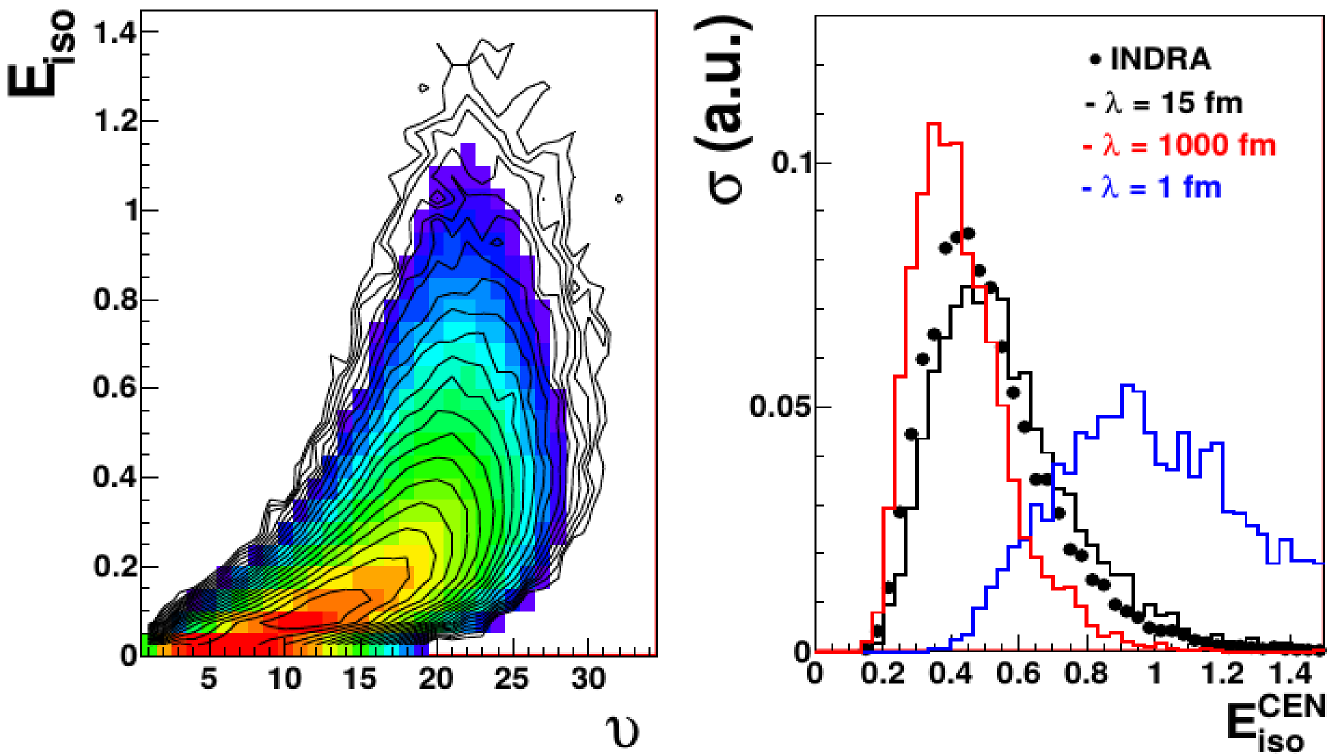
- Calculations at ***T=5 MeV*** for different densities

$\boldsymbol{\rho = 0.8\text{-}1.2\ \rho_0}$

Enhanced sensitivity for $E \approx E_{Fermi}$

Mean free path and thermalization process

INDRA data / ELIE model (micro/macro) for the isotropy ratio : *^{58}Ni+^{58}Ni @ 40A MeV*



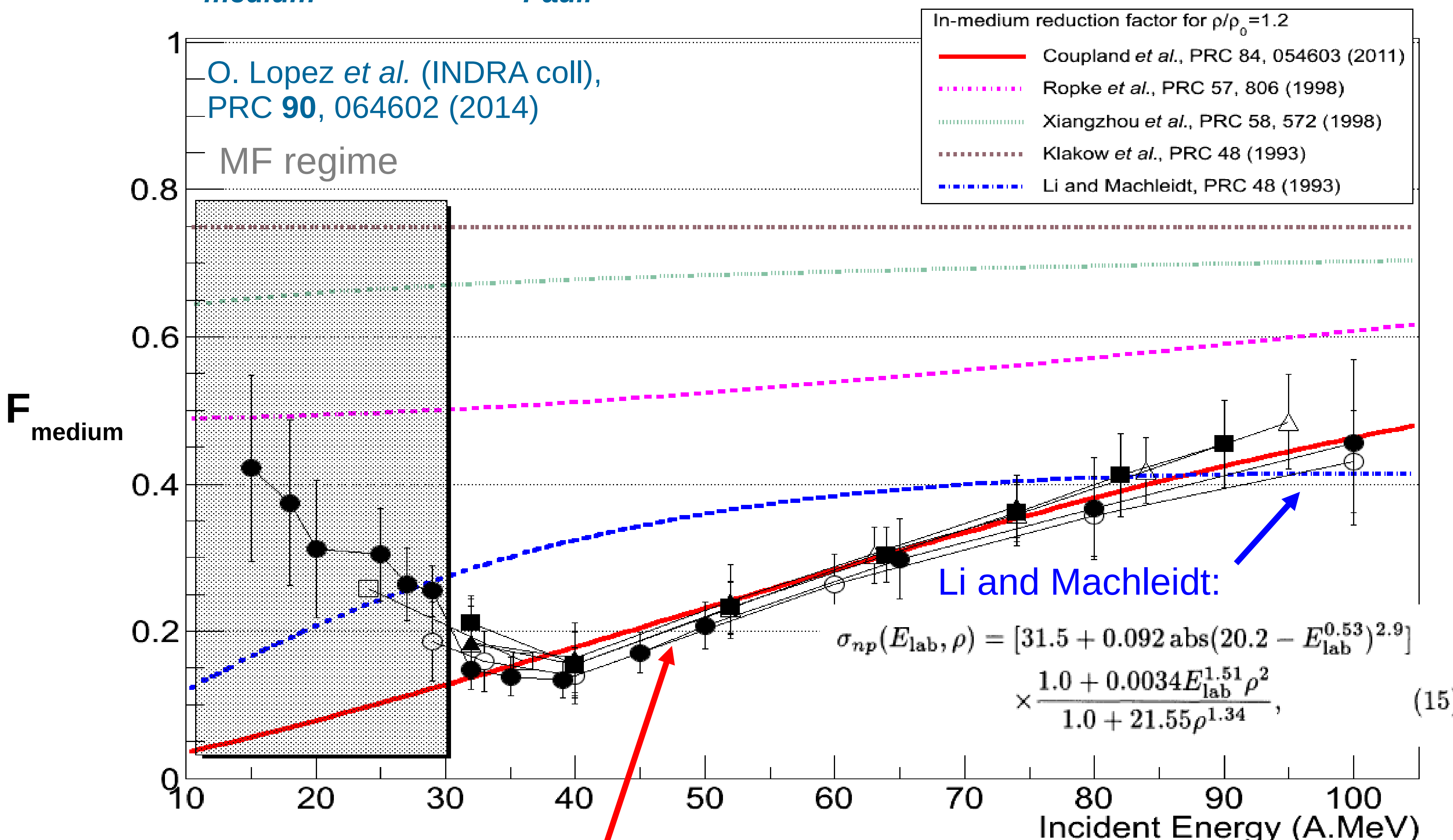
λ : mean free path for *NN* collisions in the participant zone

→ *E_{iso}* is compatible with ***λ=10-15 fm*** *(≥Rproj+Rtarg) at E_{Fermi},*

This suggests that **complete thermalization** is not achieved since the number of collisions per participant is less than 1… →What about **Isospin diffusion ?**

In-medium effects : renormalization (quenching) factor in nuclear medium

$$F_{medium} = \sigma_{NN}^{*}/(P_{Pauli} \cdot \sigma_{NN}^{free})$$

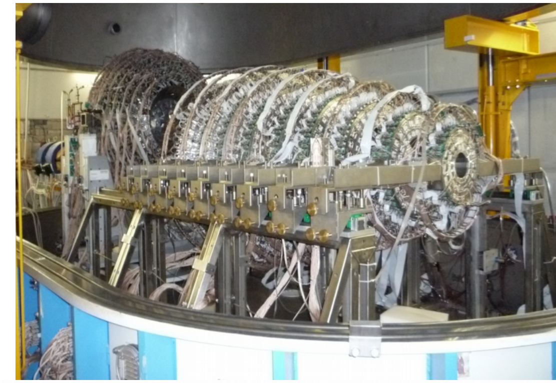


Danielewicz (phenomenologic !): $F = \sigma_0 \tanh(\sigma_{free}/\sigma_0)$**, with** $\sigma_0(mb) = 8.5/\rho^{2/3}$

Clustering in Nuclei

Clustering in α-conjugate nuclei

CHIMERA :
$^{40}Ca + ^{12}C$ @ 25A MeV



Excited ^{16}O, ^{20}Ne, ^{24}Mg for projectile fragmentation of ^{40}Ca

- ***<E*> ≈ 3.4 MeV/nucleon***
- ***$\rho = 0.7\rho_0$***

Constrained RHB

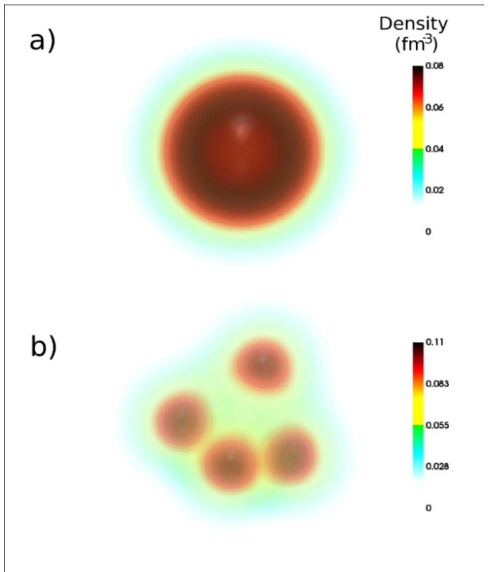
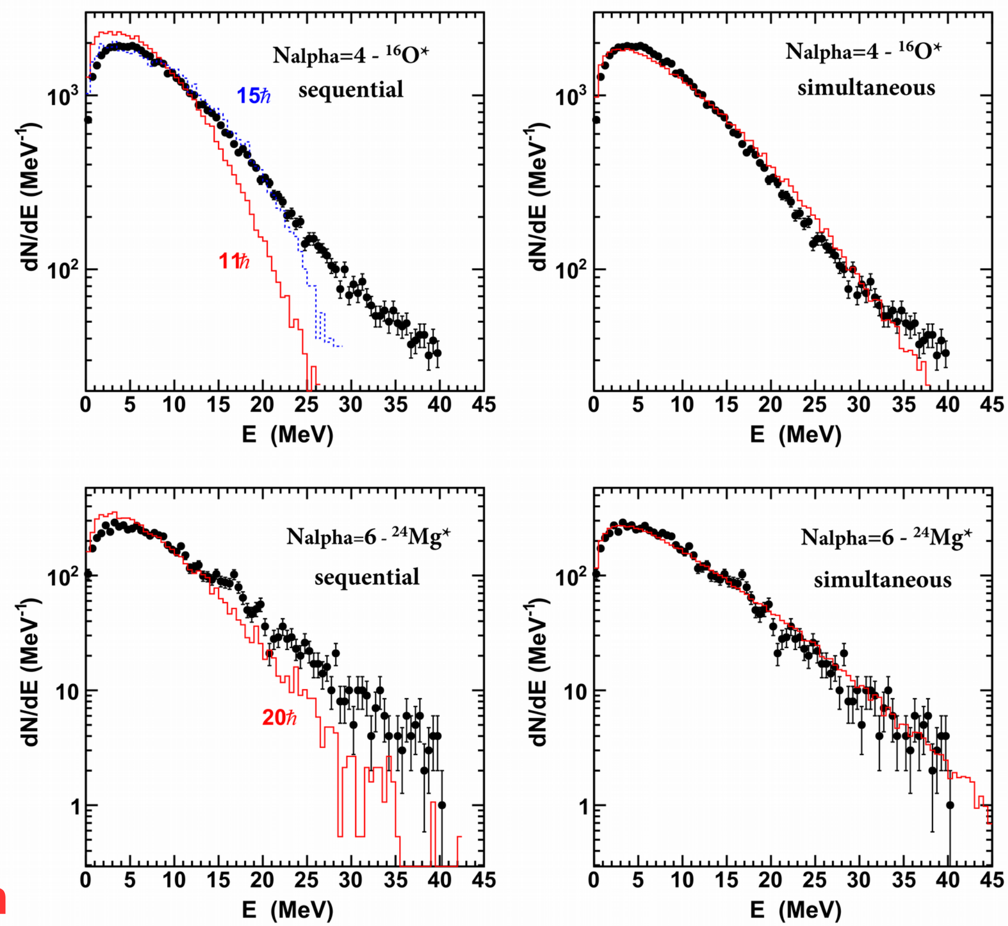


FIG. 3: (Color online) Self-consistent intrinsic nucleon density of ^{16}O for a radius constrained to 3.32 fm (a) and 3.34 fm (b).

J.-P. Ebran, E. Khan *et al.*, PRC 89 031303(R) 2014

B. Borderie et al. / Physics Letters B 755 (2016) 475–480

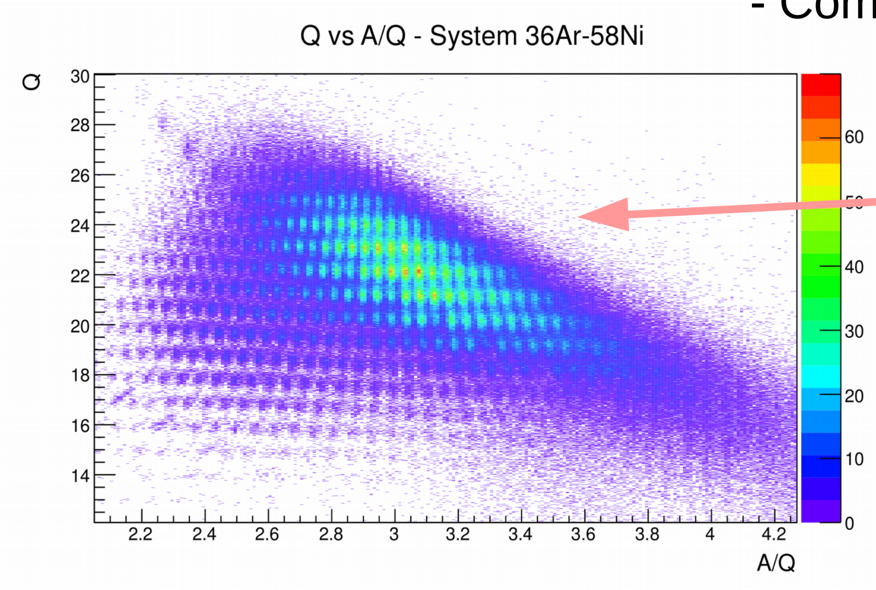


- Data agrees with a **simultaneous emission**
- Competition between **DD** (Nα) and **SD (^{8}Be)**

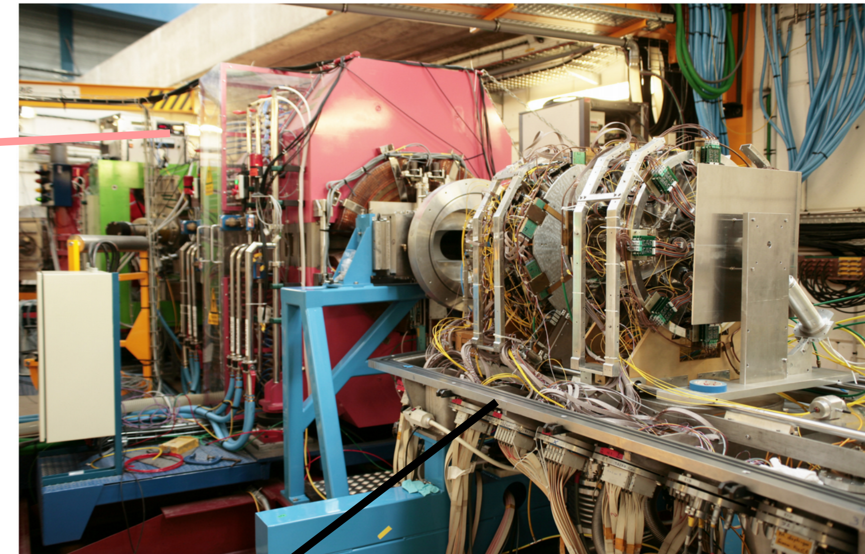
B. Borderie, AD.R. Raduta, G. Ademard, M.F. Rivet *et al.*, PLB 755 (2016)

INDRA – VAMOS coupling@ GANIL

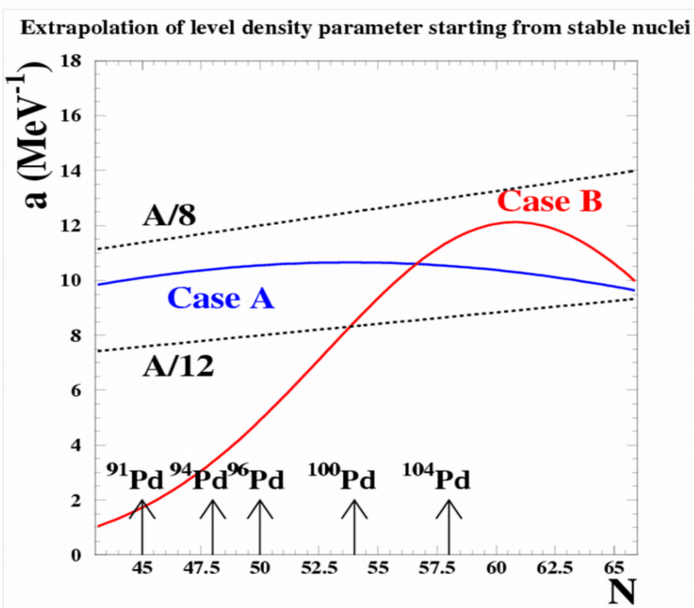
- 3 beams : ^{34}Ar, ^{36}Ar, ^{40}Ar @ 12.7-13.5 MeV/nucleon
- 3 targets : ^{58}Ni, ^{60}Ni, ^{64}Ni
- Complete Fusion (9 isotopes) : ^{92}Pd - ^{104}Pd



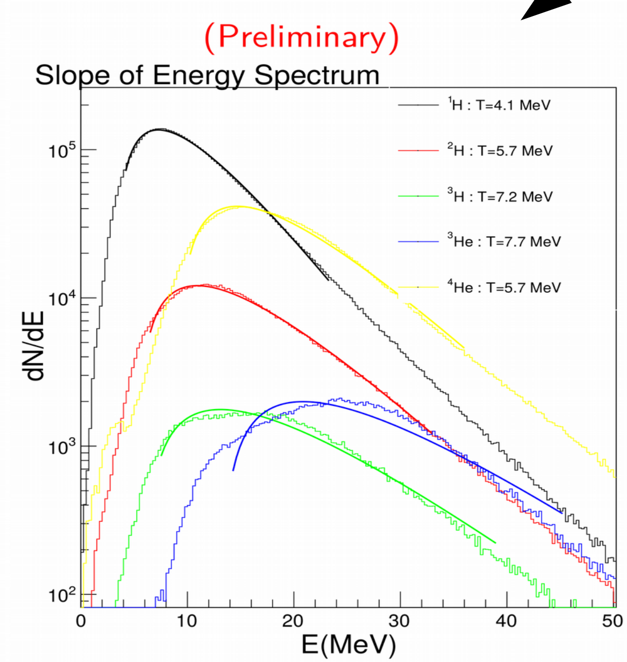
VAMOS



INDRA



extrapolation according to :
R.J. Charity Phys. Rev. C67-044611(2003)
S.I. Al-Quraishi Phys. Rev. C63-065803(2001)

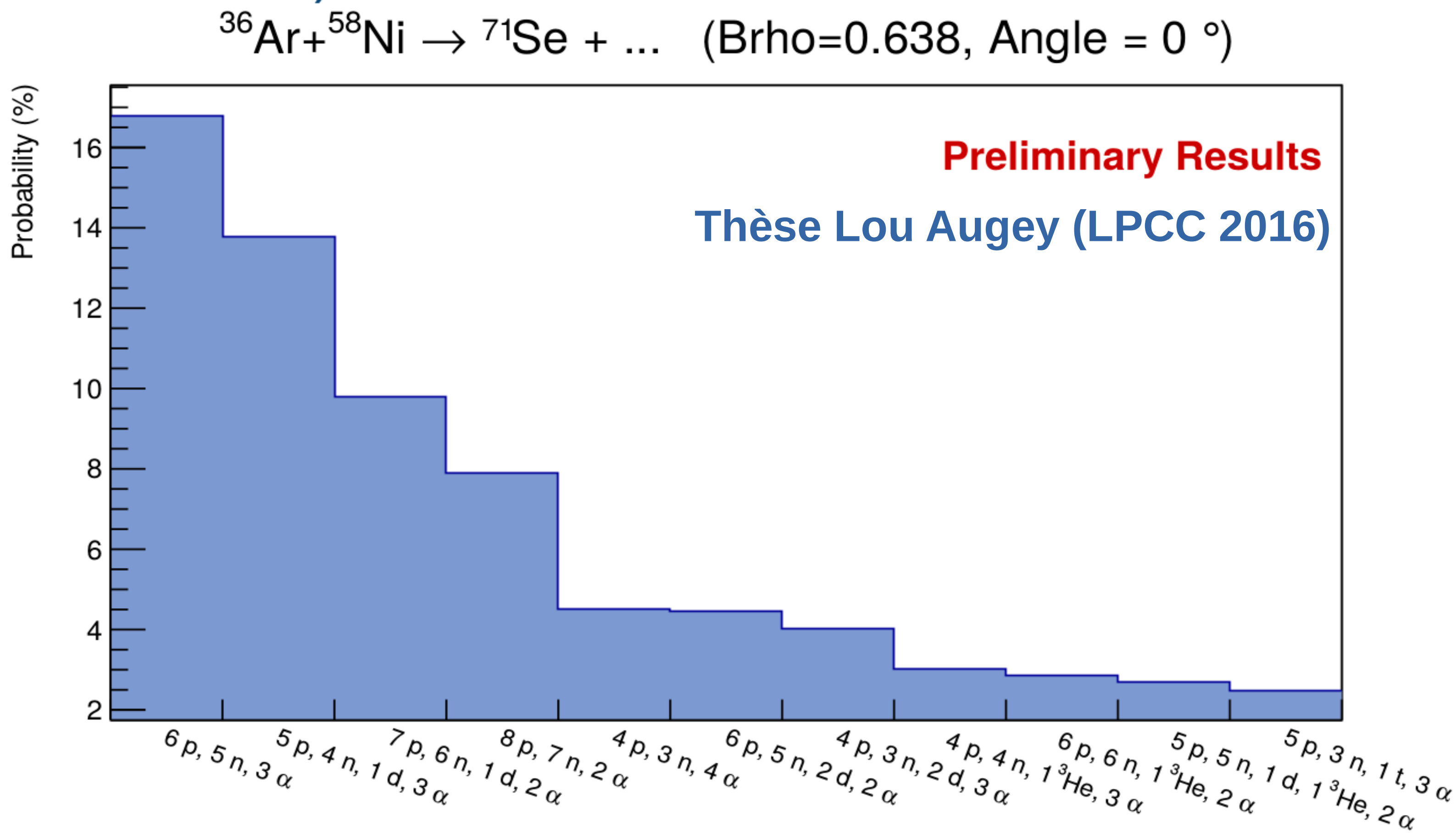


N/Z dependence for ***a*** in *p*-rich nuclei :

$E^* = aT^2$

A stringent Benchmark for Statistical Models

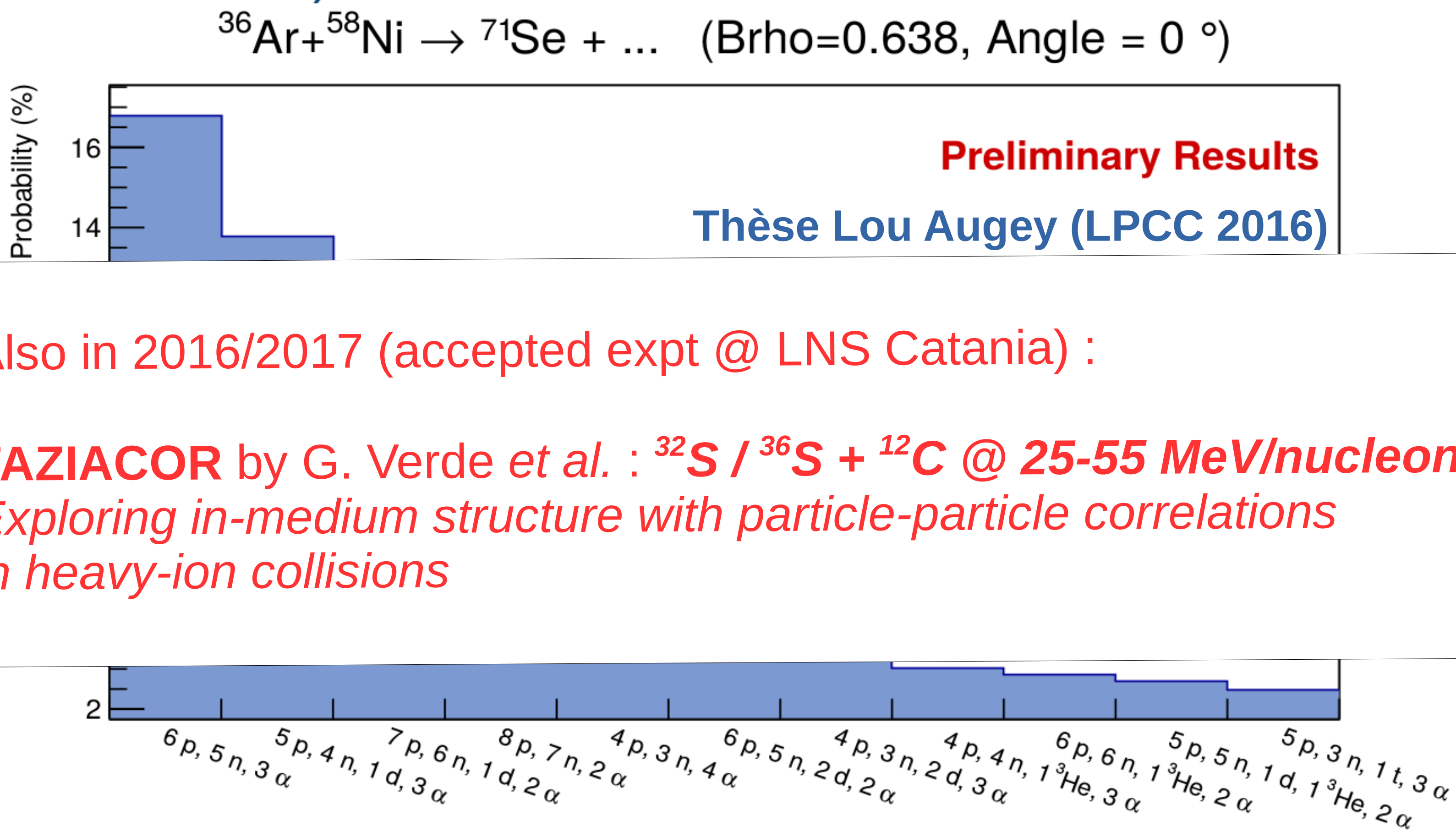
Preliminary Results : Evaporation-channels for $^{71}_{34}Se$ ($^{36}Ar +^{58} Ni$)



- Determination of all evaporation channel (± 1 charge,± 1 mass)
  → Impose strong constraints for statistical models
  → Possibility to observe angular correlation between particles

A stringent Benchmark for Statistical Models

Preliminary Results : Evaporation-channels for $^{71}_{34}Se$ ($^{36}Ar +^{58} Ni$)



Also in 2016/2017 (accepted expt @ LNS Catania) :

FAZIACOR by G. Verde *et al.* : ***^{32}S / ^{36}S + ^{12}C @ 25-55 MeV/nucleon***
Exploring in-medium structure with particle-particle correlations in heavy-ion collisions

- Determination of all evaporation channel (± 1 charge, ± 1 mass)
  → Impose strong constraints for statistical models
  → Possibility to observe angular correlation between particles

Experimental program :

Mid-term : 10 years

Coupling INDRA and FAZIA

LoI GANIL 2014
Stable beams CSS2

Isospin dep. of **multifragmentation**, radial flow and isospin **diffusion/migration**

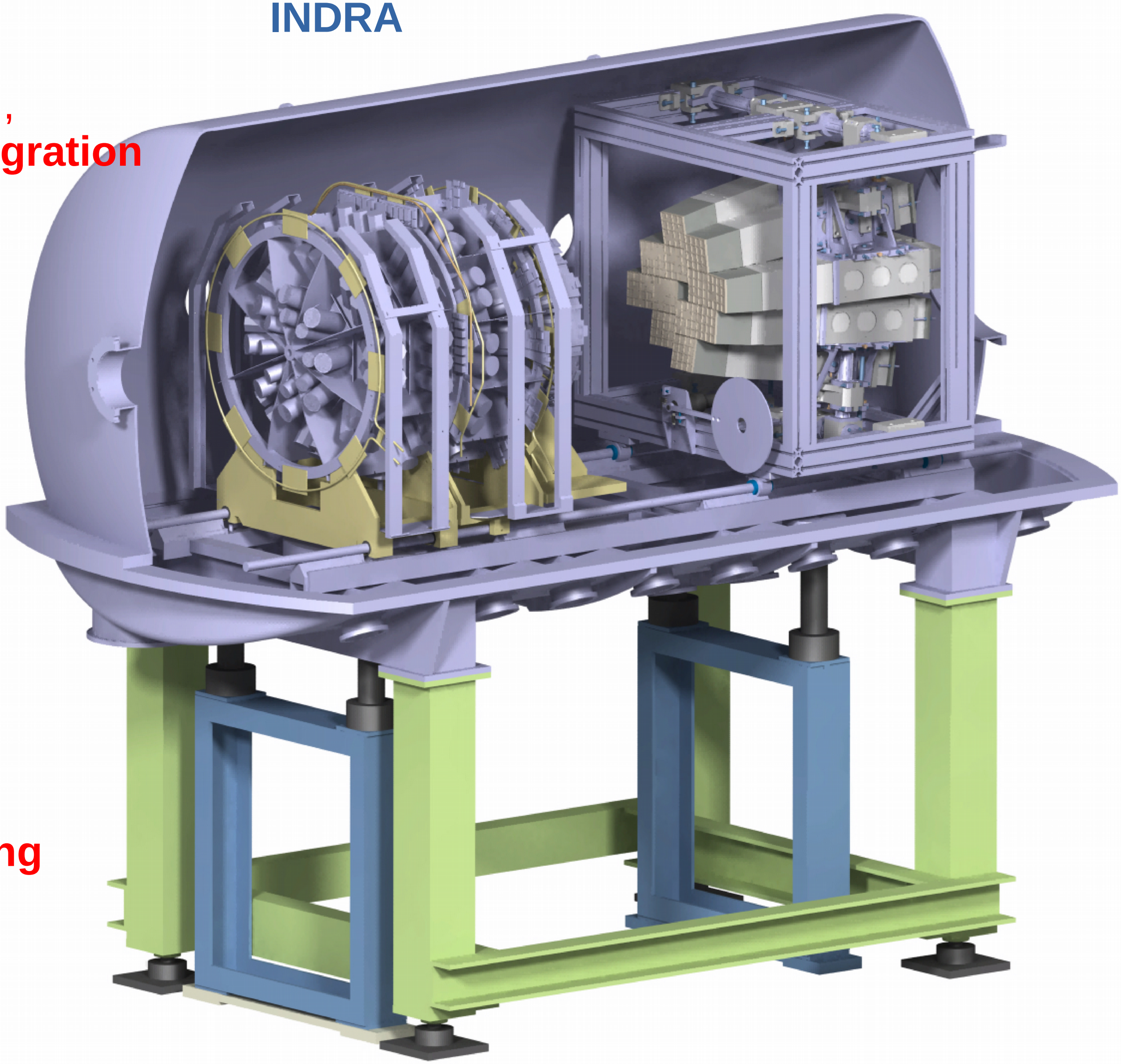
^{124,136}Xe+^{40,48}Ca *30A-50A MeV*

Vaporization @ low density
Isoscaling A_{max}

^{40,48}Ca + ^{40,48}Ca *35A-80A* MeV

Staggering (pairing) QP, **clustering**

^{80,86}Kr + ^{40,48}Ca *35A MeV*



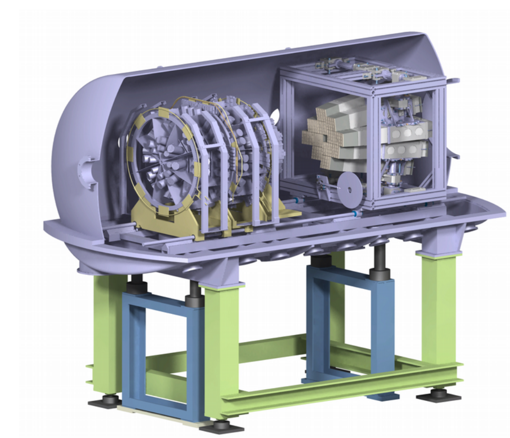
INDRA-FAZIA : 2020+ @SPIRAL2

LoI SP2 : a large "panoplie" of *n*-rich and *p*-rich beams is necessary with bombarding energies above the Coulomb barrier and up to the maximum SPIRAL2 possibilities.

- **Limiting temperatures** in hot N/Z asymmetric nuclear systems
- **N/Z dependence** of **nuclear level densities** in warm nuclei
- **Clustering** studies and validity of **statistical theories**
- Studies with **dissipative peripheral collisions** and probes of the symmetry energy
- Accessing the **nuclear symmetry energy** from **fragment isotopic distributions**

1. **Medium mass systems (A_{tot} ≈140)**
   ^{78}Zn+^{64}Ni, ^{94}Kr +^{50}Ti, ^{96}Sr + ^{48}Ca, ^{72}Kr + ^{50}Ti
2. **Heavy mass systems (A_{tot} ≈ 190)**
   $^{114-145}$Xe +^{40,48}Ca, ^{122}Cd + ^{58}Ni, ^{90}Kr + ^{90}Zr
3. **Same mass, but ≠ Z**
   ^{72,78}Kr + ^{28}Si and ^{74,80}Zn + ^{26}Mg

} E/A=5 – 10/15 MeV



Day 1 experiment (coupling FAZIA with a spectrometer)

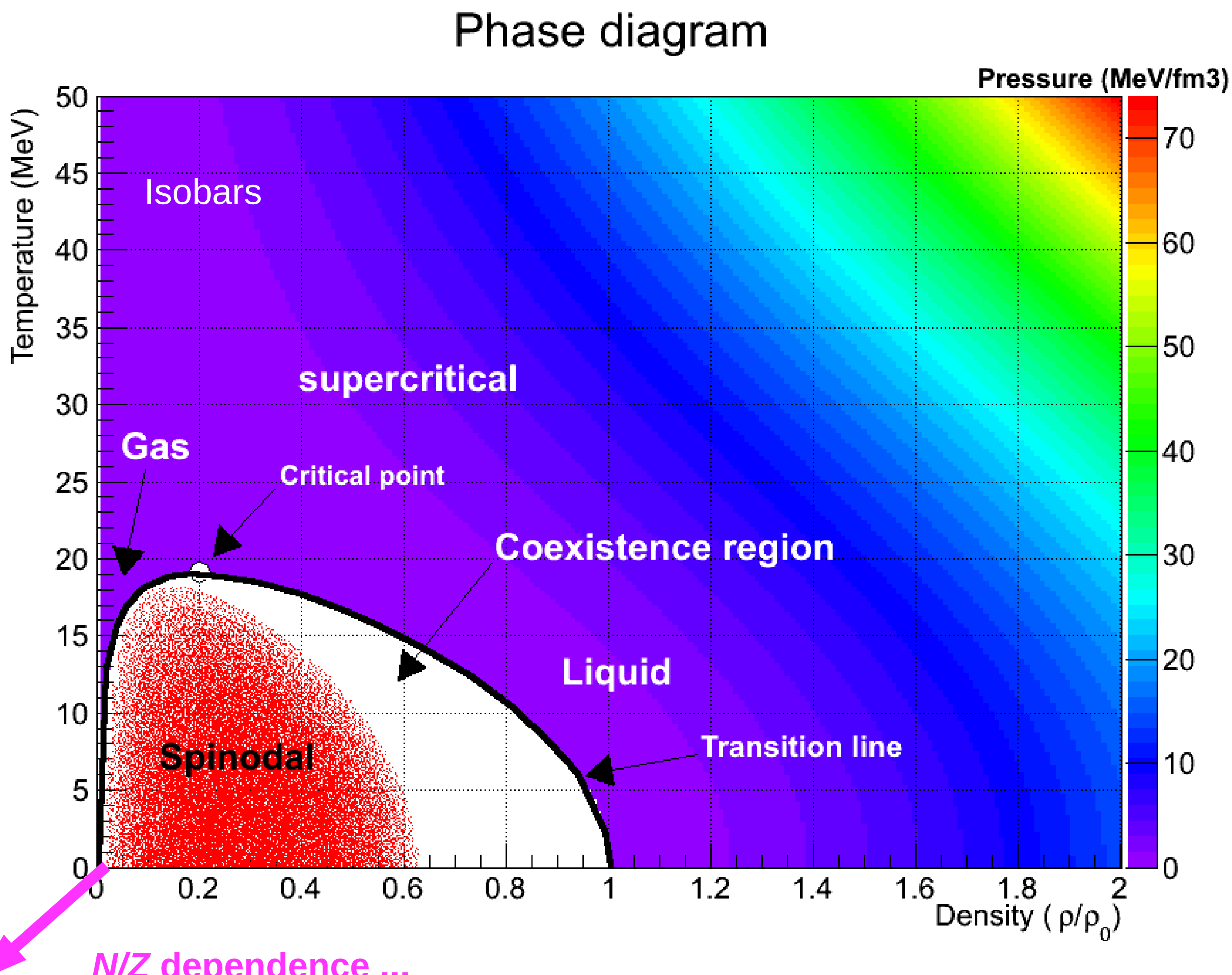
- Isospin dependence on **reaction mechanisms** : **formation/decay** of excited nuclei

$^{80-94}$Kr +^{40,48}Ca/^{12,13}C, *E= 5A* to *10A* MeV (competition between fusion and DIC)

Experimental program :

Long-term : >10 years ...

Phases and Transitions



***N/Z* dependence ...**

Concepts for Fundamental Physics

DFT approach to nuclear physics: towards an universal functional

- Study the energy functional for asymmetric nuclear matter
- Constrain the isovector part of the energy (symmetry energy)
- Produce sub- and super-saturation density matter through HI-induced reactions

Nuclear matter phase diagram and finite nuclei phase transitions

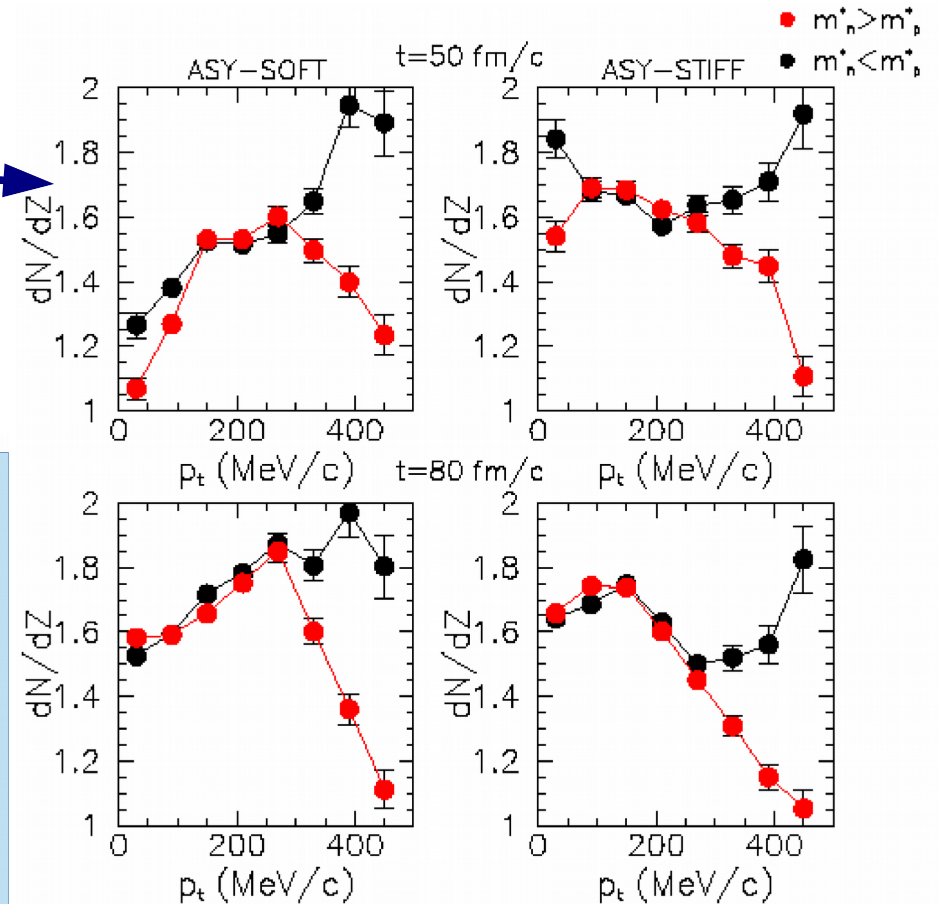
- Scan the low-temperature region of the nuclear matter phase diagram
- Characterize the phase transition (location, order, critical points, …)
- Evidence thermodynamical anomalies in finite systems
- Complementary to the ALICE Physics Program at high energy (QGP)

From finite nuclei to compact star matter

- Constrain MF models for Astrophysics studies
- Study the structures and phase properties of neutrons stars crusts

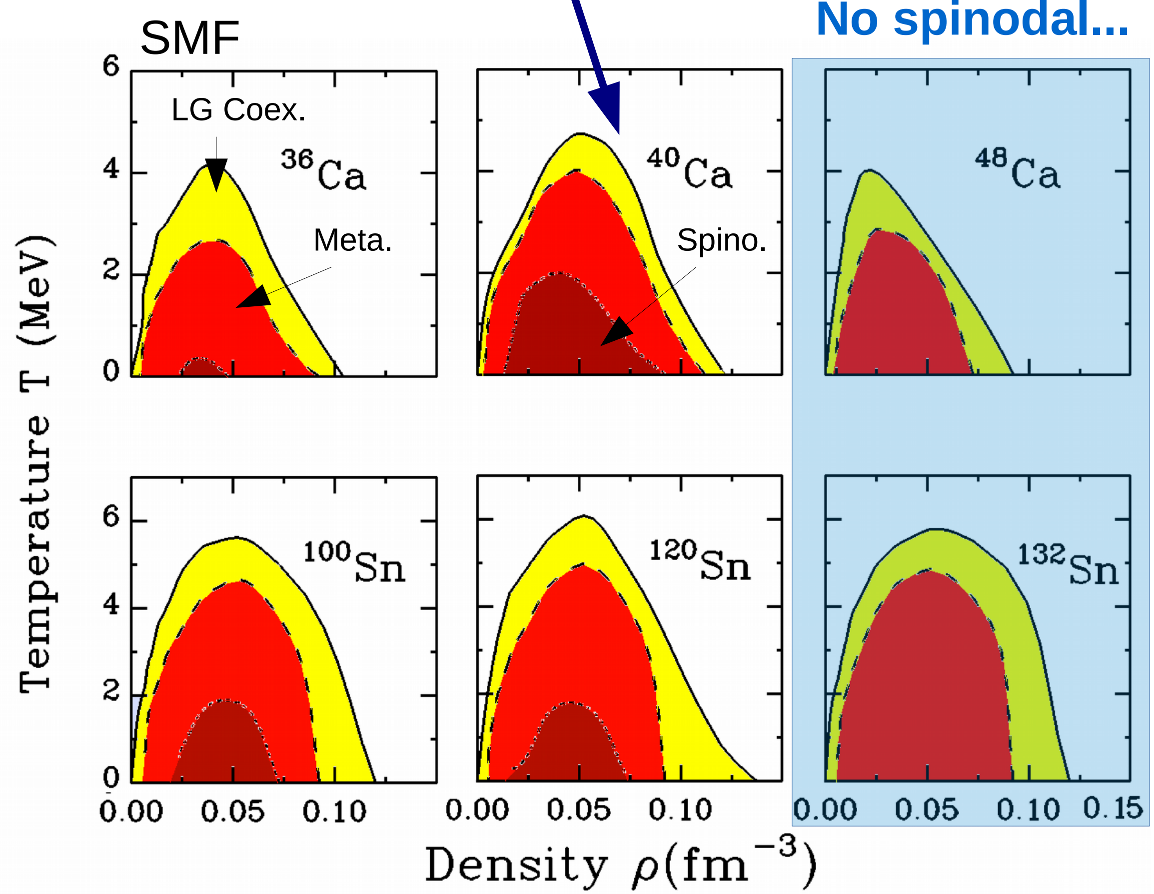
Toward the Future ...

- **Effectives Masses** and **splitting** ***p-n***



- **Isospin Exploration** of the phase diagram

No spinodal...



M. Colonna, Ph. Chomaz and S. Ayik, PRL 88 (2002) 122701

- **Spinodal decomposition** and *N/Z*
- **Cluster emissions / clustering @ low density (Mott-like...)**

Stochastic approaches beyond *MF* :
Pairing, Clustering, …
Statistical Models : N/Z, continuum, ...

To be continued ...

Key Experiments : what is needed (facility side)

(I) Density dependence of the nuclear symmetry energy (DDSE)

^{56}Ni - ^{74}Ni, ^{106}Sn -^{132}Sn, E/A = 15 – 50 MeV

(II) Neutron-Proton effective mass splitting (NPMS)

^{56}Ni - ^{74}Ni, ^{106}Sn - ^{132}Sn , E/A=50-100 MeV

(III) Isospin-dependent phase transition (IDPT)

^{56}Ni - ^{74}Ni, ^{106}Sn -^{132}Sn, ^{200}Rn - ^{228}Rn, E/A = 30 – 100 MeV

(IV) Isospin fractionation, Isoscaling (IFI)

^{56}Ni - ^{74}Ni, ^{106}Sn -^{132}Sn, ^{200}Rn - ^{228}Rn, E/A = 30 – 100 MeV

Key Points are :

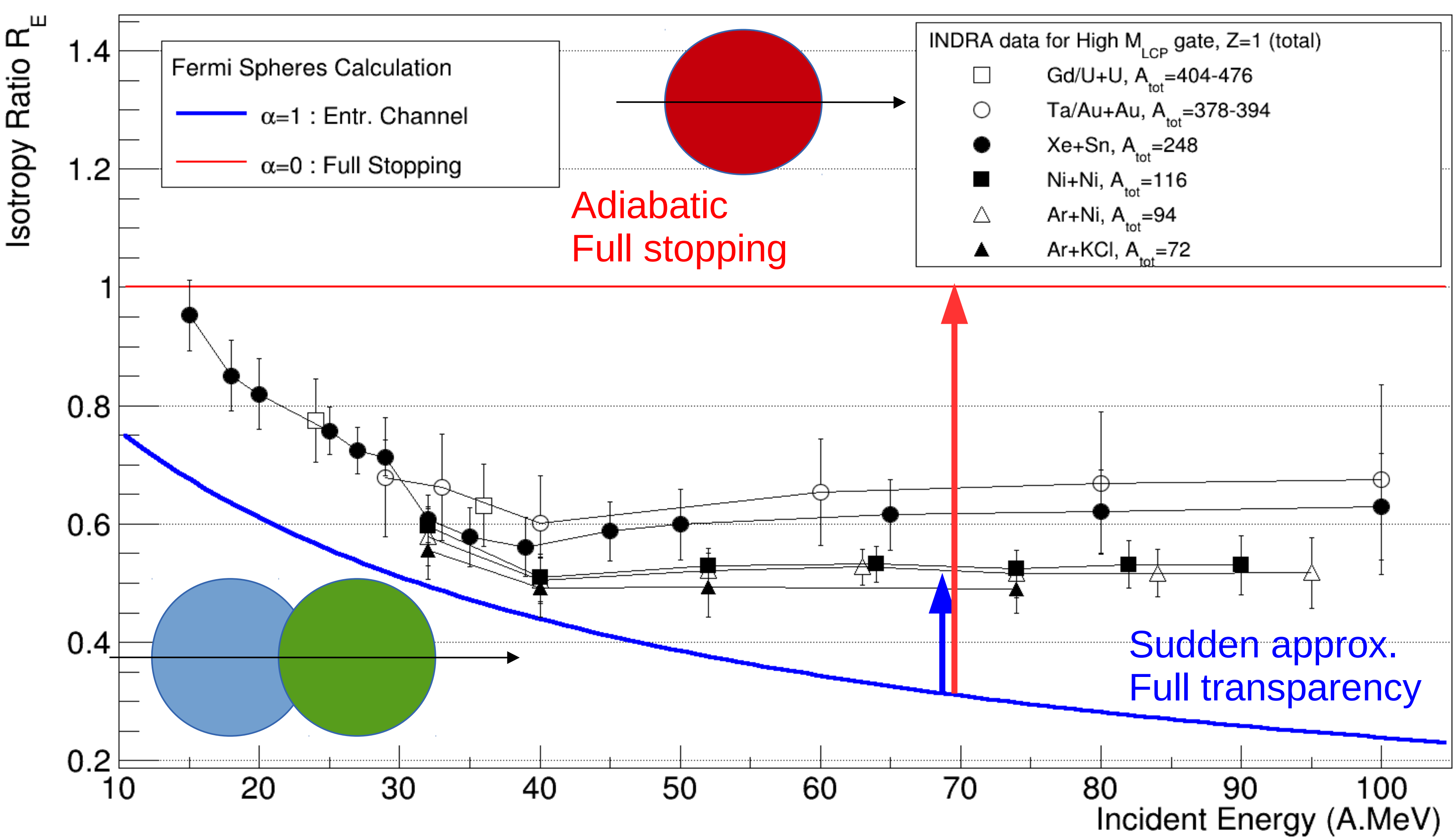
- **large panoply** of beams (light, medium, large A) over the **maximal N/Z extension**
- Beam energy range **around** and **above** the **Fermi** domain **(15-100 *A*MeV)**
- Beam intensity around **10^6-10^8pps**, small emittance, **good timing (<1ns)**

Stopping power in central *HIC*

42 (quasi)-symmetric systems,
Only protons for $<R_E>$...

Nuclear Stopping

$$R_E(\alpha) = \frac{1}{1 + 5(\alpha P_{rel}/P_{Fermi})^2}$$



Physics Motivations

➢ Dynamics of heavy ion collisions

- **Reaction mechanisms** and **transport properties**
  - Deep Inelastic, neck emission, **multifragmentation**
  - **Isospin diffusion**, nuclear **stopping**, **particle flows**
  - **In-medium** properties *: NN* mean free path and cross section

- Link to the ***EOS***
  - **Compressibility** (radial/elliptic flows)
  - **Symmetry energy** for asymetric NM

➢ Thermodynamics of (hot) nuclear matter

- **Nuclear matter** in **proto-neutron stars**
  - **bulk** properties vs **finite size** effects (surface, coulomb, nuclei)

- **Phase transitions** for **strongly correlated** systems
  - Phase diagram : **Liquid-Gas** phase transitions, **first/second order**
  - **Temperature/Density/Isospin** dependence
  - **Spinodal decomposition**

About the scale...

Deconfinement
QGP

E/A=1 GeV

λ < 1 fm
QCD

Nucleonic excitation
Hadronic regime

E/A=100 MeV

λ ≈ 3 fm
Range *NN*

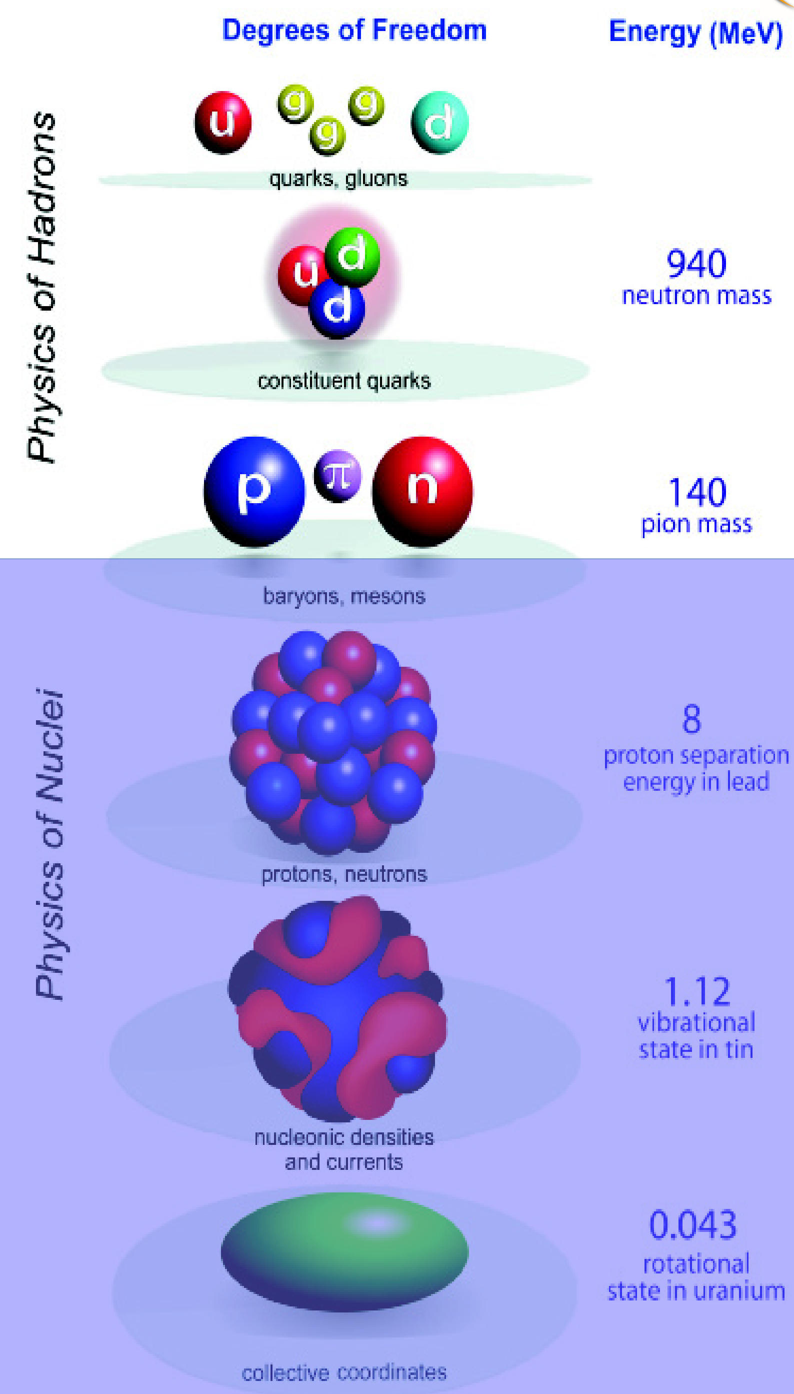
Evaporation, multifragmentation, Vaporization
Mean-Field + NN collisions
1-Body/2-Body Dissipation

E/A=10 MeV

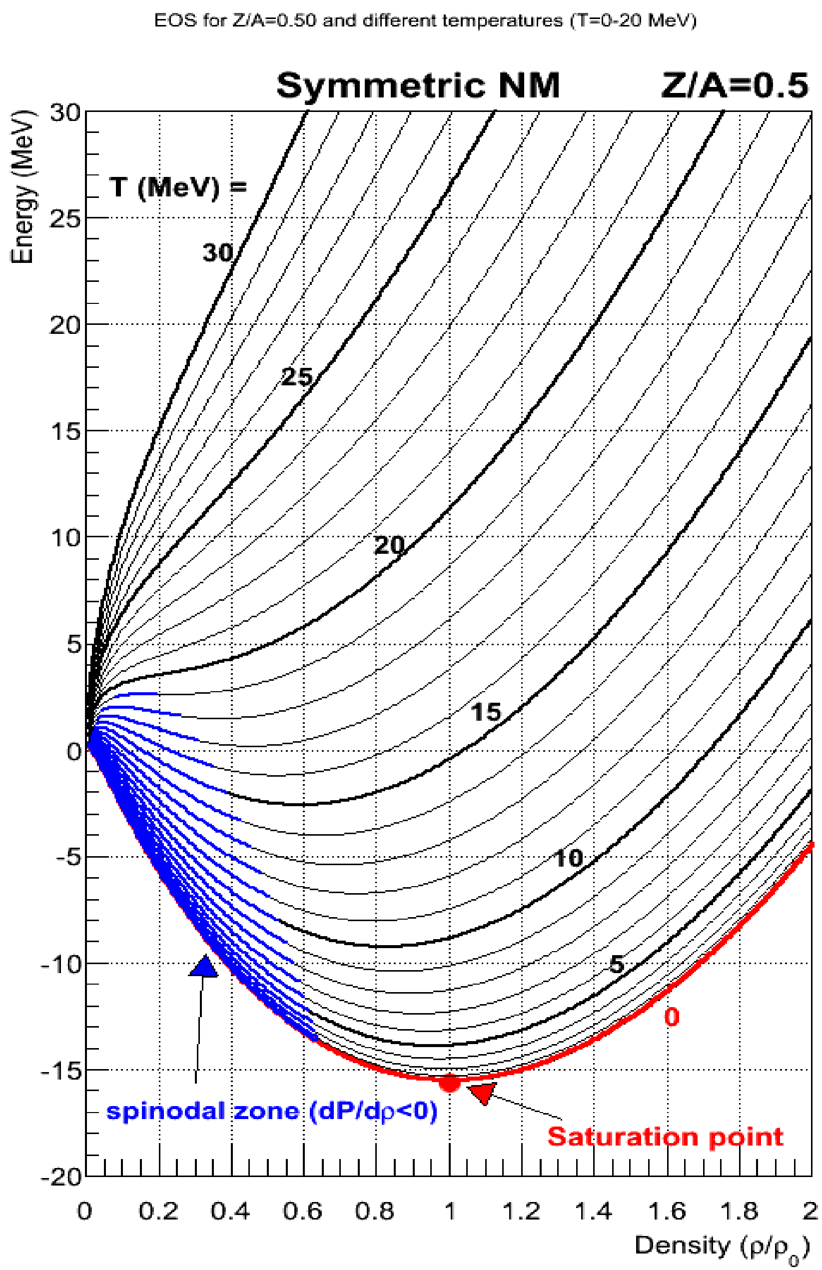
Collectives excitations, deformations
Nuclear response
Mean-field

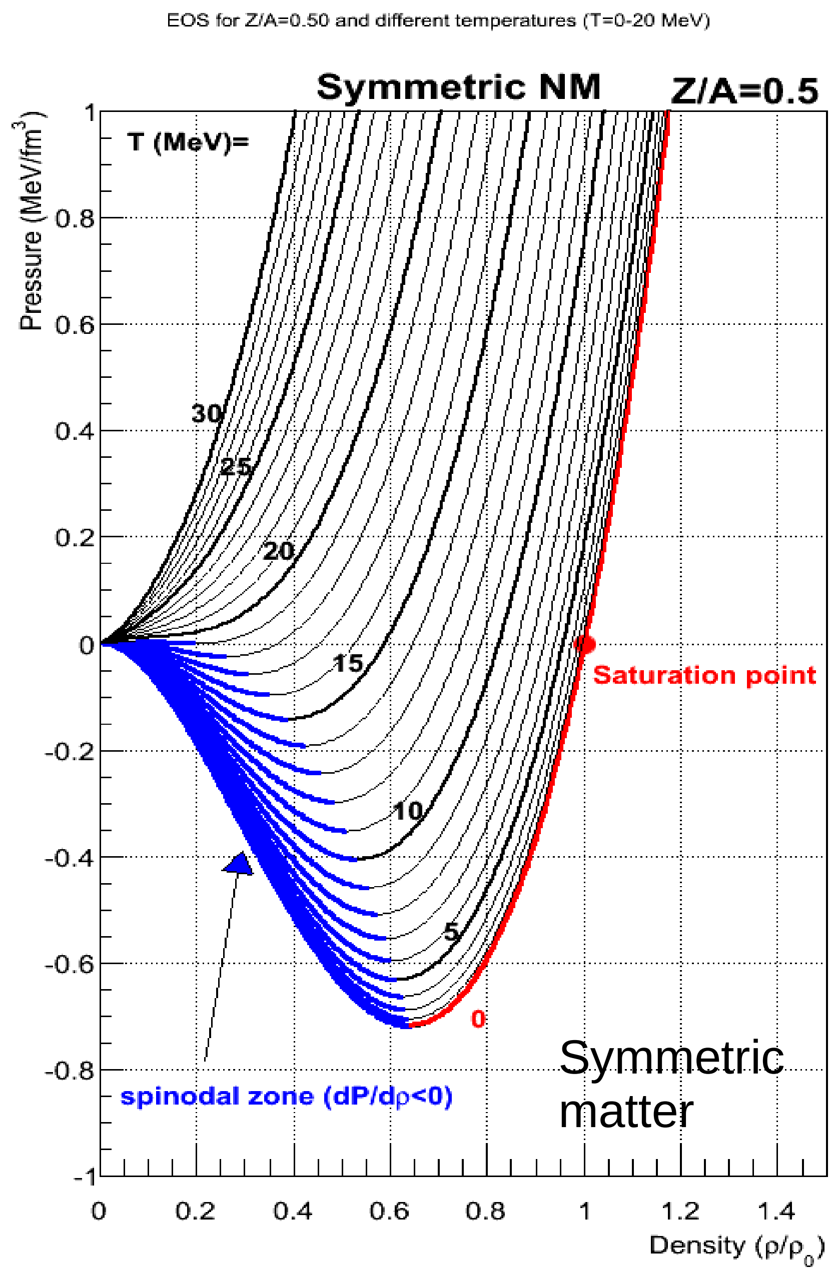
λ ≈ 10 fm
Nucleus

E/A=1 MeV



From EOS to Phase diagrams





E,P (extensive) dependence as a function of density and temperature (intensive)

Motivations

- Connection between **transport properties and the Equation of State** :

Energy dissipation [thermalization] and **isospin diffusion [Esym(ρ)]**

- Transport properties are mandatory for :
  - Description of **supernova collapse** and formation of **neutron stars**
  - Determination of the **nuclear EOS** via the underlying properties of the **nuclear interaction**
  - **Microscopic descriptions** as one of the fundamental ingredient for the dissipative features: **EOS** and **collision term**