Critical review of isospin observables for the determination of the symmetry energy

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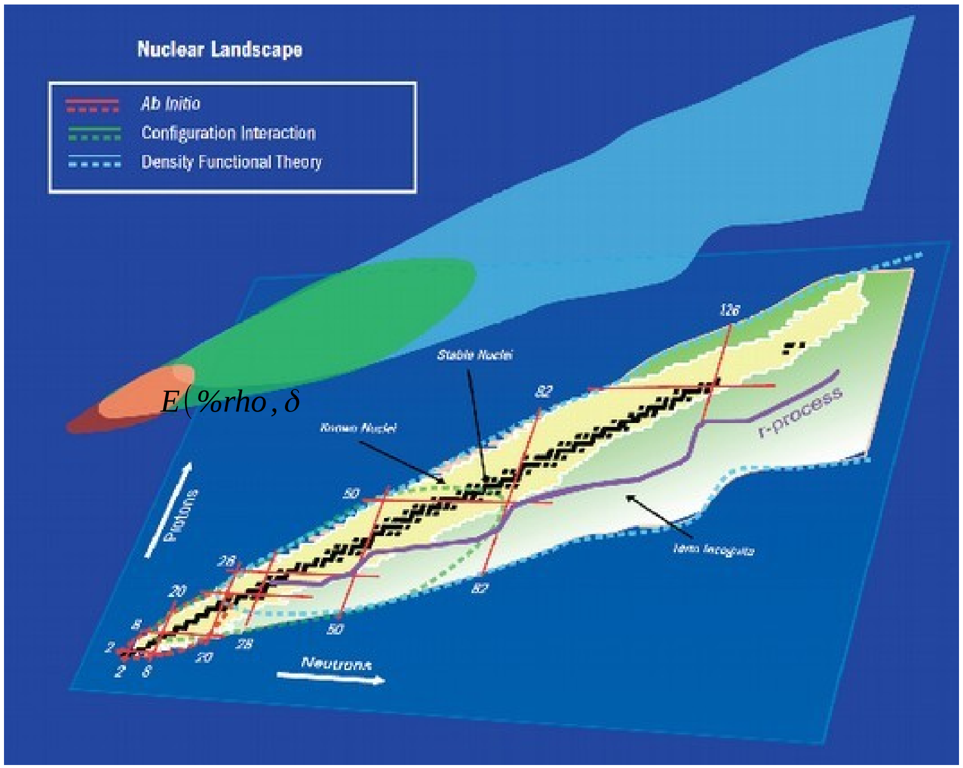
NUSYM'21, October 13th, 2021

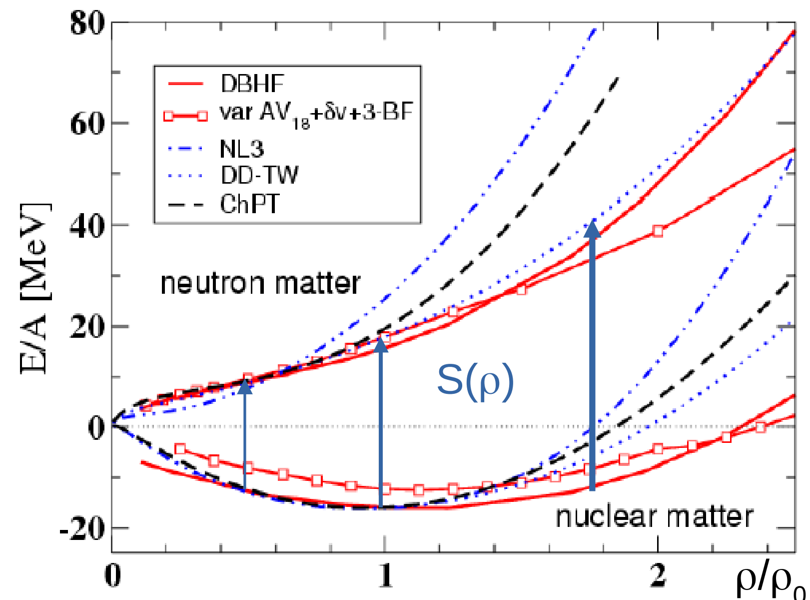
Microscopic Description of Nuclei

Energy-Density Functional theory is currently the most efficient theoretical framework to understand the structure and dynamics of medium and heavy nuclei.



Energy-Density Functionals

$$H_{eff} = E[\rho]$$



$$E(\rho,\delta)/A = E_{is}(\rho) + S(\rho)\delta^2 + O(\delta^4) \text{ (quadratic approx.)}$$

$$x = (\rho - \rho_0)/3\rho_0$$

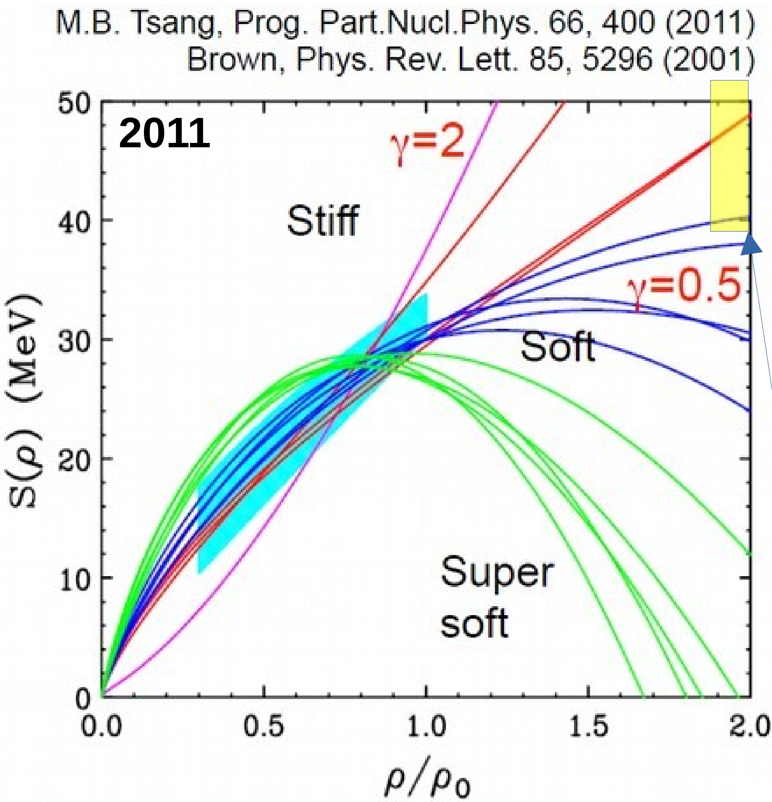
$$\delta = (\rho_n - \rho_p)/\rho$$

Taylor expansions up to 4th order around ***δ=0* (*N=Z*)** and ***x=0* (*ρ=ρ₀*)**

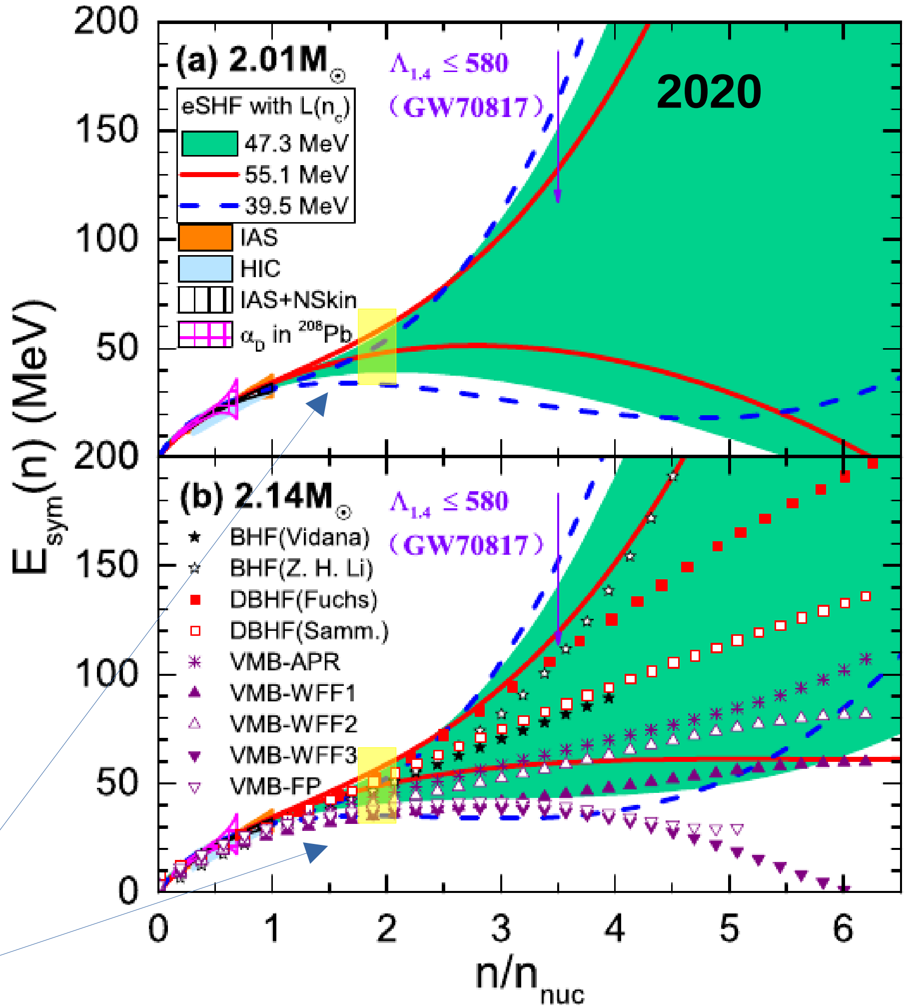
Isoscalar $E_{is}(\rho) = \mathbf{E_0} + \mathbf{K_0}x^2/2! + \mathbf{Q_0}x^3/3! + \mathbf{Z_0}x^4/4! + O(x^5)$

Isovector $S(\rho) = \mathbf{S_0} + \mathbf{L_{sym}}x + \mathbf{K_{sym}}x^2/2! + \mathbf{Q_{sym}}x^3/3! + \mathbf{Z_{sym}}x^4/4! + O(x^5)$

Density dependence of Symmetry Energy



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



Super-soft EOS is ruled out by ASY-EOS 1/2 and high NS masses (>2.1 M_o)
PSR J0740+6620, PSR J0348+0432

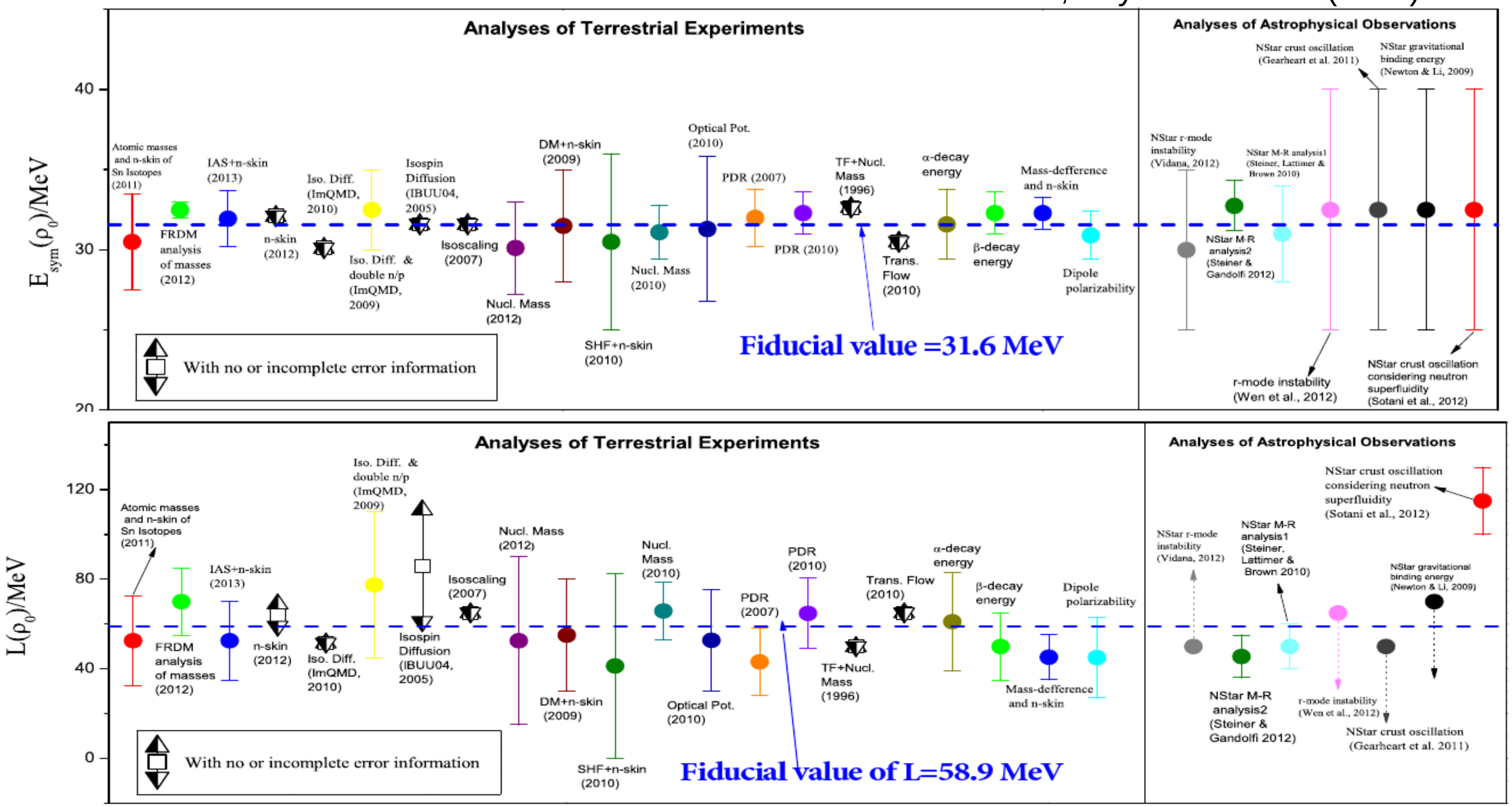
P. Russotto, et al., PLB **697**, 471 (2011)
P. Russotto, et al., PRC **94**, 034608 (2016)
Y. Zhou and L.-W. Chen, Astroph. J. **886** (1) (2019) 52

See next session on relativistic energies tomorrow afternoon

Symmetry Energy around ρ_0 (2016)

Evaluations for E_{sym}, slope L, curvature K_{sym}, ...

B.A. Li and X. Han, Phys. Lett. B727 (2016) 276

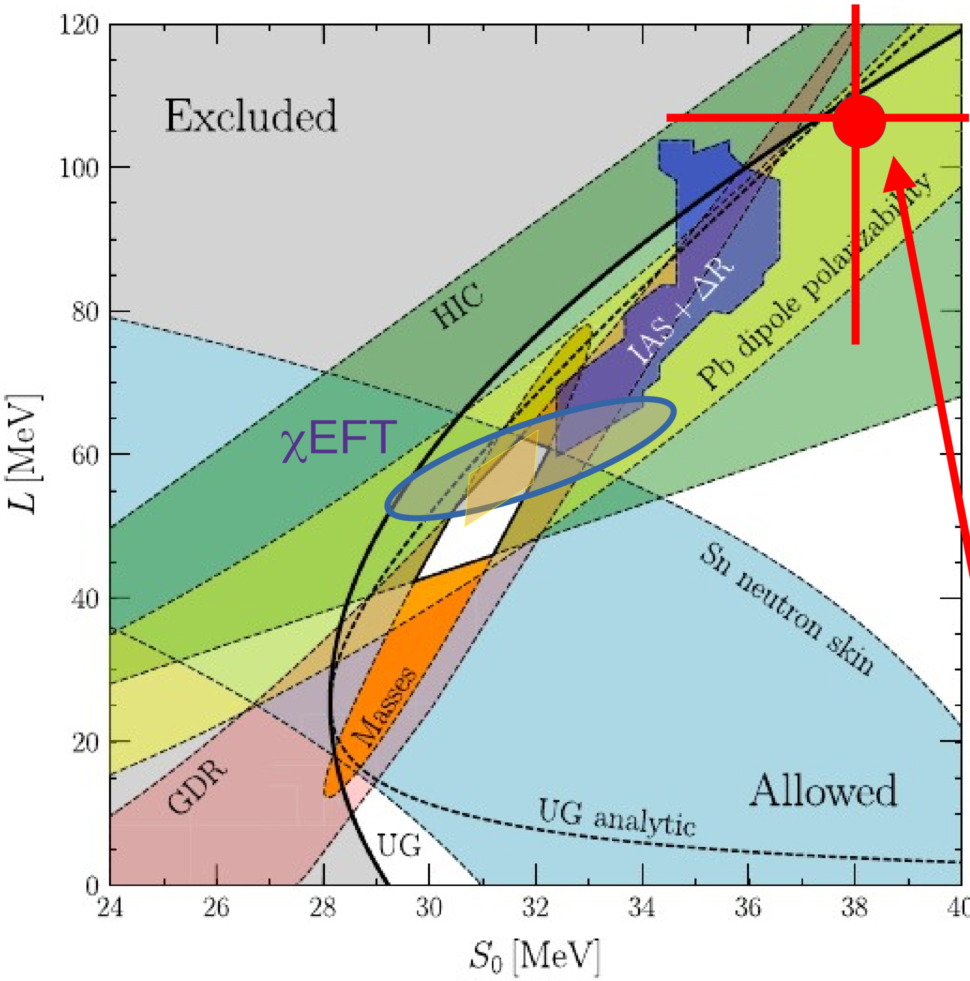


	~1%	~10%		~30%		???				
P_α	E_{sat} MeV	E_{sym} MeV	ρ_0 fm^{-3}	L_{sym} MeV	K_{sat} MeV	K_{sym} MeV	Q_{sat} MeV	Q_{sym} MeV	Z_{sat} MeV	Z_{sym} MeV
$\langle P_\alpha \rangle$	-15.8	32	0.155	60	230	-100	300	0	-500	-500
σ_{P_α}	$\pm$0.3	$\pm$2	$\pm$0.005	$\pm$15	$\pm$20	$\pm$100	$\pm$400	$\pm$400	$\pm$1000	$\pm$1000

Margueron PRC **97** (2018) 025805

Symmetry Energy around ρ_0 (III) : newcomer

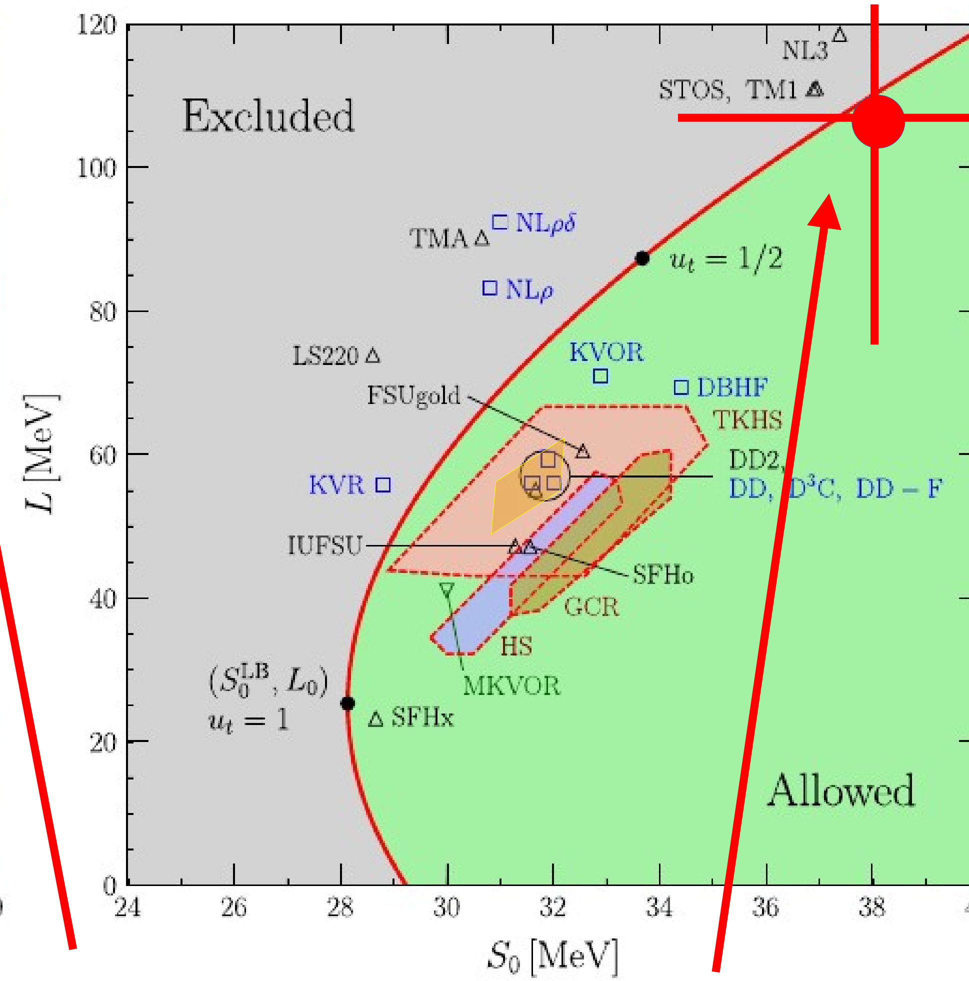
Experimental constraints



I. Tews *et al.*, Astroph. J. **848** (2017) 105

C. Drischler *et al.*, PRL **125** (2020) 202702

Model predictions



PREX-2 , B. T. Reed et al., PRL ***126*** *(2021) 172503*

S_0 = 38.1 ± 4.7 MeV

L_{sym} = 106 ± 37 MeV

Tension between PREX-2 and other experimental and theoretical evaluations

Nuclear matter at $\rho > \rho_0$

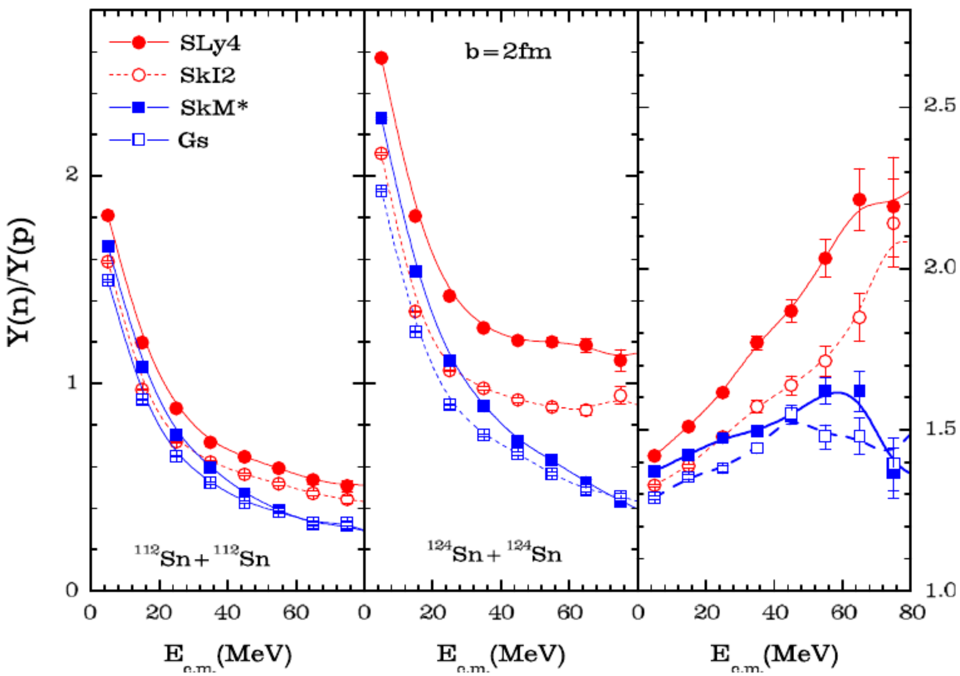
Flows

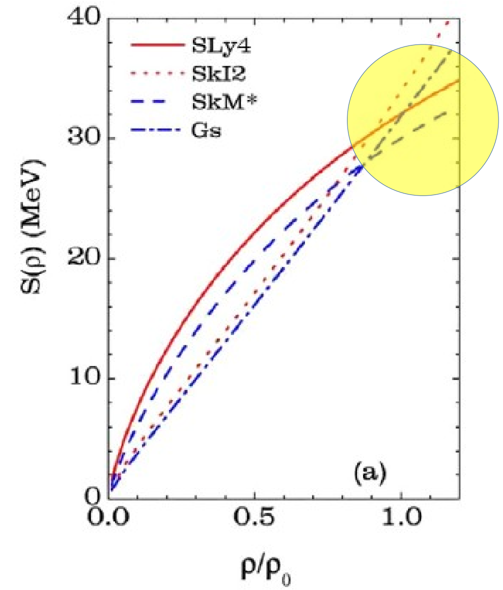
DDSE : pre-equilibrium probes (I)

Neutron and proton flows

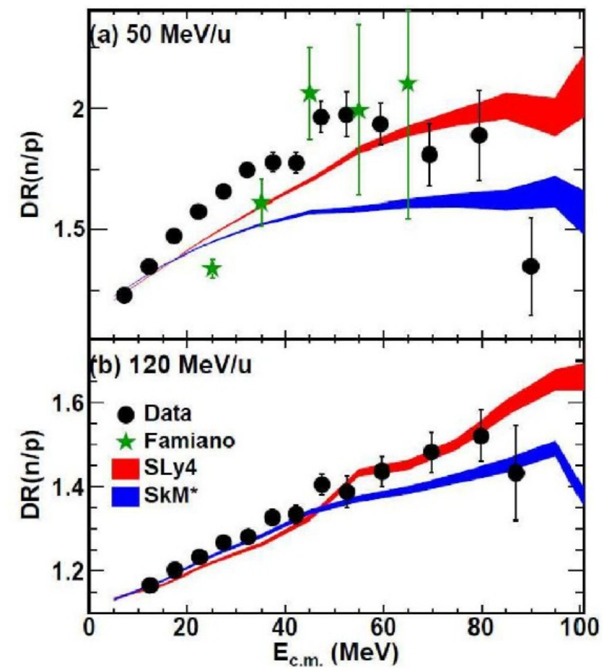
^{112,124}Sn+^{112,124}Sn at E/A=50, 120 MeV

Y. Zhang, *et al.*, PLB 732 (2014) 186





D.D.S. Coupland, *et al.*, PRC 94, 011601 (2014)



- Sensitivity to the EOS above ρ_{sat}

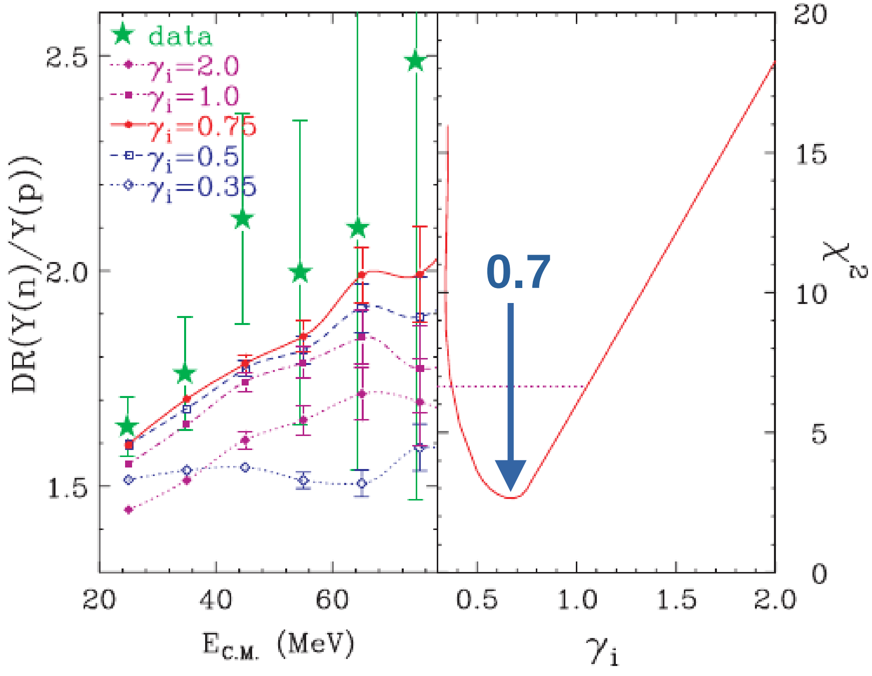
- but also effective masses

M. B. Tsang, *et al.*, PRL **102** (2009) 122701

Double n/p ratio

$$\mathrm{DR}\,(Y(n)/Y(p)) = R_{n/p}(A)/R_{n/p}(B)$$
$$= \frac{dM_n(A)/dE_{\mathrm{c.m.}}}{dM_p(A)/dE_{\mathrm{c.m.}}} \cdot \frac{dM_p(B)/dE_{\mathrm{c.m.}}}{dM_n(B)/dE_{\mathrm{c.m.}}},$$

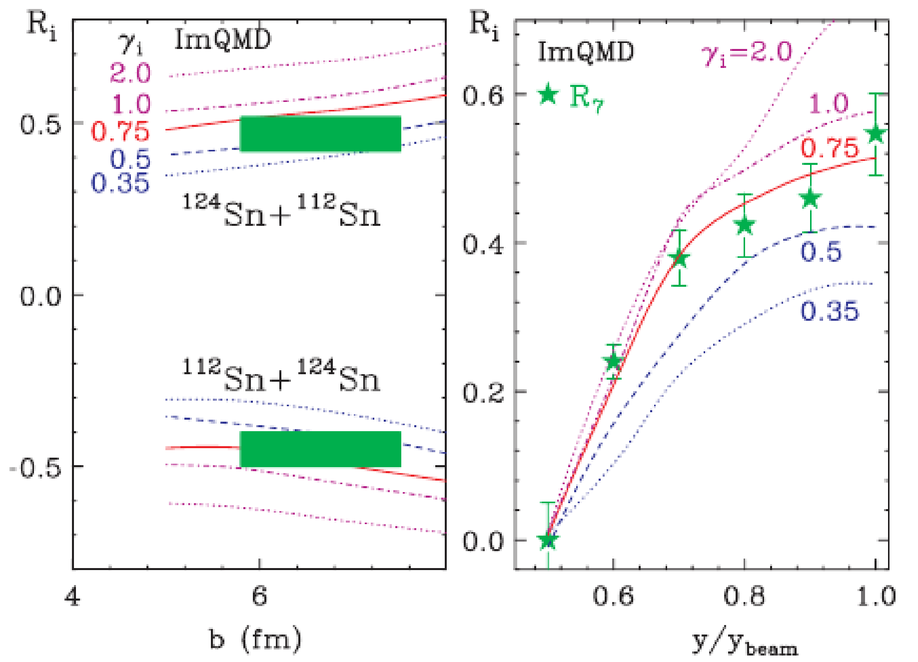
^{112,124}Sn+^{112,124}Sn at E/A=50 MeV



Soft SE with γ≈0.7 is obtained

ImQMD simulations

Isobaric ratio : mirror nuclei yields: ^{7}Li/^{7}Be



$E_{sym}(\rho) = c_{k,sym}\rho^{2/3} + c_{p,sym}\rho^{\gamma}$

γ governs the stiffness of the potential term

- γ>1 : asy-stiff
- γ<1 : soft
- γ<<1 : supersoft

Ad-hoc SE parametrization, no theoretical justification

DDSE : pre-equilibrium probes (II)

SMF + GEMINI calculations $^{112,124,132}Sn$ + $^{112,124,132}Sn$ at *E/A=50 MeV* and *b=2 fm*

Double Ratio with energy scaling

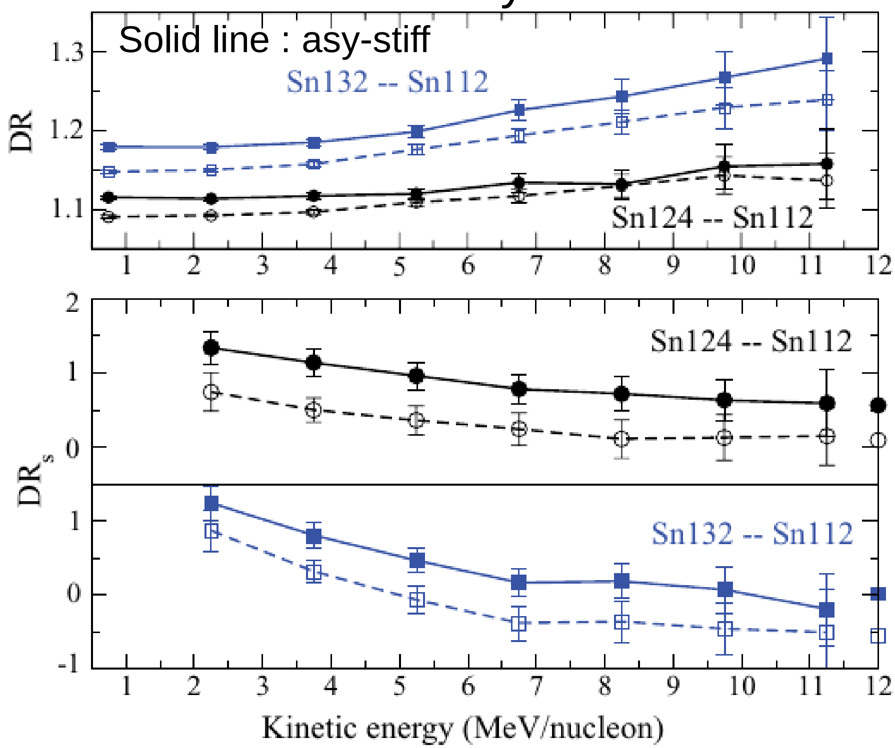
$$\mathrm{DR}(E_{\mathrm{kin}}) = (N/Z)_2/(N/Z)_1.$$

$$(N/Z)_s(E_{\mathrm{kin}}) = \frac{N}{Z}(E_{\mathrm{kin}}) - \frac{N}{Z}(E_0).$$

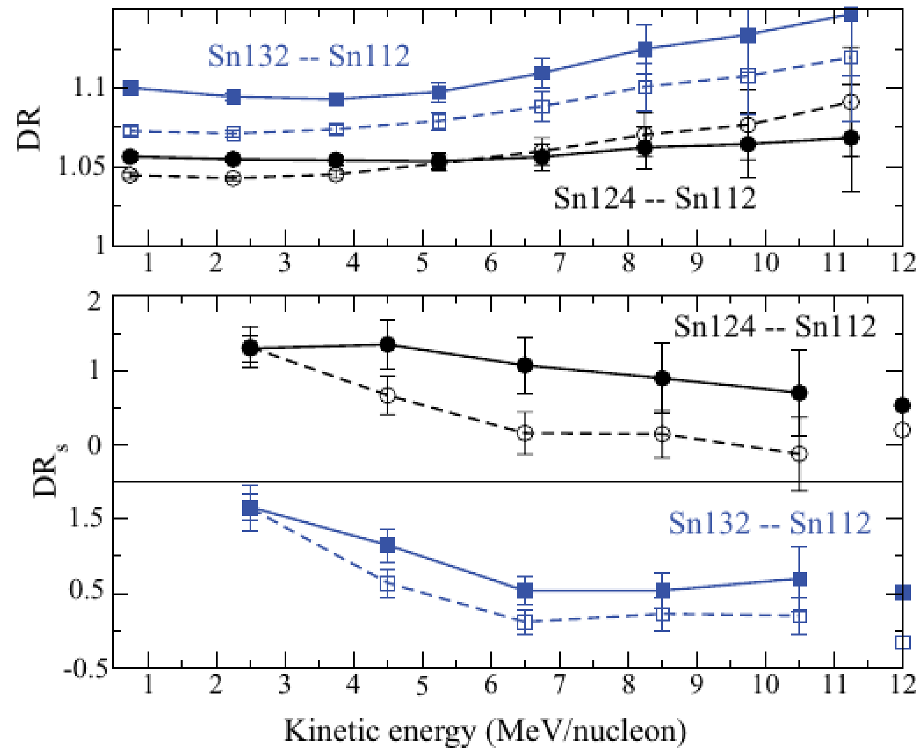
$$\mathrm{DR}_s(E_{\mathrm{kin}}) = ((N/Z)_s)_2/((N/Z)_s)_1.$$

- Small sensitivity
- More robust to secondary emissions for energetic products

Primary



Final



M. Colonna, *et al.*, PRC **78**, 064618 (2008)

Binary dissipative collisions

Isospin transport

DDSE : isospin transport in semi-peripheral reactions

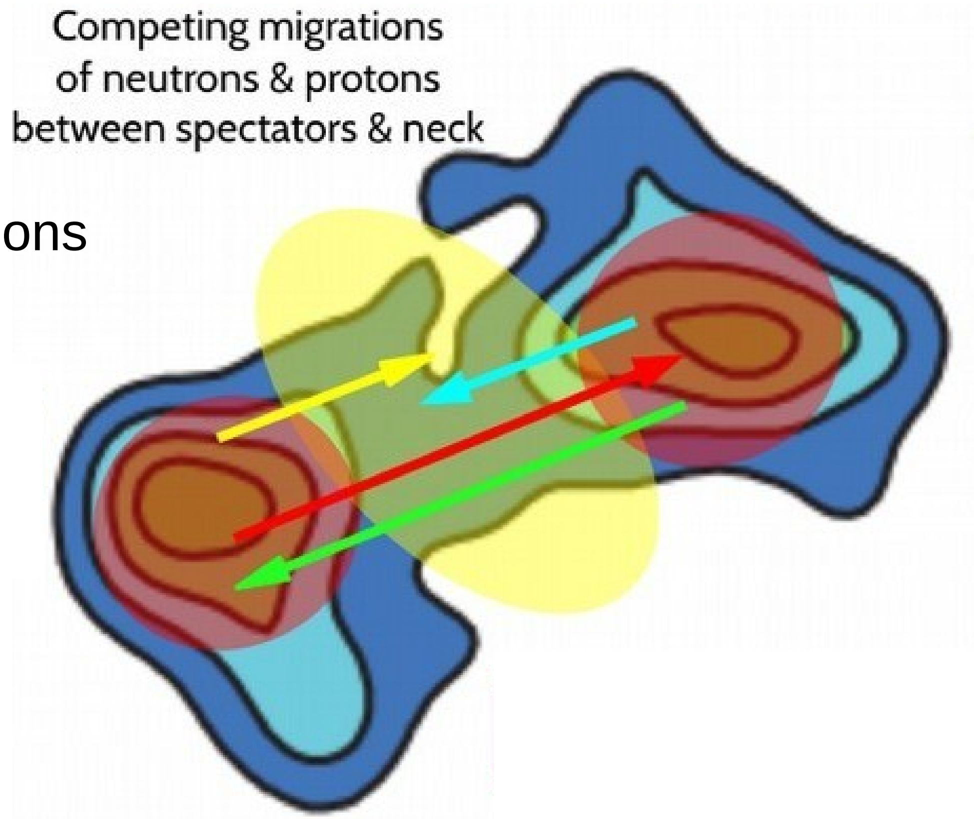
Isospin transport (flux) :

$$j_n - j_p \propto E_{sym}(\rho)\nabla I - I\left(\frac{\partial E_{sym}}{\partial \rho}\right)\nabla \rho$$

Binary dissipative collisions around **Fermi energy**

Neck and QP formation
Competition between

- **Diffusion ∇I** (QP)
- **Migration ∇ρ** (neck)



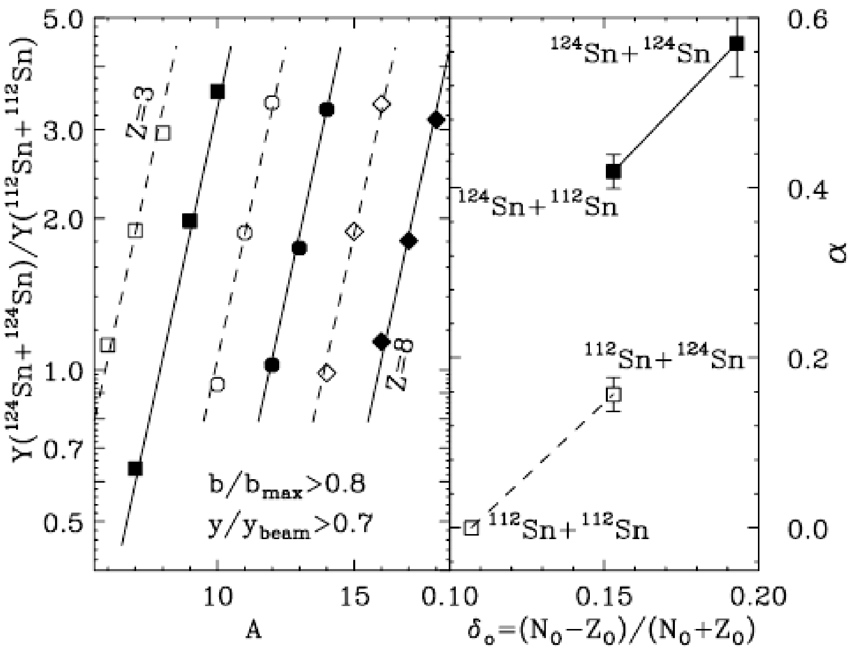
Isospin transport for semi-peripheral collisions (I)

Ratio of isotopic yields: $R_{21}(N,Z)=Y_2(N,Z)/Y_1(N,Z)$

Peripheral collisions (M_{tot}-gated) $b/b_{max}>0.8$

Isoscaling $R_{21}(N,Z) = C\exp(\alpha N + \beta Z),$

$^{112,124}Sn+^{112,124}Sn$ at $E/A=50$ MeV

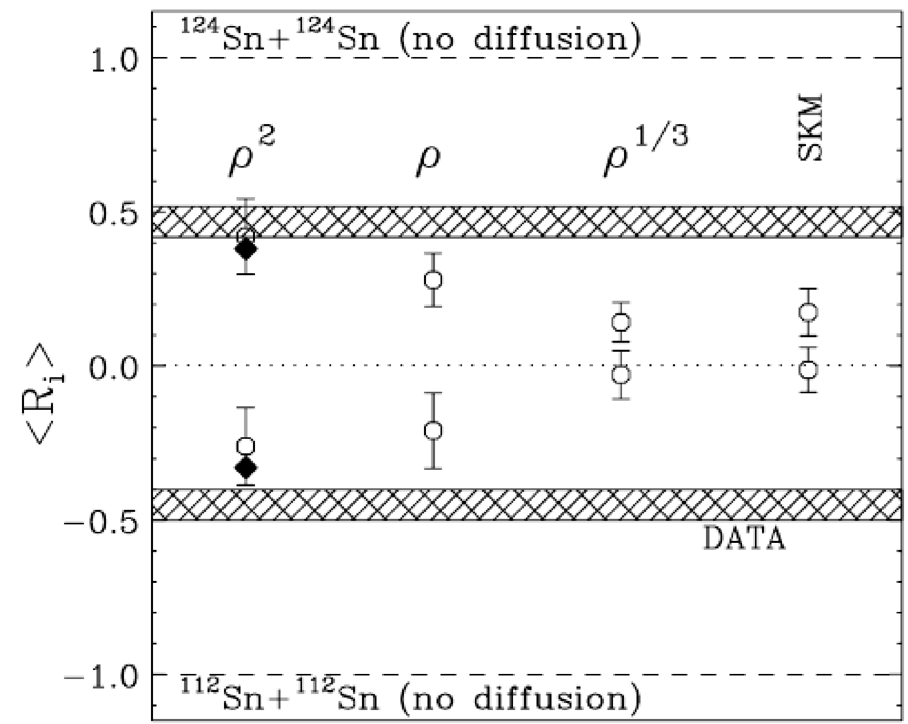


M. B. Tsang ,*et al.*, PRL **92** (2004) 062701

Isospin transport ratio

$$R_i = \frac{2x - x_{124+124} - x_{112+112}}{x_{124+124} - x_{112+112}},$$

BUU model with K_{sat}=*210 MeV*, MI



asy-stiff

asy-soft

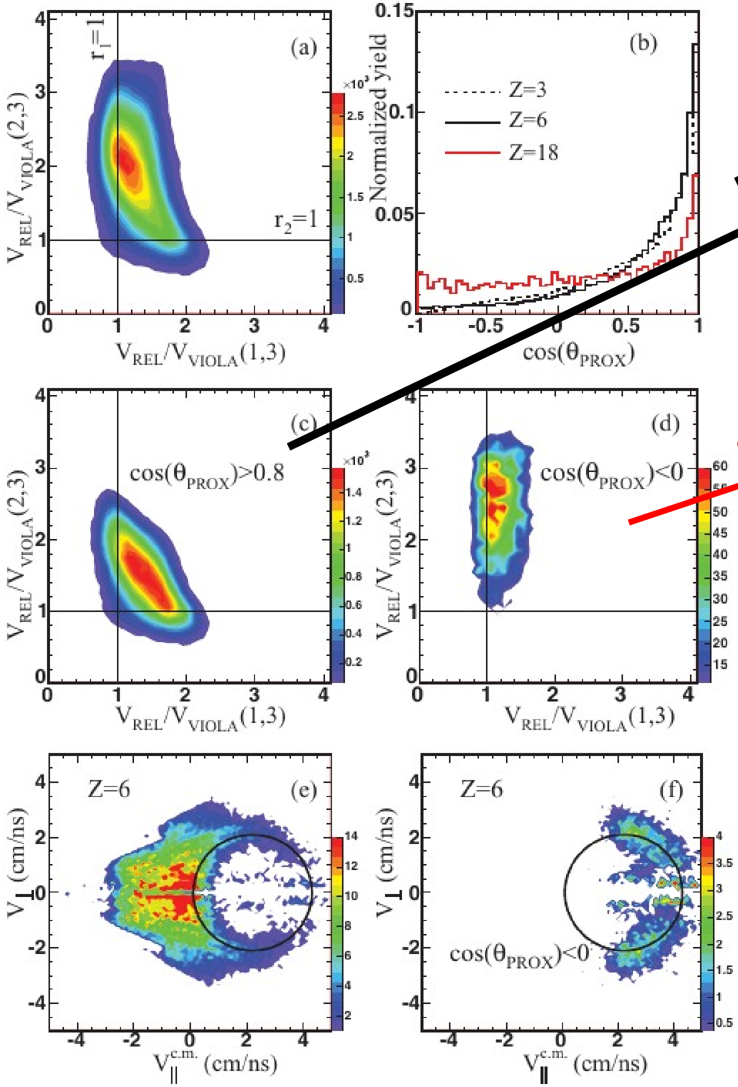
Asy-stiff (ρ^2) parametrization seems favoured
but K_{sat} and momentum-independent (MI) interaction are used

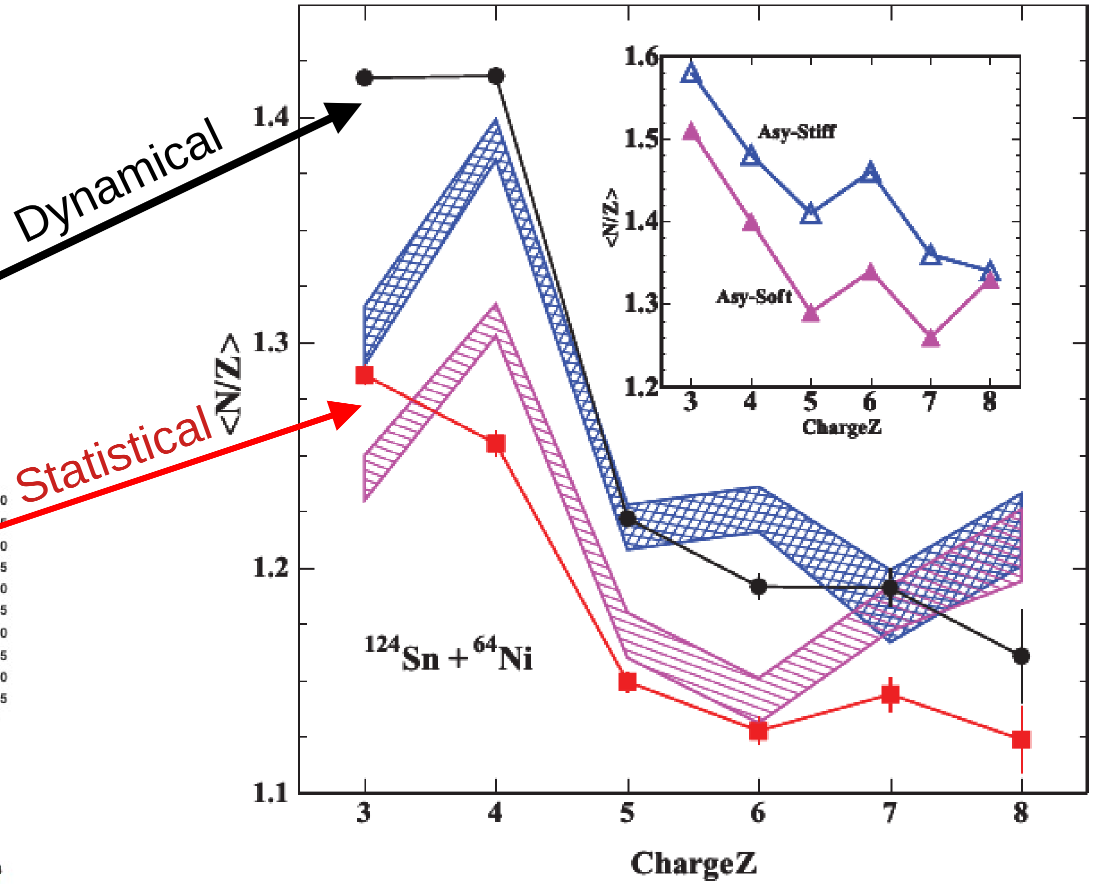
Isospin transport for semi-peripheral collisions (III)

Neck isospin content

$^{112,124}Sn+^{58,64}Ni$ at E/A=35 MeV

CHIMERA data
SMF+GEMINI calculations





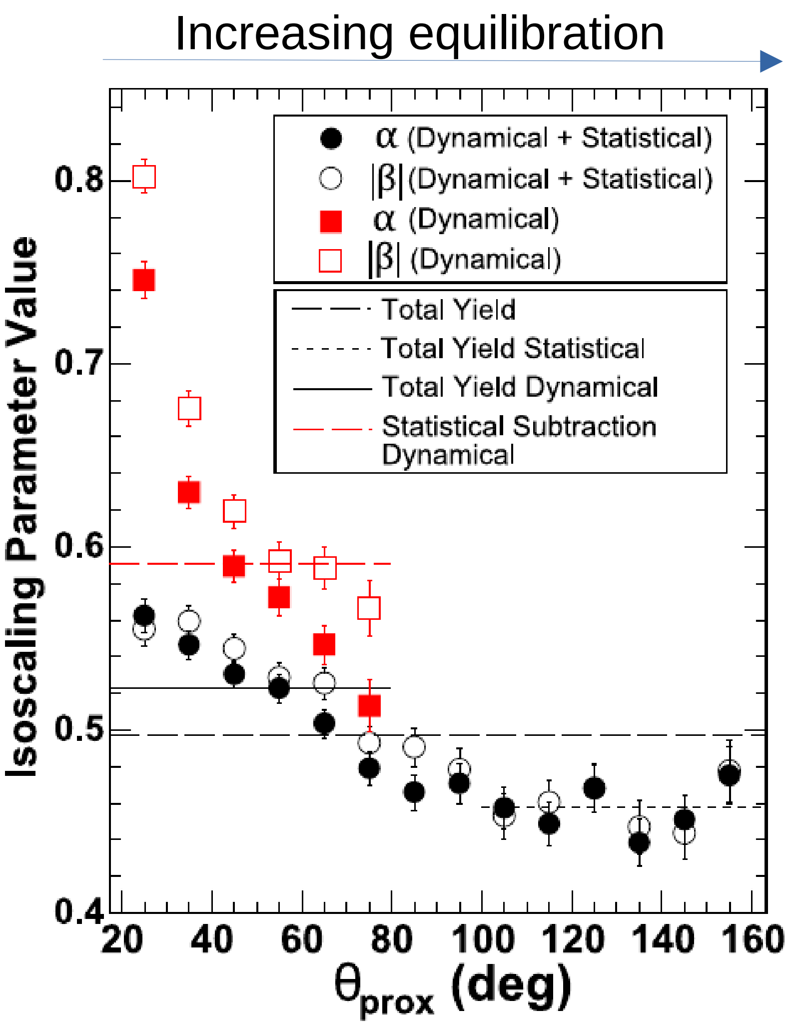
- **Larger neutron enrichment for dynamical emission**
- **Asy-stiff param. with L_{sym} = *80 MeV* is favoured**

Agreement remains qualitative, esp. Z=3-4

E. De Filippo, *et al.*, PRC 86, 014610 (2012)

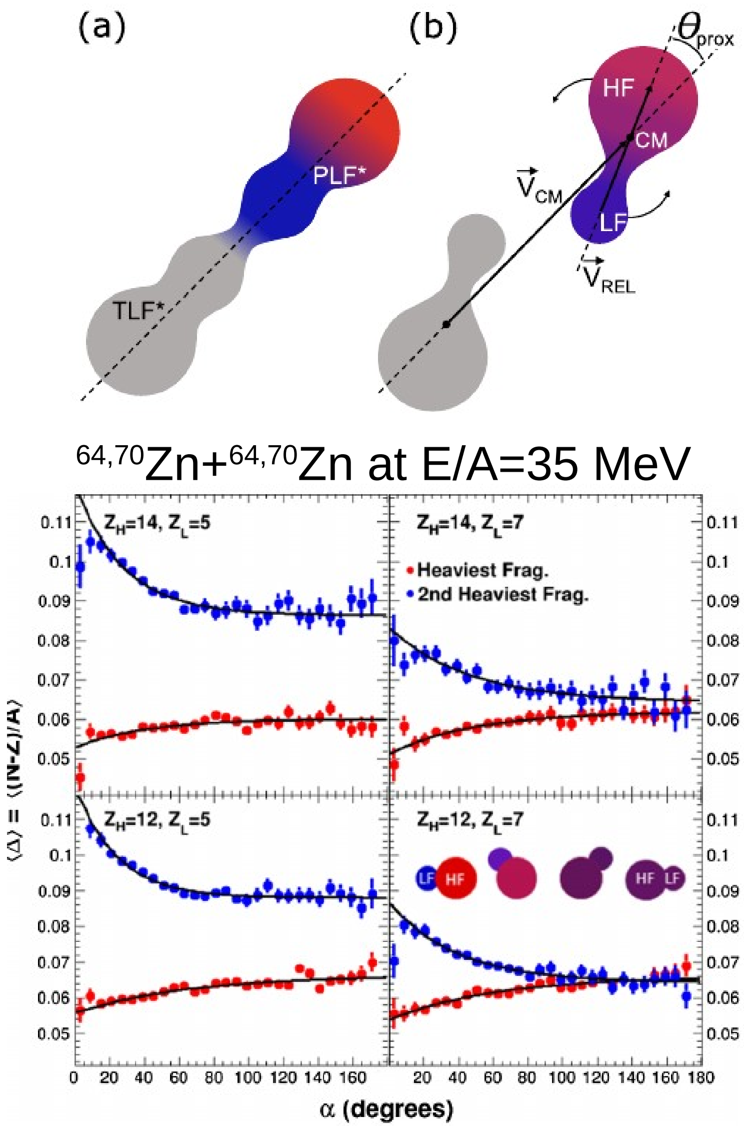
Isospin transport for semi-peripheral collisions (IV)

Isoscaling $R_{21}(N, Z) = C \exp(\alpha N + \beta Z),$



α and β isoscaling coefficients are sensitive to θ_{prox}

A. Hannaman, *et al.*, PRC **101**, 034605 (2020)
A. Jedele, *et al.*, PRL **118**, 062501 (2017)



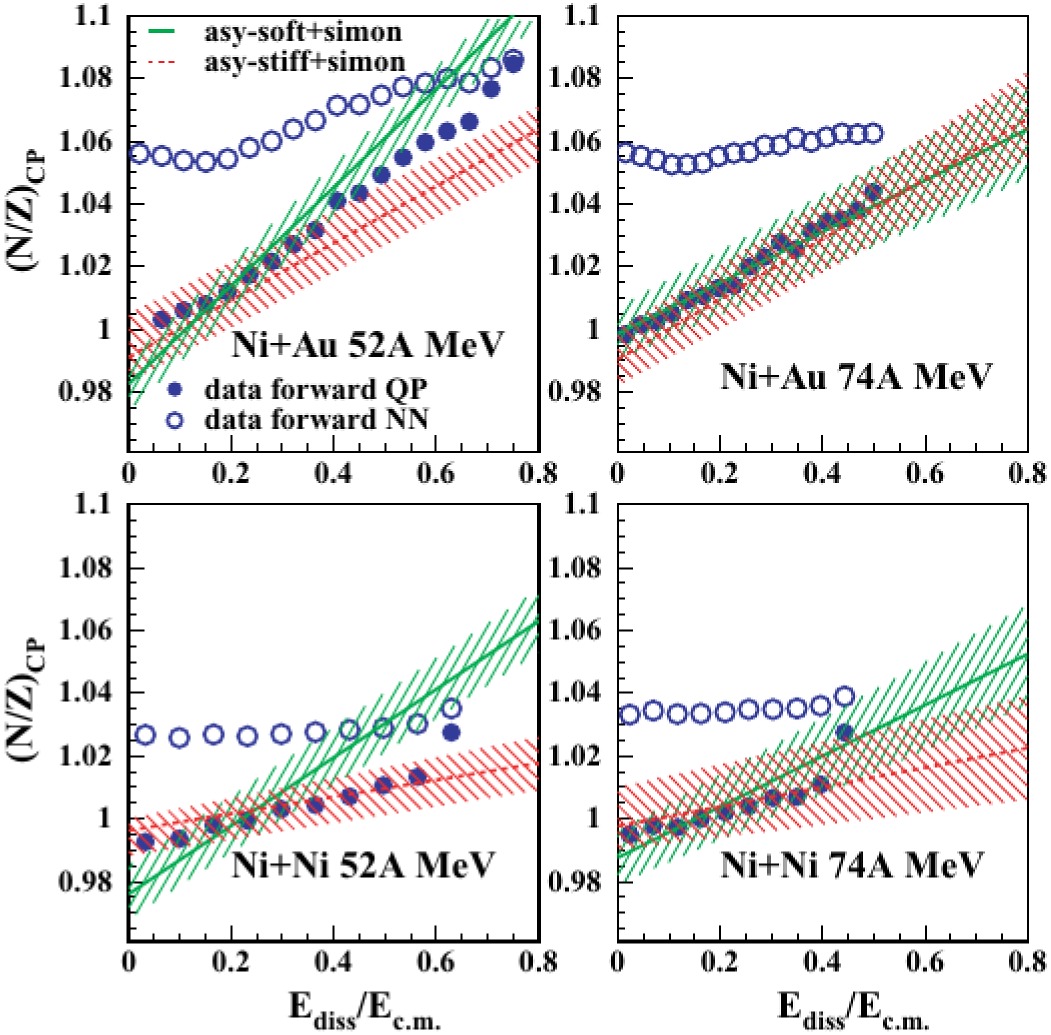
- Isospin equilibration ≈ 100 fm/c
- Commensurate to fragment production
- Much shorter than fission

Link to E_{sym} still to quantify

Isospin transport for semi-peripheral collisions (V)

Isospin content for Quasi-Projectile

INDRA data, ^{58}*Ni+*^{58}*Ni/*^{197}*Au at E/A=52,74 MeV*
BNV simulations at *b=5 fm*



- Quasi-Ni neutron-enrichment as a function of dissipation/centrality
- Asy-stiff (γ=1) case better matches
- Isospin equilibration time:

t_{eq} = 130 ± 10 fm/c

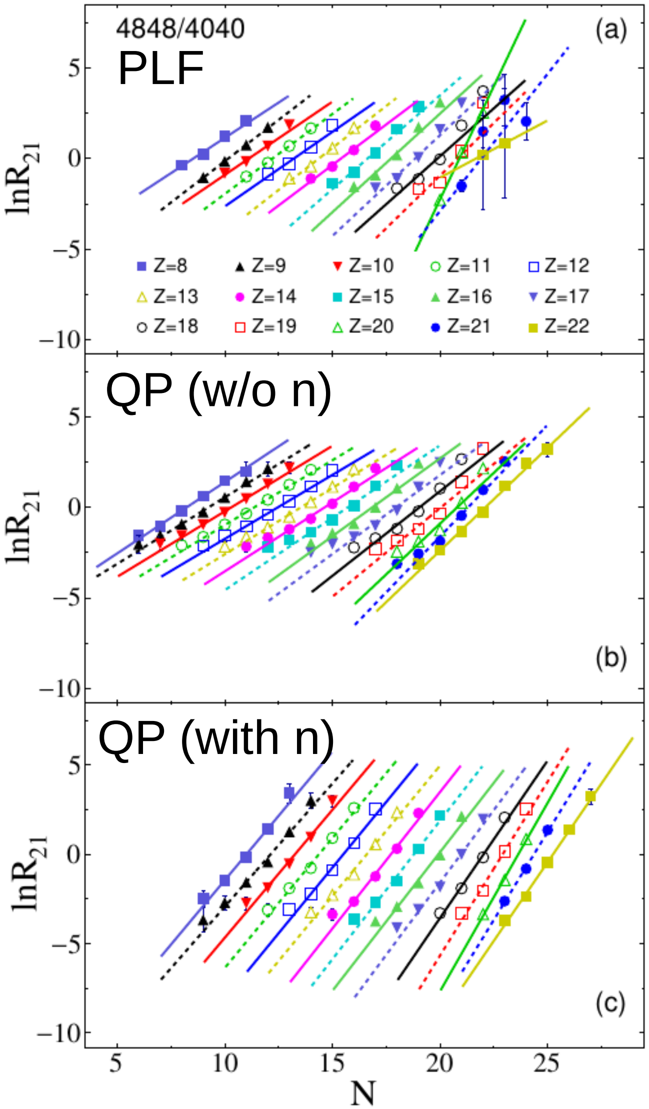
Small sensitivity
Impact parameter mixing

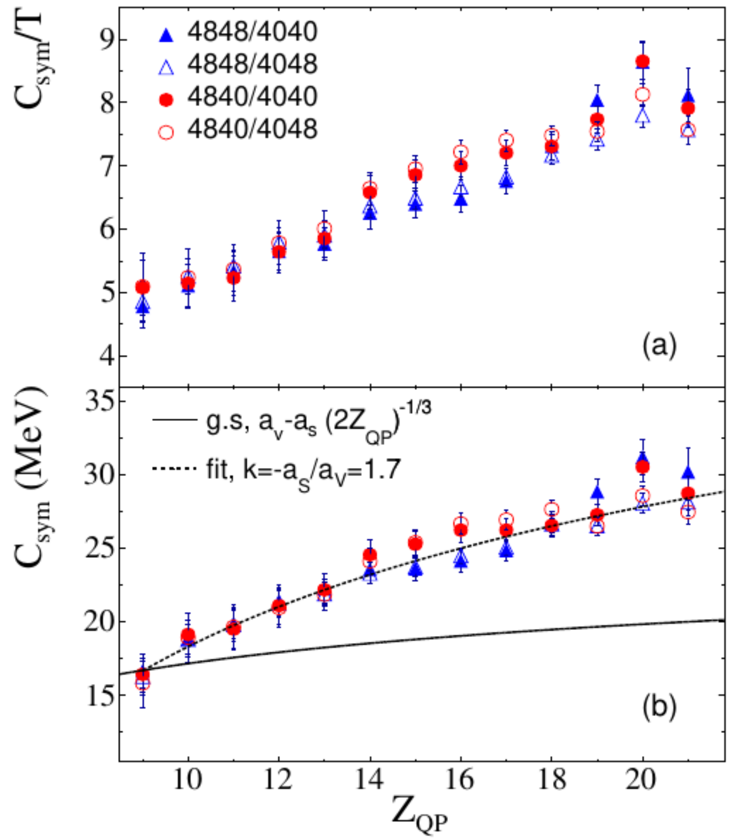
E. Galichet *et al.*, PRC **79**, 064615 (2009)

Isospin transport for semi-peripheral collisions (VI)

Isoscaling for projectile

INDRA-VAMOS data





Q. Fable *et al*., to be submitted (2021)

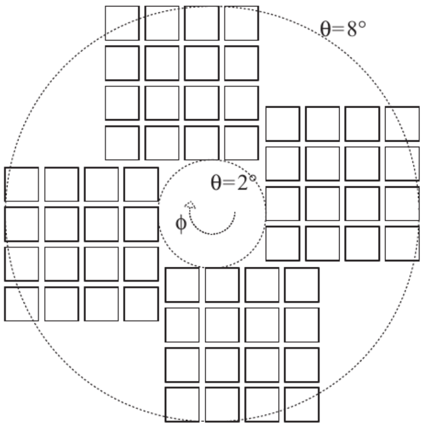
- C_{sym} from isoscaling analysis
- From AMD simulations: $\rho\ /\rho_{sat}$ = ***0.33-0.84***
- Surface-to-volume ratio: $|a_s|/a_v = 1.7$

$$C_{sym}(A) = a_v - a_s\, A^{-1/3}$$

Link to density to elucidate

Isospin transport for semi-peripheral collisions (VII)

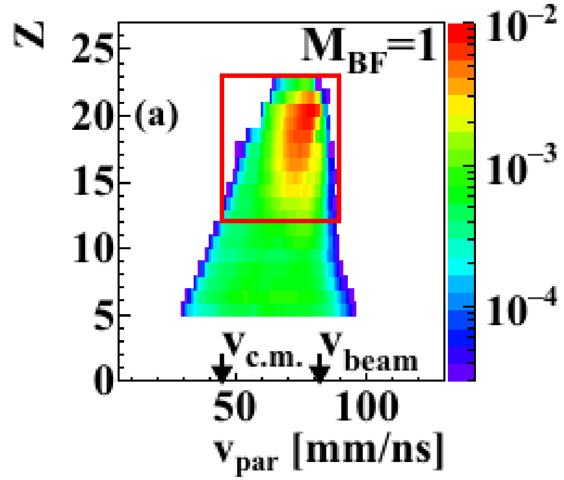
Isospin content of PLF

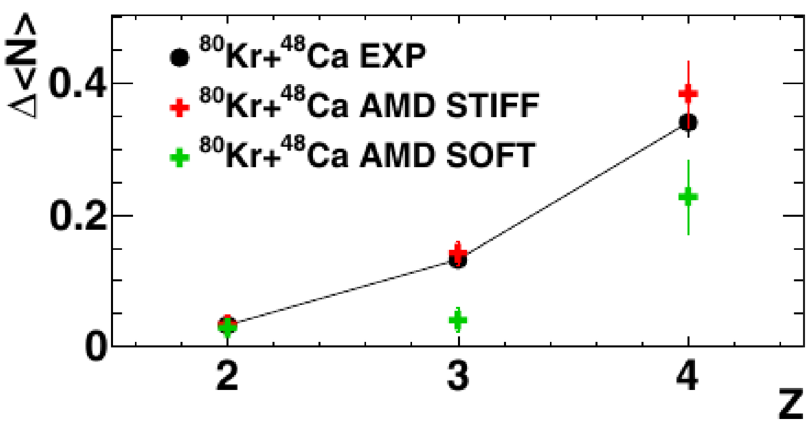


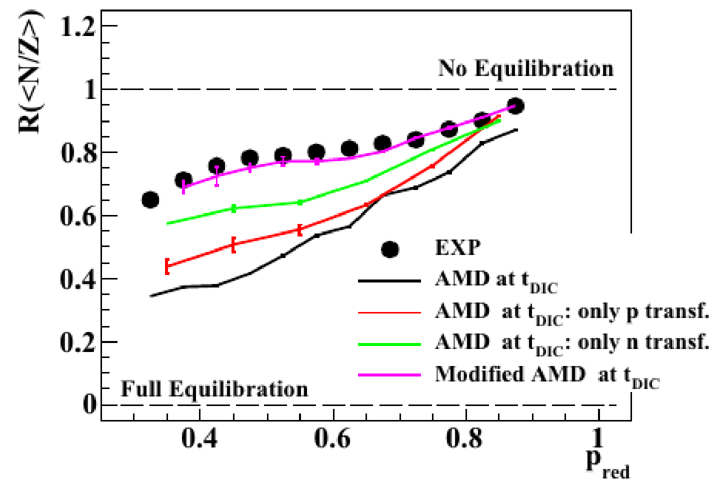
$$R(X) = \frac{2X - X^{4848} - X^{4040}}{X^{4848} - X^{4040}},$$

with: $X=(N/Z)_{max}$

FAZIA R&D setup
4 blocks θ_{lab}=2-8 *deg.*







- Difference between <*N*> of backward/forward particles for the QP residue in ^{80}*Kr*+^{48}*Ca* at *E/A=35 MeV*
- Favours a stiff symmetry energy dependence: L_{sym} *= 108 MeV*

- *AMD+GEMINI* fails to reproduce *R(N/Z)*

- modified proton (p_p) and neutron (p_n) transfert probabilities with: p_p=0.60±0.05 , p_n = 0.3±0.1

Limited acceptance (4 FAZIA blocks)

A. Camaiani, *et al.*, PRC **103**, 014605 (2021)
S. Piantelli, *et al.*, PRC **103**, 014603 (2021)

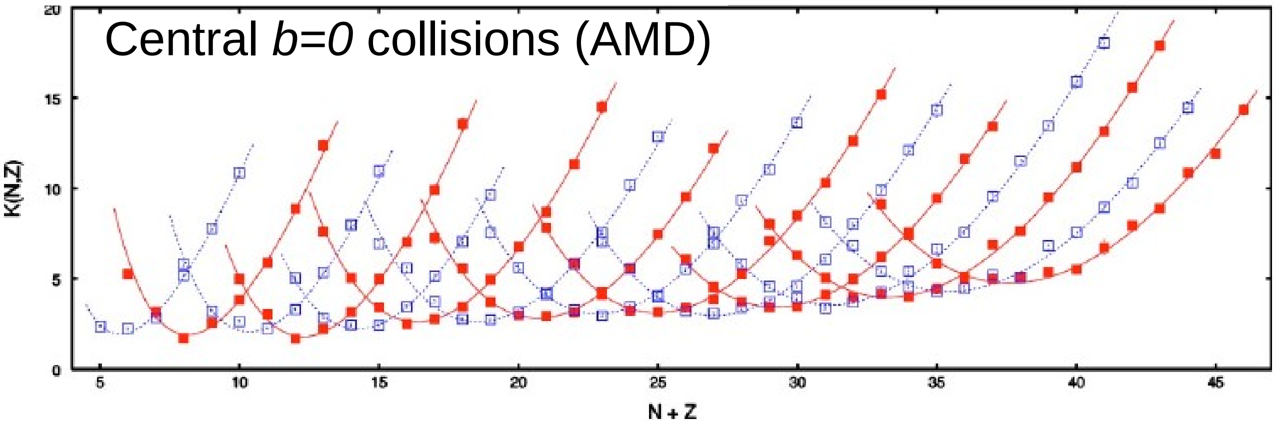
Nuclear matter at low density
Isospin distillation

DDSE at low density : isospin distillation

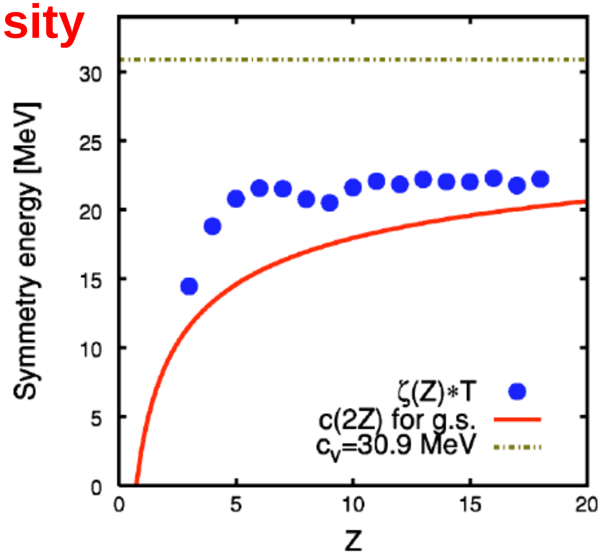
Scaled yields from all $^{40,48,60}Ca+^{40,48,60}Ca$ and $^{46}Fe+^{46}Fe$ at *E/A=35 MeV*

$$K(N,Z) = \sum^{4} w_i(N,Z)[-\ln Y_i(N,Z) + \alpha_i N + \gamma_i(Z)],$$

$$K(N,Z) = \xi(Z)N + \eta(Z) + \zeta(Z)\frac{(N-Z)^2}{N+Z},$$



Cross-check of different estimations
Link to density



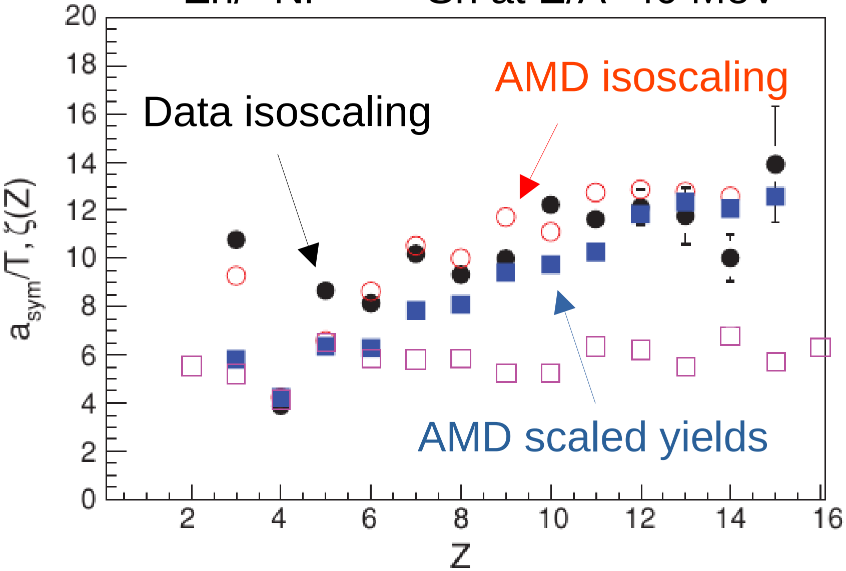
A. Ono, *et al.*, PRC **70**, 041604(R) (2004)

- Isotopic fragment yields over a wide range of *N,Z* provide an estimation of E_{sym} *with surface contribution*

- $E_{sym} \approx 20\text{-}22$ *MeV* for $\rho \approx \rho_{sat}/2 = 0.08\ fm^{-3}$

Fragmentation regime : $$4\frac{c_{\rm sym}(Z)}{T} = \frac{\alpha(Z)}{(Z^2/\langle A\rangle_1^2) - (Z^2/\langle A\rangle_2^2)}$$

$^{64,70}Zn/^{64}Ni+^{112,124}Sn$ at E/A=40 MeV



Z. Chen, *et al.*, PRC **81** , 064613 (2010)

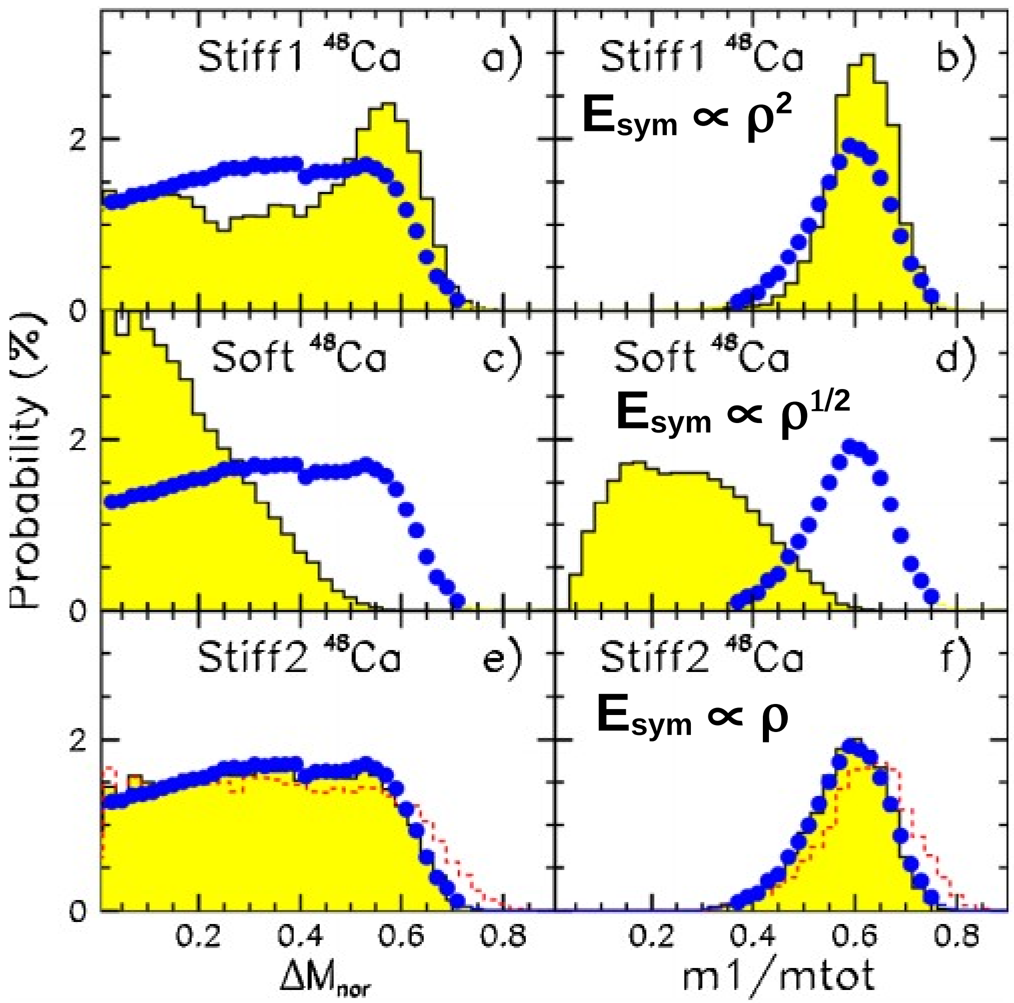
Nuclear matter at ρ_0

Incomplete fusion

Incomplete fusion : isospin dependence (I)

CHIMERA Collaboration
^{40}Ca+^{40,48}Ca at E/A=25 MeV

CoMD-II + GEMINI



$\Delta m_{nor} = (m_1 - m_2)/m_{tot}$

F. Amorini *et al.*, PRL 102, 112701 (2009)
G. Cardella et al., PRC 85, 064609 (2012)

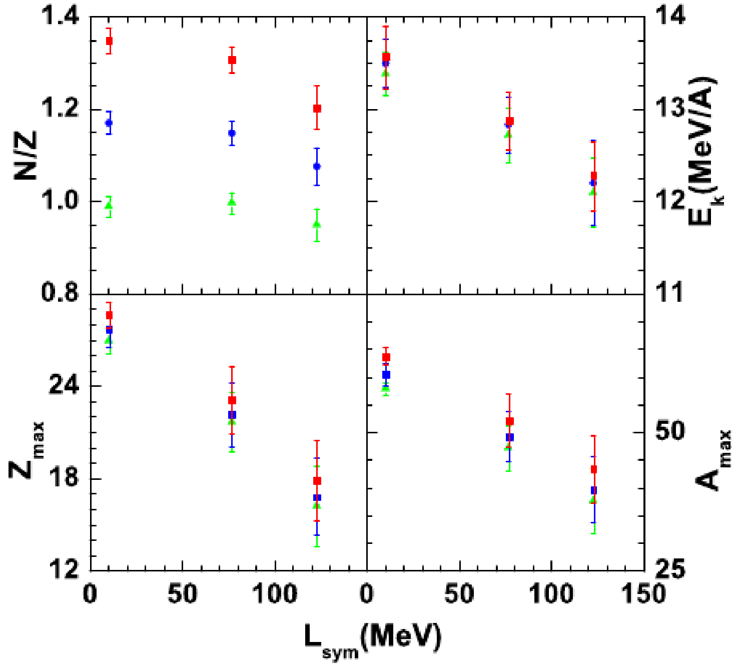
- Neutron-rich system enhances the Incomplete Fusion mechanism
- Binary reactions are at variance favoured for *N=Z* system
- “Moderately” stiff symmetry energy reproduces IF data

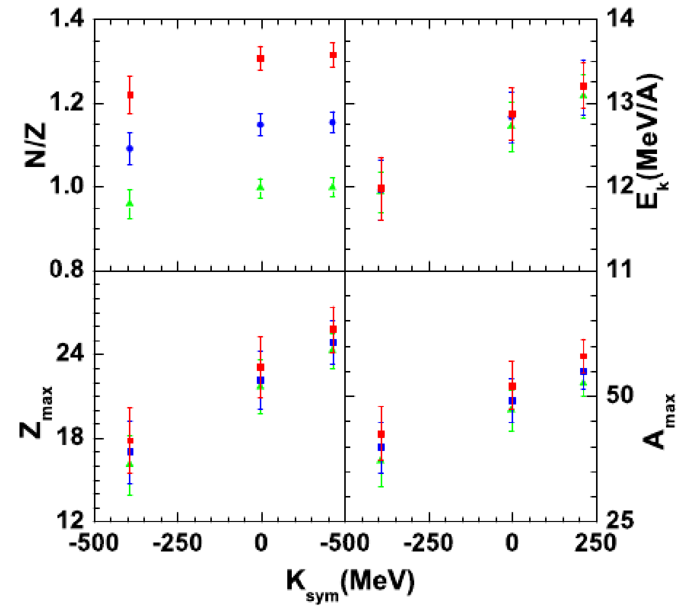
Sensitivity to EOS ?
Density around saturation

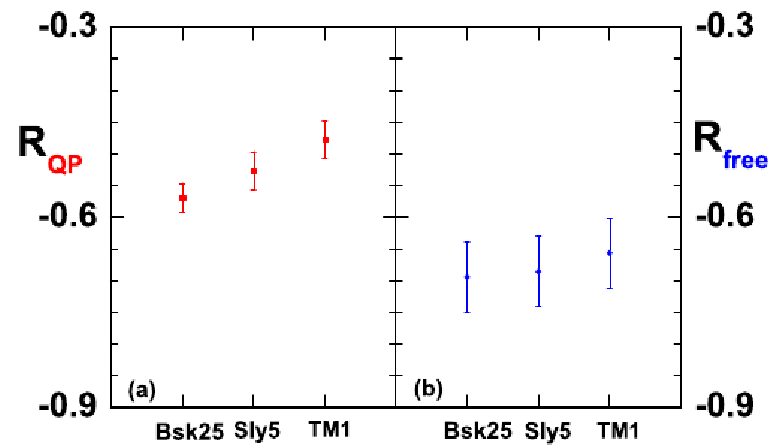
Incomplete fusion : isospin dependence (II)

BUU@VECC-MacGill + **meta-modelling***

$^{58,64}Ni+^{58,64}Ni$ *at E/A = 52 MeV*







Residue Z_{max},A_{max} sensitive to L_{sym},K_{sym}

***$R_{QP}=(N/Z)_{QP,1} / (N/Z)_{QP,2}$* robust for discriminating among different EoS parametrizations?**

*S. Mallik, G. Chaudhuri and F. Gulminelli, PRC **100**, 024611 (2019)*
*S. Mallik and F. Gulminelli, [nucl-th] arXiv:**2009.00985** (2020)*
** J. Margueron, R. Casali and F. Gulminelli, PRC **97**, 025805 (2018)*

DDSE: towards new probes

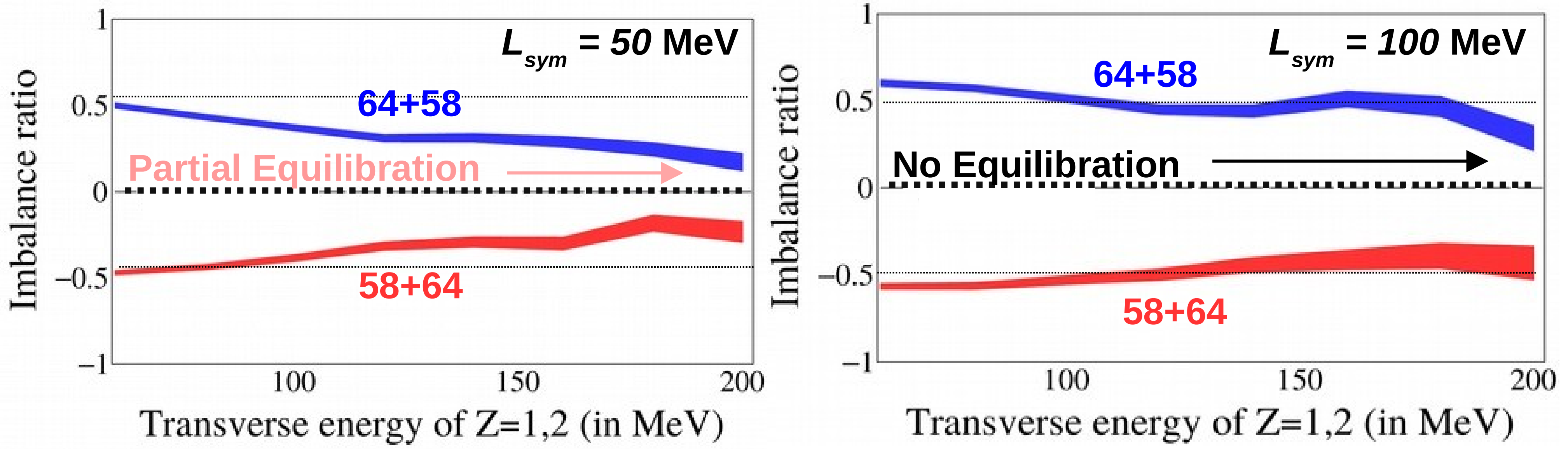
DDSE: toward new probes (I), isospin imbalance ratio

AMD+GEMINI++ filtered simulations : *2.10⁶* events

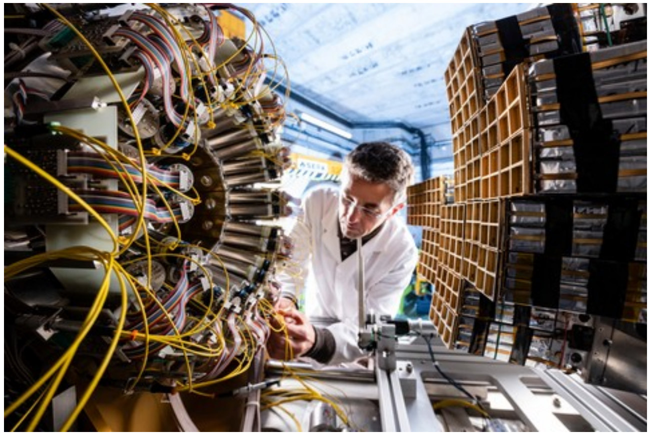
*Imbalance ratio **R** for* $\delta_{PLF} = (N_{PLF}-Z_{PLF})/A_{PLF}$

$R_X = (2X-X_1-X_2)/(X_1-X_2)$

$^{58,64}Ni + ^{58,64}Ni$ @ 32A MeV



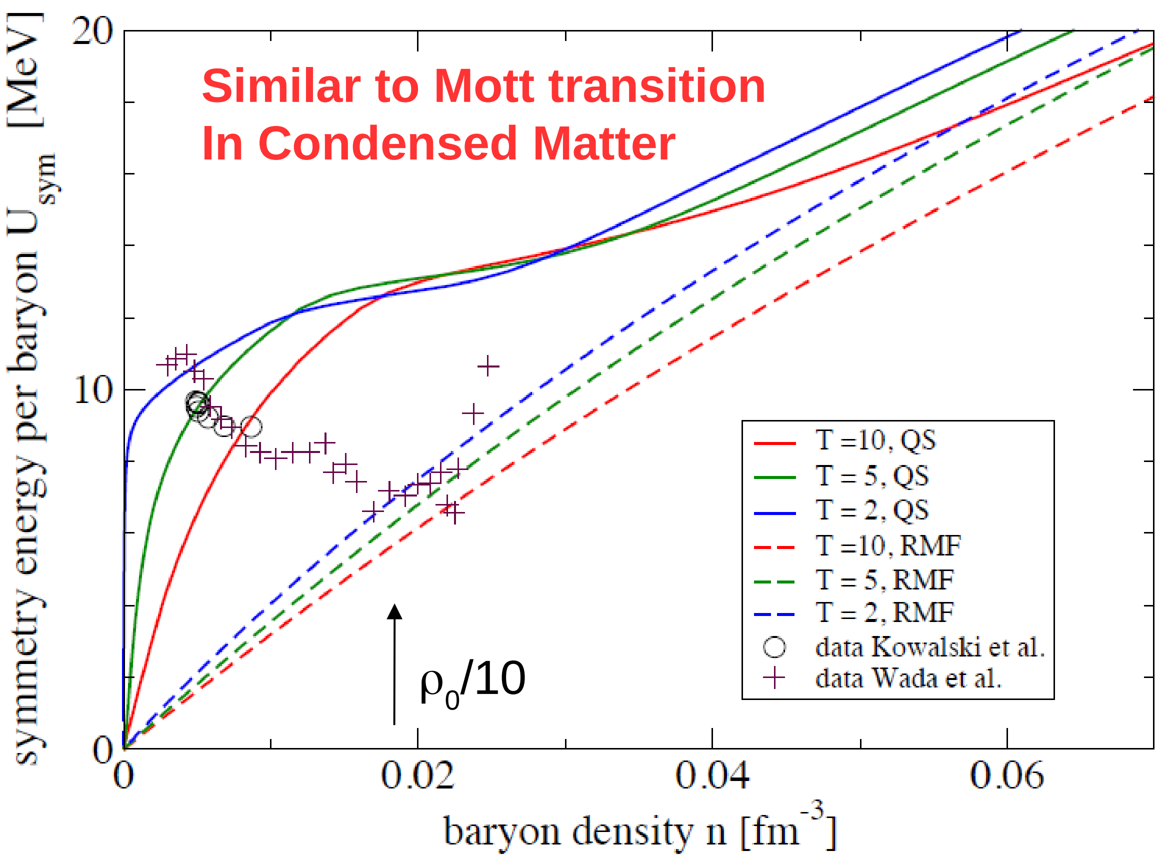
Transverse energy of *Z=1,2* : measured by INDRA
***N/Z* of *PLF* : measured by FAZIA**



E789 : performed in April-May 2019 at GANIL
Results to be released soon !

DDSE : towards new probes (II), at $\rho << \rho_0$, vaporisation

Prediction for the nuclear EOS : symmetry energy at subsaturation density ($\rho/\rho_0 \sim 1/10$) and finite temperature (*T=1-10 MeV*)



Data versus

- **Relativistic Mean Field** (*RMF* without cluster)
- **Quantum Statistical Model** (*QSM*)

K. Hagel, J.B. Natowitz, G. Röpke
Eur. Phys. Journal A **50** (2014) 39

S. Kowalski, *et al.*, PRC **75**, 014601 (2007)
R. Wada, *et al.*, PRC **85**, 064618 (2012)

Relativistic Mean field (no clusters): linear decrease of E_{sym}
QSM : formation of clusters leads to an increase of E_{sym} at (very) low densities

In-medium cluster properties as a function of ρ,T and N/Z

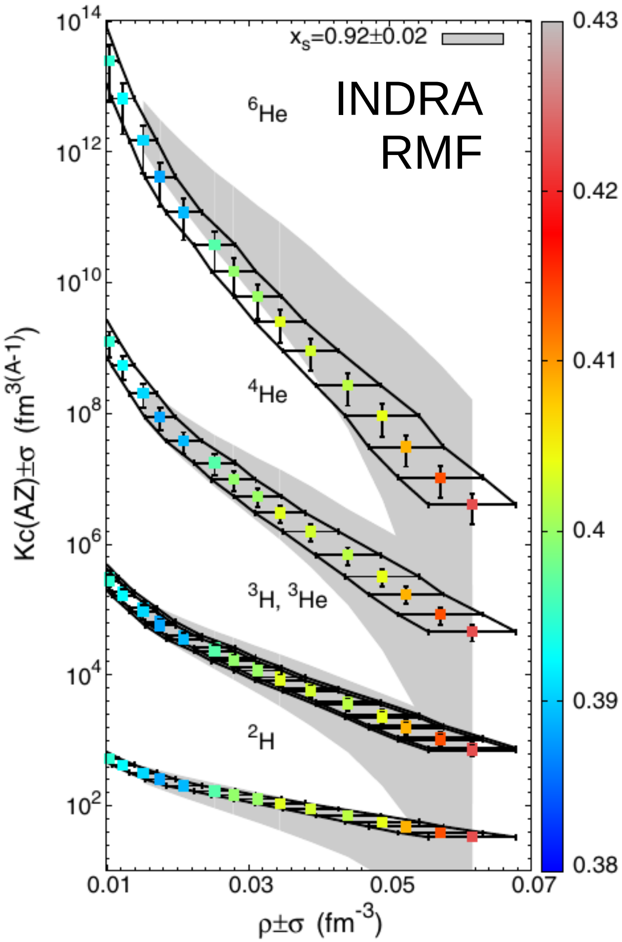
DDSE : towards new probes (II), at $\rho << \rho_0$, vaporisation

From L. Qin *et al.*, PRL **108** (2012), 172701

Equilibrium constant $K_c = \dfrac{\rho(A,Z)}{\rho_p^{\,Z}\,\rho_N^{\,N}}$

[Z,A] ⟷ *Z[p] + N[n]*

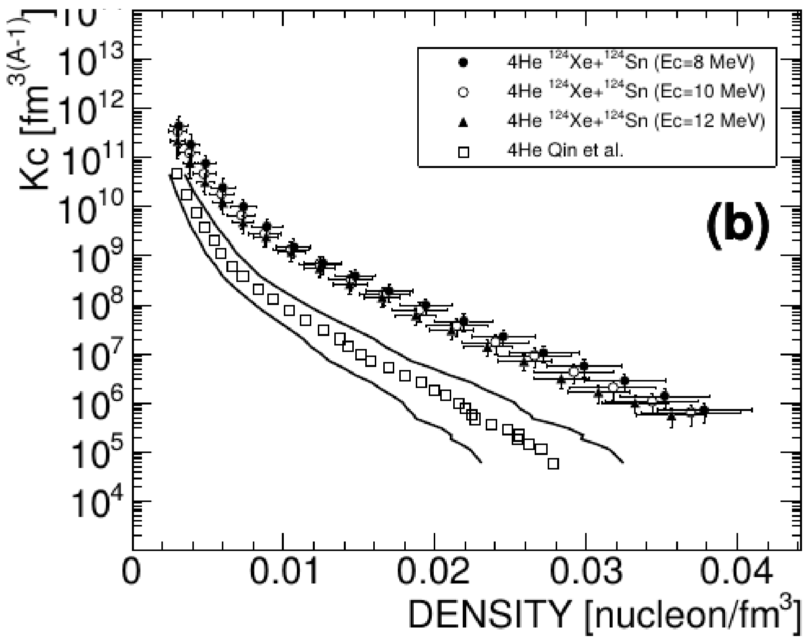
$$\frac{d^3M(A,Z)}{d^3p_A} = R_{np}^N \frac{(2s+1)\ e^{B(A,Z)/T}}{2^A}\left(\frac{h^3}{V_0}\right)^{A-1}\left(\frac{d^3M(1,1)}{d^3p}\right)^A$$



Modification of cluster-scalar coupling

$g_s(A) = x_s A g_s$

H. Pais, *et al.*,
PRC **97**, 045805 (2018)



H. Pais, *et al.*,
PRL **25**, 012701 (2020)

Differences between Texas A&M and INDRA :
- Thermodynamical path *(ρ,T)* not the same

But also : cluster binding energies : in-medium effects

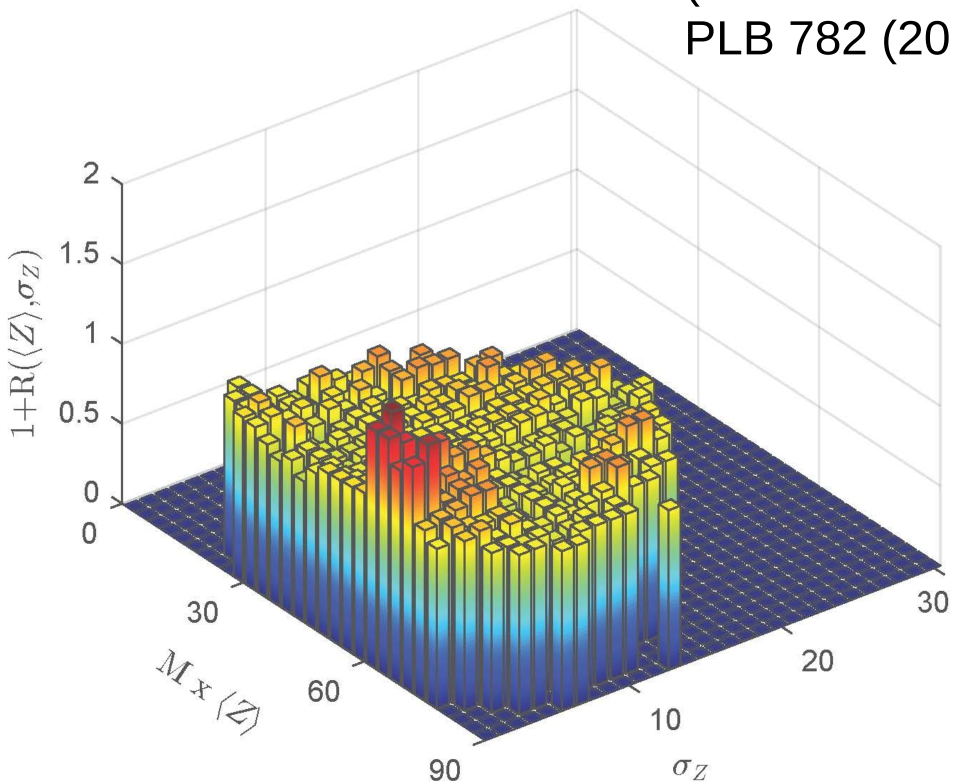
Motivations for a new *INDRA+FAZIA* experiment at *GANIL*
***^{58,64}Ni+^{58,64}Ni at E/A=52,74 MeV, E818* accepted and performed in 2022 with extension to heavier cluster (Z>2)**

DDSE : towards new probes (III), isoscalar *vs* isovector fluct.

Analysis done for *QF* events

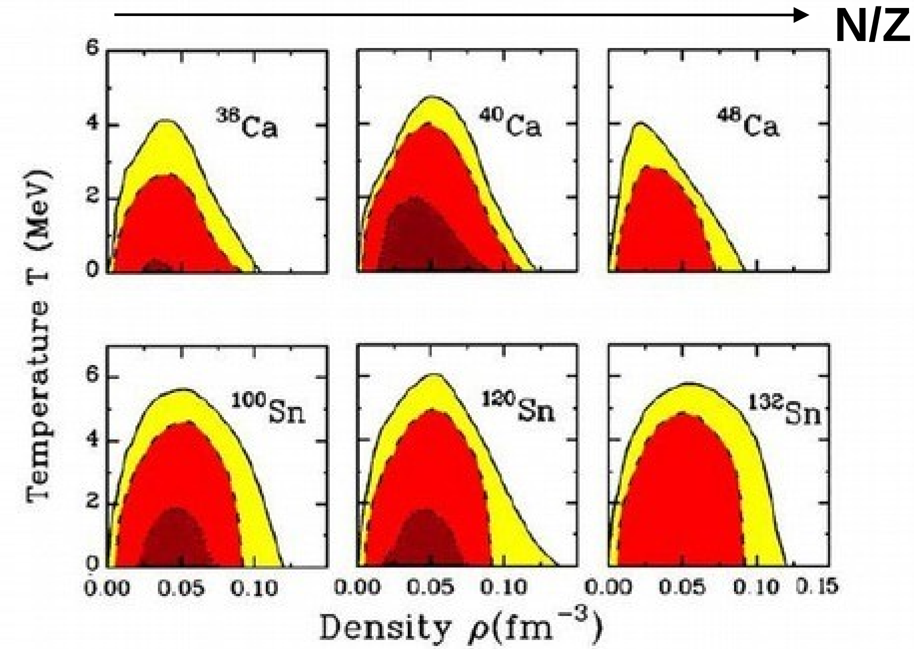
$^{124}Xe+^{112}Sn$ @ 32A,45A MeV
$^{136}Xe+^{124}Sn$ @ 32A,45A MeV

B. Borderie *et al.*
(INDRA Coll.)
PLB 782 (2018)



Spinodal instabilities are indeed reduced in neutron-rich matter !

Spinodal region is reduced



Better with *INDRA+FAZIA* : size correlations (A)

- **1st order LG Phase transition**
- **Equal-sized** fragments are **over-produced**
- Statistical confidence is **largely enhanced** (*10x* statistics) to overcome the **5σ limit** ...

DDSE : conclusions and perspectives

- Large variety of phenomena taking place around Fermi energy
- Incomplete fusion, binary dissipative collisions, neck emission, multifragmentation, Vaporisation, …
- Production of very different nuclear systems from very low densities up to saturation and excited over a broad range of temperatures, typically *T=1-20 MeV*
- Constitute a good environment to study DDSE at moderate densities in order to contribute to solve the tension brought by PREX-2
- Lot of results published so far but the consistency between them is not clear
- Interplay of different timescales for pre-equilibrium, fragment production, isospin and thermal equilibration is a great challenge for transport models

Perspectives

- Need of large scale studies to check the consistency of the results: true for both experimental AND theoretical levels
- Correlate the isospin and density information in a multi-particle framework by looking at intra-event correlations :
  PLF, neck, TLF, Incomplete Fusion, Multifragmentation, ...
- Need of a better evaluation of the sensitivity of the isospin observables: bayesian analyses, sensitivity tests, cross-checks, ...

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IWM-EC 2021

International Workshop on Multi-facets of the Equation of state and Clustering

November 23-26, 2021 | GANIL, Caen

Nuclear dynamics, from fission to multifragmentation
Isospin effects and Equation of State in nuclear reactions
Clustering phenomena and multi-particle decay
Nuclear Equation of State and Astrophysics
New experimental tools, detection techniques and facilities

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Bao An Li (Texas A&M)
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