Fragmentation mechanisms in heavy-ion collisions and stochastic transport models

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Dense Nuclear Matter Equation of State From Heavy-Ion Collisions

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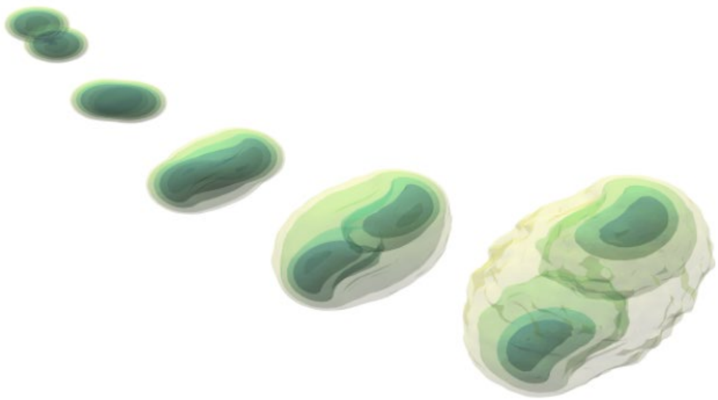
INSTITUTE for NUCLEAR THEORY



Outline

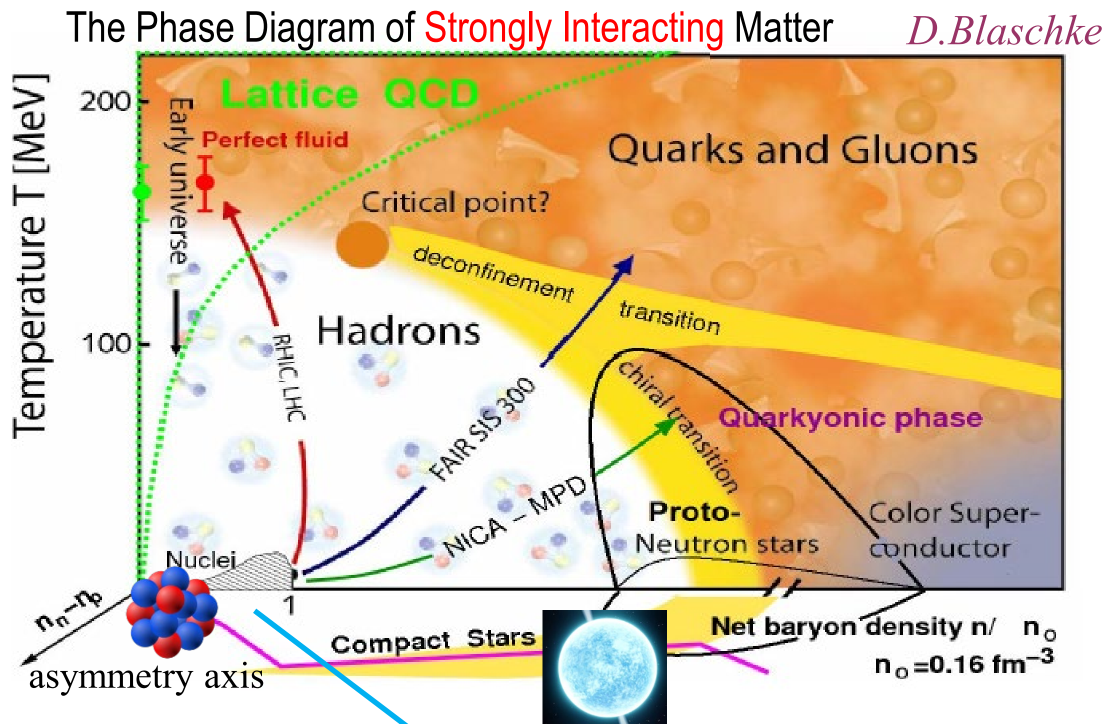
- Liquid-gas phase transitions, spinodal instabilities and fragmentation mechanisms in HIC at Fermi energies

- The tool: (stochastic) transport theories and effective interactions
→ Transport Model Evaluation Project (TMEP)

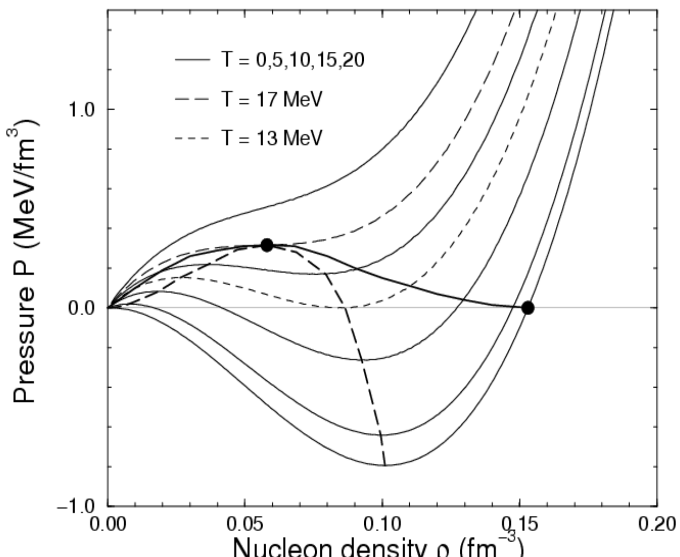
- Sensitivity of selected observables to the specific treatment of n-n correlations

Tentative "Paths" with Heavy Ion Collisions:

- From the dilute (liquid-gas) phase to high baryon and isospin density

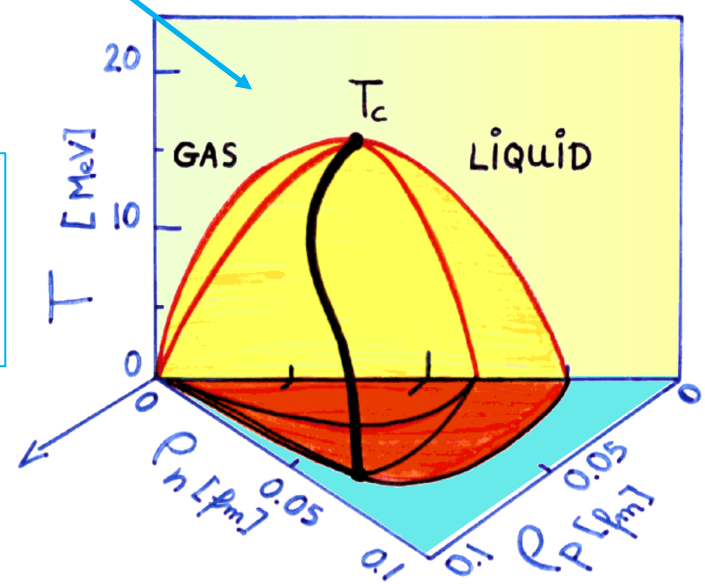


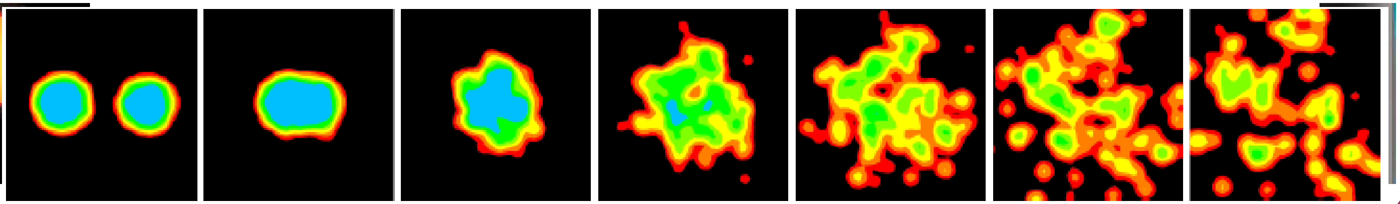
→ HIC *at beam energies below* 100 AMeV



symm. matter

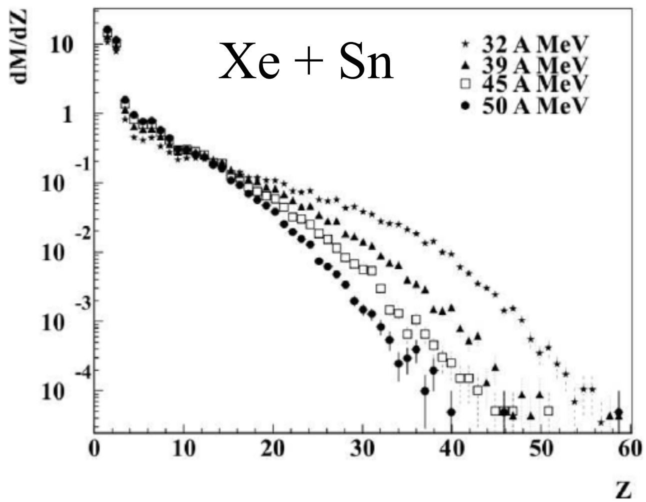
Probe the EoS of (asymmetric) nuclear matter

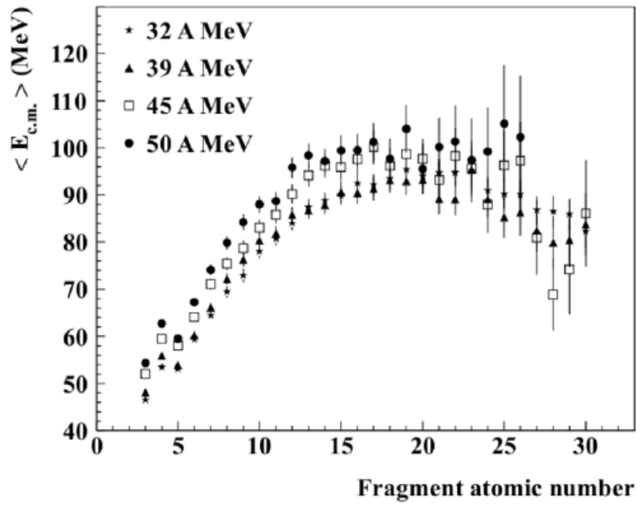




A. Ono

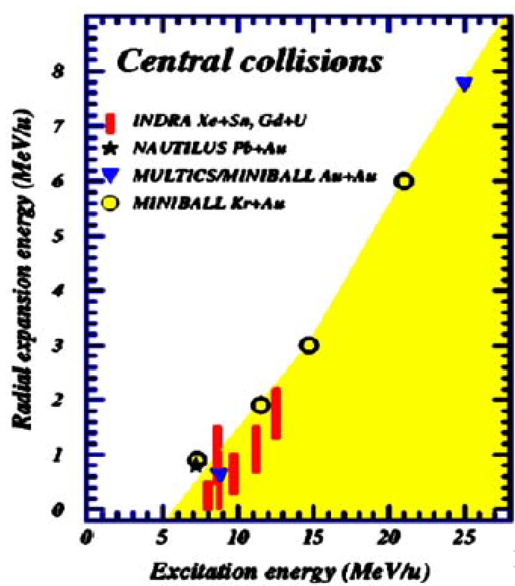
Experimental evidences





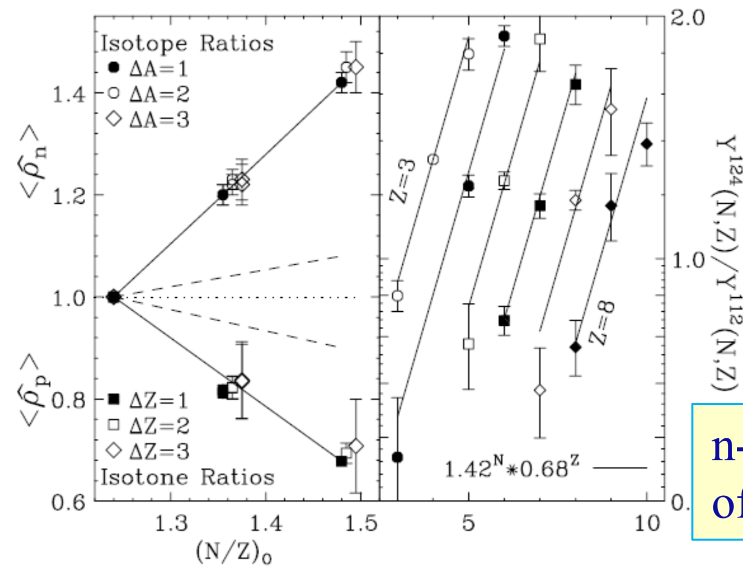
Charge distribution and average kin. energy (Indra data)

S. Hudan, et al., PRC 67 (2003) 064613



Compilation of data on radial flow

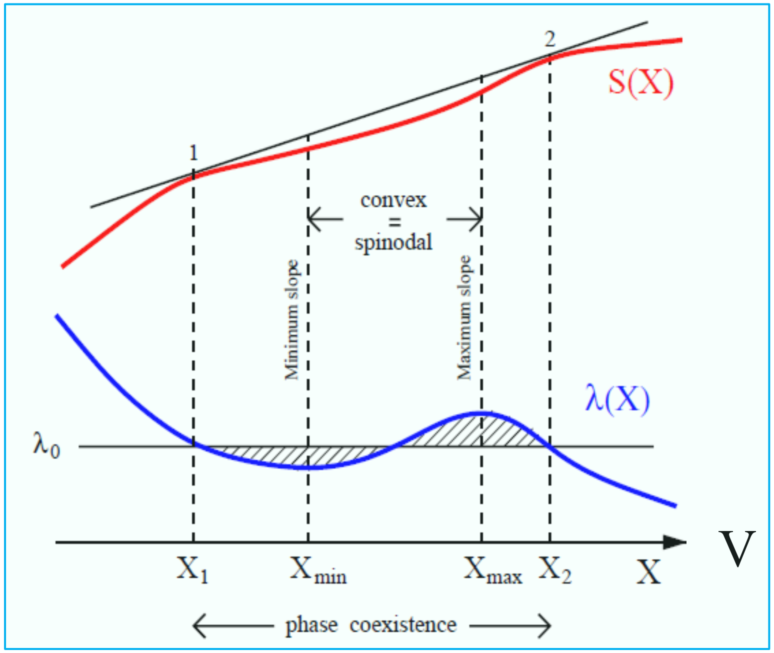
D. Durand, E. Suraud, B. Tamain, Institute of Physics, 2000



Sn + Sn
50 AMeV

n-enrichment of «gas» phase

H.Xu et al., PRL 85 (2000)

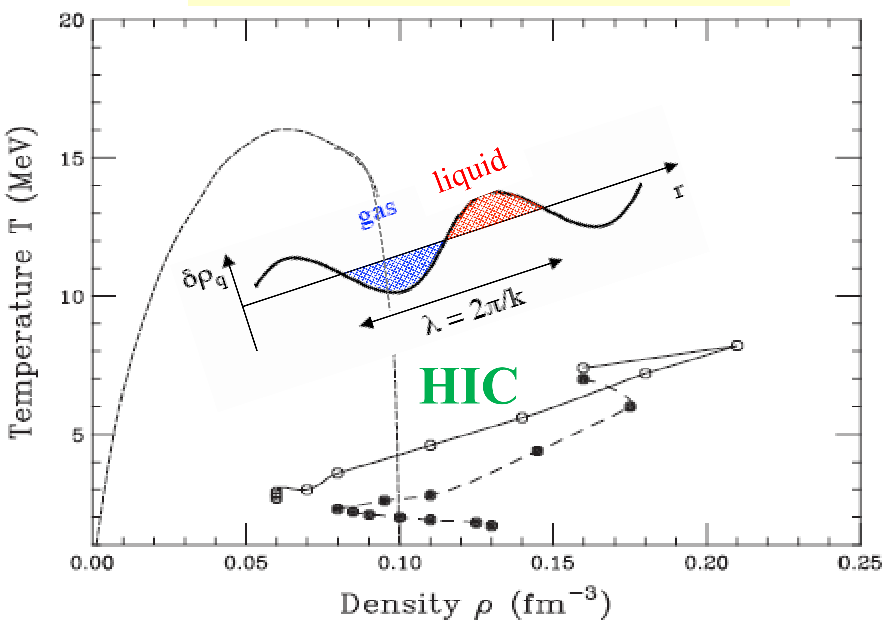


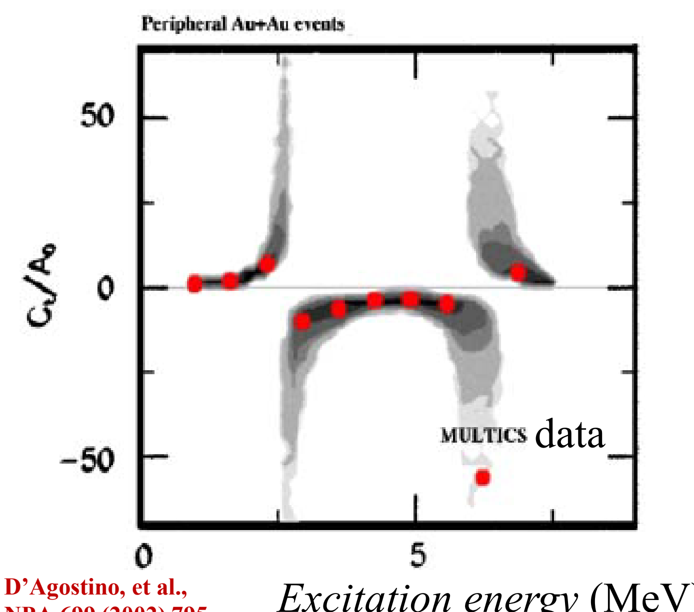
- Phase co-existence and spinodal instabilities:
→ signatures in HIC

- **Nuclear caloric curve**
J. Pochodzalla, et al., PRL 75 (1995) 1040

- **Negative specific heat** in Au + Au at 35 AMeV

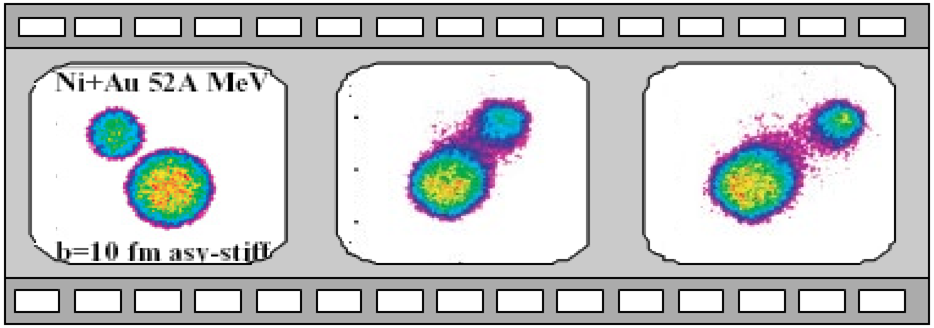
HIC trajectories at 50 AMeV



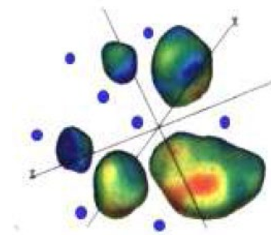


D'Agostino, et al., NPA 699 (2002) 795.

The nuclear many-body problem



- Mean-field (one-body) dynamics
- Two-body correlations



two-body density matrix — *one-body density matrix*

$$\rho_2(12,1'2') = \rho_1(1,1')\rho_1(2,2') + \delta\sigma(12,1'2')$$

one-body

$$H = H_0 + v_{1,2}$$

Mean-field (H_0) — ***Residual interaction*** ($v_{1,2}$)

Time evolution

ρ_1 : one-body density

$$i\hbar \frac{\partial}{\partial t}\rho_1(t) = [H_{eff}, \rho_1(t)] + K(\rho_1) + \delta K(\rho_1, \delta\sigma)$$

TDHF — **ETDHF**

$$K = F(\rho_1, |v|^2)$$

Average effect of the residual interaction

$$\delta K = F(v, \delta\sigma)$$

$$< \delta K >= 0$$

$$< \delta K \delta K > \rightarrow$$ *Fluctuations*

Modeling the many-body dynamics

Quantum Stochastic Mean Field (QSMF)

$$i\hbar \frac{d\rho^{(n)}}{dt} = \left[h(\rho^{(n)}), \rho^{(n)}\right]$$

TDHF +
→Fluctuations in the initial conditions:

$$\overline{\rho_{ij}^{(n)}(t_0)} = \delta_{ij} n_i,$$

$$\overline{\delta\rho_{ij}^{(n)}(t_0)\delta\rho_{kl}^{(n)}(t_0)} = \frac{1}{2}\delta_{il}\delta_{jk}\left[n_i(1-n_j) + n_j(1-n_i)\right]$$

Lacroix, Ayik, Yilmaz, PRC(2012)
Lacroix et al., EPJA52(2016)
Simenel, EPJA(2012)

Boltzmann-Langevin (BL) approach

Collision integral

$$K = g\sum_{234} W(12;34)\left[\bar{f}_1\bar{f}_2 f_3 f_4 - f_1 f_2 \bar{f}_3\bar{f}_4\right]$$

Transition rate W interpreted in terms of hard 2-body scattering

$$\bar{f} = 1 - f$$

-when statistical fluctuations larger than quantum ones

$$< \delta K(p,t)\delta K(p',t') >= C\delta(t-t')$$

$$C(\boldsymbol{p}_a, \boldsymbol{p}_b, \boldsymbol{r}, t) = \delta_{ab}\sum_{234} W(a2;34)F(a2;34)$$

$$F(12;34) \equiv f_1 f_2 \bar{f}_3\bar{f}_4 + \bar{f}_1\bar{f}_2 f_3 f_4.$$

Abe, Ayik et al., Phys. Rep. 275 (1996)
Chomaz, Colonna, Randrup, Phys. Rep. 389 (2004)
M. Colonna, PPNP 113 (2020)

Main ingredients:

- Effective interaction (self consistent mean-field)
  ex: *Skyrme, Gogny …*

- Residual interaction (NN correlations and fluctuations) → In-medium nucleon cross section

Boltzmann-Langevin dynamics: *Semi-classical approximation*

Chomaz, Colonna, Randrup
Phys. Rep. 389 (2004)
Baran, Colonna, Greco, Di Toro
Phys. Rep. 410, 335 (2005)
Lin and Danielewicz, PRC 99 (2019)
M. Colonna, PPNP 113 (2020)

Transport equation for the one-body distribution function f

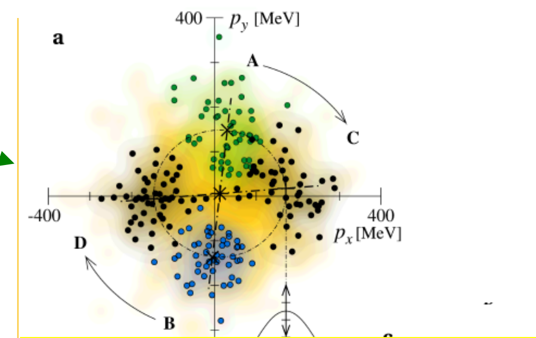
(semi-classical analog of Wigner function)

$$\frac{df(r,p,t)}{dt} = \underbrace{\frac{\partial f(r,p,t)}{\partial t} + \{f,h\}}_{\text{Vlasov}} = k[f] + \delta k$$

Vlasov

BUU

SMF, BLOB models: **Napolitani, Colonna PLB726(2013)**

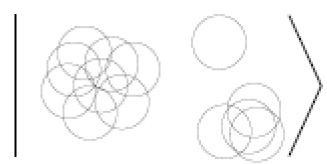


Residual interaction: stochastic NN collisions

Molecular Dynamics approaches (AMD, QMD, UrQMD,…)

A.Ono, *Phys.Rev.C59,853(1999)*
Zhang and Li, *PRC74,014602(2006)*
J.Aichelin, *Phys.Rep.202,233(1991)*
M. Papa et al., *PRC64, 024612 (2001)*
Jun Xu, *PPNP 106 (2019)*

$$|\Phi(Z)\rangle = \det_{ij}\left[\exp\left\{-\nu\left(\mathbf{r}_j - \frac{\mathbf{Z}_i}{\sqrt{\nu}}\right)^2\right\}\chi_{\alpha_i}(j)\right]$$



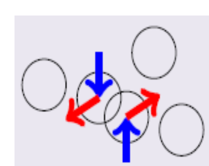
χ_{α_i} : Spin-isospin states $= p\uparrow, p\downarrow, n\uparrow, n\downarrow$

$$\mathbf{Z}_i = \sqrt{\nu}\mathbf{D}_i + \frac{i}{2\hbar\sqrt{\nu}}\mathbf{K}_i$$

ν : Width parameter $= (2.5\ \text{fm})^{-2}$

Stochastic equation of motion for the wave packet centroids Z:

$$\frac{d}{dt}\mathbf{Z}_i = \{\mathbf{Z}_i, \mathcal{H}\}_{\mathrm{PB}} + \text{stochastic NN collisions}$$



The nuclear **effective interaction**

→ • Energy density ε = E/V

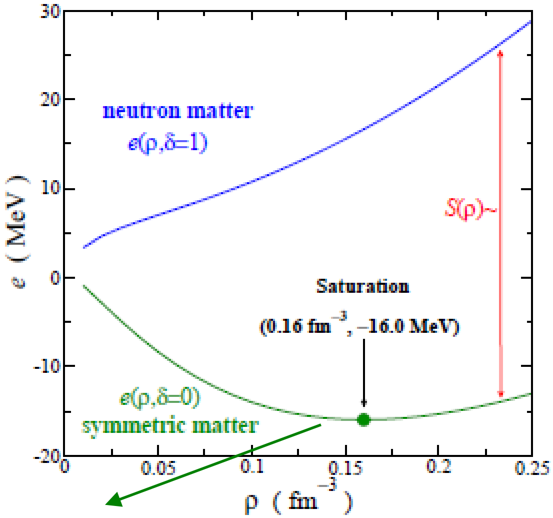
ex: Skyrme eff. interaction

$$\mathscr{E} = \frac{\hbar^2}{2m}\tau + C_0\rho^2 + D_0\rho_3^2 + C_3\rho^{\alpha+2} + D_3\rho^{\alpha}\rho_3^2 + C_{eff}\rho\tau + D_{eff}\rho_3\tau_3 +$$

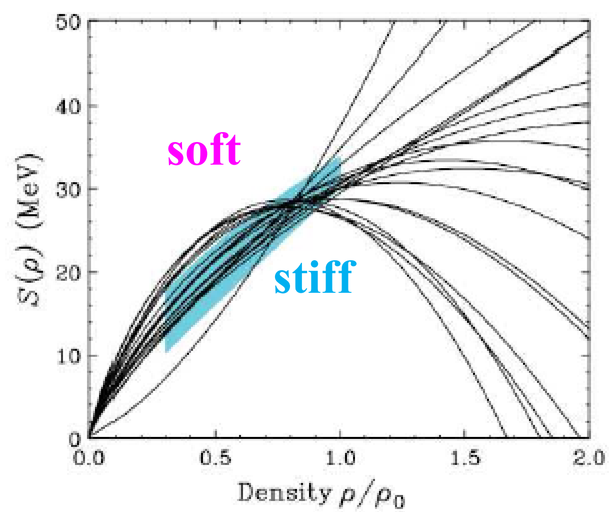
$$+C_{surf}(\bigtriangledown\rho)^2 + D_{surf}(\bigtriangledown\rho_3)^2 + \text{S.O.} + \text{pairing}$$

$\rho = \rho_n + \rho_p \quad \rho_3 = \rho_n - \rho_p \qquad \tau = \tau_n + \tau_p, \tau_3 = \tau_n - \tau_p$ *Kinetic energy densities*

• For homogeneous matter at equilibrium ⟶ EOS



compressibility K



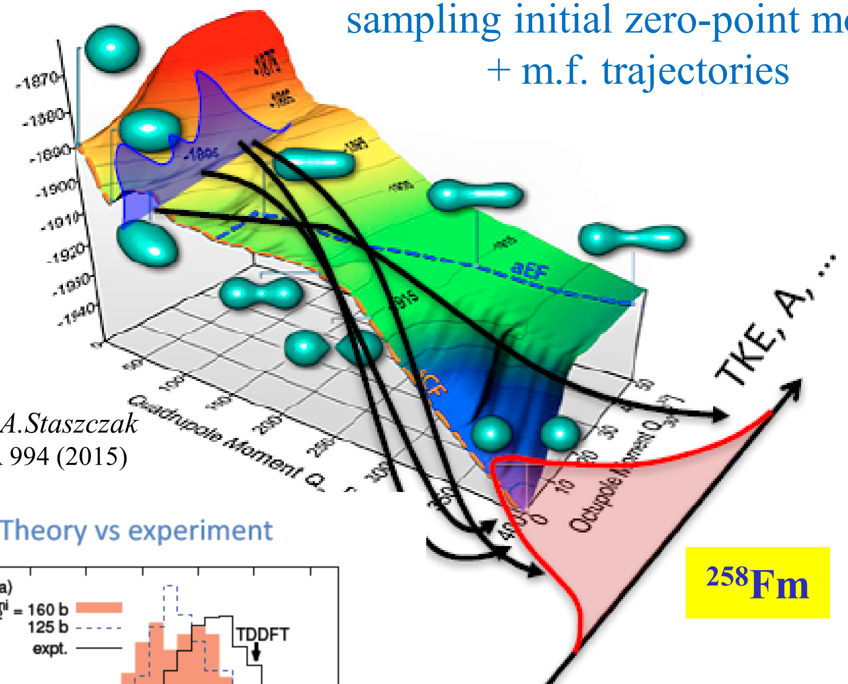
Symmetry Energy $S(\rho) = C_{sym}(\rho)$

$$E/A(\rho, \delta) = E/A(\rho, \delta=0) + S(\rho)\delta^2 + O(\delta^4)$$

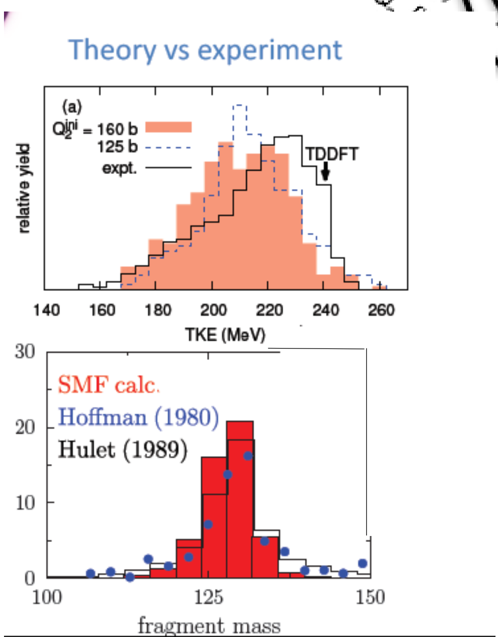
$$\delta = \frac{\rho_n - \rho_p}{\rho}$$

Beyond the independent particle picture: from fission to fragmentation at Fermi energies

Quantum SMF:
sampling initial zero-point motion
+ m.f. trajectories



from A.Staszczak
NPA 994 (2015)



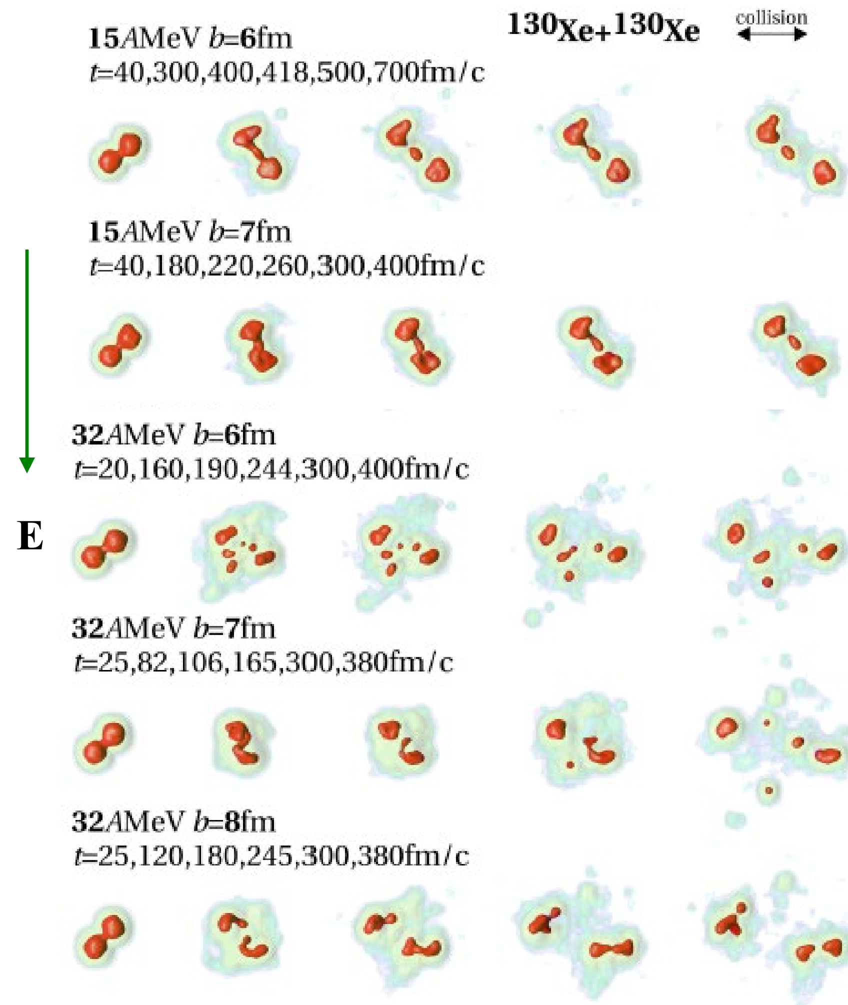
Kinetic energy and mass distribution for fission of superfluid ^{258}Fm

Tanimura, Lacroix, Ayik
Phys. Rev. Lett. (2017), EPJA52(2016)

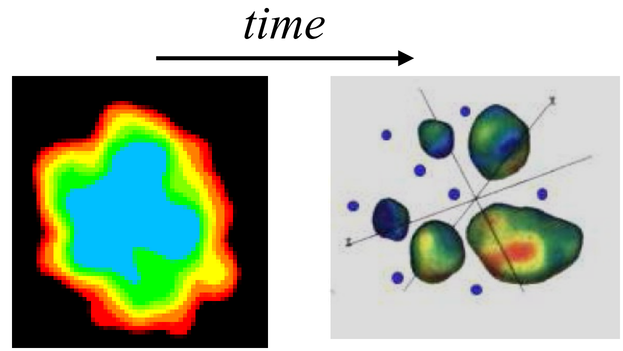
M.Bender et al., JPG 47 (2020)
Ren, Vretenar et al., PRL 128 (2022)

Fragment evolution
@ Fermi energies (**BLOB**)

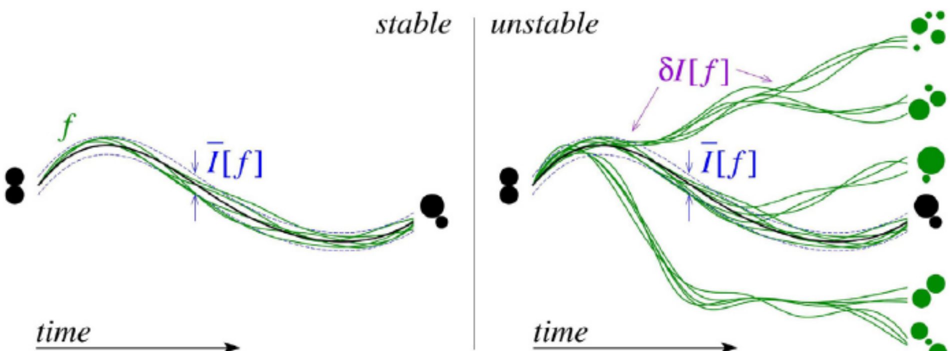
surface + volume instabilities !



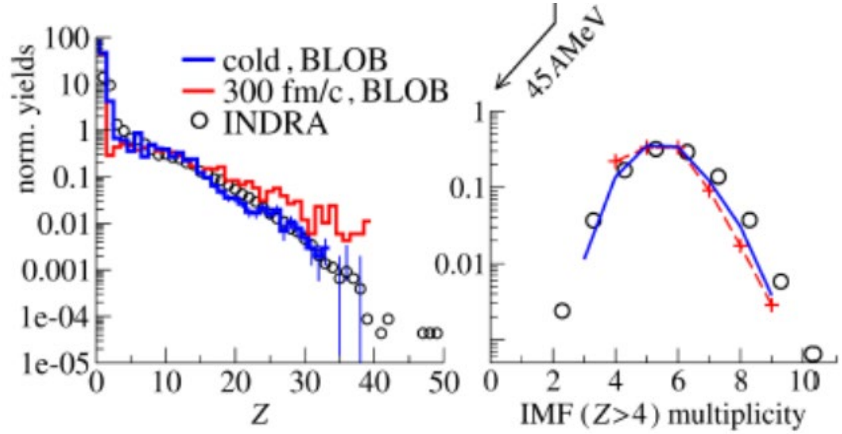
Why are fluctuations important ?



- Crucial role in presence of instabilities: Symmetry breaking and fragment formation
→ Sensitivity to incompressibility K



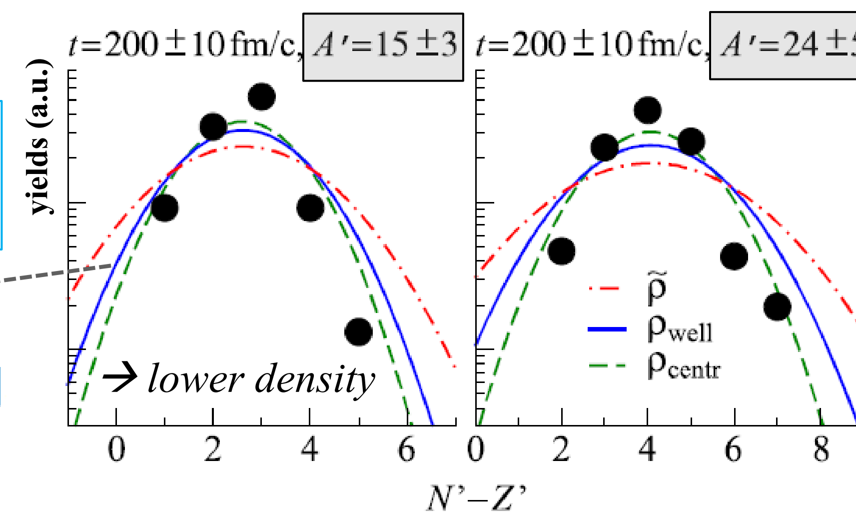
Napolitani, Colonna
EPJ,117 (2016)
M.Colonna, PPNP113 (2020)



$^{136}Xe + ^{124}Sn$, central E/A = 45 MeV/A

BLOB *results*

- Fluctuations lead to variances for fragment distributions (ex: isotopic distributions)



$$Y \approx \exp[-(\delta^2/A')C_{sym}(\rho)/T]$$

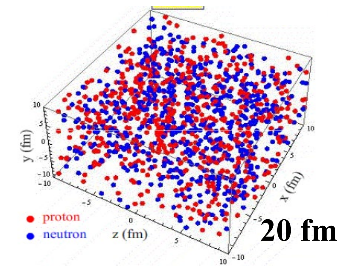
$\delta = N - Z$ *symmetry energy*

Napolitani, Colonna
PRC96, 054609 (2017)

Transport model comparison (TMEP): *where do we stand ?*

- Box simulations: test of **mean-field dynamics** (only **Vlasov**)

Symmetric matter, T = 0, compressibility K = 500 MeV



Sinusoidal perturbation:

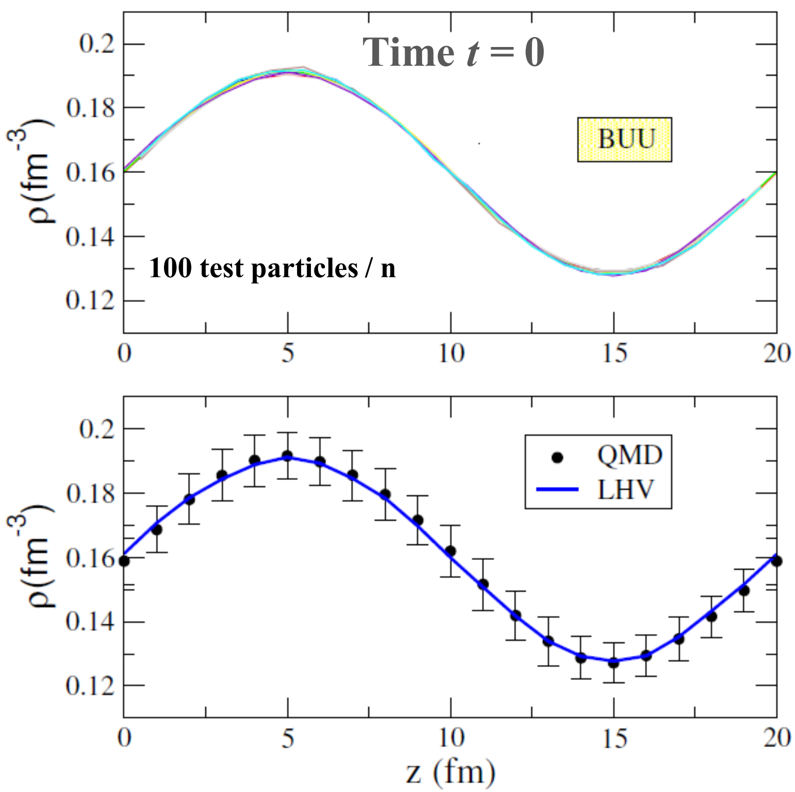
$\rho(z,t=t_0) = \rho_0 + a_\rho \sin(kz)$

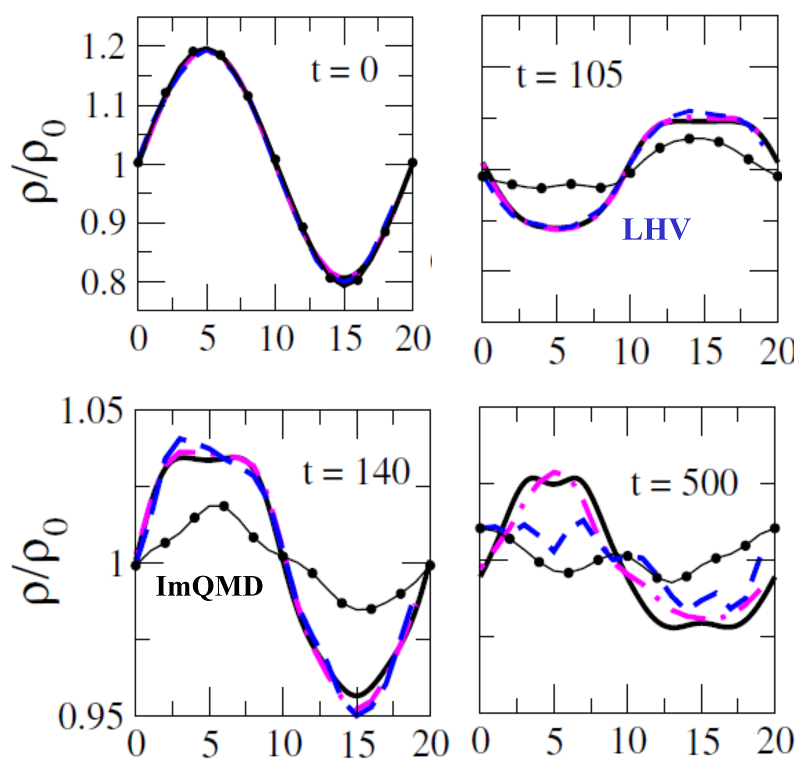
$k = 2\pi/L$, $L = 20$ fm $a_\rho = 0.2\,\rho_0$

➢ *Time propagation:* Large **damping** in QMD !

----- Exact solution (Deformed Fermi Sphere – *A.Ono*)

- - - LHV (BUU-Like) 100 TP - - - LHV 2500 TP



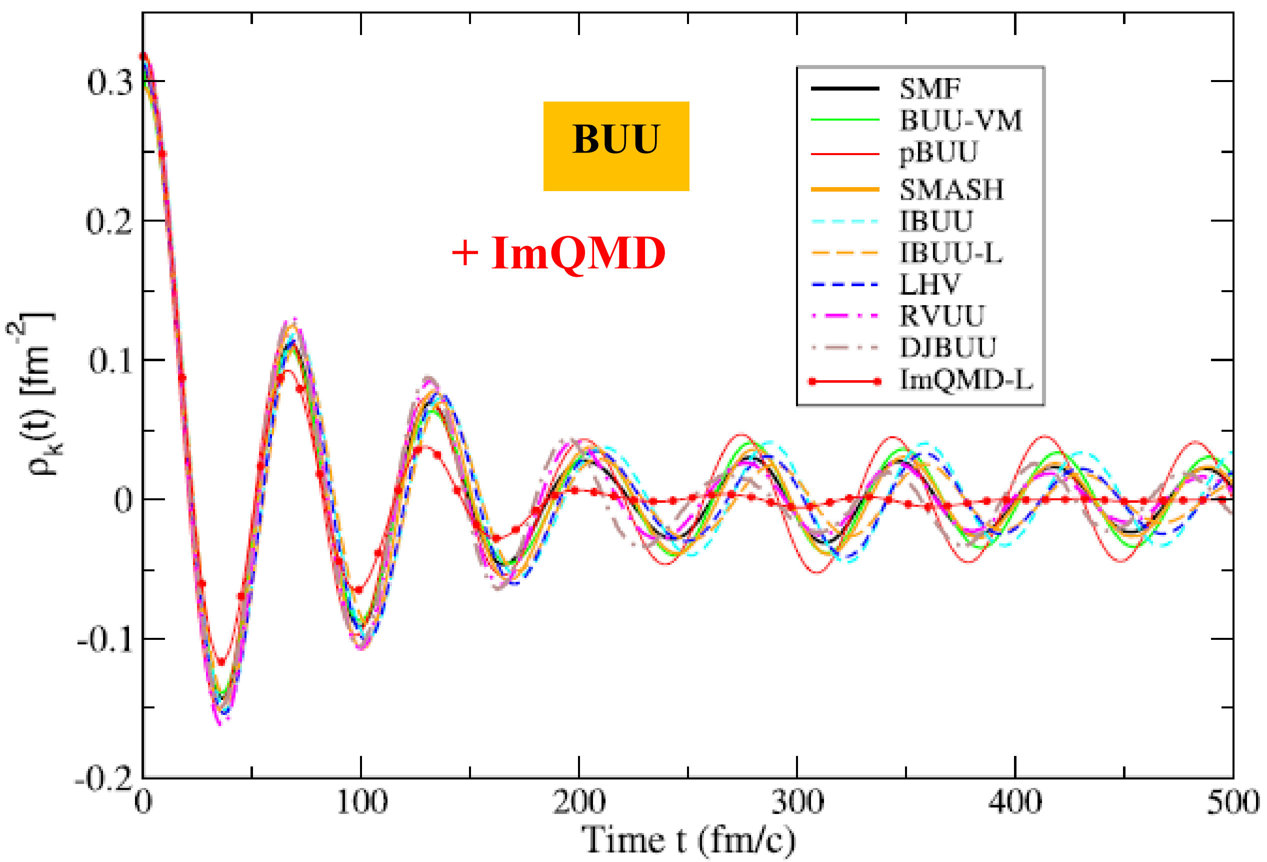


Colonna et al (TMEP), PRC104, 024603 (2021)

Oscillation frequency and damping effects

- **BUU**: dynamics is sensitive to the details of the **effective interaction** (*Skyrme* or *covariant formulation…*), though EoS is the same !
- **QMD**: the **Gaussian width** can be **tuned** to reproduce the analytical expectation for the m-f potential

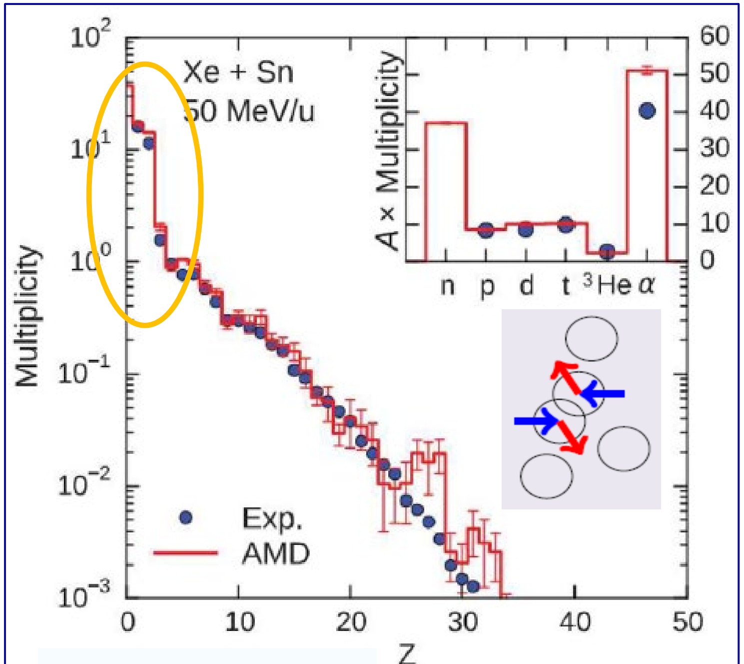
Fourier transform of density oscillations



Colonna et al (TMEP), PRC104, 024603 (2021)

Fragmentation mechanisms: role of fluctuations /correlations

central collisions

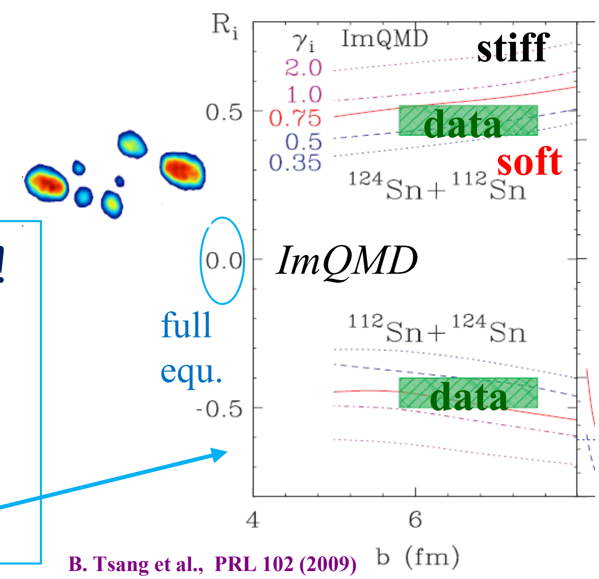


AMD + clusters

- IMF charge distribution well reproduced by **QMD** models K. Zbiri, et al., PRC 75 (2007) 034612 and *stochastic* ***mean-field*** models Napolitani, Colonna EPJ,117 (2016)

- Light cluster production is sensitive to the treatment of (higher order) n-n correlations

A. Ono, Il Nuovo Cimento C 39 (2016) 390
A.Ono, PPNP 105 (2019)

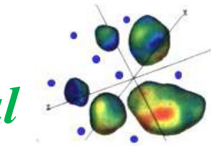


- **Isospin features** provide more stringent constraints !

- *N/Z of «gas» and «liquid» phases*
- Fragment <N>/Z vs. Z, isotopic distributions
- *Charge equibration between projectile and target*

B. Tsang et al., PRL 102 (2009)
Lynch & Tsang PLB 137098 (2022)

Effects of clustering on fragment features



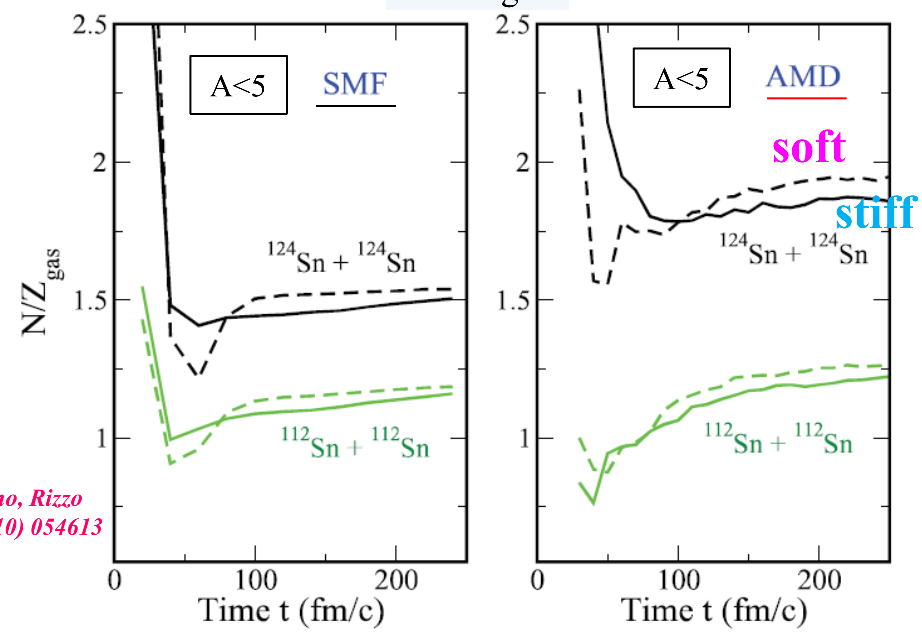
central

- Clustering effects more pronounced in QMD → protons are bound in heavier clusters

→ *Larger* **N/Z** *of the «***gas***» phase*

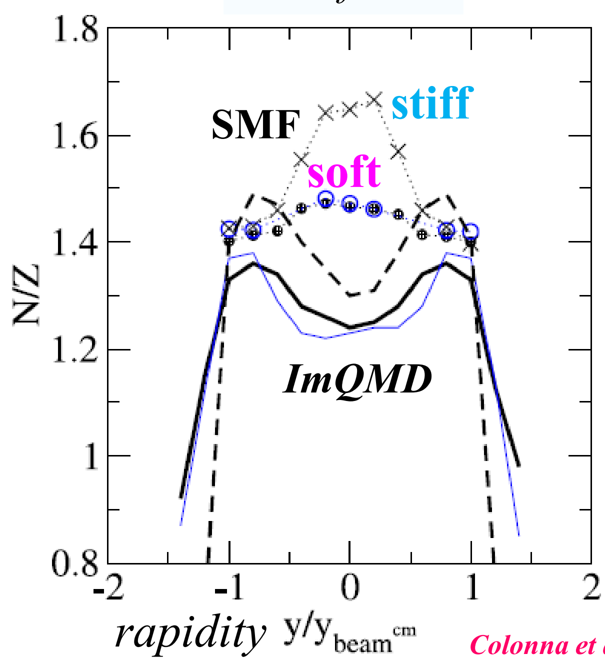
→ **IMF** *are less n-rich in* AMD

N/Z gas

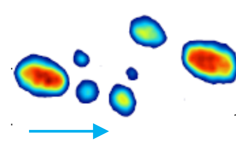


Colonna, Ono, Rizzo
PRC 82 (2010) 054613

N/Z *of* IMF

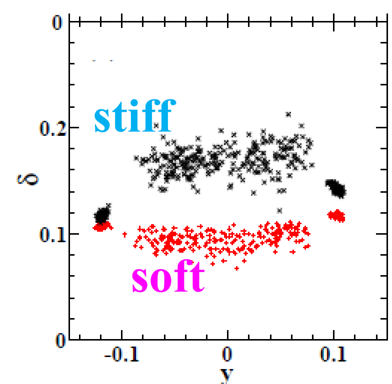


b= 6 fm



$^{124}Sn + ^{112}Sn$, 50 AMeV

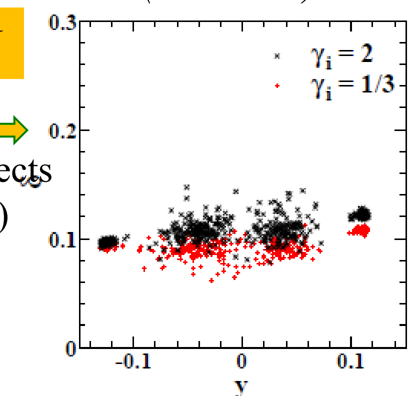
w/o clusters



pBUU

Cluster effects (d,t,He^3)

(clusters)



Colonna et al, EPJ. A 50 (2014) 30

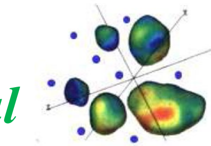
Coupland et al., PRC 84, 054603 (2011)

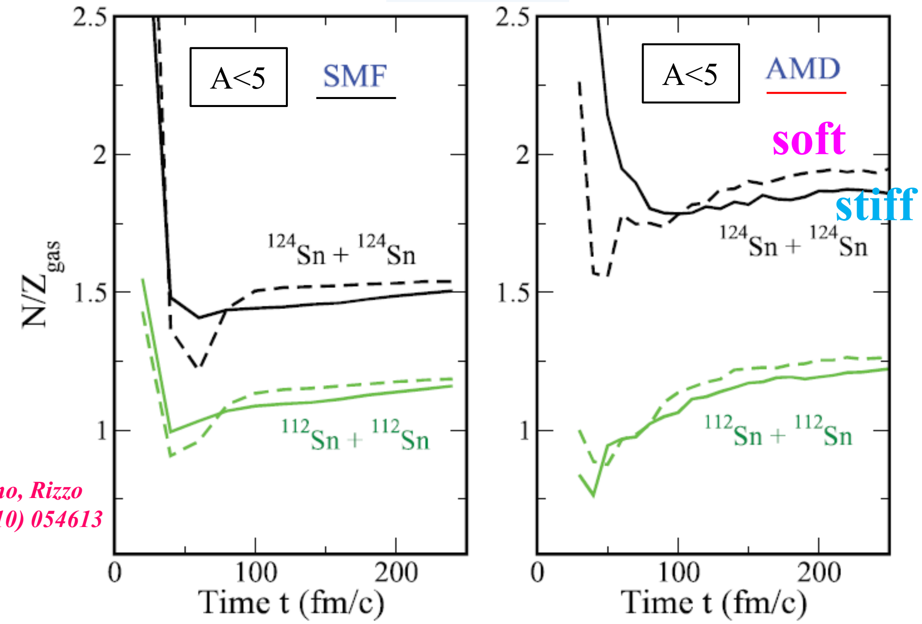
Effects of clustering on fragment features

- Clustering effects more pronounced in QMD → protons are bound in heavier clusters
→ *Larger* **N/Z** *of the «***gas***» phase*
→ **IMF** *are less n-rich in* QMD

N/Z gas

central

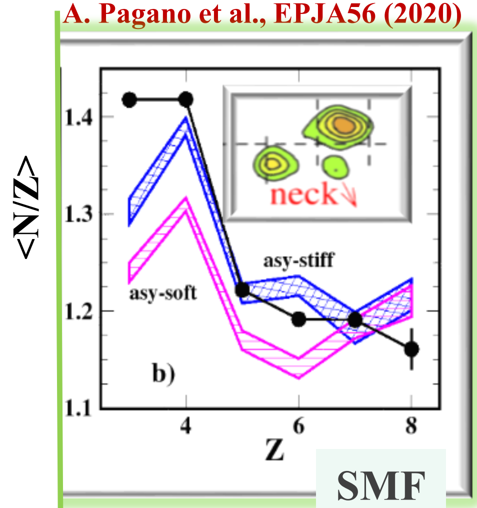




Colonna, Ono, Rizzo
PRC 82 (2010) 054613

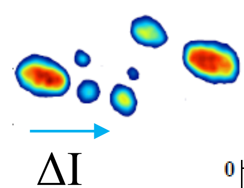
N/Z *of* IMF

E. De Filippo et al., PRC(2012)
A. Pagano et al., EPJA56 (2020)

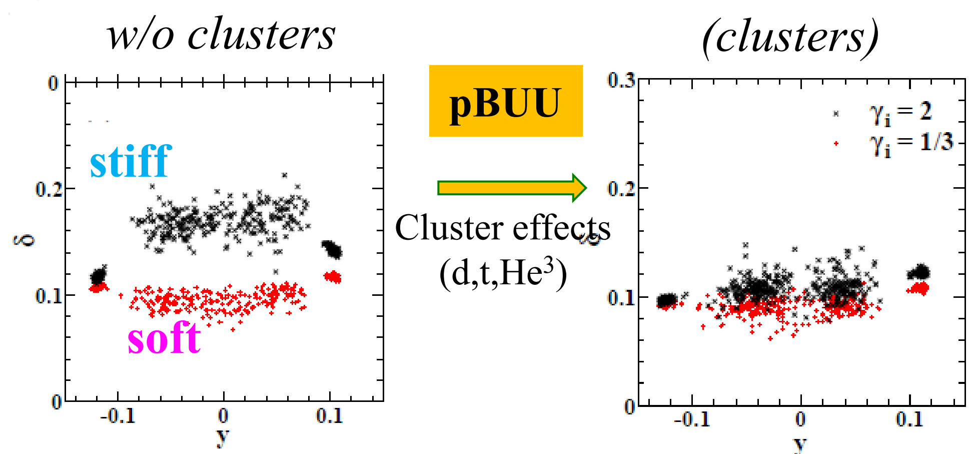


Sn + Ni, 35 AMeV (LNS data)

b= 6 fm



^{124}Sn +^{112}Sn, 50 AMeV



Coupland et al., PRC 84, 054603 (2011)

Summary and perspectives

➢ Transport theories are crucial tools to link the nuclear effective interaction (and **EoS**) to physical observables emerging from the **HIC phenomenology**
→ *Strong* **synergy** *between* **theory** *and* **experiments**

- *What improvements on the constraints of the EoS can we expect from future HI experiments ?*

HIC at **Fermi energies** (explore the *liquid-gas region* of the **EoS**, *fragmentation* and the role of the *symmetry energy)* → *new experiments* are planned with new generation 4π detectors (ex: FAZIA@GANIL).
→ *New facilities* for exotic beams could be exploited.

- *What development is necessary for transport codes to address the above question ?*

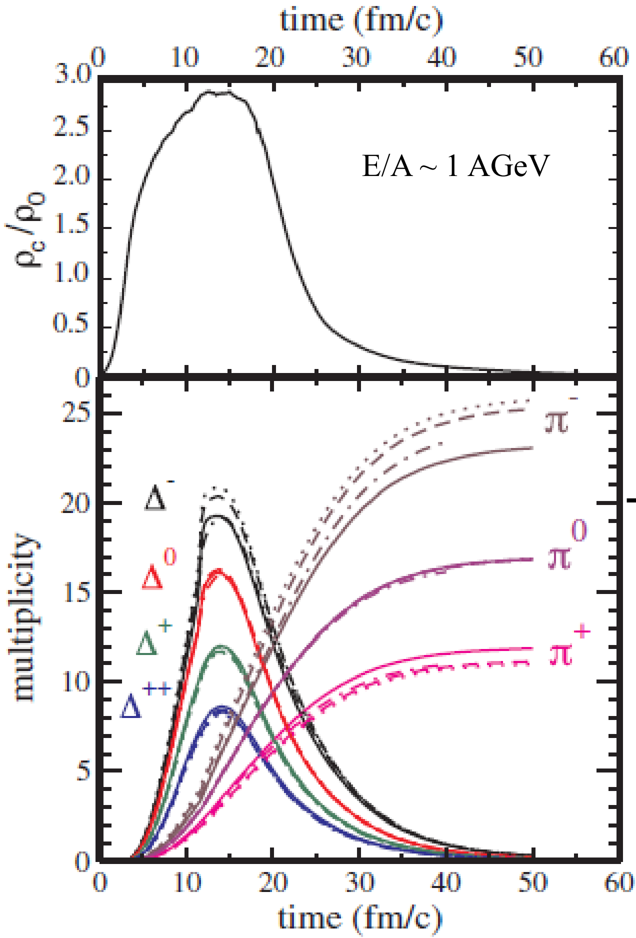
Test (higher order) **n-n correlations** in transport codes → **TMEP** +
comprehensive comparisons with available and new *experimental data*
(*light cluster emission*, *fragment N/Z* as a function of rapidity, *charge equilibration*…):

- formation mechanisms of **light clusters**
- **short range correlations** (off-shell transport dynamics ?)

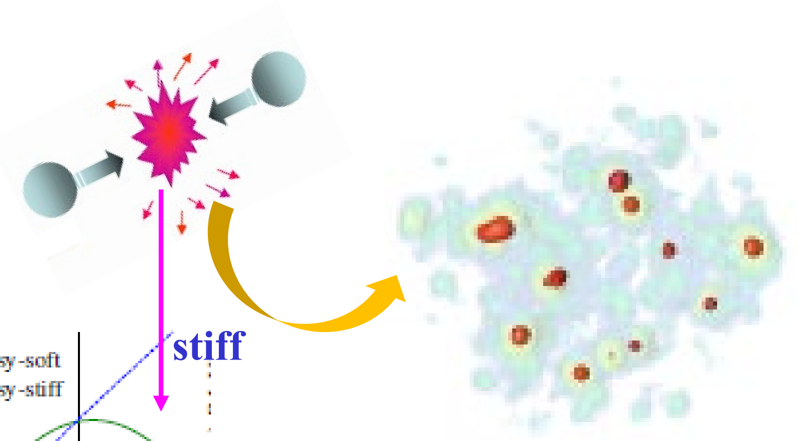
Back-up slides

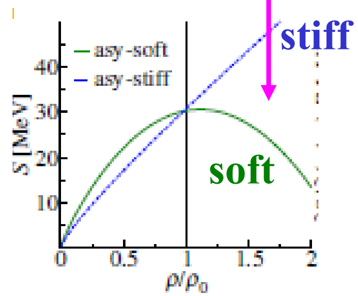
Impact of clustering on reaction dynamics at relativistic energies

- Meson production can probe the **high density** phase
- Interplay with ***cluster** emission* !



→ Pion ratios

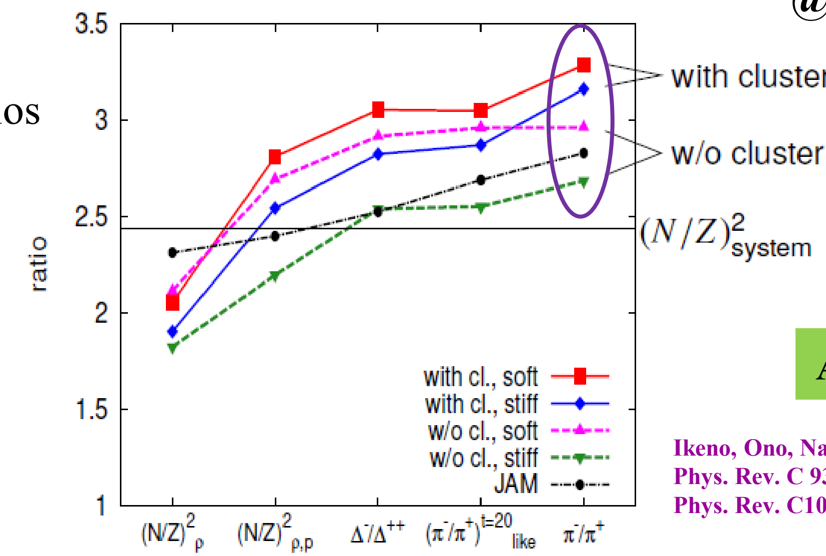




symmetry energy

$^{132}Sn + ^{124}Sn$, 270 AMeV

@ RIKEN



AMD

Ikeno, Ono, Nara, Onishi,
Phys. Rev. C 93 (2016)
Phys. Rev. C101 (2020)

Conclusions and outlook

- Transport theories provide a suitable description of the rich **HIC phenomenology**, linking the nuclear effective interaction to physical observables.

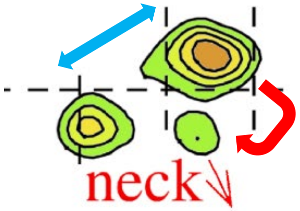
- **Synergy between theory and experiments**:
  more refined theories and more selective experiments can improve the present constraints on the **symmetry energy** from Heavy Ion Collisions

→ *Comparison of transport models:* TMEP project

- Merging **constraints** from **structure**, **HIC** and **astrophysics**

Collaborators: P.Napolitani (IPN, Orsay), TMEP collaboration

➢ Isospin transport at Fermi energies



Difference between neutron and proton flow:

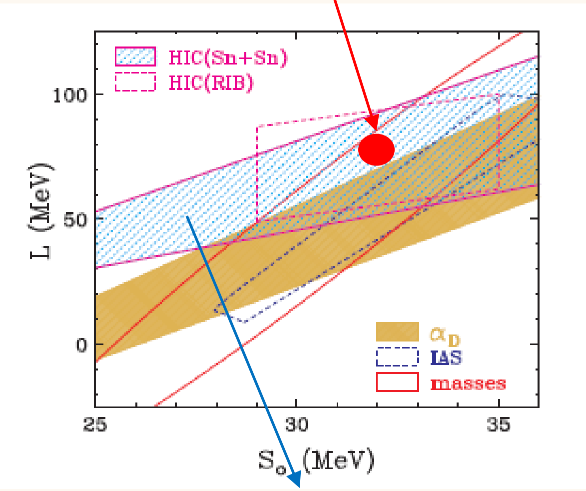
$$j_n - j_p \propto \delta\left(\frac{\partial E_{sym}}{\partial \rho}\right)\nabla\rho - \rho E_{sym}\nabla\delta$$

$$\delta = \frac{\rho_n - \rho_p}{\rho}$$

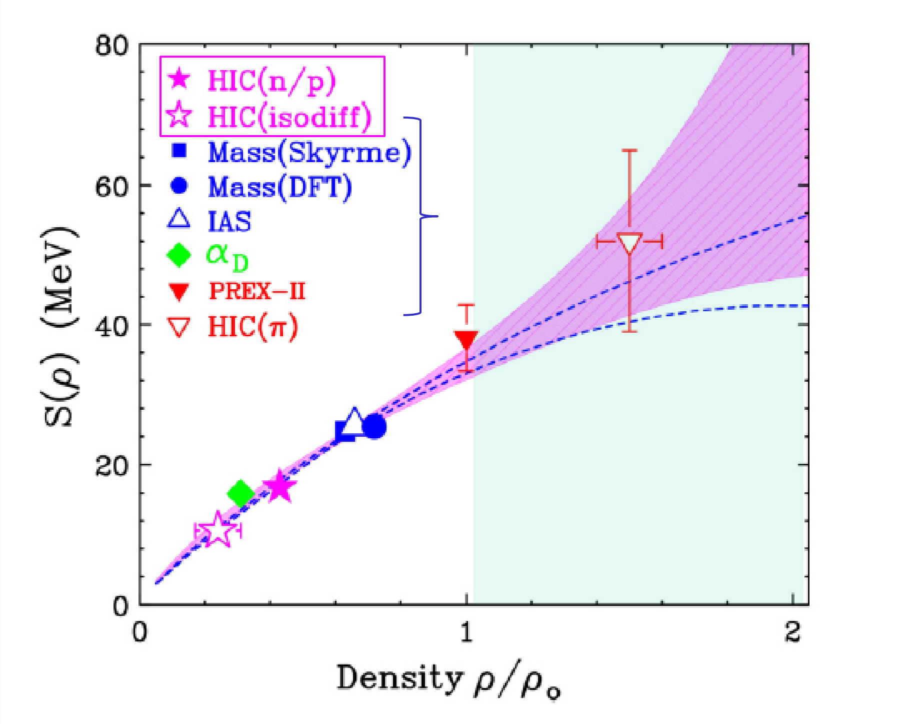
→ Isospin **diffusion** and **migration**

Symmetry Energy: heavy ion constraints

from isospin migration:
L = 75 MeV



from isospin diffusion



C.J.Horowitz et al., Jou. Phys. G41 (2014)

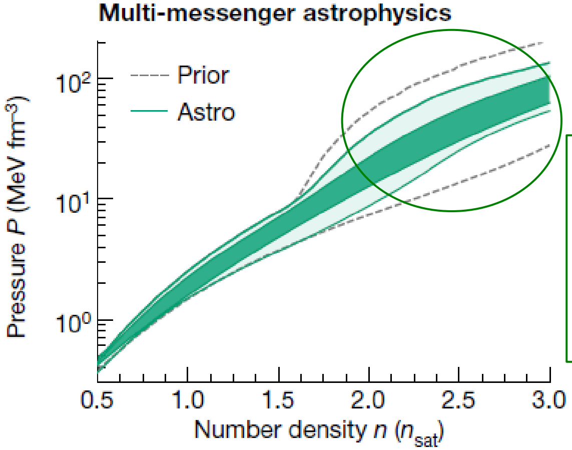
Lynch & Tsang PLB 137098 (2022)

➢ Bayesian Inference on the EoS of Neutron Star Matter

Merging nuclear structure, reactions and astro constraints

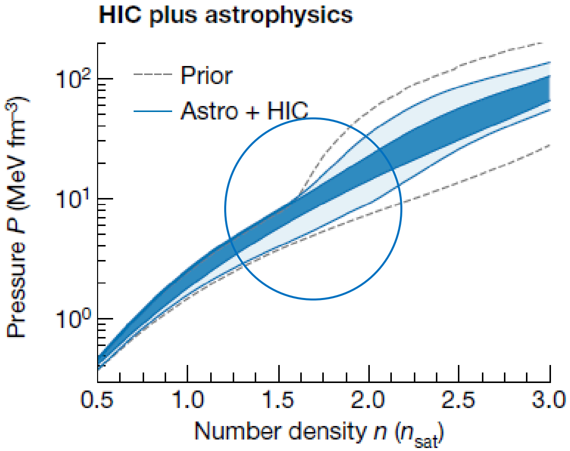
S. Huth et al., Nature 606, 276 (2022)

Astro constraints + **χEFT**



NS masses and radii (NICER)
GW signals
NS mergers

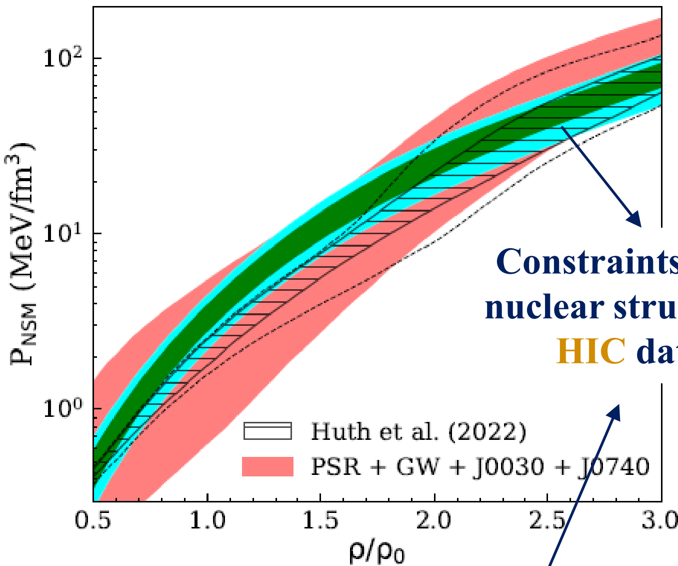
T.Dietrich et al., Science 370 (2020)



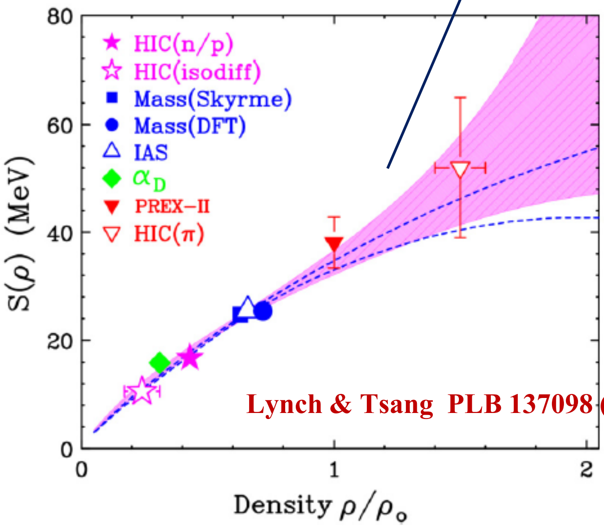
+ collective flows from HIC

P.Russotto et al., PRC 94 (2016)

From C.Y.Tsang, NuSym2022

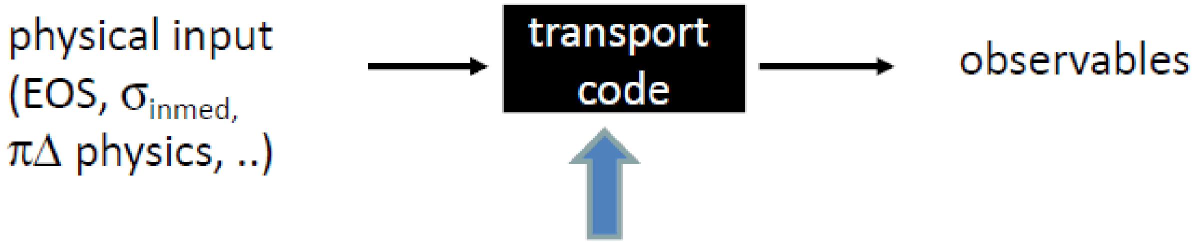


Constraints from nuclear structure + HIC data !



Lynch & Tsang PLB 137098 (2022)

➢ Challenges for transport theories



- Quite complex: simulations with many technical details
- Model dependence for some observables

→ Investigate the role of fluctuations and correlations in the description of HIC
→ Establish a sort of systematical theoretical error
→ Transport Model Evaluation (Comparison) Project -- TMEP

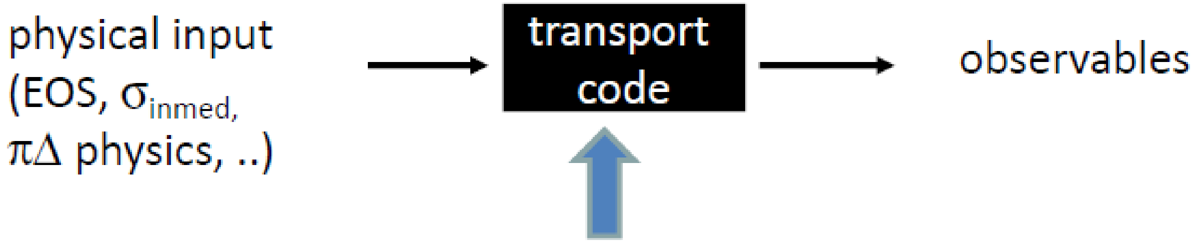
- About 30 participants

→ Calculations of **Nuclear Matter**
(box with periodic boundary conditions)

Core group:
MC (Catania)
Dan Cozma (Bucharest)
Pawel Danielewicz & Betty Tsang (MSU)
C-M Ko and Z.Zhang (Texas A&M)
Akira Ono (Sendai)
Jun Xu (Shanghai)
Herman Wolter (Munich)
Yingxun Zhang (Beijng)

test separately ingredients in a transport approach:
a) collision term without and with blocking (Cascade)
Y.X. Zhang, et al., Phys. Rev. C 97, 034625 (2018)
b) mean field propagation (Vlasov)
c) pion, Δ production in Cascade
} A.Ono et al., PRC 100, 044617 (2019); M. Colonna et al., PRC, 104, 024603 (2021)
d) instabilities , fragmentation
e) momentum dependent fields
} **in progress**
……

➢ Challenges for transport theories



- Quite complex: simulations with many technical details
- Model dependence for some observables

→ Investigate the role of fluctuations and correlations in the description of HIC
→ Establish a sort of systematical theoretical error
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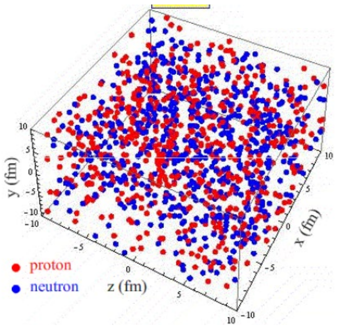
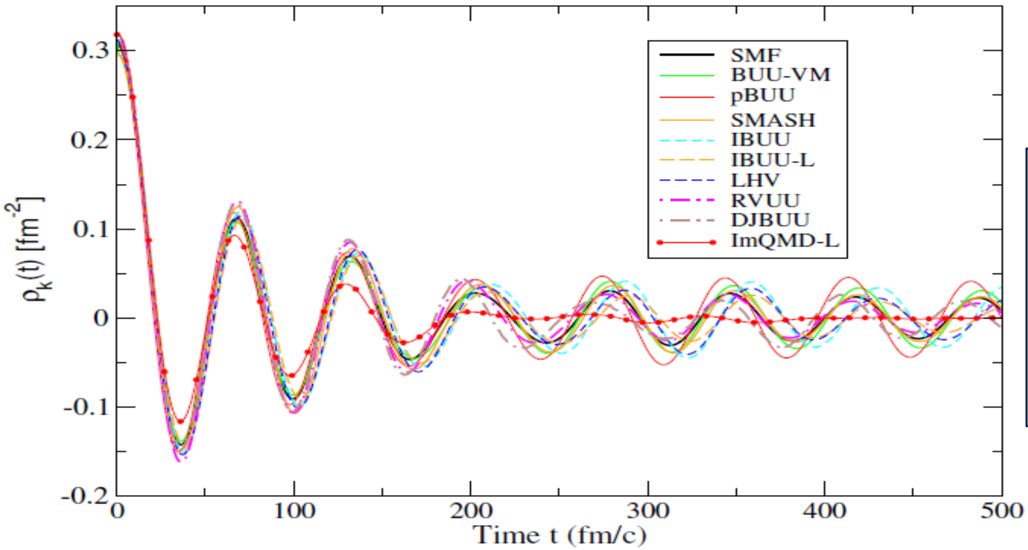




Time evolution of density perturbations for nuclear matter in a box

→ **Good agreement between several transport codes !**

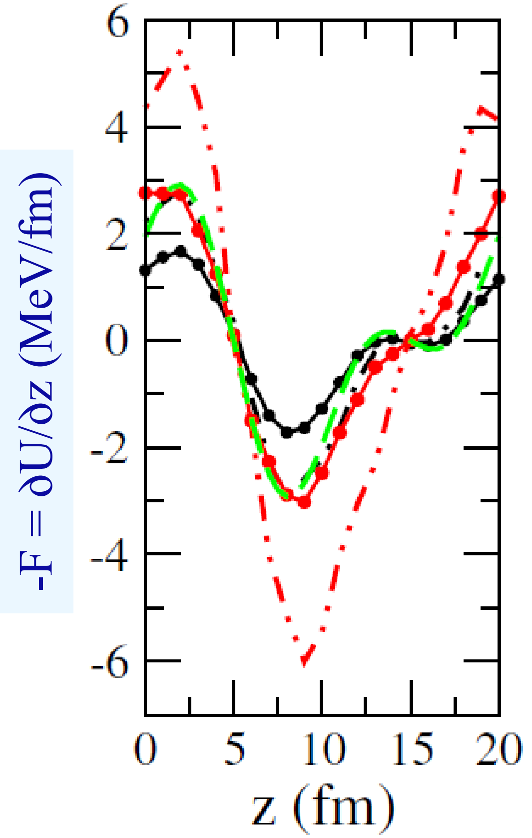
M. Colonna et al., PRC, 104, 024603 (2021)

Oscillation frequency and damping effects

→ Mean-field **gradient**

Ex: $U(\rho) = a(\rho/\rho_0) + b(\rho/\rho_0)^\sigma$

ImQMD-L Δx = 1.4 fm
ImQMD-L Δx = 0.9 fm
analytical



- **BUU**: dynamics is sensitive to the details of the **effective interaction** (*Skyrme* or *covariant formulation*…), though EoS is the same !
- **QMD**: **fluctuations** can be **tuned** to reproduce the analytical expectation for the m-f gradient

Fourier transform of density oscillations