News on the EOS from Heavy Ion reactions

XIV Convegno su Problemi di
Fisica Nucleare Teorica

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Maria Colonna
INFN - Laboratori Nazionali del Sud (Catania)

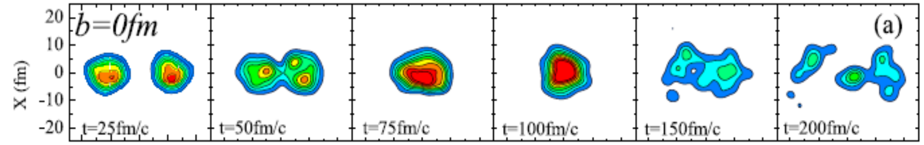
S.Burrello, C.Rizzo, M.Di Toro (LNS, Catania)
V.Baran (NIPNE HH,Bucharest), F.Matera (Firenze)
P.Napolitani (IPN, Orsay), H.H.Wolter (Munich)

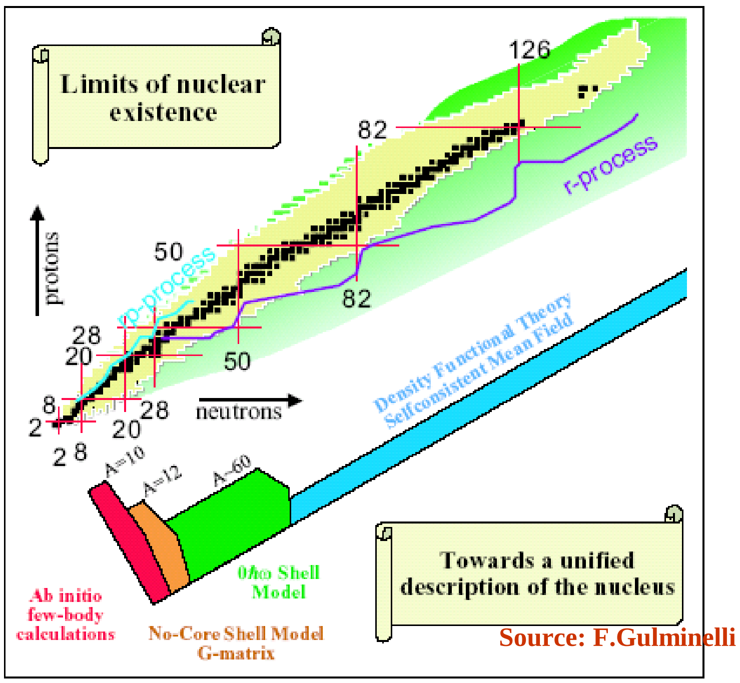
Heavy Ion Collisions: ⟶

a way to create Nuclear Matter in several conditions of ρ, T, N/Z …

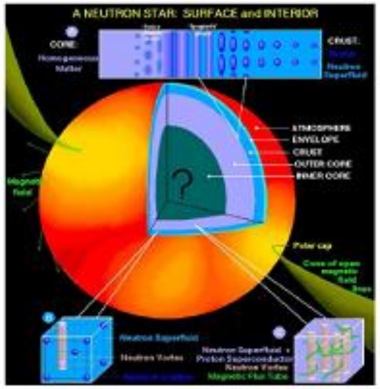
⟶ Nuclear effective interaction

⟶ Equation of State (EOS)





- Self-consistent Mean Field calculations (like HF) are a powerful framework to understand the <u>structure</u> of medium-heavy (exotic) nuclei.



- Widely employed in the <u>astrophysical</u> context (modelization of neutron stars and supernova explosion ex : Mass-Radius relation)

➢Dynamics of m.b. systems: *Semi-classical approximation*

Chomaz, Colonna, Randrup
Phys. Rep. 389 (2004)
Baran, Colonna, Greco, Di Toro
Phys. Rep. 410, 335 (2005)

Transport equation for the one-body distribution function f
(semi-classical analog of Wigner function)

$$\frac{df(r,p,t)}{dt} = \frac{\partial f(r,p,t)}{\partial t} + \{f,h\} = 0$$

Vlasov

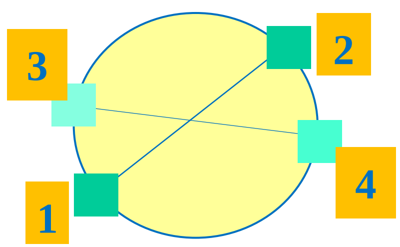
Effective interaction

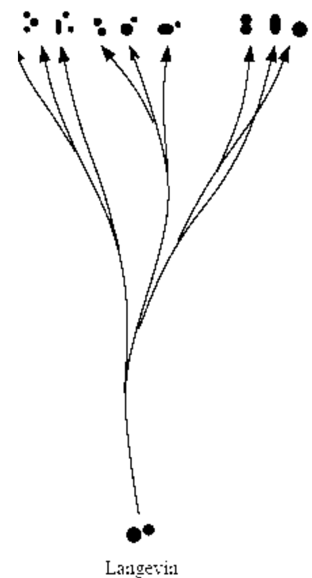
- *Two-body Collision Integral*

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

$$W(12;34) = \mathrm{v}_{rel}\left(\frac{d\sigma}{d\Omega}\right)_{12\to 34}\delta(\boldsymbol{p}_1+\boldsymbol{p}_2-\boldsymbol{p}_3-\boldsymbol{p}_4) \qquad \bar{f} = 1 - f$$

(1,2) ⟶ (3,4)





- Fluctuations in collision integral

$$\prec \delta K(\boldsymbol{r},\boldsymbol{p},t)\,\delta K(\boldsymbol{r}',\boldsymbol{p}',t') \succ = C(\boldsymbol{p},\boldsymbol{p}',\boldsymbol{r},t)\,\delta(\boldsymbol{r}-\boldsymbol{r}')\,\delta(t-t')$$

⟶ *Stochastic Mean Field (SMF) approach*

Effective interactions and symmetry energy

The nuclear interaction, contained in the Hamiltonian ***H***, is represented by effective interactions (Skyrme, Gogny, …) → energy-density functional, m.f. potential → EOS

The density dependence of E_{sym} is rather controversial, since there exist effective interactions leading to a variety of shapes for E_{sym}:

$E/A(\rho) = E_s(\rho) + E_{sym}(\rho)\,\beta^2$

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

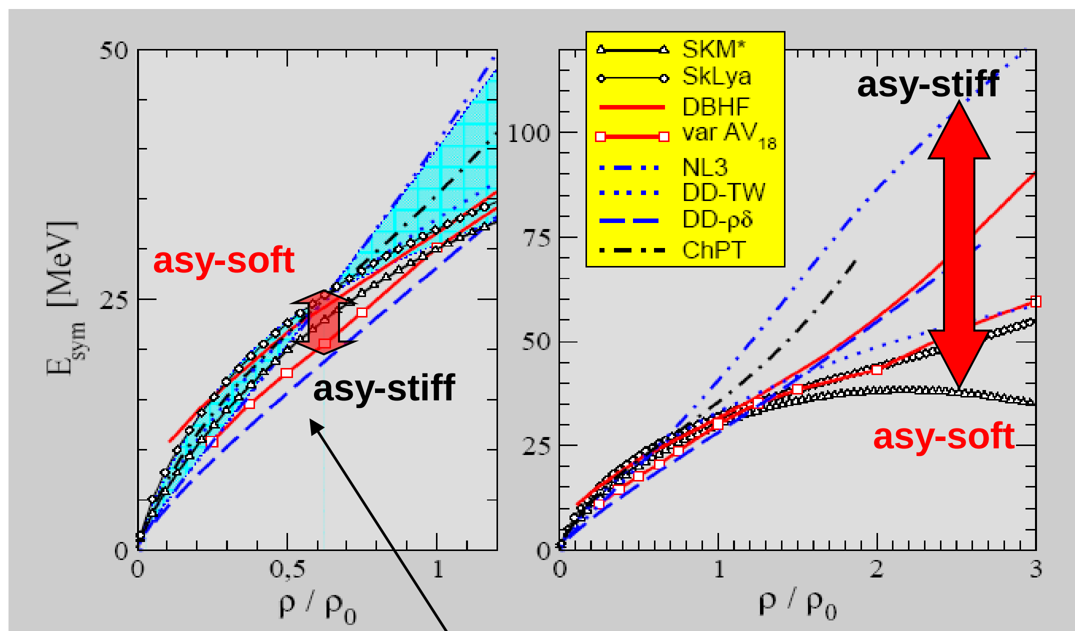
$E_{sym} \approx (\rho/\rho_0)^{\gamma}$ *around* ρ_0

$\gamma<1$ **Asysoft**, $\gamma>1$ **Asystiff**

$$E_{sym}(\rho) = S_0 + L\,\frac{\rho-\rho_0}{3\rho_0} + \dots$$

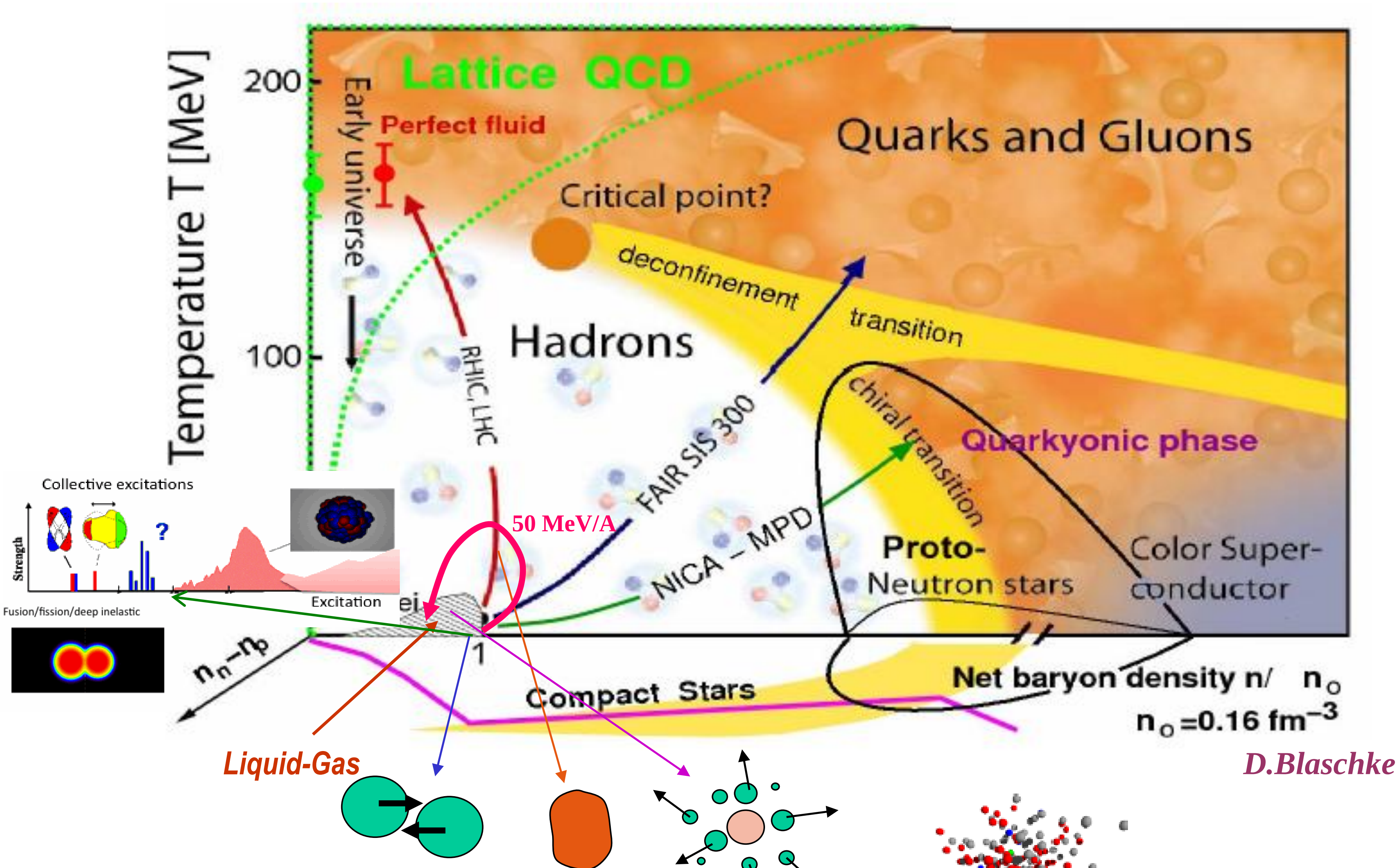
Phenomenology of HIC →
Constrain the effective interactions
→ EOS

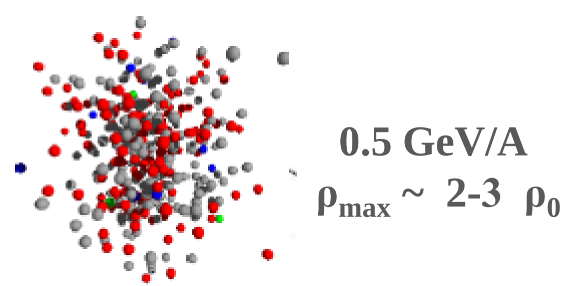
Symmetry energy



zoom at low density

Nuclear Matter Phase Diagram….updated → ***Exotic systems***





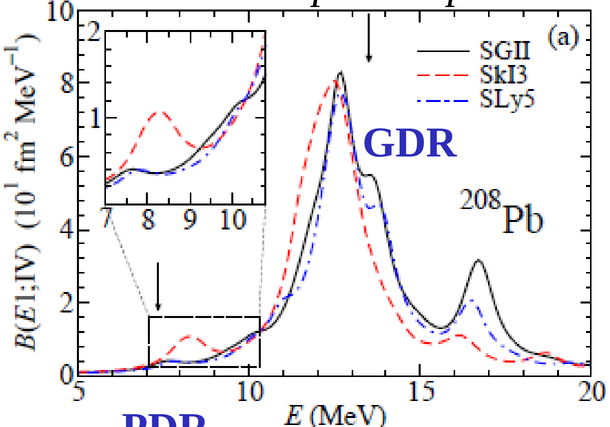
Our Tentative "Path" with Heavy Ion Collisions:
From Dilute (liquid-gas) to High Baryon and *Isospin* Density

“Exotic” collective excitations in Nuclei:

Testing the symmetry energy below normal density

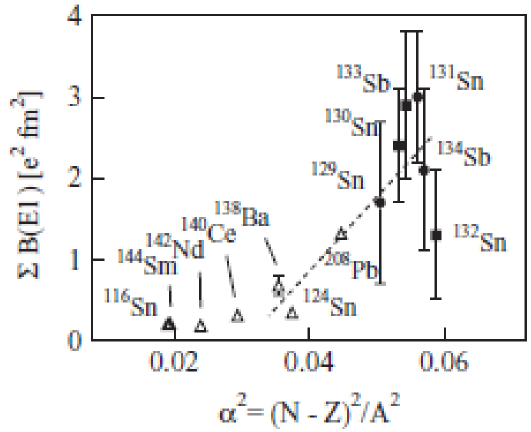
The Isovector Dipole Response (DR) in neutron-rich nuclei

Isovector dipole response



X.Roca-Maza et al., PRC 85(2012)

Pygmy dipole strength



Klimkiewicz et al.

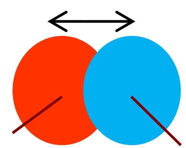
PHYSICAL REVIEW C 76, 051603(R) (2007)

$$\vec{D} = \frac{NZ}{A}\vec{X}$$

- **Giant DR**
- **Pygmy DR**

A study with transport theories

X neutrons – protons

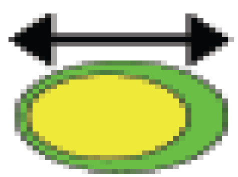


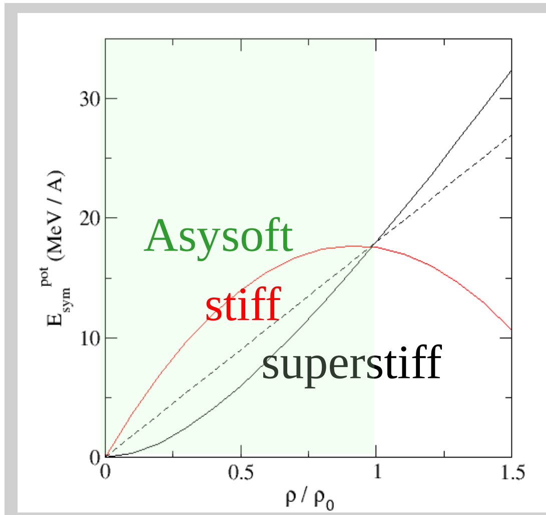
Neutron center of mass

Proton center of mass

X_c core neutrons-protons

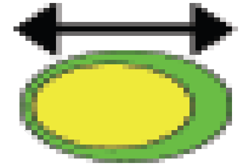
Y excess neutrons - core





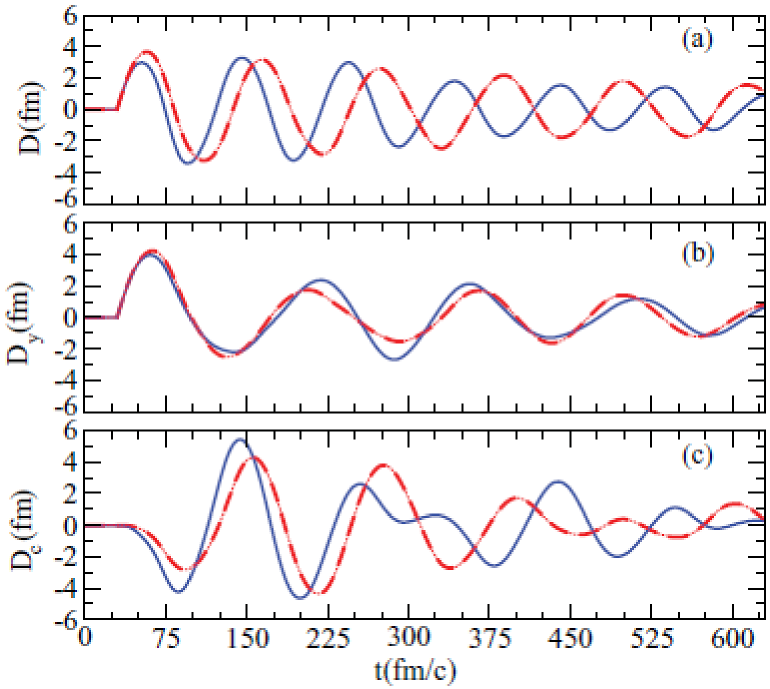
$$\vec{D} = \frac{NZ}{A}\vec{X} = \frac{ZN_c}{A_c}\vec{X}_c + \frac{ZN_e}{A}\vec{Y} \equiv \vec{D}_c + \vec{D}_y.$$

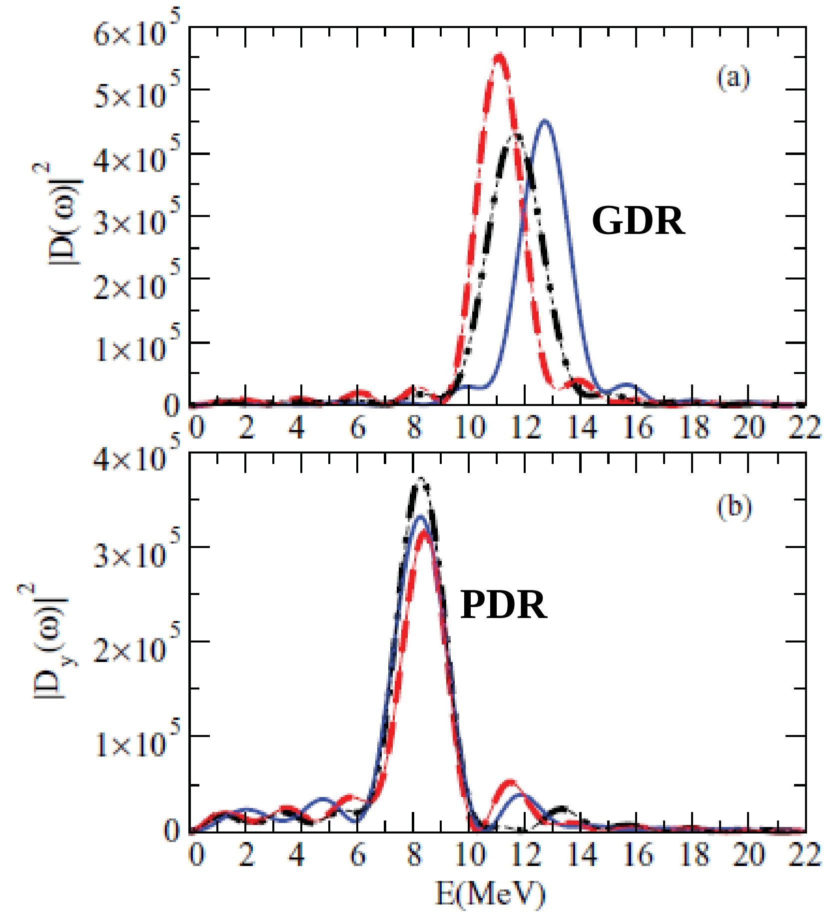
- **Pygmy**-like initial conditions (Y)



^{132}Sn

$$\vec{D} = \frac{NZ}{A}\vec{X} = \frac{ZN_c}{A_c}\vec{X}_c + \frac{ZN_e}{A}\vec{Y} \equiv \vec{D}_c + \vec{D}_y.$$





- *Neutron skin and core are coupled*

asy-EoS	E_{sym}/A (MeV)	L(MeV)
asysoft	29.9	25.0
asystiff	28.3	72.6
asysuperstiff	28.3	96.6

-- soft
-- stiff
-- superstiff

Baran et al.
PHYSICAL REVIEW C 85, 051601(R) (2012)

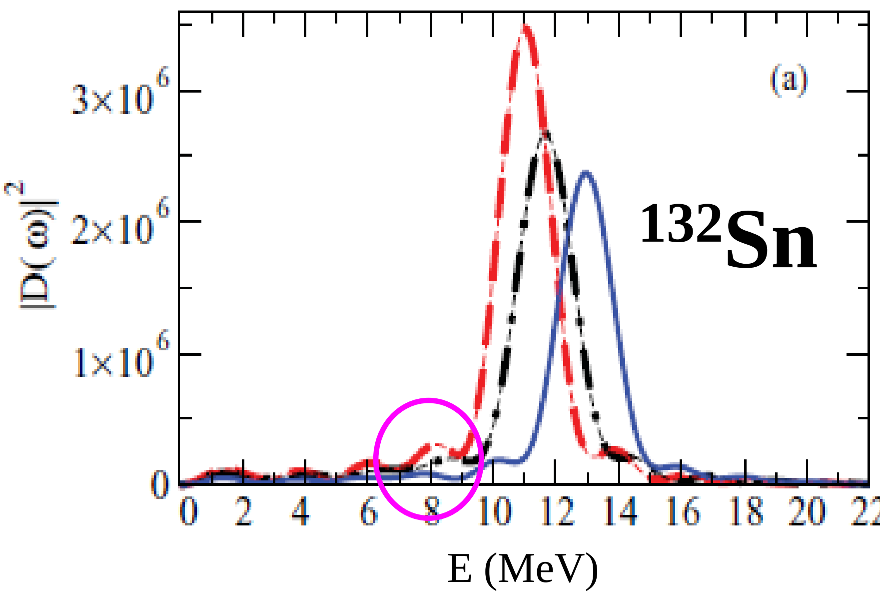
see M.Urban, PRC85, 034322 (2012)
Abrosimov,Brink,Dellafiore,Matera, NPA800, 1 (2008)

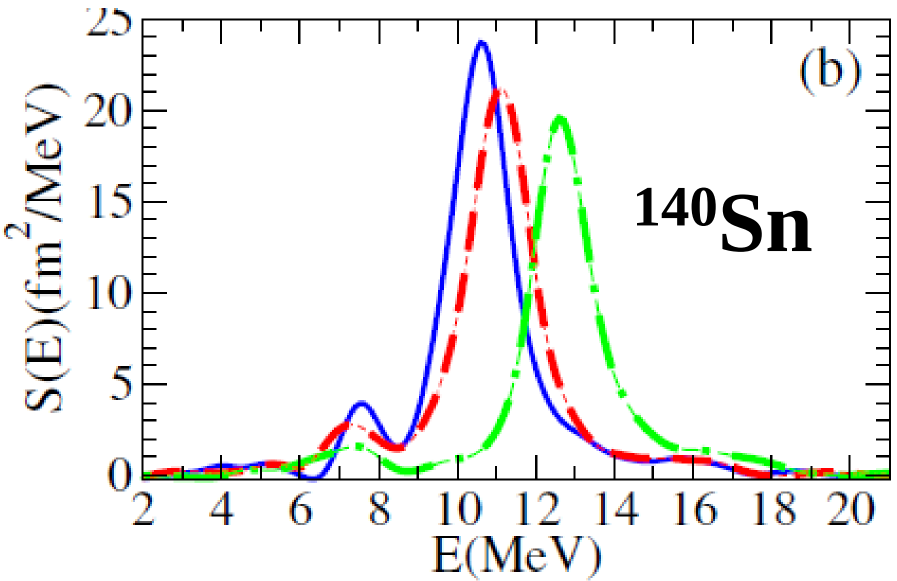
- **GDR**-like initial conditions (X)

$$V_{ext} = \eta\delta(t - t_0)\hat{D} \text{ at } t = t_0$$

Fourier transform of D ⟶
Strength of the Isovector Dipole Response

$$S(E) = \frac{Im(D(\omega))}{\pi\eta\hbar}$$





- PDR is isoscalar-like ⟶ frequency not dependent on E_{sym}
  GDR is isovector-like ⟶ dependent on E_{sym}

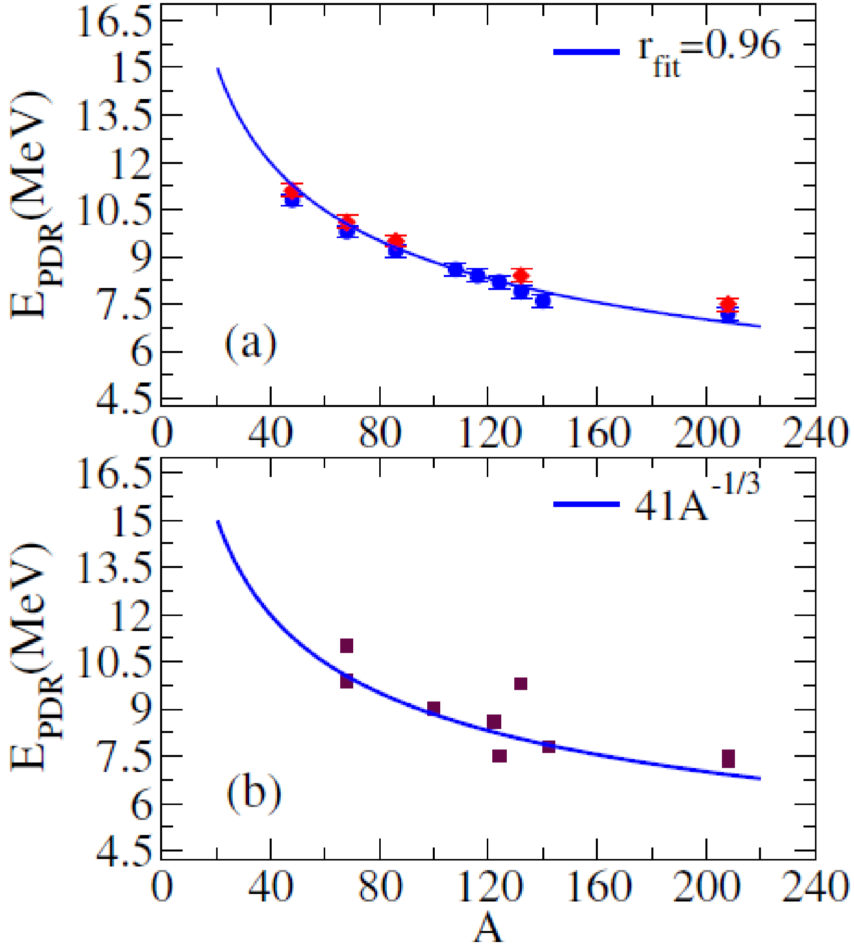
The strength in the PDR region depends on the asy-stiffness (increases with L). Same trend observed for n-skin extension

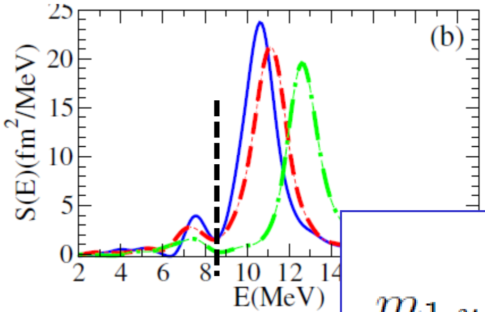
2.7 % soft
4.4 % stiff
4.5 % superstiff

see A.Carbone et al., PRC 81 (2010)

➤ PDR energy and strength: (a systematic study)

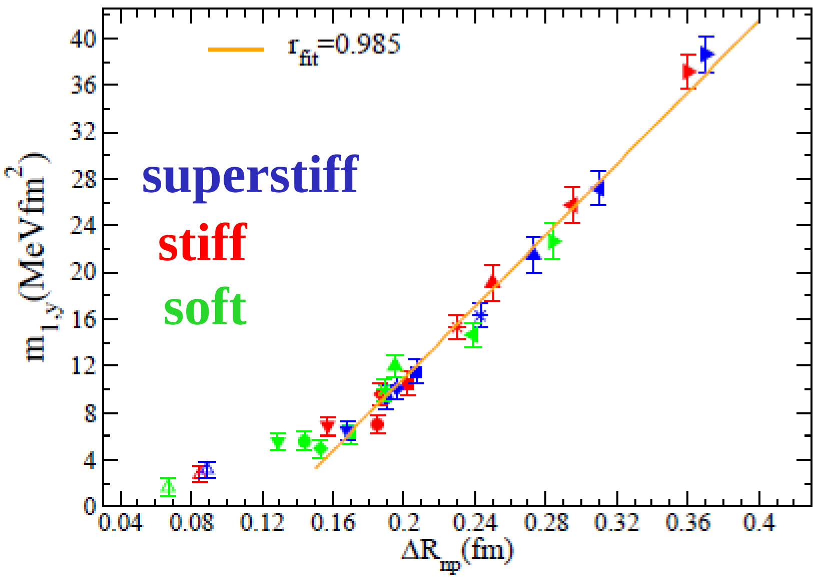
The energy centroid of the PDR as a function of the mass for Sn isotopes, ^{48}Ca, ^{68}Ni, ^{86}Kr, ^{208}Pb
$\sim 41\ A^{-1/3}$





$$m_{1,y} = \int_{PDR} ES(E)dE$$

Correlation between the EWSR exhausted by the PDR and the neutron skin extension



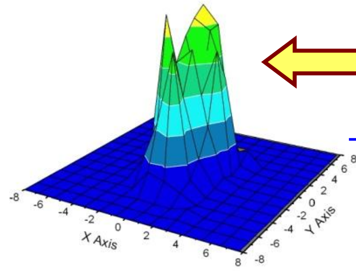
V.Baran et al., **arXiv:1306.4969, to appear in PRC**

Intermediate Energies

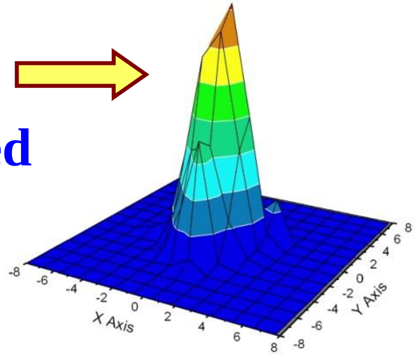
E/A ~ 0.1-1 GeV/A

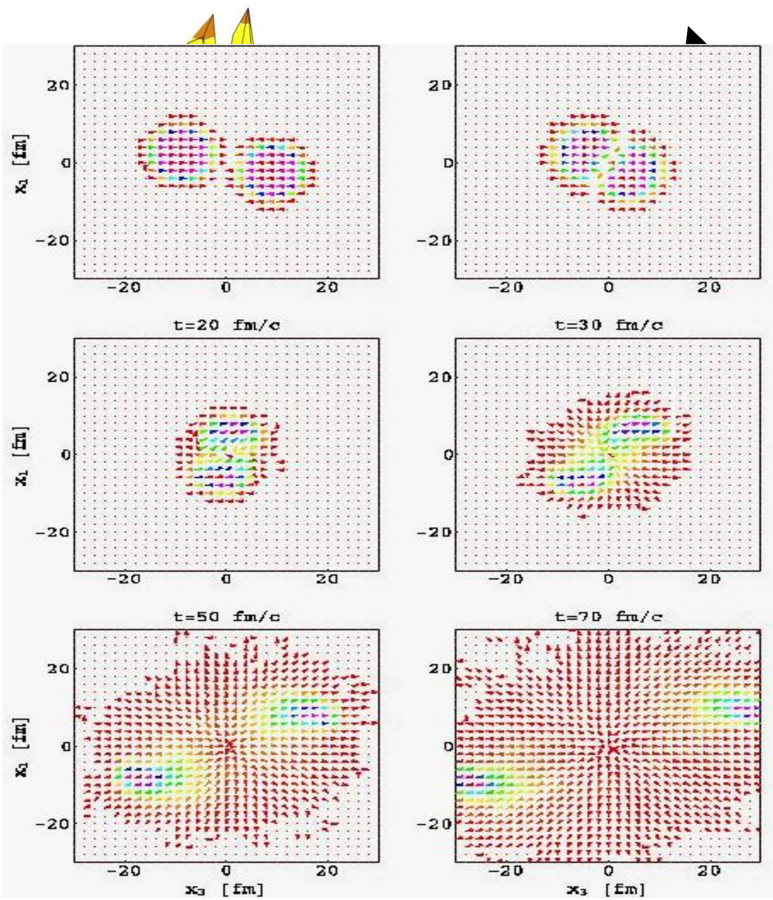
Symmetry Energy above Saturation:
Fast particle emission and flows

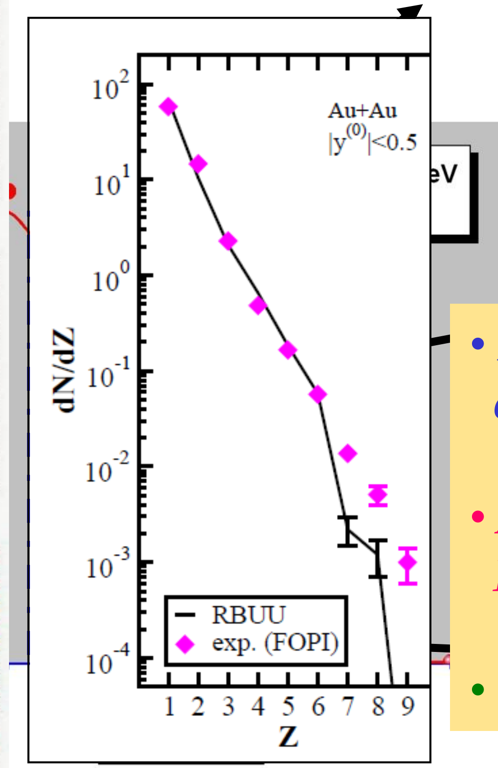
Au+Au 1AGeV central: Phase Space Evolution in a CM cell

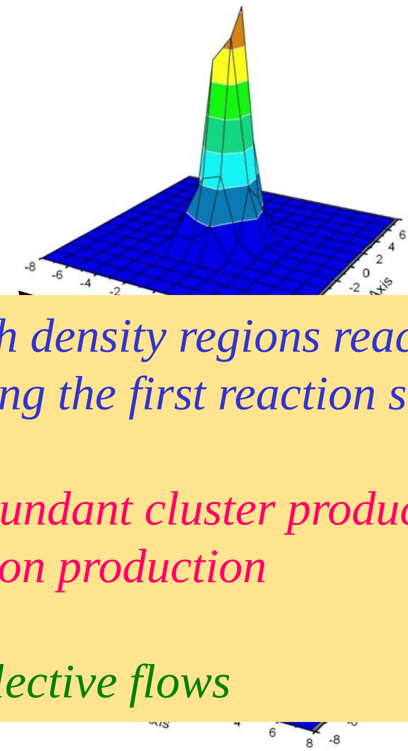


Testing EoS → Compressed Baryon Matter







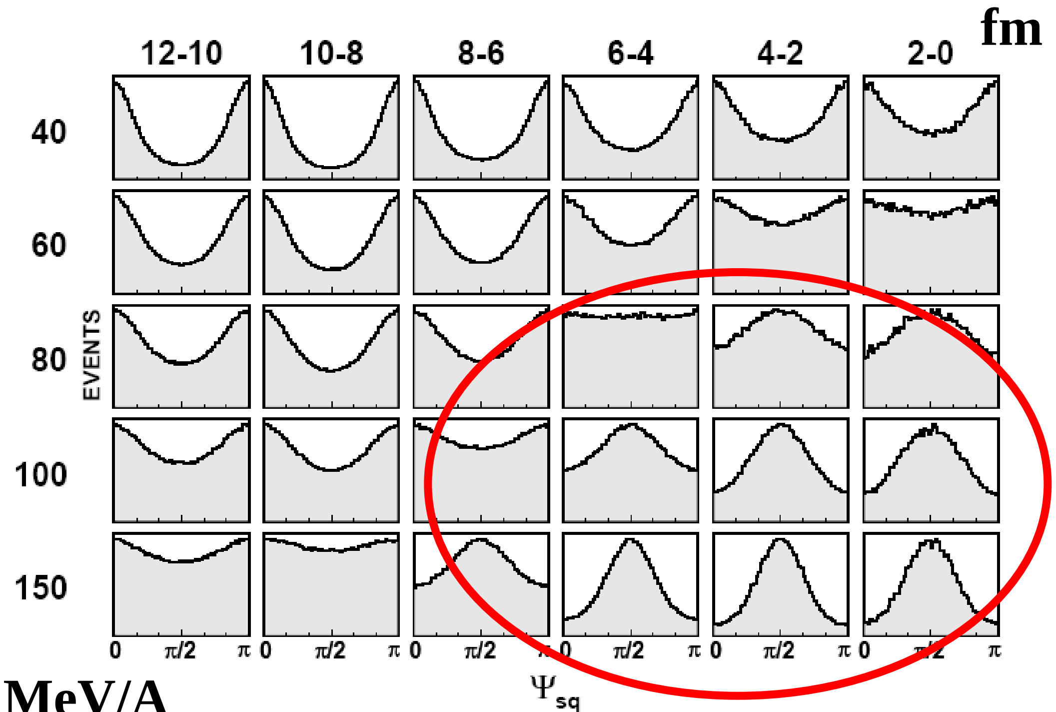


- *High density regions reached during the first reaction stage*
- *Aboundant cluster production Meson production*
- *Collective flows*

Relativistic transport simulations **(T.Gaitanos)**

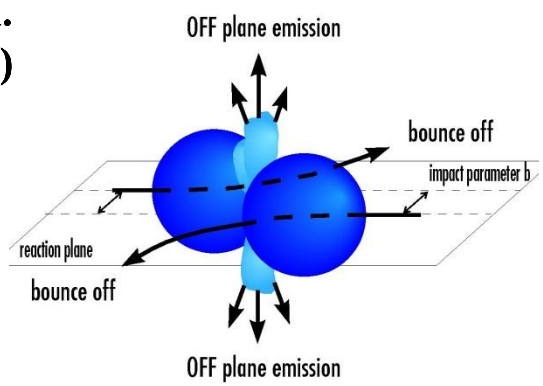
Elliptic flow

Evolution with impact parameter and energy



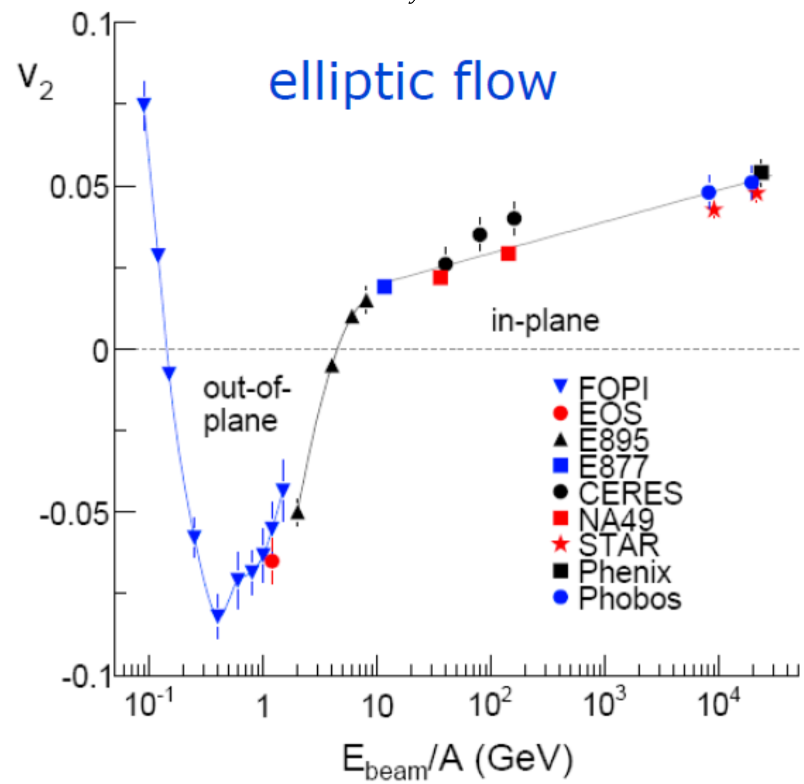
inversion of pattern: squeeze out

J.Lukasik et al.
PLB 606 (2005)



y = rapidity =
$v_{parallel}/v_{beam}$
p_t = transverse momentum

$$V_2(y, p_t) = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle_y$$

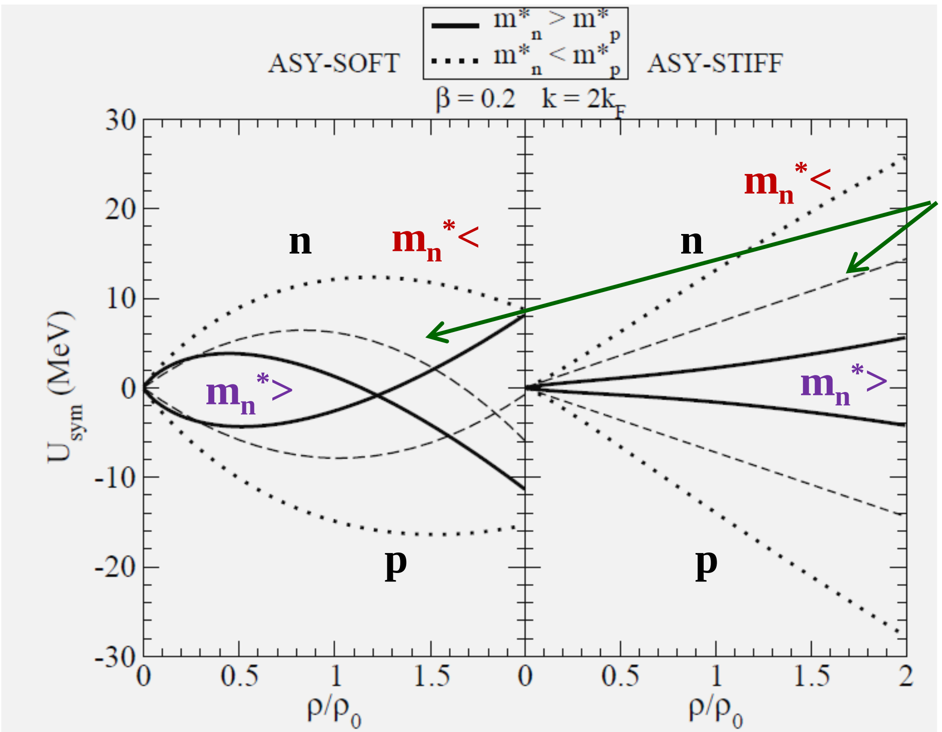


A systematics of experimental data

Neutron and Proton Symmetry potentials in asymmetric nuclear matter

$U_{n,p}(\rho, k=2k_F)$

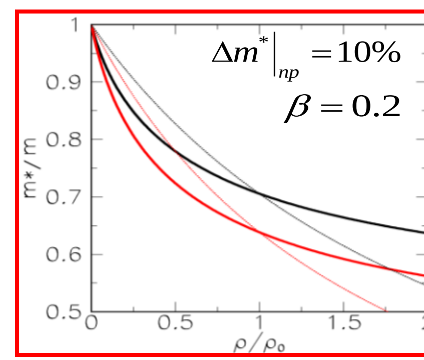
$\beta=0.2$



Momentum Indep.

$\longrightarrow$ **$U_q = U_q(\rho, k)$**

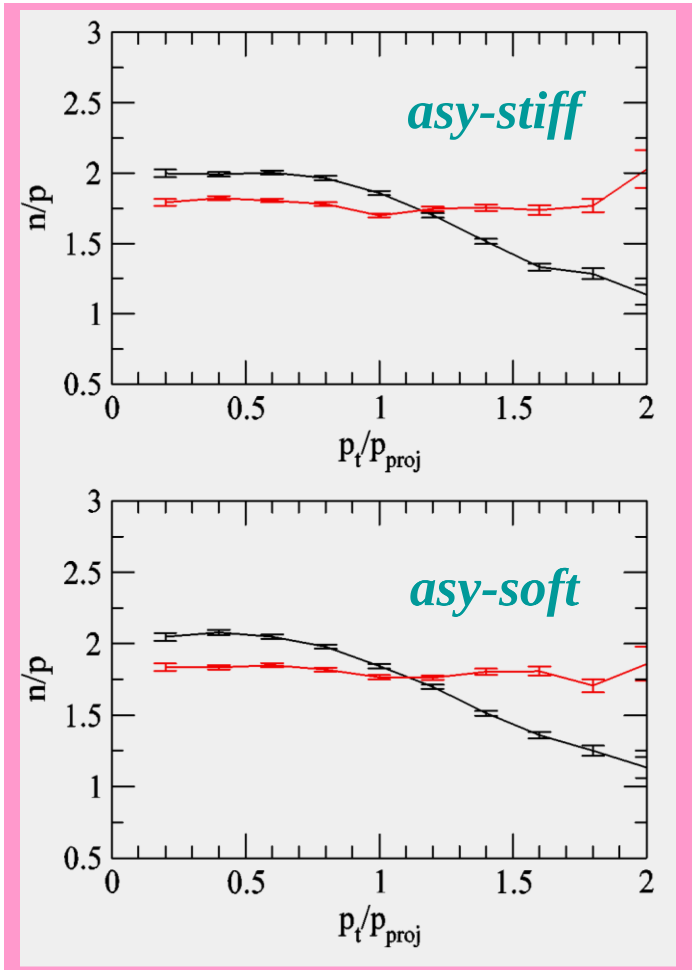
$$\frac{m_q^*}{m} = \left[1 + \frac{m}{\hbar^2 k}\frac{\partial U_q}{\partial k}\right]^{-1}$$



- **m*-splitting effect comparable to asy-stiffness effects !**

N/Z of Fast Nucleon Emission

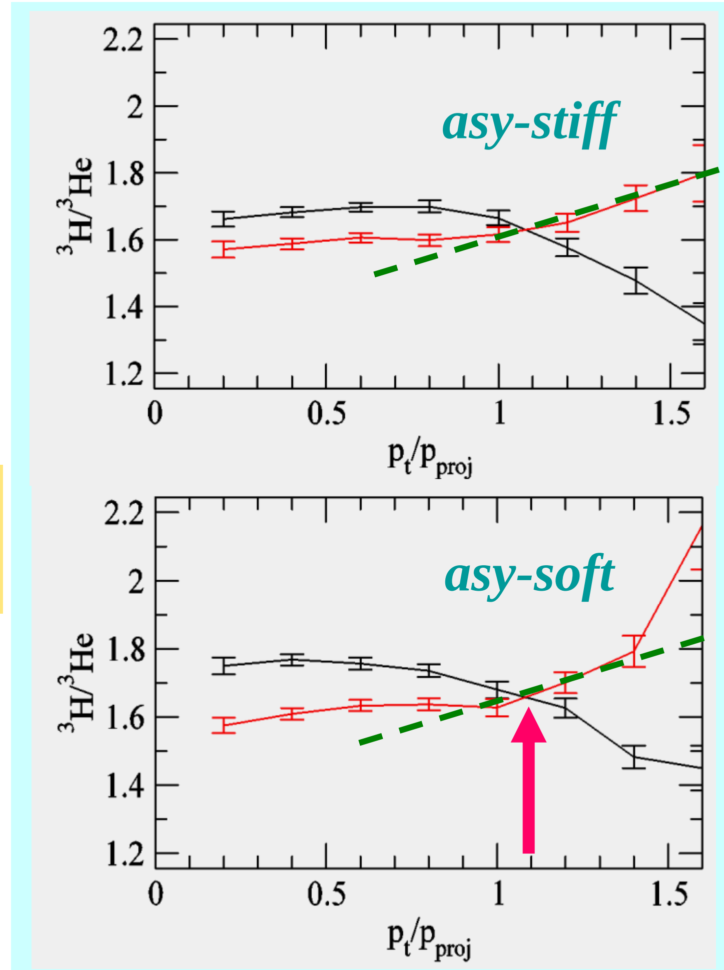
n/p ratio yields



^{197}Au+^{197}Au
400 AMeV
central,
$y \le 0.3$

- $m^*_n > m^*_p$
- $m^*_n < m^*_p$

Light isobar ^{3}H/^{3}He yields



- Observable particularly sensitive at high p_T to the mass splitting
- Qualitative trend : ratio increases only if $m^*_n < m^*_p$

V.Giordano et al., PRC 81(2010)

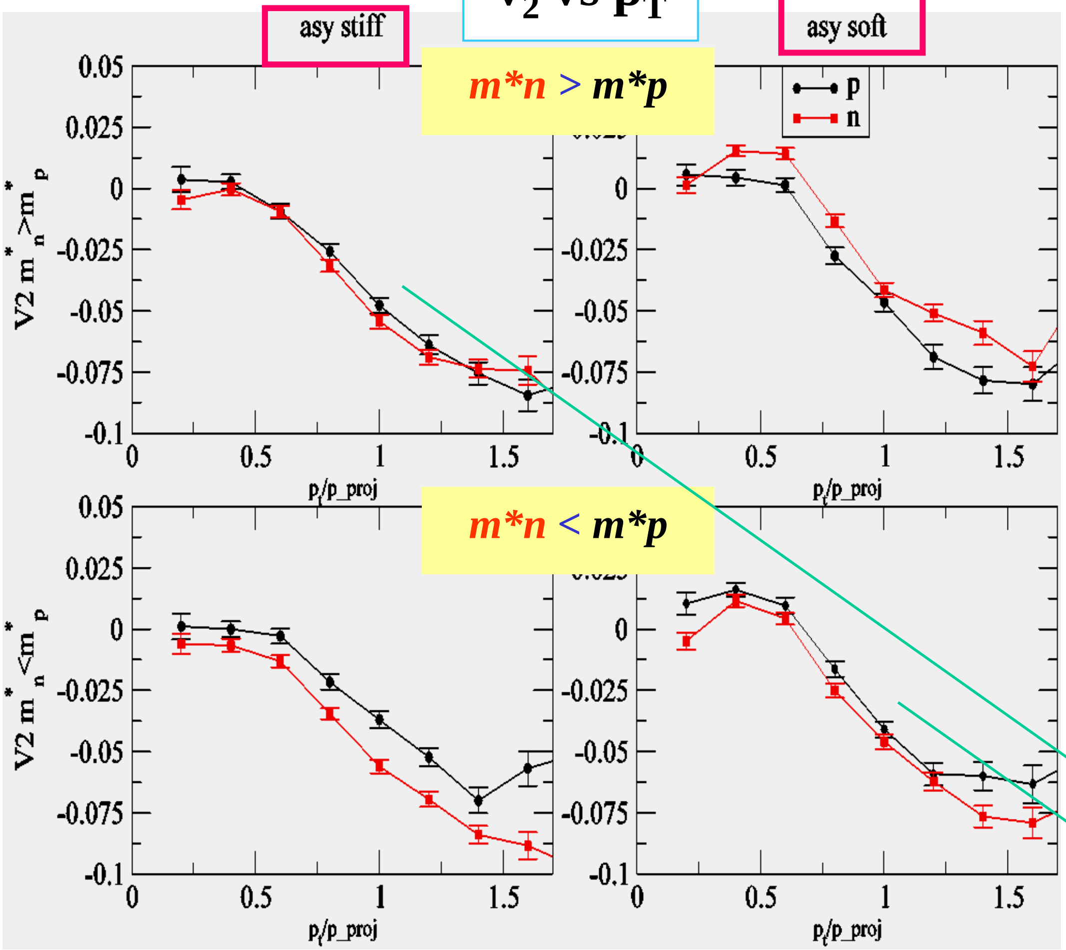
see also G.C.Yong et al., PHYSICAL REVIEW C 80, 044608 (2009)

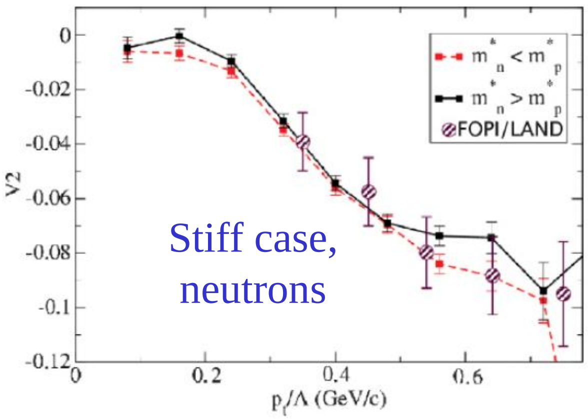
n/p Collective Flows

W.Trautmann, Nucl.Phys.A834(2010)
P.Russotto et al., PLB697,471 (2011)

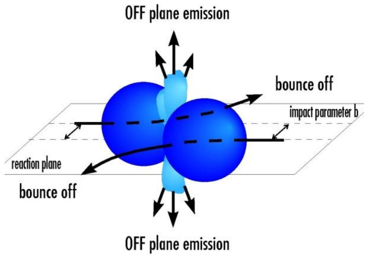
v_2 vs p_T

$y^{(0)} \leq 0.3$





○ *GSI experiment, combined data for central and mid-peripheral collisions*



Comparable flows:

⟶ Interplay between asy-stiffness and effective mass effects

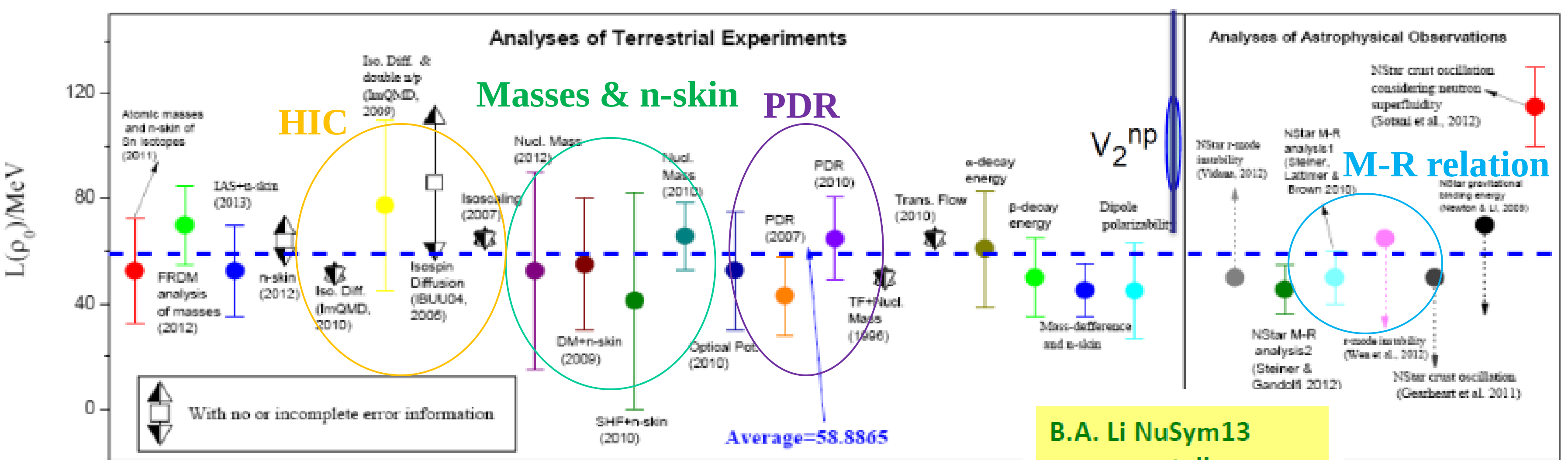
Conclusions

✓ Transport theories as a useful tool to describe nuclear dynamics in several regimes, from low to up to relativistic energies

✓ Possibility to access the nuclear effective interaction EOS, transport coefficients

✓ Sinergy with experimental activities is essential

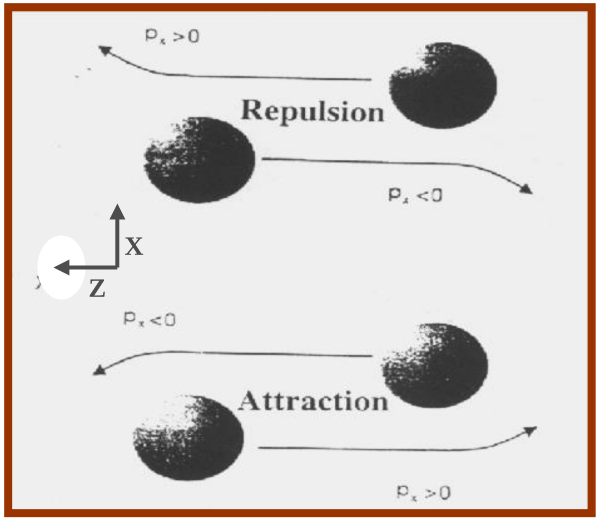
✓ Link with structure studies (masses, n-skin, PDR, …) and properties of compact stellar objects

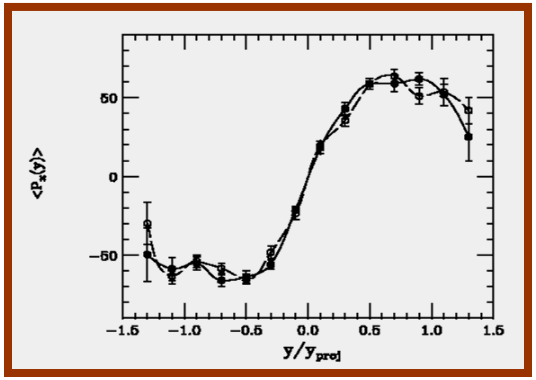


B.A. Li NuSym13 summary talk

Collective flows

In-plane (transverse)





V_1 vs. y

y = rapidity =

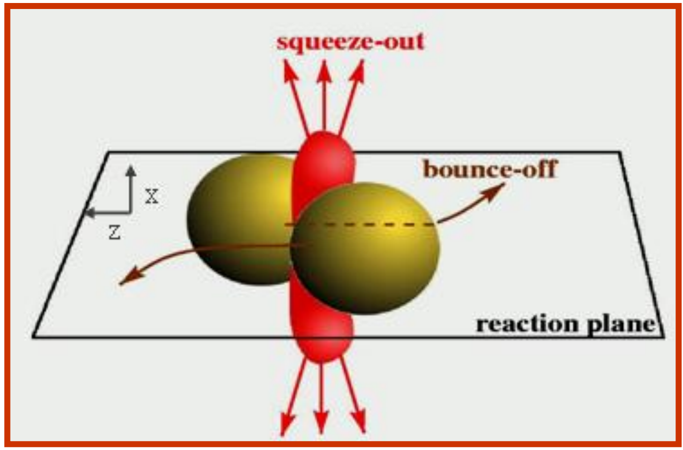
$v_{parallel}/v_{beam}$

p_t = transverse momentum

$$V_1(y, p_t) = \langle p_x \rangle / \langle p_t \rangle_y$$

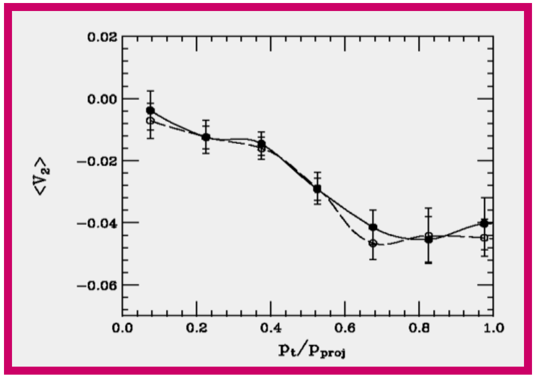
$$V_2(y, p_t) = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle_y$$

Out-of-plane (elliptic)



$$V_2 \begin{cases} = -1 & \text{full out} \\ = \ \ 0 & \text{spherical} \\ = +1 & \text{full in} \end{cases}$$

V_2 vs p_t



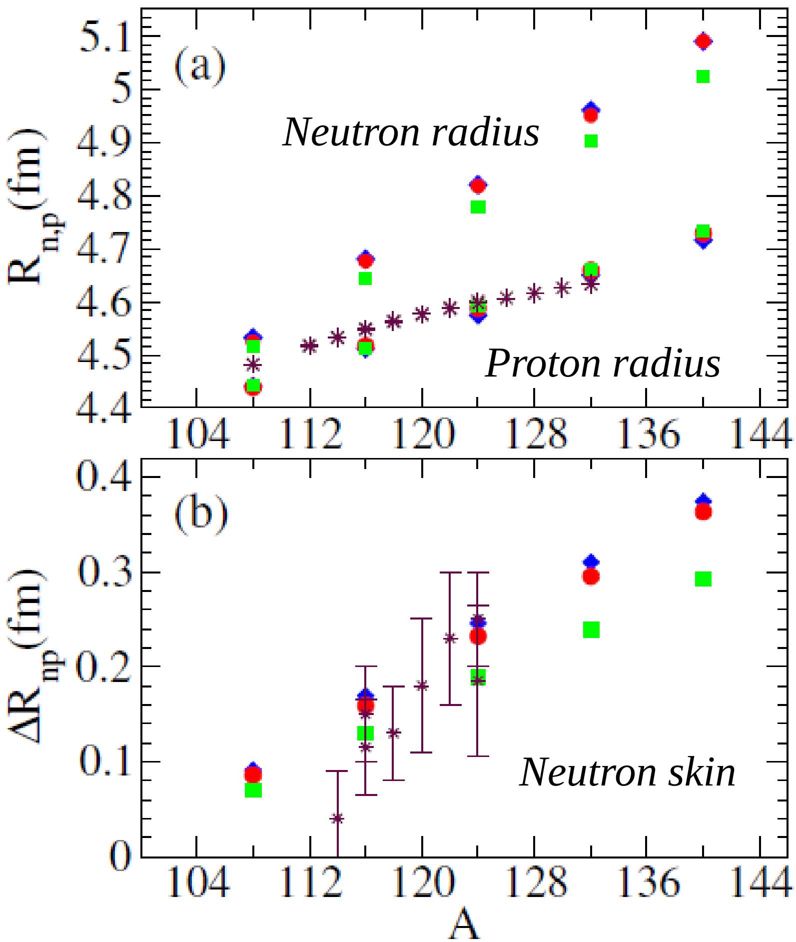
Flow observables expressed as the 1st and 2nd coefficient of the Fourier expansion of the azimuthal distribution of particles $dN/d\varphi(y,p_t) = 1 + v_1\cos(\varphi) + 2v_2\cos(2\varphi)$

$$V_1^{p-n}(p_t) = V_1^p(p_t) - V_1^n(p_t) \quad \longleftarrow \quad \textbf{Isospin} \quad \longrightarrow \quad V_2^{p-n}(p_t) = V_2^p(p_t) - V_2^n(p_t)$$

B-A Li et al. PRL(2002)

Ground state properties and nuclear radii

Sn isotopes



- soft
- stiff
- superstiff
- * data

Nuclear Data Table, & PRL 82, 3216 (1999)

E_{sym}/A (MeV)	L(MeV)
29.9	14.4
28.3	72.6
28.3	96.6

Static solution of transport equations

-Proton radii are in good agreement with experimental data

-Neutron-skin predictions agree with data (within the error bars)
-Neutron-skin increases with L

n/p collective flows   FOPI/LAND data

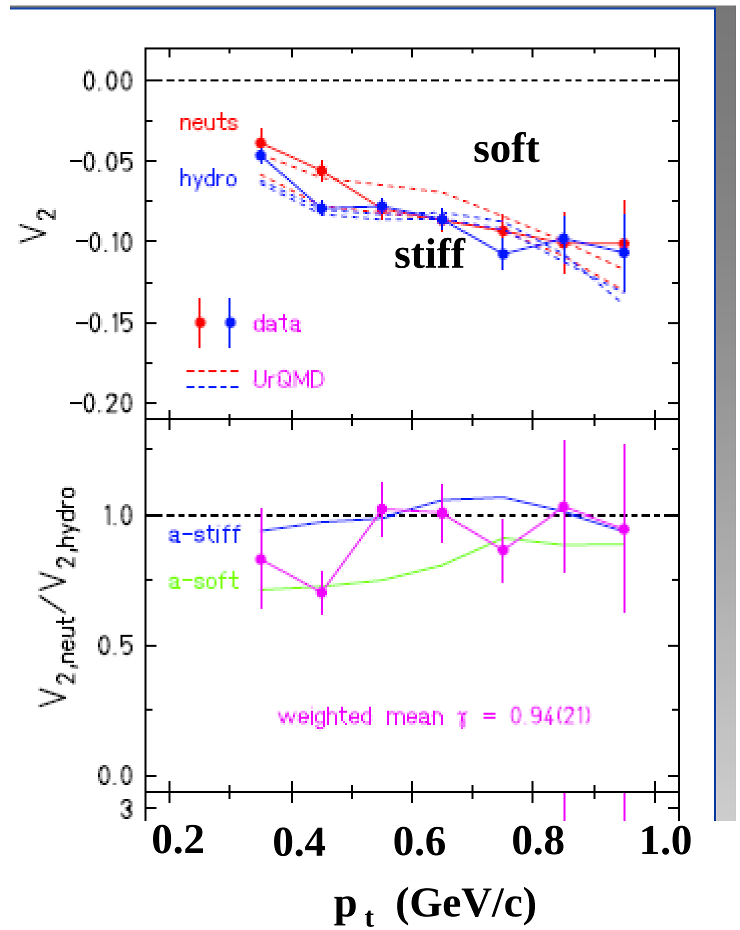
^{197}Au+^{197}Au, 400 AMeV   Combined data for central and mid-peripheral collisions

P.Russotto et al., PLB697,471 (2011)
W.Trautmann, Nucl.Phys.A834(2010)

- **Comparison with other transport calculations (UrQMD) (soft and stiff)**
  $E_{sym} \sim E_{sym}(Fermi) + \rho^{\gamma}$

- **From the ratio v_n / v_p, interpolation between predictions gives $\gamma \sim 0.9 \pm 0.3$, but …**

No Isospin Mom. Dep.



Data : hydrogen flow close to neutron flow
From a more accurate analysis, information on mass splitting !

New experiment CHIMERA/LAND to be performed at GSI