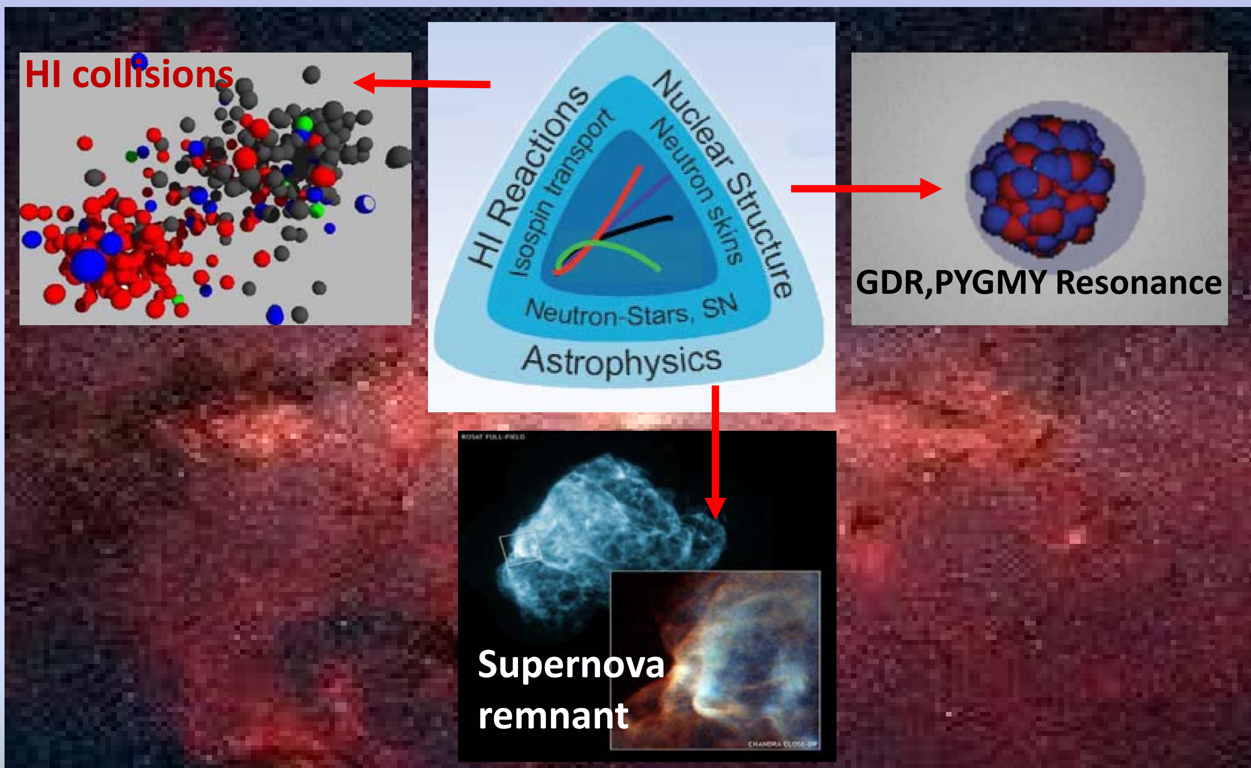
E. De Filippo (INFN Catania)

EXOCHIM  ***collaboration***

Isospin and Equation-of-State of nuclear matter: the role of symmetry energy in nuclear reactions experiments and theory

The nuclear EOS describes the relation between pressure, density, temperature and isospin asymmetry. It is an essential ingredient in nuclear physics and astrophysics, but how $E/A(\rho, \delta)$ depends on the density ρ and isospin asymmetry δ ?

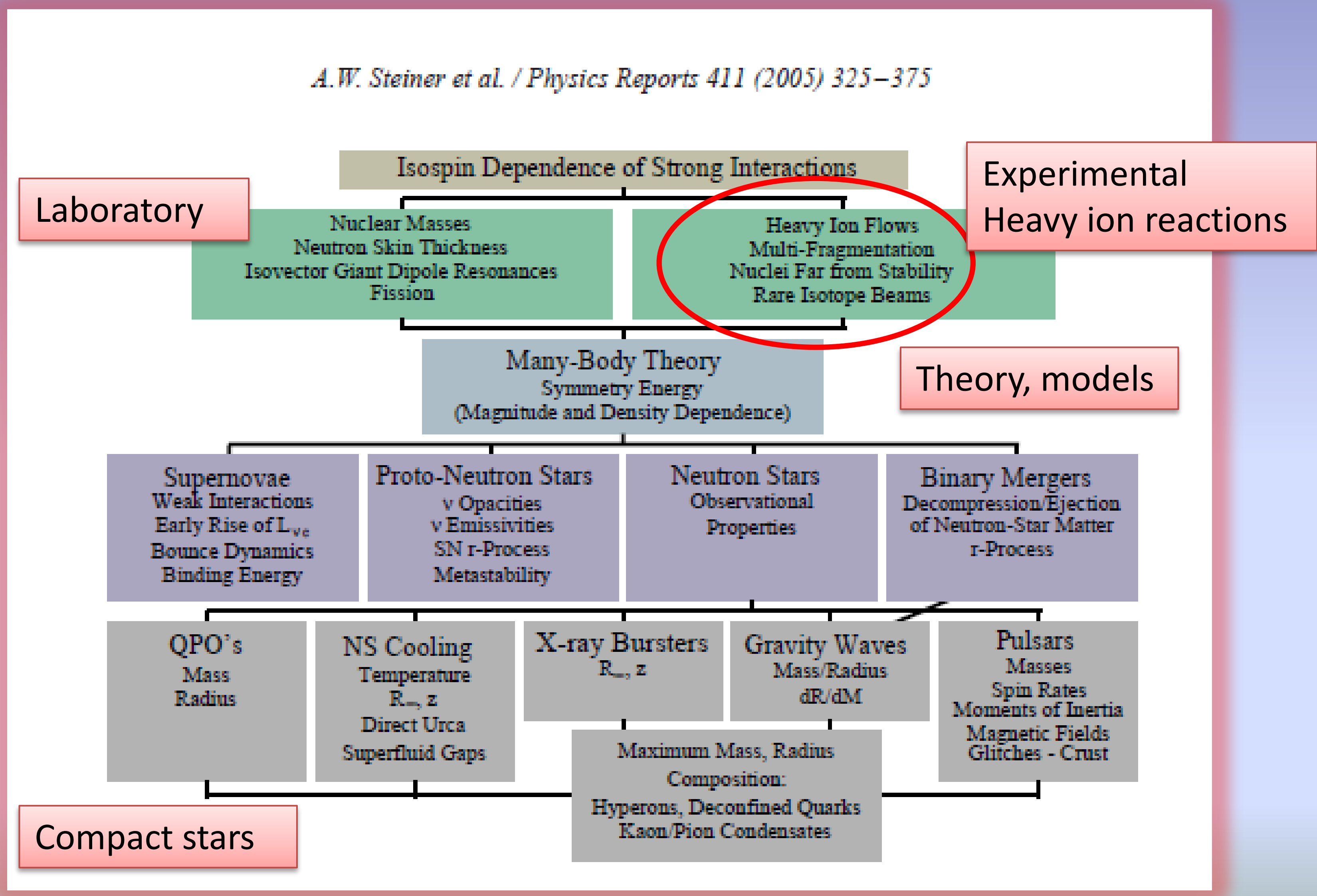


Outline

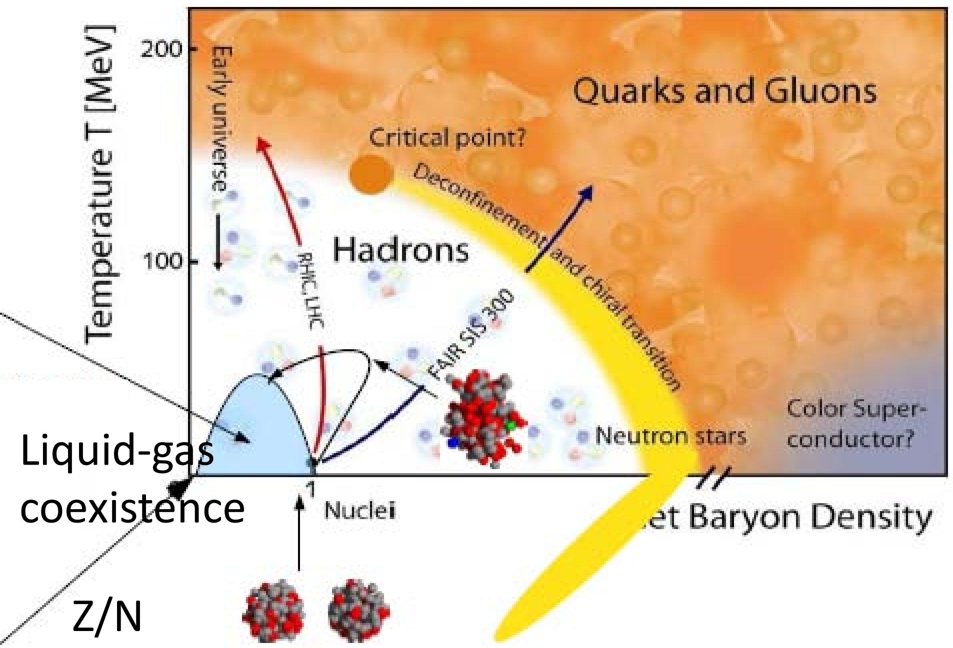
In this talk we shall mainly review some observables and tools used with heavy ions reactions in order to obtain information on the symmetry energy below and above the nuclear saturation density ρ_0

$\rho_0 \approx 0.17\ fm^{-3}$
$2.48 \times 10^{14} g/cm^3$

The role of isospin asymmetry in nuclear processes in the laboratory and in the cosmos



Heavy ion collisions (HIC): Why and how can give information on density dependence of Symmetry term of EOS ?



We need to follow the observables from initial to final states also when equilibrium is not reached

↓

Transport codes

BUU (Bolzmann equation…)
QMD (Quantum Molecular Dynamics…CoMD, IQMD, ImQMD,
UrQMD, **AMD** (Antisymmetrized Mol. Dynamics,
……………………………….)

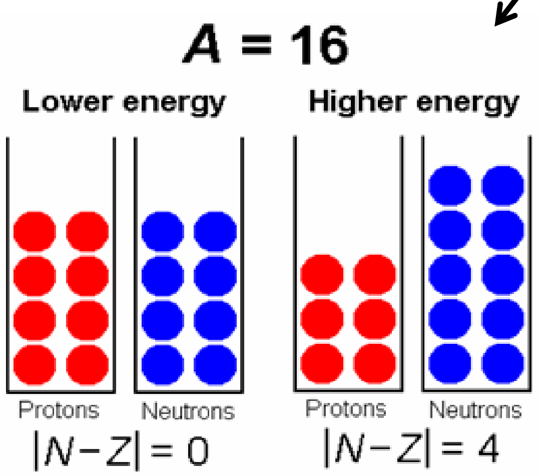
A strict correlation between EXPERIMENT and THEORY:

With HIC large density variations (density gradients) in nuclear matter can be obtained in a short timescale.

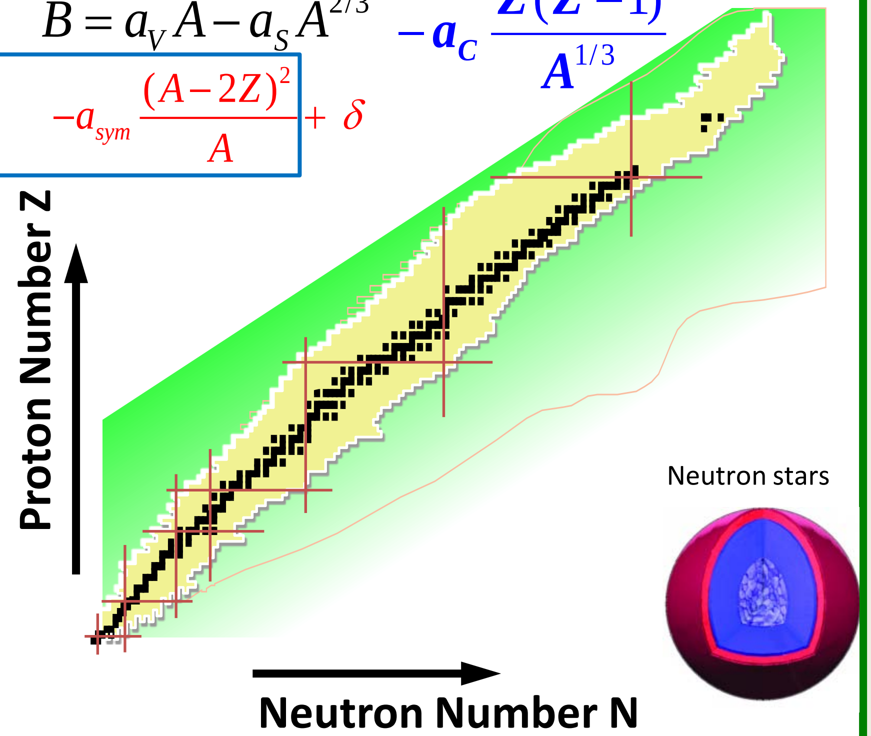
Because the EOS is an essential input to transport models the idea is that it can be constrained by comparing different OBSERVABLES from measurements to TRANSPORT MODEL calculations that describe the dynamical evolution of the process

The symmetry energy in finite nuclear matter: the basic nuclear energy formula

Bethe – Weizsäcker (1936)



$$B = a_V A - a_S A^{2/3} - a_C \frac{Z(Z-1)}{A^{1/3}} - a_{sym} \frac{(A-2Z)^2}{A} + \delta$$



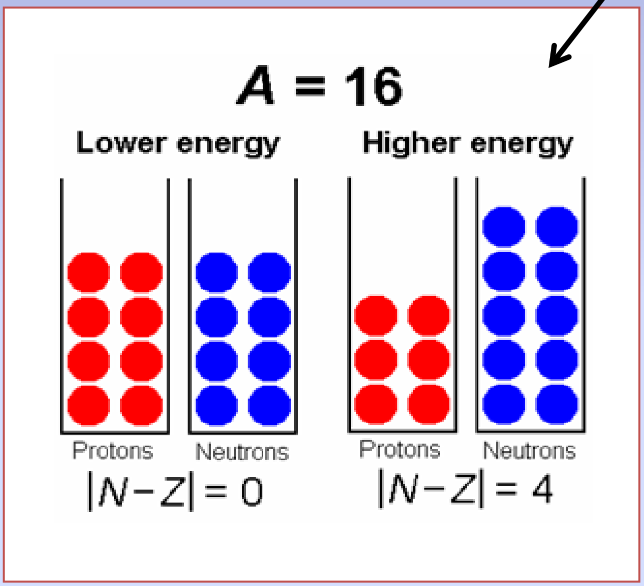
Warning: contribution of symmetry energy at saturation density is **small** respect to the other terms:

P. Danielewicz, Nucl. Phys. A727 (2003) 233: ***Surface symmetry energy***
P. Danielewitz and J. Lee, AIP Conf. 1423, 29 (2012): ***Isobaric Analog States (IAS).***
P. Moller et al: PRL108, 052201 (2012): ***Finite Range Droplet Model***

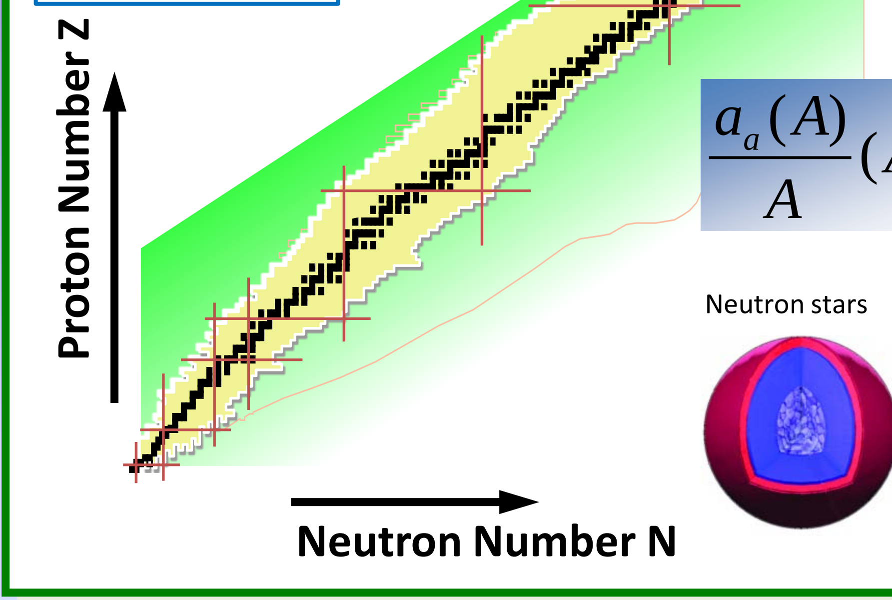
Several corrections done:
Volume and surface term
Coulomb refined
Shell corrections added
Reproduce binding energy of known nuclei in order to determine the symmetry energy

The symmetry energy in finite nuclear matter: the basic nuclear energy formula

Bethe – Weizsäcker (1936)



$$B = a_V A - a_S A^{2/3} - a_C \frac{Z(Z-1)}{A^{1/3}} - a_{sym}\frac{(A-2Z)^2}{A} + \delta$$



$$\frac{a_a(A)}{A}(A-2Z)^2$$

Neutron stars

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Several corrections done:
Volume and surface term
Coulomb refined
Shell corrections added
Reproduce binding energy of known nuclei in order to determine the symmetry energy

EOS of symmetric and neutron matter

$$E(\rho,\delta) = E(\rho,\delta=0) + E_{sym}(\rho)\delta^2 + \dots$$

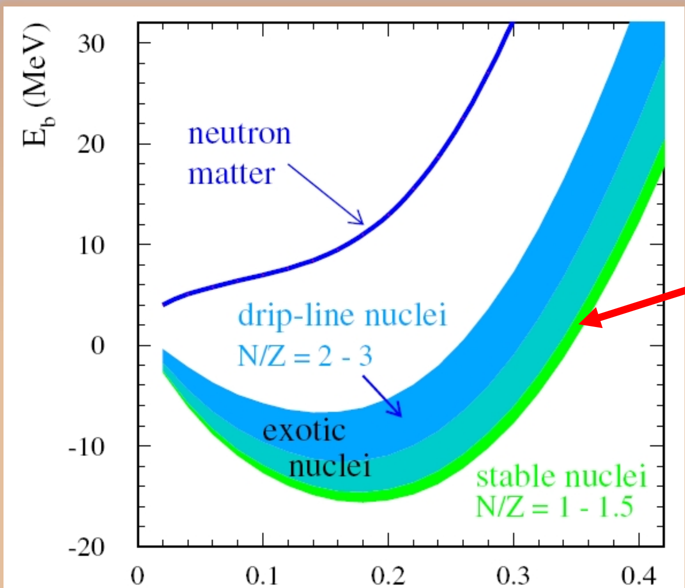
$$\delta = \frac{\rho_n - \rho_p}{\rho_n + \rho_p} = \frac{N-Z}{A}$$

$$P = \rho^2 \left.\frac{\partial (E/A)}{\partial \rho}\right|_{S=konst}$$

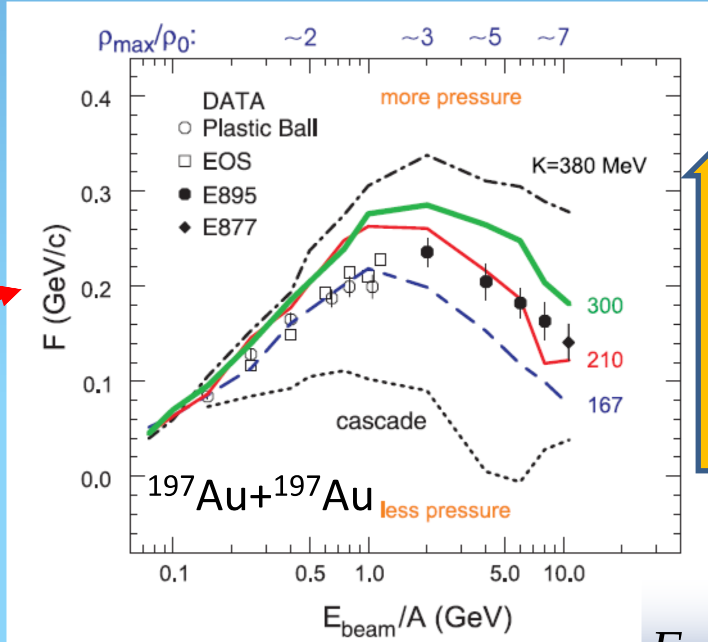
$$E(\rho,\delta=0) = E(\rho_0) + \frac{K}{18\rho_0}(\rho-\rho_0)^2$$

P. Danielewicz et al., Science 298 (2002)

$$K = \rho \left.\frac{\partial P}{\partial \rho}\right|_{S=const}$$



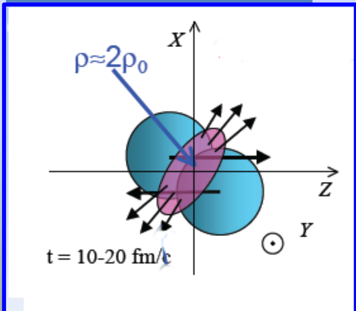
De Jong and Lenske



Constraining EOS by transverse flow

Large transverse flow, large pressure at a given density

$$F = \frac{d\langle p_x / A\rangle}{d(y/y_{cm})}$$



Isospin asymmetry is present in nuclei far from stability valley (drip-line nuclei) and astrophysical objects (neutron stars), where EOS behaviour determines important properties as the Mass and Radius.

Symmetry energy parametrizations: "common" representation

Second order espansion of symmetry energy around ρ_0

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

$$S(\rho) = S_0 + \frac{L}{3}\left(\frac{\rho-\rho_0}{\rho_0}\right) + \frac{K_{sym}}{18}\left(\frac{\rho-\rho_0}{\rho_0}\right)^2 + \ldots$$

$S_0 = E_{sym}(\rho_0)$

Strenght

$$L = 3\rho_0 \frac{dS(\rho)}{d\rho}$$

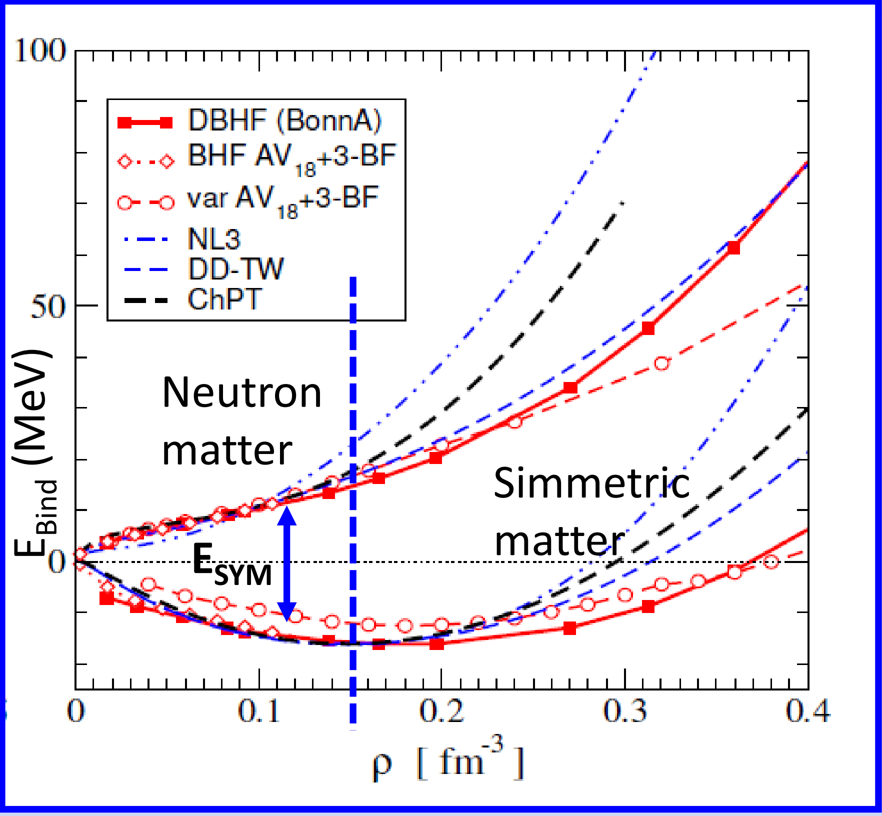
Slope

$$P_{SYM} = \rho^2 \left(\frac{dS}{d\rho}\right)_{\rho=\rho_0} = \frac{\rho_0}{3} L$$

Pressure

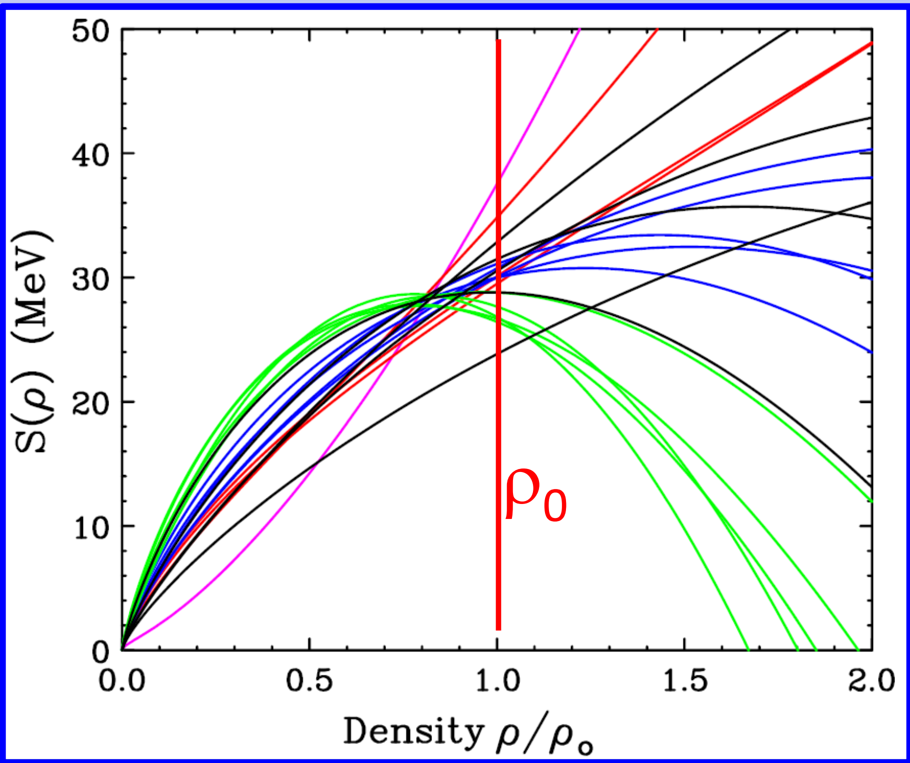
EOS of symmetric and neutron matter: the symmetry energy

Ab initio calculations (red lines) approaches



Fuchs and Wolter, EPJA 30, 5 (2006)

Phenomenological Skyrme forces with constraint from ^{100}Sn to ^{132}Sn binding energies



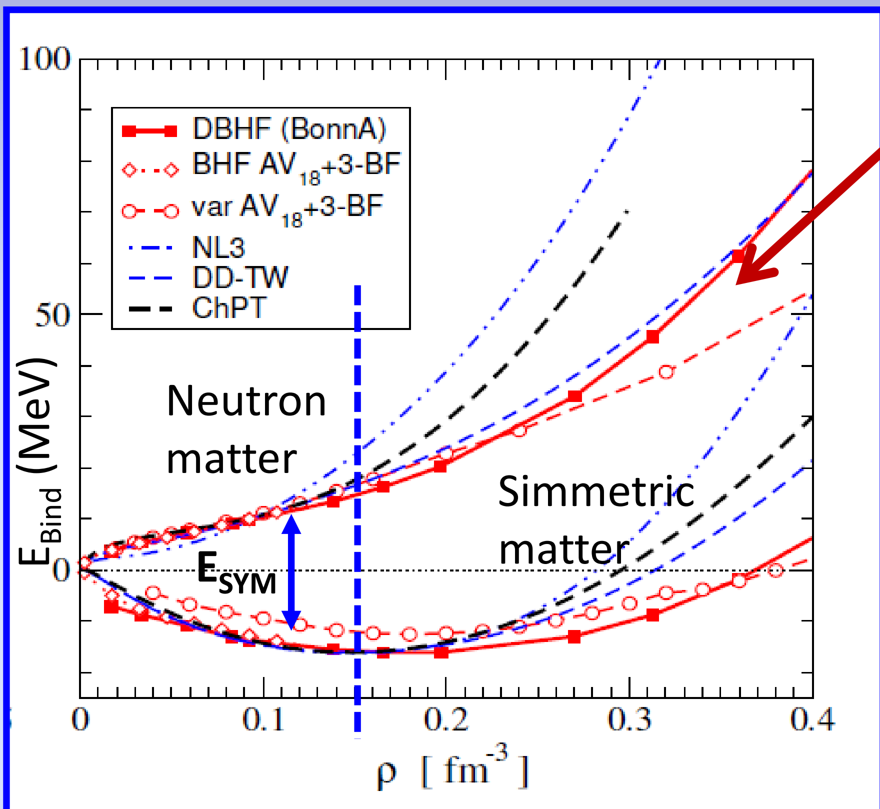
Brown (PRL 2001)

EOS of symmetric and neutron matter: the symmetry energy

Ab initio calculations (red lines) approaches

Large deviations at high densities

Phenomenological Skyrme forces with constraint from ^{100}Sn to ^{132}Sn binding energies



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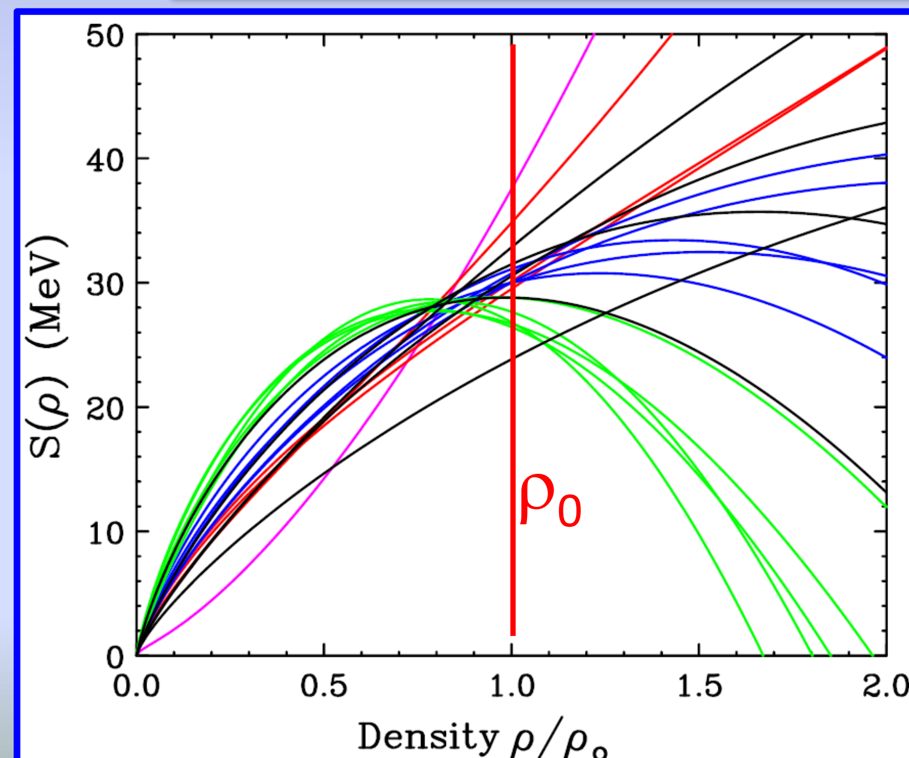
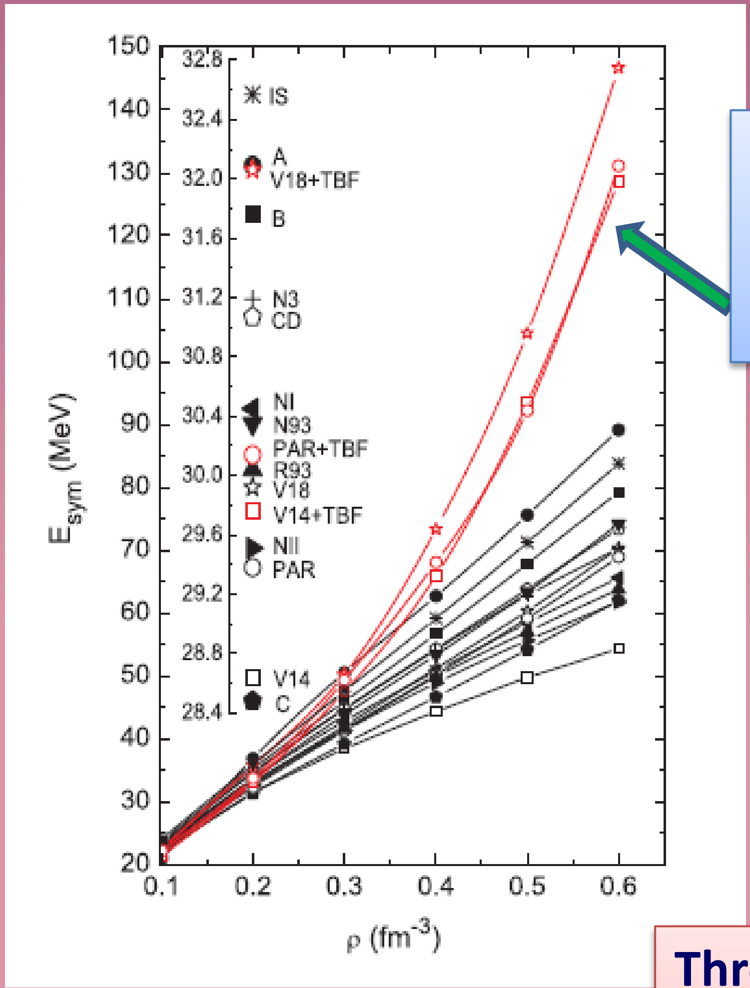


Brown (PRL 2001)

High densities: why so uncertain ?



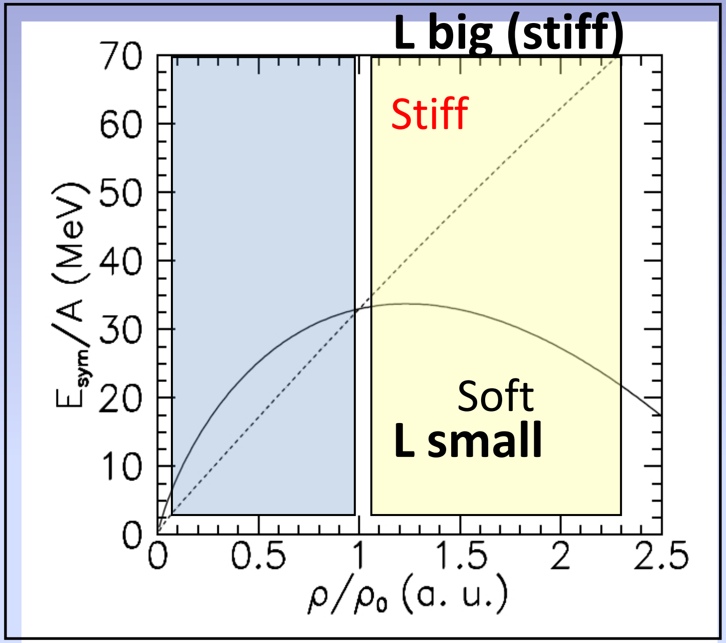
BHF + microscopic 3-body forces

The dependency on density of the potential part of symmetry energy term is poorly known in particular is largerly uncostrained for the high density behaviour $\rho \geq \rho_0$

Three body forces (TBF) enhance the symmetry energy at high density
ZH Li, U. Lombardo et al., PRC74 047304 (2006).
In neutron matter the short-range repulsive part of 3-body force is dominant.

Symmetry energy parametrizations

L is the slope of the symmetry term



Kinetic contribution (Fermi gas model)

Isospin dependence of the effective interaction

$$E_{SYM} = E_{SYM}(kin) + E_{SYM}(pot)$$

Parametrization of the potential part of symmetry energy used in **Stochastic Mean Field model** [V. Baran et al., Phys. Rep. 410, 335 (2005)]

Symmetry energy parametrizations

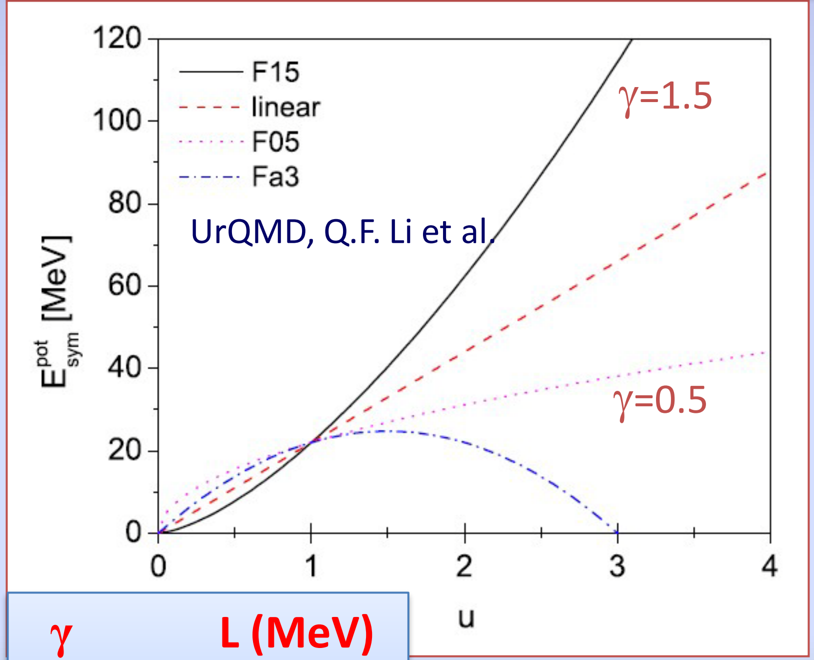
L is the slope of the symmetry term

Kinetic contribution (Fermi gas model)

Isospin dependence of the effective interaction

$$E_{SYM} = E_{SYM}(kin) + E_{SYM}(pot)$$

$$E_{sym} = E_{sym}^{kin} + E_{sym}^{pot} = 12\,\text{MeV}\cdot(\rho/\rho_0)^{2/3} + 22\,\text{MeV}\cdot(\rho/\rho_0)^{\gamma}$$



γ	L (MeV)
0.5	57
1.0	90
1.5	123

Experimental observable: an overview

OBSERVABLE $\rho<\rho_0$ (Fermi energies)

Fragment isotope distribution: isotopic and isobaric yield ratios, isoscaling

Isospin distillation/fractionaction, relative n/p densities

Isospin diffusion: isospin transport ratio R_i

Neutron/proton ratio (or double ratio)

Particle – Particle correlations, femtoscopy

Transverse flow of light charged particles

Reaction mechanisms competition

Light cluster production

Mid-rapidity emission, neck fragmentation

. . . .

Nuclear structure and collective excitations

Neutron skin thickness

Giant DR

Pygmy DR

LNL-SPES
LNS
MSU
GANIL-SPIRAL2
TAMU
…………………

OBSERVABLE $\rho>\rho_0$ HIC, relativistic energies)

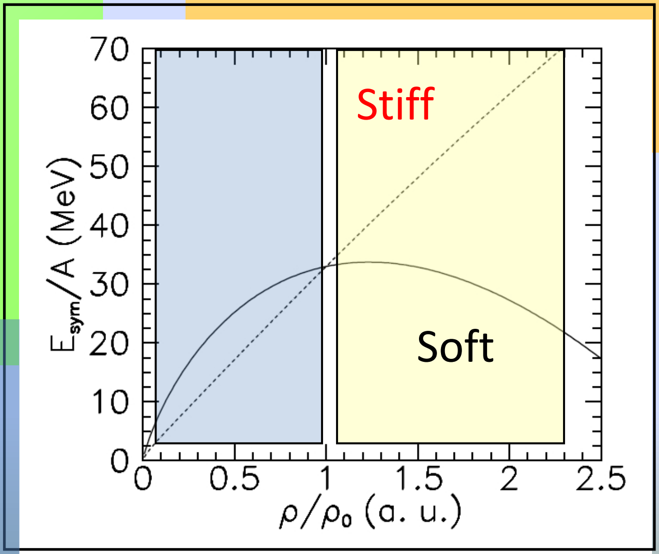
Collective flows (protons, neutrons, pions….):
Elliptic flow,Transverse flow, difference of collective flows

Charged pions π^+/π^- ratio

K^+/K^0 ratio

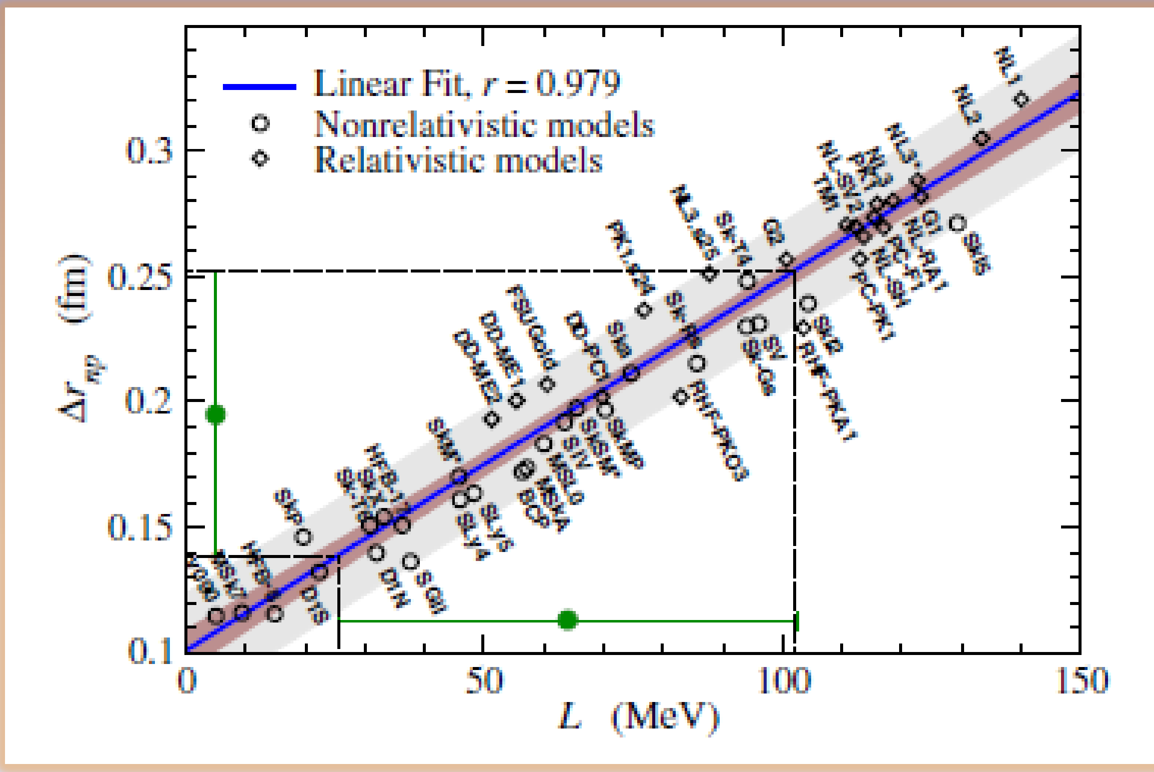
. . . .

GSI/FAIR
FRIB
RIKEN
. . . .



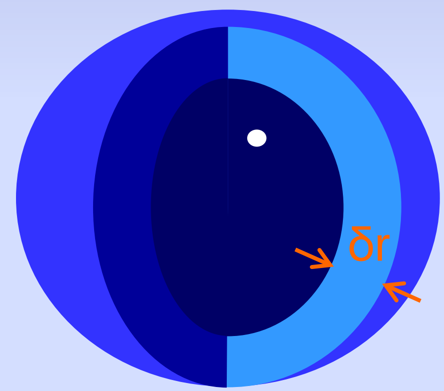
Neutron skin and the symmetry energy

Larger **L** → **ticker** neutron skin



Roca-Maza et al., PRL 106, 252501 (2011)

Empirical correlation between theoretical predictions in terms of various mean-field approaches to L around normal density and the neutron skin R.



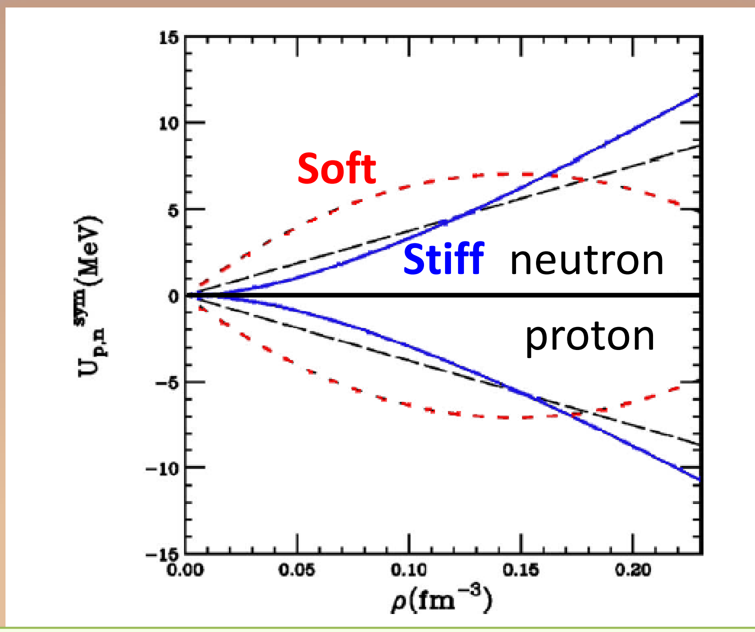
The symmetry pressure is repulsive for neutrons. The pressure is larger if S(ρ) is strongly density dependent.

Future: P-Rex and C-Rex experiments at JLAB-A on ^{208}Pb and ^{48}Ca.

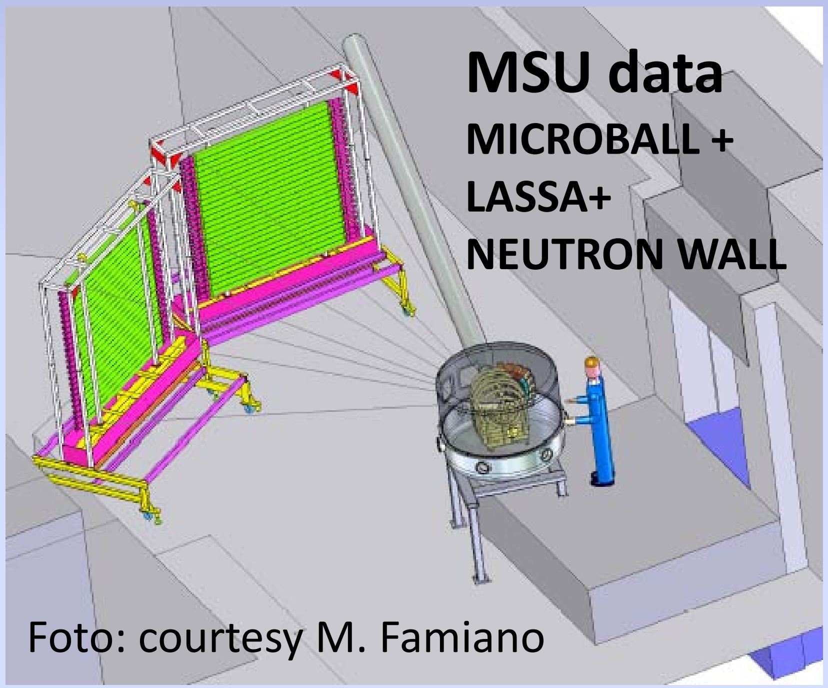
A first example: Neutron – Protons ratio (pre-equilibrium nucleons)

See: M.A. Famiano et al., PRL 97 052701, (2006)
M.B. Tsang et al., PRL 102, 122701 (2009)

The idea is to look to the ratio of neutron/proton yield in central collisions (energy spectra of transversely emitted nucleons around 90° in the c.m. system.)



V. Baran et al. Phys. Rep. 410, (2005)
Skyrme-like form for mean-field potential seen by protons and neutrons for ^{124}Sn



Double Ratio R(n/p) minimizes systematic errors, efficiency problems, etc

$$\frac{^{124}\text{Sn}+^{124}\text{Sn} \quad Y(n)/Y(p)}{^{112}\text{Sn}+^{112}\text{Sn} \quad Y(n)/Y(p)}$$

E/A=50 MeV

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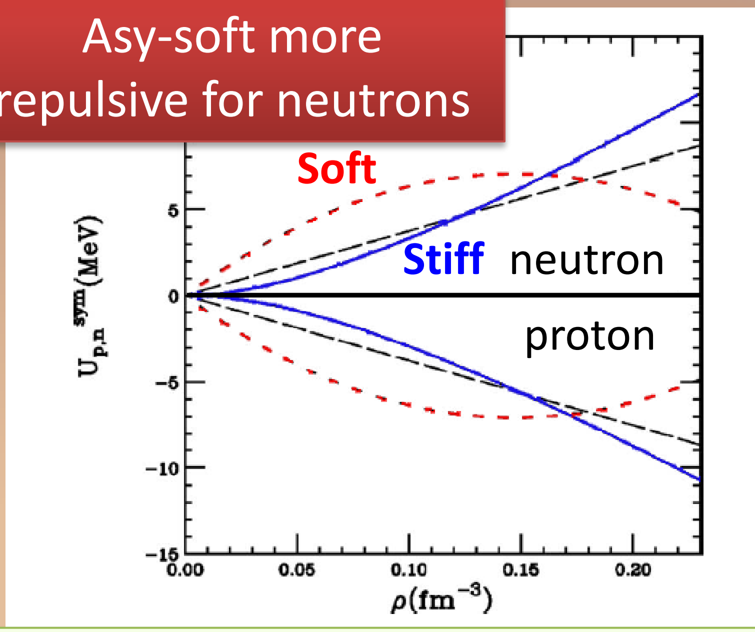
Asy-soft more repulsive for neutrons



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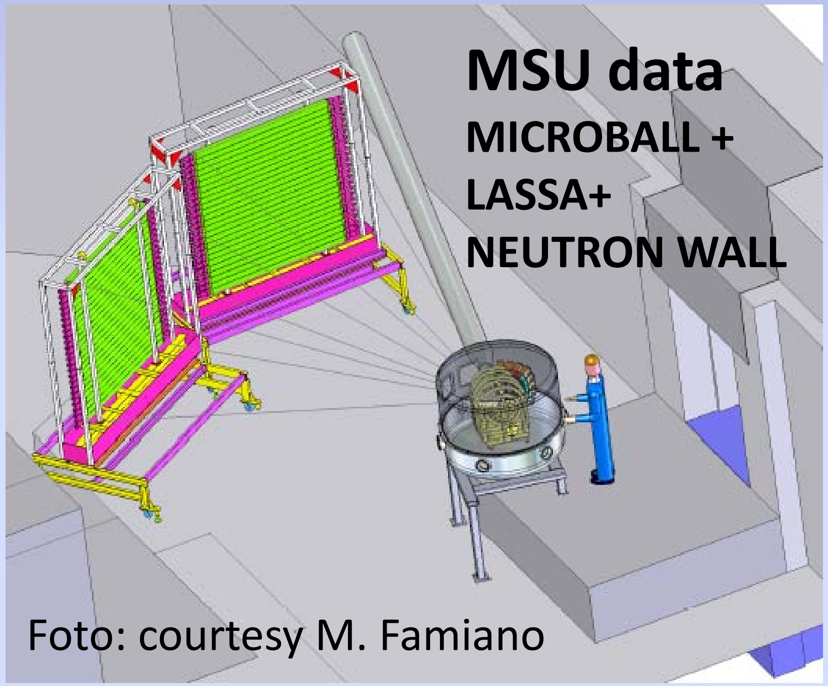

Foto: courtesy M. Famiano

Double Ratio R(n/p) minimizes systematic errors, efficiency problems, etc

$$R(n/p) = \frac{^{124}Sn+^{124}Sn \quad Y(n)/Y(p)}{^{112}Sn+^{112}Sn \quad Y(n)/Y(p)}$$

E/A=50 MeV

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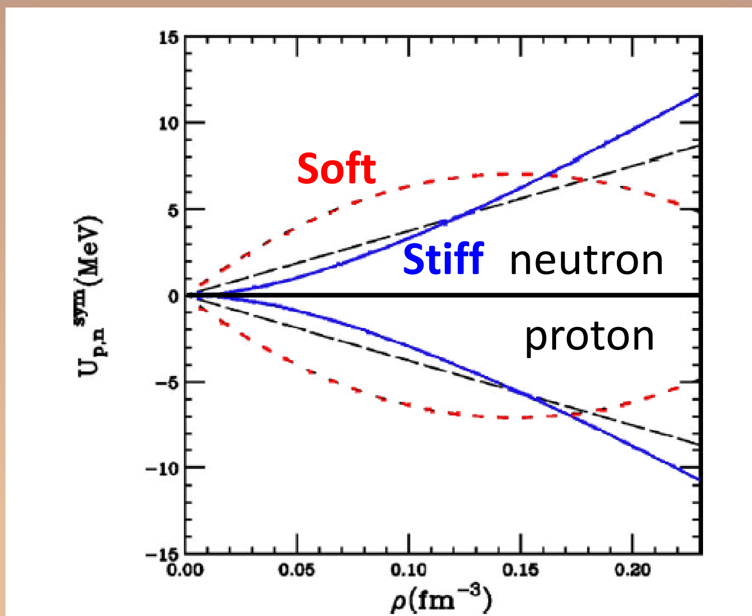

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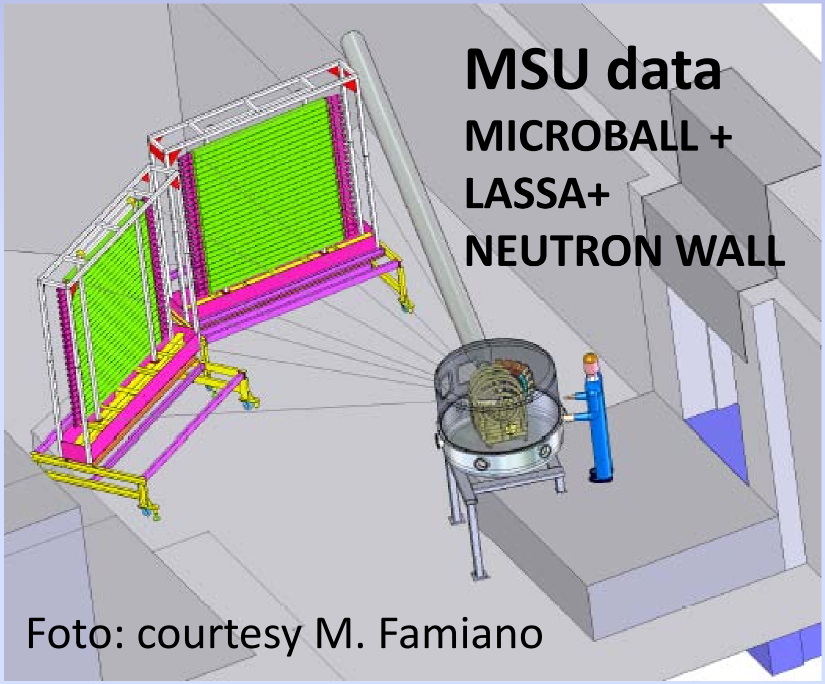

Double Ratio R(n/p) minimizes systematic errors, efficiency problems, etc

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E/A=50 MeV

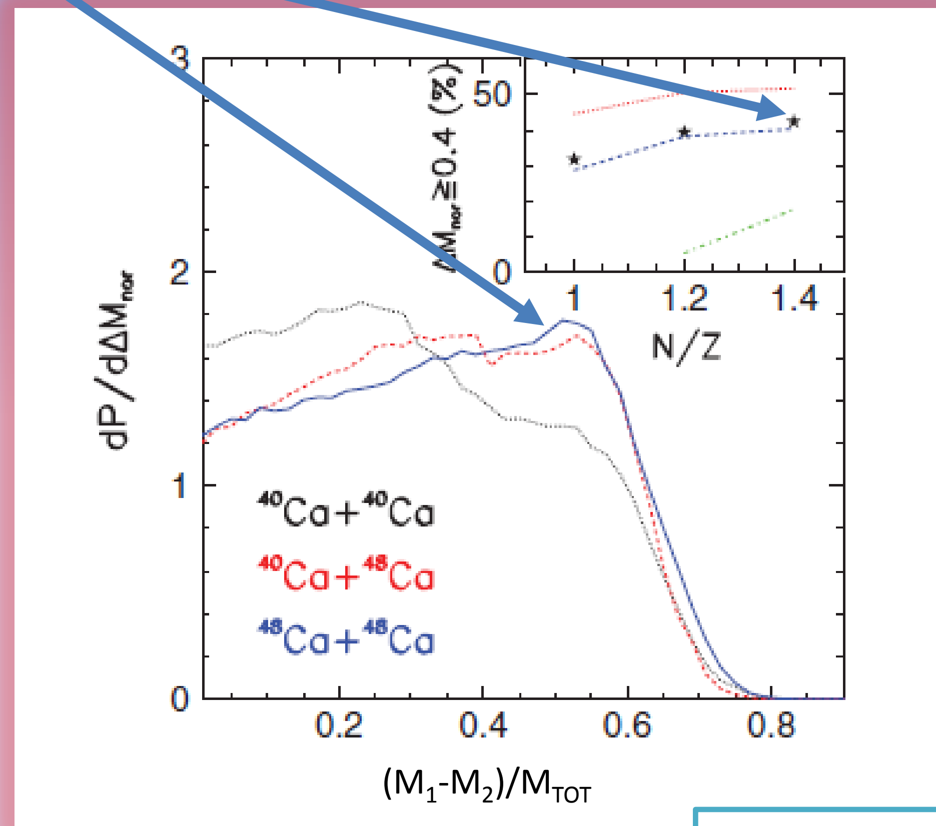
Competition of reaction mechanisms

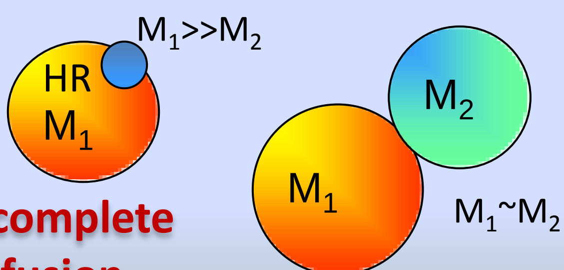
N/Z effects in competition between binary reactions and incomplete fusion. Higher probability for fusion using neutron rich systems

$^{48}Ca+^{48}Ca$, $^{40}Ca+^{48}Ca$, , $^{48}Ca+^{40}Ca$ $^{40}Ca+^{40}Ca$

25 A.MeV, *G. Cardella et al., PRC 85 084609 (2012)*

F. Amorini et al., PRL102, 112, 701 (2009)





Incomplete fusion

Binary reactions

Chimera data

Competition of reaction mechanisms

N/Z effects in competition between binary reactions and incomplete fusion. Higher probability for fusion using neutron rich systems

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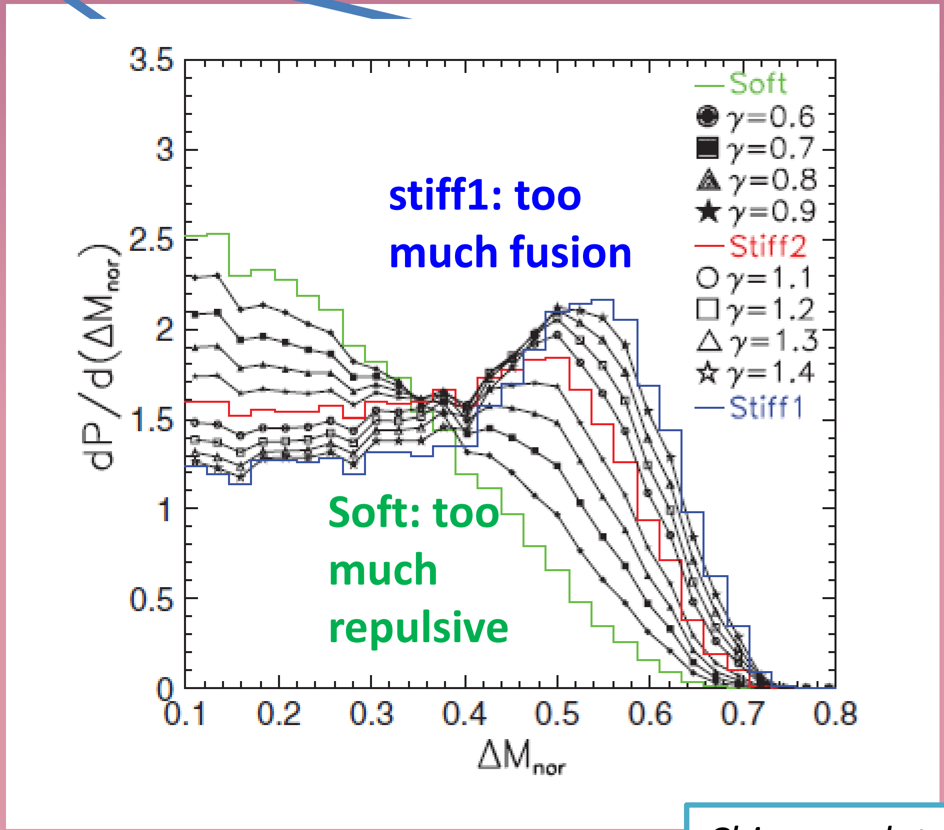
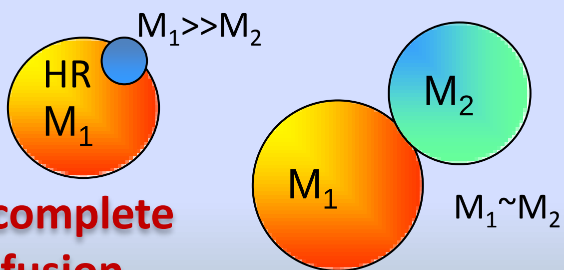


Comparison with **CoMD** model *(M. Papa et G. Giuliani, EPJA 39, 17 (2009): the good matching with experimental data is obtained by a moderately stiff symmetry energy term **(γ=1.1±0.1)***



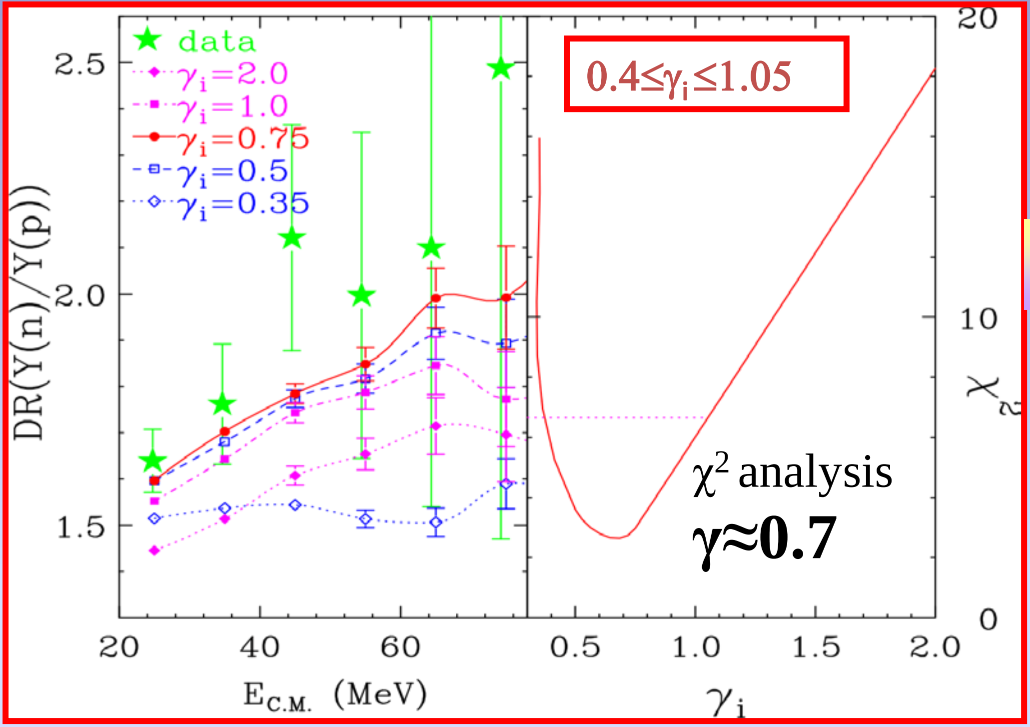
Incomplete fusion

Binary reactions

Chimera data

Neutron – Protons ratio (pre-equilibrium nucleons)

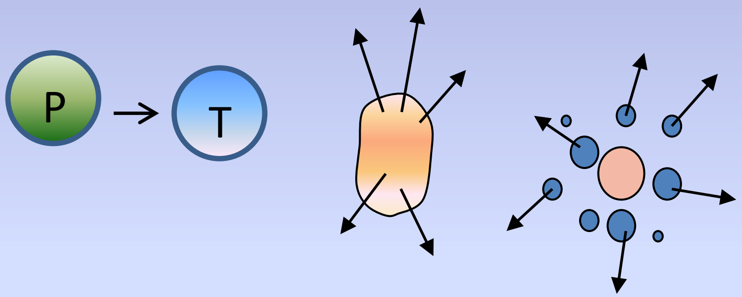
M. Famiano et al. data



M.B. Tsang et al., PRL 102 122701 (2009)
Y. Zhang et al., PLB 664 145 (2008)

ImQMD model with γ between 0.35 and 2.0 (momentum dependent mean field)

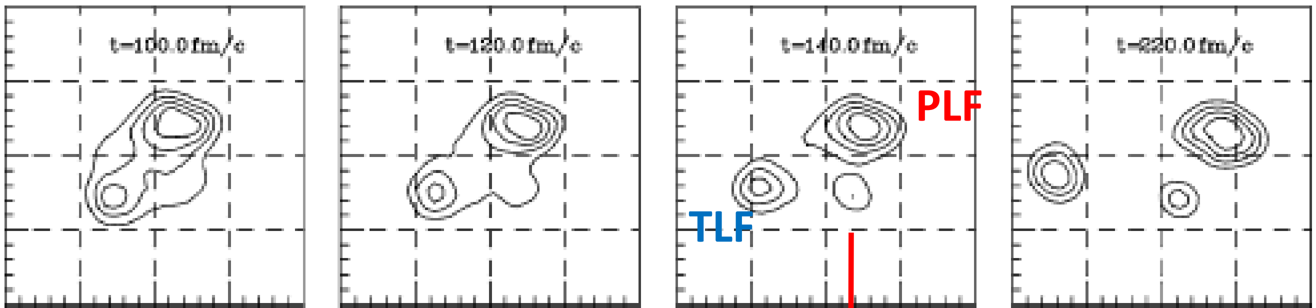
$$S(\rho) = 12.3 \cdot (\rho/\rho_0)^{2/3} + 17.6 \cdot (\rho/\rho_0)^{\gamma}$$



Nucleons are mostly emitted when system expands and breaks-up at subsaturation densities.

Probes in semi-peripheral reactions: isospin diffusion and migration →

Semi-peripheral collisions: diffusion, migration, neck fragmentation



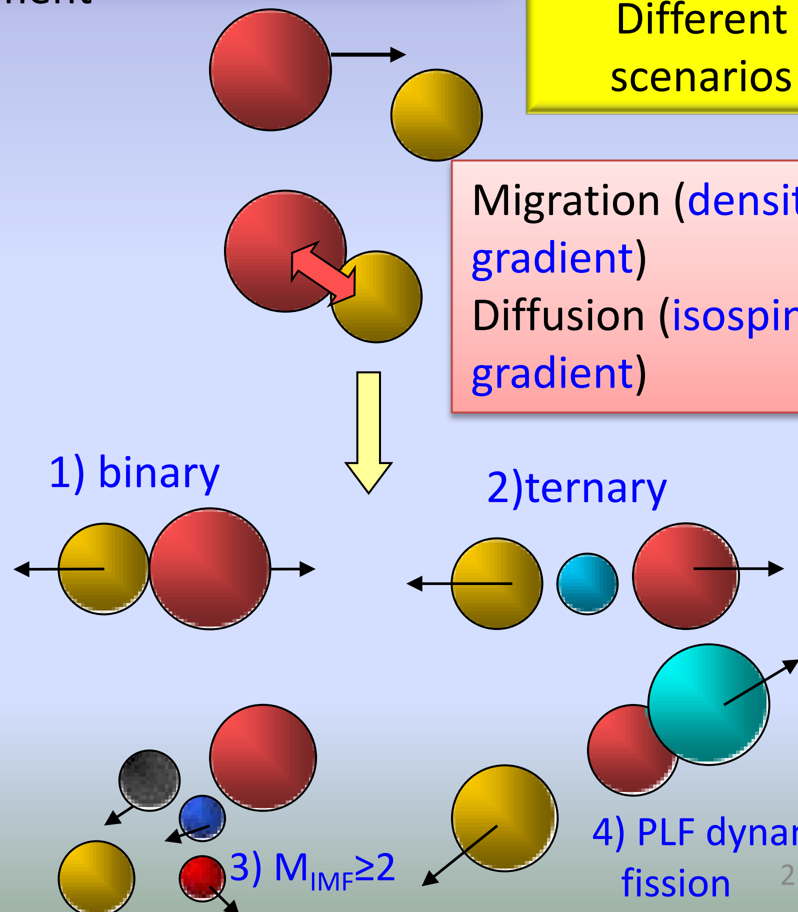
V. Baran et al., NPA730

$^{124}Sn + ^{64}Ni$
35 A.MeV

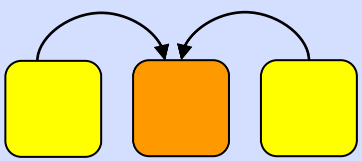
Density gradient

Different scenarios

Migration (density gradient)
Diffusion (isospin gradient)



Asymmetry flux

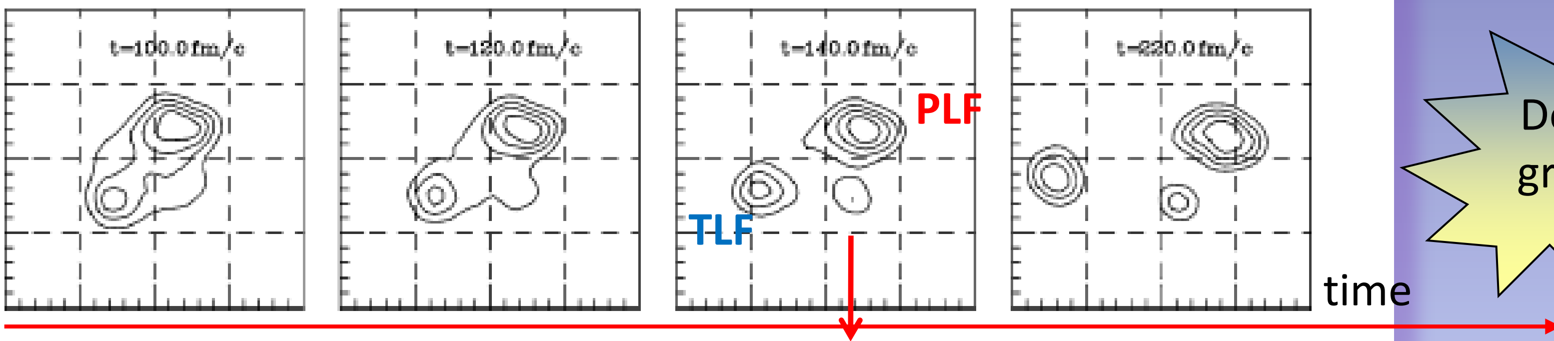


$\rho_{neck} < \rho_{PLF(TLF)}$

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

diffusion   migration

Semi-peripheral collisions: diffusion, migration, neck fragmentation



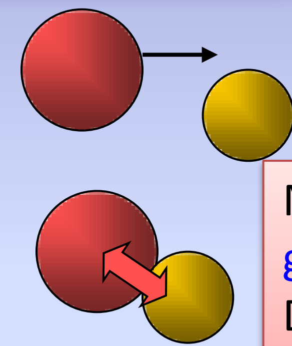
Neck fragment

V. Baran et al., NPA730

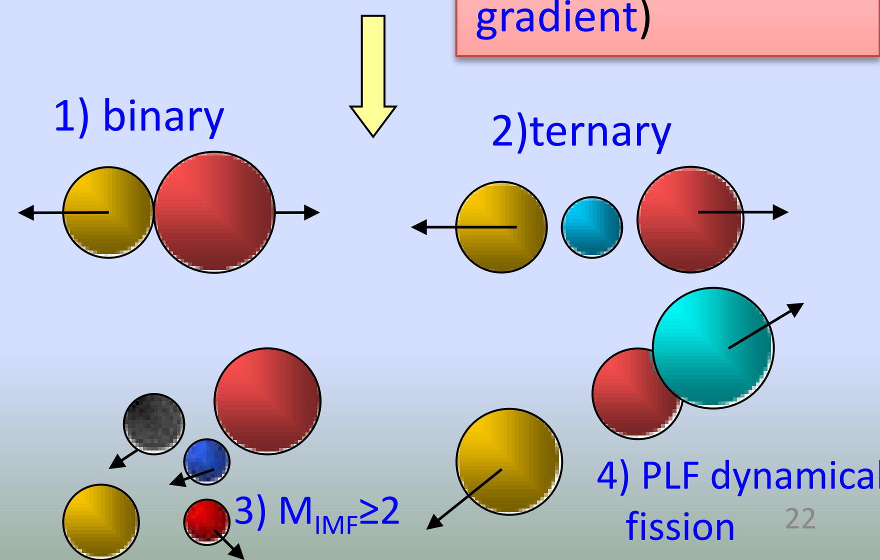
$^{124}Sn + ^{64}Ni$
35 A.MeV

Density gradient

Different scenarios



Migration (density gradient)
Diffusion (isospin gradient)



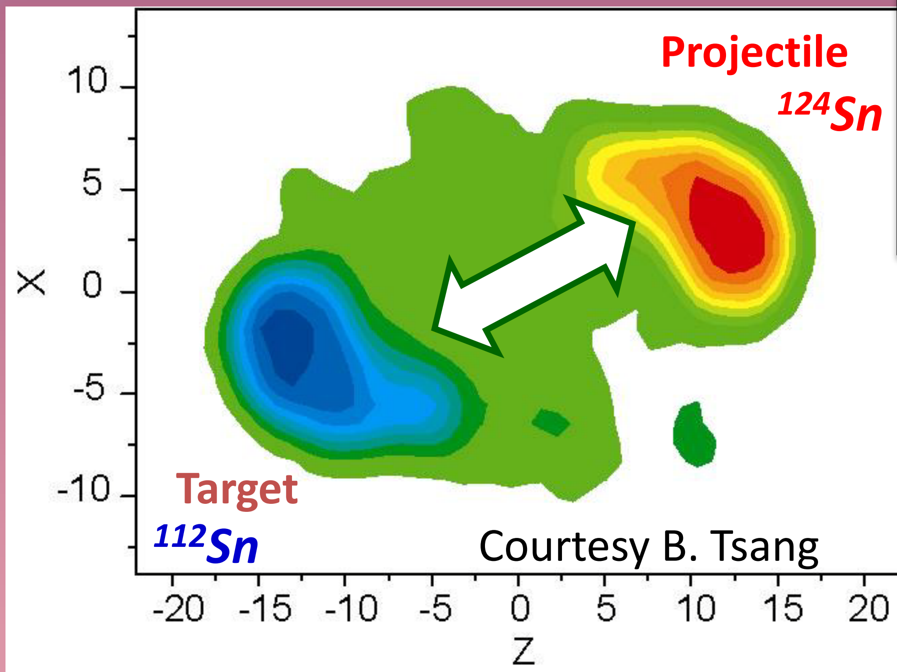
Density gradient: more neutron drift towards low density region with asy-stiff (depends upon slope of symmetry energy at low density).

Isospin gradient: N/Z equilibration through the neck is favoured by a soft symmetry term of EOS).

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

diffusion migration

Isospin diffusion → diffusion of neutrons and protons across the neck



$^{124}Sn + ^{112}Sn$ (AB) mixed → diffusion

$^{112}Sn + ^{124}Sn$ (BA) mixed → diffusion

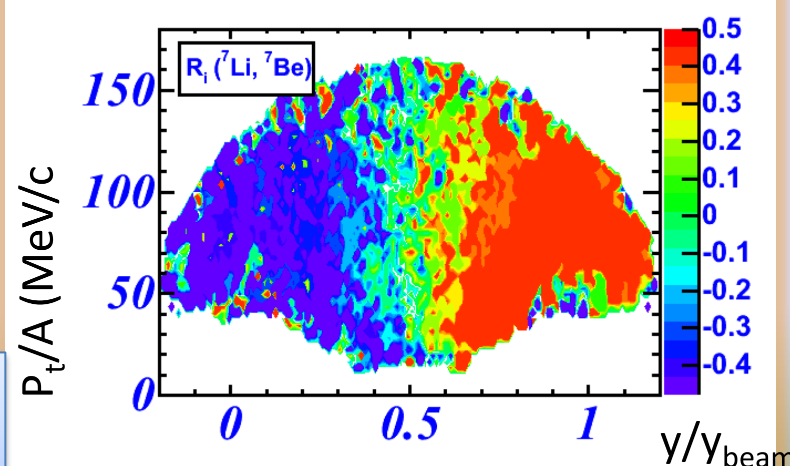
$^{124}Sn + ^{124}Sn$ (AA) neutron rich, no diffusion

$^{124}Sn + ^{124}Sn$ (BB) neutron poor, no diffusion

$$R_i(x_{AB}) = 2 \cdot \frac{x_{AB} - (x_{AA} + x_{BB})/2}{x_{AA} - x_{BB}}$$

$R_i = \pm 1$ no diffusion; $R_i = 0$ equilibration

X is an “isospin” observable and is rescaled according to R_i (transport ratio)



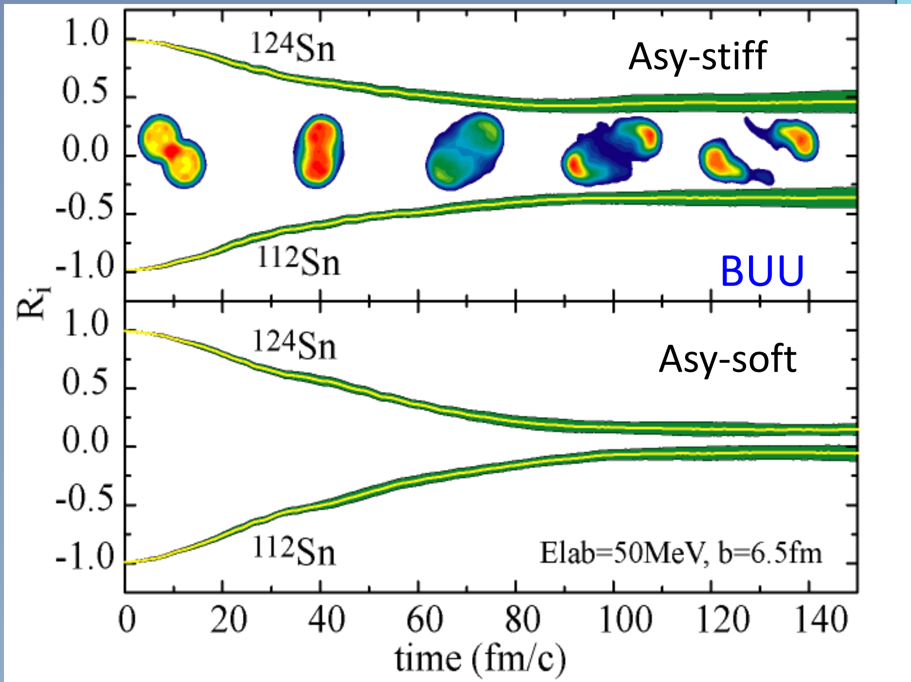
T.X. Liu et al., PRC76 034603 (2007)

$^{112}Sn + ^{124}Sn$

$R_7 = f(Y(^7Li)/Y(^7Be))$

MSU/Lassa data

Isospin diffusion → diffusion of neutrons and protons across the neck



M.B. Tsang et al., PRL92 062701 (2004)

^{124}Sn + ^{112}Sn (AB) mixed → diffusion
^{112}Sn + ^{124}Sn (BA) mixed → diffusion
^{124}Sn + ^{124}Sn (AA) neutron rich, no diffusion
^{124}Sn + ^{124}Sn (BB) neutron poor, no diffusion

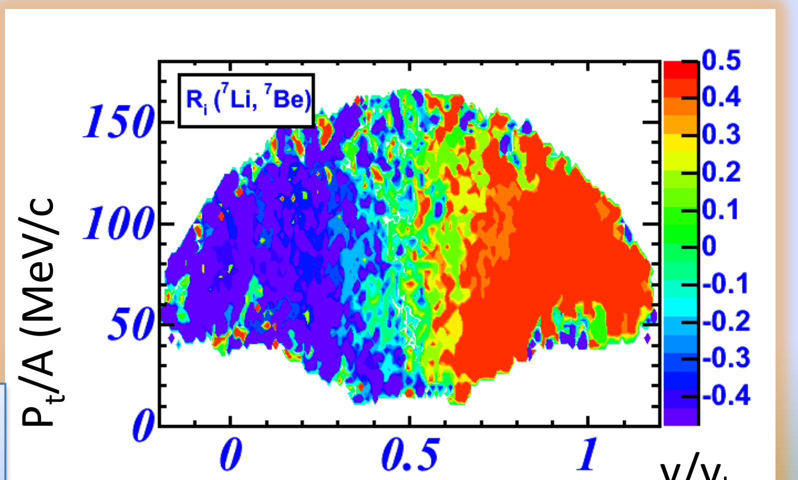
$$R_i(x_{AB}) = 2\cdot\frac{x_{AB}-(x_{AA}+x_{BB})/2}{x_{AA}-x_{BB}}$$

$R_i = \pm 1$ no diffusion; $R_i = 0$ equilibration

X is an "isospin" observable and is rescaled according to R_i (transport ratio)

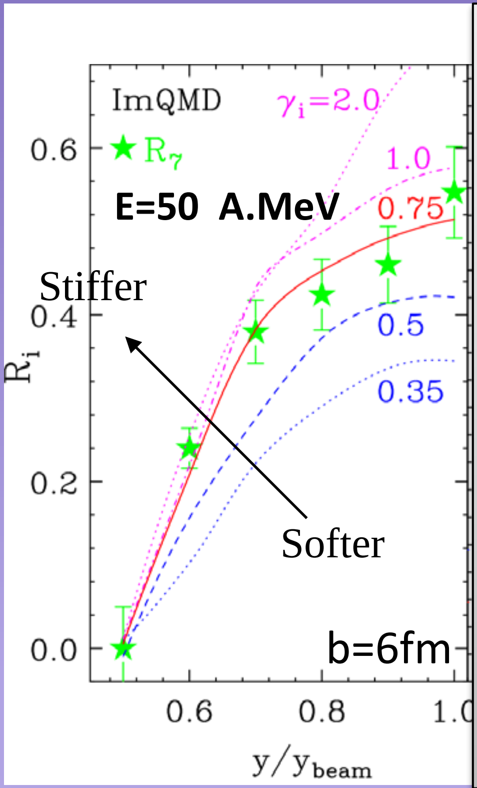
Isospin equilibration depends from **S (ρ)** value at subsaturation density and is favoured by a **SOFT term of ASY-EOS. Less mixing with a STIFF asy-EOS.**

^{112}Sn + ^{124}Sn
$R_7 = f(Y(^7Li)/Y(^7Be)$
MSU/Lassa data



T.X. Liu et al., PRC76 034603 (2007)

Isospin diffusion and equilibration:



Comparison with **ImQMD** model (Best fit obtained with γ=0.75 at b=6 fm.

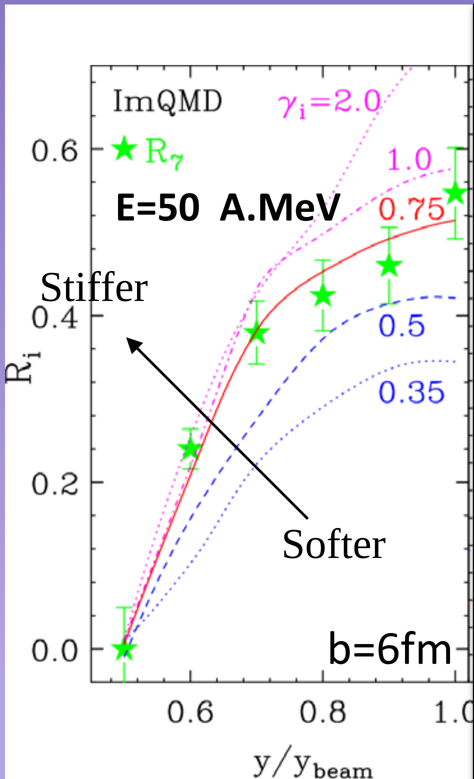
Results of χ^2 analysis on compared isospin diffusion and n/p ratios data:

0.45≤ γ ≤1
50 ≤ L ≤ 85 MeV

Studied at **MSU** 50 A.MeV (LASSA array) and at lower energy (35 A.MeV) at **INFN-LNS** with the CHIMERA array.

MSU data from M.B. Tsang, plenary talk at NN2012, Texas and PRL 102,122701 (2009)

Isospin diffusion and equilibration:



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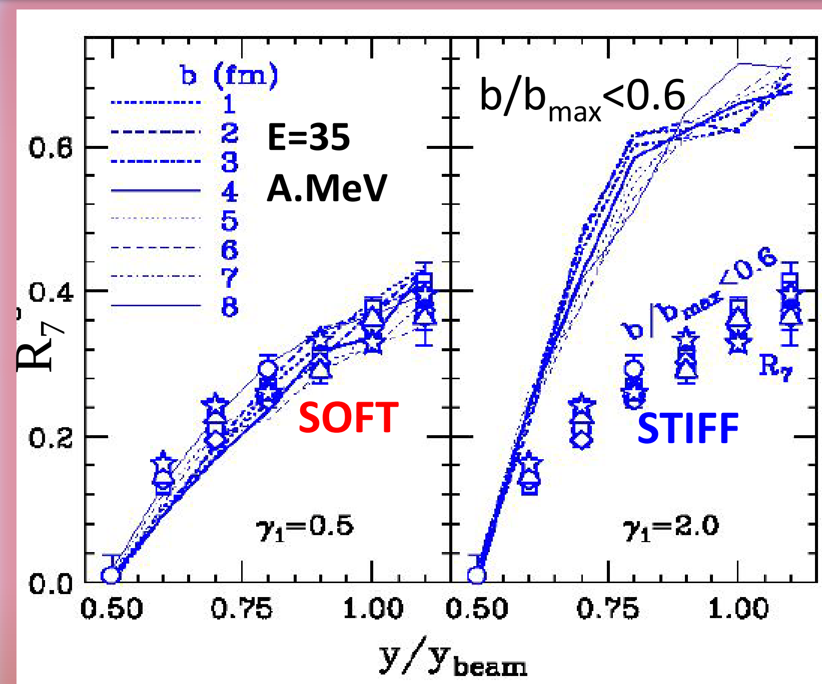
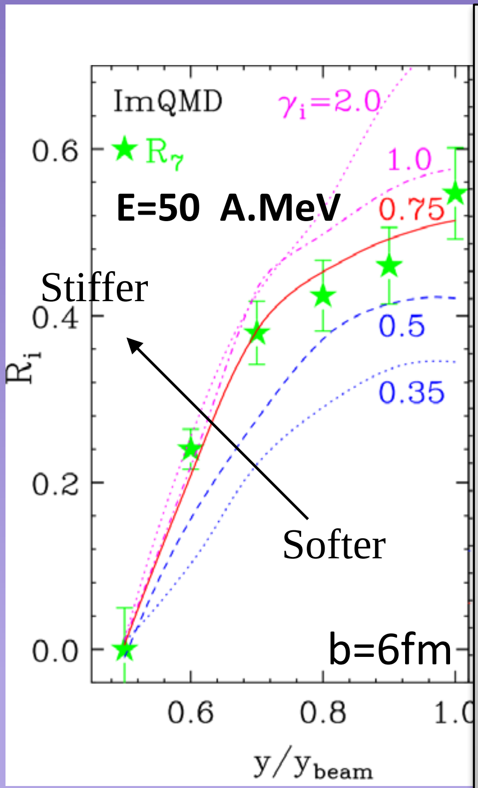
Z.Y. Sun et al, CHIMERA-MSU collaboration PRC82, 051603 (2011)

MSU data from M.B. Tsang, plenary talk at NN2012, Texas and PRL 102,122701 (2009)



Isospin diffusion and equilibration:



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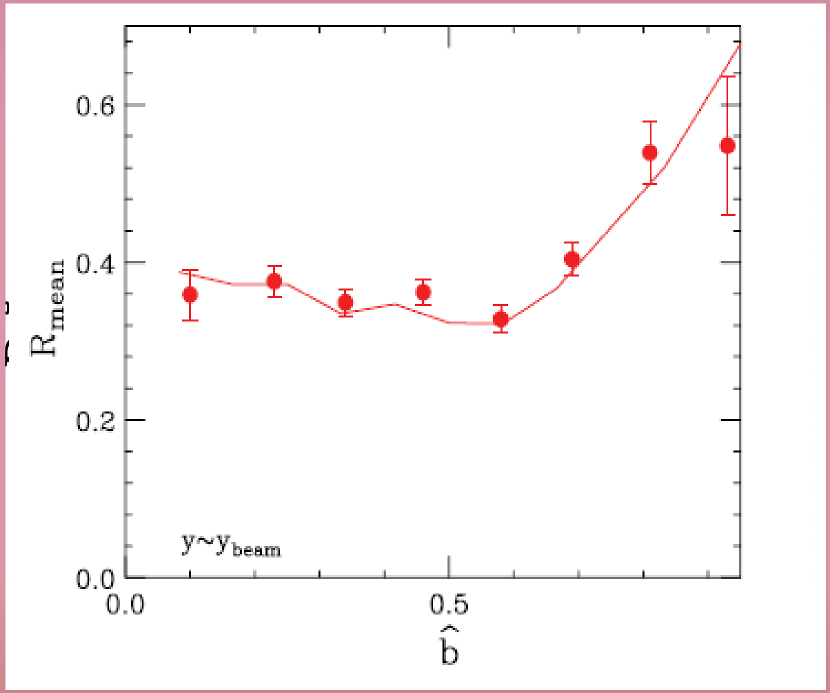


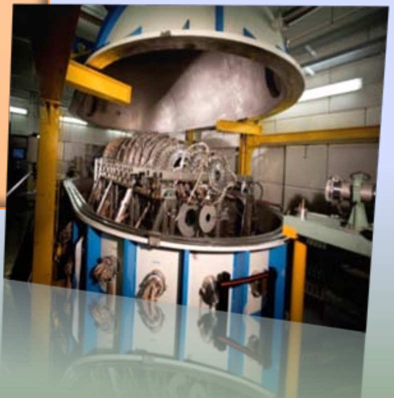
MSU data from M.B. Tsang, plenary talk at NN2012, Texas and PRL 102,122701 (2009)

Correlation between Isospin Dynamics and emission Time-scale

- ❑ Disentangling dynamic and statistical emission: space-time characterization and correlations.

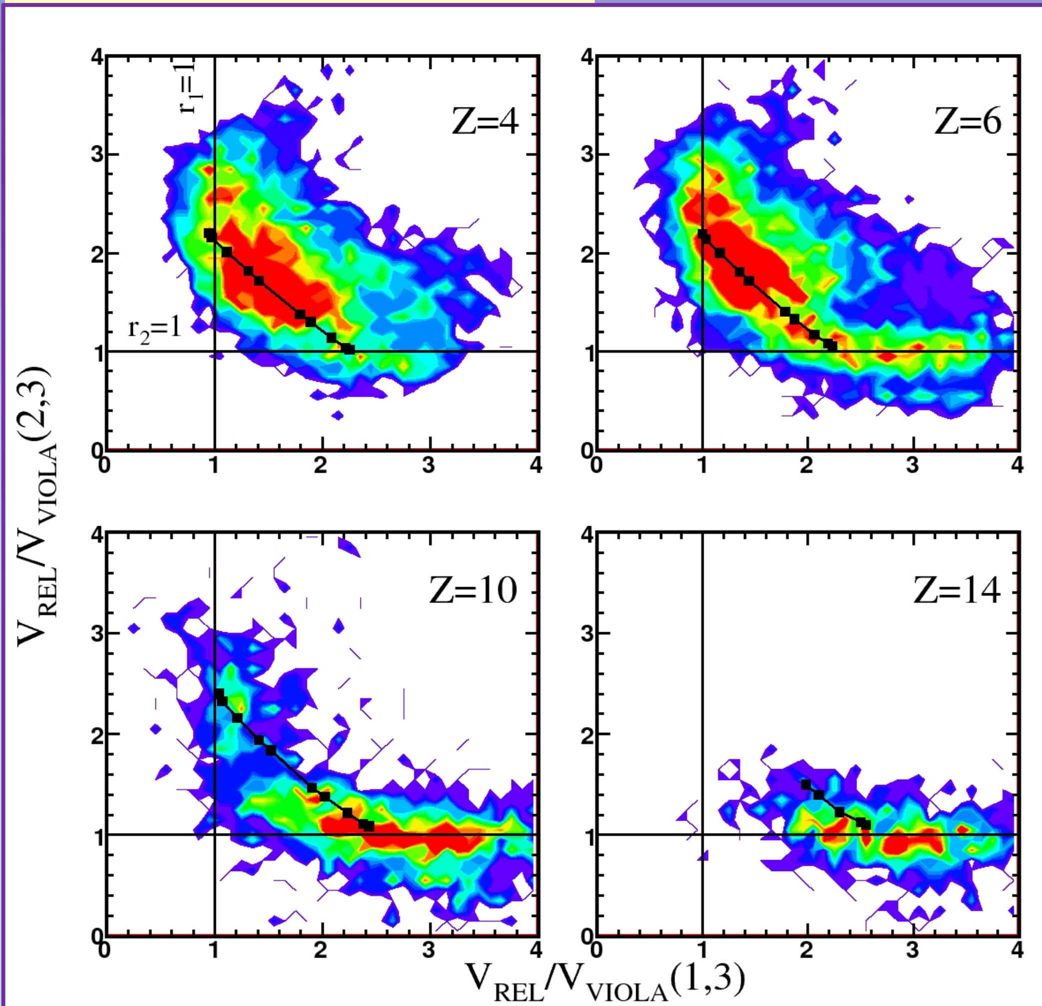
- ❑ Study of isotopic composition of fragments: isospin migration, neutron enrichment.

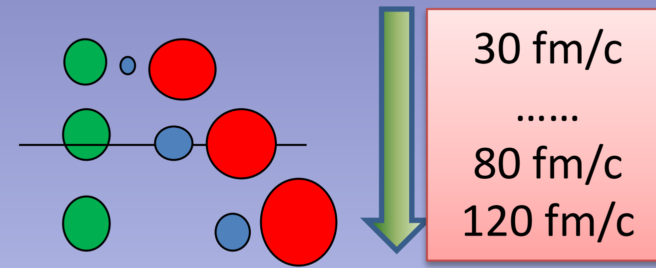
- ❑ Calculations: probing the density dependency of the symmetry energy using these new observables



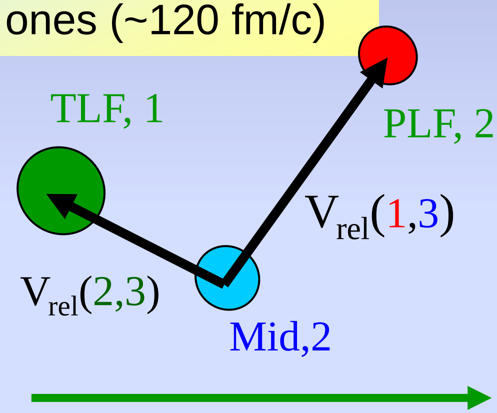
3-BODY CORRELATIONS IN TERNARY EVENTS IN DIRECT KINEMATICS

$^{64}Ni + ^{124}Sn$ + 35 A.MeV





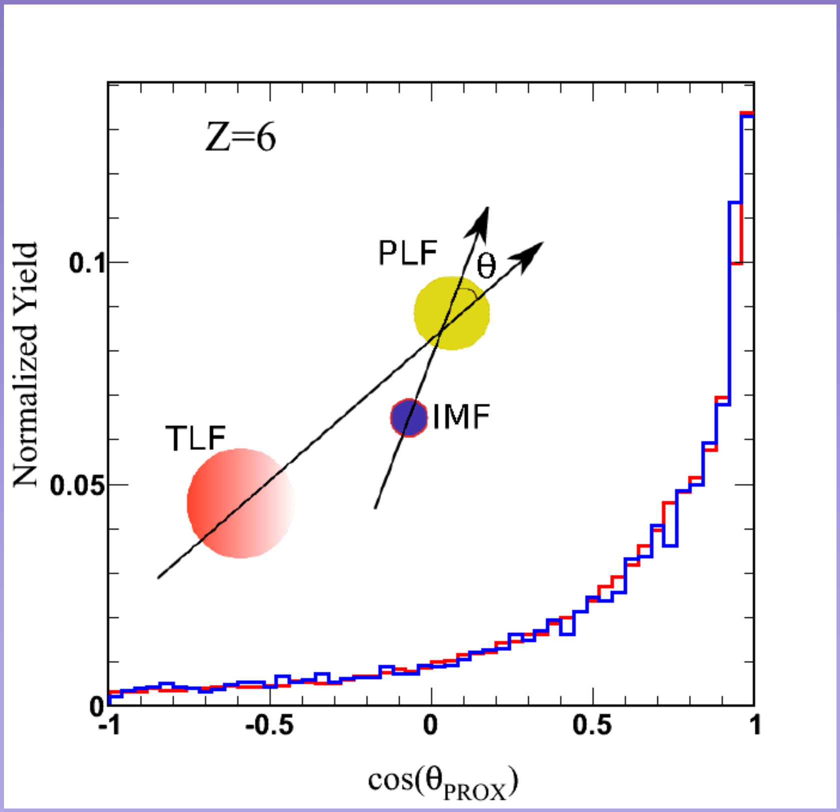
Emission cronology: light fragments are produced earlier (~40 fm/c) than heavier ones (~120 fm/c)



Relative velocities are expressed in units of the velocity corresponding to the Coulomb repulsion energy of a given subsystem according to the Viola systematics (see J. Wilczynsky et al. IJMPE 14 353 and E.d.F. et al. Phys Rev. C71, 044602, 2005).

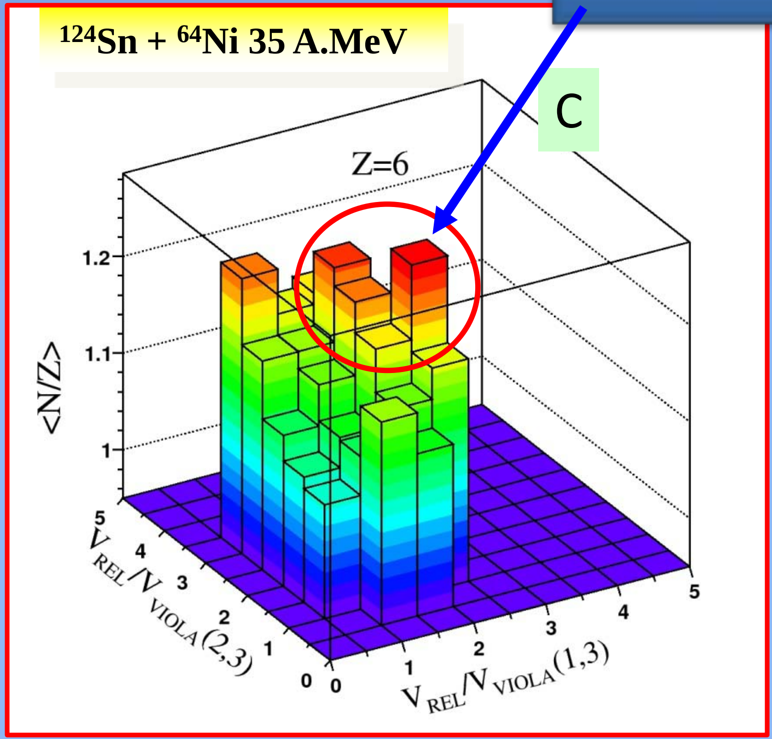
Timescale experiment: see NN2012 Conference Proceedings, S. Antonio (Texas, USA), May 27-June 1 2012, (arXiv:1209.6461)

Correlations between alignements, emission times and fragments isotopic properties



cos(θ)≈1
aligned emission of the lighter fragment in the backward emisphere of **PLF** towards midrapidity

Prompt emission in neck fragmentation: more neutron rich fragments

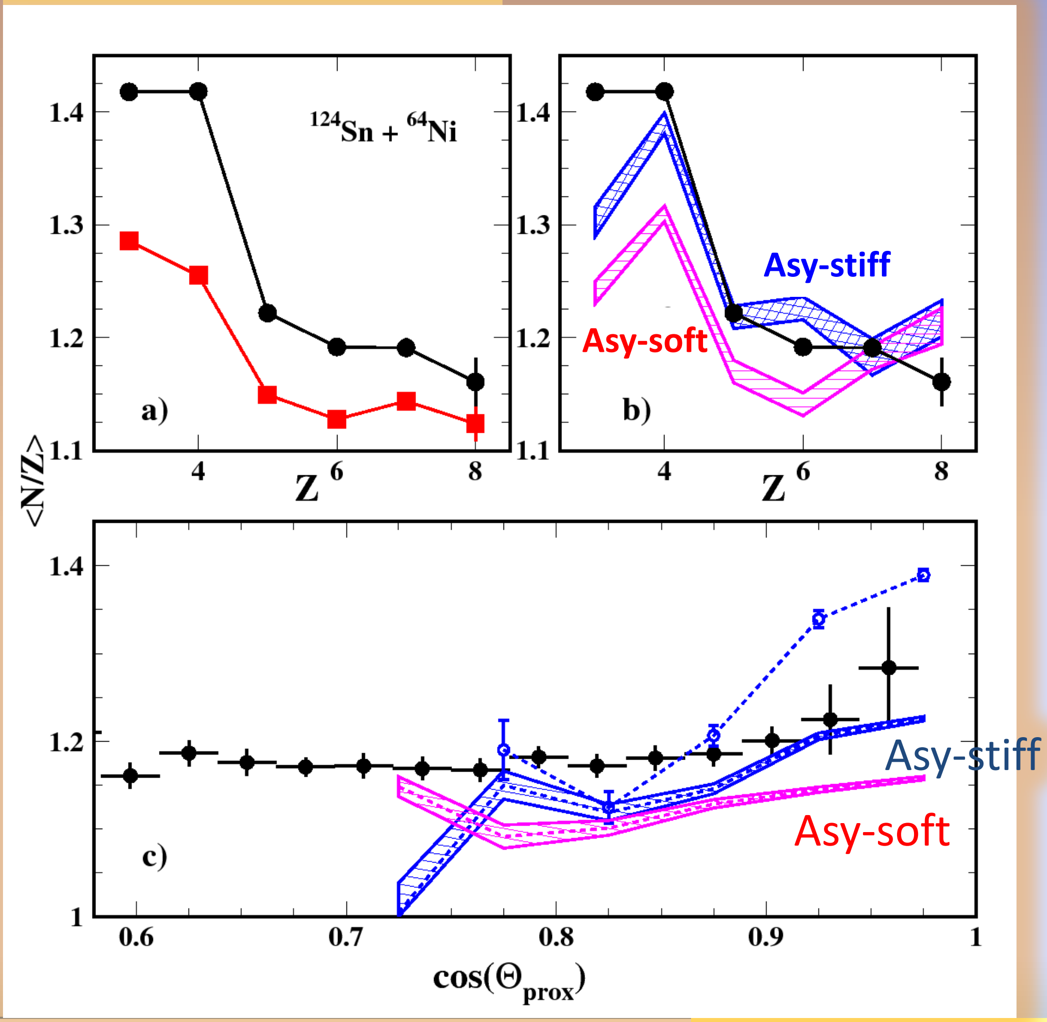


In order to study correlations between fragments formation dynamics and fragments isotopic composition we plots <N/Z> for different bins in the V_{rel}/V_{viola}(PLF-IMF) – V_{rel}/V_{viola}(TLF-IMF) plane

Correlations of different observables enhance the experimental sensitivity to select genuine effects due to isospin dynamics and constitute a strong probe for theoretical models.

Stochastic Mean Field (SMF) + GEMINI calculation

$^{124}Sn + ^{64}Ni$ 35 A.MeV



Experimental <N/Z> distribution of IMFs as a function of their atomic number compared with results of SMF (insert) and SMF+GEMINI calculations (hatchad area) for two different parametrizations of the symmetry potential (asy-soft and asy-stiff)

- Dynamically emitted particles
- Statistically emitted particles

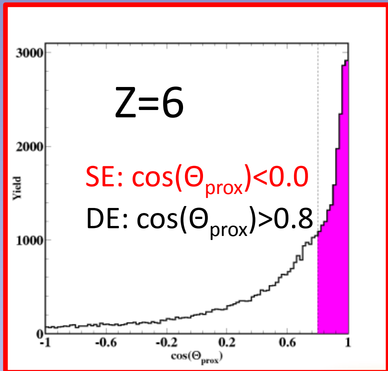
E.d.F. et al., Phys. Rev. C ***86*** *014610 (2012)*

$$L = 3\rho_0 \left(\frac{dE_{sym}(\rho)}{d\rho} \right)_{\rho=\rho_0} =$$

≈ 80 MeV for the asy-stiff

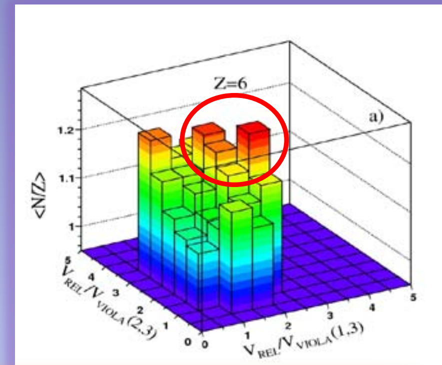
≈ 25 MeV for the asy-soft

Neck neutron enrichment; reduction of "staggering" odd-even effects

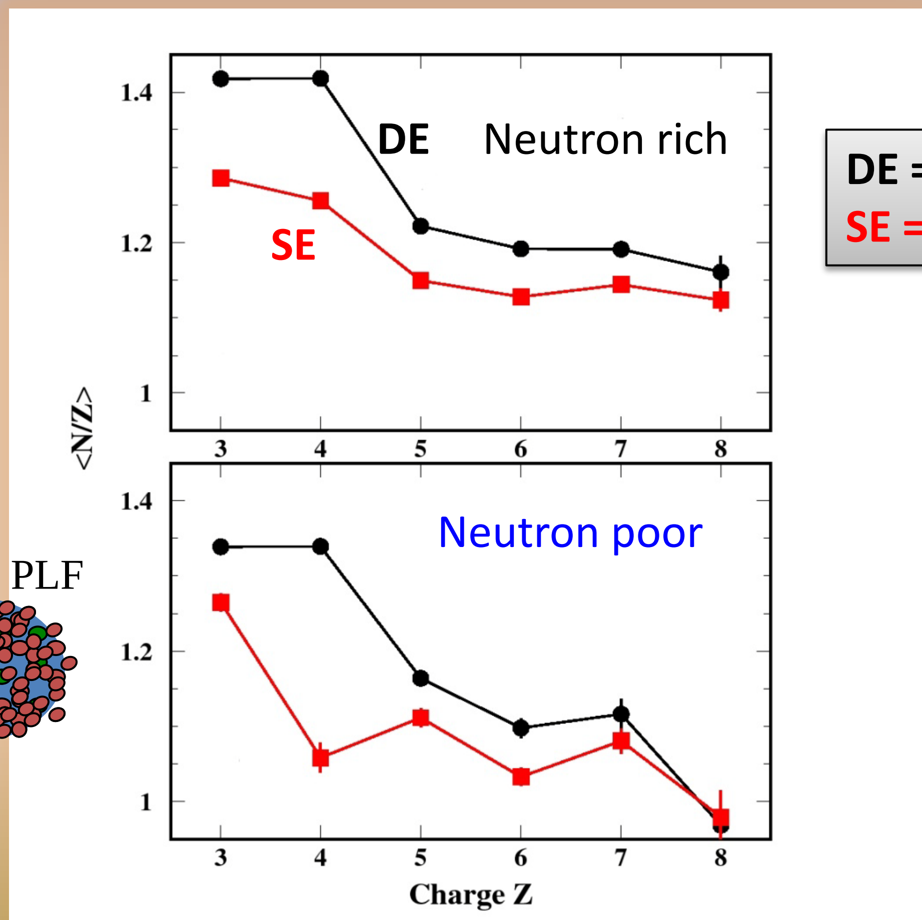


(1) Condition on $\cos(\Theta_{prox})$

+

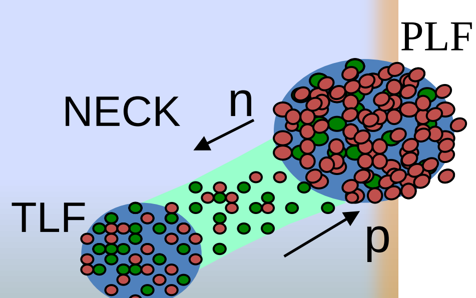


(2) Condition on V_{rel} plot



DE = Dynamical emitted

SE = Statistical emitted

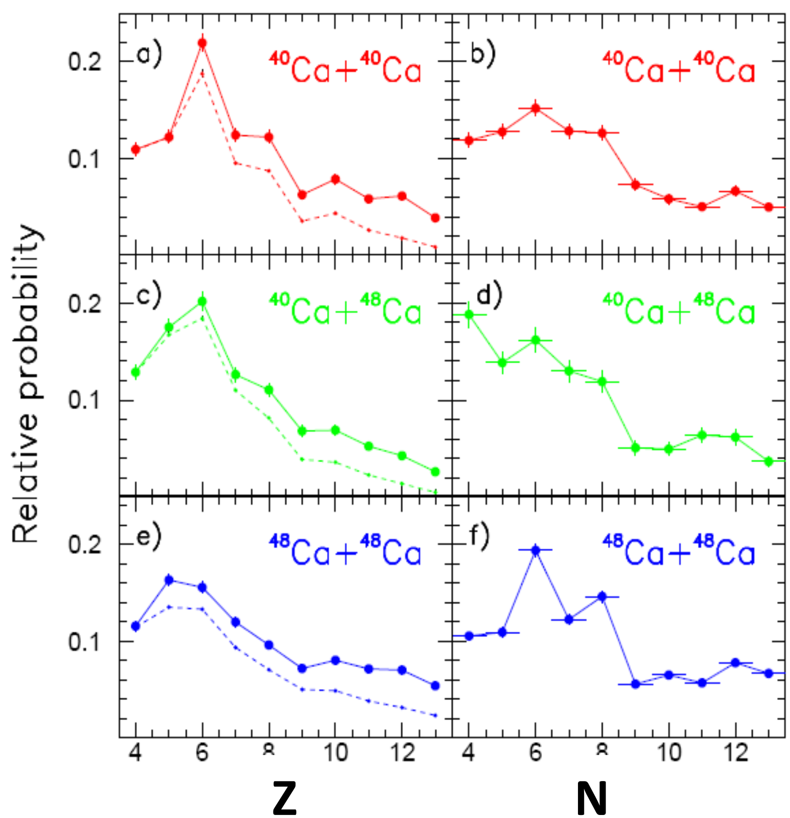


Even-odd effects on Z and N distributions of light fragments (staggering)

One proton or one neutron separation energy (pairing forces)

$^{112}Sn + ^{58}Ni$ 35 A.MeV

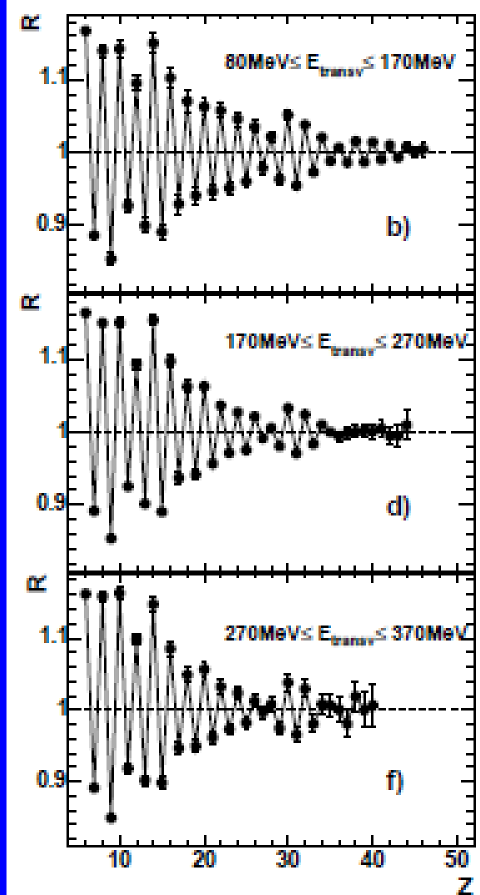
N/Z increases



Z/N increases

Chimera data

I. Lombardo et al. Phys. Rev. C84 024613 (2011).



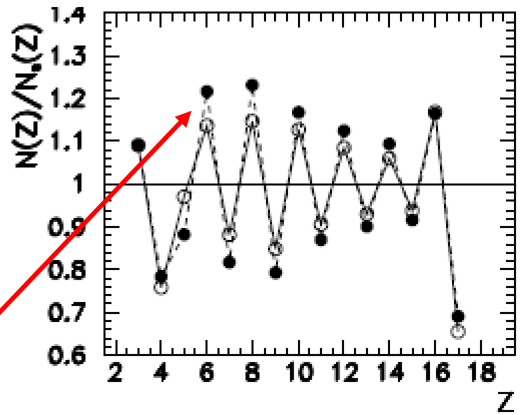
See M. D'agostino et al. Nucl. Phys. A875 (2012) 139.
M.V. Ricciardi et al., Nucl. Phys. A733, 299 (2004).
G. Ademard et al., PRC83 054619 (2011).
S. Pirrone et al. EPJ WC17 16010 (2011), ISODEC experiment

*G. Casini et al. Phys Rev C**86** 011602(R) 2012 (Chimera-Nuclex collaboration).*
No change with centrality.

Even-odd effects on Z and N distributions of light fragments (staggering)

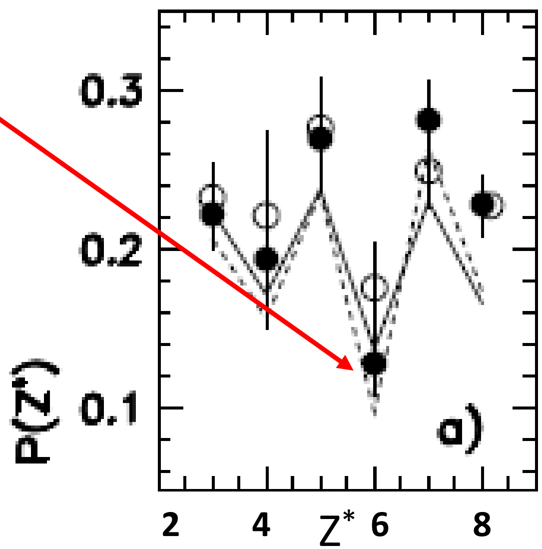
$^{32}S+^{58,64}Ni$ 14.5 A.MeV

Garfield@LNL data



Quasi projectile source, detected fragments

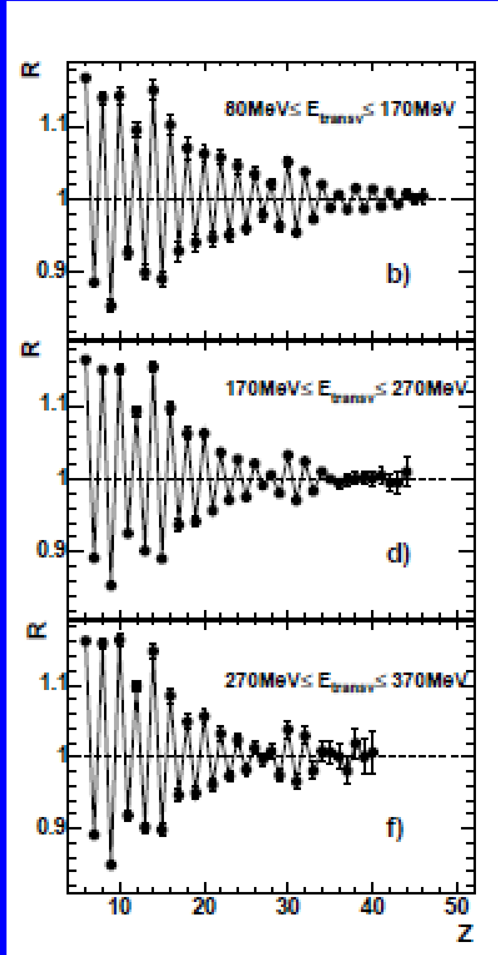
Even nuclei



Reconstructed isotopes from their lowest lying particles excited states

M. D'agostino et al. Nucl. Phys. A875 (2012) 139.

$^{112}Sn + ^{58}Ni$ 35 A.MeV



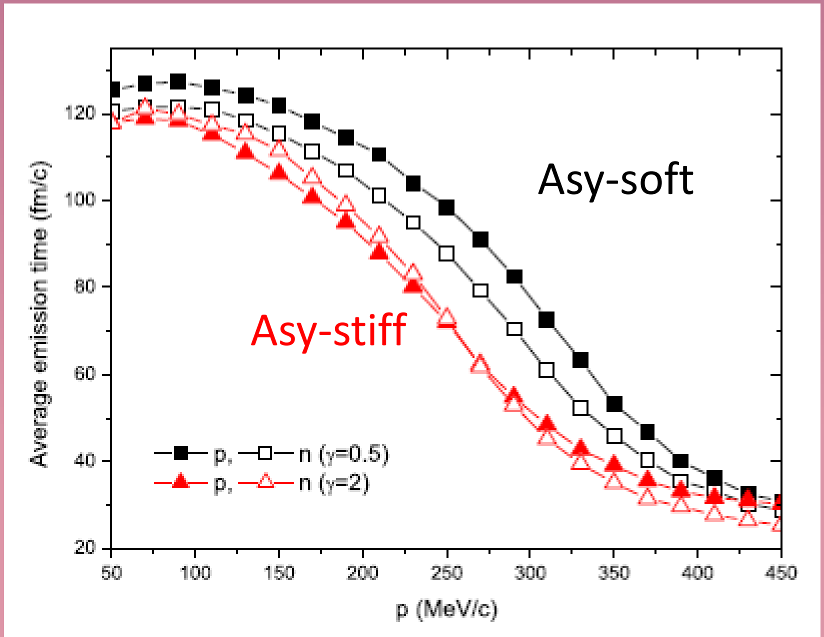
*G. Casini et al. Phys Rev C**86** 011602(R) 2012 (Chimera-Nuclex collaboration).*

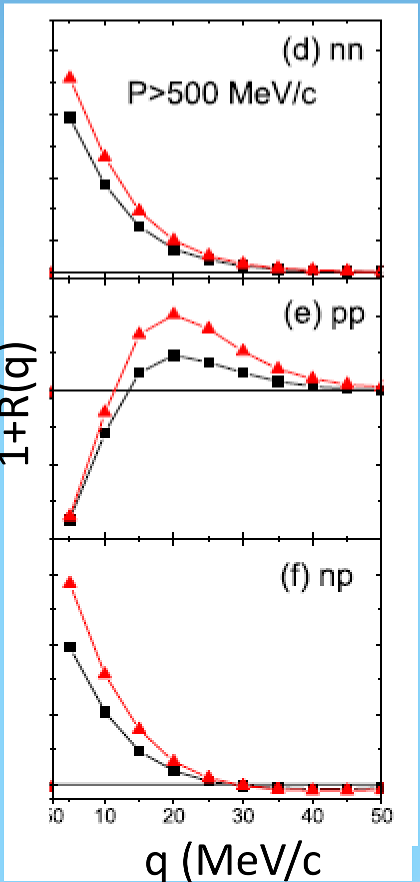
No change with centrality.

Particle-particle correlations and symmetry energy: a difficult task

IBUU simulations
$^{52}Ca + ^{48}Ca$ E/A=80 MeV, Central collisions
L.W. Chen, V. Greco , C. Ko, B-An Li, PRC68, 014605(2003)

$$1 + R(q) = k \cdot \frac{\Sigma Y_{coinc}(\vec{p}_1, \vec{p}_2)}{\Sigma Y_{evt.mixing}(\vec{p}_1, \vec{p}_2)}$$





Shorter neutron and proton average emission times and more similar n and p emission times with Esym - stiff

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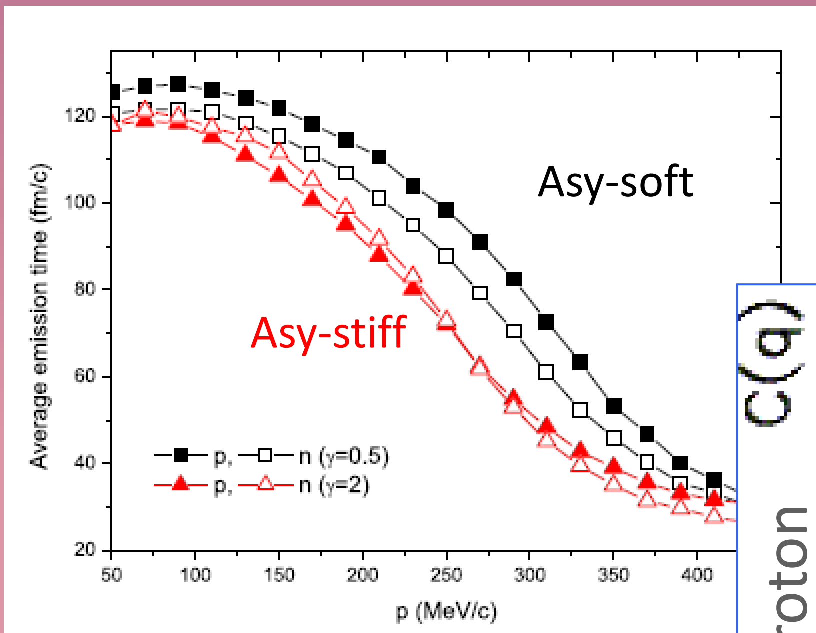

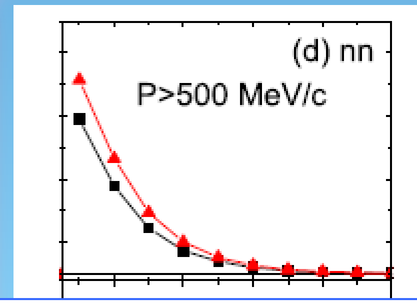

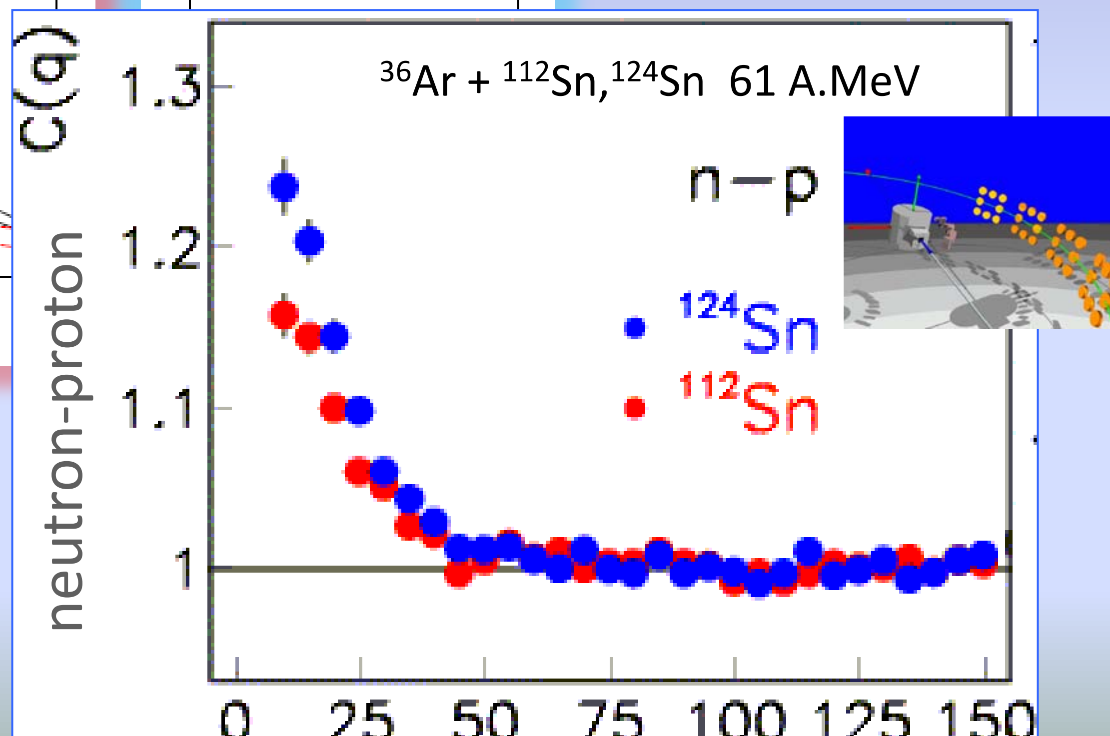

Shorter neutron and proton average emission times and more similar n and p emission times with Esym - stiff

R. Ghetti et al., PRC 69 031605 (2004) CHIC collaboration

Particle-particle correlations and symmetry energy: a difficult task

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L.W. Chen, V. Greco , C. Ko, B-An Li, PRC68, 014605(2003)

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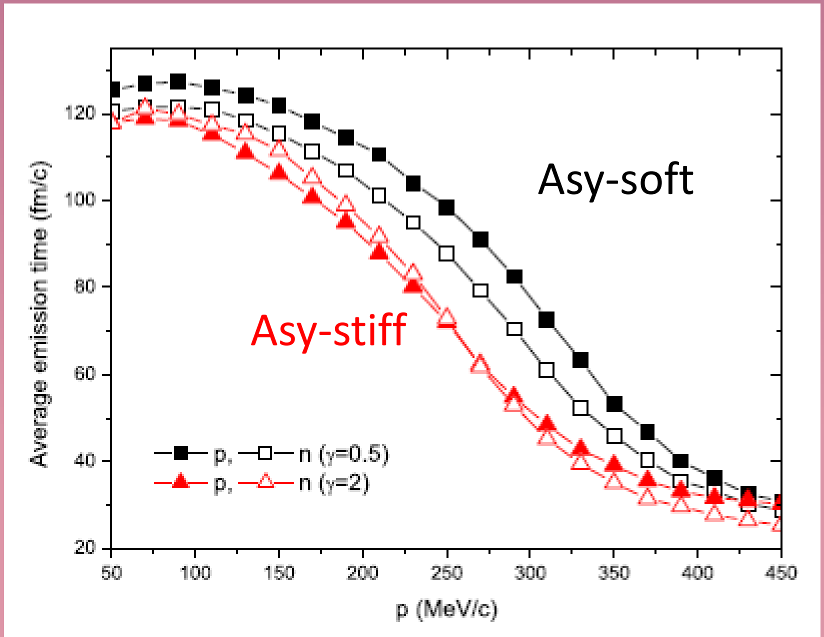
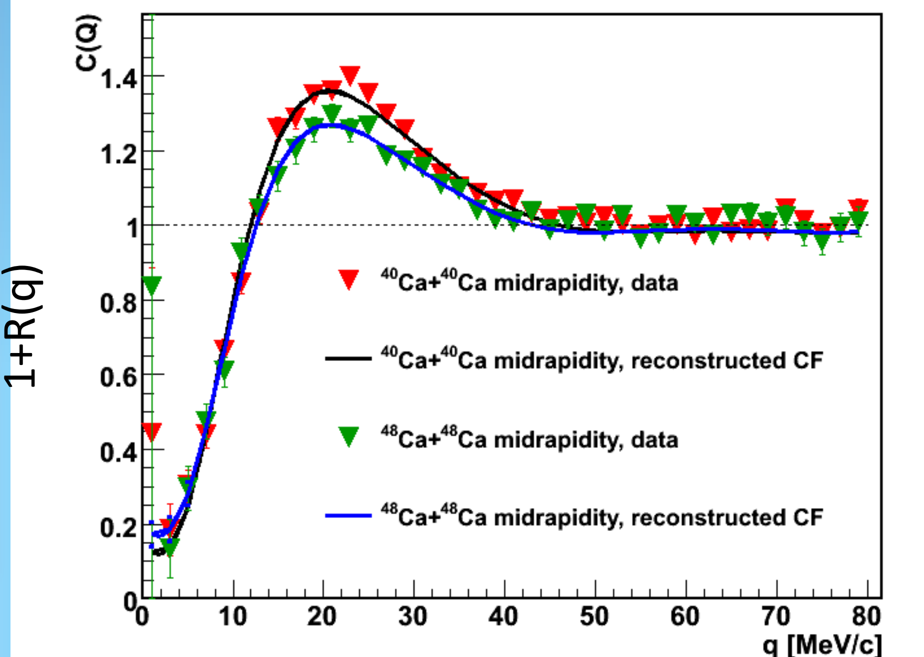
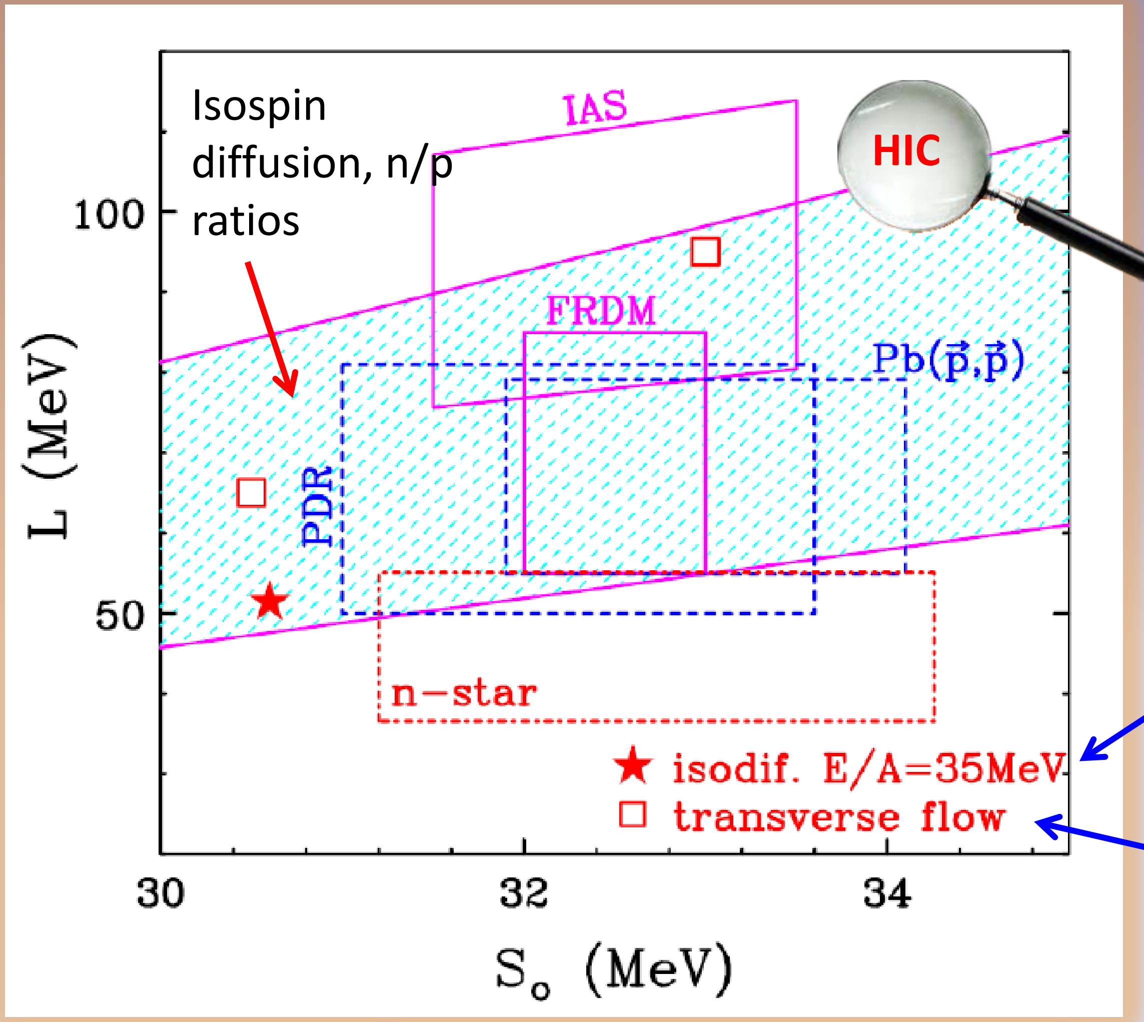




Shorter neutron and proton average emission times and more similar n and p emission times with Esym - stiff

See Henzl et al., PRC85 014606 (2012)
Larger source size for more n-rich systems: Asy-EOS, size effect… ?

Constraining the symmetry energy around and below normal nuclear density



IAS = Isobaric Analog States (Danielewicz/Lee)
PDR = Pygmy dipole resonance (Klimkiewicz et al.)
FRDM = Finite Range Droplet Model (Moller et al.)

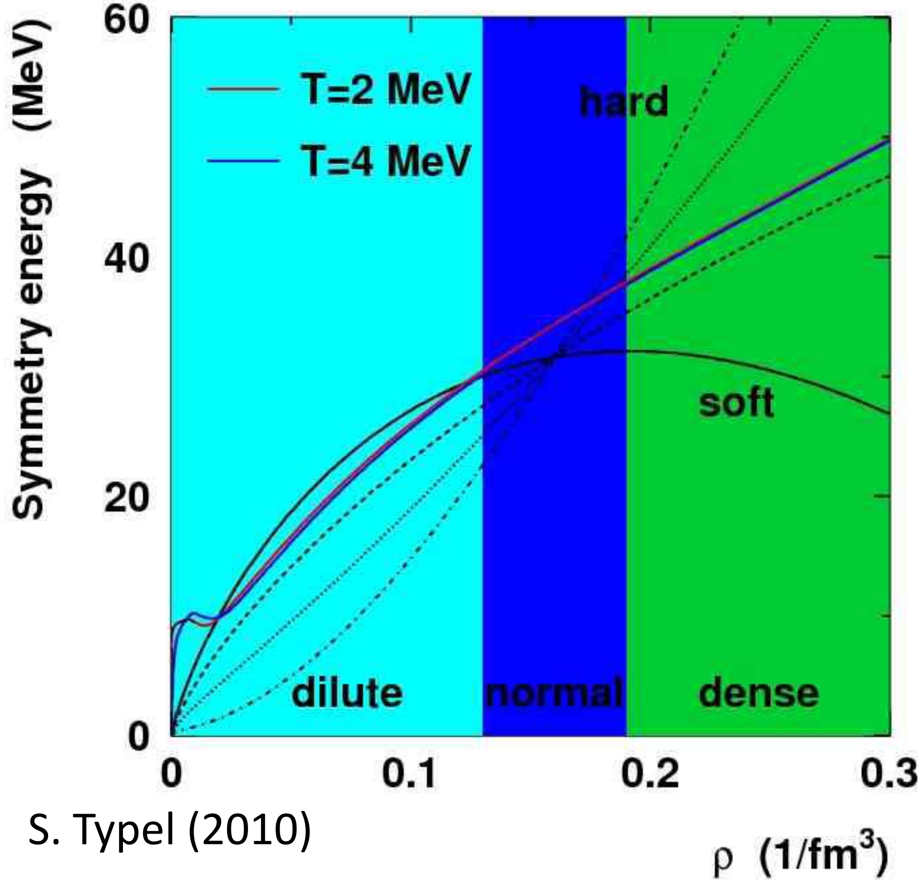
MSU-Chimera data: Z.Y. Sun et al. PRC 82 051603(R) 2010

Texas A&M data, Z. Kohley et al., PRC 83, 044601 (2011)

M.B. Tsang et al, Phys. Rev. C86, 015893 (2012)

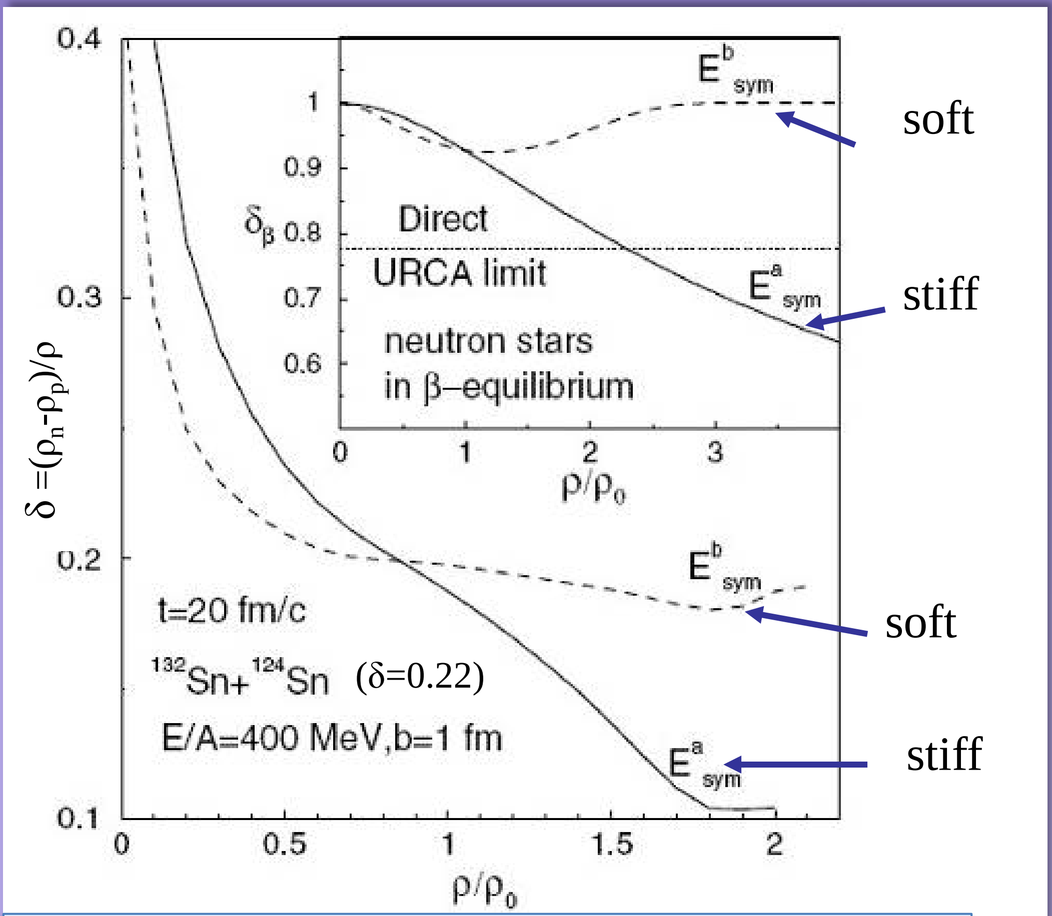
$$S(\rho) = S_0 + \frac{L}{3}\left(\frac{\rho-\rho_0}{\rho_0}\right) + \frac{K_{sym}}{18}\left(\frac{\rho-\rho_0}{\rho_0}\right)^2 + \ldots.$$

From dilute to dense matter



S. Typel (2010)

High densities: correlation with neutron stars

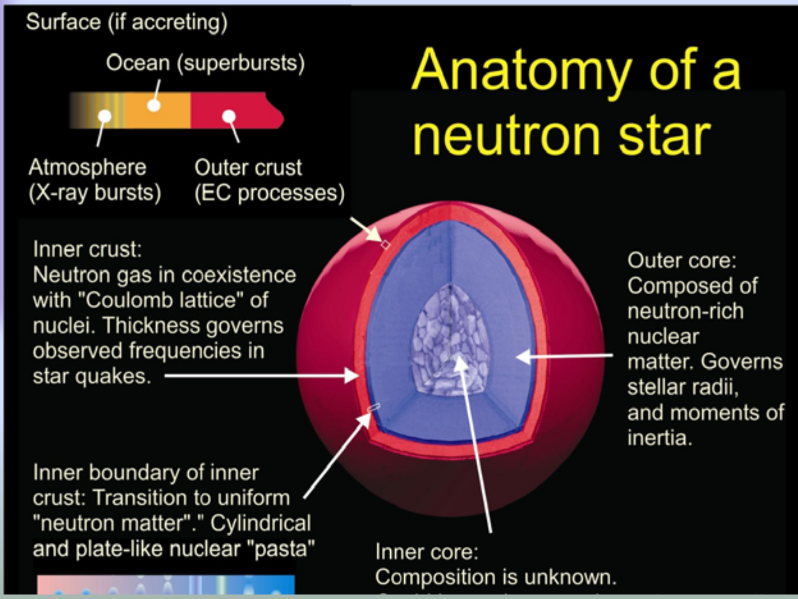


Bao-An Li, PRL 88, 192701 (2002) $^{132}Sn+^{124}Sn$ 400 A.MeV

Direct URCA process occurs in neutron stars if the proton concetration exceeds some critical value in the range 11-15%. The proton concentrations is determined by symmetry term of EOS.

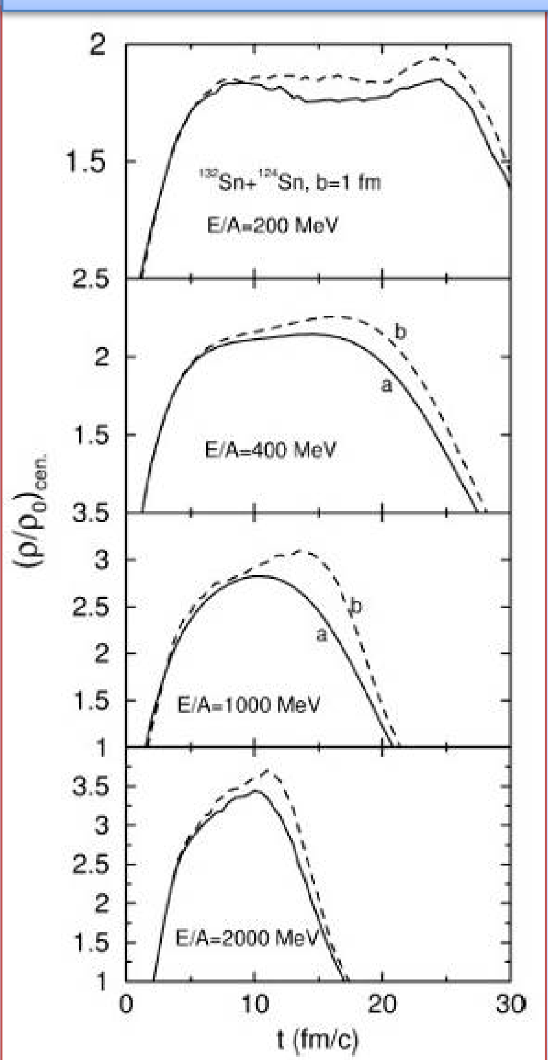
$$n \rightarrow p + e^- + \bar{\nu} \quad (beta\ decay)$$
$$p + e^- \rightarrow n + \nu \quad (electron\ capture)$$

J. M. Lattimer et al., Phys. Rev. Lett. 66, 2701 (1991).

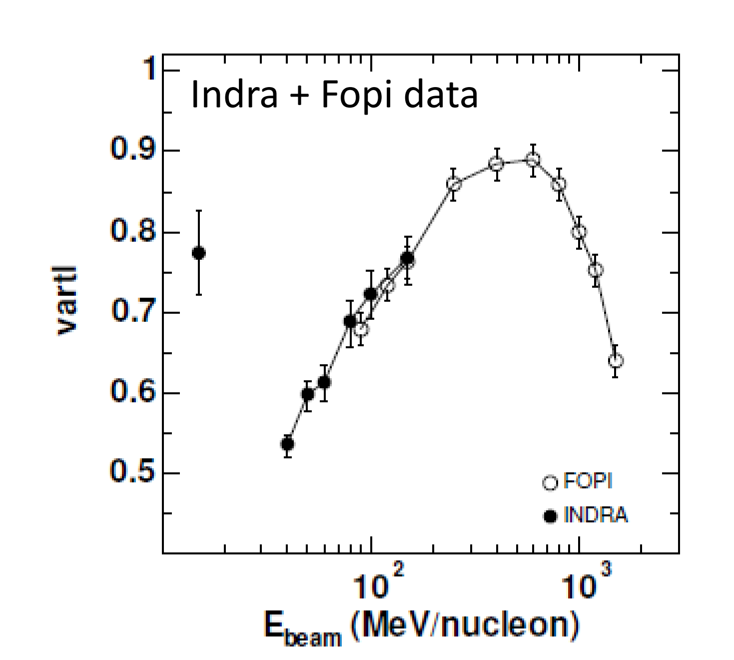


High densities and HIC

Bao-An Li, NPA 708 (2002)



Stopping the ions: comparing transverse and longitudinal rapidities (variances) for central collisions.



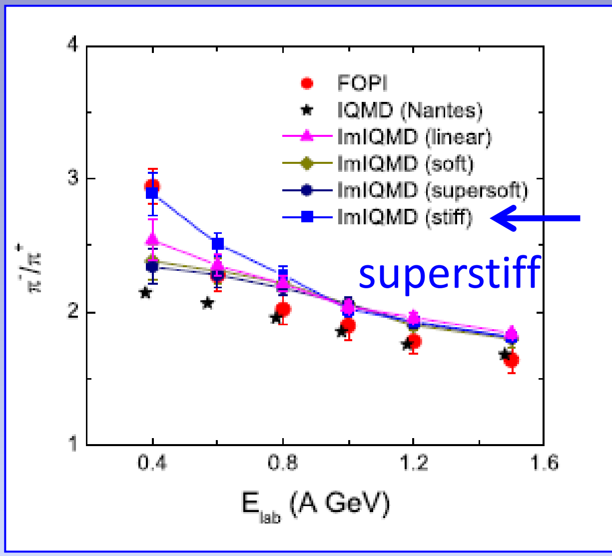
A. Andronic et al., EPJA 30 (2006)

Which densities can be explored in the early stage of the reaction ?

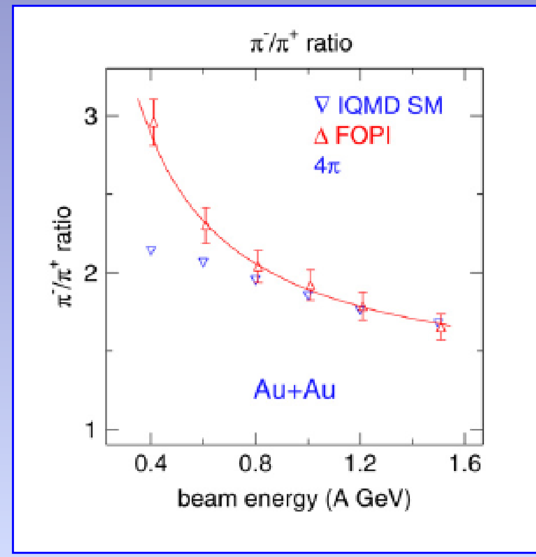
Pion production, π^-/π^+ ratio: no consistent description

Δ resonance:
$Y(\pi-)/Y(\pi+) \approx (N/Z)^2_{dense}$

Statistic model:
$\mu(\pi^+)-\mu(\pi^-)=2\ (\mu_p-\mu_n)$

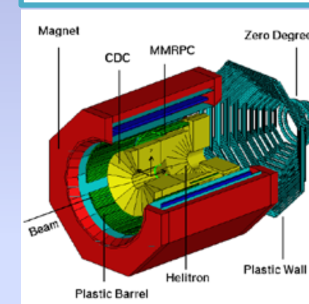


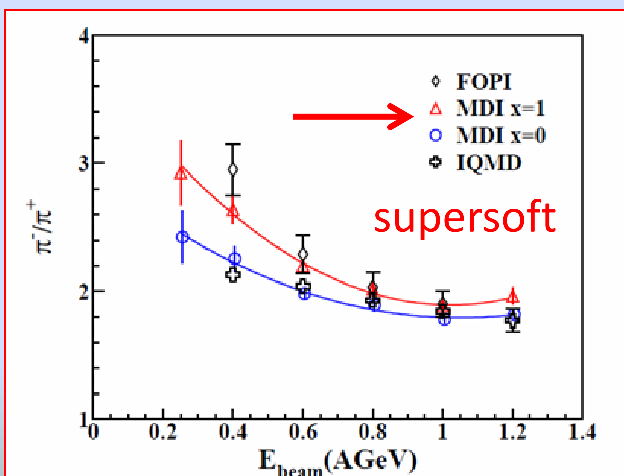
Z. Feng et al. PLB 683 140, 2010



W. Reisdorf et al. NPA 781 459, 2007

FOPI@GSI data





Z. Xiao et al. PRL 102 062509, 2009

Z. Xiao, B-An Li et al.	IBUU4	supersoft
Z. Feng et al.	IMIQMD	superstiff
G. Ferini et al.	RMF	stiff (linear)
W. Reisdorf	IQMD	soft (or no influence)

Pion production, π^-/π^+ ratio: no consistent description

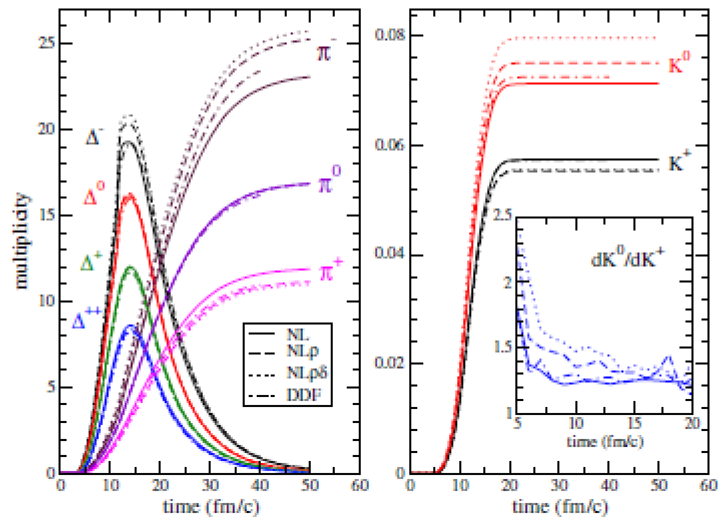
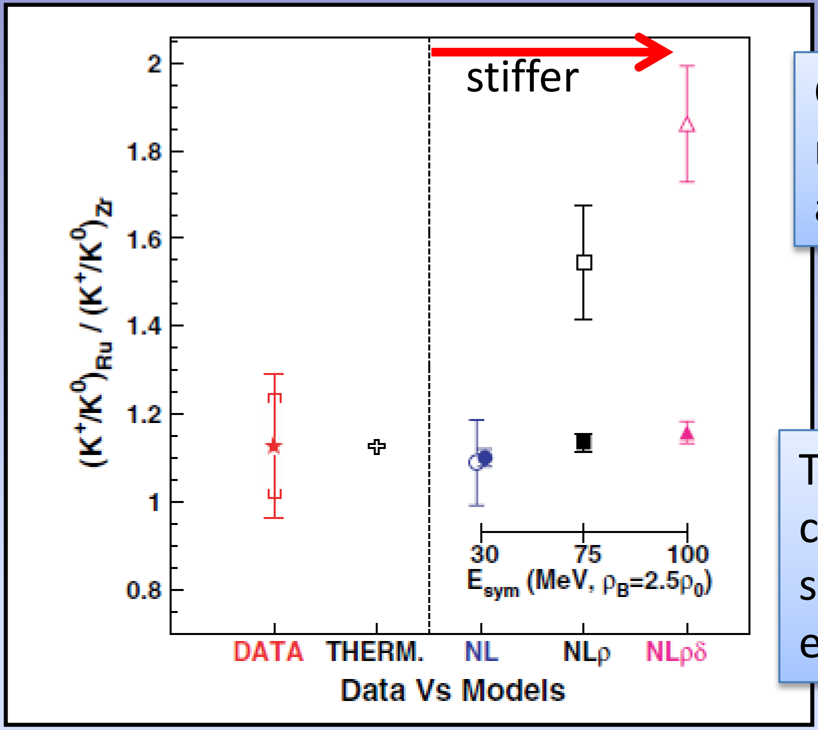


FIG. 1 (color online). Time evolution of $\Delta^{\pm,0,++}$ resonances, pions $\pi^{\pm,0}$ (left), and kaons $K^{0,+}$ (right) for a central ($b = 0$ fm impact parameter) Au + Au collision at 1*A* GeV incident energy. Transport calculation using the NL, NLρ, NL$\rho\delta$, and DDF models for the isovector part of the nuclear EOS are shown. The inset shows the differential K^0/K^+ ratio as a function of the kaon emission time.

Z. Xiao, B-An Li et al.	IBUU4	supersoft
Z. Feng et al.	IMIQMD	superstiff
G. Ferini et al.	RMF	stiff (linear)
W. Reisdorf	IQMD	soft (or no influence)

Kaon production, K^+/K^0 ratio



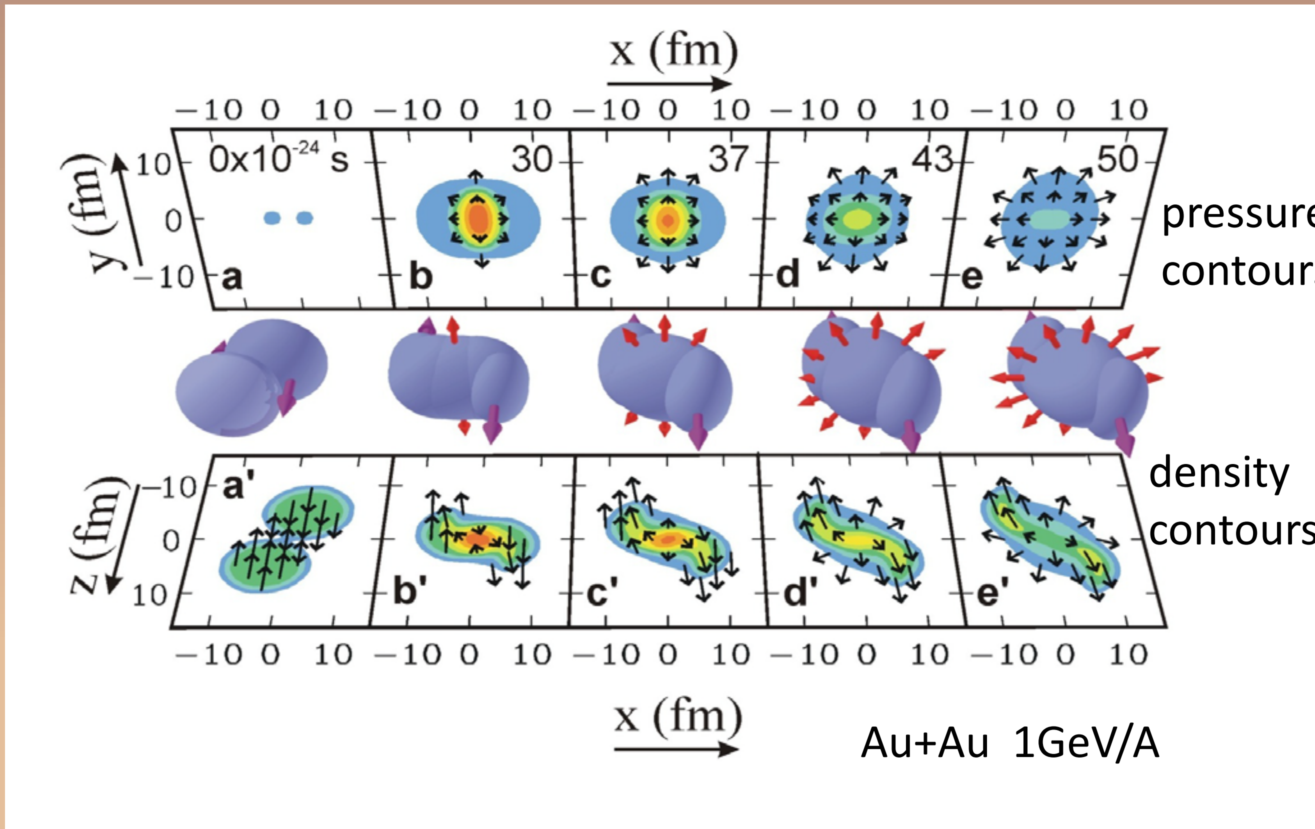
X. Lopez et al., Phys. Rev. C75 011901 (2007)

Calculations for infinite nuclear matter (Ferini et al.)

Transport model heavy ion collision (HIC, full symbols): sensitivity to symmetry energy strongly reduced.

HIC scenario (reduce sensitivity):
Fast neutron emission (mean field effect) and transformation of neutron into proton in inelastic channels.

FLOW: a classical picture (from Danielewicz, Science, 2002) and definitions



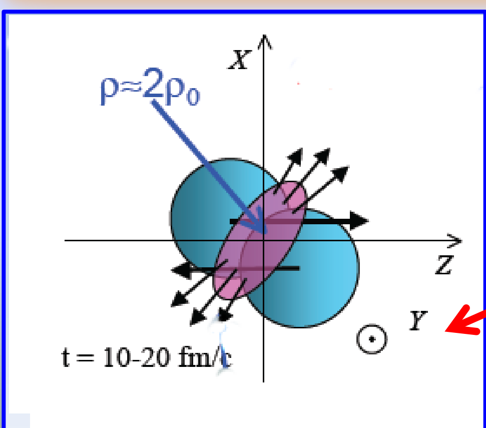
$$V_1(y, p_t) = \left\langle \frac{p_x}{p_t} \right\rangle$$

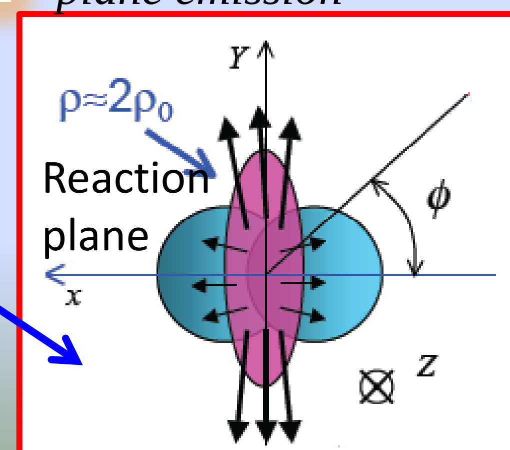
Transverse flow: *it provides information on the azimuthal anisotropy in the reaction plane*

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

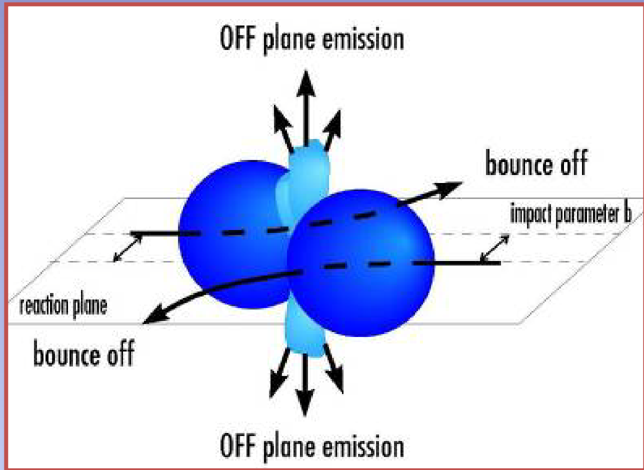
Elliptic flow: *it measures the competition between in plane and out-of-plane emission*

$$\frac{dN}{d\phi}(y, p_t) = 1 + V_1 \cos(\phi) + 2V_2 \cos(2\phi)$$



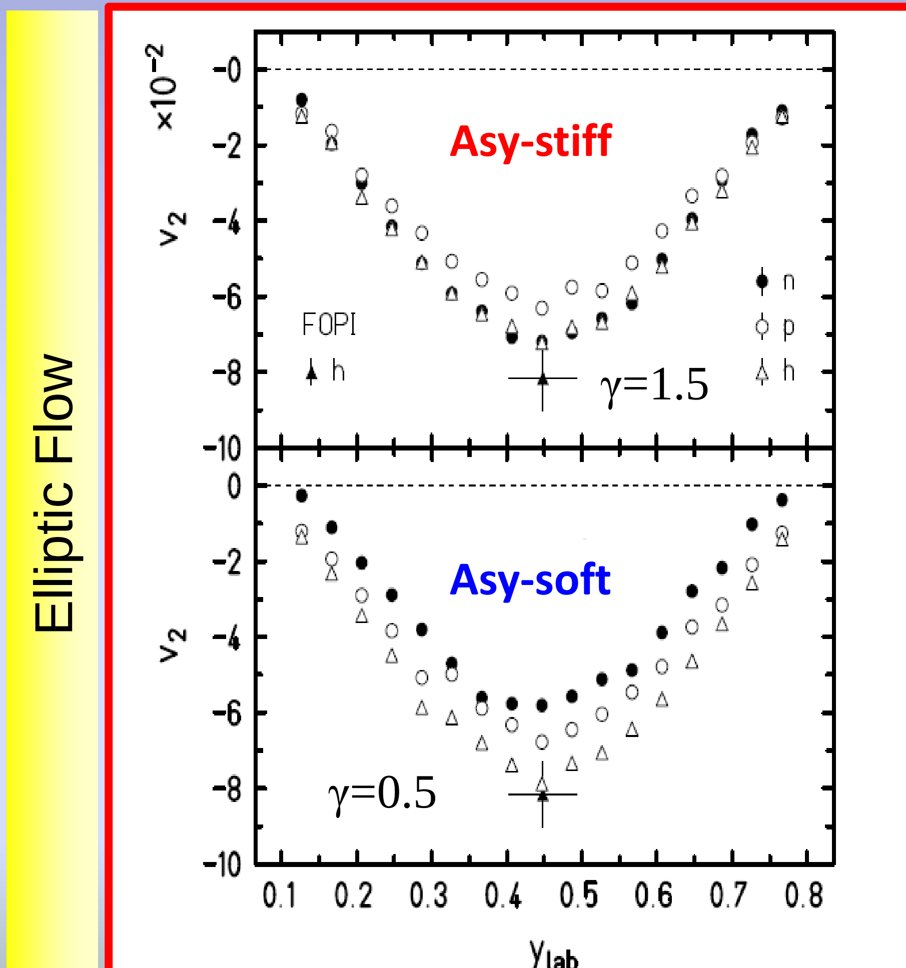


Neutron and proton elliptic flow



Squeeze-ot of neutrons sensitive to the symmetry term of EOS: *inversion of neutron and hydrogen flow*

5.5<b<7.5 fm Au+Au 400 A.MeV



Elliptic flow: competition between in plane (**V_2>0**) and out-of-plane ejection (**V_2<0**)

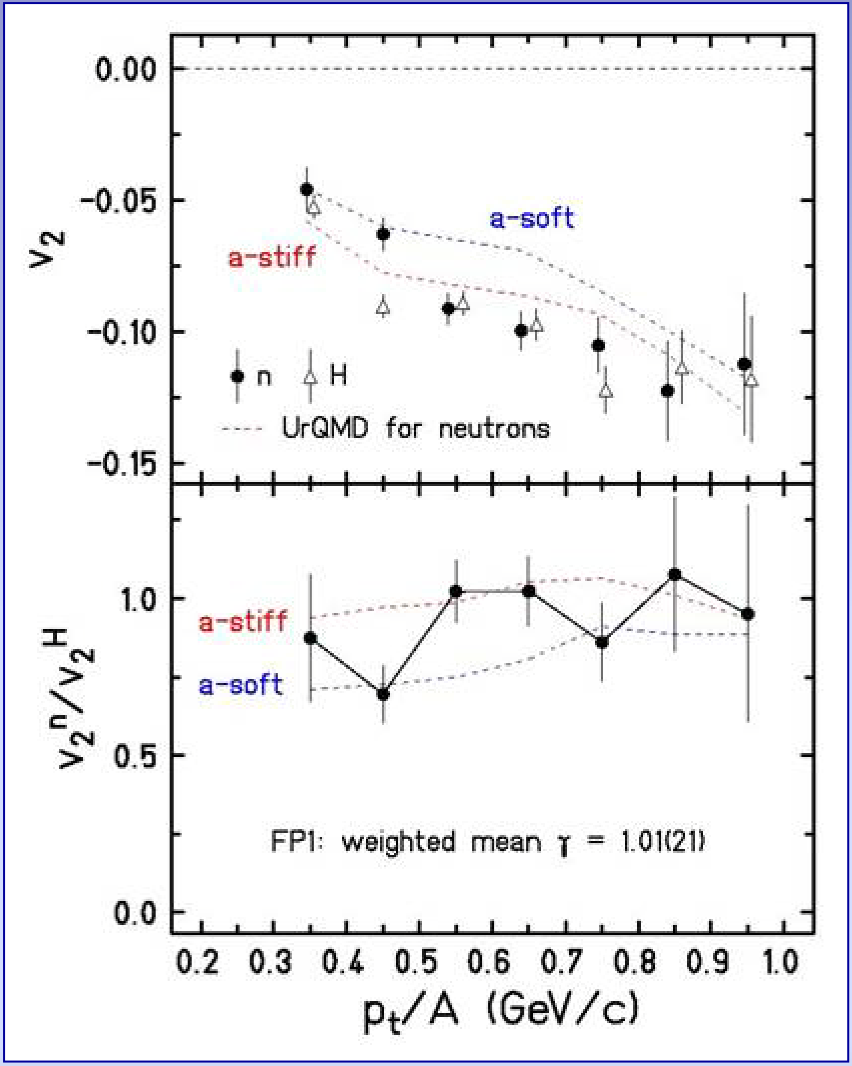
UrQMD model: significant sensitivity predicted for differential elliptic flow

(Qingfeng Li and Paolo Russotto)

P. Russotto et al., Phys. Lett. B 697(2011)

Q.F Li J. Phys. G31 1359 (2005)

Re-analysis of FOPI-LAND data on Au+Au (warning: low statistics)



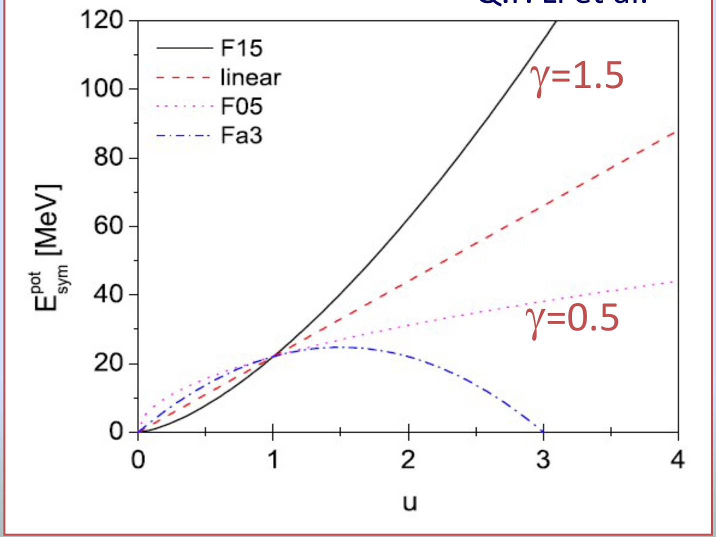
P. Russotto et al., PLB 697, 471 (2011)

W. Trautmann et H. Wolter, IJMPE21 (2012)

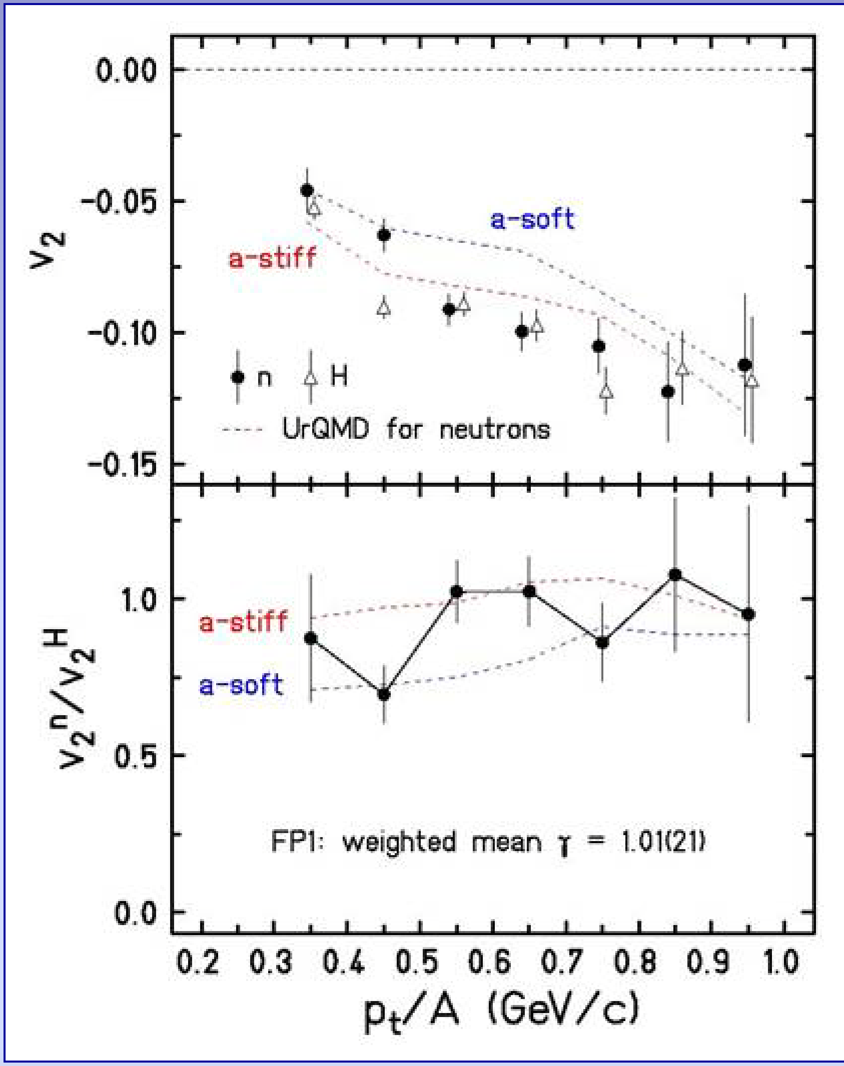
Au+Au 400 A MeV
b< 7.5 fm

neutron/hydrogen
FP1: $\gamma = 1.01 \pm 0.21$

parameters
in UrQMD,
Q.F. Li et al.



Re-analysis of FOPI-LAND data on Au+Au (warning: low statistics)



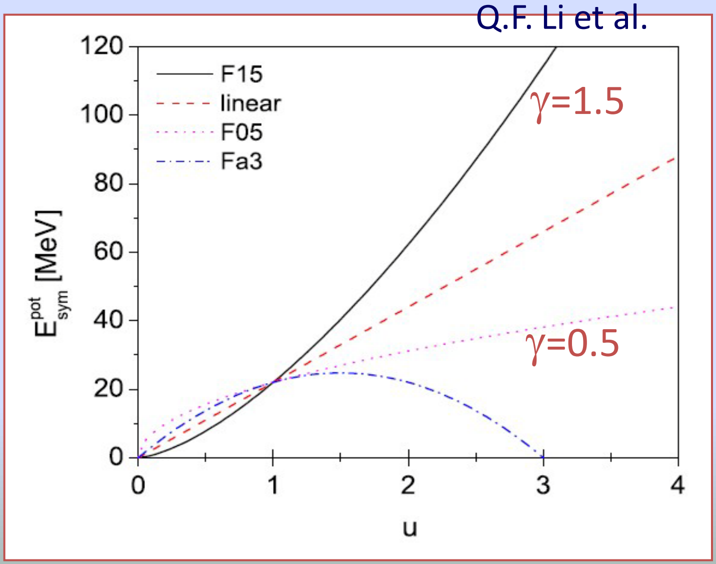
P. Russotto et al., PLB 697, 471 (2011)
W. Trautmann et H. Wolter, IJMPE21 (2012)

Au+Au 400 A MeV
b< 7.5 fm

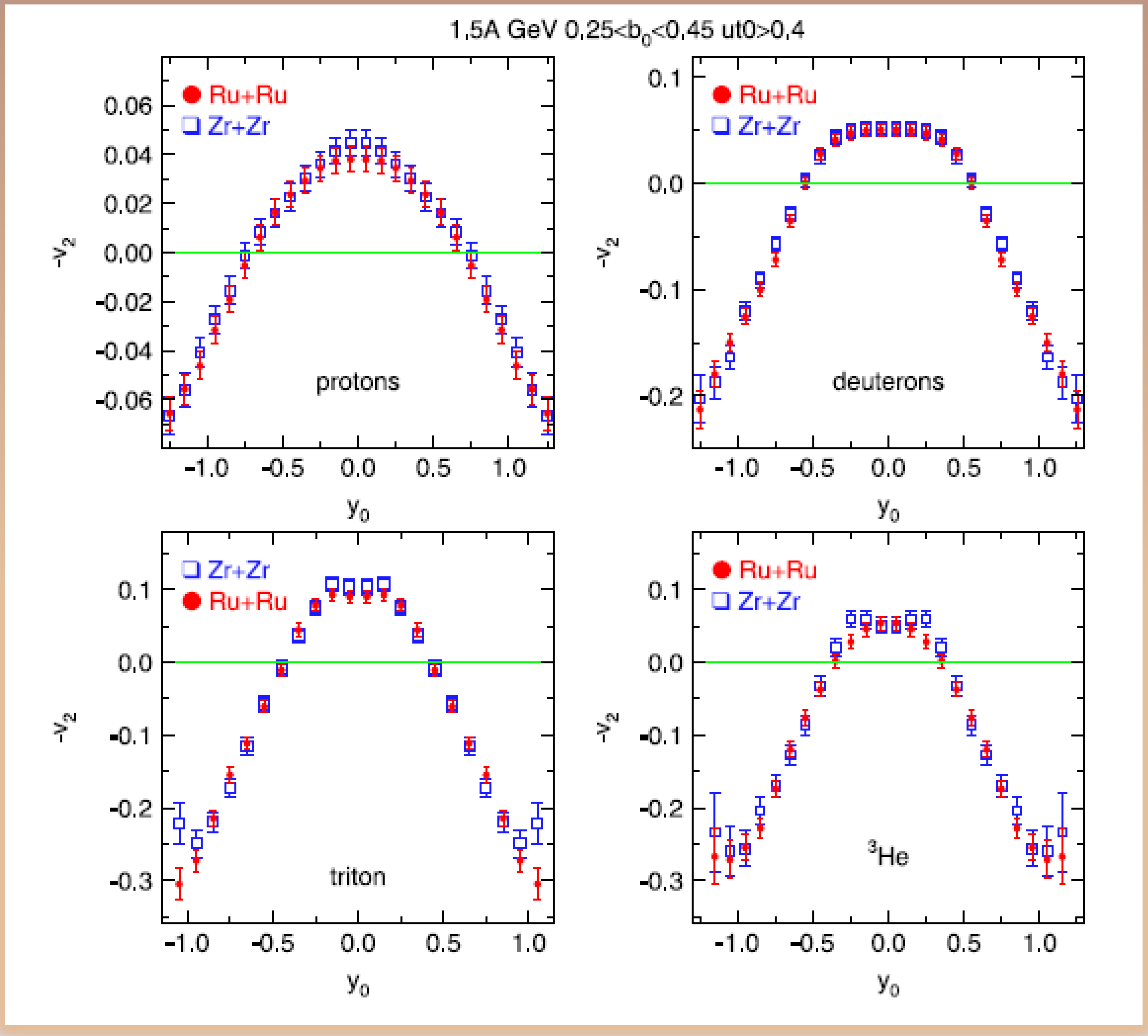
But FOPI experiment was not optimized for symmetry energy measurement

neutron/hydrogen
FP1: $\gamma = 1.01 \pm 0.21$

parameters in UrQMD, Q.F. Li et al.



A huge experimental systematics exists: FOPI measurements



Complete systematic (25 systems-energies) for flow of Light Charged Particles and observables on Pions

W. Reisdorf et al., NPA 876 (2012) NPA 781 (2007)

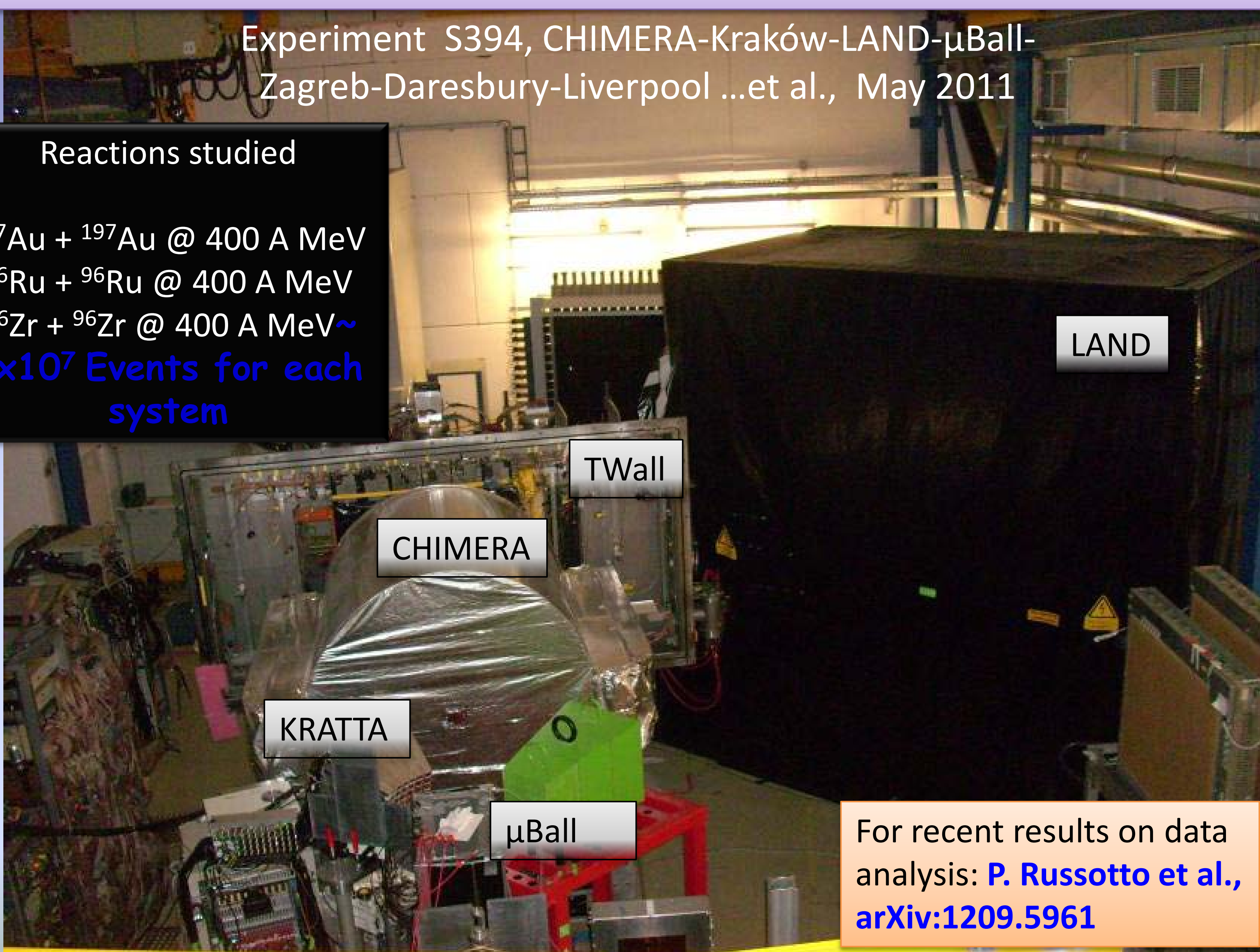
It is important when projecting new experiments or new ideas at high energies in order to study the high density behaviour of EOS to look what already exists and what is yet lacking

The S394 experiment at GSI (ASYEOS collaboration)

Experiment S394, CHIMERA-Kraków-LAND-µBall-Zagreb-Daresbury-Liverpool …et al., May 2011

Reactions studied

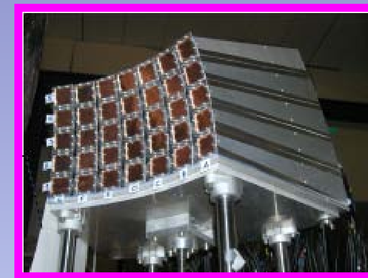
$^{197}Au + ^{197}Au$ @ 400 A MeV
$^{96}Ru + ^{96}Ru$ @ 400 A MeV
$^{96}Zr + ^{96}Zr$ @ 400 A MeV~
$5x10^7$ Events for each system



For recent results on data analysis: **P. Russotto et al., arXiv:1209.5961**

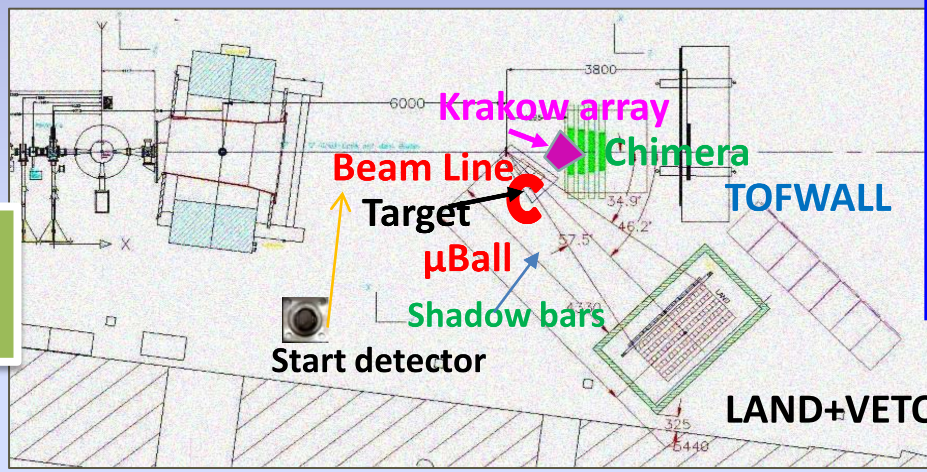
The main goal of the S394 experiment is to mesure the neutrons and protons elliptic flows in the isospin asymmetric systems: 400 A.MeV ^{197}Au+^{197}Au, ^{96}Zr+^{96}Zr, ^{96}Ru+^{96}Ru

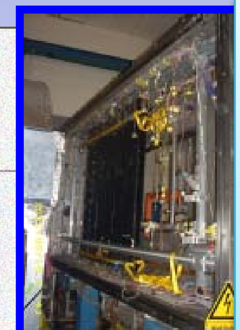
µBall: **4 rings CsI(Tl), Θ>60°. Discriminate real target vs. air interactions at backward angles. Multiplicity measurements.**



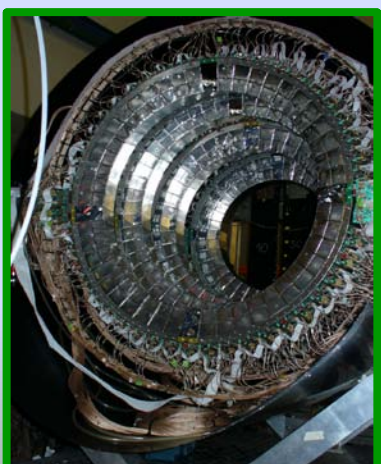
Kracow array: **35 (5x7) triple telescopes (Si-CsI-CsI) placed at 21°<Θ<60° with digital readout . Light particles and IMFs emitted at midrapidity**

Shadow bar: evaluation of scattered neutrons from materials in LAND

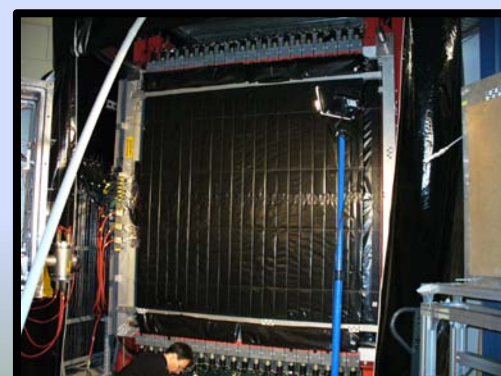




TOFWALL: **96 plastic bars Tof, Energy X-Y position. Trigger, impact parameter and reaction plane determination**



CHIMERA: **8 (2x4) rings, high granularity CsI(Tl), 352 detectors 7°<Θ<20° + 16x2 pads silicon detectors. Light charged particle identification by PSD. Multiplicity, Z, A, Energy measurement , Reaction plane determi-nation**



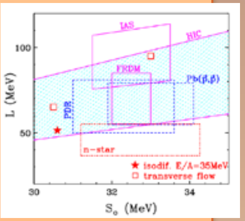
LAND: **Large Area Neutron Detector . Plastic scintillators sandwiched with Fe 2x2x1 m^3 plus plastic veto wall. New Taquila front-end electronics. Neutrons and Hydrogen detection. Flow measurements**

SUMMARY and OUTLOOK

We have seen how observables in heavy ion collisions provide unique opportunities to probe the symmetry energy over wide range of densities

At subsaturation densities:

Some consistence analysis have been obtained from HIC but with yet large uncertainties. There is for example a weak overlap between constraints from laboratory nuclear physics and from compact stars observations.



Use of new RIB facilities (exotic neutron rich, proton rich beams) . Isospin effects are enhanced by increasing the system asymmetry. Comparison with stable beam needed. (Experiments with ^{108}Sn,^{124}Sn,^{112}Sn on isospin diffusion at RIBF@Riken by MSU group)

Measure different observables at the same time. Results have to be consistent for different observables. Different models should describe data in a consisten way

Models: Look for discrepancies among different modes (the difference between the prediction between two models with the same Iso-parametrization can be larger than the difference between the results obtained by the same model with two different iso-parametrizations. It is important to compare multiple theoretical calculations to the same observable to validate the constraint.

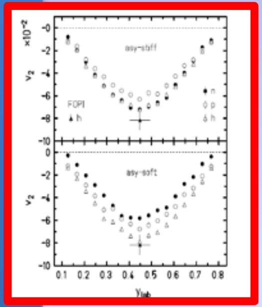
Use of femtoscopy for a precise space-time sources characterization. Neutron signals (np correlations, n/p double ratios….) .

SUMMARY and OUTLOOK

We have seen how observables in heavy ion collisions provide unique opportunities to probe the symmetry energy over wide range of densities

At supra-saturation densities:
Few experimental data to probe $E_{SYM.}$ Uncertainties in modelling the EOS at high densities.

Probes from pion and kaon ratios have given important systematics but not consistent information on E_{SYM}

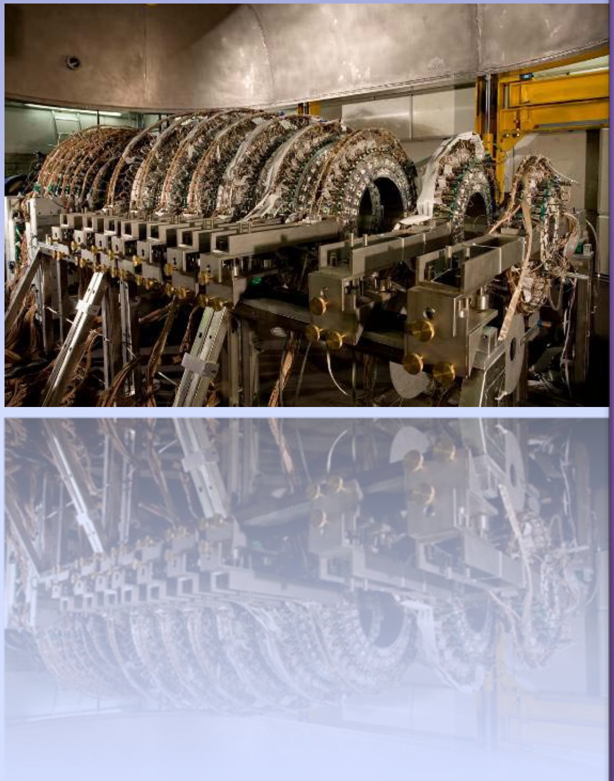


Flow measurements: the ASY-EOS experiment at GSI can be a good starting point for new results

Future efforts at RIKEN, FRIB (MSU), FAIR (GSI) with new devices (NEWLAND, SAMURAI TPC, R3B) and new RIB facilities.

GRAZIE

CHIMERA@LNS



EXOCHIM & ASYEOS collaborations

and in particular
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W. Trautmann
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