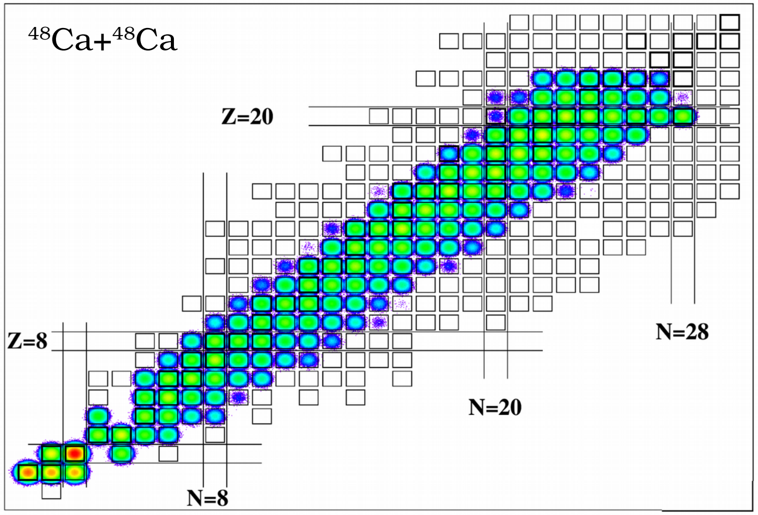
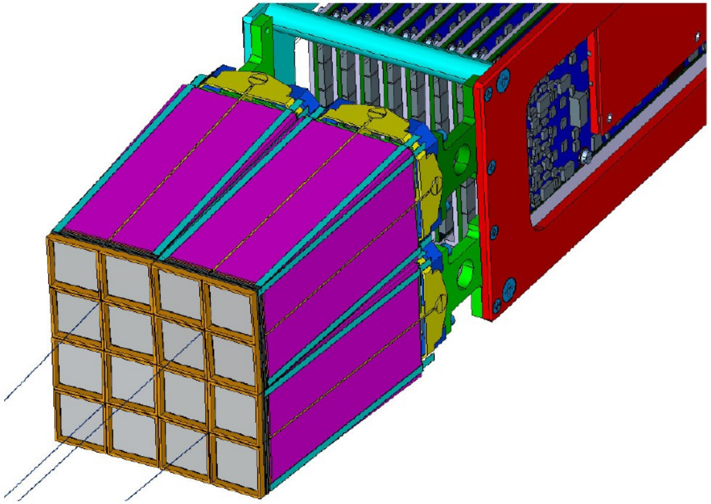
Exploring heavy-ion collisions in the Fermi regime with the FAZIA multi-telescope array





A. Camaiani

06/11/2022

ZIMÁNYI SCHOOL 2022

Budapest

INFN-LNS Campaign

0. 2004 – 2014: R & D Phase
   - The FAZIA recipe

R. Bougalt et al., Eur. Phys. J. A 50, 47 (2014).

1. 2015 ISO-FAZIA: ^{80}Kr + ^{40,48}Ca @ 35 MeV/u
   - **Break-up of the Quasi-Projectile**
   - **Isospin transport phenomena**

S. Piantelli et al, PRC 101, 034613 (2020)

S. Piantelli et al, PRC 103, 014603 (2021)

2. 2015 FAZIA-SYM: ^{40,48}Ca + ^{40,48}Ca @ 35 Mev/u
   - **Break-up of the Quasi-Projectile**
   - **Neutron-Proton equilibration**

A. Camaiani et al, Il Nuovo Cimento C, Vol. 041

A. Camaiani et al, PRC 102, 044607 (2020).

A. Camaiani et al, PRC 103, 014605 (2021)

3. 2017 FAZIA-COR: ^{20}Ne, ^{32}S + ^{12}C @ 25,50 MeV/u
   - ^{12}C Hoyle decay
   - Cluster correlations

C. Frosin – Experimental comparison with transport model calculation and cluster production in excited light systems at Fermi energies - submitted to PRC

4. 2018 FAZIA-PRE: ^{40,48}Ca + ^{12}C @ 25,40 MeV/u
   - Pre-equilibrium effects

P. Ottanelli, -
http://www.infn.it/thesis/thesis_dettaglio.php?tid=528951

5. 2018 FAZIA-ZERO (with I. Tanhiata group): ^{12}C + ^{12}C @ 62 MeV/u
   - Cross section measurement at 0°

Analysis done by Baohua Sun and co.

Heavy ion collisions in the Fermi regime

In the Fermi energy domain , i.e. **20 < E_{proj} < 50 MeV/u:**

Peripheral and semi-peripheral events

Dominant channel is the Binary one:
formation of two **excited** fragments,
which preserve memory of the entrance channel

Quasi-**P**rojectile: **QP***

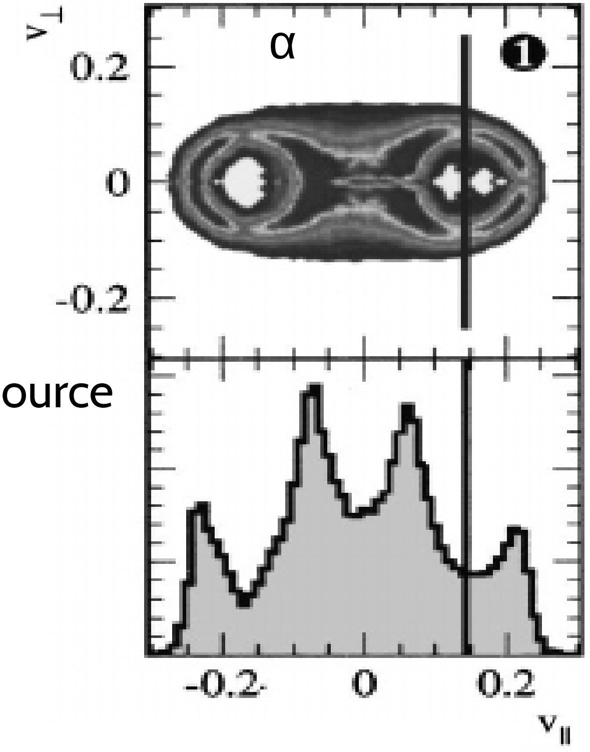
Quasi-**T**arget: **QT***

In the ejectiles we observe the superposition of two effects

- **Dynamical**: due to the projectile-target interaction
  - **Emissions towards mid-velocity**
  - **Dynamical break-up**

- **Statistical**: decay from a thermodynamically equilibrated source
  - Statistical evaporation
  - Statistical breakup

EXP:Xe + Sn @ 50 MeV/u



J.Lukasik et al., PRC55 (1997)1906

Isospin dynamics

The nuclear Equation of state is the basis of the isospin dynamics theory

$$\frac{E}{A}(\rho, I) = \frac{E}{A}(\rho) + \frac{E_{sym}}{A}(\rho) I^2$$

Symmetric matter

Asymmetric matter

$$I = \frac{N - Z}{A}$$

$$\rho = \rho_n + \rho_z$$

V. Baran et al. / Physics Reports 410 (2005) 335 - 466

$$\frac{E}{A}(\rho) = E_{sat} + \frac{1}{2} K_{sat} x^2 + \ldots$$

$$x = \frac{\rho - \rho_0}{\rho_0}$$

$$\frac{E_{sym}}{A}(\rho) = E_{sym} + L_{sym} x + \frac{1}{2} K_{sym} x^2 + \ldots$$

The symmetry energy produces a difference of the proton and neutron currents:

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

Isospin Diffusion:
Migration driven by the isospin gradient

Isospin Drift:
Migration driven by the density gradient. Neutron enrichment of the Neck?

Isospin dynamics: Isospin diffusion

The nuclear Equation of state is the basis of the isospin dynamics theory

V. Baran et al. / Physics Reports 410 (2005) 335 - 466

$$\frac{E}{A}(\rho,I)=\frac{E}{A}(\rho)+\frac{E_{sym}}{A}(\rho)I^2$$

Symmetric matter

Asymmetric matter

$$I=\frac{N-Z}{A}$$

$$\rho=\rho_n+\rho_z$$

$$\frac{E}{A}(\rho)=E_{sat}+\frac{1}{2}K_{sat}x^2+\dots$$

$$x=\frac{\rho-\rho_0}{\rho_0}$$

$$\frac{E_{sym}}{A}(\rho)=E_{sym}+L_{sym}x+\frac{1}{2}K_{sym}x^2+\dots$$

The symmetry energy produces a difference of the proton and neutron currents:

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

Isospin Diffusion:
Migration driven by the isospin gradient

Isospin dynamics: Isospin diffusion

The nuclear Equation of state is the basis of the isospin dynamics theory

V. Baran et al. / Physics Reports 410 (2005) 335 – 466

$$\frac{E}{A}(\rho, I) = \frac{E}{A}(\rho) + \frac{E_{sym}}{A}(\rho) I^2$$

Symmetric matter

Asymmetric matter

$$I = \frac{N-Z}{A}$$

$$\rho = \rho_n + \rho_z$$

$$\frac{E}{A}(\rho) = E_{sat} + \frac{1}{2} K_{sat} x^2 + \dots$$

$$x = \frac{\rho - \rho_0}{\rho_0}$$

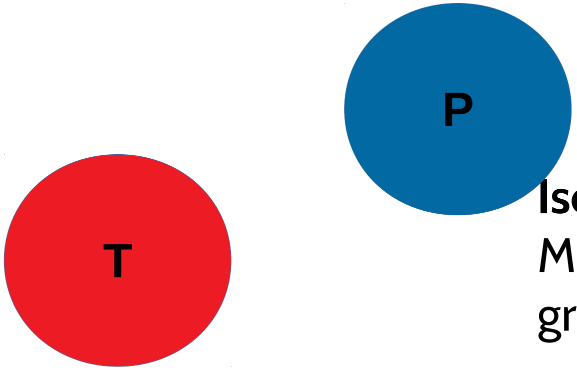
$$\frac{E_{sym}}{A}(\rho) = E_{sym} + L_{sym} x + \frac{1}{2} K_{sym} x^2 + \dots$$

The symmetry energy produces a difference of the proton and neutron currents:

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

Neutron rich projectile

Neutron deficient target



Isospin Diffusion:
Migration driven by the isospin gradient

Isospin dynamics: Isospin diffusion

The nuclear Equation of state is the basis of the isospin dynamics theory

V. Baran et al. / Physics Reports 410 (2005) 335 - 466

$$\frac{E}{A}(\rho, I) = \frac{E}{A}(\rho) + \frac{E_{sym}}{A}(\rho) I^2$$

$$I = \frac{N-Z}{A}$$

$$\rho = \rho_n + \rho_z$$

$\frac{E}{A}(\rho)$ → Symmetric matter

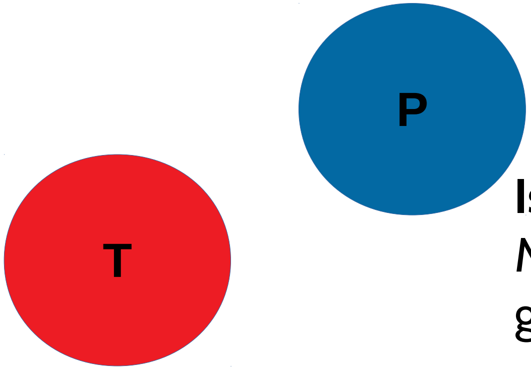
$\frac{E_{sym}}{A}(\rho) I^2$ → Asymmetric matter

$$\frac{E}{A}(\rho) = E_{sat} + \frac{1}{2} K_{sat} x^2 + \ldots \qquad x = \frac{\rho - \rho_0}{\rho_0}$$

$$\frac{E_{sym}}{A}(\rho) = E_{sym} + L_{sym} x + \frac{1}{2} K_{sym} x^2 + \ldots$$

The symmetry energy produces a difference of the proton and neutron currents:

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



Neutron rich projectile

Neutron deficient target

Isospin Diffusion:
Migration driven by the isospin gradient

Isospin dynamics: Isospin diffusion

The nuclear Equation of state is the basis of the isospin dynamics theory

$$\frac{E}{A}(\rho, I) = \frac{E}{A}(\rho) + \frac{E_{sym}}{A}(\rho)I^2$$

$$I = \frac{N-Z}{A}$$

$$\rho = \rho_n + \rho_z$$

Symmetric matter

Asymmetric matter

V. Baran et al. / Physics Reports 410 (2005) 335 – 466

$$\frac{E}{A}(\rho) = E_{sat} + \frac{1}{2}K_{sat}x^2 + \dots$$

$$x = \frac{\rho - \rho_0}{\rho_0}$$

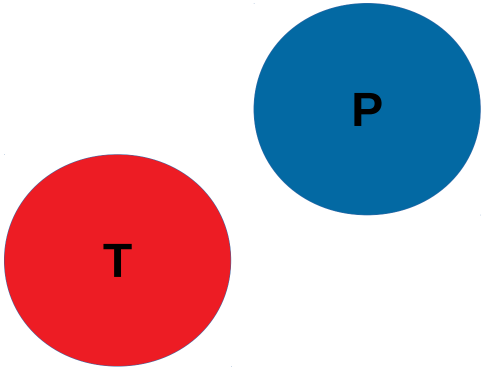
$$\frac{E_{sym}}{A}(\rho) = E_{sym} + L_{sym}x + \frac{1}{2}K_{sym}x^2 + \dots$$

The symmetry energy produces a difference of the proton and neutron currents:

Neutron rich projectile

Neutron deficient target

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



Isospin Diffusion:
Migration driven by the isospin gradient

Isospin dynamics: Isospin diffusion

The nuclear Equation of state is the basis of the isospin dynamics theory

V. Baran et al. / Physics Reports 410 (2005) 335 - 466

$$\frac{E}{A}(\rho, I) = \frac{E}{A}(\rho) + \frac{E_{sym}}{A}(\rho) I^2$$

$\frac{E}{A}(\rho)$ → Symmetric matter

$\frac{E_{sym}}{A}(\rho) I^2$ → Asymmetric matter

$$I = \frac{N - Z}{A}$$

$$\rho = \rho_n + \rho_z$$

$$\frac{E}{A}(\rho) = E_{sat} + \frac{1}{2} K_{sat} x^2 + \ldots$$

$$x = \frac{\rho - \rho_0}{\rho_0}$$

$$\frac{E_{sym}}{A}(\rho) = E_{sym} + L_{sym} x + \frac{1}{2} K_{sym} x^2 + \ldots$$

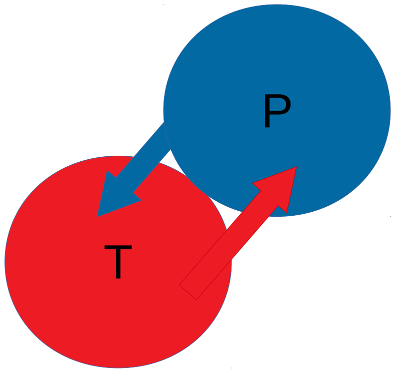
The symmetry energy produces a difference of the proton and neutron currents:

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

Neutron rich projectile

Neutron deficient target

Net flux of p and n



Isospin Diffusion:
Migration driven by the isospin gradient

Isospin dynamics: Isospin diffusion

The nuclear Equation of state is the basis of the isospin dynamics theory

V. Baran et al. / Physics Reports 410 (2005) 335 – 466

$$\frac{E}{A}(\rho, I) = \frac{E}{A}(\rho) + \frac{E_{sym}}{A}(\rho) I^2$$

Symmetric matter

Asymmetric matter

$$I = \frac{N-Z}{A}$$

$$\rho = \rho_n + \rho_z$$

$$\frac{E}{A}(\rho) = E_{sat} + \frac{1}{2} K_{sat} x^2 + \ldots$$

$$x = \frac{\rho - \rho_0}{\rho_0}$$

$$\frac{E_{sym}}{A}(\rho) = E_{sym} + L_{sym} x + \frac{1}{2} K_{sym} x^2 + \ldots$$

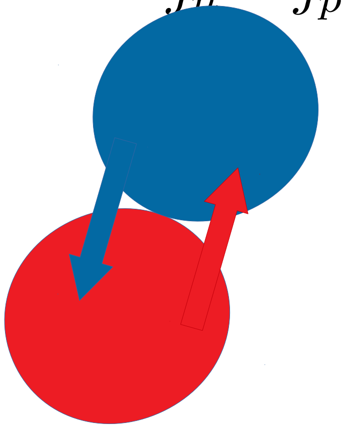
The symmetry energy produces a difference of the proton and neutron currents:

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

Neutron rich projectile

Neutron deficient target

Net flux of p and n



Isospin Diffusion:
Migration driven by the isospin gradient

Isospin dynamics: Isospin diffusion

The nuclear Equation of state is the basis of the isospin dynamics theory

V. Baran et al. / Physics Reports 410 (2005) 335 – 466

$$\frac{E}{A}(\rho, I) = \frac{E}{A}(\rho) + \frac{E_{sym}}{A}(\rho) I^2$$

Symmetric matter

Asymmetric matter

$$I = \frac{N-Z}{A}$$

$$\rho = \rho_n + \rho_z$$

$$\frac{E}{A}(\rho) = E_{sat} + \frac{1}{2} K_{sat} x^2 + \dots$$

$$x = \frac{\rho - \rho_0}{\rho_0}$$

$$\frac{E_{sym}}{A}(\rho) = E_{sym} + L_{sym} x + \frac{1}{2} K_{sym} x^2 + \dots$$

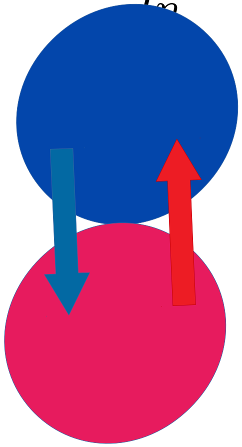
The symmetry energy produces a difference of the proton and neutron currents:

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

Neutron rich projectile

Neutron deficient target

Net flux of p and n



Isospin Diffusion:
Migration driven by the isospin gradient

Isospin dynamics: Isospin diffusion

The nuclear Equation of state is the basis of the isospin dynamics theory

$$\frac{E}{A}(\rho, I) = \frac{E}{A}(\rho) + \frac{E_{sym}}{A}(\rho) I^2$$

Symmetric matter

Asymmetric matter

$$I = \frac{N - Z}{A}$$

$$\rho = \rho_n + \rho_z$$

V. Baran et al. / Physics Reports 410 (2005) 335 - 466

$$\frac{E}{A}(\rho) = E_{sat} + \frac{1}{2} K_{sat} x^2 + \ldots$$

$$x = \frac{\rho - \rho_0}{\rho_0}$$

$$\frac{E_{sym}}{A}(\rho) = E_{sym} + L_{sym} x + \frac{1}{2} K_{sym} x^2 + \ldots$$

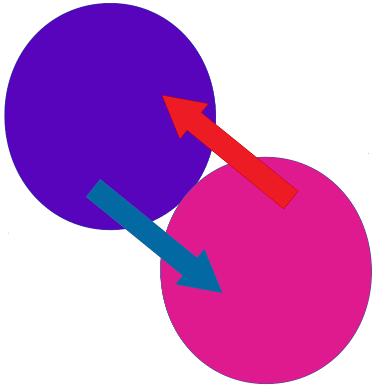
The symmetry energy produces a difference of the proton and neutron currents:

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

Neutron rich projectile

Neutron deficient target

Net flux of p and n



Isospin Diffusion:
Migration driven by the isospin gradient

Isospin dynamics: Isospin diffusion

The nuclear Equation of state is the basis of the isospin dynamics theory

$$\frac{E}{A}(\rho, I) = \frac{E}{A}(\rho) + \frac{E_{sym}}{A}(\rho) I^2$$

$$I = \frac{N - Z}{A}$$

$$\rho = \rho_n + \rho_z$$

Symmetric matter

Asymmetric matter

V. Baran et al. / Physics Reports 410 (2005) 335 – 466

$$\frac{E}{A}(\rho) = E_{sat} + \frac{1}{2} K_{sat} x^2 + \dots$$

$$x = \frac{\rho - \rho_0}{\rho_0}$$

$$\frac{E_{sym}}{A}(\rho) = E_{sym} + L_{sym} x + \frac{1}{2} K_{sym} x^2 + \dots$$

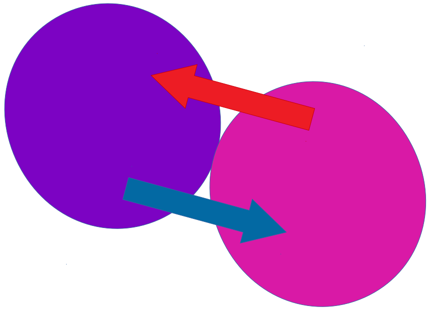
The symmetry energy produces a difference of the proton and neutron currents:

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

Neutron rich projectile

Neutron deficient target

Net flux of p and n



Isospin Diffusion:
Migration driven by the isospin gradient

Isospin dynamics: Isospin diffusion

The nuclear Equation of state is the basis of the isospin dynamics theory

V. Baran et al. / Physics Reports 410 (2005) 335 – 466

$$\frac{E}{A}(\rho, I) = \frac{E}{A}(\rho) + \frac{E_{sym}}{A}(\rho) I^2$$

$$I = \frac{N - Z}{A}$$

$$\rho = \rho_n + \rho_z$$

► Symmetric matter

► Asymmetric matter

$$\frac{E}{A}(\rho) = E_{sat} + \frac{1}{2} K_{sat} x^2 + \dots$$

$$x = \frac{\rho - \rho_0}{\rho_0}$$

$$\frac{E_{sym}}{A}(\rho) = E_{sym} + L_{sym} x + \frac{1}{2} K_{sym} x^2 + \dots$$

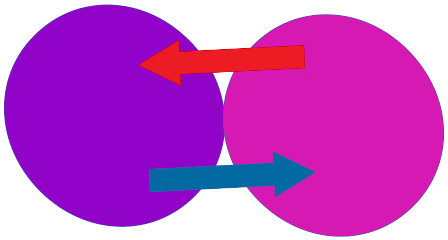
The symmetry energy produces a difference of the proton and neutron currents:

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

Neutron rich projectile

Neutron deficient target

Net flux of p and n



Isospin Diffusion:
Migration driven by the isospin gradient

Isospin dynamics: Isospin diffusion

The nuclear Equation of state is the basis of the isospin dynamics theory

V. Baran et al. / Physics Reports 410 (2005) 335 – 466

$$\frac{E}{A}(\rho, I) = \frac{E}{A}(\rho) + \frac{E_{sym}}{A}(\rho) I^2$$

► Symmetric matter

► Asymmetric matter

$$I = \frac{N-Z}{A}$$

$$\rho = \rho_n + \rho_z$$

$$\frac{E}{A}(\rho) = E_{sat} + \frac{1}{2}K_{sat}x^2 + \ldots$$

$$x = \frac{\rho - \rho_0}{\rho_0}$$

$$\frac{E_{sym}}{A}(\rho) = E_{sym} + L_{sym}x + \frac{1}{2}K_{sym}x^2 + \ldots$$

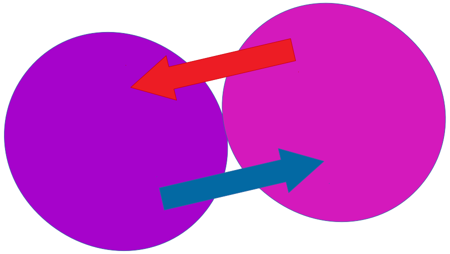
The symmetry energy produces a difference of the proton and neutron currents:

Neutron rich projectile

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

Neutron deficient target

Net flux of p and n



Isospin Diffusion:
Migration driven by the isospin gradient

Isospin dynamics: Isospin diffusion

The nuclear Equation of state is the basis of the isospin dynamics theory

V. Baran et al. / Physics Reports 410 (2005) 335 – 466

$$\frac{E}{A}(\rho, I) = \frac{E}{A}(\rho) + \frac{E_{sym}}{A}(\rho) I^2$$

Symmetric matter

Asymmetric matter

$$I = \frac{N-Z}{A}$$

$$\rho = \rho_n + \rho_z$$

$$\frac{E}{A}(\rho) = E_{sat} + \frac{1}{2}K_{sat}x^2 + \dots \qquad x = \frac{\rho - \rho_0}{\rho_0}$$

$$\frac{E_{sym}}{A}(\rho) = E_{sym} + L_{sym}x + \frac{1}{2}K_{sym}x^2 + \dots$$

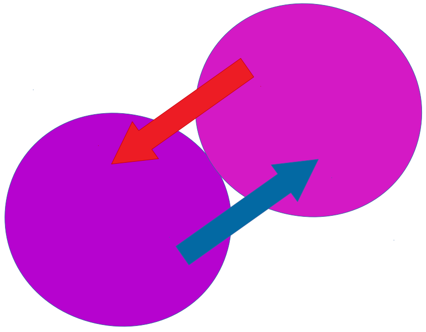
The symmetry energy produces a difference of the proton and neutron currents:

Neutron rich projectile

Neutron deficient target

Net flux of p and n

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



Isospin Diffusion:
Migration driven by the isospin gradient

Isospin dynamics: Isospin diffusion

The nuclear Equation of state is the basis of the isospin dynamics theory

V. Baran et al. / Physics Reports 410 (2005) 335 – 466

$$\frac{E}{A}(\rho, I) = \frac{E}{A}(\rho) + \frac{E_{sym}}{A}(\rho) I^2$$

$$I = \frac{N-Z}{A}$$

$$\rho = \rho_n + \rho_z$$

Symmetric matter

$$\frac{E}{A}(\rho) = E_{sat} + \frac{1}{2} K_{sat} x^2 + \dots$$

Asymmetric matter

$$\frac{E_{sym}}{A}(\rho) = E_{sym} + L_{sym} x + \frac{1}{2} K_{sym} x^2 + \dots$$

$$x = \frac{\rho - \rho_0}{\rho_0}$$

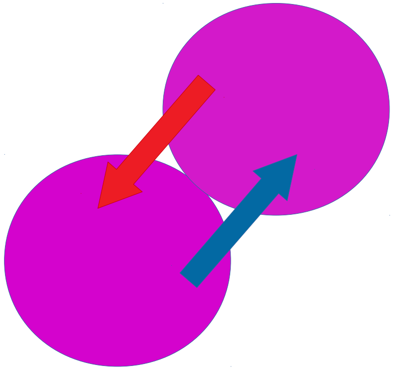
The symmetry energy produces a difference of the proton and neutron currents:

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

Neutron rich projectile

Neutron deficient target

Net flux of p and n



Isospin Diffusion:
Migration driven by the isospin gradient

Isospin dynamics: Isospin diffusion

The nuclear Equation of state is the basis of the isospin dynamics theory

V. Baran et al. / Physics Reports 410 (2005) 335 – 466

$$\frac{E}{A}(\rho,I)=\frac{E}{A}(\rho)+\frac{E_{sym}}{A}(\rho)I^2$$

Symmetric matter

Asymmetric matter

$$I=\frac{N-Z}{A}$$

$$\rho=\rho_n+\rho_z$$

$$\frac{E}{A}(\rho)=E_{sat}+\frac{1}{2}K_{sat}x^2+\ldots \qquad x=\frac{\rho-\rho_0}{\rho_0}$$

$$\frac{E_{sym}}{A}(\rho)=E_{sym}+L_{sym}x+\frac{1}{2}K_{sym}x^2+\ldots$$

The symmetry energy produces a difference of the proton and neutron currents:

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

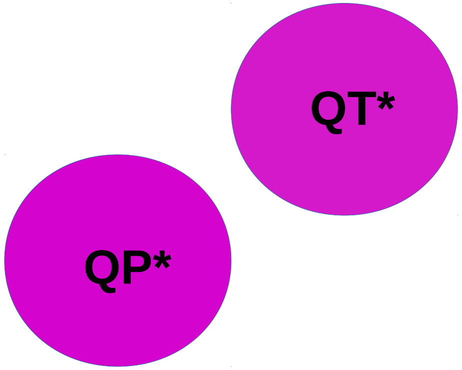
Neutron rich projectile

Neutron deficient target

Net flux of p and n

Excited Quasi Projectile

Excited Quasi Target



Isospin Diffusion:
Migration driven by the isospin gradient

V. Baran, Phys. Rev. C 72, 064620 (2005)

Once the interaction strength is fixed,
the degree of equilibration depends on the interaction time:

the more central the collision,
the more equilibrated (in isospin) the QP and the QT

Isospin dynamics: Isospin drift

The nuclear Equation of state is the basis of the isospin dynamics theory

V. Baran et al. / Physics Reports 410 (2005) 335 – 466

$$\frac{E}{A}(\rho, I) = \frac{E}{A}(\rho) + \frac{E_{sym}}{A}(\rho) I^2$$

$$I = \frac{N - Z}{A}$$

$$\rho = \rho_n + \rho_z$$

Symmetric matter

Asymmetric matter

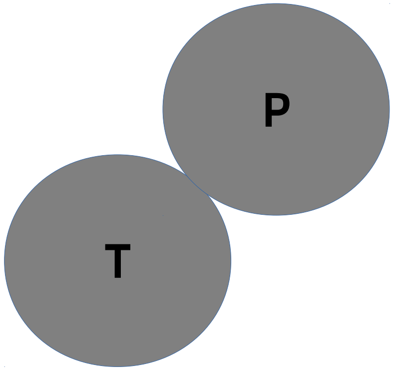
$$\frac{E}{A}(\rho) = E_{sat} + \frac{1}{2} K_{sat} x^2 + ...$$

$$\frac{E_{sym}}{A}(\rho) = E_{sym} + L_{sym} x + \frac{1}{2} K_{sym} x^2 + ...$$

The symmetry energy produces a difference of the proton and neutron currents:

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

Region at saturation density: P, T



Isospin Drift:
Migration driven by the density gradient. Neutron enrichment of the Neck?

Isospin dynamics: Isospin drift

The nuclear Equation of state is the basis of the isospin dynamics theory

V. Baran et al. / Physics Reports 410 (2005) 335 – 466

$$\frac{E}{A}(\rho, I) = \frac{E}{A}(\rho) + \frac{E_{sym}}{A}(\rho) I^2$$

Symmetric matter

Asymmetric matter

$$I = \frac{N-Z}{A}$$

$$\rho = \rho_n + \rho_z$$

$$\frac{E}{A}(\rho) = E_{sat} + \frac{1}{2}K_{sat}x^2 + \dots$$

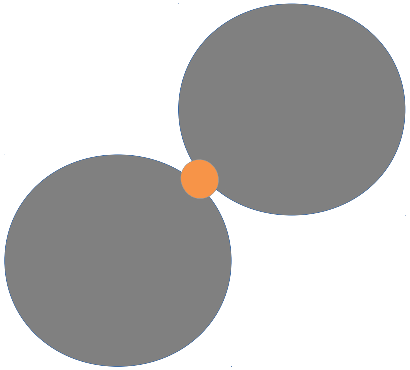
$$\frac{E_{sym}}{A}(\rho) = E_{sym} + L_{sym}x + \frac{1}{2}K_{sym}x^2 + \dots$$

The symmetry energy produces a difference of the proton and neutron currents:

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

Region at saturation density: QP, QT

Region at sub-saturation: Neck?

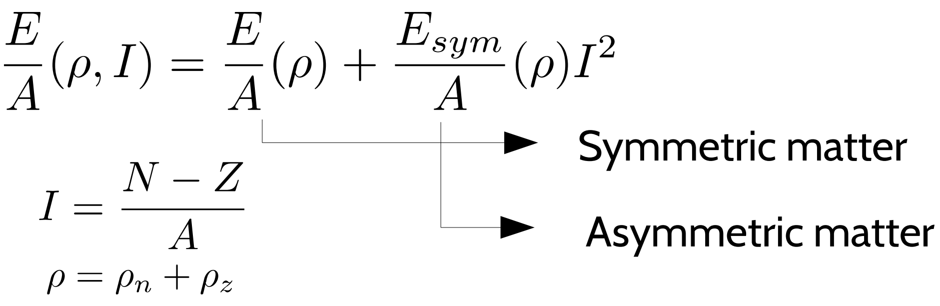


Isospin Drift:
Migration driven by the density gradient. Neutron enrichment of the Neck?

Isospin dynamics: Isospin drift

The nuclear Equation of state is the basis of the isospin dynamics theory

V. Baran et al. / Physics Reports 410 (2005) 335 – 466



$$\frac{E}{A}(\rho, I) = \frac{E}{A}(\rho) + \frac{E_{sym}}{A}(\rho)I^2$$

Symmetric matter

Asymmetric matter

$$I = \frac{N-Z}{A}$$

$$\rho = \rho_n + \rho_z$$

$$\frac{E}{A}(\rho) = E_{sat} + \frac{1}{2}K_{sat}x^2 + \ldots$$

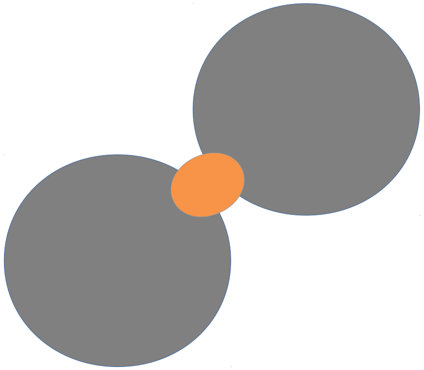
$$\frac{E_{sym}}{A}(\rho) = E_{sym} + L_{sym}x + \frac{1}{2}K_{sym}x^2 + \ldots$$

The symmetry energy produces a difference of the proton and neutron currents:

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

Region at saturation density: QP, QT

Region at sub-saturation: Neck?



Isospin Drift:
Migration driven by the density gradient. Neutron enrichment of the Neck?

Isospin dynamics: Isospin drift

The nuclear Equation of state is the basis of the isospin dynamics theory

$$\frac{E}{A}(\rho, I) = \frac{E}{A}(\rho) + \frac{E_{sym}}{A}(\rho) I^2$$

$$I = \frac{N - Z}{A}$$

$$\rho = \rho_n + \rho_z$$

Symmetric matter

Asymmetric matter

V. Baran et al. / Physics Reports 410 (2005) 335 – 466

$$\frac{E}{A}(\rho) = E_{sat} + \frac{1}{2}K_{sat}x^2 + \ldots$$

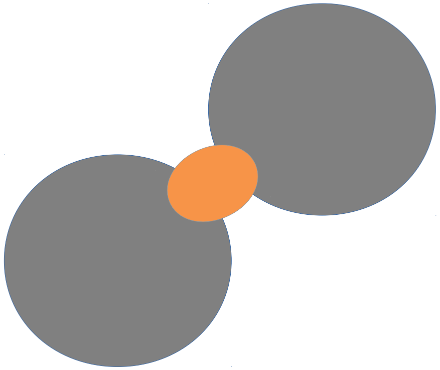
$$\frac{E_{sym}}{A}(\rho) = E_{sym} + L_{sym}x + \frac{1}{2}K_{sym}x^2 + \ldots$$

The symmetry energy produces a difference of the proton and neutron currents:

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

Region at saturation density: QP, QT

Region at sub-saturation: Neck?



Isospin Drift:
Migration driven by the density gradient. Neutron enrichment of the Neck?

Isospin dynamics: Isospin drift

The nuclear Equation of state is the basis of the isospin dynamics theory

V. Baran et al. / Physics Reports 410 (2005) 335 - 466

$$\frac{E}{A}(\rho, I) = \frac{E}{A}(\rho) + \frac{E_{sym}}{A}(\rho) I^2$$

$$I = \frac{N-Z}{A}$$

$$\rho = \rho_n + \rho_z$$

Symmetric matter

$$\frac{E}{A}(\rho) = E_{sat} + \frac{1}{2} K_{sat} x^2 + \ldots$$

Asymmetric matter

$$\frac{E_{sym}}{A}(\rho) = E_{sym} + L_{sym} x + \frac{1}{2} K_{sym} x^2 + \ldots$$

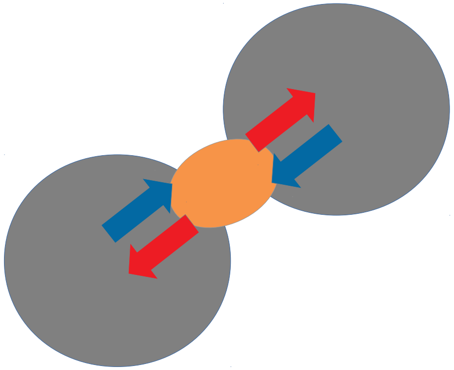
The symmetry energy produces a difference of the proton and neutron currents:

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

Region at saturation density: QP, QT

Region at sub-saturation: Neck?

Net flux of n towards the neck



Isospin Drift:
Migration driven by the density gradient. Neutron enrichment of the Neck?

Isospin dynamics: Isospin drift

The nuclear Equation of state is the basis of the isospin dynamics theory

V. Baran et al. / Physics Reports 410 (2005) 335 - 466

$$\frac{E}{A}(\rho, I) = \frac{E}{A}(\rho) + \frac{E_{sym}}{A}(\rho) I^2$$

$$I = \frac{N-Z}{A}$$

$$\rho = \rho_n + \rho_z$$

→ Symmetric matter

$$\frac{E}{A}(\rho) = E_{sat} + \frac{1}{2} K_{sat} x^2 + ...$$

→ Asymmetric matter

$$\frac{E_{sym}}{A}(\rho) = E_{sym} + L_{sym} x + \frac{1}{2} K_{sym} x^2 + ...$$

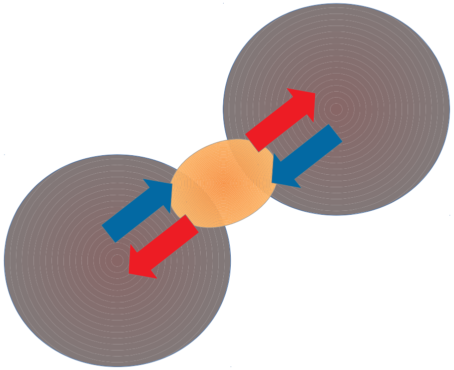
The symmetry energy produces a difference of the proton and neutron currents:

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

Region at saturation density: QP, QT

Region at sub-saturation: Neck?

Net flux of n towards the neck



Isospin Drift:
Migration driven by the density gradient. Neutron enrichment of the Neck?

Isospin dynamics: Isospin drift

The nuclear Equation of state is the basis of the isospin dynamics theory

$$\frac{E}{A}(\rho, I) = \frac{E}{A}(\rho) + \frac{E_{sym}}{A}(\rho) I^2$$

$$I = \frac{N - Z}{A}$$

$$\rho = \rho_n + \rho_z$$

Symmetric matter

Asymmetric matter

V. Baran et al. / Physics Reports 410 (2005) 335 - 466

$$\frac{E}{A}(\rho) = E_{sat} + \frac{1}{2} K_{sat} x^2 + ...$$

$$\frac{E_{sym}}{A}(\rho) = E_{sym} + L_{sym} x + \frac{1}{2} K_{sym} x^2 + ...$$

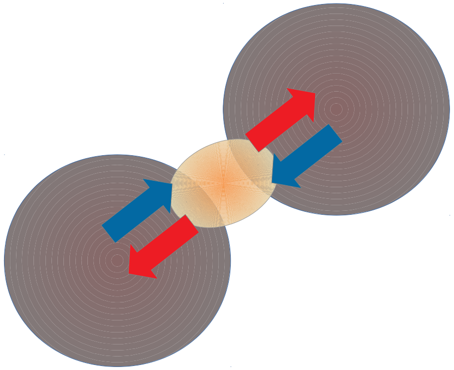
The symmetry energy produces a difference of the proton and neutron currents:

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

Region at saturation density: QP, QT

Region at sub-saturation: Neck?

Net flux of n towards the neck



Isospin Drift:
Migration driven by the density gradient. Neutron enrichment of the Neck?

Isospin dynamics: Isospin drift

The nuclear Equation of state is the basis of the isospin dynamics theory

V. Baran et al. / Physics Reports 410 (2005) 335 - 466

$$\frac{E}{A}(\rho, I) = \frac{E}{A}(\rho) + \frac{E_{sym}}{A}(\rho) I^2$$

$$I = \frac{N-Z}{A}$$

$$\rho = \rho_n + \rho_z$$

Symmetric matter

Asymmetric matter

$$\frac{E}{A}(\rho) = E_{sat} + \frac{1}{2}K_{sat}x^2 + ...$$

$$\frac{E_{sym}}{A}(\rho) = E_{sym} + L_{sym}x + \frac{1}{2}K_{sym}x^2 + ...$$

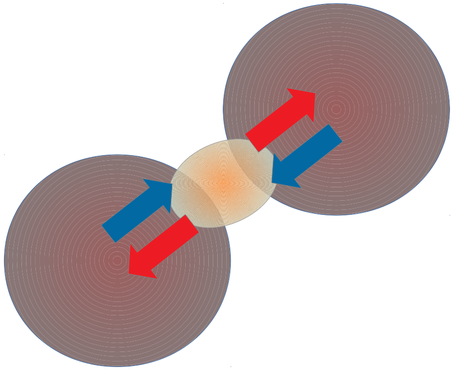
The symmetry energy produces a difference of the proton and neutron currents:

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

Region at saturation density: QP, QT

Region at sub-saturation: Neck?

Net flux of n towards the neck



Isospin Drift:
Migration driven by the density gradient. Neutron enrichment of the Neck?

Isospin dynamics: Isospin drift

The nuclear Equation of state is the basis of the isospin dynamics theory

$$\frac{E}{A}(\rho, I) = \frac{E}{A}(\rho) + \frac{E_{sym}}{A}(\rho) I^2$$

$$I = \frac{N-Z}{A}$$

$$\rho = \rho_n + \rho_z$$

Symmetric matter

Asymmetric matter

V. Baran et al. / Physics Reports 410 (2005) 335 - 466

$$\frac{E}{A}(\rho) = E_{sat} + \frac{1}{2}K_{sat}x^2 + \ldots$$

$$\frac{E_{sym}}{A}(\rho) = E_{sym} + L_{sym}x + \frac{1}{2}K_{sym}x^2 + \ldots$$

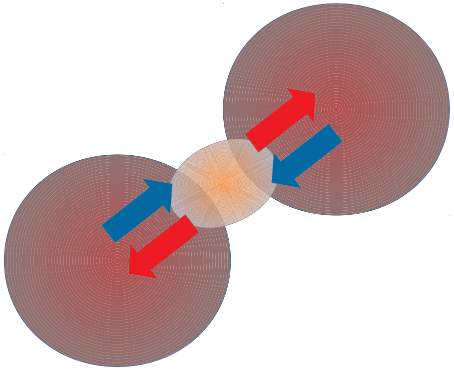
The symmetry energy produces a difference of the proton and neutron currents:

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

Region at saturation density: QP, QT

Region at sub-saturation: Neck?

Net flux of n towards the neck



Isospin Drift:
Migration driven by the density gradient. Neutron enrichment of the Neck?

Isospin dynamics: Isospin drift

The nuclear Equation of state is the basis of the isospin dynamics theory

V. Baran et al. / Physics Reports 410 (2005) 335 – 466

$$\frac{E}{A}(\rho, I) = \frac{E}{A}(\rho) + \frac{E_{sym}}{A}(\rho) I^2$$

$$I = \frac{N-Z}{A}$$

$$\rho = \rho_n + \rho_z$$

Symmetric matter

Asymmetric matter

$$\frac{E}{A}(\rho) = E_{sat} + \frac{1}{2} K_{sat} x^2 + \ldots$$

$$\frac{E_{sym}}{A}(\rho) = E_{sym} + L_{sym} x + \frac{1}{2} K_{sym} x^2 + \ldots$$

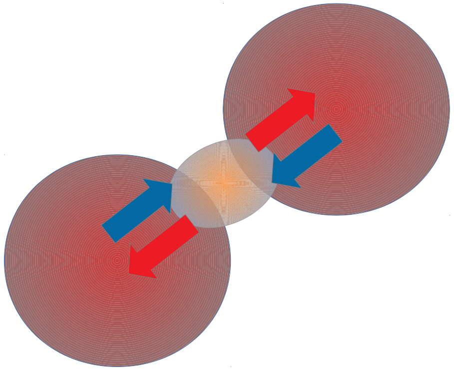
The symmetry energy produces a difference of the proton and neutron currents:

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

Region at saturation density: QP, QT

Region at sub-saturation: Neck?

Net flux of n towards the neck



Isospin Drift:
Migration driven by the density gradient. Neutron enrichment of the Neck?

Isospin dynamics: Isospin drift

The nuclear Equation of state is the basis of the isospin dynamics theory

V. Baran et al. / Physics Reports 410 (2005) 335 – 466

$$\frac{E}{A}(\rho, I) = \frac{E}{A}(\rho) + \frac{E_{sym}}{A}(\rho) I^2$$

$$I = \frac{N-Z}{A}$$

$$\rho = \rho_n + \rho_z$$

Symmetric matter

Asymmetric matter

$$\frac{E}{A}(\rho) = E_{sat} + \frac{1}{2} K_{sat} x^2 + ...$$

$$\frac{E_{sym}}{A}(\rho) = E_{sym} + L_{sym} x + \frac{1}{2} K_{sym} x^2 + ...$$

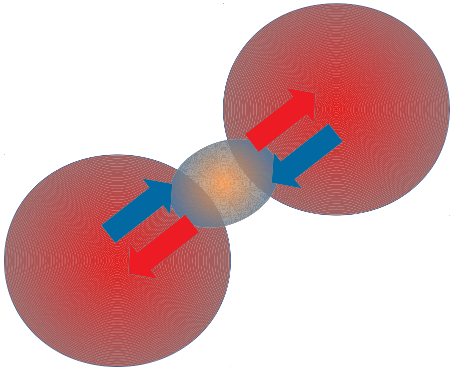
The symmetry energy produces a difference of the proton and neutron currents:

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

Region at saturation density: QP, QT

Region at sub-saturation: Neck?

Net flux of n towards the neck



Isospin Drift:
Migration driven by the density gradient. Neutron enrichment of the Neck?

Isospin dynamics: Isospin drift

The nuclear Equation of state is the basis of the isospin dynamics theory

$$\frac{E}{A}(\rho, I) = \frac{E}{A}(\rho) + \frac{E_{sym}}{A}(\rho) I^2$$

$$I = \frac{N-Z}{A}$$

$$\rho = \rho_n + \rho_z$$

Symmetric matter

Asymmetric matter

V. Baran et al. / Physics Reports 410 (2005) 335 – 466

$$\frac{E}{A}(\rho) = E_{sat} + \frac{1}{2} K_{sat} x^2 + \ldots$$

$$\frac{E_{sym}}{A}(\rho) = E_{sym} + L_{sym} x + \frac{1}{2} K_{sym} x^2 + \ldots$$

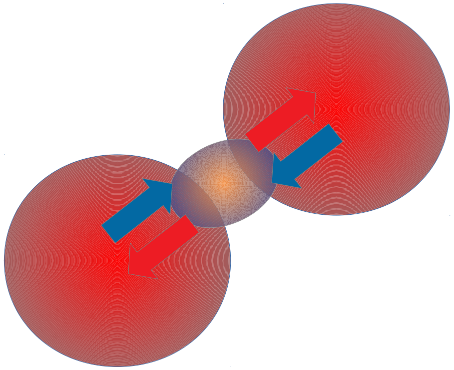
The symmetry energy produces a difference of the proton and neutron currents:

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

Region at saturation density: QP, QT

Region at sub-saturation: Neck?

Net flux of n towards the neck



Isospin Drift:
Migration driven by the density gradient. Neutron enrichment of the Neck?

Isospin dynamics: Isospin drift

The nuclear Equation of state is the basis of the isospin dynamics theory

V. Baran et al. / Physics Reports 410 (2005) 335 – 466

$$\frac{E}{A}(\rho, I) = \frac{E}{A}(\rho) + \frac{E_{sym}}{A}(\rho) I^2$$

Symmetric matter

Asymmetric matter

$$I = \frac{N - Z}{A}$$

$$\rho = \rho_n + \rho_z$$

$$\frac{E}{A}(\rho) = E_{sat} + \frac{1}{2} K_{sat} x^2 + \ldots$$

$$\frac{E_{sym}}{A}(\rho) = E_{sym} + L_{sym} x + \frac{1}{2} K_{sym} x^2 + \ldots$$

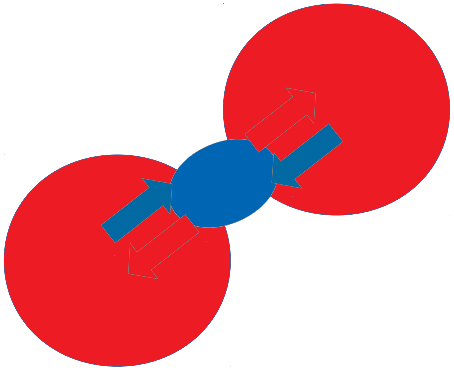
The symmetry energy produces a difference of the proton and neutron currents:

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

Region at saturation density: QP, QT

Region at sub-saturation: Neck?

Net flux of n towards the neck



Isospin Drift:
Migration driven by the density gradient. Neutron enrichment of the Neck?

Isospin dynamics: Isospin drift

The nuclear Equation of state is the basis of the isospin dynamics theory

V. Baran et al. / Physics Reports 410 (2005) 335 – 466

$$\frac{E}{A}(\rho, I) = \frac{E}{A}(\rho) + \frac{E_{sym}}{A}(\rho) I^2$$

$$I = \frac{N-Z}{A}$$

$$\rho = \rho_n + \rho_z$$

Symmetric matter

Asymmetric matter

$$\frac{E}{A}(\rho) = E_{sat} + \frac{1}{2} K_{sat} x^2 + \ldots$$

$$\frac{E_{sym}}{A}(\rho) = E_{sym} + L_{sym} x + \frac{1}{2} K_{sym} x^2 + \ldots$$

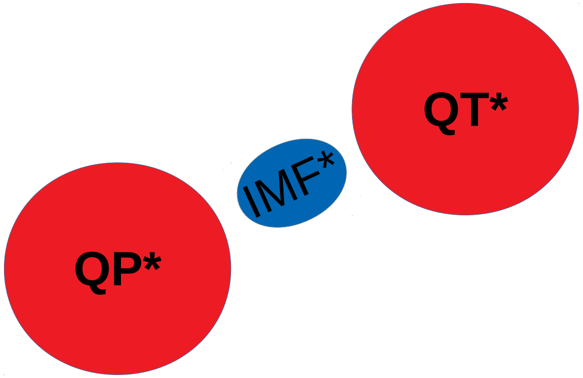
The symmetry energy produces a difference of the proton and neutron currents:

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

Region at saturation density: QP, QT

Region at sub-saturation: Neck?

Net flux of n towards the neck

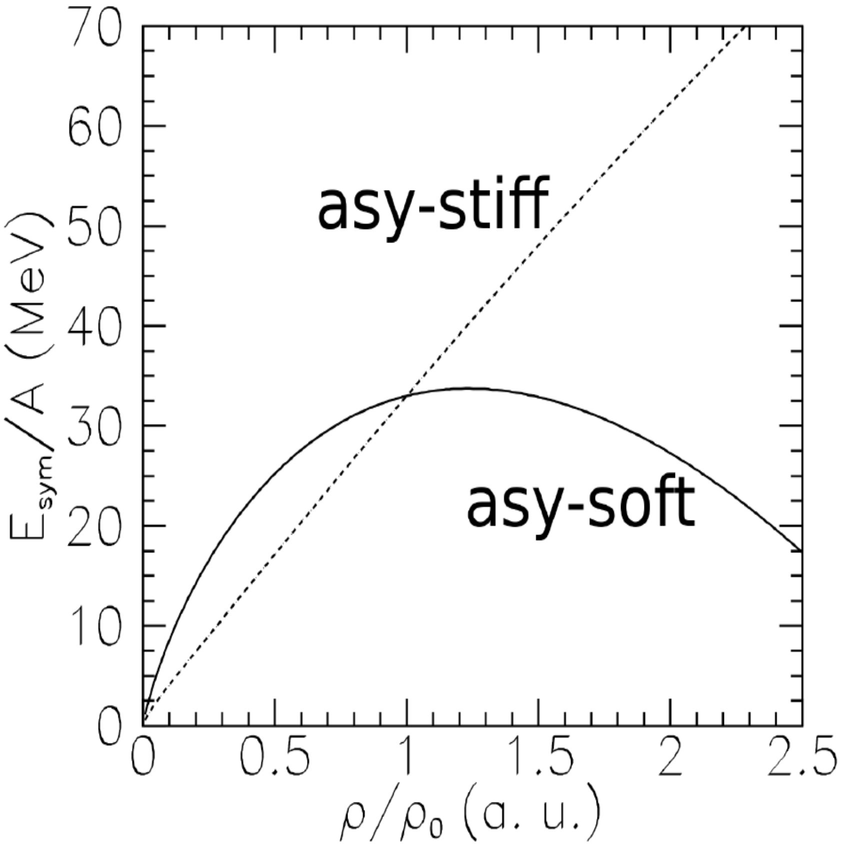


Isospin Drift: Migration driven by the density gradient. Neutron enrichment of the Neck?

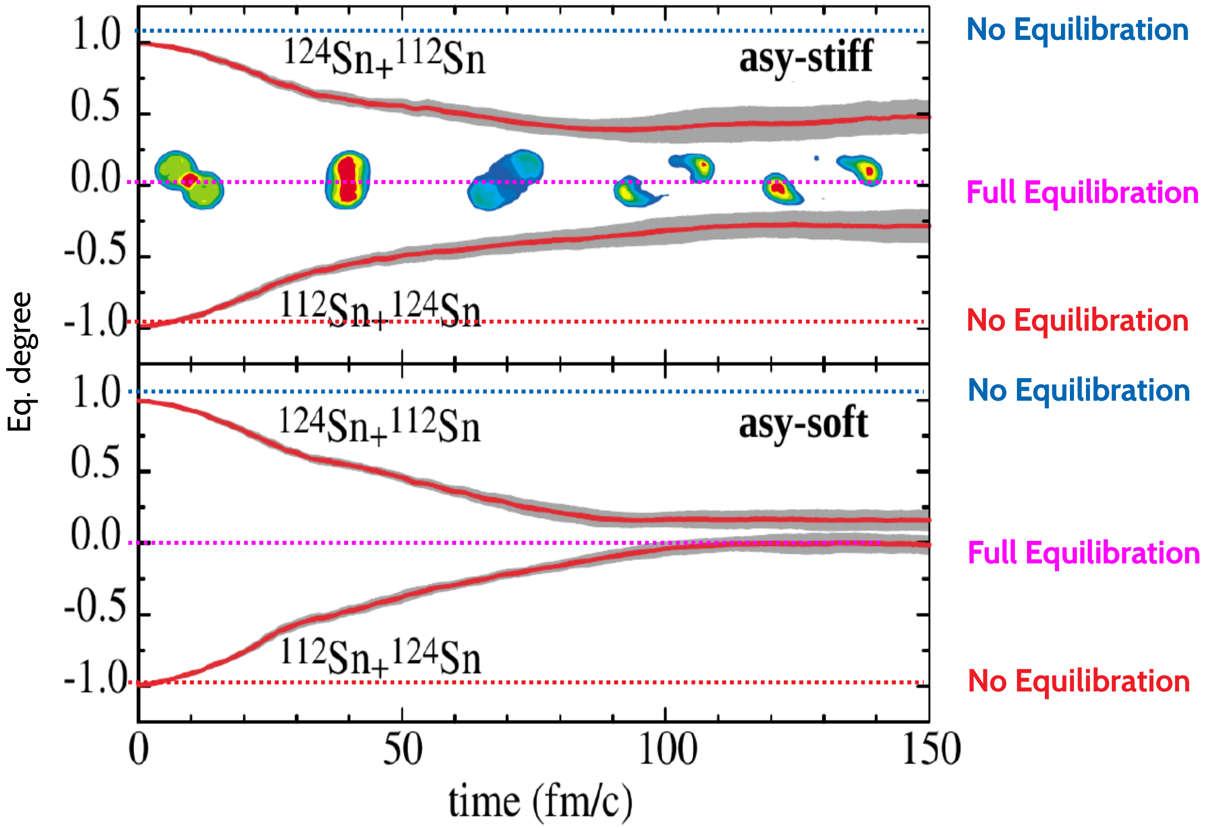
Excited n-deficient QP and QT

Excited n-rich fragment at mid-velocity

nEoS and heavy ion collisions



Transport model calculation



M. B. Tsang et al., Phys. Rev. Lett. 92, 062701 (2004)

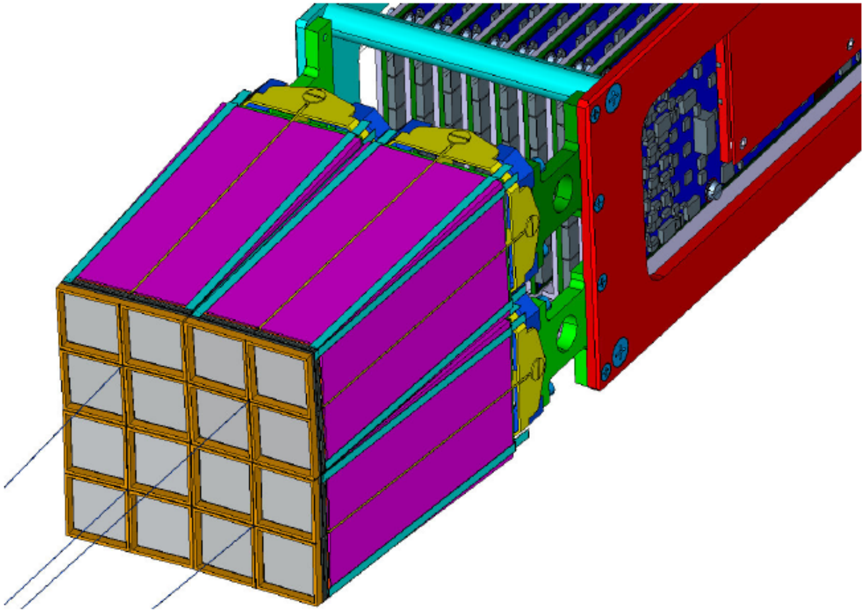
Different nEoS recipes lead to different equilibration degree

Ruling the chemical content of the formed fragments

FAZIA: Forward-angle A-Z Identification Array

FAZIA: *R. Bougalt et al., Eur. Phys. J. A 50, 47 (2014).*

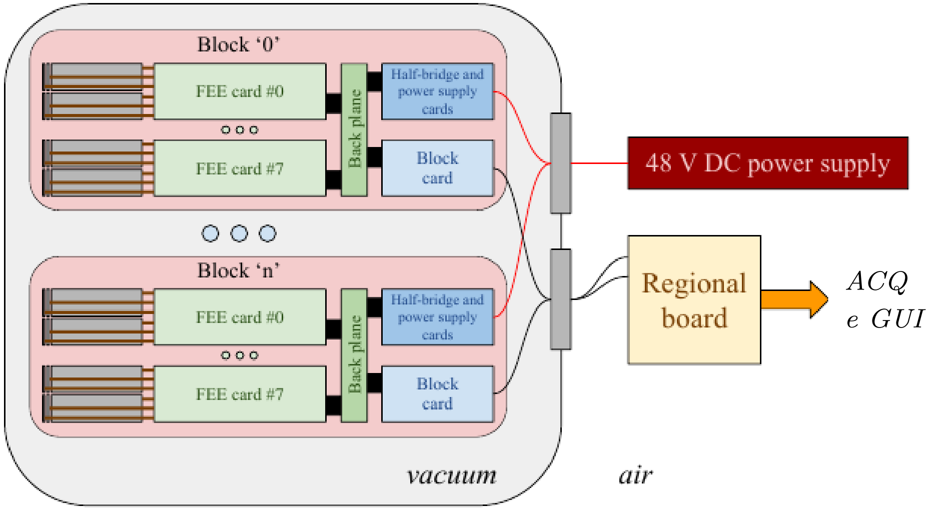
- Modular apparatus: block minimum unit
- **1 BLK = 16 telescope**
- Telescope (area 2x2 cm^2)
  - **Si1, 300um**
  - **Si2, 500um**
    - n-TD, to optimize doping uniformity
    - Thickness uniformity within ±1 μm
    - Random cut to avoid channeling
    - "reverse mounting" configuration
  - **CsI(Tl), 10cm, + photodiode**



S. Valdre et al., Nucl. Instr. And Method 930, 27 (2019)

Electronics and Acquisition:

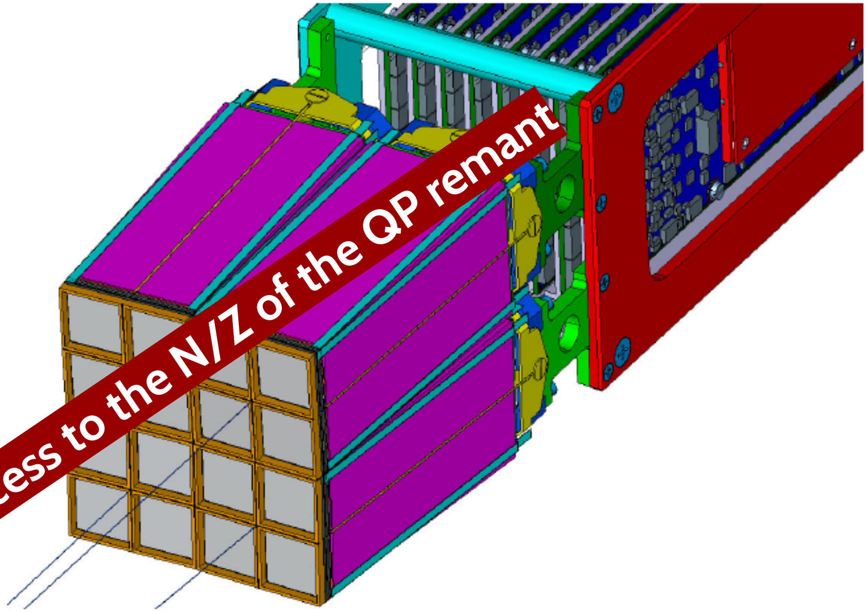
- **1 FEE** drives 2 telescope, supplying HV e digitizing signals
  - SI1→ sQH1, sQL1, sI1
  - SI2 → sQ2, sI2
  - CsI → sQ3
- 2 FPGA
  - Trigger and acquisition of sampled signals
  - Online signal shaping
- **Block card**: input/output communication
- **ReBo**: main trigger, acquisition and slow control management



FAZIA: Forward-angle A-Z Identification Array

FAZIA: *R. Bougalt et al., Eur. Phys. J. A 50, 47 (2014).*

- Modular apparatus: block minimum unit
- **1 BLK = 16 telescope**
- Telescope (area 2x2 cm^2)
  - **Si1, 300um**
  - **Si2, 500um**
    - n-TD, to optimize doping uniformity
    - Thickness uniformity within ±1 µm
    - Random cut to avoid channeling
    - “reverse mounting” configuration
  - **CsI(Tl), 10cm, + photodiode**

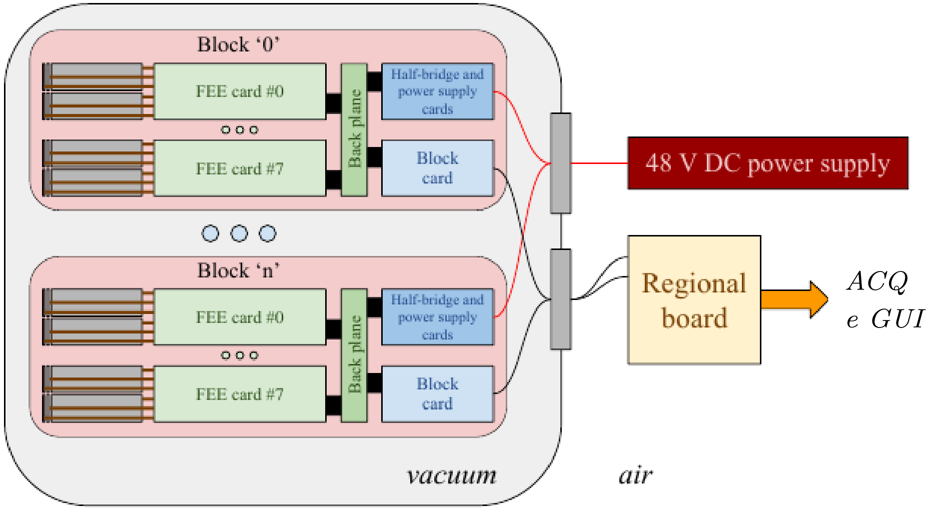


S. Valdre et al., Nucl. Instr. And Method 930, 27 (2019)

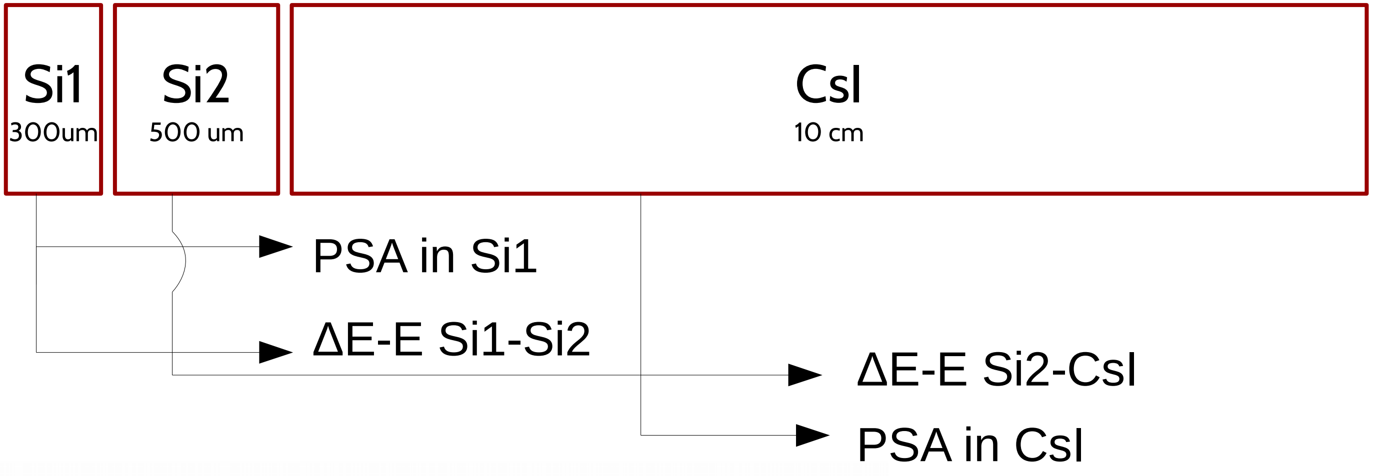
It allows isotopic identification up to Z~25, i.e. to access to the N/Z of the QP remant

Electronics and Acquisition:

- **1 FEE** drives 2 telescope, supplying HV e digitizing si s
  - SI1→ sQH1, sQL1, sI1
  - SI2 → sQ2, sI2
  - CsI → sQ3
  - 2 FPGA
    - Trigger and acquisition of sampled signals
    - Online signal shaping
- **Block card**: input/output communication
- **ReBo**: main trigger, acquisition and slow control management



FAZIA Identification methods



Si1
300um

Si2
500 um

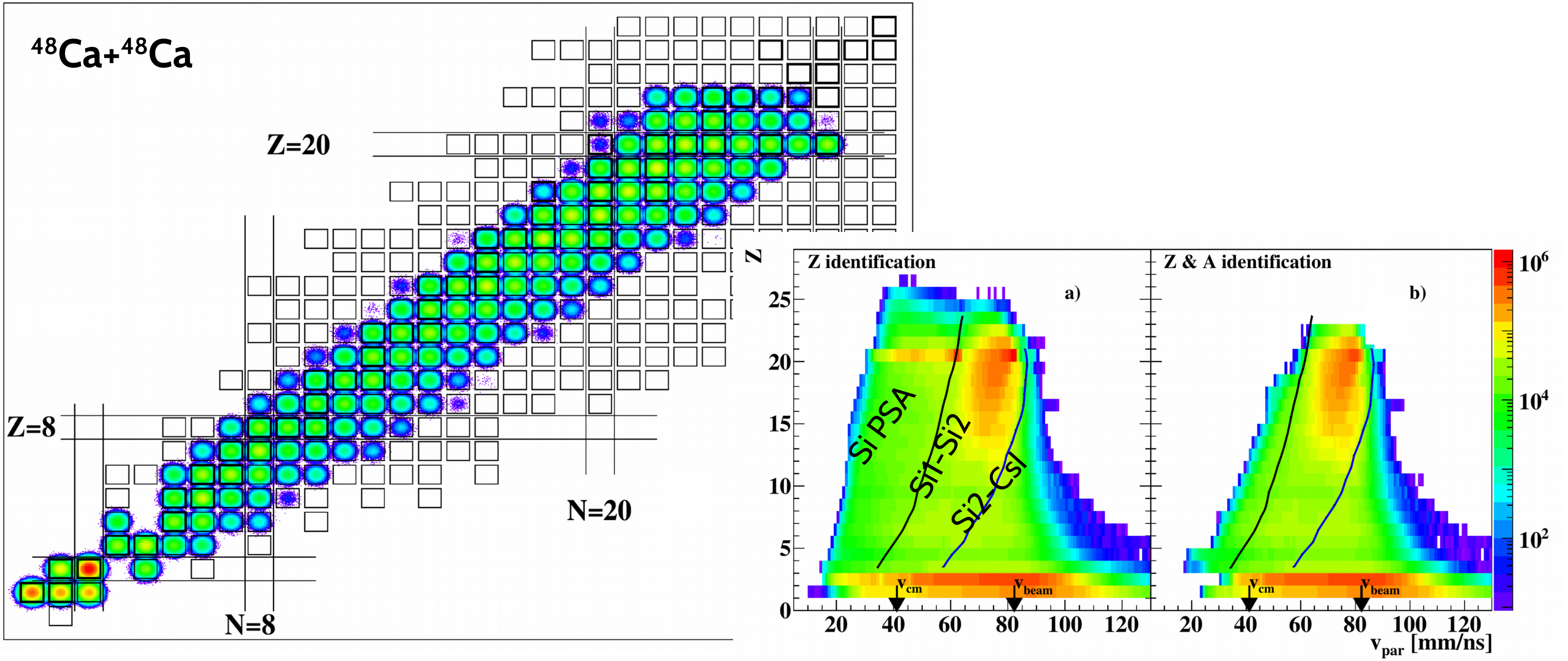
CsI
10 cm

PSA in Si1

ΔE-E Si1-Si2

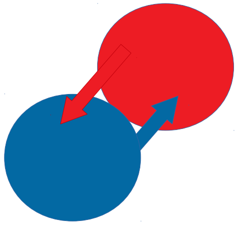
ΔE-E Si2-CsI

PSA in CsI

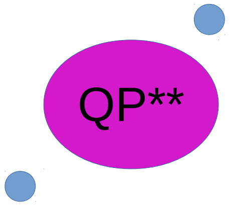


Timeline of an heavy-ion collision

Evaporative Event

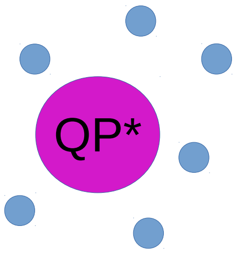


Interaction phase



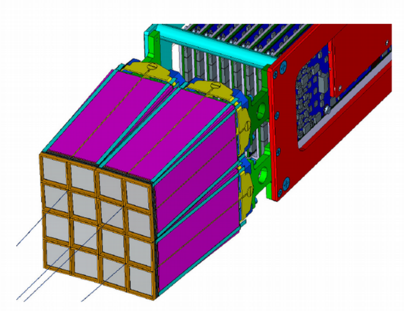
End of the interaction
t_{DIC}

Dynamical



Thermodynamical equilibrium

Statistical

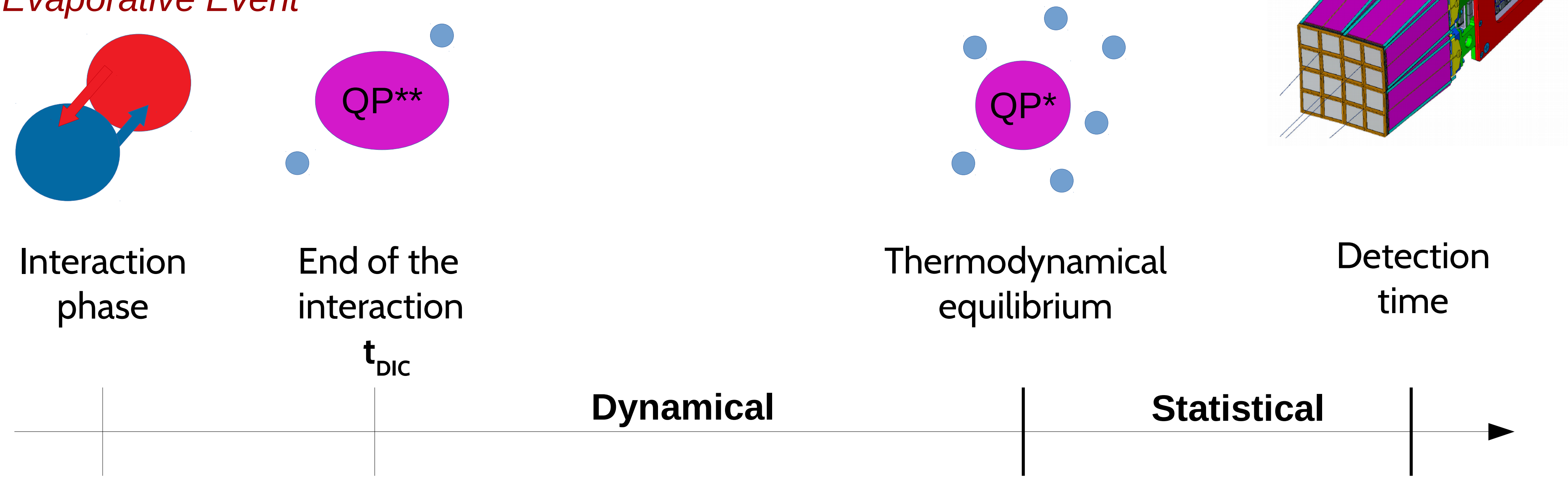


Detection time

time [fm/c]
(N.B. not in scale)

Timeline of an heavy-ion collision

Evaporative Event



time [fm/c]
(N.B. not in scale)

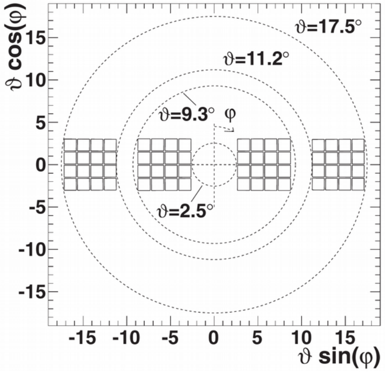
What are perturbations introduced by the dynamical and statistical emissions?

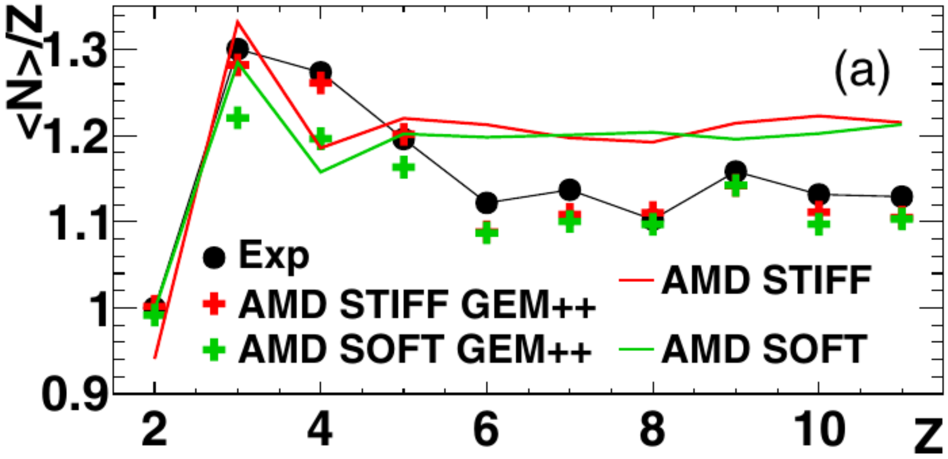
S. Piantelli et al, PRC 103, 014603 (2021)

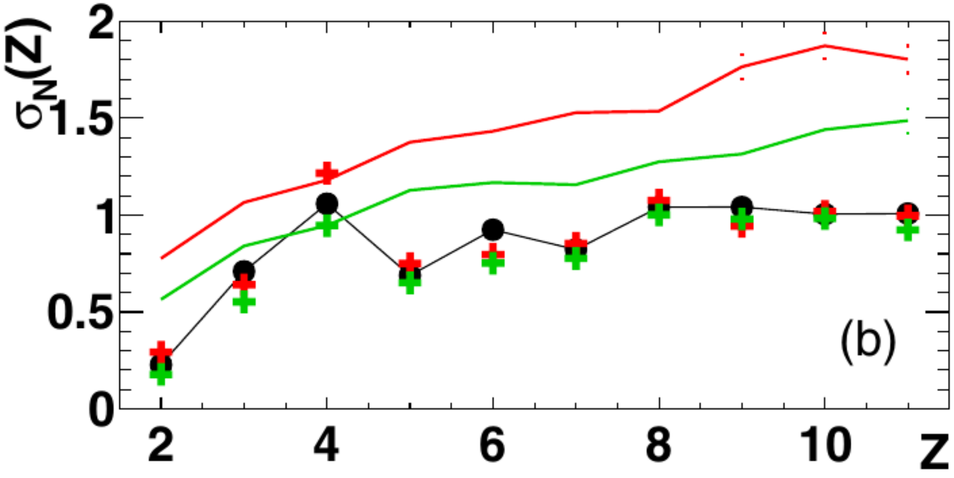
ISOFAZIA: asy-stiff or asy-soft?

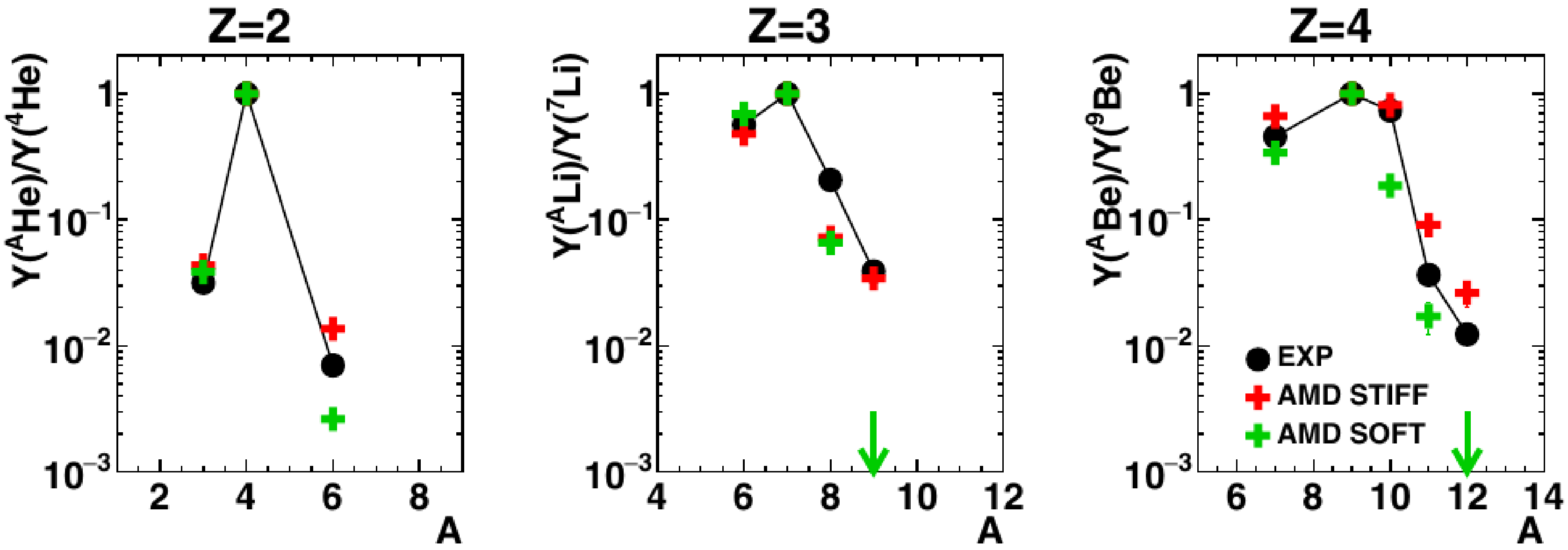
^{80}Kr + ^{40,48}Ca @ 35 MeV/u

From the QP$_E$ events, looking at the fragments accompanying the remnant





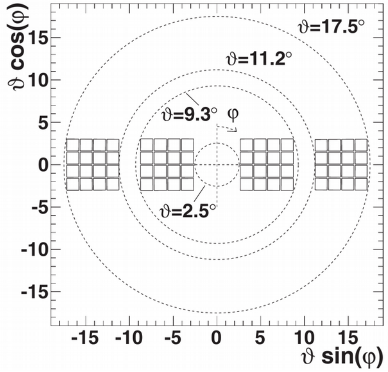




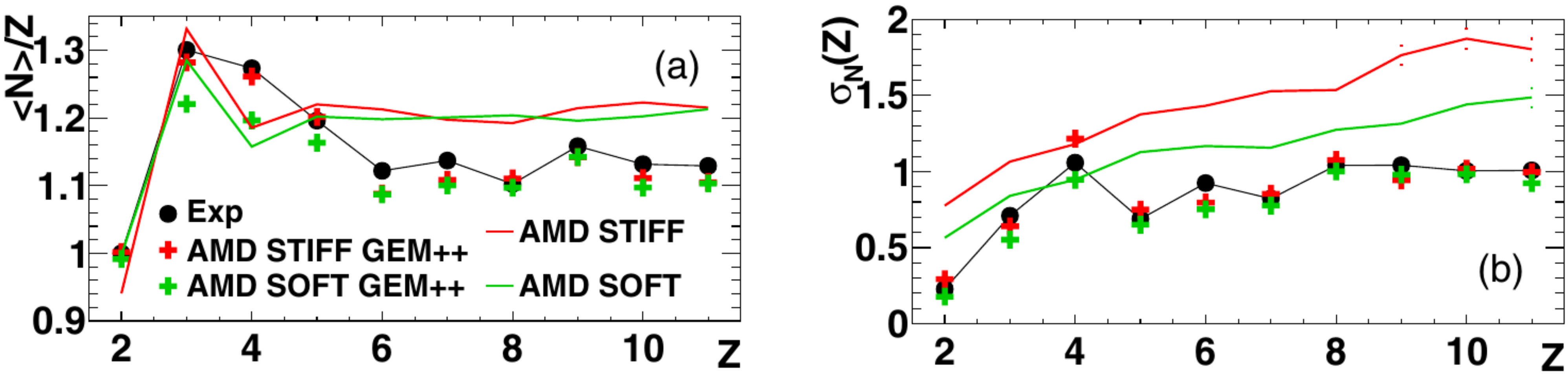
S. Piantelli et al, PRC 103, 014603 (2021)

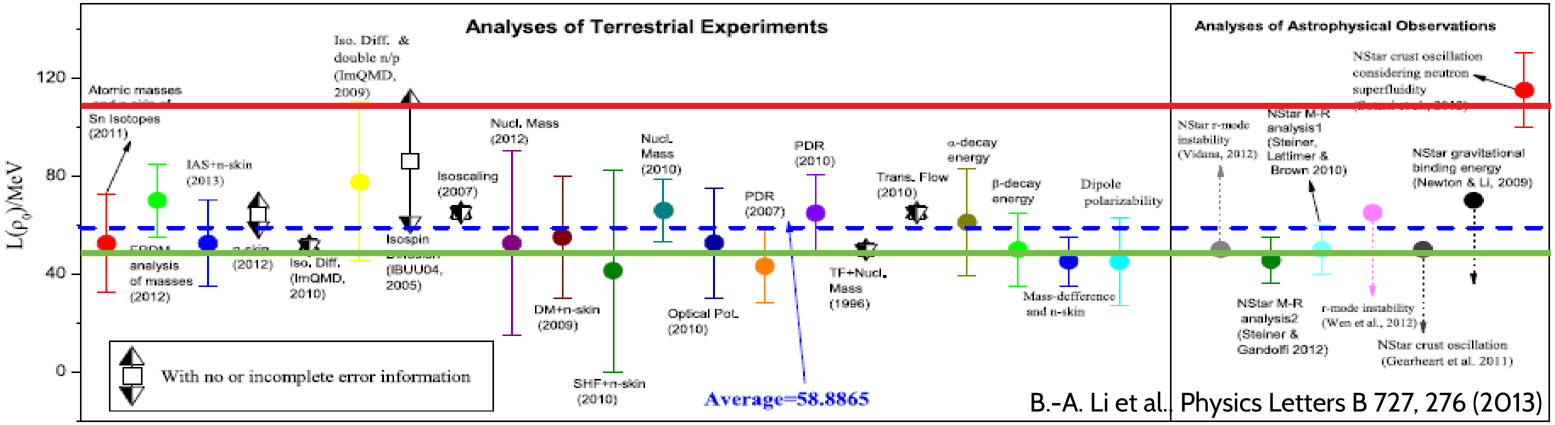
ISOFAZIA: asy-stiff or asy-soft?

^{80}Kr + ^{40,48}Ca @ 35 MeV/u



From the QP$_E$ events, looking at the fragments accompaignin the remnant



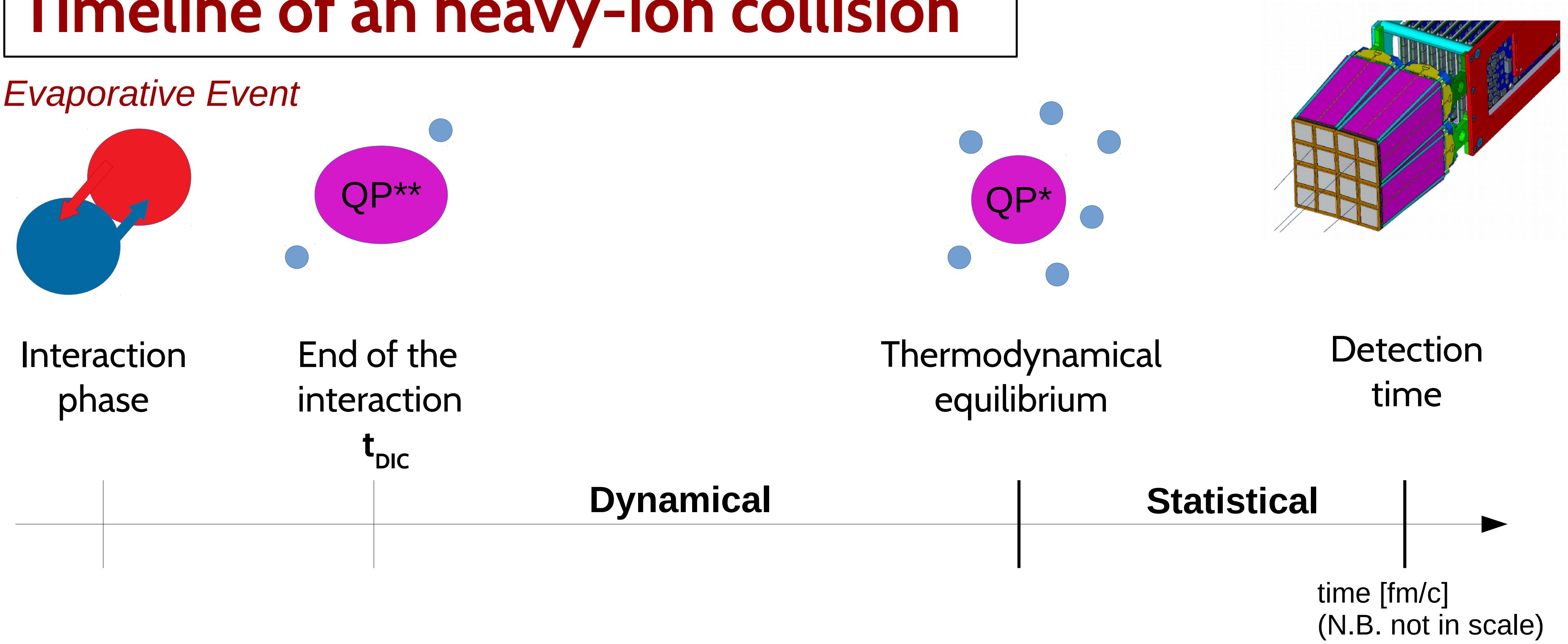


B.-A. Li et al., Physics Letters B 727, 276 (2013)

Weak indications of stiff symmetry energy, with L=108

Timeline of an heavy-ion collision

Evaporative Event



**Can the perturbations introduced by
the dynamical and statistical emissions be bypassed?**

A. Camaiani et al, PRC 102, 044607 (2020). A. Camaiani et al, PRC 103, 014605 (2021)

FAZIA-SYM

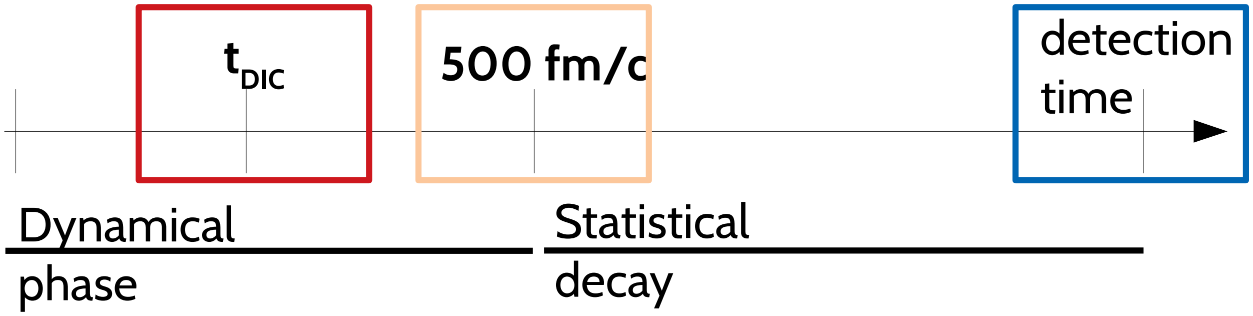
^{40}Ca+^{40}Ca

^{48}Ca+^{40}Ca @ 35 MeV/nucleon

^{48}Ca+^{48}Ca

ISOSPIN DIFFUSION: ^{48}Ca+^{40}Ca

References: ^{48}Ca+^{48}Ca & ^{40}Ca+^{40}Ca



$$R(X) = \frac{2X^{Mix} - X^{NR} - X^{ND}}{X^{NR} - X^{ND}}$$

X → the N/Z of the QP

FAZIA-SYM

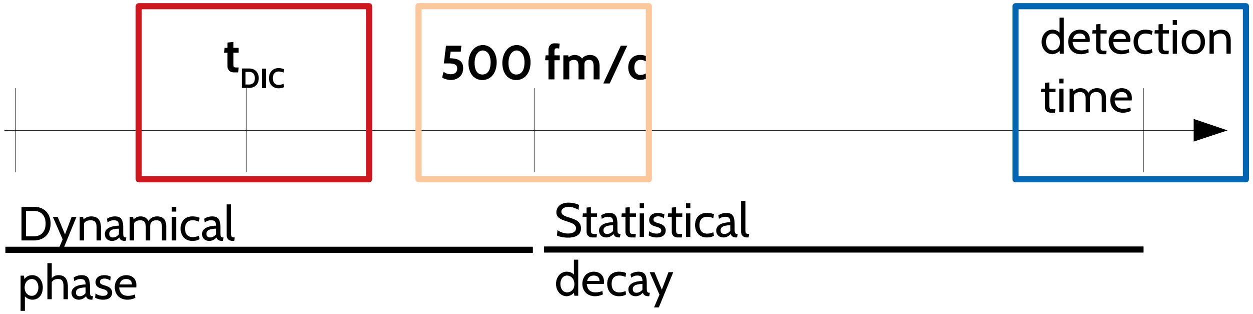
$^{40}Ca+^{40}Ca$

$^{48}Ca+^{40}Ca$ @ 35 MeV/nucleon

$^{48}Ca+^{48}Ca$

ISOSPIN DIFFUSION: $^{48}Ca+^{40}Ca$

References: $^{48}Ca+^{48}Ca$ & $^{40}Ca+^{40}Ca$

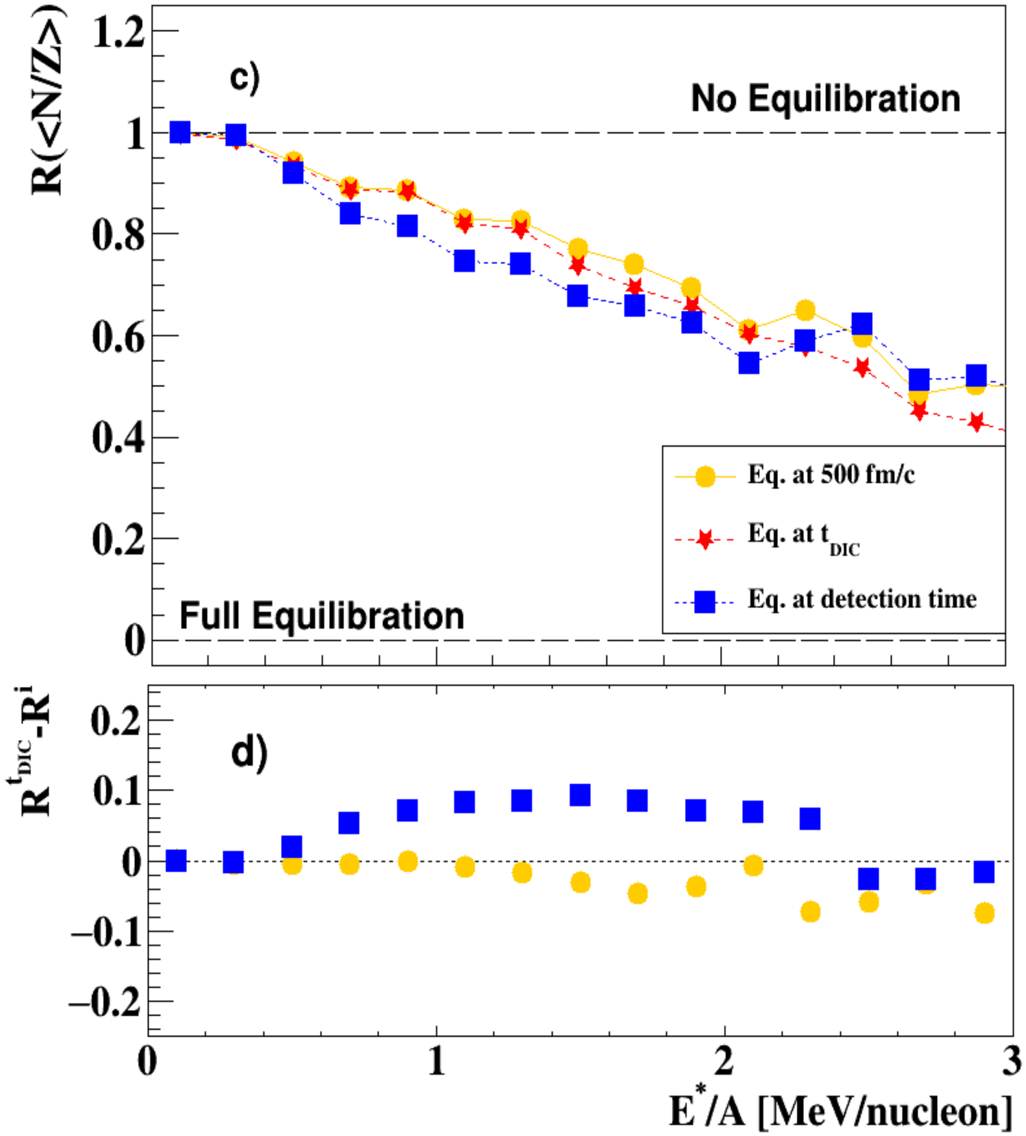

t_{DIC}

500 fm/c

detection time

Dynamical phase

Statistical decay



$$R(X) = \frac{2X^{Mix} - X^{NR} - X^{ND}}{X^{NR} - X^{ND}}$$

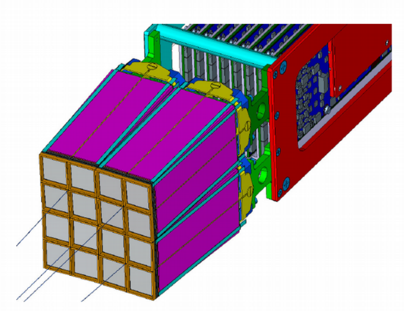
$X \longrightarrow$ the N/Z of the QP

A full model approach based on
AMD - dynamical emission
+
GEMINI – statistical emission

- Statistical decay: YES!
  At high excitation energy the evaporation is bypassed [$b_{red} = b/b_{gr} < 0.8$]
- Dynamical emission: ALMOST!
  It depends on the extent

Timeline of an heavy-ion collision

Evaporative Event



Interaction phase

End of the interaction t_{DIC}

Thermodynamical equilibrium

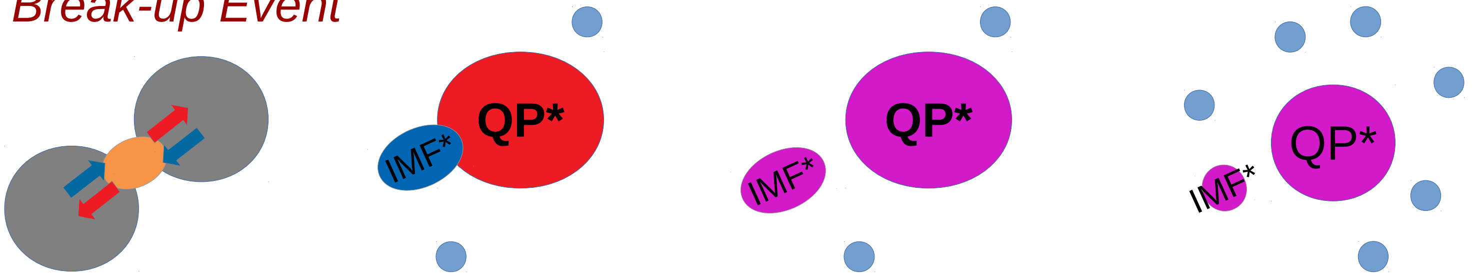
Detection time

Dynamical

Statistical

time [fm/c]
(N.B. not in scale)

Break-up Event



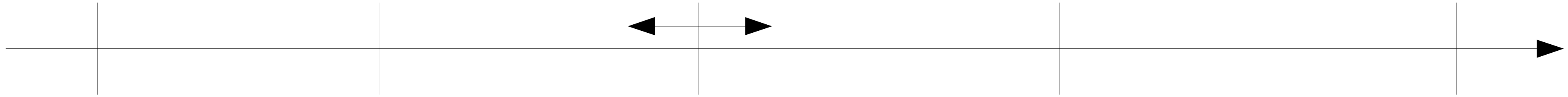
Interaction phase

End of the interaction t_{DIC}

Break up t_{split}

Thermodynamical equilibrium

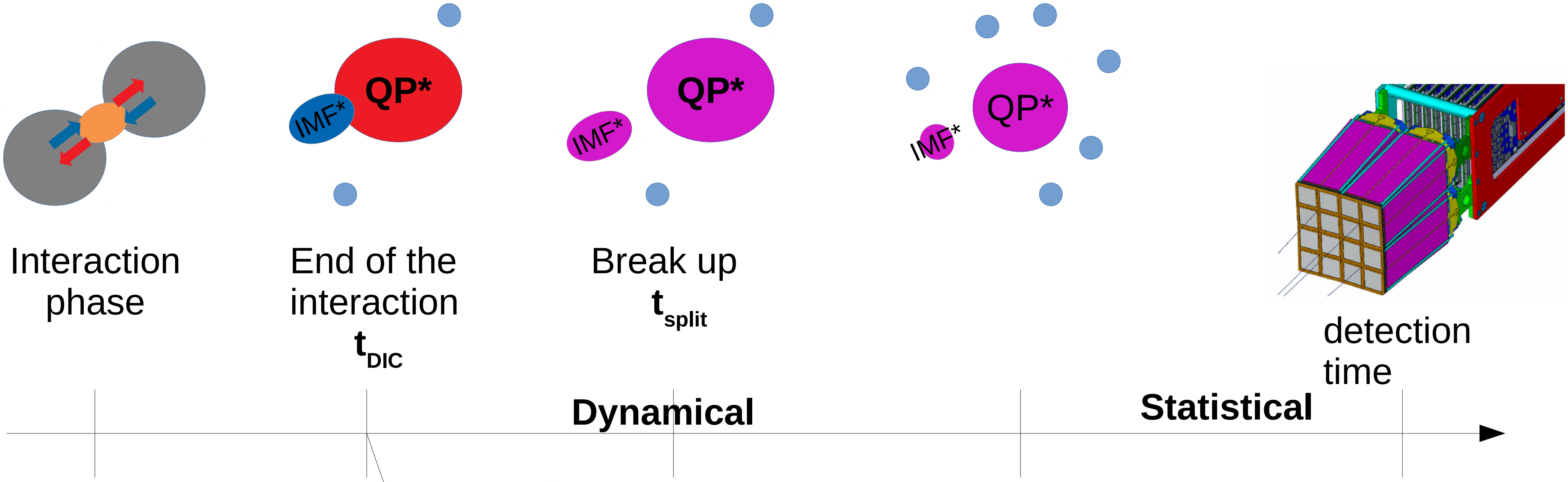
Detection time



S. Piantelli et al, PRC 101, 034613 (2020)

ISOFAZIA: QP break-up

^{80}Kr + ^{40,48}Ca @ 35 MeV/u



Interaction phase

End of the interaction t_{DIC}

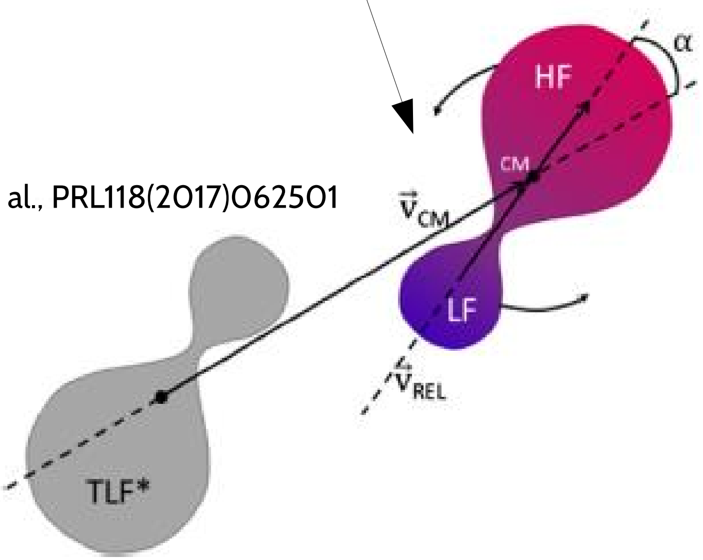
Break up t_{split}

detection time

Dynamical

Statistical

A.Jedele et al., PRL118(2017)062501



A sort of "Isospin diffusion after the drift"

α angle as a clock?

if yes, the smaller the angle, the faster the split

The faster the split, the less equilibrated in isopin the sub-system

S. Piantelli et al, PRC 101, 034613 (2020)

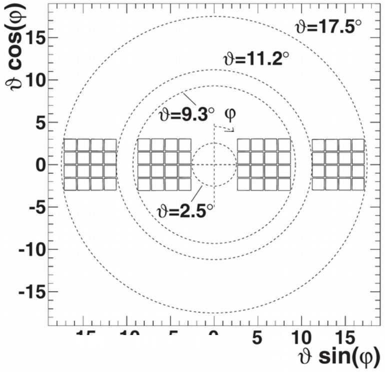
ISOFAZIA: QP break-up

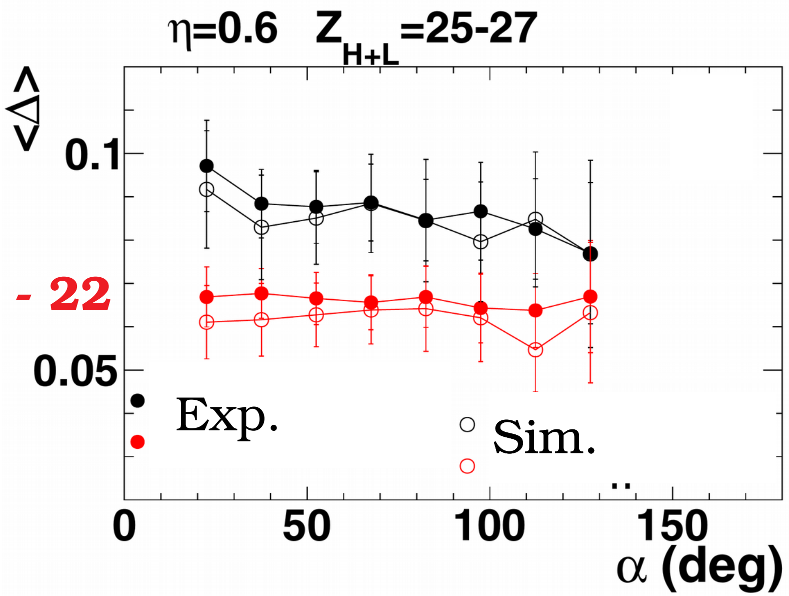
^{80}Kr + ^{40,48}Ca @ 35 MeV/u

From the detected pair in QP$_B$ events:

$$\langle\Delta\rangle = \langle\frac{N-Z}{N+Z}\rangle$$

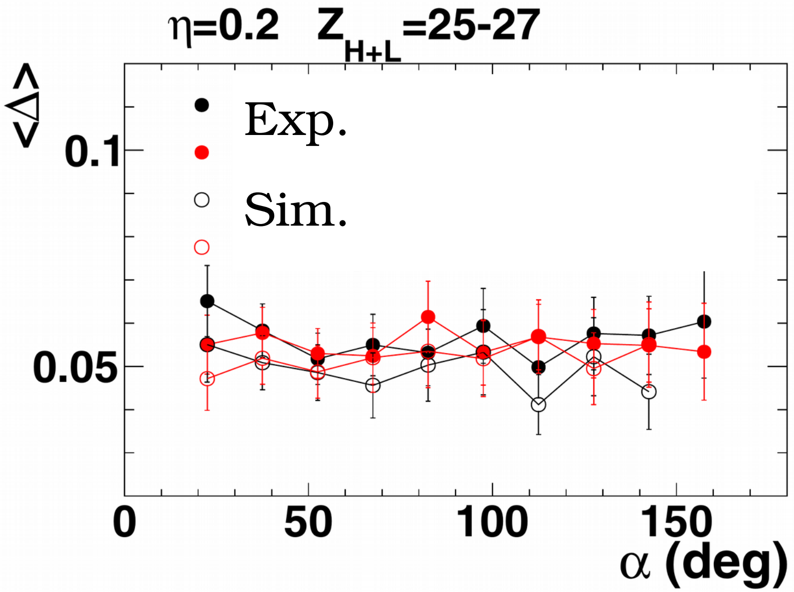
$$\eta = \frac{Z_H - Z_L}{Z_H + Z_L}$$





Z_L = 5

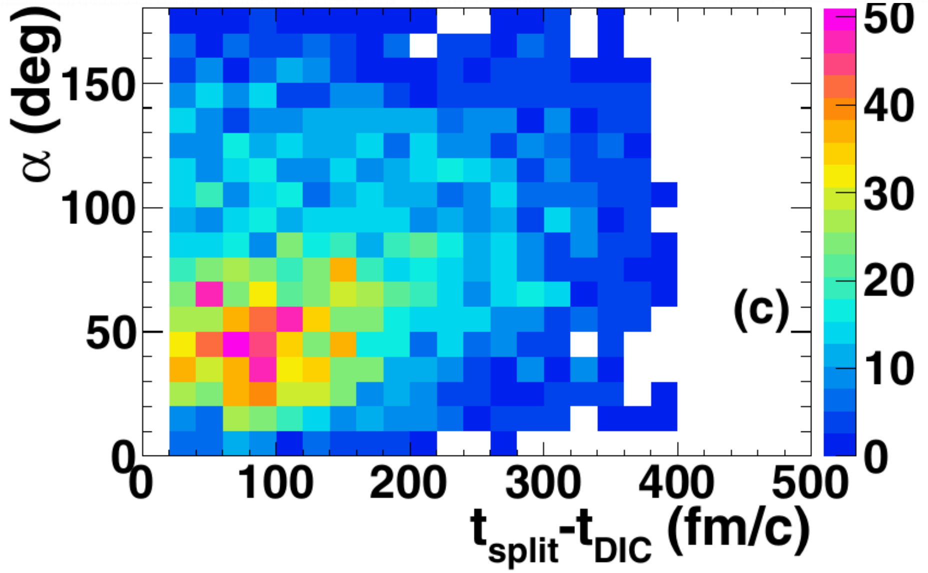
Z_H = 20 - 22



Z_L = 10-11

Z_H = 14 - 17

The AMD+Gemini model nicely reproduces the Δ vs. α trend, but...



Only a weak correlation between the α angle and the break-up time is present in AMD

INFN-LNS Campaign

0. 2004 – 2014: R & D Phase
   - The FAZIA recipe

R. Bougalt et al., Eur. Phys. J. A 50, 47 (2014).

1. 2015 ISO-FAZIA: ^{80}Kr + ^{40,48}Ca @ 35 MeV/u
   - **Break-up of the Quasi-Projectile**
   - **Isospin transport phenomena**

S. Piantelli et al, PRC 101, 034613 (2020)

S. Piantelli et al, PRC 103, 014603 (2021)

2. 2015 FAZIA-SYM: ^{40,48}Ca + ^{40,48}Ca @ 35 Mev/u
   - **Break-up of the Quasi-Projectile**
   - **Neutron-Proton equilibration**

A. Camaiani et al, Il Nuovo Cimento C, Vol. 041

A. Camaiani et al, PRC 102, 044607 (2020).

A. Camaiani et al, PRC 103, 014605 (2021)

3. 2017 FAZIA-COR: ^{20}Ne, ^{32}S + ^{12}C @ 25,50 MeV/u
   - ^{12}C Hoyle decay
   - Cluster correlations

C. Frosin – Experimental comparison with transport model calculation and cluster production in excited light systems at Fermi energies - submitted to PRC

4. 2018 FAZIA-PRE: ^{40,48}Ca + ^{12}C @ 25,40 MeV/u
   - Pre-equilibrium effects

P. Ottanelli, -
http://www.infn.it/thesis/thesis_dettaglio.php?tid=528951

5. 2018 FAZIA-ZERO (with I. Tanhiata group): ^{12}C + ^{12}C @ 62 MeV/u
   - Cross section measurement at 0°

Analysis done by Baohua Sun and co.

The next level: INDRA+FAZIA

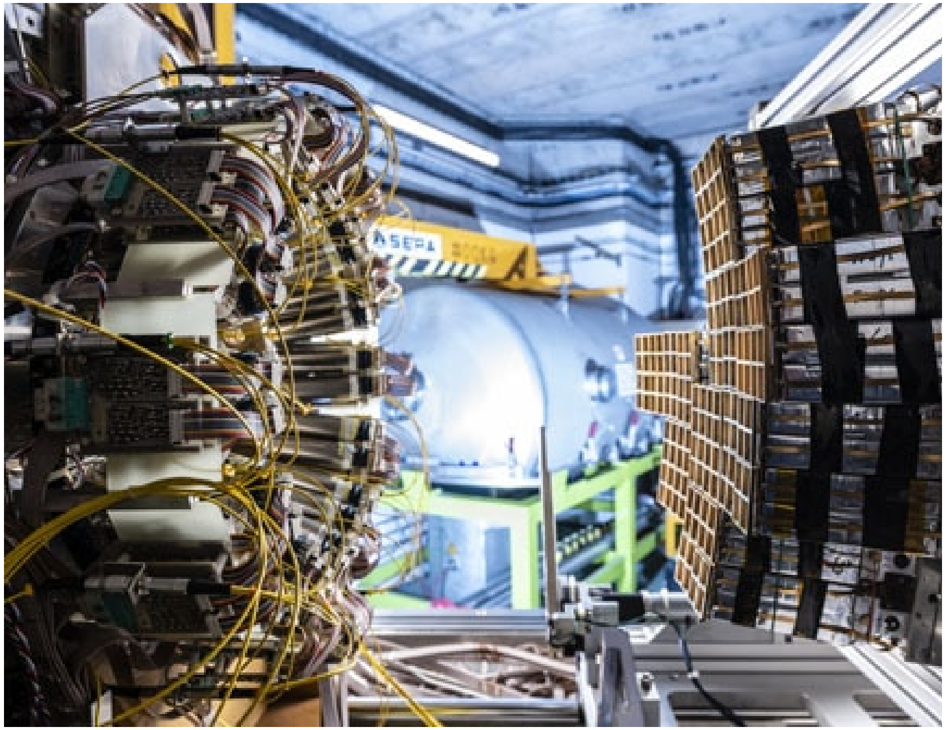
INDRA + FAZIA @ GANIL

12 FAZIA – QP phase space

INDRA – Global characterization of the event

1) ^{58,68}Ni + ^{58,68} Ni @ 32,52 MeV/u - 2019

2) ^{58}Ni, ^{36}Ar + ^{58}Ni @ 74 Mev/u - 2022



UNIVERSITÀ DEGLI STUDI FIRENZE

KU LEUVEN

INFN Istituto Nazionale di Fisica Nucleare

Thanks for your attention

A. Camaiani,[1,2,*] G. Casini,[2] S. Piantelli,[2] A. Ono,[3] E. Bonnet,[4] R. Alba,[5] S. Barlini,[1,2] B. Borderie,[6] R. Bougault,[7] C. Ciampi,[1] A. Chbihi,[8] M. Cicerchia,[9] M. Cinausero,[9,2] J.A. Dueñas,[10] D. Dell'Aquila,[11,12] Q. Fable,[7] D. Fabris,[13] C. Frosin,[1,2] J. D. Frankland,[8] F. Gramegna,[14] D. Gruyer,[7] K. I. Hahn,[15] M. Henri,[8] B. Hong,[16,17] S. Kim,[18] A. Kordyasz,[19] M. J. Kweon,[16,20] H. J. Lee,[20] J. Lemarié,[8] N. LeNeindre,[7] I. Lombardo,[21] O. Lopez,[7] T. Marchi,[14] S. H. Nam,[16,17] P. Ottanelli,[1,2] M. Parlog,[7,22] G. Pasquali,[1,2] G. Poggi,[1,2] J. Quicray,[7] A. A. Stefanini,[1,2] S. Upadhyaya,[23] S. Valdré,[2] and E. Vient[7]

[1] *Dipartimento di Fisica, Università di Firenze, Italy*
[2] *INFN, Sezione di Firenze, Italy*
[3] *Department of Physics, Tohoku University, Sendai 980-8578, Japan*
[4] *SUBATECH, Université de Nantes, IMT Atlantique,*
IN2P3/CNRS, 4 Rue Alfred Kastler, 44307 Nantes Cedex 3, France
[5] *INFN Laboratori Nazionali del Sud, Via S. Sofia 62, 95125 Catania, Italy*
[6] *Université Paris-Saclay, CNRS/IN2P3, IJCLab, 91405 Orsay, France*
[7] *Normandie Université, ENSICAEN, UNICAEN, CNRS/IN2P3, LPC Caen, 14000 Caen, France*
[8] *Grand Accélérateur National d'Ions Lourds (GANIL),*
CEA/DRF - CNRS/IN2P3, Boulevard Henri Becquerel, F-14076 Caen, France
[9] *NFN Laboratori Nazionali di Legnaro, 35020 Legnaro, Italy*
[10] *Depto. de Ingeniería Eléctrica y Centro de Estudios Avanzados en Física,*
Matemáticas y Computación, Universidad de Huelva, 21007 Huelva, Spain
[11] *Dipartimento di Chimica e Farmacia, Università degli Studi di Sassari, Sassari, Italy*
[12] *INFN - Laboratori Nazionali del Sud, Catania, Italy*
[13] *INFN Sezione di Padova, 35131 Padova, Italy*
[14] *INFN Laboratori Nazionali di Legnaro, 35020 Legnaro, Italy*
[15] *Department of Science Education, Ewha Womans University, Seoul 03760, Republic of Korea*
[16] *Center for Extreme Nuclear Matters (CENuM),*
Korea University, Seoul 02841, Republic of Korea
[17] *Department of Physics, Korea University, Seoul 02841, Republic of Korea*
[18] *Department of Science Education, Ewha Womans University, Seoul 03760, Republic of Korea*
[19] *Heavy Ion Laboratory, University of Warsaw, 02-093 Warszawa, Poland*
[20] *Department of Physics, Inha University, Incheon 22212, Republic of Korea*
[21] *INFN Sezione di Catania, 95123 Catania, Italy*
[22] *"Horia Hulubei" National Institute of Physics and Nuclear Engineering (IFIN-HH), RO-077125 Bucharest Magurele, Romania*
[23] *Faculty of Physics, Astronomy and Applied Computer Science, Jagiellonian University, 30-348 Kracow, Poland*

Nuclear Equation of state to date

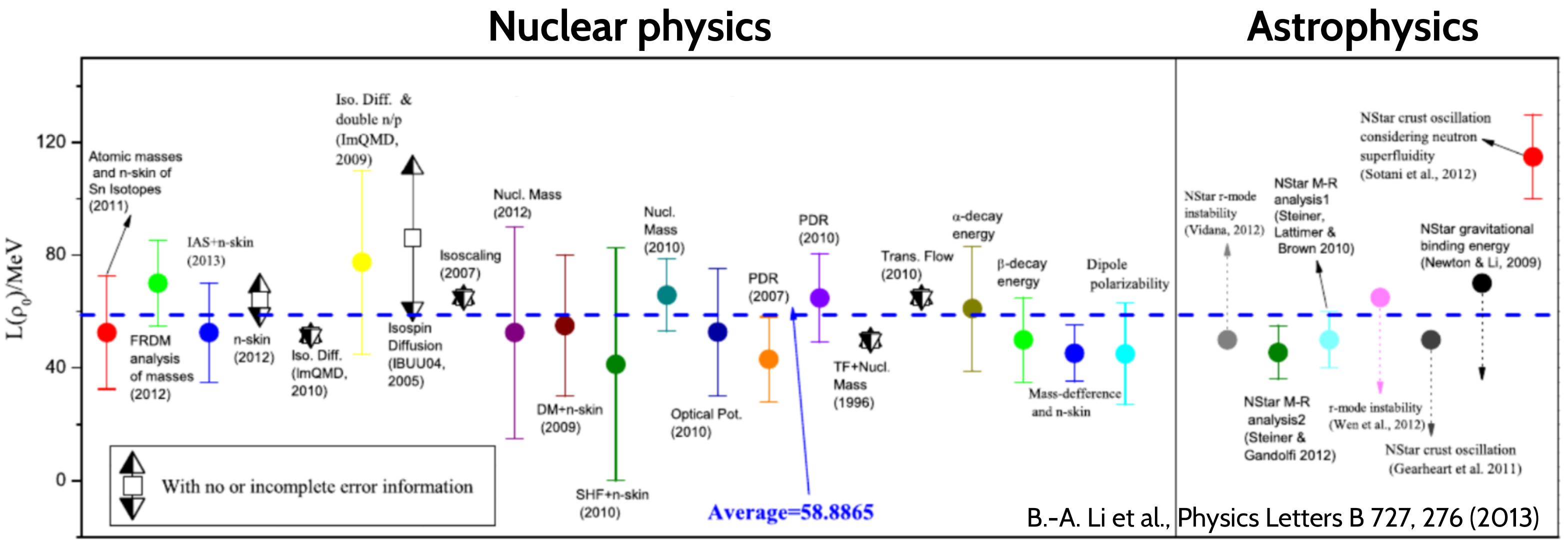
$$\frac{E}{A}(\rho) = E_{sat} + \frac{1}{2}K_{sat}x^2 + \ldots$$

$$x = \frac{\rho - \rho_0}{\rho_0}$$

$$\frac{E_{sym}}{A}(\rho) = E_{sym} + L_{sym}x + \frac{1}{2}K_{sym}x^2 + \ldots$$

	~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}	±0.3	±2	±0.005	±15	±20	±100	±400	±400	±1000	±1000

J. Margueron et al., Phys. Rev. C 97, 025805 (2018).



B.-A. Li et al., Physics Letters B 727, 276 (2013)

The FAZIA approach

Two main investigation paths followed during the years

Detection arrays

INDRA J. Pouthas et al., Nucl. Instr. and Methods A 357, 418 (1995)
CHIMERA A. Pagano et al., Nucl. Phys. A 734, 504 (2004)
Miniball/Miniwall R. D. Souza et al., NIM A 295, 109 (1990).

Large angular coverage

PROS → High detection multiplicity
Constrain the kinematics

Limited isotopic identification (Z~8)

CONS → QP decay products to extract information of the equilibration degree

Mass spectrometer

VAMOS M. Rejmund NIM A 646, 184 (2011).
MARS G. A. Souliotis et al., Phys. Rev. C 90, 064612 (2014).

Limited angular coverage

CONS → Detection multiplicity =1
No constrains to the kinematics

Excellent isotopic identification

PROS → Direct access to the Z and A of the QP

The FAZIA detector allow two combine the two approaches:
a modular detector (high detection multiplicity) +
spectroscopic identification capabilities

AMD: Antisymmetrized Molecular Dynamics

Transport model.

AMD: developed by Akira Ono, Progress in Particle and Nuclear Physics 105, 139 (2019).

Nucleus (A nucleons): Slater determinant of A gaussian wave packets

Nuclear interaction: Skyrme potential

with **stiff (L_{sym}=108MeV)** or **soft (L_{sym}=46MeV)** recipes

Time evolution: time-dependent variational principle

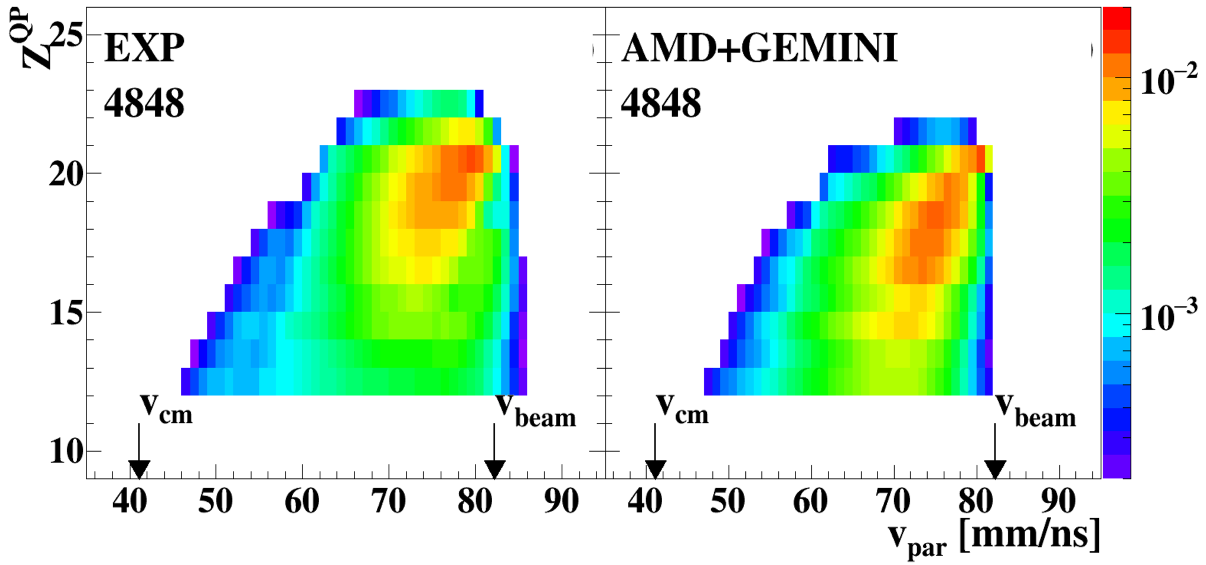
N-N collisions

In-medium effects

Cluster correlations in the final state

Dynamic calculation stopped at 500 fm/c and the **GEMINI++** as afterburner:
statistical fission and evaporation of the fragments produced by AMD

$^{48}Ca+^{48}Ca$ @ 35 MeV/u



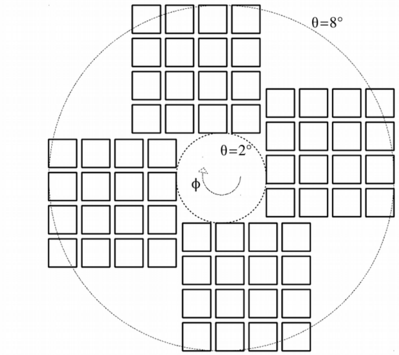
AMD+GEMINI events are filtered via software :

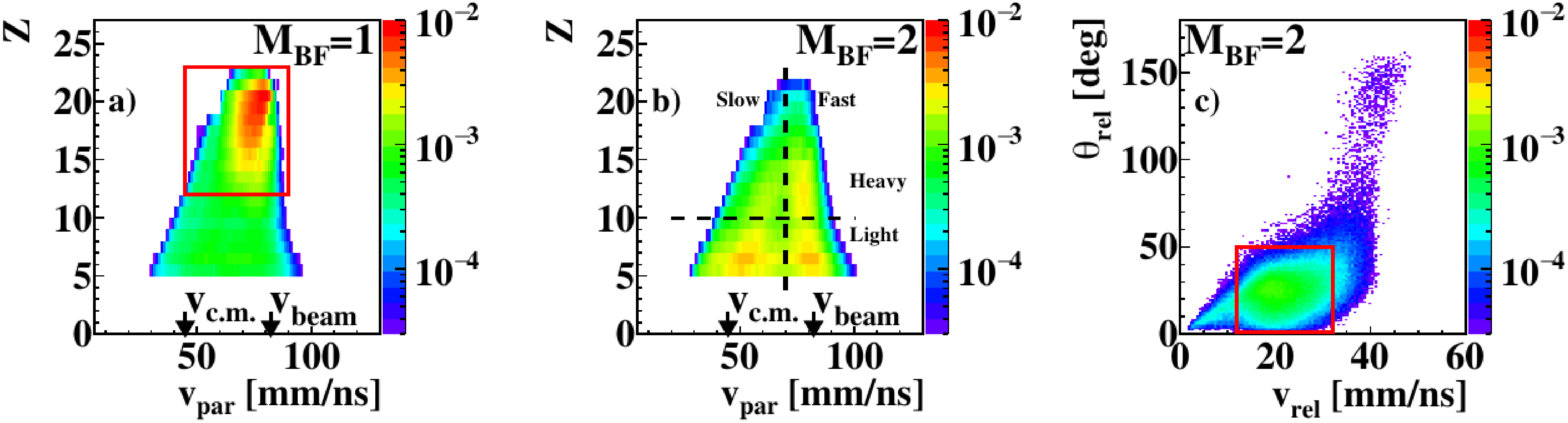
- **Geometrical acceptance**
- **Identification thresholds**
- **Detector energy resolution**

A. Camaiani et al, PRC 103, 014605 (2021)

FAZIA-SYM: n-p equilibration

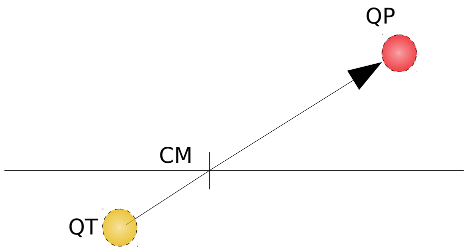
^{40,48}Ca + ^{40,48}Ca @ 35 MeV/u

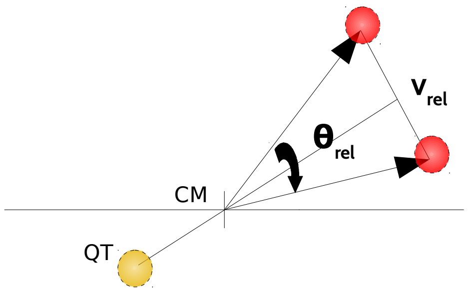




QP evaporative event

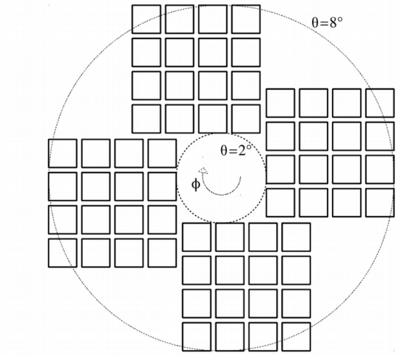
QP break-up event



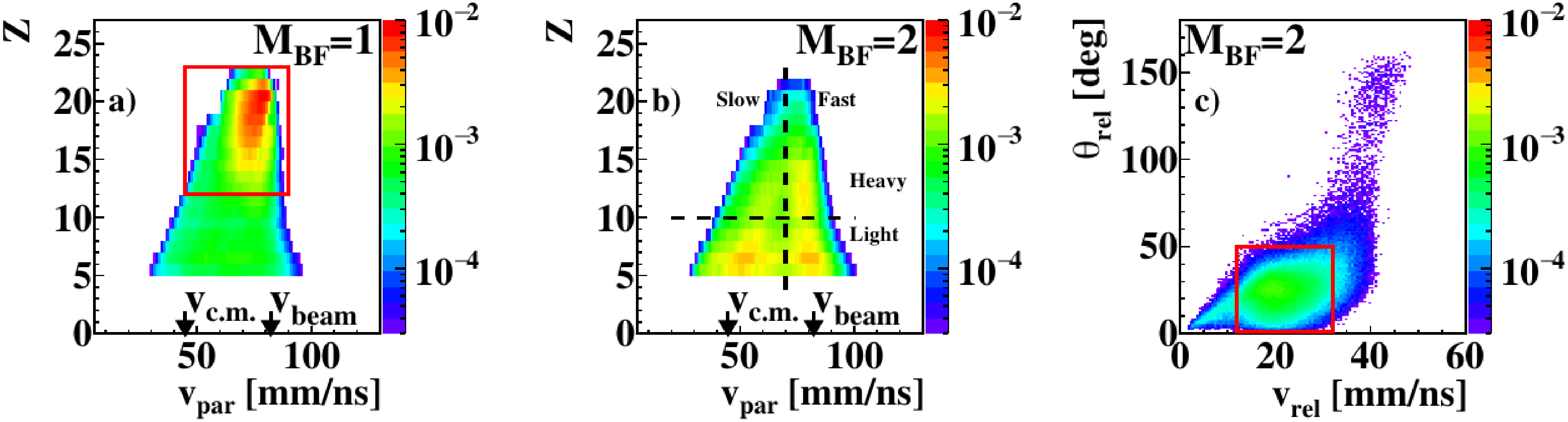


A. Camaiani et al, PRC 103, 014605 (2021)

FAZIA-SYM: n-p equilibration

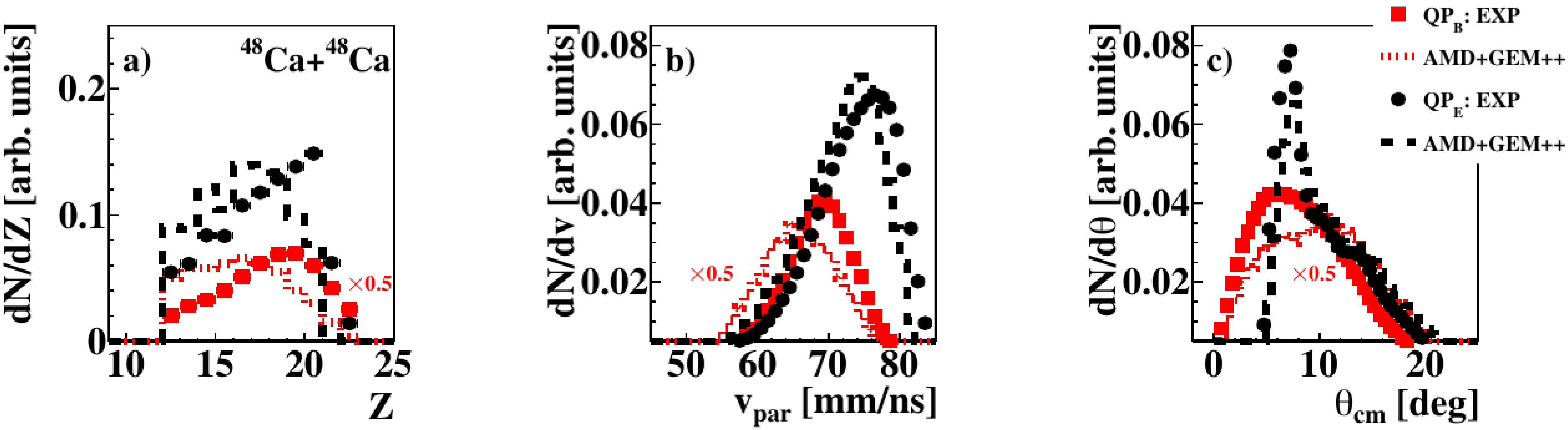


^{40,48}Ca + ^{40,48}Ca @ 35 MeV/u



QP evaporative event

QP break-up event

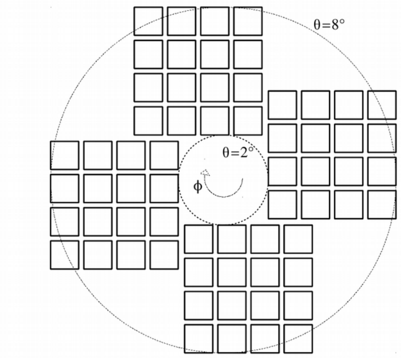


A. Camaiani et al, PRC 103, 014605 (2021)

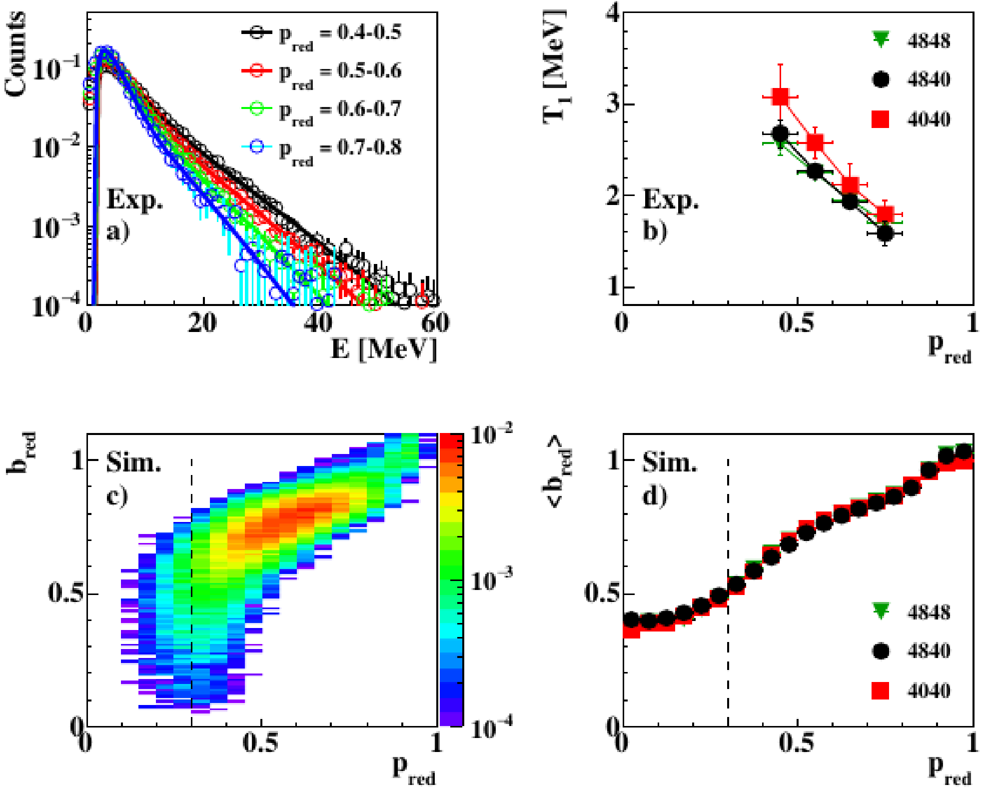
FAZIA-SYM: n-p equilibration

^{40,48}Ca + ^{40,48}Ca @ 35 MeV/u

$$p_{red} = \left(\frac{p_{par}^{QP}}{p^{beam}} \right)_{cm}$$



Reaction centrality estimator

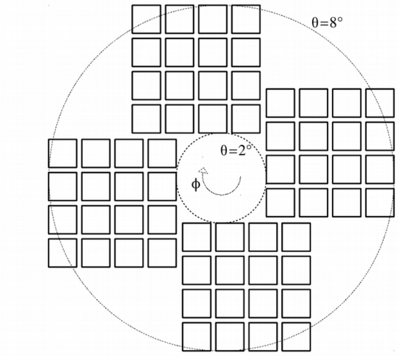


A. Camaiani et al, PRC 103, 014605 (2021)

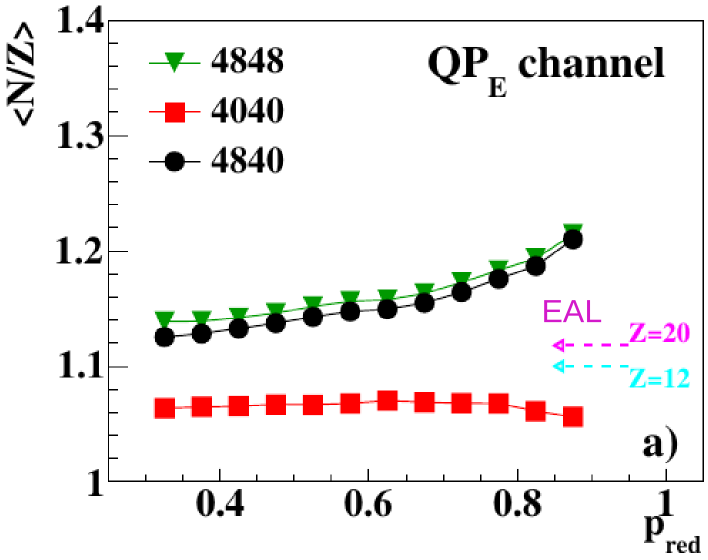
FAZIA-SYM: n-p equilibration

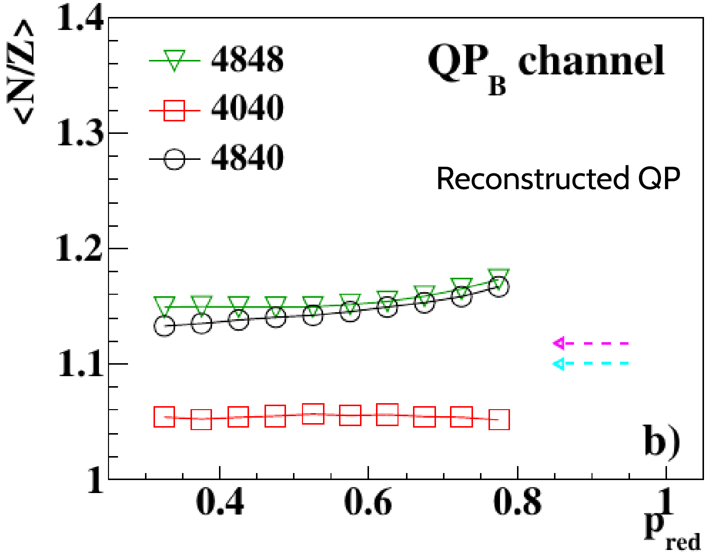
^{40,48}Ca + ^{40,48}Ca @ 35 MeV/u

$$p_{red} = \left(\frac{p^{QP}_{par}}{p^{beam}}\right)_{cm}$$

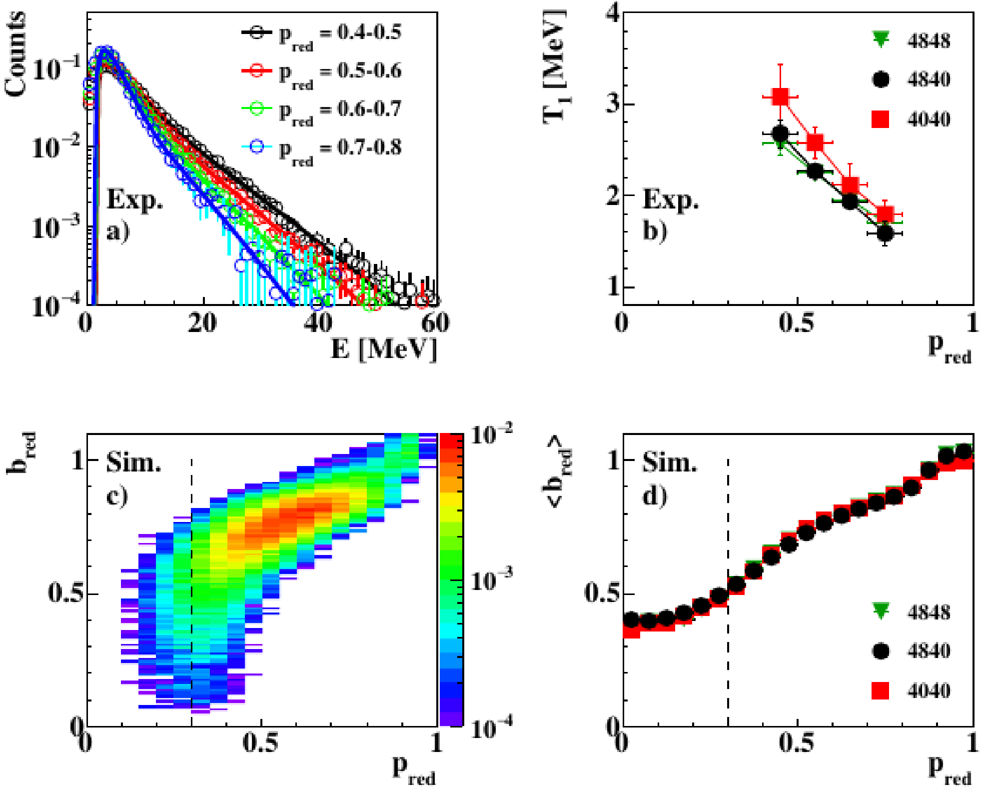


N/Z evolution with the centrality





Reaction centrality estimator



As the reaction centrality increases, the N/Z of the QP remnants approaches the EAL

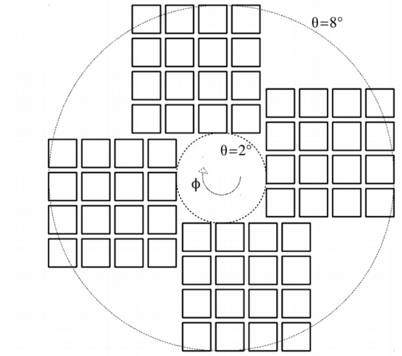
R. J. Charity, PRC 58, 1073 (1998).

A. Camaiani et al, PRC 103, 014605 (2021)

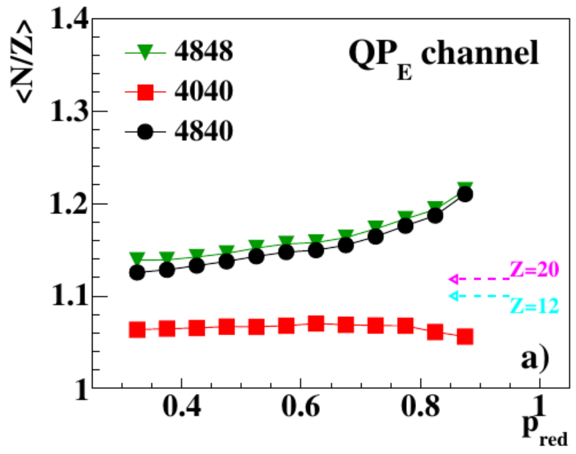
FAZIA-SYM: n-p equilibration

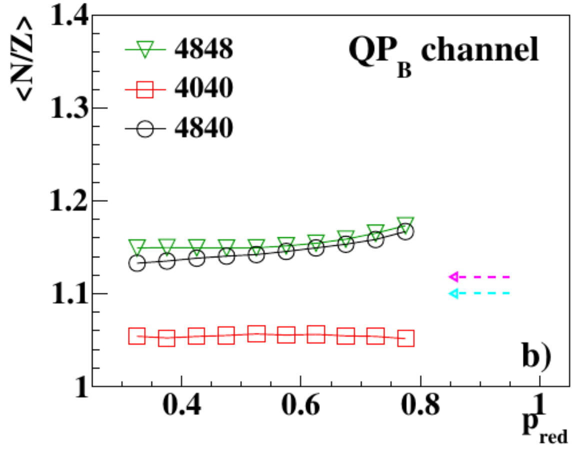
^{40,48}Ca + ^{40,48}Ca @ 35 MeV/u

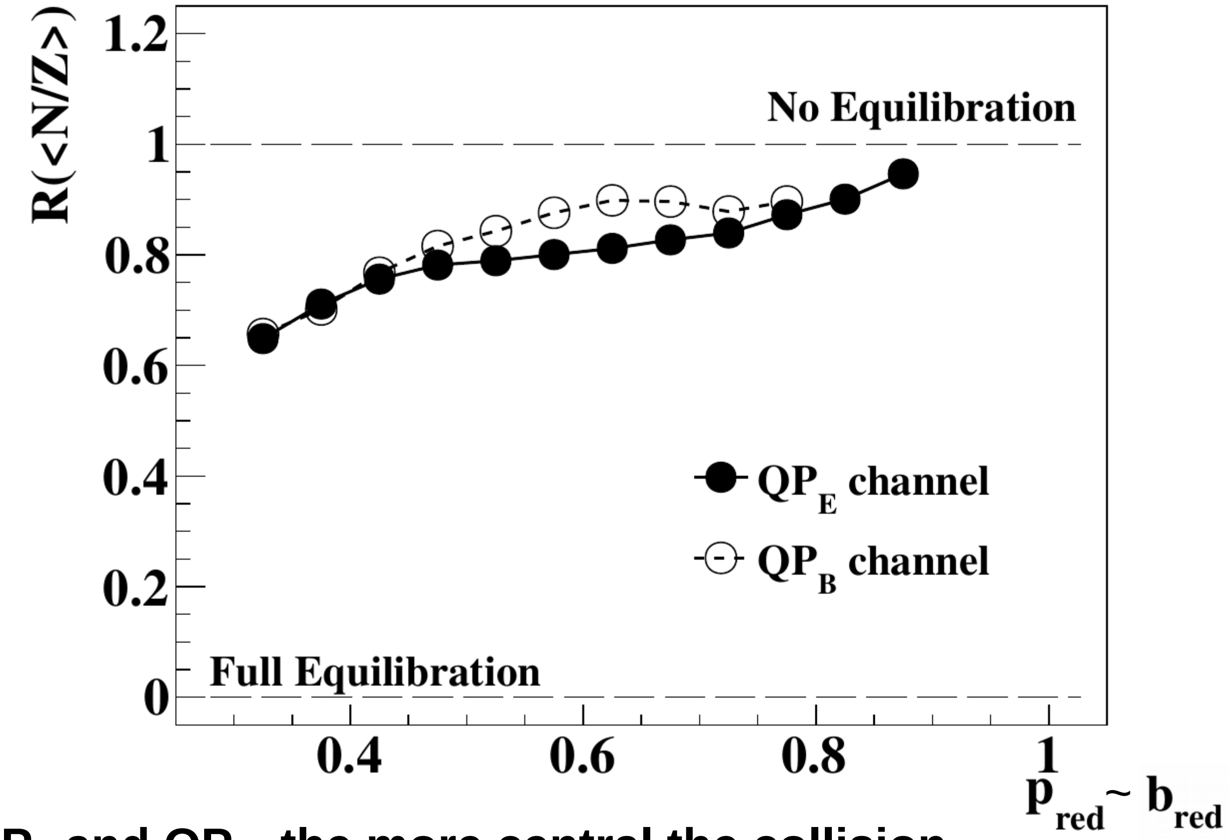
$$p_{red} = \left(\frac{p^{QP}_{par}}{p^{beam}}\right)_{cm}$$



$$R = \frac{2X^{4840} - X^{4848} - X^{4040}}{X^{4848} - X^{4040}} \qquad X = \langle N/Z \rangle$$







In both QP$_E$ and QP$_B$, the more central the collision, the more equilibrated the system

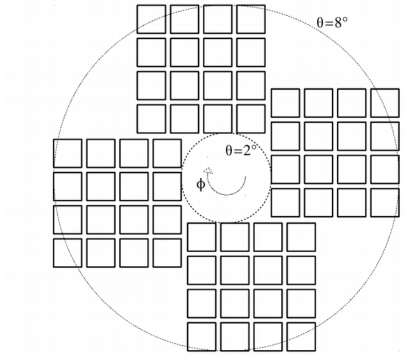
Signs of a weak process in QP$_B$ event: heavier primary source?

A. Camaiani et al, PRC 103, 014605 (2021)

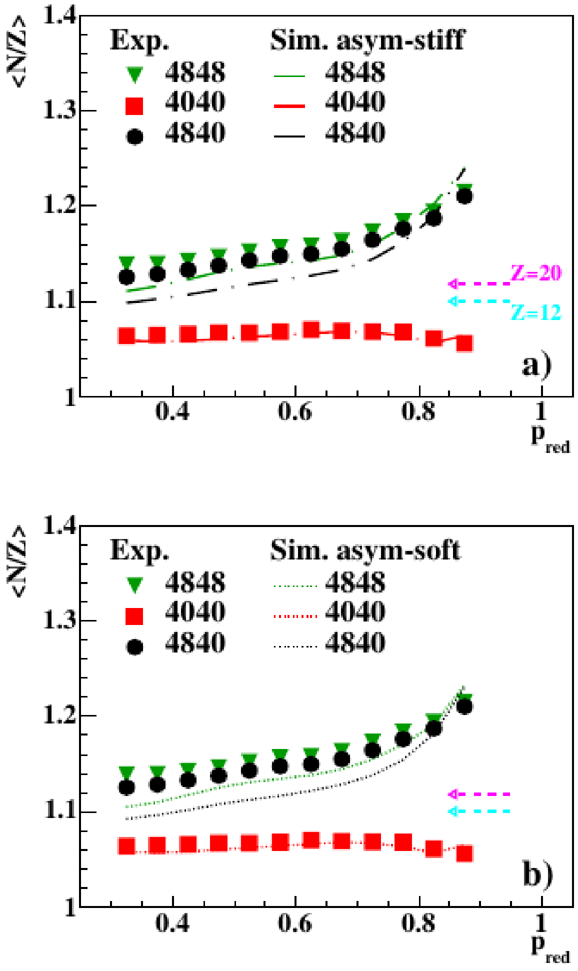
FAZIA-SYM: n-p equilibration

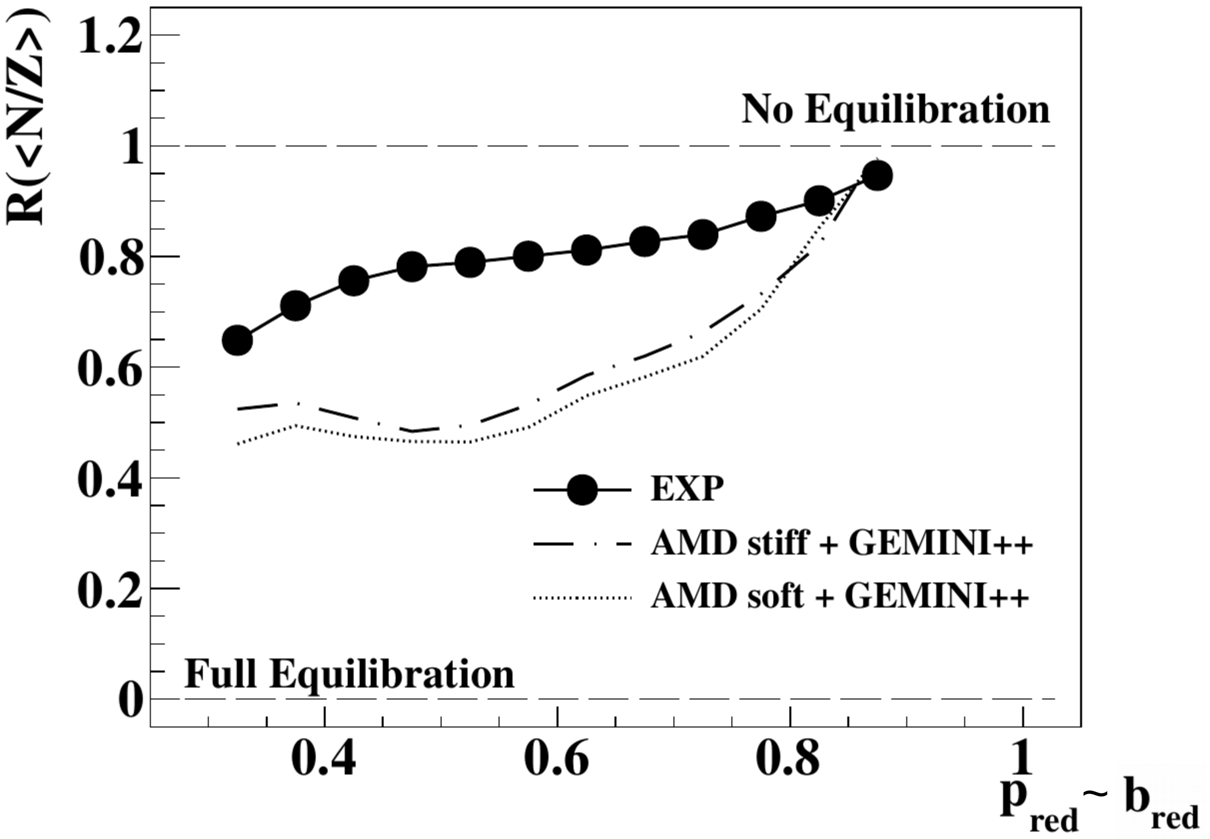
^{40,48}Ca + ^{40,48}Ca @ 35 MeV/u

$$p_{red} = \left(\frac{p^{QP}_{par}}{p^{beam}} \right)_{cm}$$



$$R = \frac{2X^{4840} - X^{4848} - X^{4040}}{X^{4848} - X^{4040}} \qquad X = \langle N/Z \rangle$$





Faster equilibration predicted by AMD+GEMINI:

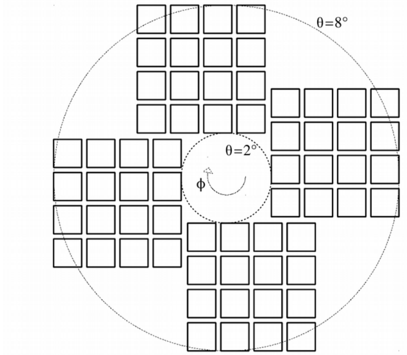
not ascribable to distortions introduced by statistical/non-statistical emission from the hot QP *A. Camaiani et al, PRC. Rev. C 102, 044607 (2020).*

A. Camaiani et al, PRC 103, 014605 (2021)

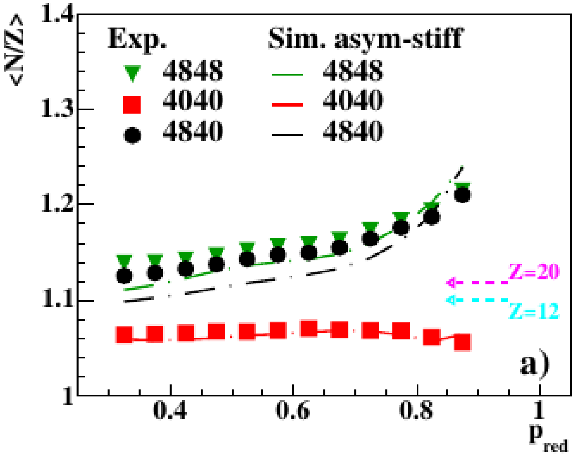
FAZIA-SYM: n-p equilibration

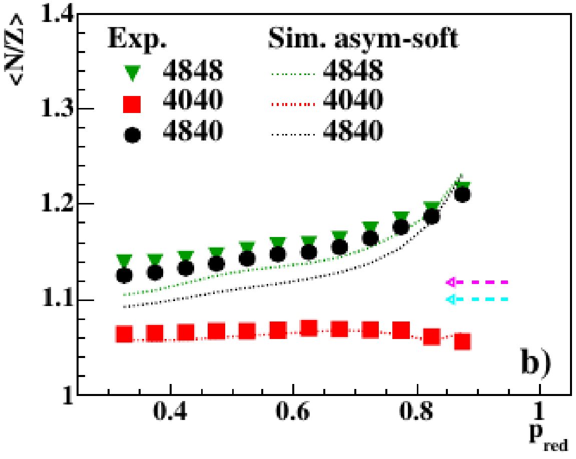
^{40,48}Ca + ^{40,48}Ca @ 35 MeV/u

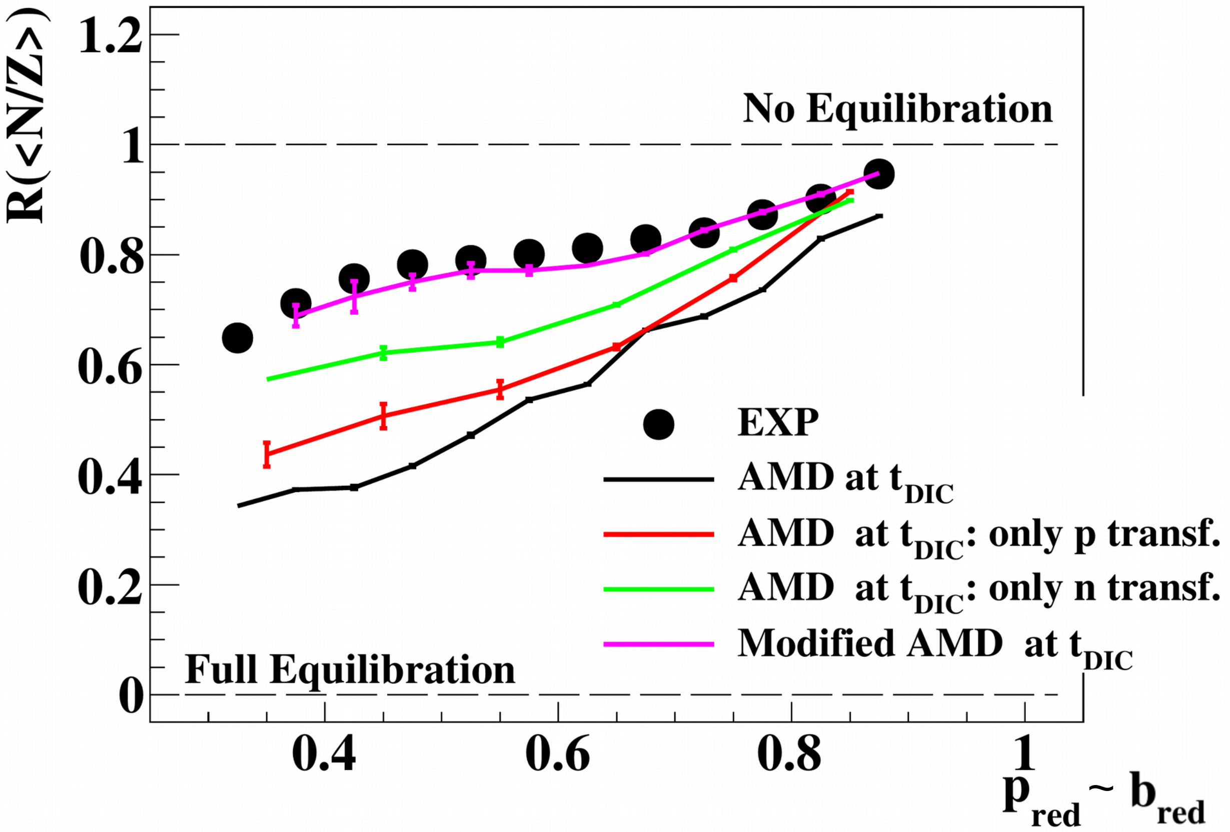
$$p_{red} = \left(\frac{p^{QP}_{par}}{p^{beam}} \right)_{cm}$$



$$R = \frac{2X^{4840} - X^{4848} - X^{4040}}{X^{4848} - X^{4040}} \qquad X = \langle N/Z \rangle$$





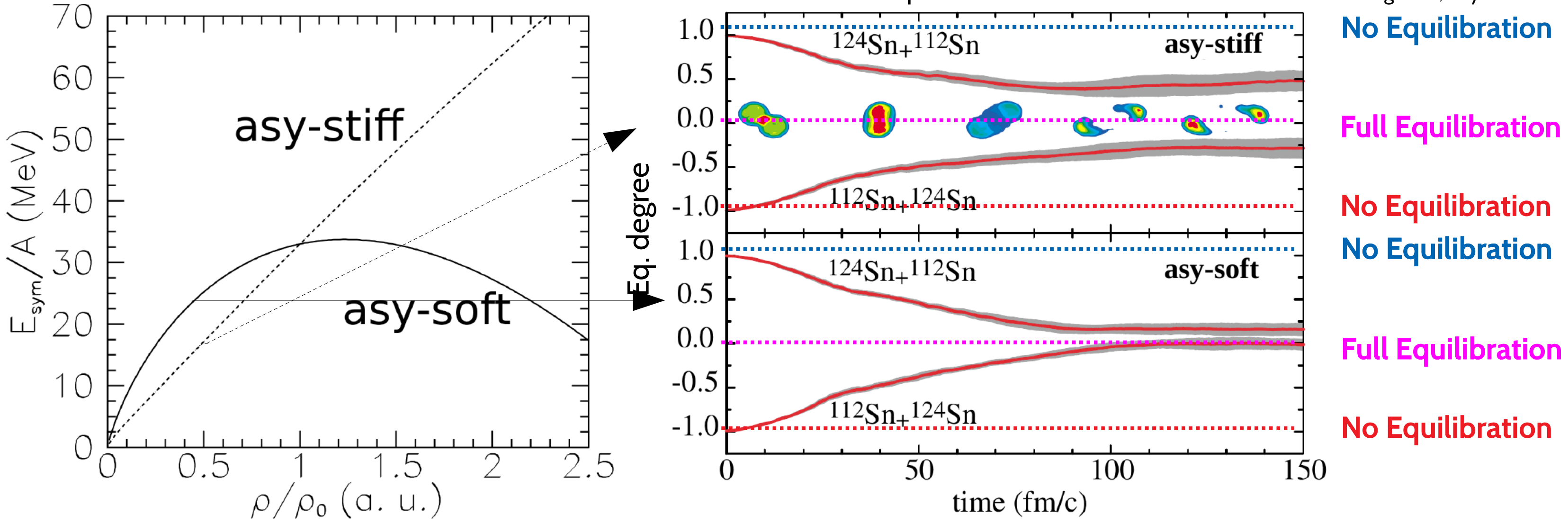


Descrepancy recovered reducing the transfer probability of about a factor 2 (most likely proton transfers) in AMD.

nEoS and isospin diffusion

Transport model calculation

M. B. Tsang et al., Phys. Rev. Lett. 92, 062701 (2004)



Different nEoS recipes lead to different equilibration degree

Isospin transport ratio

F. Rami et al., Phys. Rev. Lett. 84, 1120 (2000)

$$R(X) = \frac{2X^{Mix} - X^{NR} - X^{ND}}{X^{NR} - X^{ND}}$$

X Isospin sensitive observable

R=1 No Equilibration

R=0 Full Equilibration

R=-1 No Equilibration

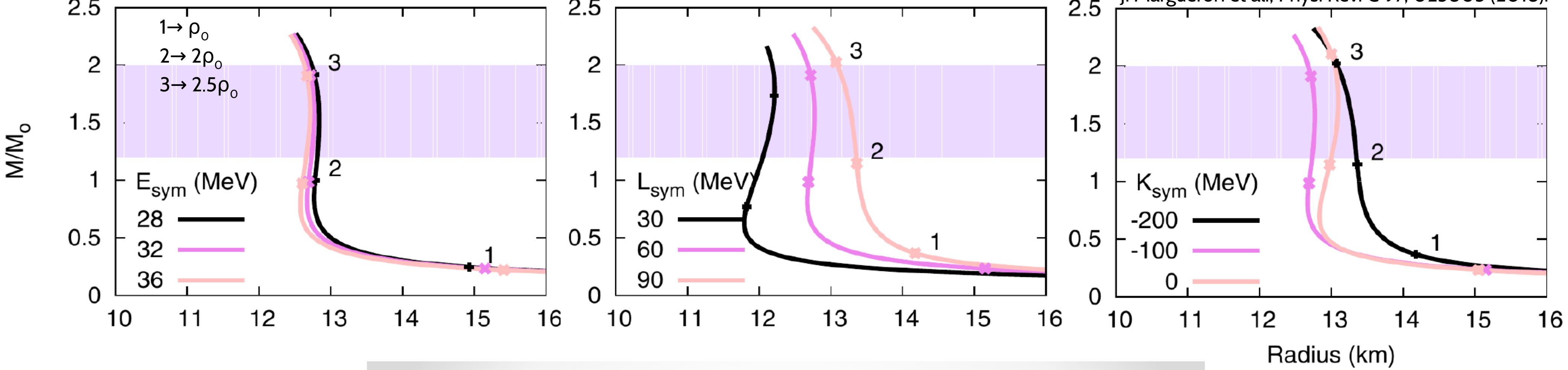
NR – Neutron rich reaction
ND – Neutron deficient reaction → References

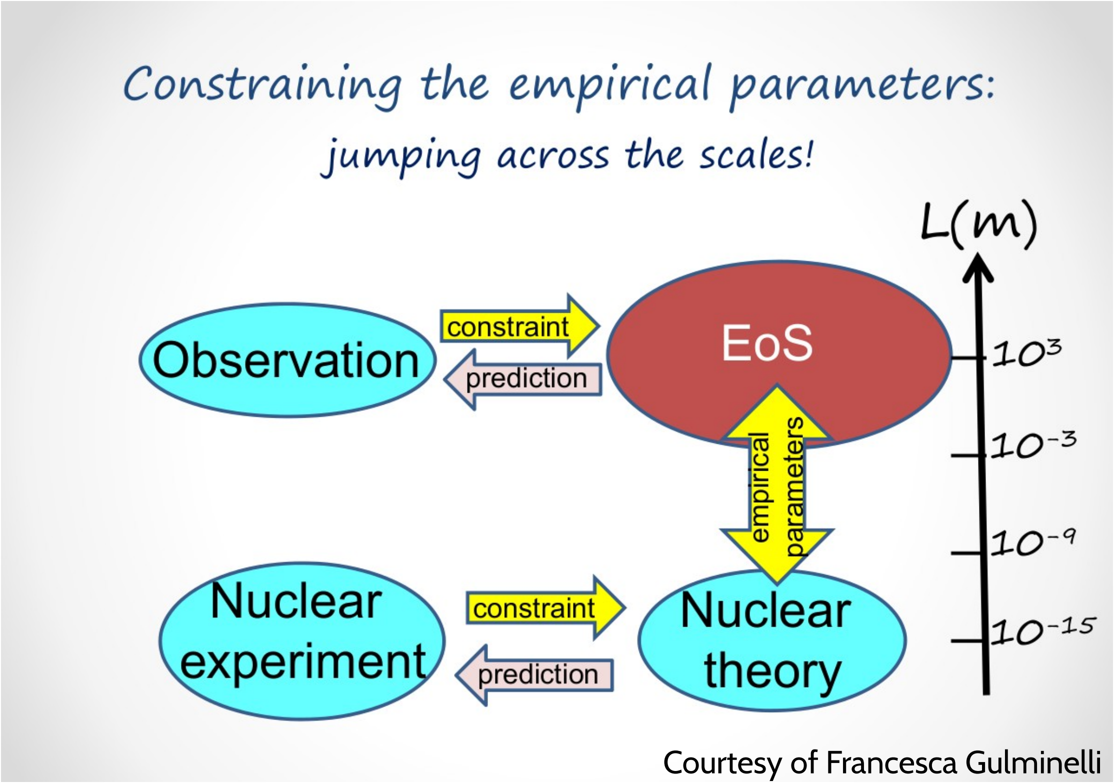
Mix – Mixed system → Isospin diffusion

Neutron stars and nEoS

From the astrophysical scale, NS properties are linked with the nEoS

J. Margueron et al., Phys. Rev. C 97, 025805 (2018).





Courtesy of Francesca Gulminelli

D. Gruyer, Talk at Colloques GANIL

Scientific goal of the FAZIASYM experiment

Isospin diffusion

1. In a binary channel
2. In the QP break up channel

Goals

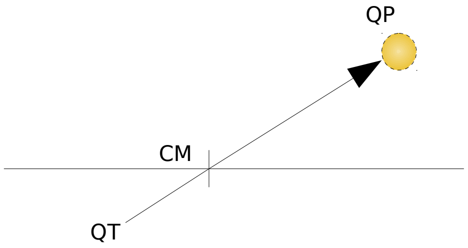
a. Equilibration degree from the direct detection of the N/Z of the QP

b. Comparison with the INDRA+VAMOS campaign

c. Attempt to extract information on the nuclear Equation of State

d. Comparison between both channels

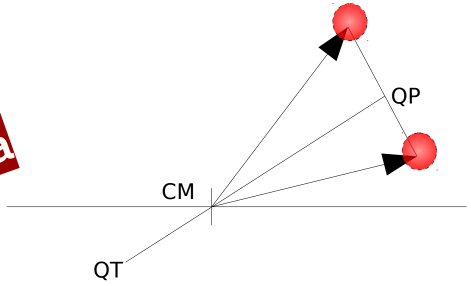
Binary Channel



QP decays trough the emission of IMF and/or LCP

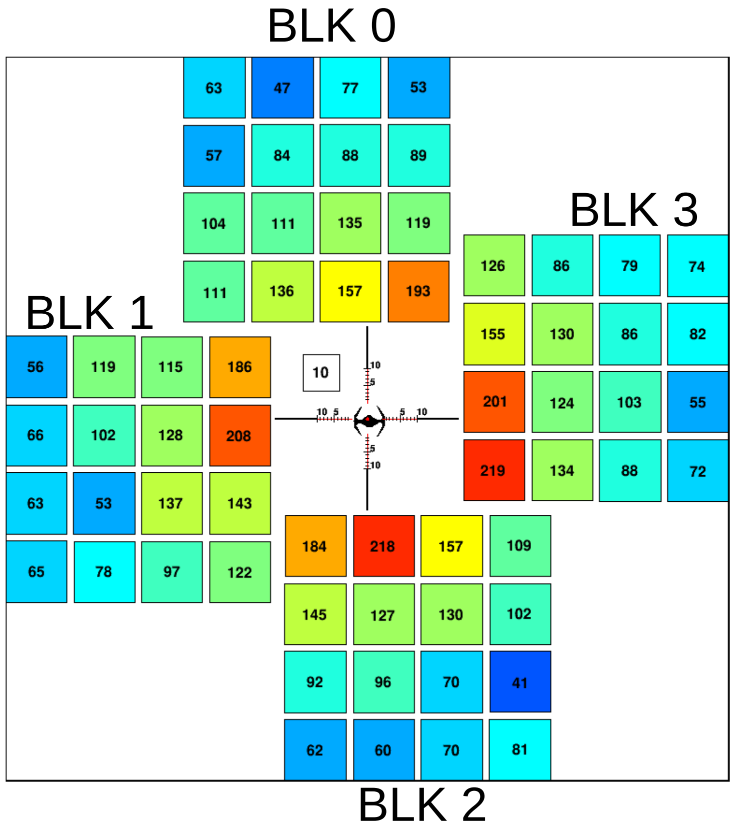
Spectroscopic resolution in Ca+Ca collisions

Break up channel



QP splits in two fragments

The FAZIASYM experiment



At the INFN Laboratori Nazionali del Sud:

- **^{40}Ca+^{40}Ca**
- **^{48}Ca+^{40}Ca**
- **^{48}Ca+^{48}Ca**

@ 35 MeV/u

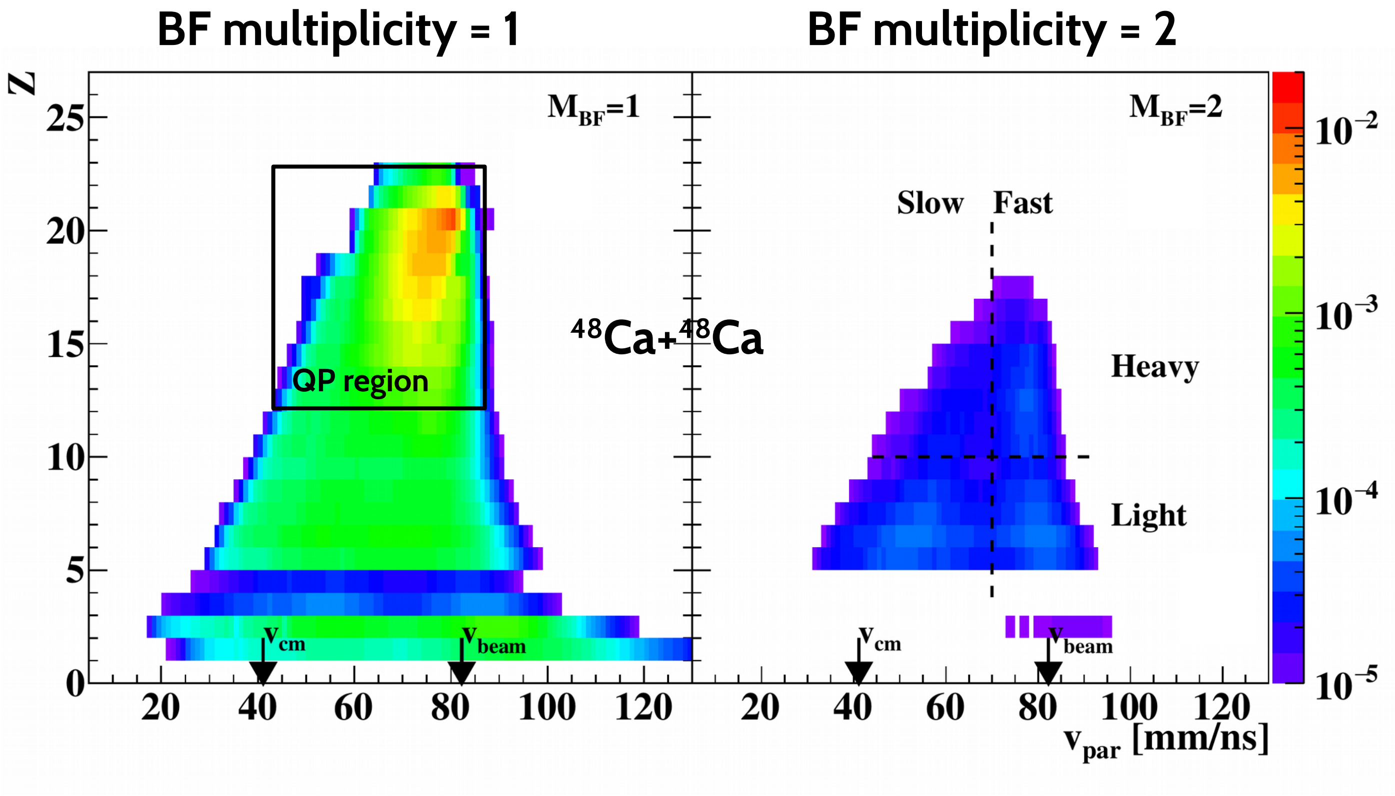
ISOSPIN DIFFUSION: ^{48}Ca+^{40}Ca

References: ^{48}Ca+^{48}Ca & ^{40}Ca+^{40}Ca

Geometry: wall configuration with 4 blocks

$\theta^{min} = 2^{\circ}$, $\theta^{max} = 8^{\circ}$ in lab. frame

Event selection



BF multiplicity = 1

BF multiplicity = 2

Vocabulary:

- LCP → Z=1 & Z=2
- IMF → Z= 3 & Z=4
- Big Fragment (BF) → Z≥5

We define QP remnant a BF with :

- $12 \leq Z^{QP} \leq 22$
- $v_{par} > v_{cm}$

We define a reconstructed QP :

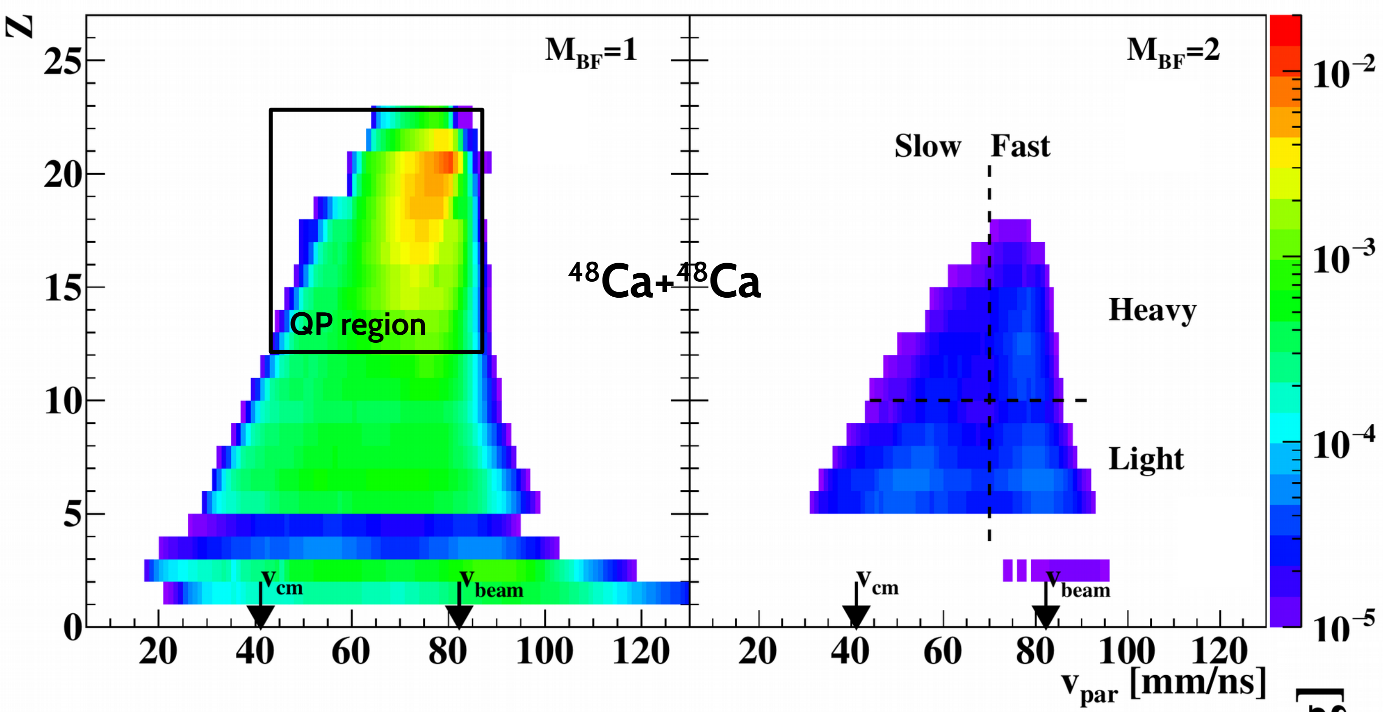
- $12 \leq Z^{rec} = Z^H + Z^L \leq 22$
- $v^H_{par} > v_{cm}$ & $v^L_{par} > v_{cm}$

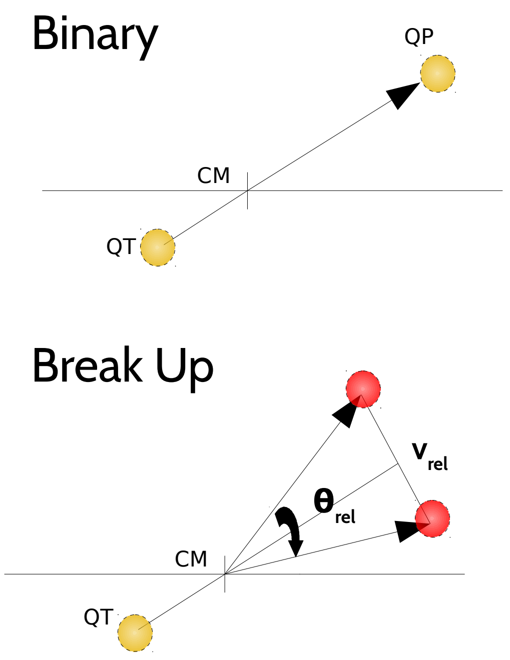
QP Remnant channel (QP$_R$)

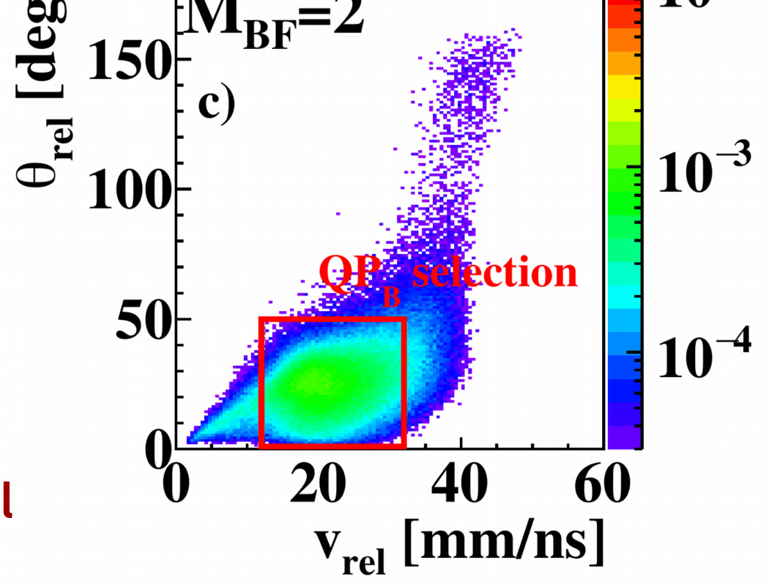
QP break up channel (QP$_B$)

Event selection

BF multiplicity = 1 **BF multiplicity = 2**







We define QP remnant a BF with :

- $12 \leq Z^{QP} \leq 22$
- $v_{par} > v_{cm}$

QP Remnant channel (QP_R)

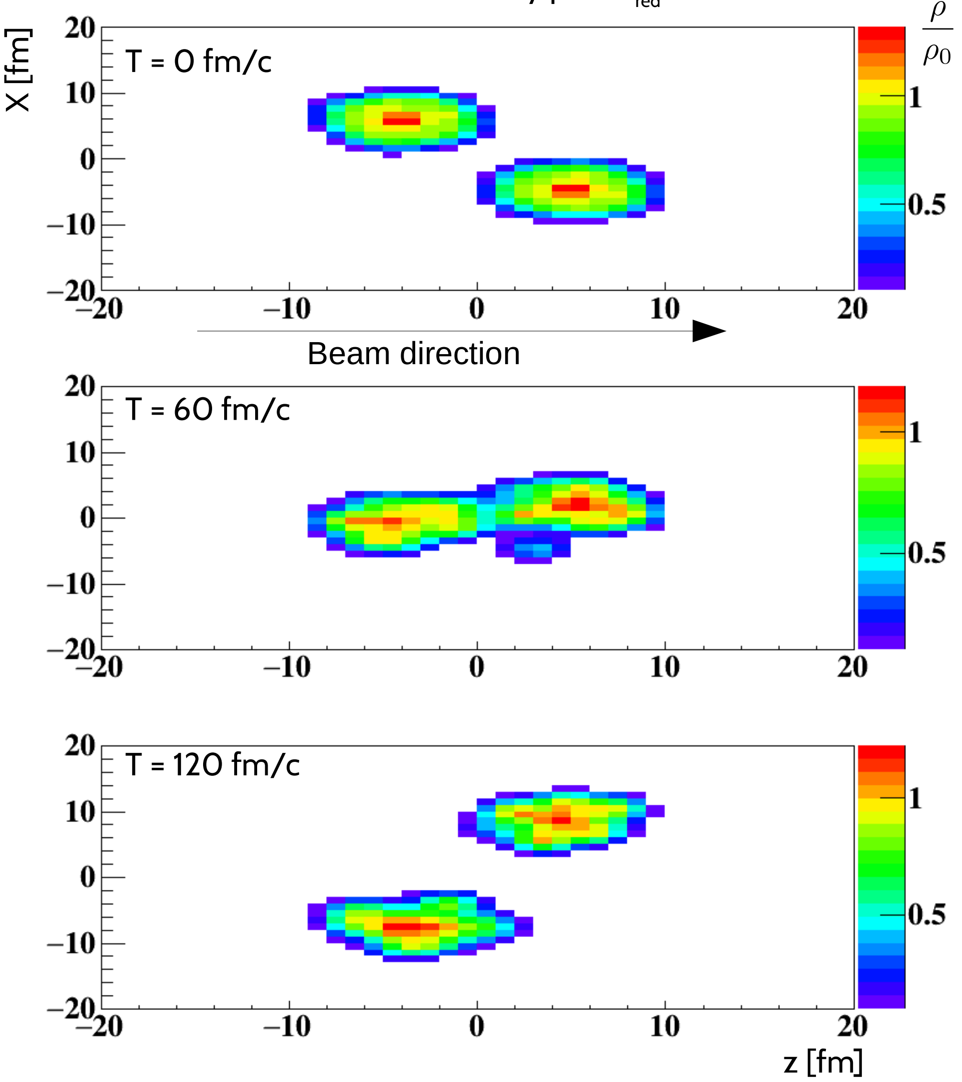
We define a reconstructed QP :

- $12 \leq Z^{rec} = Z^H + Z^L \leq 22$
- $v^H_{par} > v_{cm}$ & $v^L_{par} > v_{cm}$
- $12 < v_{rel} < 32$ mm/ns
- $\theta_{rel} < 50\,^{o}$

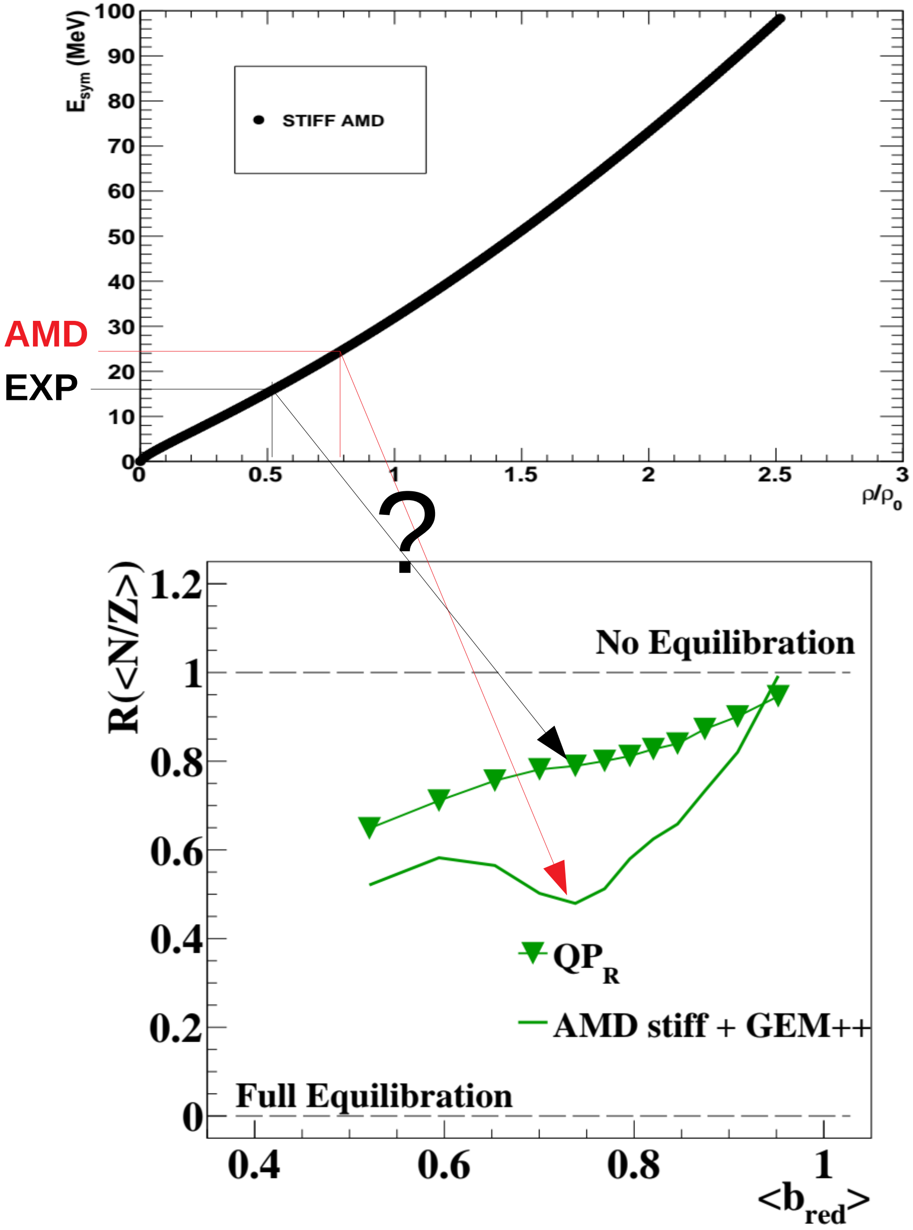
QP break up channel (QP_B)

Density evolution of the system

Normalized density plot: b_{red} ~ 0.7



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



If in the simulation
the system passes through higher density regions than in the reality, this will produce a stronger equilibration

^{12}C backing contamination

^{48}Ca beam

Main target → $N_{TOT} = N_{Ca} + N_C$

^{12}C ^{48}Ca ^{12}C

$10–500–10\,\mu g/cm^2$

Test target → $N_{C'}$

^{12}C

$300\,\mu g/cm^2$

$$N_{TOT} = N_a Q \left(\sigma_{Ca} \frac{T_{Ca}}{M_{Ca}} + \sigma_C \frac{T_C}{M_C} \right)$$

$$\frac{N_{C'}}{N_C} = \frac{Q_{C'} T_{C'}}{Q T_C}$$

$$\boxed{\frac{N_C}{N_{TOT}} = \frac{1}{1 + \frac{\sigma_{Ca} T_{Ca} M_C}{\sigma_C T_C M_{Ca}}}}$$

Contamination percentage:

QP_R → 7%

QP_B → <1%

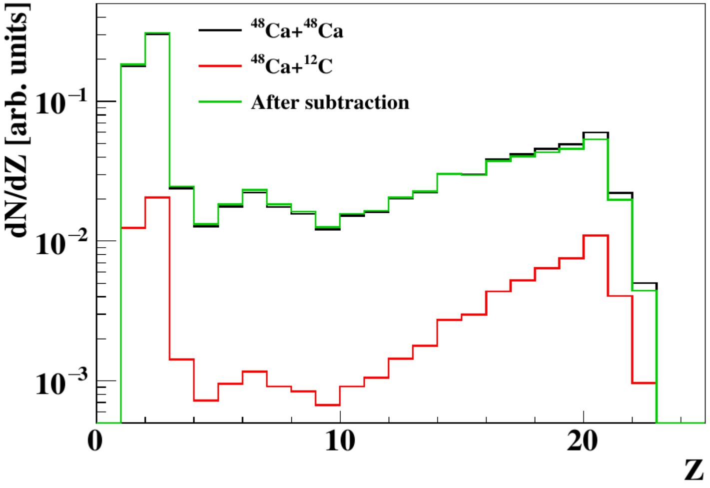


Figure A.2: *Charge distribution for the ^{48}Ca+^{48}Ca and ^{48}Ca+^{12}C reactions. ^{48}Ca+^{12}C distribution has been scaled according to the ^{12}C percentage in the ^{48}Ca target. Green line represents the distribution after the subtraction.*

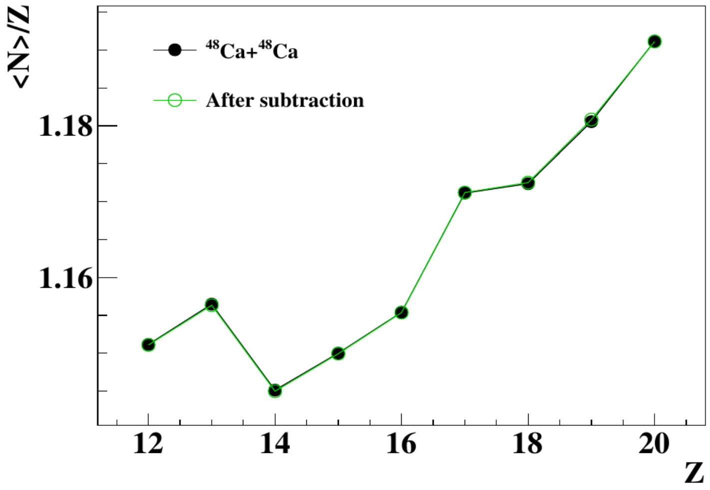


Figure A.3: *Average neutron number per charge unit as a function of the charge of the QP remnants. Black dots for the ^{48}Ca+^{48}Ca, green lines after the subtraction of the ^{48}Ca+^{12}C background.*

Beam halo background

$^{48}\mathrm{Ca}$ Beam + Halo

Beam on target $^{48}\mathrm{Ca}$ $Q = It$

Halo on target frame Al $Q' = I't$

$$N_{TOT} = N_a \left(Q\sigma_{Ca}\frac{T_{Ca}}{M_{Ca}} + Q'\sigma_{Al}\frac{T_{Al}}{M_{Al}} \right)$$

Since I' is not know,
any subtraction procedure is excluded

Comparing data with beam on target frame,
VAMOS data and beam on 48Ca target,
we can conclude that scattering on Al target frame
does not bias the data

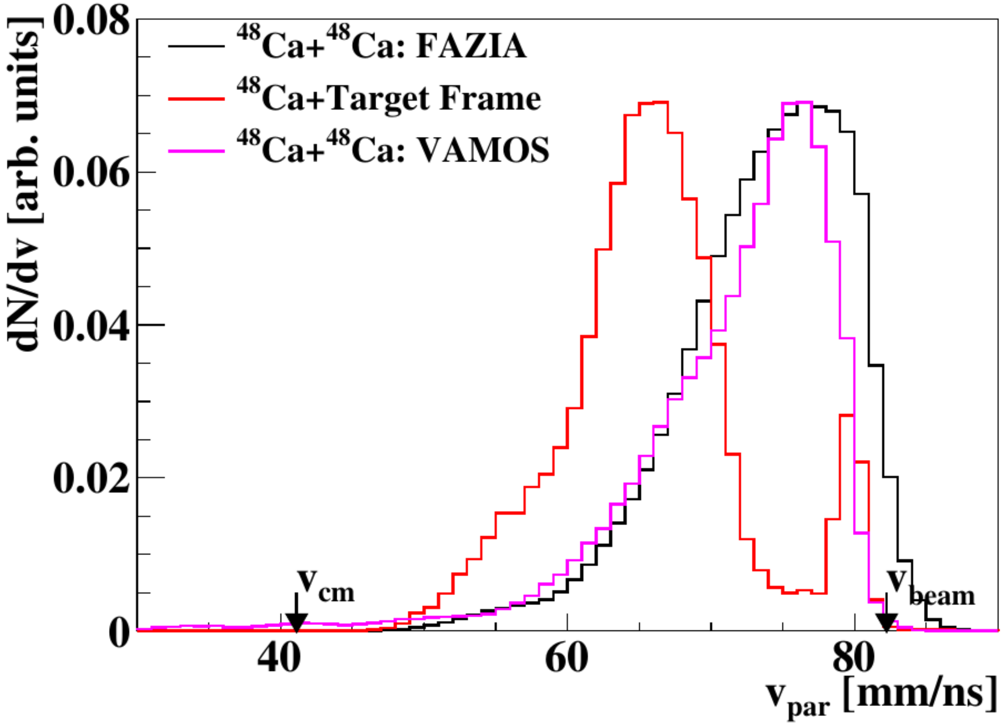


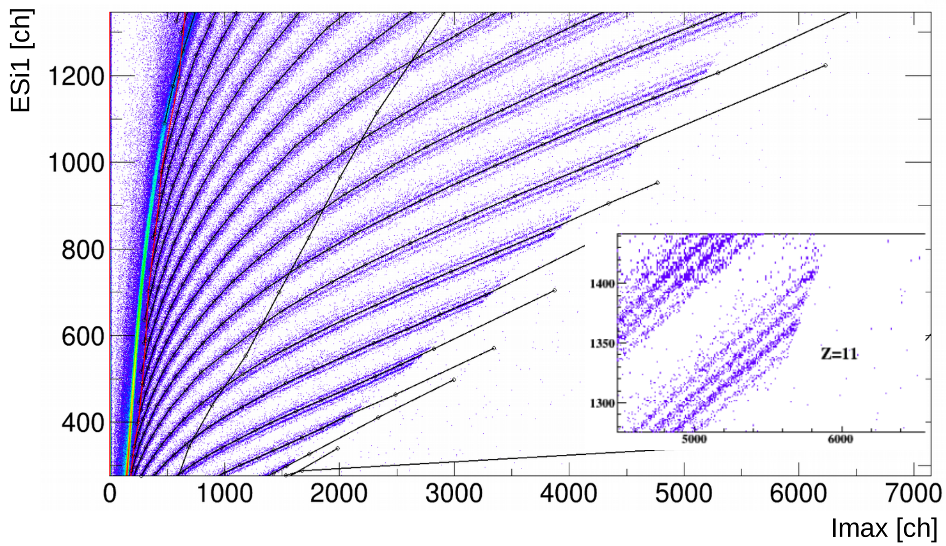
Figure A.5: *Parallel velocity distribution for $Z \geq 10$. Colors according to the legend: in particular magenta line represents the results obtained by the INDRA+VAMOS experiment for the $^{48}Ca+^{48}Ca$ system. All the distributions are normalized to the maximum of the black distribution.*

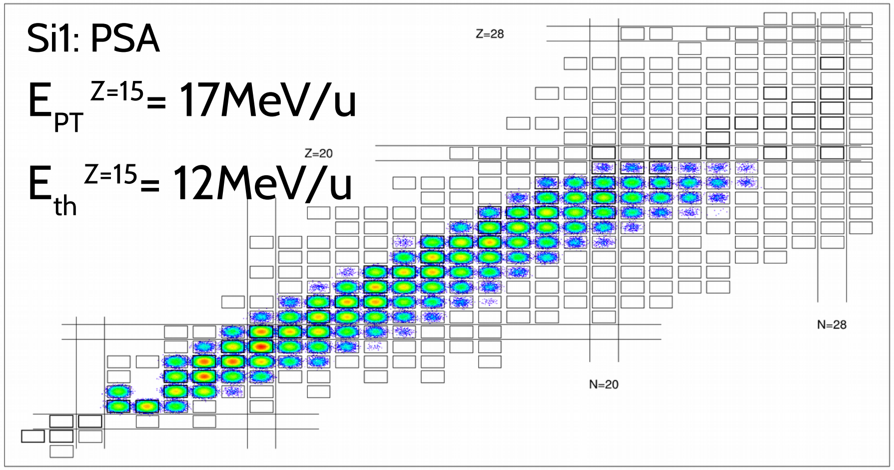
FAZIASYM: Identification methods

Si1
300um

Si2
500 um

CsI
10 cm





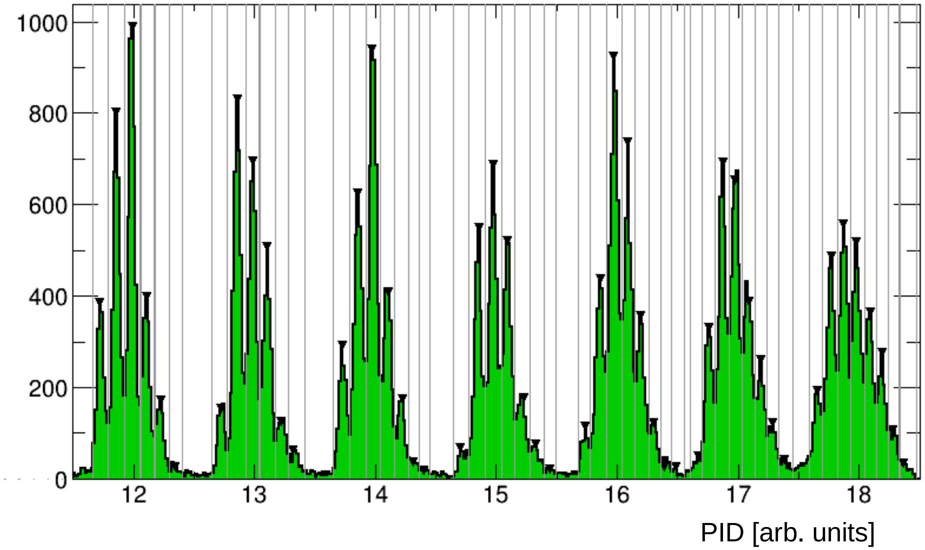
Si1: PSA

$E_{PT}^{Z=15}$= 17MeV/u

$E_{th}^{Z=15}$= 12MeV/u

PSA in Si1

- For fragments stopped in Si1
- It exploits information extracted directly from the signal shape
- Isotopic ID Z~20
- Defines the identification energy thresholds

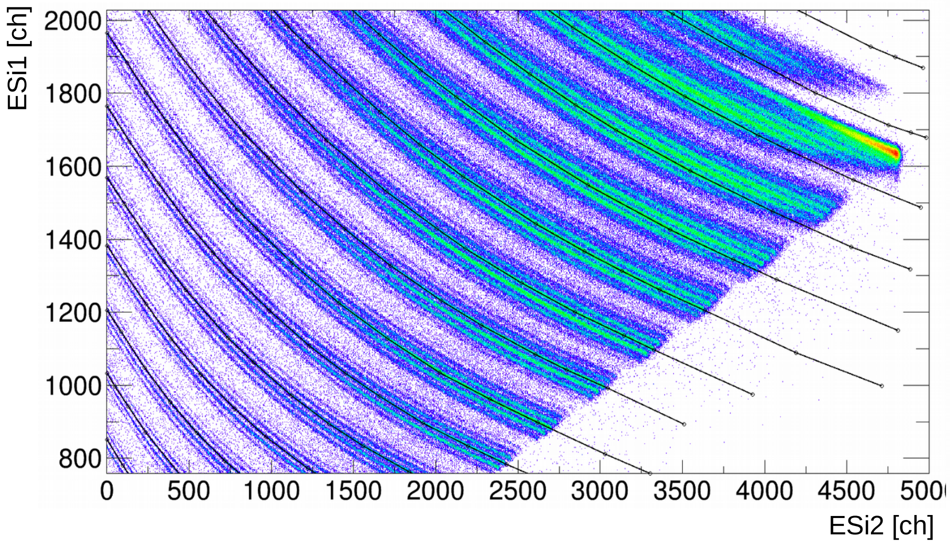


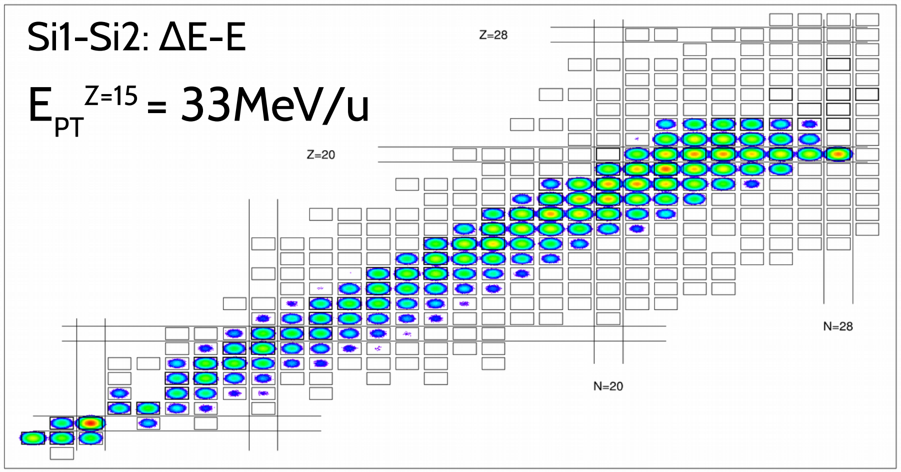
FAZIASYM: Identification methods

Si1
300um

Si2
500 um

CsI
10 cm

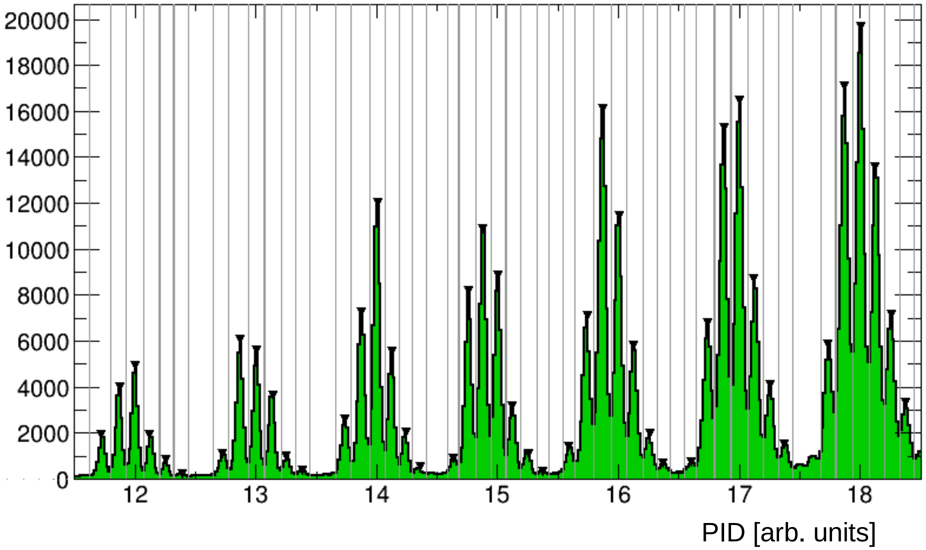



Si1-Si2: ΔE-E

$E_{PT}^{Z=15} = 33 MeV/u$

ΔE-E in Si1-Si2

- Correlation between energy loss in two consecutive layers
- Isotopic ID Z~25
- Main ID method at 35 MeV/u

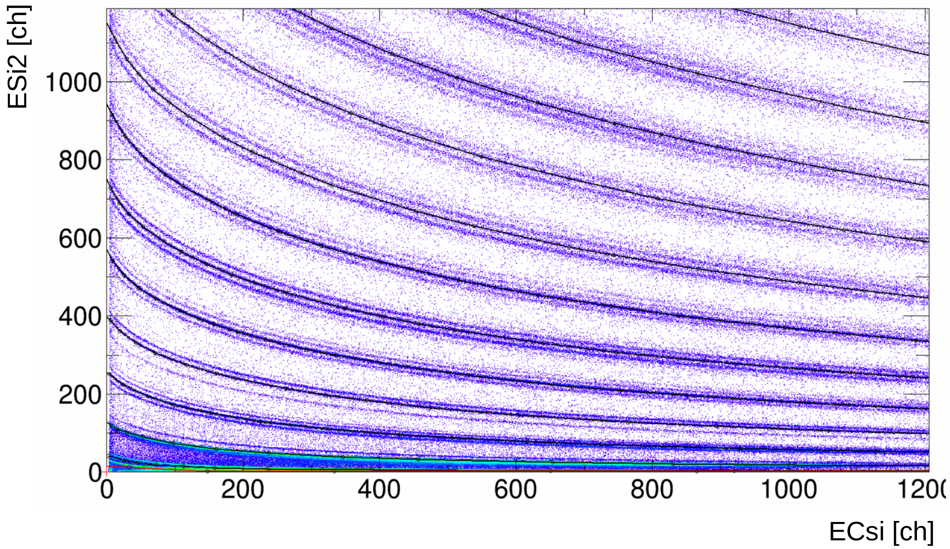


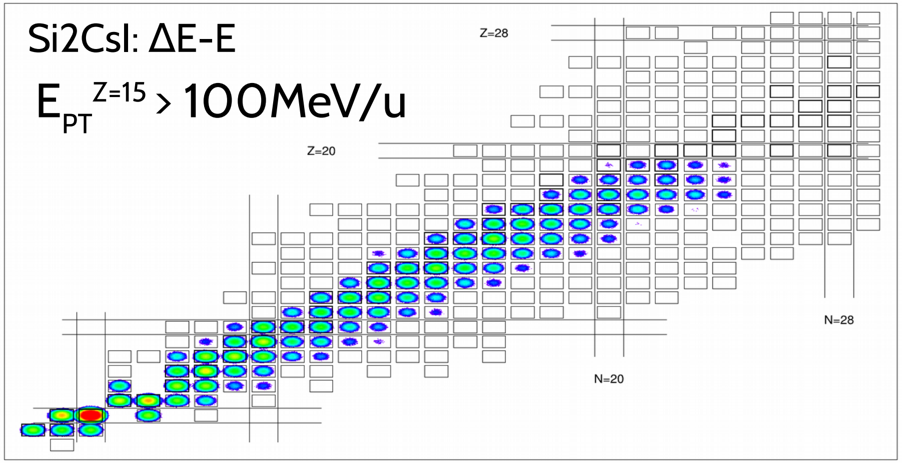
FAZIASYM: Identification methods


Si1
300um

Si2
500 um

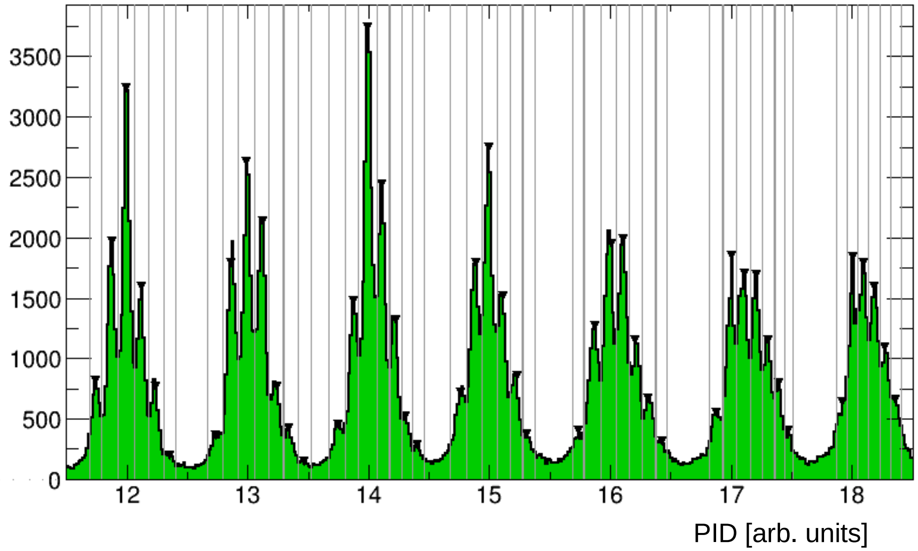
CsI
10 cm





ΔE-E in Si2-CsI

- Correlation between energy loss in two consecutive layers
- Isotopic ID comparable to Si1-Si2

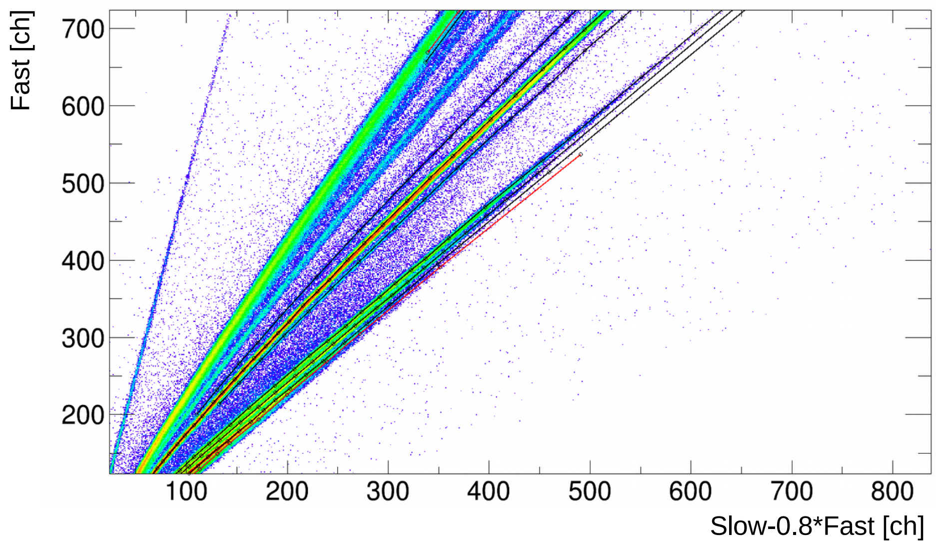


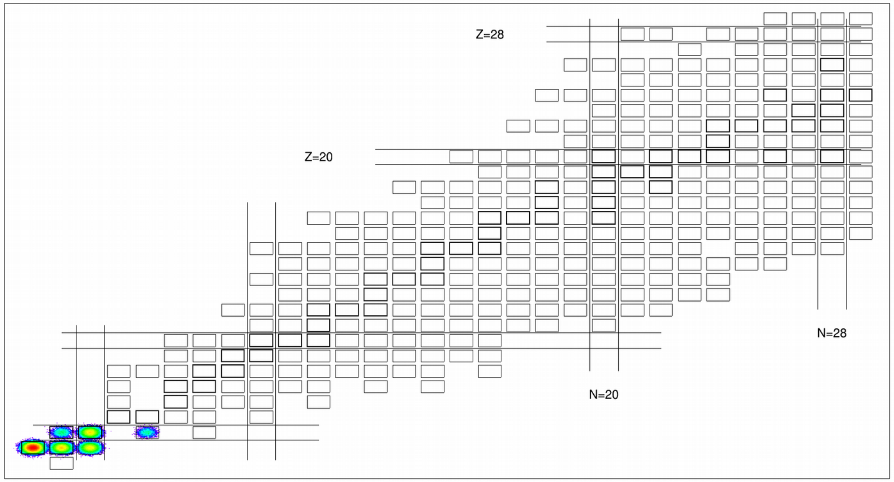
FAZIASYM: Identification methods

Si1
300um

Si2
500 um

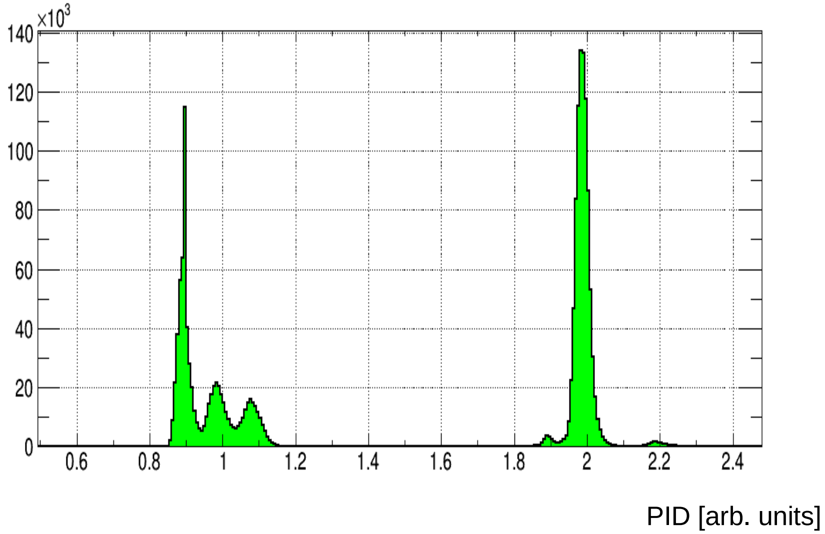
CsI
10 cm



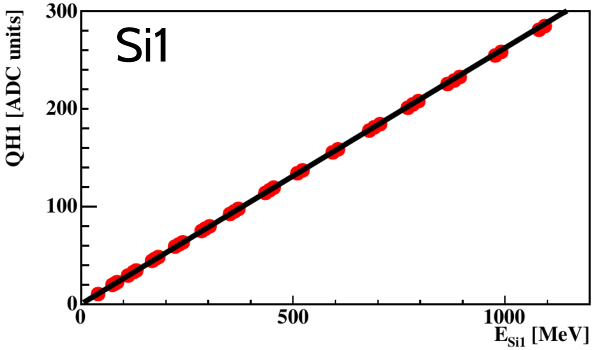


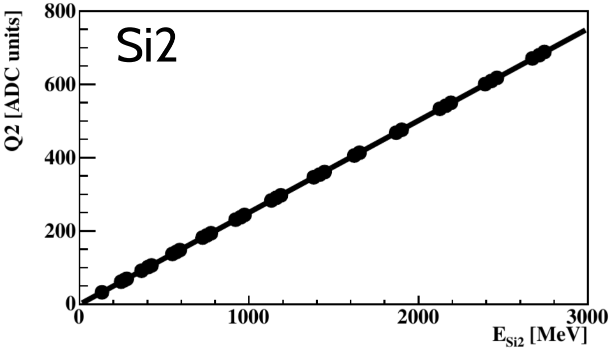
PSA in CsI

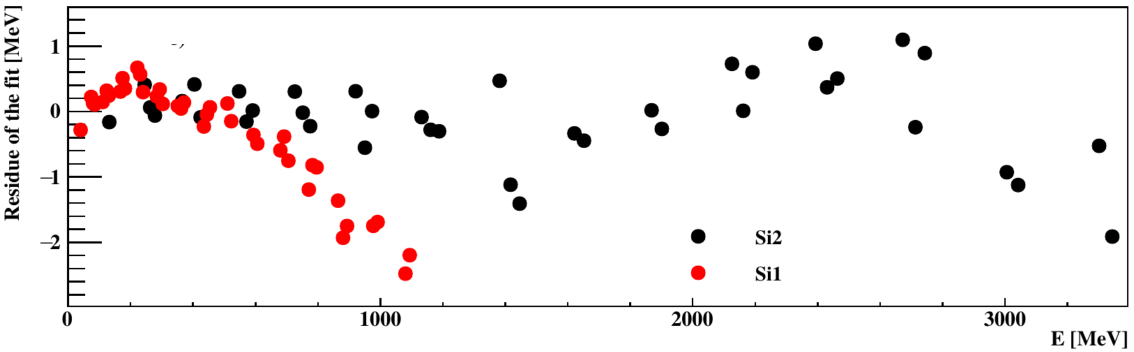
- It exploits information extracted directly from the signal shape
- Isotopic ID Z~5
- Mainly Z=1 and Z=2



FAZIASYM: Si1 Si2 energy calibrations

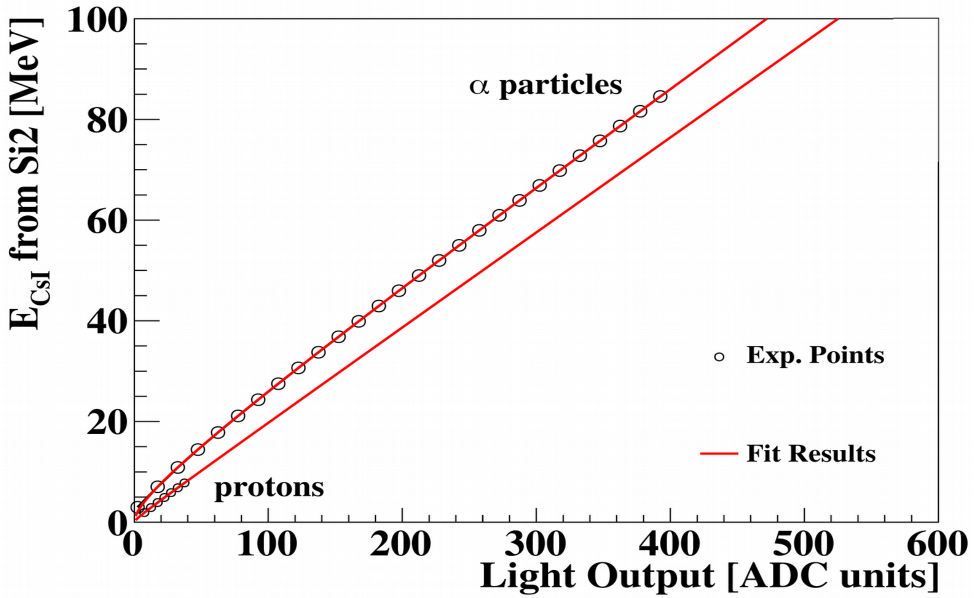


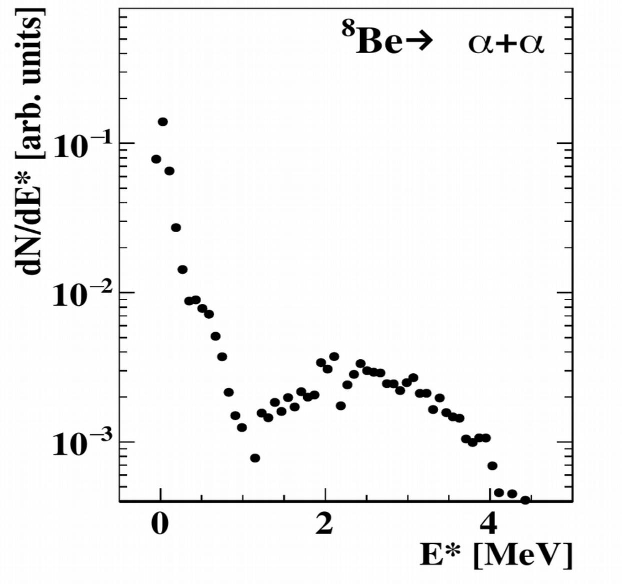




- Energy calibration from punch trought energy in Si1 and Si2
- VedaLoss as energy loss table http://indra.in2p3.fr/kaliveda/KVedaLossDoc/KVedaLoss.html. F. Hubert et al., Atomic Data and Nuclear Data Tables 46, 1 (1990)
- Uncertainty of the Si1 calibration of about 0.2% at E = 1125 MeV
- Uncertainty of the Si2 calibration of about 0.1% at E = 3200 MeV

FAZIASYM: CsI energy calibrations





$$L.O. = a_0\left\{E - AZ^2a_1\left[\ln\left(1+\frac{E}{AZ^2a_1}\right) - \frac{a_3\ln\left(\frac{E+AZ^2a_1}{AZ^2a_1+Aa_2}\right)}{1+e^{(a_3-E)/8A}} + \frac{a_3}{1+e^{(Aa_2-E)/8A}}\ln\left(\frac{AZ^2a_1}{AZ^2a_1+Aa_2}\right)\right]\right\}$$

- Light output parametrization from M. Pârlog et al. Nucl Instr and Method A 482, 675 (2002)
- Calibration only for Z=1, and Z=2 (energy of Z>2 fragments deduced from Si2 energy loss)
- Excitation energy of unbound states as cross check:
- Uncertainty of the CsI calibration below 5%