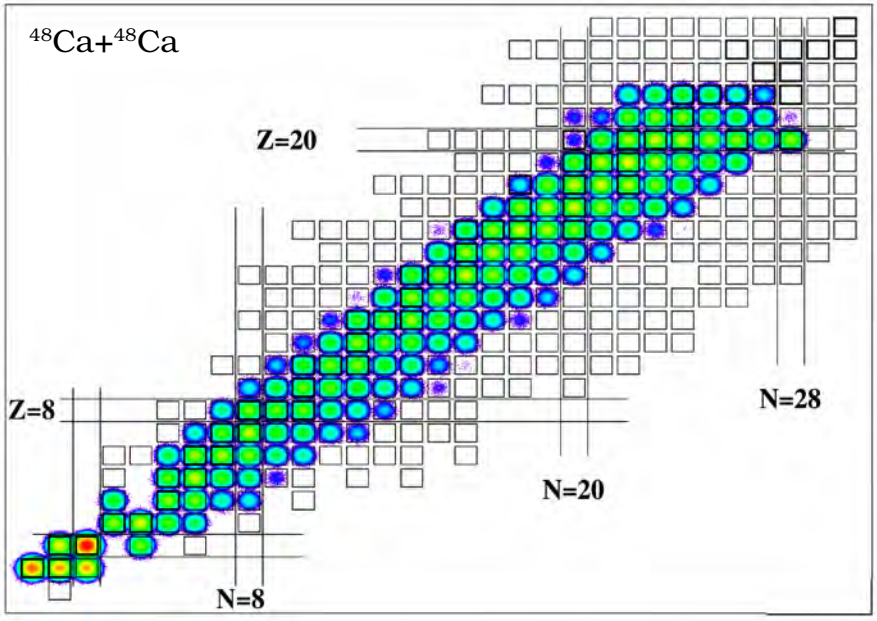
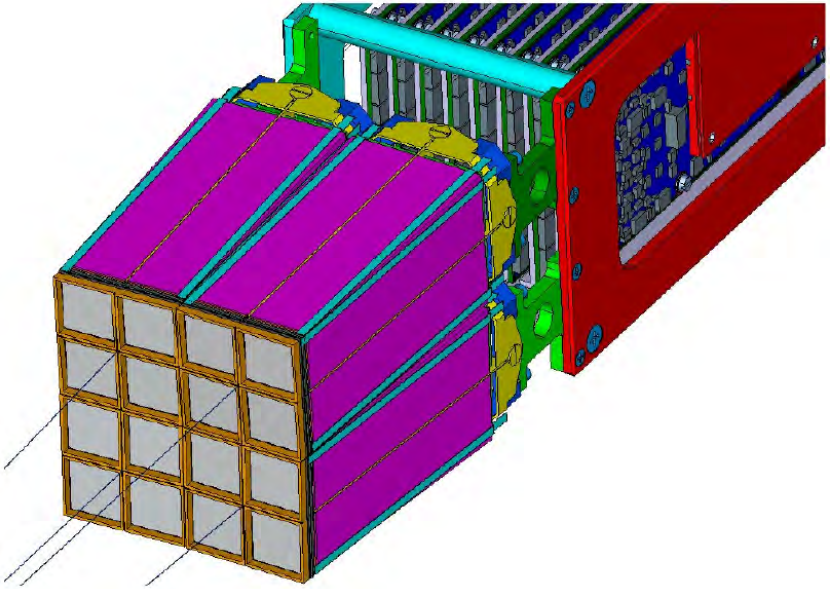
Exploring heavy-ion collisions with the FAZIA multi-telescope array





A. Camaiani

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 – Reaction mechanism and particle correlations in ligh-ion reactions at Fermi energies

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 sou
  - Statistical evaporation
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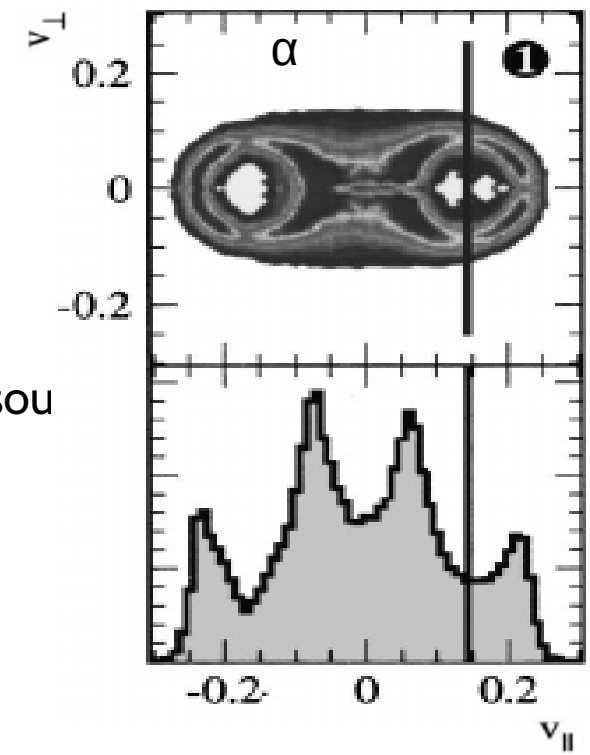
EXP:Xe + Sn @ 50 MeV/u



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

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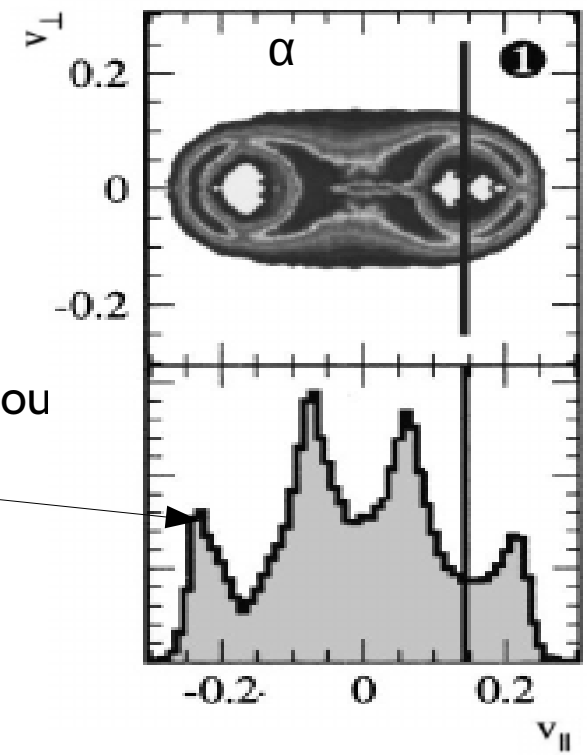

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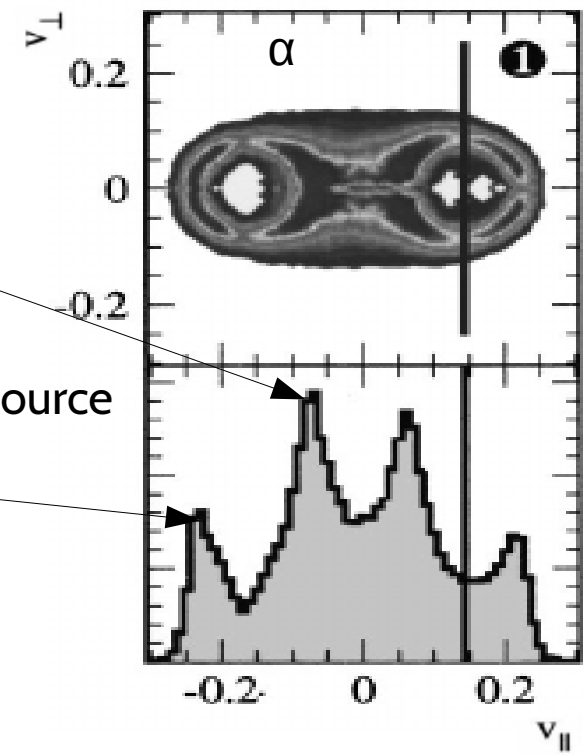

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Isospin dynamics

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

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

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

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

→ Symmetric matter

→ Asymmetric matter

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

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

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

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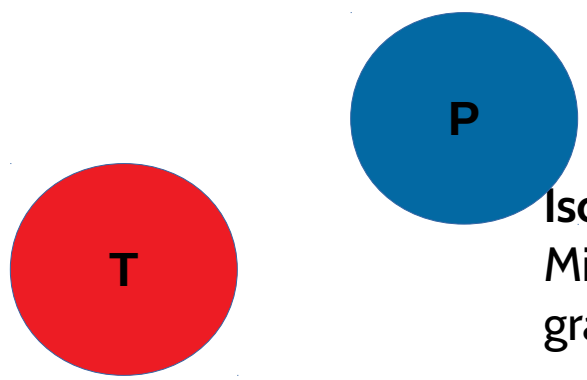

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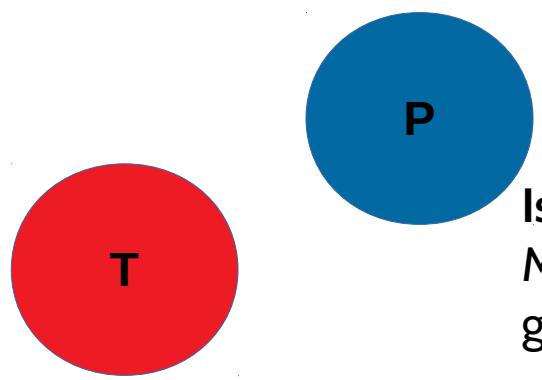

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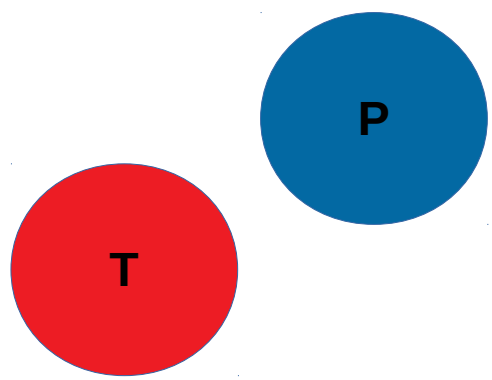

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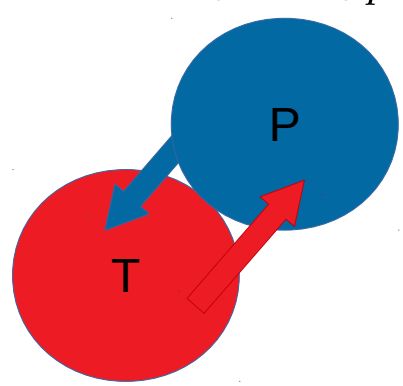

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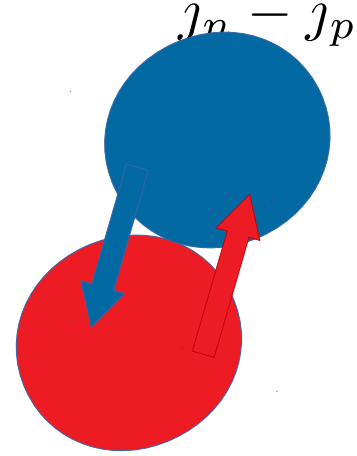

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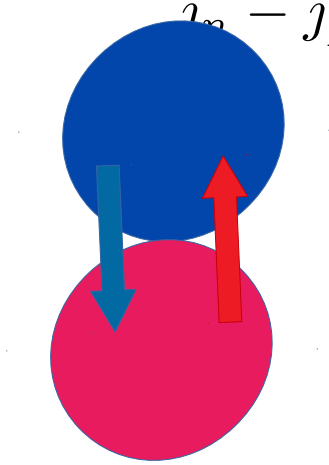

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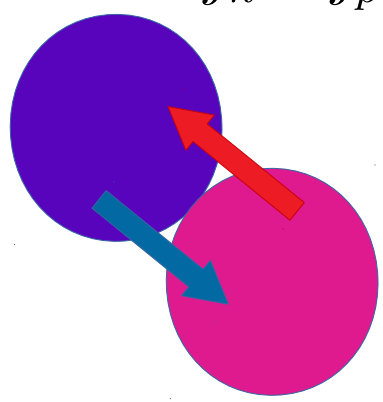

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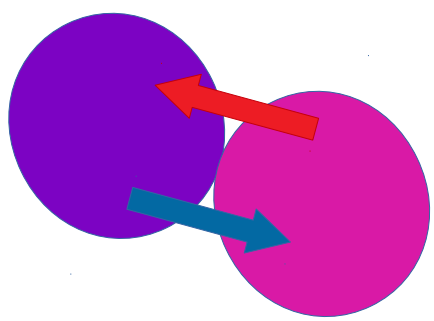

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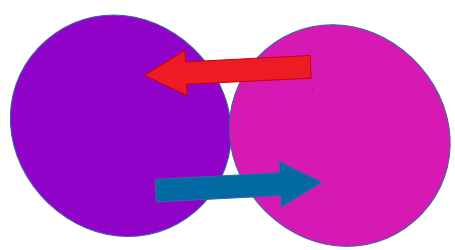

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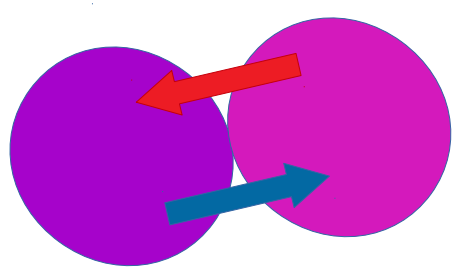

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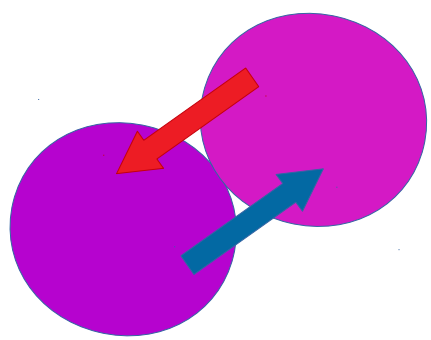

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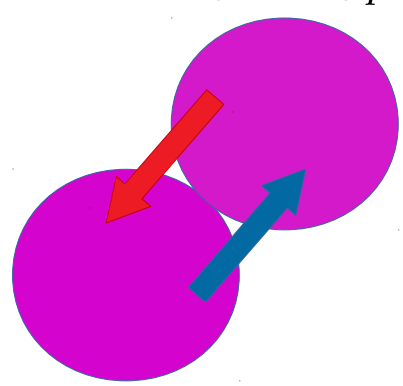

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$\frac{E}{A}(\rho)$ → Symmetric matter

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

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

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

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

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

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

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

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

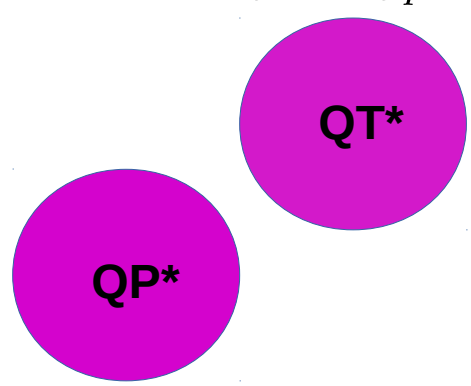
Neutron rich projectile

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 rules the isospin dynamic in heavy ion collision

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

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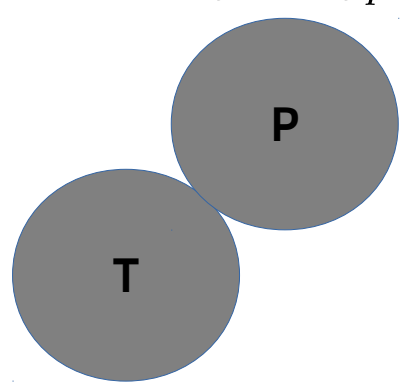
Region at saturation density: P, T



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

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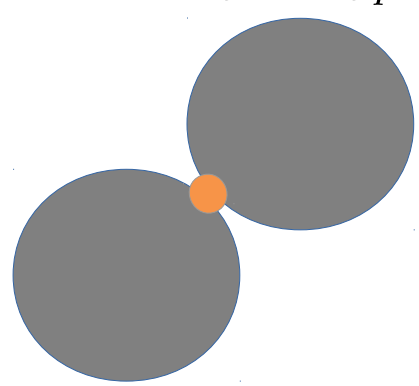
Region at saturation density: QP, QT

Region at sub-saturation: Neck?



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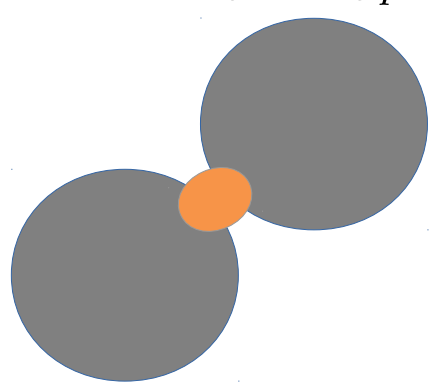

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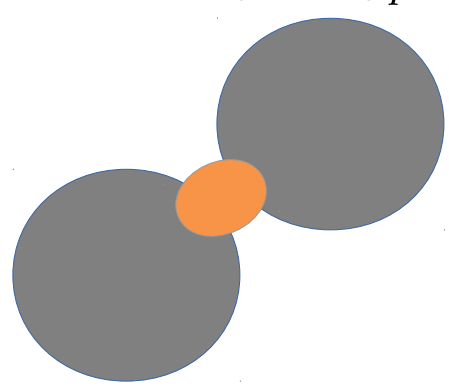

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Region at saturation density: QP, QT

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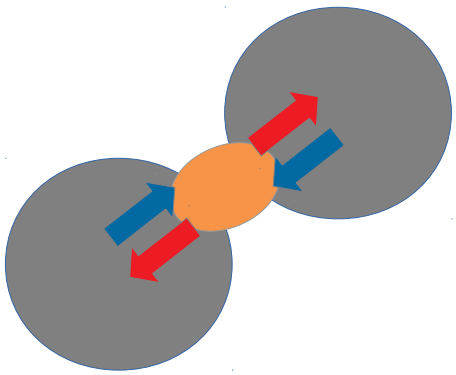
Net flux of n towards the neck



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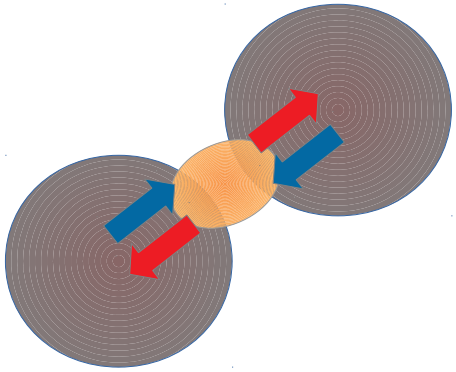

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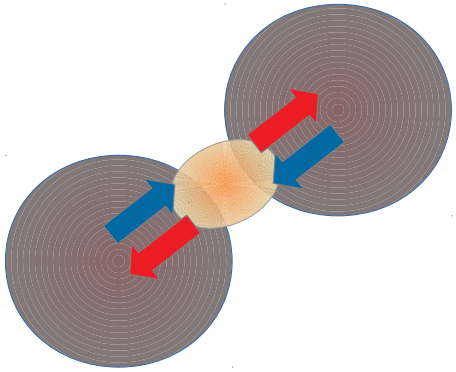

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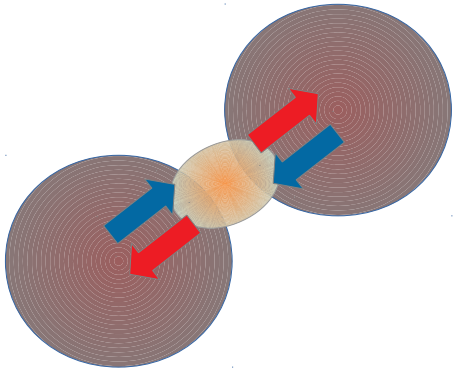

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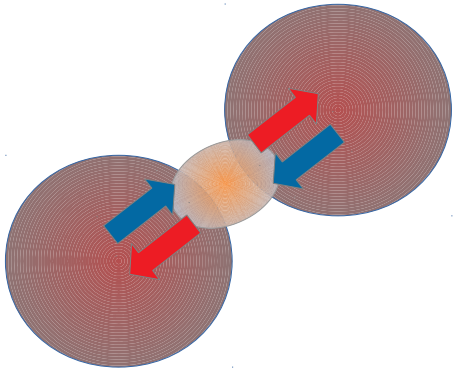

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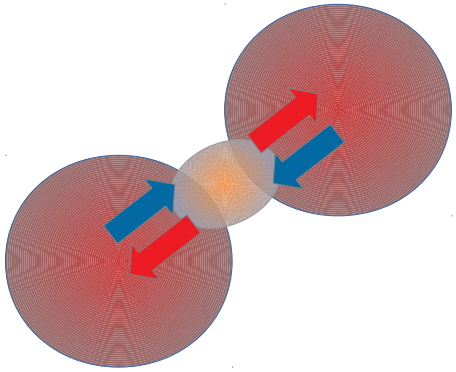

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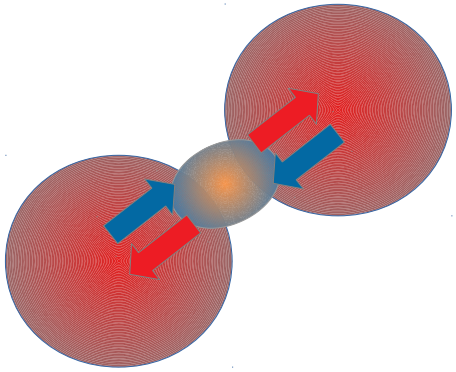

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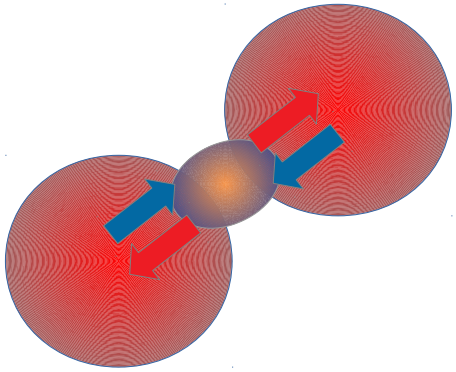

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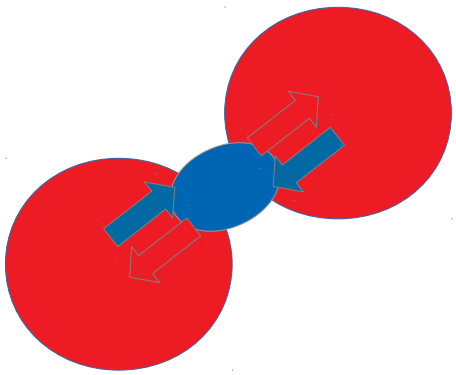

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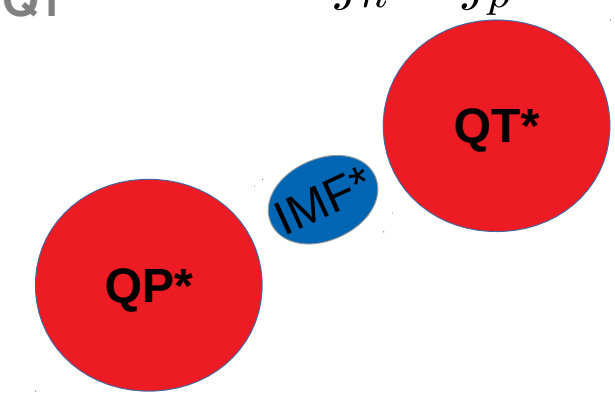

Excited n-deficient QP and QT

Excited n-rich fragment at mid-velocity

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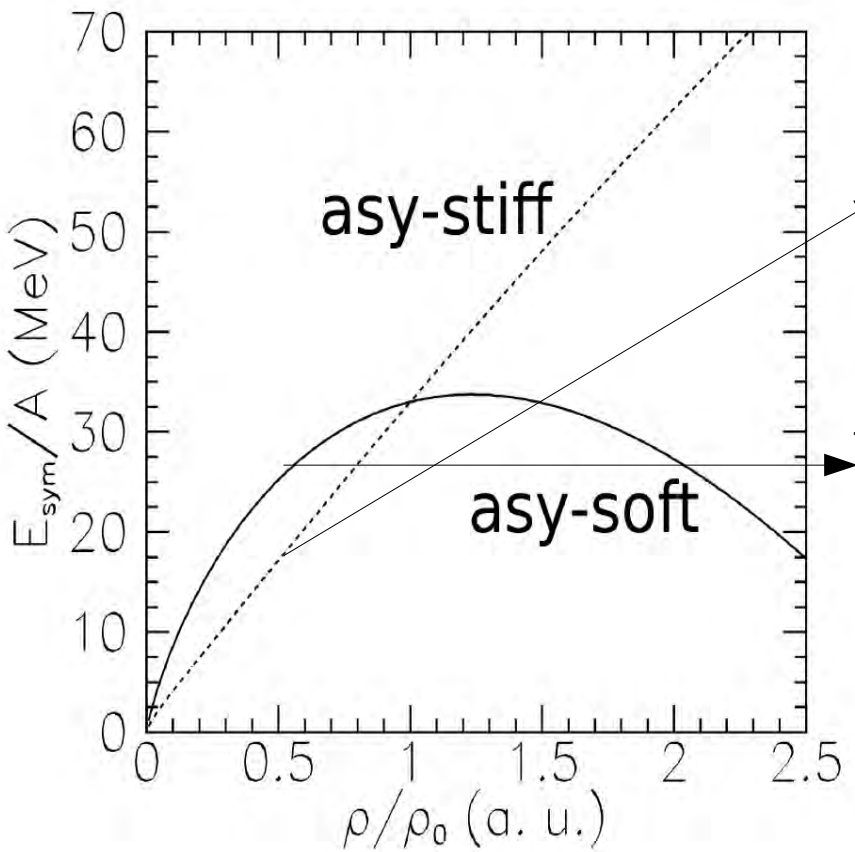
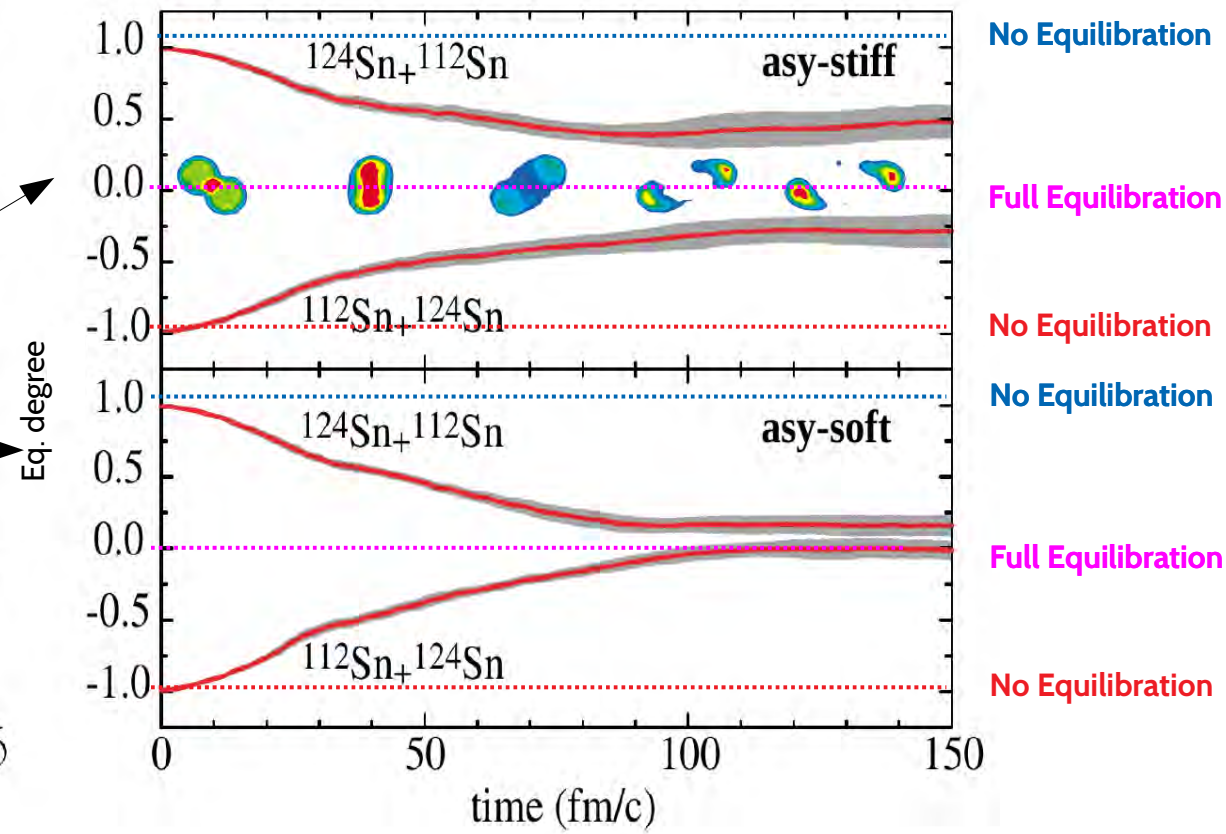
nEoS and heavy ion collisions



Transport model calculation



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

Different nEoS recipes lead to different equilibration degree

Nuclear Equation of state to date

See also W. Trautmann talks

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

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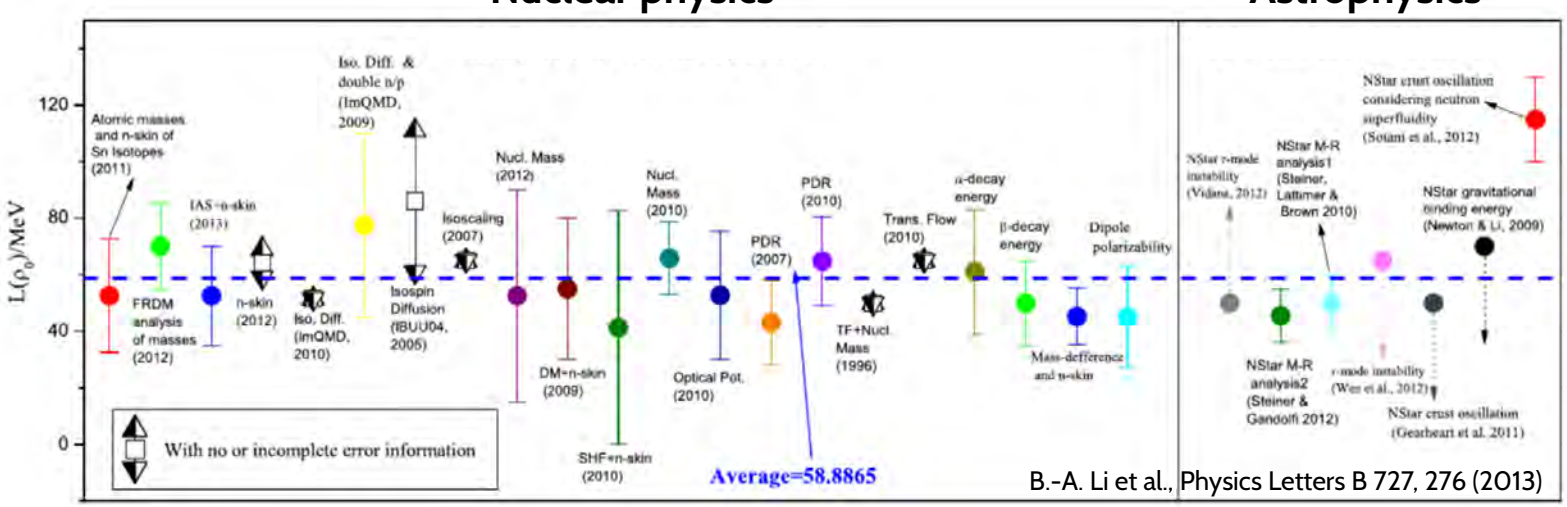
	~1%	~10%		~30%		???				
P_α	E_{sat} MeV	E_{sym} MeV	ρ_0 fm^{-3}	L_{sym} MeV	K_{sat} MeV	K_{sym} MeV	Q_{sat} MeV	Q_{sym} MeV	Z_{sat} MeV	Z_{sym} MeV
$\langle P_\alpha \rangle$	-15.8	32	0.155	60	230	-100	300	0	-500	-500
σ_{P_α}	±0.3	±2	±0.005	±15	±20	±100	±400	±400	±1000	±1000

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

Nuclear physics **Astrophysics**

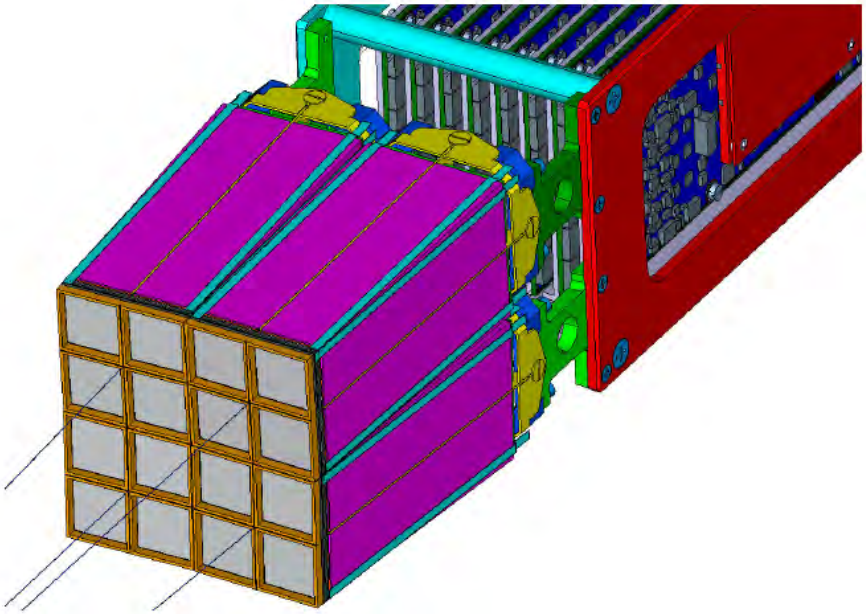


B.-A. Li et al., Physics Letters B 727, 276 (2013)

FAZIA: Forward-angle A-Z Identification Array

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

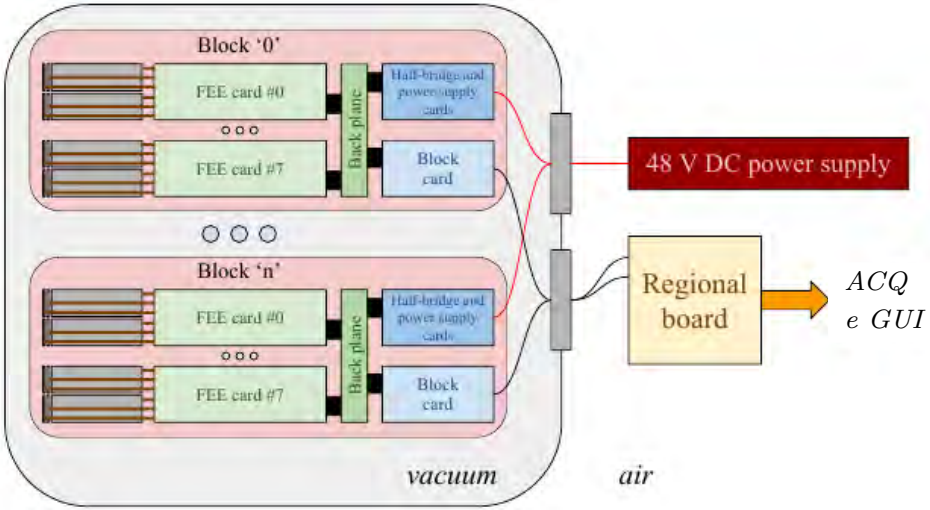
- Modular apparatus: block minimum unit
- **1 BLK = 16 telescope**
- Telescope (area 2x2 cm^2)
  - **Si1, 300um**
  - **Si2, 500um**
    - n-TD, to optimize doping uniformity
    - Thickness uniformity within ±1 µm
    - Random cut to avoid channeling
    - "reverse mounting" configuration
  - **CsI(Tl),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



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

Electronics and Acquisition:

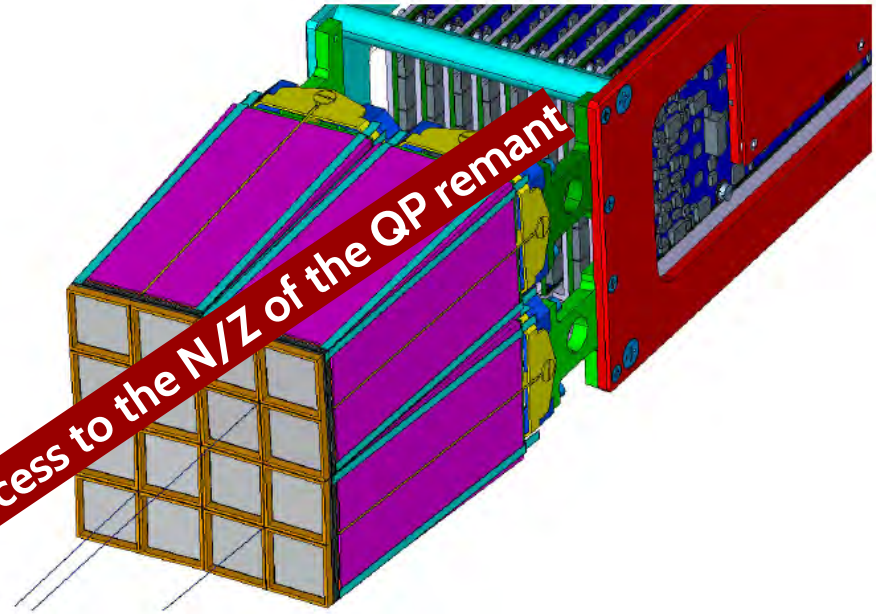
- **1 FEE** drives 2 telescope, supplying HV e digitizing signals
  - SI1→ sQH1, sQL1, sI1
  - SI2 → sQ2, sI2
  - CsI → sQ3
- 2 FPGA
  - ✓ Trigger and acquisition of sampled signals
  - ✓ Online signal shaping
- **Block card**: input/output communication
- **ReBo**: main trigger, acquisition and slow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

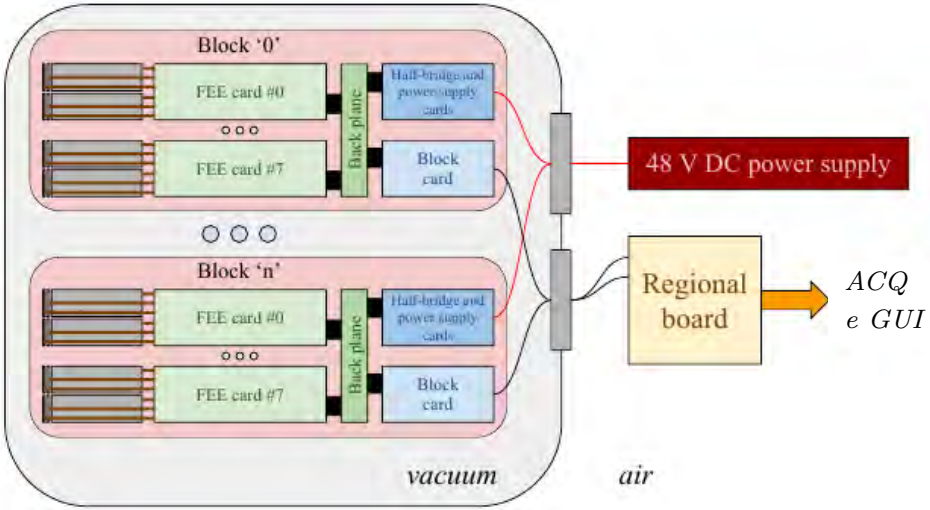


S. Valdre et al., Nucl. Instr. And Method 930, 27 (2019)

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
  - 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

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

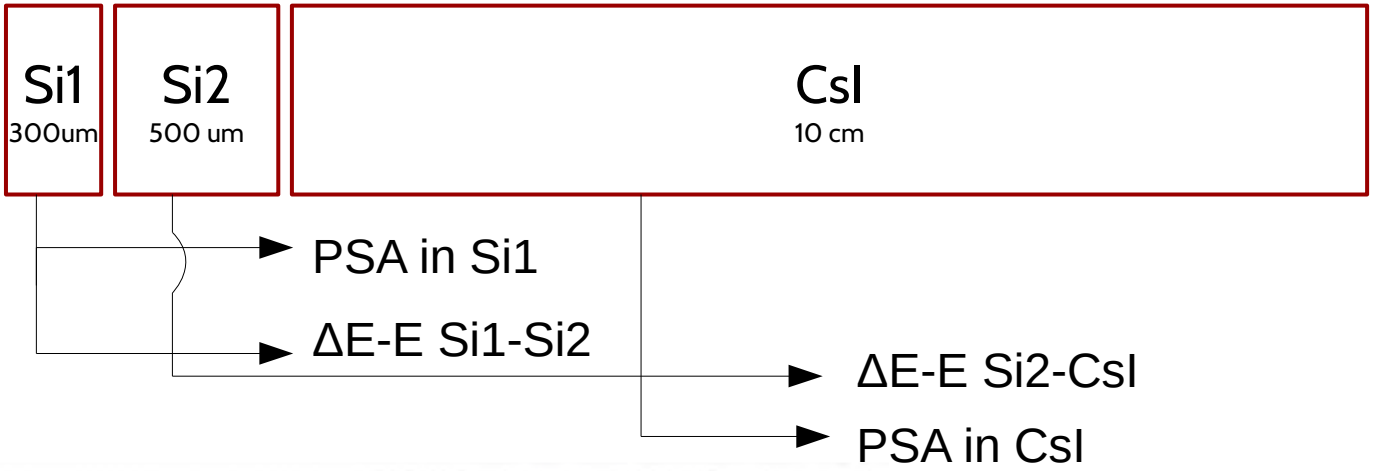
CONS → Detection multiplicity =1
No constrains to the kinematics

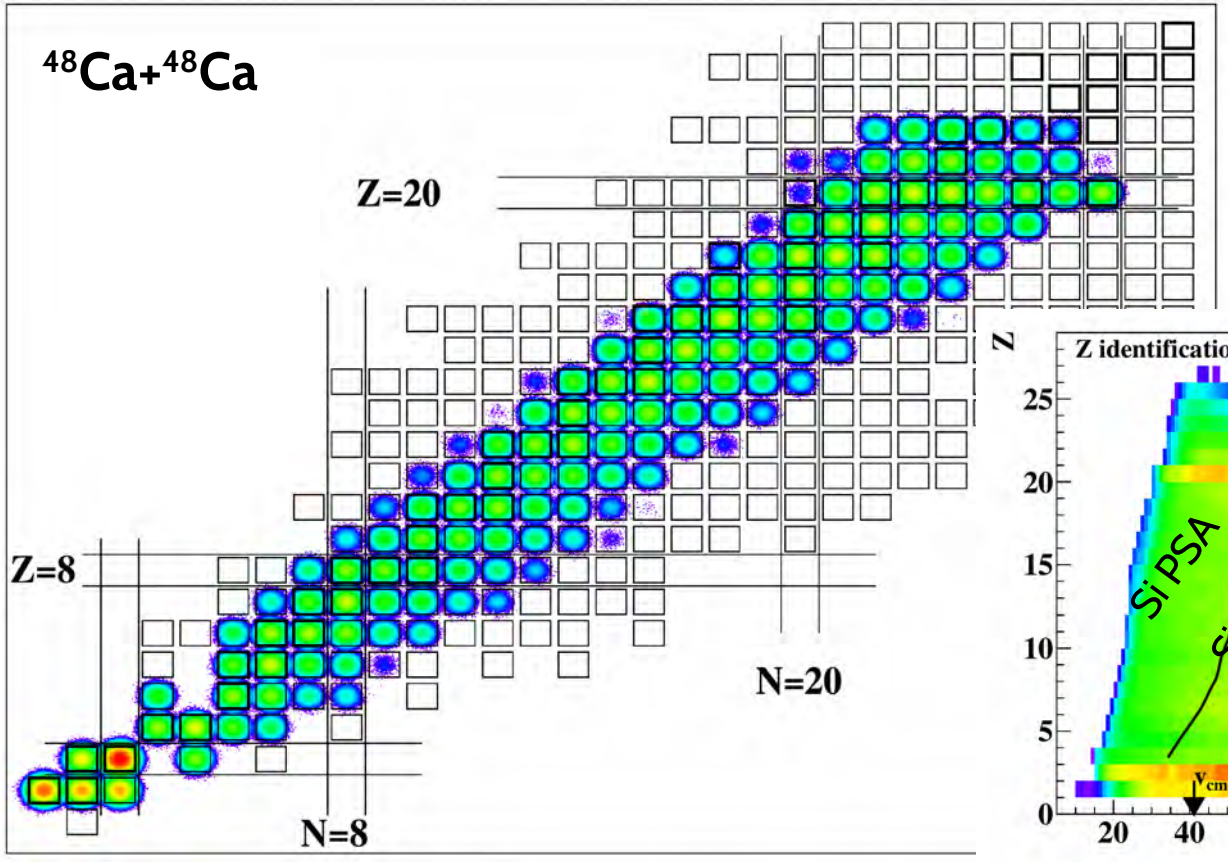
Excellent isotopic identification

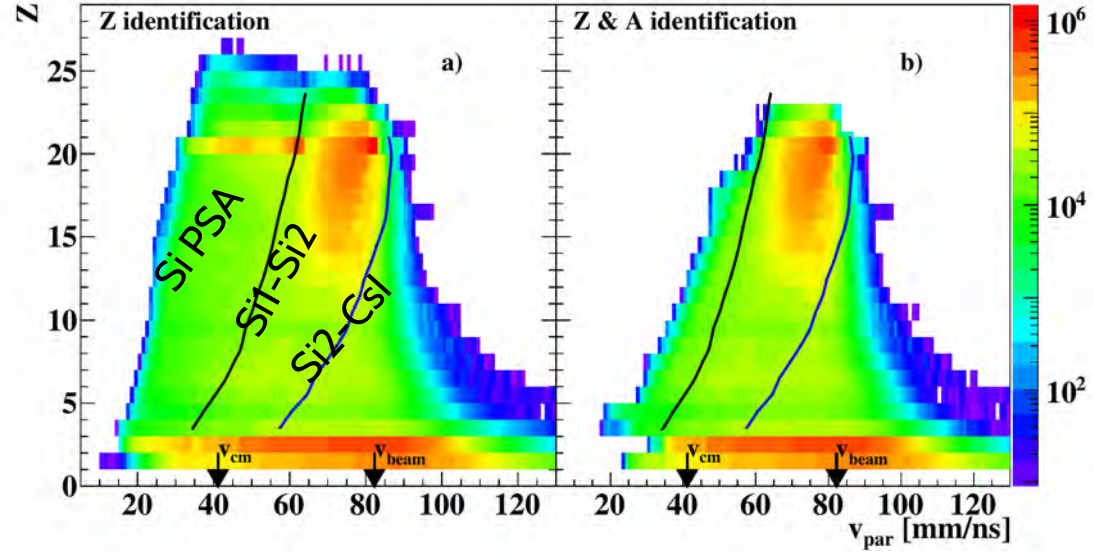
PROS → Direct access to the Z and A of the QP

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

FAZIA Identification methods

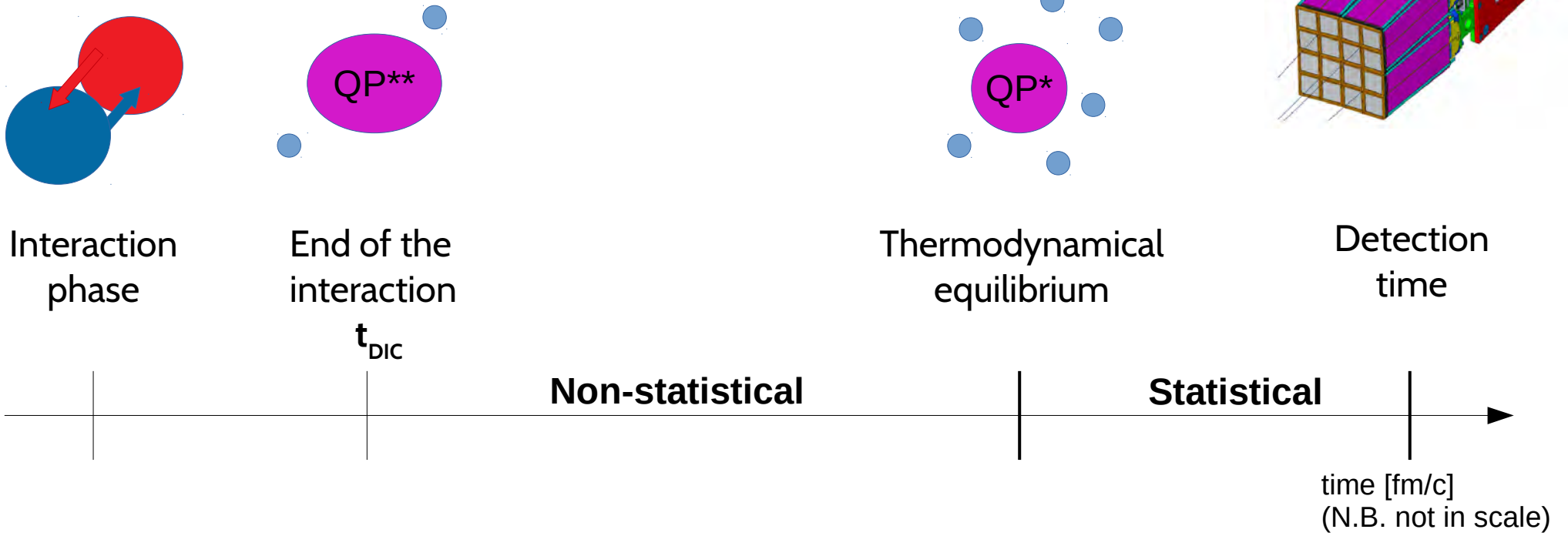






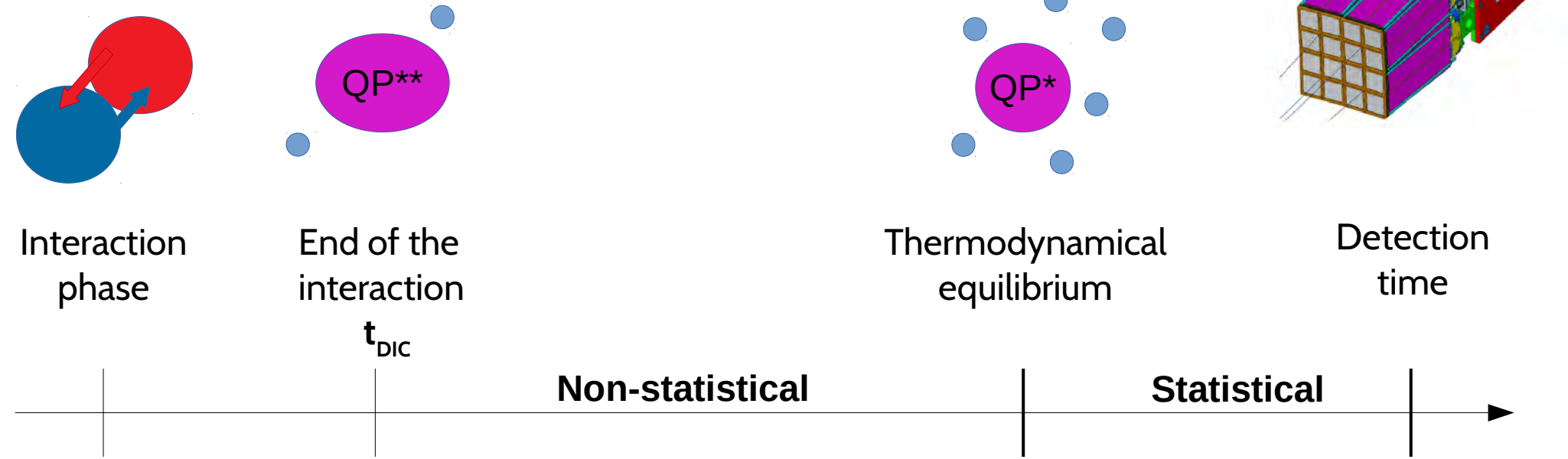
Timeline of an heavy-ion collision

Evaporative Event

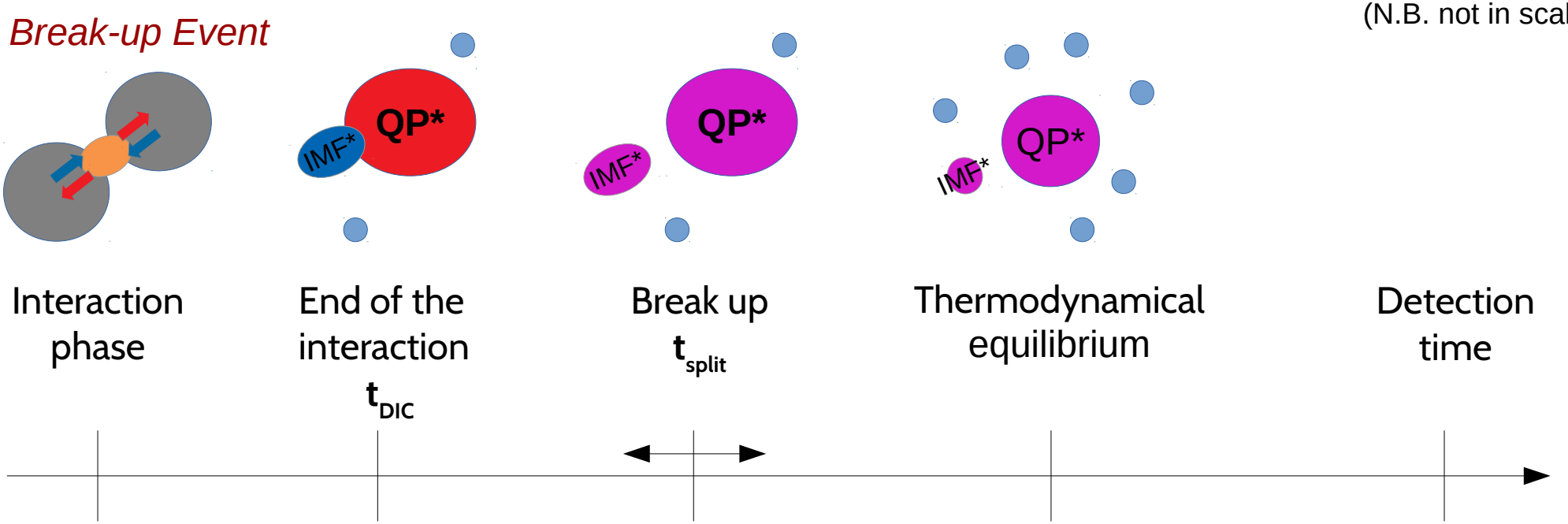


Timeline of an heavy-ion collision

Evaporative Event



Break-up Event



AMD: Antisymmetrized Molecular Dynamics

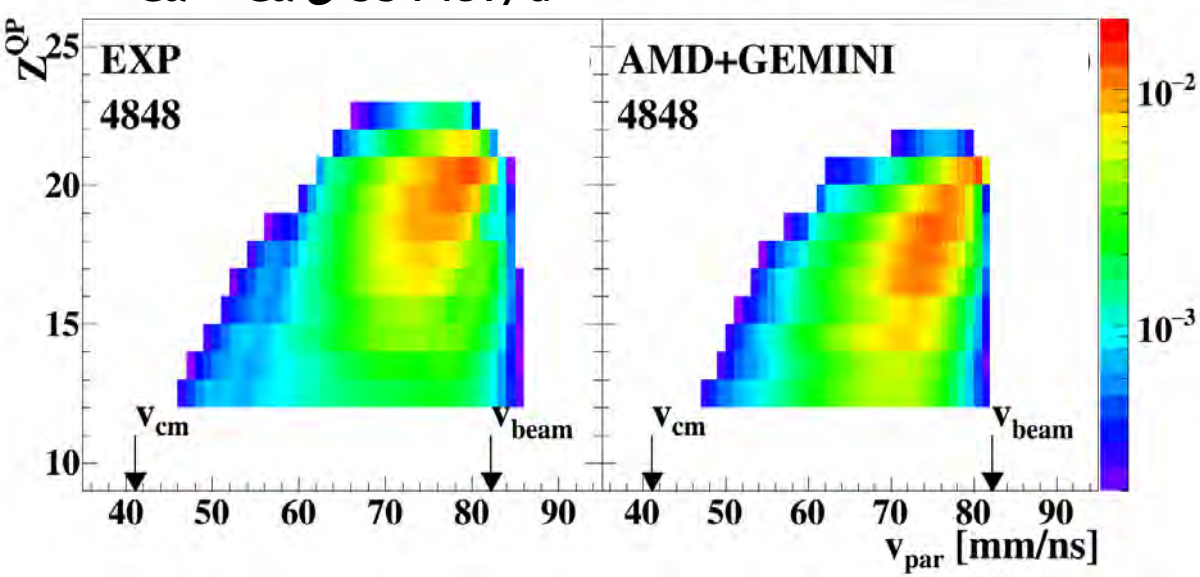
Transport model.

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

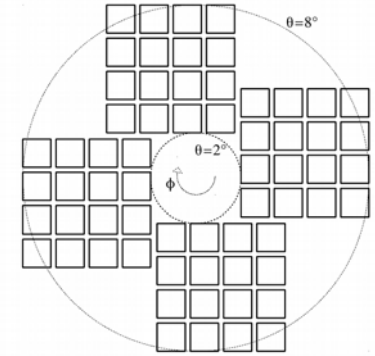


AMD+GEMINI events are filtered via software :

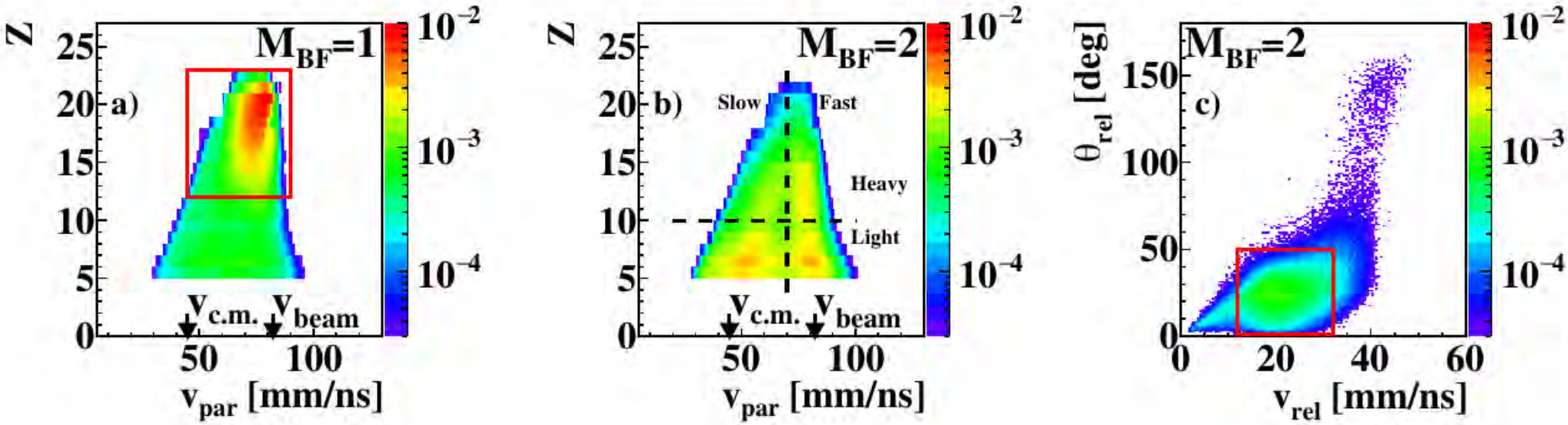
- **Geometrical acceptance**
- **Identification thresholds**
- **Detector energy resolution**

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

FAZIA-SYM: n-p equilibration

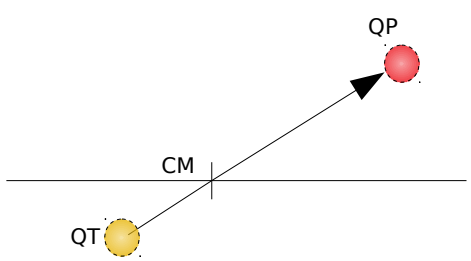


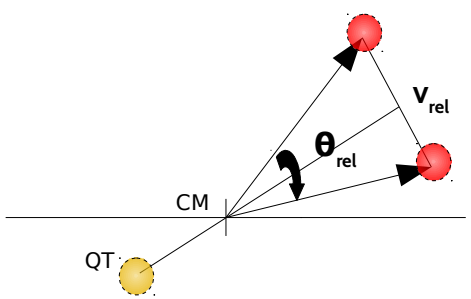
$^{40,48}Ca + ^{40,48}Ca$ @ 35 MeV/u



QP evaporative event

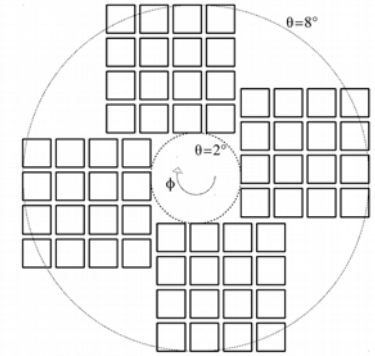
QP break-up event



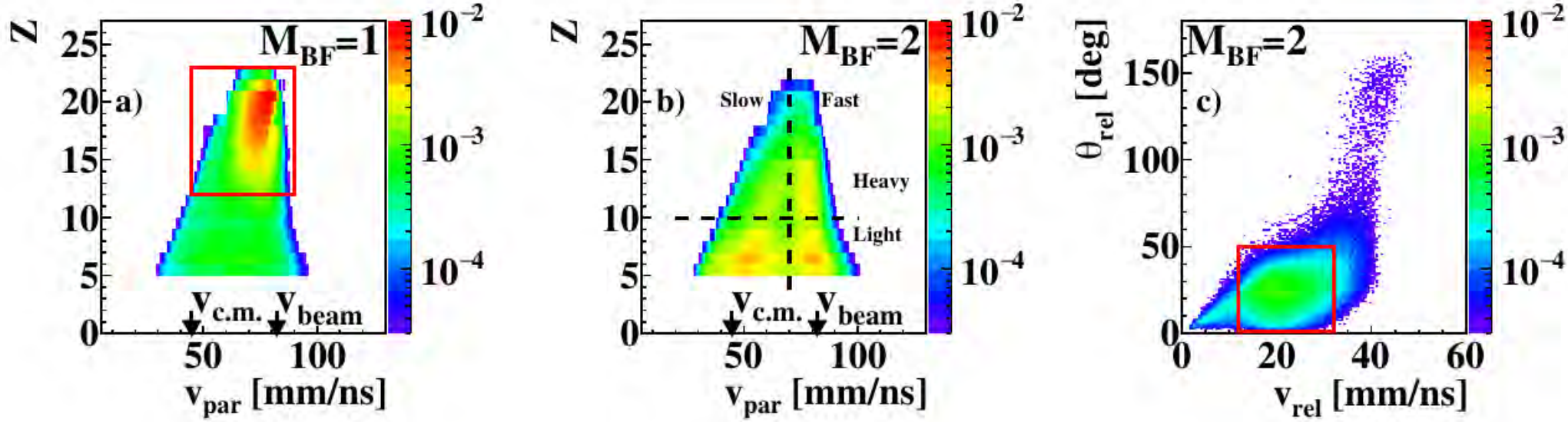


A. Camaiani et al, PRC 103, 014605 (2021)

FAZIA-SYM: n-p equilibration

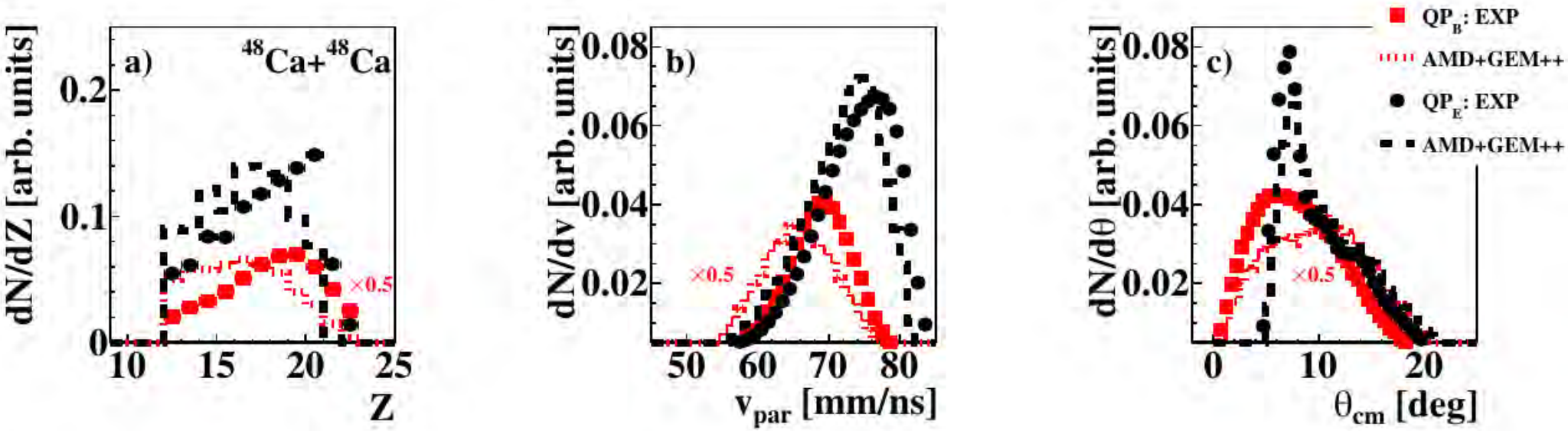


$^{40,48}Ca + ^{40,48}Ca$ @ 35 MeV/u



QP evaporative event

QP break-up event

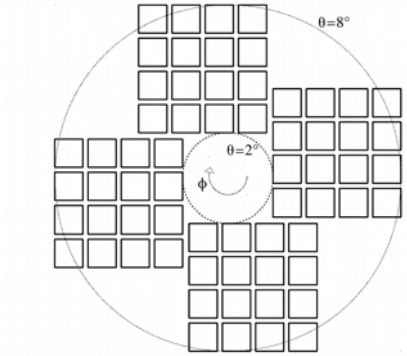


A. Camaiani et al, PRC 103, 014605 (2021)

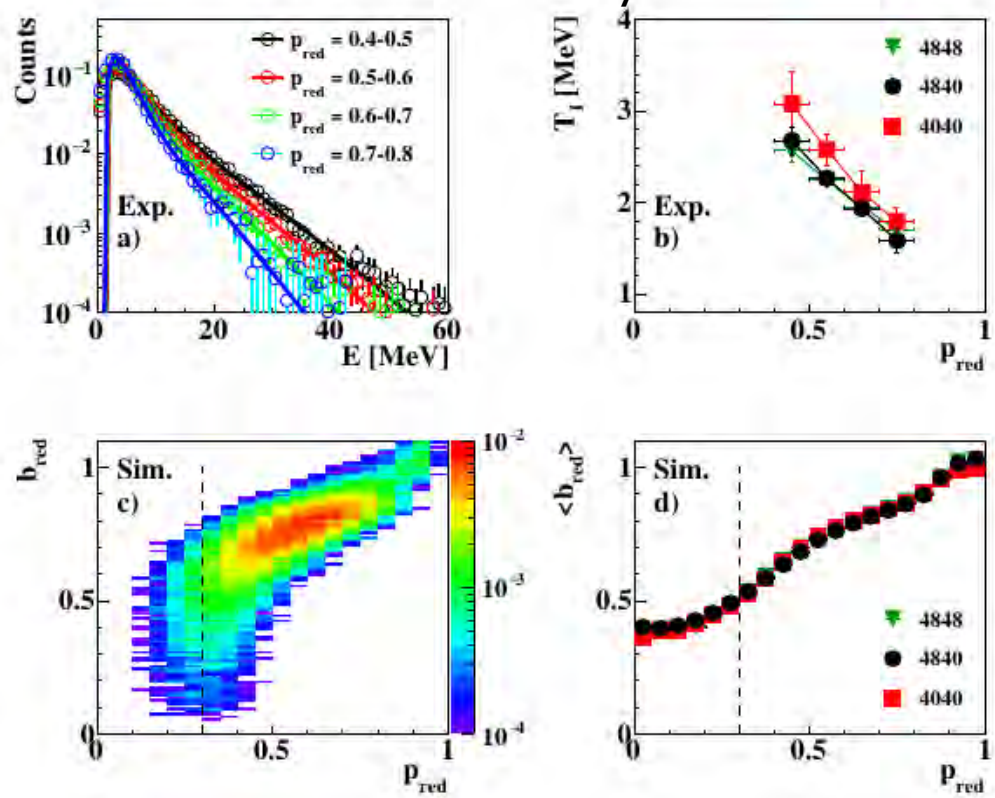
FAZIA-SYM: n-p equilibration

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

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



Reaction centrality estimator



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

FAZIA-SYM: n-p equilibration

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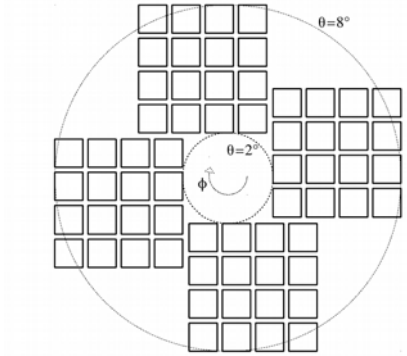
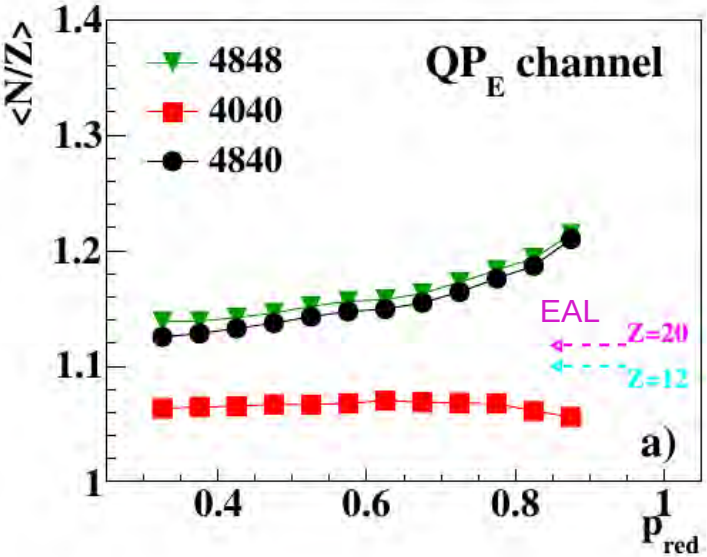
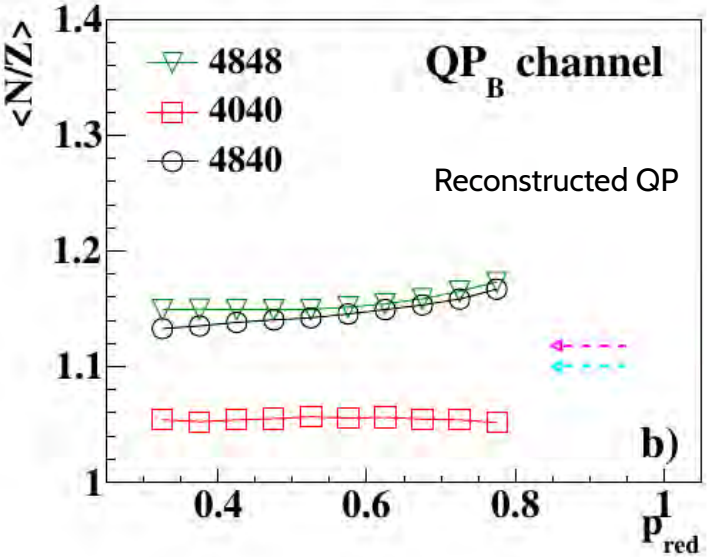
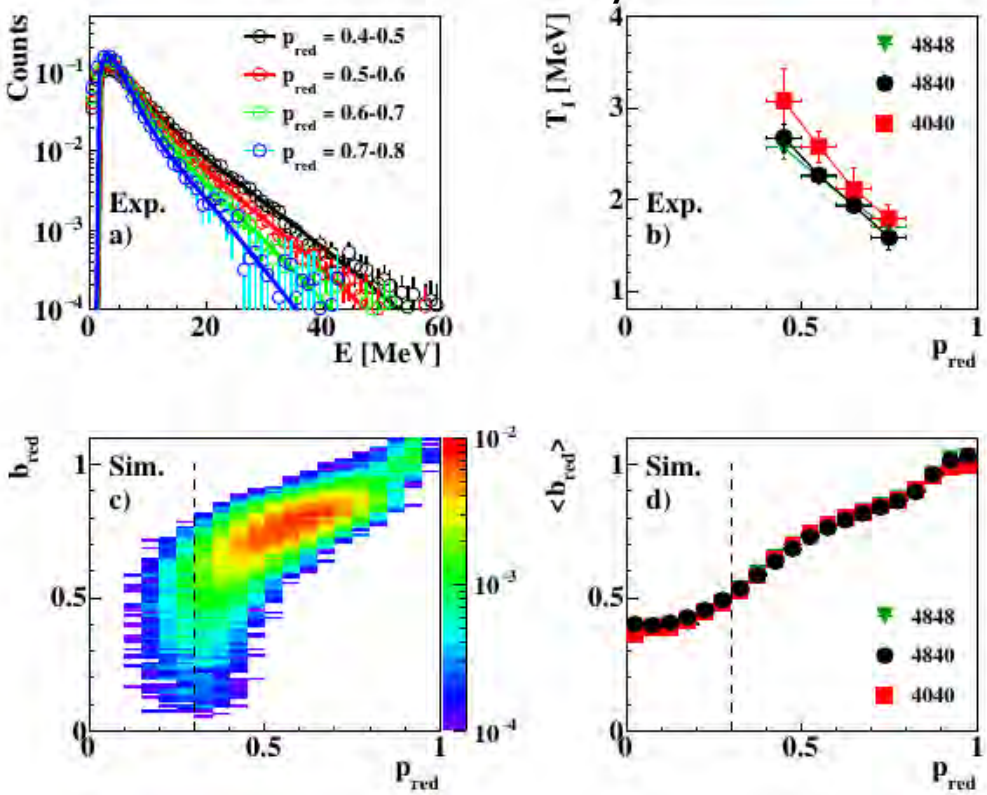


N/Z evolution with the centrality





Reaction centrality estimator



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

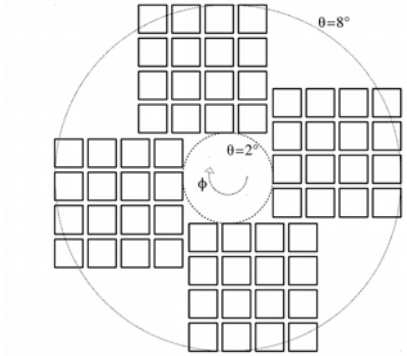
R. J. Charity, PRC 58, 1073 (1998).

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

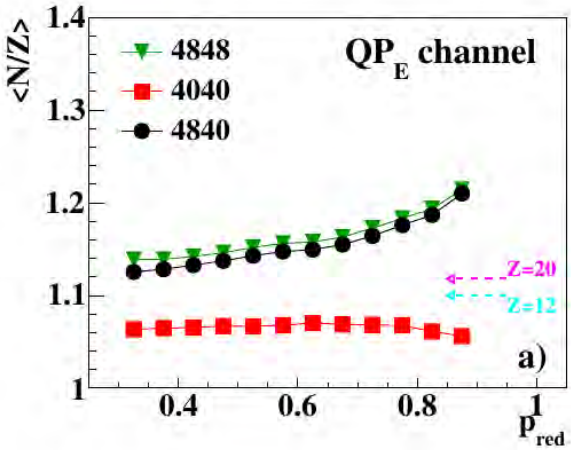
FAZIA-SYM: n-p equilibration

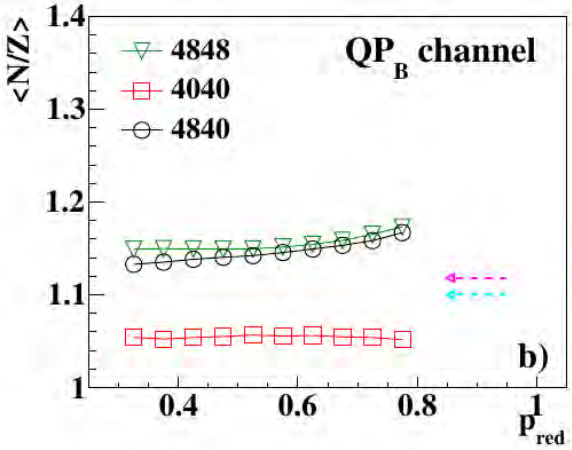
$^{40,48}Ca + ^{40,48}Ca$ @ 35 MeV/u

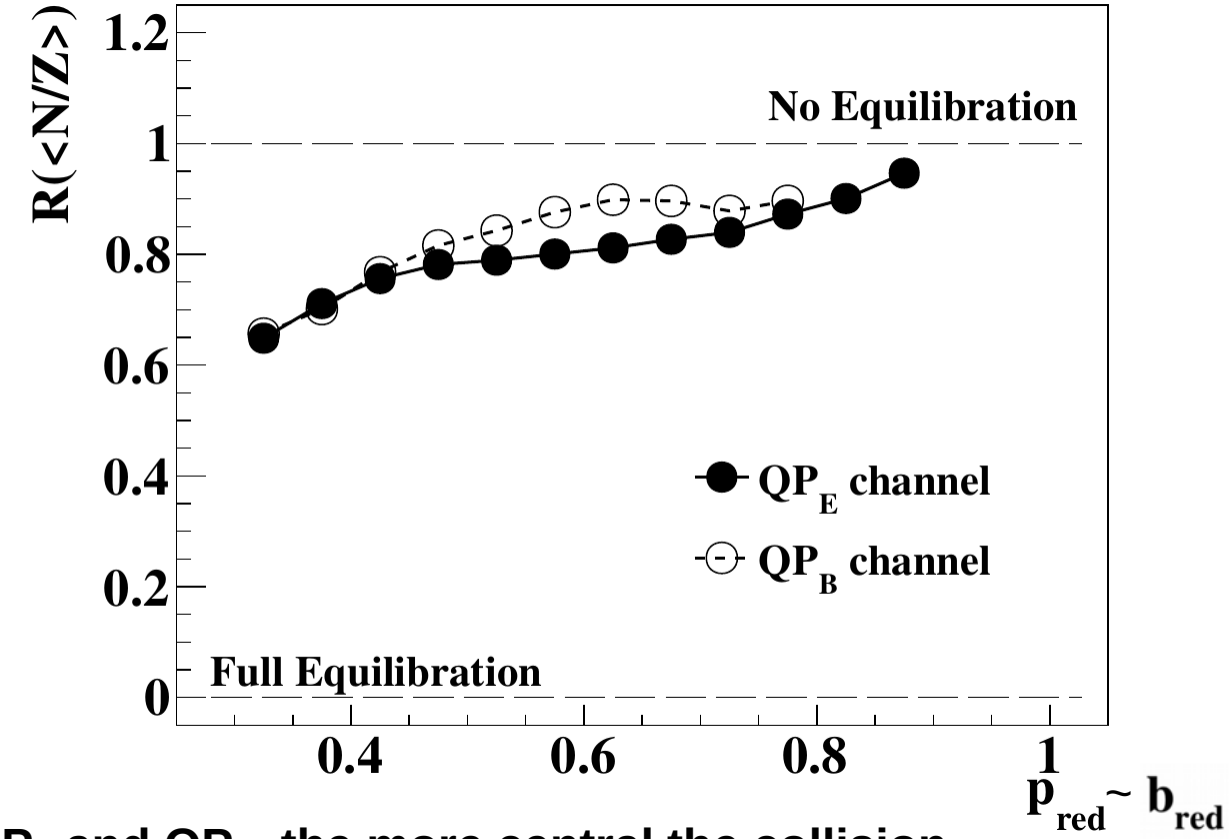
$$p_{red} = \left(\frac{p^{QP}_{par}}{p^{beam}}\right)_{cm}$$



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







In both QP_E and QP_B, the more central the collision, the more equilibrated the system

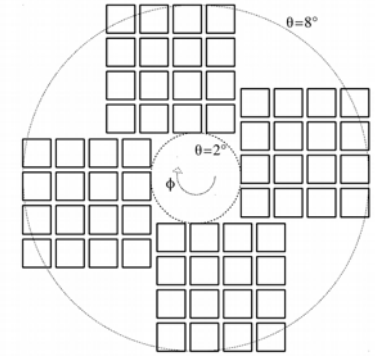
Signs of a weak process in QP_B event: heavier primary source?

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

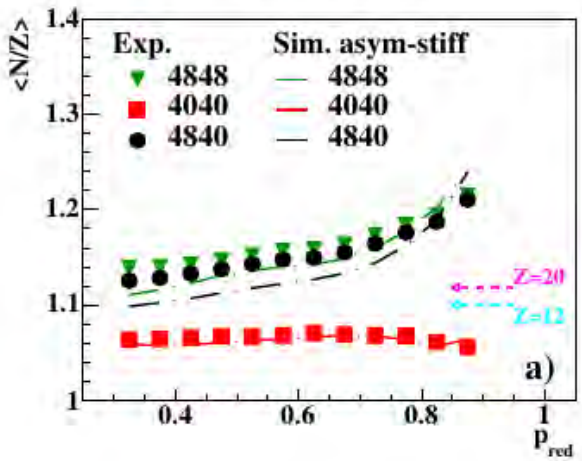
FAZIA-SYM: n-p equilibration

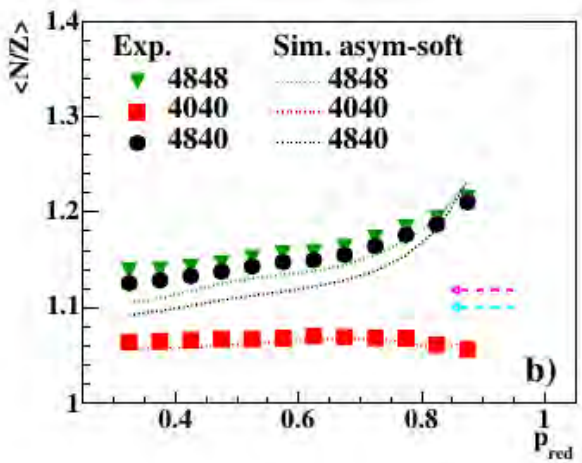
^{40,48}Ca + ^{40,48}Ca @ 35 MeV/u

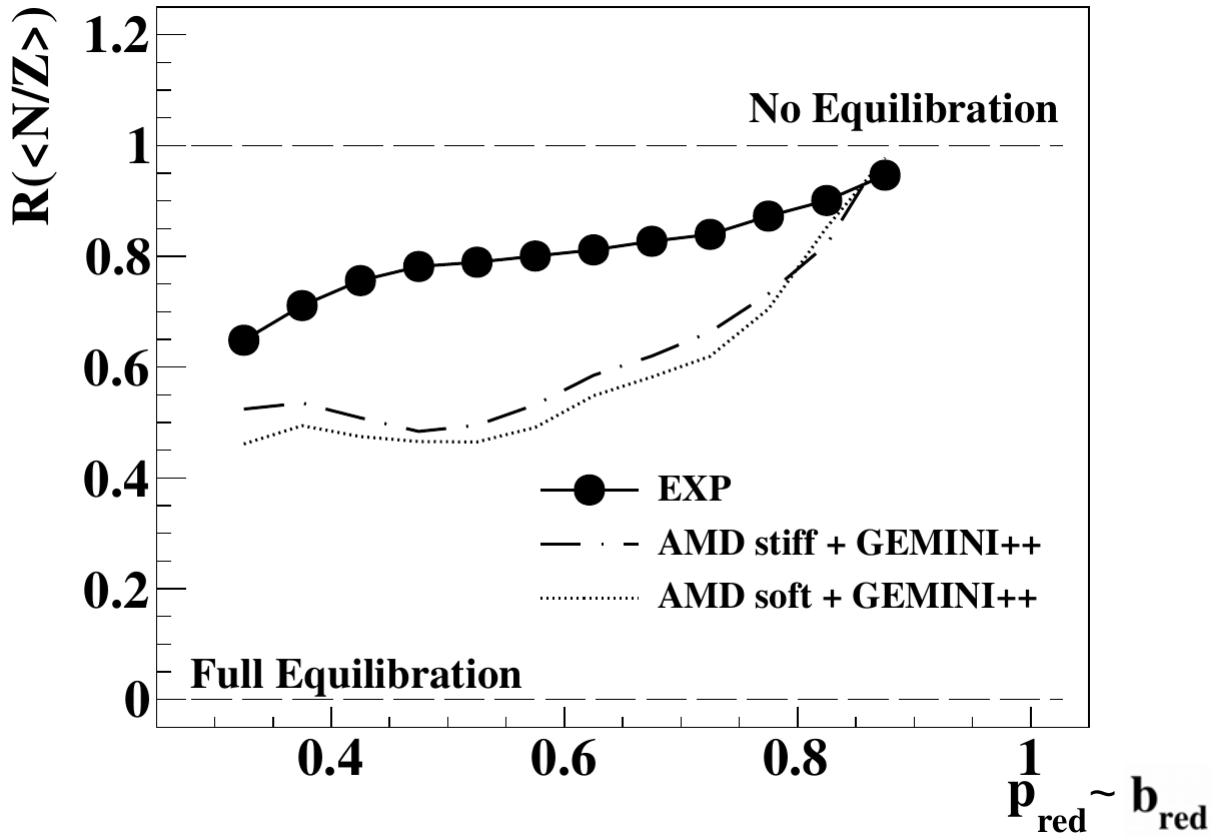
$$p_{red} = \left(\frac{p_{par}^{QP}}{p^{beam}} \right)_{cm}$$



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







Faster equilibration predicted by AMD+GEMINI:

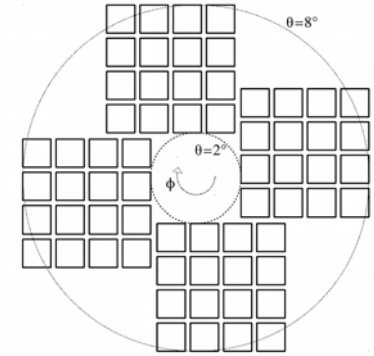
not ascribable to distortions introduced by statistical/non-statistical emission from the hot QP

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

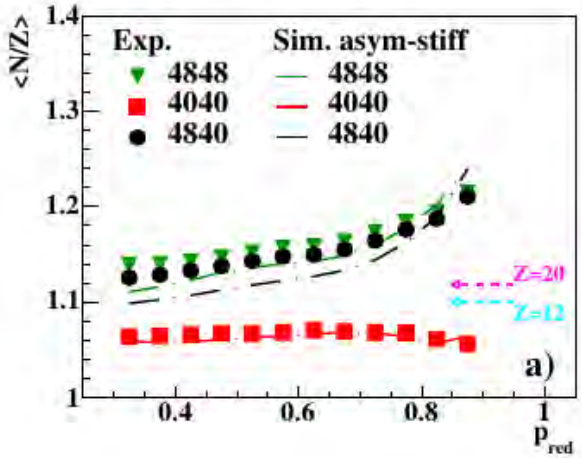
FAZIA-SYM: n-p equilibration

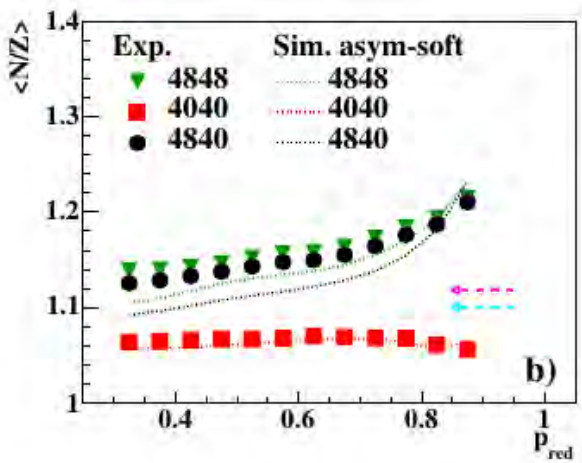
^{40,48}Ca + ^{40,48}Ca @ 35 MeV/u

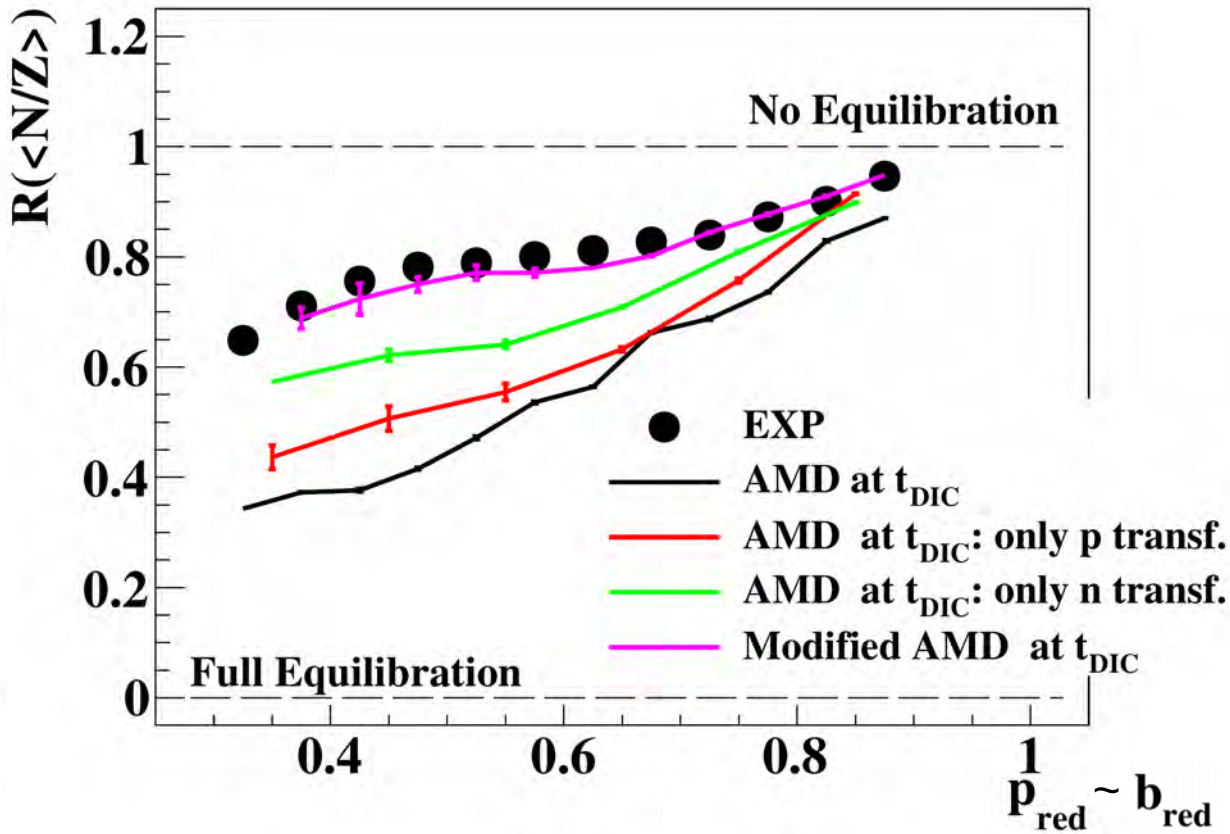
$$p_{red} = \left(\frac{p_{par}^{QP}}{p^{beam}} \right)_{cm}$$



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



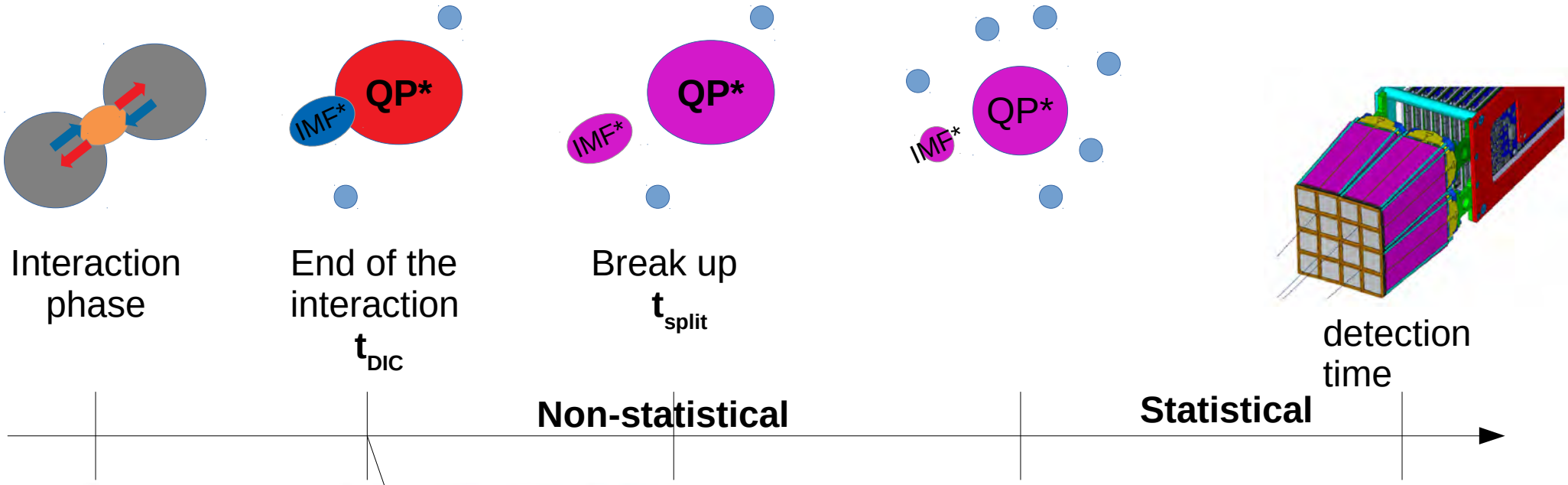




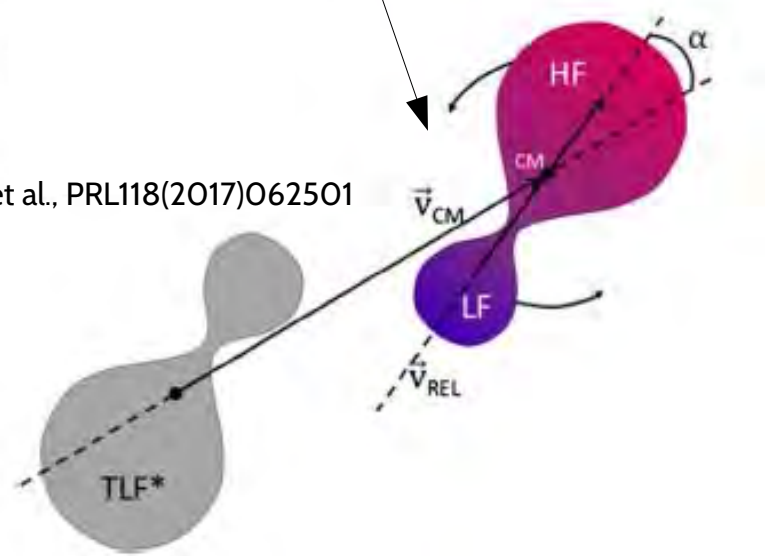
Descrepancy recovered reducing the transfer probability of about a factor 2 (most likely proton transfers) in AMD.

ISOFAZIA: QP break-up

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



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



A sort of "Isospin diffusion after the drift"

α angle as a clock?

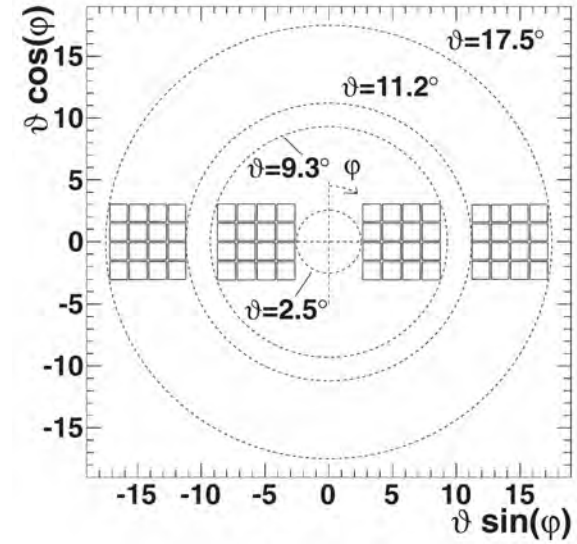
if yes, the smaller the angle, the faster the split

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



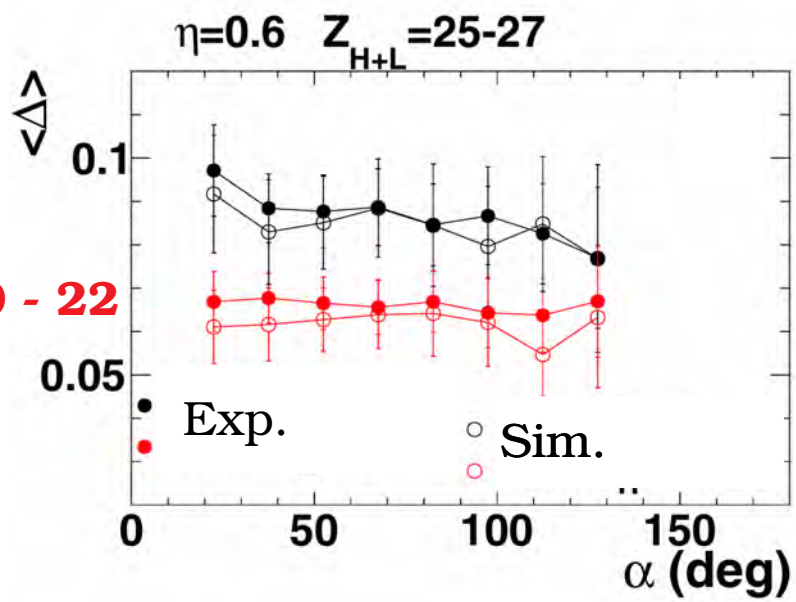
$$\langle\Delta\rangle = \langle\frac{N-Z}{N+Z}\rangle$$

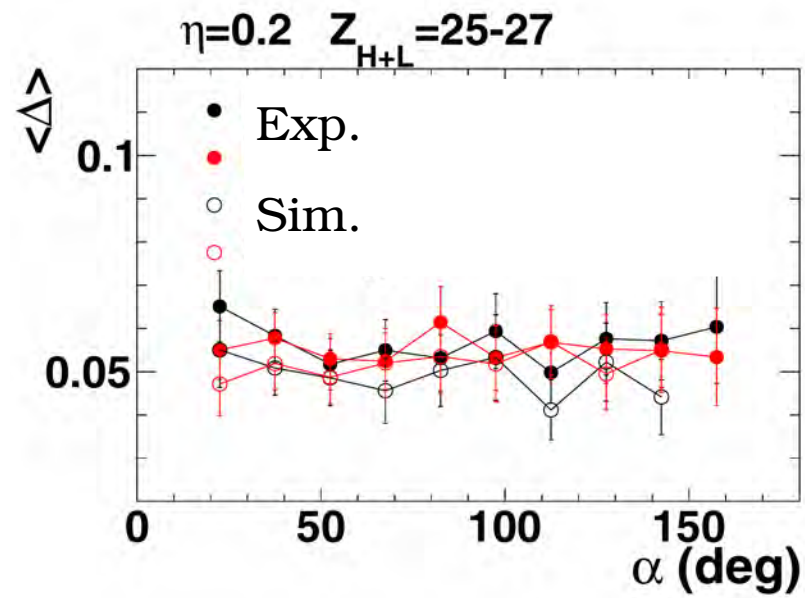
From the detected pairs in QP_B events:

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

Z_L = 5

Z_H = 20 - 22





Z_L = 10-11

Z_H = 14 - 17

Asymmetric split:

- gap in the asymmetry
- evolution of the asymmetry with α

More symmetric split:

- no gap in the asymmetry
- no evolution with α

Results in agreement with
A.Jedele et al., PRL118(2017)062501
A.Manso et al., PRC95(2018)044604

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:

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

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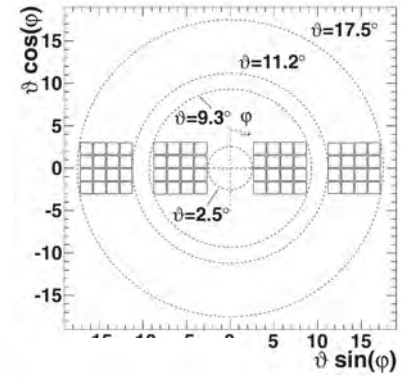
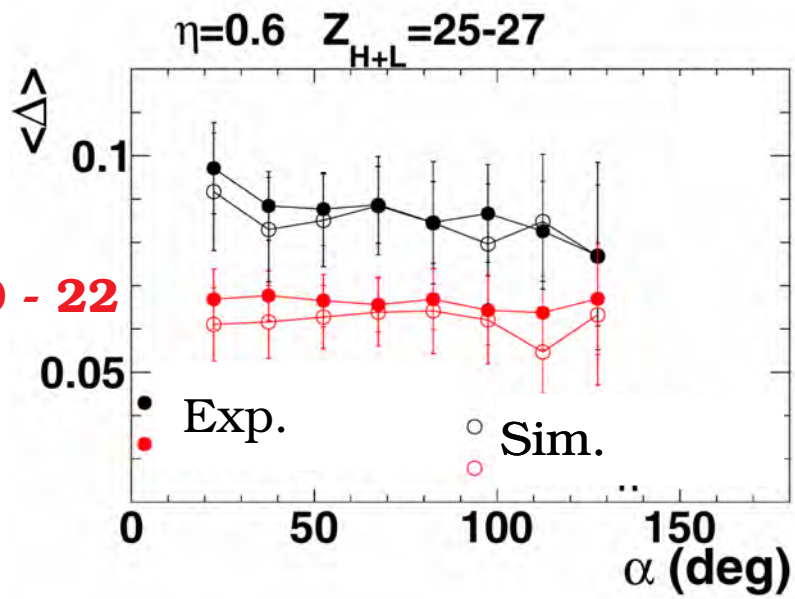
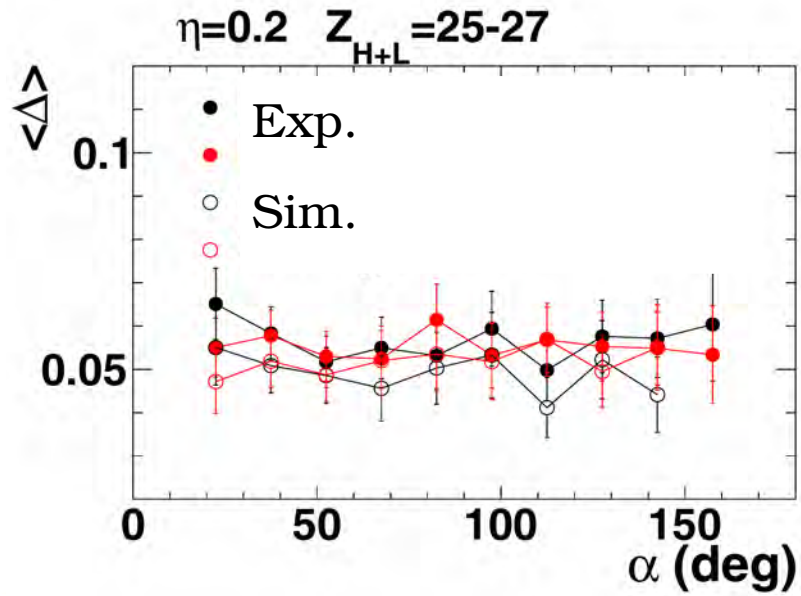


Z_L = 5

Z_H = 20 - 22

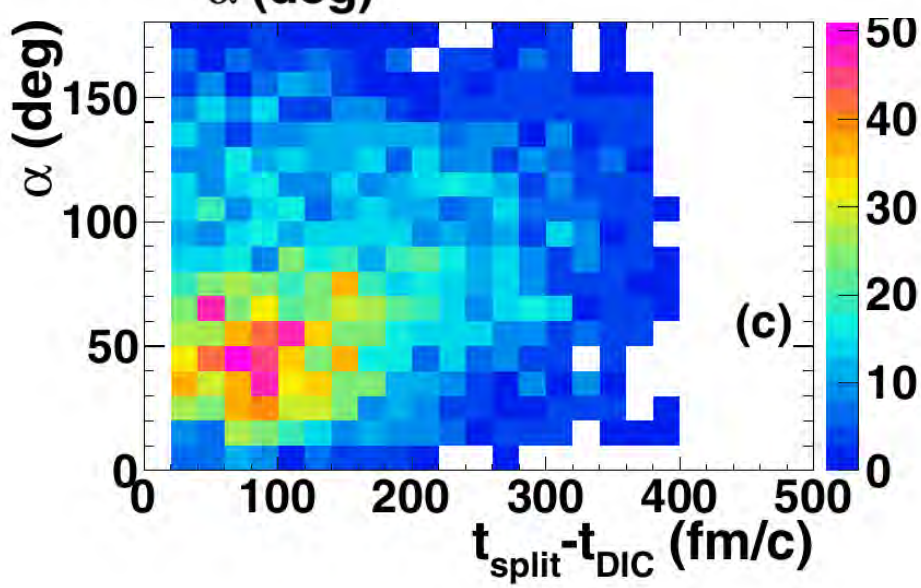




Z_L = 10-11

Z_H = 14 - 17

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



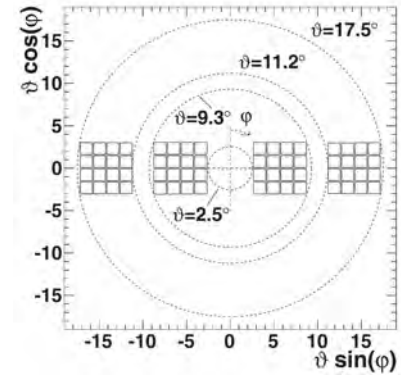
Only a weak correlation between the α angle and the break-up time is present in AMD

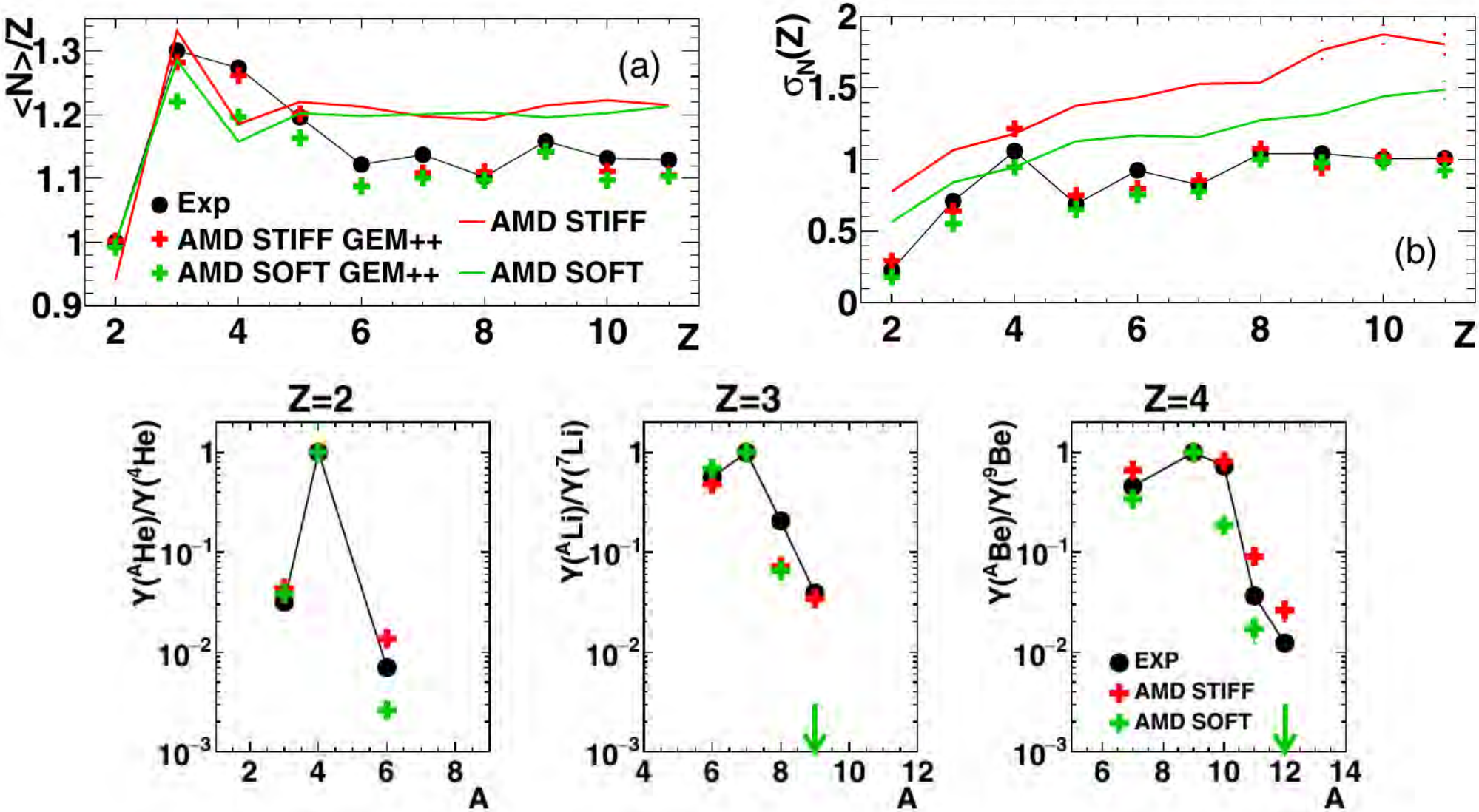
S. Piantelli et al, PRC 103, 014603 (2021)

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



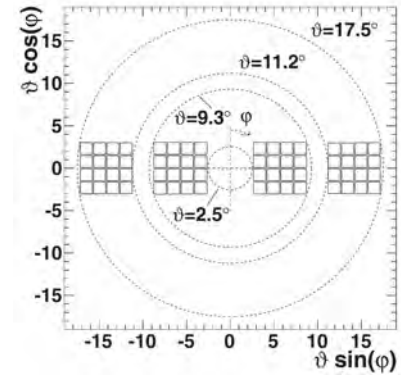


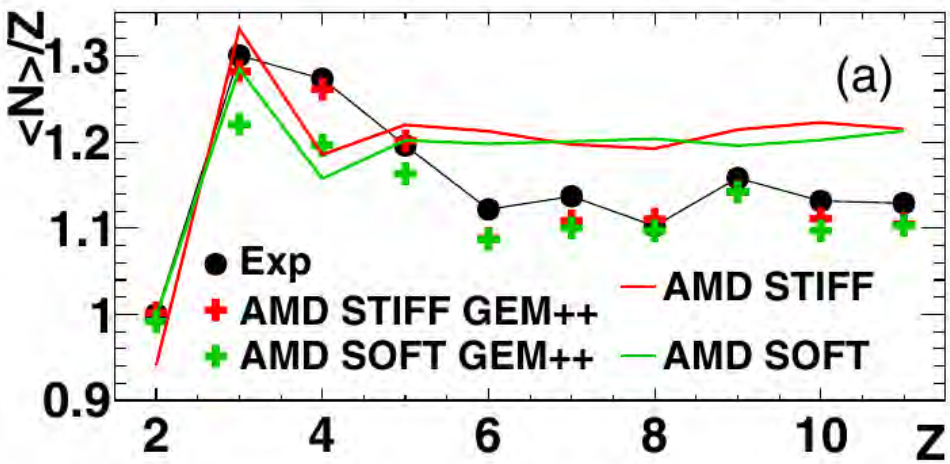
S. Piantelli et al, PRC 103, 014603 (2021)

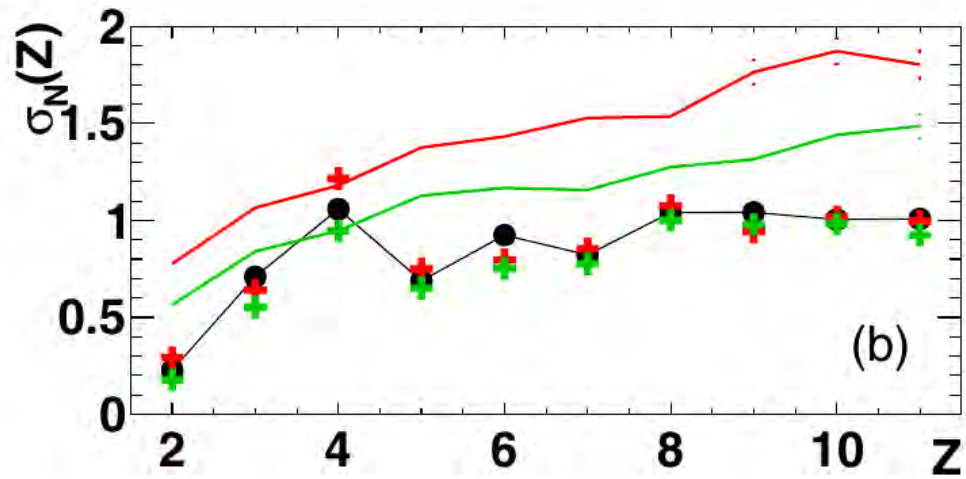
ISOFAZIA: asy-stiff or asy-soft?

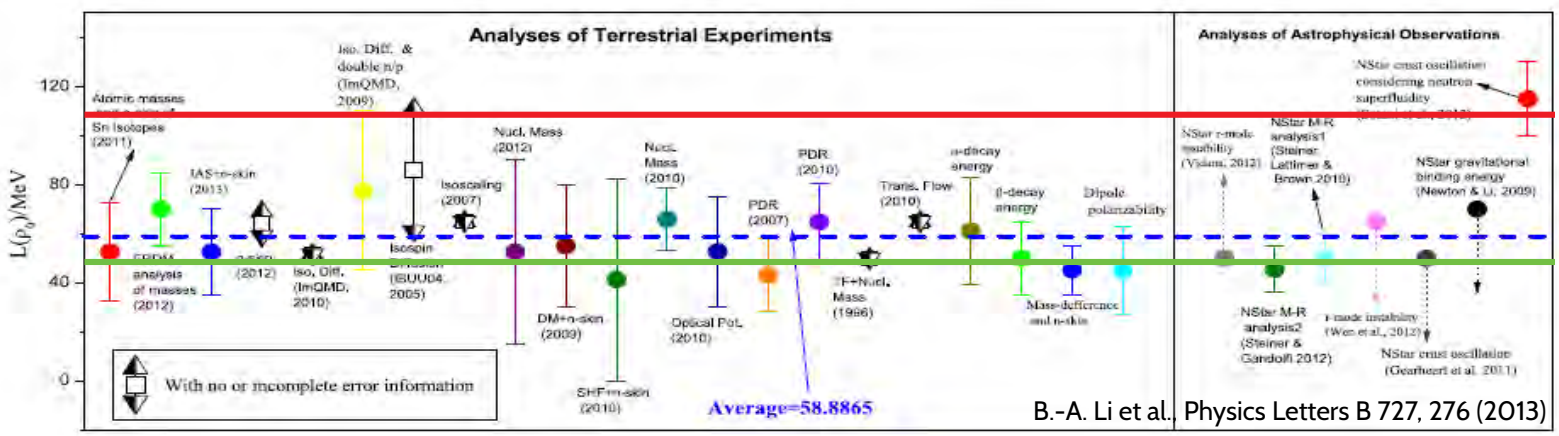
$^{80}Kr + ^{40,48}Ca$ @ 35 MeV/u

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

Summary and conclusions

The FAZIA detector opens new investigation paths, combining an excellent isotopic identification capability (up to Z~25), covering a large fragment energy range, and also proving high detection multiplicity.

Pioneering experiments have been performed in INFN – Laboratori Nazionali del Sud:

1. **FAZIA-SYM: we measured the n-p equilibration accessing the QP remnant comparing for the time evaporative and break-up channel.**

2. **ISO-FAZIA: we measured equilibration in the QP break-up sub-system.**
   Results in agreement with similar observation by the NIMROD collaboration
   Comparison with the AMD+GEMINI transport model simulation:
   indication of an asy-stiff nuclear Equation of State

And other hot news will come in the near future:

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

C. Frosin – Reaction mechanism and particle correlations in ligh-ion reactions at Fermi energies

* 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

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

Analysis on going, by Baohua Sun and co.

The next level: INDRA+FAZIA

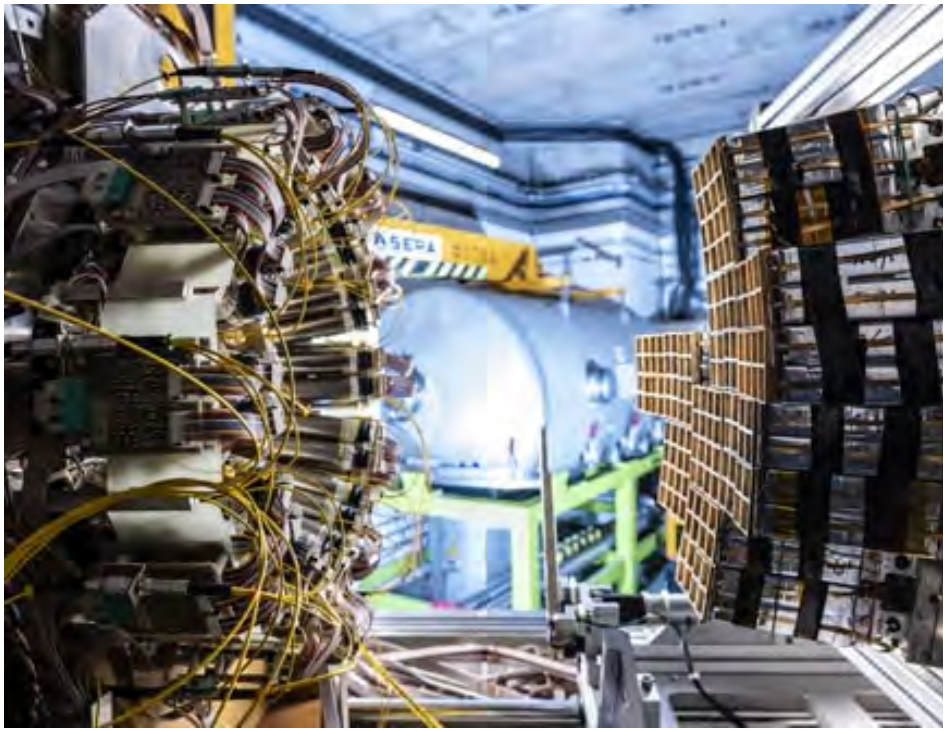
INDRA + FAZIA @ GANIL

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



Thanks for your attention

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