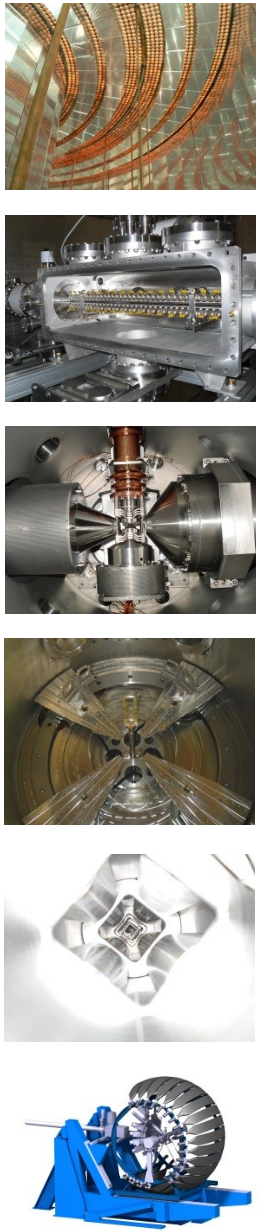


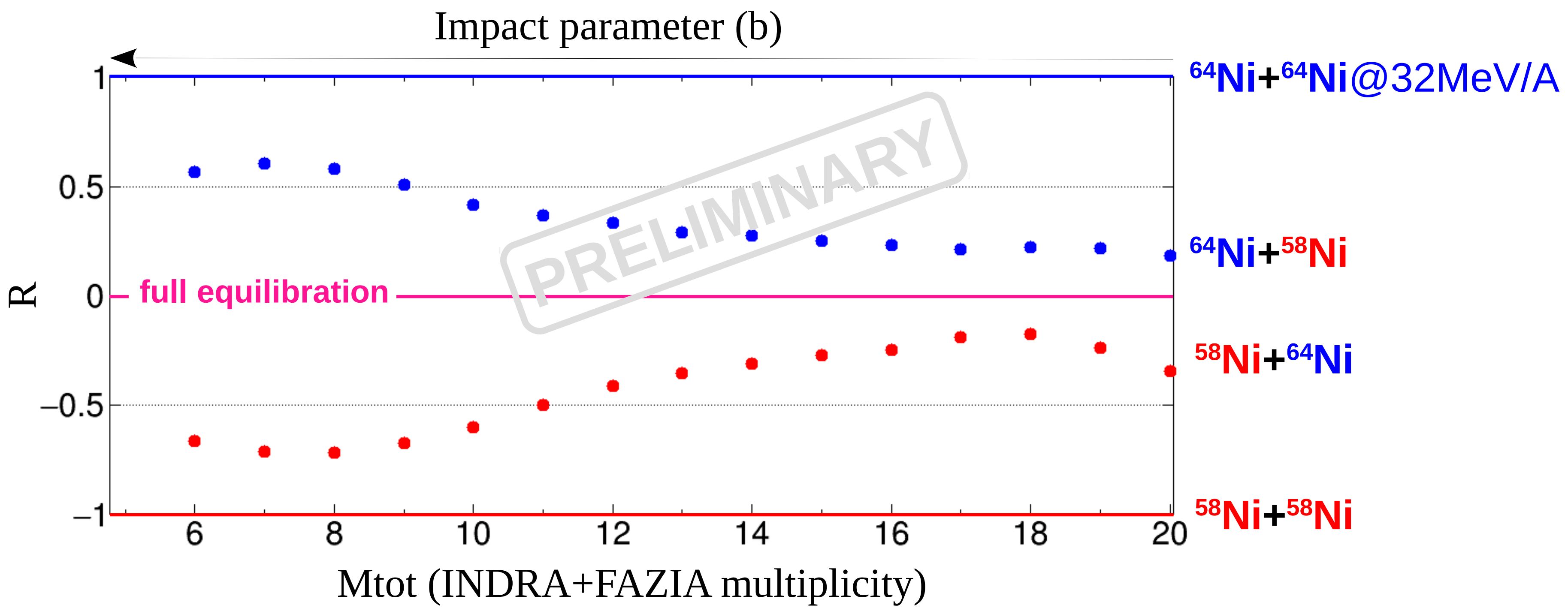
Probing nuclear dynamics and thermodynamics: the INDRA-FAZIA coupling in GANIL.

Diego Gruyer[1], R. Bougault[1], N. Le Neindre[1], O. Lopez[1], L. Manduci[1], M. Parlog[1], J. Quicray[1], E. Vient[1], A. Chbihi[2], J.D. Frankland[2], M. Henri[2], L. Morelli[2], E. Bonnet[3], B. Borderie[4], E. Galichet[4], P. Napolitani[4], S. Barlini[5], M. Bini[5], A. Camaiani[5], G. Casini[5], P. Ottanelli[5], G. Pasqualli[5], S . Piantelli[5], G. Poggi[5], S. Valdré[5], I. Lombardo[6], G. Verde[6], R. Alba[7], C. Maiolino[7], D. Santonocito[7], M . Vigilante[8], M. La Commara[8], F. Gramegna[9], M. Cicerchia[9], G. Mantovani[9], T. Marchi[9], M. Cinausero[10], D. Fabris[10], M. Bruno[11], T. Kozick[12], S. Upadhyaya[12], A. Kordyasz[13], A.A. Benitez[14], F.P. Bernal[14], J. Duenas[14], J.E. Garcia Ramos[14]

[1]LPC Caen, France. [2]GANIL, France. [3]Subatech Nantes, France. [4]IPN Orsay, France. [5]Univ./INFN Florence, Italy. [6]INFN Sezione di Catania, Italy. [7]INFN LNS Catania, Italy. [8]INFN/University Naples, Italy. [9]INFN LNL Legnaro, Italy. [10]INFN/University Padova, Italy. [11]INFN / University Bologna, Italy. [12]Jagellionian University, Cracow, Poland. [13]University Varsaw, Poland. [14]University of Huelva, Spain.

(INDRA and FAZIA Collaborations)

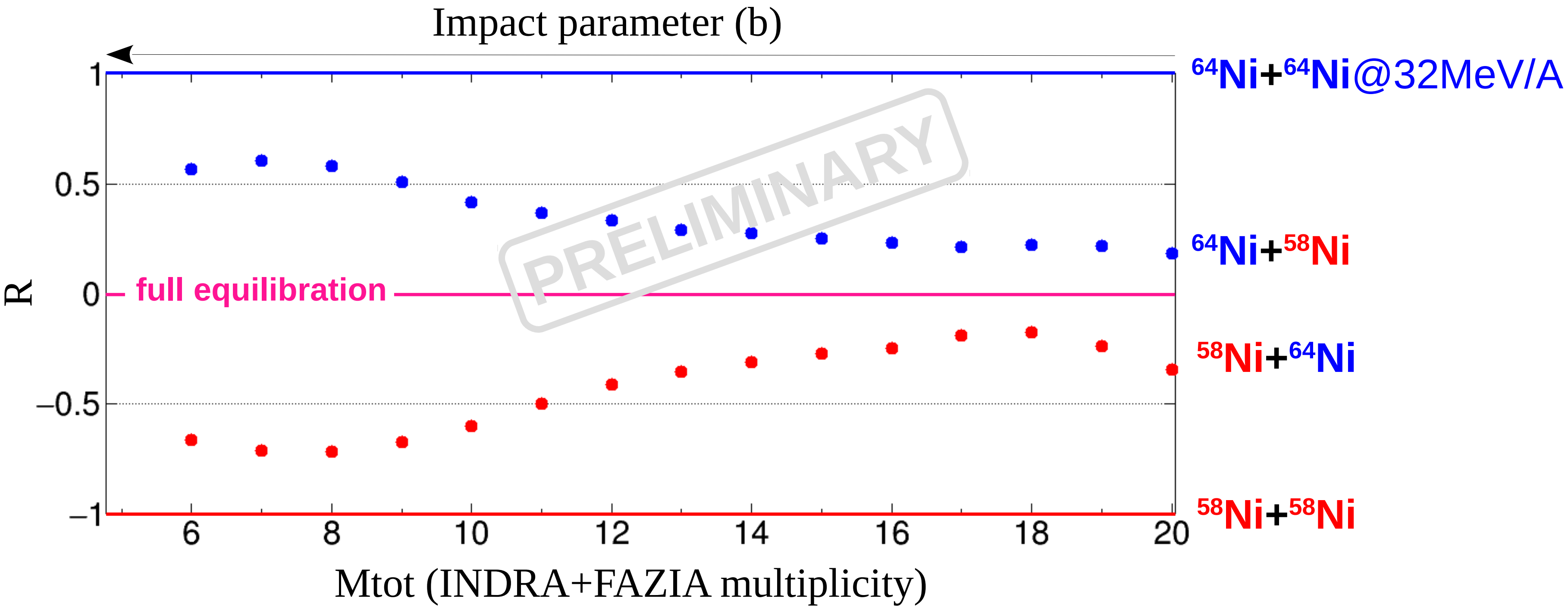
First diffusion plot with INDRA-FAZIA at GANIL



First diffusion plot with INDRA-FAZIA at GANIL

Imbalance ratio R
N/Z equilibration ratio measured with FAZIA
R = +1 (-1) : no N/Z equilibration
R = 0 : full N/Z equilibration

Total multiplicity Mtot
Number of fragments detected in INDRA and FAZIA : increases with decreasing impact parameter



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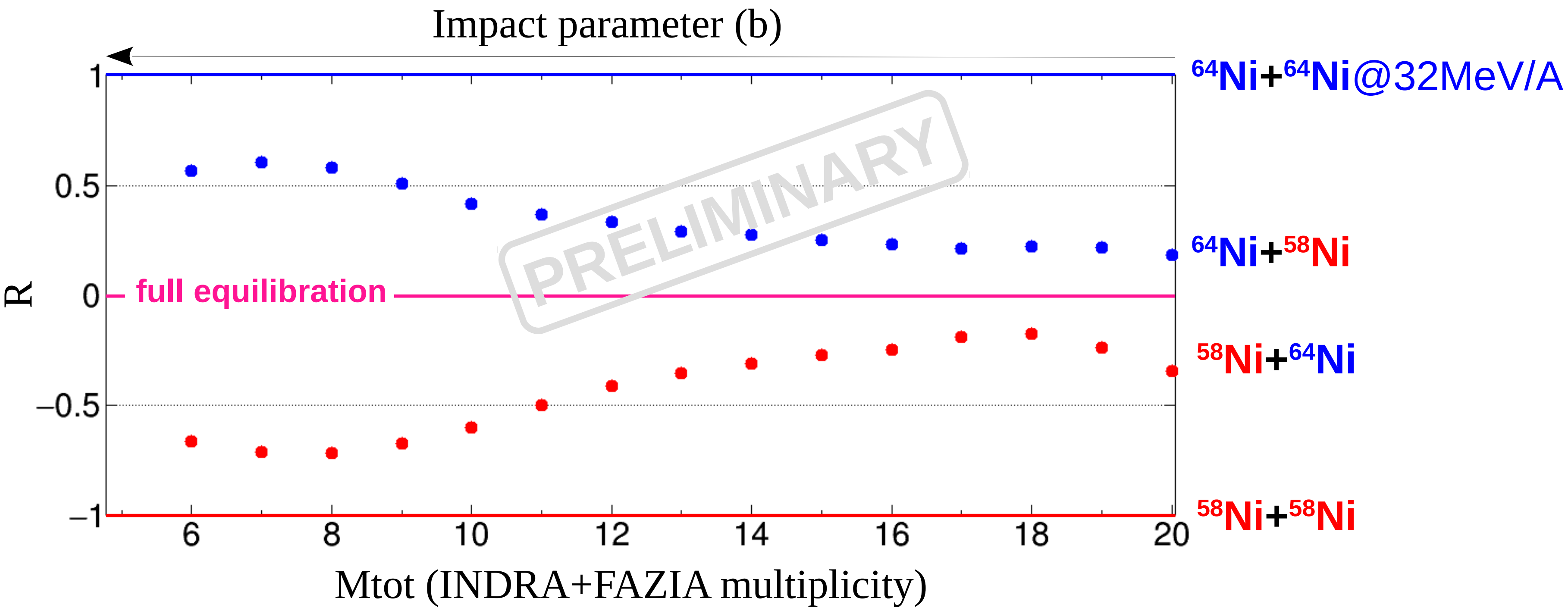
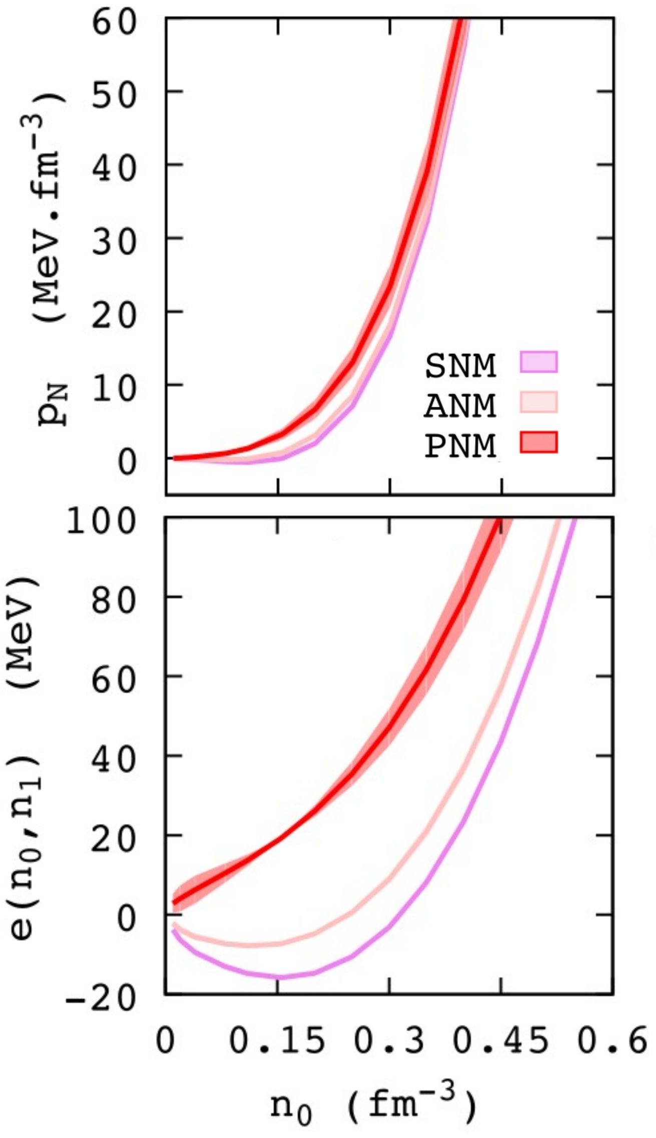


N/Z equilibration
Little equilibration at high impact parameter
Partial equilibration at low impact parameter

Data-model comparaison
Equilibration rate can constrain the nuclear equation of state

The nuclear Equation of State (EoS)



Margueron PRC **97** (2018) 025805

Dense matter
Describes how the pressure of an infinite system made of protons and neutrons evolves with density and temperature :

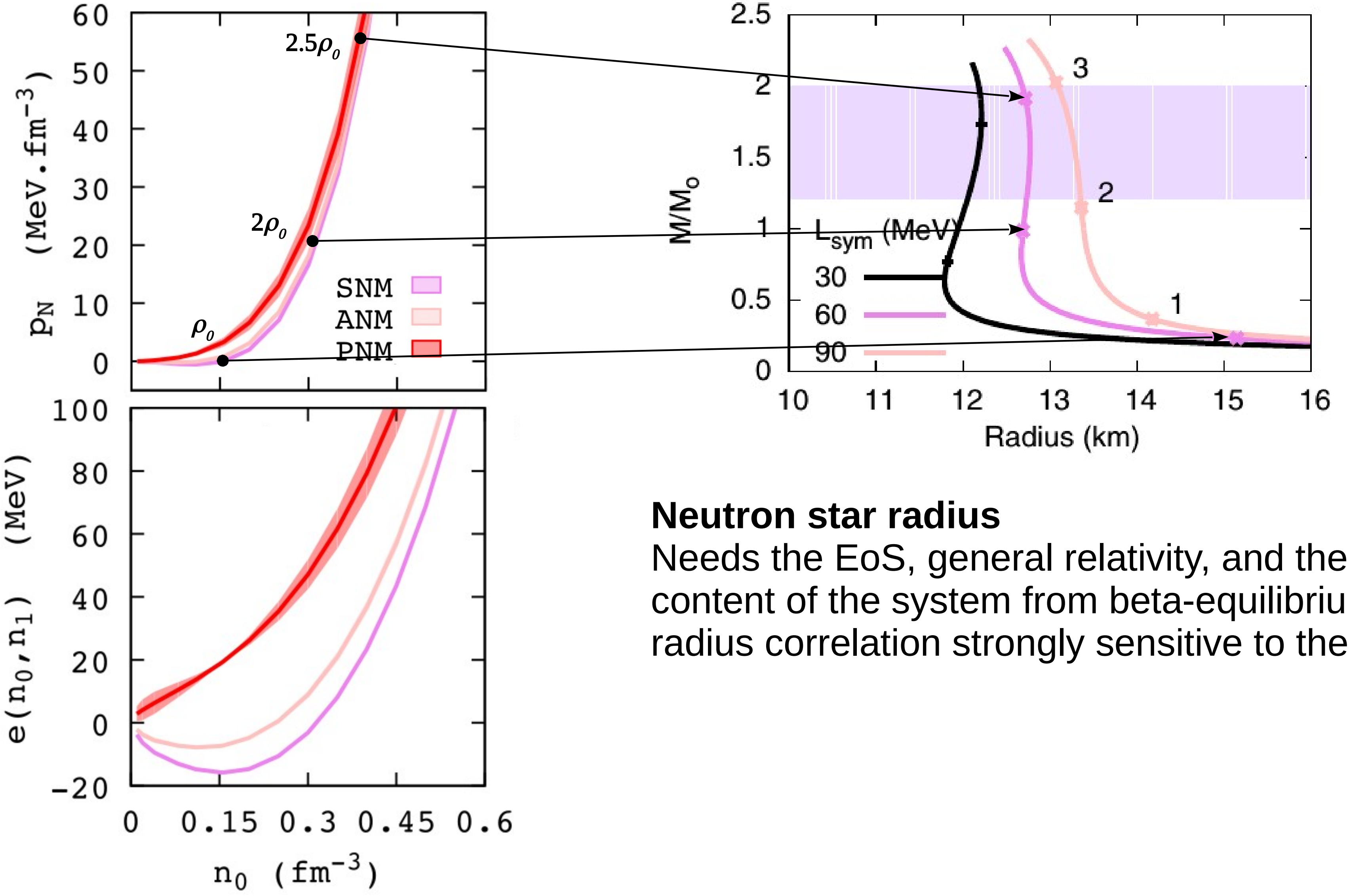
$$P(\rho,T)$$

Energy functionnal
Evolution of the energy per nucleon as a function of neutron and proton density :

$$e(\rho_n,\rho_p,T)$$

The EoS can be deduced from the energy functionnal if the isospin content of the system is known. Fundamental ingredient : in-medium nucleon interaction.

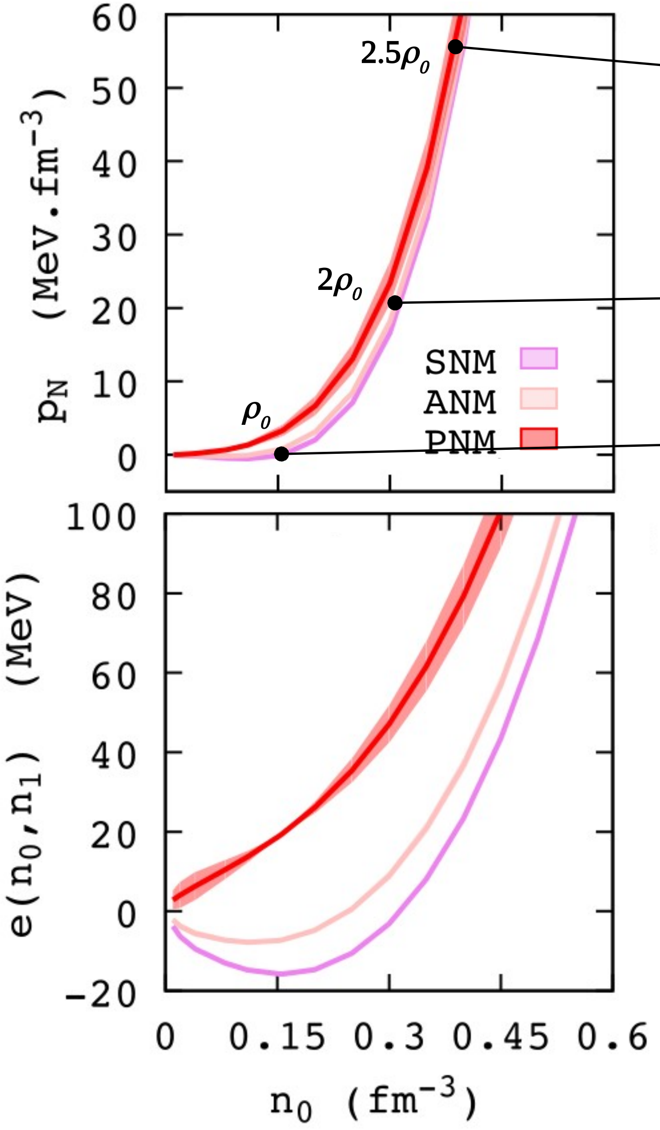
EoS and neutron star structure

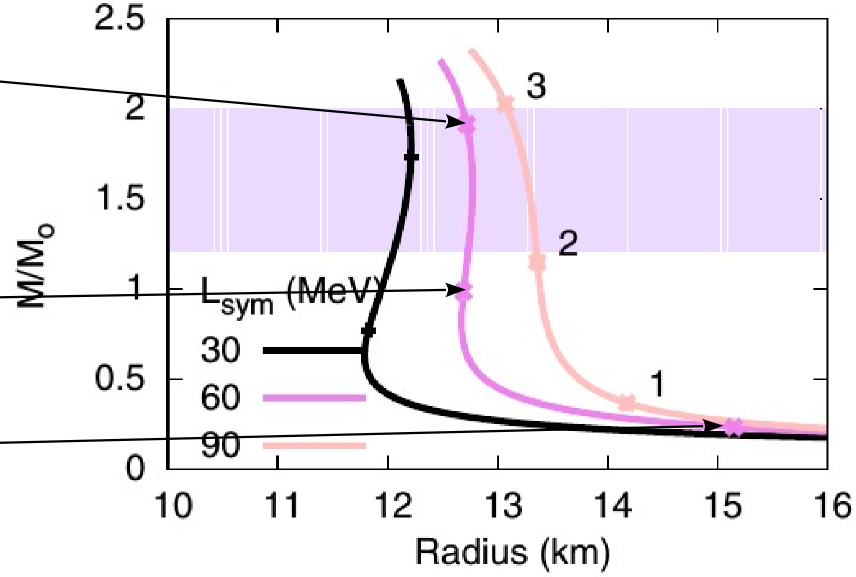


Neutron star radius
Needs the EoS, general relativity, and the sospin content of the system from beta-equilibrium. Mass-radius correlation strongly sensitive to the EoS.

Margueron PRC **97** (2018) 025805
Margueron PRC **97** (2018) 025806

EoS and neutron star structure





Neutron star radius
Needs the EoS, general relativity, and the sospin content of the system from beta-equilibrium. Mass-radius correlation strongly sensitive to the EoS.

Astrophysical observation
Any neutron star mass-radius measurement would constrain the nuclear EoS.

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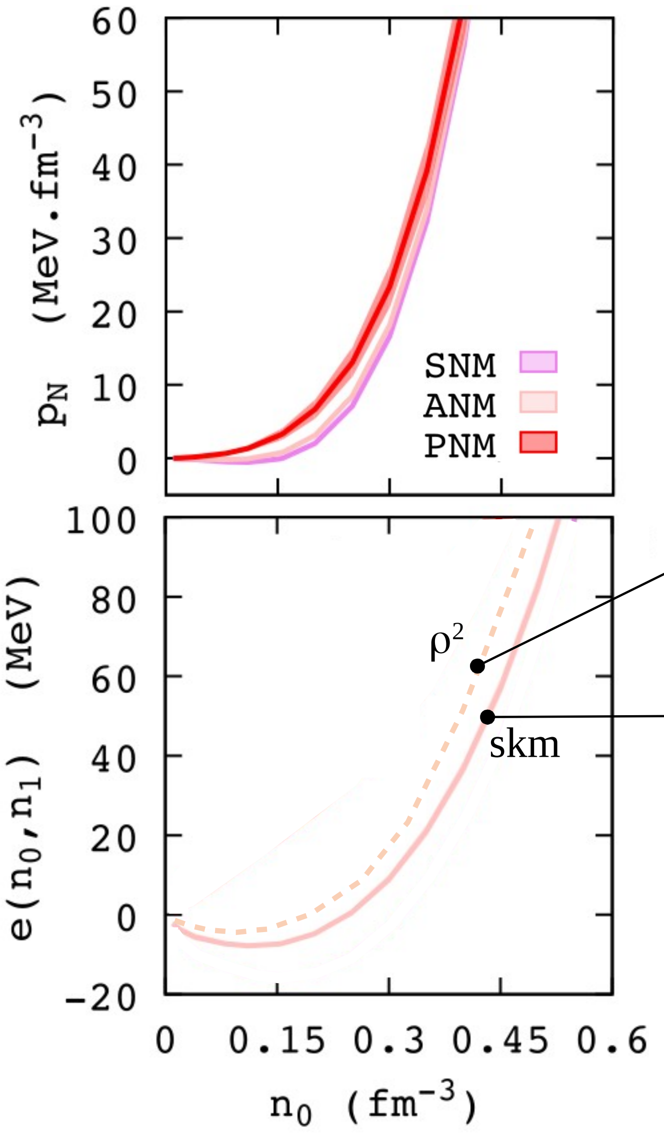
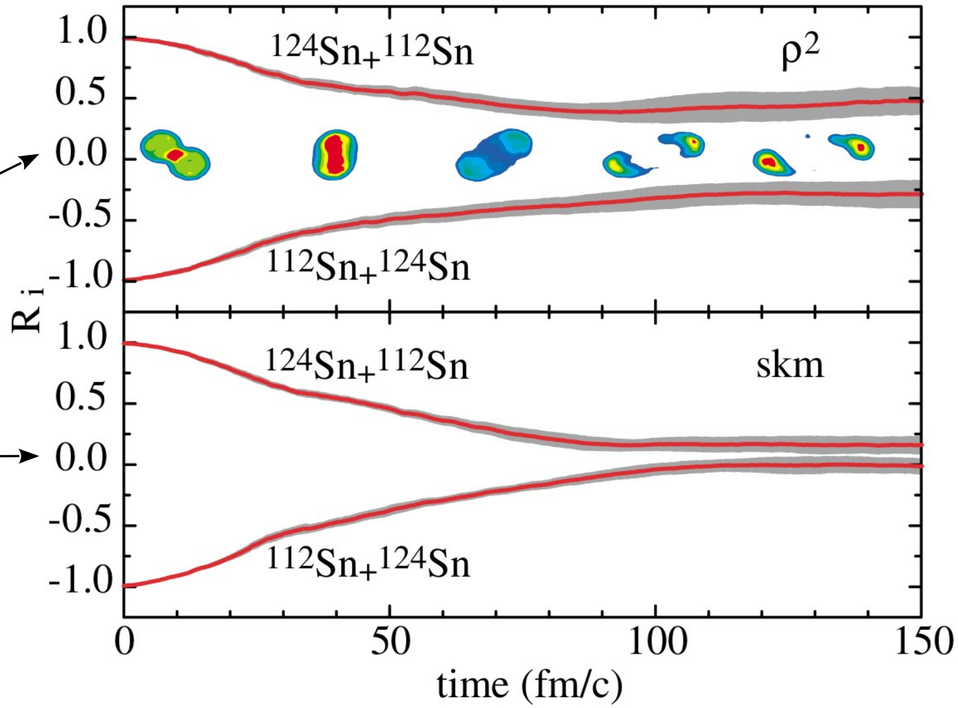
Margueron PRC **97** (2018) 025806

EoS and nuclear dynamics

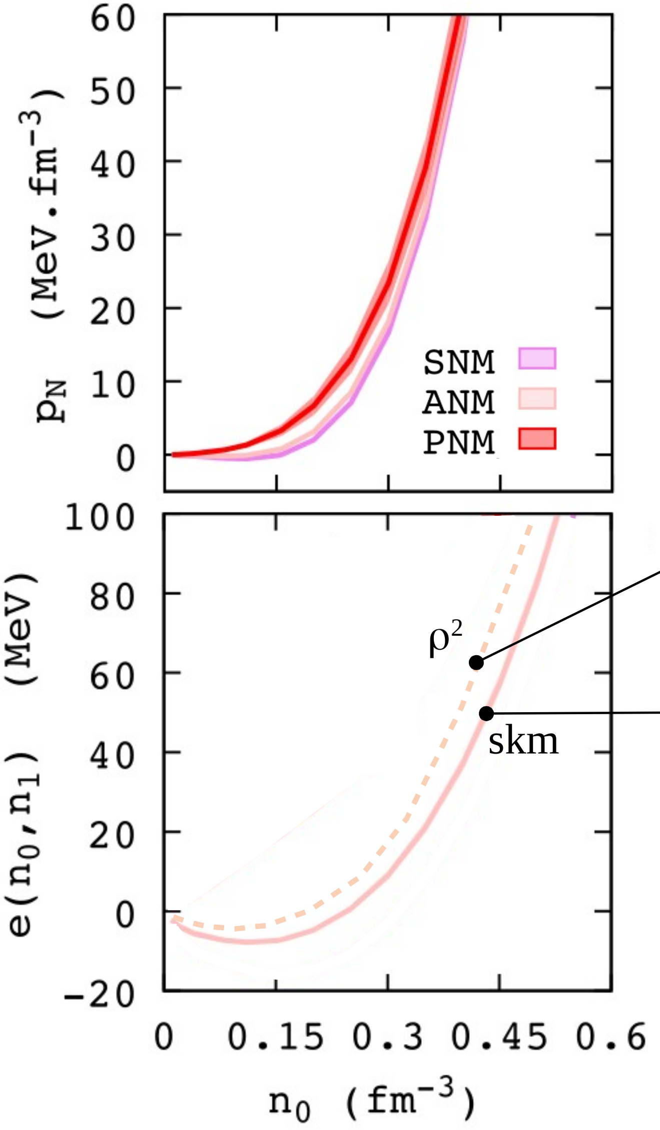


Isospin transport
Neutron/proton equilibration rate in peripheral collisions depends on the strenth of EoS isovector part.



Margueron PRC **97** (2018) 025805
Tsang, PRL 92 (2004) 062701

EoS and nuclear dynamics



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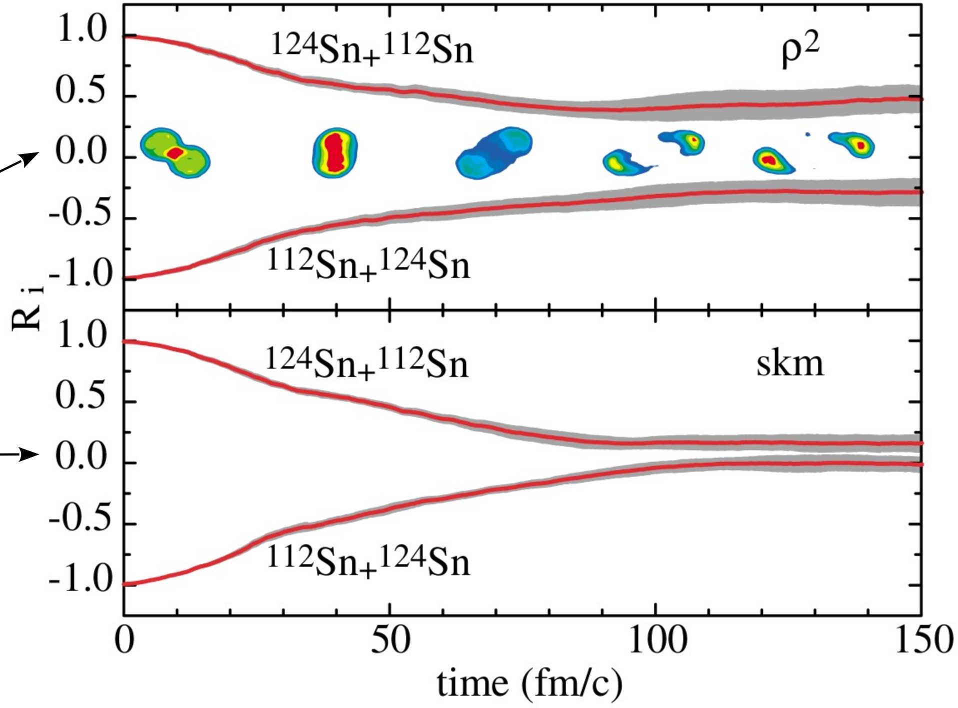

Nuclear experiment
Any experimental measurement of this rate would constrain the nuclear EoS.

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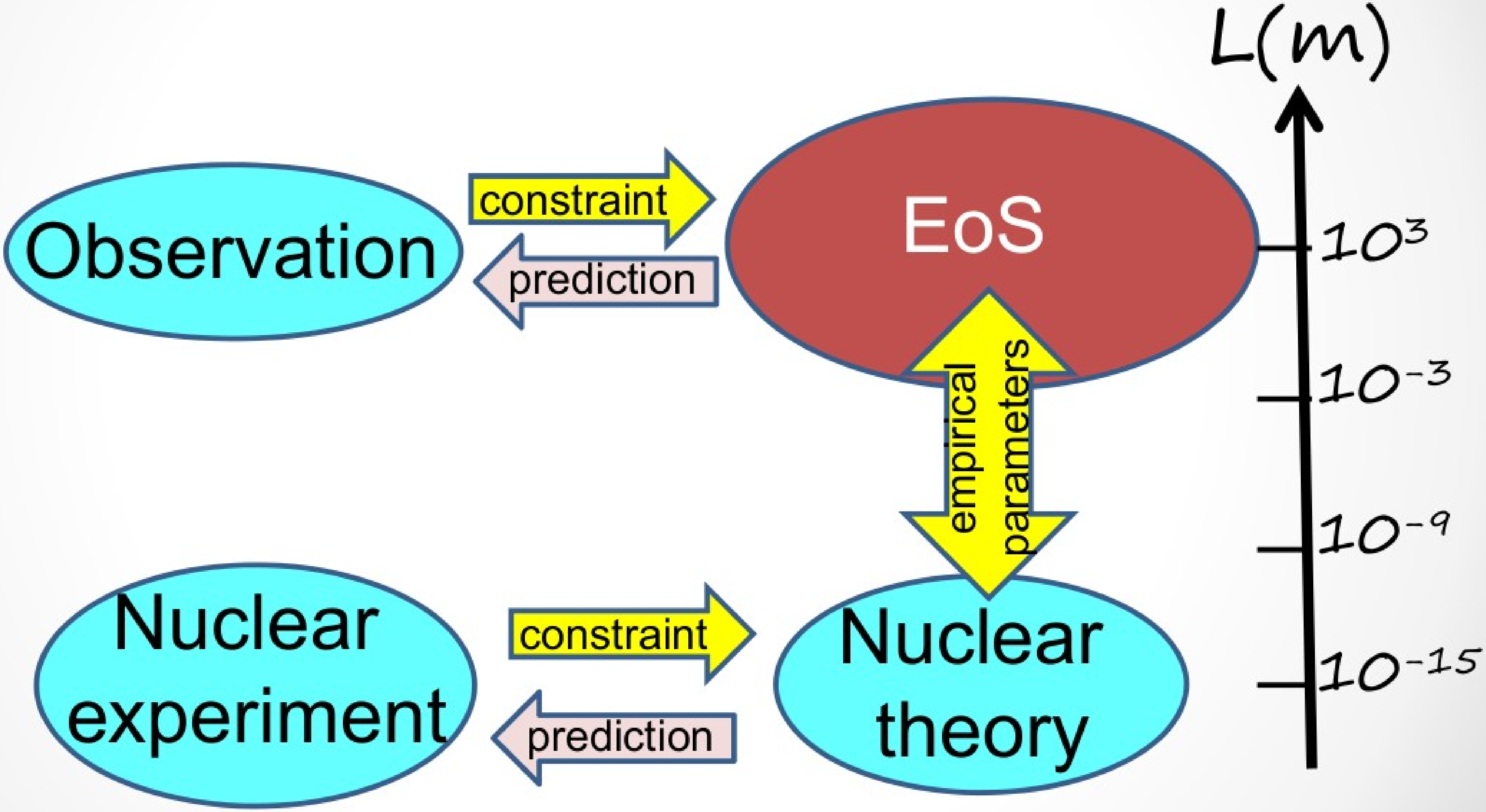
Tsang, PRL 92 (2004) 062701

Constraining the empirical parameters:

jumping across the scales!



Courtesy of Francesca Gulminelli

How to quantify the EoS ? What do we know about it ?

Isoscalar and isovertor part
The energy functional can be expanded in power of $\delta = (\rho_n - \rho_p)/\rho$ around symmetric nuclear matter ($\delta = 0$) :

$$e(\rho, \delta) = e_{is}(\rho) + e_{iv}(\rho)\delta^2 + O(\delta^3)$$

Empirical parameters
Both terms of the EoS is then Taylor expanded in power of $x = (\rho - \rho_0)/3\rho_0$ around saturation density ($\rho = \rho_0$) :

$$e_{is}(x) = E_{sat} + 1/2\, K_{sat}\, x^2 + O(x^3)$$
$$e_{iv}(x) = E_{sym} + L_{sym}\, x + 1/2\, K_{sym}\, x^2 + O(x^3)$$

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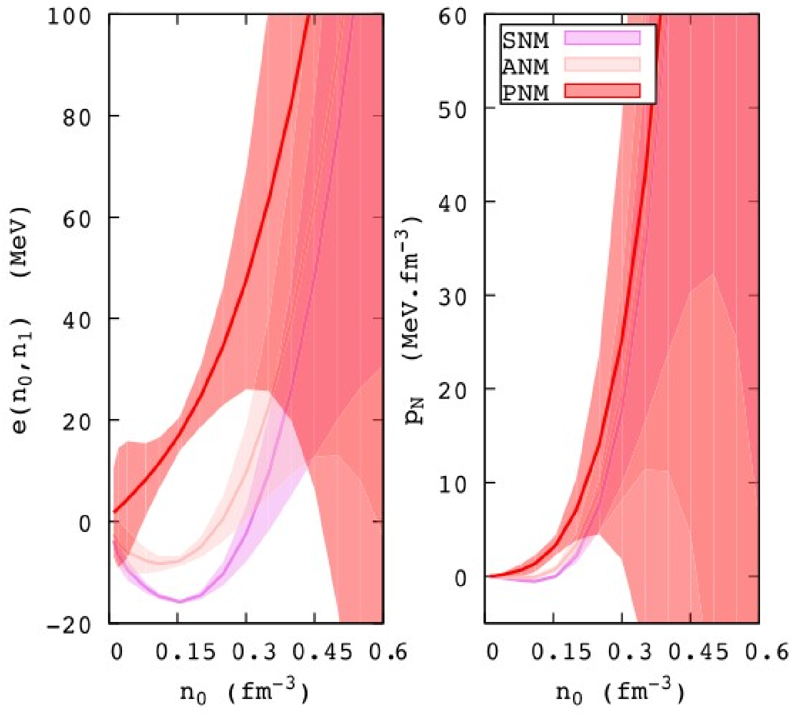


Margueron PRC **97** (2018) 025805

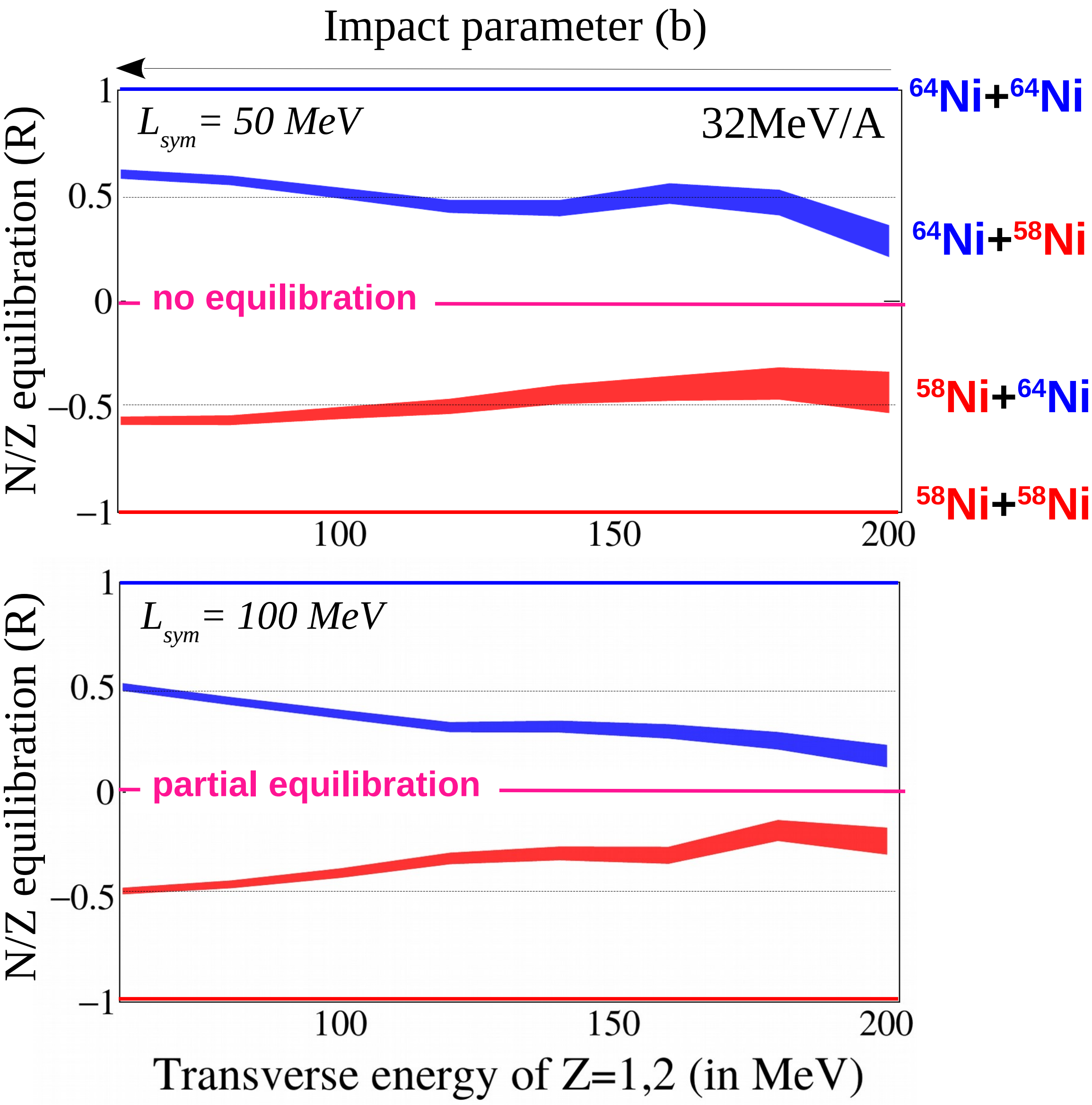
	~1%	~10%		~30%				???		
P_α	E_{sat} MeV	E_{sym} MeV	ρ_0 fm^{-3}	L_{sym} MeV	K_{sat} MeV	K_{sym} MeV	Q_{sat} MeV	Q_{sym} MeV	Z_{sat} MeV	Z_{sym} MeV
$\langle P_\alpha \rangle$	-15.8	32	0.155	60	230	-100	300	0	-500	-500
σ_{P_α}	±0.3	±2	±0.005	±15	±20	±100	±400	±400	±1000	±1000

E789 : Isospin transport and the density dependence of the symmetry energy

Isospin transport
Measure the degree of N/Z equilibration as a function of the impact parameter in ^{58,64}Ni+^{58,64}Ni collisions at 32 and 52MeV/A.

Simulations
Antisymmetrized Molecular Dynamics
Statistical decay with GEMINI
INDRA-FAZIA realistic responce
Equilibration rate depends on L_{sym}

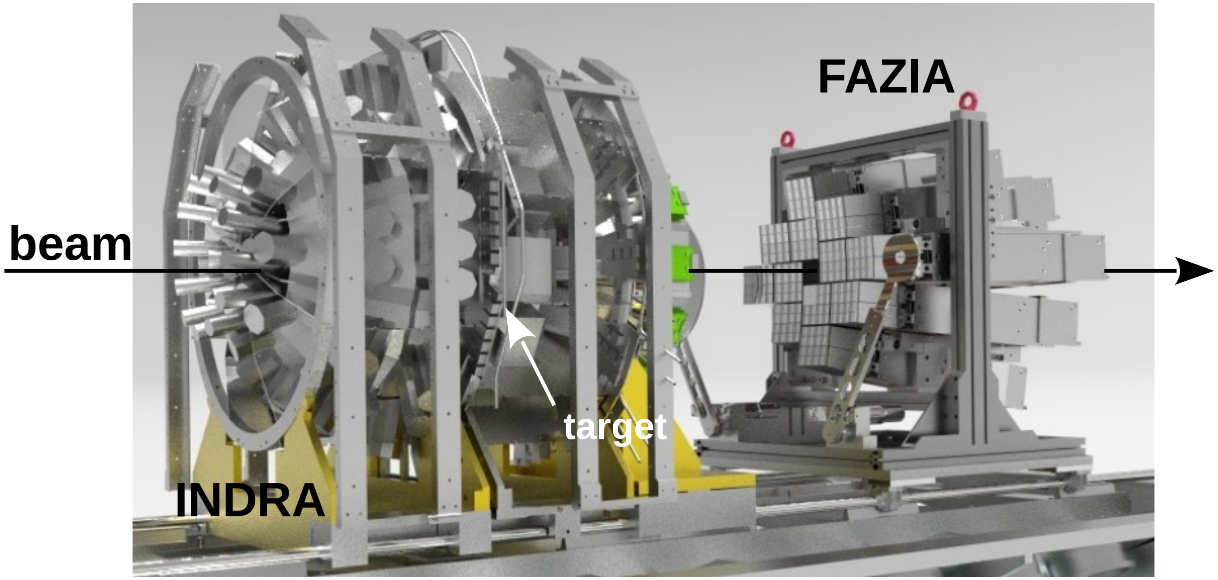
Experimental setup
INDRA-FAZIA coupling in D5
FAZIA : quasi-projectile Z and A
INDRA : almost full angular coverage



Lopez and Piantelli, E789 proposal

INDRA-FAZIA coupling in GANIL (D5)

INDRA (1993)
240 modules (θ from 14° to 178°)
Si-CsI(Tl) telescopes ($\theta < 45^\circ$)
Single CsI(Tl) ($\theta > 45^\circ$)
No gaz → no ionization chamber



Performances
Z-identification up to Z=92
A-identification up to Z=8 ($\theta < 45^\circ$)
A-identification up to Z=5 ($\theta > 45^\circ$)

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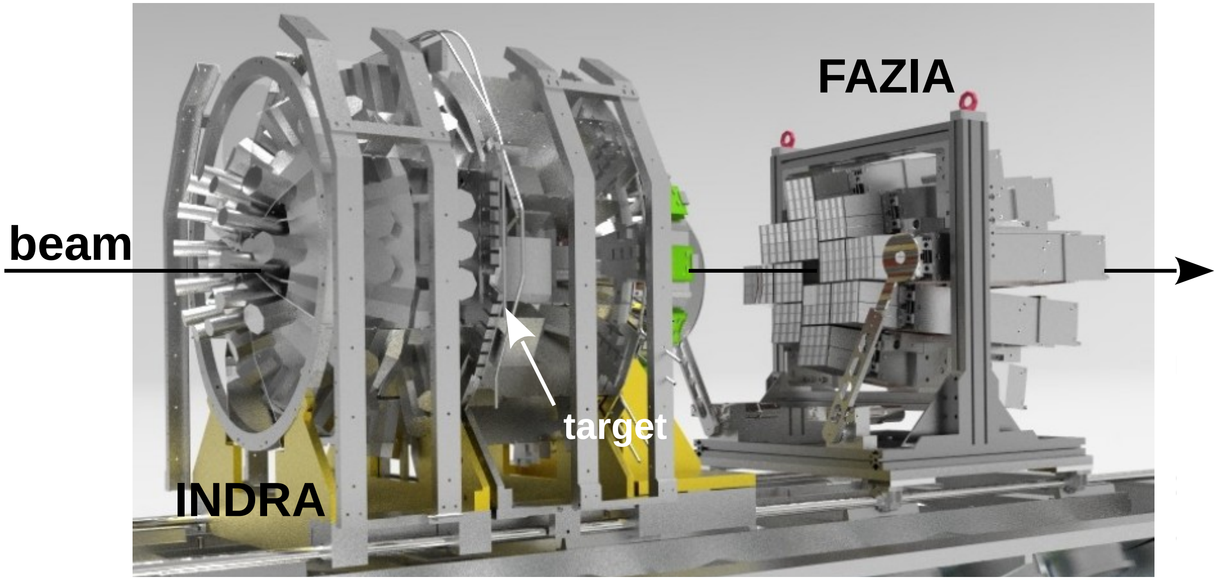
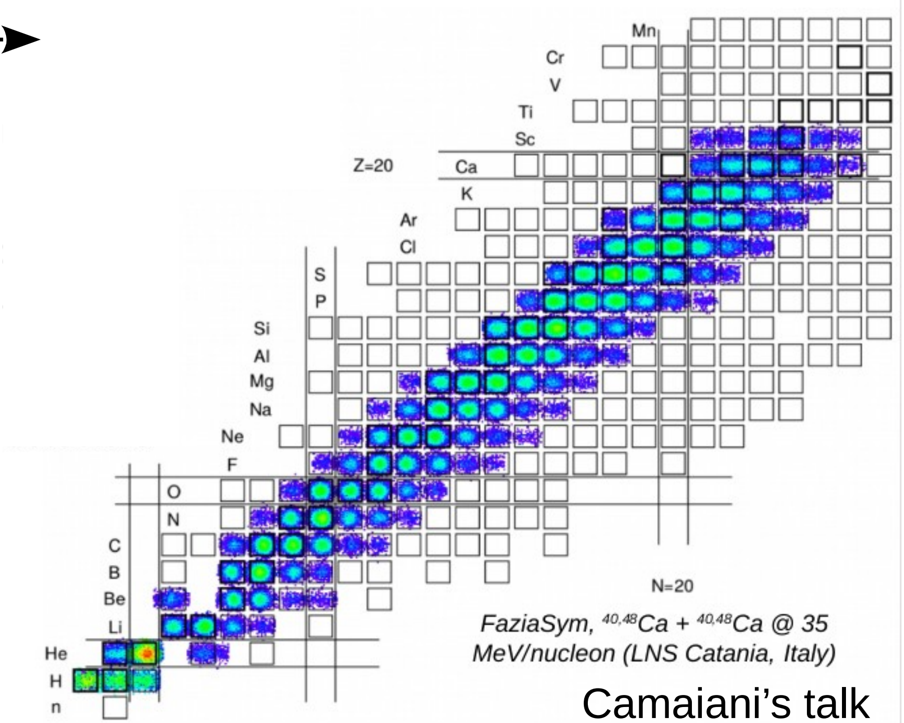


Performances
Z-identification up to Z=92
A-identification up to Z=8 (θ < 45°)
A-identification up to Z=5 (θ > 45°)

FAZIA (2015)
12 Blocks : 192 modules (θ from 1.5° to 13°)
Si-Si-CsI(Tl) telescopes

Identification methods
ΔE-E, PSA in Si, PSA in CsI(Tl)

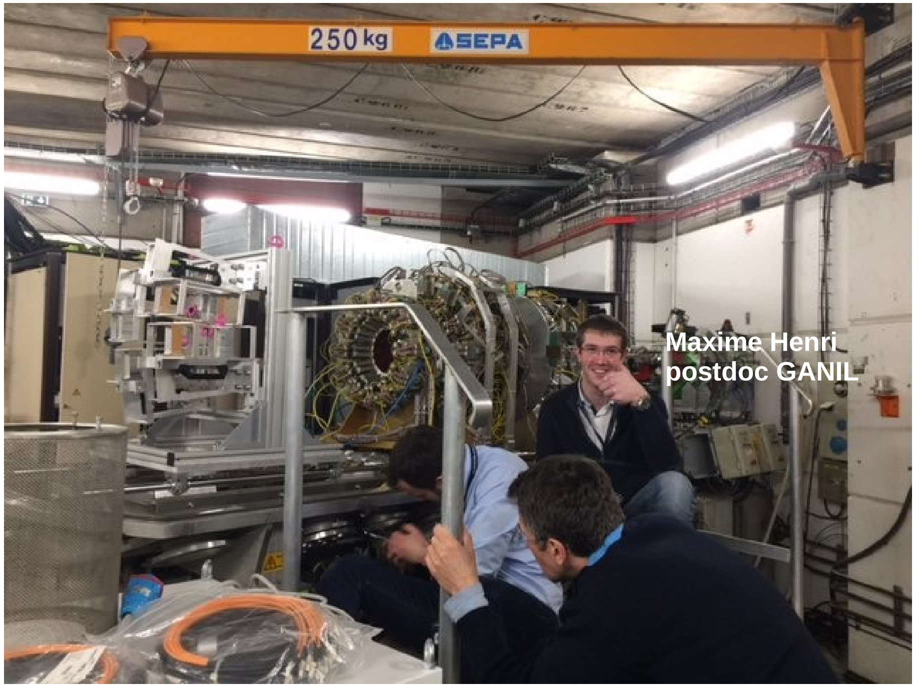
Performances
Z-identification up to Z=92
A-identification up to Z~20-25



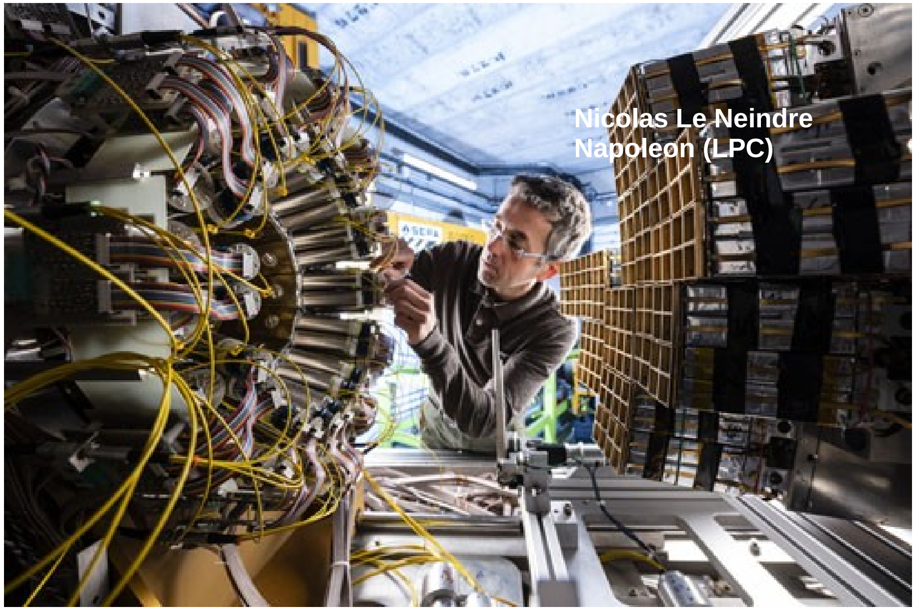
FaziaSym, ^{40,48}Ca + ^{40,48}Ca @ 35 MeV/nucleon (LNS Catania, Italy)

Camaiani's talk

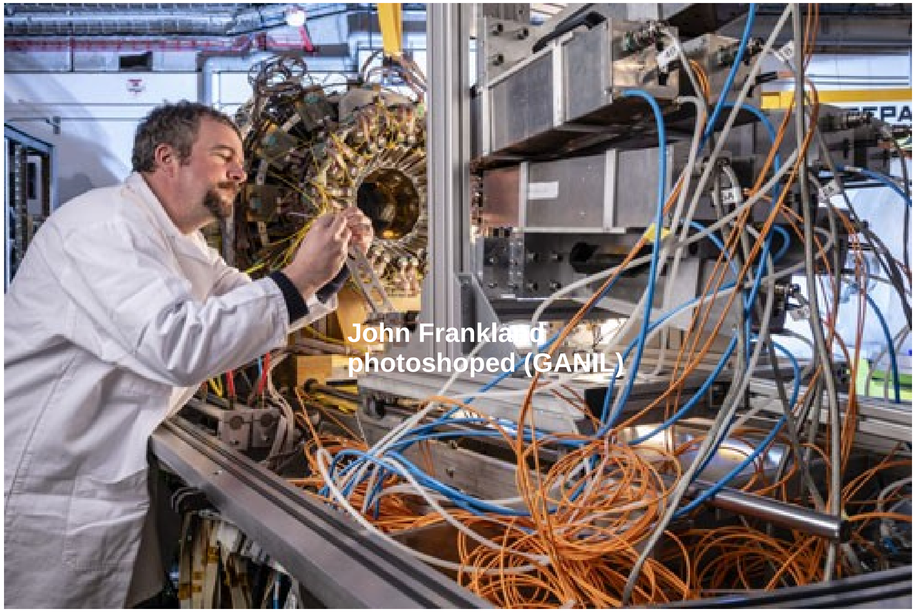
INDRA-FAZIA mounting in GANIL (D5)



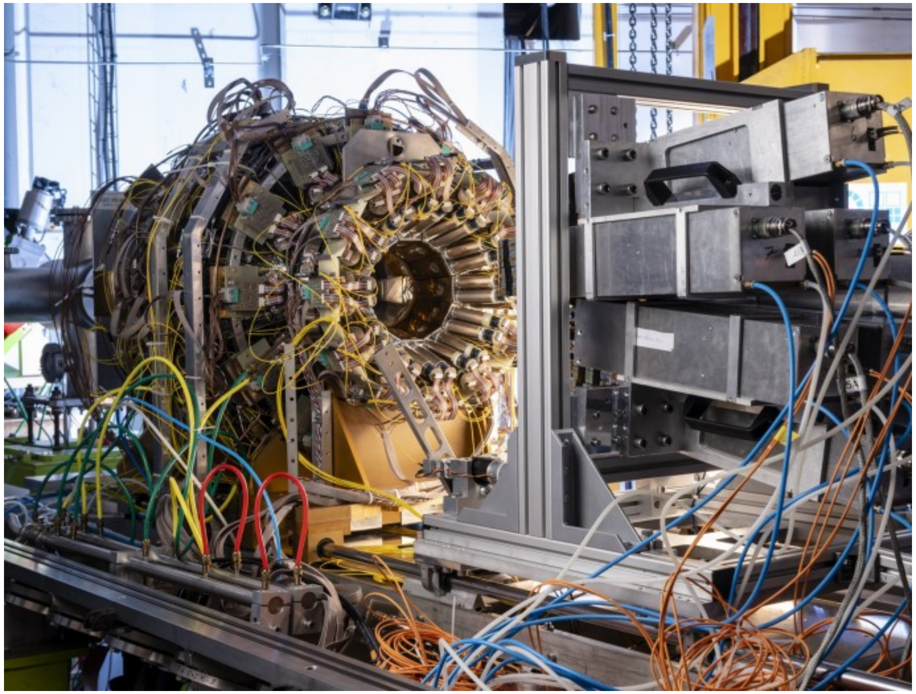
Maxime Henri
postdoc GANIL



Nicolas Le Neindre
Napoleon (LPC)



John Frankland
photoshoped (GANIL)



Acquisition coupling and event merging

Trigger settings

INDRA → multiplicity ≥ 2
FAZIA → multiplicity ≥ 2
→ multiplicity ≥ 1 downscale 100

Acquisition coupling

Each detector has its own acquisition system. To build a physical event we need an universal clock → CENTRUM

Event merging

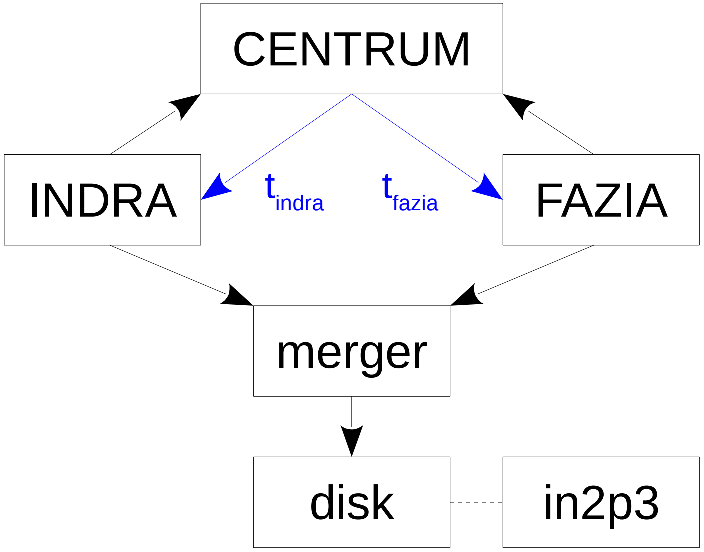
If $t_{indra} – t_{fazia}$ inside the coincidence window, the two events are merged online

Free wheeling mode

No coincidence requested, both detectors can be acquired alone

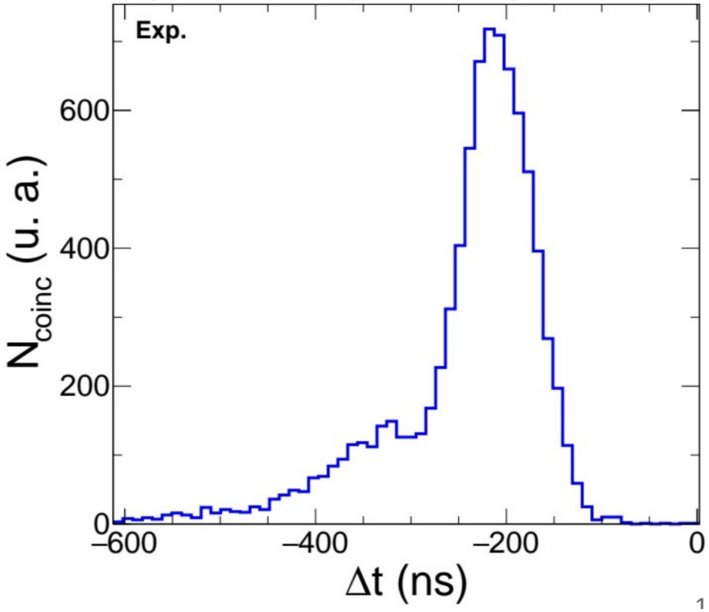
Physics mode

INDRA needs FAZIA in coincidence
FAZIA can be acquired alone only if INDRA is not in veto



CENTRUM
INDRA
t_{indra}
t_{fazia}
FAZIA
merger
disk
in2p3

Test beam: ^{13}C + ^{58}Ni @ 50 MeV/nucleon
Experiment configuration – April 2019



Overview of the data

Statistics

^{58}Ni+^{58}Ni at 32 MeV/A ~30 10^6 events
^{58}Ni+^{64}Ni at 32 MeV/A ~30 10^6 events
^{64}Ni+^{58}Ni at 32 MeV/A ~30 10^6 events
^{64}Ni+^{64}Ni at 32 MeV/A ~30 10^6 events
^{58}Ni+^{58}Ni at 52 MeV/A ~30 10^6 events
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Total **~240 10^6 events**

Data reduction

Full identification in INDRA
Full identification of particle stopped in the 2nd Si and in CsI(Tl)
PSA identification in 1st Si and detector calibration to be completed

Overview of the data

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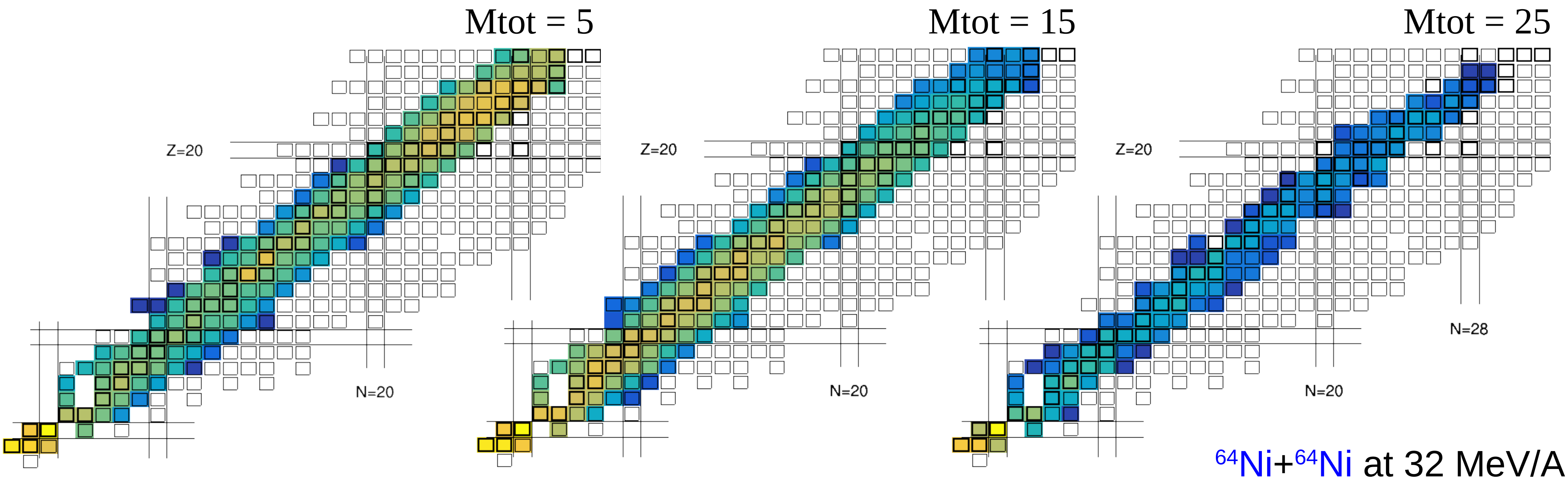
Preliminary results

The fragment size decreases with increasing violence of the collision...



^{64}Ni+^{64}Ni at 32 MeV/A

Preliminary results on isospin equilibration

Y-axis

N/Z equilibration ratio measured with FAZIA

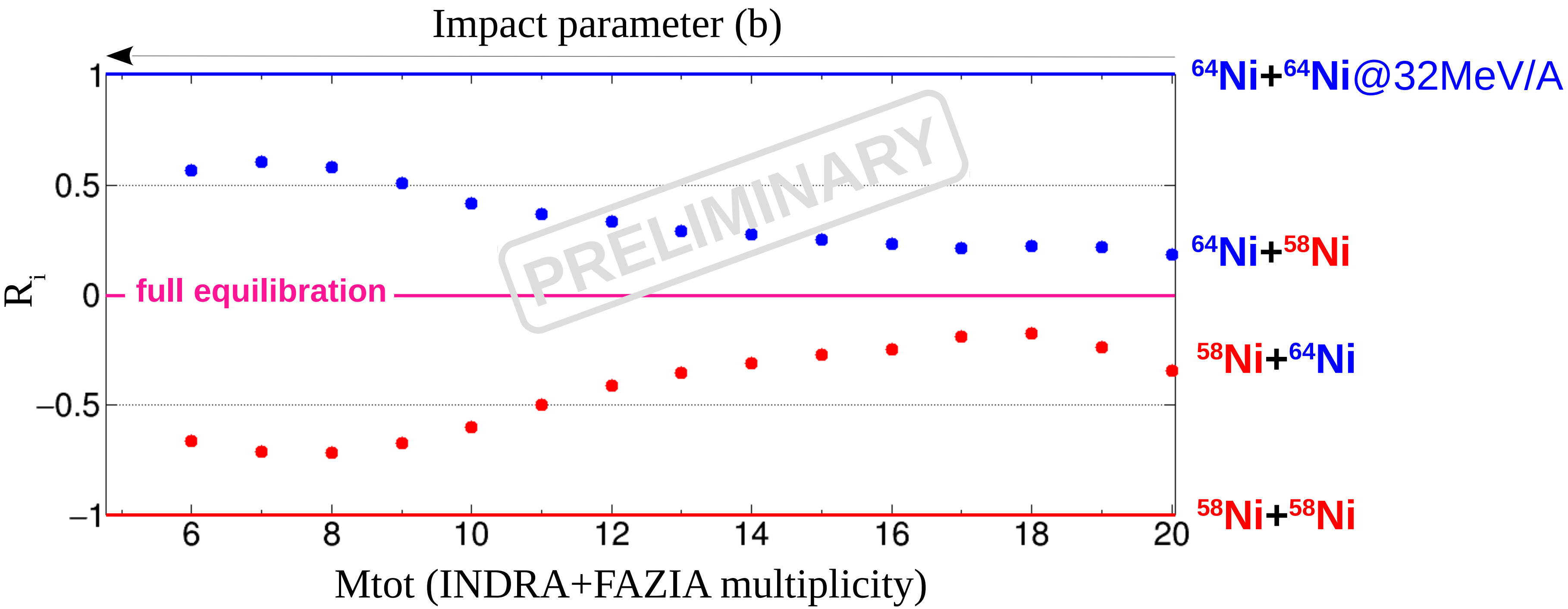
$R_i = (2X_i - X_1 - X_2)/(X_1 - X_2)$, with $X_i = (N_{PLF}/Z_{PLF})_i$

$R_i = +1\ (-1)$: no N/Z equilibration

$R_i = 0$: full N/Z equilibration

X-axis

Number of fragments detected in INDRA and FAZIA. Can be linked to the impact parameter without model assumption (J. Frankland)



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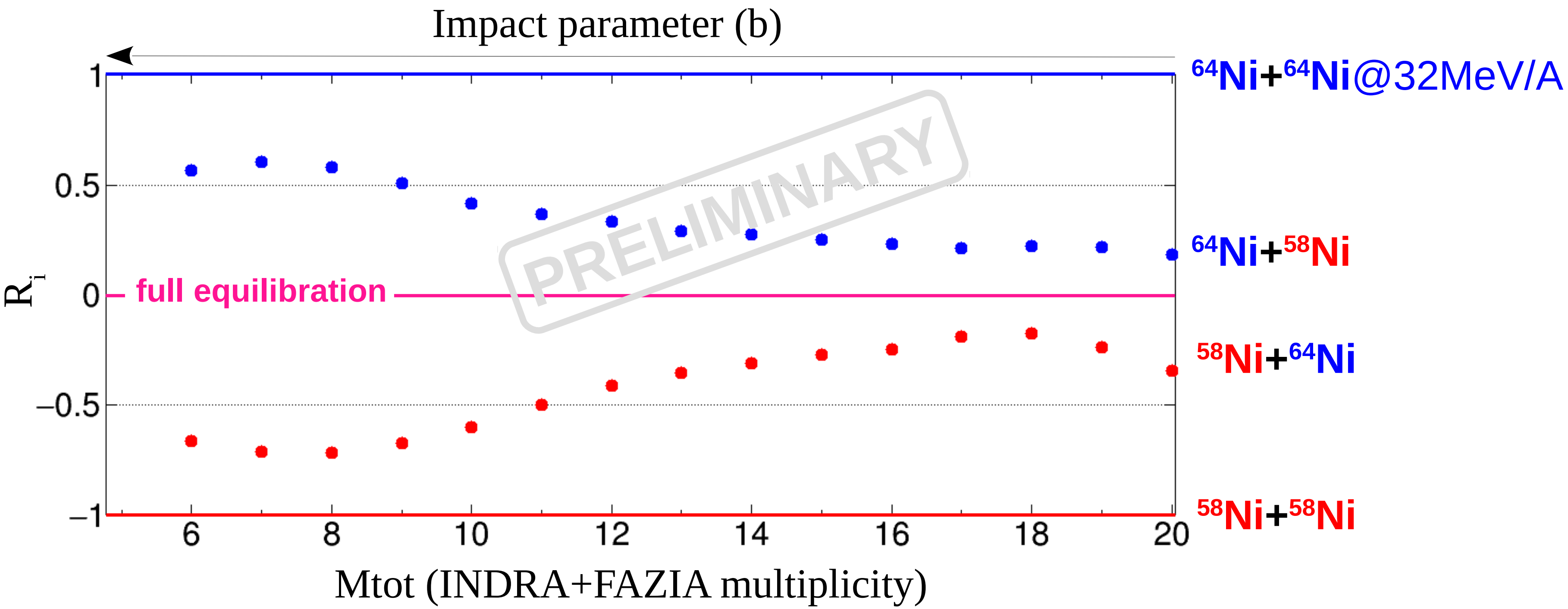


Preliminary conclusion

Little equilibration at high impact parameter

Partial equilibration at low impact parameter

To be done

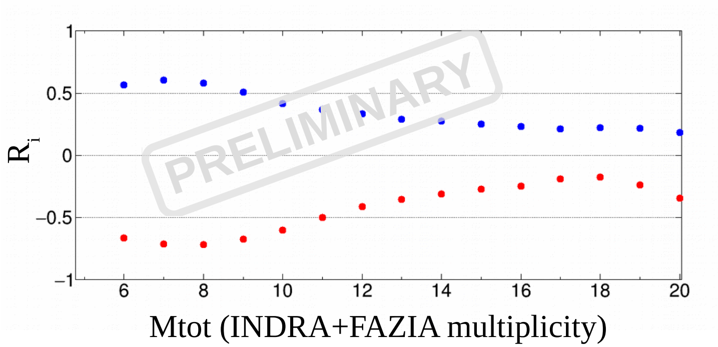
Complete the data reduction

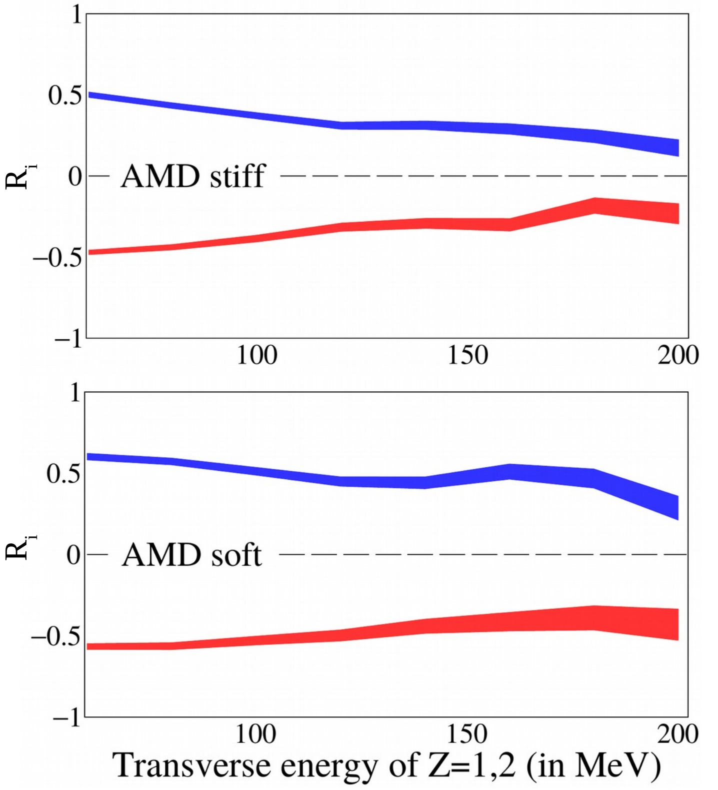
Compare with model calculations

Summary and futur plans

E789 analysis
Experiment done last spring and partially analyzed
Seems to favor the stiff equation of state (L_{sym}=100MeV)
Identification/calibration validated within few months
Data-model comparaisons to constrain EoS parameters

Students/postdoc
Joël Quicray, Ph.D. LPC (poster)
Julien Lemarié, Ph.D. GANIL
Seon Ho Nam, Ph.D. Korean University
Maxime Henri, postdoc GANIL
Future postdoc for model calculations, LPC





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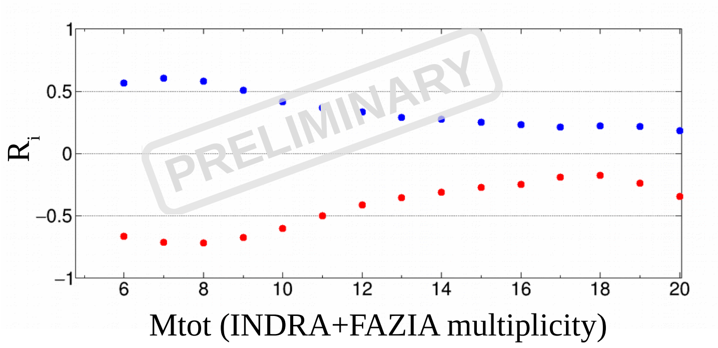

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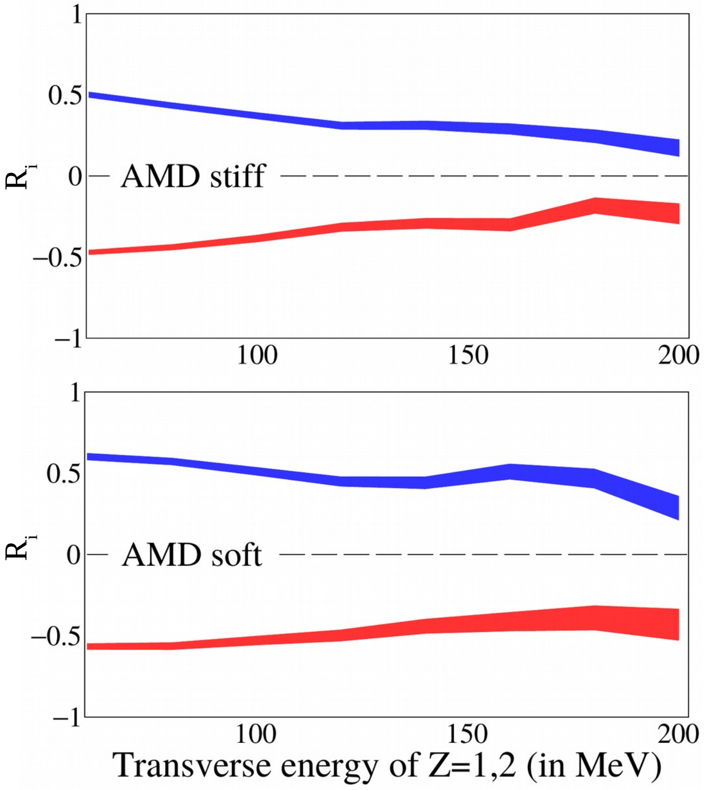
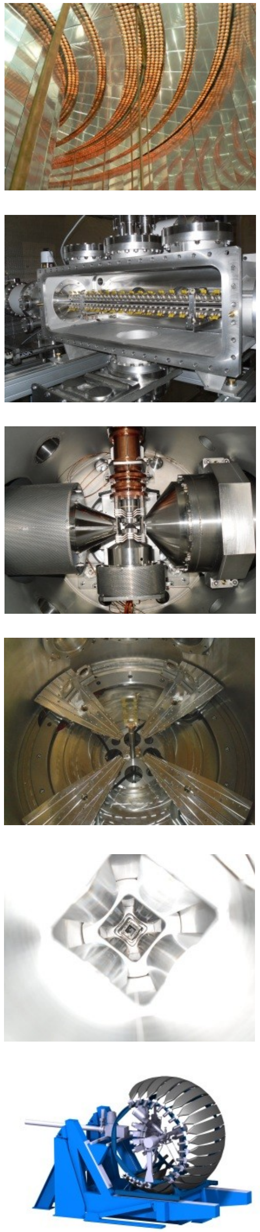


GANIL PAC 2020
1. Isospin dynamics from quasiprojectile fission fragments (Piantelli, INFN Firenze)
2. Cluster formation and decay in very excited light systems at Fermi energies (Camaiani, INFN Firenze)

FAZIA workshop
From 24 to 25 September in GANIL to discuss futur plans with FAZIA at GANIL (D5, LISE, other couplings)

Thank you for your attention



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INDRA FAZIA

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