Experimental study of the equation of state.

Abdou Chbihi (GANIL)
Quentin Fable (L2IT-IN2P3)

- Goal
  - constrain the density dependence of the symmetry energy at low densities
  - improve the knowledge of volume and surface contributions to the symmetry energy in nuclei
  - investigate the experimental isospin transport
- Precise measurement of isotopes emitted in HI-collisions at intermediate incident energies
- Determination of the symmetry energy coefficients
- Study of the isospin diffusion and isospin migration
- Conclusion

Q. Fable et al., Phys. Rev. C 107, 014604 (2023)
Q. Fable et al., Phys. Rev. C 106, 024605 (2022)

the nuclear equation of state

- property of Nuclear Matter that describes relationship between E, P, T, ρ, n-p asymmetry (δ)

$$\epsilon(\rho,\delta)=\epsilon(\rho,\delta=0)+\epsilon_{sym}(\rho).\delta^2+\ldots$$

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

- The symmetric term has been extensively studied, its stiffness established
- The asymmetric term ε_{sym} (ρ) is unknown for $\rho \neq \rho 0$

it is an important ingredient necessary to resolve many important issues in nuclear physics and Astrophysics

- it is relevant to describe:
  - structure of exotic nuclei – neutron stars
  - dynamics of HI reactions – supernovae explosions
  - gravitational waves - neutron star mergers – black holes,
  - etc.

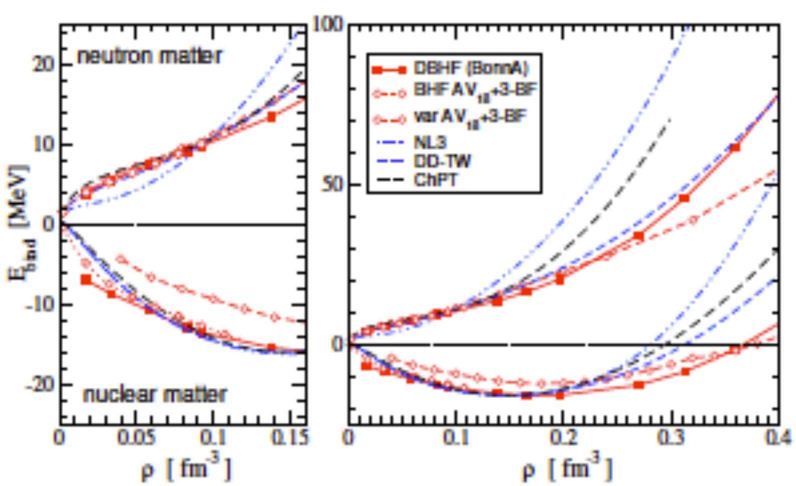
EPJ A (2014) 50.

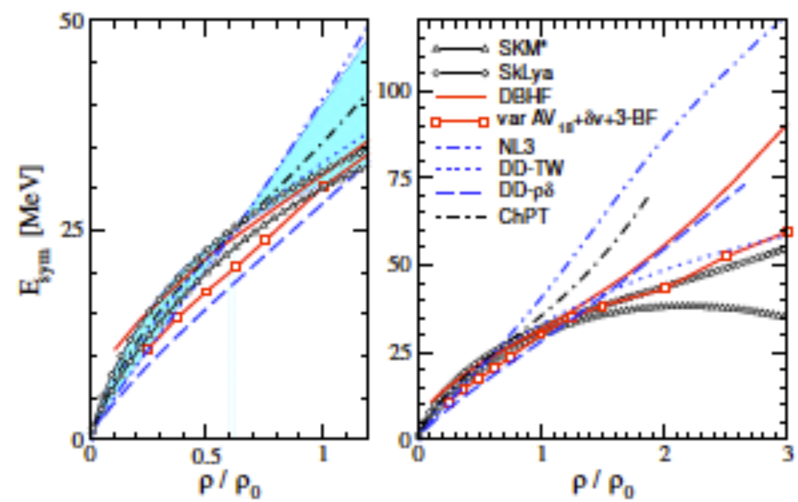
Models for EOS

- ♦ phenomenological density functionals
  - ➢ based on effective density-dependent interaction : Gogny, Skyrme forces, RMF
- ♦ Effective-Field Theory approaches
  - ➢ based on expansion on the EOS in powers of density, Fermi momentum
- ♦ Ab initio approaches
  - ➢ based on high-precision free space NN interaction.

the parameters of these models are usually constrained by nuclear properties around the saturation density and extrapolated to higher/lower densities.

-> So **we do have a relatively a good agreement between different models around saturation densities, but divergence otherwise.**

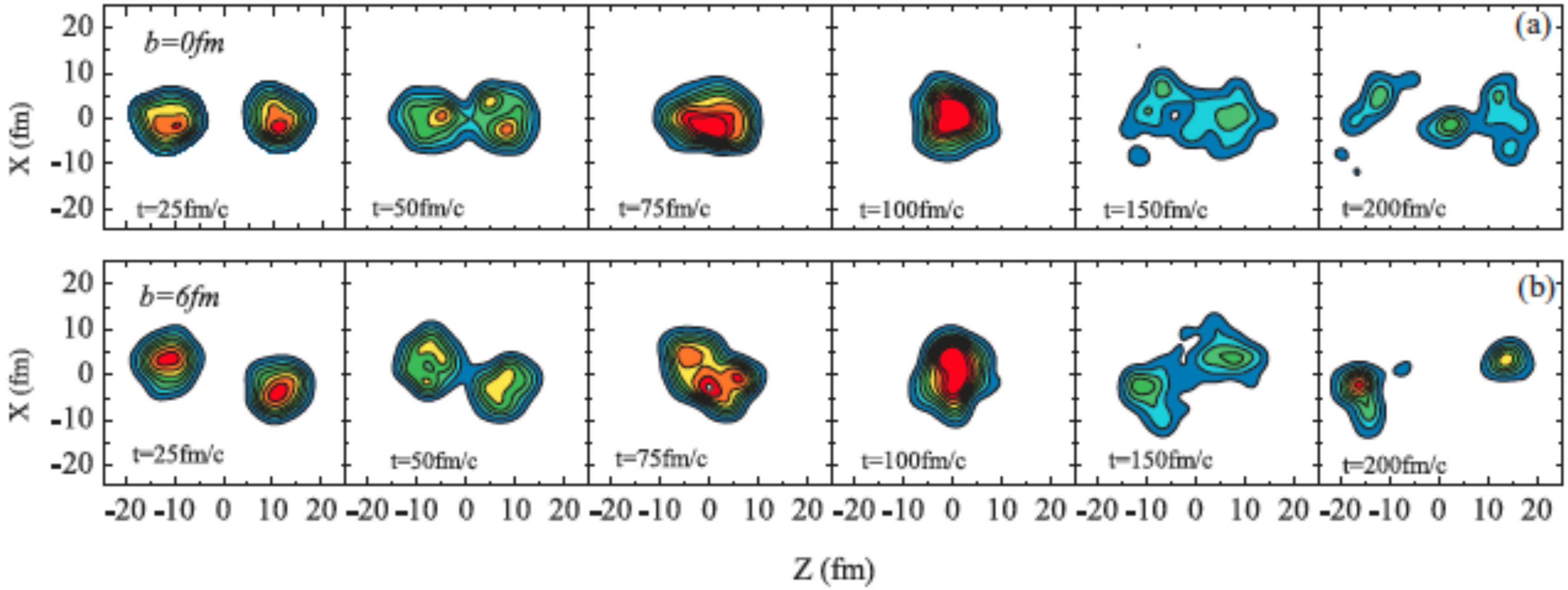




C. Fuchs and H.H. Wolter, EPJ. A.30, 5 (2006)
P. Danielewicz et al., Science 298,1592 (2002)
P. Russotto et al., EPJ. A 50: 38 (2014)
J. Margueron PRC 97, 025805, 2018

Tools to probe the EOS: heavy-ion collisions

direct emission compression/expansion fragment production +SD



- ImQMD05 Yingxun Zhang et al., PRC 85, 024602 (2012)
- time evolution of the nucleon density in the reaction plane of $^{124}Sn+^{124}Sn$ @ E/A = 50 MeV, b = 0 and 6 fm
- various densities are reached
- low densities at mid-rapidity

A few definitions:
Projectile-like-fragment (PLF): the detected fragment (PLF)
Quasi-projectile (QP): the reconstructed hot fragment before its decay
Light-charged-particles (LCP): p, d, t,3He, 4He, 6He.

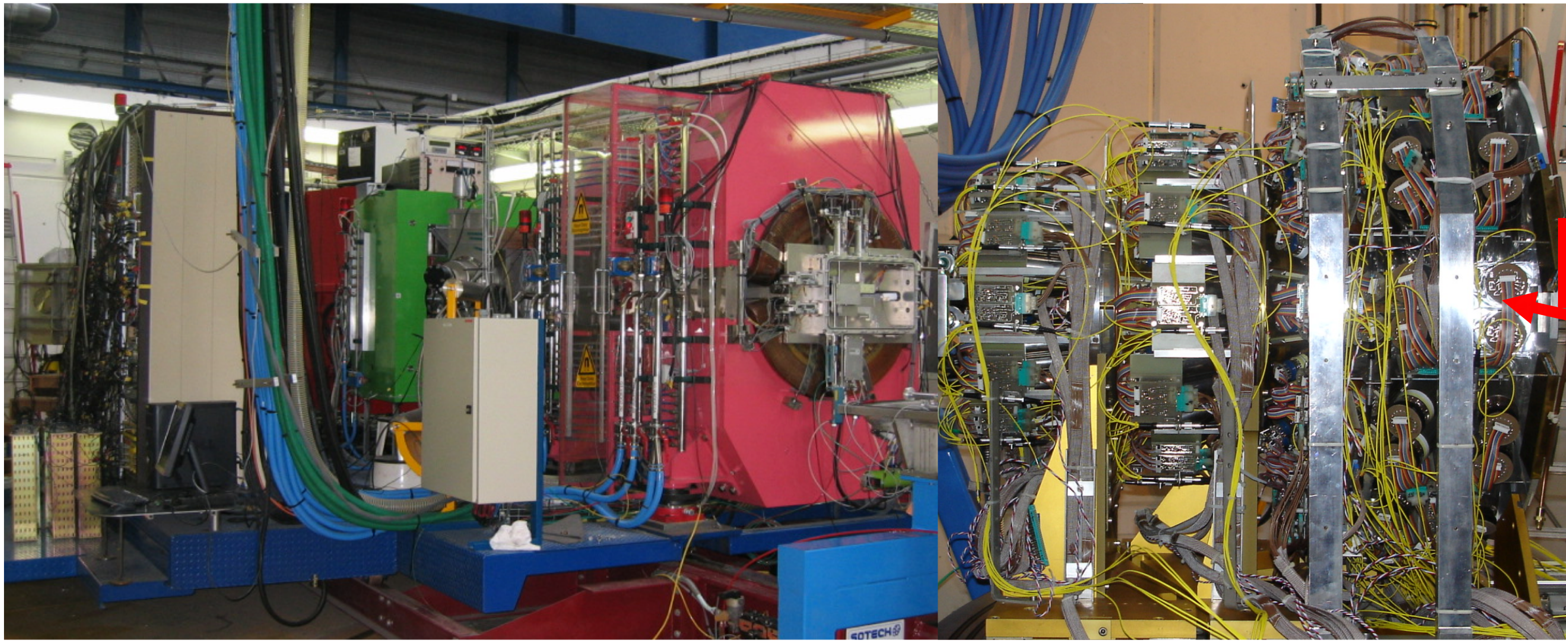
observables to probe the EOS

- **Observables Esym(ρ) :**
  - Isoscaling : provides symmetry energy coefficients
  - Drift : density gradient
  - diffusion : isospin gradient

Experiments

- $^{40}Ca+^{40}Ca$ N/Z = 1 @ E/A=35 MeV
- $^{40}Ca+^{48}Ca$ N/Z=1.2
- $^{48}Ca+^{40}Ca$ N/Z=1.2
- $^{48}Ca+^{48}Ca$ N/Z=1.4

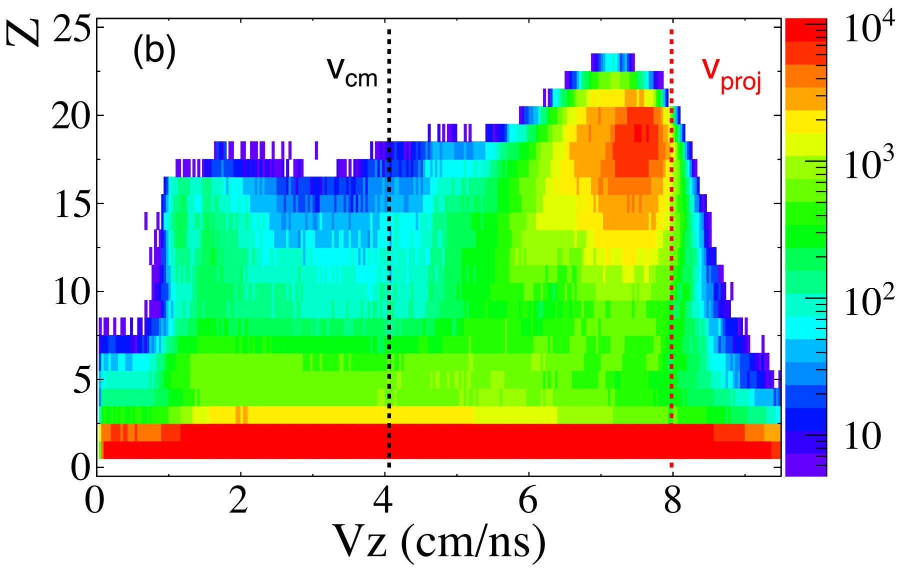
detection | Dipole | Q2 | Q1 | INDRA

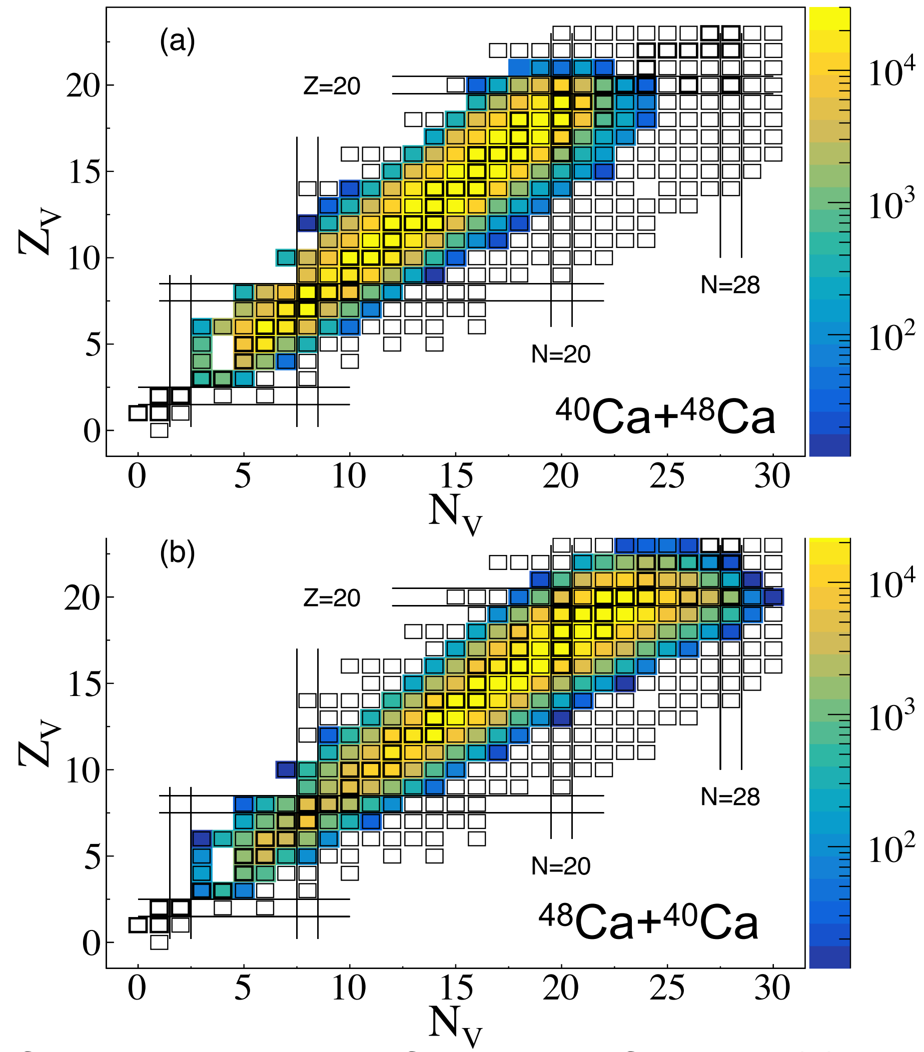


- **VAMOS high acceptance spectrometer, angle 2-7°**
  - charge and mass identification (more than 10 isotopes / Z)
  - 12 Brho sets measurements in order to cover the whole velocity range of fragments
  - special attention to the normalization between Brho based in Zgoubi package.
- **INDRA 4π detector, 7-176°**
  - Z and A identification for Z<5
  - Z identification for Z>=5

topology of the events

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





TLF-Indra
LCP-

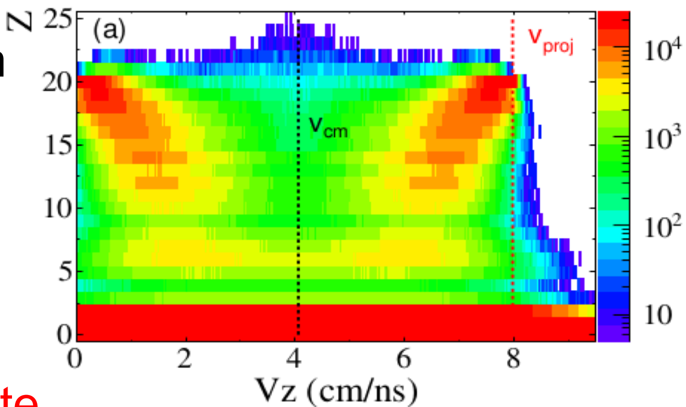
PLF-VAMOS

- Identification in charge and mass for a wide range of isotopes for Z=5-22
- Proton drip line is populated
- Memory of the entrance channel
- n-rich projectile shows broad isotopic distributions

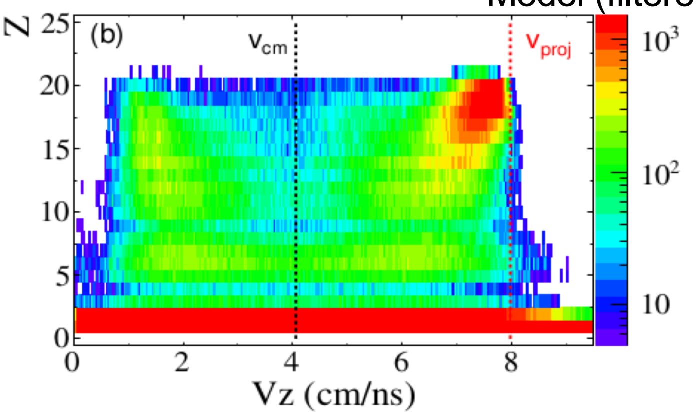
INDRA-VAMOS : model calculations

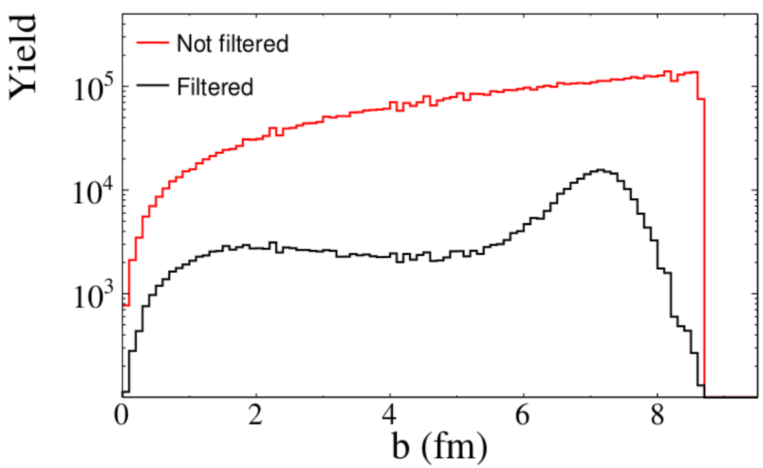
- AMD + GEMINI++ calculations
- Triangular input imp. par. distribution : 0< b < 8.5fm
- Collisions followed up to t_{lim} = 300 fm/c
- INDRA-VAMOS experimental filter (KaliVeda)
- → VAMOS angular acceptance and trigger favourite the detection of semi-peripheral collisions

Model (not filtered)



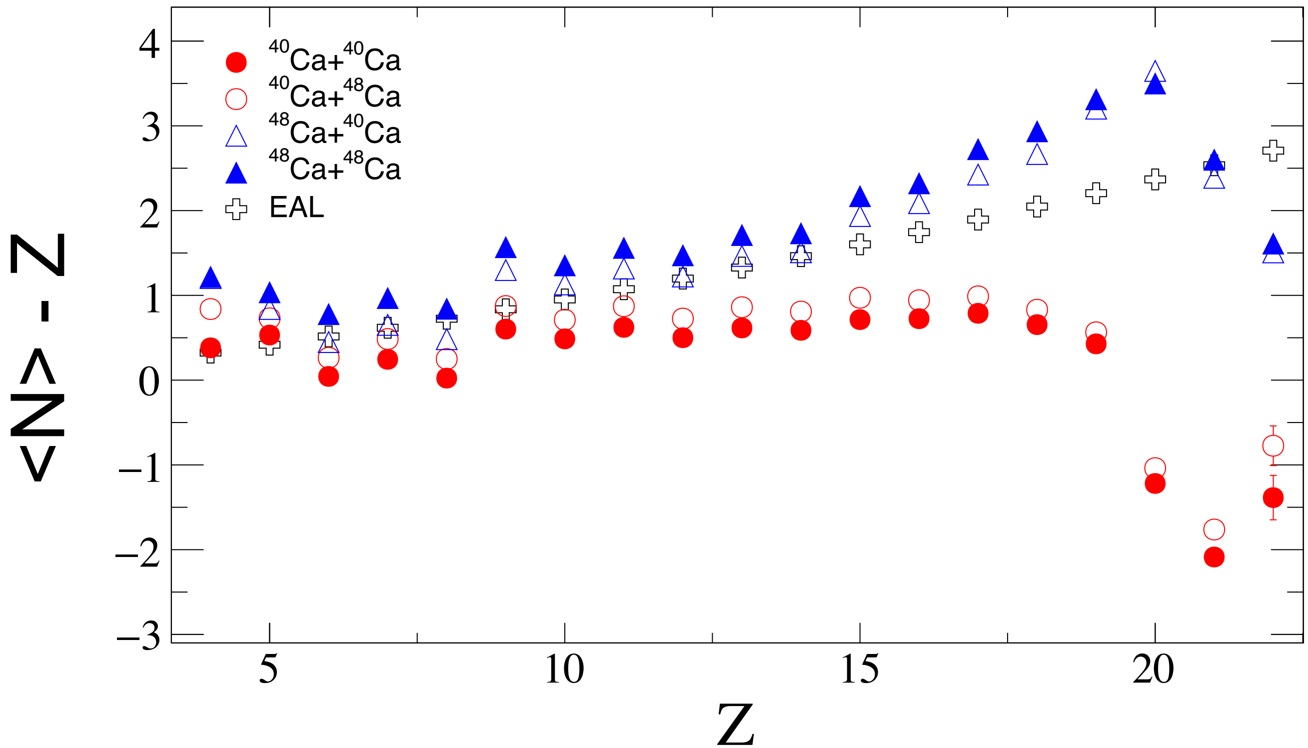
Model (filtered)





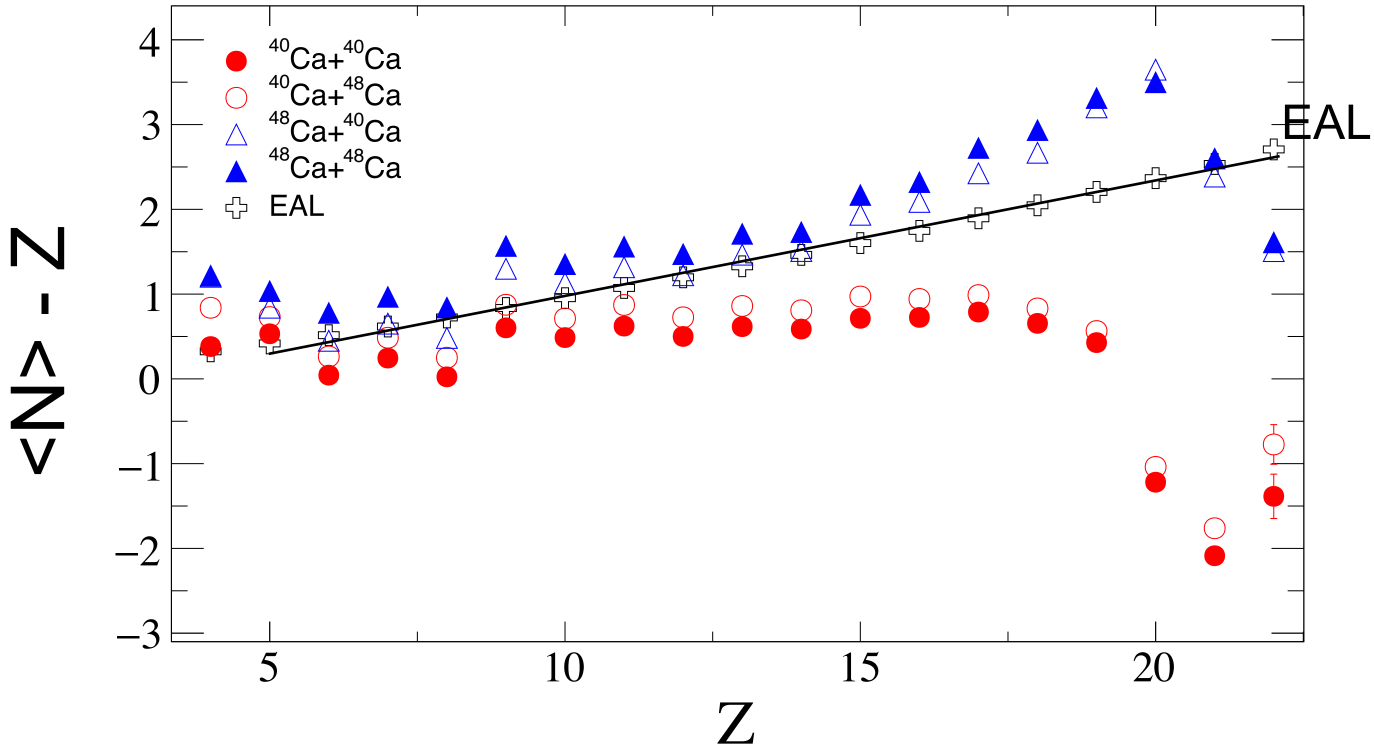
Q. Fable et al., Phys. Rev. C 106, 024605 (2022)
KaliVeda HIC analysis toolkit - http://indra.in2p3.fr/kaliveda/

Average neutron excess vs Z_{vamos}



- The fragments measured for the 48Ca projectile are more n-rich than those for the 40Ca projectile for all Z's.
- small effect of the target is observed (open symbols)
- it is experimental evidence of the isospin diffusion

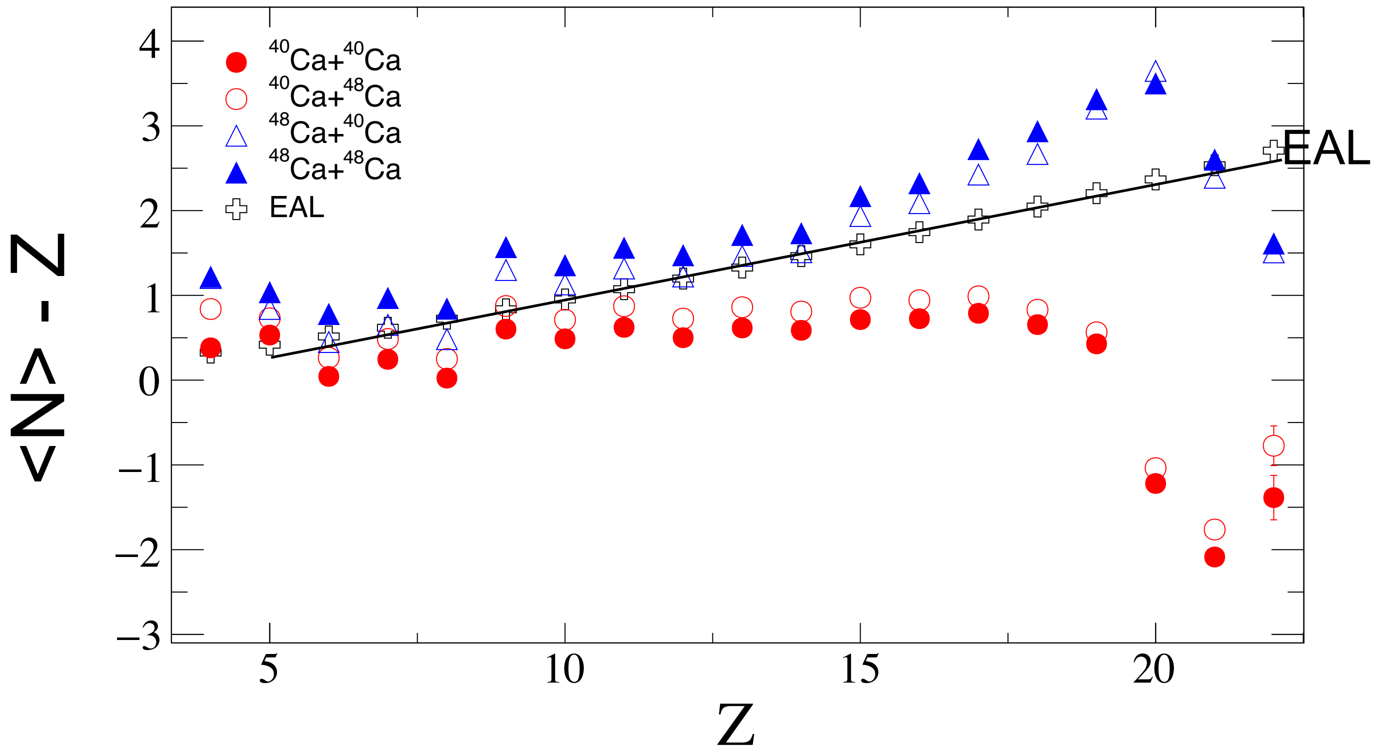
Average neutron excess vs Z_{vamos}



- EAL defined as the line in N. Chart towards which an ER of excited source moves as it cools.
- For Z = 20
  - For 48Ca projectile we observe <N>-Z = 3.5;
  - For 40Ca projectile we observe <N>-Z = -2
- Both branches are attracted towards the EAL

R. J. Charity, Phys. Rev. C 58, 1073 (1998)

Average neutron excess vs Z_{vamos}

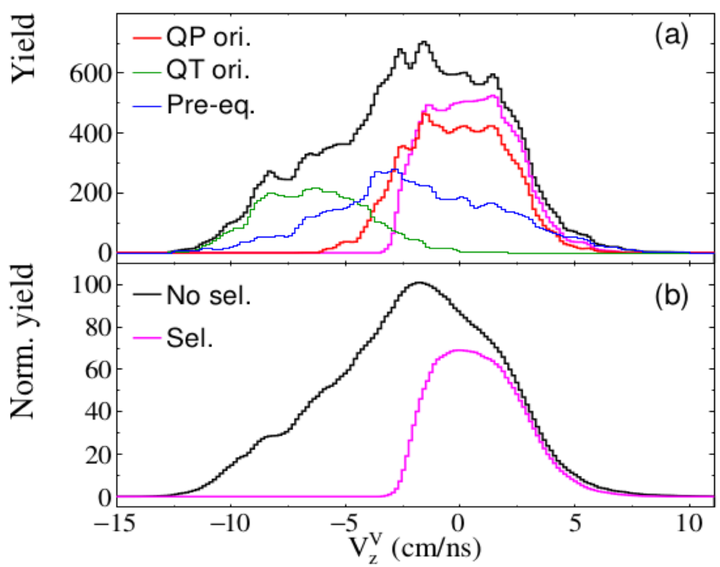


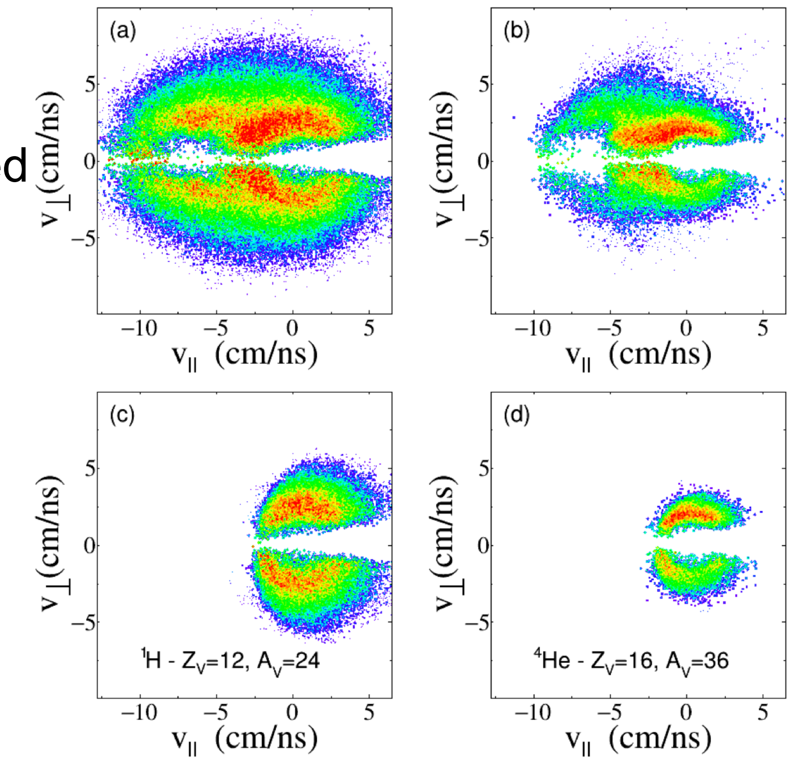
- reaching the EAL is the interplay between isospin diffusion and secondary decay
- How to disentangle the two contributions ?
- Using observables involving ratio of n-rich / n-poor systems, (isoscaling, imbalance ratio) to minimize the effect of secondary decay.
- reconstruction of primary quantities (advantage: after dynamical calculation no need of SM; at which time connect the SM, 150 – 300 fm/c ?)

Reconstruction of the primary QP

based on the comparison of Vrel(PLF-LCP) and Vrel(TLF-LCP)

- select only the LCP emitted by QP
- $(V_{TLF}-V_{LCP})/(V_{PLF}-V_{LCP}) > 1.4$ for Z=1
- $(V_{TLF}-V_{LCP})/(V_{PLF}-V_{LCP}) > 1.7$ for Z>=2
- if no TLF detected in INDRA, $<V_{TLF}>$ is used
- these cut values were validated by the AMD+GEMINI calculations





Reconstruction of the primary QP

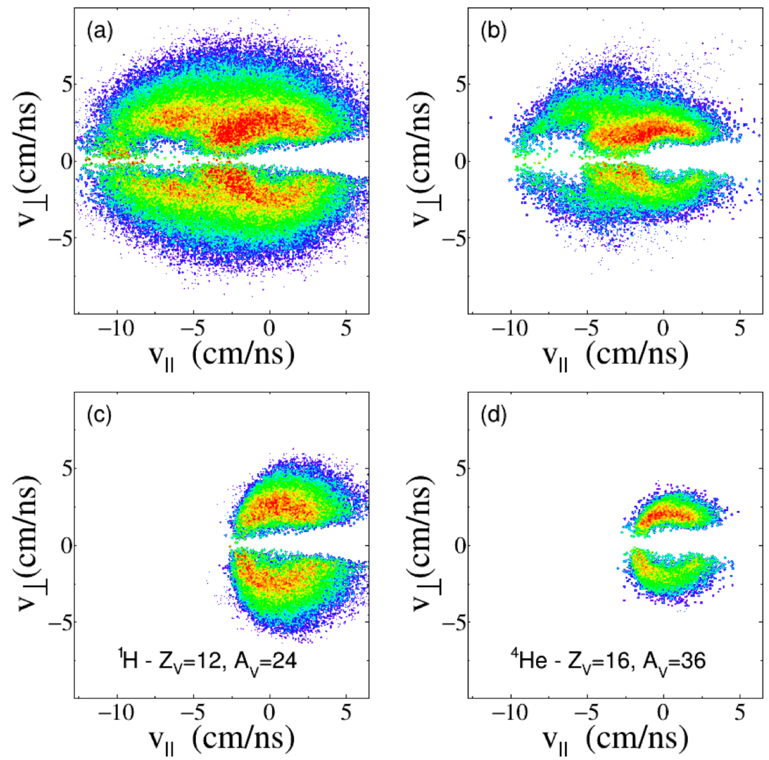
$$Z_{QP} = Z_V + \sum_i^{M_I} Z_i$$

$$\widetilde{A}_{QP} = A_V + \sum_i^{M_I} A_i$$

$$A_{QP} = \widetilde{A}_{QP} + \langle Mn(Z_{QP})\rangle^{mod}$$

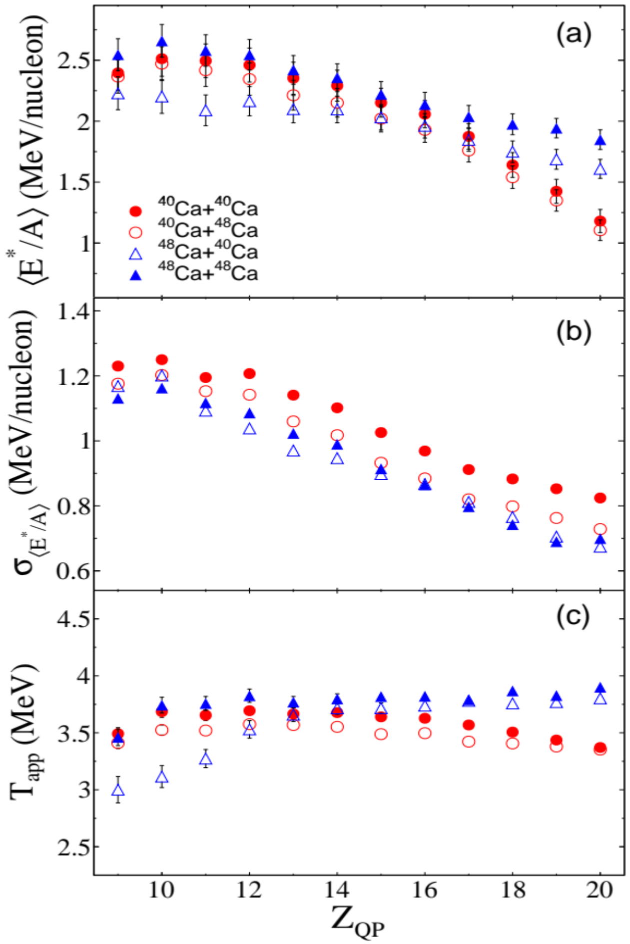
calorimetry:

$$E^* = \sum_i^{M_{CP}} Ek_i + M_n \cdot \langle Ek_n\rangle - Q$$

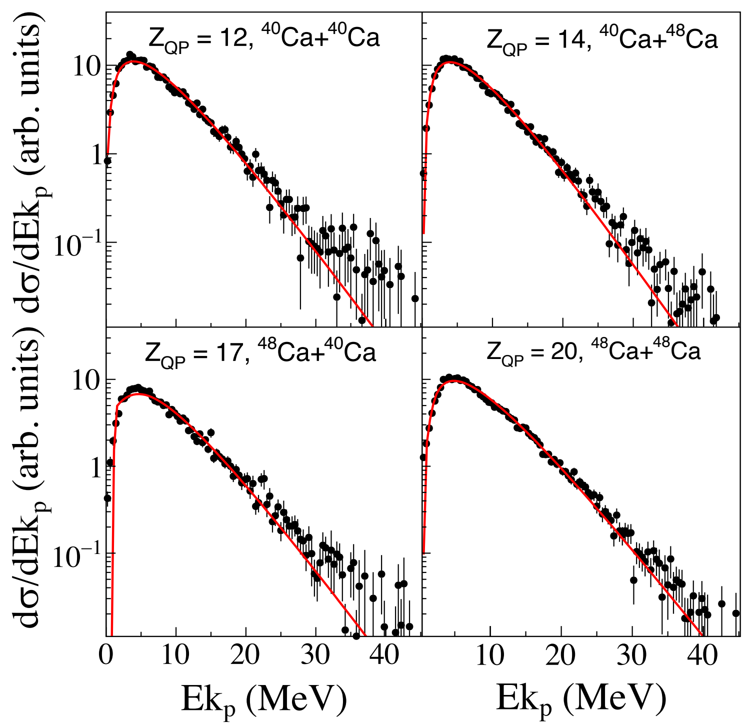


reconstruction of the QP

excitation energy of QP from calorimetry



temperature from the proton energy spectra



moderate temperature 3-4 MeV

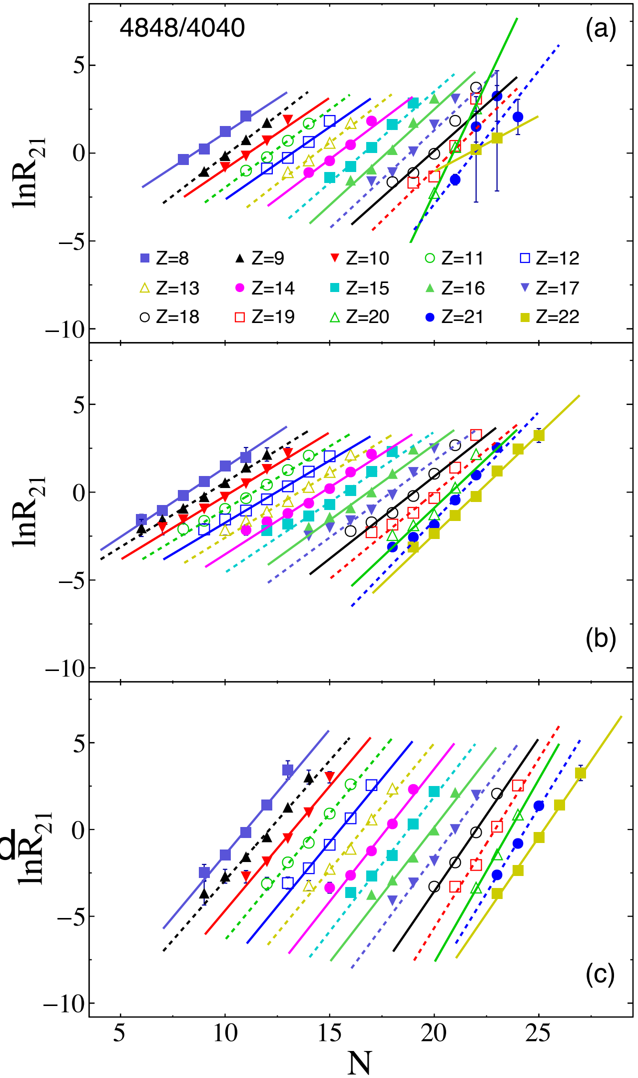
Isoscaling:

$$R_{21}(N,Z) = \frac{Y_{(2)}(N,Z)}{Y_{(1)}(N,Z)} \propto exp[\alpha N + \beta Z]$$

for cold PLF

reconstructed QP **without** neutrons

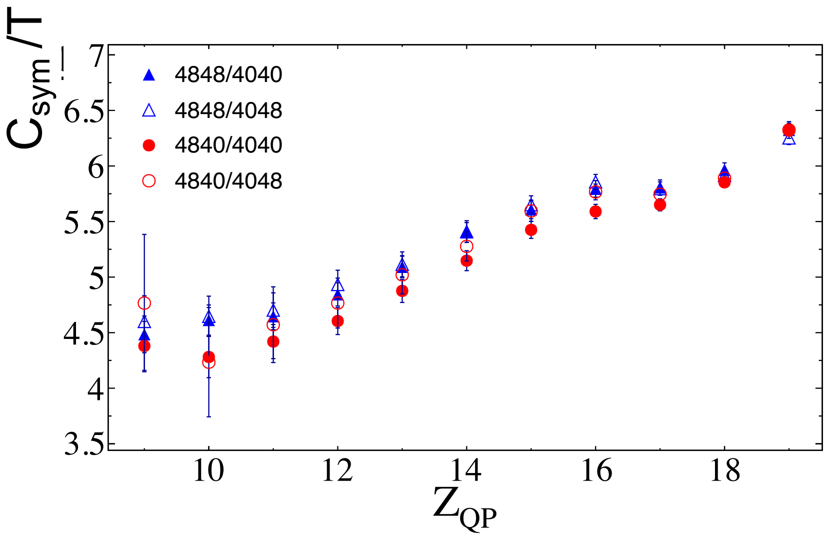
reconstructed QP **with** neutrons

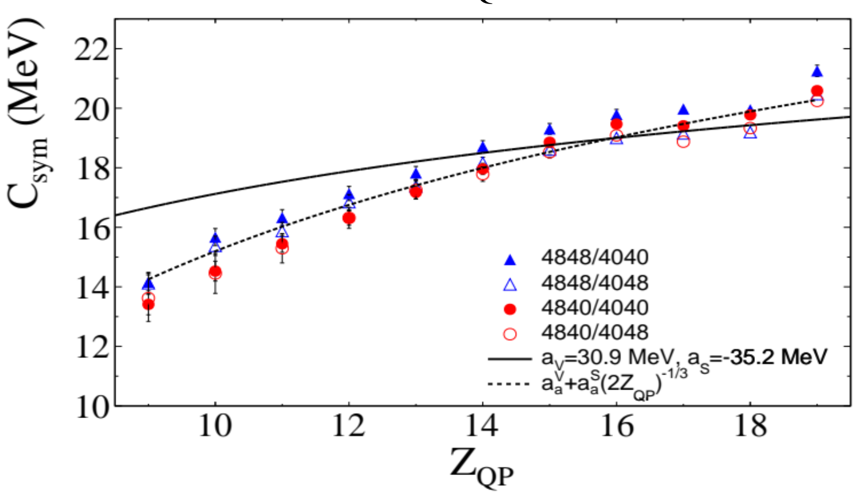


- scaling law observed in HIC in yield ratio of 2 systems differing in their neutron content;
- assuming thermal and chemical equilibrium, the isoscaling parameters α, β can be linked to n, p chemical potentials
  $\alpha = \Delta\mu_n/T \quad \beta = \Delta\mu_p/T$
- gaussian approximation of Yield in grand-canonical ens allows to link α, β to Csym & T

$$\frac{4C_{sym}}{T} = \frac{\alpha}{\left(\frac{Z}{\langle A_1(Z)\rangle}\right)^2 - \left(\frac{Z}{\langle A_2(Z)\rangle}\right)^2}$$

Isoscaling from reconstructed QP

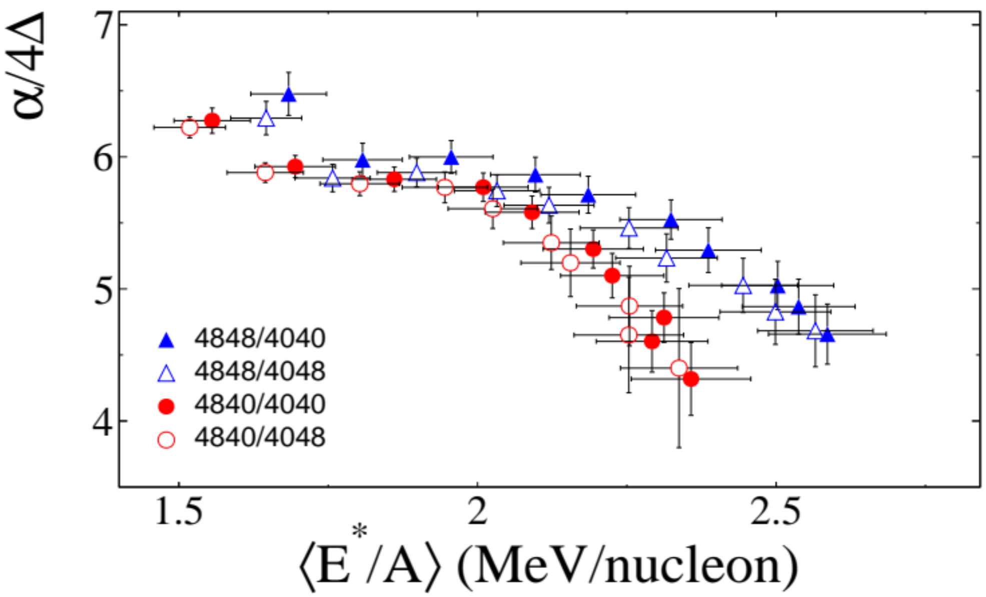




- increase of C_{sym} coefficients with increasing QP charge (size);
- large surface effect;
- Myers & Swiatecki parametrization (nuclei at g.s).
- $Csym = a_v + a_s\,(2Z_{QP})^{-1/3}$
- the fit of the data provides a_s/a_v = 1.7 much higher than fiducial g.s. value (1.14)
- Effect of measuring the hot QP ?

Q. Fable et al., Phys. Rev. C 106, 024605 (2022)

Isoscaling from reconstructed QP



- decrease of C_{sym} coefficients with E*/A;
- This a drop in α/4Δ may be related to a decrease in density

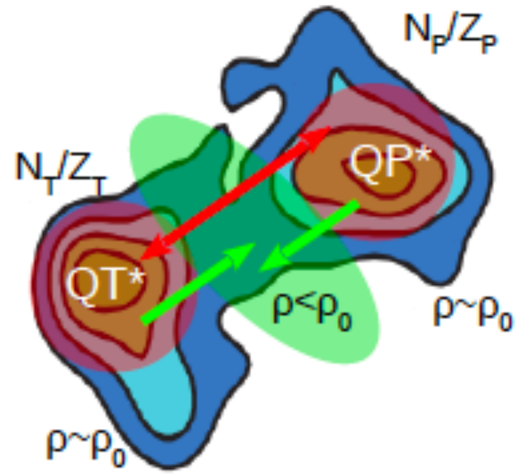
Q. Fable, AC, and INDRA Coll,

Isospin Transport

$$j_n - j_p = \left(D_n^{\rho} - D_p^{\rho}\right)\nabla\rho - \left(D_n^{\delta} - D_p^{\delta}\right)\nabla\delta$$

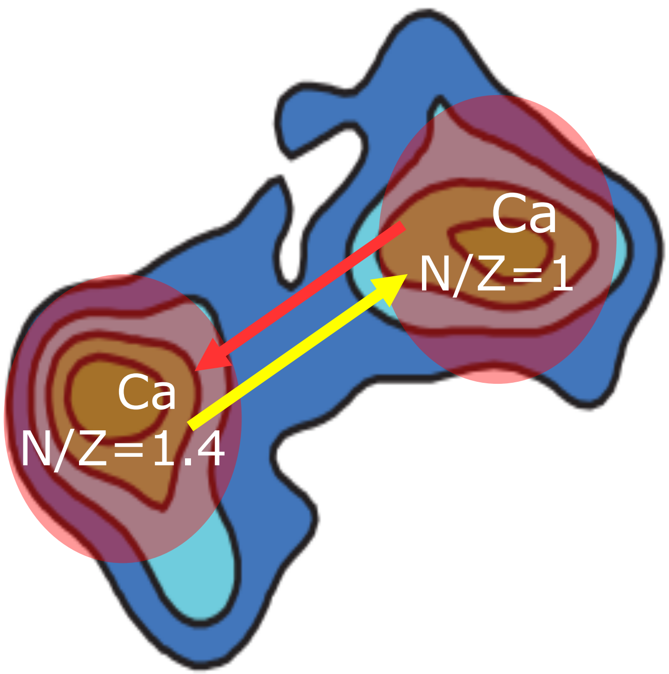
$$\propto \frac{\partial E_{sym}}{\partial \rho} \qquad \propto E_{sym}$$

$$\delta = \frac{N-Z}{N+Z}$$

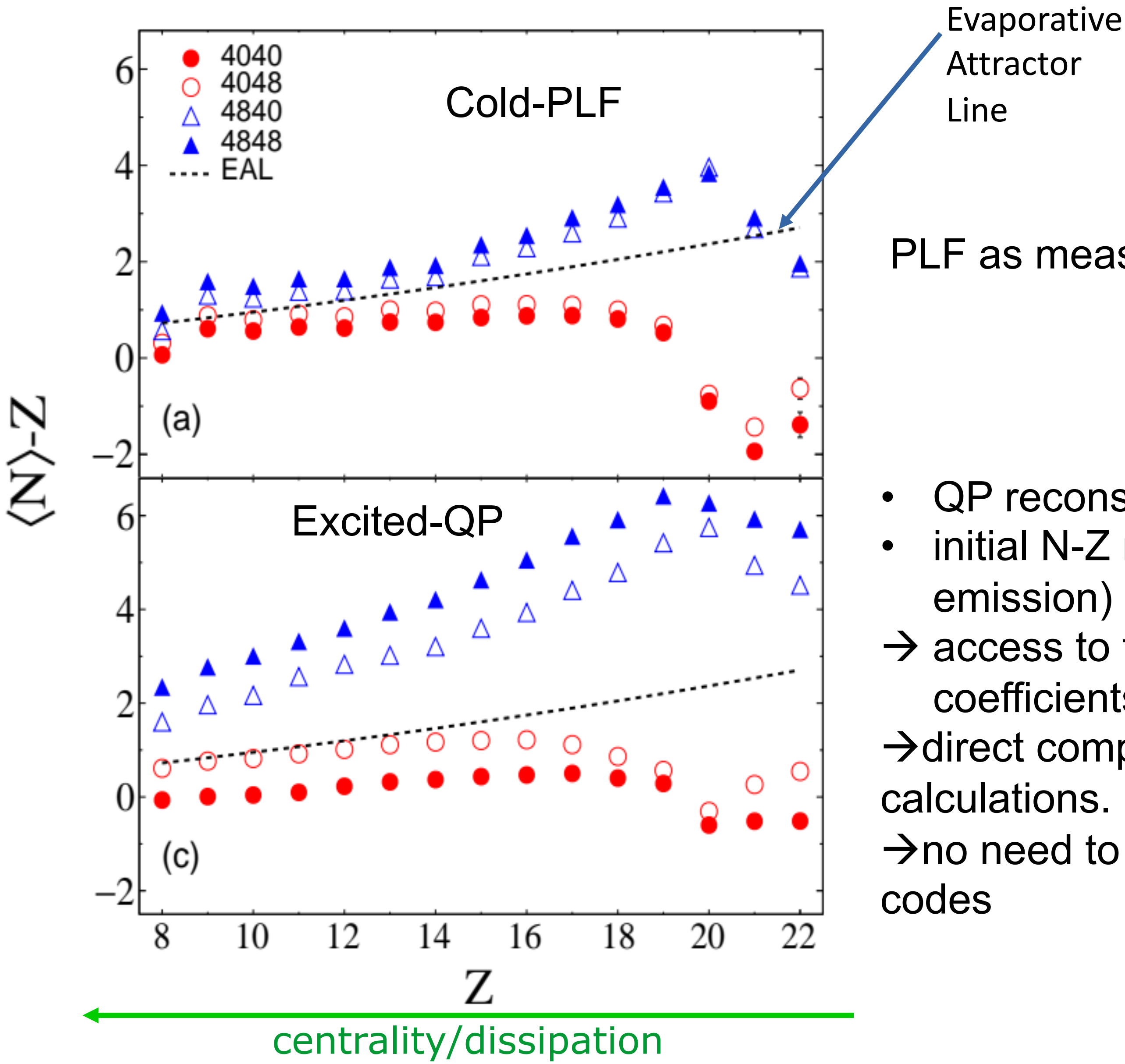


- the difference of the neutron and proton current between the 2 colliding nuclei
- density gradient: referred as drift or migration of the isospin
- isospin gradient: diffusion
- drift and diffusion depend on the interaction time :
  - Long == equilibration
  - Short == partial transparency

isospin diffusion



Disentangling between secondary decay and diffusion



PLF as measured

- QP reconstructed
- initial N-Z not reached (direct emission)

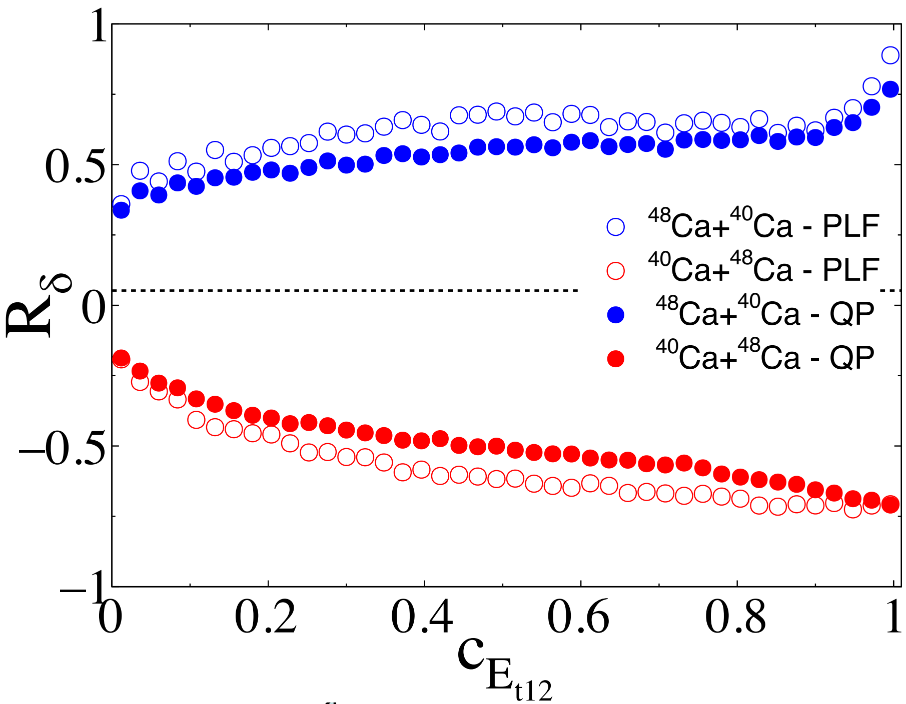
→ access to the transport coefficients

→direct comparison to transport calculations.

→no need to use an after burner codes

Imbalance ratio applied to the asymmetry

$$\delta = (N - Z)/A$$



centrality

For a given neutron rich nuclei A and neutron poor B, A+A, B+B, A+B reactions

$$R_i(X) = 2\frac{X - (X_{A+A} + X_{B+B})/2}{X_{A+A} - X_{B+B}}.$$

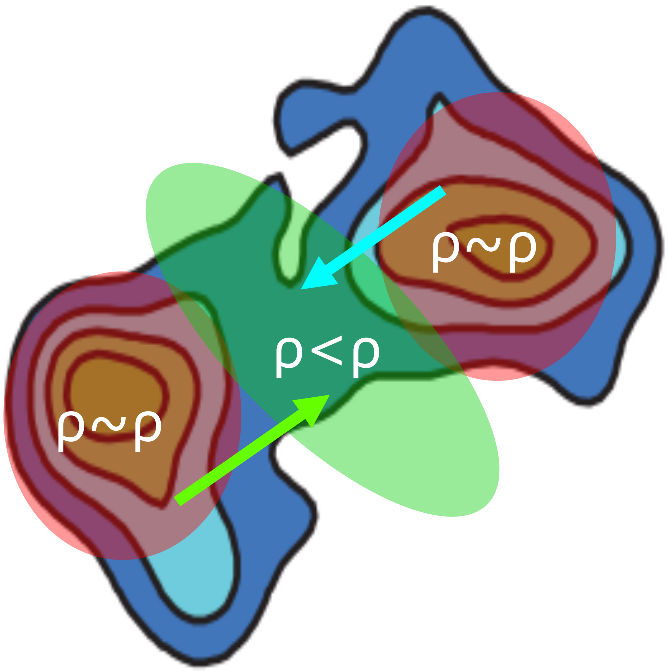
x sensitive to isospin = <N-Z>/A

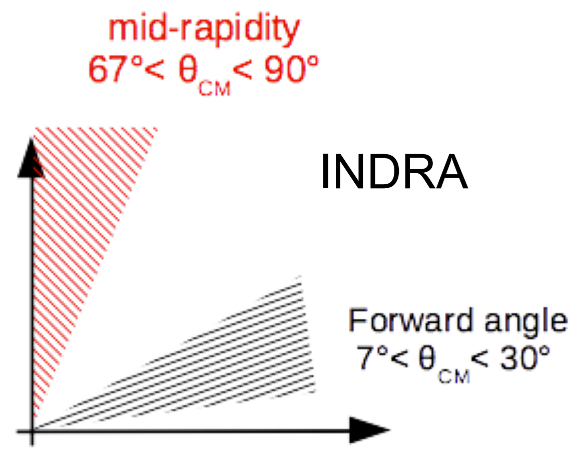
R = 0, equilibration, diffusion

R = +/- 1, no equilibration, no diffusion

- complete equilibration is not reached
- differences between primary and secondary are observed
- smoother decrease of R_δ with centrality in case of reconstructed QP than PLF

Isospin migration

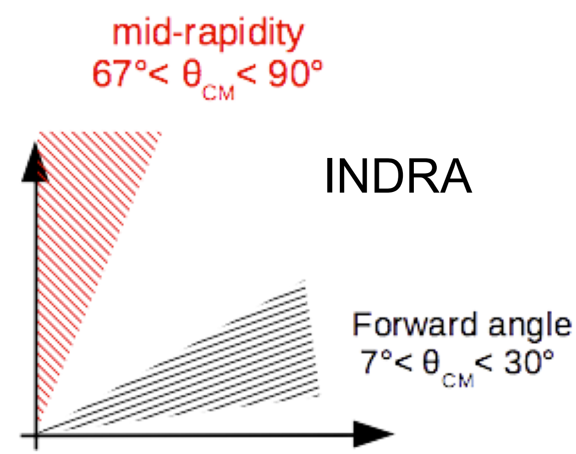


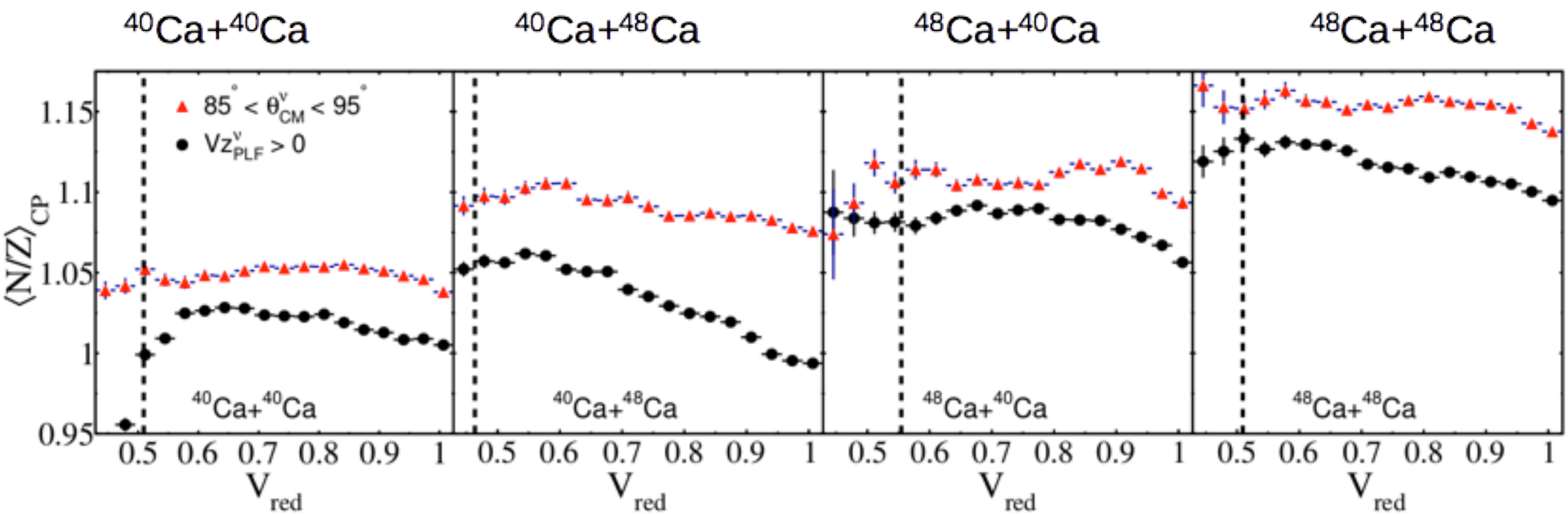


Isospin migration

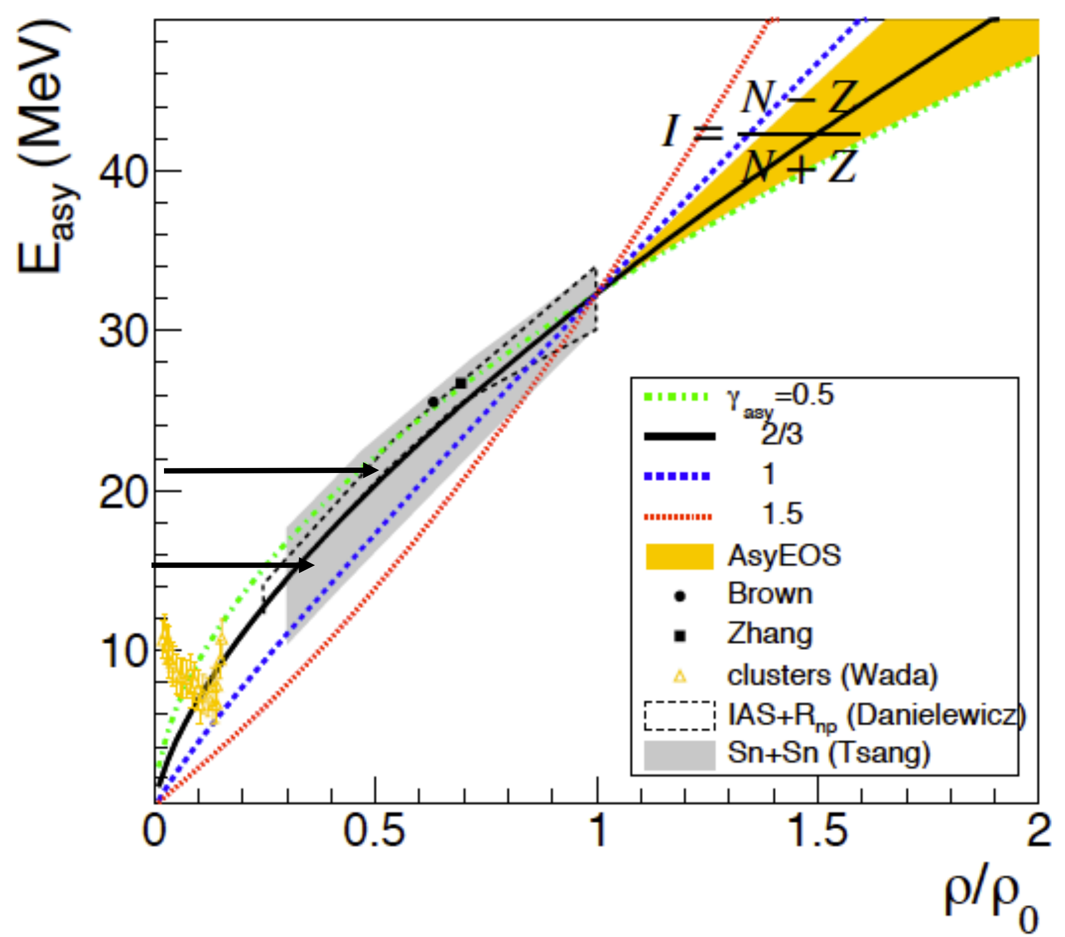
For a given range centrality :

- $\langle N/Z \rangle_{CP} = \dfrac{\sum_\nu M_\nu \frac{N_\nu}{Z_\nu}}{\sum_\nu M_\nu}$
- $\nu =^{2,3} H,^{3,4,6} He,^{6,7,8,9} Li,^{7,9,10} Be$
- Neutron-enrichment if $(\langle N \rangle / \langle Z \rangle)_{CP} > 1$





Constraining the density dependence of the symmetry energy



In progress…

courtesy of A. Le Févre

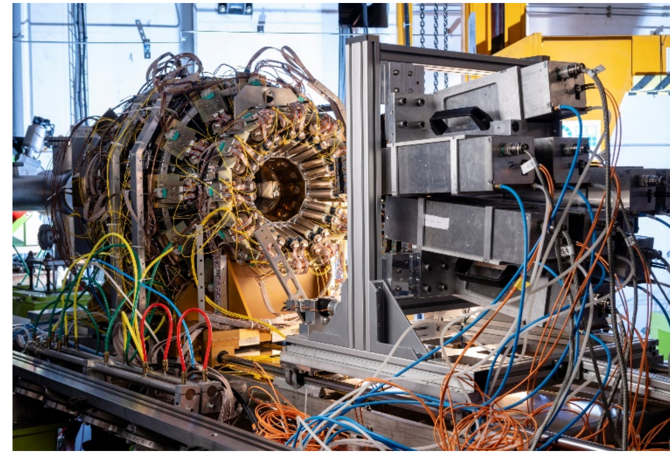
conclusion

- Symmetry energy coefficients deduced from warm QP has a large surface effect Cs/Cv =1.7
- Evidence of Isospin diffusion and isospin migration.
- The reconstruction of QP allows a direct comparison to the transport models
- Imbalance ratios indicate no complete equilibration for secondary and primary fragments at semi-peripheral collisions (b=5-7 fm). Central collisions should be investigated.
- The set of data is open to comparison to all transport models engaged to link data to the symmetry energy.

perspectives

- improve benchmarking with various transport models (AMD and BLOB (SMF))
- improve clustering methods in transport models
- imply methods to existing/future INDRA-FAZIA data

2019 INDRA-FAZIA campaign

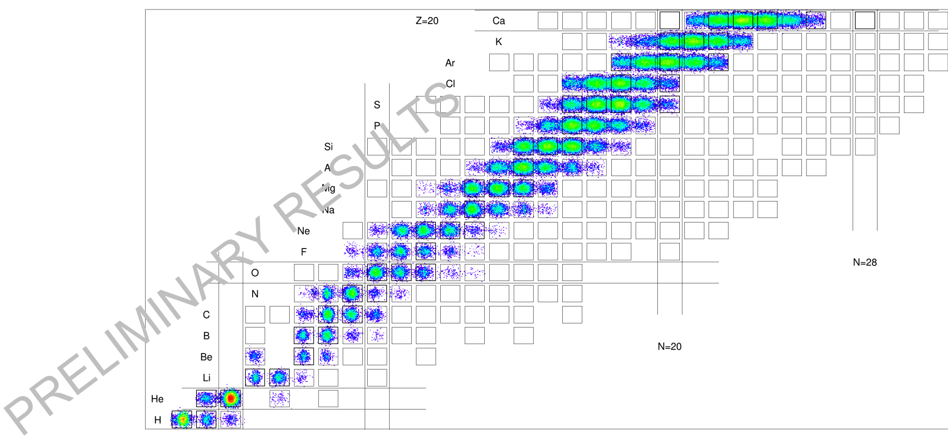


FAZIA was coupled for the first time with INDRA, replacing the forward part of this 4π multidetector for charged particles.

→ The combination of these detectors allowed for a complete A and Z identification of multi-fragment reactions

→ It allows to better constraint the EOS for nuclear matter

INDRA FAZIA



Typical Z & A identification obtained with FAZIA during the experiment

Spokespersons: O. Lopez (LPC, France), S. Piantelli (INFN, Italy)

new INDRA electronics. 2021
Mesytech

provide isotopic resolution up to Z = 13

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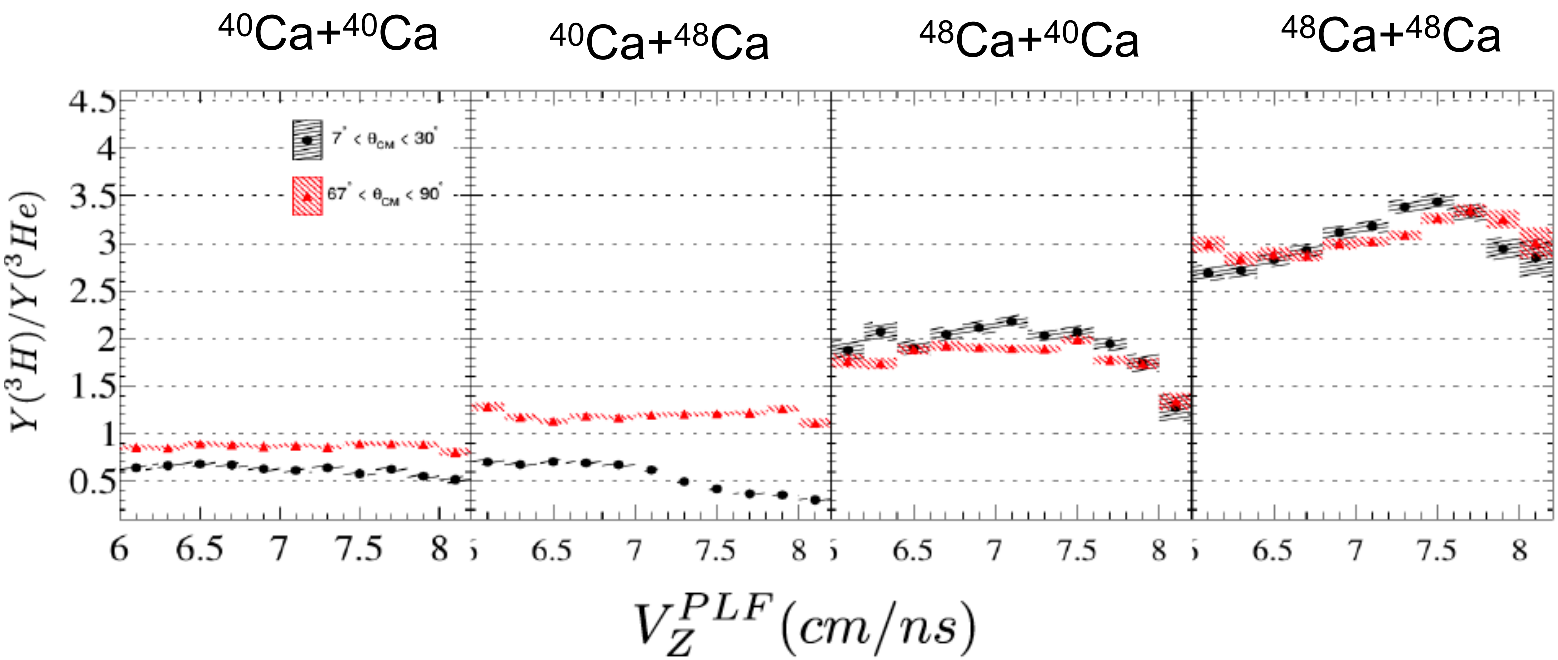
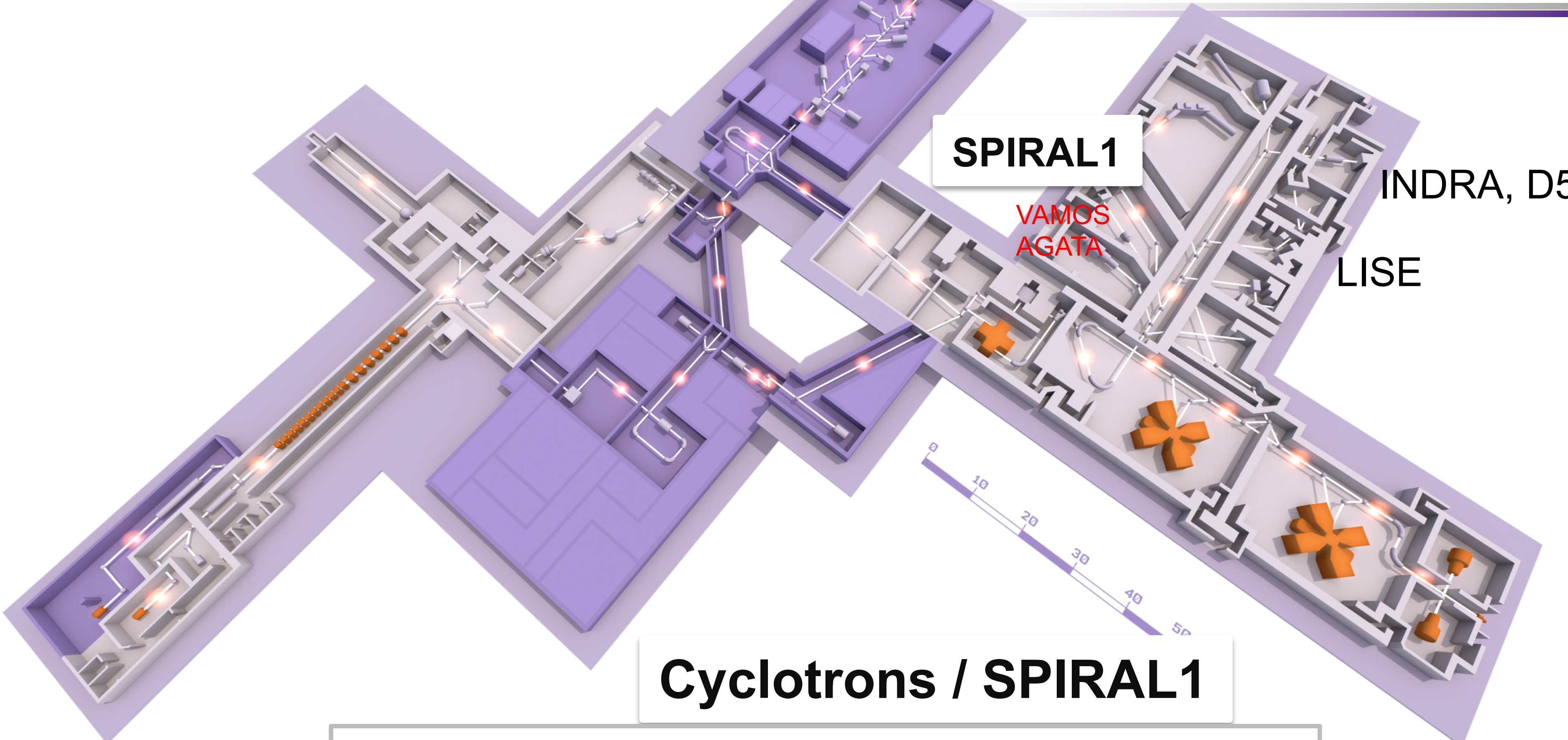
isospin migration: case of t/3He yield ratio



- Y(t)/Y(3He) at mid-rapidity increases with n-rich system
- no way to reproduce it with the AMD calculation
- improvement of the code is in progress, introduction of correlation to reproduce the clusters
- Is it migration/drift of neutron matter to the low density region at mid rapidity?

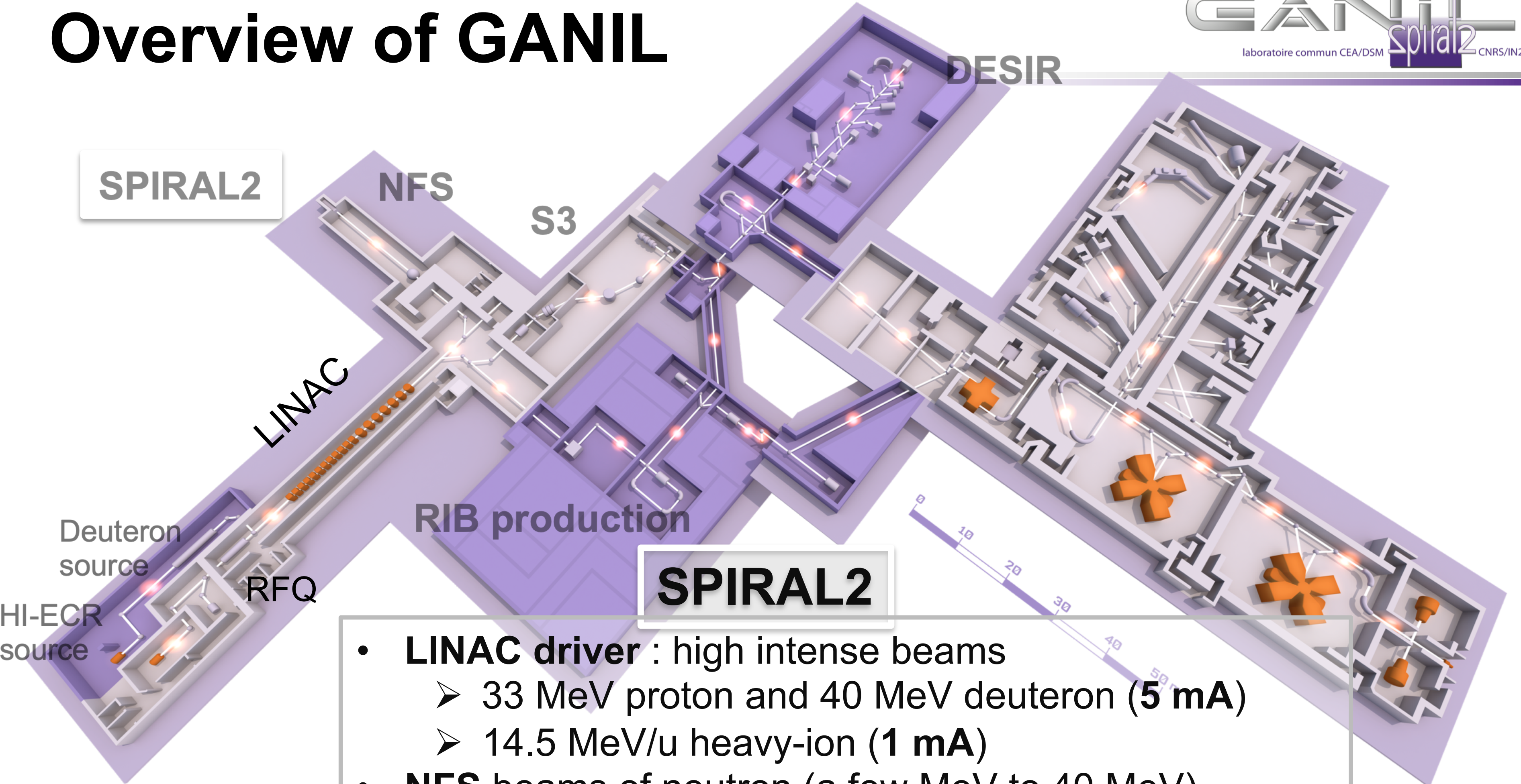
Overview of GANIL



Cyclotrons / SPIRAL1

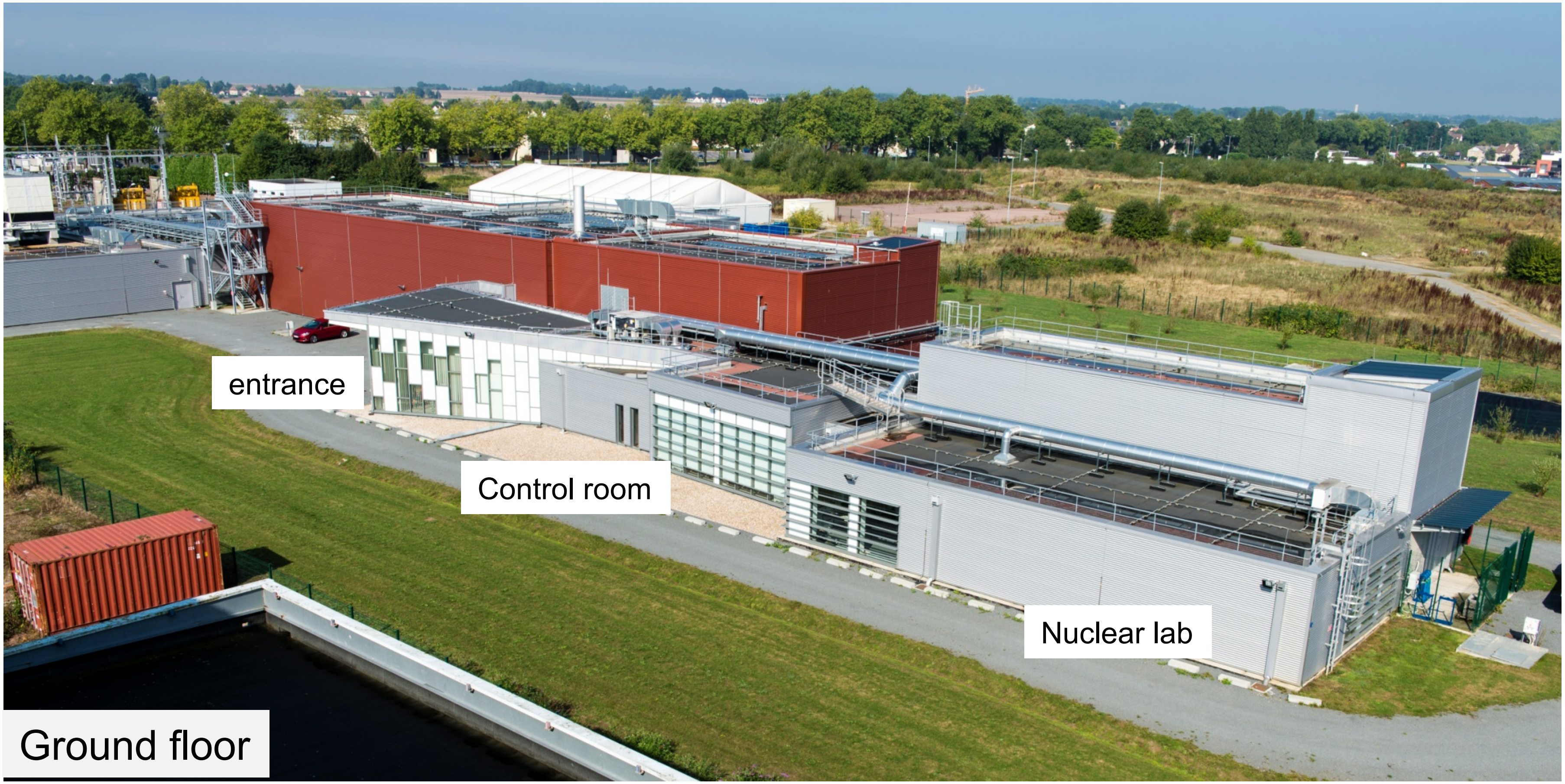
- High energy stable beams [24 – 95] MeV/u
- RIB produced by fragmentation (LISE, T ***> 10 µs>***)
- RIB with **SPIRAL1** (ISOL , T>10ms): accelerated with CIME up to 20 MeV/u

Overview of GANIL

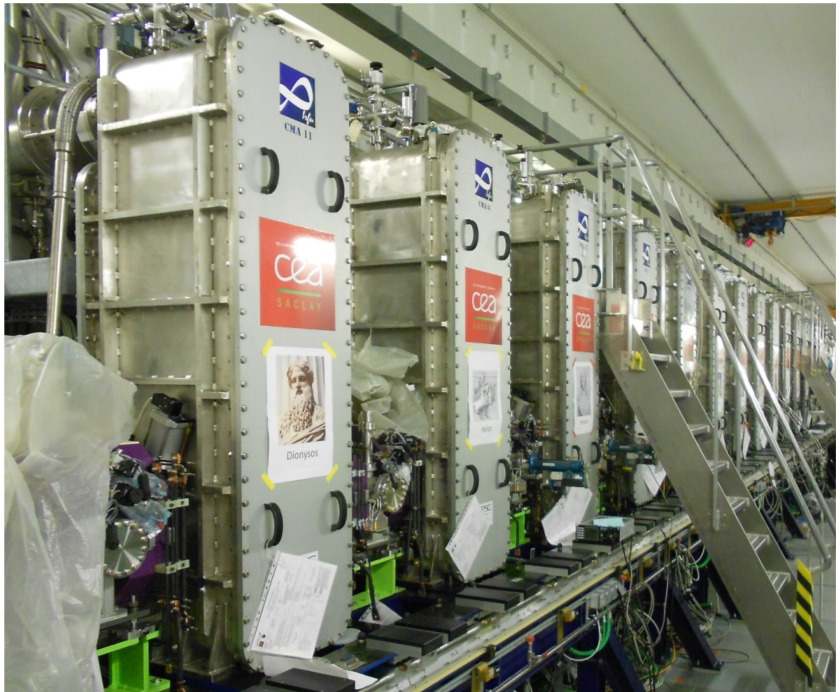


- **LINAC driver** : high intense beams
  - ➢ 33 MeV proton and 40 MeV deuteron (**5 mA**)
  - ➢ 14.5 MeV/u heavy-ion (**1 mA**)
- **NFS** beams of neutron (a few MeV to 40 MeV)
- **S3** super separator spectrometer (fusion ev. reactions, spectroscopy for SHE, N=Z). Commissioning
- DESIR: study of exotic ions at low E, from S3 / SP1
- Production of fission fragments induced by n + U reactions (stand by)

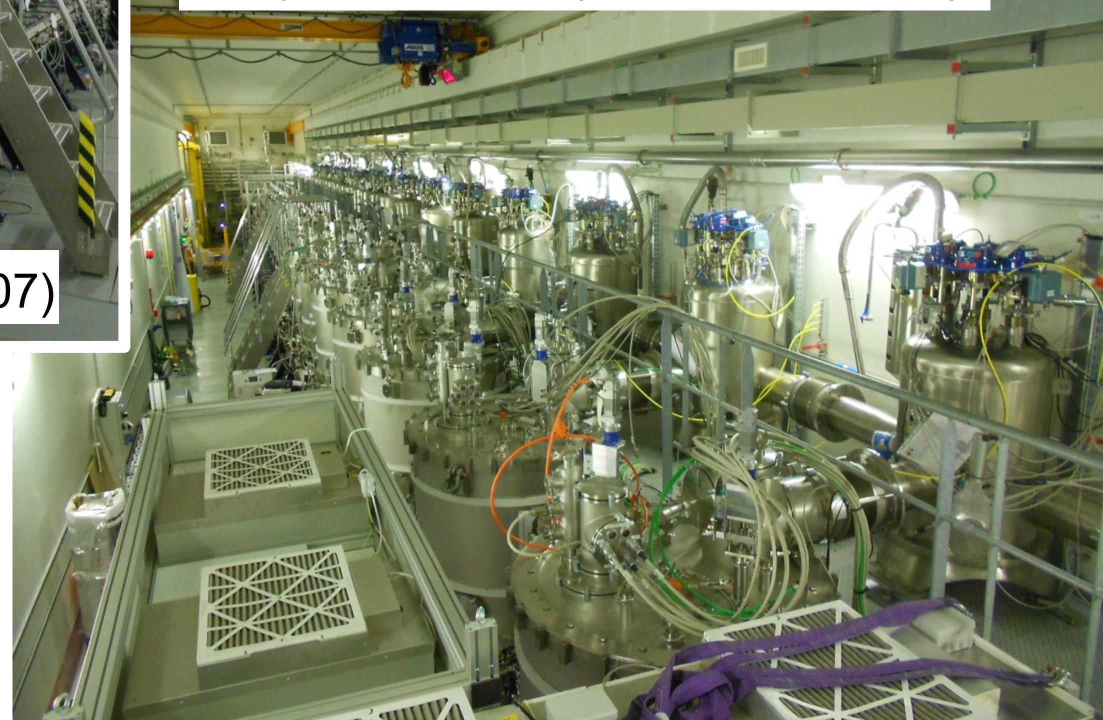
SPIRAL-2 phase 1 building



Cryomoduls



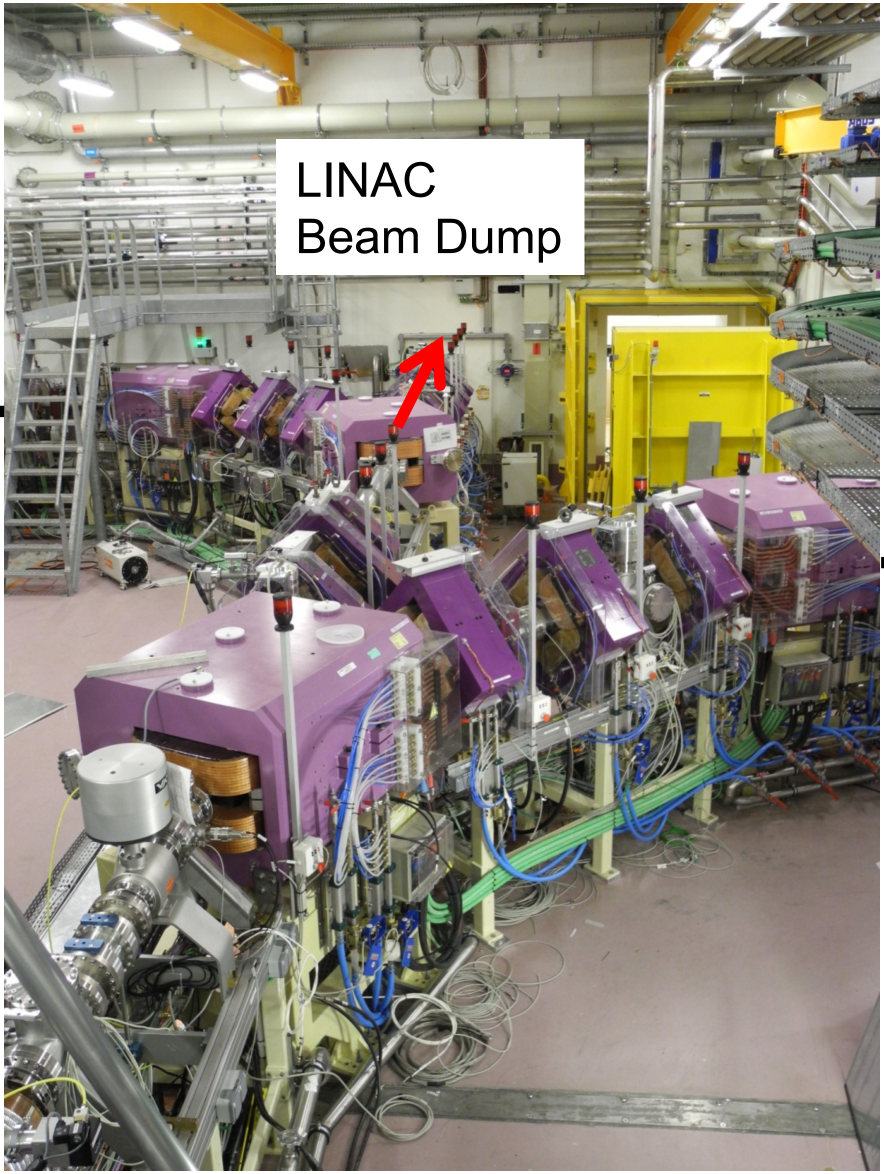
12 cryomodules A (1 cavity β=0,07)



7 cryomodules B (2 cavities β=0,12)

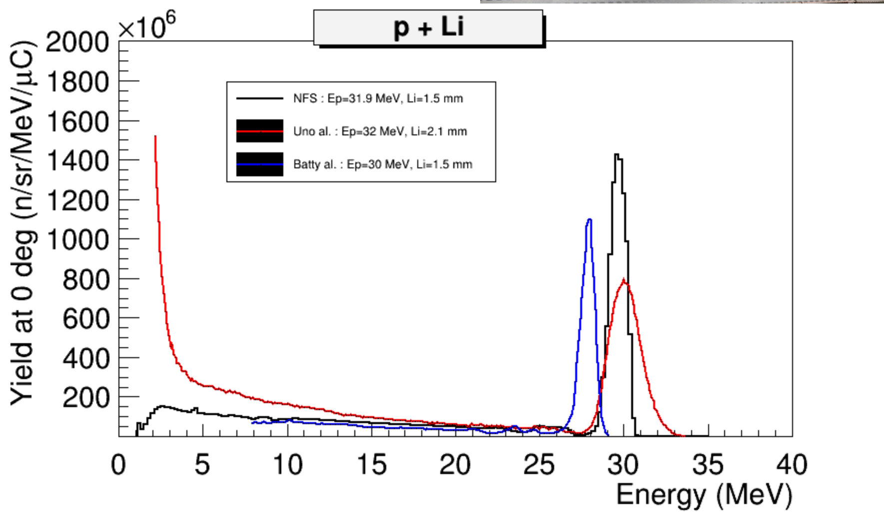
High Energy Beam Line

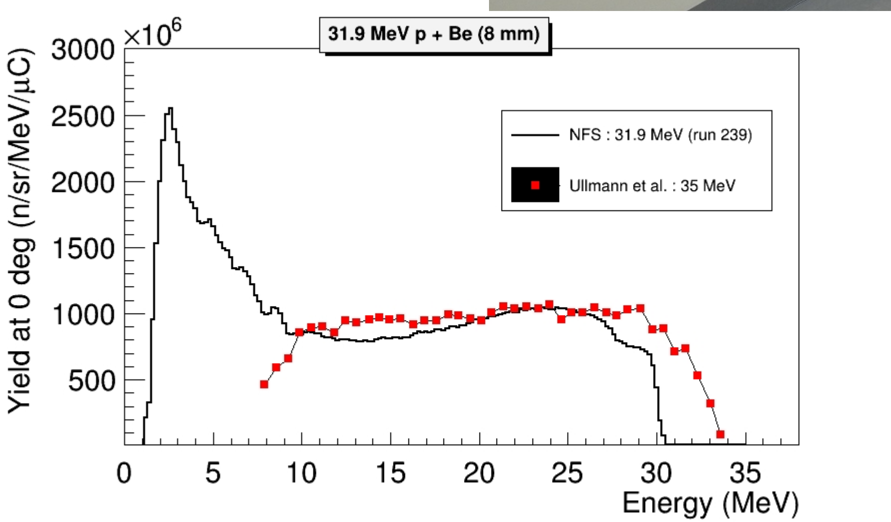
NFS

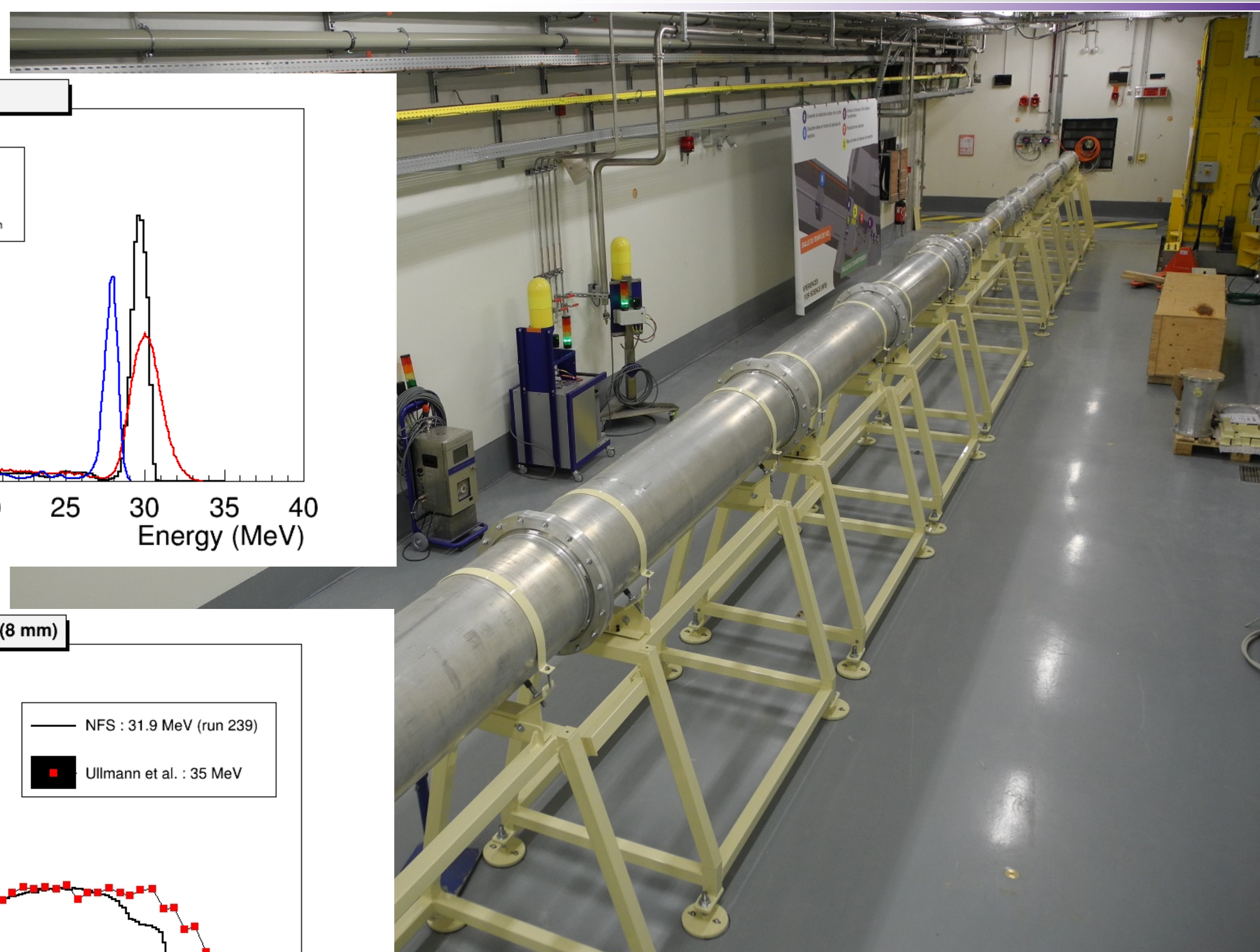


To S3 and
Production Building

neutron beams

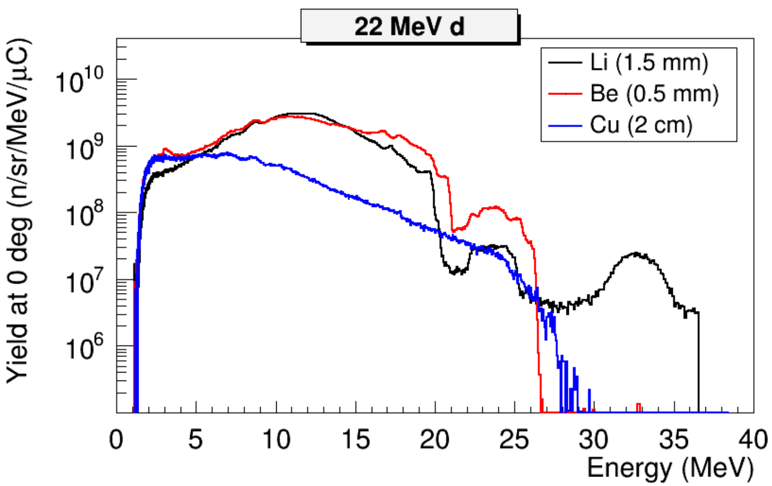


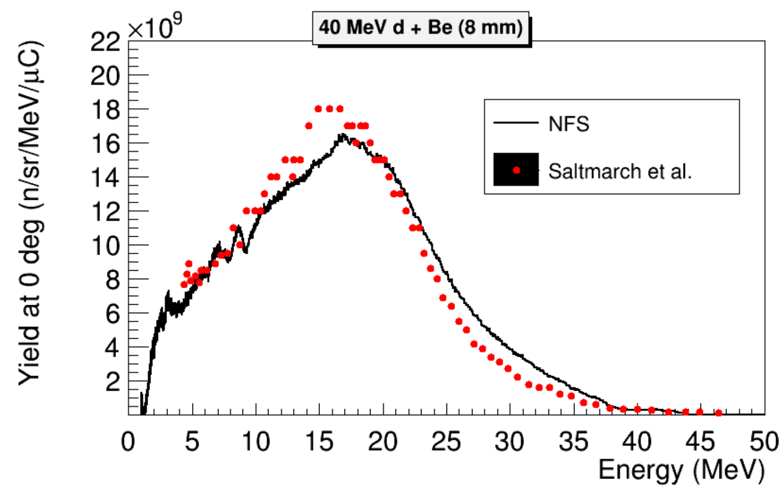




next step neutron beam produced by d

n-beam produced by d





courtesy of X. Ledoux

40 MeV d beam at 50 µA →

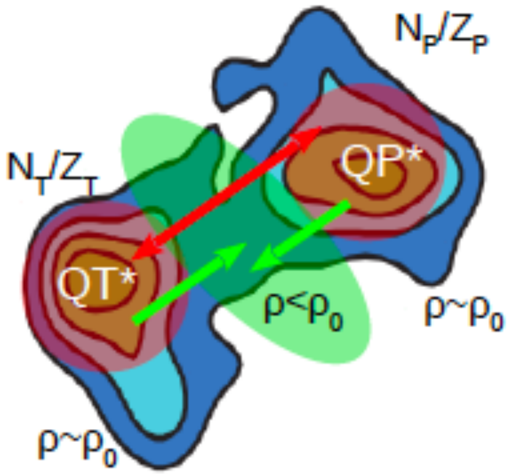
E MeV	Flux at 5 m
0-40	8.10^7 n/cm^2/s
5	2.10^6 n/cm^2/MeV/s
14	5.10^6 n/cm^2/MeV/s
30	6.10^5 n/cm^2/MeV/s

Isospin Transport

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

$$L = 3\rho_0 \frac{\partial \epsilon_{sym}(\rho)}{\partial \rho}\bigg|_{\rho=\rho_0} \qquad K_{sym} = 9\rho_0^2 \frac{\partial^2 \epsilon_{sym}(\rho)}{\partial^2 \rho}\bigg|_{\rho=\rho_0}$$

« Slope » param. « Incompressibility » param.



- the difference of the neutron and proton current between the 2 colliding nuclei
- density gradient: referred as drift or migration of the isospin
- isospin gradient: diffusion
- drift and diffusion depend on the interaction time :
  - Long == equilibration
  - Short == partial transparency