How transparent is nuclear matter ?

(from an experimental point of view)

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Outlines

Caution : work in progress...

- Mo… …ns
- Event s… …r « central » events
- Isospin equilibra…
- Isospin dependence of s…
- Isotropy ratio (energy) and expe… …terminations of λ_{NN} and σ_{NN}
- *Other probes…*

Motivations

- At low energy ($E \ll E_{Fermi}$), provide a link to **viscosity** and macroscopic (nuclear) degrees of freedom : **1-body dissipation** by the mean-field, nucleus-nucleus potential

- At high energy ($E \gg E_{Fermi}$), provide a link to microscopic (nucleonic) d.o.f and **in-medium *NN* cross section** : **2-body dissipation** by hard (elastic) *NN* collisions, *NN* interaction

- At intermediate energy ($E \approx E_{Fermi}$), exhibit the **crossover** between these 2 phenomena

Motivations (II)

- In a « pure » nuclear physics context :
  - Variety of **reaction mechanisms** in nuclear reactions : fusion, deep inelastic, incomplete fusion
  - Variety of **deexcitation processes** : evaporation, fission, multifragmentation
  - **Transport properties** of nuclear matter : equilibrations (E, N/Z)
- In the astrophysical context :
  - **supernovae collapse** and formation of **neutron stars** (EOS)

Measuring the stopping : strategy

- Do **event selection** by using a minimum-bias observable , the **total multiplicity for light charged particle (0<Z<3) : ν_{tot}**

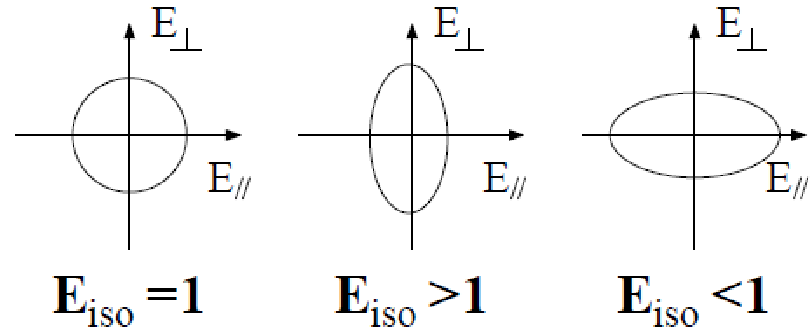
- Avoid **trivial correlations** with the isotropy variables (R_E, E_{trans}, θ_{flow}, velocities, …)

- Very **basic (simple) criterion** : applicable to all systems

- **Caution : selection of the most central events is not guaranteed (not an impact parameter selector…)**

Isotropy ratio

$$R_E = \frac{1}{2}\frac{\sum E_{\perp}}{\sum E_{\parallel}}$$

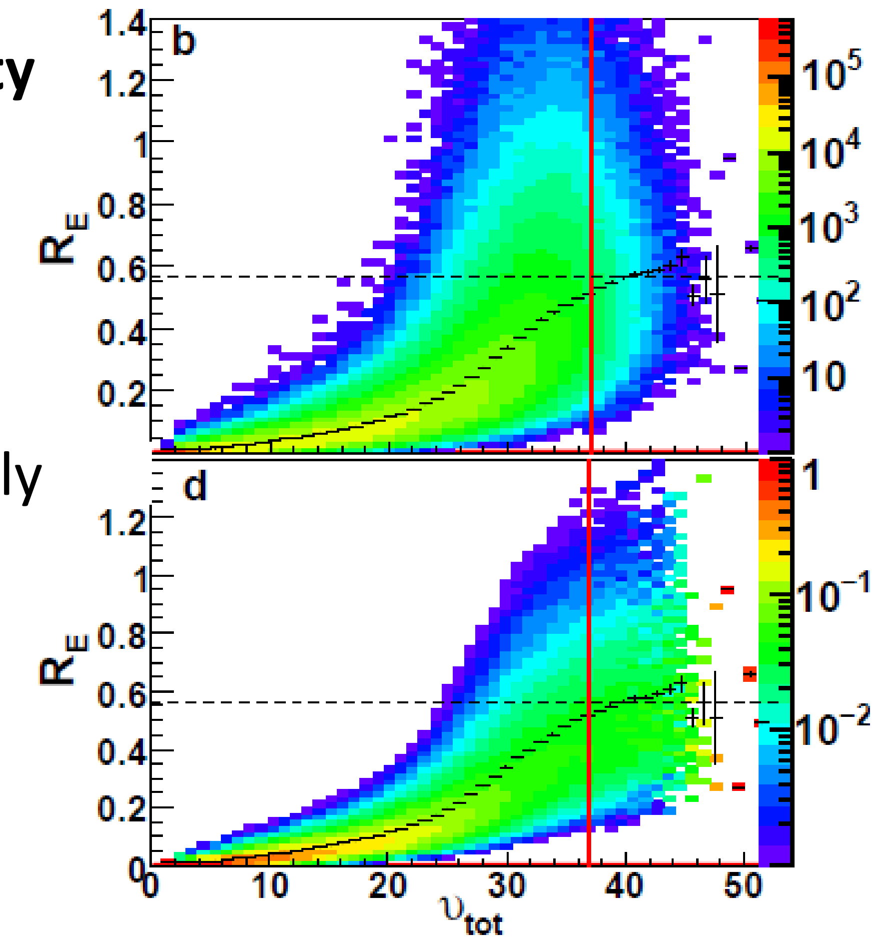


- **Saturation** of R_E at **high multiplicity**

- Define the **maximal average** $\boldsymbol{R_E}$ value

- **Large fluctuations** in R_E are partially due to **statistics**

- « Normalized » correlation to the same number of entries by bin of ν_{tot}



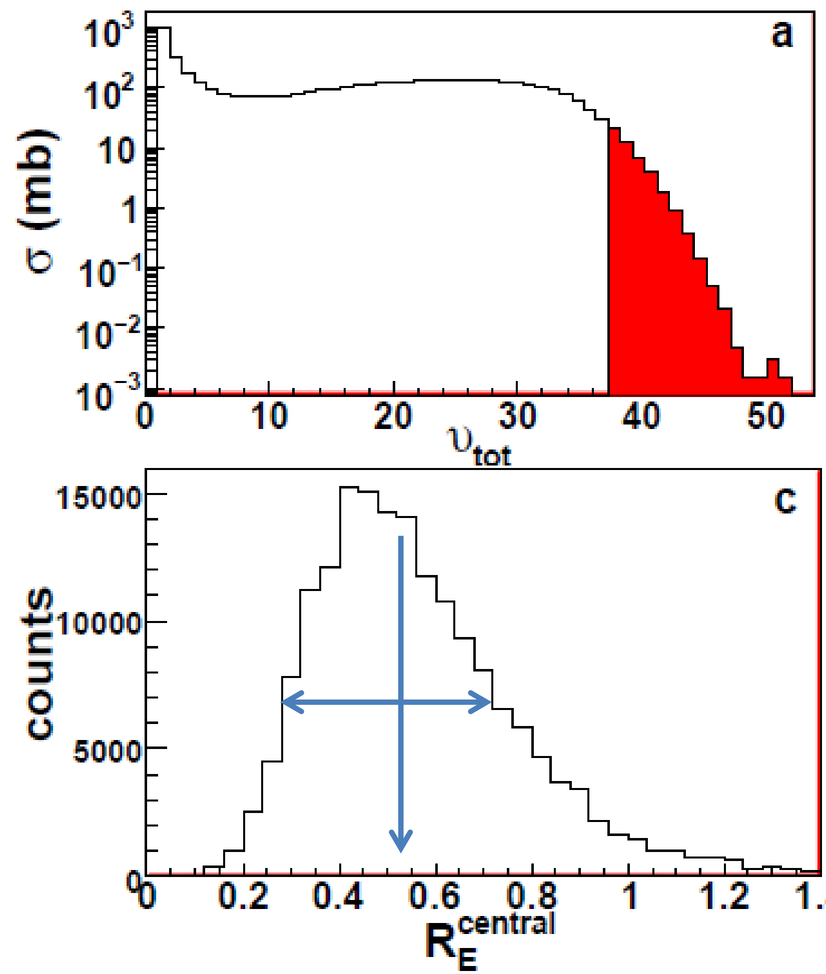
Event selection : most violent collisions selected by ν_{tot}

– ν_{tot} **cut-off** is defined by the **observed saturation** in R_E **x** ν_{tot} correlation

-Applied to **all INDRA symmetric systems**

- Corresponds roughly to ***50-100 mb*** (detected) hence to $b/b_{max} \approx 0.1$

- R_E **values** are taken by reporting the **mean** and **FWHM** values of the selected distribution



INDRA dataset

System	Incident energy (A.MeV)	A_{tot}	$(N/Z)_{tot}$	Dataset
Ar+KCl	*32 - 74*	*72*	*1.00*	*4*
Ni+Ni	*32 - 90*	*116*	*1.11*	*7*
Xe+Sn	*12 (8) - 100*	*248*	*1.39*	*15*
Xe+Sn (isospin)	*32 - 45*	*220 - 250*	*1.27 - 1.50*	*4*
Au+Au	*40-100*	*394*	*1.49*	*5*
U+U	*24,36*	*476*	*1.59*	*2*

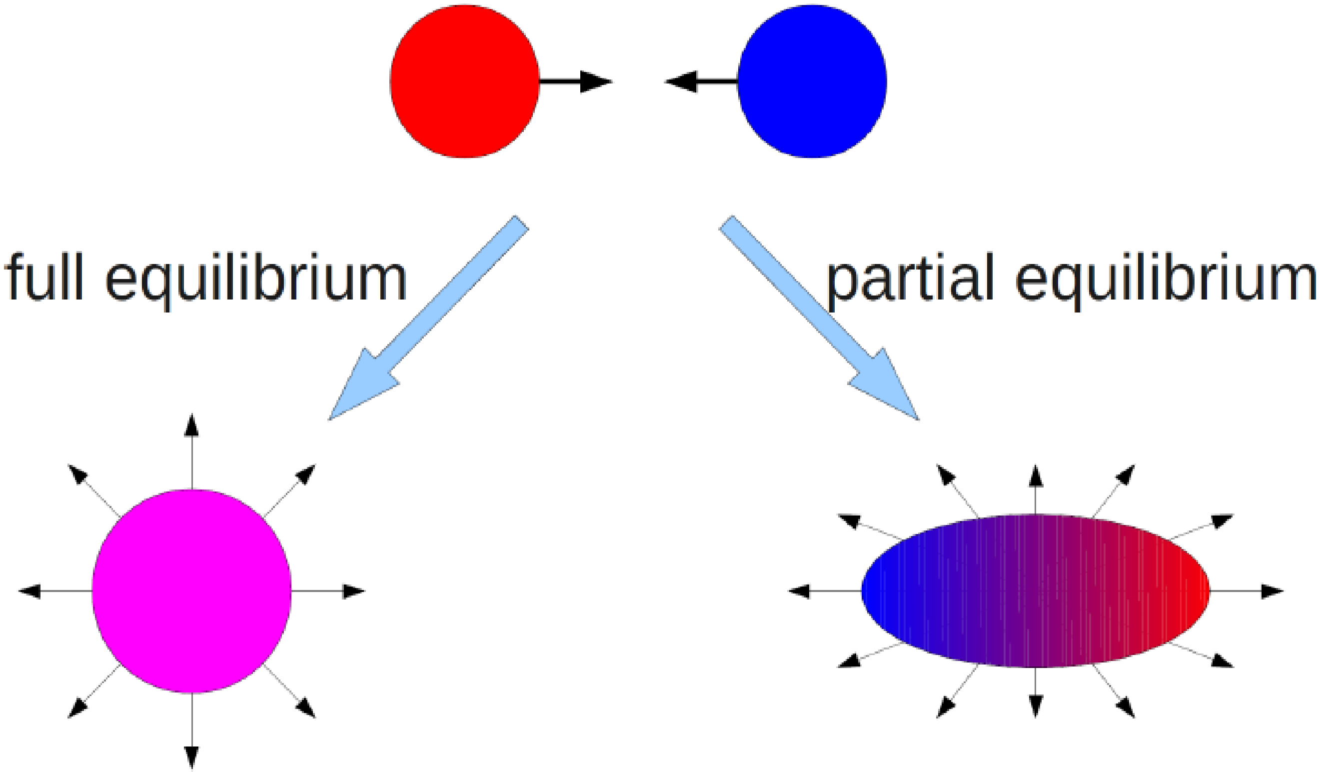
- 5 systems spanning a **large total mass and isospin** domain

- Cover the **whole Fermi energy domain** from *12A* to *100A* MeV

- Offer the **most extensive, comprehensive and exclusive** database for nuclear reactions in the Fermi energy domain

Isospin diffusion and equilibration ?

Isospin equilibration



- memory of entrance channel is lost
- same isospin everywhere

- memory of the entrance channel is partially conserved
- dependence of the isospin along the beam axis

Isospin ratio

Imbalance ratio

$$\tilde{R}_{p/t} = \frac{2R_{p/t} - R^{NN}_{p/t} - R^{PP}_{p/t}}{R^{NN}_{p/t} - R^{PP}_{p/t}}$$

where $R_{p/t}$ is the normalized yield of different particles in isospin with

the same atomic number Z.

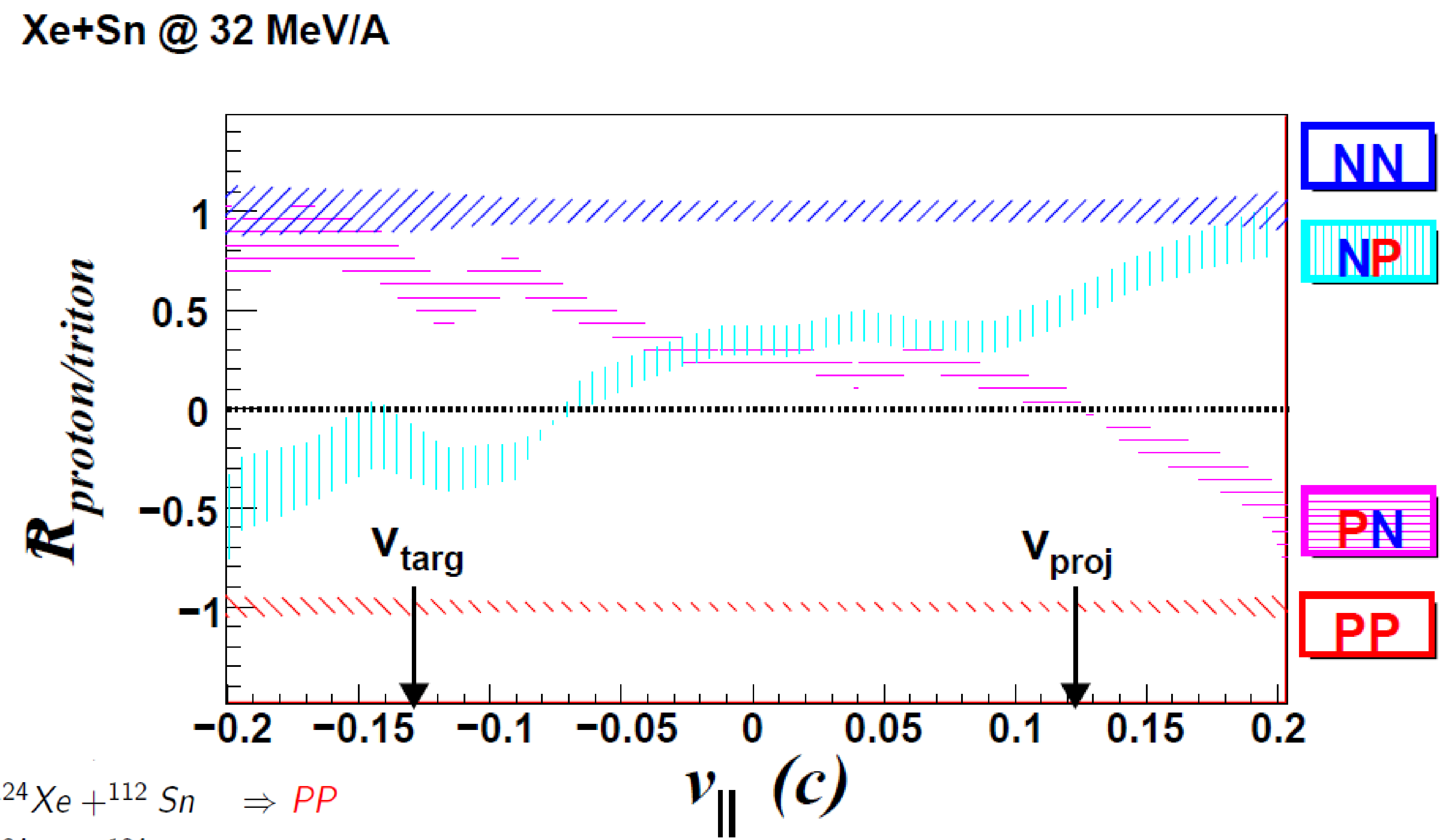
$$\tilde{R}_{proton/triton} = \begin{cases} +1 & if \quad R_{p/t} = R^{NN}_{p/t} \\ -1 & if \quad R_{p/t} = R^{PP}_{p/t} \end{cases}$$

- $^{124}Xe + ^{112}Sn \Rightarrow PP$
- $^{124}Xe + ^{124}Sn \Rightarrow PN$
- $^{136}Xe + ^{112}Sn \Rightarrow NP$
- $^{136}Xe + ^{124}Sn \Rightarrow NN$

F. Rami, PRL **84**, 1120 (2000)

V. Baran, PRC **72**, 064620 (2005)

Isospin diffusion from *p/t* ratio for central collisions (ν_{tot} selection)



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Velocity along the beam axis

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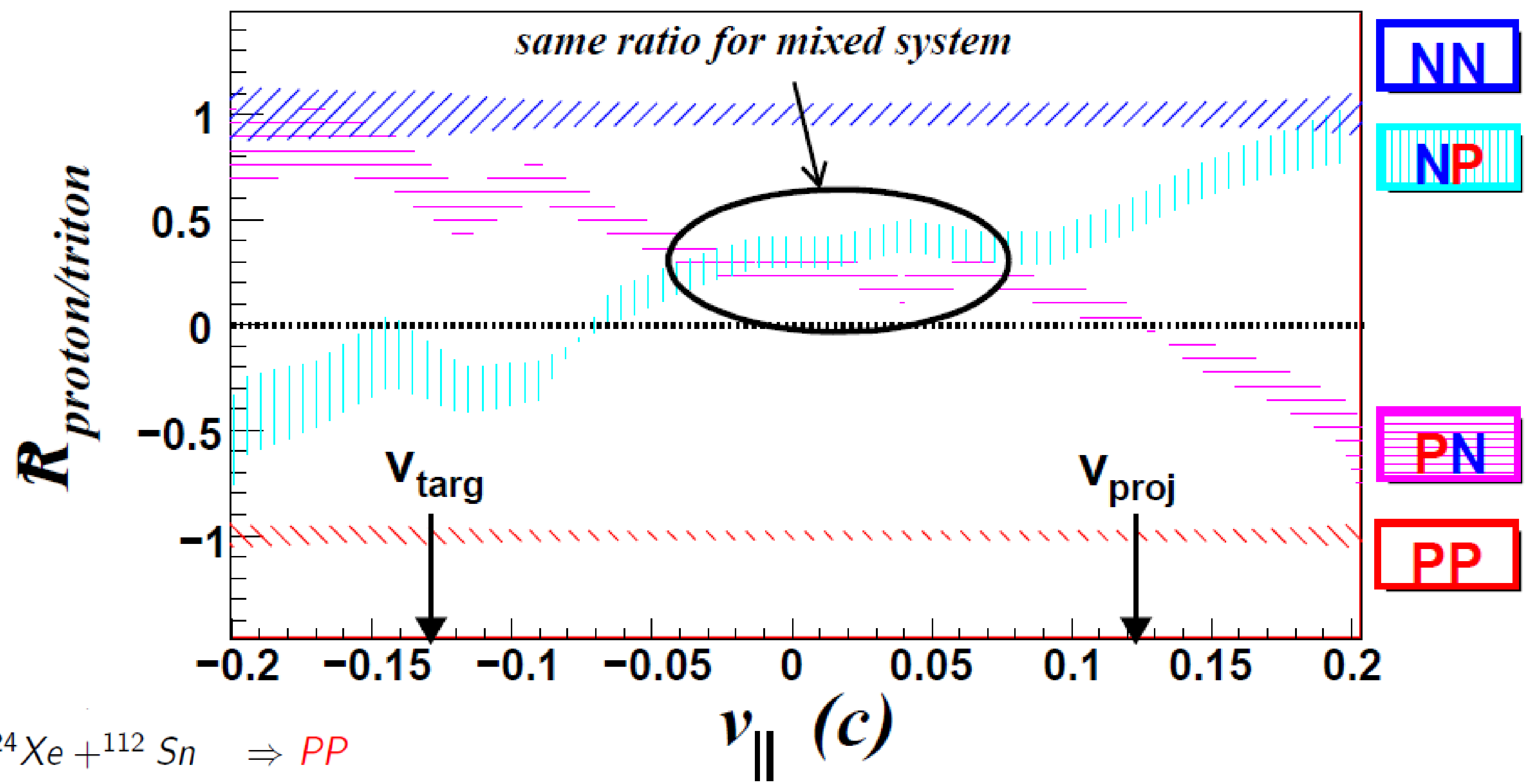
Isospin diffusion from p/t ratio for central collisions (ν_{tot} selection)

Xe+Sn @ 32 MeV/A



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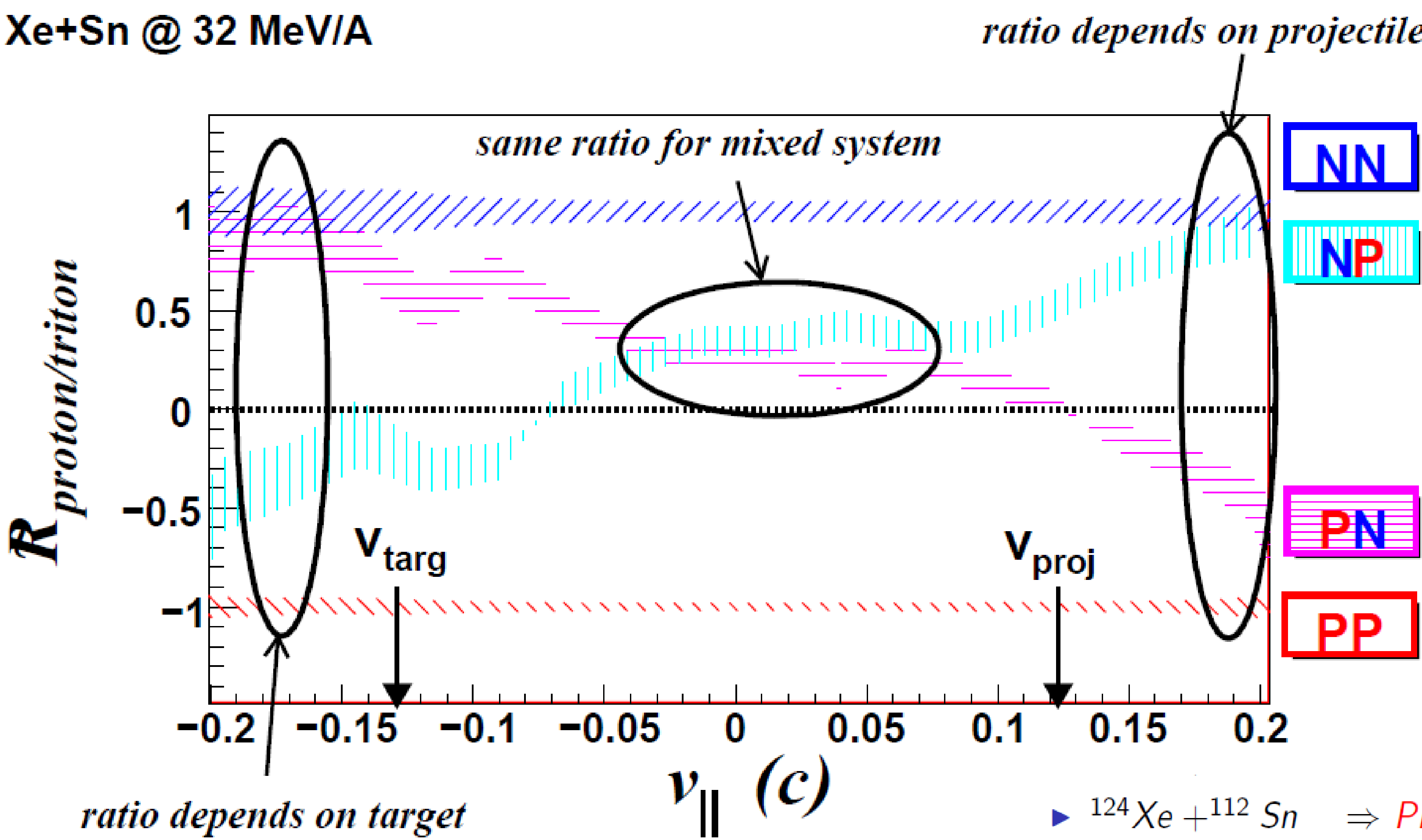

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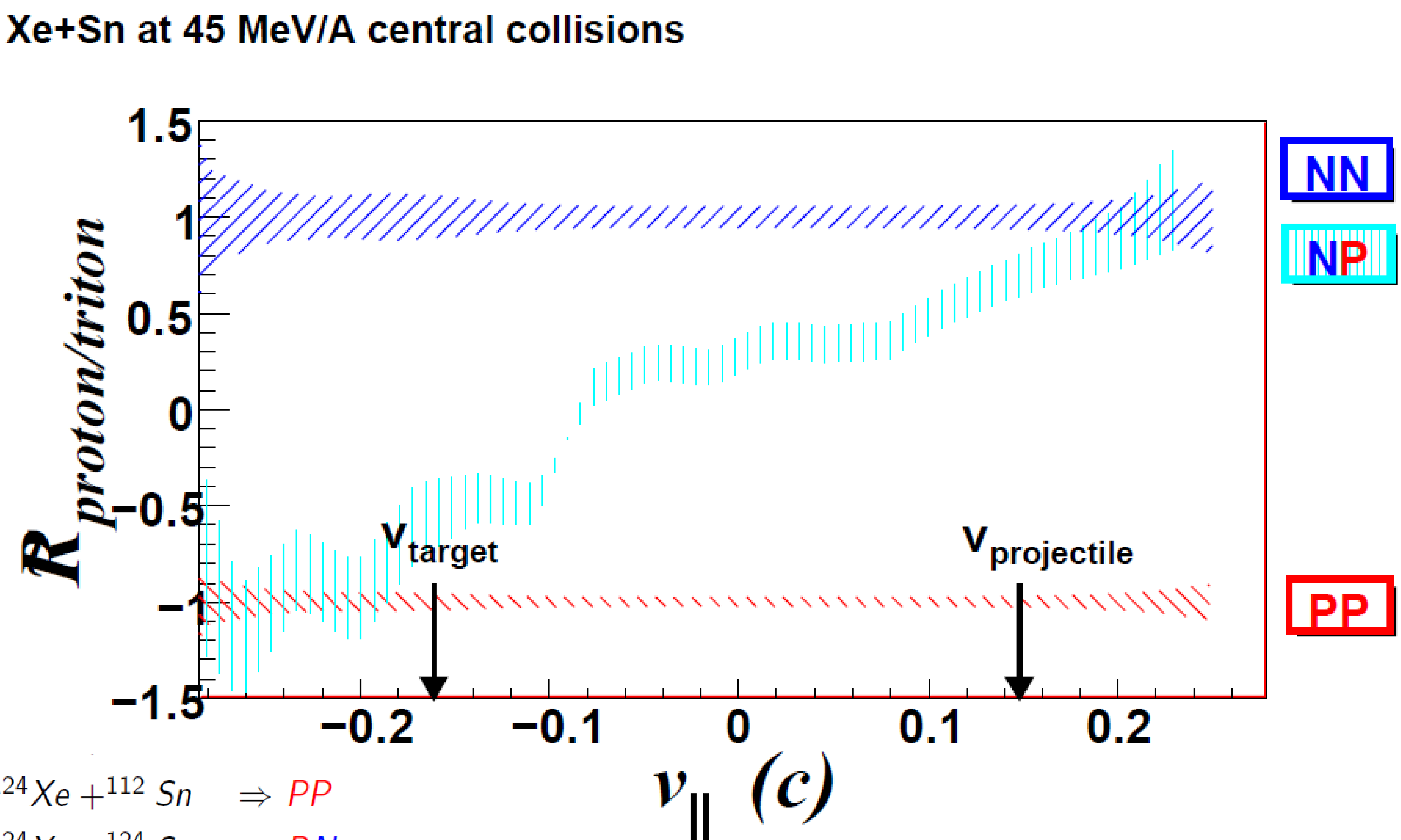

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From isospin probe : nuclear matter is semi-transparent : no full isospin equilibration

Isospin dependence for stopping ?

From IQMD calculations…

Isospin Quantum Molecular Dynamics

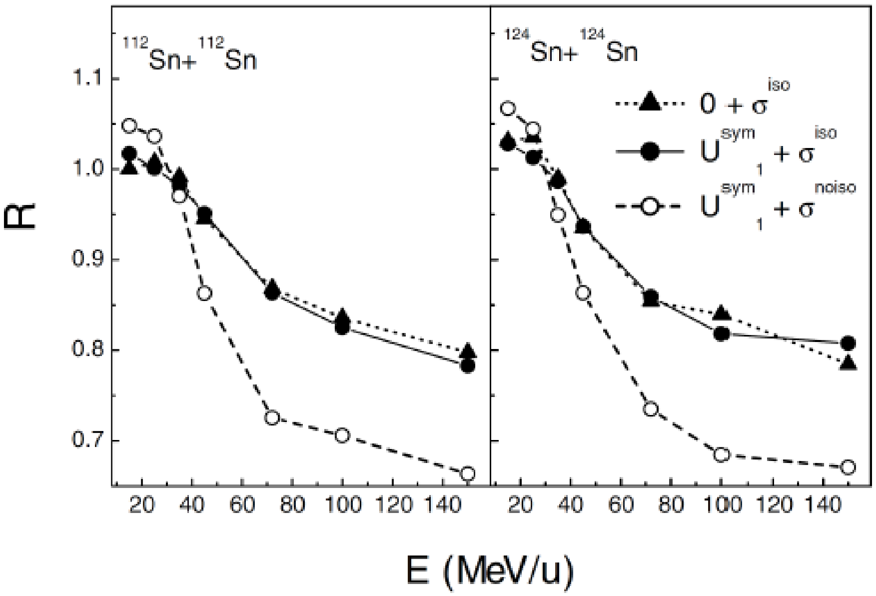
In-medium nucleon-nucleon cross-section :

$$\sigma_{NN}^{med} = \left(1 + \alpha \frac{\rho}{\rho_0}\right) \sigma_{NN}^{free}$$

Interaction potential :

$$U = U^{Sky} + U^{Yuk} + U^{coul} + U^{Pauli} + U^{MDI}$$

$$+ U^{sym}$$



Observation on momentum isotropy R:

- No effect of U^{sym}
- the isospin of entrance channel has no effect
- dependence of the nucleon-nucleon cross-section

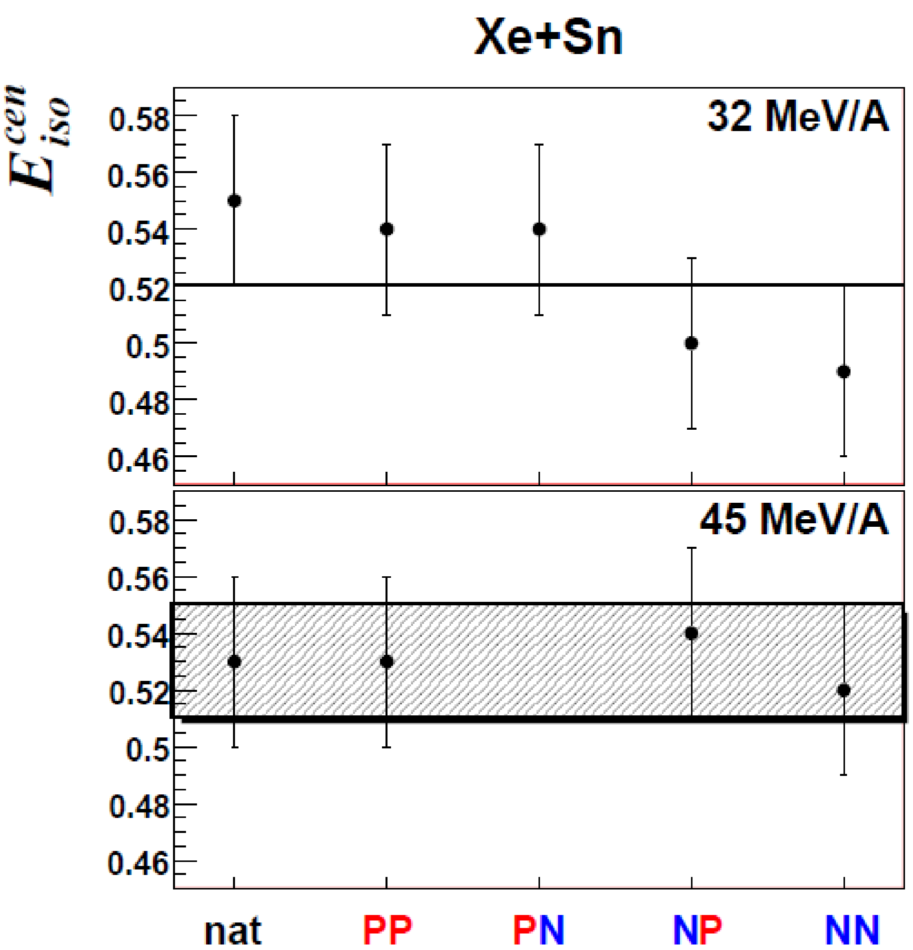
J.-Y. Liu, *et al.*, PRL **86** 975 (2001)

From experimental Data...

Isospin effect

- $^{129}Xe + ^{119}Sn \Rightarrow$ nat
- $^{124}Xe + ^{112}Sn \Rightarrow PP$
- $^{124}Xe + ^{124}Sn \Rightarrow PN$
- $^{136}Xe + ^{112}Sn \Rightarrow NP$
- $^{136}Xe + ^{124}Sn \Rightarrow NN$

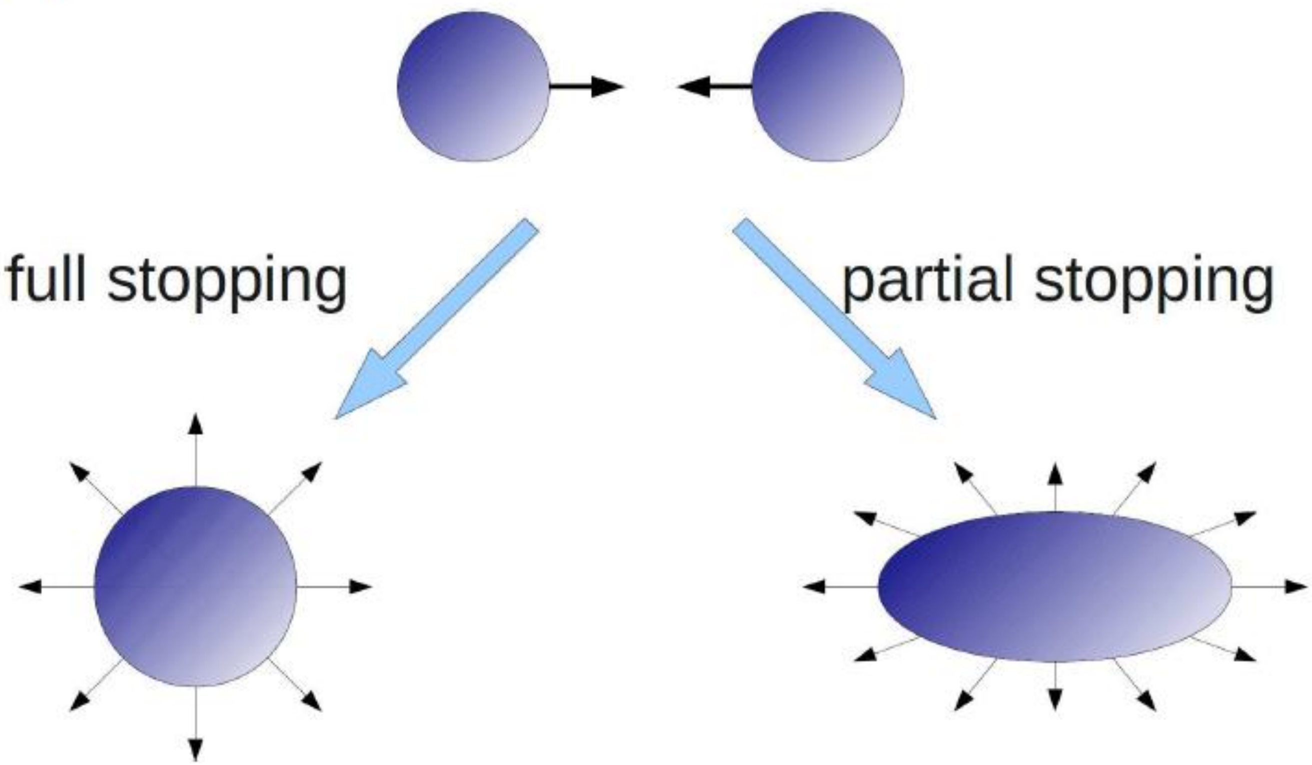
- Error bars are here systematics



No clear dependence is observed in this incident energy range but isospin excursion Δ(N/Z) is only ~ *15%*

Energy dissipation
and thermalization ?

Stopping power measurement

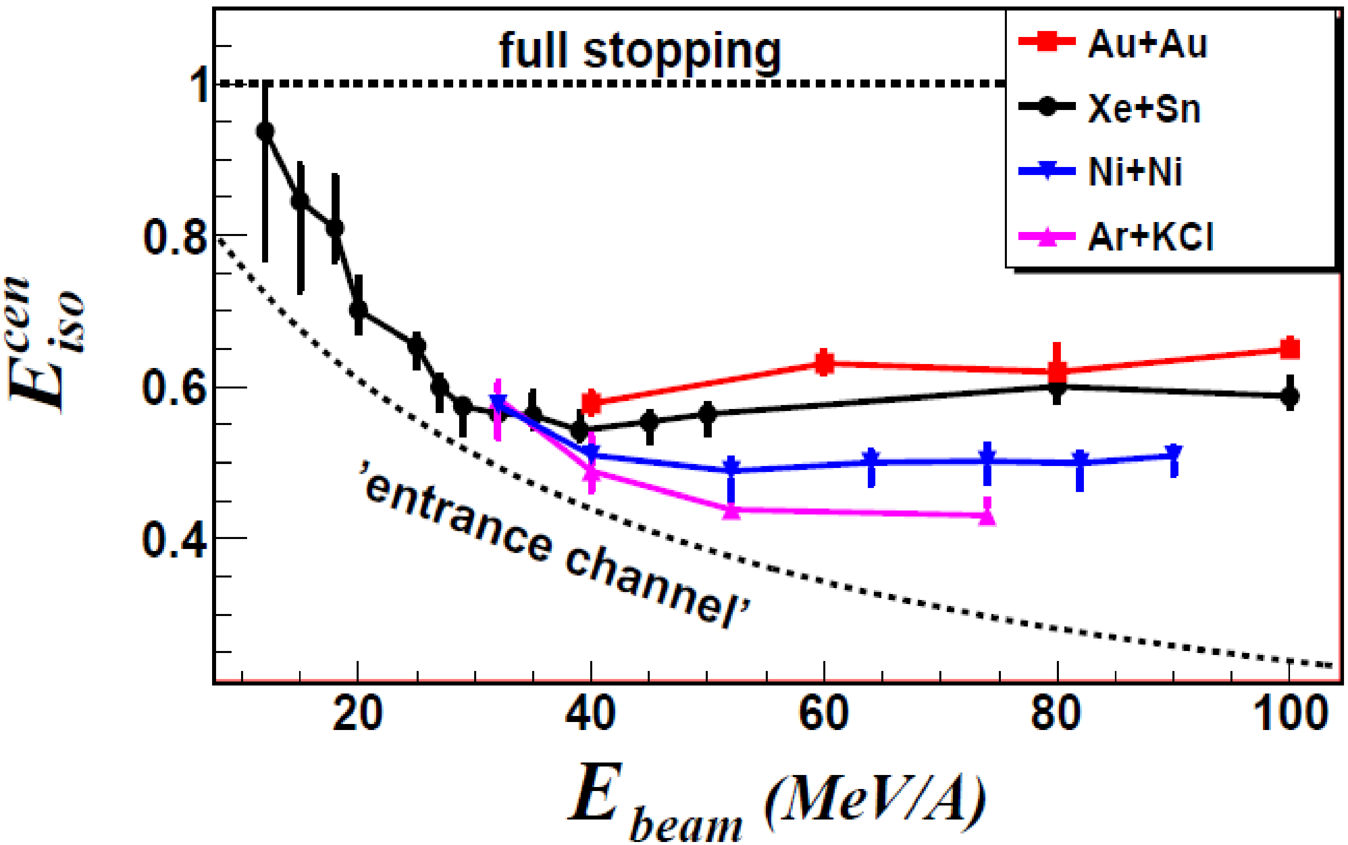


- memory of entrance channel is lost
- no preferential axis

- memory of the entrance channel is partially conserved
- preferential direction along the beam axis

Situation in 2010 : ***G. Lehaut et al., PRL 104, 232701 (2010)***

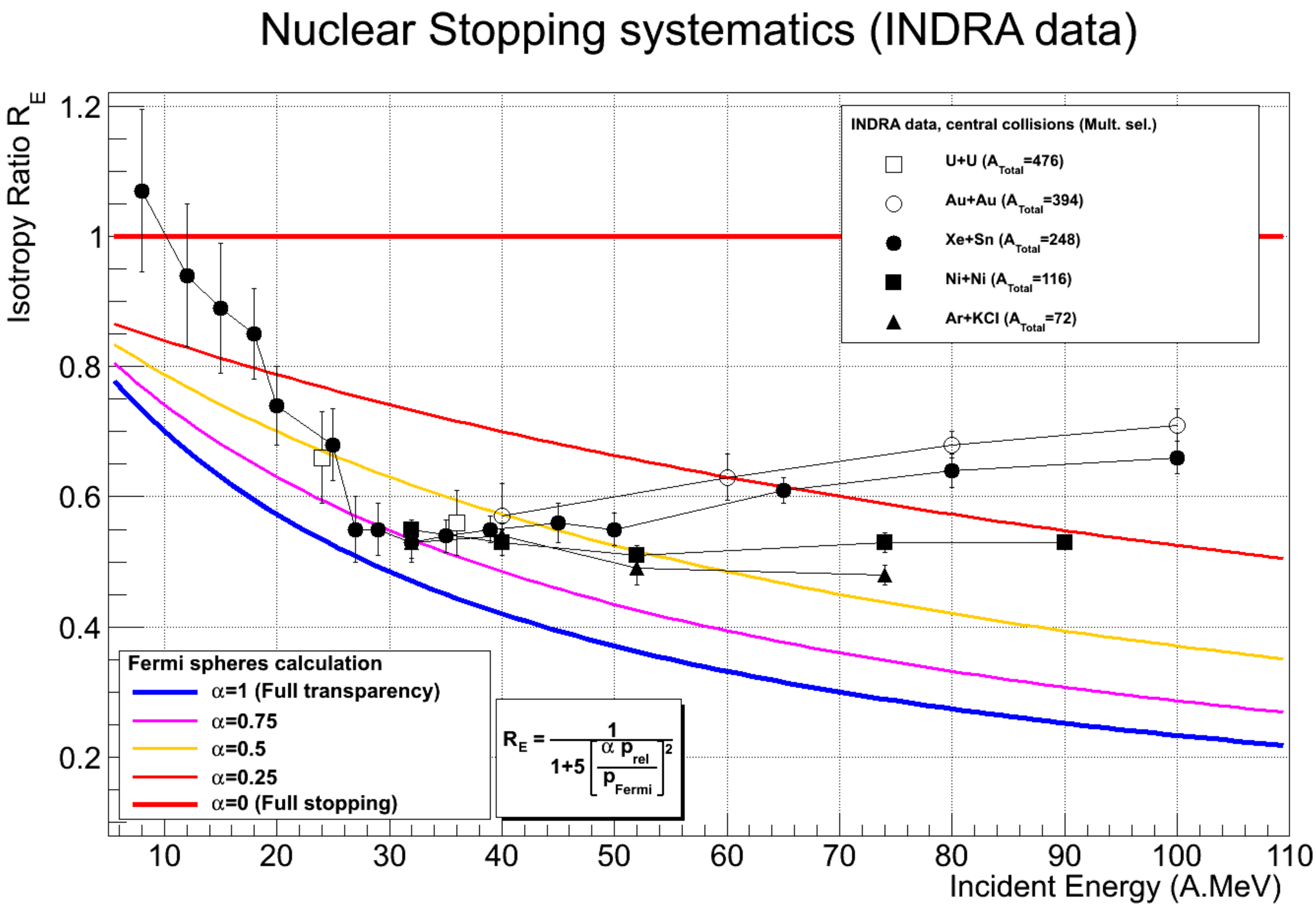
Systematics



2 regimes :

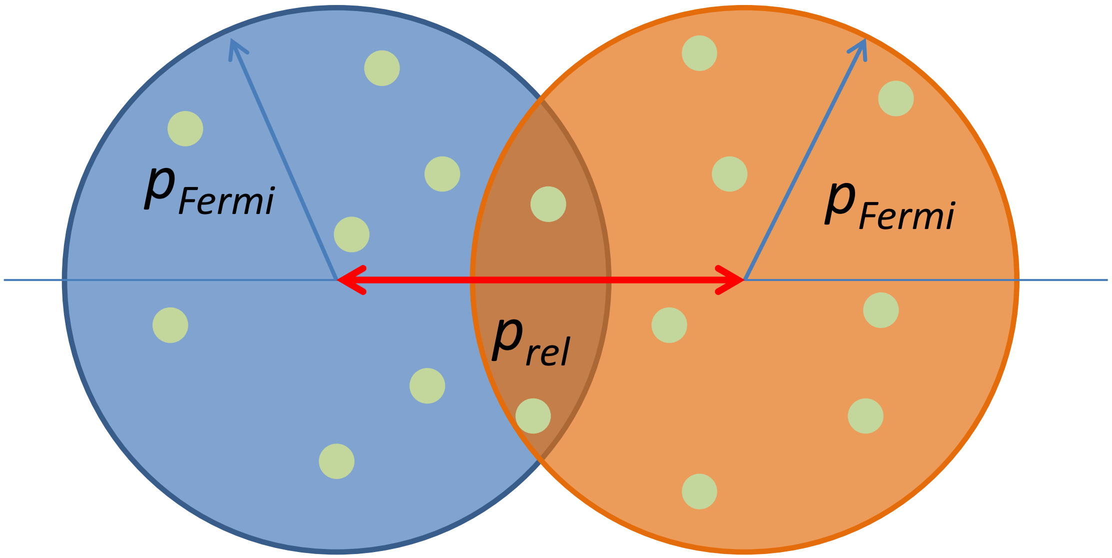
- Below *30-35A MeV*, **Mean-Field** picture and **1-dissipation** : **viscosity**
- Above *35A MeV*, **elastic *NN* collisions** and **2-dissipation** : λ_{NN} and σ_{NN}

Situation in 2012 : *one system added (U/Gd+U) + extension to low E_{inc}*



Entrance channel estimate for R_E

Fermi spheres with radius p_{Fermi}, separated by the relative momentum $p_{rel}=\mu V_{rel}$

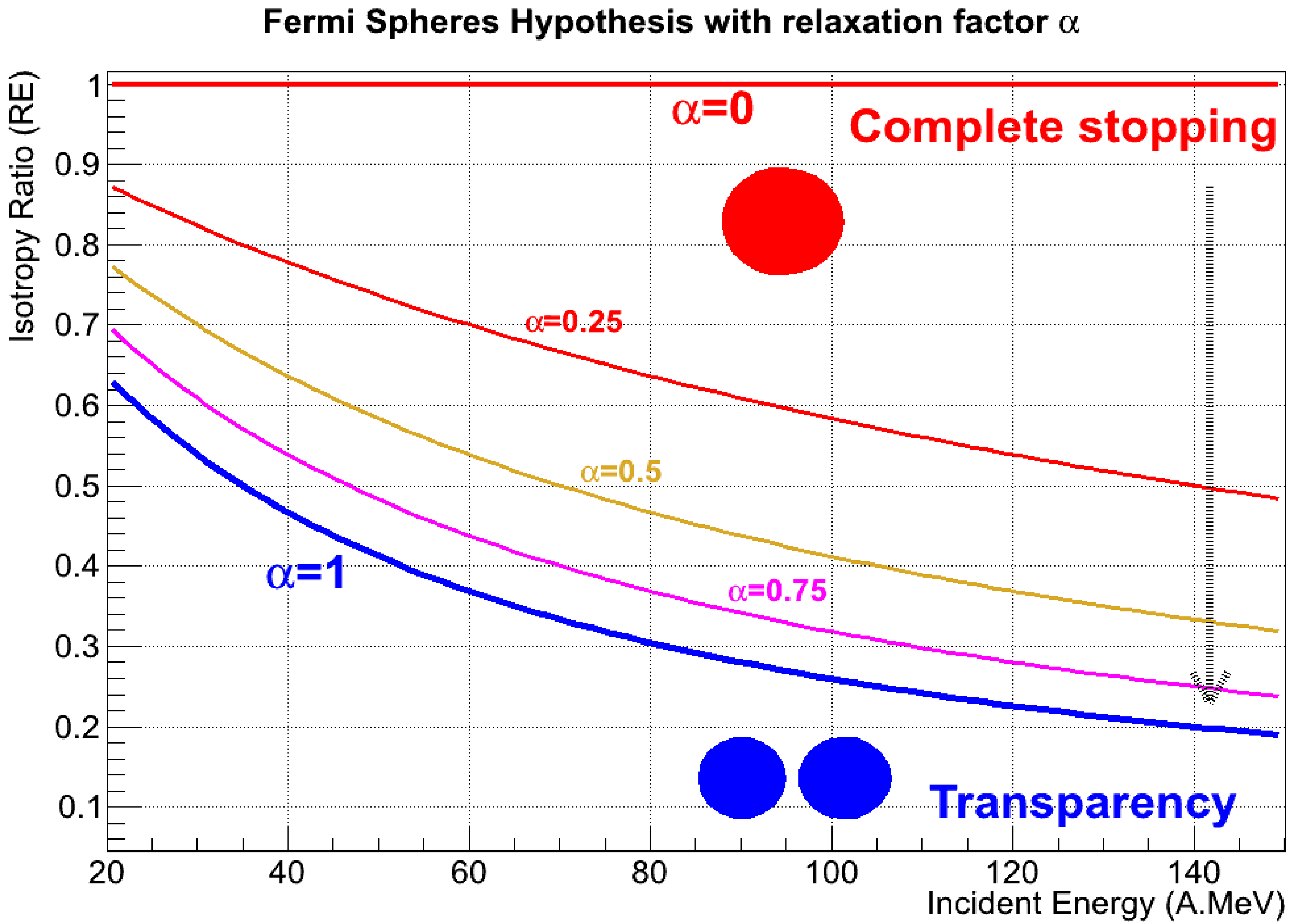


For an **infinite number** of particles sampled in these 2 distributions, we obtain :

$$R_E = \frac{1}{1+5\left[\frac{\alpha\, p_{rel}}{p_{Fermi}}\right]^2}$$

where α between *0* and *1* measures the dissipation

In pratice, *N>10-15* is enough to get <R_E>



Clusterization effects ? *see Zhang et al., Phys. Rev. C 84, 034612 (2011)*

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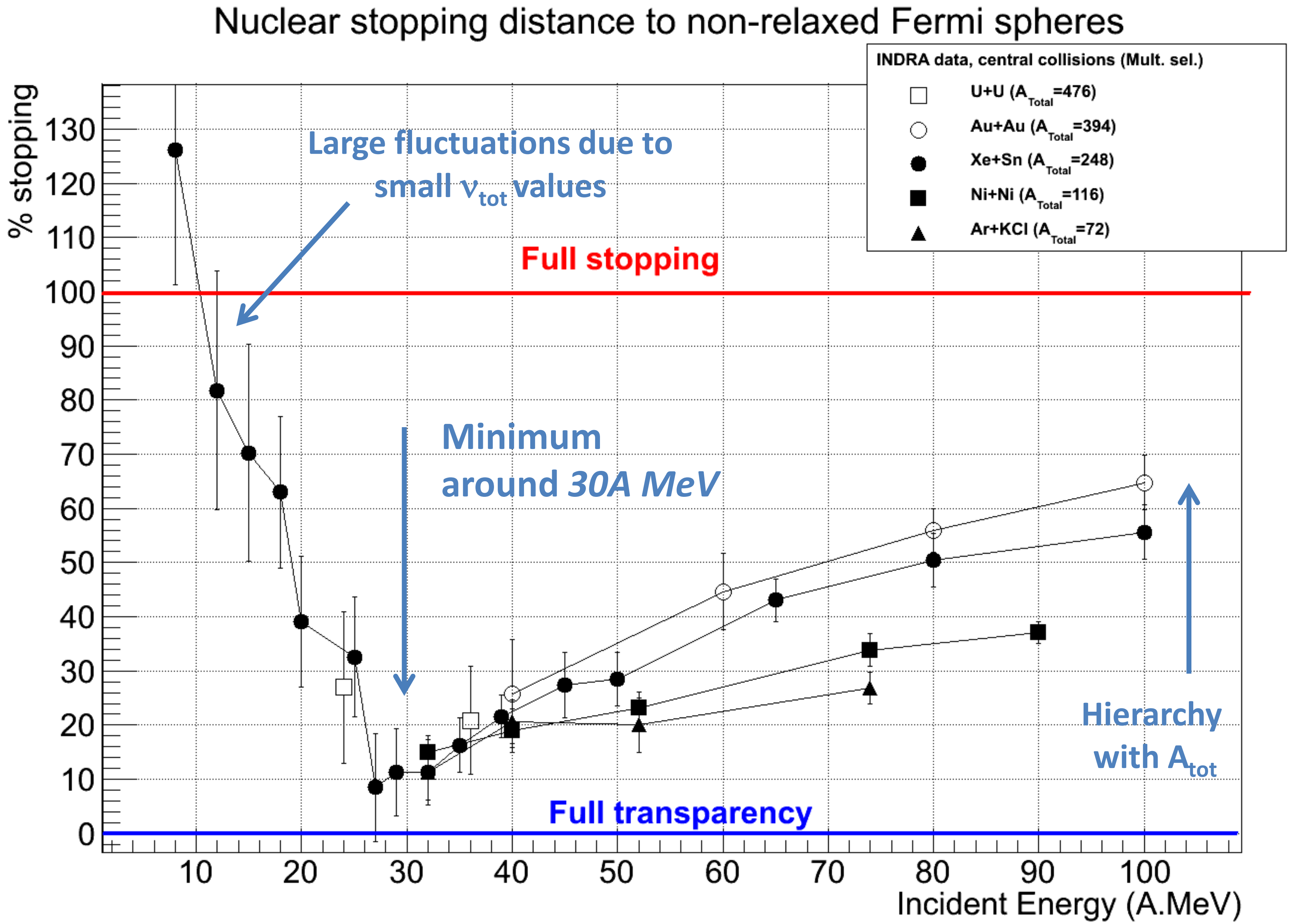
Percentage of stopping/transparency



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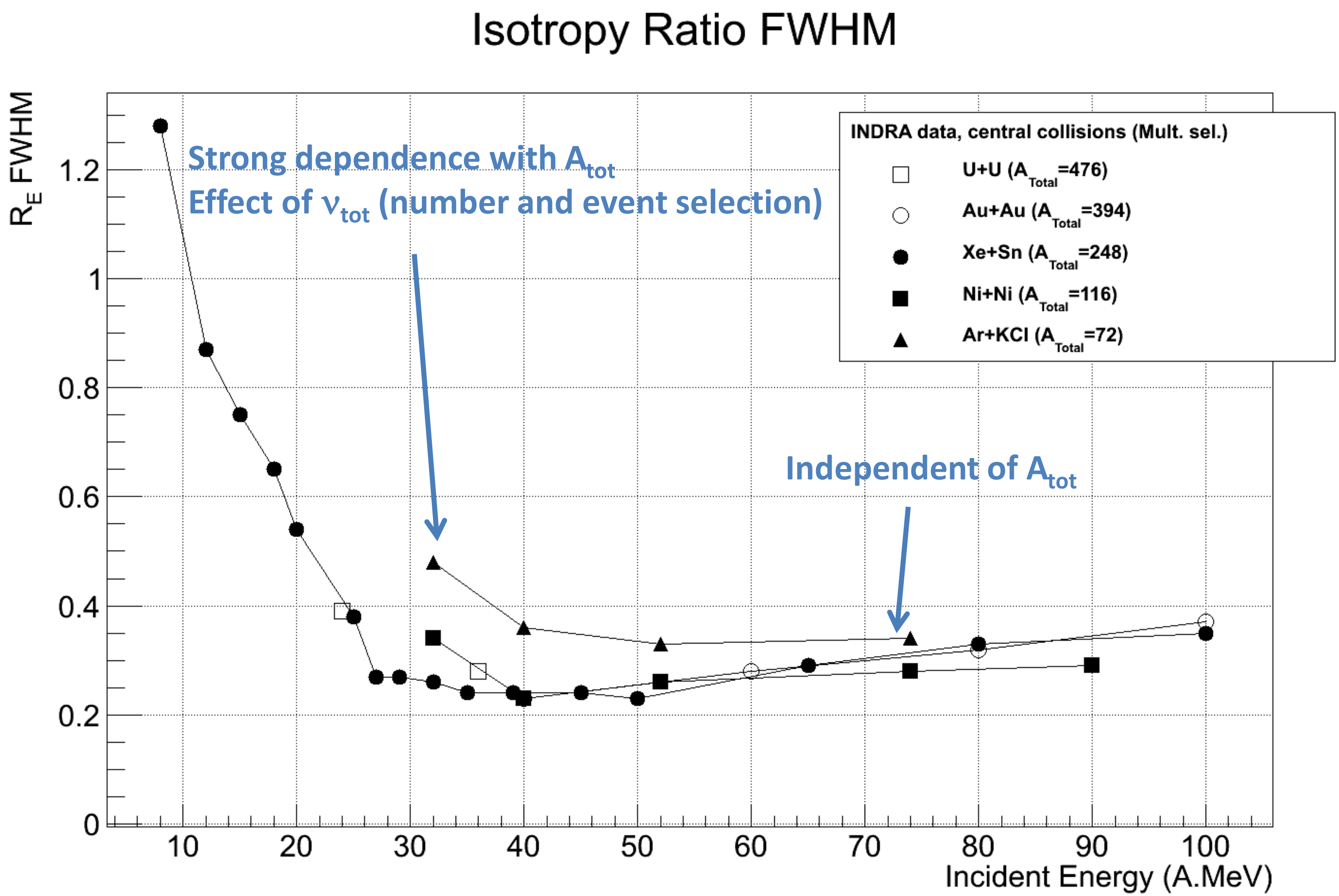
Widths / fluctuations* …



* Very sensitive to the event selection (impact parameter range)

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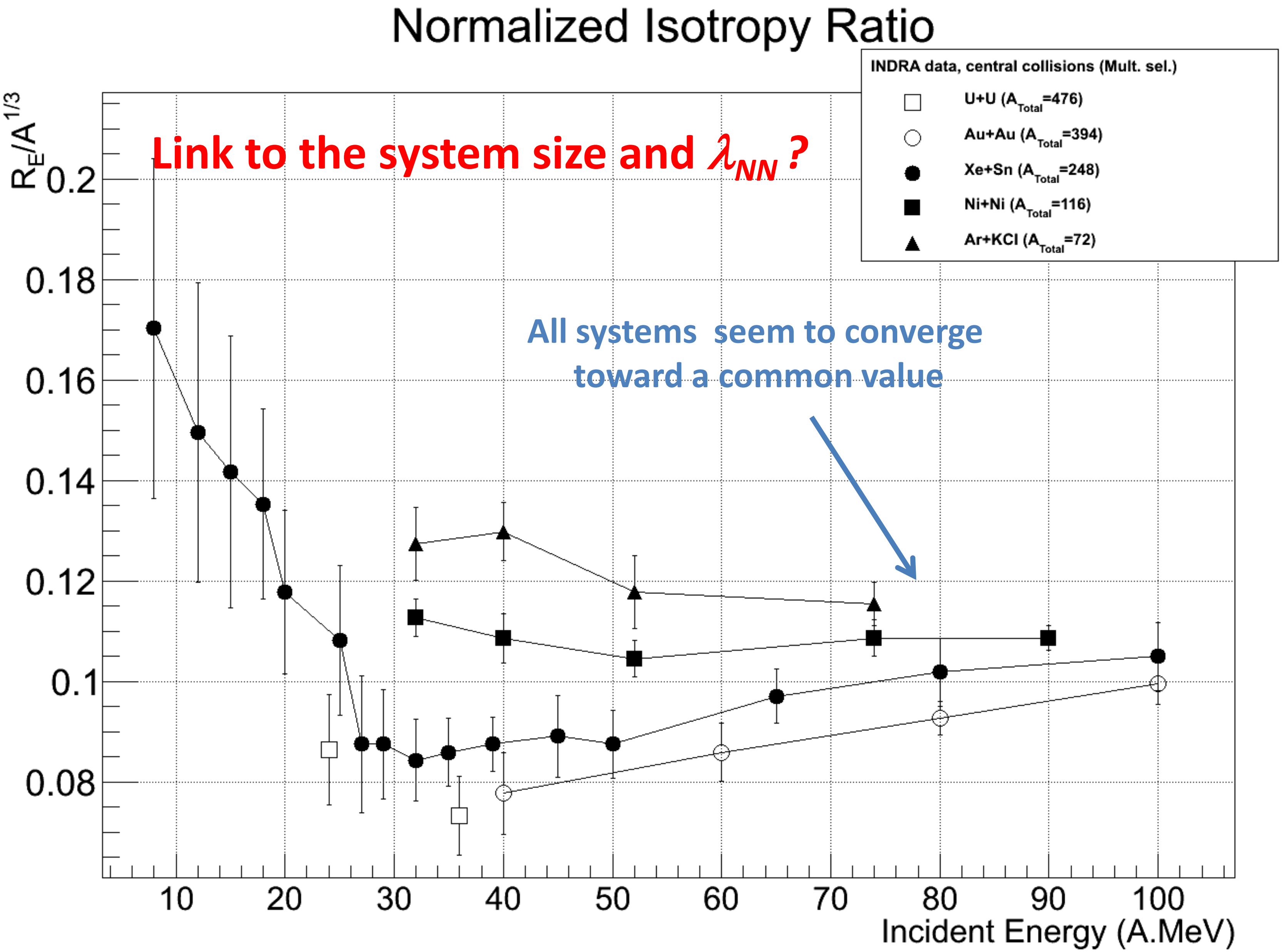
Scaling with the system size A_{tot}



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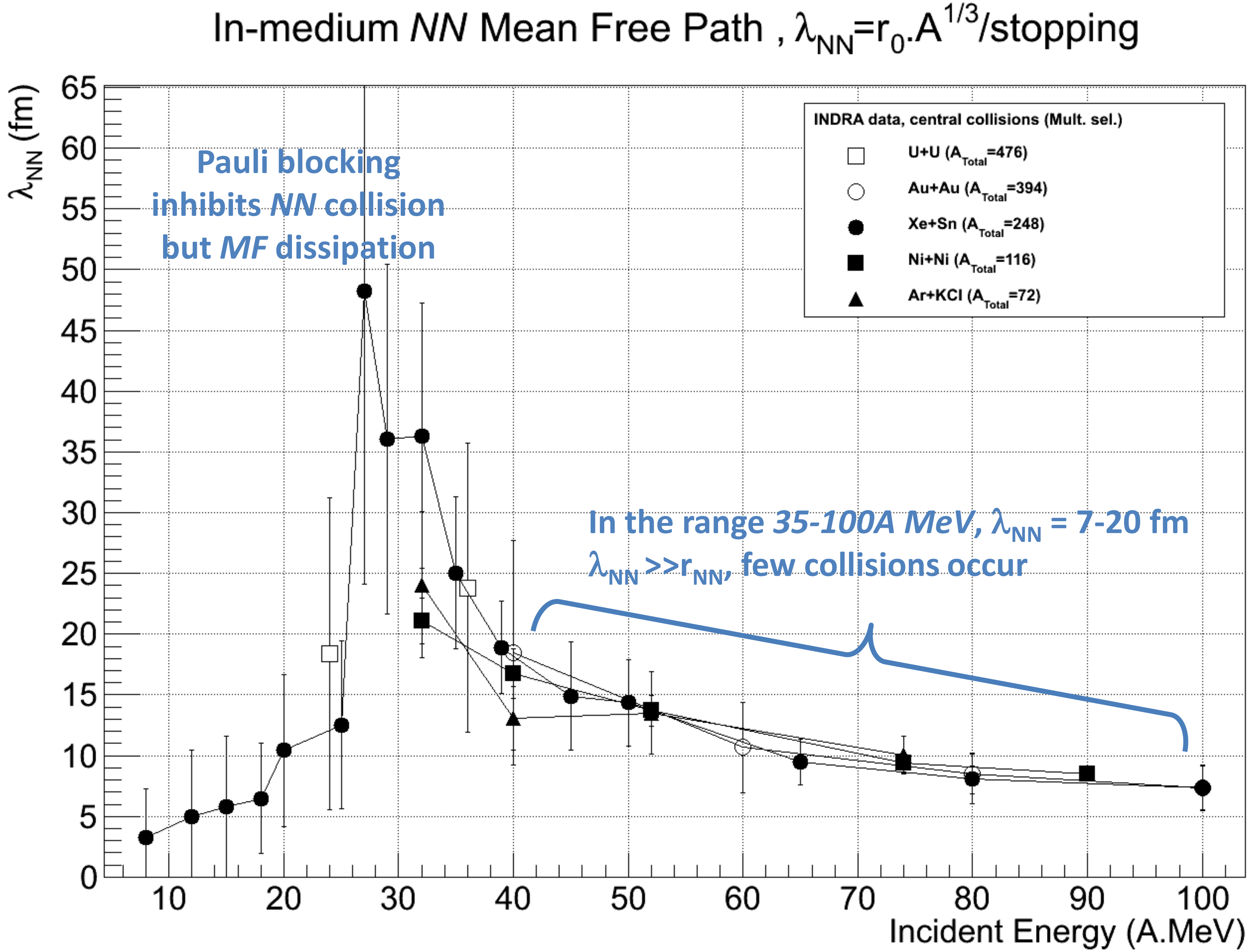
Estimation of the mean free path for nucleons in NM



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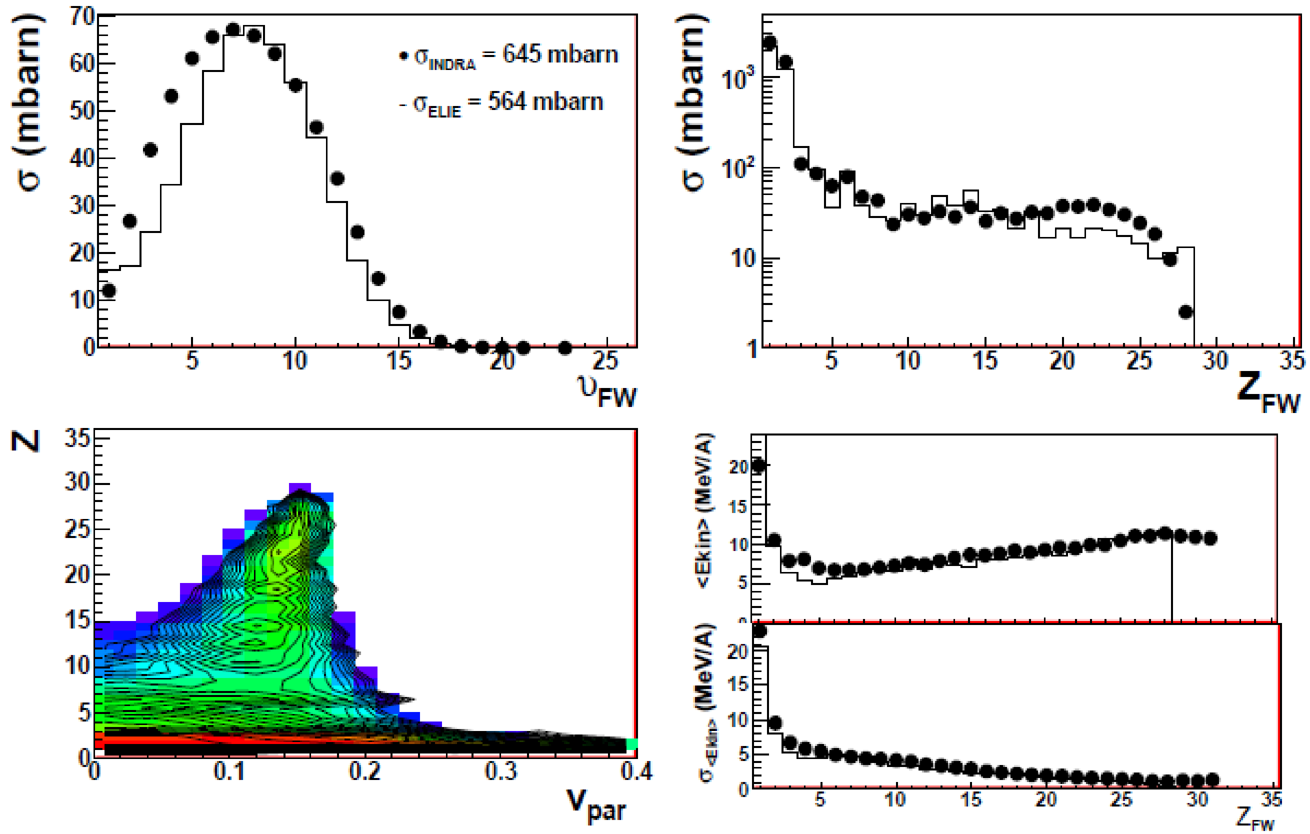
Partitions and kinematics

$Ni + Ni@52A.MeV$

INDRA : selection $Z_{tot}^{FW} \in [0.8; 1.2]$ ELIE filtered : selection $Z_{tot}^{FW} \in [0.8; 1.2]$



- An excellent agreement between ELIE and the INDRA data is found

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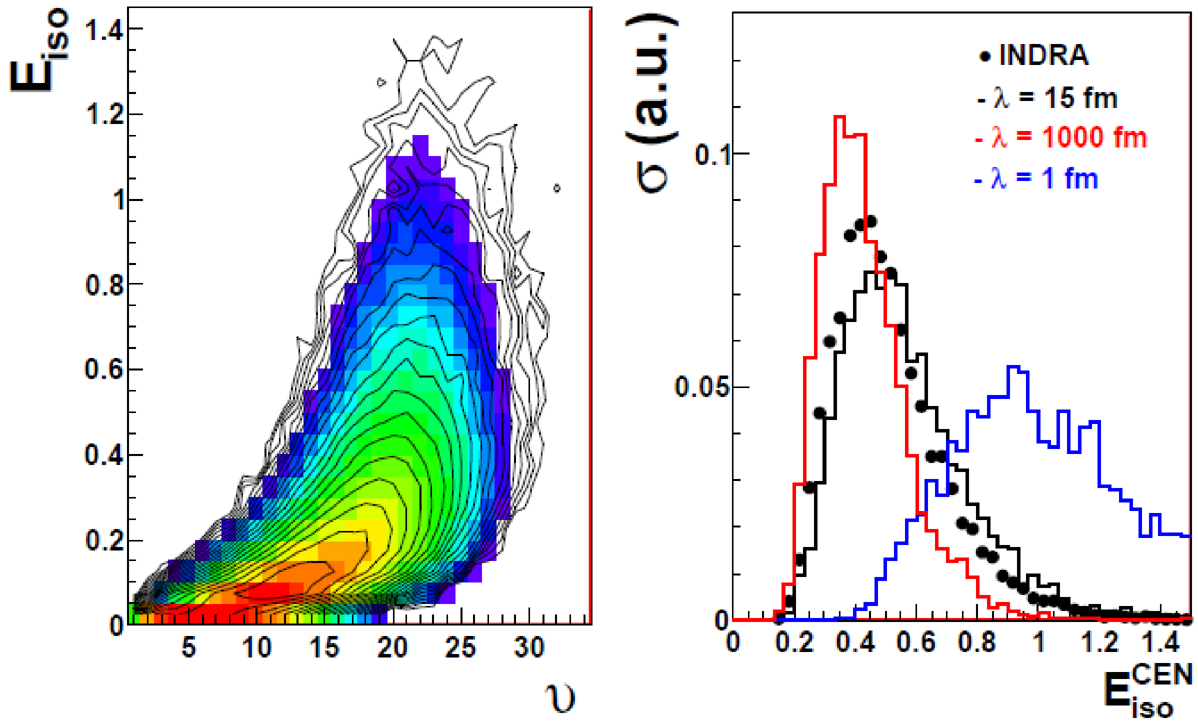
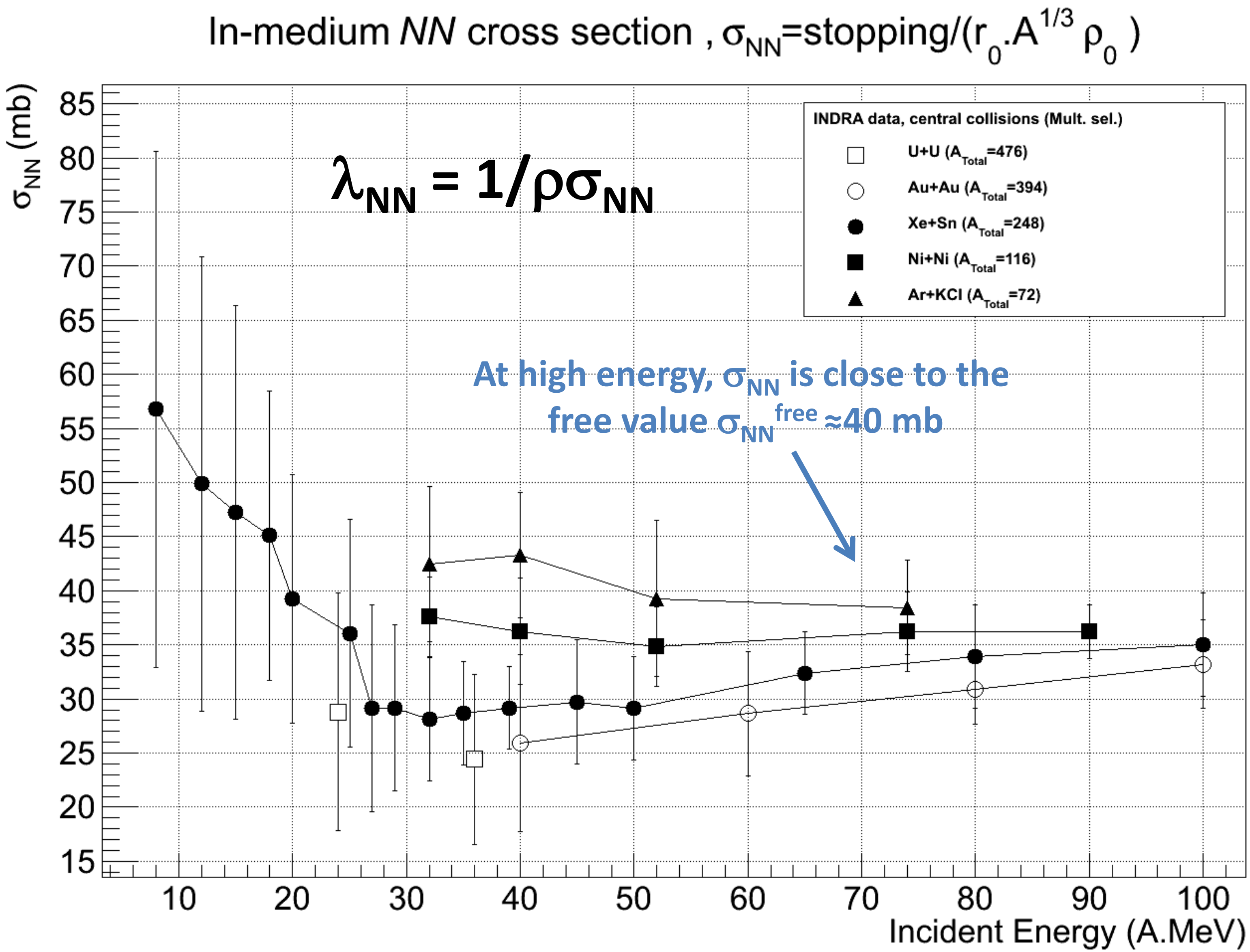
Comparison on stopping:
$Ni + Ni@52A.MeV$, central collisions $\nu > 26$



- sensitivity to λ is found for E_{iso}^{cen}, especially for $\lambda < (R_{proj} + R_{targ})$
- data is closer to $\lambda = 15$ fm ($> R_{proj} + R_{targ}$), suggesting no complete thermalization since the number of collisions per participant is less than 1.

Experimental *NN* cross-section estimate from λ_{NN}



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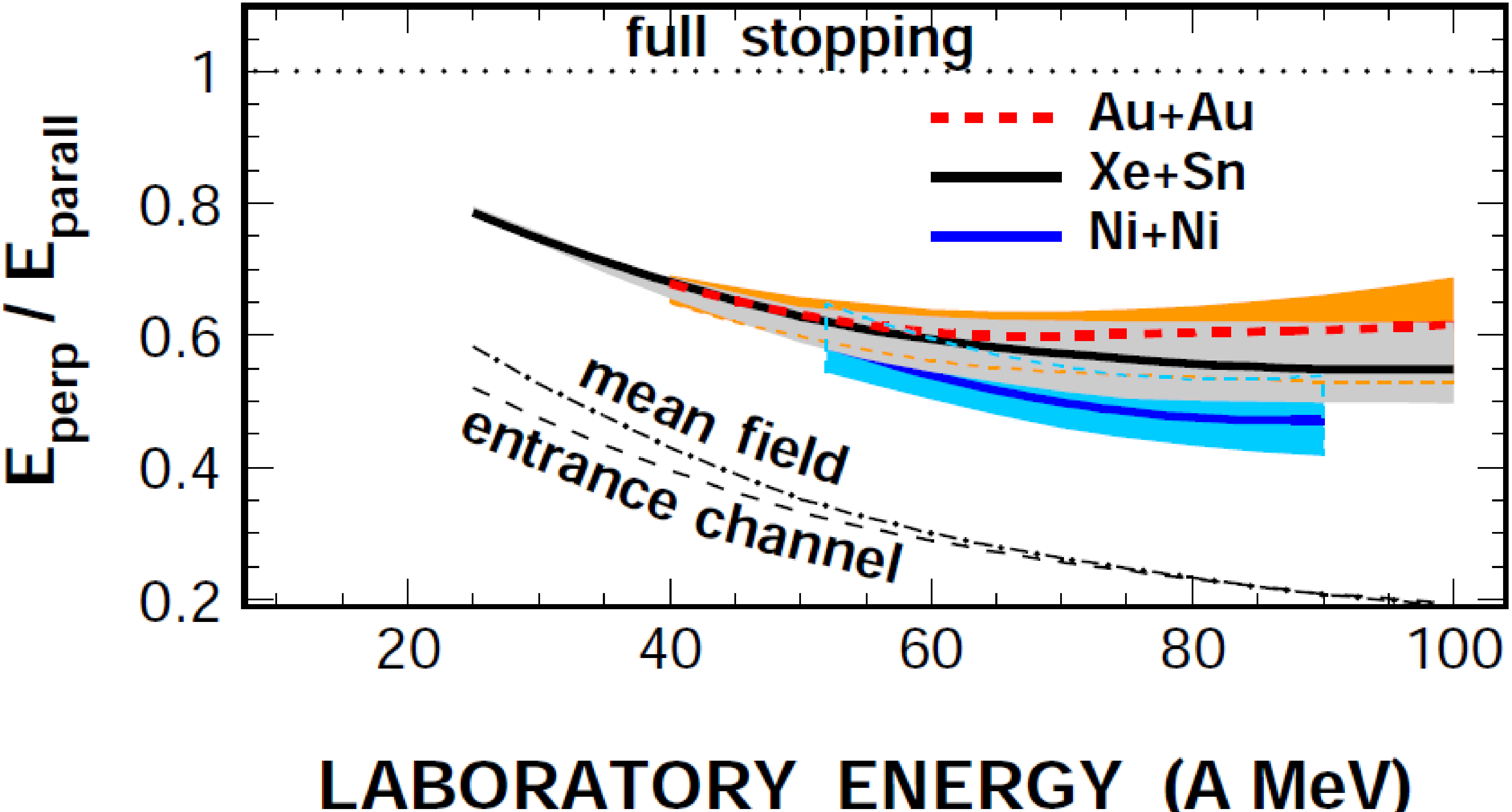
Comparison with a transport model

Landau-Vlasov* : Gogny + variable σ_{NN}

σ_{NN} ±20% of free σ_{NN}

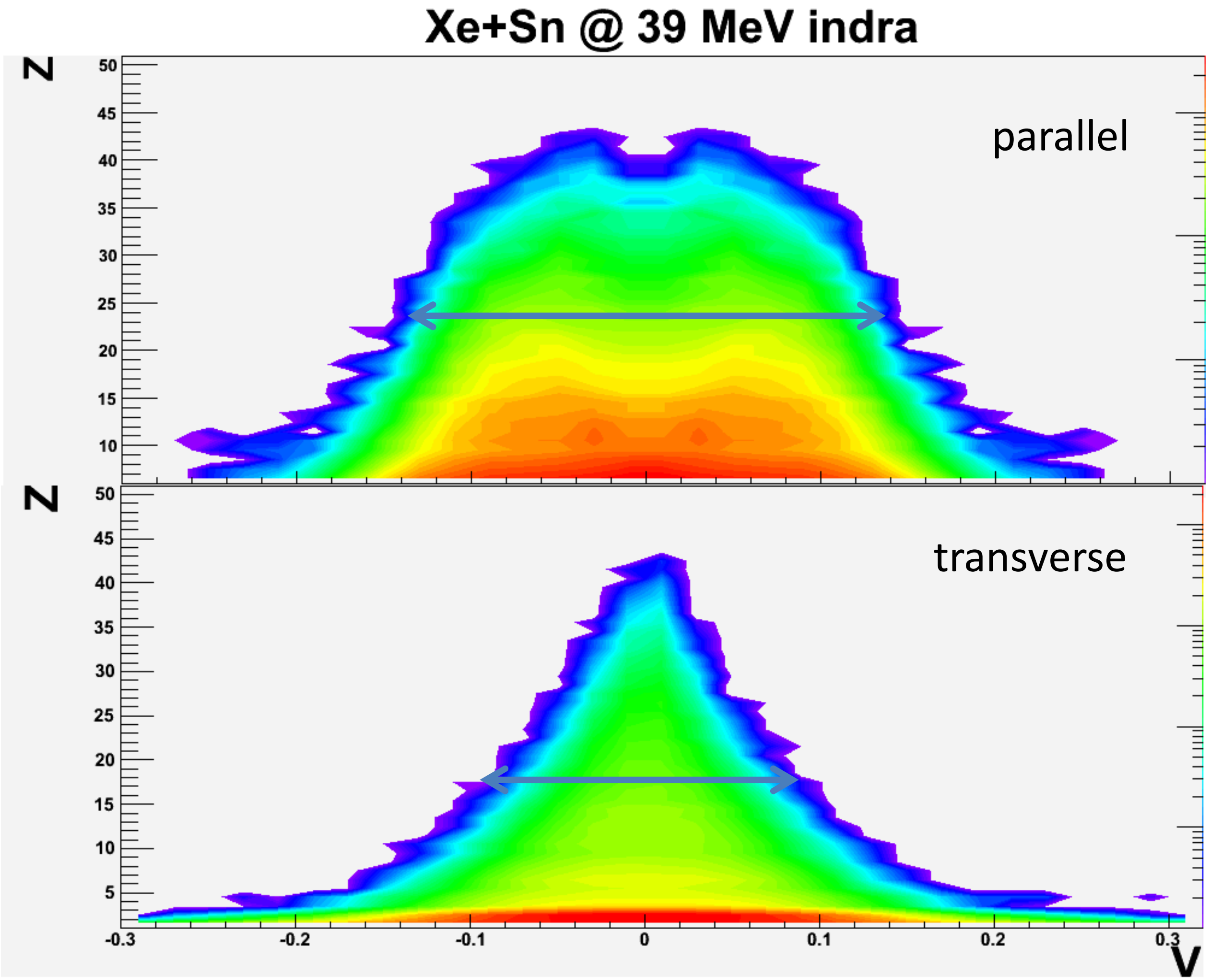


** Courtesy of Ph. Eudes and Z. Basrak*

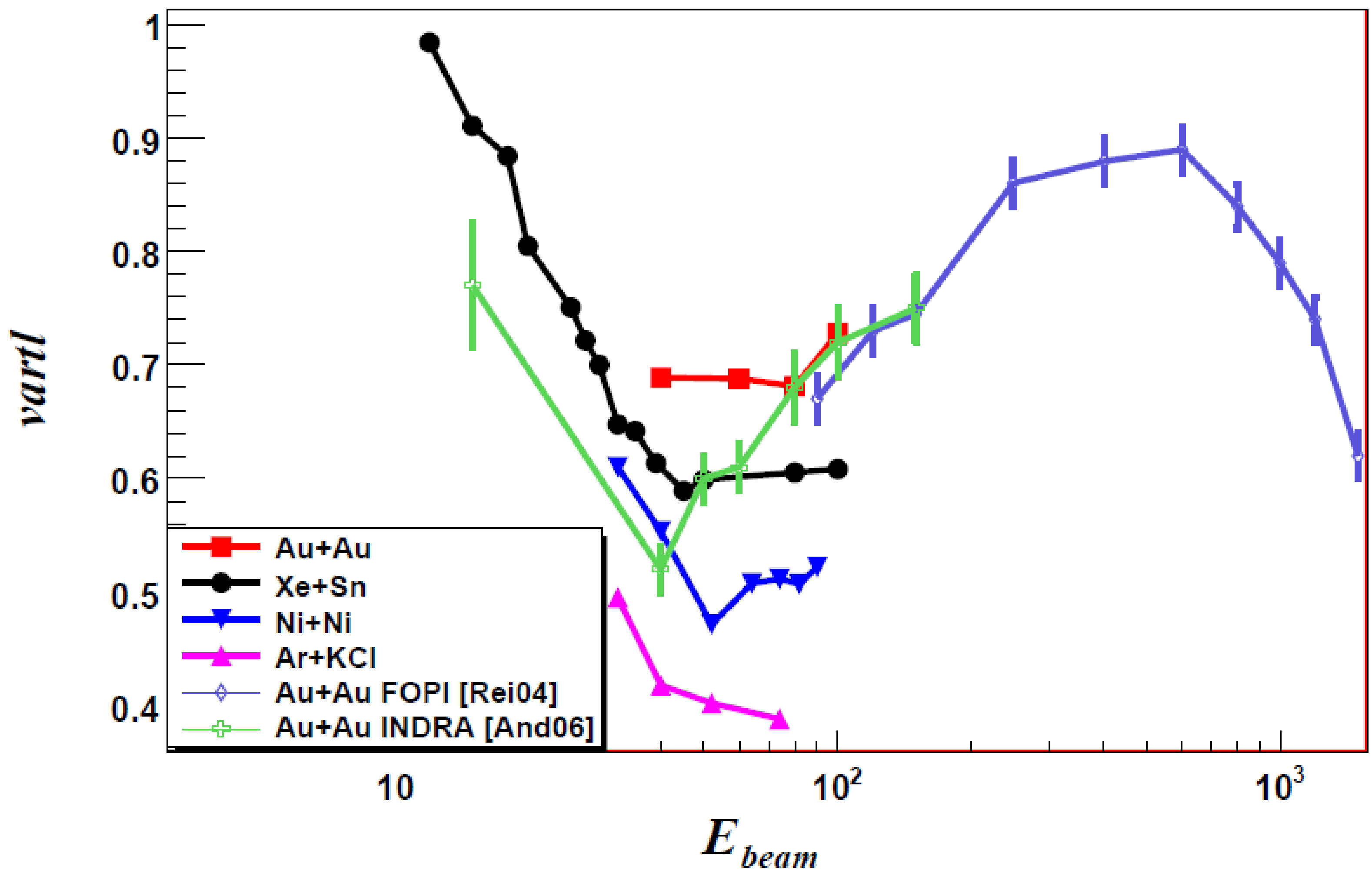
New probes …

Ratio of velocity variances : *vartl*

$$vartl = \frac{variance(y_\perp)}{variance(y_\parallel)}$$



Vartl systematics from FOPI/INDRA data

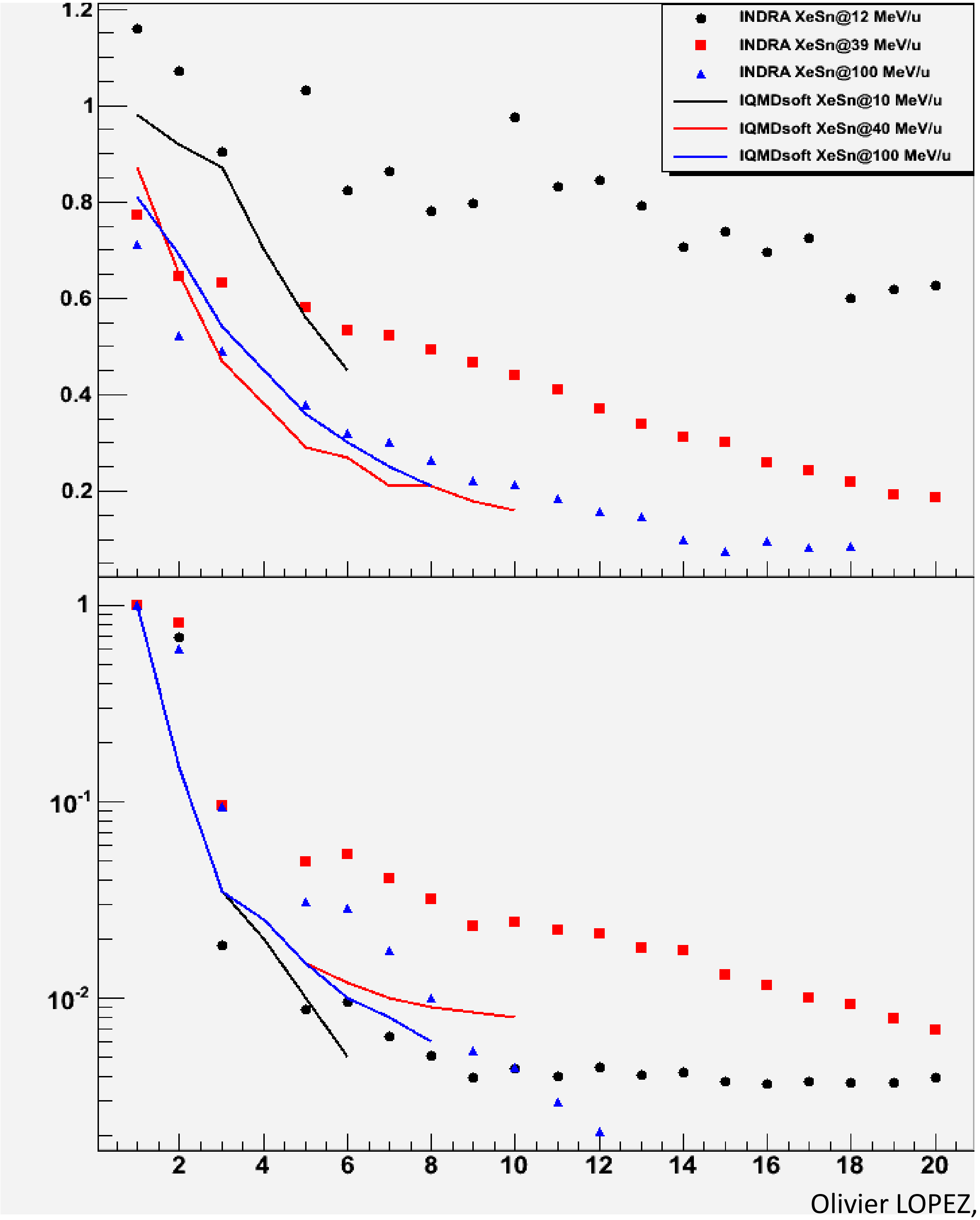


[And06] A. Andronic, J. Lukasik, W. Reisdorf, W. Trautmann. *Systematics of stopping and flow in Au+Au collisions*, Eur. Phys. J. A **30**, 31-46 (2006).

Vartl and production yield

vartl

Yield (Z=1)



IQMD fails to reproduce *vartl* and *yield* for E/A<100 MeV

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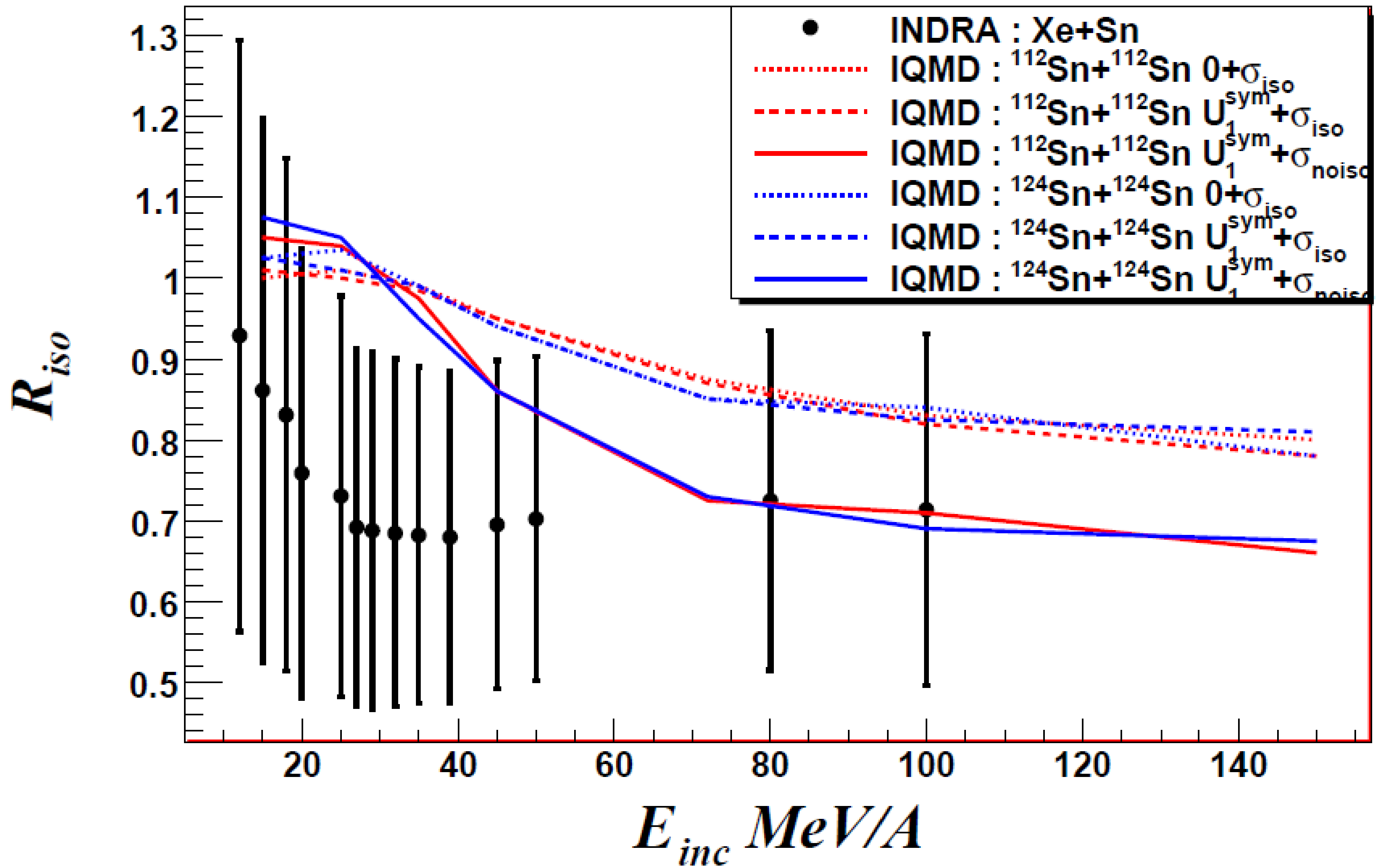
Stringent test for transport model…



But here R_{iso} is determined after *t=200 fm/c, no fragment formation …*

Conclusions

-**Transparency** of nuclear matter is reported around Fermi Energy and above by looking at **isospin** and **energy ratios**

- 2 **distinct mechanisms** for dissipation (Mean-Field/NN collisions) with a **sharp transition** around ***30A MeV***

- no **isospin dependence** for the stopping : **isovector channels** for *NN* collision (nn/pp, np) ?

- at low energy : (bulk) **viscosity** can be accessed by studying stopping

- At high energy : λ_{NN} **and** σ_{NN} can be experimentally estimated :
λ_{NN} is rather large ($\lambda_{NN} \approx 10\text{-}15$ *fm*) and $\sigma_{NN}^{in\text{-}medium}$ close to σ_{NN}^{free}

Provide a **stringent benchmark** for any kind of transport model
-Request for comparison with microscopic transport models