Evidenze sperimentali di transizione di fase liquido-gas nei nuclei

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NUCL-EX Collaboration:
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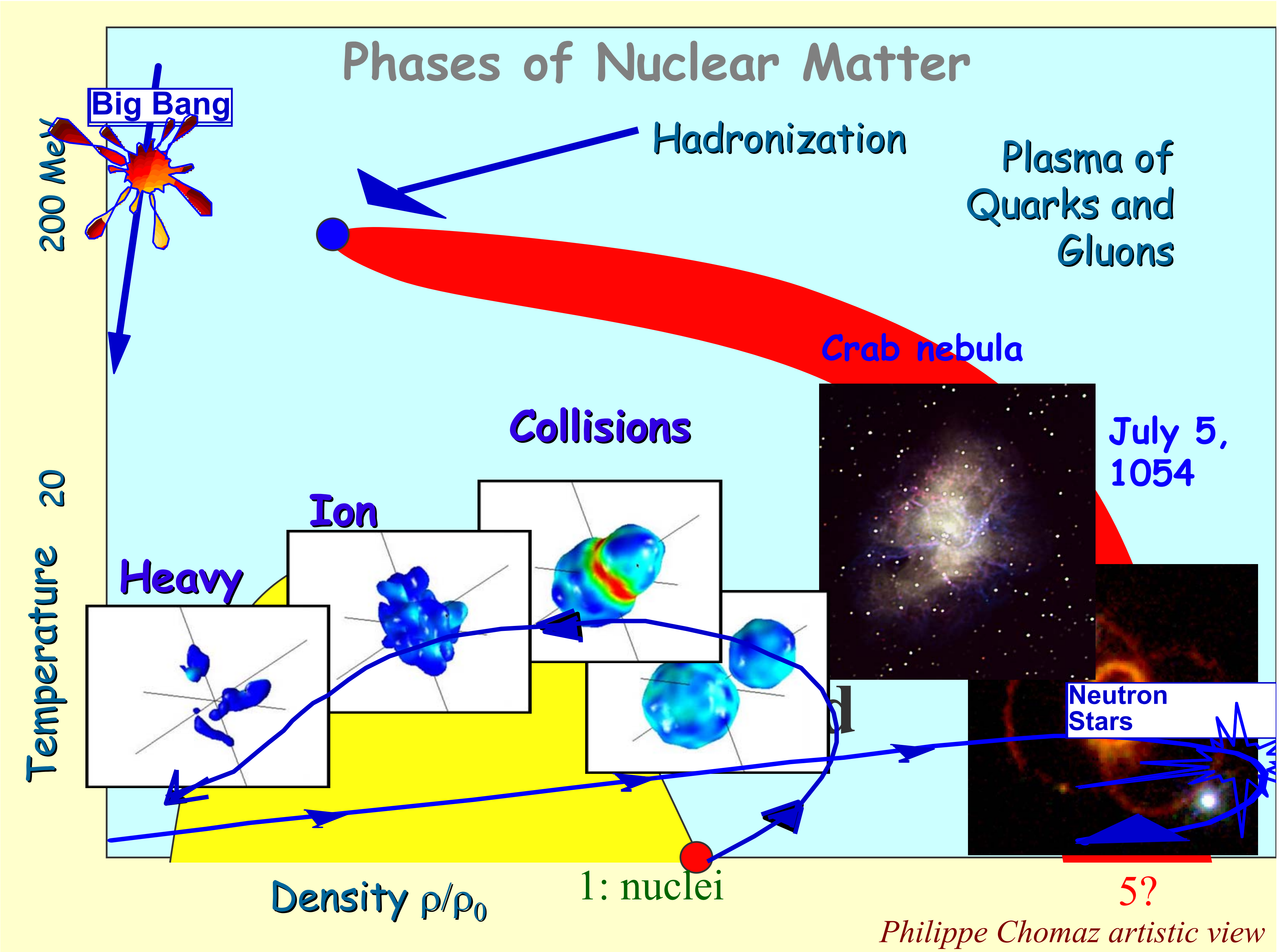
INFN – Laboratori Nazionali di Legnaro
LPC e GANIL – Caen (Francia)
IPN – Orsay (Francia)

Schema

- Che osservabili prevede la teoria nelle transizioni di fase
- Cosa si misura e come
- Come si analizzano i dati: osservabili, sorting
- Confronto fra dati e teoria
- Cosa ancora si deve misurare

Non necessariamente in questo ordine !!!



Phases of Nuclear Matter
Big Bang
200 MeV
Hadronization
Plasma of Quarks and Gluons
Crab nebula
July 5, 1054
Collisions
Ion
Heavy
20
Temperature
Neutron Stars
Density ρ/ρ0
1: nuclei
5?
Philippe Chomaz artistic view

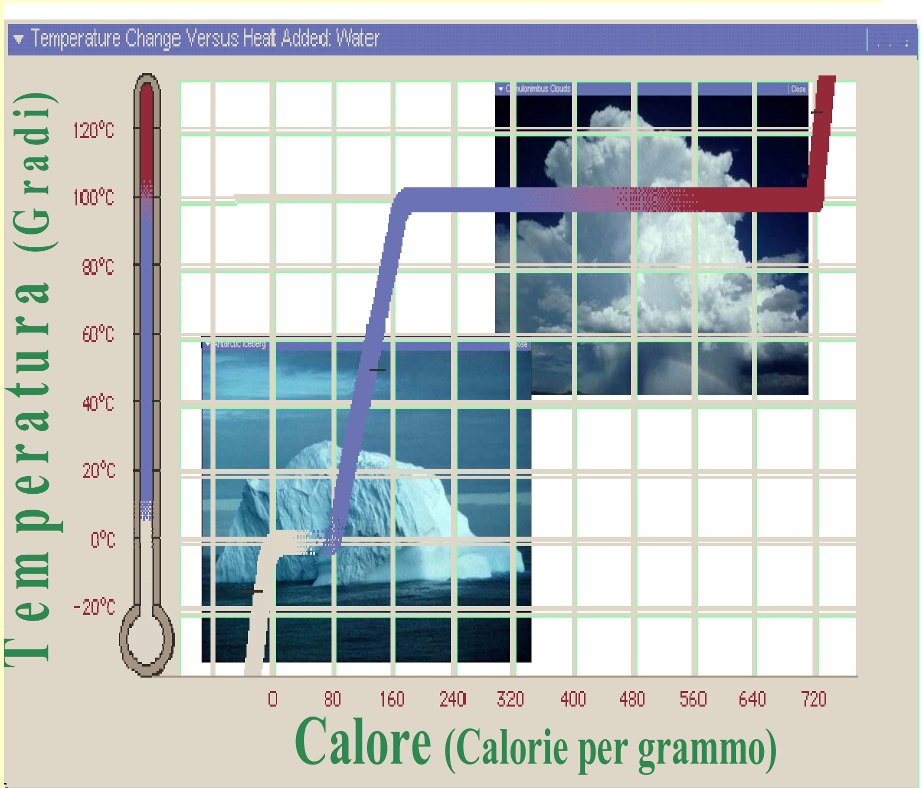
Transizioni di fase: Keywords

	QG Plasma	Liquid-Gas
Soppressione di canali	J/Ψ	Risonanza gigante di dipolo
Fenomeno critico	deconfinamento	multiframmentazione
Tempi di equilibrio e di rilassamento	$t_{eq} \approx 1$ fm/c	$t_{eq} \approx 100$ fm/c
Parametri critici	Temperatura critica ($T_c \approx 170$ MeV) Esponenti critici	Temperatura critica ($T_c \approx 5$ MeV) Esponenti critici
Fluttuazioni	temperatura e molteplicita'	energia (capacita' termica negativa)
Ordine della transizione	Primo o secondo?	Primo o secondo?

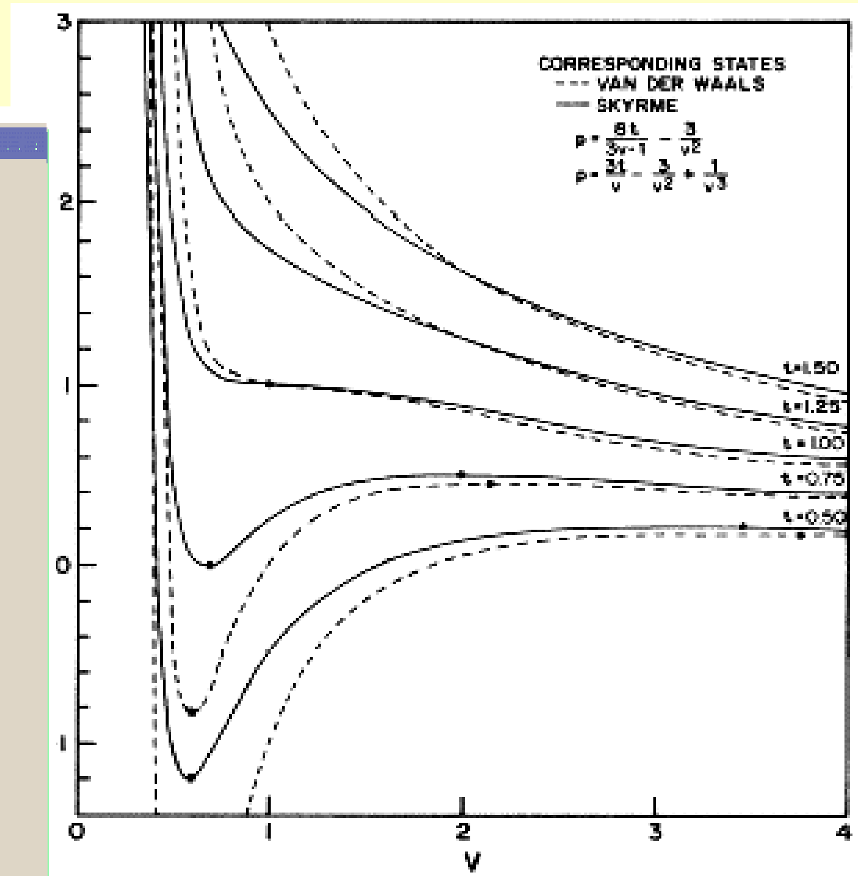
Forze nucleari:

Simili a forze di Van der Waals

repulsive a piccole distanze
attrattive a grandi distanze



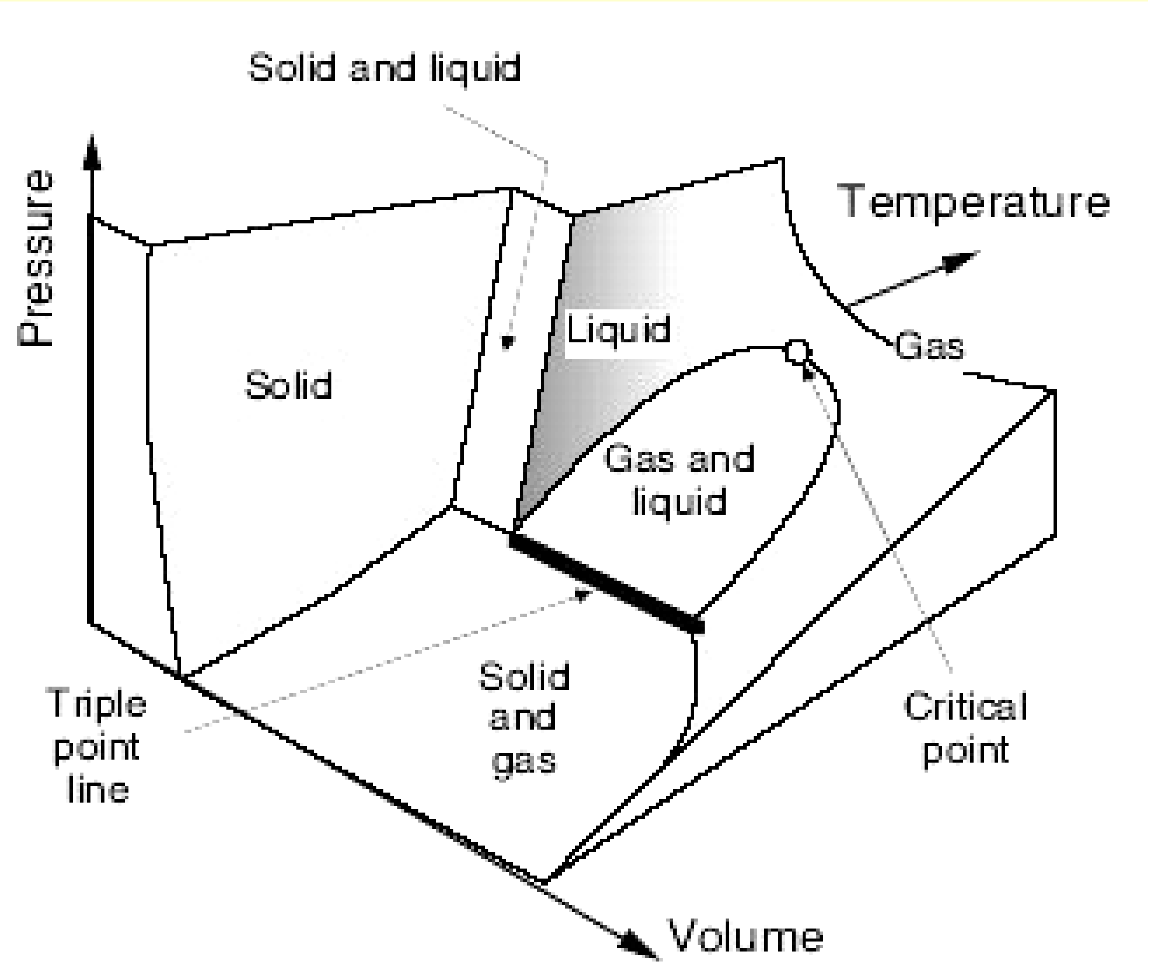
H.Jaqaman et al. PRC27(1983)2782



Equazione di stato della materia nucleare

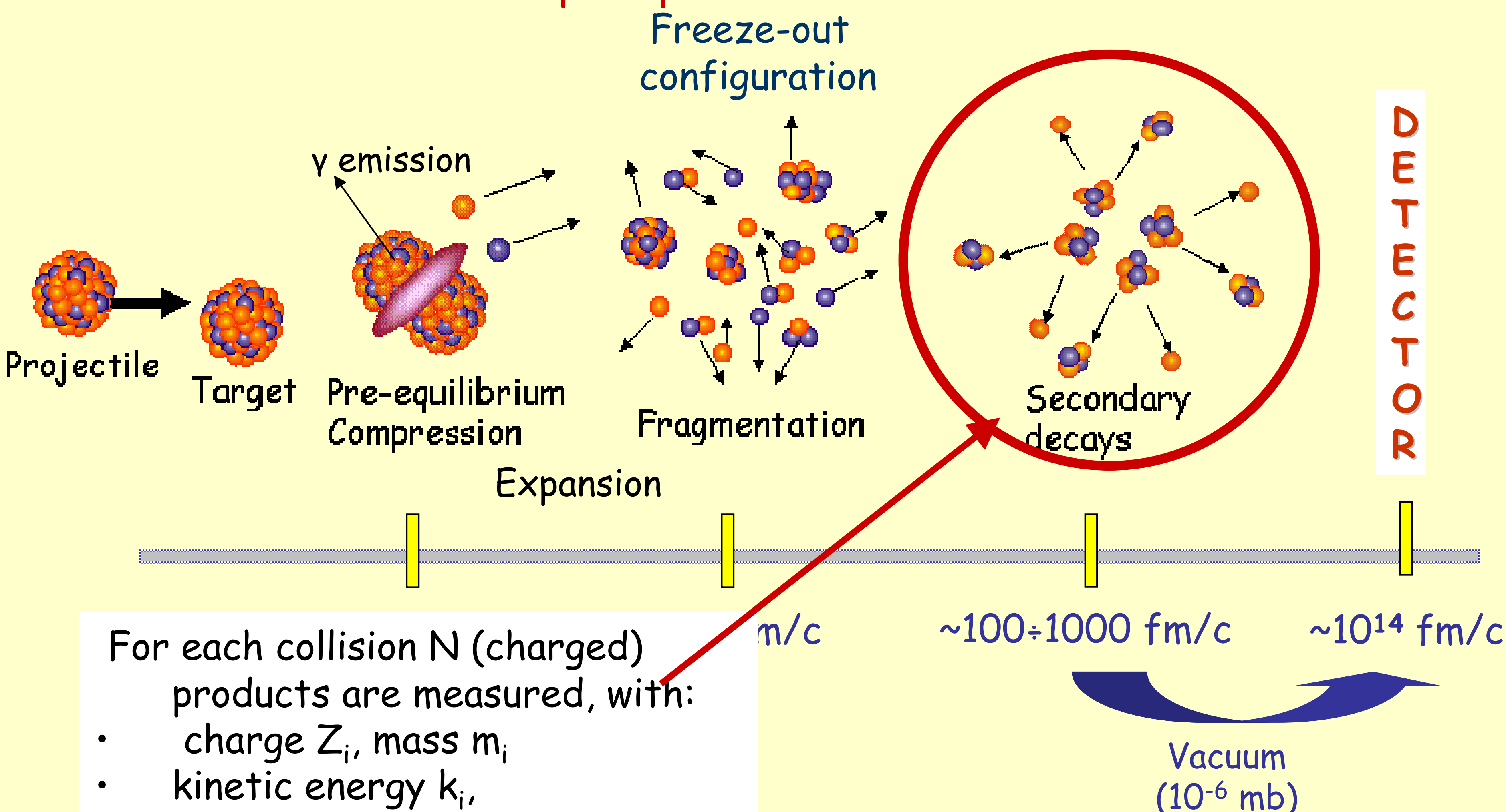
Sono possibili transizioni di fase?

Il nucleo a basse energie di eccitazione si comporta come un liquido (formula di massa di Weizsäcker) ad alta energie di eccitazione come un gas (modello a gas di Fermi)



Heavy Ion collisions at intermediate energies

Inclusive observables correspond to averages, weighted on the impact parameter



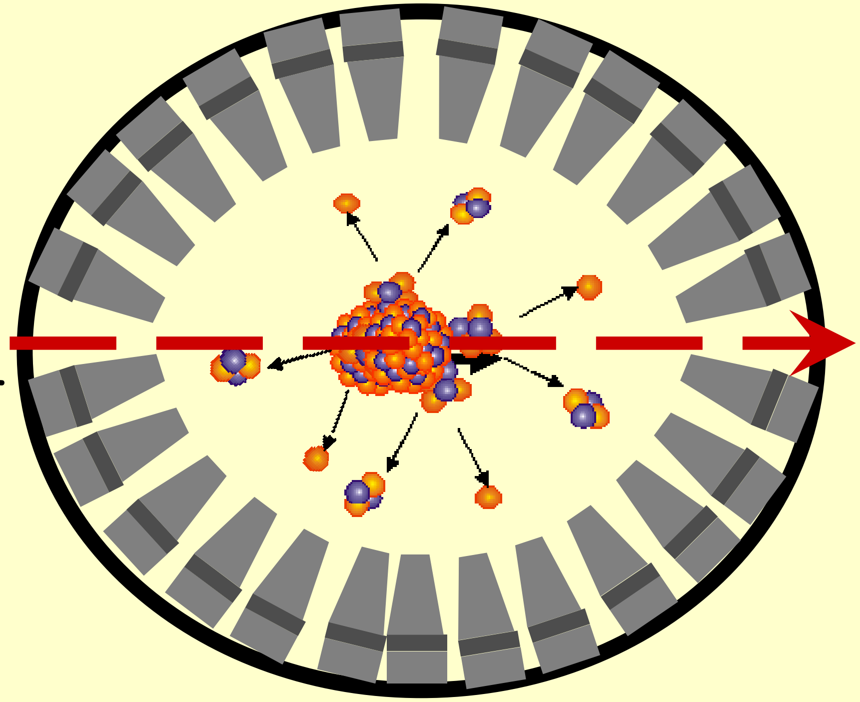
For each collision N (charged) products are measured, with:

- charge Z_i, mass m_i
- kinetic energy k_i,
- flying direction θ_i, φ_i

$(i=1,N_1)$

H.I. Collisions , intermediate energies (10-100 AMeV): 1-st generation 4π devices

- Z_i, k_i, θ_i, φ_i are measured for almost all charged products, event by event, with high energy resolution (few %) and low energy thresholds (gas detectors)
- Fragments and particles are detected at ~10^{14} fm/c, as they were at 10^{3} fm/c, since the propagation in vacuum does not allow further interactions with matter.



- m_i are measured only for light products
- neutrons and γ are quite often not measured

- Statistical multidimensional analyses performed on global (event) observables allow to sort the events in classes of centrality.
- The decaying system can be identified and its calorimetric excitation energy can be estimated from the energy balance:

$$E^* + m_0 = \sum_{i=1}^{M} (m_i + k_i) + M_n (m_n + k_n)$$

How many detection cells are needed?

N = expected multiplicity,
X = number of detectors
ε = geometrical coverage/4π = probability to detect 1 particle ε(1)

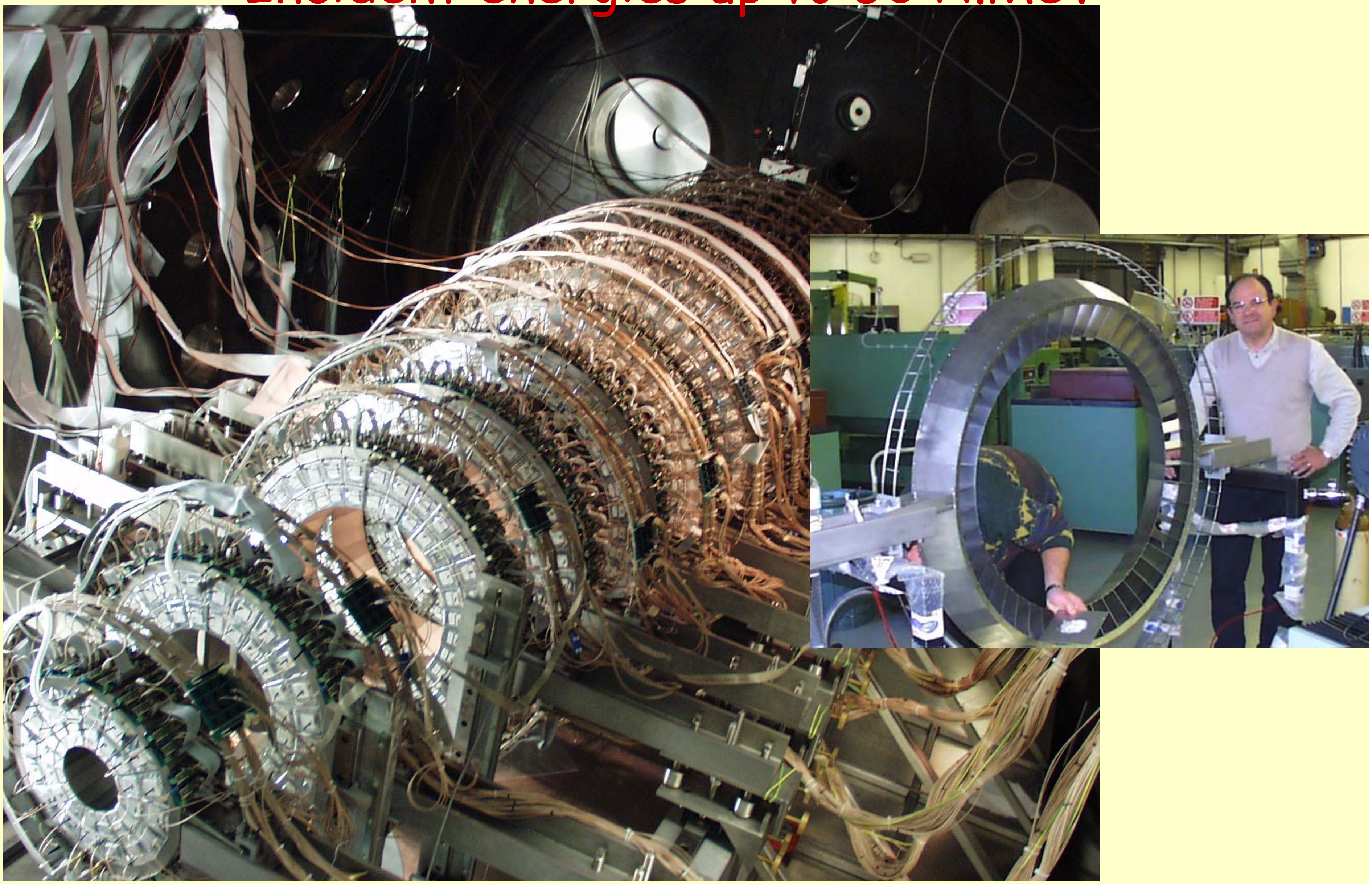
- $\varepsilon(N) = \varepsilon(1)^N$
- $P(\text{double}) = (N-1)/(2X)$

A reasonable compromise is P(double)~few%

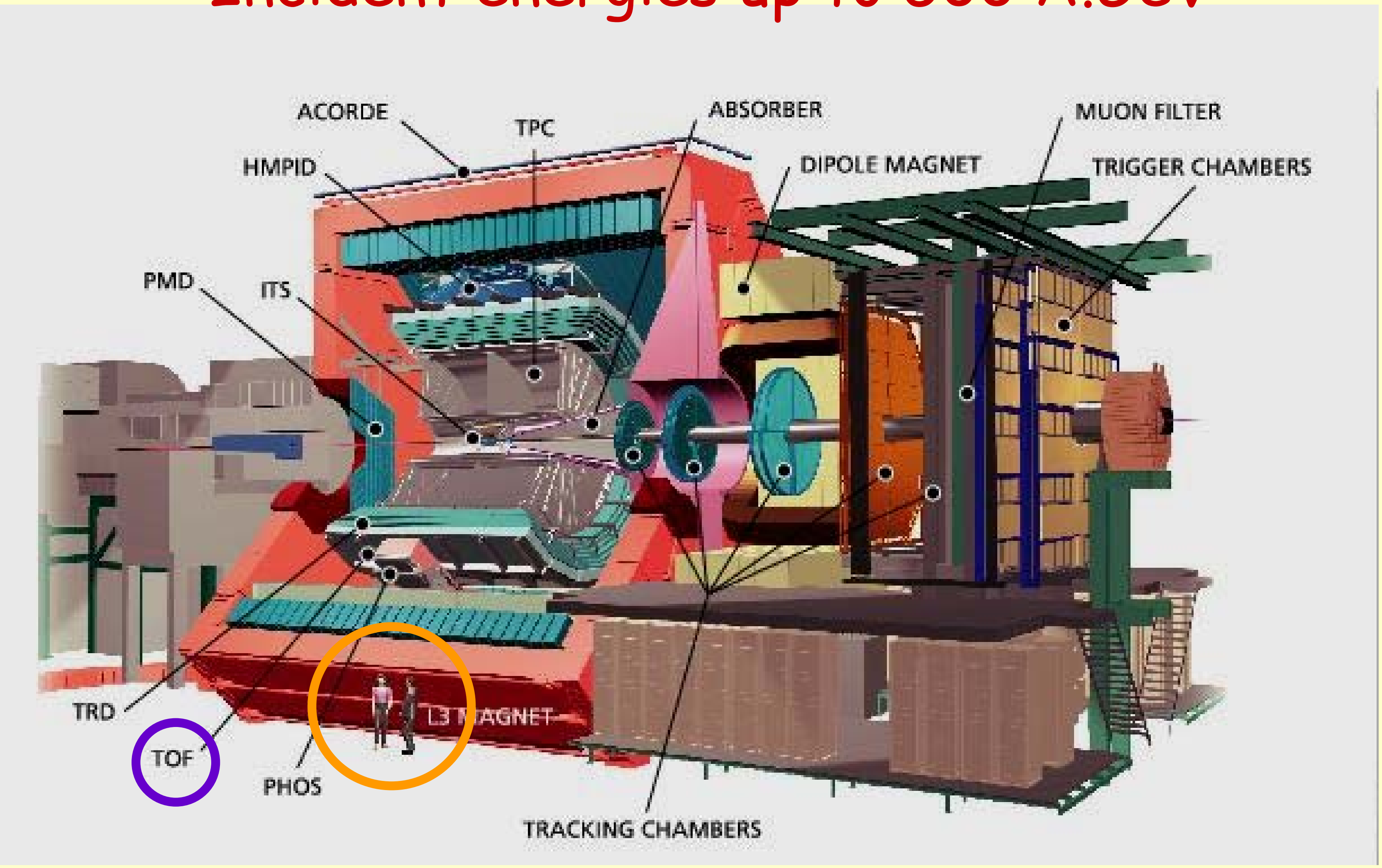
P(double) = 1% → X=250 for N=50,
→ X=2500 for N=500
. . . . etc.

Chimera detector@LNS (CT) (~10^3 detection cells)

Incident energies up to 50 A.MeV



Alice detector@CERN (CH)
Incident energies up to 500 A.GeV



157 000 cells, 150 m² for TOF

Structure of the measured quantities

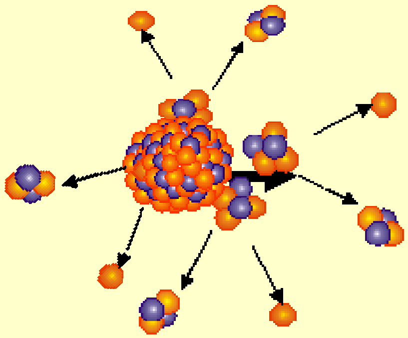
event Primary quantities:

1. N_1 $(Z_i, m_i, k_i, \theta_i, \varphi_i, i=1,N_1)$
2. N_2 $(Z_i, m_i, k_i, \theta_i, \varphi_i, i=1,N_2)$
3. N_3 $(Z_i, m_i, k_i, \theta_i, \varphi_i, i=1,N_3)$
4. N_4 $(Z_i, m_i, k_i, \theta_i, \varphi_i, i=1,N_4)$
5. N_5 $(Z_i, m_i, k_i, \theta_i, \varphi_i, i=1,N_5)$

. . . .

X N_X $(Z_i, m_i, k_i, \theta_i, \varphi_i, i=1,N_X)$

X = about 10^8
(some GigaBytes-> some TeraBytes after analysis)



Each event = N (charged) products,
- charge Z_i, mass m_i
- kinetic energy k_i,
- flying direction θ_i, φ_i $(i=1,N_1)$

Structure of the calculated quantities

e.g. Moments $m_k = \sum Z_i^k$,

$m_0 = N$, $m_1 = N \langle Z \rangle$, $m_2 = N (\sigma^2 - \langle Z \rangle^2)$, etc.

1. $N_1 (Z_i, m_i, k_i, \theta_i, \varphi_i, i=1,N_1)$
2. $N_2 (Z_i, m_i, k_i, \theta_i, \varphi_i, i=1,N_2)$
3. $N_3 (Z_i, m_i, k_i, \theta_i, \varphi_i, i=1,N_3)$
4. $N_4 (Z_i, m_i, k_i, \theta_i, \varphi_i, i=1,N_4)$
5. $N_5 (Z_i, m_i, k_i, \theta_i, \varphi_i, i=1,N_5)$

. . . .

X $N_X (Z_i, m_i, k_i, \theta_i, \varphi_i, i=1,N_X)$

$m_0^{(1)}, m_1^{(1)}, m_2^{(1)}, \ldots$
$m_0^{(2)}, m_1^{(2)}, m_2^{(2)}, \ldots$
$m_0^{(3)}, m_1^{(3)}, m_2^{(3)}, \ldots$
$m_0^{(4)}, m_1^{(4)}, m_2^{(4)}, \ldots$
$m_0^{(5)}, m_1^{(5)}, m_2^{(5)}, \ldots$
....
$m_0^{(X)}, m_1^{(X)}, m_2^{(X)}, \ldots$

Correlations

Global quantities:

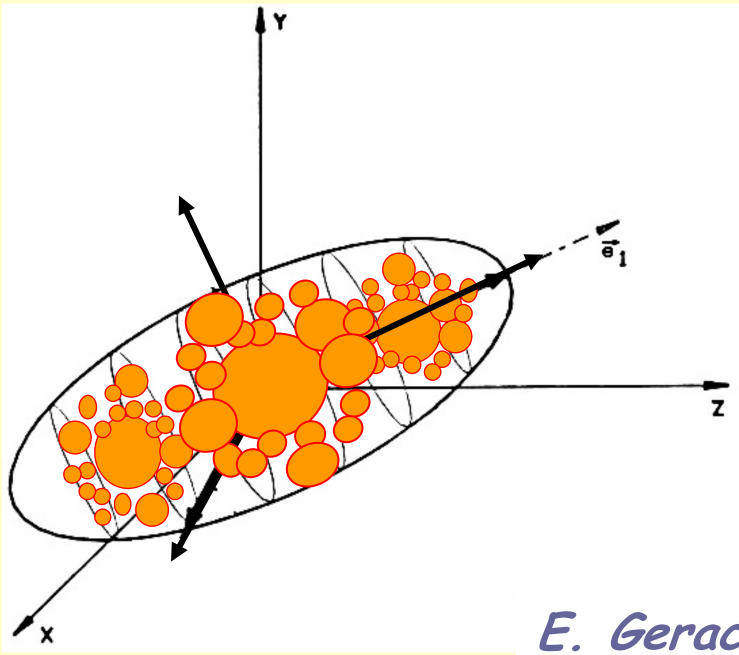
Energy balance:

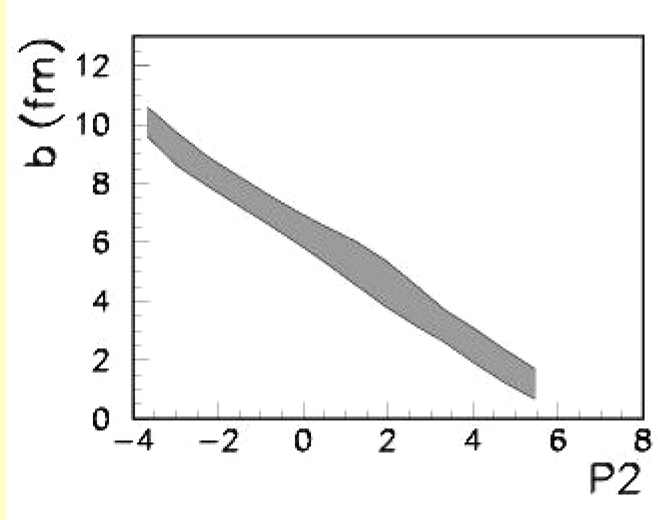
$$E^* + m_0 = \sum_{i=1}^{M} (m_i + k_i) + M_n (m_n + k_n)$$

"Flow" tensor:

$$T_{ij} = \sum_{k=1}^{M} p_i^{(k)} p_j^{(k)} w^{(k)} \quad (i,j = 1,3)$$

Sorting the events with a multidimensional analysis
Principal components/Neural networks

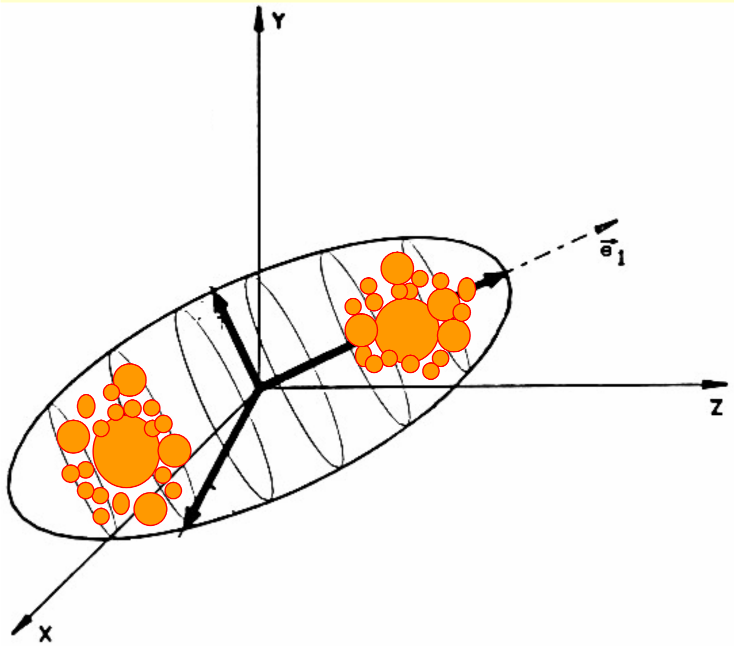




E. Geraci et al.,NPA732(2004)173,NPA734 (2004)524

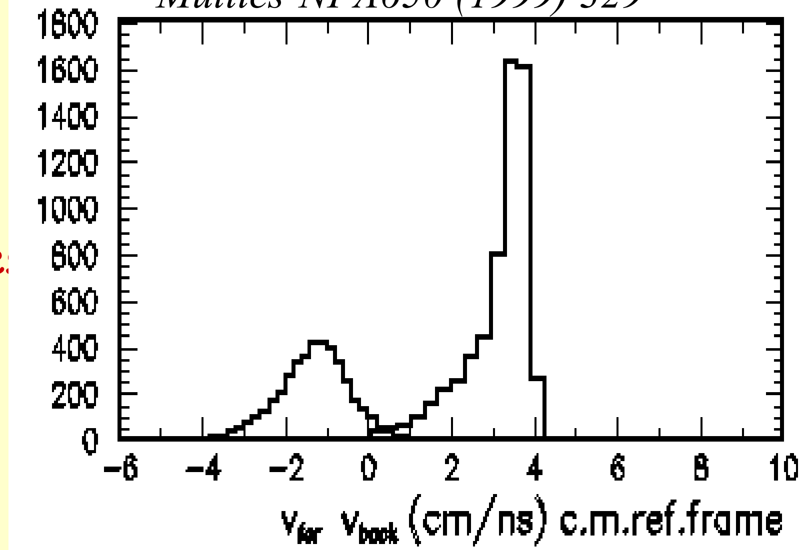
"Flow" tensor: $$T_{ij} = \sum_{k=1}^{M} p_i^{(k)} p_j^{(k)} w^{(k)} \ (i,j = 1,3)$$

Sorting the events: multidimensional analysis

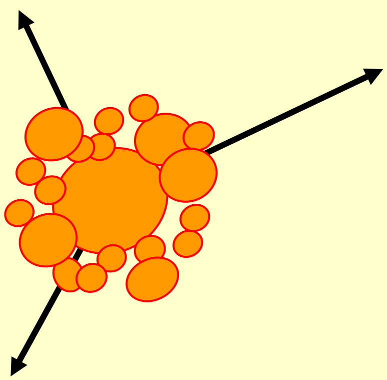


Peripheral collisions: many sources

Multics-NPA650 (1999) 329

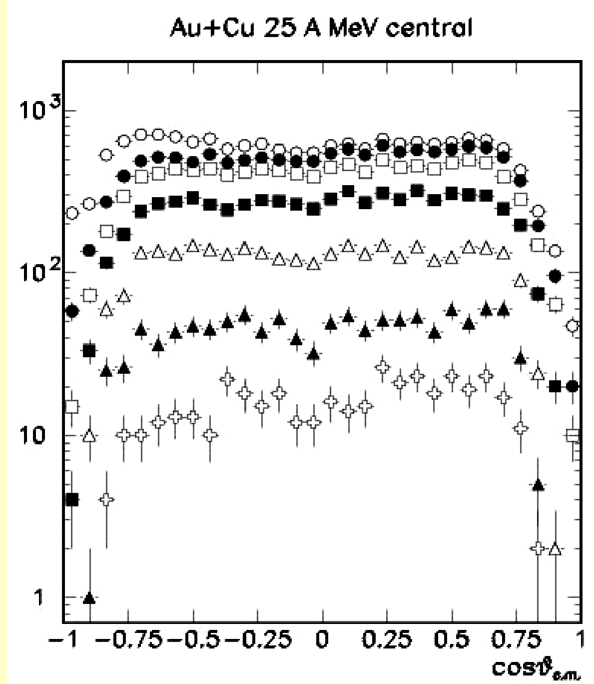


Central collisions: one source

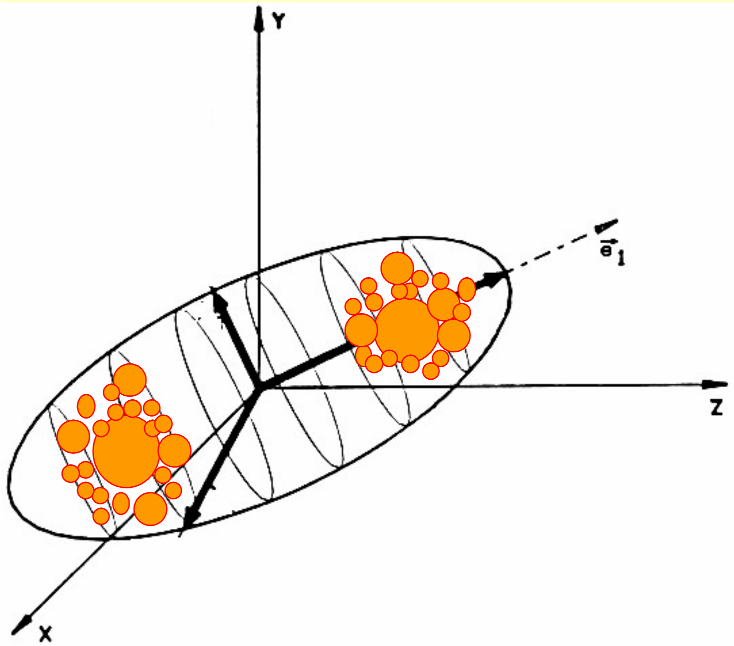


Z>8 open circles
>18 full points
>28 open squares
>38 full squares
>48 open triangles
>58 full triangles
>68 open crosses

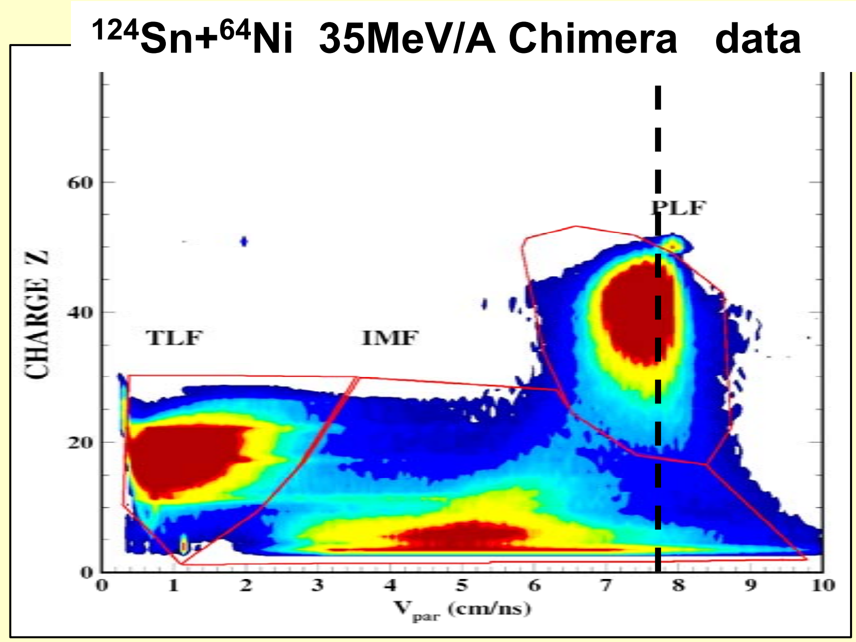
MulticsNPA734(2004)487



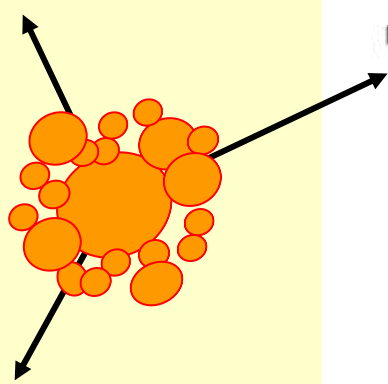
Sorting the events: multidimensional analysis

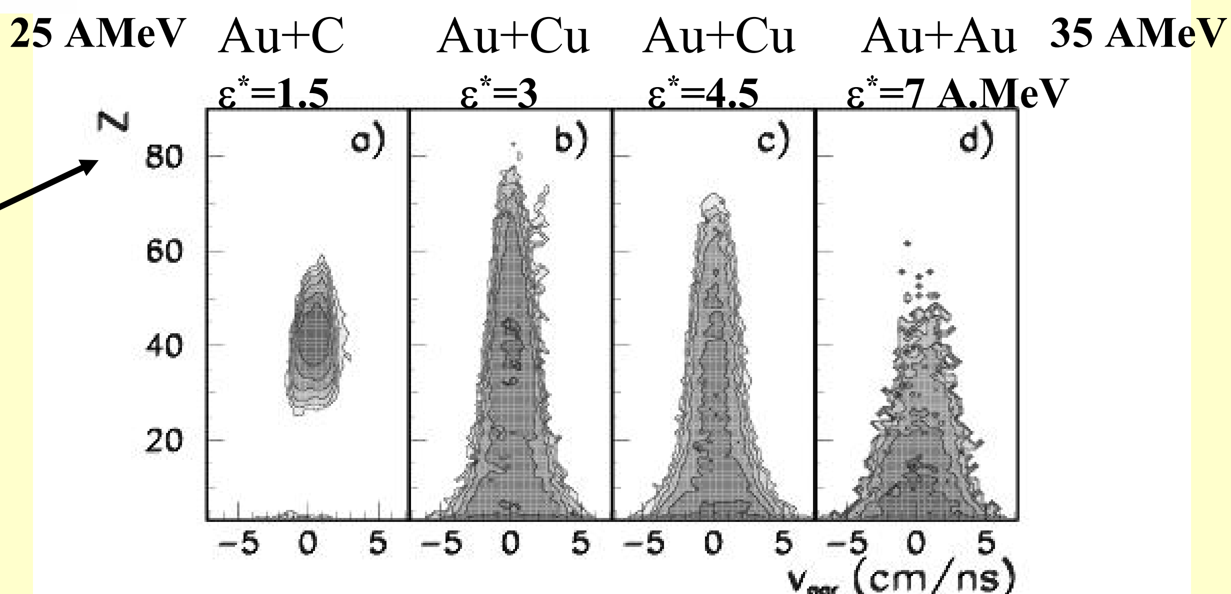


Peripheral collisions: many sources



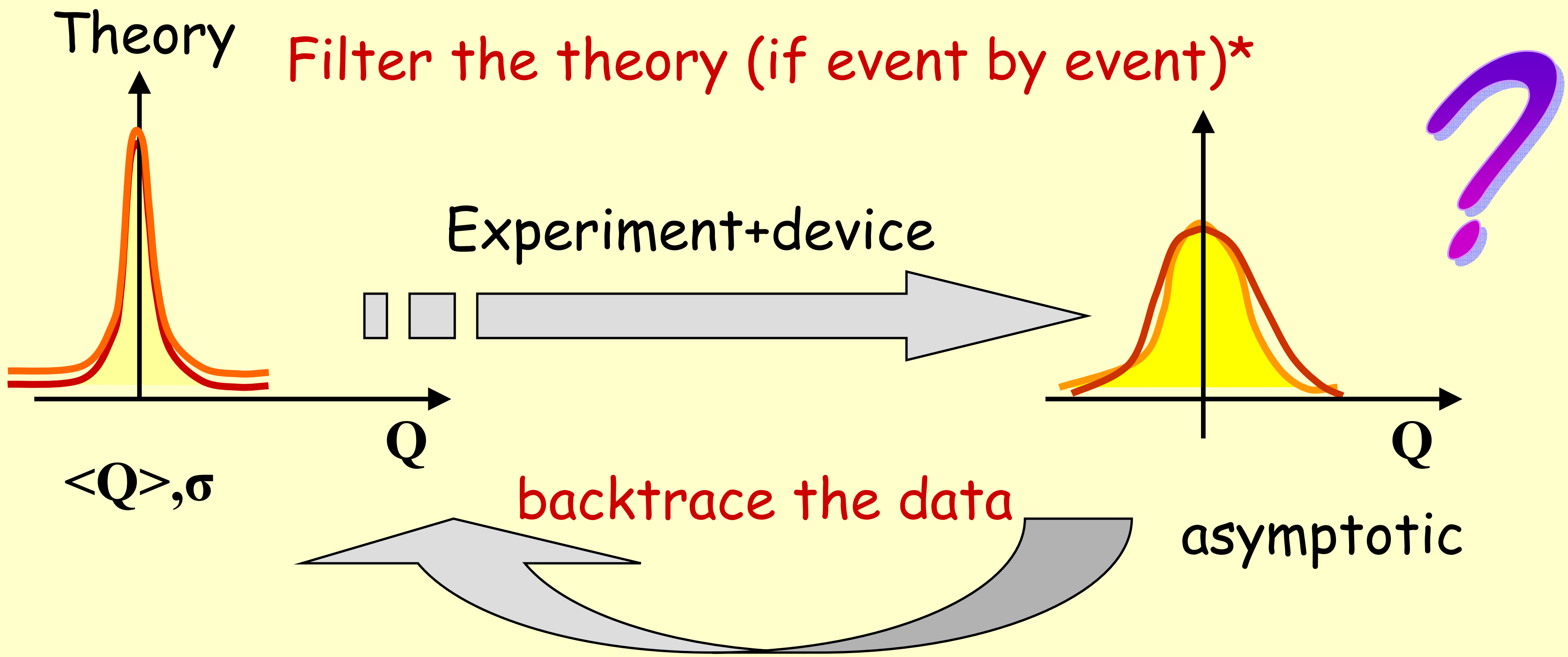
Central collisions: one source





Multics-NPA724 (2003) 329

Dalla previsione del fenomeno alla rivelazione



* To be compared with data, Coulomb trajectories are needed.

True for:

- Statistical models
- Classical Molecular Dynamics

Not still true for: Lattice gas model

False for: percolation

Modelli statistici: esplorazione dello spazio delle fasi
Tutte le partizioni sono equiprobabili

SMM: J.Bondorf et al. NPA 443 (1985) 321, NPA 444 (1985) 460

MMMC: D.E. Gross Phys.Rep. 1993,

MMC: Al.&Ad. Raduta, NPA 1999

Nel caso piu' semplice, gli input sono: A_0, E_0=Energia termica di A_0

- Da considerazioni geometriche viene calcolata la probabilita' $p(A_0,M)$ che un sistema di A_0 nucleoni venga diviso in M parti intere,

  servono formule ricorsive, infatti un sistema con A_0 = 100 si puo' rompere in 10^8 modi.
- Si estrae una molteplicita' M*, secondo la distribuzione di probabilita' $p(A_0,M)$
- Si determina (random) la massa degli M* frammenti (partizione di un intero in M* parti),
- Si determina la energia associata alla partizione scelta e la si accetta se:

  Q-valore+Coulombiano<= E_0

  l'energia rimanente $\Rightarrow$ moto termico& energia interna delle M parti

. . . .

seguono momenti termici iniziali,

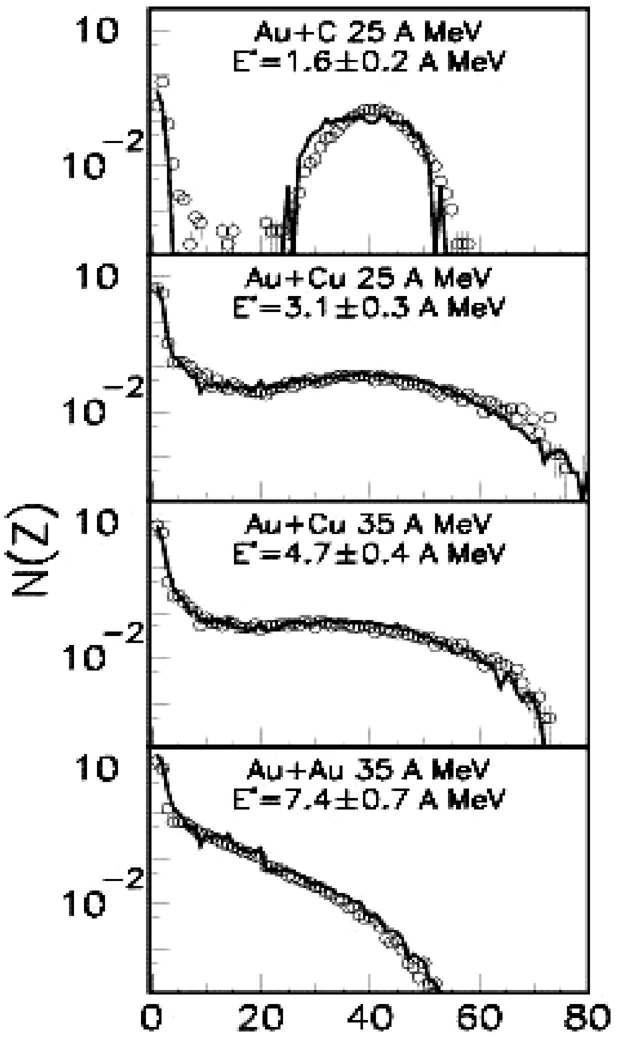
traiettorie coulombiane

decadimenti secondari, etc.

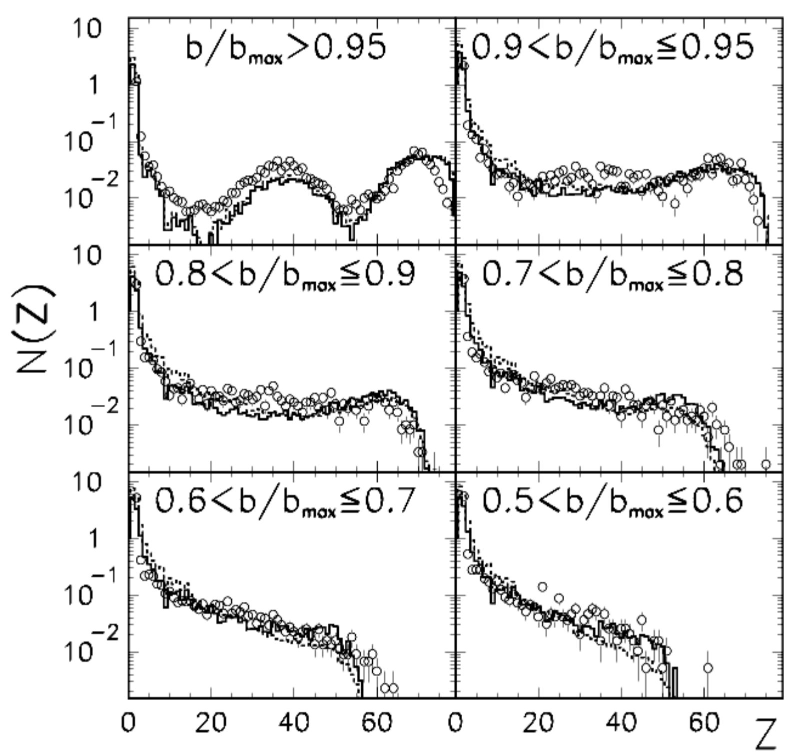
Failure: residual nuclear interaction

Checking equilibrium: uniform population of the available phase space

Central collisions



Multics-NPA724 (2003) 329



Multics-NPA650 (1999) 329

Au source:
peripheral collisions
symbols: data
lines: thermal model (SMM)
$\langle \varepsilon^* \rangle$= 1.5, 2.5, 3.5, 4.5, 5, 6 AMeV

Static observables from liquid+vapor to droplets are reproduced by thermal models

Transizioni di fase: modello di Fisher

(M. E. Fisher, Rep. Prog. Phys. 30 (1967) 615)

La variazione di energia libera quando si forma una goccia di liquido di massa A da un gas di A+B nucleoni (A e B in equilibrio, cioe' alla stessa temperatura e pressione) e' data dalla differenza fra:

$G_{con\ goccia} = \mu_\ell A + \mu_g B + 4\pi R^2 \sigma(T) + T\,\tau \ln A$

$G_{no\ goccia} = \mu_g (A+B)$, dove

$4\pi R^2 \sigma$ = tensione superficiale della goccia,

$T\,\tau \ln A$ = termine che tiene conto che la goccia e' finita e la sua superficie e' chiusa

Fisher inoltre scrive il termine di superficie $4\pi R^2 \sigma(T) = 4\pi r_0^2 A^{2/3} \sigma(T)$ come $a_s (T_c - T) A^\sigma$ con σ esponente che descrive il rapporto superficie/volume della goccia e tiene conto del fatto che al punto critico liquido e vapore sono indistinguibili.

si puo' anche includere δC = variazione della energia di Coulomb, *(J.Lopez and C.Dorso,World Scientific -2000)*

Transizioni di fase: modello di Fisher

M. E. Fisher, Rep. Prog. Phys. 30 (1967) 615

La probabilita' (insieme gran canonico) di formazione di una goccia di massa A, a partire da un gas di A+B nucleoni e':

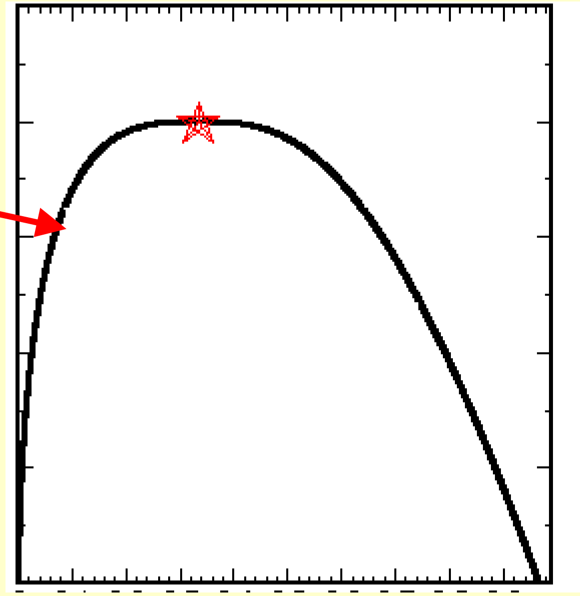
$$P(A) = Y_0 \exp\left[-\frac{\Delta G}{T}\right] =$$

$$= Y_0\, A^{-\tau} \exp\left[\frac{\mu_g - \mu_\ell}{T} A - \frac{a_s (T_c - T) A^{\sigma}}{T}\right]$$

Alla coesistenza $\mu_g = \mu_\ell$

Al punto critico $\mu_g = \mu_\ell$

$a_s(T-Tc)=0$



$\Rightarrow P(A) = Y_0\, A^{-\tau}$

Classical Molecular Dynamics
(A.Bonasera)

In the classical molecular dynamics model it is assumed that the nucleus is made up of A nucleons that behave classically. These particles move under the influence of a pairwise spherical interaction potential V given by [4]

$$V_{np}(r)=V_r[\exp(-\mu_r r)/r-\exp(-\mu_r r_c)/r_c]$$

$$-V_a[\exp(-\mu_a r)/r-\exp(-\mu_a r_a)/r_a],$$

$$V_{nn}(r)=V_{pp}(r)=V_0[\exp(-\mu_0 r)/r-\exp(-\mu_0 r_c)/r_c], \quad (1)$$

where $r_c=5.4$ fm is a cutoff radius and V_{np} is the potential acting between a neutron and a proton while V_{nn} is the potential acting between two identical nucleons. The first interaction is attractive at large r and repulsive at small r, while the latter is purely repulsive. In this way, no bound state of identical nucleons can exist.

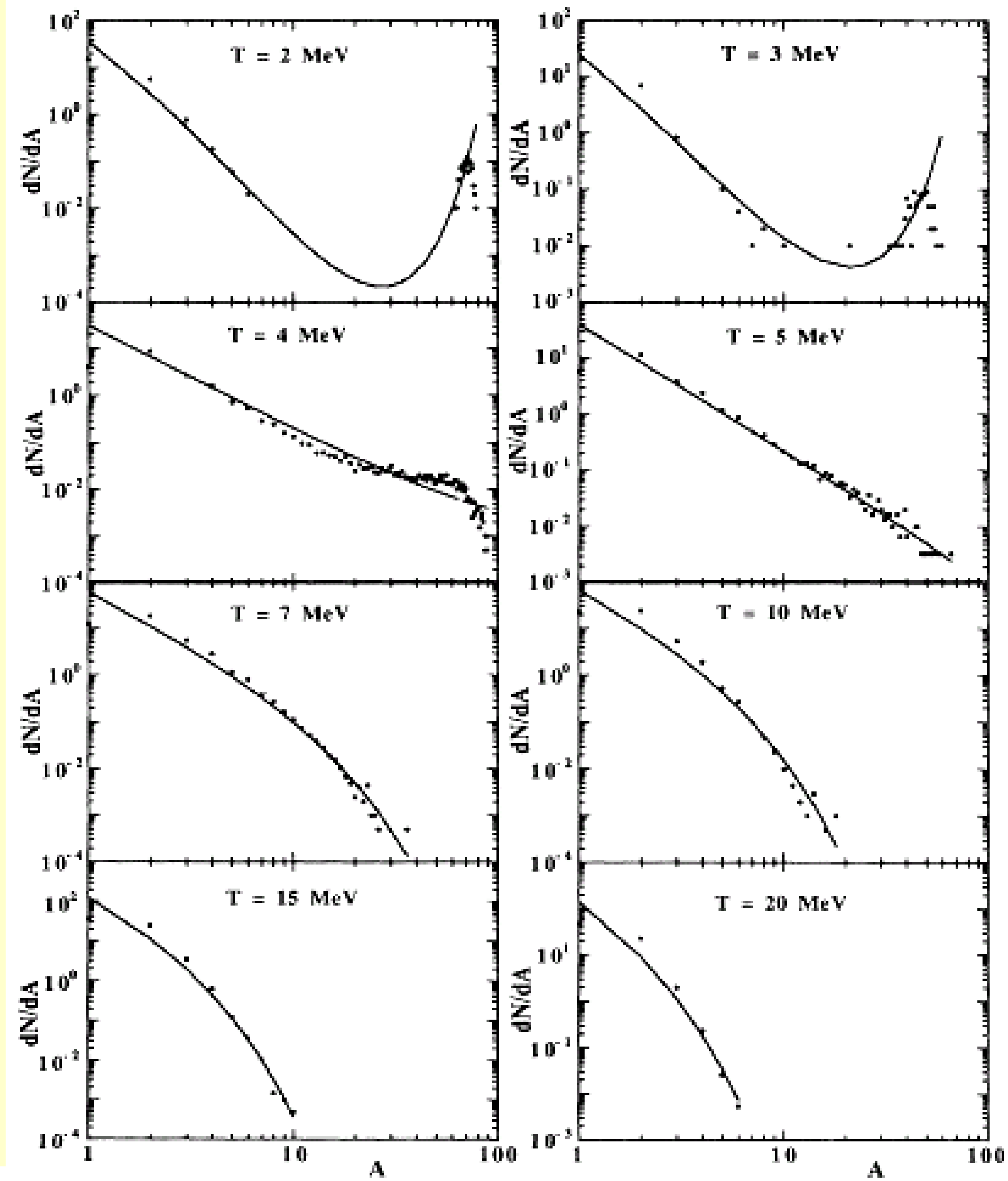
M. Belkacem, V. Latora, A. Bonasera PRC 52(1995)271

Classical Molecular Dynamics

(A.Bonasera)

$$P(A) = Y_0 \exp\left[-\frac{\Delta G}{T}\right] =$$

$$= Y_0 A^{-\tau} \exp\left[\frac{\mu_g - \mu_\ell}{T} A - \frac{a_s (T_c - T) A^{\sigma}}{T}\right]$$

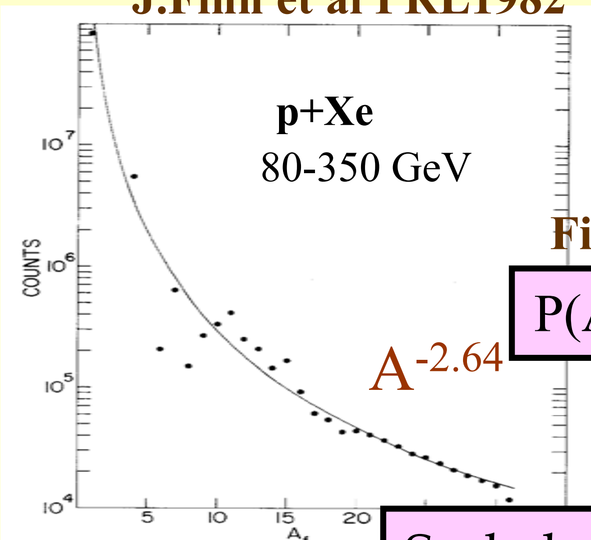


M. Belkacem, V. Latora, A. Bonasera PRC 52(1995)271

Data: Self similarity and scaling

Power-laws are free of scales
All the information falls on a single curve

J.Finn et al PRL1982

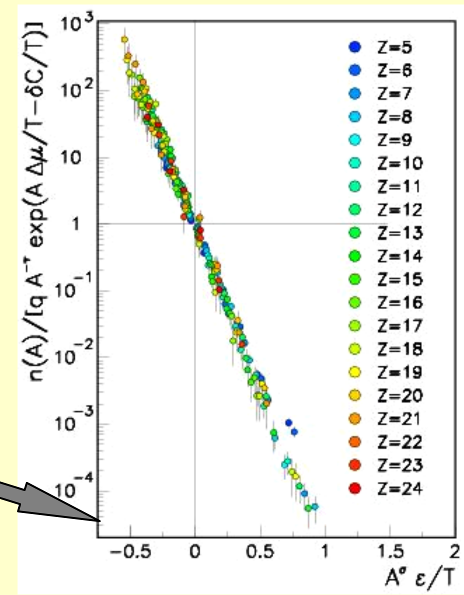


Fisher 1967

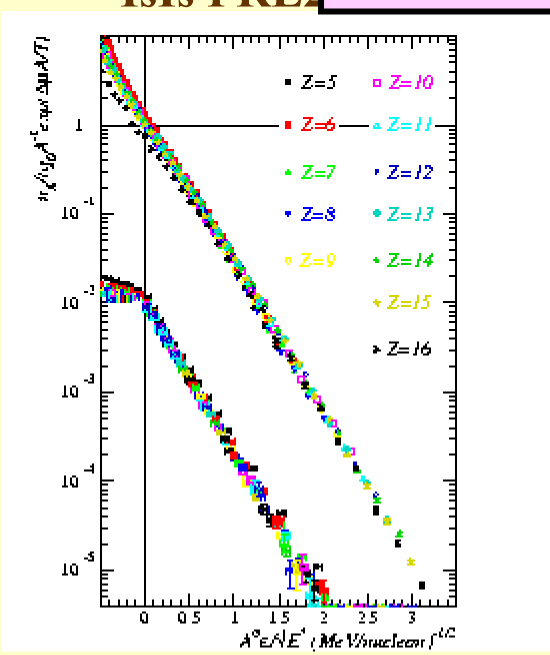
$$P(A)=Y_0A^{-\tau}\exp\left(A\,\Delta\mu/T-c_0\varepsilon A^{\sigma}/T\right)$$

Scaled yield: $P(A)/[Y_0A^{-\tau}\exp(A\,\Delta\mu/T)]$
Scaled temperature: $\varepsilon A^{\sigma}/T$

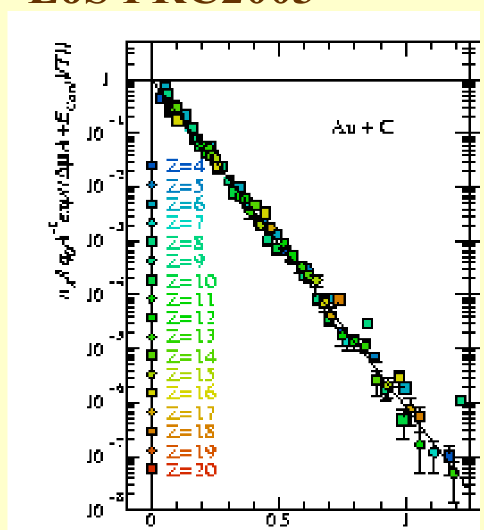
Multics NPA724 (2003) 455



IsIs PRL2



EoS PRC2003



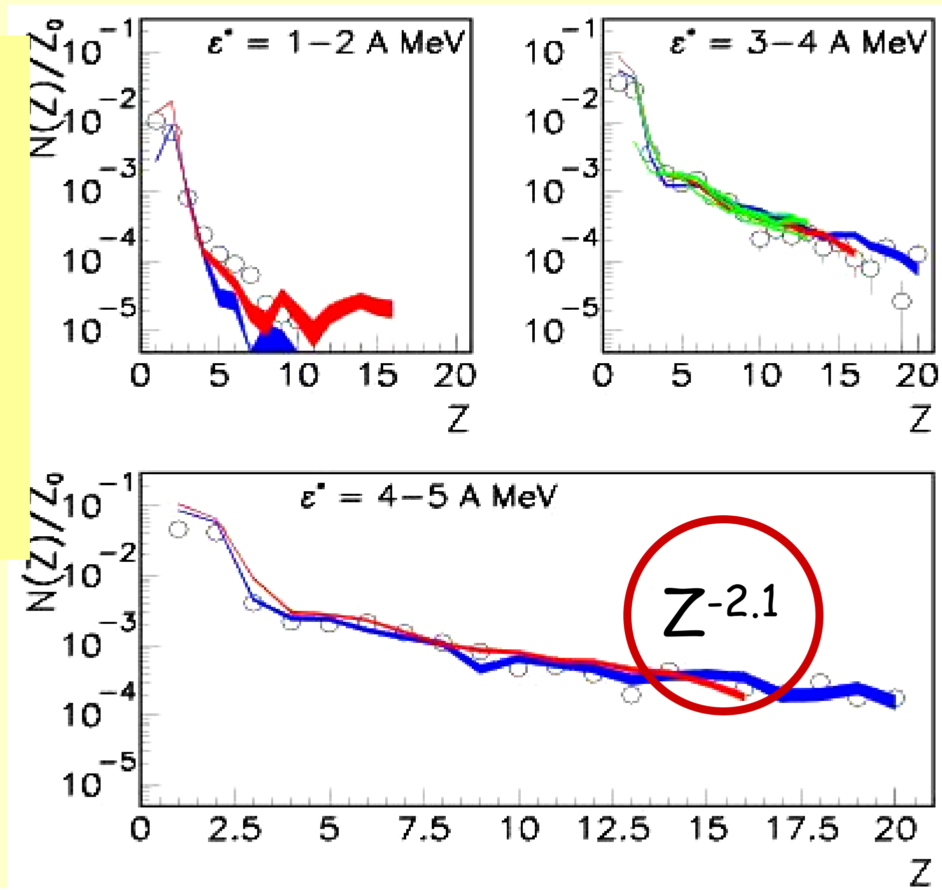
	Au	Liquid-Gas
τ	2.1±0.1	2.196 ±0.024
σ	0.66±0.02	0.647 ±0.006
ε^*_c	4.4 ± 0.1 AMeV	

1-st generation 4π devices & stable beams

- More information on
  WCI 2003-2005 in:
  http://cyclotron.tamu.edu/wci3/

  world-wide review of the field of dynamics and thermodynamics with nucleonic degrees of freedom

- For all multifragmentation experiments, independently on the entrance channel, the region in which power-laws are observed in reaction observables corresponds to E*/A = 5 +/-1 A.MeV
  Within a phase-transition scenario, this value represents the transition energy.

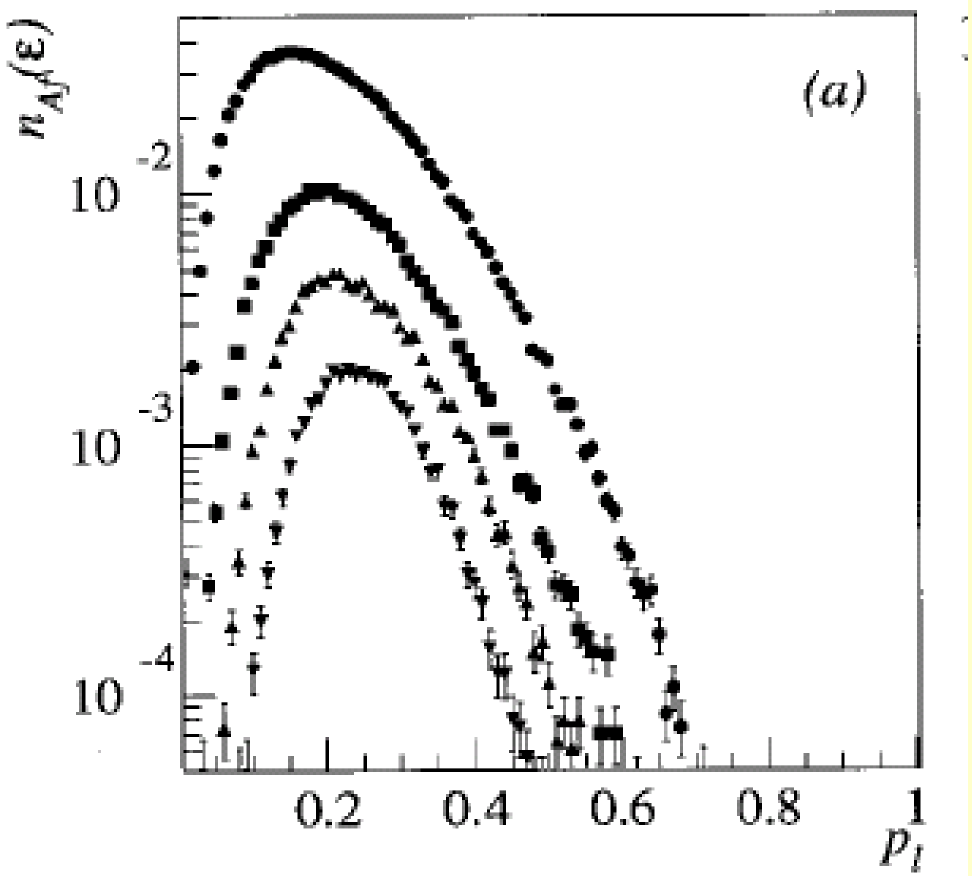


Multics: Central from Z_0=85 to Z_0=100 (lines)
Multics: Au peripheral Z_0=79 (symbols)
Isis: π+Au 8 GeV/c NPA734(2004)487
Fasa: p,α+Au 4-14 GeV NPA709(2002)392

Critical exponents from moment analysis

$$P(A) = Y_0 \exp\left[-\frac{\Delta G}{T}\right] =$$

$$= Y_0\, A^{-\tau} \exp\left[\frac{\mu_g - \mu_\ell}{T} A - \frac{a_s\,(T_c - T) A^{\sigma}}{T}\right]$$



P(A) ha un massimo ad una temperatura T_{max} (A) diverso per ogni A.

Dall'andamento di T_{max} (A) vs.A si puo' ricavare σ.

Dai due esponenti σ, τ si possono ricavare altri esponenti critici, tramite le relazioni:

$$\beta = (\tau\text{-}2)/\sigma,\ \gamma = (3\text{-}\tau)/\sigma$$

e studiare (per dati e modelli) i momenti:

$$m_1 = \sum n_s s \sim |\varepsilon|^{\beta}$$
$$m_2 = \sum n_s s^2 \sim |\varepsilon|^{-\gamma}$$
$$m_k = \sum n_s s^k \sim |\varepsilon|^{(\tau-1-k)/\sigma}$$

per verificare la compatibilita' delle loro distribuzioni e le loro correlazioni con un comportamento critico

Critical « correlations » of static moments

Classical
Molecular
Dynamics
(A.Bonasera)

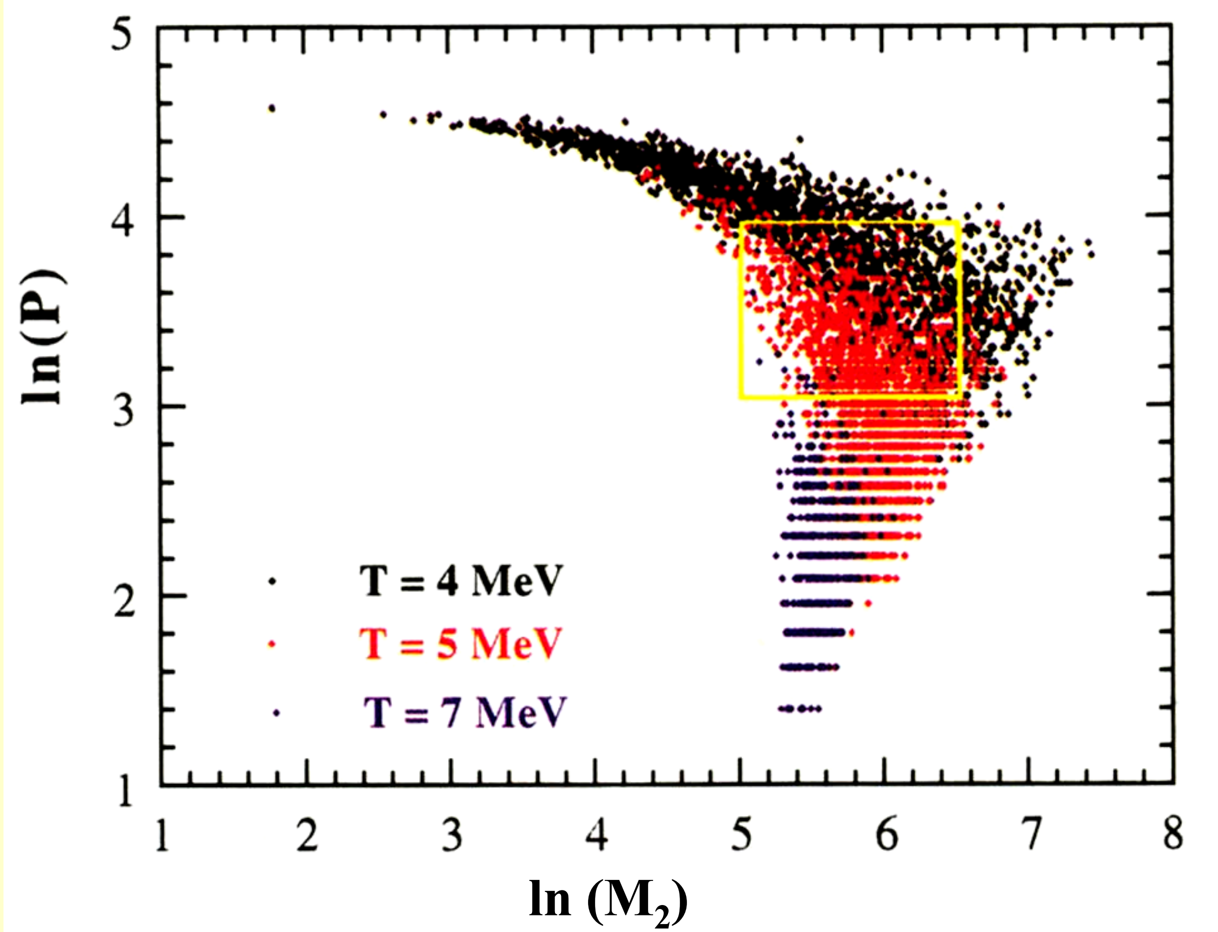
the logarithm of the largest cluster P in each event versus the logarithm of the second moment S_2 of the cluster size distribution of the remaining fragments in the event. This plot is generally called Campi scatter plot.

M. Belkacem, V. Latora, A. Bonasera PRC 52(1995)271

$\sigma = (\tau-2)/\beta$, $\gamma = (3-\tau)/\sigma$

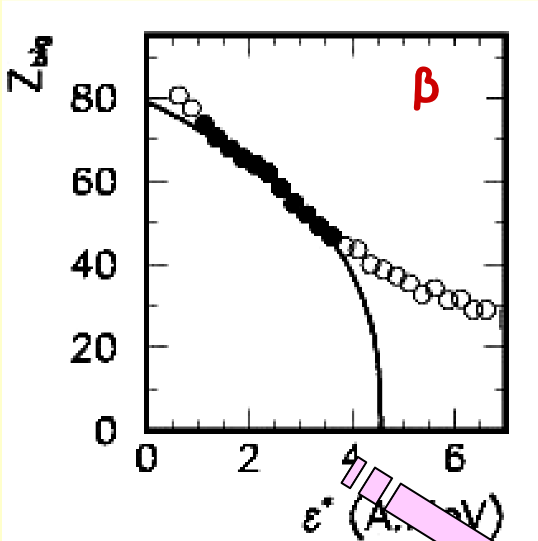
$$m_1 = \sum n_s s \sim |\varepsilon|^{\beta}$$
$$m_2 = \sum n_s s^2 \sim |\varepsilon|^{-\gamma}$$
$$m_k = \sum n_s s^k \sim |\varepsilon|^{(\tau-1-k)/\sigma}$$

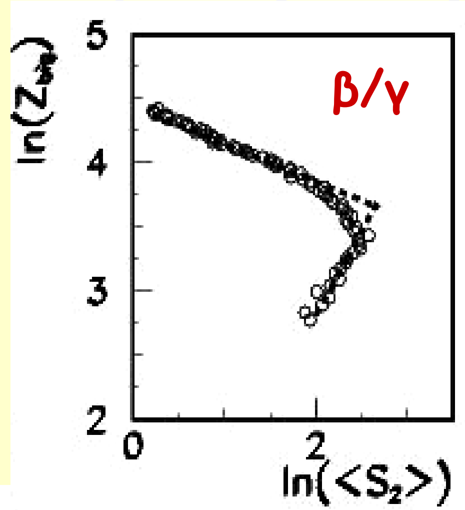
liquid branch and
gas branch
meet at the
critical region

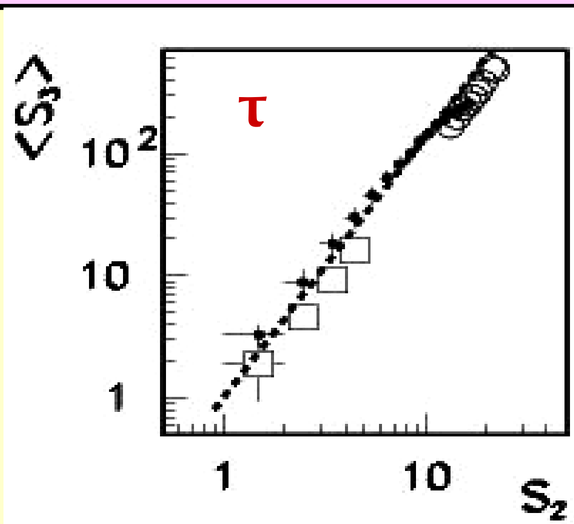


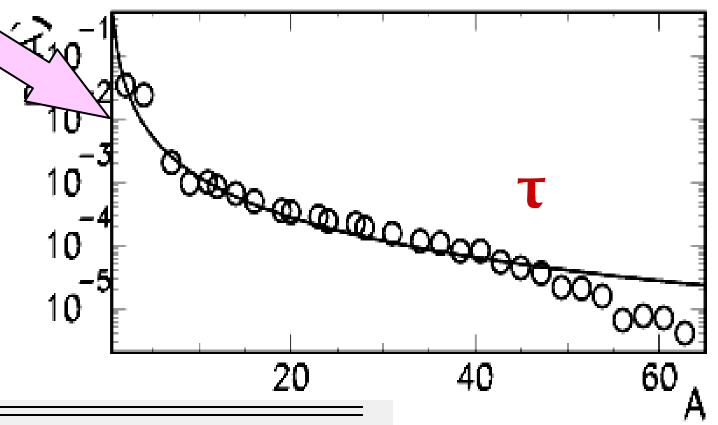
Critical exponents from moment analysis (data)

$$m_1 = \sum n_s s \sim |\varepsilon|^{\beta}$$
$$m_2 = \sum n_s s^2 \sim |\varepsilon|^{-\gamma}$$
$$m_k = \sum n_s s^k \sim |\varepsilon|^{(\tau-1-k)/\sigma}$$
$$\sigma = (\tau-2)/\beta$$









	Au	Liquid-Gas
τ	2.13±0.04	2.196 ±0.024
γ	1.29±0.01	1.24 ±0.01
β	0.31±0.04	0.305 ±0.005

ε^*_{crit} = 4.5 ± 0.2 AMeV

Multics-NPA650 (1999) 329

EoS: PRC 62 (2000) 064603

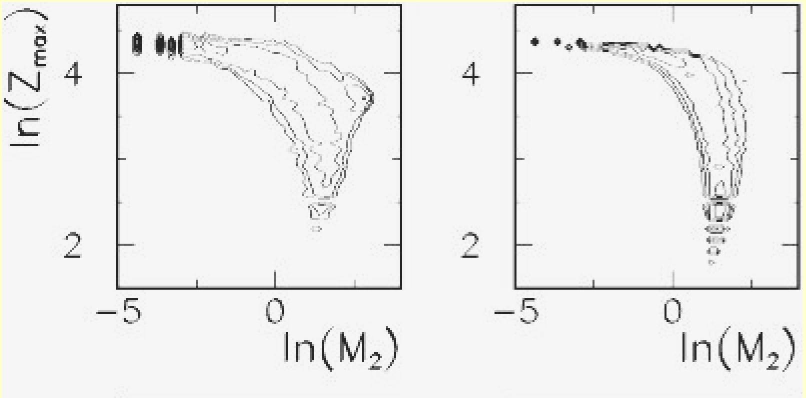
Exponent/system	Au + C
τ	2.2±0.1
σ	0.64±0.05
$\gamma = \frac{3-\tau}{\sigma}$	1.3±0.2
γ_+ (matching)	1.4±0.3
γ_- (matching)	1.4±0.3
$\langle\gamma\rangle$ (matching)	1.4±0.3
$\Delta\gamma$ (matching)	0.0±0.4
ν (hyperscaling)	0.63±0.07

Exponents	This work
	2.22 ± 0.46 [Eq. (30)]
τ	2.31 ± 0.03 [Eq. (12)]
	2.13 ± 0.10 [Eq. (26)]
β	0.33 ± 0.01
γ	1.15 ± 0.06
σ	0.68 ± 0.04

Nimrod PRC71(2005)054606

Perche' studiare le correlazioni?

Data Toy model



Segnali necessari
e/o (?)
sufficienti?

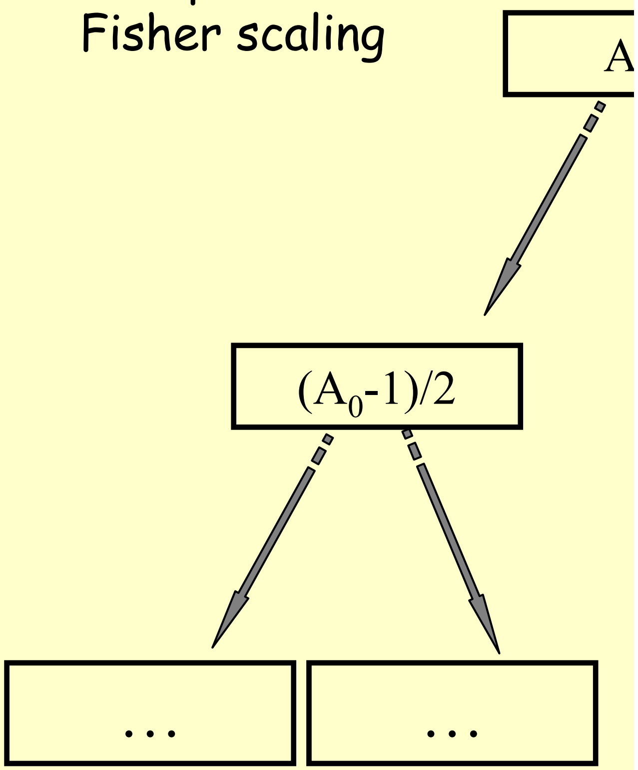
No power law !!!

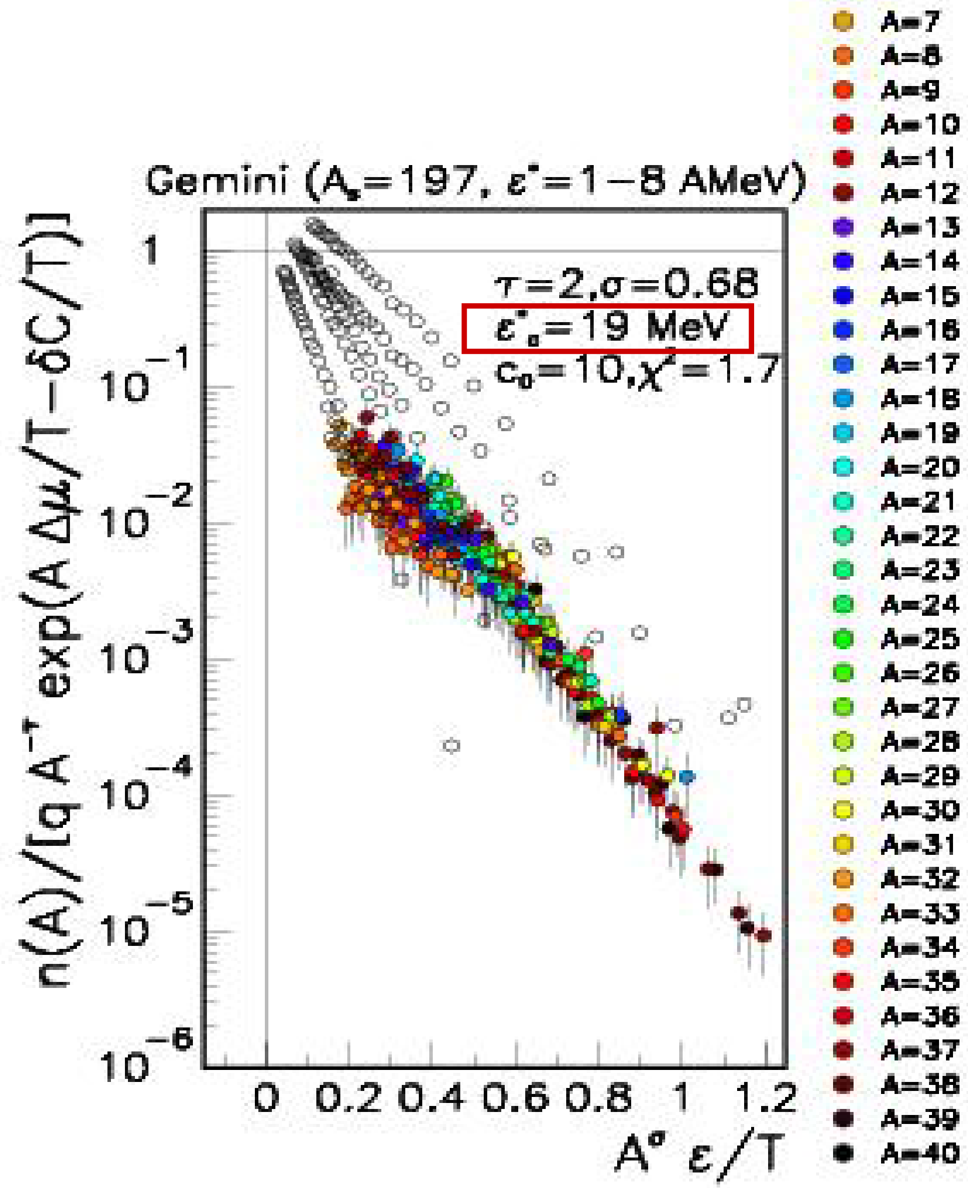
Review paper:

A. Bonasera, M. Bruno, C. O. Dorso and P. F. Mastinu, Riv. Nuovo Cimento 23, 1 (2000)

Sequential binary decays: evaporation&fission (Gemini)

Size distributions exponential,
not free of scales,
not compatible with Fisher scaling

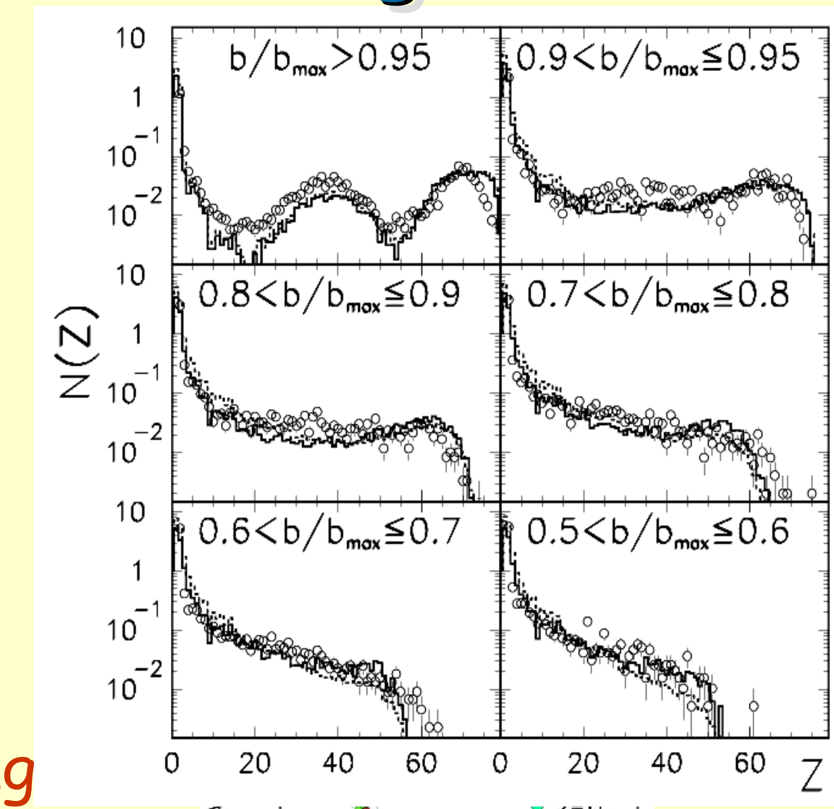


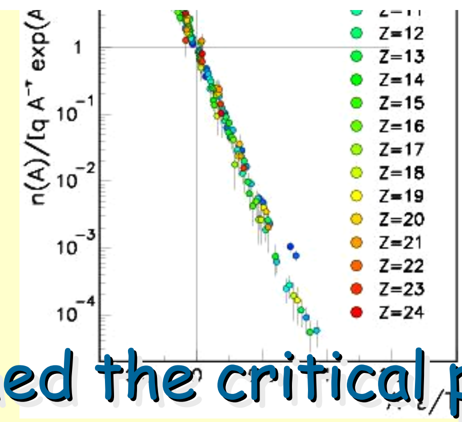


Liquid-gas phase transition: is the game over?

We observed:

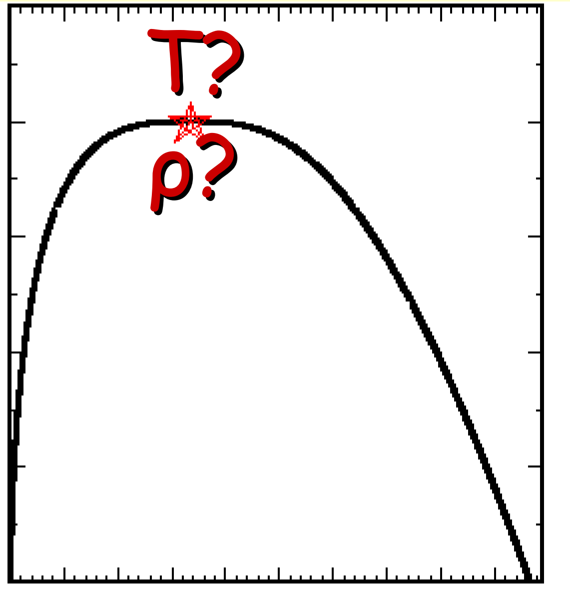
- suppression/enhancement of branching ratios (liquid-gas)
- fragment yields described by critical exponents (liquid-gas universality class)
- equilibrated collisions behaving as a universal process, independent of the entrance channel





Can we conclude that the system reached the critical point?

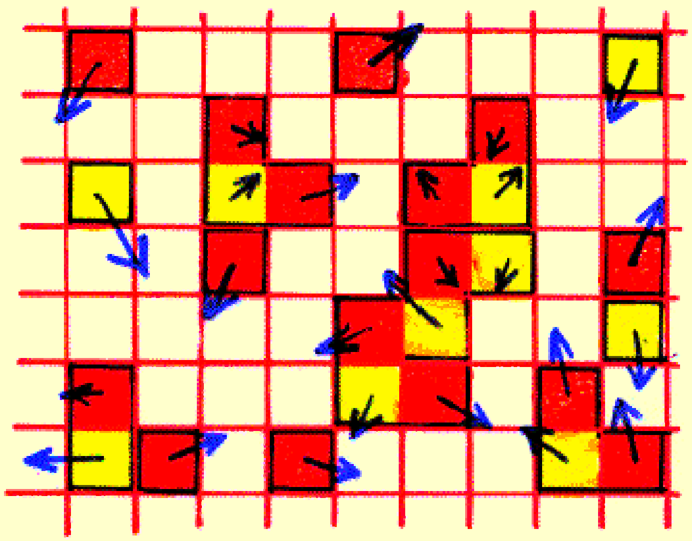
Liquid-gas phase transition: is the game over?



We have to

- thermodynamically characterize the system (T,ρ)
- look at more observables
- look at thermodynamical models

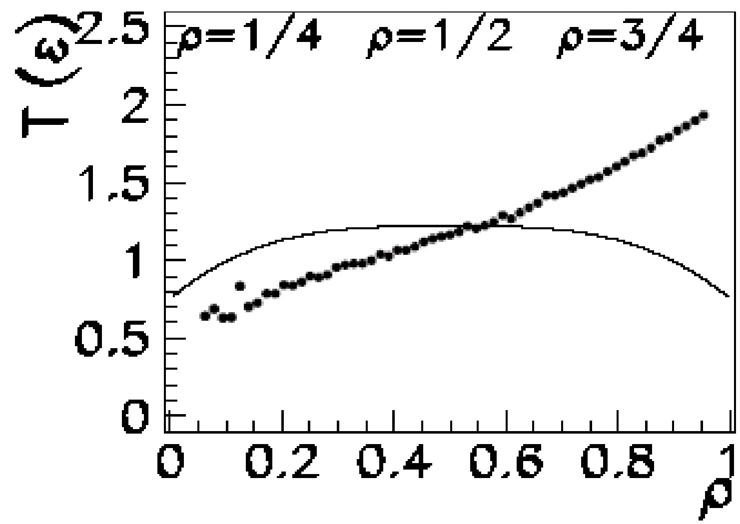
Lattice gas model



The system is finite:

power-laws are found at all densities

Also inside the coexistence region



- Cubic lattice (L^3),
- A_0 nucleons occupy A_0 sites , $\rho = A_0/L^3$
- occupancy (τ =0,1) from the partition sum:

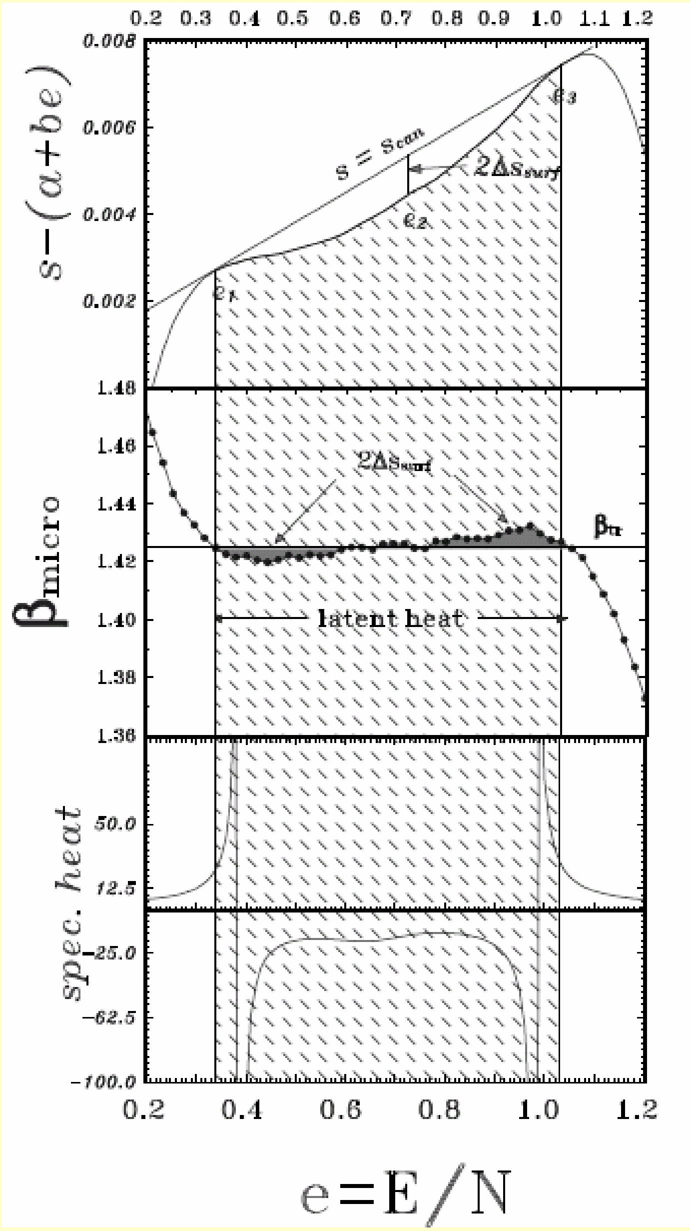
$$Z(A_0,\beta)=\sum W(E) \exp(-\beta E)$$

- interaction among nearest neighboring

$$H = \sum_{i=1}^{n} \frac{p_i^2}{2m} \tau_i^2 + \sum_{i \neq j} \epsilon \tau_i \tau_j$$

F. Gulminelli, V.Duflot, Ph.Chomaz
PRL 1999

Finite systems-Thermodynamical anomalies



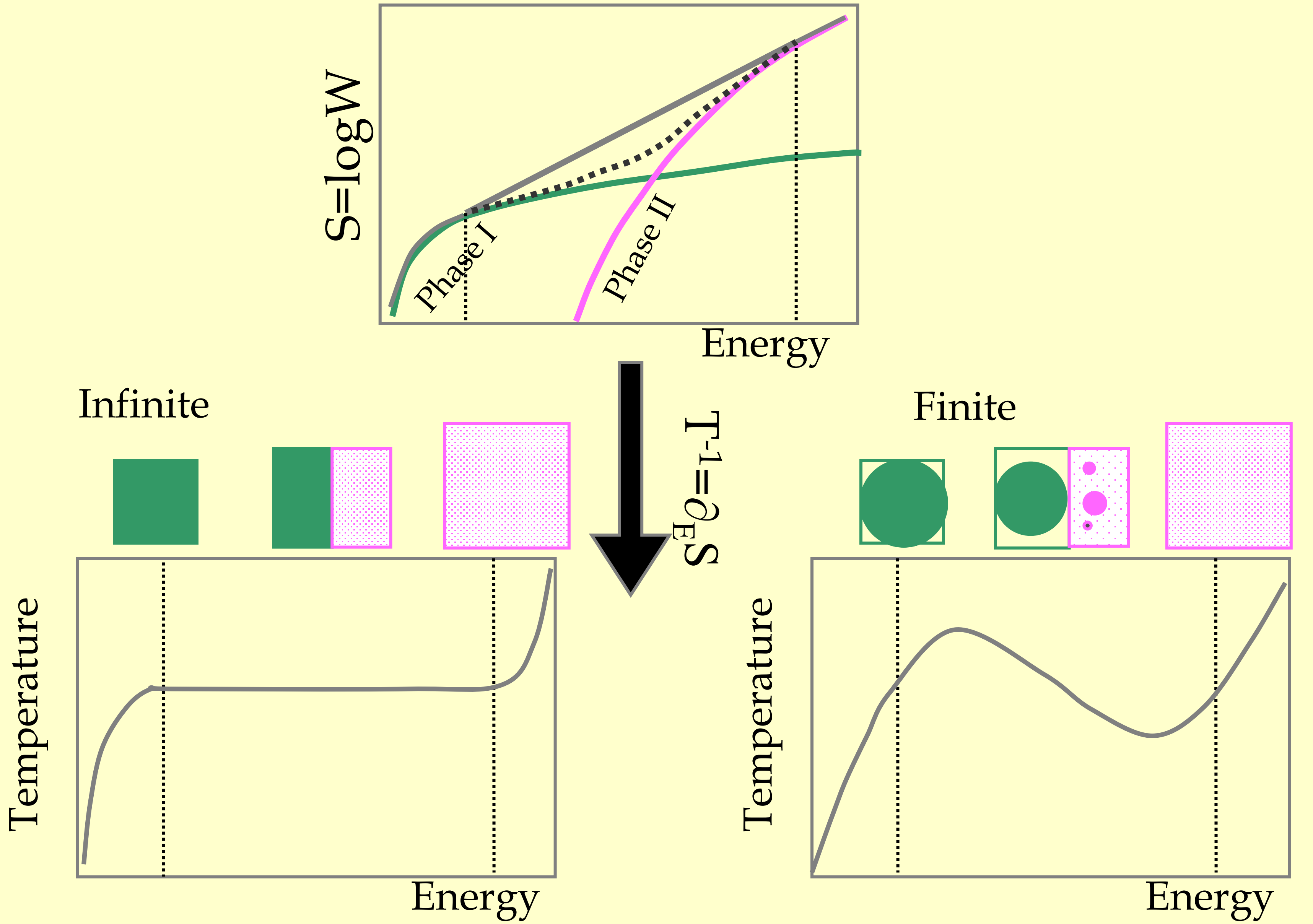
D.H.E. Gross, A. Ecker, and X.Z. Zhang. Microcanonical thermodynamics of first order phase transitions studied in the potts model. *Ann. Physik*, 5:446–452, $\boxed{1996,}$ and http://xxx.lanl.gov/abs/cond-mat/9607150.

The surface gives a negative contribution to S

$\beta = T^{-1} = \partial_E S$

$C = \partial_T E$

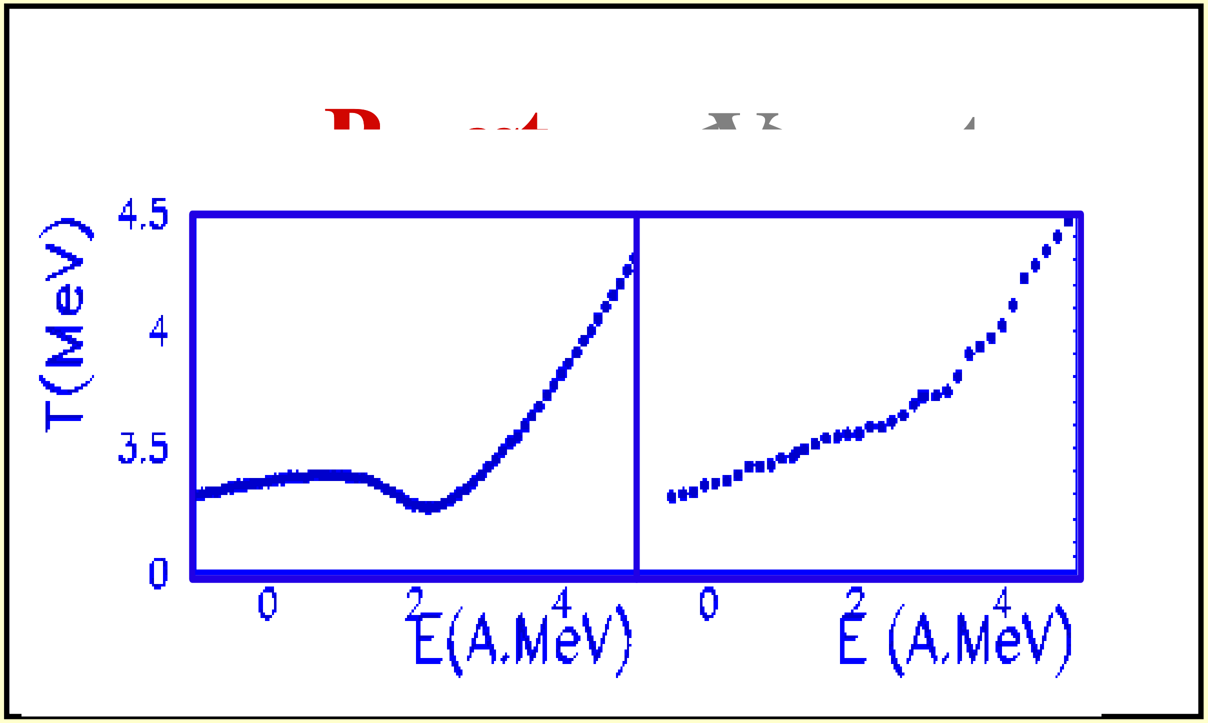
Finite systems-Thermodynamical anomalies



M.S.Challa 1988, D.Gross 1996

Lattice gas model

The caloric curve
depends on the transformation



(ideal gas)

$\partial T = \partial E / C_V$

$\partial T = \partial E / C_p$

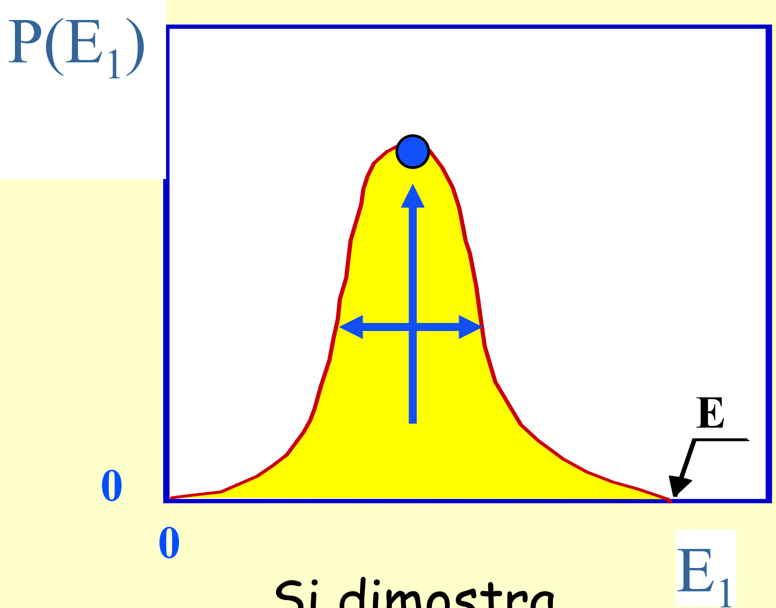
Microcanonical heat capacity of finite systems

Ph. Chomaz, F. Gulminelli NPA 647 (1999) 153

Suddividiamo un sistema con energia E in due sottosistemi 1 e 2, tali che

$$E = E_1 + E_2$$

$$\boxed{P(E_1) = \frac{W_1(E_1)W_2(E_2)}{W(E)}}$$



Si dimostra analiticamente che:

(S.K. Ma Statistical mechanics- Chap.6)

- In corrispondenza del valore piu' probabile:

$$1/T_1 = \partial S_1/\partial E_1 = \partial S_2/\partial E_2 = 1/T_2 = 1/T$$

- Le fluttuazioni di E_1

$$\boxed{\sigma_1^{\,2} = \frac{C_1 C_2}{T^{-2}\ (C_1+C_2)}}$$

$$C_1 = \partial E_1/\partial T \qquad C_2 = \partial E_2/\partial T$$

- Il calore specifico del sistema $C \sim= C_1 + C_2$

$$\boxed{C = \frac{C_1^{\,2}}{(C_1 - \sigma_1^{\,2}/T^2)}}$$

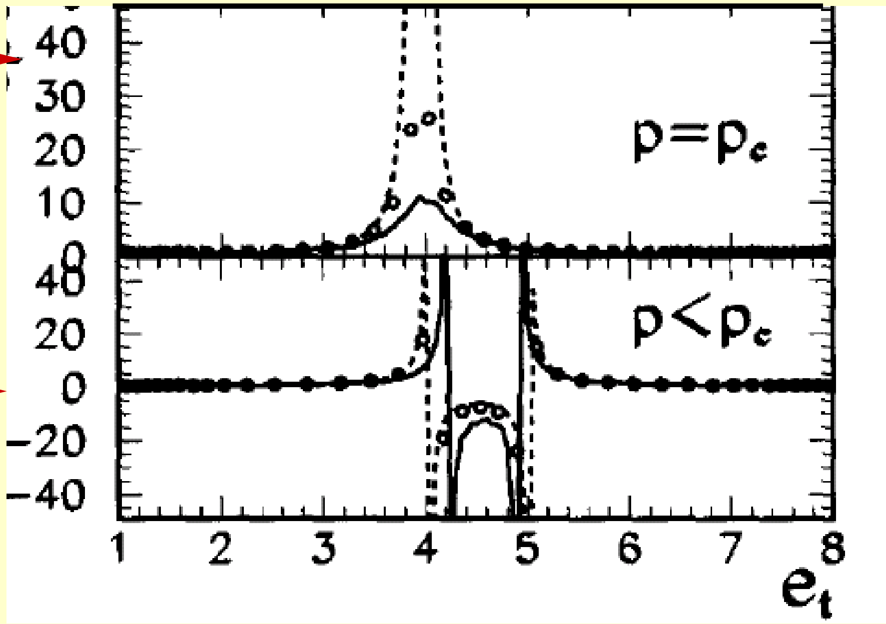
Microcanonical heat capacity of finite systems

Ph. Chomaz, F. Gulminelli NPA 647 (1999) 153

$C = C_1^2/(C_1-\sigma_1^2/T^2)$

2nd order

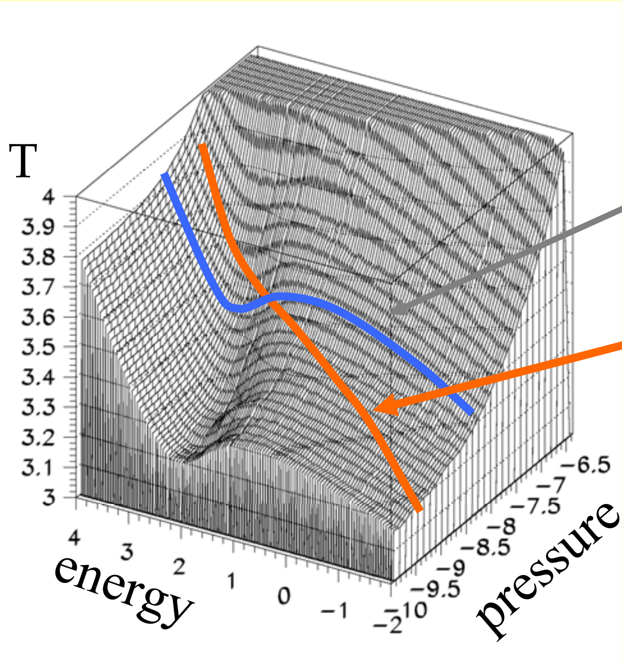
1st order

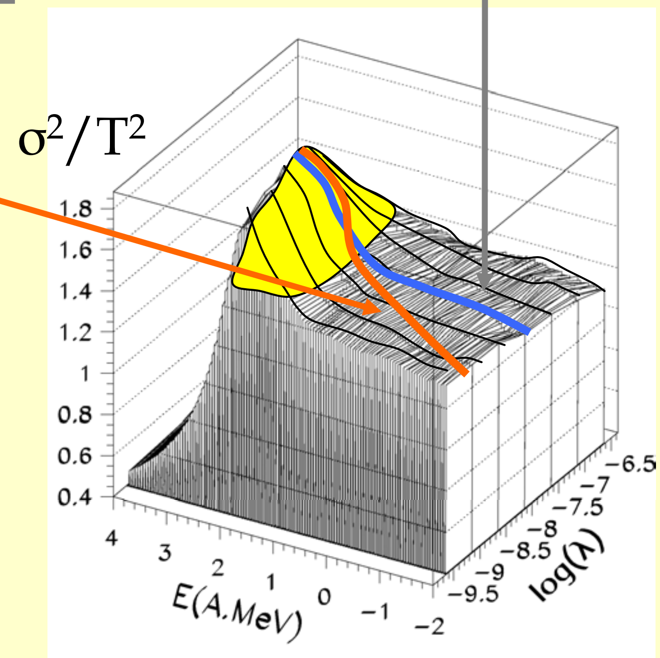


[2] It should be noticed that in the canonical case the energy fluctuations of the subsystem 1 are independent of the total fluctuations and only give information on the heat capacity of the subsystem itself. This will not be the case in a microcanonical ensemble because then the fluctuations in the subsystem 1 are correlated to the fluctuations in subsystem 2 through the total energy conservation constraint.

Advantages of studying abnormal fluctuations

Lattice Gas Model





The caloric curve
depends on the transformation

Fluctuations are unique

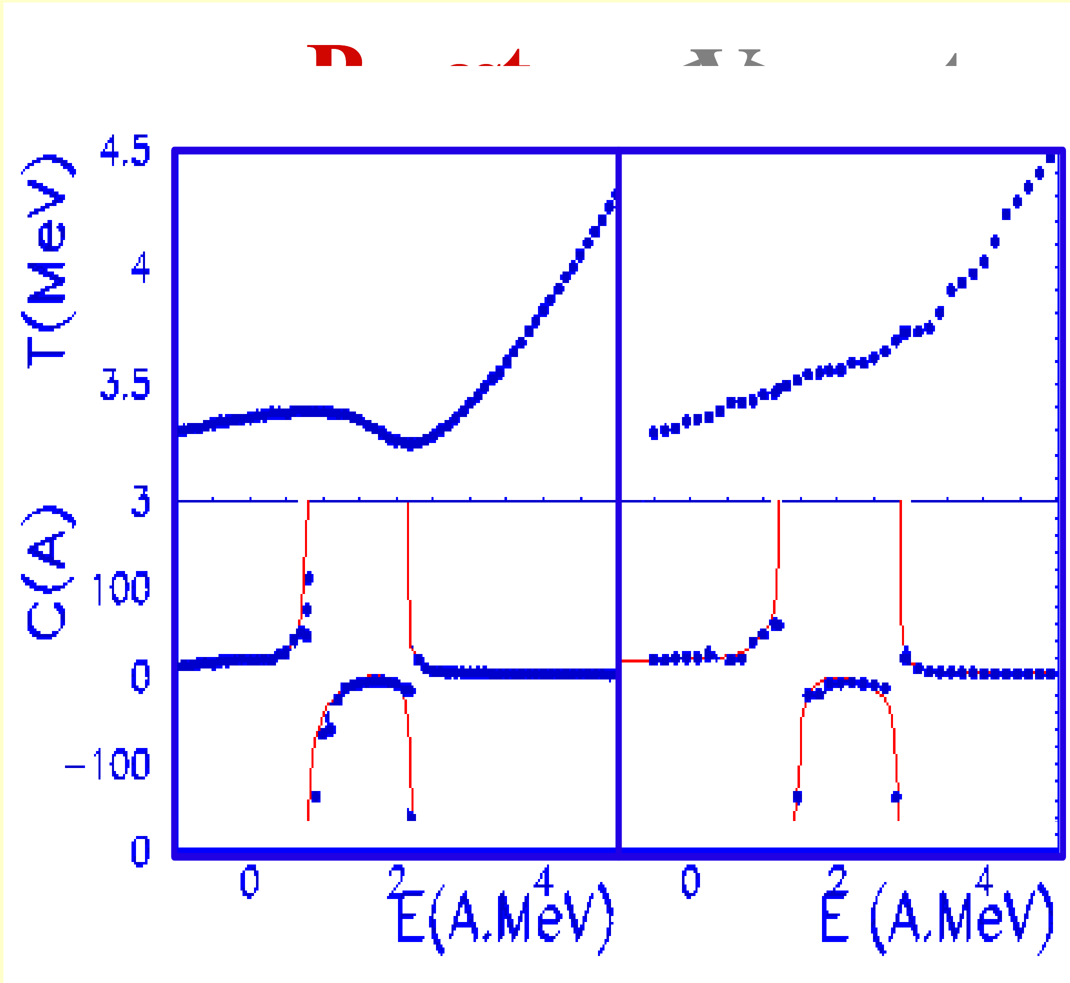
Ph. Chomaz, F. Gulminelli Nucl. Phys. A 749 (2005) 3

Microcanonical thermodynamics of finite systems

Lattice Gas Model

- The caloric curve depends on the transformation

- Fluctuations are independent on the transformation,
  they are state variables



Microcanonical thermodynamics of finite systems

Events sorted as a function of E^* (calorimetry)

$$E^* = E_{config} + E_{kin}$$

$$E^* = E_{coul}(V) + Q_v + E_{int}(T) + E_{tr}(T)$$

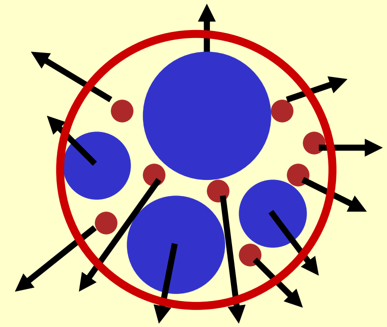
We can back-trace from data

- the average volume (ρ) of the system
- the temperature T

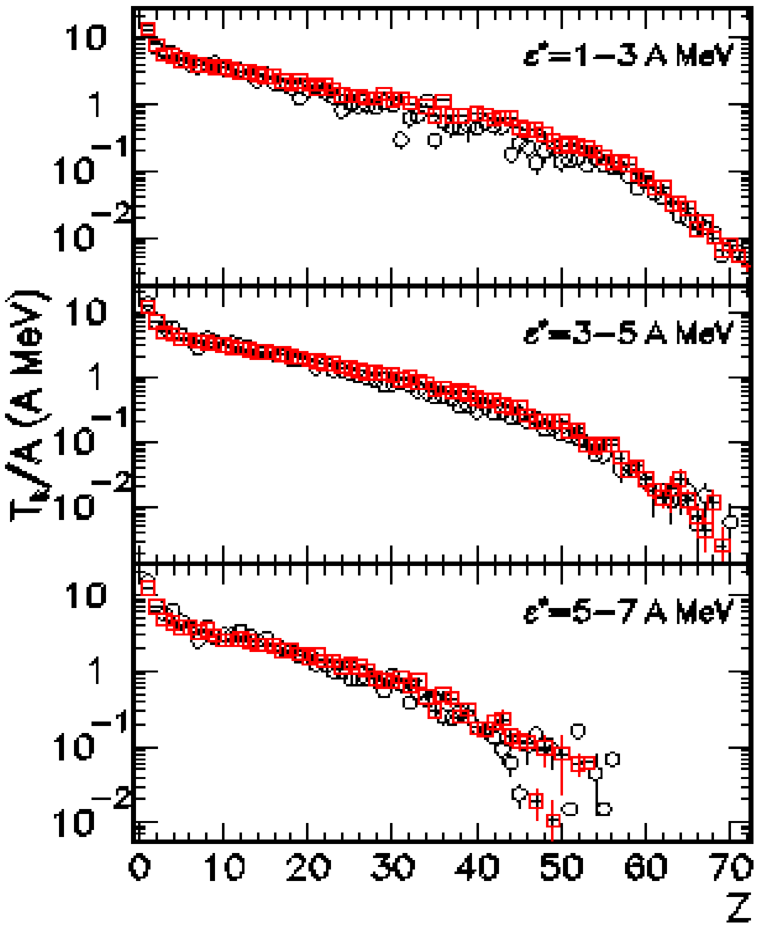
under the constraint of energy conservation

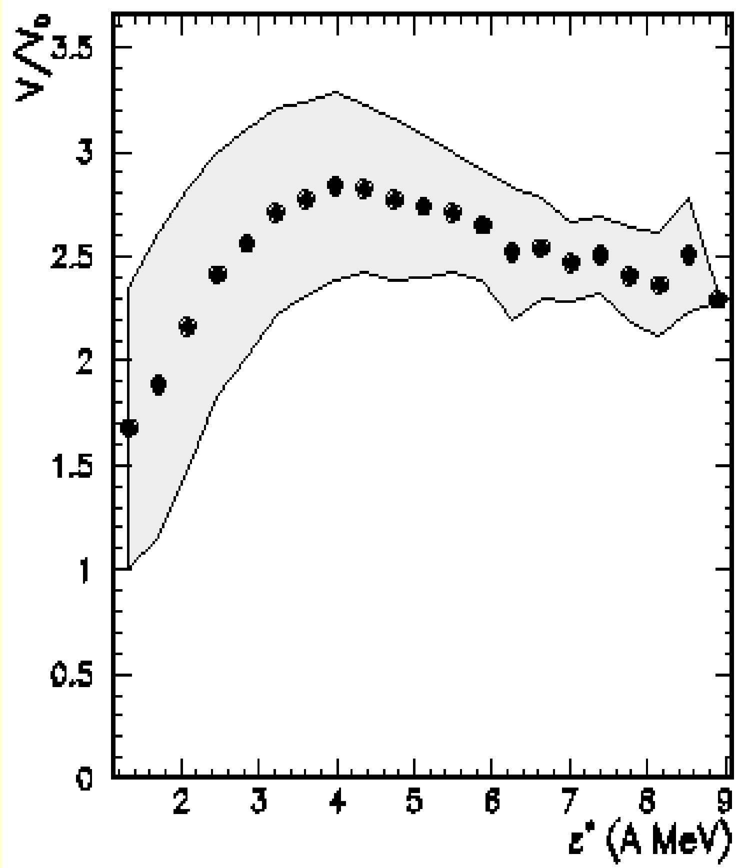
Multics-Nucl.Phys.A699(2002)795

Early information from measured observables: average volume



Circles=Multics data
Squares=Coulomb trajectories



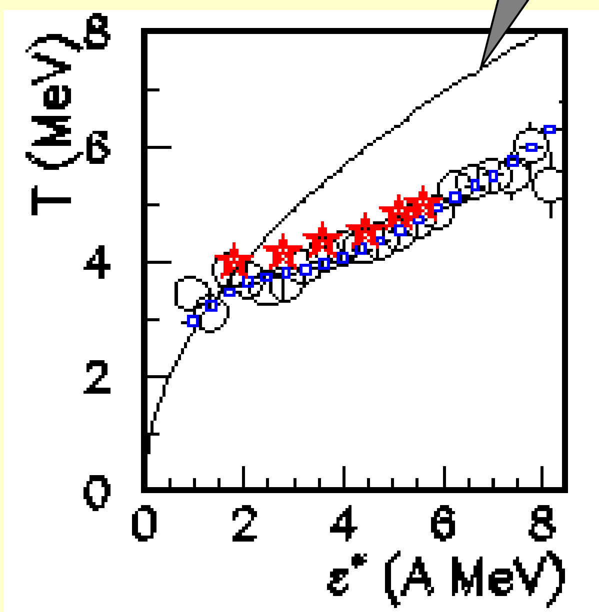


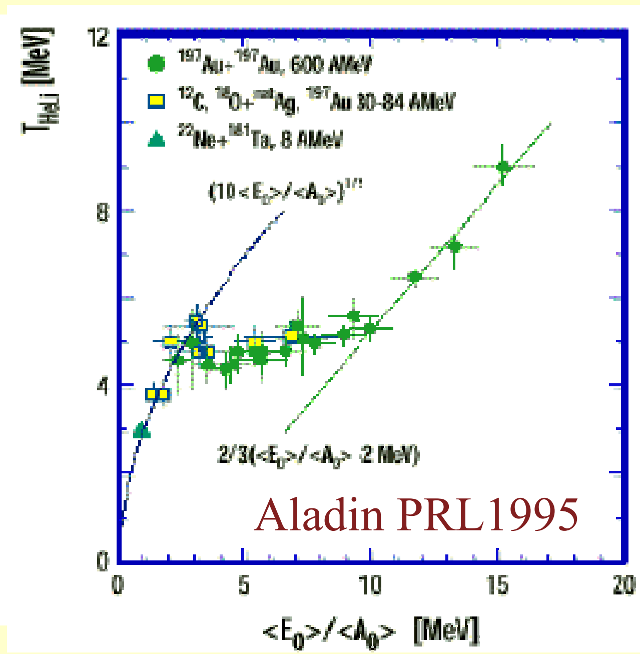
Early information from measured observables : Temperature

Liquid-drop

■ $\langle E_{kin} \rangle = (3/2) \langle m-1 \rangle T + \langle \Sigma a A_{IMF} \rangle T^2$

Multics-NPA699(2002)795





○ $$T = \left\langle \frac{E_{tr}}{(3/2)m - 1} \right\rangle$$

★ Isotope thermometer

P.M.Milazzo,PRC58(1998) 953

● Indra correlation data

N.Marie,PRC58(1998)256

T, E_{int} from independent measurements/methods

Microcanonical heat capacity from fluctuations

$$E^* = E_{config} + E_{kin} \qquad (\sigma^2_{config} = \sigma^2_{kin})$$

$$\begin{cases} E_{config} = Q_v + E_{coul}(V) \\ E_{kin} = E_{trasl}(T) + E_{internal}(T) \end{cases}$$

The system being thermodynamically characterized:

Ph.Chomaz , F.Gulminelli, NPA 647(1999) 153

$$C = C_{kin}^2 / (C_{kin} - \sigma_{kin}^2 / T^2)$$

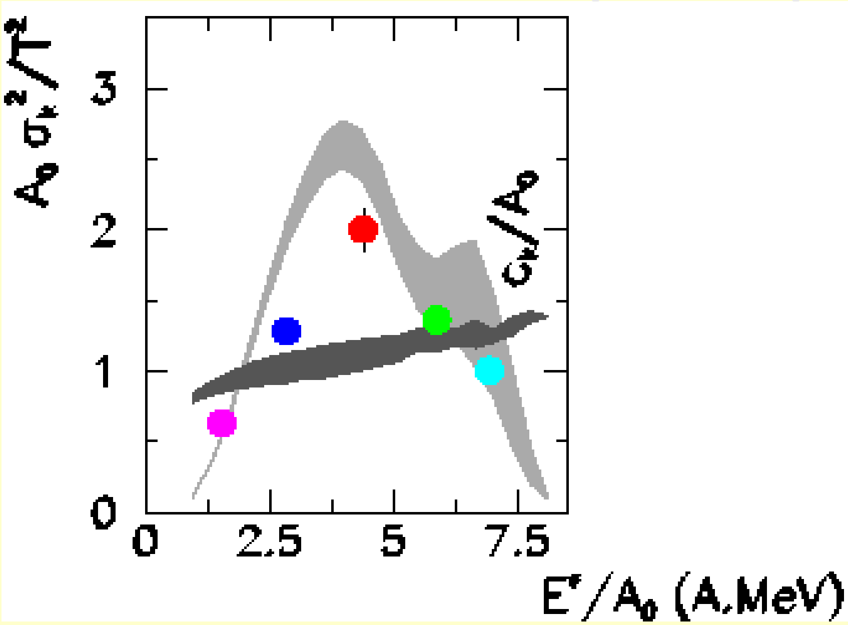
where:

$$C_{kin} = dE_{kin}/dT$$

Microcanonical fluctuations larger than the canonical expectation?

Multics-PLB473 (2000) 219;NPA699 (2002) 795;NPA734 (2004) 512

Heat capacity from fluctuations



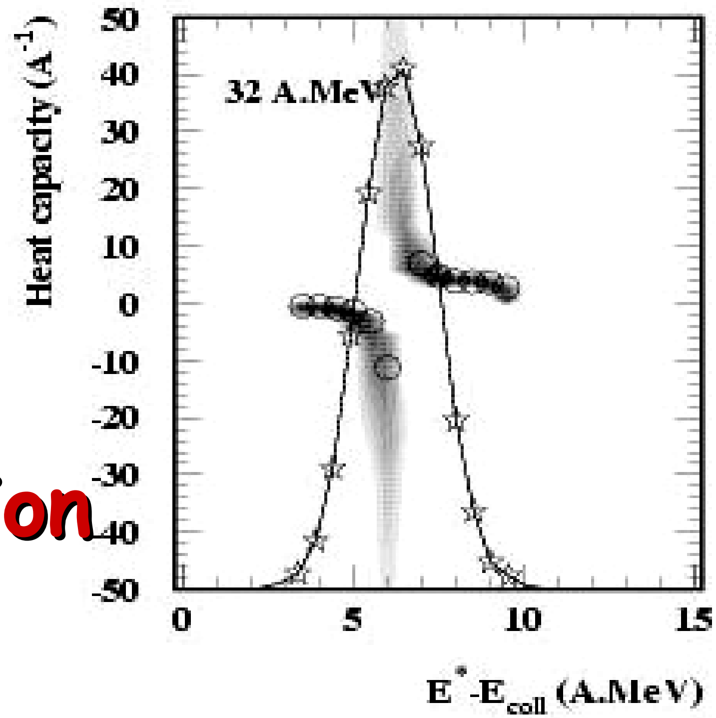
Multics:
PLB473 (2000) 219
NPA699 (2002) 795
NPA734 (2004) 512

Grey area: peripheral collisions

Points: central collisions:

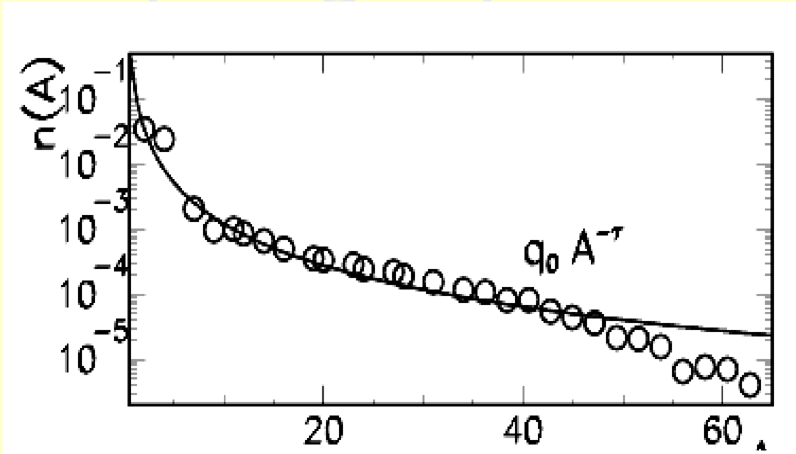
Au+C	Au+Cu	Au+Au

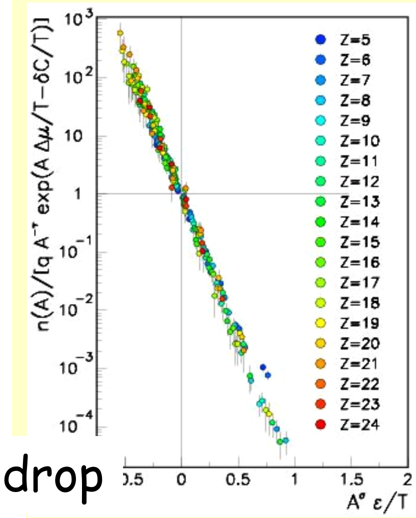
NPA699(2002)795

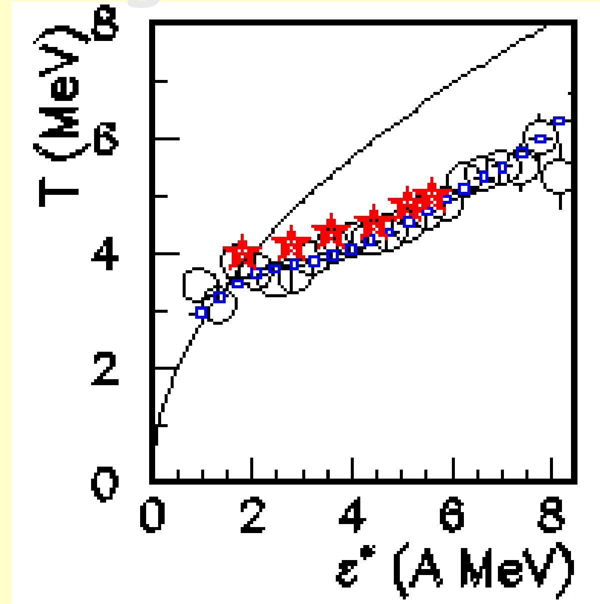


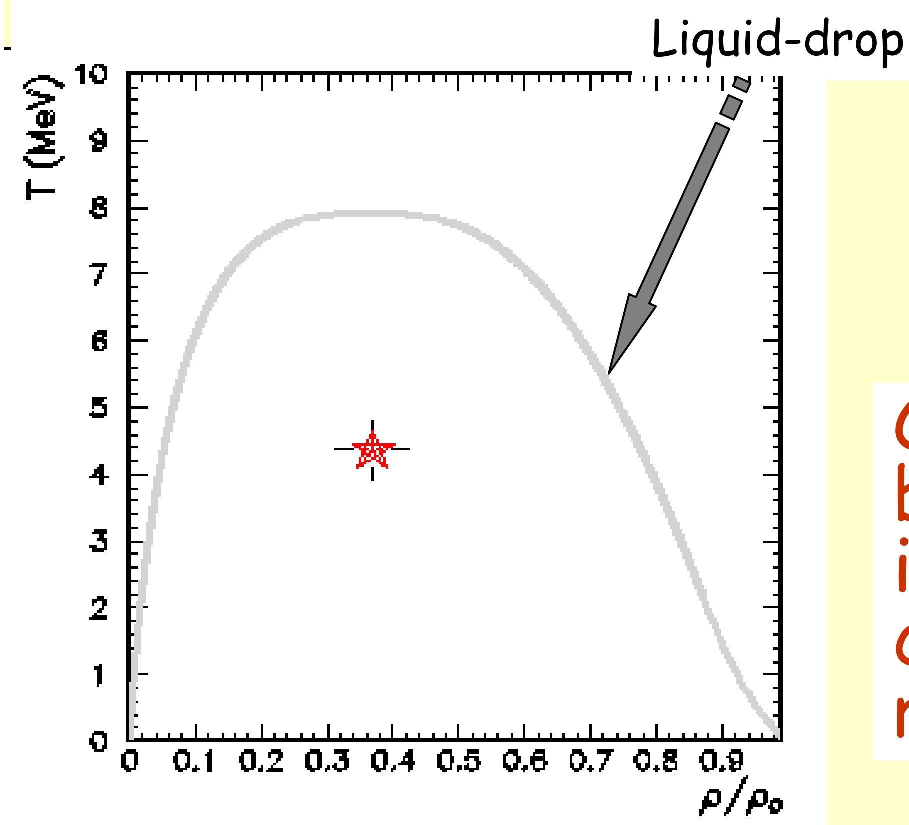
1-st order phase transition

Liquid-gas phase transition: is the game over?

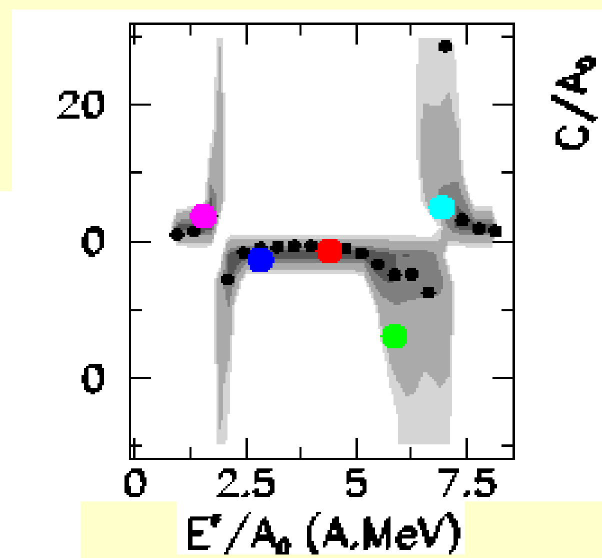








Critical behavior inside the coexistence region



What is left for future measurements?

- A better quantitative nuclear metrology of hot nuclei
- <u>Coincident</u> experimental information are needed on:

•critical partitioning of the system, fluctuations

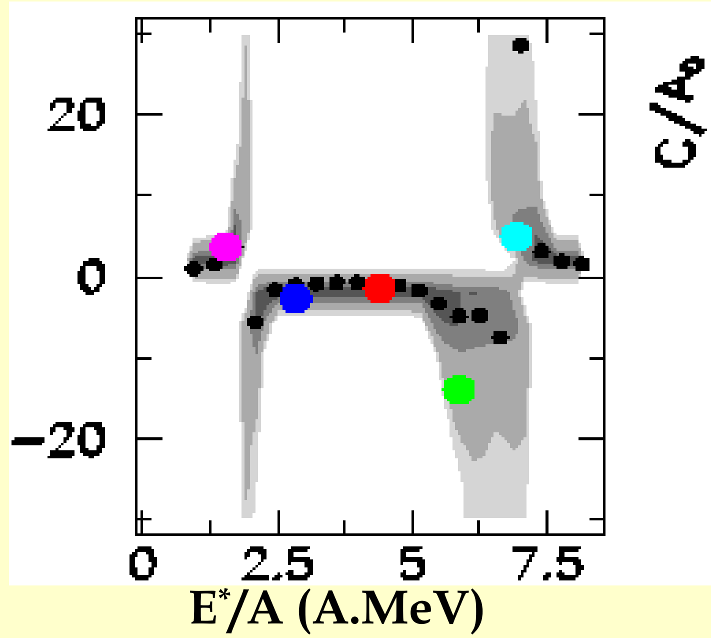
•calorimetric excitation energy

•isotopic temperature

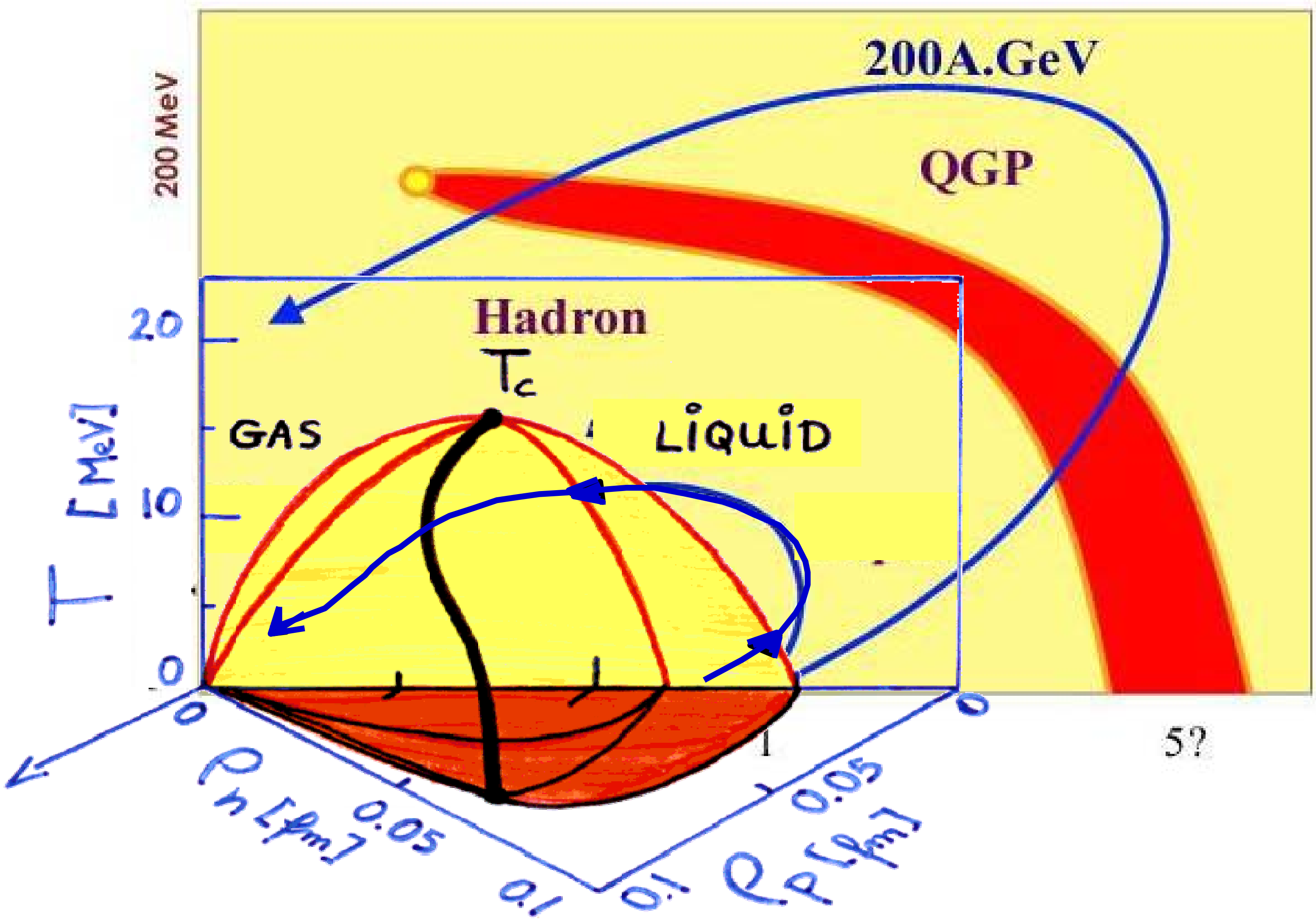
•proximity of the decay products

4π mass and charge detection !!

Multics NPA 2004



Multics	E_1=2±0.3	E_2=6.5±0.7
Isis	E_1=2.5	E_2 =7.
Indra		E_2=6.±0.5

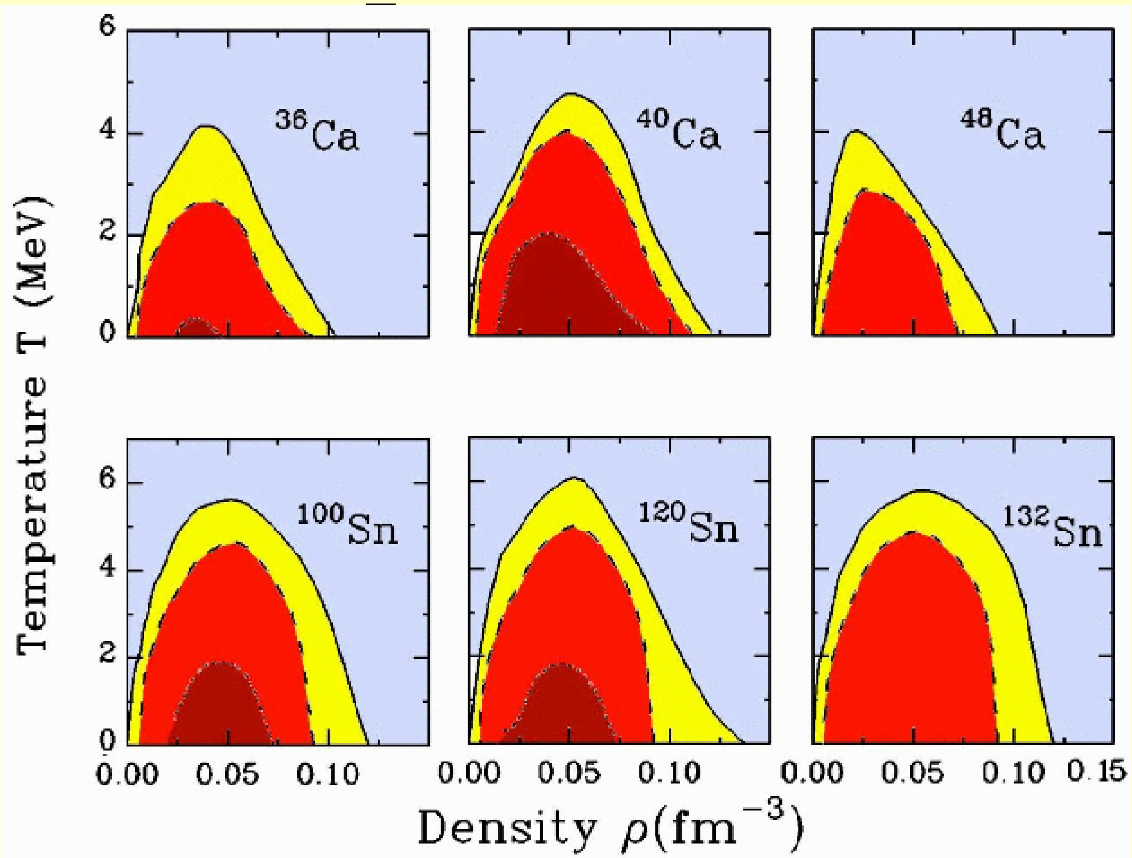


200A.GeV
QGP
200 MeV
Hadron
T_c
GAS
LIQUID
T [MeV]
20
10
0
ρ_n [fm]
0.05
0.1
ρ_p [fm]
5?
1

What is left for future measurements?

the 3-rd dimension of the EoS

2-nd generation devices and exotic beams are needed, to fully investigate the phase transition



M.Colonna et al.,PRL 88(2002) 122701

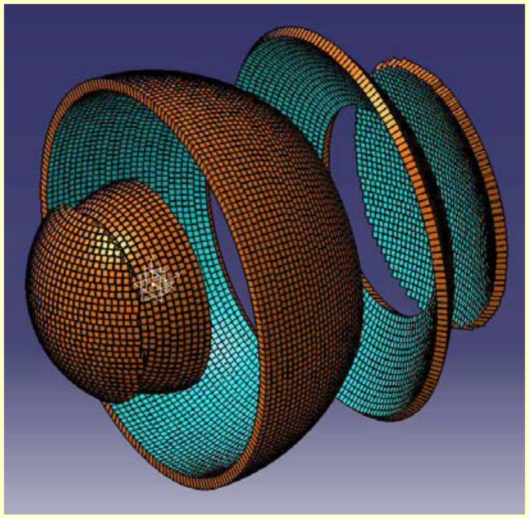
by changing:
- the Coulomb properties
- the isospin content

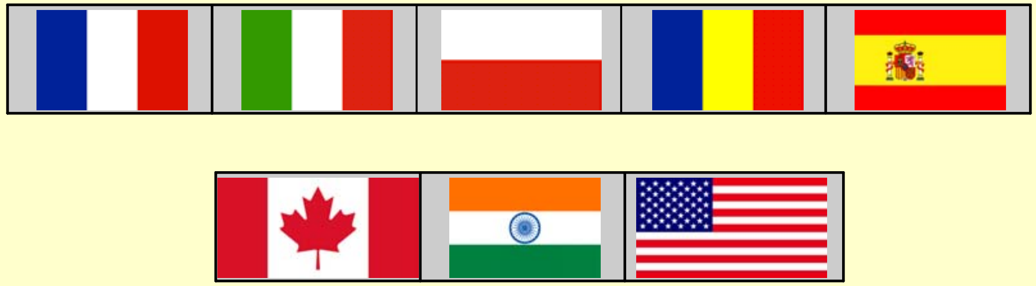
of the fragmenting source

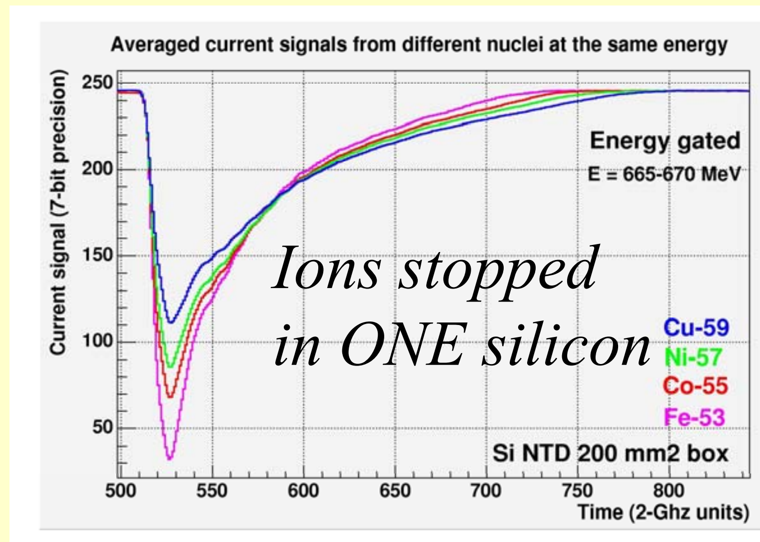
Instability growth time
100 fm/c (dashed/orange)
50 fm/c (dotted/red)

More asymmetric systems are less unstable

FAZIA : Four π A-Z Identification Array







- ~6000 telescopes
- Compactness of the device
- Ebeam from Barrier up to 100 A.MeV
- Telescopes: Si-ntd/Si-ntd/CsI
- Possibility of coupling with other detectors
- Complete Z (~70) and A (~50) id.
- Low-energy & identification threshold
- Digital electronics for pulse-shape id.

[redacted]

Systems and subsystems

S.K. Ma Statistical mechanics- Chap.6

Relazione fra la entropia di un sistema e le entropie dei suoi sottosistemi.

Dividiamo il sistema in due parti, 1 e 2 non interagenti

$$\begin{aligned} W_1(E_1) &= \exp(S_1(E_1)) \\ W_2(E_2) &= \exp(S_2(E_2)) \\ E &= E_1 + E_2 \end{aligned} \tag{1}$$

$$\begin{aligned} W(E) &= \int_0^E \int_0^E dE_1 dE_2 W_1(E_1) W_2(E_2) \delta(E - E_1 - E_2) \\ &= \int_0^E dE_1 W_1(E_1) W_2(E - E_1) \\ &= \int_0^E dE_1 \exp(S_1(E_1) + S_2(E - E_1)) \end{aligned} \tag{2}$$

$$P_1^E\left(E_1\right) = \frac{W_1\left(E_1\right)W_2\left(E-E_1\right)}{W\left(E\right)} \tag{3}$$

Lavoriamo attorno al massimo di $S_1\left(E_1\right)+S_2\left(E-E_1\right)$ [1], che corrisponde all'equilibrio termico $T_1=T_2=T$, con

$$T_i^{-1}\left(E_i\right) = \frac{\partial S_i}{\partial E_i}\left(E_i\right). \tag{4}$$

L'espansione in serie di S_1+S_2 nell'intorno del massimo porta a [2]:

$$\begin{aligned} S_1(E_1)+S_2(E_2) &= S_1(\bar{E}_1)+S_2(\bar{E}_2)+\frac{1}{T}(E_1-\bar{E}_1+E_2-\bar{E}_2) \\ &- \frac{1}{2}\left[\frac{1}{K_1}(E_1-\bar{E}_1)^2+\frac{1}{K_2}(E_2-\bar{E}_2)^2\right]+\ldots \end{aligned} \tag{5}$$

con:

$$\frac{1}{K_i} = -\left(\frac{\partial^2 S_i}{\partial E_i^2}\right)_{E_i=\bar{E}_i} = \frac{1}{T^2 C_i} \tag{6}$$

dove

$$C_i = \frac{\partial \bar{E}_i}{\partial T} \tag{7}$$

Il massimo sia in $E_1 = \bar{E_1}$, $E_2 = \bar{E_2} = E - \bar{E_1}$. Il termine corrispondente alla derivata prima di $S_1 + S_2$ va a 0, quindi:

$$P_1^E(E_1) = \frac{\exp\left(S_1\left(\bar{E_1}\right) + S_2\left(E - \bar{E_1}\right) - \frac{1}{2}\left[\frac{(E_1-\bar{E_1})^2}{K_1} + \frac{(E_1-\bar{E_1})^2}{K_2}\right]\right)}{\int_0^E d\,E_1 \exp\left(S_1(E_1) + S_2(E - E_1)\right)} \tag{8}$$

$$= \frac{\exp\left(S_1\left(\bar{E_1}\right) + S_2\left(E - \bar{E_1}\right) - \frac{1}{2}\left[\frac{(E_1-\bar{E_1})^2}{K}\right]\right)}{\exp\left(S_1\left(\bar{E_1}\right) + S_2\left(E - \bar{E_1}\right)\right)\int_0^E d\,E_1 \exp\left(\frac{-(E_1-\bar{E_1})^2}{2K}\right)}$$

con

$$K = \frac{K_1 K_2}{K_1 + K_2} = \frac{1}{\frac{1}{K_1} + \frac{1}{K_2}} \tag{9}$$

$K > 0$ perche' la derivata seconda di $S_1 + S_2$ sia negativa (massimo), $K_i \neq 0$, ma non necessariamente $K_i > 0$. Sostituendo[3]:

$$z = E_1 - \bar{E_1}, \quad dz = dE_1, \quad \int_0^E \to \int_{-z_1^*}^{z_1^*} \to \int_{-\infty}^{\infty} = 2\int_0^{\infty} \tag{10}$$

$$P_1^E(E_1) = \frac{\exp\left(\frac{-(E_1-\bar{E_1})^2}{2K}\right)}{\int_{-\infty}^{\infty} d\,z \exp\left(\frac{-z^2}{2K}\right)} = \frac{1}{\sqrt{2\pi K}}\exp\left(\frac{-(E_1-\bar{E_1})^2}{2K}\right) \tag{11}$$

Segue:

- $P_1^E\,(E_1)$ gaussiana normalizzata (area =1) $(\bar{E}_1, \sigma_1^2)$, con valore massimo $\frac{1}{\sqrt{2\pi K}}$,
- $\sigma_1^2 = K = \frac{1}{\frac{1}{K_1}+\frac{1}{K_2}} = \frac{1}{\frac{1}{C_1 T^2}+\frac{1}{C_2 T^2}} = T^2 \frac{C_1 C_2}{C_1+C_2}$
- $\bar{C} = C_1 + C_2 = \frac{C_1^2}{(C_1 - \frac{\sigma_1^2}{T^2})}$

Isotope analysis

Grand-canonical approach : $Y(N,Z) \propto \exp\left[(-F(N,Z) + \mu_n N + \mu_p Z)/T\right]$

T from double ratios: $\dfrac{Y(He^3)/Y(He^4)}{Y(Li^6)/Y(Li^7)}$

Isoscaling :

Two reactions :
- ✓ $(Z/A)_1 \neq (Z/A)_2$
- ✓ $T_1 = T_2$ $V_1 = V_2$
- ✓ $\alpha_q = (\mu_{q2} - \mu_{q1})/T$

$$R_{iso}^{(1,2)}(N,Z) = \frac{Y_2(N,Z)}{Y_1(N,Z)} \propto \exp\left[\alpha_n N + \alpha_p Z)\right]$$

Approximate link to symmetry energy C_{sym}:

$$\alpha_n = \frac{\Delta\mu_n}{T} = \frac{4C_{sym}}{T}\left([Z/A]^2_{(1)} - [Z/A]^2_{(2)}\right)$$

Isobaric ratio (for mirror nuclei) :

$$\frac{Y(N_1, Z_1)}{Y(N_2, Z_2)} \approx \frac{\rho_n}{\rho_p} e^{\Delta B/T}$$

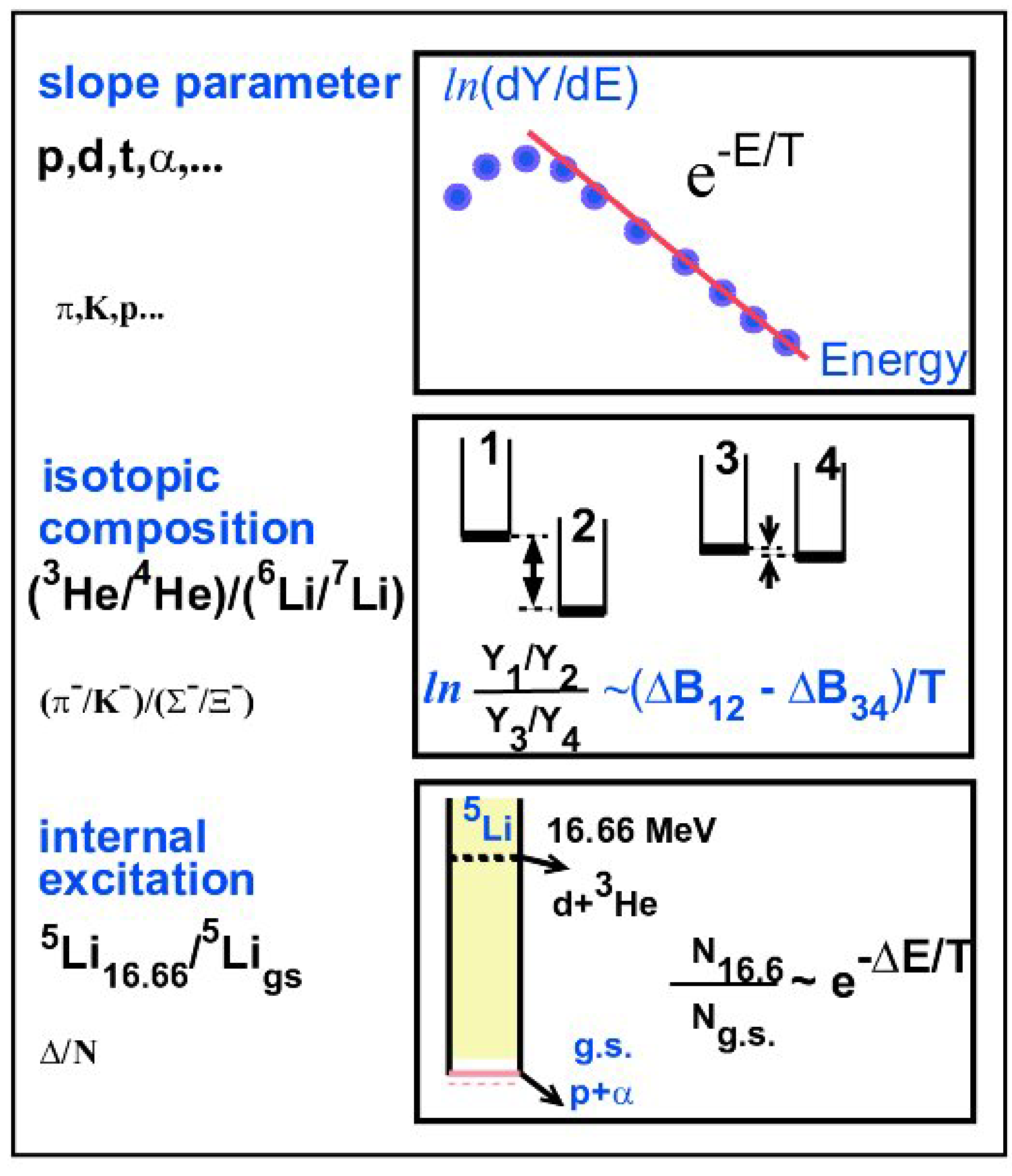
Temperatura

Ipotesi: equilibrio

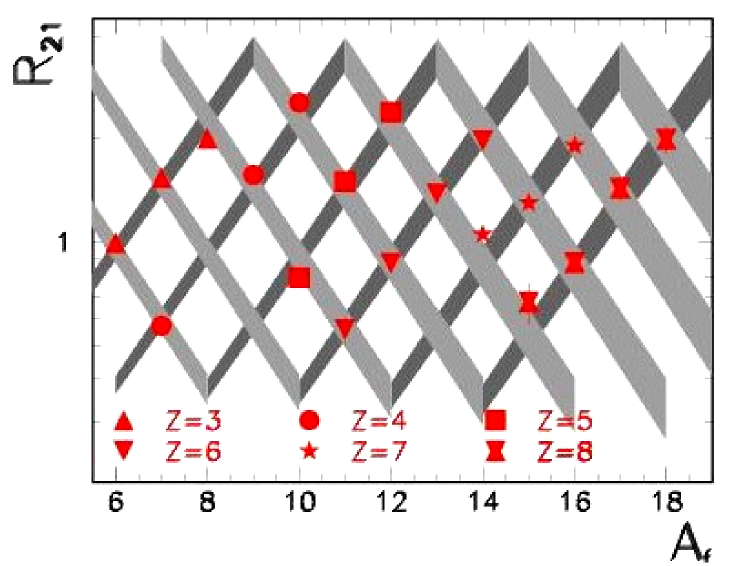
slope: effetti dinamici

doppio rapporto isotopico
si elimina la dipendenza
dalle proprieta' chimiche

popolazione di stati eccitati



Symmetry energy and free nucleon densities



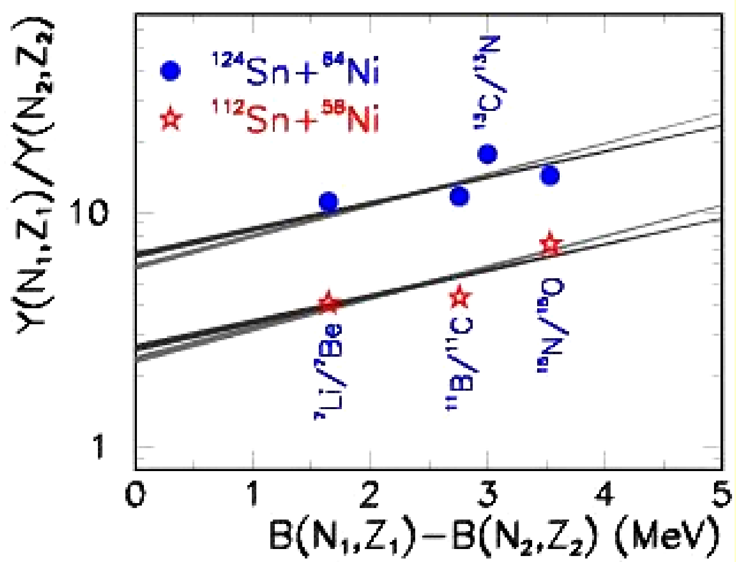
Isotopic ratio :

$$R_{21}(N,Z) = \frac{Y_{124}\,_{Sn+^{64}Ni}(N,Z)}{Y_{112}\,_{Sn+^{58}Ni}(N,Z)} \propto e^{\alpha N+\beta Z}$$

$$C_{sym} = \frac{\alpha T}{\left(\frac{Z}{A}\right)_1^2 - \left(\frac{Z}{A}\right)_2^2}$$

α = 0.44 ± 0.01

Symmetry Energy~18-20 MeV



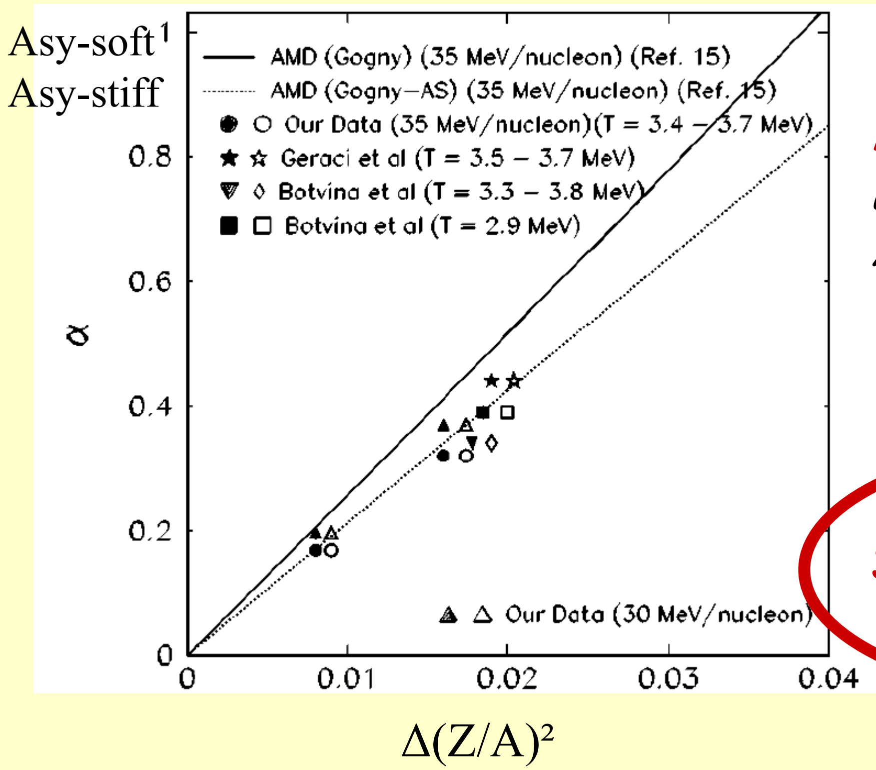
Isobaric ratio (for mirror nuclei) :

$$\frac{Y(N_1,Z_1)}{Y(N_2,Z_2)} \approx \frac{\rho_n}{\rho_p} e^{\Delta B/T}$$

$^{112,124}Sn+^{58,64}Ni$ 35 AMeV central collisions
CHIMERA-REVERSE Experiment

E. Geraci, et al., Nucl. Phys. A 732 (2004) 173, Nucl .Phys. A734 (2004) 524

Extraction of symmetry energy



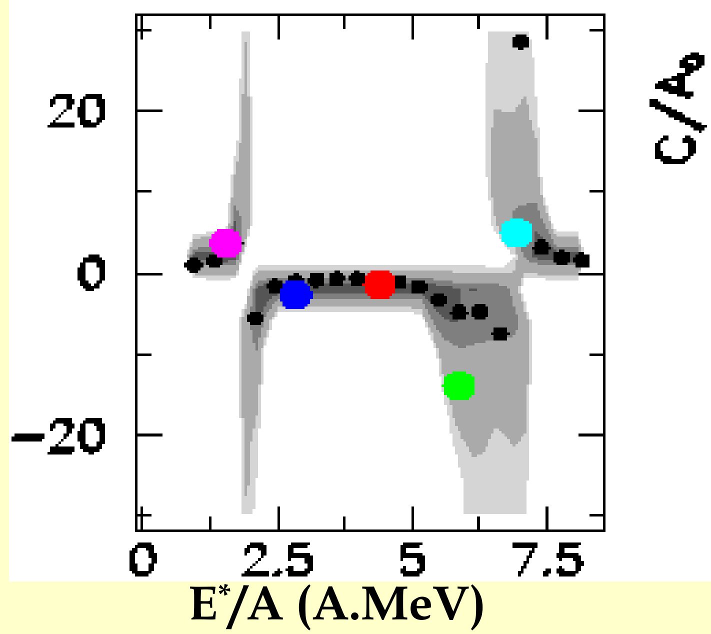
*D.Shetty et al., P. R.C **70** (2004) 011601*
E.Geraci et al.,NPA732(2004)
A.Botvina et al., PRC65(2002):

Sequential feeding?

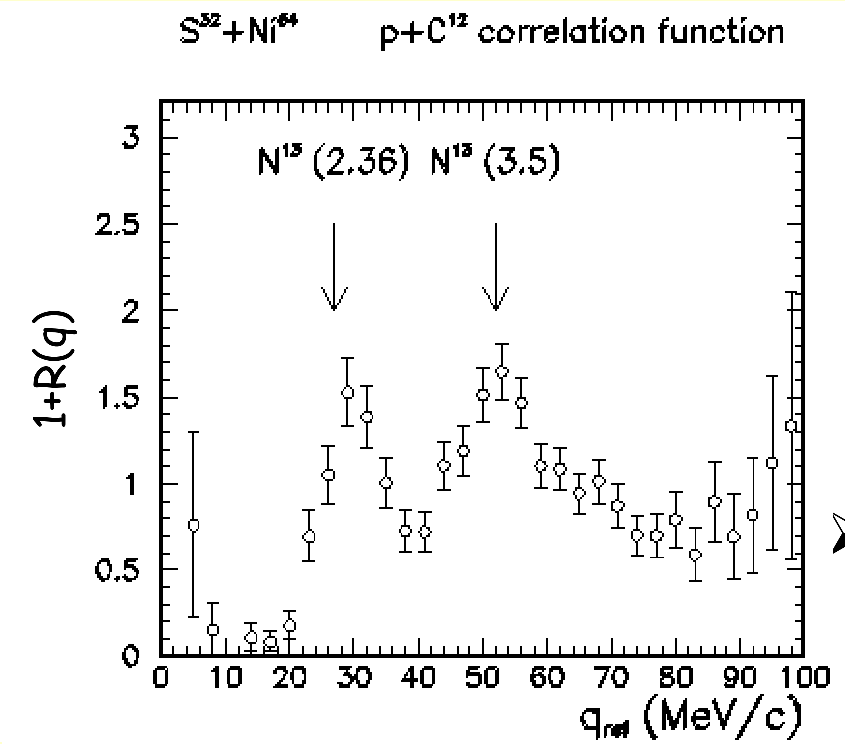
Conclusions

- **The physics of hot nuclei: a unique laboratory**
  - for the thermodynamics of finite, charged, 2-component systems
  - for a quantitative nuclear metrology
  - for interdisciplinary connections

Multics NPA 2004



Multics	E_1=2±0.3	E_2=6.5±0.7
Isis	E_1=2.5	E_2 =7.
Indra		E_2=6.±0.5



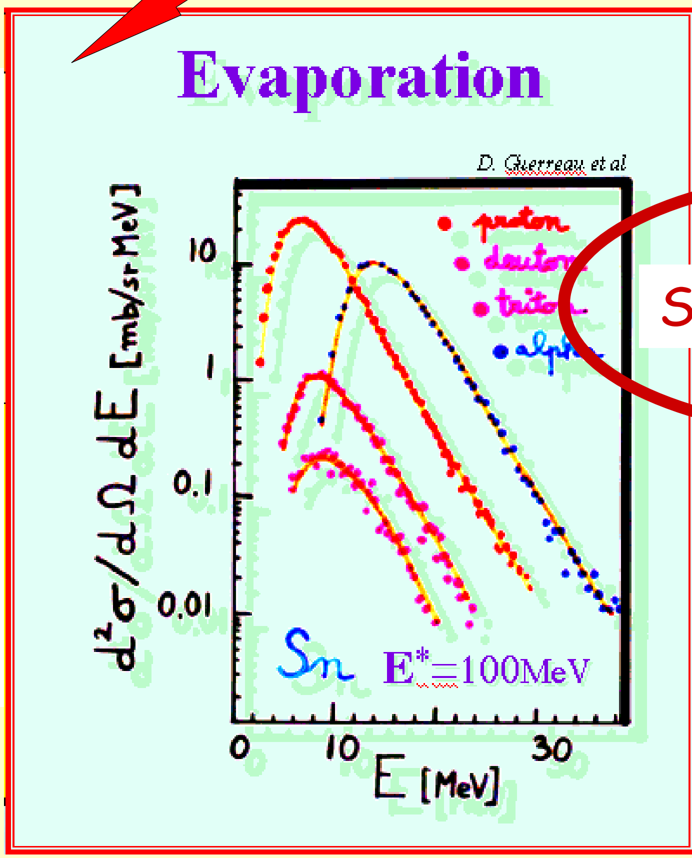
nucl-ex collaboration&garfield

- **We need:**
  - 4π mass and charge detection
  - 20-50 A.MeV radioactive beams

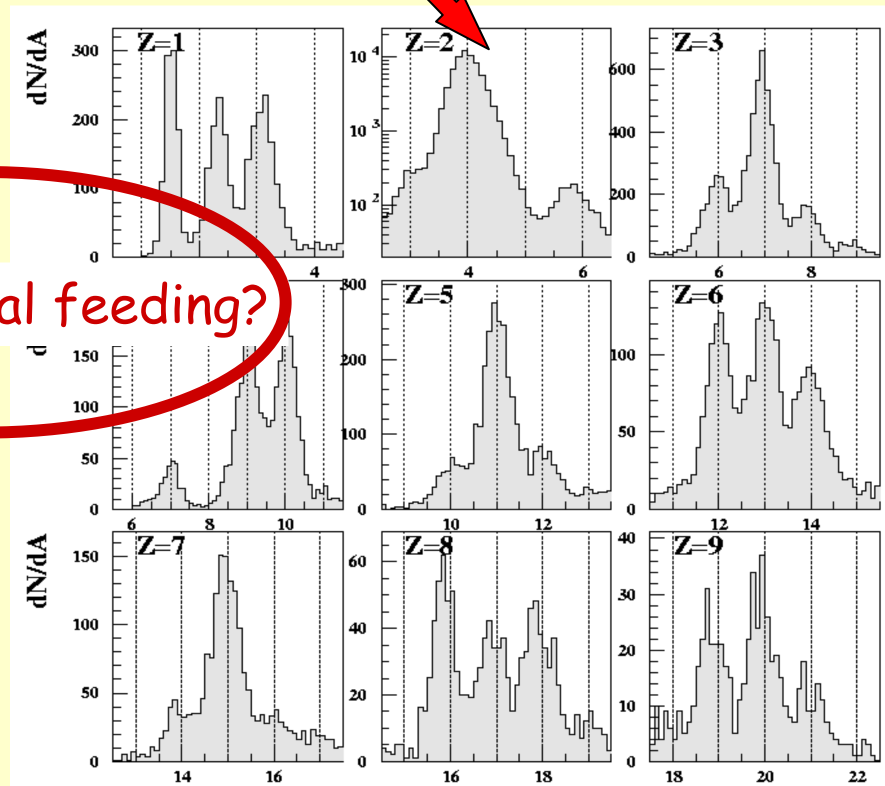
Temperature and caloric curve

For the *caloric curve* one needs to measure:

- Heavy residue (or QP)
- Slopes of 1-st chance l.c.p. energy spectra
- Isotopes (for double ratios)



Sequential feeding?



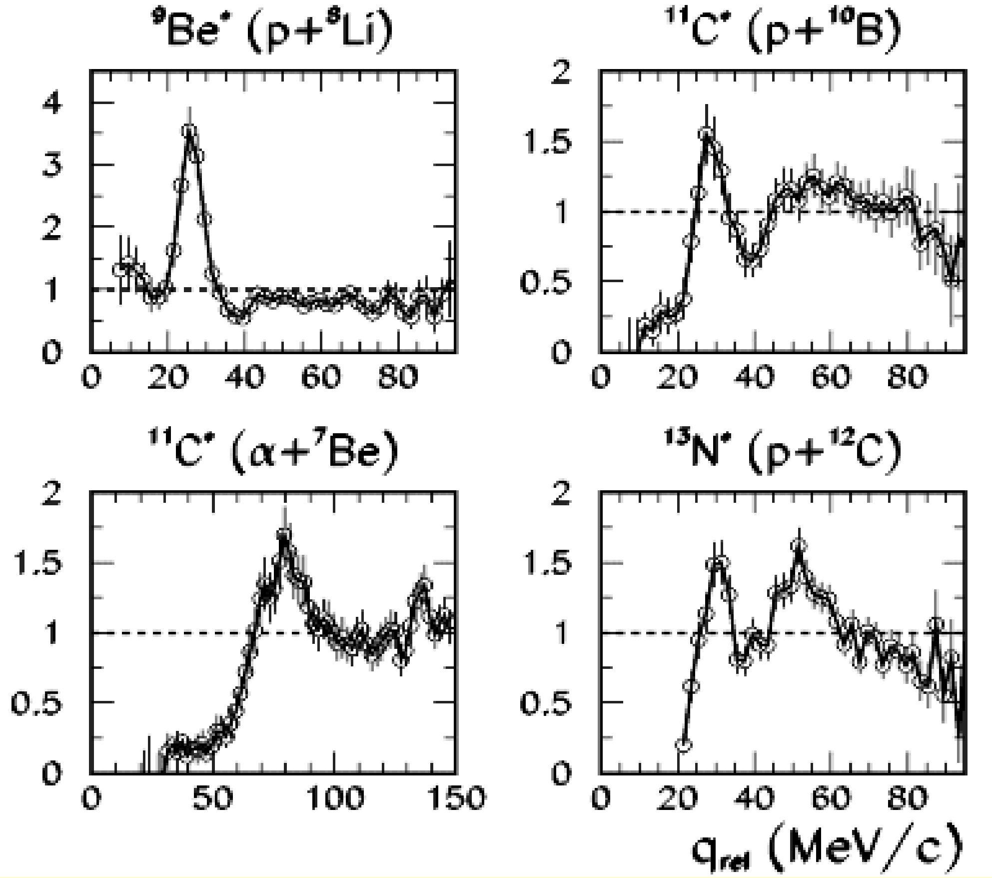
N.Le Neindre et al , NIM A490 (2002) 251

Experiments with n-rich/poor systems

$^{32}S+^{58,64}Ni$ 14.5 AMeV 3-IMF events

Observed 35 resonances, from He^4 (d+d) to Ne^{20} ($\alpha+O^{16}$)

A rough calculation of "feeding correction" through correlation functions suggests an increase of T by 0.5 MeV for few % of decrease in the He^4 yield

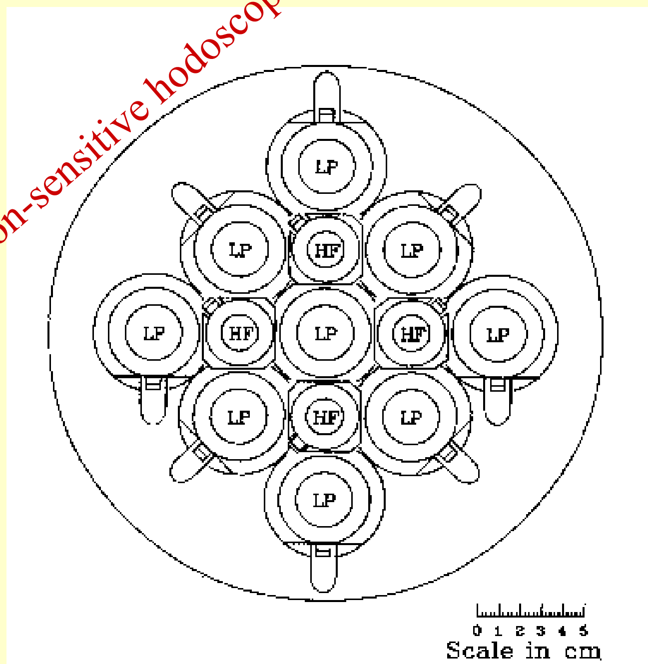


Before drawing conclusions on temperature, densities:

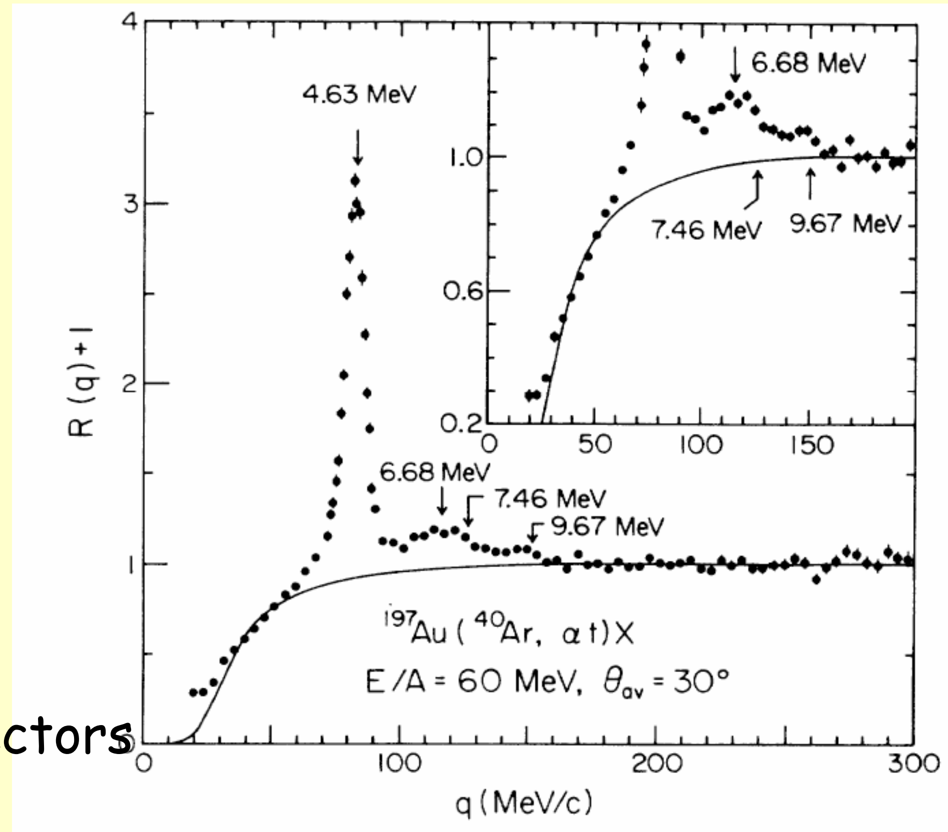
- Isotope emission time scales have to be checked through correlation functions

nucl-ex collaboration&garfield@LNL

Resonance spectroscopy



t-α correlation function (Li^{7*})



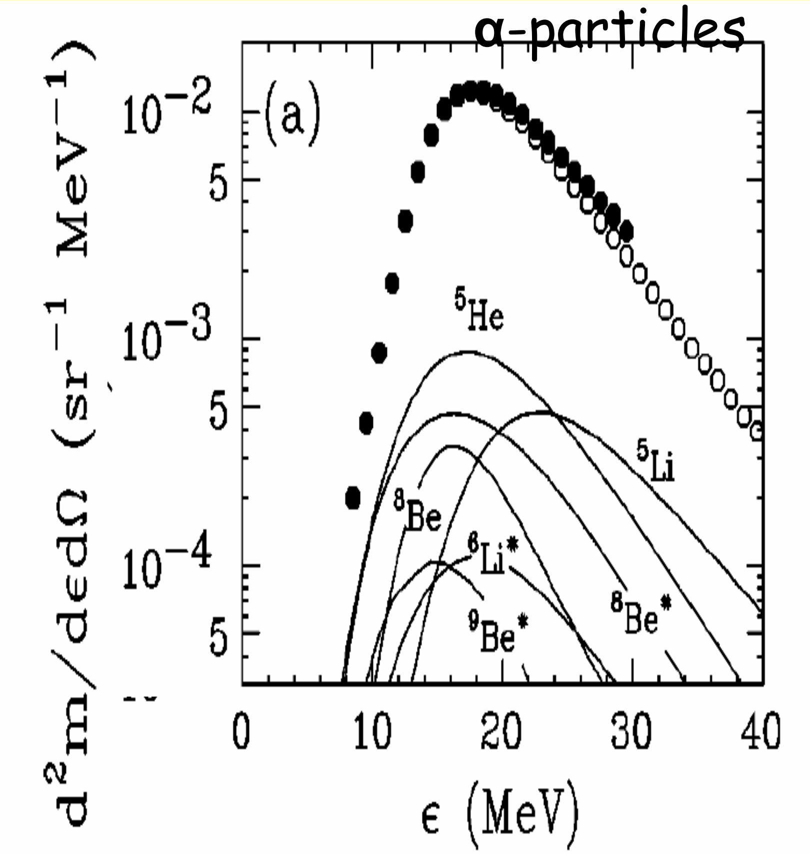
Pochodzalla et al., PRC35 (1987)1695

m=multiplicity, N=number of detectors

- $\varepsilon(m) = \varepsilon(1)^m$
- P(double)=(m-1)/(2N)

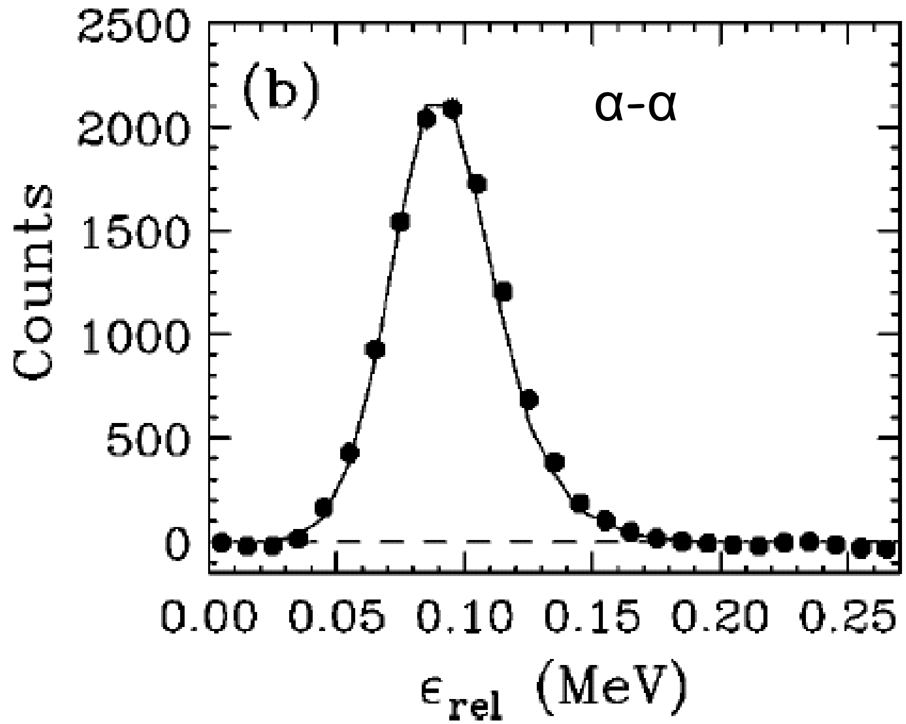
A reasonable compromise is P(double)<5%
For m=3 N=10

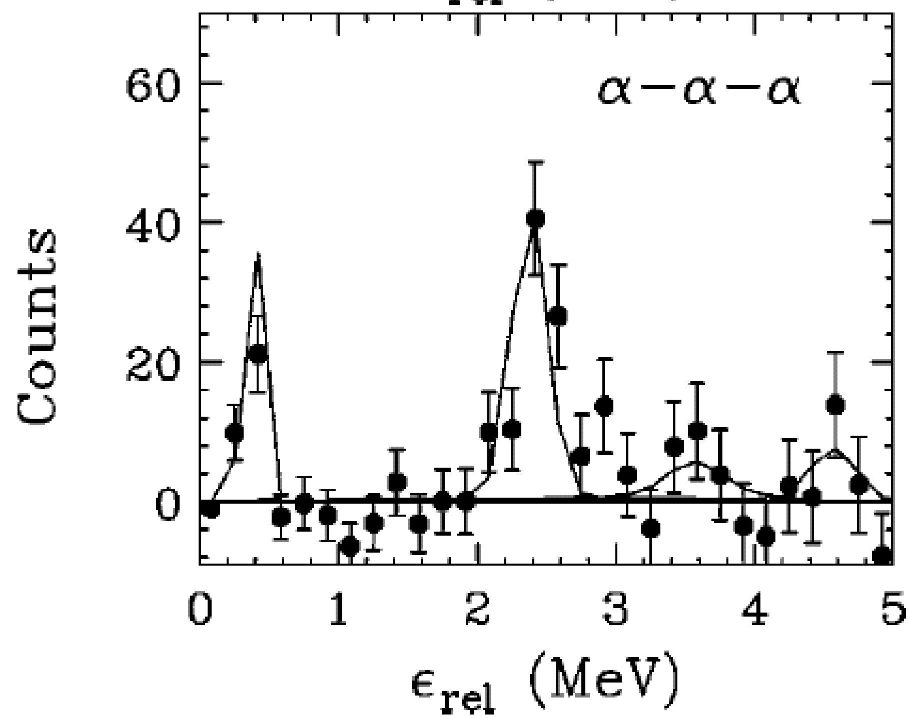
Why many-body correlations?

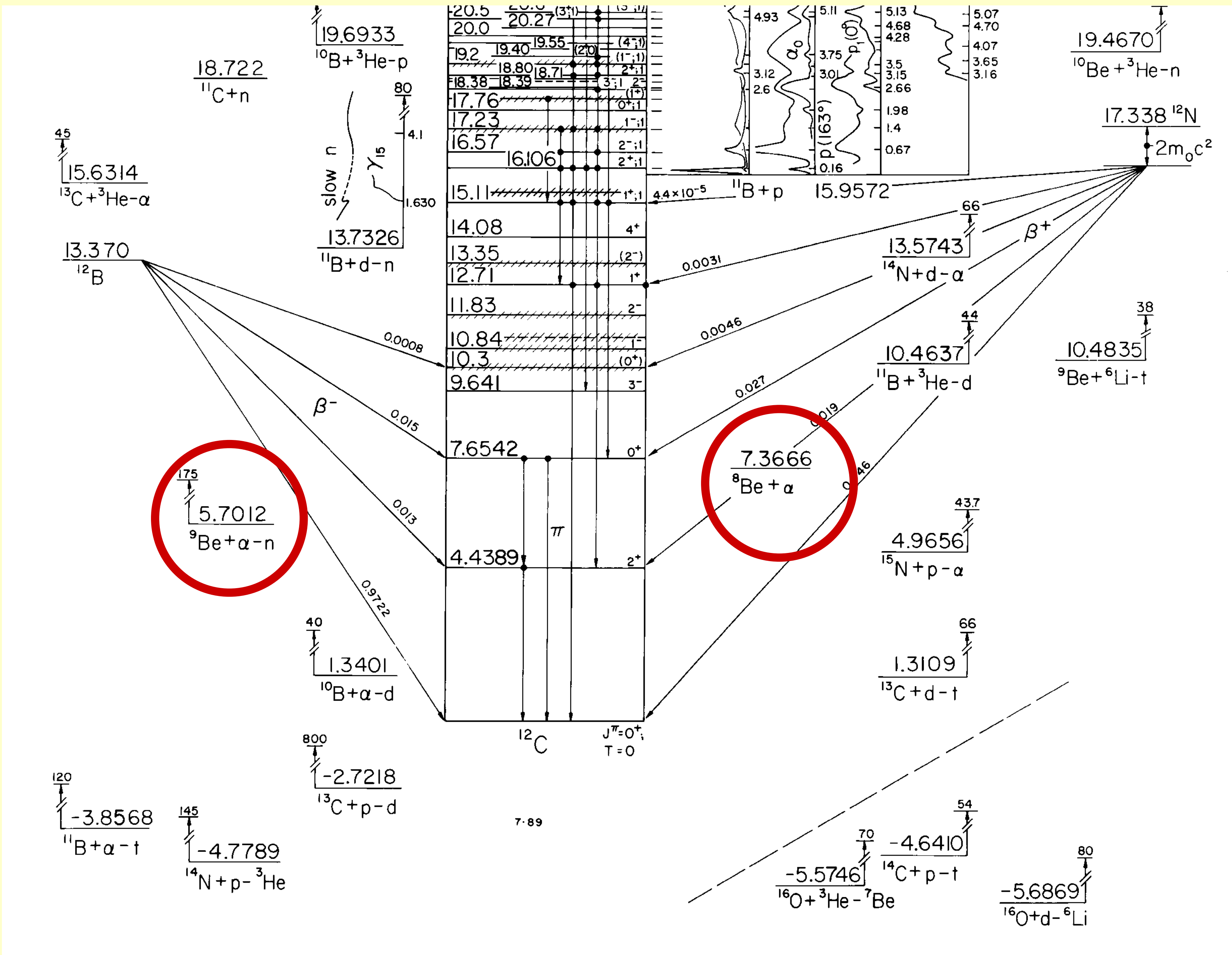


R.J. Charity et al., PRC63 024611
^{60}Ni+^{100}Mo 11 A.MeV

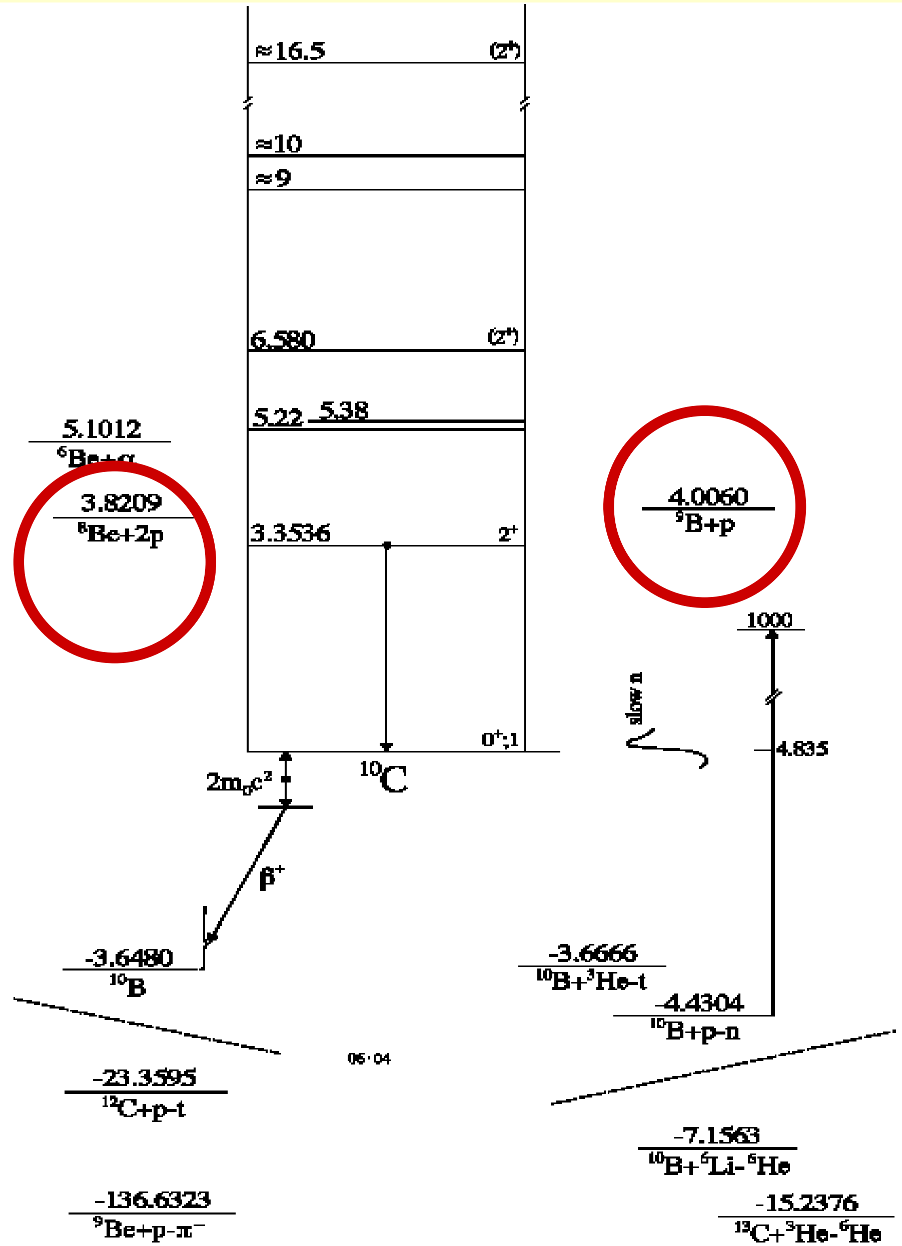
Δθ≈ 0.6° → high granularity
but in a limited angular coverage
& not HR full identification







19.6933
$^{10}B+^{3}He-p$
18.722
$^{11}C+n$
19.4670
$^{10}Be+^{3}He-n$
15.6314
$^{13}C+^{3}He-\alpha$
13.7326
$^{11}B+d-n$
17.338 ^{12}N
$2m_0c^2$
13.370
^{12}B
15.9572
$^{11}B+p$
13.5743
$^{14}N+d-\alpha$
10.4637
$^{11}B+^{3}He-d$
10.4835
$^{9}Be+^{6}Li-t$
β^-
β^+
7.6542
4.4389
7.3666
$^{8}Be+\alpha$
5.7012
$^{9}Be+\alpha-n$
4.9656
$^{15}N+p-\alpha$
1.3401
$^{10}B+\alpha-d$
1.3109
$^{13}C+d-t$
^{12}C
$J^{\pi}=0^+;$ T = 0
-2.7218
$^{13}C+p-d$
-3.8568
$^{11}B+\alpha-t$
-4.7789
$^{14}N+p-^{3}He$
-5.5746
$^{16}O+^{3}He-^{7}Be$
-4.6410
$^{14}C+p-t$
-5.6869
$^{16}O+d-^{6}Li$
20.5
20.0
20.27
19.2
19.40
19.55
18.80
18.71
18.38
18.39
17.76
17.23
16.57
16.106
15.11
14.08
13.35
12.71
11.83
10.84
10.3
9.641
slow n
γ_{15}
0.0008
0.015
0.013
0.9722
0.0031
0.0046
0.027
0.019
0.46
4.4×10^{-5}
π
7·89



≈16.5
(2+)
≈10
≈9
6.580
(2+)
5.22
5.38
5.1012
6Be+α
3.8209
8Be+2p
4.0060
9B+p
3.3536
2+
1000
slow n
4.835
0+;1
2m0c2
10C
β+
-3.6480
10B
-3.6666
10B+3He-t
-4.4304
10B+p-n
06·04
-23.3595
12C+p-t
-7.1563
10B+6Li-6He
-136.6323
9Be+p-π−
-15.2376
13C+3He-6He

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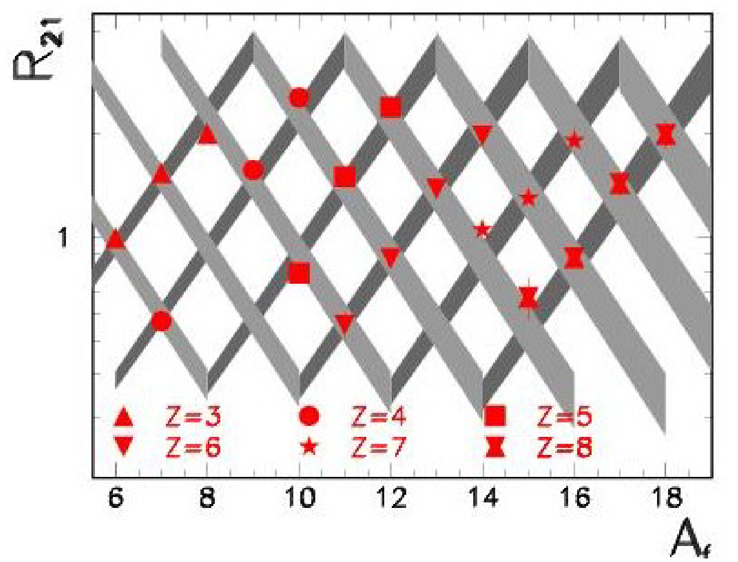

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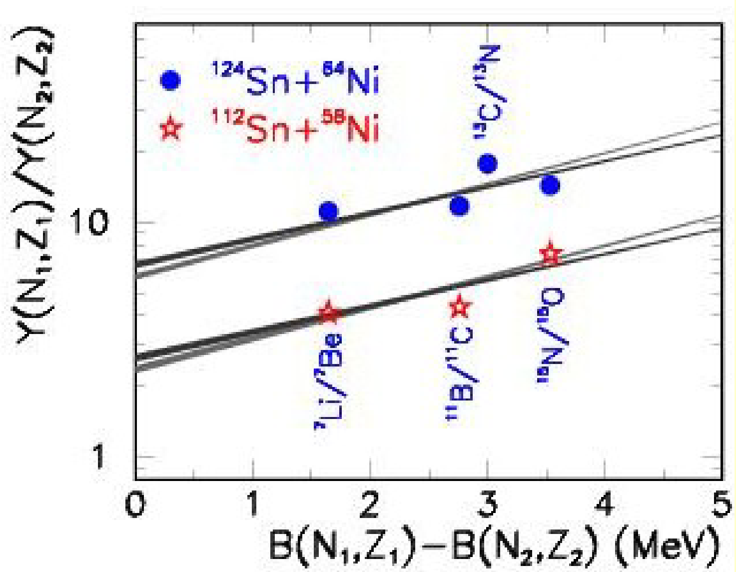
C_{sym}= Symmetry Energy~18-20 MeV

D.Shetty et al., P. R.C **70** (2004) 011601



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E. Geraci, et al., Nucl. Phys. A 732 (2004) 173, Nucl .Phys. A734 (2004) 524