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Clustering effects in heavy-ion Fermi energy reactions

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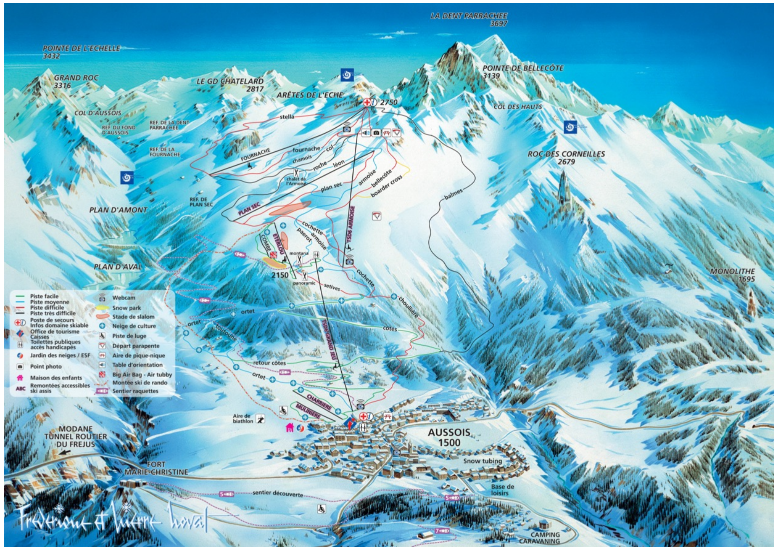

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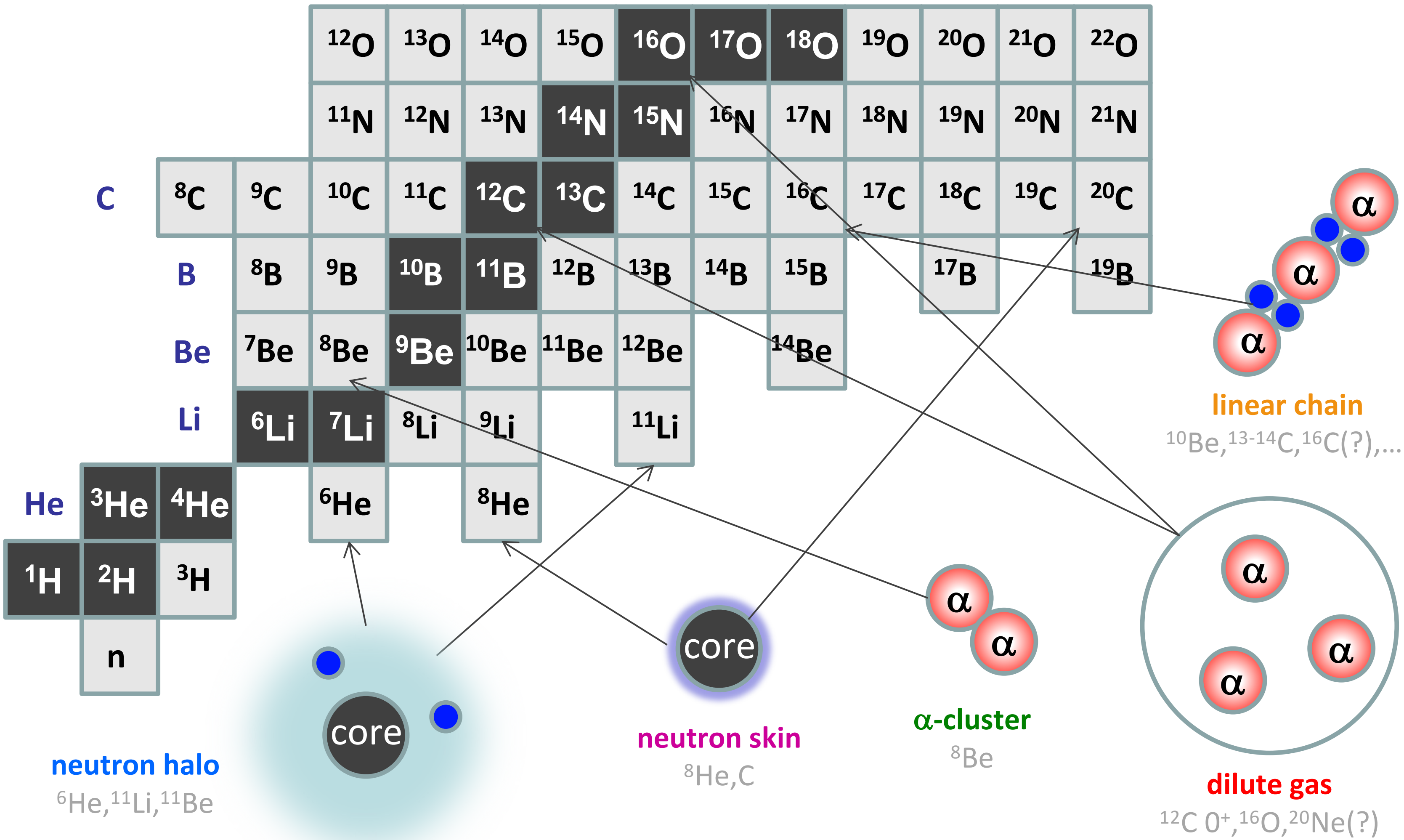
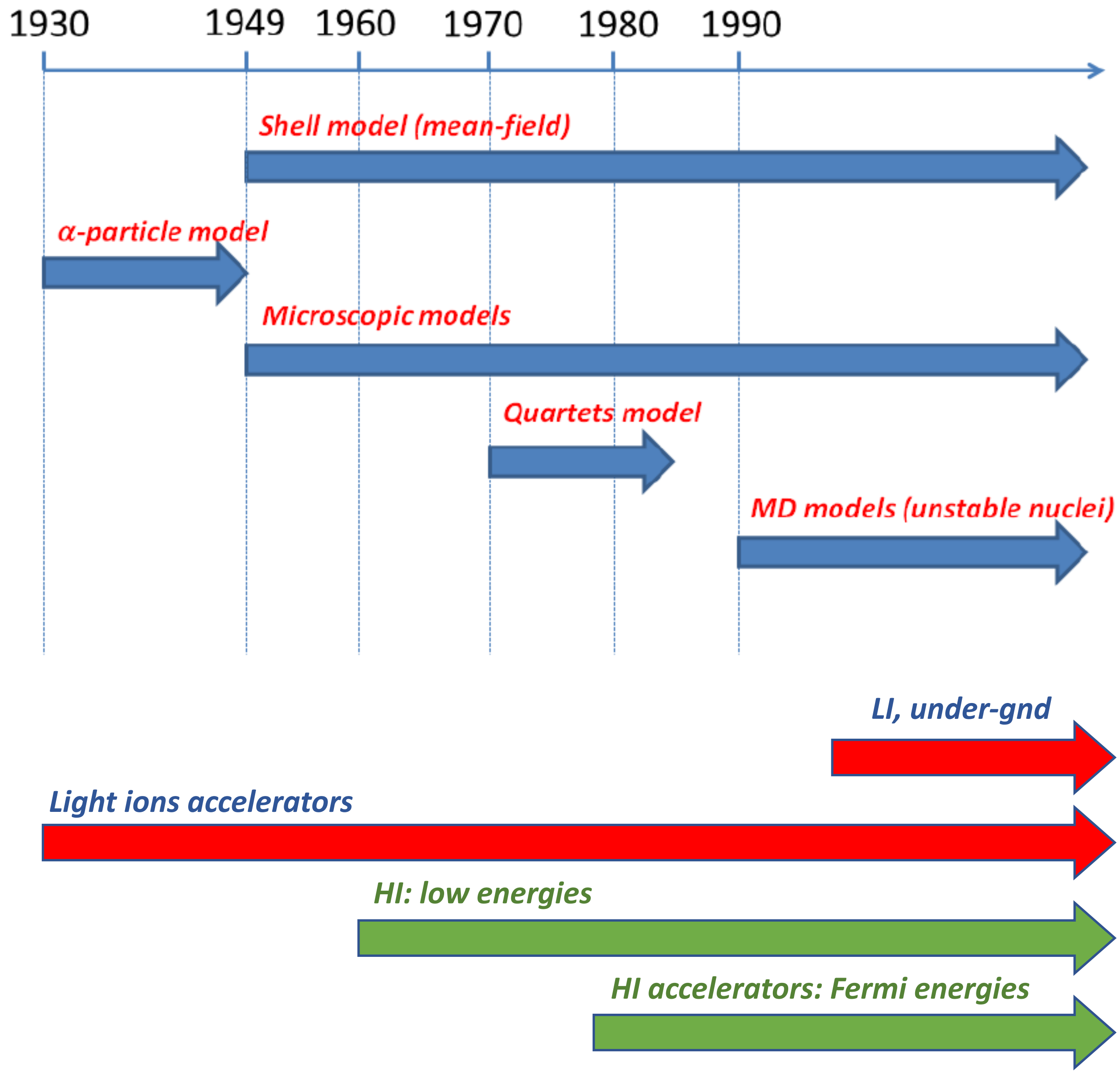
Complexity of nuclear force → deviation from the *sphericity*: axial deformation (collective behaviours), spatial re-organization of nucleons in bounded sub-units (*cluster model*).



Clustering and experimental devices



1961: Britt and Quinton discovered *incomplete fusion* → cluster structure of the projectile can play a role on the *reaction mechanism*!

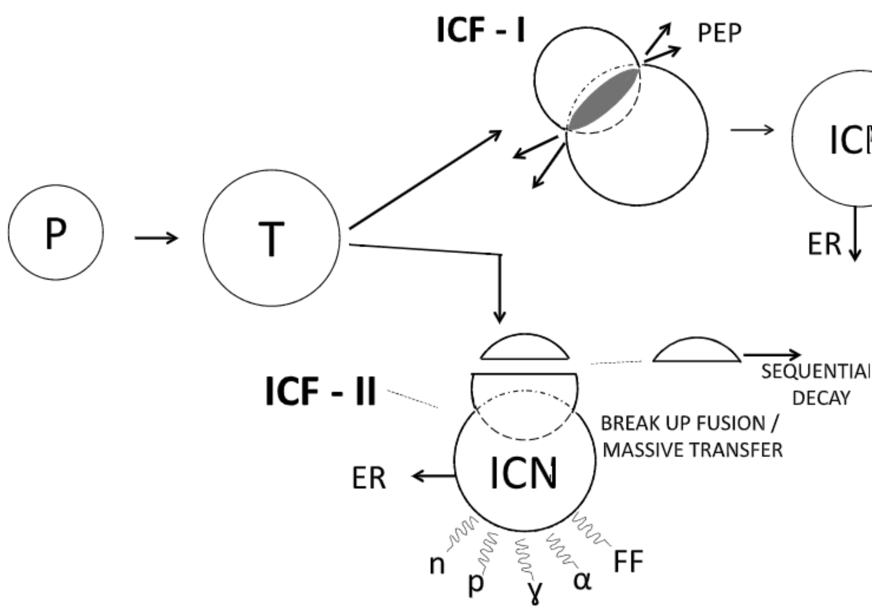
PHYSICAL REVIEW VOLUME 124, NUMBER 3 NOVEMBER 1, 1961

Alpha Particles and Protons Emitted in the Bombardment of Au^{197} and Bi^{209} by C^{12}, N^{14}, and O^{16} Projectiles*†

HAROLD C. BRITT‡ AND ARTHUR R. QUINTON
Yale University, New Haven, Connecticut

(Received June 12, 1961)

A more *modern picture* of incomplete fusion (*type I* and *type II*) reactions



Physics Reports 845 (2020) 1–58
Contents lists available at ScienceDirect
Physics Reports
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ELSEVIER

Incomplete fusion reactions using strongly and weakly bound projectiles

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See also V. Jha et al, Phys. Rep. 845 (2020)

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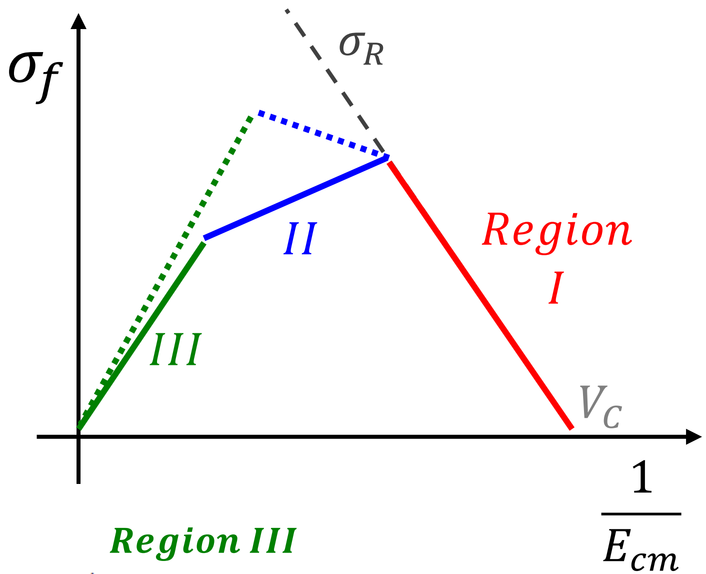
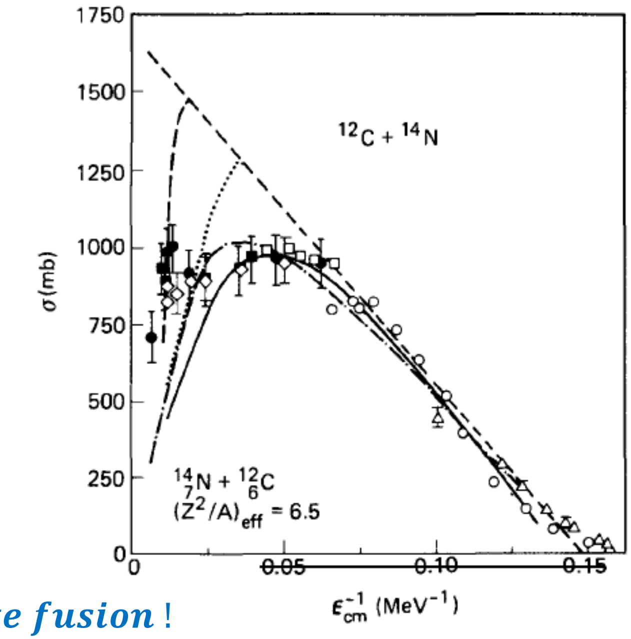
Fusion *above* barrier: dynamics vs structure effects

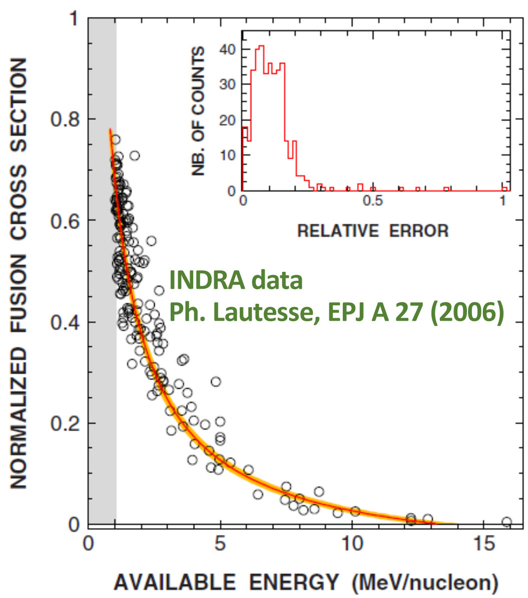


Le Sech & Ngo, *Physique Nucleaire*, Dunod



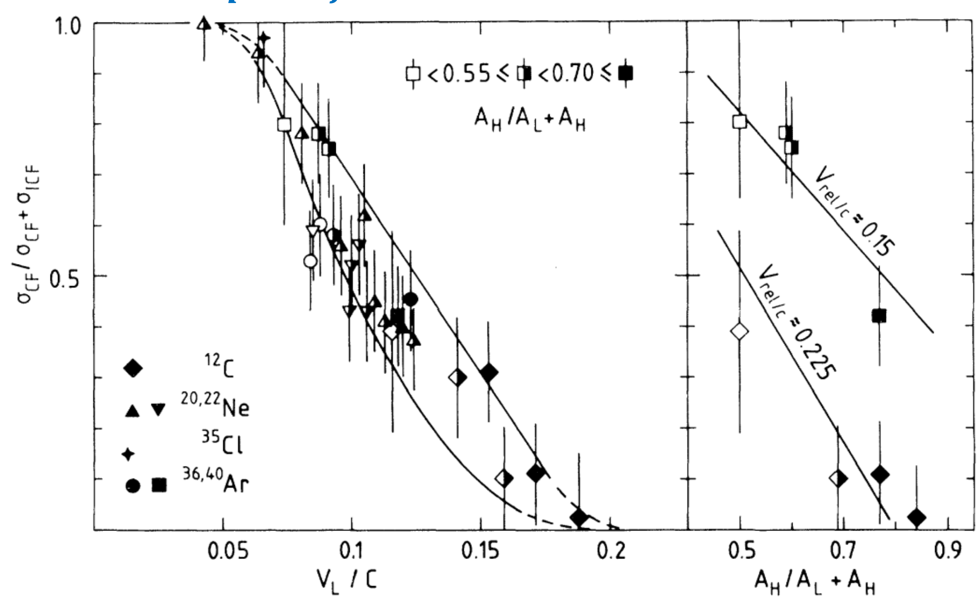
P. Frobrich, *Phys. Rep.* 116 (1984)

Region III



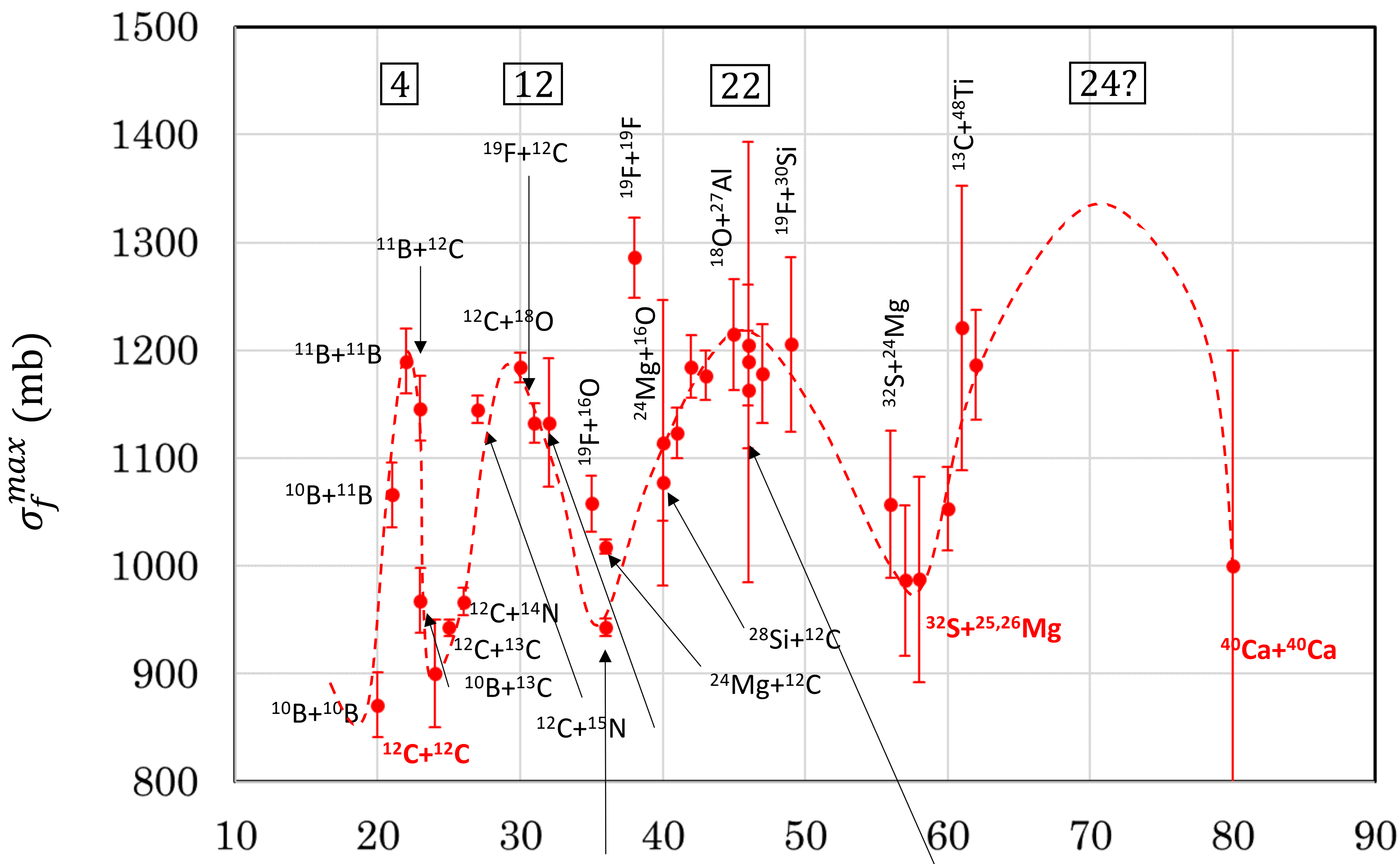
P. Eudes et al, *Phys. Rev.* 90 (2014)

Incomplete fusion !



W. Morgenstern et al, *Phys. Rev. Lett.* 52 (1984)

Maxima of complete fusion



- ***Secular* increase of σ_f^{max}**
- **Pseudoperiod?**

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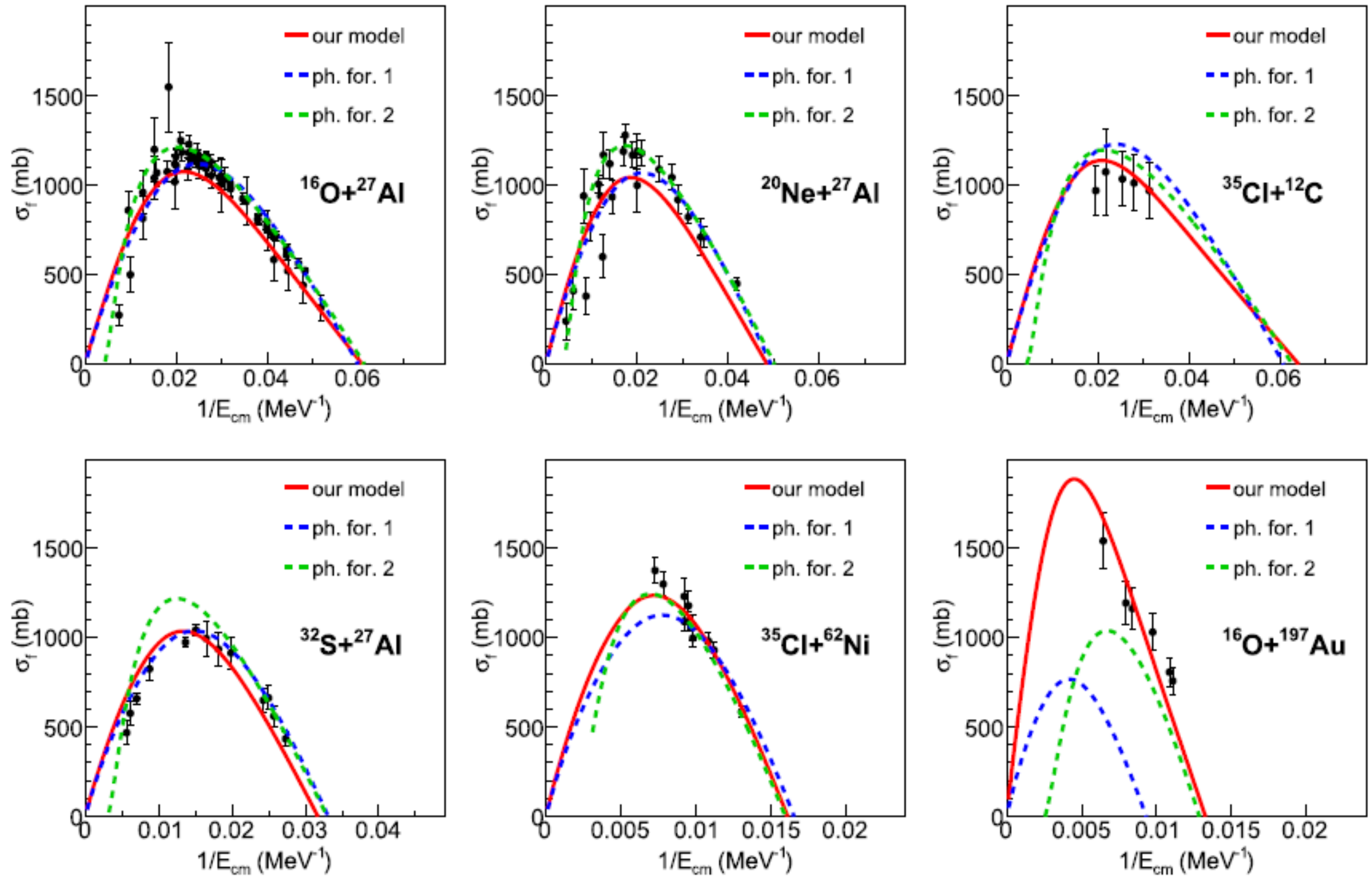
- Clustering effects in HI fusion → *tiny effects*!
- *Deviations* from *phenomenological model* predictions
- Modified SOD method to describe σ_f for a very broad dataset above U_C

$$\sigma_f = \frac{C_1}{E}$$

Mass asyı



Kailas and Gupta, Z. Phys. A 302 (1981)
Porto and Sambataro, Nuovo Cim. A 83 (1984)

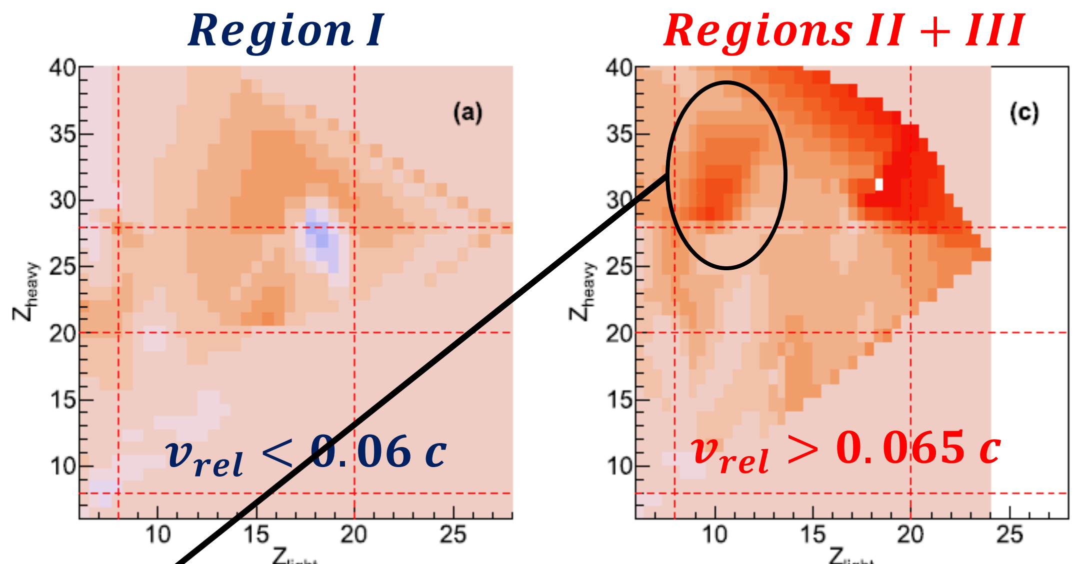
Clustering effects in complete fusion?

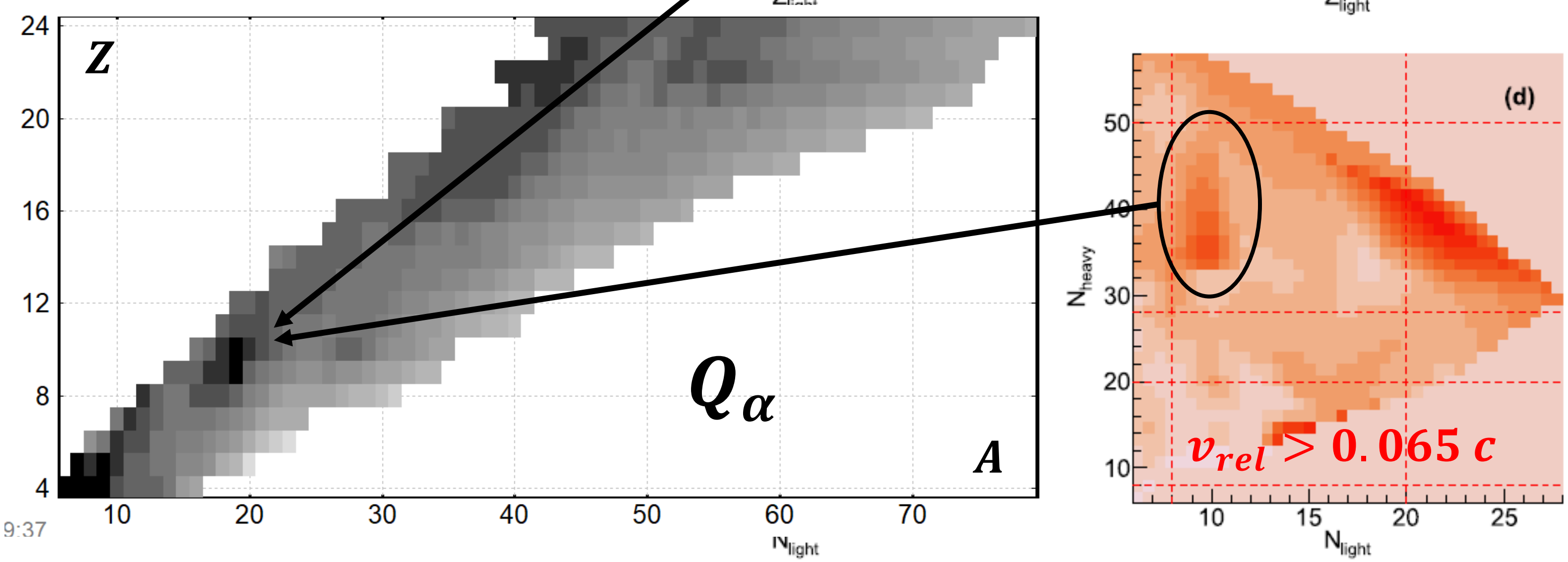
- *Deviation plots* → influence of *shell closures* at small $v_{rel} = \sqrt{2(E_{cm} - V_C)/\mu}$
- Clustering effects at large v_{rel}

Deviation plots for σ_{fus}:

Data > model

Data < model





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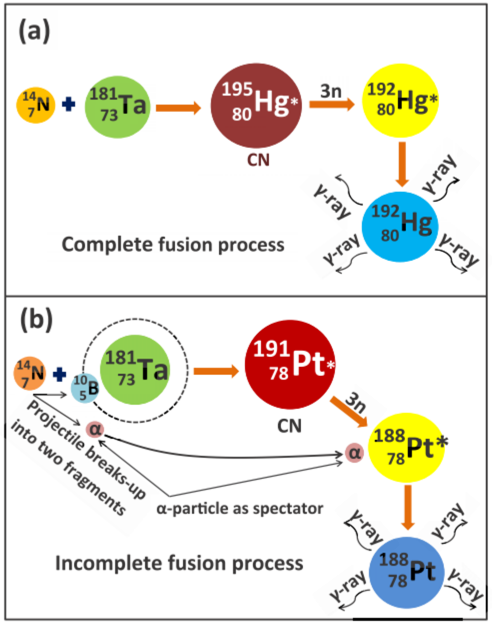
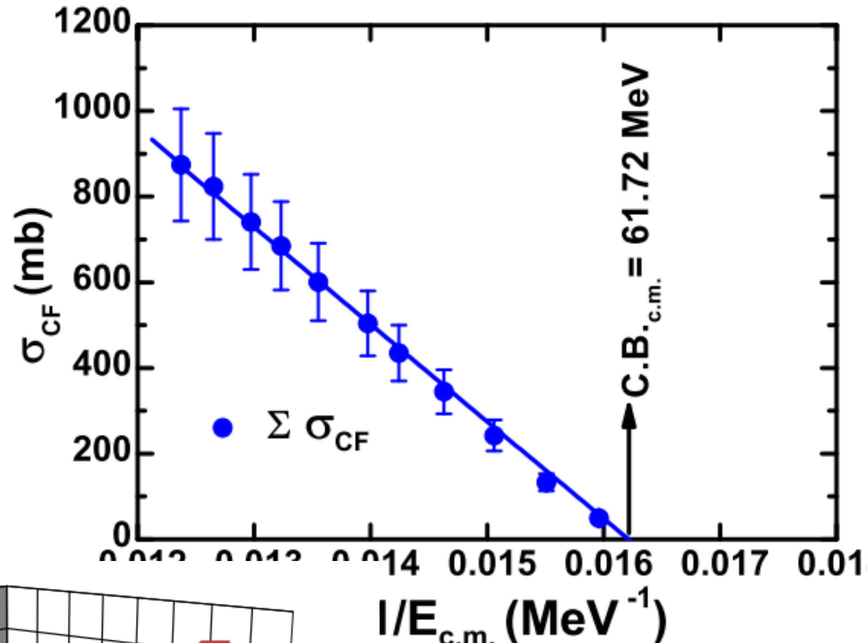
clustering effect → enhance ICF, suppress CF

Systematic studies **are fundamental in this type of physics**

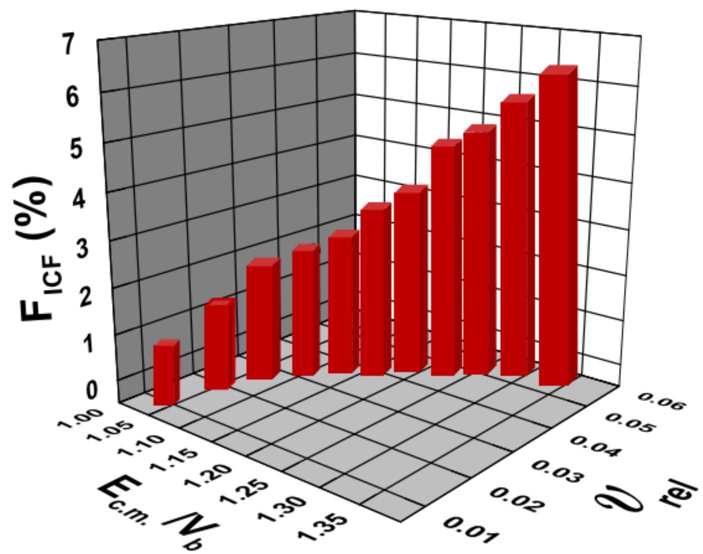
→ some of them *very recently* reported, mainly from Indian groups

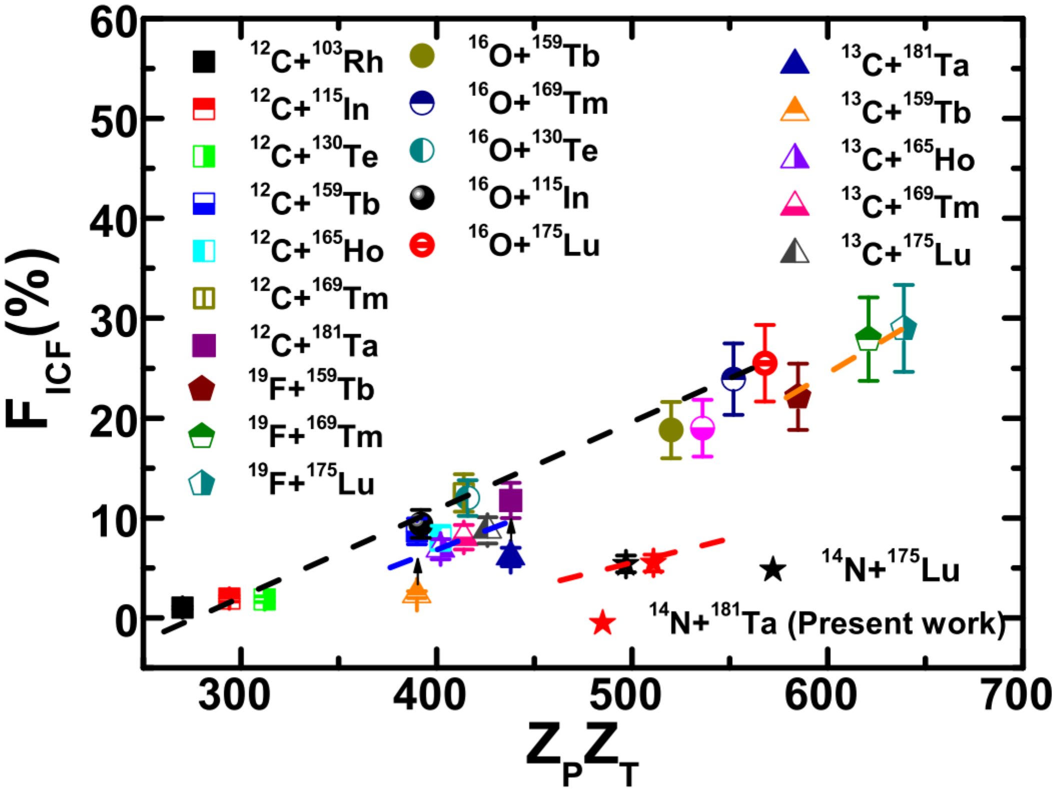


Stack method +offline gamma ER tagging to get excitation functions



ICF versus CF cross sections determined also by means of complete fusion model calculations (as PACE4)

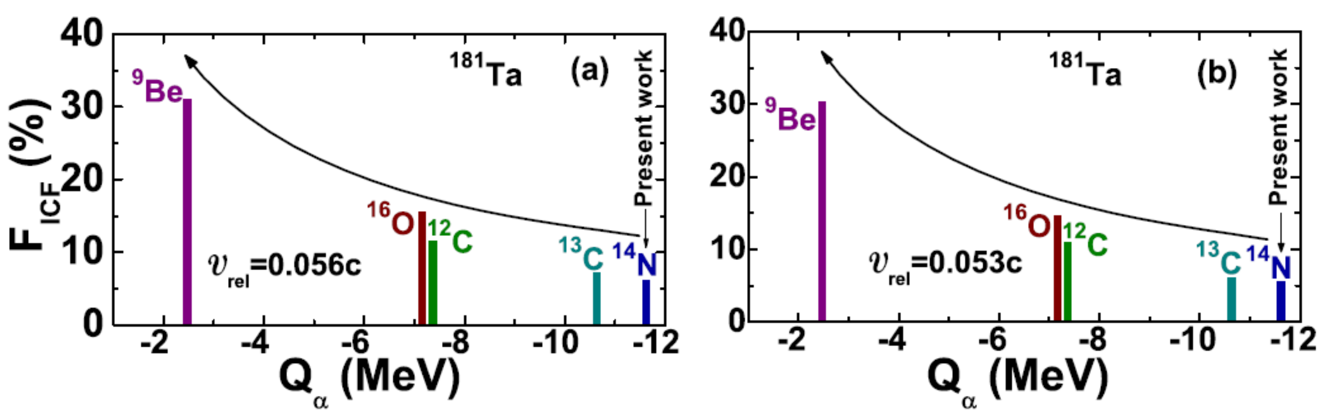


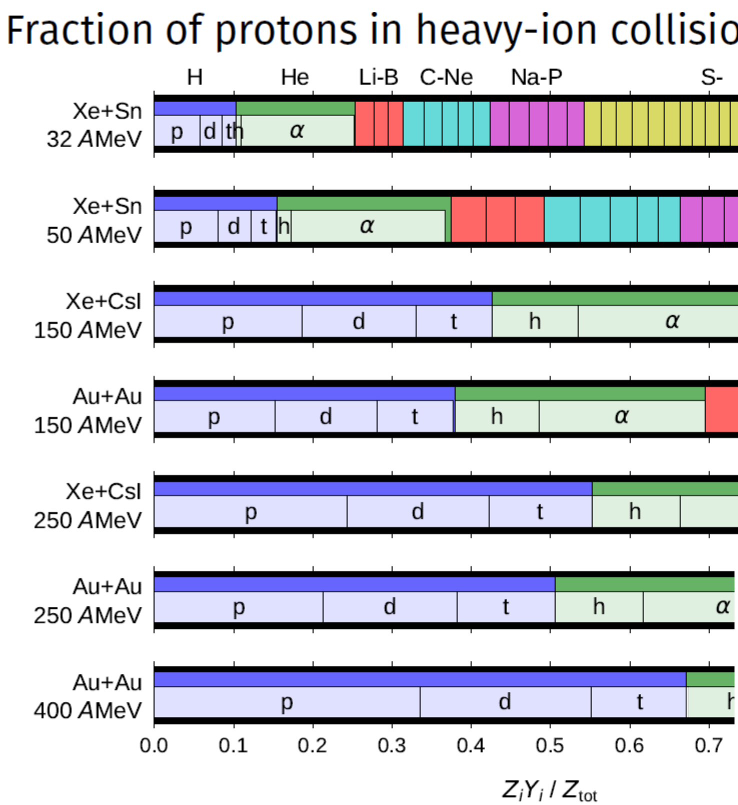


ICF fraction determined for very mass asymmetric systems, with well bound projectile of the *p* shell (C,O) and ^{19}F

- Strong dependence on Z_pZ_t → Coulomb break-up of the projectile in the trajectory of approach
- Evidend dependence on Q_α: more data are vital to unveil the full trend!

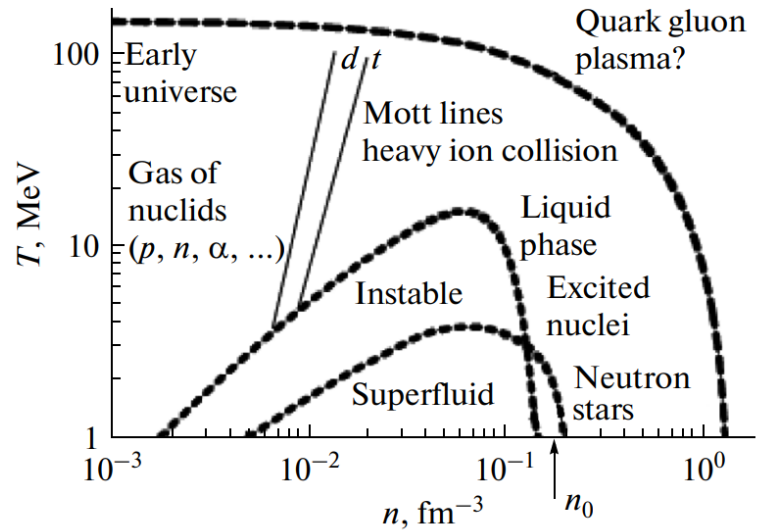
- Shell effect on ^{16}O are *overcame* by *Q-value effects* for large v_{rel}
- Important to look to the S_α factors!





A. Ono, ICNT 2017
A. Ono, IWM-EC 2021

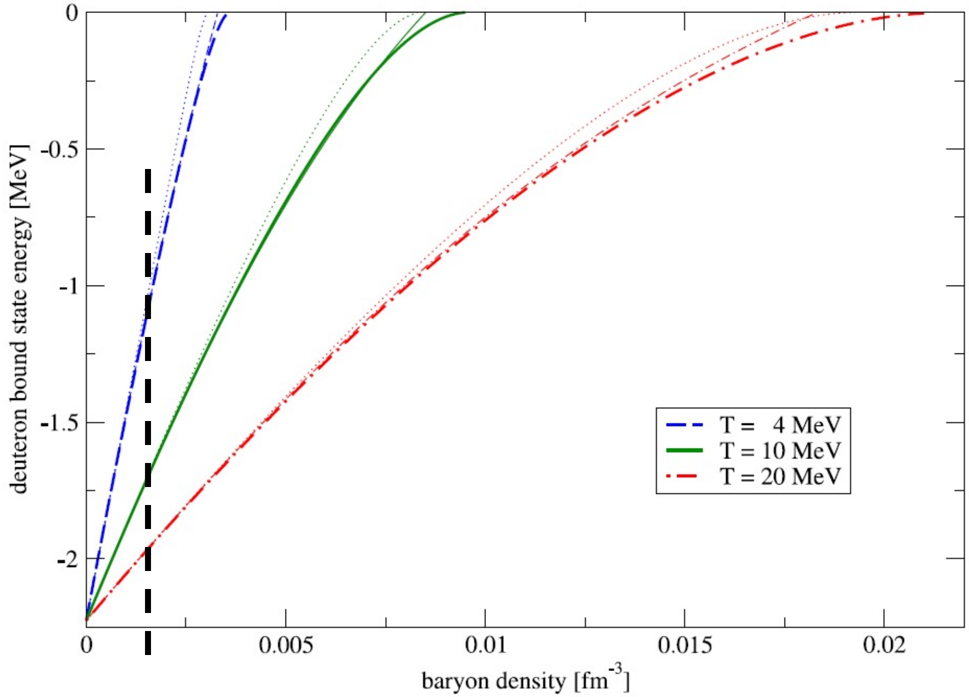
INDRA: Hudan et al., PI
FOPI: Reisdorf et al., N



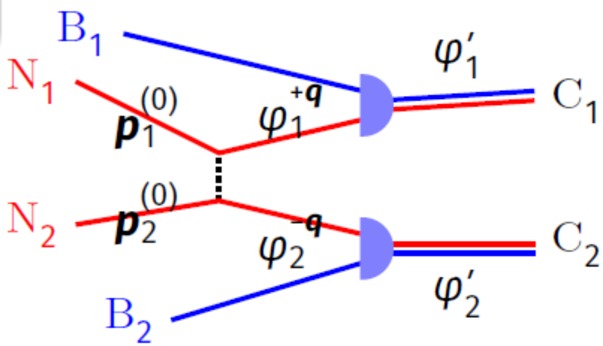
G. Ropke, Phys. Part. Nucl. 46 (2015)

ρ > Mott density → the cluster will dissolve in the medium

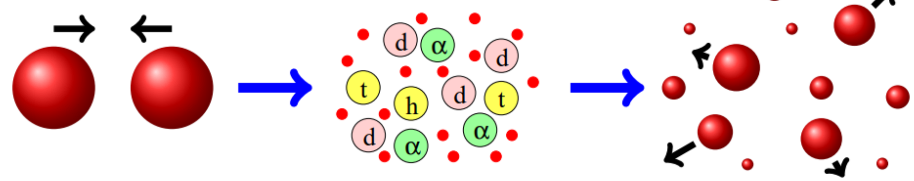
Density too large **→ the surrounding nucleons will** ***modify the binding*** **(or** ***destroy*****) the cluster**



Multi-fragmentation and clustering

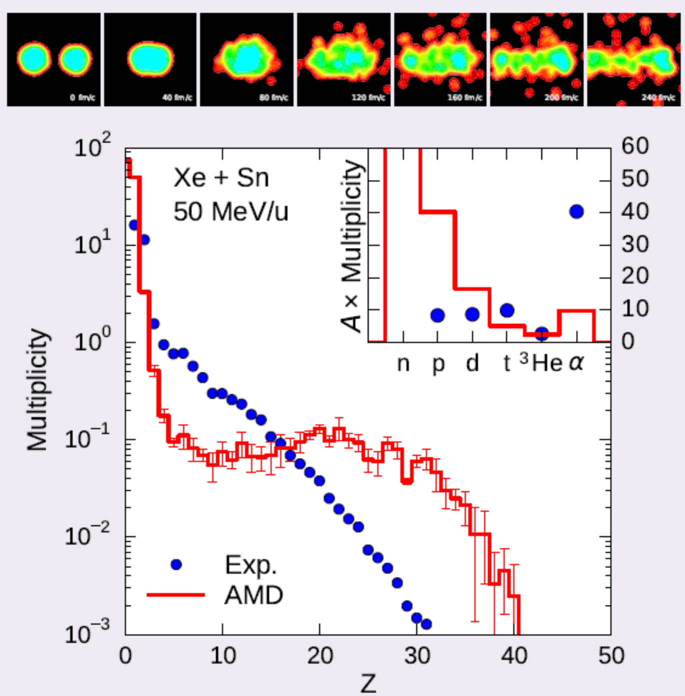


Collisions of two nuclei (e.g., Xe + Sn at 50 MeV/nucleon, $b \approx 0$)

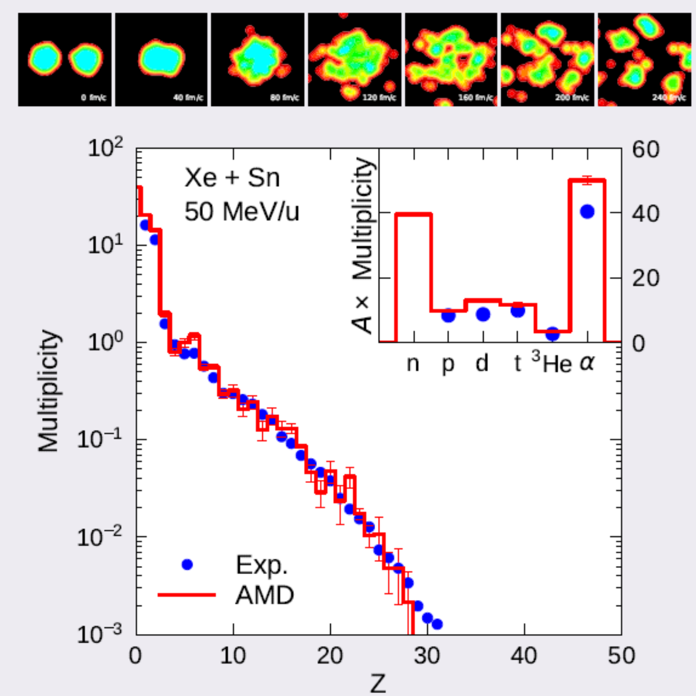


Light-cluster correlations

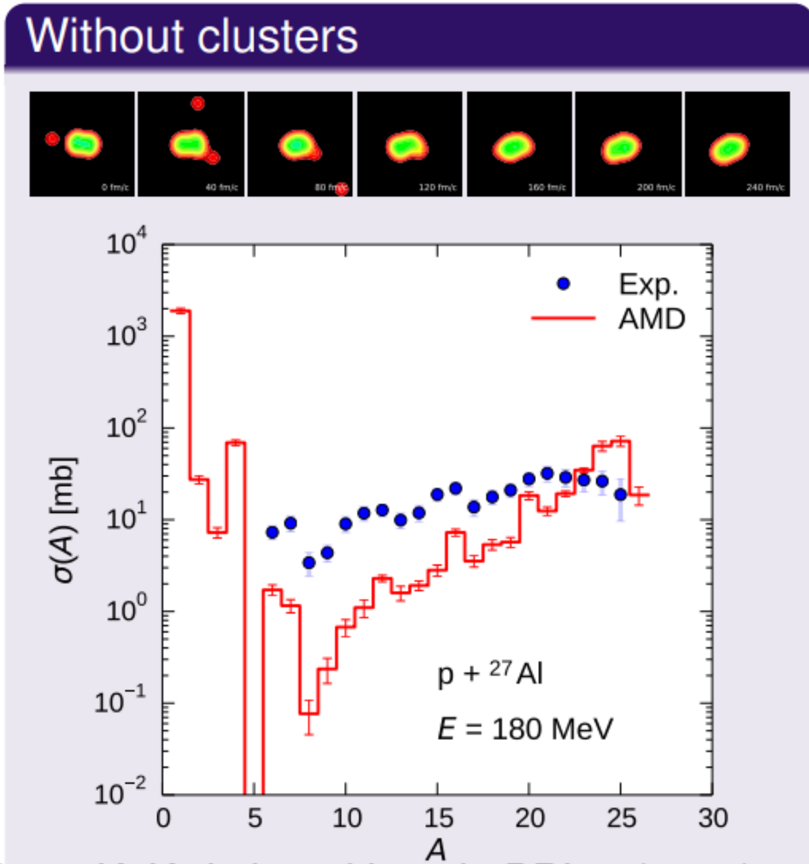
Without clusters

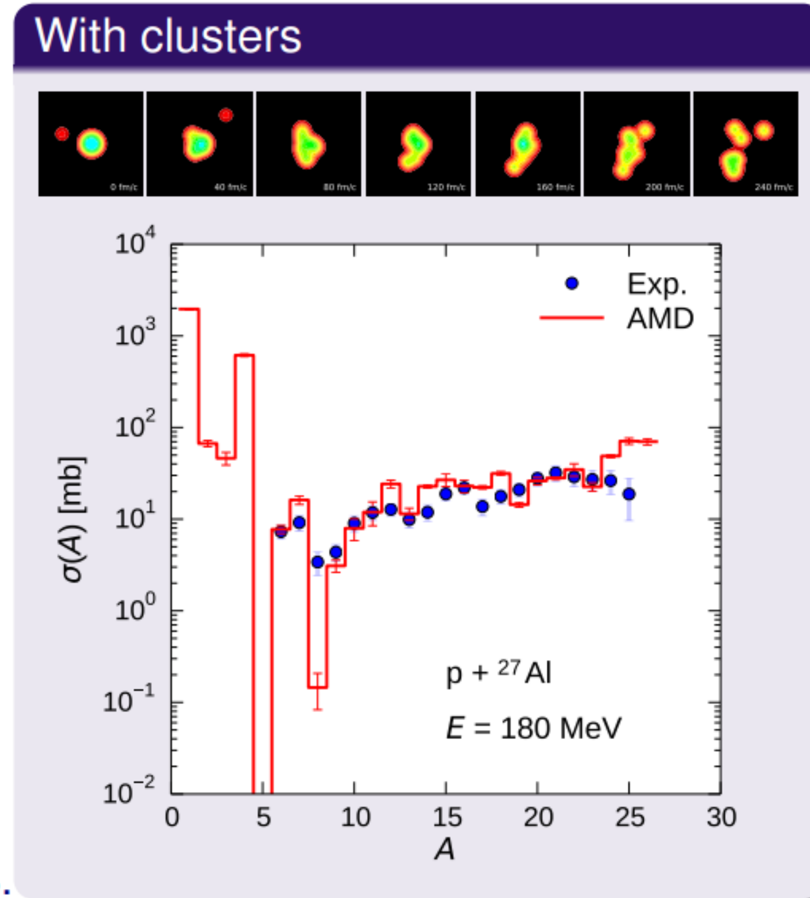


With clusters



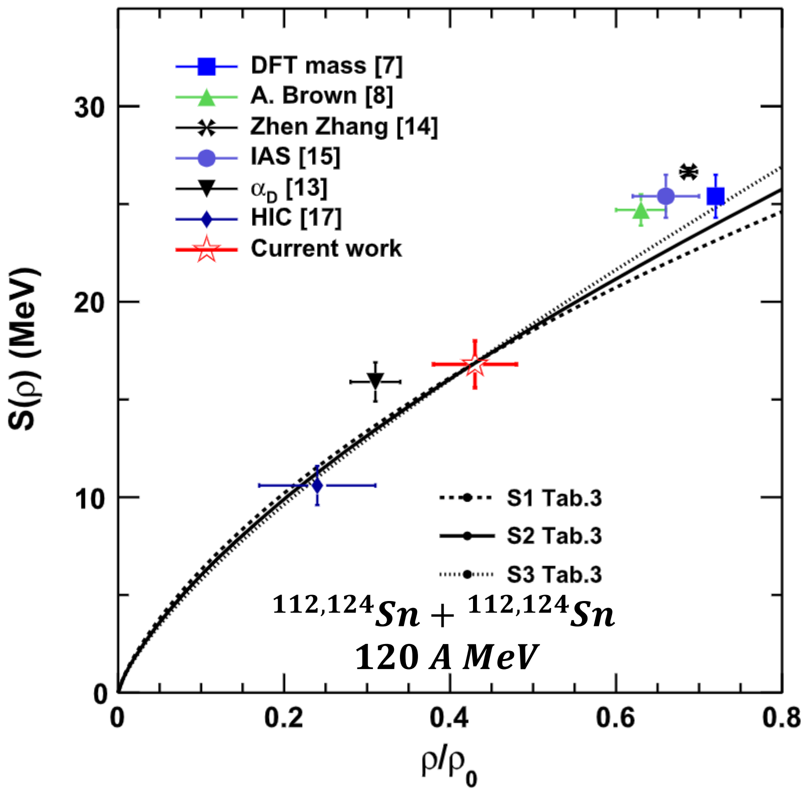
INDRA data: Hudan et al., PRC67 (2003) 064613.





Data: K. Kwiatkowski et al., PRL50(1983)1648.

- **Sizeable impact in *applied physics* (space, hadrotherapy etc) → absolute x-sect**
- **Disentangle the *in-medium* two-nucleon cross sections**



At *high* baryonic densities:

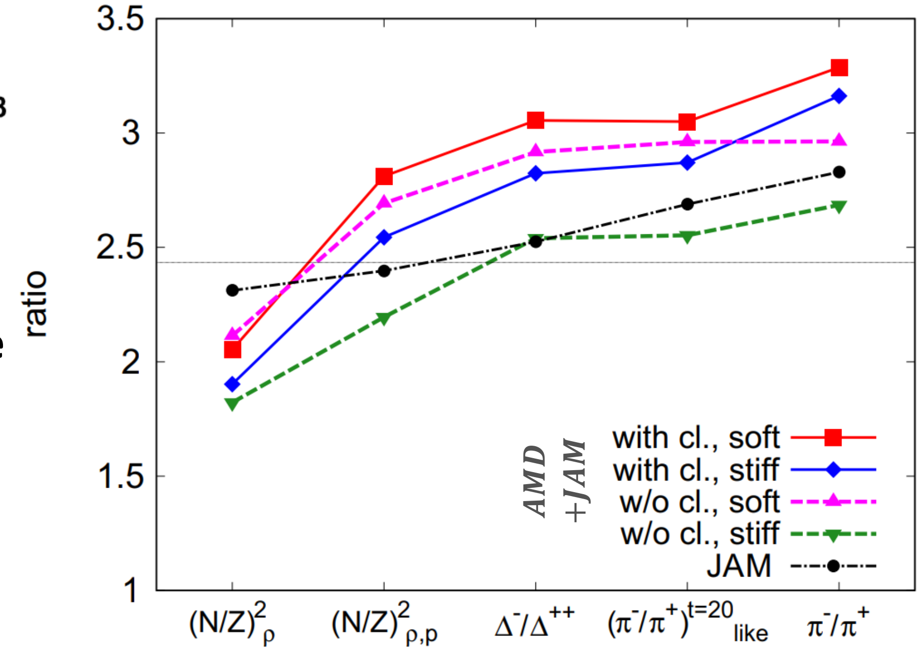
- AMD calculations (nucleon dynamics) + JAM (hadronic cascade model for sub-nuclear d.o.f.)
- Effect of n-clusterization on ratios sensitive to the symmetry energy

At *low* baryonic densities:

- Transport models → difficulties in reproducing the yields of light isotopes
- the coalescence invariant (CI) neutron and proton spectra → free nucleons + bound nucleons in $1 < A < 5$ isotopes

P. Morfouace et al, Phys. Lett. B 799 (2019)

$^{132}Sn + ^{124}Sn\ @\ 300\ A\ MeV$



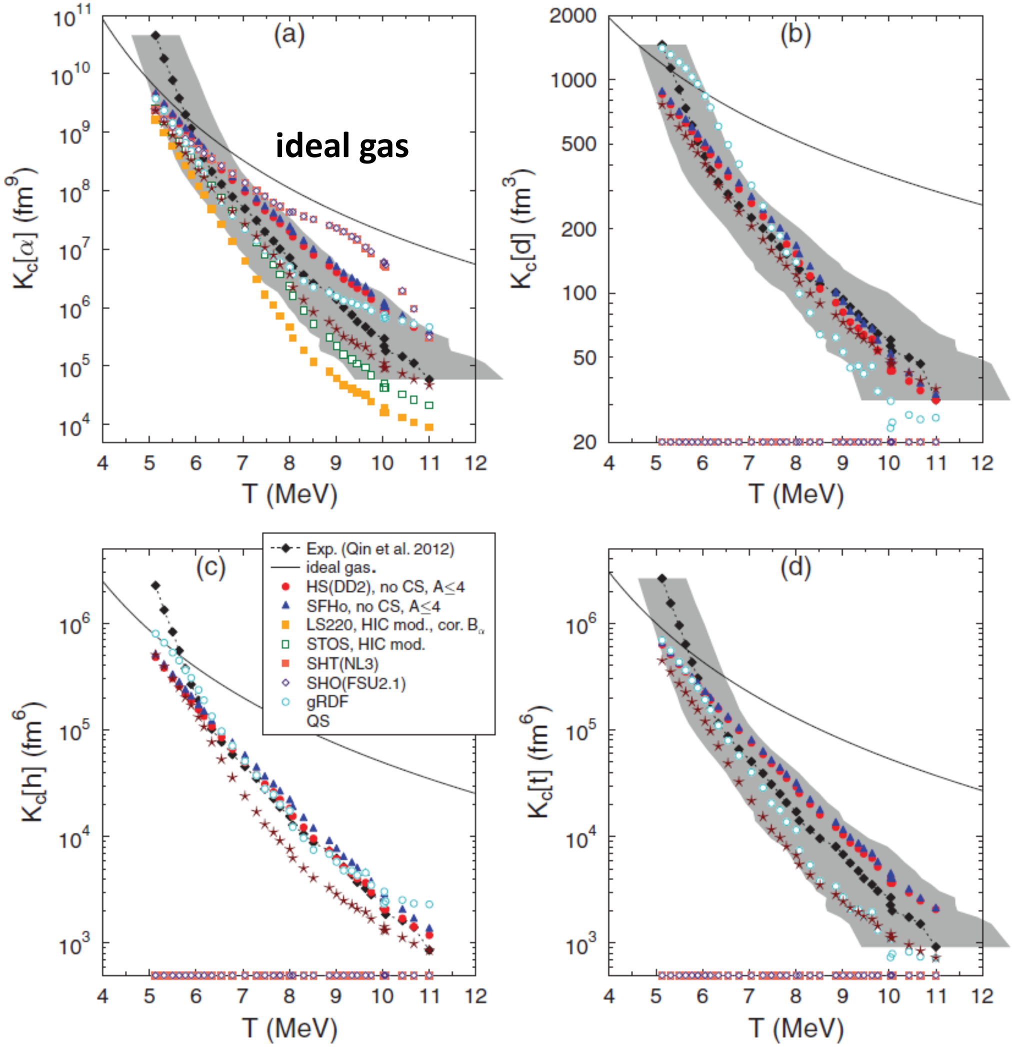
A (recent) chemical viewpoint of clustering production in HIC

$$Zp + Nn \leftrightarrow A(N,Z)$$

Equilibrium constant for a given cluster:

$$K_{eq} \equiv \frac{[A(N,Z)]}{[p]^Z[n]^N} = \frac{\rho(A,Z)}{\rho_p^Z \cdot \rho_n^N}$$

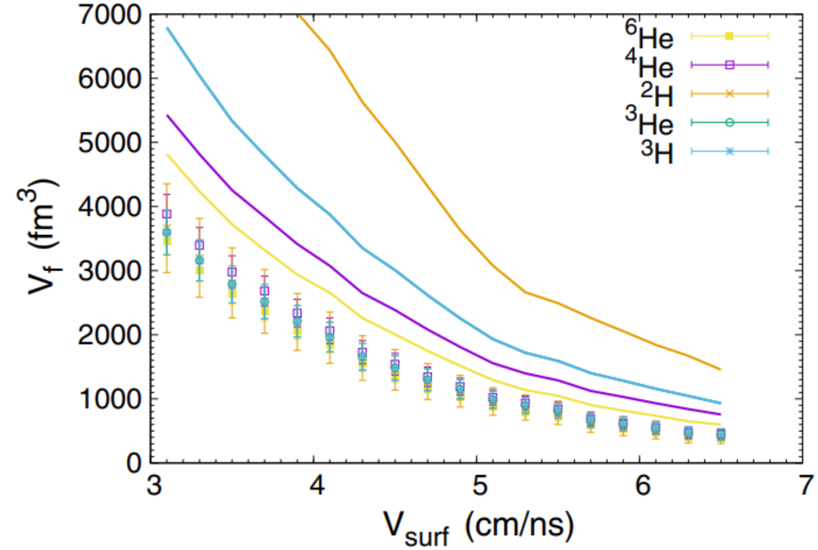
- **Type II SN → warm and dilute nuclear matter**
- **Formation of clusters in the envelope of the proto-neutron star**
- **Cluster influence on neutrino wind → nucleosynthesis in the r-process**
- **HIC → terrestrial laboratory to probe EoS involved in SN-II**

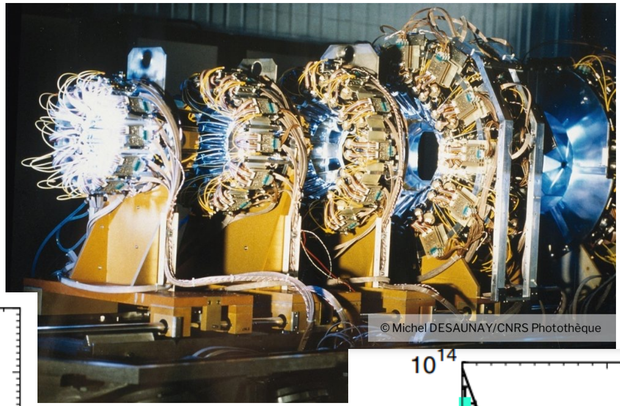


M. Hempel et al, PRC 94 (2015) 045805

$$Zp + Nn \leftrightarrow A(N,Z)$$

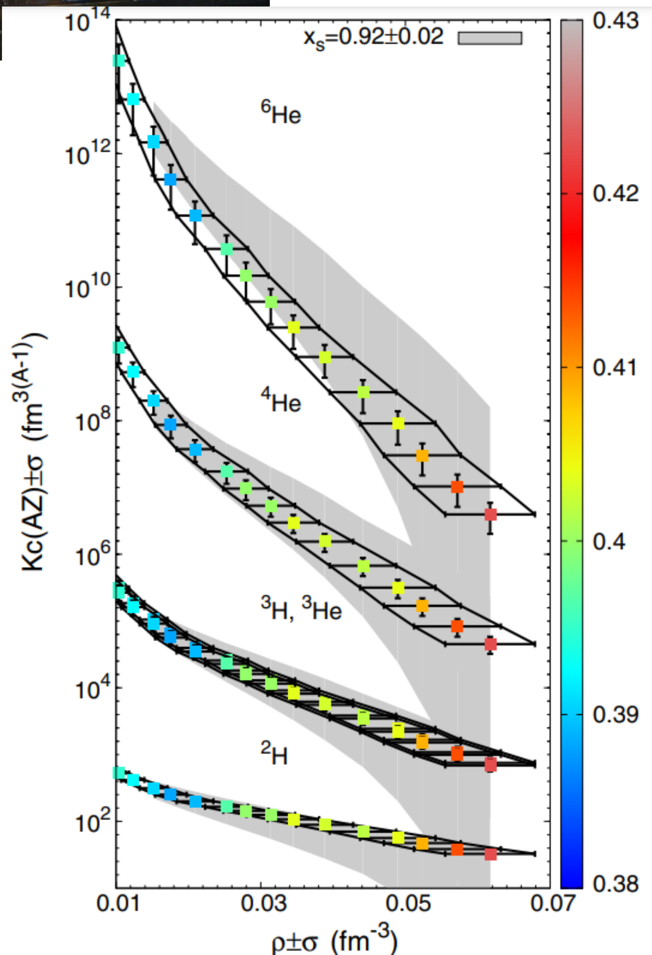
$$K_{eq} \equiv \frac{[A(N,Z)]}{[p]^Z[n]^N} = \frac{\rho(A,Z)}{\rho_p^Z \cdot \rho_n^N}$$



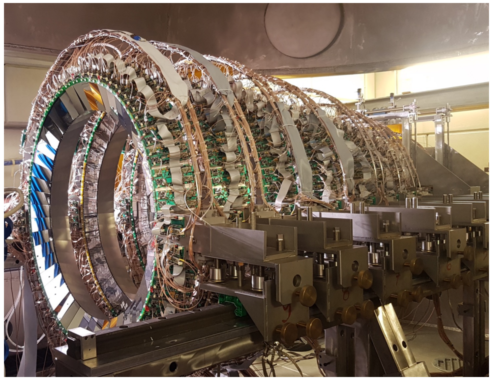


INDRA @ GANIL

Xe+Sn

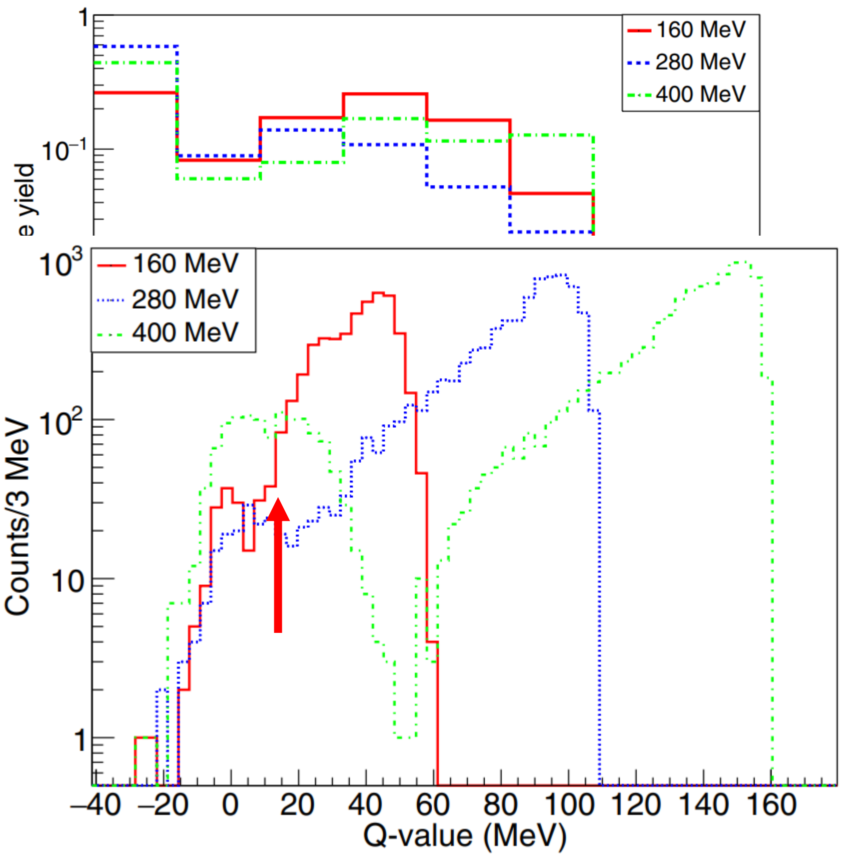


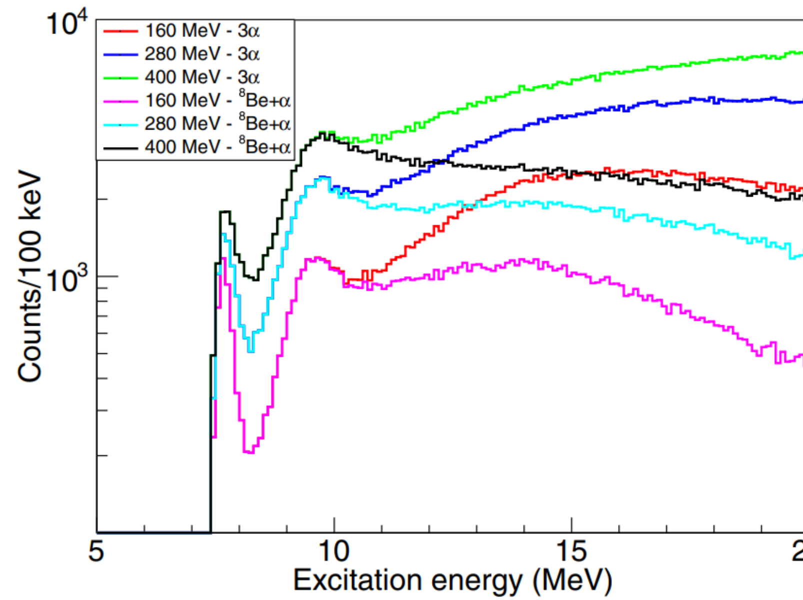
- **Deviation from the *ideal gas* prescription in the estimate of the source volume → data driven *corrections***
- ***Smaller* in-medium modifications**
- ***See also* the A. Rebillard-Soulié talk**



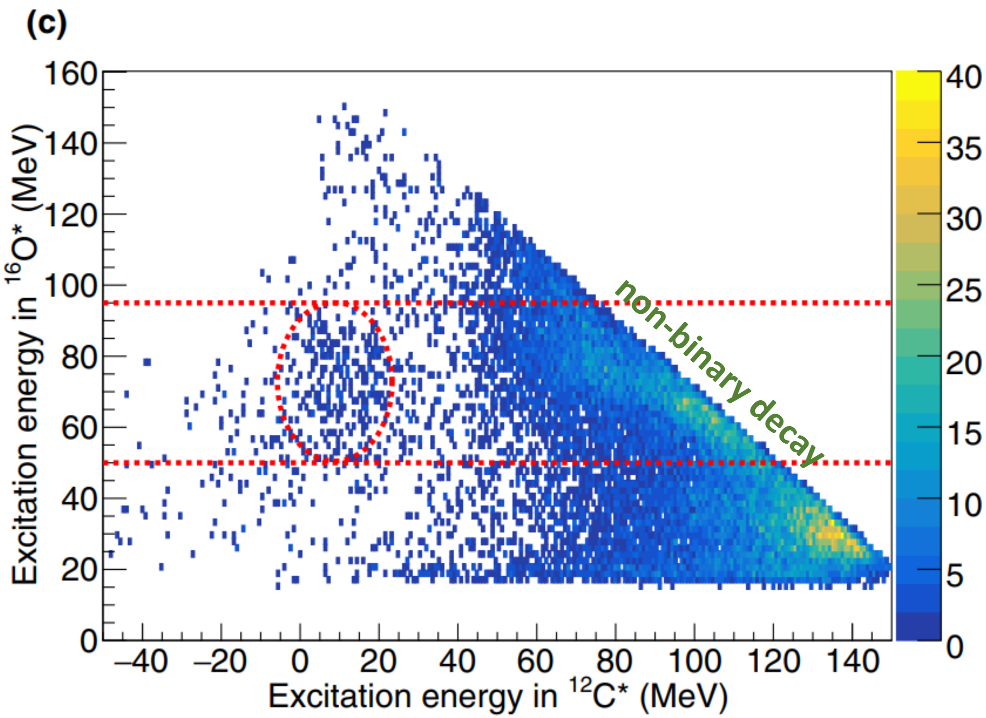
CHIMERA experiment: $^{16}O+^{12}C$ at 10 - 25 A MeV

- *many-alpha events* with a HI multi-detector
- Decay patterns of excited states in ^{28}Si
- Clustering decay (e.g. $^{12}C_{Hoyle}+^{16}O_{14.44MeV}$) vs *sequential* decay
- Binary kinematics reconstruction + invariant mass methods



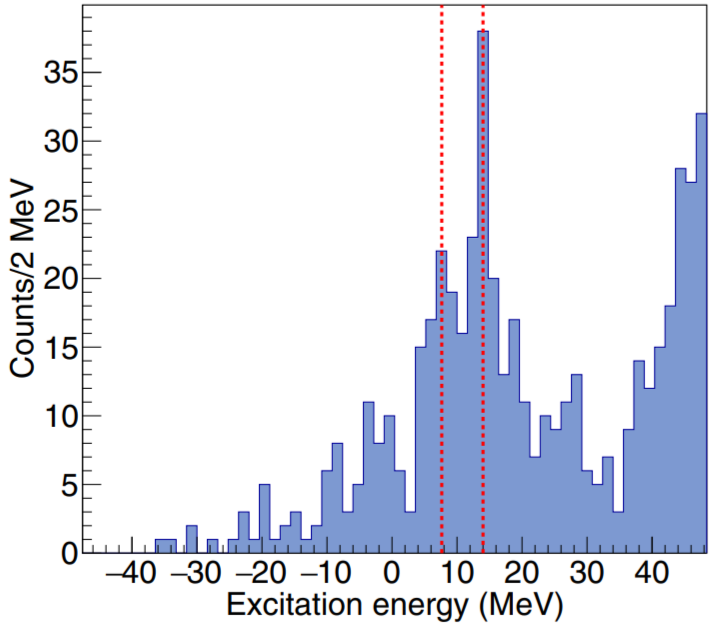


Sequential **mechanism preferred →**
no (or vanishingly small) 4α yield coming from $^{16}O^*(0^+_6)$ decay



Decay of ^{28}Si into an Oxygen-16 and a Carbon-12

→ *excitation energy map* of such binary-like disassembly



- **Class of states (or a zone) in the ^{16}O* excitation energy spectrum that is *accompanied* by ^{12}C in the GS, the Hoyle state or in the 4^+ state at 14 MeV**
- **To be investigated by using *higher angular* and *energy* resolution arrays!**

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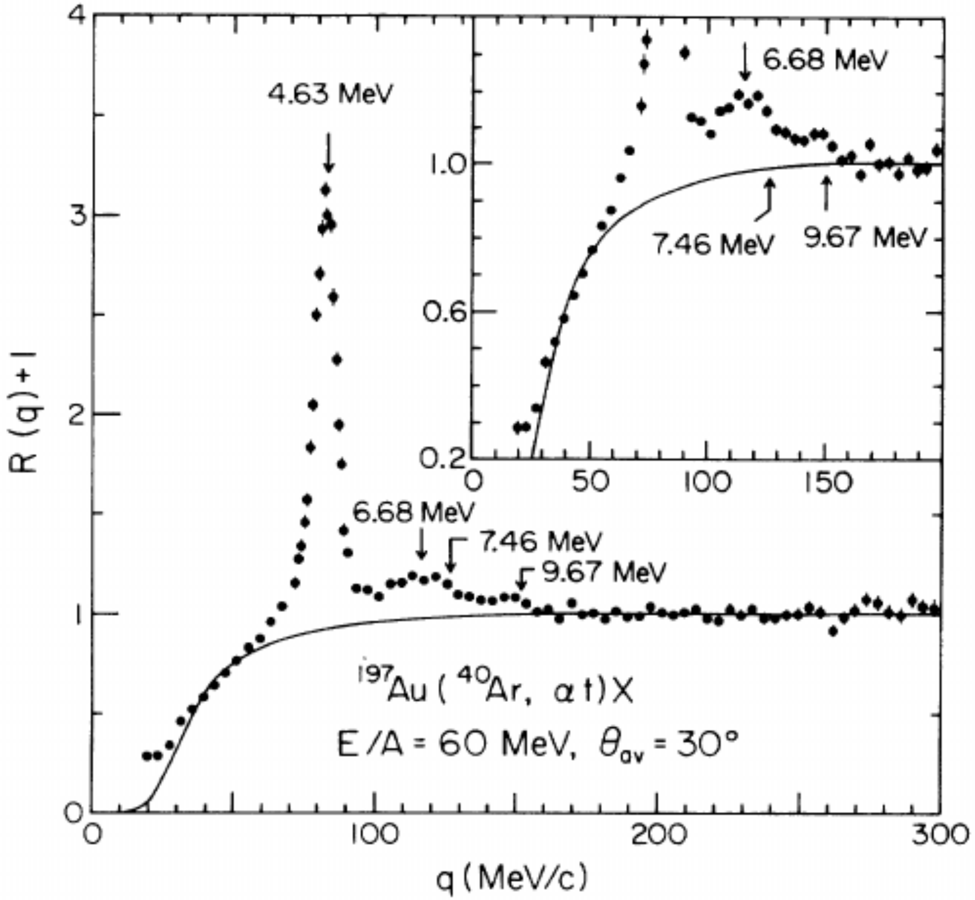
- *heavy nuclear systems* → complex collision dynamics
- multi-particle correlations → *Correlation functions* R(q): resonant states produced *in-medium*.

$$R(q)+1=\frac{\sum Y_{1,2}(\vec{p}_1,\vec{p}_2)}{\sum Y_1(\vec{p}_1)Y_2(\vec{p}_2)}$$

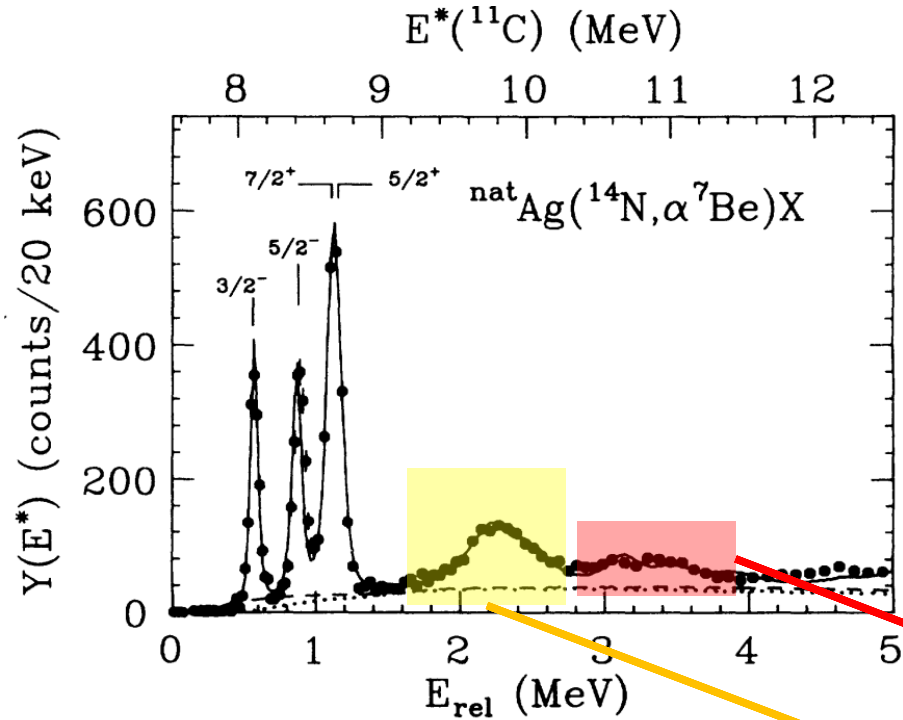


2-particle *correlation function* $R(q)$ obtained in ^{40}Ar+^{197}Au at 60 A MeV

- structure of ^{7}Li (t-α correlations)
- Spectroscopy of known excited states
- Analog works in H-E physics: properties of the medium from resonance analysis

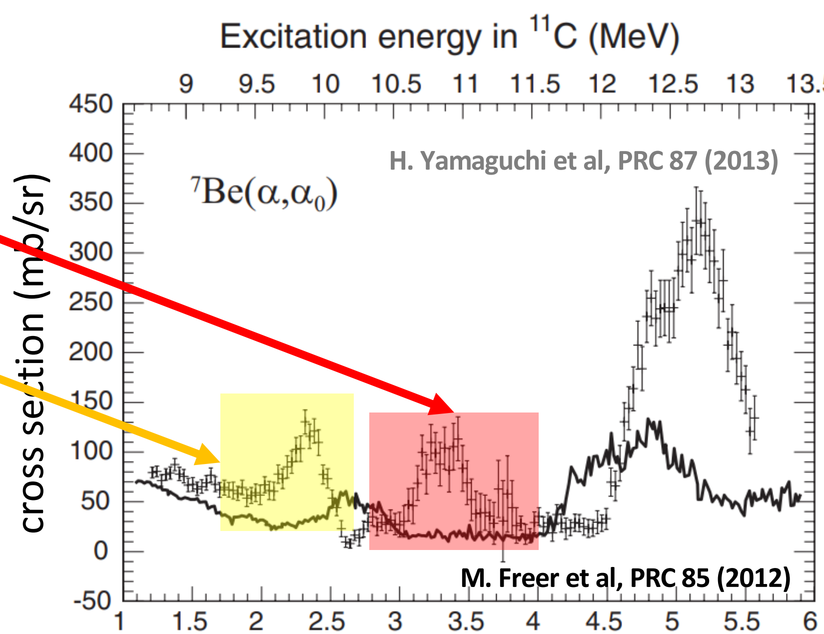
J. Pochodzalla et al, Phys. Rev. C 35 (1987) 1695

Study of the *coincidence yields* in binary decay channels involving α particle emission → *clustering* studies



^{7}Be + α decay of ^{11}C «ante litteram» :

- **unbound states in ^{11}C well before the RIBs!**



Help to *discriminate* between two TTIK RES experiments with very different excitation energy scales!

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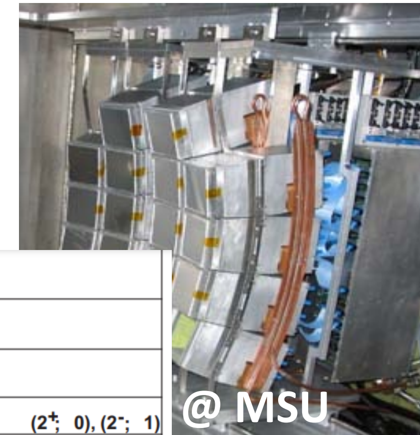
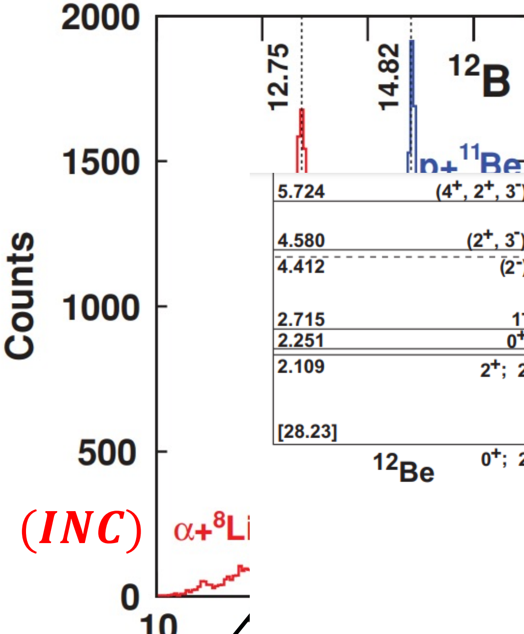
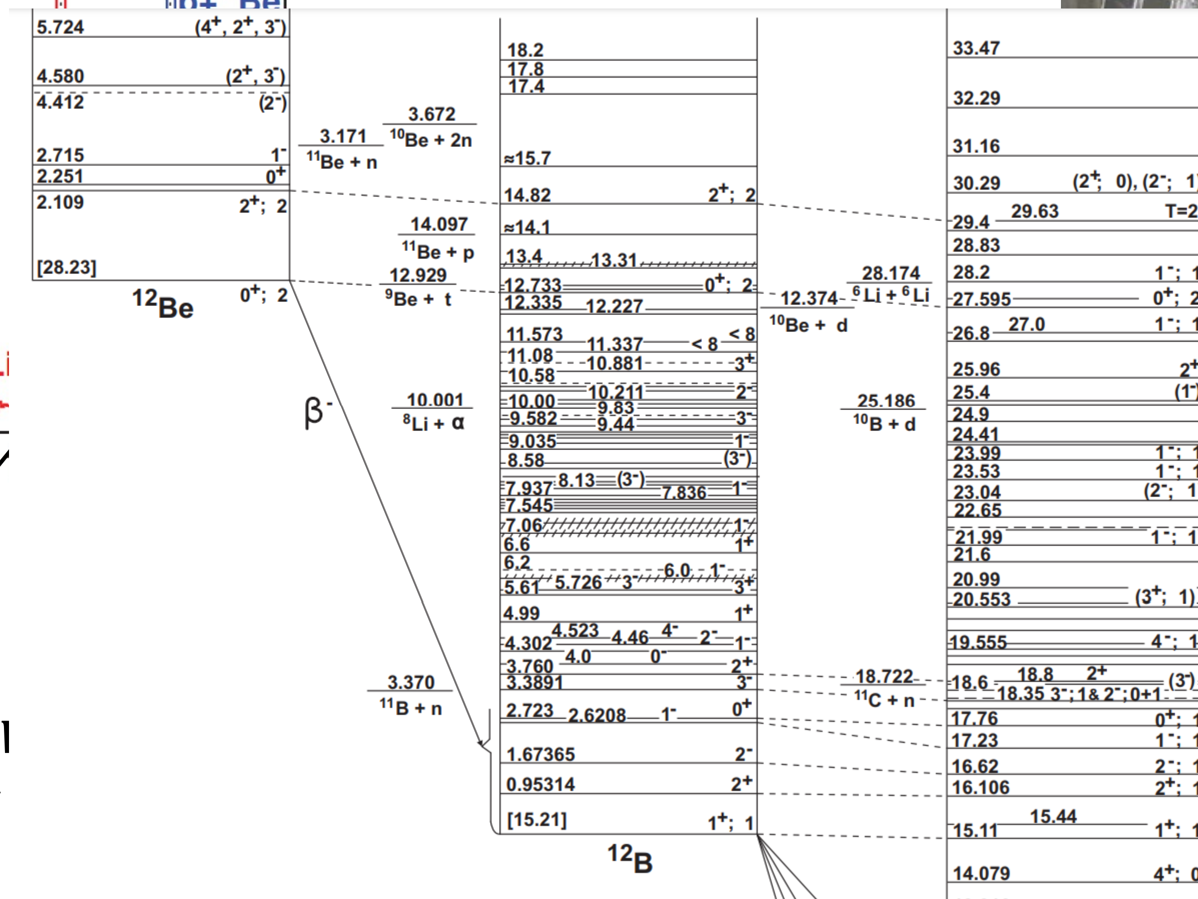
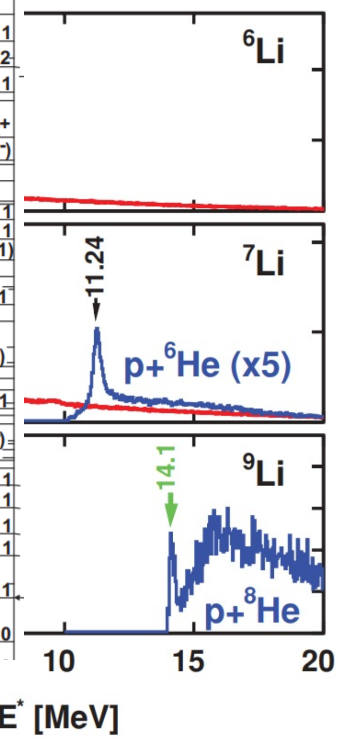
Study of the *coincidence yields* in binary decay channels involving α particle emission → *clustering* studies

$$^{12}Be + ^{12}C, CH_2$$









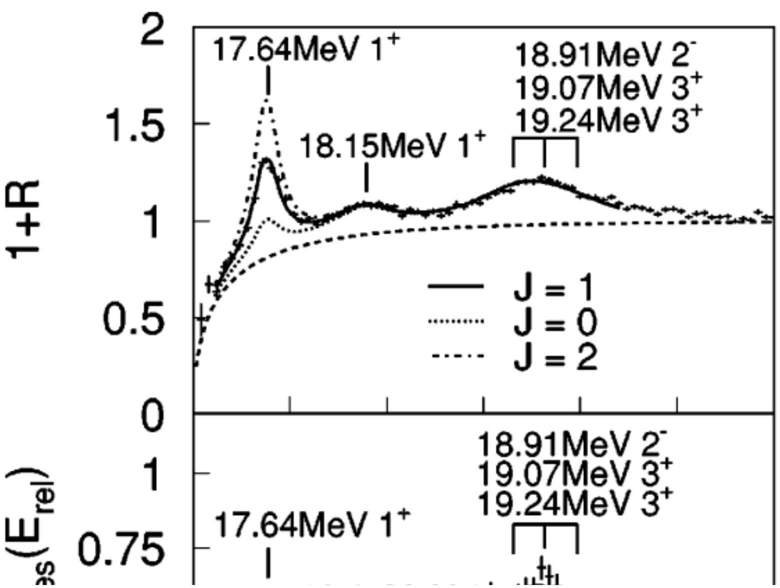
$T = 2$

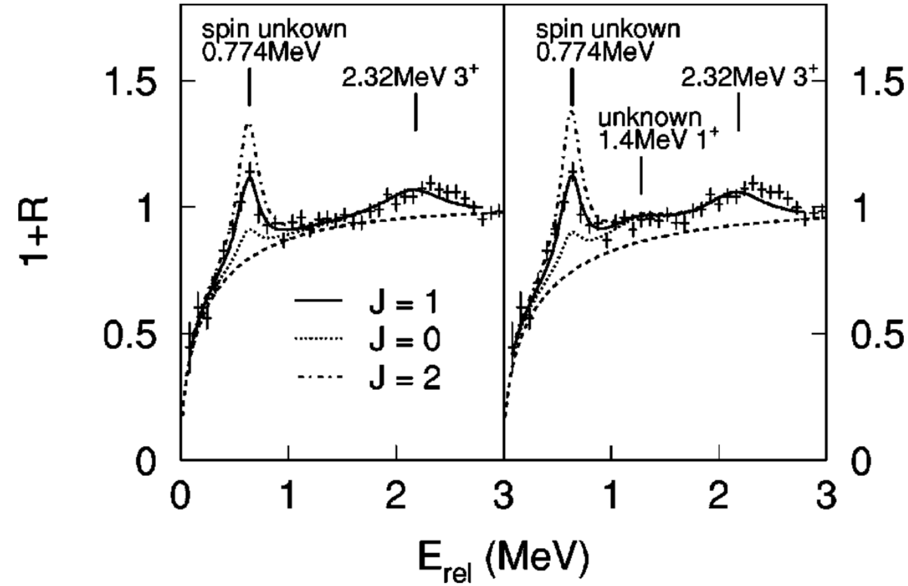
$\Gamma < 40\ keV$

$\Gamma \approx 1\ keV$

$$Y_{corr}(E_{rel}) = \frac{N}{\pi} e^{-E/T} \sum_i (2J_i + 1) \left[\frac{\Gamma_i / 2}{(E - E_i)^2 + \Gamma_i^2 / 4} \right];$$

$^{8}Be \rightarrow p + {}^{7}Li$

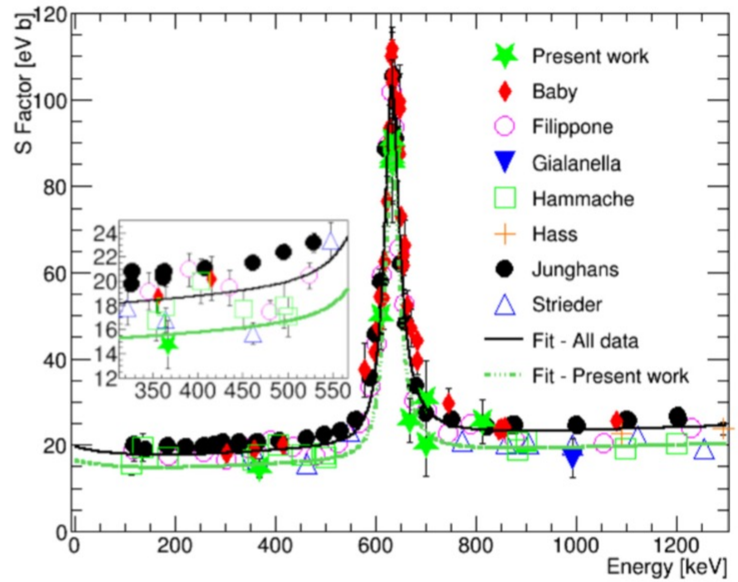




$^{7}Be(p,\gamma)^{8}B$

^{8}B Levels

E(level)	J^{π}	$T_{1/2}$	Comments
0.0			
767.7 *29*		35.7 keV *6*	Γ_{γ}=2.52×10^{-2} eV *11*; Γ_p=35.7 keV *6* E(level): from weighted average of E=769.5 keV *100* ^{7}Be(p,γ) (1983Fi13 *30* ^{7}Be(p,γ) (2003Ju04). Γ_{γ}: average of 24.8 meV 29 (2003Ba51), 25.3 meV 12 (2003Ju04) and 2 42 (1983Fi13). Γ_p: from (2003Ju04).
2.32×10^{3} *2*	3^{+}		Γ_{γ}=0.10 eV *5*; Γ_p≈350 keV Γ_{γ}: from reanalysis of (2003Ju04).
≈3.5×10^{3}	2^{-}		



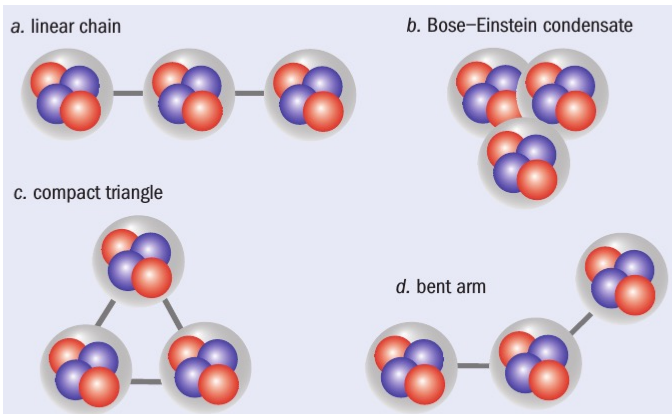
R. Buompane et al, Phys. Lett. B 824 (2022)

W.P. Tan et al. Phys. Rev. C 69 (2004) 061304

A very special case: the Hoyle state in ^{12}C

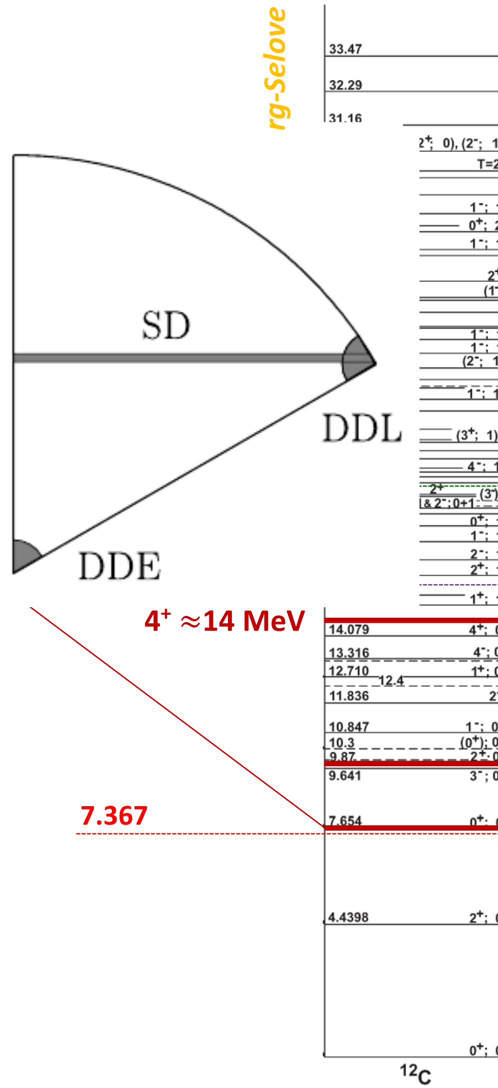
Cluster state **of ^{12}C located at 7.654 MeV (0^+) → a pronounced cluster nature**
→ quite unusual and not well understood properties
→ challenging open question in nuclear physics

E_x = 7.654 MeV
$J^\pi = 0^+$



D. Jenkins and O. Kirsebom, The Secret of Life, Physics World Feb. 2013

(a) linear chain: α-cluster model
(b) Bose-Einstein condensate: microscopic models (GCM, RGM)
(c) compact triangle: ACM
(d) bent-arm: microscopic models (Faddev three-body formalism)



^{11}C + n

^{11}B + p

4+ ≈14 MeV

M. Freer et al., Phys. Rev. C 83, 034314 (2011)

2^+ 9.75 MeV

7.367

^{8}Be + α

Hoyle band

4^+
2^+
0^+

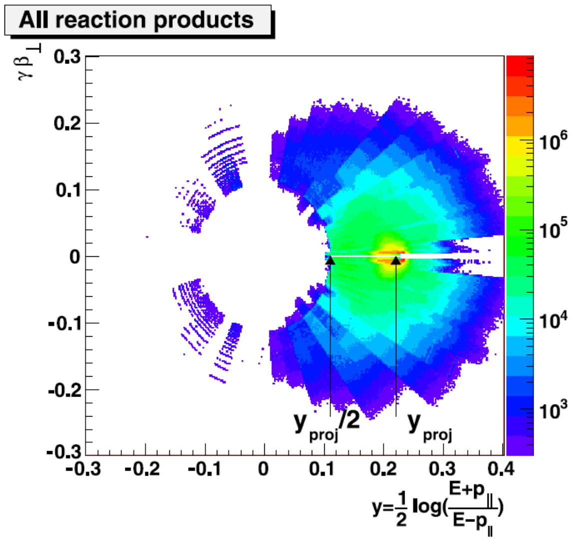
$$E_x = \frac{\hbar^2}{2I} J(J+1)$$

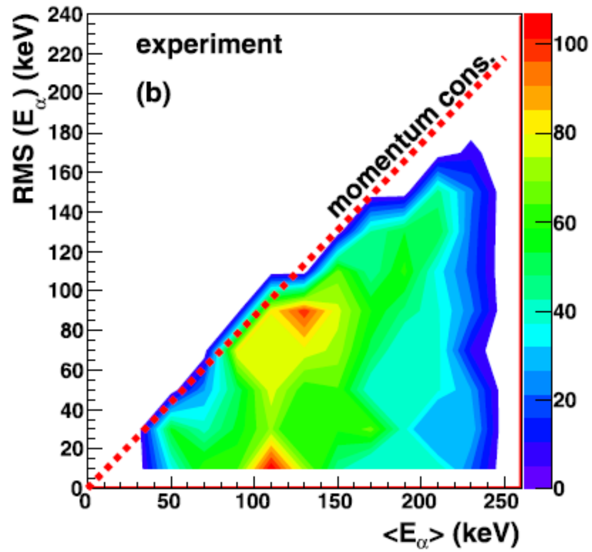
M. Itoh et al., Phys. Rev. C **84**, 054308 (2011).
M. Freer et al., Phys. Rev. C **80**, 041303 (2009).
W. R. Zimmerman, N. E. Destefano, M. Freer, M. Gai, and F. D. Smith, Phys. Rev. C **84**, 027304 (2011).

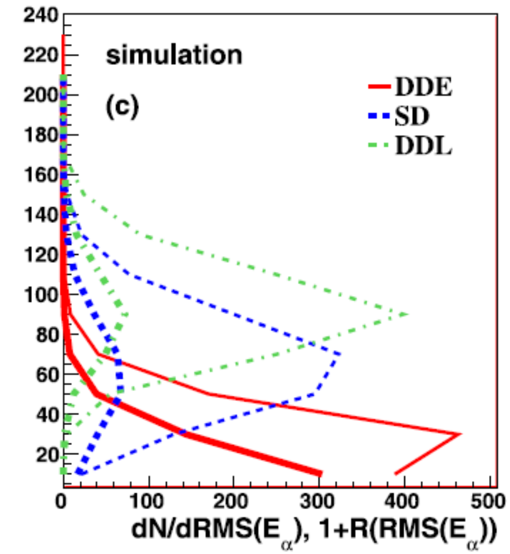
M. Freer et al, Rev. Mod. Phys. 90 (2018) 035004

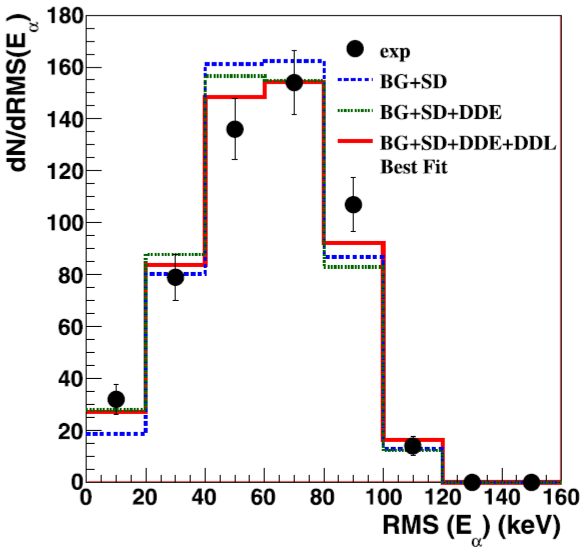
CHIMERA experiment: $^{40}Ca+^{12}C$ at 25 A MeV

- QP decay emission → peripheral collisions





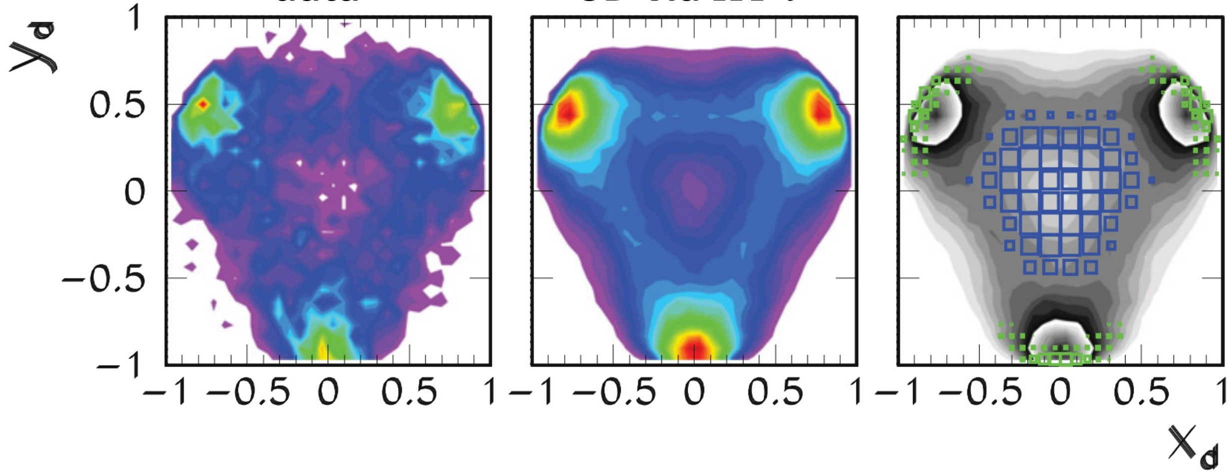




$7.5 \pm 4\%\ DDE$!

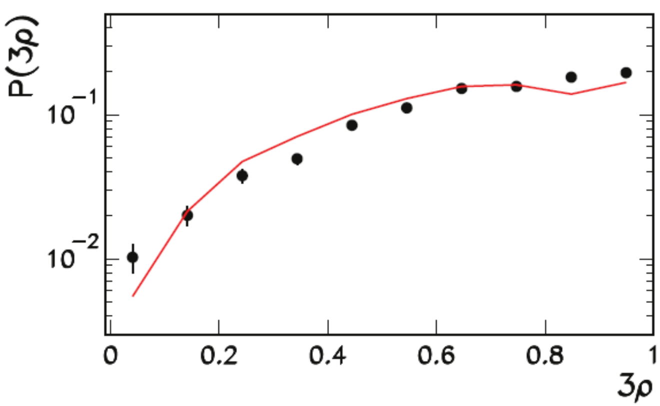
- «Hoyle» hypothesis (1953): 100 % SD
- Freer et al (1994): <4% DD
- Triggered an *intense campaign of measurements*!
- *See* the D. Dell'Aquila talk *tomorrow*

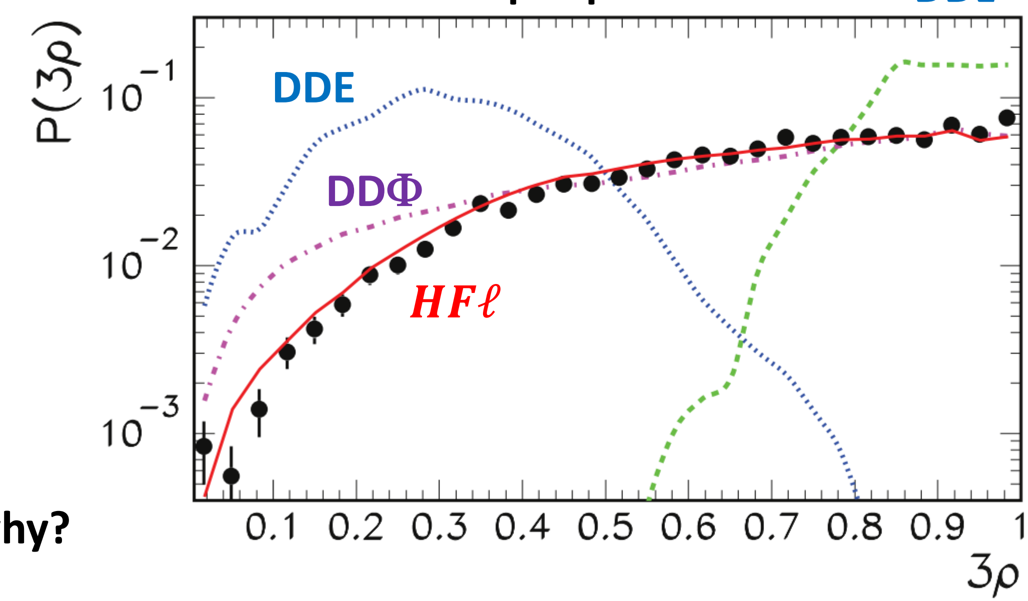
GARFIELD experiment: $^{12}C+^{12}C$ at ≈ 8 A MeV



Sampling of multi alpha emission in the phase space:

- **Peripheral**
- **Central (low statistics)**



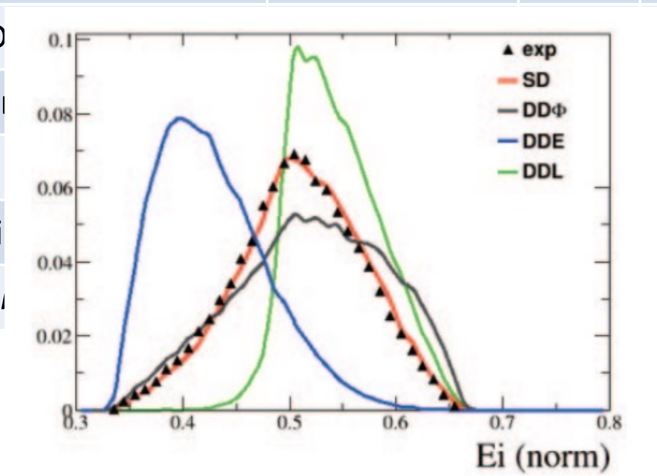


$BR_{DD} = 1.1 \pm 0.8\,\%$

At smaller *dampings* → only U.L., why?

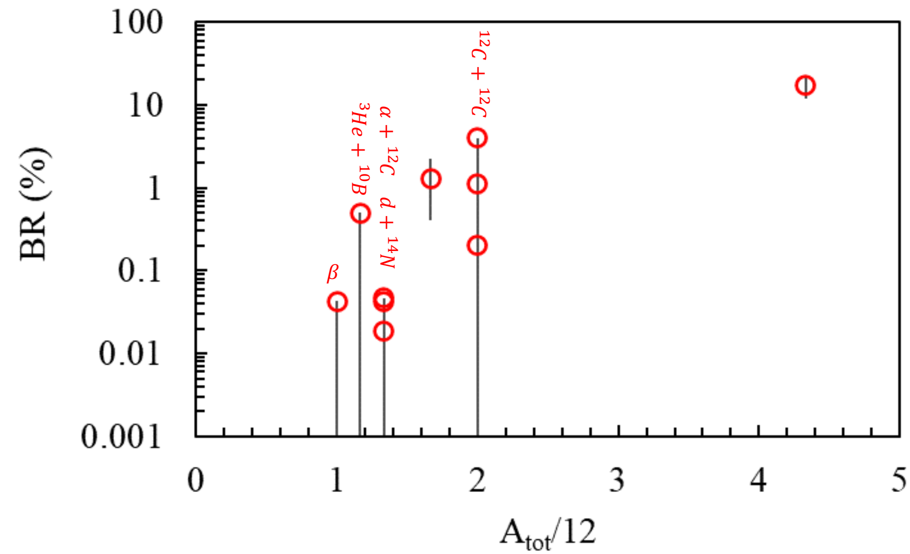
A brief summary on the «rush»

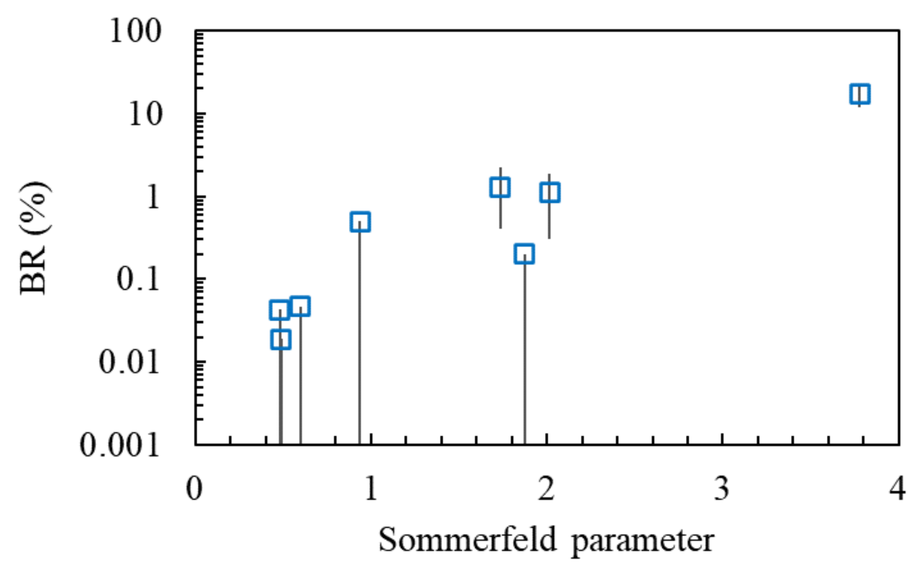
Experiment	Γ_{DD}/Γ (%)	type	year
M. Freer et al.	< 4	L.I.	1994
Ad.R. Raduta *et al.*	17.0 ± 5.0	H.I.	2011
J. Manfredi et al.	< 3.9	H.I.	2012
O.S. Kirsebom et al.	< 0.5	L.I.	2012
T.K. Rana et al.	0.91 ± 0.14	L.I.	2013
M. Itoh et al.	< 0.2	L.I.	2014
L. Morelli et al.	1.1 ± 0.8	H.I.	2016
D. D			2017
R. S			2017
T.K.			2019
J. Bi			2020
R. S			2020



FAZIA data: $^{20}Ne+^{12}C$, 25 A MeV

A. Rebillard et al, Nuovo Cim. C 45 (2022)





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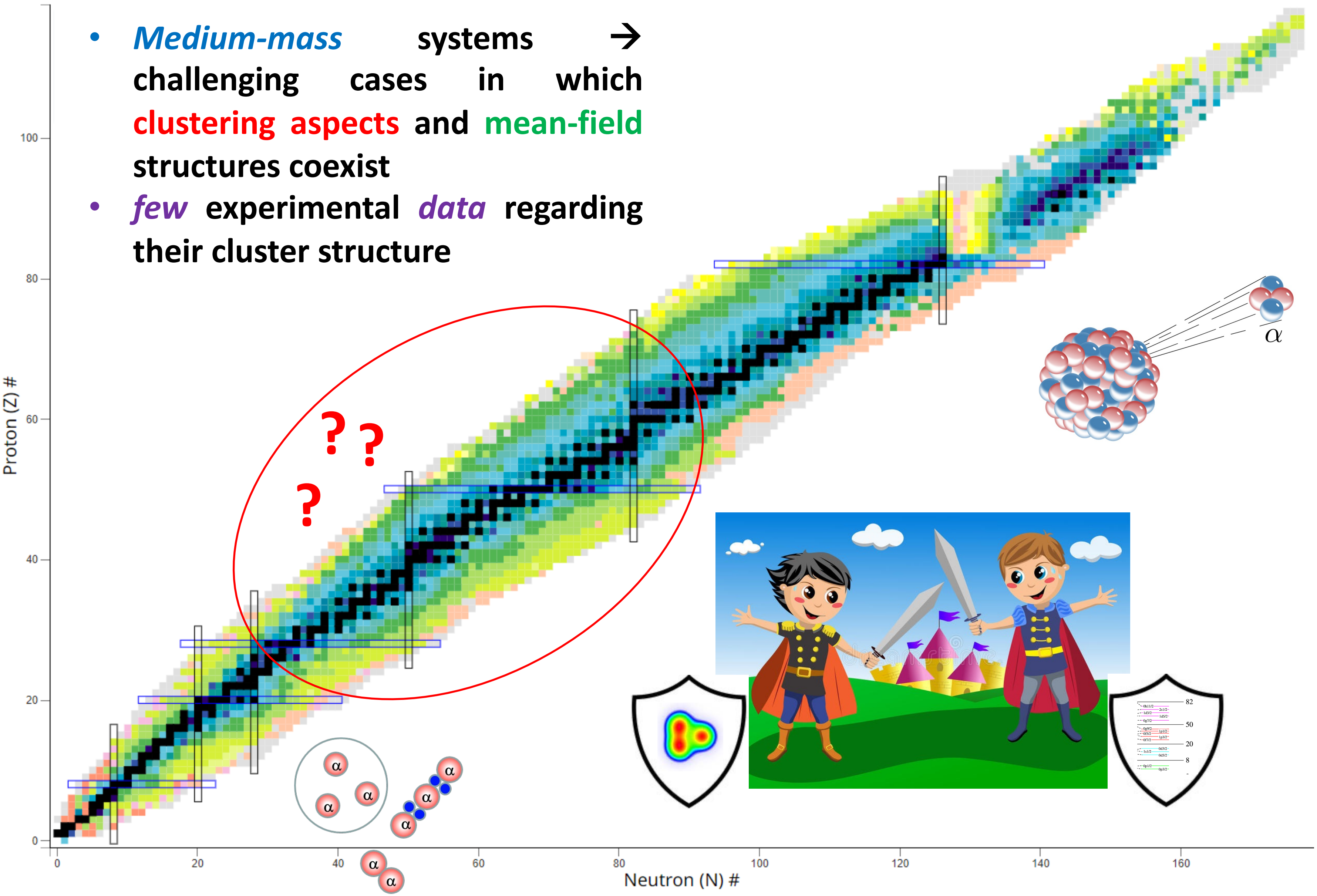
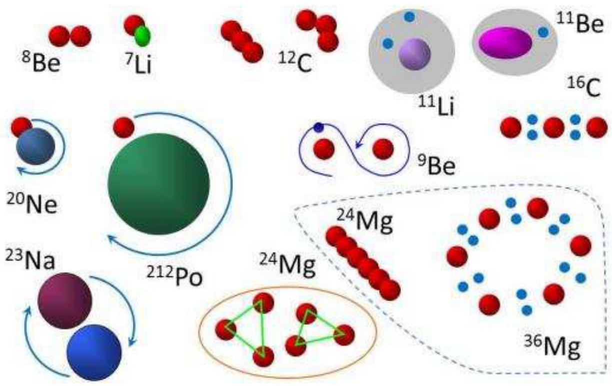
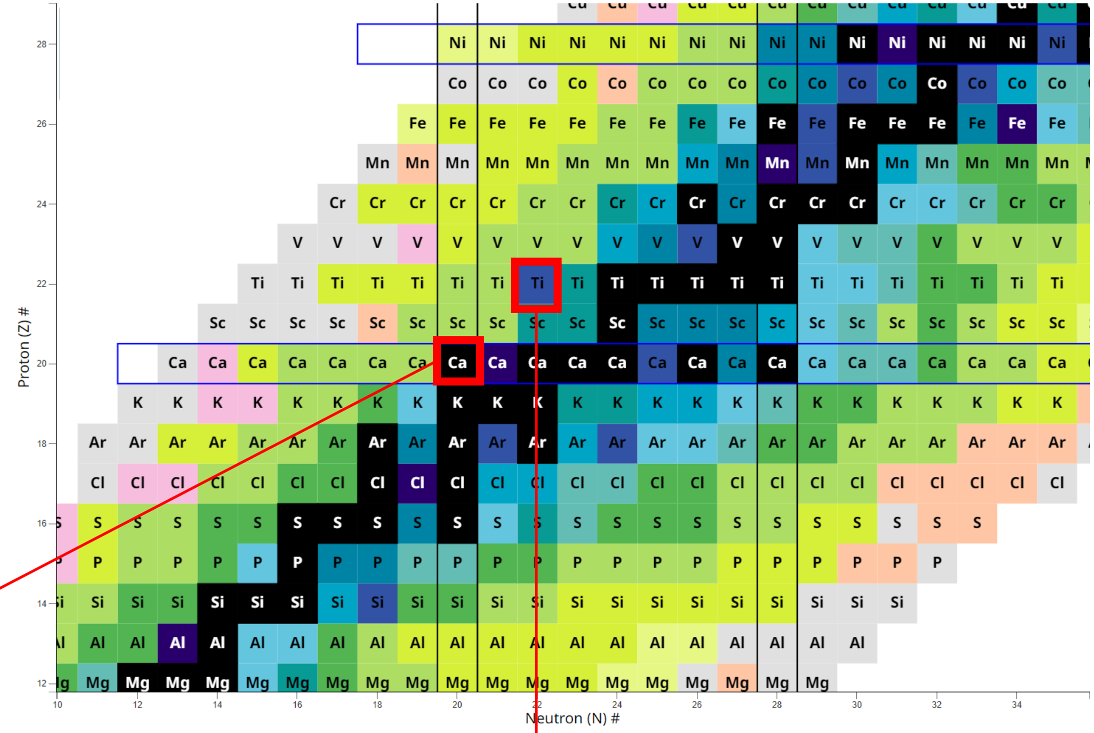
- *Medium-mass* systems → challenging cases in which clustering aspects and mean-field structures coexist
- *few* experimental *data* regarding their cluster structure



An interesting example: Ti isotopes

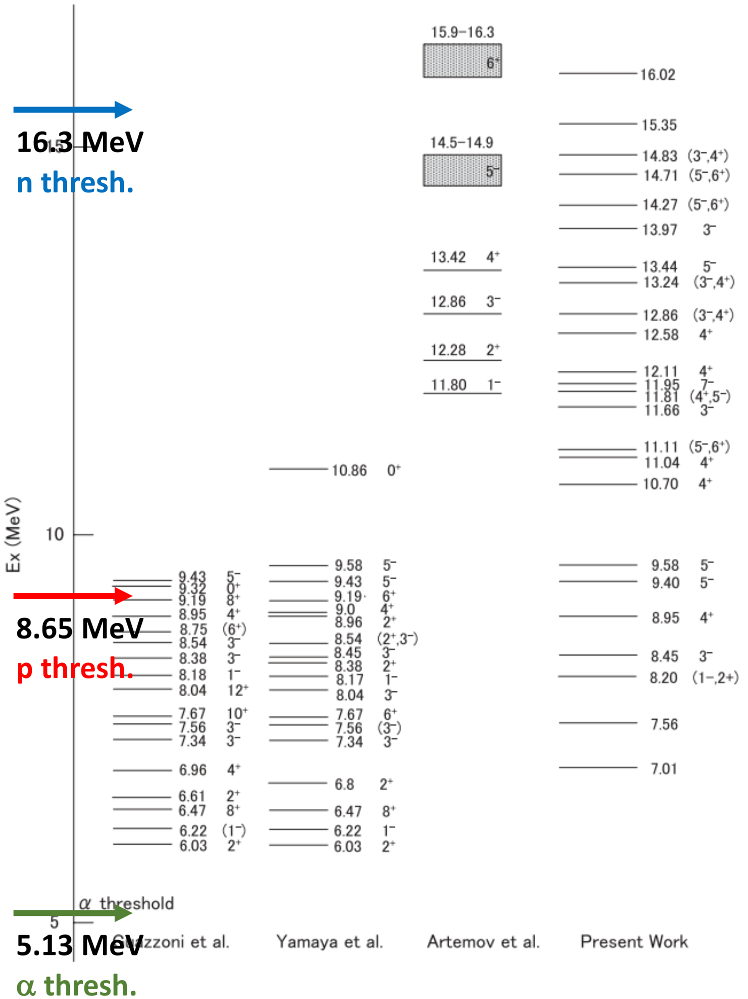




^{40}Ca, the last self-conjugate system to be stable

1) To which degree *clustering survives* with increasing mass?
2) Could a strong *Coulomb term* modify or destroy clustering?
3) Could the presence of a *doubly-magic core* trigger the occurrence of clustering with an α outside of the core?

Clustering and Shell effects in Ti isotopes



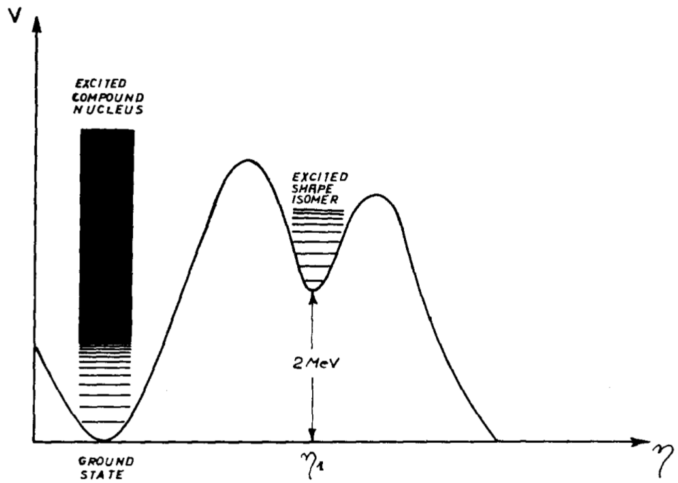
^{44}Ti

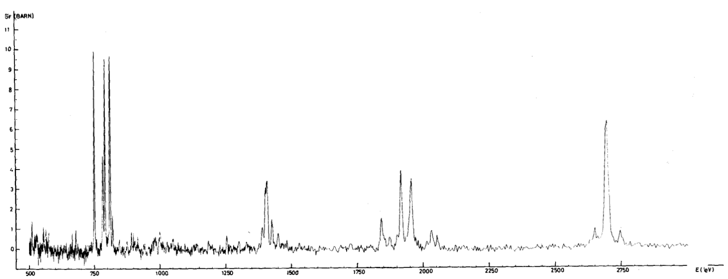
T. Yamaya et al., *Phys. Rev. C* 42 (1990) 1953
M. Fukada et al., *Phys. Rev. C* 80 (2009) 064613
K.P. Artemov et al., *Phys. Atom. Nucl.* 58 (1995) 177
J. John et al., *Phys. Rev.* 177 (1969) 1755
D. Frekers et al., *Nucl. Phys. A* 394 (1983) 189

- **new experiment at GANIL to probe ^{44,48,52}Ti clustered states with Thick Target Inverse Kinematics (TTIK) RES**
- **^{44,52}Ti → doubly magic core + α?**
- **Too many resonances $(E_x \simeq 10-17\ MeV)$ to perform an R-matrix calculation**
- **Novel methods needed to analyze data**
- **possible *recurrent pattern* on the excitation function? → modelling clustering in medium mass systems**

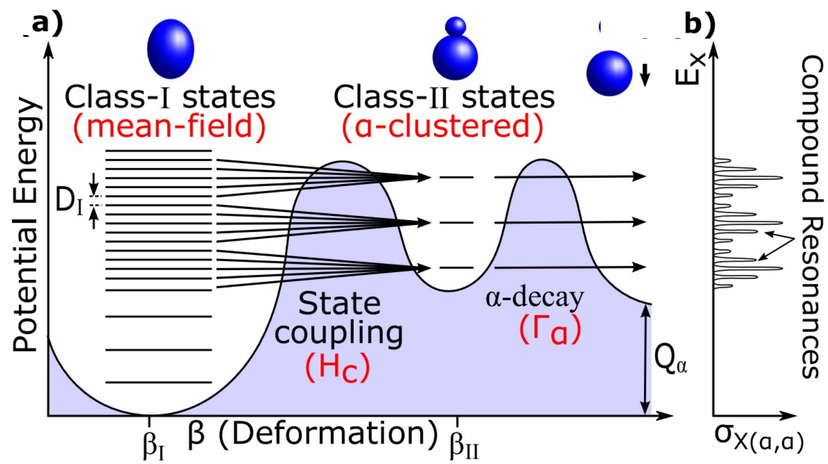
An interesting *analogy* comes from HI fission (V. Strutinsky, 1967)

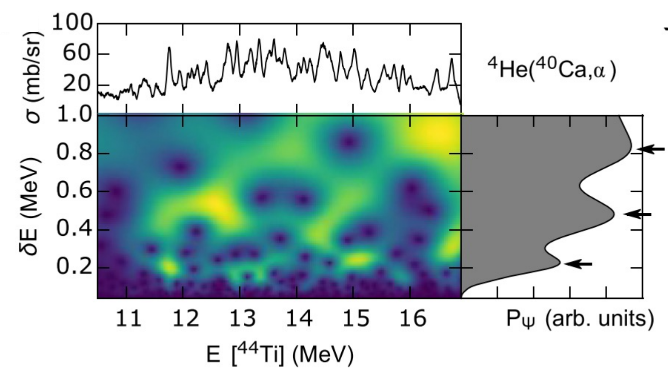
Sub-threshold fission of ^{240}Pu





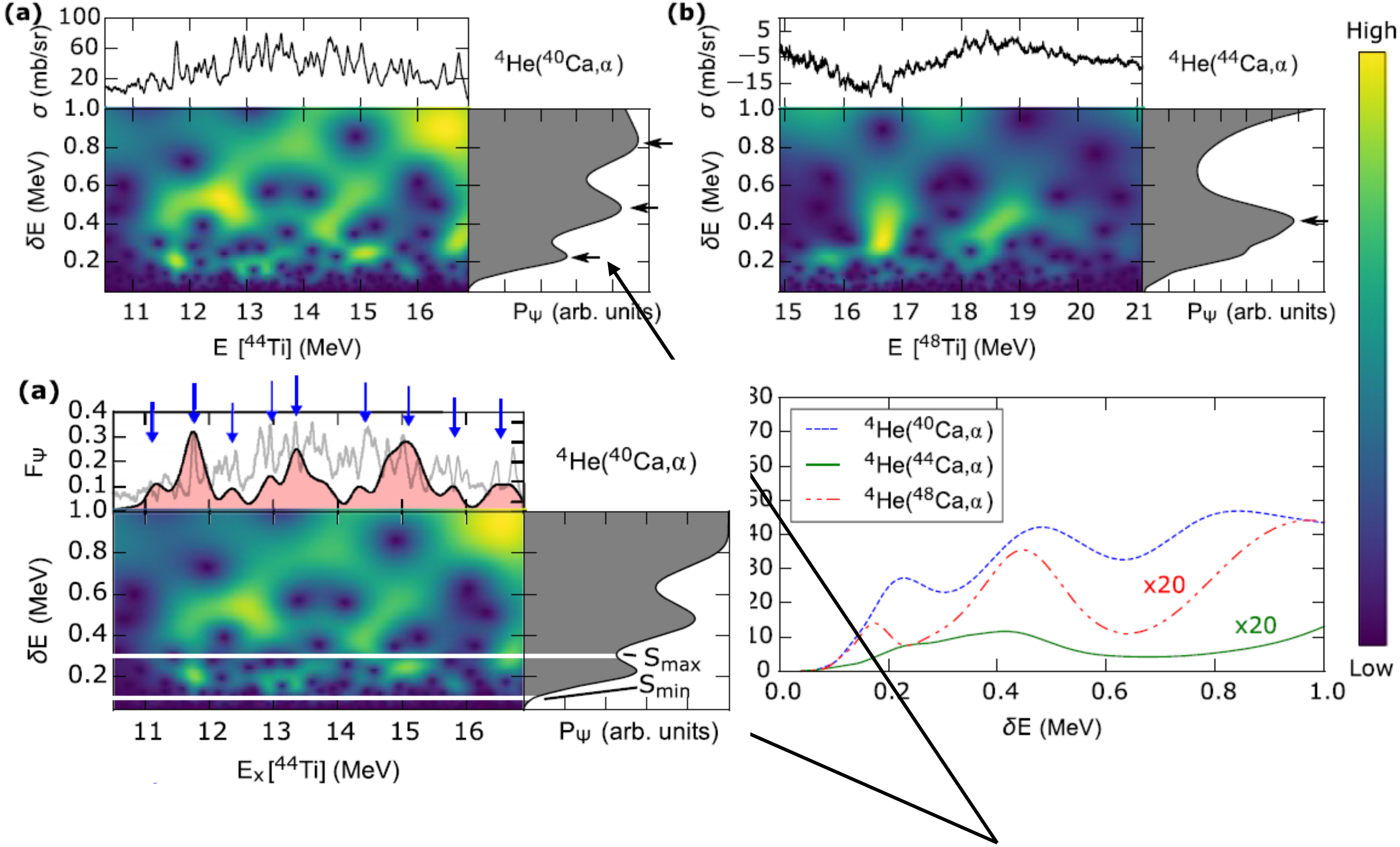
^{44}Ti results from TTIK elastic scattering data





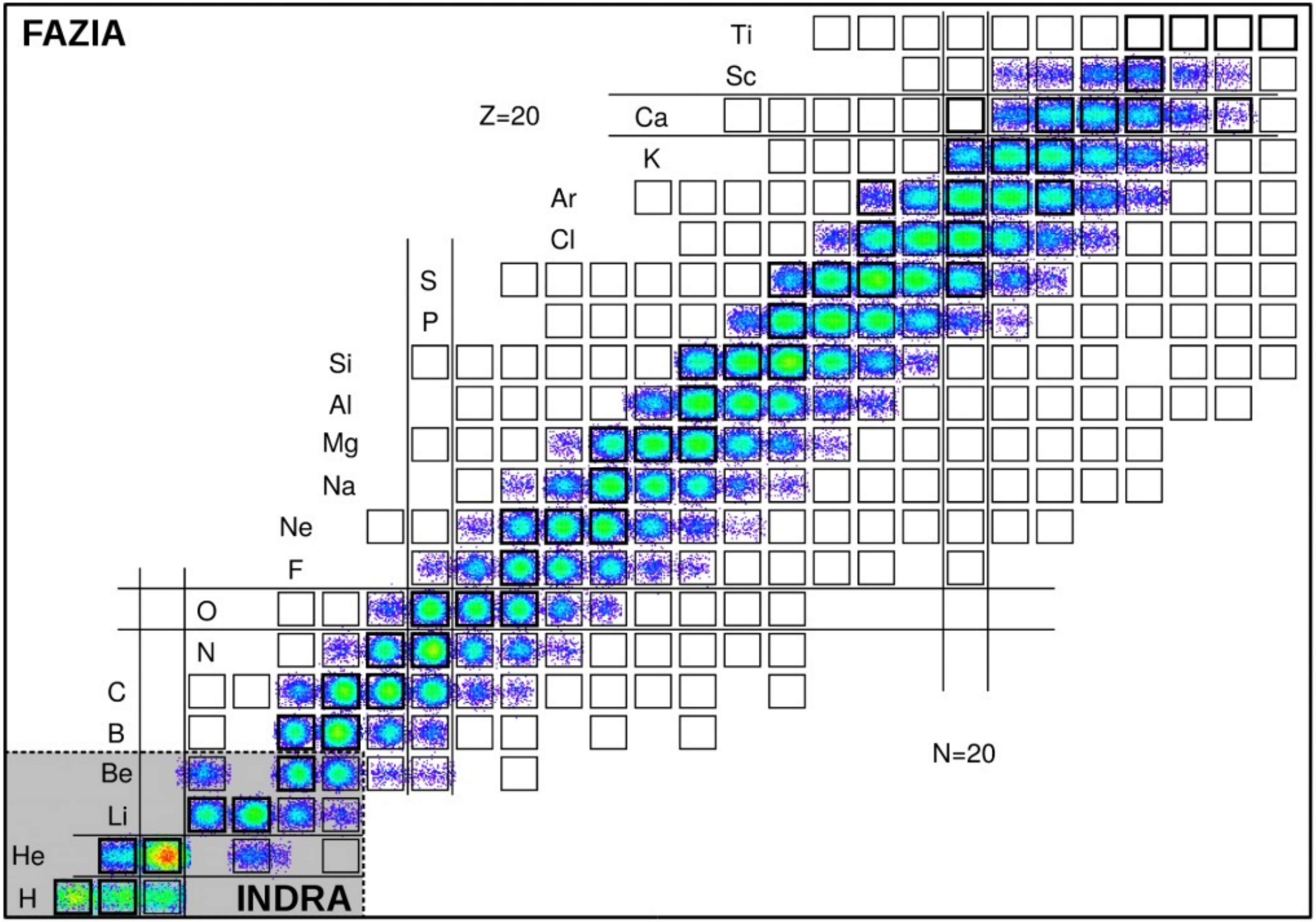
E. Migneco and J.P Theobald, NPA 112 (1968)

Energy *scale* analysis (CWT) of *spectrograms* associated to *RES cross sections*



(broad) α cluster states → *fragmented* strengths

Doubly magic core + α cluster ?



N. Le Neindre et al, NIM A 701 (2013) 145

- α-transfer in inverse kinematics → $^{40,42,44,48}Ca$ beams at Fermi energies on ^{6}Li targets to populate ^{X}Ti states

- particularly *selective* to possibly alpha-clustered states in $^{44,48}Ti$

- investigate *all* energetically allowed *decay channels*, thanks to the identification capabilities of INDRA-FAZIA

$$^{6}\mathrm{Li} + {}^{40}\mathrm{Ca} \longrightarrow \mathrm{d} + {}^{44}\mathrm{Ti}^{*} \longrightarrow \mathrm{d} + {}^{40}\mathrm{Ca} + \alpha$$

$$^{6}\mathrm{Li} + {}^{40}\mathrm{Ca} \longrightarrow \mathrm{d} + {}^{44}\mathrm{Ti}^{*} \longrightarrow \mathrm{d} + {}^{43}\mathrm{Sc} + \mathrm{p}$$

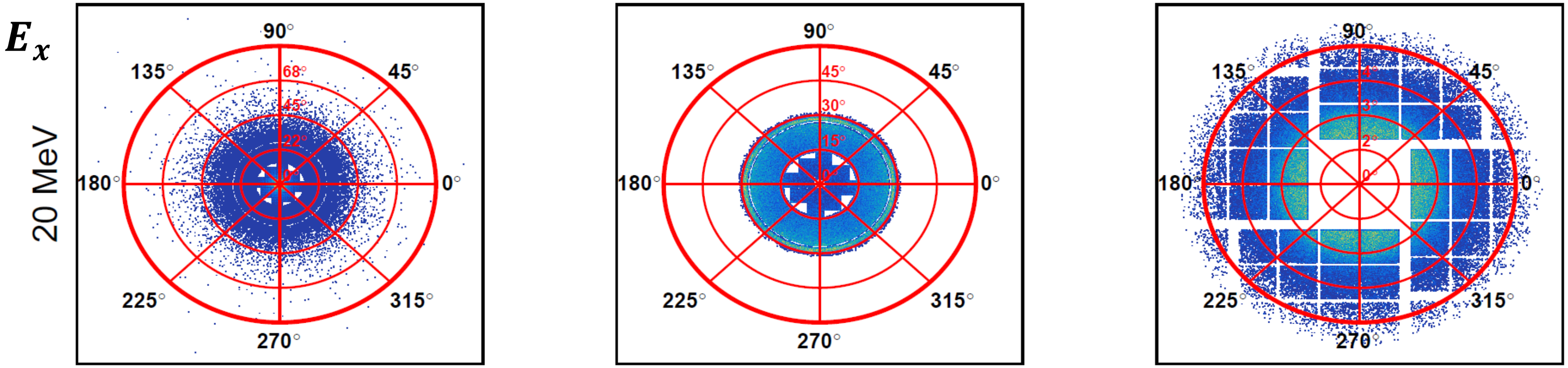
- The Γ_α/Γ *branching ratios* can be used as a *direct* indication of the formation of $\alpha+^{40}Ca$ clustered states → novelty for mid-mass nuclei at large Ex!

- BR distribution in the ROI of Ex from 12 MeV to 20 MeV

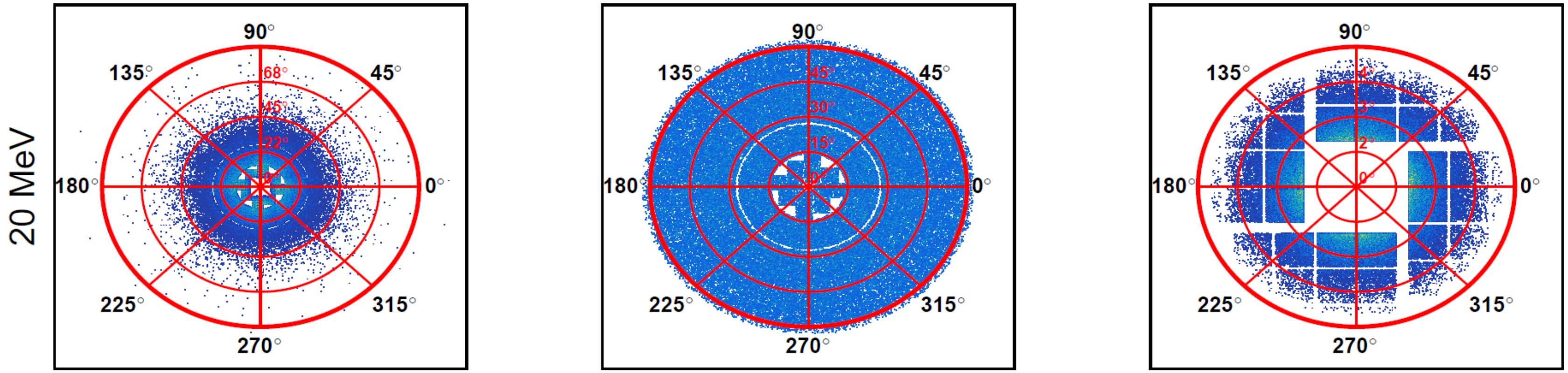
- fully reconstructed events (triple-coincidences), to reduce the background from contaminant processes

- To probe the feasibility of the experiment → a set of detailed Monte Carlo simulations that account for the geometry and performance of INDRA-FAZIA

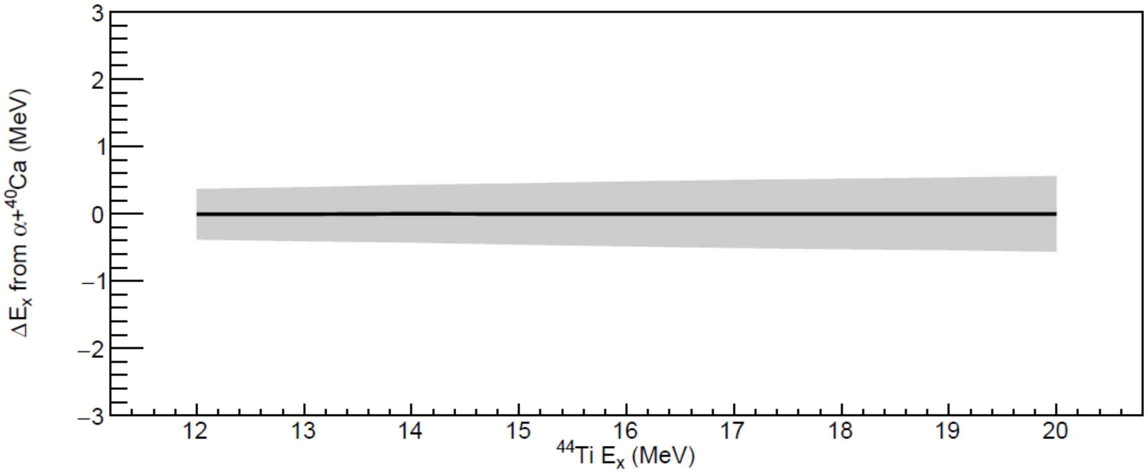
Polar coordinates plots for triple-coincidence events involving α-decay of ^{44}Ti



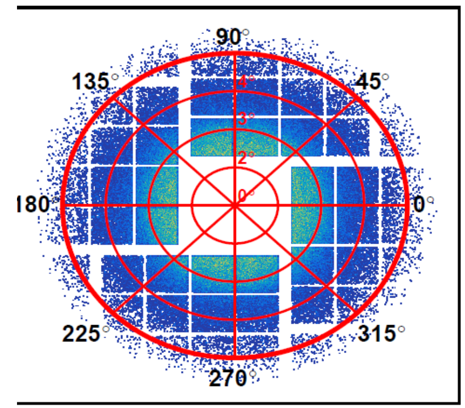
Polar coord. plots for triple-coincidence events involving proton-decay of ^{44}Ti

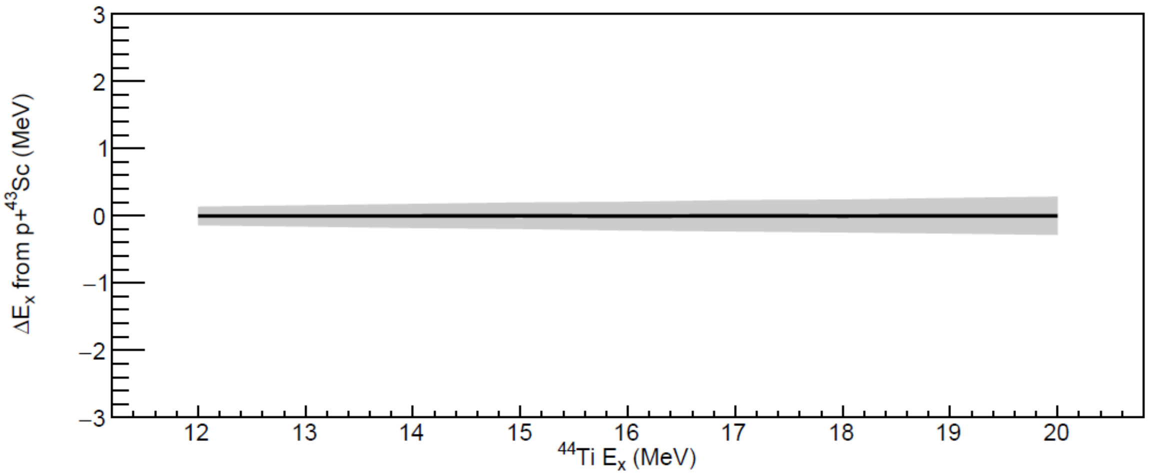


Several other cases → also with RIBS !

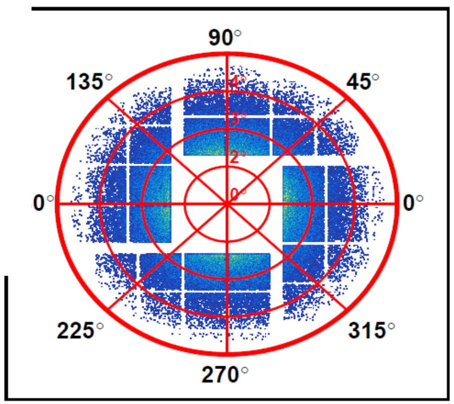


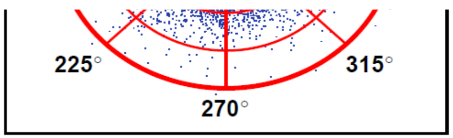
lving <u>α-decay</u> of ^{44}Ti

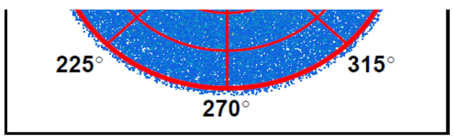




<u>proton-decay</u> of ^{44}Ti







Several other cases → also with RIBS !

Heavy ion physics **at intermediate energies (≈ 10 – 200 A MeV) and clustering:**

- **Impact of clustering on *reaction mechanism competition* (CF, ICF ..)**
- **Cluster formation in very dilute environments → HIC, medium effect**
- **Impact of clustering in nuclear dynamics → Symmetry energy, xs-scales**
- **Chemical equilibrium and EOS for dilute matter**
- **Cluster decay of highly excited self-comjugate nuclei (many α decay)**
- **HIC and particle-particle correlations → spectroscopy!**
- **HIC and Hoyle state → still open questions**
- **HIC multi-detectors as tool for α-transfer reactions → medium mass nuclei**
-
- **… and *many other* beautiful features!**

Thank you for the attention!