

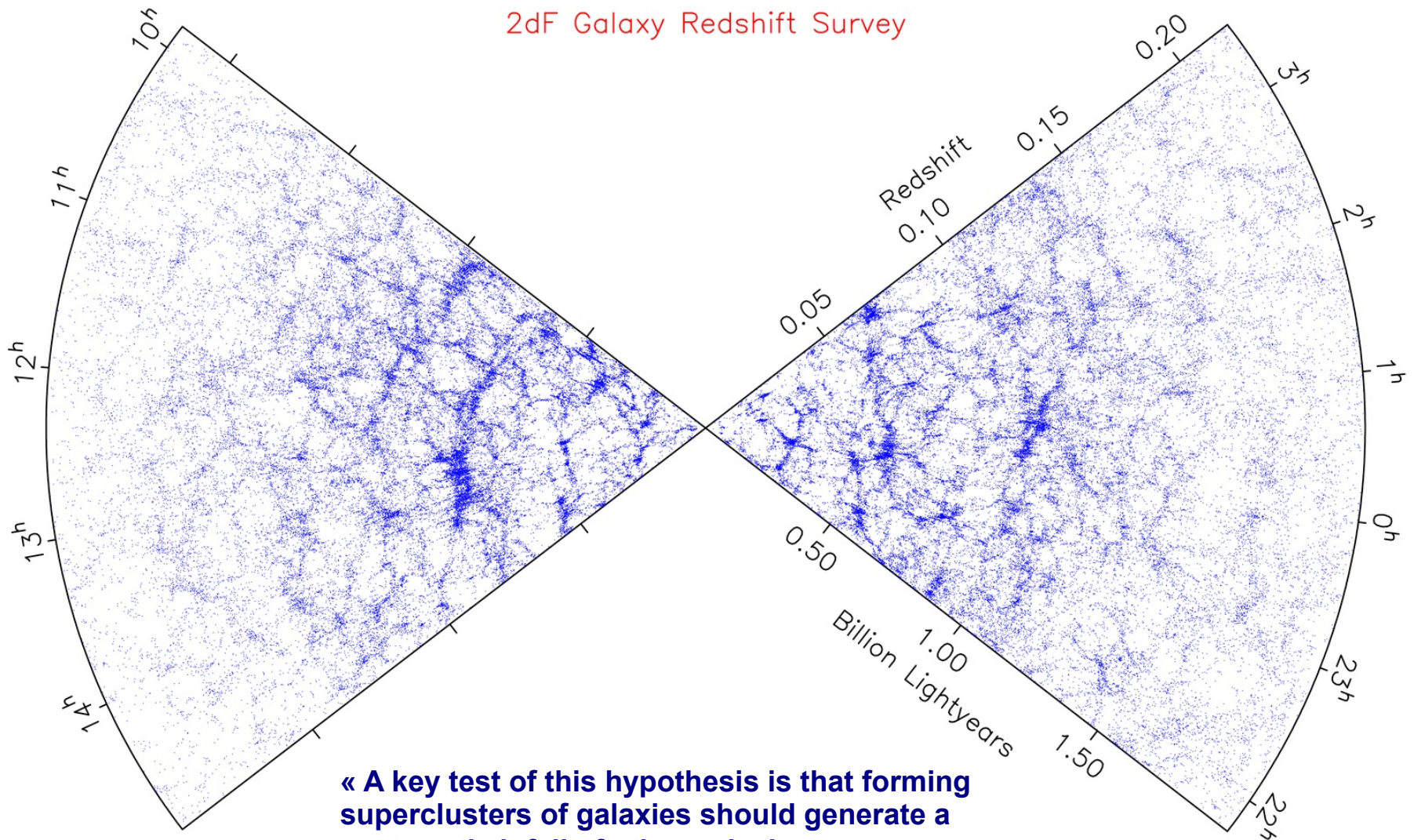
# Les agrégats nucléaires par les méthodes moléculaires

Sandrine Courtin  
IPHC et USIAS, Strasbourg



# Introduction

2dF Galaxy Redshift Survey



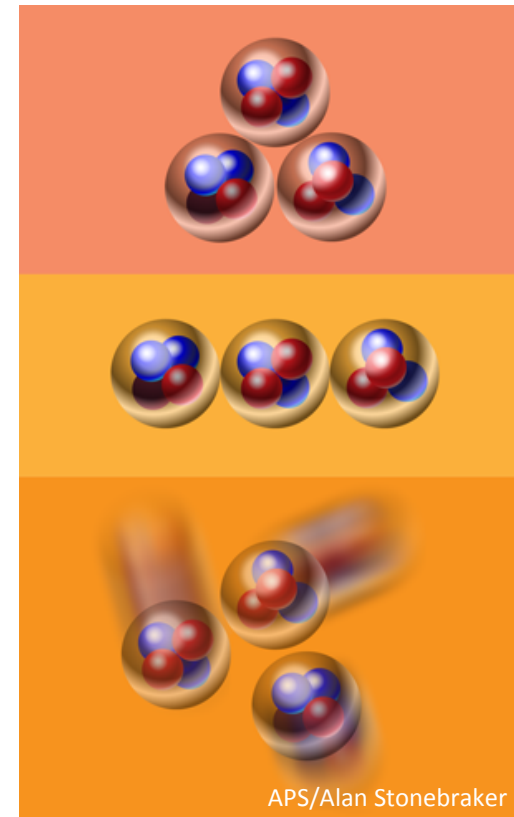
**« A key test of this hypothesis is that forming superclusters of galaxies should generate a systematic infall of other galaxies. »**

Nature **410**, 169 (2001)



# Introduction

- Des états excités basés sur des agrégats  $\alpha$  ?  
Un sous-espace 'cluster', une projection sur ce sous-espace ?  
Existe t'il une description géométrique ?  
( $^{20}\text{Ne}$ , Zhou et al., PRL2013)
- Quelques points théoriques :  
Calculs 'cluster'  
Champ moyen  
Ab initio
- Du point de vue expérimental :  
Fragmentation  
De nouveaux états  
De nouveaux noyaux  
Les transitions électromagnétiques  
Un pont vers l'astrophysique

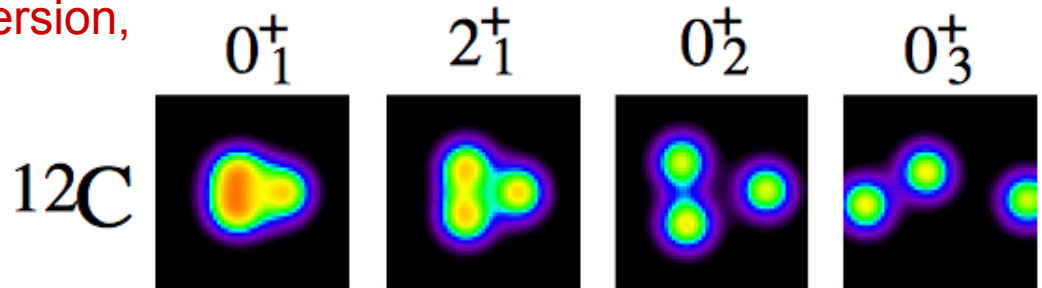
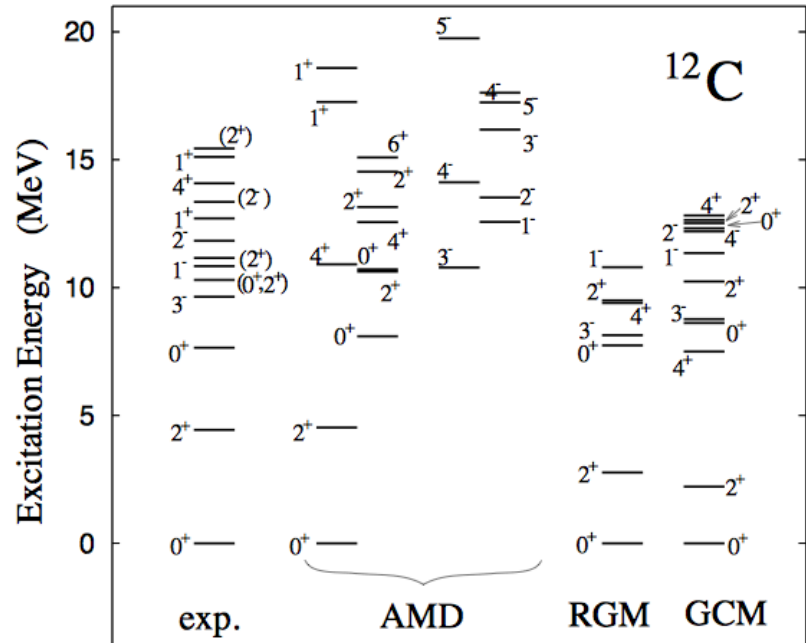


$^{12}\text{C}$  ...  $^{12}\text{C}$  ?



# Calculs AMD

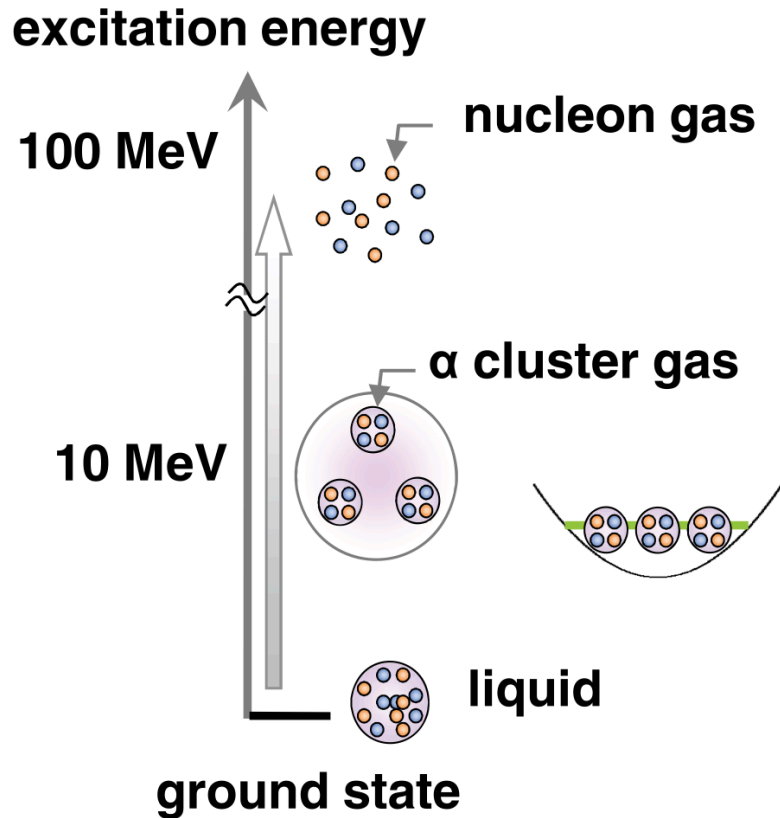
- Système : produit antisymétrisé de paquets d'onde gaussiens,
- f.o. comme une superposition de dét. de Slater,
- centres des paquets d'ondes = paramètres variationnels,
- AMD indép. temps et TDAMD (systèmes à haute  $E^*$ ).
- Forts succès : agrégats, riches en neutrons légers, îlot d'inversion, SD



Y. Kanada-En'yo, M. Kimura and A. Ono, Prog. Theor. Exp. Phys. (2012) 01A202



# Condensation, gaz, liquide, cristal



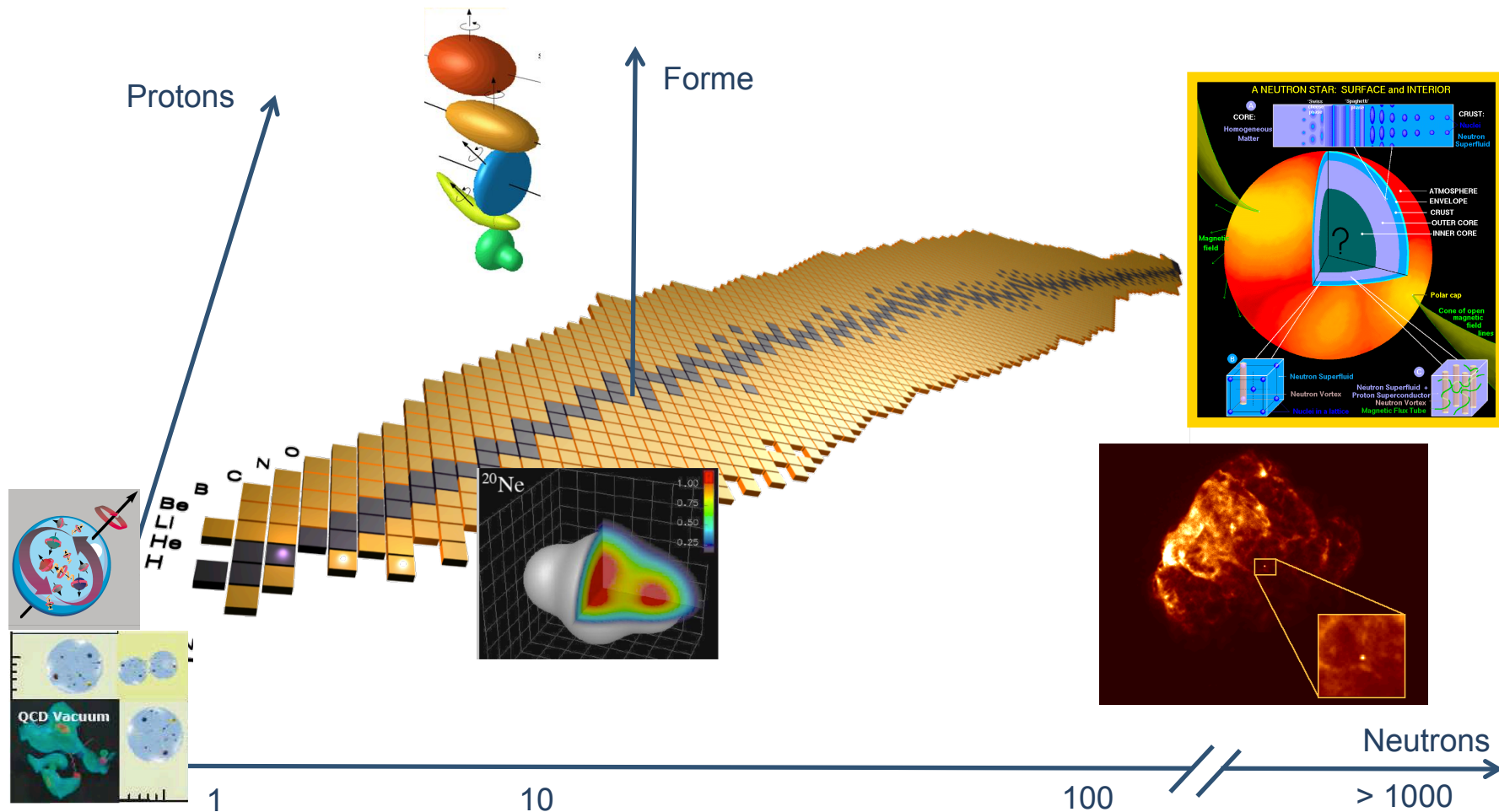
Etats à basse densité proches du seuil de breakup  
 $3\alpha$  et  $4\alpha$  dans  $^{12}\text{C}$  and  $^{16}\text{O}$

Y. Funaki, T. Yamada, H. Horiuchi, G. Röpke, P. Schuck,  
A. Tosaki., Few Body Systems 2013

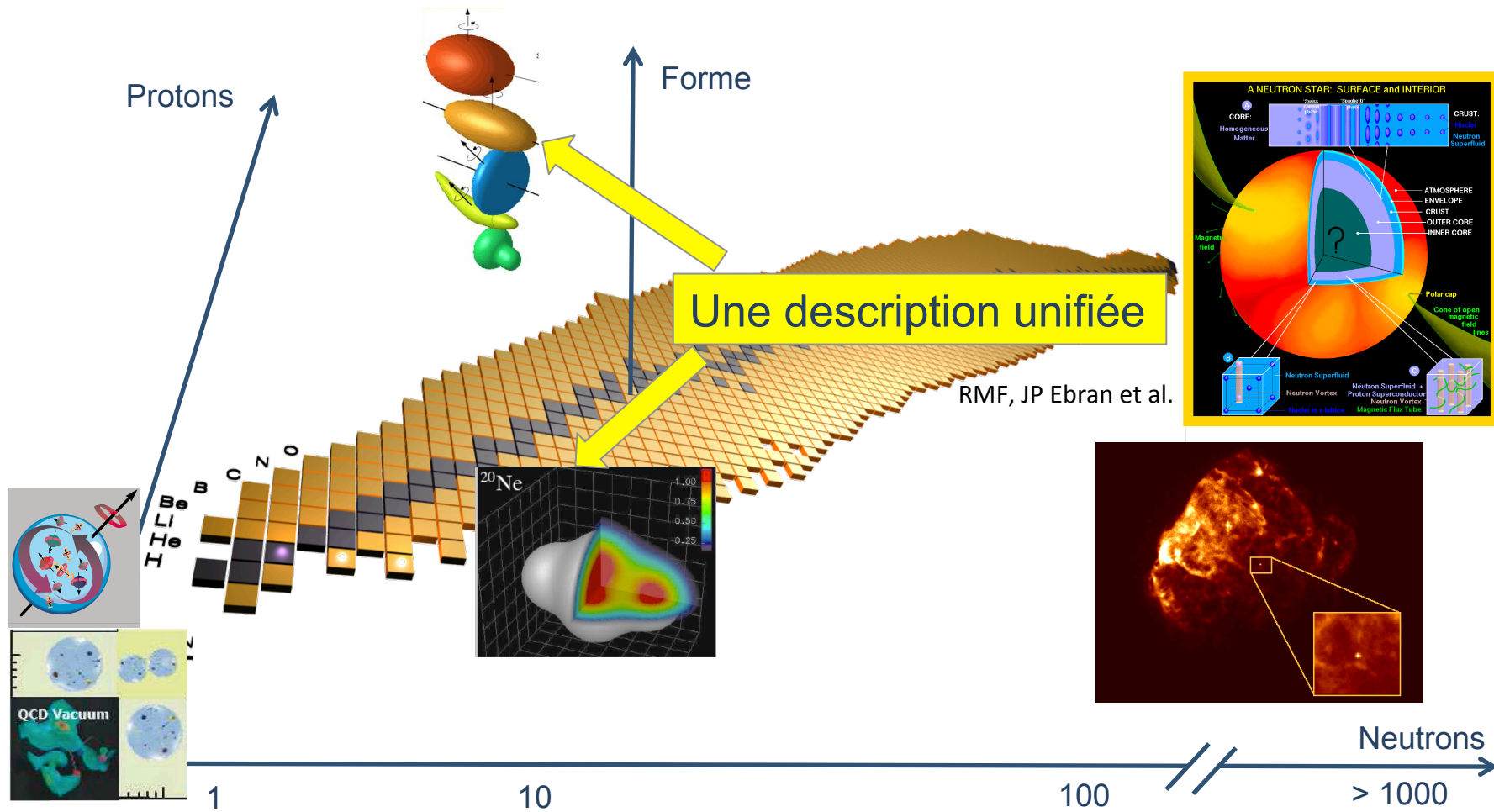
H. Horiuchi, Progress of Theoretical Physics Supplement No. 192, 2012



# Condensation, gaz, liquide, cristal

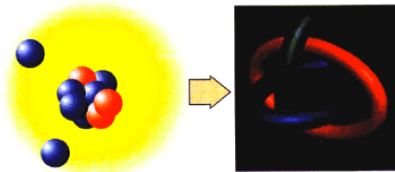


# Condensation, gaz, liquide, cristal



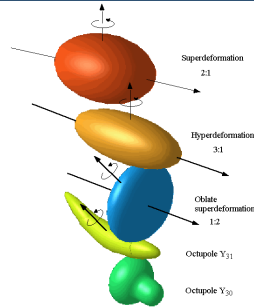
# Condensation, gaz, liquide, cristal

Halo

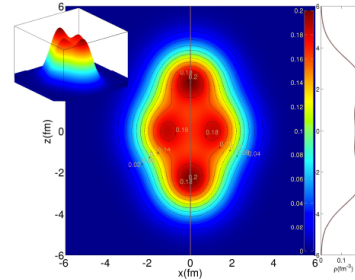


$$\alpha_{loc} = b/r_0$$

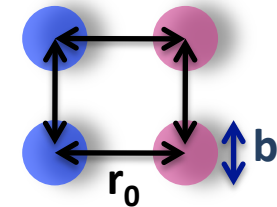
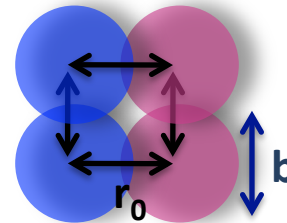
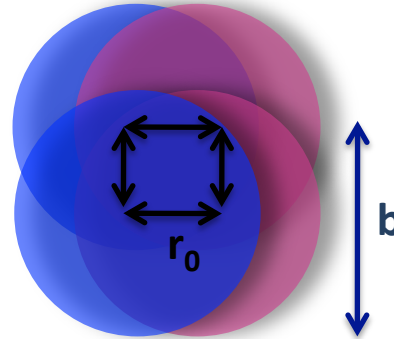
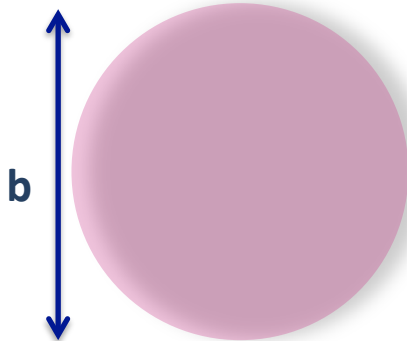
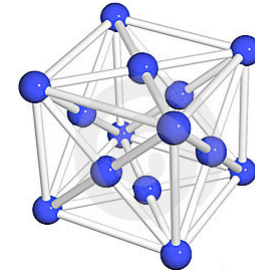
Liquide quantique



Cluster



Cristal



- Différents états nucléaires en fonction de  $\alpha_{loc}$ .
- $\alpha_{loc} > 1$ , lourds
- $\alpha_{loc} < 1$ , légers
- **Accord expérience**

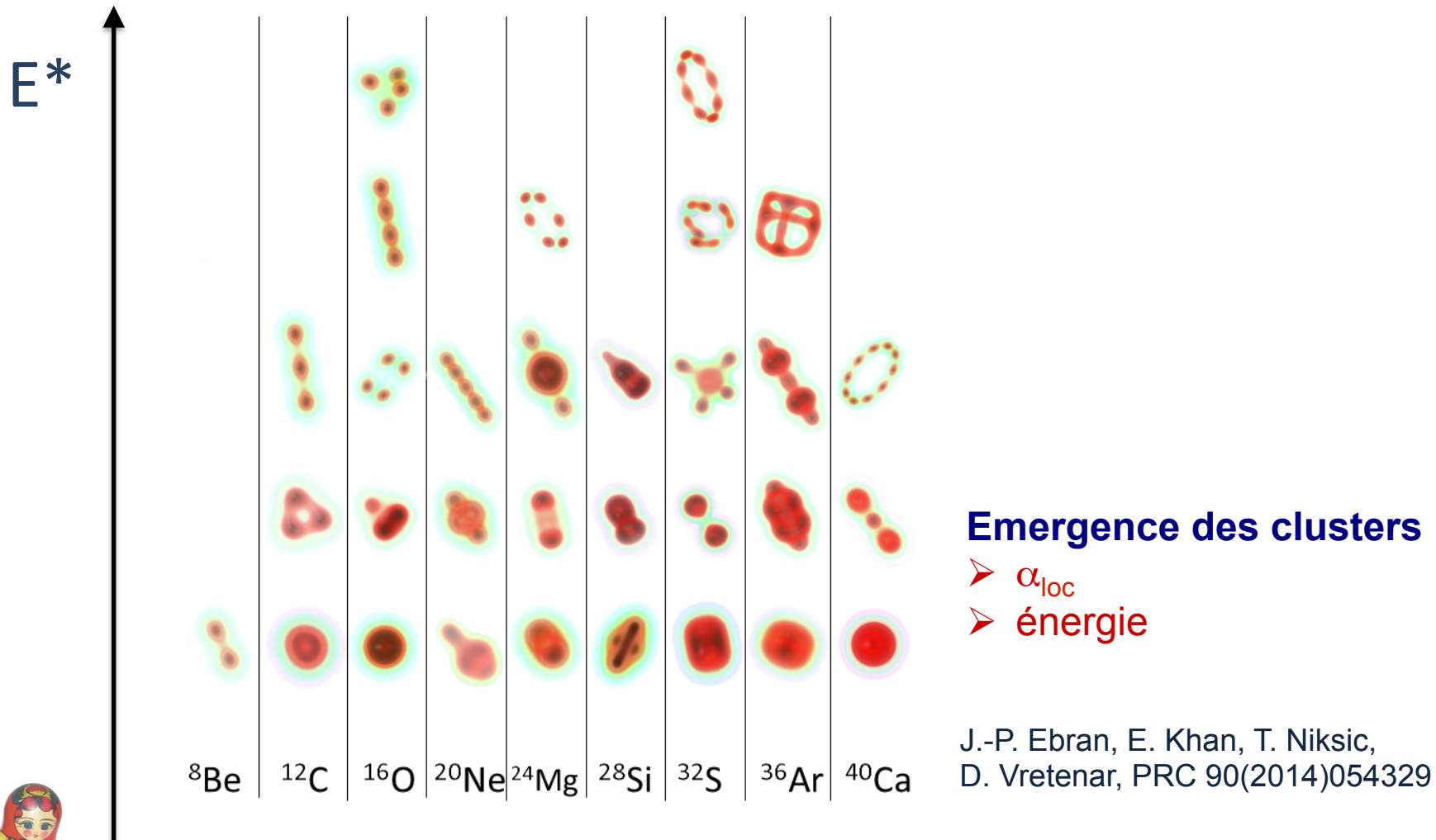
J.-P. Ebran, E. Khan, T. Niksic, D. Vretenar, Nature 487(2012)341





# Condensation, gaz, liquide, cristal

Fondements microscopiques au diagramme de Ikeda



# Description ab initio

- No-core SM

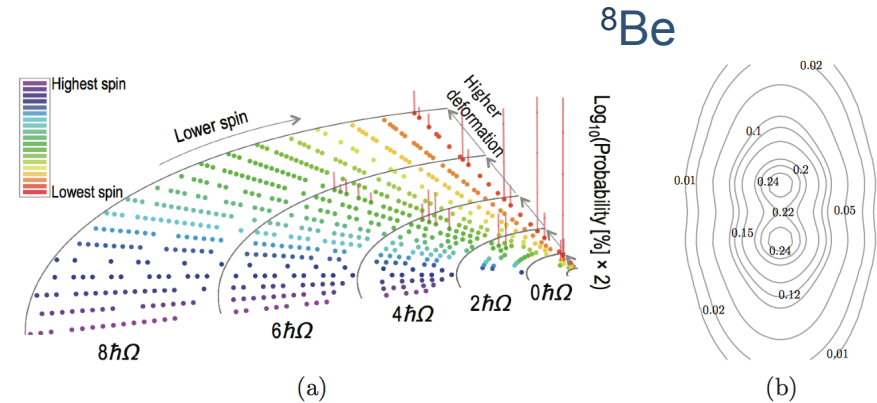
Navratil et al. PRL 84, PRC 62 (2000)

Interactions à 2 corps  
dédites des forces réalistes

CD-Bonn, Argonne V8

Espaces :  $0\hbar\omega$ ,  $2\hbar\omega$ ,  $4\hbar\omega$  /  $1\hbar\omega$ ,  $3\hbar\omega$ ,  $5\hbar\omega$

Applications  $^{12}\text{C}$ .



Dreyfuss et al., PRL 2013

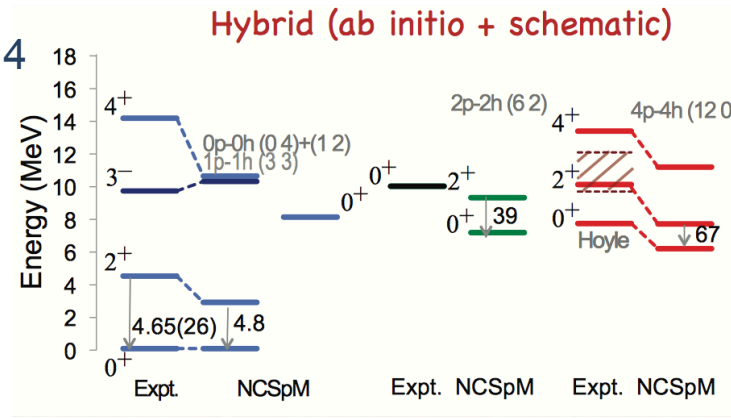
Launey et al., J.of. Phys. CS 2014

Symmetry adapted no-core SM

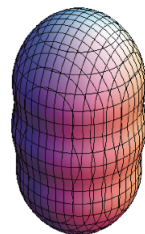
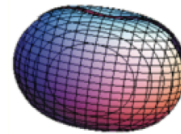
base symplectique

(états OH à 1 particule)

Interaction N corps



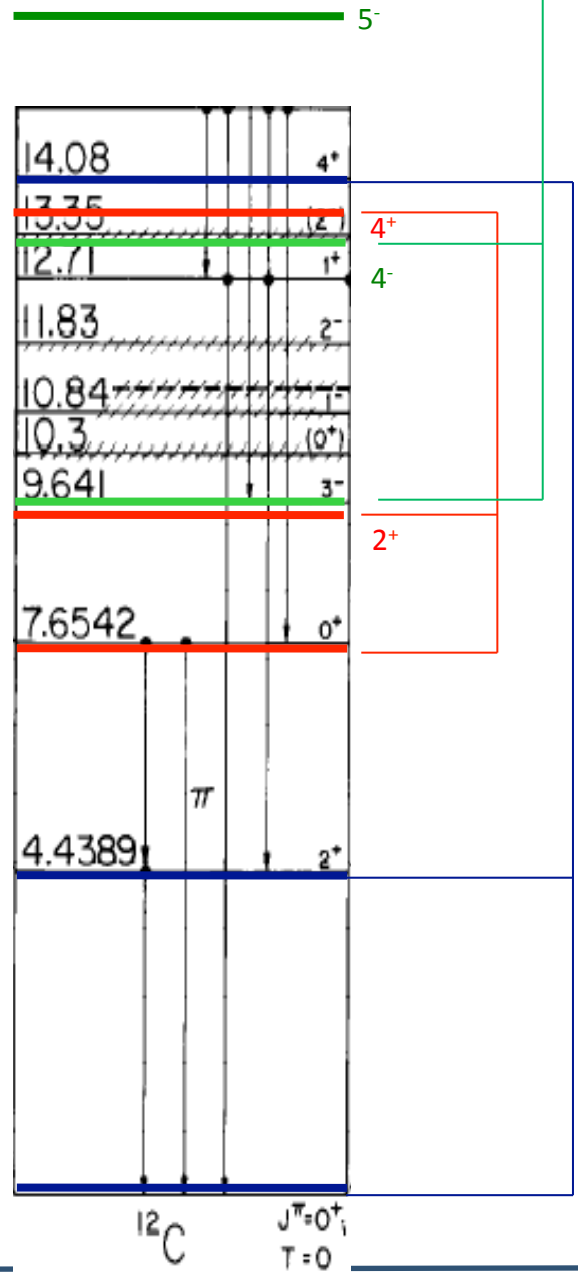
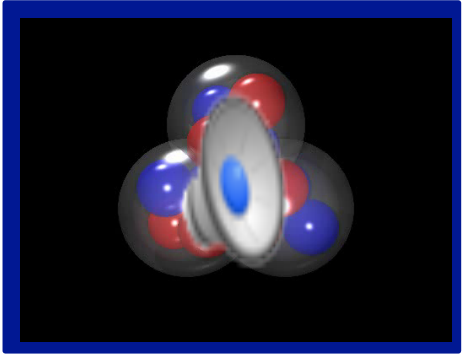
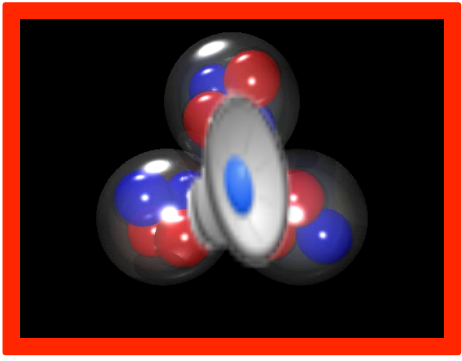
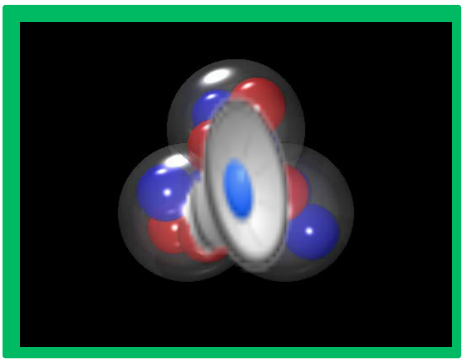
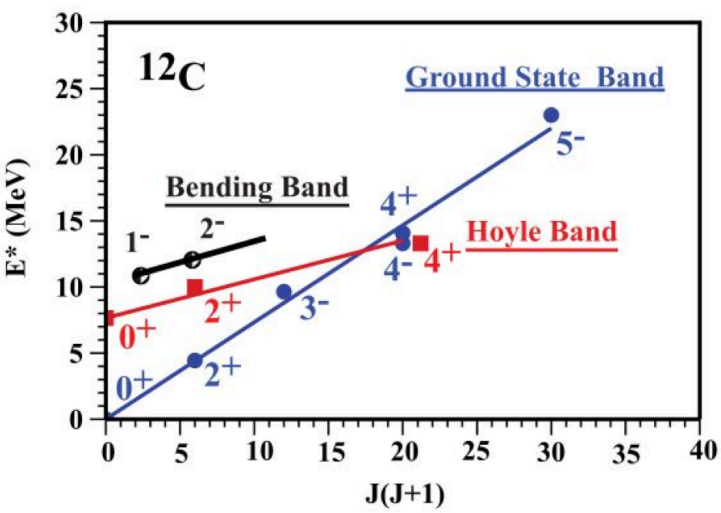
$^{12}\text{C}$



(b)



# $^{12}\text{C}$ , bande de Hoyle



## Obs. : de nouveaux états

- Freer et al. PRC 76 (2007) 034320
- Freer et al. PRC 80 (2009) 041303(R)
- Hyldegaard et al. PRC 81 (2010) 024303
- Zimmerman et al. PRC 84 (2011) 027304
- Itoh et al. PRC 84 (2011) 054308
- Freer et al. PRC 83 (2011) 034314
- Kirsebom, Few-Body Syst 54 (2013) 755
- Zimmerman et al. PRL 110, 152502 (2013)
- Itoh et al. J. Phys. Conf. Ser. 436 (2013) 012006
- Marin-Lambarri et al. PRL 113 (2014) 012502
- Laursen et al. J. Phys. Conf. Ser. 569 (2014) 012073

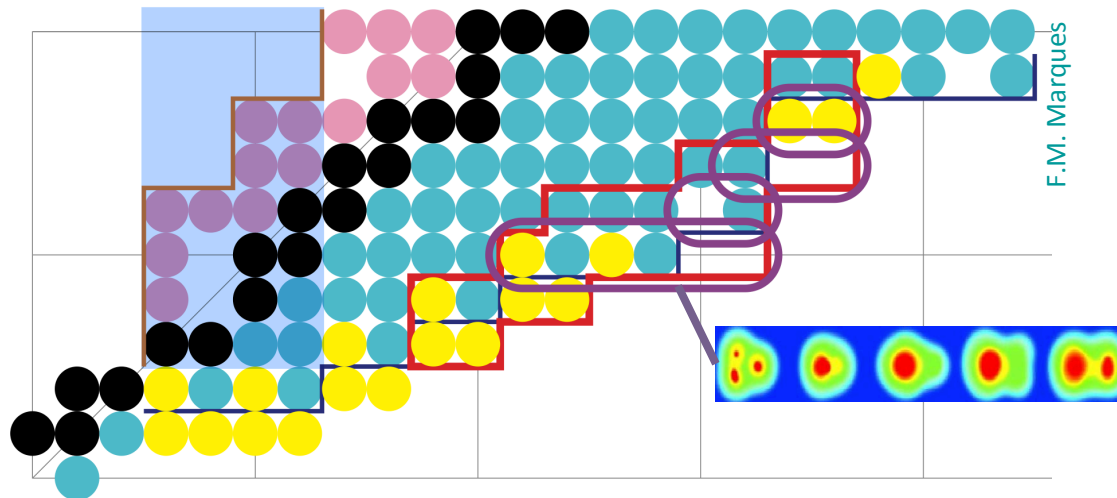
Algebraic model / Symétrie triangulaire  $\mathcal{D}_{3h}$

© M. Freer

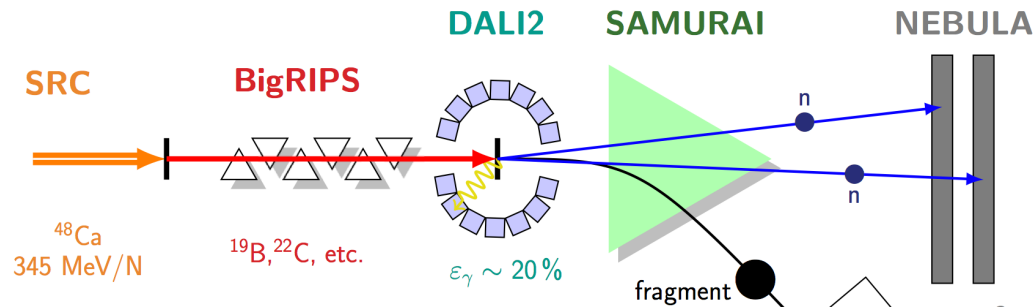


# Riches en neutrons : des agrégats à la drip-line

- Isotopes les plus riches en neutrons de Bore et de Carbone



- Campagne SAMURAI @ Riken  
'clusters autour de la dripline'  
 $^{12}\text{Li}$  à  $^{26}\text{O}$  en '1 tir' (25 noyaux !)  
**Nouvelle cartographie de la drip-line**
- Résultats sur la structure de  
 $^{16-21}\text{B}$  /  $^{21,22}\text{C}$  /  $^{22-25}\text{N}$  /  $^{25,26}\text{O}$
- Le noyau à halo de  $2n$  le plus lourd  $^{22}\text{C}$



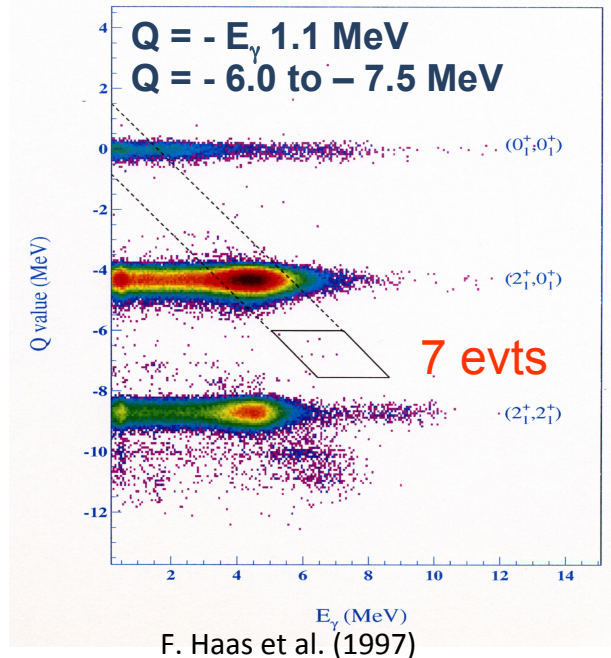
F. M. Marquès, S. Leblond, Q. Deshayes, J. Gibelin, N.A. Orr et al.



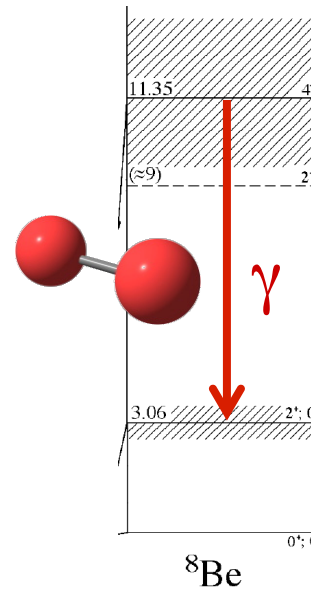
# Transitions électromagnétiques comme sonde des agrégats

- Des  $\gamma$  entre états cluster, la signature expérimentale !

Une expérience pionnière dans  $^{24}\text{Mg}(^{12}\text{C}-^{12}\text{C})$



Des résultats récents dans  $^8\text{Be}(\alpha-\alpha)$



$$B(E2) = 25.8 \pm 8.4 \text{ W.u.}$$

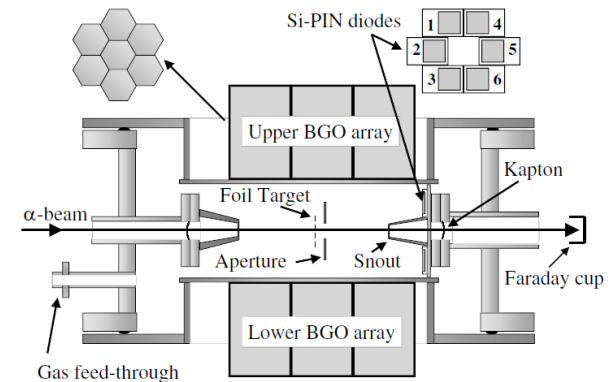


FIG. 2. A schematic of the experimental setup.

V.M. Datar et al. (PRL 2005 & 2013)

- Une signature manquante dans les clusters 'lourds'
- Nouveaux développements techniques : résultats ( $^{24}\text{Mg}(^{12}\text{C}-^{12}\text{C})$ ,  $\text{LaBr}_3$ )



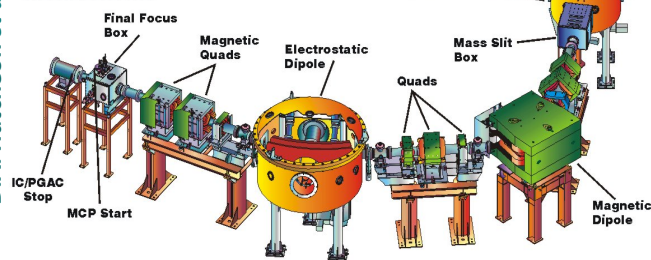
# Transitions électromagnétiques comme sonde des agrégats

- Décroissance  $\gamma$  de résonances moléculaires  
Campagnes  $^{24}\text{Mg}(^{12}\text{C}-^{12}\text{C})$  et  $^{28}\text{Si}(^{12}\text{C}-^{16}\text{O})$  à Triumf, Vancouver

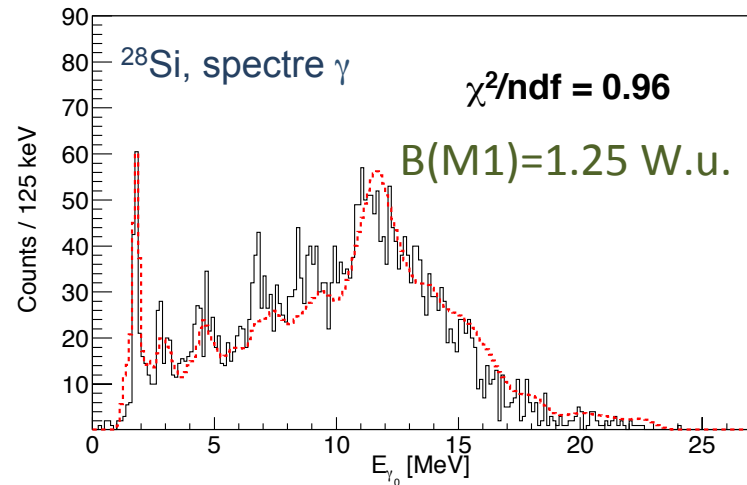
D.A. Hutcheon et al., NIM A 498, 190 (2003).

**DRAGON**  
Detector of Recoils And  
Gammas Of Nuclear reactions

Recoil Detectors



Sélection des reculs  $^{28}\text{Si} / ^{24}\text{Mg}$  à  $0^\circ$  :  $N_{\text{RC}}/N_{\text{faisceau}} = 10^{-12}$



D. Lebhertz, S. Courtin et al. Phys.Rev. C 85 (2012) / A. Goasduff, S. Courtin et al., PRC 89 (2014)

- $E > \text{CB}$ , très forte alimentation d'états déformés - bande prolate, octupolaire.
- $E < \text{CB}$ , très forte alimentation d'états  $1^+$ ,  $T = 1$  .  $B(\text{M1})=1.25 \text{ W.u.}$

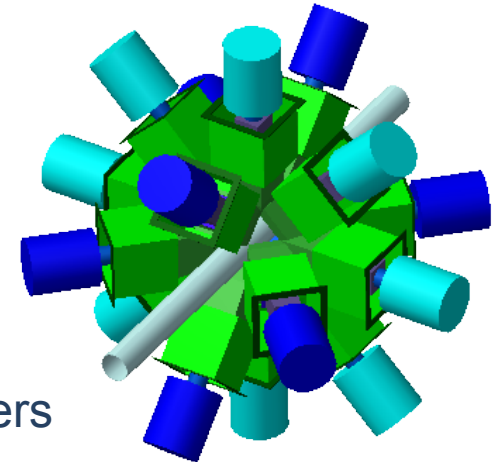
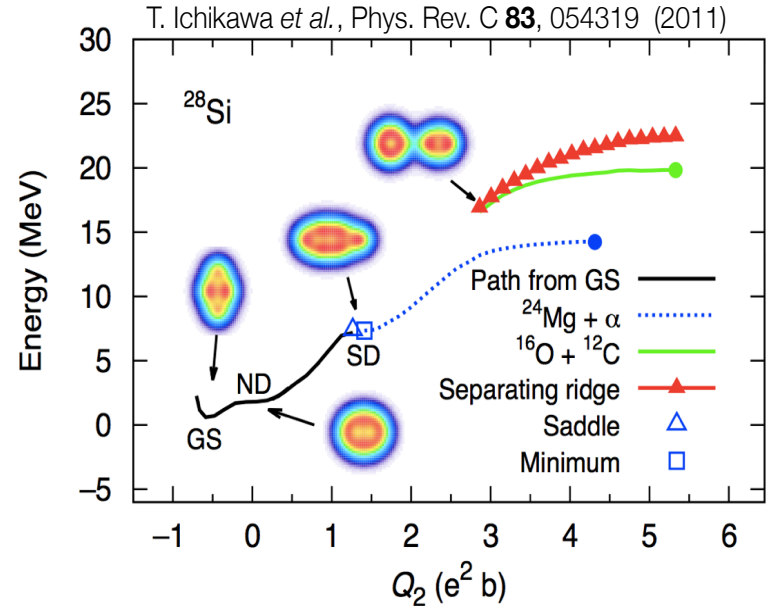
Excitations 'spin-flip' des noyaux  $N=Z$

Résonance moléculaire connectée à la résonance géante (ISGQR)



# Agrégats et SD

- $^{36}\text{Ar}$  : bande SD**,  $^{24}\text{Mg}(^{20}\text{Ne}, 2\alpha)^{36}\text{Ar}$ ,  $0^+$  à  $E = 4329$  keV  
 (C. Svensson *et al.* *Phys.Rev.Lett.* 85 (2000))  
 bande 4p-4h,  $\beta_2 = 0.46 \pm 0.03$   
 Dans cette bande,  $4^+ \rightarrow 2^+$ , avec  $B(E2) = 53 \pm 9$  W.u.
- $^{40}\text{Ca}$  : bande SD**,  $^{28}\text{Si}(^{20}\text{Ne}, 2\alpha)^{40}\text{Ca}$ ,  $0^+$  à  $E = 5213$  keV  
 (E. Ideguchi *et al.* *Phys.Rev.Lett.* 22 (2001))  
 bande 8p-8h,  $\beta_2 = 0.59 \pm 0.09$   
 Dans cette bande,  $4^+ \rightarrow 2^+$  avec  $B(E2) = 170 \pm 40$  W.u.  
 $B(E2)$ s MC en bon accord
- $^{28}\text{Si}$**  : des prédictions théoriques MC et AMD  
 (Y. Taniguchi *et al.* 2009, T. Ichikawa *et al.* 2011)  
 Principalement une structure  $\alpha + ^{24}\text{Mg}$   
 GS oblate + ND band  
 Bande SD (à  $\sim 14$  MeV,  $I \sim 6\hbar^2/\text{MeV}$ )  
 Exp.  $^{28}\text{Si}(\alpha, \alpha')$  RCNP Osaka (D. Jenkins, D. Montanari *et al.*)  
 Grand Raiden + CAGRA  
 Oct. 2016

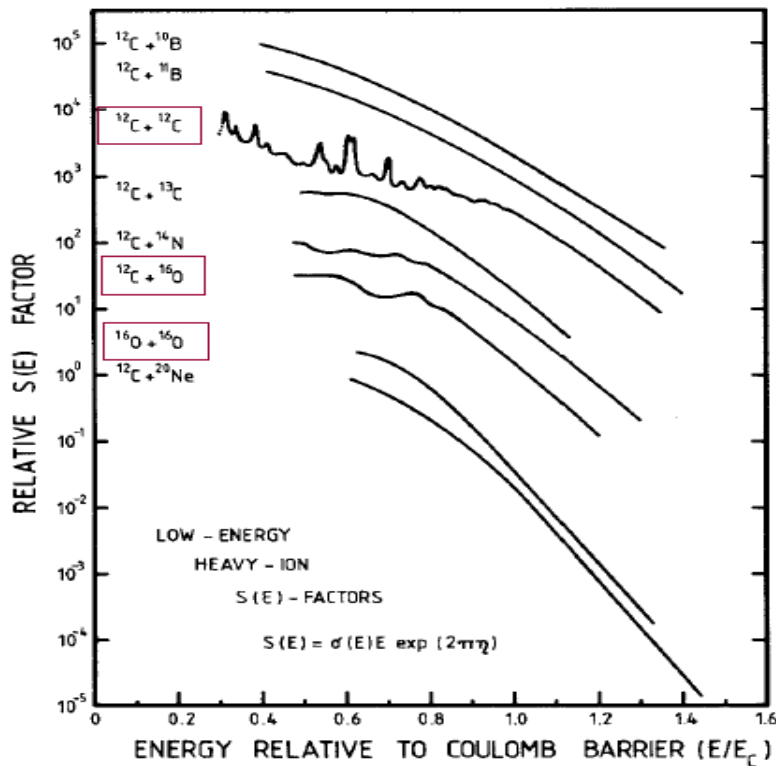


CAGRA, 16 clovers

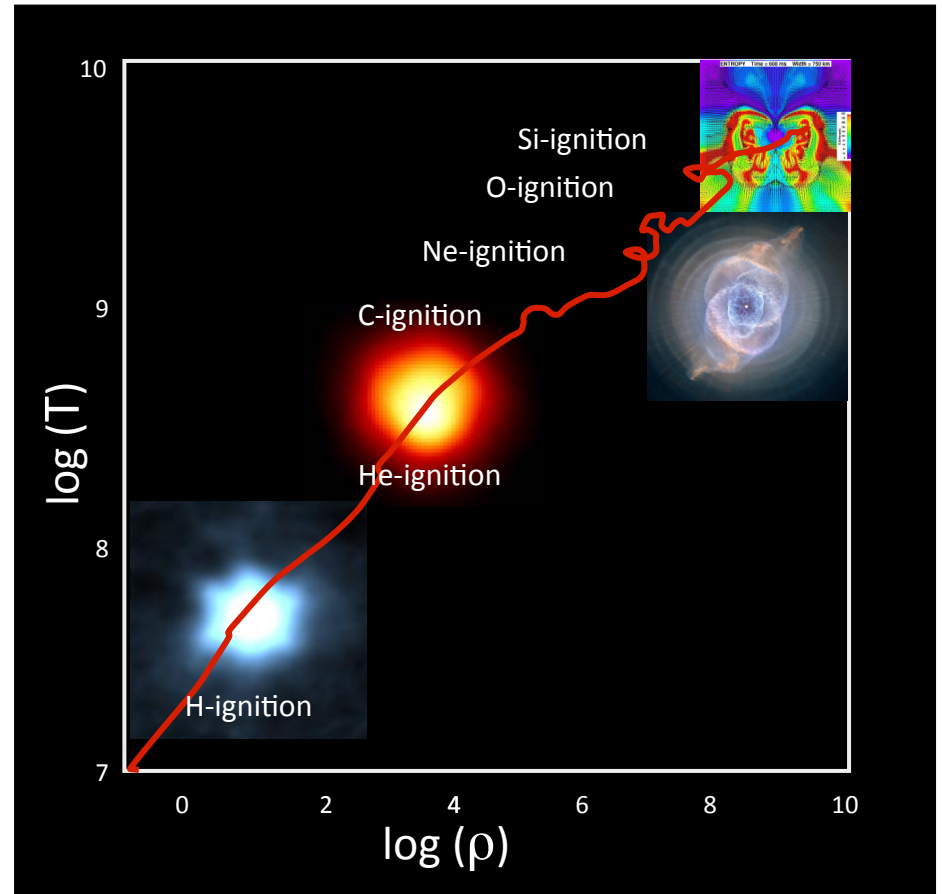


# Agrégats & astrophysique

- La réaction de fusion  $^{12}\text{C}+^{12}\text{C}$



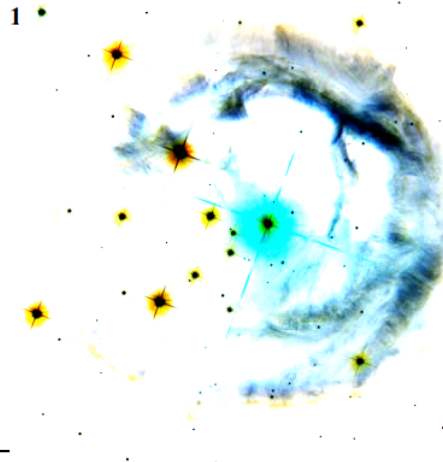
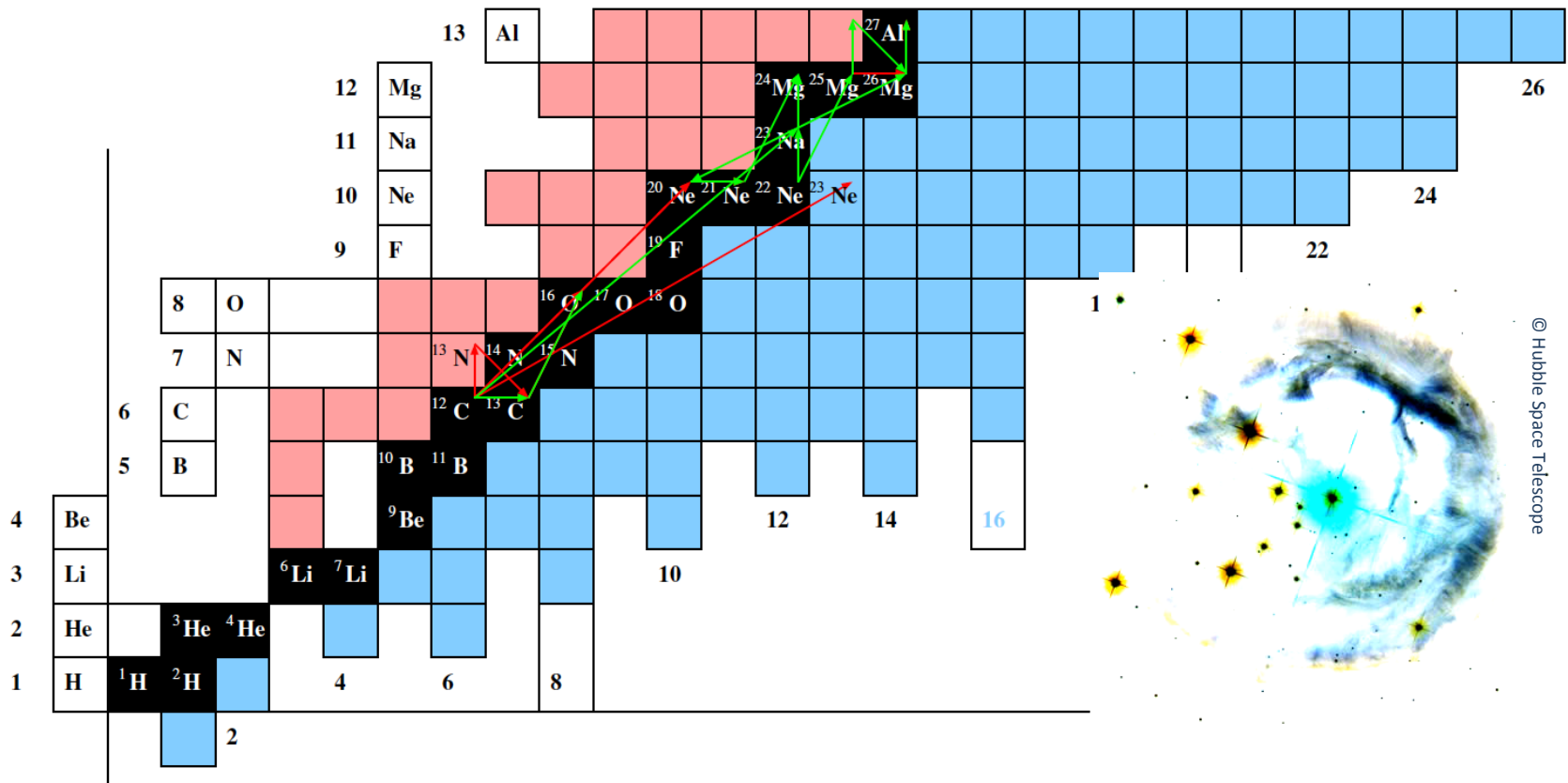
R. Stokstad et al., Phys.Rev.Lett. 37 (1976)



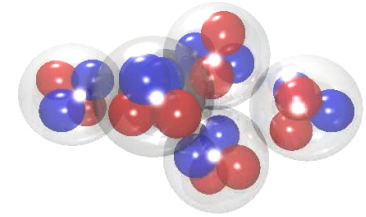


# Agrégats & astrophysique

- La réaction de fusion  $^{12}\text{C}+^{12}\text{C}$  - nucléosynthèse



# Agrégats & astrophysique

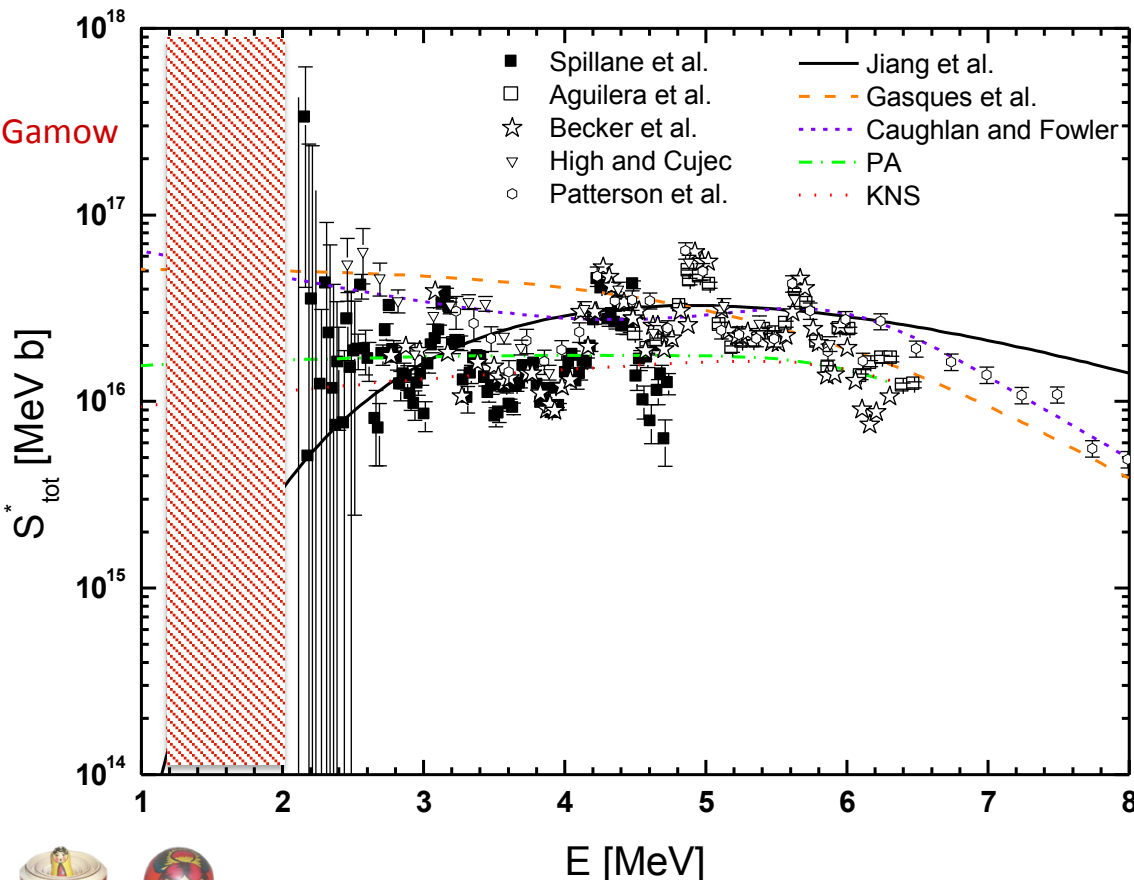


- La réaction de fusion  $^{12}\text{C}+^{12}\text{C}$

(toute) une histoire expérimentale et théorique

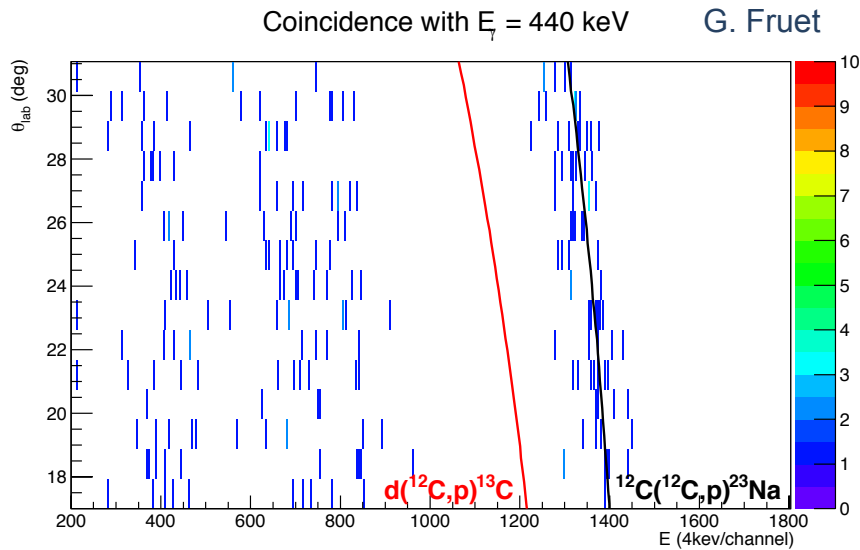
- + J.R. Patterson *et al.*, APJ 157, 367, (1969)
- G.J. Michaud and E.W. Vogt, PRC 5, 350, (1972)
- + M.G. Mazarakis and W.E. Stephens, PRC 7, 1280, (1973)
- - R.G. Stokstad *et al.*, PRL 37, 888, (1976)
- + P.R. Christensen *et al.*, Nucl. Phys. A 280, 189, (1977)
- + M.D. High and B. Čujec, NIM A 282, 181, (1977)
- + K.-U. Kettner *et al.*, PRL 38, 377, (1977)
- + K.A. Erb *et al.*, PRC 22, 507, (1980)
- + H.W. Becker *et al.*, Z. Phys. A 303, 305, (1981)
- Y. Suzuki and K.T. Hecht, Nucl. Phys. A 388, 102, (1982)
- + B. Čujec *et al.*, PRC 39, 1326, (1989)
- L.R. Gasques *et al.*, PRC 72, 025806, (2005)
- + E.F. Aguilera *et al.*, PRC 73, 064601, (2006)
- + L. Barrón-Palos *et al.*, Nucl. Phys. A 779, 318, (2006)
- + D. Jenkins *et al.*, PRC 76, 044310, (2007)
- + C.L. Jiang *et al.*, PRC 75, 015803, (2007)
- + T. Spillane *et al.*, PRL 98, 122501, (2007)
- + J. Zickefoose, Ph.D. thesis, U. of Connecticut (2010)
- + C.L. Jiang *et al.*, NIM A 682, 12, (2012)
- + X. Fang *et al.*, Jour. Phys. 420, 012151, (2013)
- + C.L. Jiang *et al.*, PRL 110, 072701, (2013)
- A.A. Aziz *et al.*, PRC 91, 015811, (2015)
- + B. Bucher *et al.*, PRL 114, 251102, (2015)
- + A. Tumino *et al.*, EPJ Conf. 117, 09004, (2016)

ruit  
es



# Agrégats & astrophysique

- La réaction de fusion  $^{12}\text{C}+^{12}\text{C}$

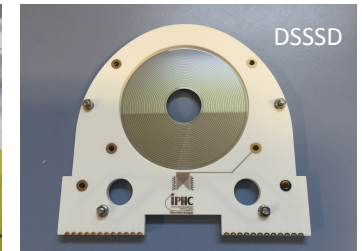
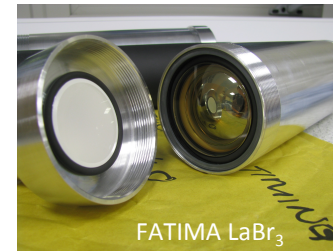
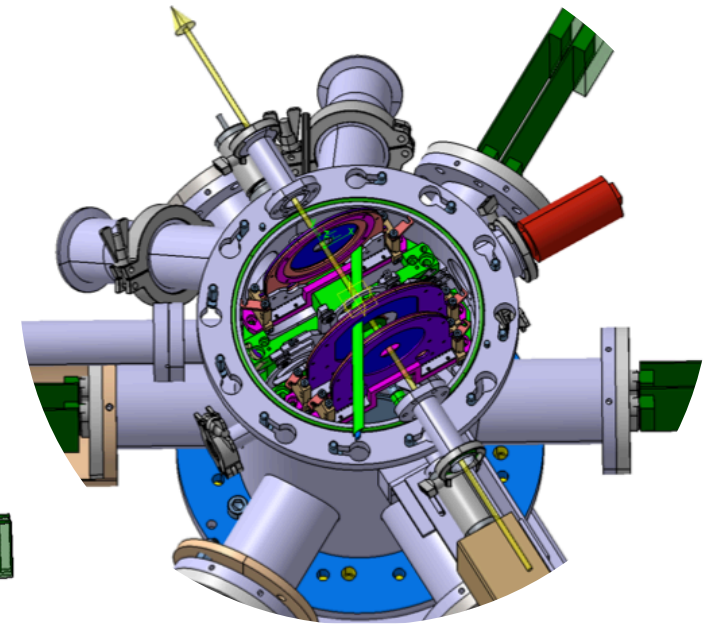
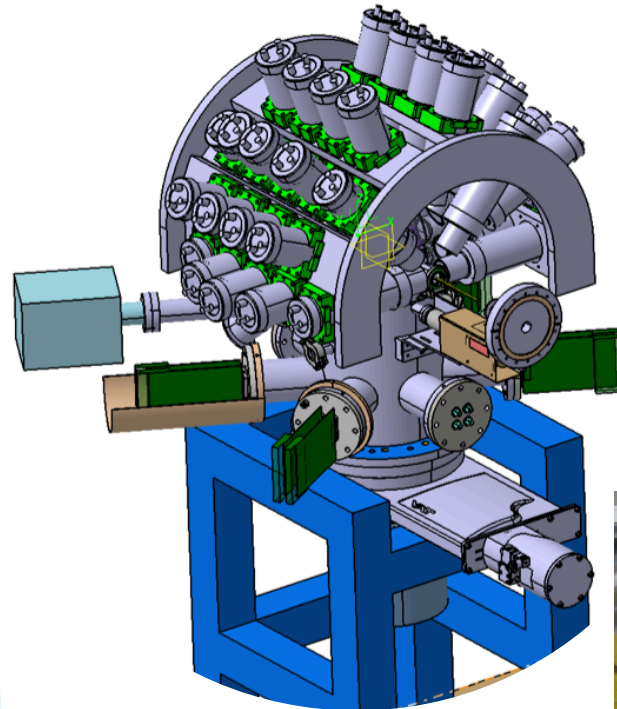


Exp. Gammasphere, Argonne National Laboratory, CL .Jiang



# Agrégats & astrophysique

- La réaction de fusion  $^{12}\text{C}+^{12}\text{C}$  : projet STELLA
  - Chambre à réaction vide poussé
  - Particules DSSSD / céramique
  - Gammas : 36 LaBr<sub>3</sub>(Ce)
  - Cible tournante
  - $I_{\text{Faisceau}} > 1 \mu\text{A}$

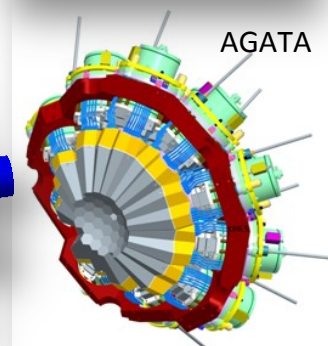
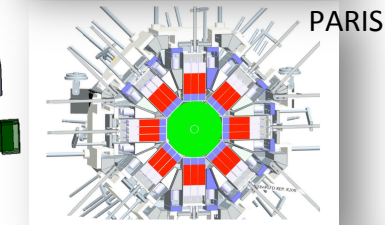
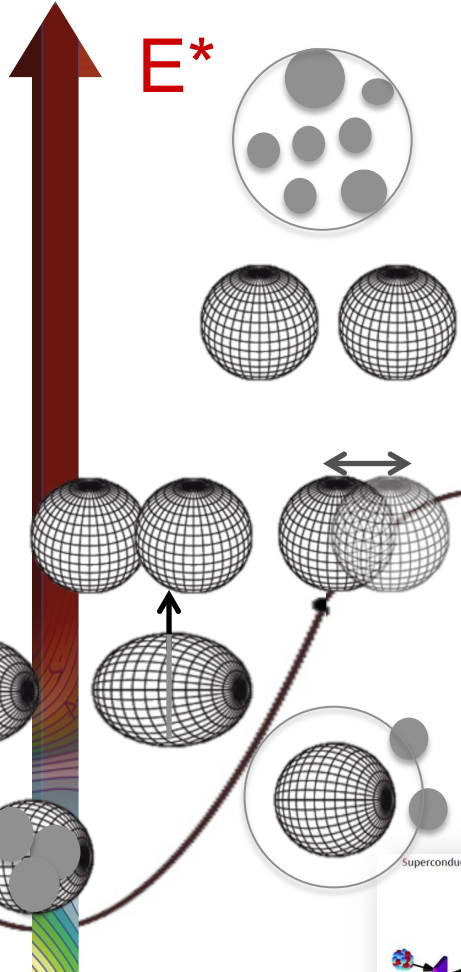


# Conclusions I

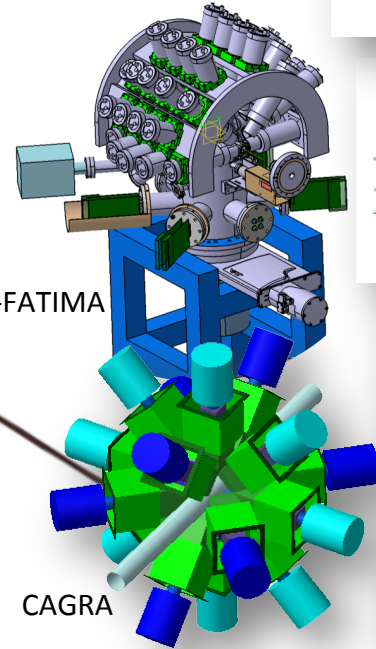
- Agrégats : ingrédient essentiel pour comprendre la structure nucléaire – les corrélations nucléaires
- Challenges pour le futur
  - Une description unifiée de  $^{12}\text{C}$  ( $^{16}\text{O}$ )
  - Un traitement à partir des degrés de liberté nucléoniques
  - Clusters et observables :  
Transitions  $\gamma$  entre états clusters  
Riches en neutrons, drip-line  
Identification des résonances moléculaires aux extrêmes



# Conclusions II

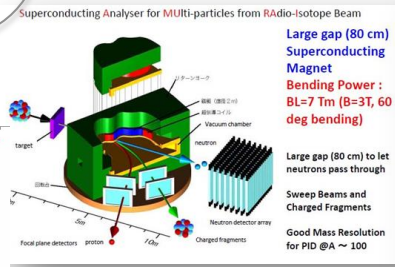


STELLA-FATIMA

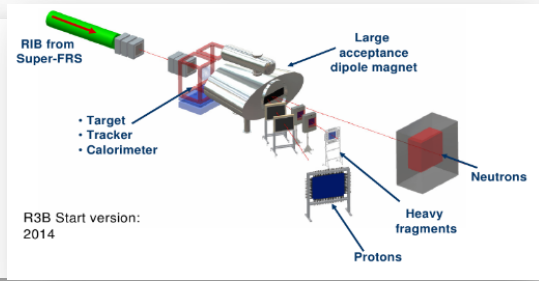


CAGRA

SAMURAI at RIKEN



R3B at FAIR

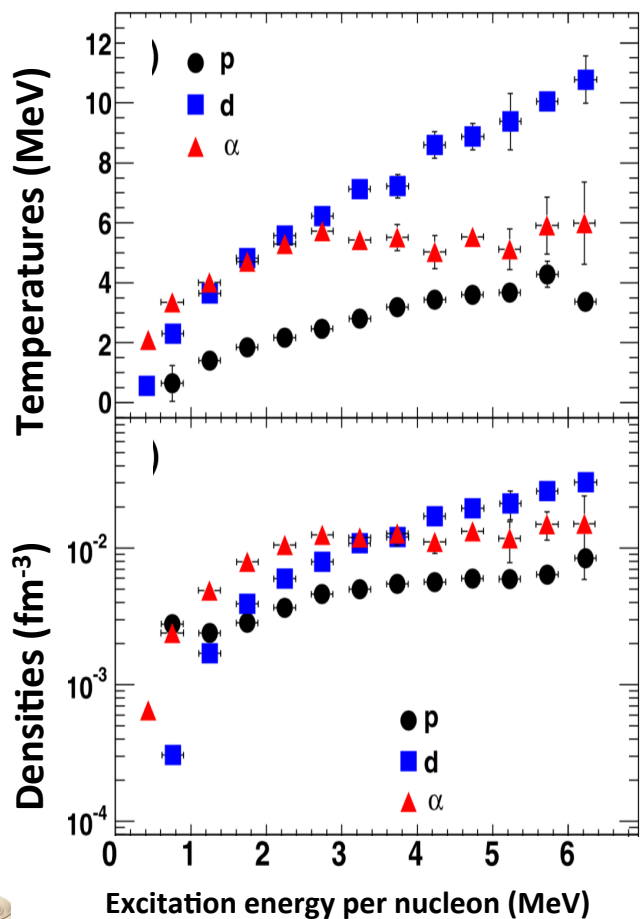
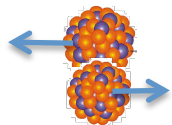


ANDROMEDE

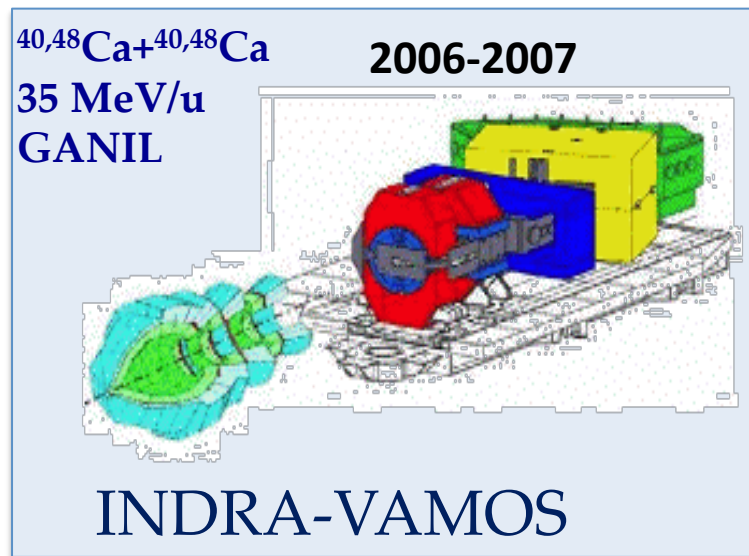
Spiral2



# Boson and fermion densities in peripheral collisions



Signals of BEC phenomena in alpha cluster emission from hot projectile-like fragments

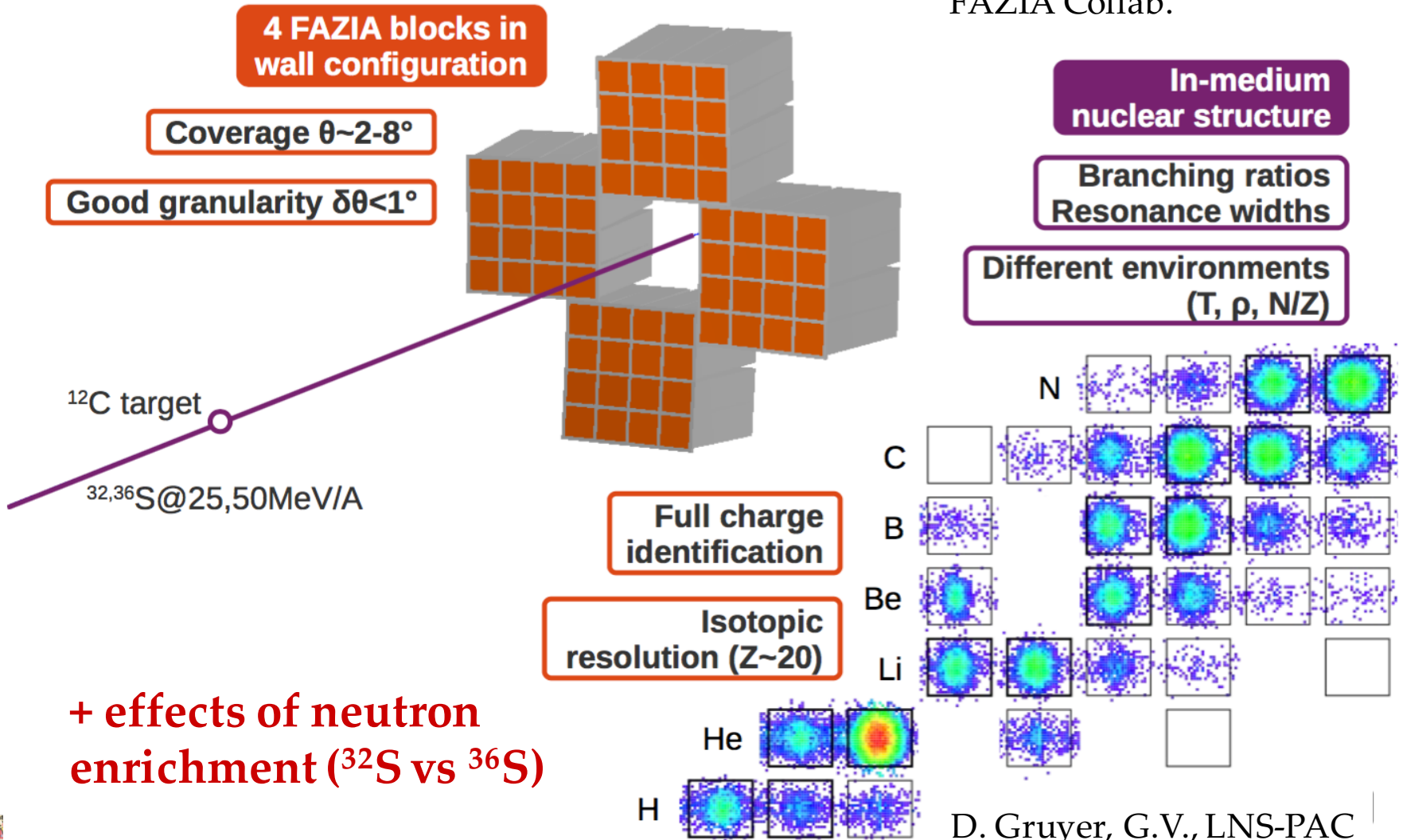


P. Marini, H. Zheng, M. Boisjoli, G. Verde, A. Chbihi et al.  
 Phys. Lett. B 756, 194 (2016)



# FAZIA-COR experiment @ LNS

G. Verde, D. Gruyer  
FAZIA Collab.

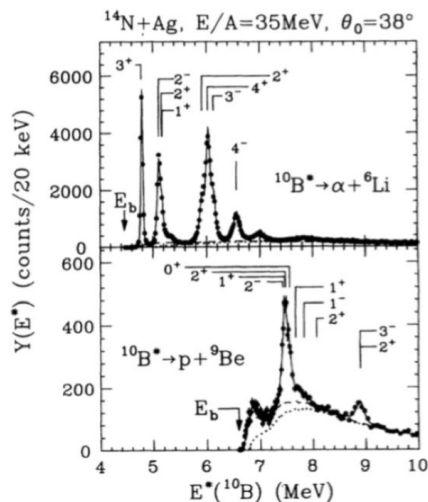
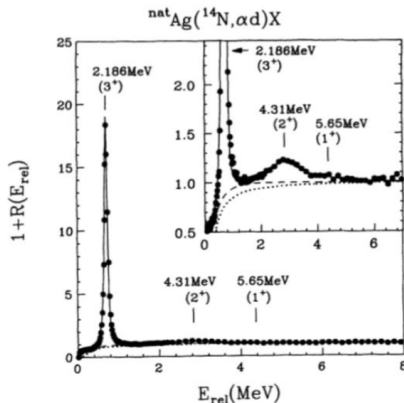


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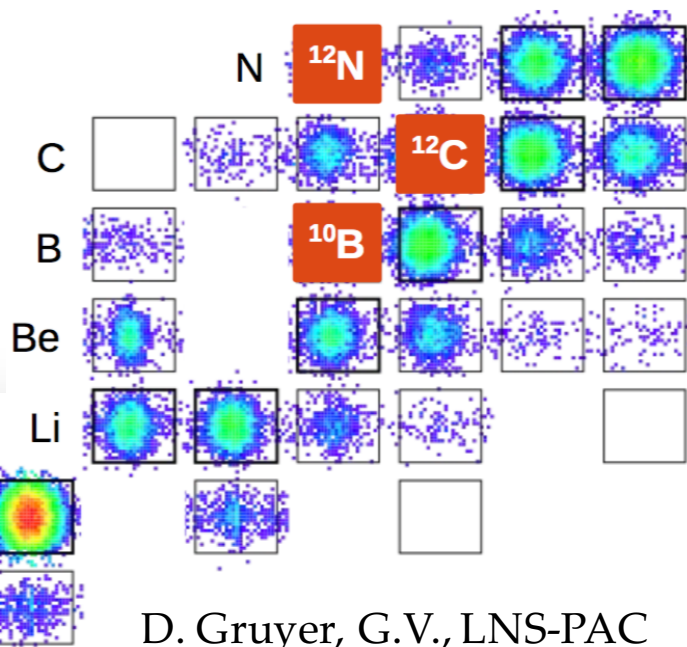
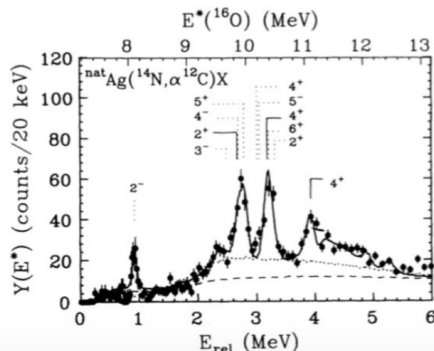
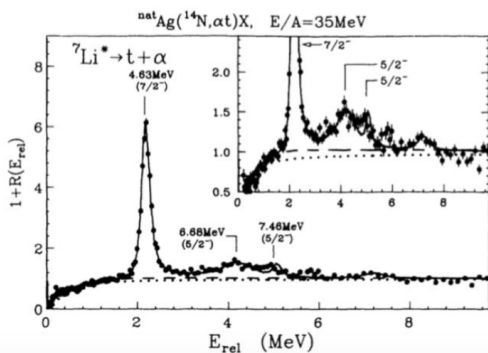




# Plenty of physics cases...



$^{12}\text{N} \rightarrow ^{11}\text{C} + \text{p}$   
 $^{10}\text{B} \rightarrow ^6\text{Li} + \alpha, ^8\text{Be} + \text{d}, ^9\text{Be} + \text{p}$   
 $^{12}\text{C} \rightarrow ^8\text{Be} + \alpha, \alpha + \alpha + \alpha$   
 ...other cases...



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