24th European Conference on Few-Body Problems in Physics

University of Surrey, Guildford, UK (2–6/09/2019)

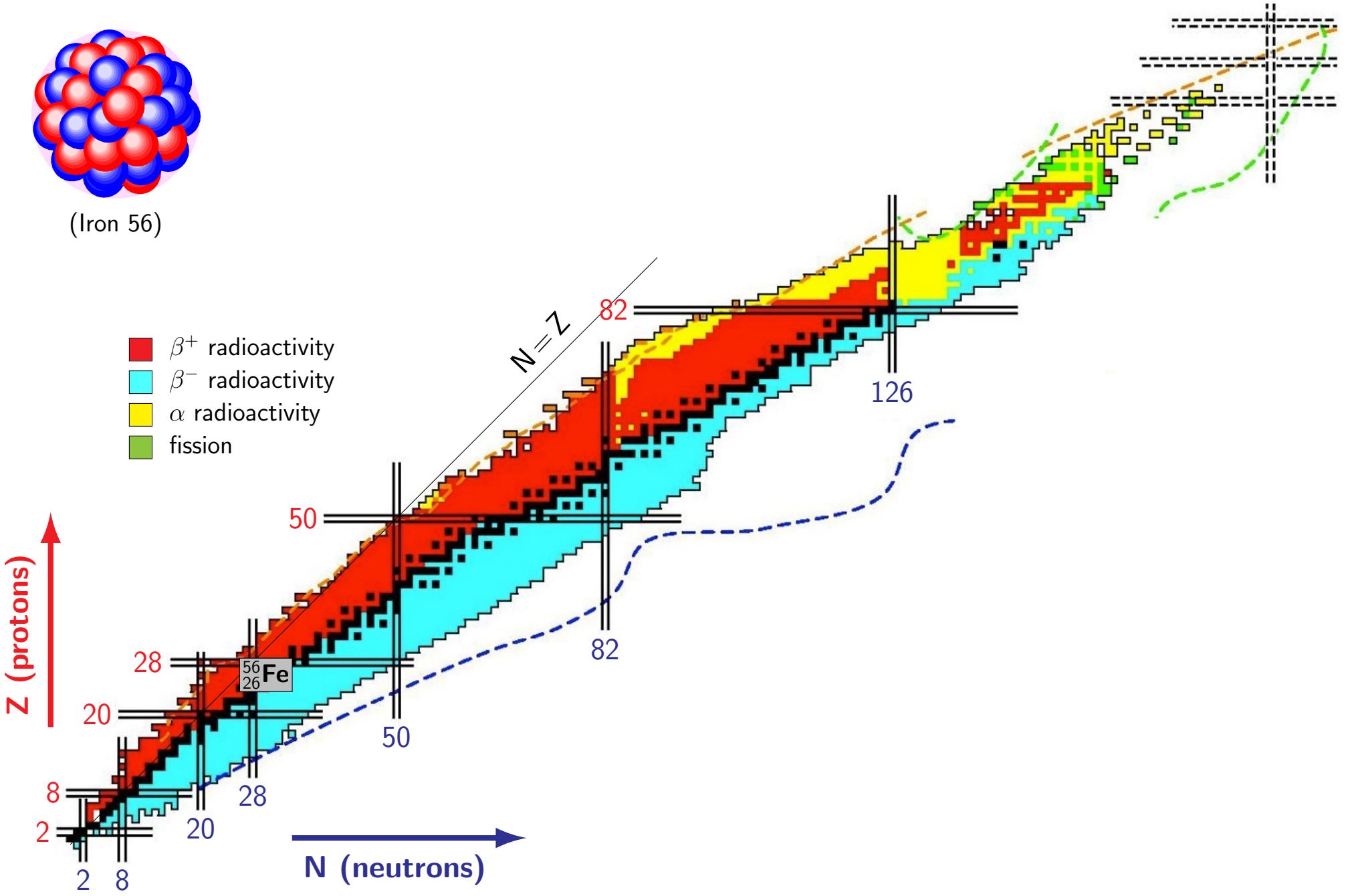
Exotic structures in Exotic nuclei

F. Miguel Marqués

lpc caen
laboratoire de physique corpusculaire

The limits of the nuclear landscape

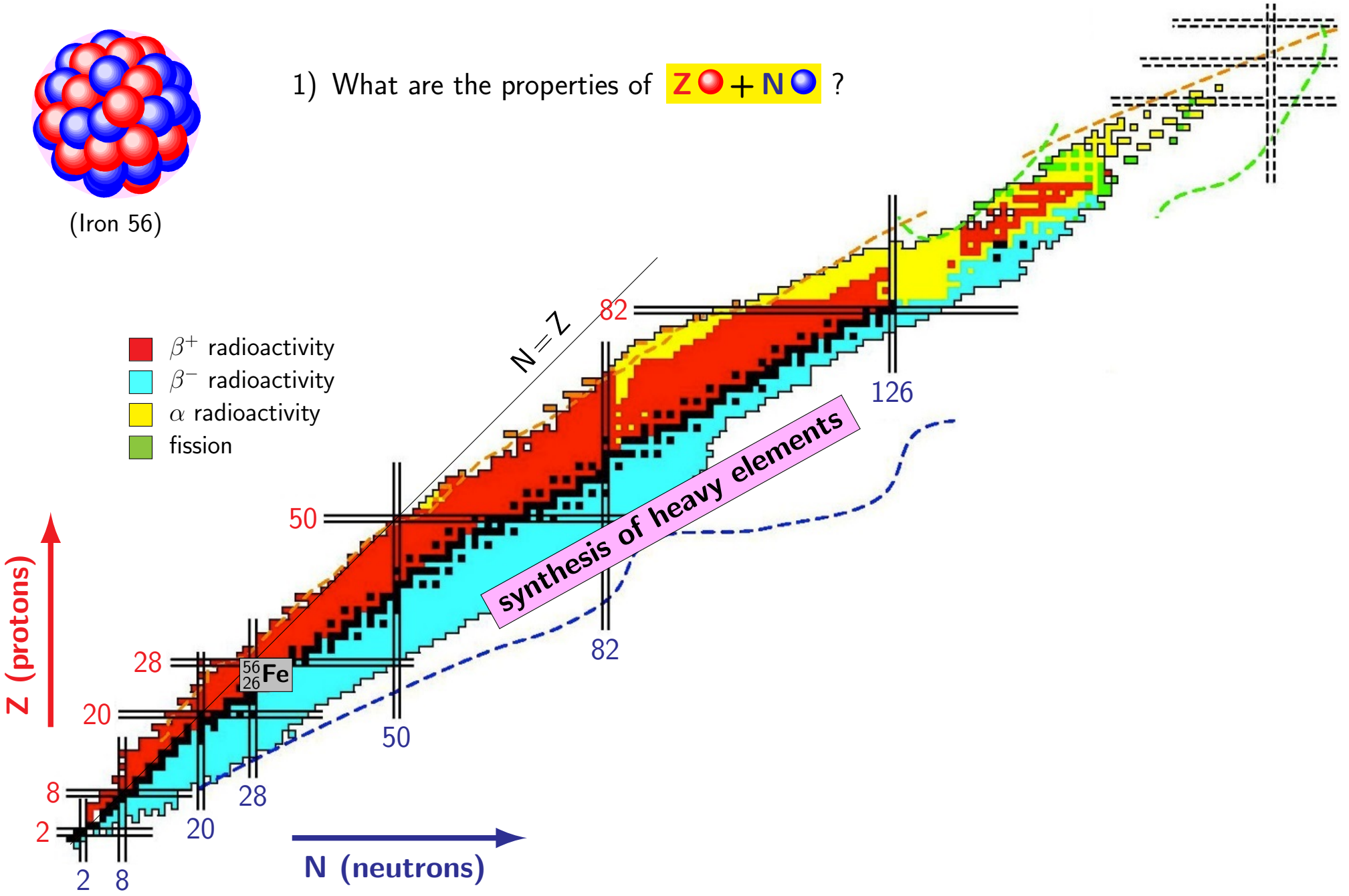
(Iron 56)



The limits of the nuclear landscape

(Iron 56)

1) What are the properties of Z + N ?



The limits of the nuclear landscape

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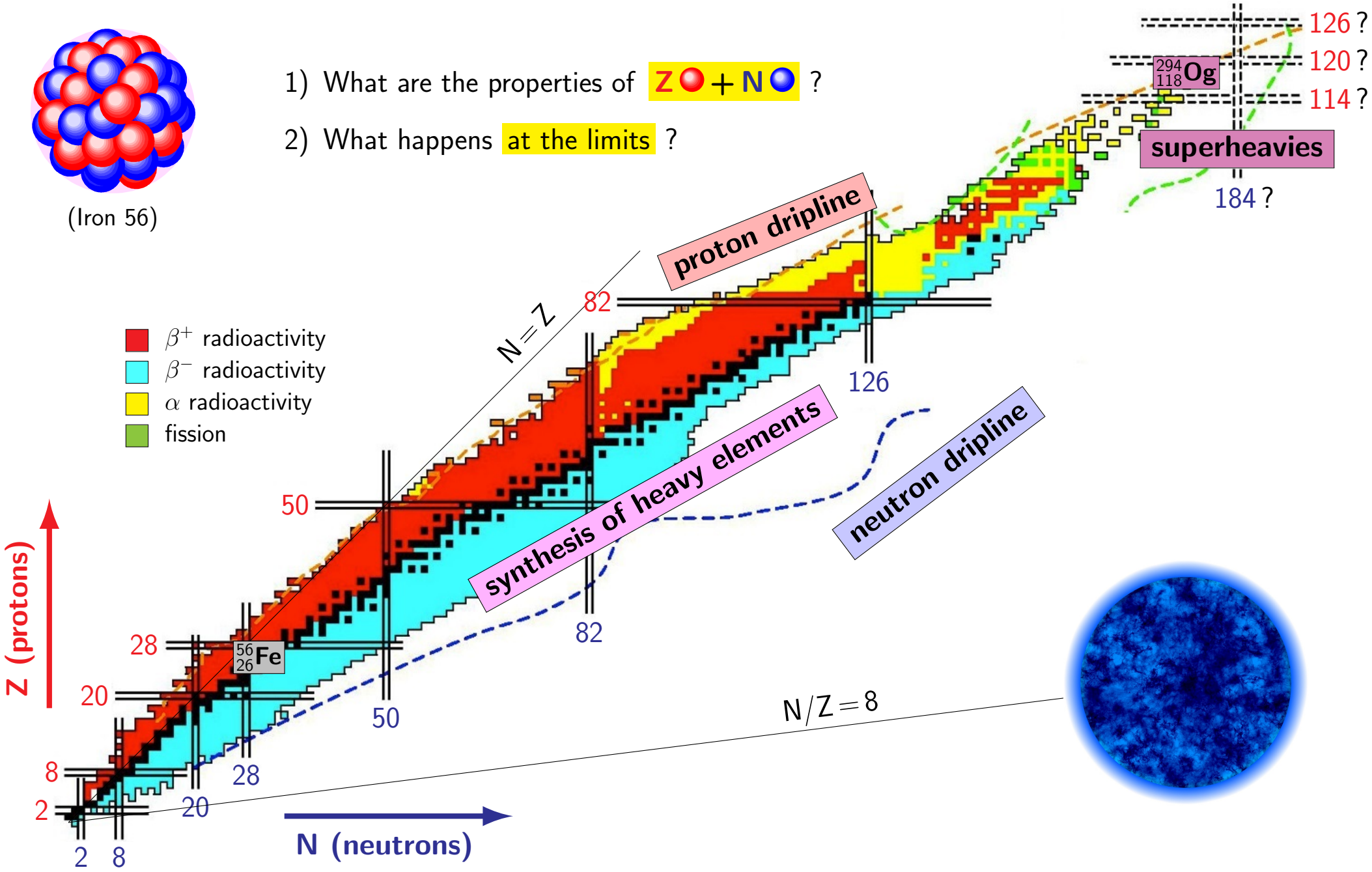
1) What are the properties of Z + N ?

2) What happens at the limits ?



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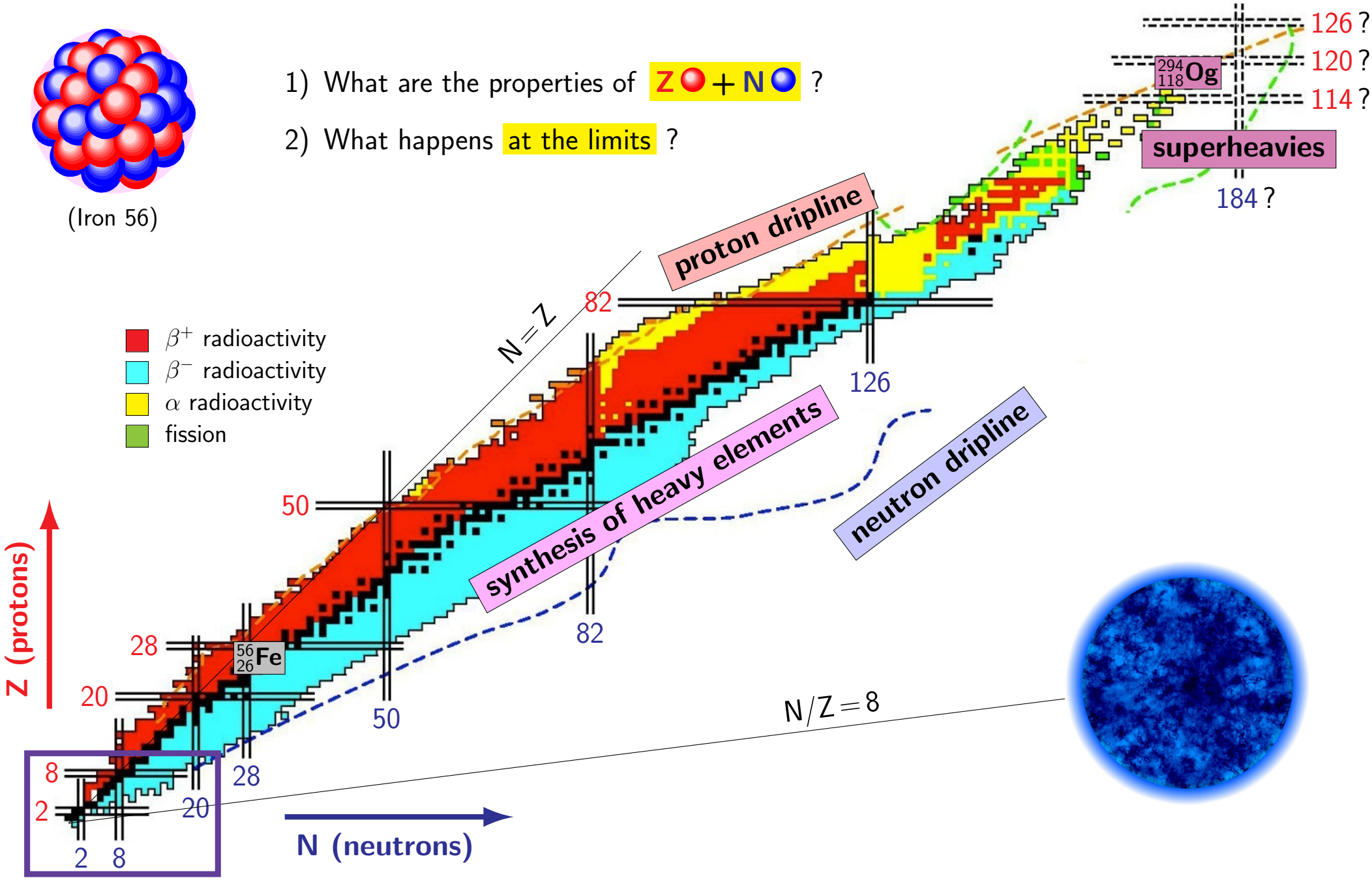
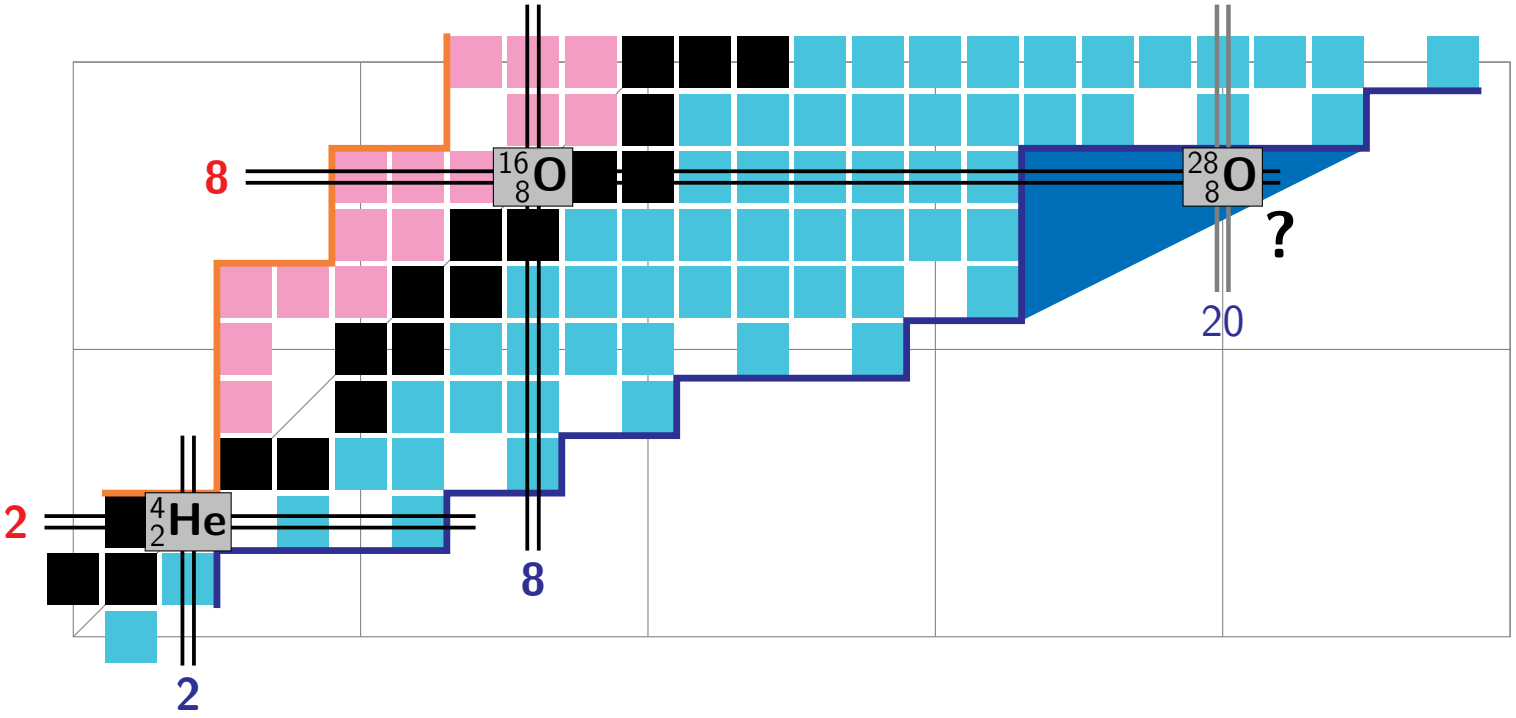
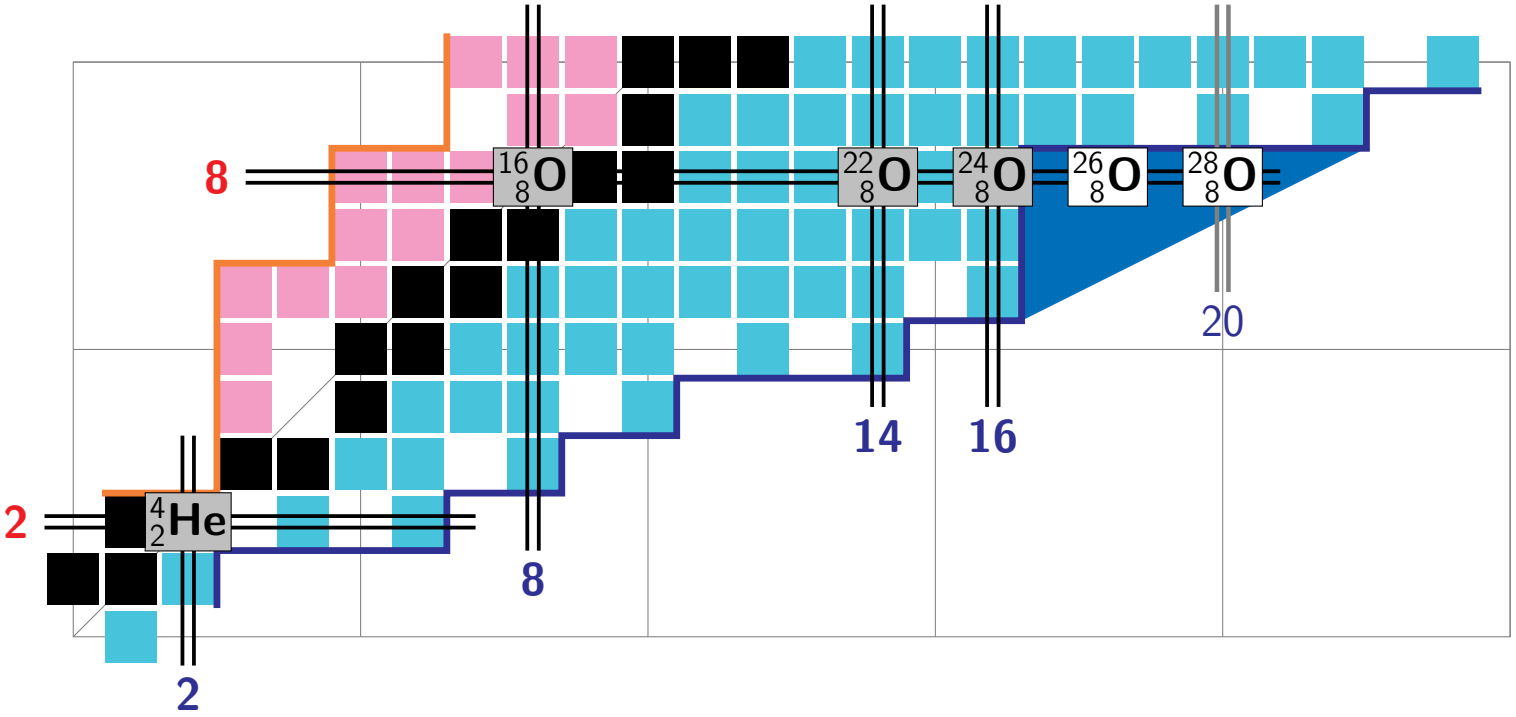


The exotic limits of exotic nuclei



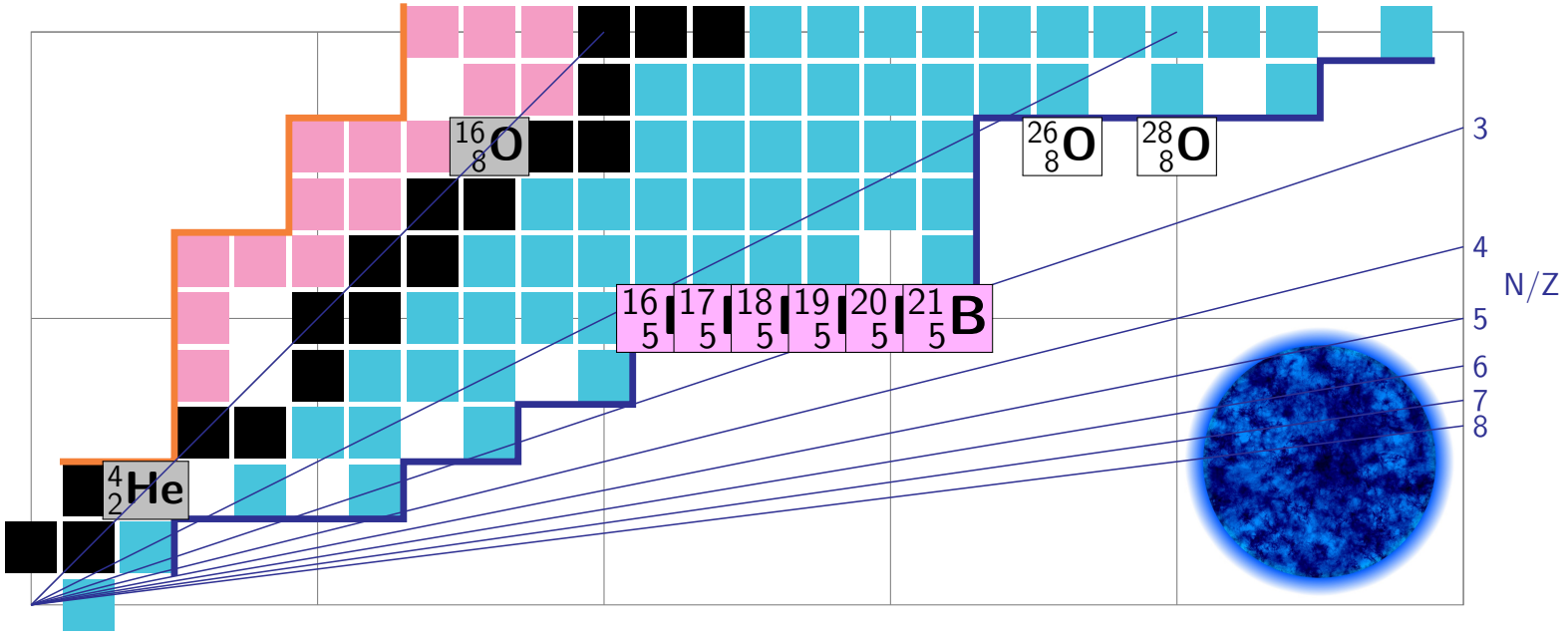
- "**Oxygen anomaly**" ?

The exotic limits of exotic nuclei



- "**Oxygen anomaly**" : N = 20 $\rightarrow$ **14** & **16**

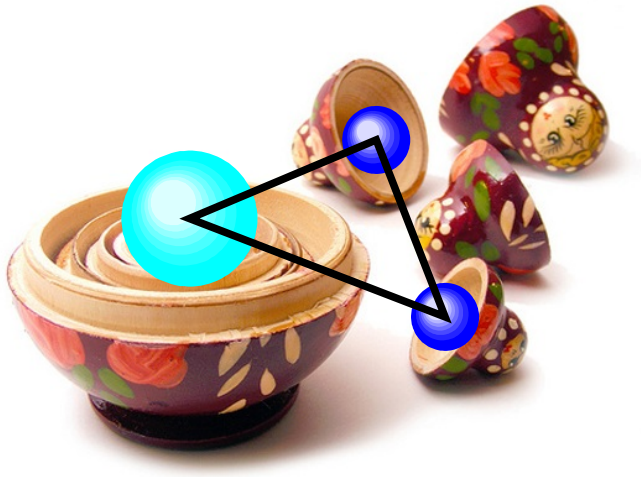
The exotic limits of exotic nuclei



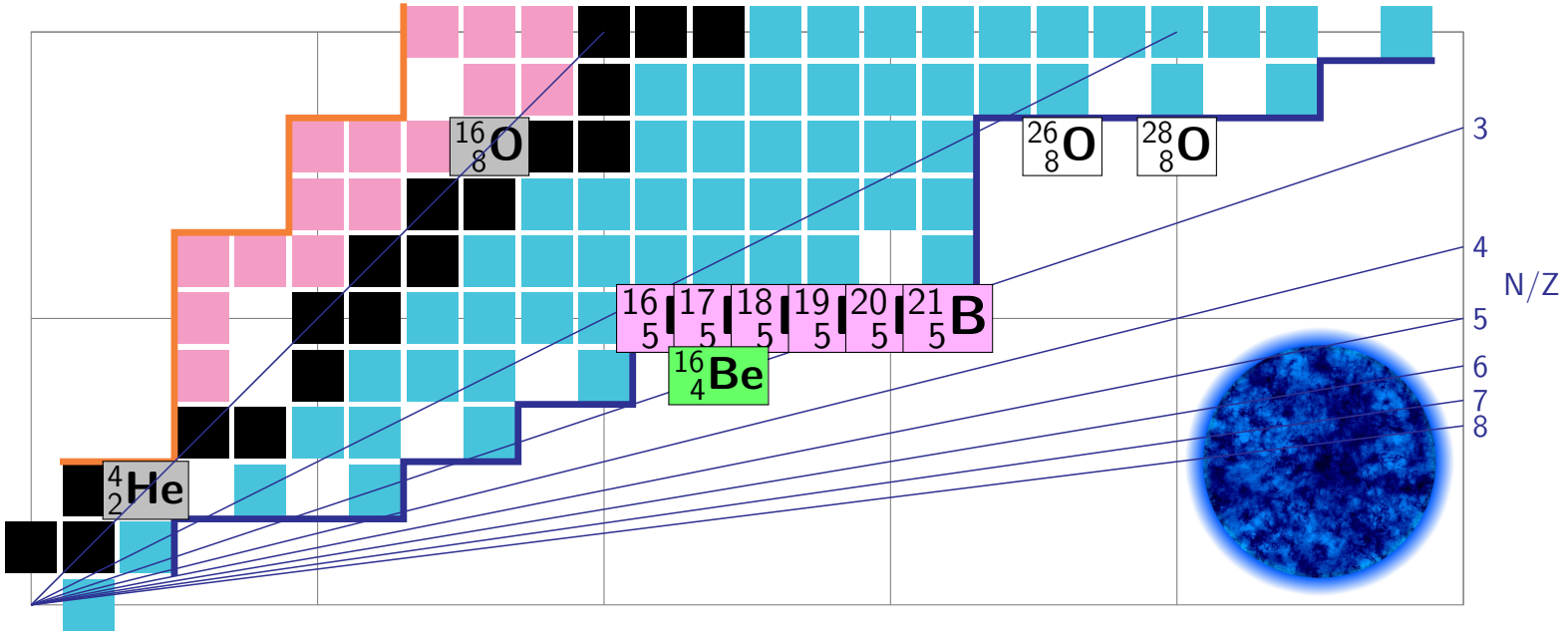
- Access to extreme N/Z ratios :

  ❶ Z = 5 (**SAMURAI Day-1**) :

  → literally exotic structures !



The exotic limits of exotic nuclei



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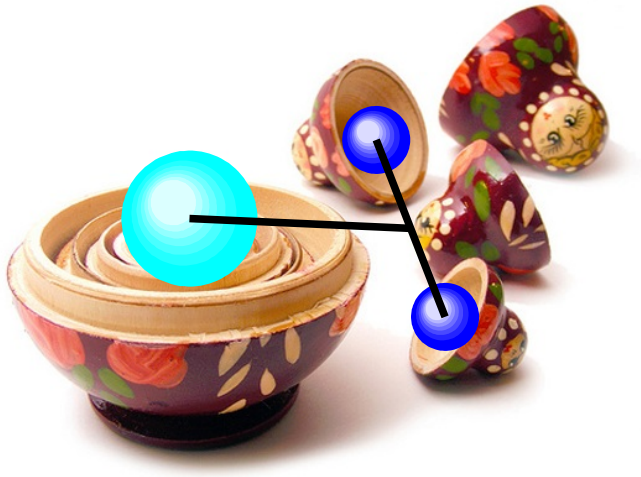

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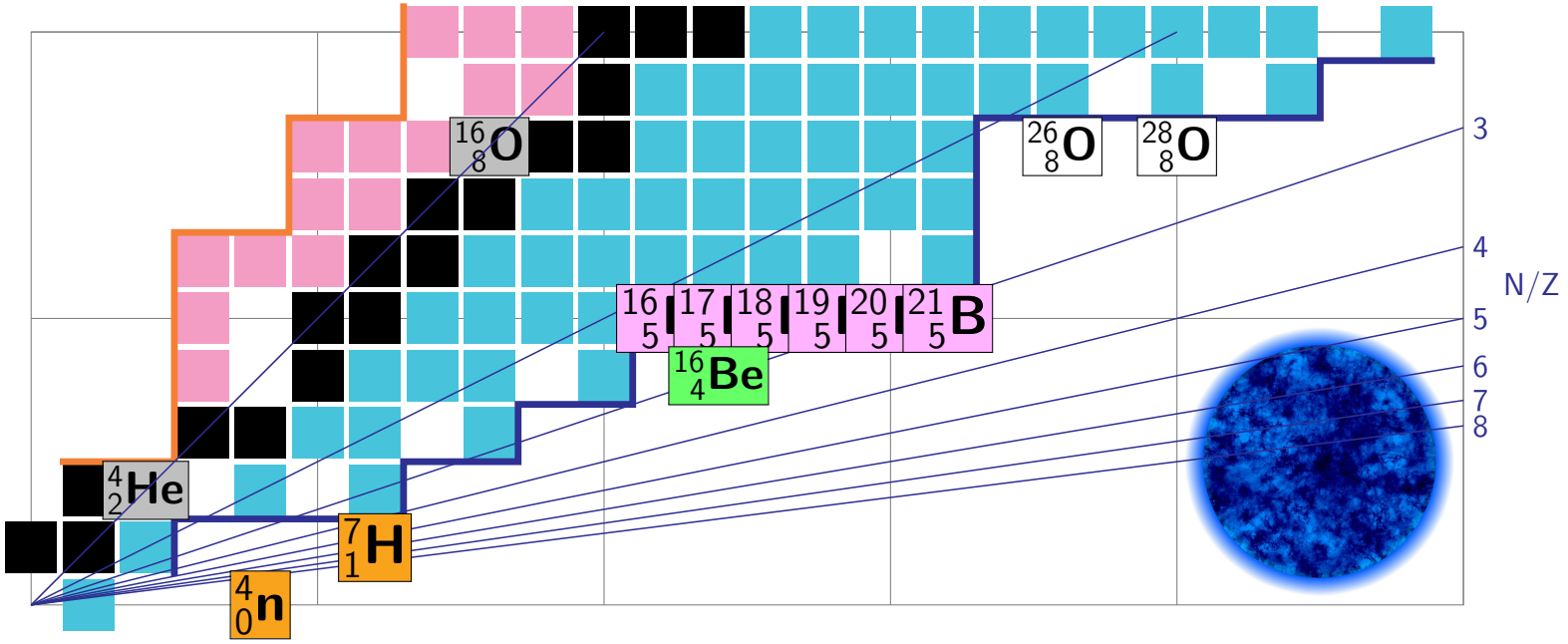

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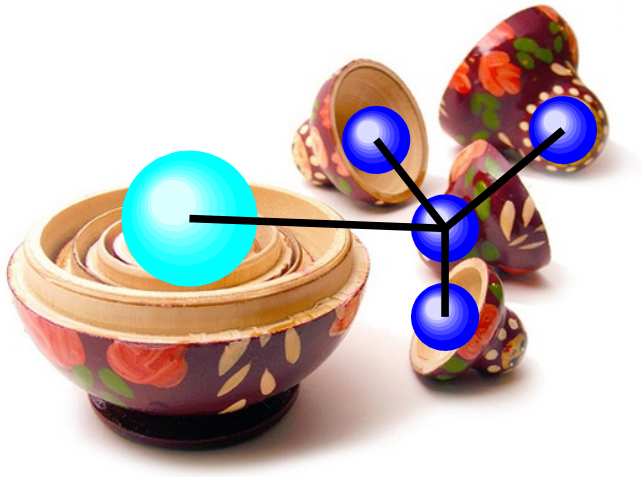
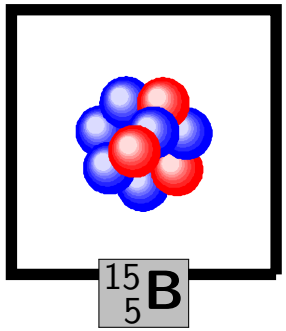
❸ Z = 1 & Z = 0 (**SAMURAI S34**) :

→ multineutron physics !



The Boron 'Matryoshka'



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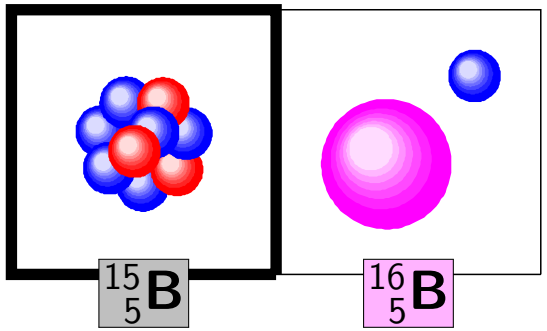

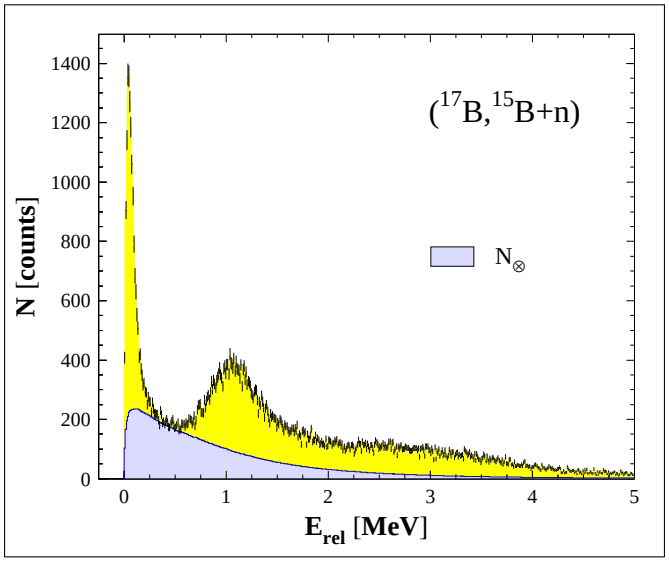

$\rightarrow$ $E_{gs} \sim 40$ keV

$\rightarrow$ $\frac{\delta m}{m} \sim 10^{-7}$!

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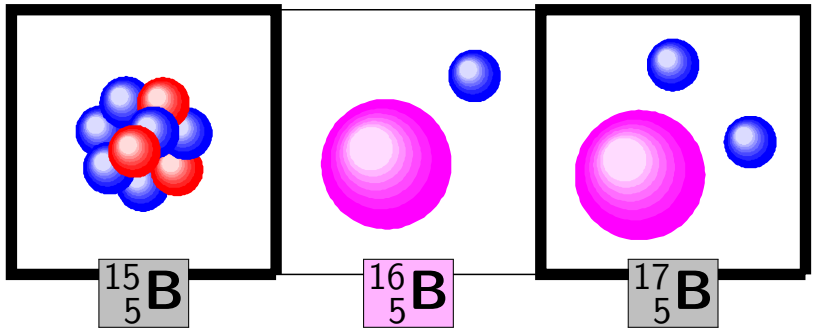

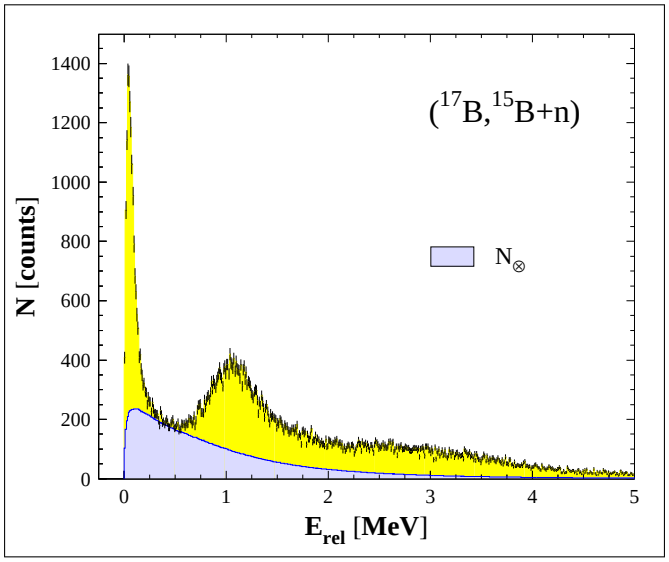

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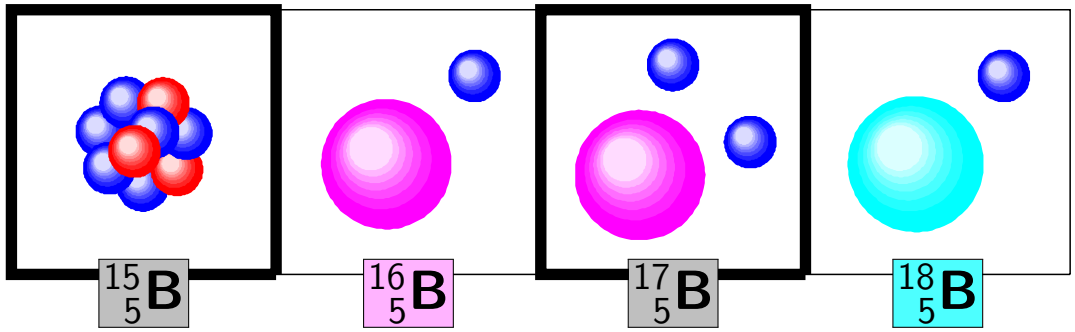

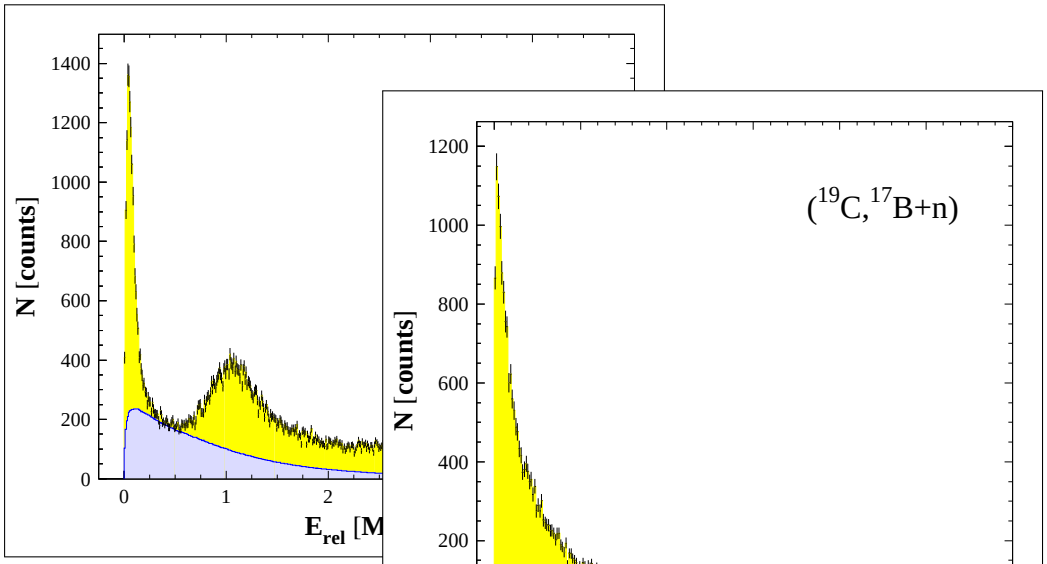

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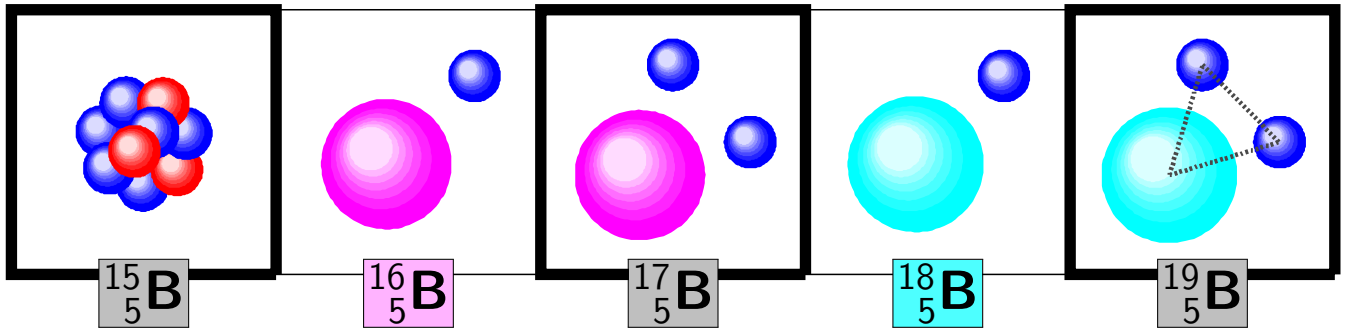

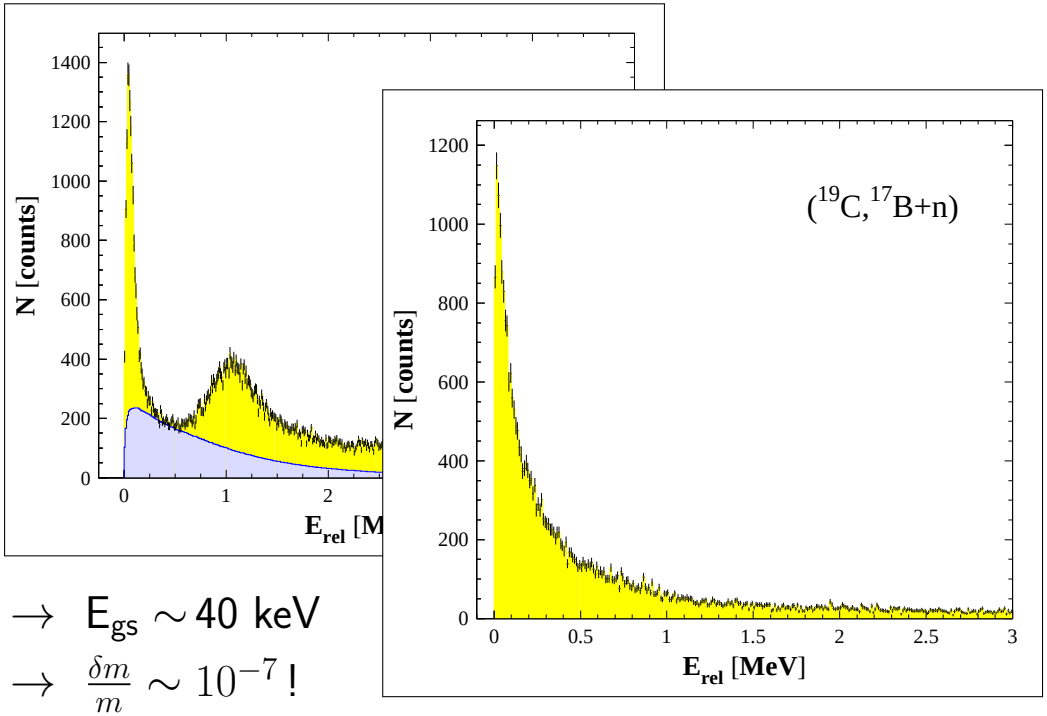

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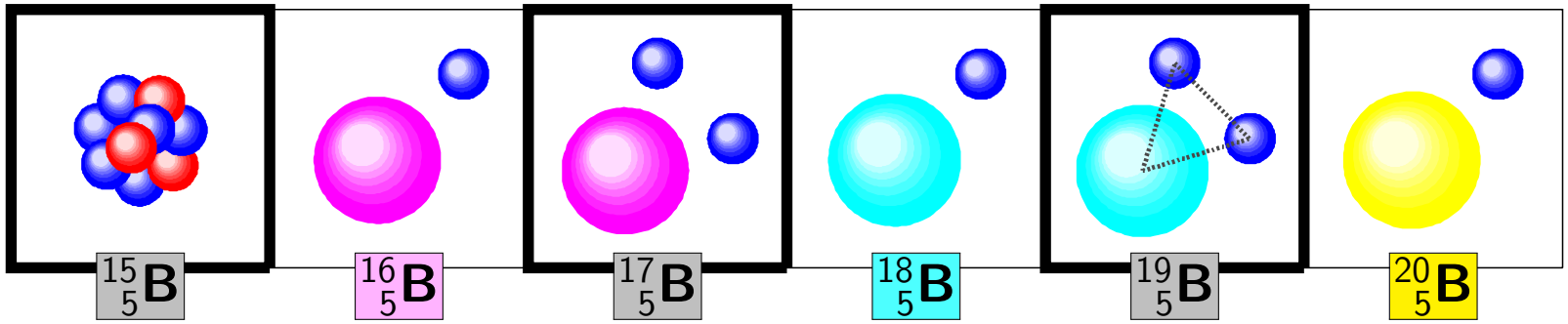

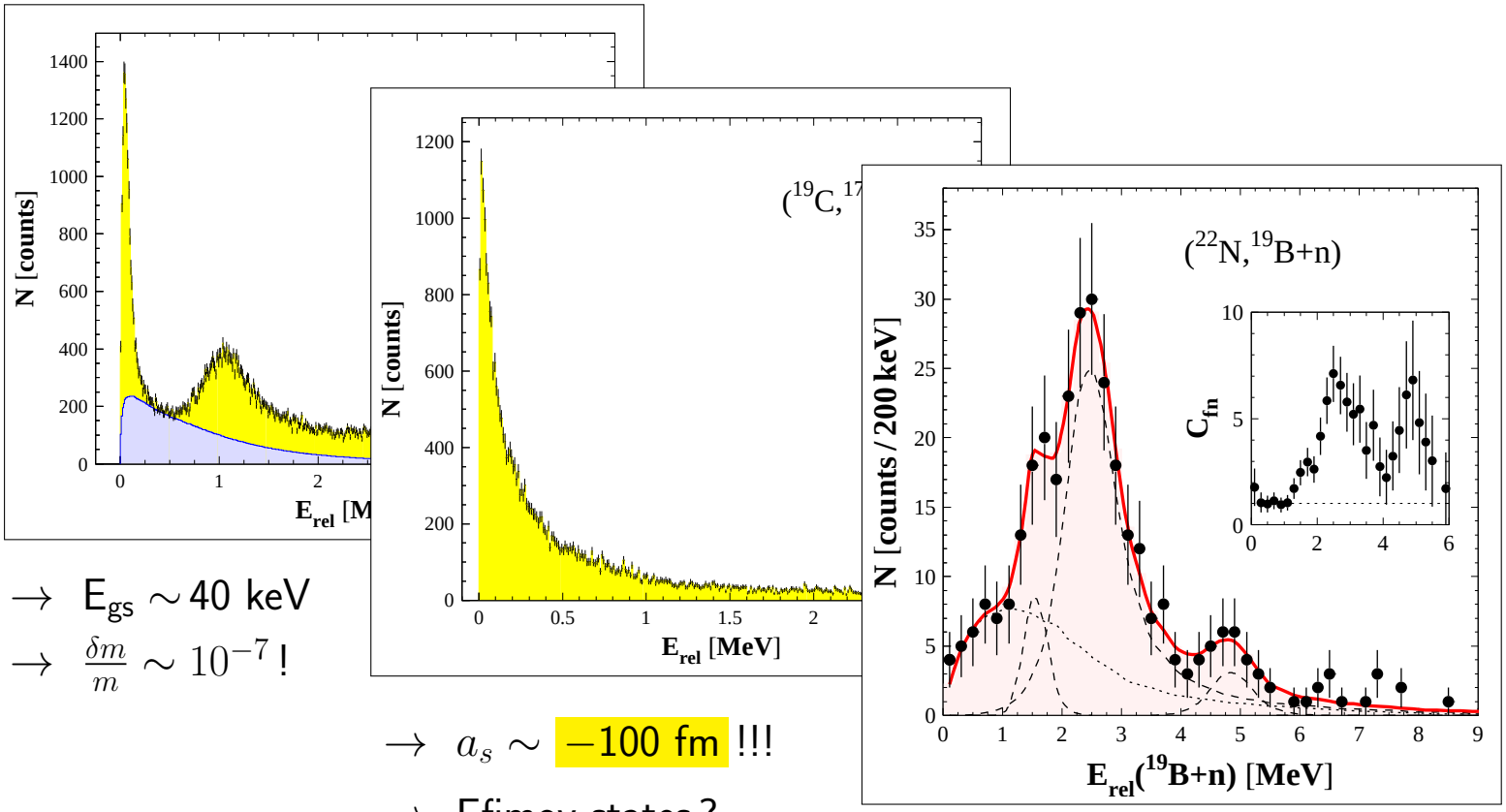

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Leblond, PRL 121 (2018) 262502

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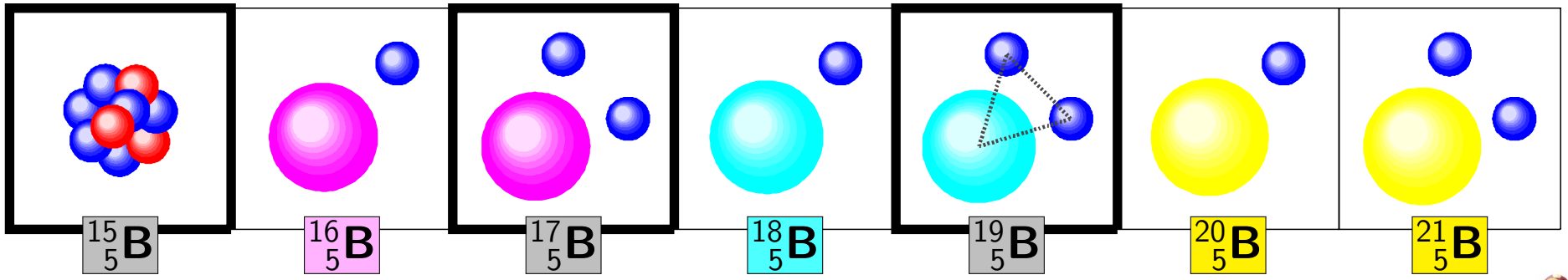

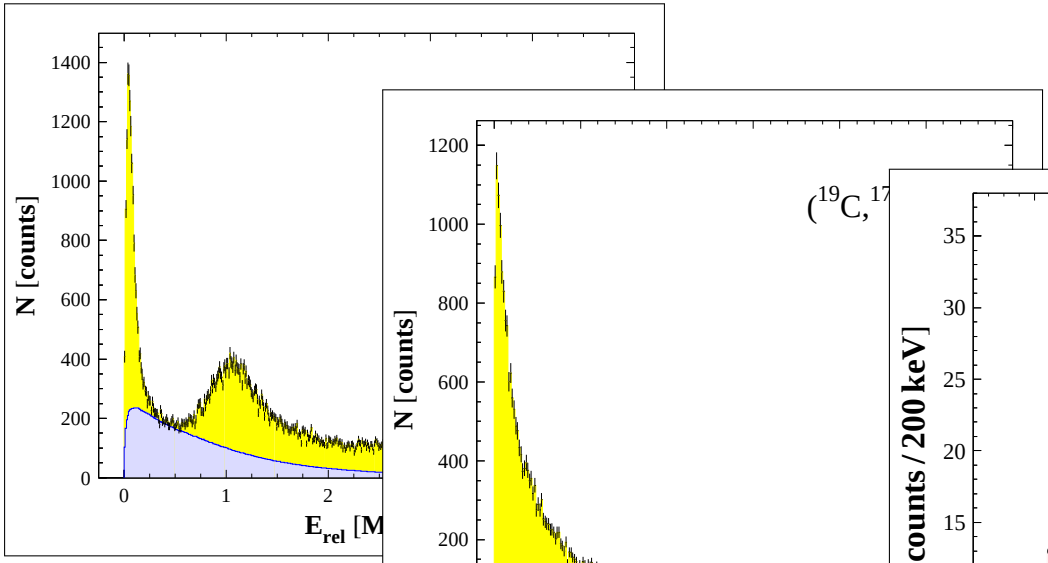

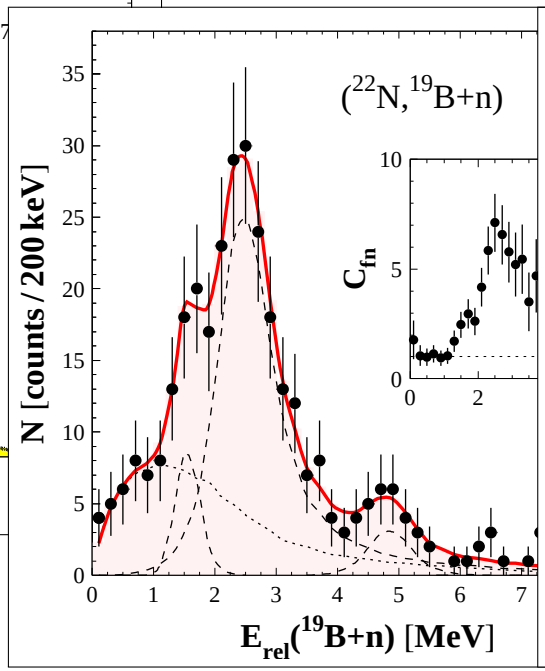

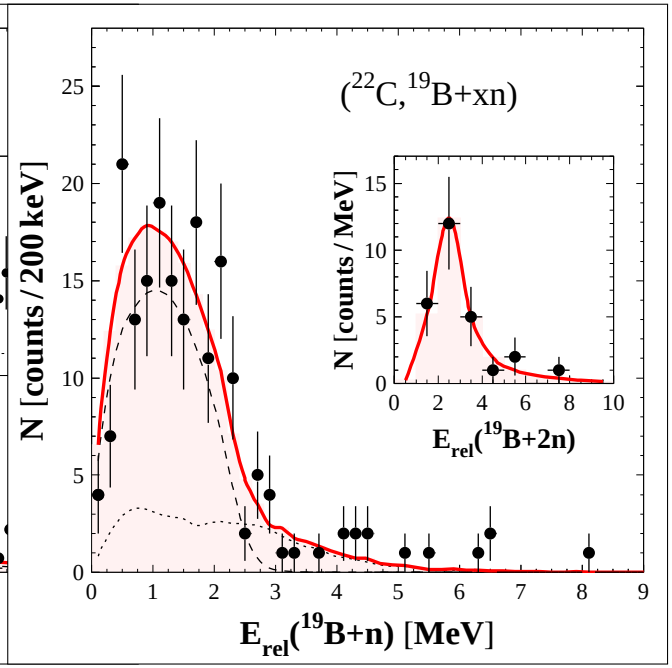

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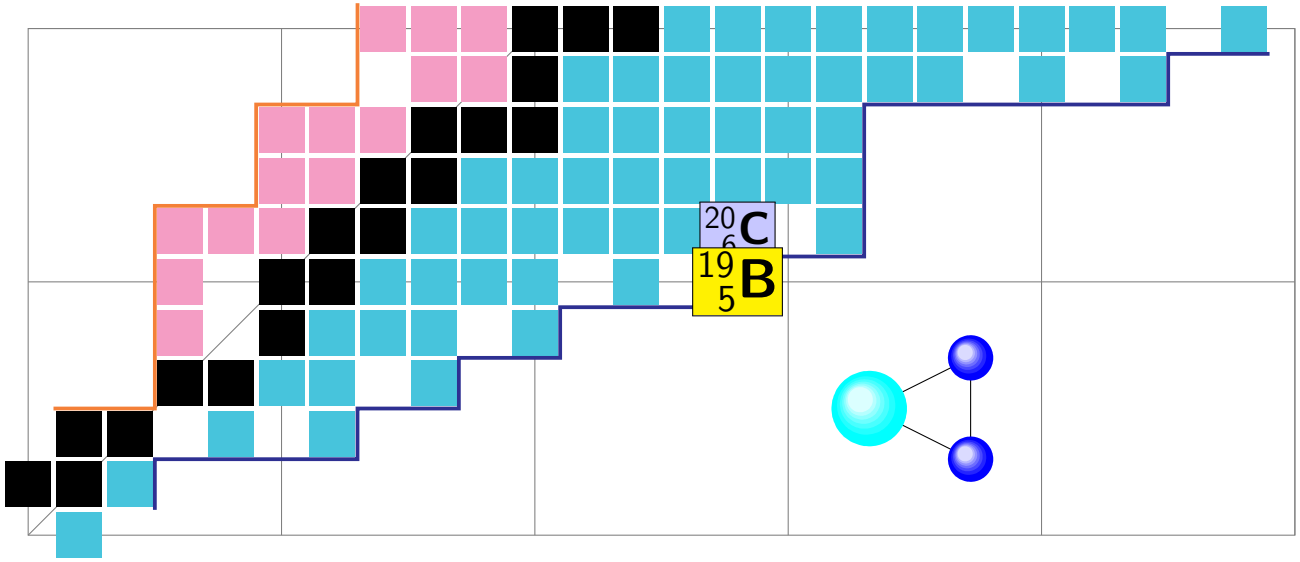
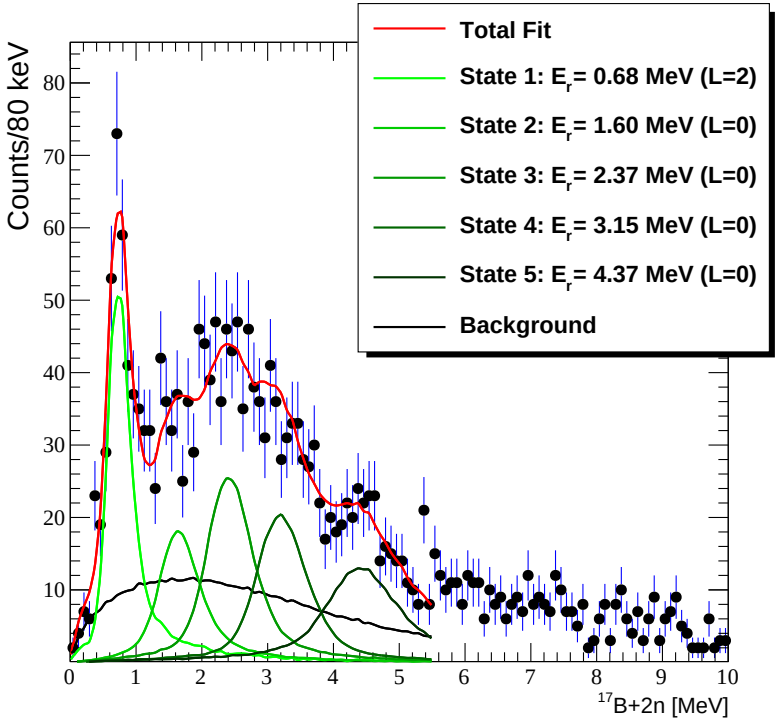
Leblond, PRL 121 (2018) 262502 → 2n emitter !

Boron 19 : two scattering lengths ! [J. Gibelin]





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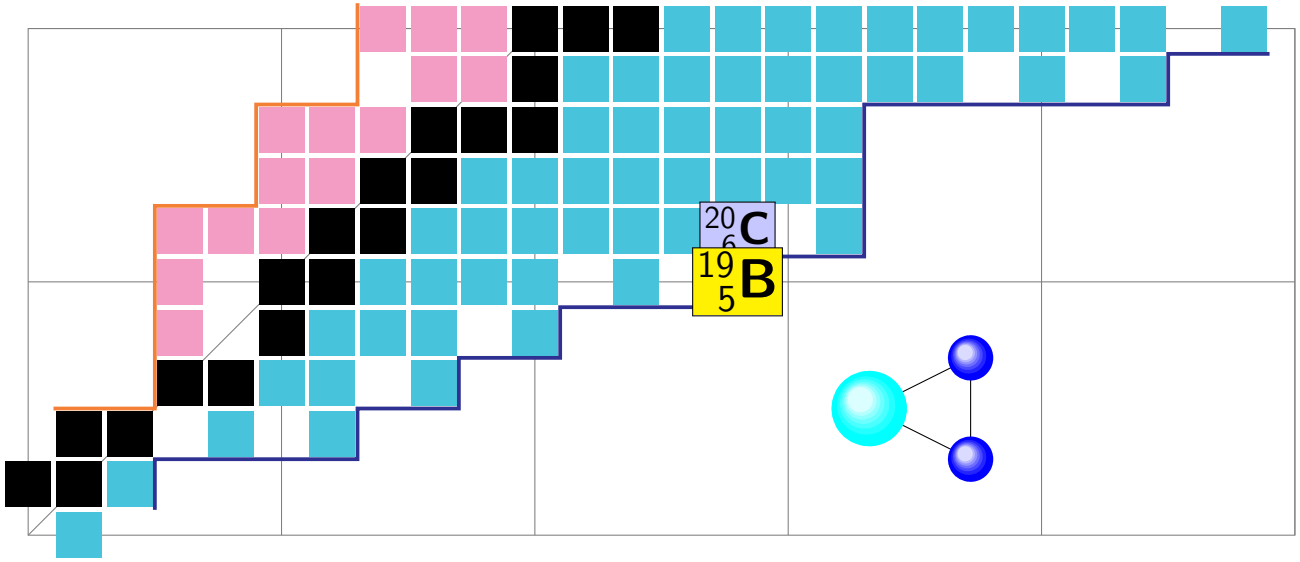

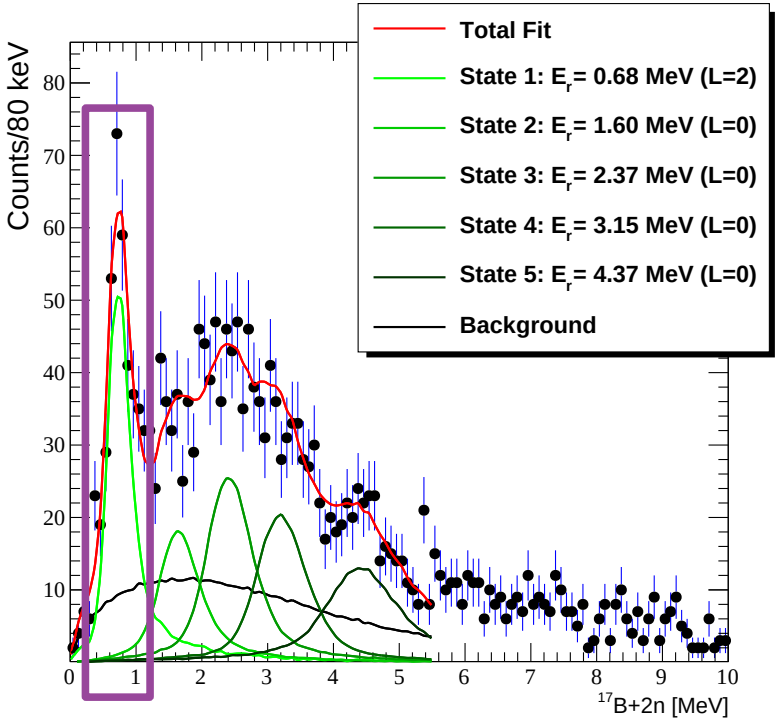

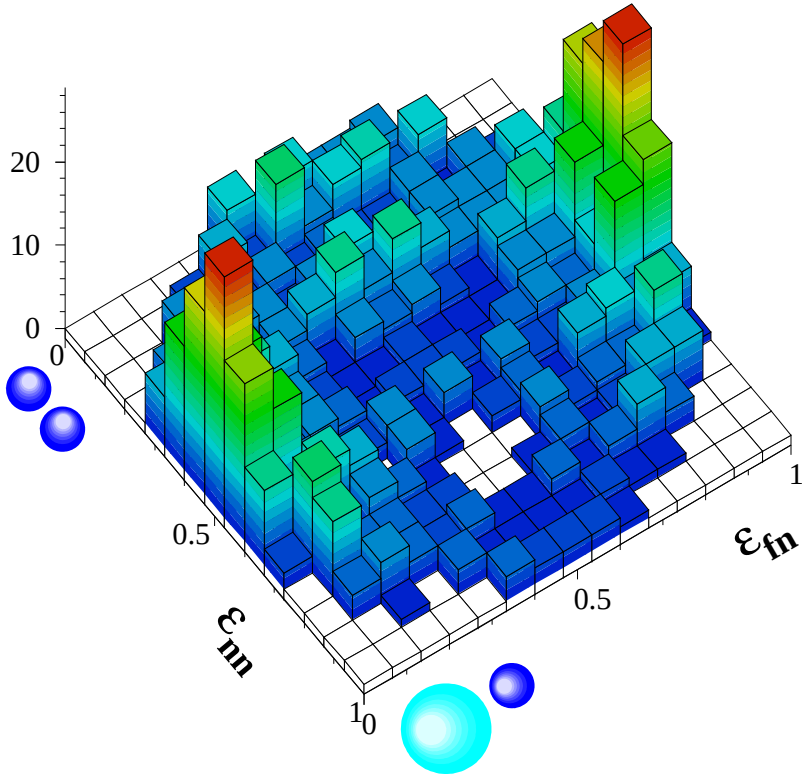

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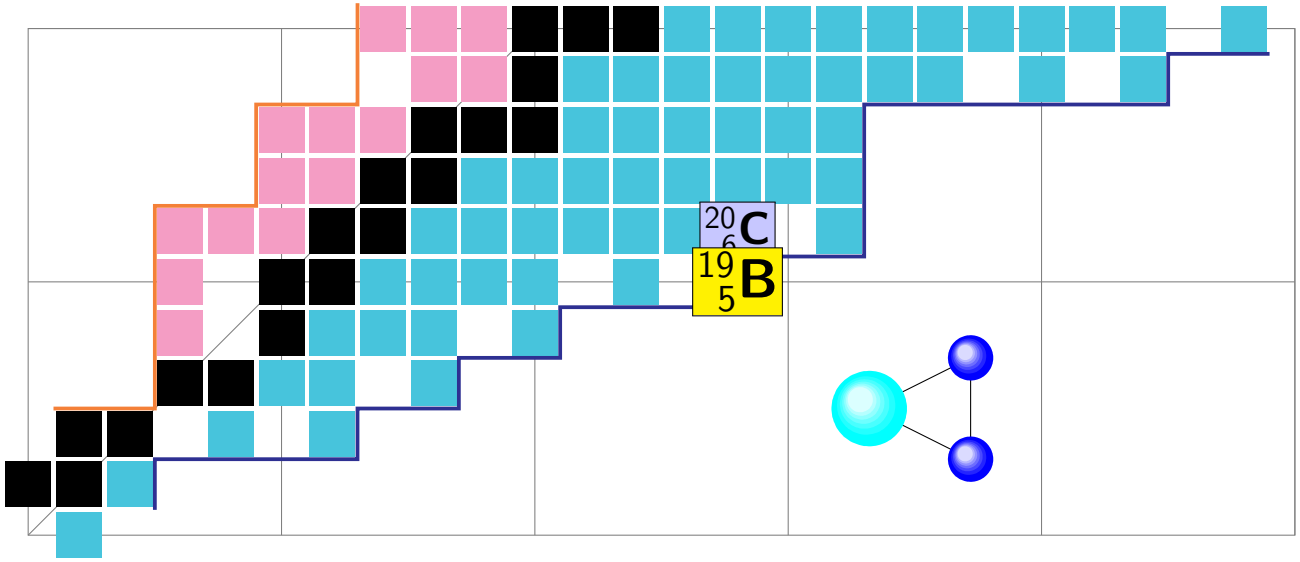

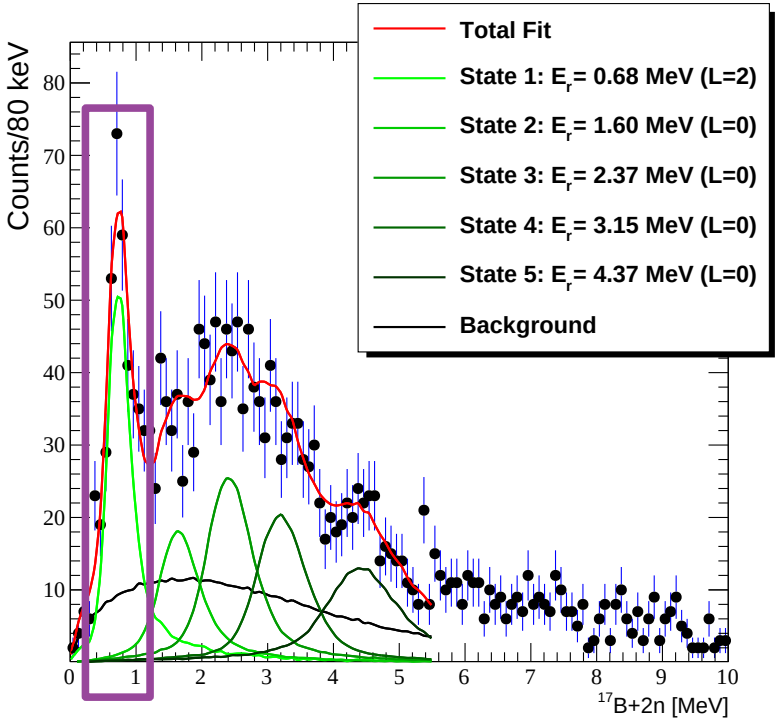

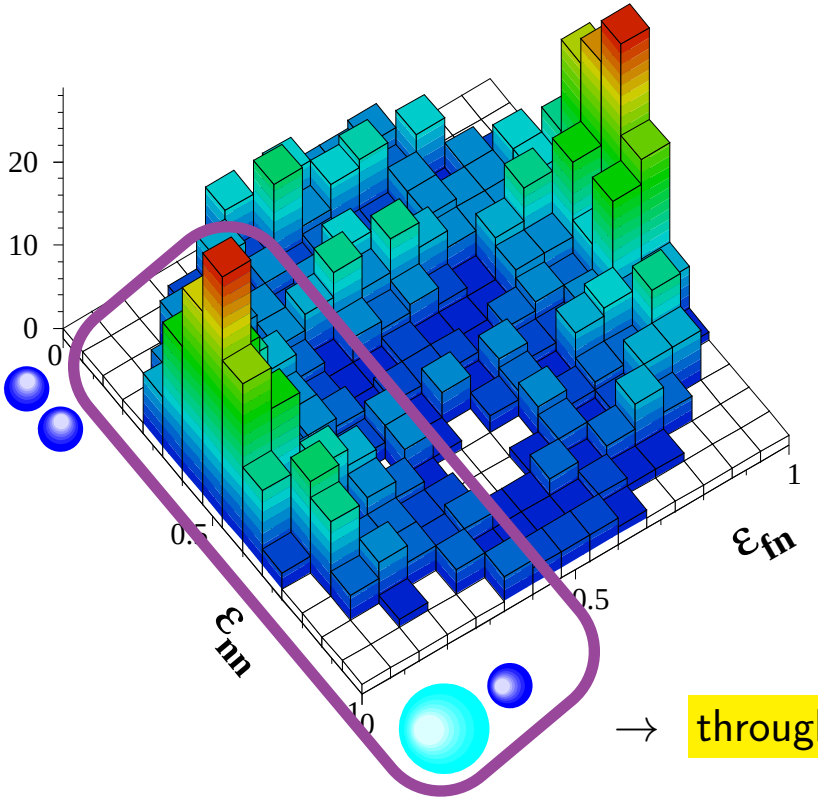

→ through ^{18}B !

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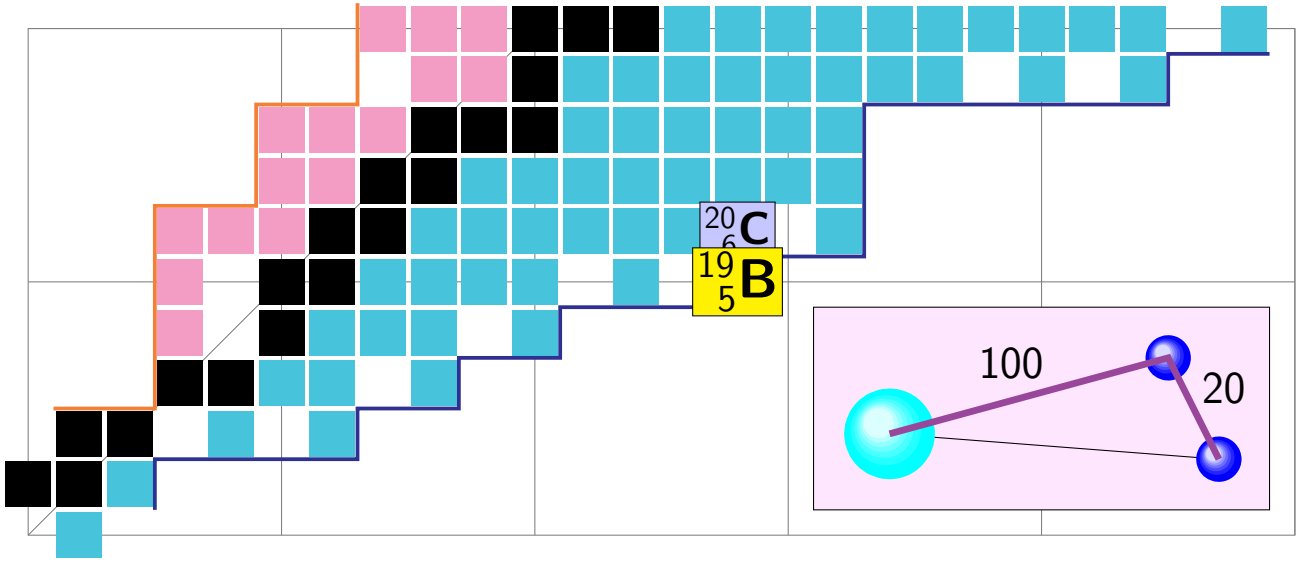
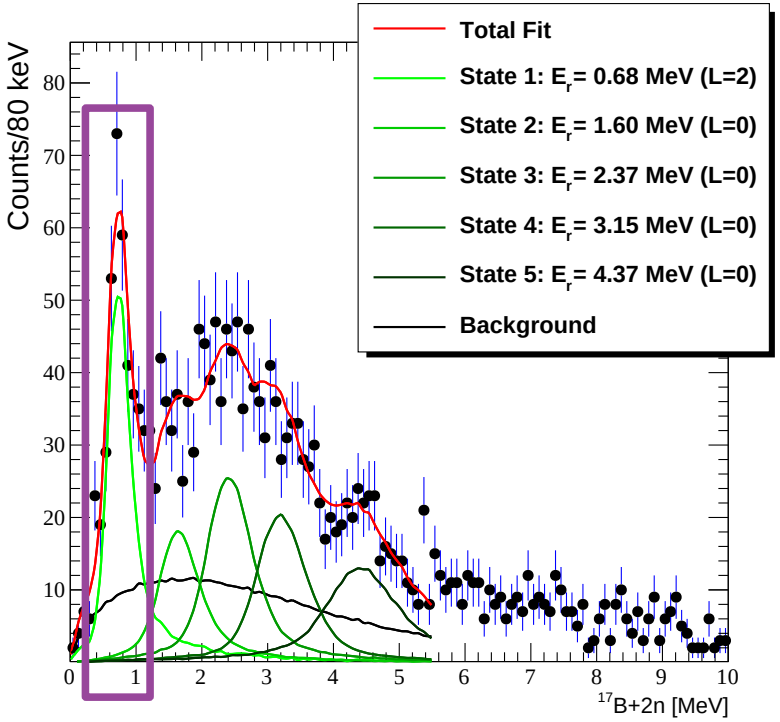
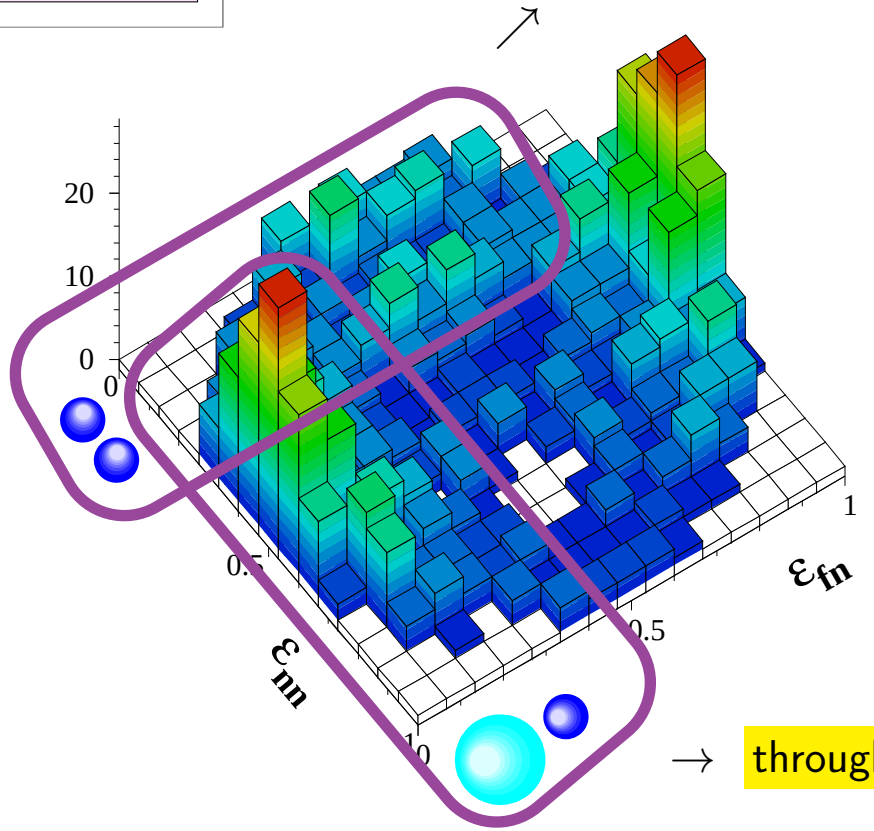




low ε_{nn} FSI !



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17B+n+n : Efimov trimer ? [Hiyama, Lazauskas, Carbonell]

- Efimov effect :

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  Naidon & Endo, Rep Prog Phys 80, 5 (2017)

  → induced long-range interaction

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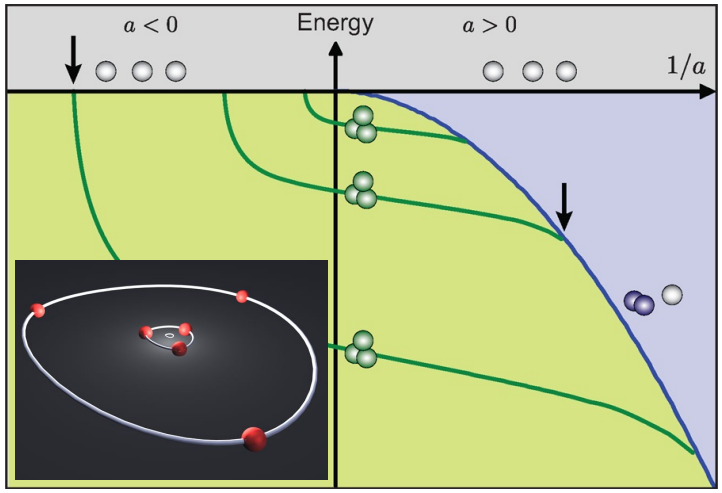

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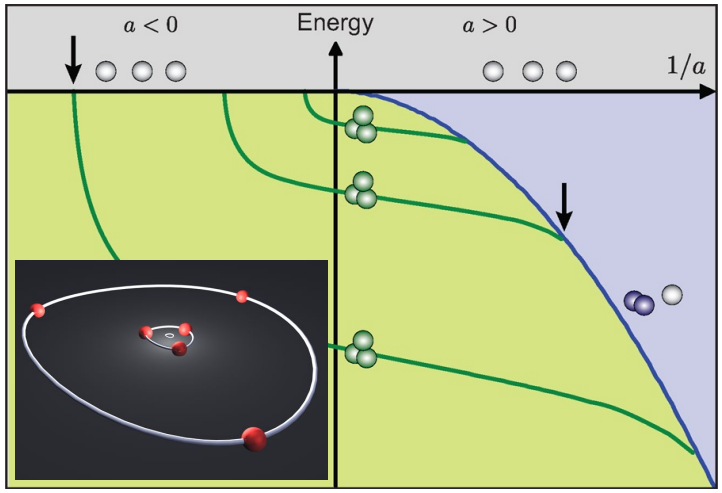
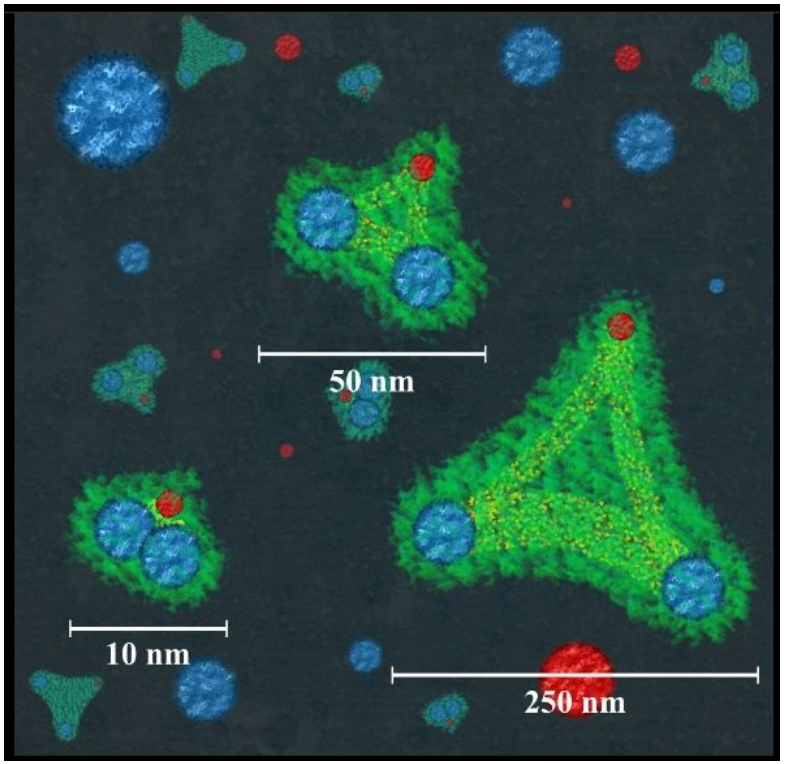


Pires, PRL 112 (2014) 250404



phys.org : Li-Cs-Cs "*exotic giant molecules*"

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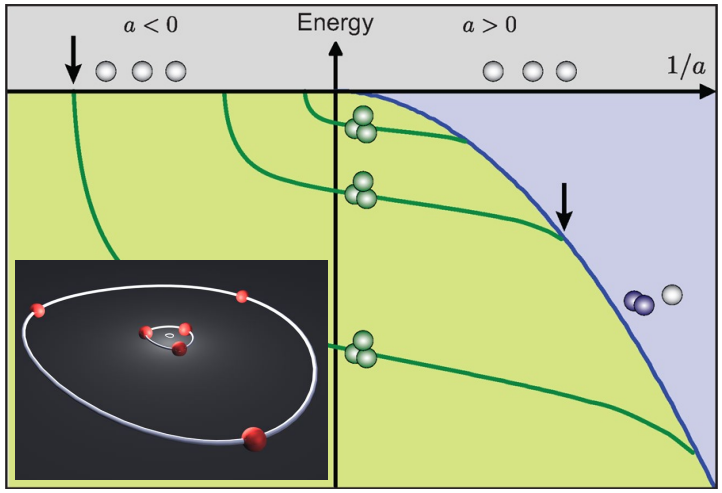

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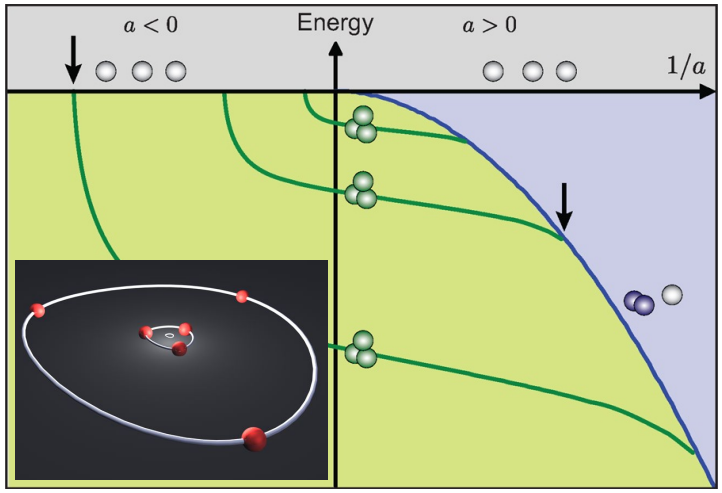

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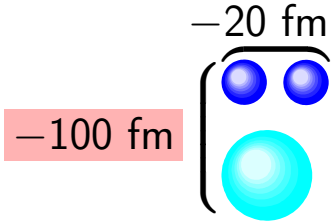
Hiyama, PRC 100 (2019) 011603R



$\Longrightarrow$ $S_{2n}(^{19}B) = 0.14 \pm 0.39$ MeV

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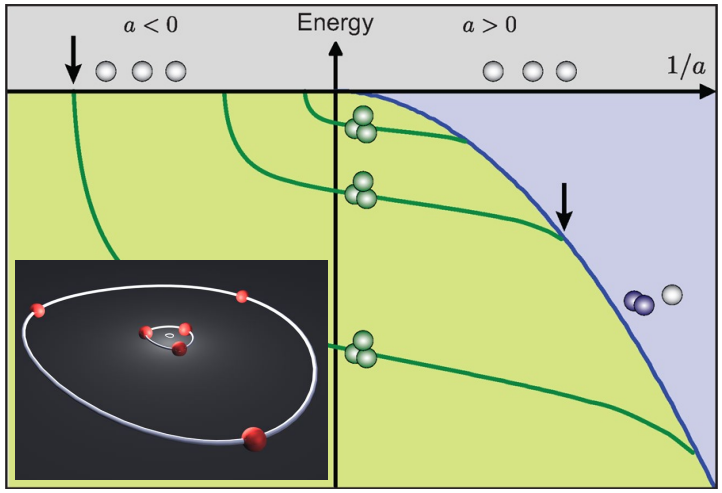

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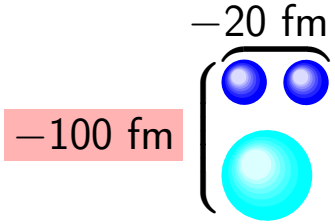

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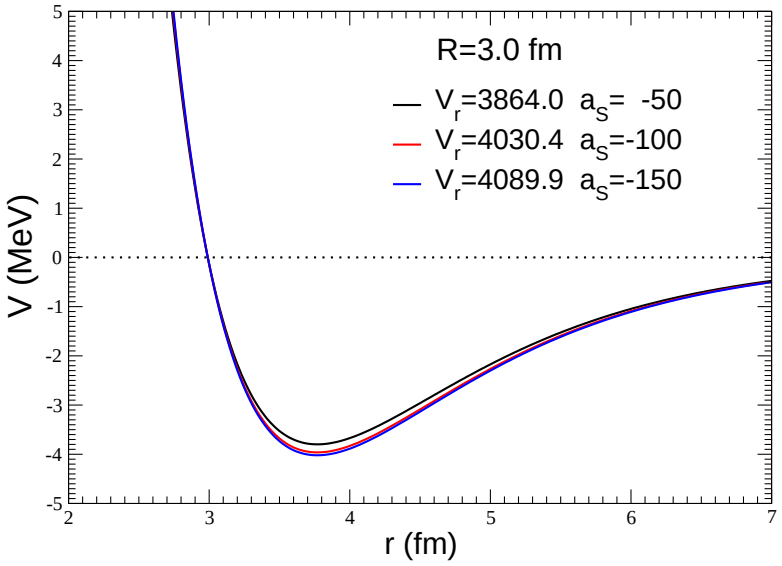
- $V(^{17}\text{B-n}) = V_r \left(e^{-\mu r} - e^{-\mu R}\right) \frac{e^{-\mu r}}{r}$

  → $\mu = 1/m_\pi$

  → $R = R_{\text{rms}}(^{17}B)$

Carbonell, EFB24



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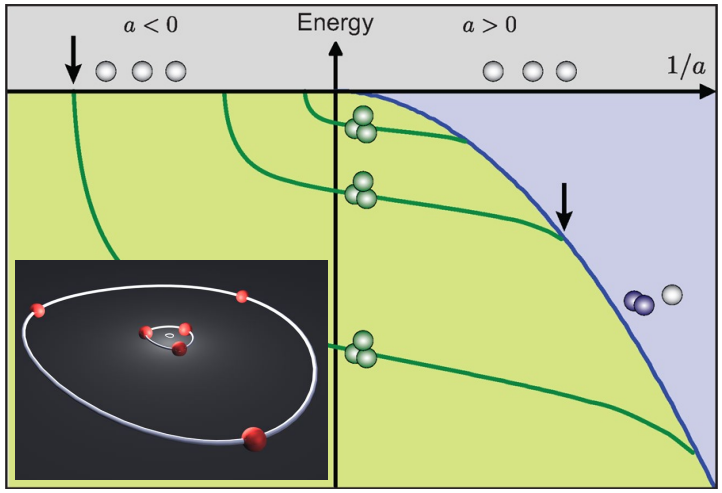


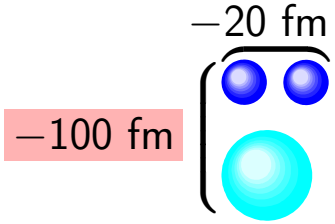
- Efimov physics :

  → Universality if $|a_s| \gg r_0$ ...

  → number of trimers $\gtrsim 1$ ...

- Three-body calculation !

Hiyama, PRC 100 (2019) 011603R



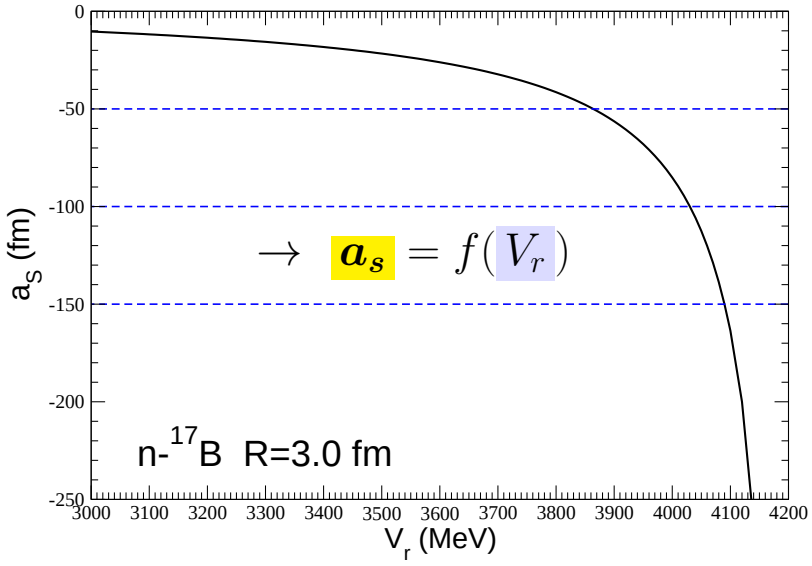
$\Longrightarrow$ $S_{2n}(^{19}B) = 0.14 \pm 0.39$ MeV

- $V(^{17}\text{B-n}) = V_r \left(e^{-\mu r} - e^{-\mu R}\right) \frac{e^{-\mu r}}{r}$

  → $\mu = 1/m_\pi$

  → $R = R_{\text{rms}}(^{17}B)$

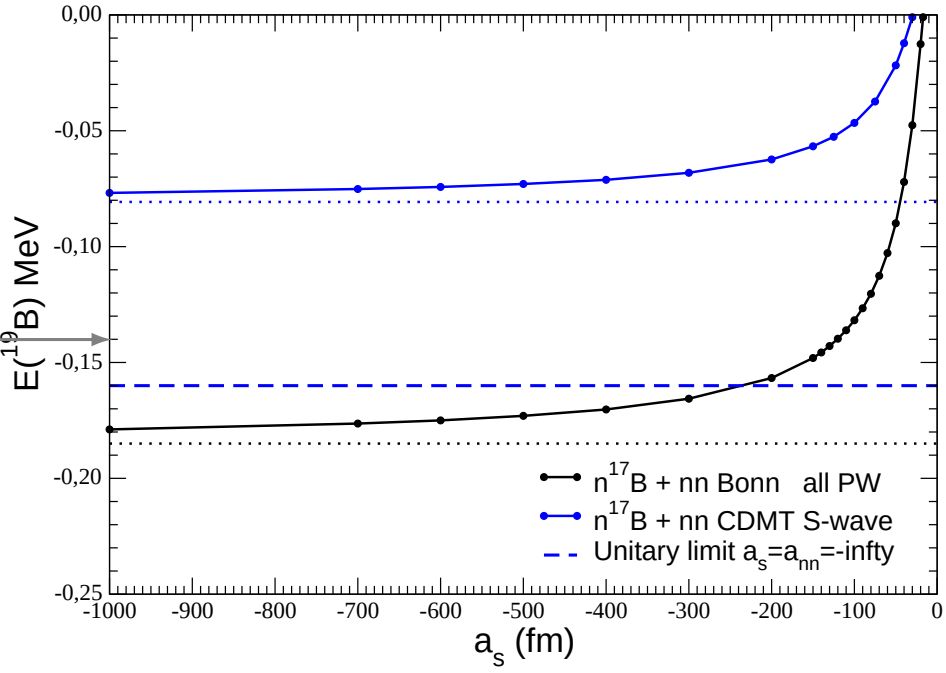
Carbonell, EFB24



- n-n : Bonn A (all waves) / CD MT13 (s wave)

17B+n+n : Unitary Limit ! [Hiyama, Lazauskas, Carbonell]

- Faddeev equations / GEM :



- ✔ ^{18}B virtual state
- ✔ ^{19}B bound state (L=0) !
- ✔ predicts unbound excited states !

$$\rightarrow \quad E(-150 \text{ fm}) \approx \begin{cases} 0.23 - i\,0.23 \ (L{=}1) \\ 0.80 - i\,1.10 \ (L{=}2) \end{cases}$$

$$\rightarrow \quad E = f(a_s, R) \ldots$$

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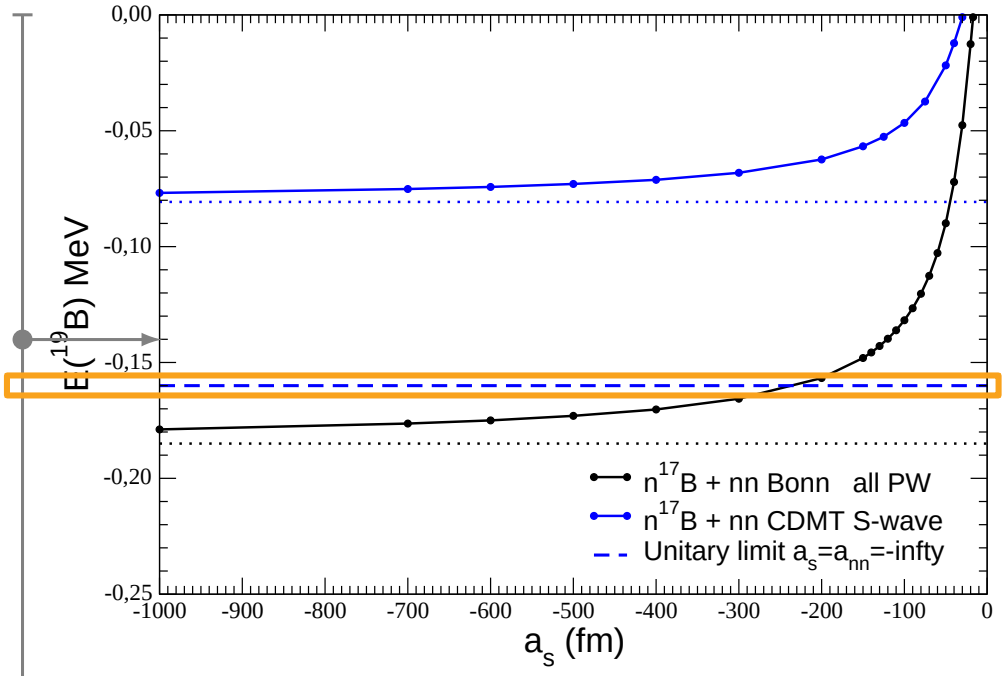

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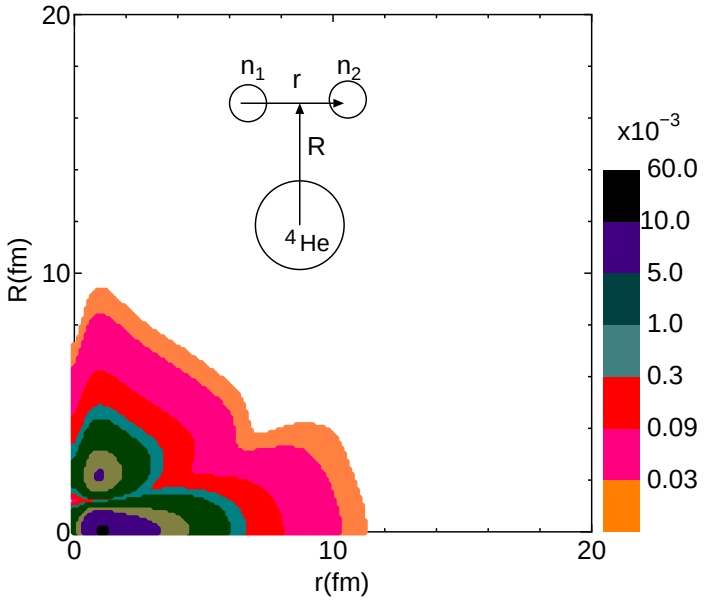
- Efimov physics ?
  - ✔ good description @ Unitary Limit !
  - ✘ $|\Psi(r,R)|^2$: 'standard' halo nucleus ?



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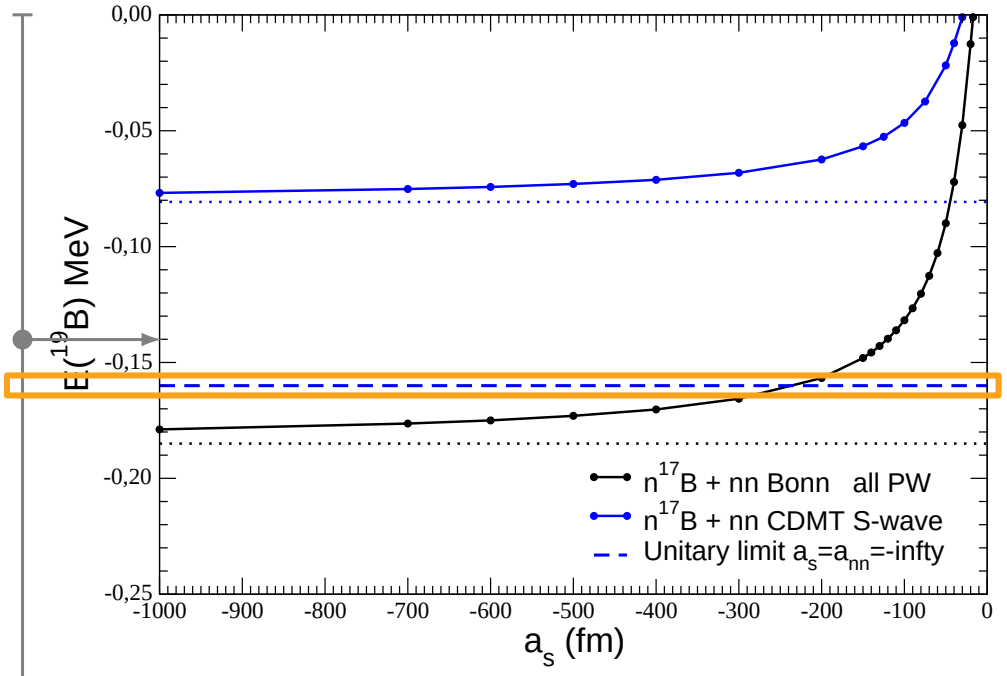

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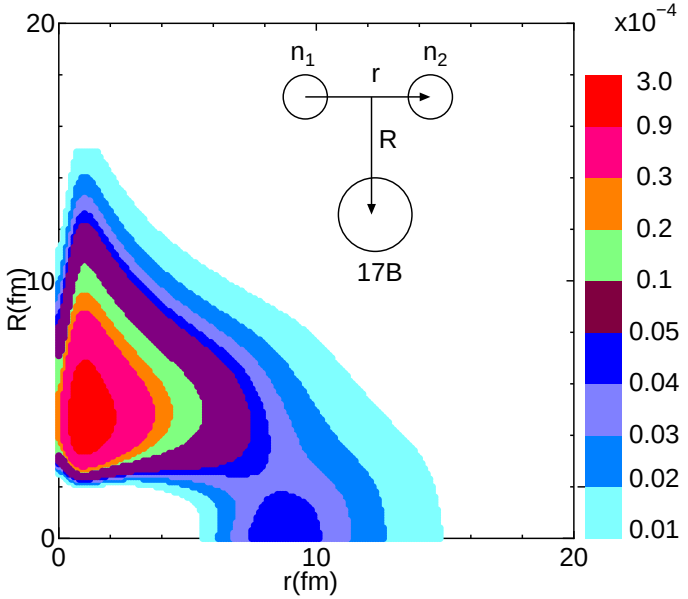

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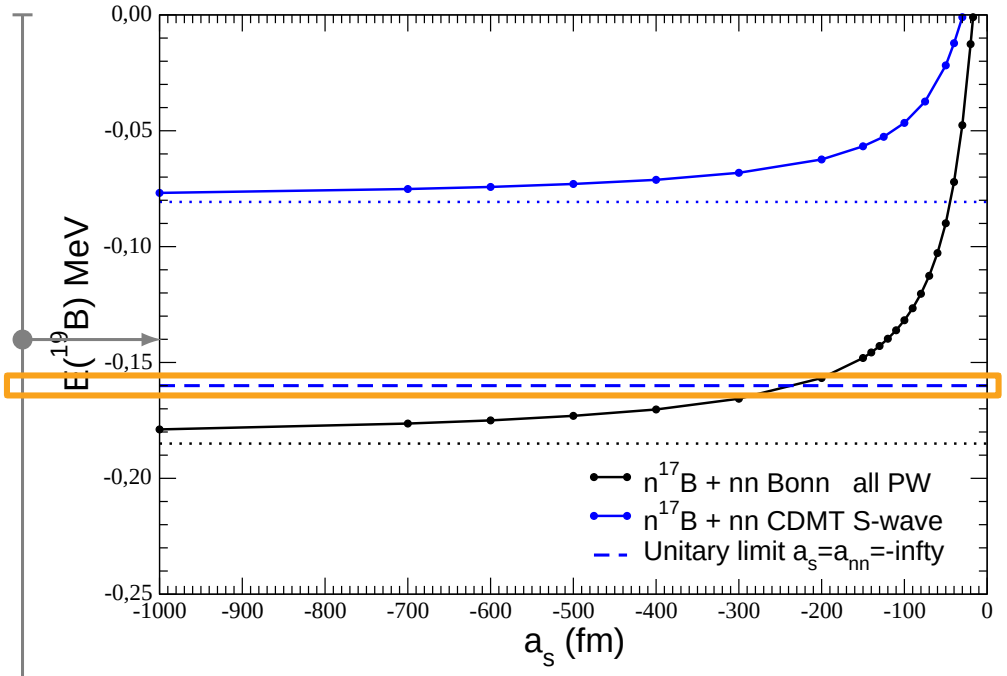

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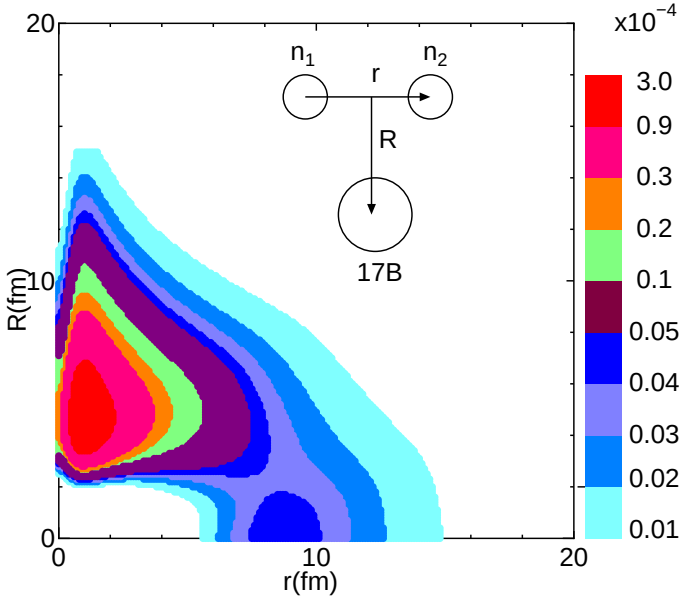


- ✘ other trimers unlikely ($a_s \sim$ kfm)
- ✔ only binary inputs (no 3NF) !!!

$\rightarrow$ extensible to ^{20,21}B $\equiv$ ^{17}B+3,4n ...

Carbonell, EFB24

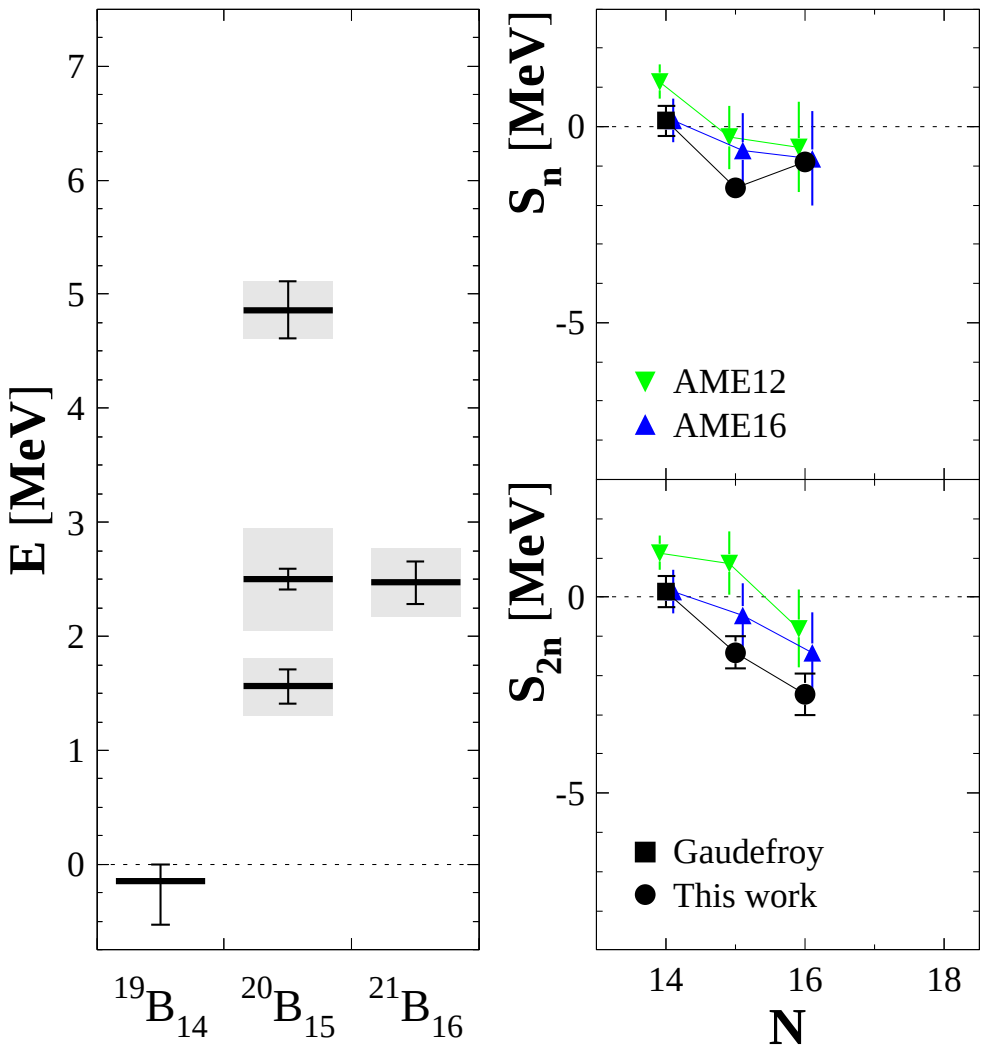
Boron 20 & 21 : masses & multineutron emission

- Evaluation of mass excess :

Isotope	AME12	AME16	Experiment
^{19}B	58.78(40)	59.77(53)	59.77(35)
^{20}B	67.13(70)	68.45(80)	70.27(38)
^{21}B	75.72(90)	77.33(90)	78.38(43)

Wang, Chinese Phys. C 41 (2017) 030003

- lower by $\sim$3 MeV
- new data (^{19}B, ^{22}C, ^{23}N) improve trends !



Leblond, PRL 121 (2018) 262502

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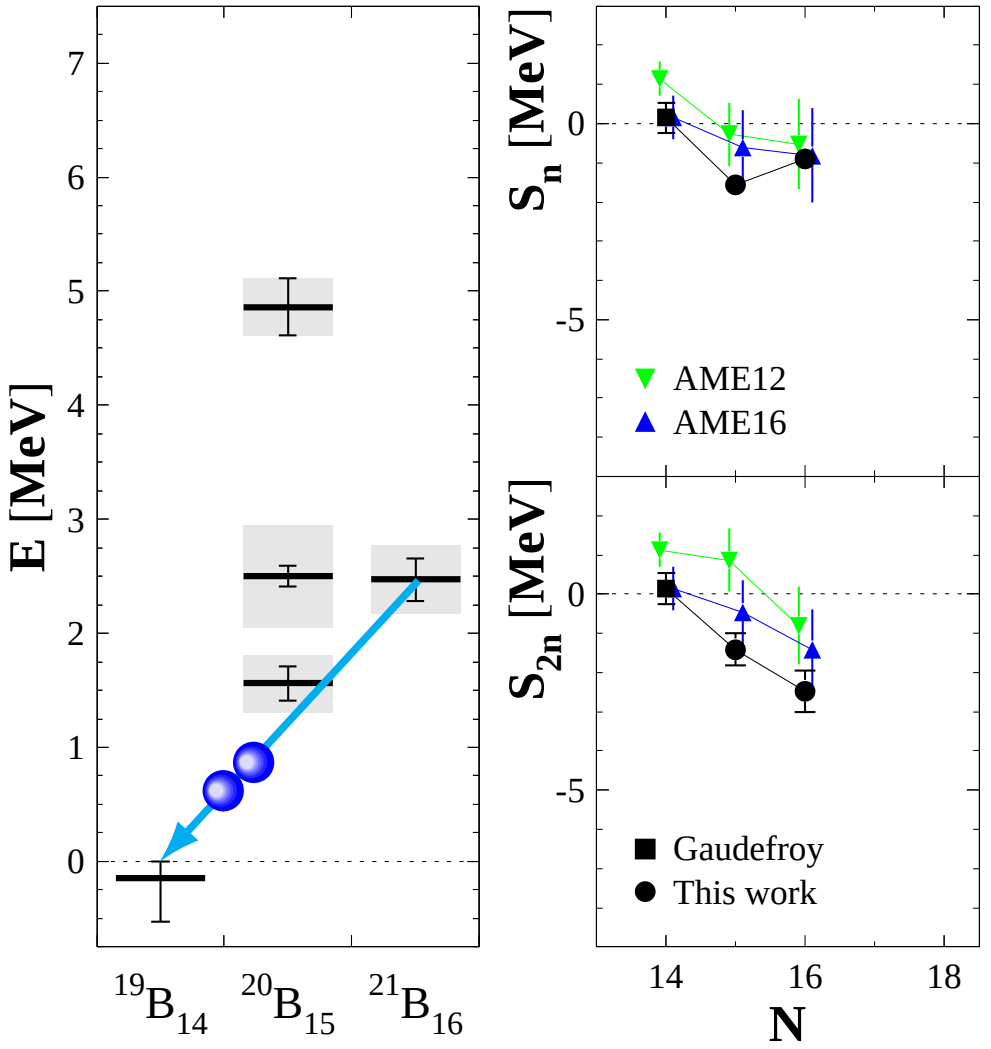

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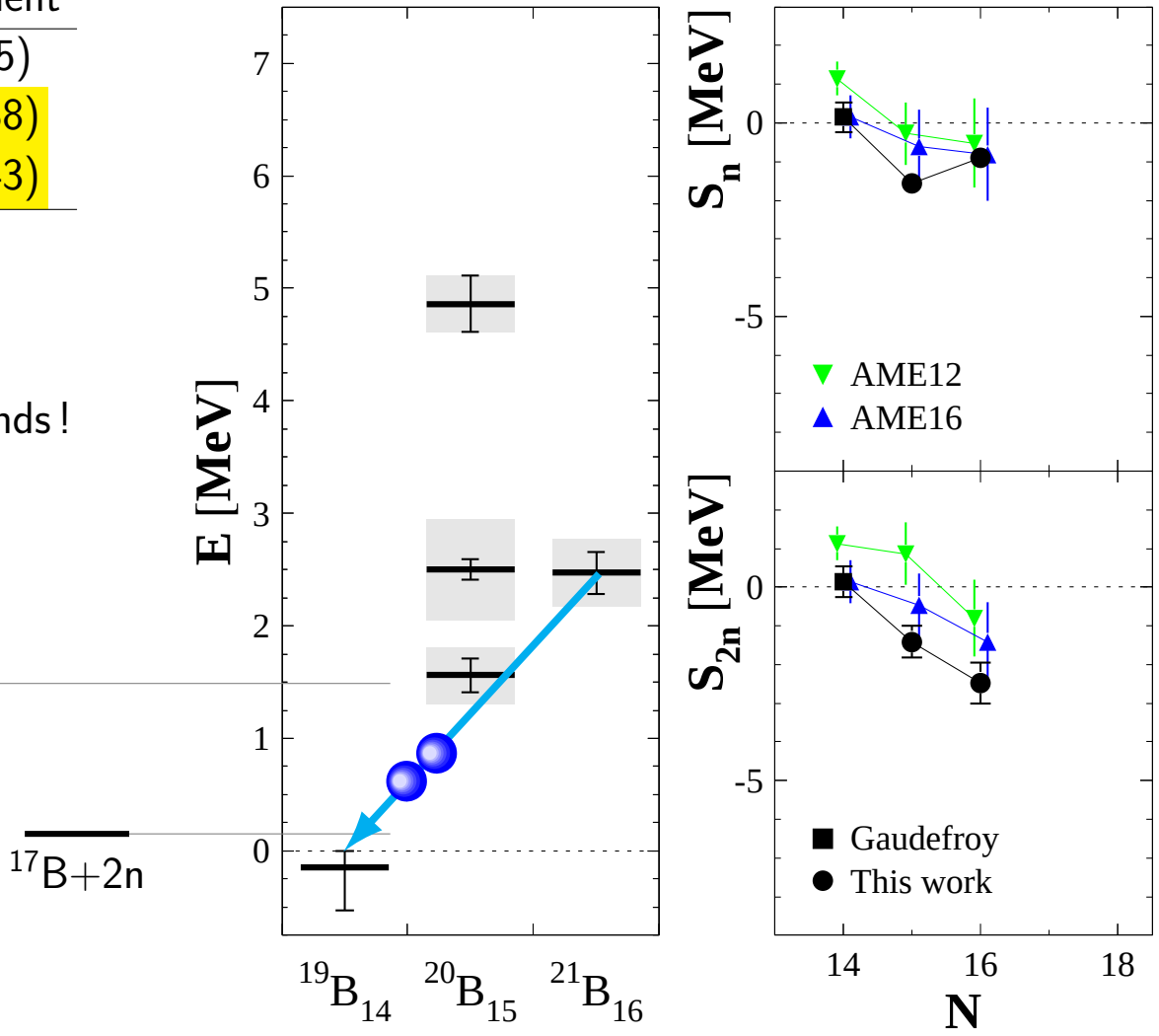

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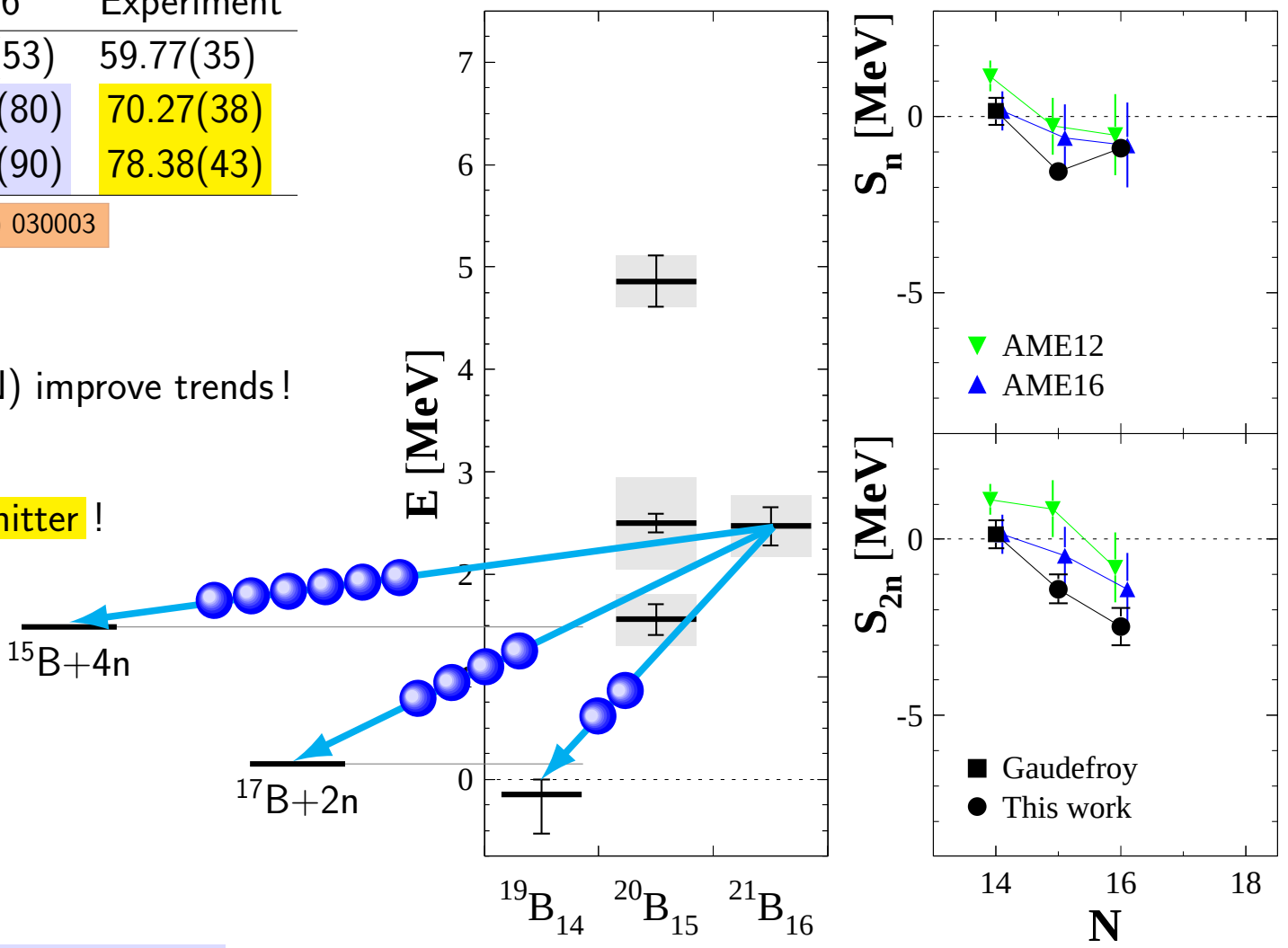
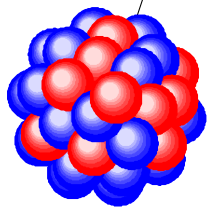
→ first candidate for 4n/6n emitter ???



Leblond, PRL 121 (2018) 262502

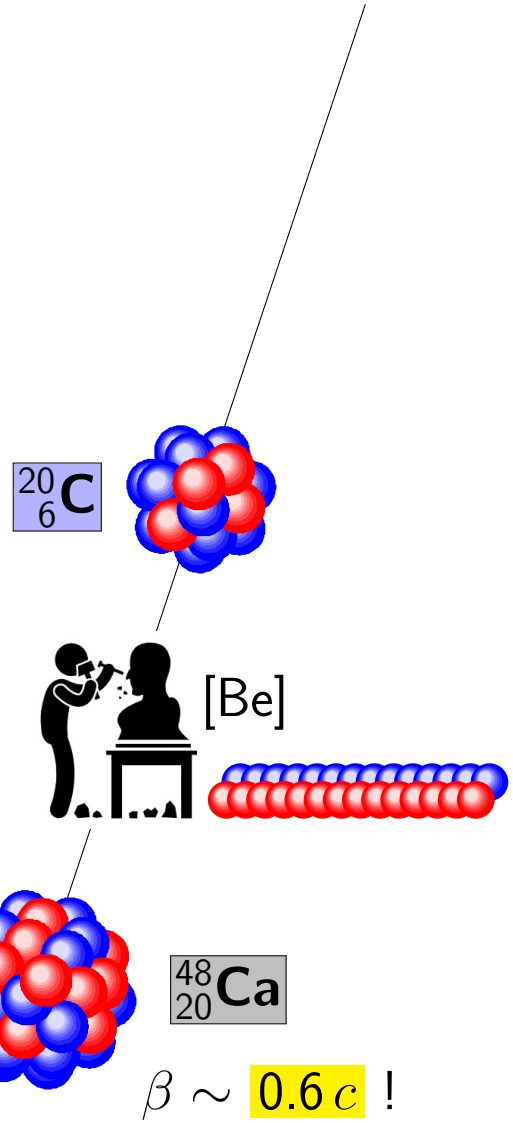
Sculpting exotic structures



$^{48}_{20}\mathrm{Ca}$

$\beta \sim 0.6\,c$!

Sculpting exotic structures



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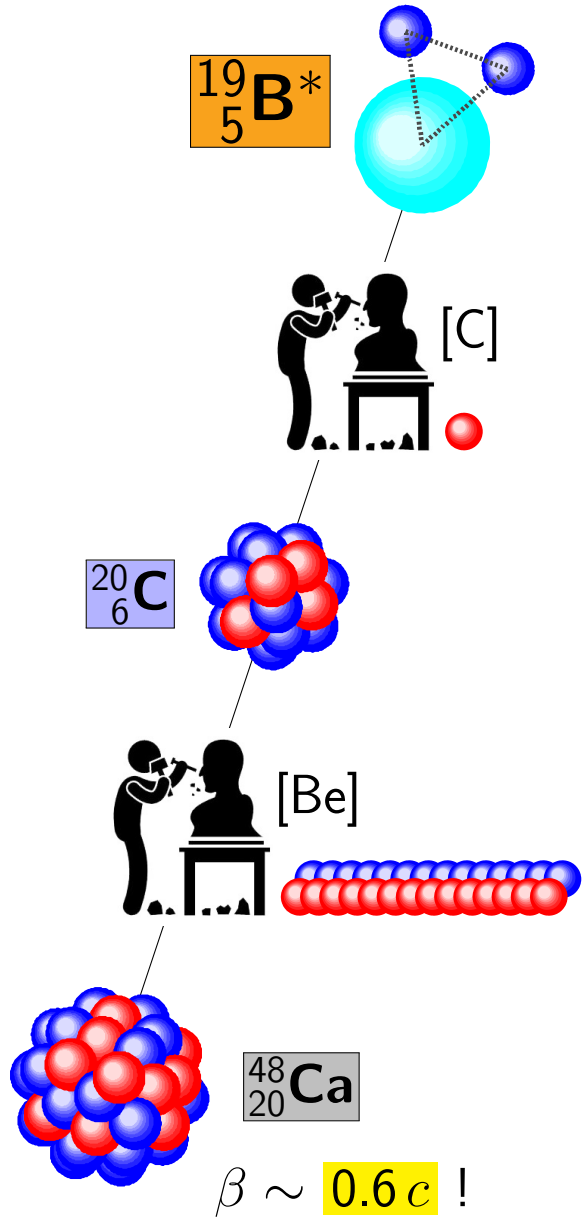
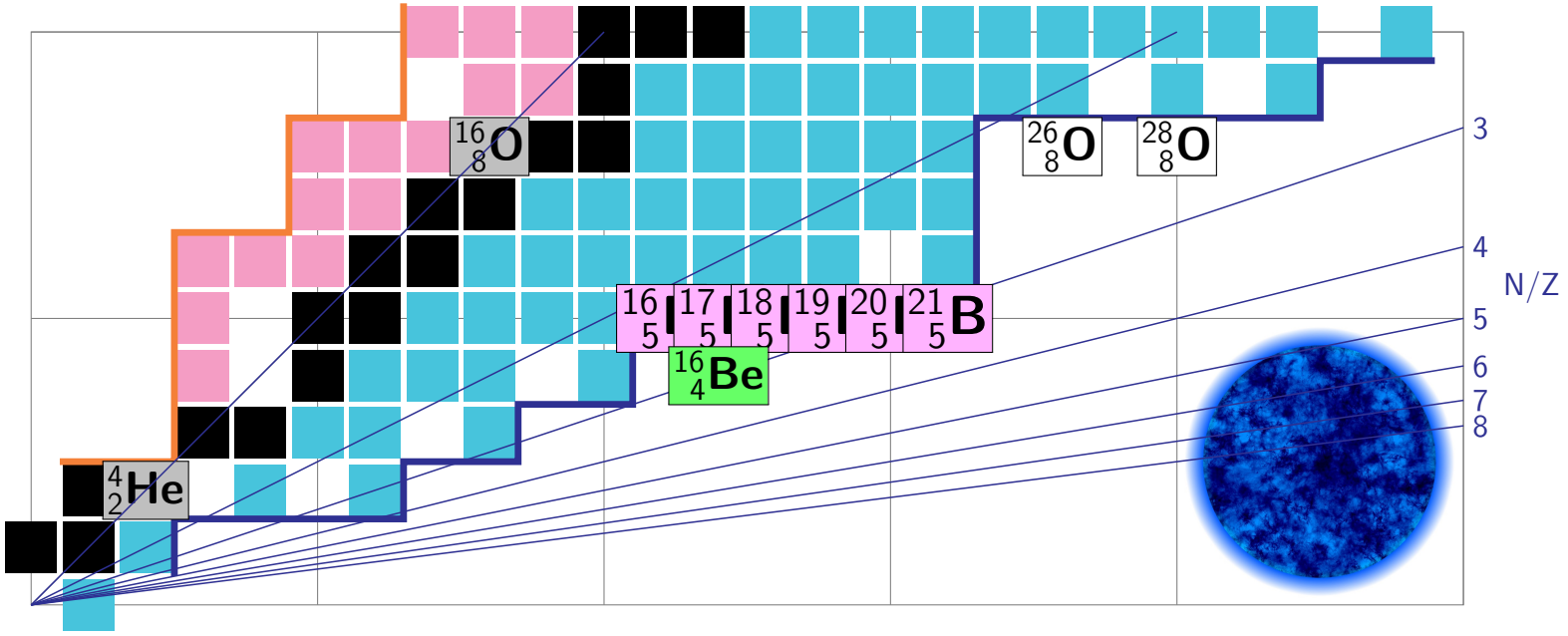


The exotic limits of exotic nuclei



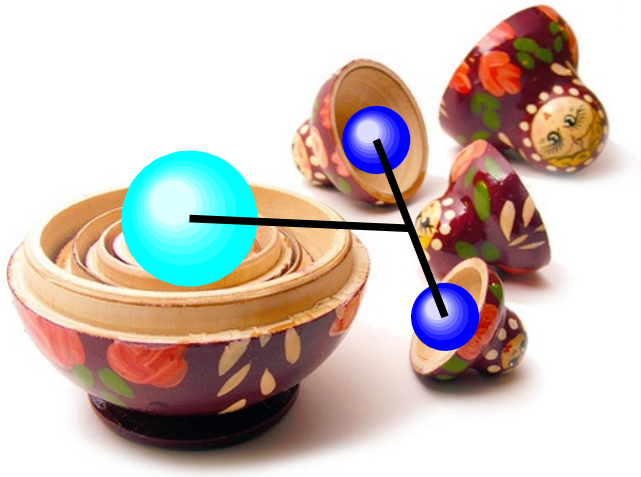
- Access to extreme N/Z ratios :

  ❶ Z = 5 (**SAMURAI Day-1**) :

  → literally exotic structures !

  ❷ Z = 4 (**SAMURAI S18**) :

  → 2n emission/decay ?



Discovery of the "dineutron" ?

PHYSICAL REVIEW LETTERS

Featured in Physics | Editors' Suggestion

First Observation of Ground State Dineutron Decay: ^{16}Be

A. Spyrou, Z. Kohley, T. Baumann, D. Bazin, B. A. Brown, G. Christian, P. A. DeYoung, J. E. Finck, N. Frank, E. Lunderberg, S. Mosby, W. A. Peters, A. Schiller, J. K. Smith, J. Snyder, M. J. Strongman, M. Thoennessen, and A. Volya

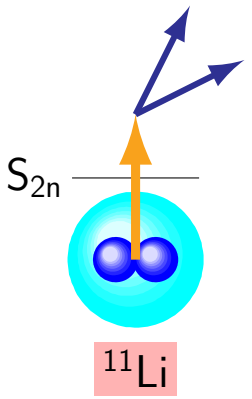
Phys. Rev. Lett. **108**, 102501 – Published 9 March 2012

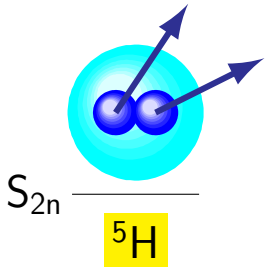
Physics See Focus story: Nuclei Emit Paired-up Neutrons

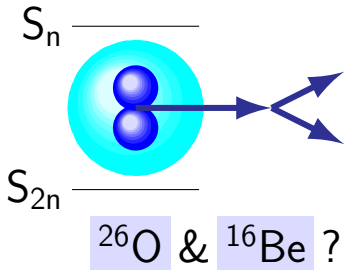
Article | References | Citing Articles (65) | PDF | HTML | Export Citation

ABSTRACT

We report on the first observation of dineutron emission in the decay of ^{16}Be. A single-proton knockout reaction from a 53 MeV/u ^{17}B beam was used to populate the ground state of ^{16}Be. ^{16}Be is bound with respect to the emission of one neutron and unbound to two-neutron emission. The dineutron character of the decay is evidenced by a small emission angle between the two neutrons. The two-neutron separation energy of ^{16}Be was measured to be 1.35(10) MeV, in good agreement with shell model calculations, using standard interactions for this mass region.







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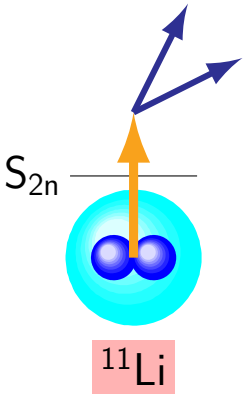

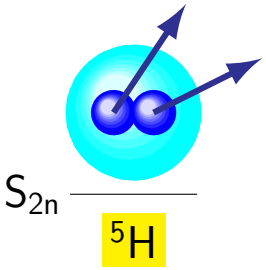

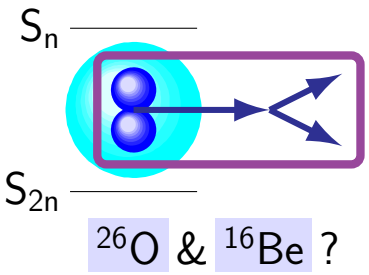

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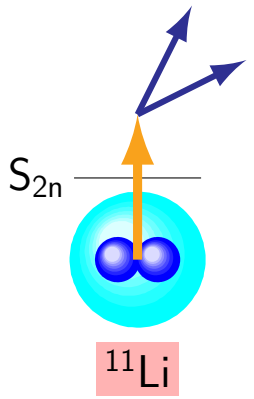
. . .

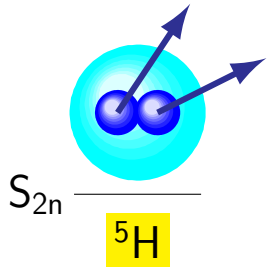
COMMENTS & REPLIES

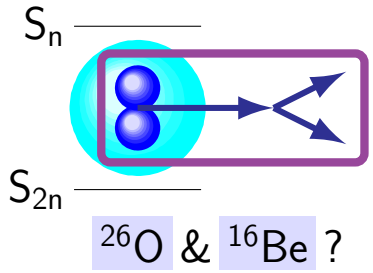
Comment on "First Observation of Ground State Dineutron Decay: ^{16}Be"

F. M. Marqués, N. A. Orr, N. L. Achouri, F. Delaunay, and J. Gibelin

Phys. Rev. Lett. **109**, 239201 (2012)

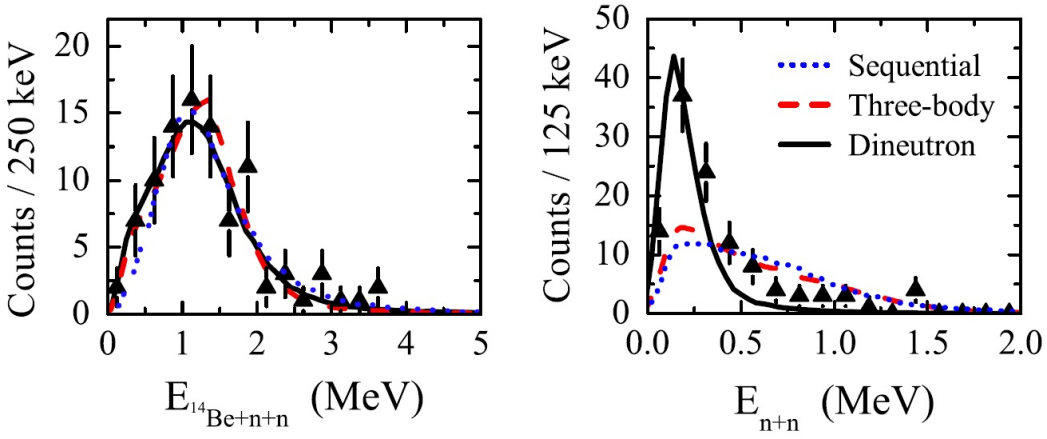


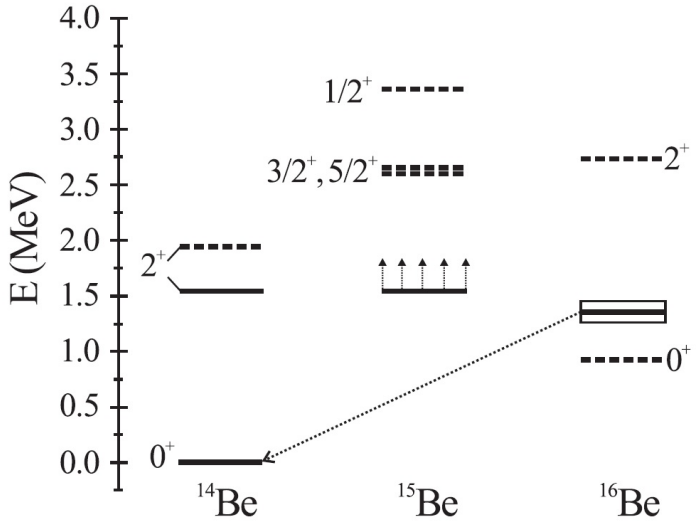




New view on Beryllium 16 [B. Monteagudo]

Spyrou, PRL 108 (2012) 102501





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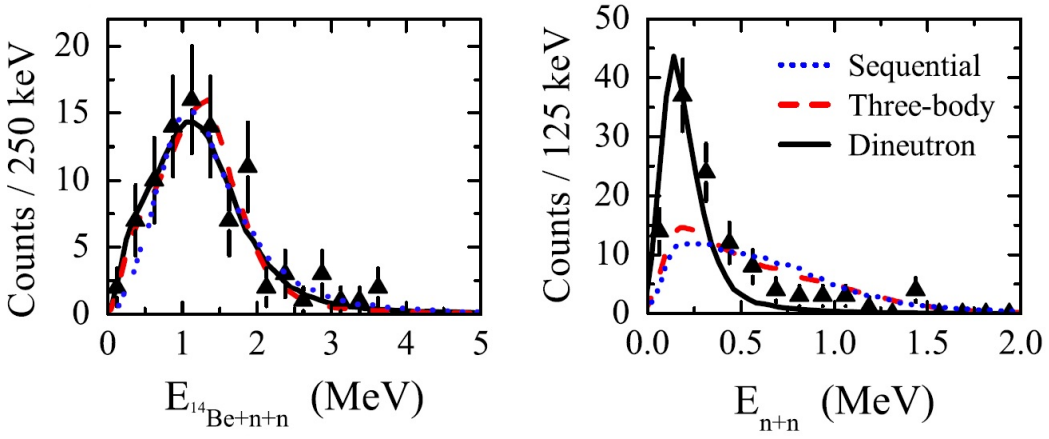

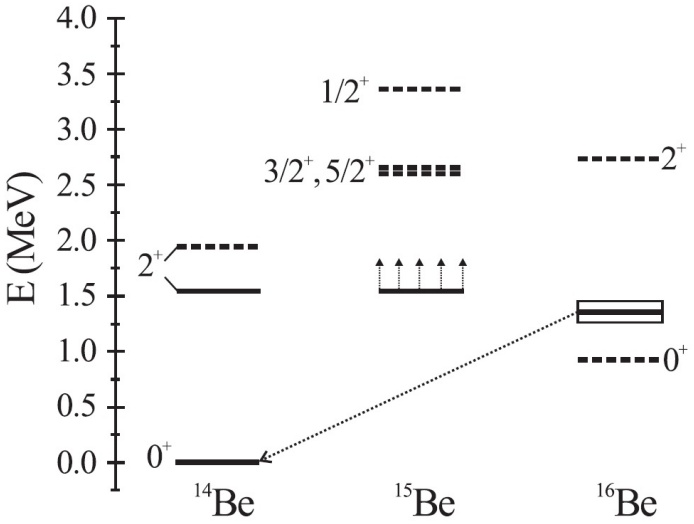

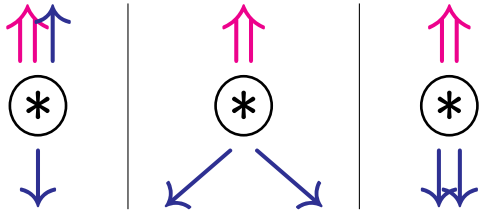

FMM, PRL 109 (2012) 239201

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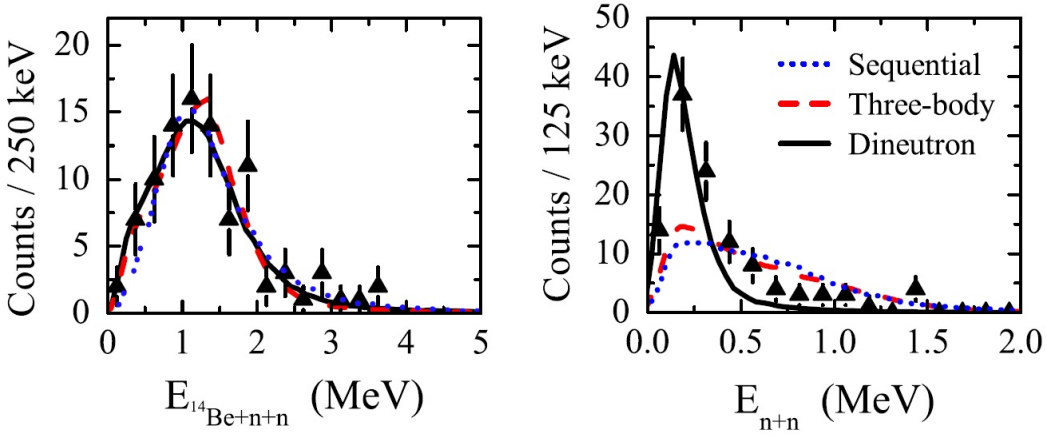
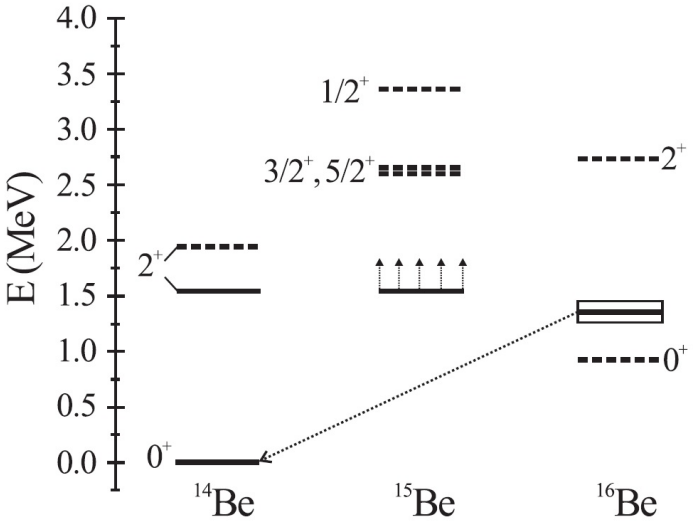
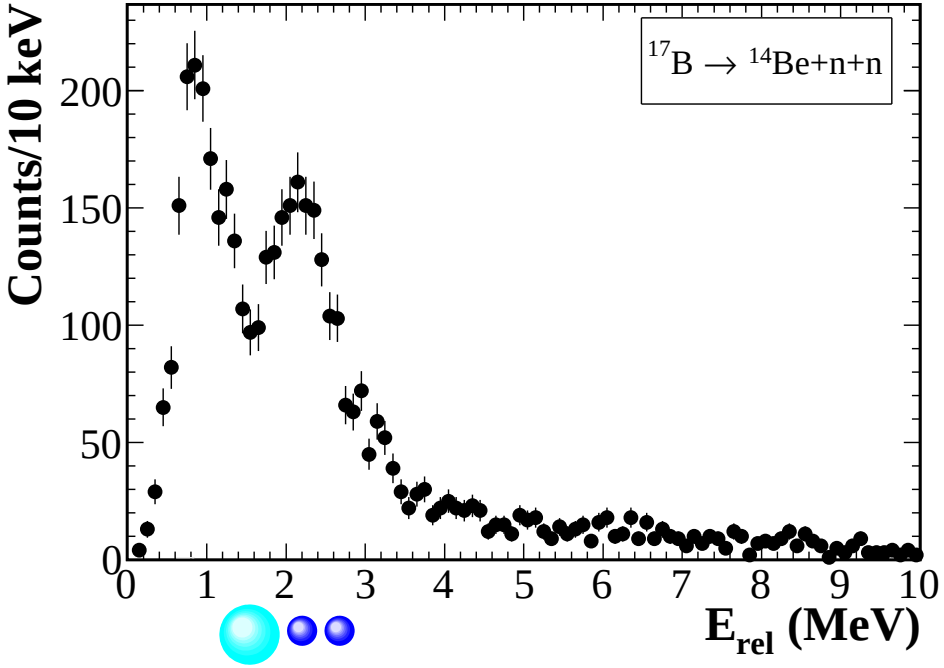
Spyrou, PRL 108 (2012) 102501







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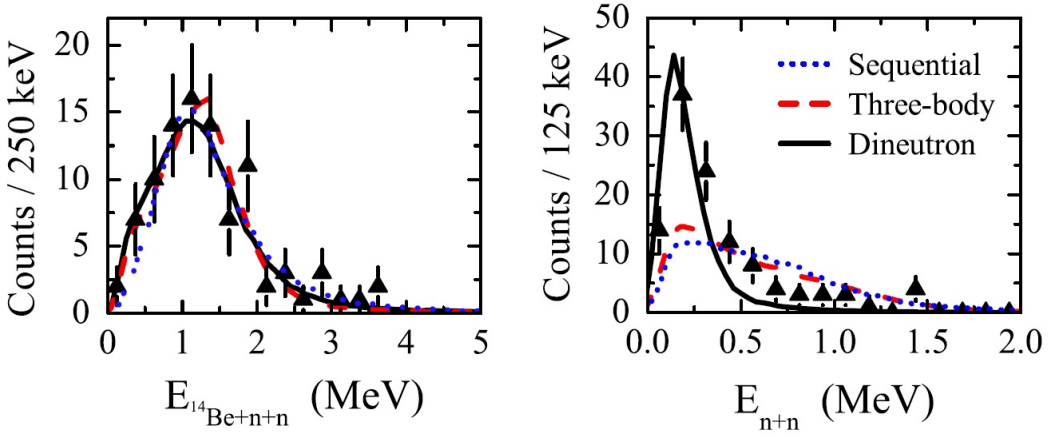
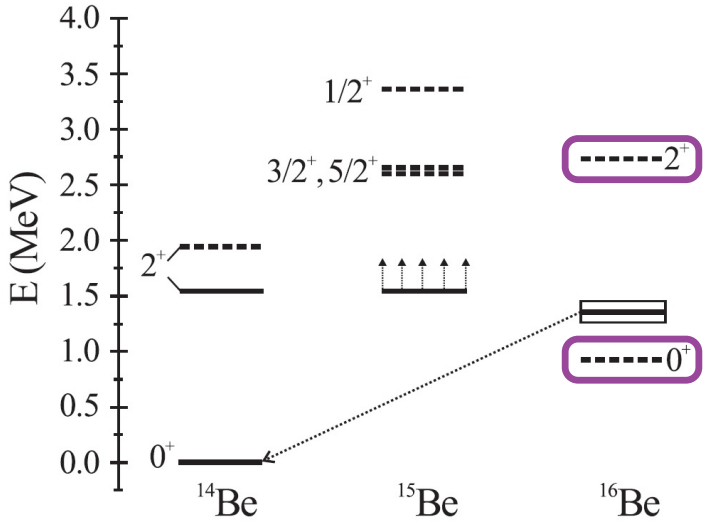
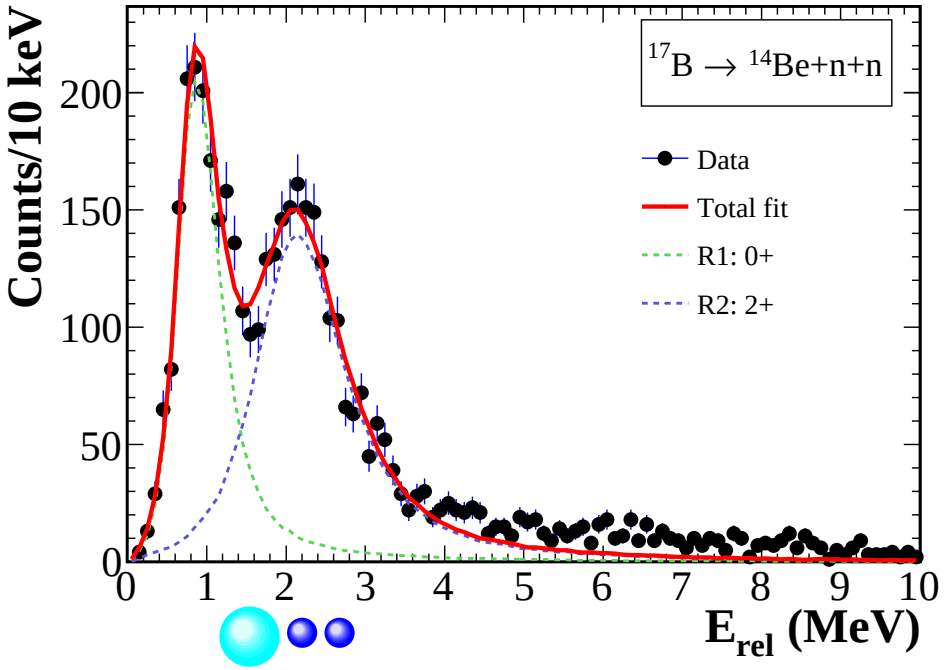
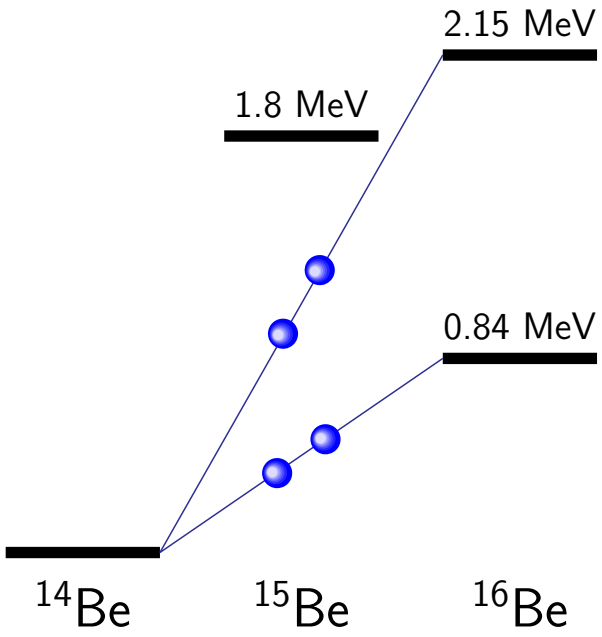
Spyrou, PRL 108 (2012) 102501



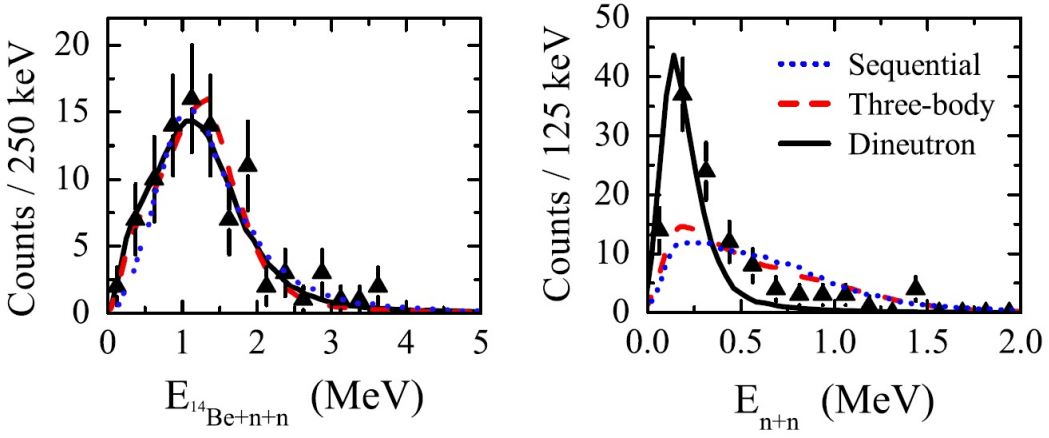


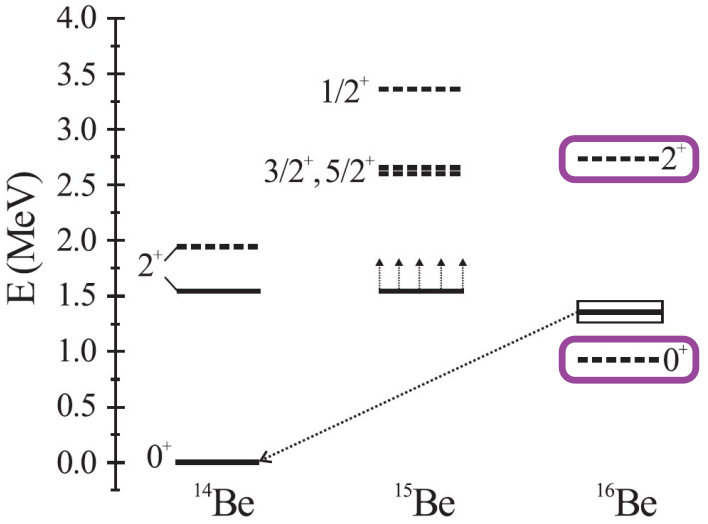


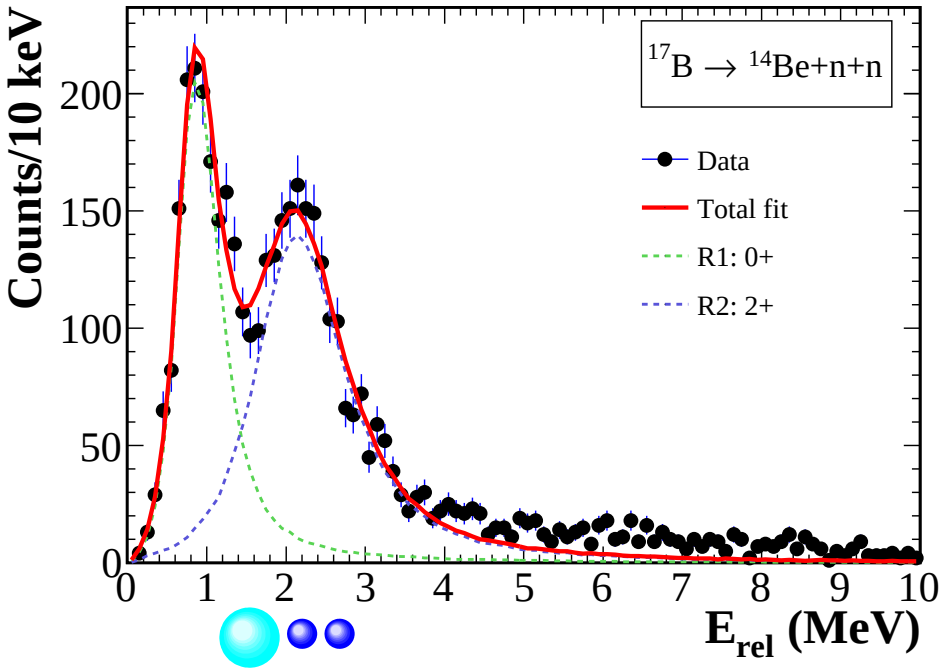


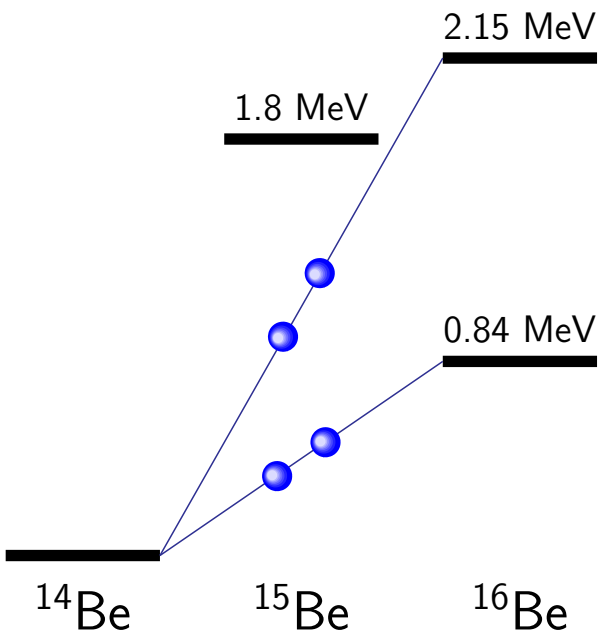
New view on Beryllium 16 [B. Monteagudo]

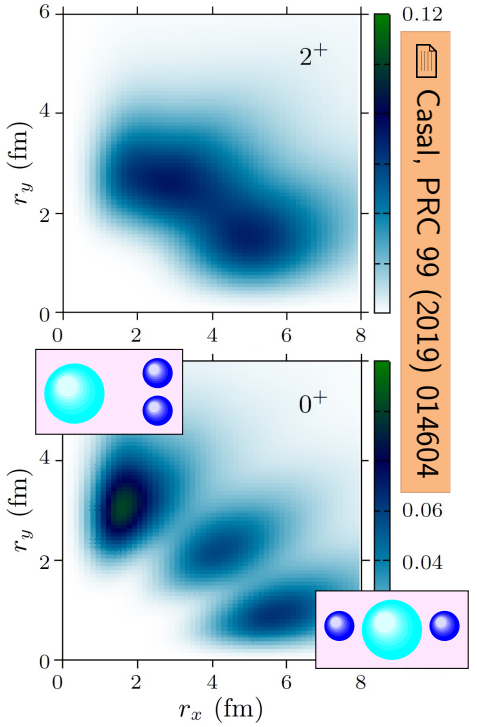
Spyrou, PRL 108 (2012) 102501





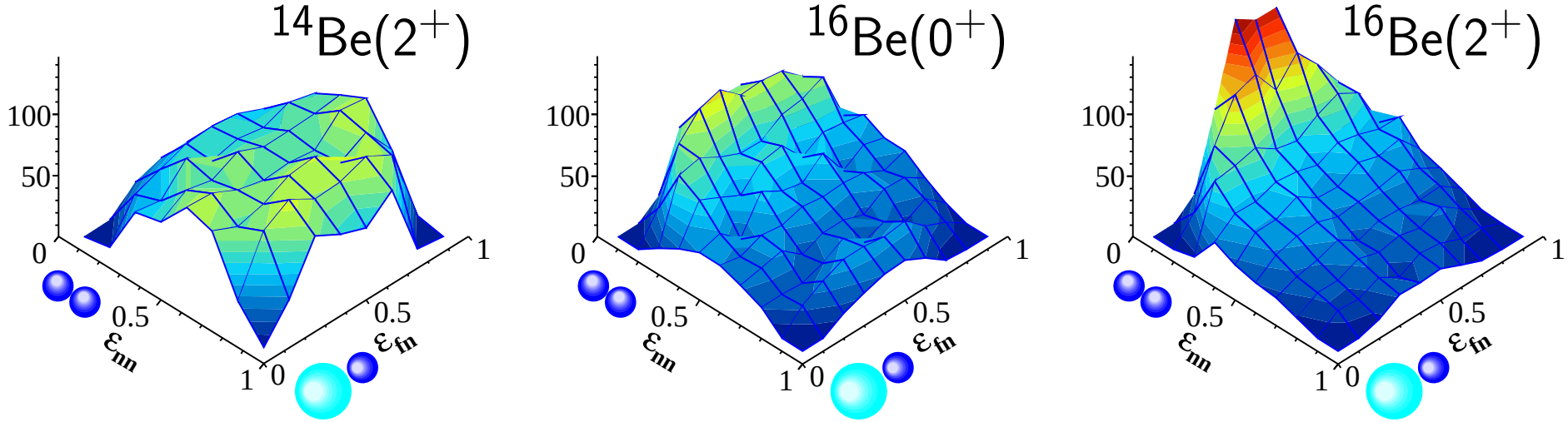






Probing the 2n wave function [B. Monteagudo]

- Dalitz plot of 2n decay :



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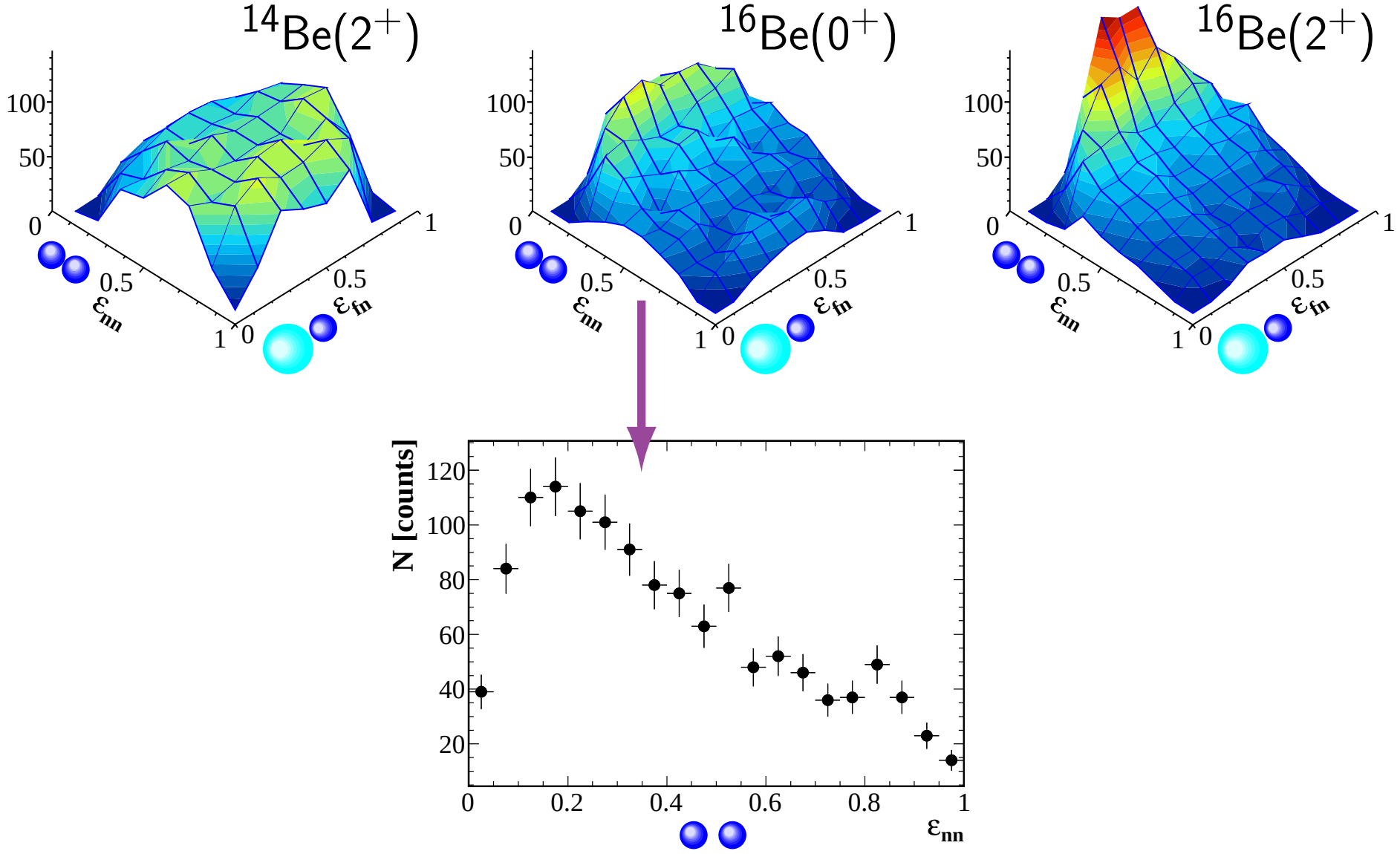

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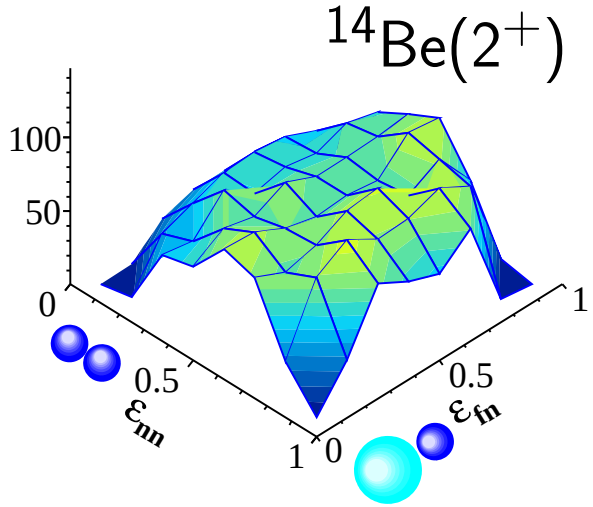
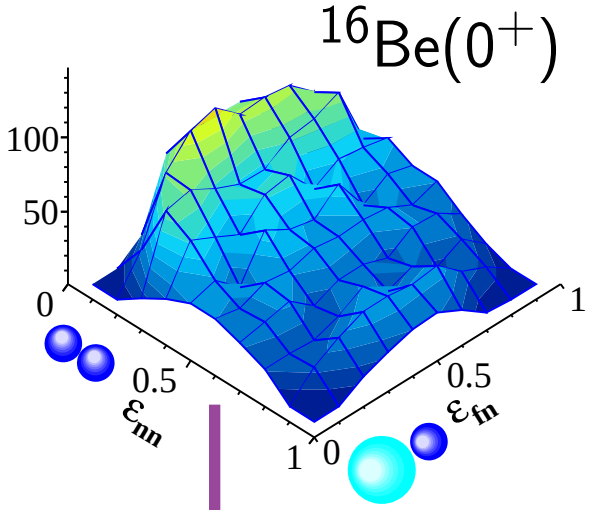
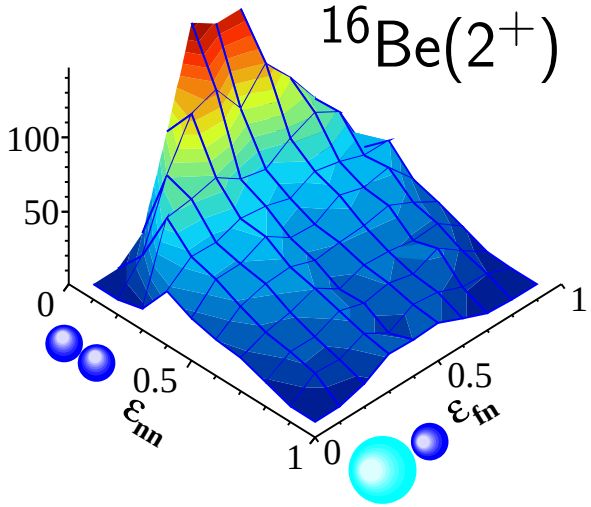
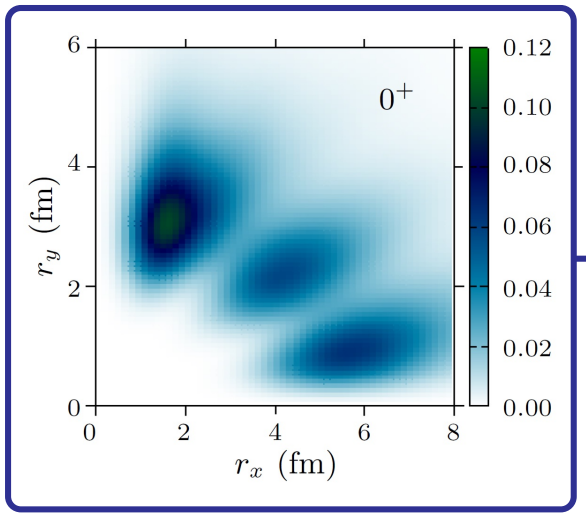
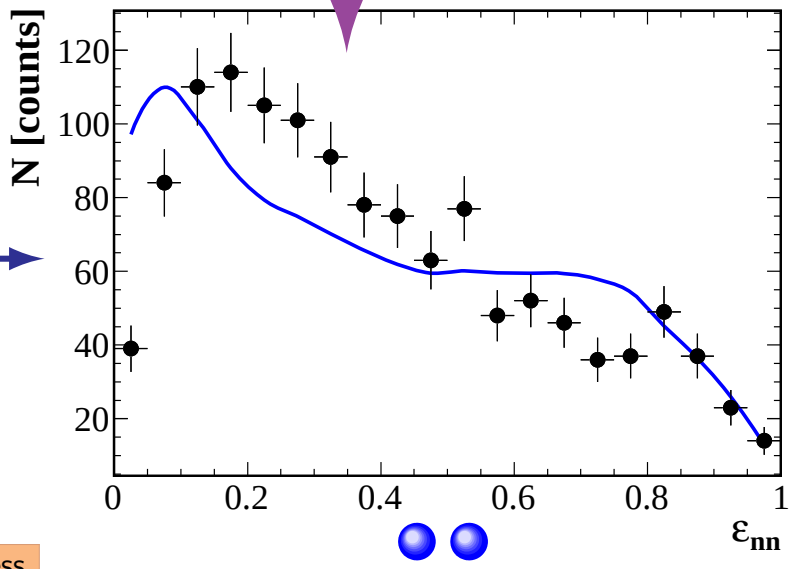






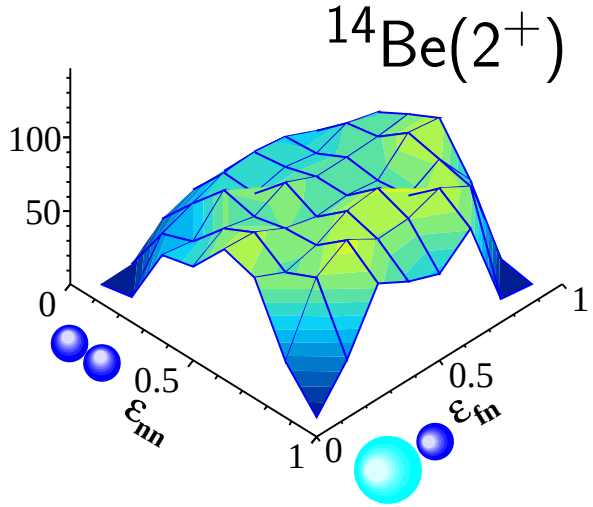


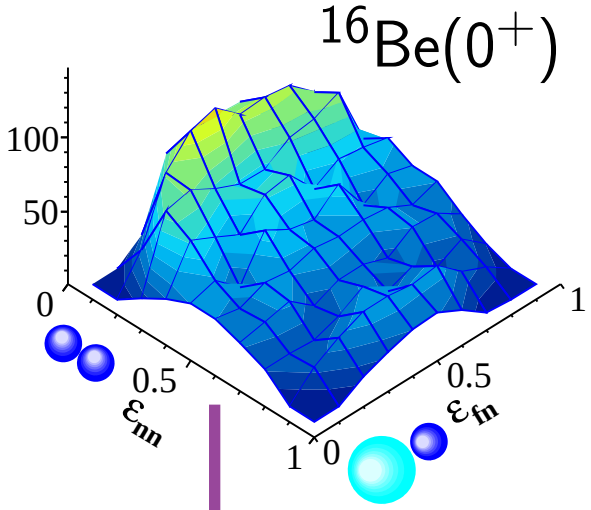


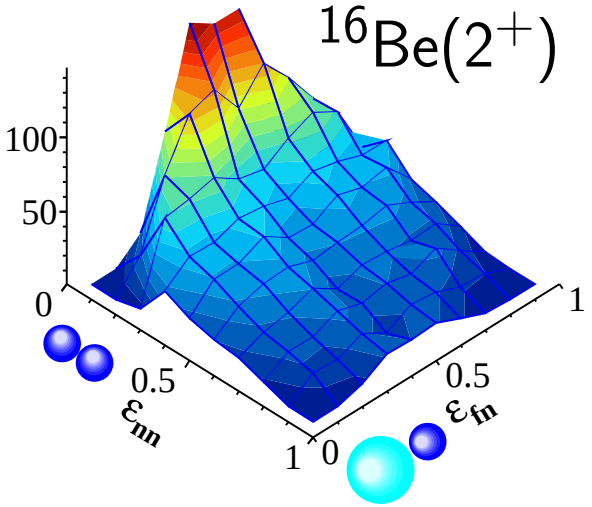
Casal & Monteagudo, in progress

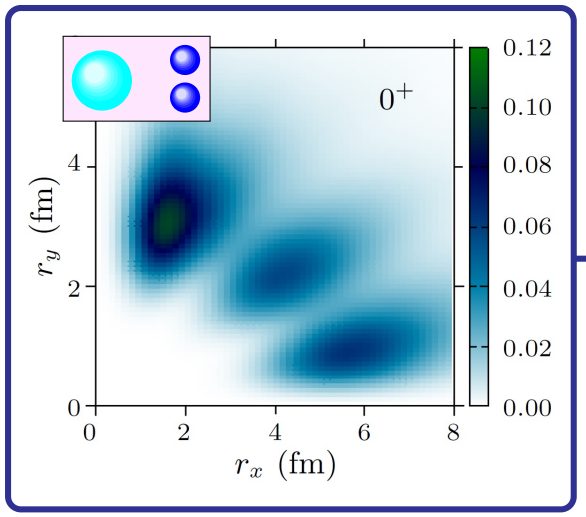
Probing the 2n wave function [B. Monteagudo]

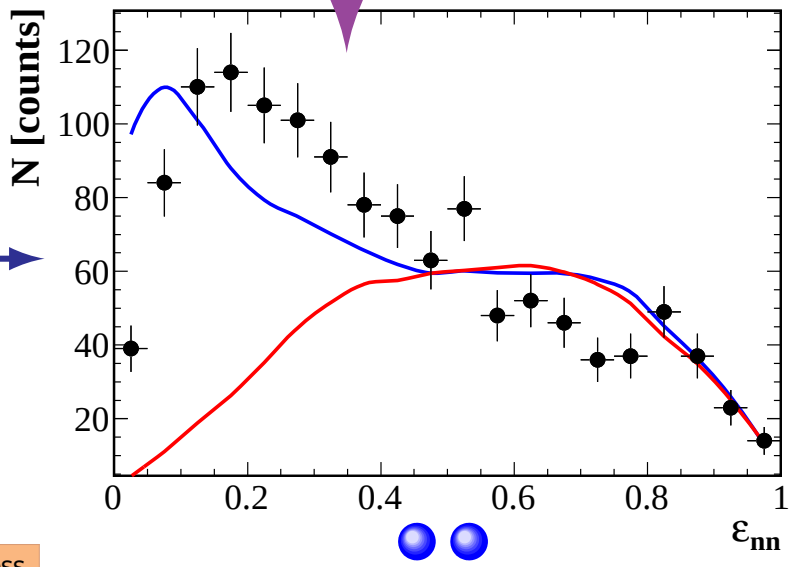
- Dalitz plot of 2n decay :

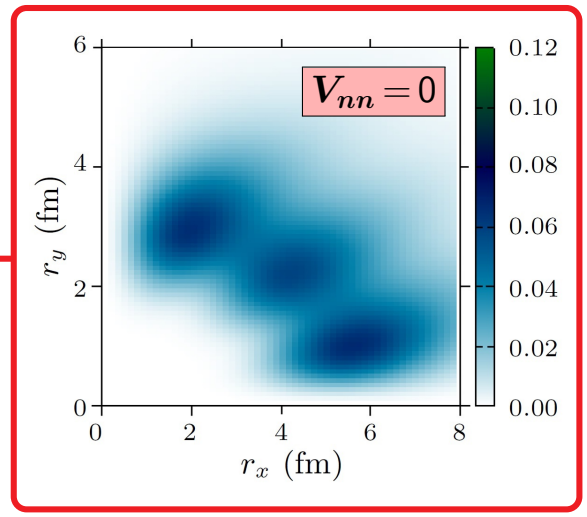








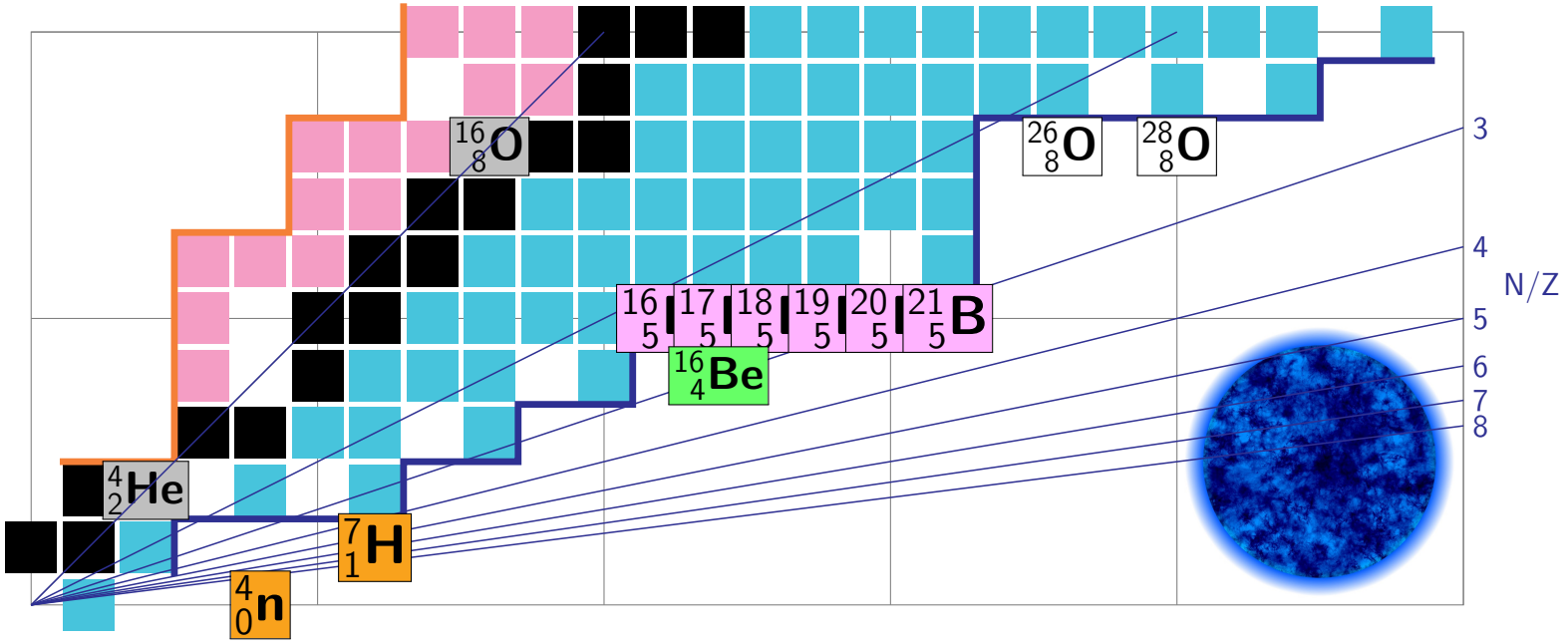




Casal & Monteagudo, in progress

J. Casal, EFB24

The exotic limits of exotic nuclei



- Access to extreme N/Z ratios :

❶ Z = 5 (**SAMURAI Day-1**) :

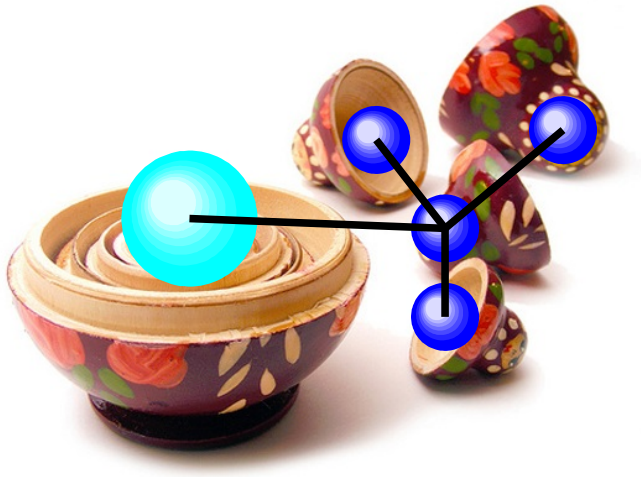
→ literally exotic structures !

❷ Z = 4 (**SAMURAI S18**) :

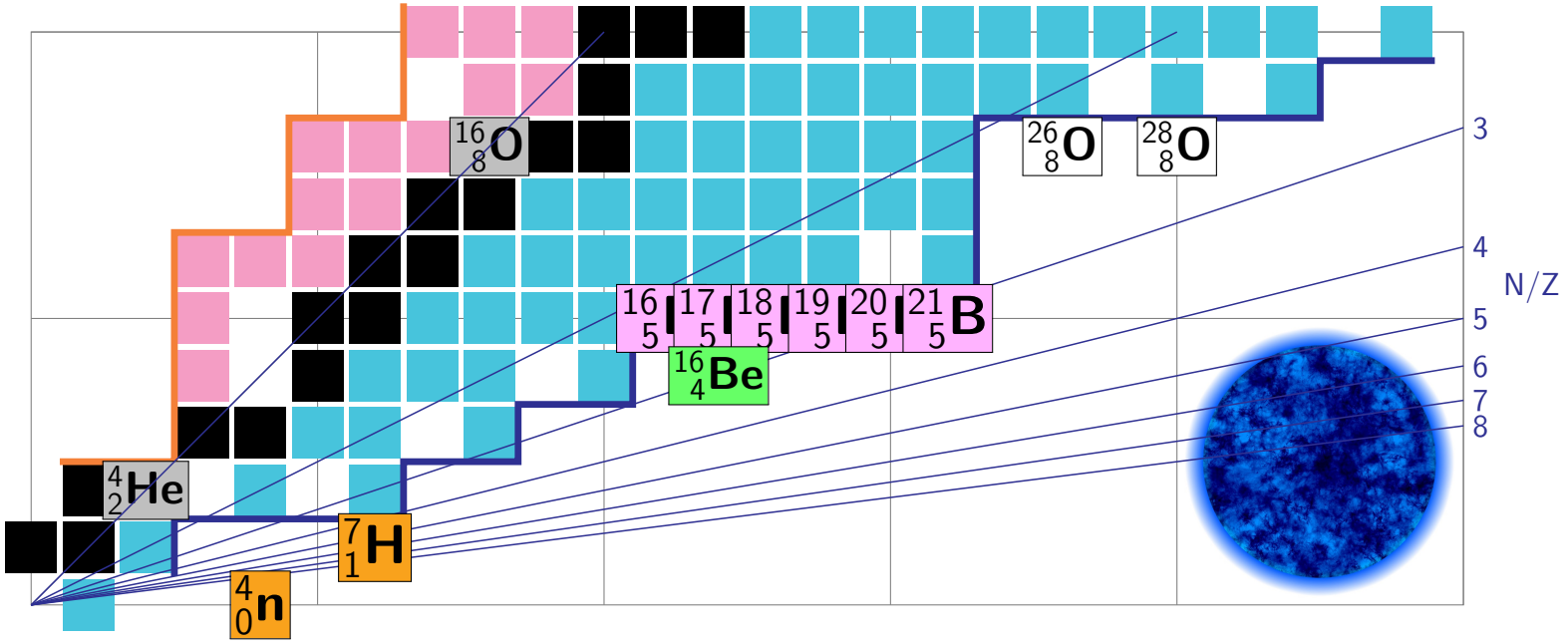
→ 2n emission/decay ?

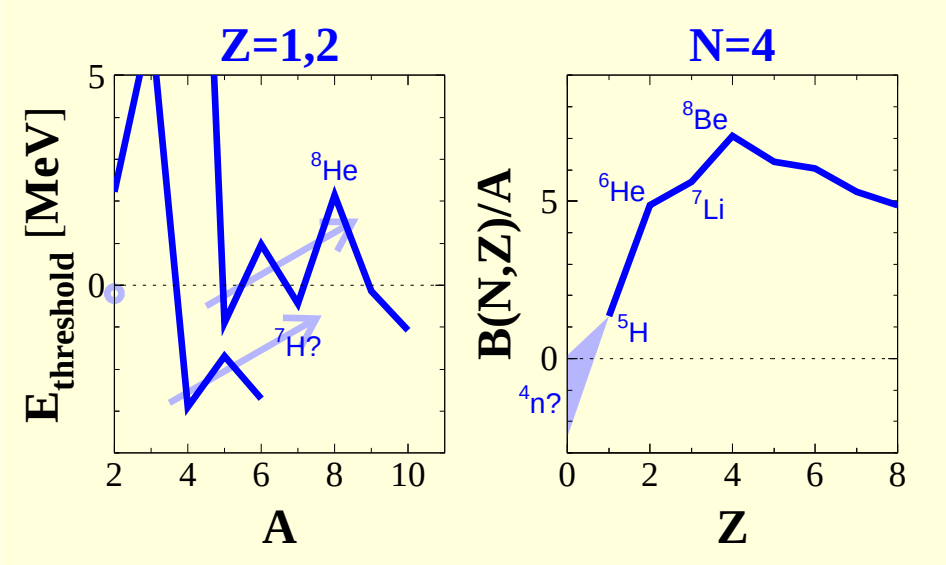
❸ Z = 1 & Z = 0 (**SAMURAI S34**) :

→ multineutron physics !

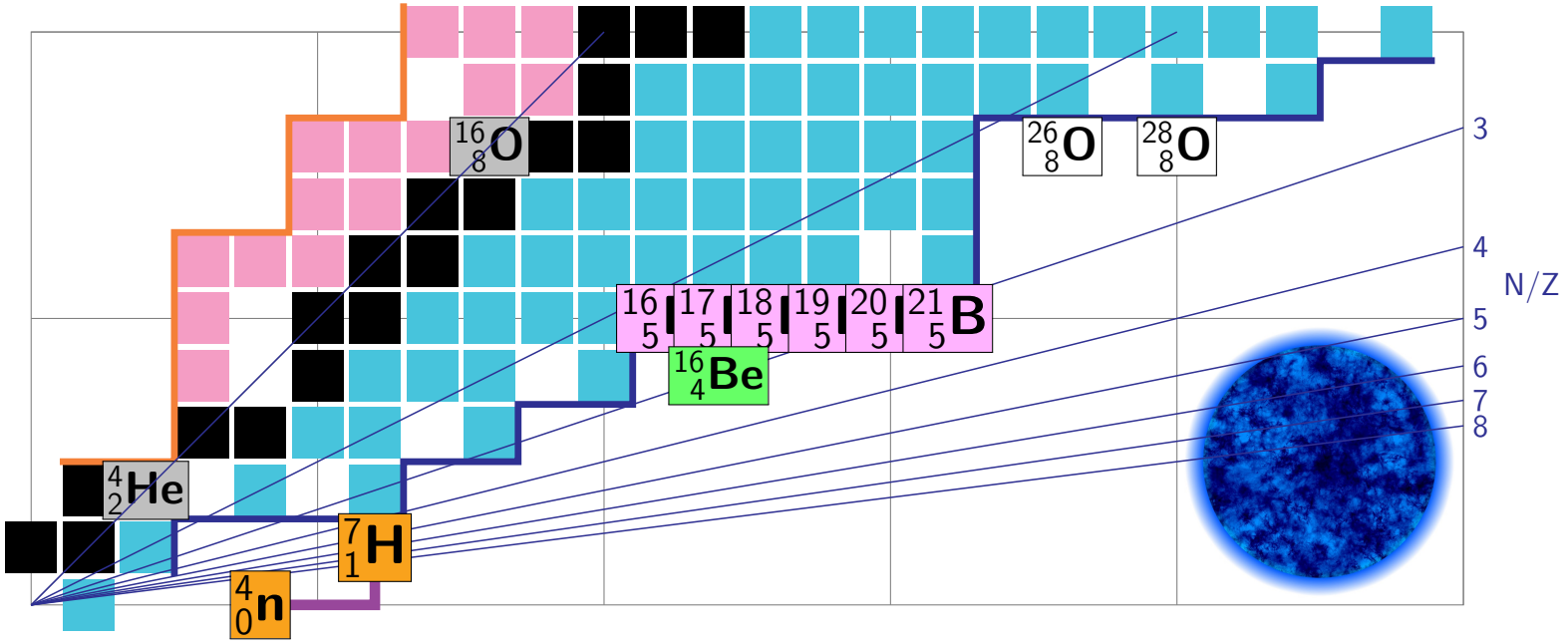


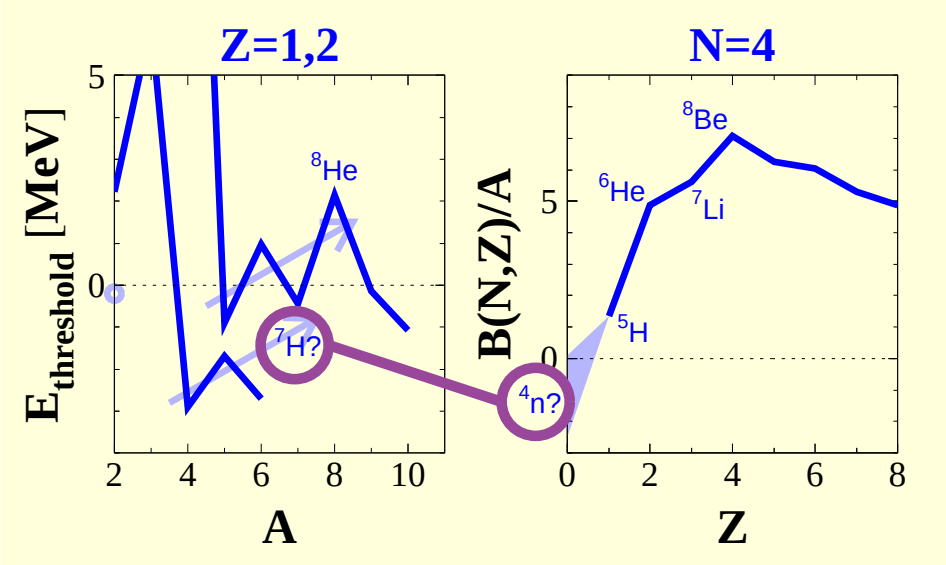
Hydrogen 7 & Tetraneutron : tiny 'neutron stars'





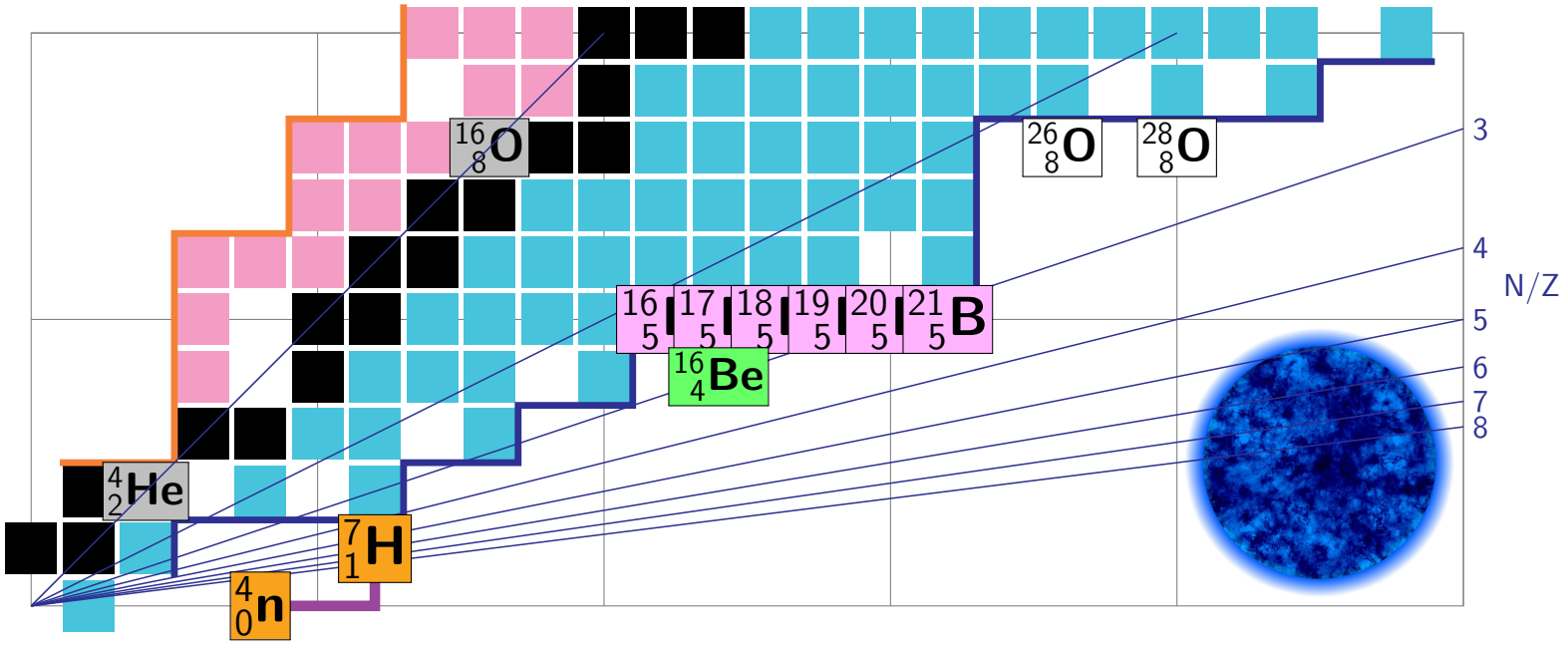
Hydrogen 7 & Tetraneutron : tiny 'neutron stars'

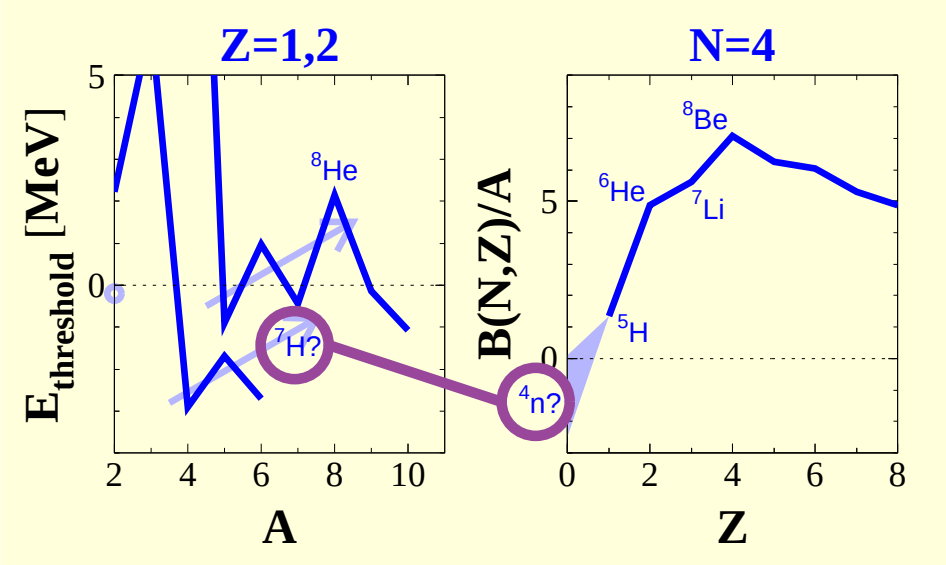




- Ambiguous and contradictory signals :
  - ✘ low statistics & resolutions
  - ✘ backgrounds (targets, binary channels)
  - ✘ missing mass : no neutron detection

Hydrogen 7 & Tetraneutron : tiny 'neutron stars'





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  - ✘ low statistics & resolutions
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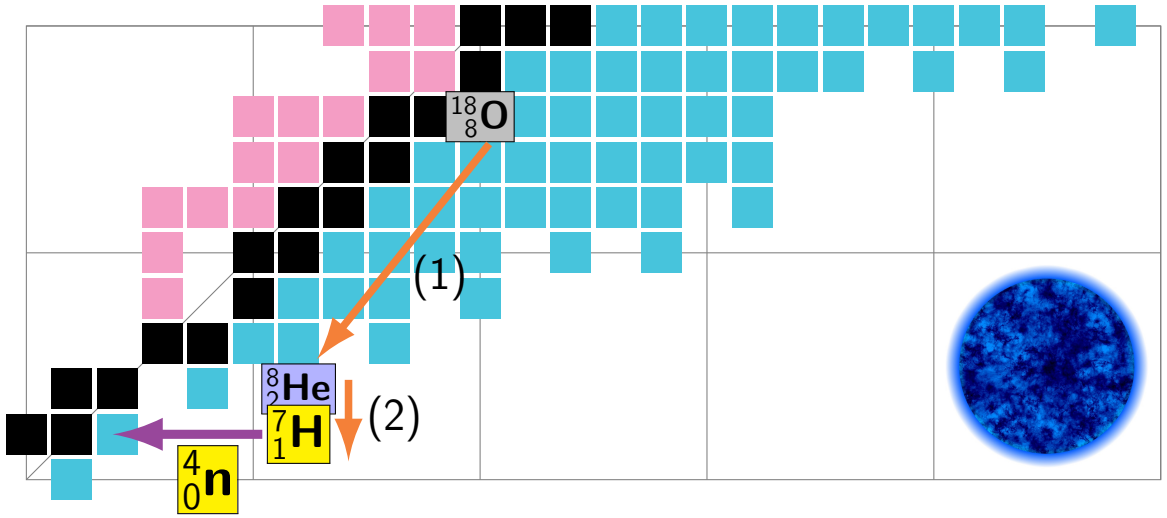
  - ✘ missing mass : no neutron detection

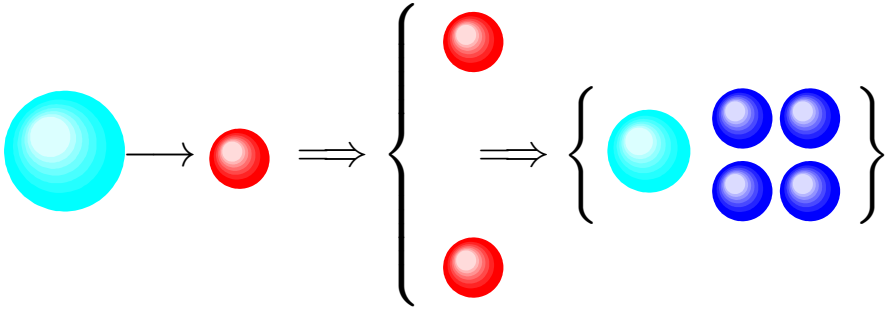
  ⇨ ^{7}H & ^{4}n proposal with $\varepsilon(4n) \gg 0$!

  FMM/Yang, NP1512-SAMURAI34

Hydrogen 7 & Tetraneutron 'emission' ?

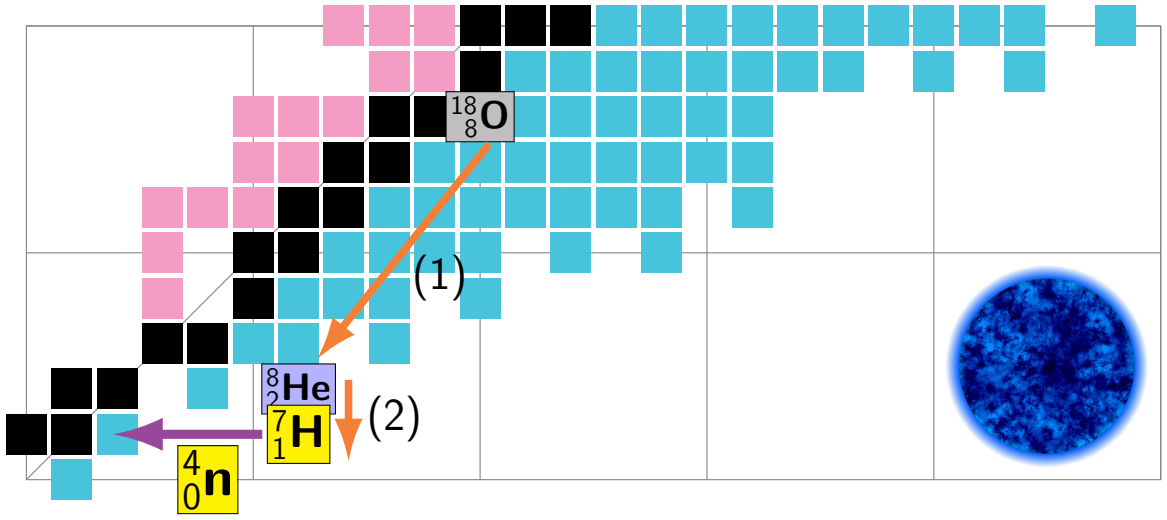


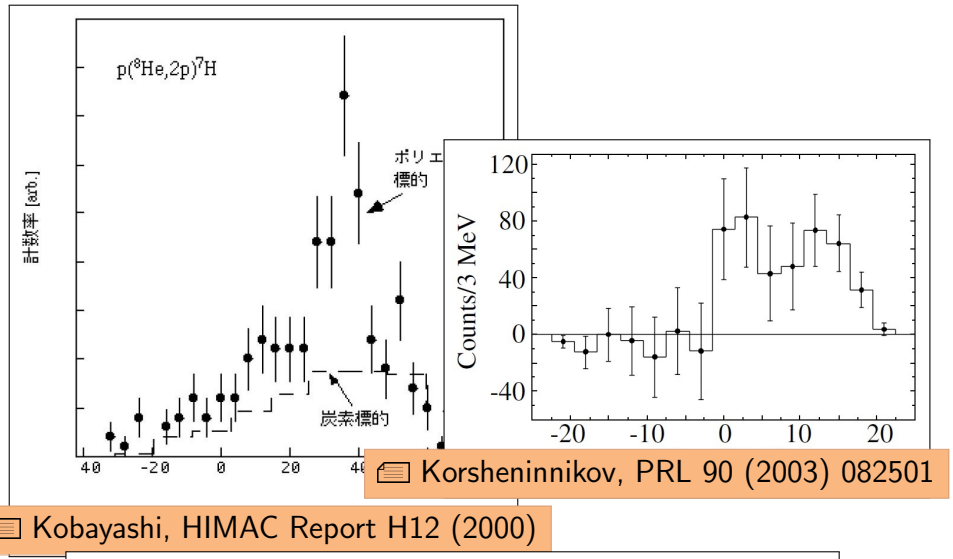
^{8}He (p,2p) ^{7}H @ 150 MeV/N :



→ 7-body final state !

Hydrogen 7 & Tetraneutron 'emission' ?

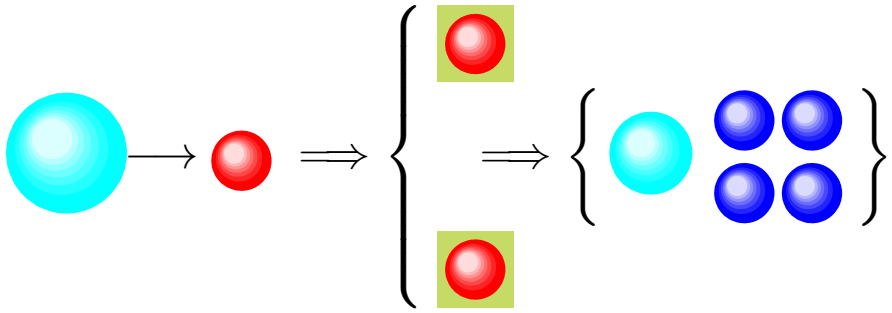




Kobayashi, HIMAC Report H12 (2000)

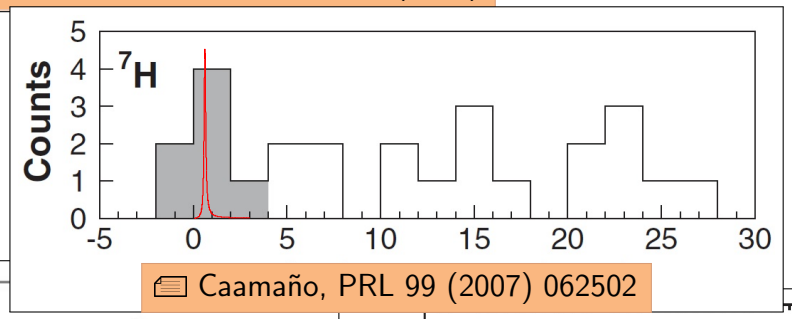
Korsheninnikov, PRL 90 (2003) 082501

^{8}He (p,2p) ^{7}H @ 150 MeV/N :

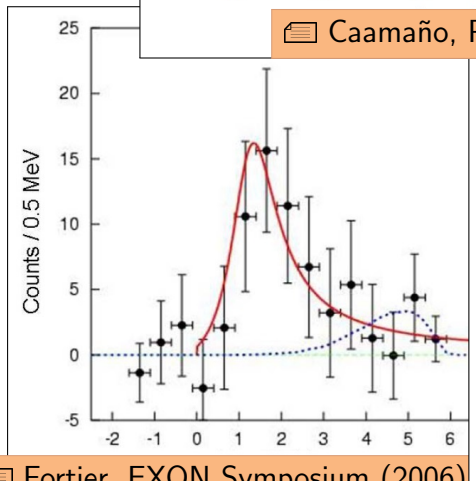


→ 7-body final state !

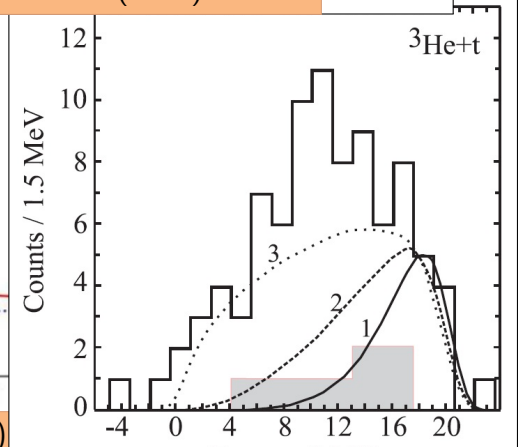
→ FWHM ∼ few MeV



Caamaño, PRL 99 (2007) 062502

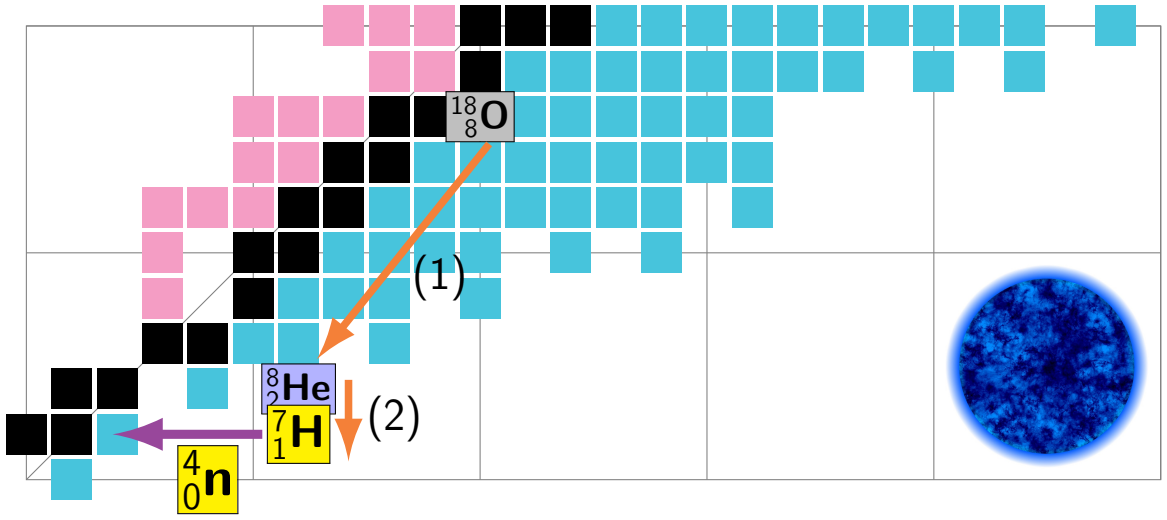


Fortier, EXON Symposium (2006)



Nikolskii, PRC 81 (2010) 064606

Hydrogen 7 & Tetraneutron 'emission' ?



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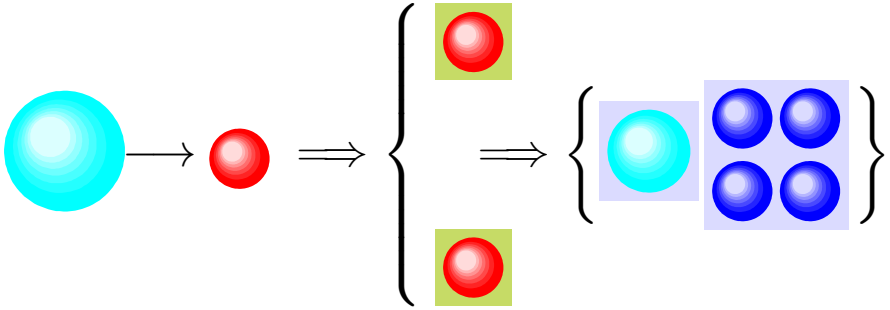
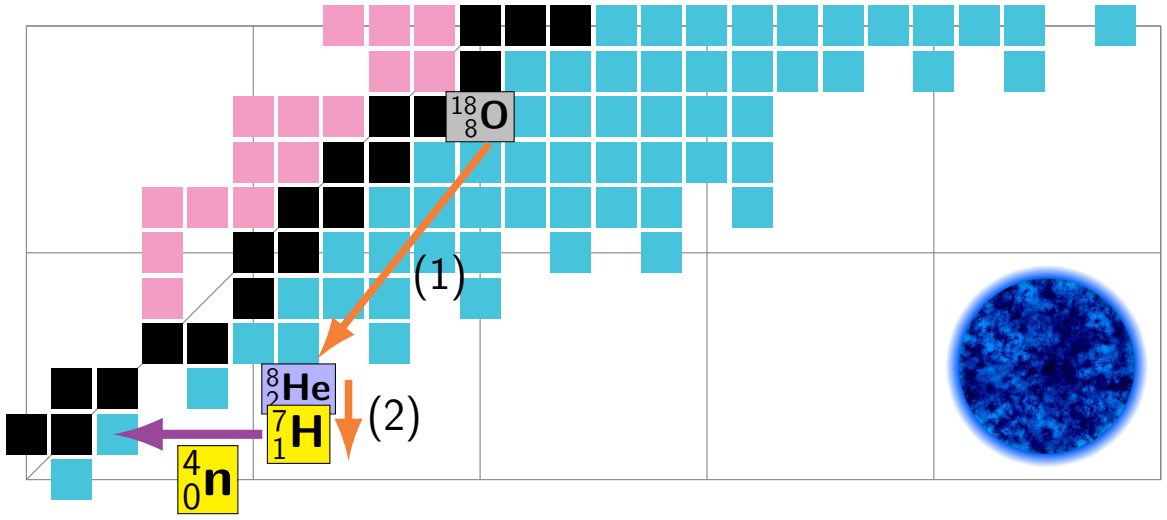


→ 7-body final state !

→ FWHM ∼ few MeV → 100 keV !

- **MINOS** liquid H target :
  → high luminosity (*statistics*)
  → proton angles (*resolution*)
- **DALI** NaI crystals :
  → proton energies (*efficiency*)
- **SAMURAI** :
  → triton momentum
  (*resolution & correlations*)
- **NEBULA** + **NeuLAND** :
  → 3/4 neutron momenta
  (*efficiency, resolution & correlations*)

Hydrogen 7 & Tetraneutron 'emission' ?



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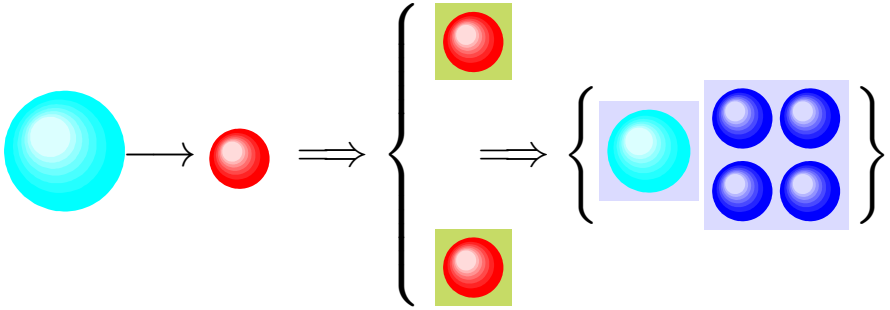
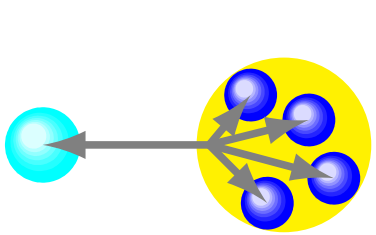


→ 7-body final state !

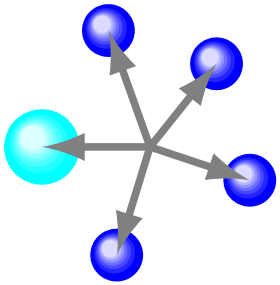
→ FWHM ∼ few MeV → 100 keV !

→ (2p+t+3n) ∼ 150 keV !

angular correlations → E(4n) !

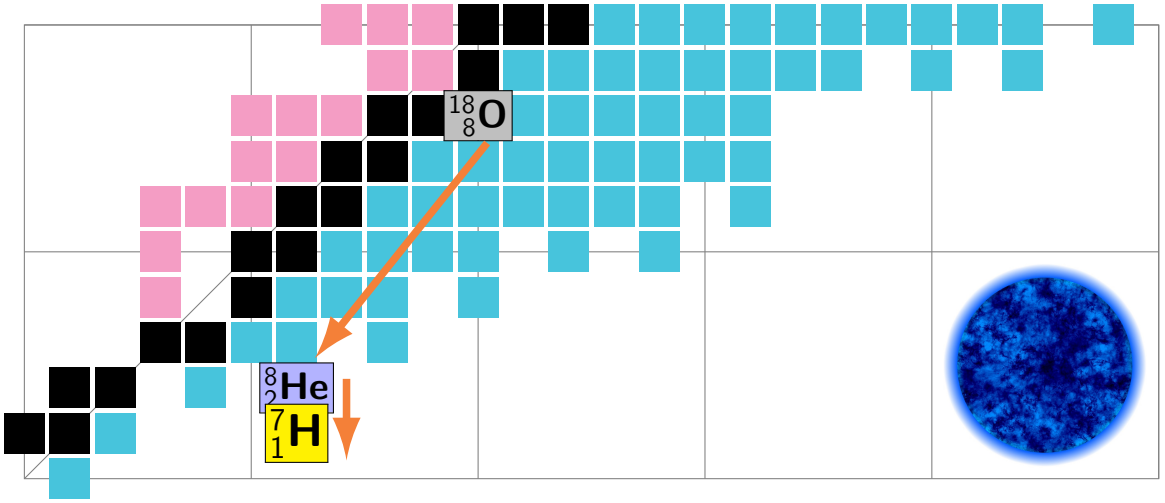


(2-body PS)

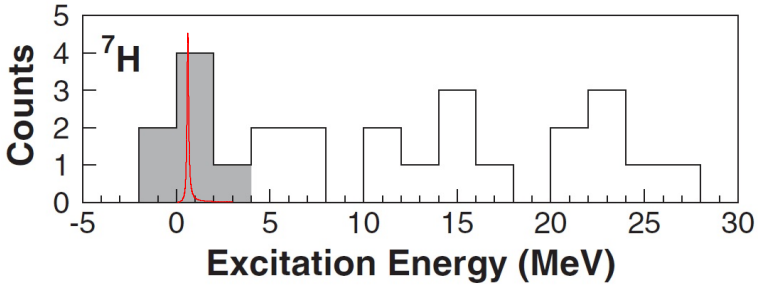


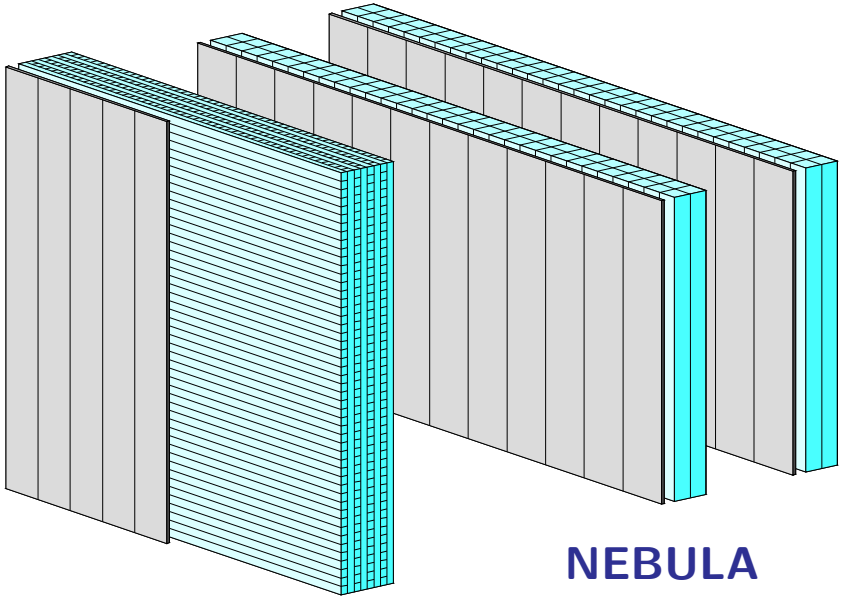
(5-body PS)

Expected results : MC simulations

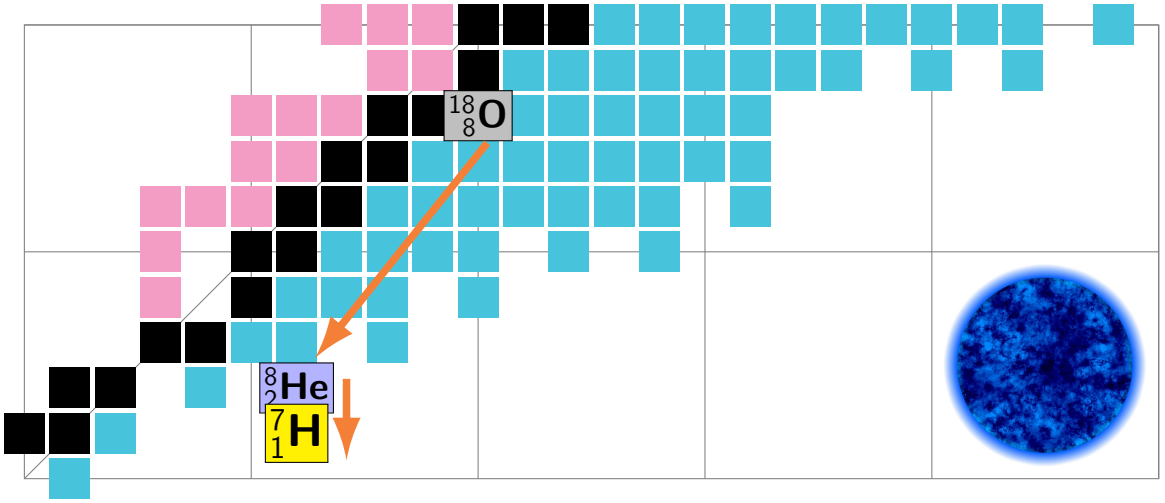


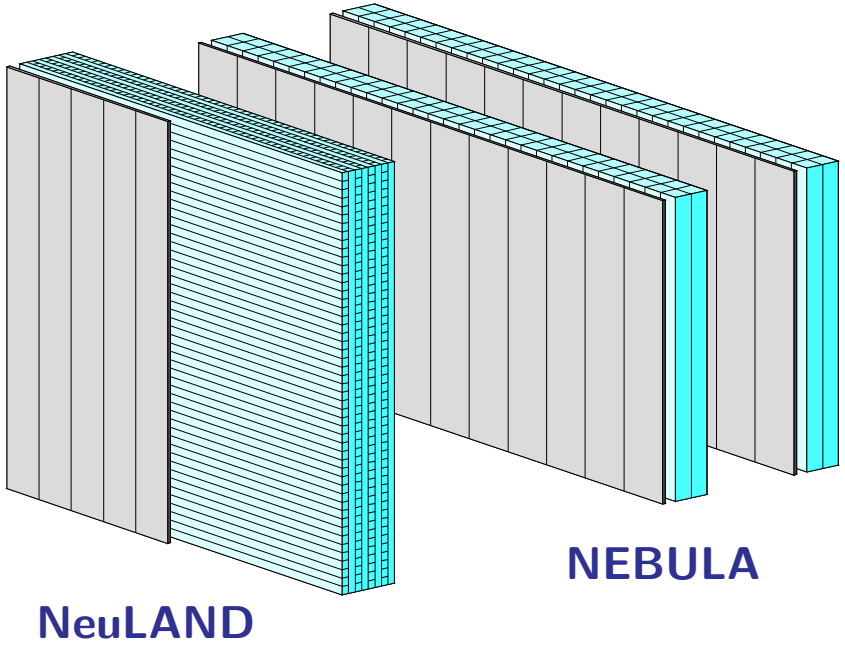
Caamaño, PRL 99 (2007) 062502



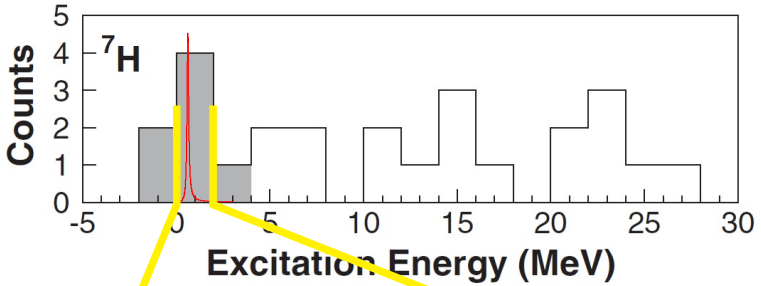


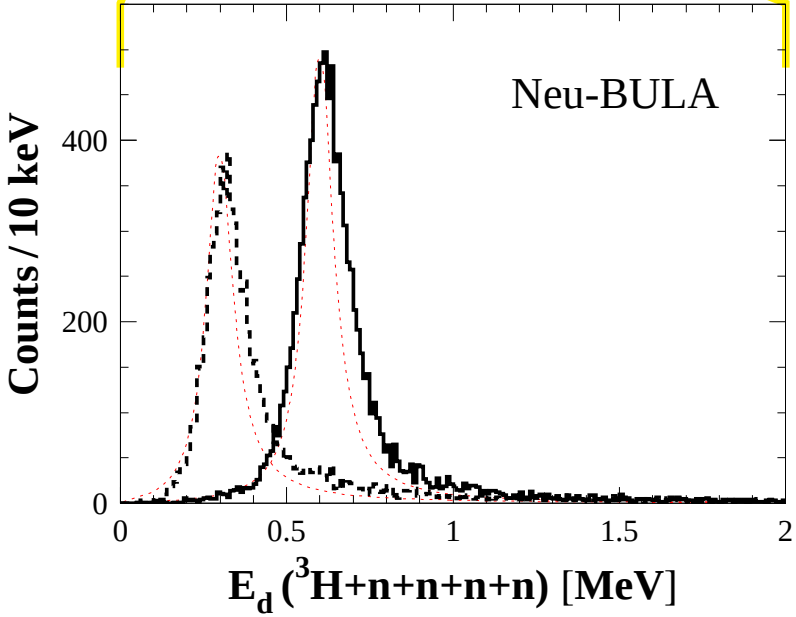
Expected results : MC simulations



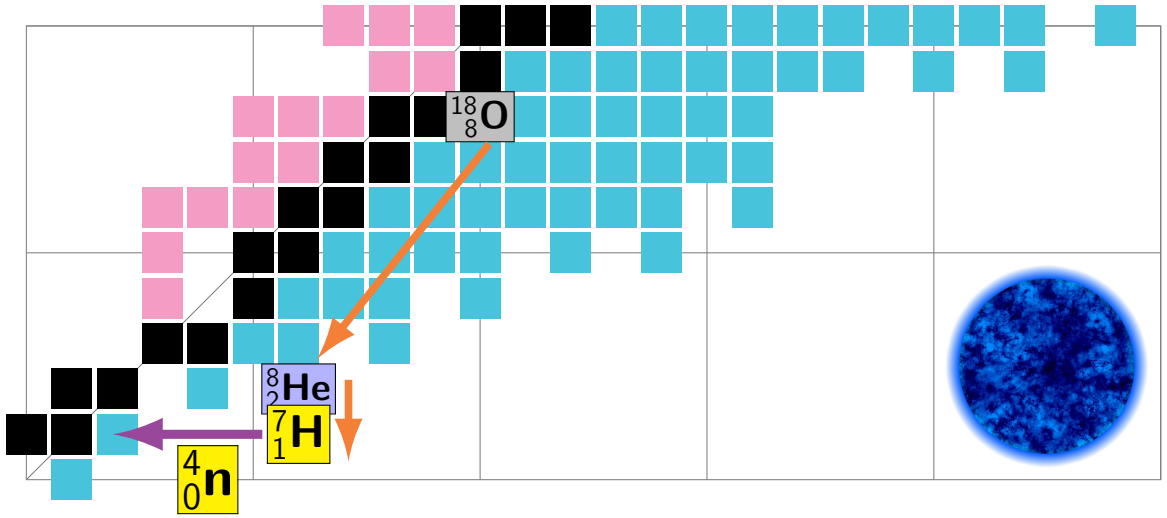


Caamaño, PRL 99 (2007) 062502



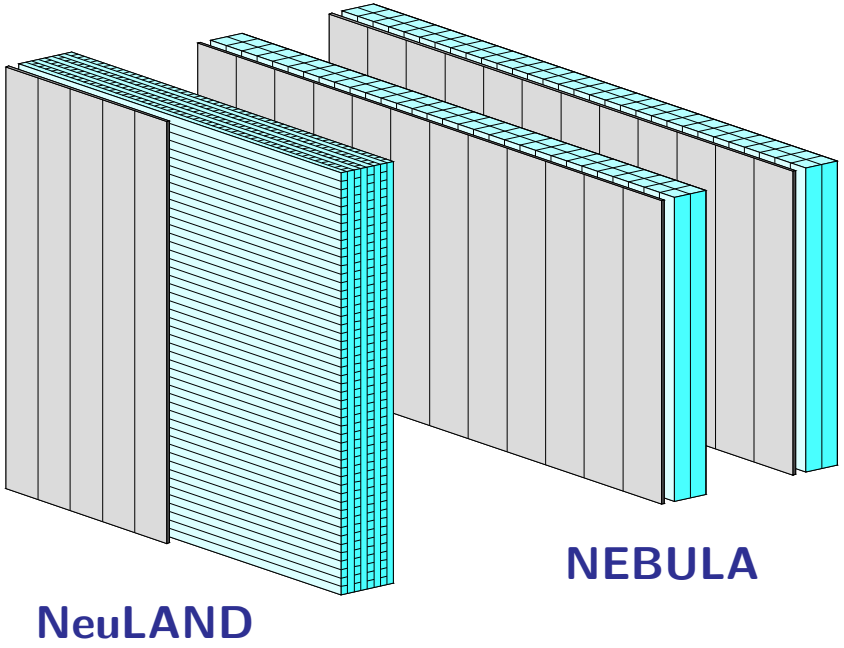


First online 'results' [A. Revel]

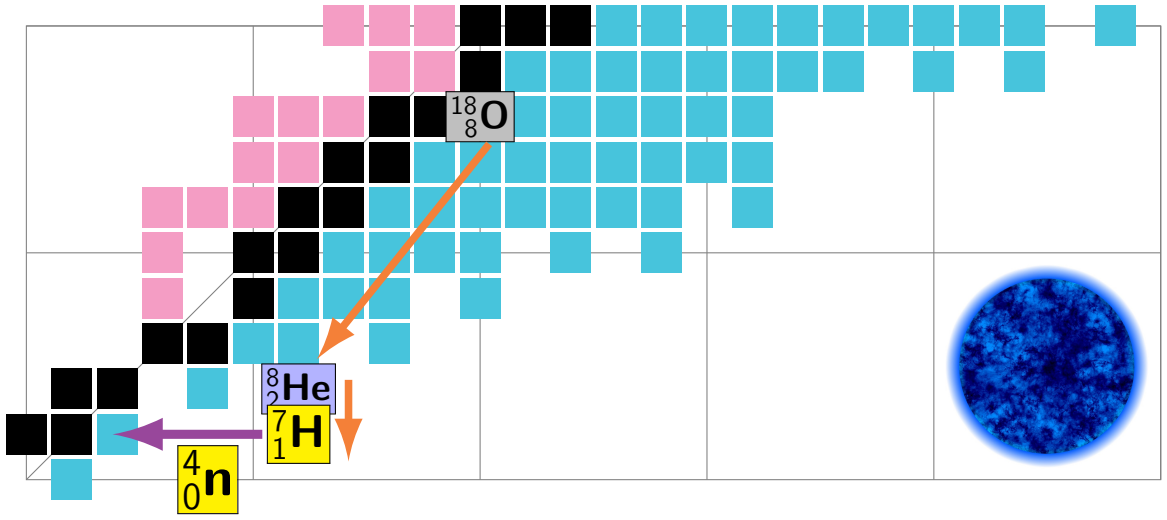


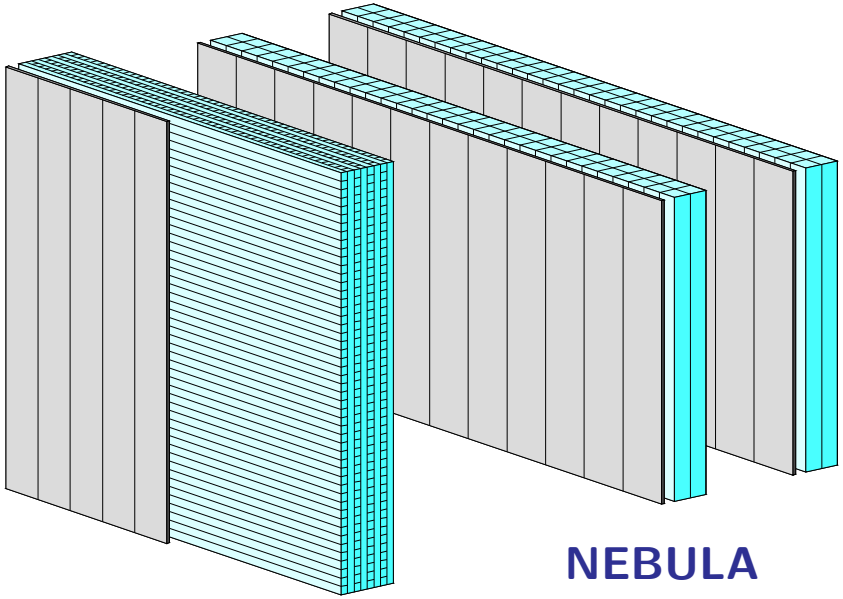
- Online analysis : ^{8}He (p,2p) ^{3}H+^{4}n
  - ✔ ^{8}He on target
  - ✔ 2p detected
  - ✔ ^{3}H detected

  → $\geqslant$ 4 bars ???

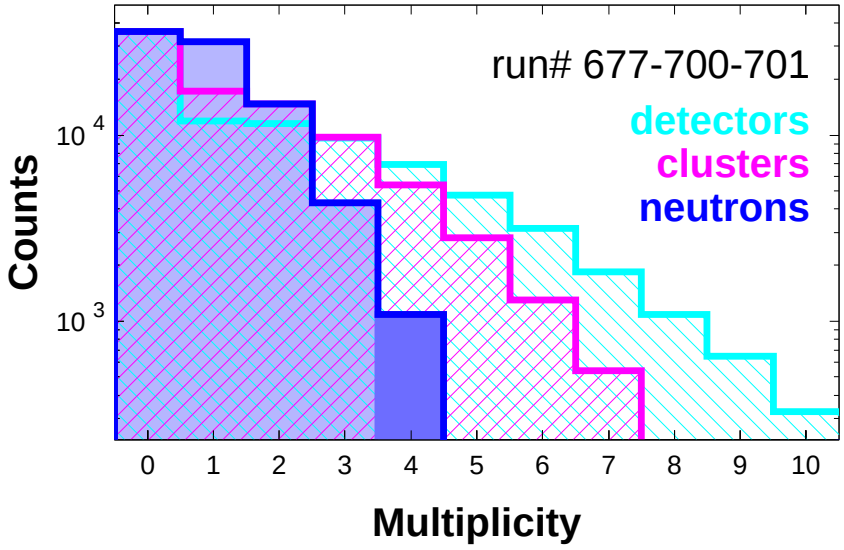


First online 'results' [A. Revel]





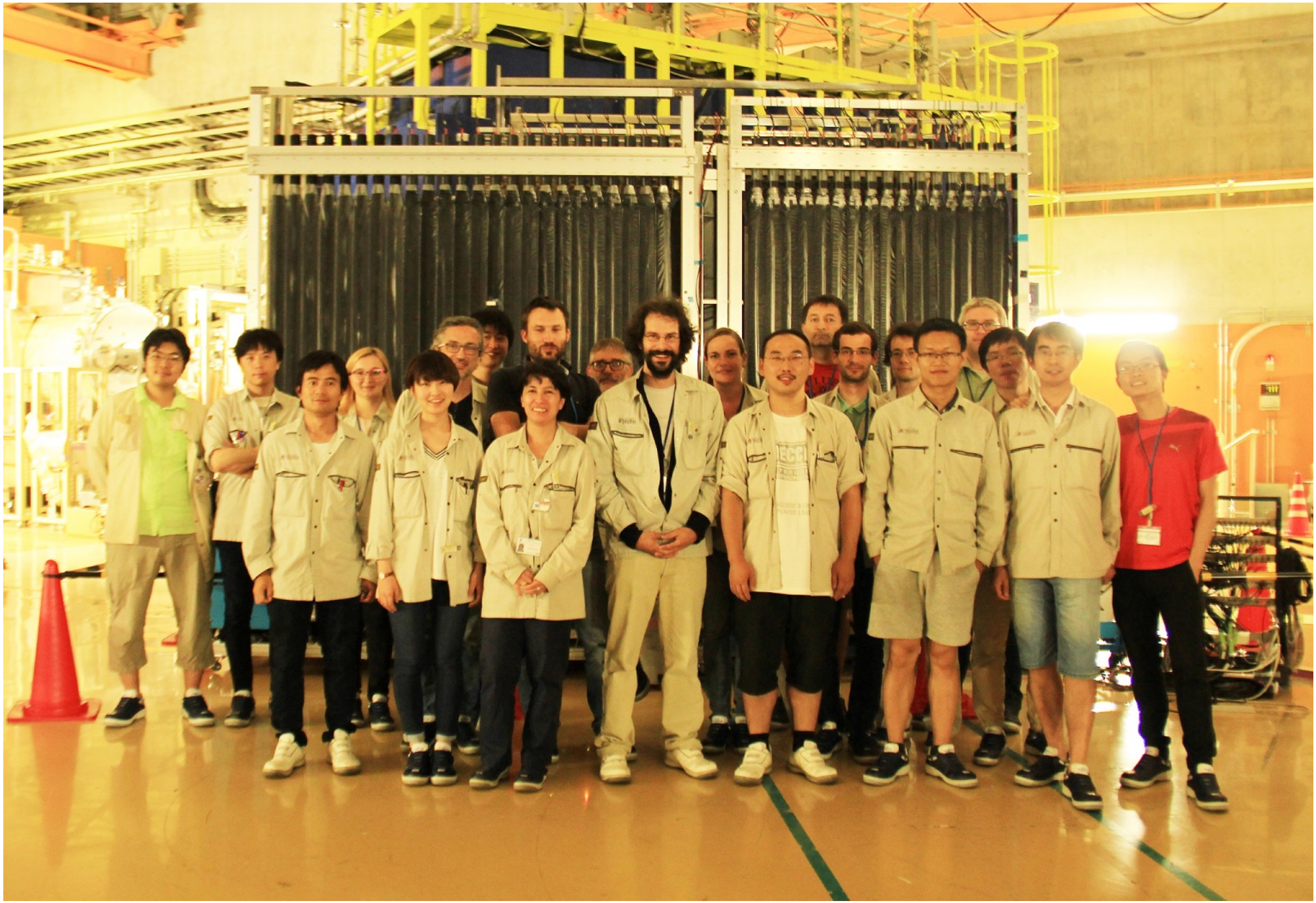
- Online analysis : ^{8}He (p,2p) ^{3}H+^{4}n
  - ✔ ^{8}He on target
  - ✔ 2p detected
  - ✔ ^{3}H detected
  - → $\geqslant$ 4 bars ???



→ total events : ≈ 50k !!!

→ still 1–2 years : calibrations ...

SAMURAI S34 collaboration (part)



RIKEN : SAMURAI (& MINOS-DALI-NeuLAND-NEBULA)

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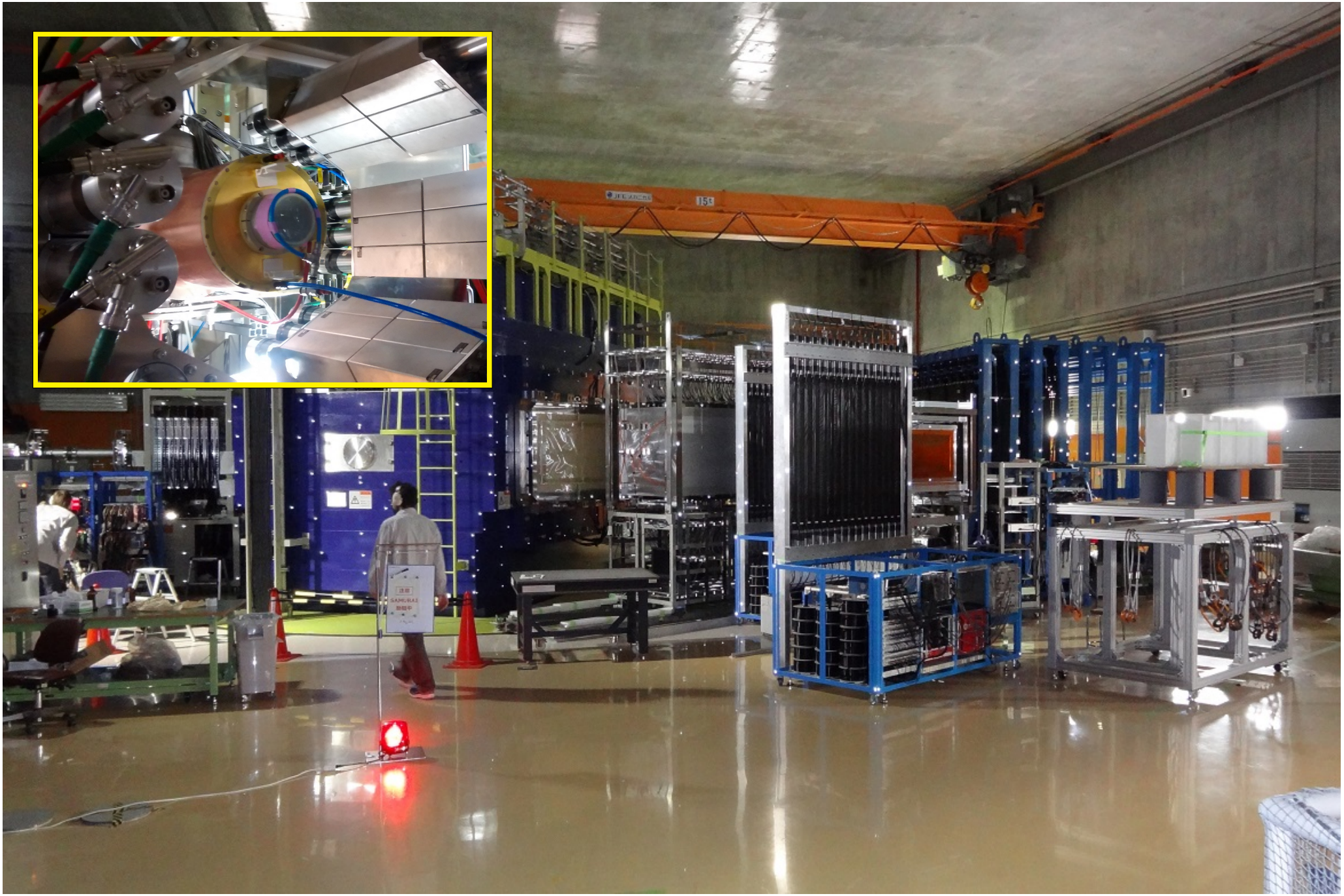
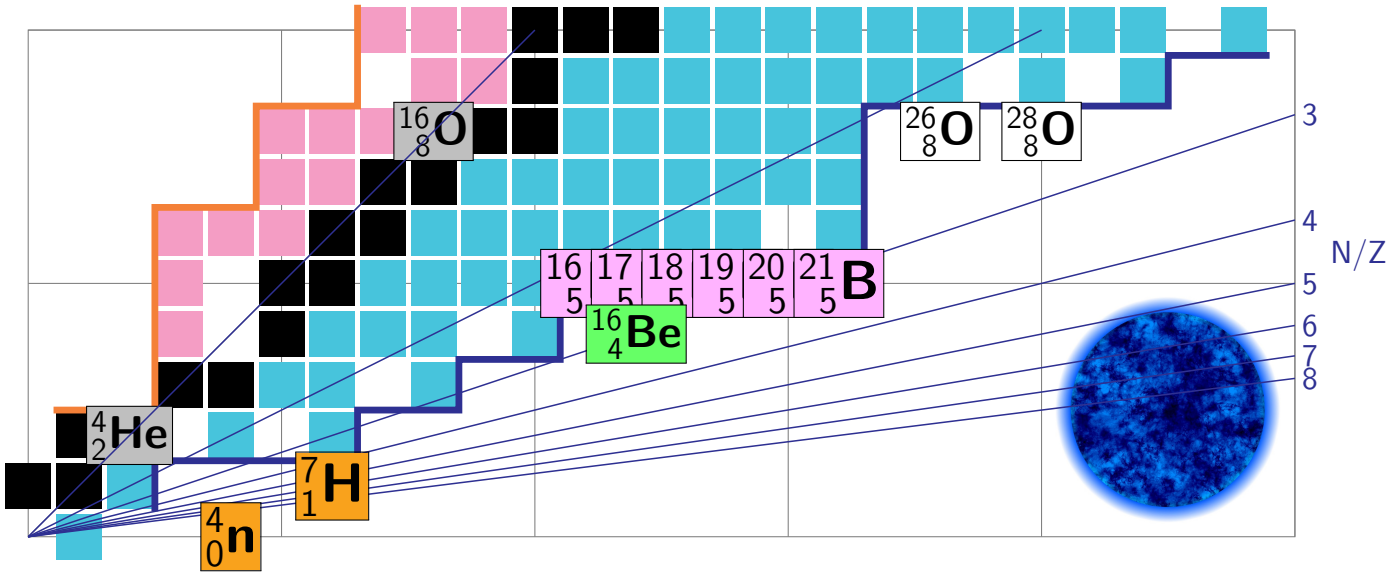


Summary & perspectives



- Extreme N/Z regime :
  - $Z=5$: exotic phenomena !
    - → Efimov trimers ?
    - → 2/4/6n emission ...
  - $Z=4$: 2n emission from ^{16}Be !
  - $Z=1$ & $Z=0$: multineutron physics !
    - → definitive location of ^{7}H & ^{4}n ...
    - → benchmark for many-neutron models