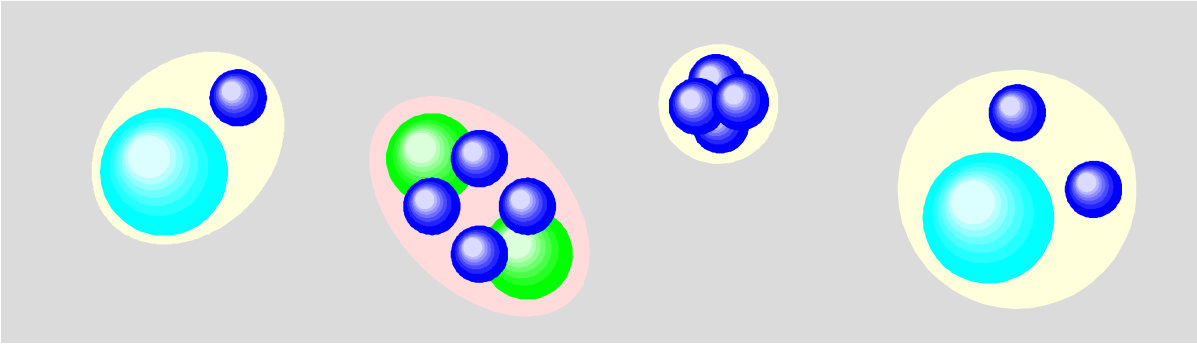
ESNT Workshop

CEA/SPhN, May 30-31 2013

Localization and Clustering in Atomic Nuclei

"AROUND THE NEUTRON DRIPLINE"



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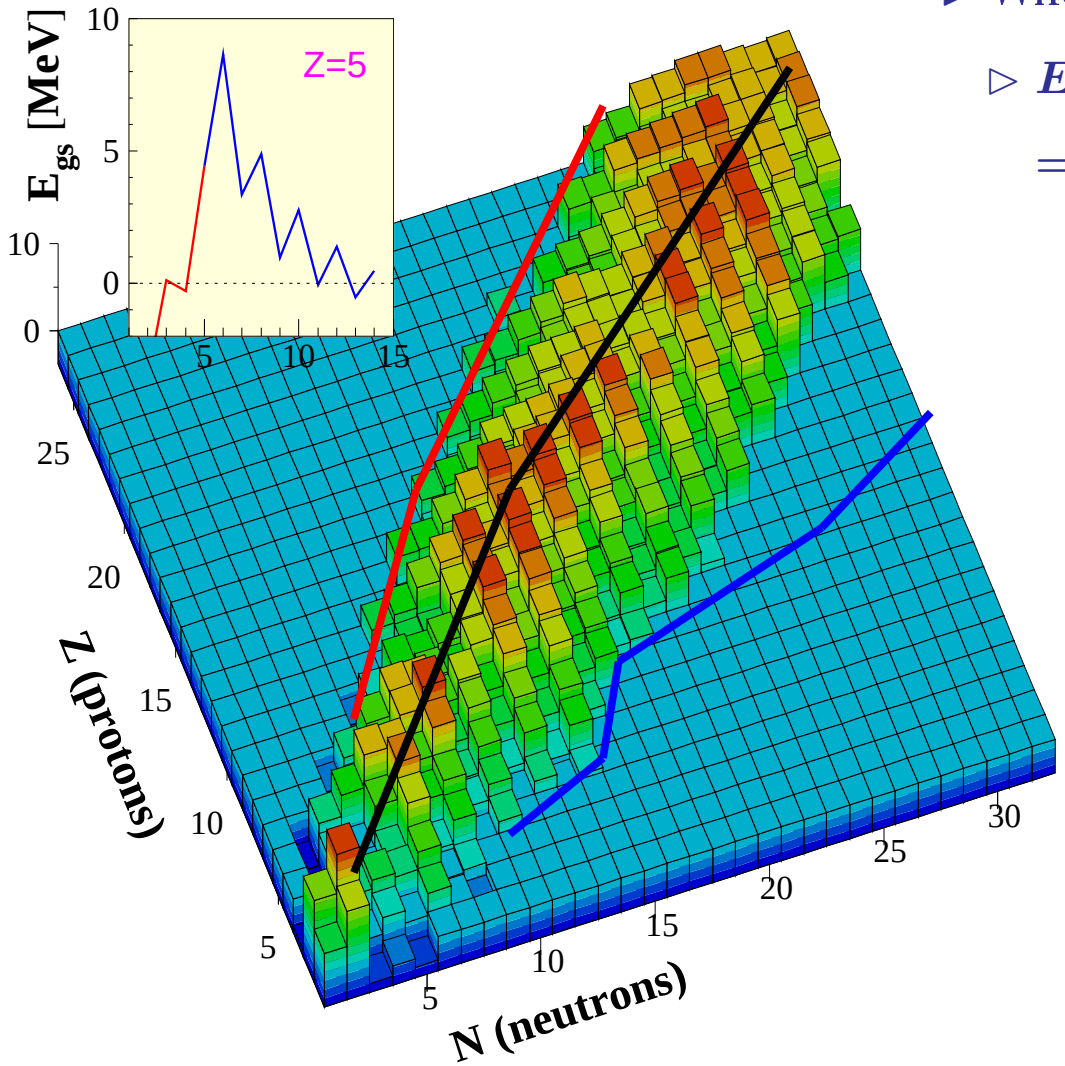
LPC Orr et al.
CHARISSA Freer, Catford et al.
DEMON Hanappe, Stuttgé et al.
SAMURAI Motobayashi, Yoneda et al.
NEBULA Nakamura, Kondo et al.

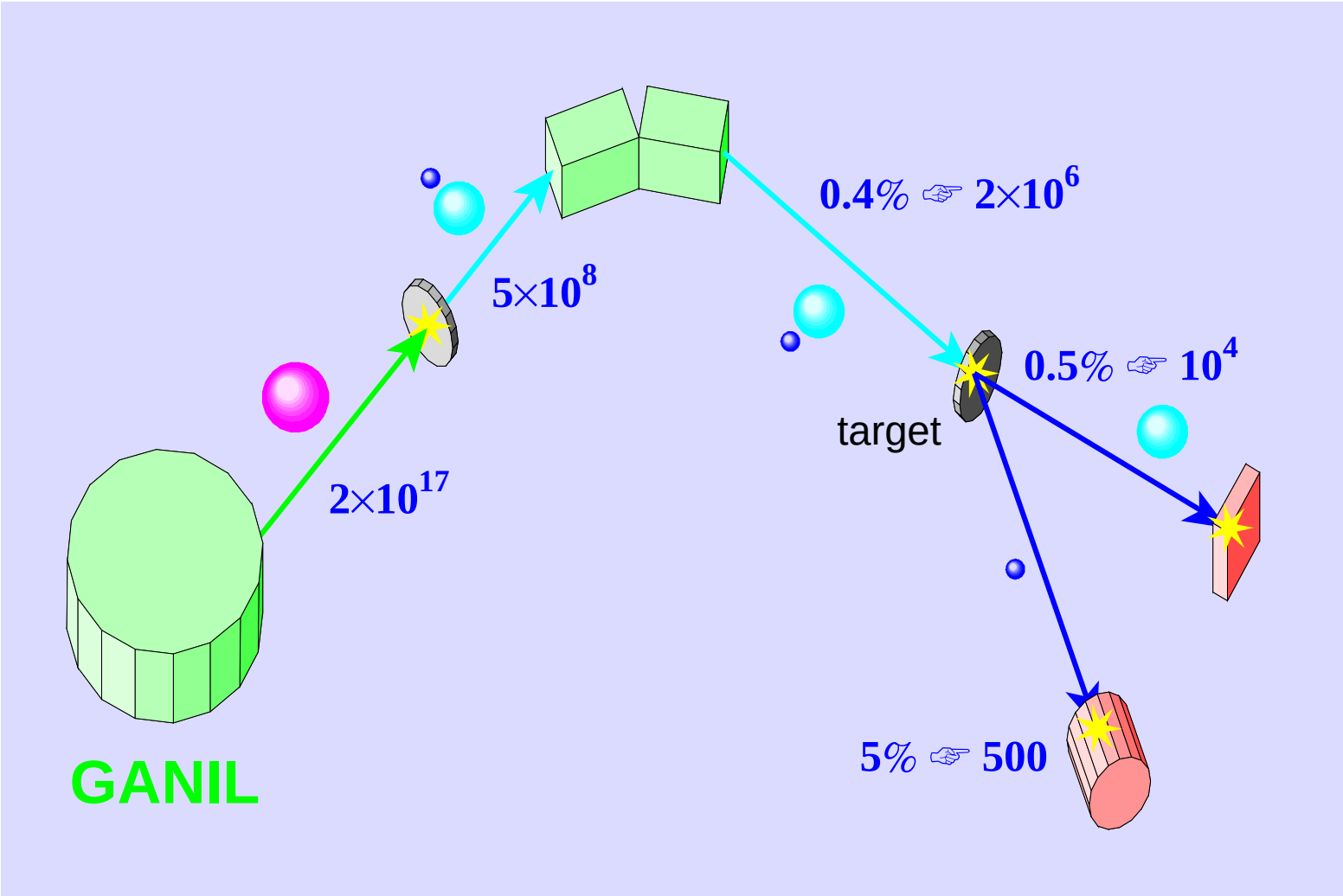
Hicham Al Falou
Benoît Laurent
Anne Leprince
Giacomo Randisi
Sylvain Leblond

THE LIMITS OF STABILITY



- Where are the drip lines ?
  - $E_{gs}(N,Z)$
    $= \min\left[\sum M(n_i,z_i)\right] - M(N,Z)$
  - The neutron dripline :
    - access to extreme (N,Z) !!!
    - limited to light nuclei ...
    - many interesting phenomena
  - In order to probe it :
    - intense n-rich beams
    - efficient neutron detectors

- $^{40}Ar \longrightarrow {}^{19}C \rightarrow {}^{18}C + n$ ('94) :



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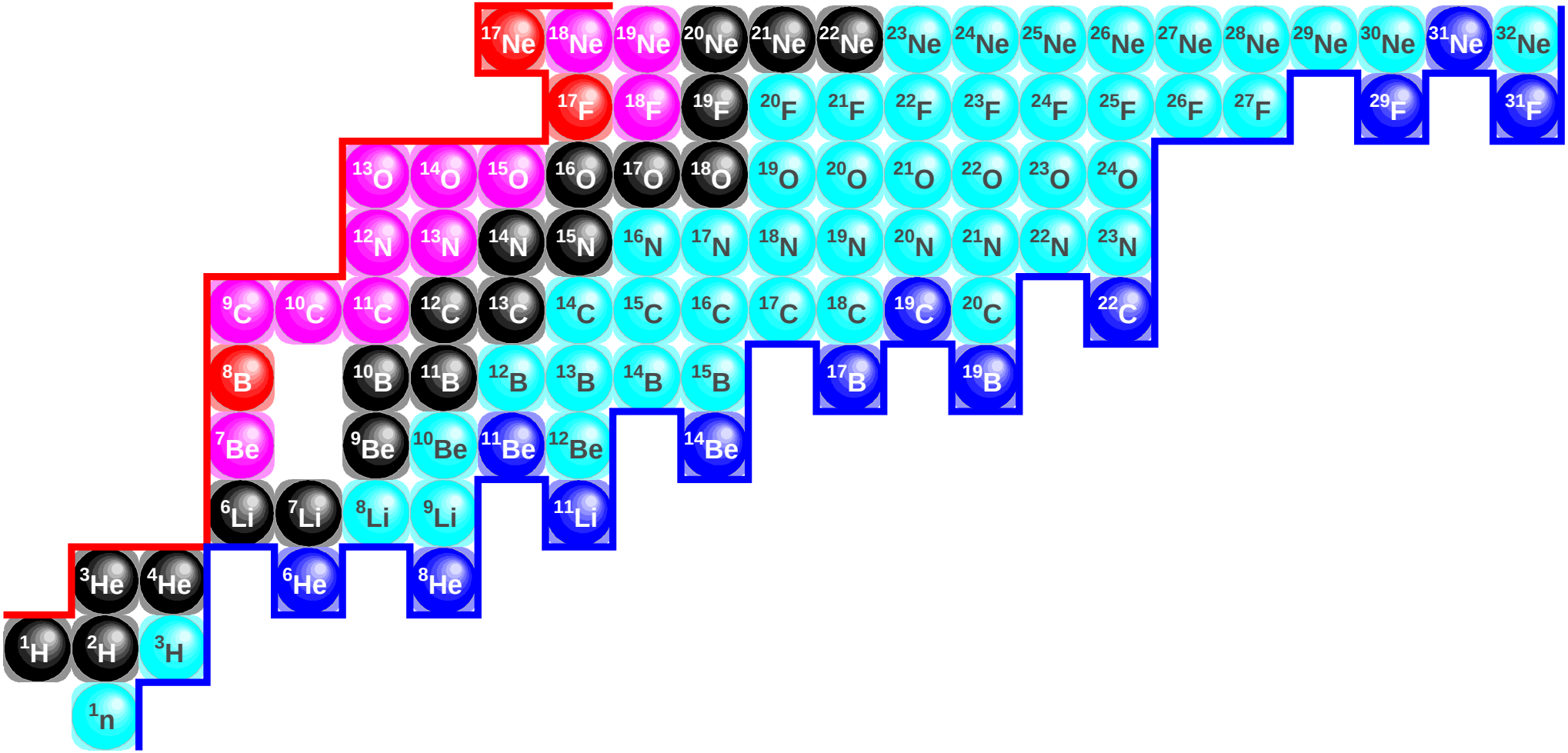

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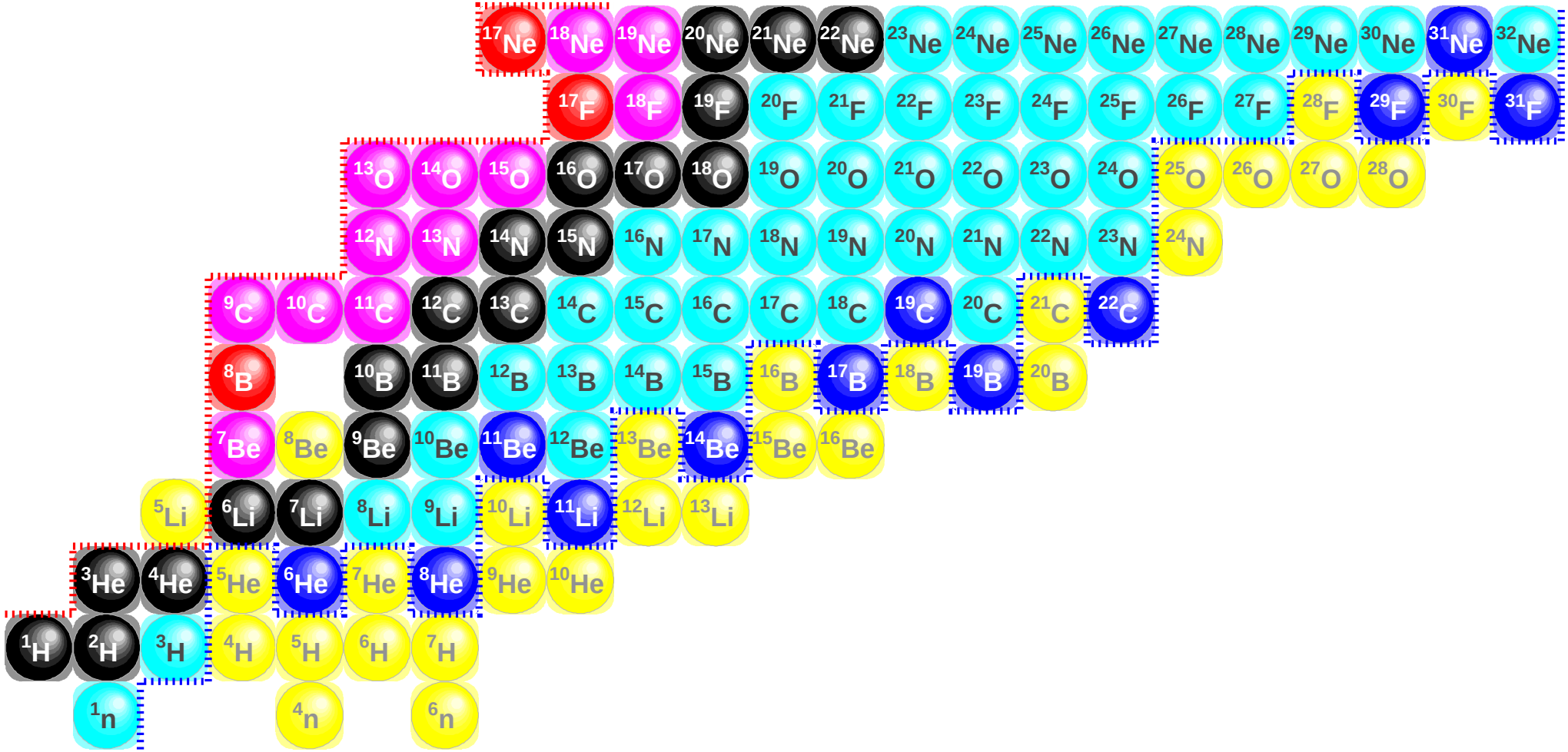

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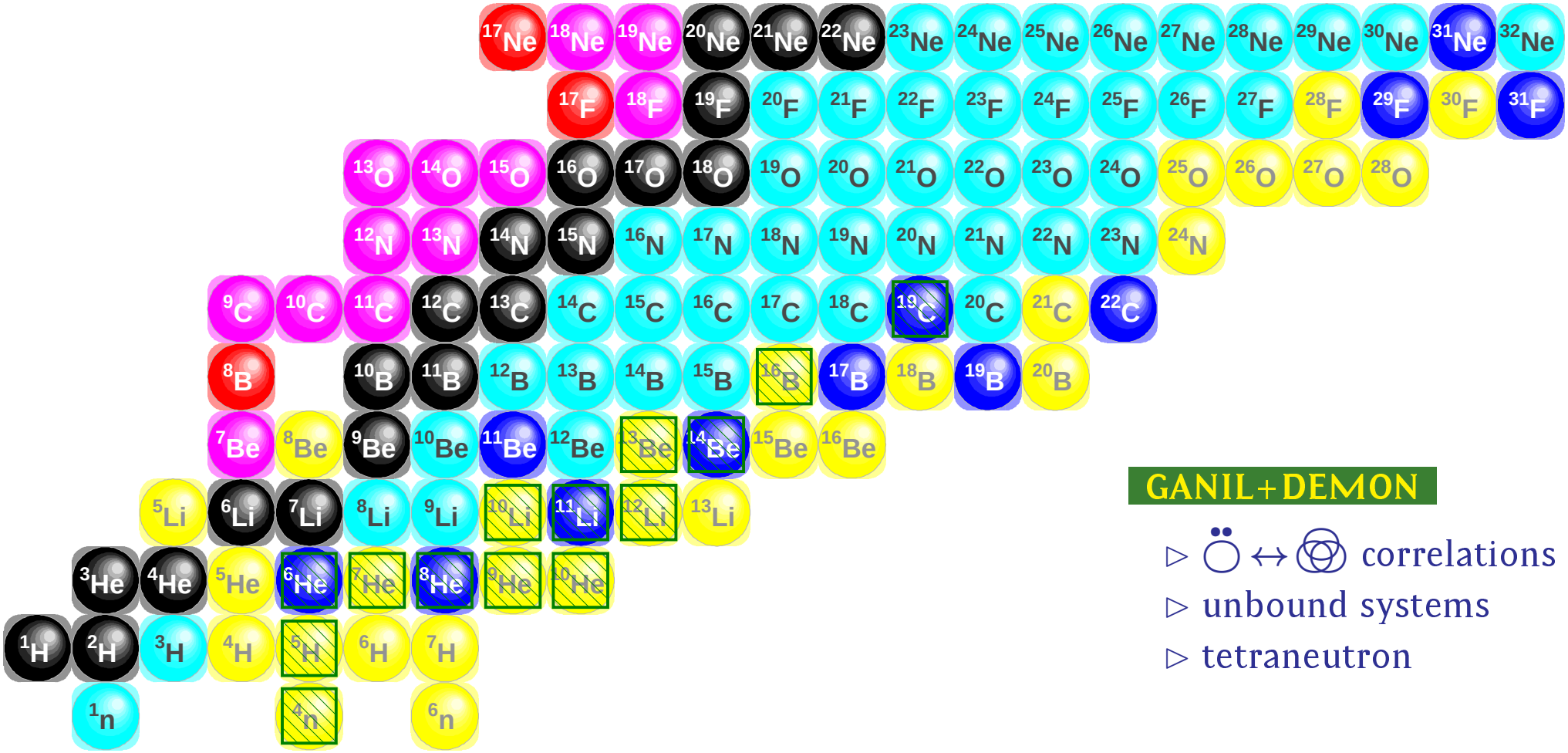
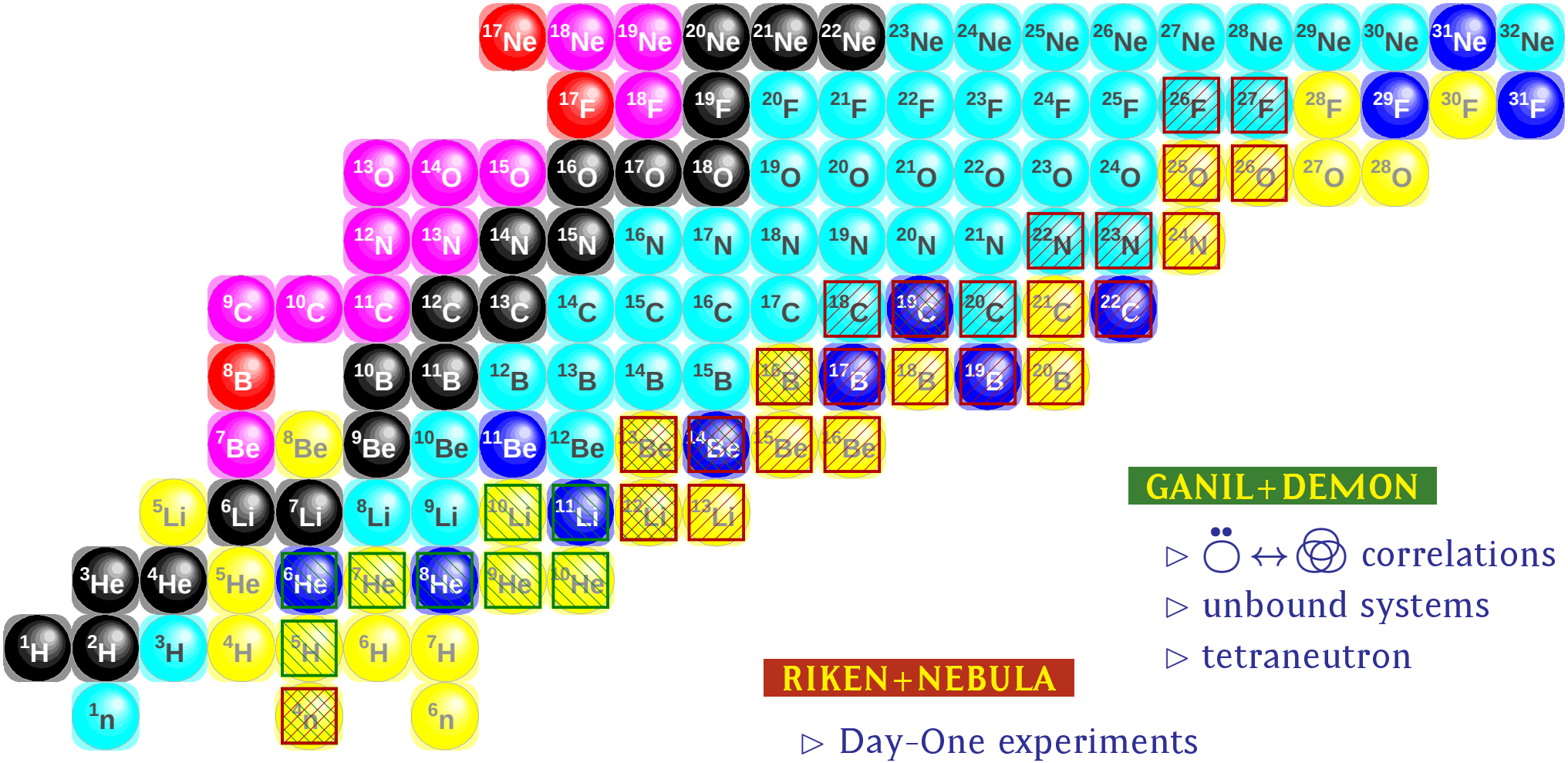


GANIL+DEMON

- ▷ correlations
- ▷ unbound systems
- ▷ tetraneutron

AROUND THE NEUTRON DRIPLINE



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RIKEN+NEBULA

- ▷ Day-One experiments
- ▷ short term : ^{4}n

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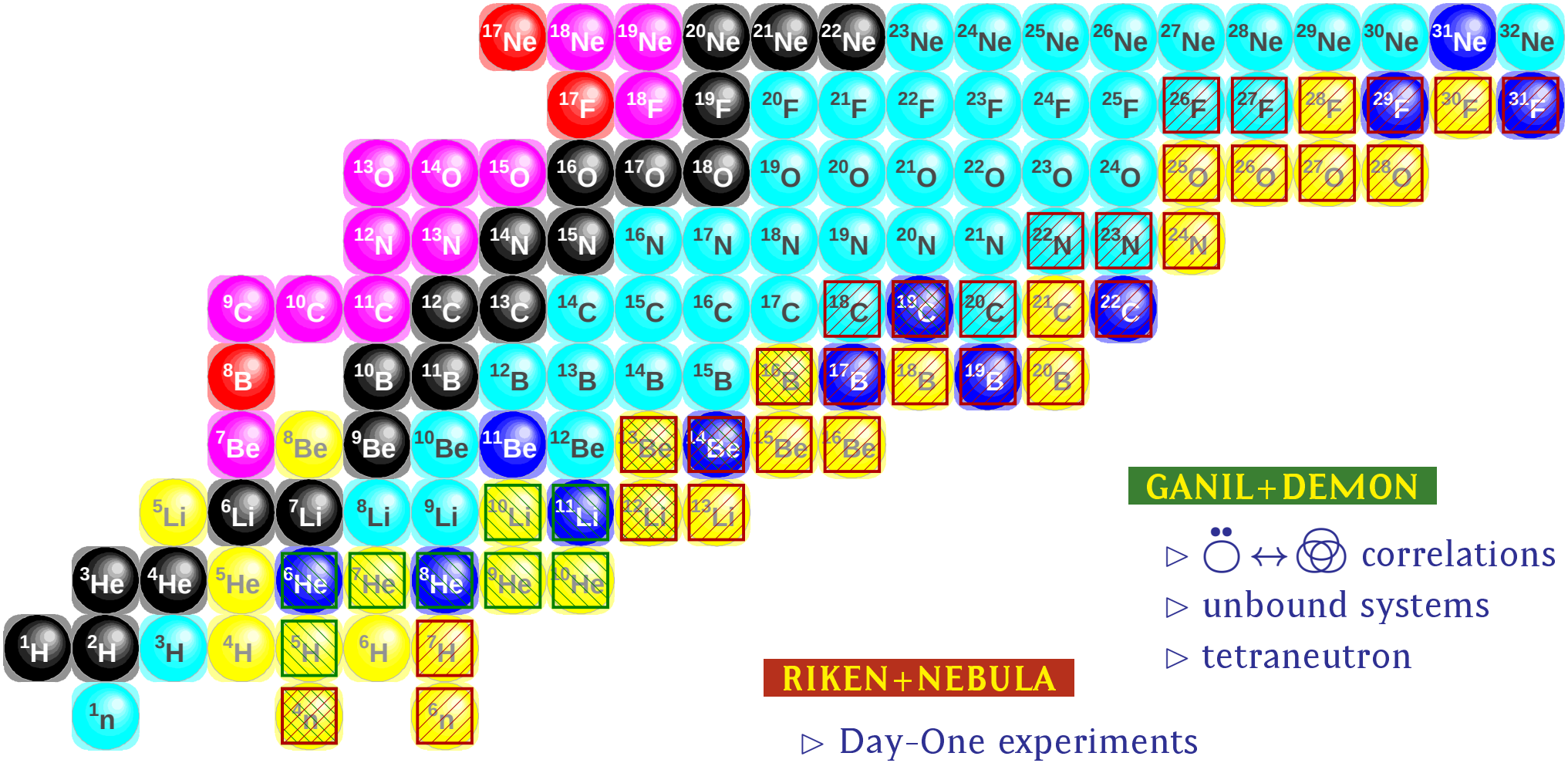

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RIKEN+NEBULA

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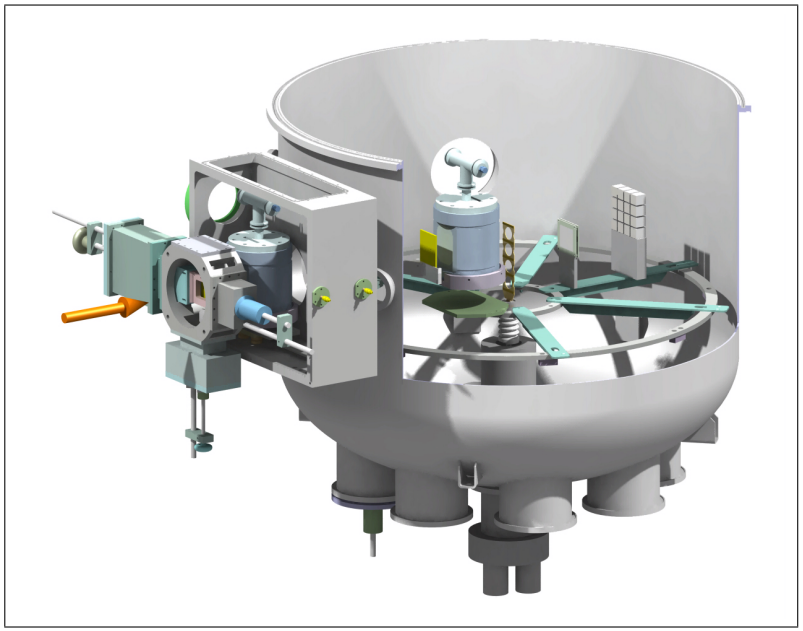
- ▷ short term : ^{4}n

RIKEN+EXPAND

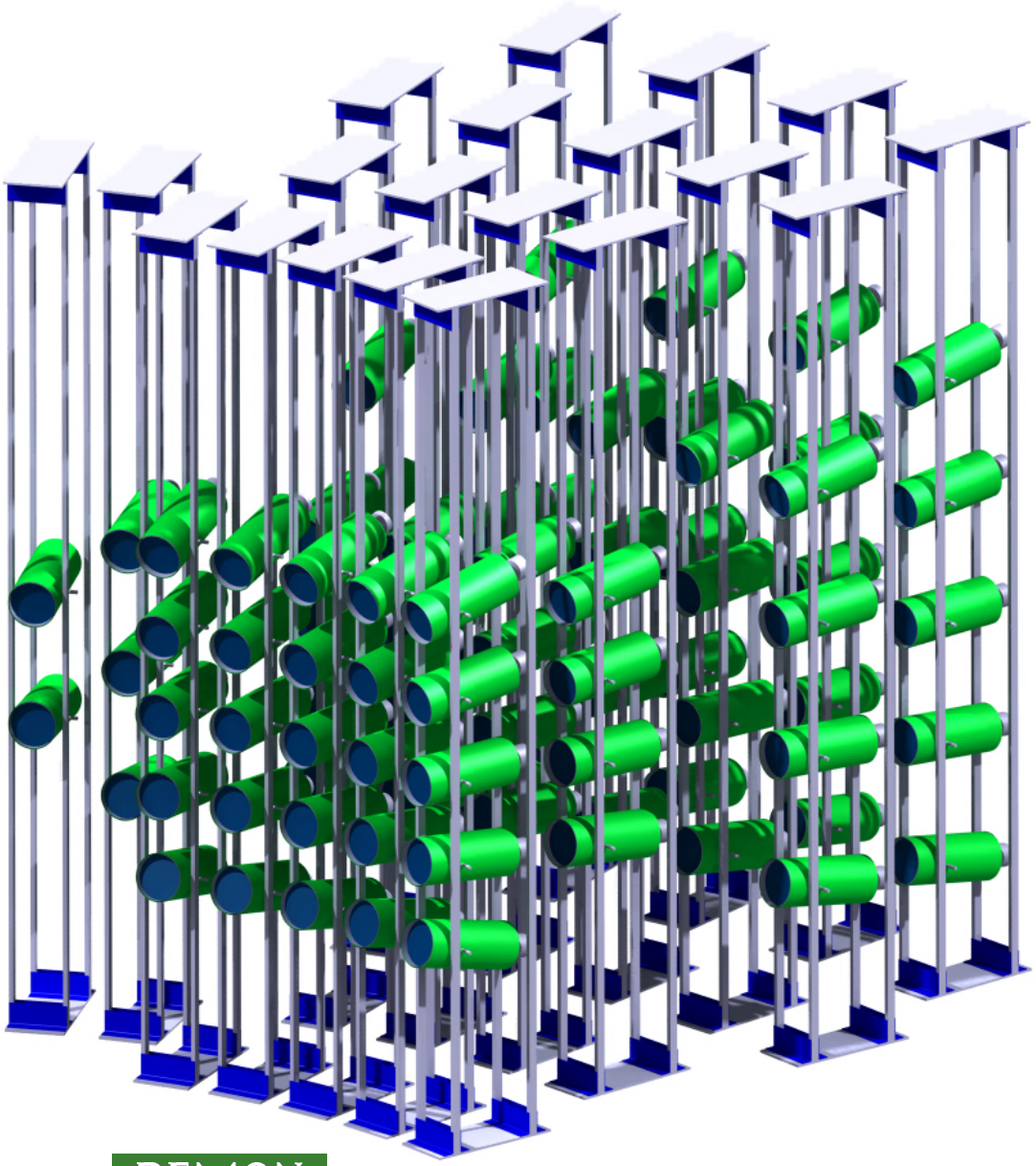
- ▷ ^{28}O, ^{7}H, ^{4,6}n ...

GANIL+DEMON



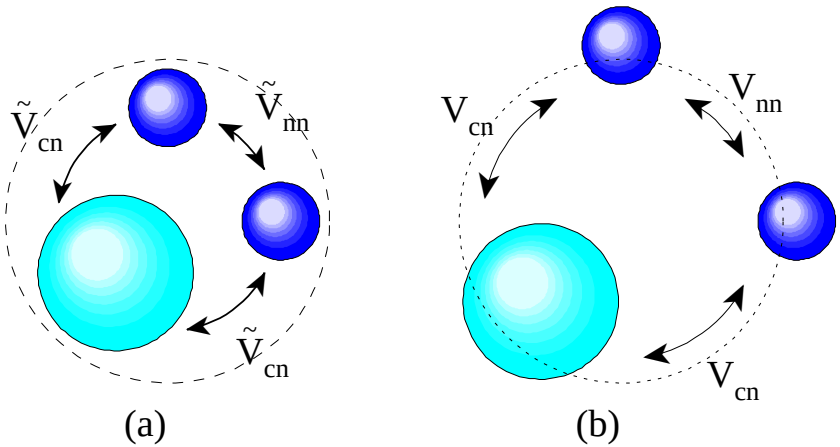
CHARISSA

LISE

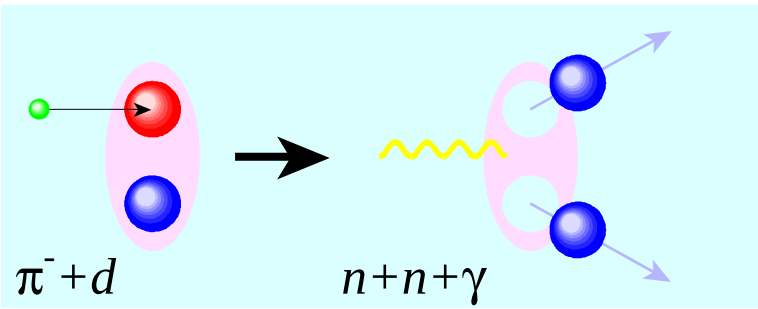


DEMON

- Borromean systems :



- The neutron-neutron interaction :



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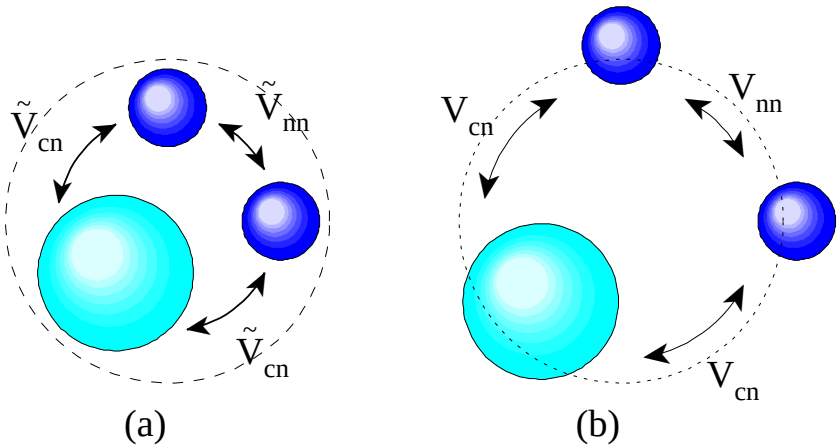

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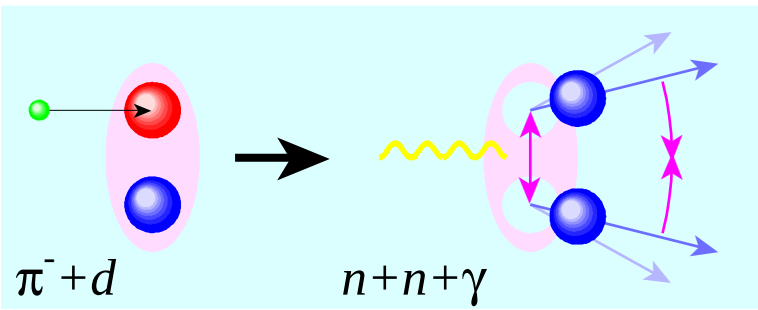


▷ final state modified by V_{nn} !

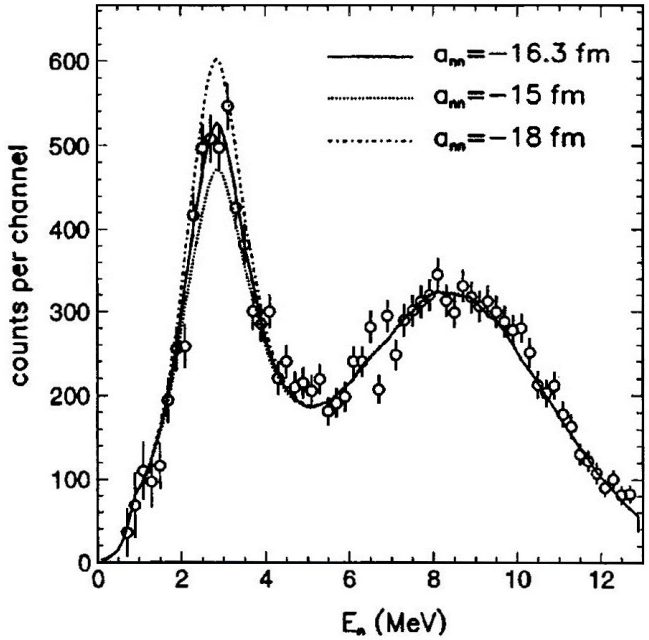
▶ How is it modified ?

▷ by the n-n distance

▷ by the n-n interaction

$$\sigma(q) \approx \Omega(q) \times \left| \int \psi_d \, \psi_s^*(a_{nn}) \, d^3r \right|^2$$

$$\approx \Omega(q) \times \frac{1}{1 + q^2 \, {a_{nn}}^2}$$



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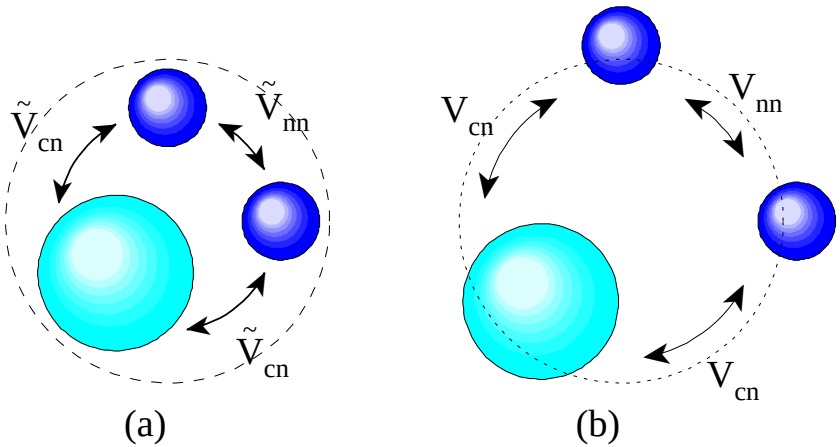

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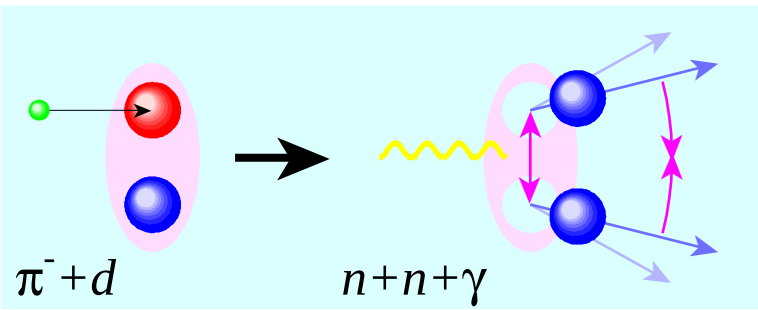

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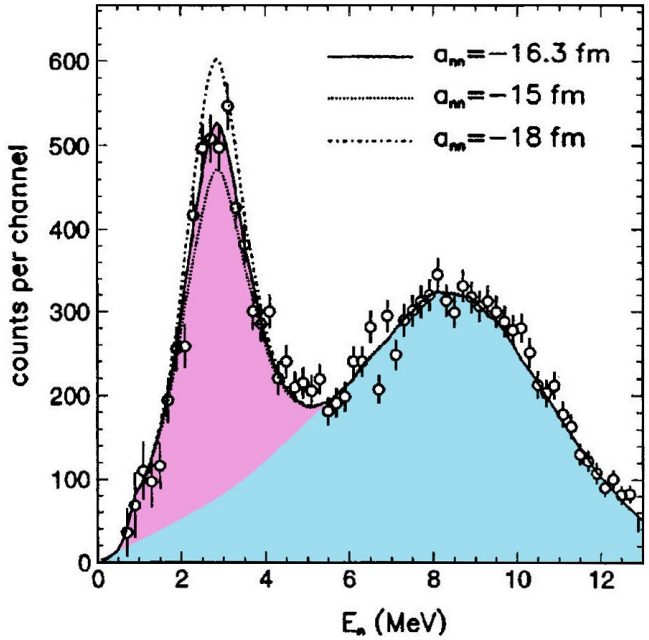
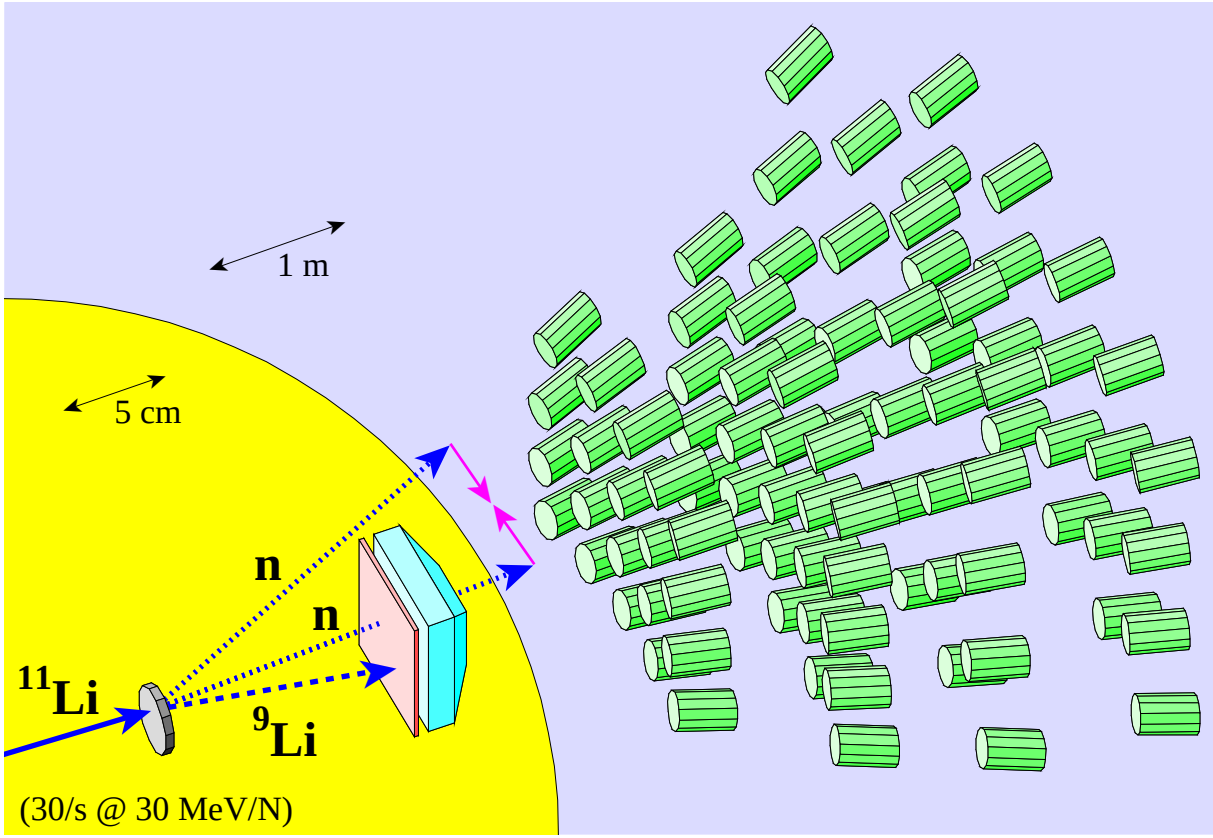
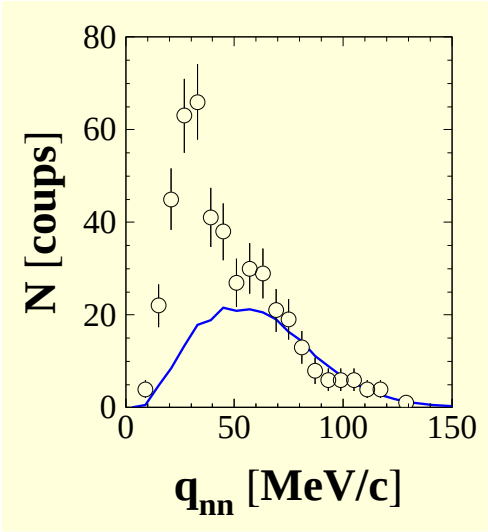


▶ The halo of ^{11}Li :  ↔  ?





▷ $\sigma(q) \equiv \Omega(q) \times C_{nn}\{\psi(r_{nn}), a_{nn}\}$:

⇝ $\sigma(q)$ is measured

⇝ event mixing provides $\Omega(q)$ ...

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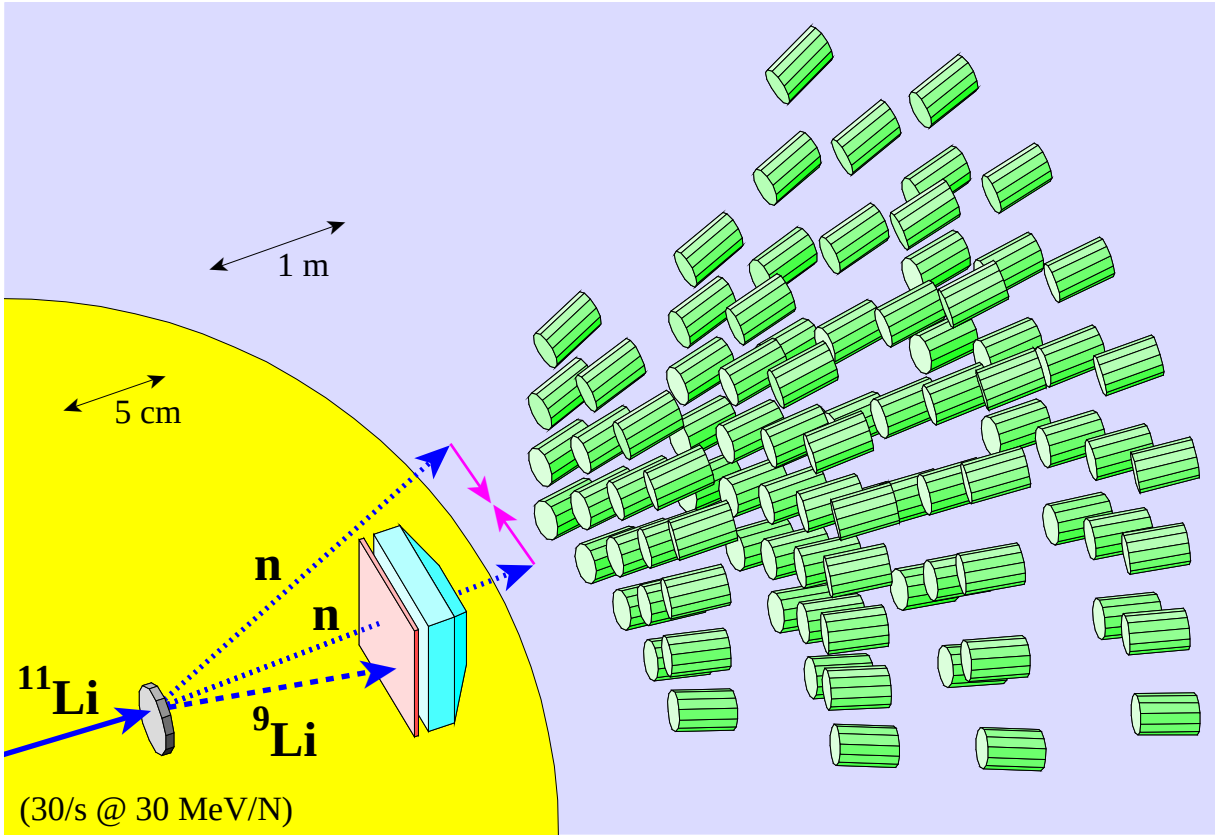

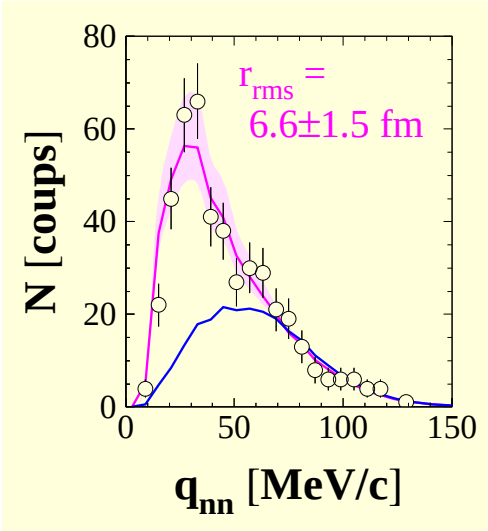

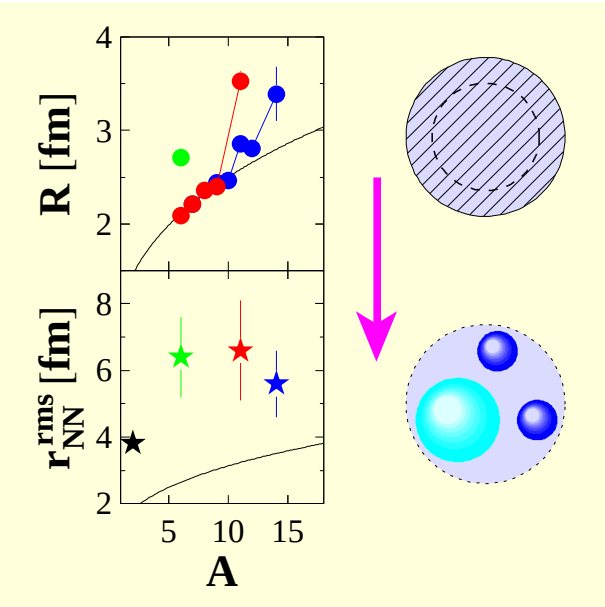

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CORRELATION FACTOR & SOURCES

▶ The neutron-neutron FSI

[Lednicky & Lyuboshits, SJNP 35 (1982) 770] :

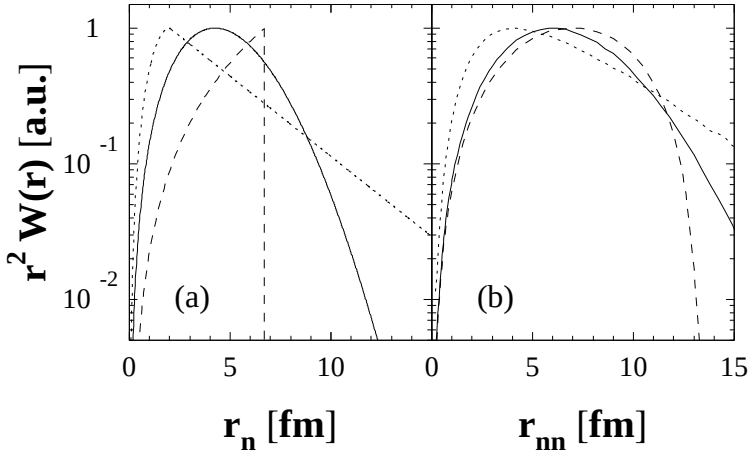
$$C(p_1,p_2) \;=\; 1 \;+\; \underbrace{\langle b_0(q,p)\rangle}_{B_0\equiv\mathrm{QSS}} \;+\; \underbrace{\langle b_i(q,p)\rangle}_{B_i\equiv\mathrm{FSI}}$$

$$\begin{aligned}
x &= x_1 - x_2 = (r_1,t_1)-(r_2,t_2)\\
B_0 &= -\frac{1}{2}\langle\cos(qx)\rangle = -\frac{1}{2}\int W(x)\,\cos(qx)\,d^4x\\
B_i &= \frac{1}{2}\left\{|f(k^\star)|^2\langle|\phi_{p_1p_2}(x)|^2\rangle + 2\,\Re\Big[f(k^\star)\langle\phi_{p_1p_2}(x)\cos(qx/2)\rangle\Big]\right\}\\
&= \int 2\pi\, r_T\, dr_T\, dr_L\, dt\; W(x)\left\{|f(k^\star)\phi_{p_1p_2}(x)|^2 + \right.\\
&\quad \left. 2\,\Re[f(k^\star)\phi_{p_1p_2}(x)]\,J_0(q_T r_T/2)\cos[q_0(r_L-vt)/2v]\right\}
\end{aligned}$$

$$\underbrace{\begin{aligned} t &= 0\\ W(x_i) &= e^{-r_i^2/2r_0^2}\\ W(x) &= e^{-r^2/4{r_0}^2}\end{aligned}}_{\Downarrow}$$

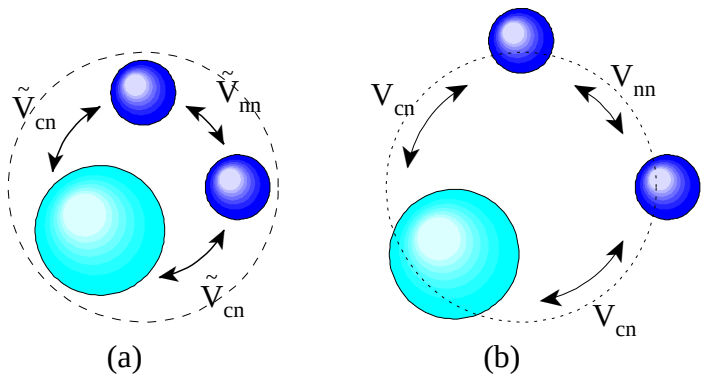
$$\begin{aligned}
C(q) \;\approx\; 1 &- \tfrac{1}{2}\exp(-q^2r_0^2)\\
&+\frac{|f|^2}{4r_0^2}\left(1-\frac{d_0}{2\sqrt{\pi}r_0}\right)\\
&+\frac{\Re f}{\sqrt{\pi}r_0}F_1(qr_0) - \frac{\Im f}{2r_0}F_2(qr_0)
\end{aligned}$$

▶ Different n sources $[r_n^{\mathrm{rms}}]$:

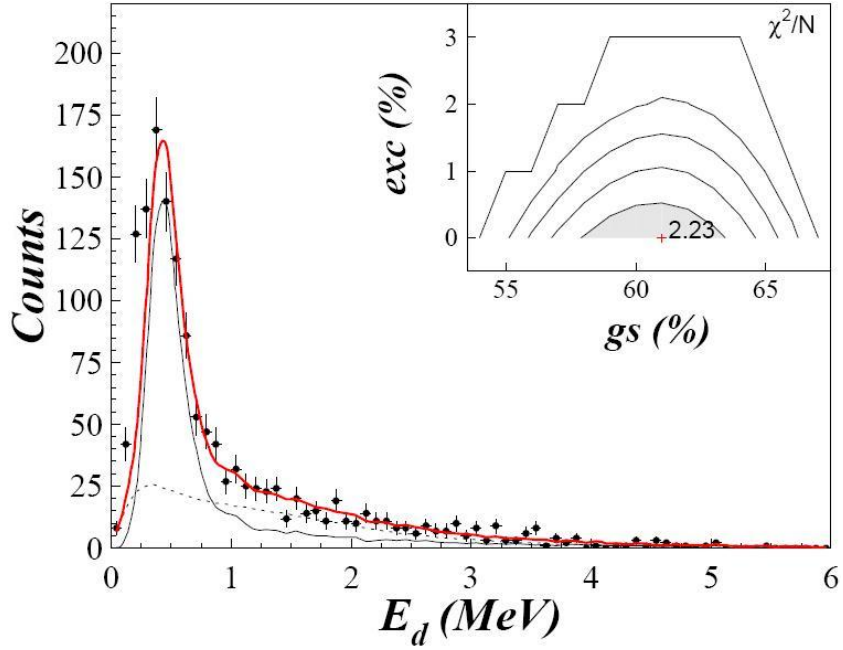


▷ similar n-n sources !

▶ Borromean systems ...



- ^{8}He*(C) $\rightarrow$ ^{6}He+nn @ 15 MeV/N :
  - ^{6}He+n decay energy :



$\rightsquigarrow$ ^{7}He, one state (gs) !

$\rightsquigarrow$ very narrow, $\Gamma = 0.16$ MeV

$\rightsquigarrow$ very easy to identify !

$\rightsquigarrow$ long-lived $\rightarrow$ $\hbar c/\Gamma = 1250$ fm/c ...

▶ $^{8}He^{*}(C) \rightarrow {}^{6}He+nn$ @ 15 MeV/N :

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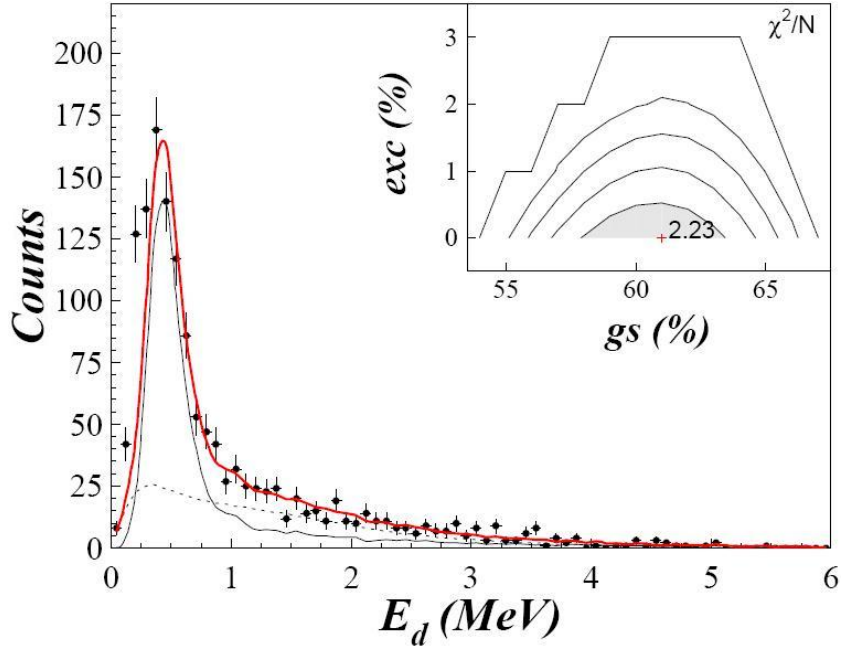

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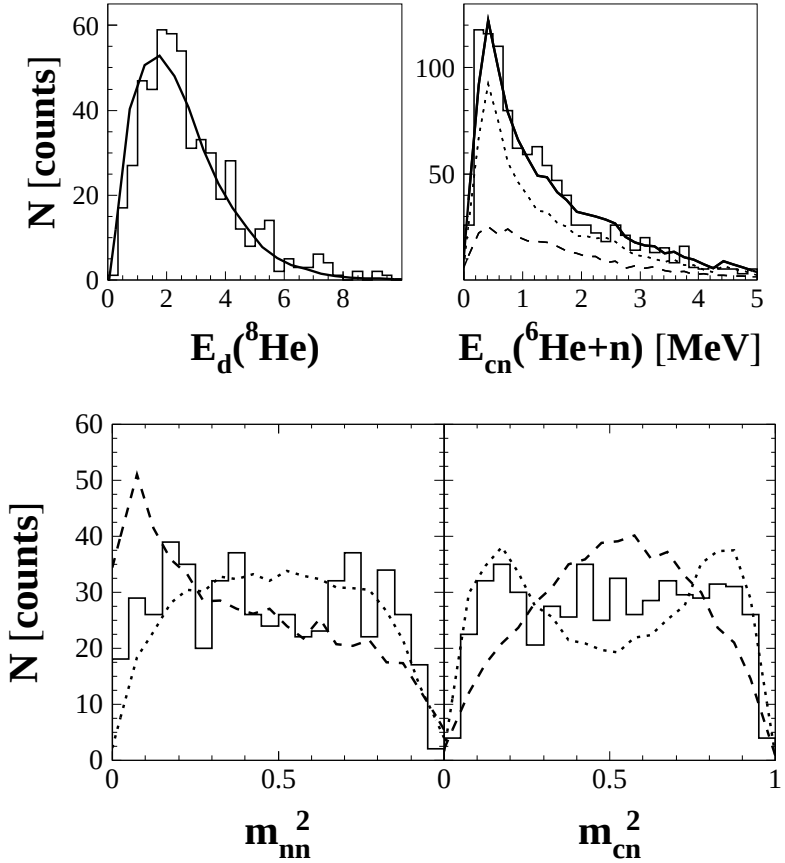
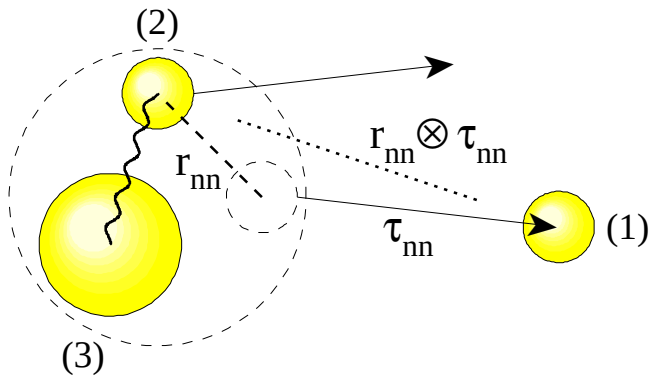
▷ $^{6}He+nn$ coincidences :



⇝ both nn and ^{7}He signals !

⇝ direct/sequential models ...

▶ $^{8}He^{*}(C) \rightarrow {}^{6}He + nn$ @ 15 MeV/N :



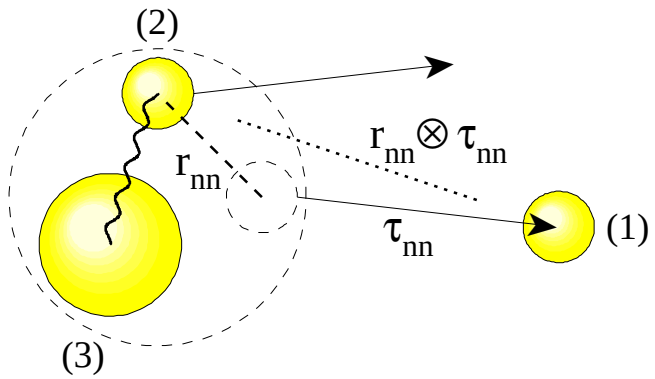
▷ direct/sequential ratio from $^{6}He + n$

$[30\%] \Rightarrow {}^{6}He + nn \quad [\otimes\, C_{nn}(r_0)]$

$[70\%] \Rightarrow {}^{7}He + n$
$\downarrow (\tau_0) \quad [\otimes\, C_{nn}(r_0, \tau_0)]$
$^{6}He + n$

⇝ vary (r_0, τ_0) and check χ^2 surface

▶ ^{8}He*(C) → ^{6}He+nn @ 15 MeV/N :



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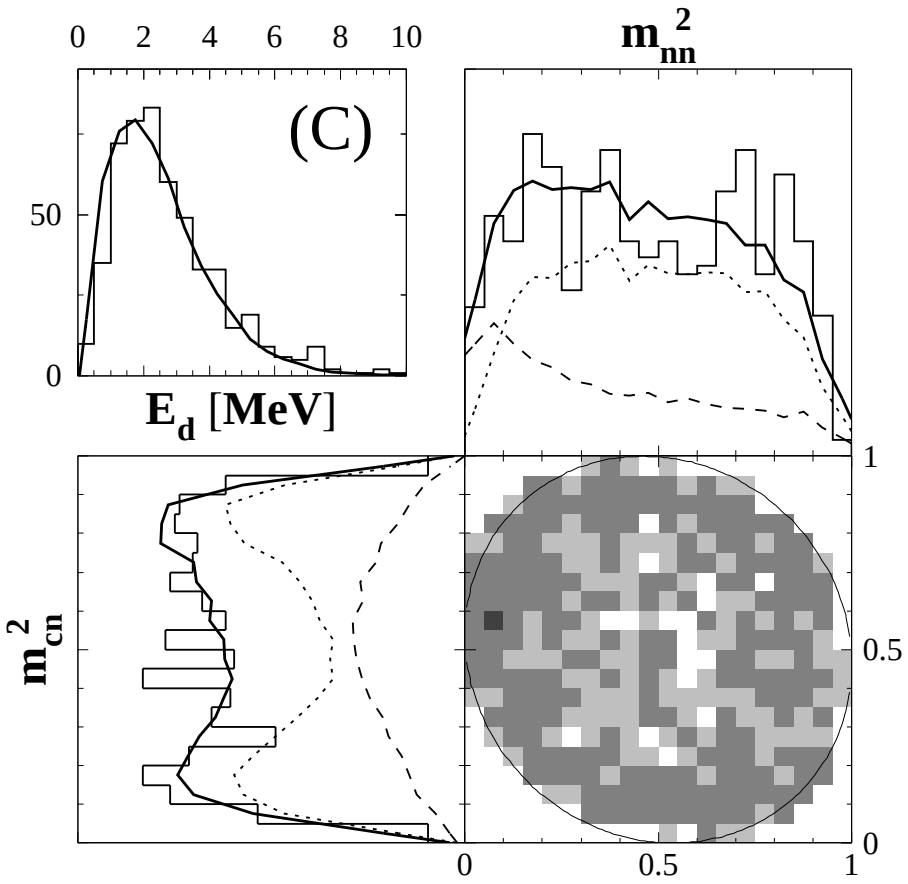

$$r_{nn}^{\rm rms} = 7.3 \pm 0.6 \text{ fm}$$
$$\tau_0 = 1400 \pm 400 \text{ fm/c}$$

$$\tau(^7\text{He}) = 1250 \text{ fm/c !}$$

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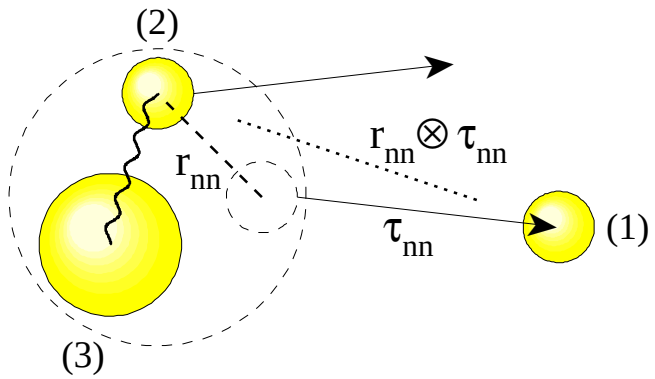

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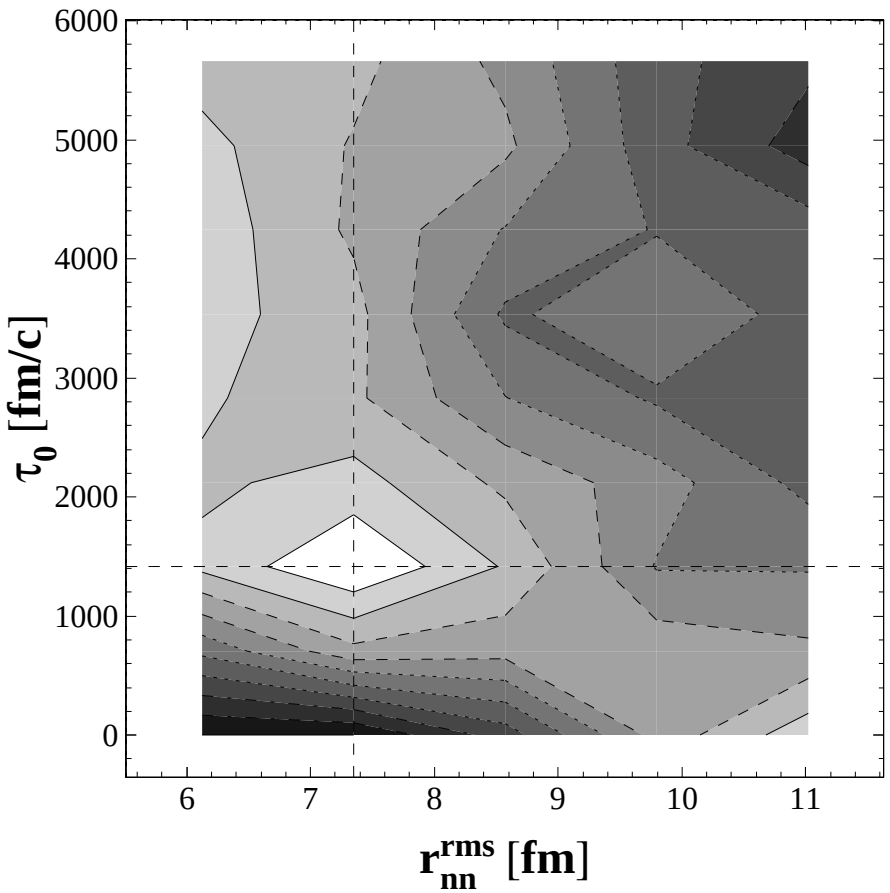

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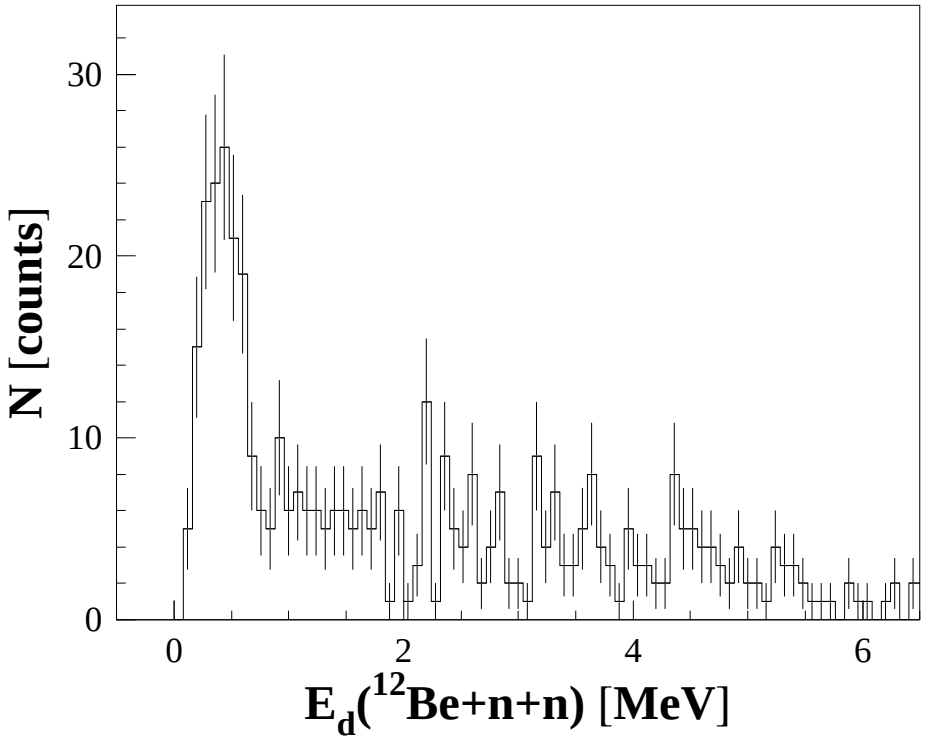
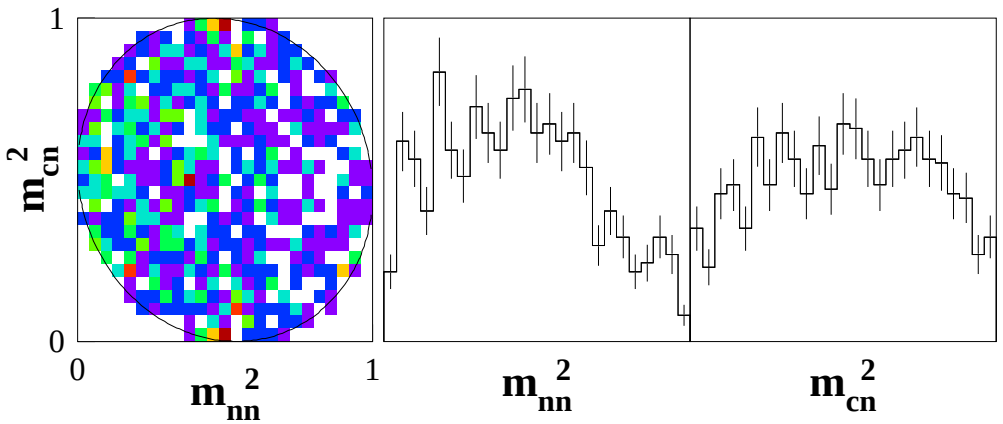
A. LEPRINCE : SIZE OF EXCITED STATES ...

▶ $^{15}B(C) \rightarrow {}^{14}Be^{*} \rightarrow {}^{12}Be + nn$ @ 35 MeV/N :





▷ very clean spectrum :

⇝ 2^{+} plus broad structure (no bck) !

⇝ some n-n FSI ...

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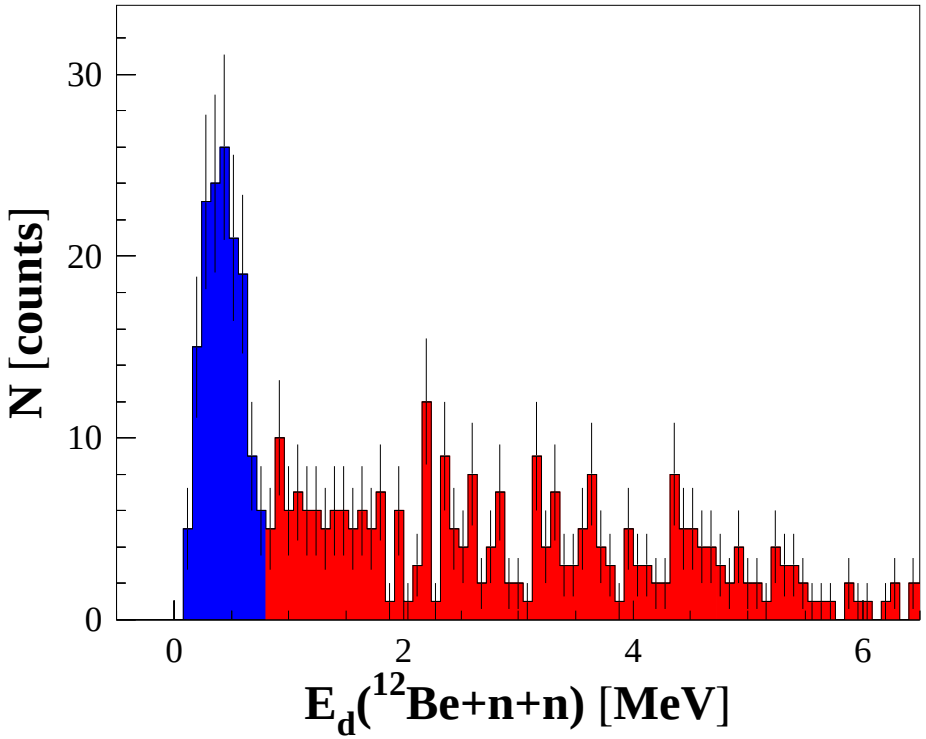
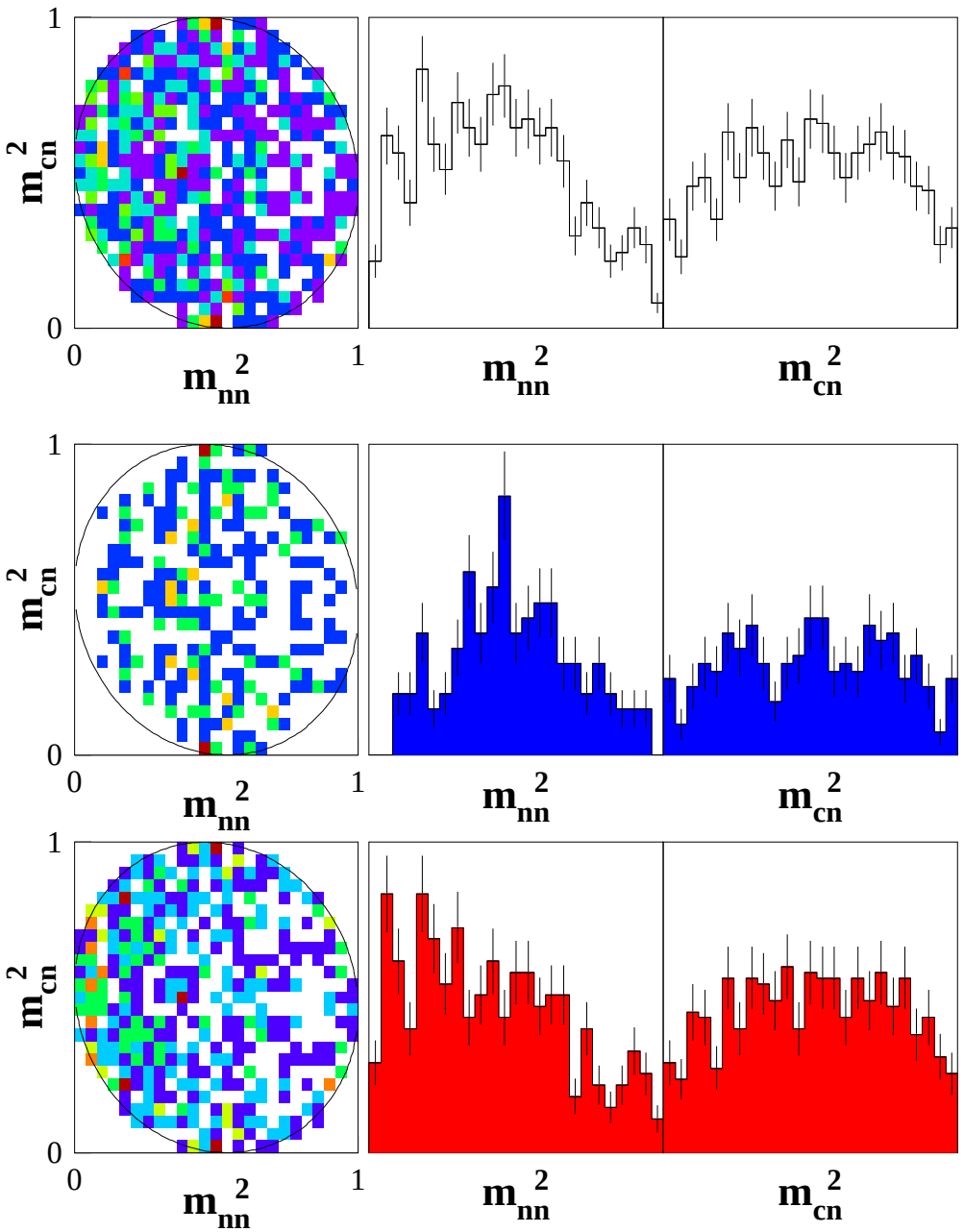




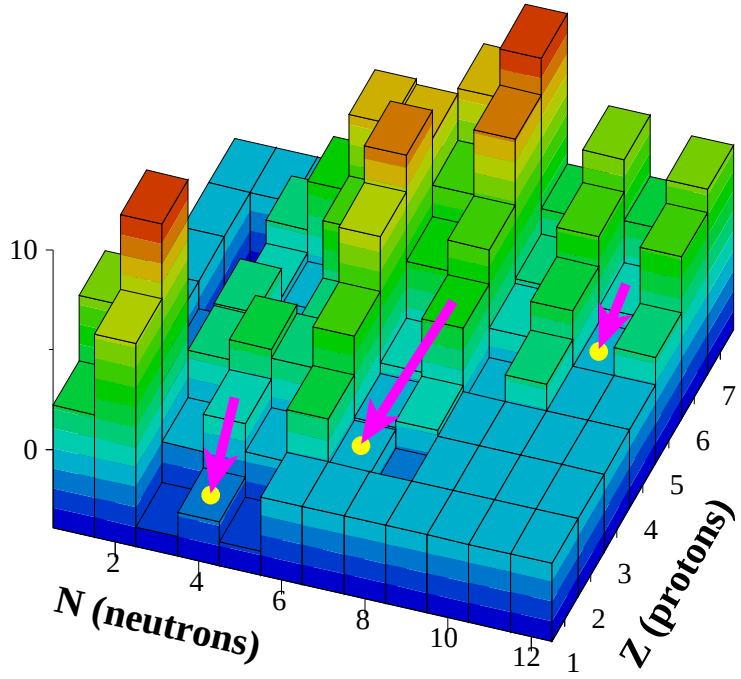
▷ very clean spectrum :

⇝ 2^{+} plus broad structure (no bck) !

⇝ almost no n-n FSI for the 2^{+} !

⇝ ☹ "contraction" beyond ... ?

FORMATION OF UNBOUND NUCLEI



- how to dive into the sea ?
  - ▷ strip nucleons from a beam !
- how to find a "nucleus" ?

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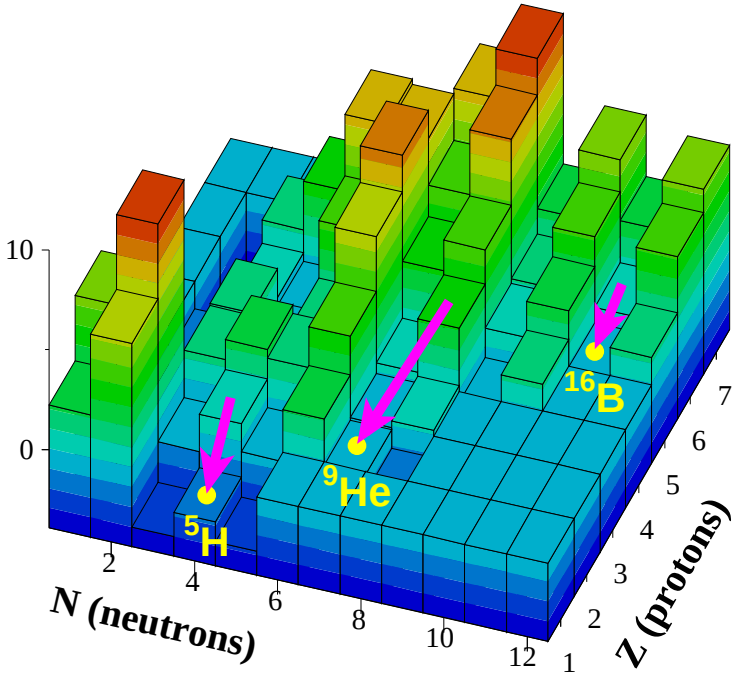
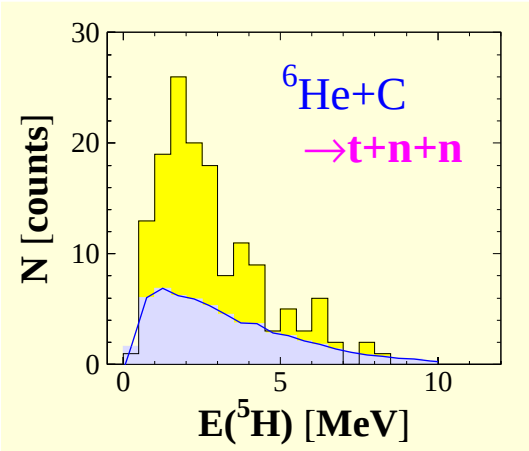
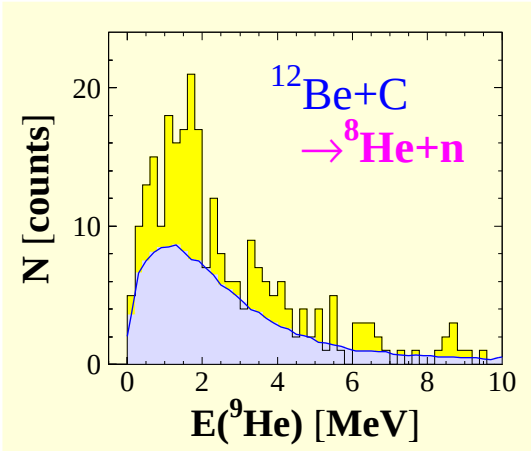
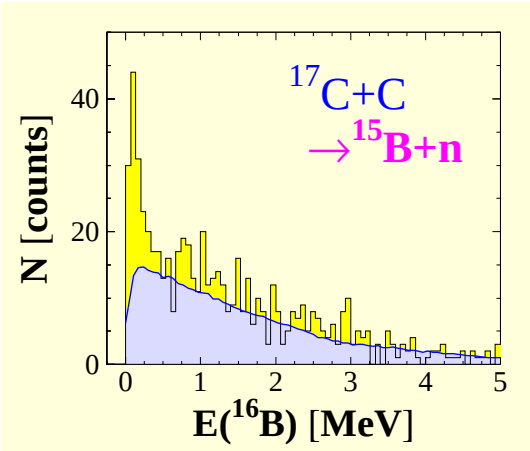


- how to dive into the sea ?
  - ▷ strip nucleons from a beam !
- how to find a "nucleus" ?
  - ▷ look for energy levels ...
  - ▷ better than "missing mass" ?

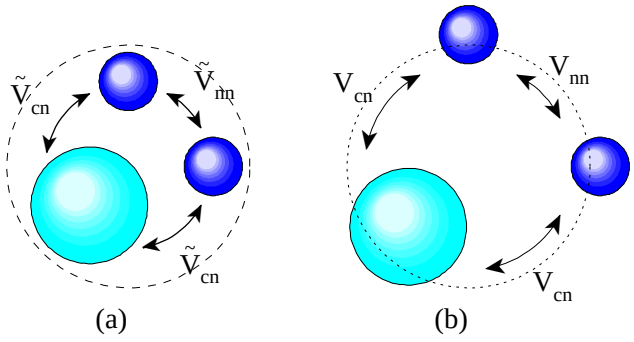




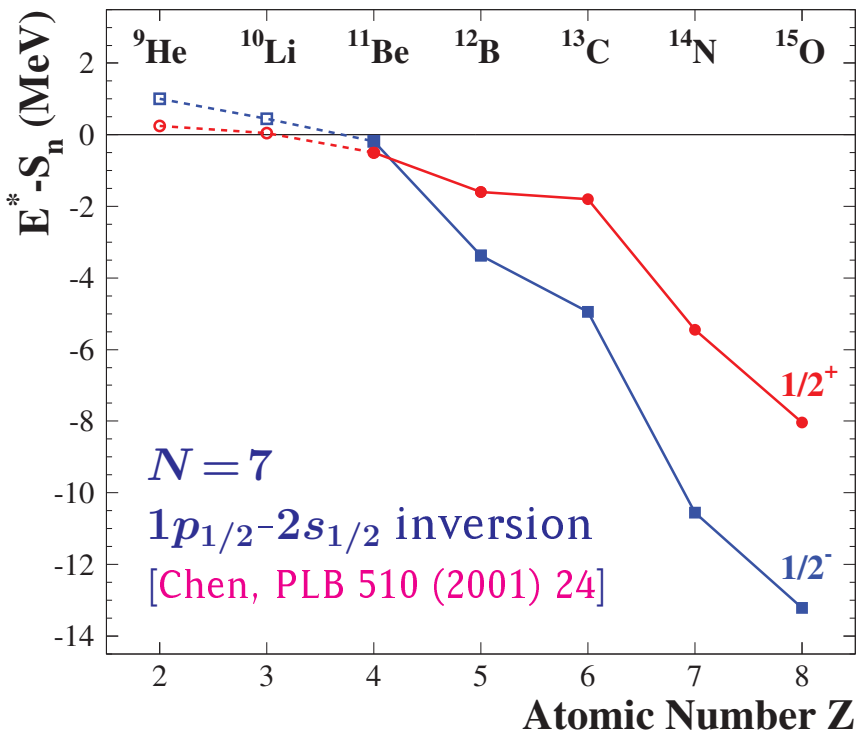


ACROSS THE DRIPLINE

- Ingredients of :



- Evolution across the dripline :



ACROSS THE DRIPLINE

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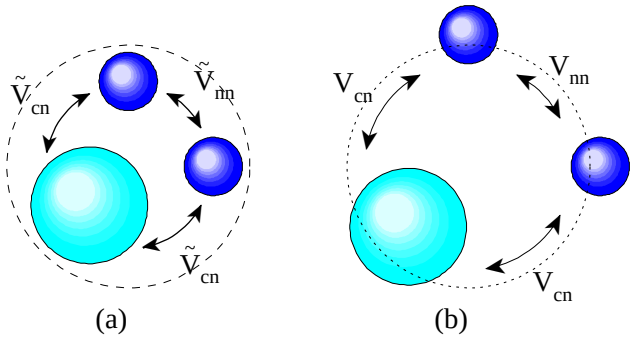

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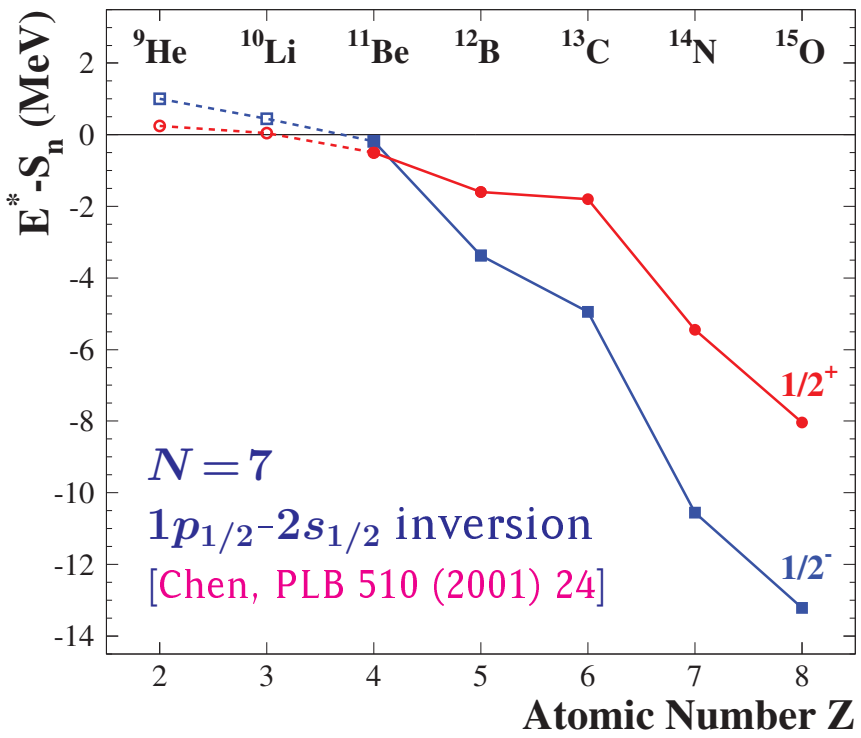
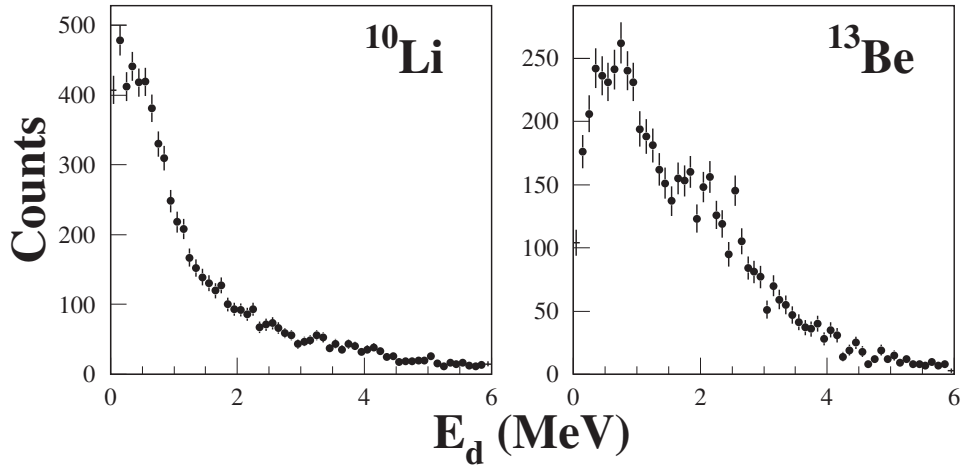
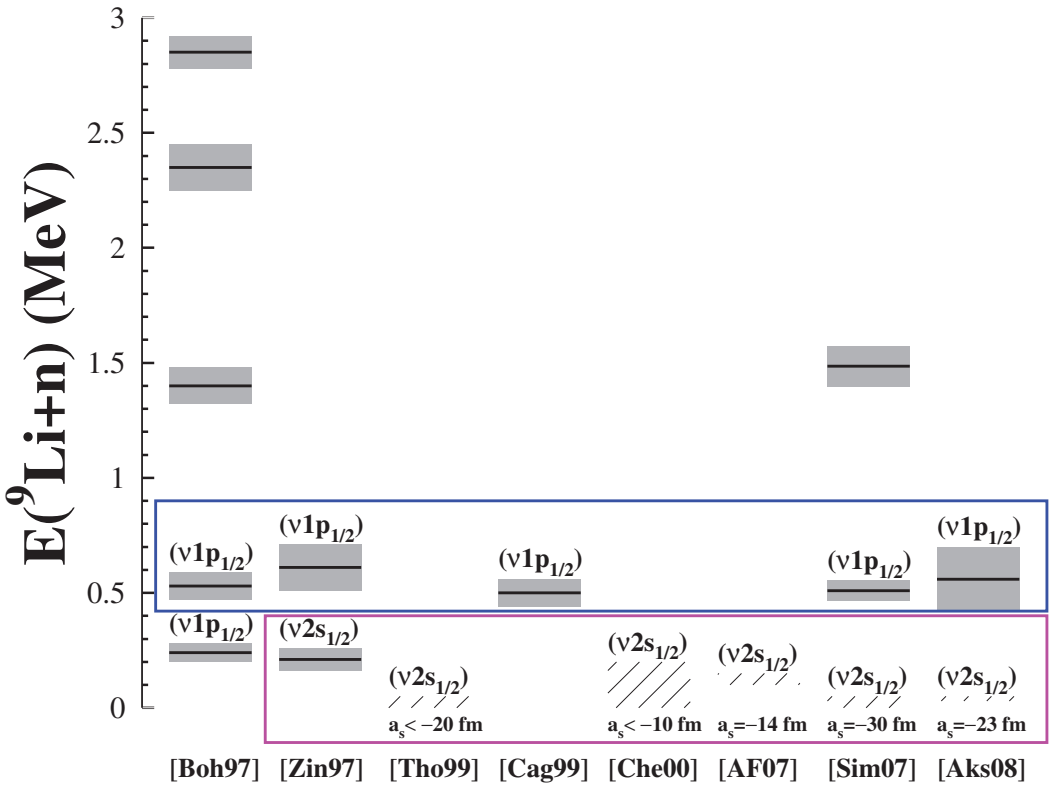


- Experimental technique :
  - ▷ ^{14}B knockout or fragmentation :
    - ⇝ fragment-n states & continuum



  - ▷ fit fragment+n data with :
    - ⇝ resonances (E_r, Γ_r)
    - ⇝ virtual states $(\ell=0, a_s)$
    - ⇝ fragment+n event mixing
  - ▷ ^{7}He : cross-check !

- ^{11}Be p-knockout : $\Delta\ell \approx 0$
  - ▷ access to $\nu s_{1/2}$ (^{10}Be $\otimes$ $\nu 2s_{1/2}$)
- ^{14}B fragmentation : $\Delta\ell \neq 0$
  - ▷ access to $\nu s_{1/2}$, $\nu p_{1/2}$



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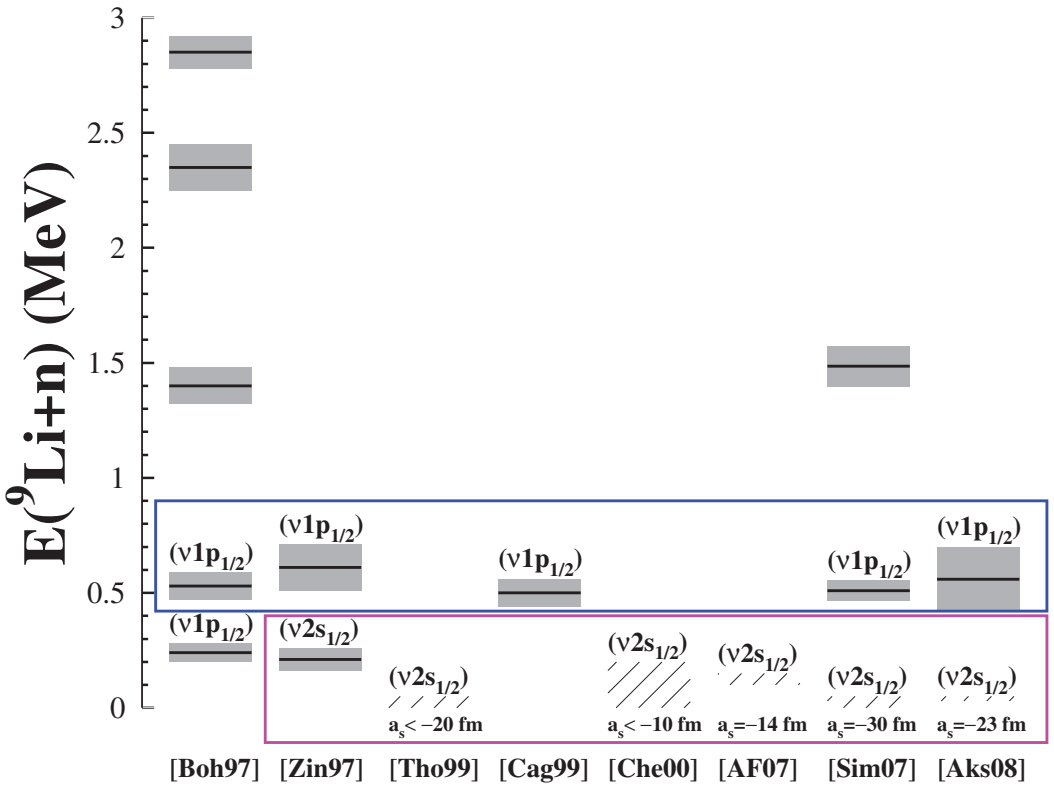
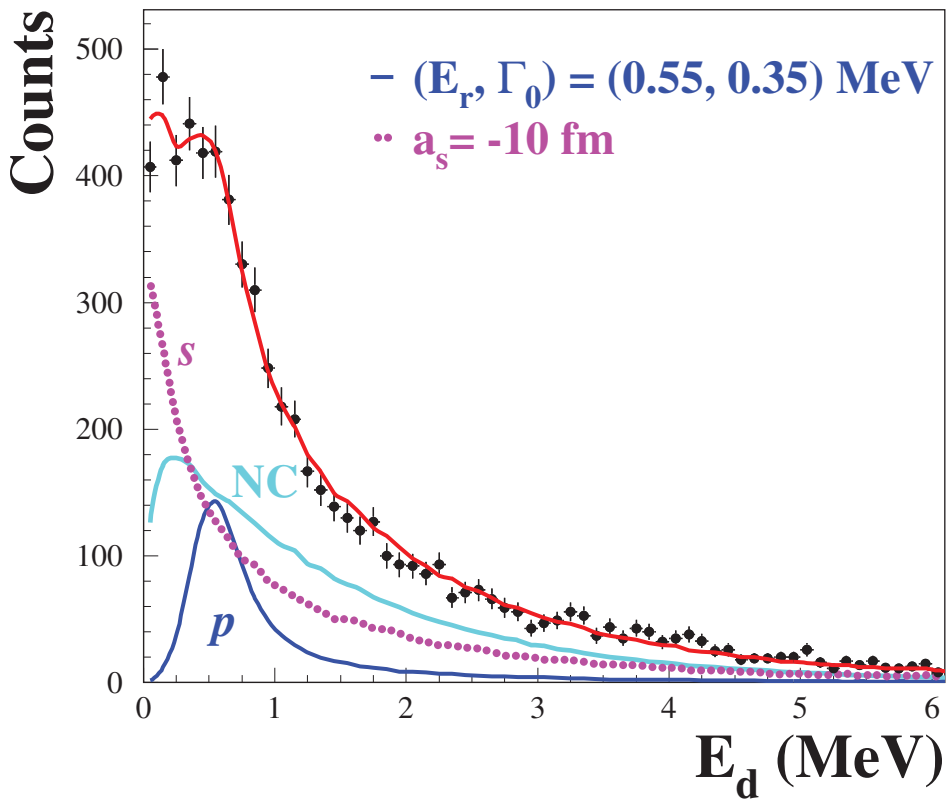
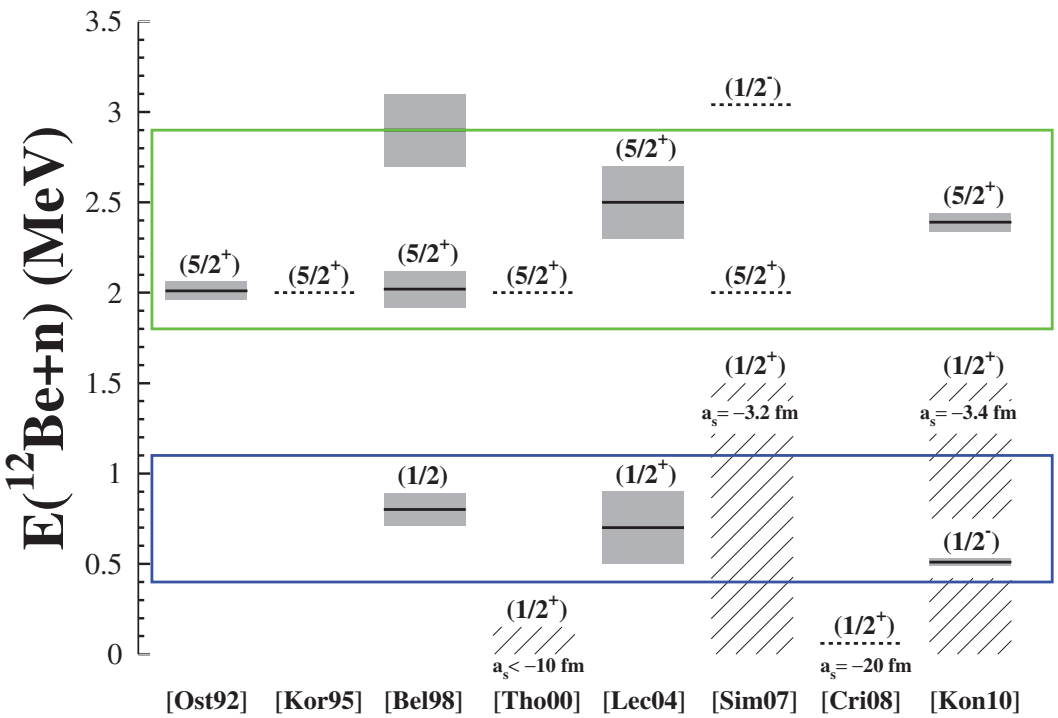


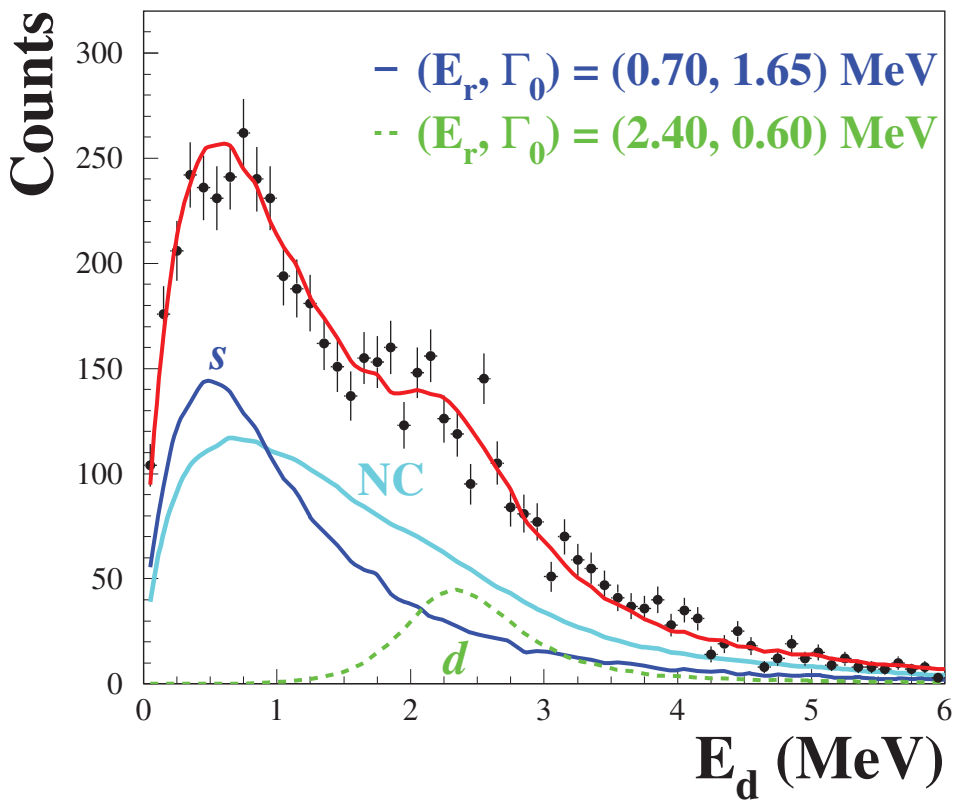


$N = 7$ $\nu 1p_{1/2}$-$\nu 2s_{1/2}$ inversion confirmed !

G. RANDISI : BERYLLIUM 13

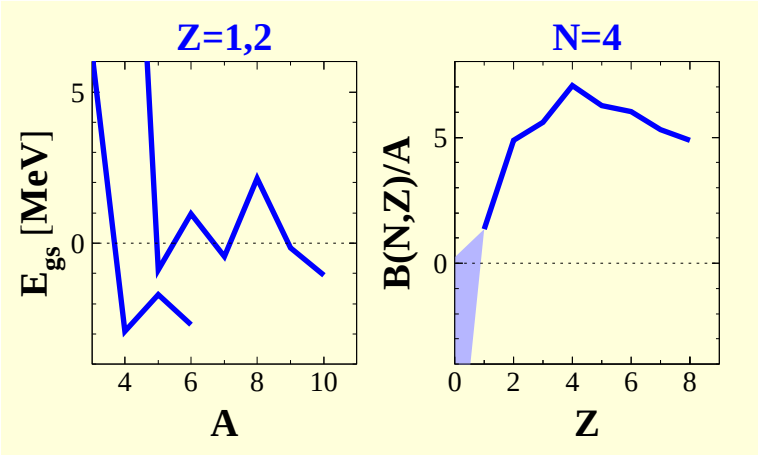
- ^{14}B p-knockout : $\Delta\ell \approx 0$
  (^{13}B $\otimes\, \nu 2s_{1/2} + {}^{13}$B $\otimes\, \nu 2d_{5/2}$)
  - ▷ access to $\nu 2s_{1/2}$, $\nu 1d_{5/2}$



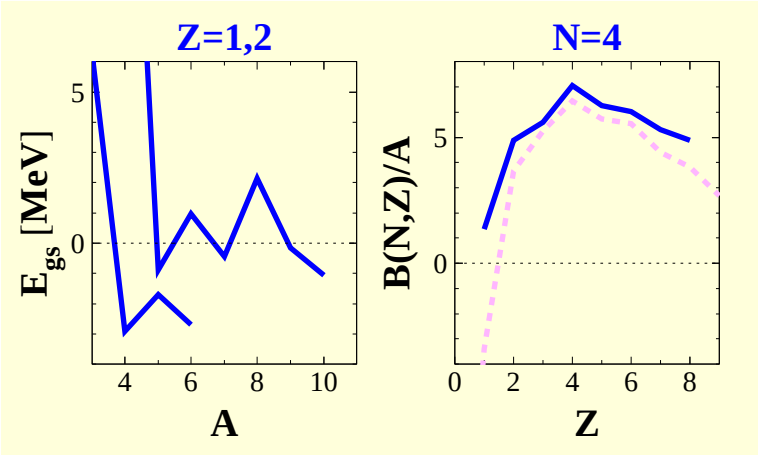


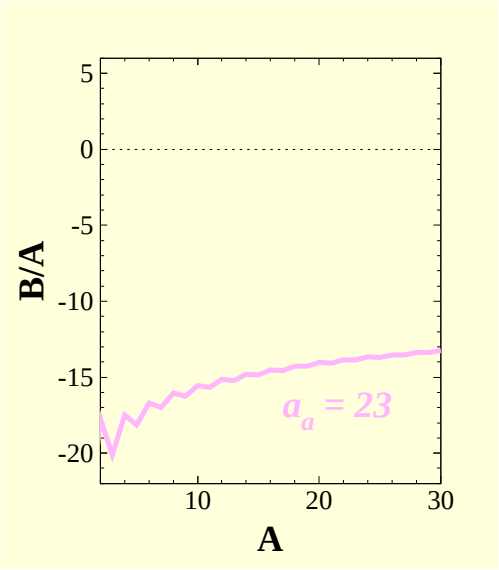
$N = 9$ $\nu 1d_{5/2}$-$\nu 2s_{1/2}$ inversion !

- Neutral nuclei & the liquid drop :



► Neutral nuclei & the liquid drop :





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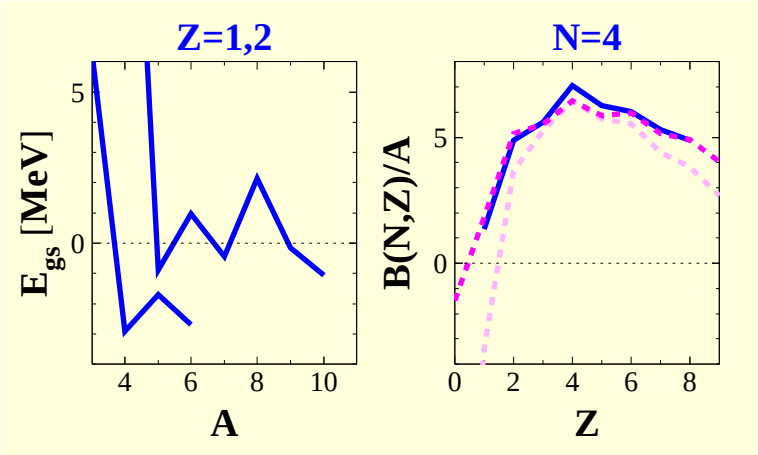
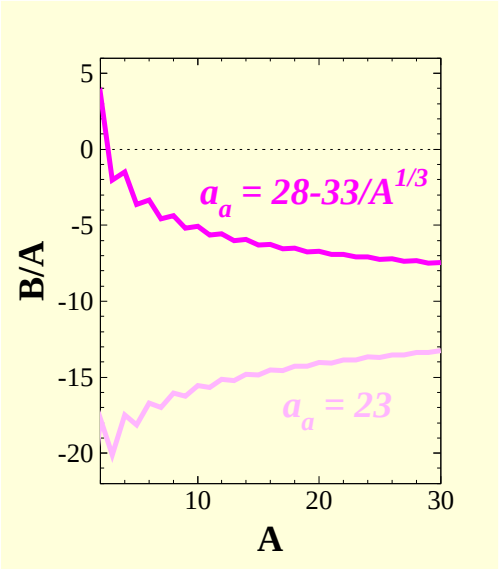
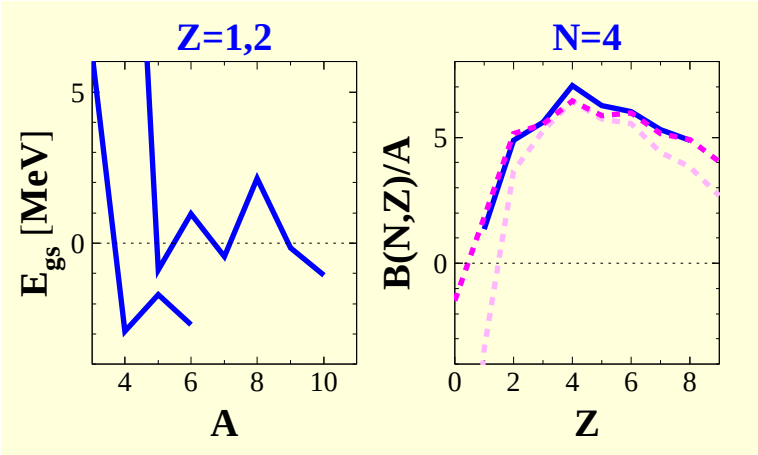
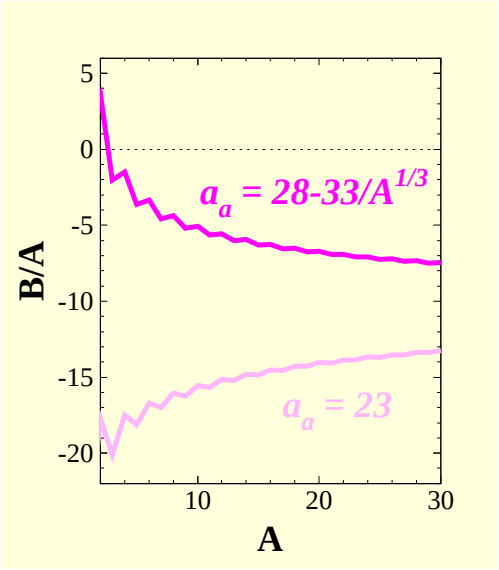


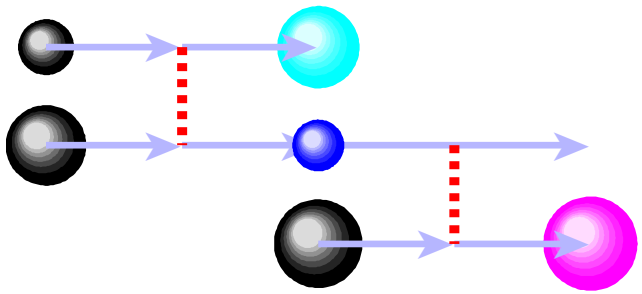


- Neutral nuclei & the liquid drop :



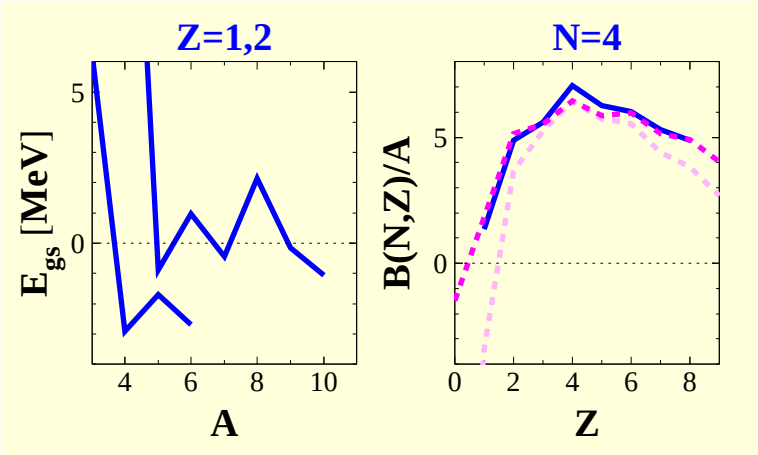


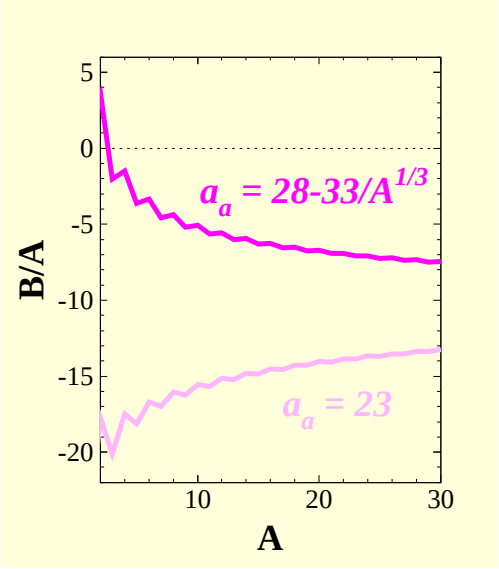
- 1960s-2000s :



⇝ binary or two-step reactions

- Neutral nuclei & the liquid drop :





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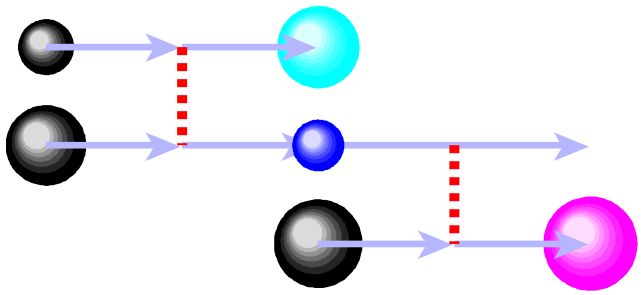
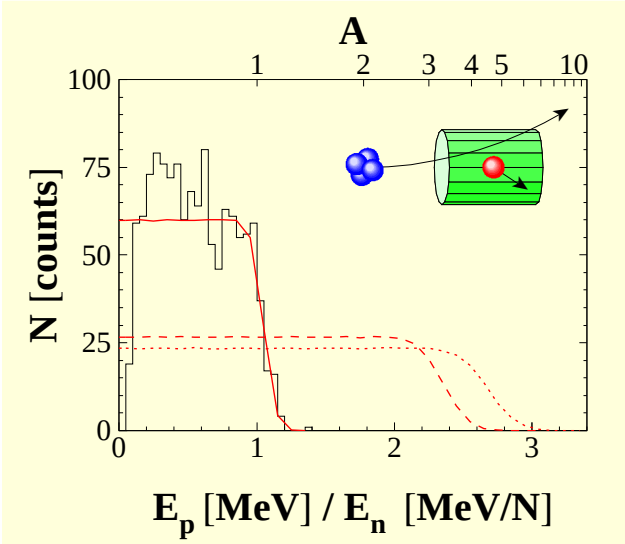
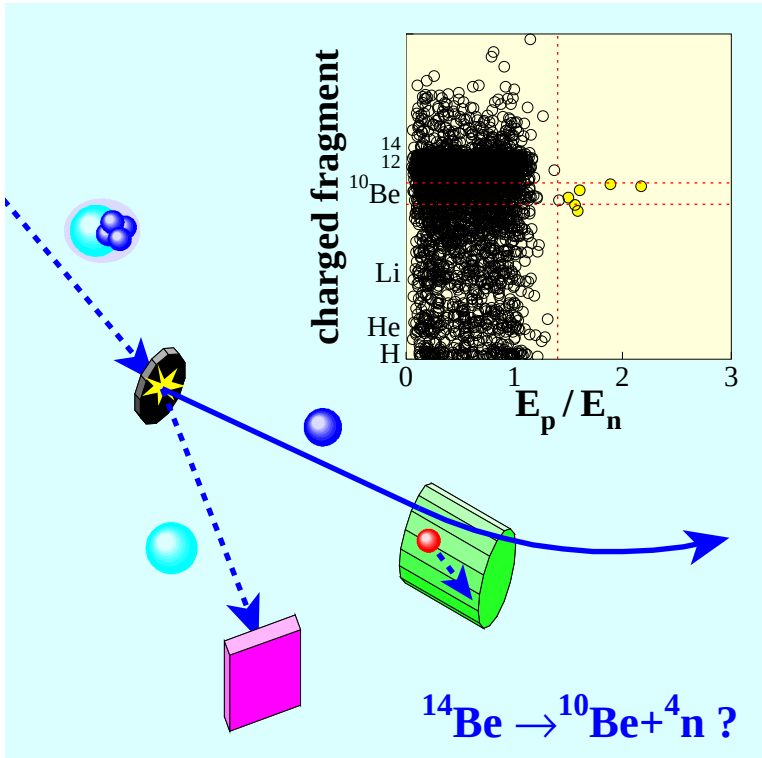


⇝ binary or two-step reactions

- GANIL+ DEMON :





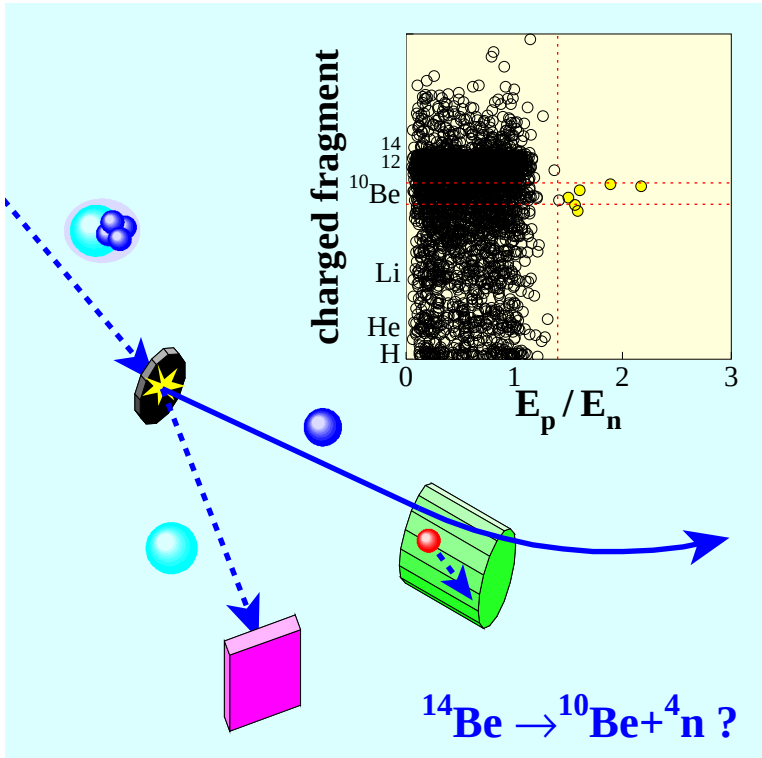
$$^{14}\mathrm{Be} \xrightarrow{(C)} {}^{10}\mathrm{Be} + {}^{4}\mathrm{n} \qquad ('01,'02)$$

$$^{8}\mathrm{He} \xrightarrow{(C)} {}^{4}\mathrm{He} + {}^{4}\mathrm{n} \qquad ('02)$$

$$^{12/14}\mathrm{Be} \xrightarrow{(C)} 2\alpha + {}^{4/6}\mathrm{n} \qquad ('02)$$

$$^{8}\mathrm{He} \xrightarrow{(d)} {}^{4}\mathrm{He} + d\ [+{}^{4}\mathrm{n}] \qquad ('04)$$

$$^{15}\mathrm{B} \xrightarrow{(C)} {}^{14}\mathrm{Be}^{*} \rightarrow {}^{4}\mathrm{n} \qquad ('06)$$



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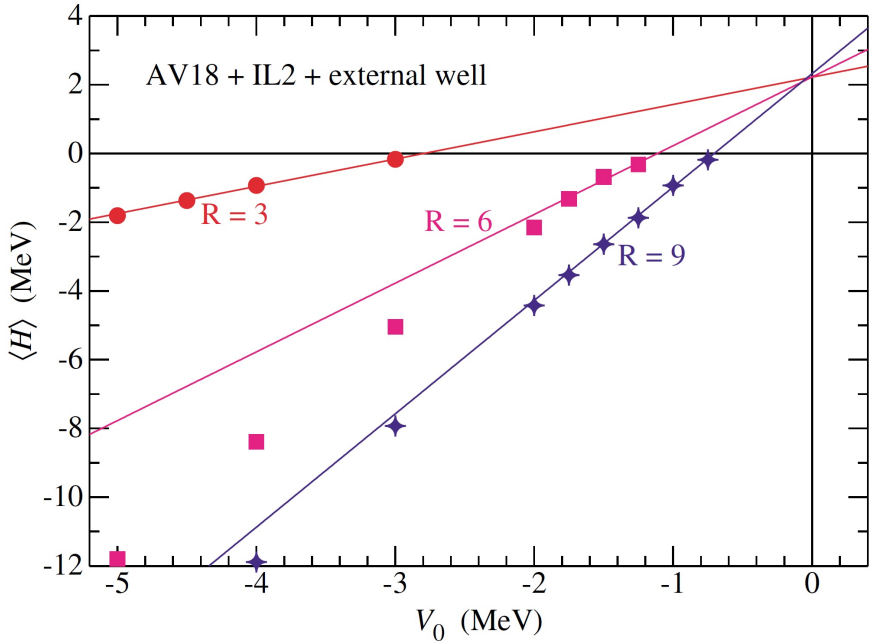
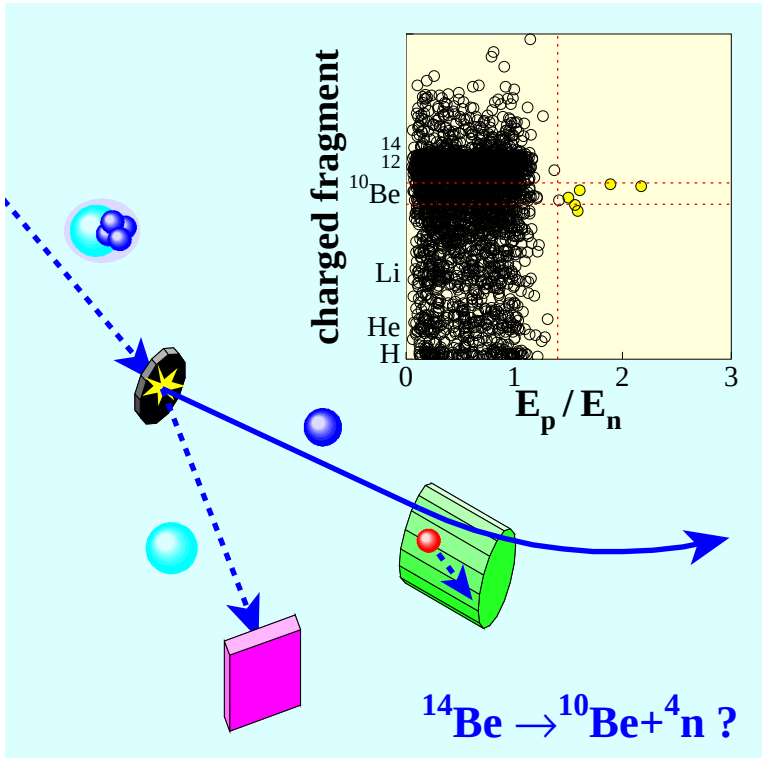
$$^{15}\mathrm{B} \xrightarrow{(C)} {}^{14}\mathrm{Be}^{*} \rightarrow {}^{4}\mathrm{n} \quad ('06)$$

- transfer [Beaumel] :

$$^{8}\mathrm{He} \xrightarrow{(d)} {}^{6}\mathrm{Li}\,[+{}^{4}\mathrm{n}] \quad ('02,'04)$$



- "modern" calculations :
  - ▷ $({}^{4}\mathrm{n}, p)$ scattering [Bertulani]
  - ▷ bound/resonance ? [Pieper, Carbonell]



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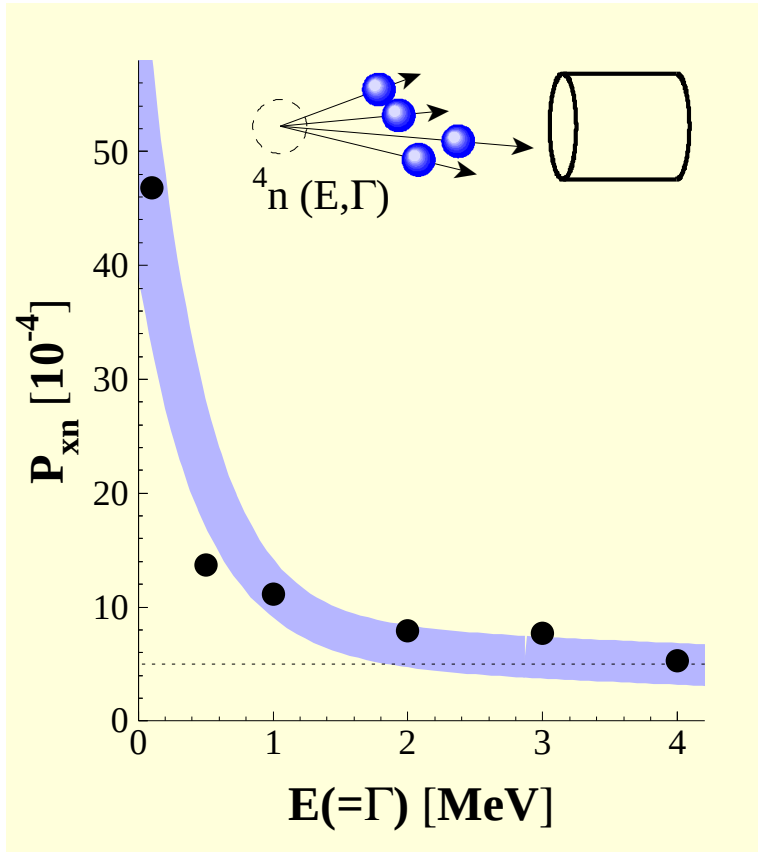
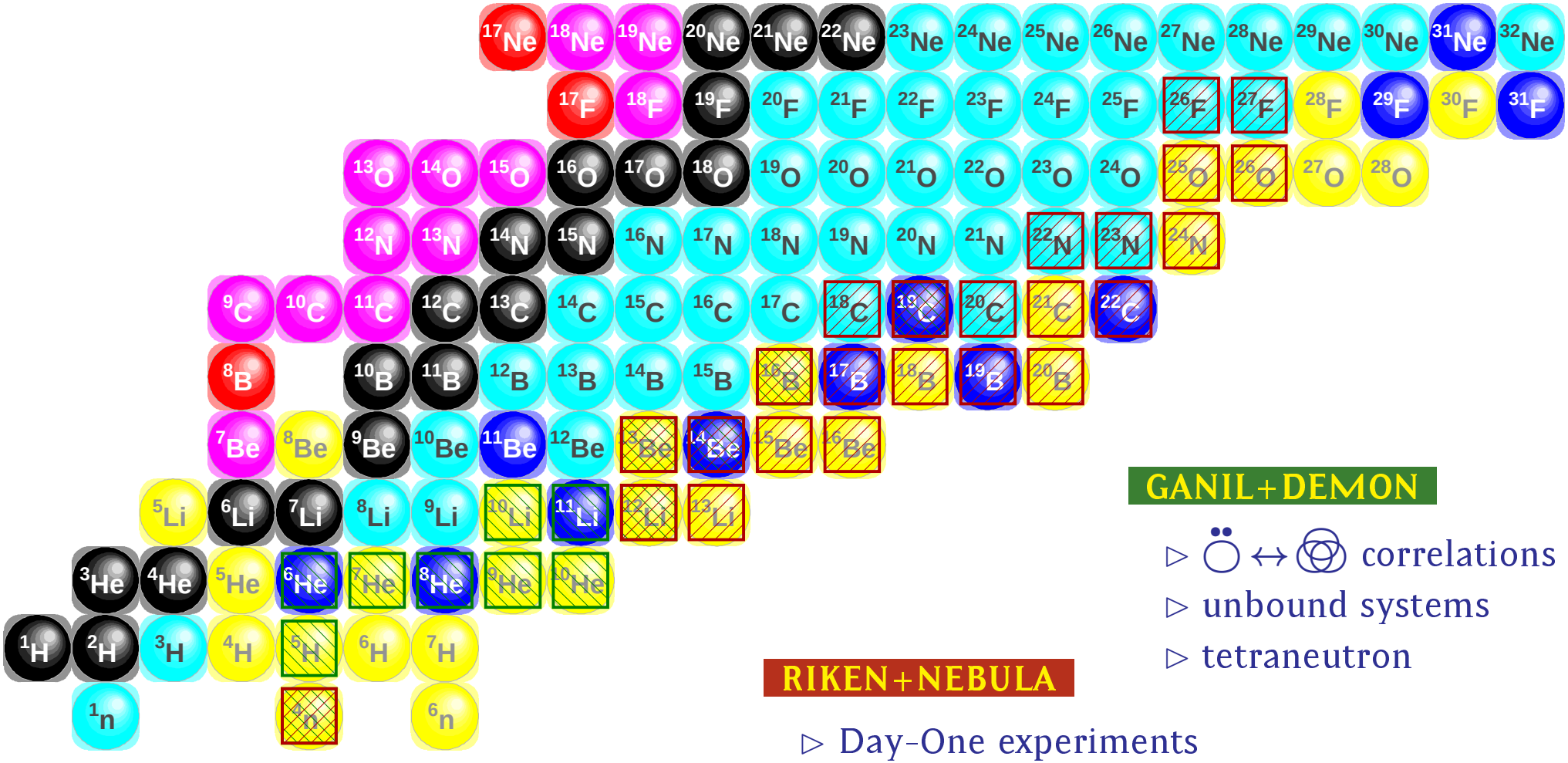
▶ P_{xn} due to ^{4}n resonance :



▷ $P_{xn} \times 10$!

▷ 4-n phase space : lower limit ...

AROUND THE NEUTRON DRIPLINE



GANIL+DEMON

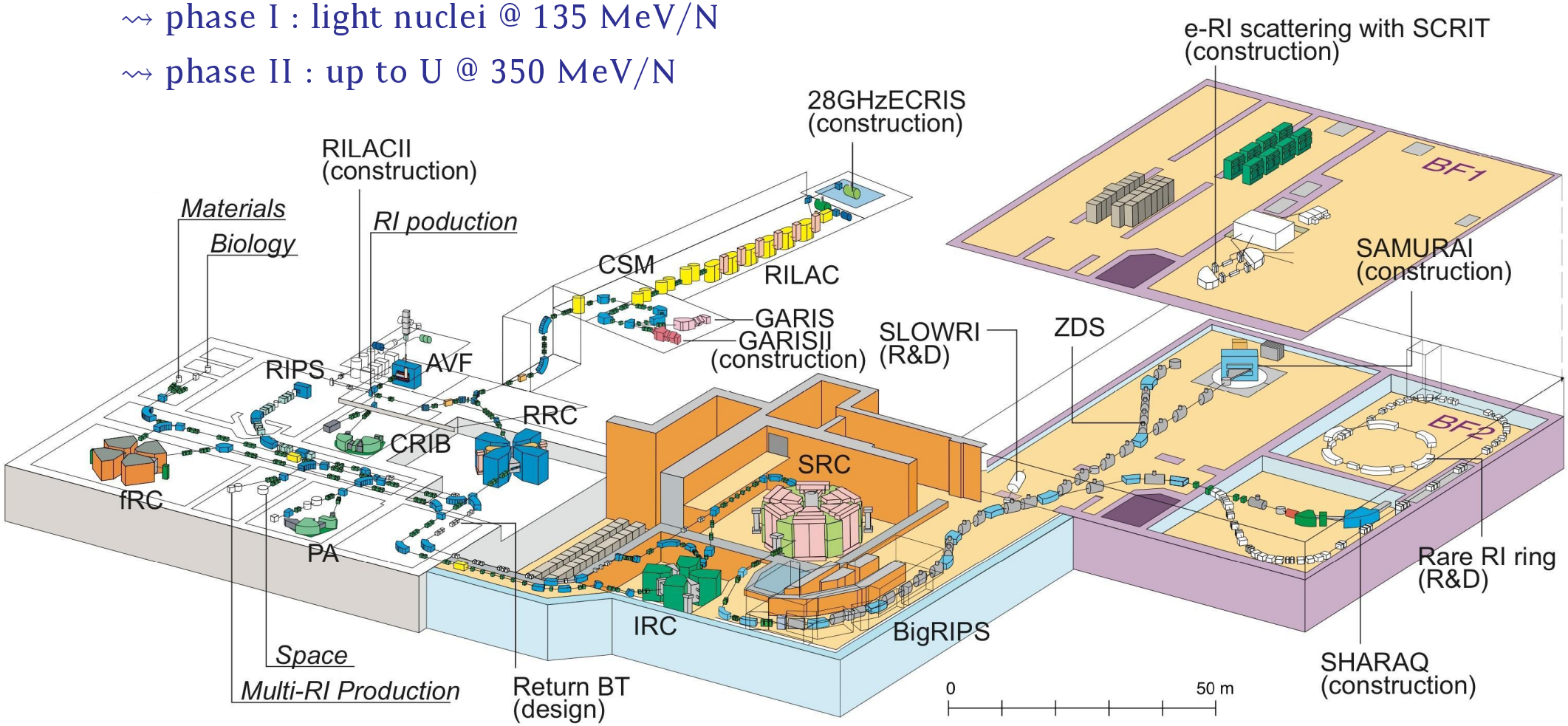
- ▷ correlations
- ▷ unbound systems
- ▷ tetraneutron

RIKEN+NEBULA

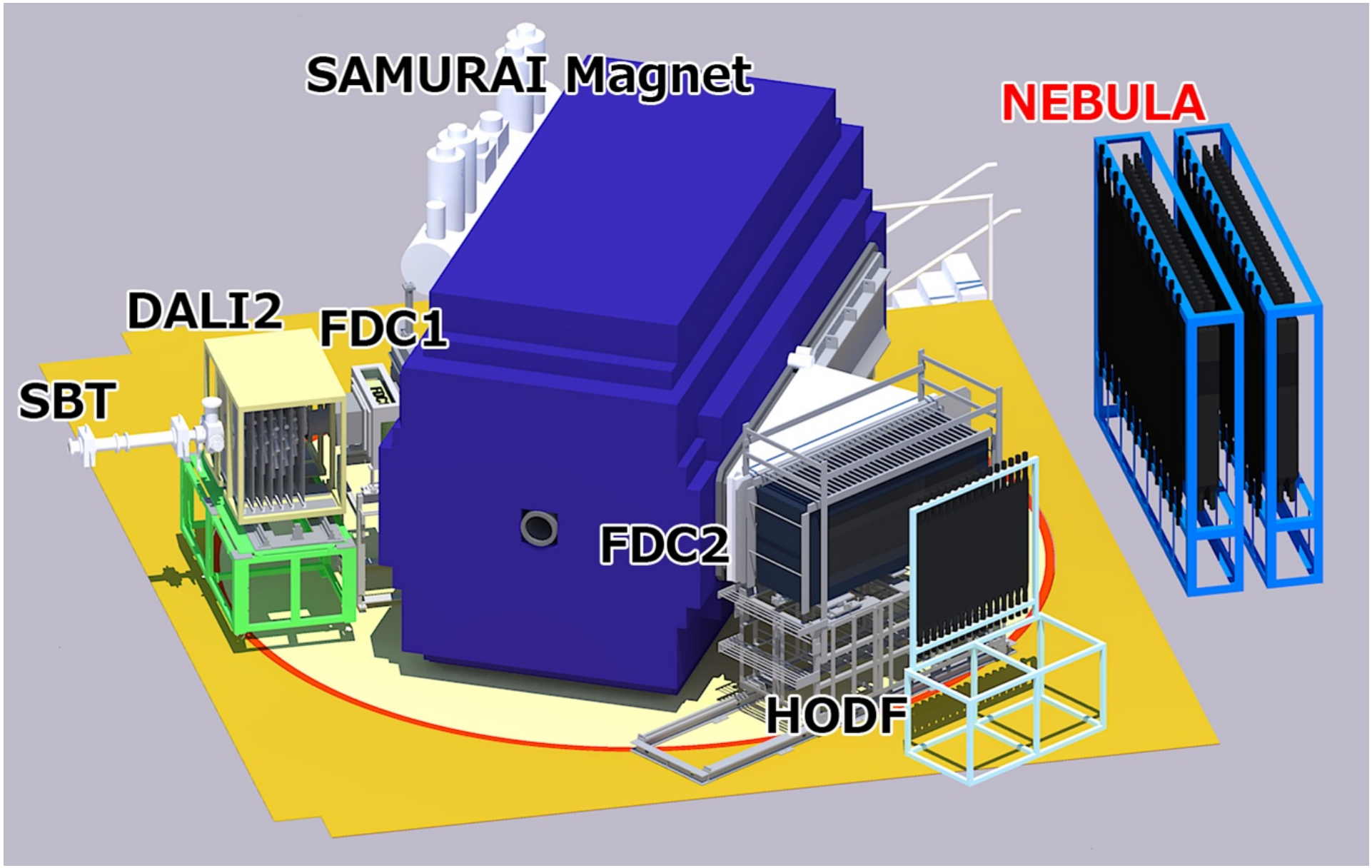
- ▷ Day-One experiments
- ▷ short term : ^{4}n

Radioactive Isotope Beam Factory

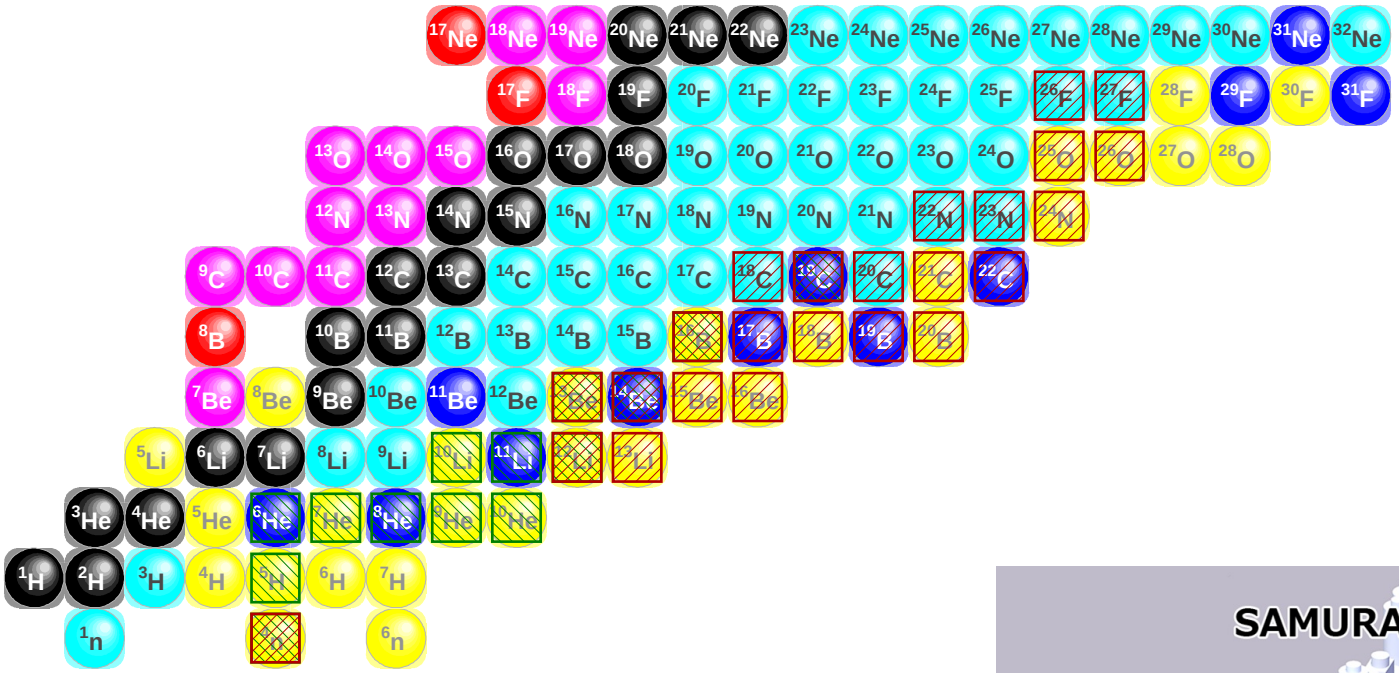
- ▷ variety of very exotic beams with world's highest intensity !
- ▷ projectile fragmentation & in-flight fission
  - ⇝ phase I : light nuclei @ 135 MeV/N
  - ⇝ phase II : up to U @ 350 MeV/N



SAMURAI+NEBULA



S. LEBLOND : DAY-ONE EXPERIMENTS

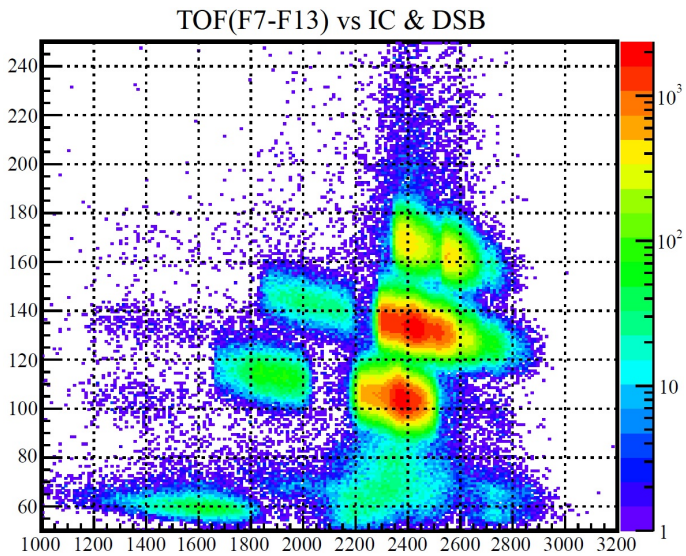


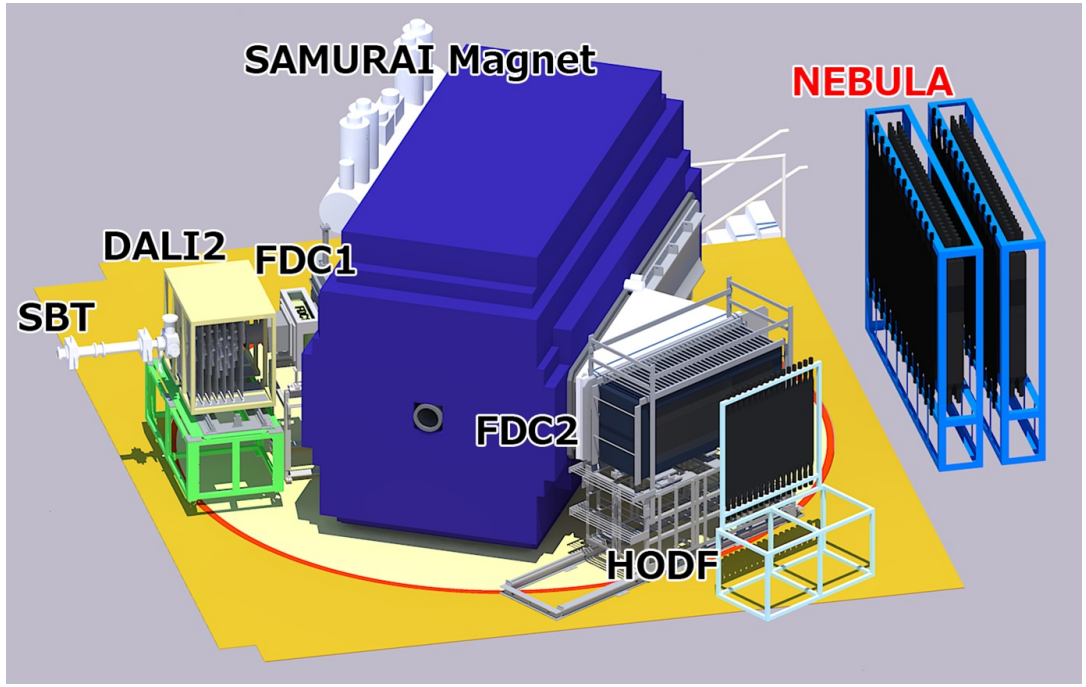
Structure of ^{19}B/ ^{22}C

- ▷ ^{48}Ca + BigRIPS = 50/15 pps !
- ▷ Ö ≡ ⊛

(18)^{19}B ⇝ ^{17,19}B & ^{19}C

(21)^{22}C ⇝ ^{20,22}C & ^{22}N





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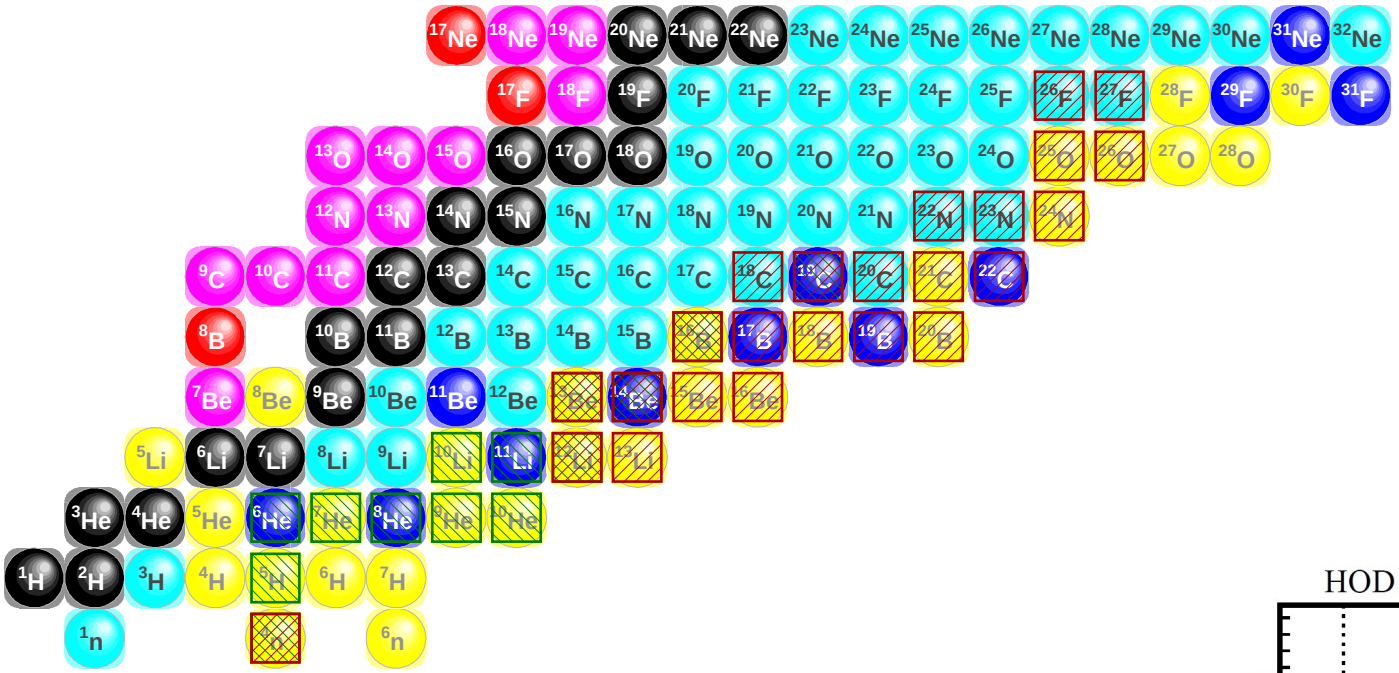

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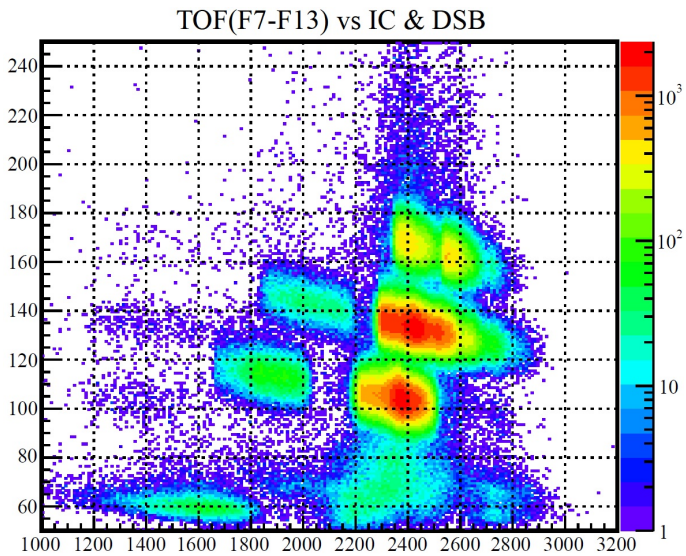
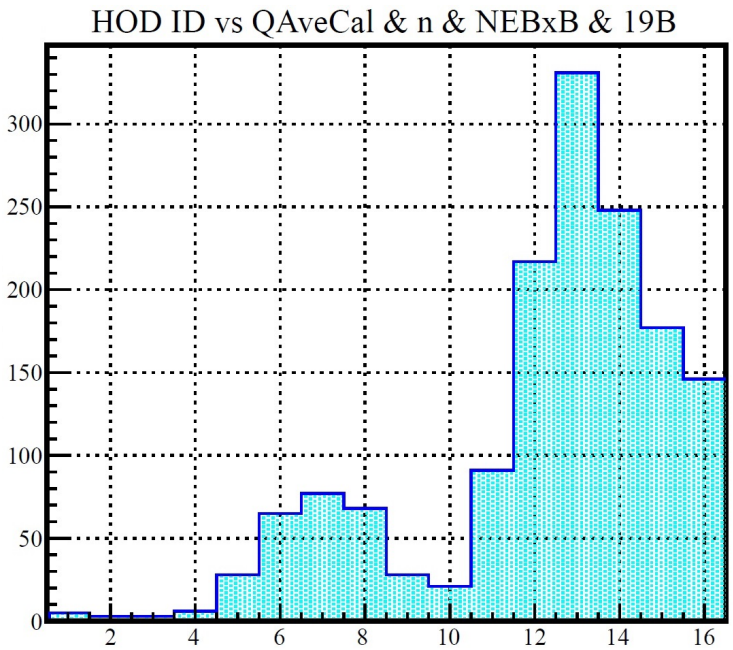
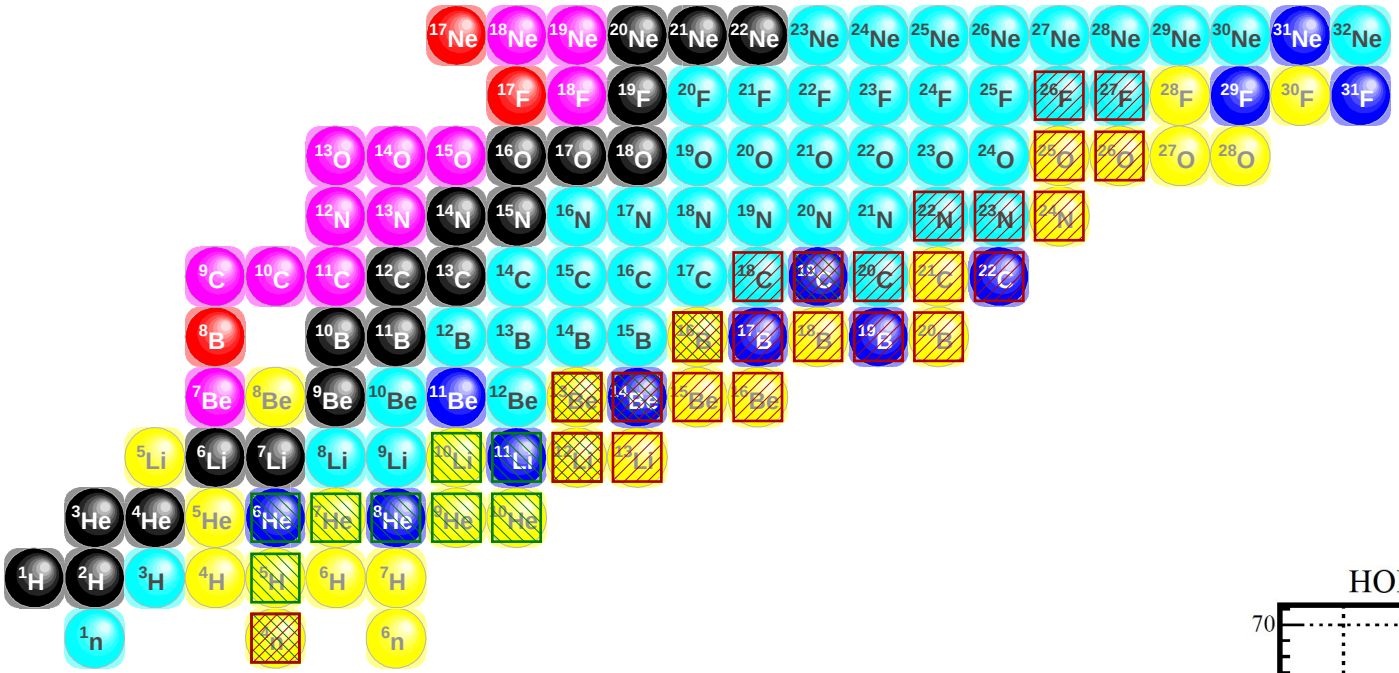




^{19}B → ^{14,12}Be + xn

S. LEBLOND : DAY-ONE EXPERIMENTS



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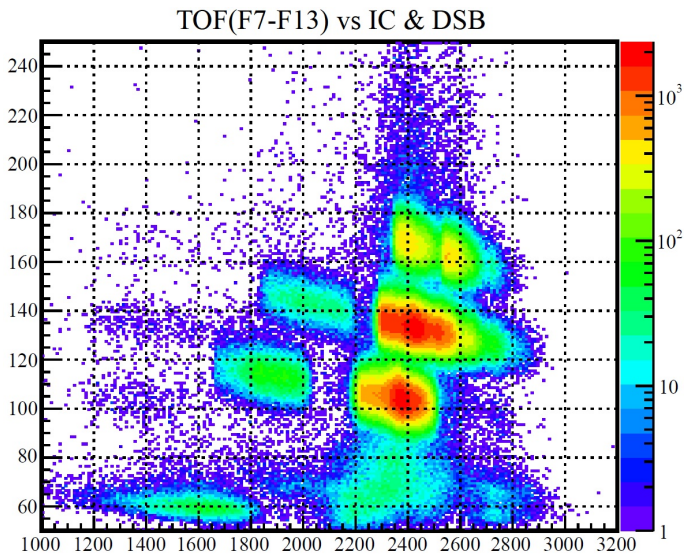
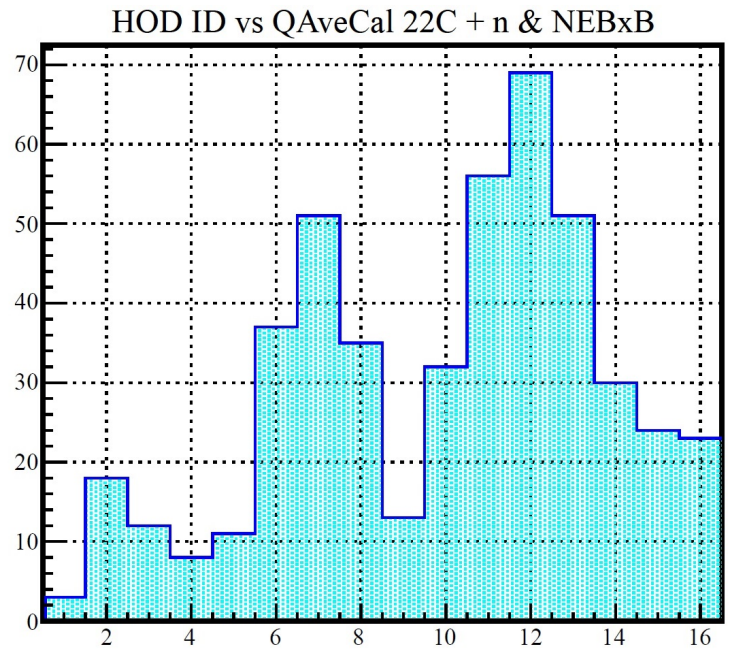
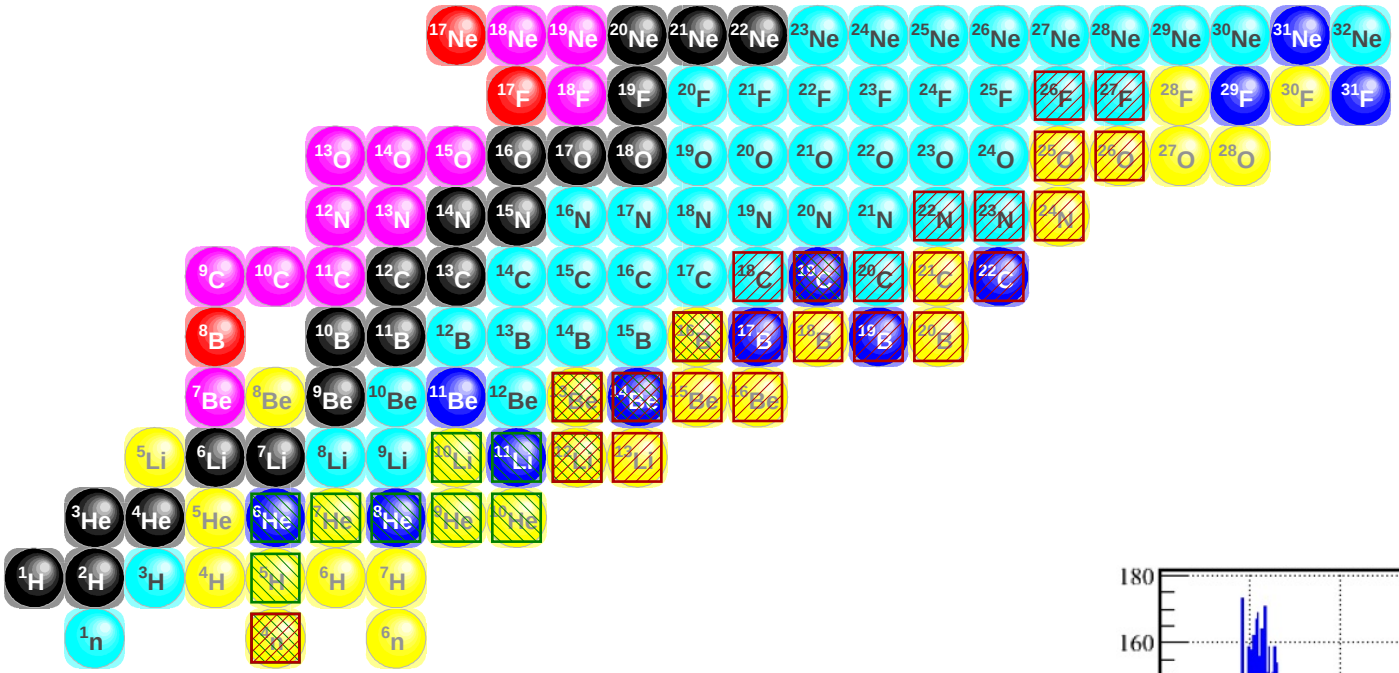




^{22}C → ^{19,17,15}B + xn

S. LEBLOND : DAY-ONE EXPERIMENTS



Structure of ^{19}B/ ^{22}C

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- ▷ ⌀ ≡ ⊛

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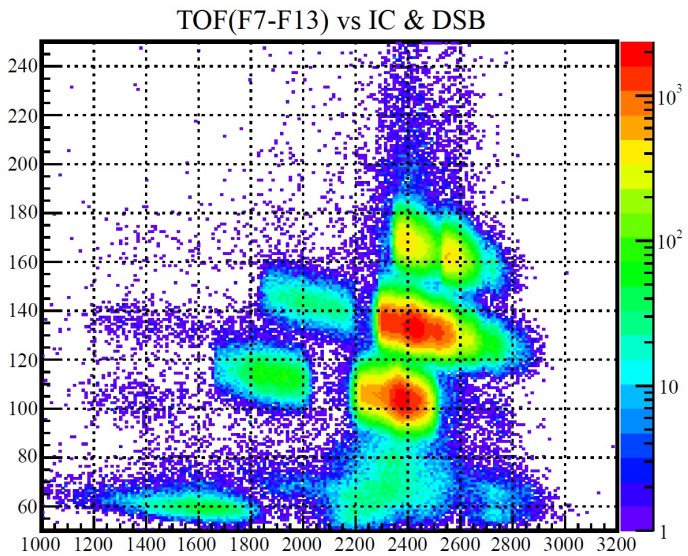
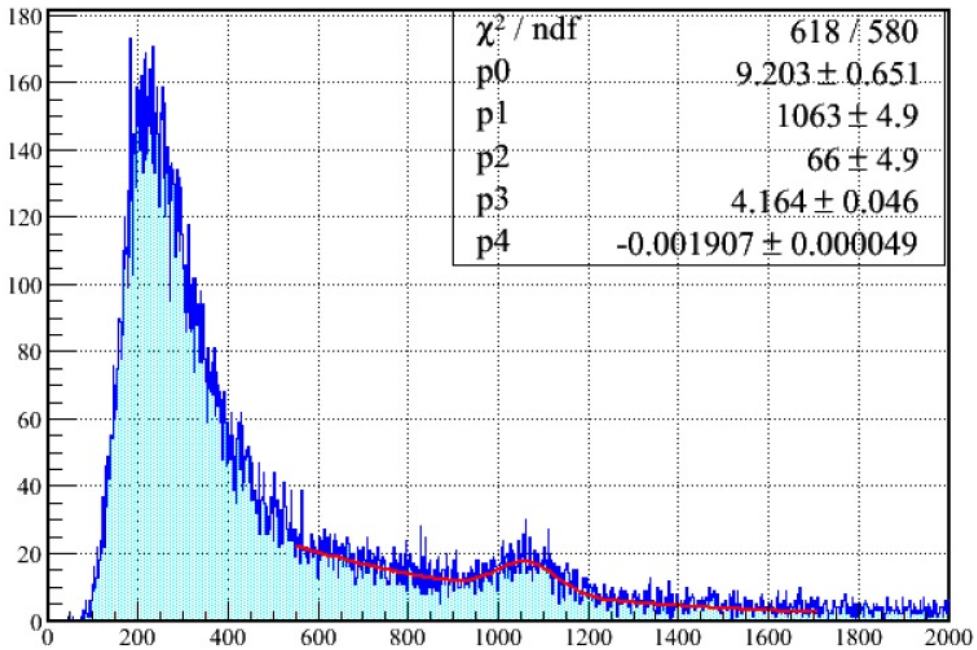
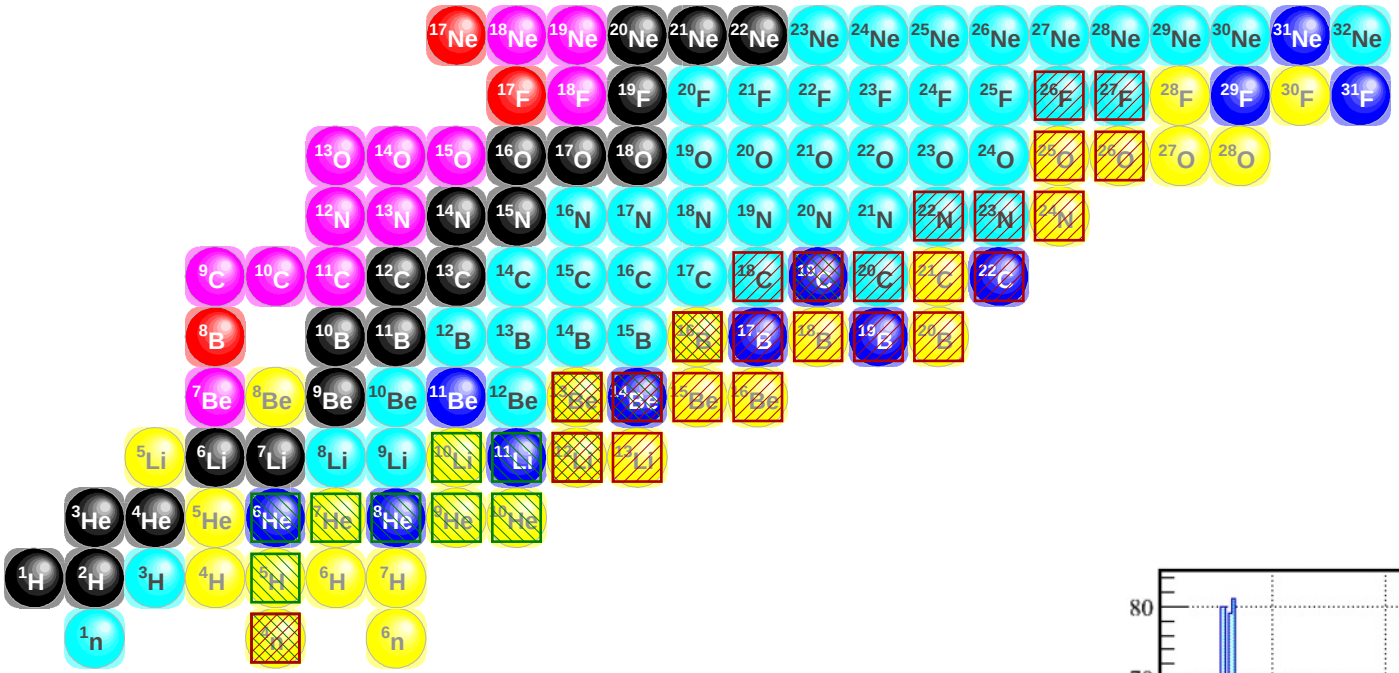




^{17}B → ^{17}B + γ

S. LEBLOND : DAY-ONE EXPERIMENTS



Structure of ^{19}B/ ^{22}C

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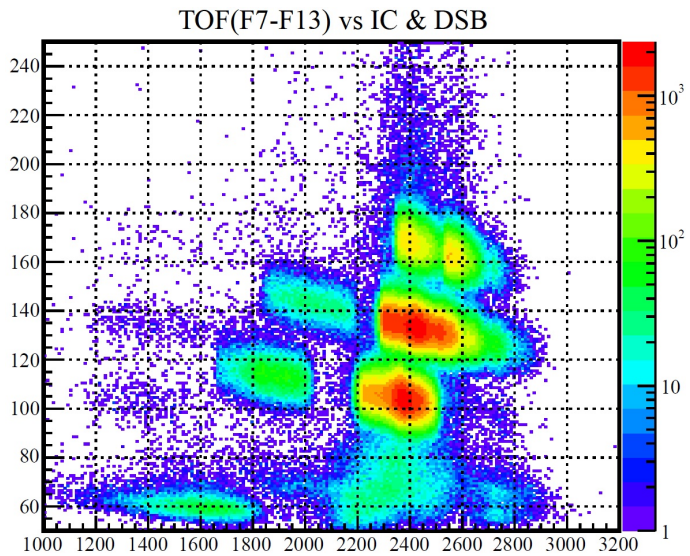
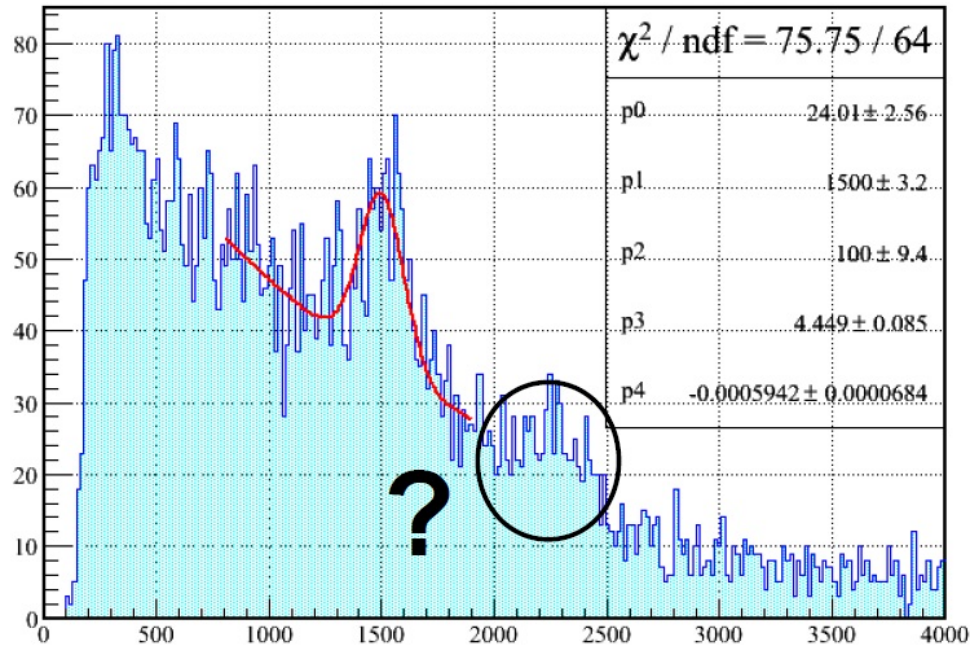
(21)^{22}C ⇝ ^{20,22}C & ^{22}N

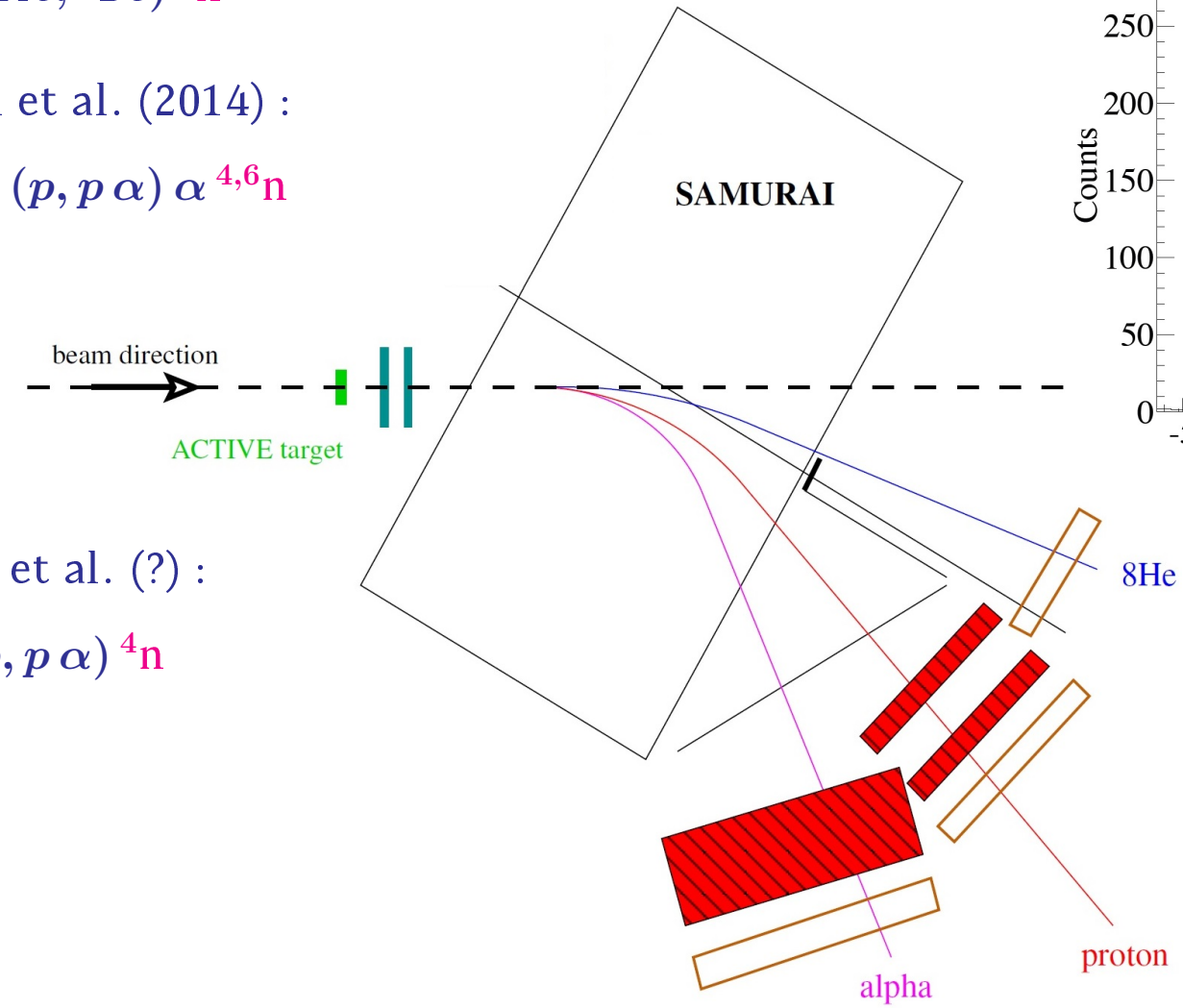


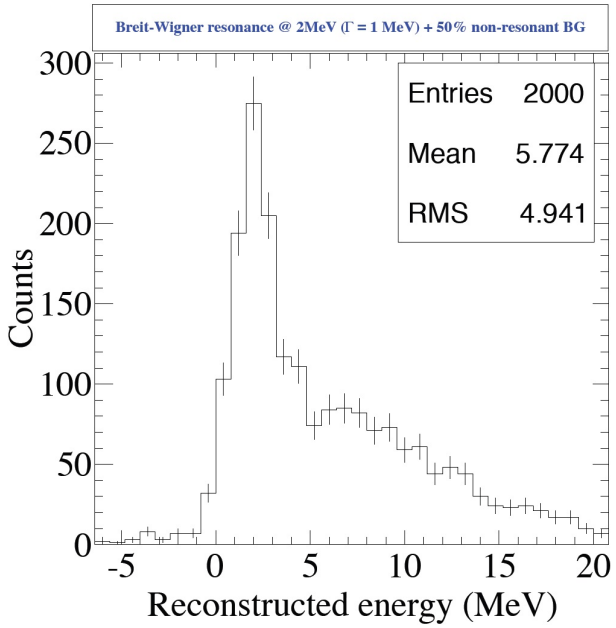


^{19}C → ^{18}C + γ

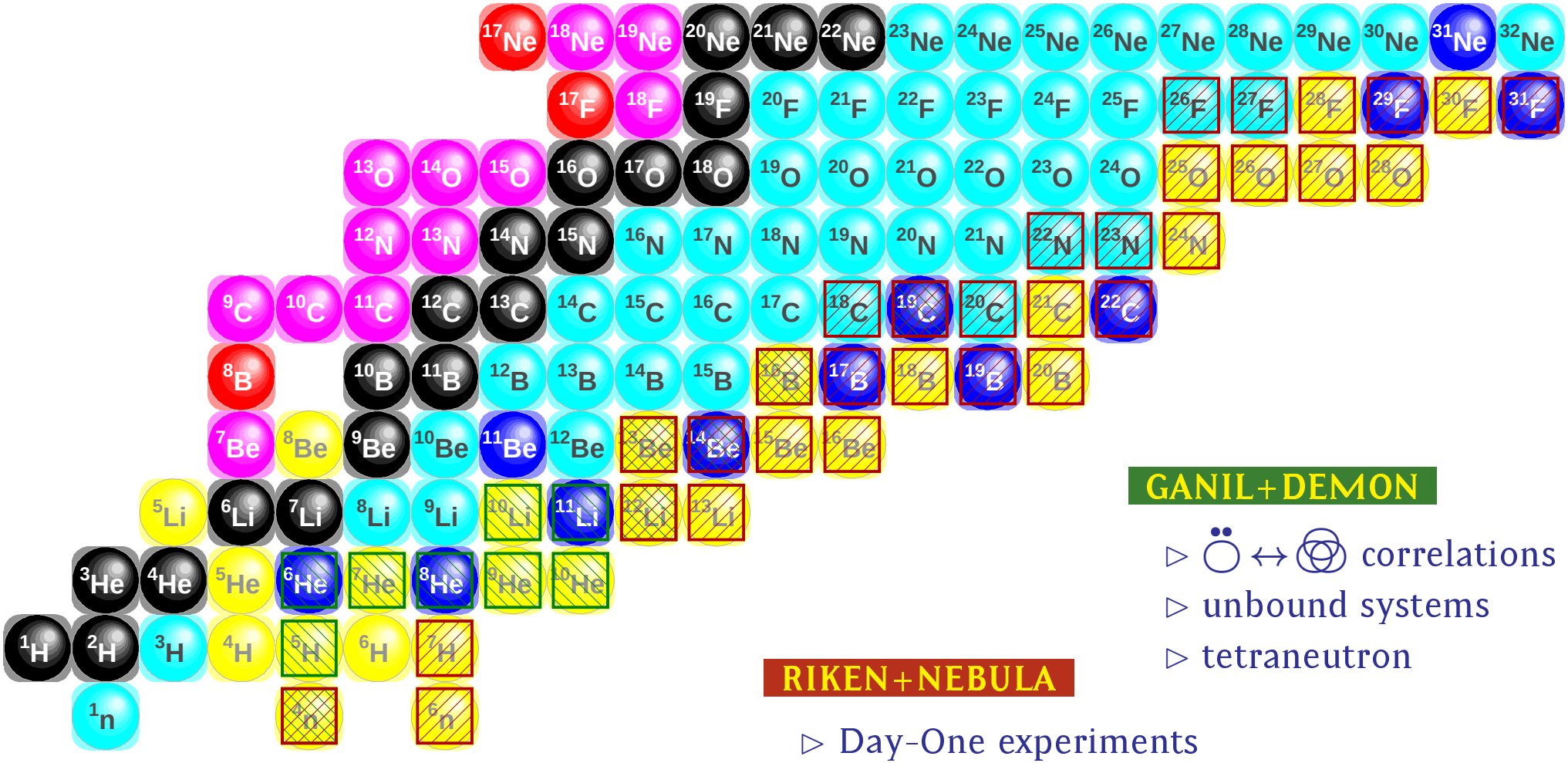
MULTI-NEUTRONS AT RIKEN

- Shimoura et al. (2012) :
  - ^{4}He (^{8}He, ^{8}Be) ^{4}n
- Beaumel et al. (2014) :
  - ^{12,14}Be $(p, p\,\alpha)\,\alpha$ ^{4,6}n
- Aumann et al. (?) :
  - ^{8}He $(p, p\,\alpha)$ ^{4}n





AROUND THE NEUTRON DRIPLINE



GANIL+DEMON

- ▷ correlations
- ▷ unbound systems
- ▷ tetraneutron

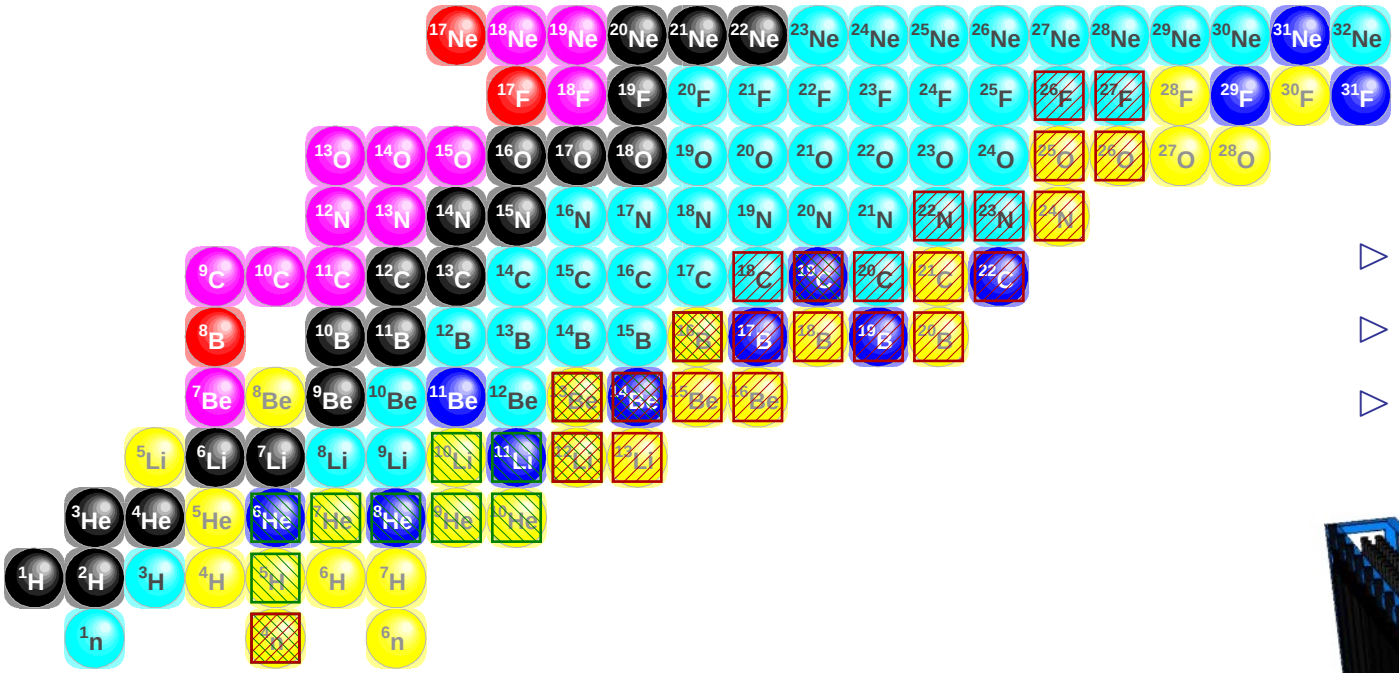
RIKEN+NEBULA

- ▷ Day-One experiments
- ▷ short term : ^{4}n

RIKEN+EXPAND

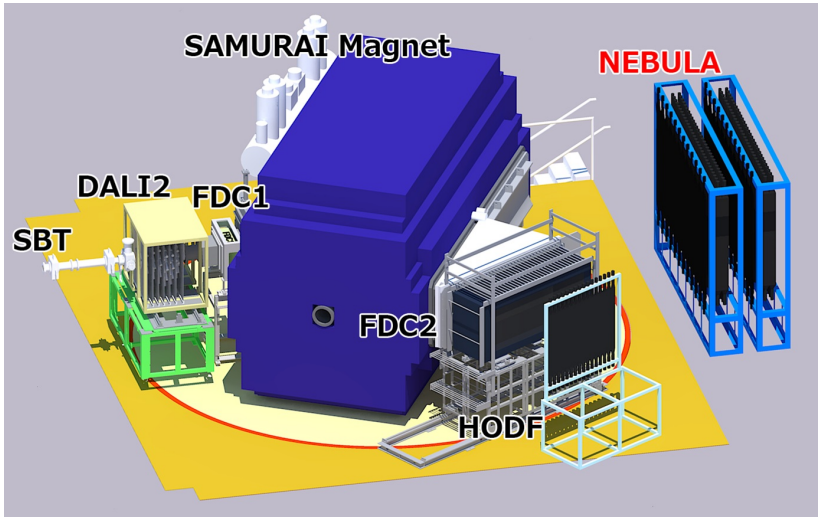
- ▷ ^{28}O, ^{7}H, ^{4,6}n ...

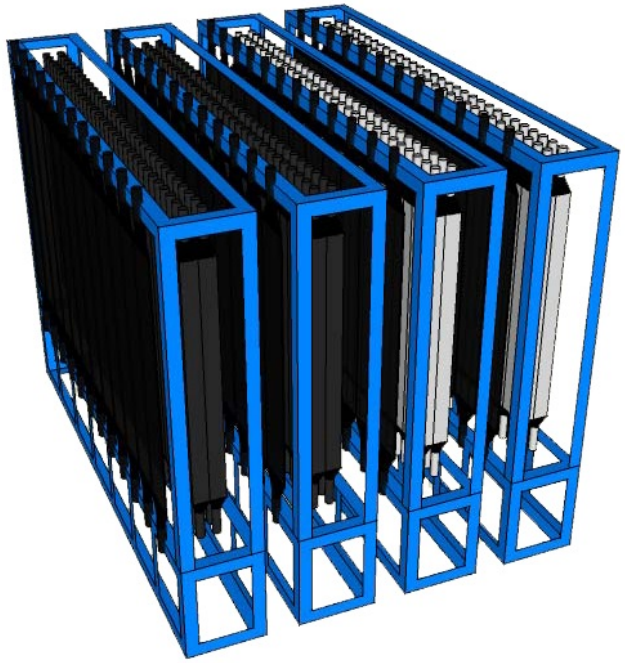
EXPAND : NEBULA+



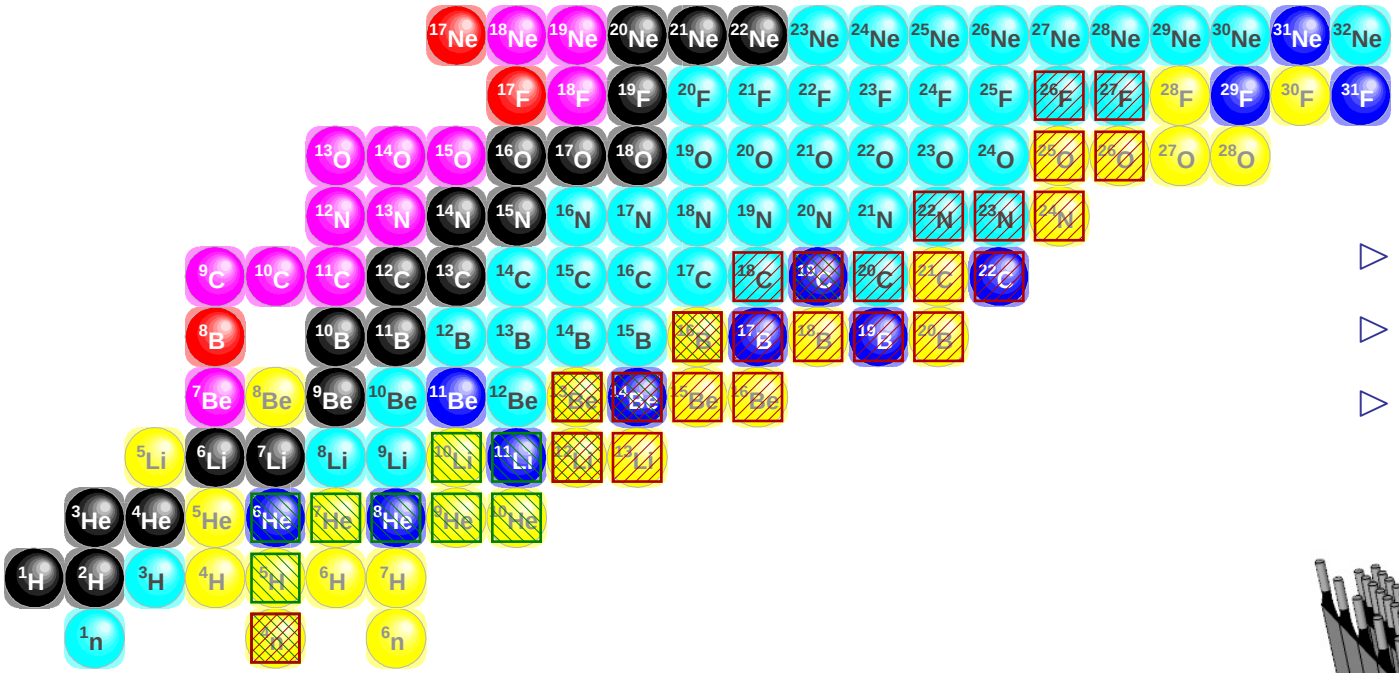
NEBULA+

- ▷ 240 neutron modules
- ▷ 48 veto modules
- ▷ 2+2 walls : ^{28}O, ^{7}H, ^{4,6}n !





EXPAND : NEBULA+



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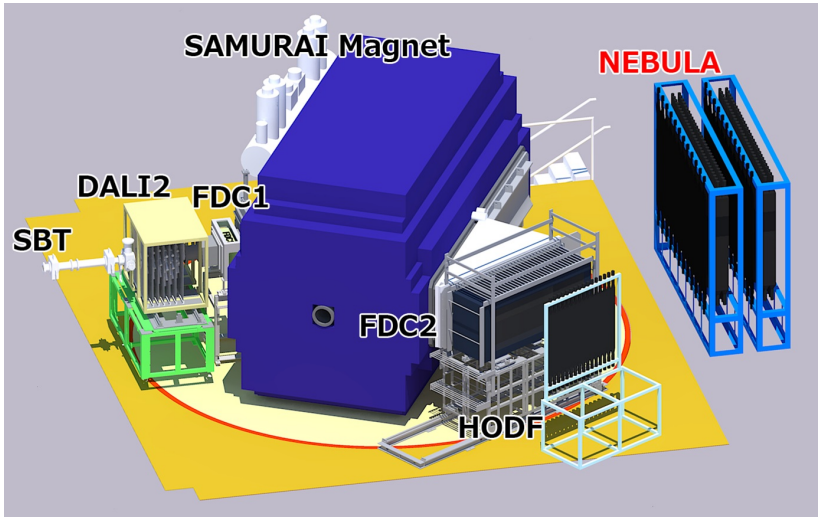
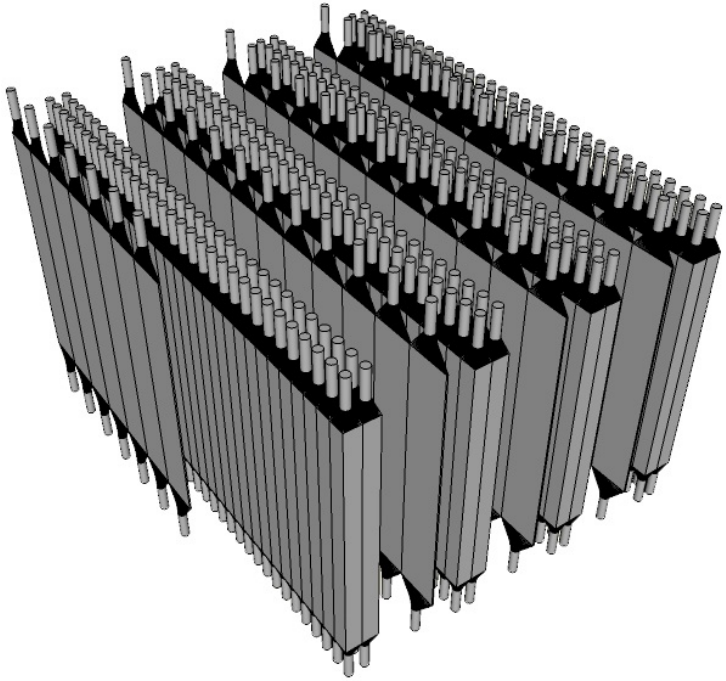
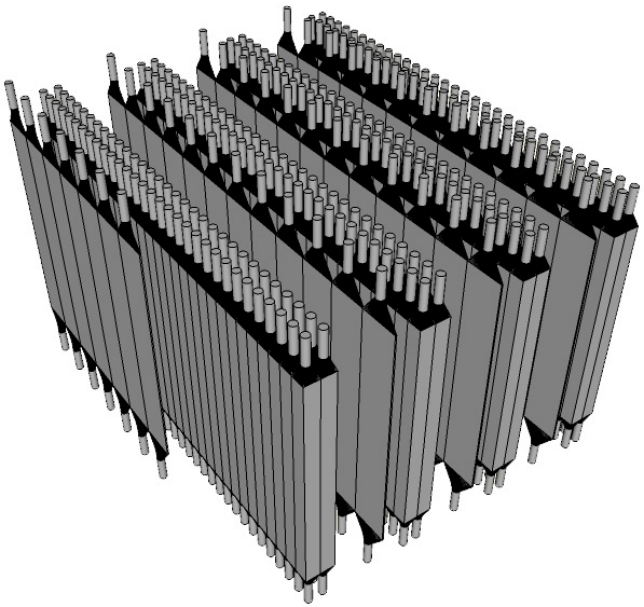
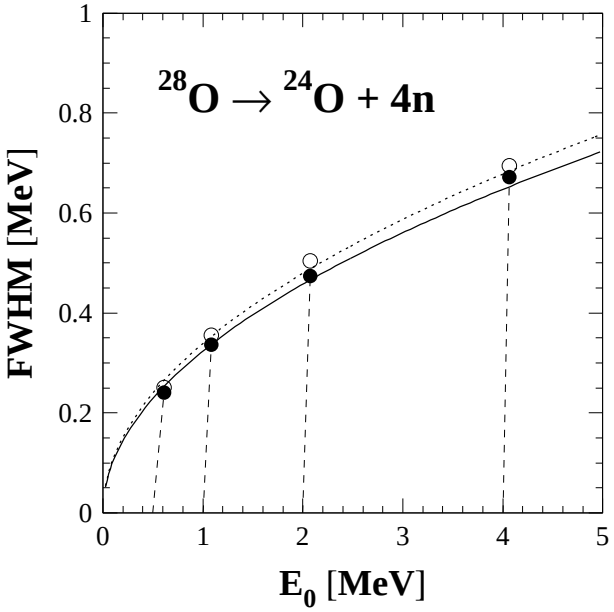


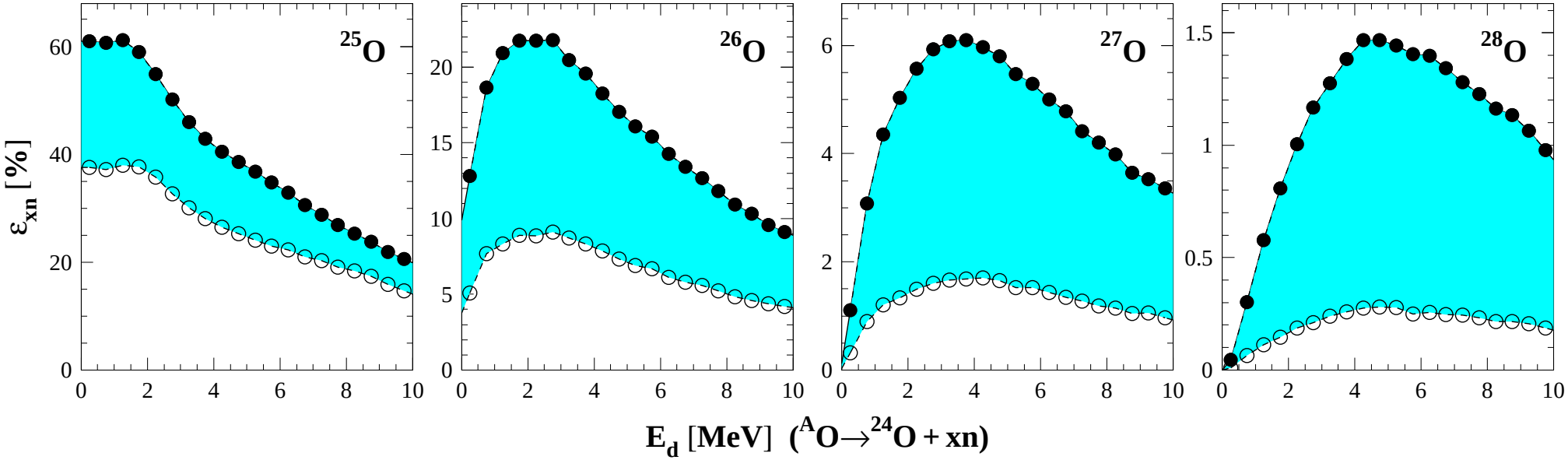


▶ EXPAND : ANR (800 k€)

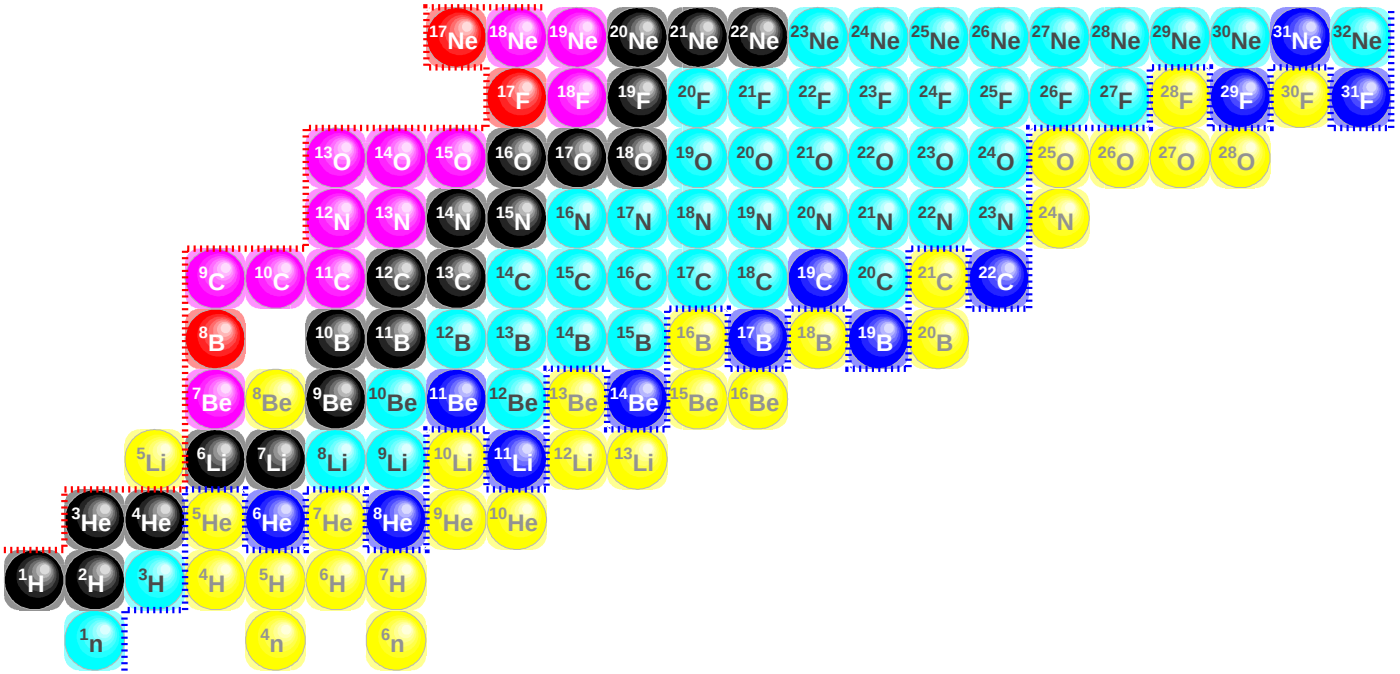
MONTE-CARLO SIMULATIONS

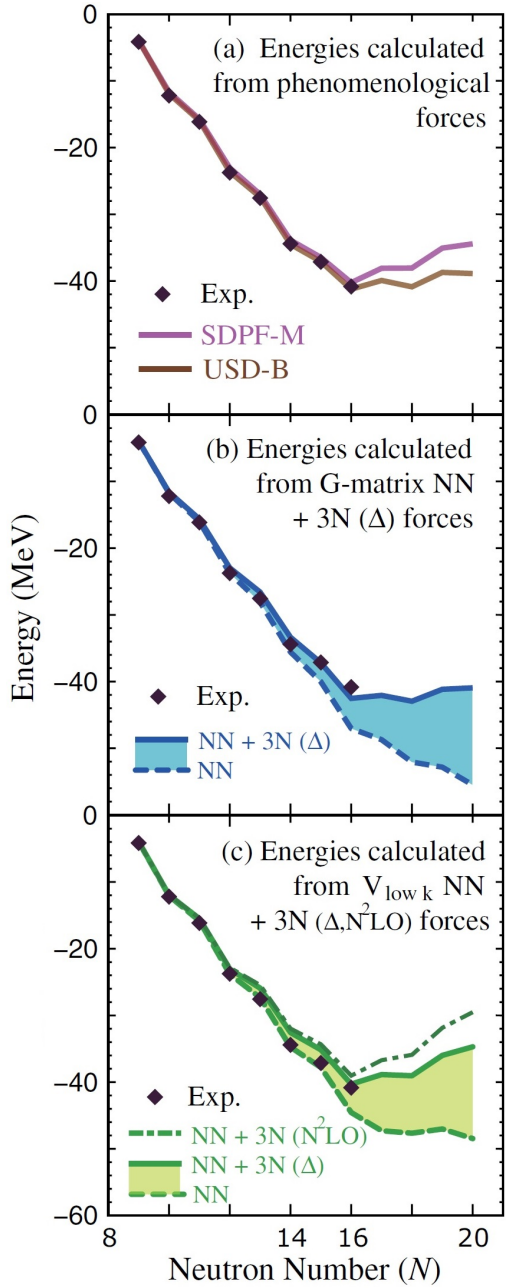






OXYGEN 28





- The "Oxygen anomaly"

  [Otsuka, PRL 105 (2010) 032501] :

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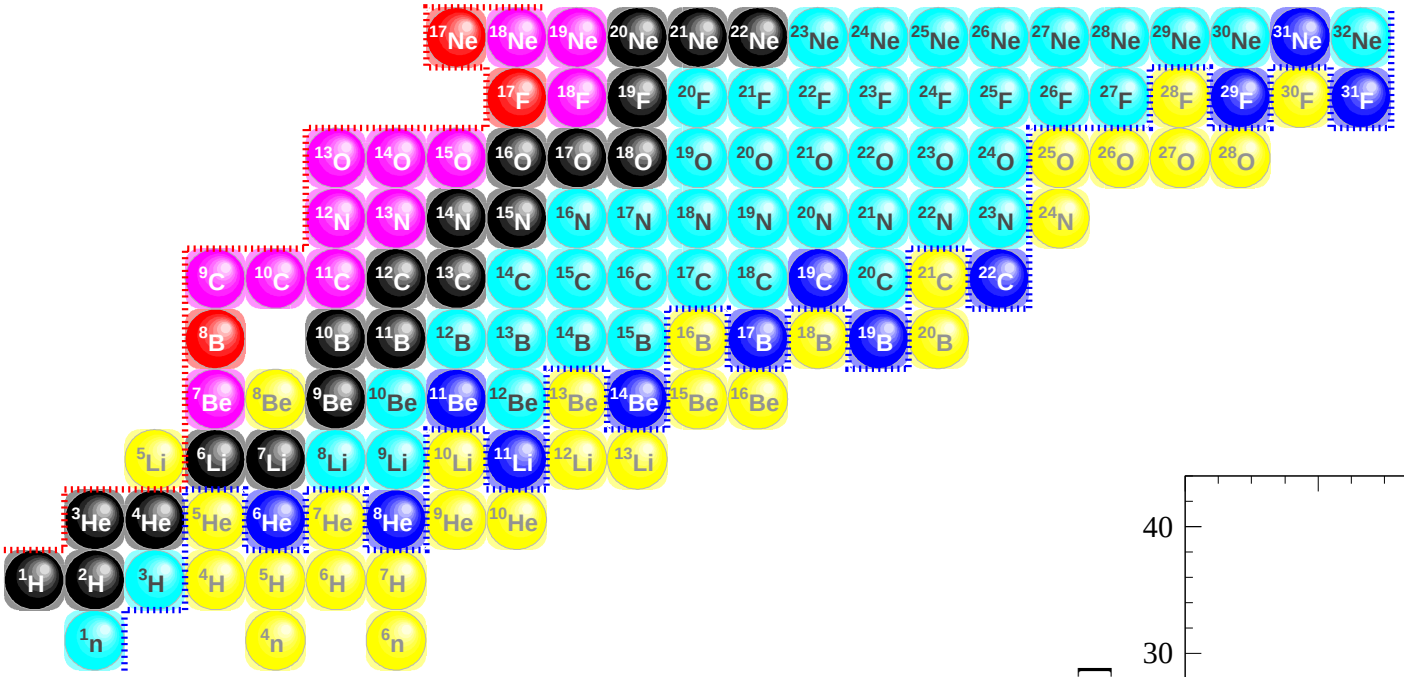
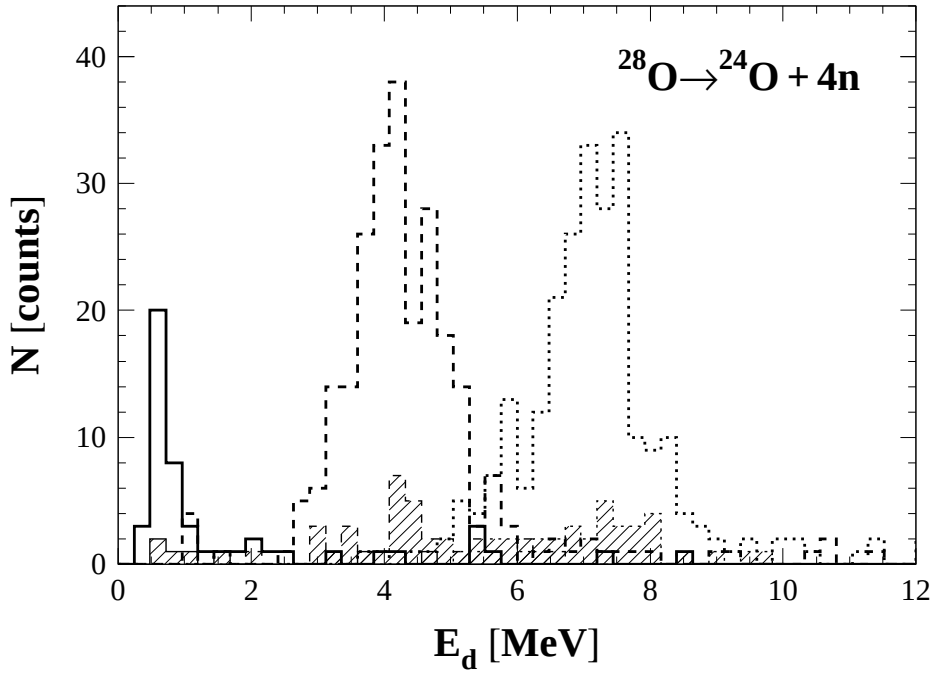
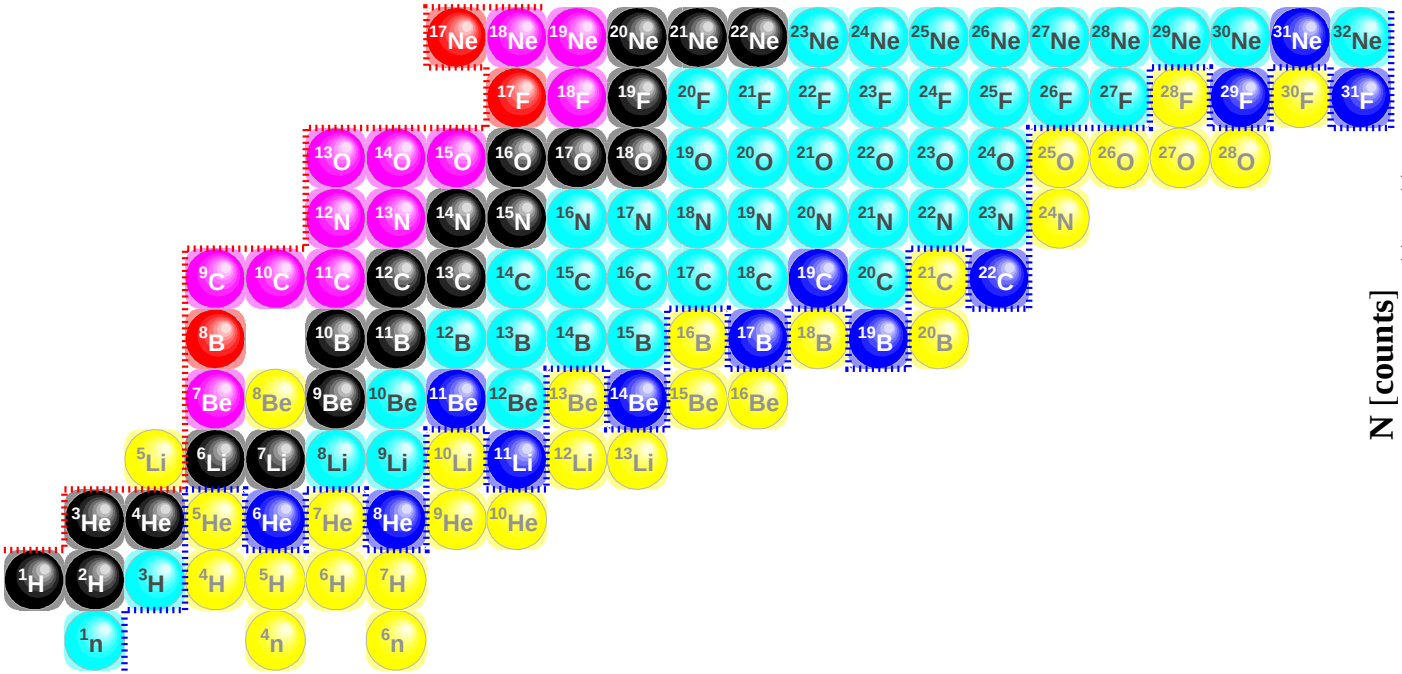
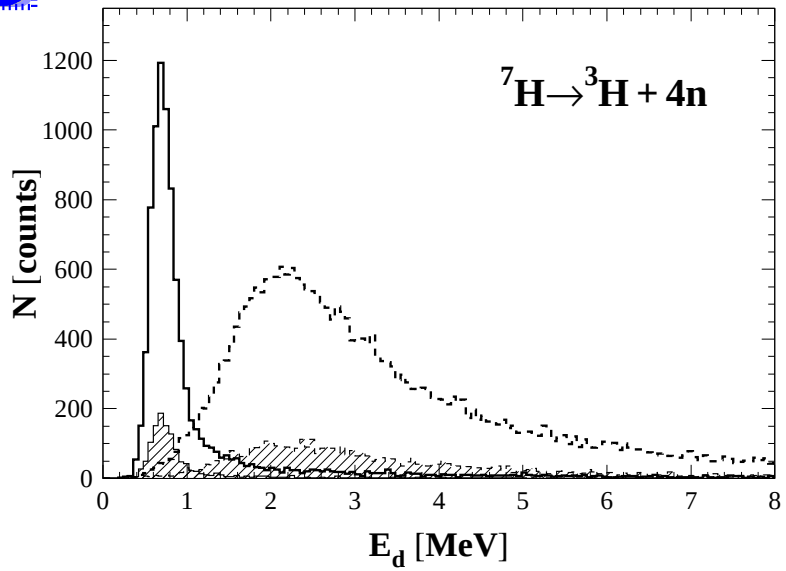


- The "Oxygen anomaly"
  [Otsuka, PRL 105 (2010) 032501] :
  - ▷ ^{29}F beam at 25/s
  - ▷ MINOS Hydrogen target
  - ▷ $(p, 2p)$ about 1 mb
  - ⇝ 10 days = 150 ^{24}O+4n !
  - ⇝ heaviest ⊚ : ^{29,31}F !!!



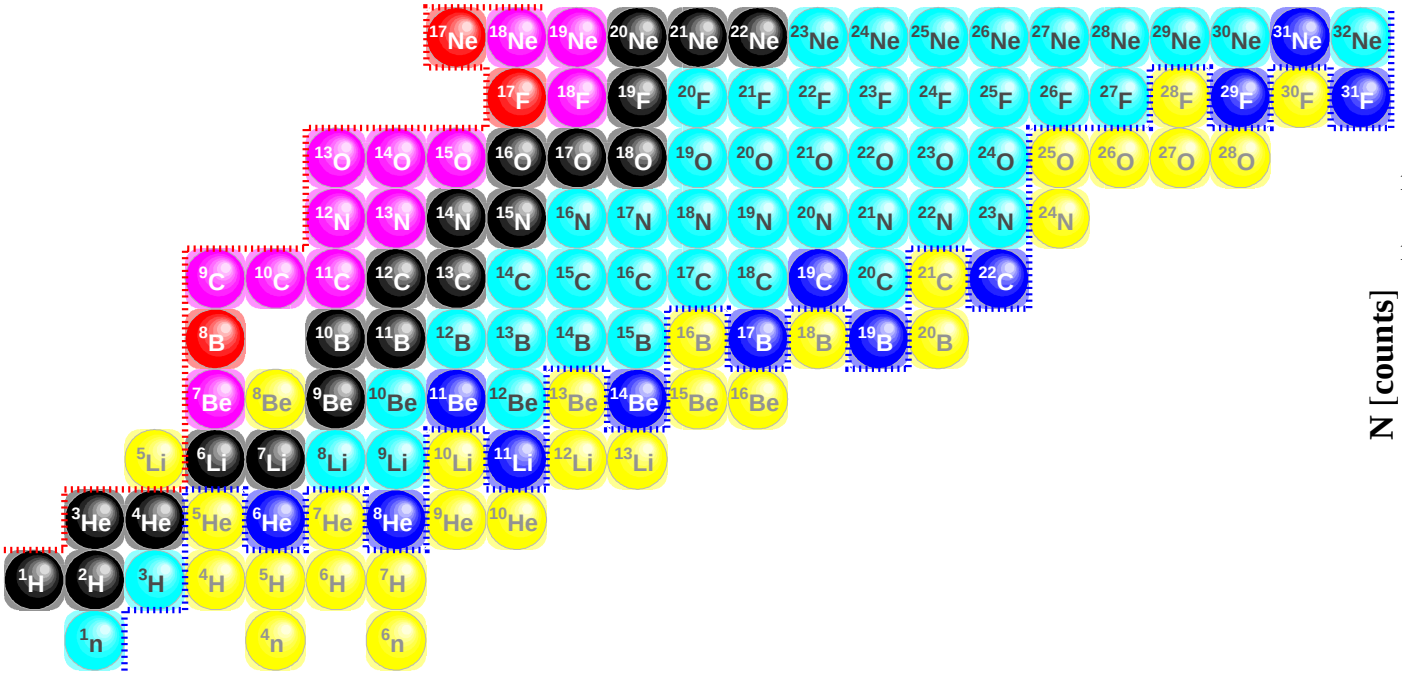
HYDROGEN 7 & MULTI-NEUTRONS

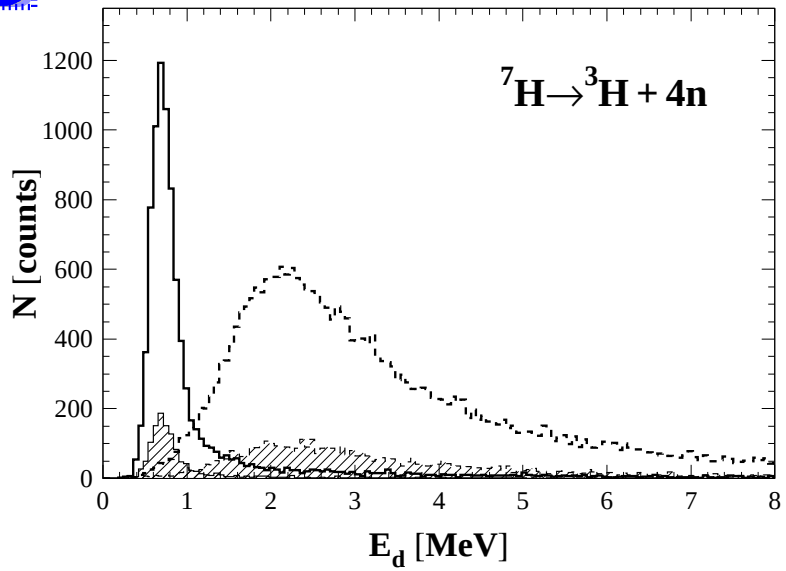




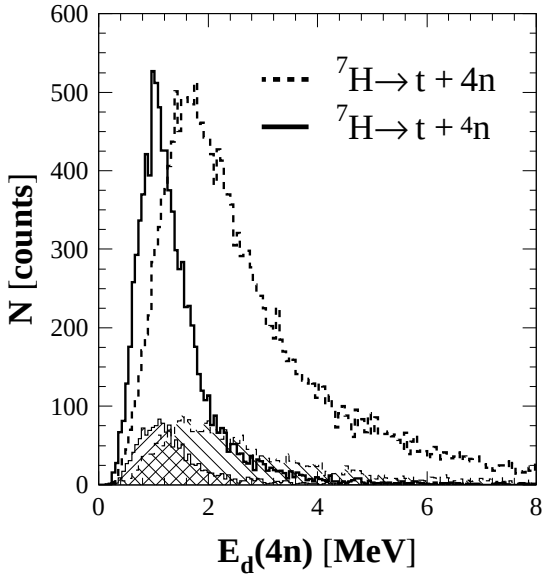
- Tiny "neutron stars" :
  - ▷ ^{8}He/^{9}Li beams on C
    - ⇝ 7 days = 30,000 ^{3}H+4n !

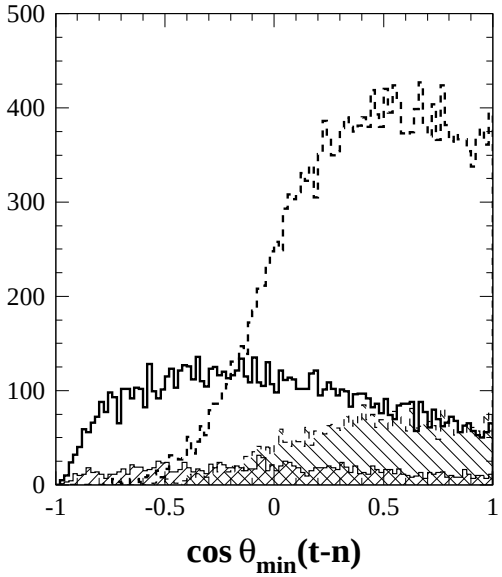
HYDROGEN 7 & MULTI-NEUTRONS





- Tiny "neutron stars" :
  - ▷ ^{8}He/^{9}Li beams on C
    - ⇝ 7 days = 30,000 ^{3}H+4n !
  - ▷ 30% decay into ^{4}n
  - ▷ angular correlations ^{3}H-4n ...
- Re-arrange walls for ^{6}n ...





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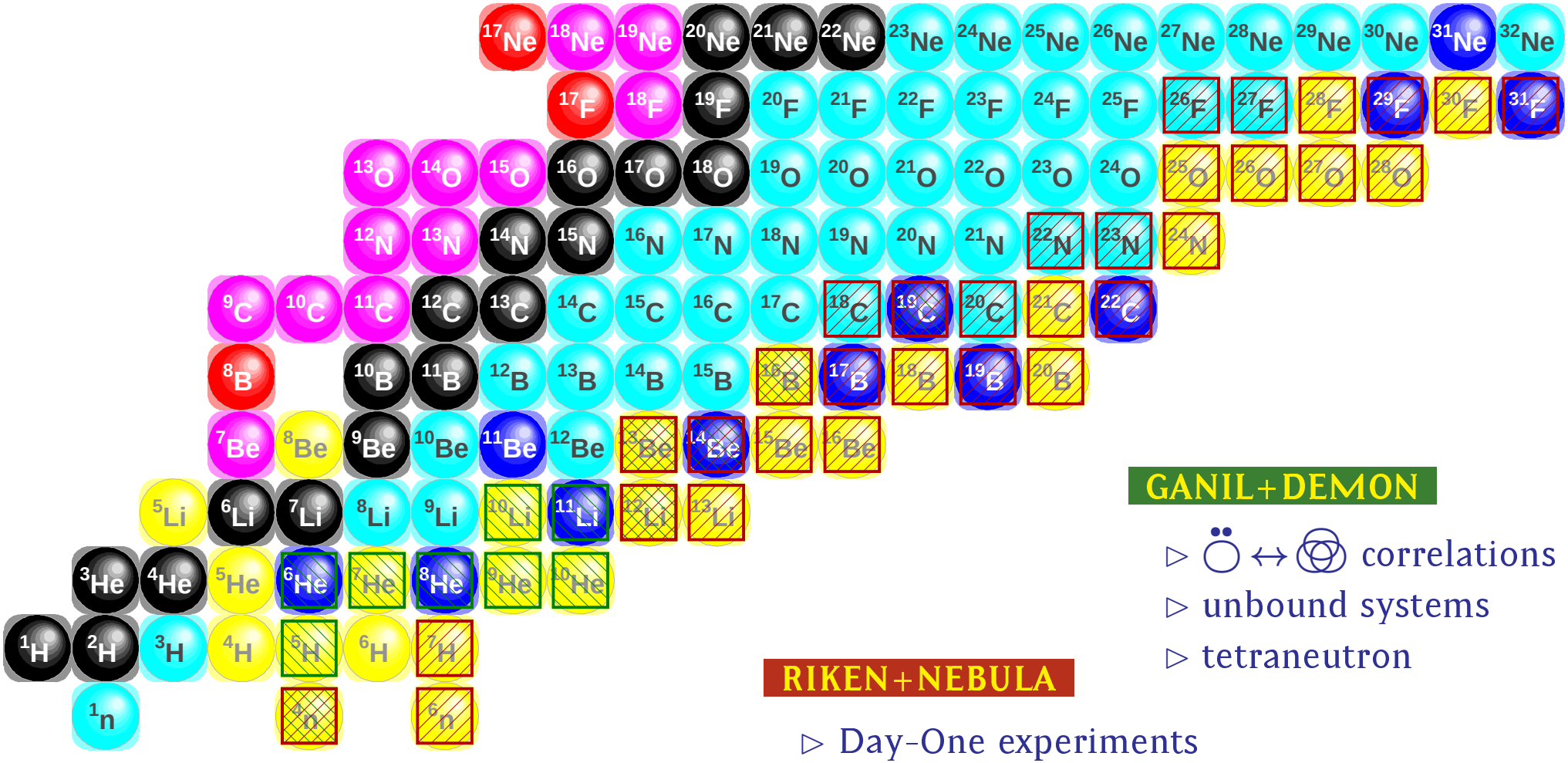

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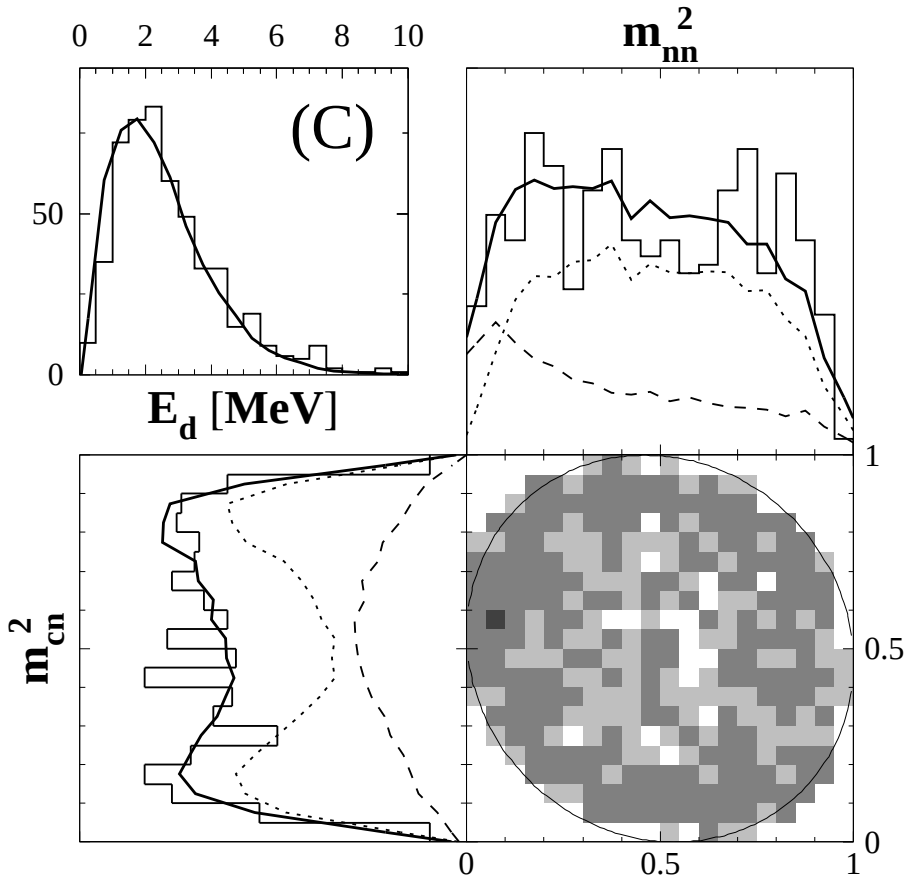
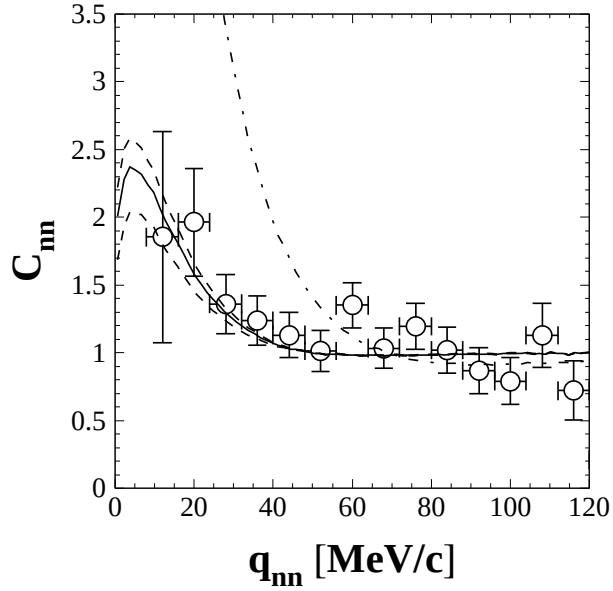
▶ $^{8}He^{*}(C) \rightarrow {}^{6}He + nn$ @ 15 MeV/N :





$$r_{nn}^{\mathrm{rms}} = 7.3 \pm 0.6 \text{ fm}$$
$$\tau_0 = 1400 \pm 400 \text{ fm/c}$$

▶ $^{8}He^{*}(Pb) \rightarrow$ direct breakup !