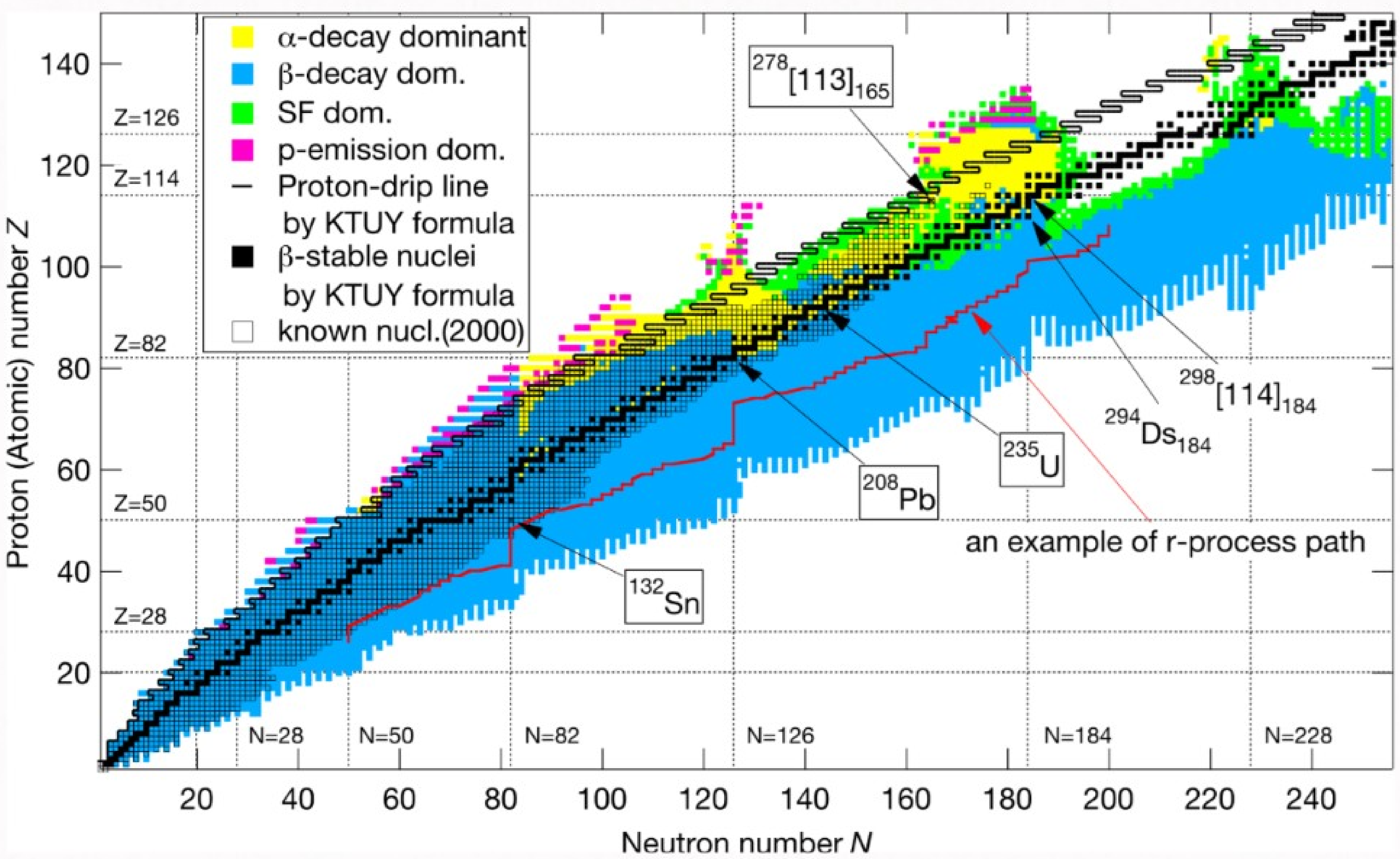
Nuclear Physics (31)

Exotic nuclear structures

(Halo nuclei,
Borromean nuclei,
α-particle clusters, etc.)

RECAP

Nuclear Structure → Big mess



1) A ≤ 10-12 → Ab-initio

(Solve Schrödinger)

2) For the rest → Nuclear models

SM, Collective, Liquid drop ...

But there are a few exceptional nuclei

↓

1) Do not fit into conventional nuclear models

2) Allow for simplifying assumptions

⇓

A few of these nuclei can be solved w/ few body methods

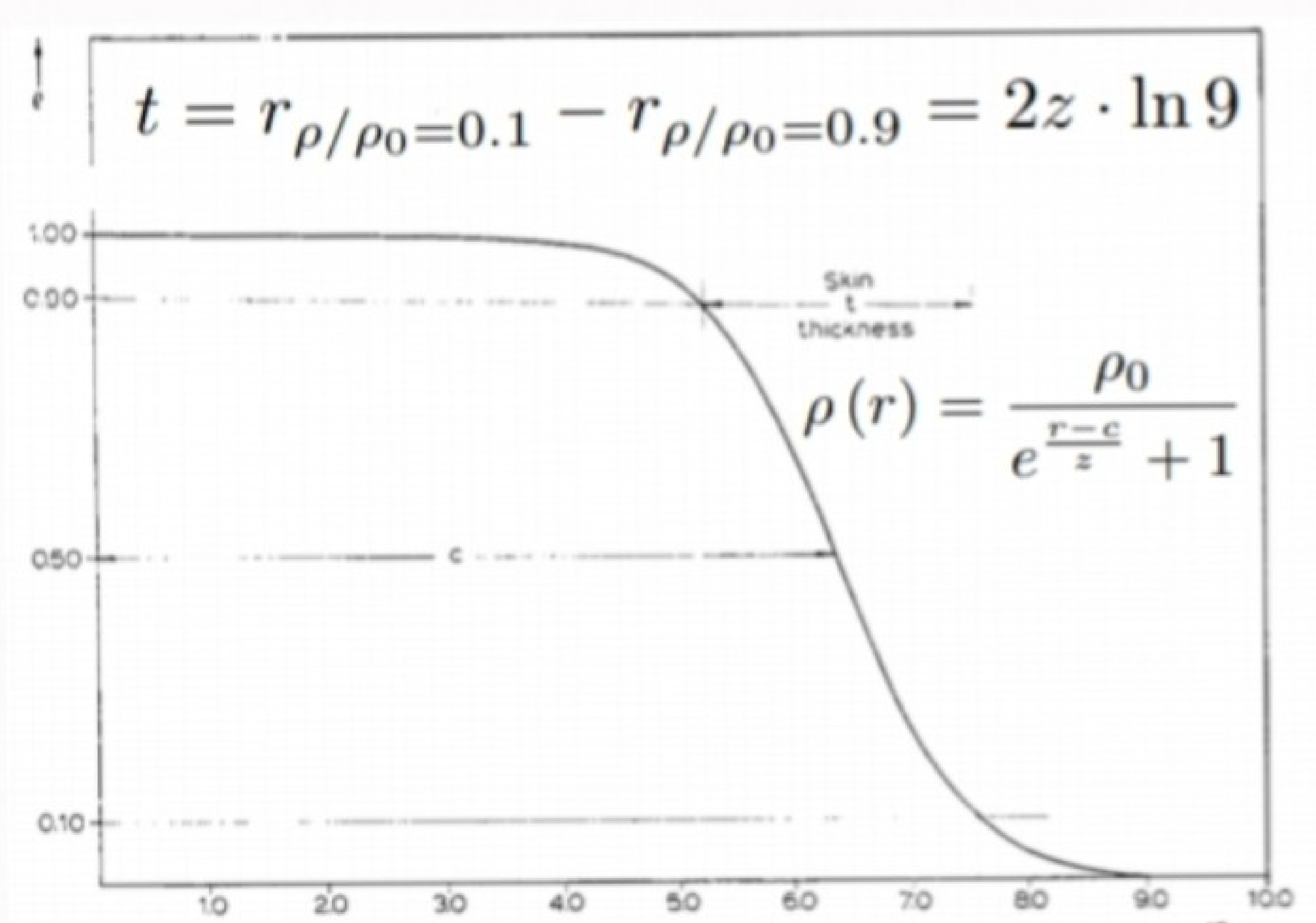
Halo nuclei

1) Standard nuclei

→ Saturation

$\frac{B}{A} \sim (8-9)\,\text{MeV}$, $\rho \sim 0.16\,\text{fm}^{-3}$

⇒ constant density

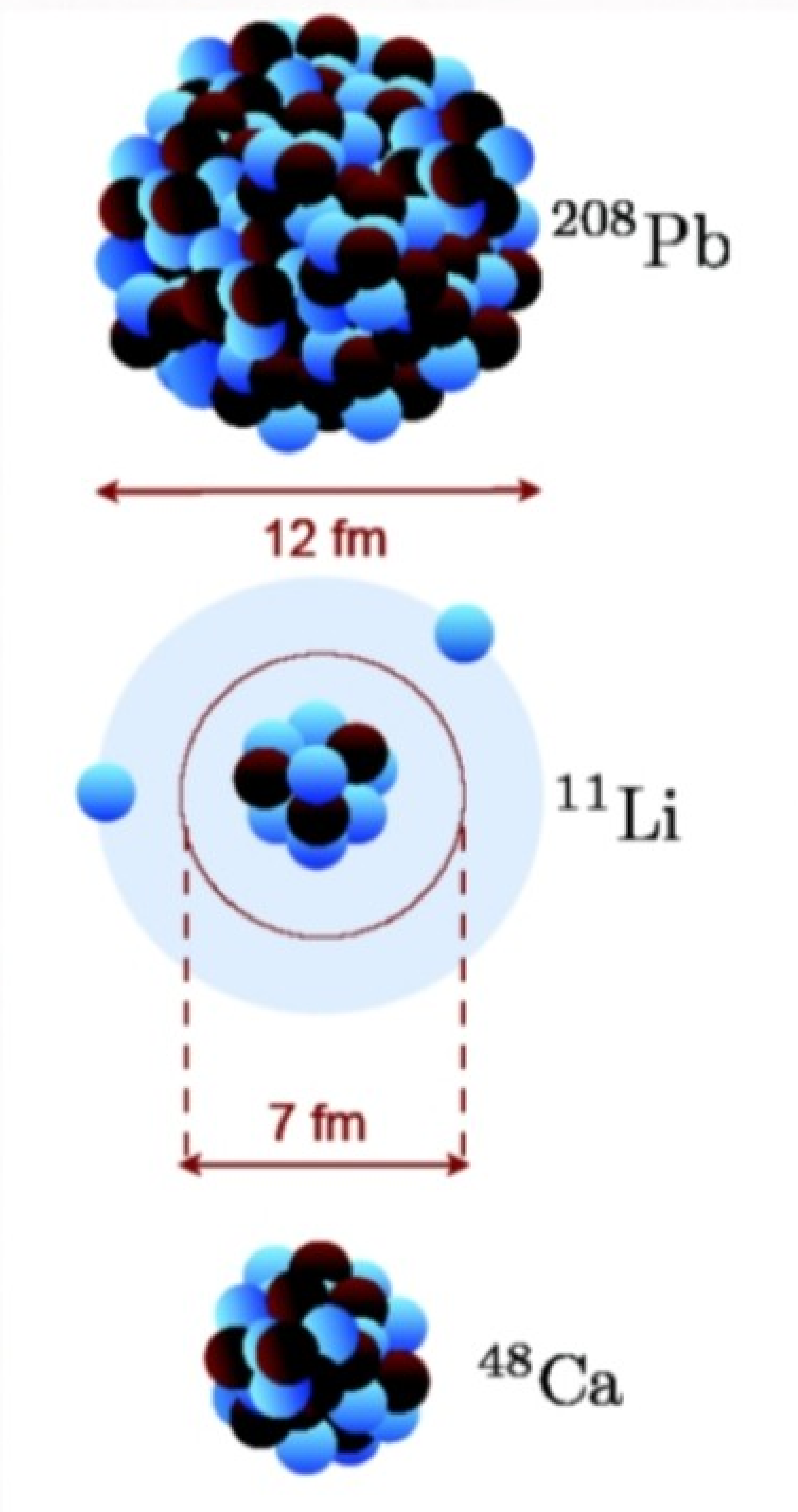


taken from ref. [5]

Reminder → Hofstadter experiment & Woods-Saxon parametrization

But not all nuclei are like this

2) Halo nuclei: **CORE + HALO**

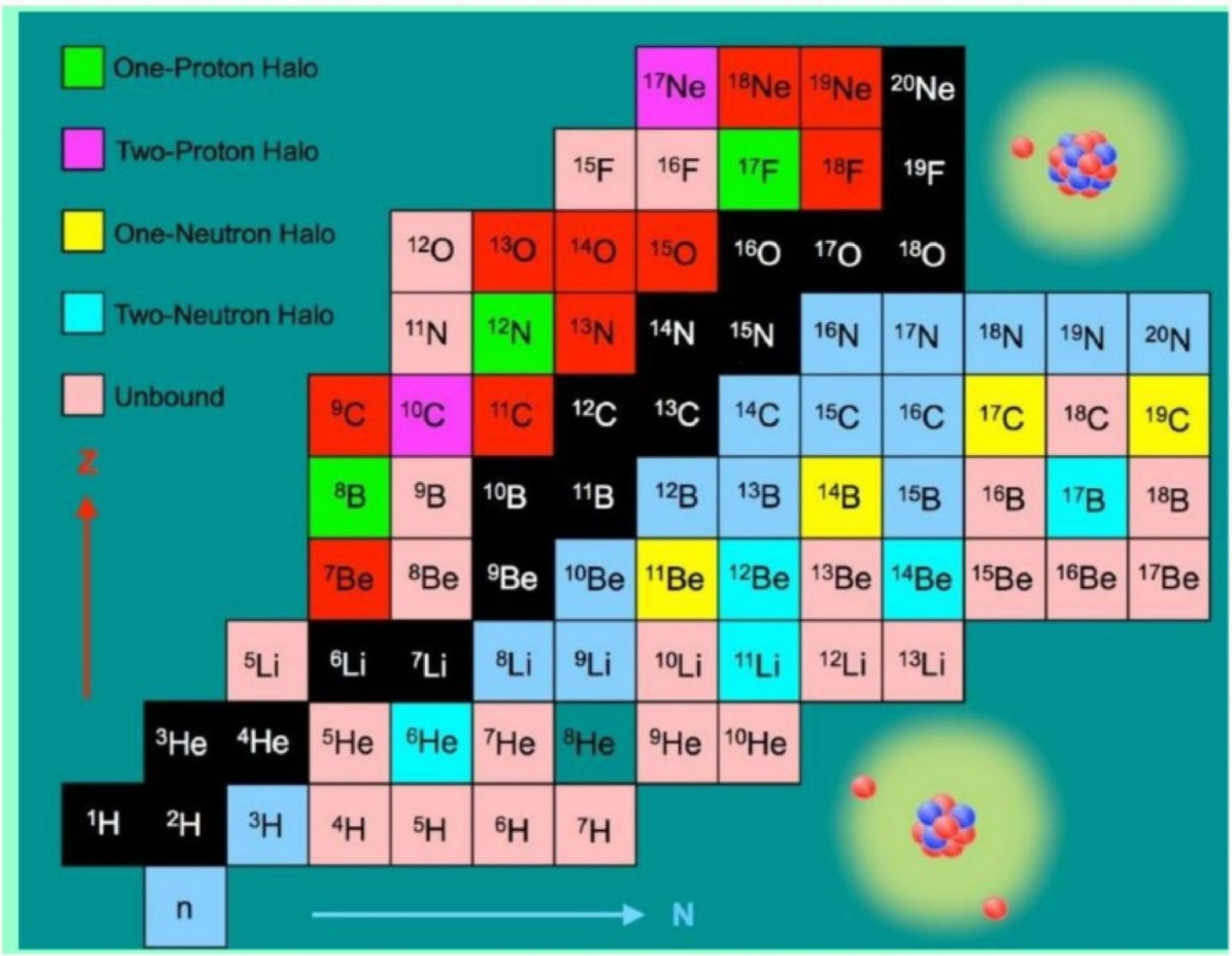


$^{11}Li \rightarrow {}^{9}Li + 2n$

- ^{9}Li → CORE → "Normal nucleus"
- $2n$ → HALO → Large

↳ **^{11}Li is as big as ^{208}Pb**

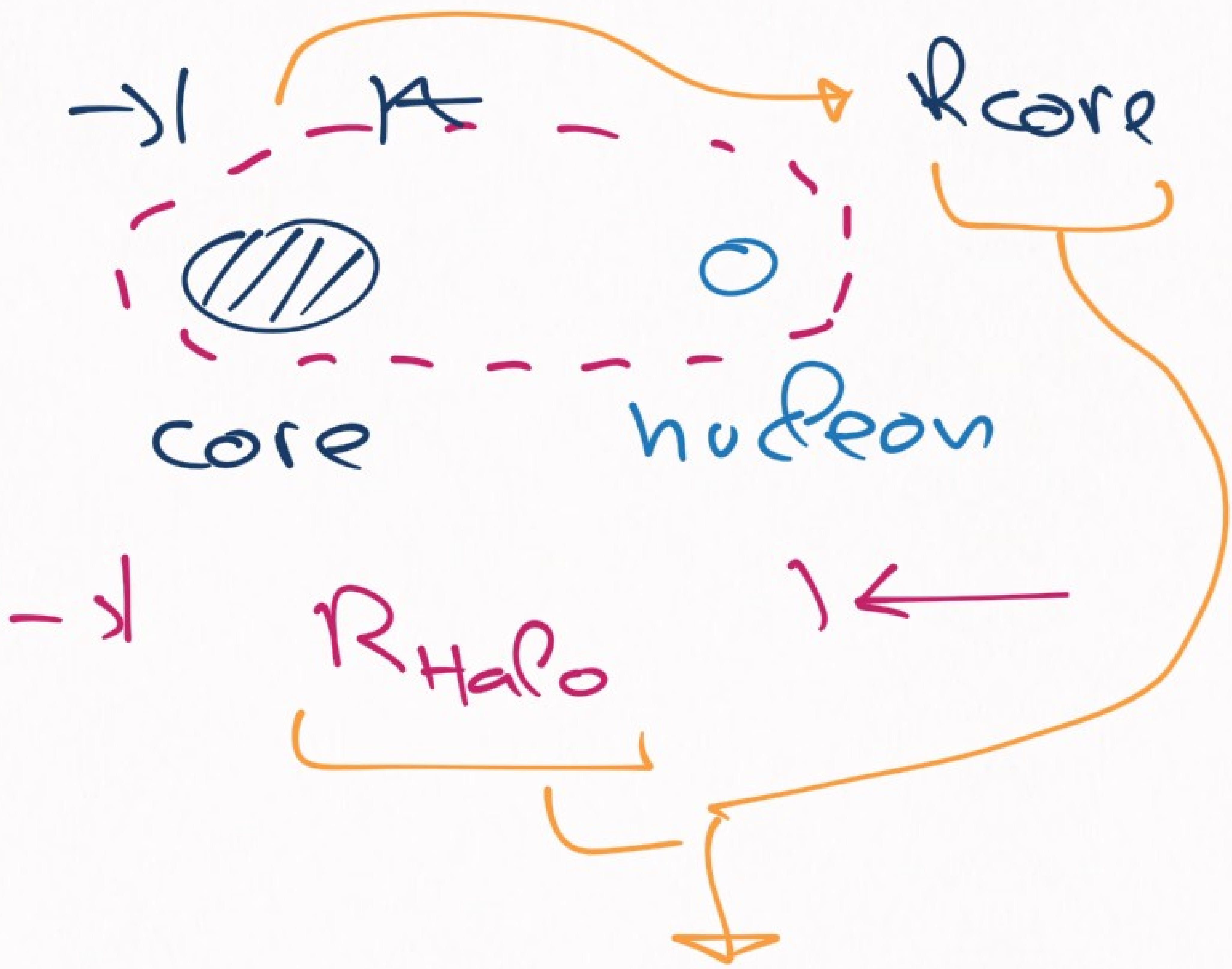
A few halo nuclei:



⇒ ∃ many examples

DESCRIPTION OF HALO NUCLEI

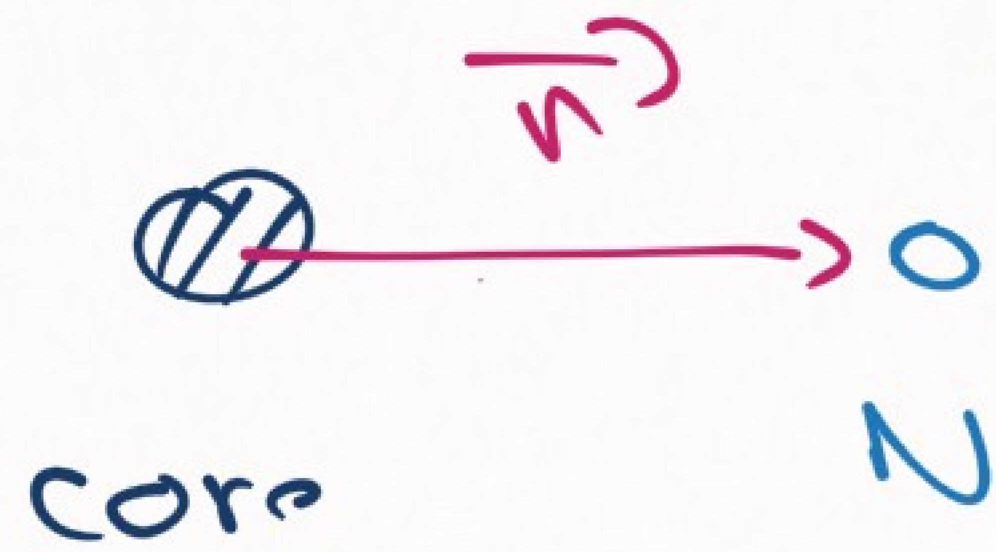
1) One nucleon halo



$$R_{Halo} \gg R_{core}$$

⇒ We can treat the core as a point particle

⇒ It's a two-body problem



$$V_{core-nucleon}(\vec{r}) = C\,\delta^{(3)}(\vec{r})$$

CONTACT-THEORY

(+ regularization)

$\Rightarrow$ Easy to describe

Examples $\rightarrow$

$^{8}B \simeq {}^{7}Be + p$ (p-wave)

$^{8}Li \simeq {}^{7}Li + n$ (p-wave)

$$\phi_{^{8}Li}(\vec{r}) \rightarrow A_p\left(1+\frac{1}{\gamma r}\right)e^{-\gamma r}$$

From this picture, we can easily explain a few reactions:

$$p + {}^7Be \rightarrow {}^8B + \gamma$$

(important for solar neutrino production)

$$n + {}^7Li \rightarrow {}^8Li + \gamma$$

(isospin mirror of previous reaction)

⇒ Calculations are really easy (but not explained in this course)

2) Two-nucleon halo

→ Very easy 3-body problem

Examples → ^6He, ^6Li, ^6Be

↓

^4He (core) + nn / np / pp

Description:

$^4He + n$ → a) no bound state

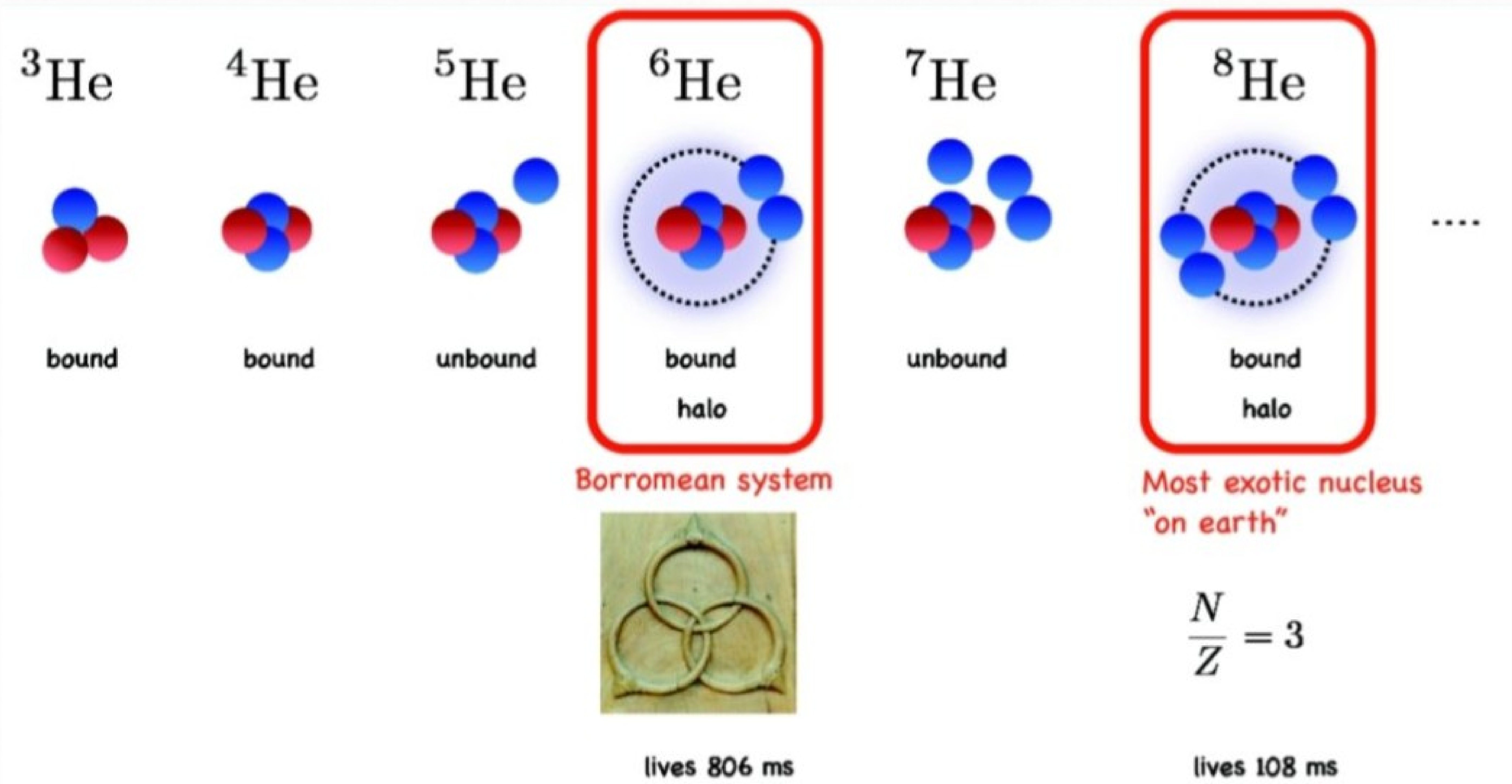
b) p-wave resonance

↙

V_{cn} to reproduce resonance

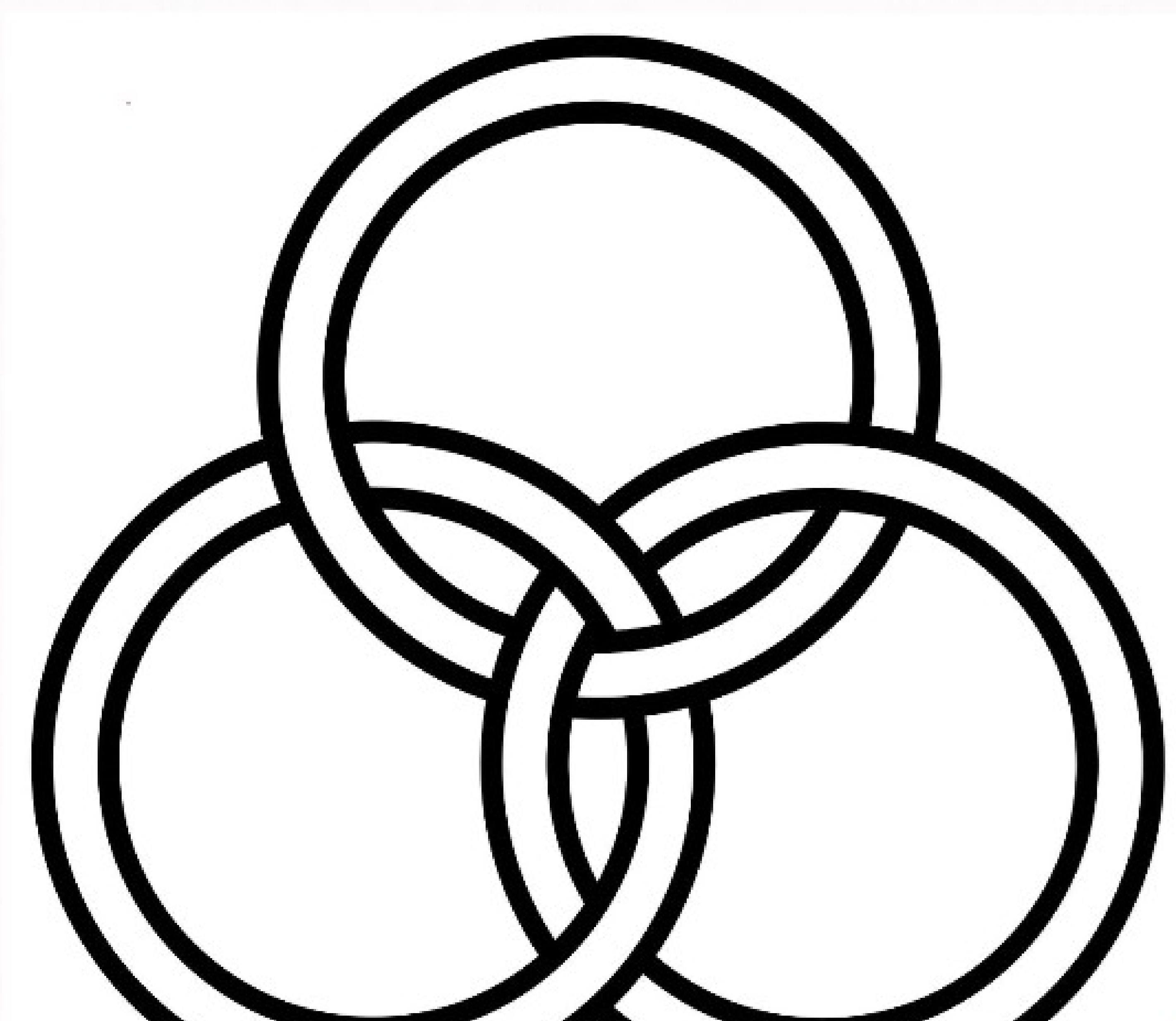
⇒ predict ^6He

2.a) Borromean nuclei



→ CORE + 1N UNBOUND

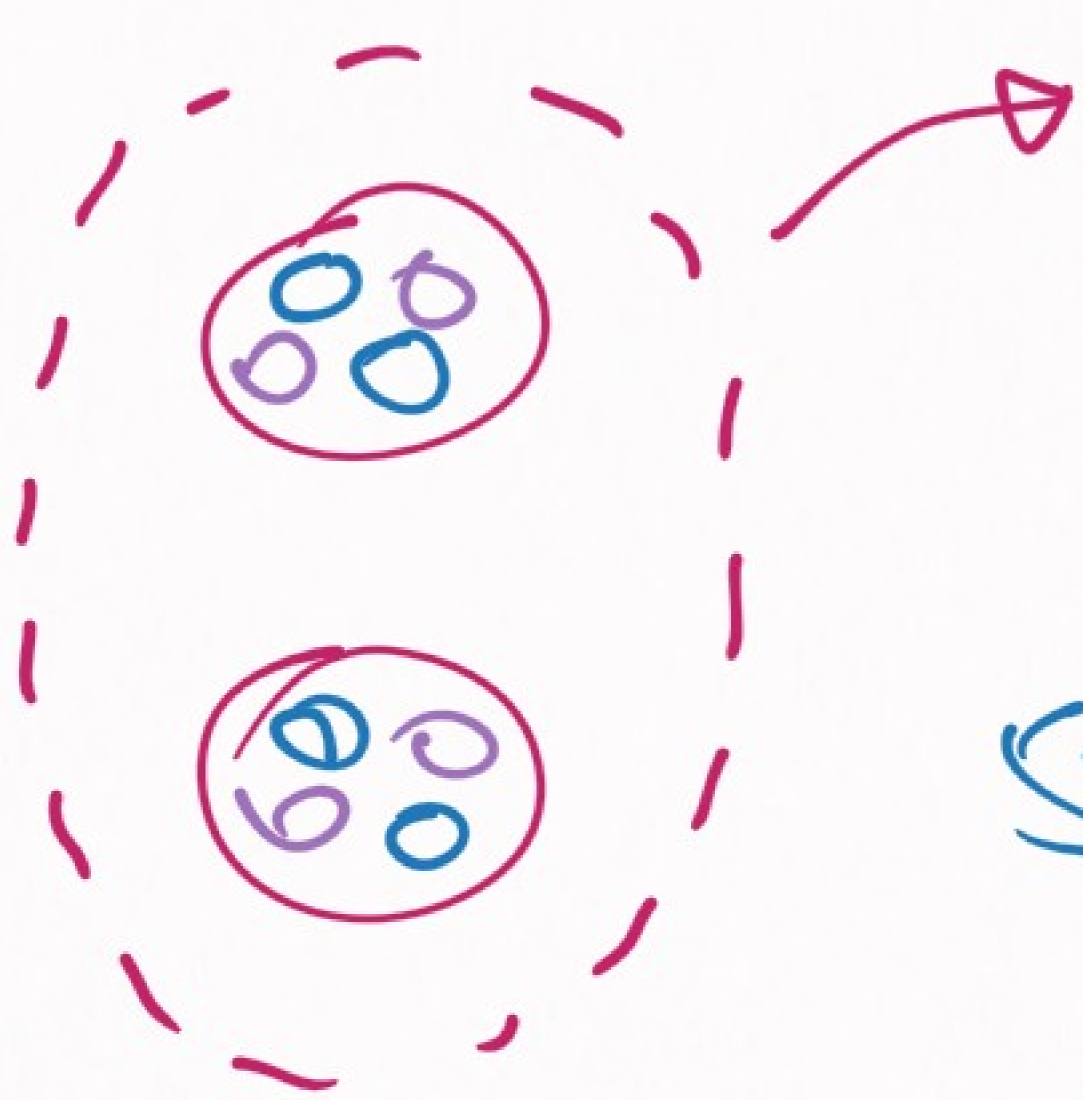
→ CORE + 2N BOUND



→ Comes from BORROMEAN RINGS (Remove one ring and they fall apart) (Coat of arms of Borromeo family)

Examples → ^{6}He, ^{11}Li, ^{11}Be

α - clusters

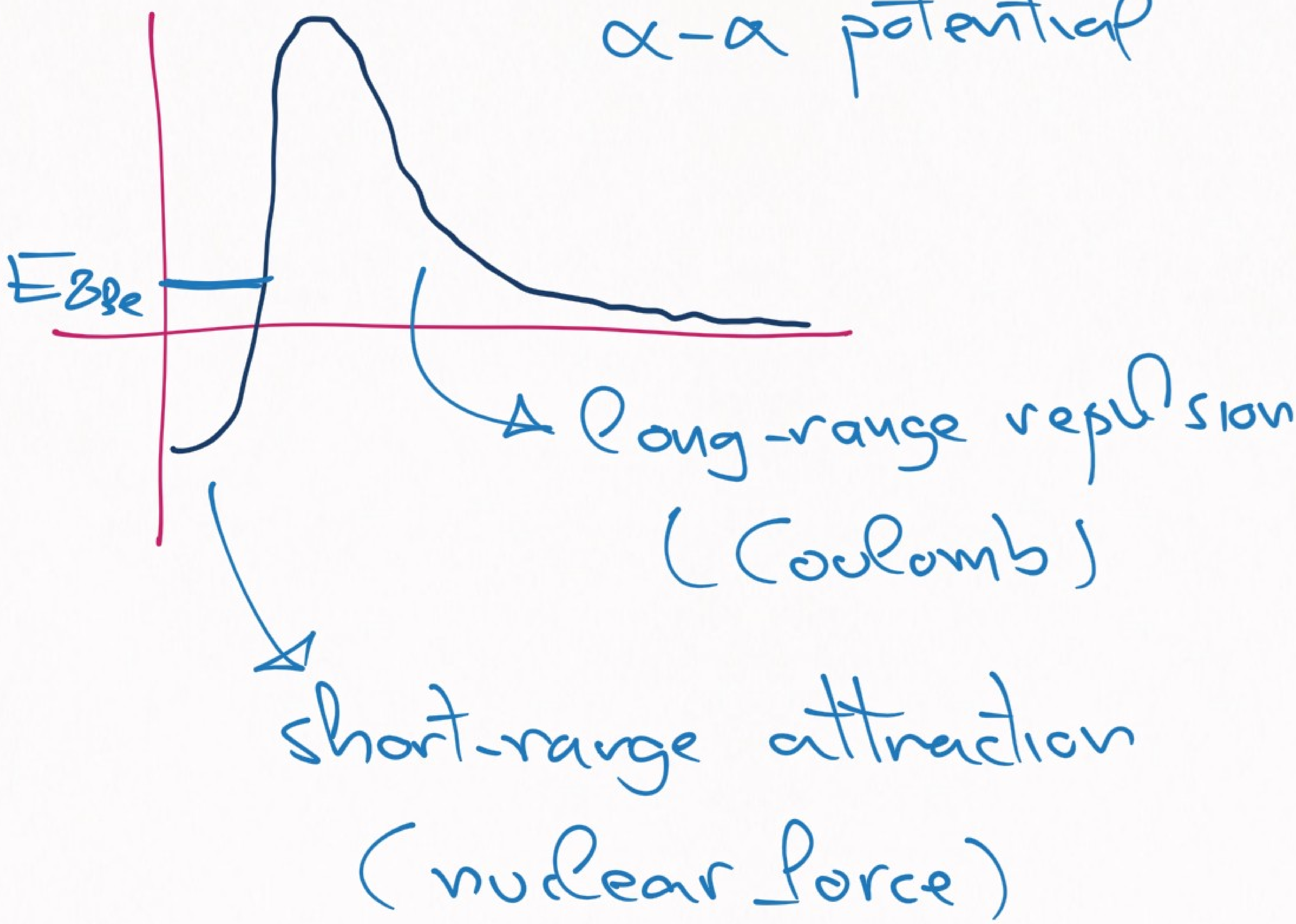


^{8}Be → Standard example

a) not bound

b) but a shallow S-wave resonance

α-α potential



$$E(^8Be) = E_R - \frac{i}{2}\Gamma_R$$

$E_R = 91.8$ keV

$\Gamma_R = 5.57$ eV

^8Be → **HOYLE STATE**

a) $\nexists$ A = 5, 8 stable nuclei

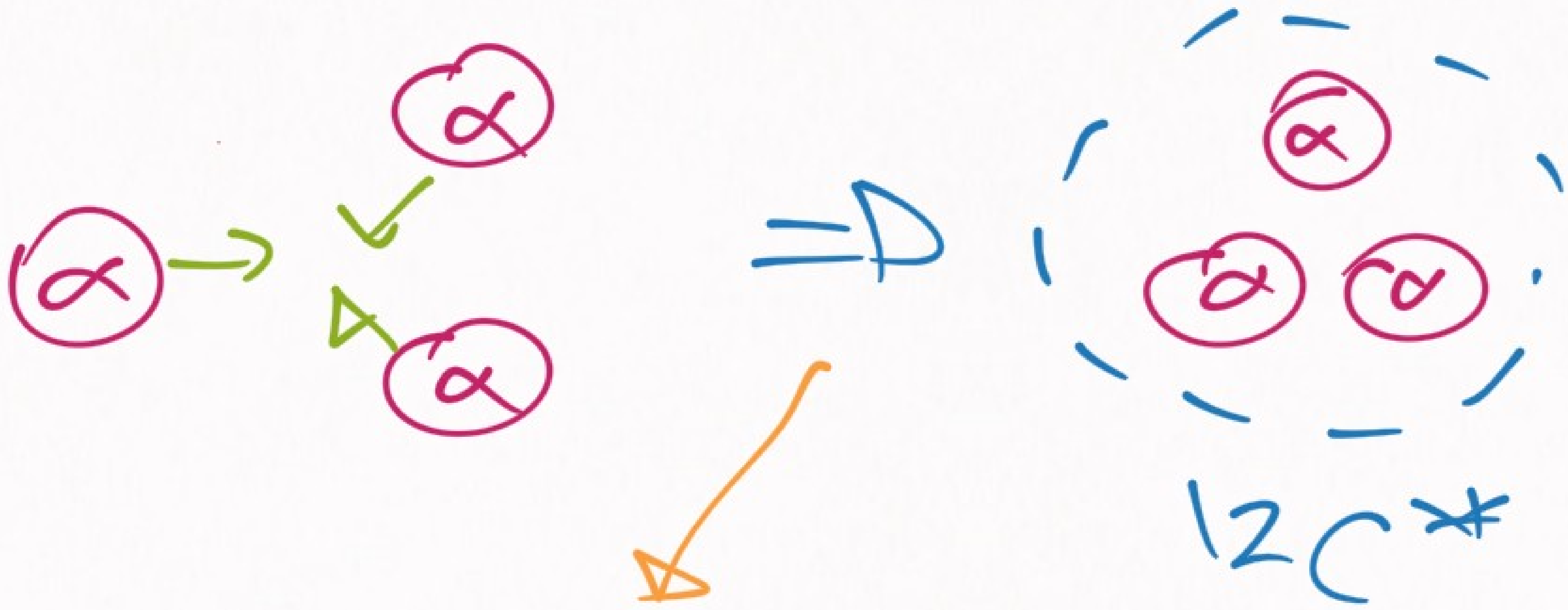
b) But $\exists$ a lot of ^{12}C in the universe

PROBLEM → [Producing ^{12}C inside stars requires some A = 8 intermediate state]

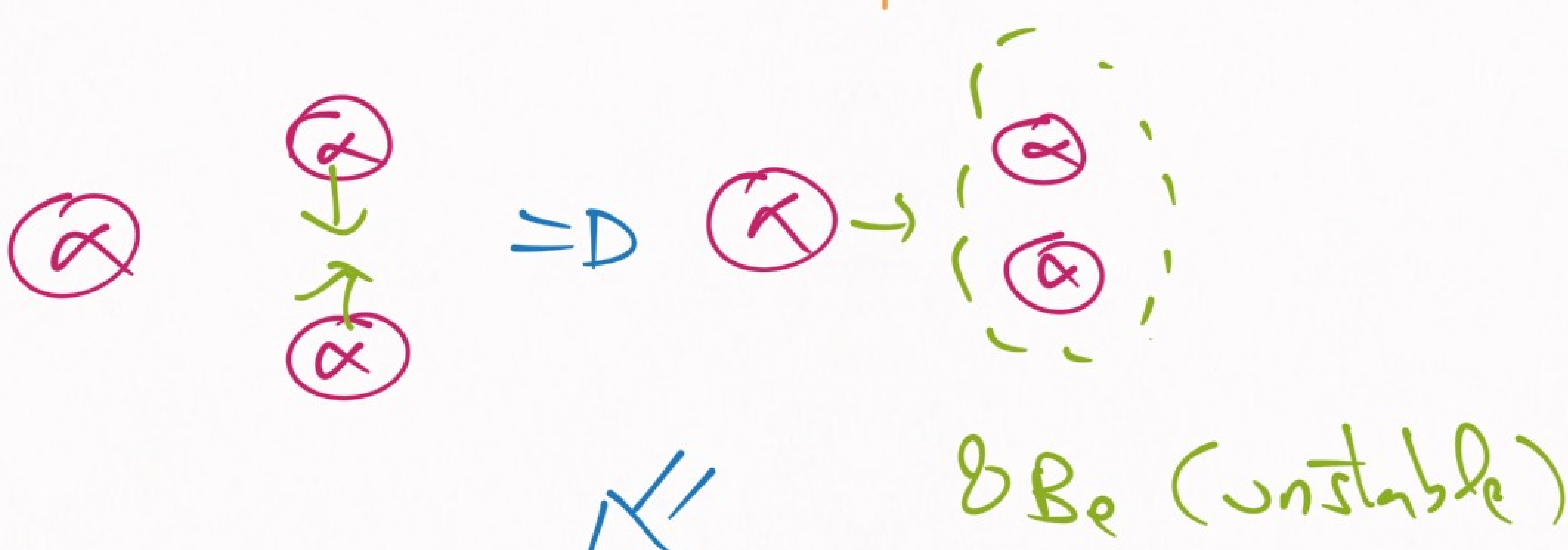
HOYLE → [Deduced the location of the necessary ^8Be resonance]

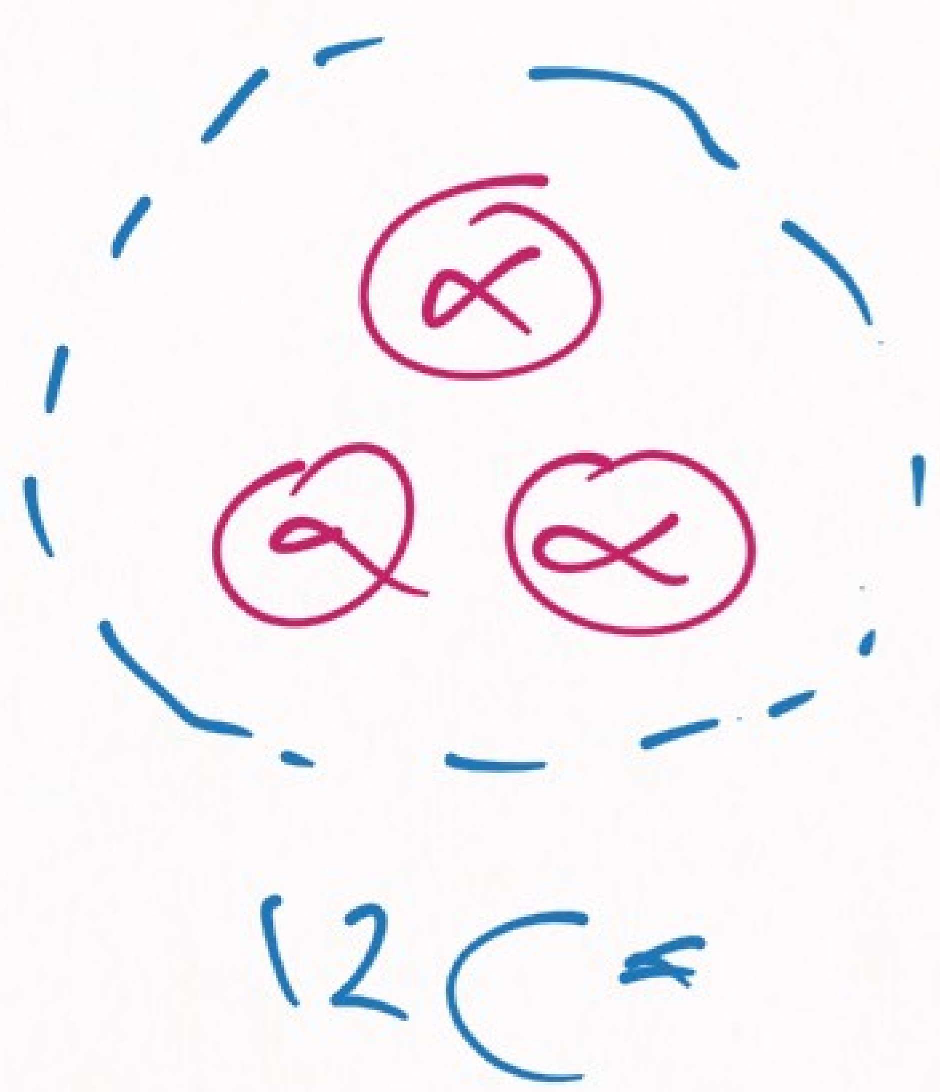
LATER FOUND IN EXPERIMENTS

HOYLE STATE → [TRIPLE-α PROCESS]



Extremely improbable





⇒ [Much more probable process]

^8Be $\qquad$ $^{12}C^*$ ($\to {}^{12}C$)

$\Downarrow$ $\qquad$ $\Downarrow$

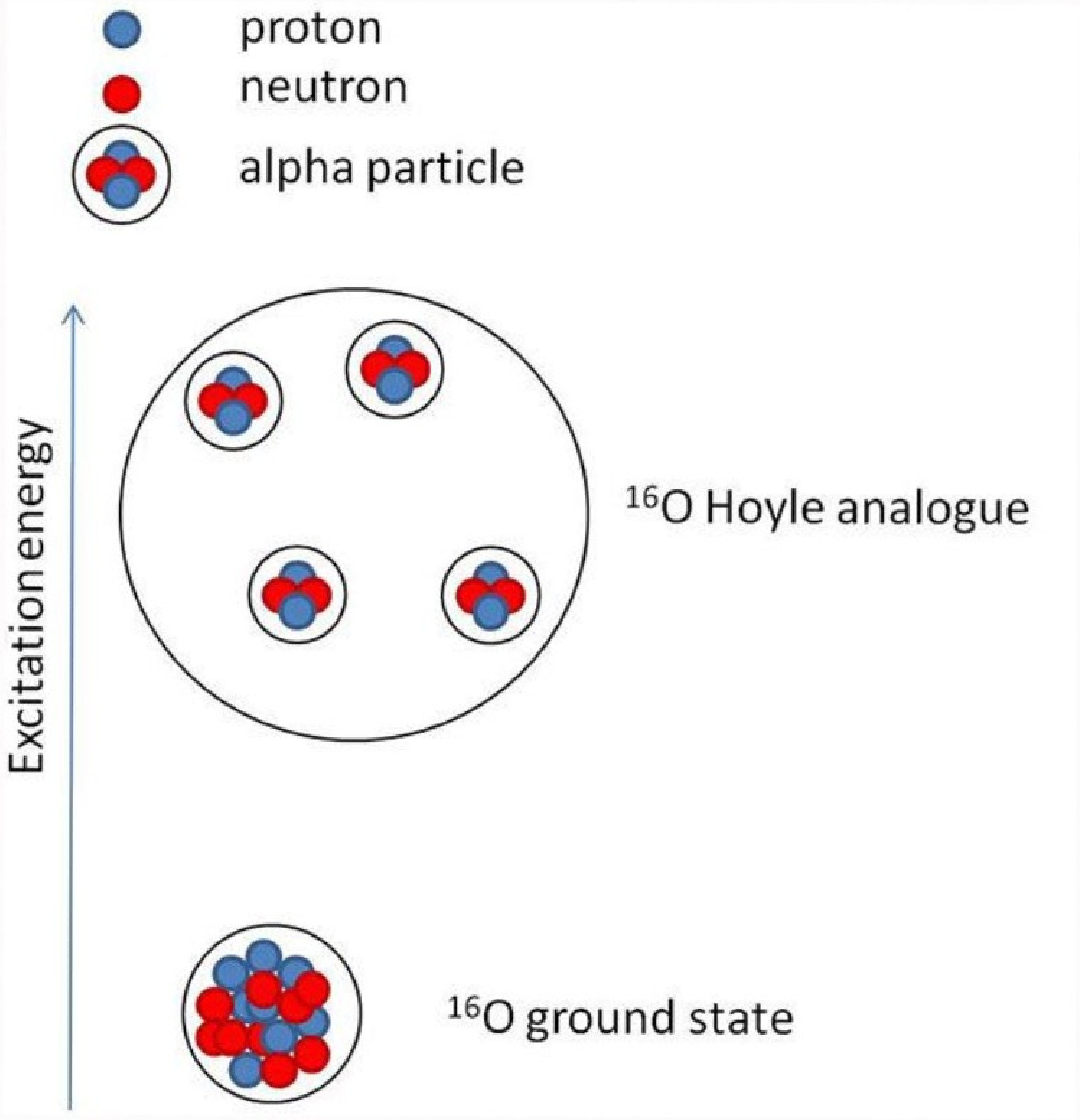
2α system $\qquad$ 3α system

$\downarrow$

A = 2,3 Schrödinger equation w/ short-range potential

↳ much easier than A = 8,12 system

This also happens in heavier nuclei (not only $^{12}C^*$)



$^{16}O^*$

↓

^{16}O

Works because α-particle is relatively compact

HYPERNUCLEI

$N \to qqq$ / $q = u, d$ $\quad I = 1/2$, $S = 1/2$

$|p\rangle = |udd\rangle$

$|n\rangle = |uud\rangle$

But $\exists$ many more baryons (and they can form bound states)

$\Lambda \to uds$ / $I = 0$, $S = 1/2$

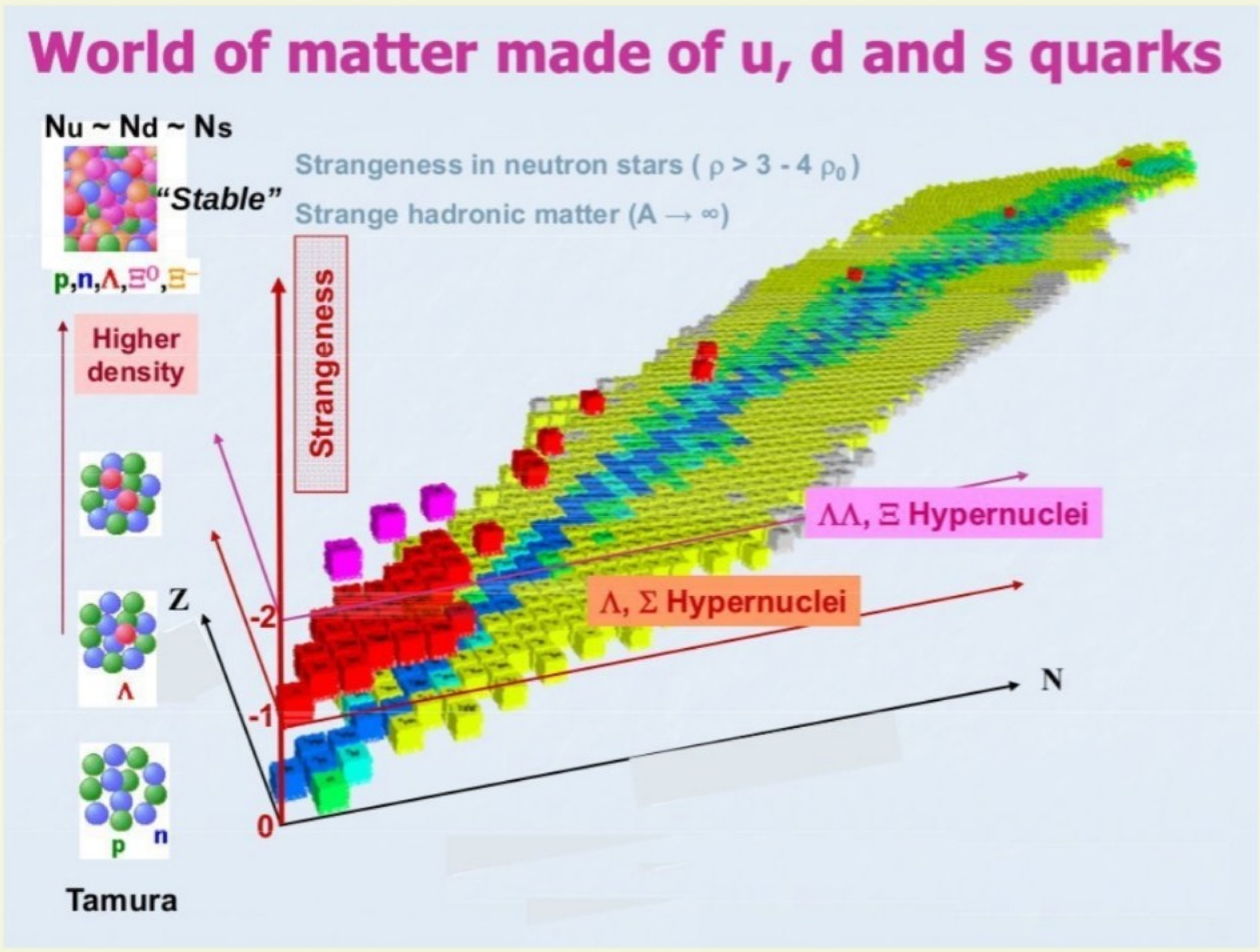
$\Sigma \to qqs$ / $q = u, d$ $\quad I = 1$, $S = 1/2$

$\Xi \to qss$ / $q = u, d$ $\quad I = 1/2$, $S = 1/2$

Λ, Σ, Ξ → They can also bind w/ nucleons

HYPERNUCLEUS

> 30 Λ-hypernuclei:



→ Basically an extension of the nuclear chart

Λ, Σ, Ξ → not nucleons

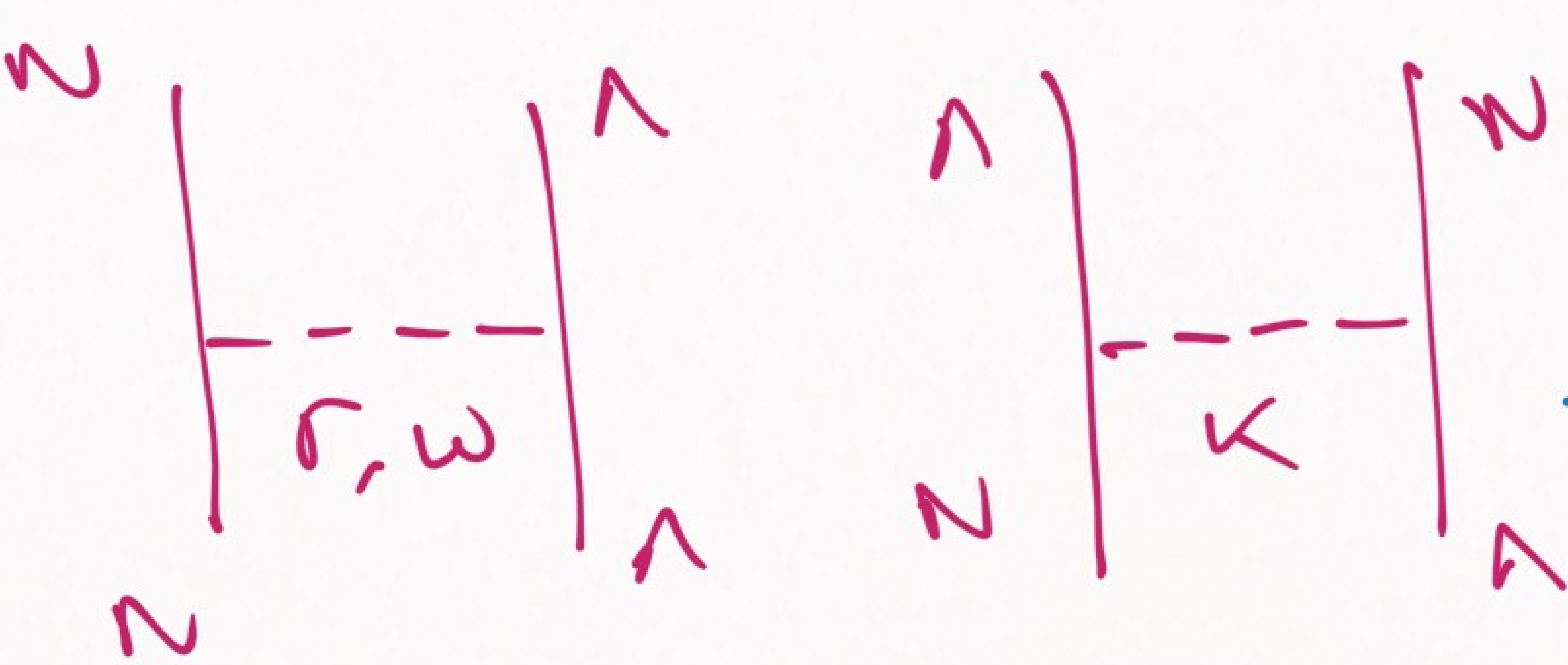
Pauli principle:

A-nucleons + 1Λ

⇒ Λ can be in S-wave

⇓

Binding becomes likely w/ many nucleons (even if ΛN interaction weak)

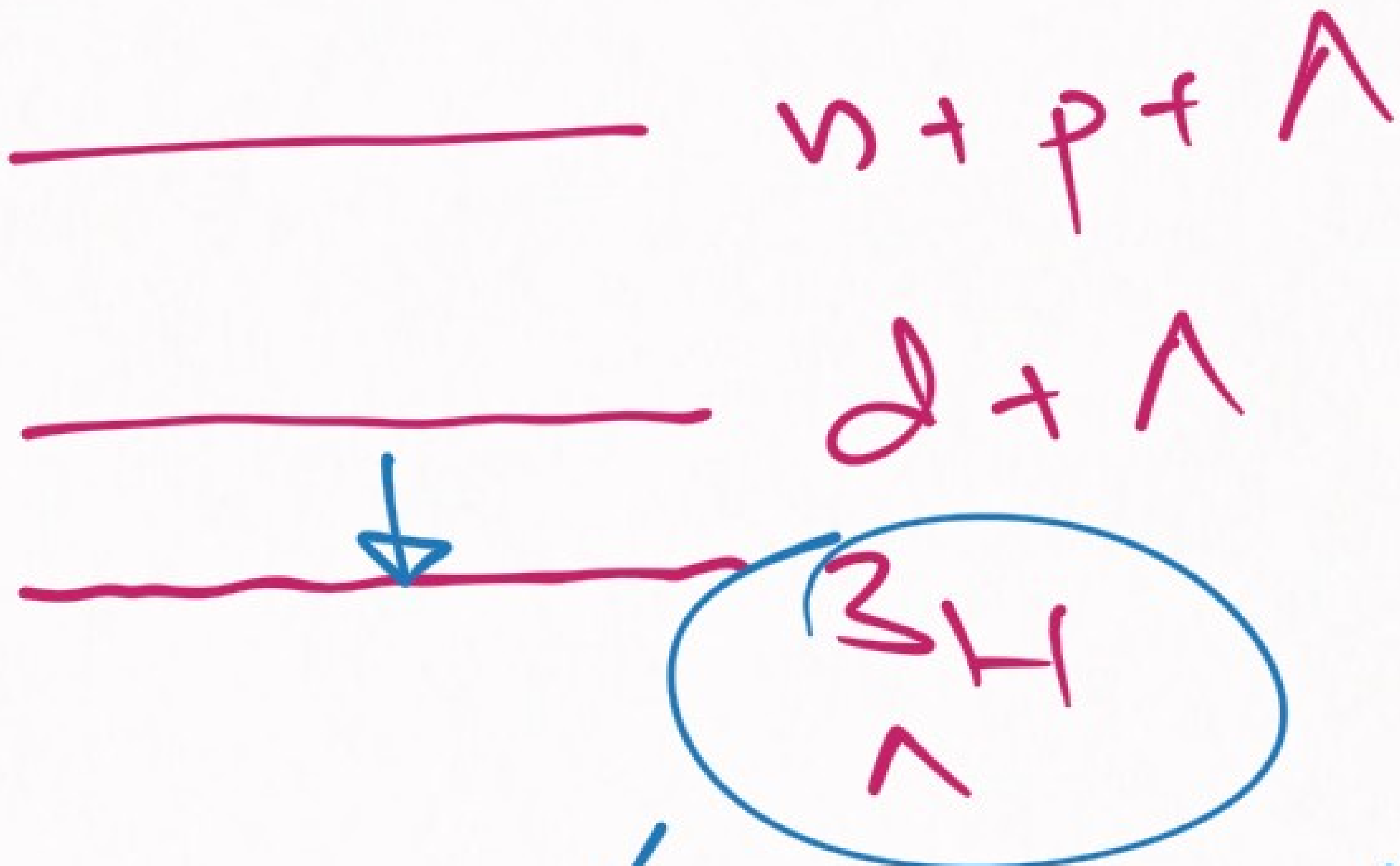


→ short-ranged

(no π, ρ)

Hypertriton → $^3_\Lambda H$ (npΛ)

Simplest hypernucleus



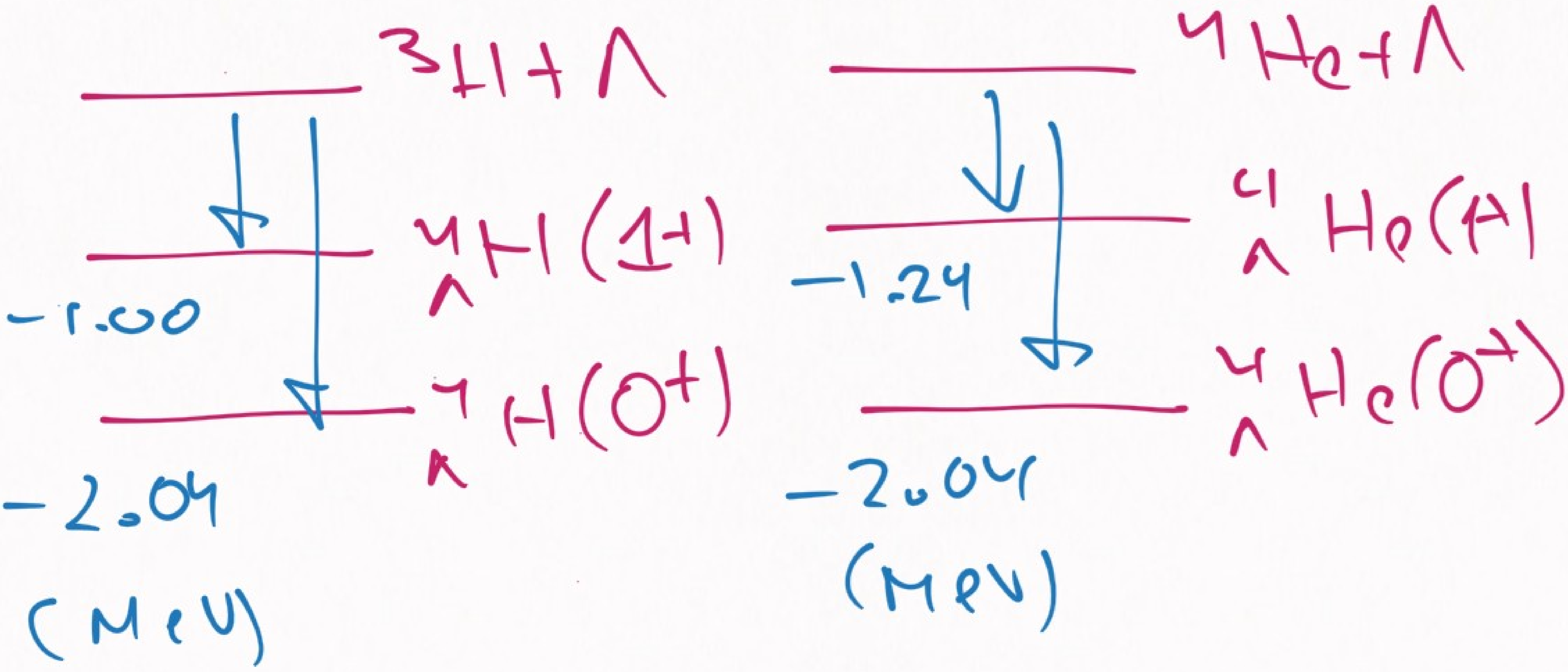
0.13 MeV below dΛ threshold

$$B(^3_\Lambda H) = 2.22 + 0.13 \simeq 2.35\ \text{MeV}$$
(± 0.05)

↓

Barely bound

$^{4}_{\Lambda}H$ & $^{4}_{\Lambda}He$



Again, slightly bound

—— o ——

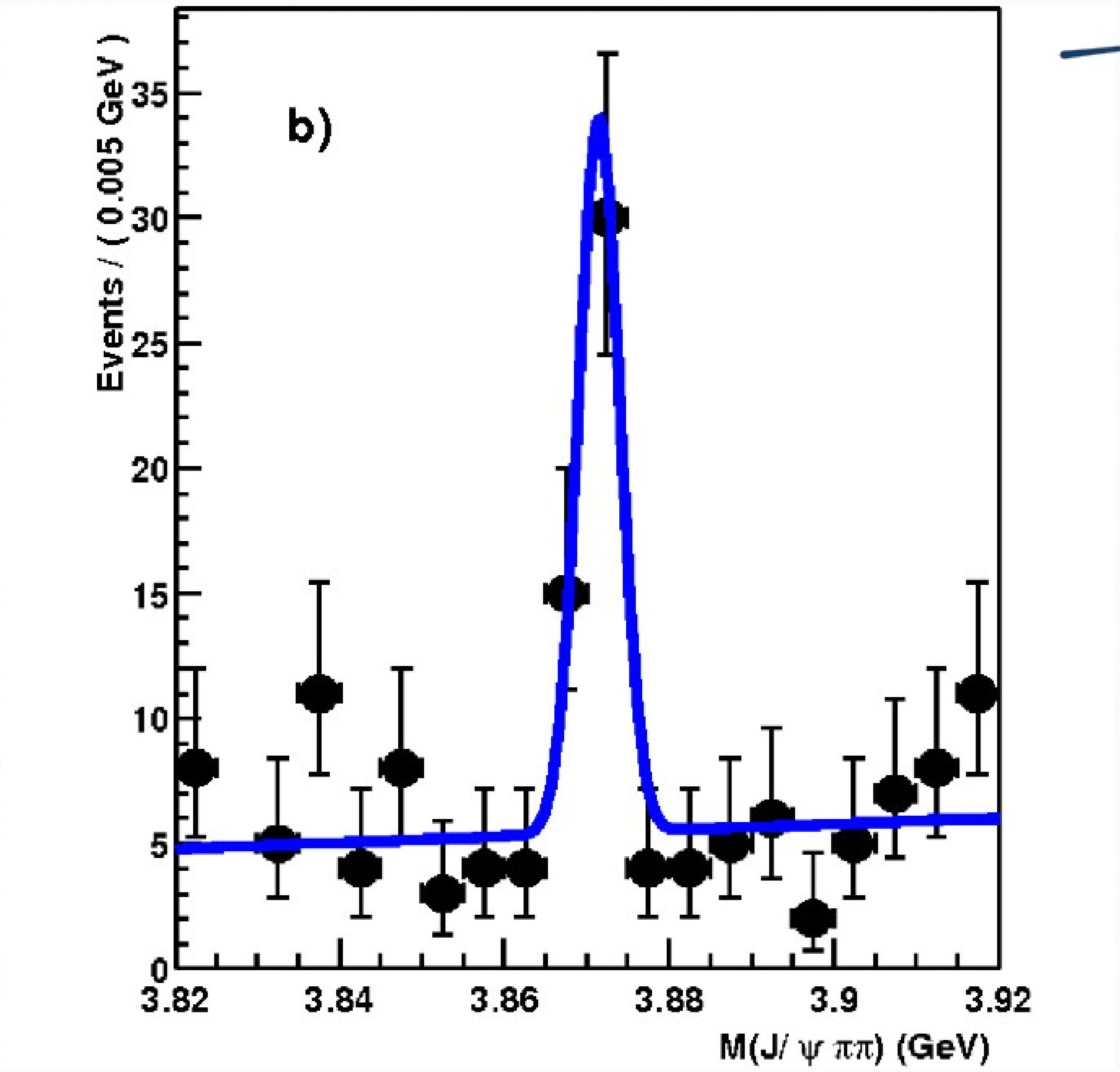
$^{4}_{\Sigma}He$ → Σ hypernucleus

$^{12}_{\Xi}B$ → Cascade (Ξ) hypernucleus

HADRONIC MOLECULES

→ Generic bound states of two or more hadrons

⇓



→ X(3872)

↓

$D^* \bar{D}$ bound state ?

↓

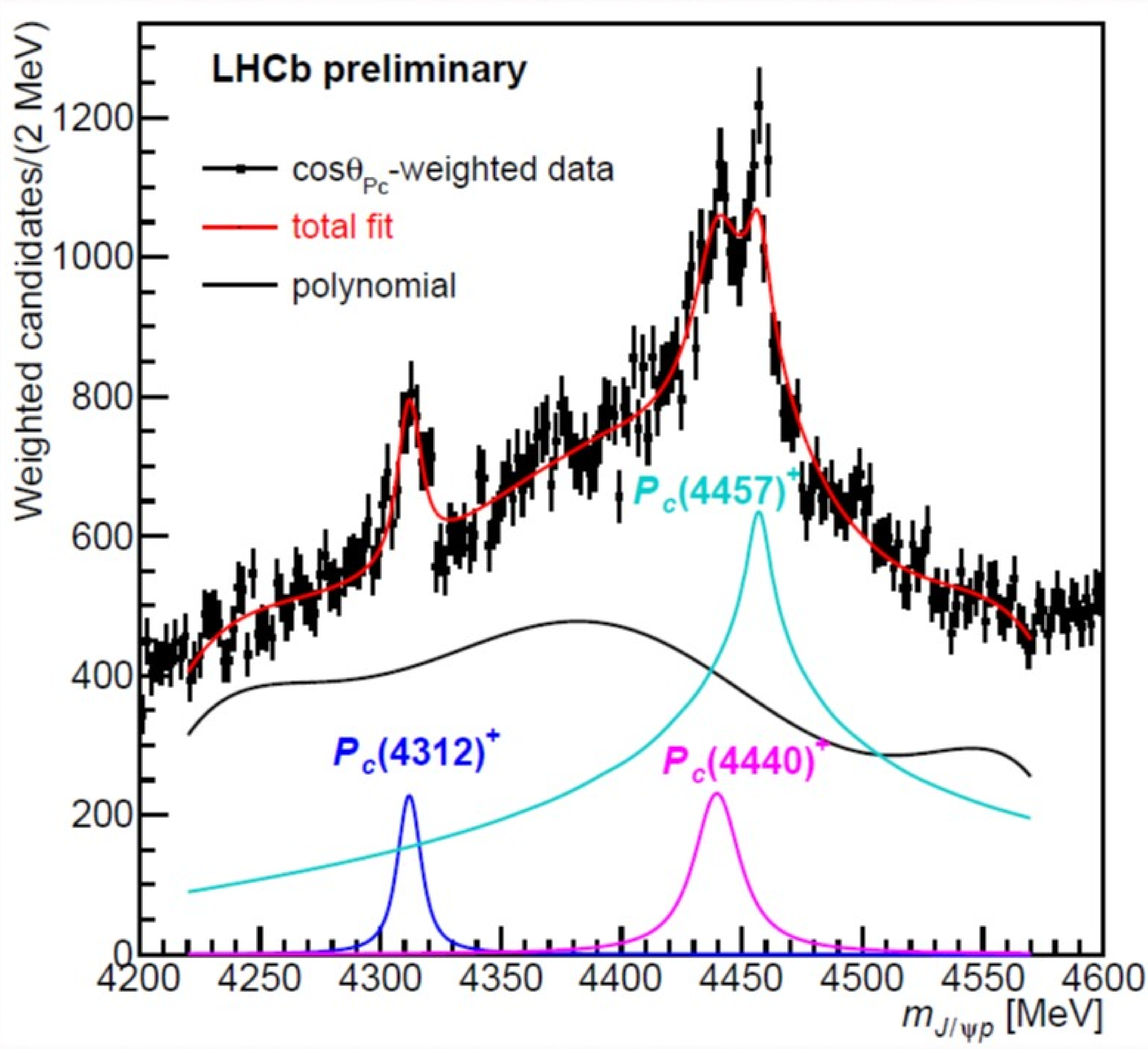
probably

⇓

D, D^* → $c\bar{q}$ / $q = u, d$

D → $J^P = 0^-$

D^* → $J^P = 1^-$



LHCb Pentaquarks

$P_c(4312) \longrightarrow \bar{D}\Sigma_c$, $J^P = \frac{1}{2}^-$

$P_c(4440)$
$P_c(4457)$ $\Big] \longrightarrow \bar{D}^*\Sigma_c$, $J^P = \frac{1}{2}, \frac{3}{2}^-$

(probably, but not sure)

$\Sigma_c \Rightarrow cqq$ / $q = u, d$ $J = 1$
$S = 1/2$

Hadronic molecules

- → Endless possibilities
- → Analogous (to an extent) to nuclear physics
- → Nice side-project for a nuclear theorist

With this, we reach the end!

→ Begin doing the exercises!
(don't wait till last moment)

→ Ask me if you don't know how to do them