L16

## Thermal Env. of Stars:

Max-Boltz Dist. ($v = |\vec{v}|$)

$$f(v)\,dv = \left(\frac{m_i}{2\pi kT}\right)^{3/2} 4\pi v^2 e^{-\frac{m_i v^2}{2kT}}\,dv$$

For Energy Prod. or Nucleosyn. need...

## Reaction Rates:

$$\text{Reactions}/_{m^3\text{-}s} = R(v) = \frac{N_{targ}}{m^3} \times \sigma(E) \times \left(\frac{\#\text{ incident part.}}{m^2\text{-}s}\right)$$

$n_i v$

↳ density ($N/m^3$)

$$= n_i n_T \sigma(E) v$$

&

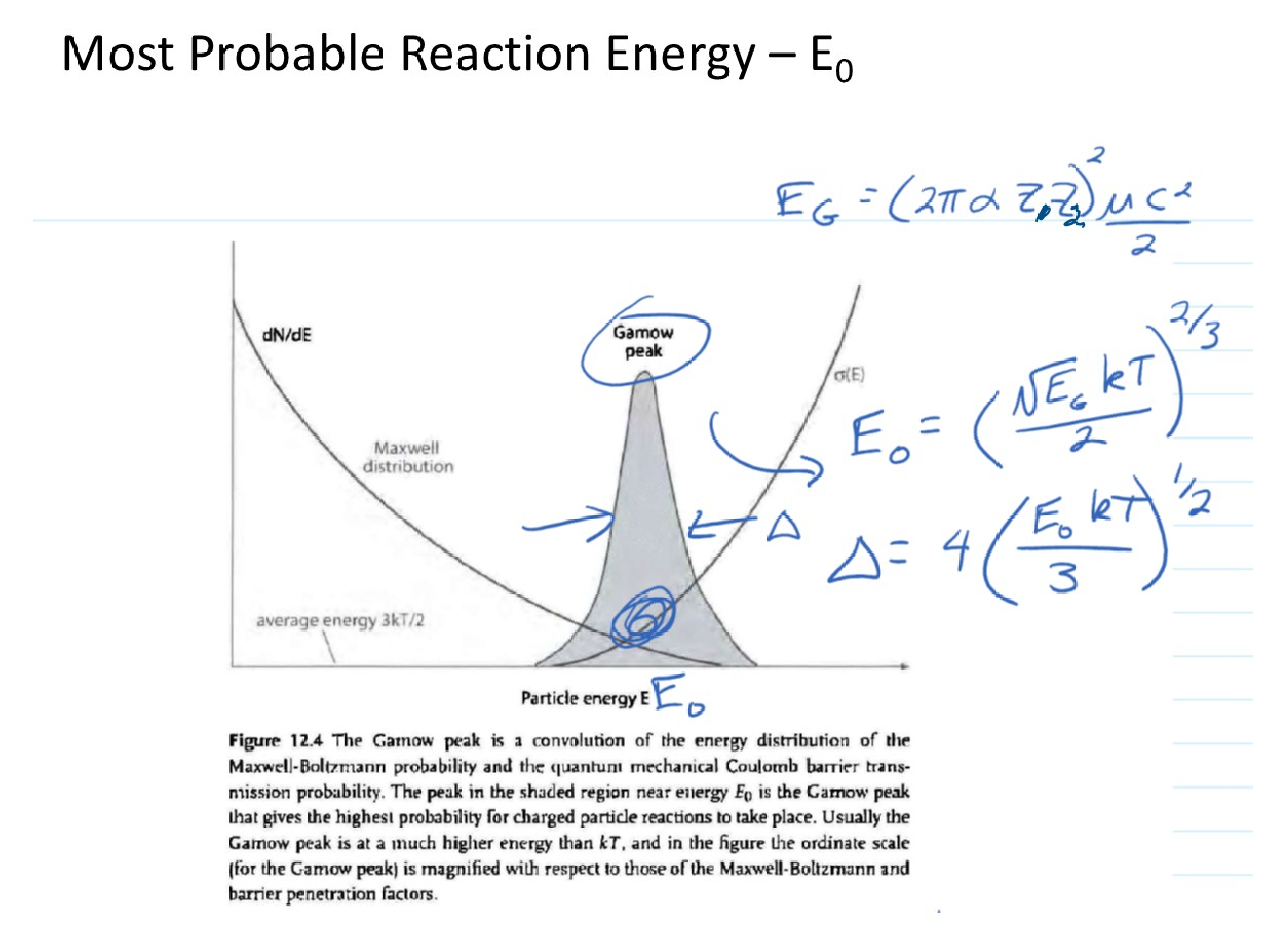
## Normalized Rate:

$$r = \frac{R}{n_T n_i} = \sigma(v) v$$

& average over MB: $\langle r \rangle = \langle \sigma(v) v \rangle_{\text{over } f(v)}$ ↗ most probable $E_0$

⇒ For non-res. charged particles get a peak in $\langle r \rangle$ due to balance of M.B. & Coulomb Penetrat. see PIC for definition of $E_0$ & $\Delta$

↳ Gives $\langle r \rangle$ vs. $T$



Most Probable Reaction Energy – $E_0$

$$E_G = (2\pi\alpha Z_1 Z_2)^2 \frac{\mu c^2}{2}$$

$$E_0 = \left(\frac{\sqrt{E_G}\, kT}{2}\right)^{2/3}$$

$$\Delta = 4\left(\frac{E_0\, kT}{3}\right)^{1/2}$$

**Figure 12.4** The Gamow peak is a convolution of the energy distribution of the Maxwell-Boltzmann probability and the quantum mechanical Coulomb barrier transmission probability. The peak in the shaded region near energy $E_0$ is the Gamow peak that gives the highest probability for charged particle reactions to take place. Usually the Gamow peak is at a much higher energy than $kT$, and in the figure the ordinate scale (for the Gamow peak) is magnified with respect to those of the Maxwell-Boltzmann and barrier penetration factors.

E.g. for H burning:

$T_6 = 15$, $kT = 1.3$ keV

$E_0 = 19$ keV  $\Delta = 12$ keV

for He burning:

$T_6 = 200$, $kT = 20$ keV

$E_0 = 300$ keV, $\Delta = 170$ keV

& can calc. $\langle r \rangle$ using $S(E_0)$

⇒ For neutron capture (non-res)

$\sigma \propto \frac{1}{v}$ & $\langle \sigma(v) v \rangle \neq f(E)$

then many $\langle r \rangle_{ij}$ give reaction Network to calc Energy/time or $\frac{N_i(t)}{\sum N_i}$ = abundances

## Reaction Network Examples:

Solar H-burning: "pp chain" ($4p \to {}^4He$)

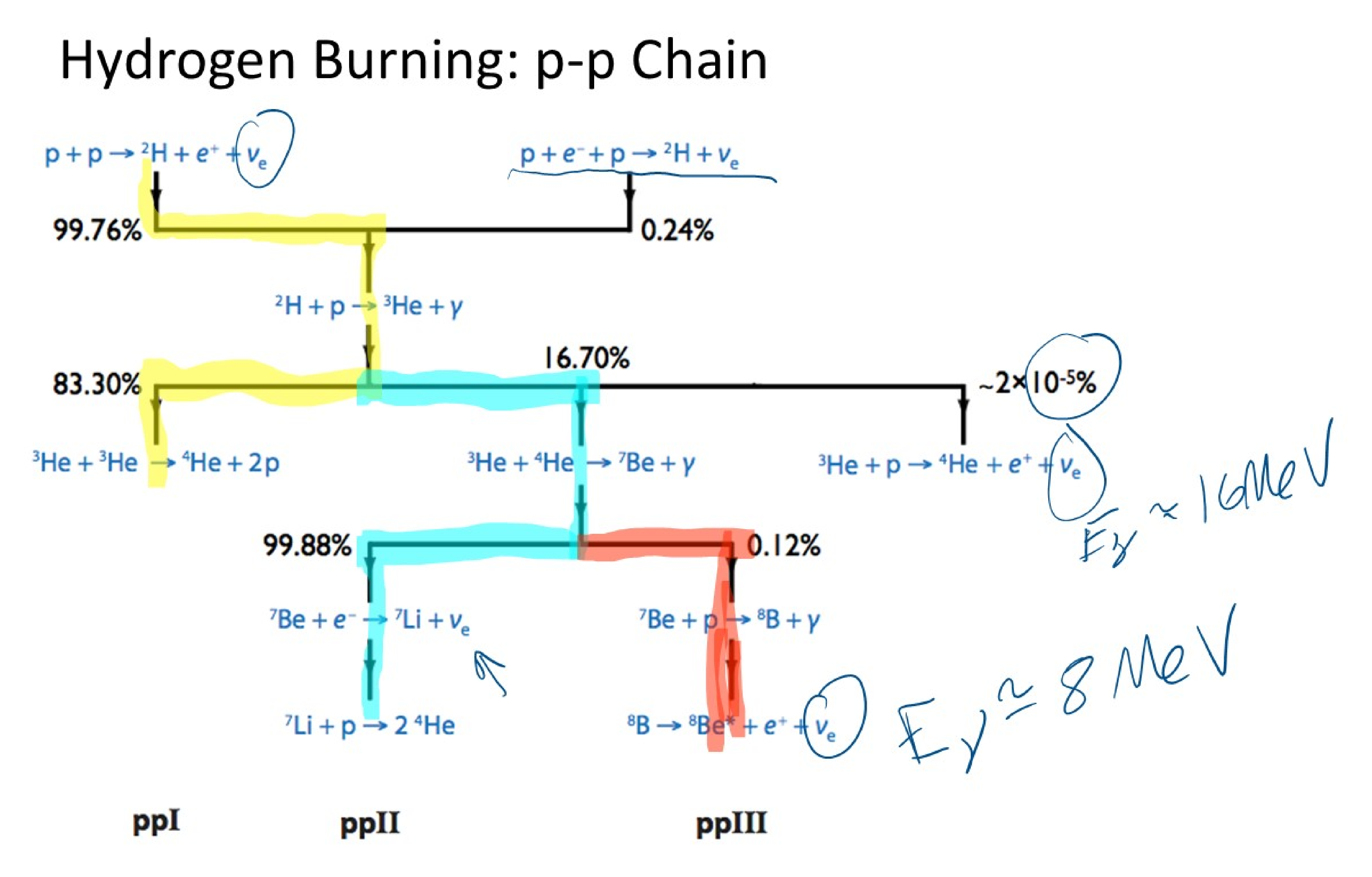
e.g. via $p+p \to d+e^+ + \nu_e$ (weak) ($\ll$ pb)

$p+d \to {}^3He + \gamma$ (EM) ($<$ nb)

${}^3He + {}^3He \to {}^4He + 2p$ (strong) ($<$ mb)

$+\ 26.2\ \mathrm{MeV/cycle}$

see PIC



Hydrogen Burning: p-p Chain

At slighlly higer temp. can do $4p \to {}^4He$ w $^{12}C$, $^{14}N$ as catalyst

see CNO PIC...

# Hydrogen Burning: CNO Chain

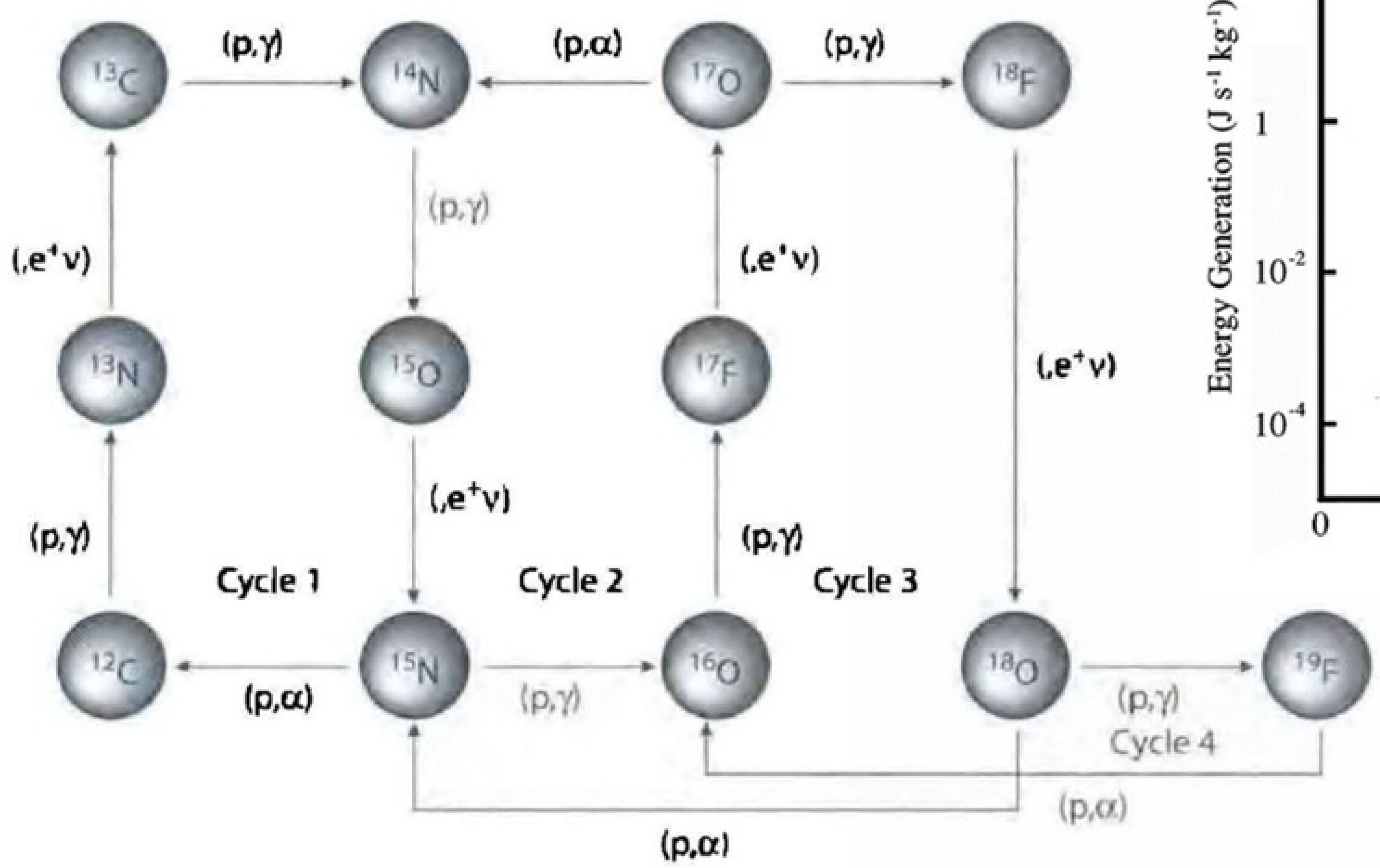
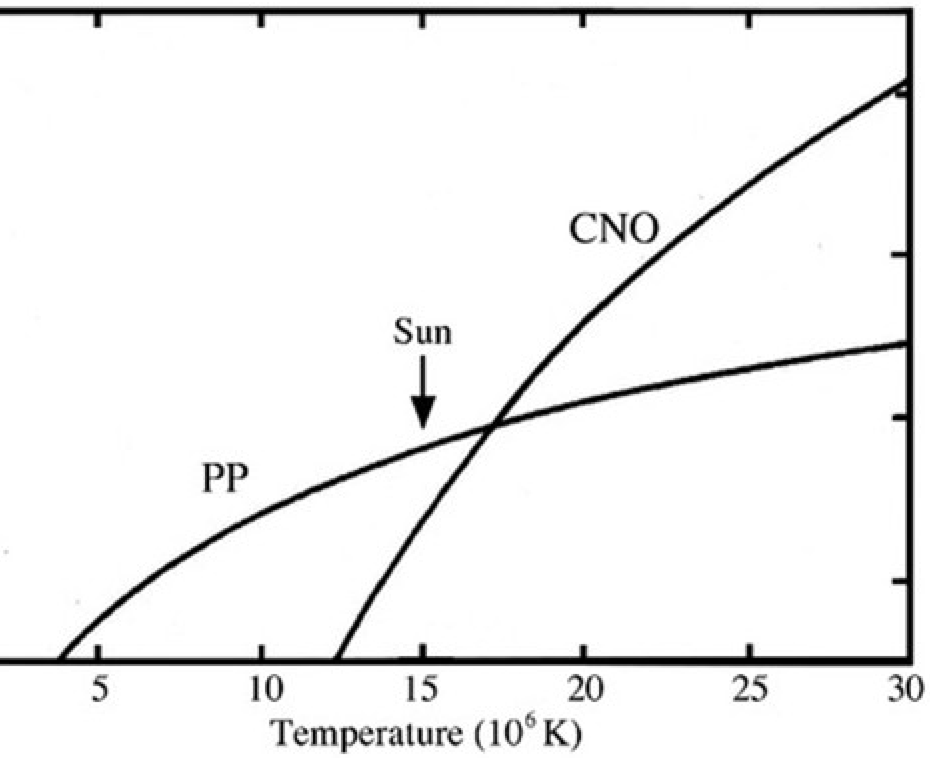


**Figure 12.8** The various CNO cycles. The left part is the CN cycle where only C and N serve as catalysis for the conversion of four protons into $^4$He. Here the slowest fusion reaction is the (p,$\gamma$) reaction on $^{14}$N, whereas the slower $\beta$-decay has a half-life of 9.97m. In the CNO cycle 2 (middle), there is leakage from the CN cycle to the ON cycle through the branching at $^{15}$N. The flow is returned to the CN cycle (which cycles 1000 times for each ON cycle) through $^{17}O(p,\alpha)^{14}$N. The right part represents additional cycles linking into the CNO cycle through the $^{17}O(p,\gamma)^{18}$F reaction [courtesy of Frank Timmes].



## Helium Burning Network:

Complication: No stable isotopes of any element w/ $A = N + Z = \underline{\underline{8}}$ or $A = \underline{\underline{5}}$

How to make $^{12}C$ ?

Consider $^{8}Be$ gnd state $\Gamma \simeq 5.6\,eV$

$\tau \simeq 10^{-16}\,s$

@ $T_6 = 100$, $^4He + ^4He$ transit time $\approx 10^{-19}\,s$

Look @ Energy level ...

Does $^8Be$ live long enough to get $^4He + ^8Be \rightarrow {}^{12}C + \gamma$ ??

@ $T_6 = 200$

$E_0 = 240\,keV$ w/ $\Delta = 170\,keV$

Can we produce enough $^{12}C$ to make us ??

⇔ Fred Hoyle (1953):

Non-resonant "triple-alpha" process could not make enough $^{12}C$ "...and all life." 1960.

Only <u>resonant</u> reaction could work ∴

$E_0 \pm \frac{\Gamma}{2}$

⇒ must be a excited state in $^{12}C$

"just right"

not too high E

" " low E

" " hi spin

not parity = (−)

$^8Be + {}^4He$

7.3 MeV

?? not $1^-, 2^+, \ldots$

4.44 MeV ——— $2^+$

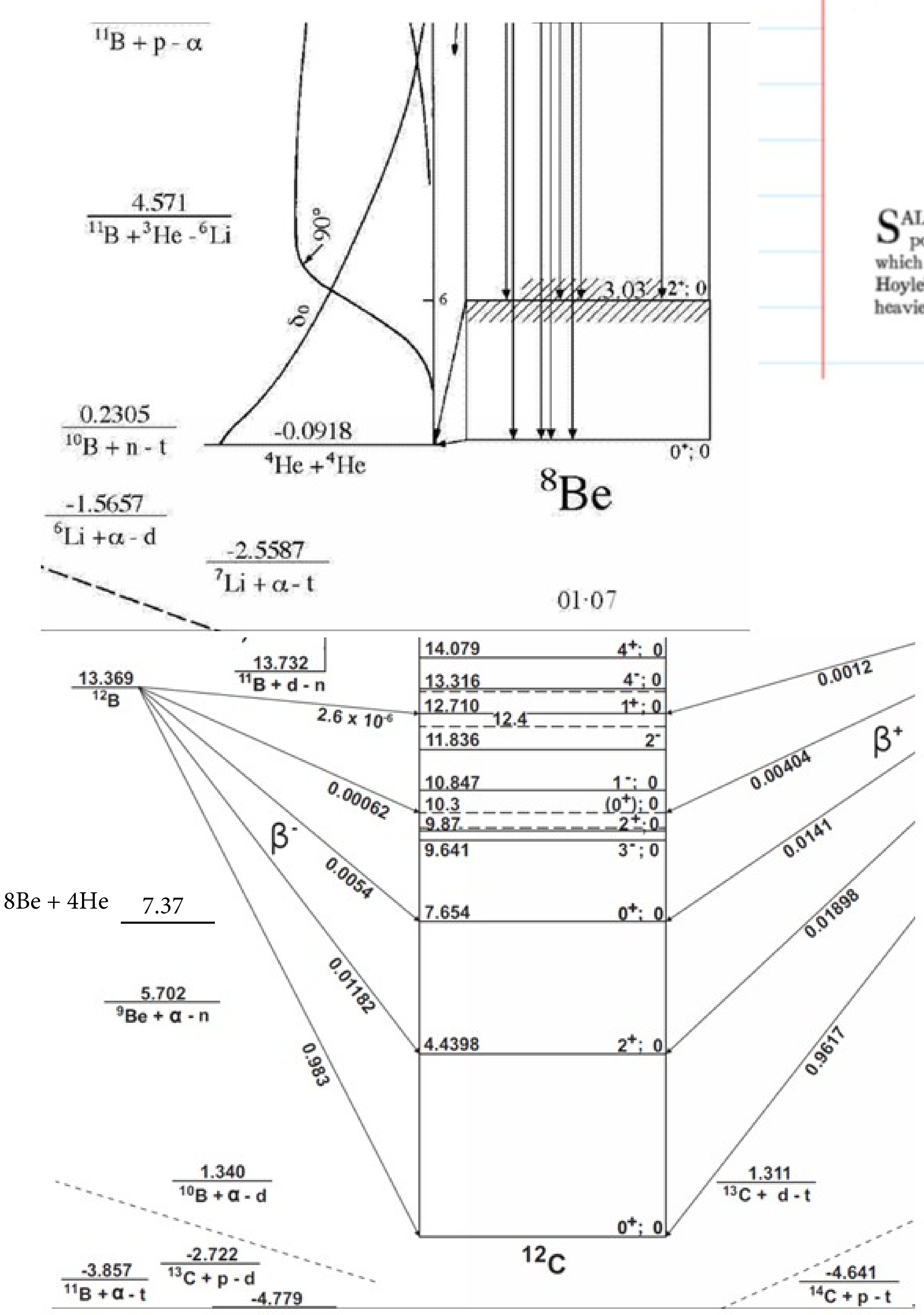
0 ——— $0^+$

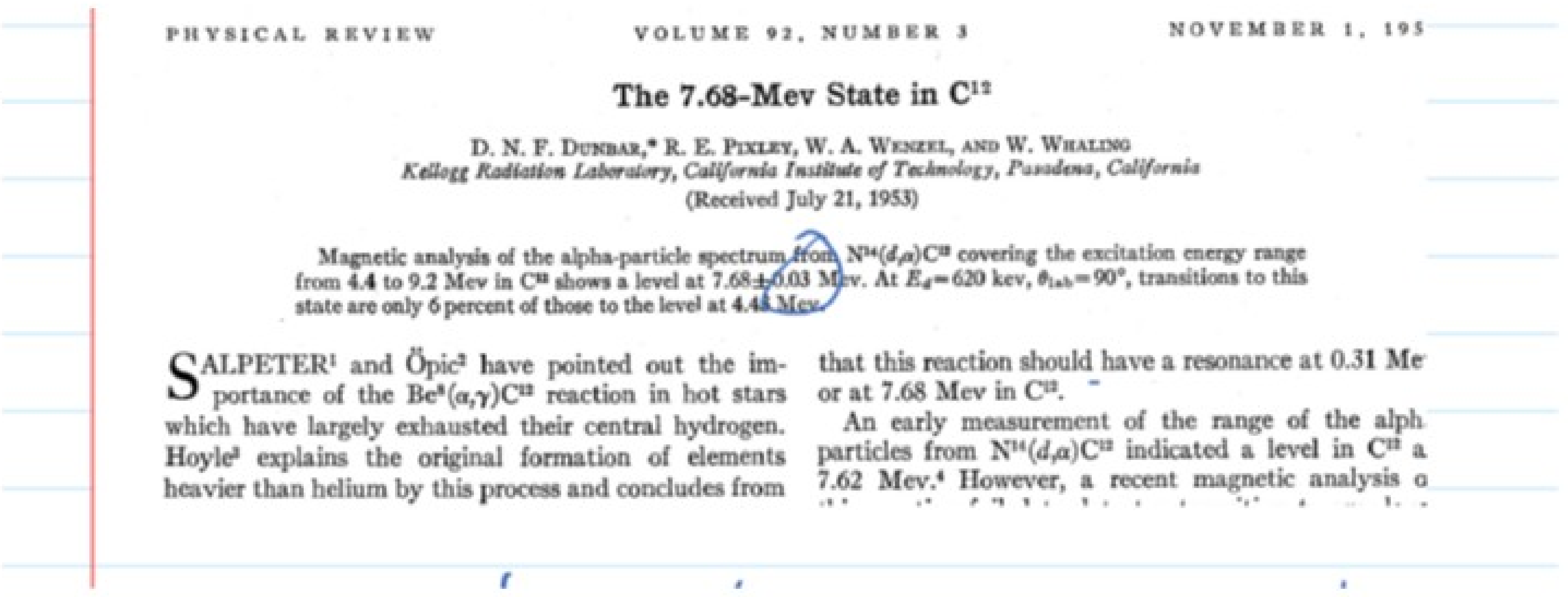
$^{12}C$

Kellogg Lab Exp found it!

@ E = 7.68 MeV

# Triple-α Process





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## The 7.68-Mev State in $C^{12}$

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(Received July 21, 1953)

Magnetic analysis of the alpha-particle spectrum from $N^{14}(d,\alpha)C^{12}$ covering the excitation energy range from 4.4 to 9.2 Mev in $C^{12}$ shows a level at 7.68±0.03 Mev. At $E_d$=620 kev, $\theta_{lab}$=90°, transitions to this state are only 6 percent of those to the level at 4.43 Mev.

SALPETER[1] and Öpic[2] have pointed out the importance of the $Be^8(\alpha,\gamma)C^{12}$ reaction in hot stars which have largely exhausted their central hydrogen. Hoyle[3] explains the original formation of elements heavier than helium by this process and concludes from that this reaction should have a resonance at 0.31 Me or at 7.68 Mev in $C^{12}$.

An early measurement of the range of the alph particles from $N^{14}(d,\alpha)C^{12}$ indicated a level in $C^{12}$ a 7.62 Mev.[4] However, a recent magnetic analysis o

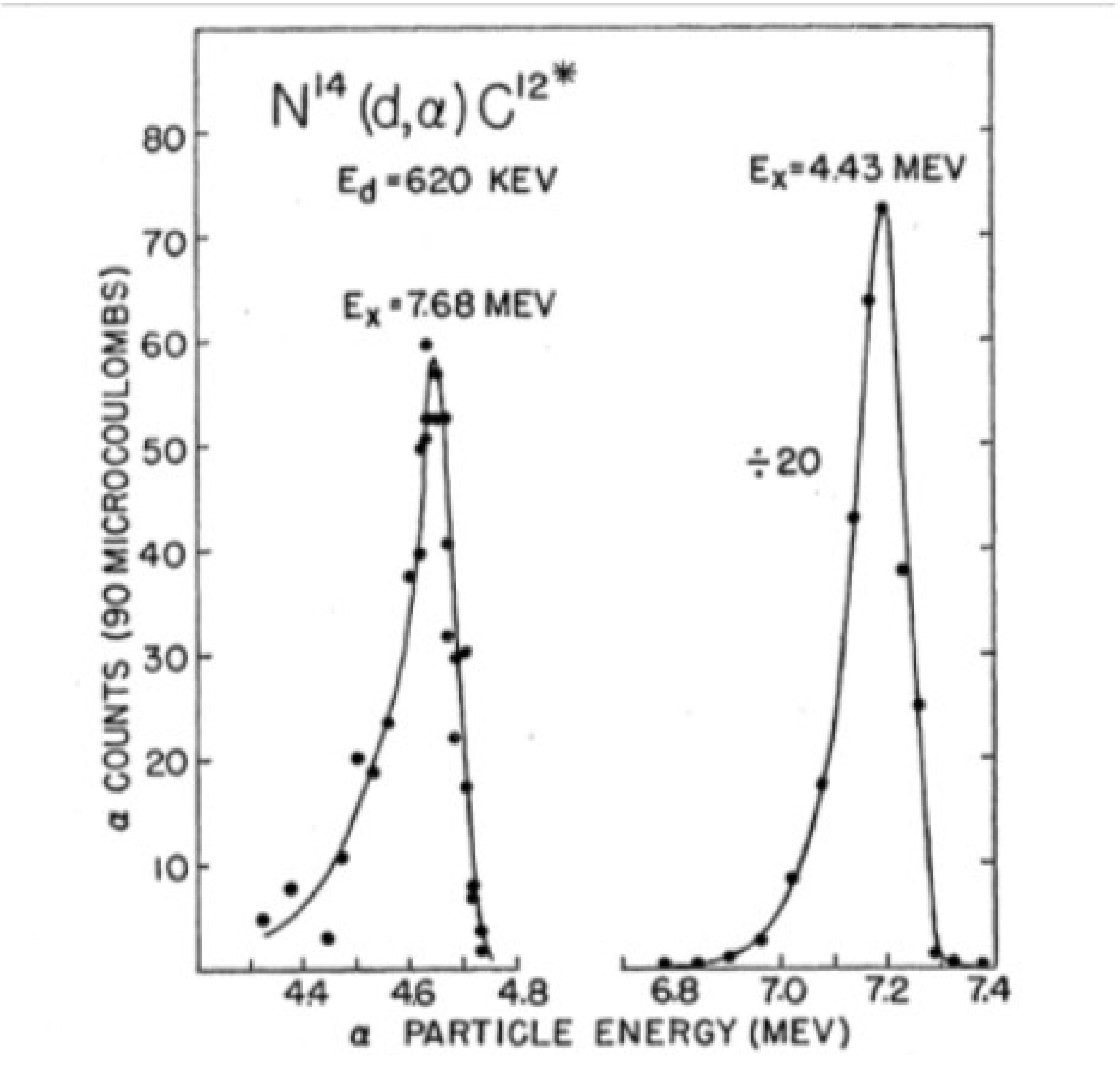


FIG. 1. Alpha spectrum from $N^{14}(d,\alpha)C^{12}$ obtained with a thick $NH_3$ target. No other groups were observed in the range $E_\alpha$=3.7 −7.4 Mev of magnitude 1 percent of the group to the 4.43-Mev state. The spectrometer was set at $\theta_{lab}$=90°.

7.65 MeV state = "... secret of life"

But what happens next?

⟺ $^{12}C + \alpha \rightarrow {}^{16}O + \gamma$

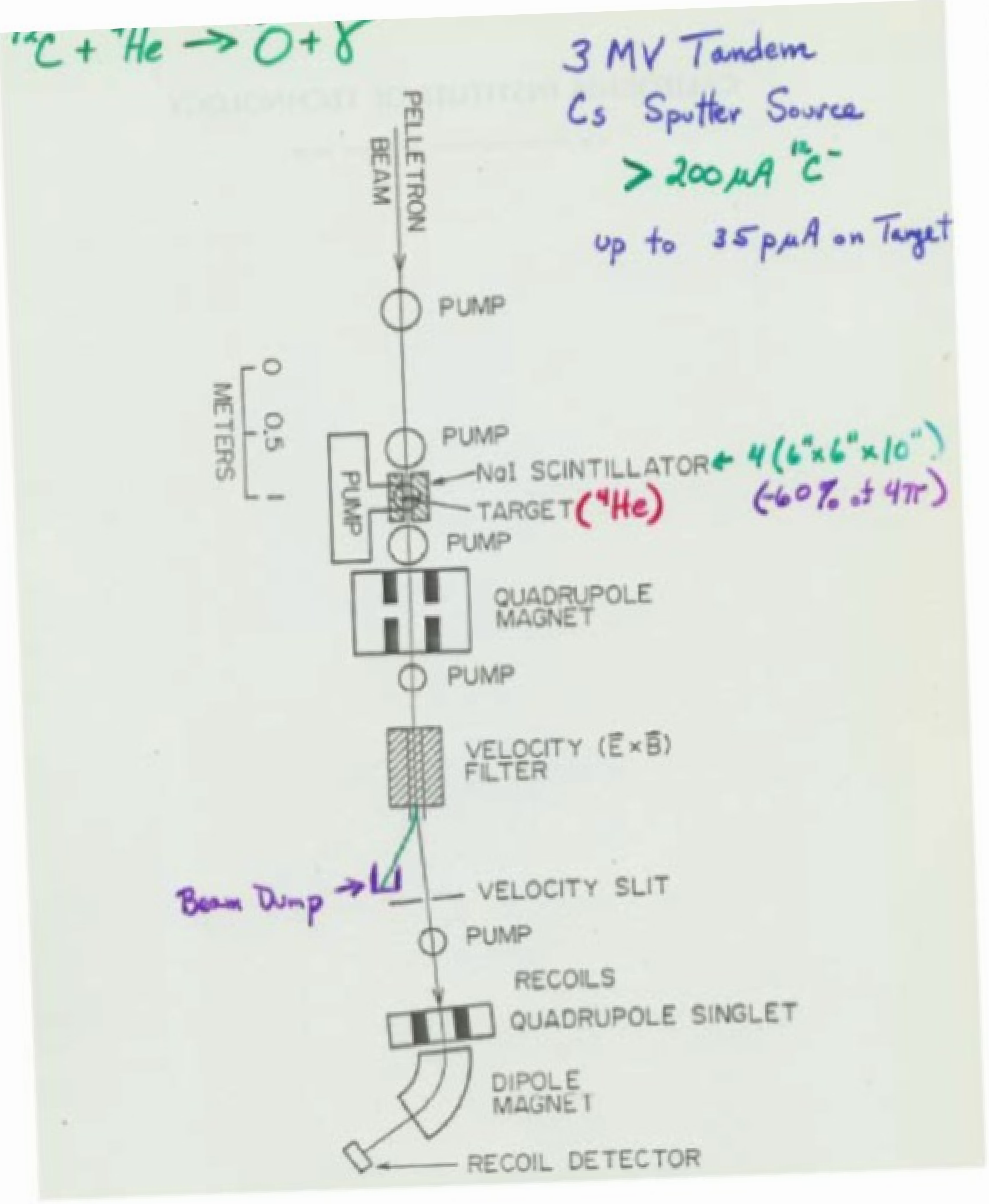
If this is strongly resonant then all $^{12}C$ consumed. However...

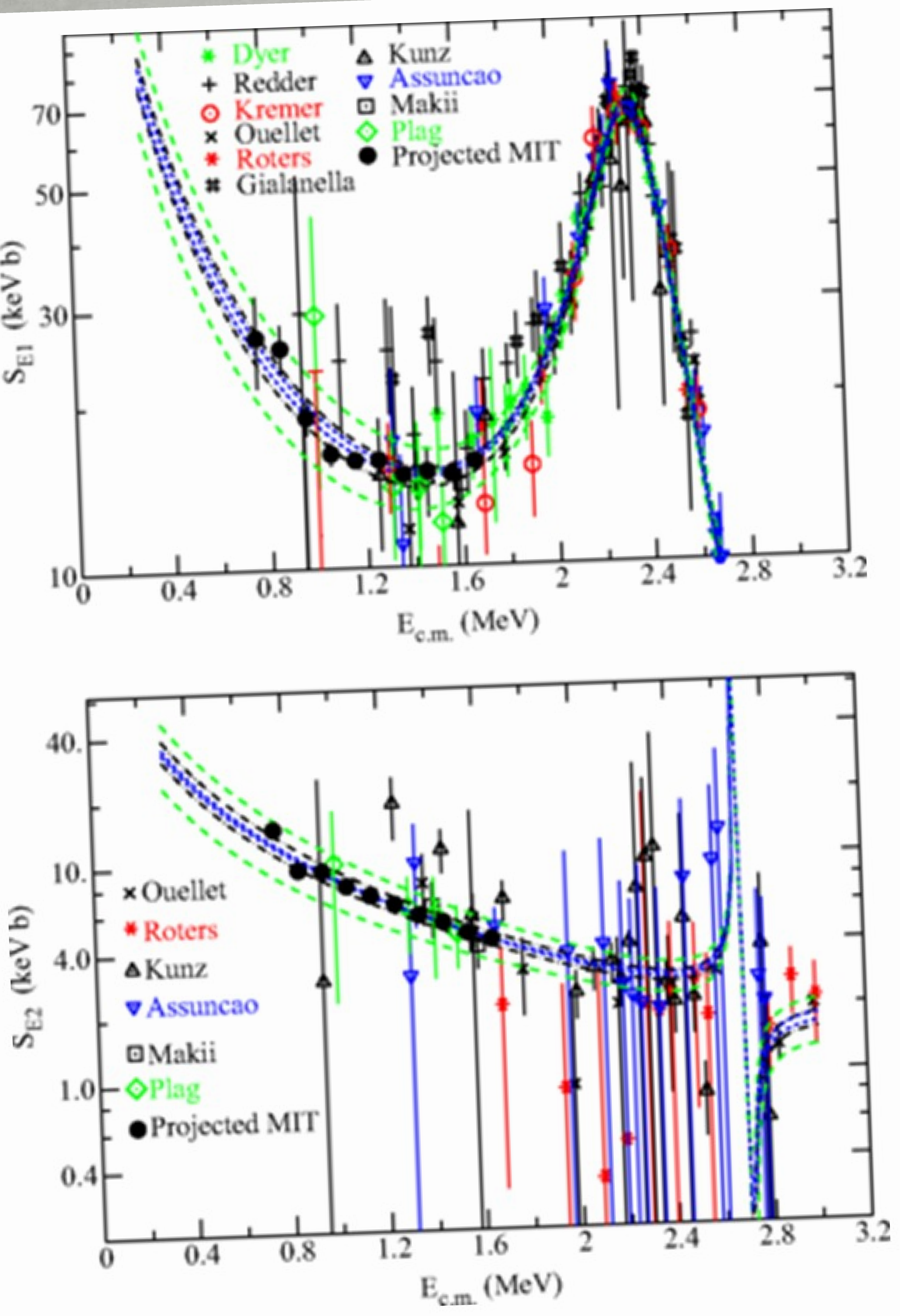
It is resonant but capture is surpressed since resonance is $1^-$ & $^{16}O$ is $0^+$

$\rightarrow$ E1

⇒ Very hard to measure, but very important (Nucleosyn. & GW)

## $^{12}C + \alpha \rightarrow {}^{16}O + \gamma$ Reaction





Next step: $^{16}O + \alpha \rightarrow {}^{20}Ne + \gamma$ is highly supressed due to ang. mom. mismatch

He-burning stops here (see Fig)

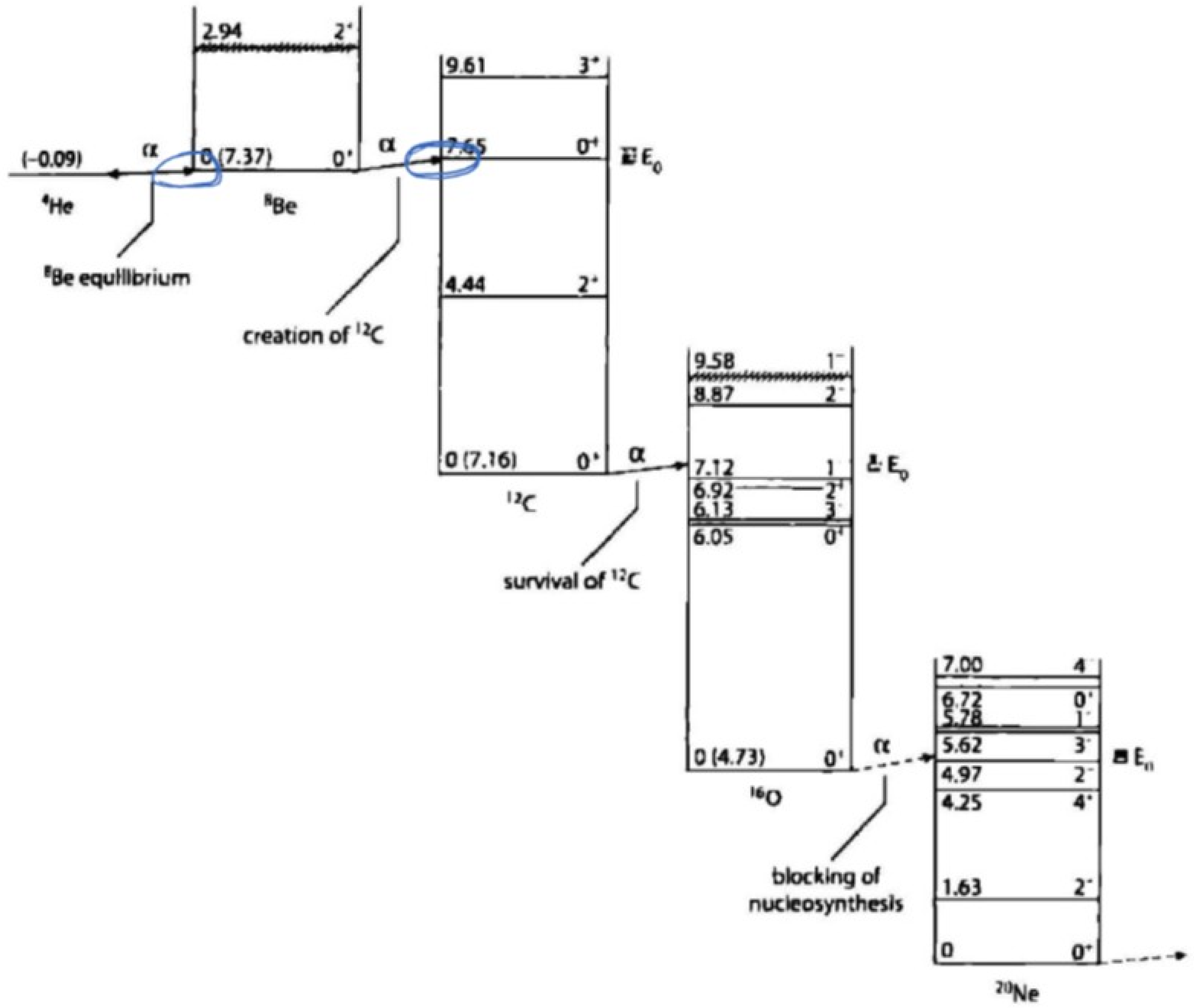


**Figure 12.11** Energy levels of nuclei participating in thermonuclear reactions during the helium burning stage in red giant stars (adapted from [RR88]). The survival of both $^{12}C$ and $^{16}O$ in red giants, believed to be the source of terrestrial abundances depends upon fortuitous circumstances of nuclear level structures and other properties in these nuclei.

For $M_* \lesssim 5 M_\odot$ Core Fusion stops & Star goes to Red Giant ⇒ then to White Dwarf

But for $M_* \simeq 10 M_\odot$ more burning possible b/c large grav. energy gives higher $T_{core}$ ⇒ $T_6 \sim 500$ this allows:

C-burning: $^{12}C + ^{12}C \to ^{20}Ne + \alpha$

$\to ^{23}Na + p$

then $\to ^{23}Mg + n$

O-burning: $^{16}O + ^{16}O \to ^{28}Si + \alpha$ $T_6 = 3000$

then $\to ^{32}S + \gamma$

Si-burning?

@ $T_6 \sim 5000$ BBR allows

$^{28}Si + \gamma \to ^{24}Mg + \alpha$ ⟺ new source of $^{4}He$

⋮

$^{28}Si + \alpha \to ^{32}S + \gamma$

$^{32}S + \alpha \to ^{36}Ar + \gamma$

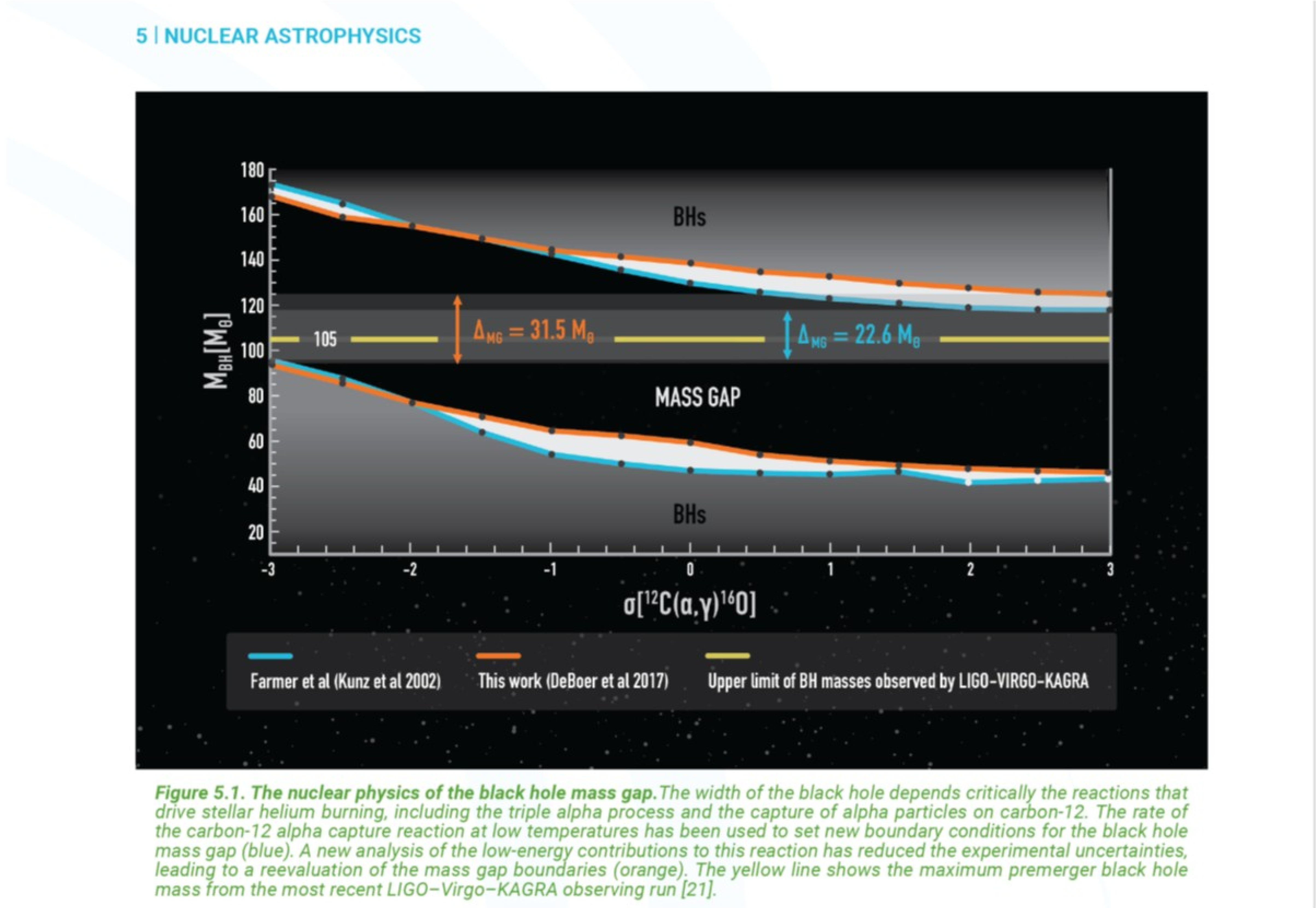
$+\alpha$ … … $Ca \to Ti \to ^{52}Fe \to ^{56}Ni$

then $^{56}Ni \xrightarrow{\beta} ^{56}Co \xrightarrow{\beta} \underline{^{56}Fe}$

Nuclear burning & Stellar Nucleosyn. stops @ $^{56}Fe$ since Fusion impossible beyond this

Next time: need to use neutrons

# Reaction Figure from 2023 Nuclear Physics Long-Range Plan ($^{12}C + \alpha \rightarrow {}^{16}O + \gamma$)



**5 | NUCLEAR ASTROPHYSICS**

***Figure 5.1. The nuclear physics of the black hole mass gap.*** *The width of the black hole depends critically the reactions that drive stellar helium burning, including the triple alpha process and the capture of alpha particles on carbon-12. The rate of the carbon-12 alpha capture reaction at low temperatures has been used to set new boundary conditions for the black hole mass gap (blue). A new analysis of the low-energy contributions to this reaction has reduced the experimental uncertainties, leading to a reevaluation of the mass gap boundaries (orange). The yellow line shows the maximum premerger black hole mass from the most recent LIGO–Virgo–KAGRA observing run [21].*