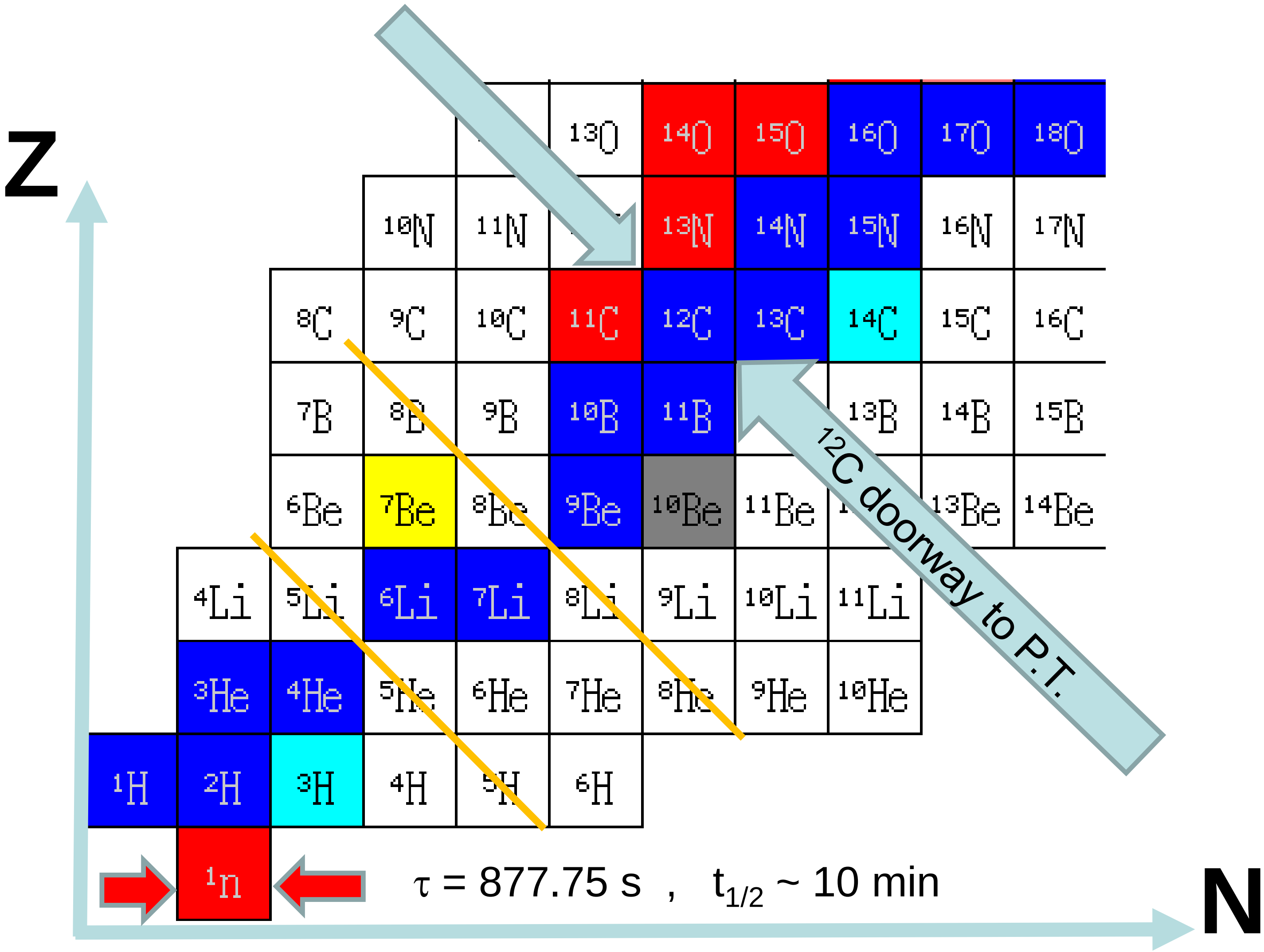
Inelastic deexcitation of the Hoyle State

L. G. Sobotka

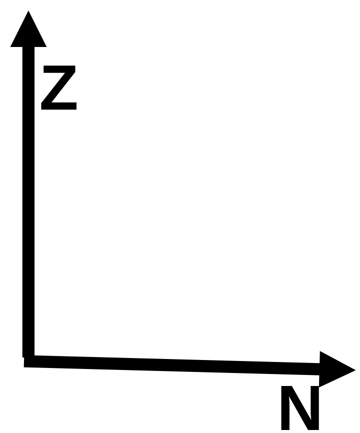


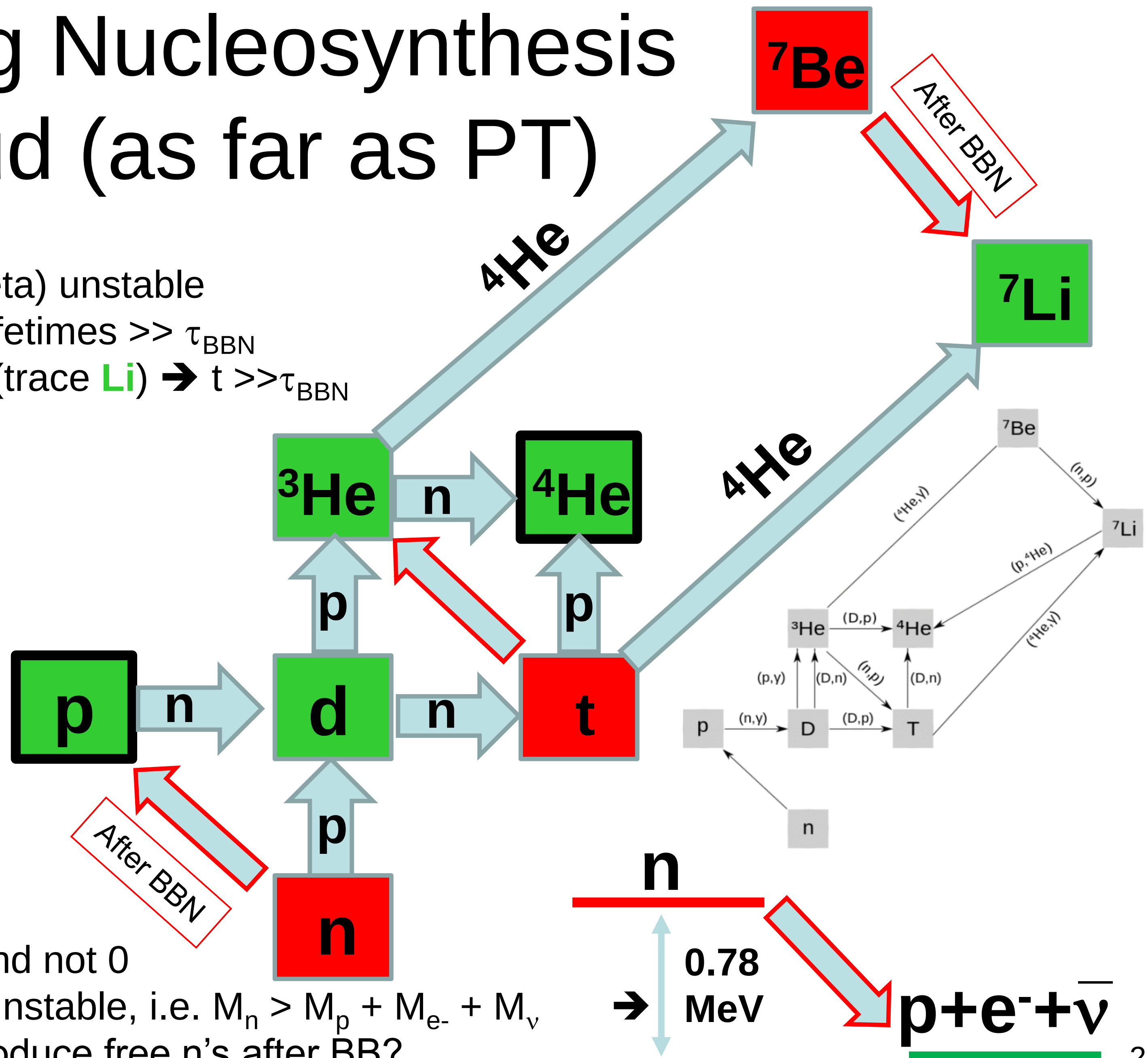
Big-Bang Nucleosynthesis
Big Dud (as far as PT)

NOTE:

n, **t** and ^{7}**Be** are (beta) unstable
but have lifetimes >> τ_{BBN}

Only **p, d,** ^{3}**He,**^{4}**He** (trace **Li**) ➔ t >>τ_{BBN}





ALSO NOTE:

The PT starts at 1 and not 0

BECAUSE the n is unstable, i.e. $M_n > M_p + M_{e-} + M_\nu$ ➔

How does nature produce free n's after BB?

With only a few exceptions: stars, either in life or death, produce the rest of PT

What our sun does (~ 85% truth)

$2\{p + p \rightarrow d + e^+ + \nu + Q_1\}$

$2\{p + d \rightarrow {}^3He + Q_2\}$

$\{{}^3He + {}^3He \rightarrow {}^4He + 2p + Q_3\}$

$4p \rightarrow {}^4He + 2e^+ + 2\nu + Q_{tot}$

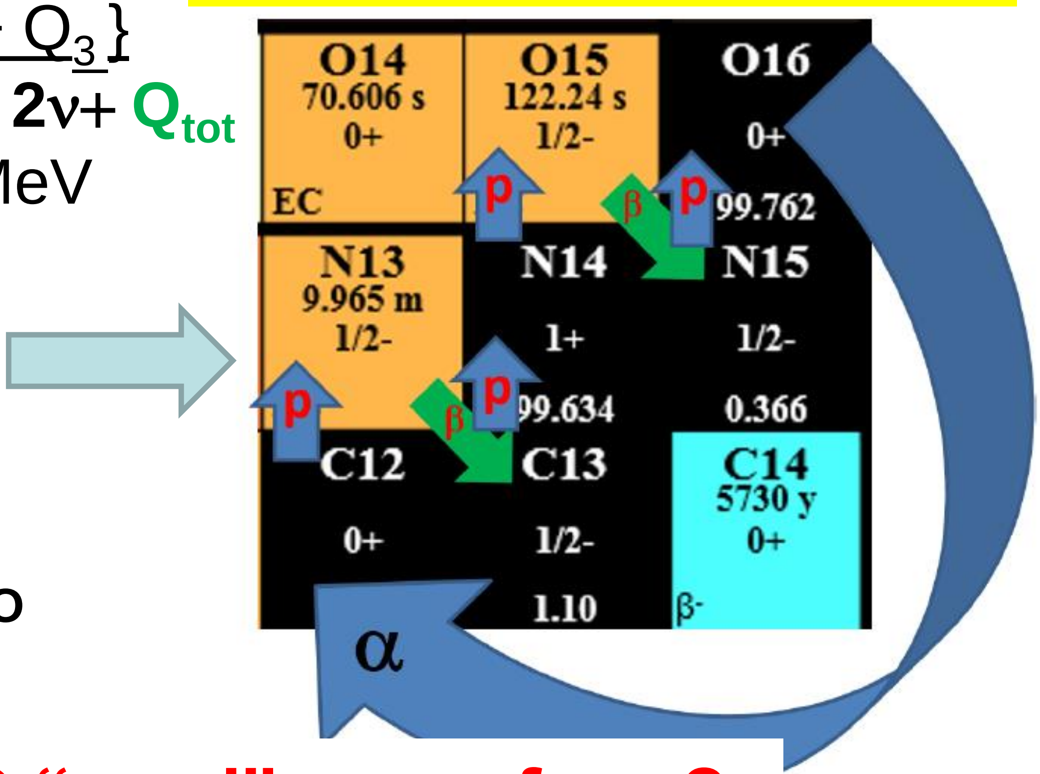
$Q_{tot} = 2Q_1 + 2Q_2 + Q_3 = 27.6$ MeV

With CNO process ➔ allows for ^{13}C and ^{15}N NMR

With ^{13}C ….. ➔ neutrons via

$^{13}C + \alpha \rightarrow {}^{17}O \rightarrow {}^{16}O + n$

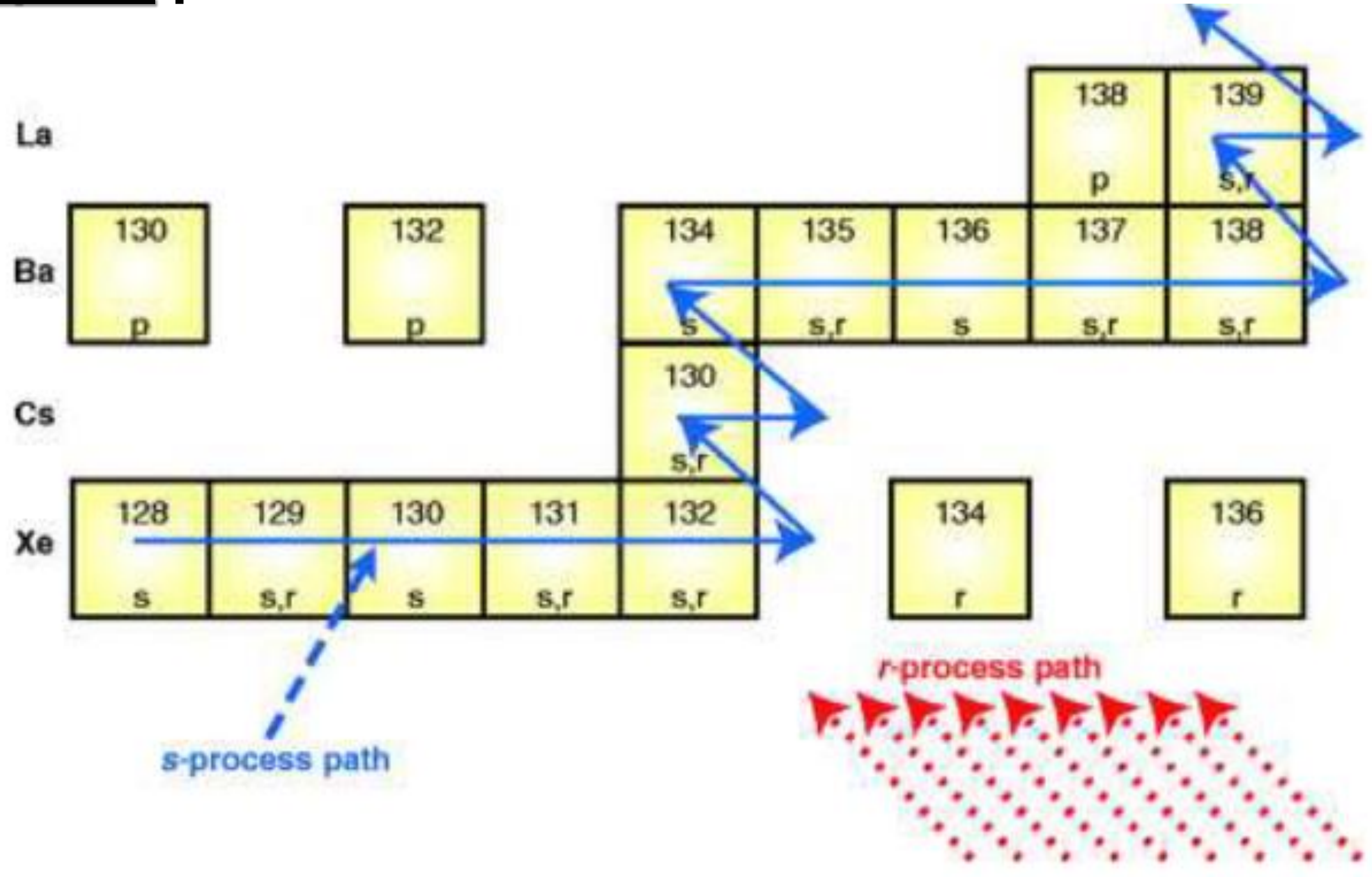
these are the n's for s-process



To repair part of the lie ……
The sun also uses ^{12}C to catalyze
The "CNO process" that does
EXACTLY the same thing, i.e.
$4p \rightarrow {}^4He + 2e^+ + 2\nu + Q_{tot}$ **but ALSO**
Gives us ^{13}C & $^{14,15}N$

BUT where does the ^{12}C "seed" come from?

Nuclei heavier than Fe come (mostly) from slow and fast <u>n-capture</u> processes

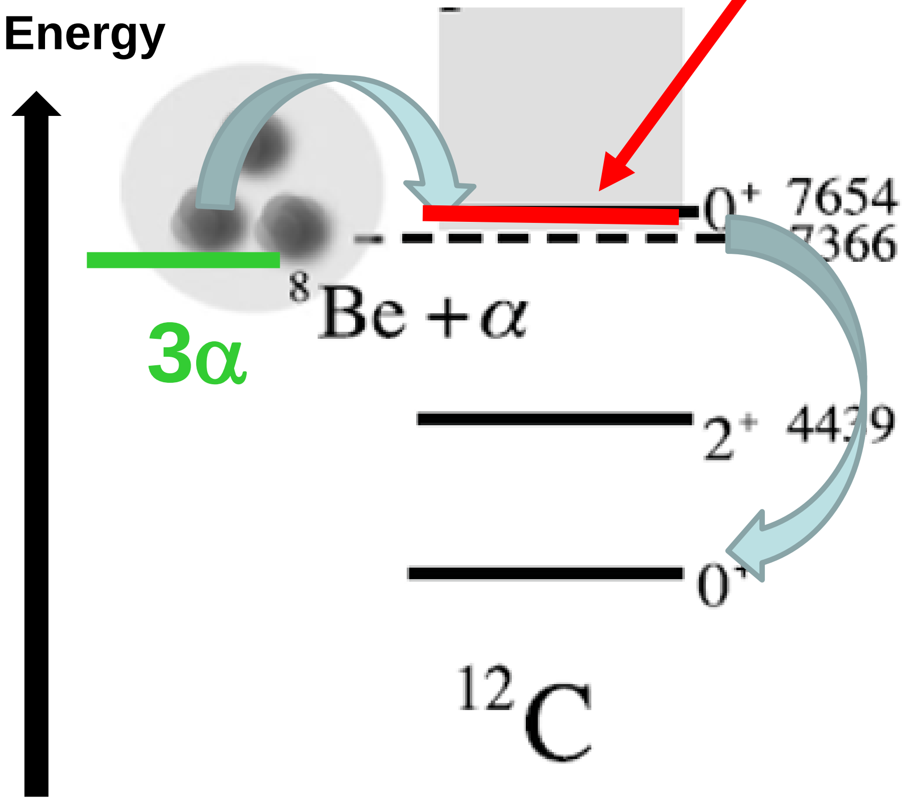


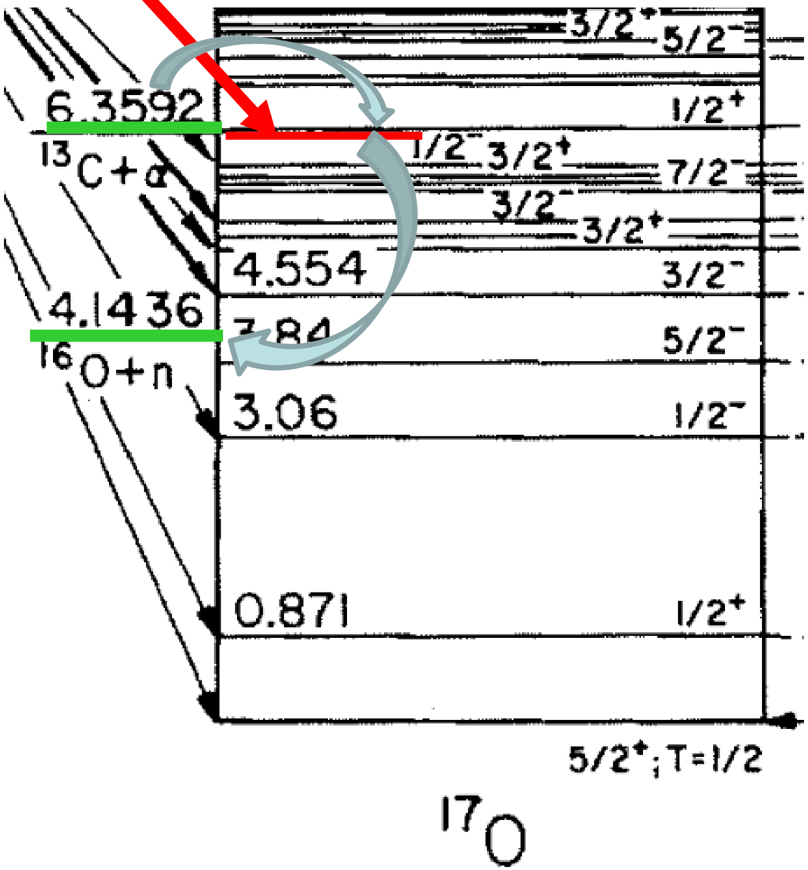
BUT where do the n's (post BBN) for s(low) and r(apid) n-capture come from?

Two Anthropic motivating cases of resonances near thresholds

$^{12}C^*$ ^{17}O

Energy





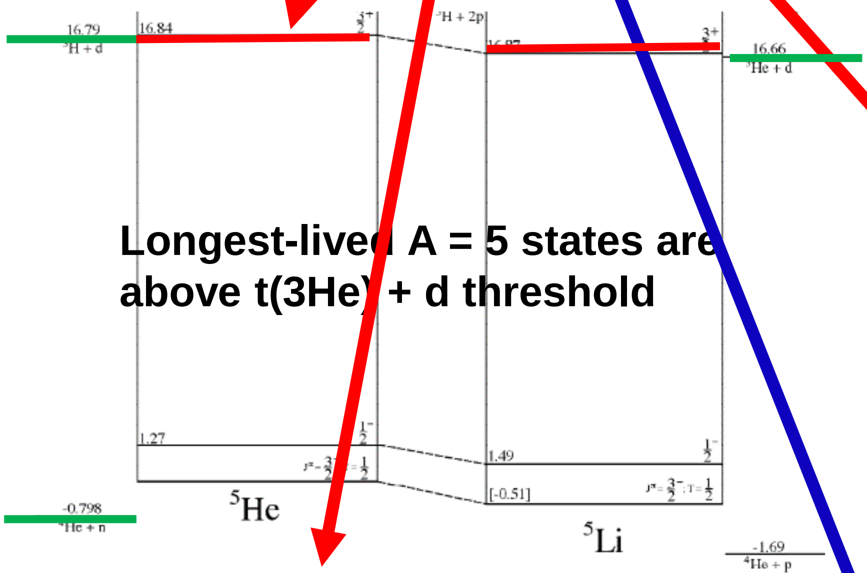
Generates seed for all ALL heavier elements

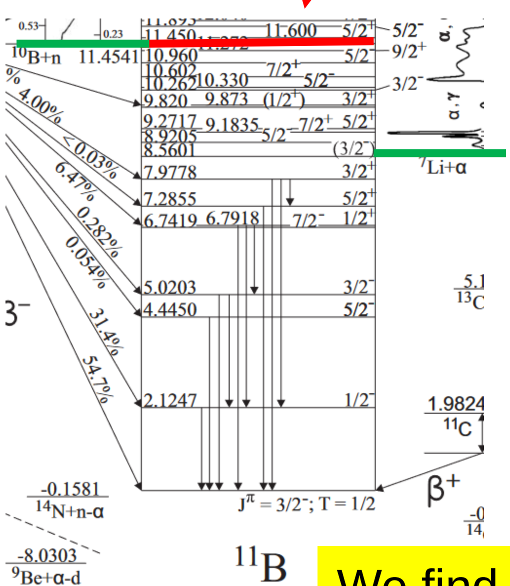
generates neutrons for the s-process ~ ½ of heavy element synthesis

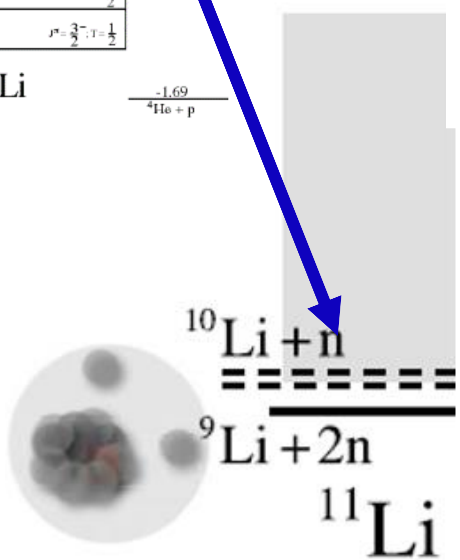
Why: these resonances are doorways BUT so – so much more!

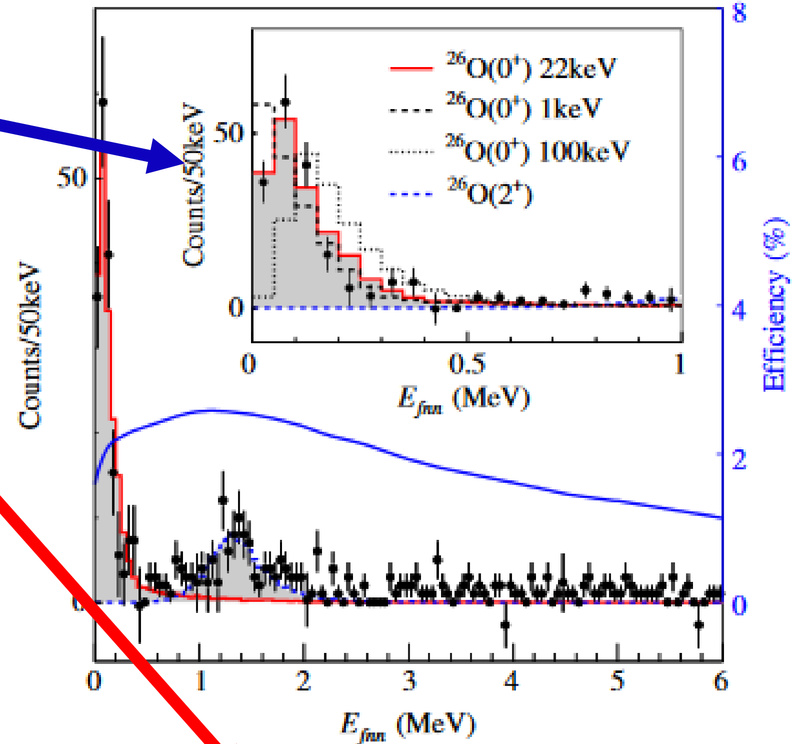
Near thresholds require OS-QM
A = 5, ^{11}B, ^{11}Li, ^{15}F, ^{26}O

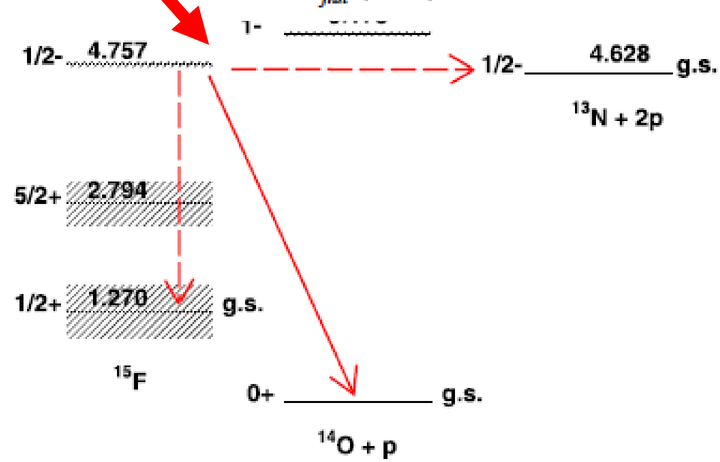
Longest-lived A = 5 states are above t(3He) + d threshold





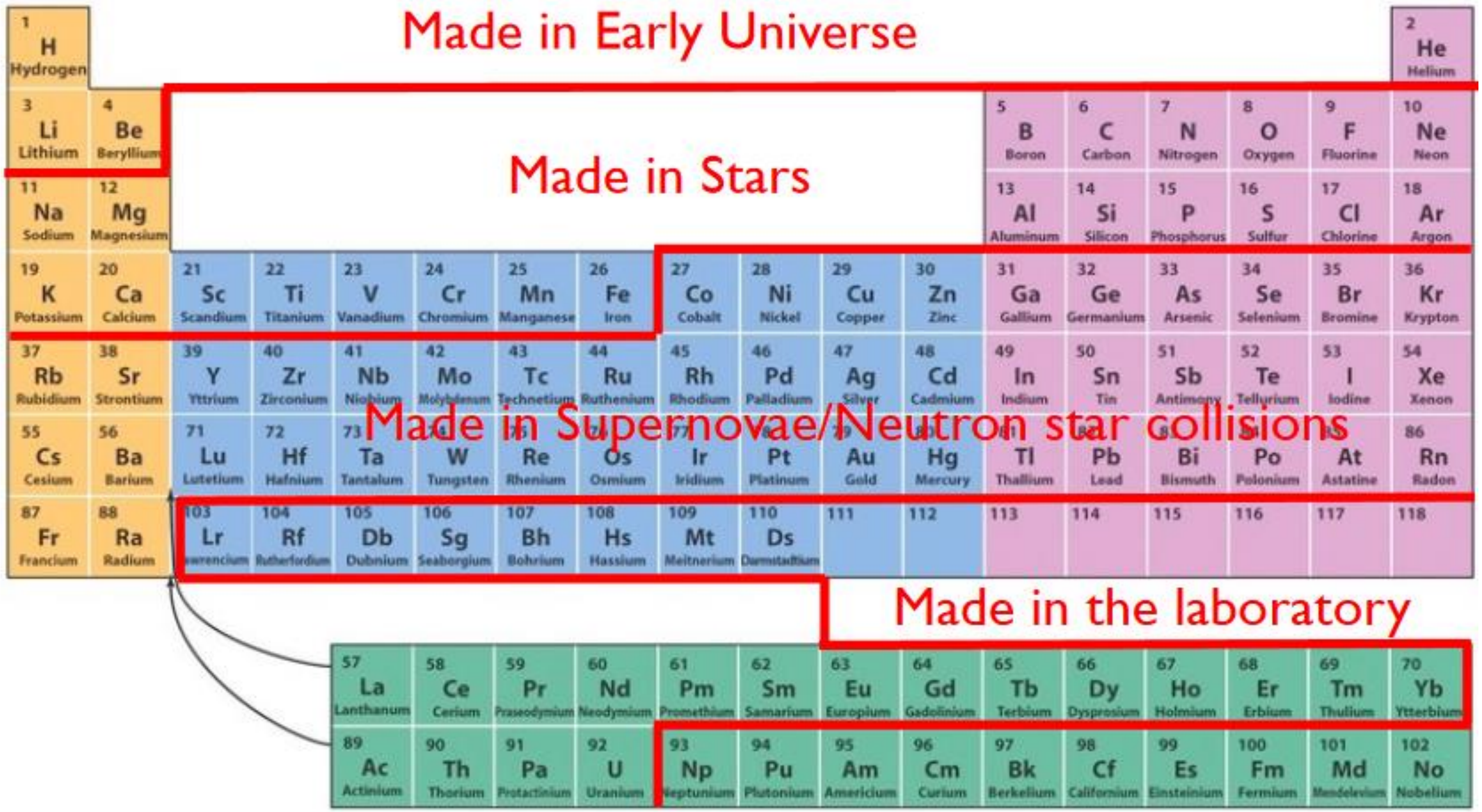






We find the cases OFF NS paths as interesting as those on a path.

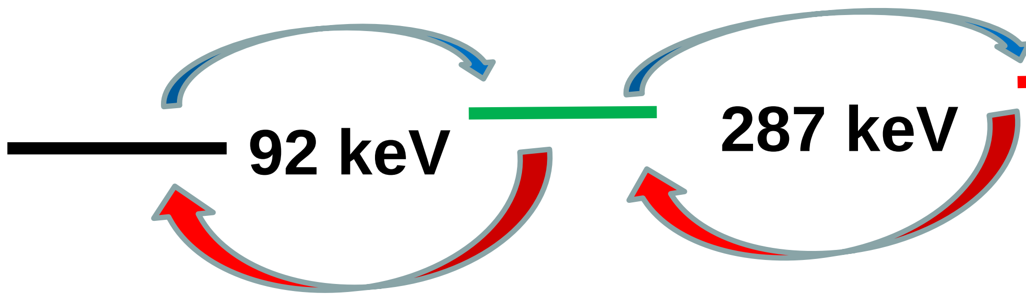
When/Where elements are made

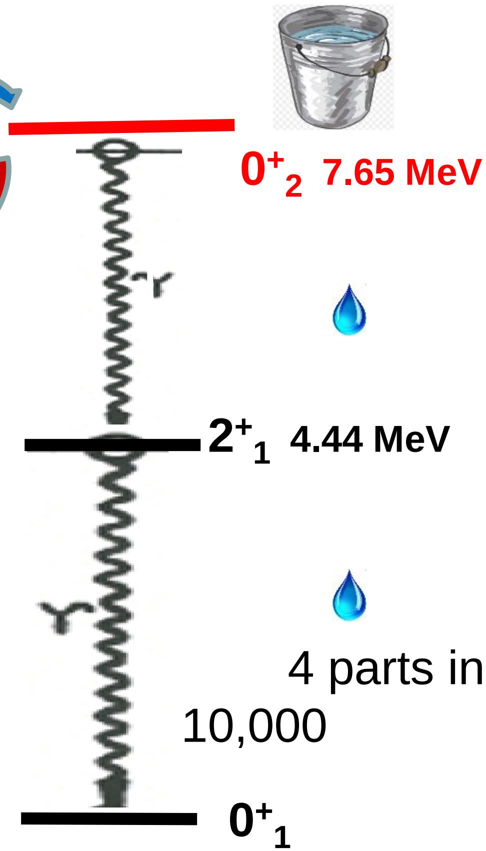


Hoyle state – doorway to Periodic Table

$(\alpha + \alpha) + \alpha \leftrightarrow {}^{8}Be + \alpha \leftrightarrow {}^{12}C_{Hoyle}$

(5.57 ev → 118 as) (9.3 ev → 71 as)





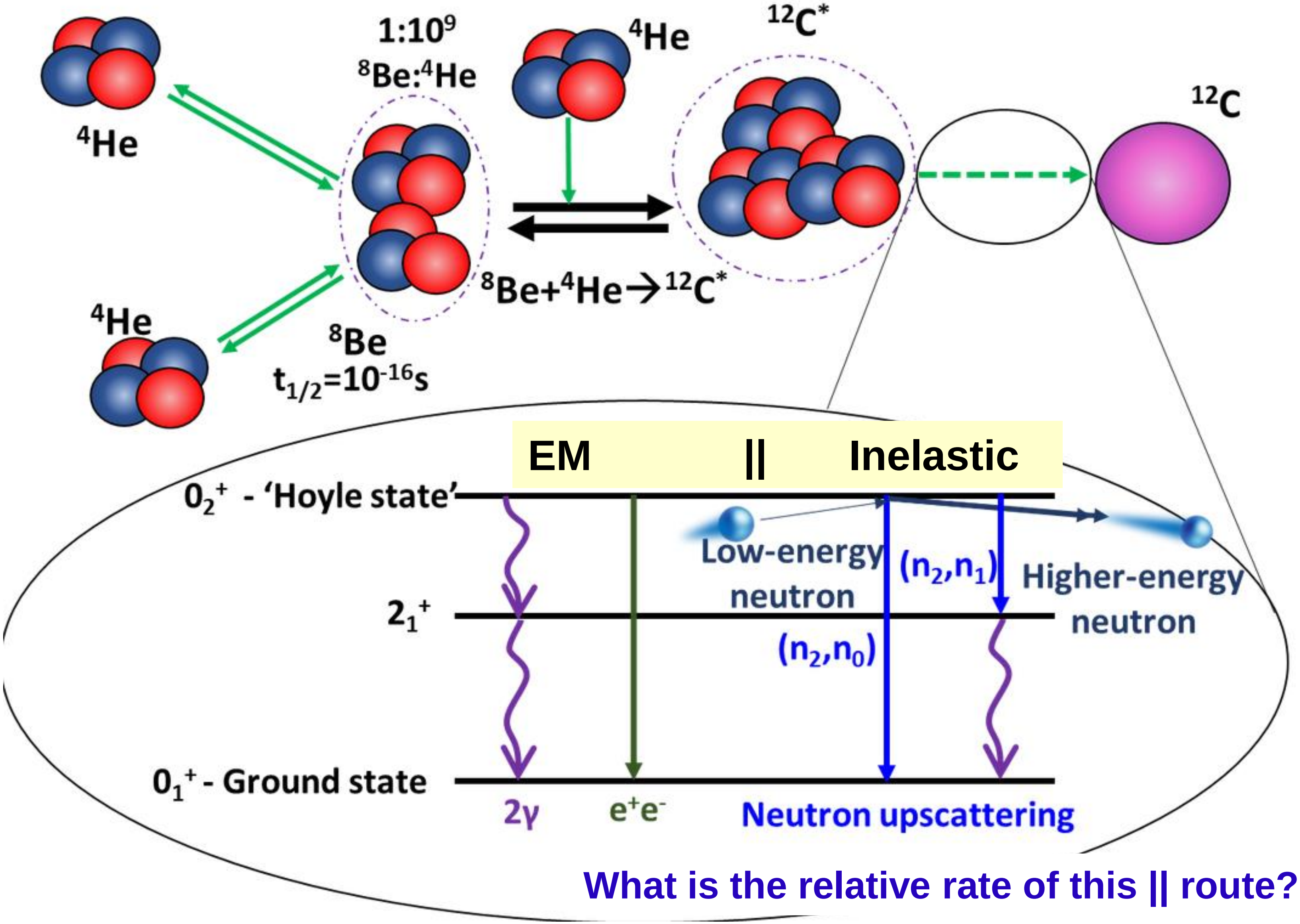
EM decay 4/10,000

→Hoyle's mostly just fall apart

→The measly drips → P.T.

Because ←dynamical→ there is an $[{}^{8}Be]_{eq}$ & $[{}^{12}C_{Hoyle}]_{eq}$

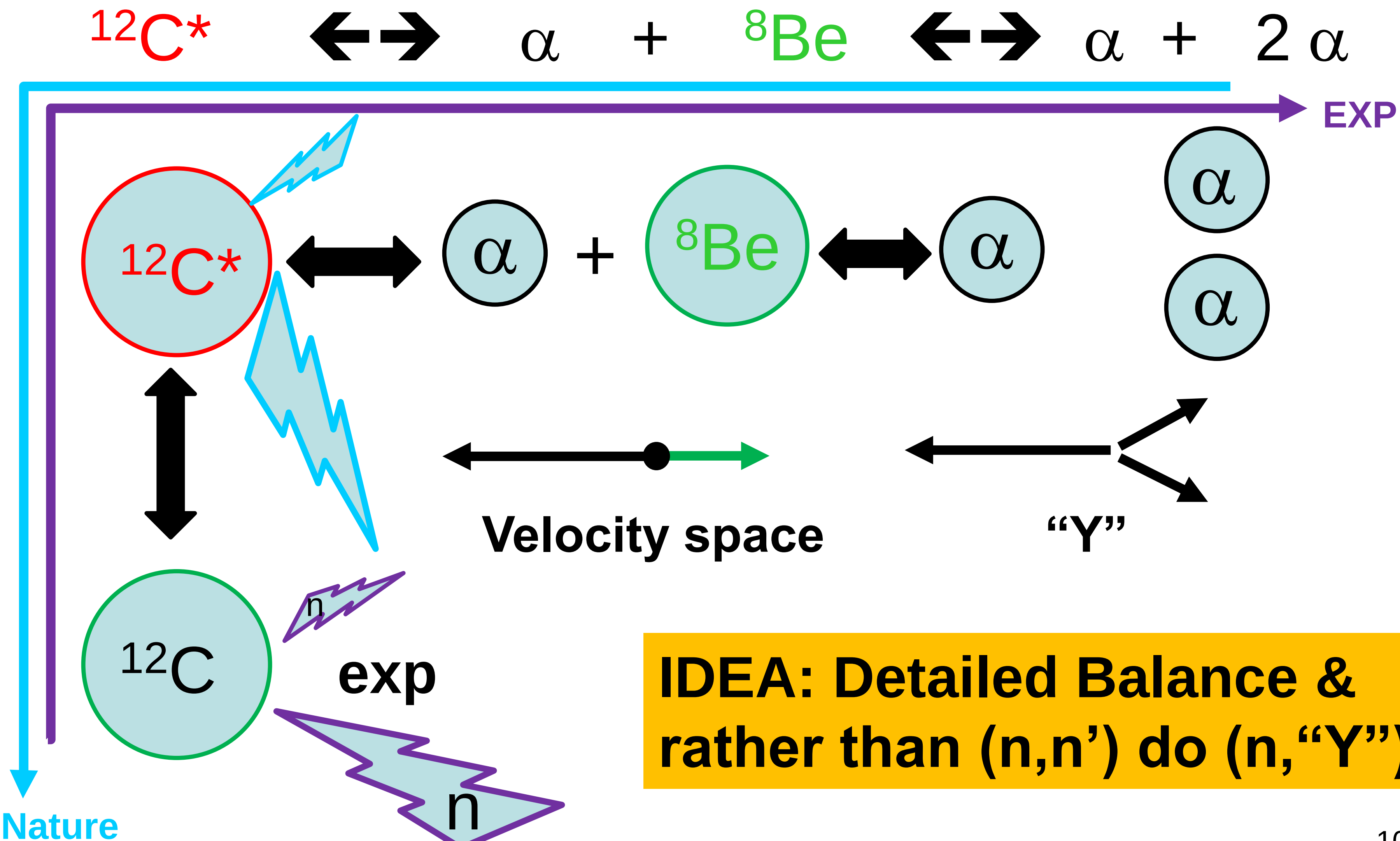
Review and || route



What is the relative rate of this || route?

J. W. Truran & B.-Z. Kozlovsky, Ap. J. 158,1021 (1969).

Idea: microscopic reversibility & detect "Y"



IDEA: Detailed Balance & rather than (n,n') do (n,"Y")

Detailed Balance

In equilibrium each elementary process is in equilibrium with its reverse process

1. At equilibrium the one-way rates must be equal ➔ = ⬅

$$R_{\rightarrow}[1/cm^3 s] = N_n N_{12C} < \sigma_{\rightarrow} v >_{MB} = N_{n'} N_{12C*} < \sigma_{\leftarrow} v >_{MB} = R_{\leftarrow}[1/cm^3 s]$$

2. The forward/backward Maxwellian averaged cross section ratio is just equal to the number ratio (or K_{eq}) and thus equal to a partition function ratio.
➔ The neutron partition functions drop out as T & m are the same and all that remains are the spin degeneracy ratio and the difference in energies.

$$\frac{< \sigma_{\leftarrow} v >_{MB}}{< \sigma_{\rightarrow} v >_{MB}} = \frac{N_n N_{12C}}{N_{n'} N_{12C*}} = \frac{q_n q_{12C}}{q_{n'} q_{12C*}} = \left(\frac{q_n}{q_{n'}}\right)\left[\frac{q_{12C}}{q_{12C*}}\right] = (1)\left[\frac{2I+1}{2I'+1} e^{-\Delta E/kT}\right]$$

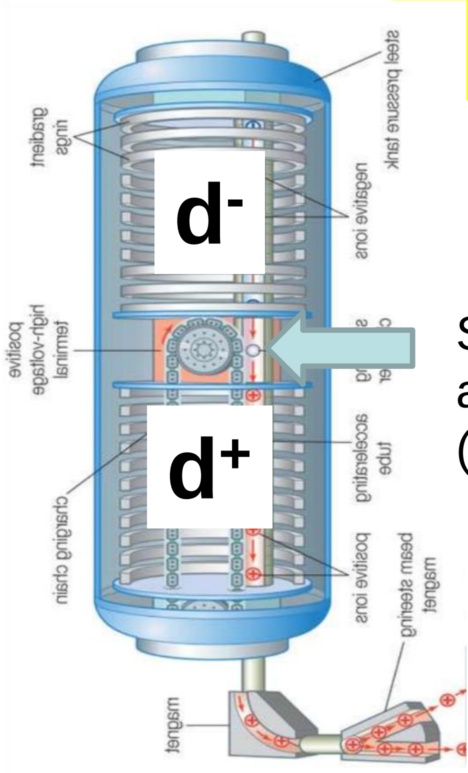
3. BTW, the Maxwellian averaged cross sections are just…..

$$< \sigma v >_{MB} = \left({}^{8}\!\big/_{\pi\mu} \right)^{1/2} \left(\frac{1}{kT} \right)^{3/2} \int_0^\infty E \sigma(E) e^{-E/kT} dE$$

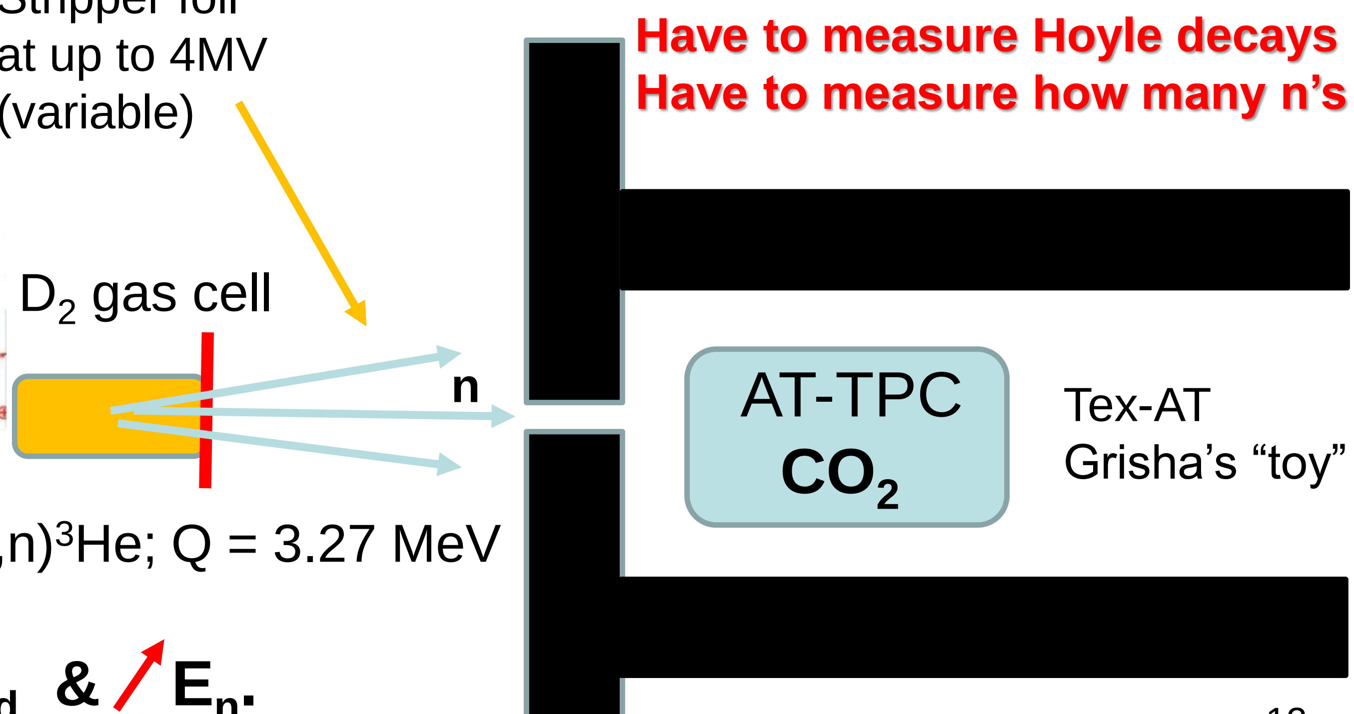
TAMU's TPC (TexAT) moved to Ohio U. EAL ➔ to detect "Y" 's from $^{12}C_{gs}$(n,"Y") $^{12}C_{Hoyle}$

Ion source

d^-



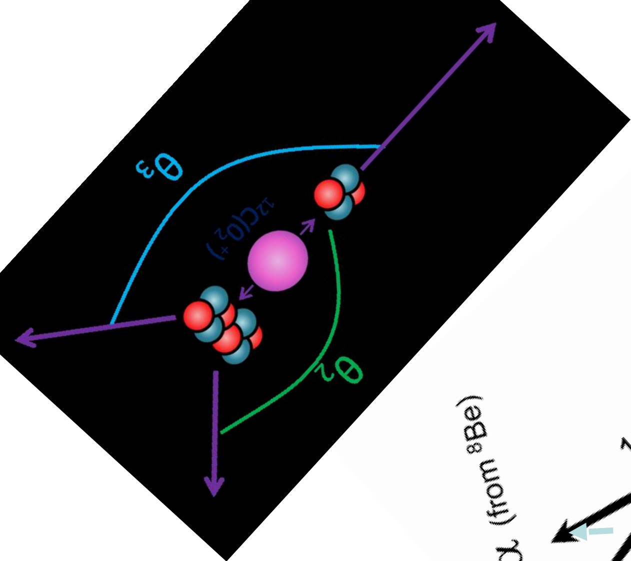
Stripper foil
at up to 4MV
(variable)

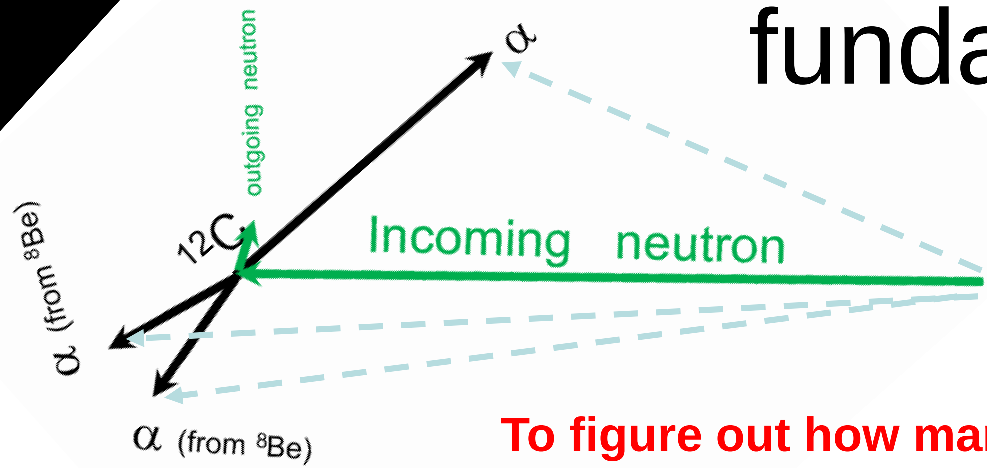


d(d,n)^{3}He; Q = 3.27 MeV

↗terminal V: ↗E_d & ↗E_n.

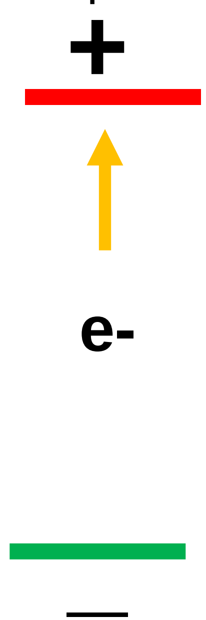
AT-TPC fundamentals

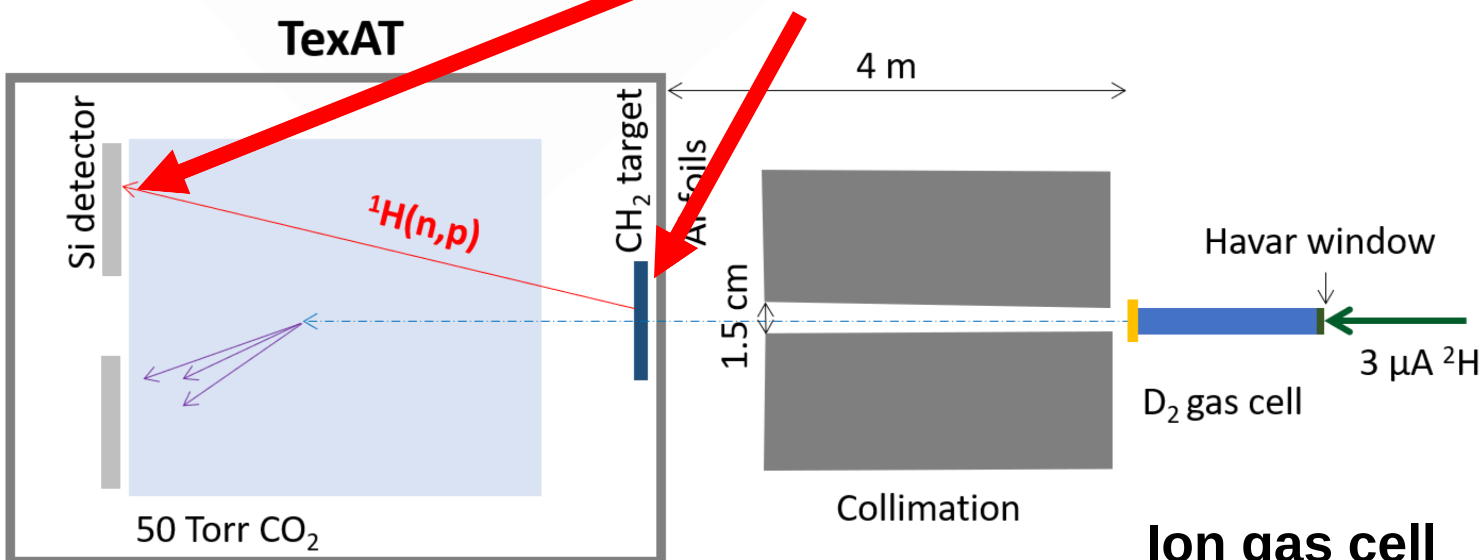




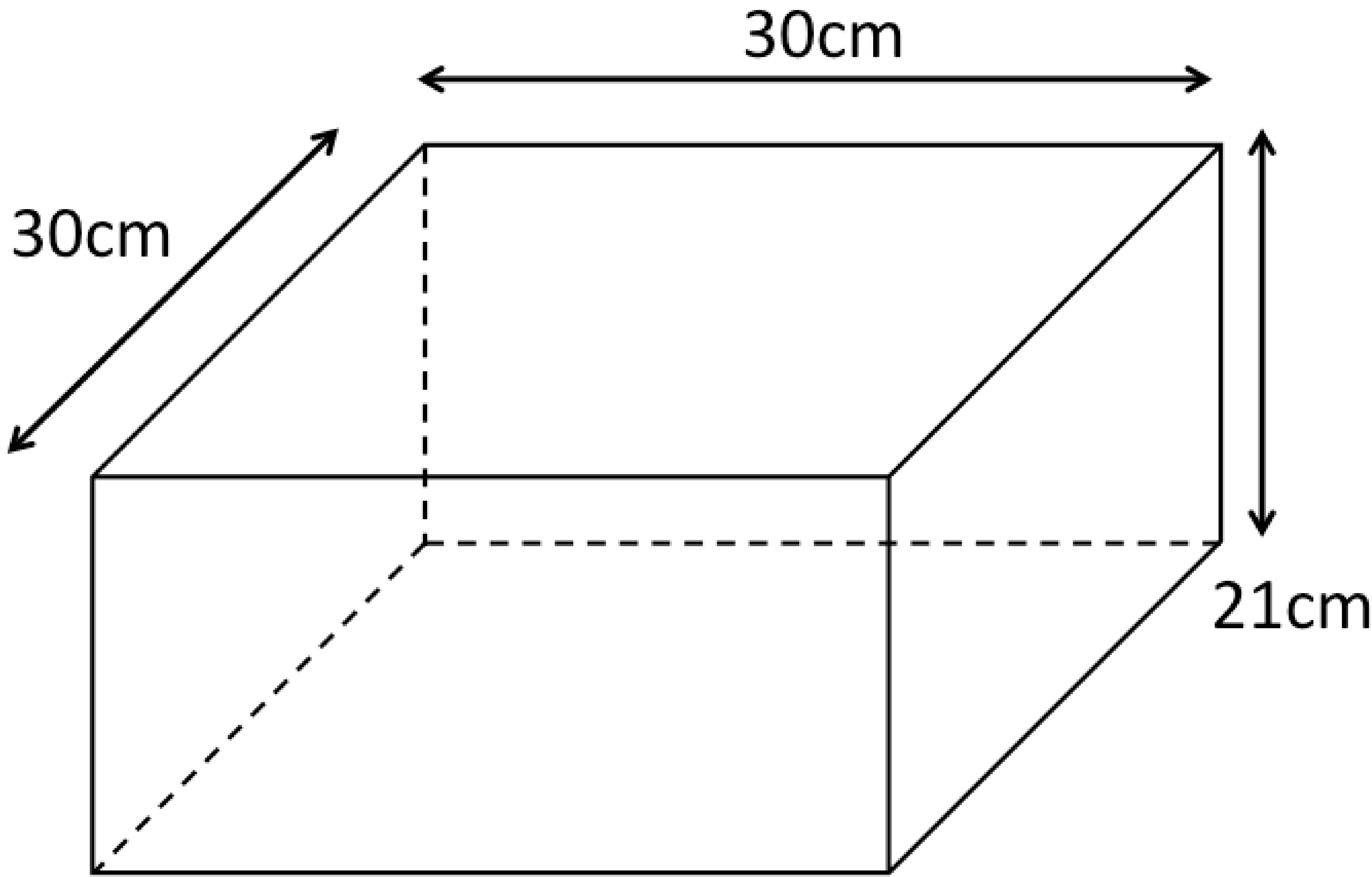
To figure out how many neutrons
… primary method (n,p)

Micro pattered anode



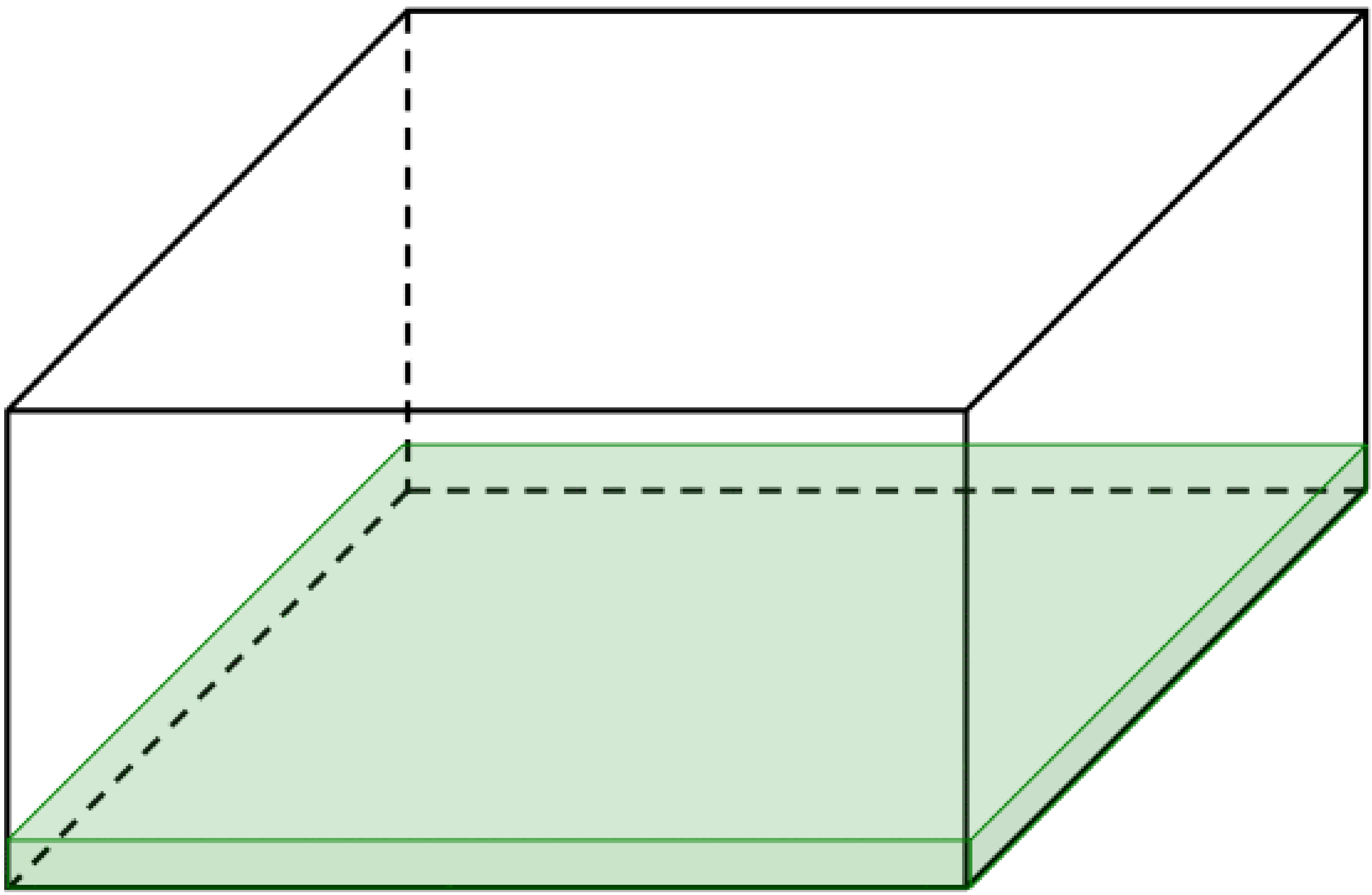


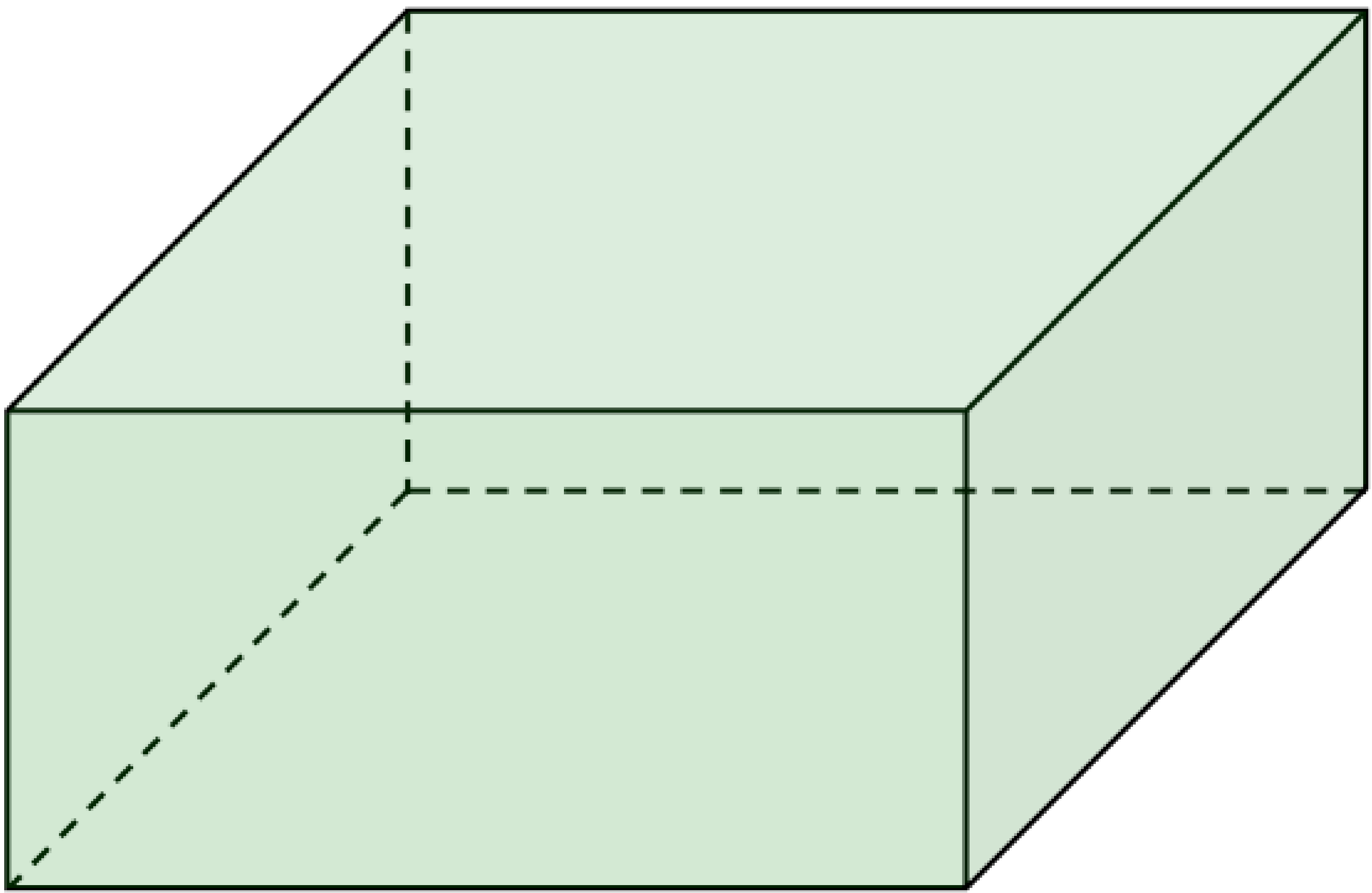
Ion gas cell
$D(d,n)^3He$



Time Projection Chamber

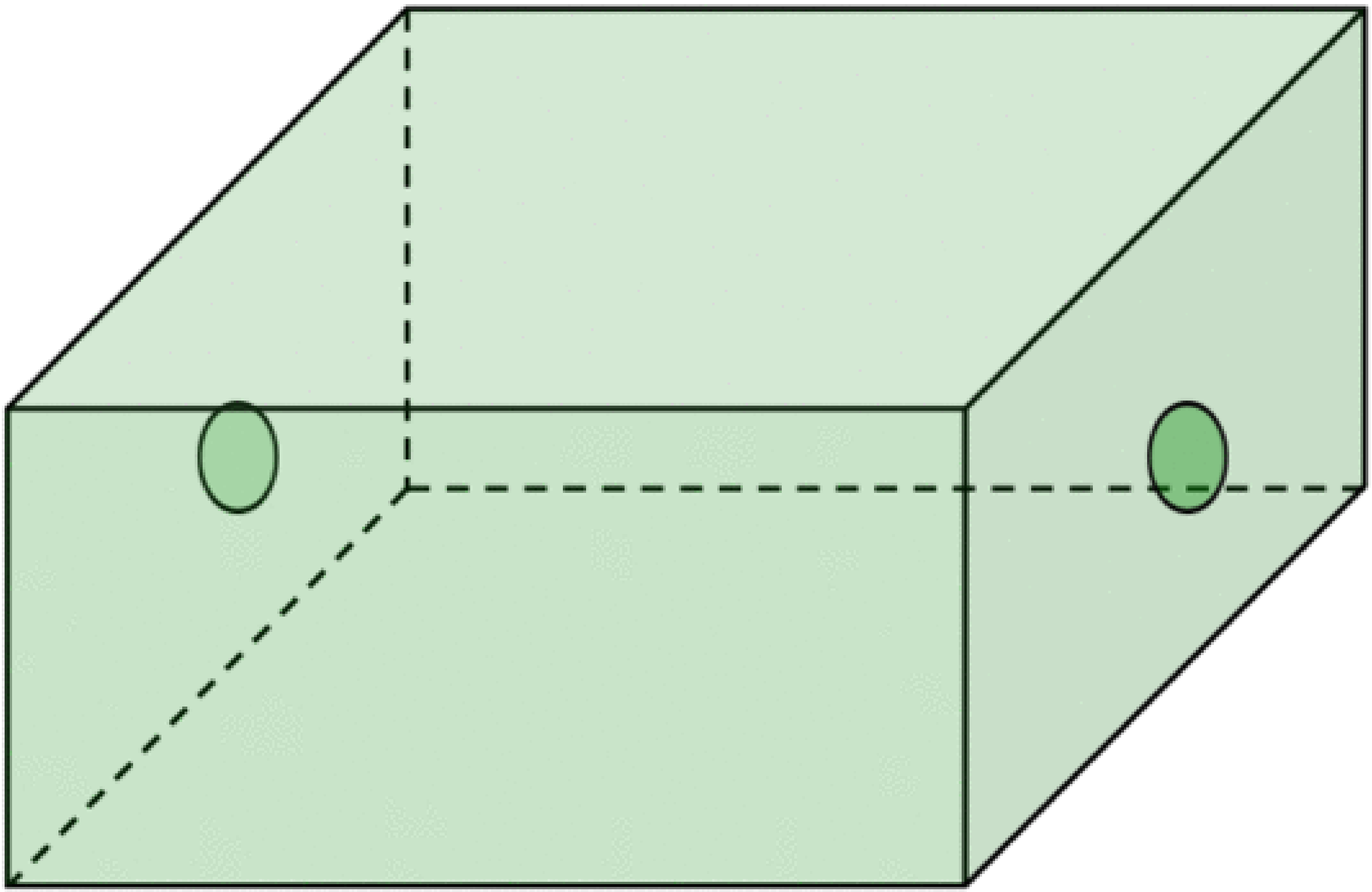
CO_2



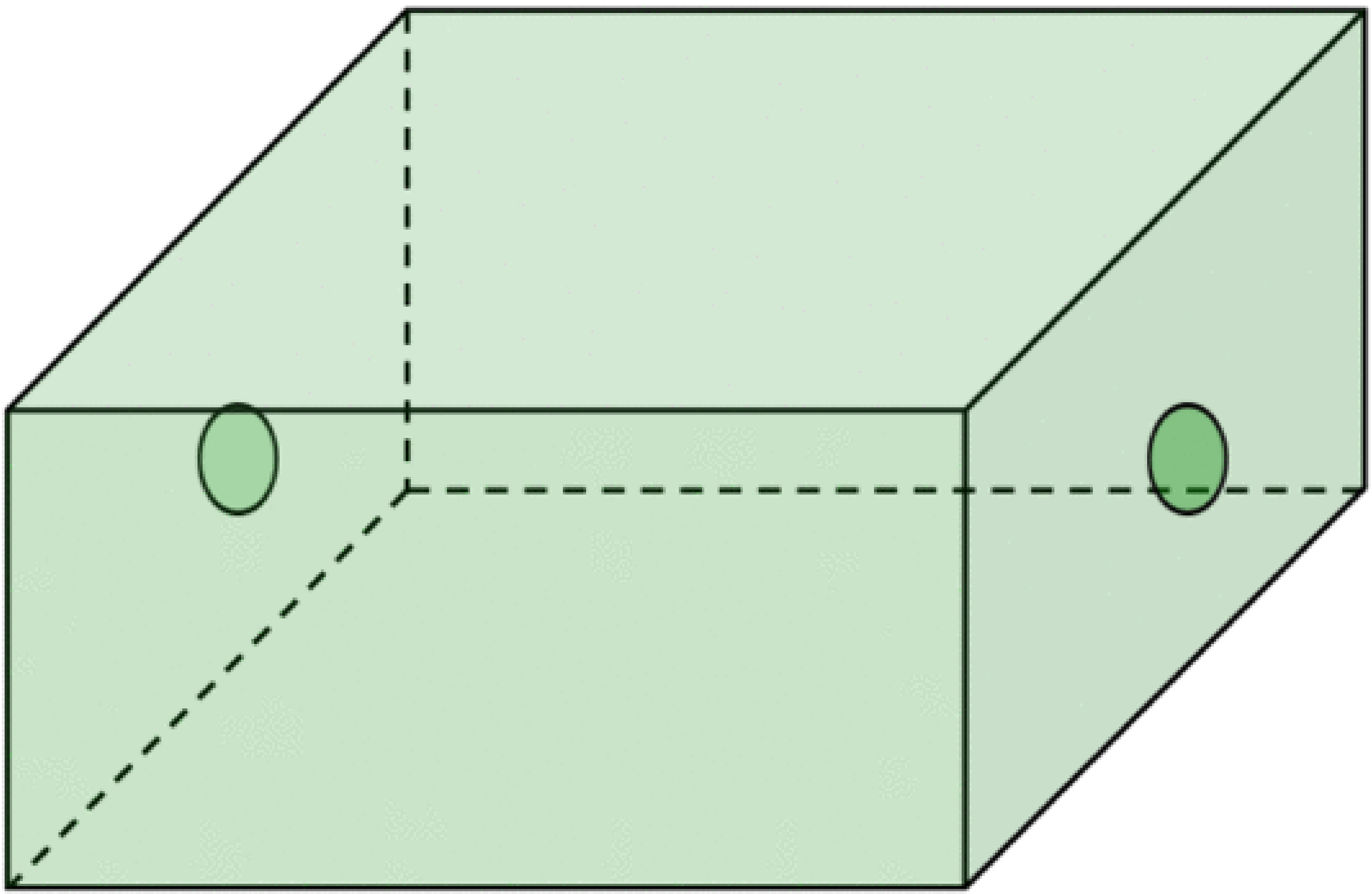


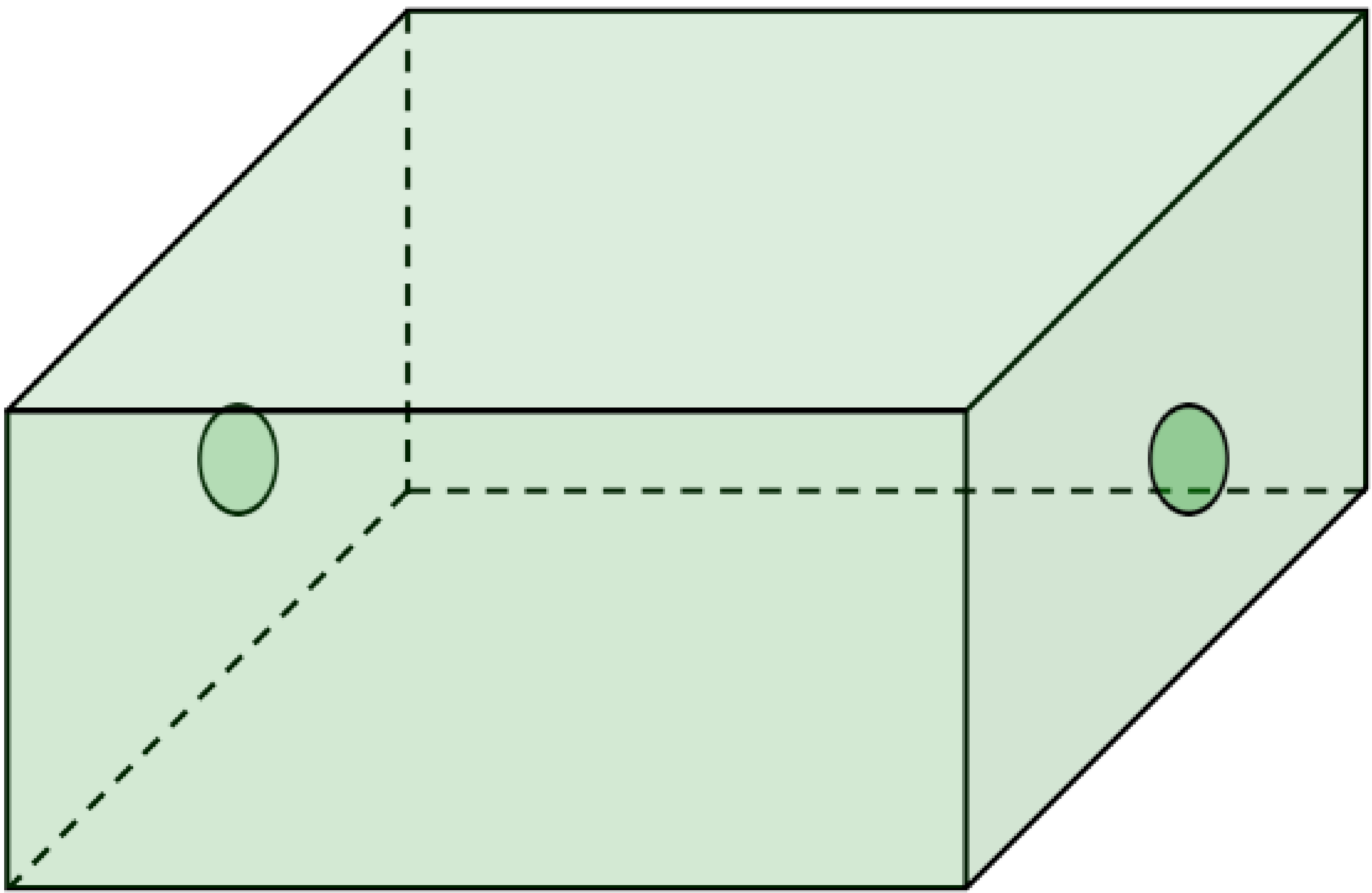
10^8 γ/s or 10^6 n/s

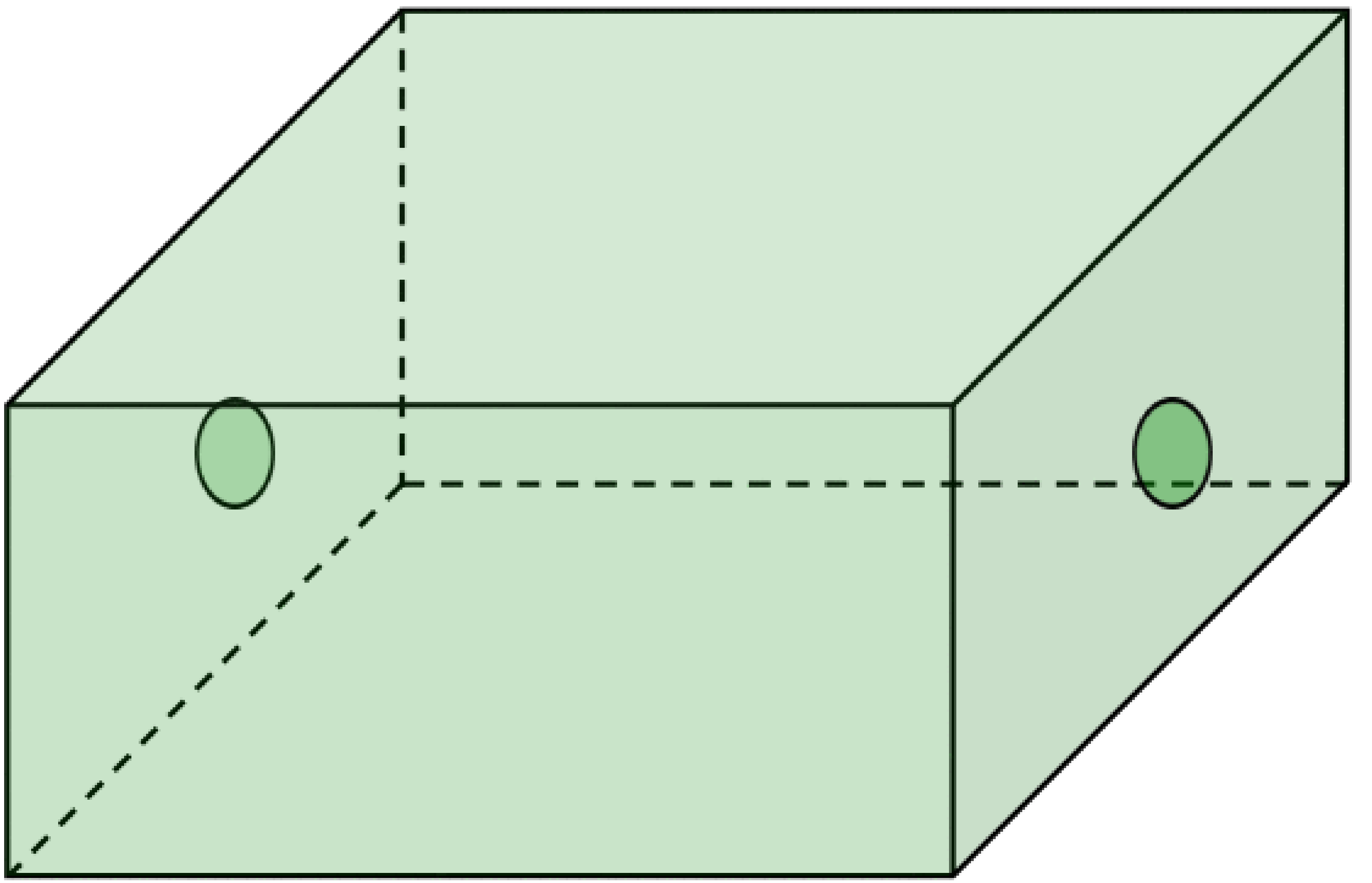
γ's circularly polarised

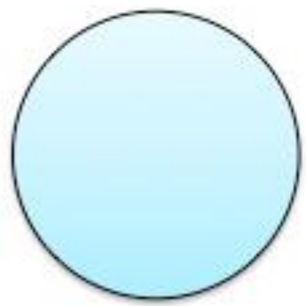


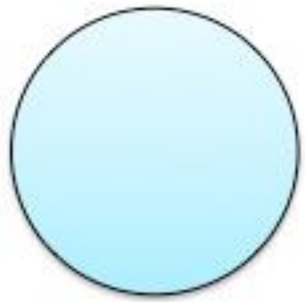
$\sigma_\gamma \approx 130$ keV, $\sigma_n \approx 300$ keV,



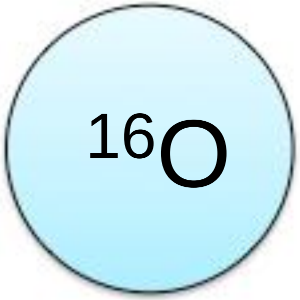


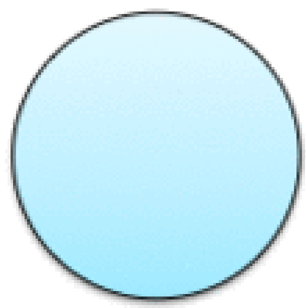


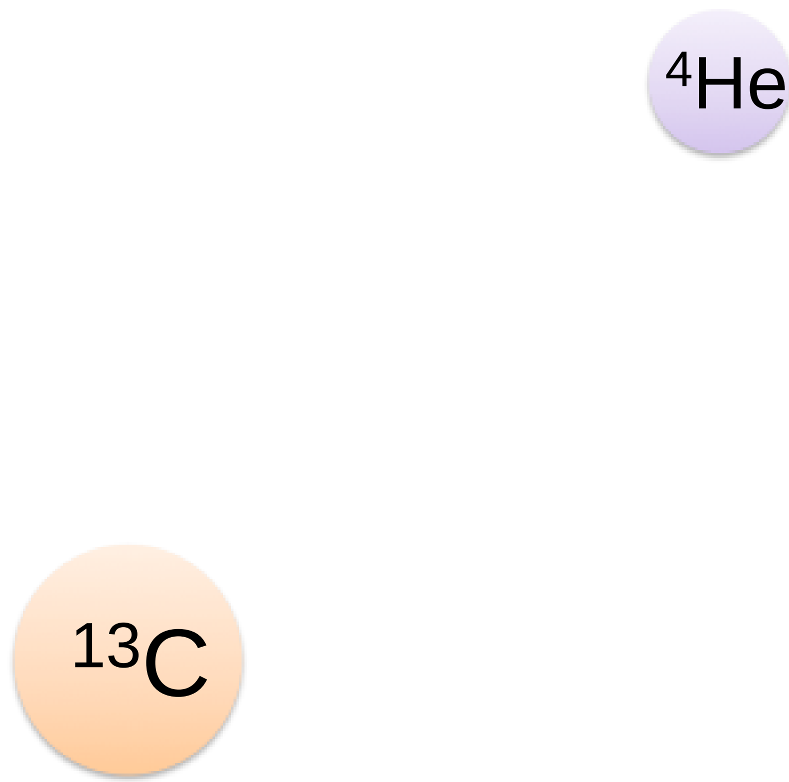


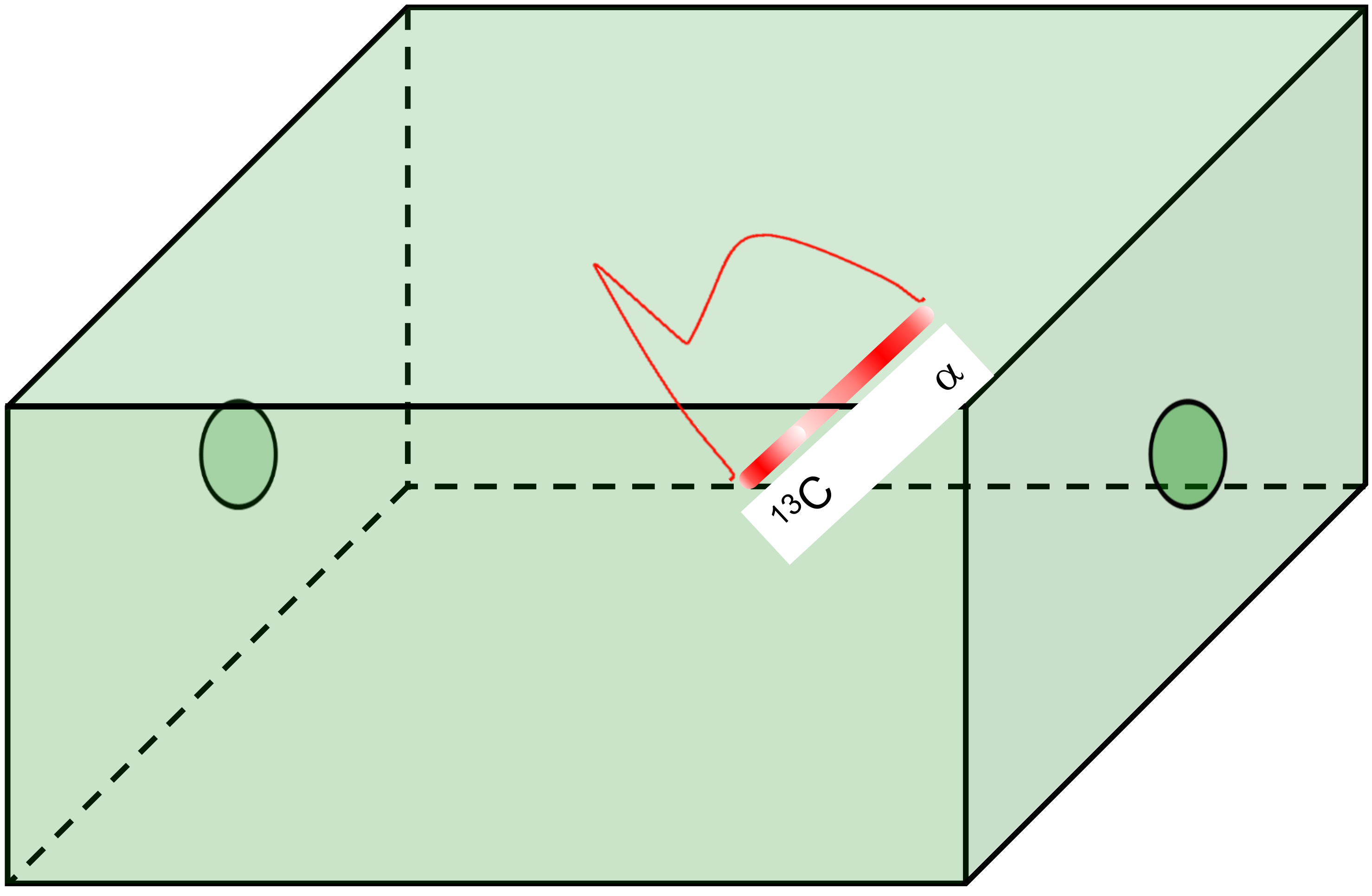


^{12}C or ^{16}O

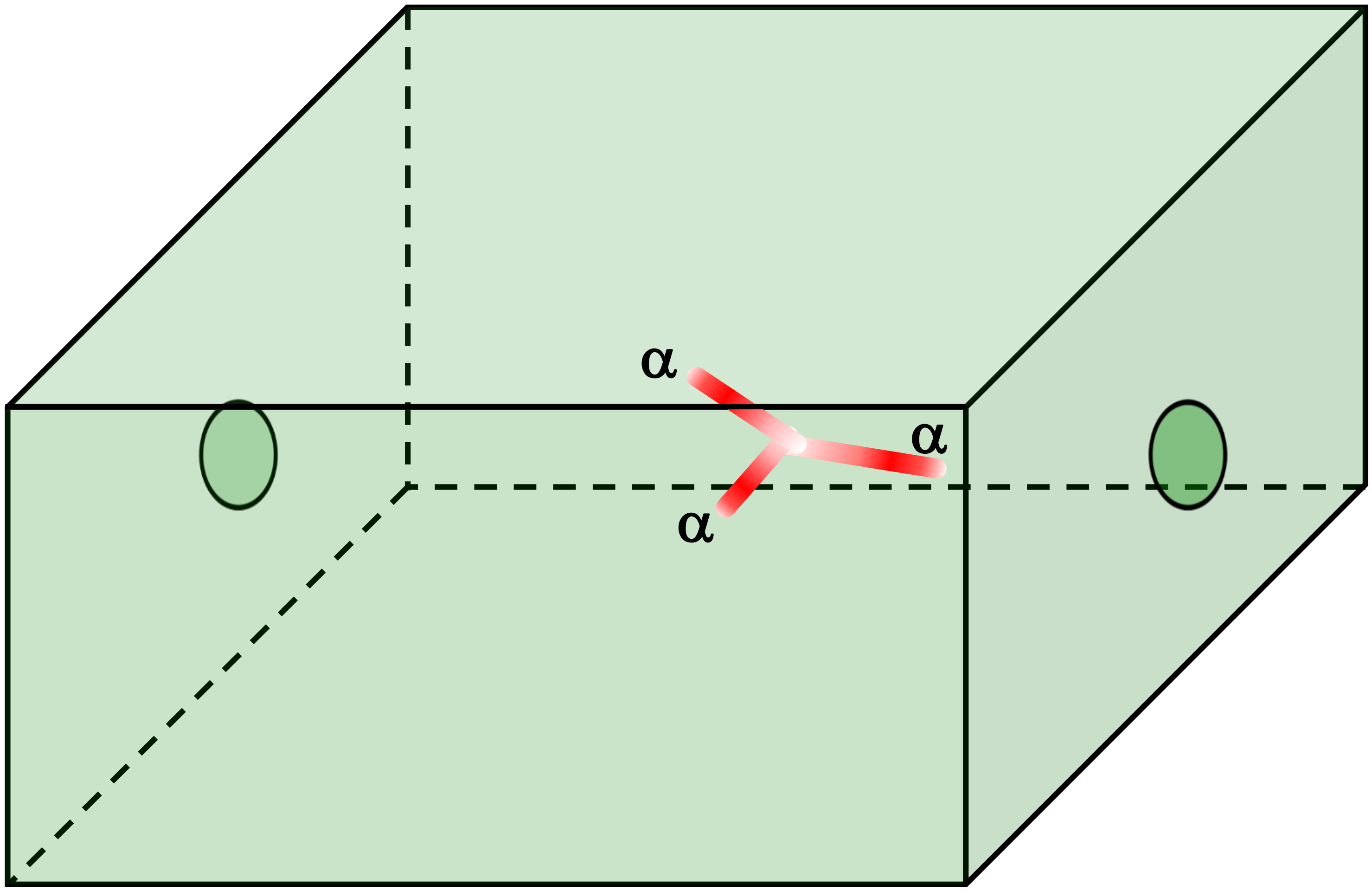

^{16}O

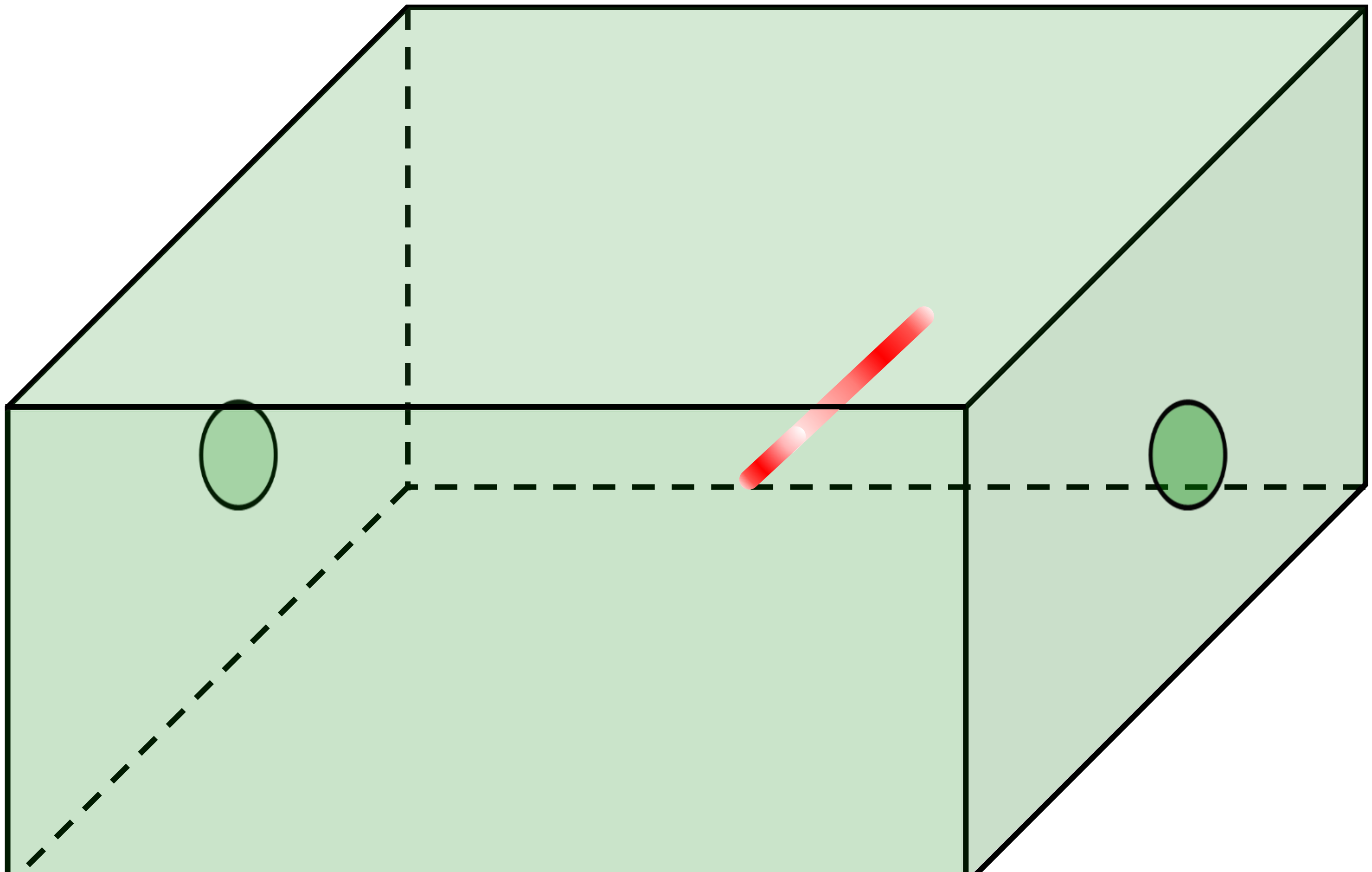


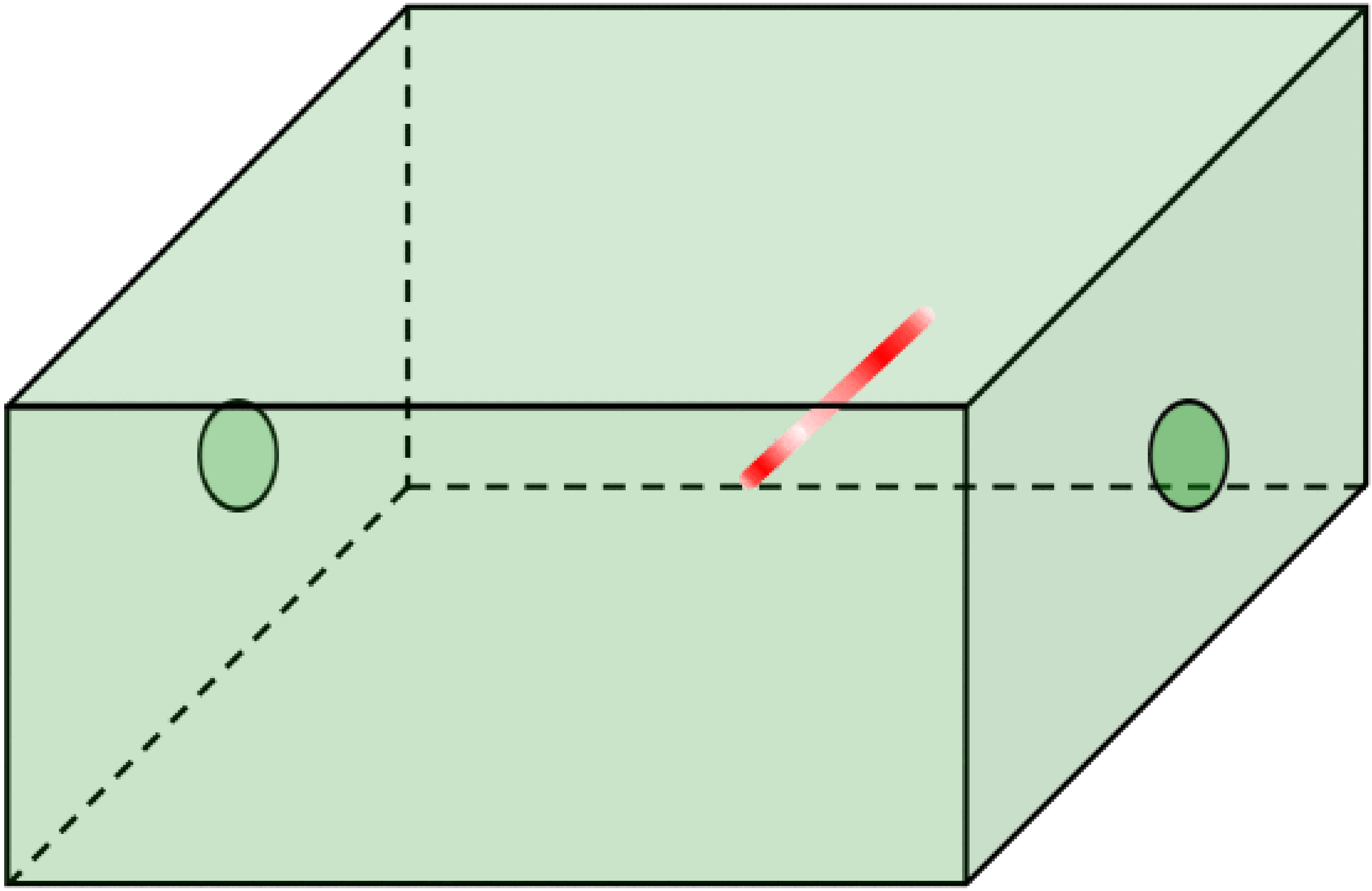

^{4}He
^{13}C

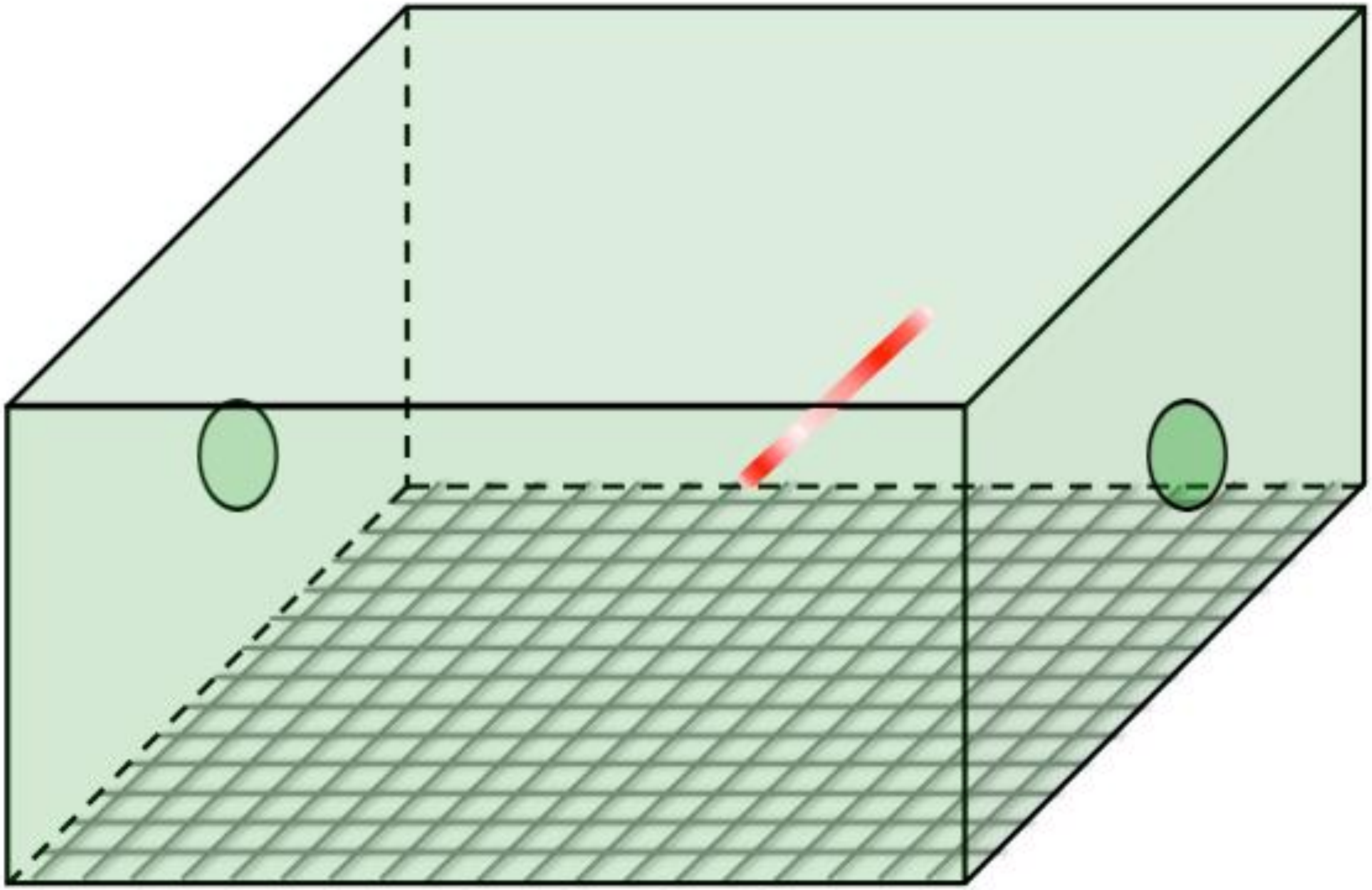


¹³C
α

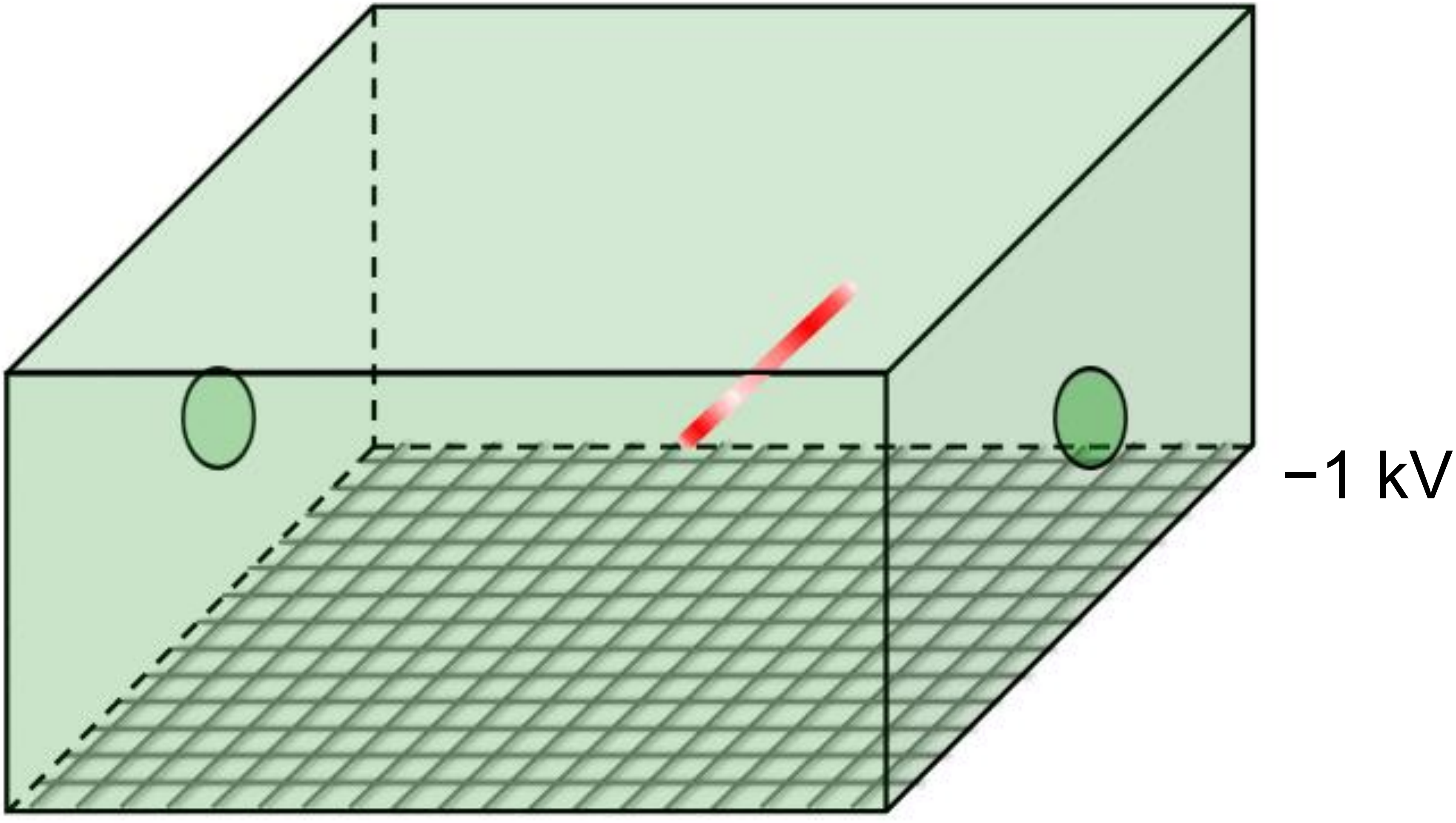

α
α
α

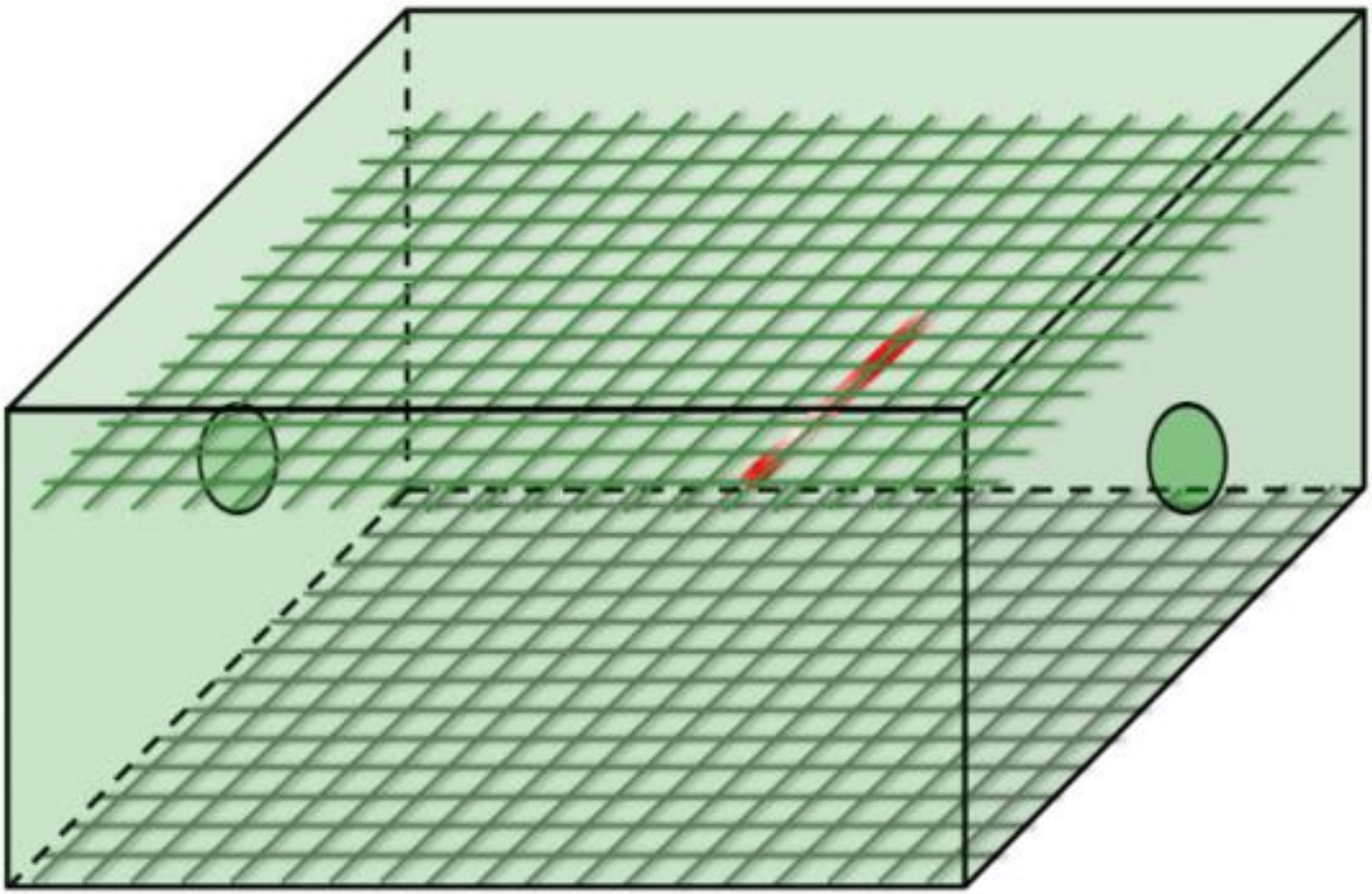


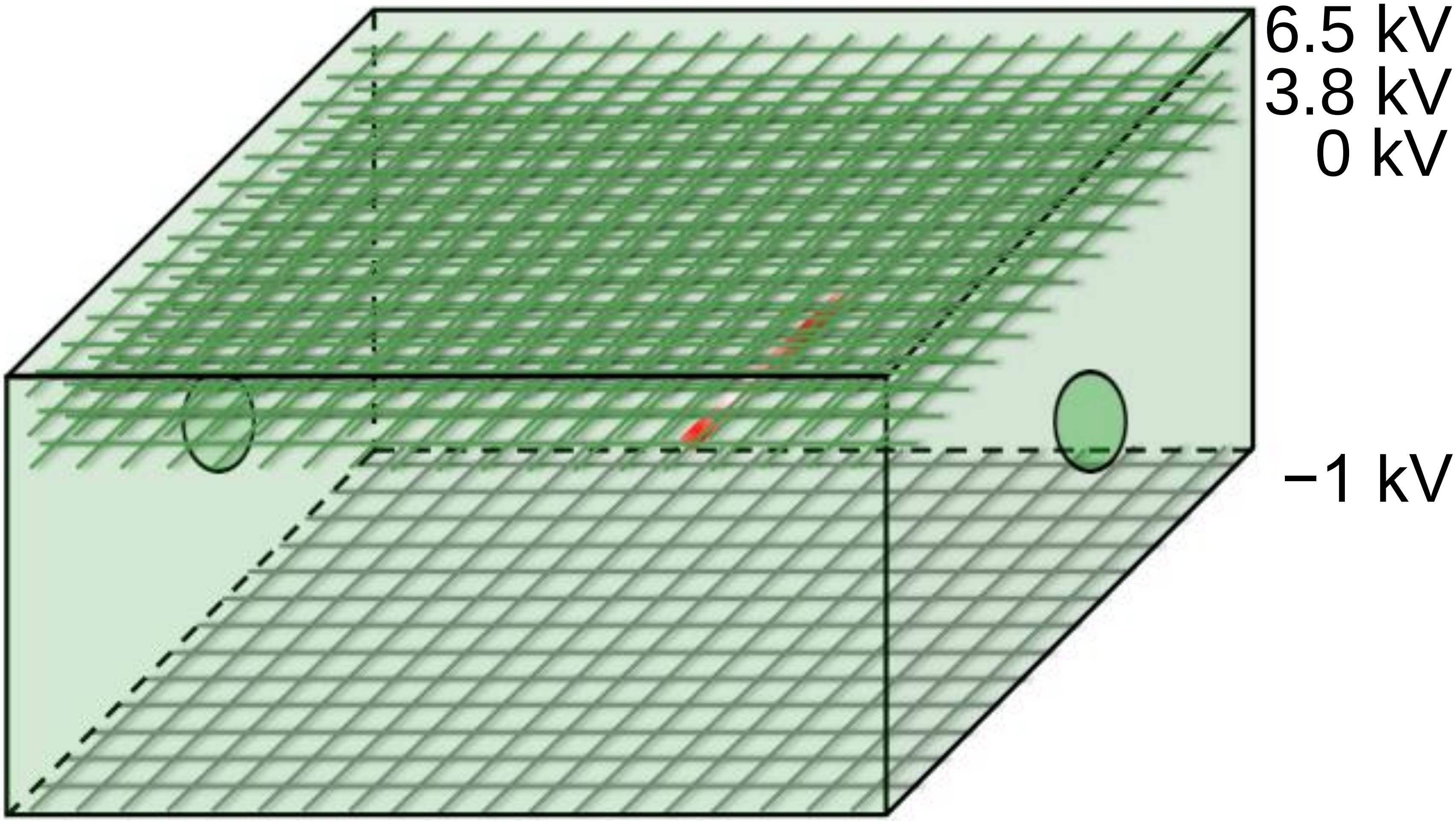




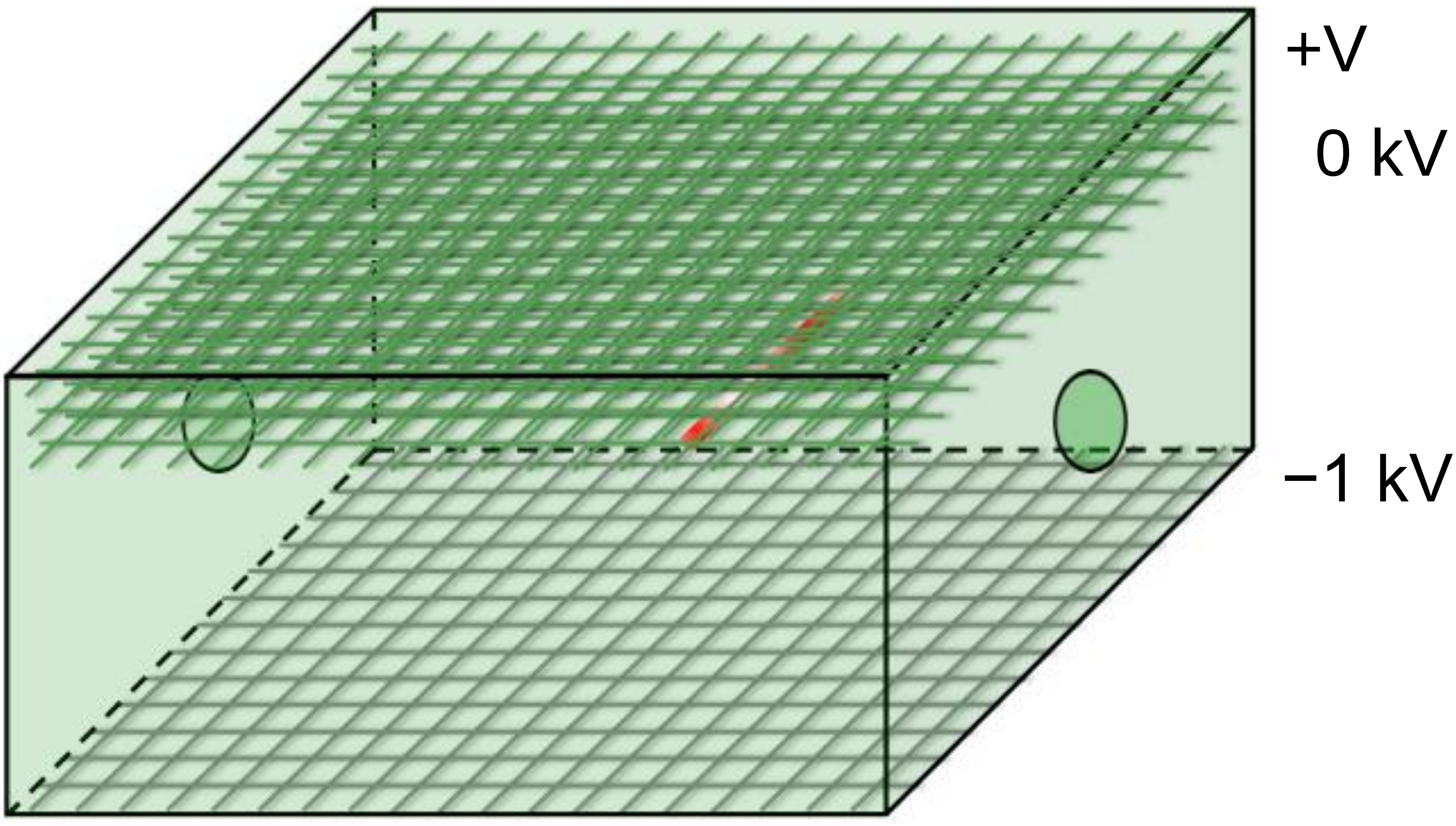
(Repeller) Cathode


−1 kV

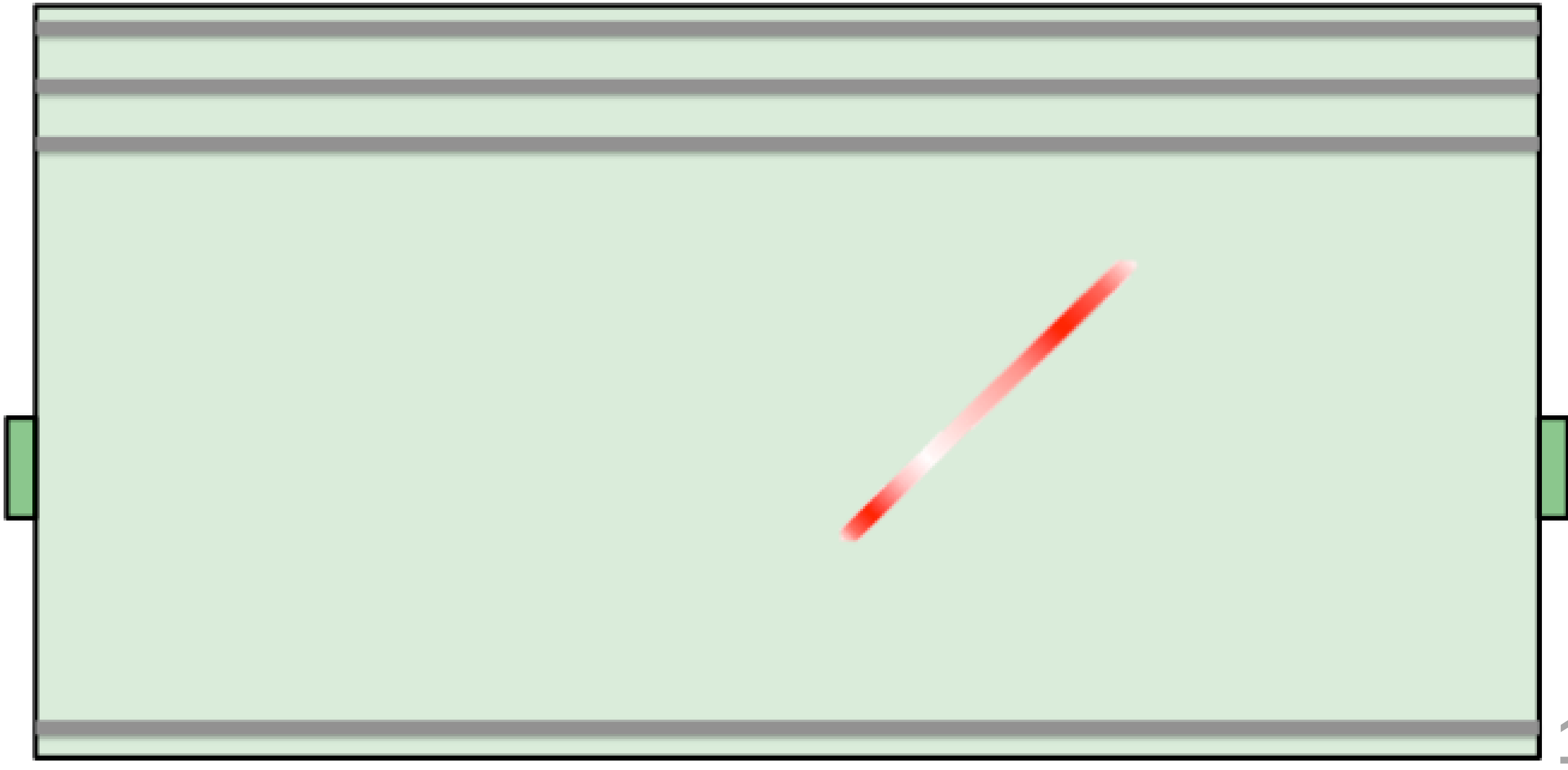

0 kV
−1 kV

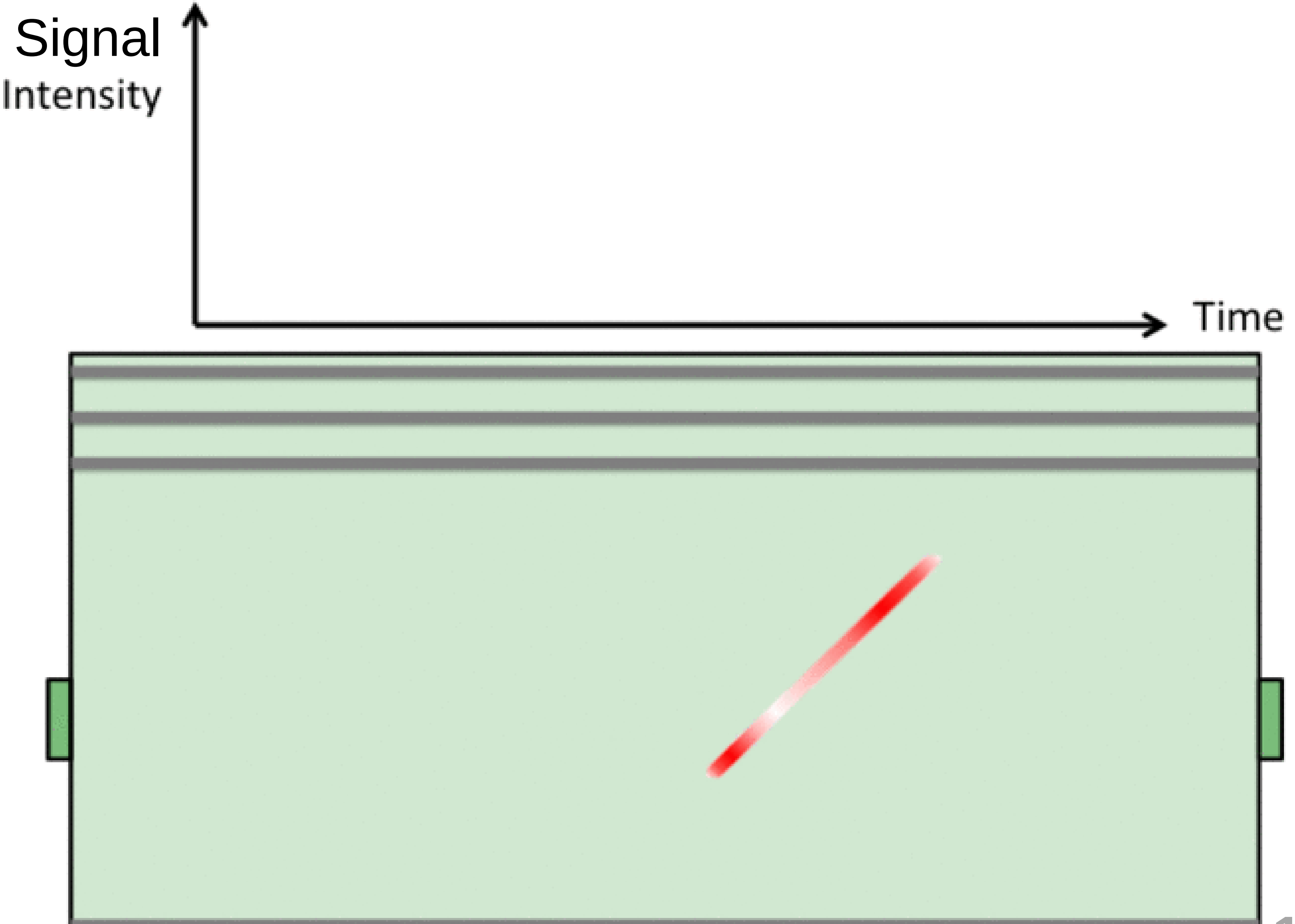

6.5 kV
3.8 kV
0 kV
−1 kV

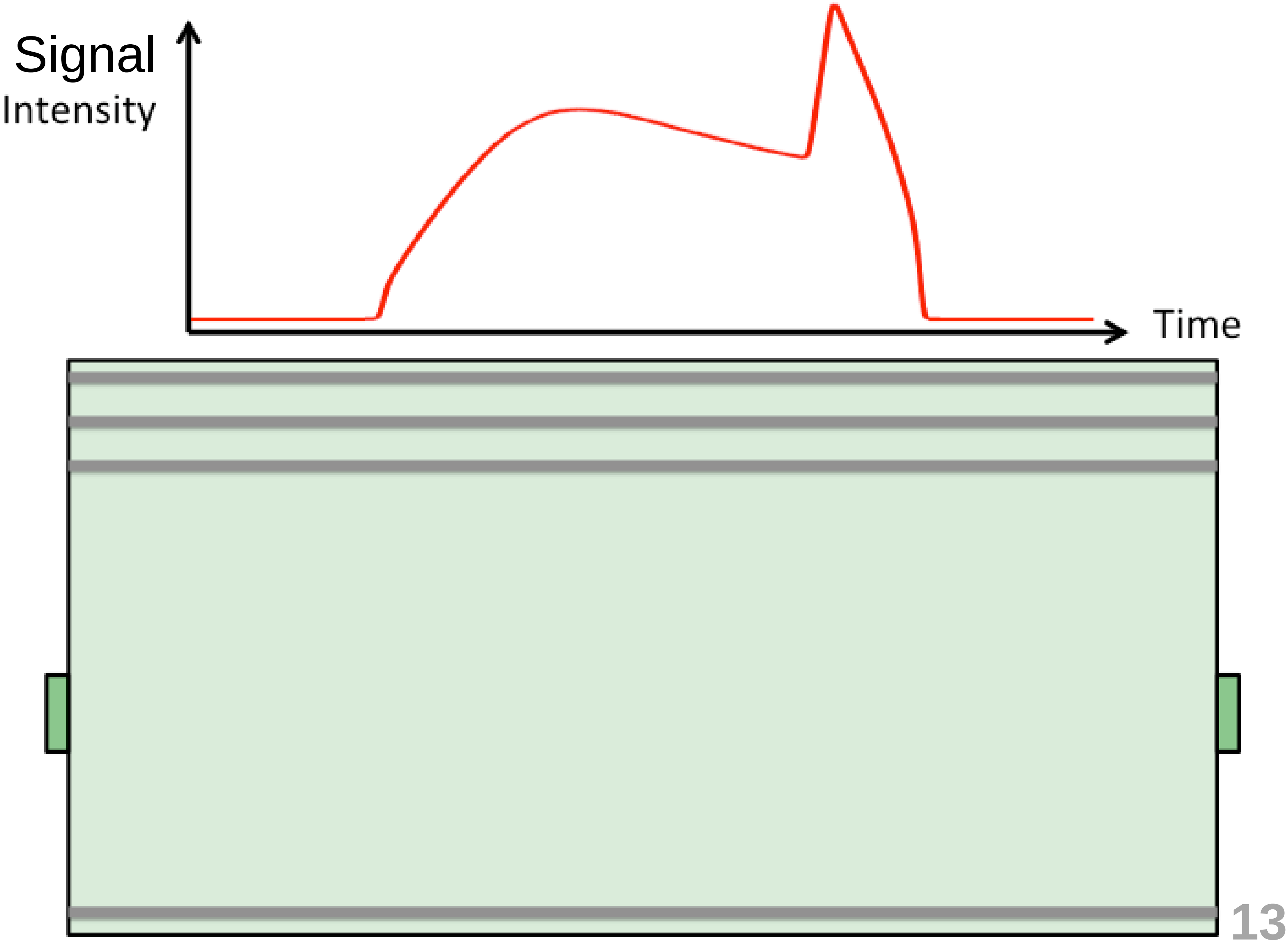
Avalanche grids /micro patterned anode

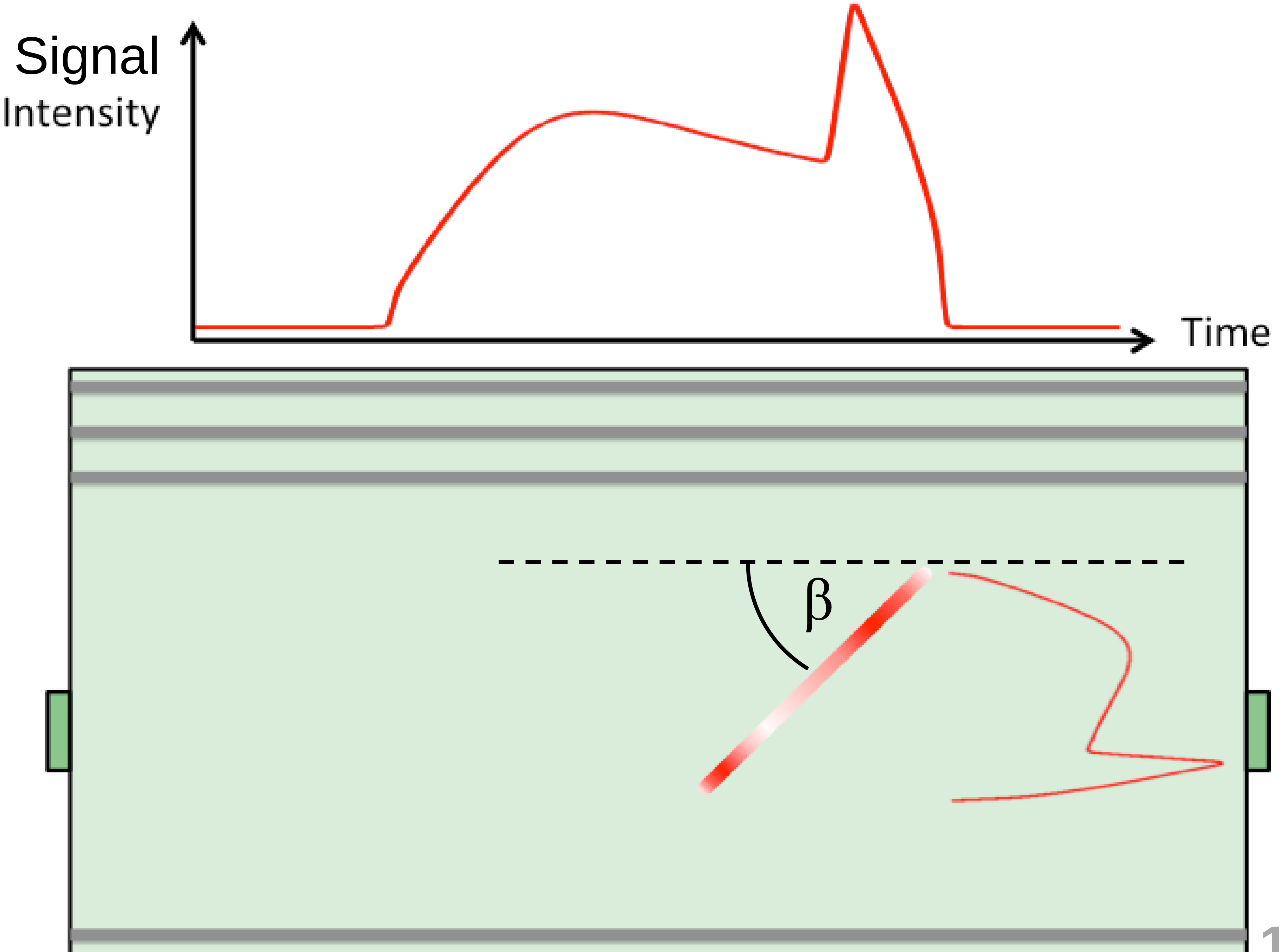


Side view

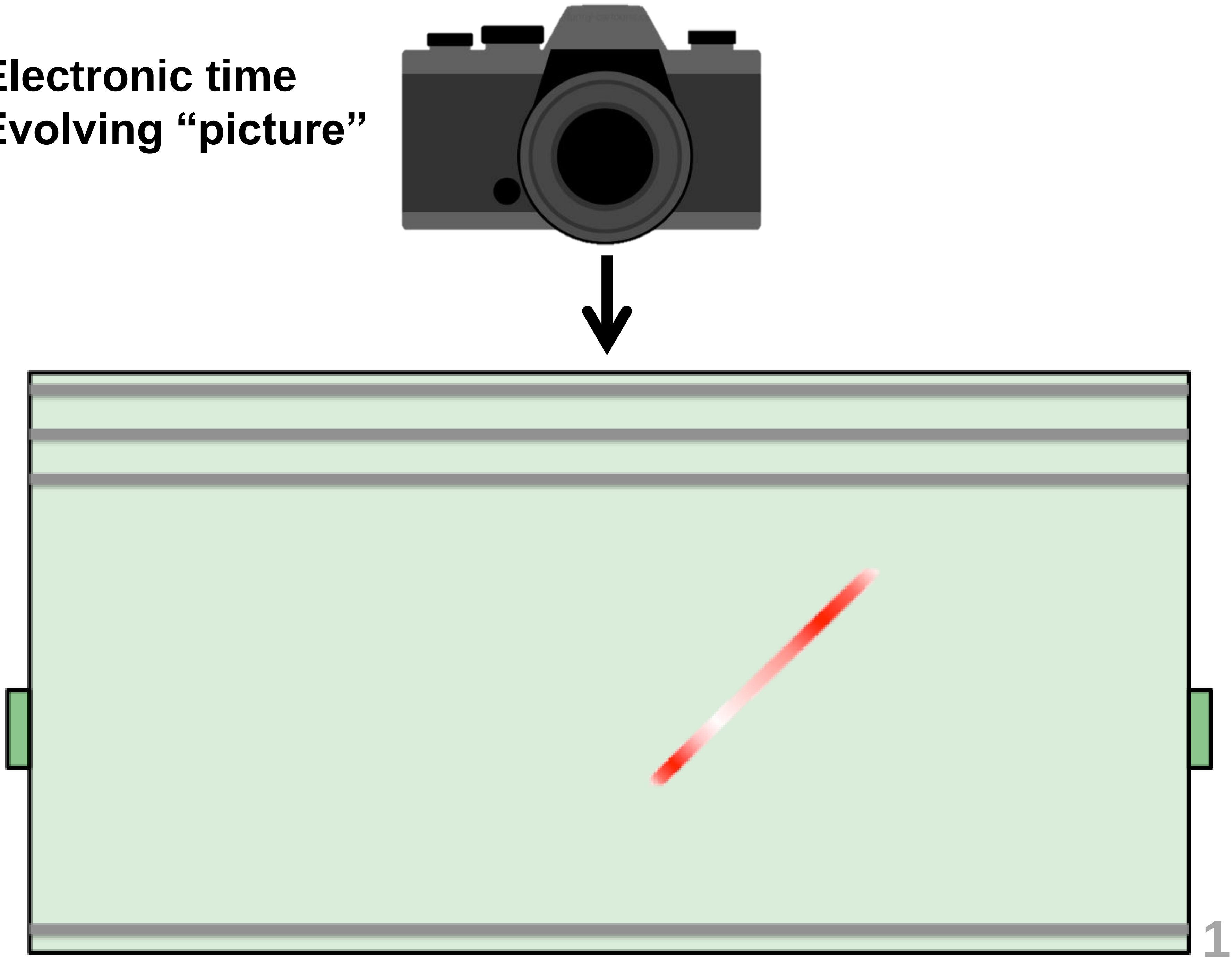


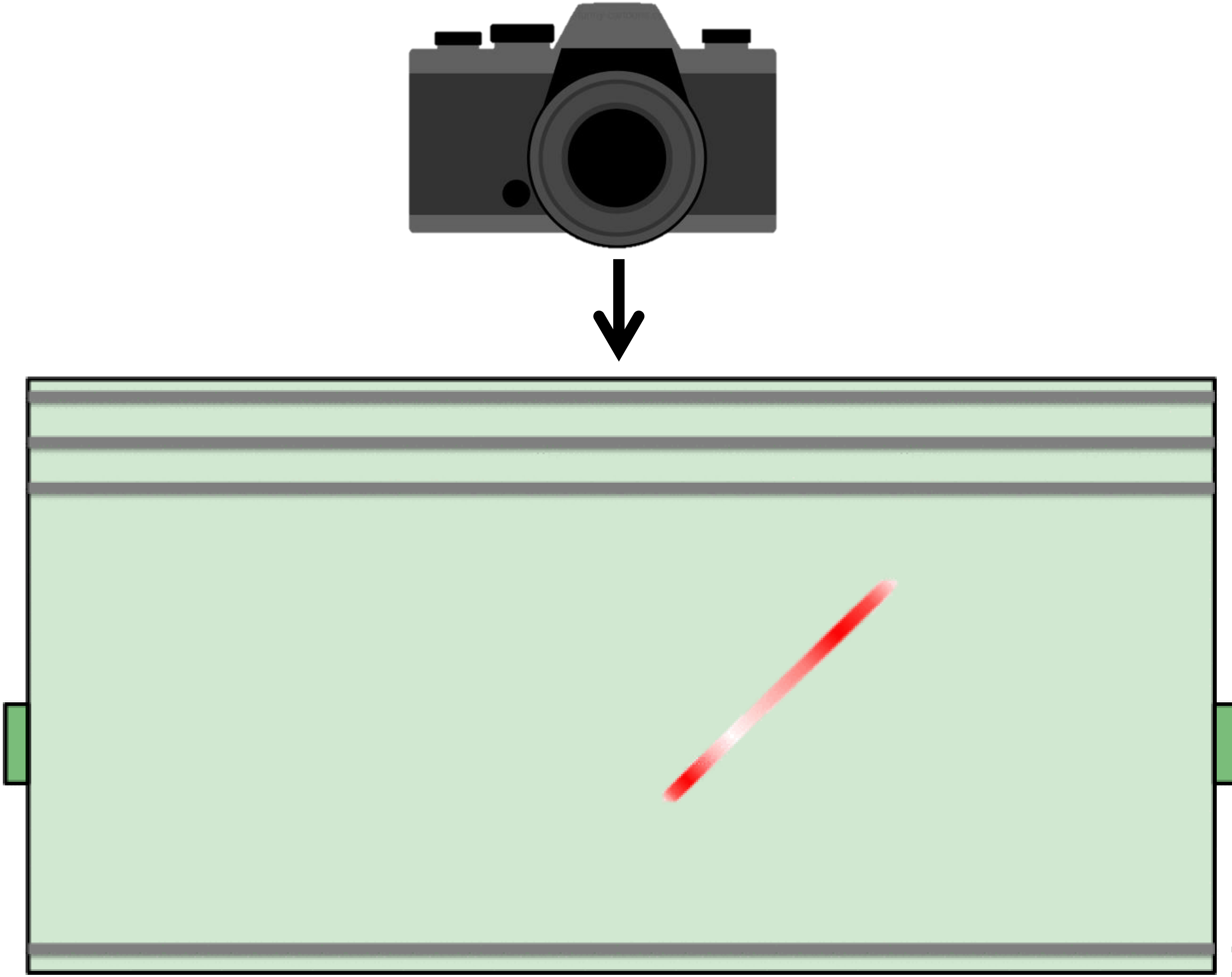

Signal
Intensity
Time

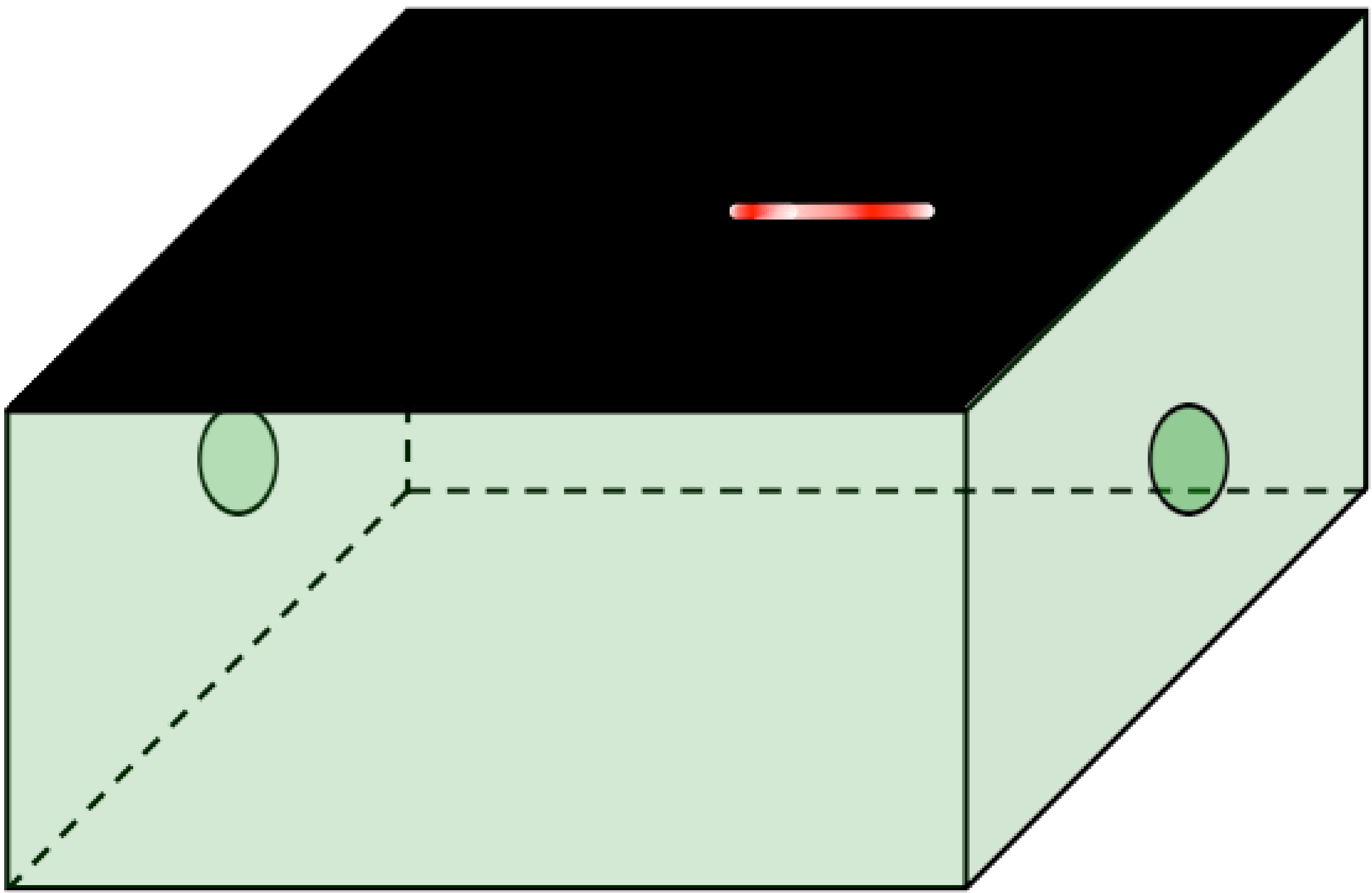

Signal
Intensity
Time

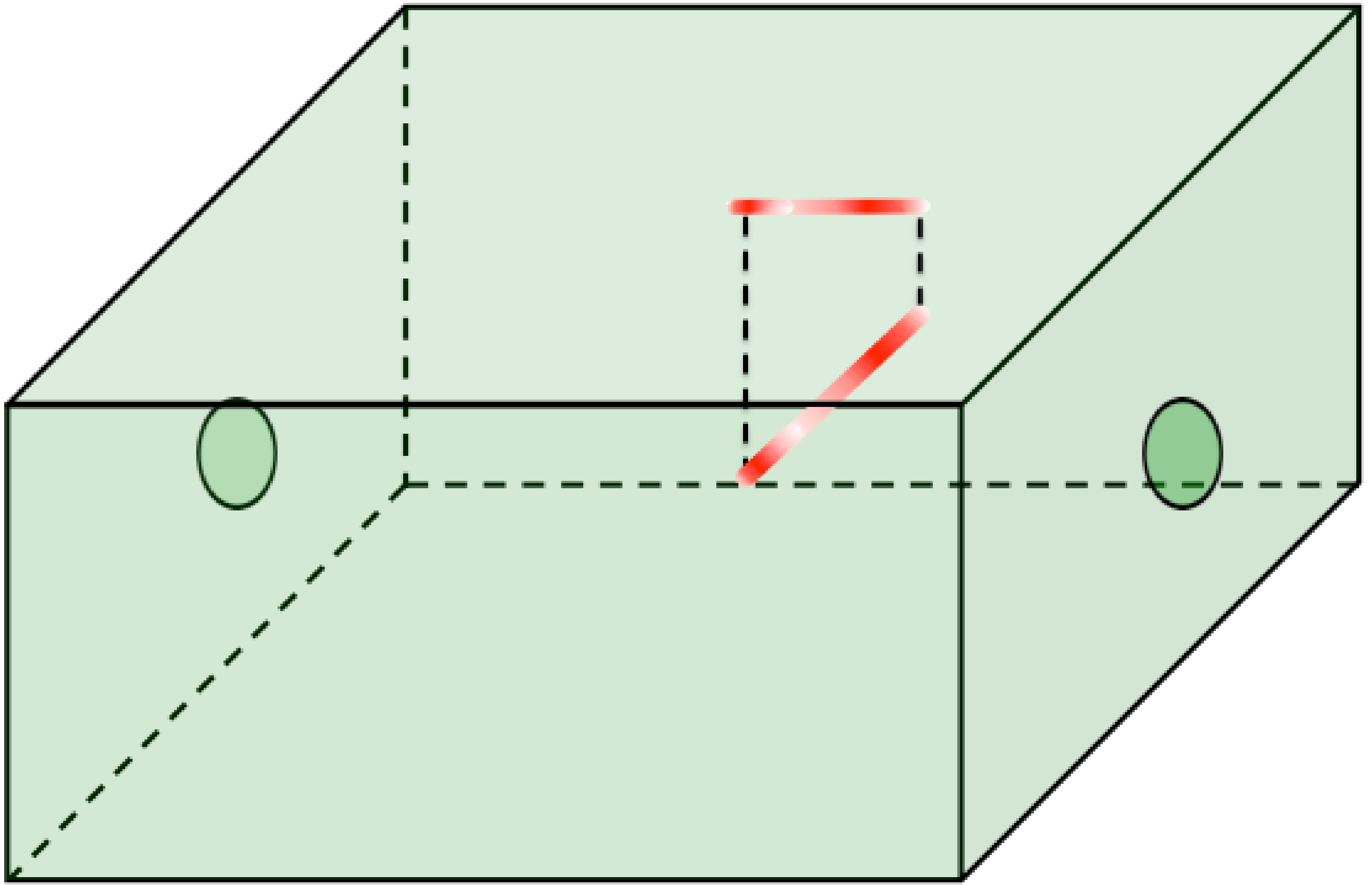

Signal
Intensity
Time
β

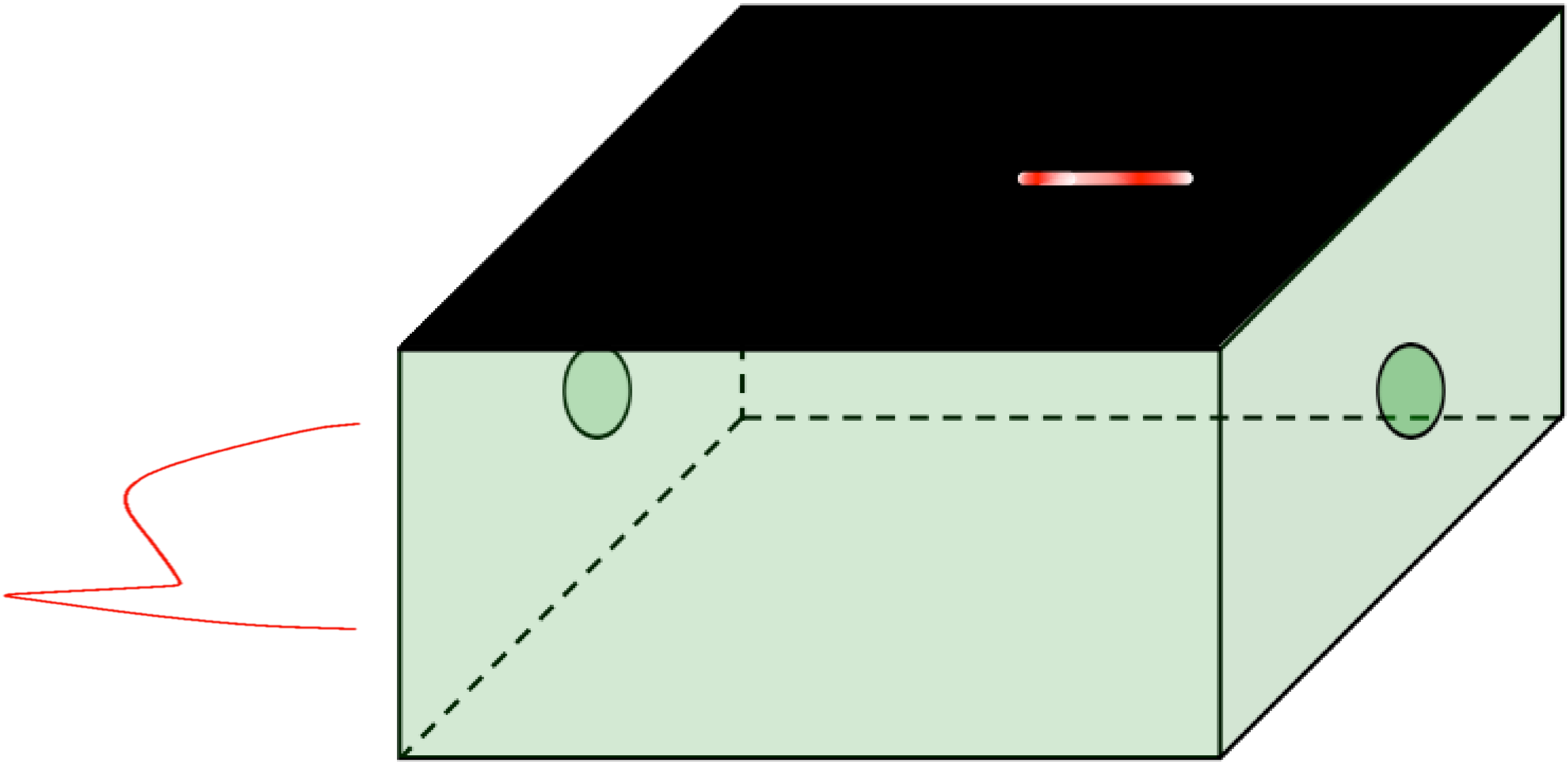
Electronic time
Evolving "picture"



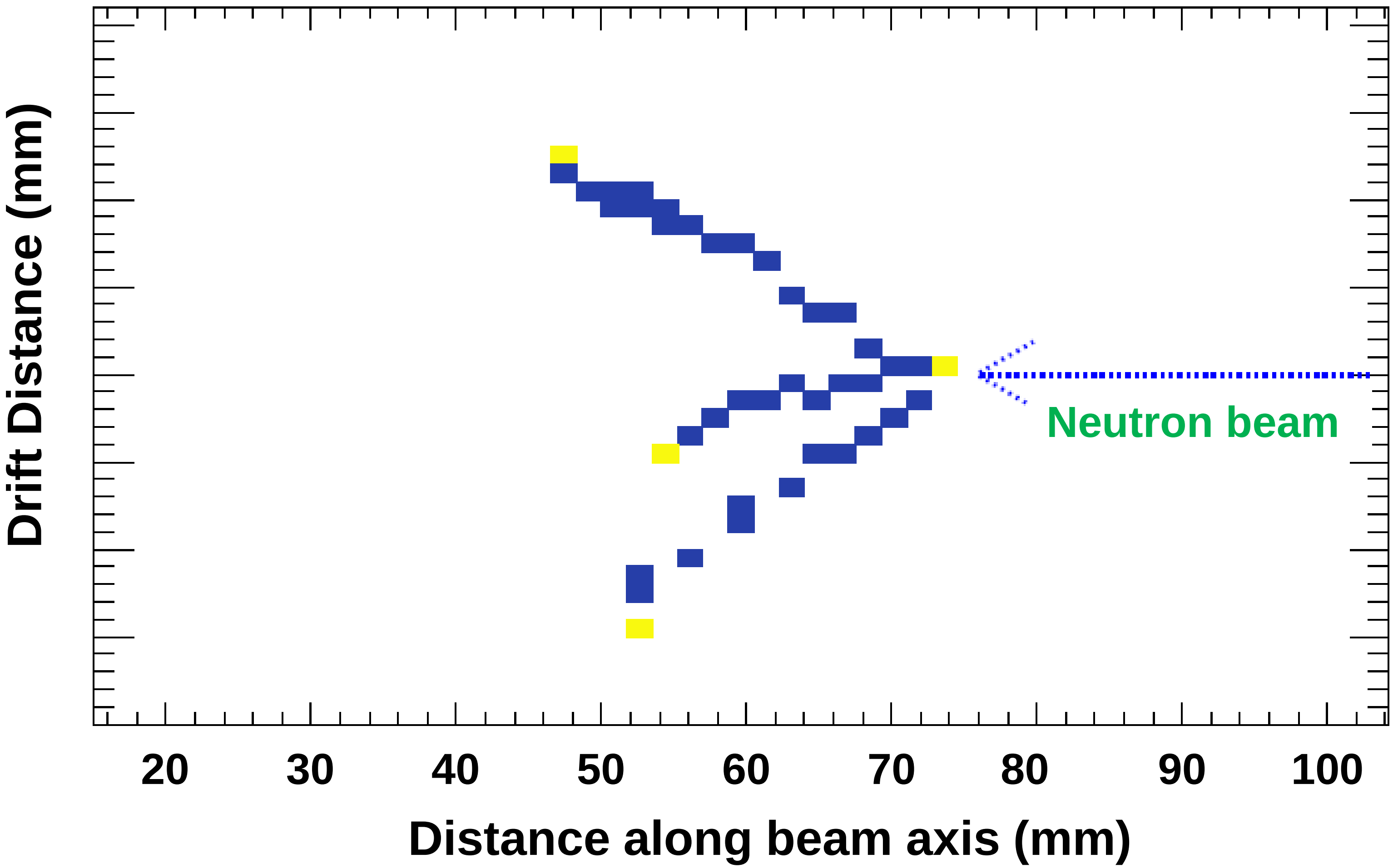


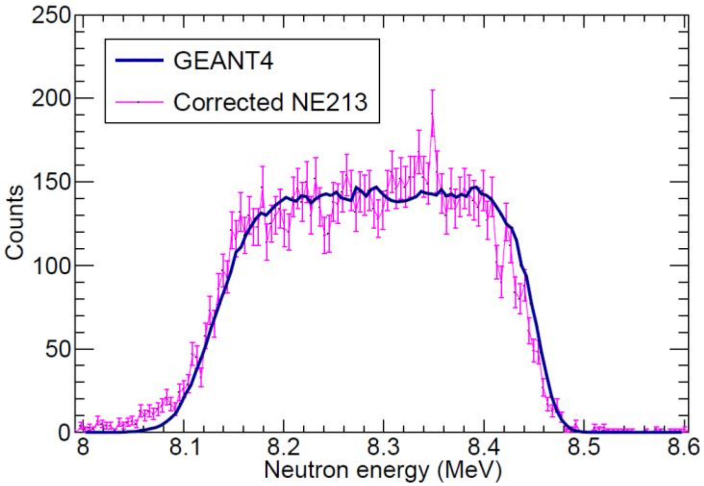


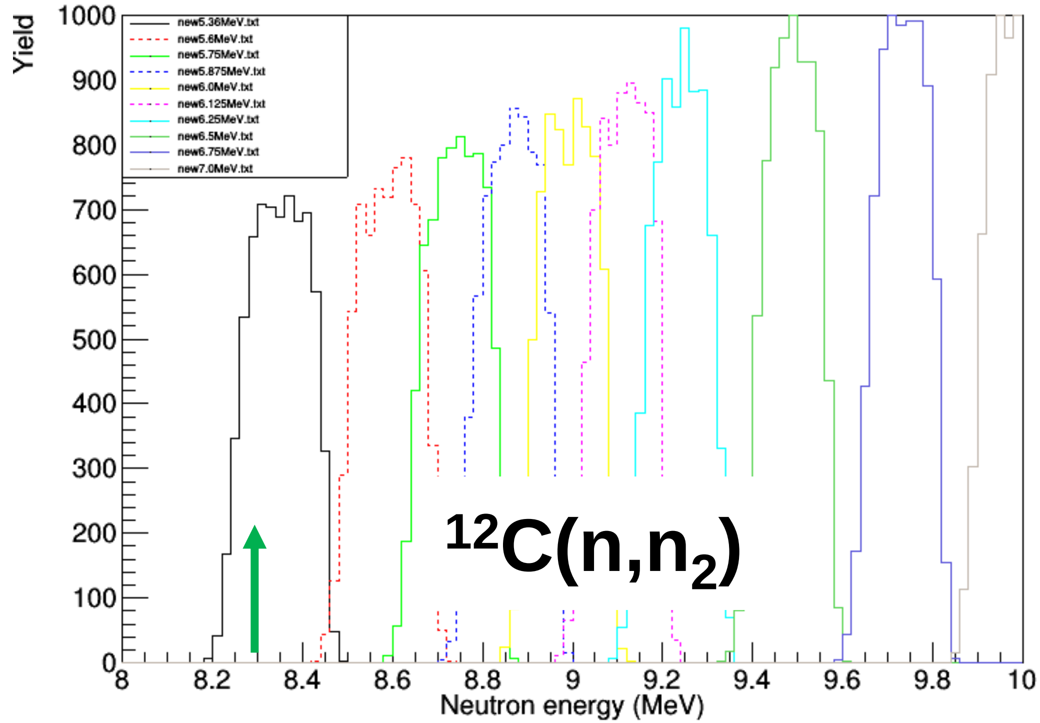


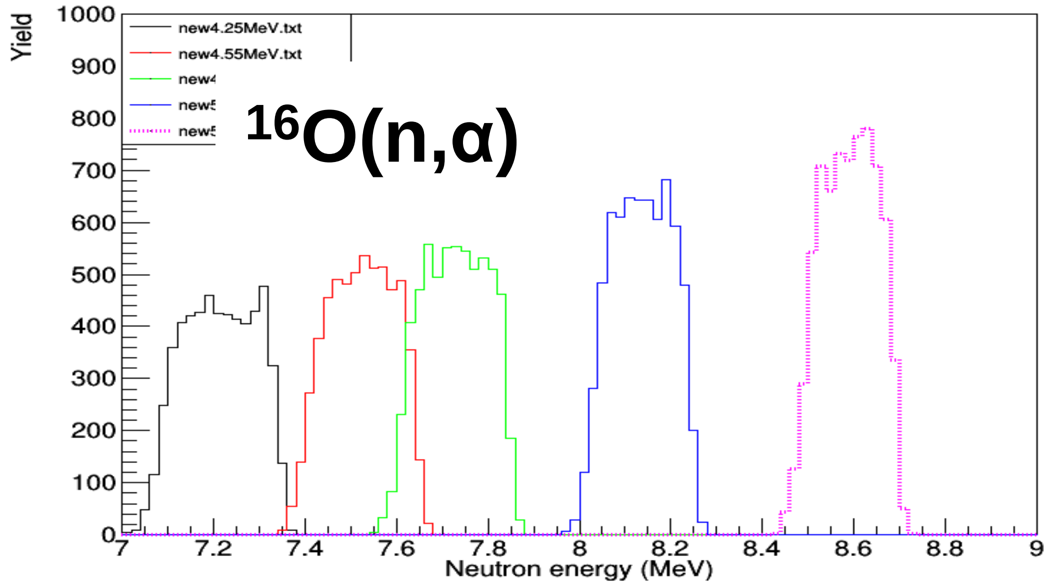


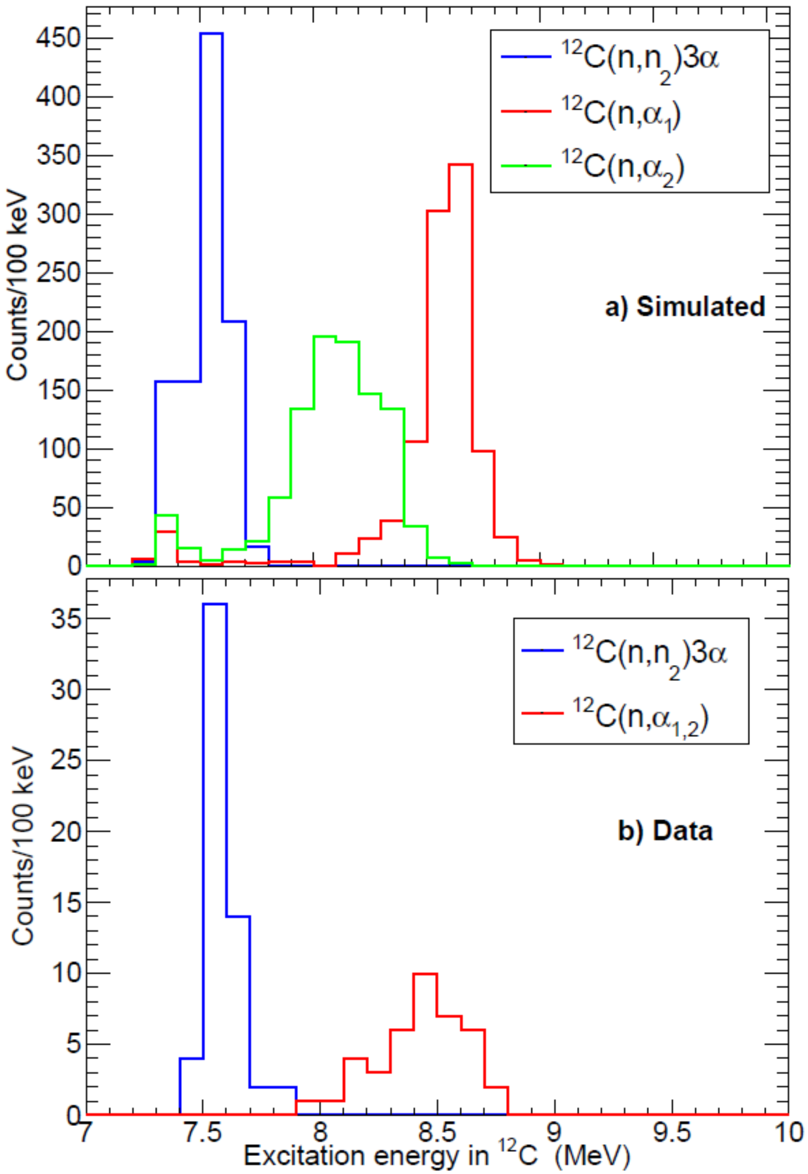
Combining the 2D image and the 1D time projection
→ <u>3D path of the track – angular distributions</u>

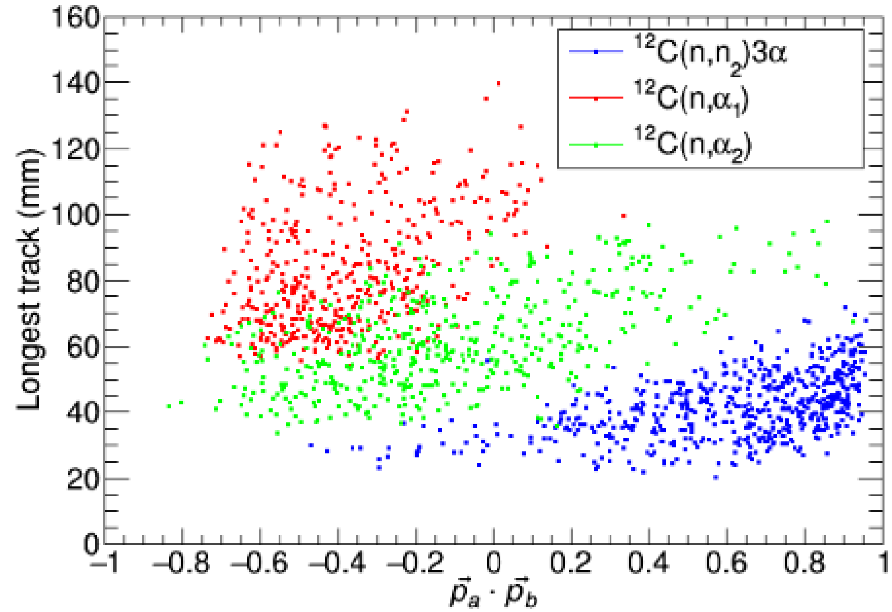

Drift Distance (mm)
Neutron beam
20
30
40
50
60
70
80
90
100
Distance along beam axis (mm)


GEANT4
Corrected NE213
Counts
Neutron energy (MeV)
0
50
100
150
200
250
8
8.1
8.2
8.3
8.4
8.5
8.6

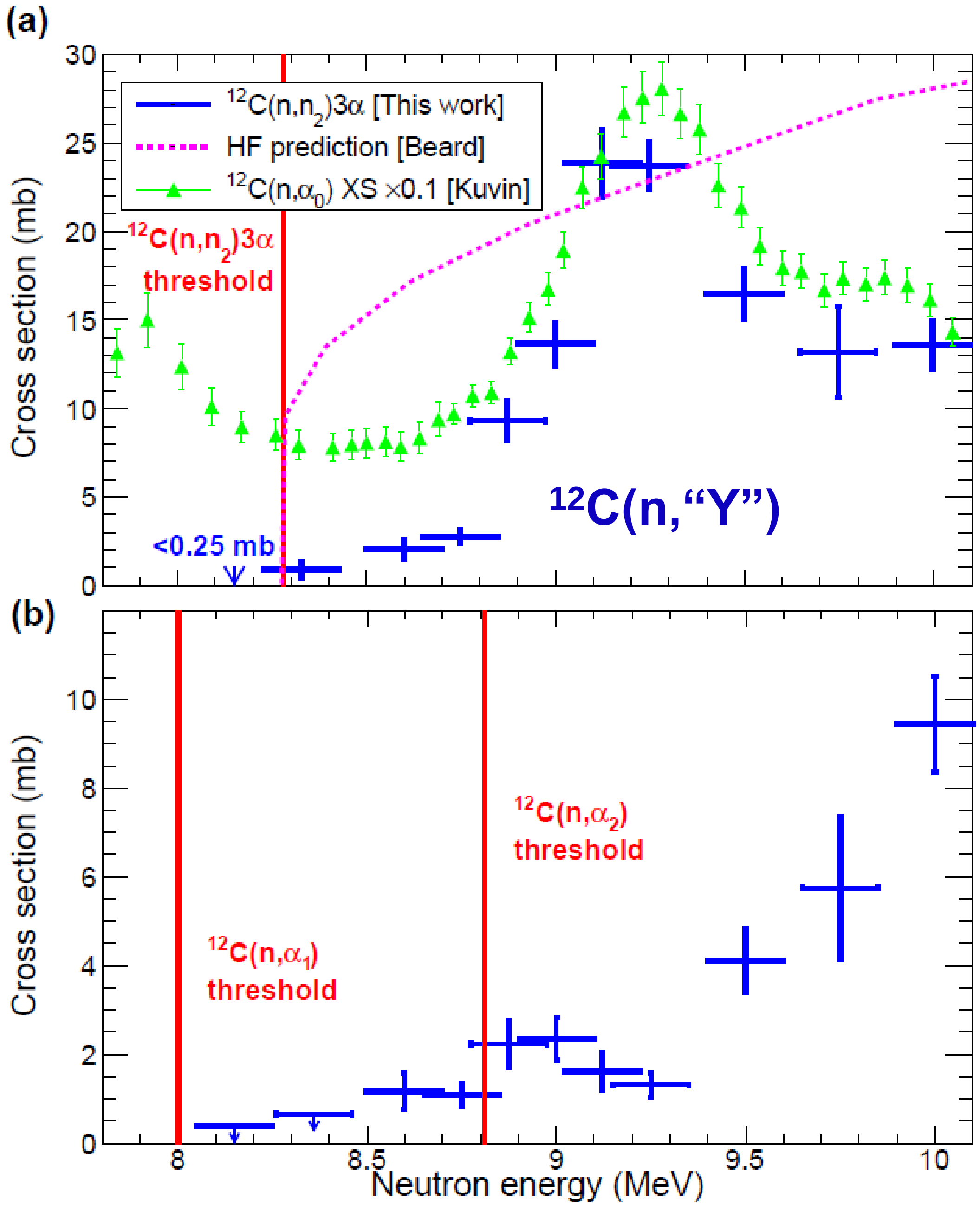

Yield
new5.36MeV.txt
new5.6MeV.txt
new5.75MeV.txt
new5.875MeV.txt
new6.0MeV.txt
new6.125MeV.txt
new6.25MeV.txt
new6.5MeV.txt
new6.75MeV.txt
new7.0MeV.txt
$^{12}C(n,n_2)$
Neutron energy (MeV)
0
100
200
300
400
500
600
700
800
900
1000
8
8.2
8.4
8.6
8.8
9
9.2
9.4
9.6
9.8
10

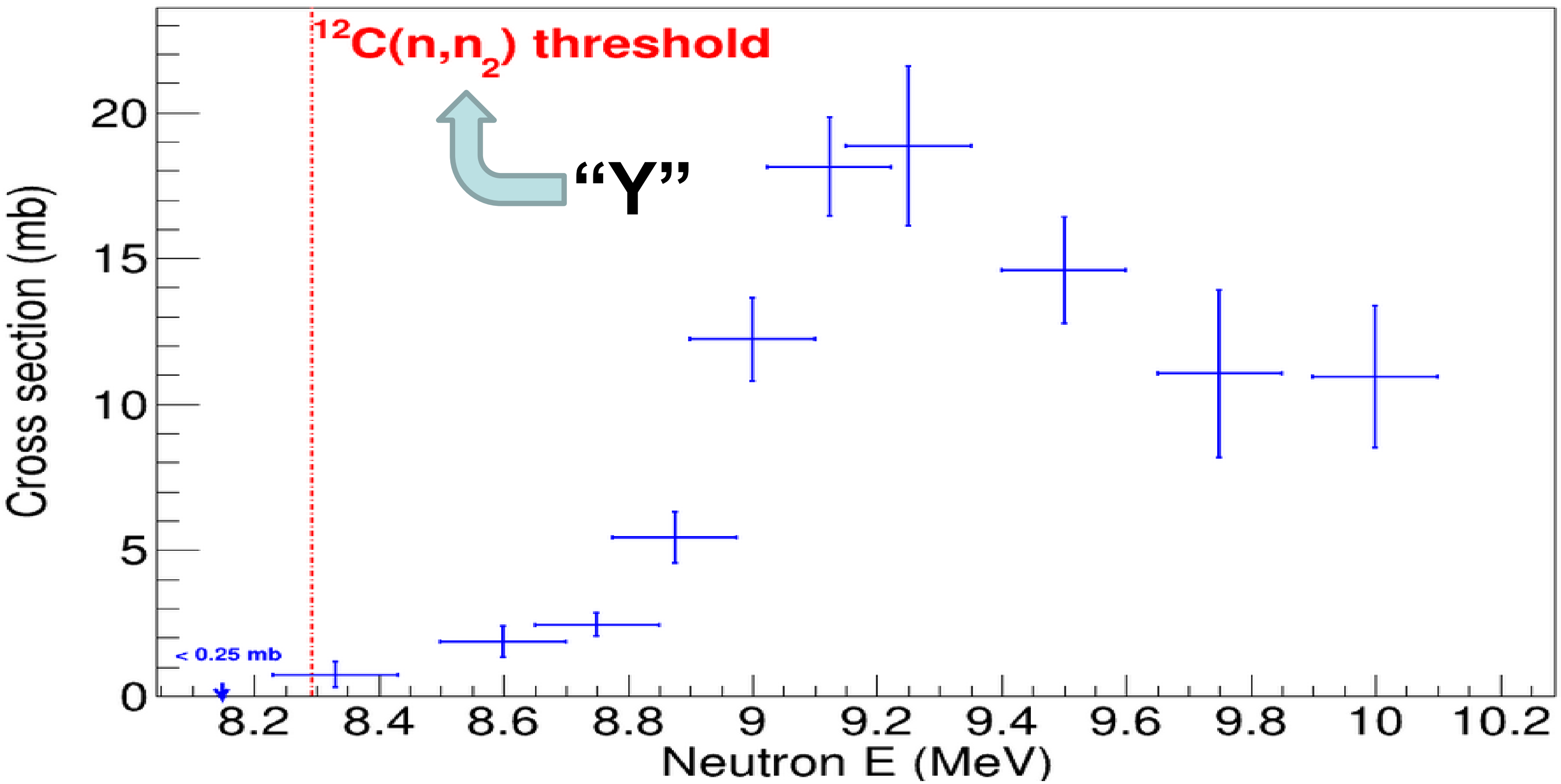

Yield
new4.25MeV.txt
new4.55MeV.txt
new4
new5
new5
$^{16}O(n,\alpha)$
Neutron energy (MeV)
0
100
200
300
400
500
600
700
800
900
1000
7
7.2
7.4
7.6
7.8
8
8.2
8.4
8.6
8.8
9

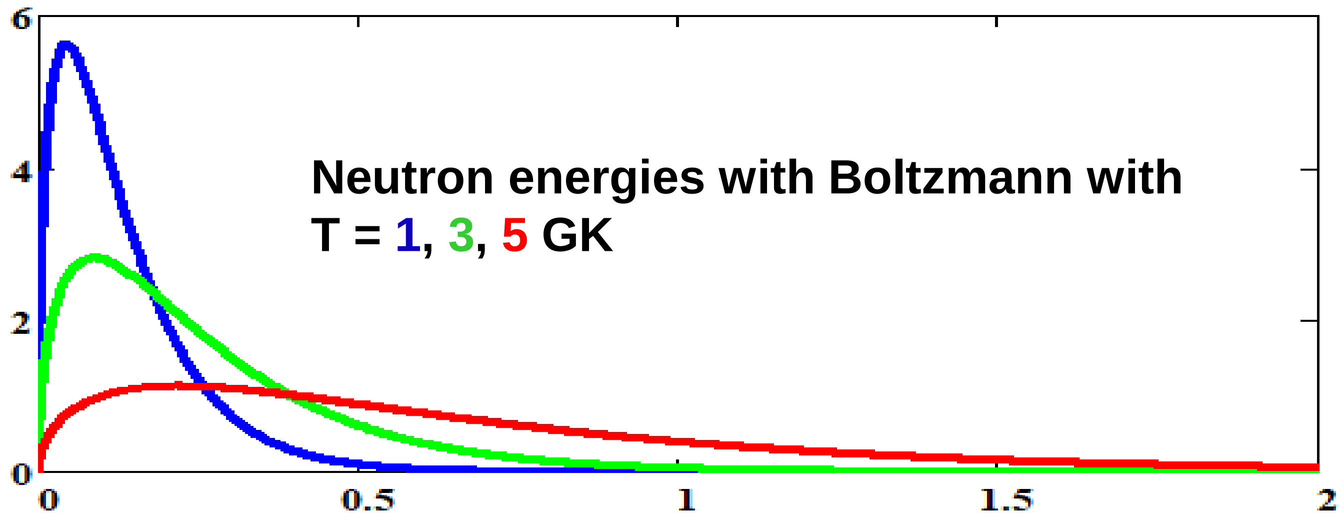




Jack Bishop's brilliant analysis


(a)
Cross section (mb)
^{12}C(n,n$_2$)3α [This work]
HF prediction [Beard]
^{12}C(n,α$_0$) XS ×0.1 [Kuvin]
^{12}C(n,n$_2$)3α threshold
<0.25 mb
^{12}C(n,"Y")
(b)
Cross section (mb)
^{12}C(n,α$_2$) threshold
^{12}C(n,α$_1$) threshold
Neutron energy (MeV)


$^{12}C(n,n_2)$ threshold
"Y"
< 0.25 mb
Cross section (mb)
Neutron E (MeV)
0
5
10
15
20
8.2
8.4
8.6
8.8
9
9.2
9.4
9.6
9.8
10
10.2


Neutron energies with Boltzmann with
T = 1, 3, 5 GK
0
2
4
6
0
0.5
1
1.5
2

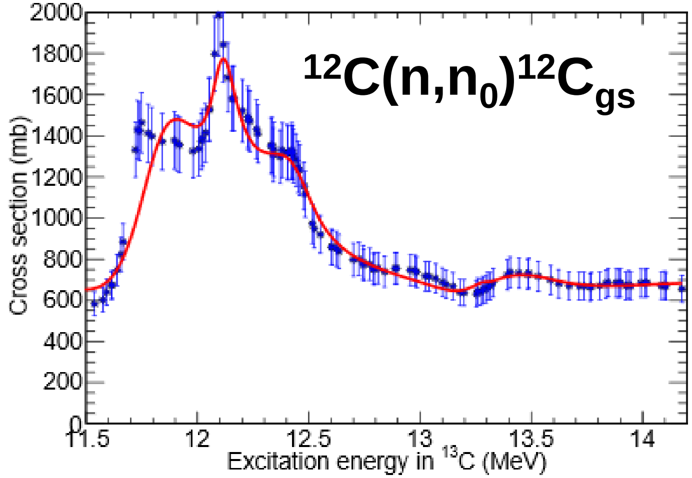


Figure 4: $^{12}C(n, n_0)$ cross section (points) overlaid with multi-channel R-Matrix fit in red.

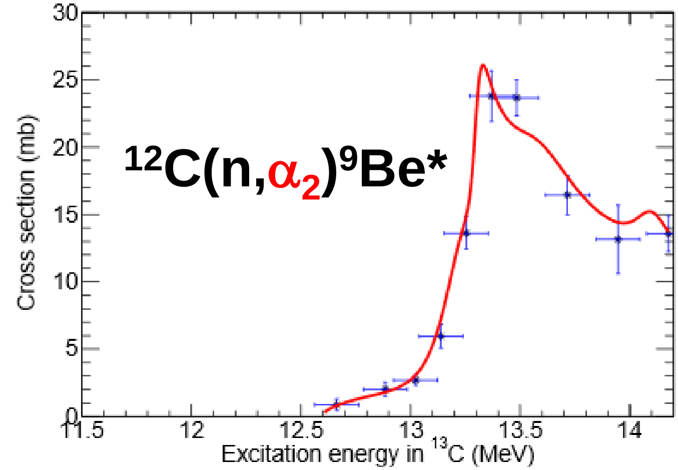


Figure 6: $^{12}C(n, n_2)$ cross section from this work (points) overlaid with multi-channel R-Matrix fit in red.

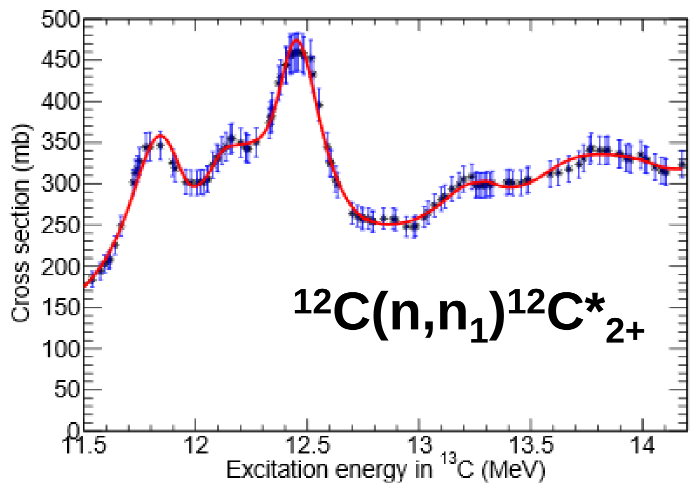


Figure 5: $^{12}C(n, n_1)$ cross section (points) overlaid with multi-channel R-Matrix fit in red.

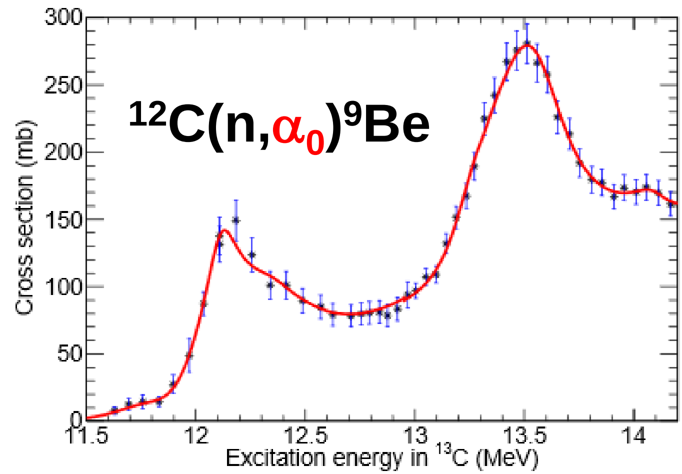


Figure 7: $^{12}C(n, \alpha_0)$ cross section (points) overlaid with multi-channel R-Matrix fit in red.

Table 1: Excited states in ^{13}C included in the R-Matrix fit in the astrophysical range of interest

Spin parity	E_x (MeV)	Γ_{n0} (keV)	Γ_{n1} (keV)	Γ_{n2} (keV)	Γ_{α_0} (keV)
$\frac{1}{2}^+$	13.28	0.2	2.7	106.8	15.5
$\frac{3}{2}^-$	13.28	146.5	71.6	44.7	291.3
$\frac{7}{2}^-$	13.57	54	8.1	15.4	366.1
$\frac{5}{2}^+$	13.76	401.9	1065.6	0.7	201.8

The bottom line …..to get amplification need: high [n] & HOT

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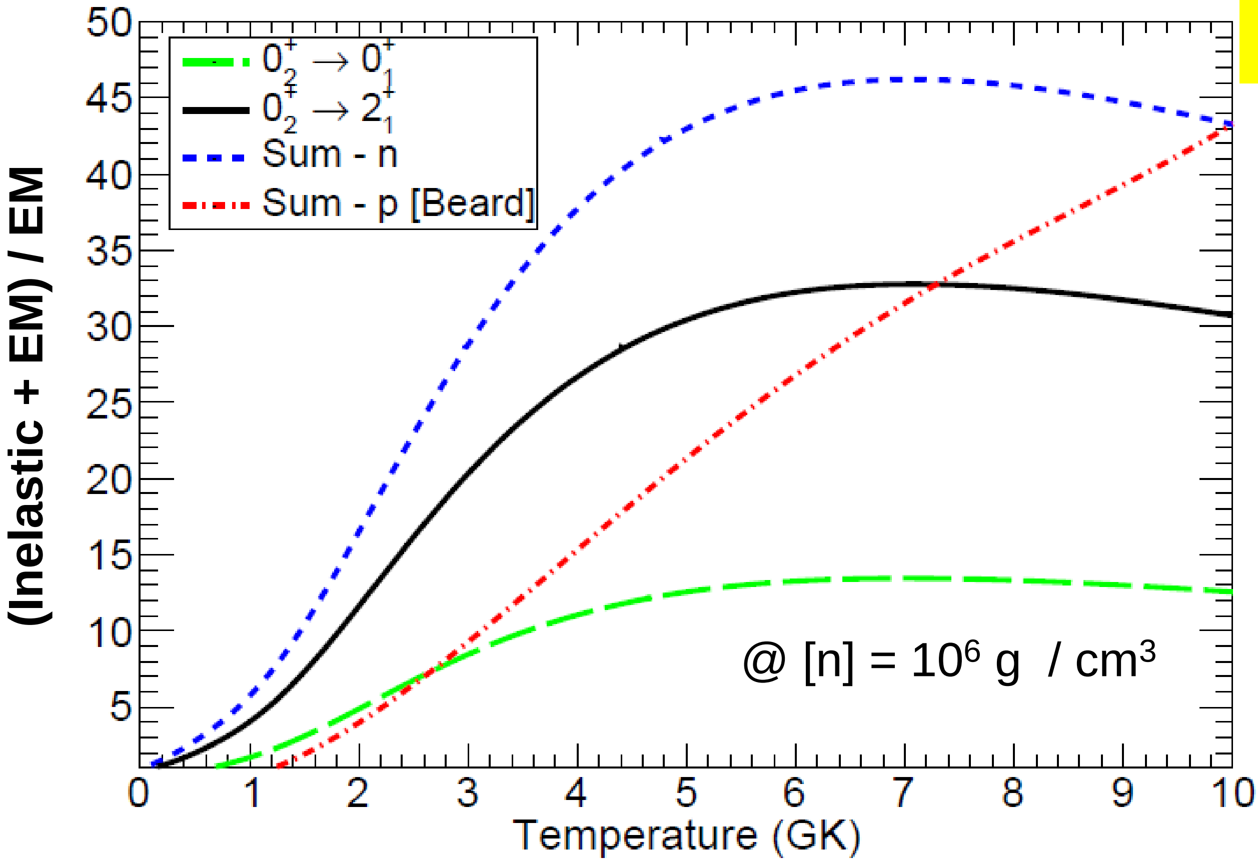
***TAMU** + OU + WU …*



Neutron-upscattering enhancement of the triple-alpha process

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Is ^{12}C – the seed for the PT – made by inelastic upscattering or EM decay?

?? (unlikely upscattering…) ??

But now astro folks who simulate stellar life and death (spirals) have the cross sections they need.

Nature

Robin Smith ➔
Jack Bishop ➔

Note: not yet plumbed the $^{13}C(\alpha,n)^{16}O$

Experiment