The $^{18}O(\alpha, \gamma)^{22}Ne$ reaction measurement with DRAGON in inverse kinematics

Dhruval Shah

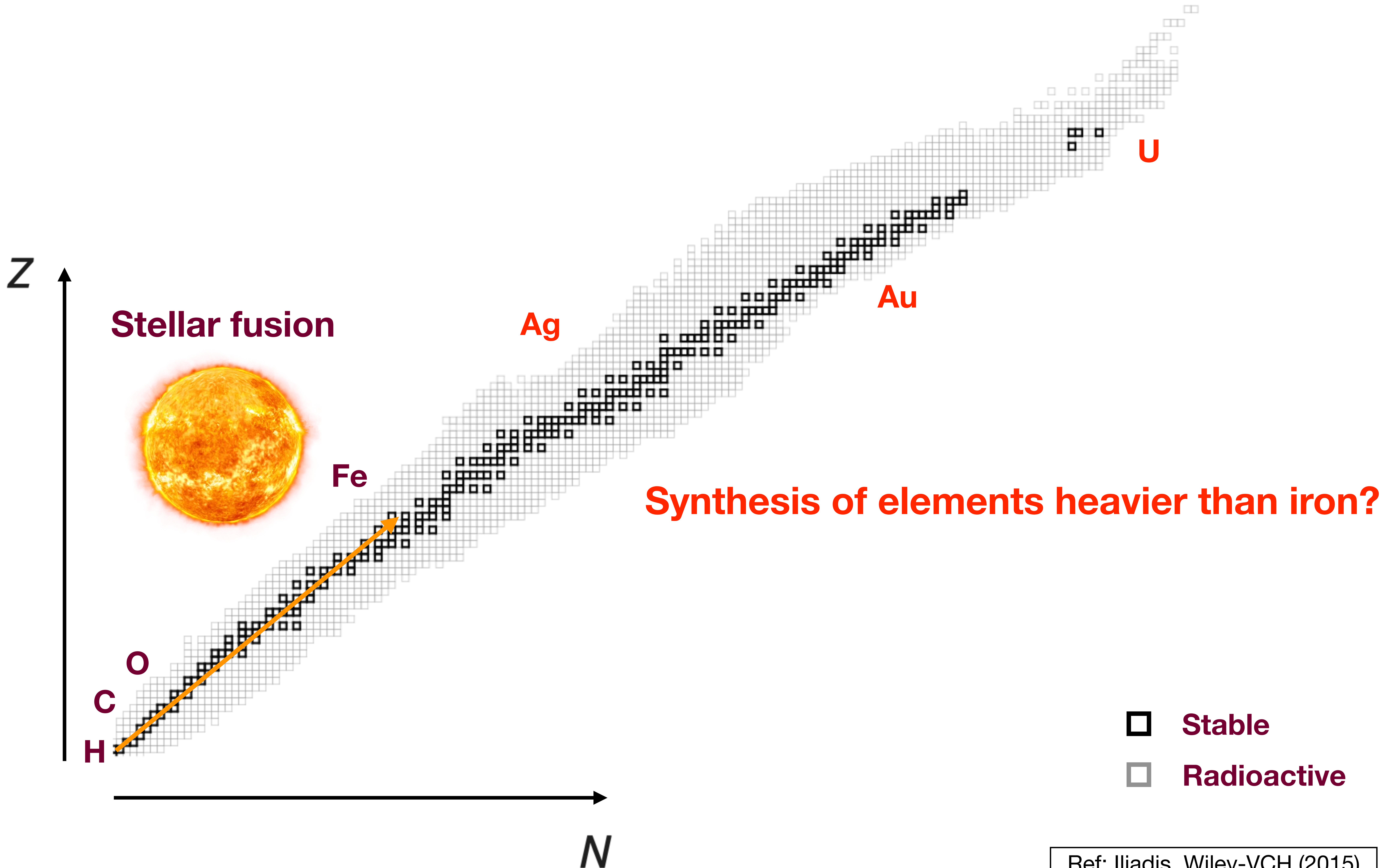
Advisor: Dr. Alan Chen

CAP Congress

June 22, 2026

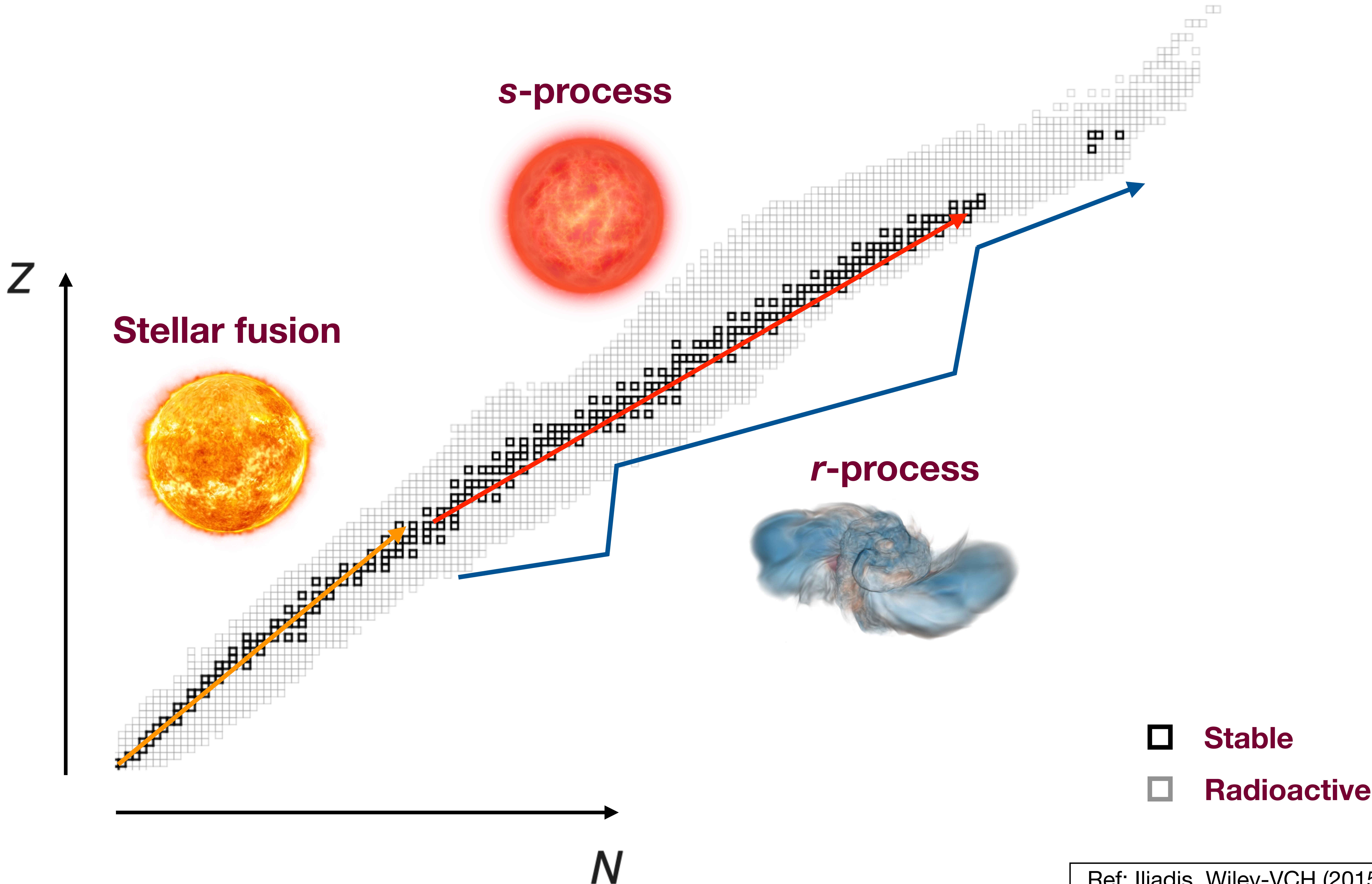
Image: Spitzer, Hubble, and Chandra. Cassiopeia A

Nuclear chart



Ref: Iliadis. Wiley-VCH (2015)
Image: A. Psaltis

Nuclear chart



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Nuclear chart

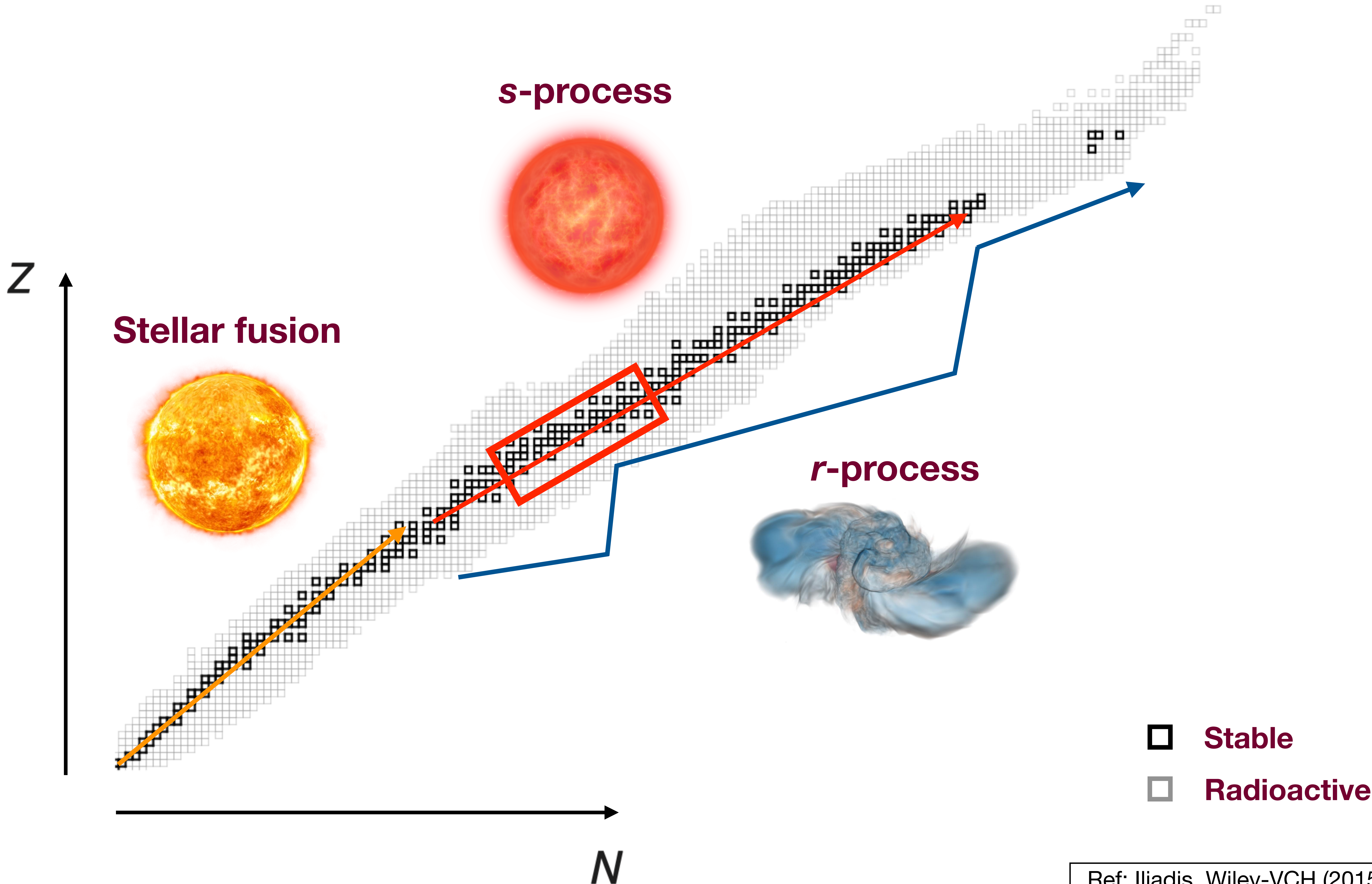

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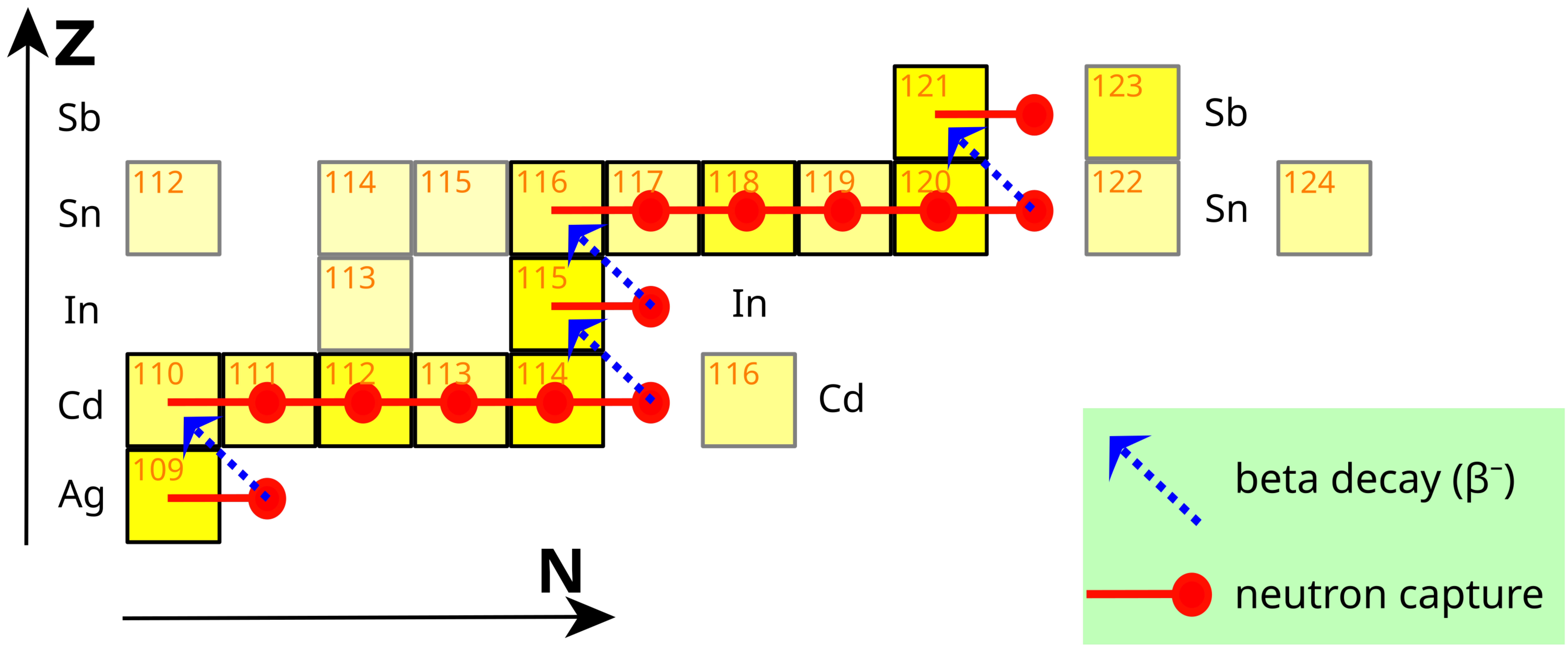
Image: A. Psaltis

Slow neutron-capture process (s-process)

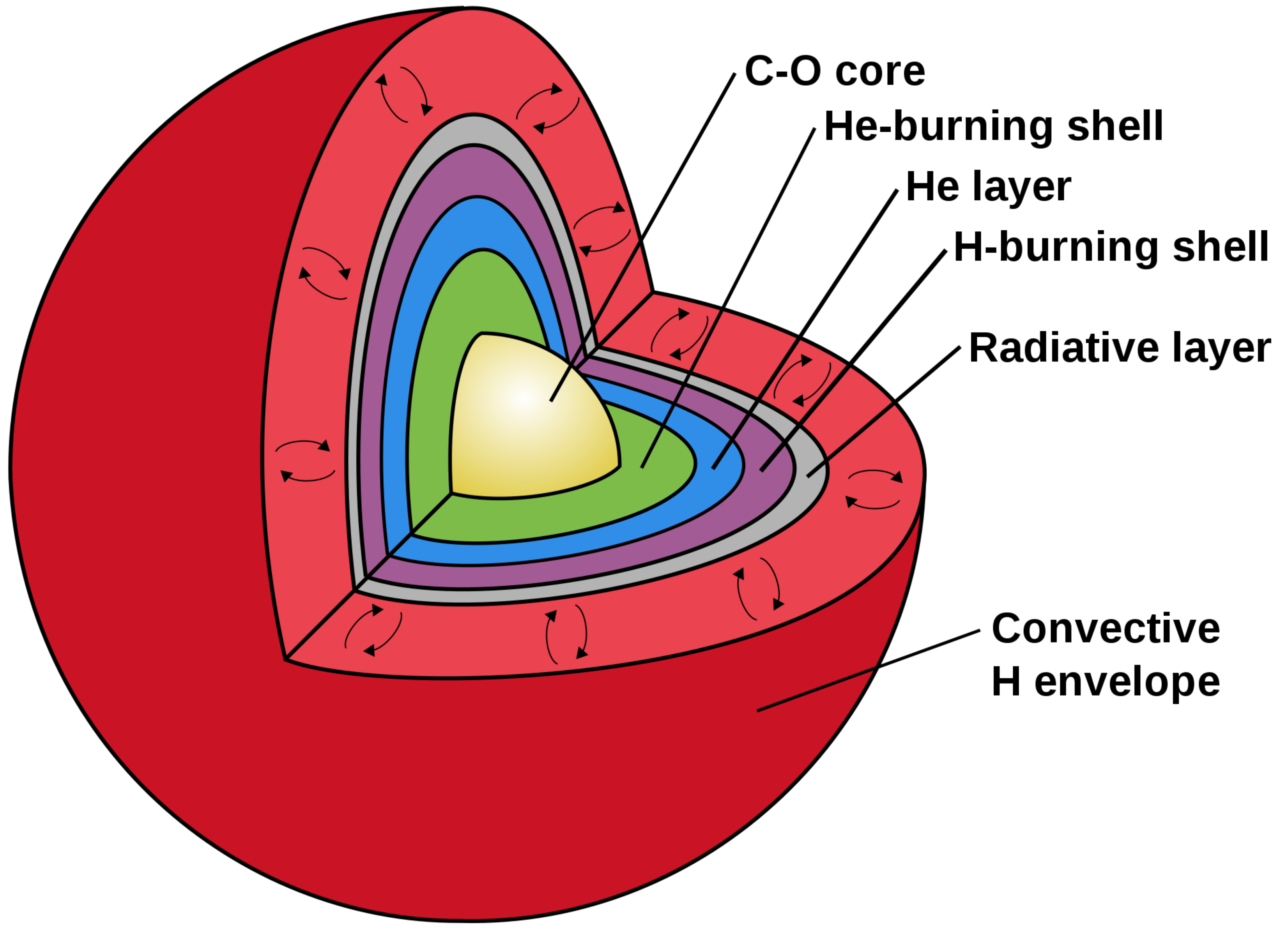
- Synthesizes approximately half of the elements heavier than iron
- Neutron captures on nuclei close to stability, compete with beta decay



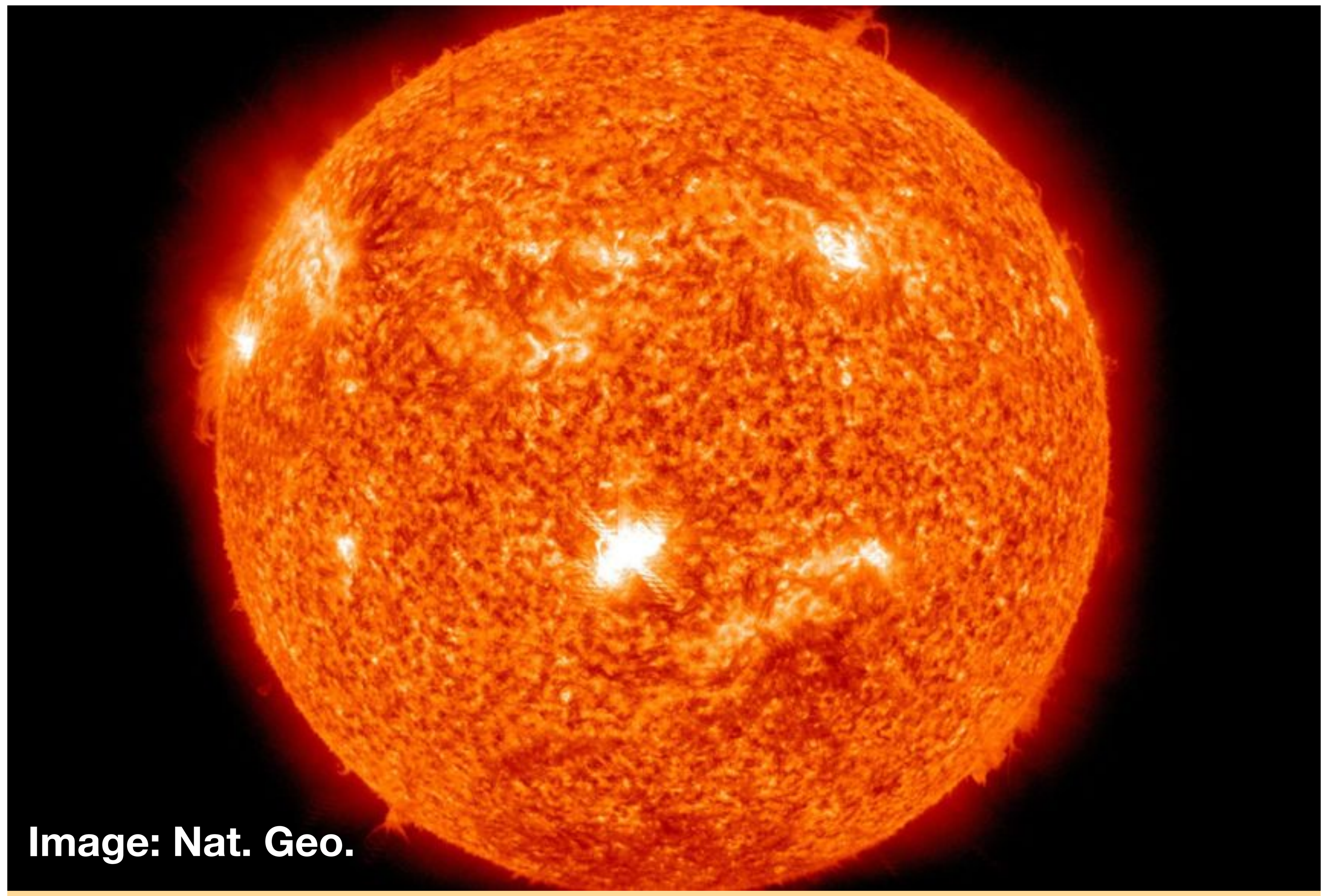
s-process: Astrophysical sites

<u>Main component</u>

- Low-mass asymptotic giant branch (AGB) stars (1.5–3 $M_\odot$)
- Exhaustion of H and He in the core → He-rich shell
- Synthesizes elements with mass number ~ 90–209



Structure of an AGB star



Our Sun will become an AGB star!

Ref: Lugaro *et al*. Annu. Rev. Nucl. Part. Sci. (2023)

s-process: Astrophysical sites

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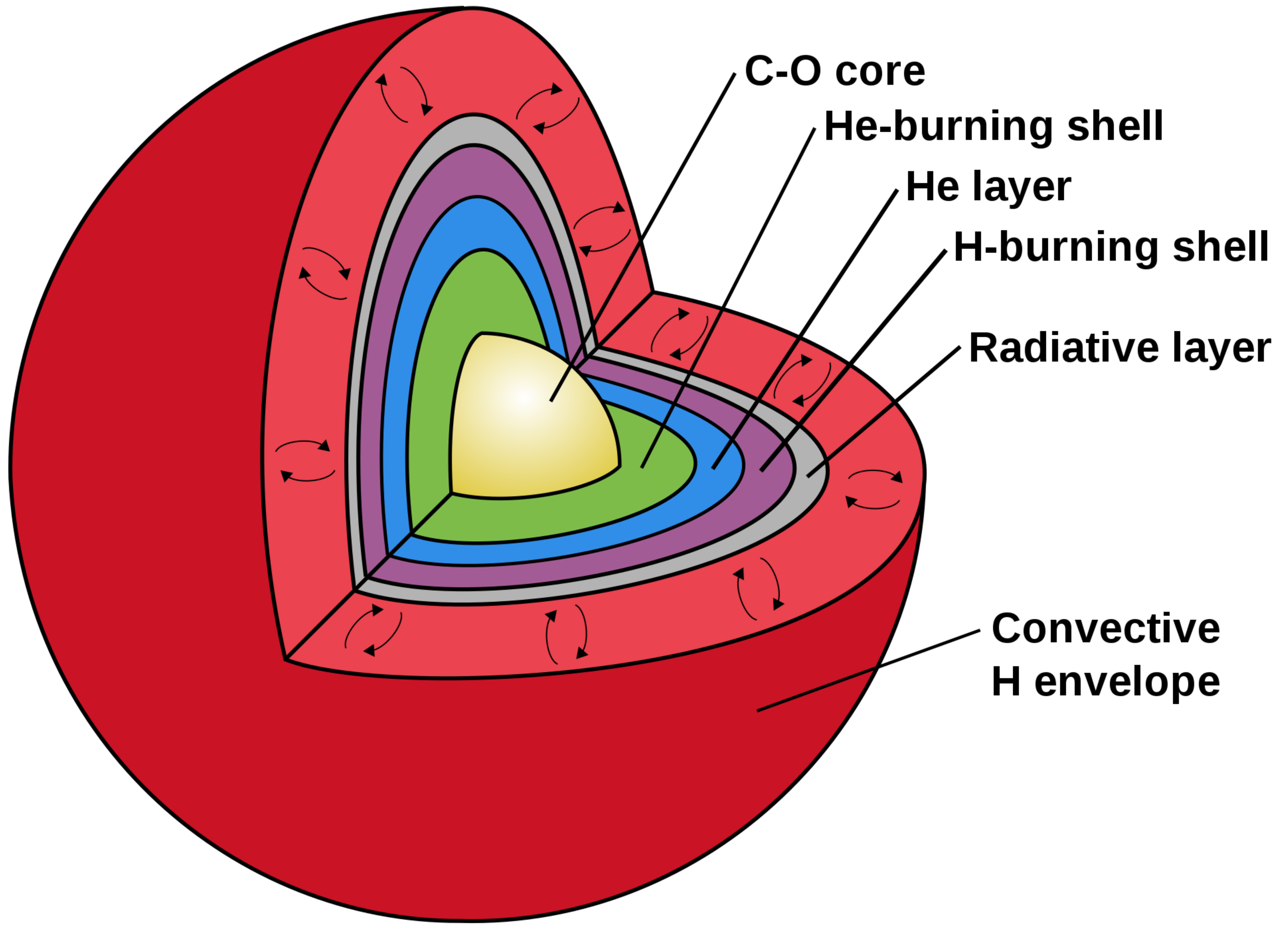
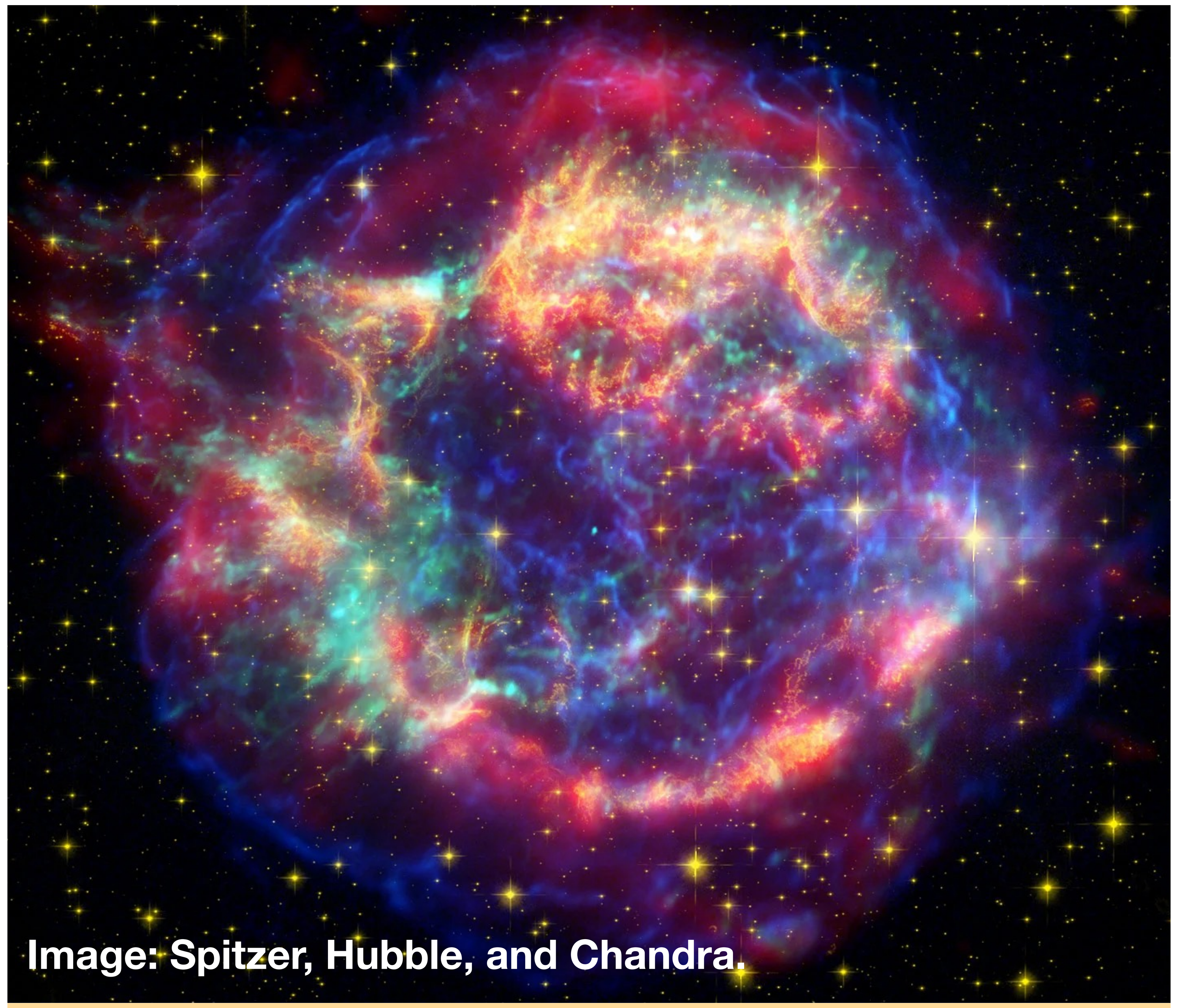


Structure of an AGB star

Weak component

- Core He burning of massive stars (above ~10$M_\odot$)
- Massive stars → end as core-collapse supernovae (SN)
- Synthesizes elements with mass number ~ 60–90



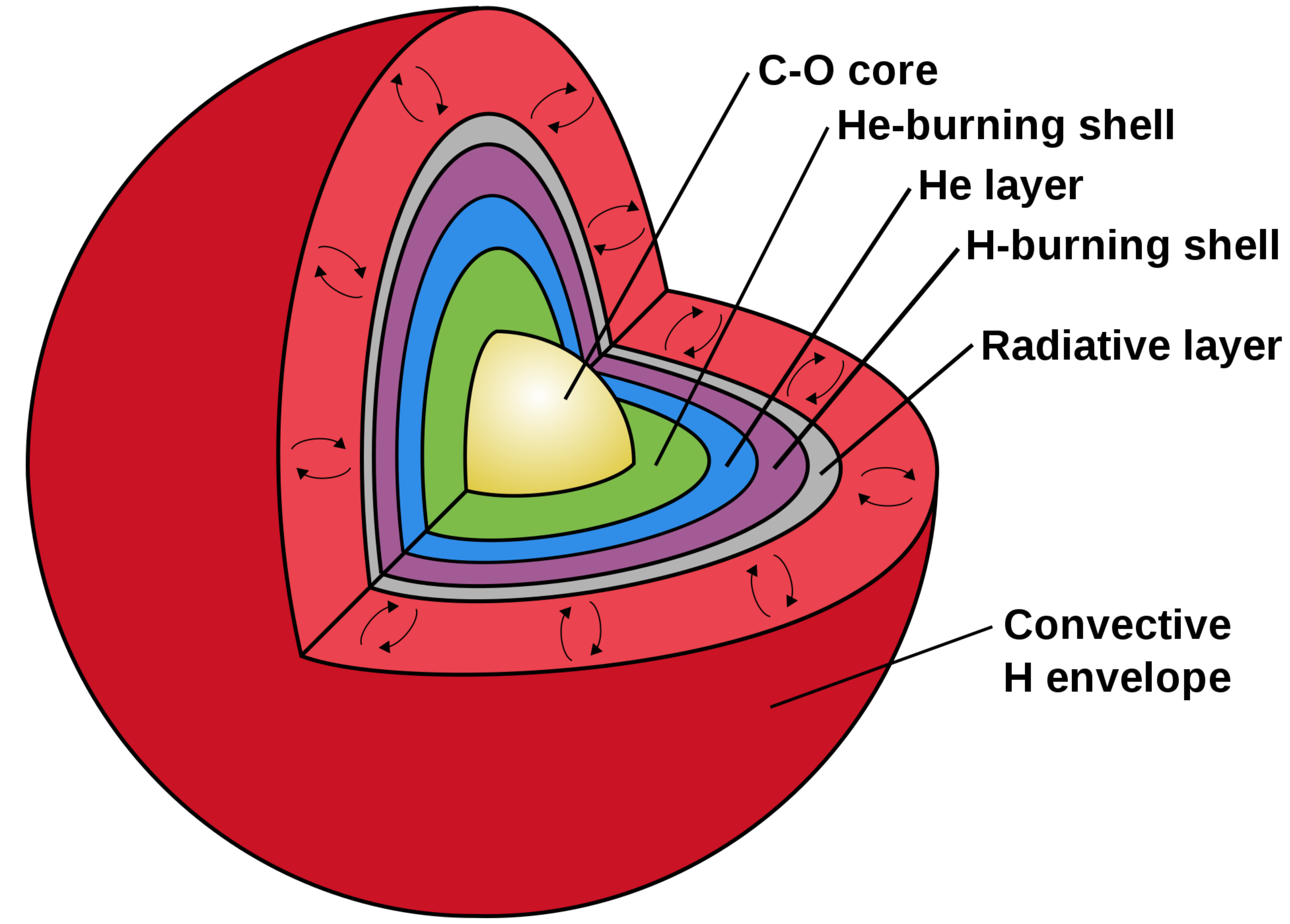
Cassiopeia A SN remnant

Ref: Lugaro *et al*. Annu. Rev. Nucl. Part. Sci. (2023)

s-process: Neutron sources

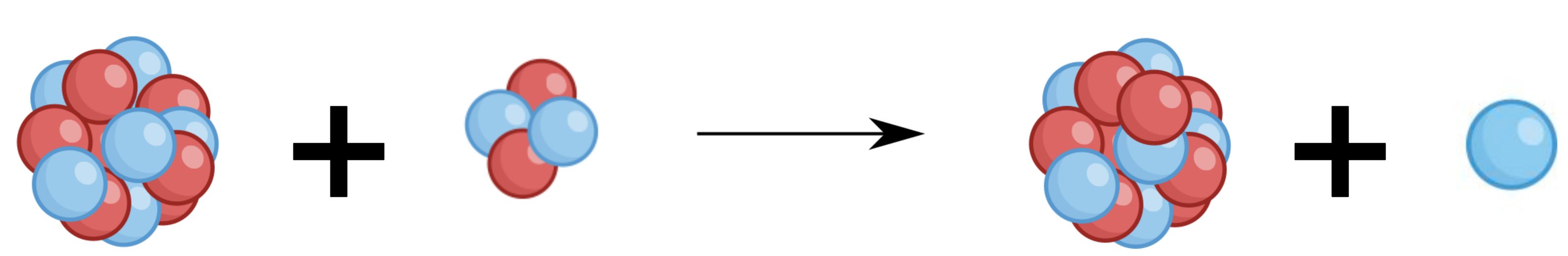
Main component (AGB stars)

- **$^{13}C(\alpha, n)^{16}O$** → key source (~95% of the abundance)
- **$^{22}Ne(\alpha, n)^{25}Mg$** → minor source (~5% of the abundance)
- $^{22}Ne(\alpha, n)^{25}Mg$ significantly impacts the *s*-process branchings



Structure of an AGB star

X(α, n)Y:



X α Y n

Ref: Lugaro *et al*. Annu. Rev. Nucl. Part. Sci. (2023)

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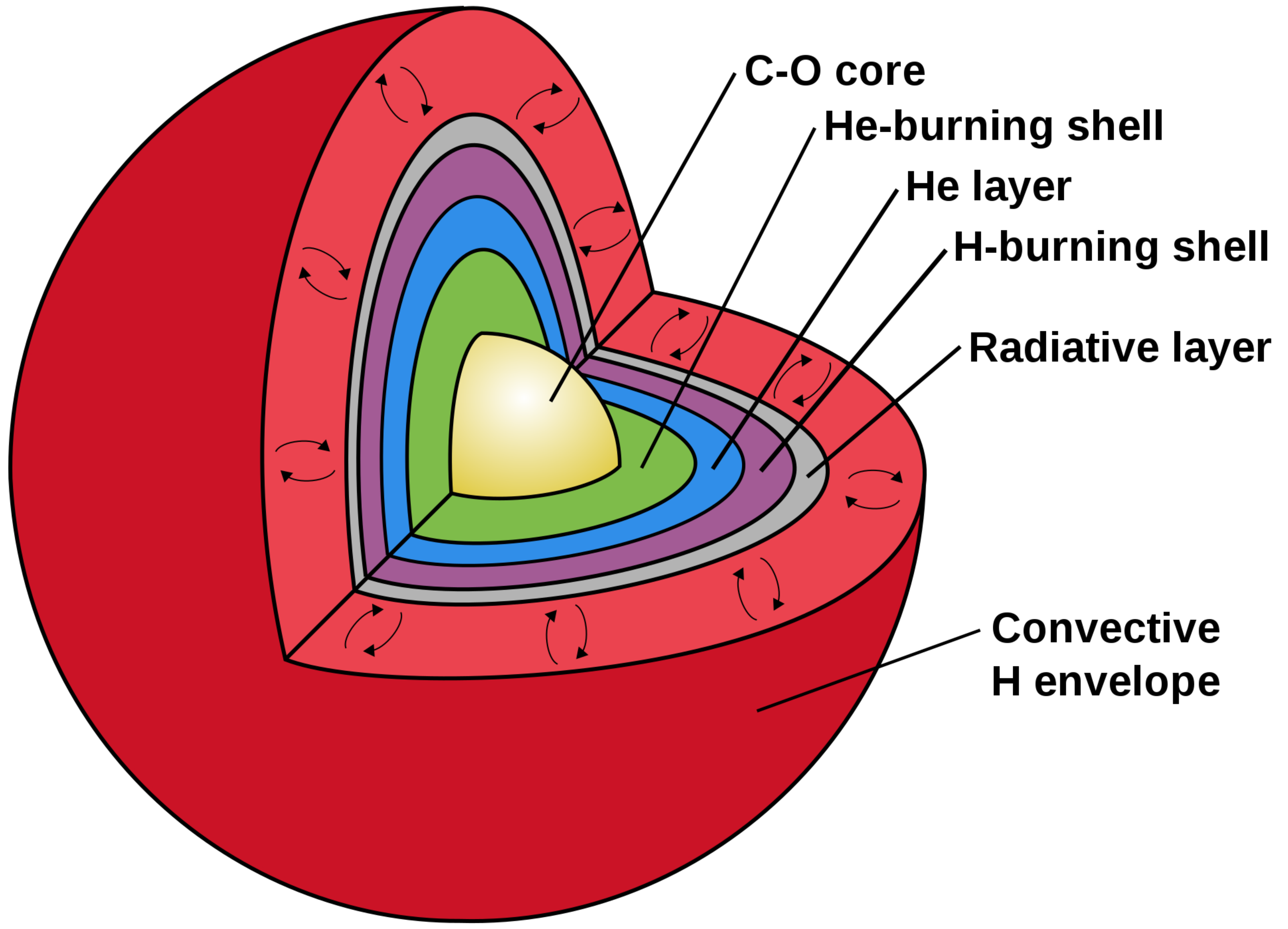

Structure of an AGB star

Weak component (Massive stars)

- **$^{22}Ne(\alpha, n)^{25}Mg$** → dominant neutron source

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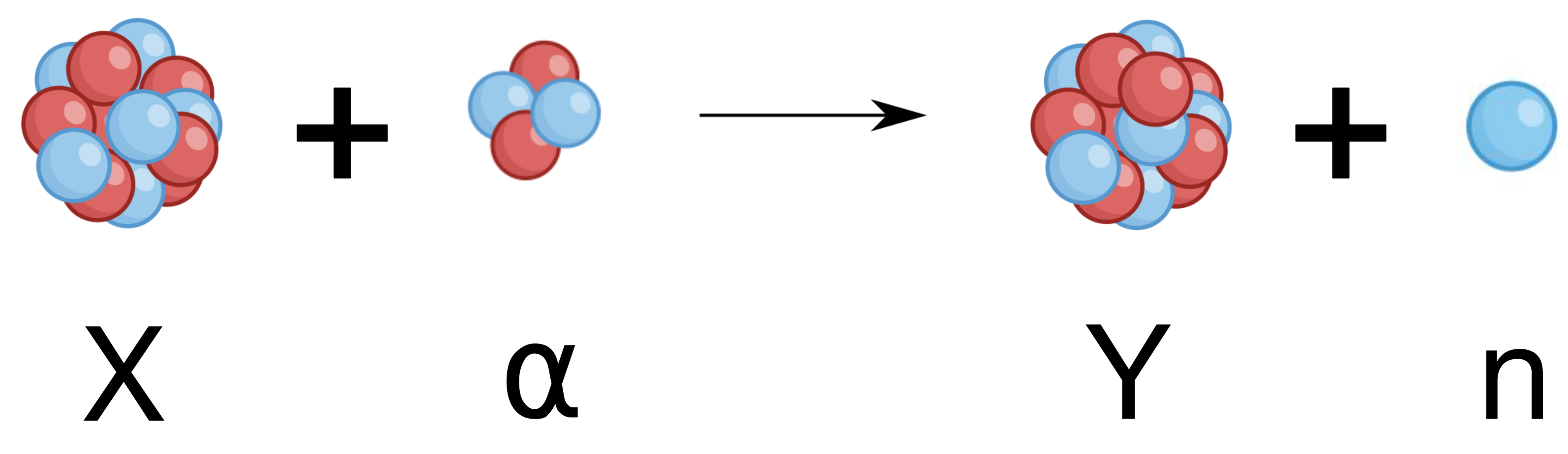

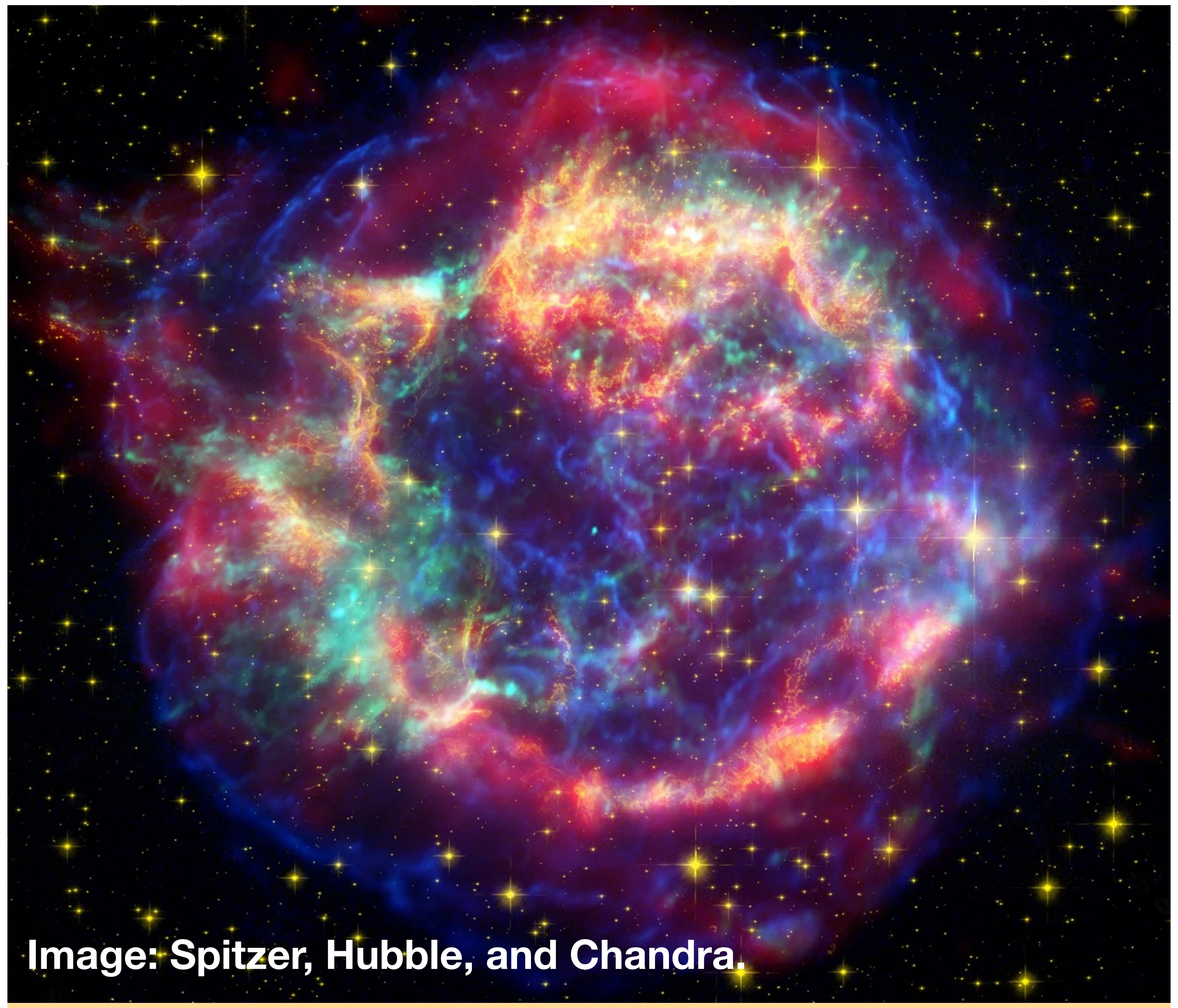

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- ^{22}Ne(α, n)^{25}Mg significantly impacts the *s*-process branchings

^{18}O(α, γ)^{22}Ne

↓

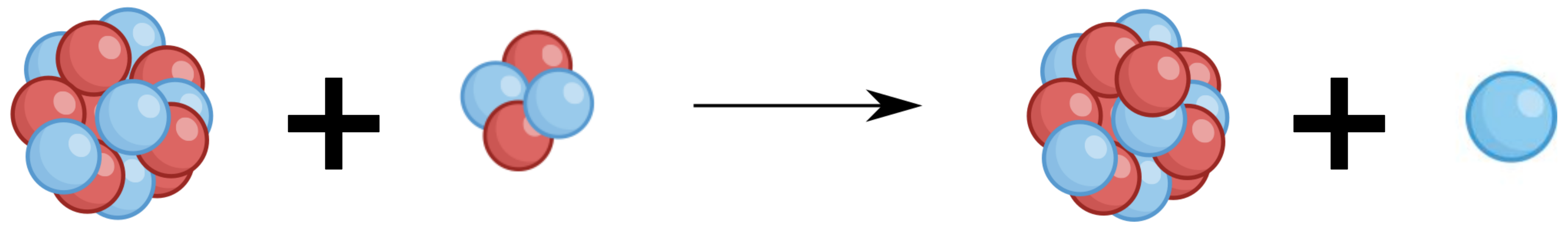
^{22}Ne(α, n)^{25}Mg

Weak component (Massive stars)

- **^{22}Ne(α, n)^{25}Mg** → dominant neutron source

- Dictates the abundance of ^{22}Ne
- Affects the efficiency of ^{22}Ne(α, n)^{25}Mg

X(α, n)Y:



X α Y n

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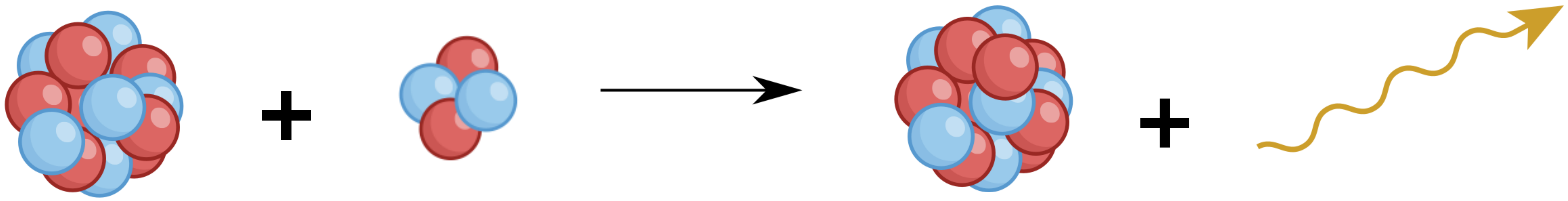
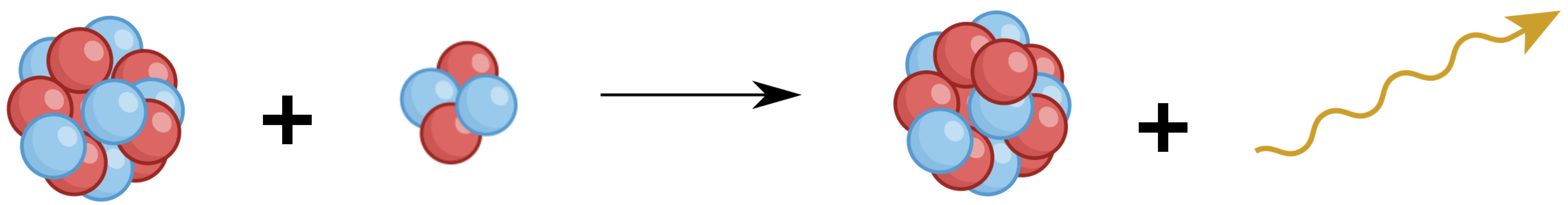
$^{18}O(\alpha, \gamma)^{22}Ne$ reaction



^{18}O | ^{4}He (α) | ^{22}Ne | Gamma-ray (γ)

$^{18}O(\alpha, \gamma)^{22}Ne$ reaction



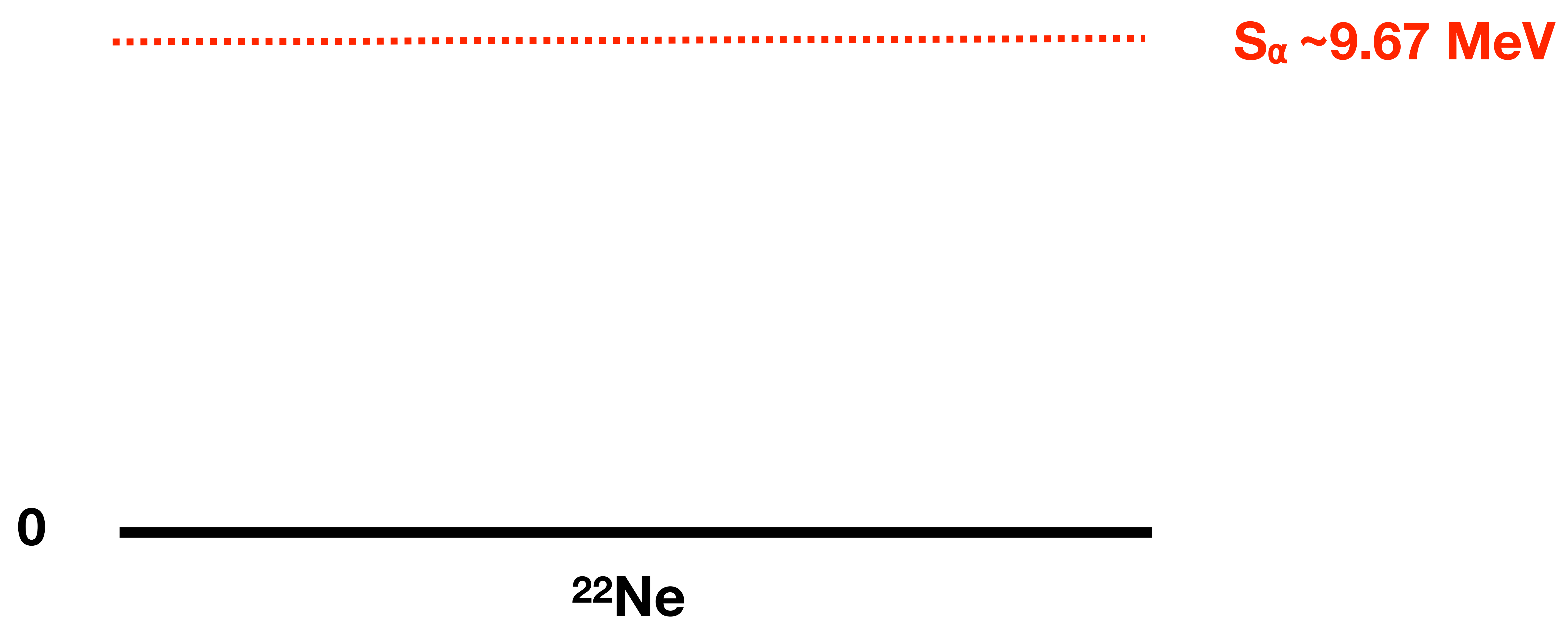
- Rate of this reaction depends on the nuclear properties of the resonances in ^{22}Ne

$$\text{reaction rate} \propto \underbrace{\omega\gamma}_{\text{resonance strength}} \, e^{-\frac{E_r}{kT}}$$

E_r → resonance energy

Resonances for $^{18}\mathrm{O}(\alpha, \gamma)^{22}\mathrm{Ne}$

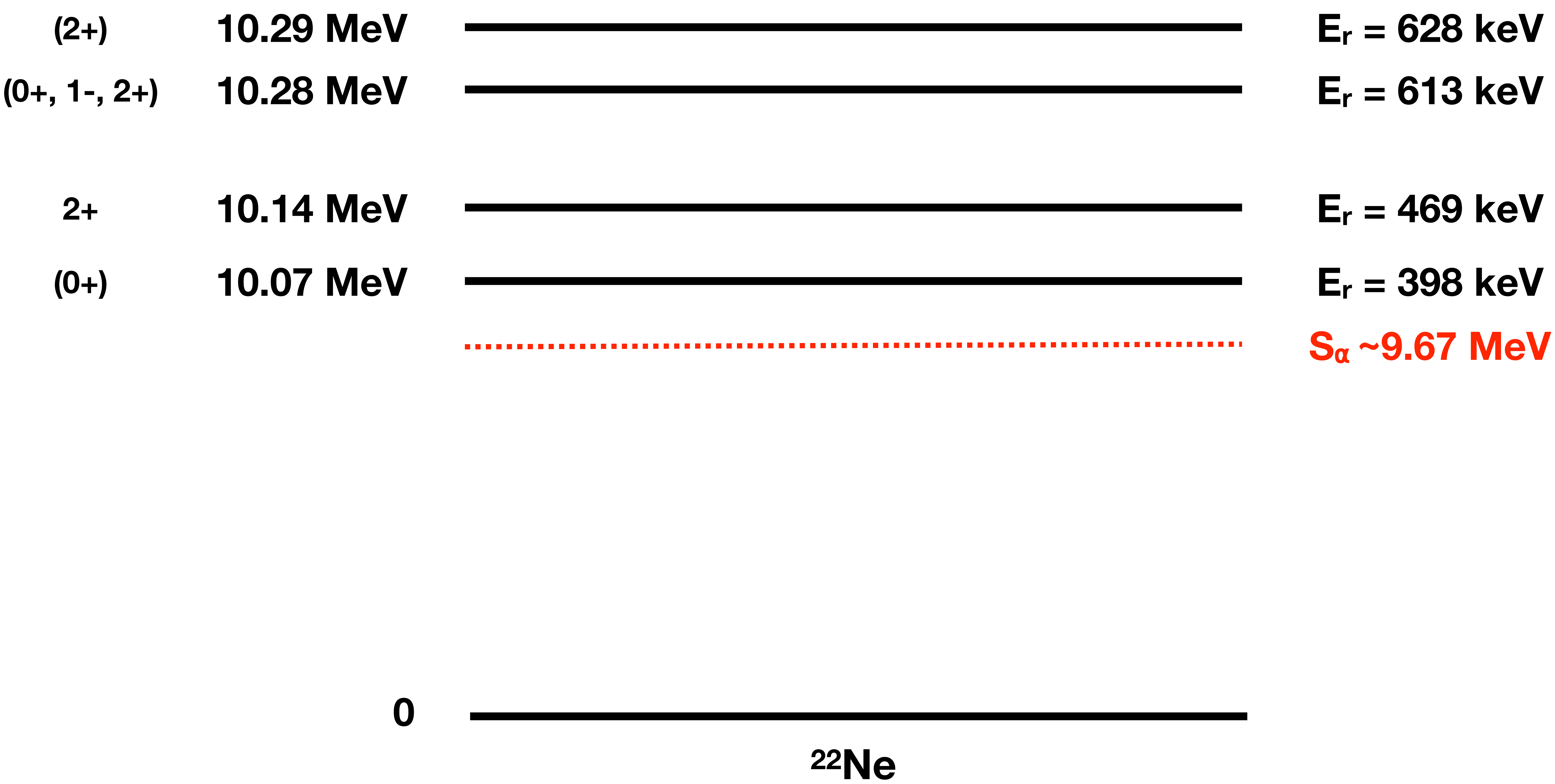
Nuclear excited states of $^{22}\mathrm{Ne}$ that provide an enhancement to the reaction rate



Resonances for $^{18}O(\alpha, \gamma)^{22}Ne$

Nuclear excited states of ^{22}Ne that provide an enhancement to the reaction rate

Temperature ~ 100 — 400 MK



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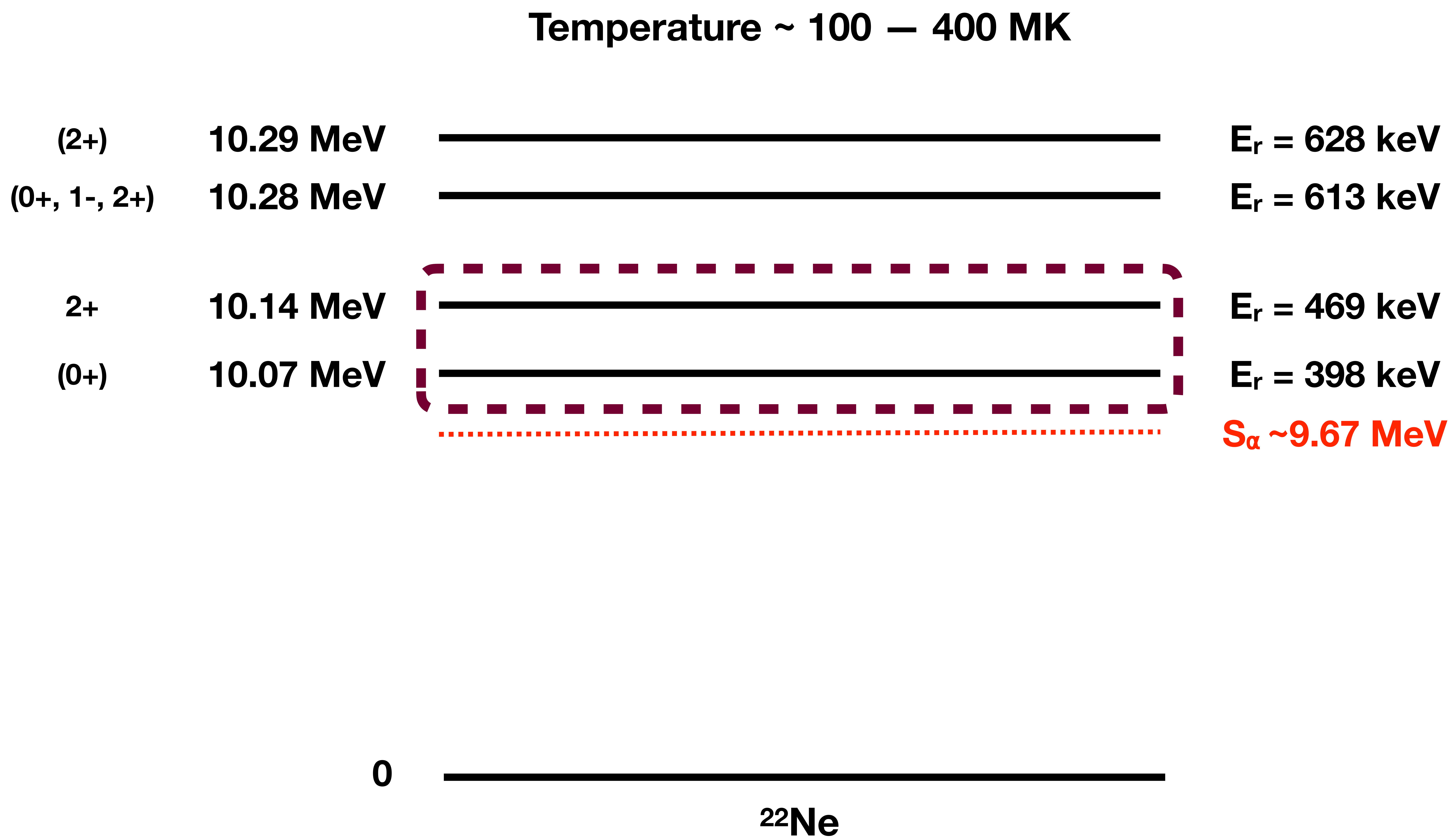

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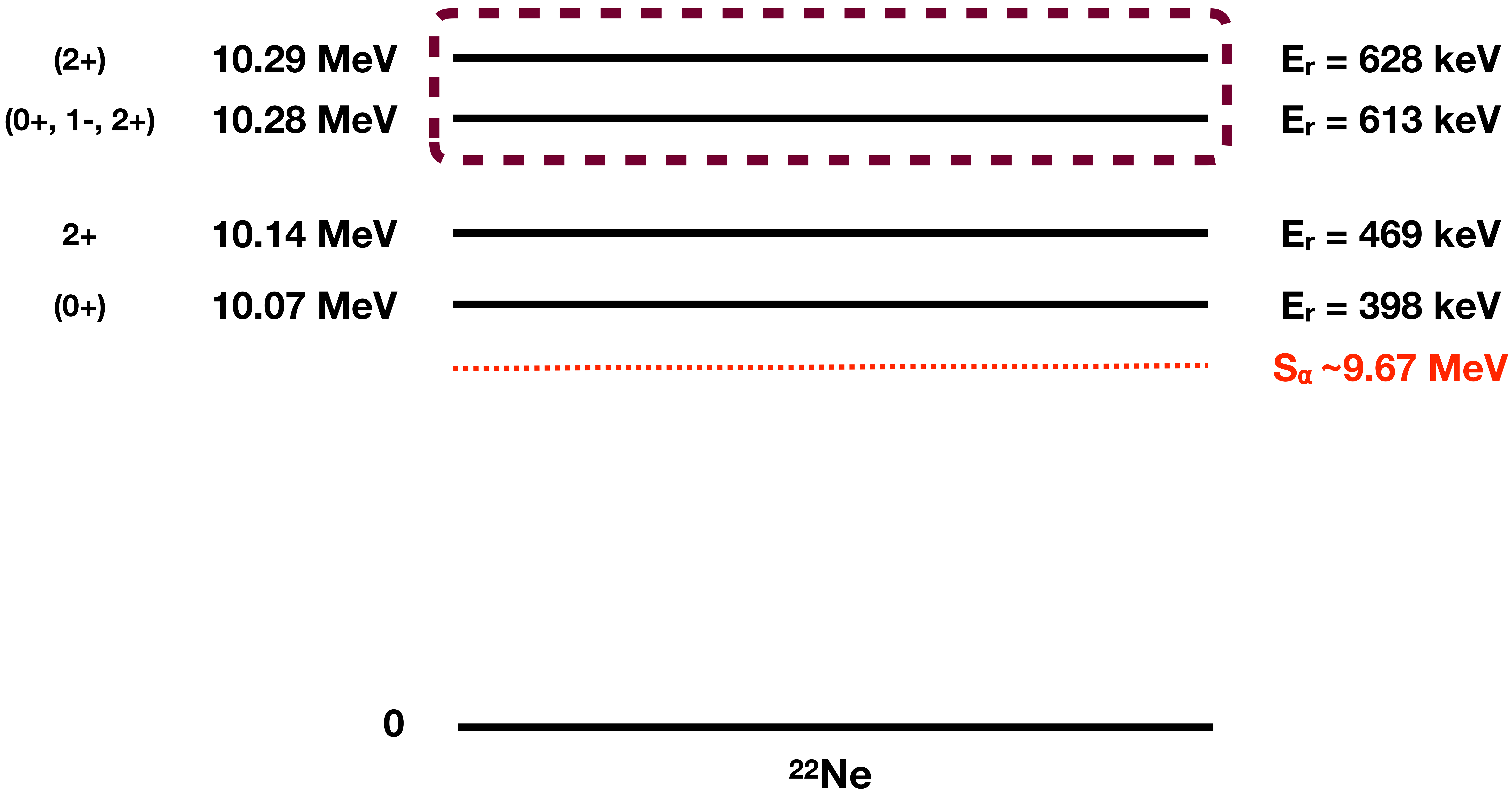

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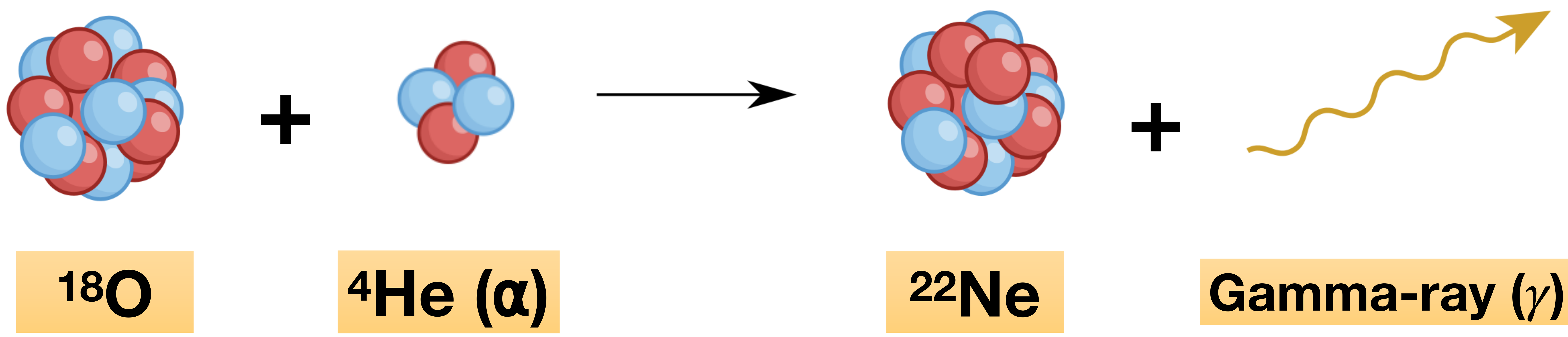

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$$\text{reaction rate} \propto \underbrace{\omega\gamma}_{\text{resonance strength}} \, e^{-\frac{E_r}{kT}}$$

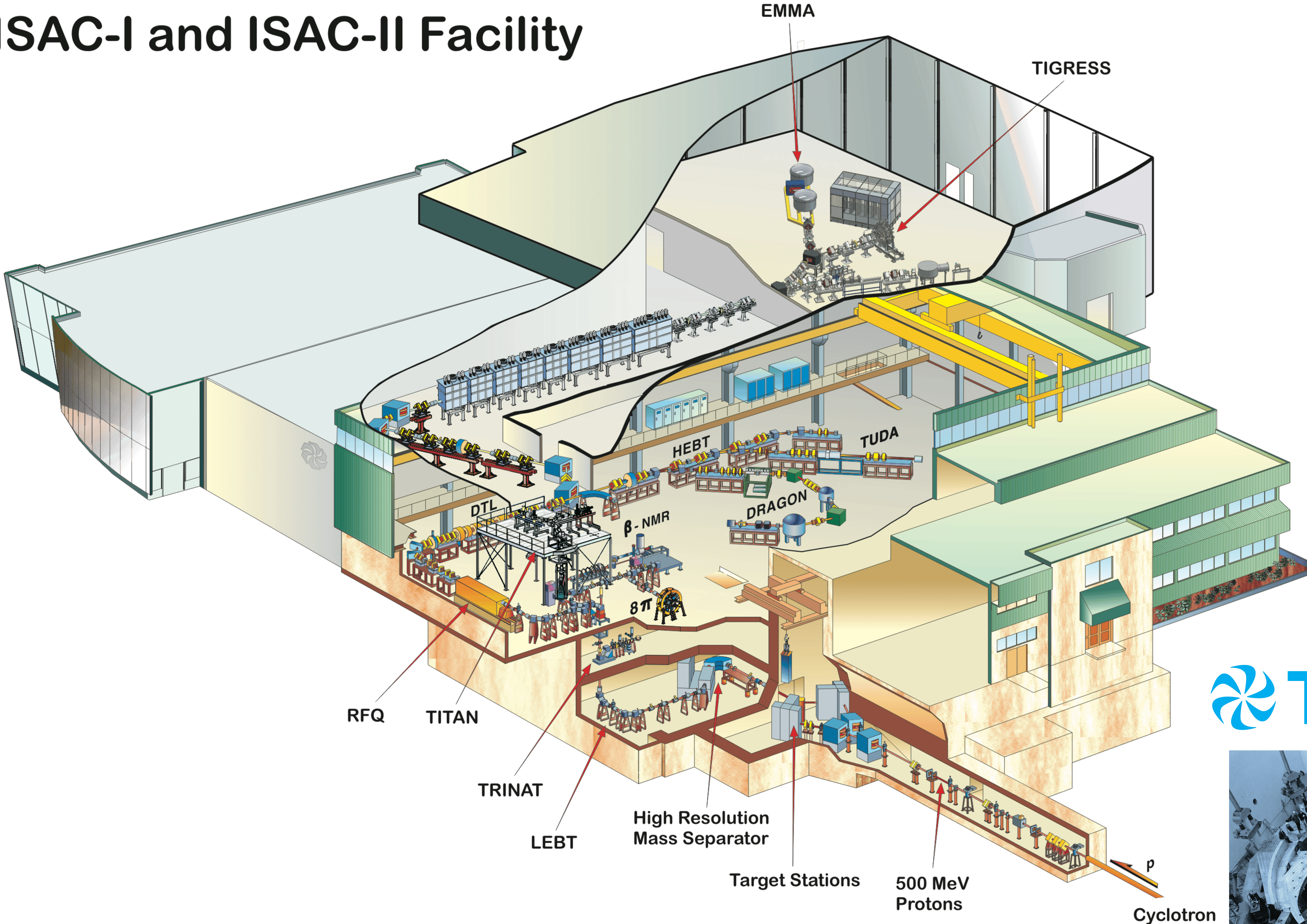
E_r → **resonance energy**

resonance strength

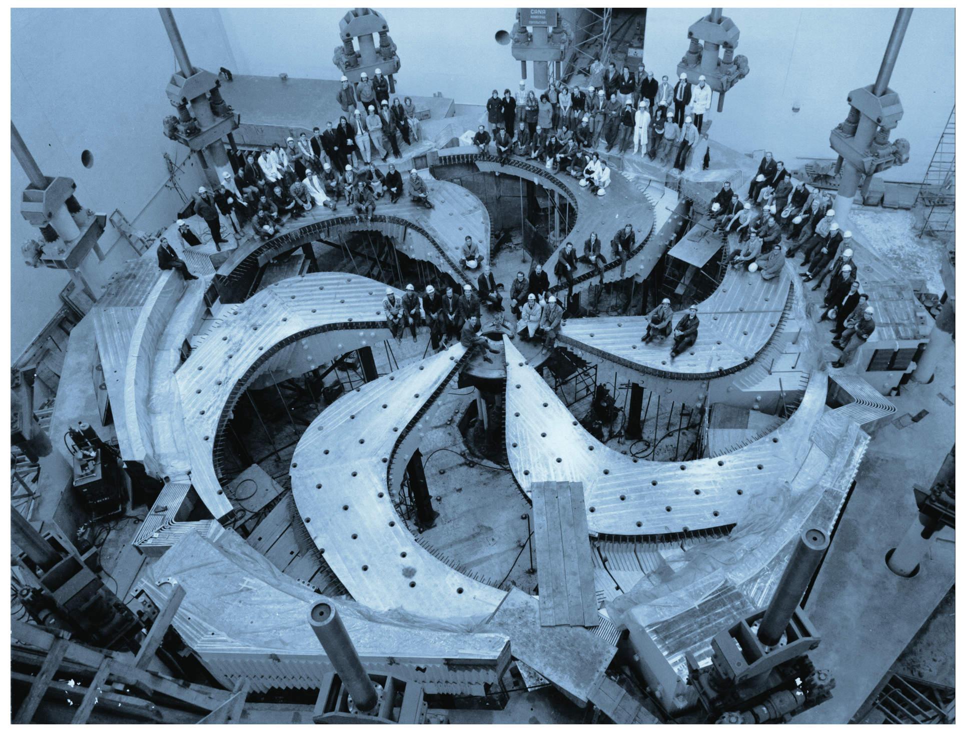
- **Recent experiments: Wang *et al.* PRL (2023) and Dombos *et al.* PRL (2022)**
- **New indirect measurement: Greaves *et al.* PRC (2026)**
- **All previous measurements in "normal" kinematics (light beam on heavy target)**

Measurement of $^{18}O(\alpha, \gamma)^{22}Ne$

ISAC-I and ISAC-II Facility



TRIUMF



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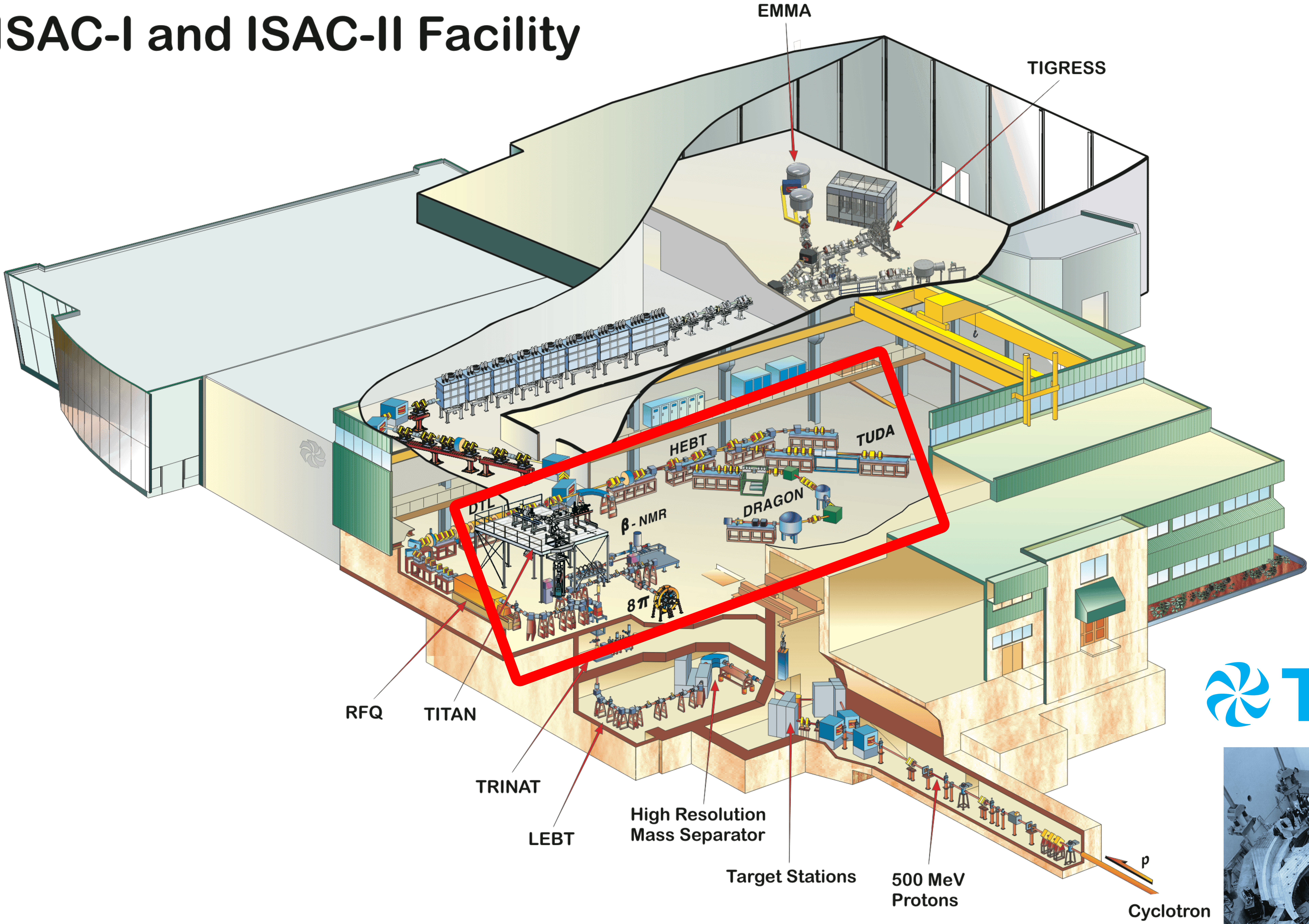

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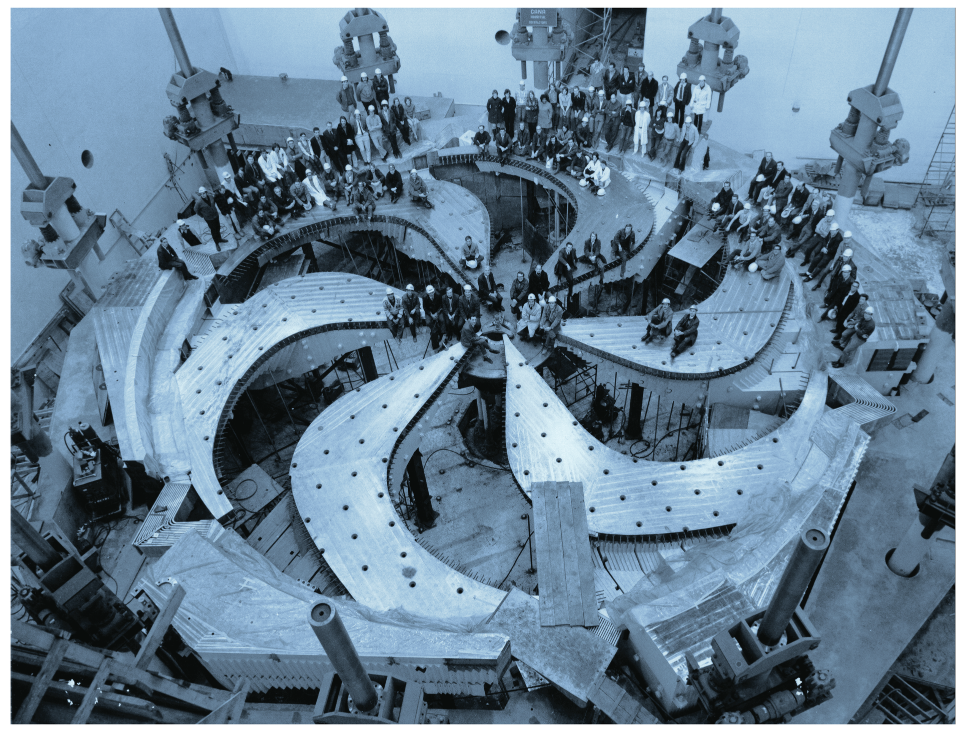
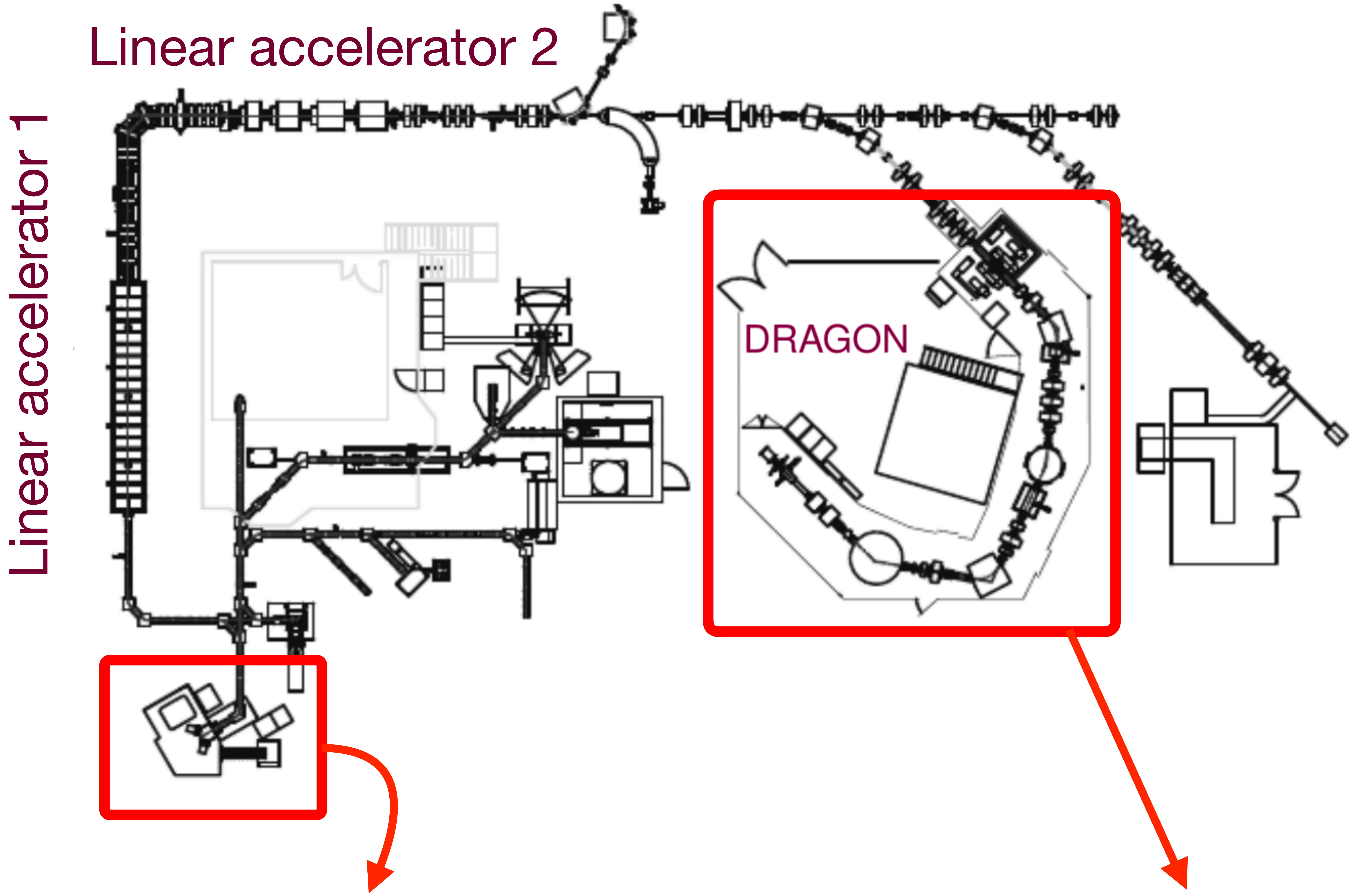


ISAC I experimental hall



- **Off-Line Ion Source (OLIS)**
- **Produces ^{18}O stable beam**

First inverse kinematics measurement of $^{18}O(\alpha, \gamma)^{22}Ne$

DRAGON: Detector of recoils and gamma-rays of nuclear reactions

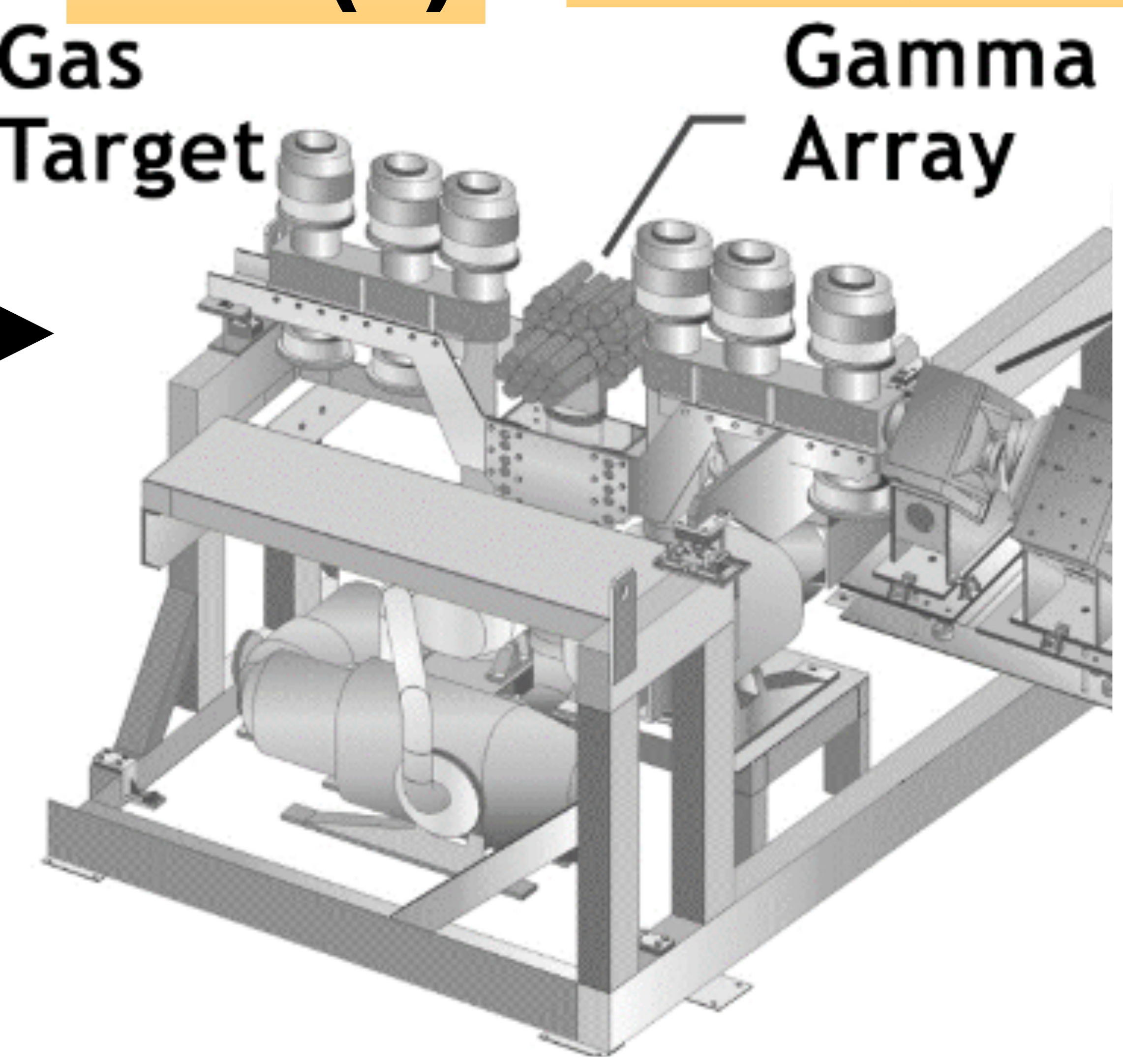
^{4}He (α)

Detect γ-rays (BGO)

^{18}O beam

~3.5 MeV

~10^{11} particles/sec



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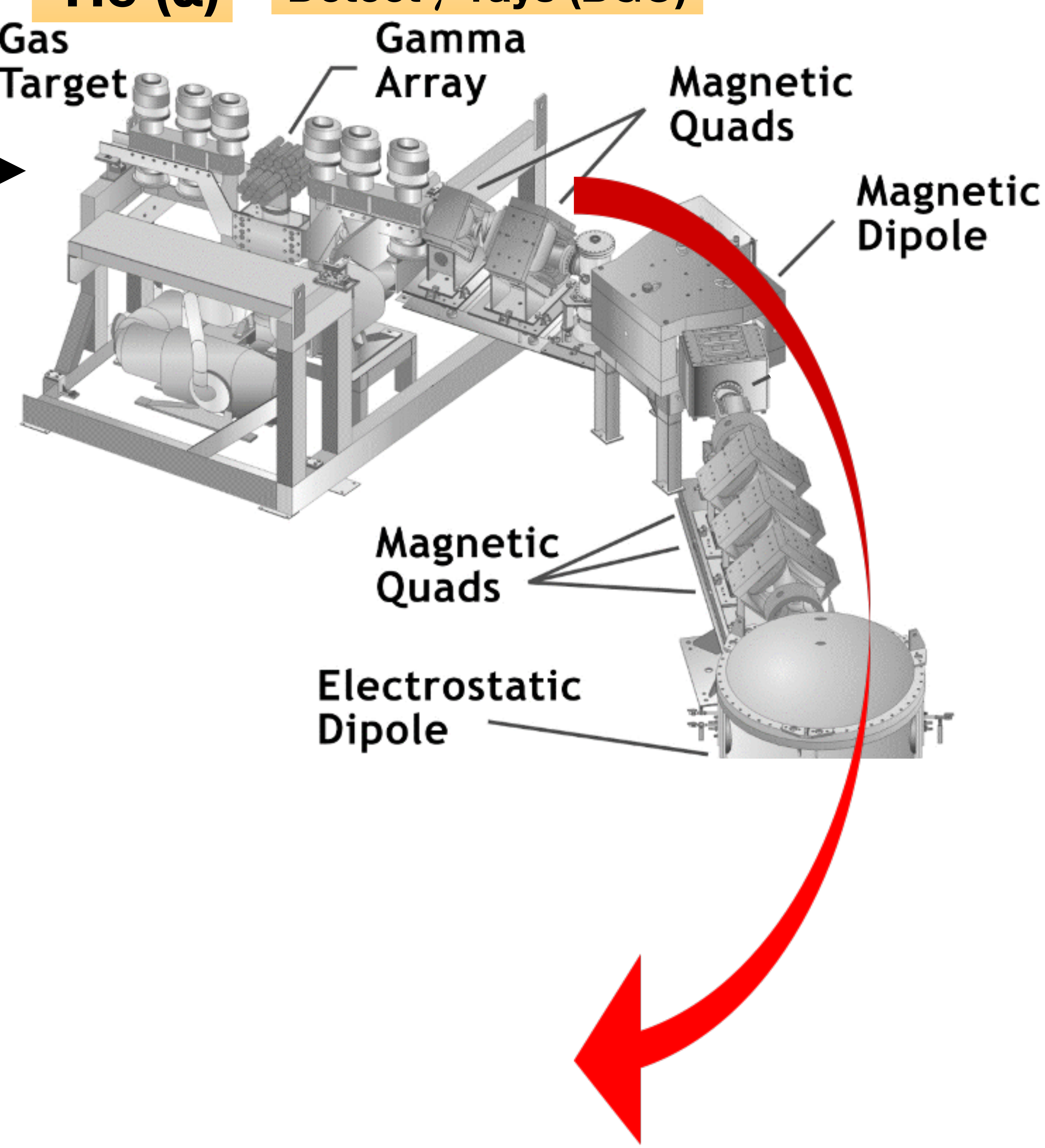

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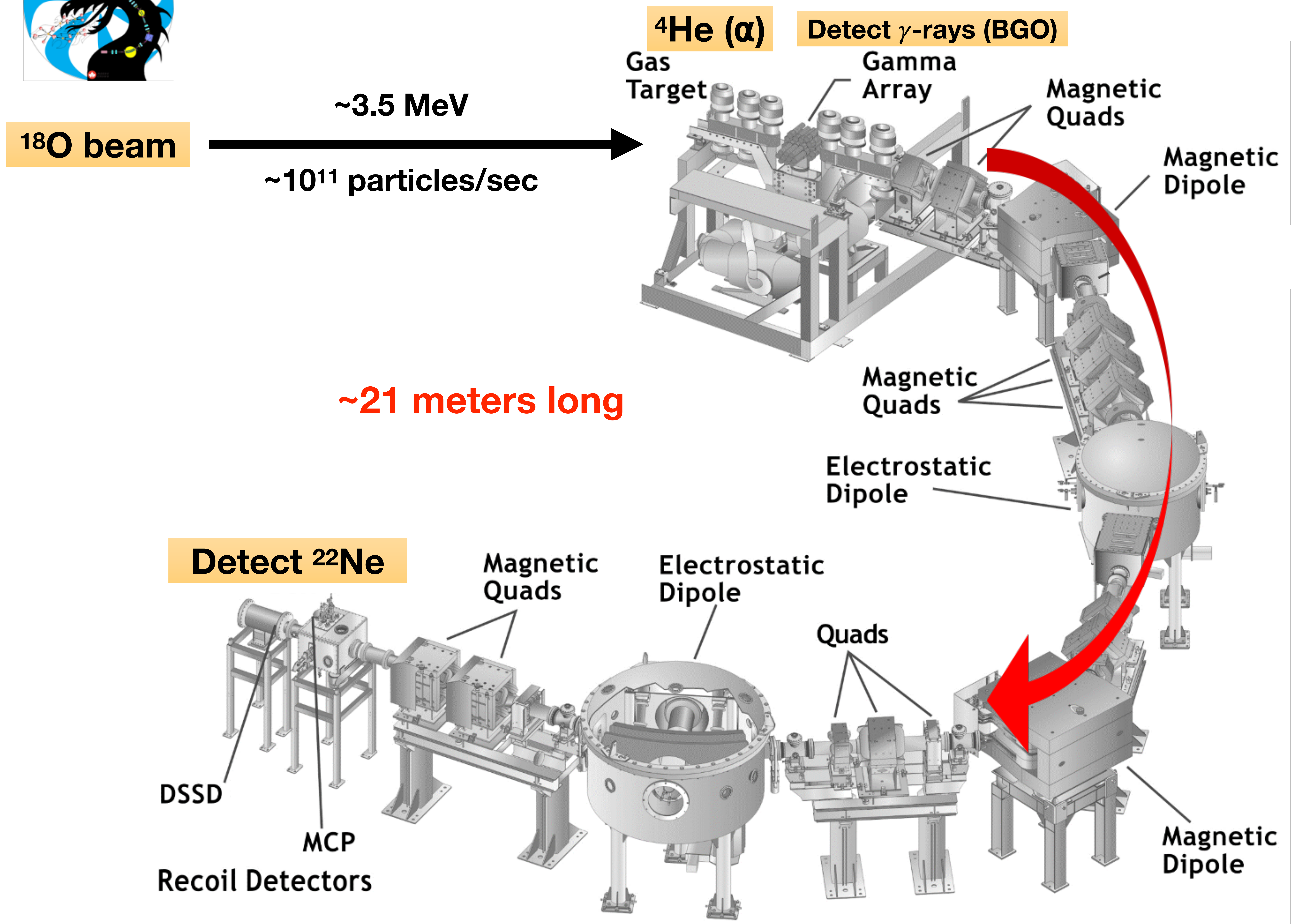

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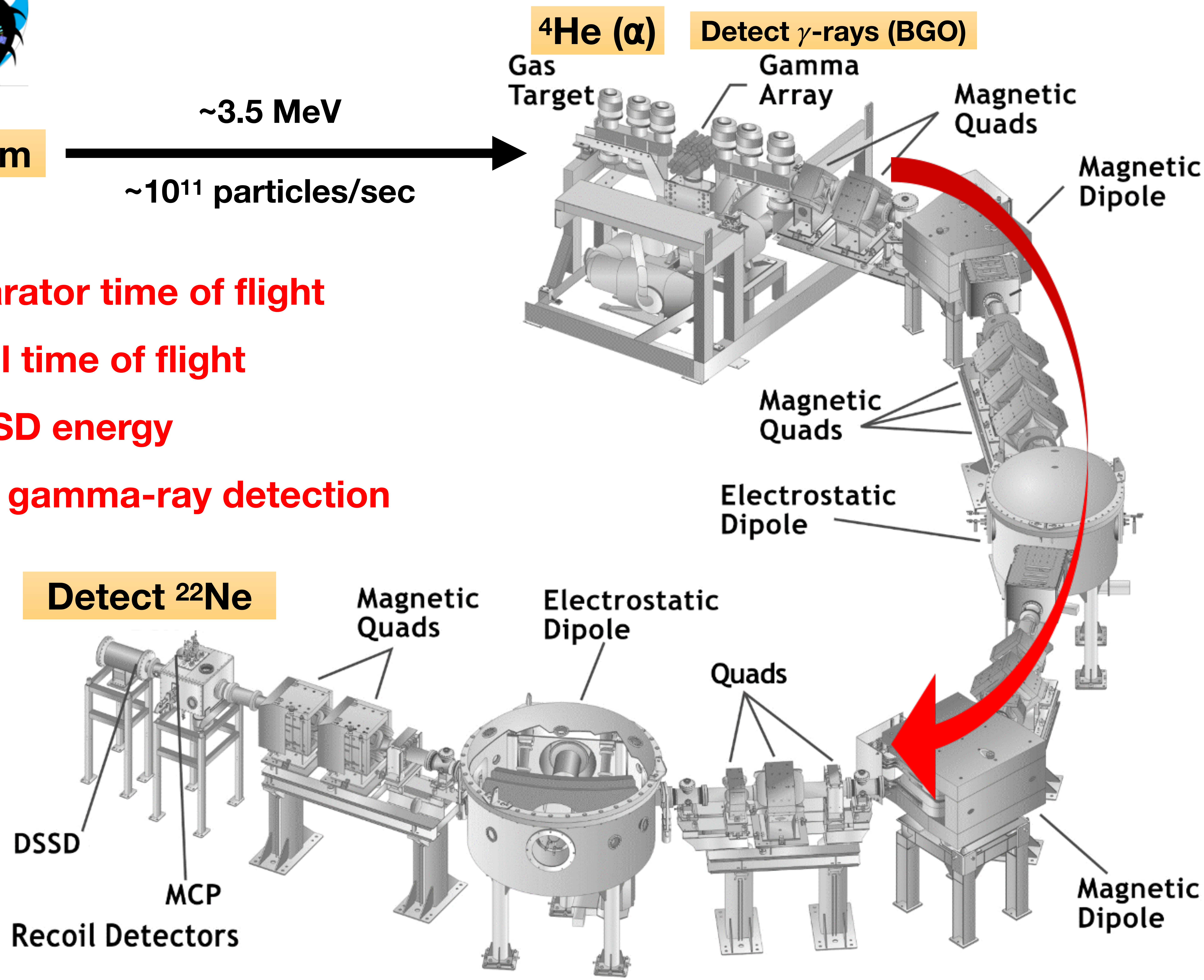
DRAGON: Detector of recoils and gamma-rays of nuclear reactions

^{18}O beam

~3.5 MeV

~10^{11} particles/sec

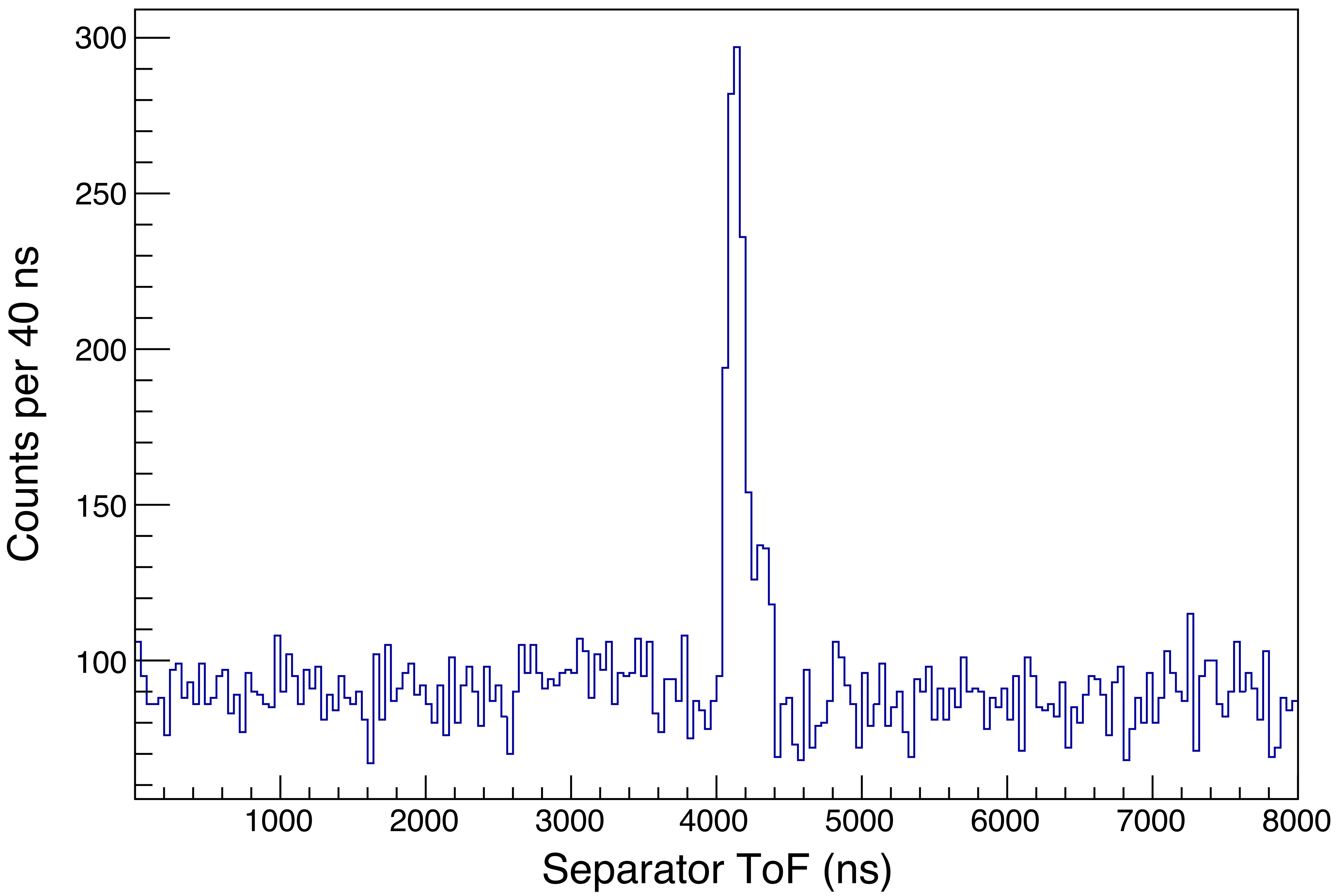
- Separator time of flight
- Local time of flight
- DSSSD energy
- BGO gamma-ray detection

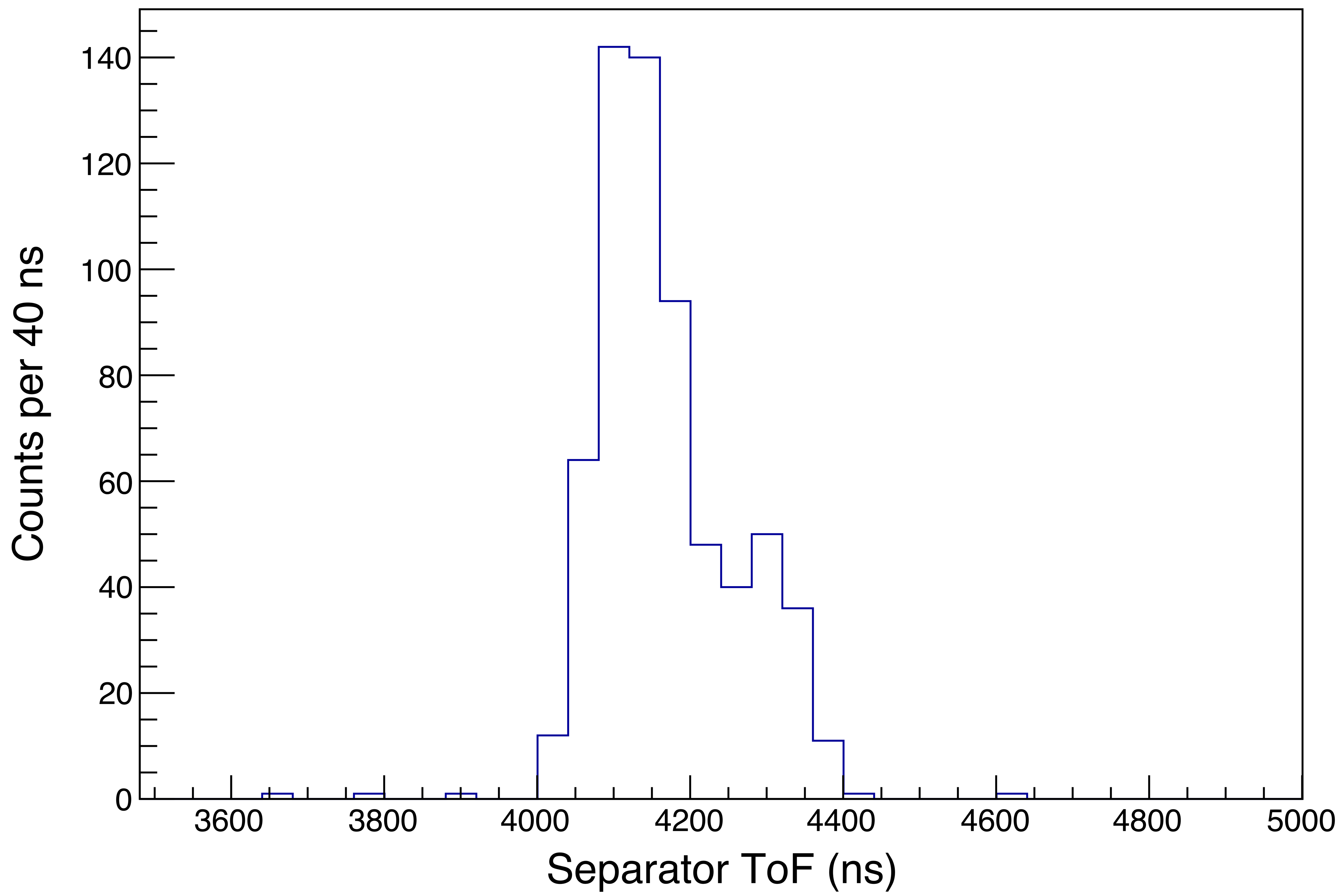


Ref: Hutcheon *et al.* Nucl. Instr. Meth. (2003)

Separator time of flight (ToF)

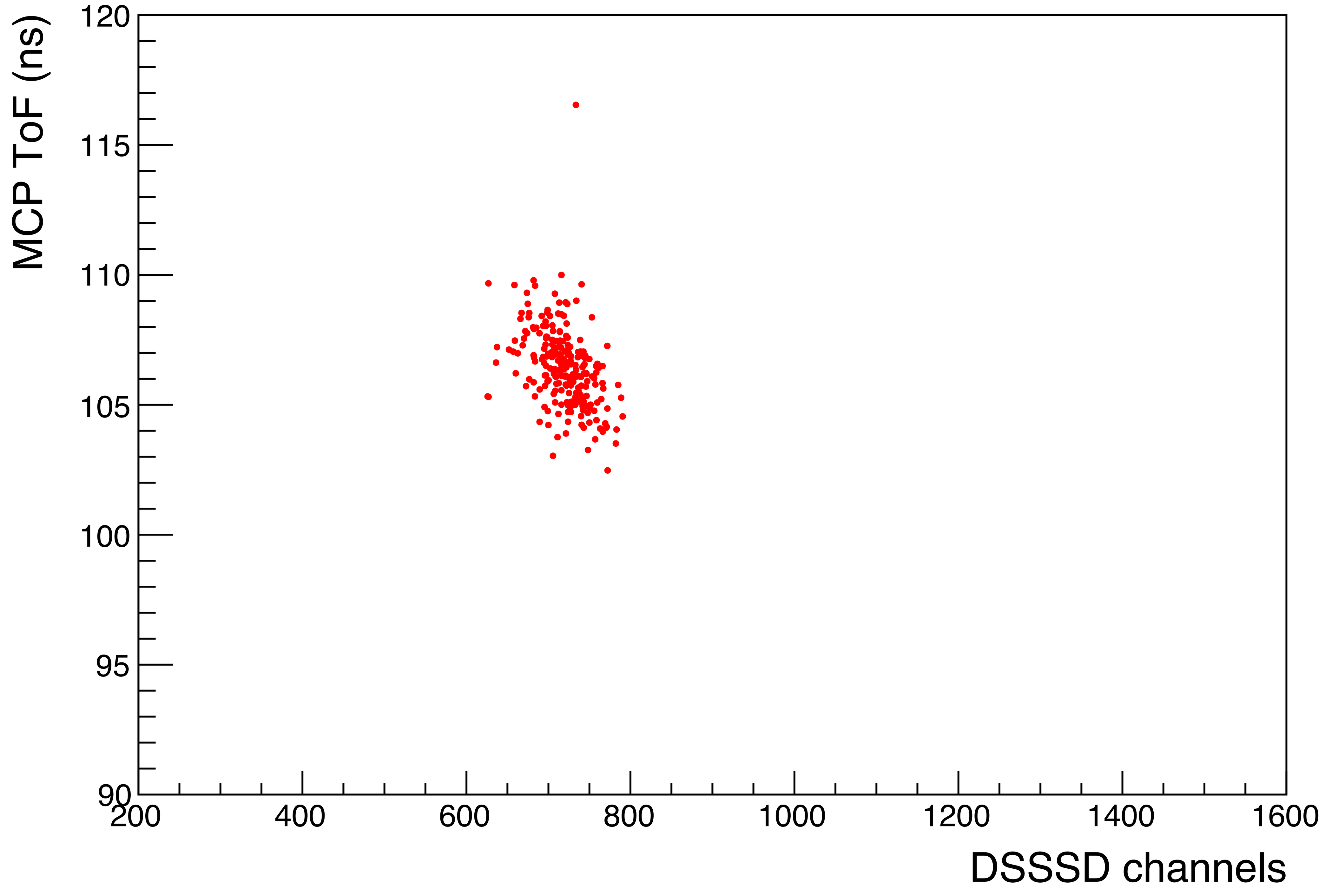
E_r = 628 keV





E_r = 628 keV

Preliminary



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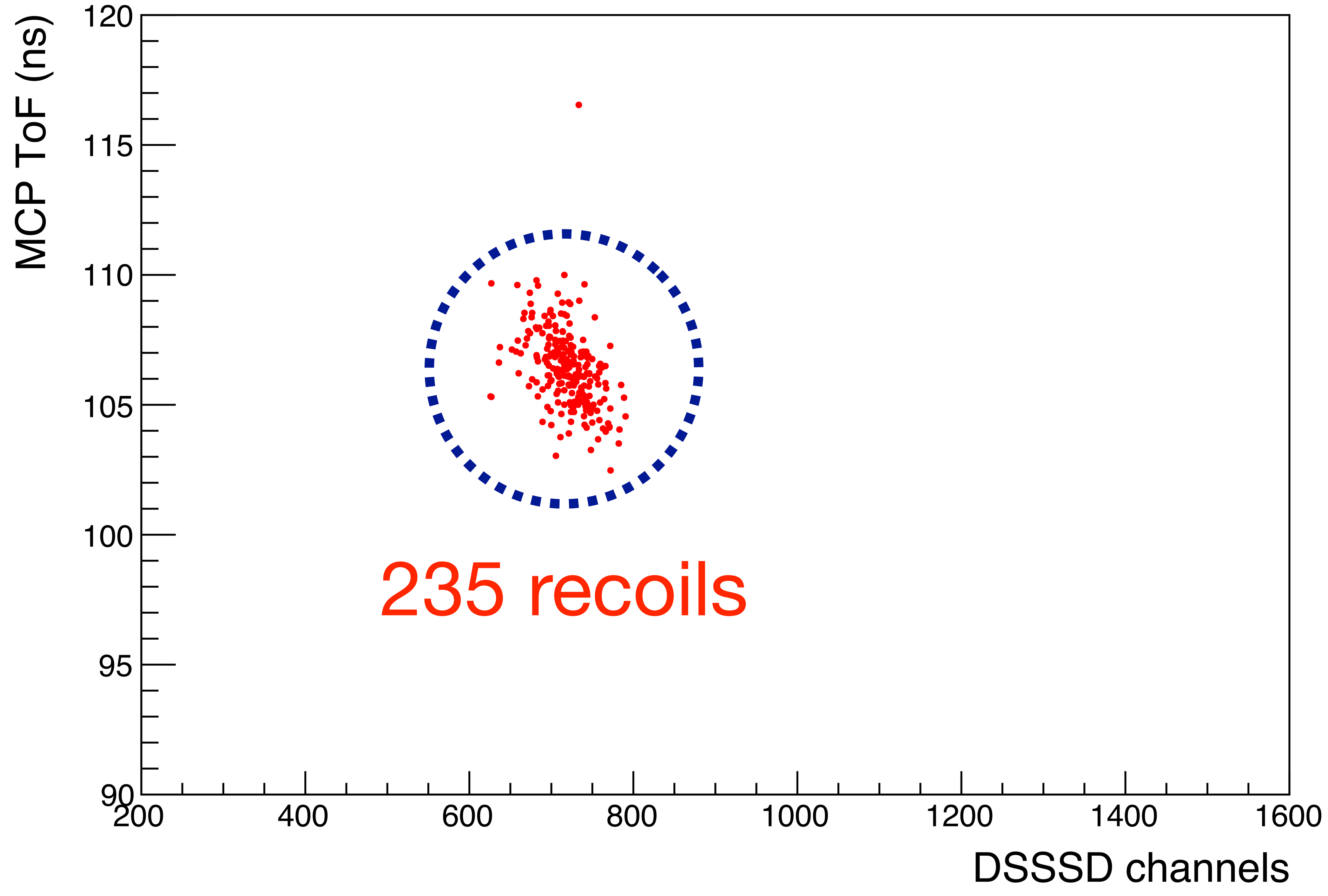

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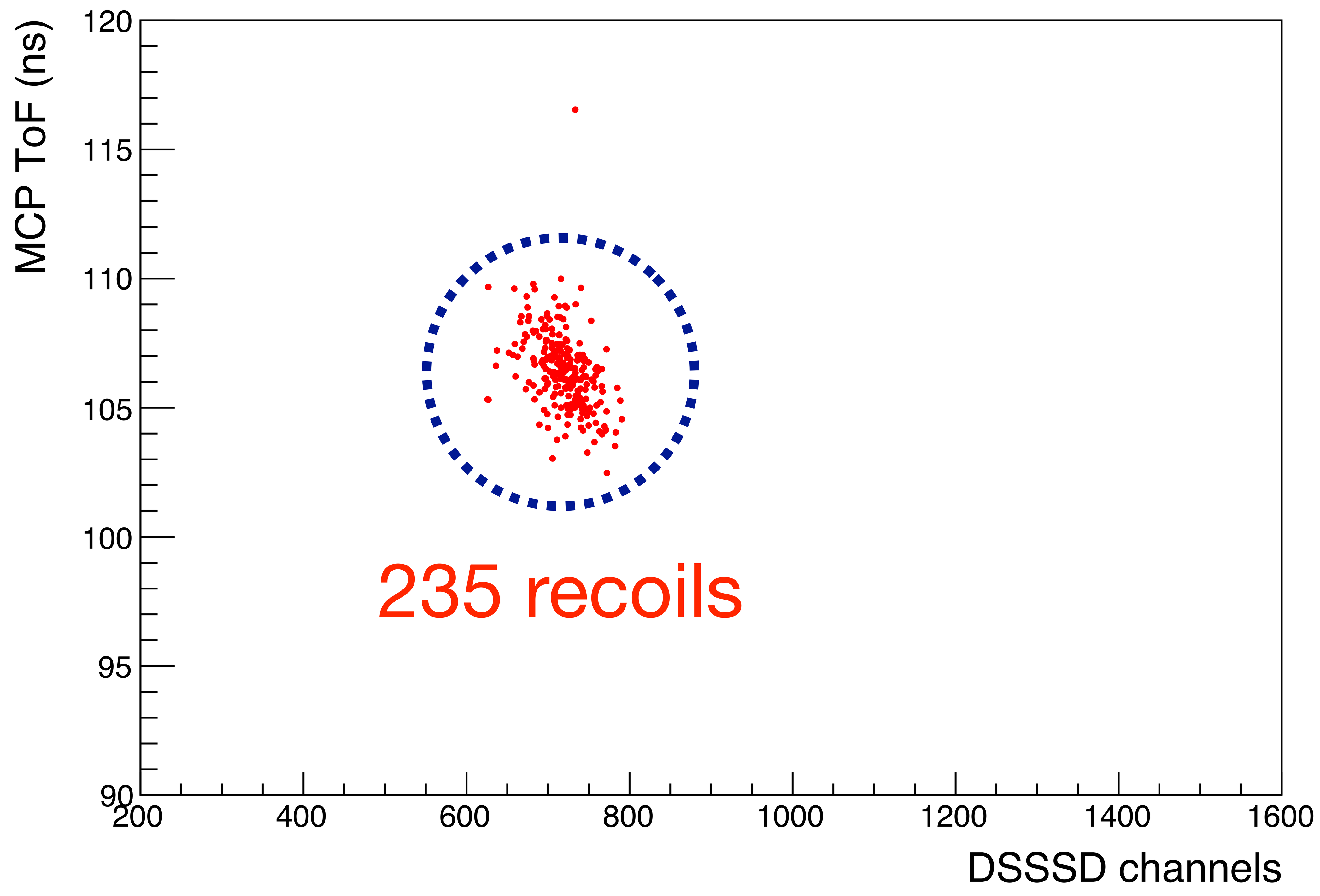
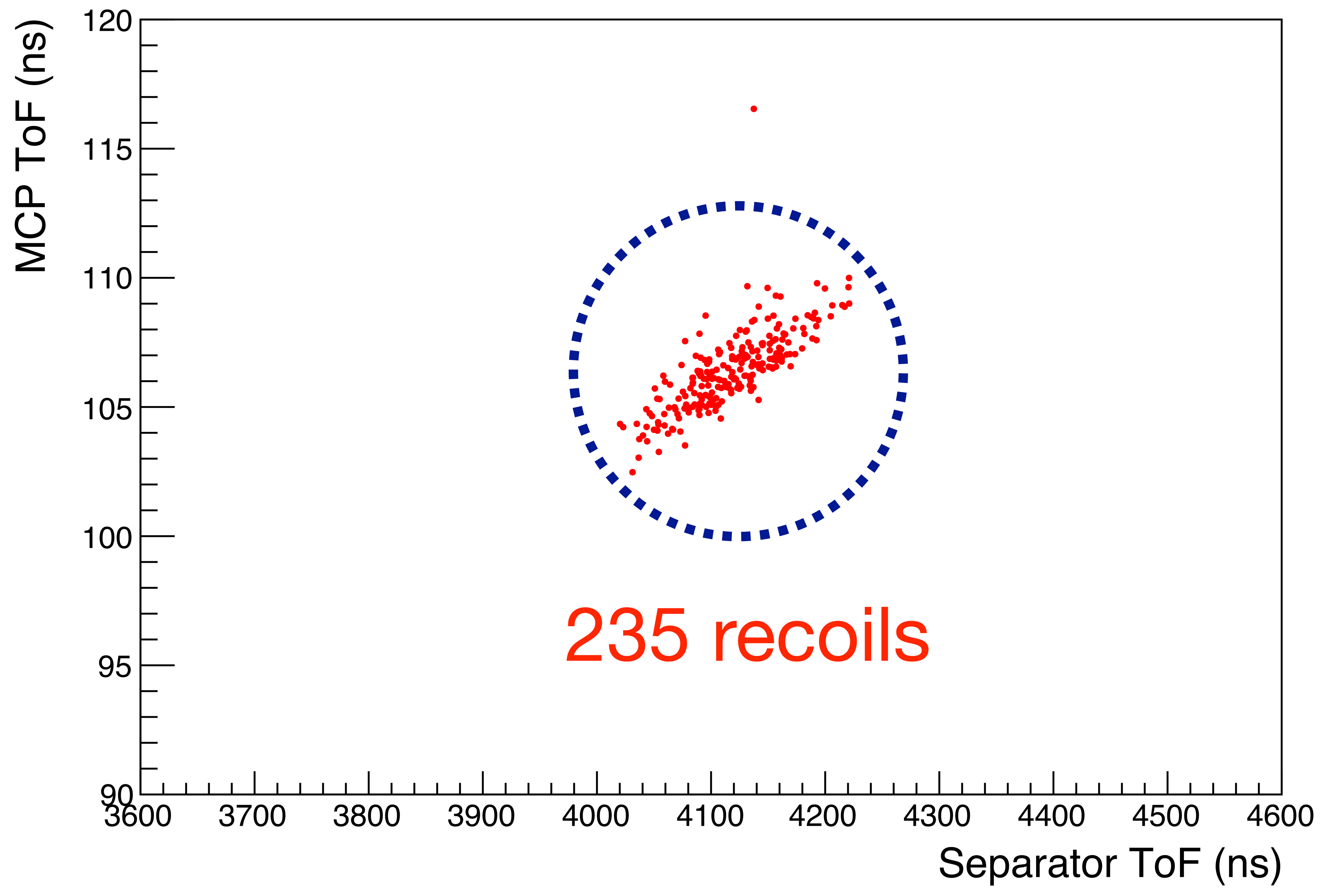
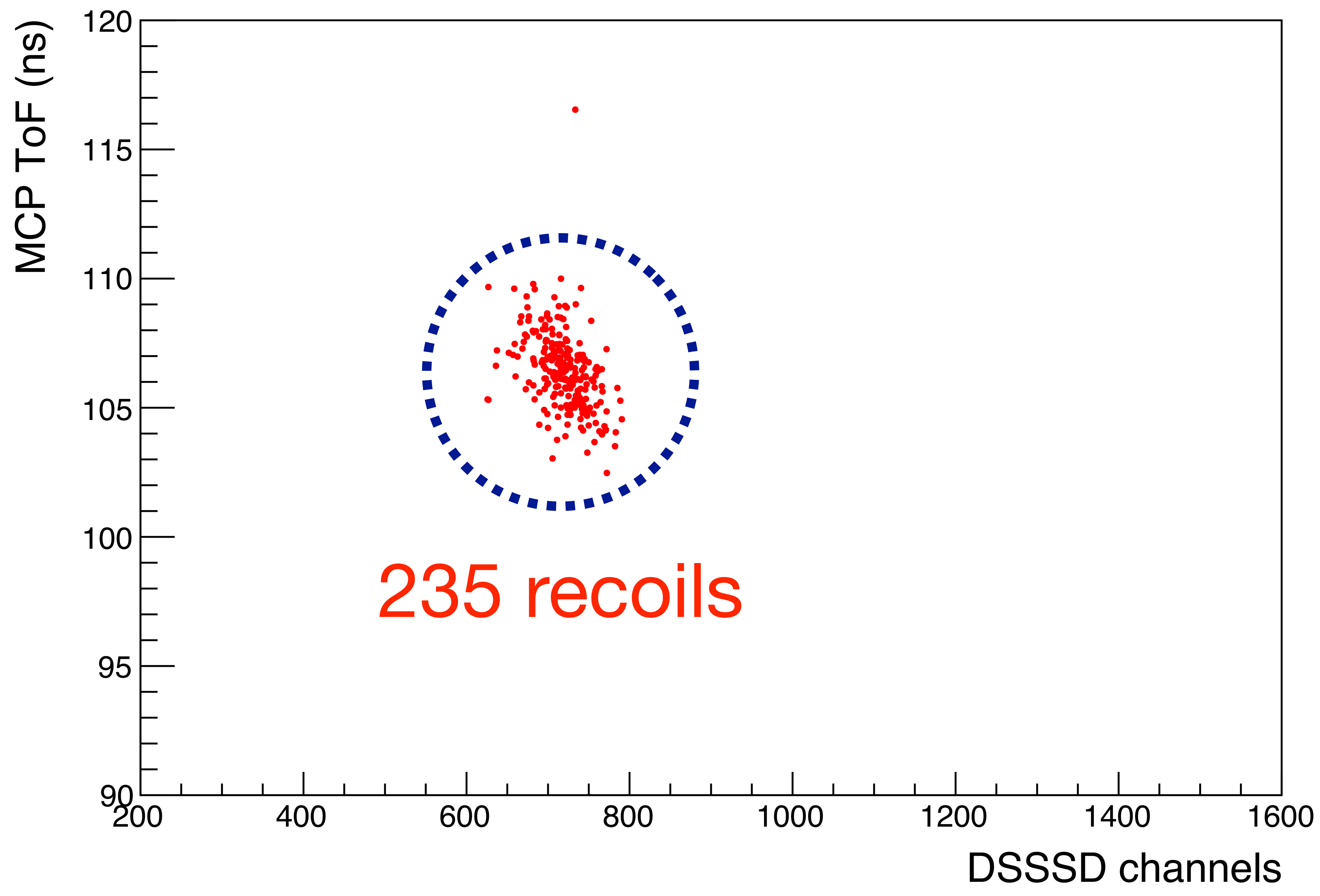


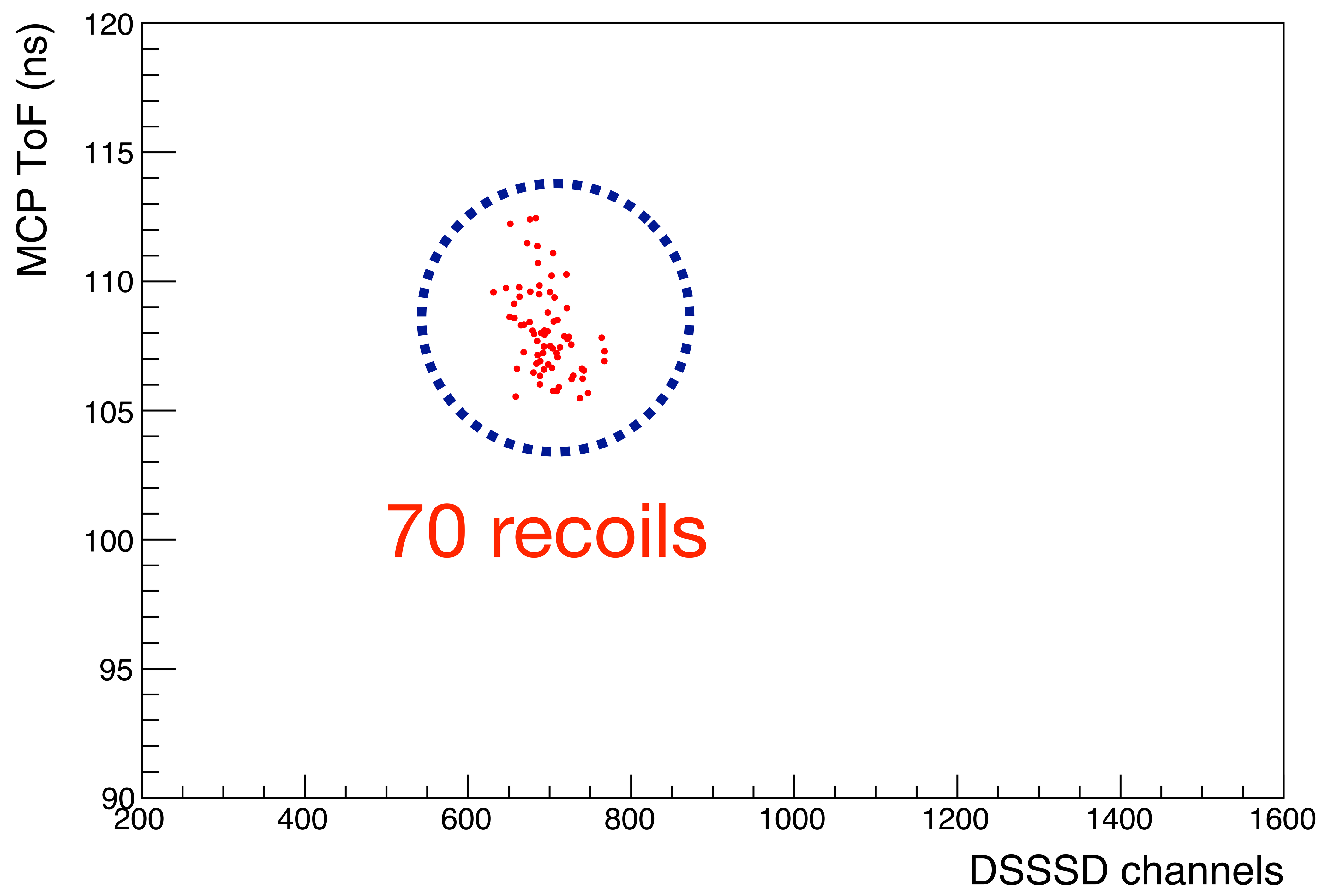


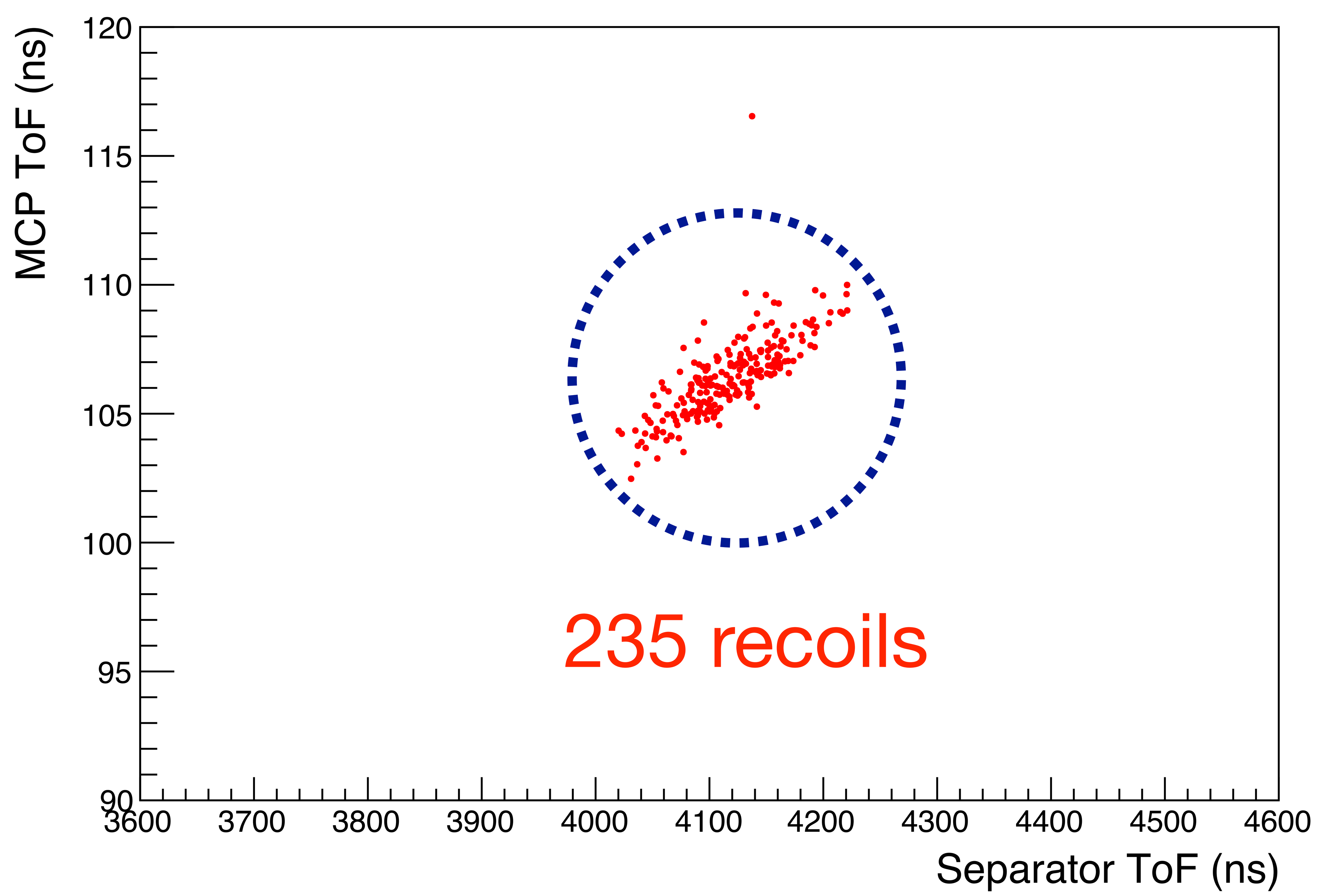
E_r = 628 keV

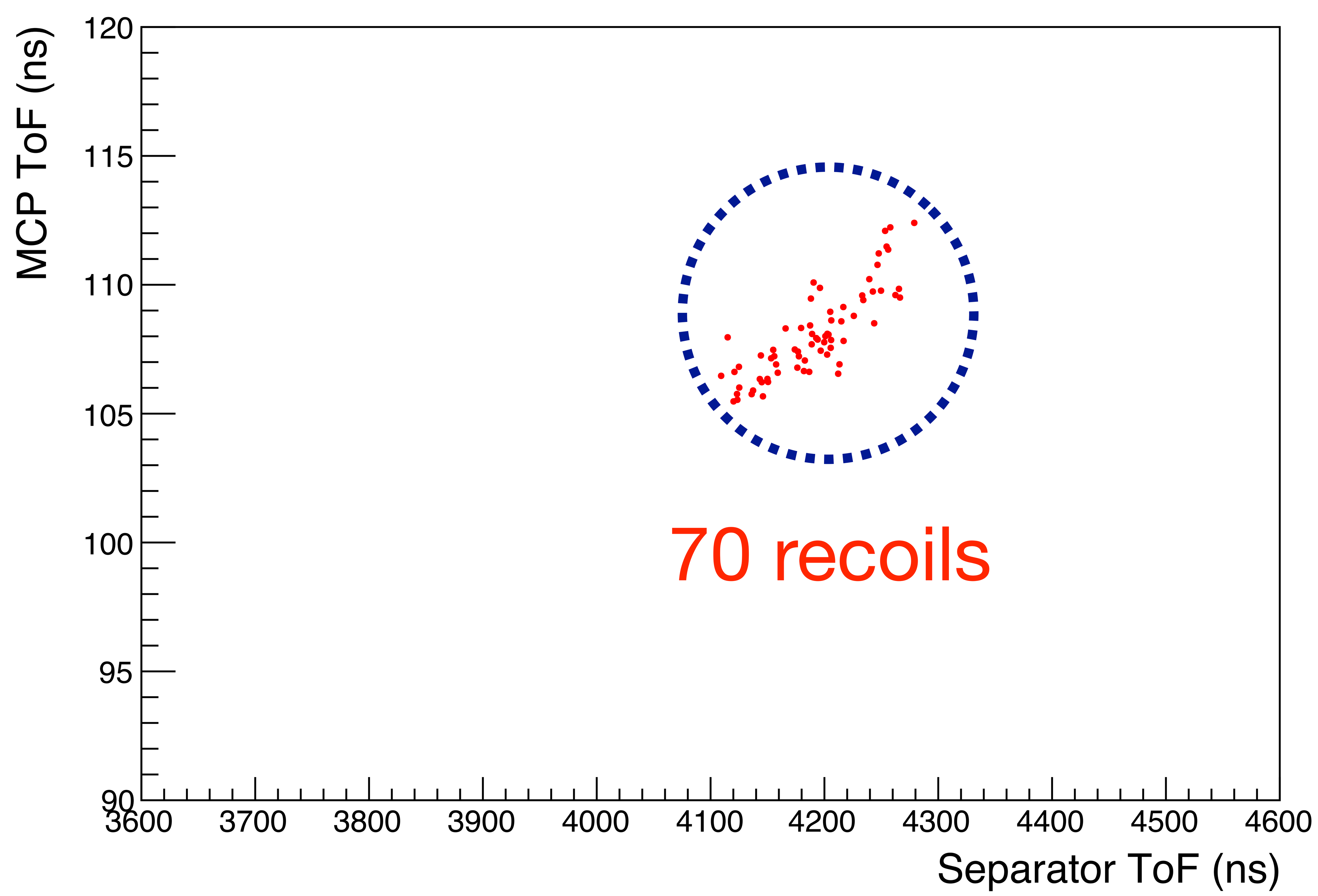
Preliminary

E_r = 613 keV



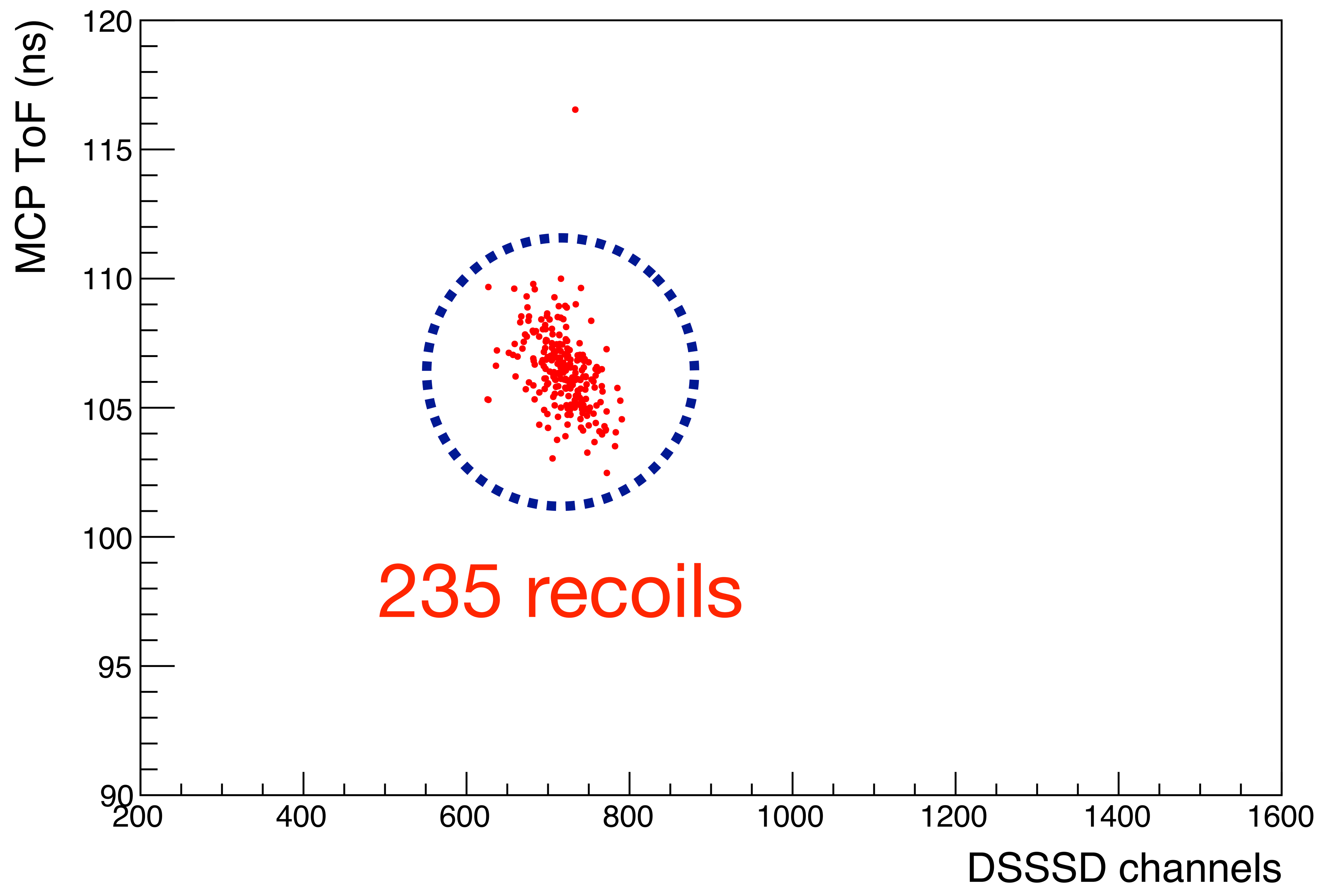


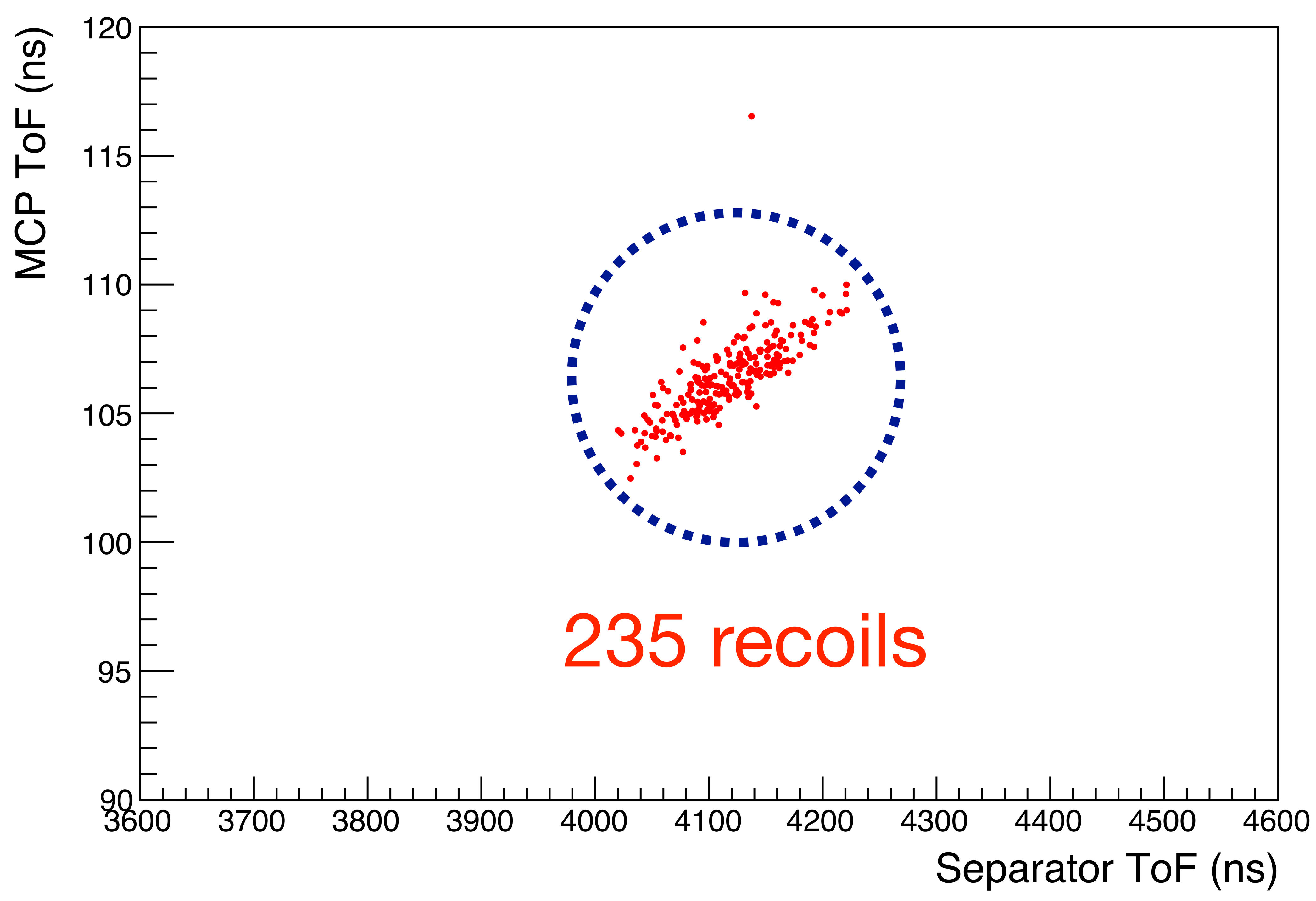




E_r = 628 keV

Preliminary





Recoil yield

↓

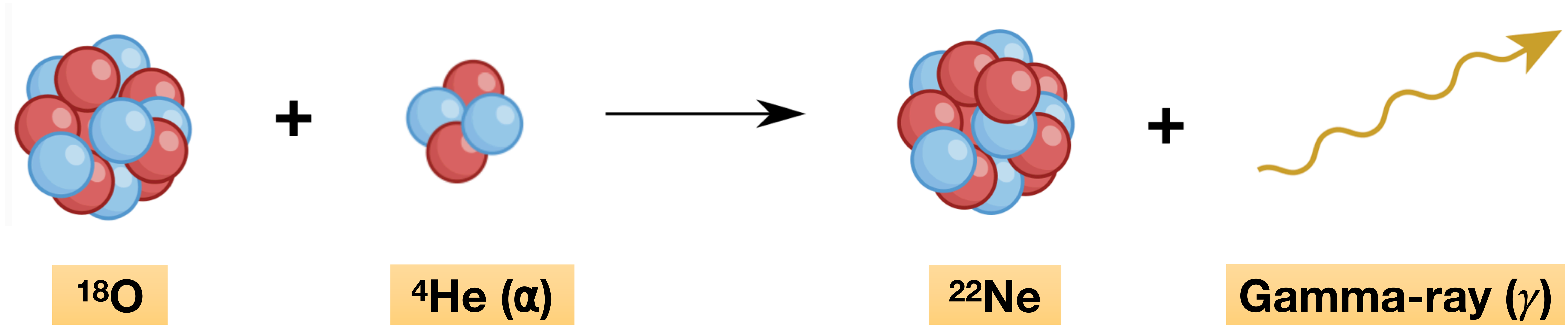
Resonance strength

↓

Reaction rate

(Compare to current literature)

Summary



- First inverse kinematics measurement of $^{18}O(\alpha, \gamma)^{22}Ne$
- Preliminary results with recoil yield
- Determine resonance strengths and energies
- Calculate the thermonuclear reaction rate

Acknowledgments:

Dr. Alan Chen
(McMaster)

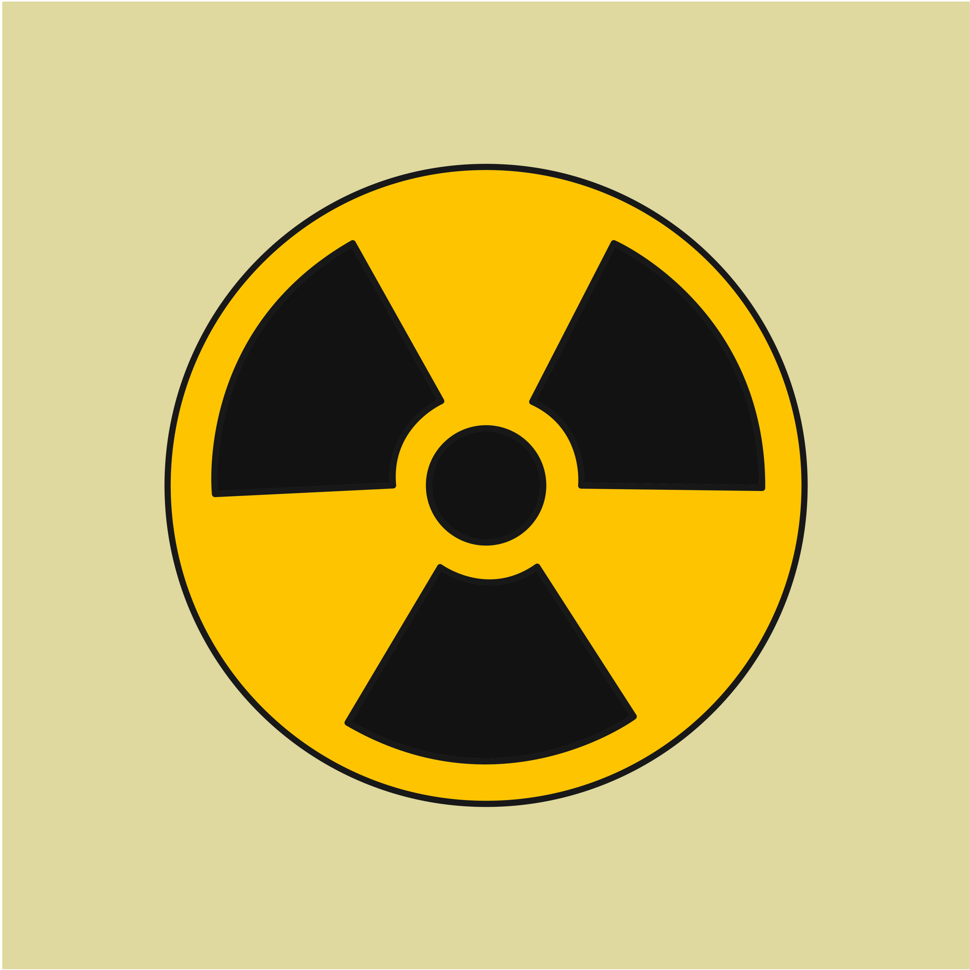
Dr. Thanassis Psaltis
(Saint Mary's)

Dr. Annika Lennarz
(TRIUMF/McMaster)

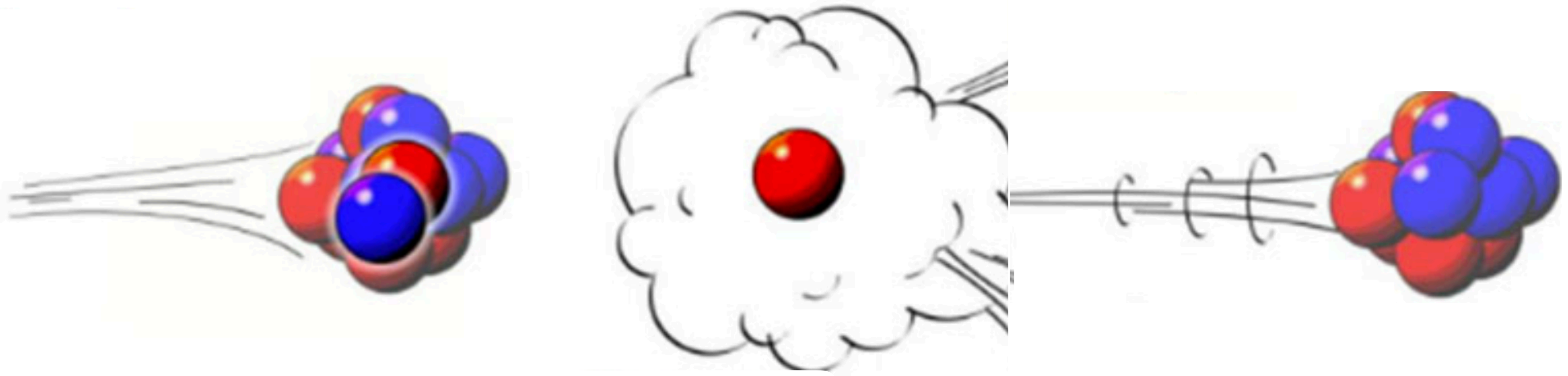
DRAGON collaboration

Backup slides

Inverse kinematics



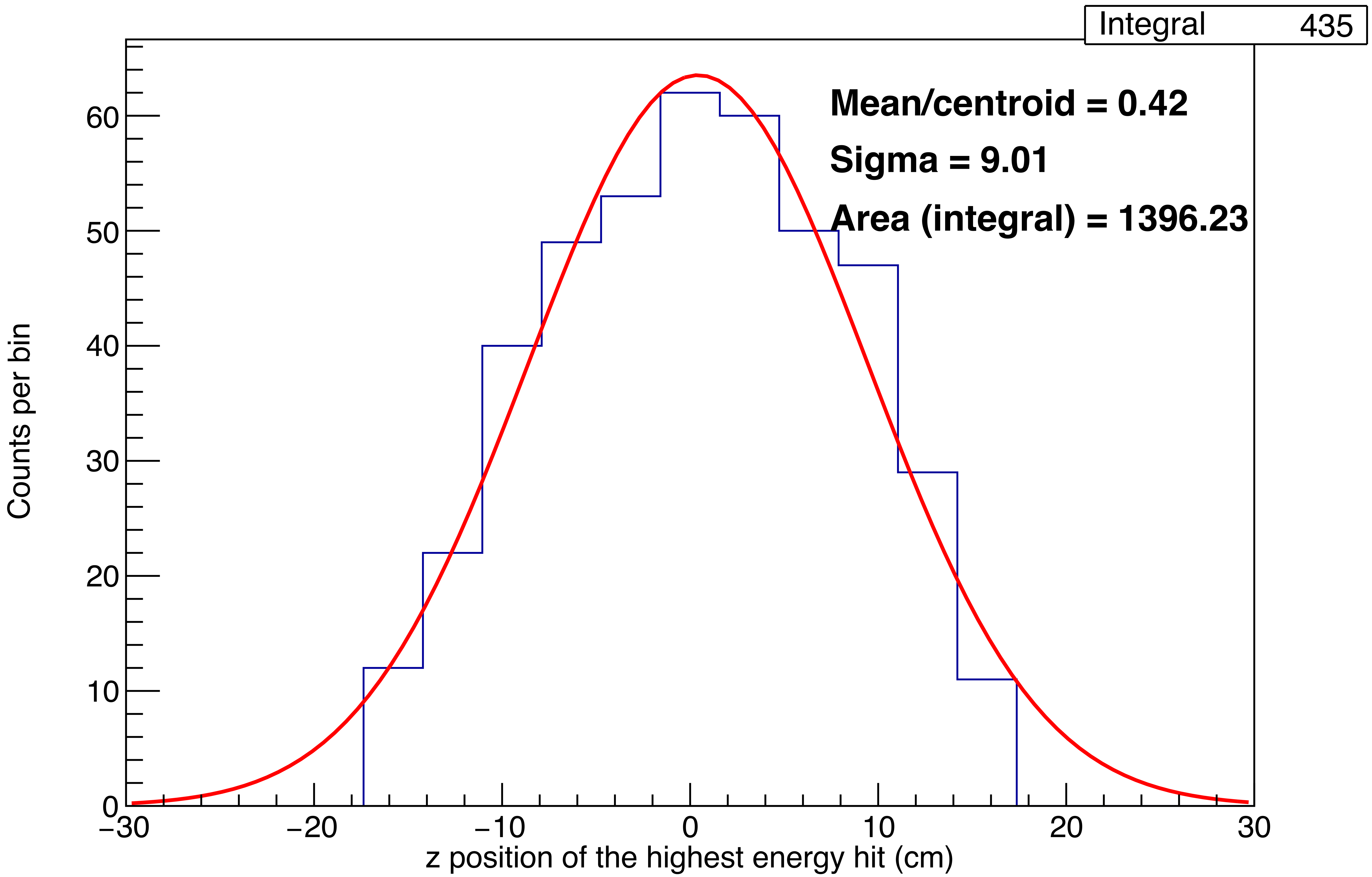
- Heavy radioactive beam on light target
- Challenging to make radioactive targets!



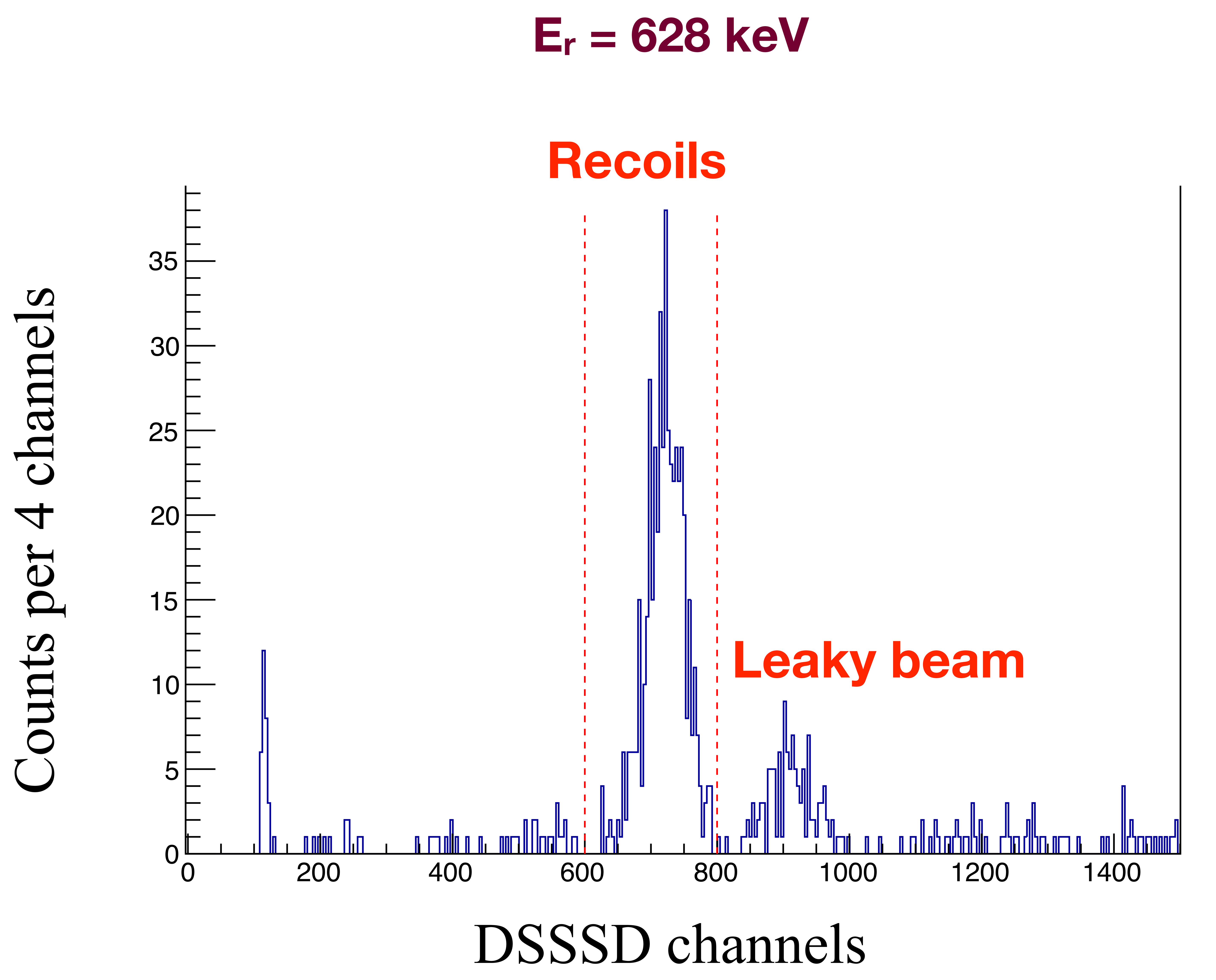
Beam **Target**

Forward focused recoils

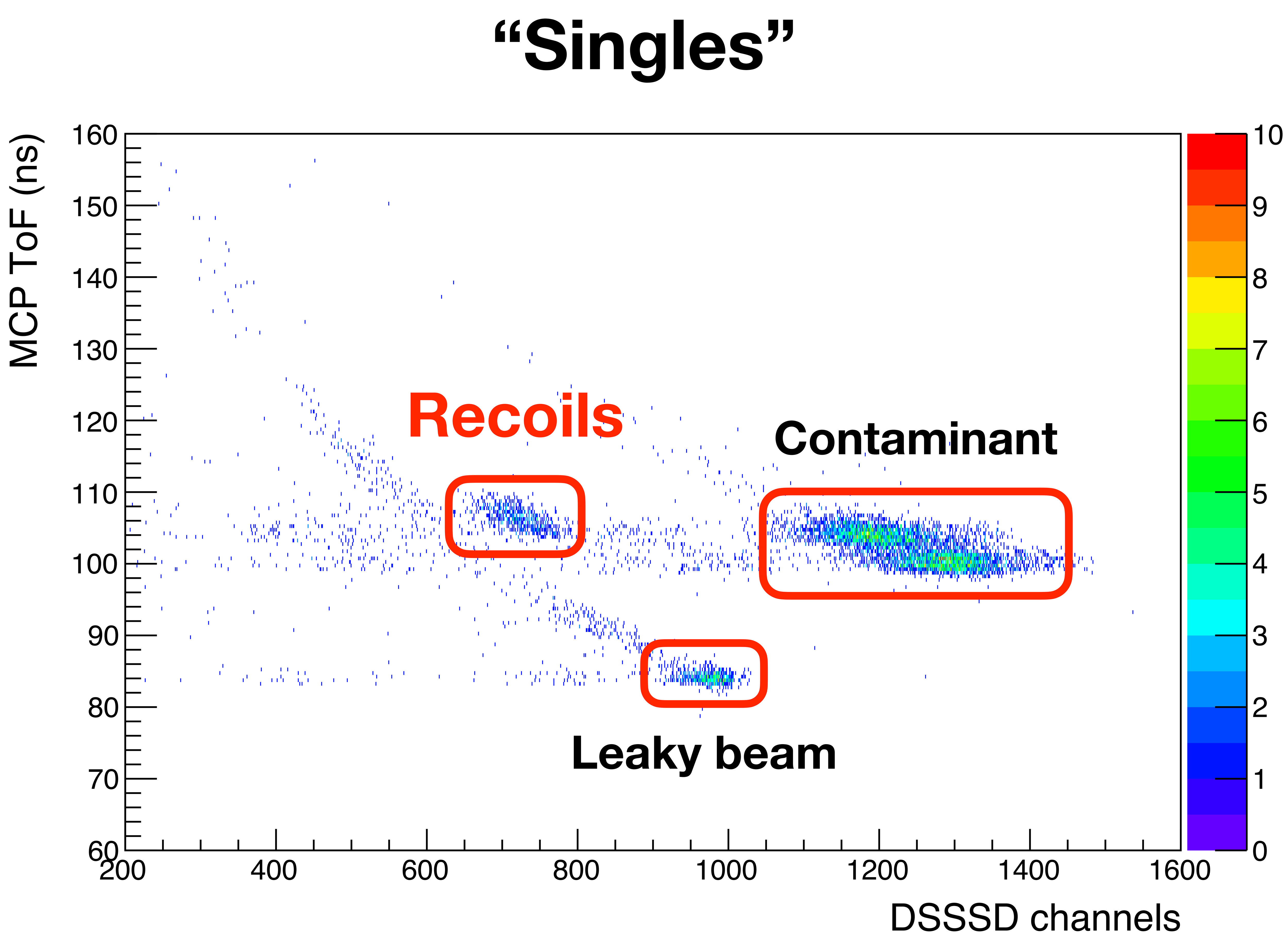
BGO z-distribution for determining the resonance energy



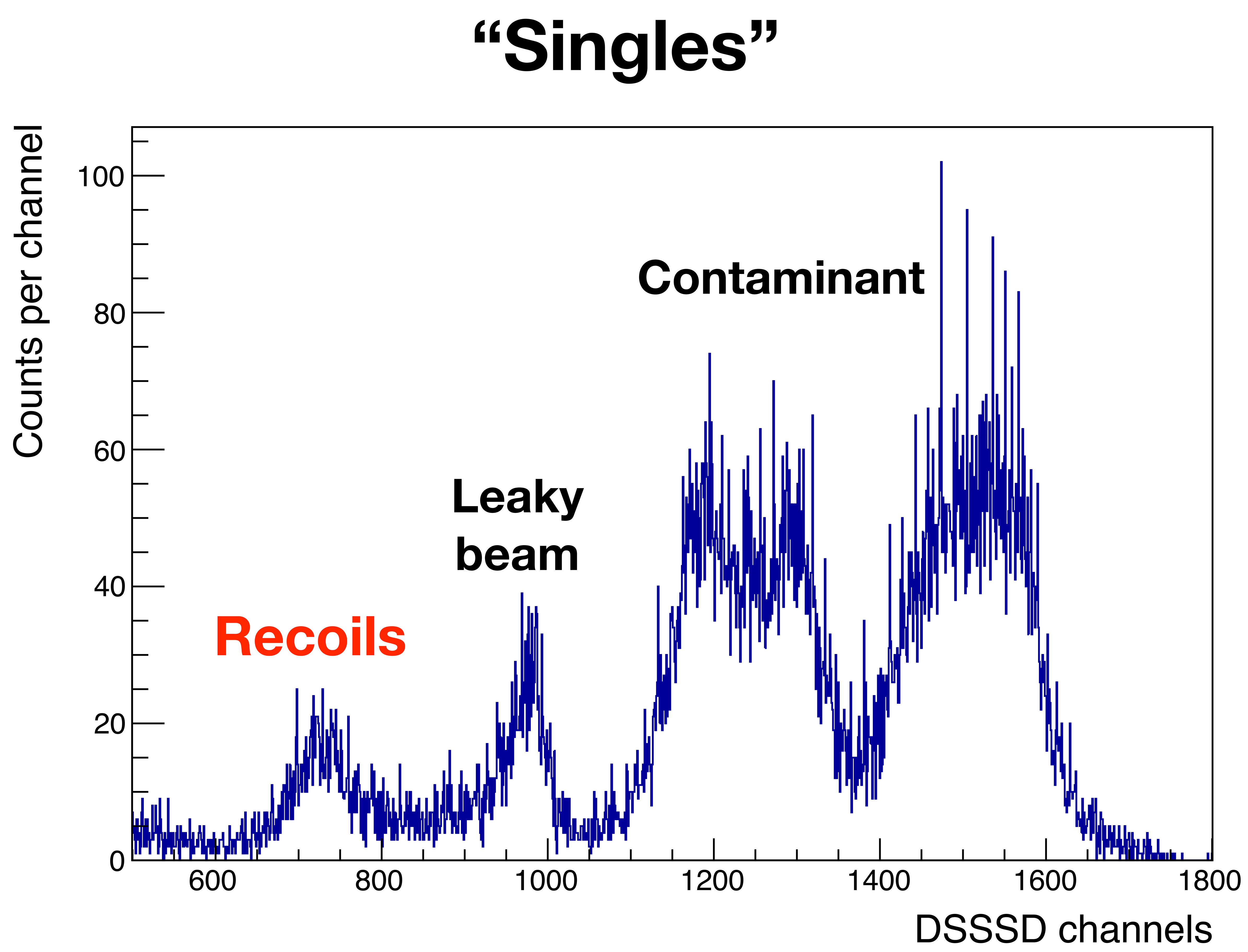
DSSSD coincidences



E_r = 628 keV

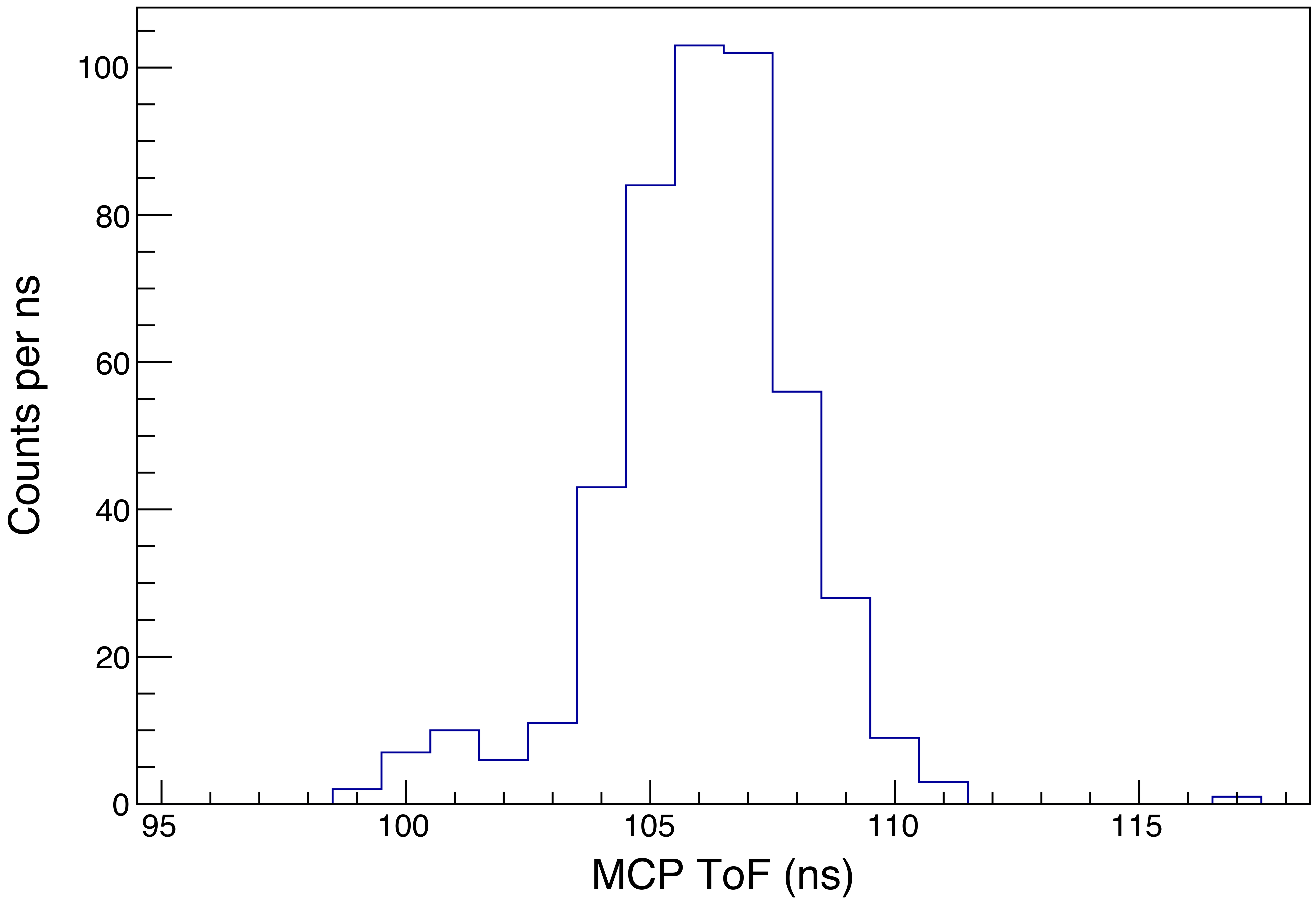


"Singles"
MCP ToF (ns)
160
150
140
130
120
110
100
90
80
70
60
200
400
600
800
1000
1200
1400
1600
DSSSD channels
10
9
8
7
6
5
4
3
2
1
0
Recoils
Contaminant
Leaky beam

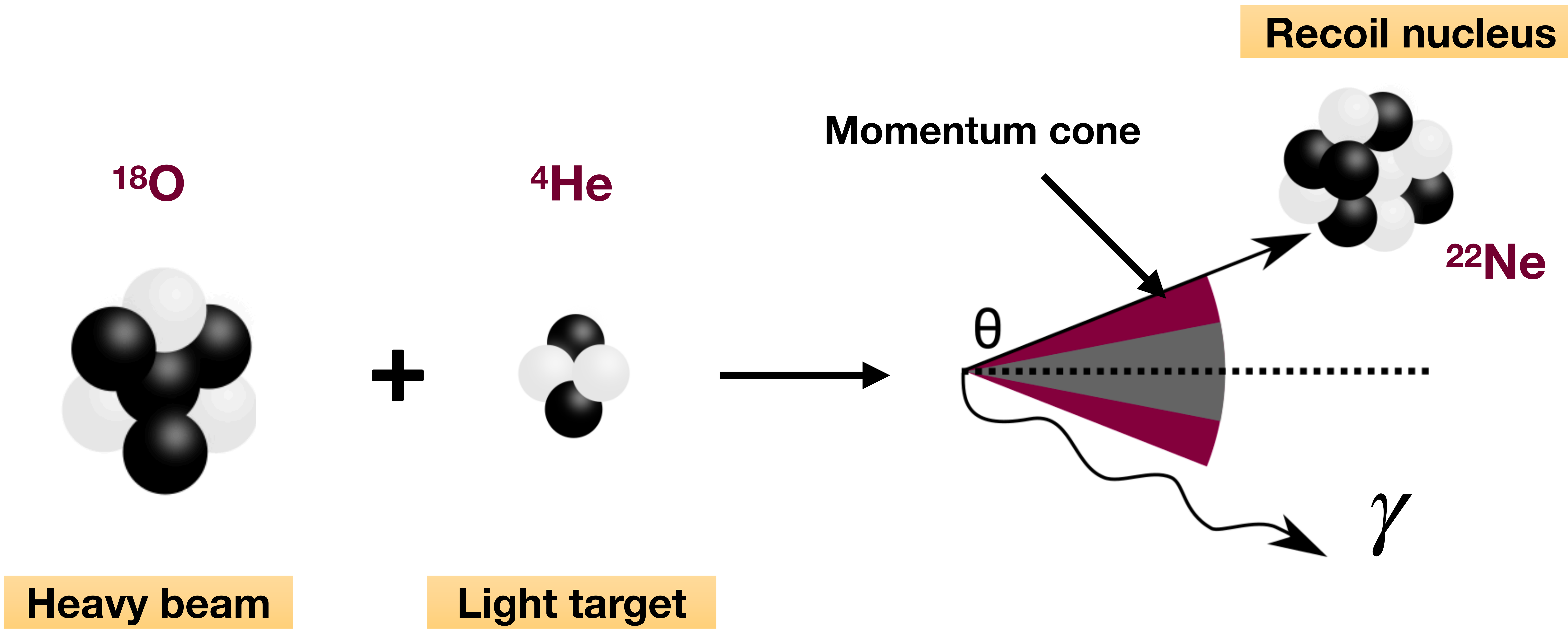


"Singles"
Counts per channel
100
80
60
40
20
0
600
800
1000
1200
1400
1600
1800
DSSSD channels
Contaminant
Leaky
beam
Recoils

Local time of flight for E_r = 628 keV



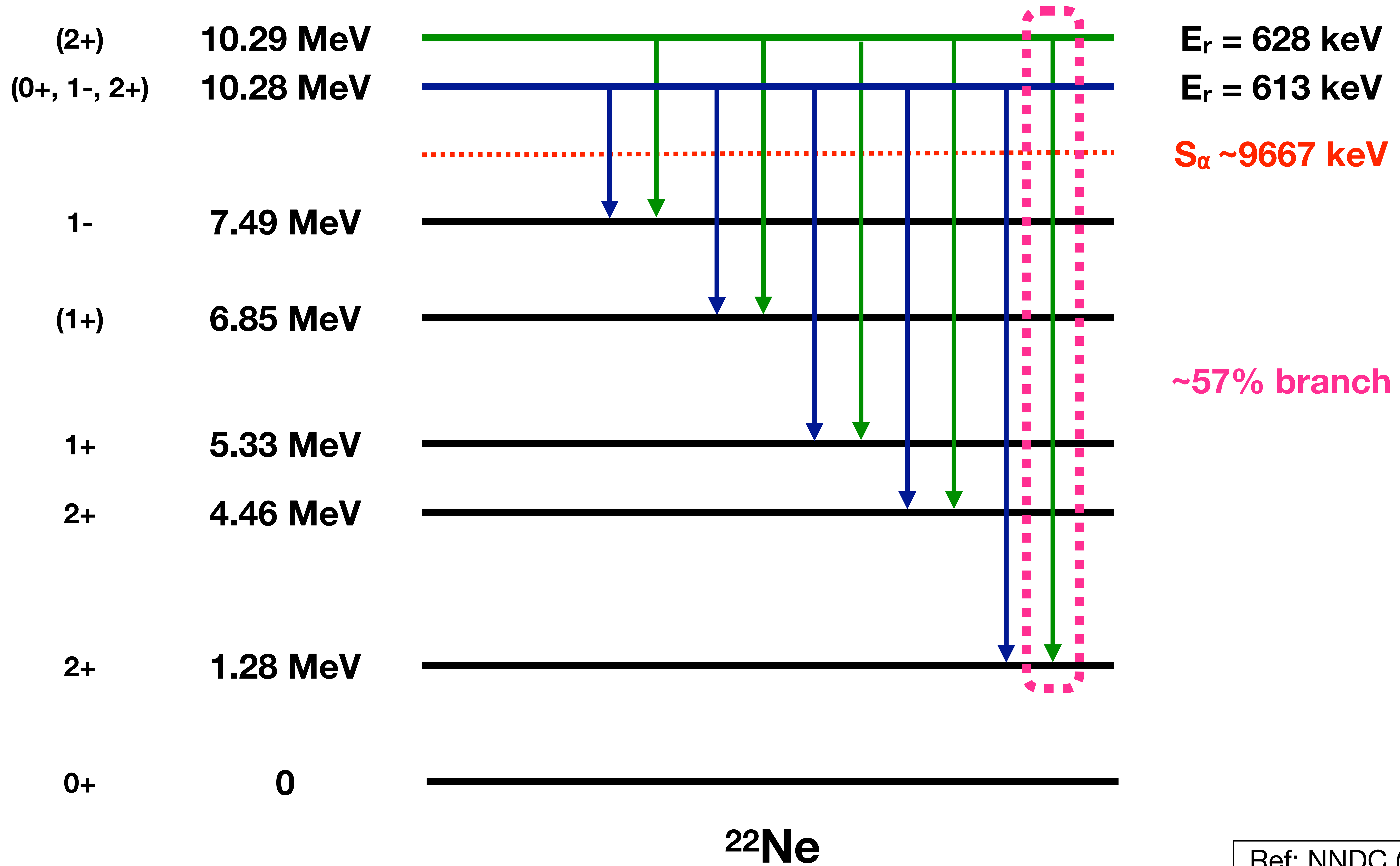
Recoil cone angle



DRAGON acceptance: θ ~ 21 mrad

$^{18}O(\alpha, \gamma)^{22}Ne$: θ_{max} ~ 30 mrad

Gamma-decay from resonance states

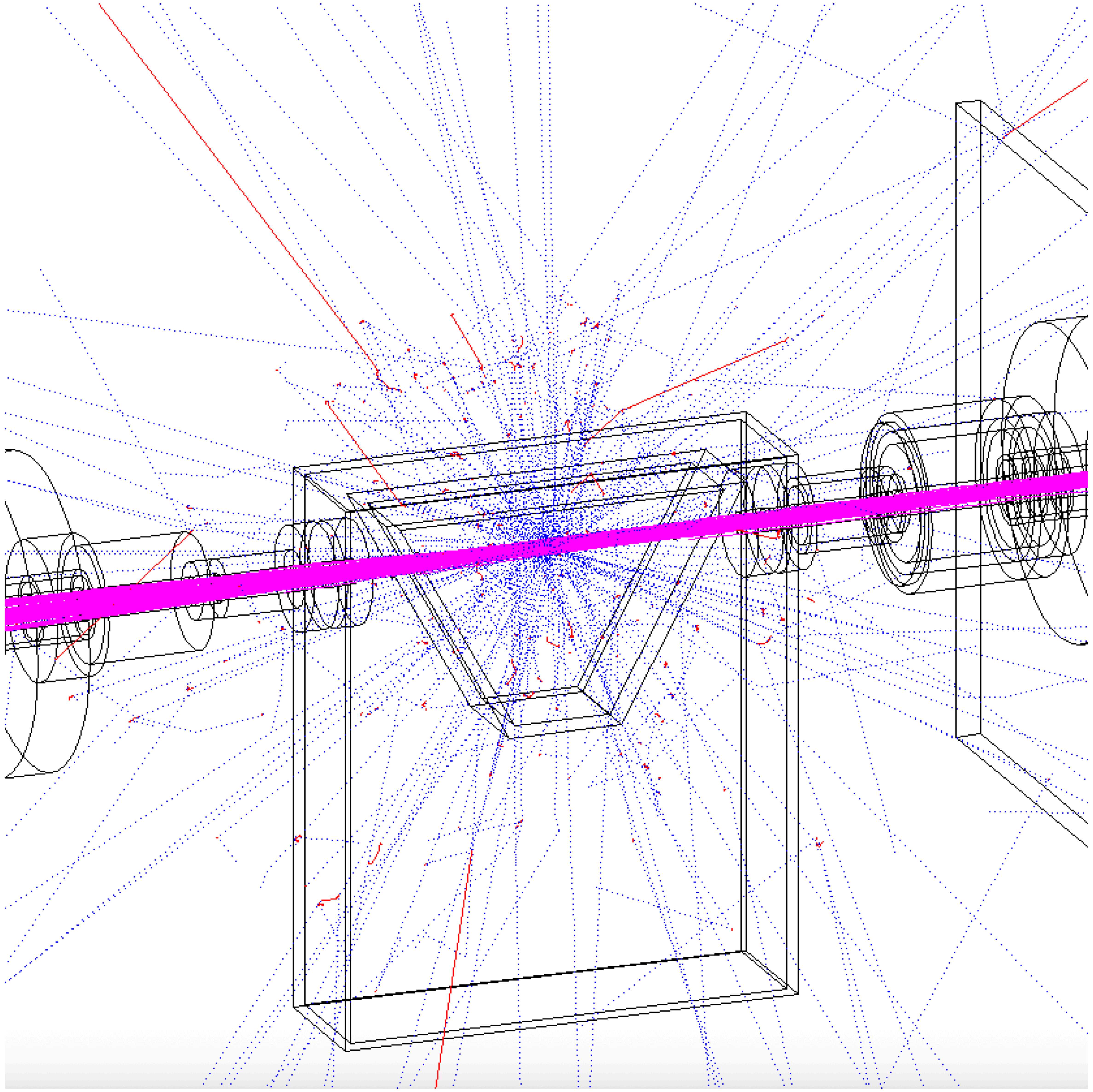


Ref: NNDC (ENSDF)

GEANT simulations: Systematic uncertainties

Need to find out:

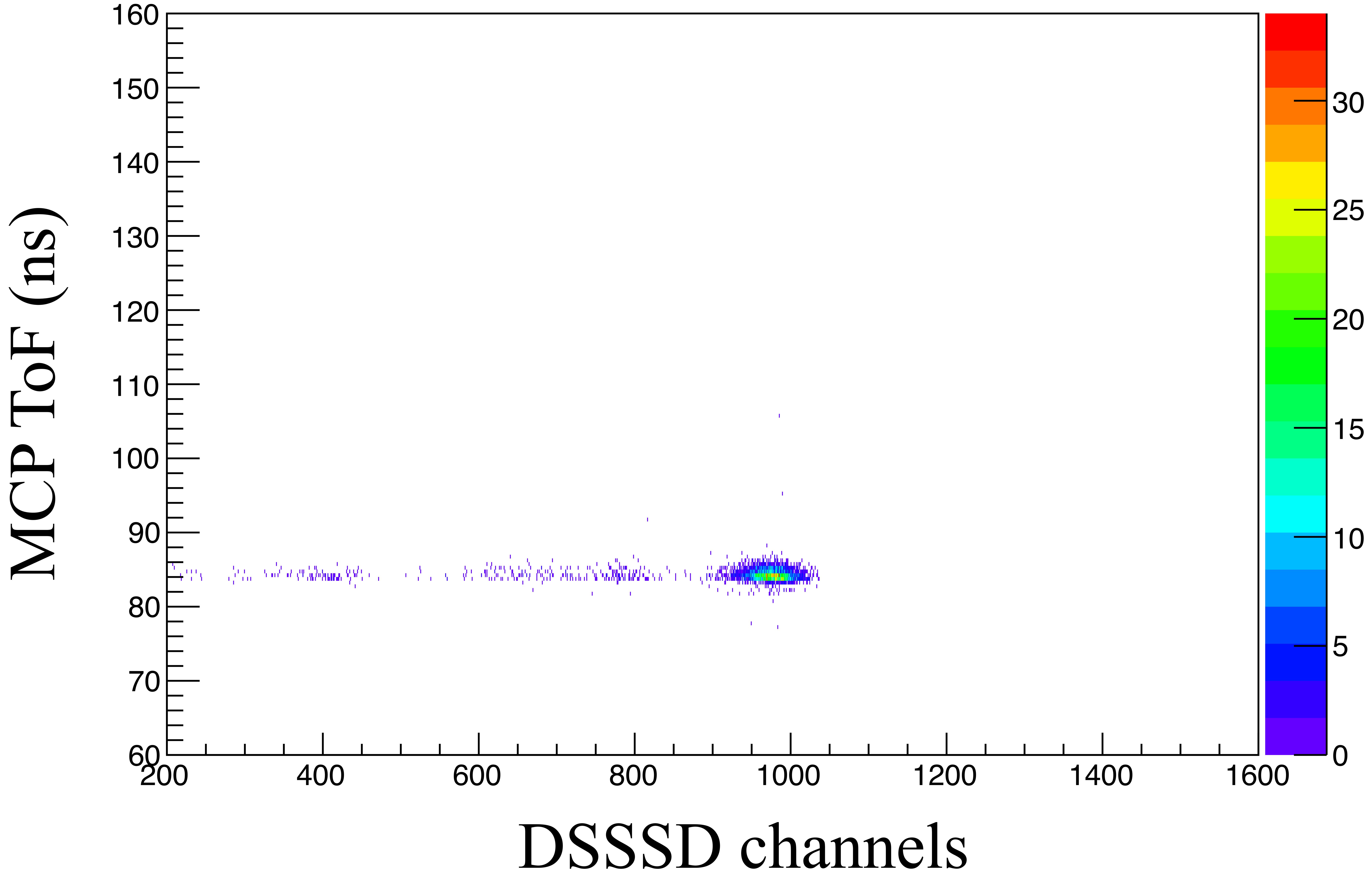
1. **Separator transmission**
2. **BGO efficiencies**



DRAGON gas target: 100 simulated events

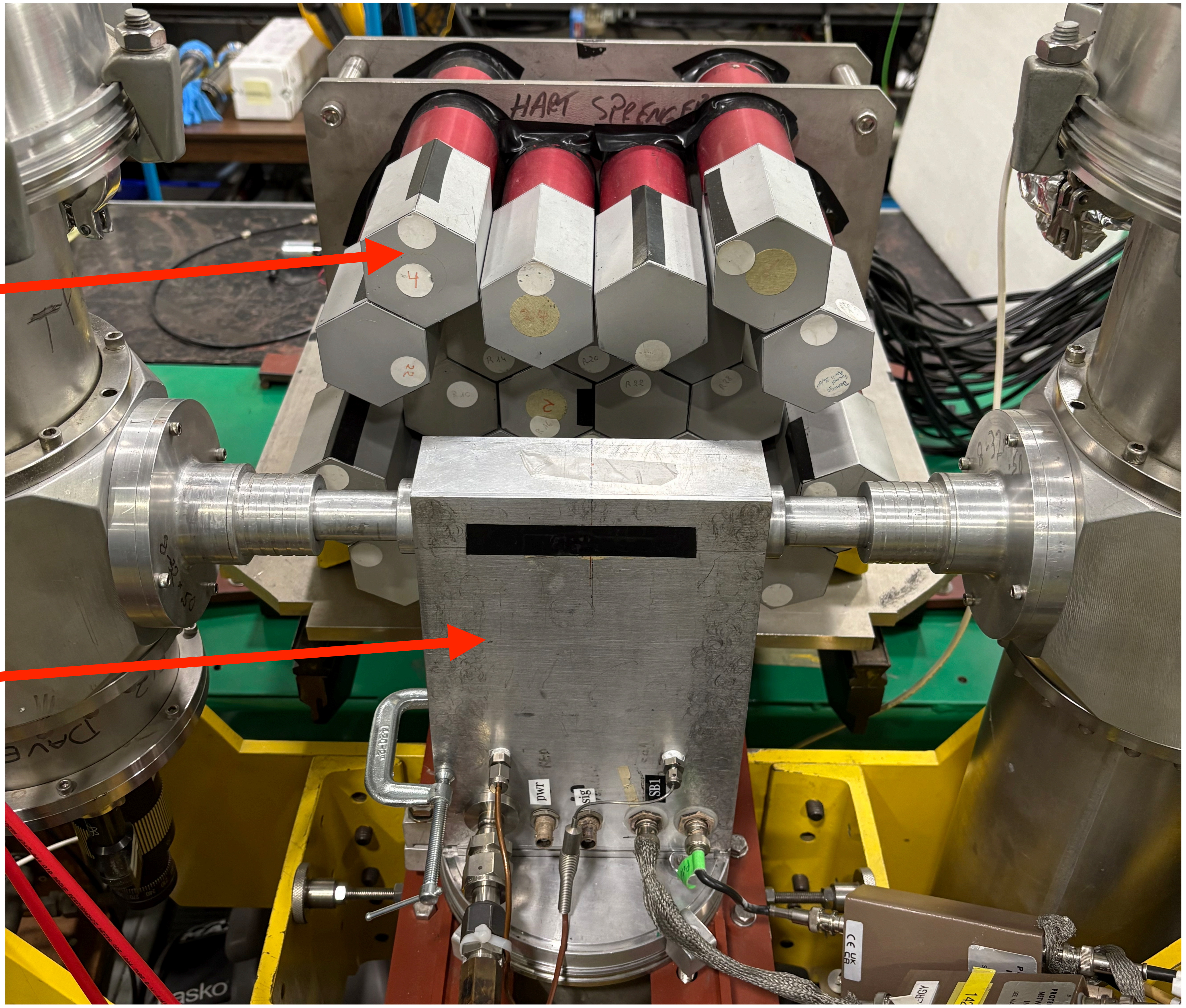
Attenuated beam run

E_r = 628 keV



BGO array for gamma-rays

Windowless gas target (^4He)




DRAGON
recreates the nuclear reactions
that occur inside exploding stars
TRIUMF | DRAGO
How and where
were the universe
elements created

s-process: Neutron source

- Thermal pulse from the He-rich shell raises the temperature (in AGB stars)
- ^{14}N build up from the CNO cycles is used (in massive stars)
- Initiates the following reaction sequence in both sites:

$$^{14}N(\alpha, \gamma)^{18}F \rightarrow {}^{18}F(\beta^{+} \nu)^{18}O \rightarrow {}^{18}O(\alpha, \gamma)^{22}Ne \rightarrow {}^{22}Ne(\alpha, n)^{25}Mg$$

Neutron source

Ref: Annu. Rev. Nucl. Part. Sci. 2023. 73:315–40